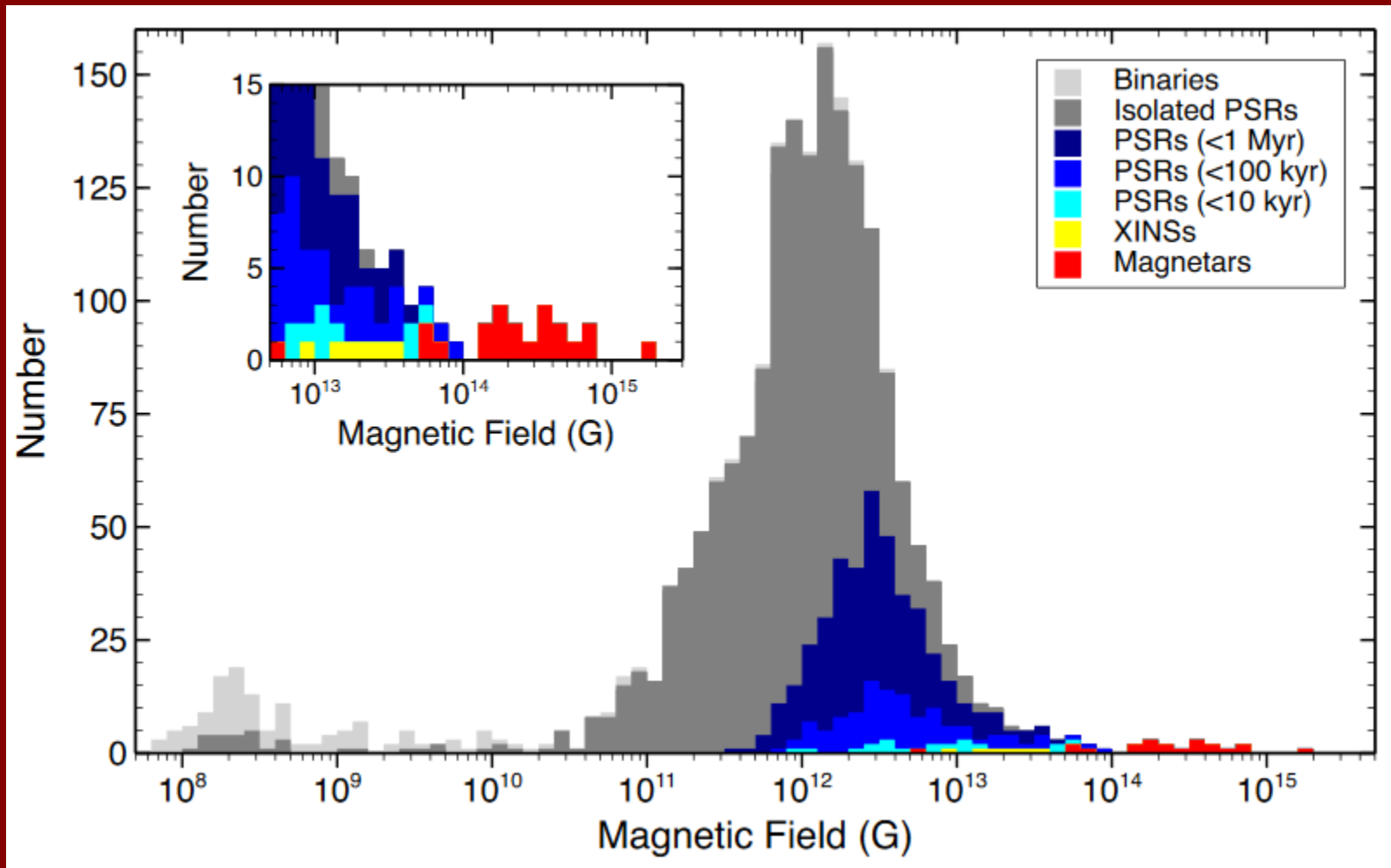


Magnetars: SGRs and AXPs

Magnetic field distribution



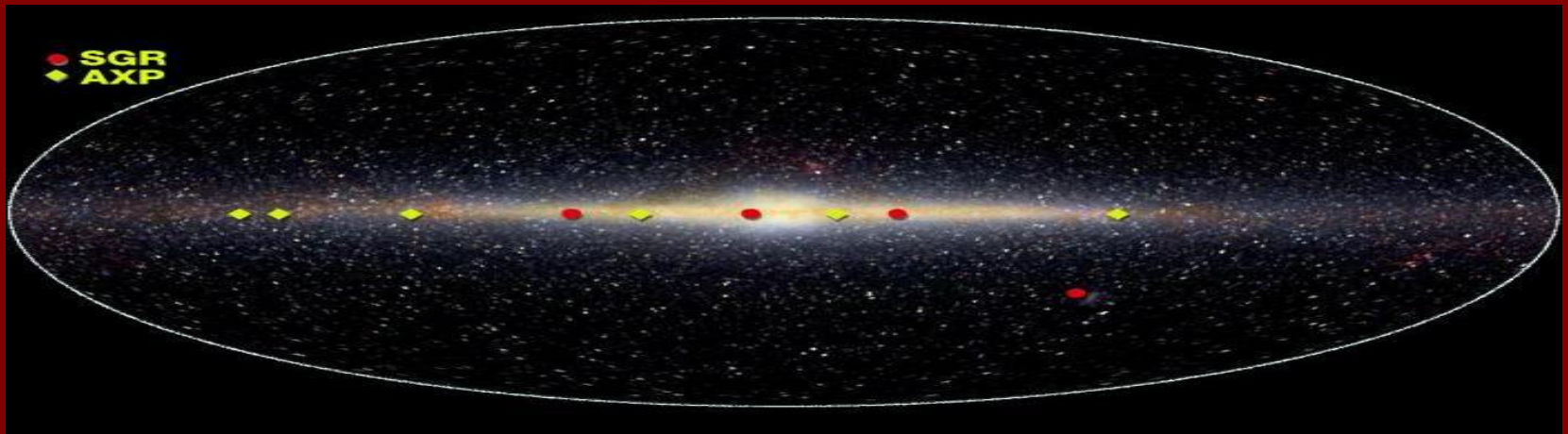
Fields from P-Pdot using magneto-dipole formula

1805.01680 (taken from Olausen, Kaspi 2014)

Magnetars in the Galaxy

- ~24 SGRs and AXPs, plus 6 candidates, plus radio pulsars with high magnetic fields (about them see arXiv: 1010.4592)...
- Young objects (about 10^3 - 10^5 year).

Catalogue: <http://www.physics.mcgill.ca/~pulsar/magnetar/main.html>



(see a recent review in arXiv:1503.06313 and the catalogue description in 1309.4167)

Birth rate of magnetars

Fraction of magnetars among NSs is uncertain.

Typically, the value $\sim 10\%$ is quoted (e.g. 0910.2190).
This is supported observationally and theoretically.

Recent modeling favours somehow larger values: 1903.06718.
However, the result is model dependent.
In particular, it depends on the model of field decay.

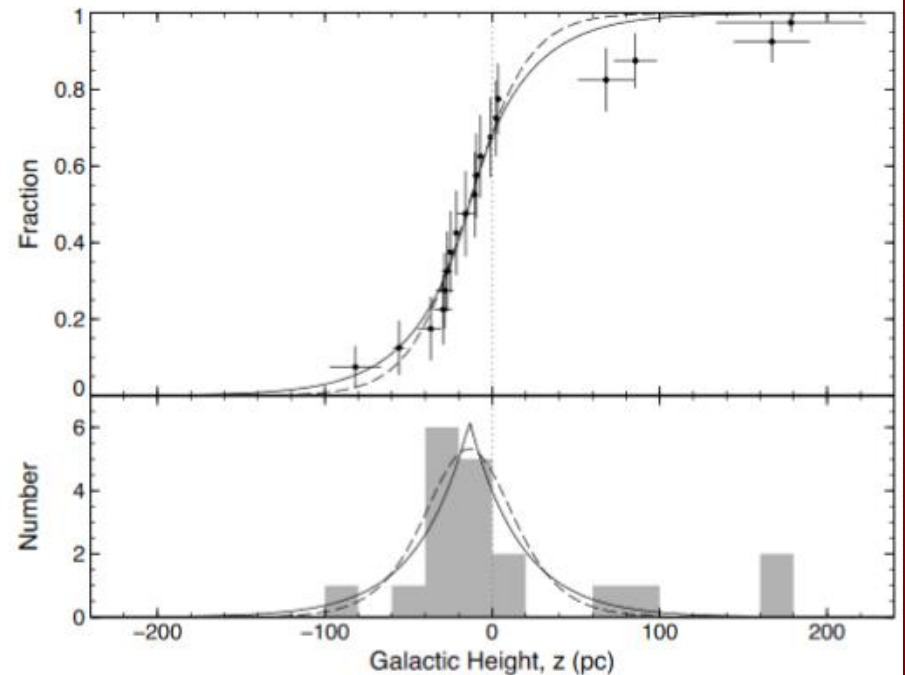
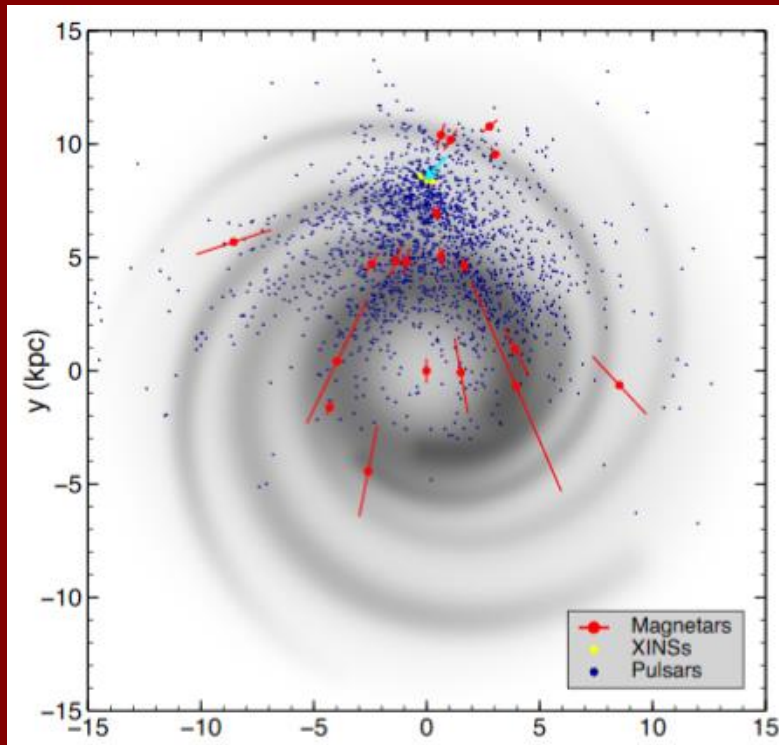
Several of magnetars
are related to SNRs.

Many of magnetars
show glitches.

Name ^b	P (s)	B^c (10^{14} G)	Age ^d (kyr)	$\dot{E}^e$ 10^{33} erg s ⁻¹	D^f (kpc)	L_X^g 10^{33} erg s ⁻¹	Band ^h
CXOU J010043.1-721134	8.02	3.9	6.8	1.4	62.4	65	...
4U 0142+61	8.69	1.3	68	0.12	3.6	105	OIR/H
SGR 0418+5729	9.08	0.06	36000	0.00021	~2	0.00096	...
SGR 0501+4516	5.76	1.9	15	1.2	~2	0.81	OIR/H
SGR 0526-66	8.05	5.6	3.4	2.9	53.6	189	...
1E 1048.1-5937	6.46	3.9	4.5	3.3	9.0	49	OIR
(PSR J1119-6127)	0.41	4.1	1.6	2300	8.4	0.2	R/H
1E 1547.0-5408	2.07	3.2	0.69	210	4.5	1.3	O?/R/H
PSR J1622-4950	4.33	2.7	4.0	8.3	~9	0.4	R
SGR 1627-41	2.59	2.2	2.2	43	11	3.6	...
CXOU J164710.2-455216	10.6	<0.66	>420	<0.013	3.9	0.45	...
1RXS J170849.0-400910	11.01	4.7	9.0	0.58	3.8	42	O?/H
CXOU J171405.7-381031	3.82	5.0	0.95	45	~13	56	...
SGR J1745-2900	3.76	2.3	4.3	10	8.3	<0.11	R/H
SGR 1806-20	7.55	20	0.24	45	8.7	163	OIR/H
XTE J1810-197	5.54	2.1	11	1.8	3.5	0.043	OIR/R
Swift J1822.3-1606	8.44	0.14	6300	0.0014	1.6	>0.0004	...
SGR 1833-0832	7.56	1.6	34	0.32	...	...	...
Swift J1834.9-0846	2.48	1.4	4.9	21	4.2	<0.0084	...
1E 1841-045	11.79	7.0	4.6	0.99	8.5	184	...
(PSR J1846-0258)	0.327	0.49	0.73	8100	6.0	19	...
3XMM J185246.6+003317	11.56	< 0.41	> 1300	< 0.0036	~7	< 0.006	...
SGR 1900+14	5.20	7.0	0.9	26	12.5	90	H
SGR 1935+2154	3.24	2.2	3.6	17	...	...	...
1E 2259+586	6.98	0.59	230	0.056	3.2	17	OIR/H
<i>SGR 0755-2933</i>	...	...	...	...	...	...	...
<i>SGR 1801-23</i>	...	...	...	...	...	...	...
<i>SGR 1808-20</i>	...	...	...	...	...	...	...
<i>AX J1818.8-1559</i>	...	...	...	...	...	...	...
<i>AX J1845.0-0258</i>	6.97	...	...	...	...	2.9	...
<i>SGR 2013+34</i>	...	...	...	...	...	...	...

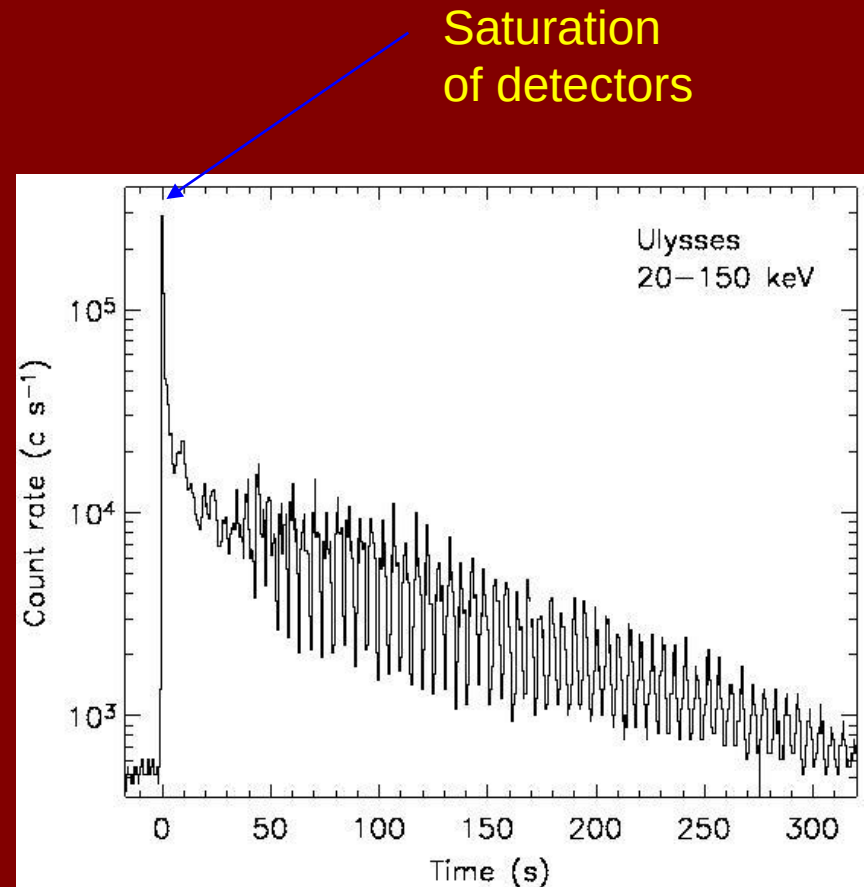
Spatial distribution

Scale height ~ 20 pc



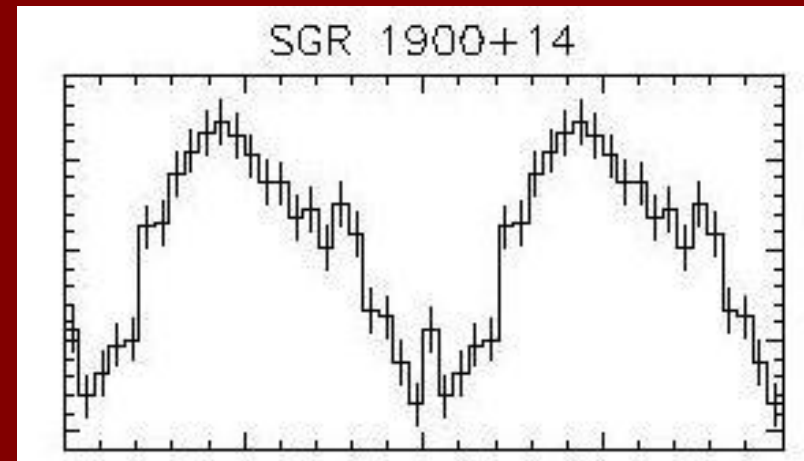
Soft Gamma Repeaters: main properties

- Energetic “Giant Flares” (GFs, $L \approx 10^{45}$ - 10^{47} erg/s) detected from 3 (4?) sources
- No evidence for a binary companion, association with a SNR at least in one case
- Persistent X-ray emitters, $L \approx 10^{35}$ - 10^{36} erg/s
- Pulsations discovered both in GFs tails and persistent emission, $P \approx 5$ -10 s
- Huge spindown rates, $\dot{P}/P \approx 10^{-10} \text{ s}^{-1}$



SGRs: periods and giant flares

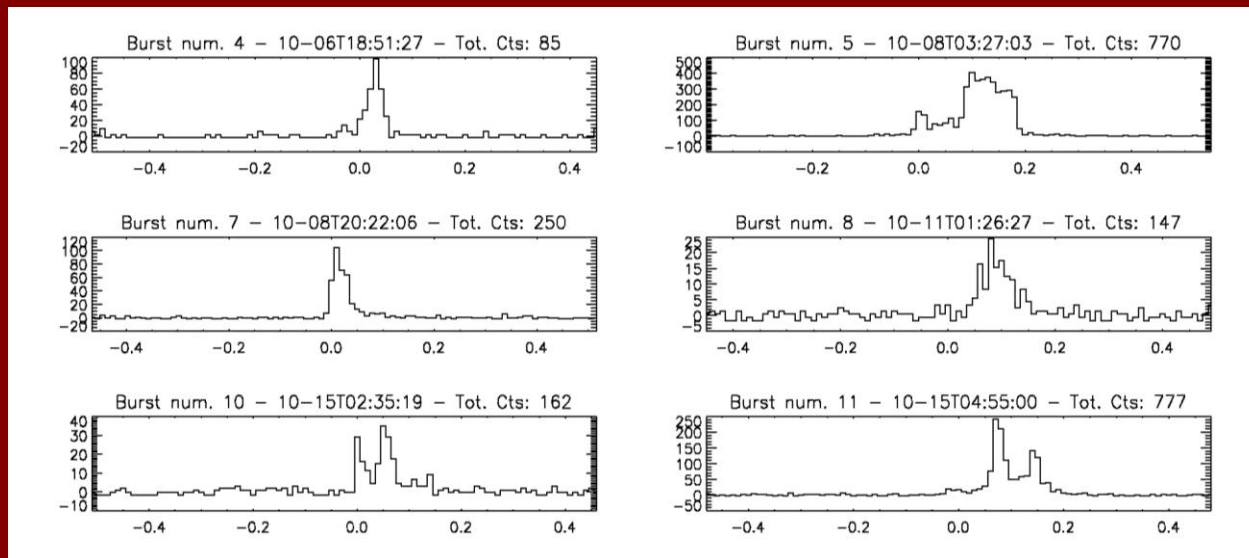
	P, s	Giant flares
■ 0526-66	8.0	5 March 1979
■ 1627-41	2.6	18 June 1998 (?)
■ 1806-20	7.5	27 Dec 2004
■ 1900+14	5.2	27 Aug 1998



See reviews in Turolla et al. arXiv: 1507.02924
Beloborodov, Kaspi arXiv: 1703.00068

Soft Gamma Repeaters

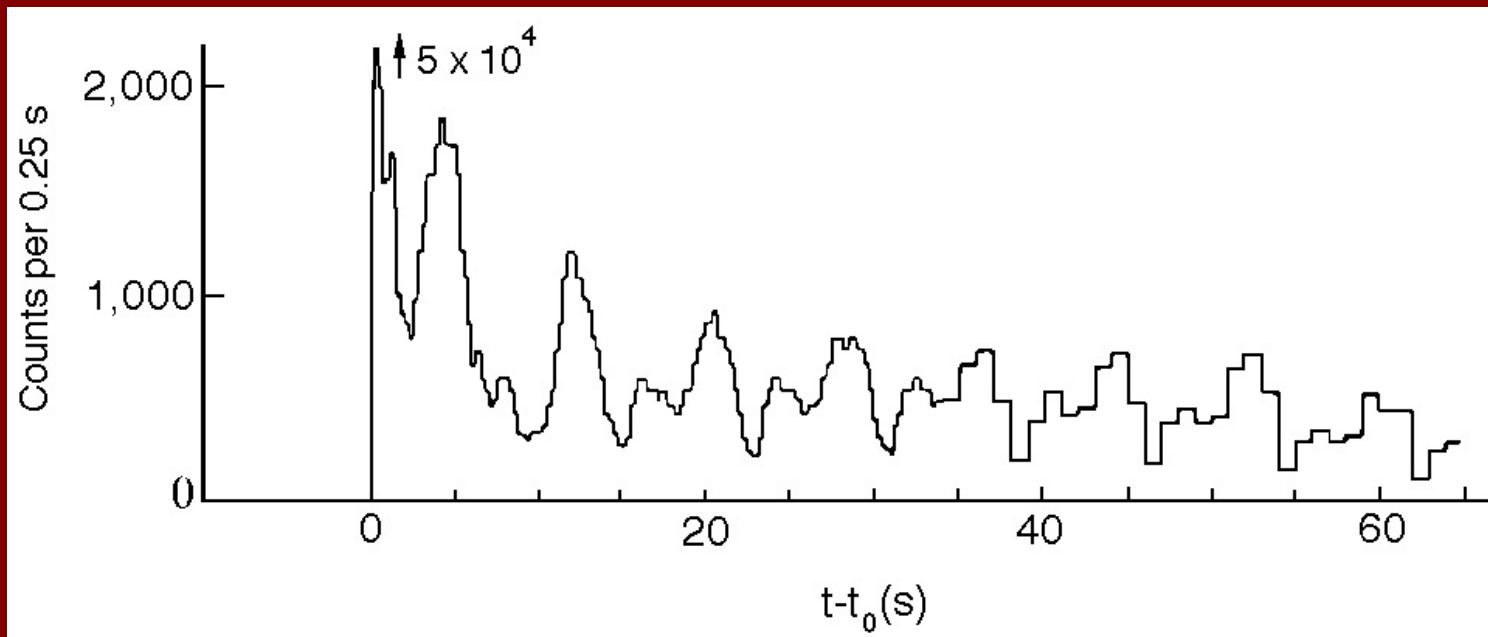
- Rare class of sources, ~12 confirmed
- Frequent bursts of soft γ -/hard X-rays:
 $L < 10^{42}$ erg/s, duration < 1 s



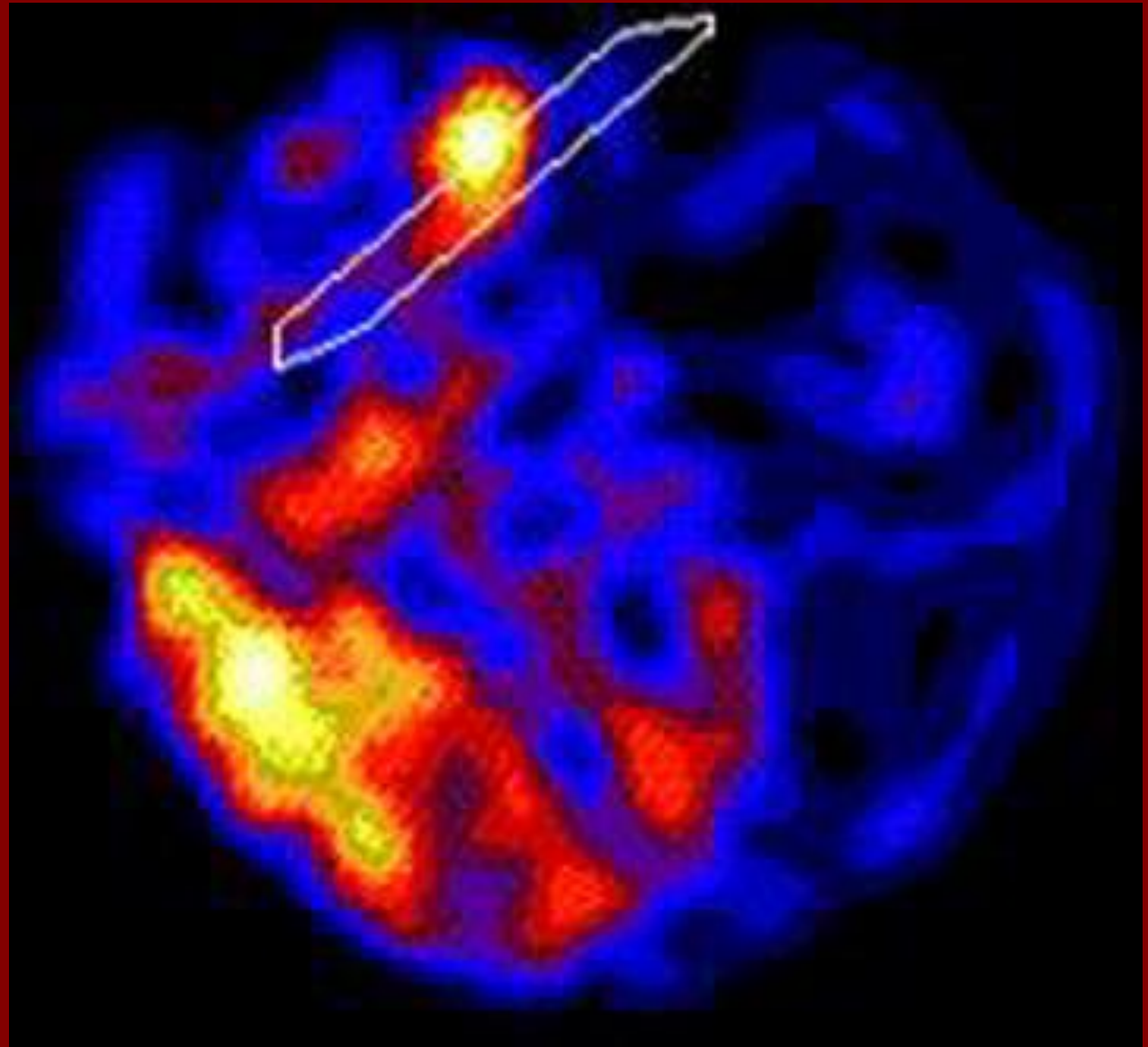
Bursts from SGR 1806-20 (INTEGRAL/IBIS, Götz et al 2004)

Historical notes

- 05 March 1979. The "Konus" experiment & Co. Venera-11,12 (Mazets et al., Vedrenne et al.)
- Events in the LMC. SGR 0520-66.
- Fluence: about 10^{-3} erg/cm²



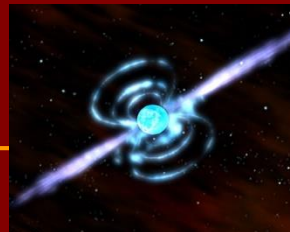
N49 – supernova
remnant in the
Large Magellanic
cloud
(e.g. G. Vedrenne
et al. 1979)



Main types of activity of SGRs

- Weak bursts. $L < 10^{42}$ erg/s
- Intermediate. $L \sim 10^{42} - 10^{43}$ erg/s
- Giant. $L < 10^{45}$ erg/s
- Hyperflares. $L > 10^{46}$ erg/s

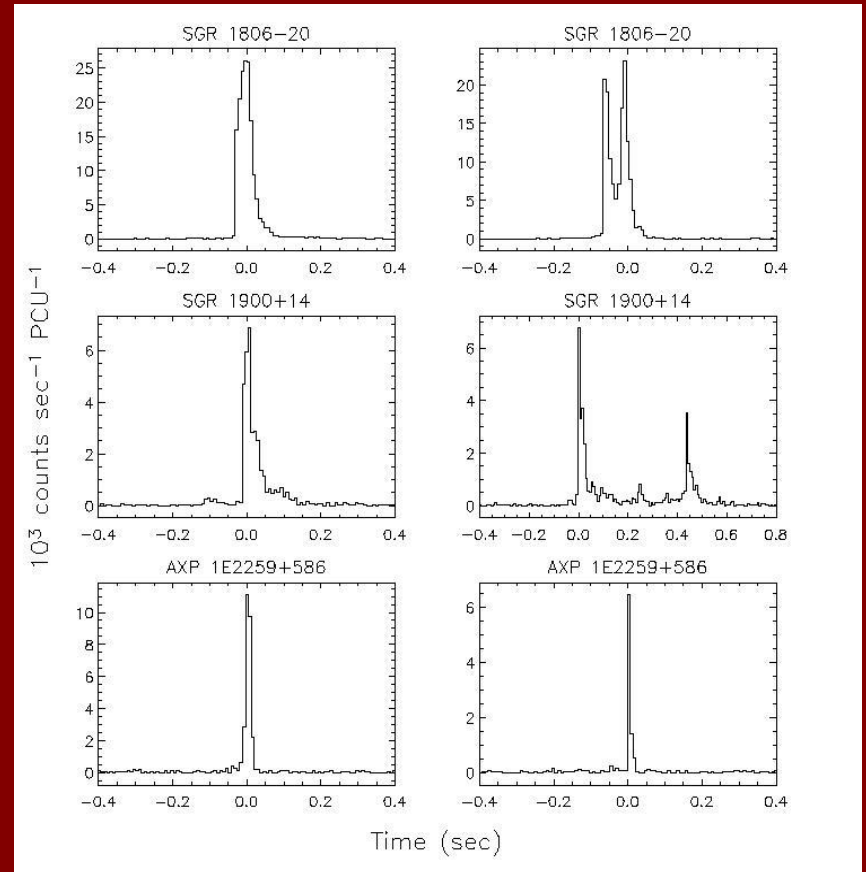
*Power distribution is similar
to the distribution of earthquakes
in magnitude*



See the review in
Rea, Esposito
1101.4472

Normal bursts of SGRs and AXPs

- Typical weak bursts of SGR 1806-29, SGR 1900+14 and of AXP 1E 2259+586 detected by RXTE

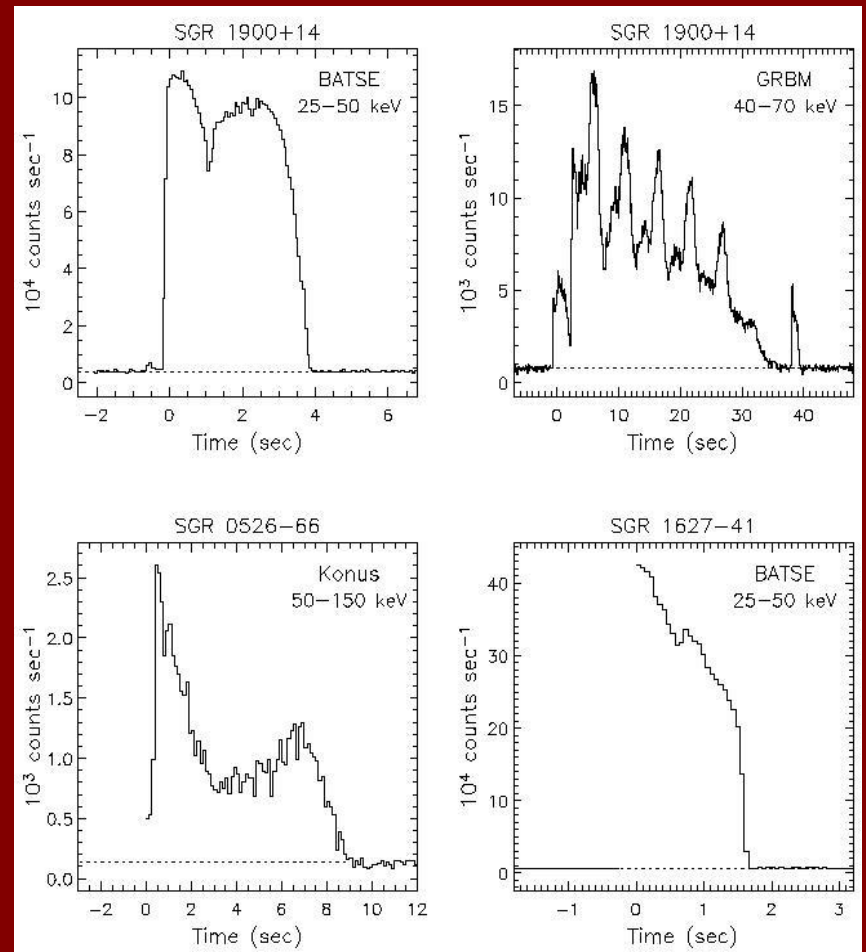


(from Woods, Thompson 2004)

Intermediate SGR bursts

Examples of intermediate bursts.

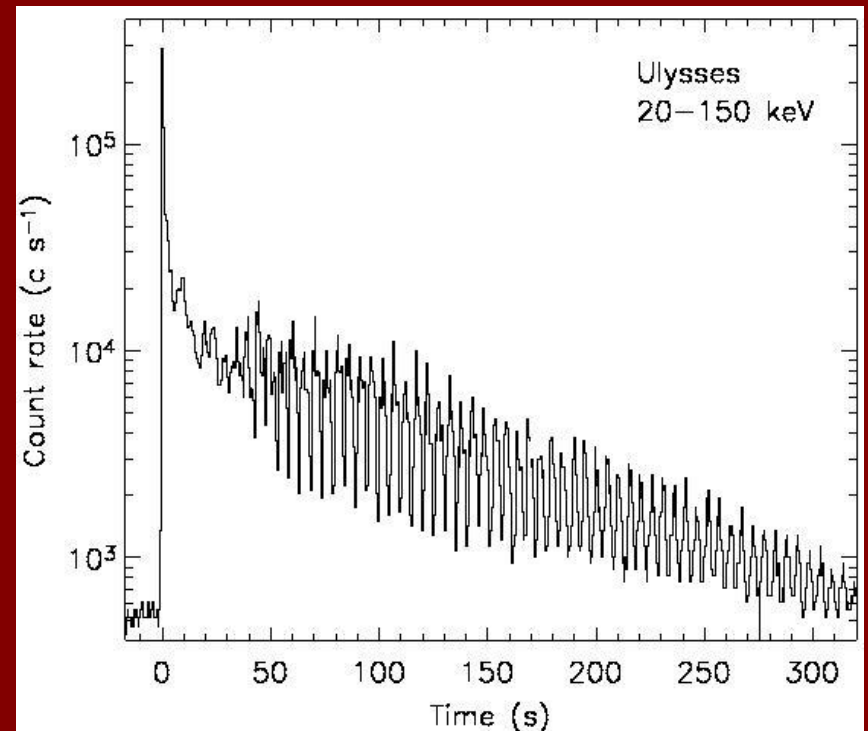
The forth (bottom right) is sometimes defined as a giant burst (for example by Mazets et al.).



(from Woods, Thompson 2004)

Giant flare of the SGR 1900+14 (27 August 1998)

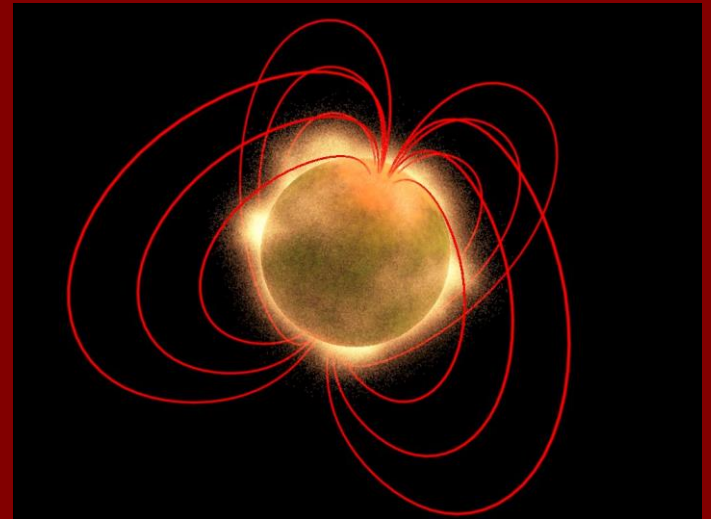
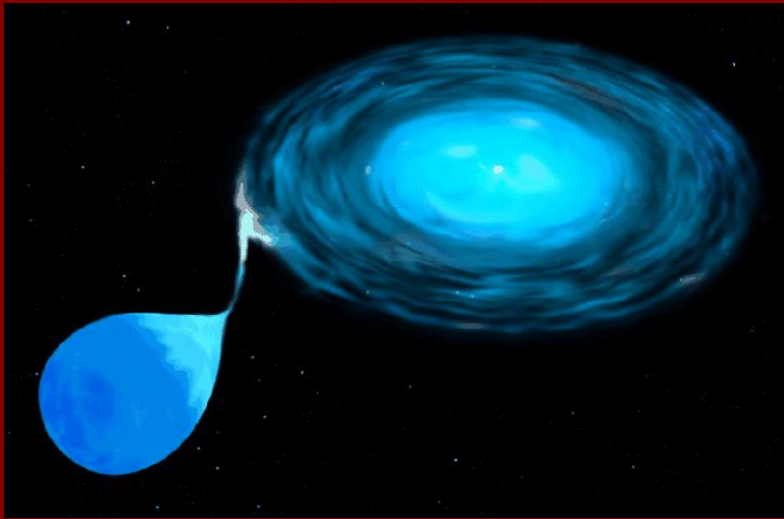
- Ulysses observations
(figure from Hurley et al.)
- Initial spike 0.35 s
- $P=5.16$ s
- $L > 3 \times 10^{44}$ erg/s
- $E_{\text{TOTAL}} > 10^{44}$ erg



Anomalous X-ray pulsars

Identified as a separate group in 1995.
(Mereghetti, Stella 1995 Van Paradijs et al.1995)

- Similar periods (5-10 sec)
- Constant spin down
- Absence of optical companions
- Relatively weak luminosity
- Constant luminosity



Anomalous X-ray Pulsars: main properties

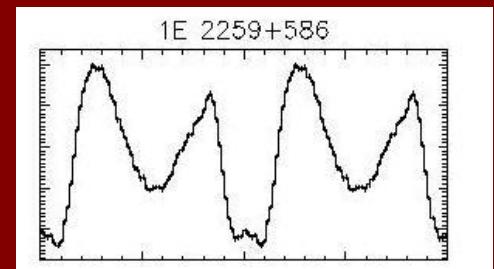
- Twelve sources known:
1E 1048.1-5937, 1E 2259+586, 4U 0142+614,
1 RXS J170849-4009, 1E 1841-045,
CXOU 010043-721134, AX J1845-0258,
CXOU J164710-455216, XTE J1810-197,
1E 1547.0-5408, PSR J1622-4950, CXOU J171405.7-381031
- Persistent X-ray emitters, $L \approx 10^{34} - 10^{35}$ erg/s
- Pulsations with $P \approx 2 - 10$ s (0.33 sec for PSR 1846)
- Large spindown rates, $\dot{P}/P \approx 10^{-11} \text{ s}^{-1}$
- No evidence for a binary companion, association with a SNR in several cases

Known AXPs

Sources

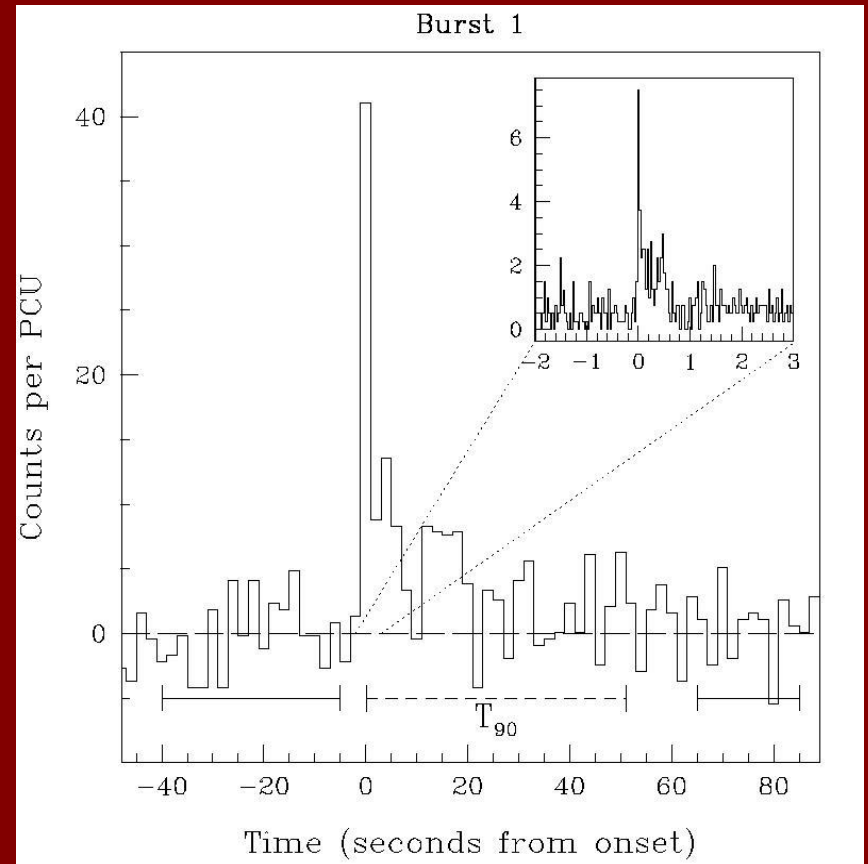
Periods, s

CXO 010043-7211	8.0
4U 0142+61	8.7
1E 1048.1-5937	6.4
1E 1547.0-5408	2.1
CXOU J164710-4552	10.6
1RXS J170849-40	11.0
XTE J1810-197	5.5
1E 1841-045	11.8
AX J1845-0258	7.0
PSR J1622-4950	4.3
CXOU J171405.7-381031	3.8
1E 2259+586	7.0

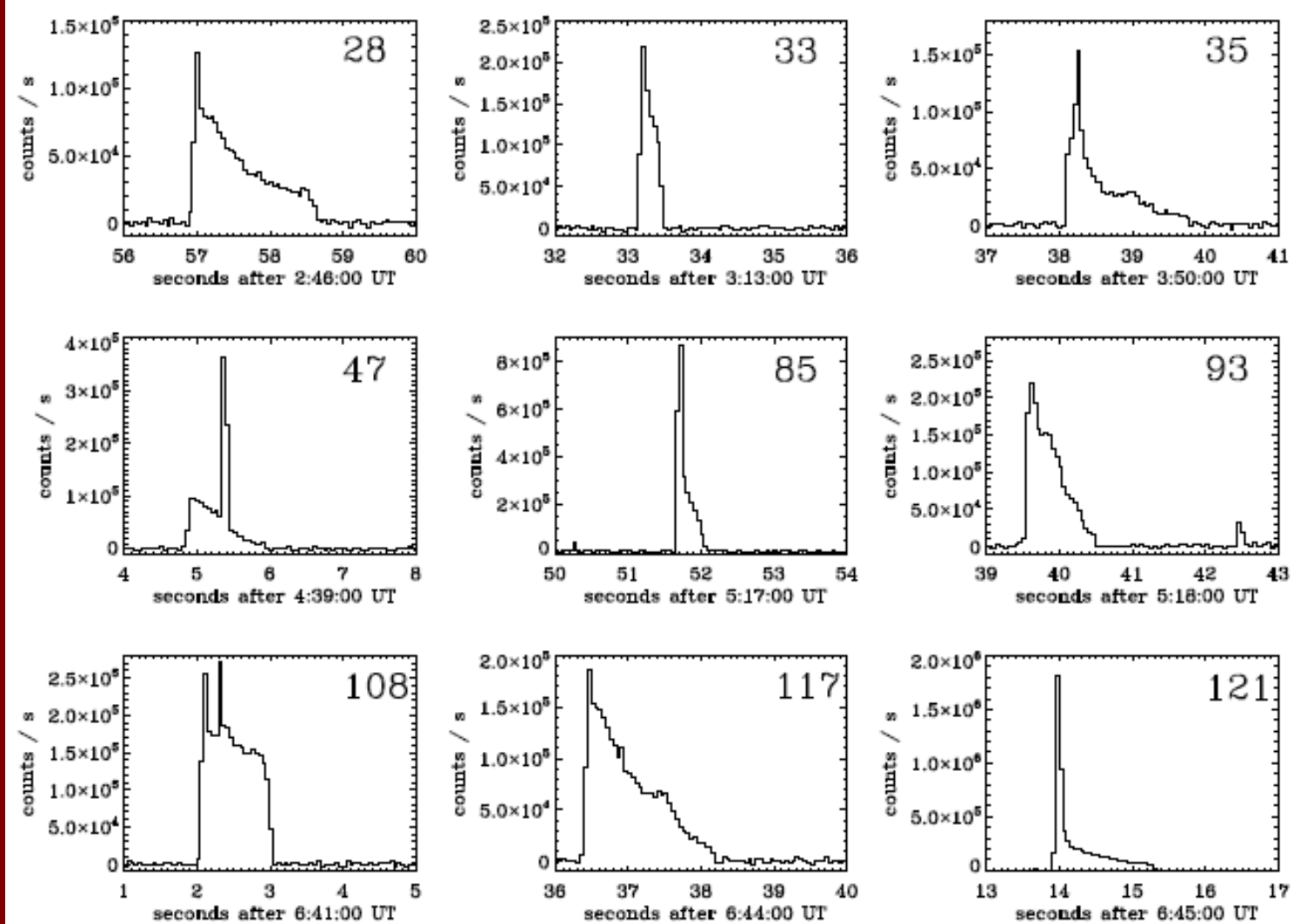


Are SGRs and AXPs brothers?

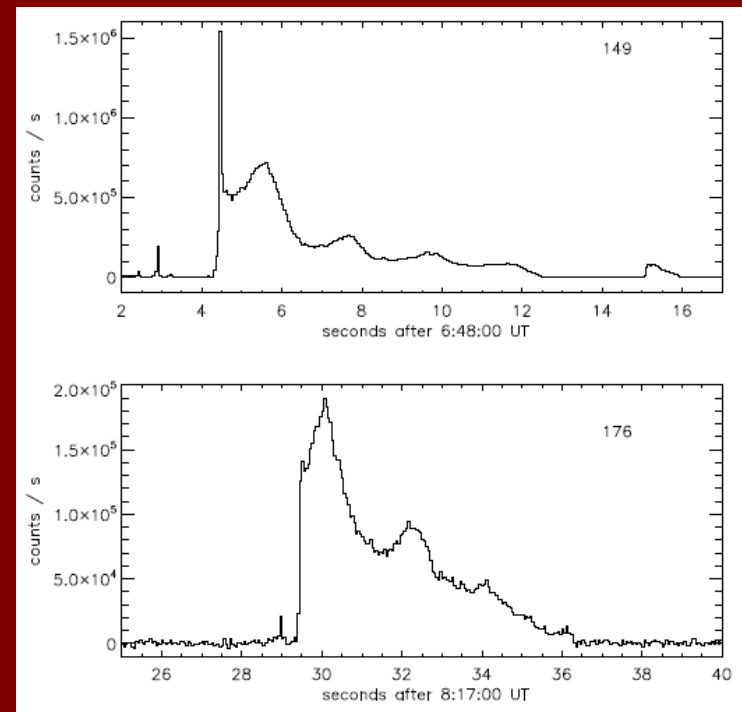
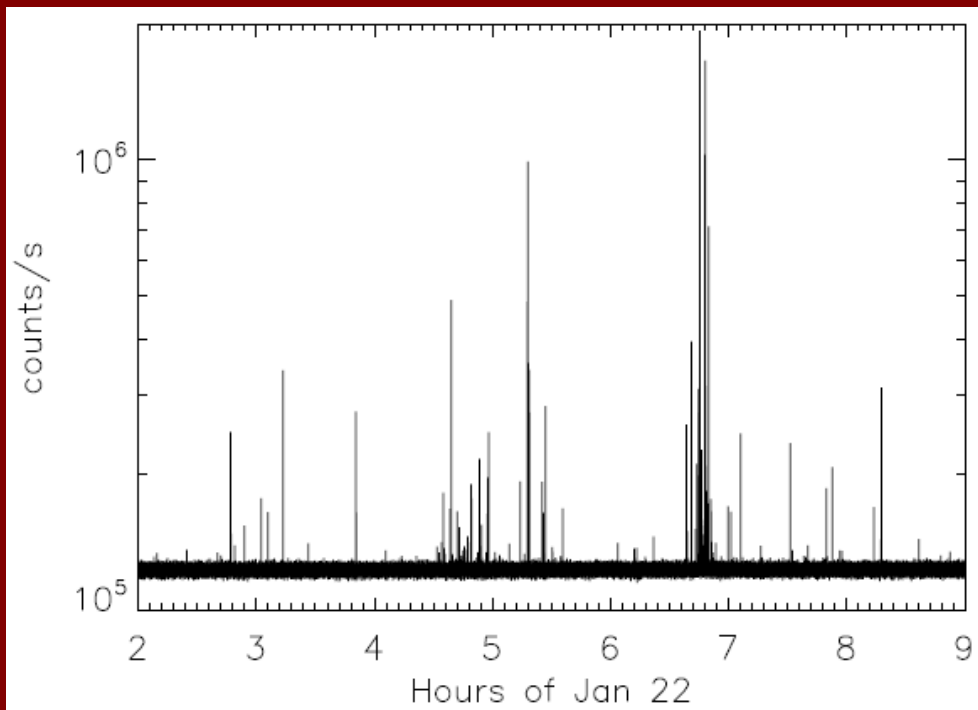
- Bursts of AXPs (more than half burst)
- Spectral properties
- Quiescent periods of SGRs (0525-66 since 1983)



Bursts of the AXP 1E1547.0-5408

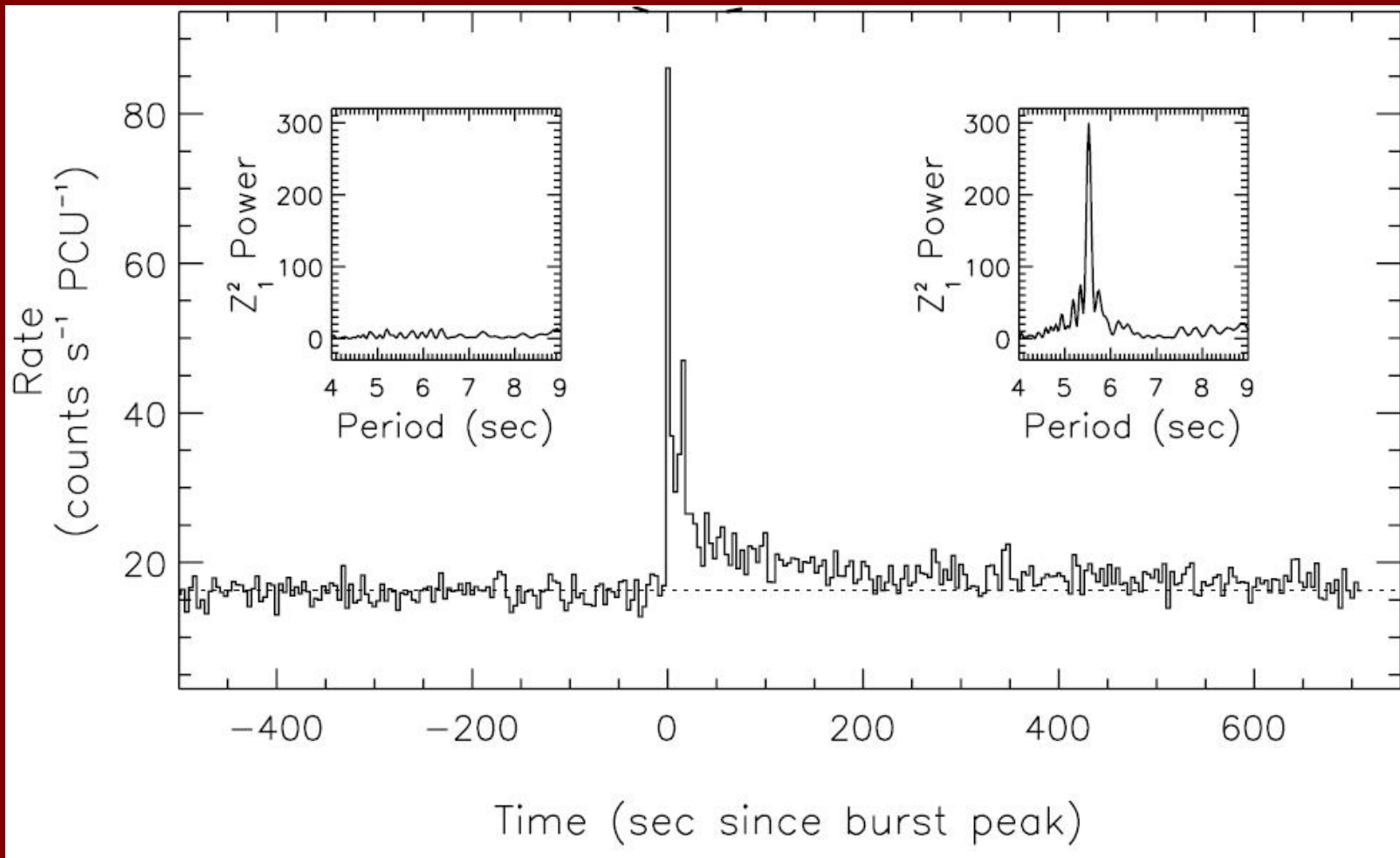


Bursts of the AXP 1E1547.0-5408



Some bursts have pulsating tails with spin period.

Unique AXP bursts?



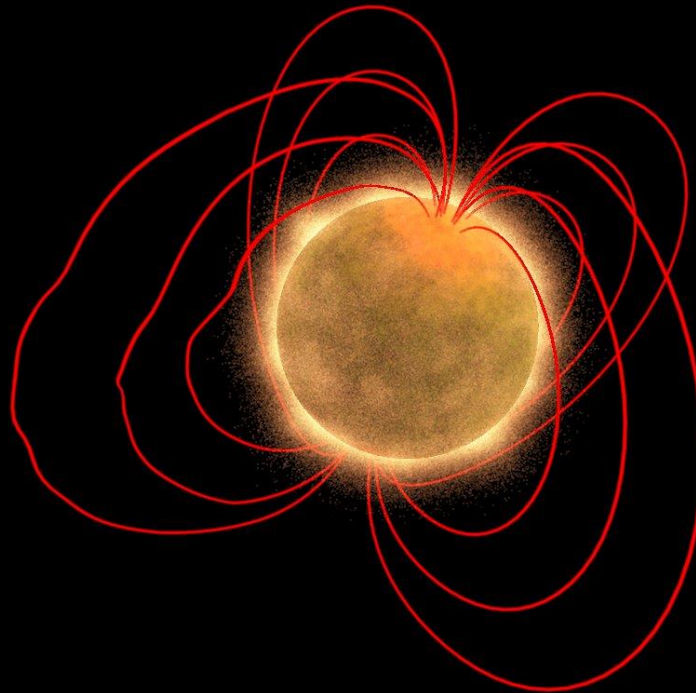
Bursts from AXP J1810-197. Note a long exponential tail with pulsations.

(Woods et al. 2005 astro-ph/ astro-ph/0505039)

A Tale of Two Populations ?

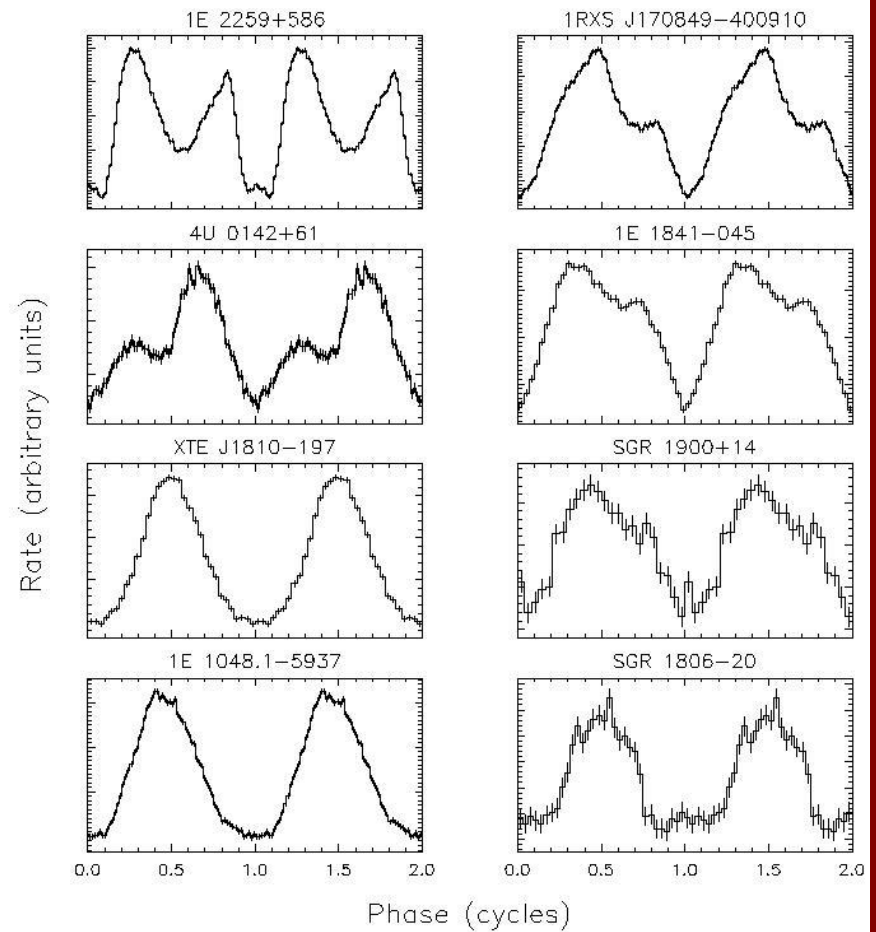
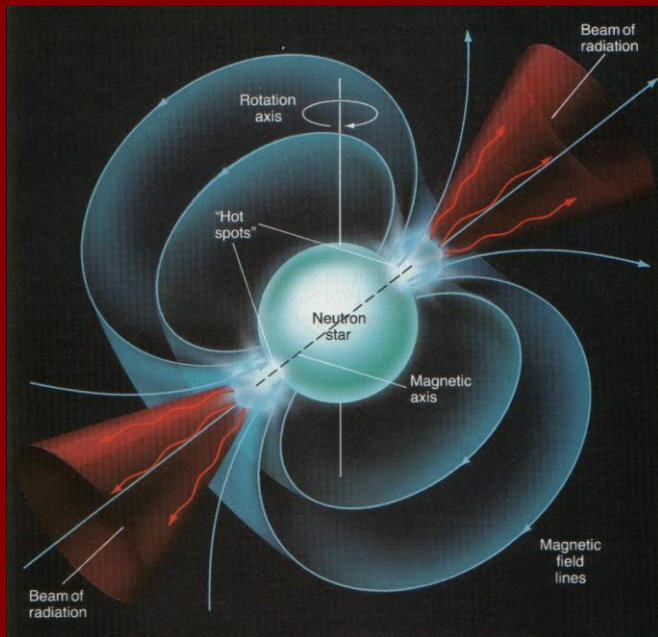
SGRs: bursting
X/γ-ray sources

A Magnetar



R < 10 km
Pulsed X-ray emission: a neutron star

Pulse profiles of SGRs and AXPs

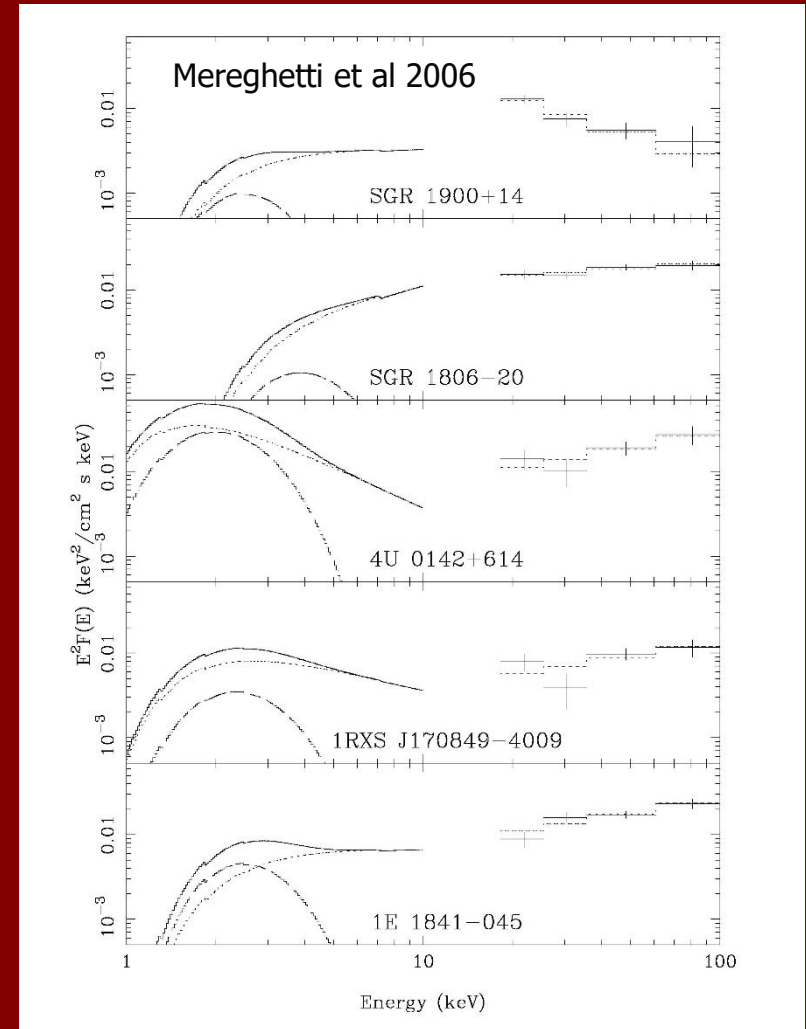


Hard X-ray Emission

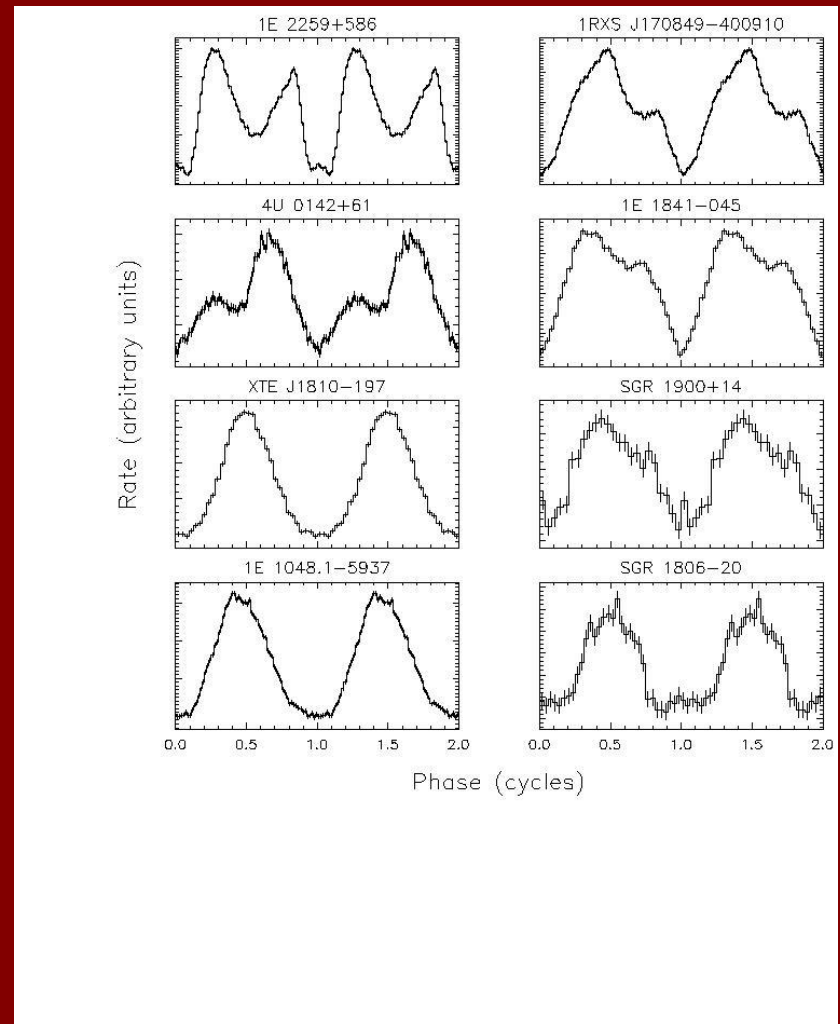
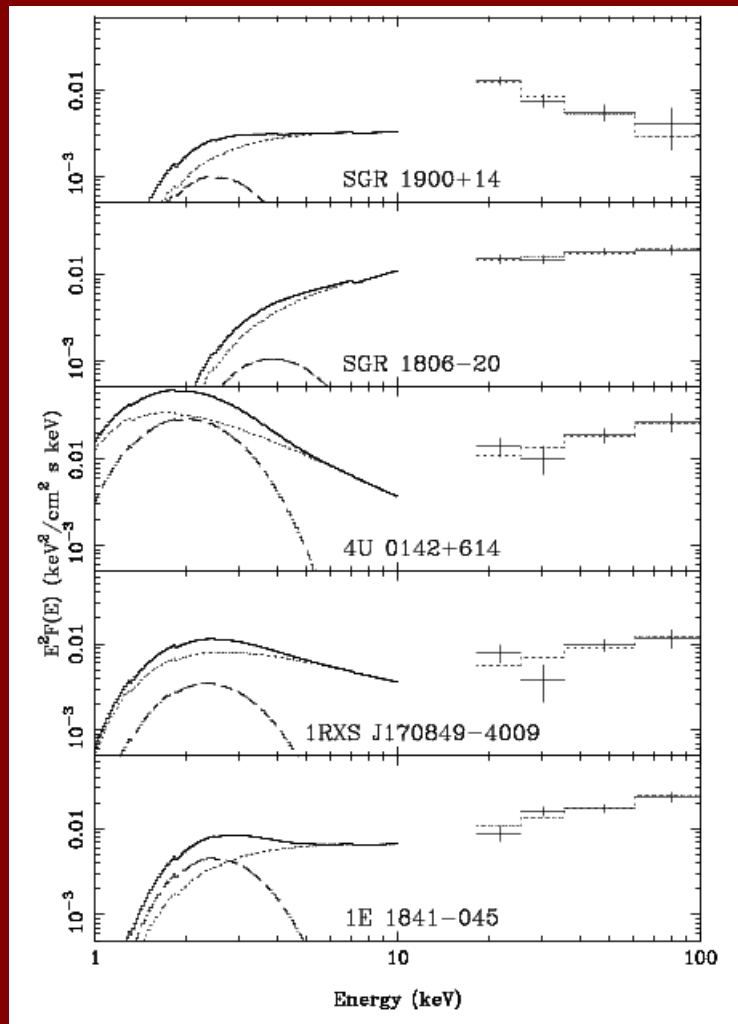
INTEGRAL revealed substantial emission in the 20 -100 keV band from SGRs and APXs

Hard power law tails with $\Gamma \approx 1-3$
(see 1712.09643 about spectral modeling)

Hard emission pulse

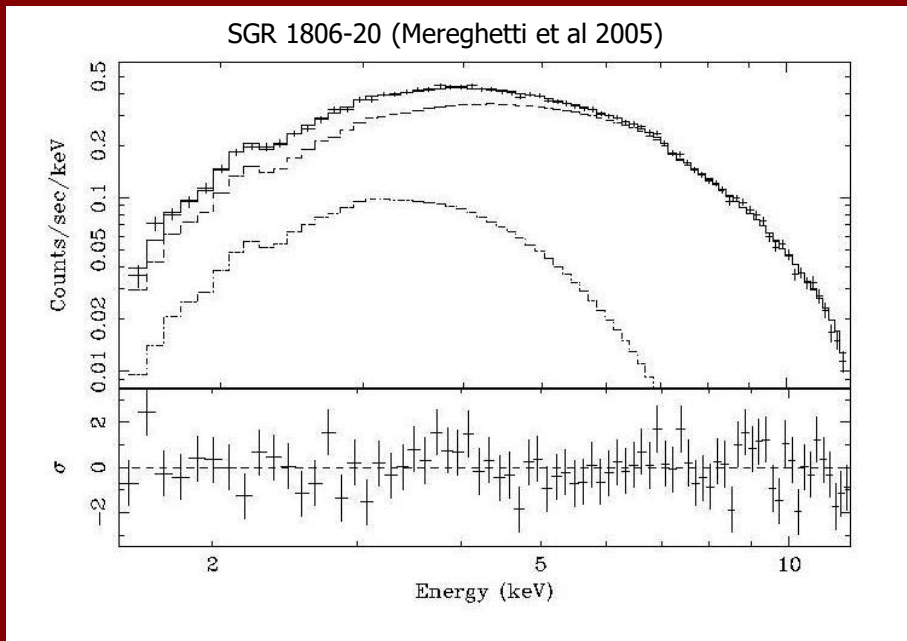


SGRs and AXPs

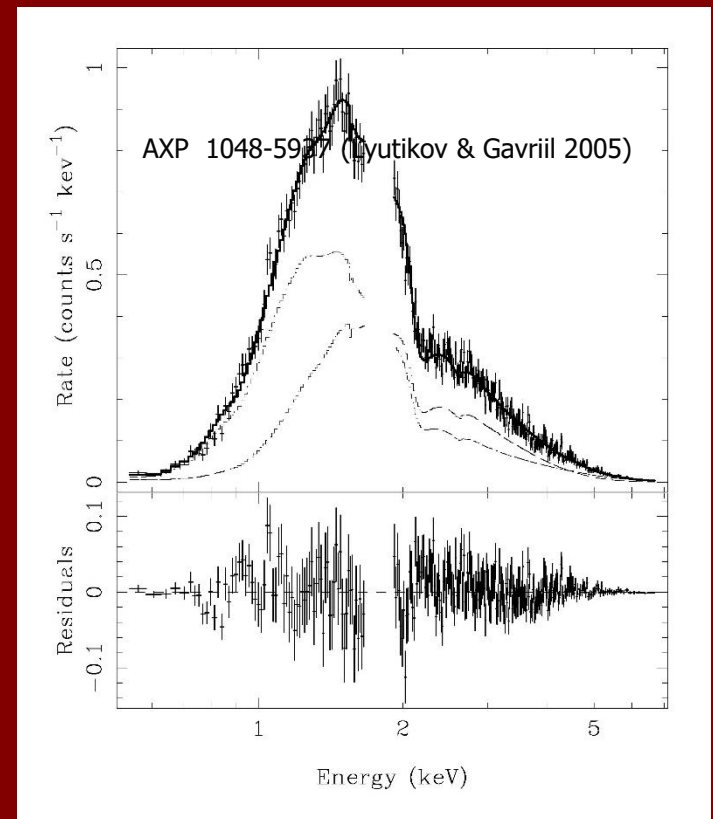


SGRs and AXPs soft X-ray Spectra

- 0.5 – 10 keV emission is well represented by a blackbody plus a power law



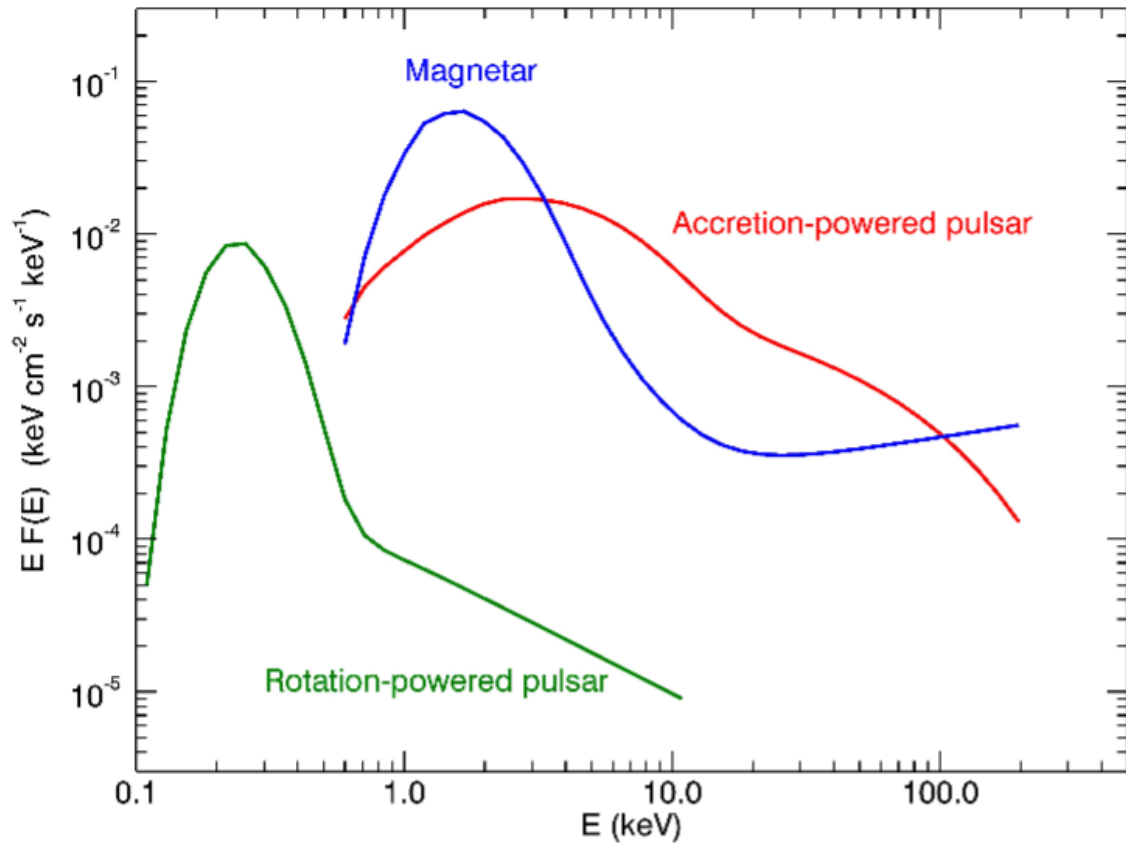
See also discussions in:
arXiv: 1001.3847, 1009.2810



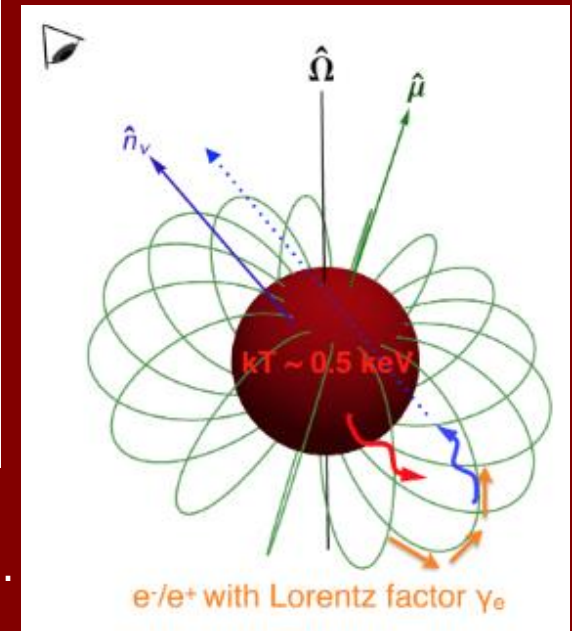
SGRs and AXPs soft X-ray Spectra

- $kT_{\text{BB}} \sim 0.5 \text{ keV}$, does not change much in different sources
- Photon index $\Gamma \approx 1 - 4$,
AXPs tend to be softer
- SGRs and AXPs persistent emission is variable (months/years)
- Variability is mostly associated with the non-thermal component

Magnetar spectra in comparison

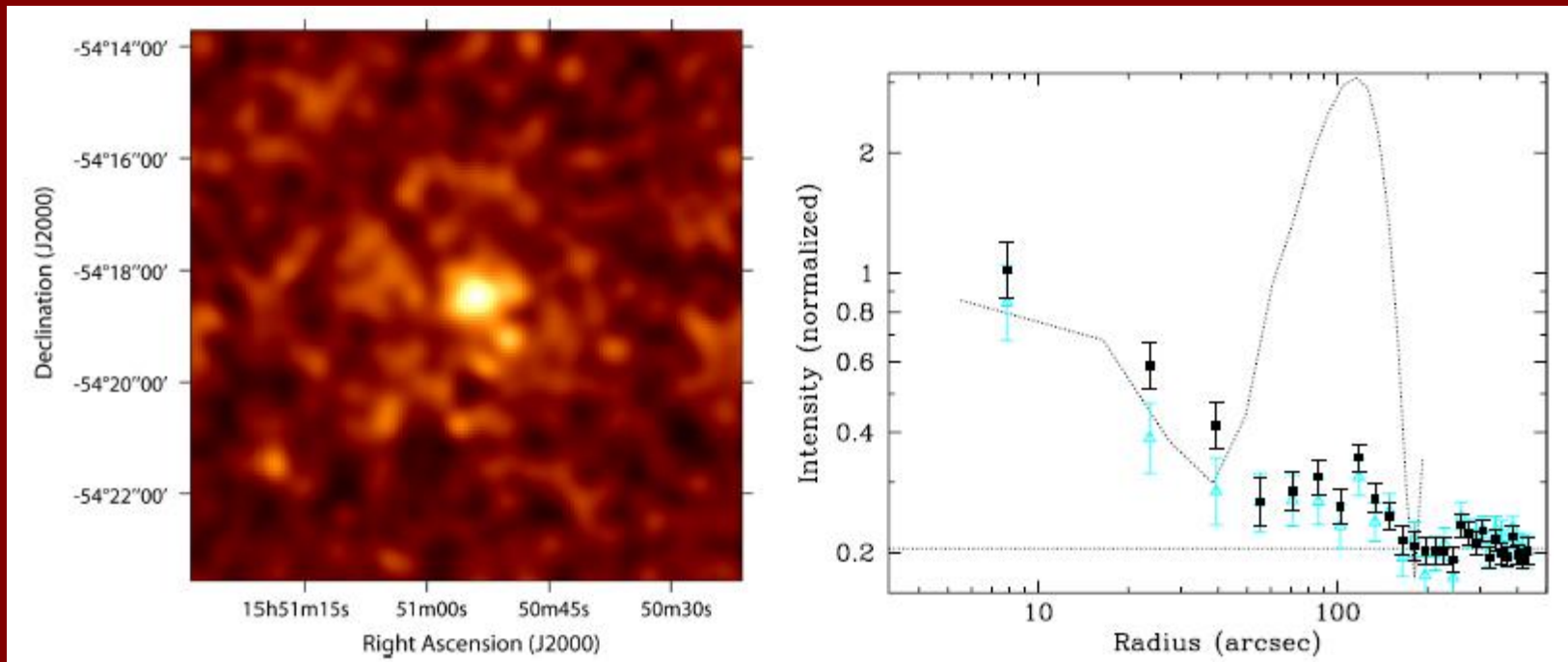


Hard tails can be due to upscattering of thermal photons from the surface in the magnetosphere.



And what about AXPs and PSRs?

1E1547.0-5408 – the most rapidly rotating AXP (2.1 sec)
The highest rotation energy losses among SGRs and AXPs.
Bursting activity.

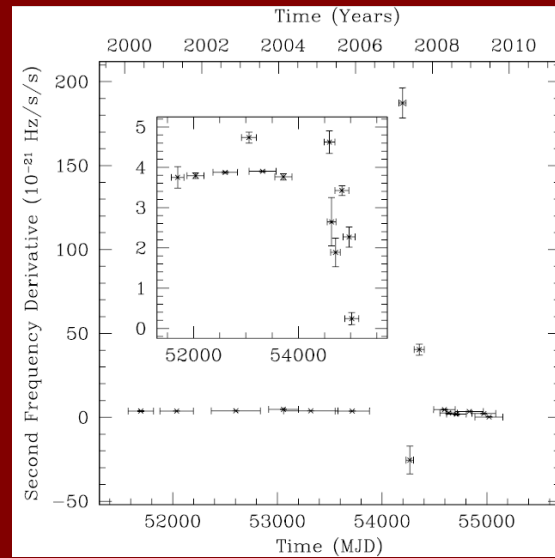
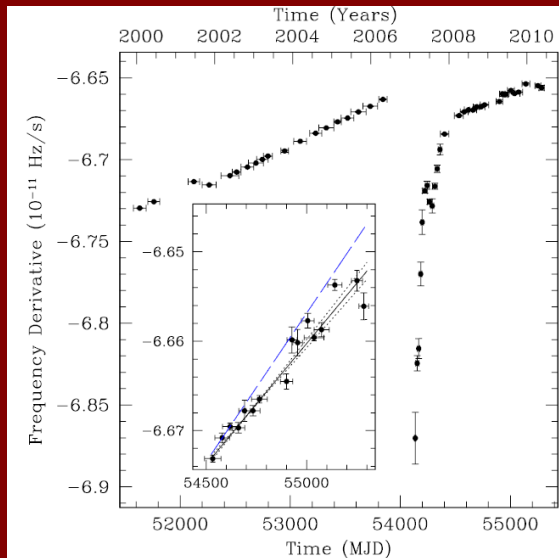


Pulsar wind nebulae around an AXP.

0909.3843

See 1902.10712 about radio observations of magnetars.

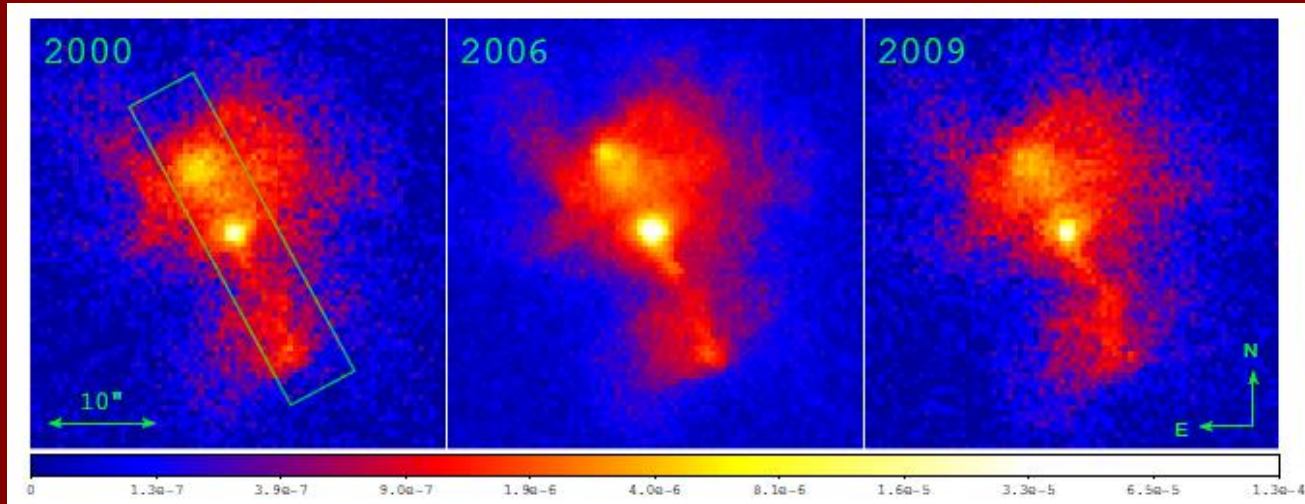
Postburst properties of PSR J1846-0258



The pulsar showed a glitch.
A period of magnetar-like activity was started.
After the burst parameters of the pulsar changed.

$n=2.65 \rightarrow n=2.16$

Timing noise was increased
(was very small for a magnetar before bursts)

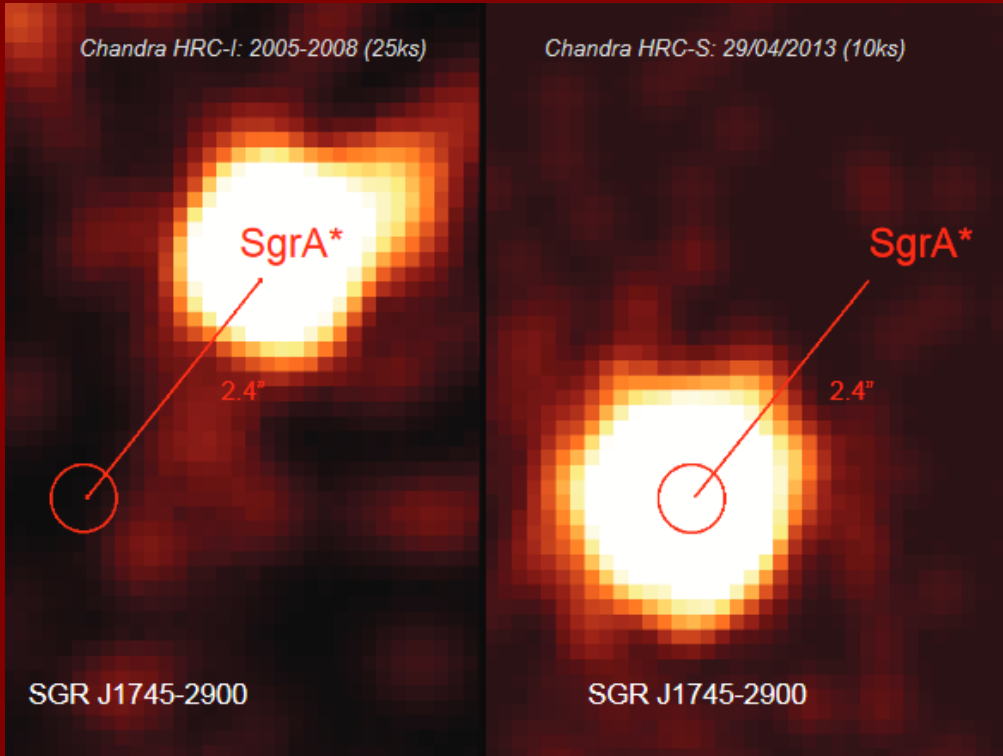


Galactic center magnetar

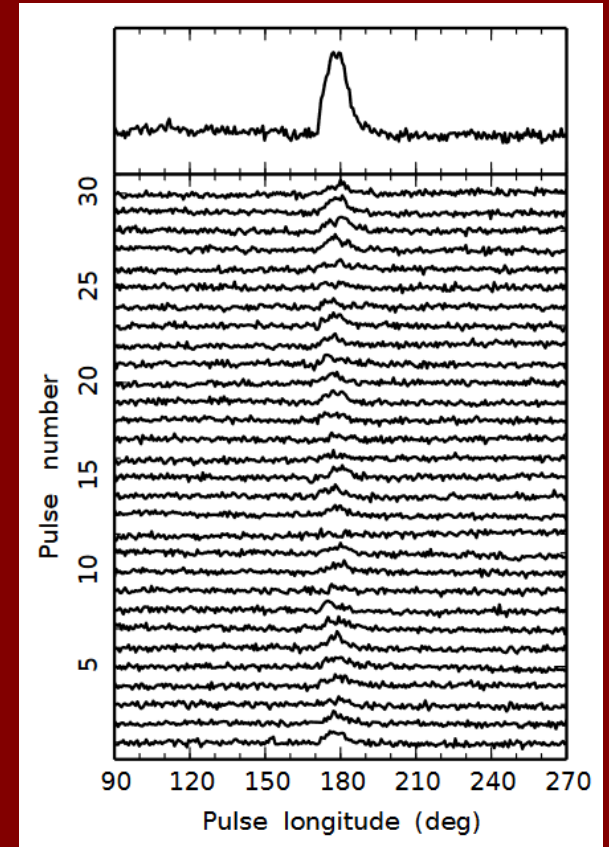
SGR/PSR J1745-2900

Radio pulsations detection in 2013
The largest dispersion measure
and rotation measure among PSRs.

1307.6331



<1 pc from Sgr A*



1802.07884

Generation of the magnetic field

The mechanism of the magnetic field generation is still unknown.

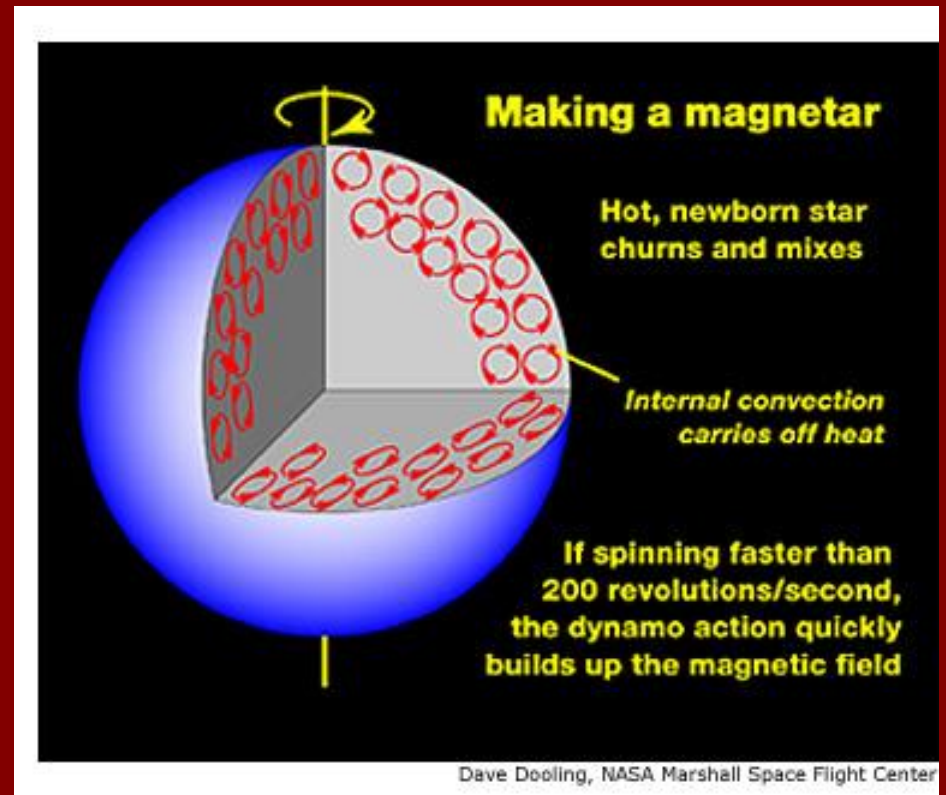
Turbulent dynamo

α - Ω dynamo (Duncan, Thompson)

α^2 dynamo (Bonanno et al.)

or their combination

In any case, initial rotation of a protoNS is the critical parameter.



Strong field via flux conservation

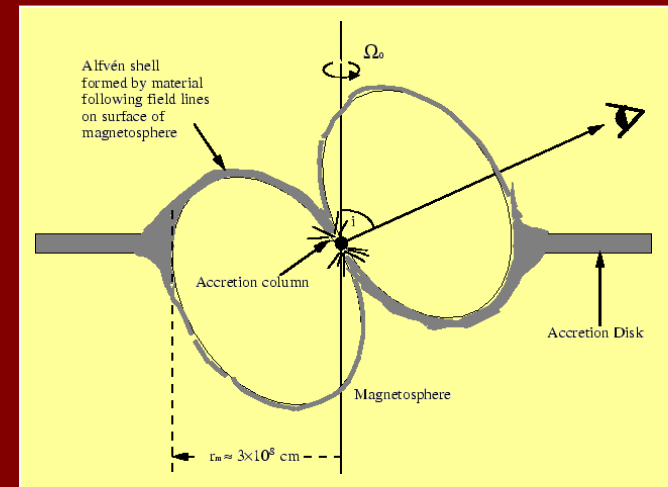
There are reasons to suspect that the magnetic fields of magnetars are not due to any kind of dynamo mechanism, but just due to flux conservation:

1. Study of SNRs with magnetars (Vink and Kuiper 2006, see also 1708.01626). If there was a rapidly rotating magnetar then a huge energy release is inevitable. No traces of such energy injections are found.
2. There are few examples of massive stars with field strong enough to produce a magnetars due to flux conservation (Ferrario and Wickramasinghe 2006)

Still, these suggestions can be criticized (Spruit arXiv: 0711.3650)

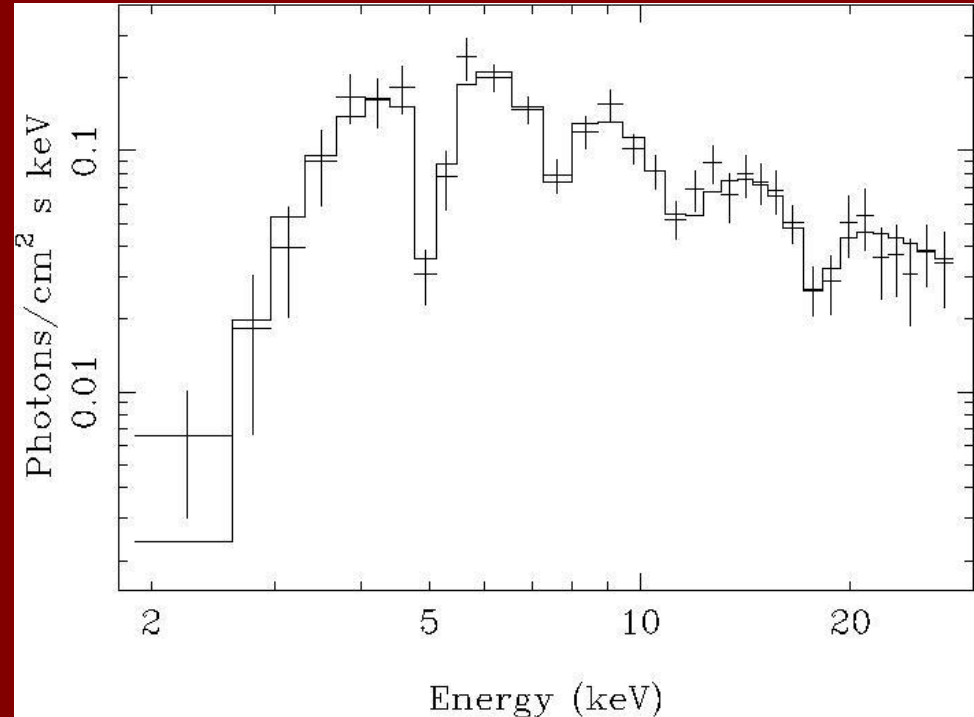
Alternative theory

- Remnant fallback disc
- Mereghetti, Stella 1995
- Van Paradijs et al. 1995
- Alpar 2001
- Marsden et al. 2001
- Problems
- How to generate strong bursts?
- Discovery of a passive disc in one of AXPs (Wang et al. 2006).
A new burst of interest to this model.
- Timing noise analysis contradicts accretion (1806.00401)



Magnetic field estimates

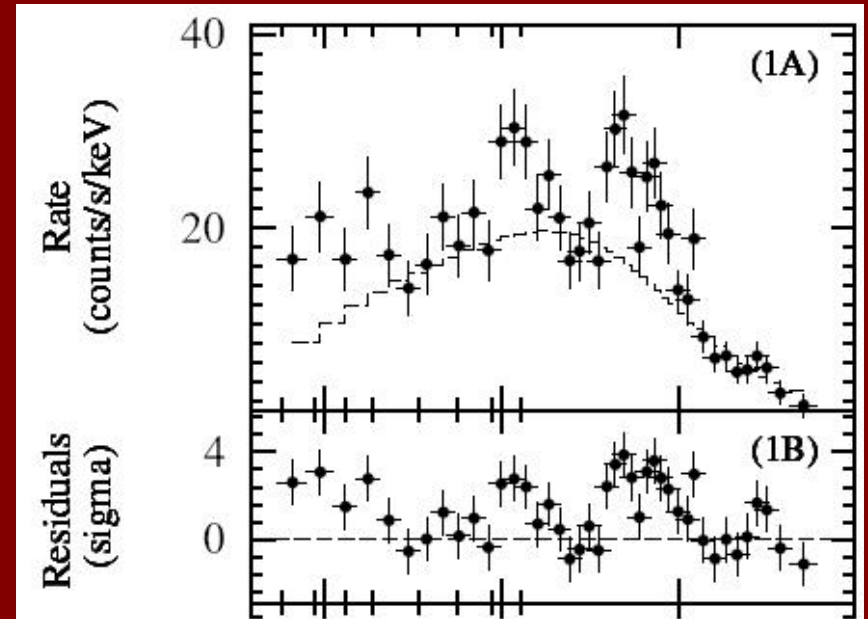
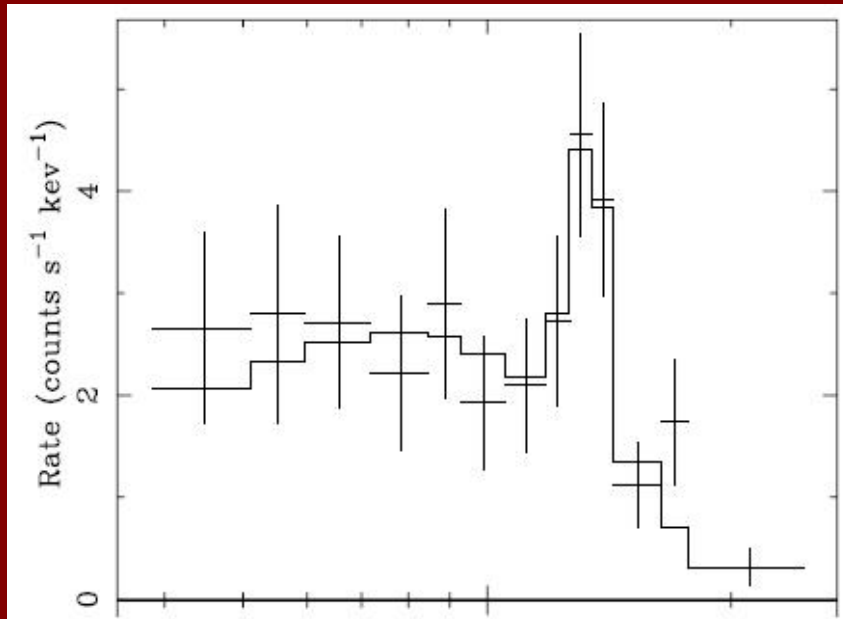
- Spin down
- Long spin periods
- Energy to support bursts
- Field to confine a fireball (tails)
- Duration of spikes (alfven waves)
- Direct measurements of magnetic field (cyclotron lines)



Ibrahim et al. 2002

Spectral lines claims

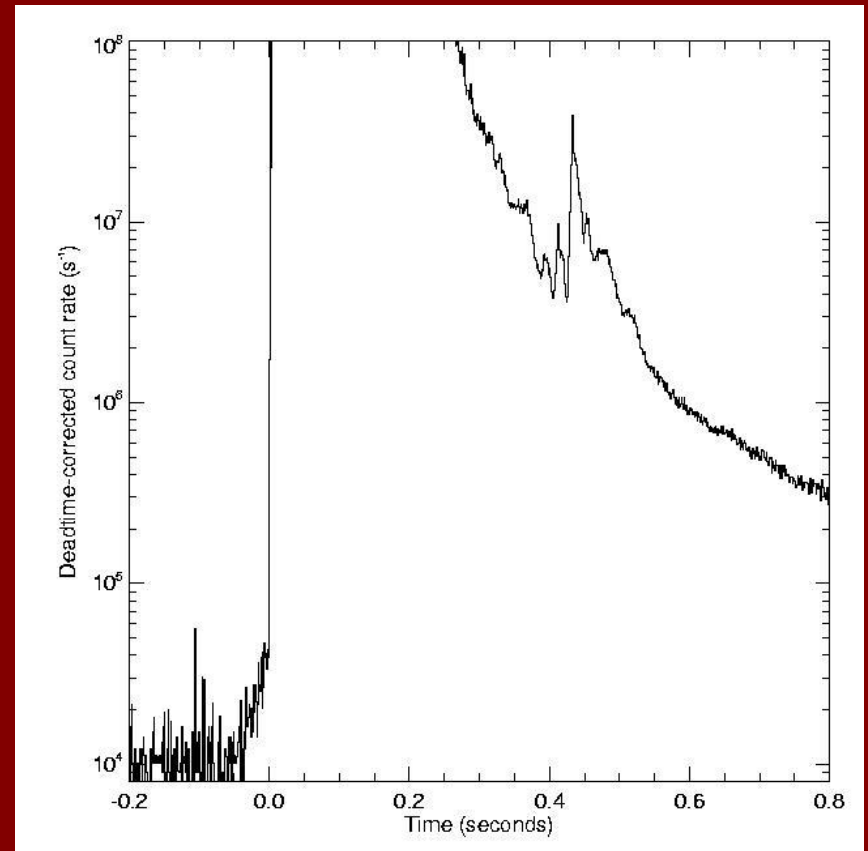
All claims were done for RXTE observations (there are few other candidates).
All detections were done during bursts.



1E 1048.1-5937 Gavriil et al. (2002, 2004) 4U 0142+61 Gavriil et al. (2007)

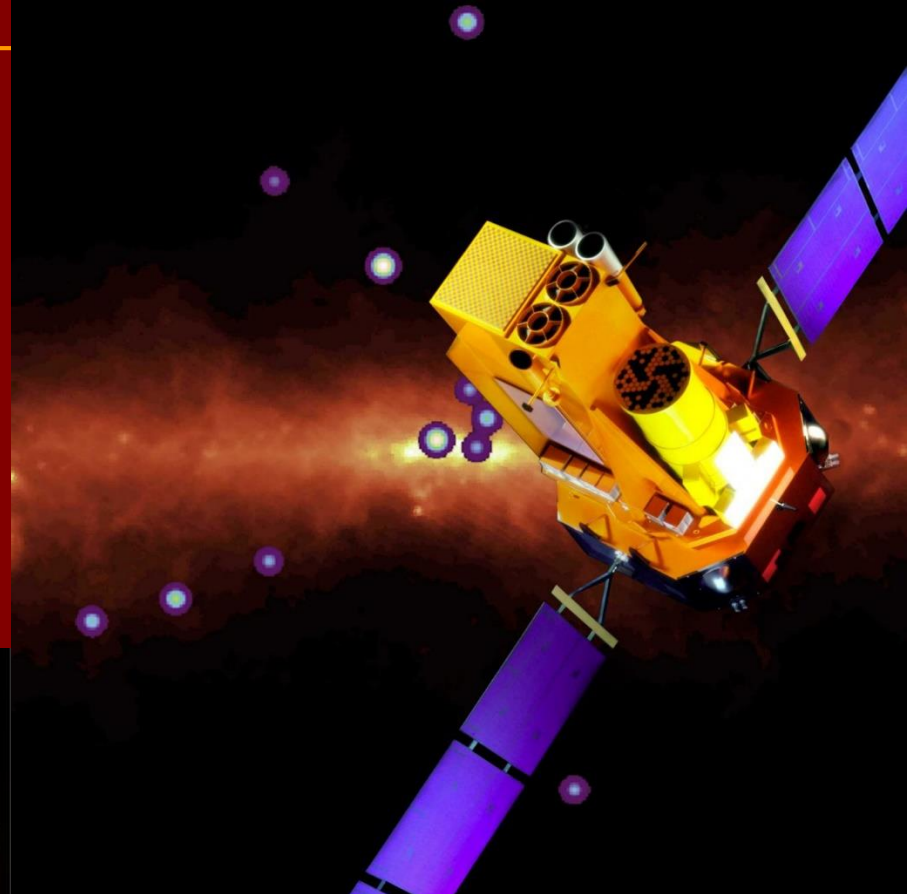
Hyperflare of SGR 1806-20

- 27 December 2004 A giant flare from SGR 1806-20 was detected by many satellites: Swift, RHESSI, Konus-Wind, Coronas-F, Integral, HEND, ...
- 100 times brighter than any other!





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-
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Integral

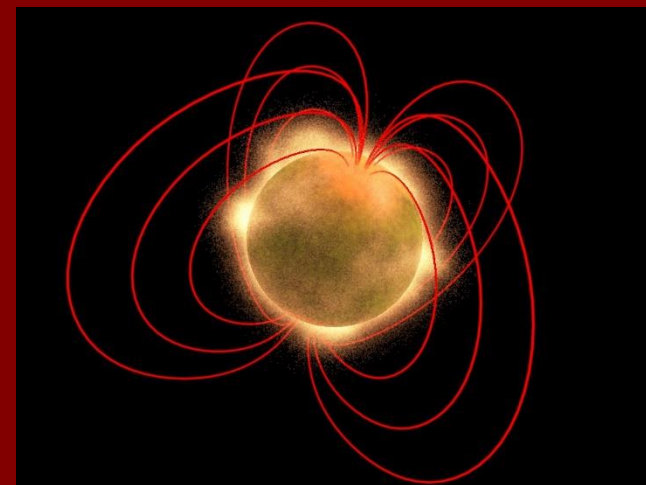


RHESSI

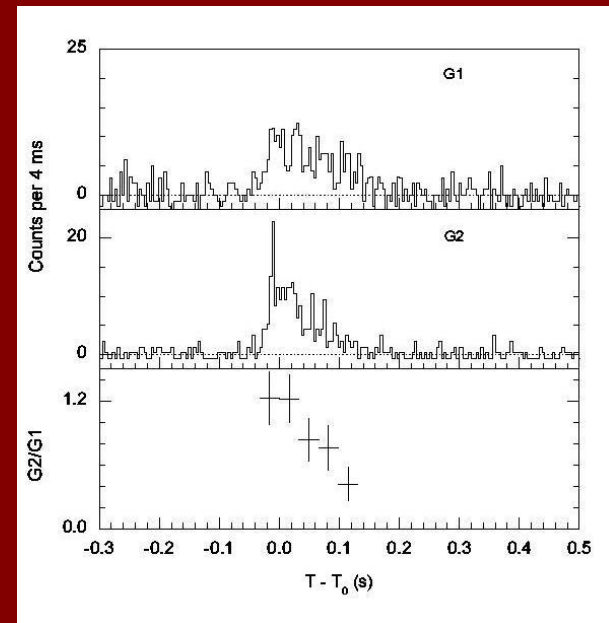
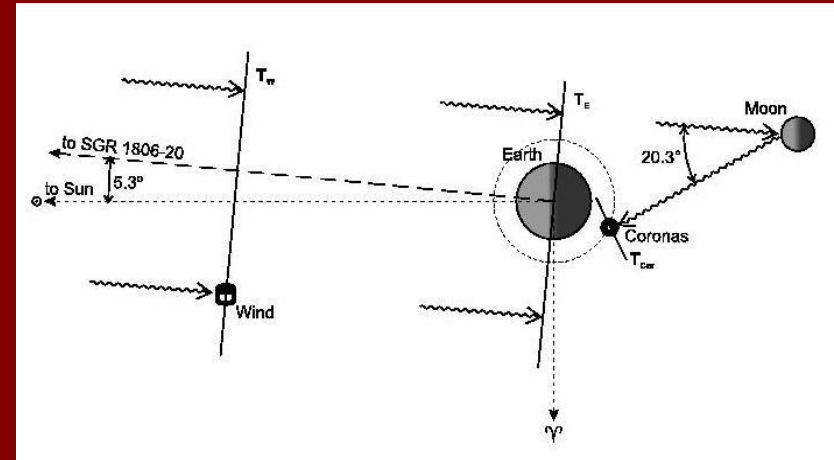
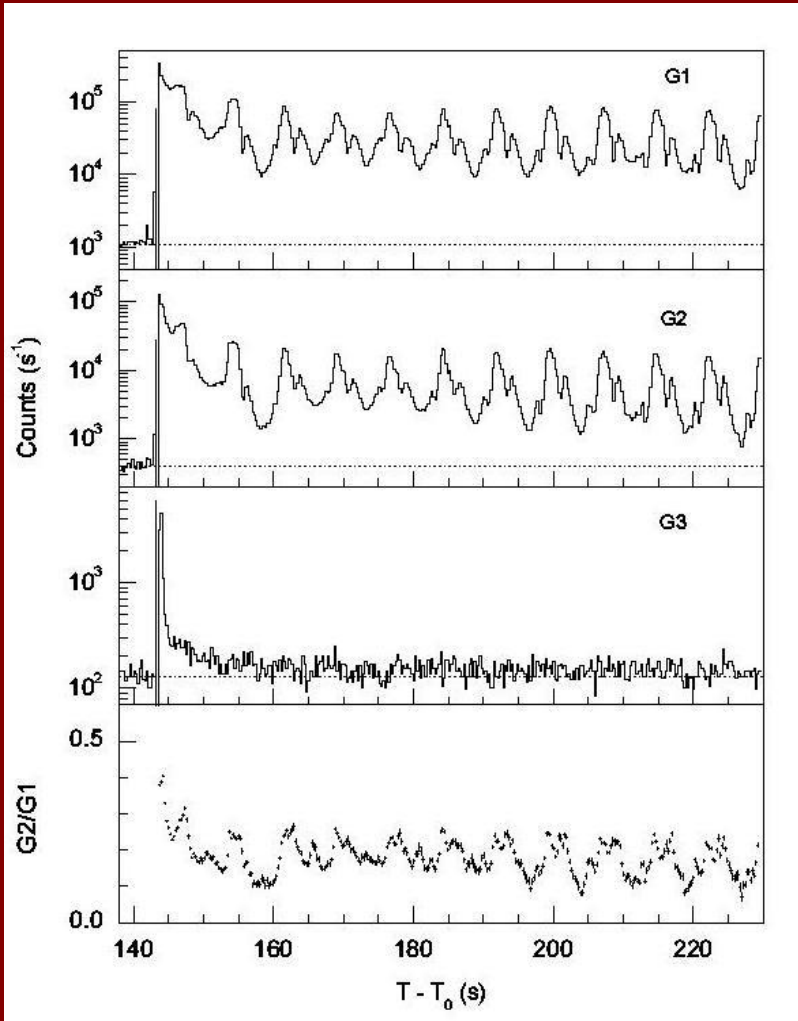
27 Dec 2004:

Giant flare of the SGR 1806-20

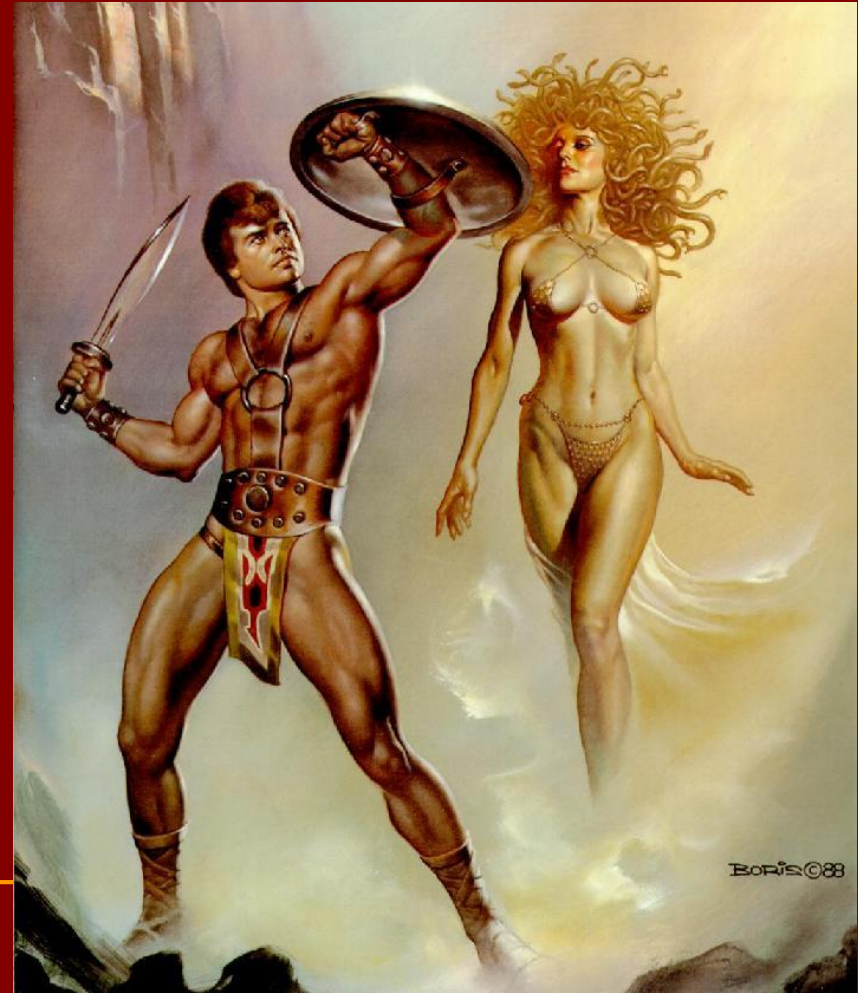
- Spike 0.2 s
- Fluence 1 erg/cm²
- $E(\text{spike}) = 3.5 \cdot 10^{46}$ erg
- $L(\text{spike}) = 1.8 \cdot 10^{47}$ erg/s
- Long «tail» (400 s)
- $P = 7.65$ s
- $E(\text{tail}) = 1.6 \cdot 10^{44}$ erg
- Distance 15 kpc — see the latest data in arXiv: 1103.0006



Konus observations

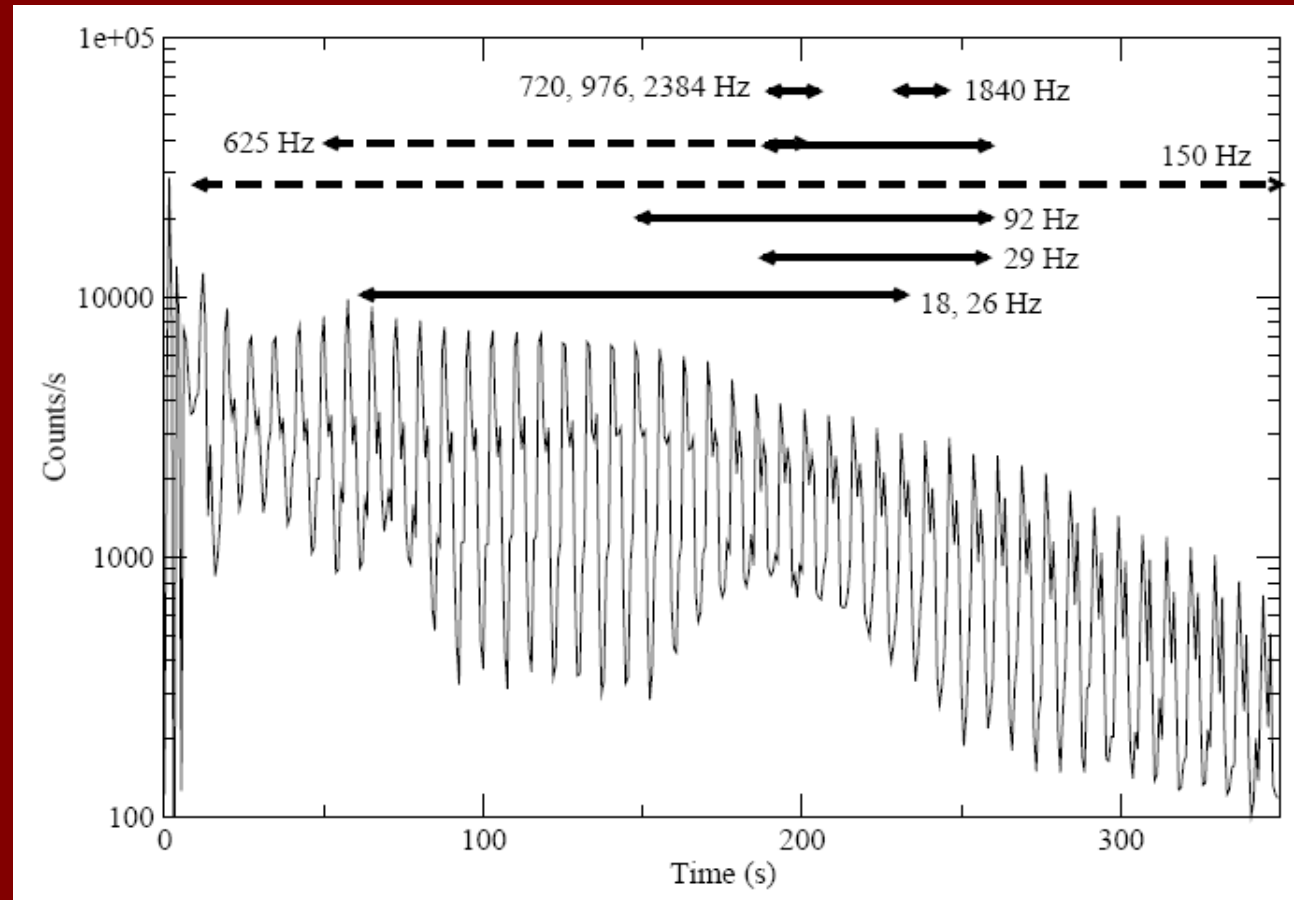


The myth about Medusa



QPO in tails of giant flares of SGRs

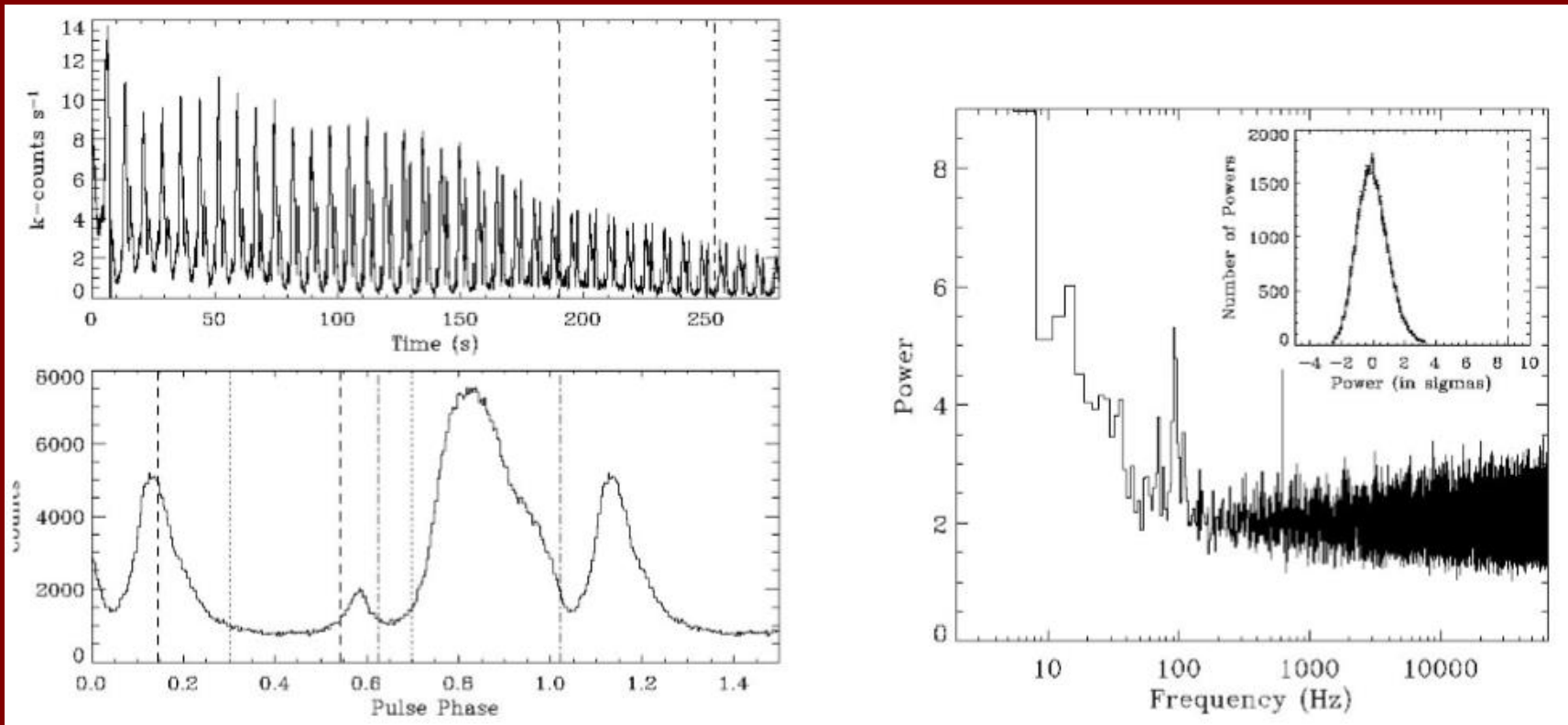
A kind of quasi periodic oscillations have been found in tail of two events (aug. 1998, dec. 2004). They are supposed to be torsional oscillations of NSs, however, it is not clear, yet.



(Israel et al. 2005 astro-ph/0505255,
Watts and Strohmayer 2005 astro-ph/0608463)

QPO in SGR 1806-20 giant flare

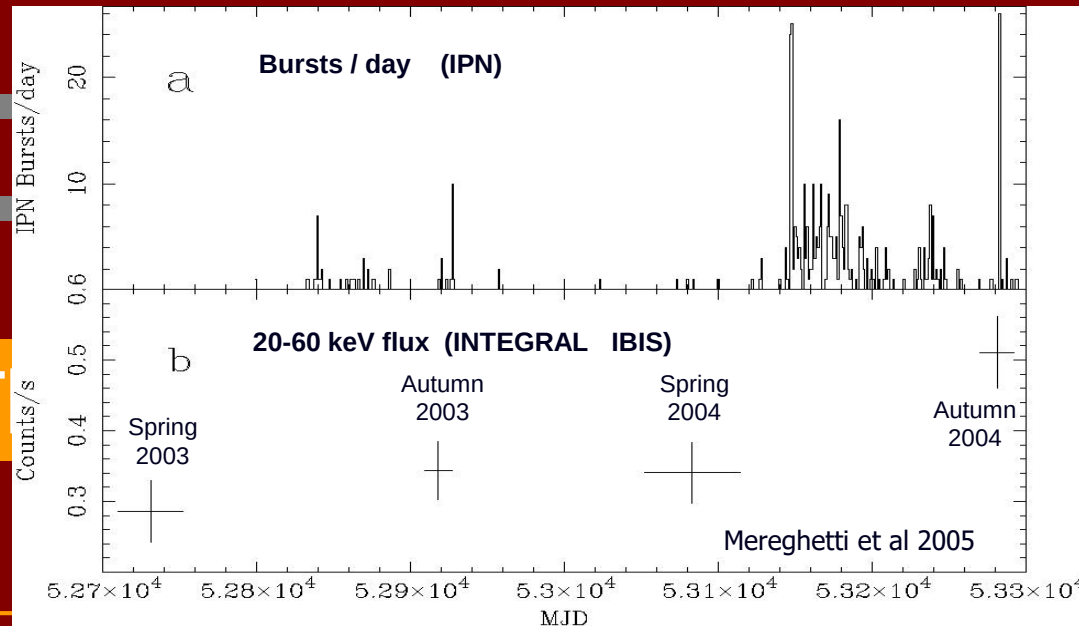
Power spectrum made by averaging nine 3 s segments from the time interval marked by dashed lines in the top left panel. The 92 Hz and 625 Hz QPOs are clearly visible, and the inset illustrates the significance of the 625 Hz feature (from Strohmayer & Watts, 2006)



See fresh analysis in 1808.09483

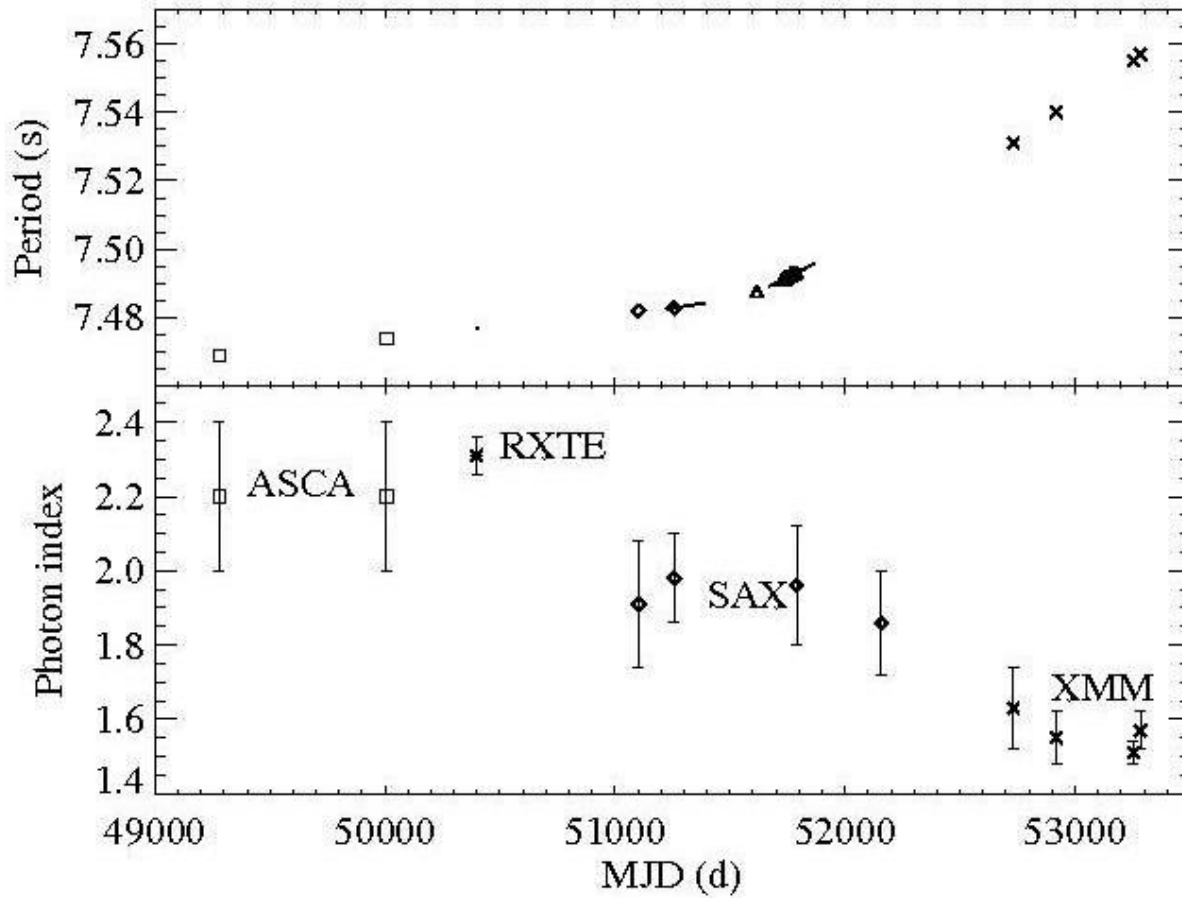
SGR 1806-20 - I

SGR 1806-20 displayed a gradual increase in the level of activity during 2003-2004 (Woods et al 2004; Mereghetti et al 2005)



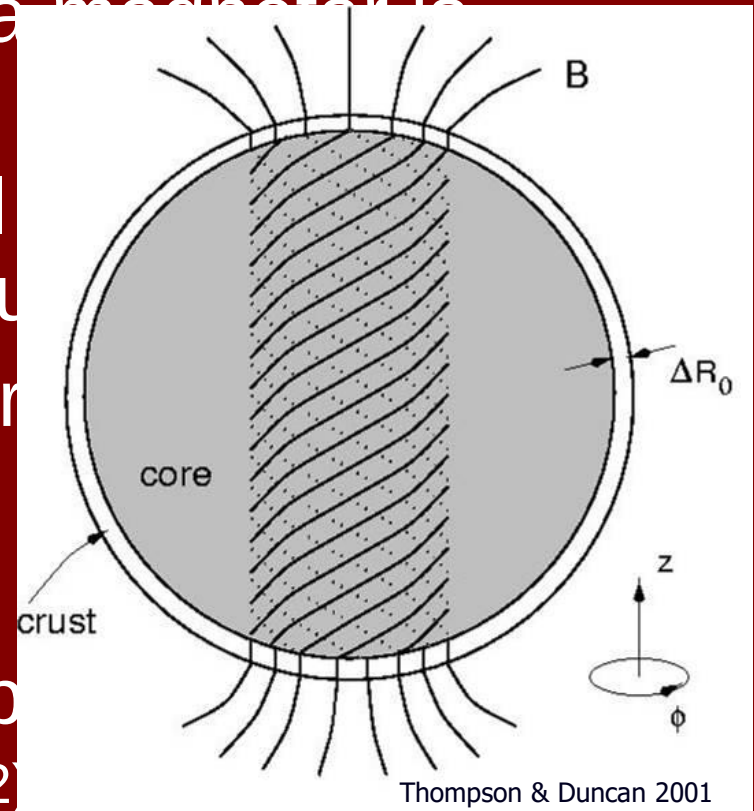
SGR 1806-20 - II

- Four XMM-Newton observations before the burst (the last one was on 2005)
- Pulsar period is 7.5 s
- $\dot{P} \sim 10^{-12}$ s/s
- Blackbody spectrum with $kT \sim 100$ eV
- Hard X-ray emission with peak value ~ 100 keV
- The energy of the burst is $\sim 10^{36}$ erg

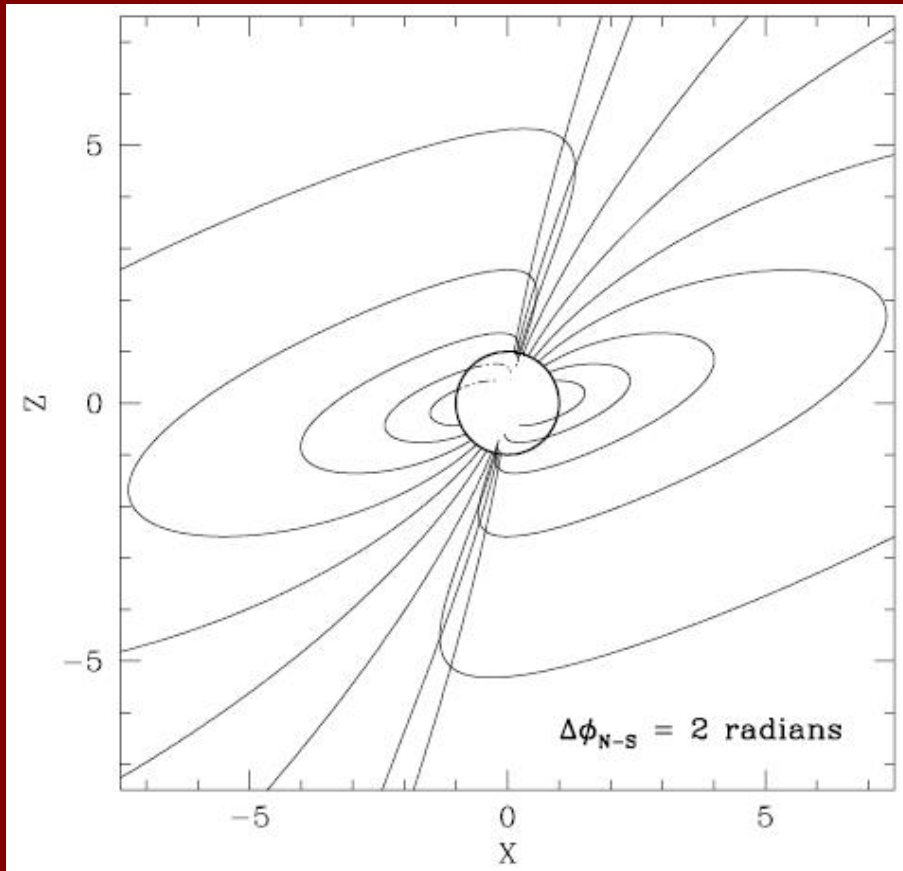


Twisted Magnetospheres – I

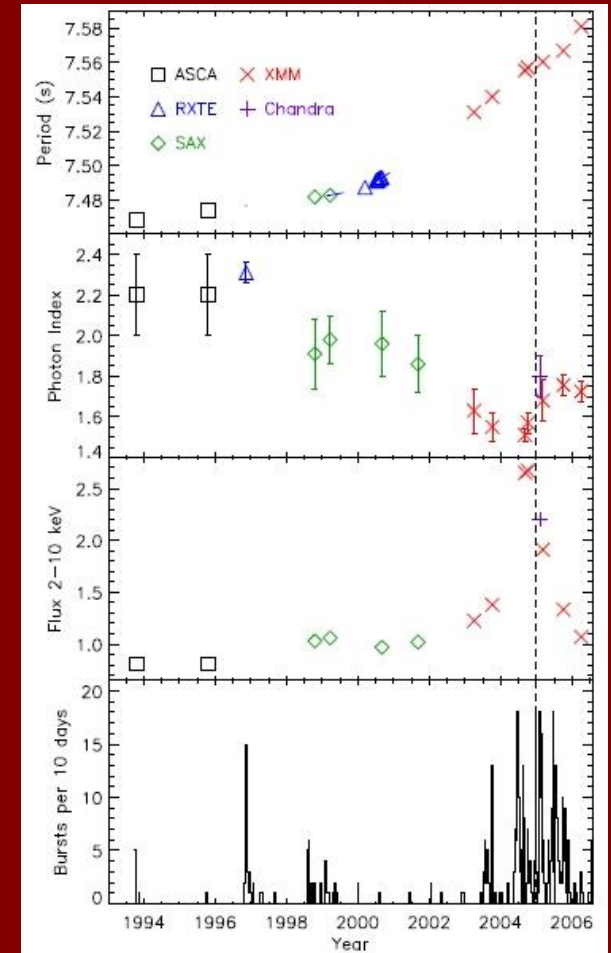
- The magnetic field inside a magnetar is “wound up”
- The presence of a toroidal field induces a rotation of the surface
- The crust tensile strength resists the deformation
- A gradual (quasi-plastic ?) deformation of the crust
- The external field twists up (Thompson, Lyutikov & Kulkarni 2002)



Growing twist

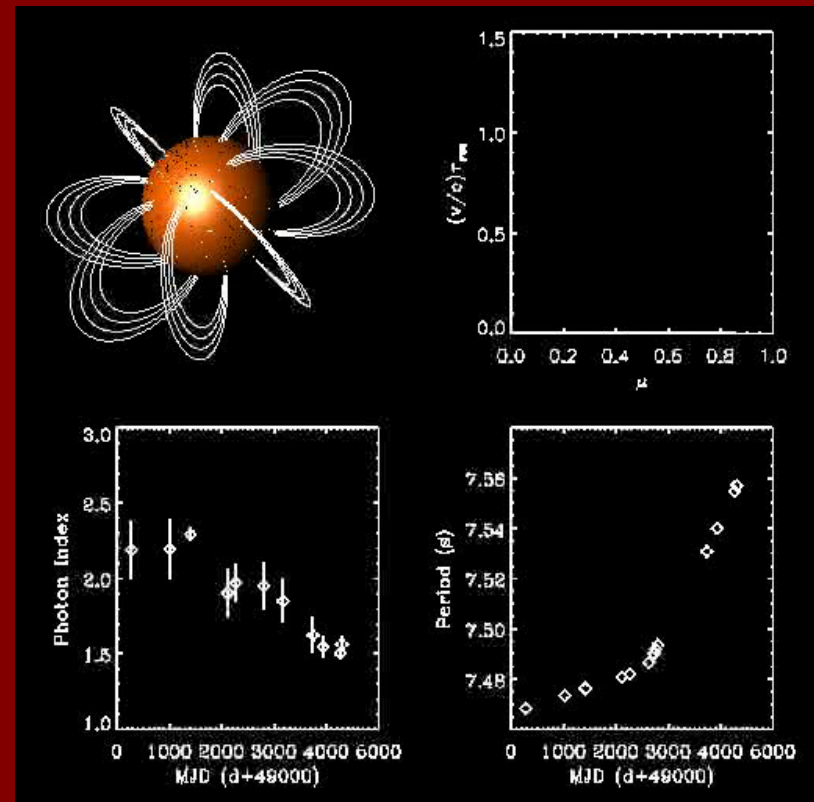


(images from Mereghetti arXiv: 0804.0250)



A Growing Twist in SGR 1806-20 ?

- Evidence for spectral hardening AND enhanced spin-down
- Γ -Pdot and Γ -L correlations
- Growth of bursting activity
- Possible presence of proton cyclotron line only during bursts



All these features are consistent with an increasingly twisted magnetosphere

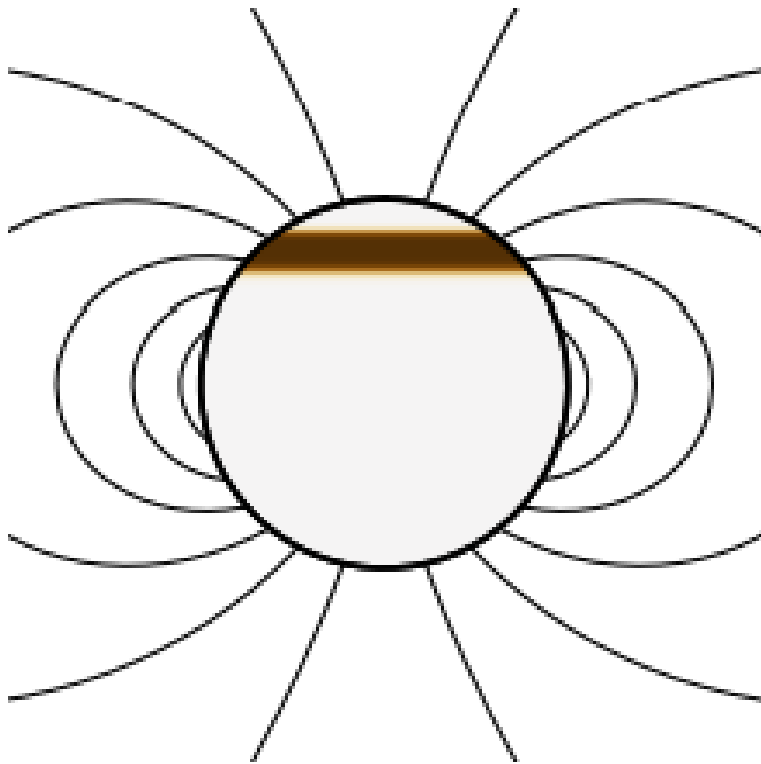
Twisted magnetospheres

- Twisted magnetosphere model, within magnetar scenario, in general agreement with observations
- Resonant scattering of thermal, surface photons produces spectra with right properties
- Many issues need to be investigated further
 - Twist of more general external fields
 - Detailed models for magnetospheric currents
 - More accurate treatment of cross section including QED effects and electron recoil
 - 10-100 keV tails: up-scattering by (ultra)relativistic ($e^\pm$) particles ?
 - Create an archive to fit model spectra to observations

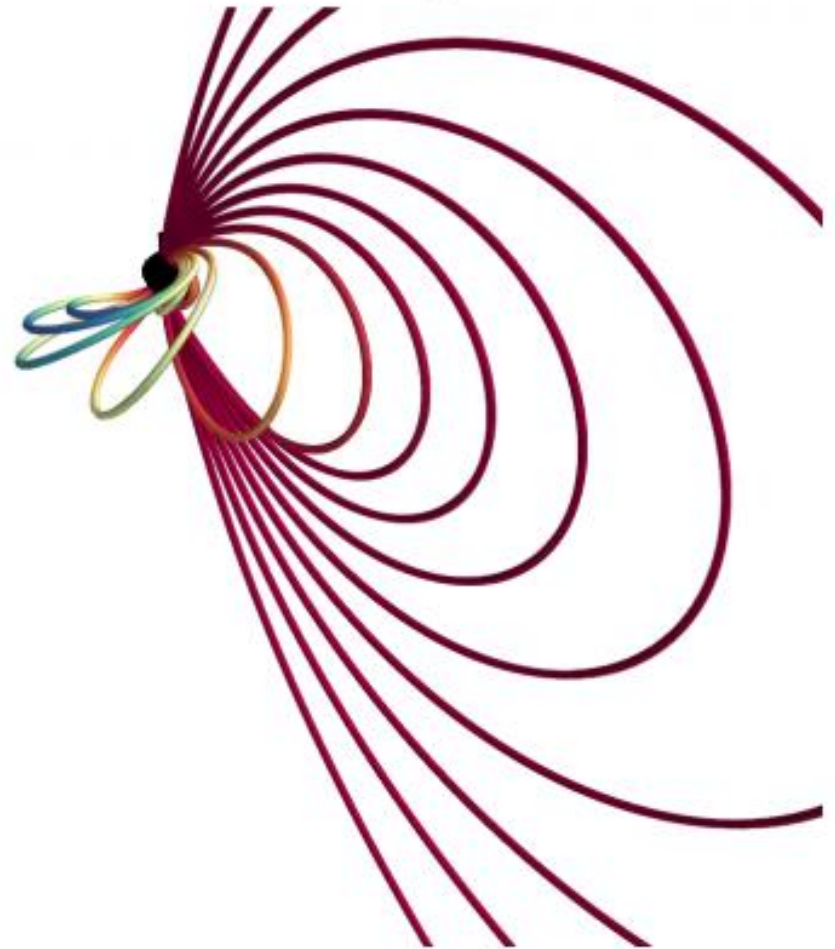
See, for example, arXiv: 1008.4388 and references therein
and more recent studies in 1201.3635

Non-global twist model

(c) Ring

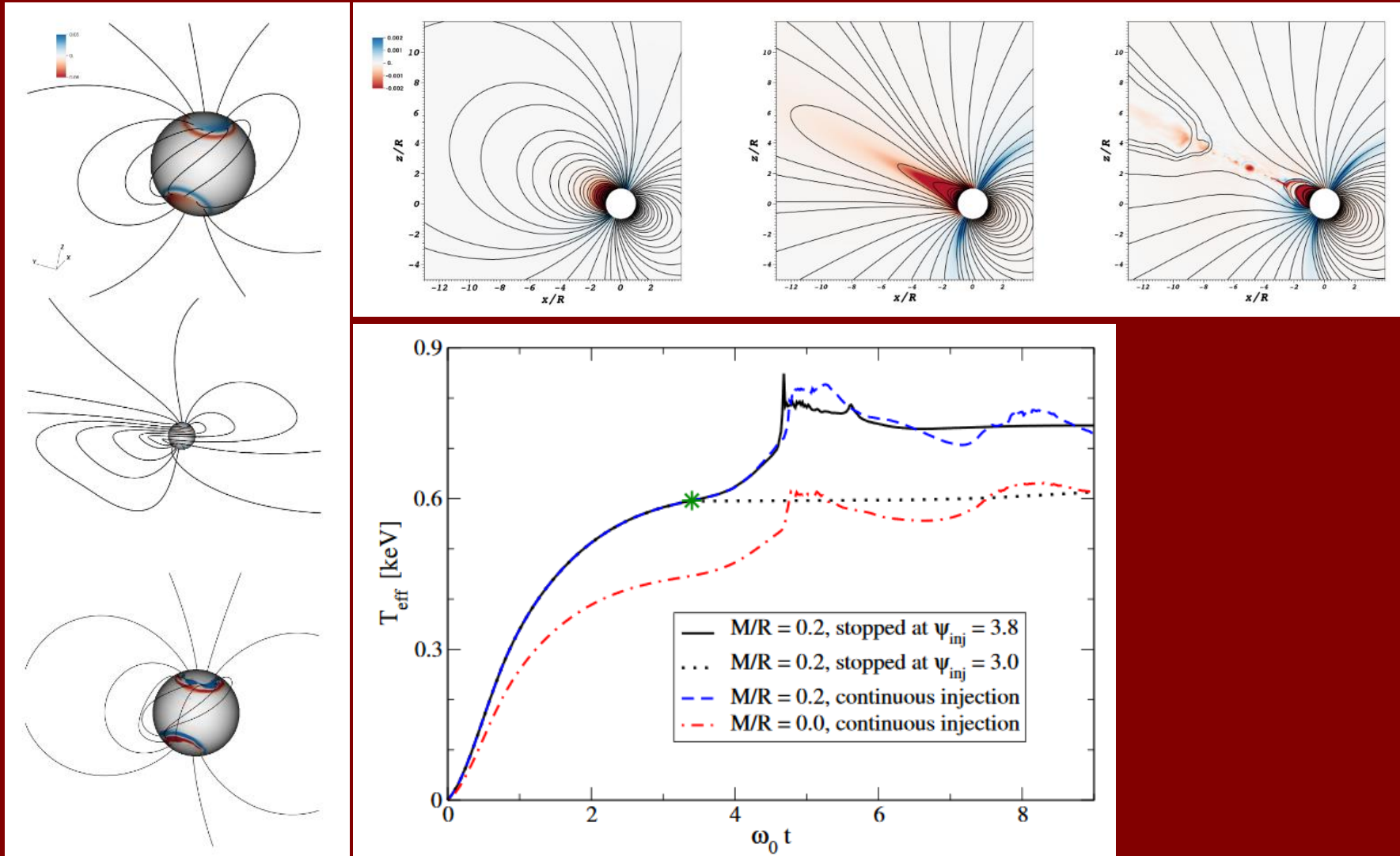


Ring

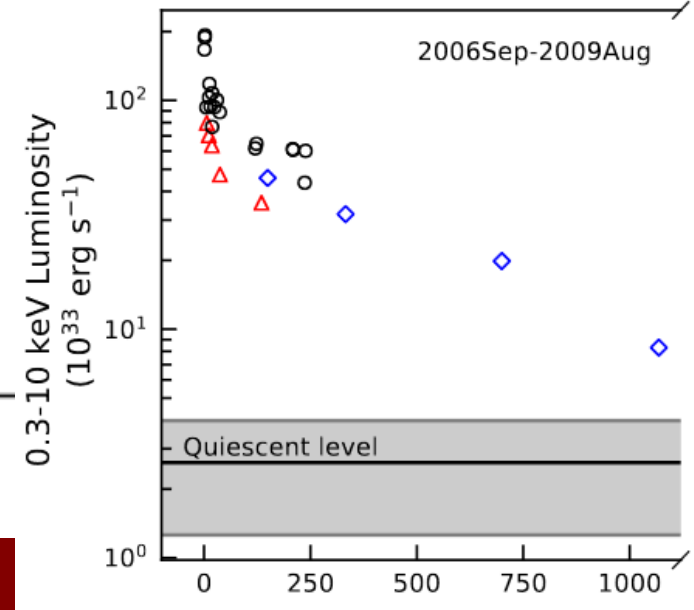
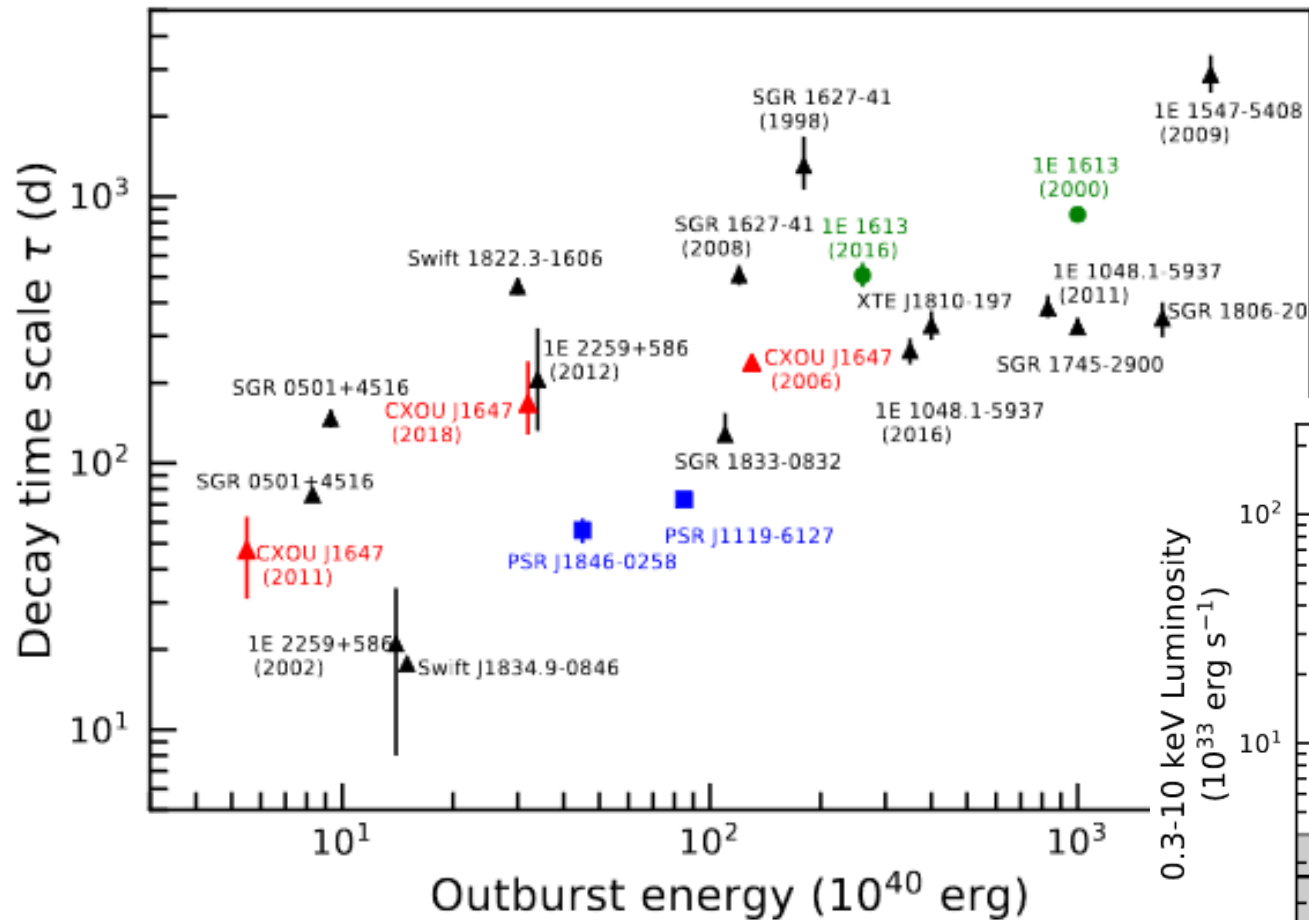


Energy in the twist: $\sim I^2 R_{\text{NS}} / c^2$
Twist decay time ~ 1 yr for typical parms

Numerical simulation of the twist



Outburst decay vs. released energy



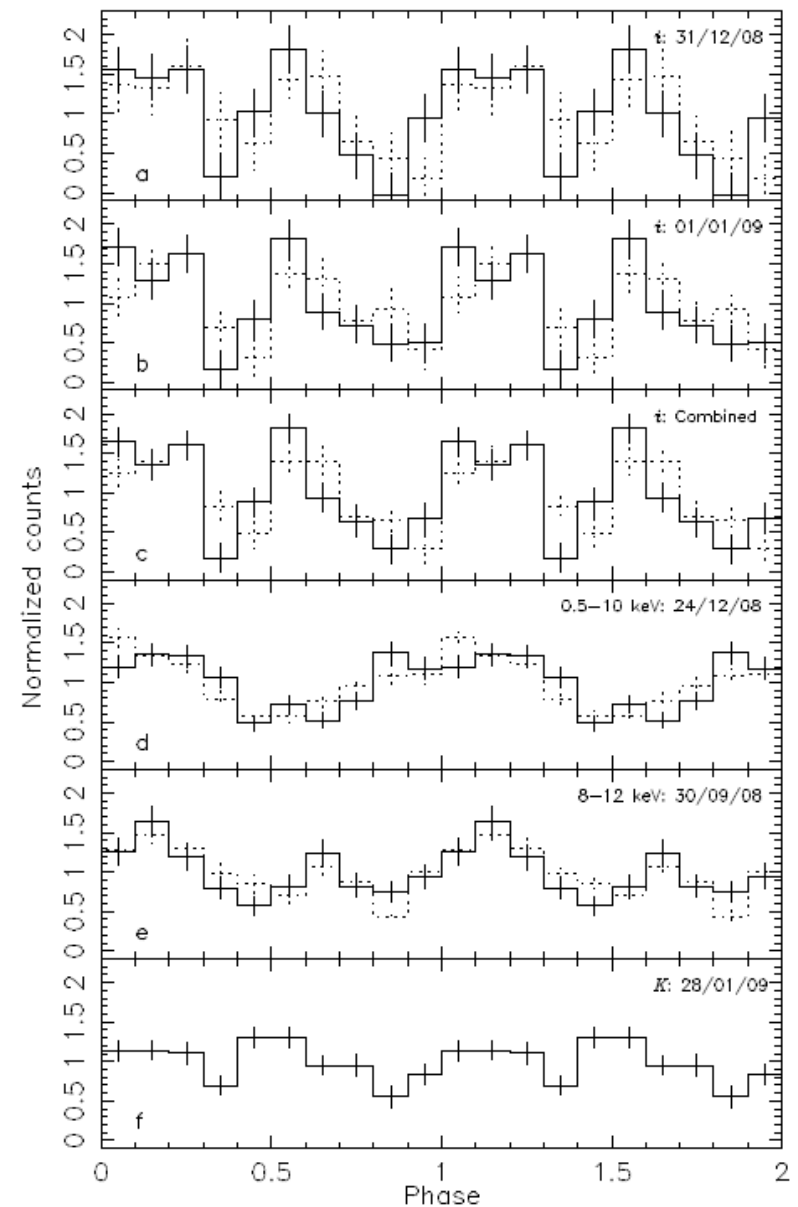
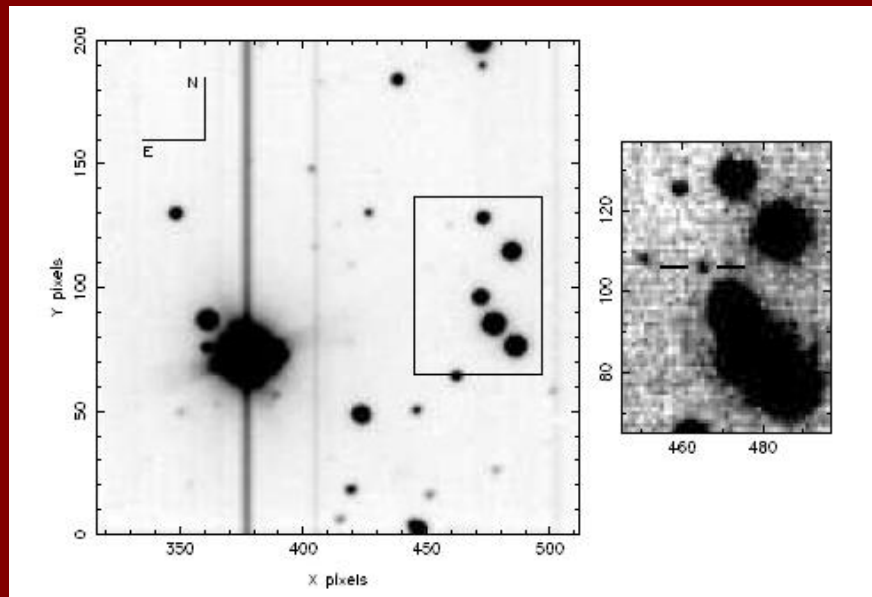
Optical pulsations

SGR 0501+4516

$P=5.76$ s

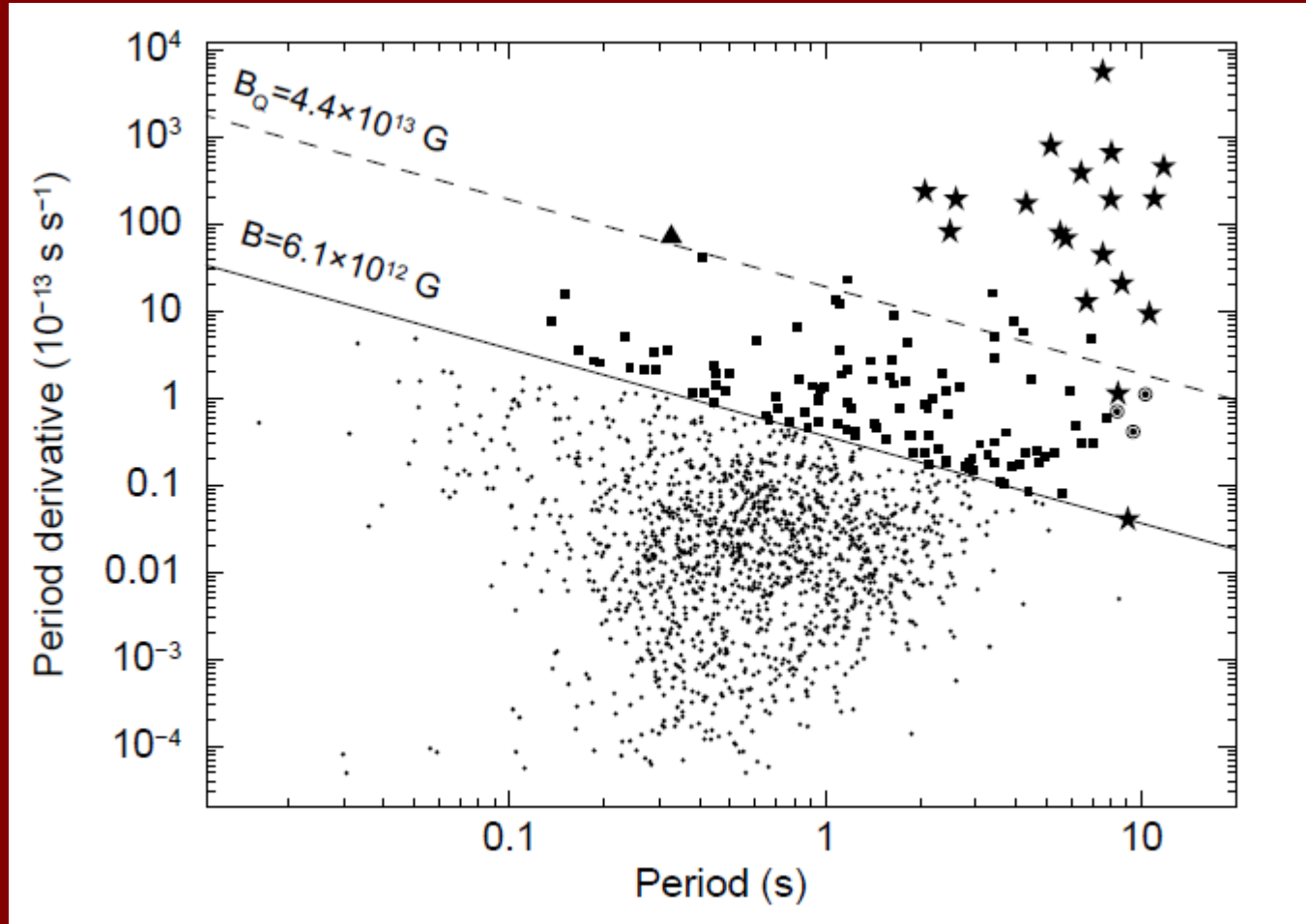
$d=0.8$ kpc – the closest!

4.2m William Herschel Telescope



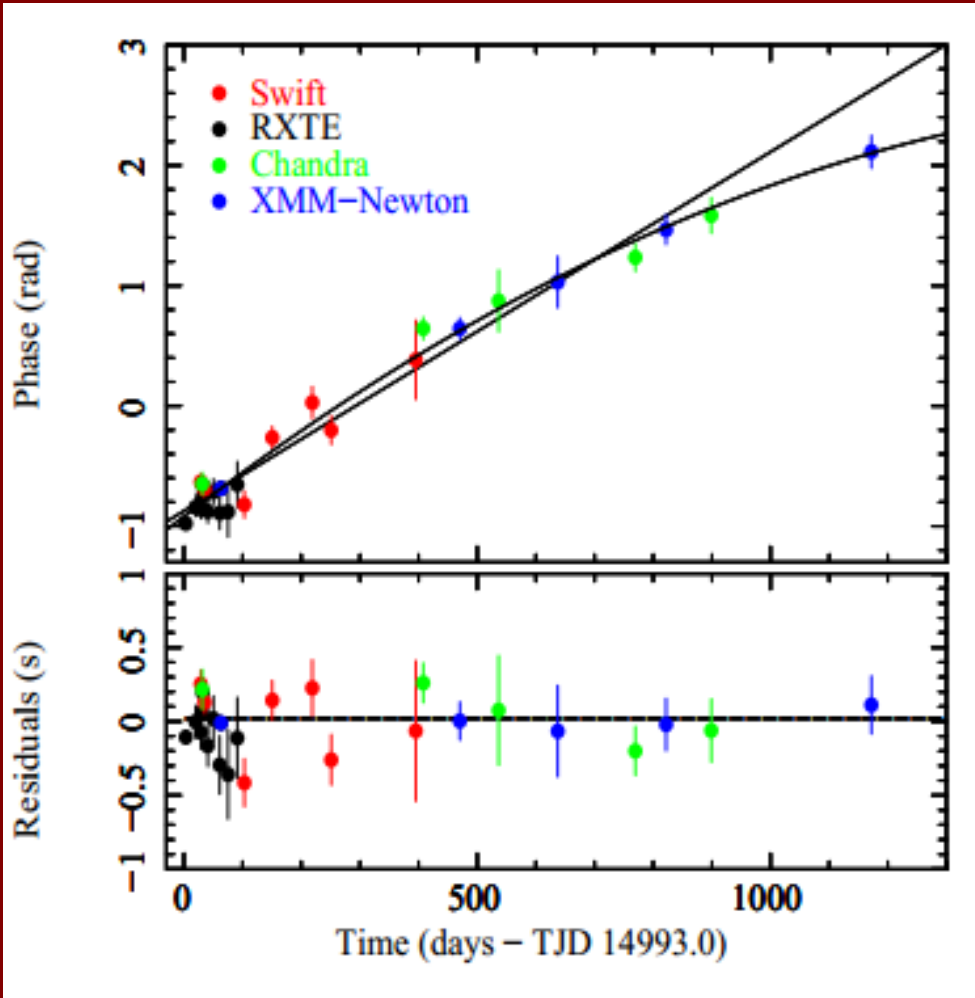
Low-field magnetars

SGR 0418+5729 and Swift J1822.3–160



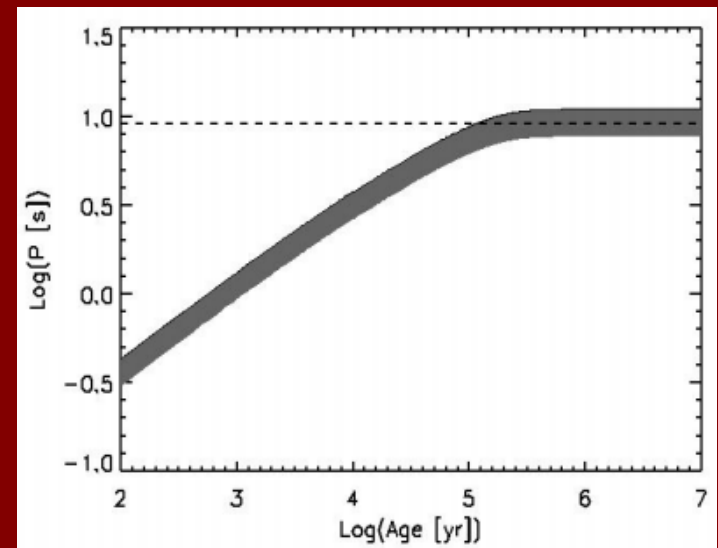
See a review in [arXiv:1303.6052](https://arxiv.org/abs/1303.6052)

The first low-field magnetar



Only after ~ 3 years of observations it was possible to detect spin-down.

The dipolar field is $\sim 6 \cdot 10^{12}$ G.

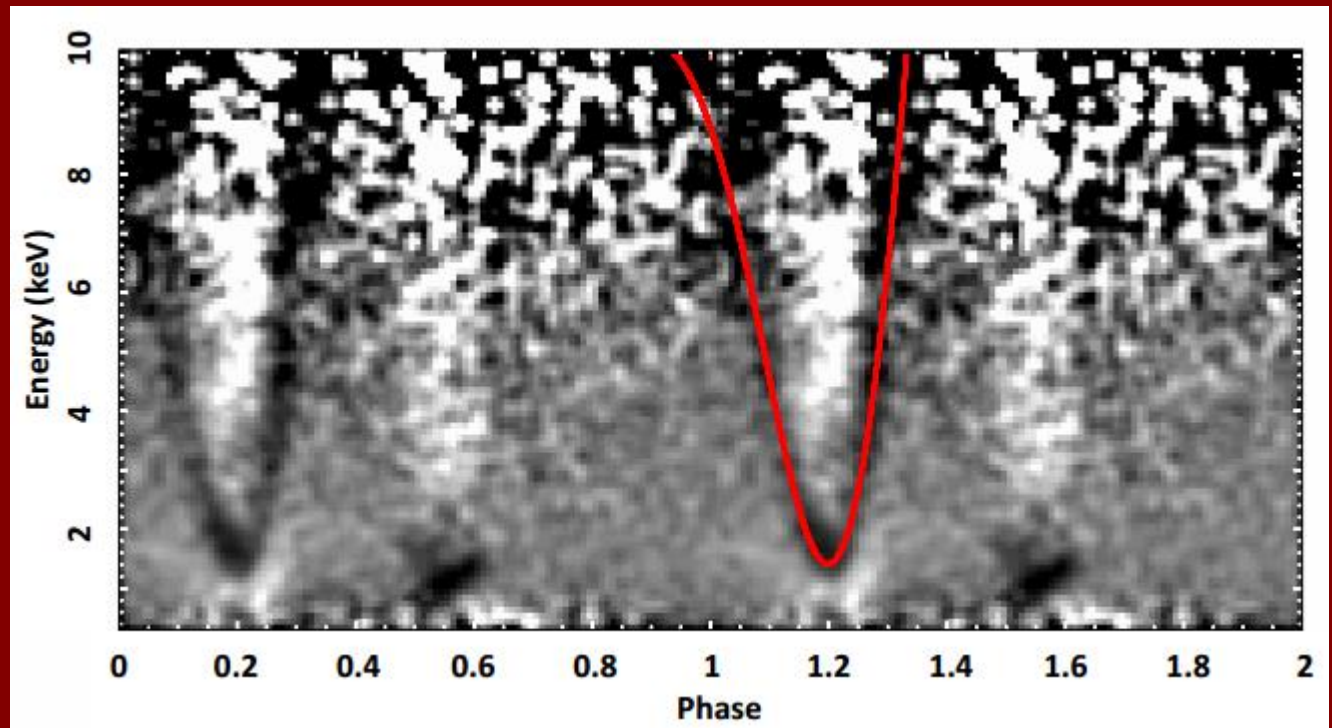


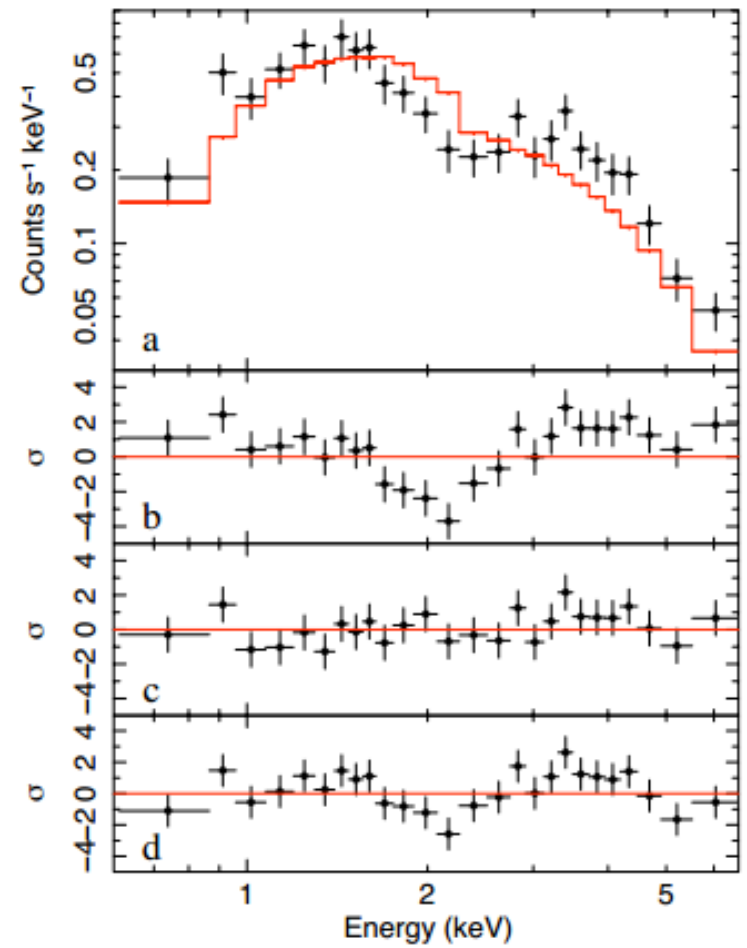
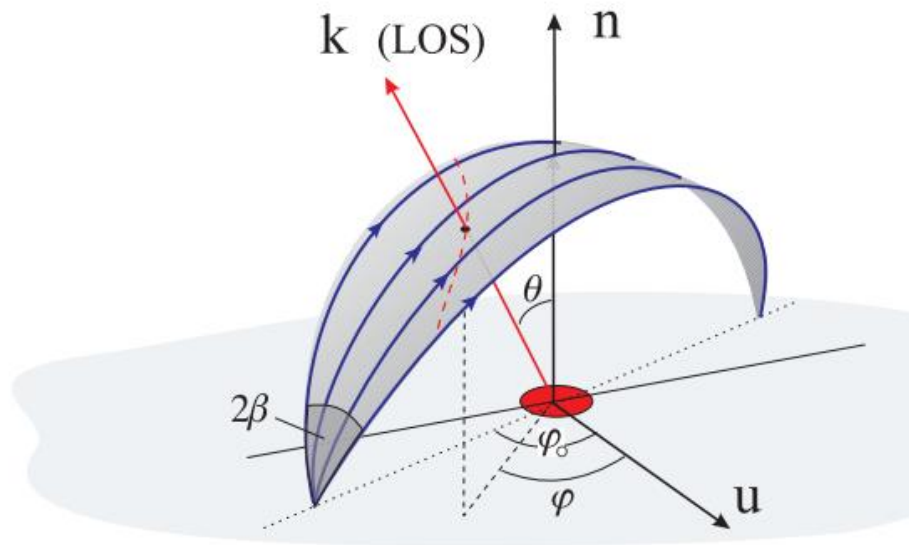
The dipolar field could decay, and activity is due to the toroidal field.

Large field (at last) ... But multipoles!

XMM-Newton observations allowed to detect a spectral line which is variable with phase.

If the line is interpreted as a proton cyclotron line, then the field in the absorbing region is $2 \cdot 10^{14} - 10^{15}$ G





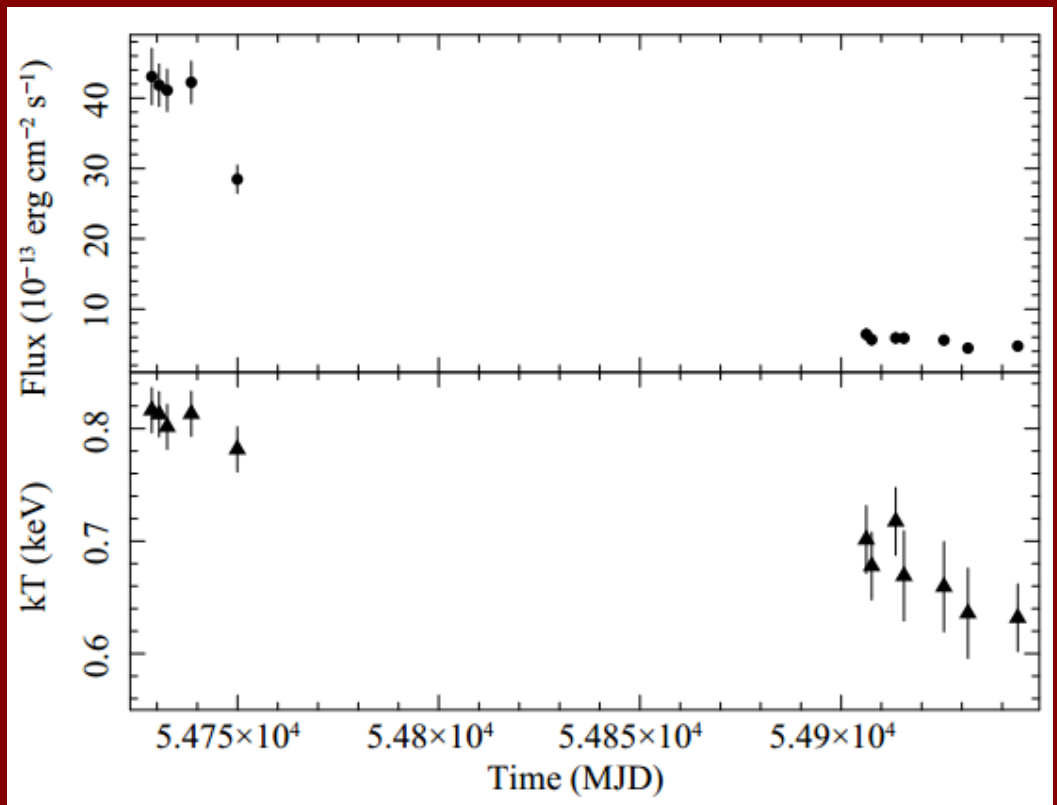
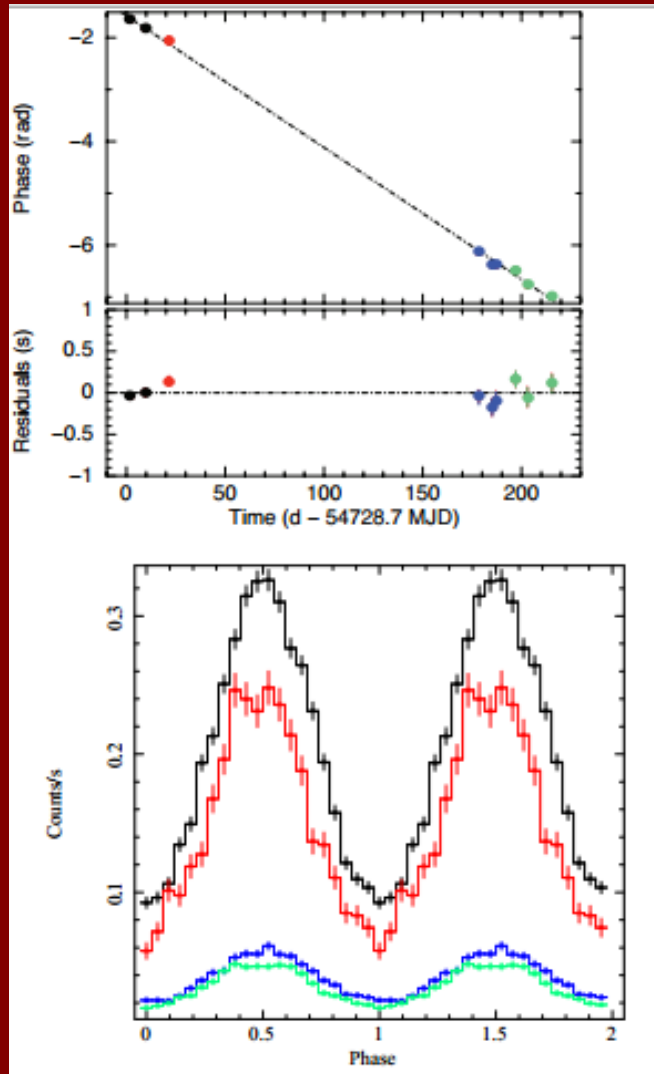
Another low-field magnetar

3XMM J185246.6+003317

$P=11.5$ s No spin-down detected after 7 months

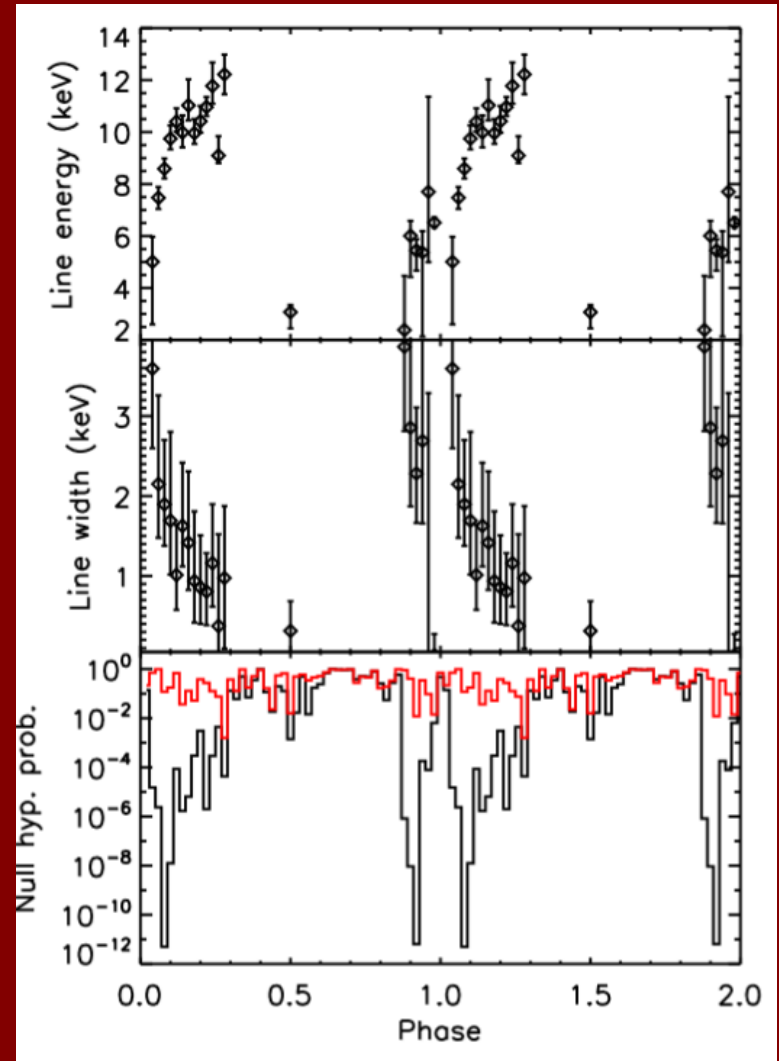
$B < 4 \times 10^{13}$ G

Transient magnetar

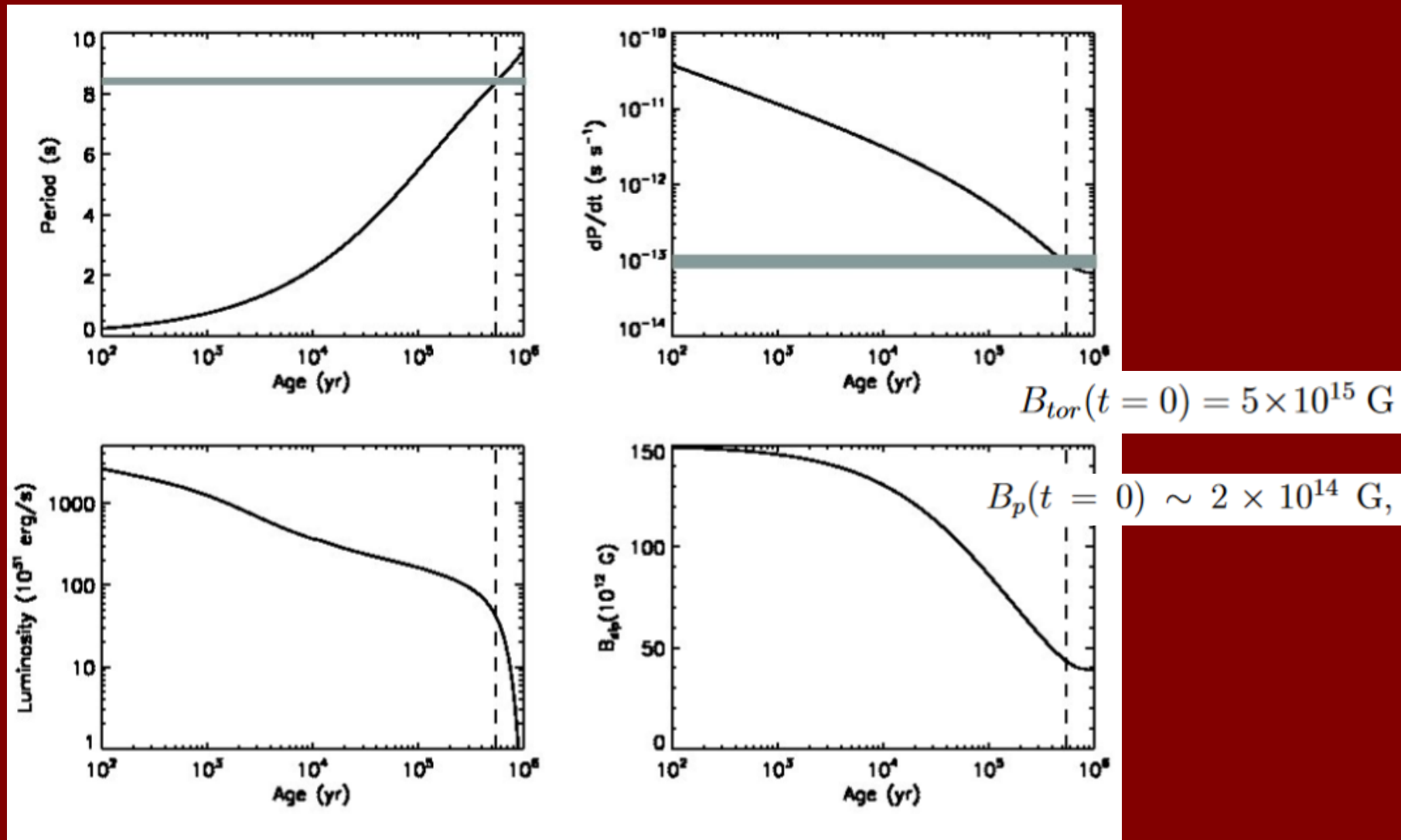


More lines in low-field magnetars

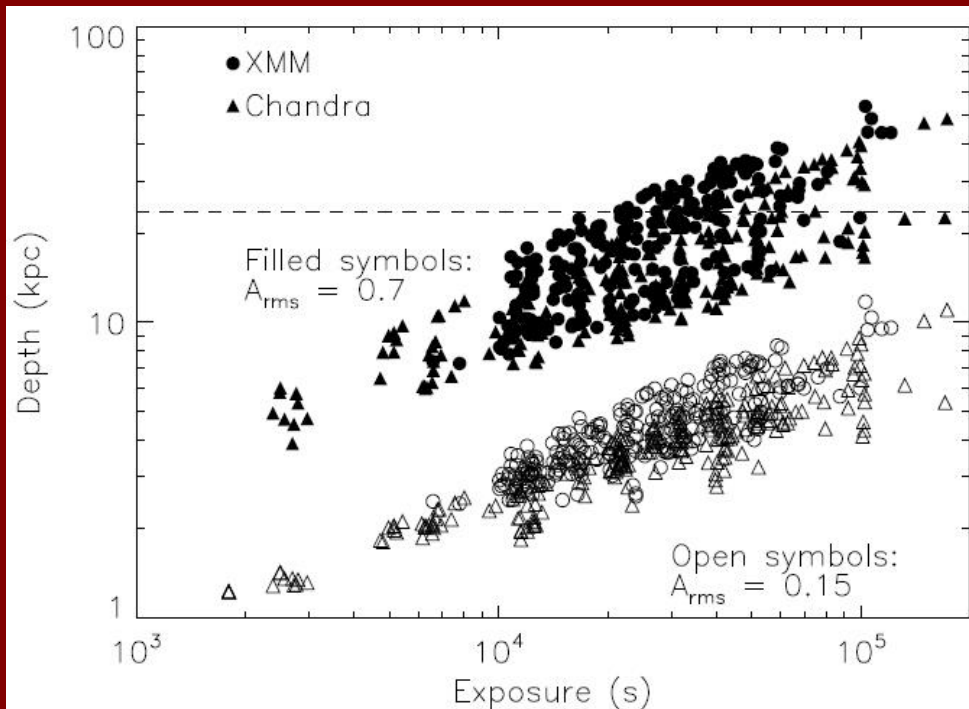
phase-dependent absorption line



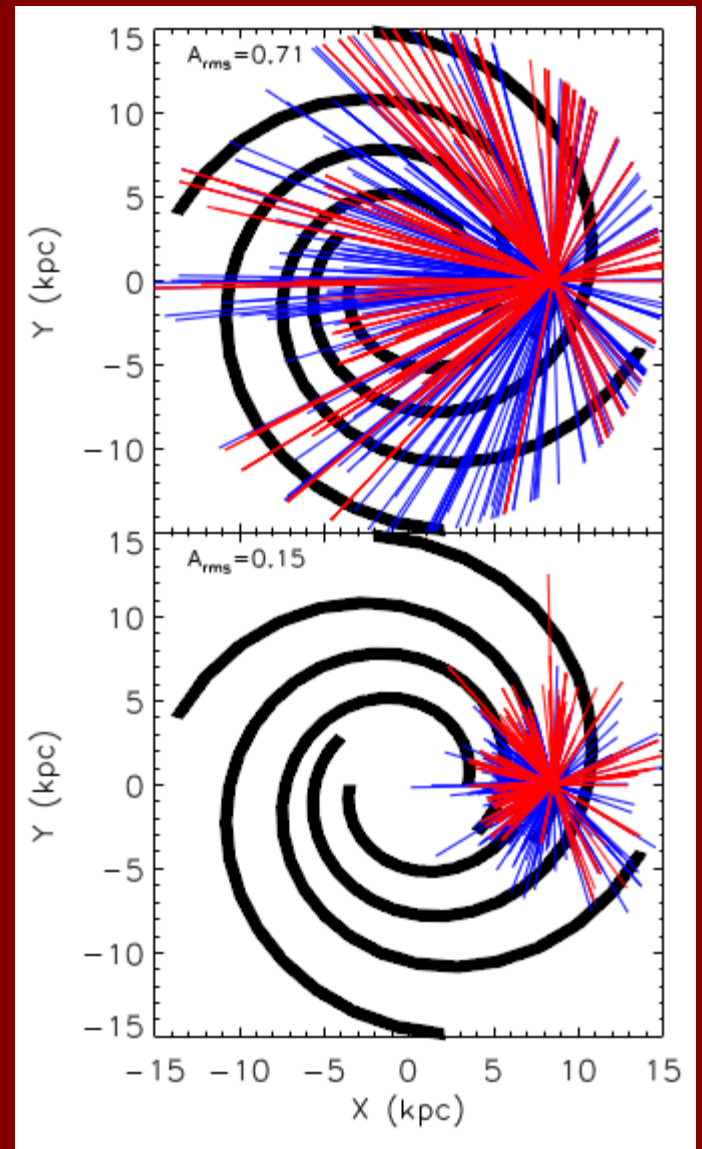
Old evolved sources?



How many magnetars?



<540 barely-detectable ($L=3 \cdot 10^{33}$ $A_{\text{rms}}=15\%$)
 59^{+92}_{-32} easily detectable ($L=10^{35}$ $A_{\text{rms}}=70\%$)



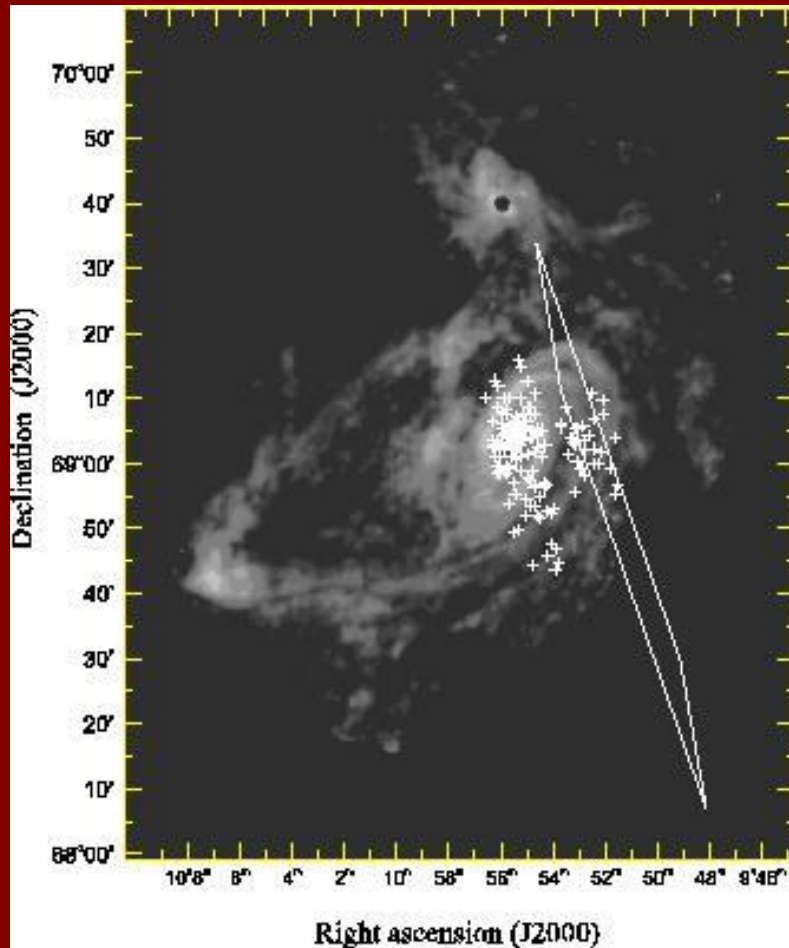
Extragalactic giant flares

Initial enthusiasm that most of short GRBs can be explained as giant flares of extraG SGRs disappeared.

At the moment, we have a definite deficit of extraG SGR bursts, especially in the direction of Virgo cluster (Popov, Stern 2006; Lazzatti et al. 2006).

However, there are several good candidates.

Extragalactic SGRs



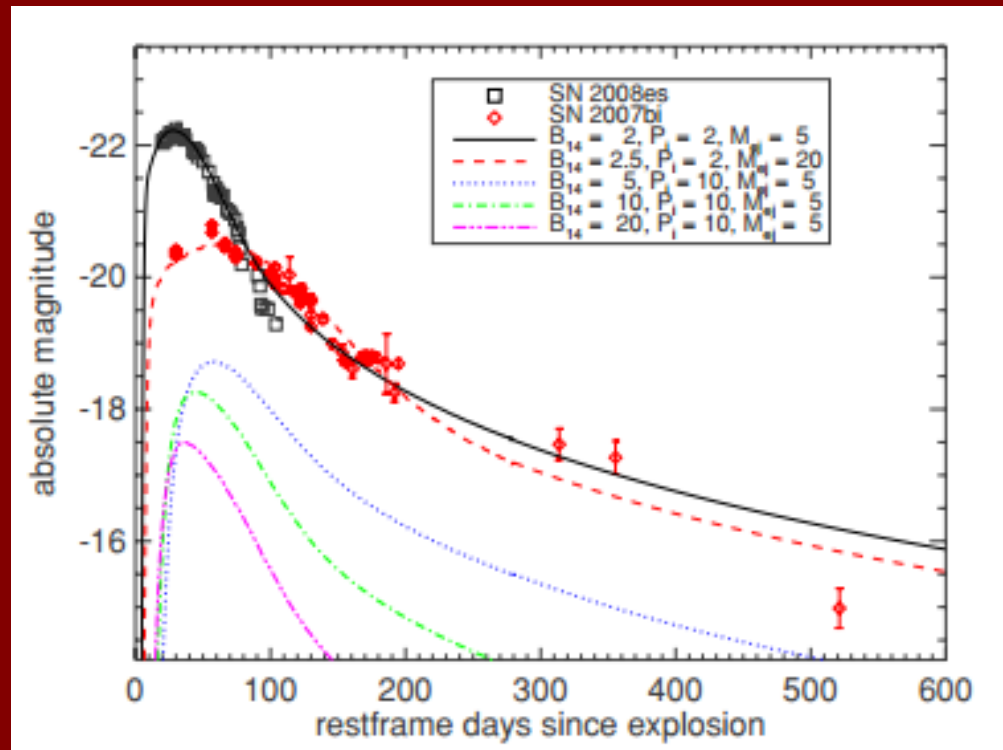
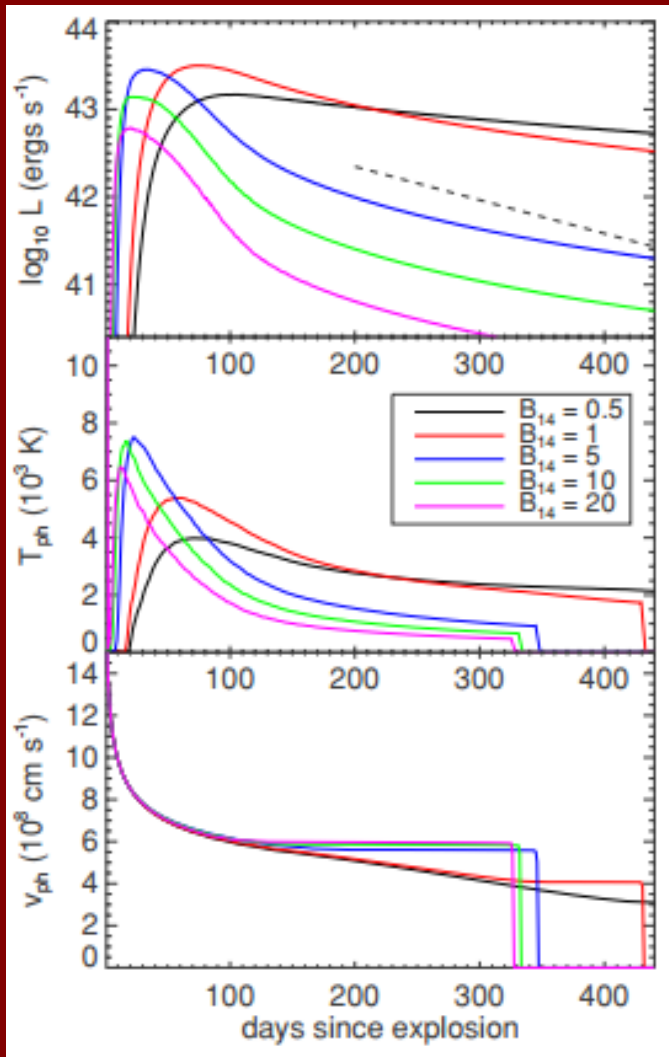
It was suggested long ago (Mazets et al. 1982) that present-day detectors could already detect giant flares from extragalactic magnetars.

However, all searches in, for example, BATSE database did not provide clear candidates (Lazzati et al. 2006, Popov & Stern 2006, etc.).

Finally, recently several good candidates have been proposed by different groups (Mazets et al., Frederiks et al., Golenetskii et al., Ofek et al, Crider).

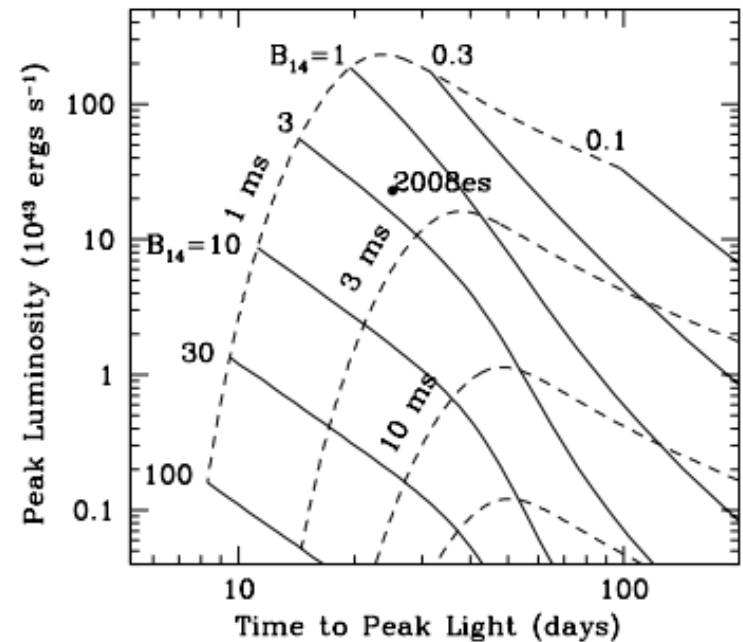
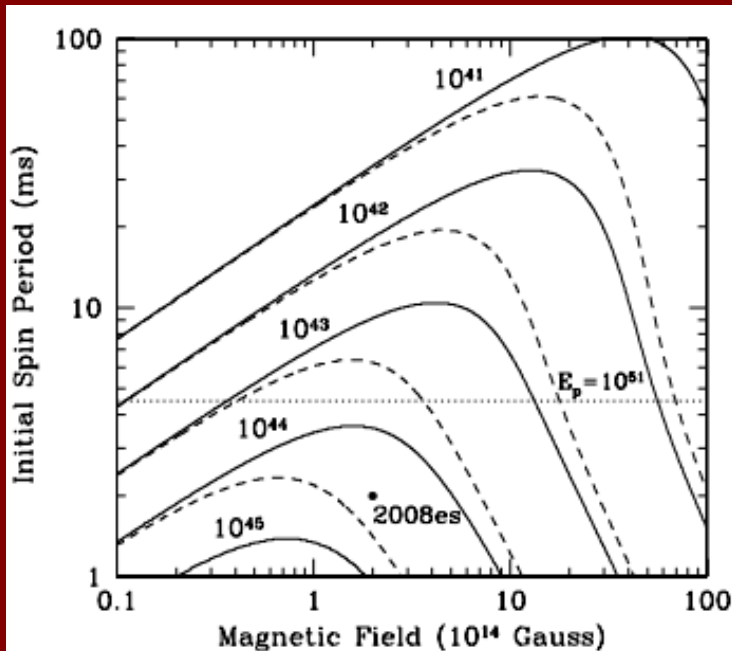
Magnetars and supernovae

With large field and short spin a newborn NS can contribute a lot to the luminosity of a SN.

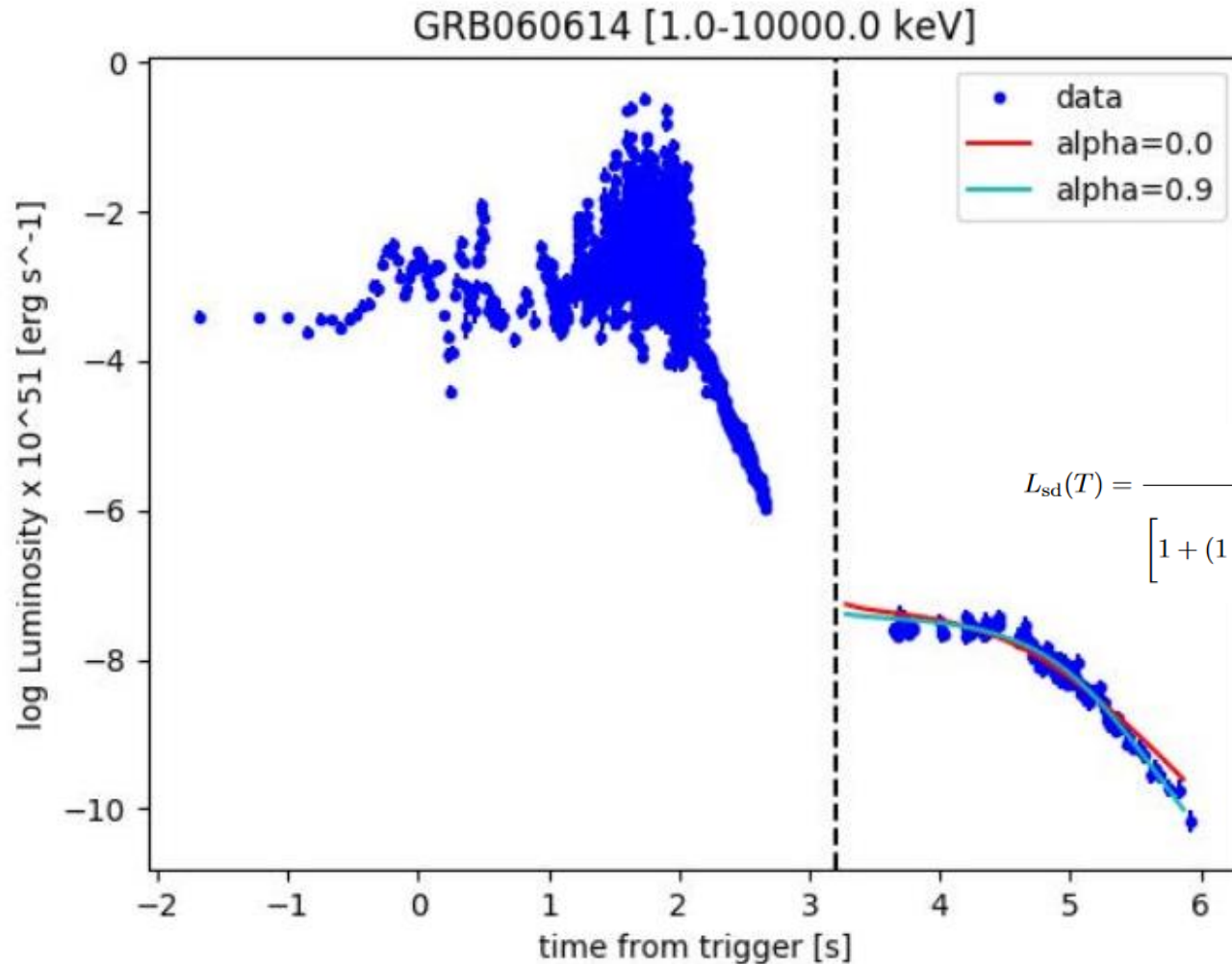


Parameters needed

For short initial spin periods it is not even necessary to have magnetar scale B.



Magnetars and GRBs



$$L_{\text{sd}} = \frac{\mu^2}{c^3} \Omega^4 (1 + \sin^2 \theta)$$

$$L_{\text{sd}}^{(N-1)} = L_{\text{sd}} \left(\frac{\Omega}{\Omega_i} \right)^{-2\alpha}$$

$$n = 3 - 2\alpha.$$

$$L_{\text{sd}}(T) = \frac{L_{\text{sd},i} \frac{2-\alpha}{\left[1 + (1-\alpha) \frac{T}{\tau_i}\right]^{1-\alpha}}}{\tau_i \left[1 + (1-\alpha) \frac{T}{\tau_i}\right]^{1-\alpha}} = \frac{E_{\text{spin},i} \frac{2-\alpha}{\left[1 + (1-\alpha) \frac{T}{\tau_i}\right]^{1-\alpha}}}{\tau_i \left[1 + (1-\alpha) \frac{T}{\tau_i}\right]^{1-\alpha}},$$

What is special about magnetars?

Link with massive stars

There are reasons to suspect that magnetars are connected to massive stars (astro-ph/0611589, but see 1708.01626).

Link to binary stars

There is a hypothesis that magnetars are formed in close binary systems (astro-ph/0505406, 0905.3238).

The question is still on the list.



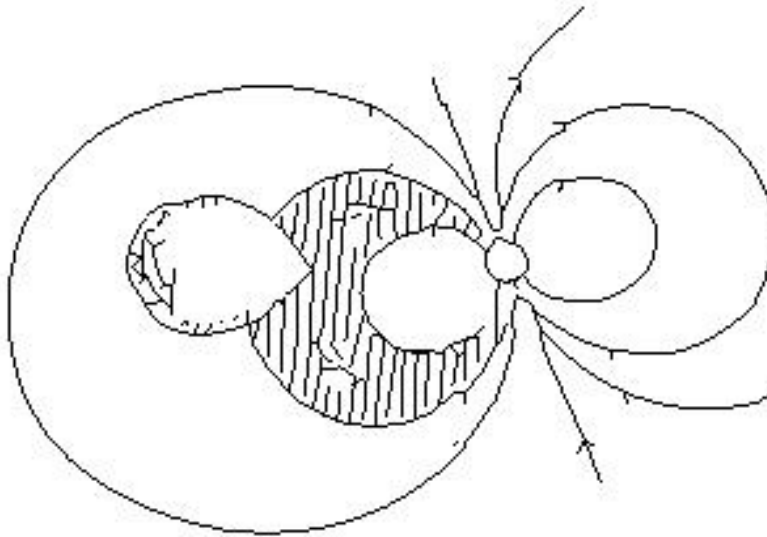
AXP in Westerlund 1 most probably has a very massive progenitor $>40 M_{\text{solar}}$.

Are there magnetars in binaries?

At the moment all known SGRs and AXPs are isolated objects.

About 10% of NSs are expected to be in binaries.

The fact that all known magnetars are isolated can be related to their origin, but this is unclear.



If a magnetar appears in a very close binary system, then an analogue of a *polar* can be formed.

The secondary star is inside the huge magnetosphere of a magnetar.

This can lead to interesting observational manifestations.

Magnetor

[arXiv:0803.1373](https://arxiv.org/abs/0803.1373)

Few candidates have been proposed based on long spin periods and large Pdots:
1203.1490, 1208.4487, 1210.7680, 1303.5507

Conclusions

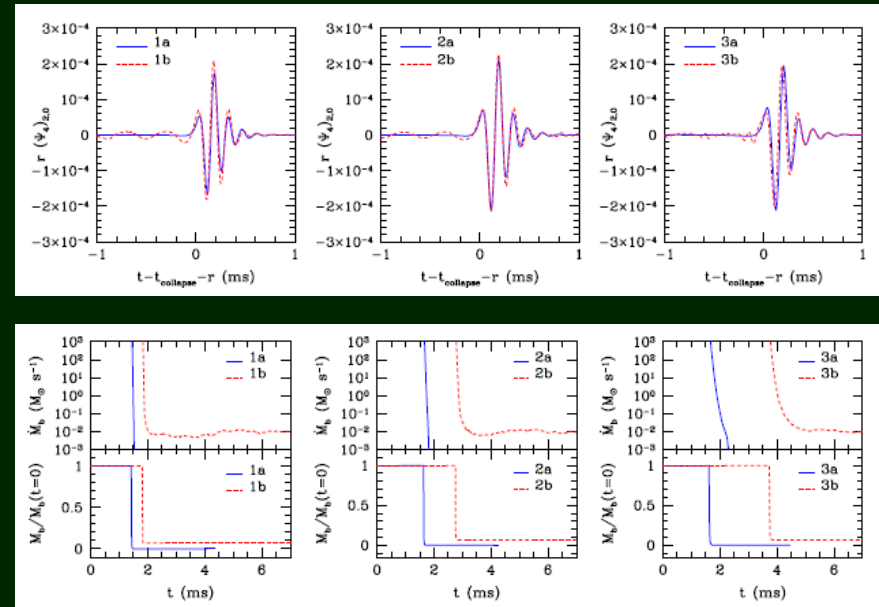
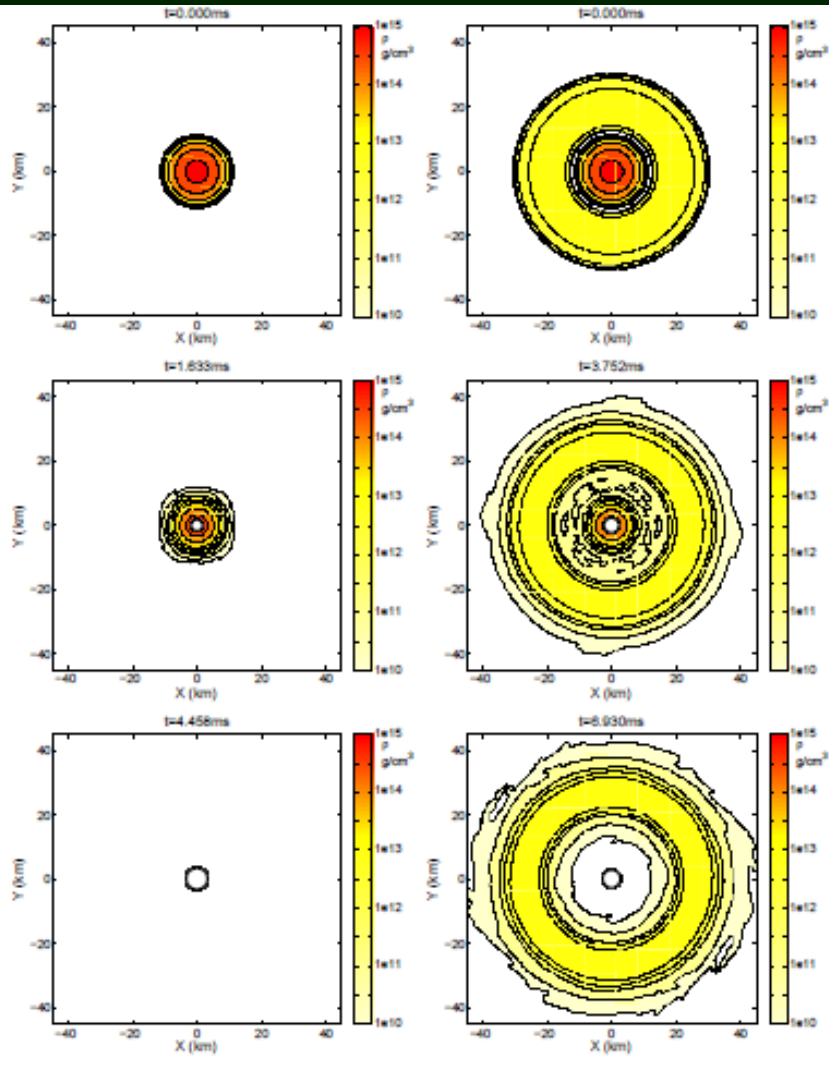
- Two classes of magnetars: SGRs and AXPs
- Similar properties (but no giant flare in AXPs, yet?)
- Hyperflares (27 Dec 2004)
- Transient magnetars
- About 10% of newborn NSs
- Links to PSRs (and others?)
- Twisted magnetospheres

Papers to read

- Woods, Thompson astro-ph/0406133 – old classical review
- Mereghetti arXiv: 0804.0250
- Rea, Esposito arXiv: 1101.4472 - bursts
- Turolla, Esposito arXiv: 1303.6052 - Low-field magnetars
- Mereghetti et al. arXiv: 1503.06313
- Turolla, Zane, Watts arXiv: 1507.02924 – Big general review
- Beloborodov, Kaspi arXiv: 1703.00068
- Esposito et al. arXiv: 1803.05716
- Coti Zelati et al. arXiv: 1710.04671 – outbursts
- Gourgouliatos, Esposito 1805.01680 – magnetic fields

Black holes: Introduction

NS to BH



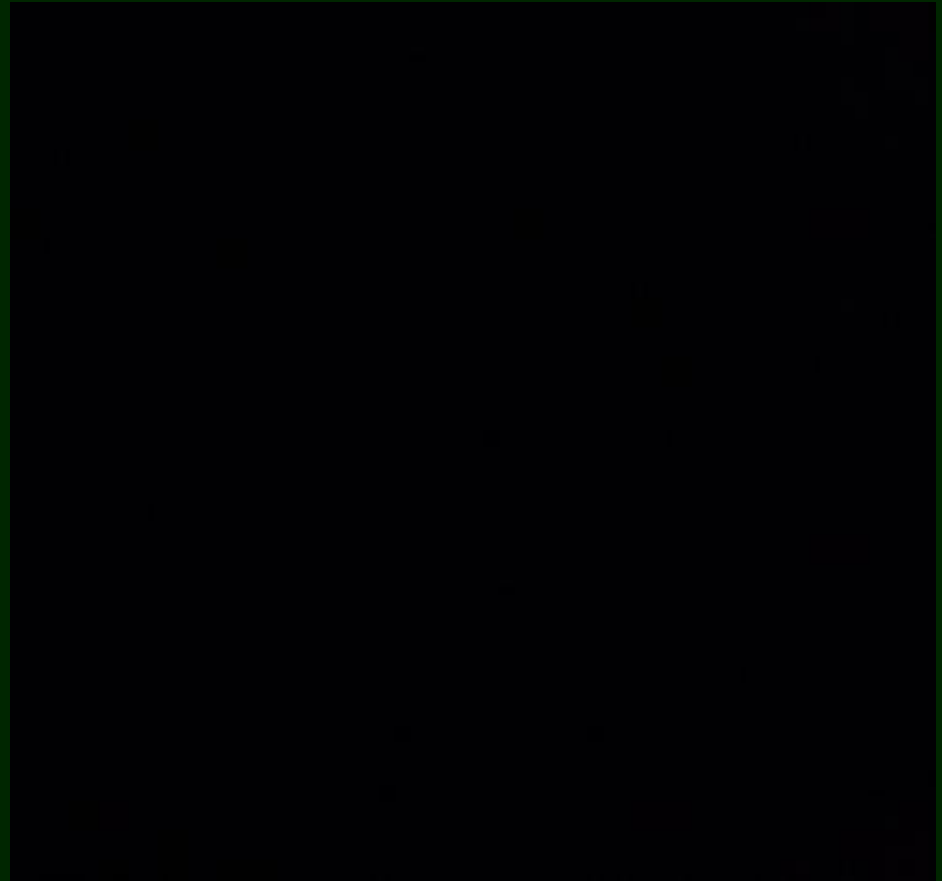
The authors studied collapse from NS to BH. Calculations were done for two cases: with and without massive (7%) disc. If a disc is present then such objects can appear as sGRB. GW signal is weak, and so they are a subject for the third generation of detectors.

Main general surveys

- [astro-ph/0610657](#) [Neven Bilic](#) BH phenomenology
- [astro-ph/0604304](#) [Thomas W. Baumgarte](#) BHs: from speculations to observations
- [hep-ph/0511217](#) [Scott A. Hughes](#) Trust but verify: the case for astrophysical BHs
- [arXiv: 0907.3602](#) [Josep M. Paredes](#) Black holes in the Galaxy
- [arXiv: 1003.0291](#) [S.-N. Zhang](#) Astrophysical Black Holes in the Physical Universe
- [arXiv: 1312.6698](#) [Narayan, McClintock](#) Observational Evidence for Black Holes
- [arXiv: 1711.10256, 1810.07032, 1810.07041](#) [C. Bambi](#)
Astrophysical black holes: several reviews
- [arXiv: 1808.01507](#) [Eric Curiel](#) The Many Definitions of a Black Hole
- [arXiv: 1809.09130](#) [Michela Mapelli](#) Astrophysics of stellar black holes

BHs as astronomical sources

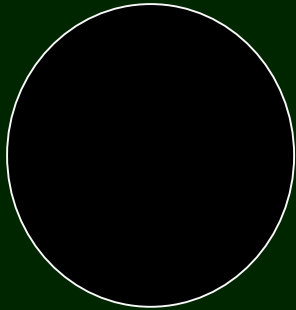
- **Primordial BHs.**
Not discovered, yet. Only upper limits (mostly from gamma-ray observations).
- **Stellar mass BHs.**
There are more than twenty good candidates in close binary systems.
Accretion, jets. Observed at all wavelengths.
Isolated stellar mass BHs are not discovered up to now.
But there are interesting candidates among microlensing events.
- **Intermediate mass BHs.**
Their existence is uncertain, but there are good candidates among ULX.
Observed in radio, x-rays, and optics.
- **Supermassive BHs.**
There are many (dozens) good candidates with mass estimates.
In the center of our Galaxy with extremely high certainty there is supermassive BH.
Accretion, jets, tidal disruptions of normal stars.
Observed at all wavelengths.



Что такое черная дыра?

Для физика

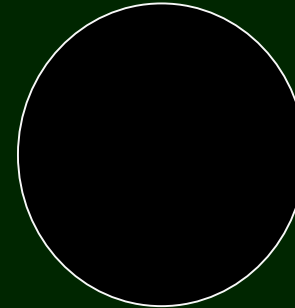
Обладает определенными внутренними свойствами



Объект, обладающий горизонтом.

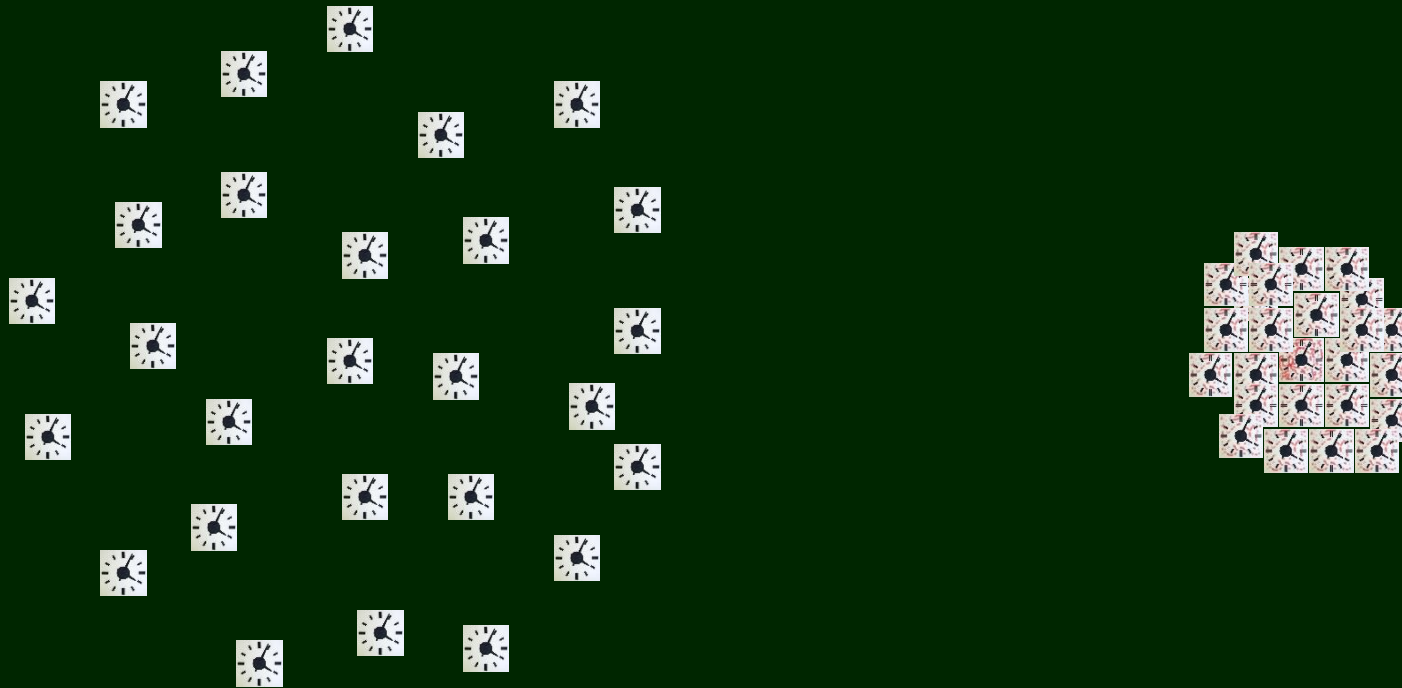
Для астронома

Обладает определенными внешними проявлениями



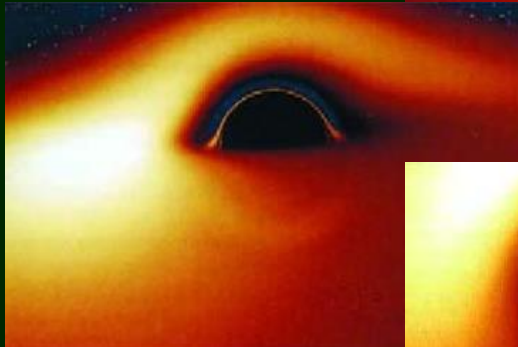
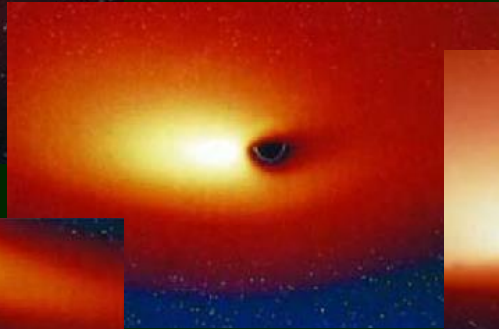
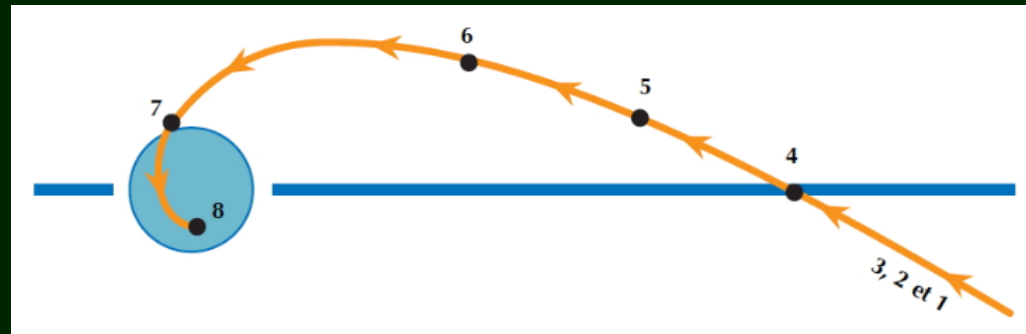
Компактное (размер горизонта) массивное тело, не проявляющее признаков наличия поверхности, и чьи недра недоступны для наблюдений.

Коллапс облака

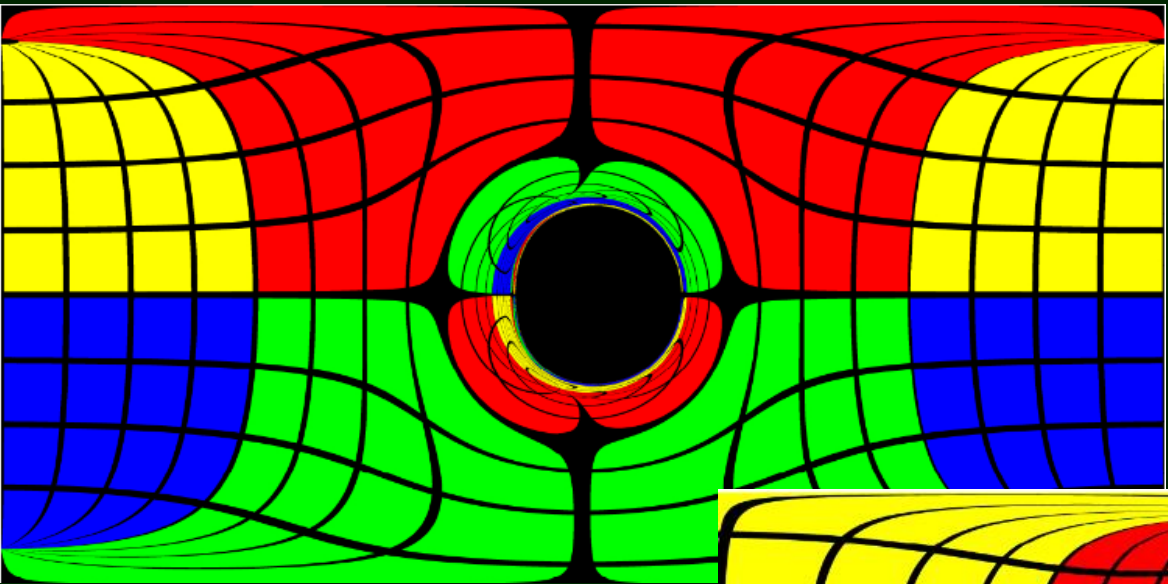


Мы всегда видим часы в центре,
но они все краснее и краснее...

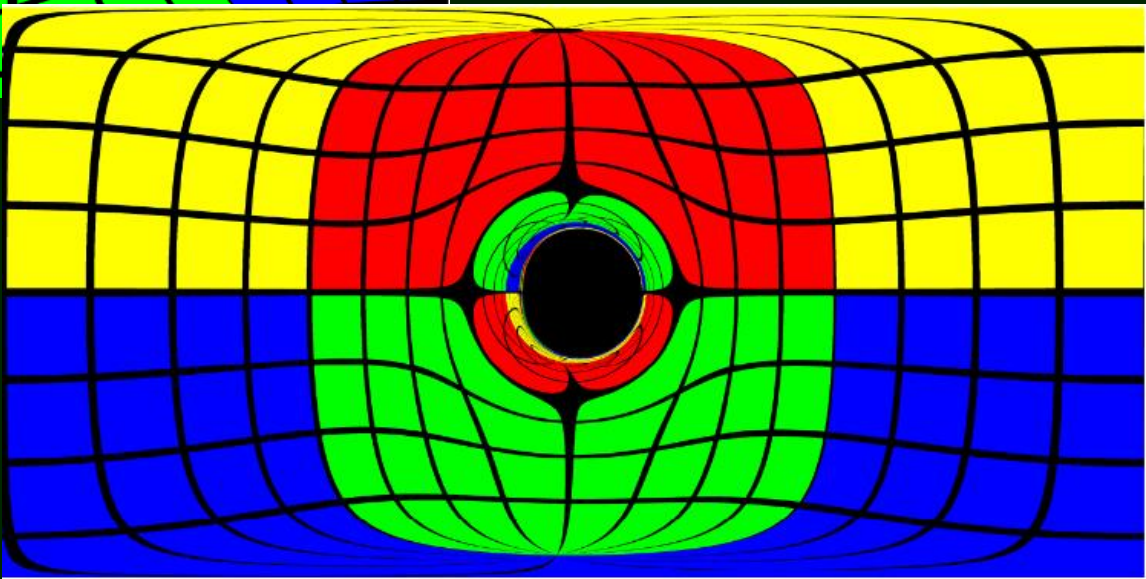
Falling into a BH



BH virtual reality



Observers at $10 R_g$.
Left: at rest.
Right (bottom): free-falling.



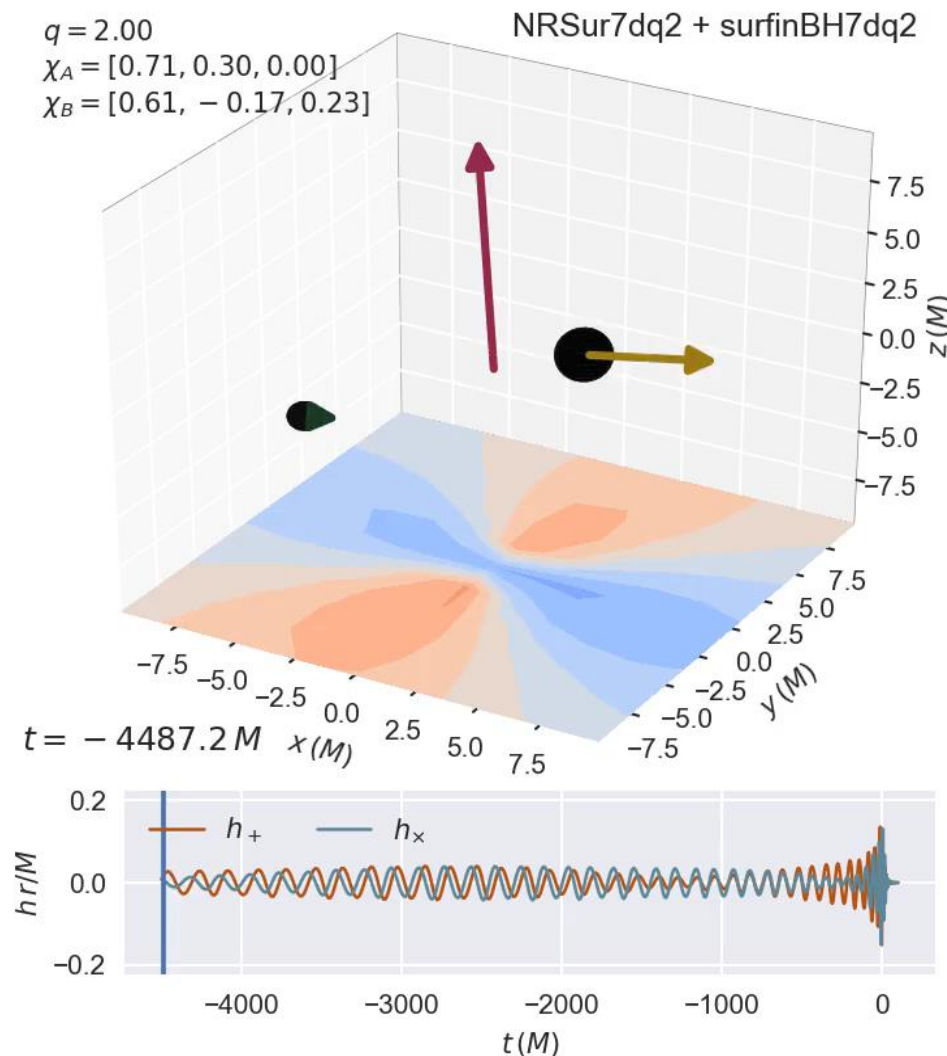
Video for Sgr A*



<https://www.youtube.com/watch?v=SXN4hvp977s>

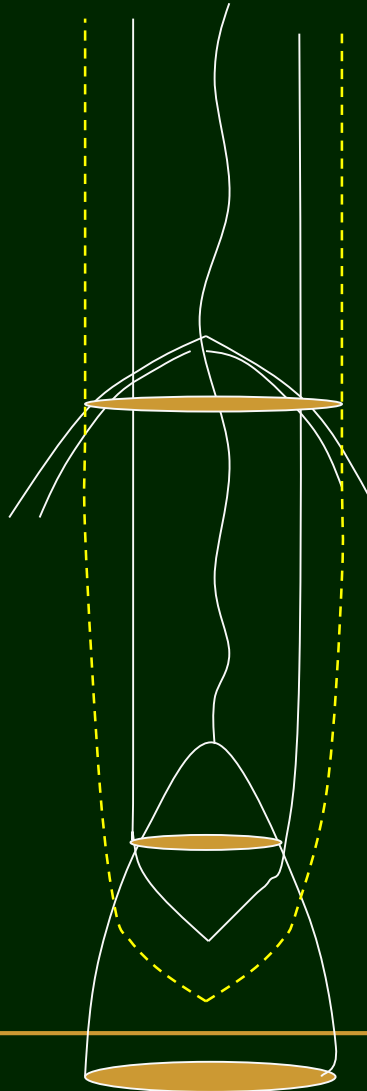
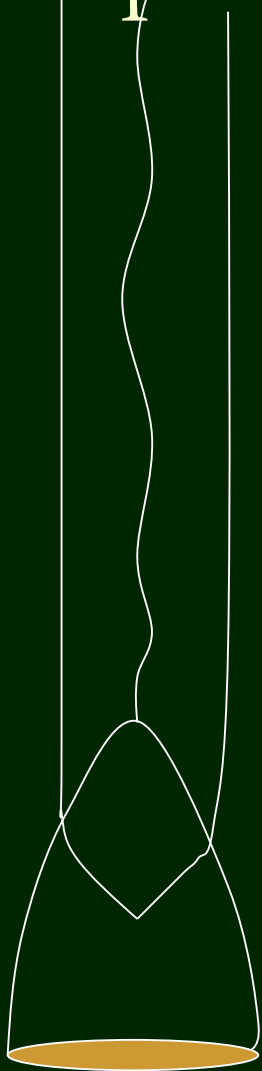
<https://blackholecam.org/>

Binary BH visualization



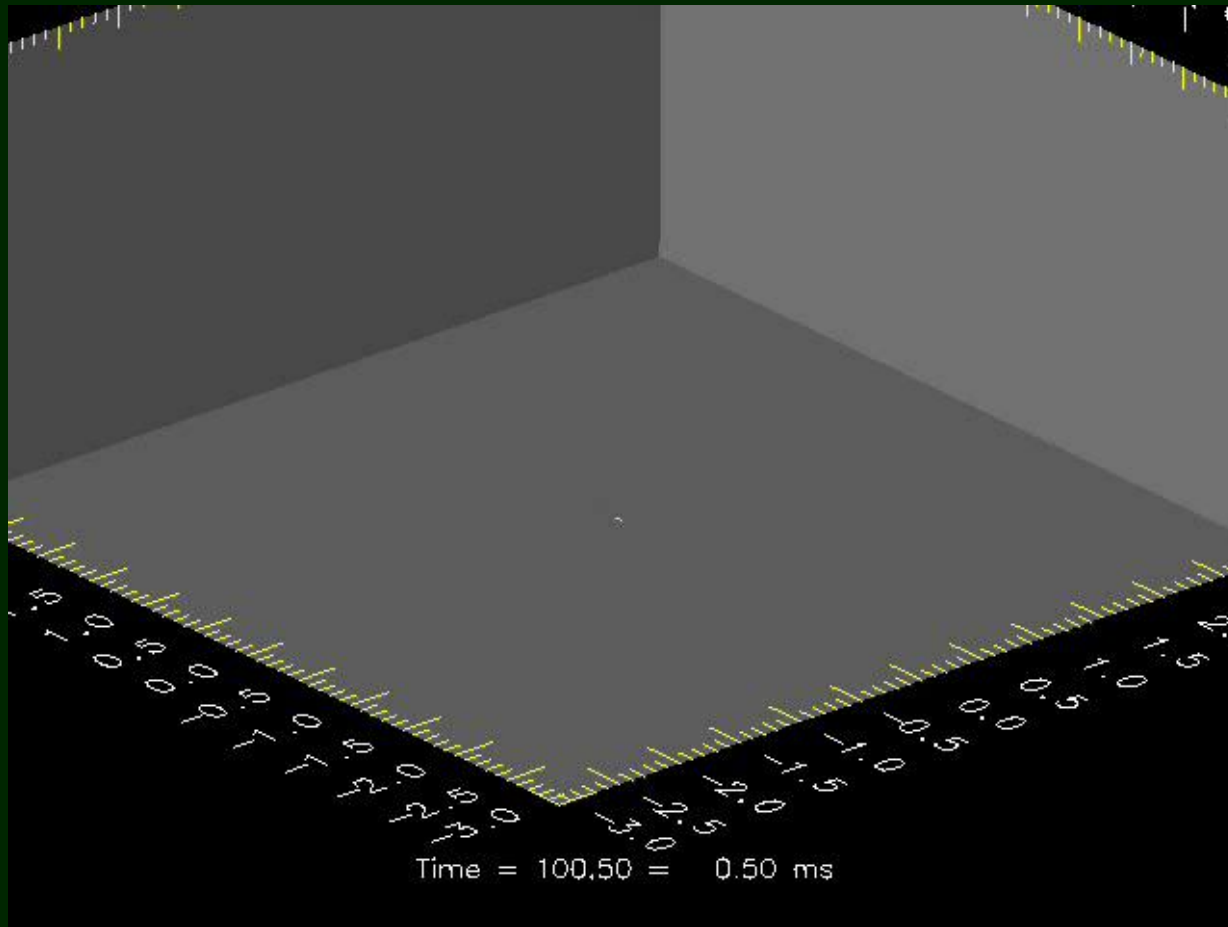
The black holes are shown as oblate spheres, with arrows indicating their spins. The orbital angular momentum is indicated by the pink arrow at the origin. The colors in the bottom-plane shows the value of the plus polarization of the GW as seen by an observer at that location; red means positive and blue means negative, notice the quadrupolar pattern of the radiation. In the subplot at the bottom, we show the plus and cross polarizations as seen from the camera viewing angle.

Горизонты

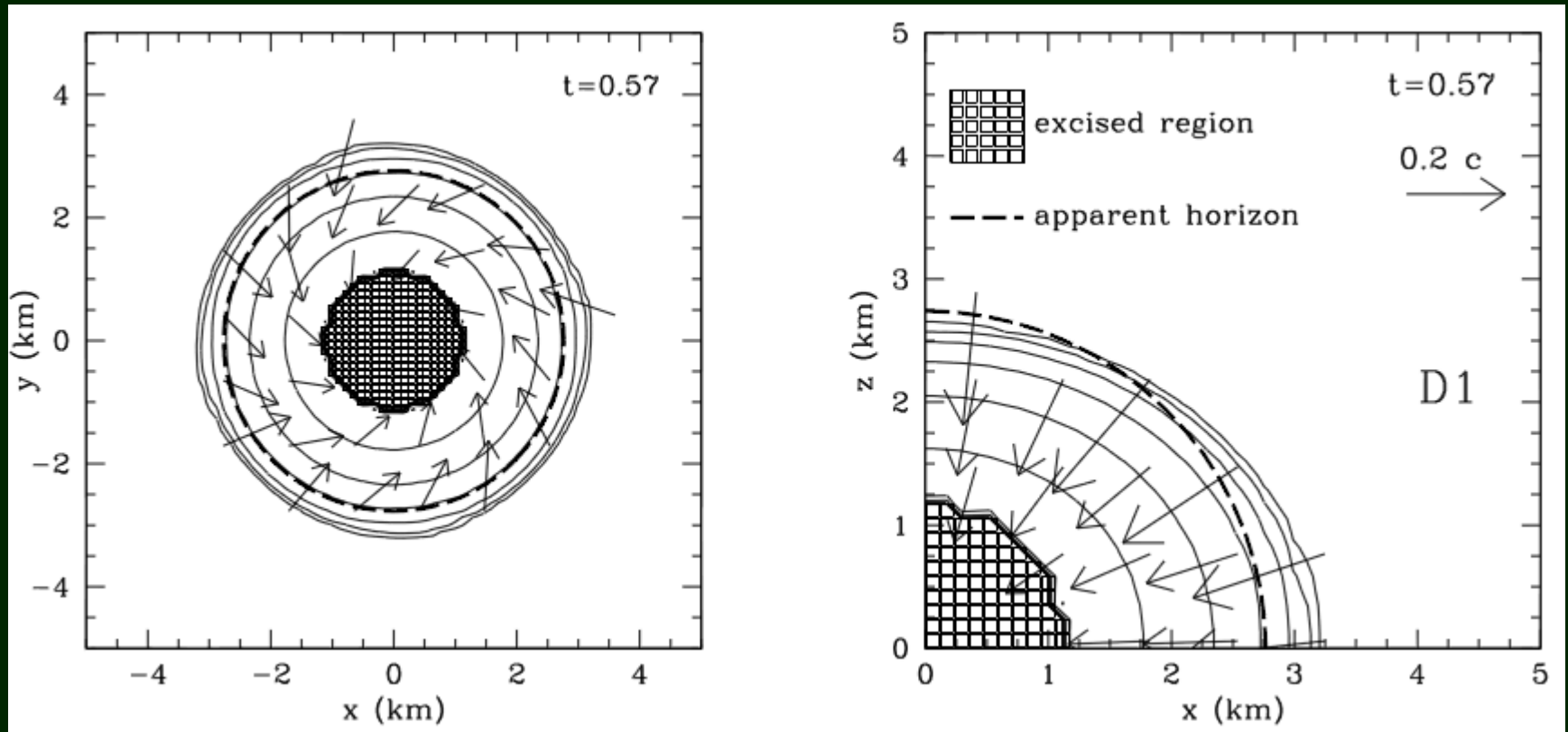


Теорема об отсутствии волос:
«Черные дыры не имеют волос».
Черная дыра полностью описывается
массой и вращением.

Horizons appearance



ΚΟΛΛΑΠΣ

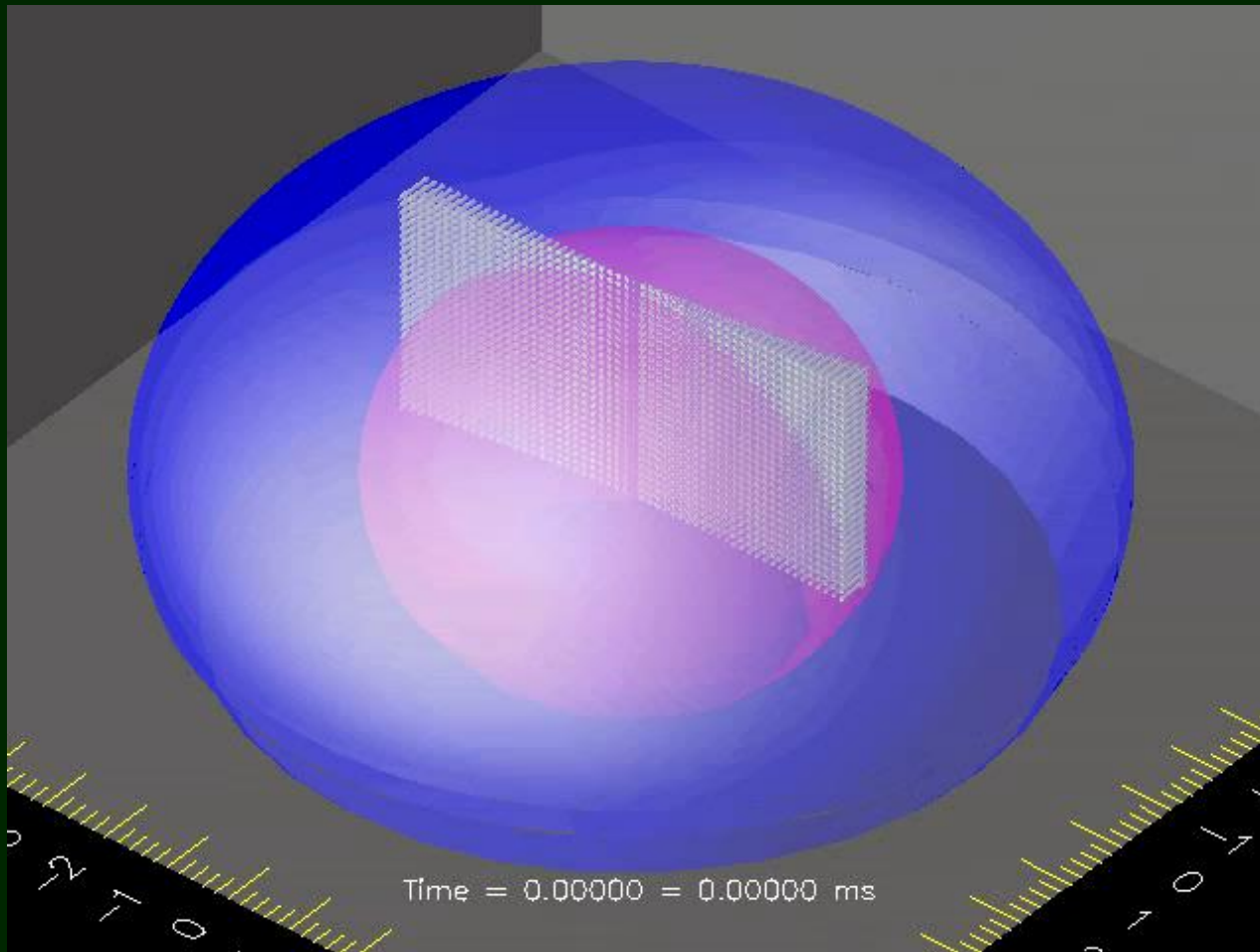


Apparent horizon position is calculated at every time step.

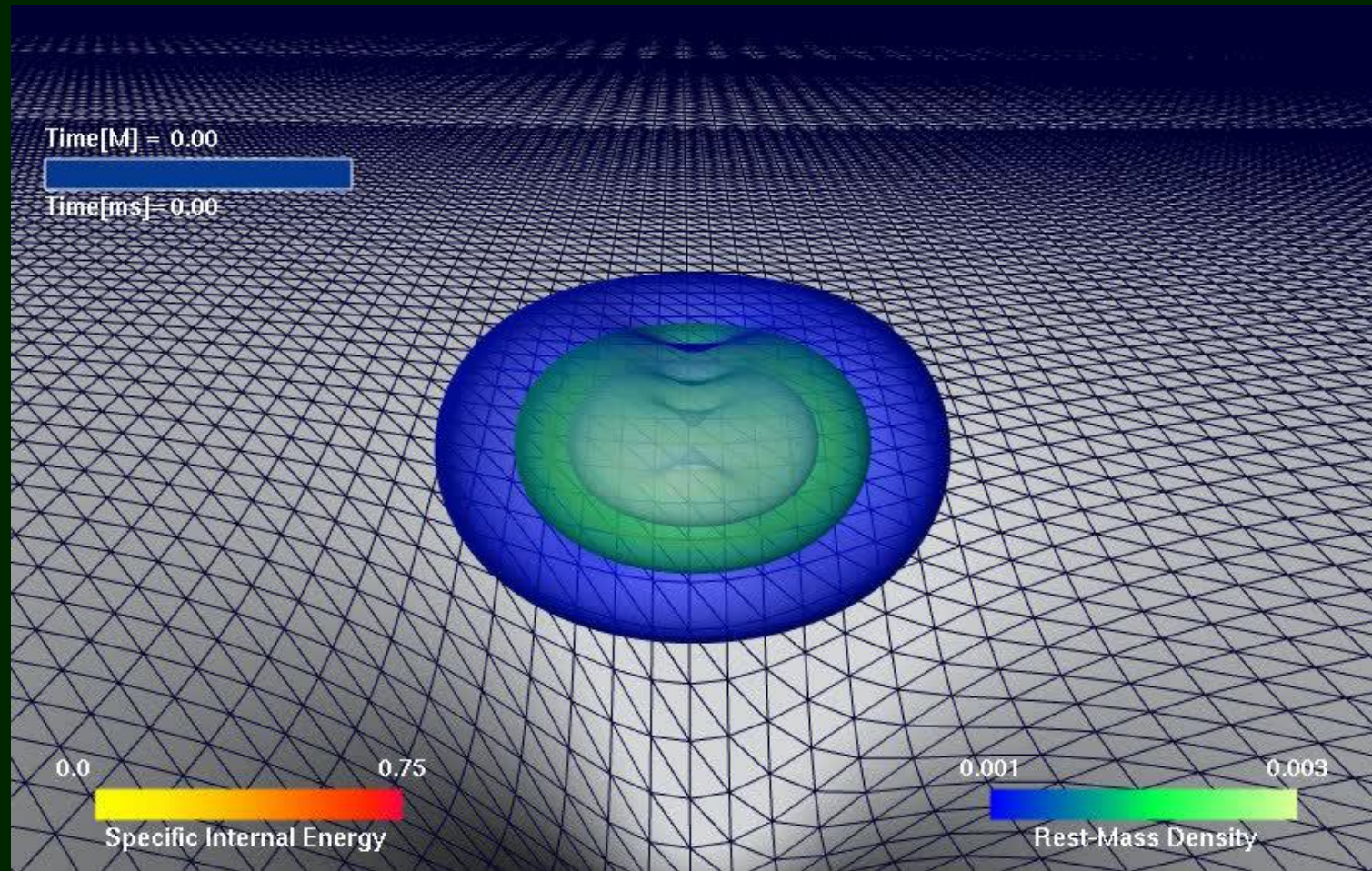
The event horizon (which is growing from zero to its final position and is always outside the apparent horizon) is calculated a posteriori, i.e. after calculations are finished.

L. Baiotti, Rezzolla et al.

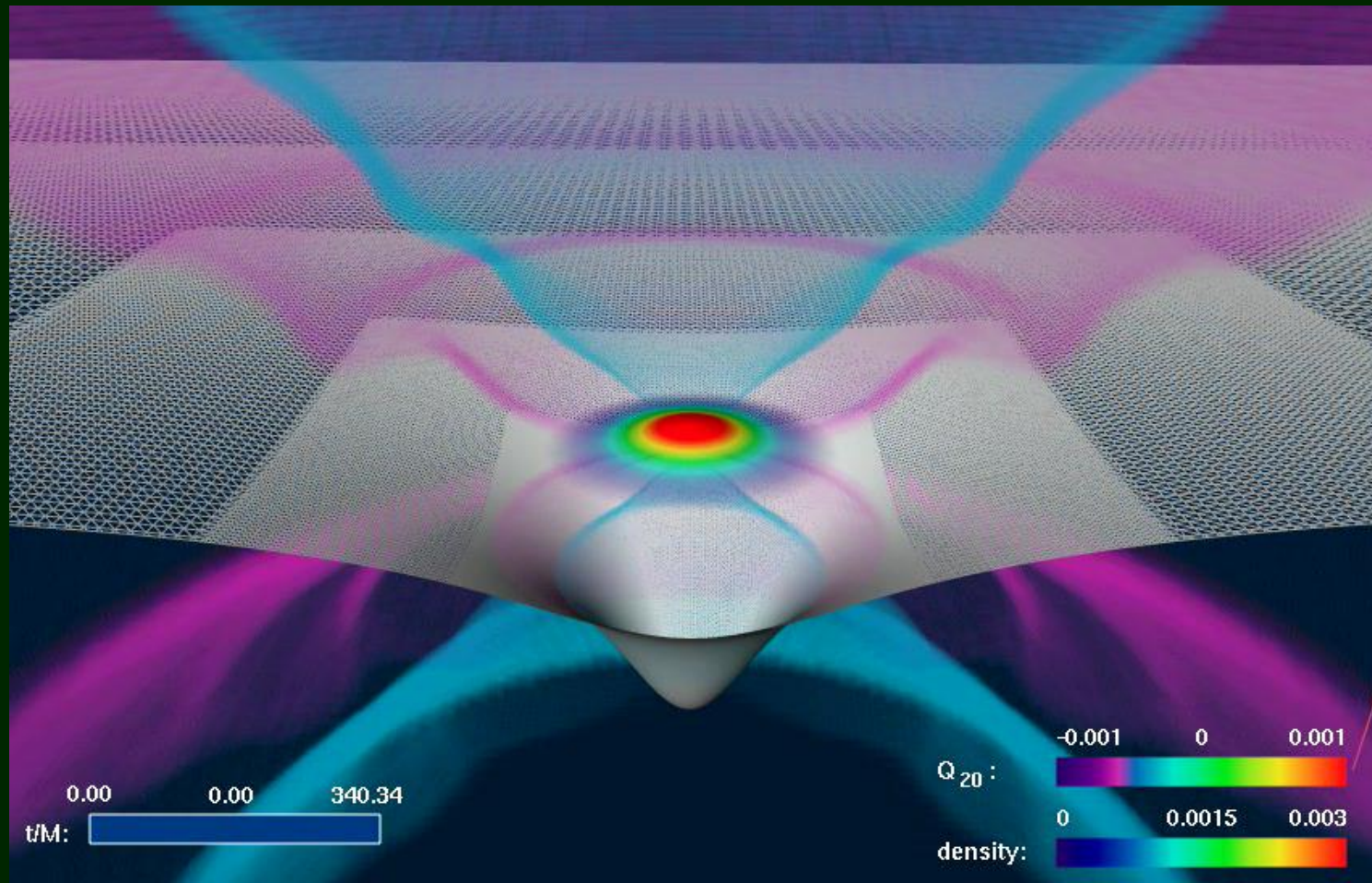
gr-qc/0403029



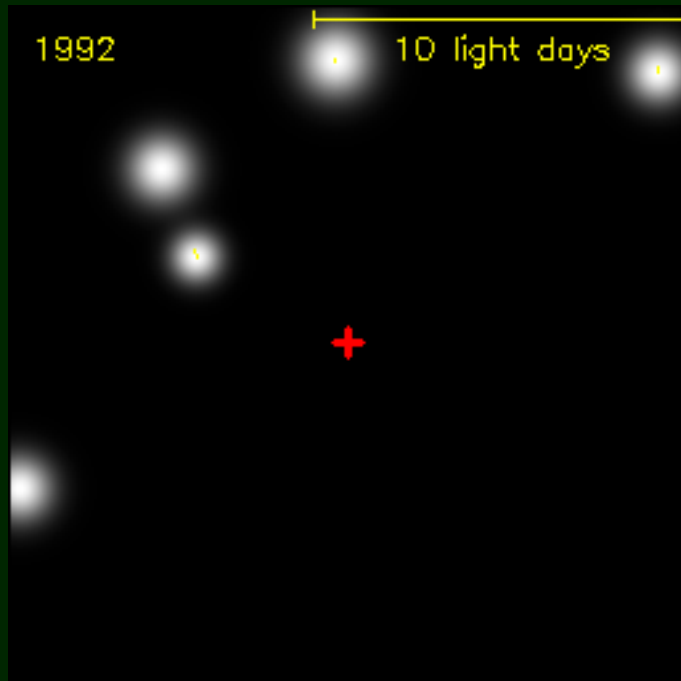
Collapse of a rotating star



Collapse and GW emission

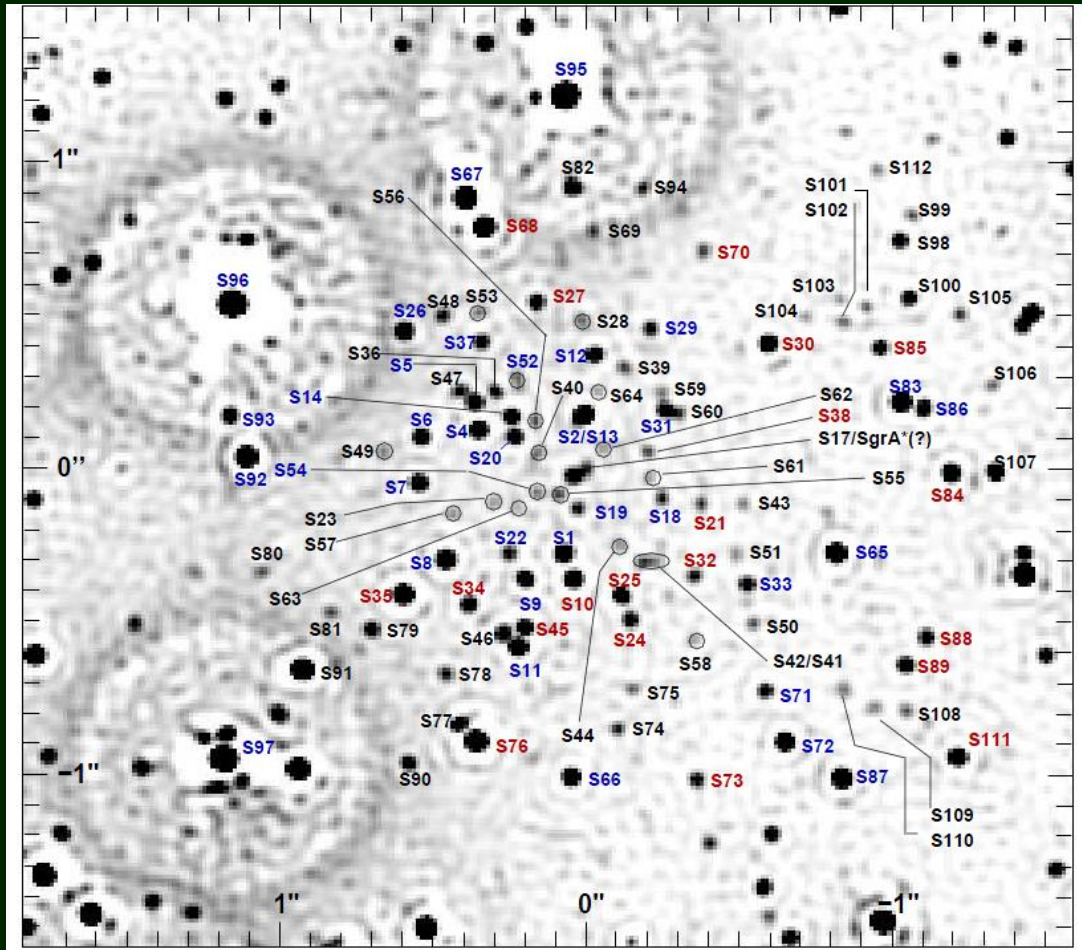


The most certain BH – Sgr A*



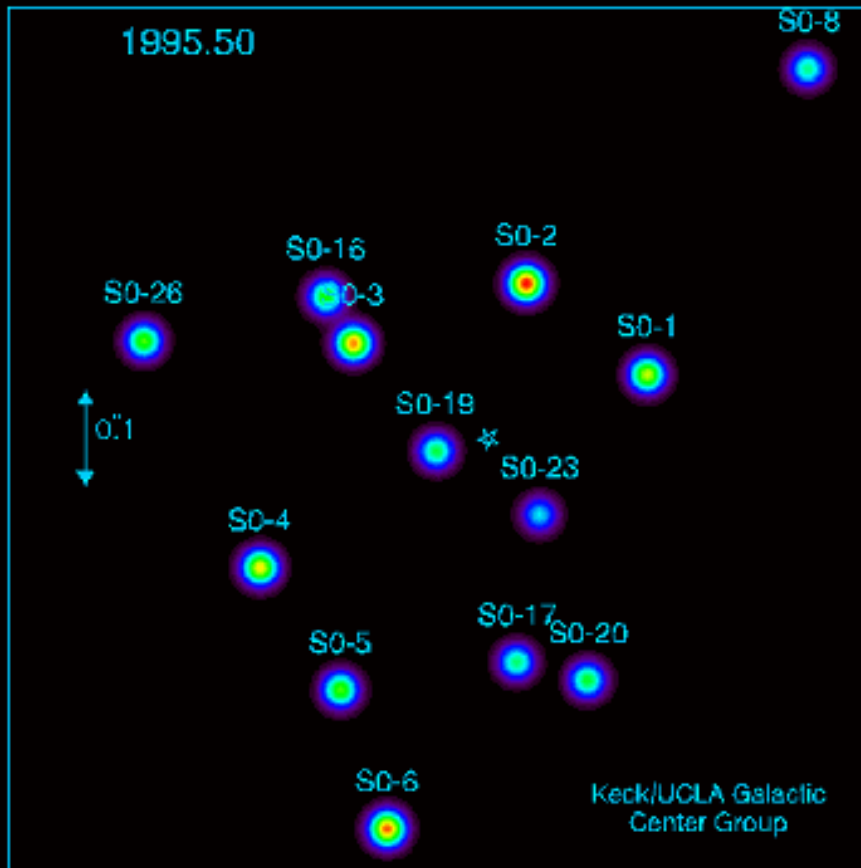
Stellar orbits from 1992 till 2007

(see the reference
in gr-qc/0506078)



arXiv: 0810.4674

... and it becomes more and more certain

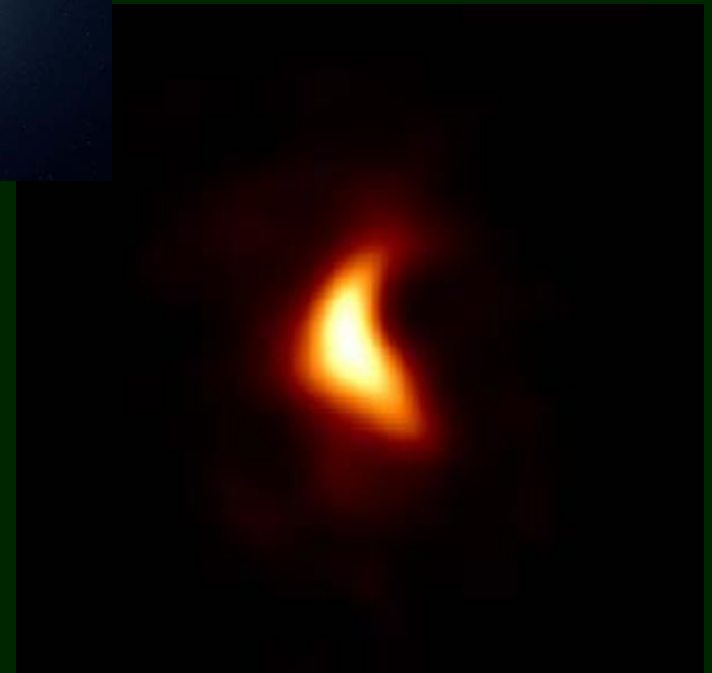
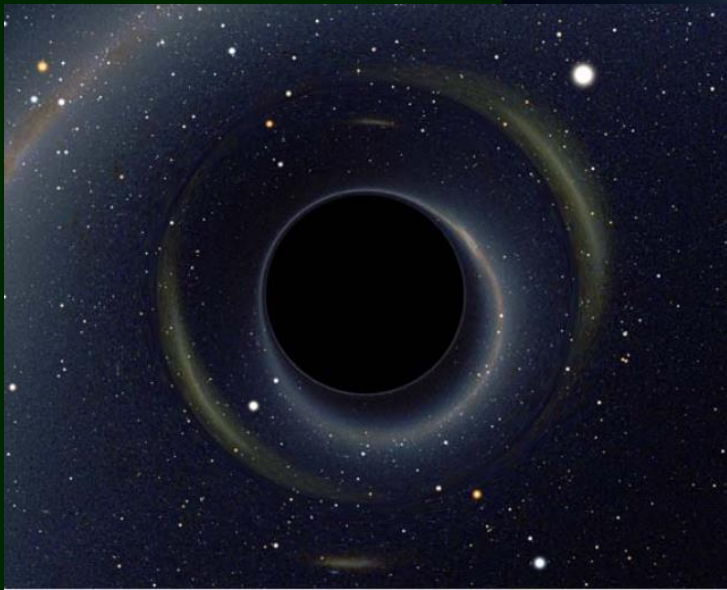
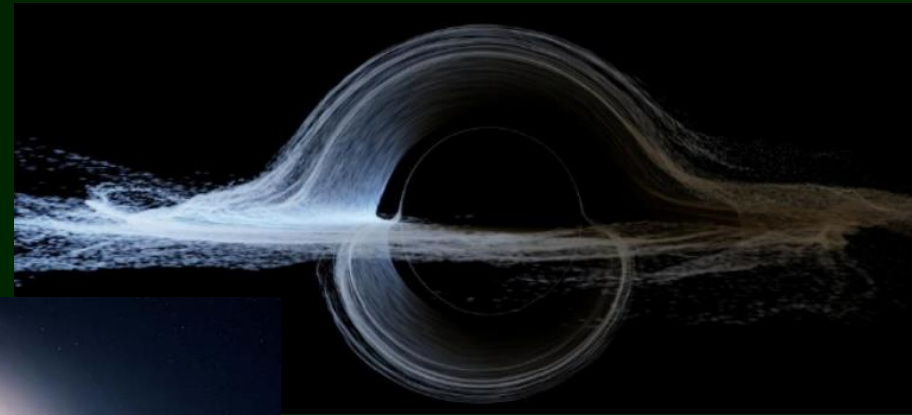
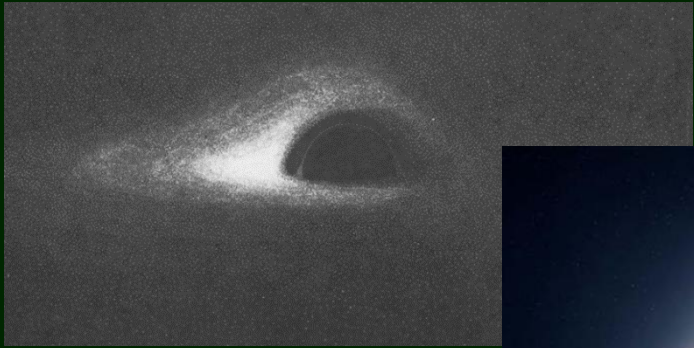


Observations are going on.
So, the number of stars with
well measured orbits grows.

$$M_{\text{BH}} \sim 4\text{--}5 \times 10^6 M_{\text{solar}}$$

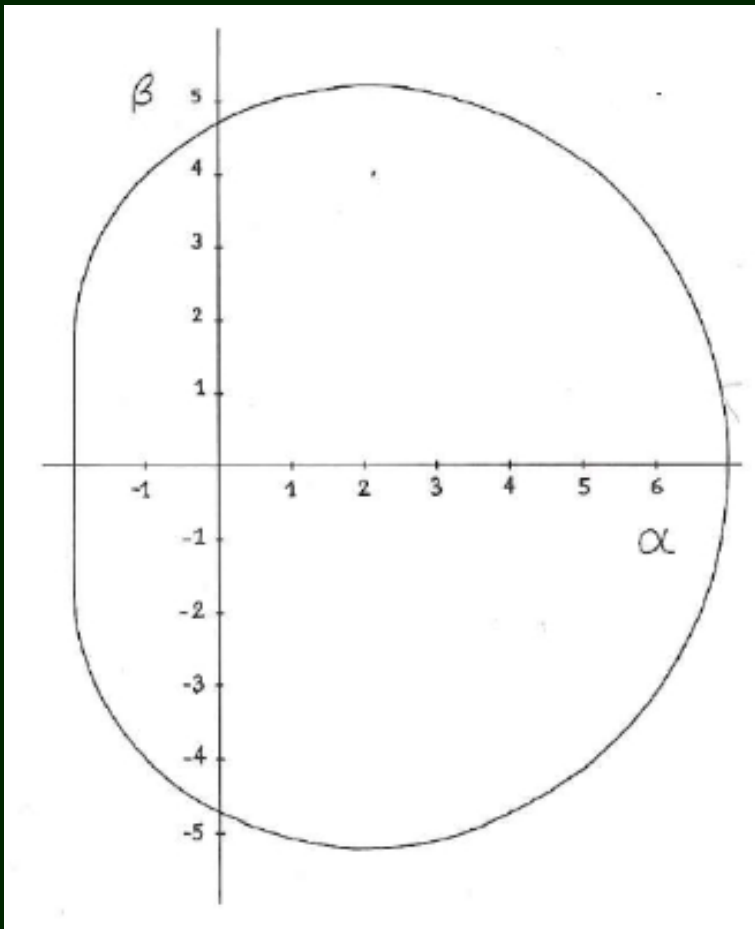
See the reference in [gr-qc/0506078](https://arxiv.org/abs/gr-qc/0506078)
New data in [arXiv: 0810.4674](https://arxiv.org/abs/0810.4674)
Recent review - [1311.1841](https://arxiv.org/abs/1311.1841)

BH visualization



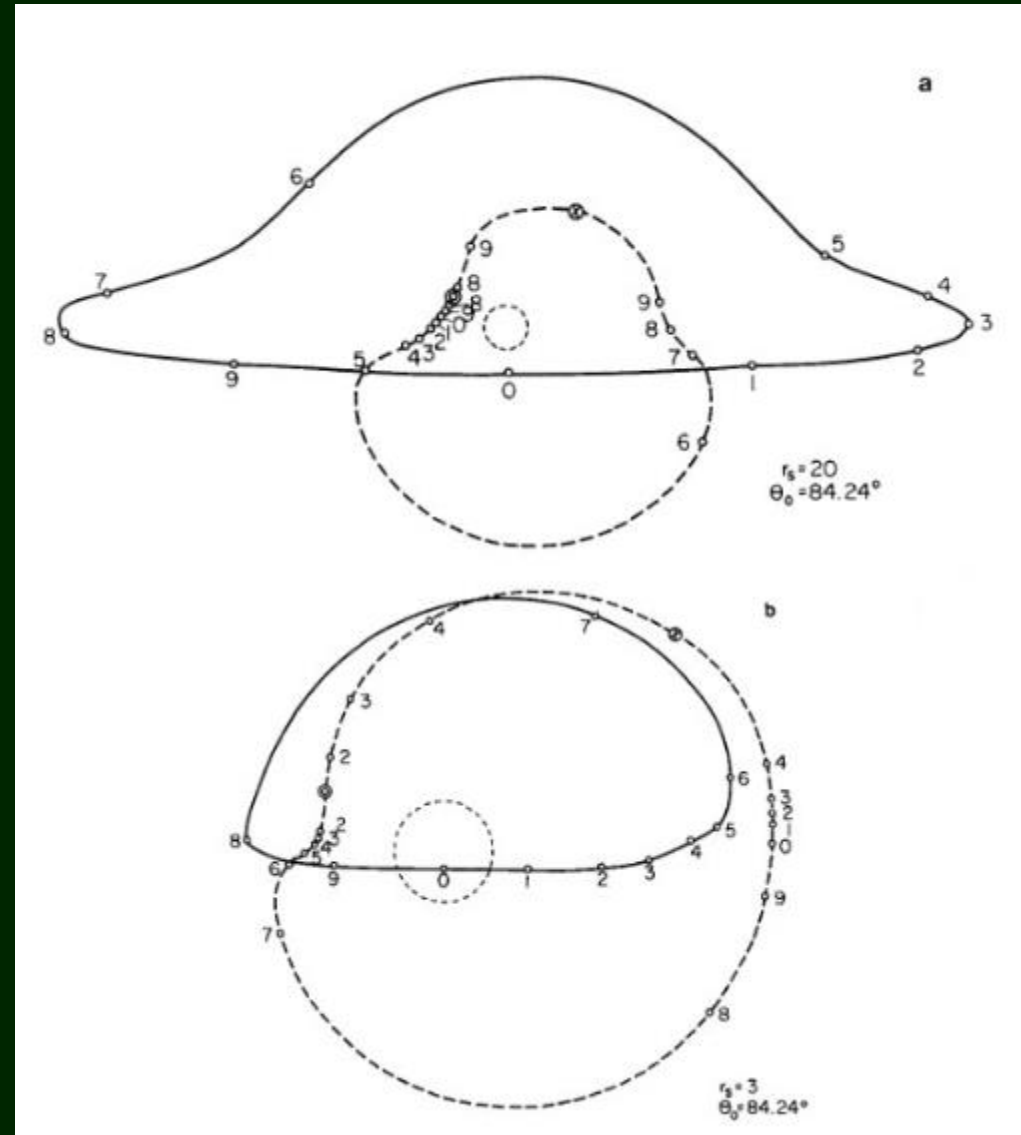
1804.03909, see also 1902.11196

First calculations



Both for an extremally rotating BH

Cunningham, Bardeen 1973



See a review in 1902.11196

Supernovae

Schematic representation of the evolutionary stages from stellar core collapse through the onset of the supernova explosion to the neutrino-driven wind during the neutrino-cooling phase of the proto-neutron star.

The horizontal axis gives mass information.

M_{hc} is the mass of the subsonically collapsing, homologous inner core.

The vertical axis shows corresponding radii.

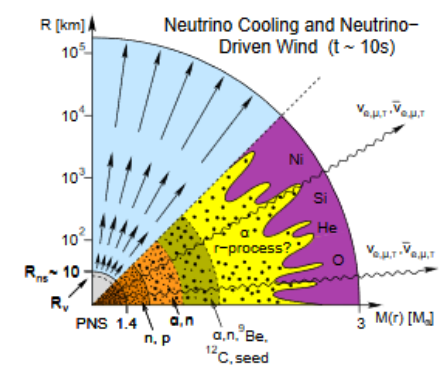
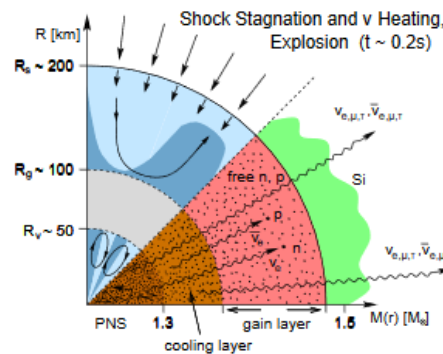
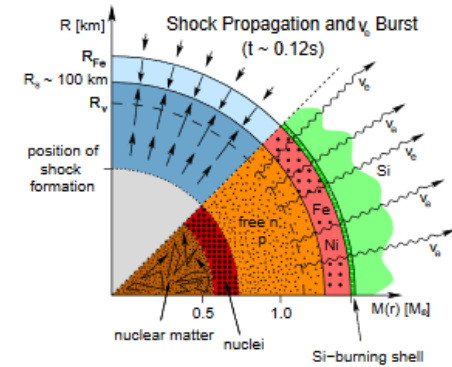
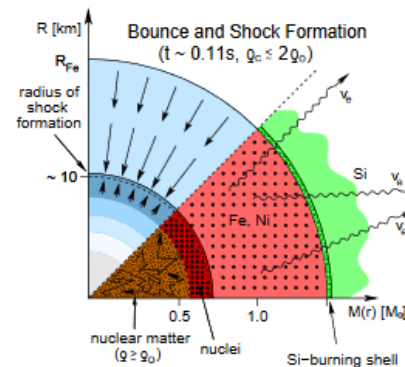
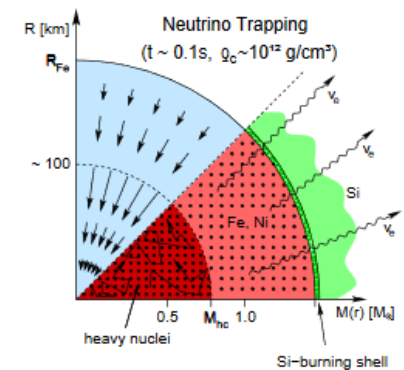
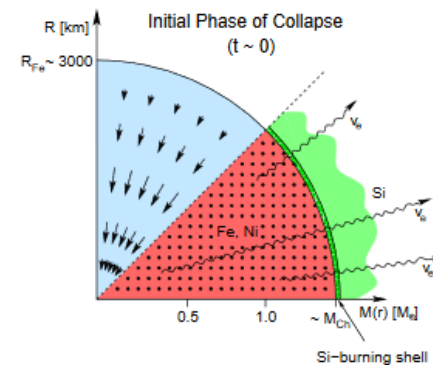
R_{Fe} - iron core radius;

R_s - shock radius;

R_g - gain radius;

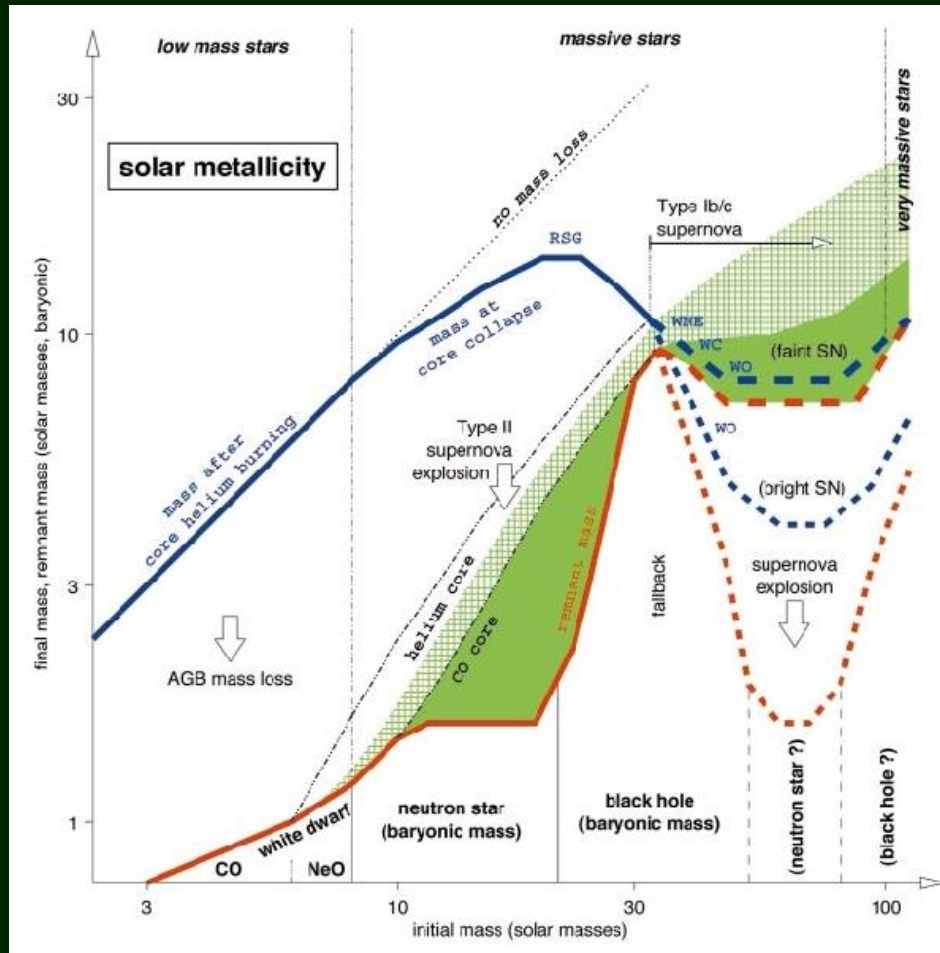
R_{ns} - neutron star radius;

R_v - neutrinosphere.



Stellar mass BHs.

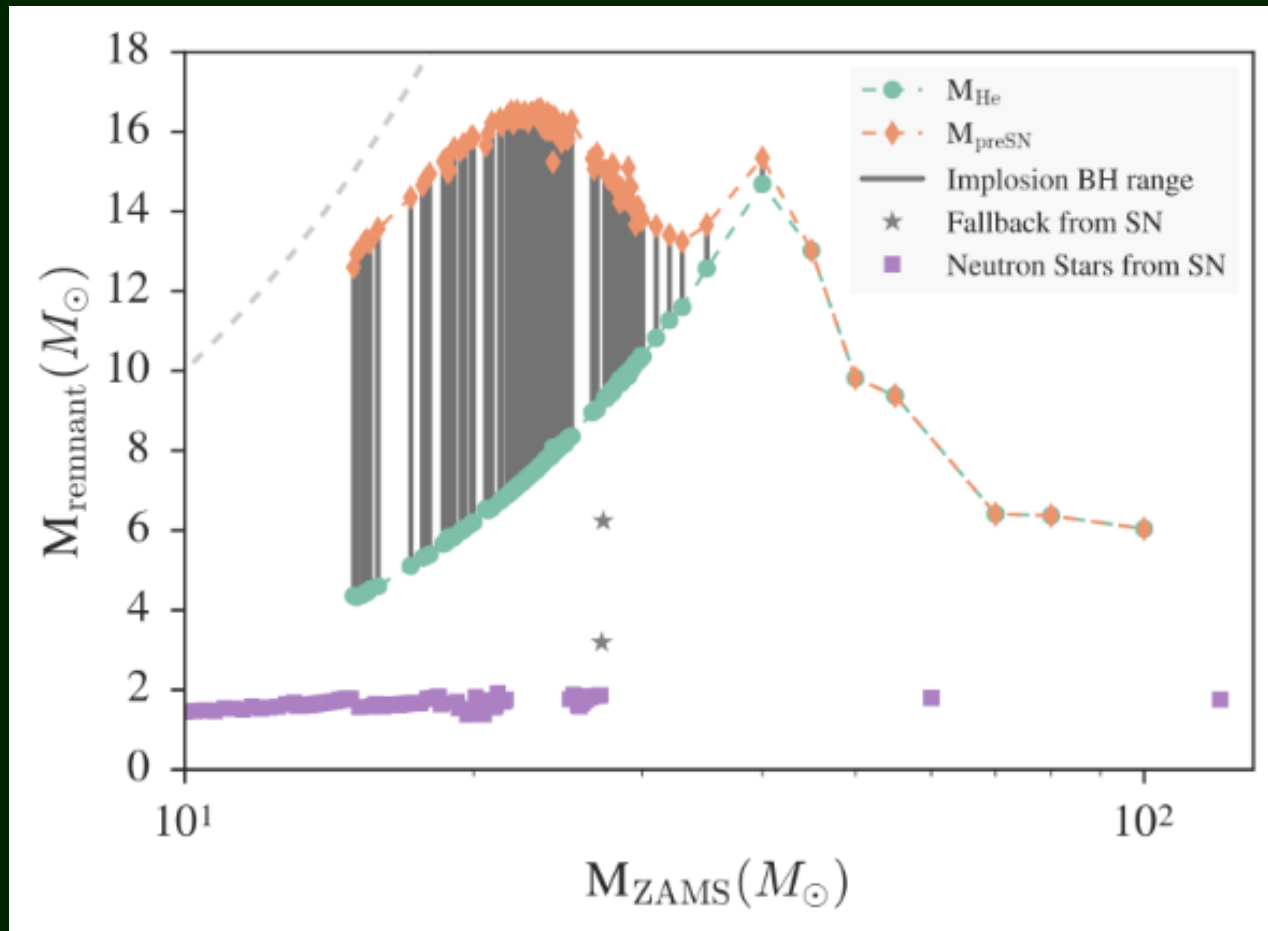
The case of solar metallicity.



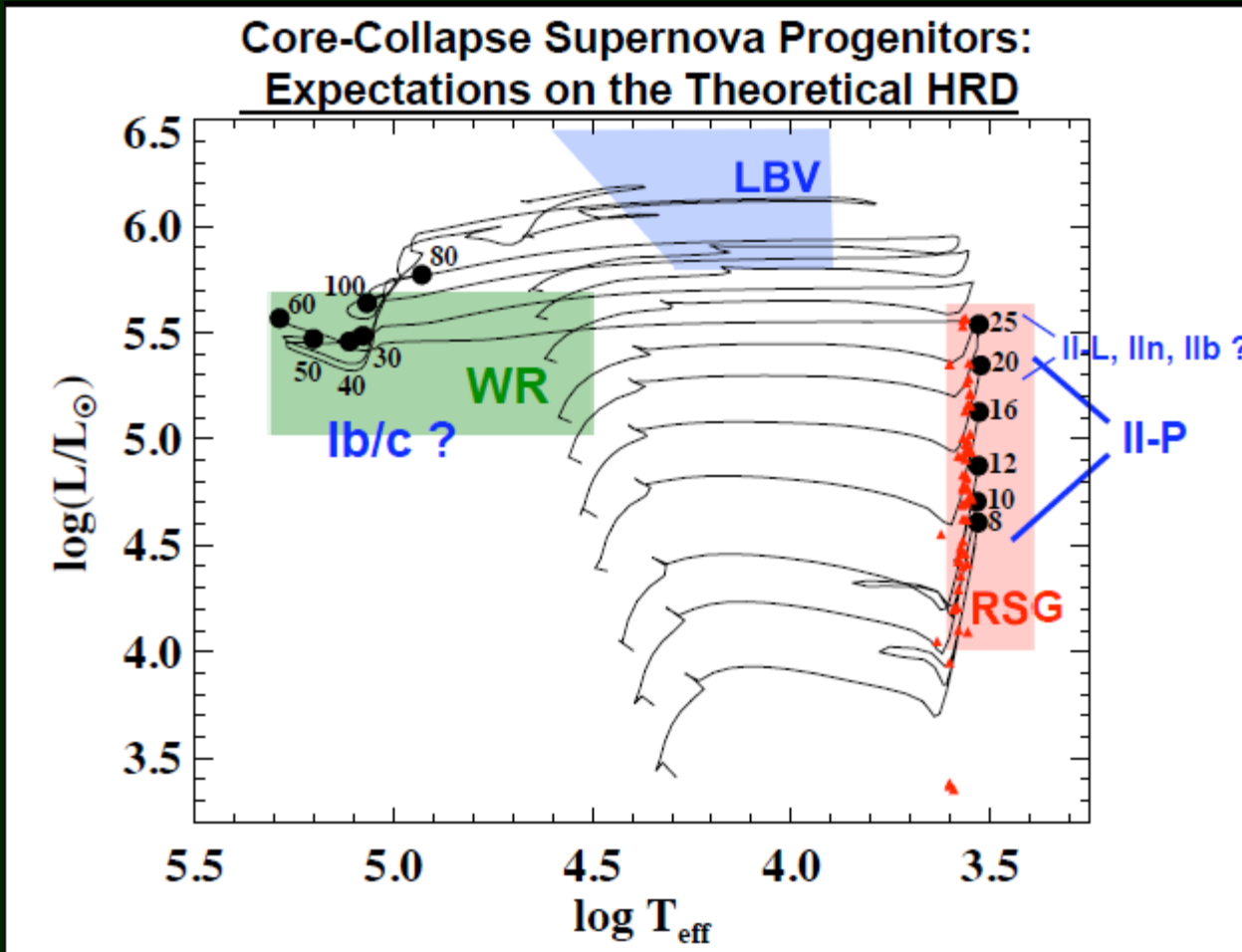
BHs are formed by massive stars. The limiting mass separating BH and NS progenitors is not well known. In addition, there can be a range of masses above this limit in which, again NSs are formed (also, there can be a range in which both types of compact objects form).

See 1011.0203 about progenitors

Initial mass vs. final: ZAMS vs. compact object

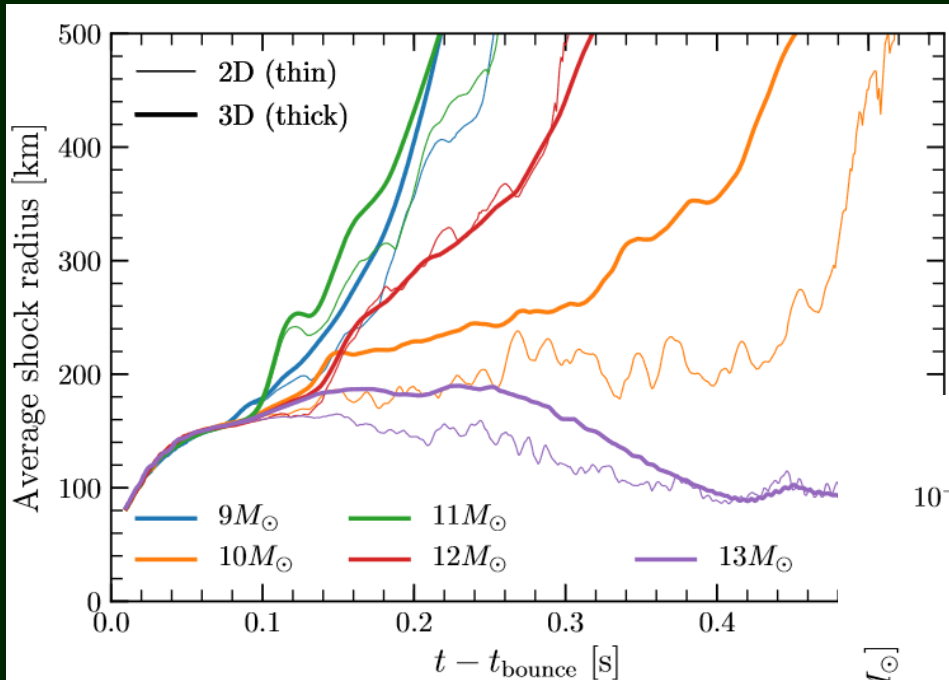


Supernova progenitors

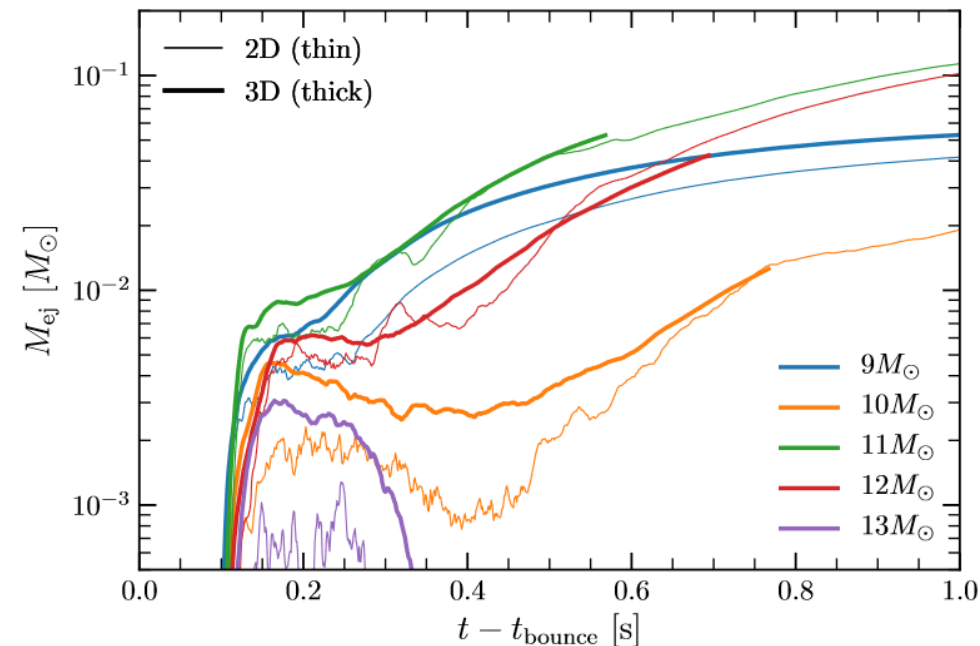


However, there are claims that most of stars $>18M_{\odot}$ produce BHs (see a review in Smartt arXiv: 1504.02635)

No explosions for 13 solar mass?

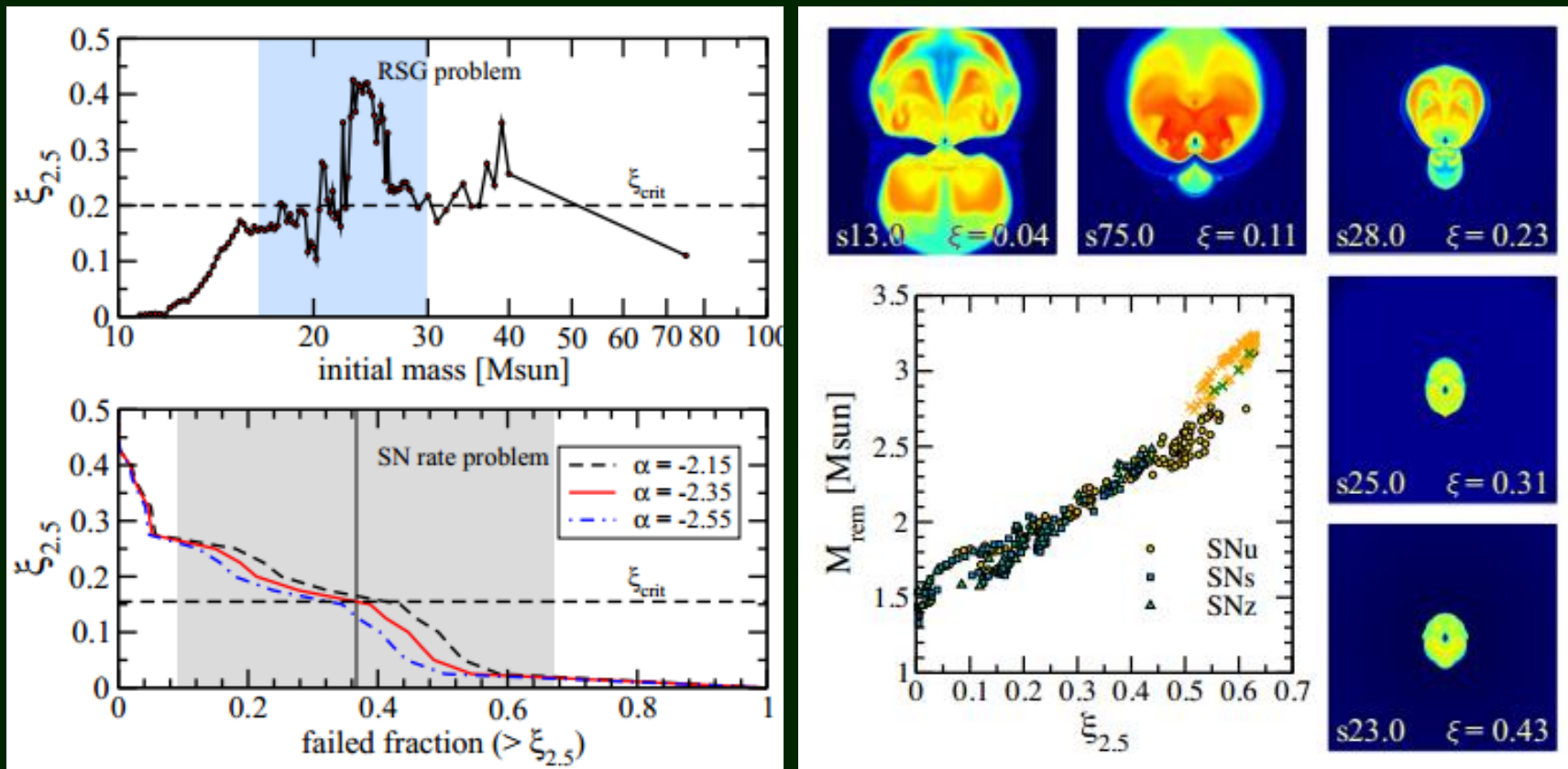


Probably non-rotating progenitors with $12 < M < 14$ solar mass do not explode.



Which stars form BHs?

It is proposed that stars with compact internal structure ($M \sim 20\text{-}30$ Msolar) form BHs not NSs. This explains data on RGs and the SN rate.



Transients from BH formation

Supergiant progenitors of BHs can have huge convective envelopes.

Convective motions in the outer parts of supergiants generate mean horizontal flows at a given radius with velocities of ~ 1 km/s.

Failed explosions of supergiants - in which the accretion shock onto the neutron star does not revive, leading to black hole formation - may often produce accretion discs that can power day-week (blue supergiants) or week-year (yellow and red supergiants) non-thermal and thermal transients through winds and jets.

These transients will be especially time variable because the angular momentum of the accreting material will vary substantially in time. Observed sources such as Swift J1644+57, iPTF14hls, and SN 2018cow, as well as energetic Type II supernovae (OGLE-2014-SN-073) may be produced by this mechanism.

$$v_h \sim \frac{v_c}{\sqrt{4\pi}} \frac{H}{r}$$

$$j_{\text{rand}} \sim \frac{H v_c}{\sqrt{4\pi}} \sim 6 \times 10^{17} \frac{r v_c}{10^3 R_\odot \text{ km s}^{-1}} \left(\frac{H/r}{0.3} \right) \text{ cm}^2 \text{ s}^{-1}$$

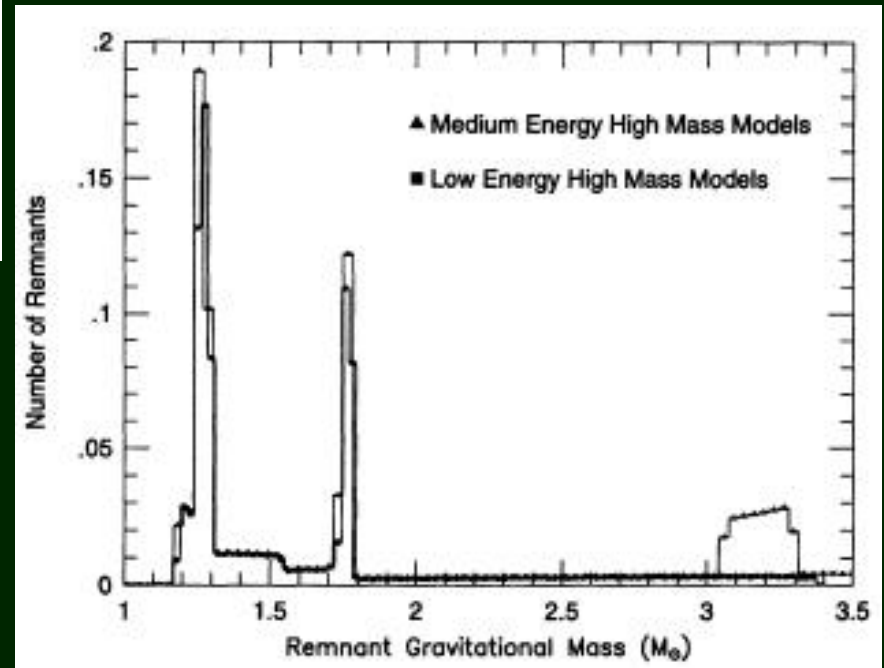
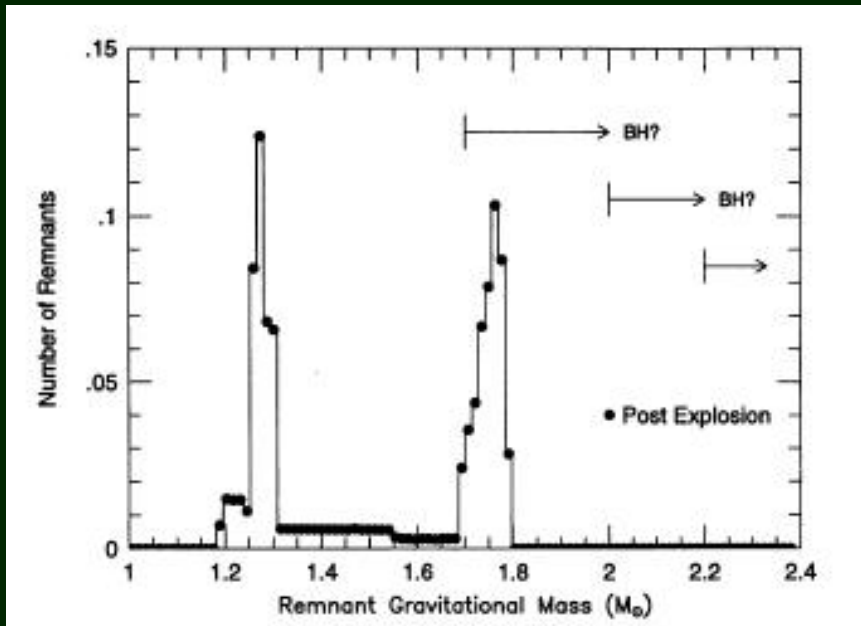
v_c (~ 10 km/s) –
convective velocity

v_h – horizontal velocity

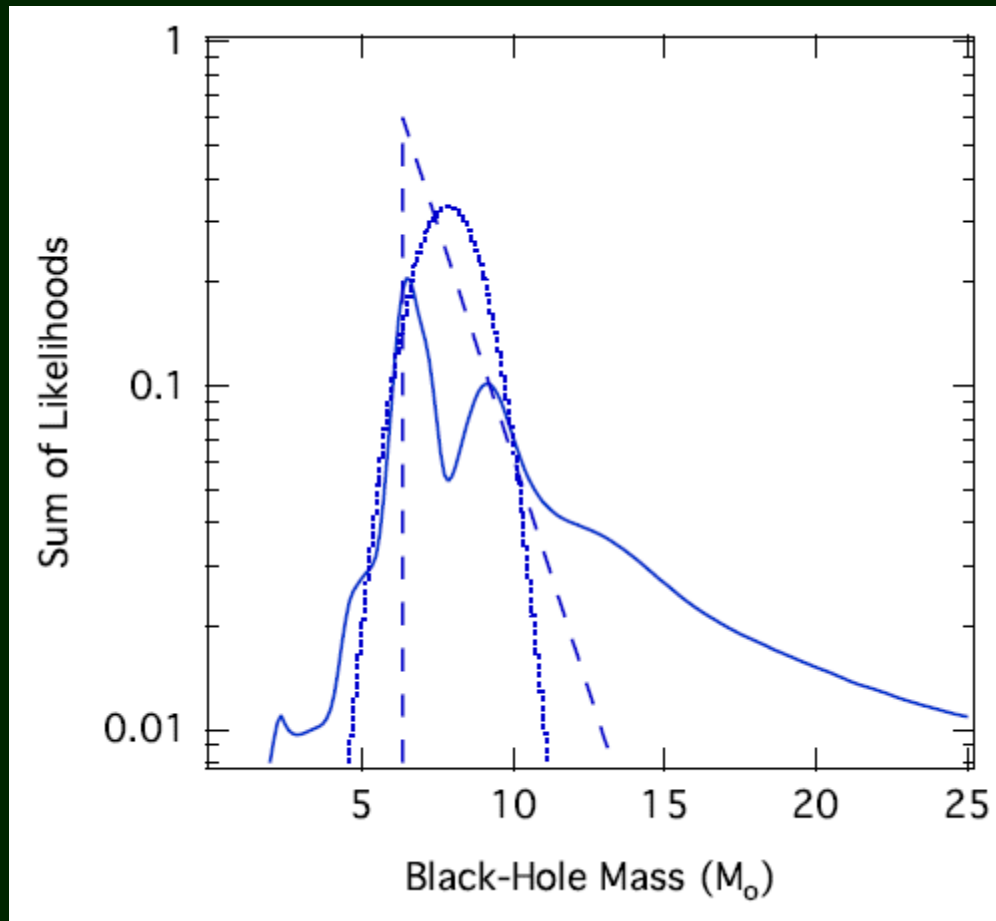
$$j_{\text{ISCO}} = 1.15 - 3.5 \frac{GM}{c} \sim 0.5 - 1.5 \times 10^{17} \left(\frac{M}{10 M_\odot} \right) \text{ cm}^2 \text{ s}^{-1}$$

Mass spectrum of compact objects

Results of numerical models

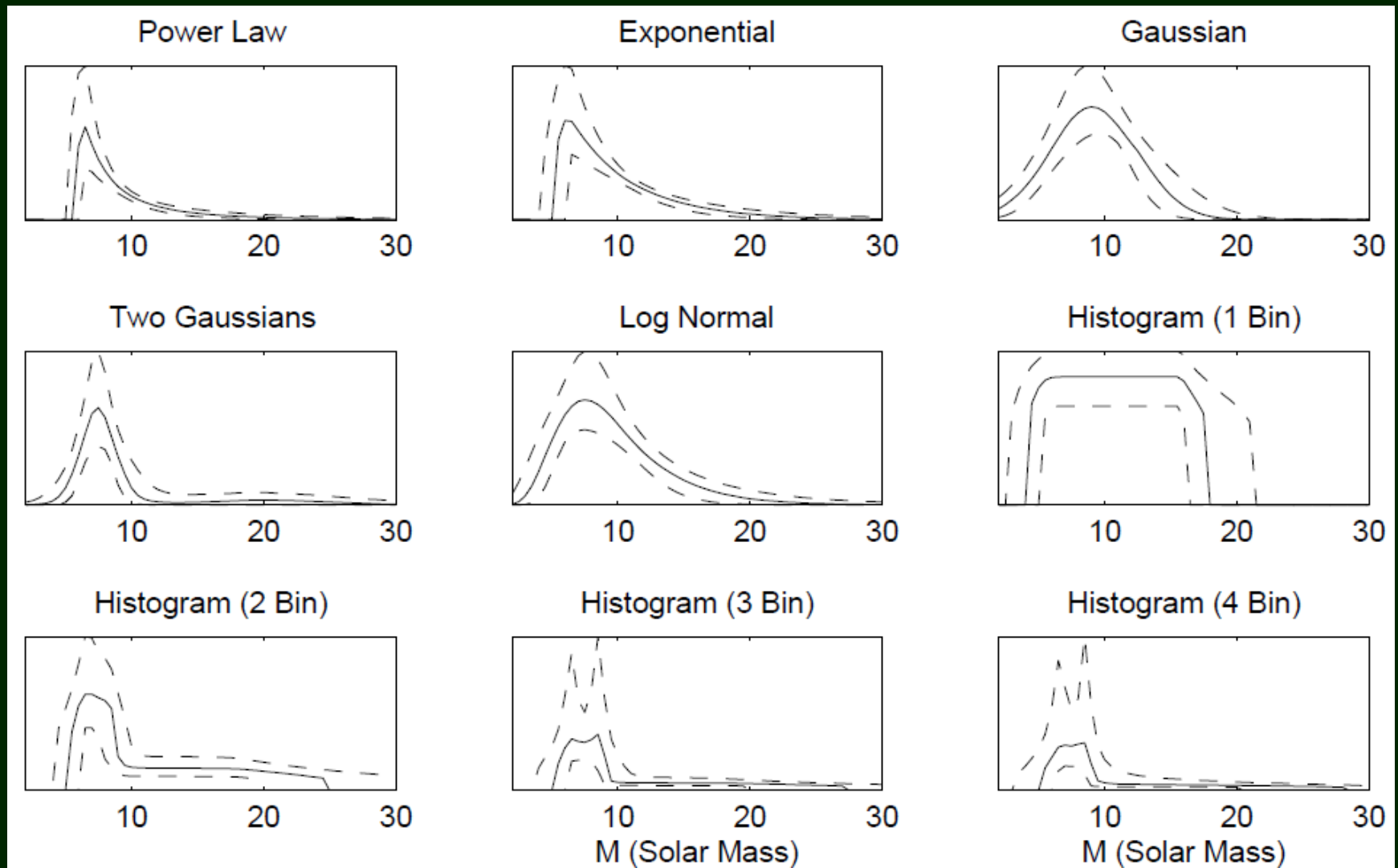


BH mass function

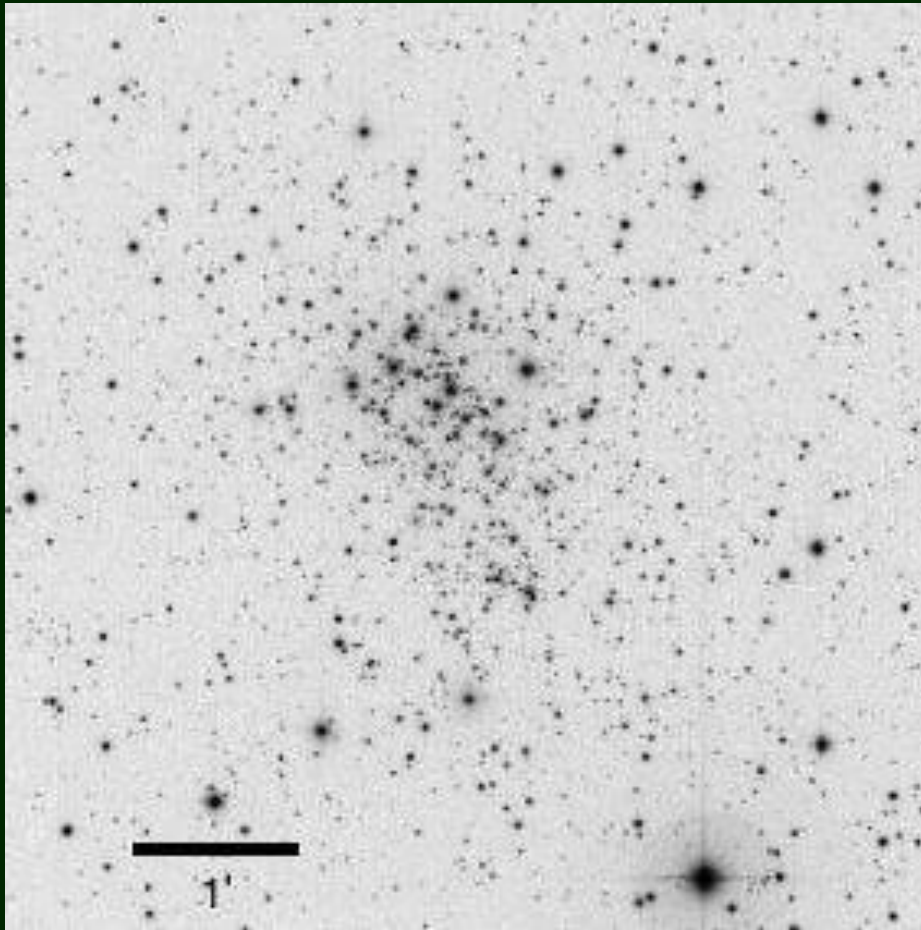


Likelihood based on 16 systems

BH mass distribution



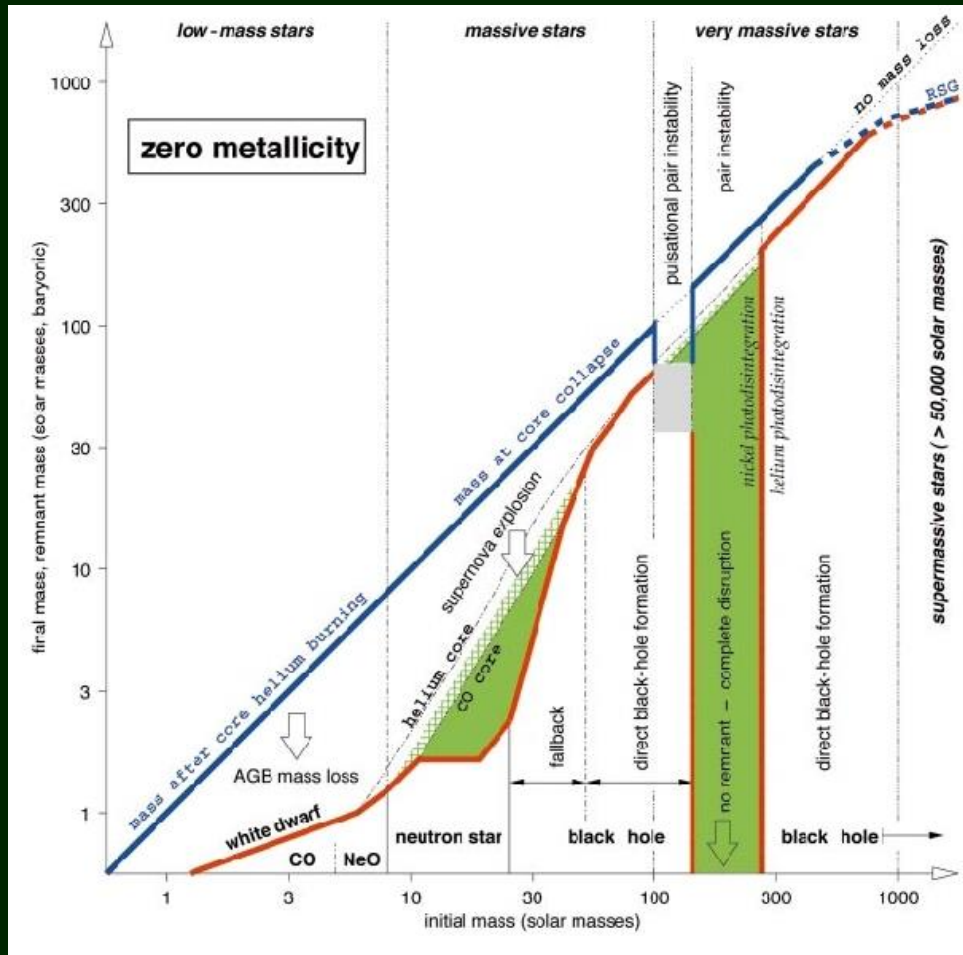
A NS from a massive progenitor



Anomalous X-ray pulsar in the cluster
Westerlund1 most probably has
a very massive progenitor, $>40 M_{\odot}$.

Stellar mass BHs.

The case of zero metallicity



Pop III massive stars could produce very massive BHs which became seeds for formation of supermassive BHs.

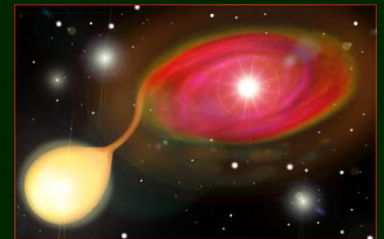
BHs and NSs in close binary systems

Studying close binaries with compact objects we can obtain mass estimates for progenitors of NSs and BHs (see, for example, Ergma, van den Heuvel 1998 A&A 331, L29).

An interesting result was obtained for the NS system GX 301-2. The progenitor mass was found to be equal to 50 solar masses or more. On the other hand, for many systems with BHs estimates of progenitor masses are lower: 20-50 solar masses.

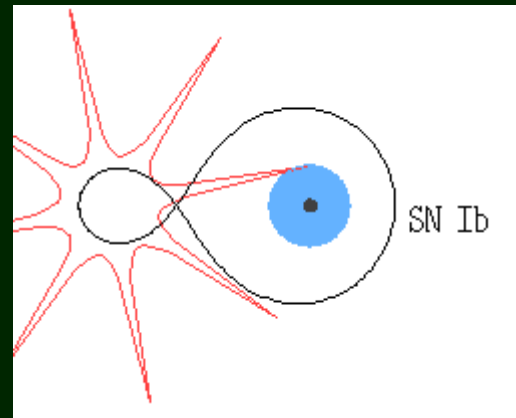
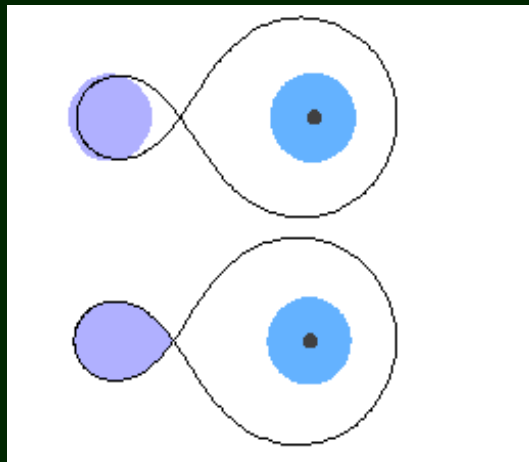
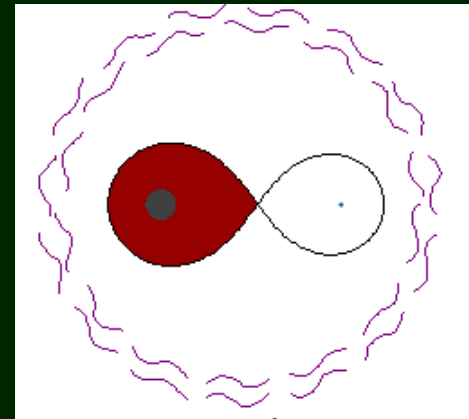
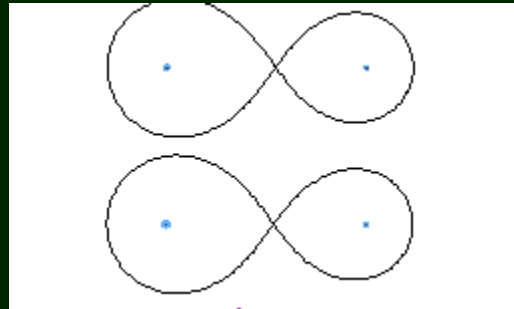
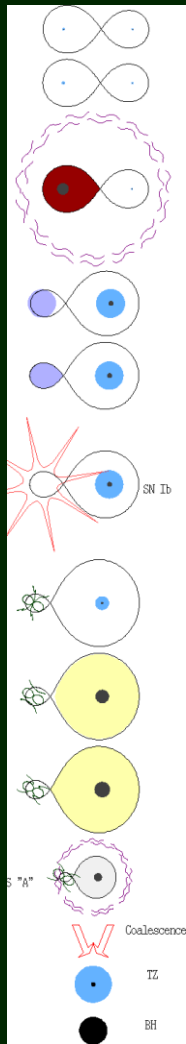
Finally, for the BH system LMC X-3 the mass of the progenitor is estimated as >60 solar masses.

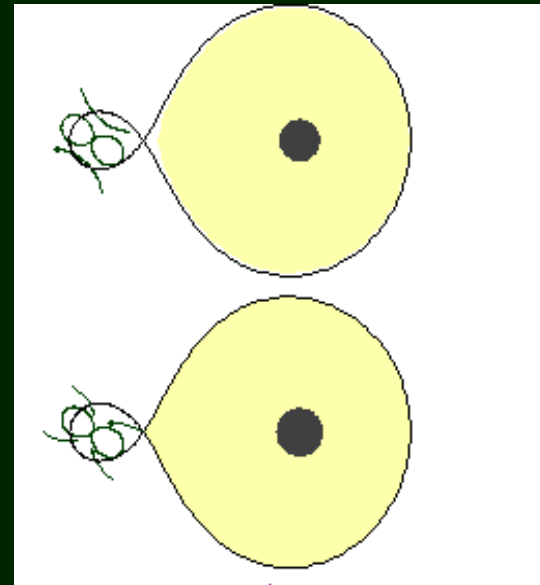
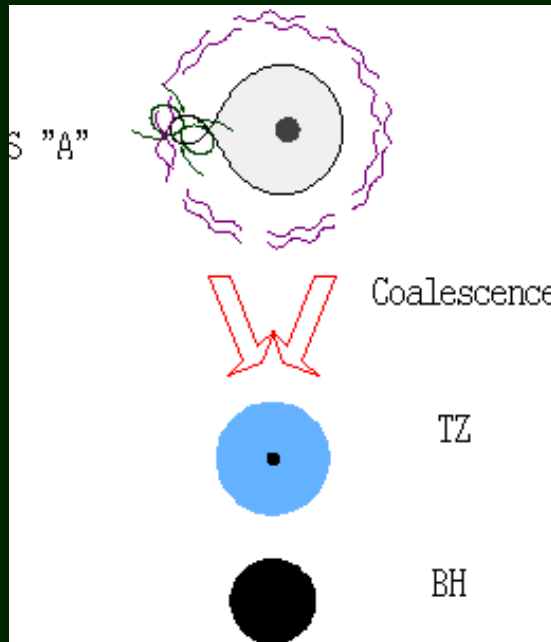
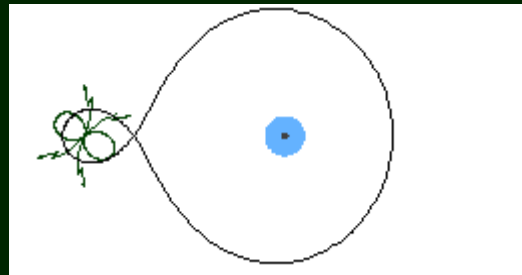
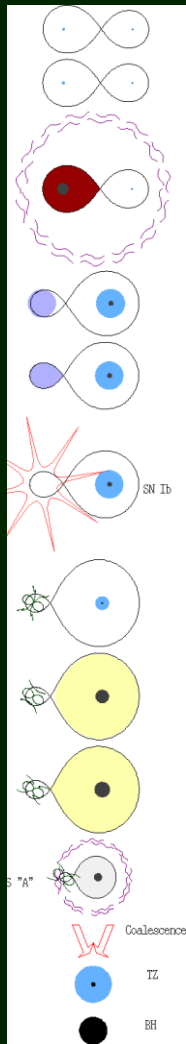
So, the situation is rather complicated. Most probably, in some range of masses, at least in binary systems, both variants are possible.



Binary evolution

A BH can be formed even from stars each below the limit.





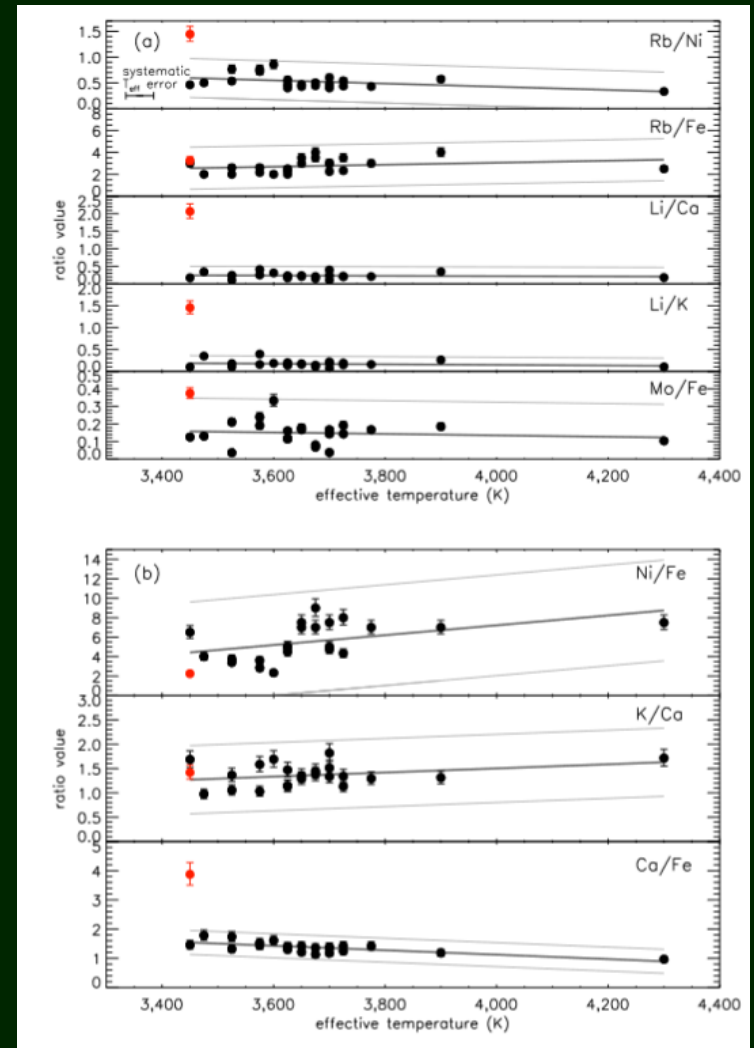
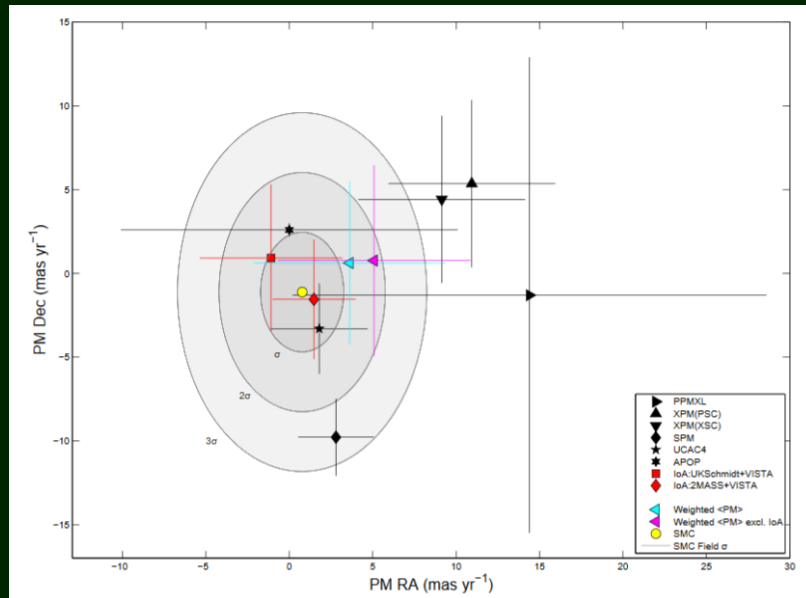
“Scenario machine” calculations

Thorne-Zytzkow candidates

Chemical composition anomalies.

Discussion:

1. Large proper motion – not in SMC
1601.05455
2. In SMC 1602.08479
Gaia DR2 confirms 1804.10192



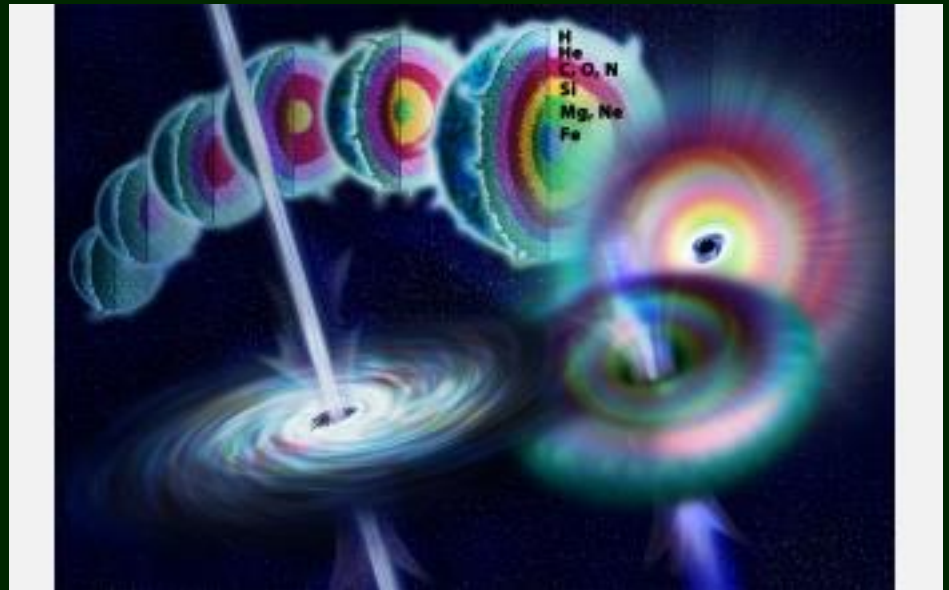
1406.0001

GRBs and BHs

According to the standard modern model of long GRBs, a BH is the main element of the “central engine”.

So, studying GRBs we can hope to get important information about the first moments of BH's life.

See a very brief review in
[arXiv:1302.6461](https://arxiv.org/abs/1302.6461)

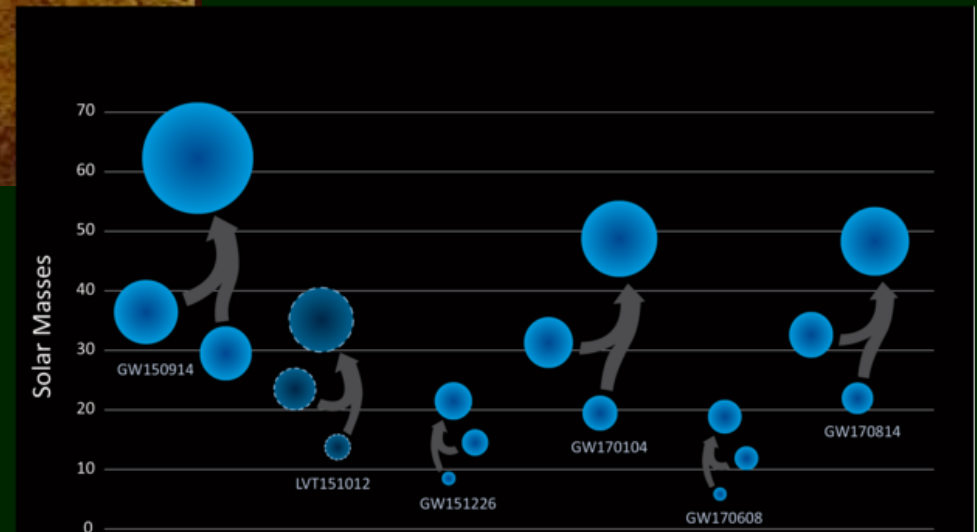


BHs from GW signals



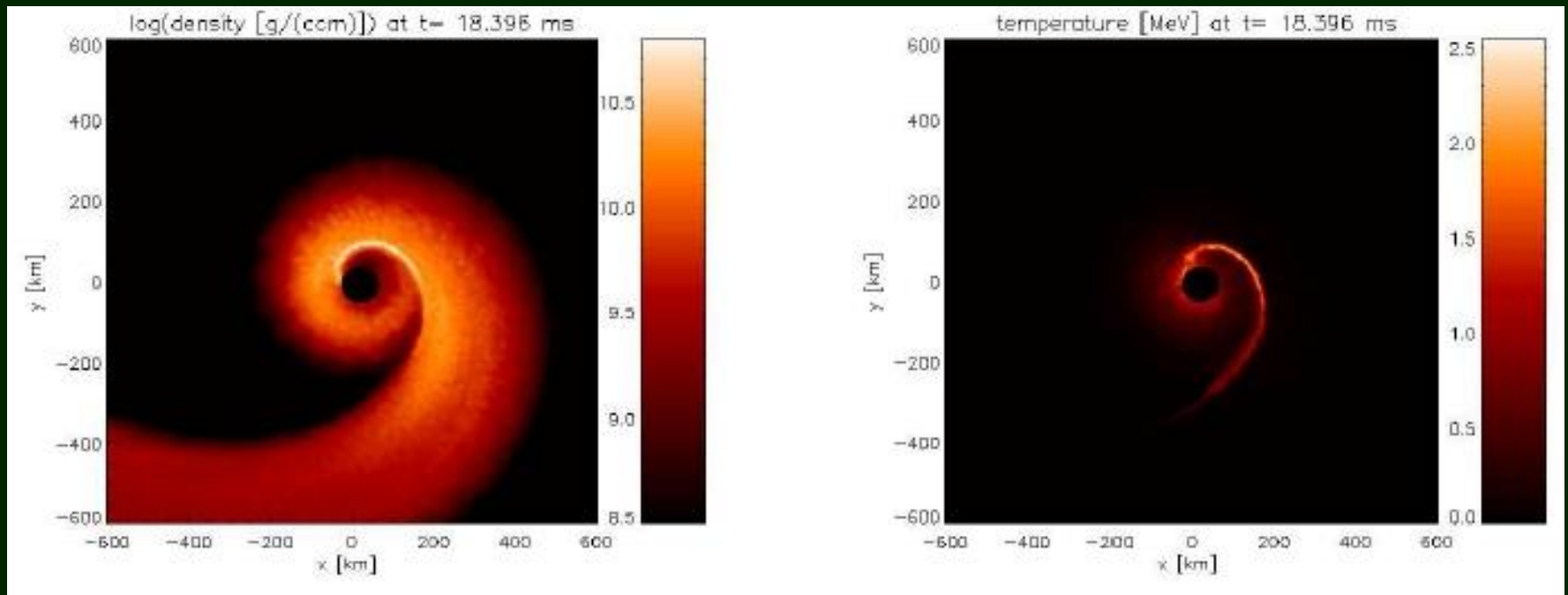
LIGO measure signals from compact object mergers.

These signals are more powerful for larger masses. So, even being rarer per unit volume, BH+BH mergers are more frequent in the data.



NS and BH coalescence

Some numerical models show (astro-ph/0505007, 0505094) that such events do not produce GRBs. Some show that they do.

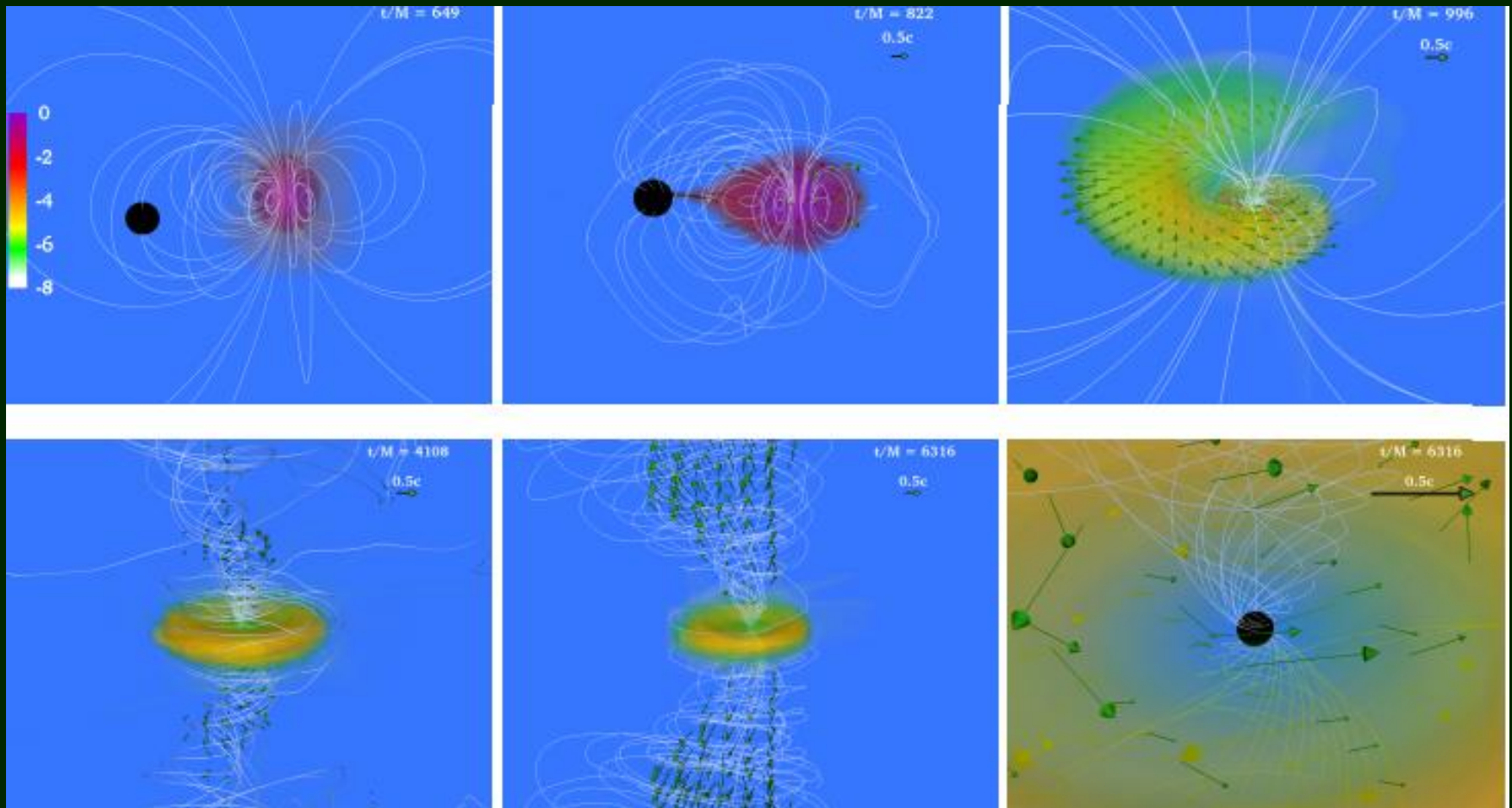


BH-NS mergers are still a popular subject of studies:

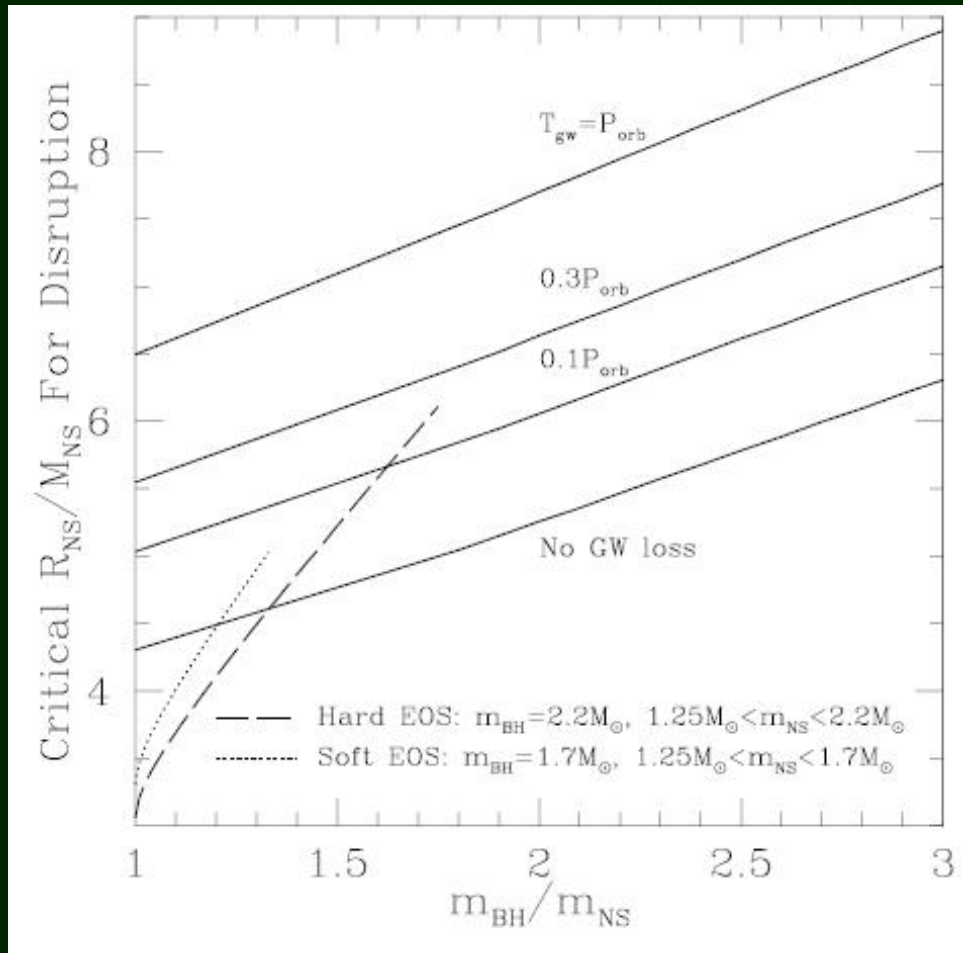
1105.3175, 1103.3526, 1210.8153, 1302.6297, 1301.5616, 1304.3384.

Magnetic field jet launch

Neutron star magnetic field helps to launch the jet. But disc is still necessary!



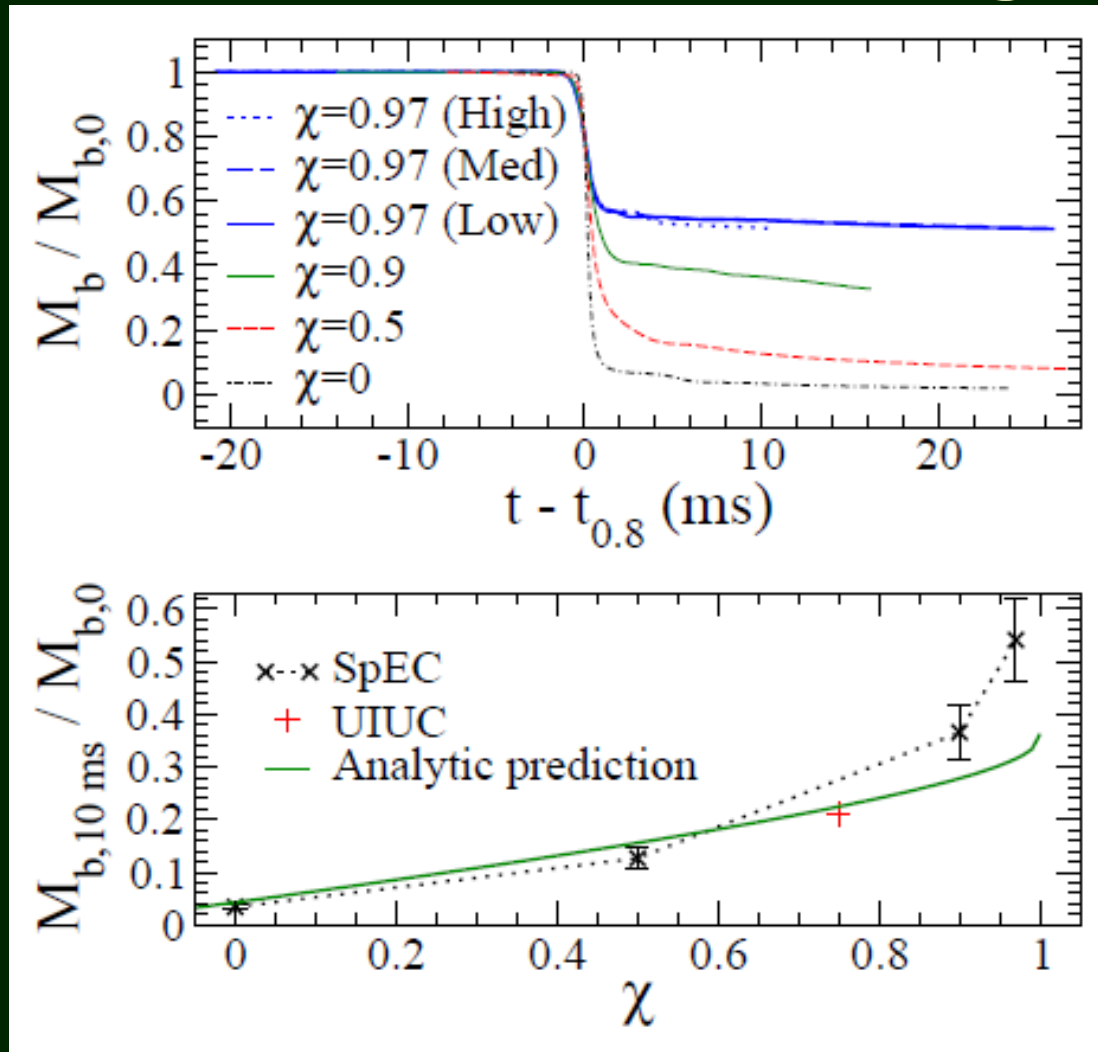
Prompt mergers of NSs with BHs



Coleman Miller demonstrated that in NS-BH coalescence most probably there is no stable mass transfer and an accretion disc is not formed. This means – **no GRB!**

The top solid line is constructed by assuming that the neutron star will plunge when, in one full orbit, it can reduce its angular momentum below the ISCO value via emission of gravitational radiation. The next two solid lines reduce the allowed time to 30 and 10% of an orbit. The bottom line ignores gravitational radiation losses entirely.

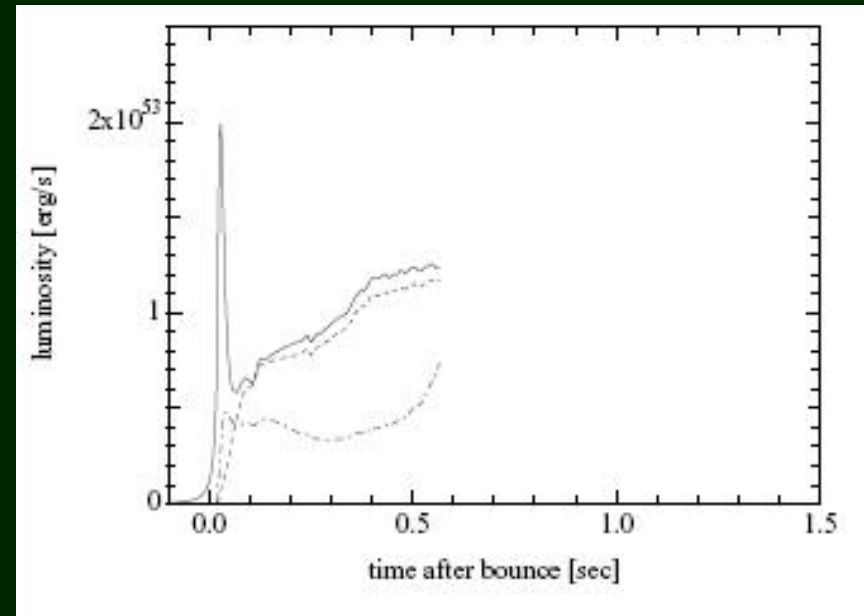
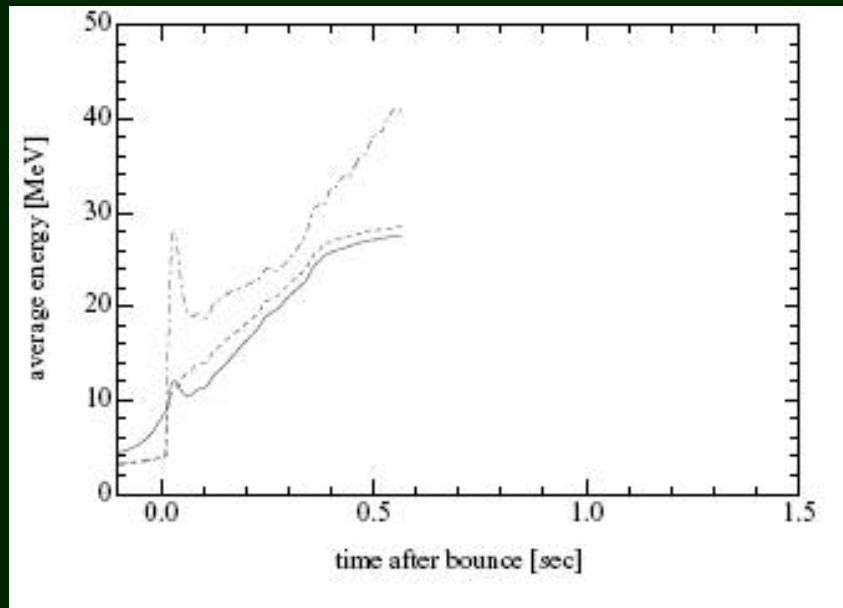
Extremal BH-NS mergers



It is possible to form a massive disc around a BH during BH-NS merger. However, not for non-rotating BHs.

Supernovae

The neutrino signal during a (direct) BH formation must be significantly different from the signal emitted during a NS formation. (arXiv: 0706.3762)



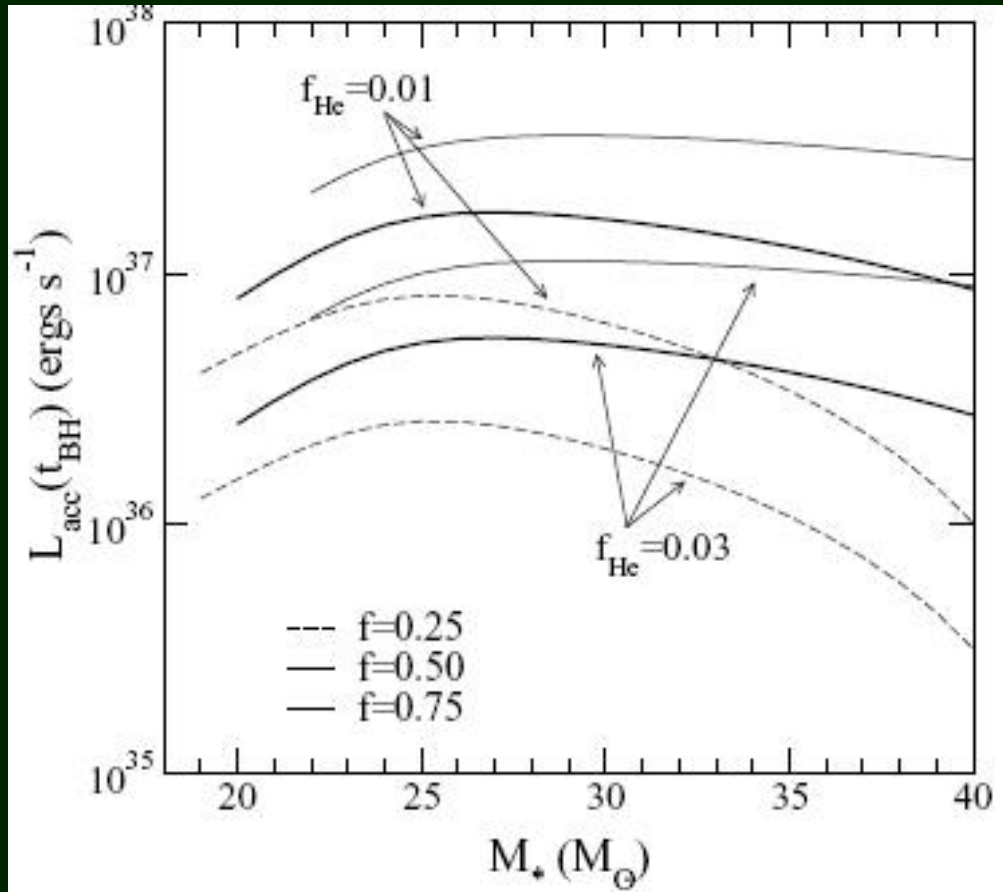
*Different curves are plotted for different types of neutrino:
electron – solid, electron anti-neutrino – dashed, mu and tau-neutrinos – dot dashed.*

Constant growth of neutrino energy and a sharp cut-off indicate a BH formation. Result depends on the EoS.

See some new results in: arXiv:0809.5129

BH formation in a PNS collapse and neutrino spectra

BH signatures in SN light curves



$$\dot{M} \propto t^{-5/3}$$

$$L_{\text{acc}}(t) = L_{\text{Edd}} \left(\frac{t}{t_{\text{dust}}} \right)^{-25/18}$$

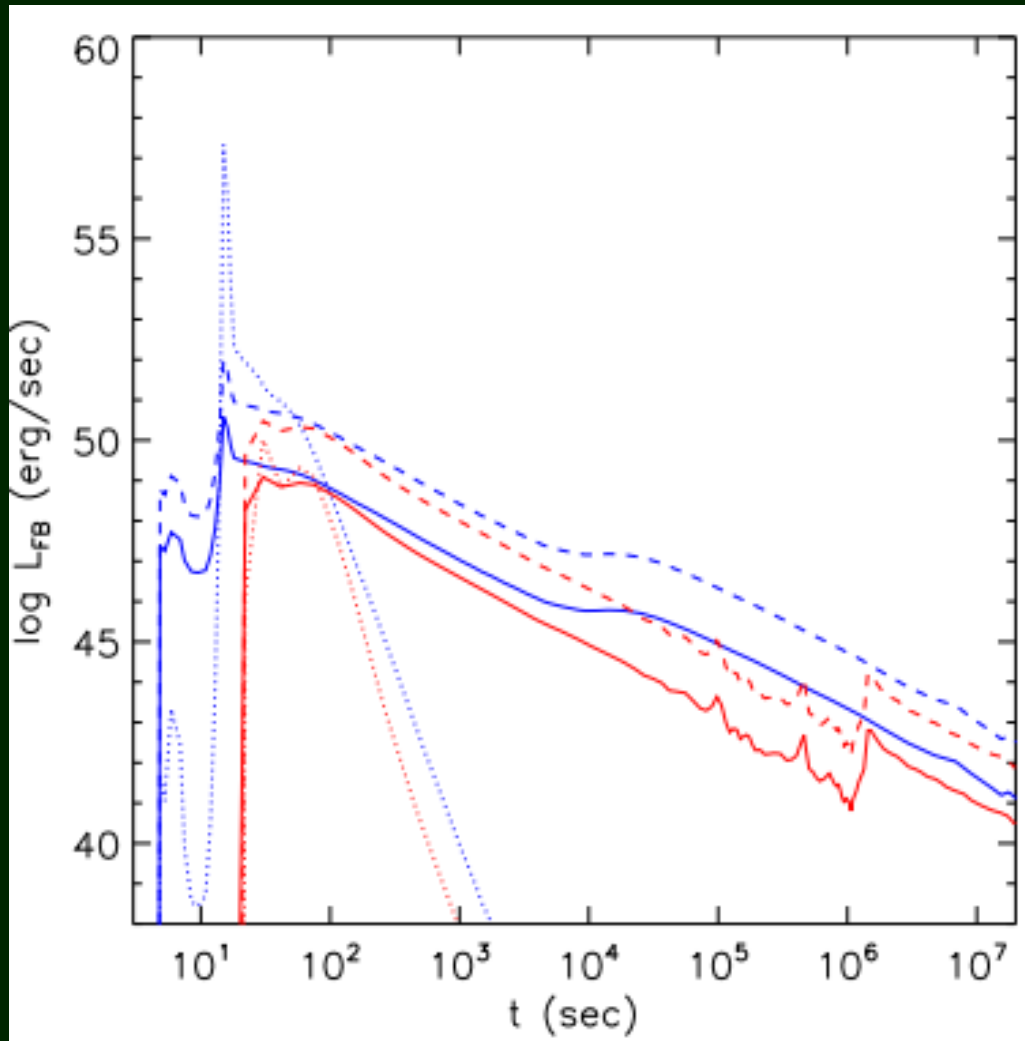
For this plot no radioactive heating is taken into account.

An accreting BH can “emerge” after ~few months-years.

Balberg, Shapiro astro-ph/0104215

(see also Zampieri et al., 1998, ApJ 505, 876)

New calculations



Several mechanisms of energy release in a fall-back are calculated:

- “accretion heating” (solid line)
- neutrino annihilation (dotted line)
- Blandford-Znajek emission (dashed line).

Estimates show that fallback can potentially lead to large amount of energy deposition to the ejecta, powering super-luminous supernovae.

A BH birth???

EVIDENCE FOR A BLACK HOLE REMNANT IN THE TYPE IIL SUPERNOVA 1979C

D. J. PATNAUDE, A. LOEB, & C. JONES

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

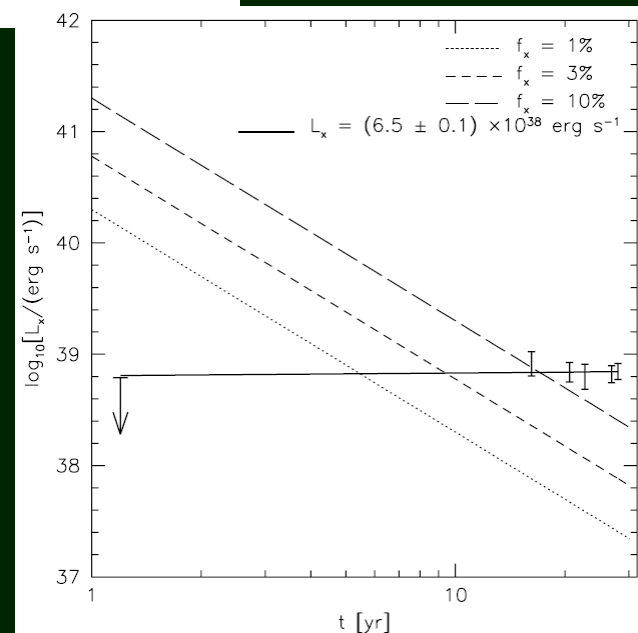
Draft version December 8, 2009

ABSTRACT

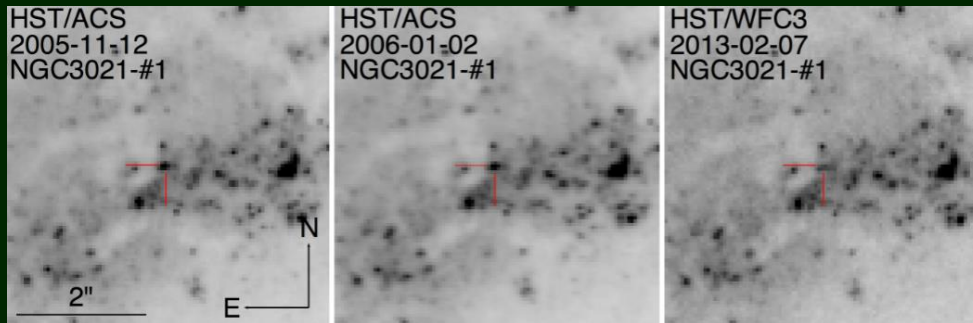
We present an analysis of archival X-ray observations of the Type IIL supernova SN 1979C. We find that its X-ray luminosity is remarkably constant at $(6.5 \pm 0.1) \times 10^{38} \text{ erg s}^{-1}$. The high and steady luminosity is evidence for a stellar-mass ($\sim 5\text{--}10M_{\odot}$) black hole accreting material from either a supernova fallback disk or possibly from a binary companion. We find that the bright and steady X-ray light curve is not consistent with either a model for a supernova powered by magnetic braking of a rapidly rotating magnetar, or a model where the blast wave is expanding into a dense circumstellar wind.

TABLE 1
X-RAY OBSERVATIONS OF SN 1979C

Δt yr	Count Rate 10^{-4} cps	F_X^a $10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$	L_X^b $10^{38} \text{ erg s}^{-1}$	Mission
0.7	< 3.0	< 2.3	< 6.3	<i>Einstein</i> (HRI)
16.2	6.7 ± 0.7	3.0 ± 0.3	8.2 ± 0.9	<i>ROSAT</i> (HRI)
20.6	$42. \pm 2.0$	2.5 ± 0.2	6.9 ± 0.6	<i>Chandra</i> (ACIS-S)
22.7 ^c	...	2.3 ± 0.3	6.3 ± 0.7	<i>XMM-Newton</i> (MOS)
26.9	$40. \pm 0.8$	2.4 ± 0.2	6.6 ± 0.5	<i>Chandra</i> (ACIS-S)
28.0	$43. \pm 0.3$	2.6 ± 0.2	7.0 ± 0.5	<i>Chandra</i> (ACIS-S)



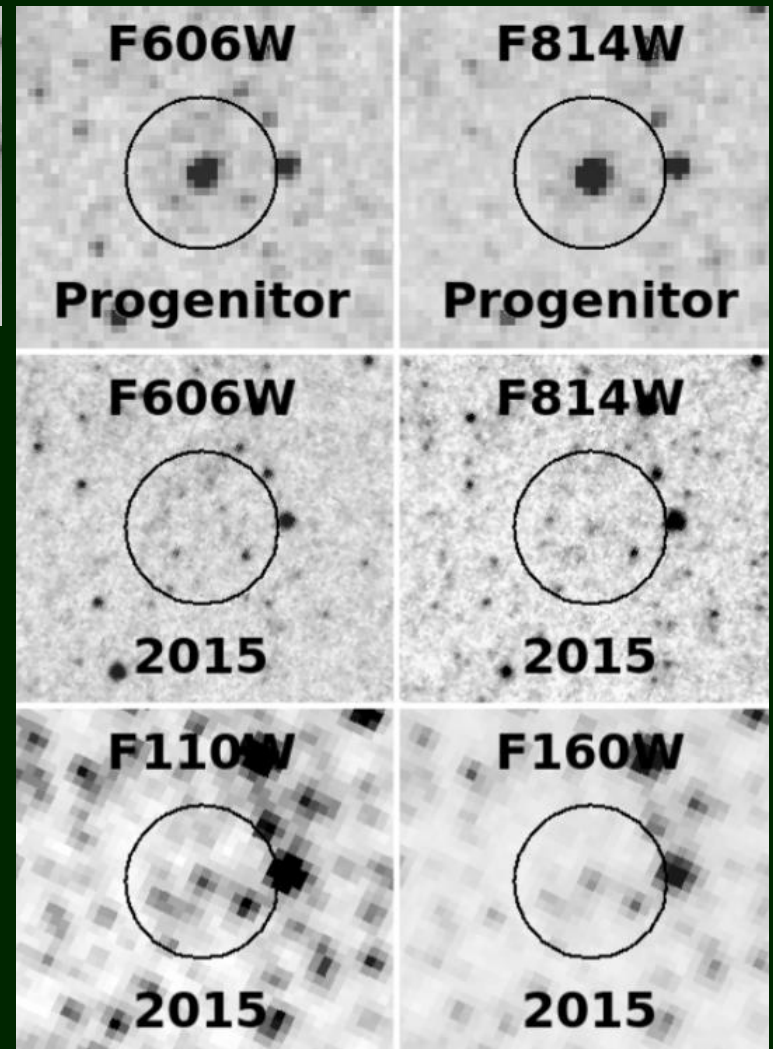
Disappearance of stars



The event is consistent with the ejection of the envelope of a red supergiant in a failed supernova and the late-time emission could be powered by fallback accretion onto a newly-formed black hole.

Progenitor mass ~ 23 -28 solar.
Consistent with the missing RSG problem.

In 2018 ~ 30 examples of identified SN progenitors are known, and there ~ 40 upper limits (1802.07870).



1609.01283

Conclusions

- There can be different kinds of BHs: PBH, stellar, IMBH, SMBH
- Stellar mass BHs can be observed due to
 - accretion in binaries
 - GRBs
 - GW
 - in SN
- Mass interval for stellar mass BH formation is not certain

Isolated BHs

Early works

«Halos around black holes» Soviet Astronomy – Astronom. Zhurn (1971)

In this paper accretion onto isolated BHs from the ISM was studied for different BH masses (including intermediate).

Dynamics of accretion, the role of turbulence, the role of magnetic fields in the ISM, spectrum.

Synchrotron radiation of magnetized plasma, which is heated during accretion up to 10^{12} K (here the temperature means the average energy of electrons motion perpendicular to magnetic field lines).

(Development of this approach see in [astro-ph/0403649](https://arxiv.org/abs/astro-ph/0403649))



Victorij Shvartsman

Basic formulae

$$\begin{aligned}\dot{M} &\sim \pi r_{\text{cap}}^2 \rho_{\text{gas}} V \\ &\approx 7.4 \times 10^{13} \text{ g s}^{-1} \left(\frac{M}{M_{\odot}} \right)^2 \left(\frac{n_{\text{gas}}}{10^2 \text{ cm}^{-3}} \right) \left(\frac{V}{10 \text{ km s}^{-1}} \right)^{-3} \\ &\approx 5.3 \times 10^{-4} \dot{M}_{\text{Edd}} \left(\frac{M}{M_{\odot}} \right) \left(\frac{n_{\text{gas}}}{10^2 \text{ cm}^{-3}} \right) \left(\frac{V}{10 \text{ km s}^{-1}} \right)^{-3}\end{aligned}$$

$$v_{\text{turb}} \sim 1.1 (r/1\text{pc})^{0.38} \text{ km s}^{-1},$$

Velocity of turbulent motions

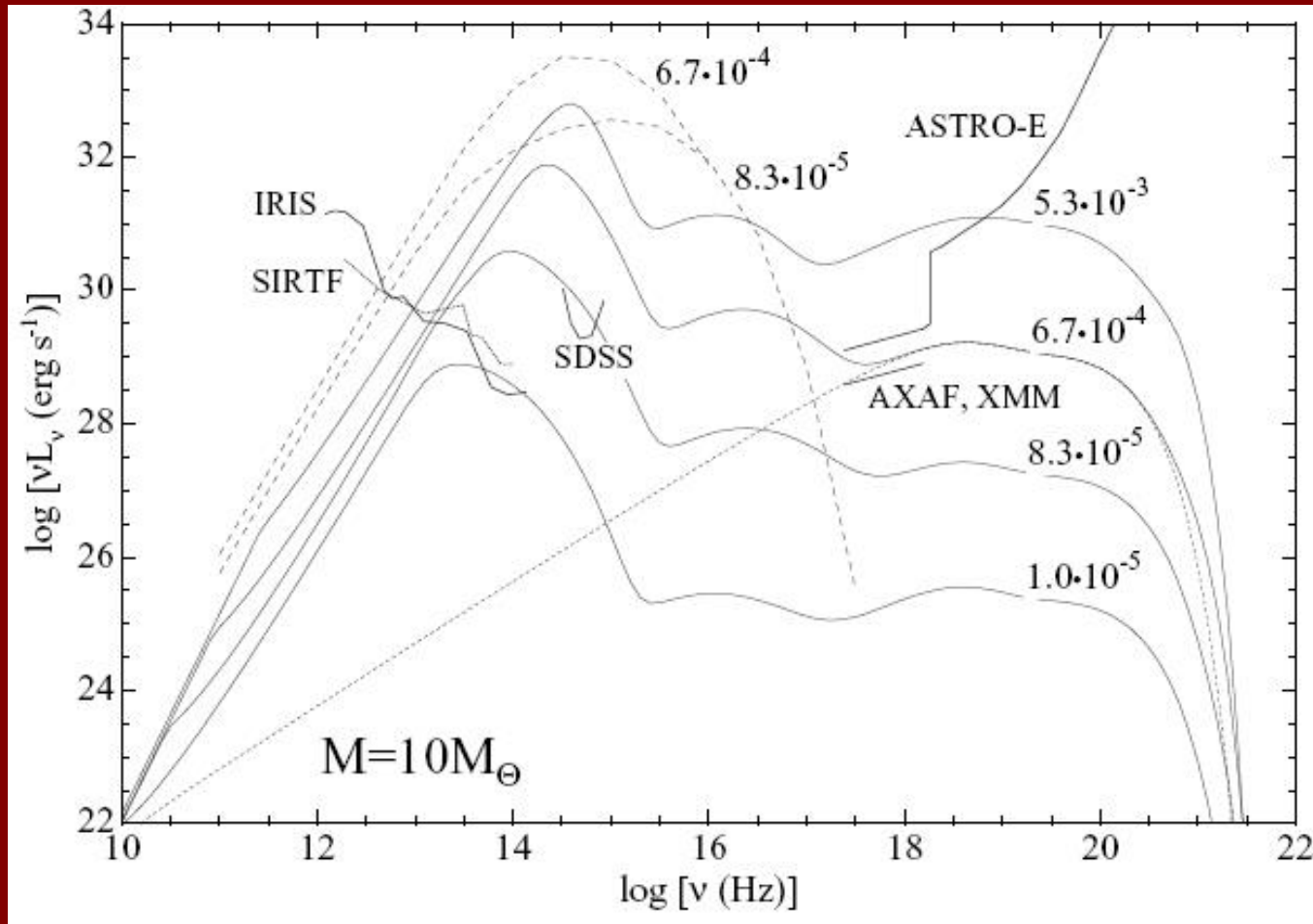
$$V \lesssim 52 (r_g/r_{\text{ofl}})^{0.18} (M/M_{\odot})^{0.14} \text{ km s}^{-1}$$

The critical velocity corresponding to an accretion disc formation.

(Fujita et al. 1998)

See also A&A 381, 1000 (2002)

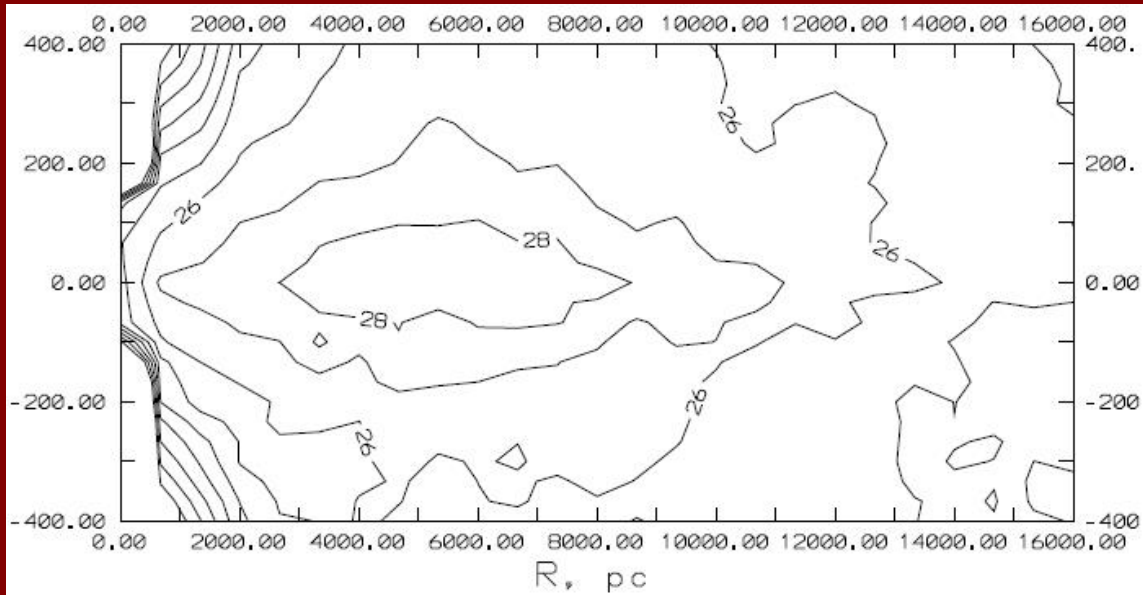
Isolated accreting BHs



ADAF
10 solar masses

The objects mostly
emit in X-rays or IR.

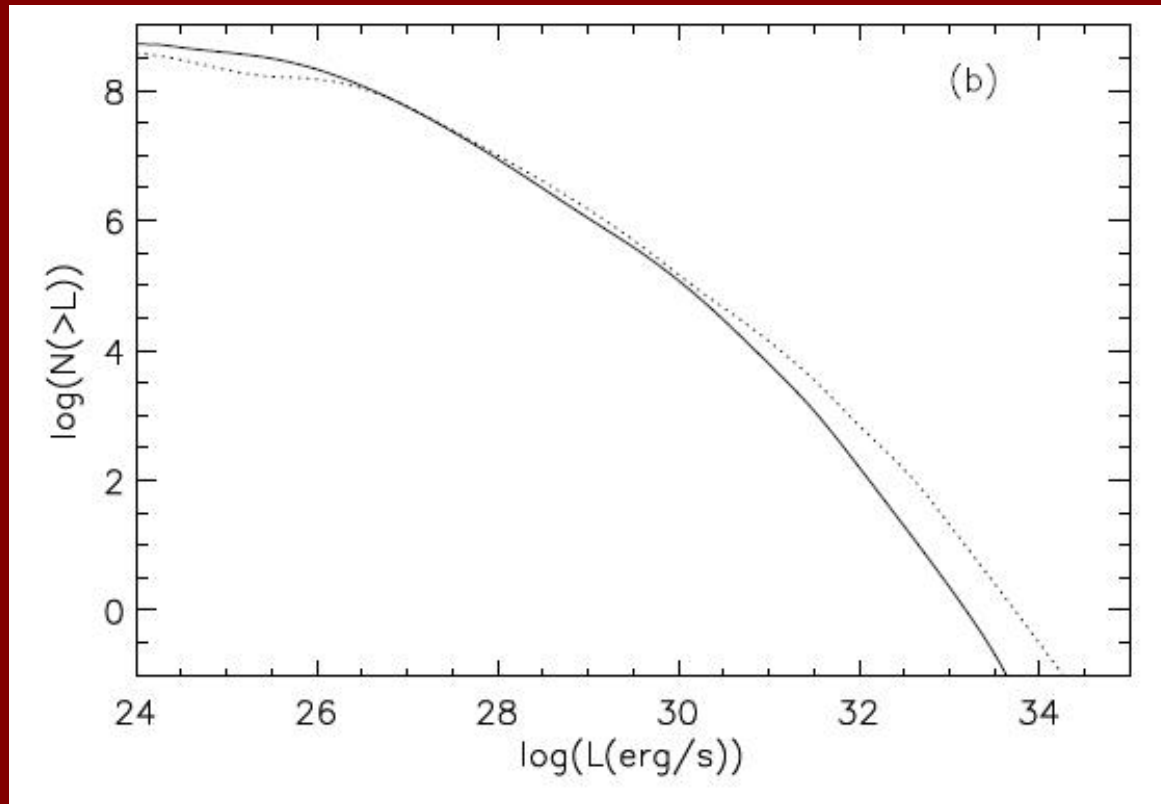
The galactic population of accreting isolated BHs



The luminosity distribution is mostly determined by the ISM distribution, then – by the galactic potential.

It is important that maxima of the ISM distribution and distribution of compact objects roughly coincide. This results in relatively sharp maximum in the luminosity distribution.

Searching in deep surveys



Agol, Kamionkowski (astro-ph/0109539) demonstrated that satellites like XMM or Chandra can discover about few dozens of such sources.

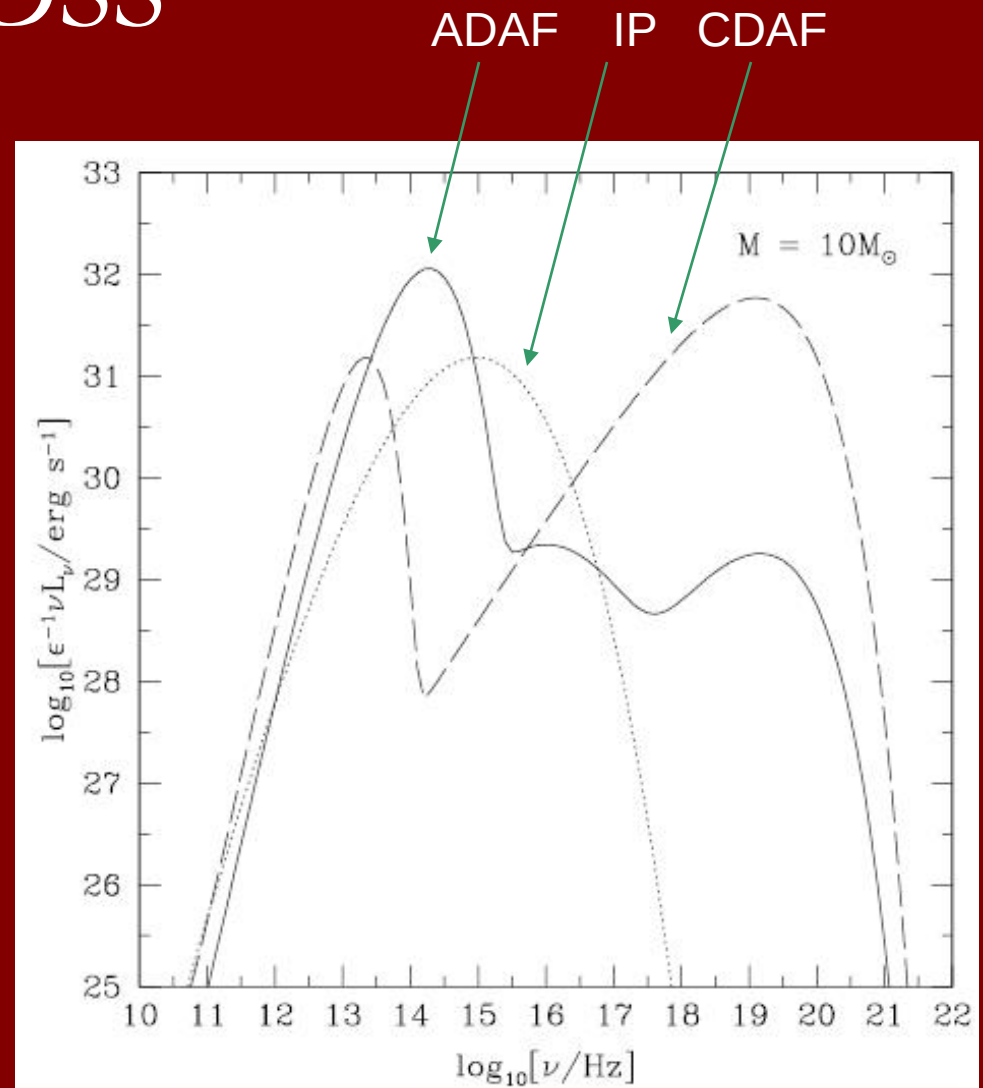
However, it is very difficult to identify isolated accreting BHs.

Digging in the SDSS

The idea is that the synchrotron emission can appear in the optical range and in X-rays.

Cross-correlation between SDSS and ROSAT data resulted in 57 candidates.

Regime of accretion and its efficiency are poorly known



Radio emission from isolated BHs

$$L_R \sim L_X^{0.7}$$

The task for LOFAR?

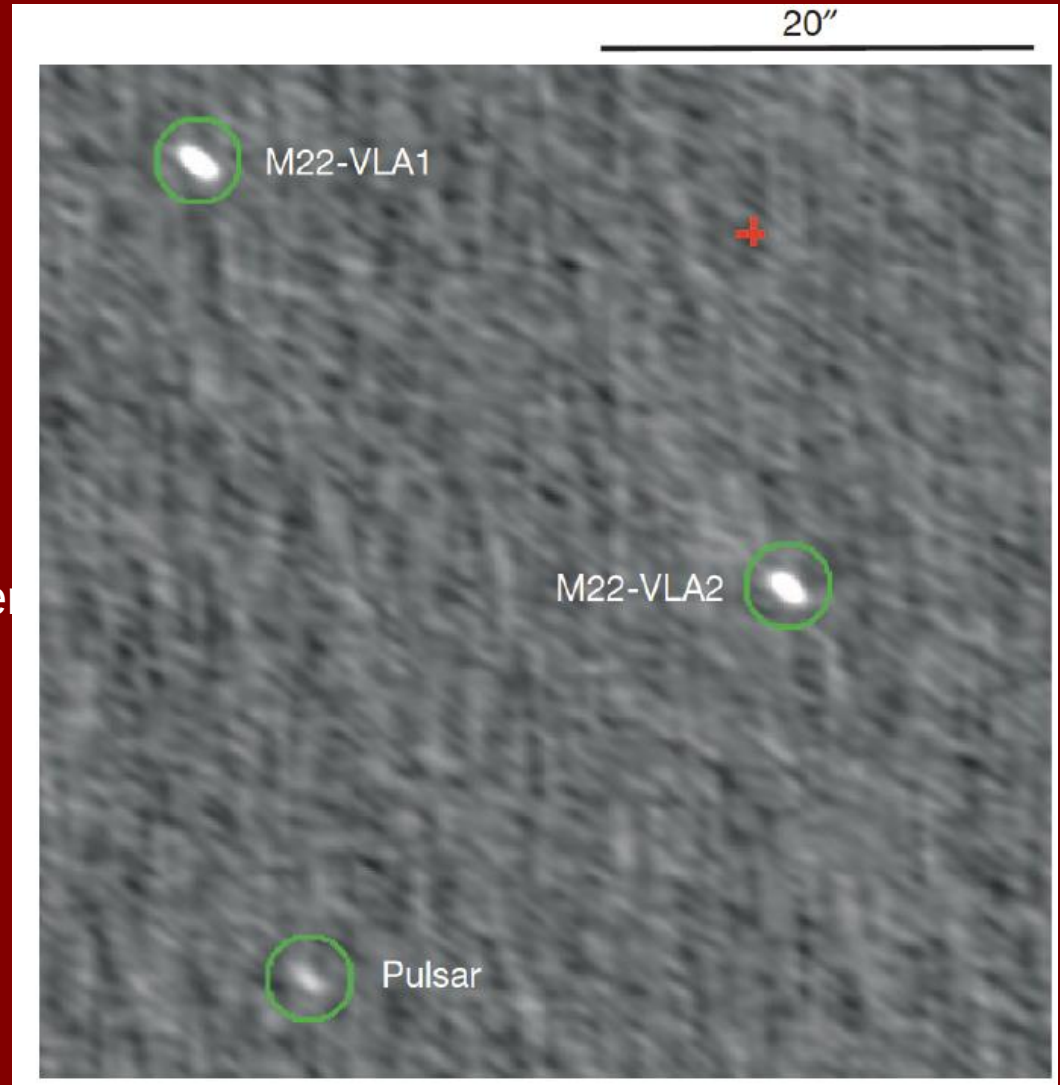
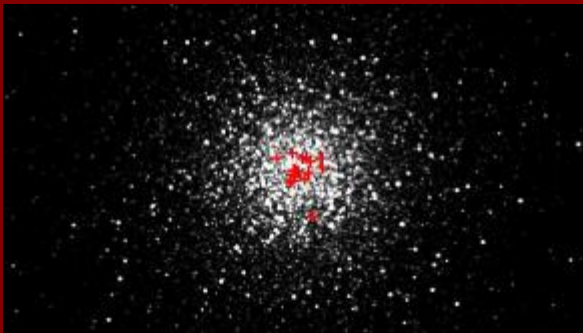
Phase/type	M_{BH}	n_H	T_{ISM}	N_{BH}	L_X	d_{radio}	N_{radio}
GMC Core	10	10^5	10^4	~ 1	5×10^{33}	12	~ 1
GMC/cold neutral	10	10^3	10^4	1.3×10^6	5×10^{29}	0.7	400
warm ISM	10	0.4	10^4	5×10^7	7×10^{22}	.005	0
hot ISM	10	0.01	10^6	5×10^7	5×10^{13}	10^{-5}	0
GMC/cold, fast halo IMBH	2600	10^3	10^4	30	8×10^{30}	15	10
IMBH/disk pop/cold ISM	260	10^3	10^4	*	8×10^{33}	40	*
IMBH/disk pop/GMC	260	10^5	10^4	*	8×10^{37}	800	*
IMBH/disk pop/warm ISM	260	0.4	10^4	*	1×10^{27}	0.5	*

Two isolated BHs in a globular cluster?

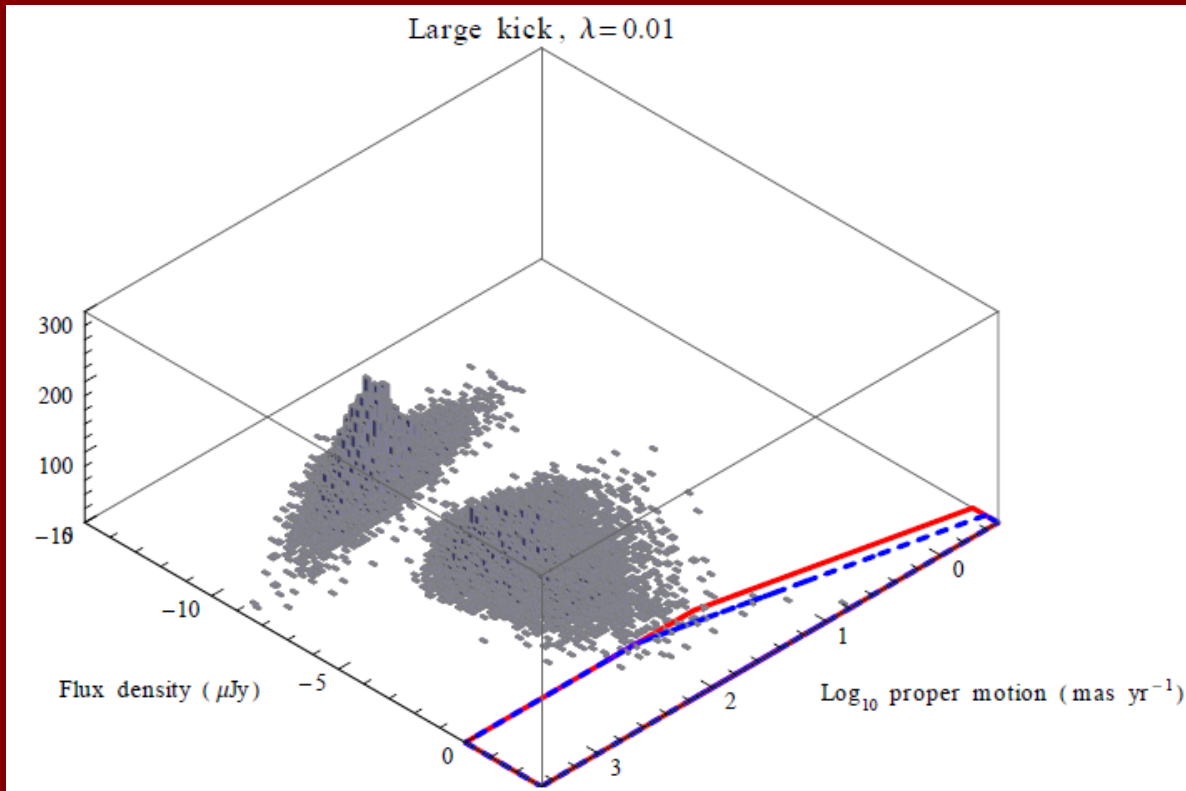
eVLA observations showed two flat-spectrum sources without X-ray or/and optical identifications.

Most probably, they are accreting BHs. Probably, isolated.

Numerical model for the cluster evolution and the number of BHs was calculated in the paper 1211.6608.



New calculations for radio IBHs



The authors calculate if IBHs can be detected by SKA and other future survey if the accrete from the ISM. Different assumptions about initial velocities and accretion efficiency are made.

SKA will be effective in discovering isolated accreting BHs due to their radio emission.

Electron-positron jets from isolated BHs

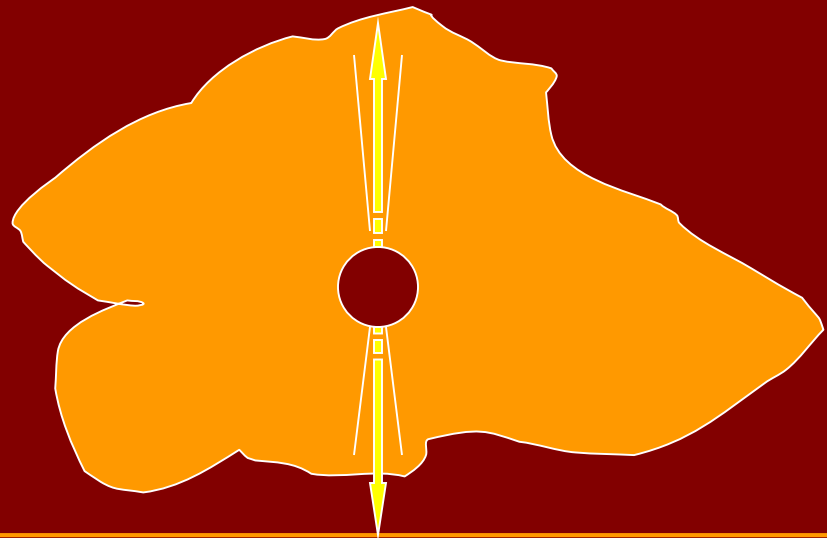
The magnetic flux, accumulated on the horizon of an IBH because of accretion of interstellar matter, allows the Blandford–Znajek mechanism to be activated.

So, electron–positron jets can be launched.

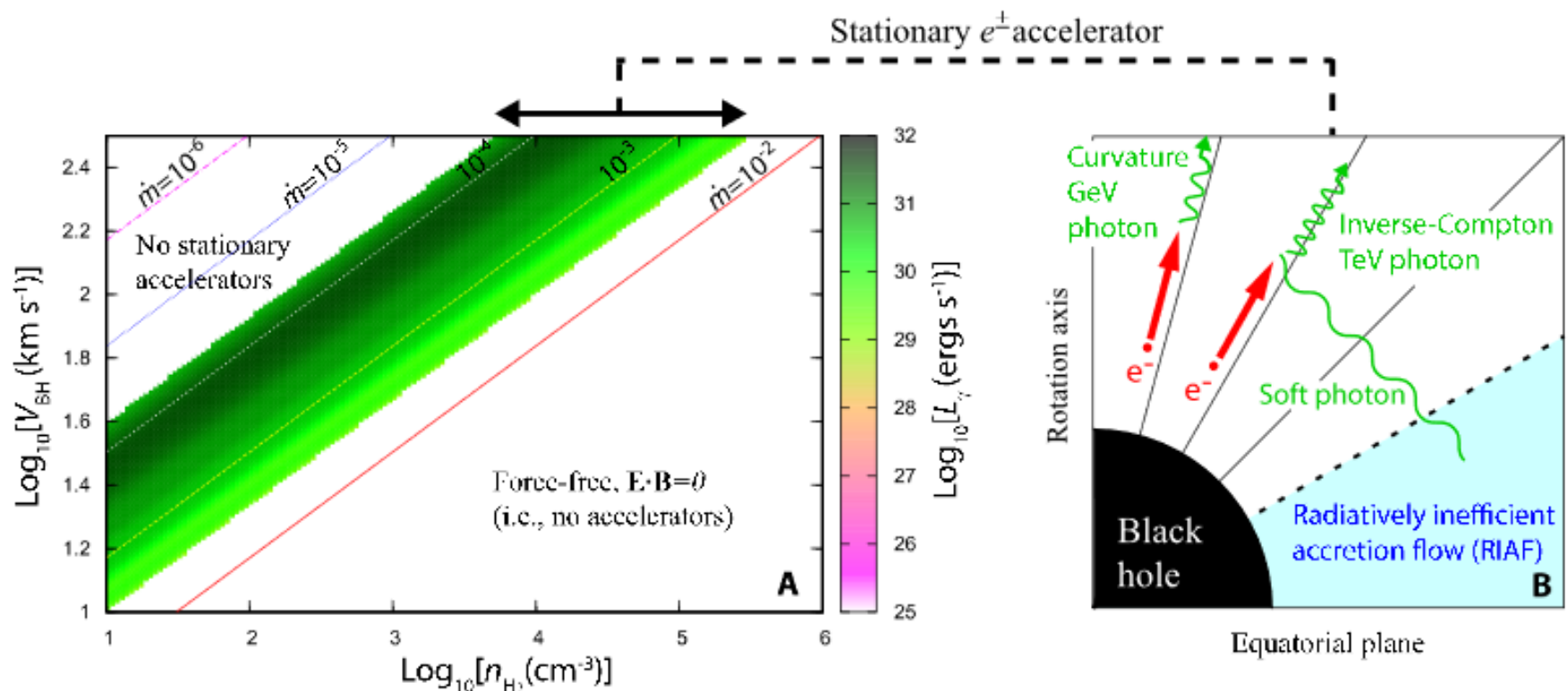
Such jets are feasible electron accelerator which, in molecular clouds, allows electron energy to be boosted up to ~ 1 PeV.

These sources can contribute both to the population of unidentified point-like sources and to the local cosmic-ray electron spectrum.

The inverse Compton emission of these locally generated cosmic rays may explain the variety of gamma-ray spectra detected from nearby molecular clouds.



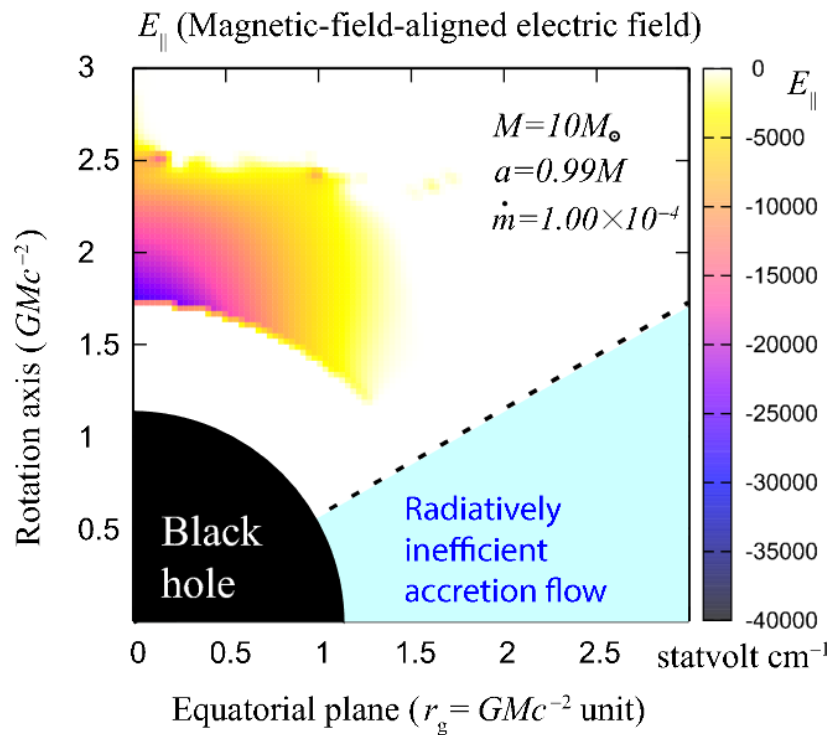
IBHs in molecular clouds as TeV sources



Rotation is important!

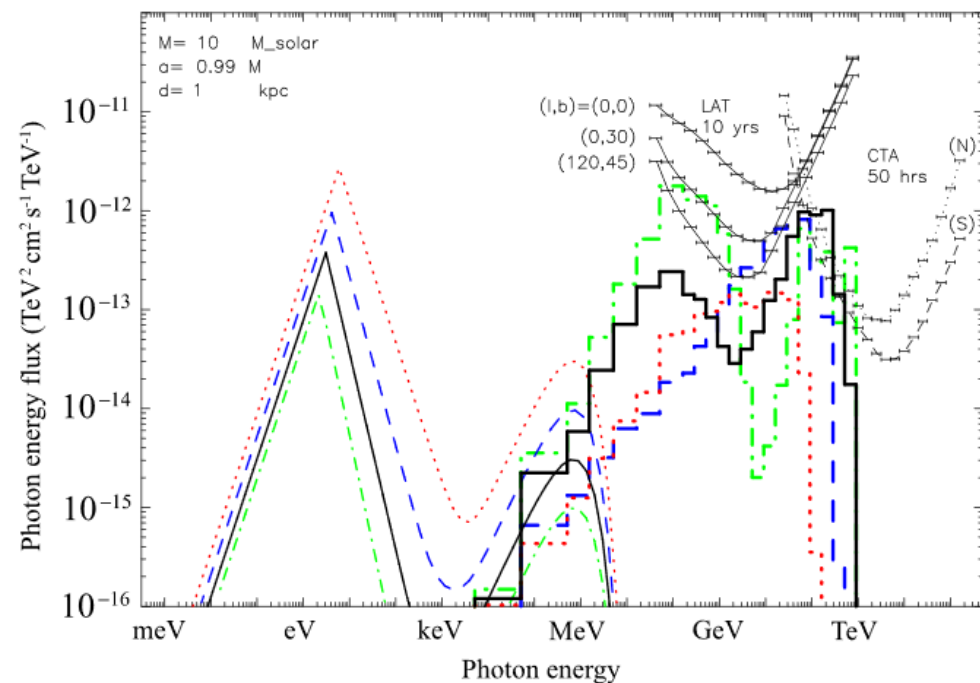
The black holes rotational energy is electromagnetically extracted via the Blandford-Znajek process.

Particle acceleration by rotating IBHs



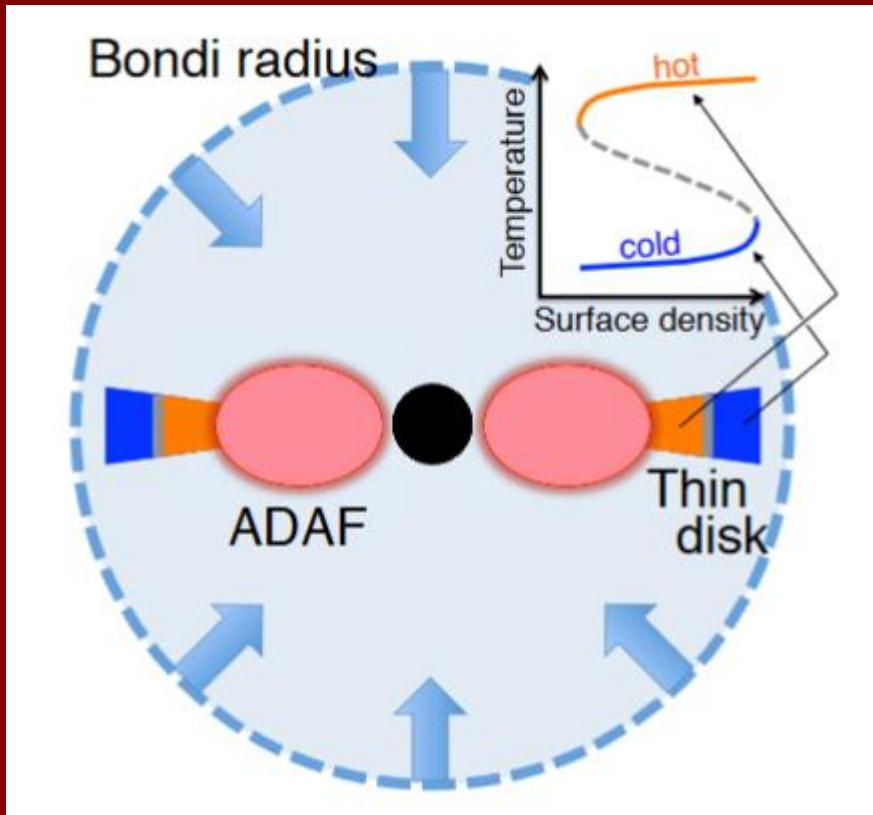
The red dotted, blue dashed, black solid, and green dash-dotted curves correspond to the dimensionless accretion rate of $10^{-3.5}$, $10^{-3.75}$, 10^{-4} , and $10^{-4.25}$, respectively.

The distance is assumed to be 1 kpc.

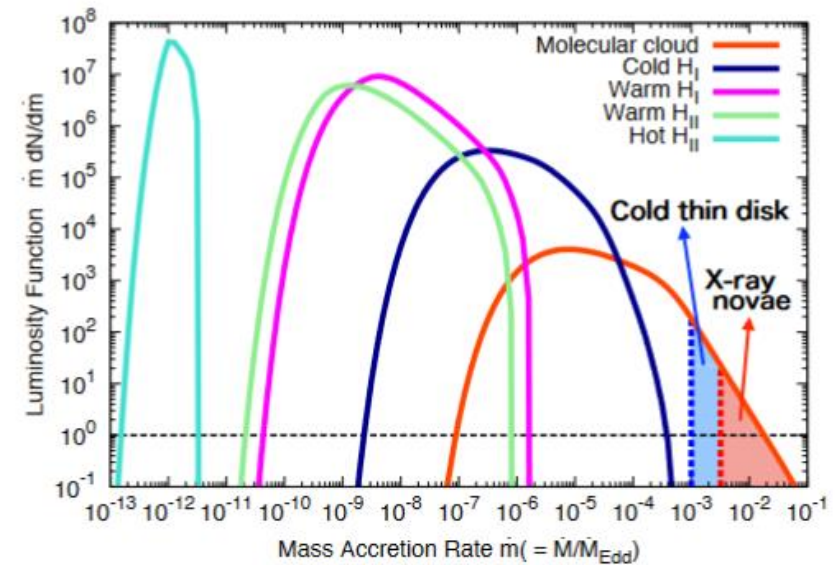


The thin curves on the left denote the input spectra of the ADAF. Such soft photons illuminate the accelerator in the polar funnel. The thick lines denote the spectra of the gamma-rays emitted from the accelerator.

X-ray nova and accreting isolated BHs



Around accreting isolated BHs in molecular clouds it is possible to have conditions (hydrogen-ionization disk instability) necessary for X-ray nova appearance.



Up to several event per year.
Then some of known X-ray nova
with unidentified companions,
can be due to isolated BHs.

Detailed study of AIBHs

$$\dot{M} = \lambda \cdot 4\pi \frac{(GM)^2 \rho}{(v^2 + c_s^2)^{3/2}}$$

$$\approx 3.7 \times 10^{15} \text{ g s}^{-1}$$

$$\cdot \left(\frac{\lambda}{0.1} \right) \left(\frac{M}{10 \text{ M}_\odot} \right)^2 \left(\frac{\rho}{10^3 \text{ cm}^{-3} m_p} \right) \left[\frac{v^2 + c_s^2}{(10 \text{ km s}^{-1})^2} \right]^{-3/2}$$

$$\eta = \begin{cases} \eta_{\text{std}} (\dot{M} / \dot{M}_{\text{th}}) & (\text{when } \dot{M} < \dot{M}_{\text{th}}) \\ \eta_{\text{std}} & (\text{when } \dot{M}_{\text{th}} < \dot{M} < 2\dot{M}_{\text{Edd}}). \end{cases}$$

RIAF (radiatively-inefficient accretion flow).
Below some threshold the luminosity is reduced.

$$L = \eta \dot{M} c^2$$

$$= 3.4 \times 10^{37} \text{ erg s}^{-1}$$

$$\cdot \eta \lambda \left(\frac{M}{10 \text{ M}_\odot} \right)^2 \left(\frac{\rho}{10^3 \text{ cm}^{-3} m_p} \right) \left[\frac{v^2 + c_s^2}{(10 \text{ km s}^{-1})^2} \right]^{-3/2}$$

Most of AIBHs
are in the RIAF state.

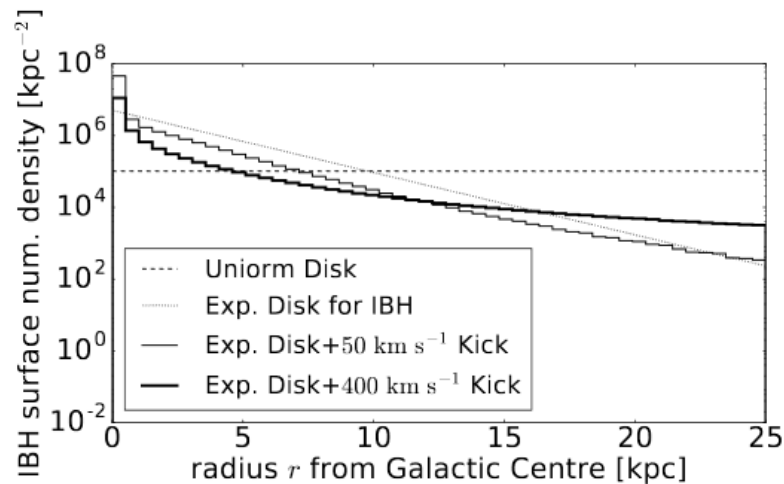
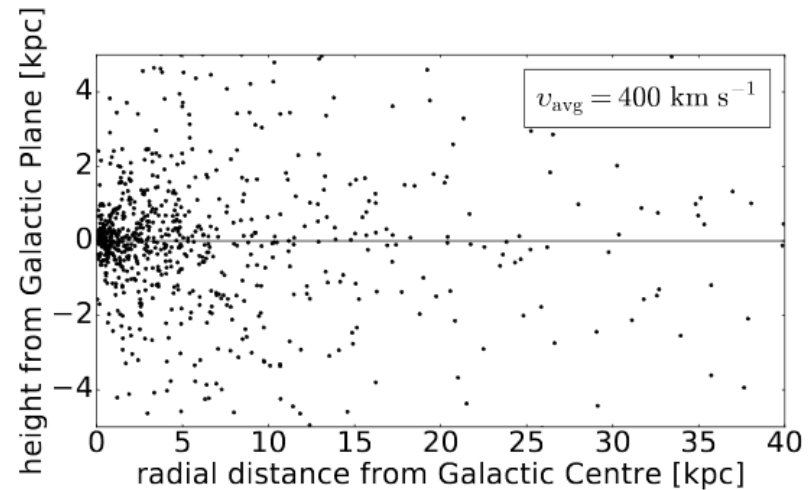
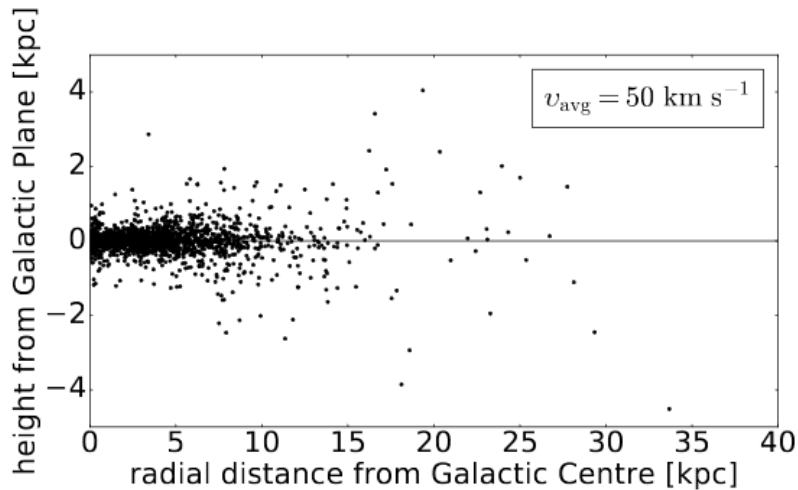
$L = 9.0 \times 10^{32} \text{ erg s}^{-1}$ **RIAF**

$$\cdot \left(\frac{\lambda}{0.1} \right)^2 \left(\frac{M}{10 \text{ M}_\odot} \right)^3 \left(\frac{\rho}{10^3 \text{ cm}^{-3} m_p} \right)^2 \left[\frac{v^2 + c_s^2}{(10 \text{ km s}^{-1})^2} \right]^{-3}$$

$L = 3.4 \times 10^{35} \text{ erg s}^{-1}$ **Standard**

$$\cdot \left(\frac{\lambda}{0.1} \right) \left(\frac{M}{10 \text{ M}_\odot} \right)^2 \left(\frac{\rho}{10^3 \text{ cm}^{-3} m_p} \right) \left[\frac{v^2 + c_s^2}{(10 \text{ km s}^{-1})^2} \right]^{-3/2}$$

Spatial distribution

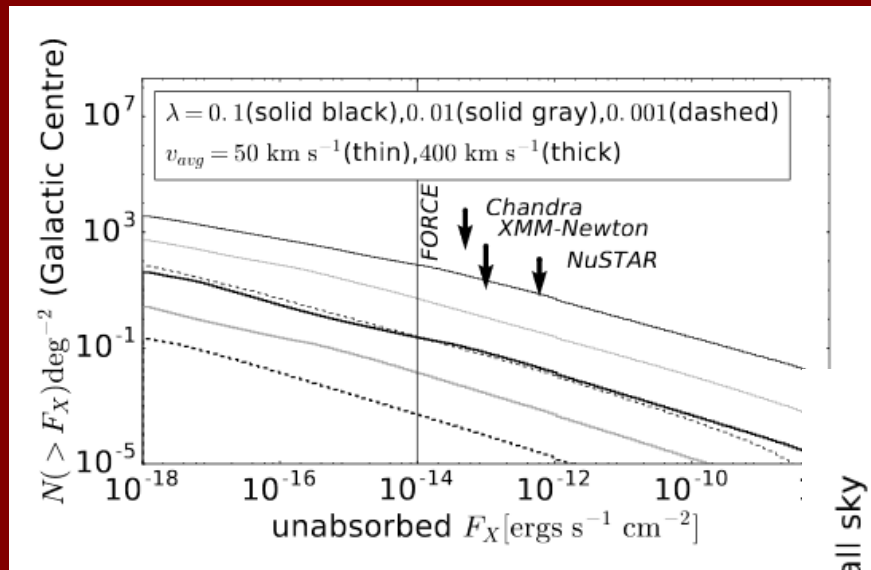


Many BHs leave the Galaxy
for average velocity $>200 \text{ km/s}$

Observability

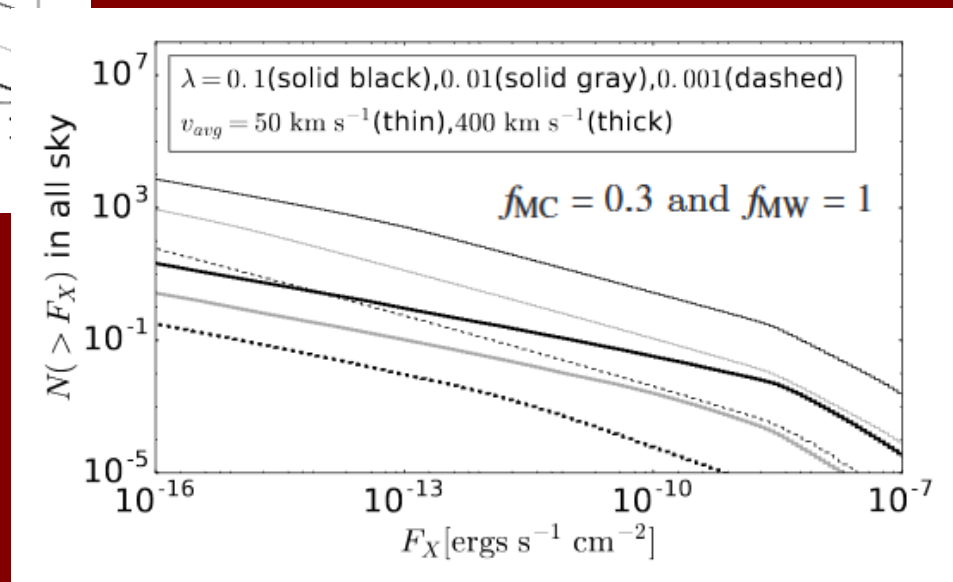
$$dF_{\text{ph}}/d\epsilon_{\text{ph}} \propto \epsilon_{\text{ph}}^{-\zeta}$$

Power-law spectrum in the RIAF regime (hard state)

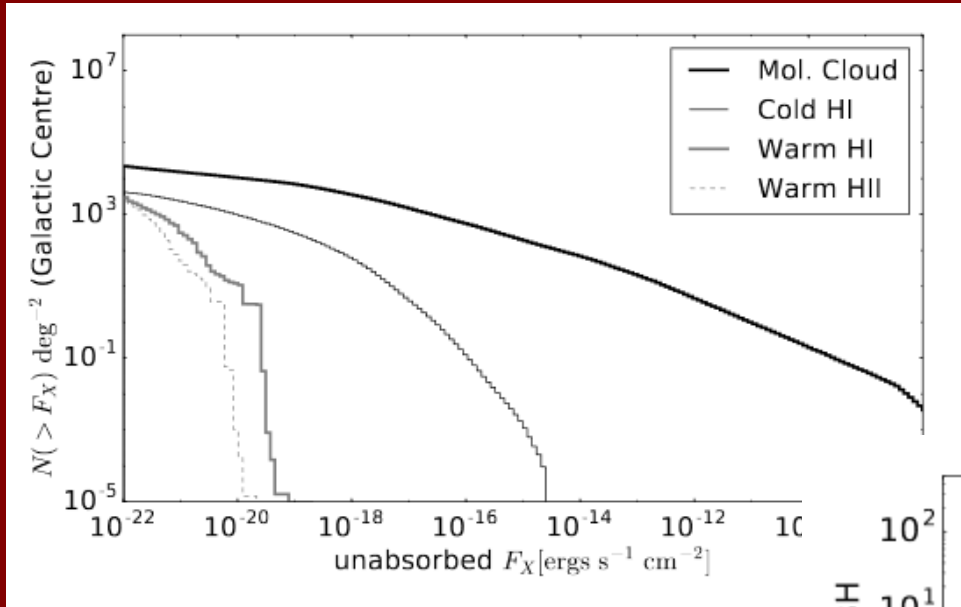


The authors focus on harder X-ray emission than in ROSAT case

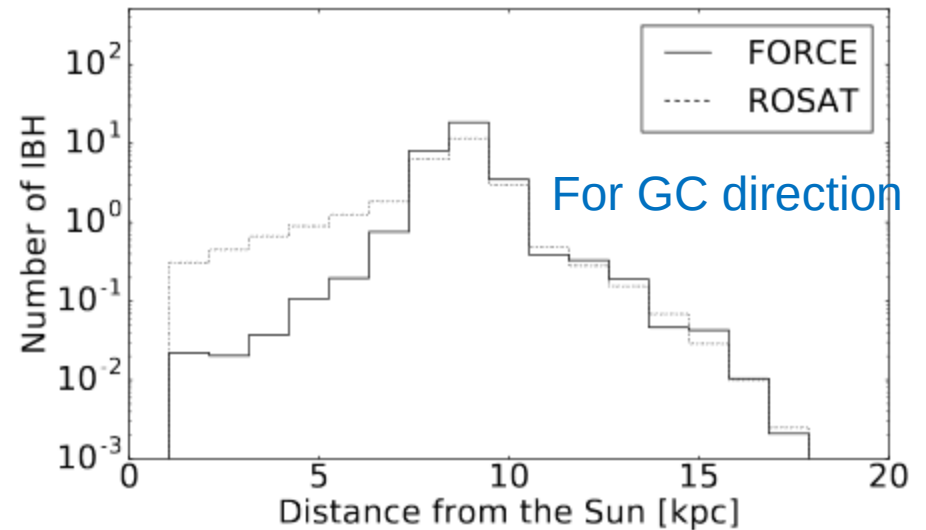
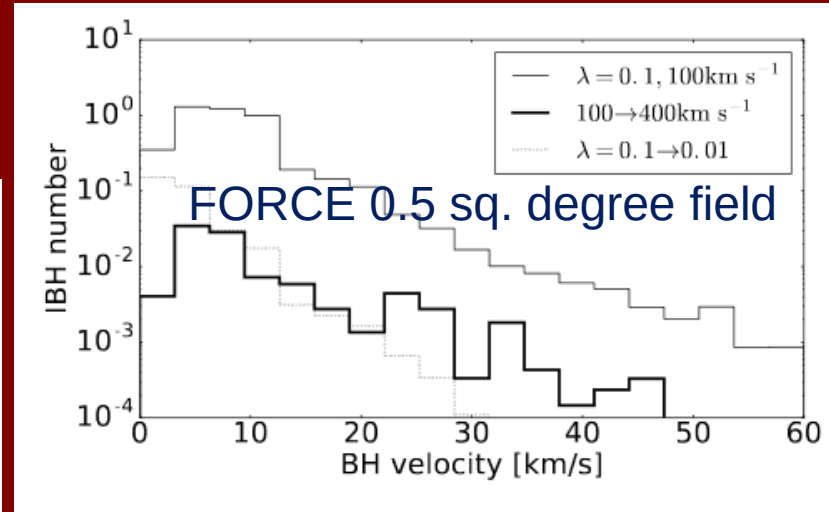
	$v_{\text{avg}} [\text{km s}^{-1}]$				
	50	100	200	300	400
bulge	0.018	1.4×10^{-3}	0.067	3.7×10^{-3}	9.1×10^{-3}
disc	32	4.5	0.79	0.19	0.086



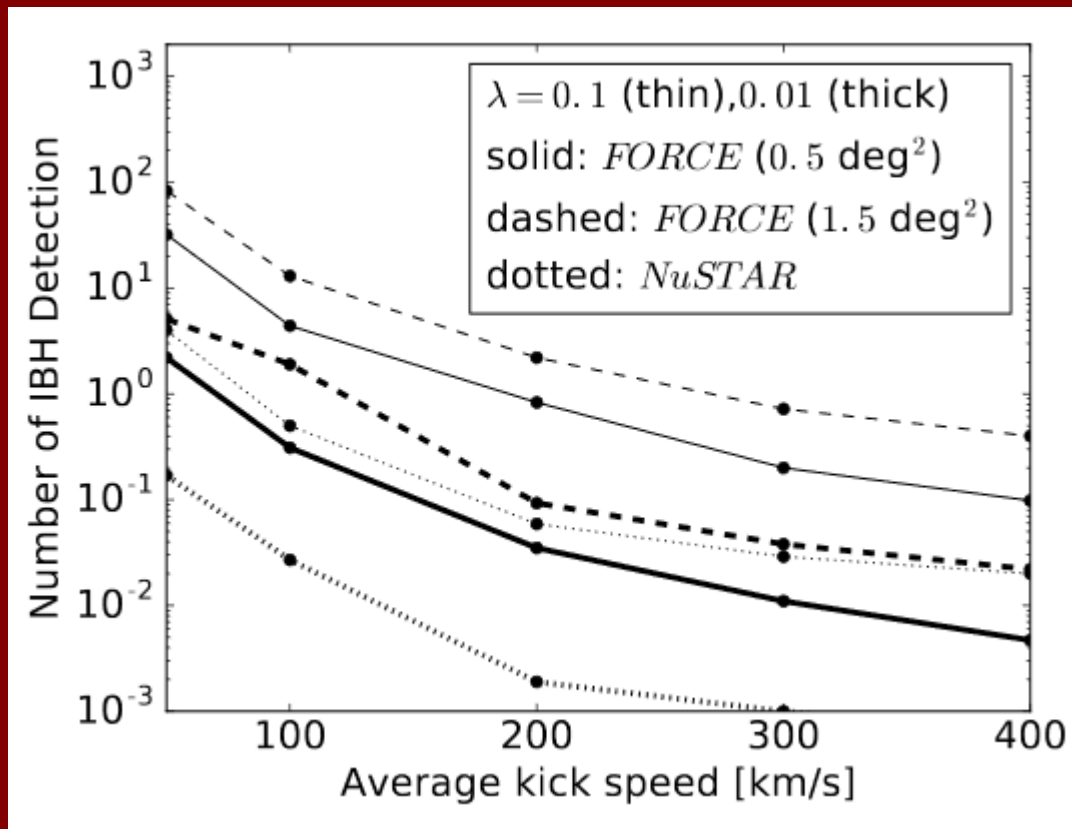
Properties of AIBHs



AIBHs from dense ISM regions contribute more.

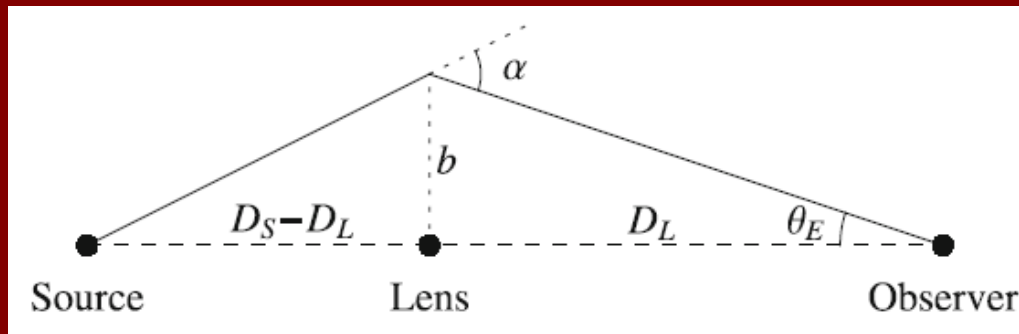


Deep survey towards the Galactic center



FORCE is a japanies project,
if approved – then to be launched in mid 2020s.

Gravitational microlensing - 1



Probability of microlensing is small.
For stars it is $\sim 10^{-5} - 10^{-6}$ per year.

$$b = D_L \theta_E,$$

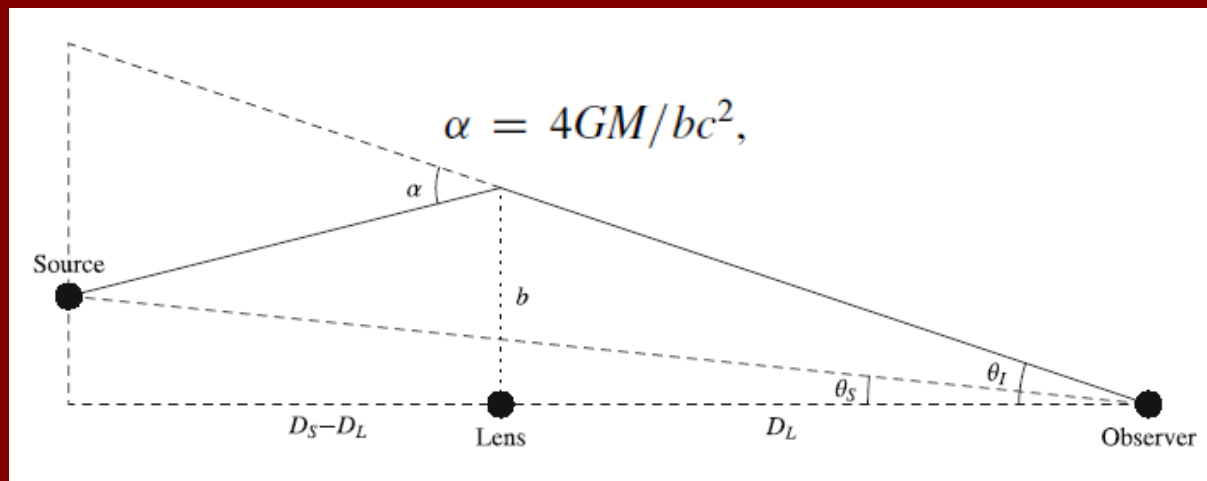
$$\alpha = b/D_L + b/(D_S - D_L).$$

$$\theta_E = \sqrt{\kappa M \pi_{\text{rel}}}; \quad \kappa \equiv \frac{4G}{c^2 \text{AU}} \simeq 8.14 \frac{\text{mas}}{M_\odot},$$

$$\pi_{\text{rel}} = \text{AU}(D_L^{-1} - D_S^{-1})$$

$$\tau = \int dD_L \pi (D_L \theta_E)^2 n(D_L) \sim \frac{4\pi G M n}{c^2} D^2 = \frac{4\pi G \rho}{c^2} D^2 \sim \frac{G M_{\text{tot}}}{D c^2} \sim \frac{v^2}{c^2}$$

Gravitational microlensing - 2



$$(\theta_I - \theta_S)D_S = \alpha(D_S - D_L)$$

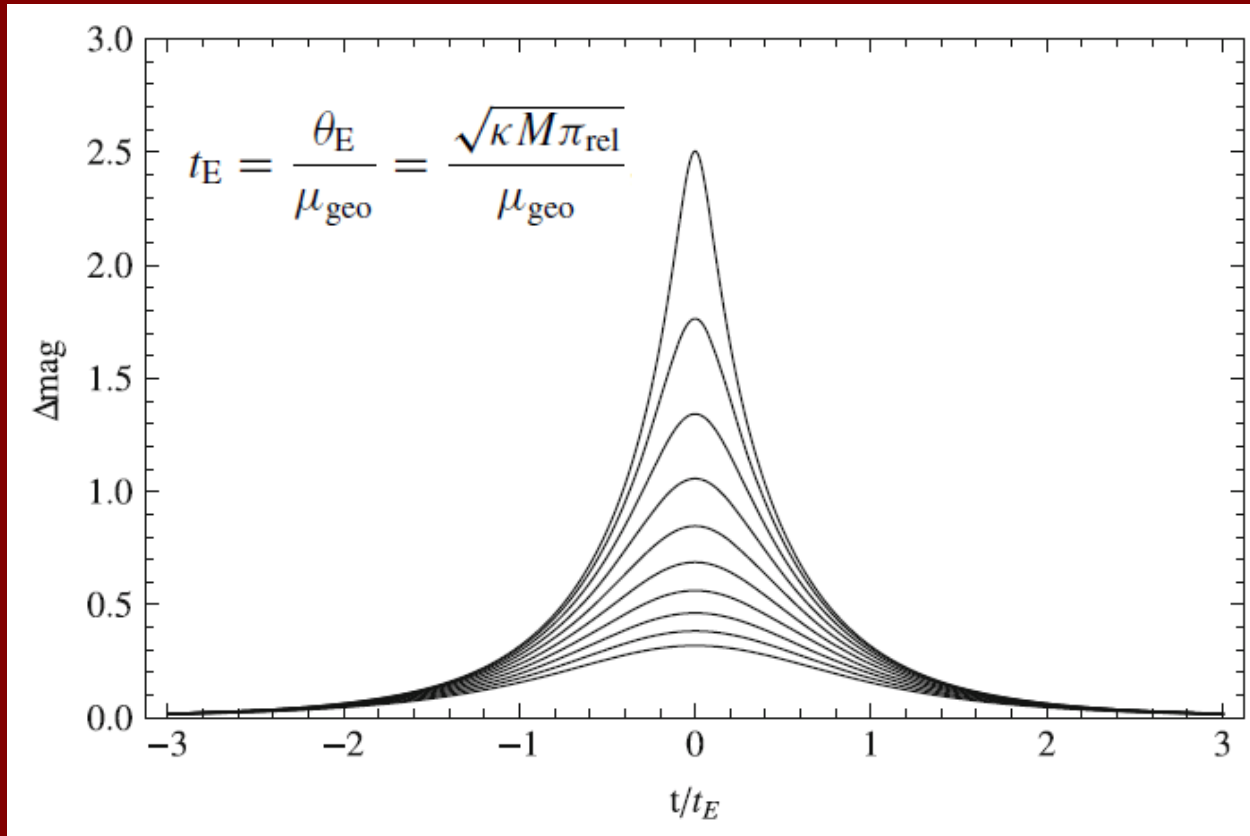
$$\theta_I(\theta_I - \theta_S) = \frac{4GM\pi_{\text{rel}}}{c^2 \text{AU}} \equiv \theta_E^2.$$

$$A_{\pm} = \pm \frac{u_{\pm}}{u} \frac{\partial u_{\pm}}{\partial u} = \frac{A \pm 1}{2}$$

$$u_{\pm} = \frac{u \pm \sqrt{u^2 + 4}}{2}; \quad u \equiv \frac{\theta_S}{\theta_E} \quad u_{\pm} \equiv \frac{\theta_{I,\pm}}{\theta_E}.$$

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} = (1 - Q^{-2})^{-1/2}; \quad Q \equiv 1 + \frac{u^2}{2},$$

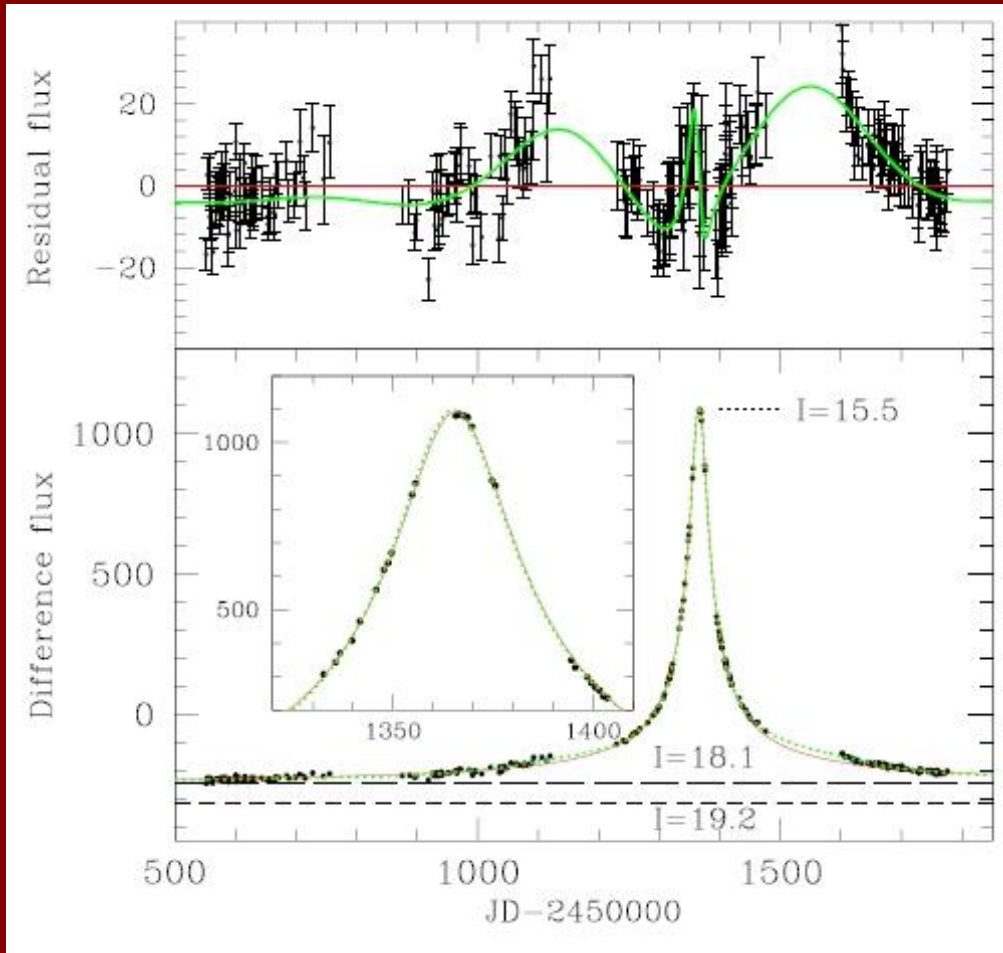
Light curves for point lenses



$$F(t) = f_s A(\mathbf{u}(t; t_0, u_0, t_E), \rho) + f_b;$$

$$\mathbf{u}(t; t_0, u_0, t_E) = (\tau(t), \beta) = \left(\frac{t - t_0}{t_E}, u_0 \right).$$

Microlensing and isolated BHs

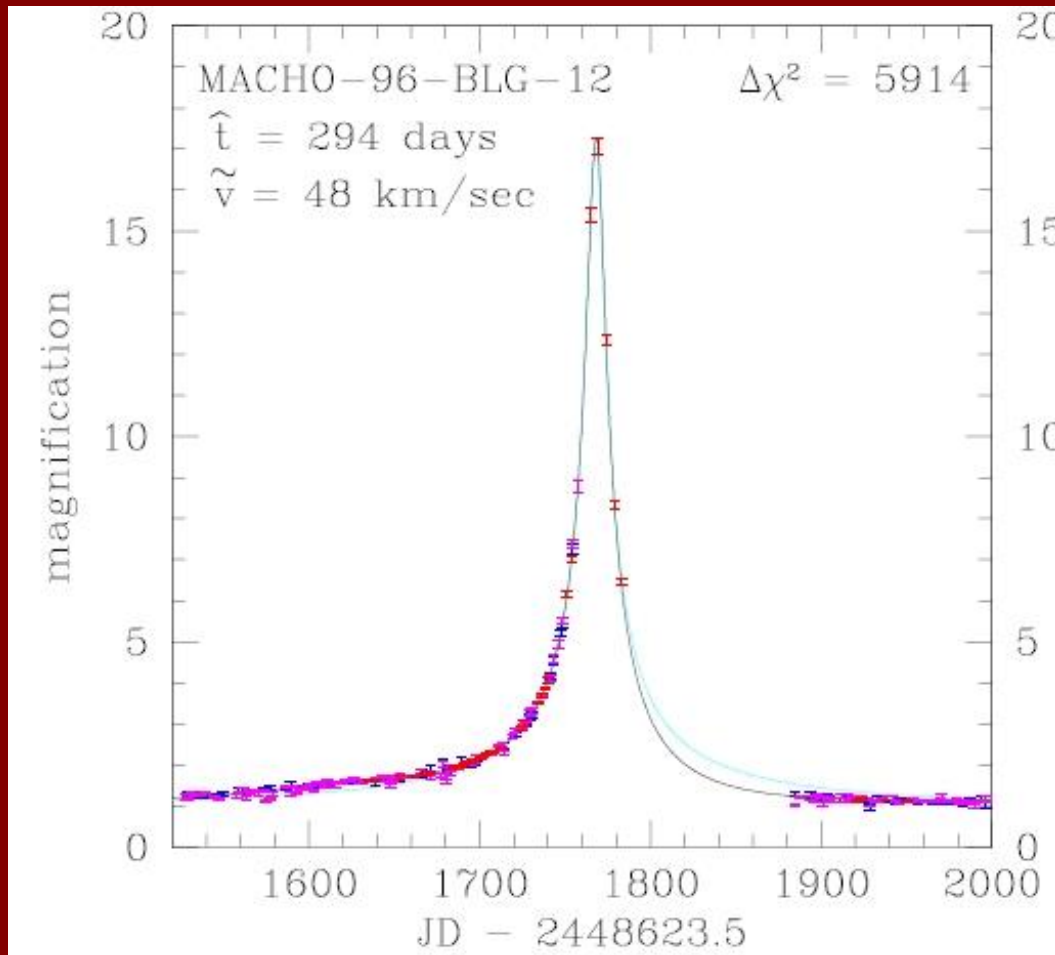


Event OGLE-1999-BUL-32

A very long event: 641 days.

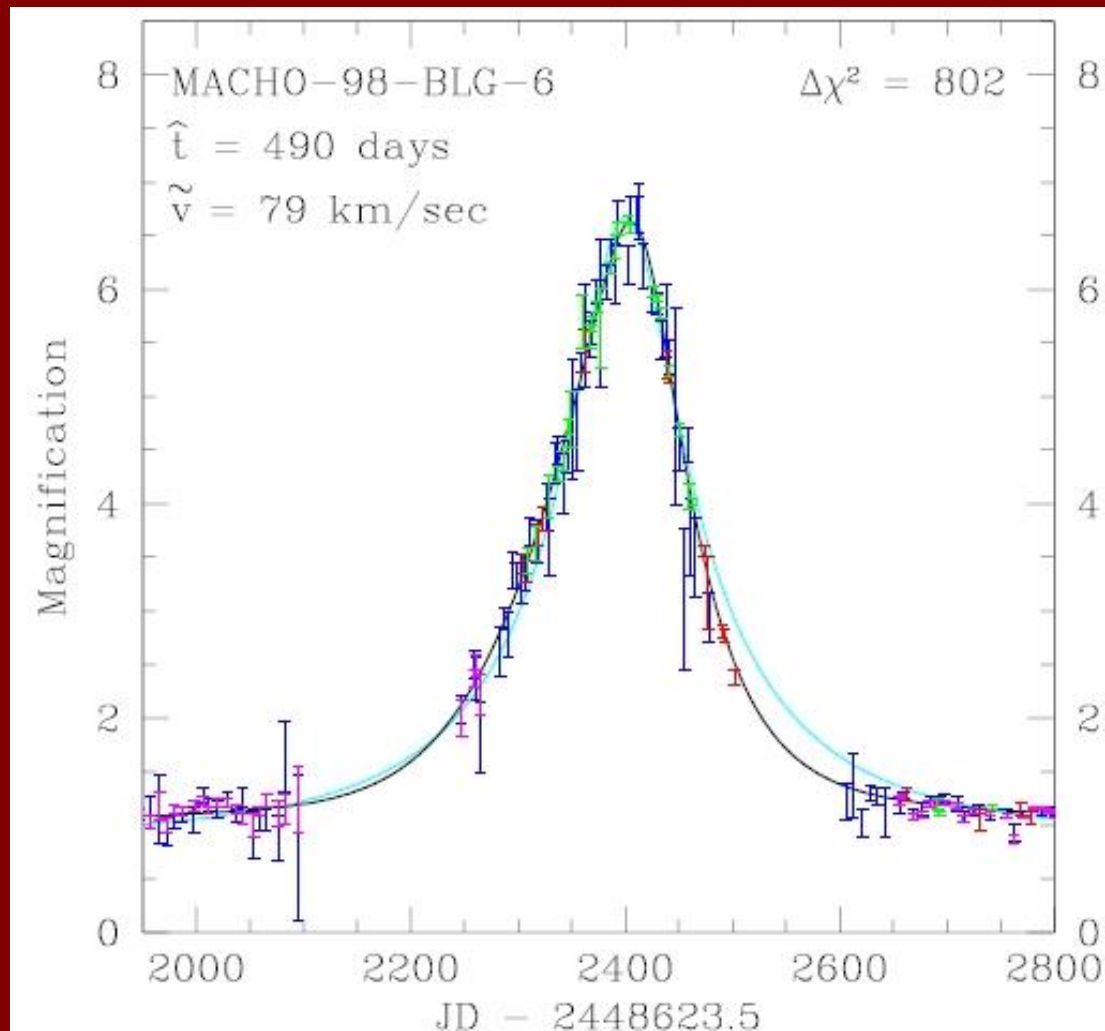
Mass estimate for the lense $>4 M_0$

Microlensing – the MACHO project



MACHO-96-BLG-6
3-16 solar masses.

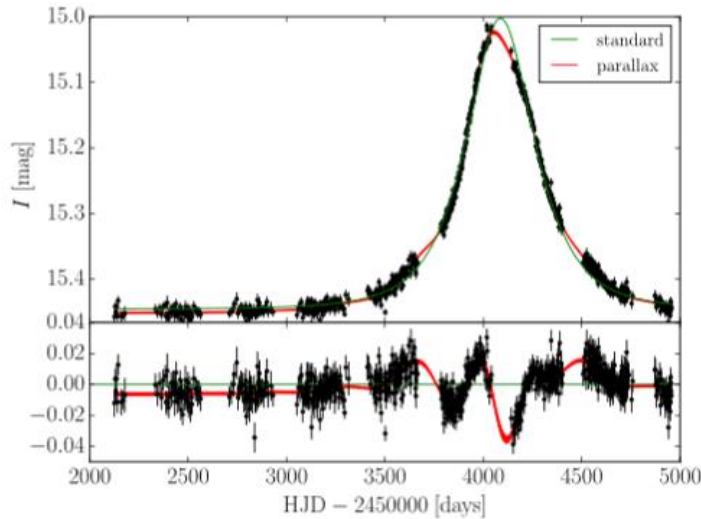
Again MACHO!



MACHO-98-BLG-6
3-13 solar masses.

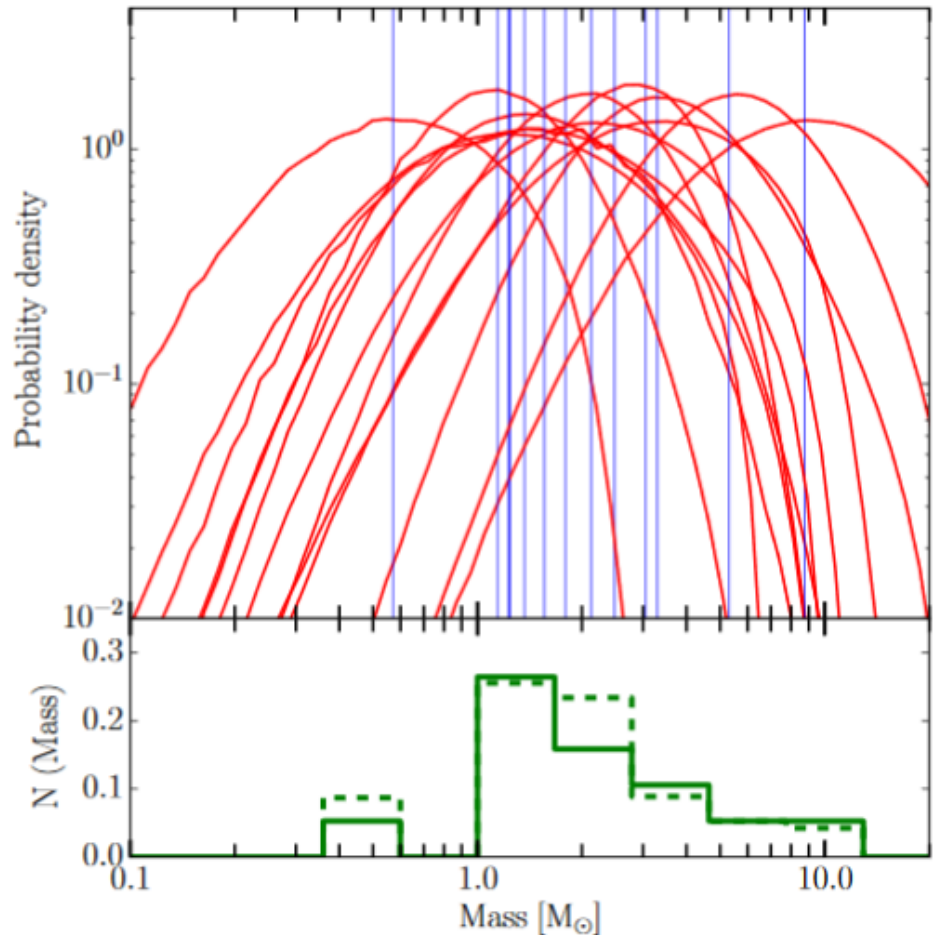
More examples

OGLE-III data



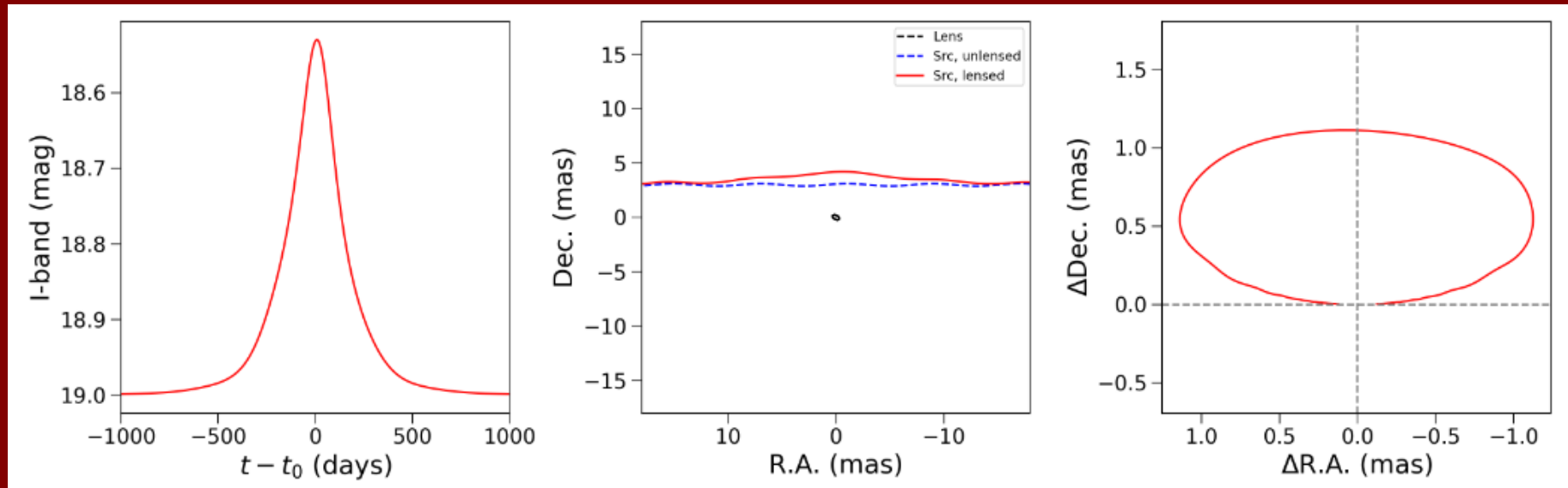
OGLE3-ULENS-PAR-02
8.7 solar masses at 1.8 kpc

Altogether 13 candidates
for WD, NS, or BH lensing.



1509.04899, see also 1601.02830

Photometric and astrometric



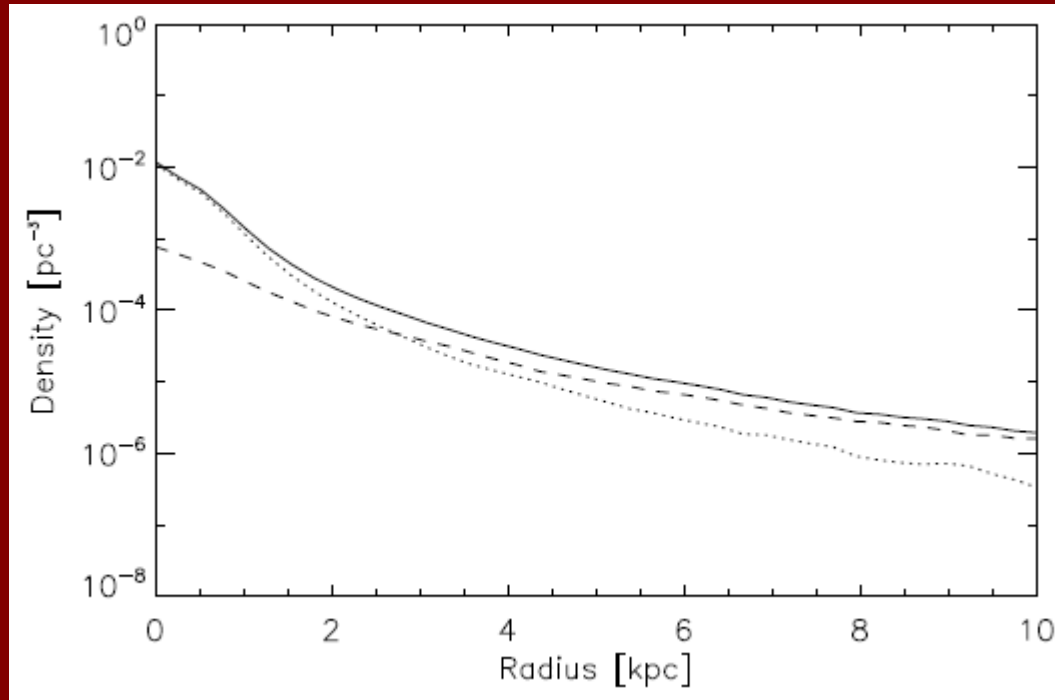
Photometry and astrometry for a black hole at 3 kpc
lensing a background star at 6 kpc with a relative proper motion of 8 mas yr^{-1} .

Left: Photometric light-curve.

Center: Astrometry of the lens and source, with parallax, as would be seen on the sky.

Right: Astrometry of the lensed source after the proper motion is removed.

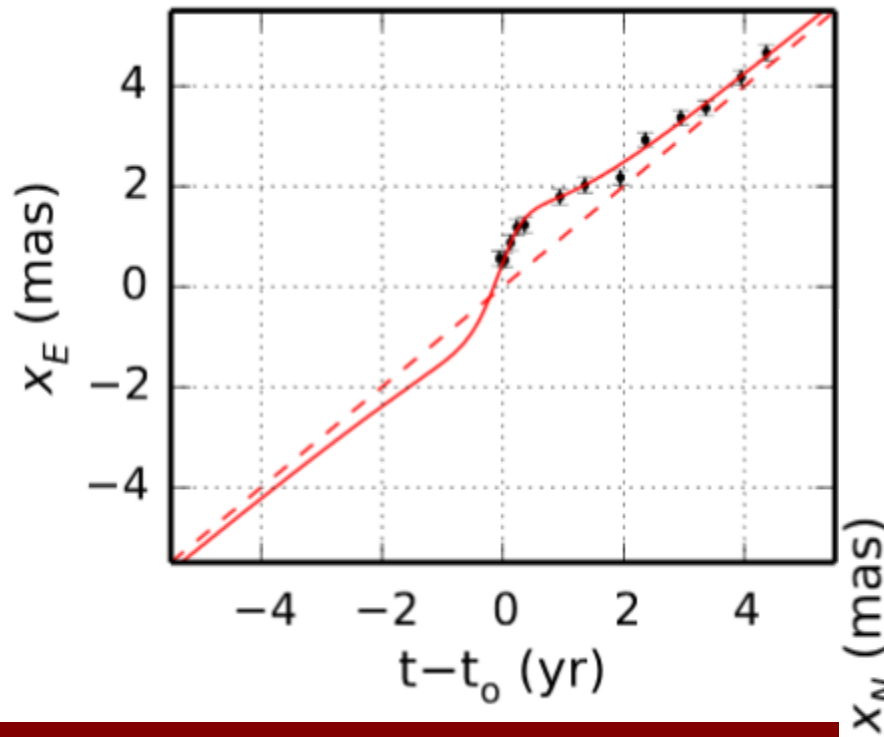
Probabilities of lensing



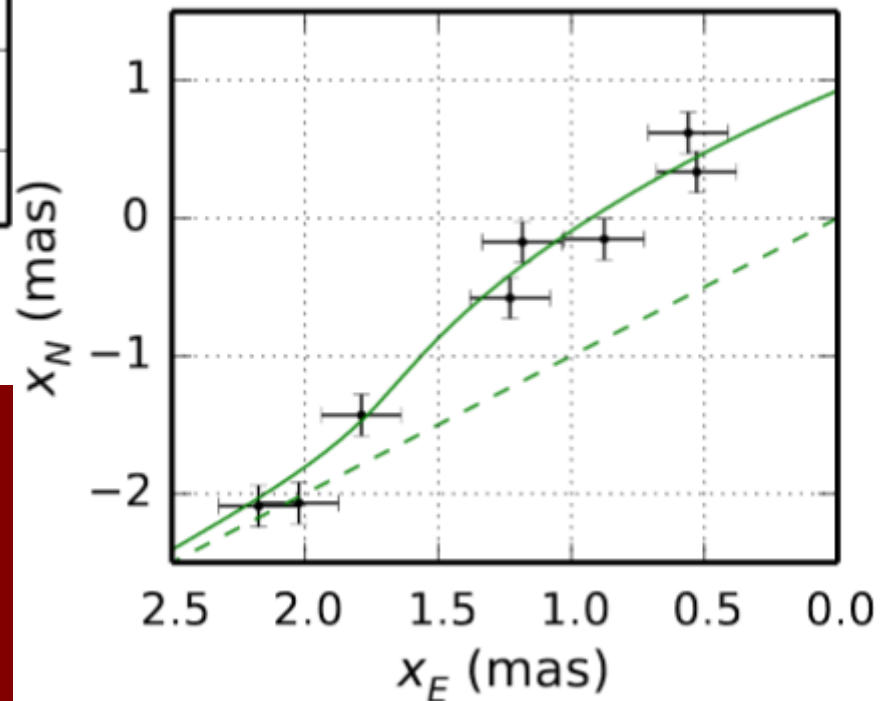
30-40% of events with >100 days are due to black holes

l.o.s. (l, b)	Γ_{star} [10^{-5} star $^{-1}$ yr $^{-1}$]	$\langle t_E \rangle_{star}$ [days]	Γ_{NS} [10^{-6} star $^{-1}$ yr $^{-1}$]	$\langle t_E \rangle_{NS}$ [days]	Γ_{BH} [10^{-6} star $^{-1}$ yr $^{-1}$]	$\langle t_E \rangle_{BH}$ [days]
($0^\circ, 0^\circ$)	2.67	16	1.47	25	0.38	67
($1^\circ, -3^\circ.9$)	0.52	20	0.40	28	0.10	77

Astrometric microlensing and BHs



A simulation of the 2D astrometric shift due a 10 solar masses BH at 4 kpc microlensing a background source at 8 kpc with a relative proper motion of 7 mas/yr and impact parameter $u_0=0.5$.

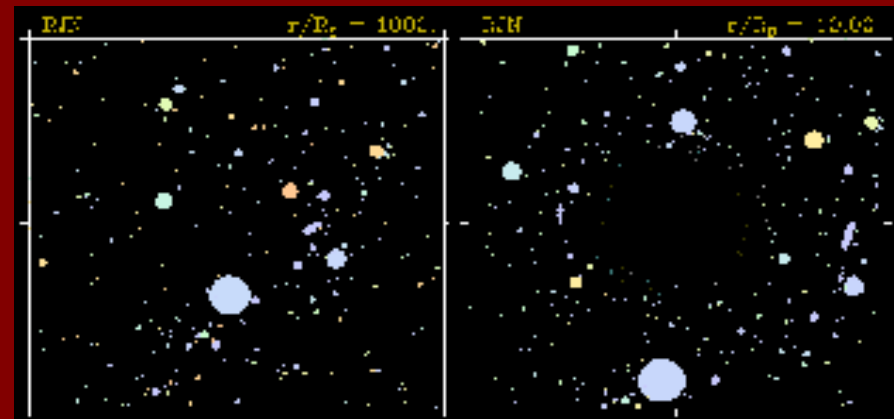


Also Gaia can contribute.

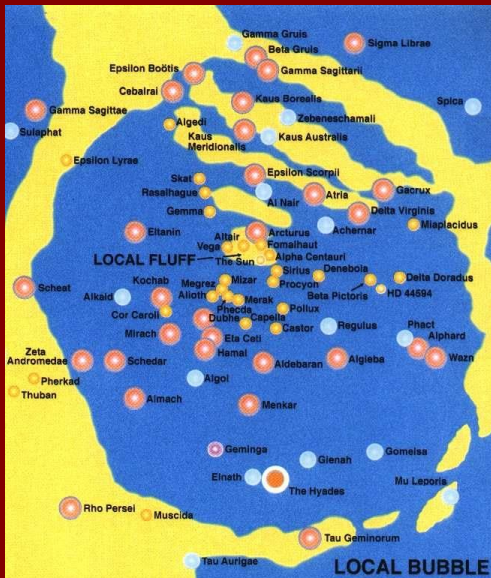
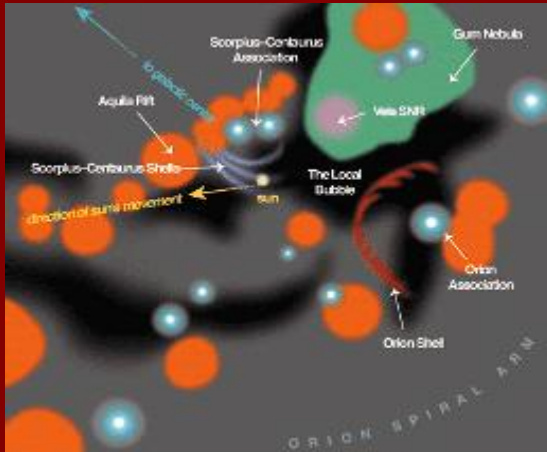
Black holes around us

- Black holes are formed from very massive stars
- It is very difficult to see an isolated black hole:
 - Microlensing
 - Accretion
 -?
- It is very important to have even a very approximate idea where to search. Let us look at our neighbourhood....

There should be about several tens of million isolated BHs in the Galaxy



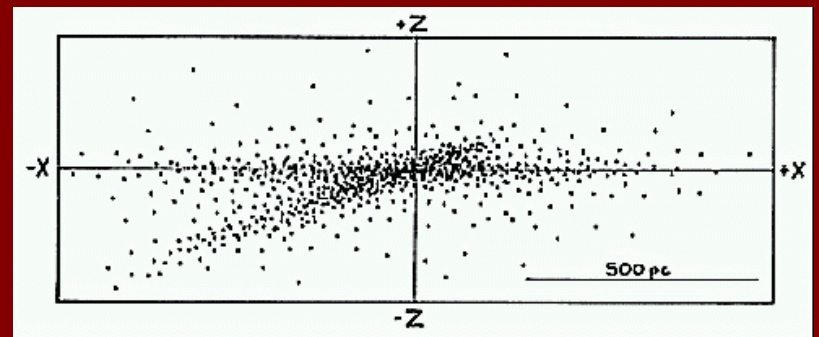
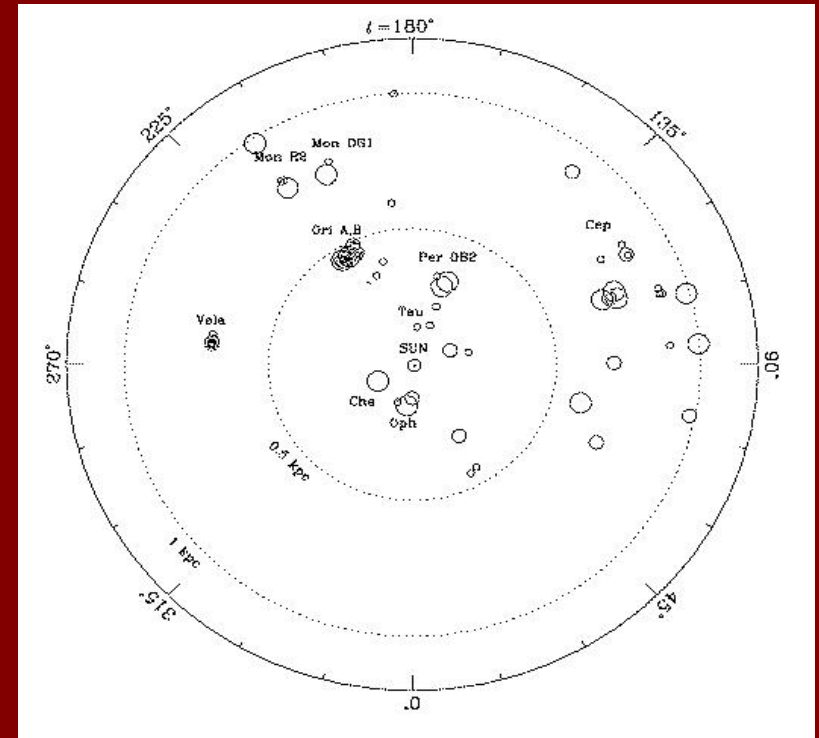
The Solar proximity



- The solar vicinity is not just an average “standard” region
- The Gould Belt
- $R=300-500$ pc
- Age: 30-50 mill. years
- 20-30 SN in a Myr (Grenier 2000)
- The Local Bubble
- Up 6 SN in several Myrs

The Gould Belt

- Poppel (1997)
- $R=300 - 500$ pc
- The age is about 30-50 million years
- A disc-like structure with a center 100-150 pc from the Sun
- Inclined respect to the galactic plane by $\sim 20^\circ$
- 2/3 of massive stars in 600 pc from the Sun belong to the Belt

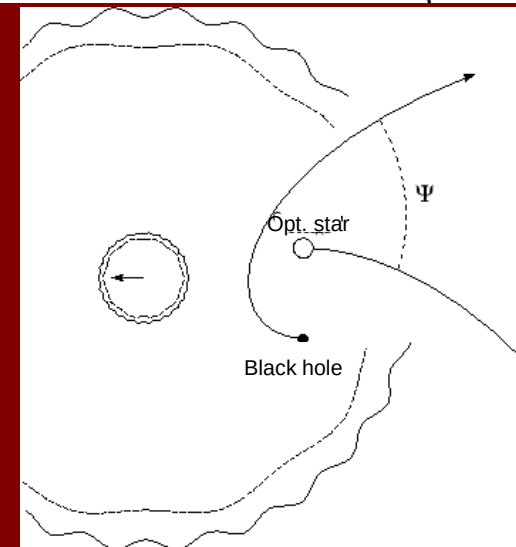
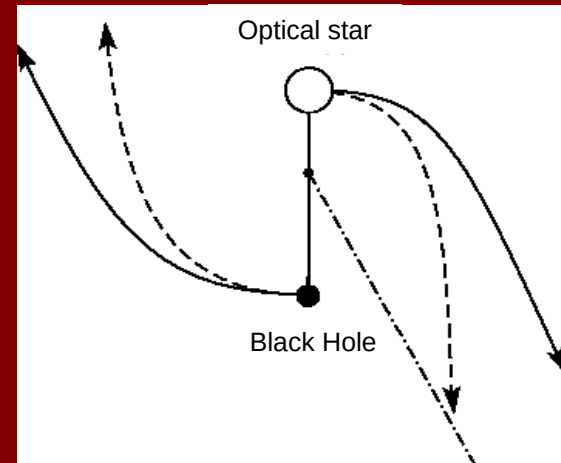
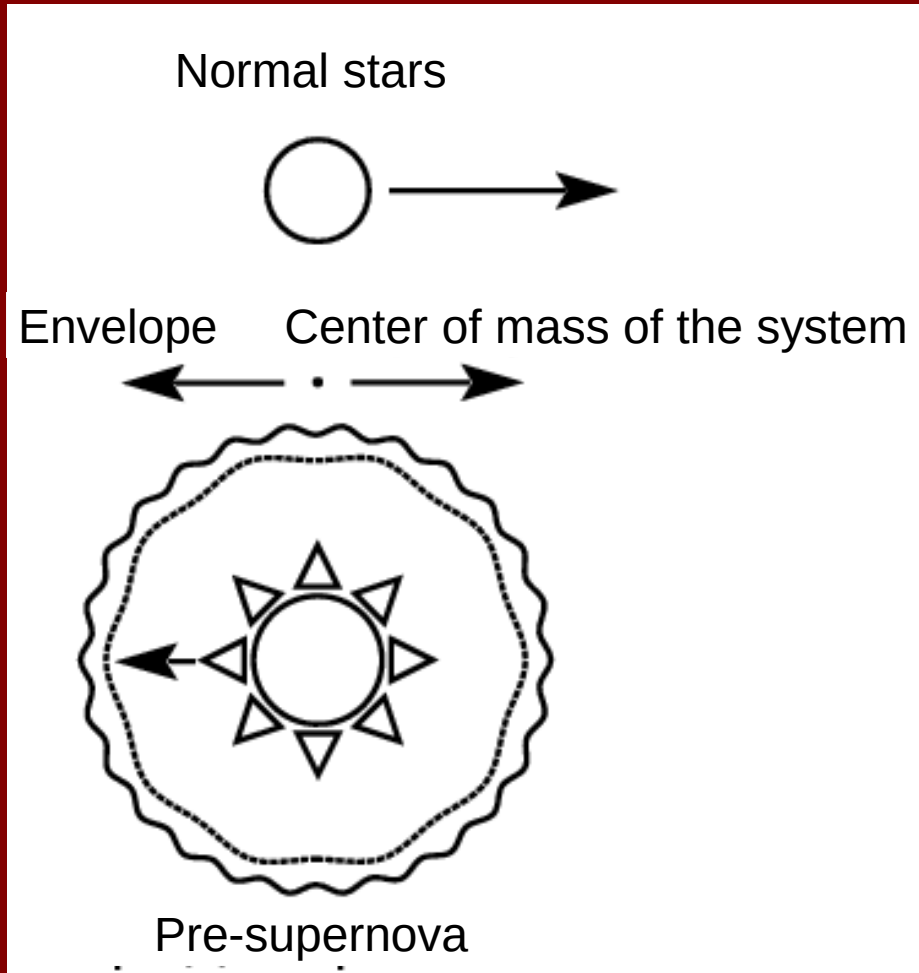


Close-by BHs and runaway stars

- 56 runaway stars inside 750 pc (Hoogerwerf et al. 2001)
- Four of them have $M > 30 M_{\text{solar}}$

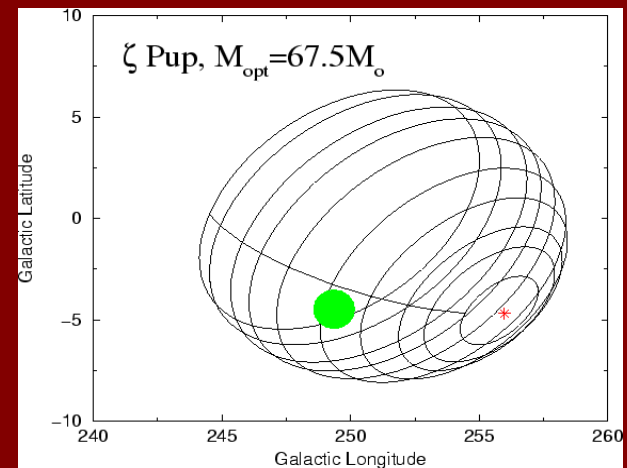
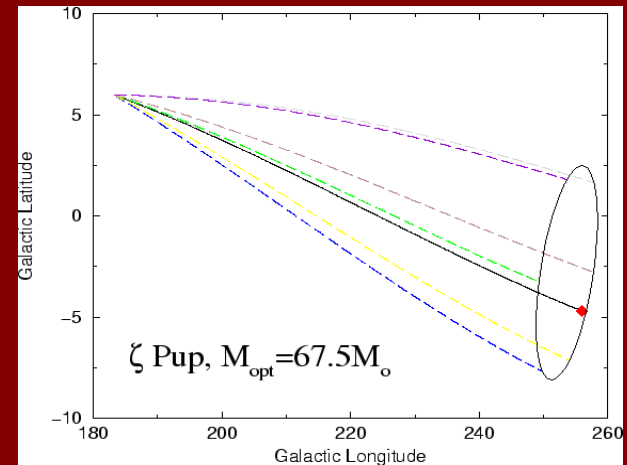
Star	Mass	Velocity km/s	Age, Myr
ξ Per	33	65	1
HD 64760	25-35	31	6
ς Pup	67	62	2
λ Cep	40-65	74	4.5

SN explosion in a binary



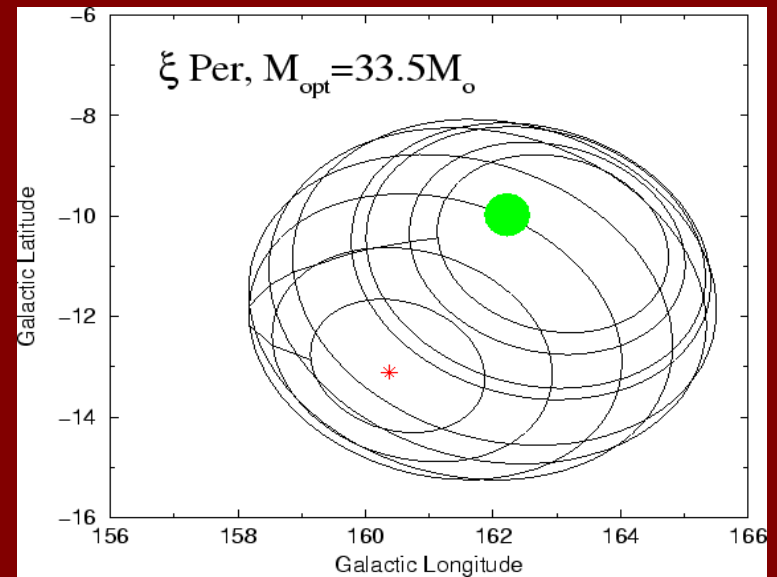
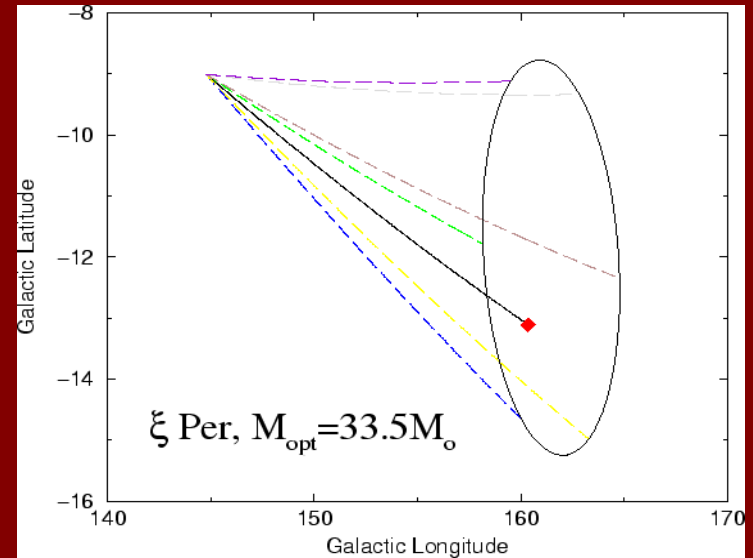
ζ Pup

- Distance: 404-519 pc
- Velocity: 33-58 km/s
- Error box: $12^\circ \times 12^\circ$
- N_{EGRET} : 1

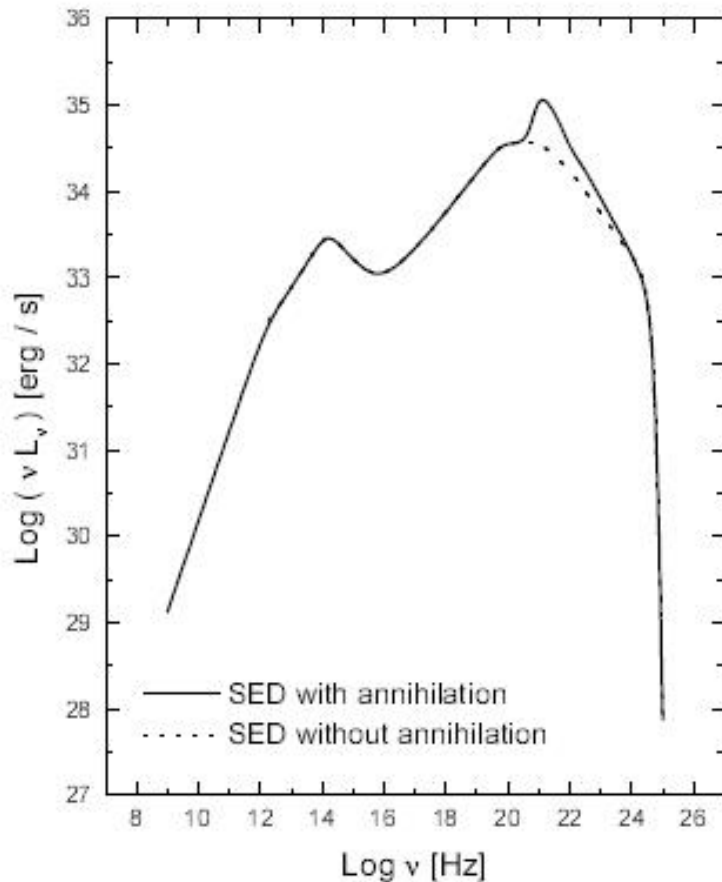


ξ Per

- Distance: 537-611 pc
- Velocity: 19-70 km/s
- Error box: $7^\circ \times 7^\circ$
- N_{EGRET} : 1



Gamma-ray emission from isolated BHs



Kerr-Newman isolated BH.

Magnetosphere. $B \sim 10^{11} \text{ G}$

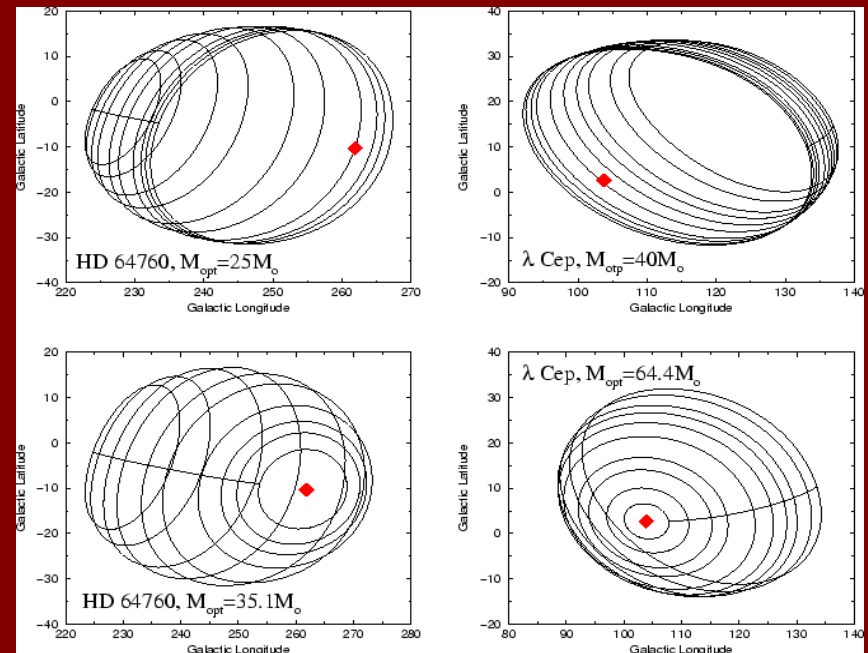
Jets.

See details about this theory
in Punsly 1998, 1999.

astro-ph/0007464, 0007465 – application to EGRET sources

Runaway BHs

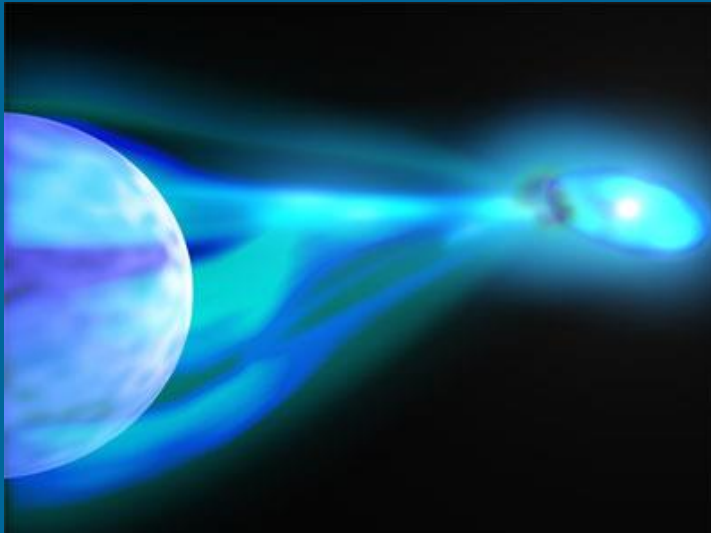
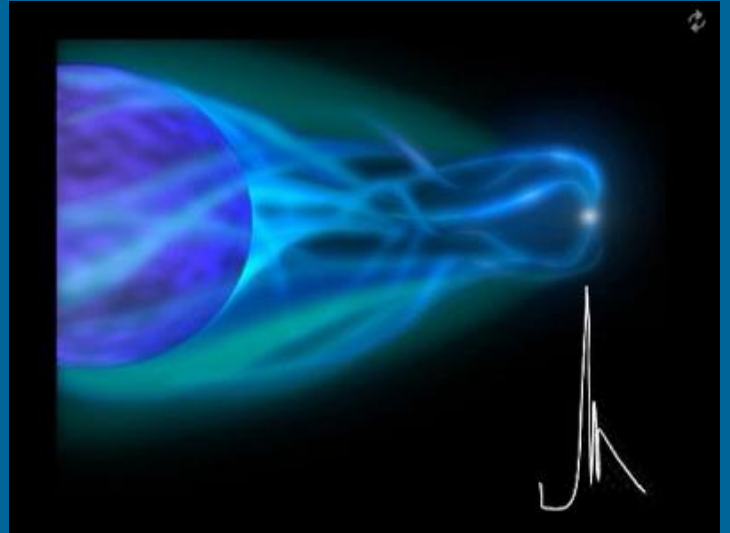
- Approximate positions of young close-by BHs can be estimated basing on data on massive runaway stars
- For two cases we obtained relatively small error boxes
- For HD 64760 and for λ Cep we obtained very large error boxes (40-50°)
- Several EGRET sources inside



Resume

1. Accreting stellar mass isolated BHs
 - They should be! And the number is huge!
 - But sources are very weak.
 - Electron-positron jets and/or radio sources
 - Problems with identification, if there are no data in several wavelengths
2. Microlensing on isolated stellar mass BHs
 - There are several good candidates
 - But it is necessary to find the black hole ITSELF!
3. Exotic emission mechanisms
 - As all other exotics: interesting, but not very probable
 - If it works, then GLAST will show us isolated BHs
4. Runaway stars
 - A rare case to make even rough estimates of parameters
 - Error-boxes too large for any band except gamma-rays
 - All hope on the exotic mechanisms (Torres et al. astro-ph/0007465)

BH binaries

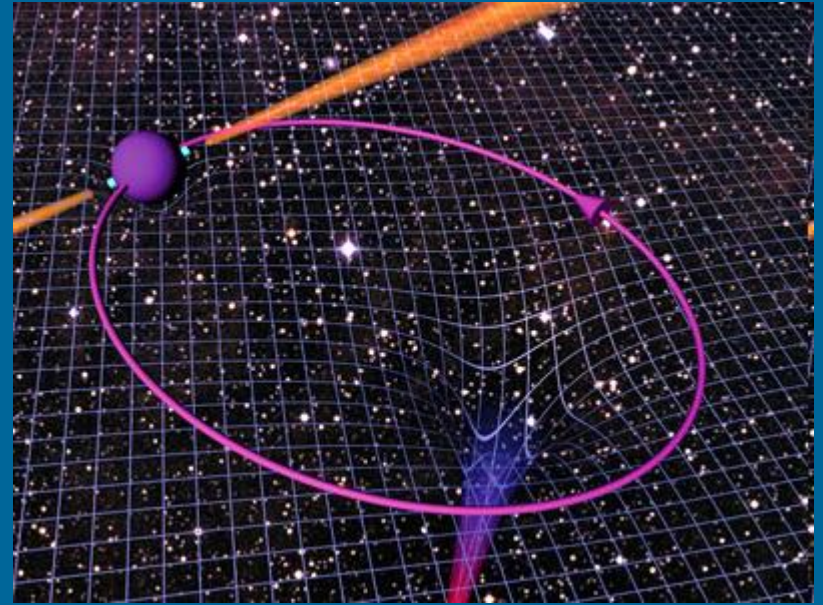
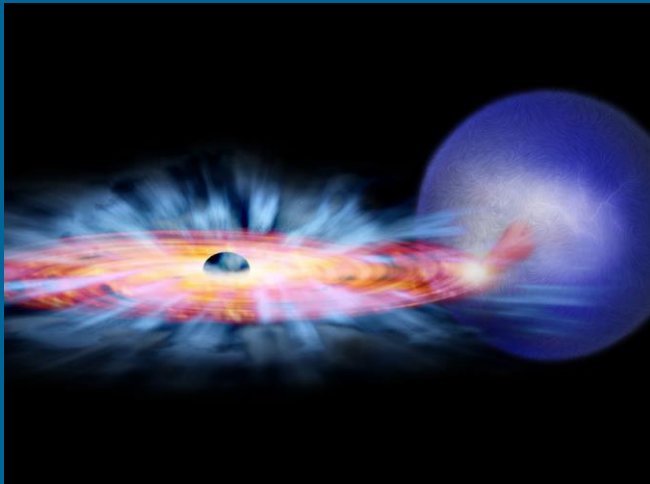


Black hole binaries

- High mass (few)
- Low-mass (majority)
- ULX – ultraluminous X-ray sources

Most of low-mass are transients.

Microquasars.



A hope for PSR+BH binary

- Either due to evolution
(one per several thousand normal PSRs)
- Either due to capture
(then – few in the central pc,
see arXiv: 1012.0573)

X-ray observations: Cyg X-1



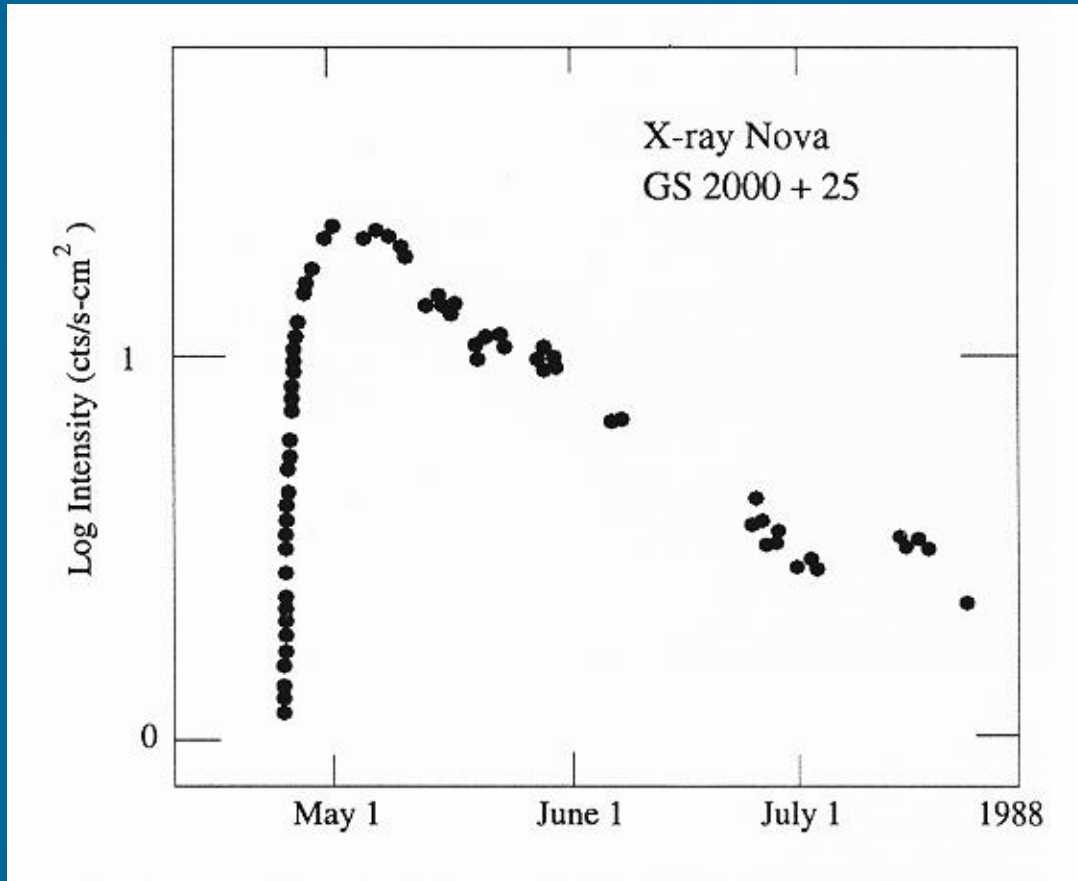
“In the case of Cyg X-1
black hole – is the most
conservative hypothesis”

Edwin Salpeter

The history of exploration
of binary systems with BHs
started about 40 years ago...

Recent mass measurement
for Cyg X-1 can be found in
[arXiv:1106.3689](https://arxiv.org/abs/1106.3689)

X-ray novae



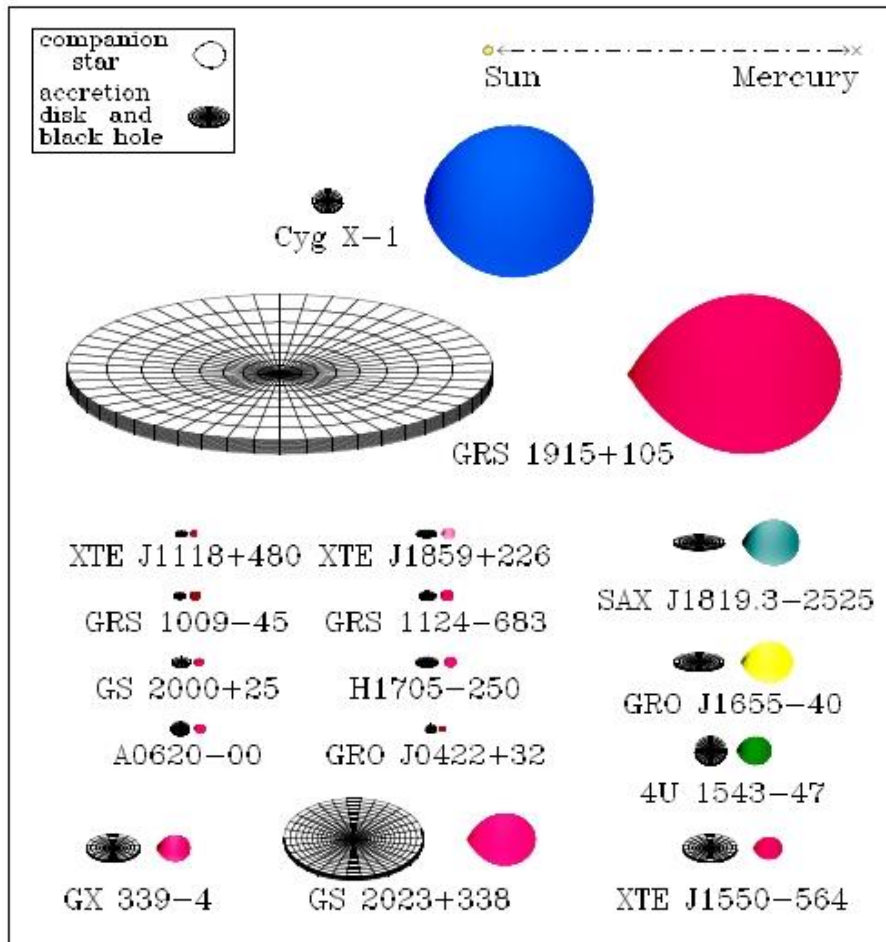
Low-mass binaries
with BHs

One of the best candidates

In the minimum it is
possible to see the
secondary companion,
and so to get a good mass
estimate for a BH.

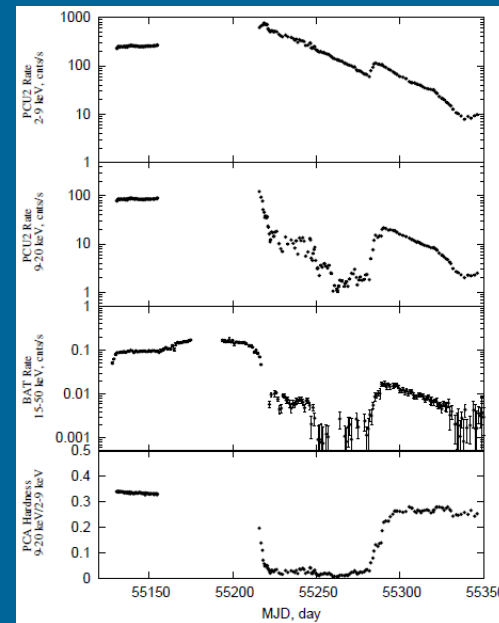
BH candidates

Black Hole Binaries in the Milky Way



Among 20 good galactic candidates
17 are X-ray novae.
3 belong to HMXBs
(Cyg X-1, LMC X-3, GRS 1915+105).

New candidates still appear.



Candidates properties

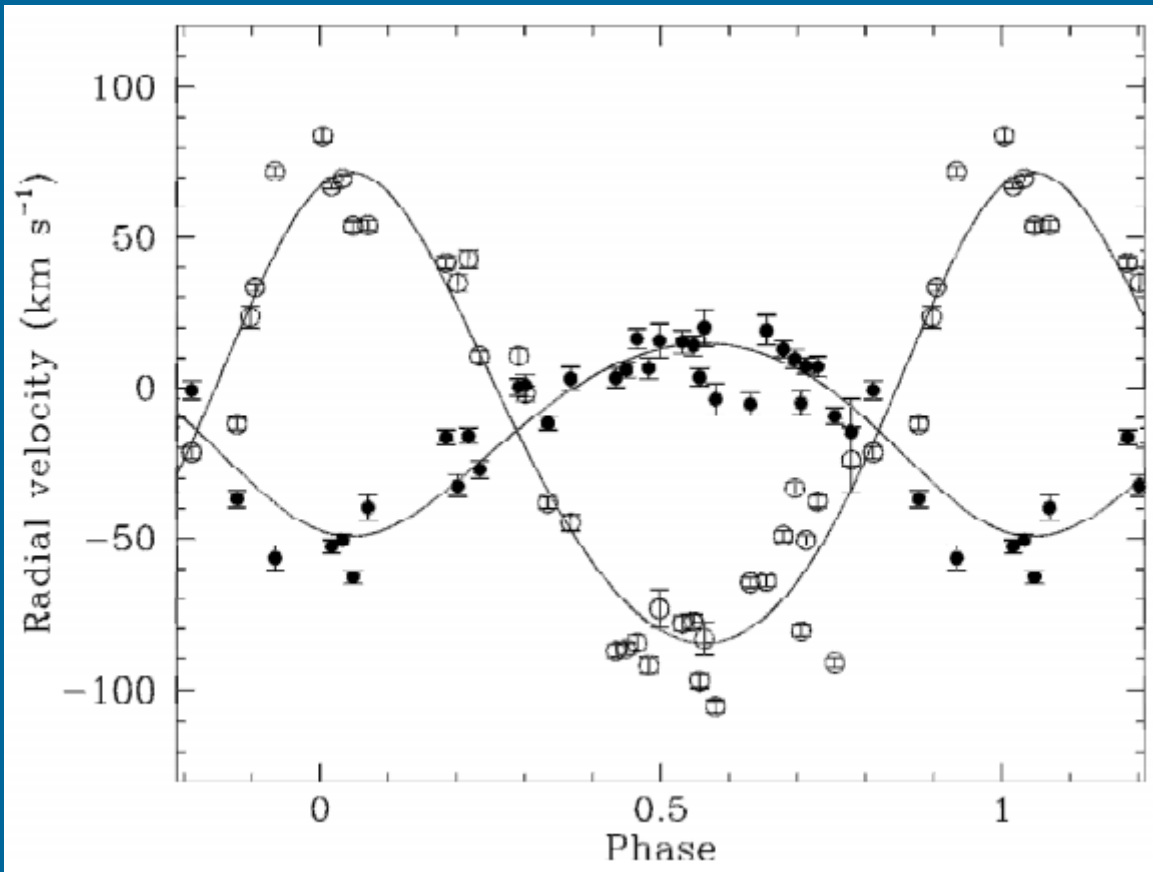
Table 1: Twenty confirmed black holes and twenty black hole candidates^a

Coordinate Name	Common ^b Name/Prefix	Year ^c	Spec.	P _{orb} (hr)	f(M) (M _☉)	M ₁ (M _☉)
0422+32	(GRO J)	1992/1	M2V	5.1	1.19±0.02	3.7–5.0
0538–641	LMC X–3	–	B3V	40.9	2.3±0.3	5.9–9.2
0540–697	LMC X–1	–	O7III	93.8 ^d	0.13±0.05 ^d	4.0–10.0: ^e
0620–003	(A)	1975/1 ^f	K4V	7.8	2.72±0.06	8.7–12.9
1009–45	(GRS)	1993/1	K7/M0V	6.8	3.17±0.12	3.6–4.7: ^e
1118+480	(XTE J)	2000/2	K5/M0V	4.1	6.1±0.3	6.5–7.2
1124–684	Nova Mus 91	1991/1	K3/K5V	10.4	3.01±0.15	6.5–8.2
1354–64 ^g	(GS)	1987/2	GIV	61.1 ^g	5.75±0.30	–
1543–475	(4U)	1971/4	A2V	26.8	0.25±0.01	8.4–10.4
1550–564	(XTE J)	1998/5	G8/K8IV	37.0	6.86±0.71	8.4–10.8
1650–500 ^h	(XTE J)	2001/1	K4V	7.7	2.73±0.56	–
1655–40	(GRO J)	1994/3	F3/F5IV	62.9	2.73±0.09	6.0–6.6
1659–487	GX 339–4	1972/10 ⁱ	–	42.1 ^{j,k}	5.8±0.5	–
1705–250	Nova Oph 77	1977/1	K3/7V	12.5	4.86±0.13	5.6–8.3
1819.3–2525	V4641 Sgr	1999/4	B9III	67.6	3.13±0.13	6.8–7.4
1859+226	(XTE J)	1999/1	–	9.2: ^e	7.4±1.1: ^e	7.6–12.0: ^e
1915+105	(GRS)	1992/Q ^l	K/MIII	804.0	9.5±3.0	10.0–18.0
1956+350	Cyg X–1	–	O9.7Iab	134.4	0.244±0.005	6.8–13.3
2000+251	(GS)	1988/1	K3/K7V	8.3	5.01±0.12	7.1–7.8
2023+338	V404 Cyg	1989/1 ^f	K0III	155.3	6.08±0.06	10.1–13.4

(astro-ph/0606352) Also there are about 20 “candidates to candidates”.

Detector MAXI recently added several new BH candidates

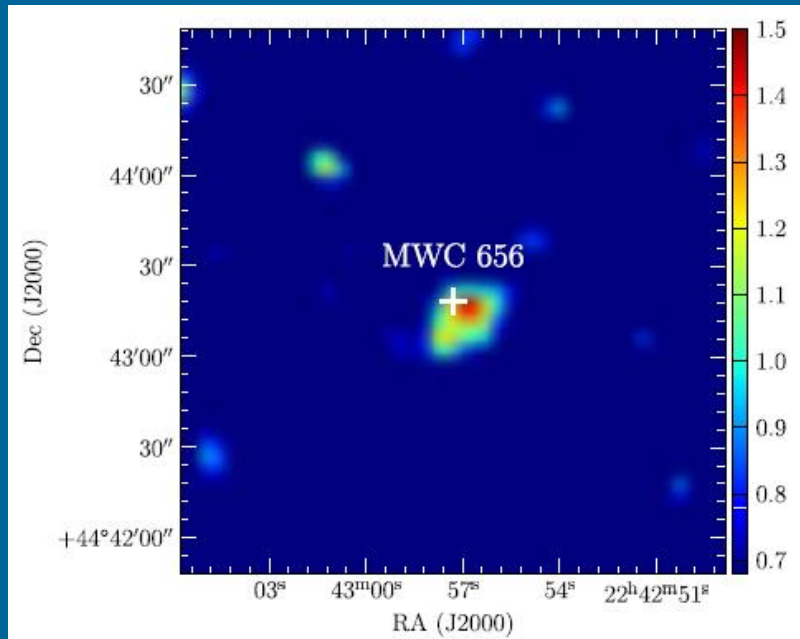
The first Be-BH binary in MWC 656



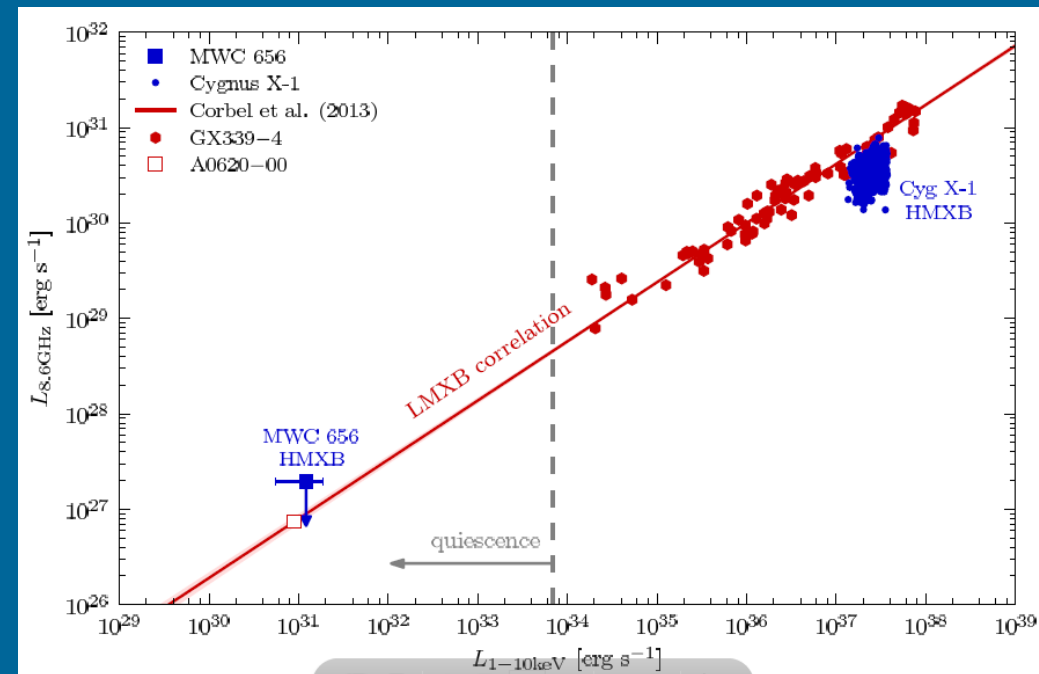
Compact object has a mass
3.8 – 6.9 Msolar.

X-ray luminosity is low

X-rays from MWC656

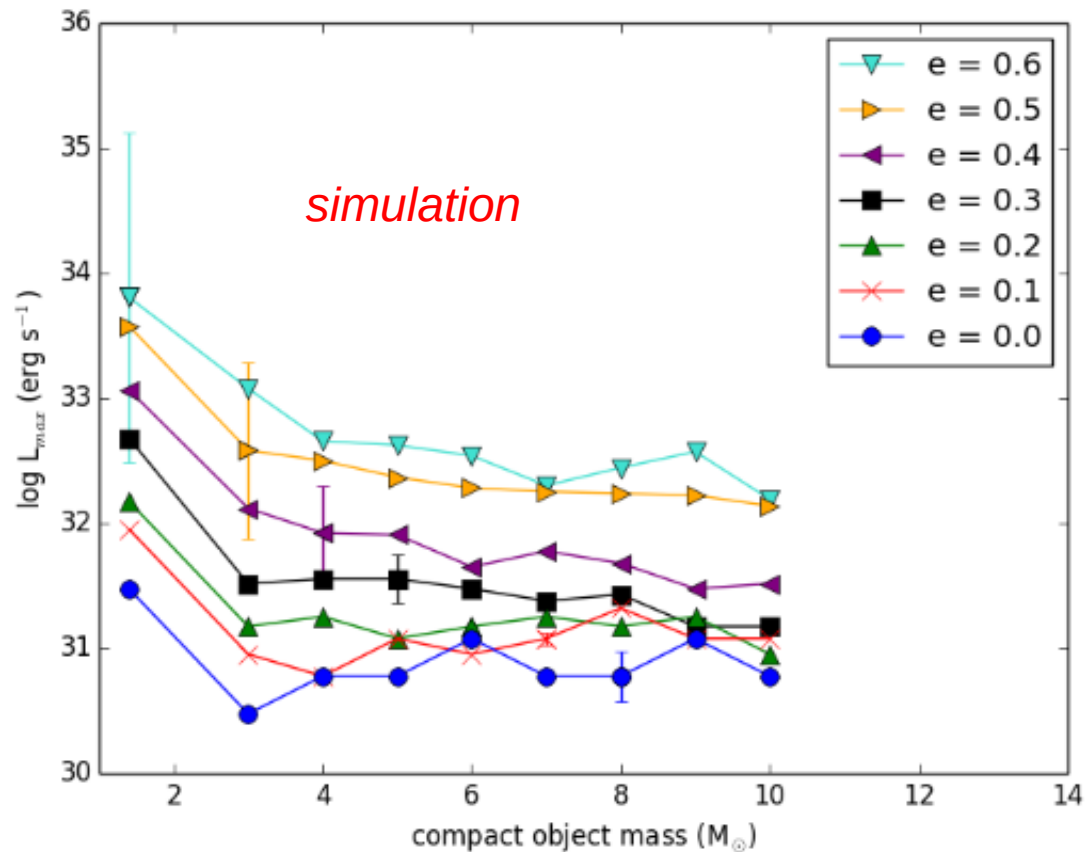


XMM-Newton

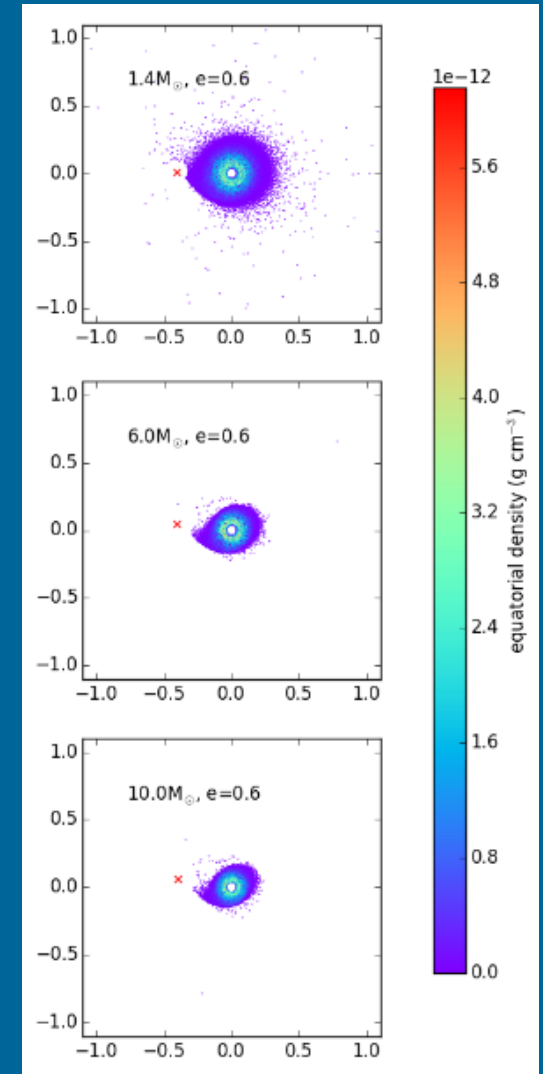


Became fainter since 2014.

BH/Be are fainter than NS/Be

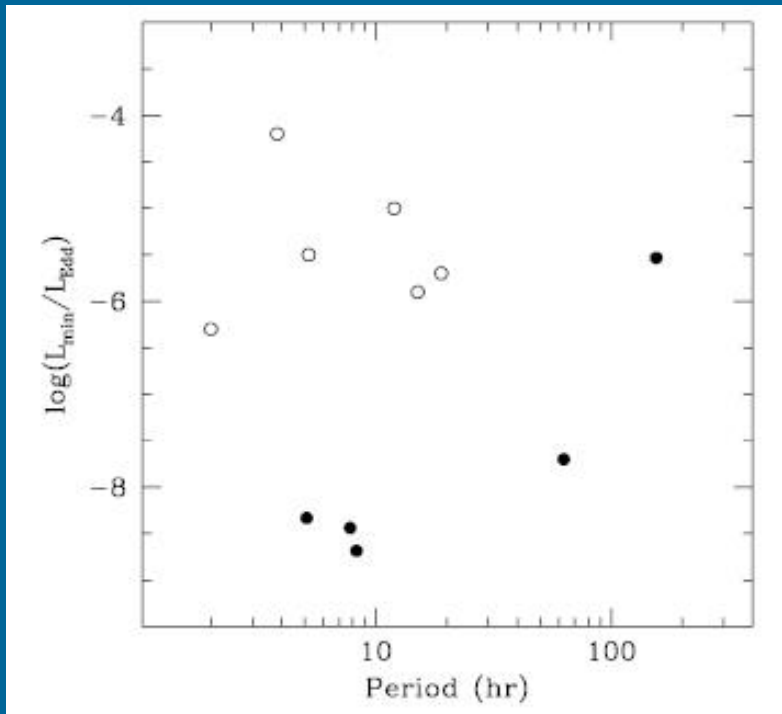


BH systems are fainter even for the same efficiency due to disc truncation. Lower efficiency can help to explain better why BH/Be systems are rarer than NS/Be.

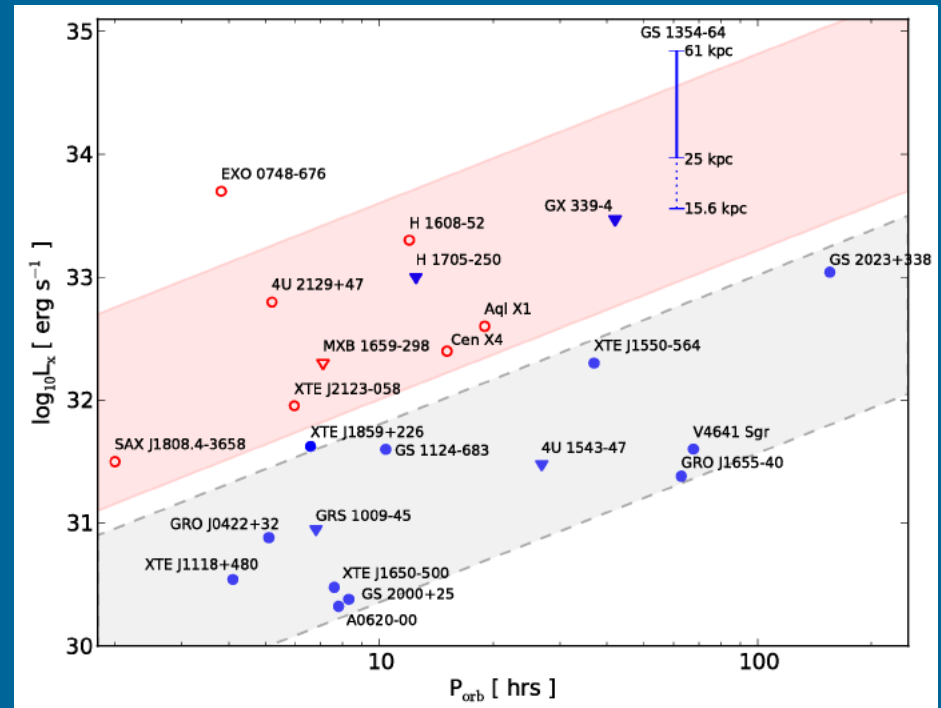


1804.05749

Quescent luminosity vs. Orbital period

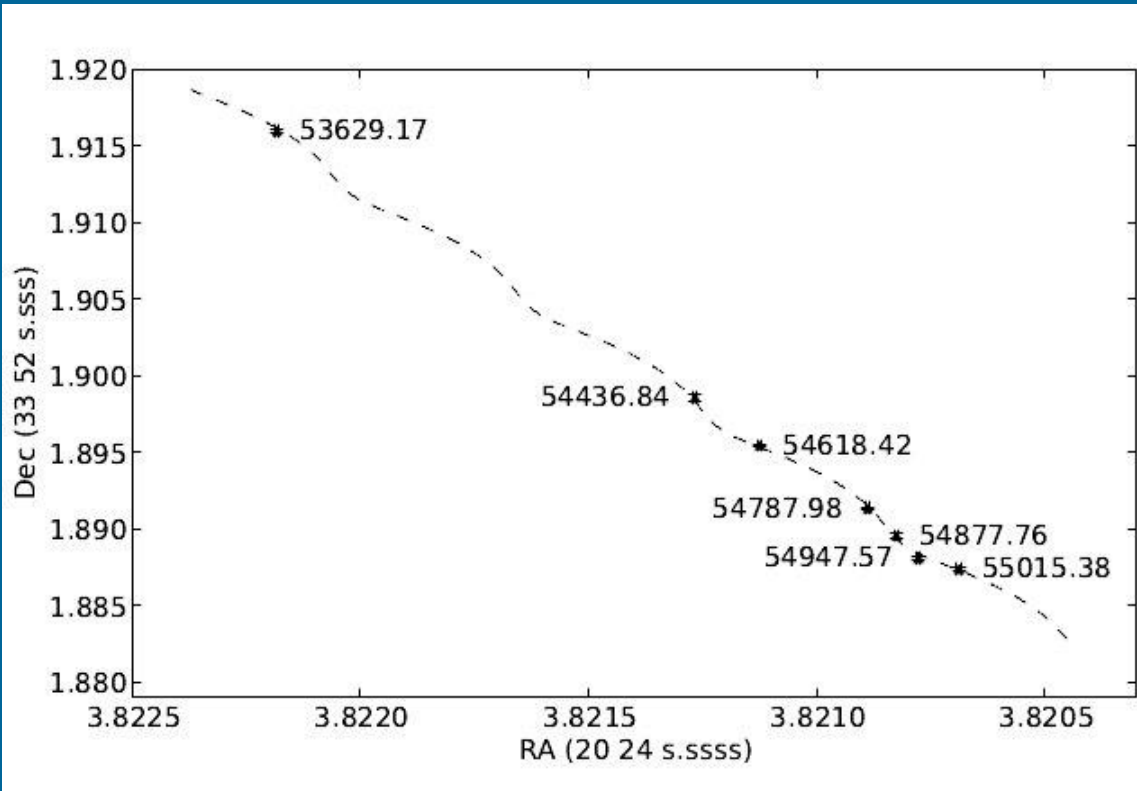


Open symbols – neutron stars
black symbols – black holes.



Red – NS systems.
Blue – BHs.
arXiv: 1105.0883

Distance to V404 Cyg

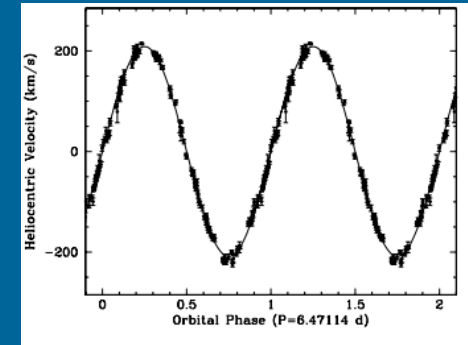


The parallax was measured.
The new distance estimate is 2.25-2.53 kpc.
It is smaller than before.
Correspondently, flares luminosity is lower, and so they are subEddington.

arXiv:0910.5253

Parallax is also measured for Cyg X-1 (arXiv:1106.3688)

Mass determination



$$f_v(m) \frac{m_x^3 \sin^3 i}{(m_x + m_v)^2} = 1,038 \cdot 10^{-7} K_v^3 P (1 - e^2)^{3/2},$$

here m_x , m_v - masses of a compact object and of a normal (in solar units), K_v - observed semi-amplitude of the line of sight velocity of the normal star (in km/s), P - orbital period (in days), e - orbital eccentricity, i - orbital inclination (the angle between the line of sight and the normal to the orbital plane).

As one can see, the mass function of the normal star is the absolute lower limit for the mass of the compact object.

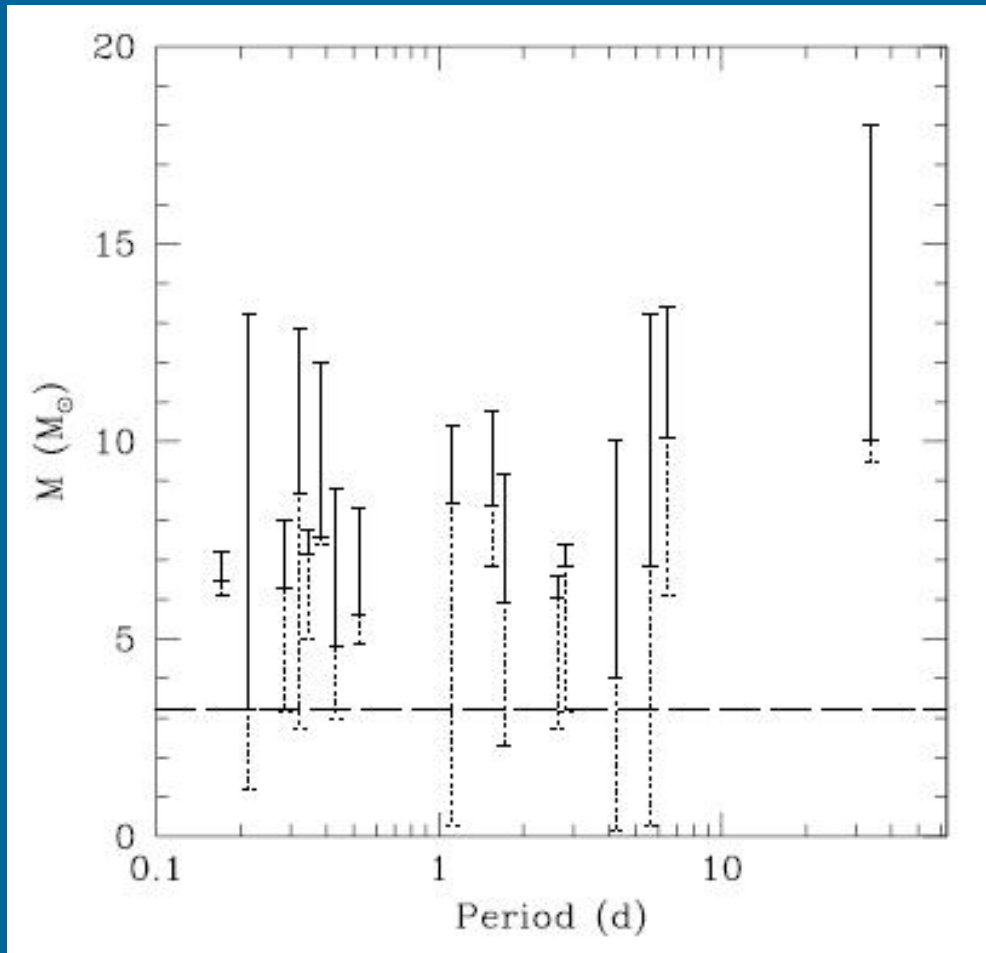
The mass of the compact object can be calculated as:

$$m_x = f_v(m) \left(1 + \frac{m_v}{m_x}\right)^2 \frac{1}{\sin^3 i}.$$

So, to derive the mass of the compact object in addition to the line of sight velocity it is necessary to know independently two more parameters: the mass ratio $q = m_x/m_v$, and the orbital inclination i .

Mass estimates for BHs (including IMBHs) are well reviewed recently in 1311.5118

Black hole masses



The horizontal line corresponds to the mass equal to 3.2 solar.

Some more results on masses

Paredes
arXiv: 0907.3602

System	P_{orb} [days]	$f(M)$ [$M_{\odot}$]	Donor Spect. Type	Classification	M_x [$M_{\odot}$]
GRS 1915+105	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	"	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
M33 X-7 ^a	3.453	—	O7 III	—	15.65 ± 1.45
LMC X-1	4.229	0.14 ± 0.05	07 III	"	> 4
XTE J1819-254	2.816	3.13 ± 0.13	B9 III	IMXB/Transient	7.1 ± 0.3
GRO J1655-40	2.620	2.73 ± 0.09	F3/5 IV	"	6.3 ± 0.3
BW Cir	2.545	5.74 ± 0.29	G5 IV	LMXB/Transient	> 7.8
GX 339-4	1.754	5.8 ± 0.5	—	"	—
LMC X-3	1.704	2.3 ± 0.3	B3 V	HMXB/Persistent	7.6 ± 1.3
XTE J1550-564	1.542	6.86 ± 0.71	G8/K8 IV	LMXB/Transient	9.6 ± 1.2
IC 10 X-1 ^b	1.455	7.64 ± 1.26	—	Wolf-Rayet	32.7 ± 2.6
4U 1543-475	1.125	0.25 ± 0.01	A2 V	IMXB/Transient	9.4 ± 1.0
H1705-250	0.520	4.86 ± 0.13	K3/7 V	LMXB/Transient	6 ± 2
GS 1124-684	0.433	3.01 ± 0.15	K3/5 V	"	7.0 ± 0.6
XTE J1859+226	0.382	7.4 ± 1.1	—	"	—
GS2000+250	0.345	5.01 ± 0.12	K3/7 V	"	7.5 ± 0.3
A0620-003	0.325	2.72 ± 0.06	K4 V	"	11 ± 2
XTE J1650-500	0.321	2.73 ± 0.56	K4 V	"	—
GRS 1009-45	0.283	3.17 ± 0.12	K7/M0 V	"	5.2 ± 0.6
GRO J0422+32	0.212	1.19 ± 0.02	M2 V	"	4 ± 1
XTE J1118+480	0.171	6.3 ± 0.2	K5/M0 V	"	6.8 ± 0.4

M33 X-7 $15.65 \pm 1.45 M_{\text{Solar}}$ (Orosz et al. 2007).

Eclipsing binary IC10 X-1 32 ± 2.6 (Silverman and Filippenko 2008)

Systems BH + radio pulsar: a Holy Grail

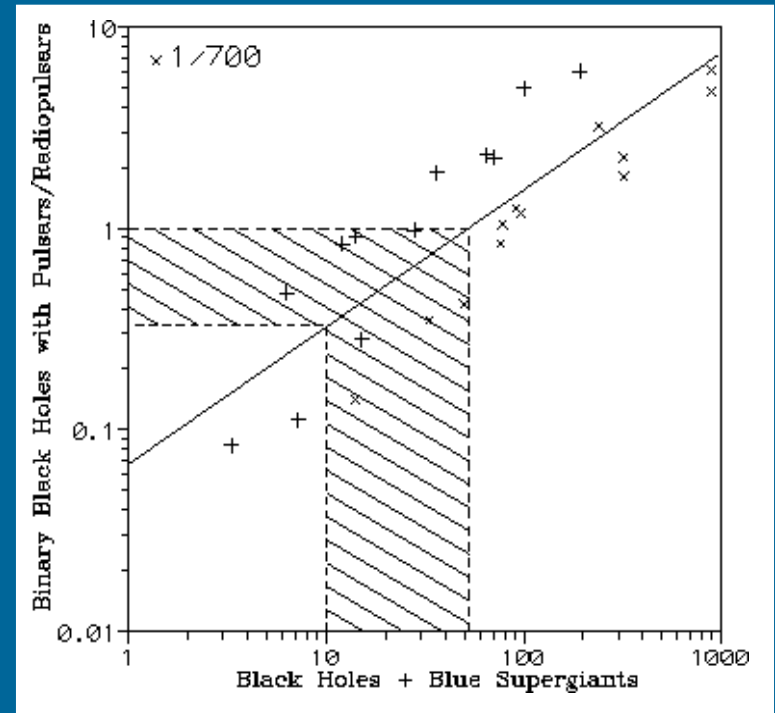
The discovery of a BH in pair with a radio pulsar can provide the most direct proof of the very existence of BHs.

Especially, it would be great to find a system with a millisecond pulsar observed close to the orbital plane.

Computer models provide different estimates of the abundance of such systems.

Lipunov et al (1994) give an estimate about one system (with a PSR of any type) per 1000 isolated PSRs.

Pfahl et al. (astro-ph/0502122) give much lower estimate for systems BH+mPSR: about 0.1-1% of the number of binary NSs. This is understandable, as a BH should be born by the secondary (i.e. initially less massive) component of a binary system.



What can be done with such systems if they are detected by SKA was studied recently in 1409.3882. Mainly related to gravity tests.

BH+pulsar binaries and FAST

Birth rate of NS+BH binaries $\sim 0.6\text{-}13 \text{ Myr}^{-1}$

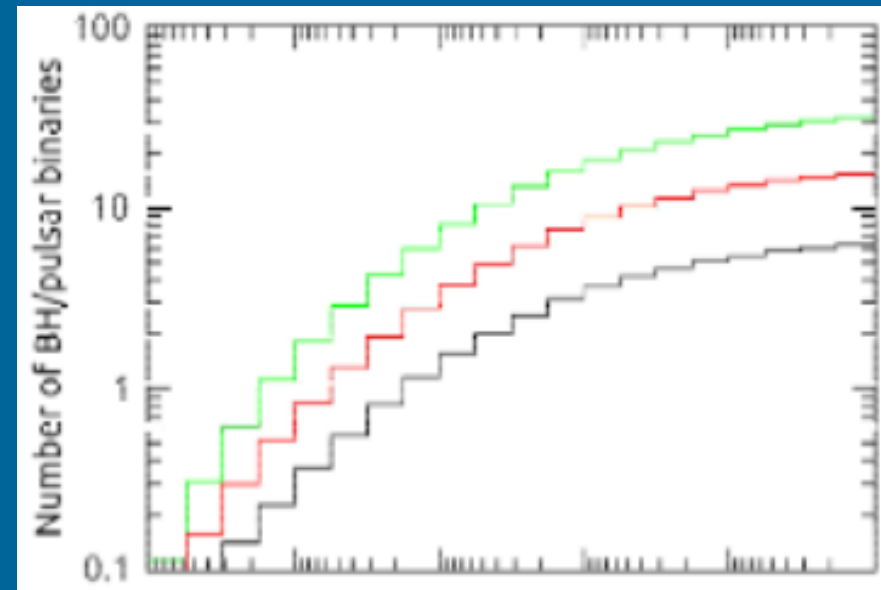
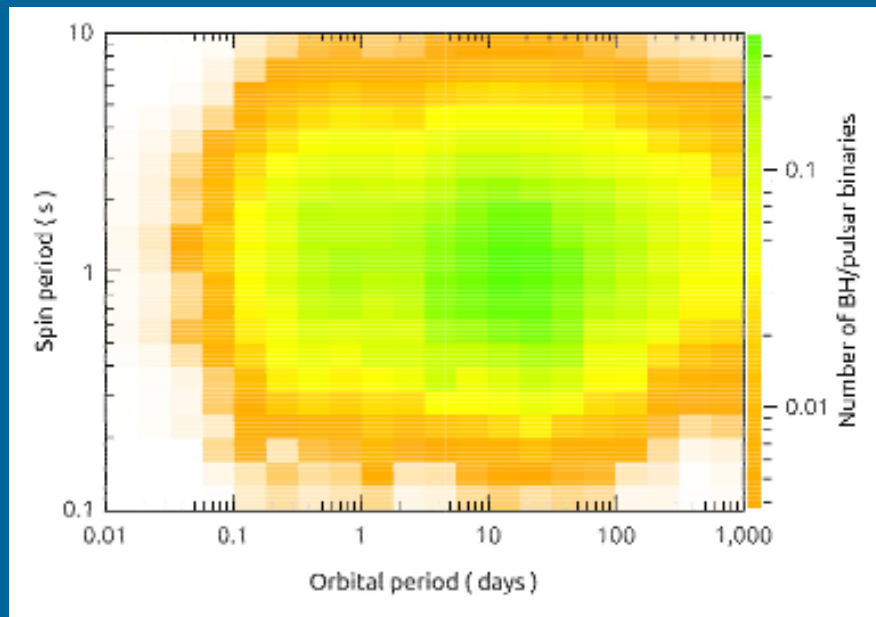
Thus, $\sim 10^4\text{-}10^5$ in the Galaxy.

Difficult to have a msecPSR.

Thus, typical spin periods $\sim 1 \text{ s}$.

3-80 BH+PSR binaries.

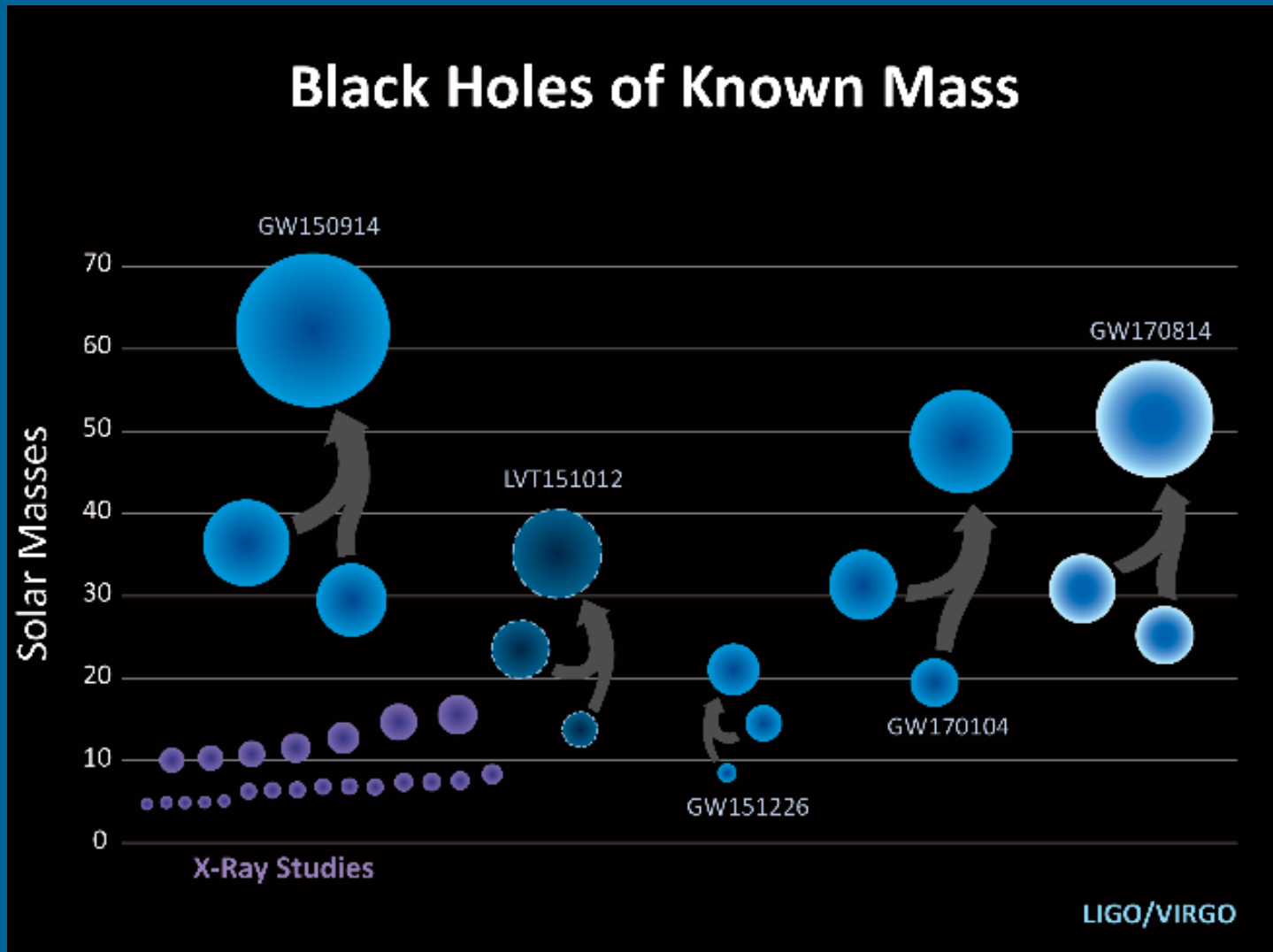
$\sim 10\%$ of them can be detected by FAST.



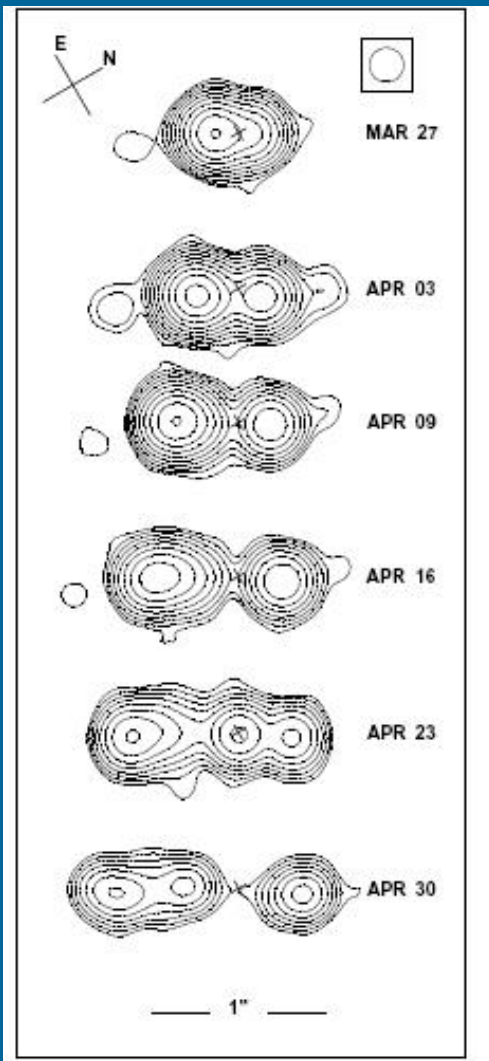
Flux density at 1.4 GHz (mJy)

$$\sigma_{\text{NS_kick}} = 150 \text{ km/s}$$

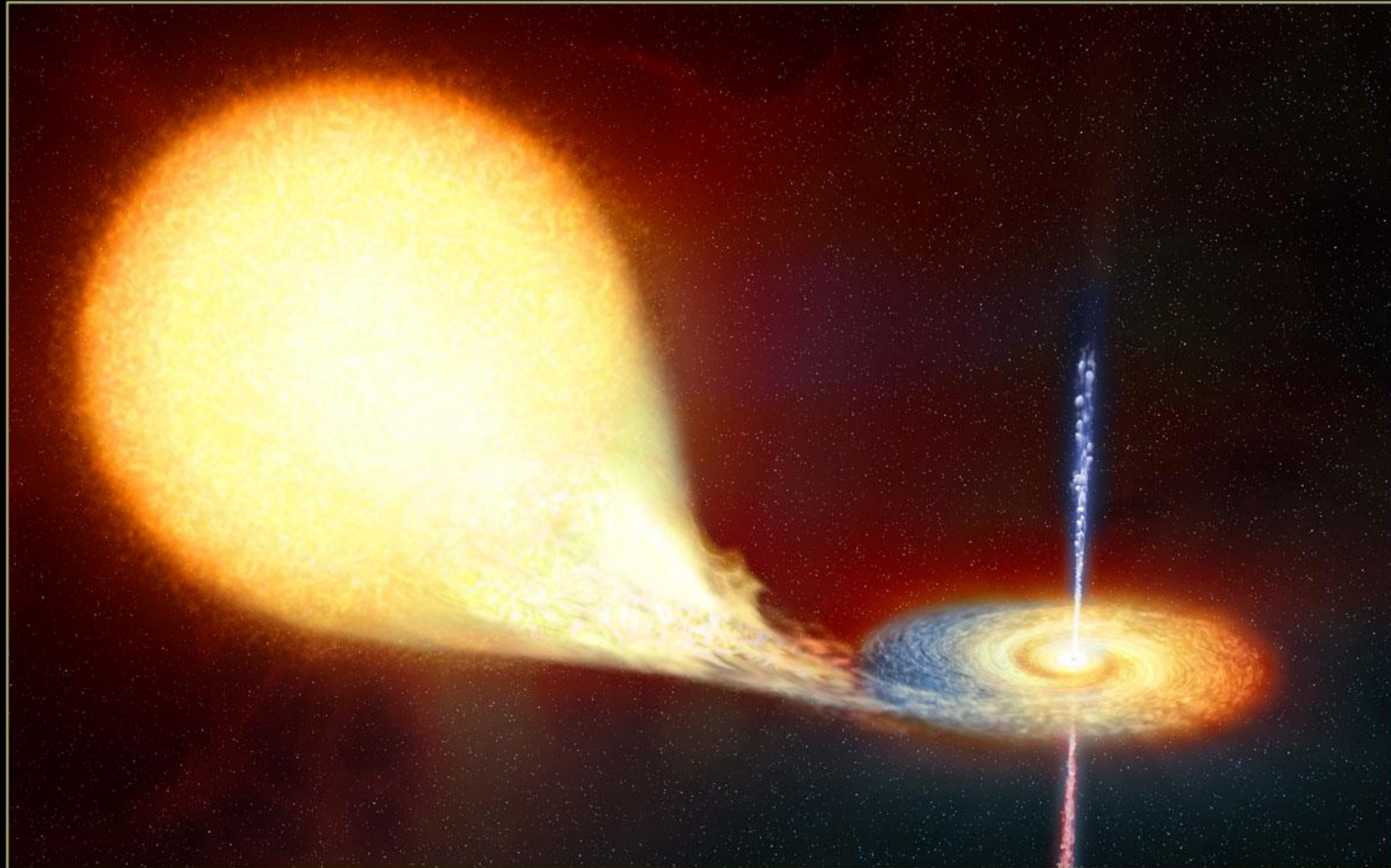
BH+BH. Coalescence.



Jet from GRS 1915+105



VLA data. Wavelength 3.5 cm.



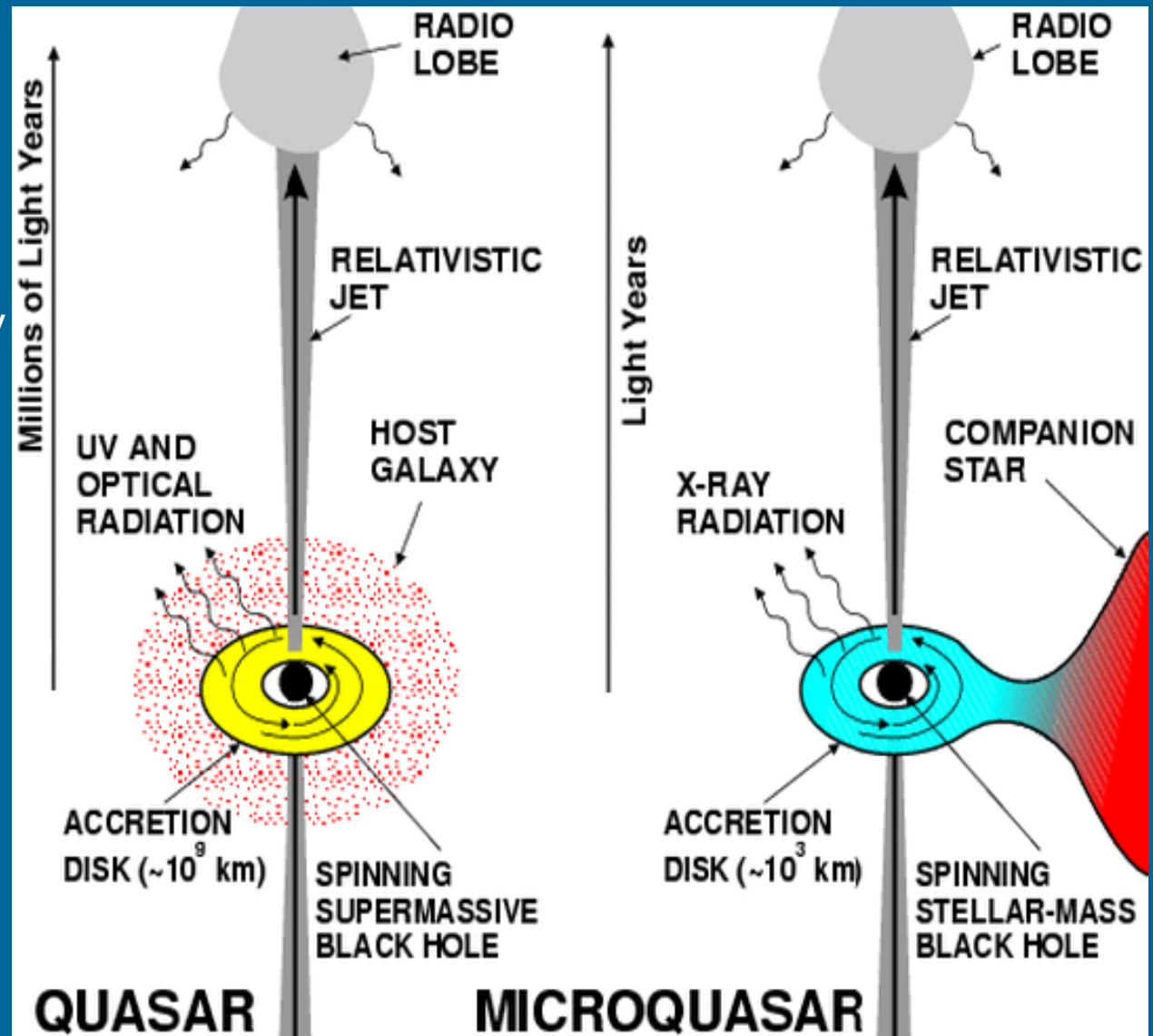
MICROQUASAR

©2004 European Space Agency
www.esa.int/sci/msp/

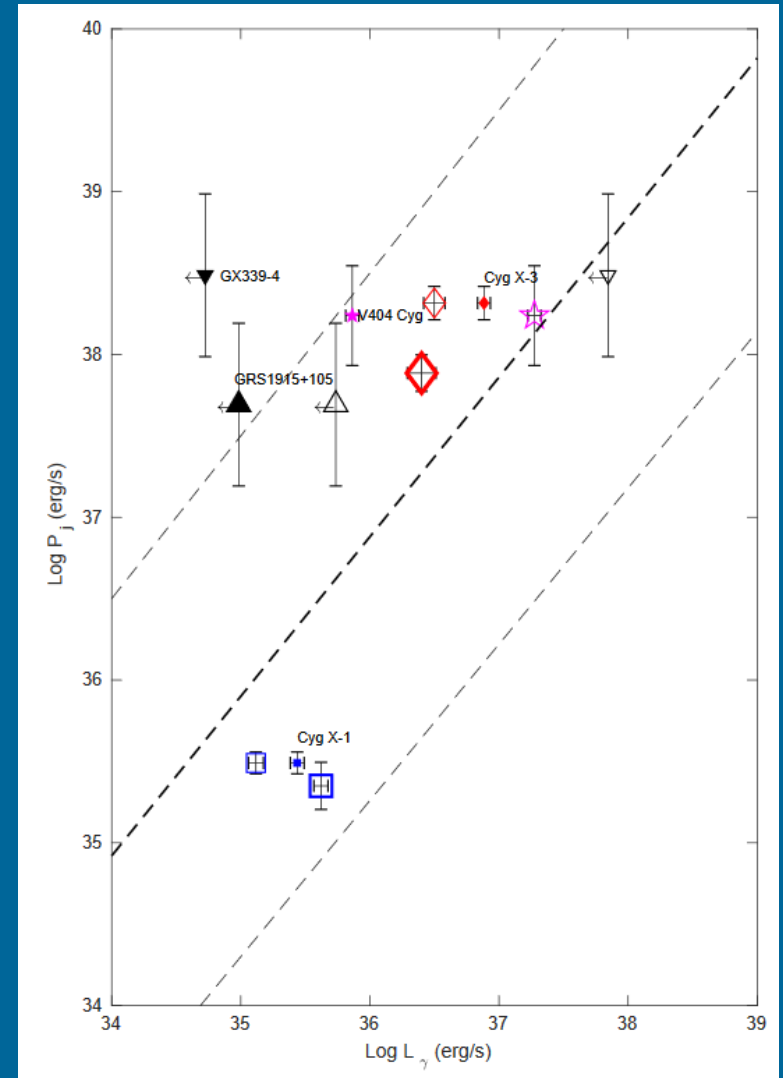
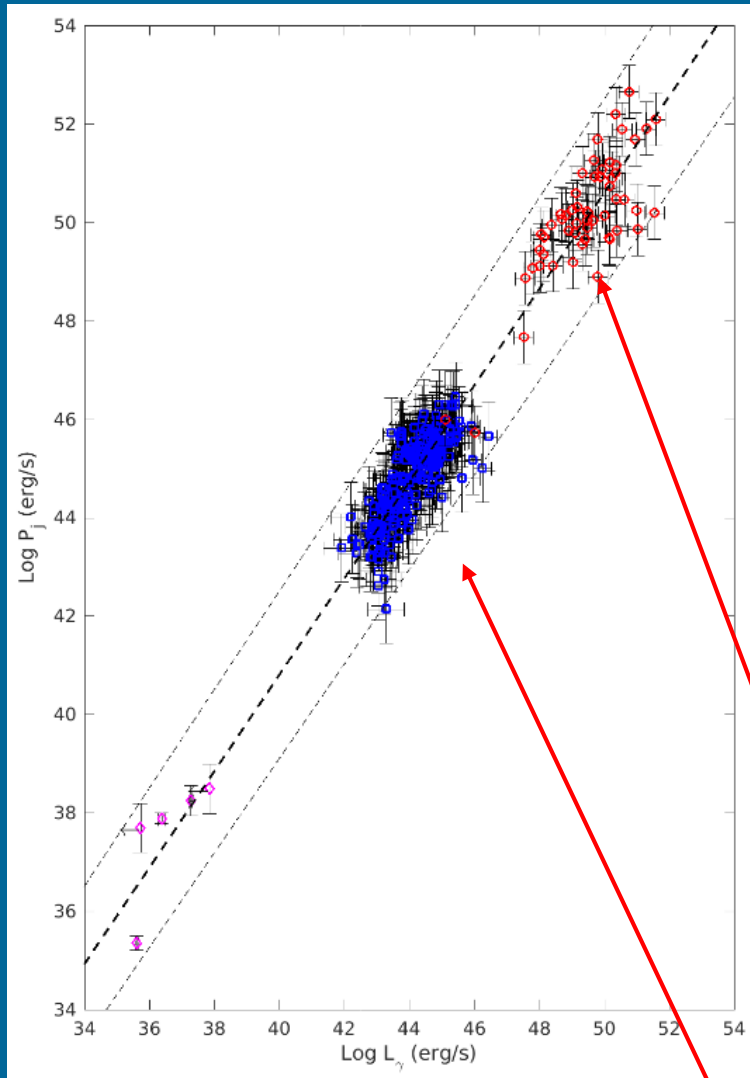
See a brief review in 1106.2059

$T \sim 10^7 \text{ K } M^{-1/4}$ —
last stable orbit
temperature at
Eddington luminosity

Optics/UV – QSO
X-ray - μ QSO



Jet-luminosity relation

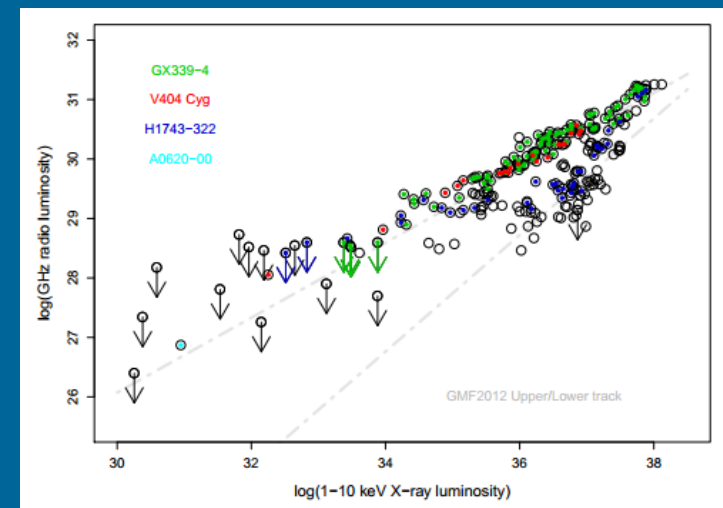
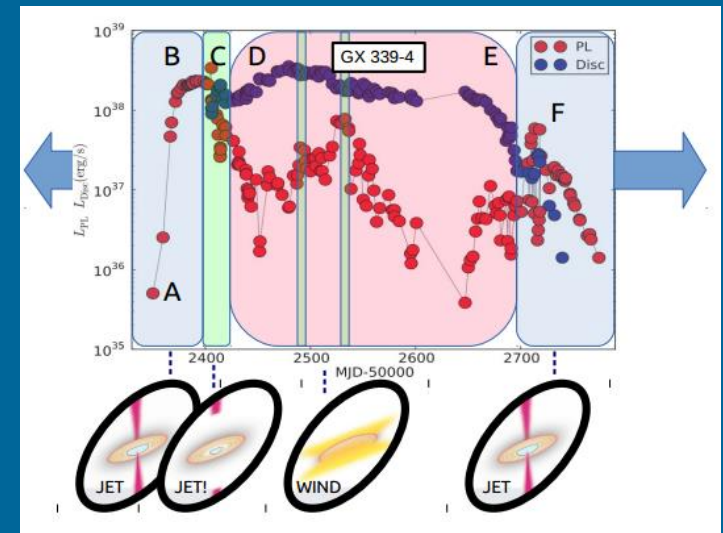
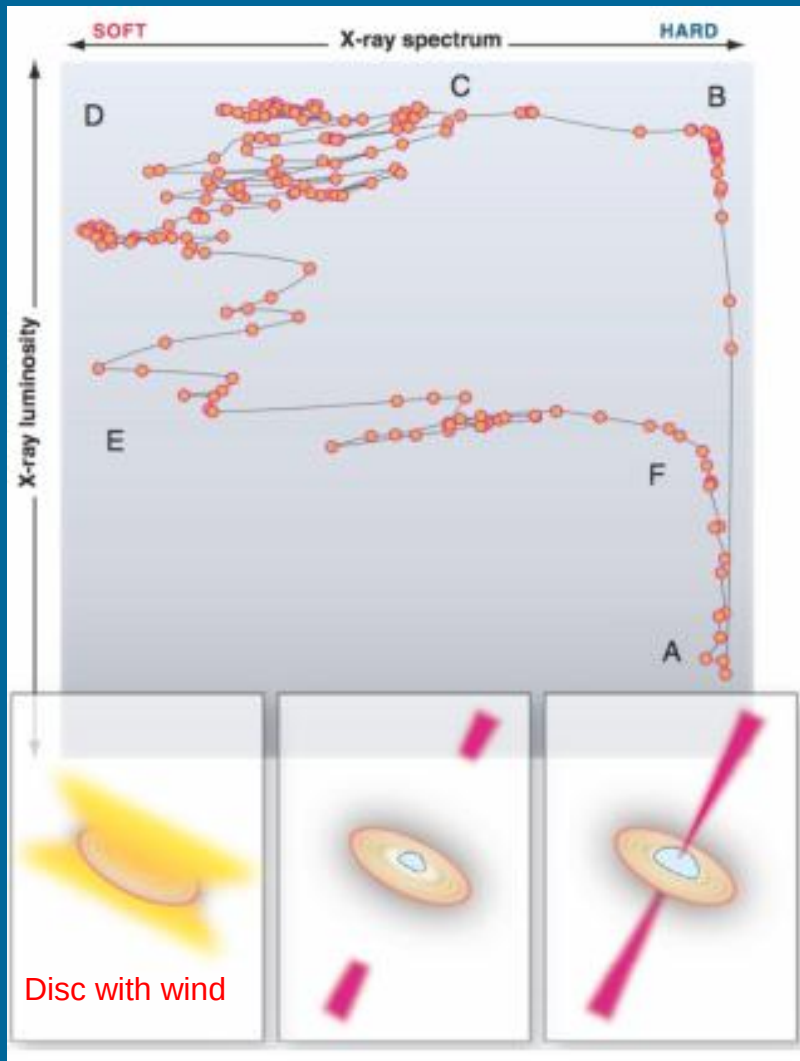


1705.09191

Blazars

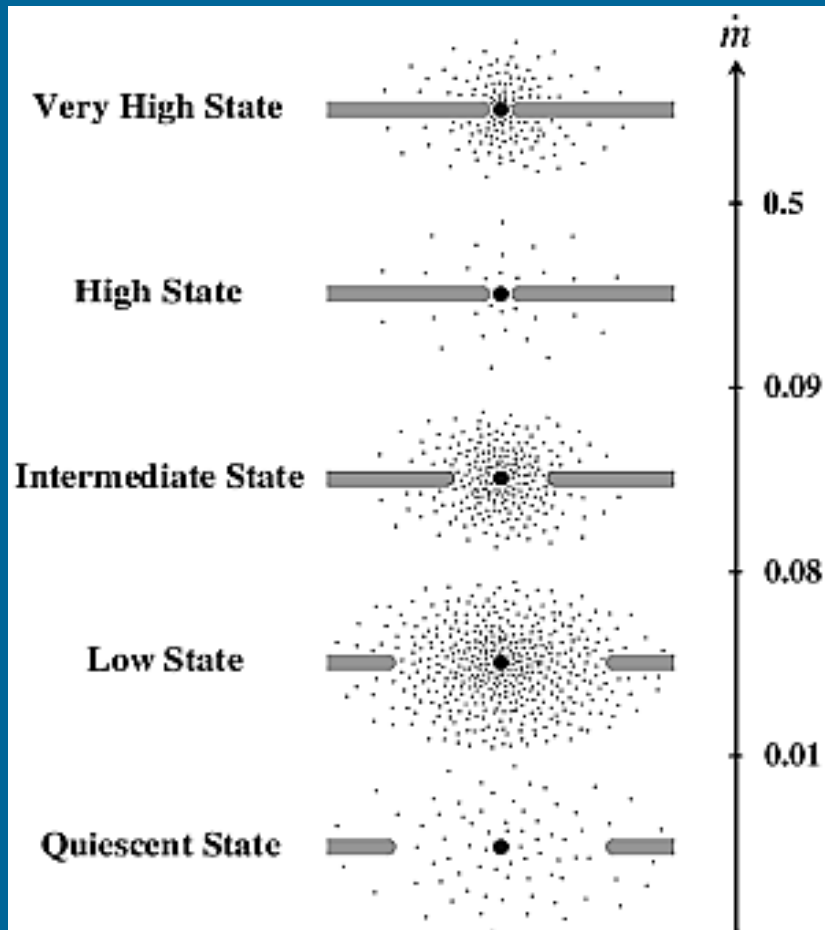
GRBs

Large review on jets from binaries



A large recent review can be found in 1407.3674

States (luminosity+spectrum+jet+variability)



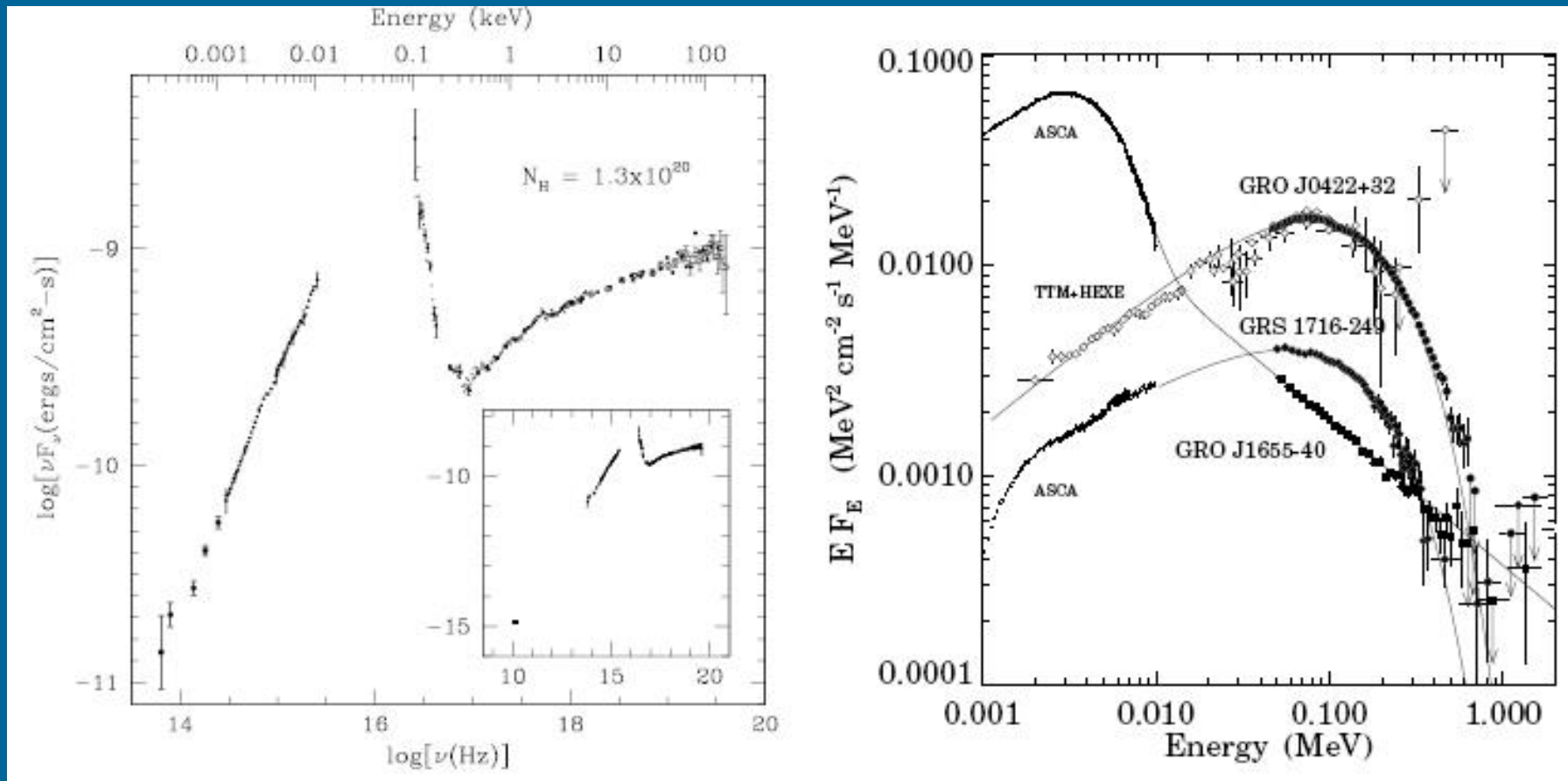
The understanding that BH binaries can pass through different “states” (characterized by luminosity, spectrum, and other features, like radio emission) appeared in 1972 when Cyg X-1 suddenly showed a drop in soft X-ray flux, rise in hard X-ray flux, and the radio source was turned on.

Now there are several classifications of states of BH binaries.

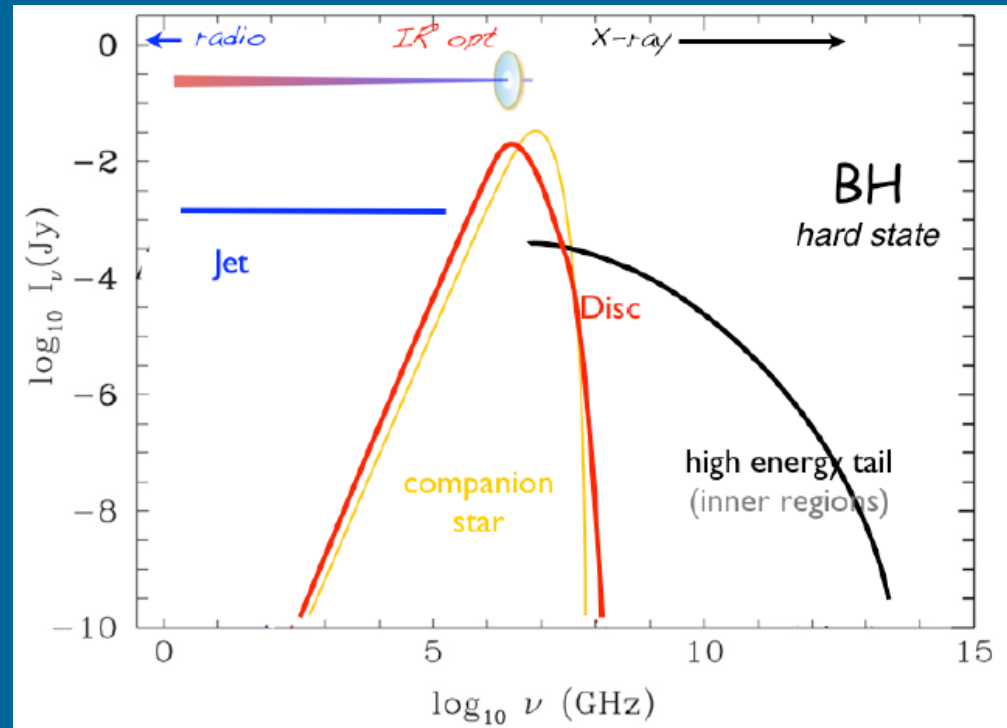
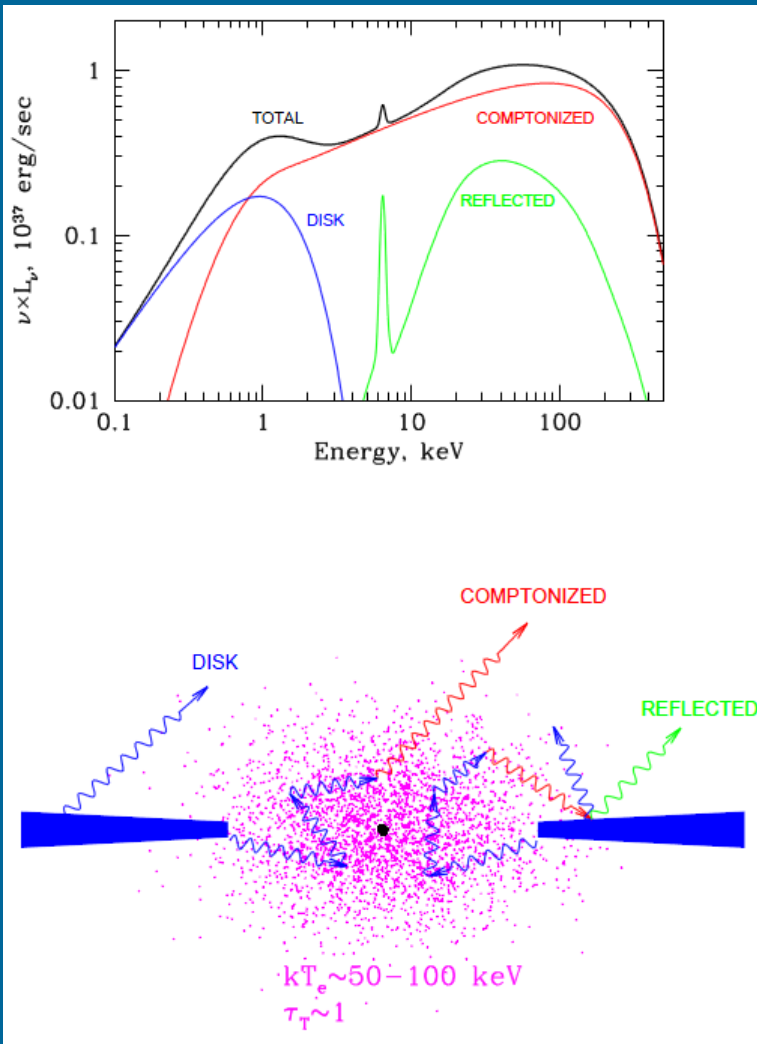
[astro-ph/0306213](https://arxiv.org/abs/astro-ph/0306213) McClintock, Remillard
Black holes on binary systems

Accretion onto BHs was recently reviewed in 1304.4879

Spectra of BH candidates



Different components of a BH spectrum



1104.0097

Accretion geometry
and photon paths at
the hard state

Three-state classification

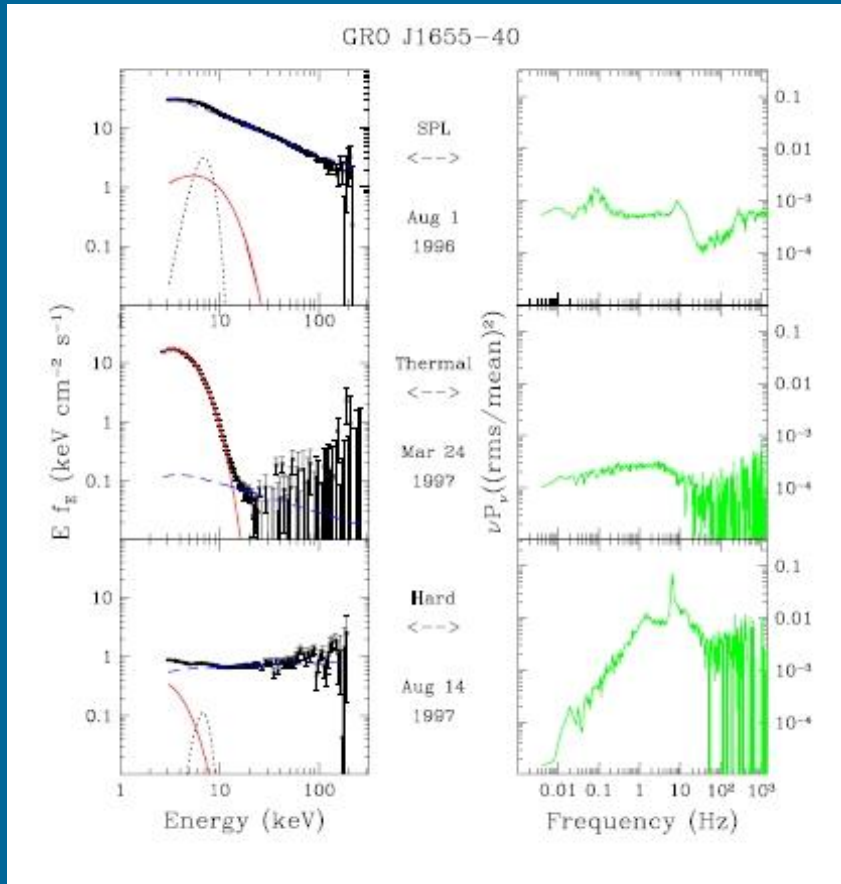
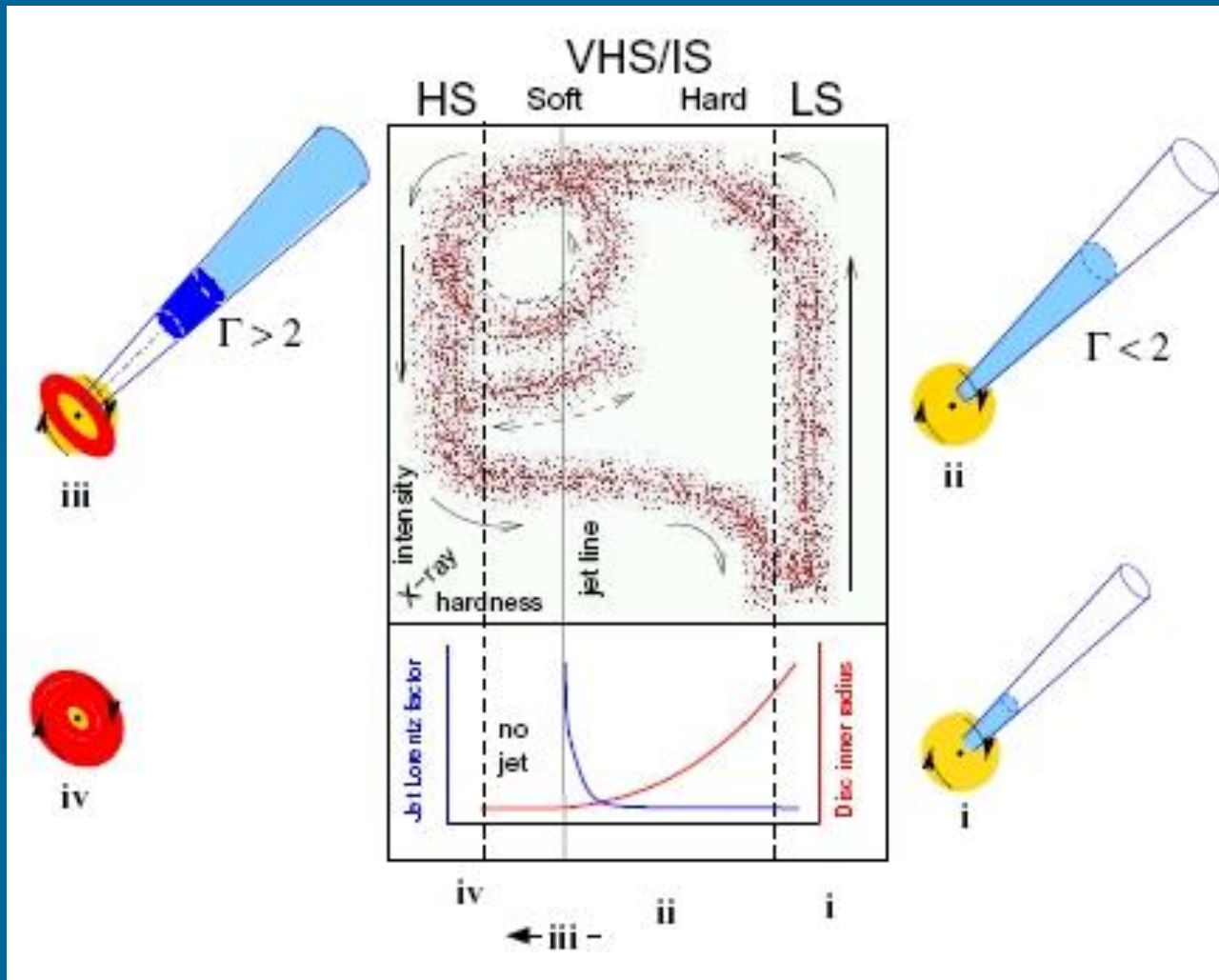


Table 2: Outburst states of black holes: nomenclature and definitions

New State Name (Old State Name)	Definition of X-ray State ^a
Thermal (High/Soft)	Disk fraction $f^b > 75\%$ QPOs absent or very weak: $a_{\text{max}}^c < 0.005$ Power continuum level $r^d < 0.075^e$
Hard (Low/Hard)	Disk fraction $f^b < 20\%$ (i.e., Power-law fraction $> 80\%$) $1.4^f < \Gamma < 2.1$ Power continuum level $r^d > 0.1$
Steep Power Law (SPL) (Very high)	Presence of power-law component with $\Gamma > 2.4$ Power continuum level $r^d < 0.15$ Either $f^b < 0.8$ and 0.1–30 Hz QPOs present with $a^c > 0.01$ or disk fraction $f^b < 50\%$ with no QPOs

In this classification the luminosity is not used as one of parameters.

Discs and jets

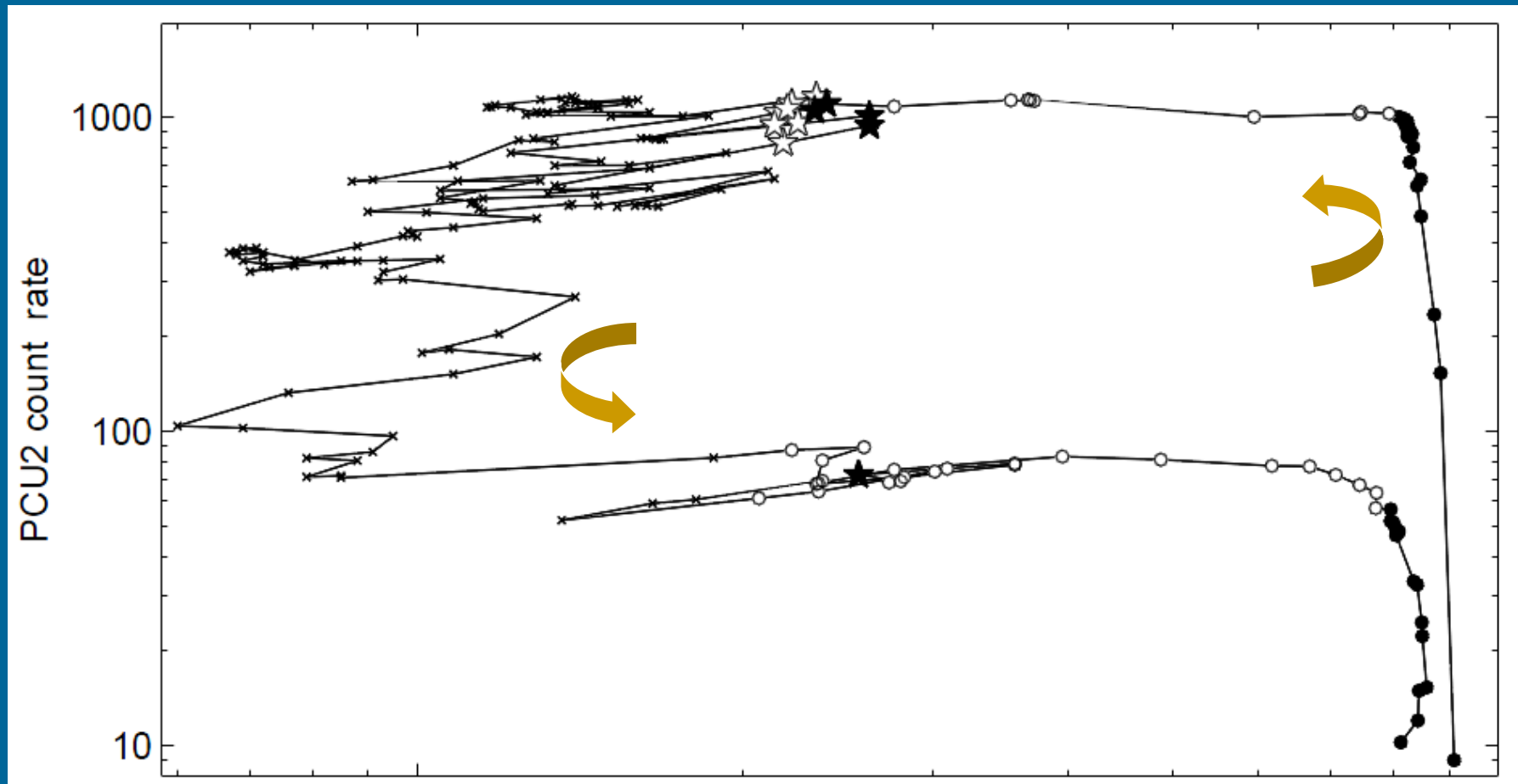


The model for systems with radio jets

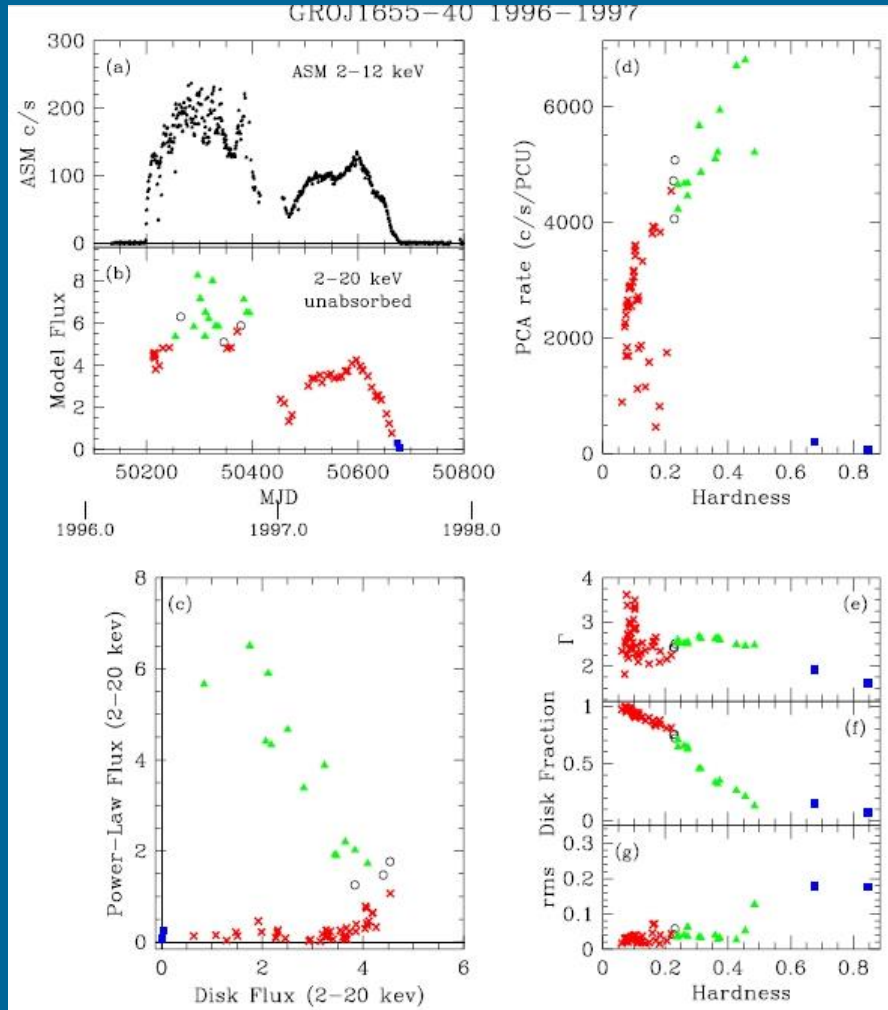
LS – low/hard state
 HS – high/soft state
 VHS/IS – very high and intermediate states

The shown data are for the source GX 339-4.

Hardness vs. flux: state evolution

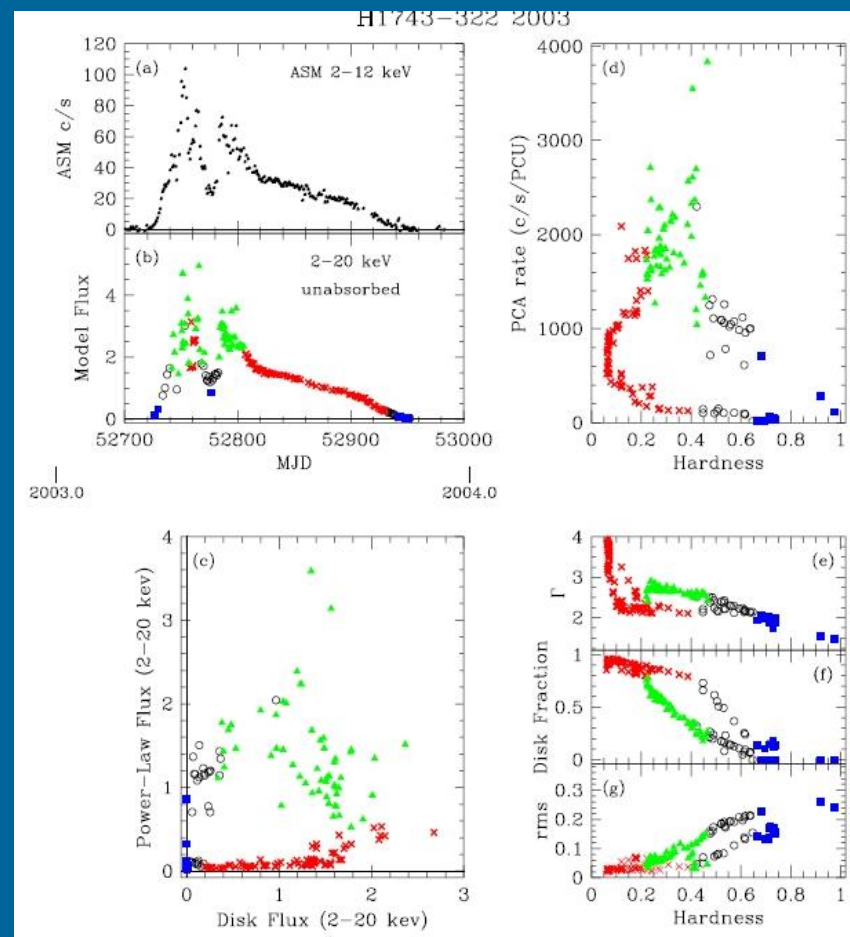
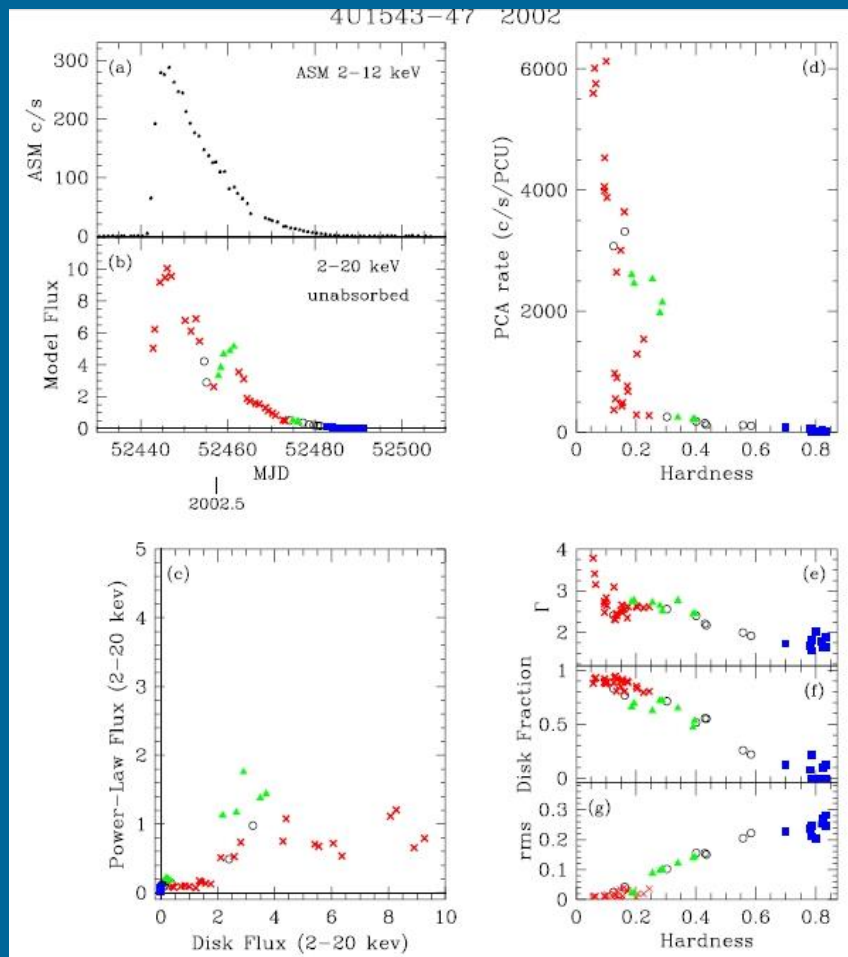


GRO J1655-40 during a burst



Red crosses – thermal state,
Green triangles – steep power-law (SPL),
Blue squares – hard state.

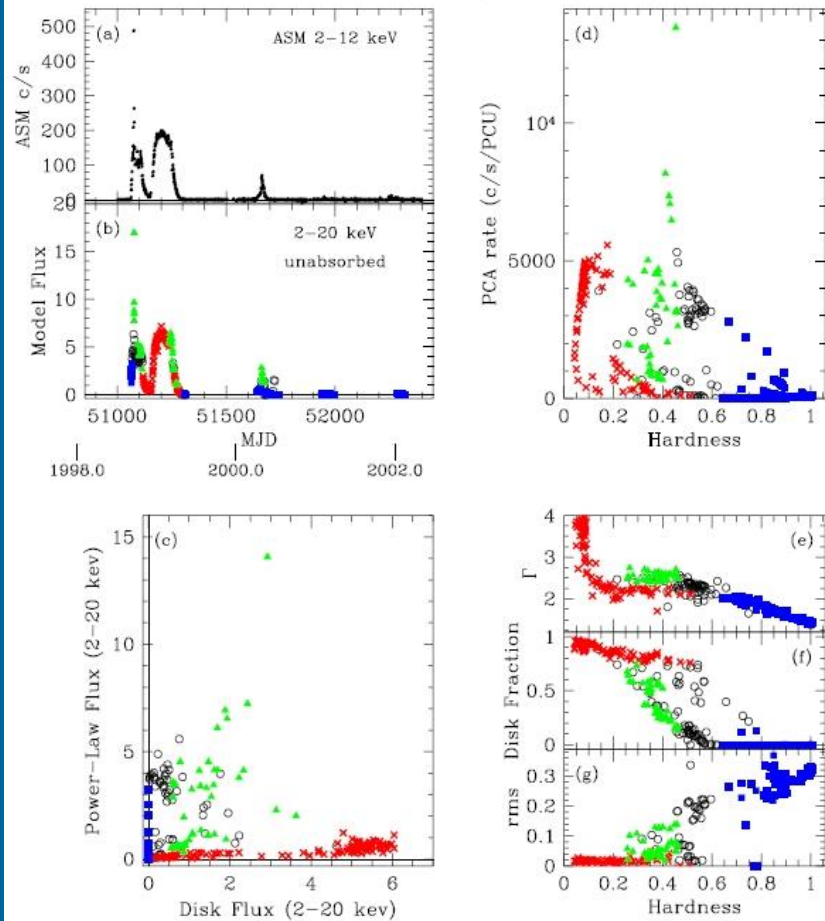
4U 1543-47 and H1743-322



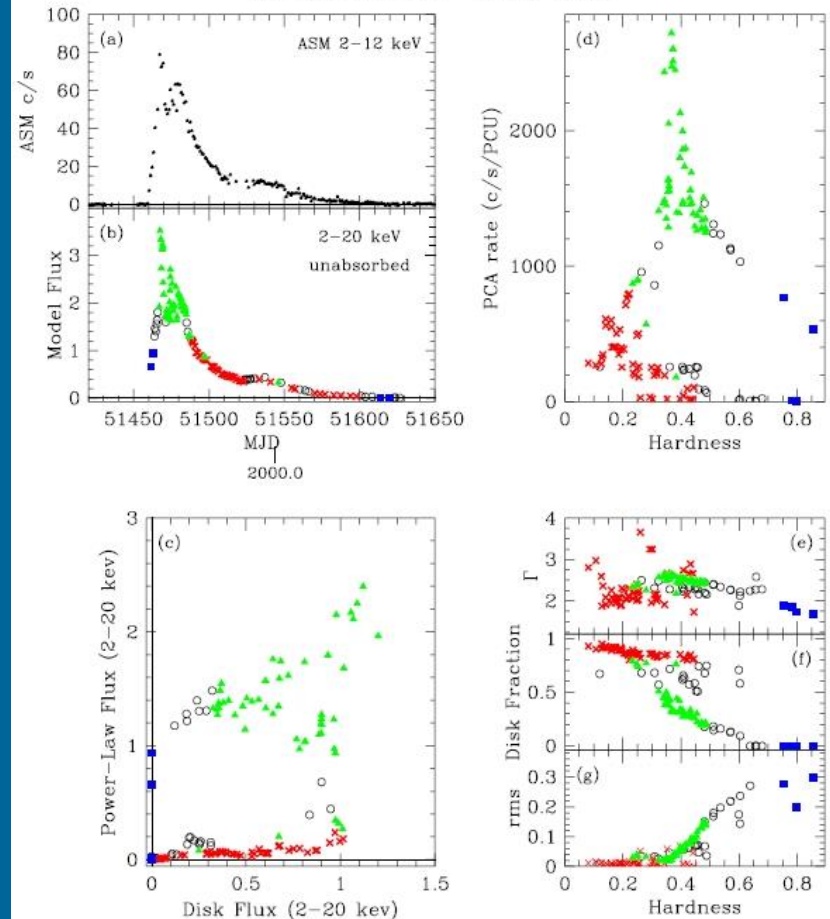
(Remillard, McClintock [astro-ph/0606352](https://arxiv.org/abs/astro-ph/0606352))

XTE J1550-564 and XTE J1859-226

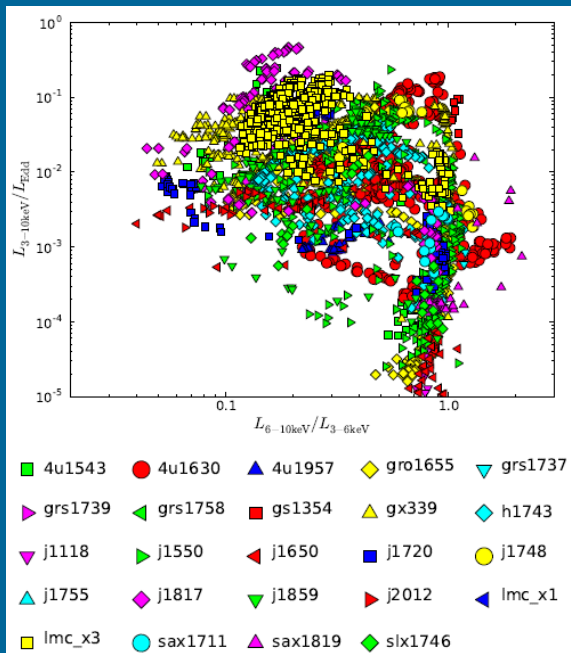
XTE J1550-564 1998-1999; 2000; 2001; 2002



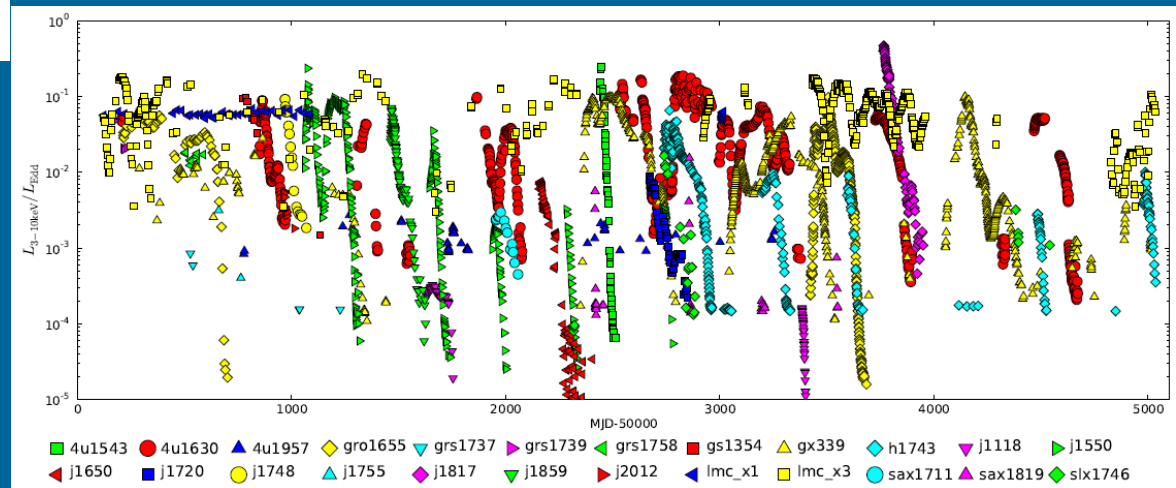
XTE J1859+226 1999-2000



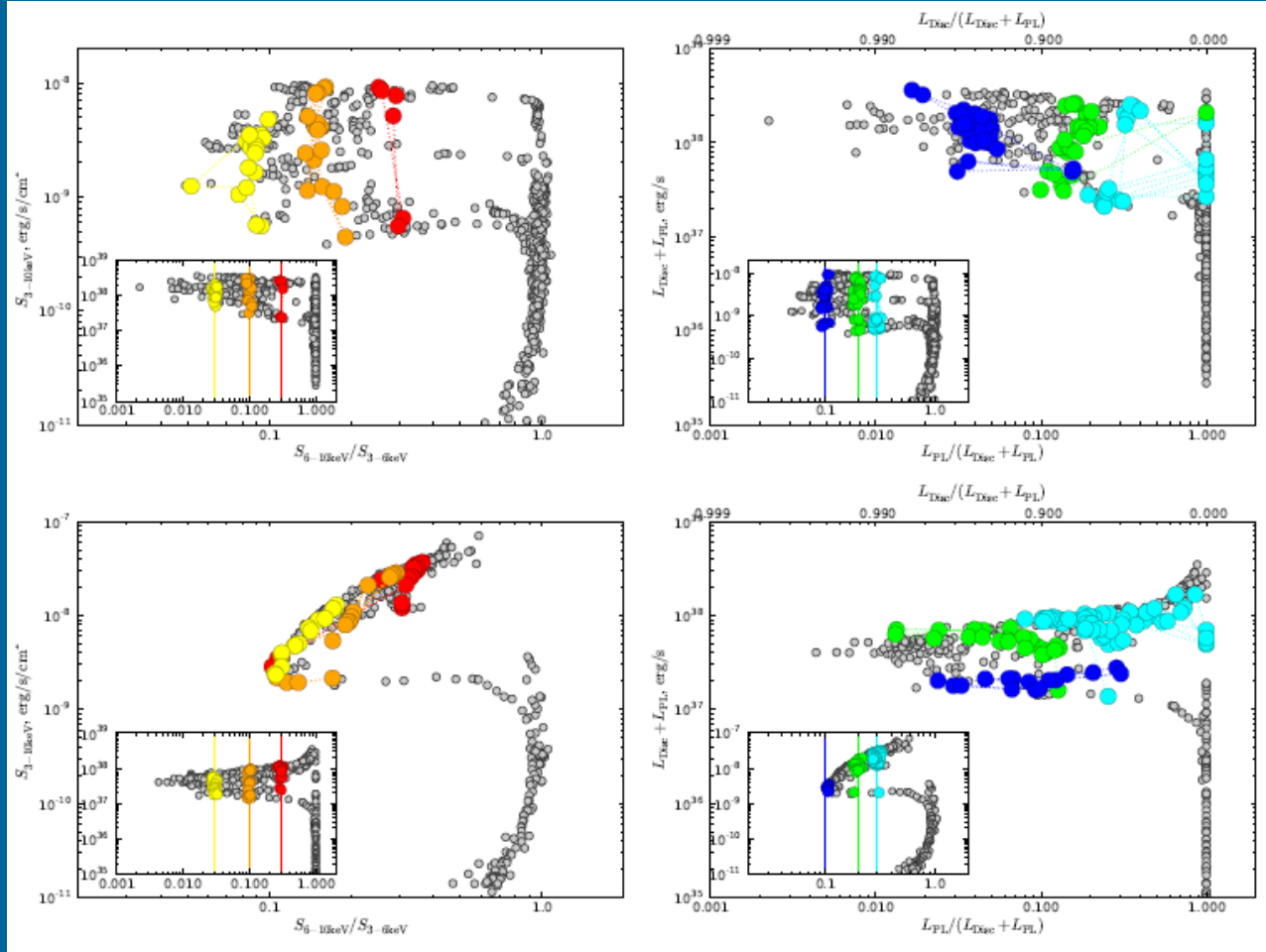
Recent large set of data



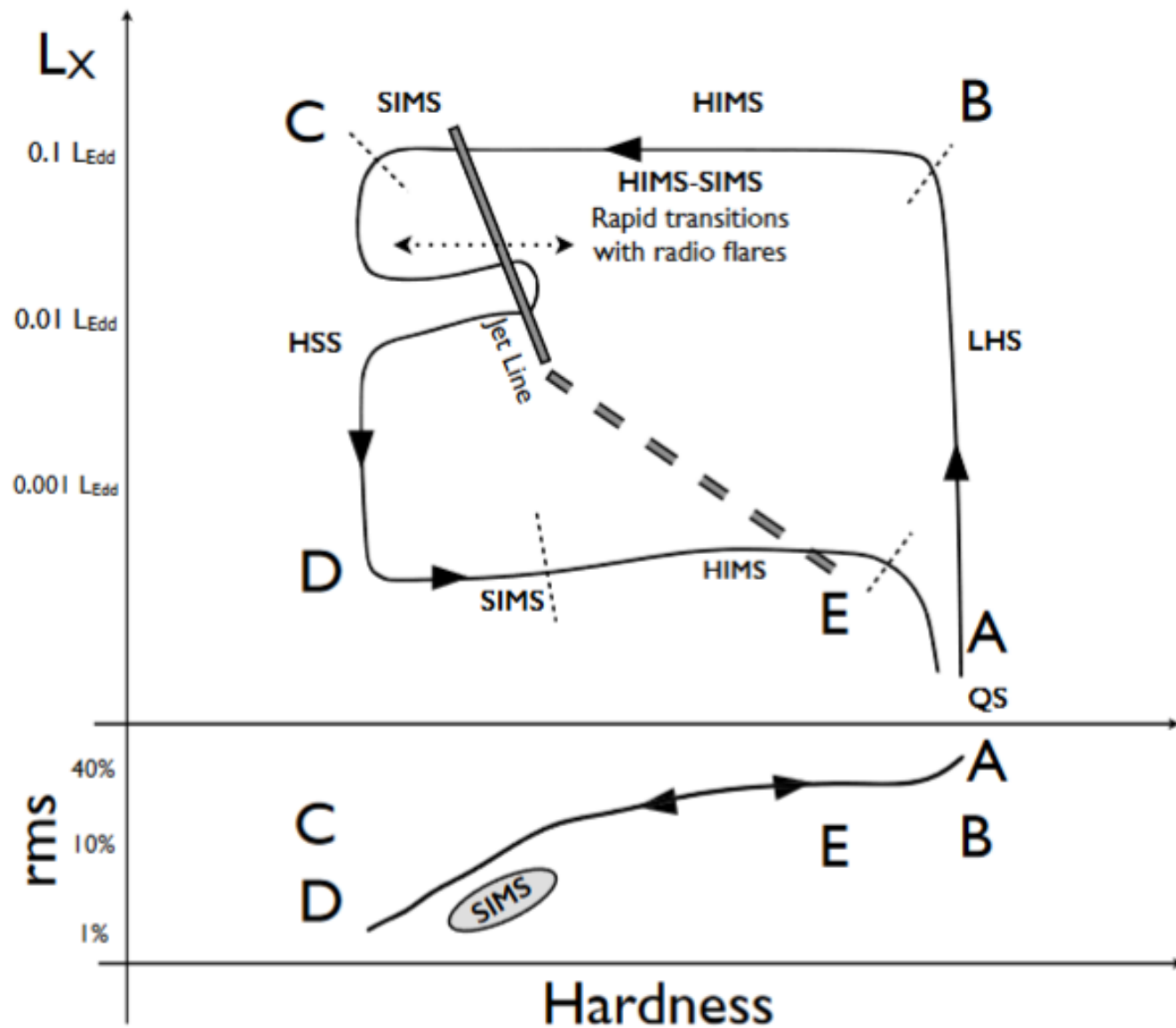
RXTE data
25 LMXBs



Hardness Intensity Diagram (HID) and Disc Fraction Luminosity Diagram (DFLD)

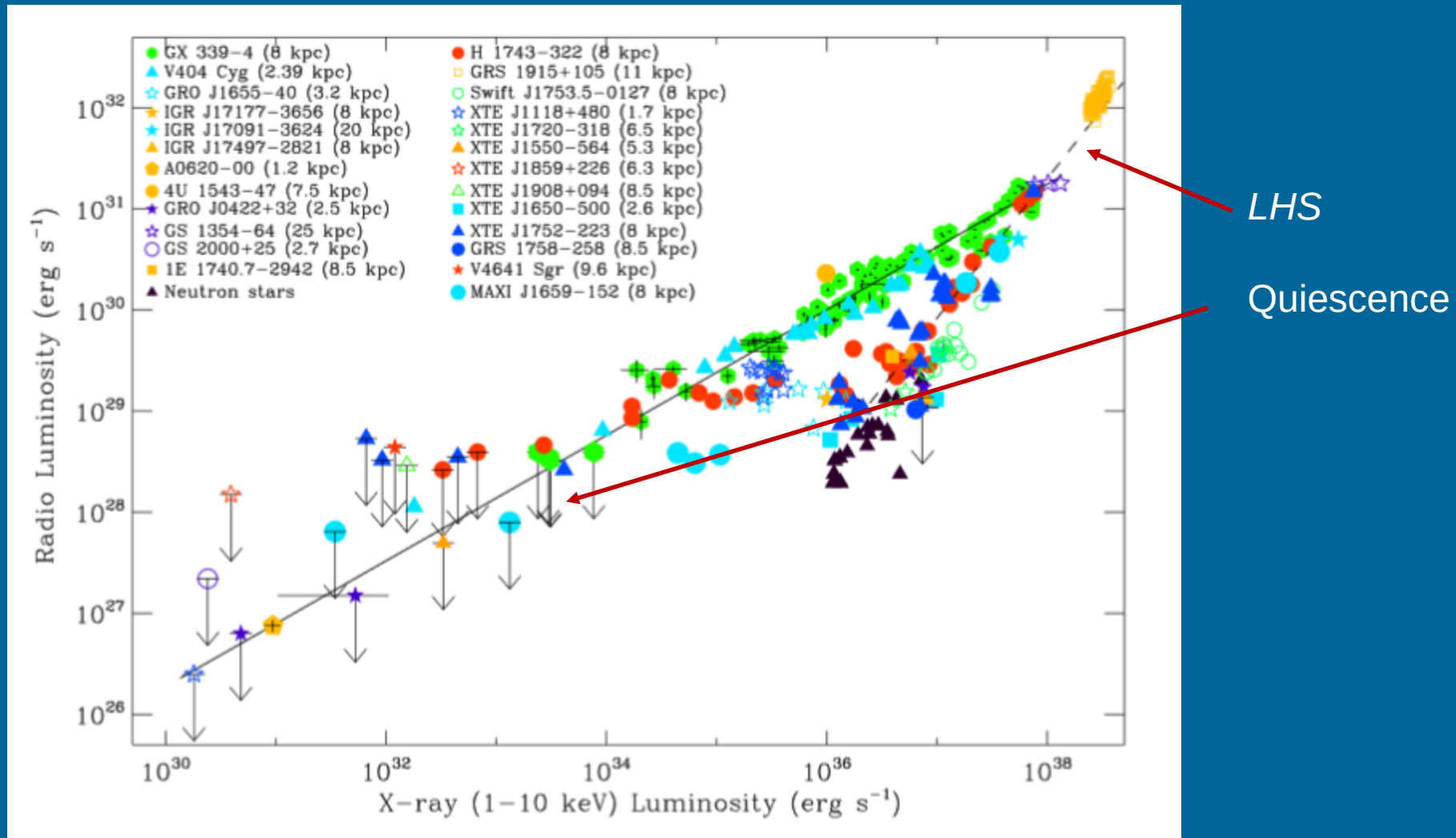


LEFT: HID with specific disc fractions highlighted
 RIGHT: DFLD with specific X-ray colours highlighted.
 The highlighted disc fractions are red 0.3, orange 0.1, yellow 0.03; and the highlighted X-ray colours are cyan 0.3, green 0.2, blue 0.1.
 TOP: GX 339-4,
 DOWN: GRO 1655-40



See p.17-19 for a very clear description.

X-ray – radio correlation



Summary of states with jets in BH binaries

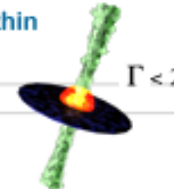
JET LINE AREA:

- 2 - 50% L_{Edd} .
- High-frequency QPOs (after).
- Type A & B QPOs (after).
- See radio ejecta (fast) each "crossing" of jet line.
- RMS drop ("The Zone") associated with ~ 0.2 Hz lowest frequency Lorentzian, close to ejecta time.



HIMS:

- Disk starts near ISCO.
- Transition starts around 2 - 50% L_{Edd} .
- Type C QPOs.
- IR drops.
- Radio starts going optically thin and variable (new ejecta?).

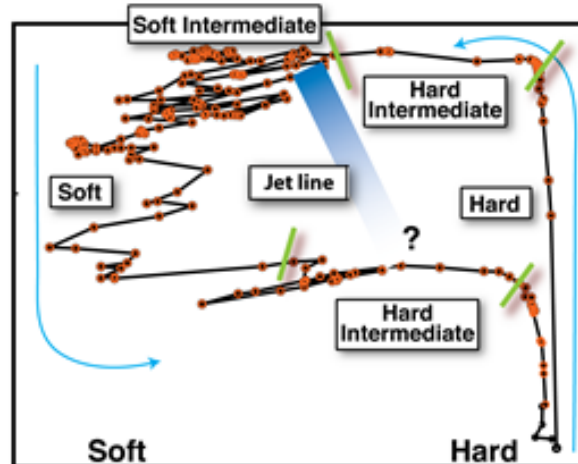


SOFT STATE:

- Optically nuclear thin jet radio emission observed initially, but quenched by at least 20-50x by full transition. Detected radio flux not nuclear?
- Type C QPOs.
- Non-thermal power law extending to $\sim$ MeV.
- Thin disk ~ 0.1 - $1.0 L_{\text{Edd}}$ at ISCO.



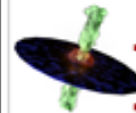
X-ray Luminosity



Spectral Hardness
(spectral slope, soft=steep, hard=flat)

HARD STATE:

- Disk moves in to $\sim$ few R_g by 10% L_{Edd} .
- Lorentzian/broad noise components.
- High RMS variability.
 - Flat spectrum jet up to IR/opt.
 - Compact jet sometimes resolved.
 - Radio/IR/X-ray correlations.
 - Reflection "bump".



T. Belloni
A. Celotti
S. Corbel
R. Fender
E. Gallo
M. Hanke
E. Kalemci

D. Maitra
S. Markoff
I. McHardy
M. Nowak
P.-O. Petrucci
K. Pottschmidt
J. Wilms

HIMS:

- Same as upper branch but:
 - No optically thin radio flare.
 - Radio recovers close to hard state.
 - Lower flux level (hysteresis).

QUIESCENCE:

- Thin disk recessed to $> 10^2 R_g$.
- BB component seen in UV/Optical.
- Disk 10-100x more luminous than LX. By $\sim 10^{-4} L_{\text{Edd}}$.
- No iron lines?



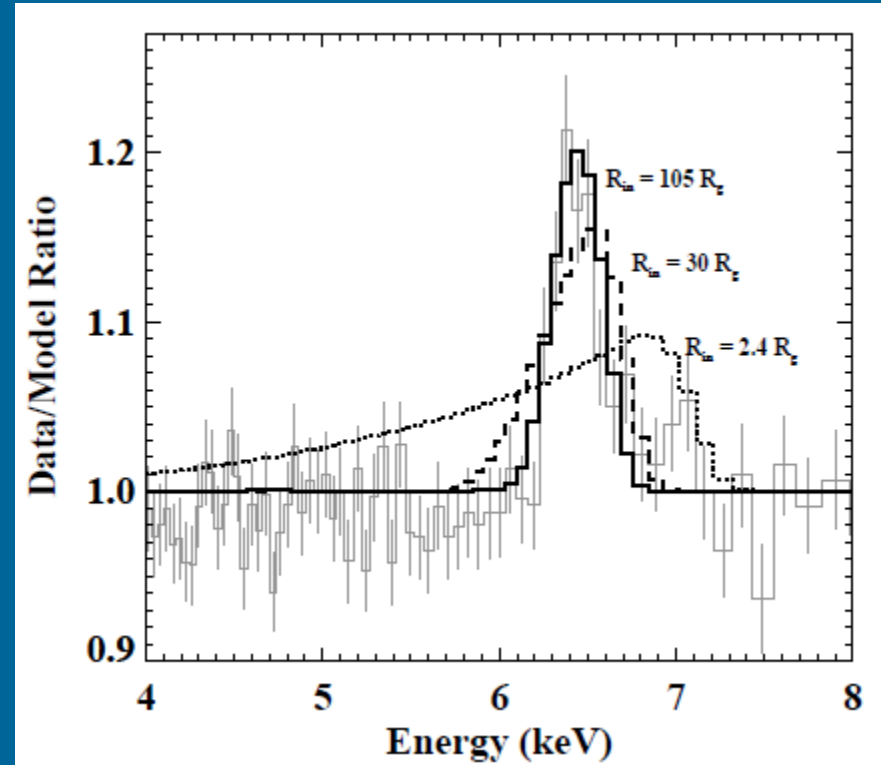
Probing the Accretion/Outflow Connection in
X-Ray Binaries and Active Galactic Nuclei

Inner disk boundary

In BH binaries there are different spectral and luminosity states. It was suggested that the inner disk boundary moves significantly from stage to stage.

For the first time the effect is measured thanks to iron line data.

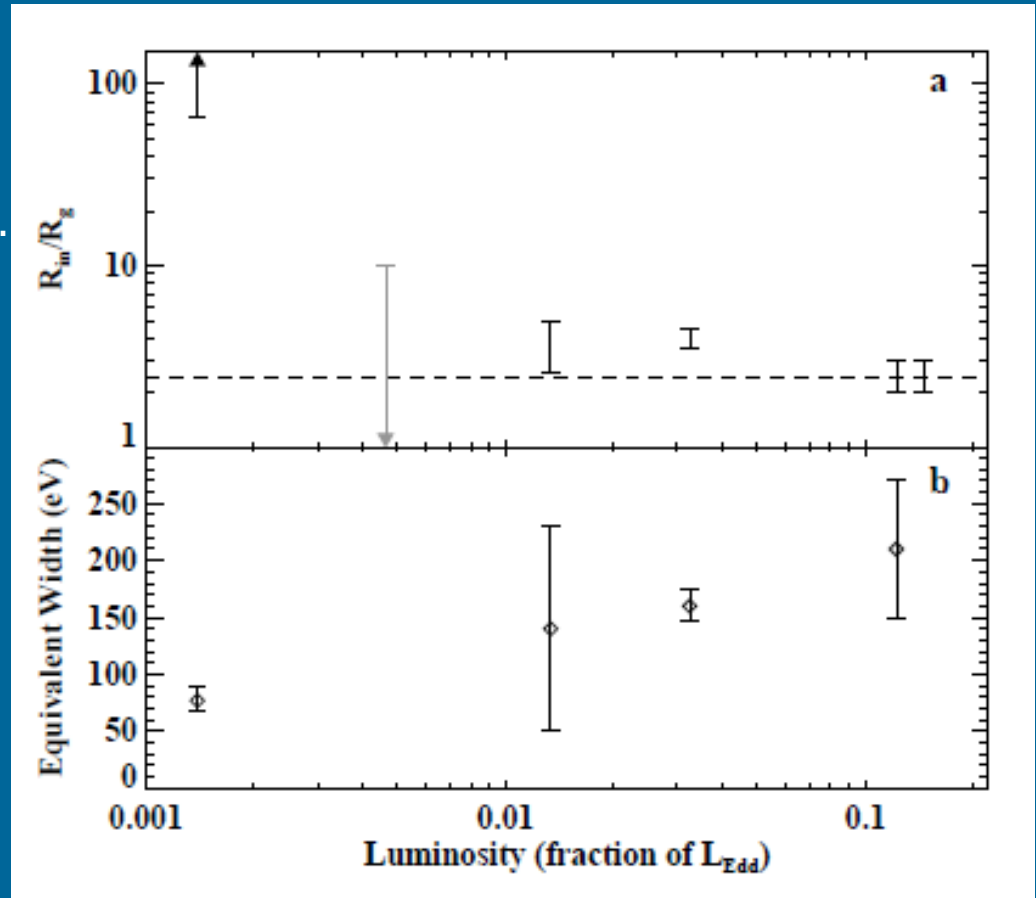
At low luminosity the inner disk boundary is far from the BH.



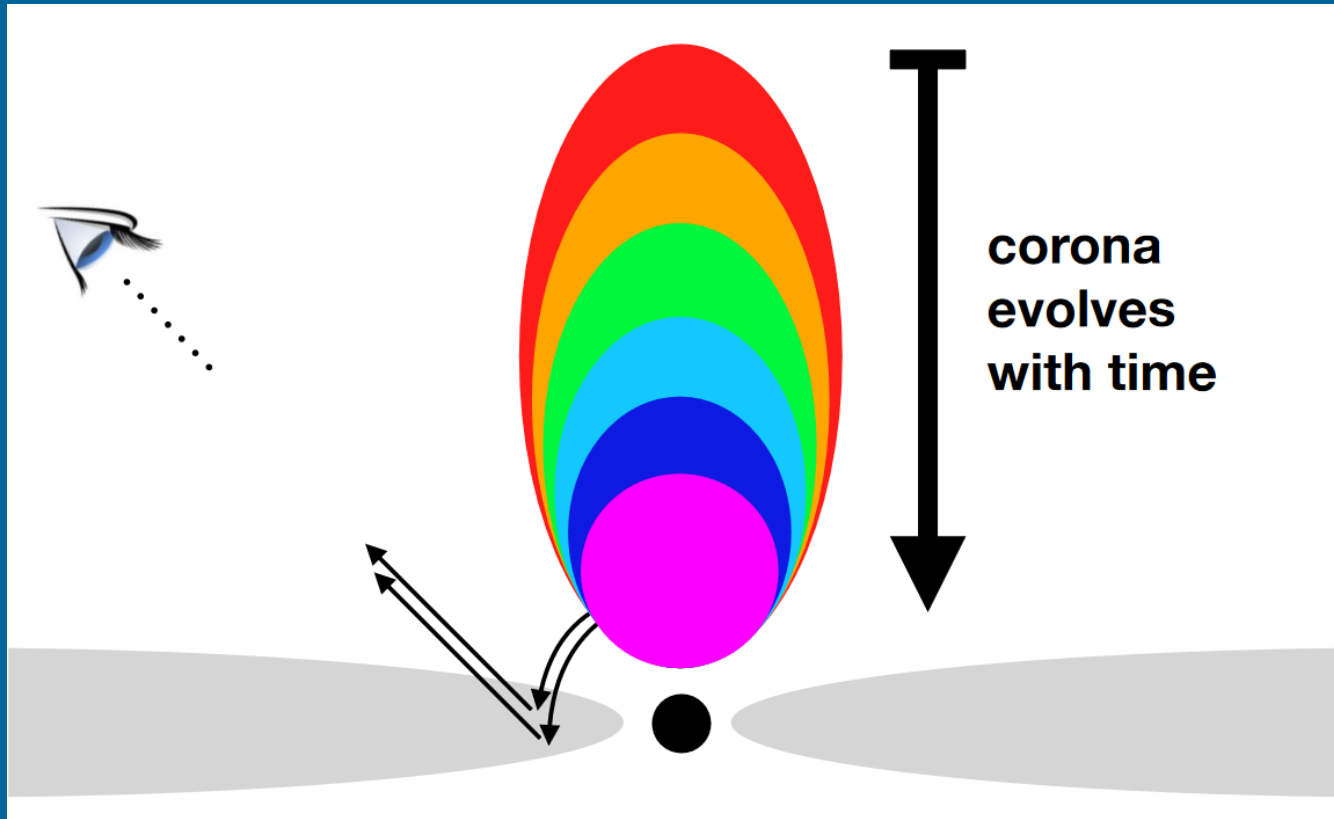
Inner disc boundary

Position of the inner disc boundary is clearly different at different luminosities: from 0.1 to 0.001 L_{Edd} .

In a separate paper another group of scientists put constraints on the spin rate of the BH in this system.



Disc truncation or corona expansion?

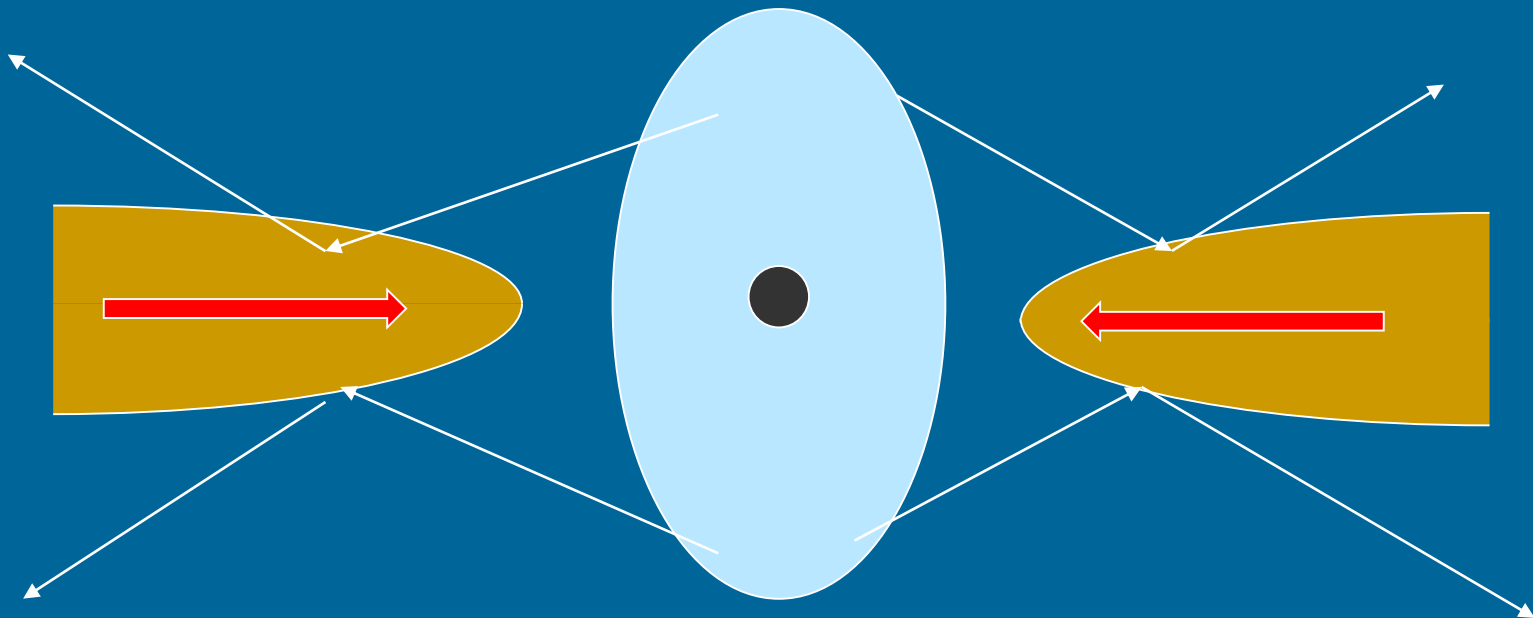


In the case of MAXI J1820+070 observations suggest that changes are mostly not due to modification of the inner disc radius, but due to changes in the hot corona size.

The result is based on time lags between corona and disc emission.

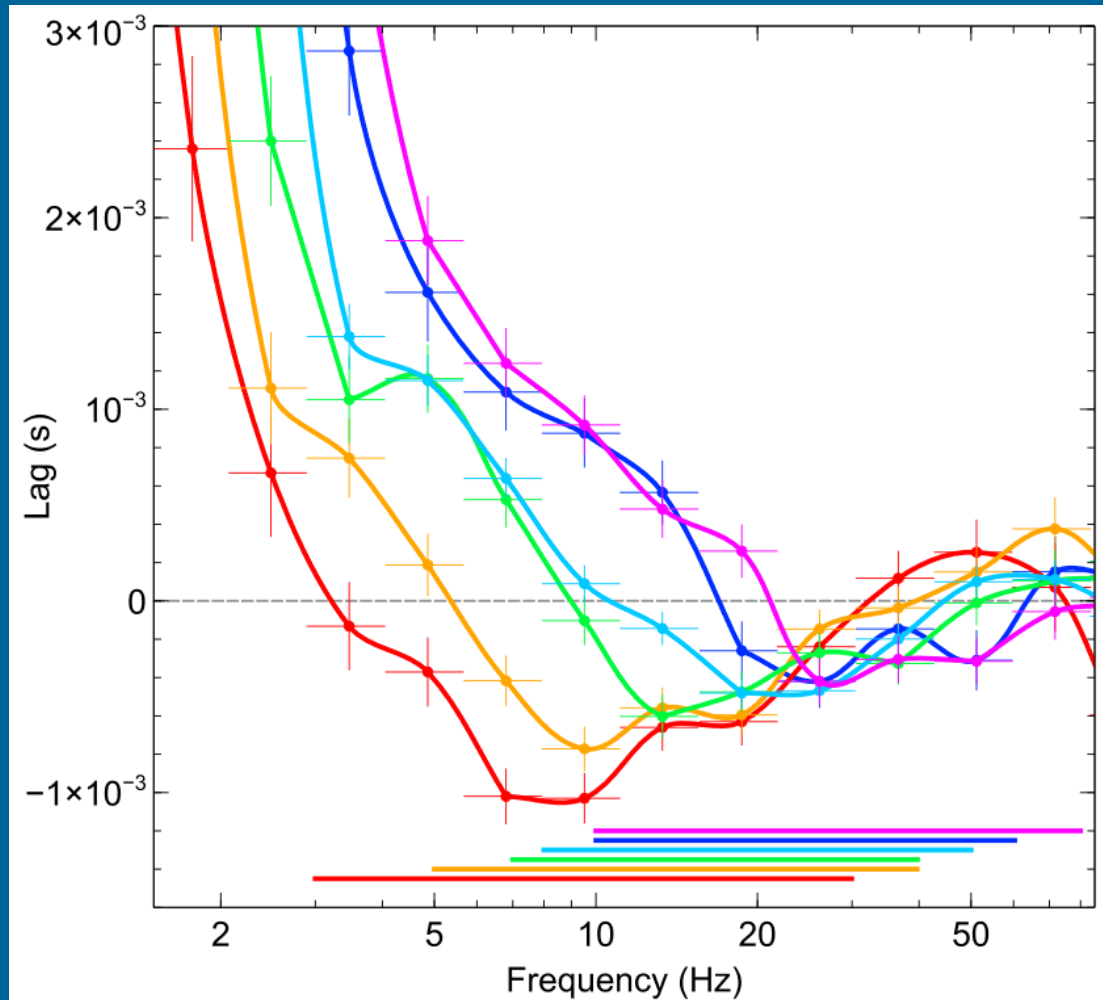
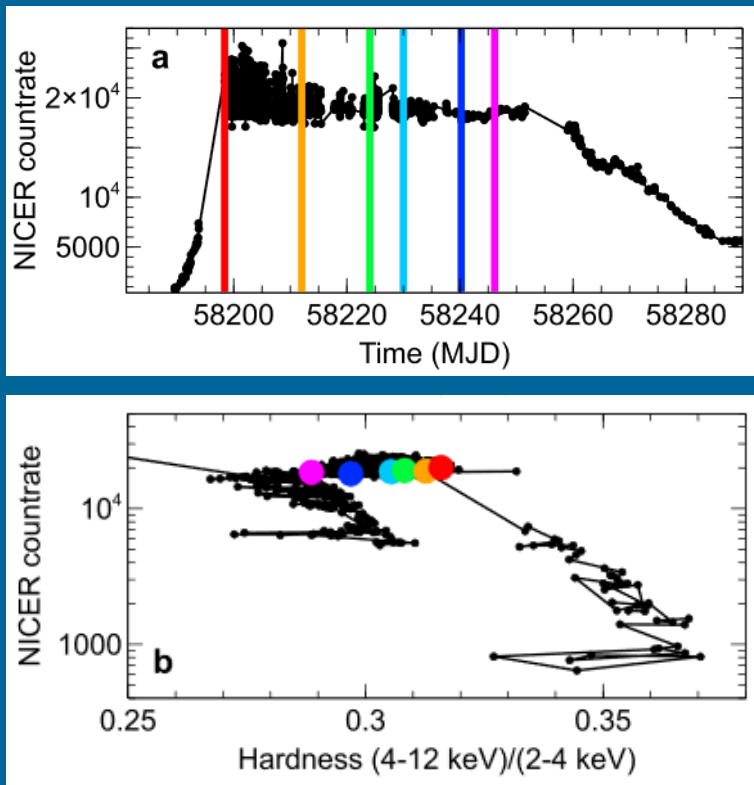
Scheme of time lags

Low-frequency hard lags (soft before hard)
is due to propagation of disturbances in the disc

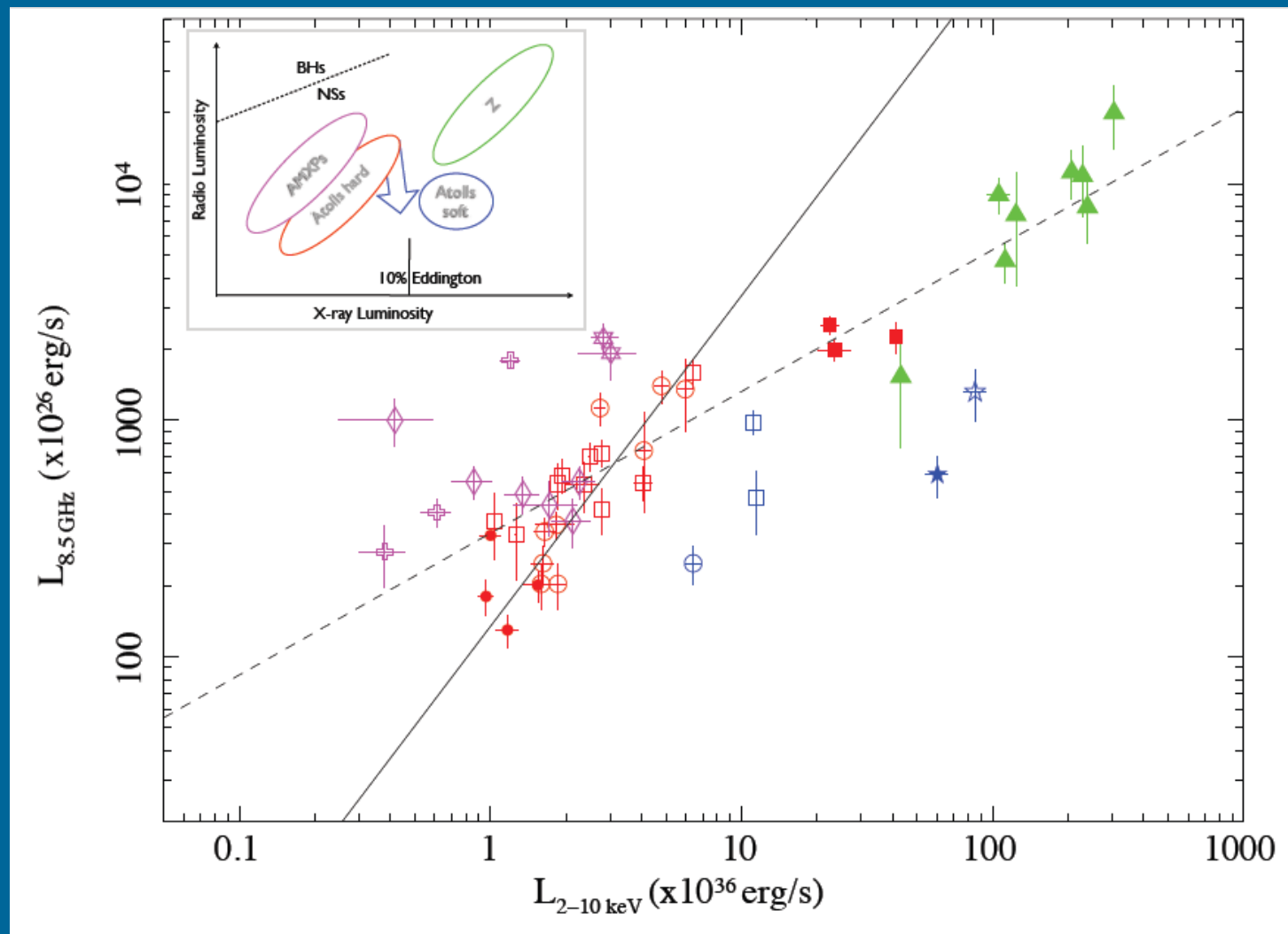


High-frequency soft lag (hard before soft) is due to irradiation of the disc by corona

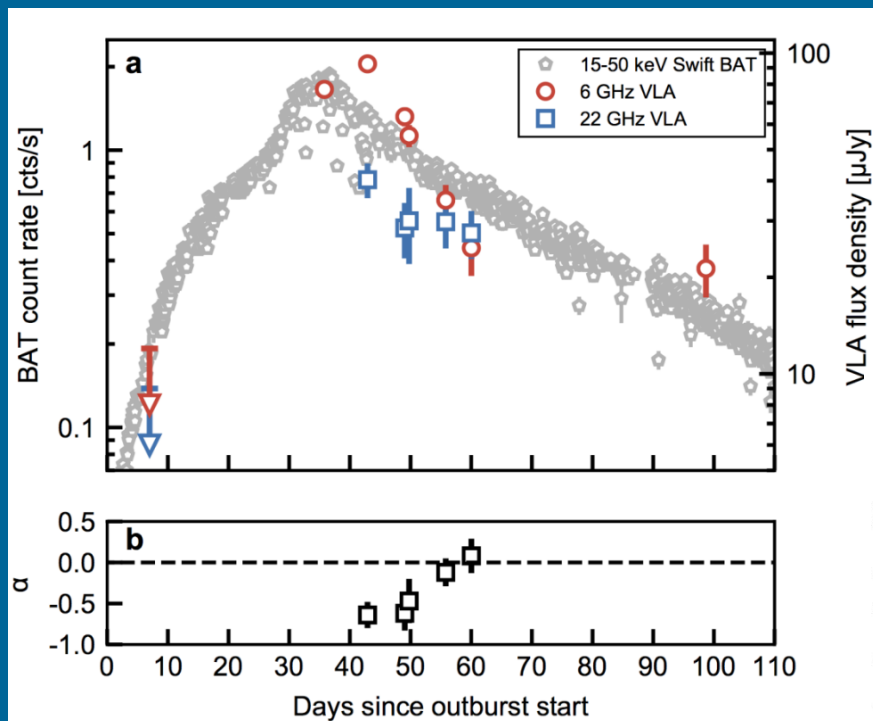
Hard lags and soft lags



NS jets



A jet from normally magnetized NS



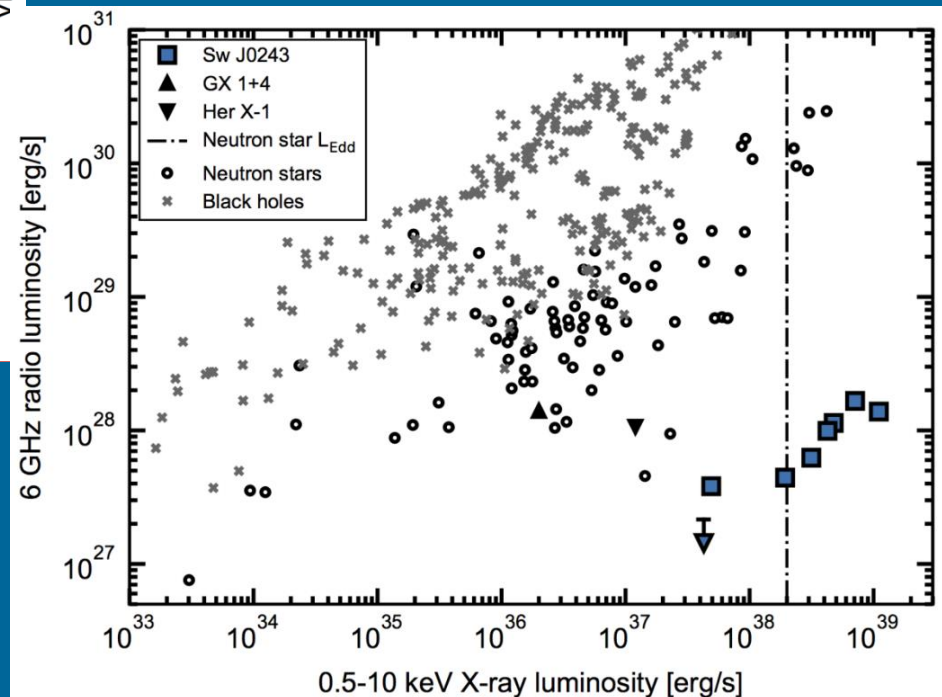
VLA detection of emission from Swift J0243.6+6124.

Spin period ~ 10 sec.

Before jets have been detected from rapidly spinning NSs.

Blandford-Znajek, not Blandford-Payne.

$$L_R \propto L_X^{0.54 \pm 0.16}$$



Spin NS and BH

- arXiv:1106.3690 1308.4760

The Extreme Spin of the Black Hole in Cygnus X-1

- arXiv:1109.6008

Suzaku Observations of 4U 1957+11:

Potentially the Most Rapidly Spinning Black Hole in (the Halo of) the Galaxy

- arXiv:1112.0569

Observational Evidence for a Correlation Between Jet Power and Black Hole Spin

- arXiv:1204.5854

On the determination of the spin of the black hole in Cyg X-1
from X-ray reflection spectra

- arXiv:1211.5379

Jet Power and Black Hole Spin:

Testing an Empirical Relationship and Using it to Predict the Spins of Six Black Holes

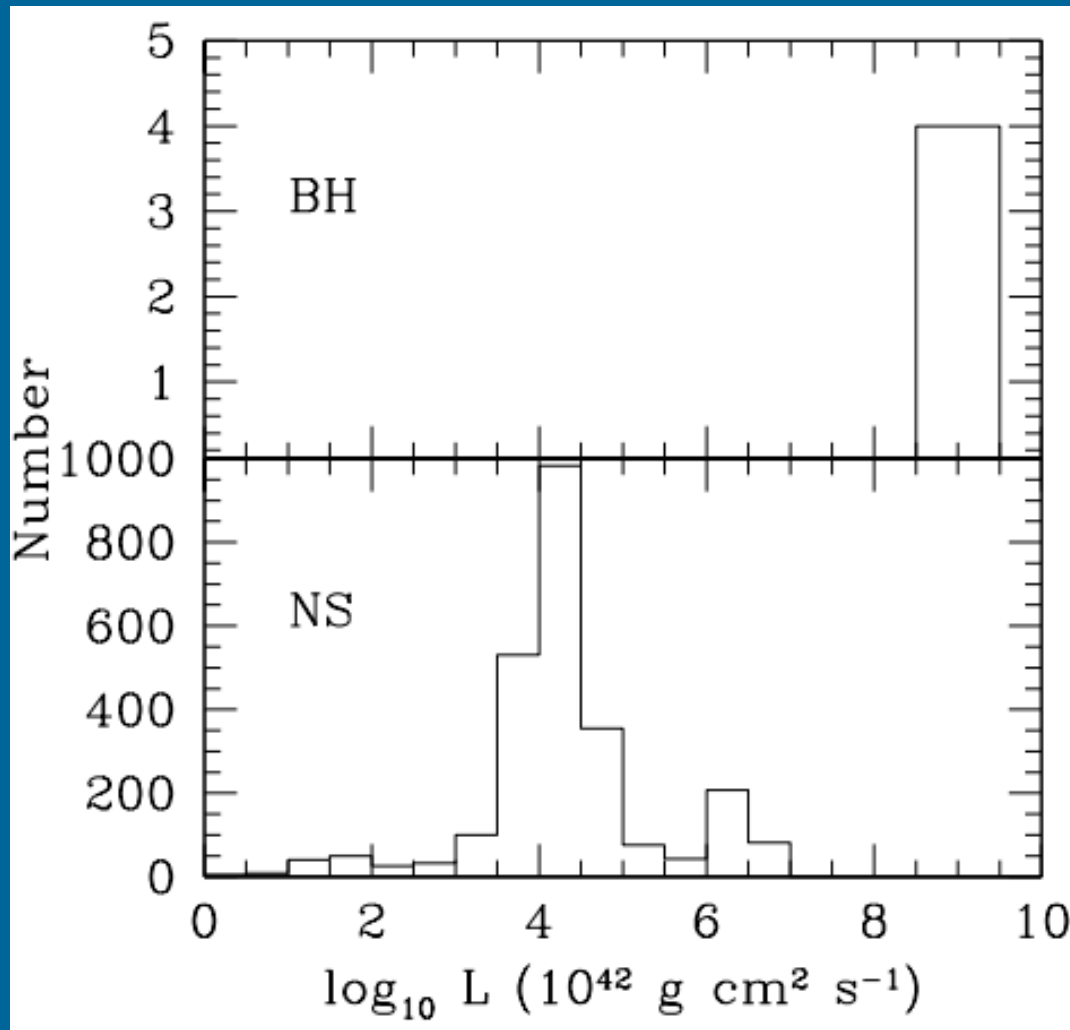
- arXiv:1303.1583

Black Hole Spin via Continuum Fitting and the Role of Spin in Powering Transient Jets

- 1309.3652 Precise mass and spin measurements for a stellar-mass black hole
through X-ray timing: the case of GRO J1655-40

Mass and spin determinations are reviewed in 1408.4145 and spin in 1507.06153

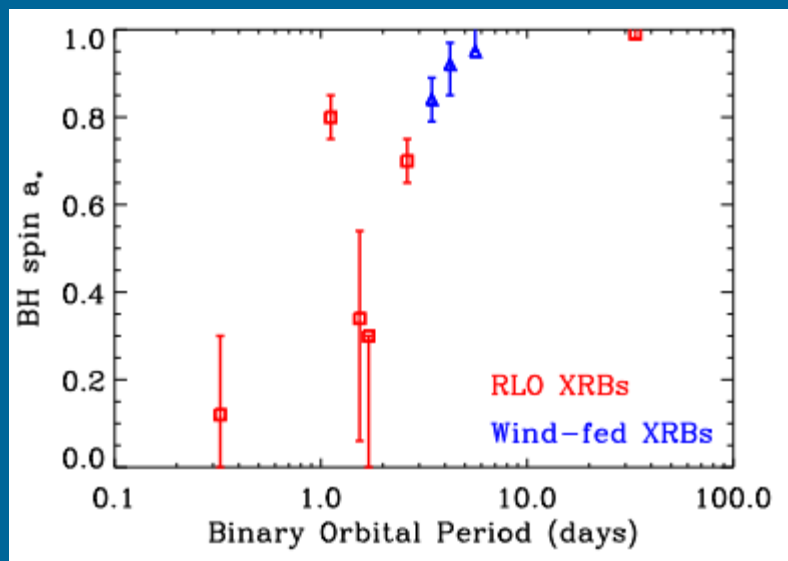
NSs vs. BHs



BHs win!!!!

They do not loose momentum.

Origin of BH spin

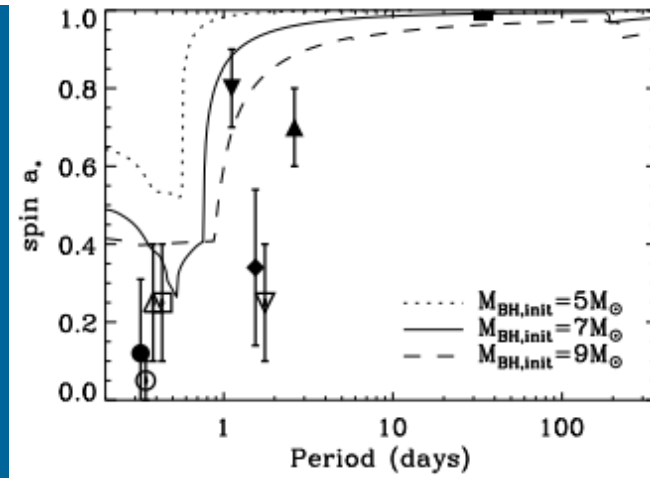
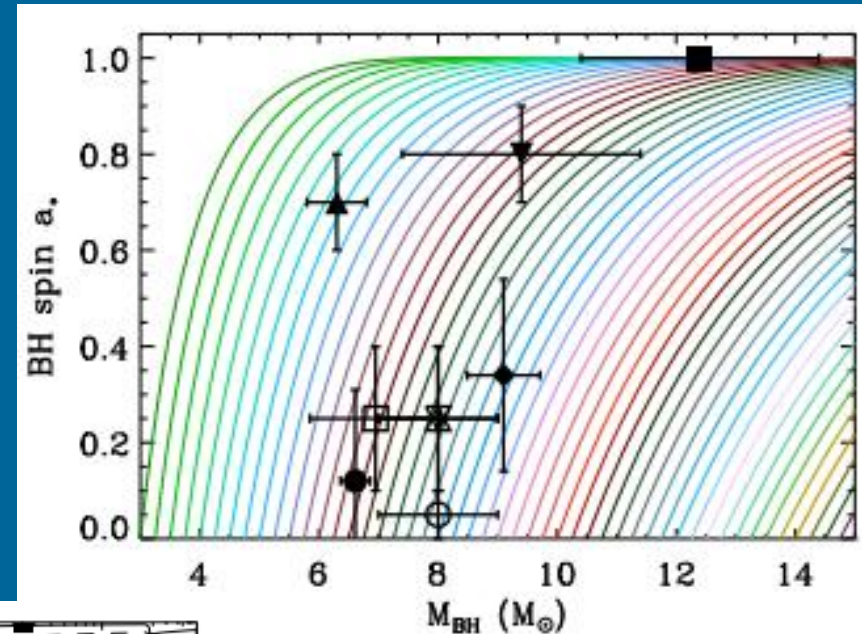
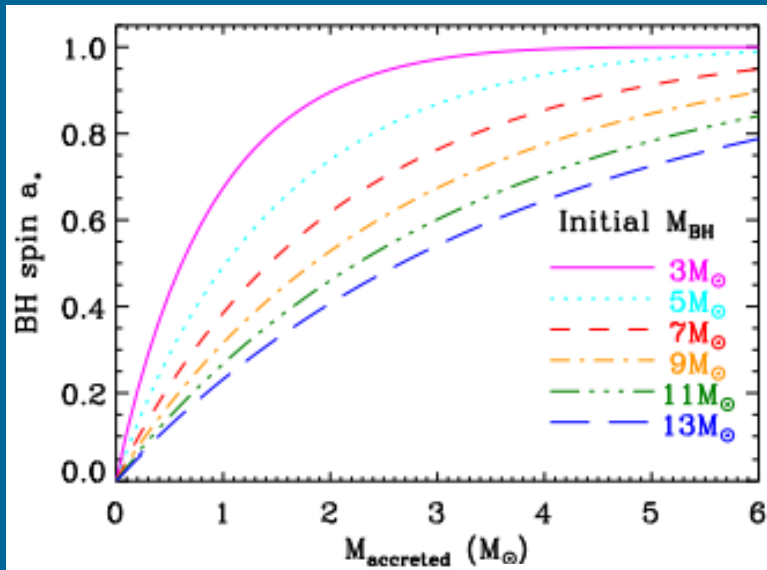


Spin is due to accretion.

BHs accrete (on average)
~1.5 solar mass

Source	MT Type ^b	P_{orb} (days) ^b	Spin a_*	Reference
GRS 1915+105	RLO	33.5	> 0.98	McClintock et al. (2006)
Cyg X-1	Wind	5.6	> 0.95	Gou et al. (2011)
LMC X-1	Wind	4.23	$0.92^{+0.05}_{-0.07}$	Gou et al. (2009)
M33 X-7	Wind	3.45	0.84 ± 0.05	Liu et al. (2008, 2010)
4U 1543-47	RLO	1.15	0.80 ± 0.05	Shafee et al. (2006)
GRO J1655-40	RLO	2.62	0.70 ± 0.05	Shafee et al. (2006)
XTE J1550-564	RLO	1.54	$0.34^{+0.20}_{-0.28}$	Steiner et al. (2011)
LMC X-3	RLO	1.7	$< 0.3^c$	Davis et al. (2006)
A0620-00	RLO	0.33	0.12 ± 0.18	Gou et al. (2010)

Spin (and mass) growth due to accretion



The hypothesis is that spin is gained due to accretion (at birth $a=0$).

QPO

BH candidates demonstrate two main types of QPOs:
Low-frequency (0.1-30 Hz) and high-frequency (40-450 Hz).

Low-frequency QPOs are found in 14 out of 18 objects.
They are observed during different states of sources.
Probably, in different states different mechanisms of QPO are working.

High-frequency QPOs are known in a smaller number of sources.
It is supposed that frequencies of these QPOs correspond to the ISCO.

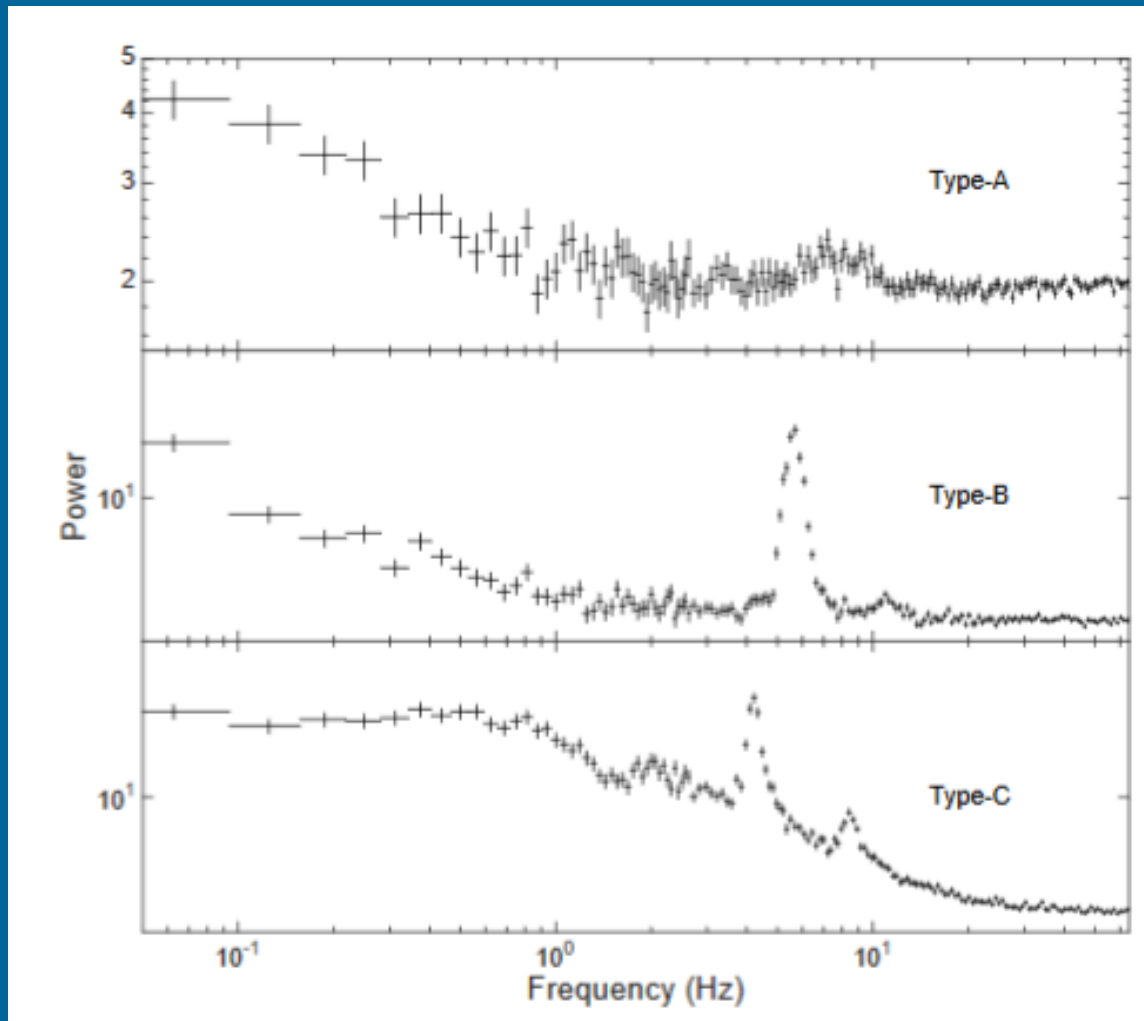
Recent reviews:

arXiv:1207.2311

High-Frequency Quasi-Periodic Oscillations in black-hole binaries
and 1603.07885

Different types of variability in BH sources are also discussed in 1407.7373
and 1603.07872

Low-frequency QPO

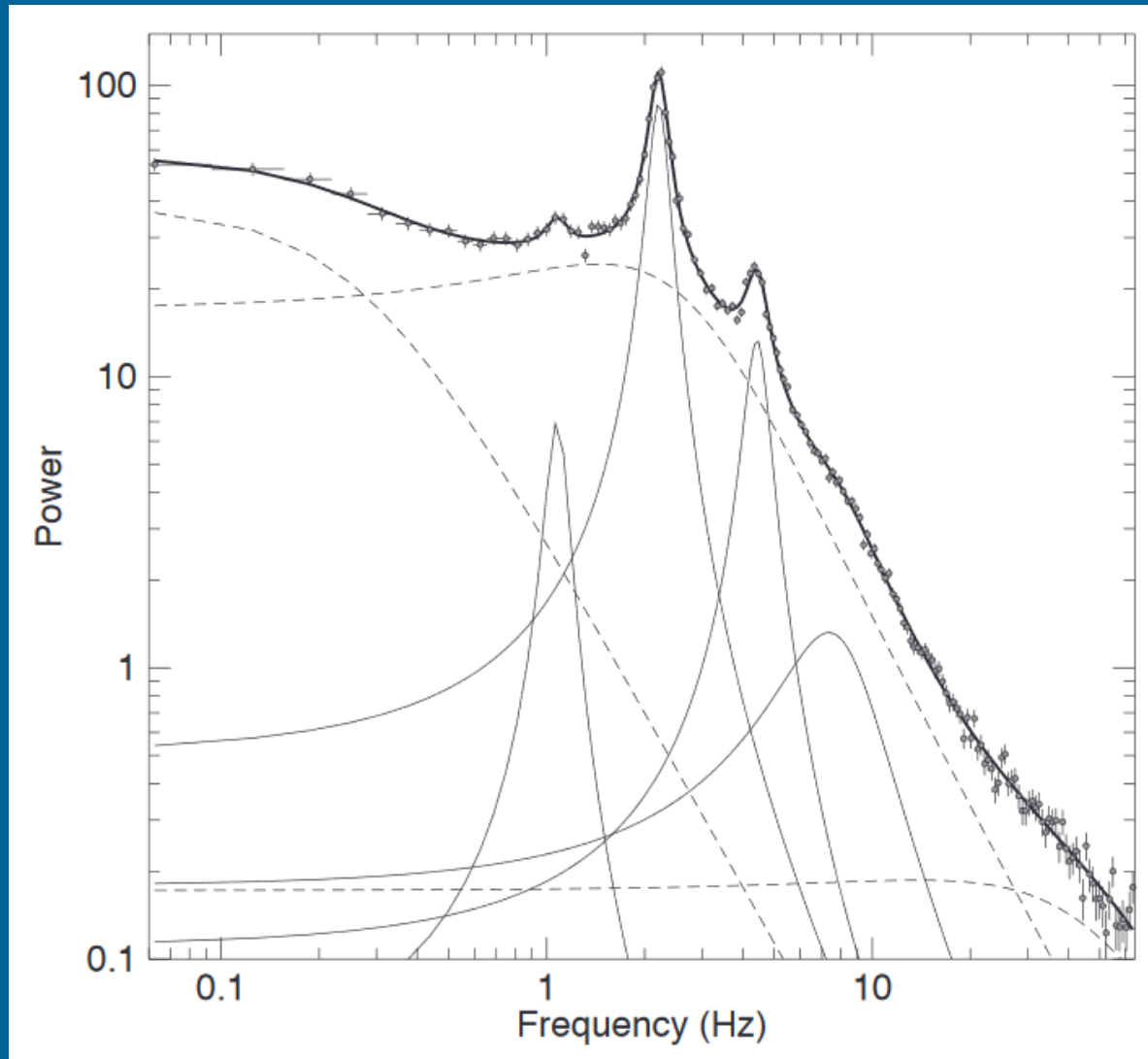


Disc instabilities ?

Jets?

Disc instabilities ?

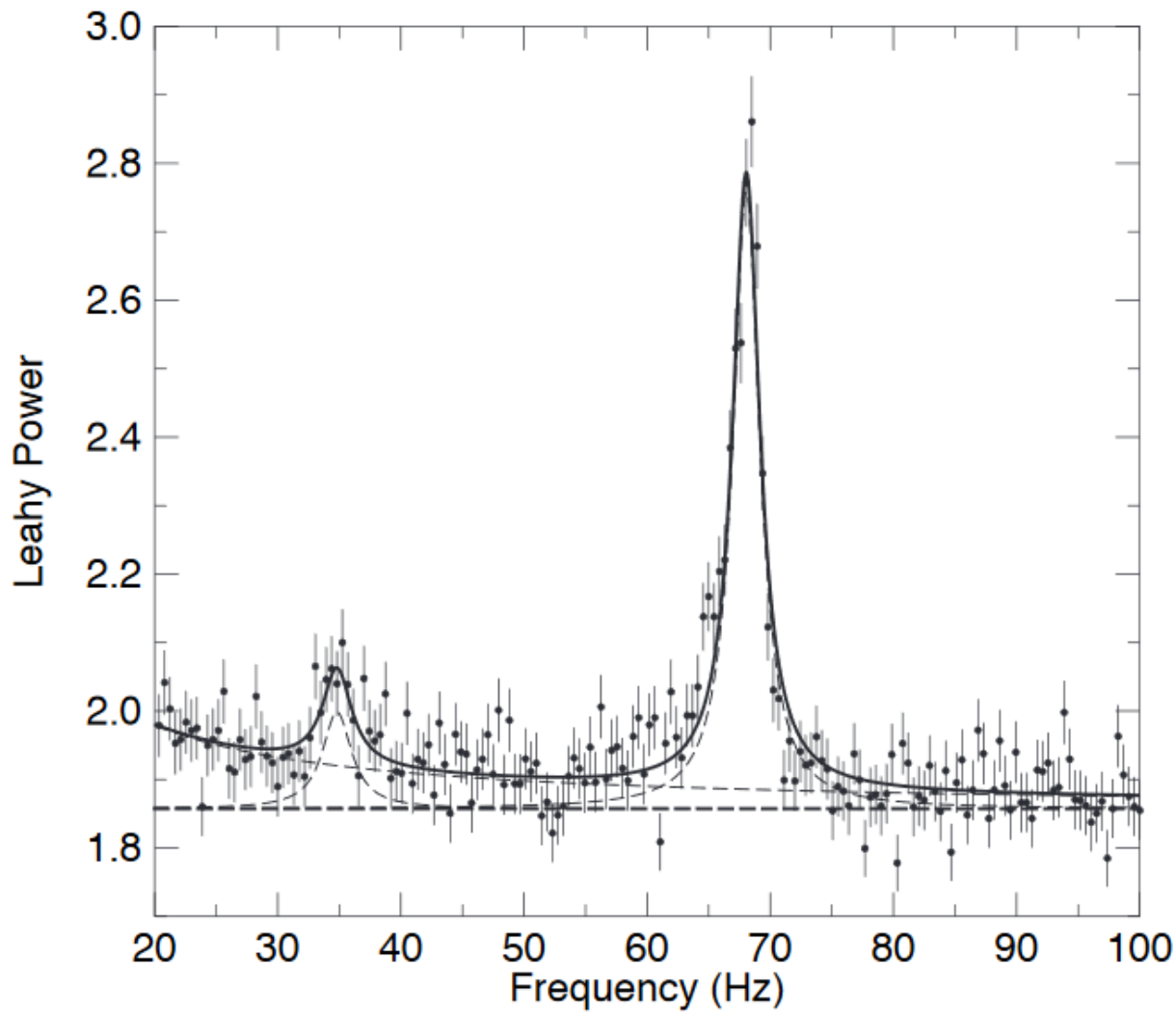
GRS 1915+105



Low-frequency QPO

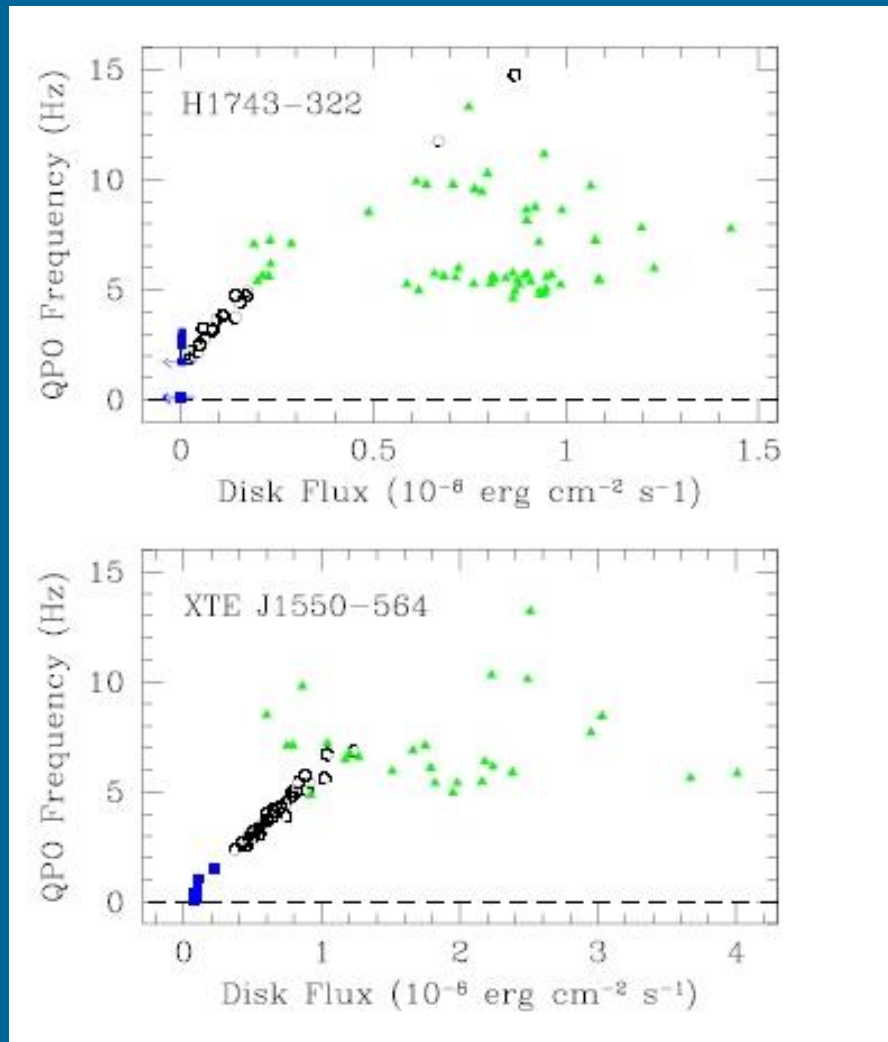
1902.06586

GRS 1915+105



High-frequency QPO

QPO and flux from a disc

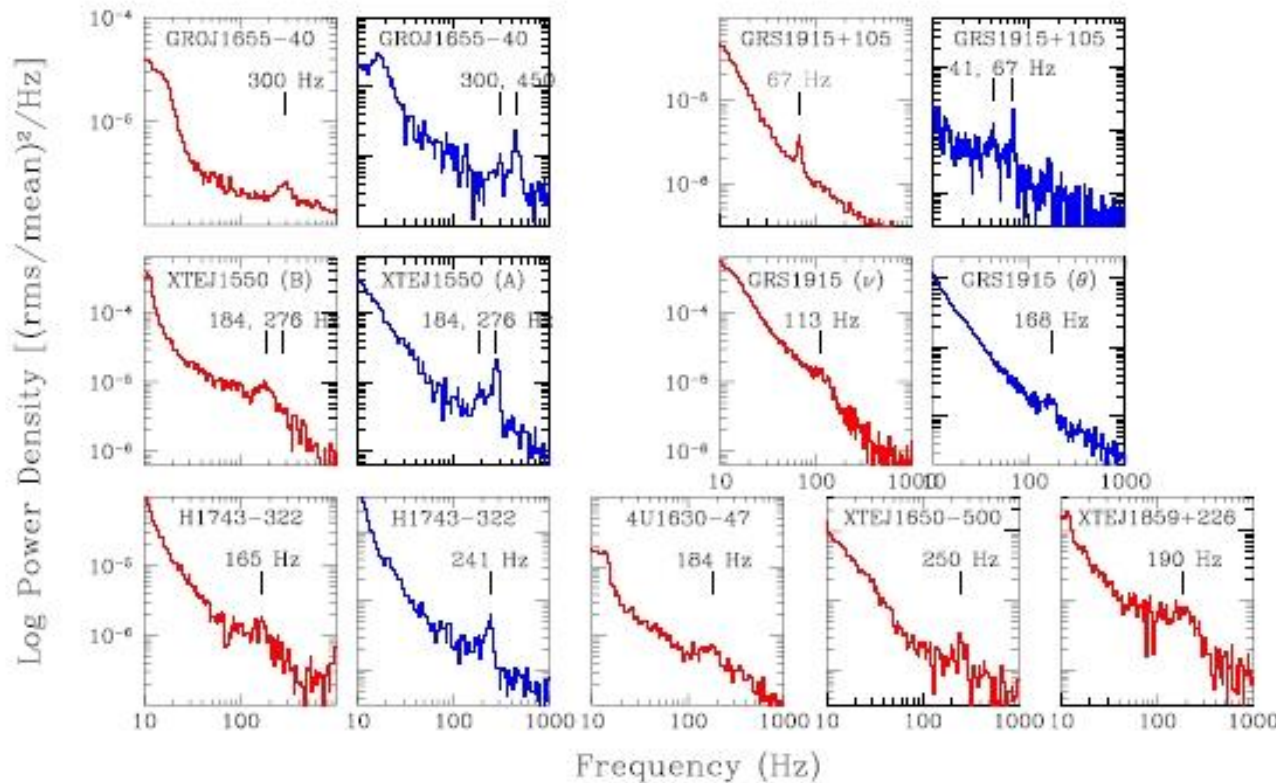


SPL – green triangles
Hard – blue squares
Intermediate states – black circles

Low-frequency QPOs
(their frequency and amplitude)
correlate with spectral parameters.

Probably, QPO mechanisms
in the hard state
and in the SPL state are different.

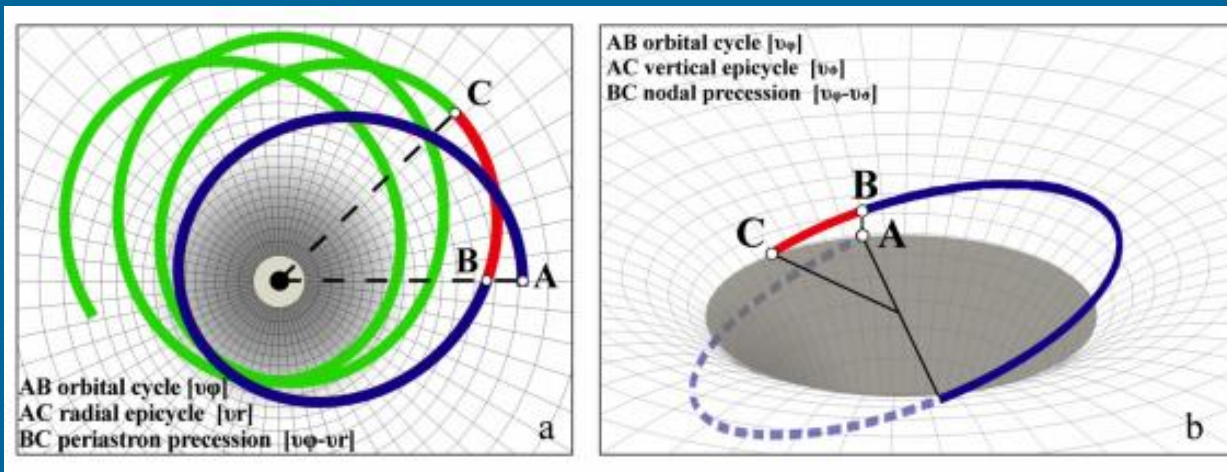
QPO at high (for BHs) frequency



All QPO at >100 Hz are observed only in the SPL state.

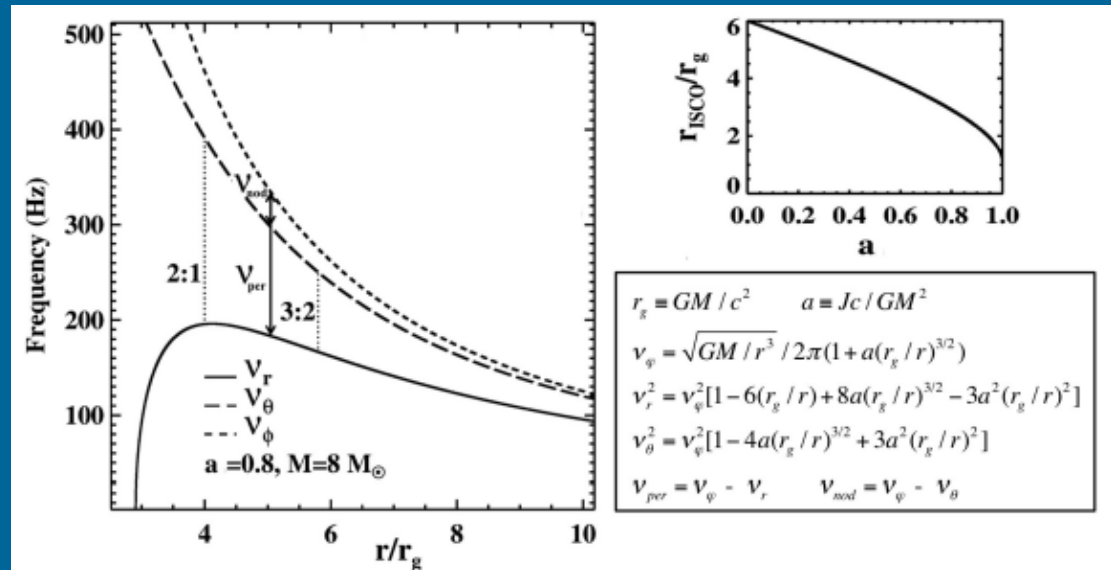
Blue curves: for the range 13-30 keV.
Red curves: for a wider range (towards lower energies).

Possible interpretations



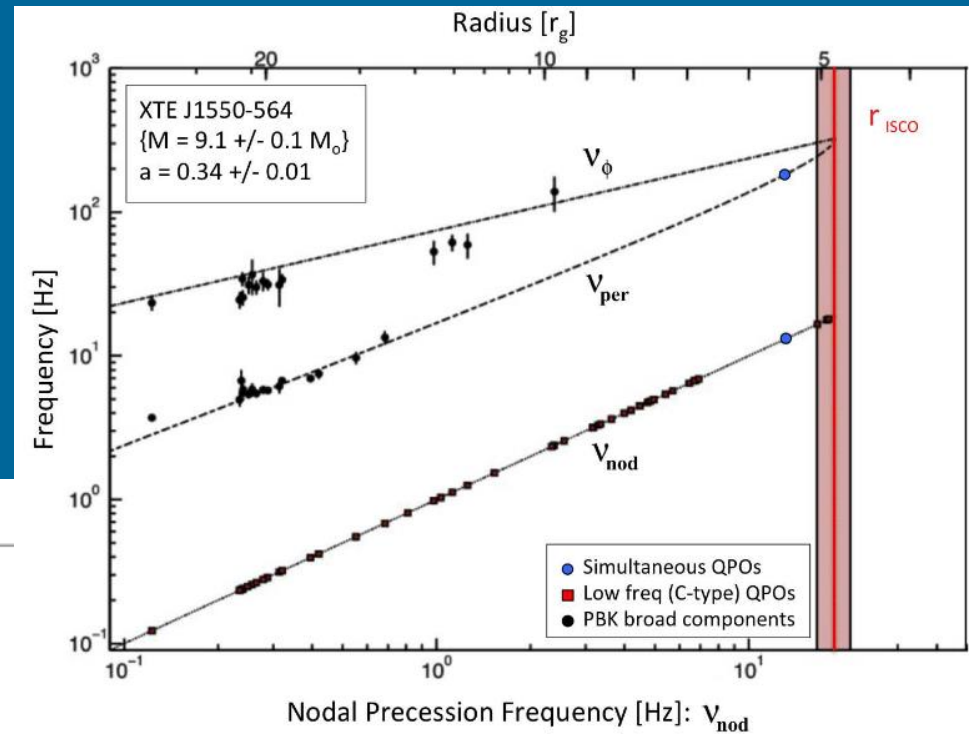
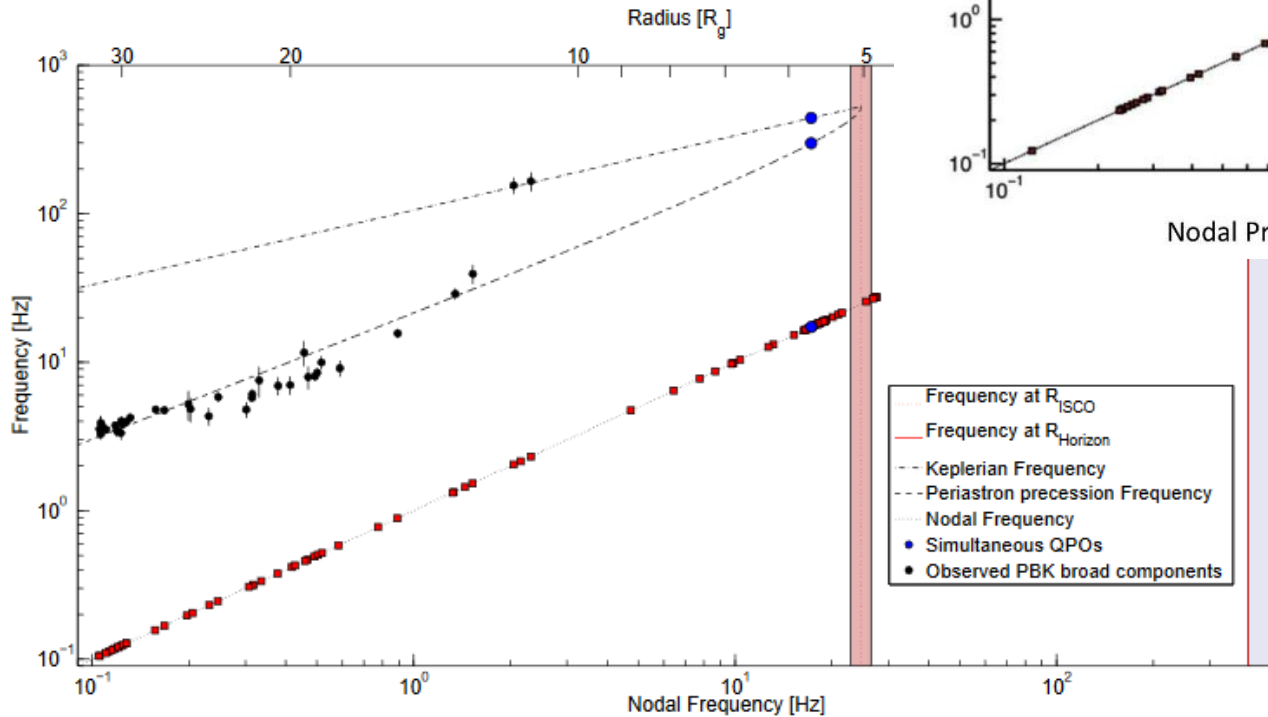
v_ϕ – Keplerian frequency
 v_r – radial epicyclic
 v_θ – vertical epicyclic

periastron precession
 frequency $v_\phi - v_r$
 nodal precession
 frequency $v_\phi - v_\theta$



Correlations

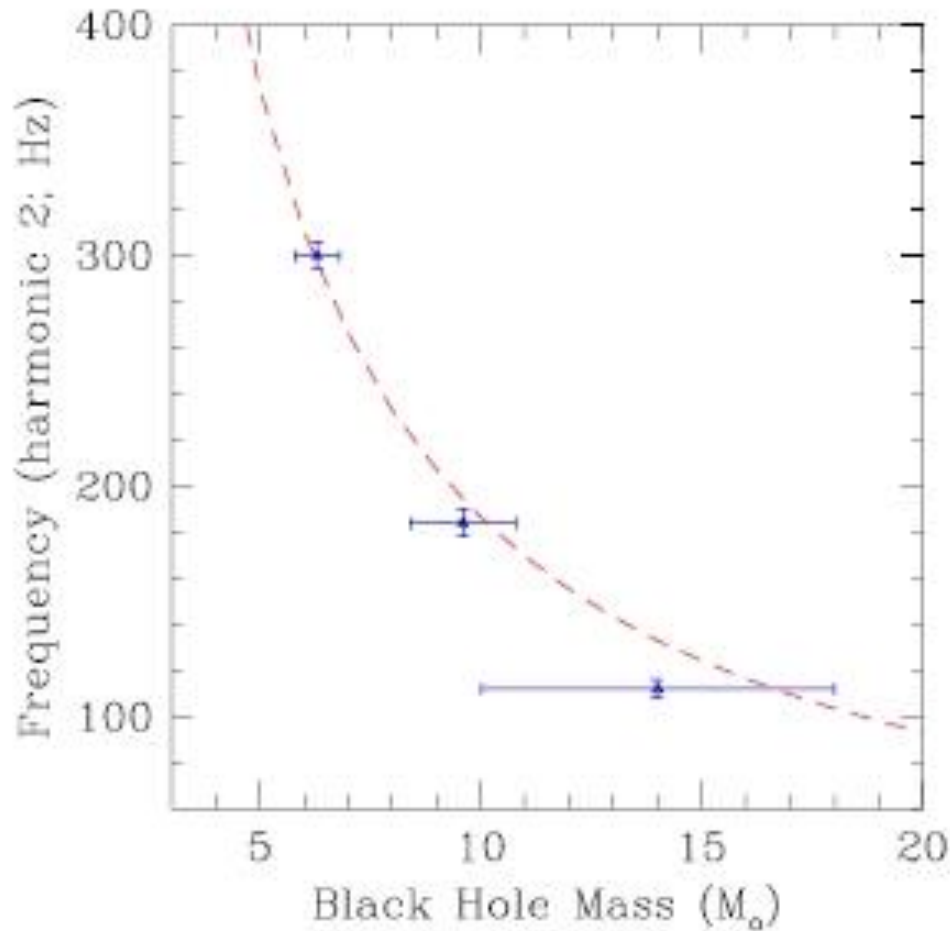
GRO J1655-40



GRO J1550-40

1902.06586

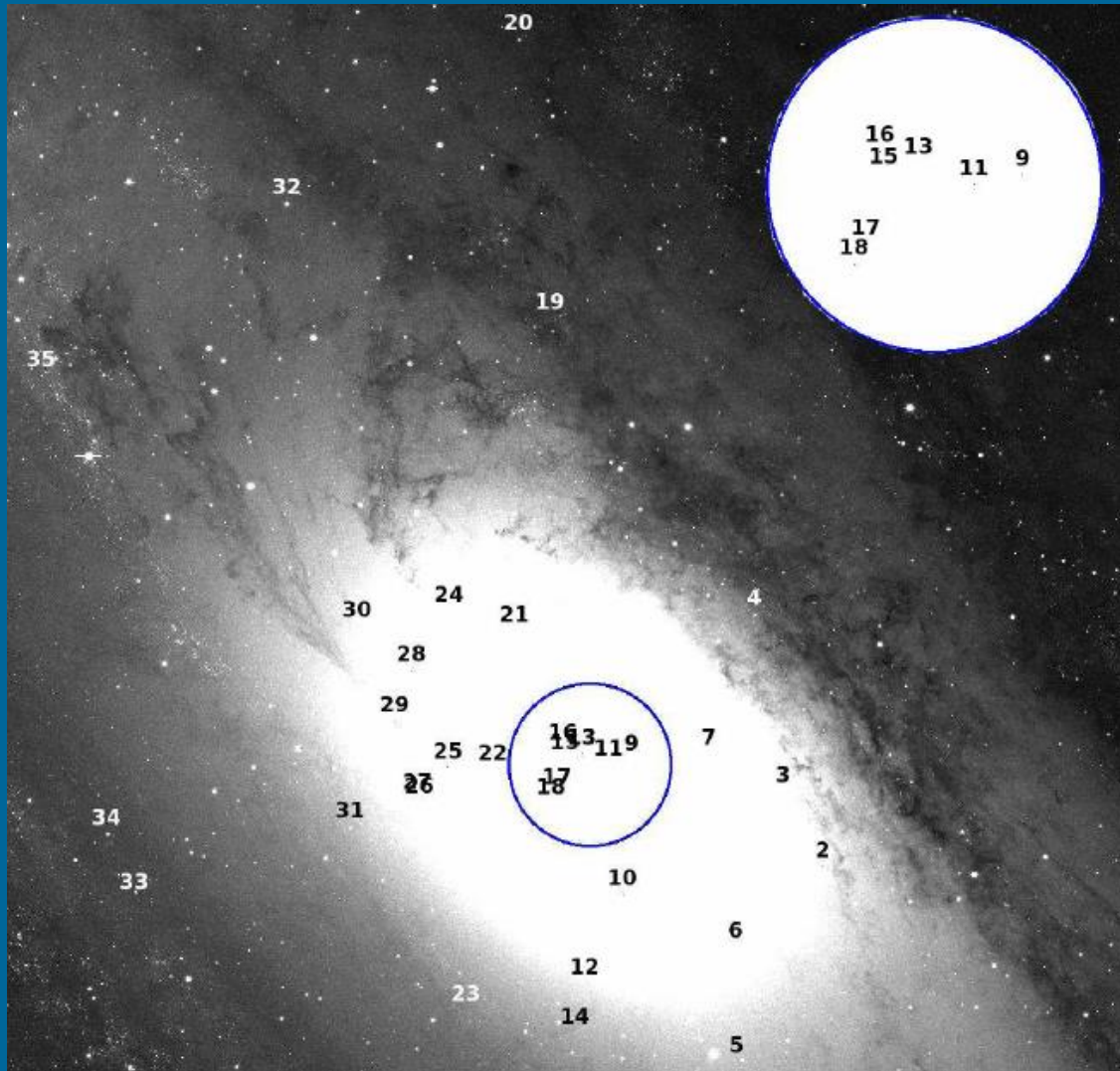
QPOs and BH masses



XTE J1550-564,
GRO J1655-40,
GRS 1915+105

Dashed line is plotted
for the relation
 $v_0 = 931 \text{ Hz } (M/M_{\odot})^{-1}$
The ordinate shows $2v_0$

Extragalactic BHs: the case of M31



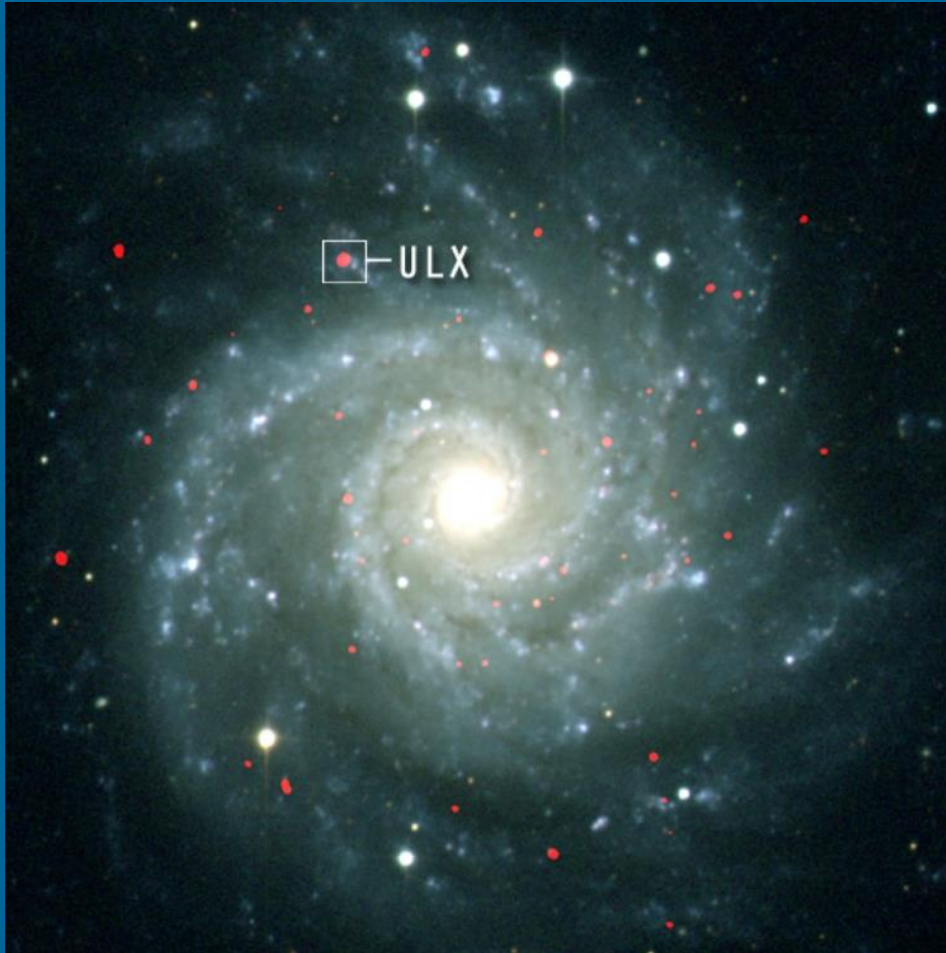
Chandra identification of 26 new black hole candidates in the central region of M31

50 BHCs in M31

Classification is mainly based on spectral properties.

Src	ID	$D_{M31}/''$	$L_{\text{Max}}^{\text{H}}$	Γ_{Max}	$L_{\text{Min}}^{\text{H}}$	Γ_{Min}	N_{O}	DC 1	DC 2	$\chi^2_{\text{con}}/\text{dof}$
S109	BH1	15.85	37 (5)	1.5 (3)	14.1 (17)	1.4 (3) ^a	P			230/76
S111	T1	6.24	18.3 (17)	2.0 (4)	<0.06	1.9 (5) ^a	2	0.04	0.06	234/79
S117	T2	5.11	53 (3)	4.9 (6)	<0.04	1.7	1	0.05	0.05	3957/99
S122	BH2	5.28	15 (2)	1.47 (7) ^a	1.73 (15)	1.47 (7) ^a	P			1527/164
S151	BH3	4.06	31 (2)	2.5 (5)	4.31 (17)	1.552 (15) ^a	P			28720/166
S159	BH4	4.63	5.5 (5)	1.89 (7) ^a	0.39 (0.10)	1.89 (7) ^a	P			3999/167
S167	BH5	6.85	7.9 (1.6)	1.5 (1) ^a	1.7 (2)	1.5 (1) ^a	P			568/157
S168	BH6	4.83	19.0 (18)	1.58 (3) ^a	0.6(2)	1.58 (3) ^a	P			5639/162
S179	BH7	2.49	21 (2)	2.7 (5)	4.9(13)	1.69 (3) ^a	P			669/168
S199	BH8	19	19 (3)	1.8 (4)	<0.4	1.37 (15) ^a	Many	0.33	0.33	664/26
S214	BH9	0.9	8.5 (4)	2.36 (16) ^a	0.05	2.36 (16) ^a	3	0.08	0.09	3482/94
S223	BH10	2.78	4.5(4)	1.64 (5) ^a	0.55(7)	1.64 (5) ^a	P			4983/167
S233	T5	0.66	9.8(13)	2.0 (5)	<0.04	1.7	2	0.02	0.06	317/100
S236	BH11	0.41	23(2)	1.41 (7) ^a	<0.05	1.41 (7) ^a	1 (turn off)	0.16	0.12	2319/95
S251	U2	9.2	320 (8)	3.9 (5)	<0.4	1.7	1	0.11	0.08	61651/69
S265	BH12	4.52	9.0(18)	2.5 (9)	1.5(2)	2.08 (4)	P			3701/167
S269	BH13	0.26	4.9(3)	1.78 (5) ^a	0.76(8)	1.78 (5) ^a	P			3625/170
S276	BH14	5.55	14 (2)	2.9 (7)	<0.05	2.6 (3) ^a	1	0.30	0.17	8381/98
S286	BH15	0.5	7.9 (9)	1.61 (4) ^a	1.2 (2)	1.61 (4) ^a	P			3472/170
S287		2.1	20.5 (5)	3.67 (13)	0.07(2)	1.7	1	0.05	0.03	82/92
S289	BH16	0.62	26.3 (6)	1.58 (3) ^a	0.6 (2)	1.58 (3) ^a	P			16817/164
S293	B128	4.96	5.9 (5)	1.64 (10) ^a	<0.03	1.64 (10) ^a	2	0.14	0.13	2348/87
S297	BH17	0.89	8.0 (3)	1.91 (4) ^a	0.73 (14)	1.91 (4) ^a	P			4602/170
S299	BH18	1.12	20 (2)	1.50 (2) ²	6.8 (8)	1.8 (3)	P			842/170
S300	BH19	9.26	21 (3)	1.9 (6)	0.75(18)	1.84 (5) ^a	P			9096/127
S322		1.62	13 (2)	2.5 (6)	<0.04	1.7	1	0.02	0.04	227/72
S327	BH20	15.1	62 (3)	1.14 (14)	30 (2)	1.89 (2) ^a	P			587/73
S330	T8	8.4	2.7 (4)	2.10 (17) ^a	<0.06	2.10 (17) ^a	1 (turn on)	0.73	0.79	2941/158
S331	T13	1.6	6.1 (6)	4.02 (17)	<0.0016	1.7	1	0.018	0.05	171/45
S335	BH21	3.2	20.6(17)	1.9 (4)	5.6 (4)	1.7	P			441/108
S339	T9 / U1	2.4	394 (2)	?	<0.025	1.74 (2) ^a	1	0.06	0.04	37255/89
S345	BH22	2	23 (2)	1.70 (5) ^a	0.82 (18)	1.7	P			5782/108
S353		3.5	5.8 (15)	1.6 (3) ^a	<0.05	1.70 (5) ^a	5	0.20	0.21	1984/112
S358	BH23	5.7	8.9(13)	2.5 (6)	<0.18	1.6 (3) ^a	P			651/167
S365		2.8	14(2)	2.9 (9)	<0.009	1.78 (4)	1	0.06	0.04	503/60
S372	BH24	4.3	7.2(13)	1.8 (4)	2.8(3)	2.37 (19) ^a	P			801/168
S373	BH25	2.9	7.2 (11)	1.9 (6)	3.1(9)	1.78 (8)	P			406/107
S386	BH26	3.6	8.2 (13)	1.84 (5) ^a	1.3 (2)	1.4 (3)	P			5245/170
S389	BH27	3.6	13.0 (18)	2.01 (5) ^a	0.37 (9)	1.84 (5) ^a	P			14549/170
S391	BH28	4.2	7.7 (3)	1.69 (4) ^a	1.8 (2)	2.1 (5)	P			2885/169
S396	BH29	4.1	46.8 (5)	1.46 (8) ^a	<0.07	1.69 (4) ^a	1	0.05	0.05	20445/99
S411	BH30	5.6	12 (2)	1.9 (6)	<0.16	1.46 (8) ^a	Many	0.26	0.42	2667/145
S415	BH31	5.1	20 (3)	1.6 (3)	7.5 (14)	1.9 (2) ^a	P			511/102
S438	BH32	13.2	14.2 (12)	1.6 (2)	<0.007	1.47 (2) ^a	3	0.70	0.13	3195/76
S448		6.9	97 (6)	3.8 (4)	<0.04	1.58 (2) ^a	2	0.06	0.10	3198/89
S484	BH33	9.8	10 (3)	1.94 (6) ^a	1.4 (2)	1.7	P			1450/111
S487	BH34	10.1	10.2 (13)	1.9 (5)	3.3 (11)	1.94 (6) ^a	P			100/39
S497	BH35	13.9	12.8 (15)	1.7 (4)	1.07 (16)	1.49 (5) ^a	P			2578/78

Ultraluminous X-ray sources



ULXs are sources with fluxes which correspond to an isotropic luminosity larger than the Eddington limit for a 10 solar mass object.

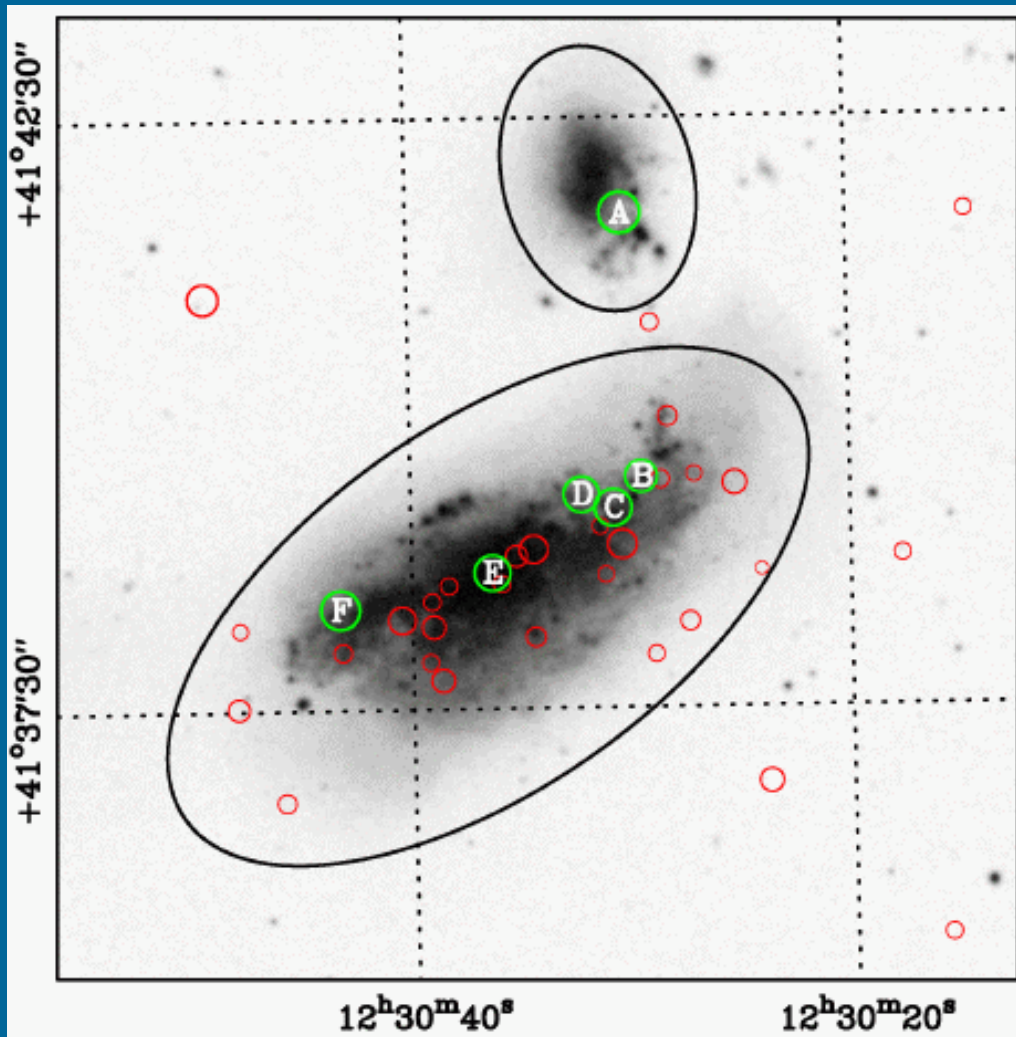
Now many sources of this type are known. Their nature is unclear. Probably, the population contains both: stellar mass BHs with anisotropic emission and intermediate mass BHs.

Recent reviews:

1702.05508 - short

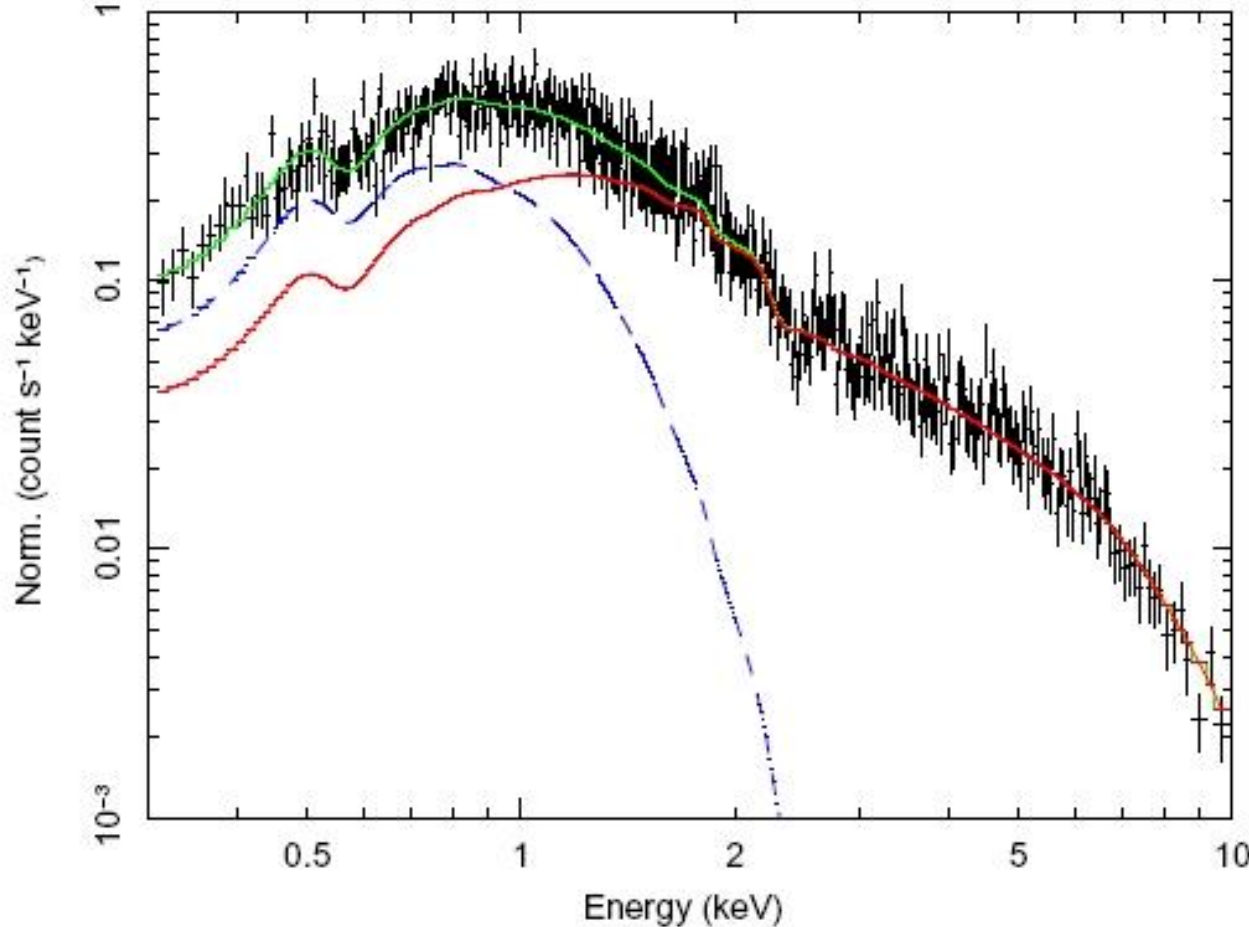
1703.10728 - long

ULXs in NGC 4490 and 4485



Six marked sources are ULXs

Spectrum of the ULX in NGC 1313



NGC 1313 X-1

Green line –
the IMBH model.

Red – power-law.

Blue – multi-color disc.

ULX in galaxies of different types

In the following two slides there are images of several galaxies from the SDSS in which positions of ULXs are marked.

Crosses (x) mark sources with luminosities $>10^{39}$ erg/s.

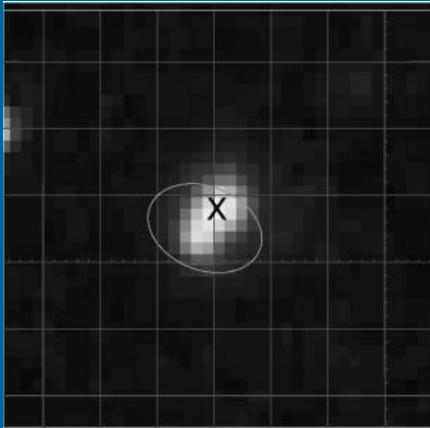
Pluses (+) mark sources with luminosities $>5 \cdot 10^{38}$ erg/s.

The size of one square element of the grid is 1.2 arcminute (except IZW 18, in which case the size is 0.24 arcminute in right ascension and 0.18 in declination).

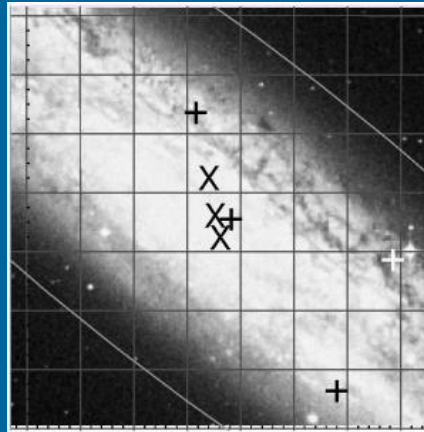
Galaxies NGC 4636, NGC 1132, NGC 4697, NGC 1399 are ellipticals, IZW 18 – irregular, the rest are spiral galaxies.

Ellipses mark the 25-th magnitude isophotes (this a typical way to mark the size of a galaxy).

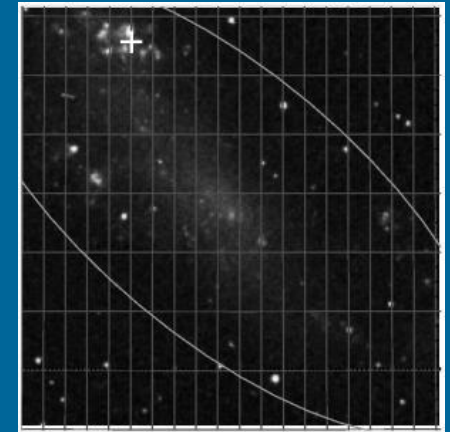
ULX in galaxies of different types



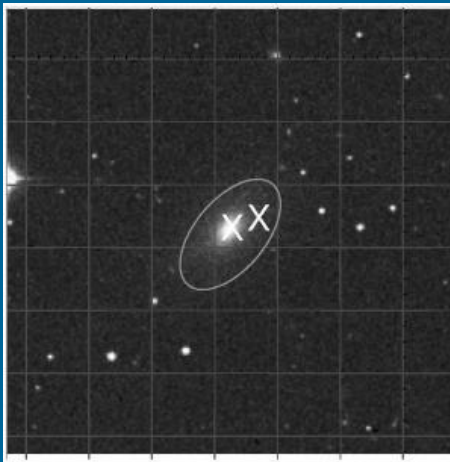
IZW 18



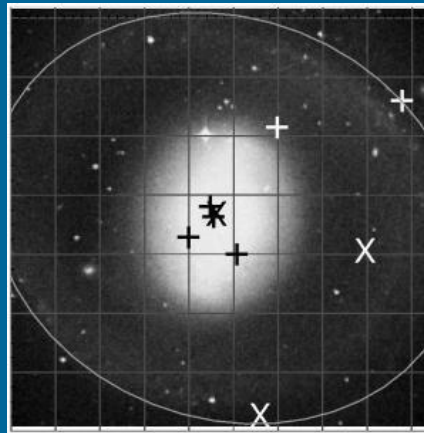
NGC 253



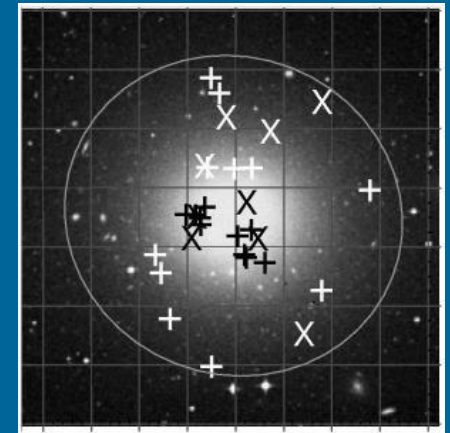
IC 2574



NGC 1132

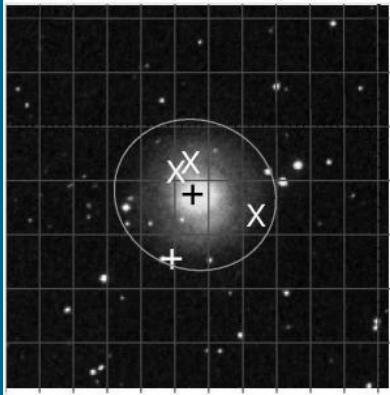


NGC 1291

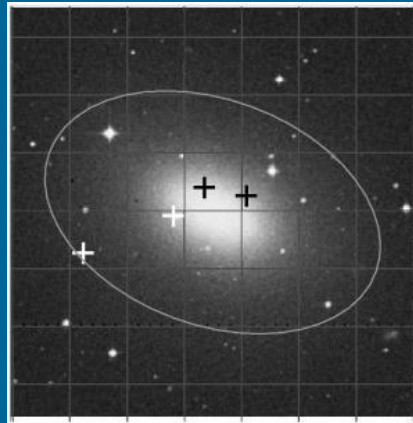


NGC 1399

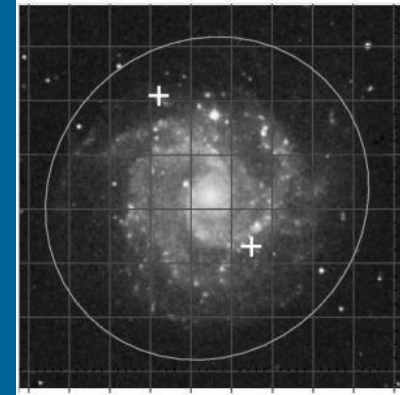
ULX in galaxies of different types



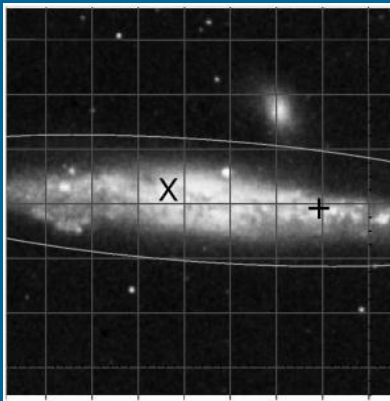
NGC 2681



NGC 4697

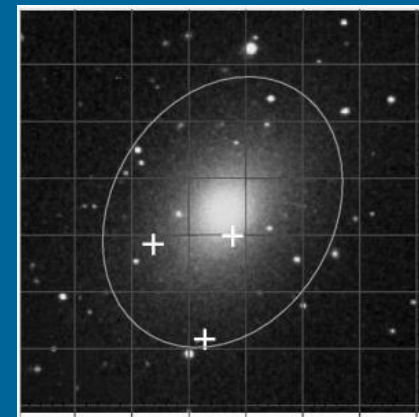


NGC 3184



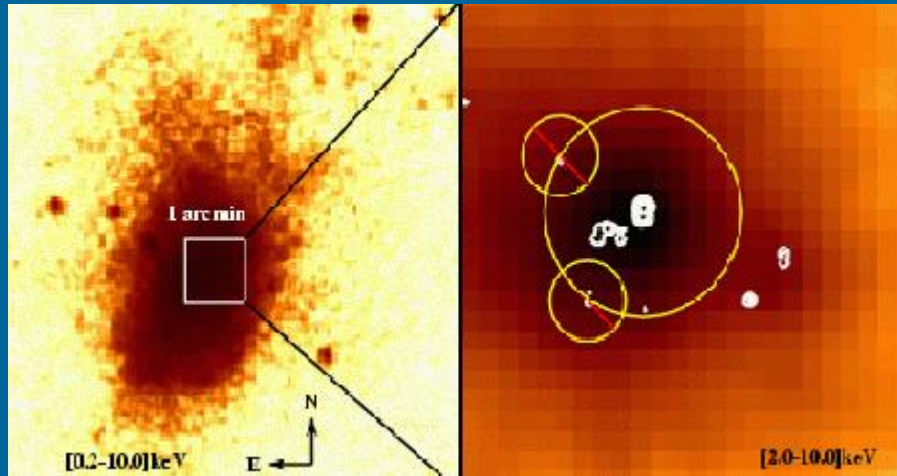
NGC 4631

Large sample of
host galaxies for ULX:
1108.1372



NGC 4636

The source X-1 in M82



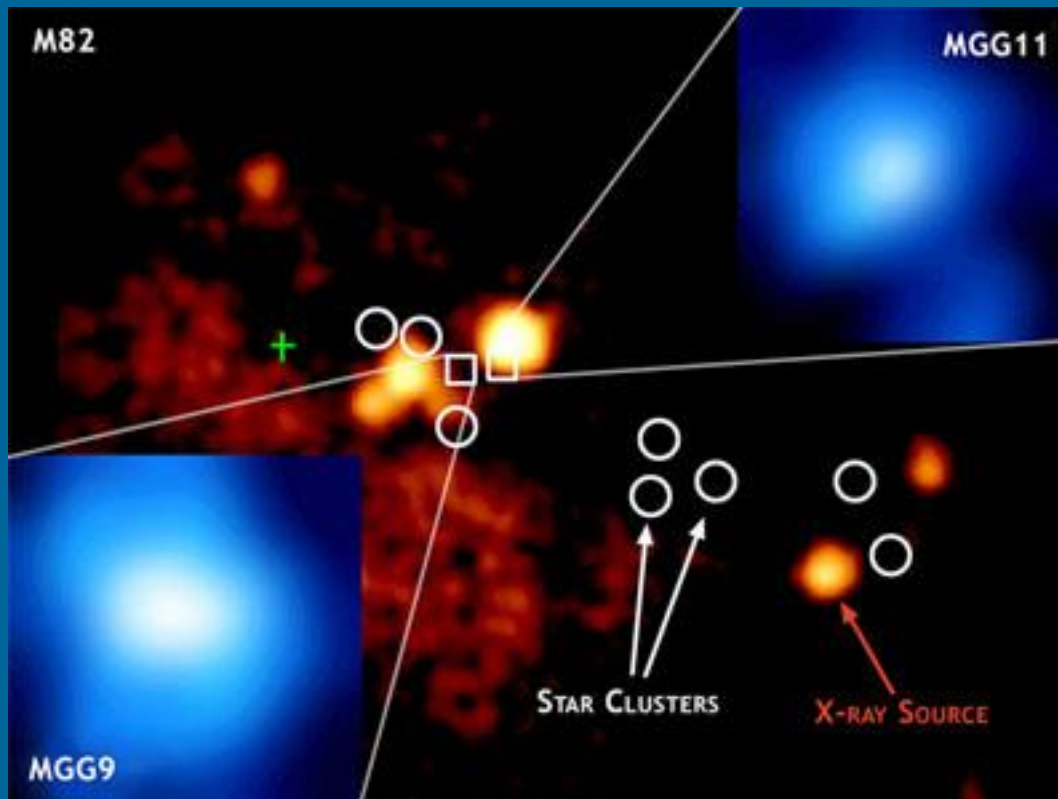
The source M82 X-1 is one of the most luminous, and so it is the best candidate to be an intermediate mass BH.

QPOs are observed in this source. Their properties support the hypothesis of an intermediate mass BH.

QPO was recently detected (1309.6101).
Scaling points to masses 10^4 - 10^5 solar masses.

Pasham et al. (2014) estimated the mass to be 400 Msolar
Nature **513**, 74–76 (04 September 2014)

M82, stellar clusters and ULXs



Intermediate mass BHs can be formed in dense stellar clusters.

See, however, 0710.1181 where the authors show that for solar metallicity even very massive stars most probably cannot produce BHs massive enough.

McCrady et al (2003)

<http://www.nature.com/nature/journal/v428/n6984/full/nature02448.html>

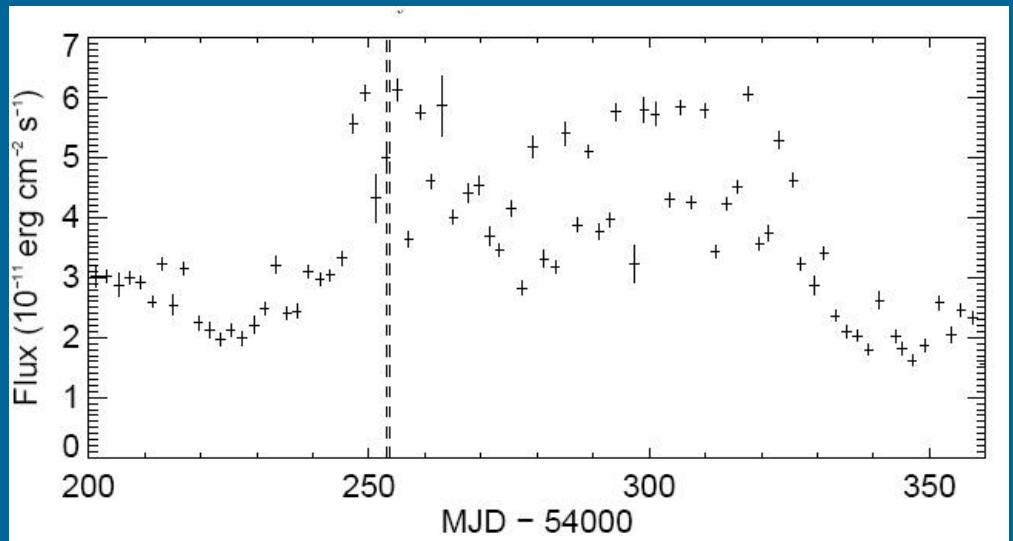
X41.4+60 in M82

79-day burst. Isotropic luminosity $\sim 5 \cdot 10^{40}$ erg/s

Hard state. Usually $L \sim 0.3 L_{\text{edd}}$, here there are indications (photon index $\Gamma = 1.6$) that it is even $\sim 0.1 L_{\text{edd}}$.

QPOs.

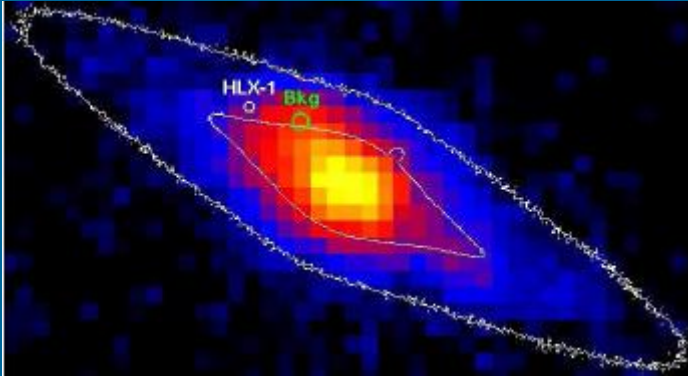
Altogether: mass $\sim$ few 1000 Solar.



RXTE + Chandra observations

(Kaaret et al. 0810.5134)

The most luminous ULX: HLX-1 in the galaxy ESO 243-49,

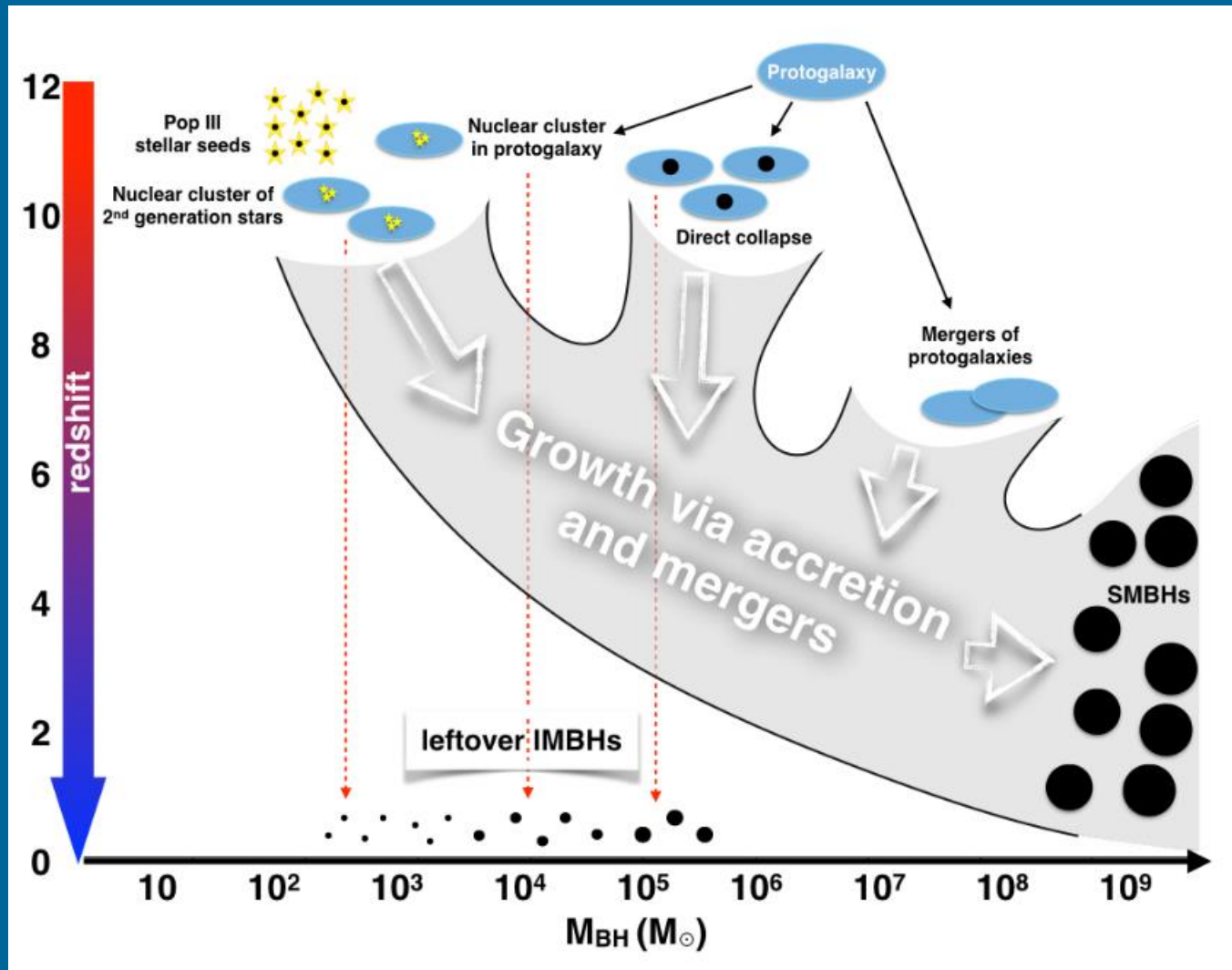


$L > 10^{42}$ erg/s
 $M \sim 500 M_{\odot}$

1011.1254, 1104.2614

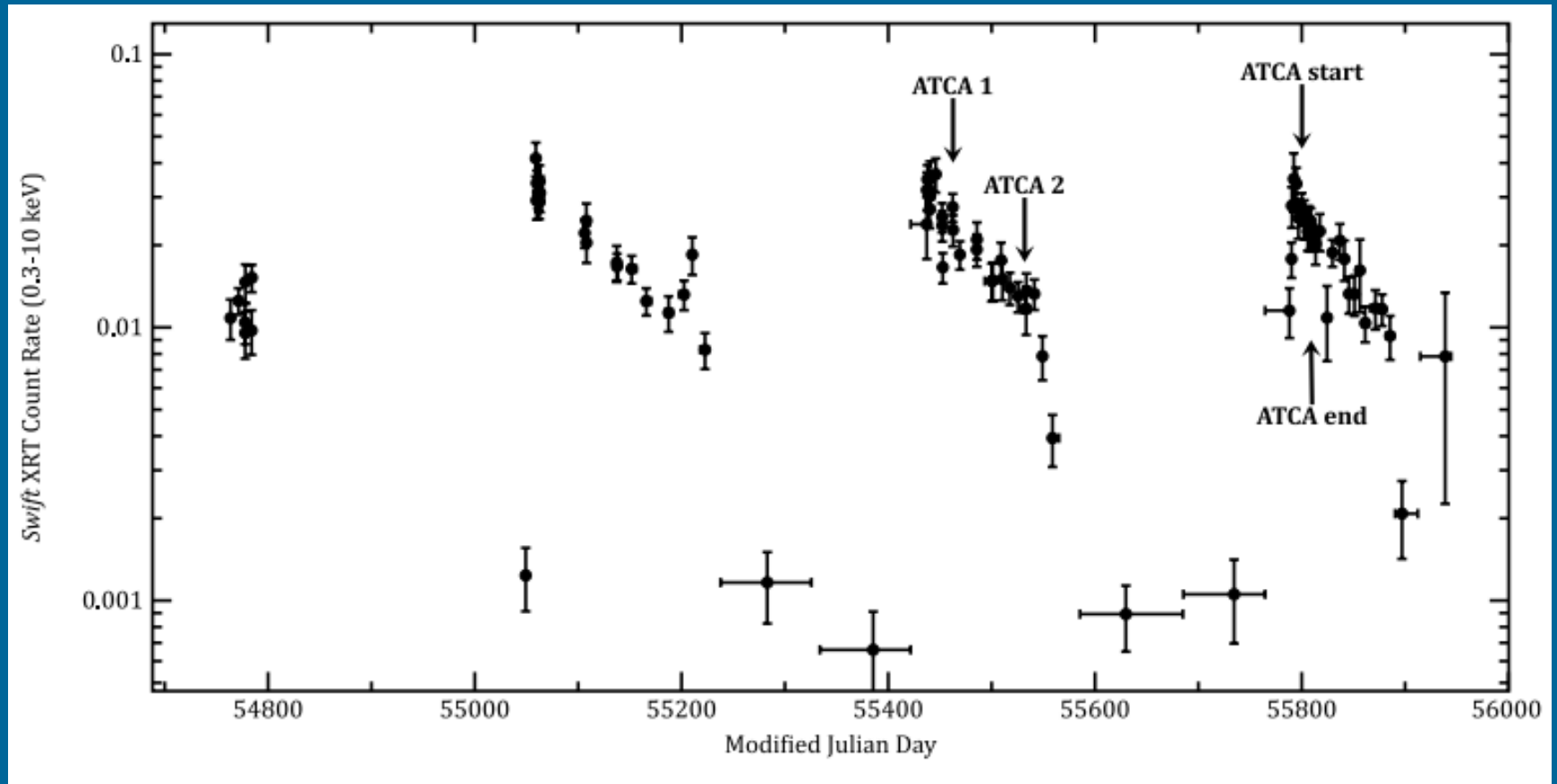
New data about this source: 1108.4405; 1203.4237; 1210.4169; 1210.4924

Origin of IMBHs



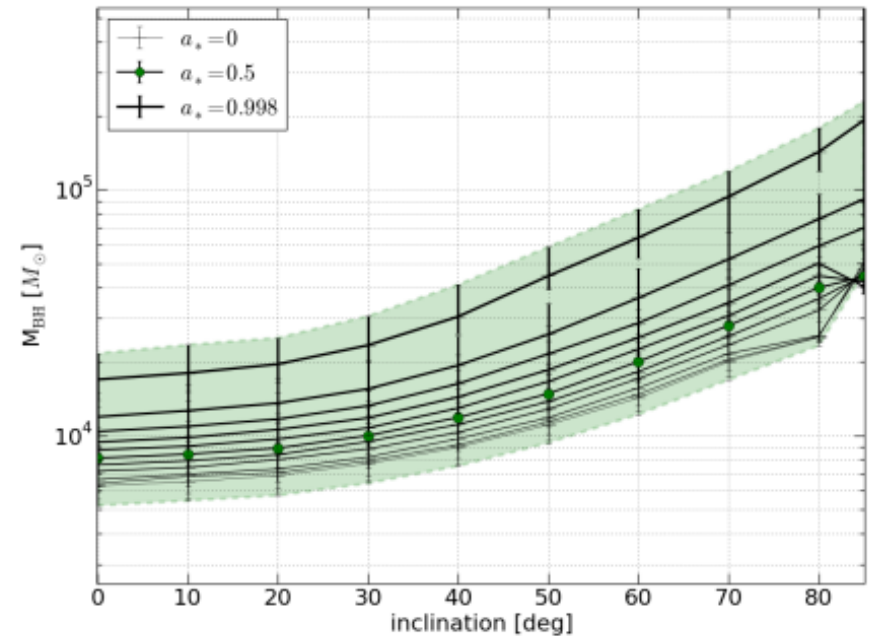
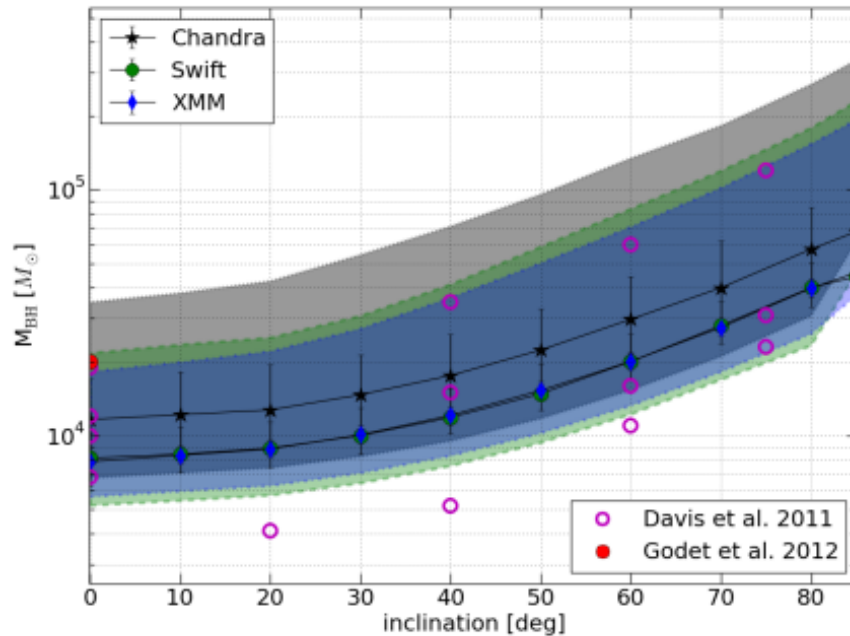
State transitions in ESO 243-49 HLX-1

Mass is estimated to be 10^4 - 10^5 Msolar



More mass estimates for HLX-1

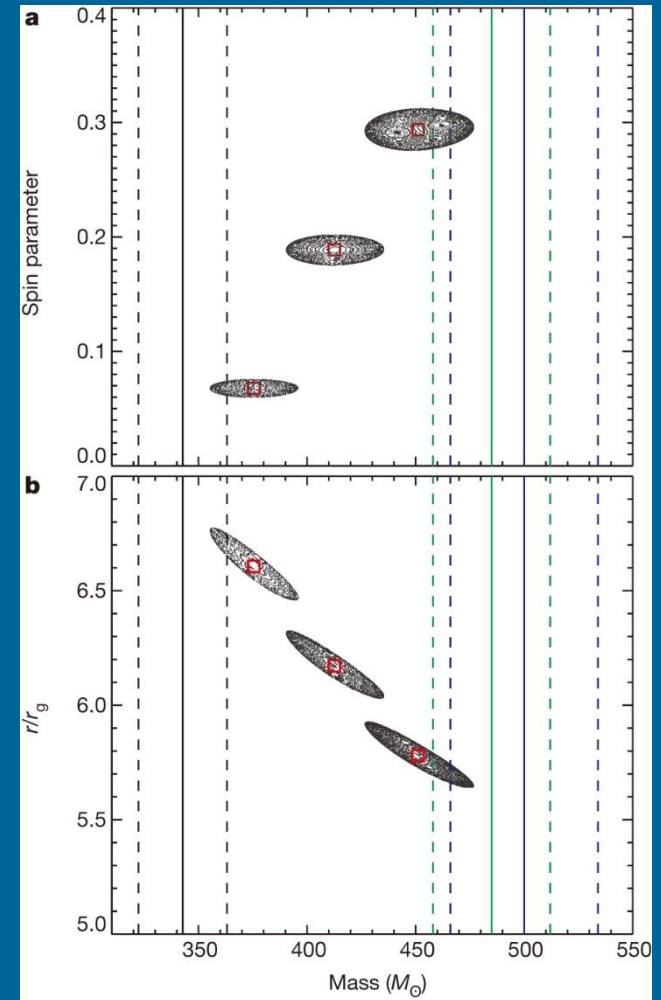
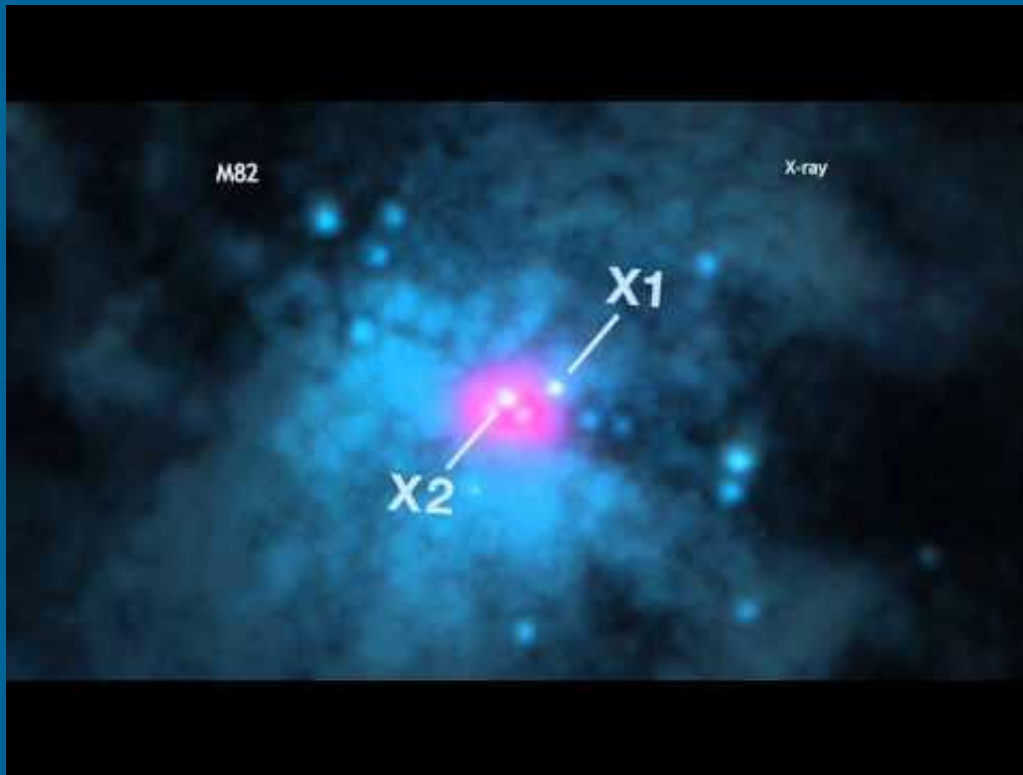
Taking into account all uncertainties the mass is still large



Accretion model for this source was presented in 1402.4863

Heavy BH in M82

Pasham et al. (Nature 2014)
дают оценку массы для X-1
около 400 масс Солнца.



IMBH in an ULXs

For the first time for one source there are both – spectral and timing – data showing evidence in favor of an IMBH.

$$M_{\text{BH}} \sim 10^3 - 10^4 M_{\text{solar}}$$

Evidence for an Intermediate Mass Black Hole in NGC 5408 X-1

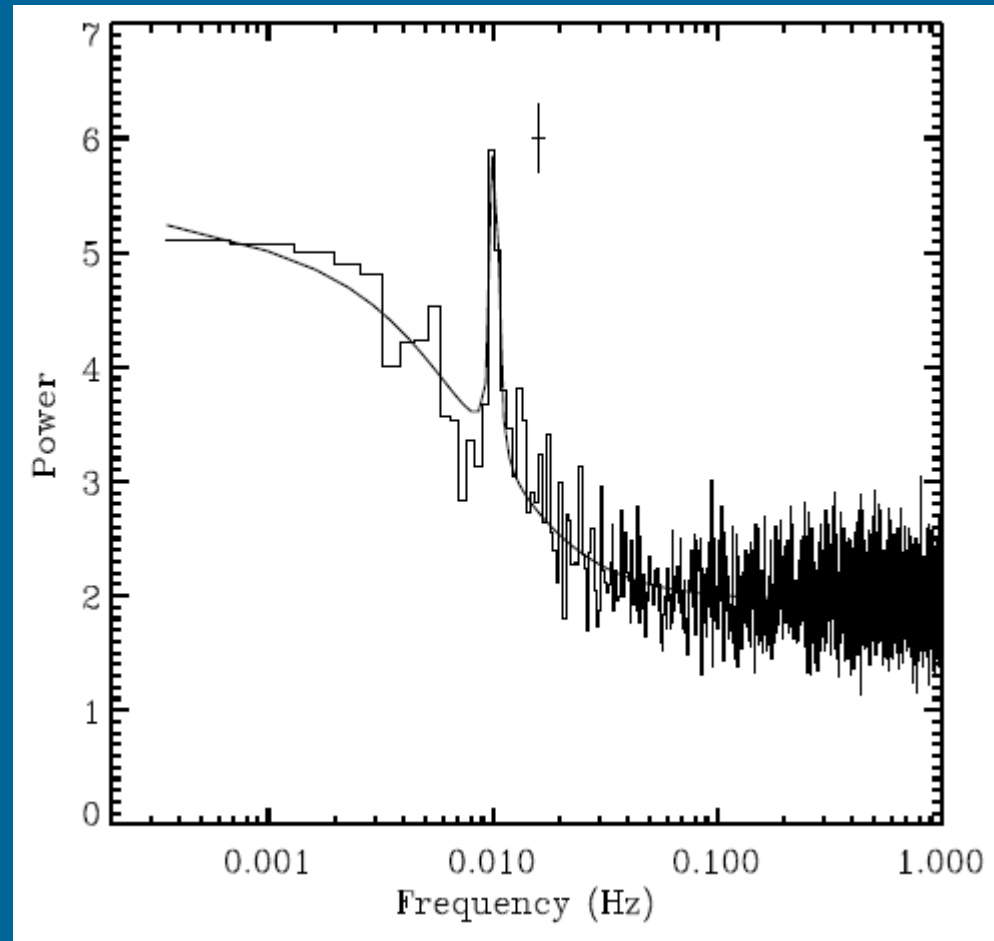
Tod E. Strohmayer¹ & Richard F. Mushotzky¹

ABSTRACT

We report the discovery with XMM-Newton of correlated spectral and timing behavior in the ultraluminous X-ray source (ULX) NGC 5408 X-1. An ≈ 100 ksec pointing with XMM/Newton obtained in January, 2008 reveals a strong 10 mHz QPO in the > 1 keV flux, as well as flat-topped, band limited noise breaking to a power law. The energy spectrum is again dominated by two components, a 0.16 keV thermal disk and a power-law with an index of ≈ 2.5 . These new measurements, combined with results from our previous January 2006 pointing in which we first detected QPOs, show for the first time in a ULX a pattern of spectral and temporal correlations strongly analogous to that seen in Galactic black hole sources, but at much higher X-ray luminosity and longer characteristic time-scales. We find that the QPO frequency is proportional to the inferred disk flux, while the QPO and broad-band noise amplitude (root mean squared, rms) are inversely proportional to the disk flux. Assuming that QPO frequency scales inversely with black hole mass at a given power-law spectral index we derive mass estimates using the observed QPO frequency - spectral index relations from five stellar-mass black hole systems with dynamical mass constraints. The results from all sources are consistent with a mass range for NGC 5408 X-1 from 1000 - 9000 $M_{\odot}$. We argue that these are conservative limits, and a more likely range is from 2000 - 5000 $M_{\odot}$. Moreover, the recent relation from Gierlinski et al. that relates black hole mass to the strength of variability at high frequencies (above the break in the power spectrum) is also indicative of such a high mass for NGC 5408 X-1. Importantly, none of the above estimates appears consistent with a black hole mass less than $\approx 1000 M_{\odot}$ for NGC 5408 X-1. We argue that these new findings strongly support the conclusion that NGC 5408 X-1 harbors an intermediate mass black hole.

Low-frequency QPO (2008 data)

NGC 5408 X-1 behaves very much like a Galactic stellar-mass BH system with the exception that its characteristic X-ray time-scales are 100 times longer, and its luminosity is greater by a roughly similar factor.

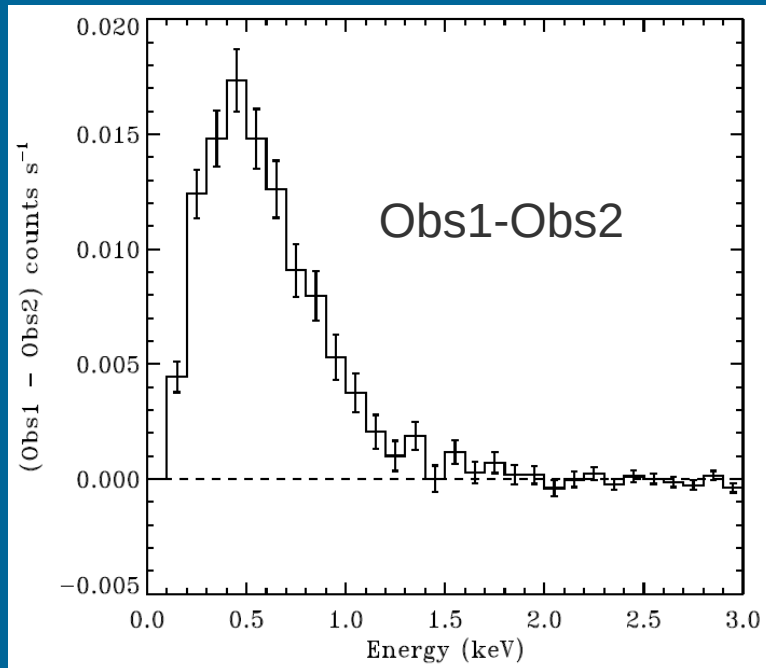


E>1 keV

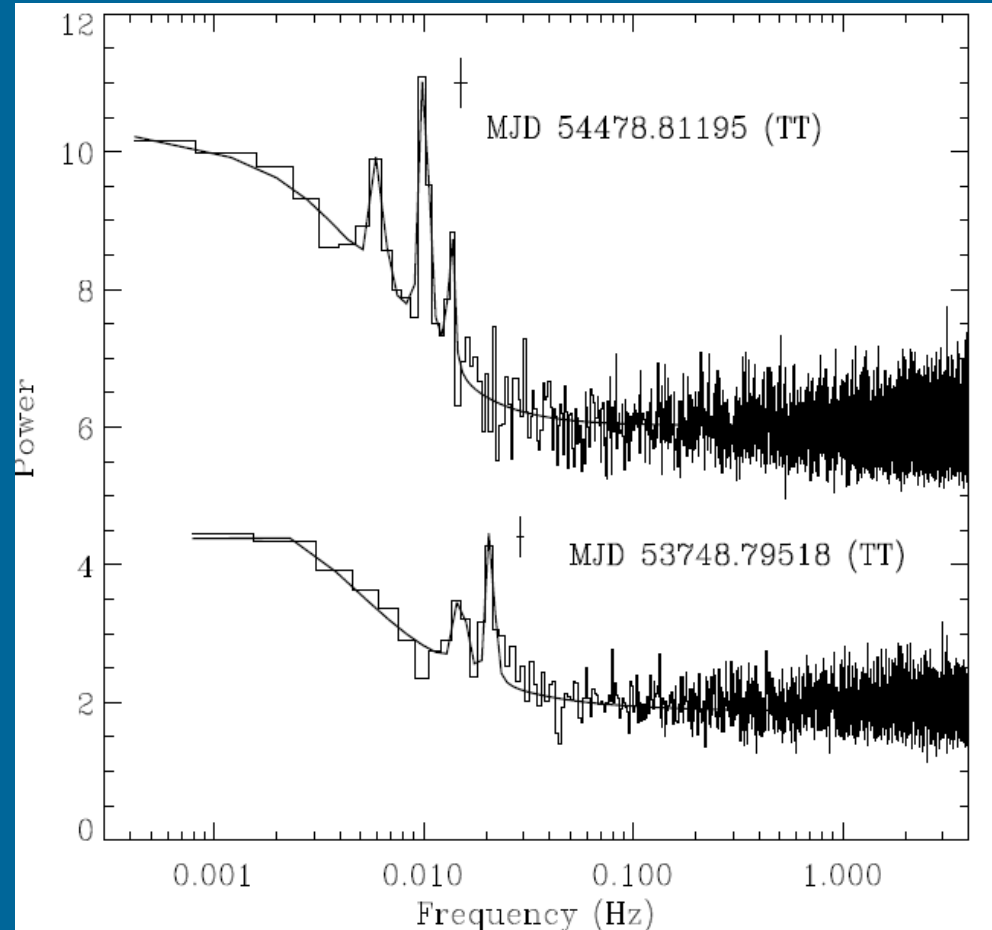
Comparison of two observations

Obs1 – 2006

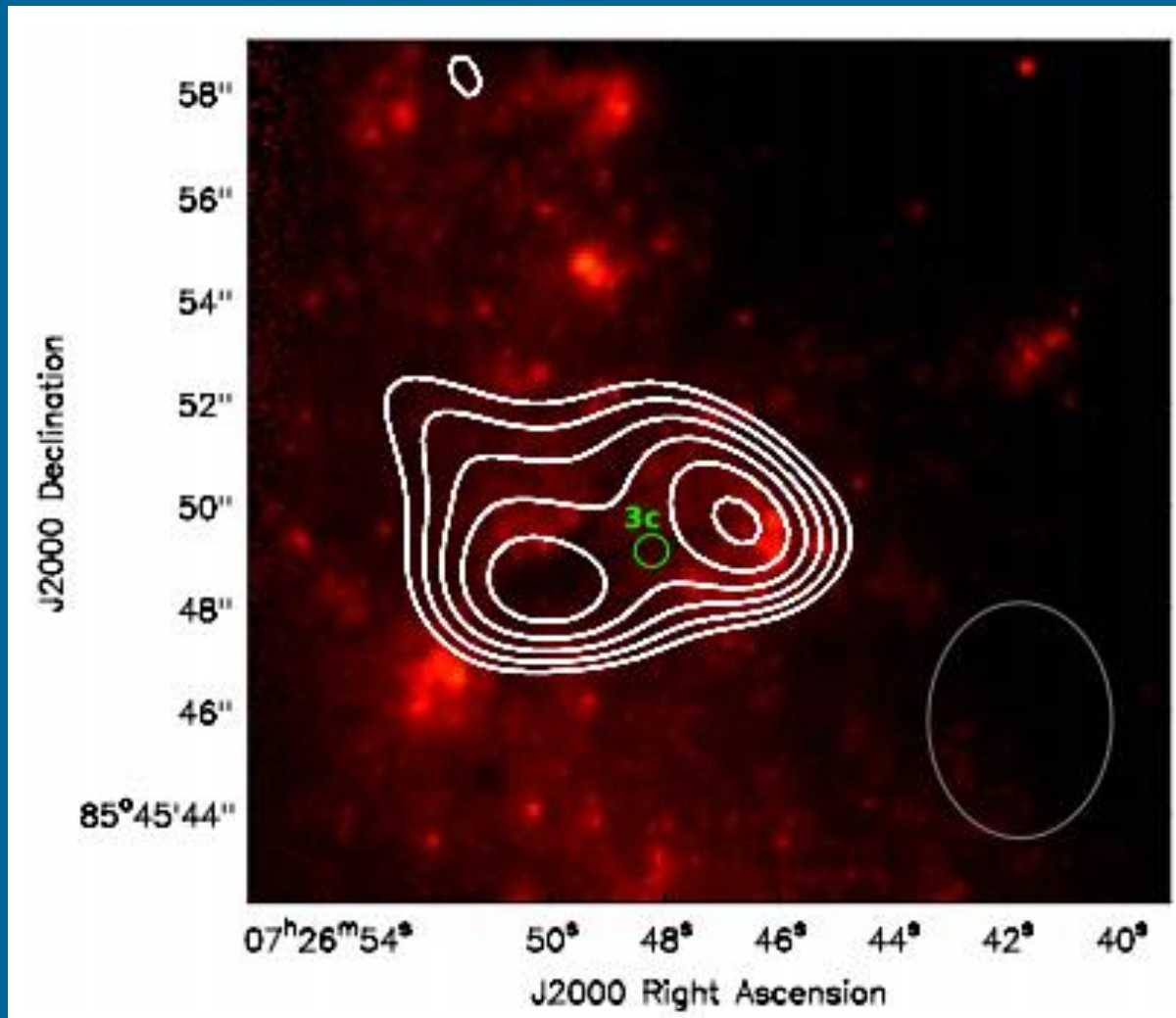
Obs2 – 2008



Obs1 was brighter, but all difference is due to soft (disc) component.

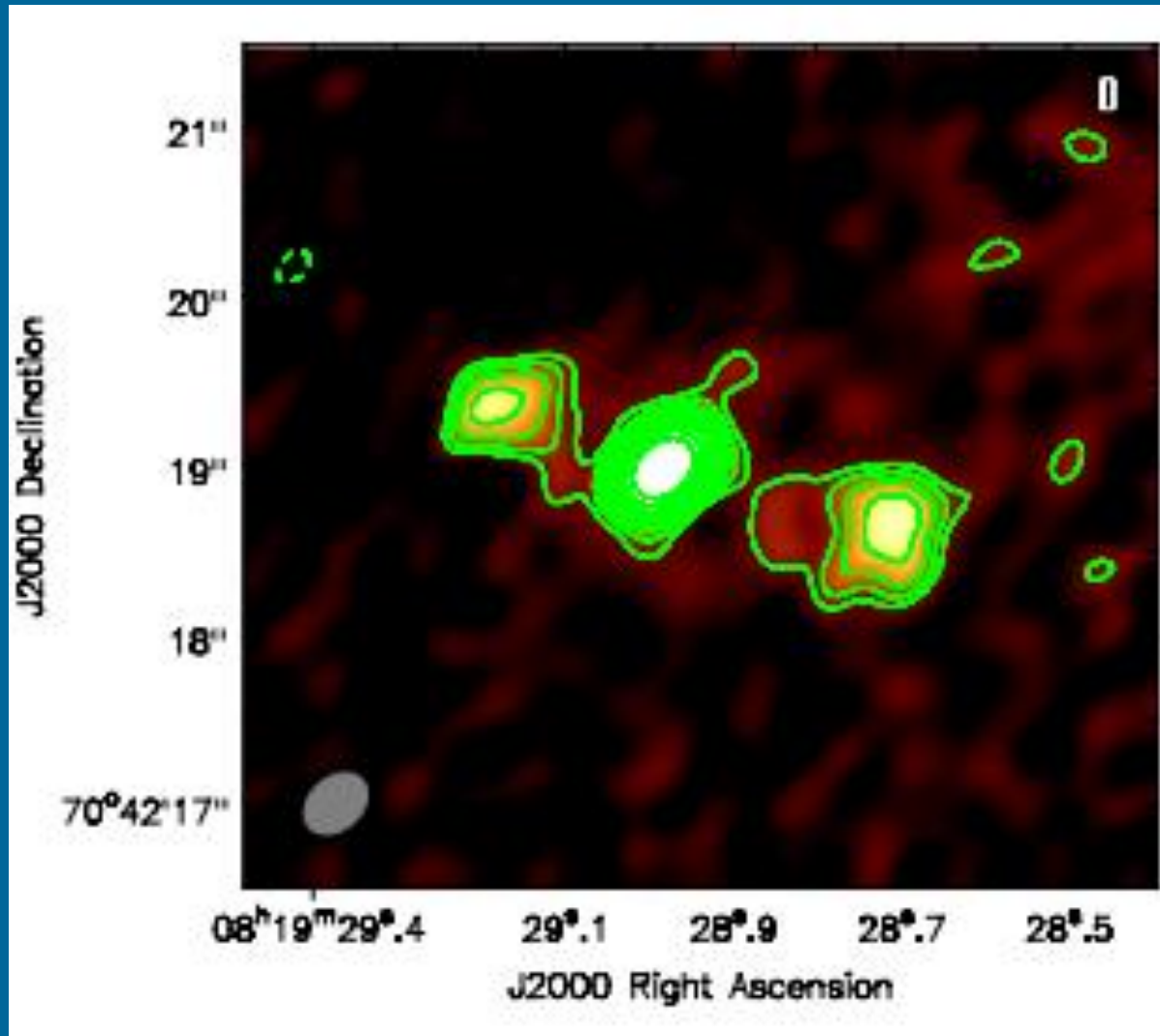


Jet from an ULX in NGC 2276



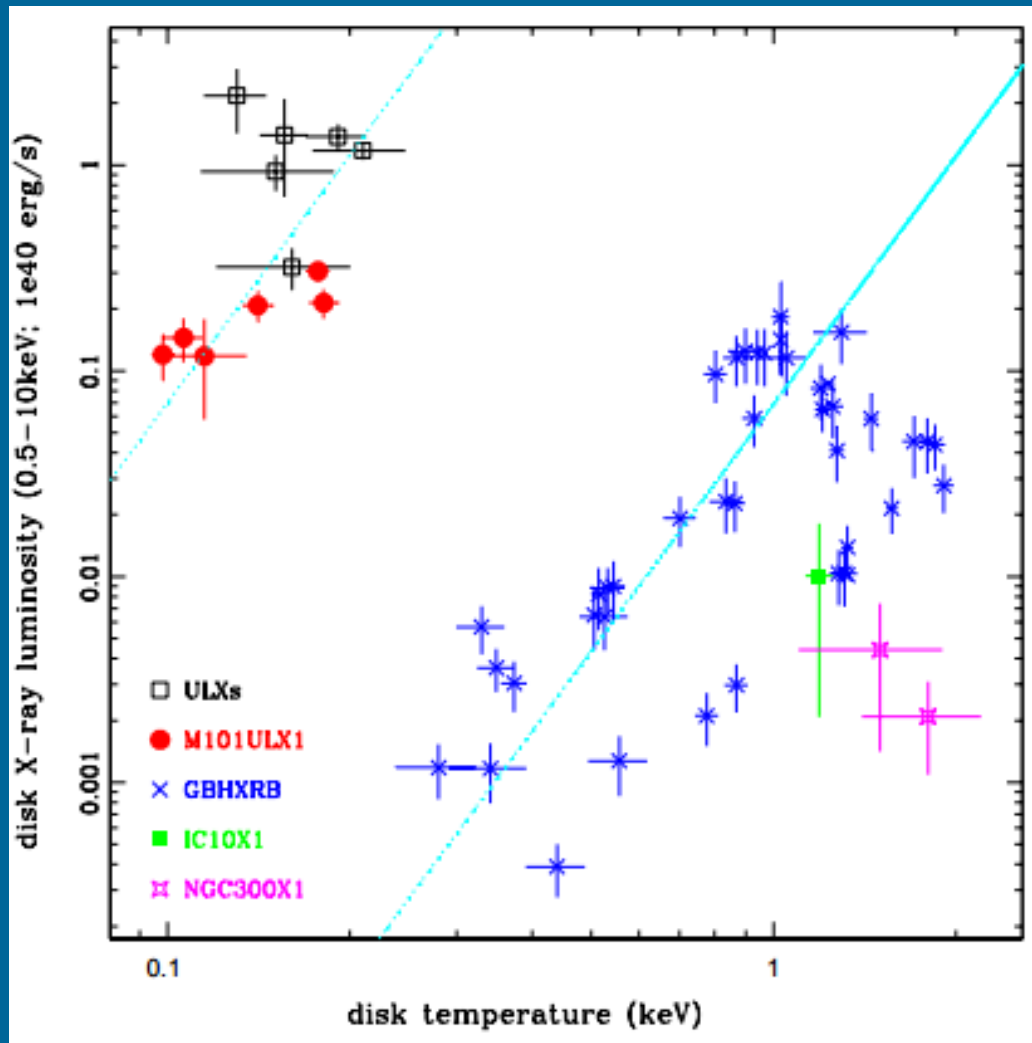
650 pc radio lobes
Scaling from usual BHs
gives the mass estimate
 $4.7 \cdot 10^3 < M < 8.5 \cdot 10^5$

Jet from ULX Holmberg II X-1



Mass limits are poor:
 $M > 25 M_{\text{solar}}$

Strange accretion in the ULX in M101



The authors determined the orbital period and determined properties of the companion.

The BH mass is estimated to be ~ 20 -30 Msolar.

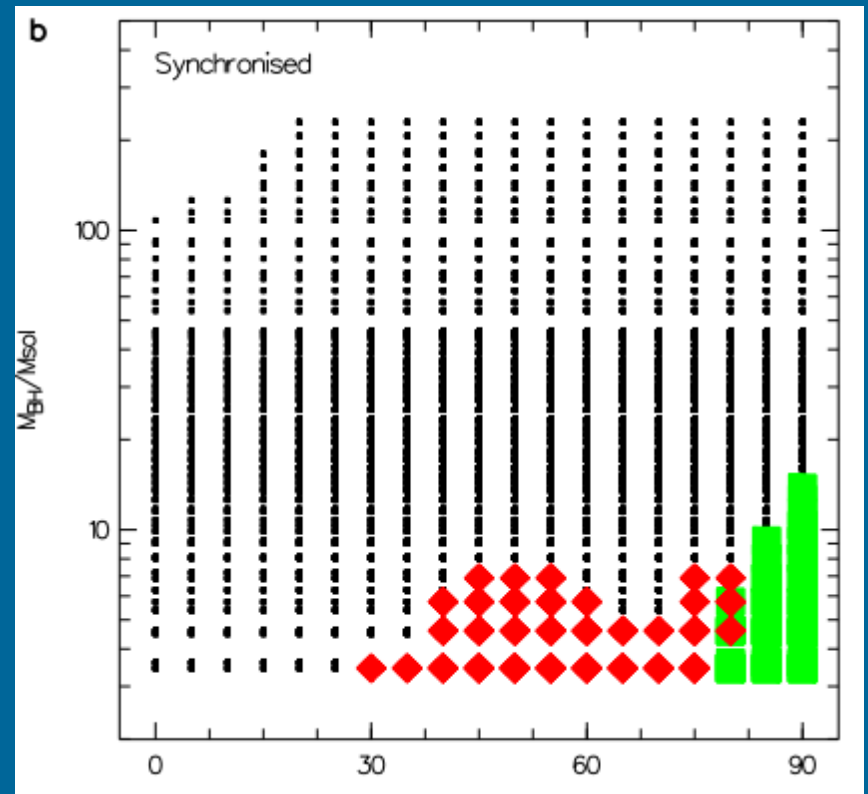
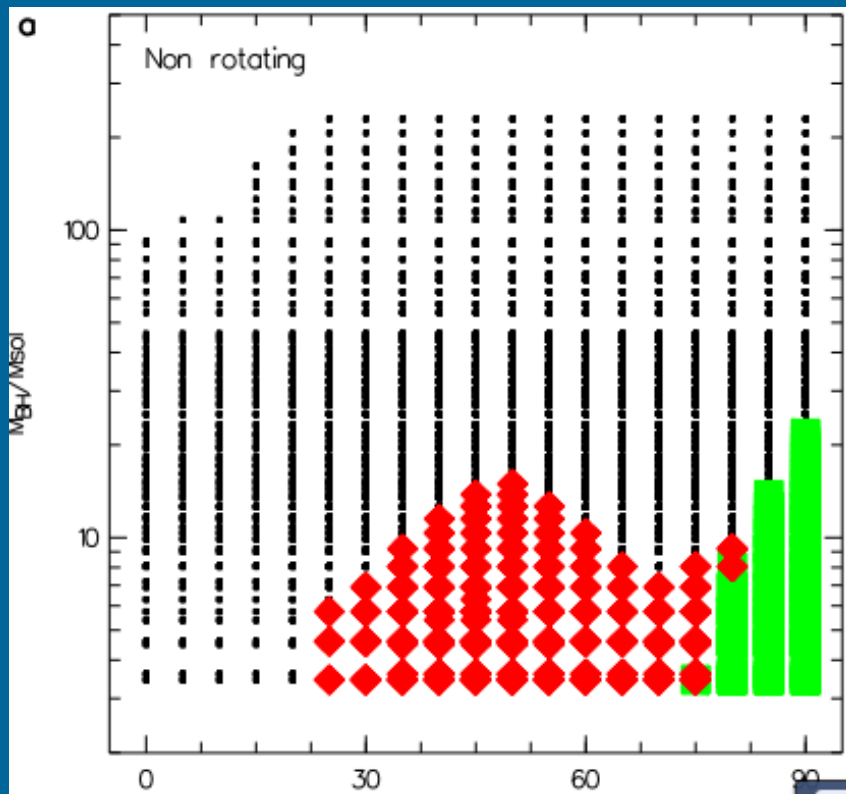
However, soft X-ray spectra is unexpected for such low mass.

Normal BH in an ULX

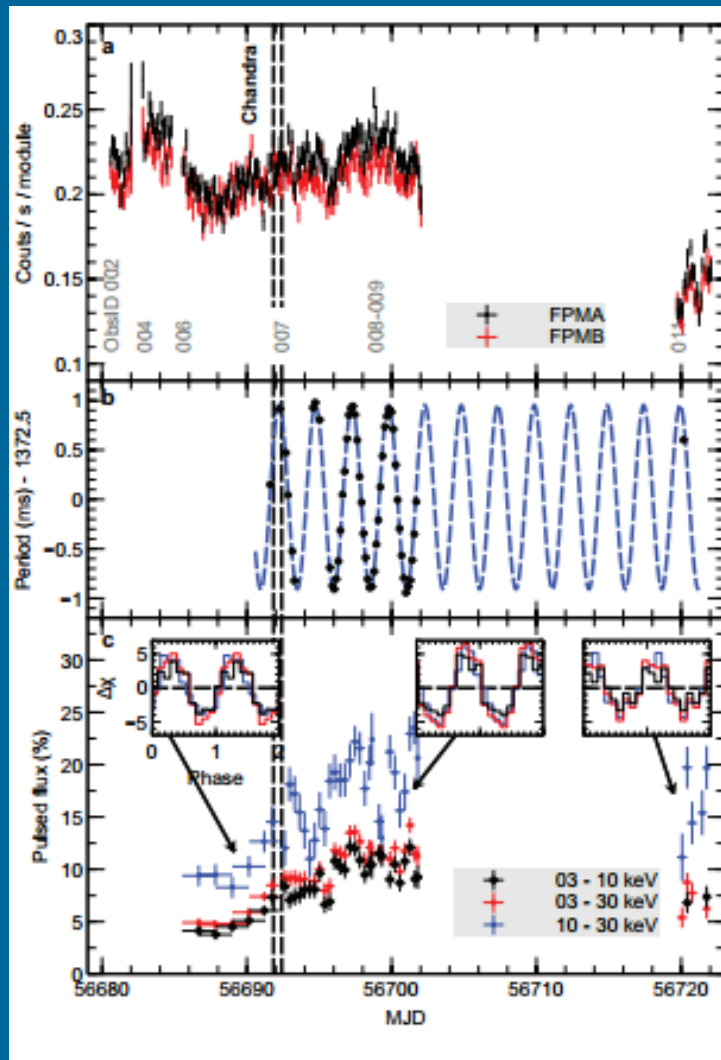
P13 in the galaxy NGC 7793

BH mass 7-15 M_{solar}

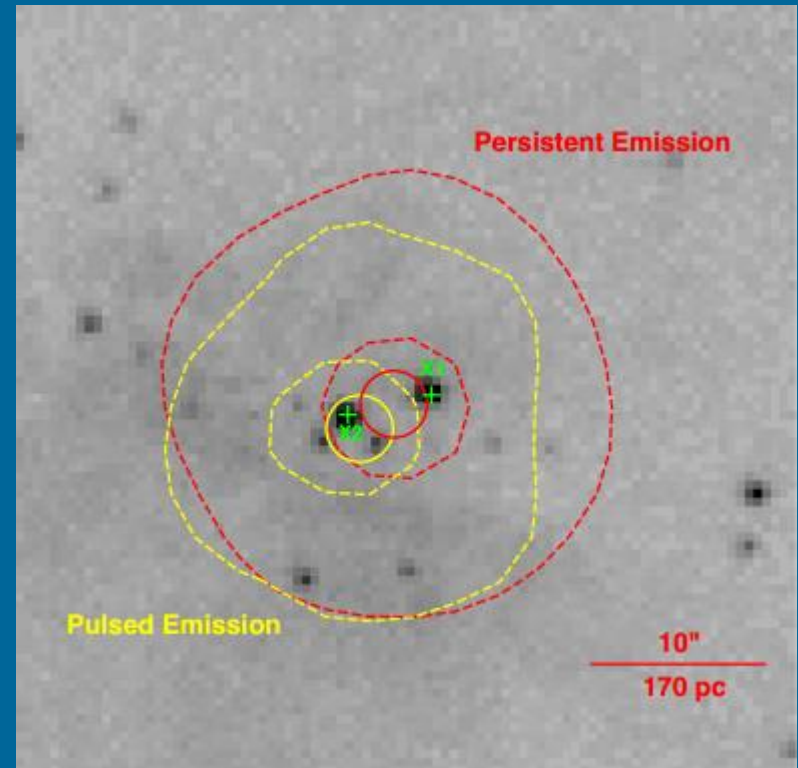
(depending on rotation)



A NS in an ULX!!!!



Pulsations with 1.37 s period found!



New search through archive data for other examples of pulsars in ULX failed to find any ([1410.7264](#))

1410.3590

Now: three NS ULXs

Recent results on NSs in ULXs

In 2018 already four ULXs with NSs are known.

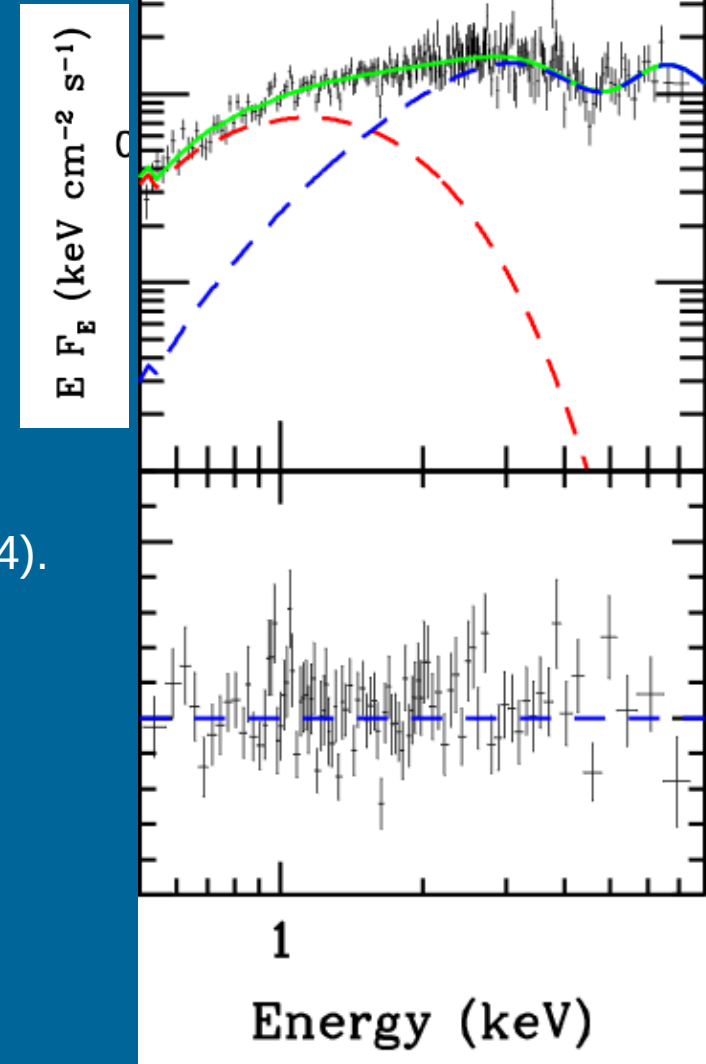
- Outflow (0.24c) in ULX NGC300. 1803.02367
- Cyclotron resonance line in ULX NGC300. 1803.07571
- Cyclotron line in ULX M51. 1803.02376
- New indirect arguments in favour of NSs in ULXs. 1803.04424

Cyclotron line in ULX M51

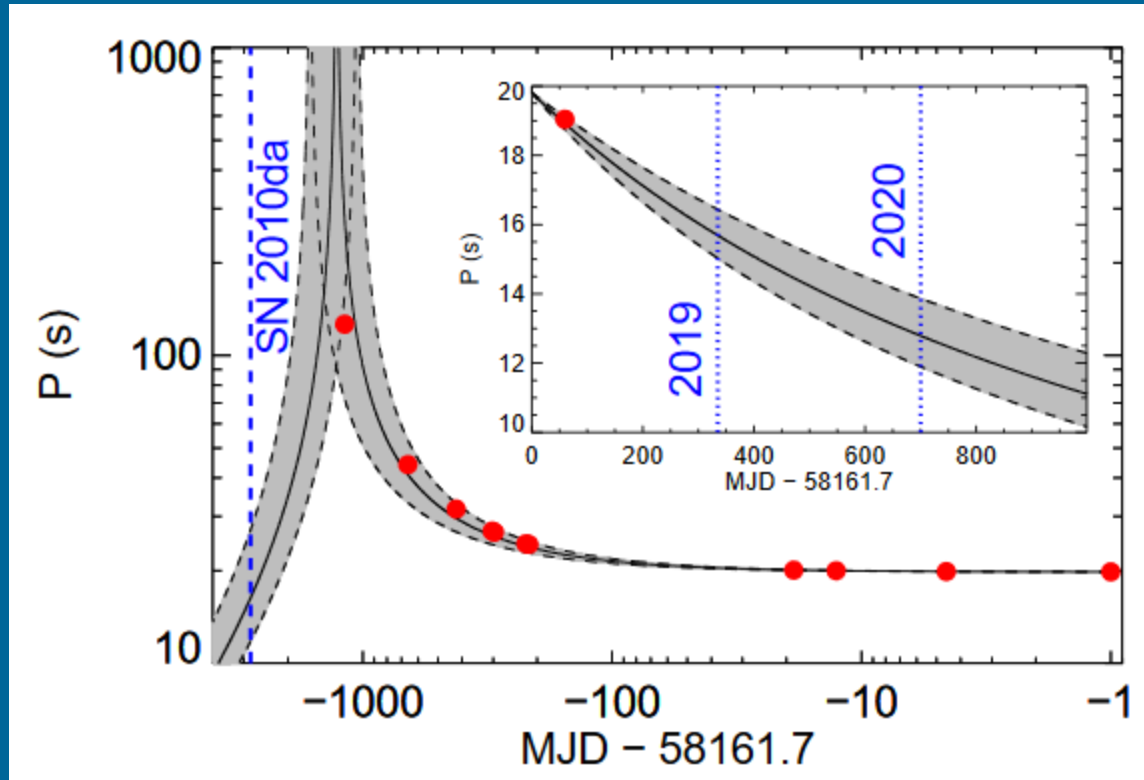
$\sim 10^{12}$ G dipolar field.
Strong dipole field is excluded,
but strong multipoles are still possible.

A big question: are there magnetars in ULX?

Recent studies suggest that – no (see 1903.03624).



Fantastic spin evolution of the ULX in NGC 300



About SN2010da see 1605.07245.
This might be not a core collapse, but an eruption on a massive evolved star.

Torque reversal in 2014?

The population of ULXs

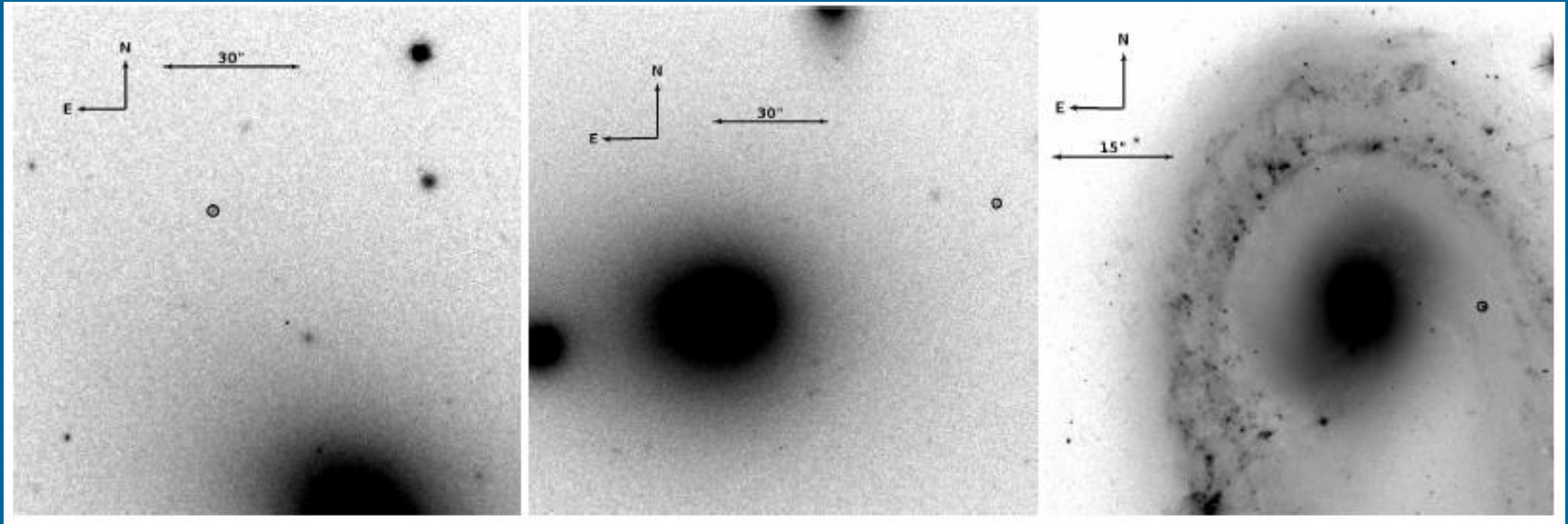
Most probably, the population of ULXs is not uniform.

1. Intermediate mass BHs
2. Collimated emission from normal stellar mass BHs
3. Accreting neutron stars
4. Different types of sources (pulsars, SNR, contamination)
5. Background sources.

The population can grow significantly (~500-600 new candidates) due to new surveys, like 2XMM slew survey (arXiv: 1011.0398), and some other projects (arXiv: 1002.4299).

Mass estimates for BHs (including IMBHs) are well reviewed recently in 1311.5118

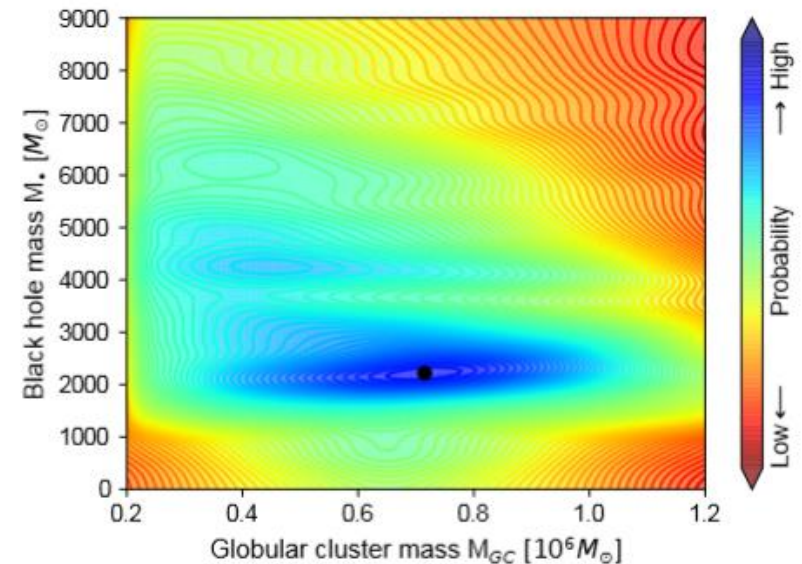
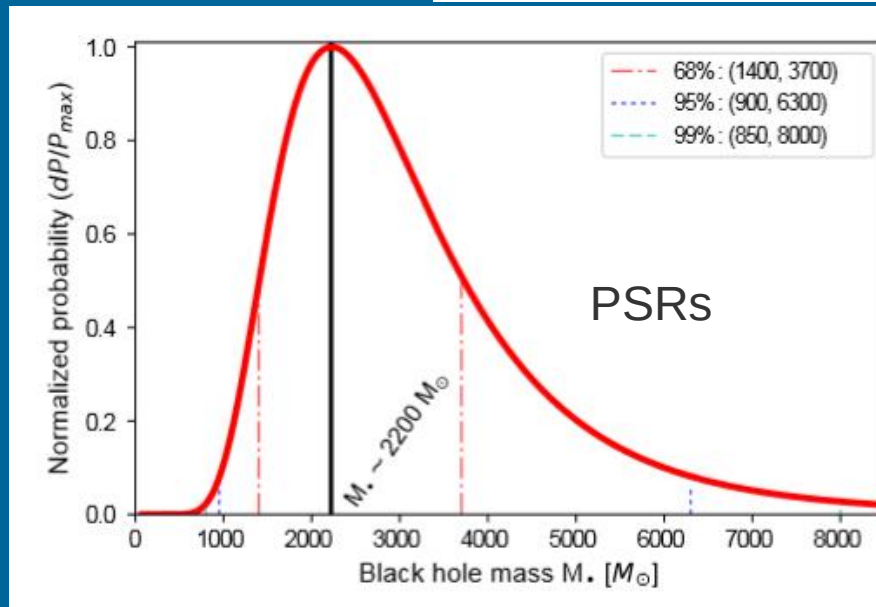
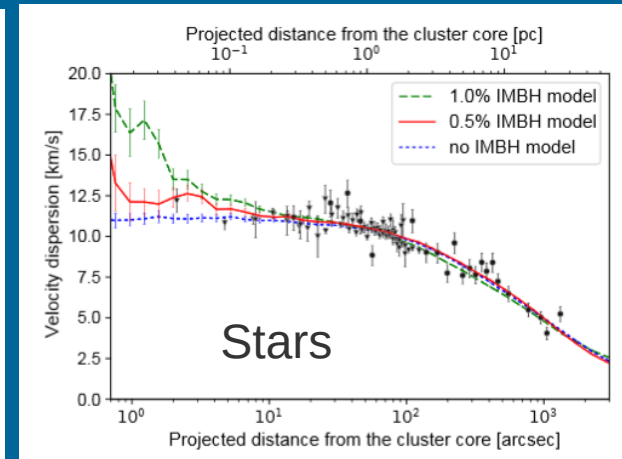
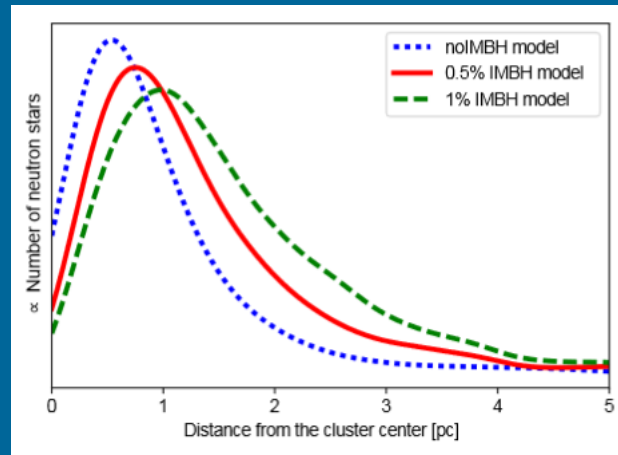
Background sources



Three out of four studied objects appeared to be background AGNs.
The only true ULX is in a spiral galaxy. Two out of false – in ellipticals.

IMBH in 47 Tuc?

Cluster dynamics was probed with radio pulsars.

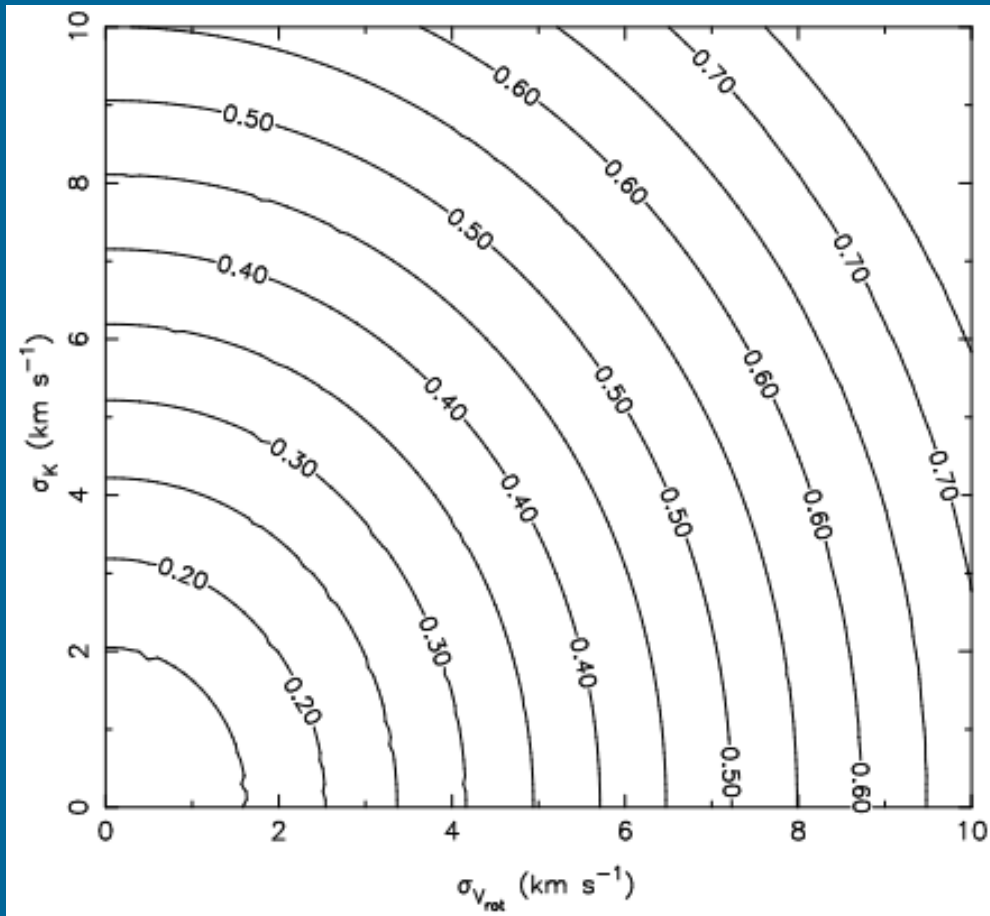


List of reviews

- Catalogue of LMXBs. Li et al. arXiv:0707.0544
- Catalogue of HMXBs. Li et al. arXiv: 0707.0549
- Modeling accretion: Done et al. arXiv:0708.0148
- Accretion discs: Lasota 1505.02172
- Galactic BH binaries: Paredes arXiv: 0907.3602 
- BH states: Belloni arXiv: 0909.2474; Dunn et al. arXiv: 0912.0142
- X-ray BH binaries: Gilfanov arXiv: 0909.2567
- X-ray observations of ULXs: Roberts. arXiv:0706.2562
- BH binaries and microquasars: Zhang. arXiv: 1302.5485
- BH transients: Belloni. arXiv:1109.3388, 1603.07872
- ULXs: Kaaret et al. 1703.10728, Fabrika 1702.005508
- QPO: Motta 1603.07885
- BH spin: Middleton 1507.06153
- IMBHs: Koliapanos 1801.01095, Mezcua 1705.09667
- BH coalescence: Schutz 1804.06308
- BH-BH binaries (stellar and supermassive): Celoria et al. 1807.11489

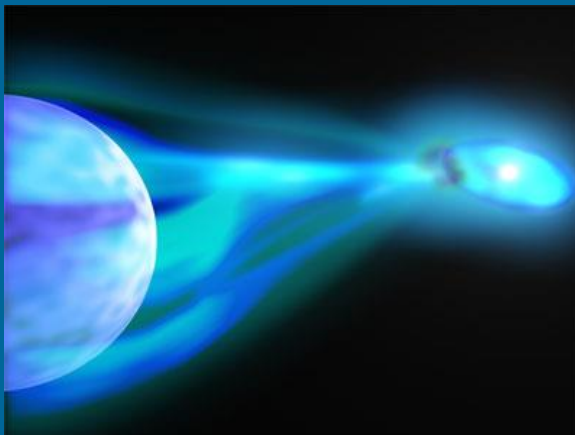
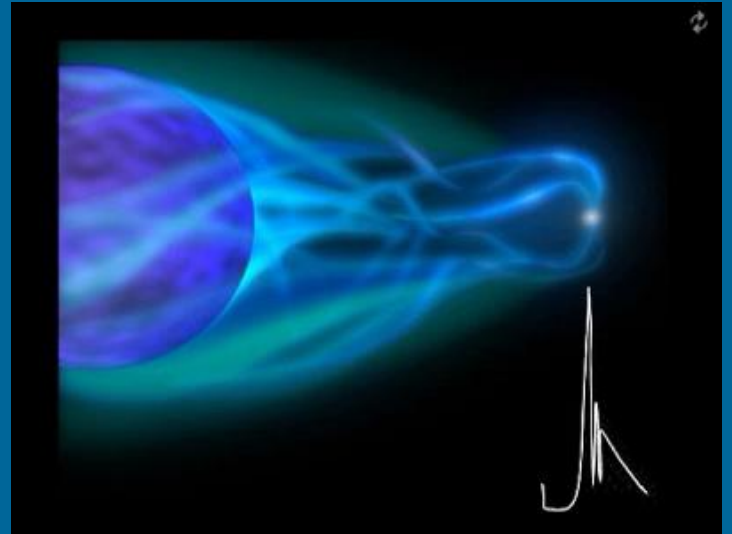
New mass estimate for LMC X-3

6.98 $\pm$ 0.56 Msolar



In addition, new data on the spin of the BH in LMC X-3 is given in 1402.0148/ Spin is low: 0.2 $\pm$ 0.2.

X-ray binaries

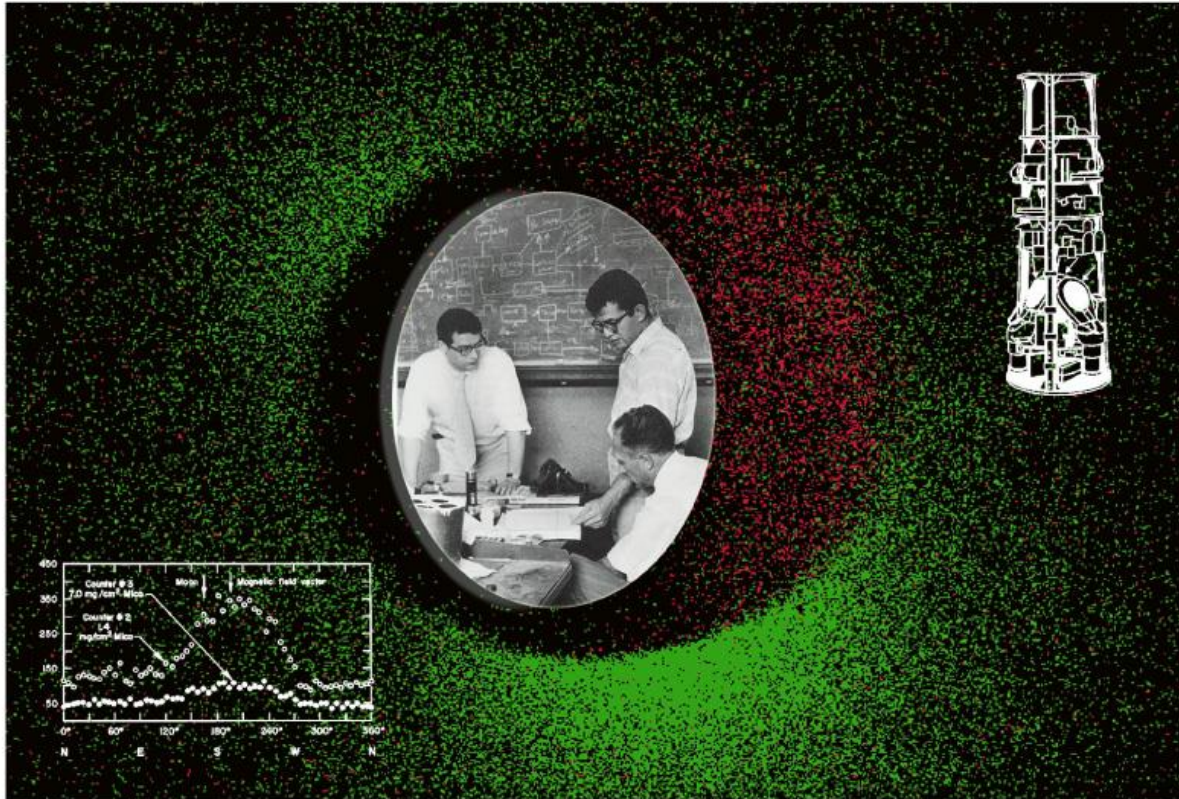


Rocket experiments. Sco X-1

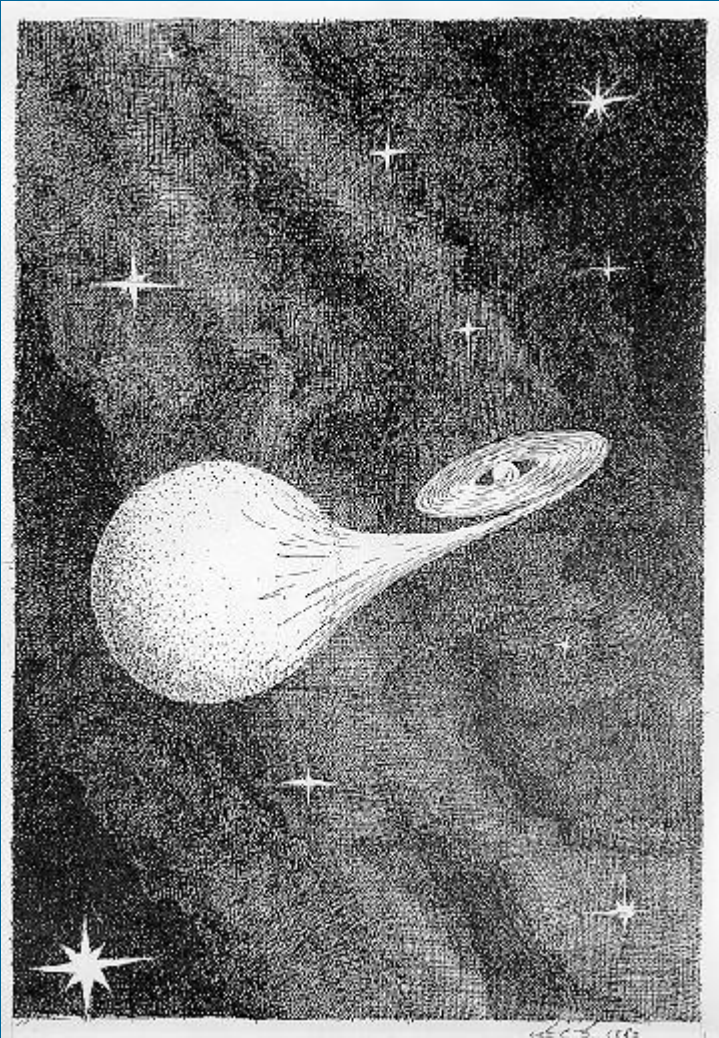
Giacconi et al. 1962

ROSAT Januar 2003

Max-Planck-Institut für
extraterrestrische Physik



Binaries are important and different!



Wealth of observational manifestations:

Visual binaries → orbits, masses

Close binaries → effects of mass transfer

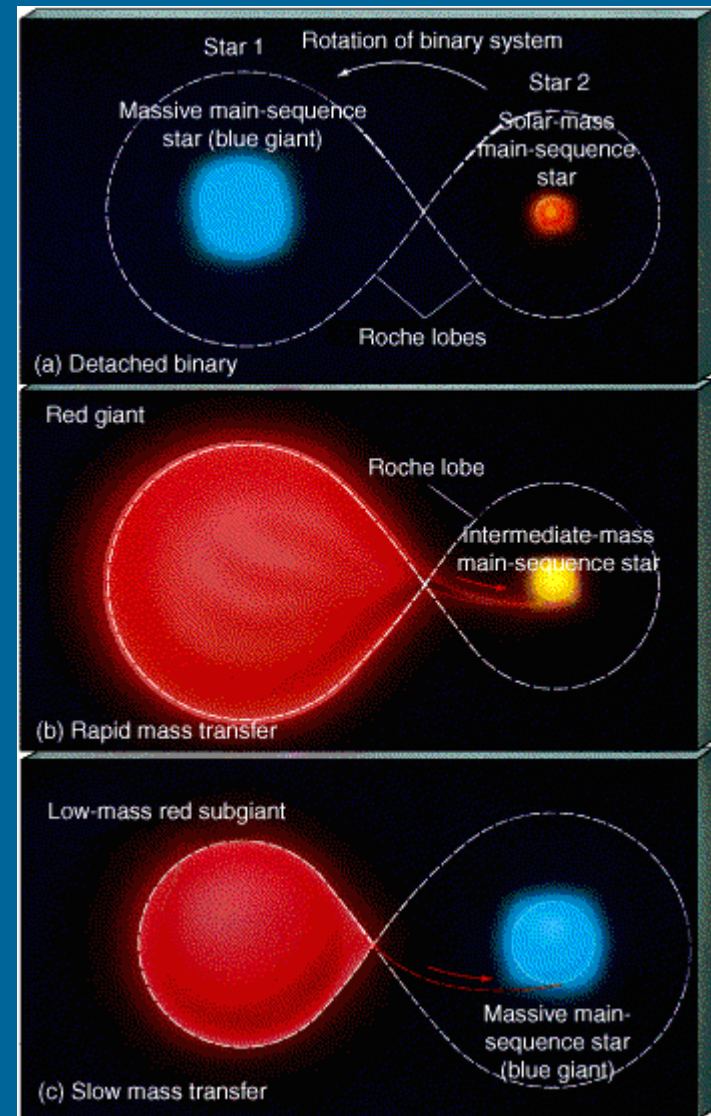
Binaries with compact stars →

X-ray binaries, X-ray transients,
cataclysmic variables, binary pulsars,
black hole candidates, microquasars...

Algol paradox

Algol (β Per) paradox:
late-type (lighter) component
is at more advanced
evolutionary stage
than the early-type (heavier) one!

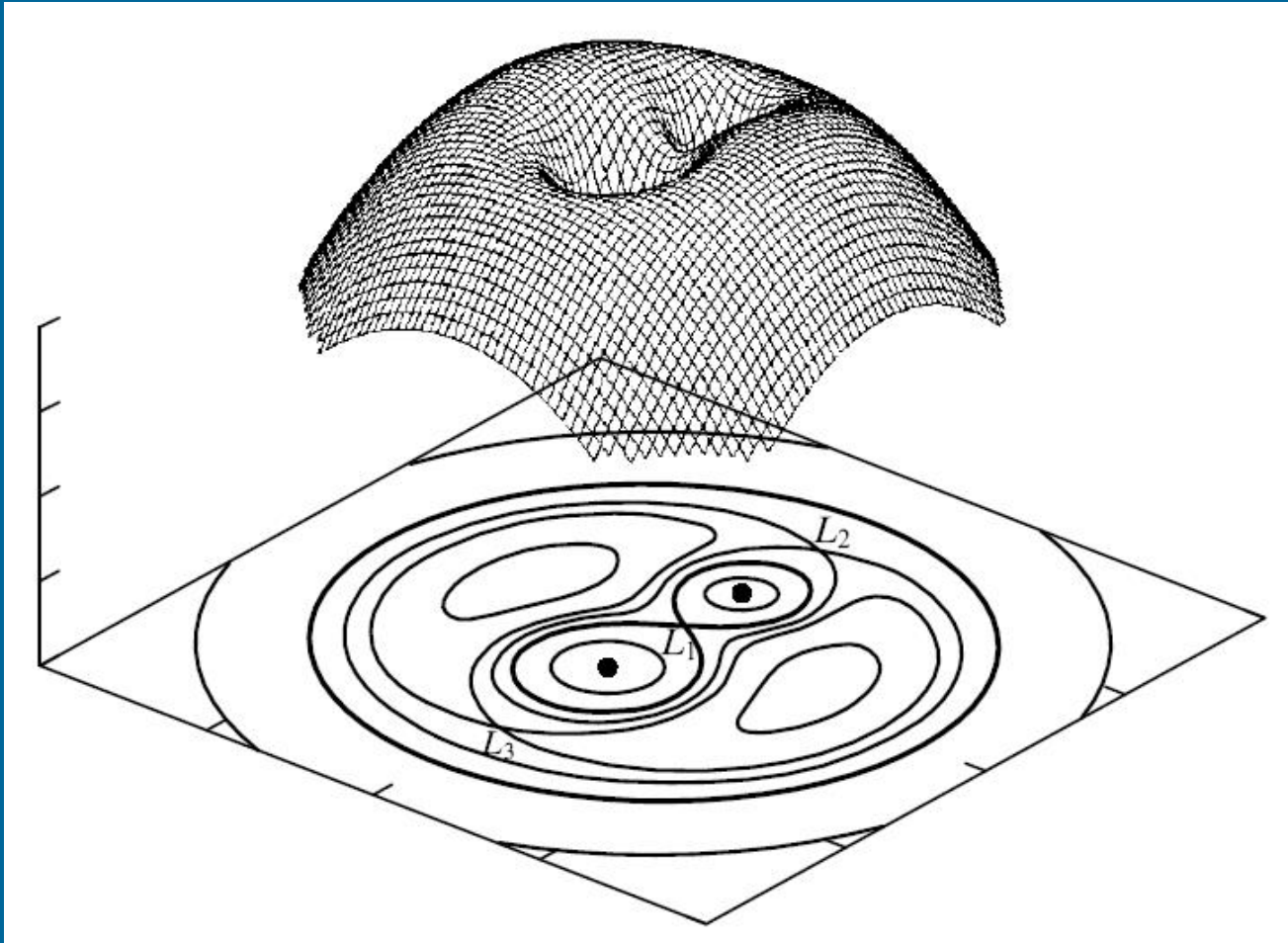
Key to a solution:
component mass reversal due to
mass transfer at earlier stages!



0.8 $M_{\odot}$ G5IV

3.7 $M_{\odot}$ B8 V

Roche lobes and Lagrange points



Three-dimensional representation of the gravitational potential of a binary star (in a corotating frame) and several cross sections of the equipotential surfaces by the orbital plane. The Roche lobe is shown by the thick line

Roche surface

Inner
Lagrangian
point

L_4

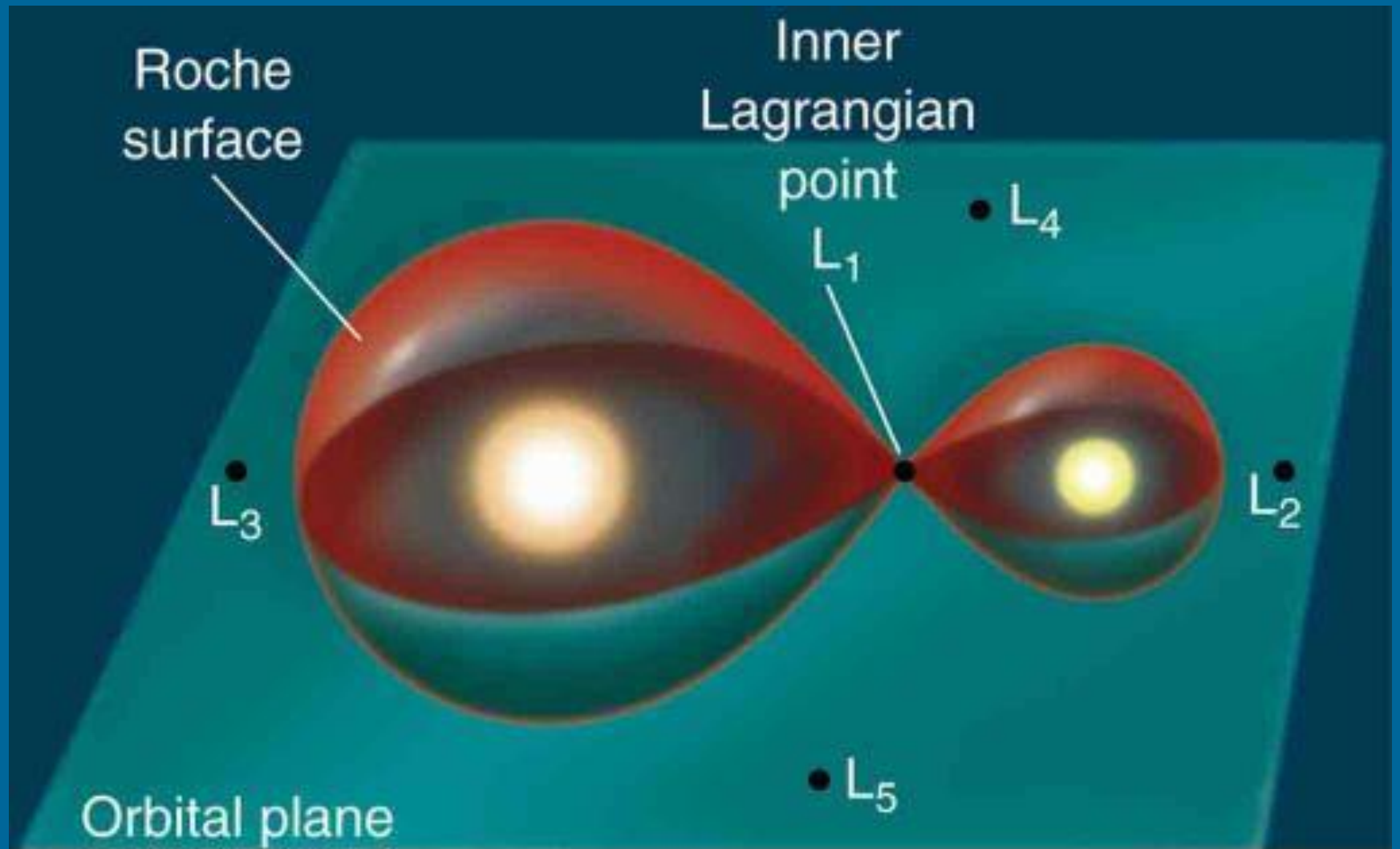
L_1

L_3

L_2

L_5

Orbital plane



Roche Potential

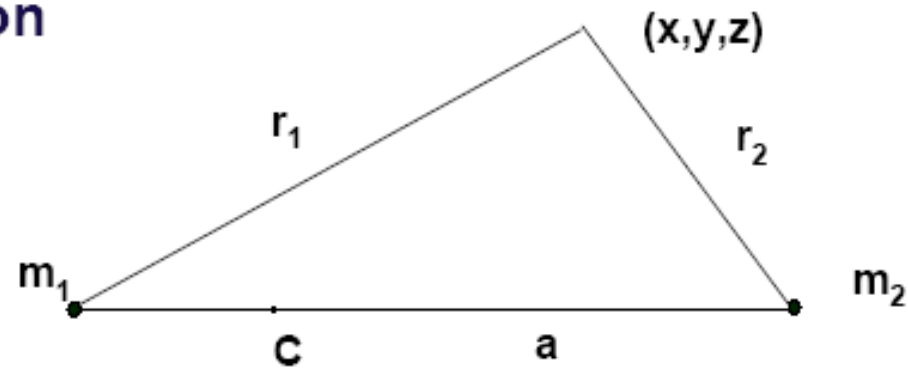
Assumes:

synchronous rotation

circular orbit

2 point masses

rotating frame



$$\omega^2 = \left(\frac{2\pi}{P} \right)^2 = \frac{G M}{a^3}$$

$$r_1^2 = x^2 + y^2 + z^2 \quad r_2^2 = (x - a)^2 + y^2 + z^2$$

$$\frac{x_c}{a} = \frac{m_2}{M} = \frac{q}{1+q} \quad q \equiv \frac{m_2}{m_1} \leq 1$$

$$\Phi = -\frac{G m_1}{r_1} - \frac{G m_2}{r_2} - \frac{\omega^2}{2} \left[(x - x_c)^2 + y^2 \right]$$

Dimensionless Roche Potential

factor out $-\frac{\omega^2}{2} = -\frac{G M}{2 a^3}$ and $x \rightarrow \frac{x}{a}$, etc.

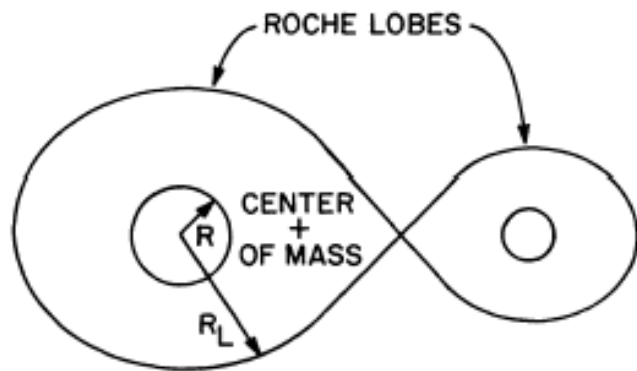
$$\Phi(x, y, z) = -\frac{\omega^2}{2} \Phi_N\left(\frac{x}{a}, \frac{y}{a}, \frac{z}{a}\right)$$

dimensionless Roche Potential:

$$\Phi_N(x, y, z) = \frac{2}{(1+q)} \frac{1}{r_1} + \frac{2q}{(1+q)} \frac{1}{r_2} + \left(x - \frac{q}{(1+q)}\right)^2 + y^2$$

Describes shape of potential surfaces independently of the mass and size of the system.

single parameter : q

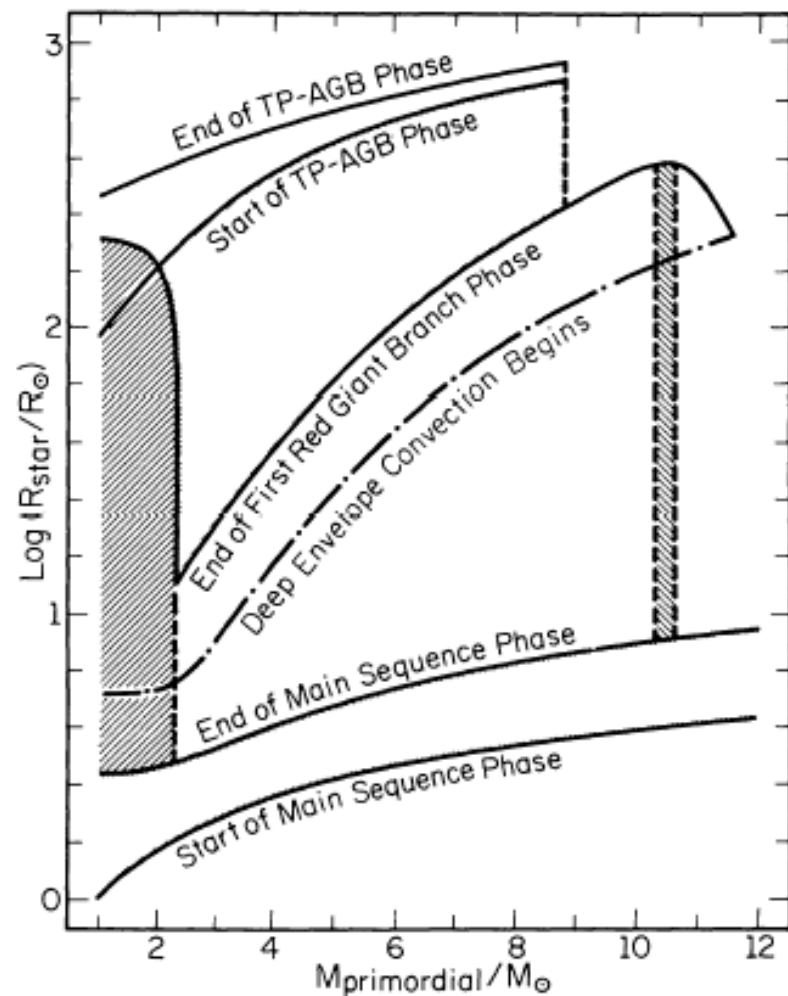


$\longleftrightarrow A \longleftrightarrow$

$$R_{iL} \sim 0.52 \left(\frac{m_i}{m_{\text{tot}}} \right)^{0.44} A$$

WHEN $R_i > R_{iL}$

$\Rightarrow$ ROCHE-LOBE OVERFLOW

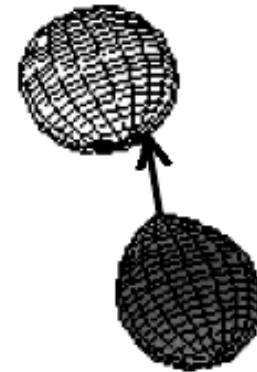


Binaries in Roche-Lobes

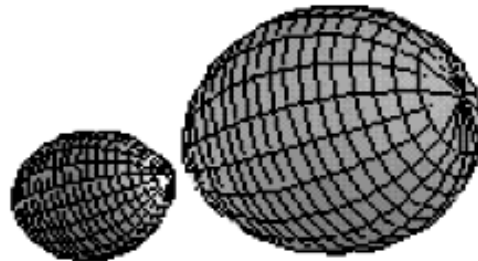
detached



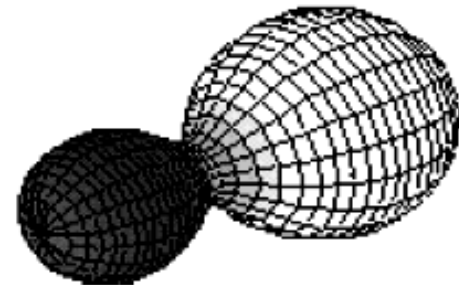
**semi-detached
(Algol)**



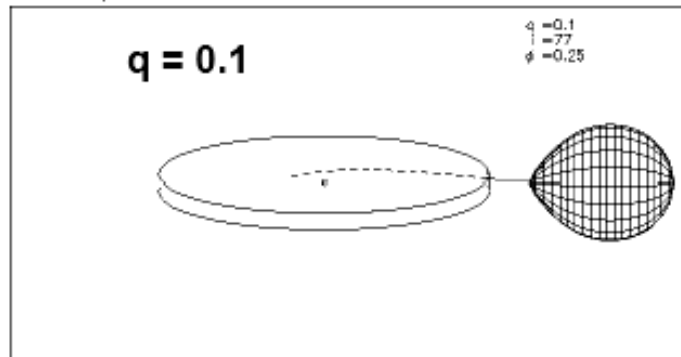
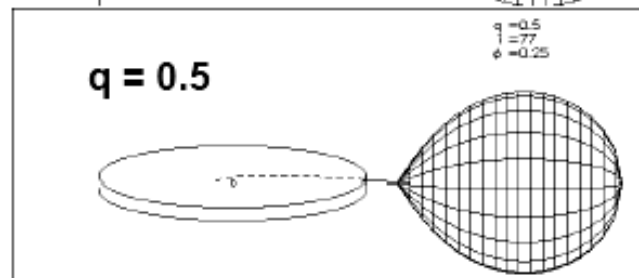
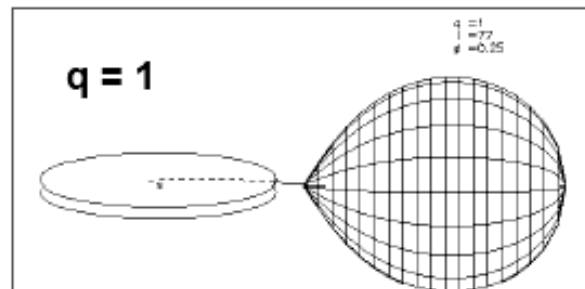
close to contact



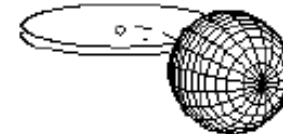
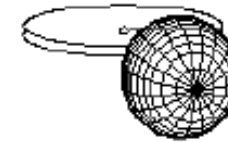
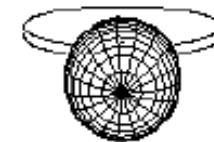
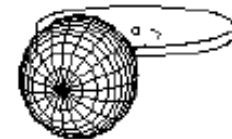
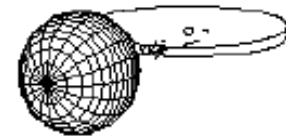
contact (W UMa)



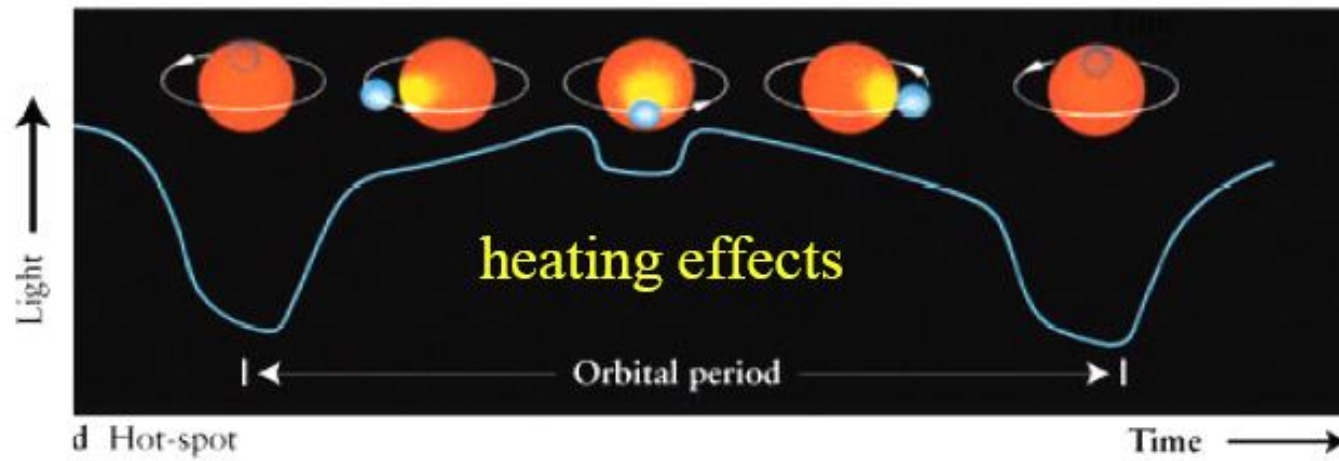
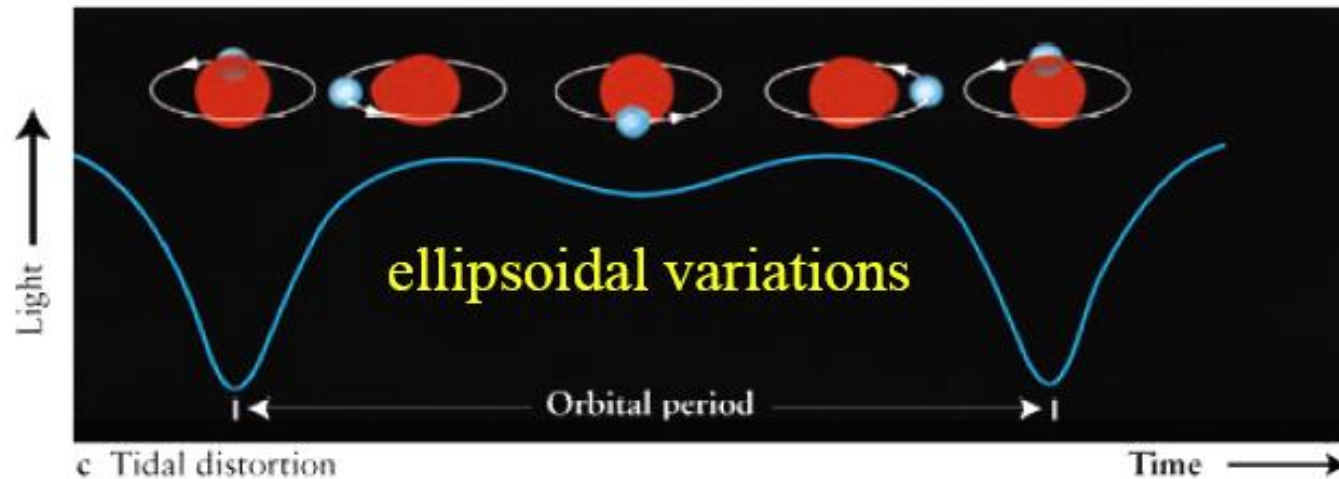
Roche Lobes



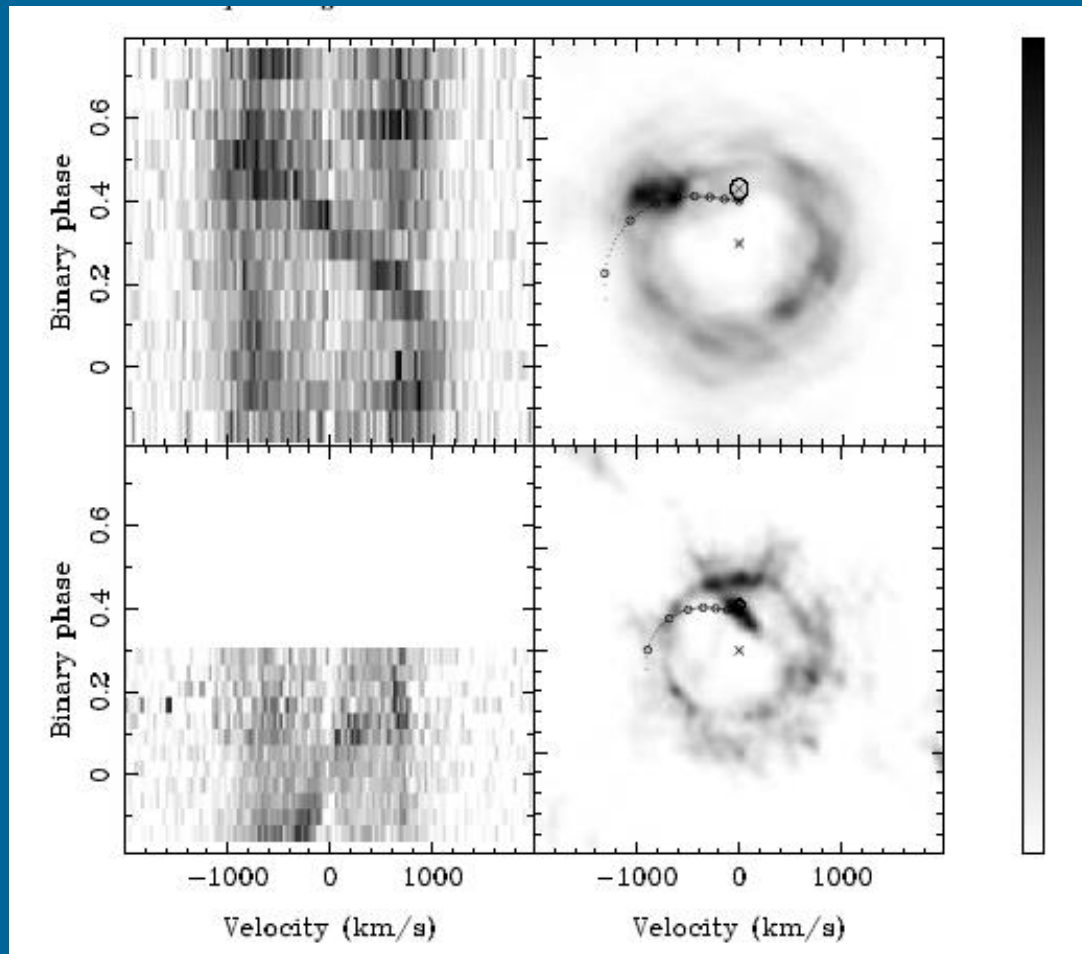
eclipses



Proximity Effects



GS 2000+25 and Nova Oph 1997



On the left – H α spectrum,
On the right – the Doppler image

← GS 2000+25

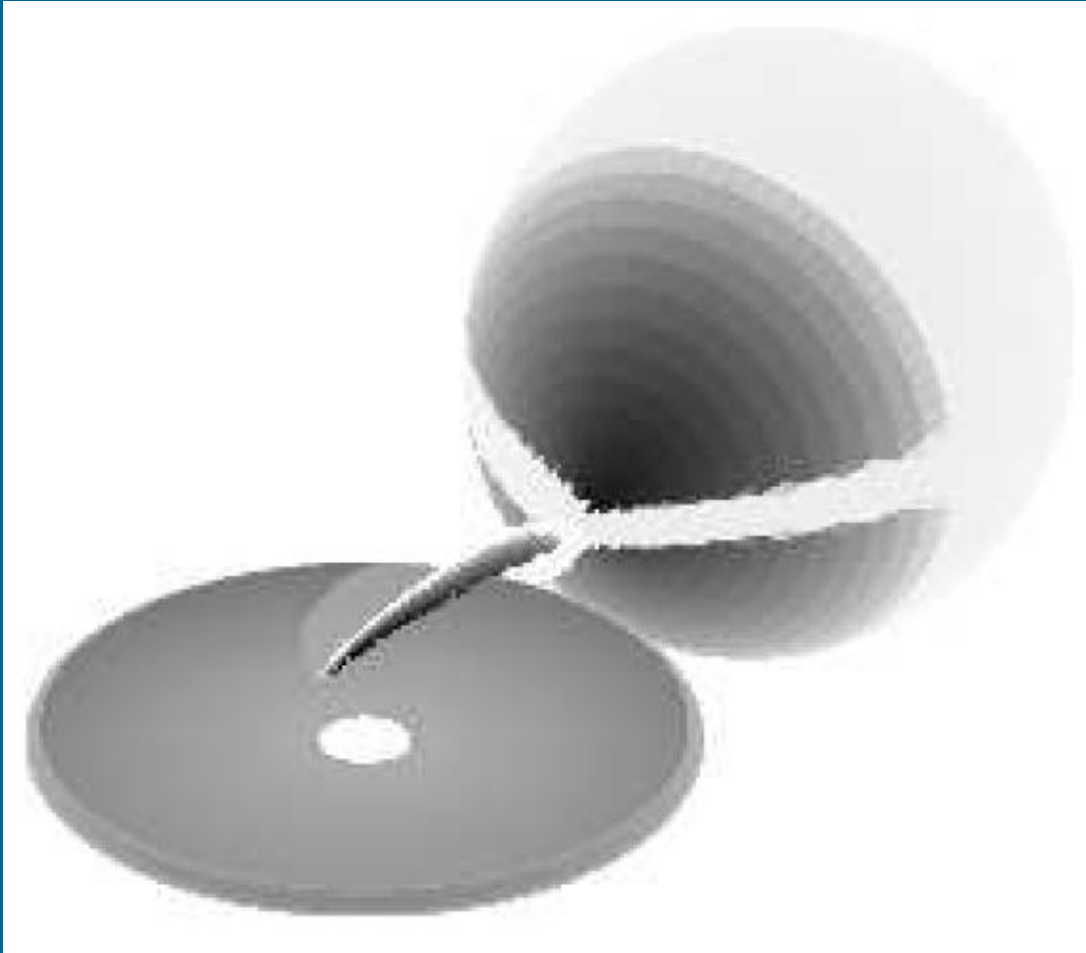
← Nova Oph 1997

See a review in Harlaftis 2001
(astro-ph/0012513)

(Psaltis astro-ph/0410536)

There are eclipse mapping, doppler tomography (shown in the figure),
and echo tomography (see 0709.3500).

Models for the XRB structure



Heating of the donor star and irradiation.

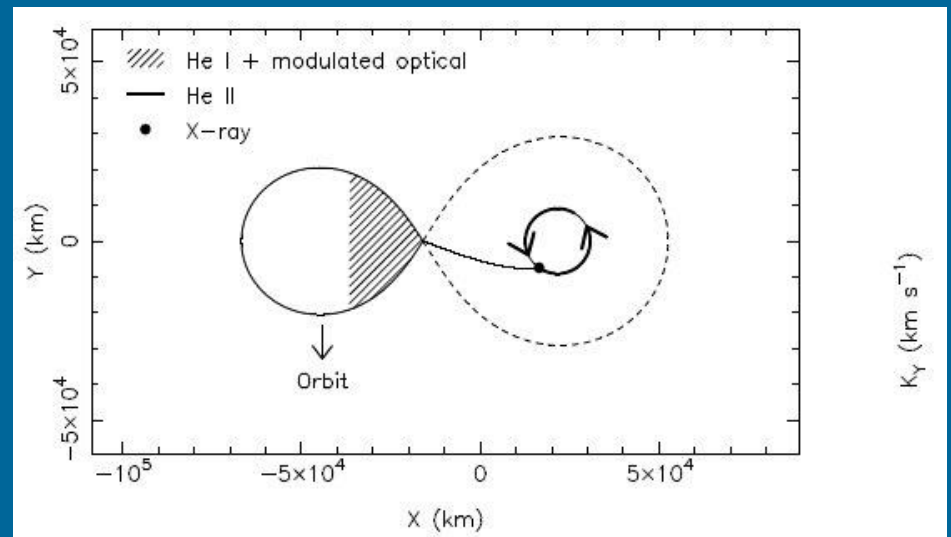
Analysis of time delays between X-ray and optics allows to derive the structure of the system.

The tightest binary

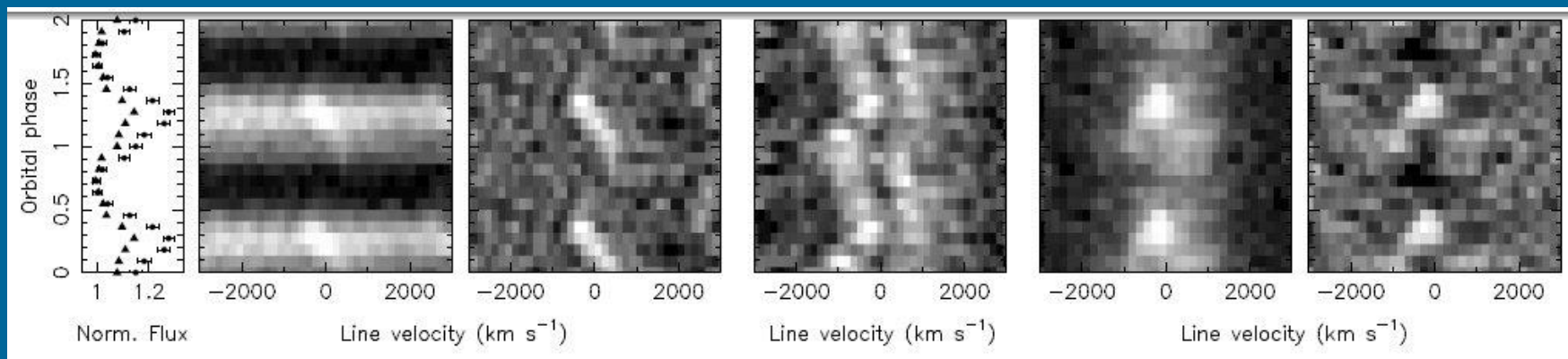


HM Cancri

Two white dwarfs.
Orbital period 321 seconds!
Distance between stars: $< 100\,000$ km.
Orbital velocity $> 1\,000\,000$ km per hour!
Masses: 0.27 and 0.55 solar
Gravitational wave emission



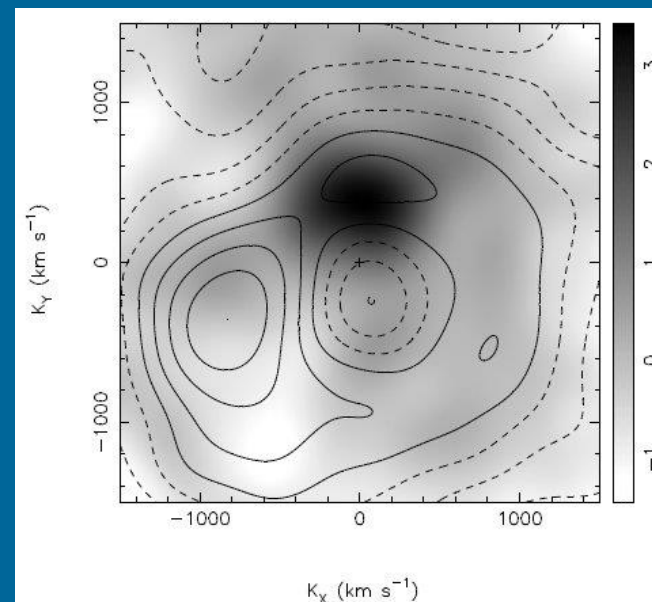
How is it measured?



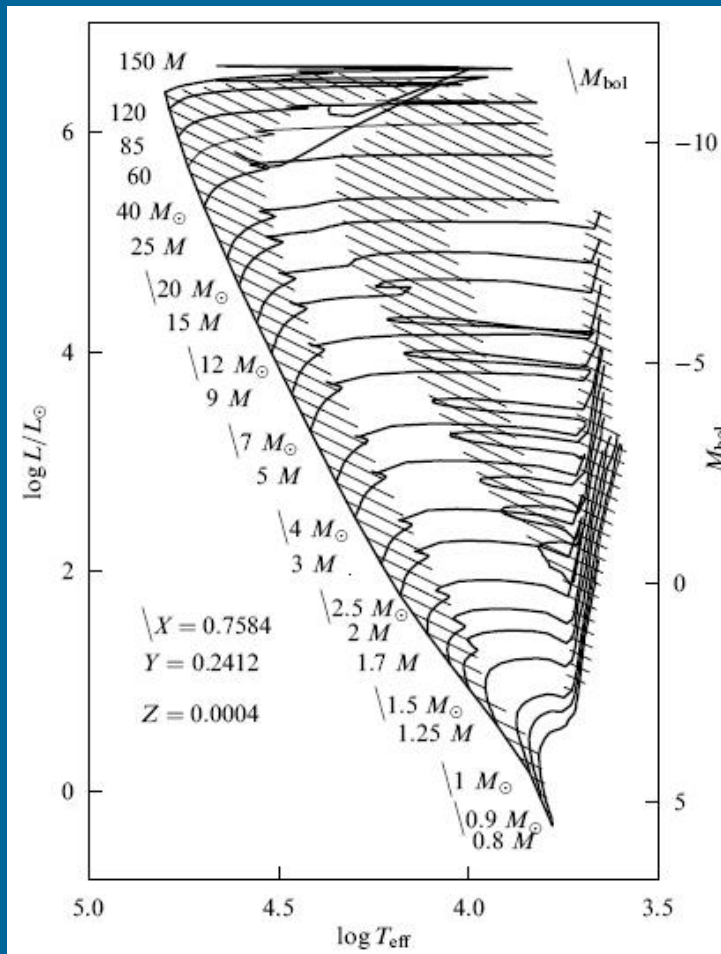
Spectra obtained by the Keck telescope.
Due to orbital motion spectral lines are shifted:
one star – blueshifted, another – redshifted.
The effect is periodic with the orbital period.

Doppler tomograms of He I 4471 (gray-scale) and
He II 4686 (contours).

The (assumed) irradiation-induced He I 4471
emission from the secondary star has been aligned
with the positive K_Y -axis.



Evolution of normal stars



Evolutionary tracks of single stars with masses from 0.8 to 150 $M_{\odot}$. The slowest evolution is in the hatched regions (Lejeune T, Schaerer D *Astron. Astrophys.* 366 538 (2001))

A track for a normal 5 solar mass star

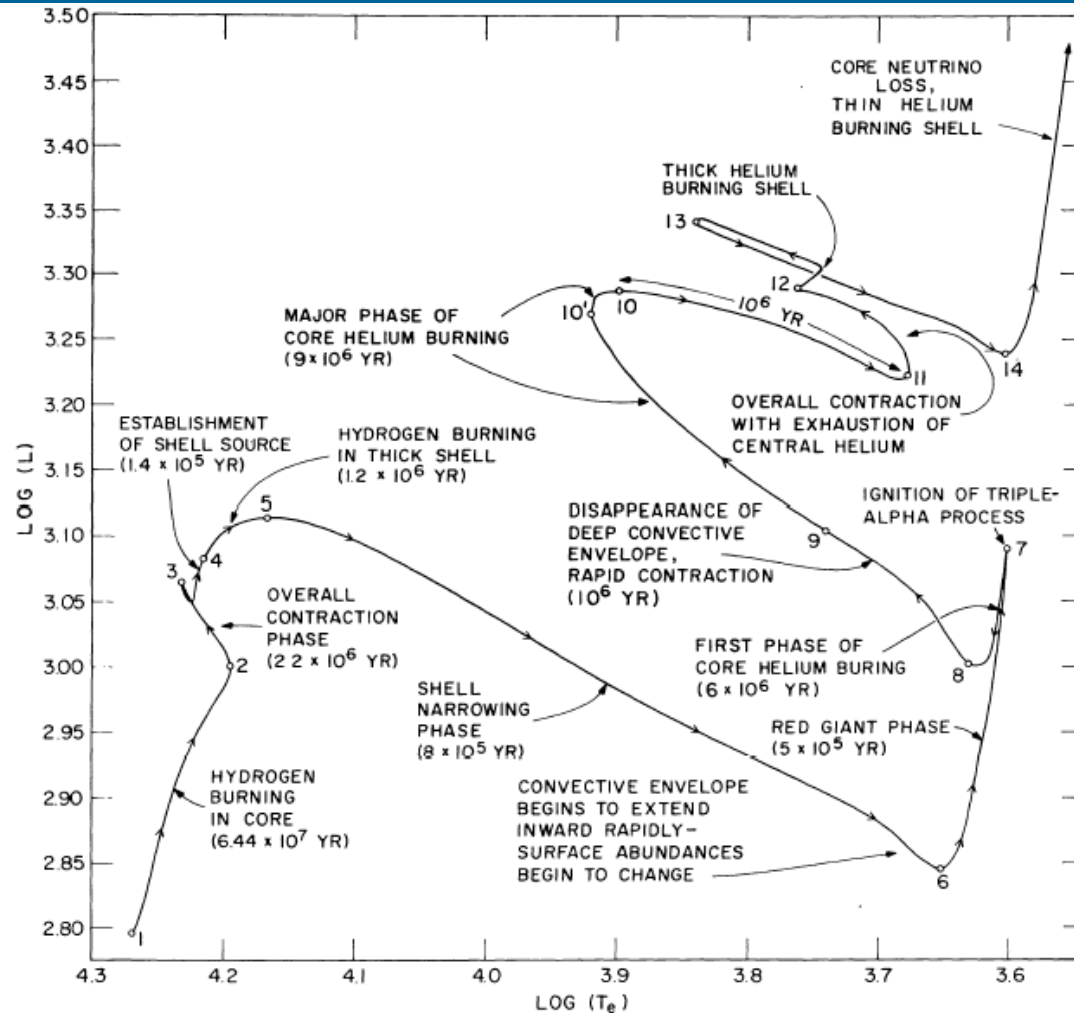
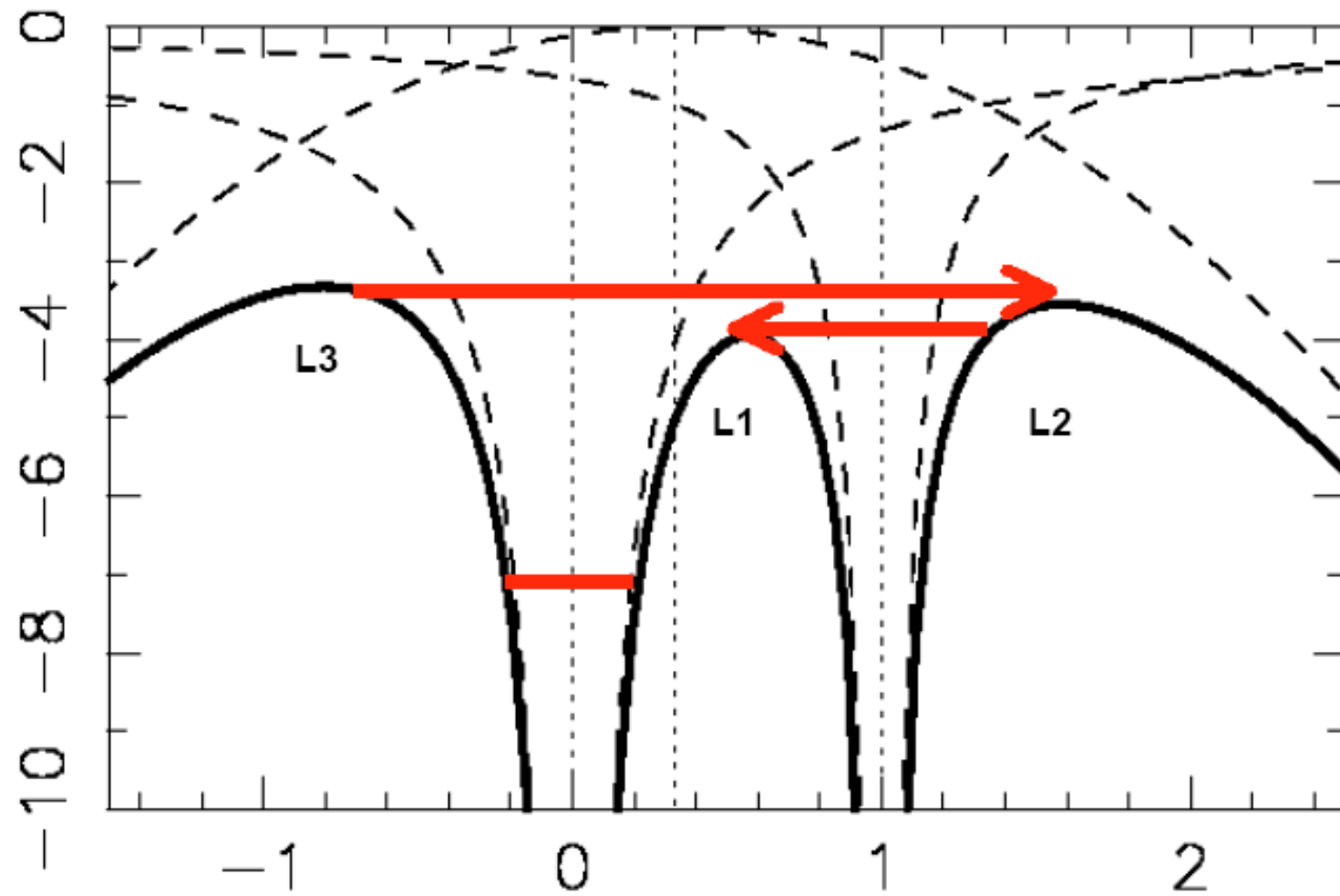
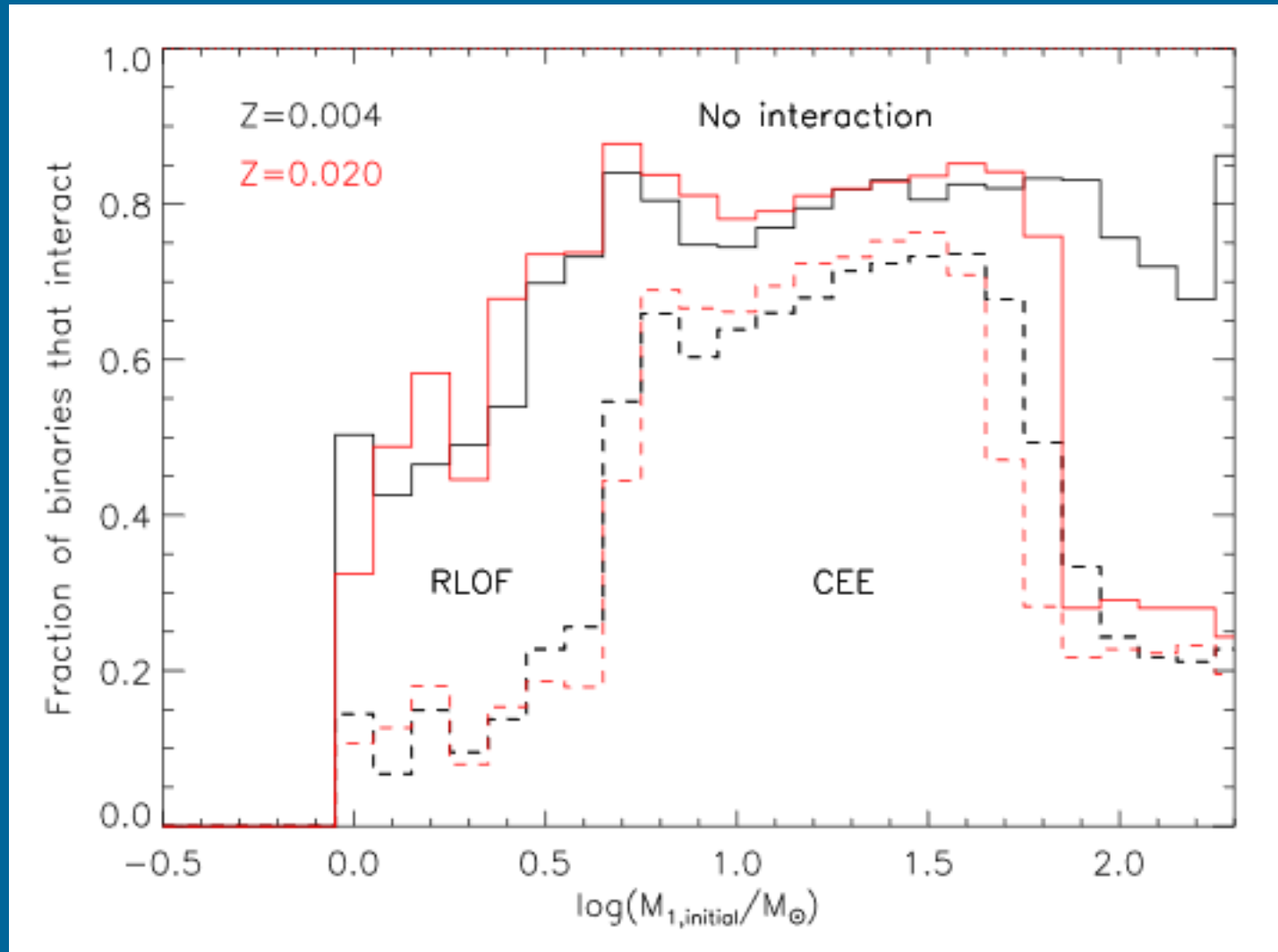


FIG. 2.—The track in the H-R diagram of a theoretical model star of mass $5 M_{\odot}$ and of Population I composition. Text beside various portions of the track describe an important physical process occurring within the star at the indicated position. From Iben (1967c).

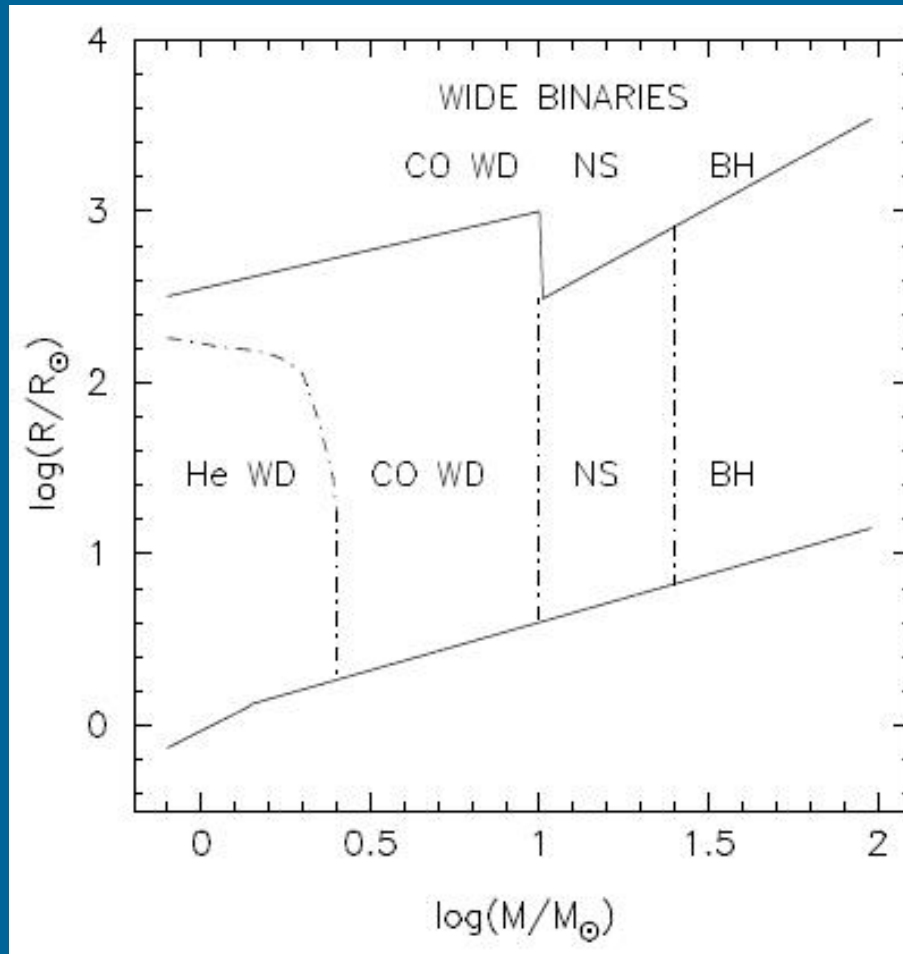
Mass transfer and loss



How often do binaries interact?



Progenitors and descendants



Descendants of components of close binaries depending on the radius of the star at RLOF.

The boundary between progenitors of He and CO-WDs is uncertain by several $0.1M_\odot$.

The boundary between WDs and NSs by $\sim 1M_\odot$, while for the formation of BHs the lower mass limit may be even by $\sim 10M_\odot$ higher than indicated.

[Postnov, Yungelson 2007]

Mass loss and evolution

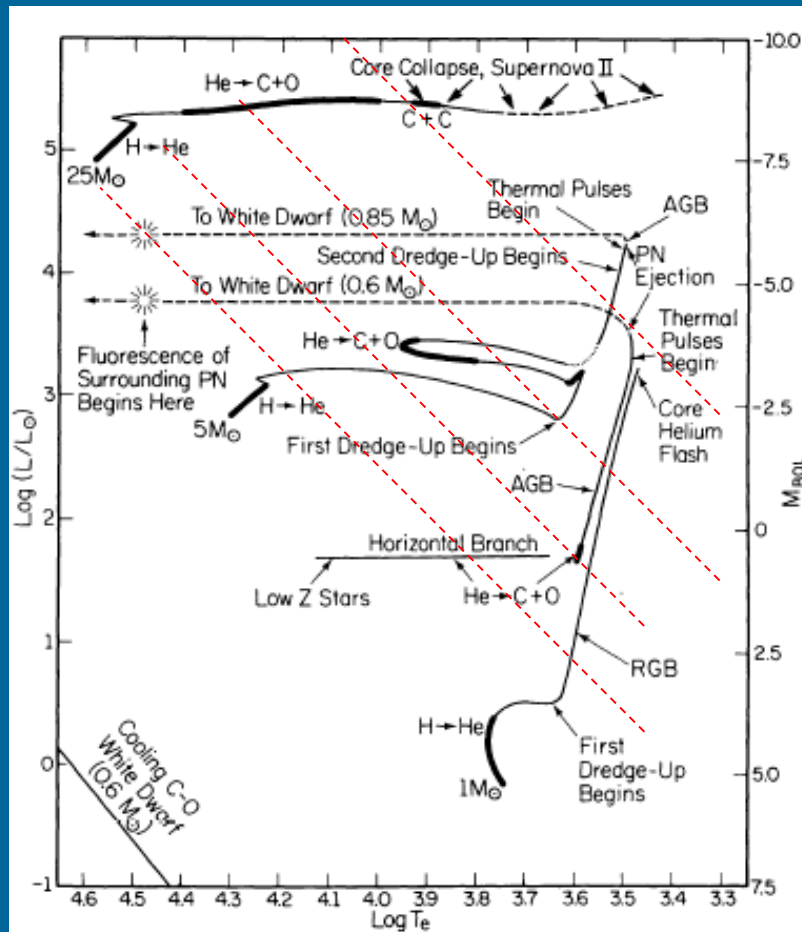


FIG. 5.—Tracks in the H-R diagram of theoretical model stars of low ($1 M_{\odot}$), intermediate ($5 M_{\odot}$), and high ($25 M_{\odot}$) mass. Nuclear burning on a long time scale occurs along the heavy portions of each track. The places

Mass loss depends on which stage of evolution the star fills its Roche lobe

If a star is isentropic (e.g. deep convective envelope - RG stage), mass loss tends to increase R with decreasing M which generally leads to unstable mass transfer.

Evolution of a 5M star in a close binary

Mass loss stages

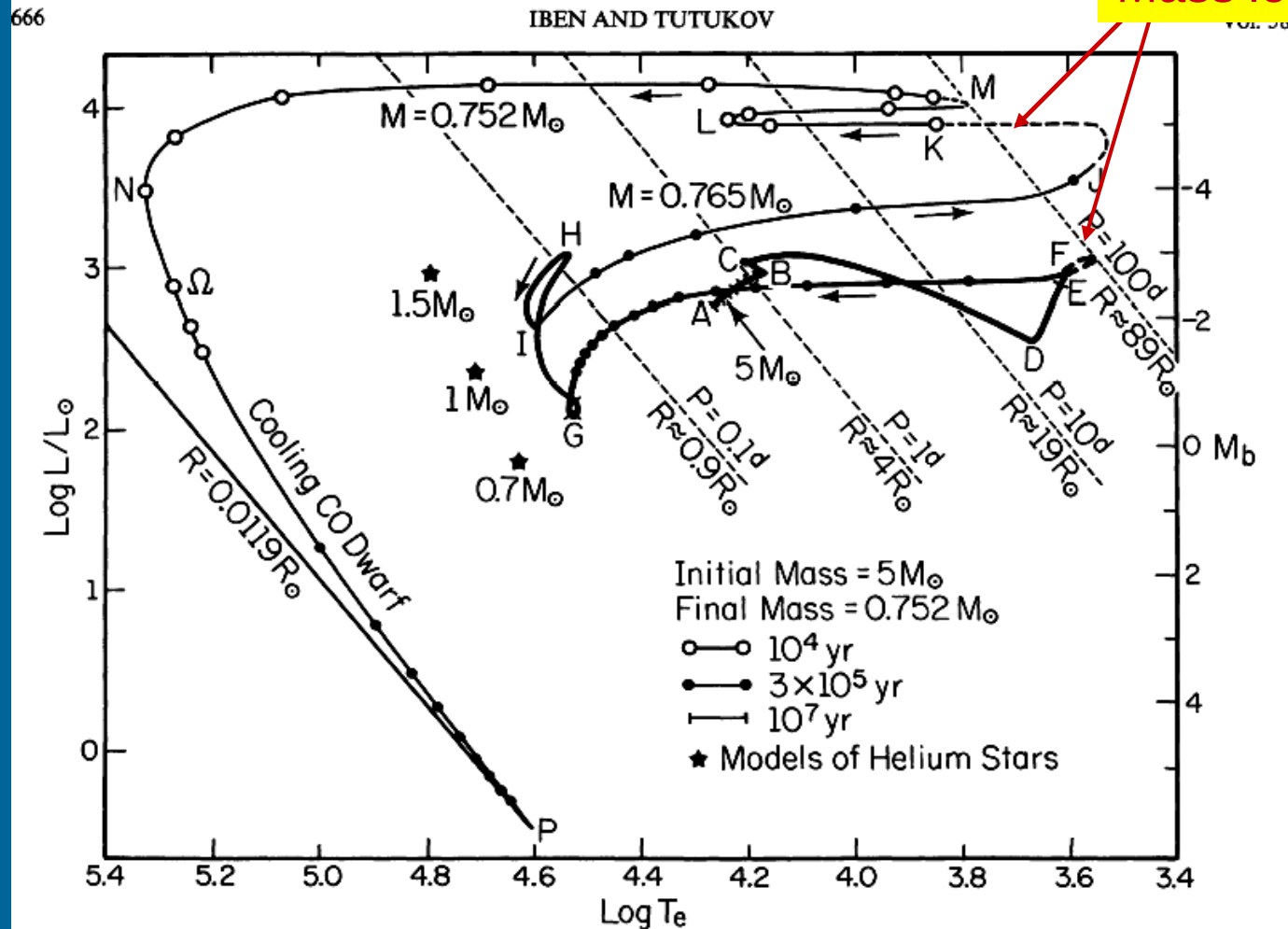


FIG. 1.—Evolution in the H-R diagram of a binary component of initial mass $5M_{\odot}$. Initial composition parameters are $X = 0.7$, $Z = 0.02$. The positions of helium model stars are given by the filled, five-pointed “stars” (Paczynski 1971). Lines of constant orbital period and Roche-lobe radius for a system consisting of two $5M_{\odot}$ unevolved stars are also shown. The temperature of the CO shell reaches a maximum at the point Ω along the track. The main parameters of the stellar model at other labeled points (A, B, ...) are presented in Table 1. Mass loss occurs along dashed portions of the track (E to F; J to K). Time evolution is measured by tick marks (10^7 yr), filled circles (3×10^5 yr), and open circles (10^4 yr).

Different cases for Roche lobe overflow

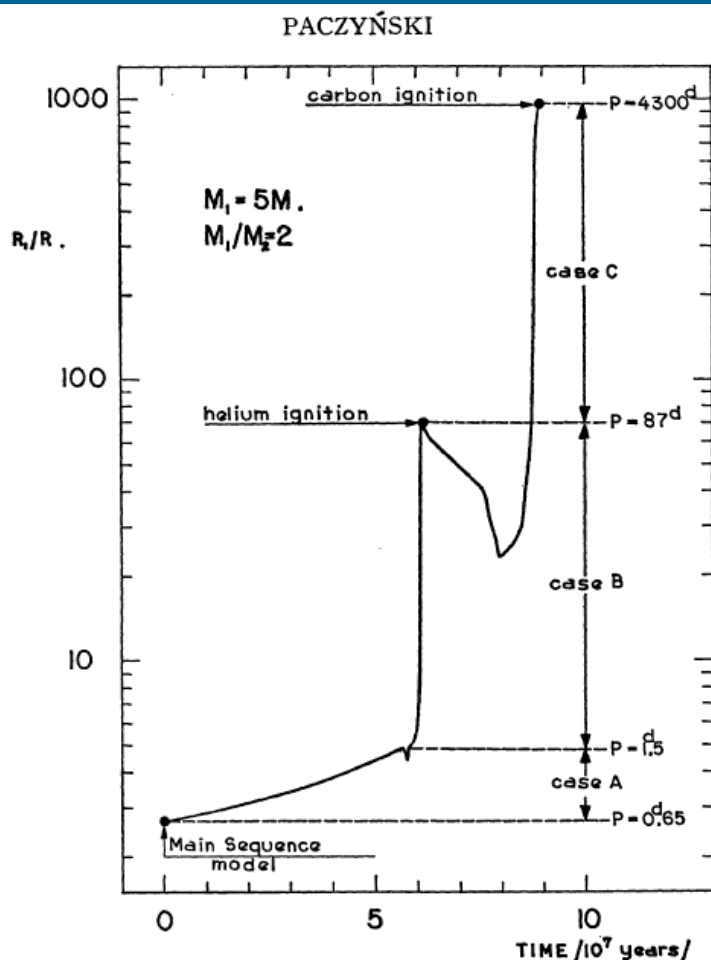


FIGURE 1. The time variation of the radius of a $5 M_\odot$ star. The ranges of orbital corresponding to the evolution with mass exchange in cases A, B, and C are indicated. A mass ratio of $M_1/M_2 = 2$ is adopted.

Three cases of mass transfer loss by the primary star (after R.Kippenhahn)

In most important case B mass transfer occurs on thermal time scale:

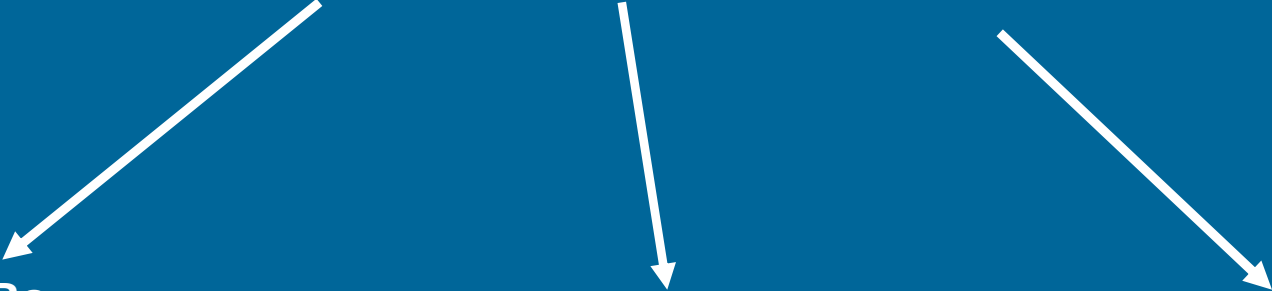
$$dM/dt \sim M/\tau_{KH}, \quad \tau_{KH} = GM^2/RL$$

In case A: on nuclear time scale:

$$dM/dt \sim M/t_{nuc}$$

$$t_{nuc} \sim 1/M^2$$

Close binaries with accreting compact objects



LMXBs

Roche lobe overflow.
Very compact systems.
Rapid NS rotation.
Produce mPSRs.

IMXBs

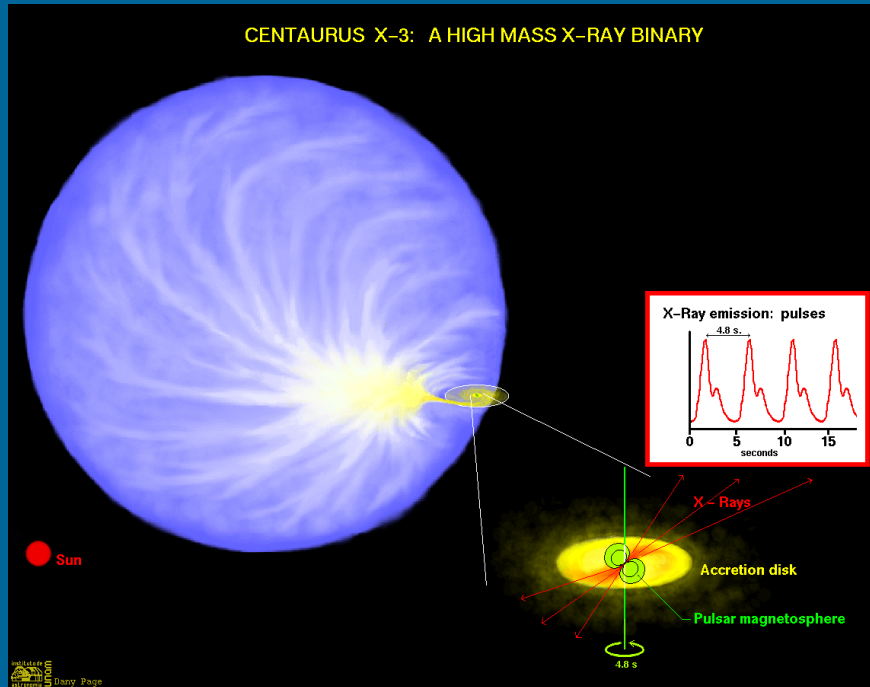
Very rare.
Roche lobe overflow.
Produce LMXBs(?)

HMXBs

Accretion from
the stellar wind.
Mainly Be/X-ray.
Wide systems.
Long NS spin periods.
Produce DNS.

Among binaries ~ 40% are close and ~96% are low and intermediate mass ones.

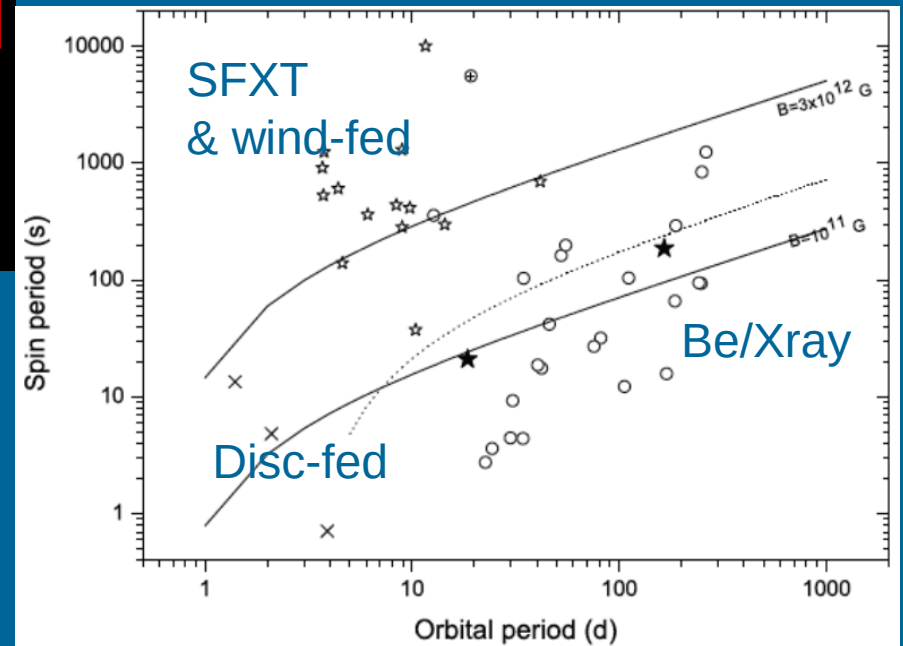
HMXBs



>100 in the Galaxy and >100 in MC

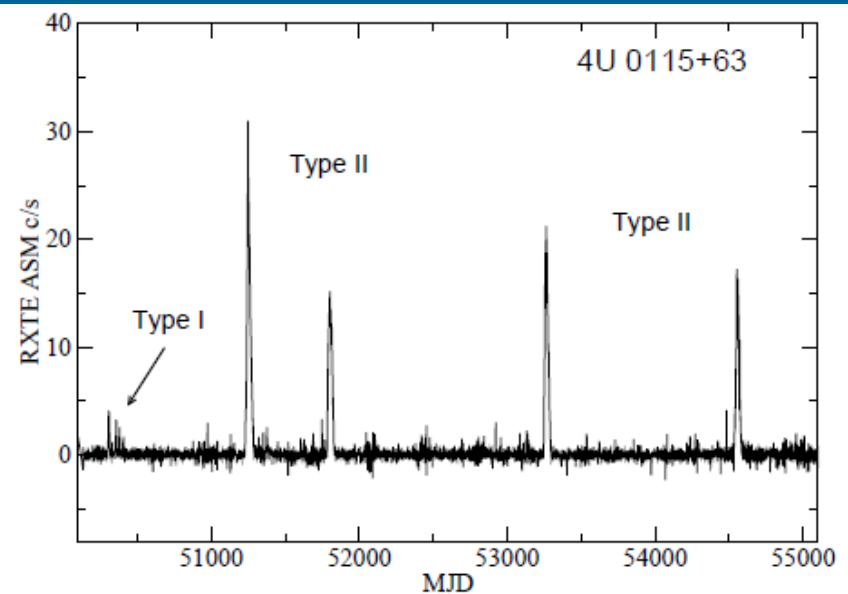
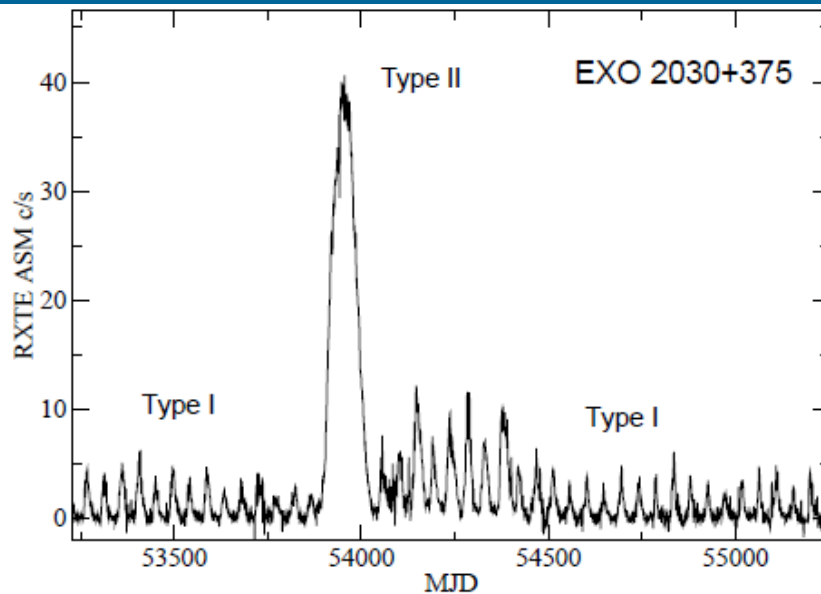
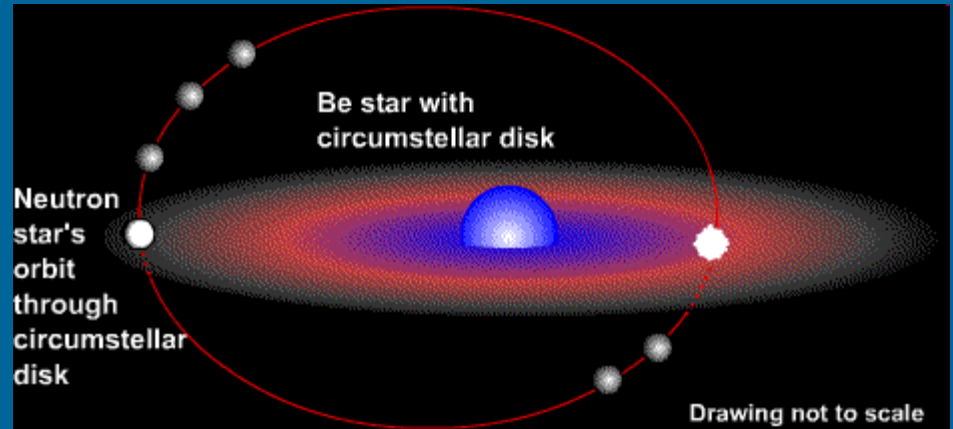
Different types:

- Be/Xray binaries
- SFXT
- “Normal” supergiants
 - disc-fed
 - wind-fed

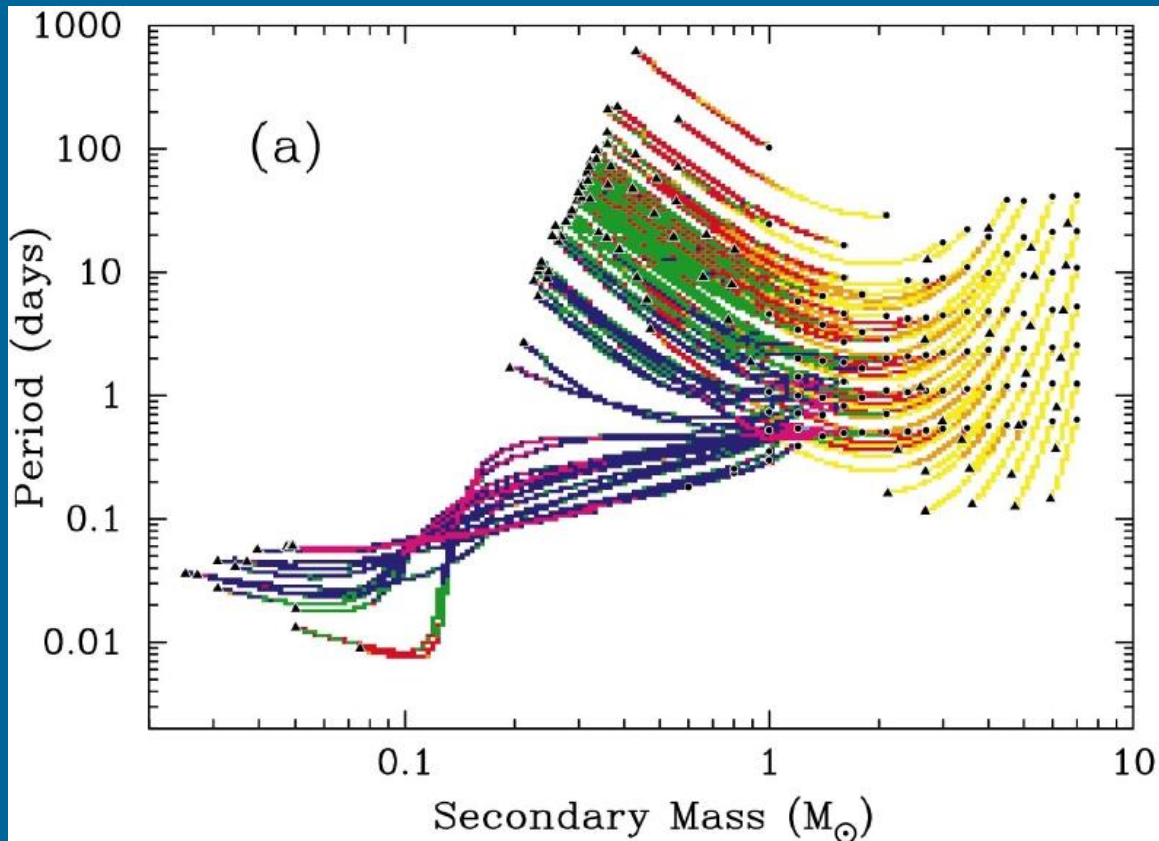


Be/X-ray binaries

Very numerous.
Mostly transient.
Eccentric orbits.



Intermediate mass X-ray binaries



Most of the evolution time systems spend as an X-ray binary occurs after the mass of the donor star has been reduced to $<1M_{\odot}$

Otherwise, more massive systems experiencing dynamical mass transfer and spiral-in.

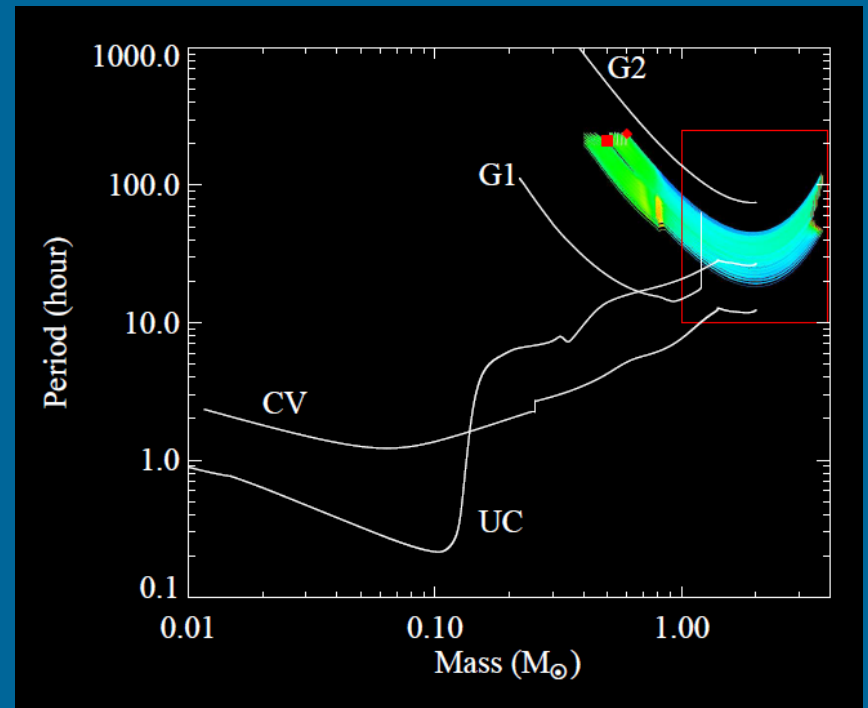
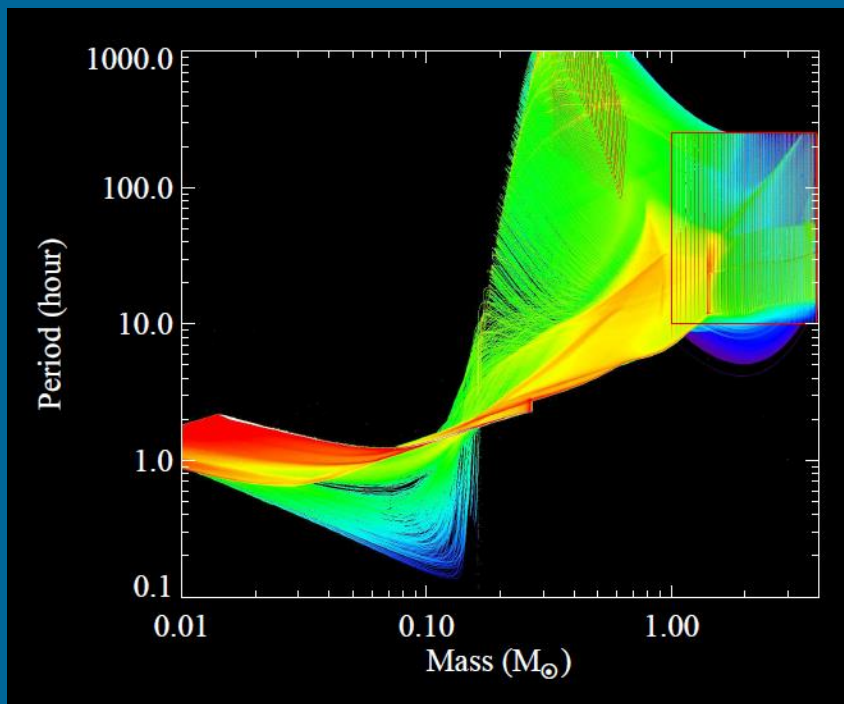
The color of the tracks indicates how much time systems spend in a particular rectangular pixel in the diagrams (from short to long: yellow, orange, red, green, blue, magenta, cyan).

New calculations and specific systems

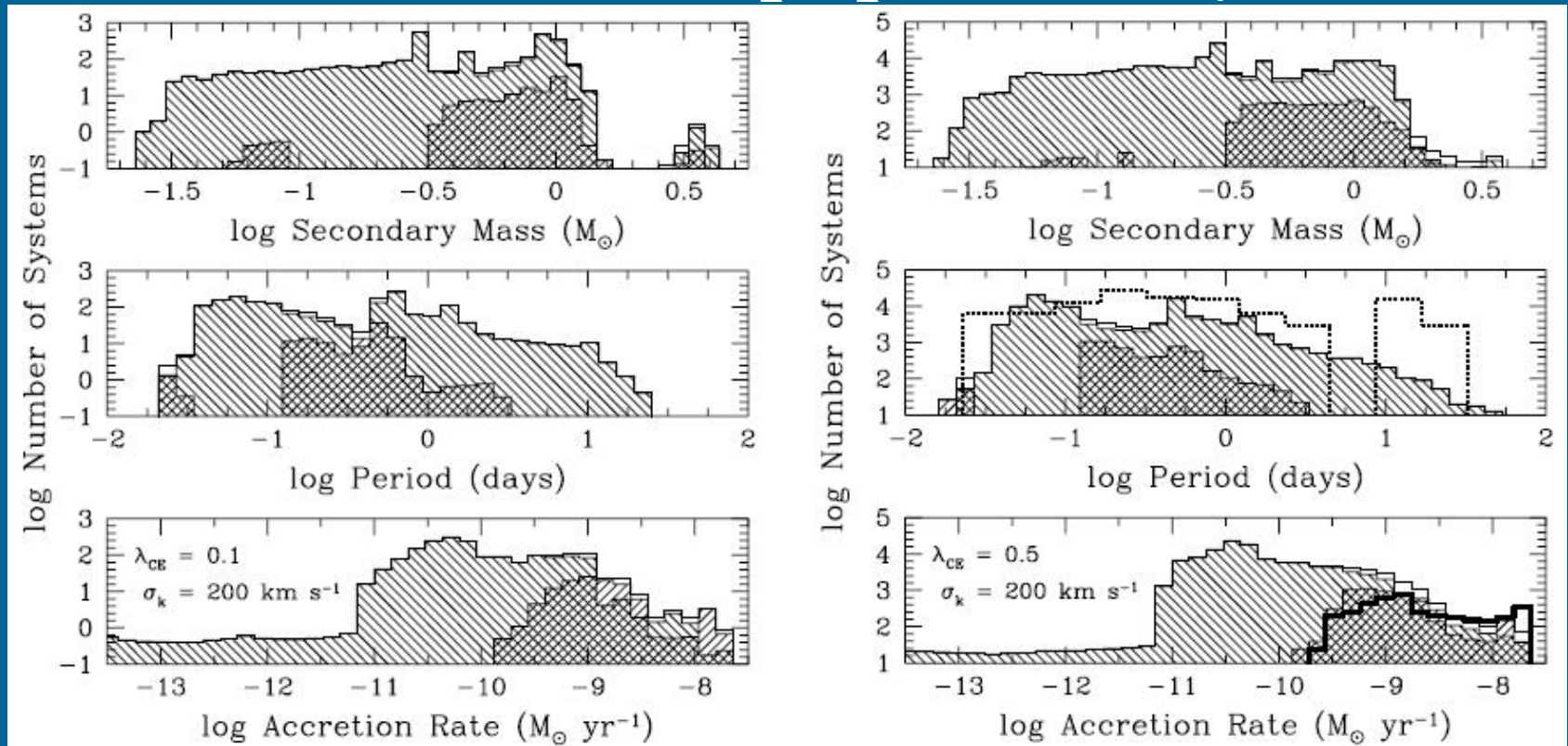
The task: to reproduce with a new code PSR J1614-2230

Red box shows the initial grid of models

The PSR is a “relative” of Cyg X-2

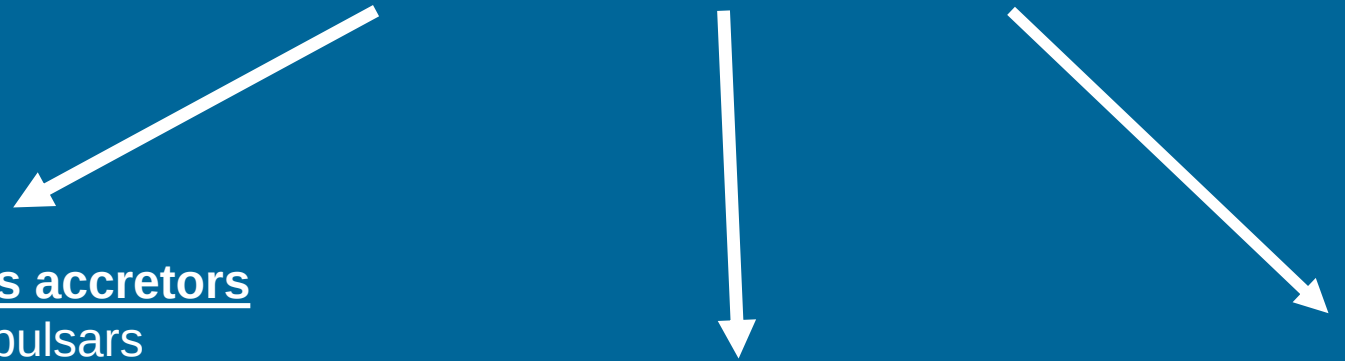


IMXBs and LMXBs population synthesis



The hatched regions indicate persistent (+45) and transient (-45) X-ray sources, and the enclosing solid histogram gives the sum of these two populations. Overlaid (dotted histogram) on the theoretical period distribution in the figure on the right is the rescaled distribution of 37 measured periods (Liu et al. 2001) among 140 observed LMXBs in the Galactic plane.

Low mass X-ray binaries



NSs as accretors

X-ray pulsars
Millisecond X-ray pulsars
Bursters
Atoll sources
Z-type sources

WDs as accretors

Cataclysmic variables

- Novae
- Dwarf novae
- Polars
- Intermediate polars

Supersoft sources (SSS)

BHs as accretors

X-ray novae
Microquasars
Massive X-ray binaries

LMXBs with NSs or BHs

The latest large catalogue (Li et al. arXiv: 0707.0544) includes 187 galactic and Magellanic Clouds LMXBs with NSs and BHs as accreting components. Donors can be WDs, or normal low-mass stars (main sequence or sub-giants). Many sources are found in globular clusters. Also there are more and more LMXBs found in more distant galaxies.

In optics the emission is dominated by an accretion disc around a compact object. Clear classification is based on optical data or on mass function derived from X-ray observations. If a source is unidentified in optics, but exhibits Type I X-ray bursts, or just has a small (<0.5 days) orbital period, then it can be classified as a LMXB with a NS. In addition, spectral similarities with known LMXBs can result in classification.

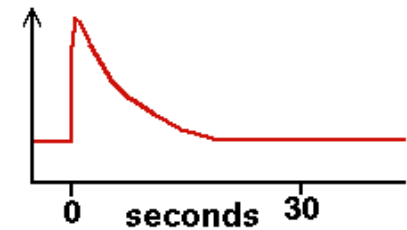
A Low Mass X-Ray Binary: 4U 1820-30



White Dwarf

130,000 km

X-Ray Emission: BURSTS



X - Rays

Accretion Disk

Neutron Star

1,200 km/sec

SUN

Semidetached binary systems
of small and intermediate masses

AML (W UMa)
Merging at MS
MS or Giant
2%

5

Merging in CE
7

He* + MS

6
WD + MS or SG
35%

11
WD + MS

10
WD
0.2%

8
WD
0.2%

4
SN II NS
0.7%

3
WD
18%

12
CV, SSS
0.7%

AIC

LMXB

13
WD + sdHe*

14
SN or N?

15
Binary WD
14%

16
SN Ia
0.6%

17
sdB

18
AM CVn
0.1%

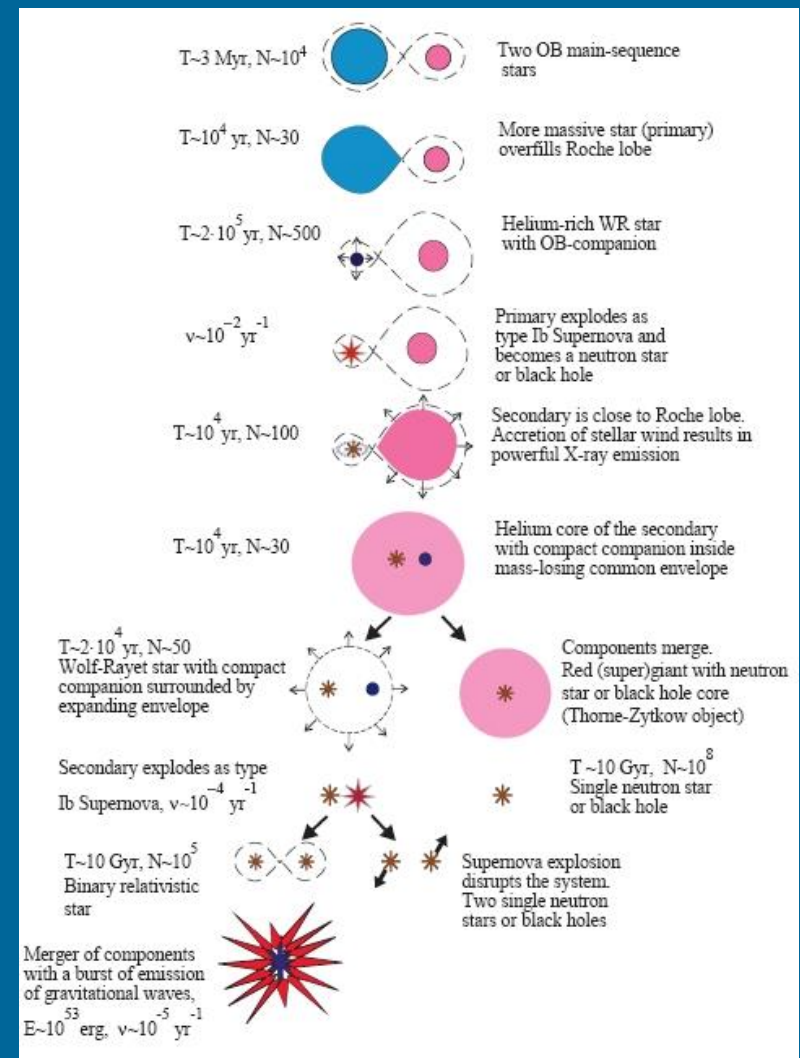
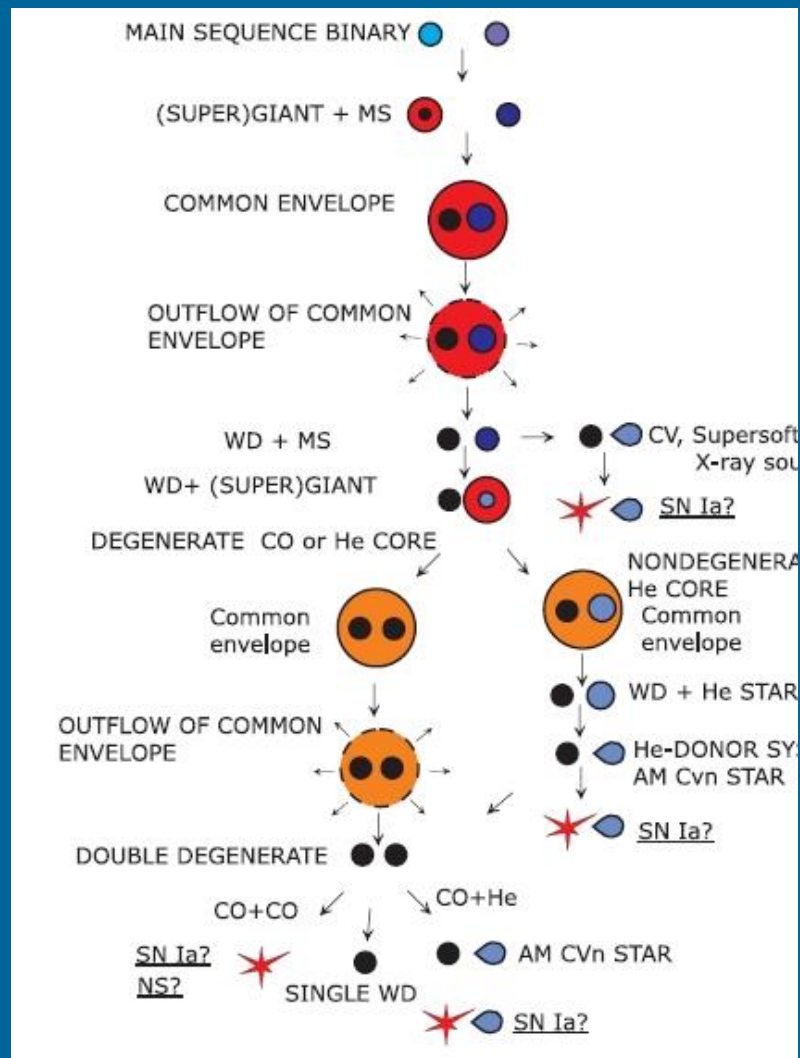
19
LMXB

20
SN Ia
0.6%

21
sdB

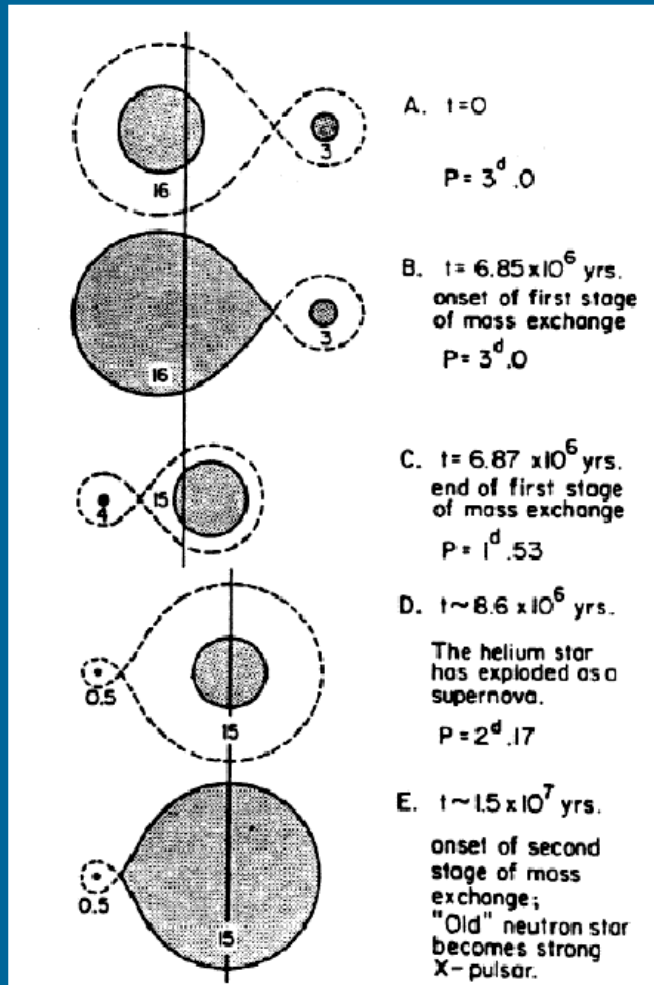
[Yungelson L R, in Interacting Binaries: Accretion, Evolution, Out-Comes 2005]

Evolution of close binaries



(Postnov, Yungelson 2007)

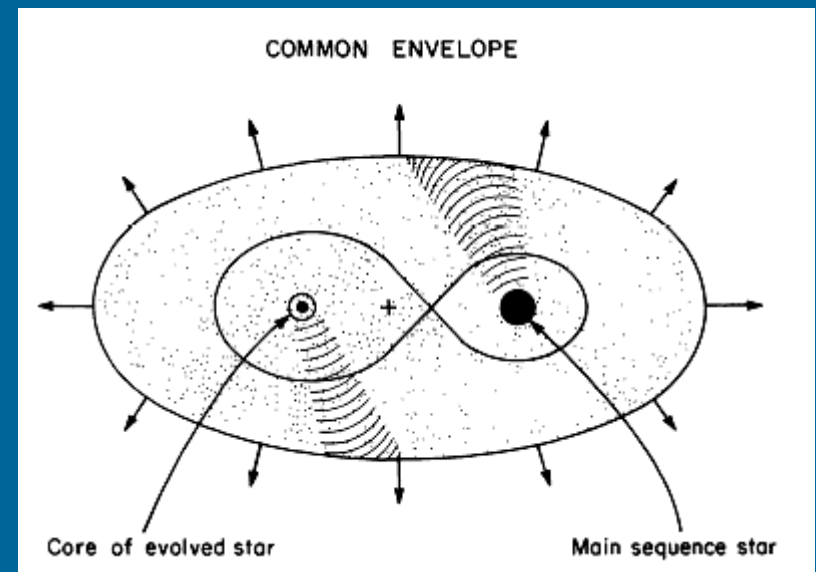
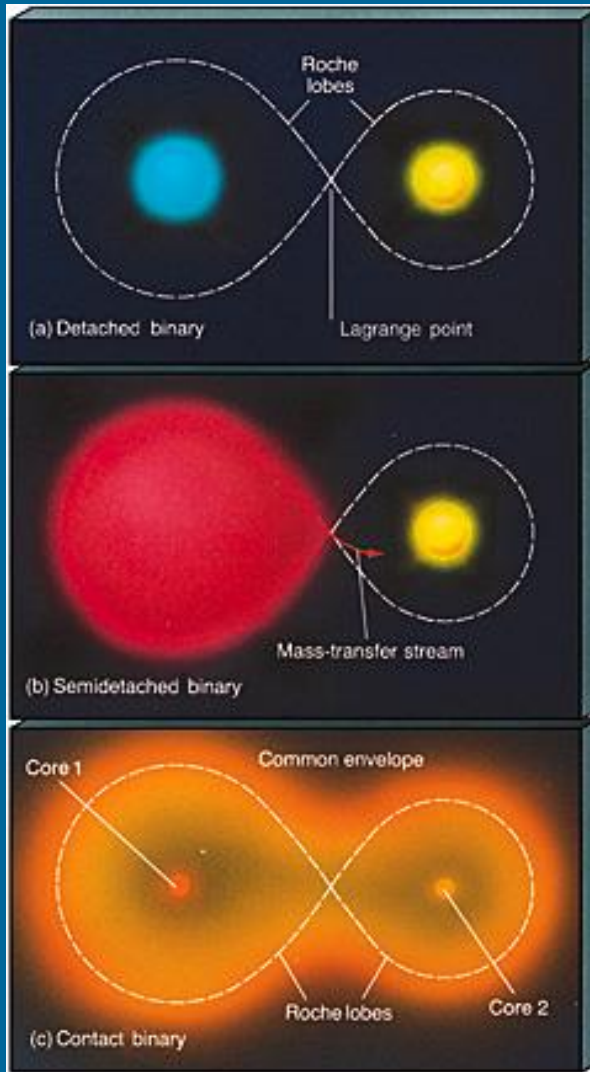
First evolutionary “scenario” for the formation of X-ray binary pulsar



Common envelope

Problem: How to make close binaries with compact stars (CVs, XRBs)?
Most angular momentum from the system should be lost.

Non-conservative evolution:
Common envelope stage
(B.Paczynski, 1976)



Dynamical friction is important

Tidal effects on the orbit (Zahn, 1977)

1. Circularization

$$\begin{aligned} t_{\text{circ}} &\sim (q(1+q)/2)^{-1} (a/R)^8 \\ &\sim 10^6 q^{-1} ((1+q)/2)^{5/3} P^{16/3} \quad \text{years} \end{aligned}$$

2. Synchronization of component's rotation

$$t_{\text{sync}} \sim q^{-2} (a/R)^6 \sim 10^4 ((1+q)/2q)^2 P^4 \quad \text{years}$$

Both occur on a much shorter timescale than stellar evolution!

Conservative mass transfer

$$M = M_1 + M_2 = \text{const}$$

$$\text{Assuming (B.Paczynski): } J_{orb} = \frac{M_1 M_2}{M} \sqrt{aM} = \text{const}$$

$\Rightarrow$ Change of orbital parameters after mass transfer:

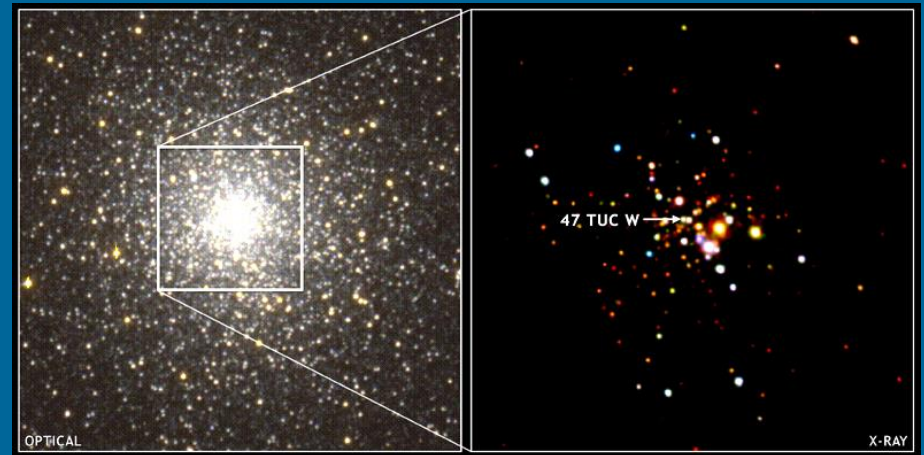
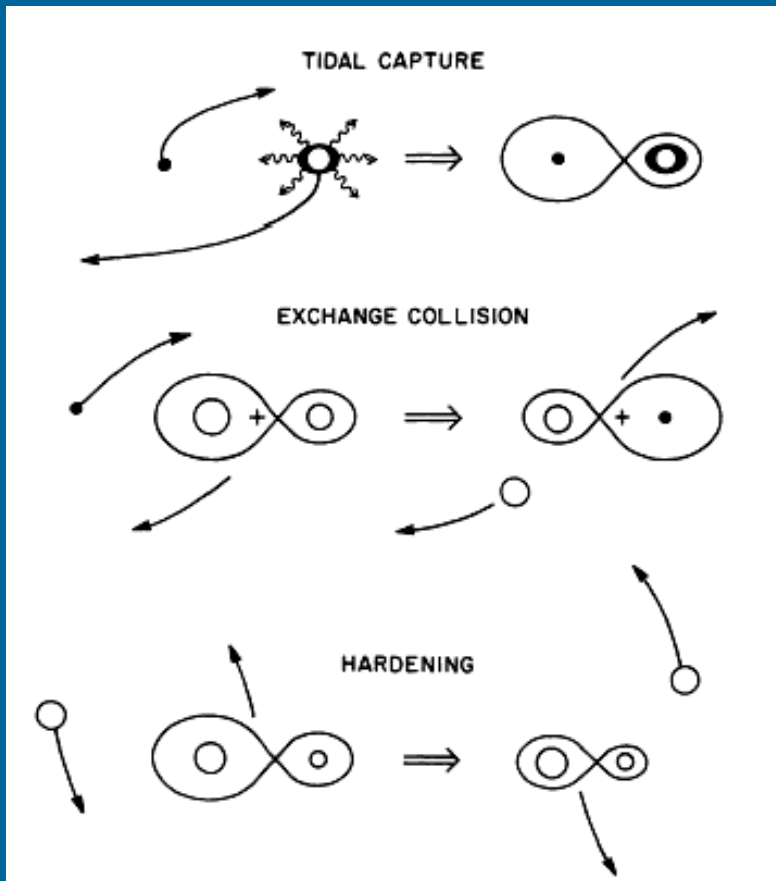
$$M_1' = M_1 - \Delta M, \quad M_2' = M_2 + \Delta M,$$

$$\frac{\Delta a}{a} = 2\Delta M \frac{M_2 - M_1}{M_1 M_2} \quad \begin{cases} > 0, & \text{if } M_2 > M_1 \\ < 0, & \text{if } M_2 < M_1 \end{cases}$$

Non-conservative evolution

- *Massive binaries: stellar wind, supernova explosions, common envelopes*
- *Low-massive binaries: common envelopes, magnetic stellar winds, gravitational wave emission (CVs, LMXBs)*
- *Stellar captures in dense clusters (LMXBs, millisecond pulsars)*

Binaries in globular clusters



Hundreds close XRB and millisecond pulsars are found in globular clusters

Formation of close low-mass binaries is favored in dense stellar systems due to various dynamical processes

Isotropic wind mass loss

- Effective for massive early-type stars on main sequence or WR-stars
- Assuming the wind carrying out specific orbital angular momentum yields:

$$a(M_1 + M_2) = \text{const} \rightarrow$$

$$\Delta a/a = -\Delta M/M > 0$$

The orbit always gets wider!

Supernova explosion

- First SN in a close binary occurs in almost circular orbit $\rightarrow \Delta M = M_1 - M_c$, M_c is the mass of compact remnant
- Assume SN to be instantaneous and symmetric

Energy-momentum conservation $\Rightarrow$

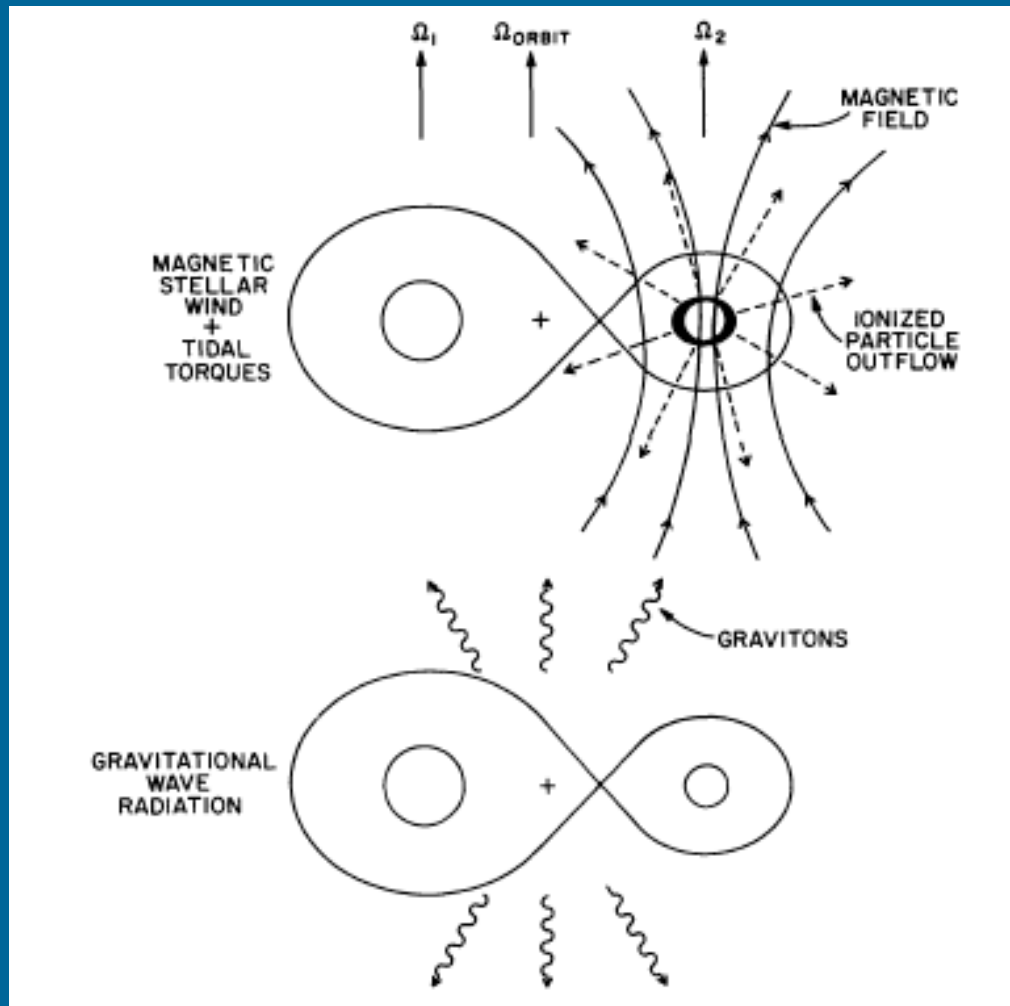
$$\frac{a_f}{a_i} = \left[2 - \frac{M_1 + M_2}{M_c + M_2} \right]^{-1}$$

$$e = \frac{\Delta M}{M_c + M_2}$$

$\rightarrow$ If more than half of the total mass is lost, the system becomes unbound

BUT: Strong complication and uncertainty: Kick velocities of NS!

Angular momentum loss



- Magnetic stellar wind.

Effective for main sequence stars with convective envelopes
 $0.3 < M < 1.5 M_{\odot}$

- Gravitational radiation.

Drives evolution of binaries with $P < 15$ hrs

Especially important for evolution of low-mass close binaries!

Mass loss due to MSW and GW

Axial rotation braking of single G-dwarfs (Skumanich, 1972)

$$V \sim t^{-1/2}, \text{ where } t \text{ is the age}$$

Physics: stellar wind plasma ``streams" along magnetic field lines until $\rho v^2 \sim B^2(r)/4\pi$, so carries away much larger specific angular momentum (Mestel).

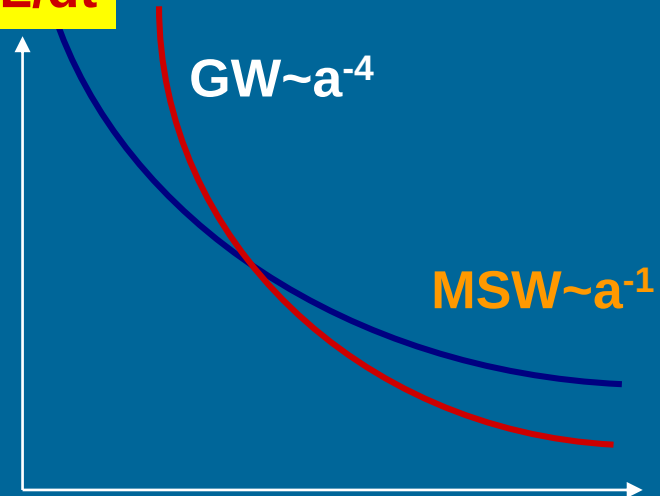
Assume the secondary star in a low-mass binary ($0.4 \leq M_2 \leq 1.5 M_\odot$) experiences m.s.w. Tidal forces tend to keep the star in corotation with orbital revolution: $\omega_2 = \omega$. Angular momentum conservation then leads to:

$$\frac{dL_{orb}}{dt} = \frac{dJ_2}{dt}$$

Recalling that: $L_{orb} = \mu \omega a^2$ and using Kepler's 3d law we get

$$\frac{d \ln L_{orb}}{dt} \sim - \frac{R_2^4}{M_1} \frac{GM^2}{a^5} \Rightarrow$$

dL/dt

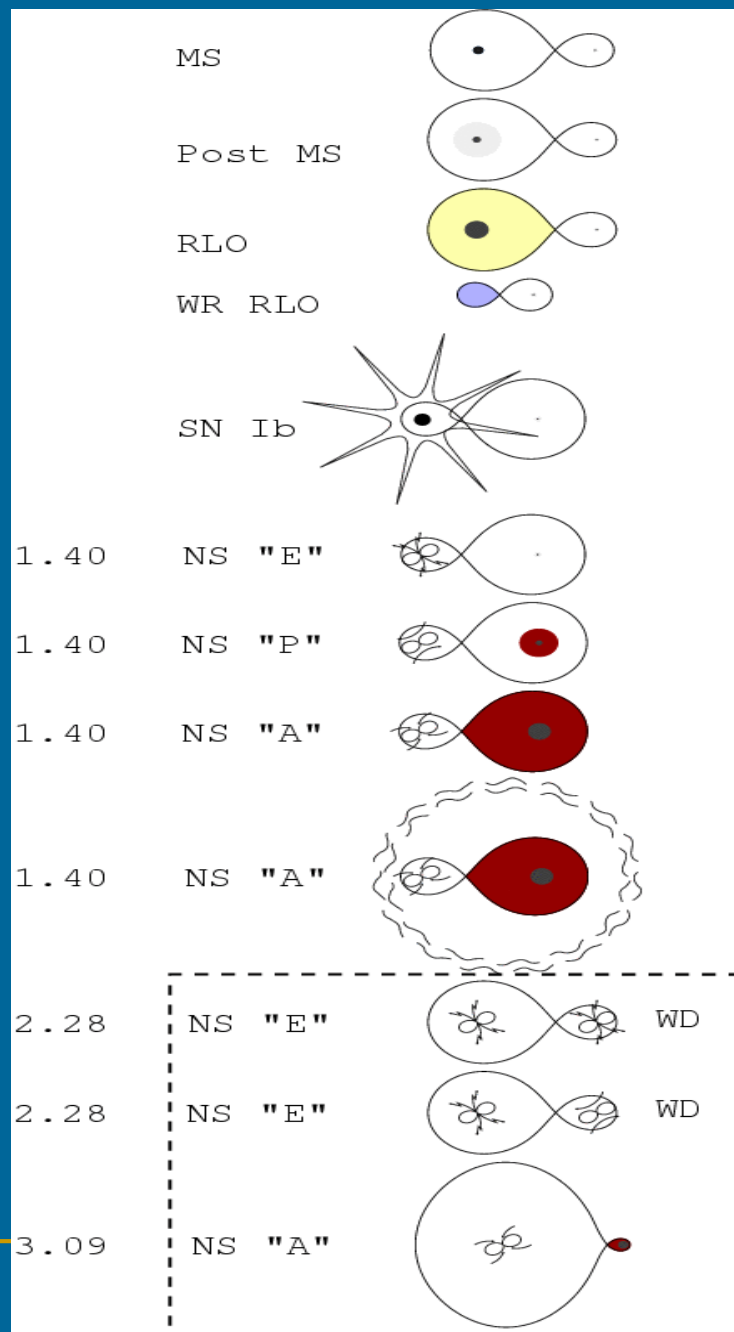


MSW is more effective at larger orbital periods, but GW always wins at shorter periods! Moreover, MSW stops when $M_2 \sim 0.3-0.4 M_\odot$ where star becomes fully convective and dynamo switches off.

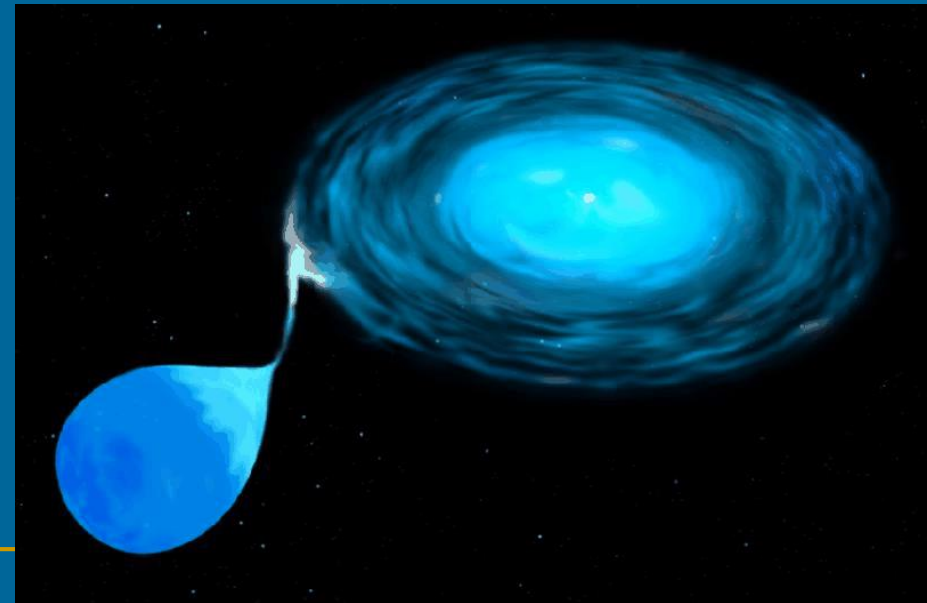
Binary evolution: Major uncertainties

- All uncertainties in stellar evolution (convection treatment, rotation, magnetic fields...)
- Limitations of the Roche approximation (synchronous rotation, central density concentration, orbital circularity)
- Non-conservative evolution (stellar winds, common envelope treatment, magnetic braking...)
- For binaries with NS (and probably BH): effects of supernova asymmetry (natal kicks of compact objects), rotational evolution of magnetized compact stars (WD, NS)

Evolution



NSs can become very massive during their evolution due to accretion.



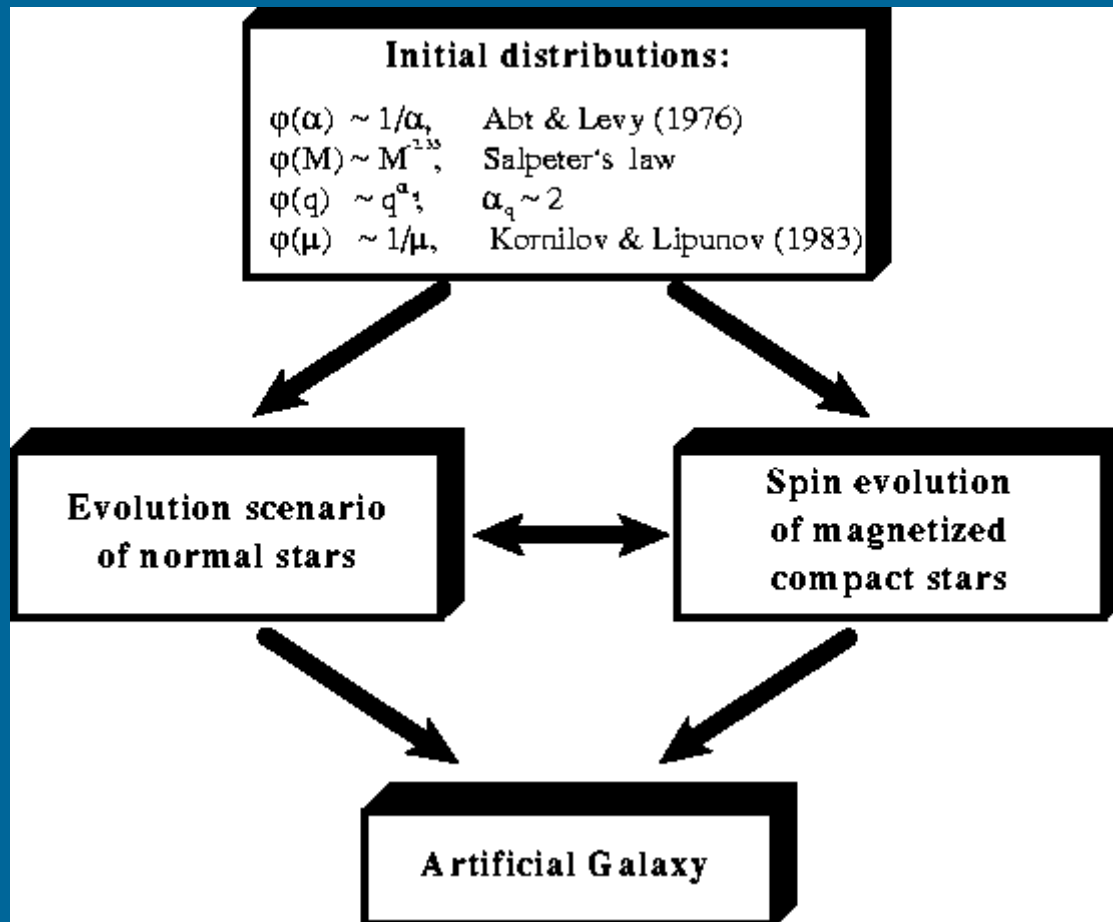
Population synthesis of binary systems

Interacting binaries are ideal subject for population synthesis studies:

- There are many of them observed
- Observed sources are very different
- However, they come from the same population of progenitors...
- ... whose evolution is non-trivial, but not too complicated.
- There are many uncertainties in evolution ...
- ... and in initial parameter
- We expect to discover more systems
- ... and more types of systems
- With new satellites it really happens!

See a review on binary popsynthesis in 1808.06883

Scenario machine

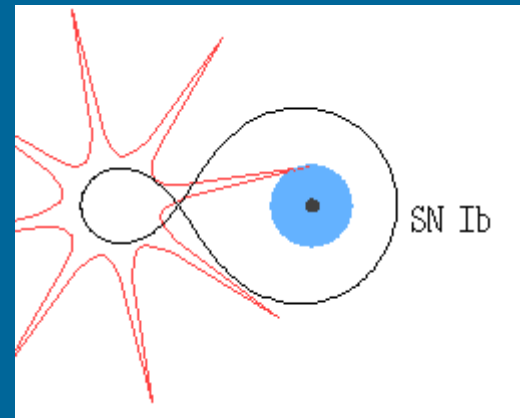
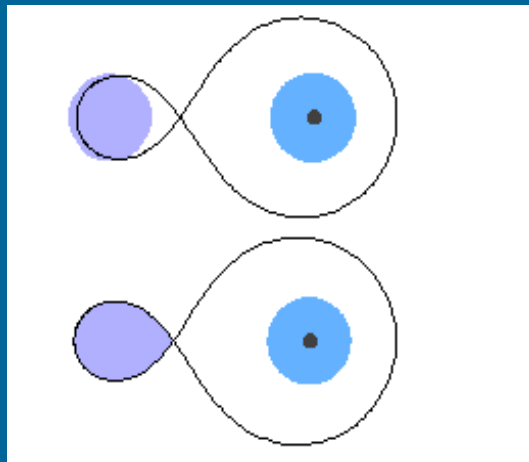
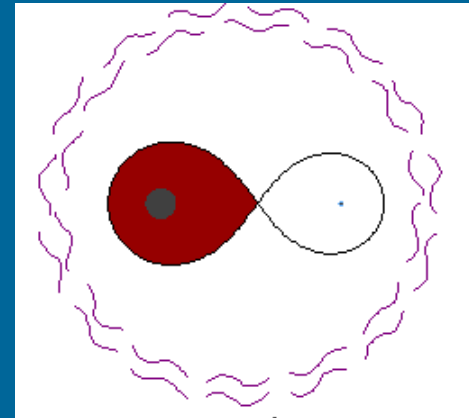
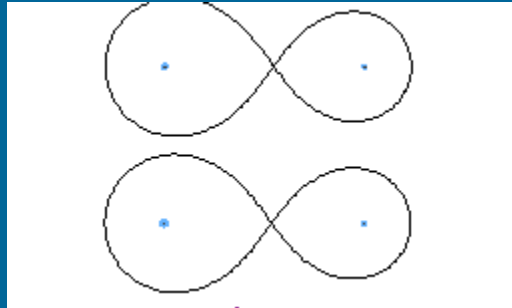
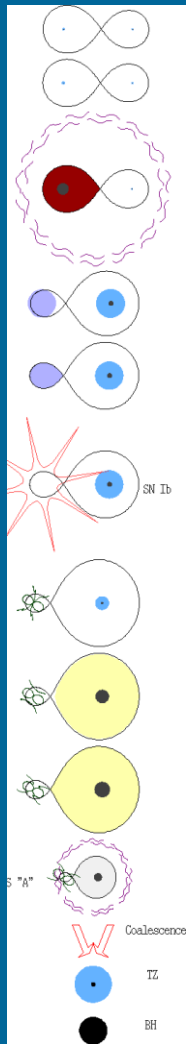


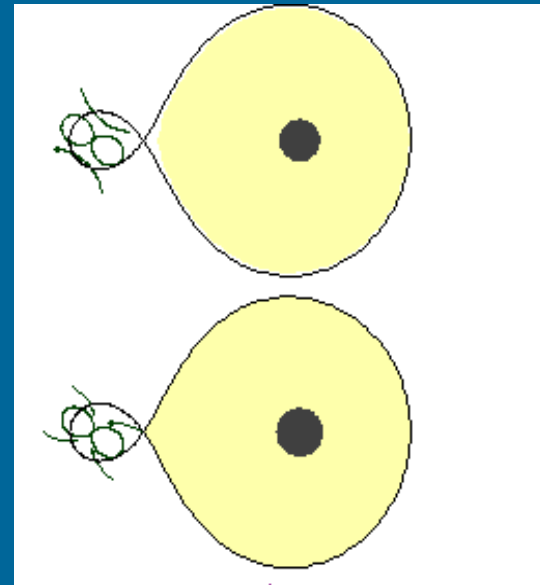
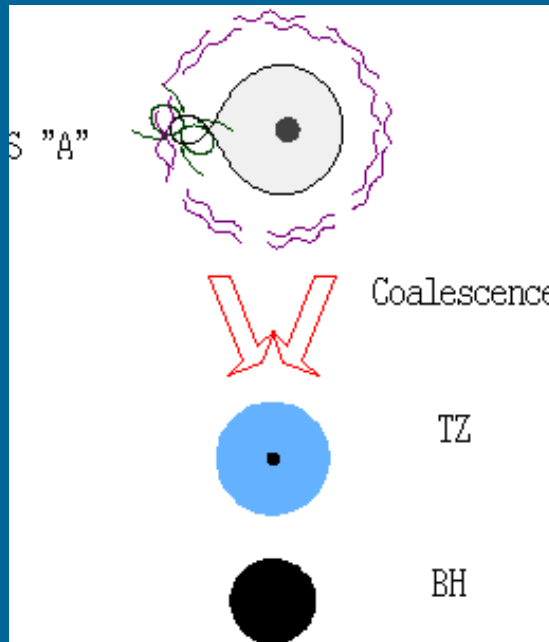
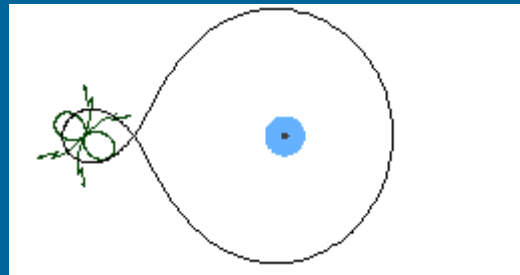
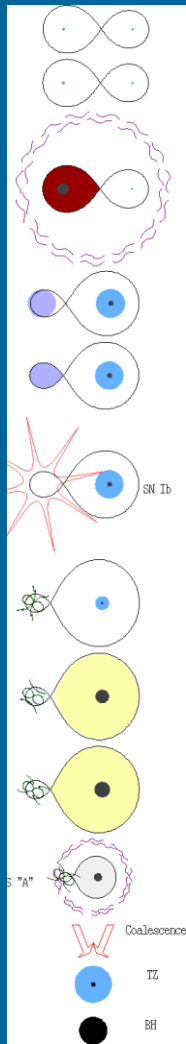
There are several groups in the world which study evolution of close binaries using population synthesis approach.

Examples of topics

- Estimates of the rate of coalescence of NSs and BHs
- X-ray luminosities of galaxies
- Calculation of mass spectra of NSs in binaries
- Calculations of SN rates
- Calculations of the rate of short GRBs

Evolution of close binaries





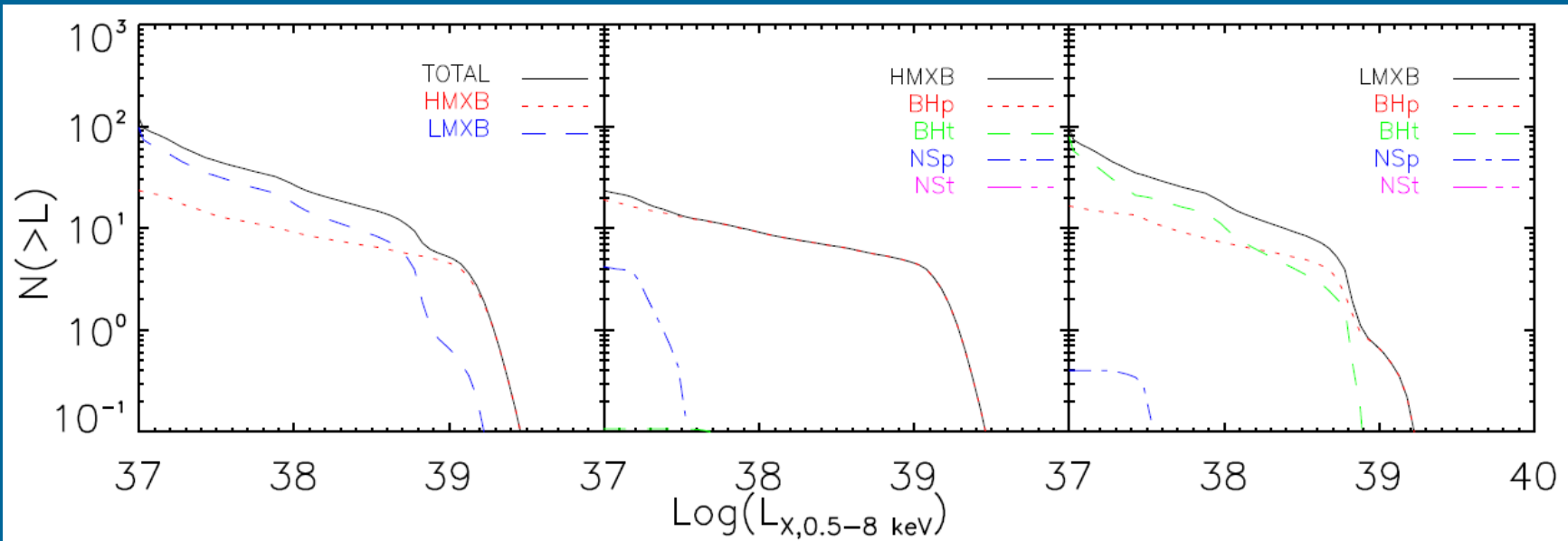
("Scenario Machine" calculations)

<http://xray.sai.msu.ru/sciwork/>

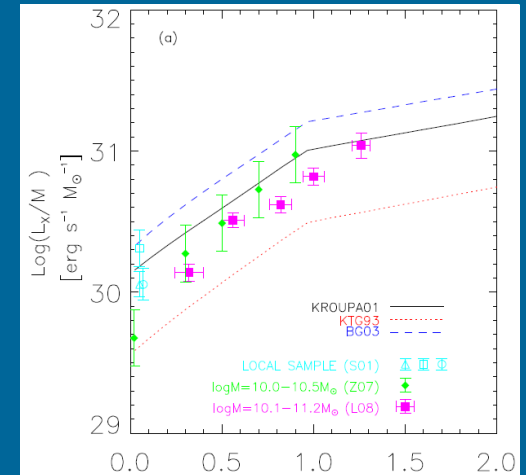
The role of binaries in the properties of galaxies

The authors use the code by Hurley et al.
to model X-ray luminosity of a late-type galaxy.

cumulative X-ray luminosity function

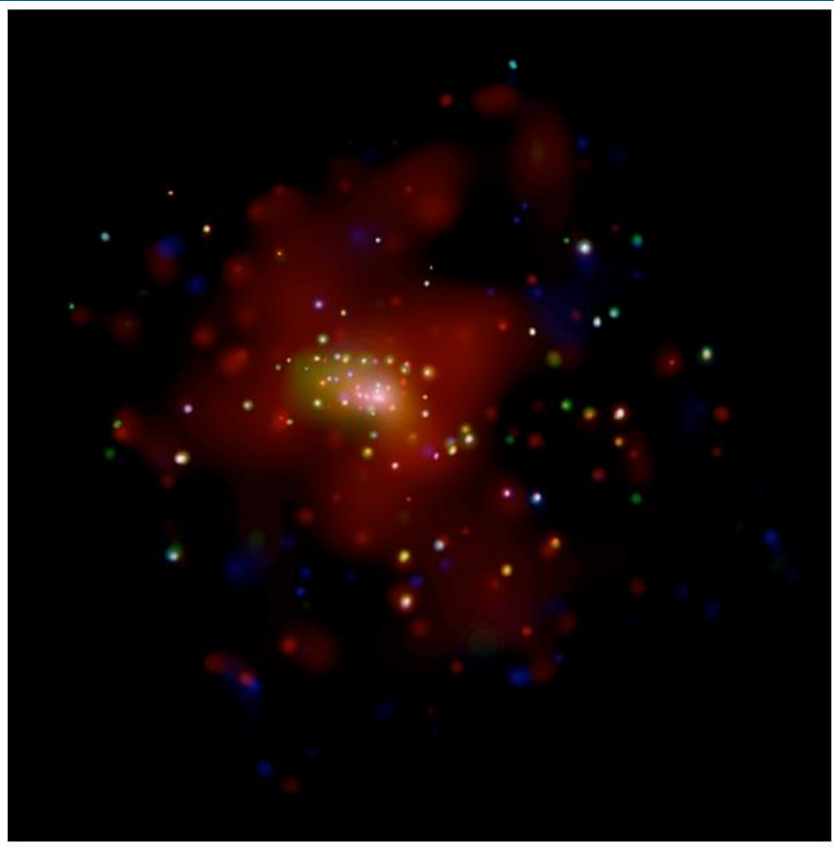


Evolution of L_x with z

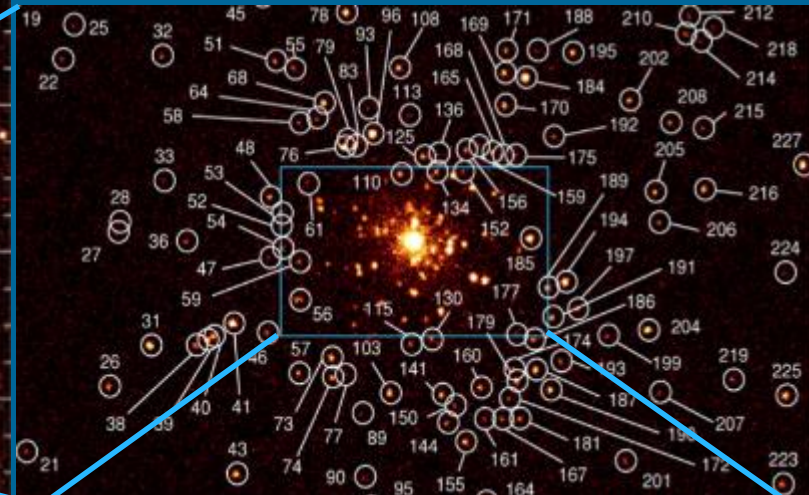
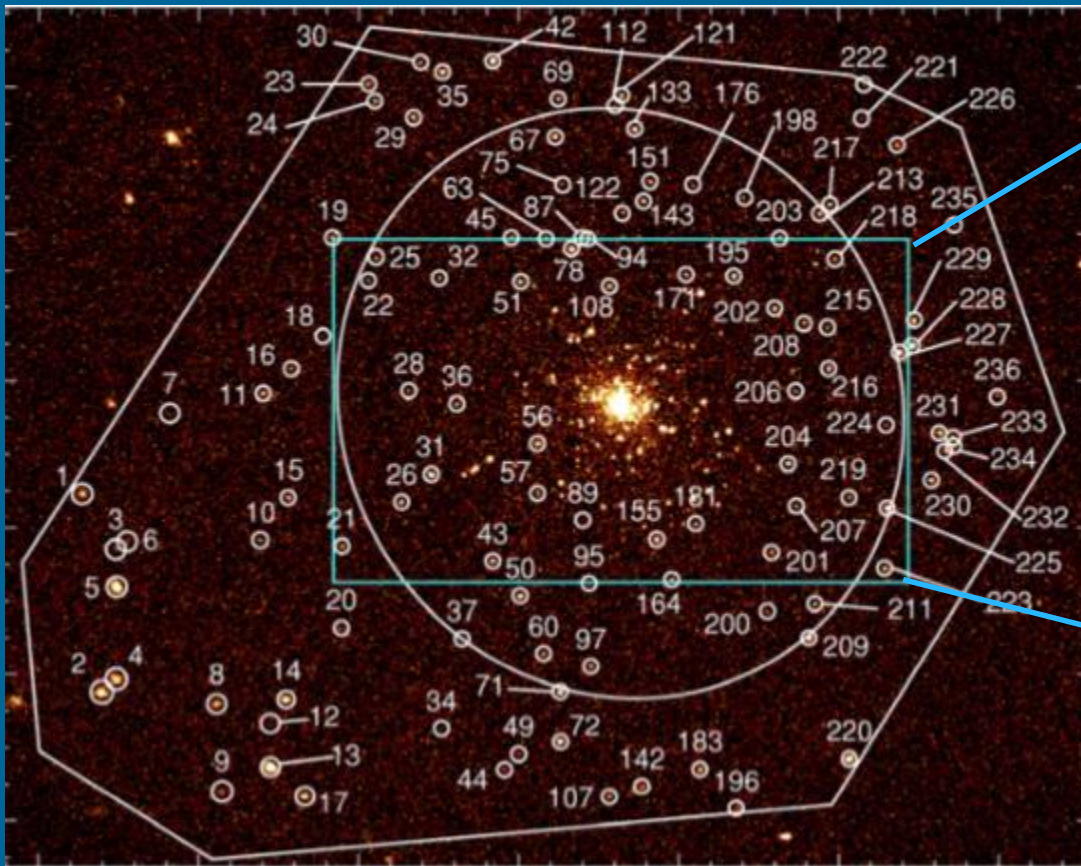


Extragalactic binaries

It is possible to study galactic-like binaries up to 20-30 Mpc.
For example, in NGC 4697 80 sources are known thanks to *Chandra*
(this is an early type galaxy, so most of the sources are LMXBs).



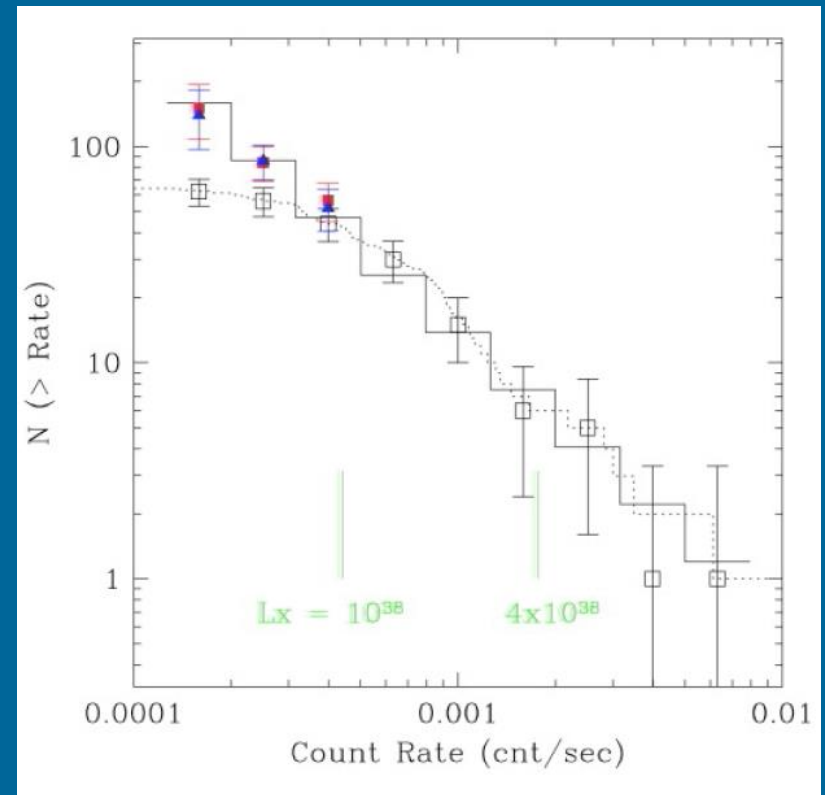
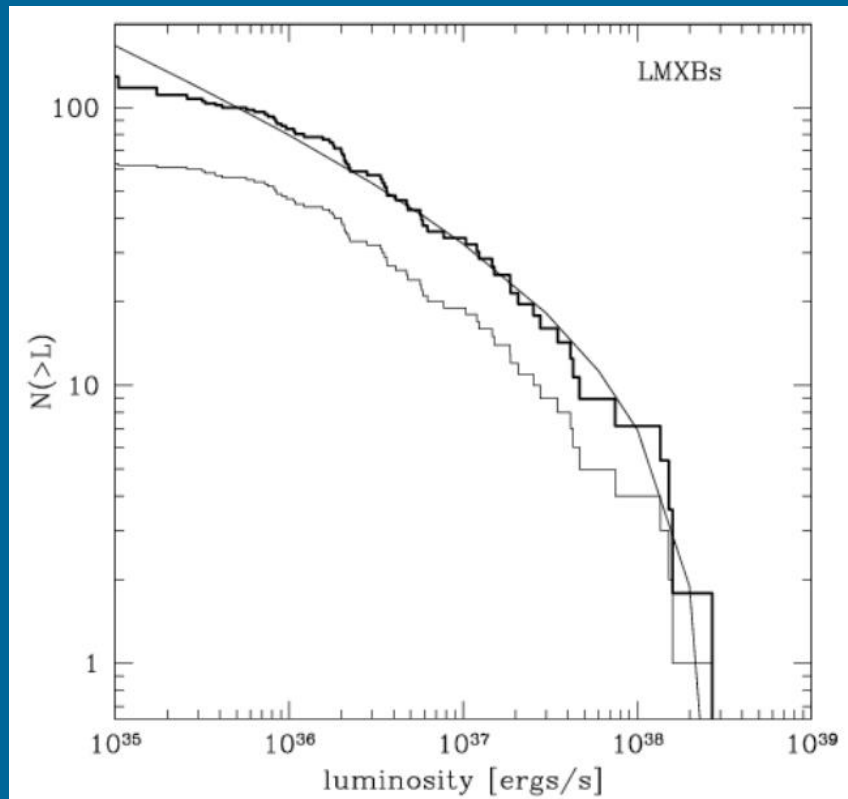
NGC 4278



Chandra data

1903.01970

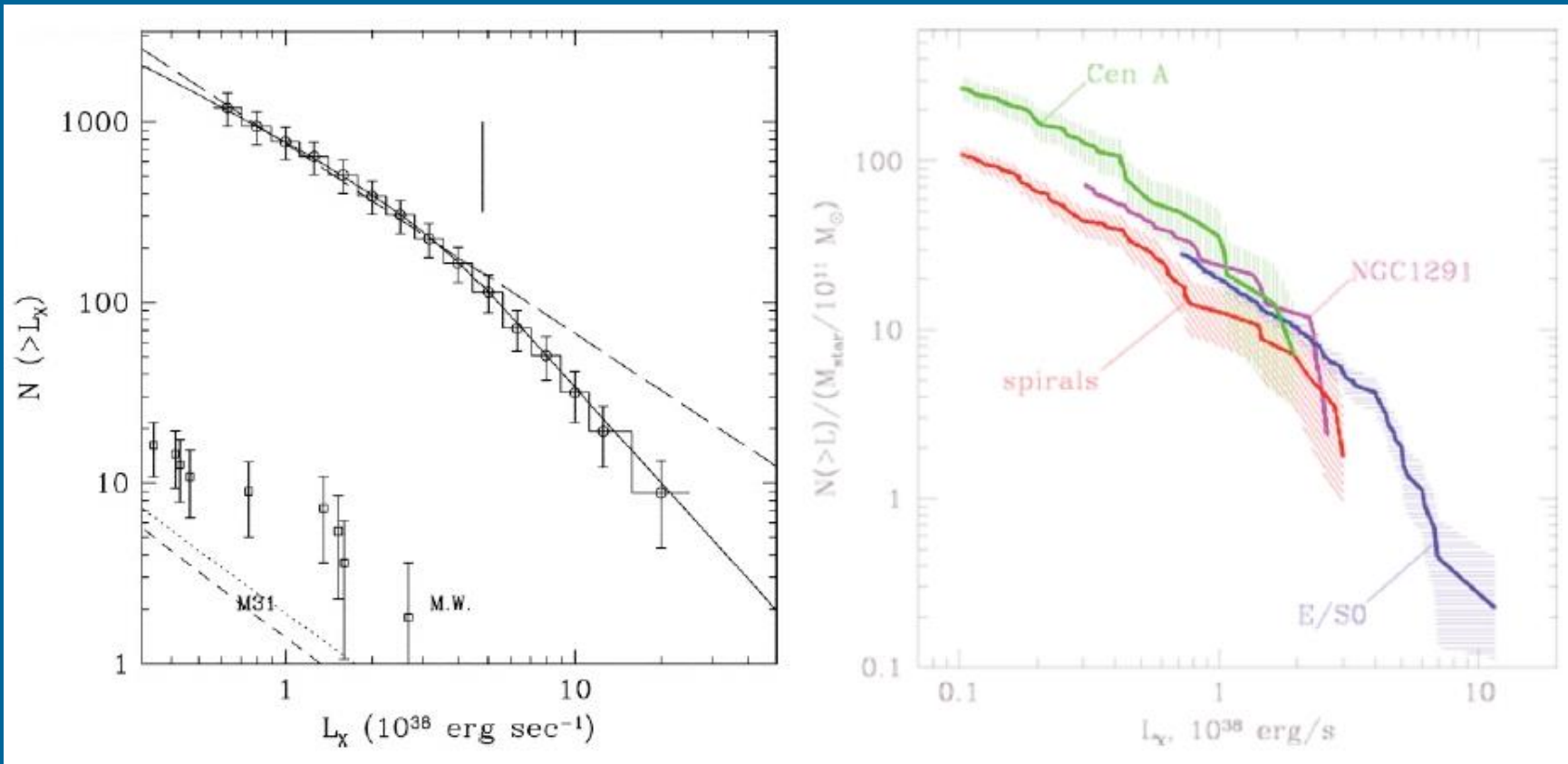
LMXBs luminosity function



LMXB Galactic luminosity function
(Grimm et al. 2002)

LMXB luminosity function for NGC 1316
(Kim and Fabbiano 2003)

LMXBs luminosity function



Cumulated XLF for 14 early-type galaxies.

(see Fabbiano astro-ph/0511481)

List of reviews

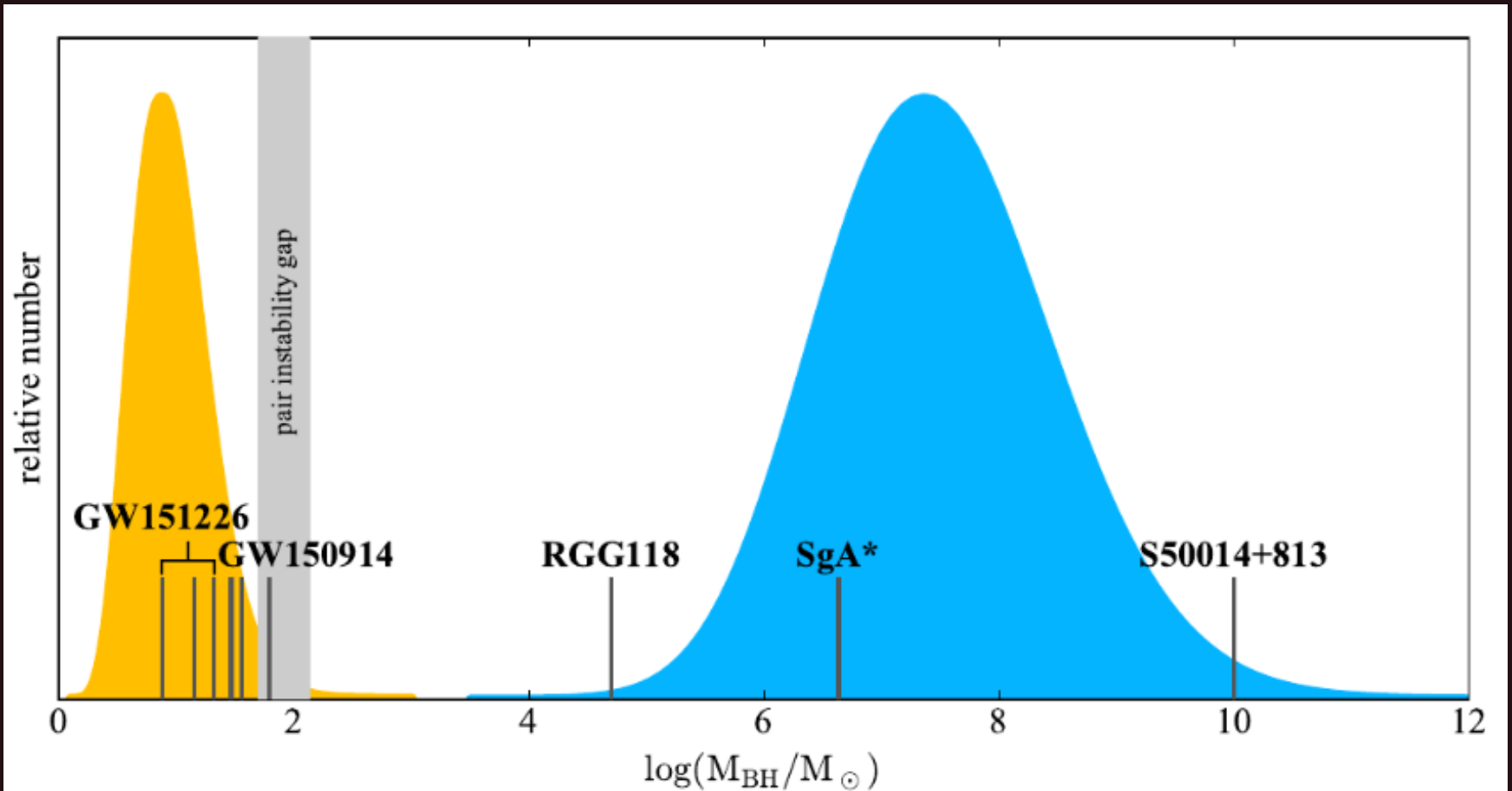
- Catalogue of LMXBs. Li et al. arXiv:0707.0544
- Catalogue of HMXBs. Li et al. arXiv: 0707.0549
- Evolution of binaries. Postnov & Yungelson. astro-ph/0701059
- Extragalactic XRBs. Fabbiano. astro-ph/0511481, 1903.01970
- General review on accreting NSs and BHs. Psaltis. astro-ph/0410536
- CVs
 - Evolution. Ritter. arXiv:0809.1800
 - General features. Smith. astro-ph/0701564
- Modeling accretion: Done et al. arXiv:0708.0148
- NS binaries: Sudip Bhattacharyya arXiv: 1002.4480
- Be/X-ray binaries: Pablo Reig arXiv: 1101.5036
- Population synthesis. Popov & Prokhorov. Physics Uspekhi (2007)
- X-ray emission from black-hole and neutron-star binaries Belloni 1803.03641



Supermassive black holes



Black hole masses



Plan of the lecture

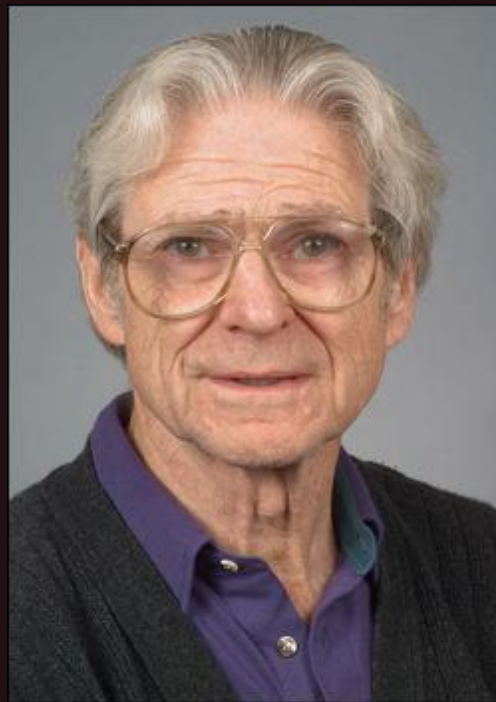
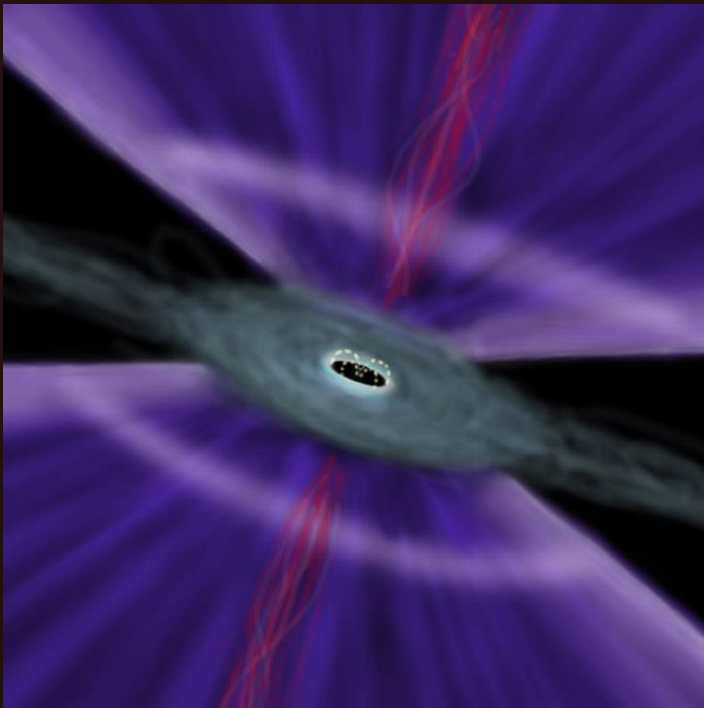
1. General information about SMBHs.
2. “Our” certain black hole: Sgr A*.
3. SMBHs: from radio to gamma. AGNs.
4. Mass measurements

Main reviews

- [arxiv: 1609.03562, 0907.5213](#) **Supermassive Black Holes**
- [astro-ph/0512194](#) **Constraints on Alternatives to Supermassive Black Holes**
- [astro-ph/0411247](#) **Supermassive Black Holes in Galactic Nuclei:
Past, Present and Future Research**
- [arXiv: 0904.2615, 1001.3675, 1108.5102](#) **Mass estimates (methods)**
- [arXiv: 1302.2643](#) **The Mass of Quasars**
- [arXiv: 1504.03330](#) **Elliptical Galaxies and Bulges of Disk Galaxies:
Summary of Progress and Outstanding Issues**
- [arXiv: 1501.02171](#) **The Galactic Center Black Hole Laboratory**
- [arXiv: 1501.02937](#) **Galaxy bulges and their massive black holes**
- **IMBHs: Koliapanos 1801.01095, Mezcua 1705.09667**
- [arXiv: 1707.07134](#) **AGN**

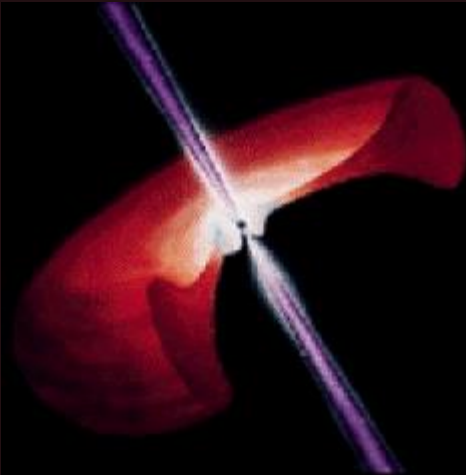
Some history

The story starts in 60-s when the first quasars have been identified (Schmidt 1963). Immediately the hypothesis about accretion onto supermassive BHs was formulated (Salpeter, Zeldovich, Novikov, Linden-Bell).

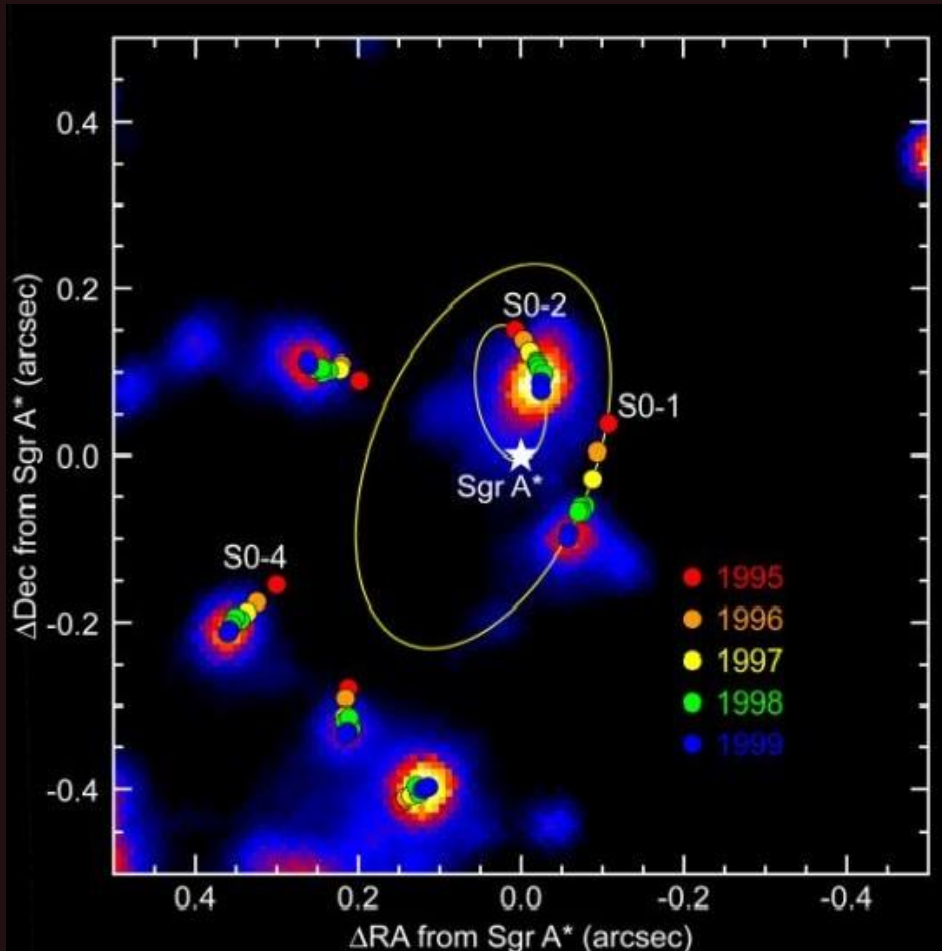


General info

- All galaxies with significant bulges should have a SMBH in the center.
- SMBH are observed already at redshifts $z \sim 6$ and even further
- Several percent of galaxies have active nuclei
- Now we know tens of thousand of quasars and AGNs, all of them can be considered as objects with SMBHs
- Measured masses of SMBHs are in the range $10^6 - 10^{10}$ solar masses.
- Masses are well-measured for tens of objects.
- The most clear case of a SMBH is Sgr A*.



Sgr A*



The case of Sgr A* is unique. Thanks to direct measurements of several stellar orbits it is possible to get a very precise value for the mass of the central object.

Also, there are very strict limits on the size of the central object. This is very important taking into account alternatives to a BH.

The star SO-2 has the orbital period 15.2 yrs and the semimajor axis about 0.005 pc.

See [astro-ph/0309716](#) for some details

The region around Sgr A*



The result of summation of 11 expositions by Chandra (590 ksec).

Red 1.5-4.5 keV,
Green 4.5-6 keV,
Blue 6-8 keV.

The field is 17 to 17 arcminutes
(approximately 40 to 40 pc).

Multiwavelength observations of Sgr A*
are summarized in 1501.02164.

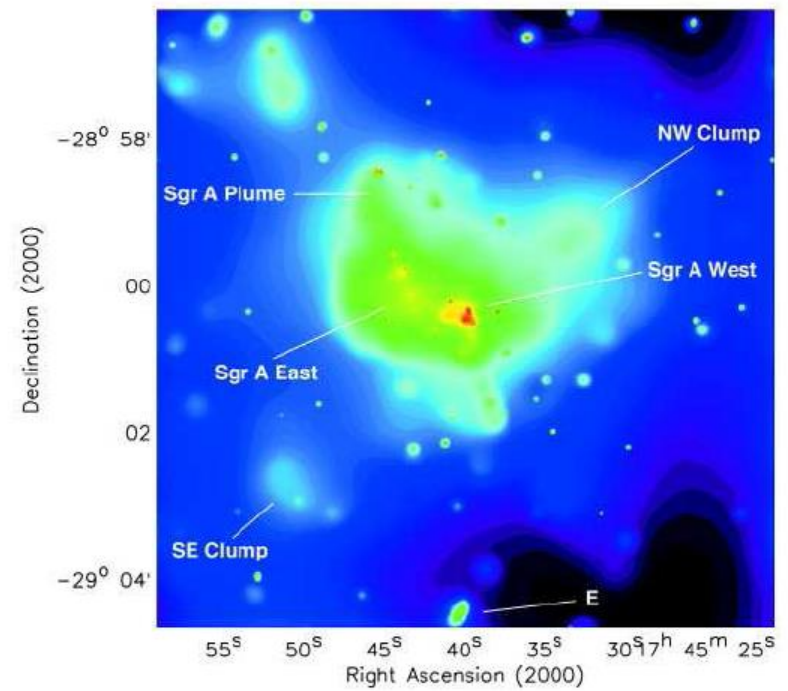
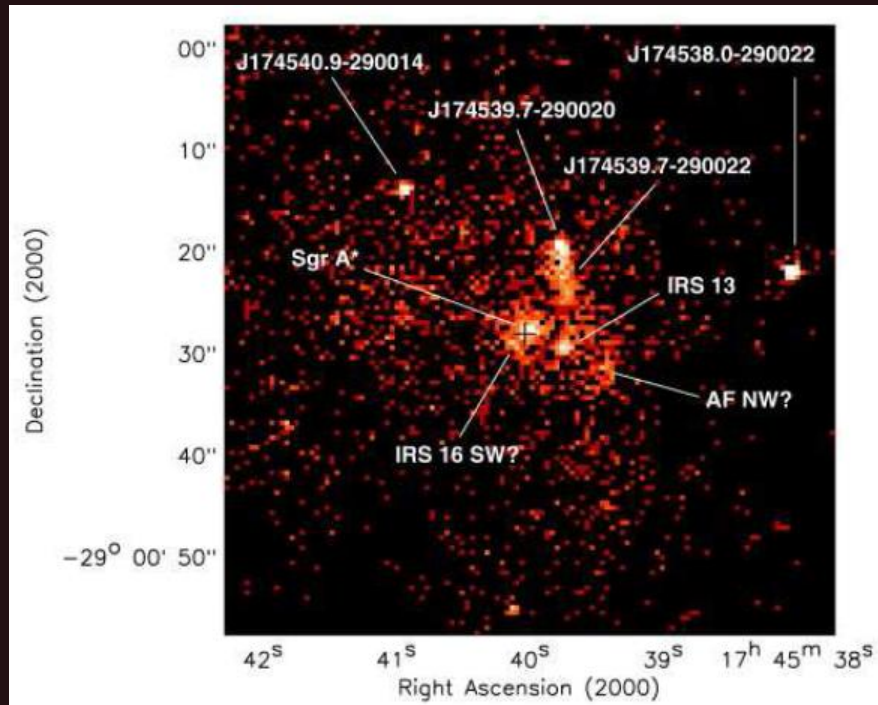
(Park et al.; Chandra data)
[astro-ph/0311460](https://arxiv.org/abs/astro-ph/0311460)

A closer look

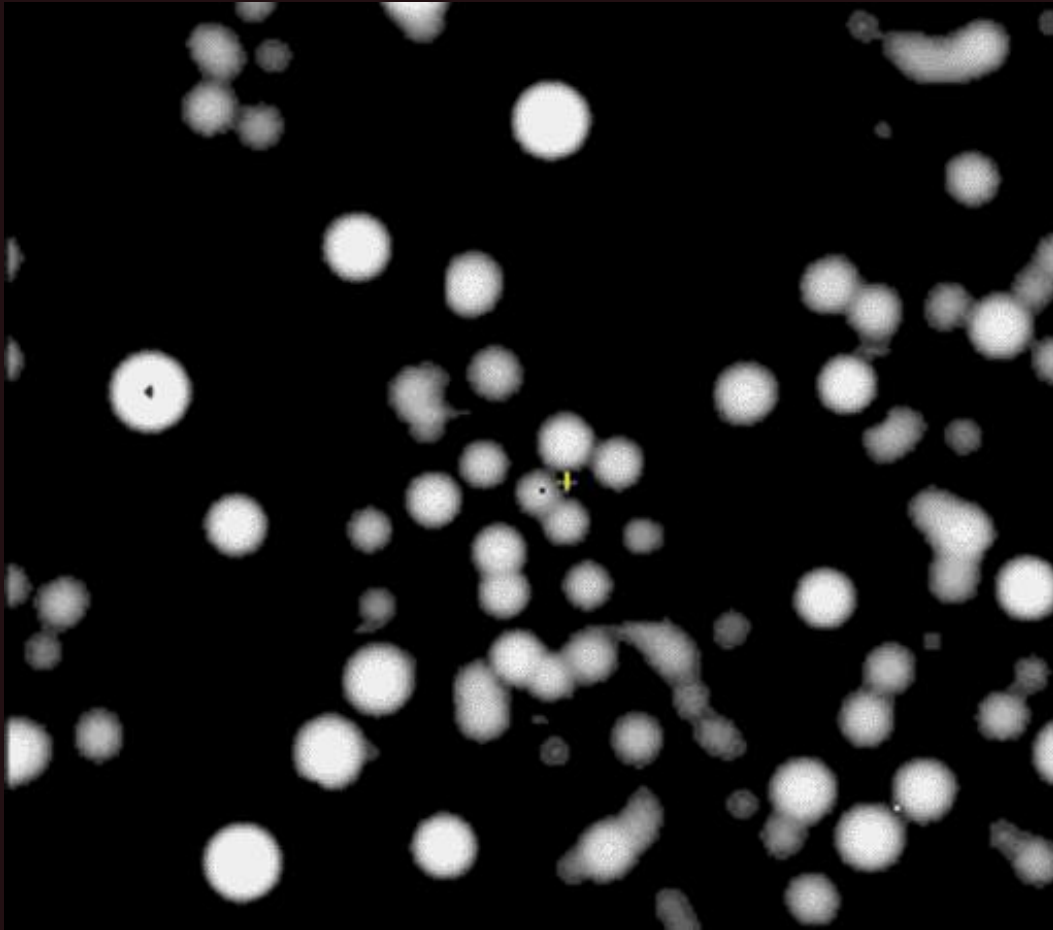
Chandra. 2-10 keV

2.4 pc

20 pc



Stellar dynamics around Sgr A*

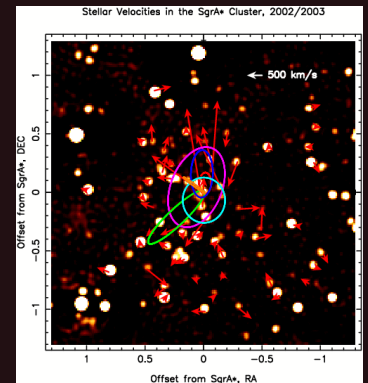


With high precision we know stellar dynamics inside the central arcsecond ([astro-ph/0306214](#))

The BH mass estimate is $\sim 4 \times 10^6 M_\odot$

It would be great to discover radio pulsars around Sgr A* ([astro-ph/0309744](#)).

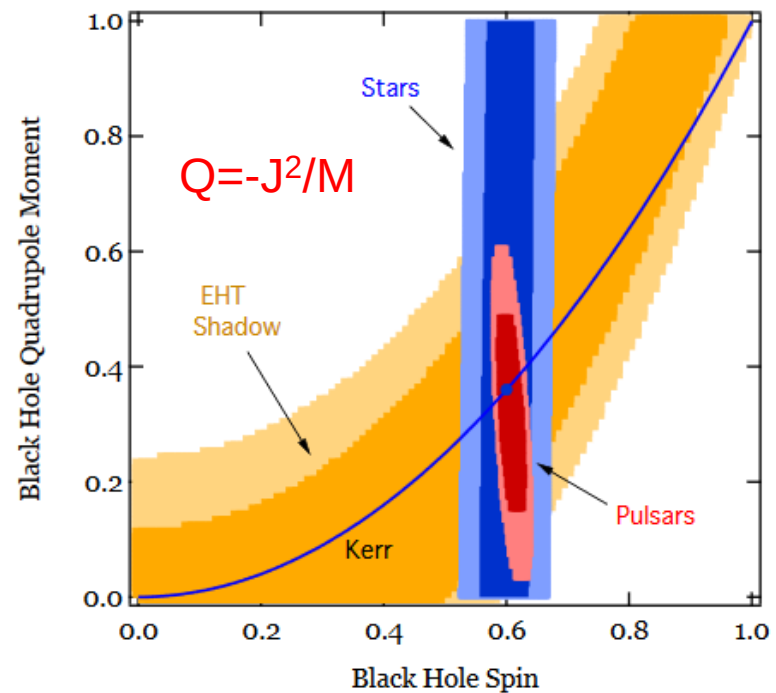
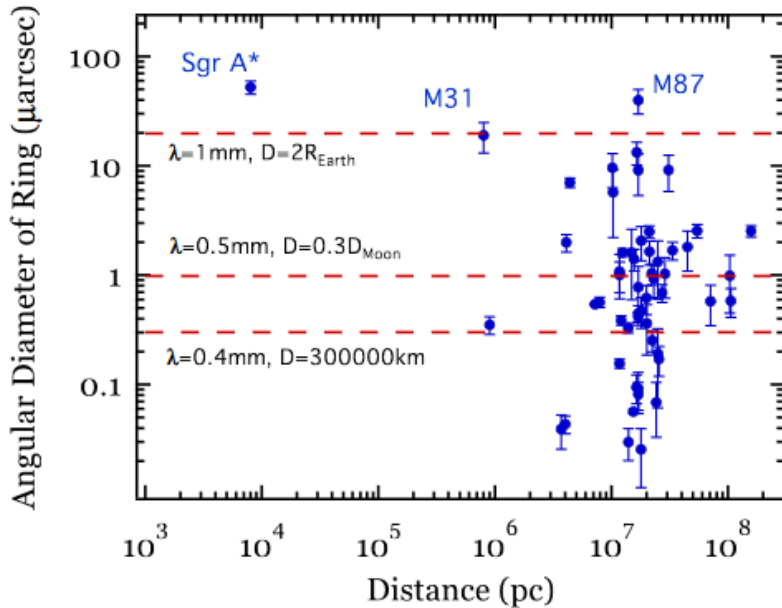
(APOD [A. Eckart](#) & [R. Genzel](#))



See more data in 0810.4674

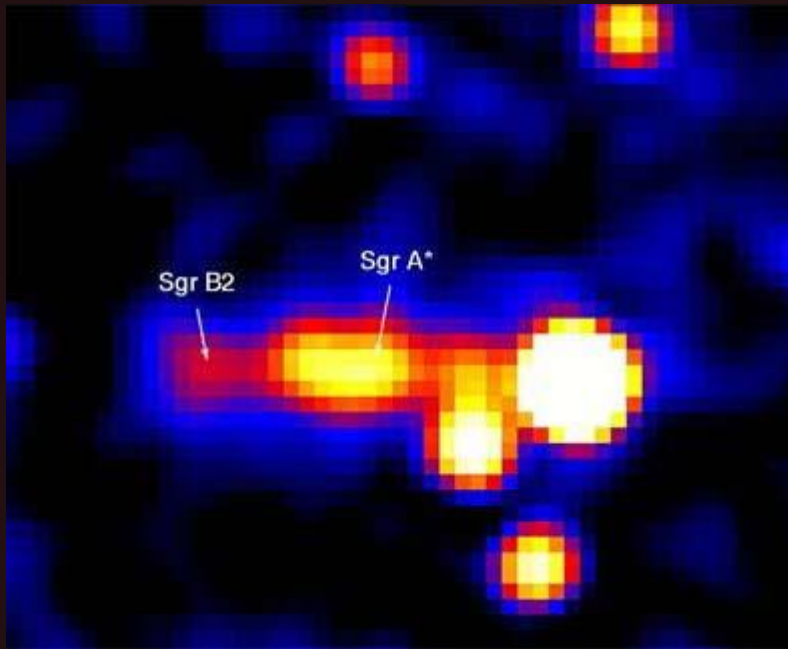
Stars-star interactions can be important: arXiv 0911.4718

General relativity test, EHT, etc.



In the very near future Sgr A* might be the best laboratory to study GR. EHT observations and identifications of PSRs in the vicinity of the BH might help to probe the no-hair theorem and determine the main properties of the BH with high precision.

Observations aboard Integral



(Revnivtsev et al.)

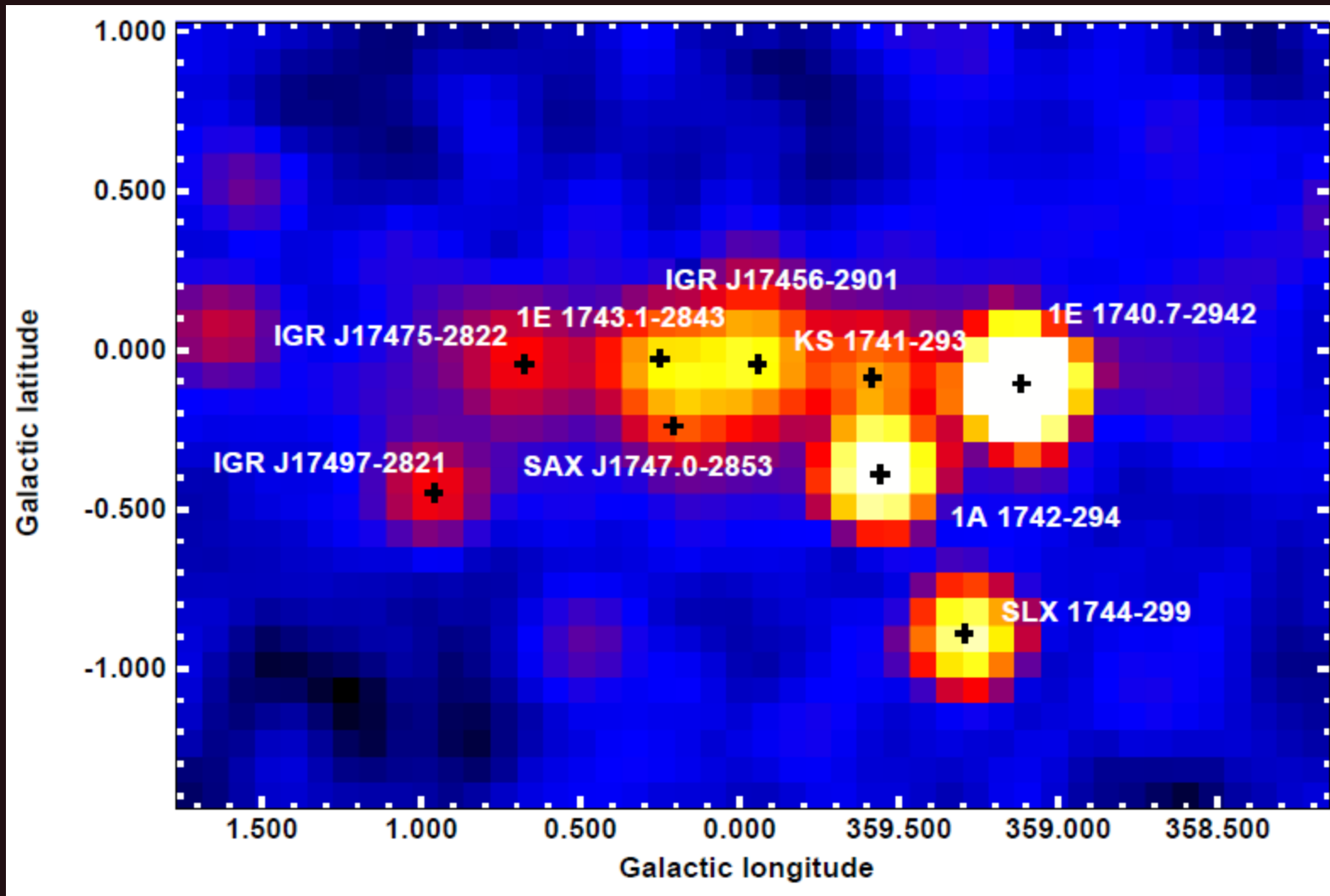
**The galactic center region
is regularly monitored
by Integral.**

At present “our” black hole is not active.
However, it was not so in the past.

It is suspected that about 350 years ago
Sgr A* was in a “high state”.
Now the hard emission generated by Sgr A*
at this time reached Sgr B2.
Sgr B2 is visible due to fluorescence
of iron.

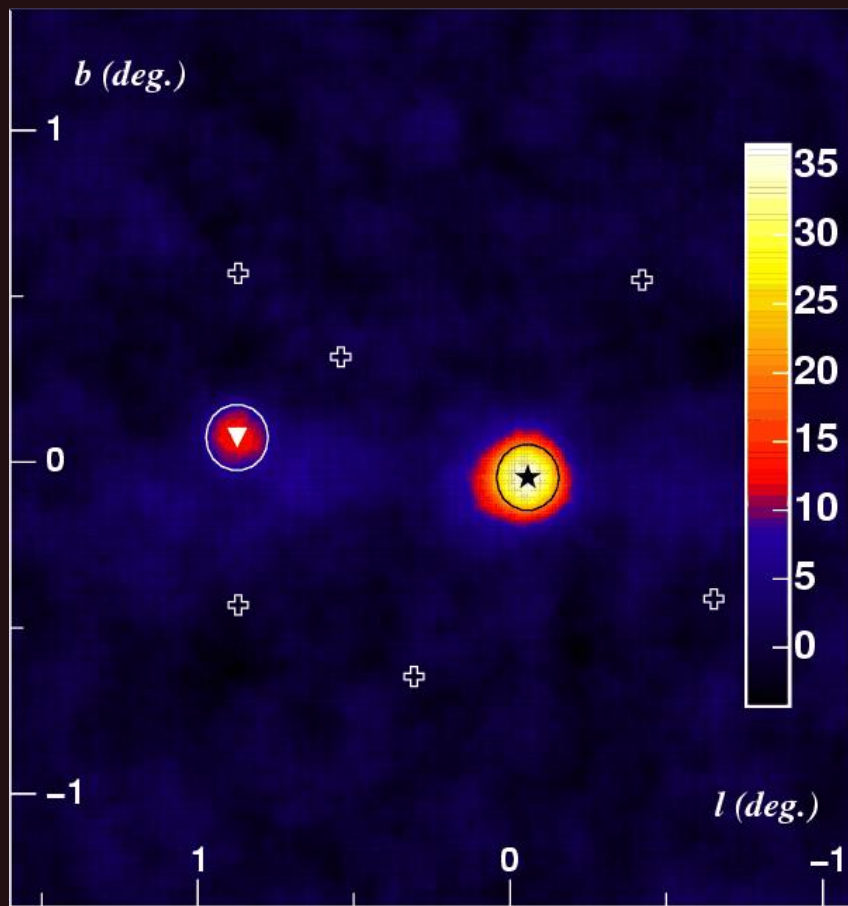
Probably, there have been several strong
flares in the past 1307.3954.

More Integral data



1007.4174

Sgr A* and H.E.S.S.



See [astro-ph/0503354](#), 0709.3729

Still, resolution is not good enough to exclude the contribution of some near-by (to Sgr A*) sources.

(Aharonian et al. 2005)

X-ray bursts from Sgr A*

Bursts can happen about once in a day.
The flux is increased by a factor of a few (sometimes even stronger).

A bright burst was observed on Oct. 3, 2002 ([D. Porquet et al. astro-ph/0307110](#)).

Duration: 2.7 ksec.

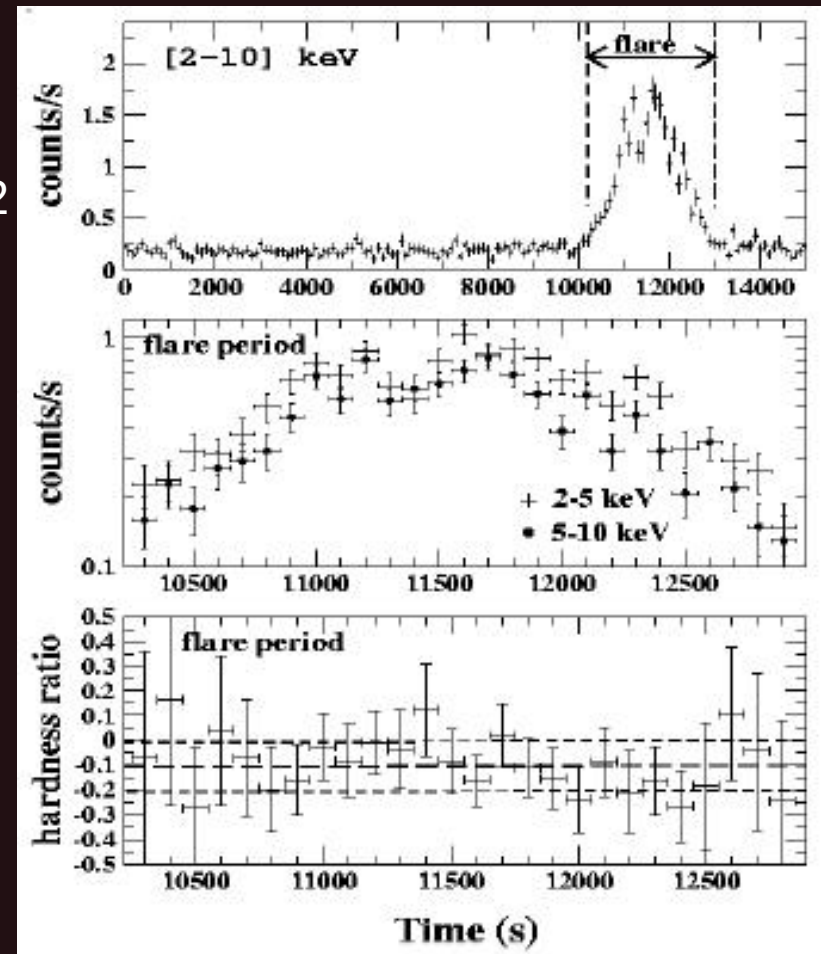
The flux increased by a factor ~ 160 .

Luminosity: $3.6 \cdot 10^{35}$ erg/s.

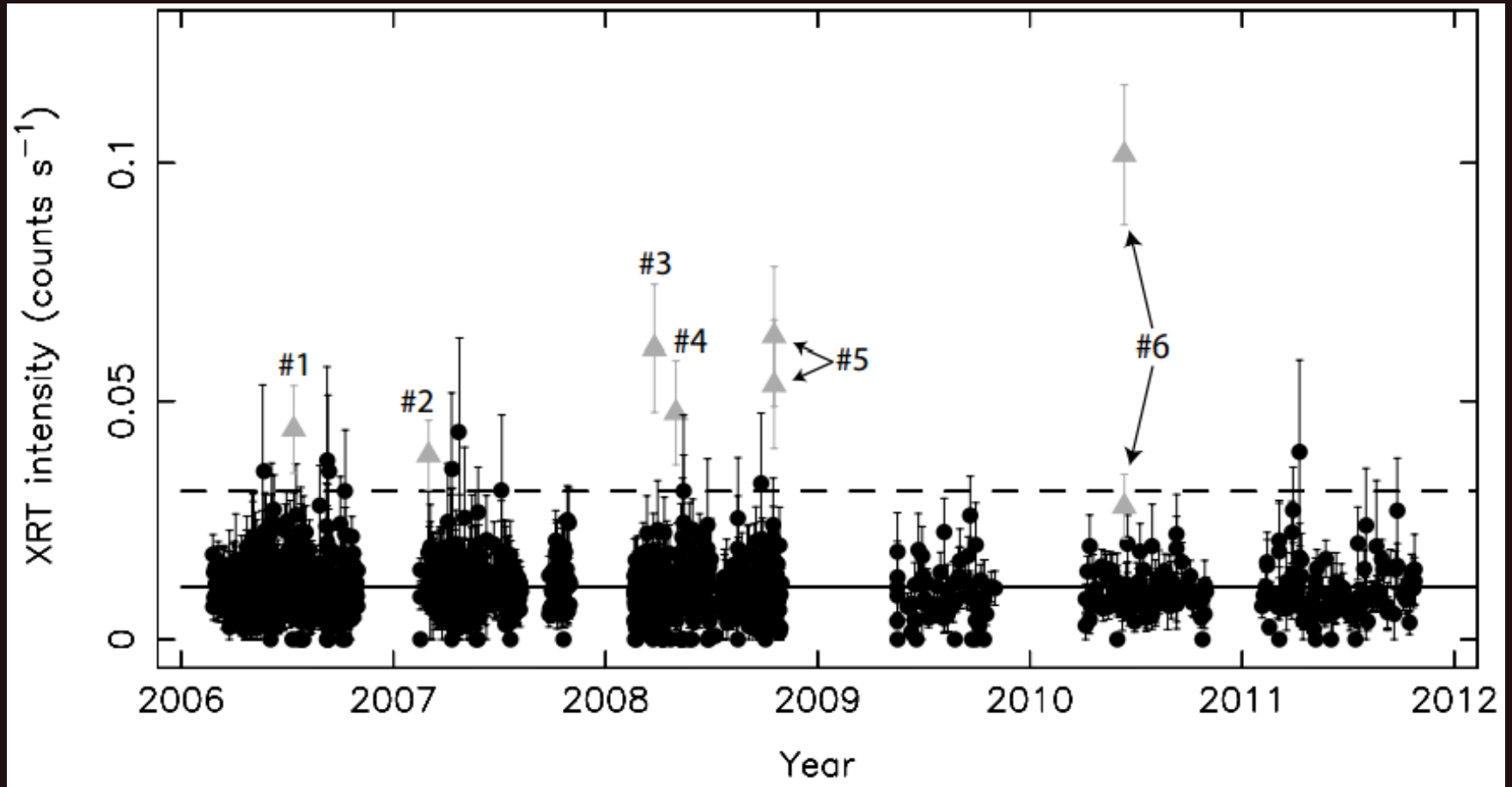
In one of the bursts, on Aug. 31, 2004, QPOs have been discovered.

The characteristic time: 22.2 minutes ([astro-ph/0604337](#)).

In the framework of a simple model this means that $a=0.22$.



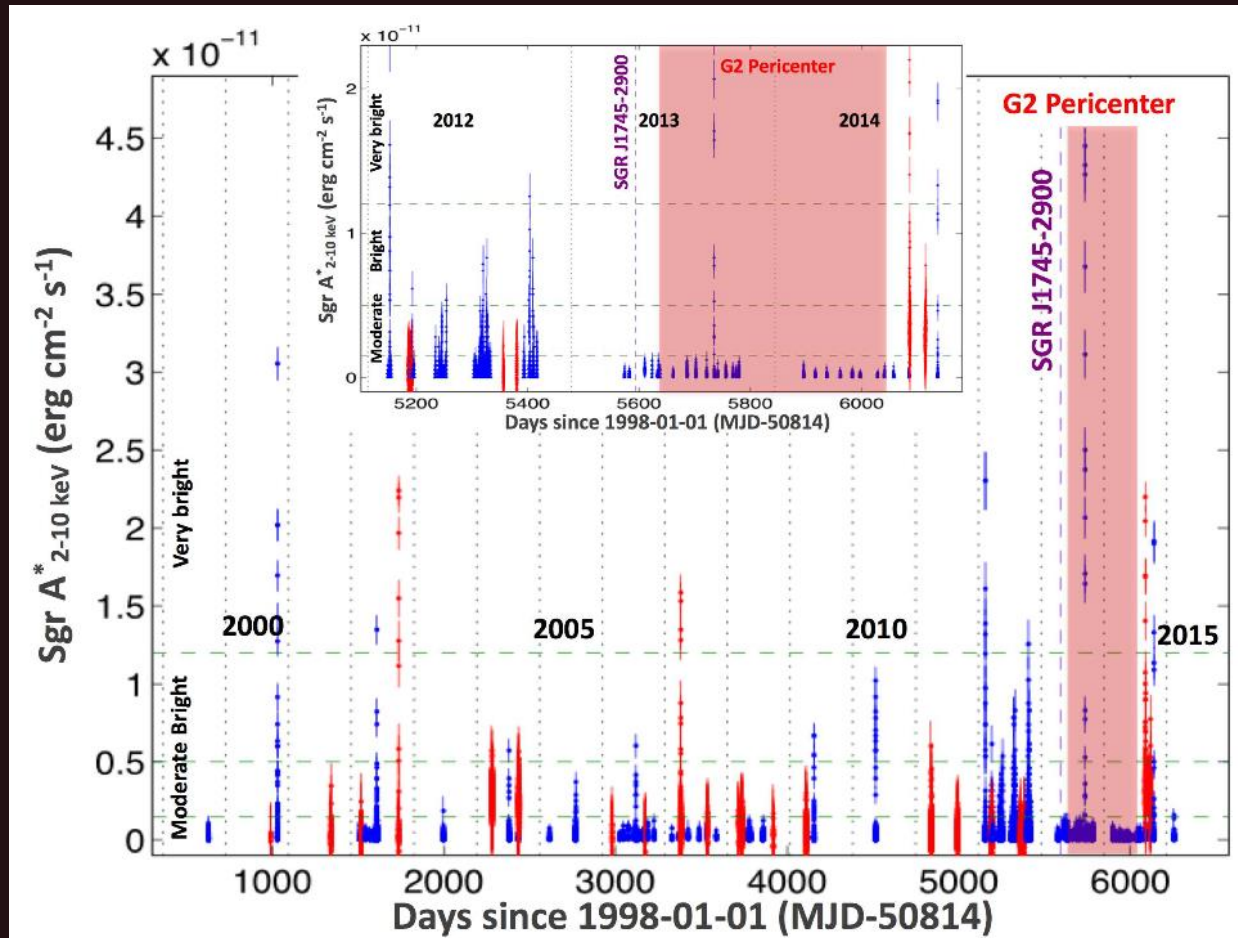
SWIFT monitoring of Sgr A*



1210.7237

See 1501.02171 about accretion physics around Sgr A*

XMM-Newton and Chandra monitoring of Sgr A*

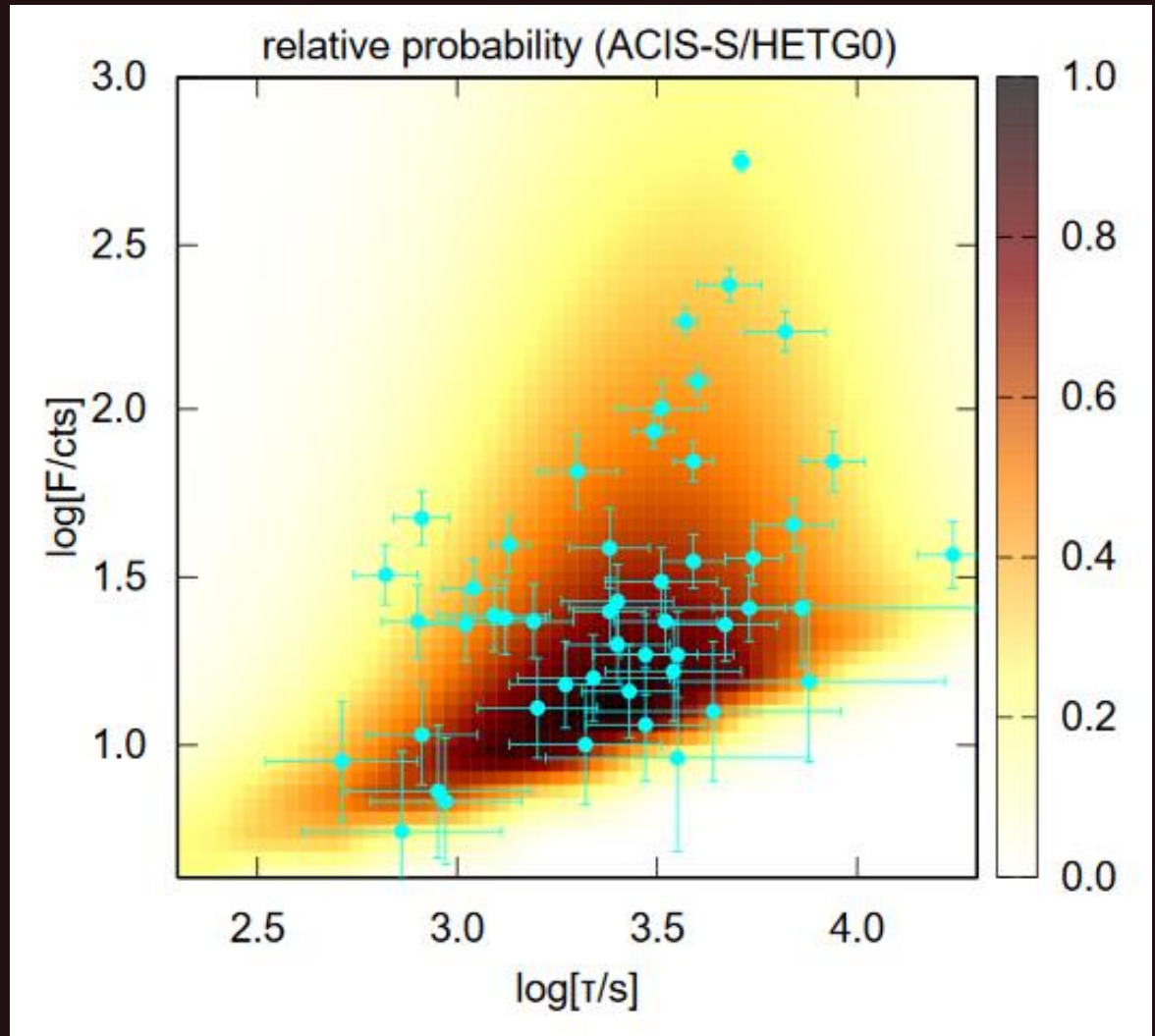


Plenty of data during all time of Chandra and XMM-Newton observations.

Very detailed statistics.

Chandra monitoring

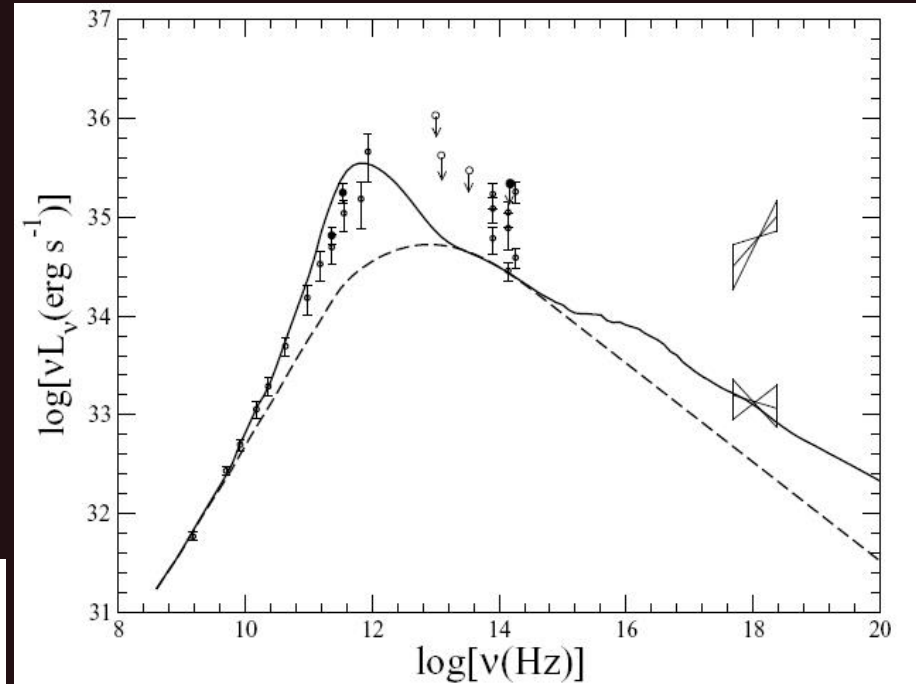
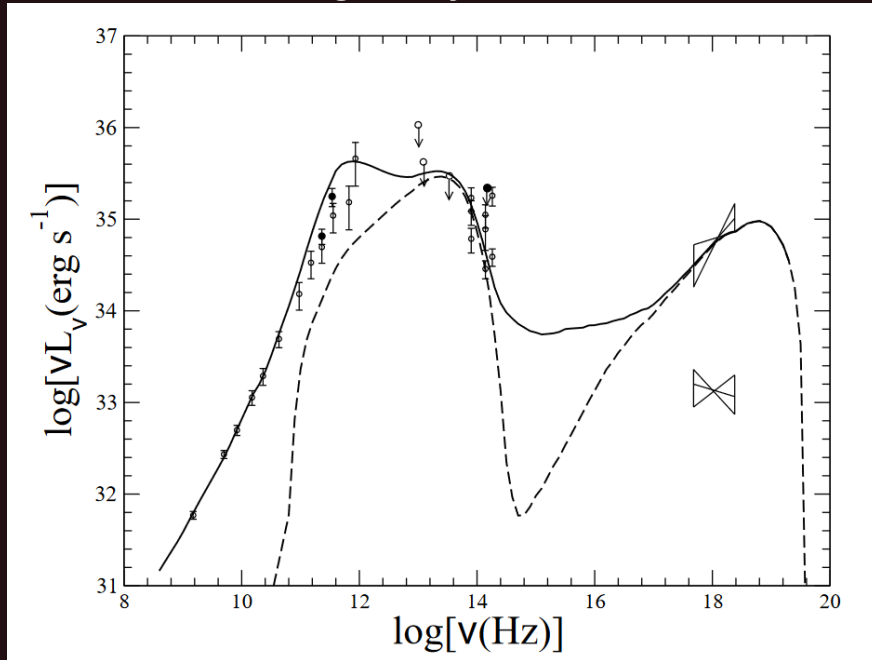
1999-2012



1709.03709

IR burst of Sgr A*

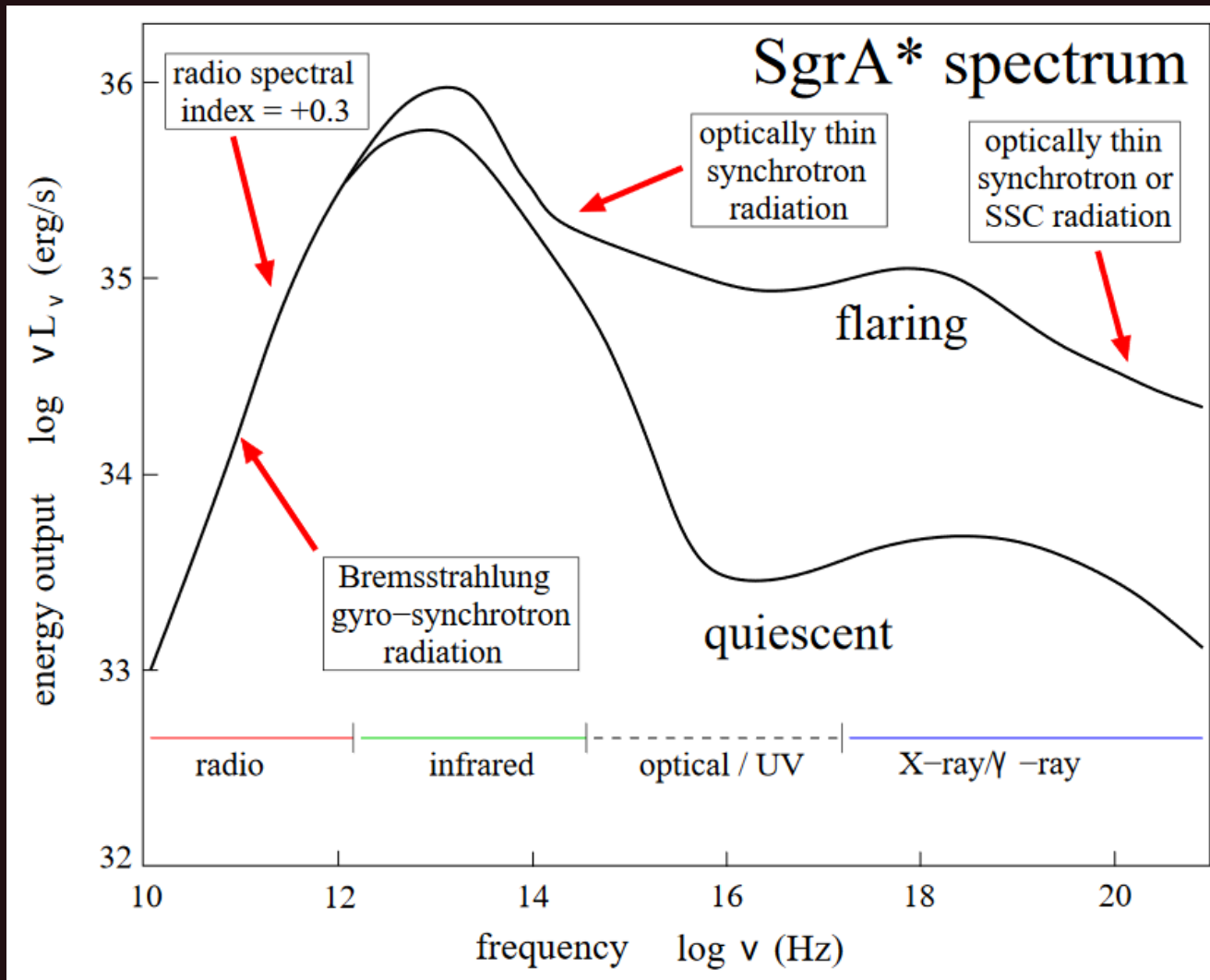
Observations on Keck, VLT.
The scale of variability was
about 30 minutes.
This is similar to variability
observed in X-rays.
The flux changed by a factor 2-5.



Non-thermal synchrotron?

([Feng Yuan](#), [Eliot Quataert](#), [Ramesh Narayan](#) astro-ph/0401429)

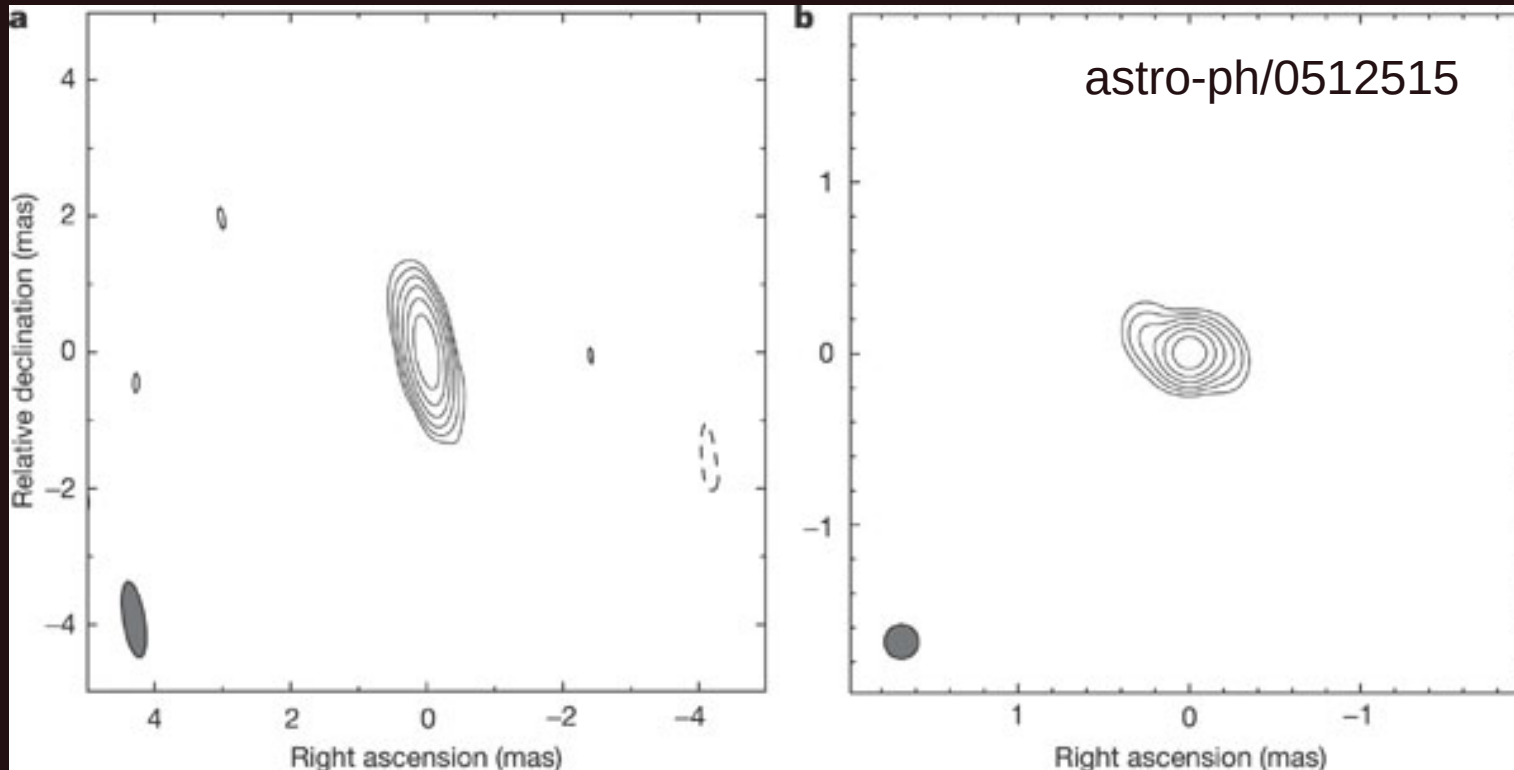
Sgr A* spectrum



See a review in 1806.00284

Constraints on the size of Sgr A*

Using VLBI observations a very strict limit was obtained for the size of the source Sgr A*: 1. a.e.

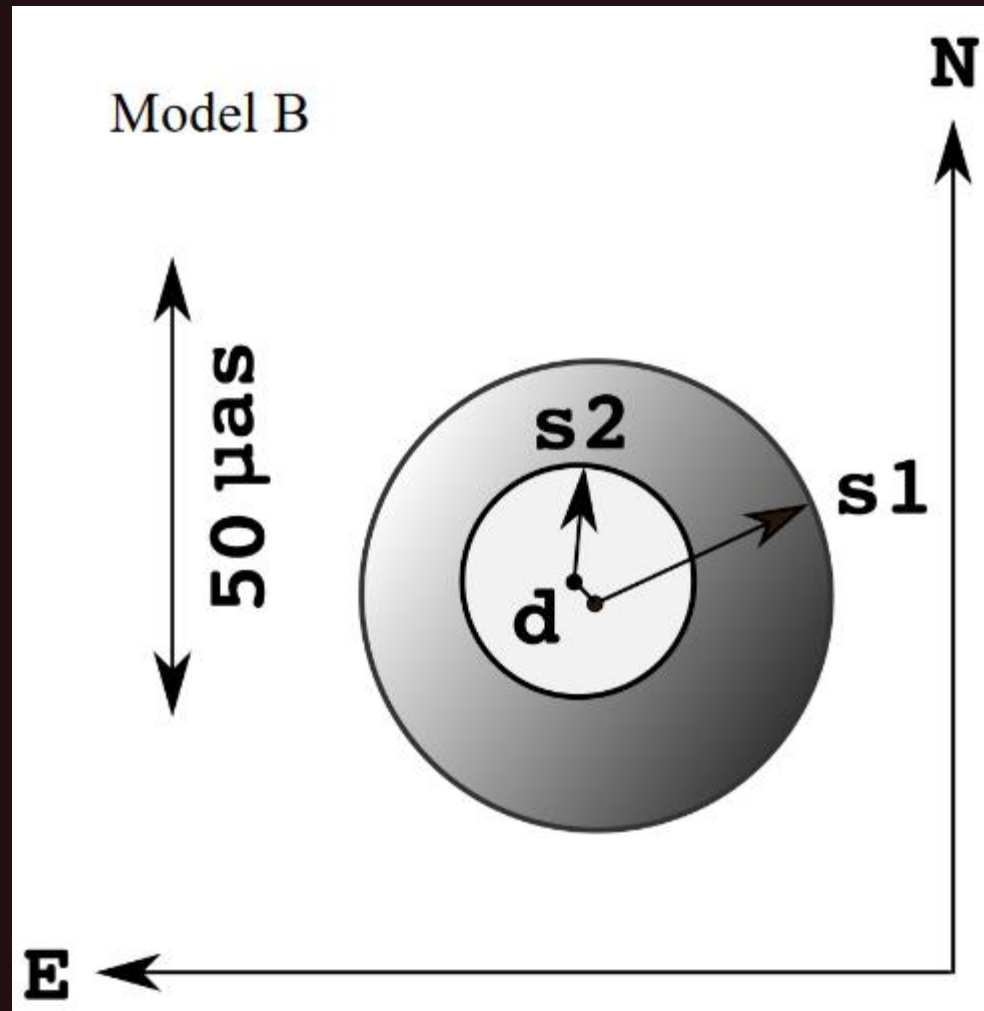


New VLBI observations demonstrate variability at 1.3mm from the region about few Schwarzschild radii. arXiv: 1011.2472

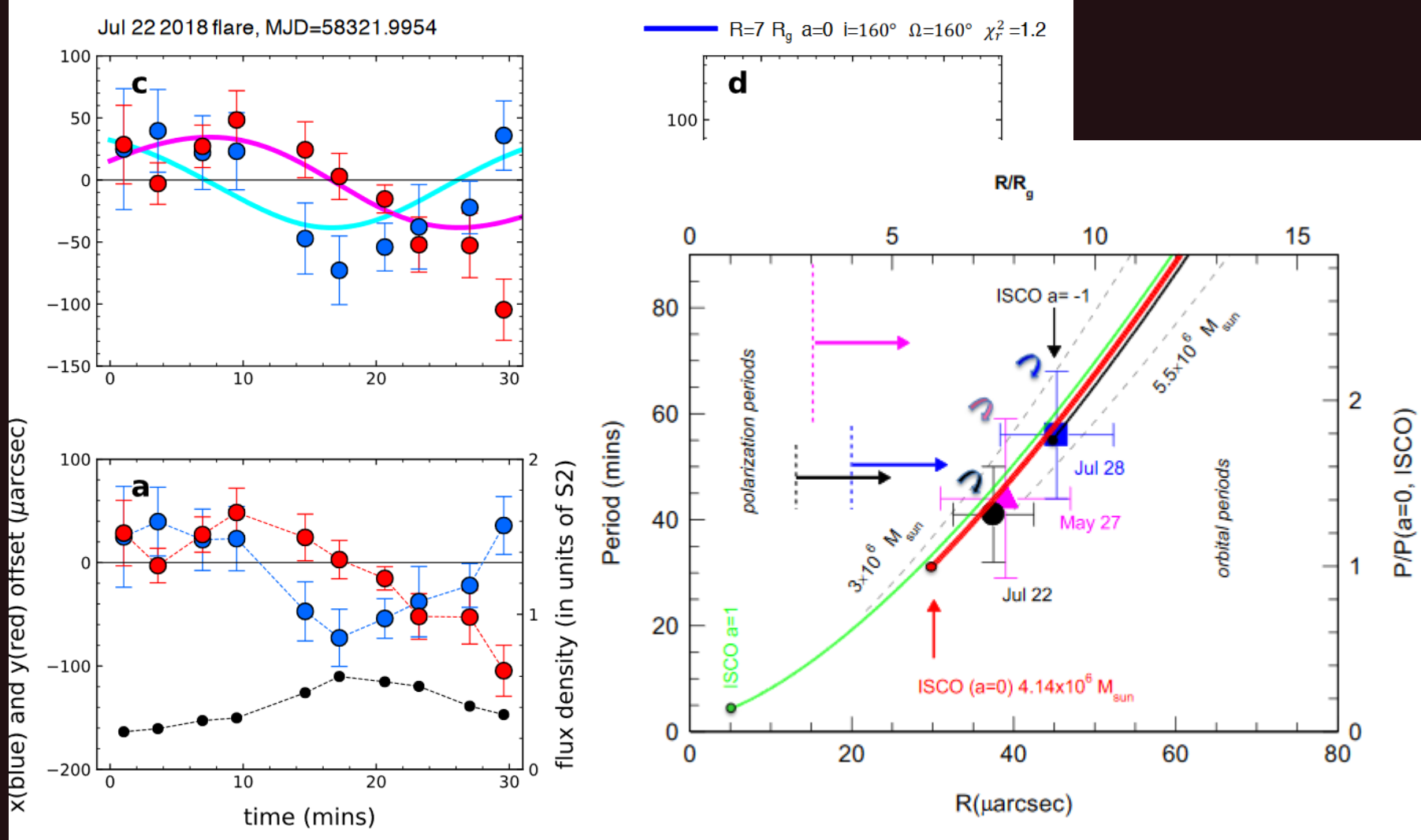
Strict limits on the size and luminosity with known accretion rate provides arguments in favor of BH interpretation (arXiv: 0903.1105)

Structure at 3 R_g in Sgr A*

EHT 2013
VLBI 1.3 mm
30 μ arcsec

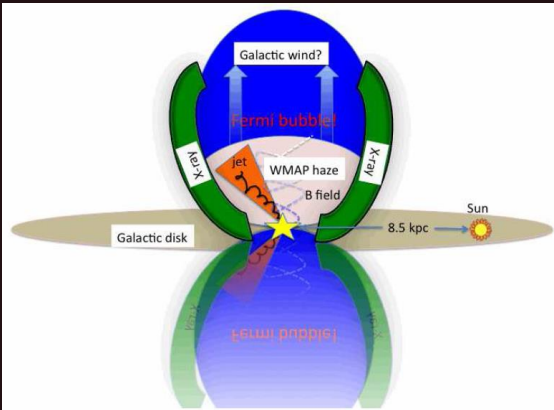
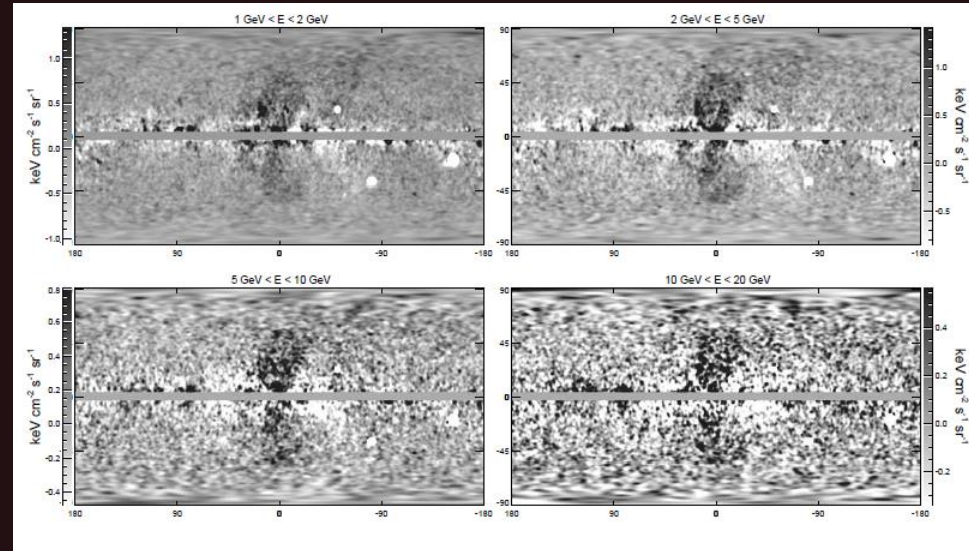
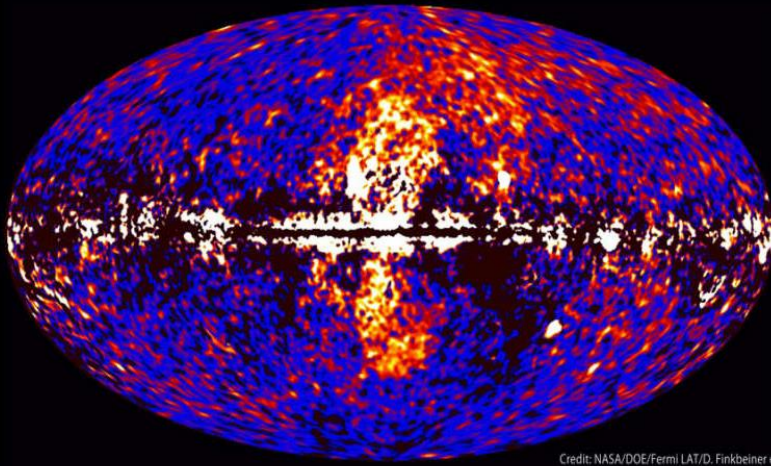


Orbital motion near ISCO in Sgr A*



Bubbles in the center of the Galaxy

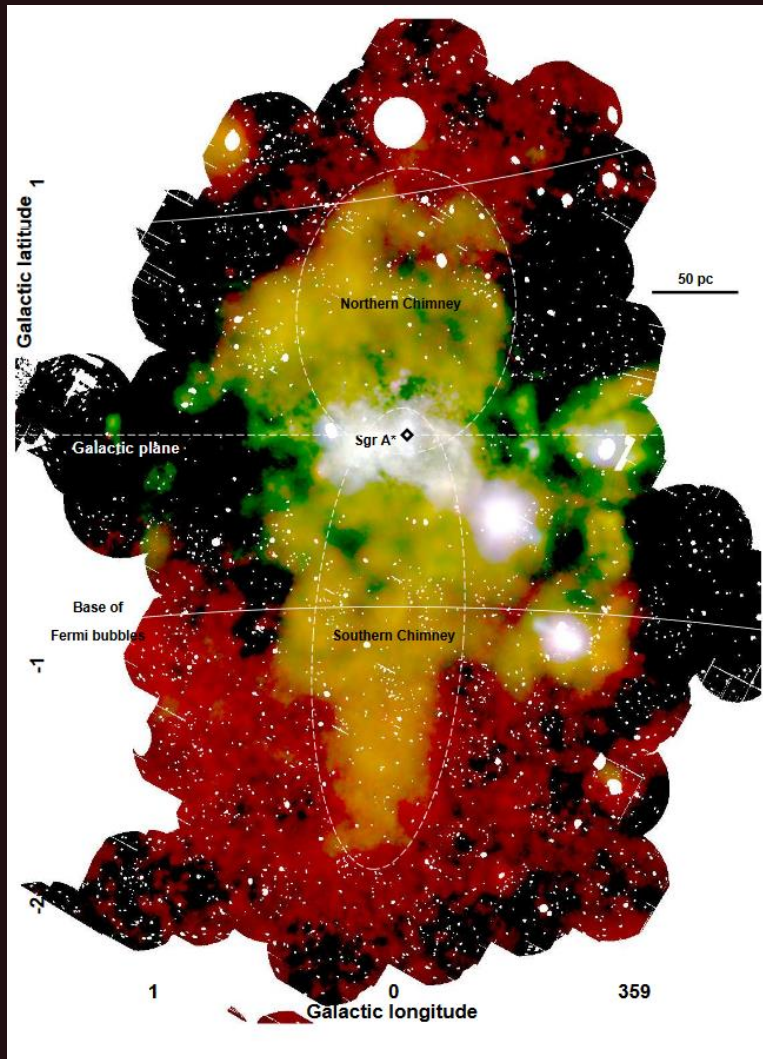
Fermi data reveal giant gamma-ray bubbles



Structures have been already detected in microwaves (WMAP) and in soft X-rays (ROSAT)

New structures: galactic chimney

Through these “chimneys” energy from episodically active central engine is channeled to fermi Bubbles.

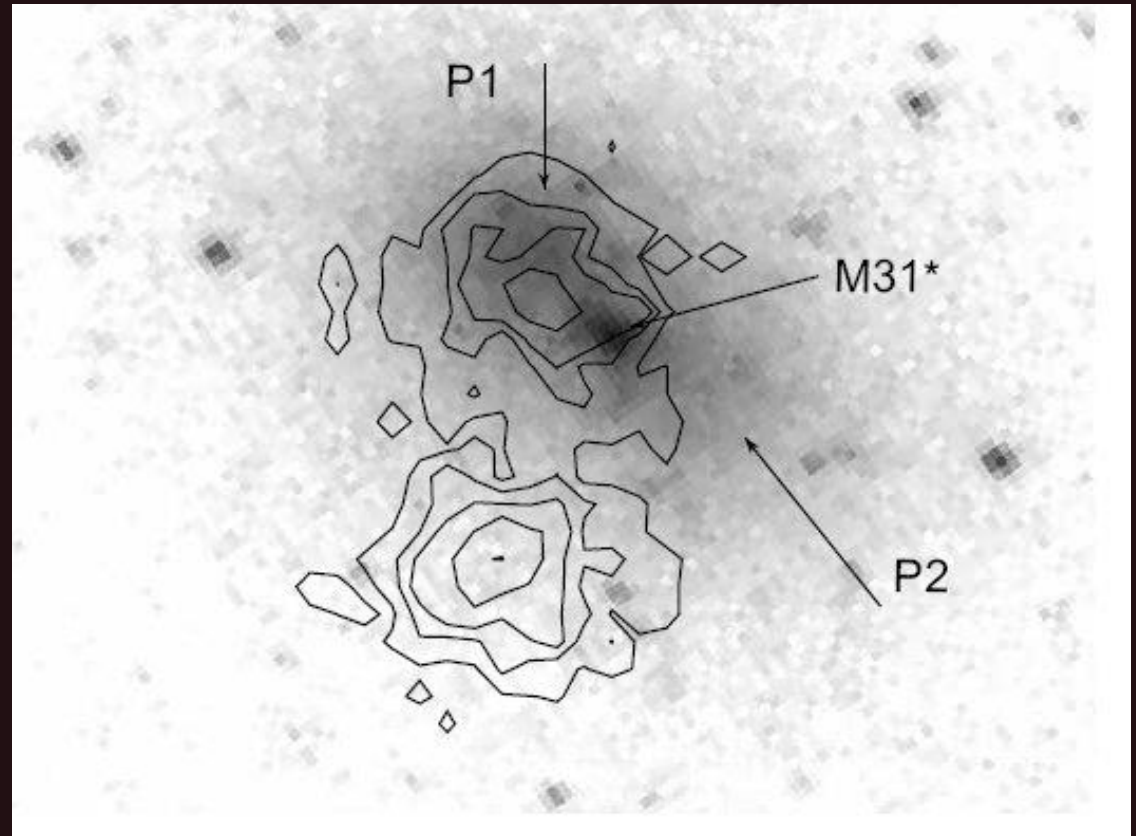


M31

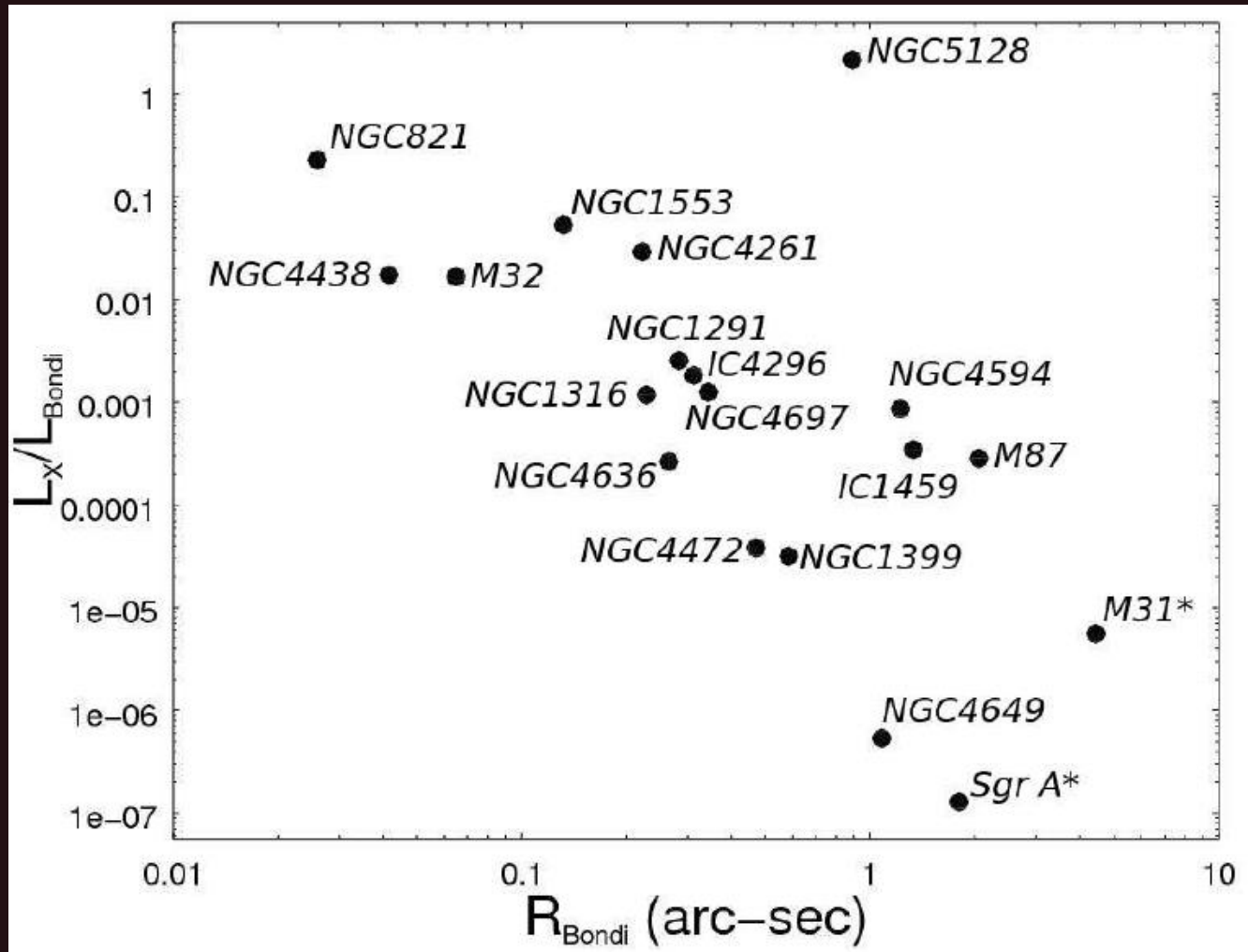
Probably, thanks to observations on Chandra and HST the central SMBH was discovered in M31 (astro-ph/0412350).

$M \sim (1-2) 10^8 M_{\text{solar}}$
 $L_x \sim 10^{36} \text{ erg/s}$

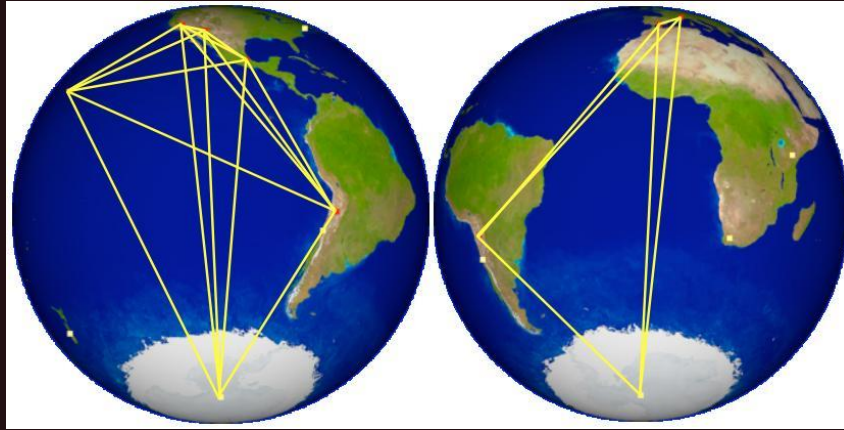
See recent data in
arXiv: 0907.4977



A “large” BH in M31



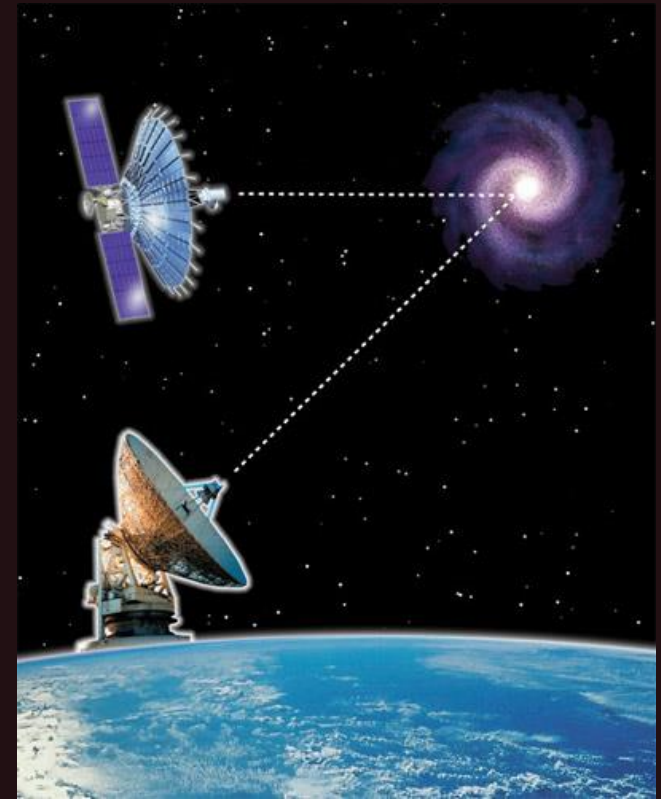
Observational projects: horizon



Event Horizon telescope

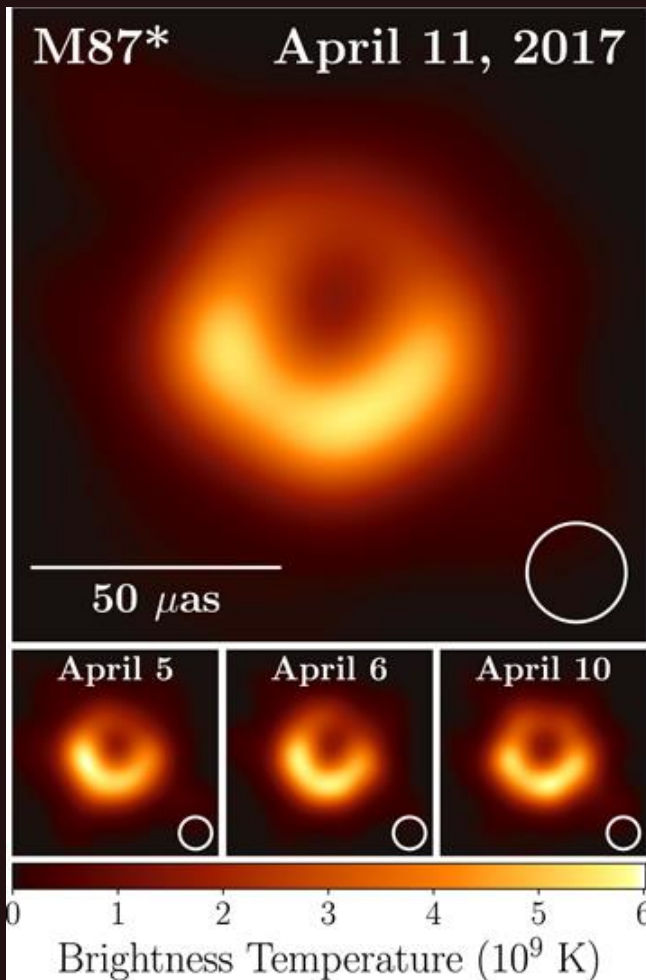


ALMA+mm-VLBI



Radioastron

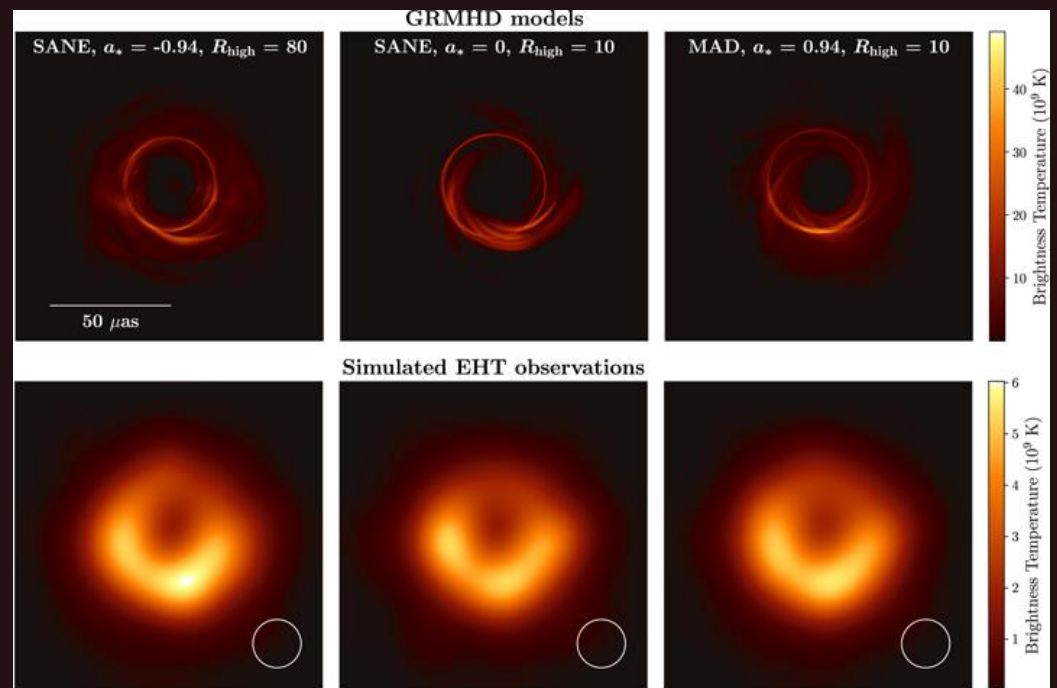
SMBH in M87



EHT 2017

Announced April 10, 2019

Structure, mass measurements,
spin orientation

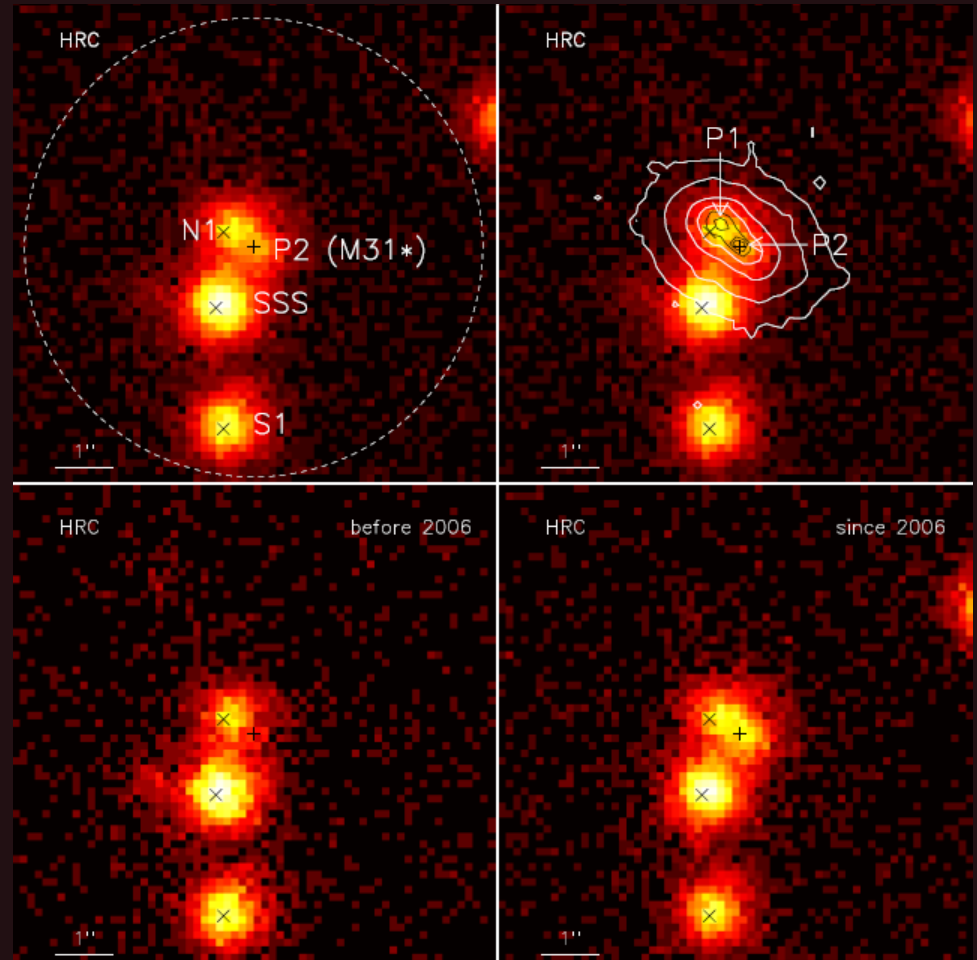


Activity of the M31 SMBH

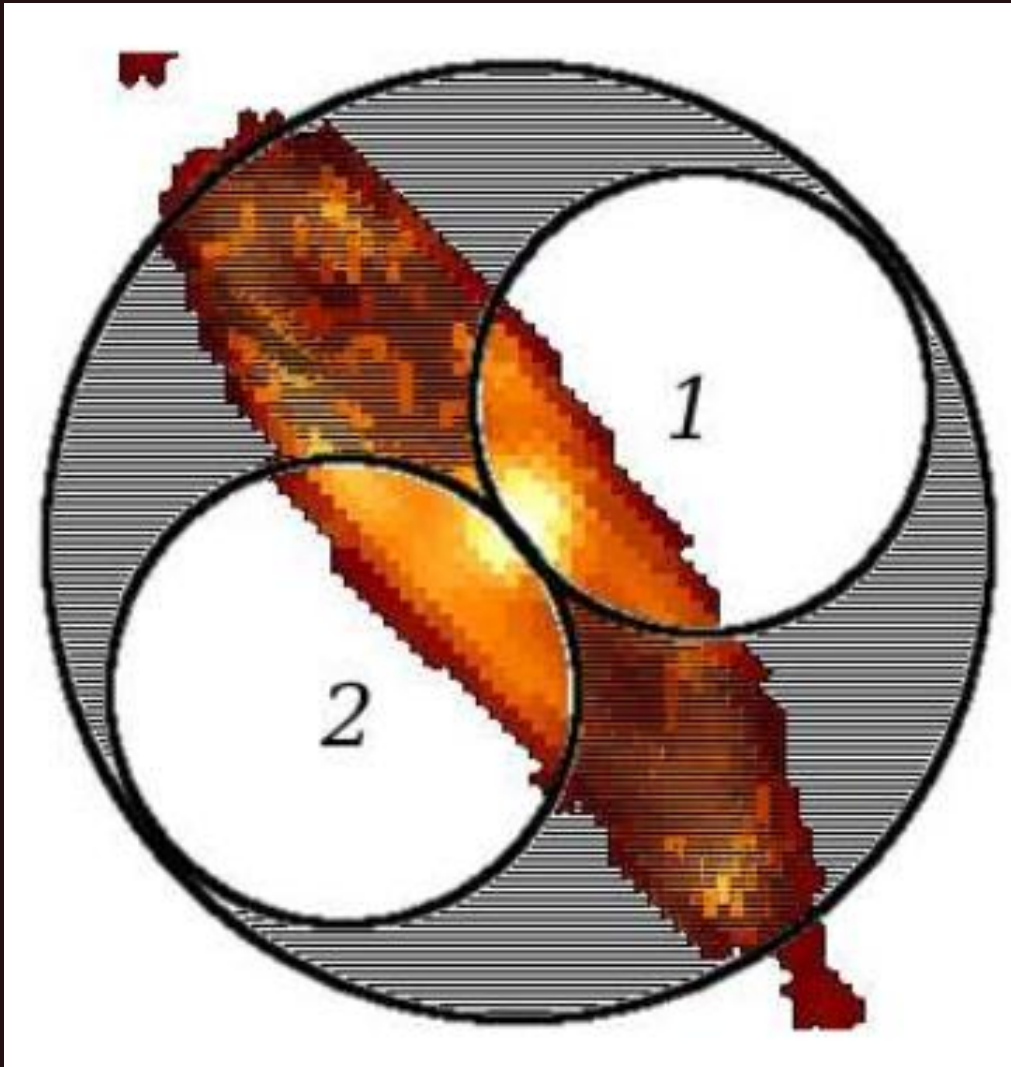
SMBH with 100-200 solar masses.

Mostly in the quiescent state.
Luminosity is billions of times less than the Eddington.

Recently, bursts similar to the activity of Sgr A* have been detected from the SMBH in M31.



Fermi bubbles analogues in M31?



Using Fermi data the authors demonstrated that the shape of gamma-ray image is more consistent with a structure similar to Fermi bubbles in our Galaxy.

Active galactic nuclei and quasars

The classification is not very clear

- Quasars
 - a) radio quiet (two types are distinguished)
 - b) radio loud
 - c) OVV (Optically Violently Variable)
- Active galaxies
 - a) Seyfert galaxies (types 1 and 2)
 - b) radio galaxies
 - c) LINERs
 - d) BL Lac objects

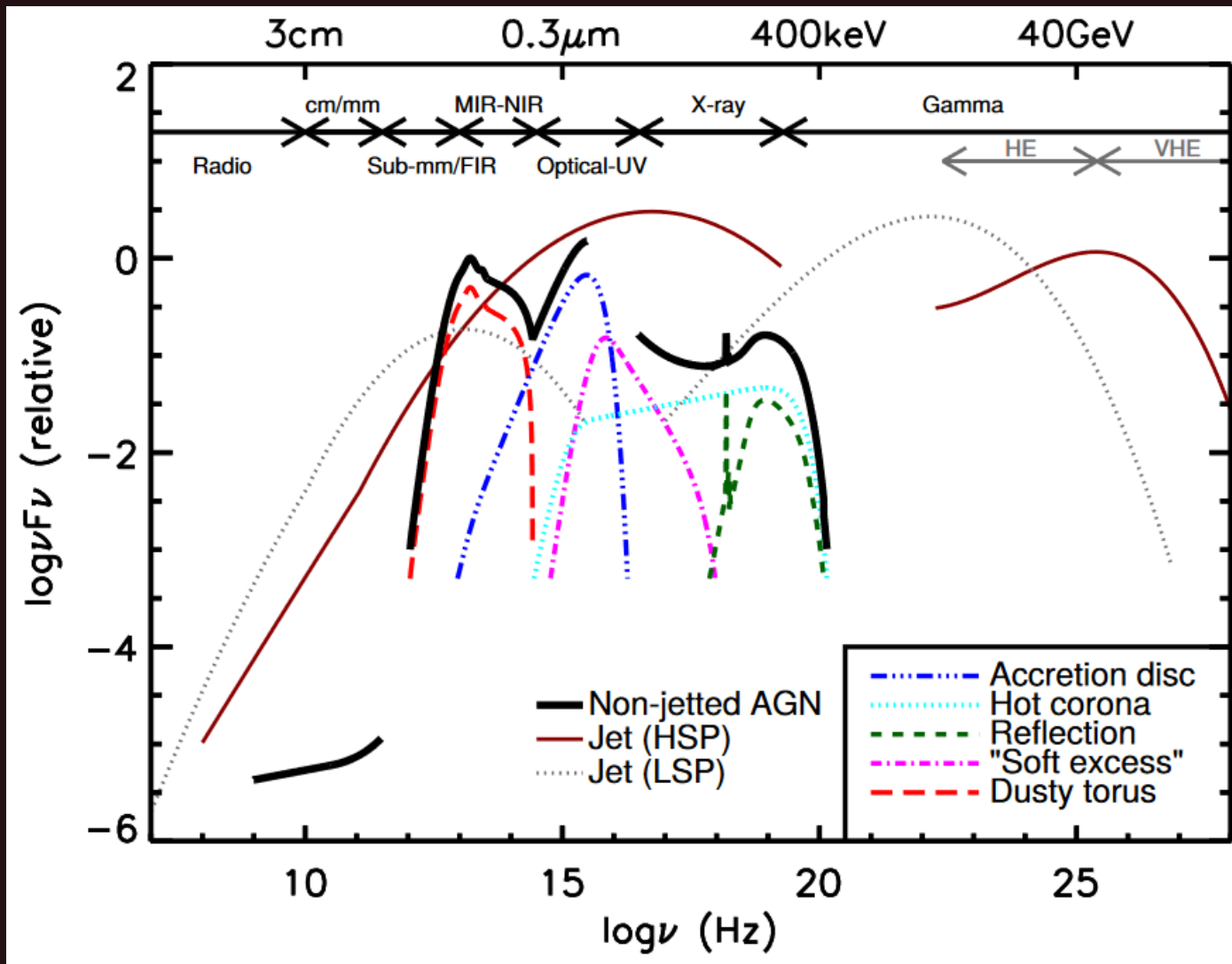


- Radio quiet
 - a) radio quiet quasars, i.e. QSO (types 1 and 2)
 - b) Seyfert galaxies
 - c) LINERs
- Radio loud
 - a) quasars
 - b) radio galaxies
 - c) blazars (BL Lacs и OVV)

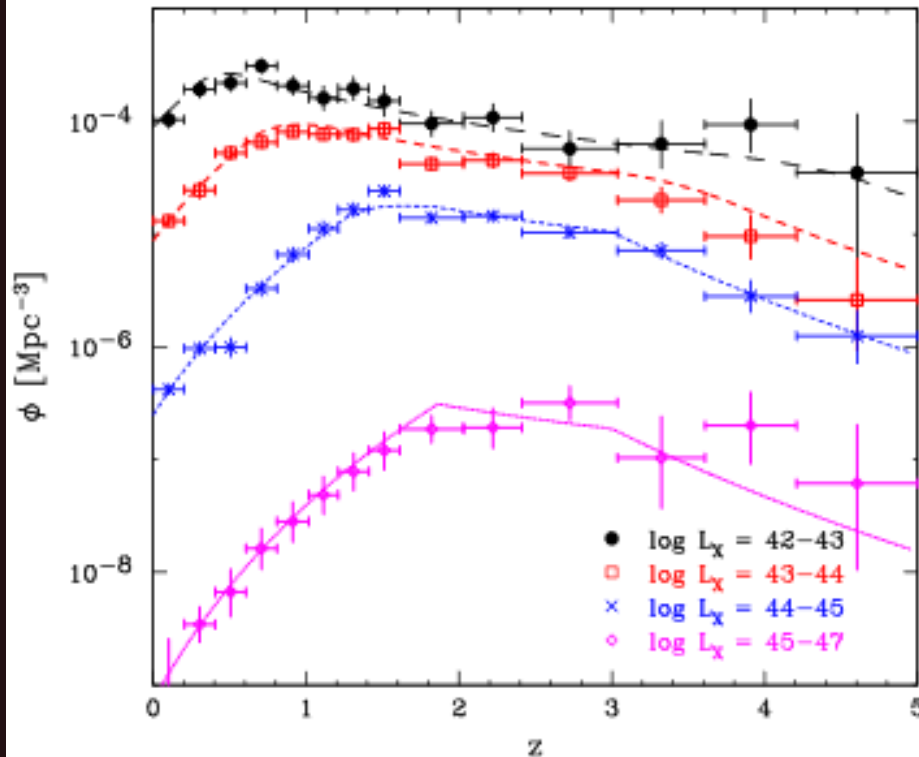
(see, for example, [astro-ph/0312545](https://arxiv.org/abs/astro-ph/0312545))

A popular review can be found in arXiv: 0906.2119

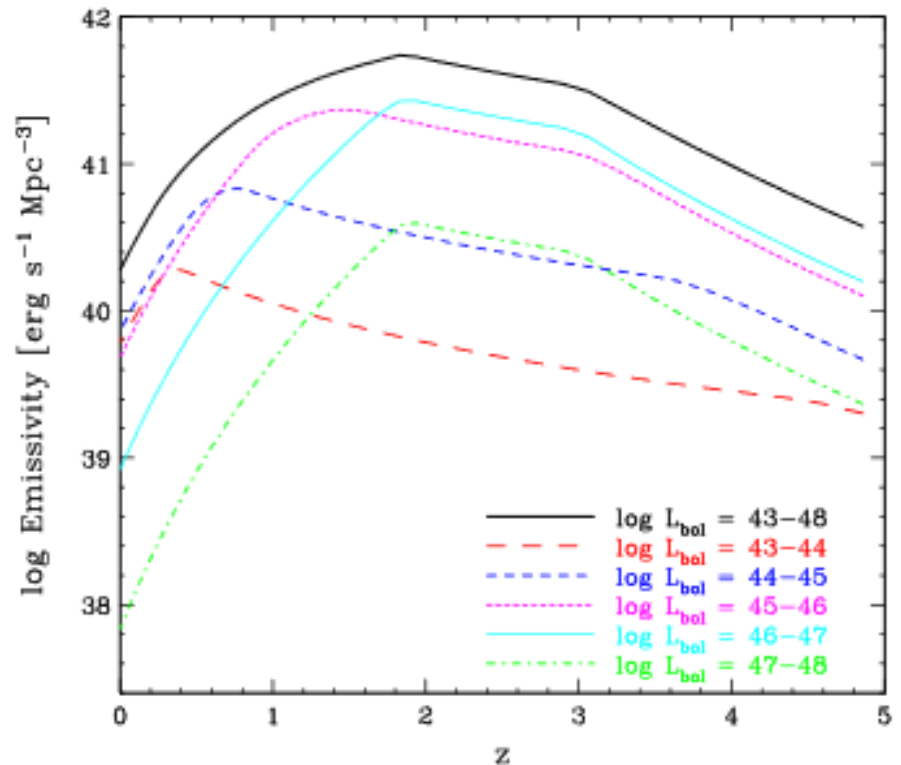
Spectra of AGNs



X-ray observations of AGNs

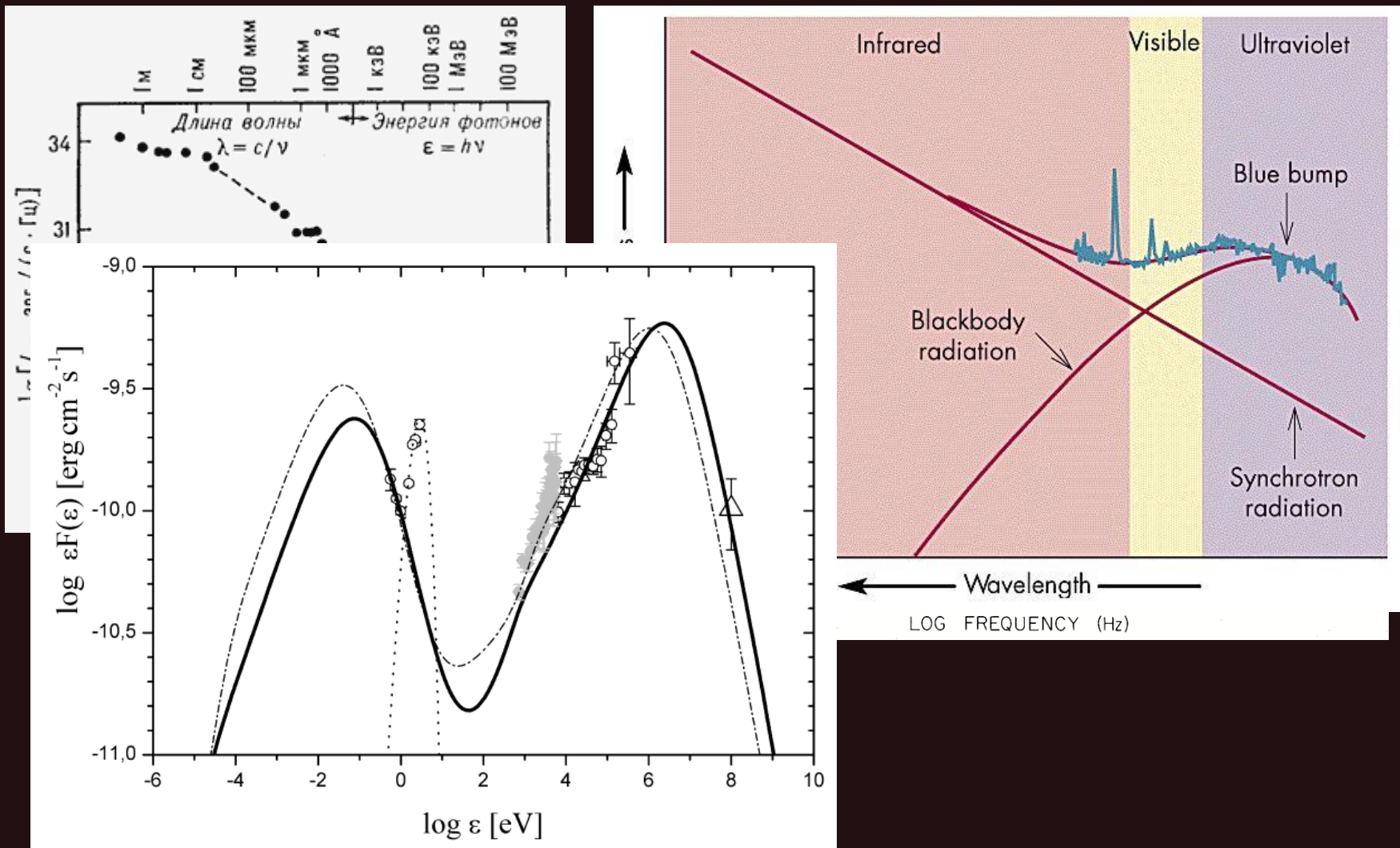


Comoving number density vs. redshift for AGNs, selected from multiple X-ray surveys, in four rest-frame 2–10 keV luminosity classes.

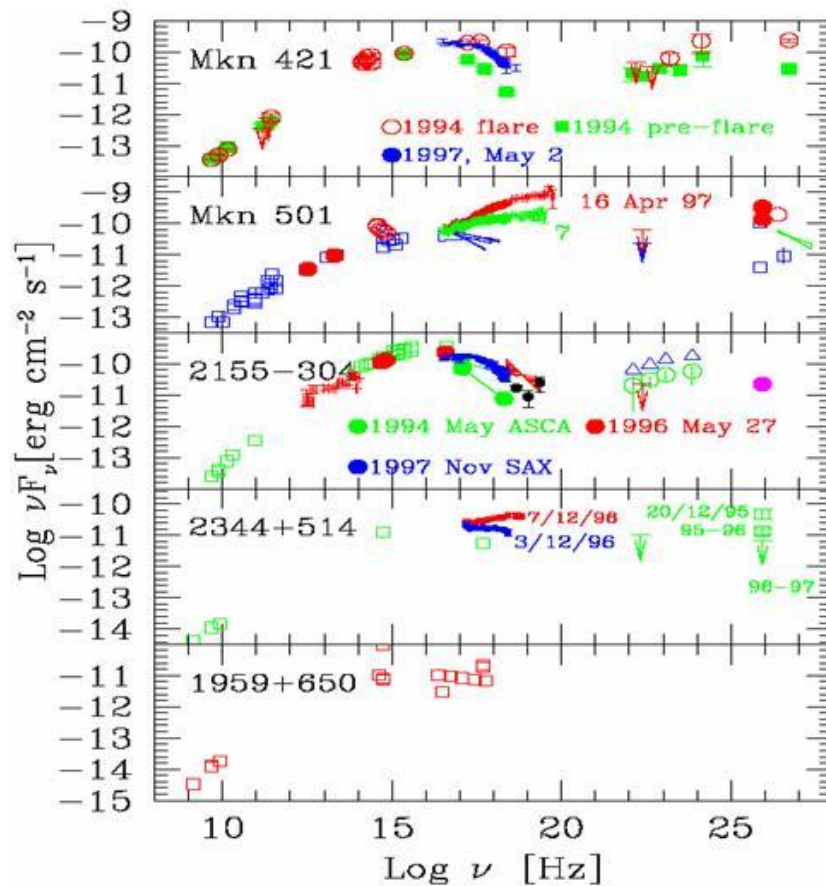


Comoving bolometric luminosity density vs. redshift for the same AGN sample in six bolometric luminosity classes.

Quasars spectra



Spectra of BL Lacs

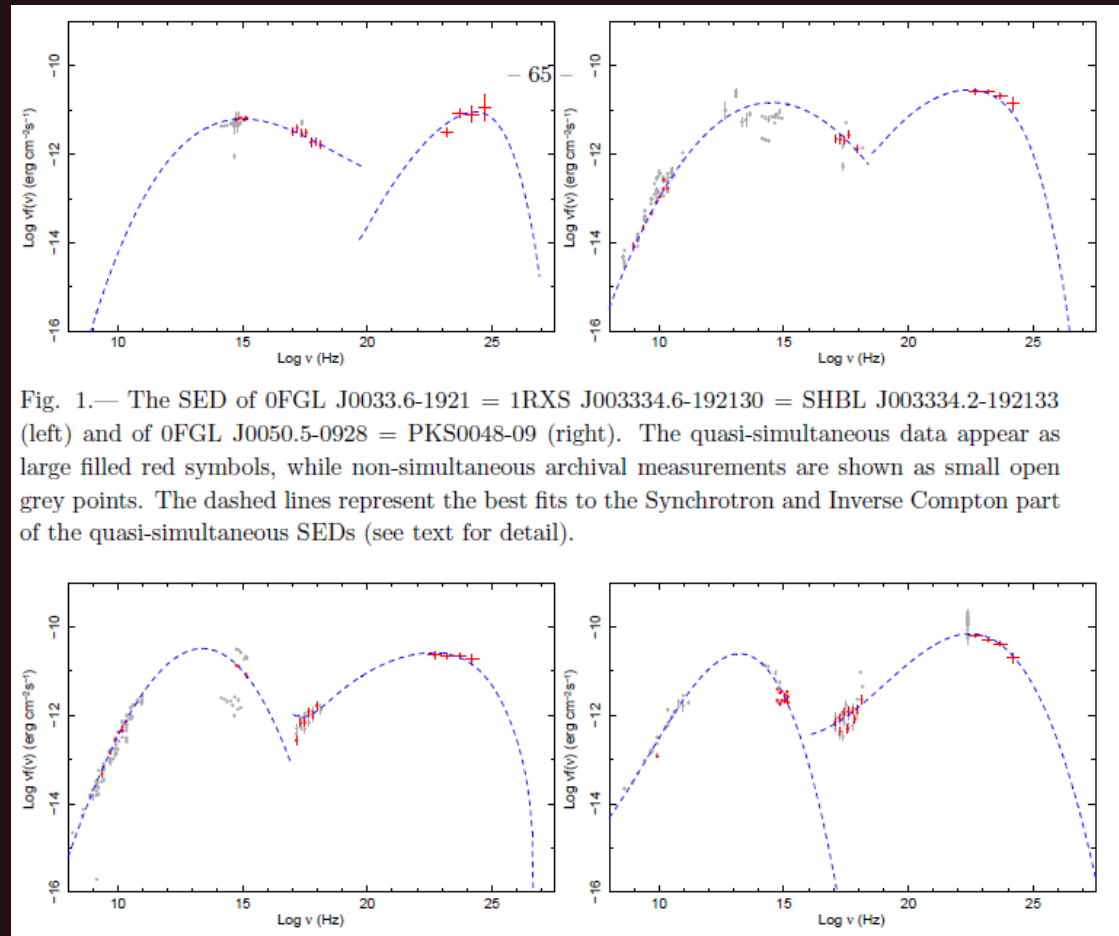


In the framework of the unified model BL Lacs (and blazars, in general) are explained as AGNs with jets pointing towards us.

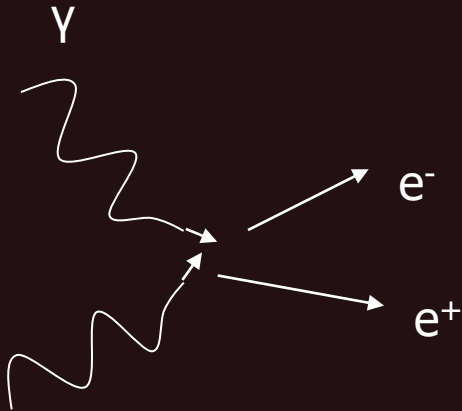
Fermi observations of blazars:

Huge set of data

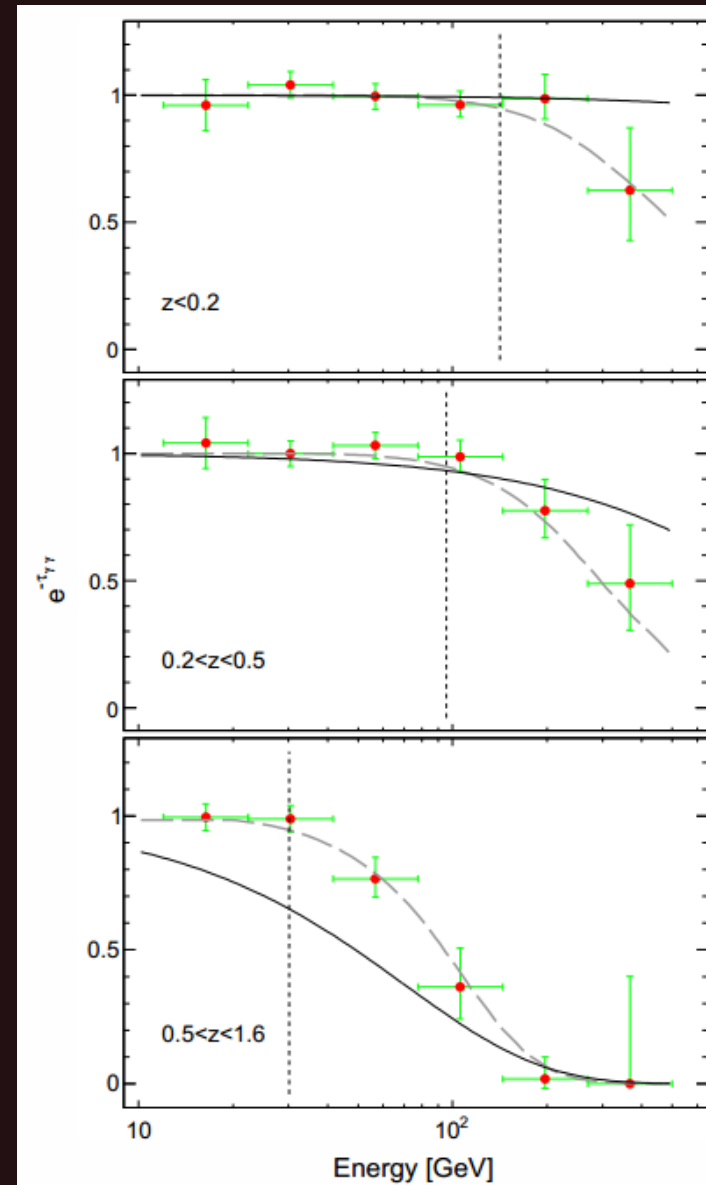
In the third Fermi catalogue
(1501.02003)
>1100 AGNs



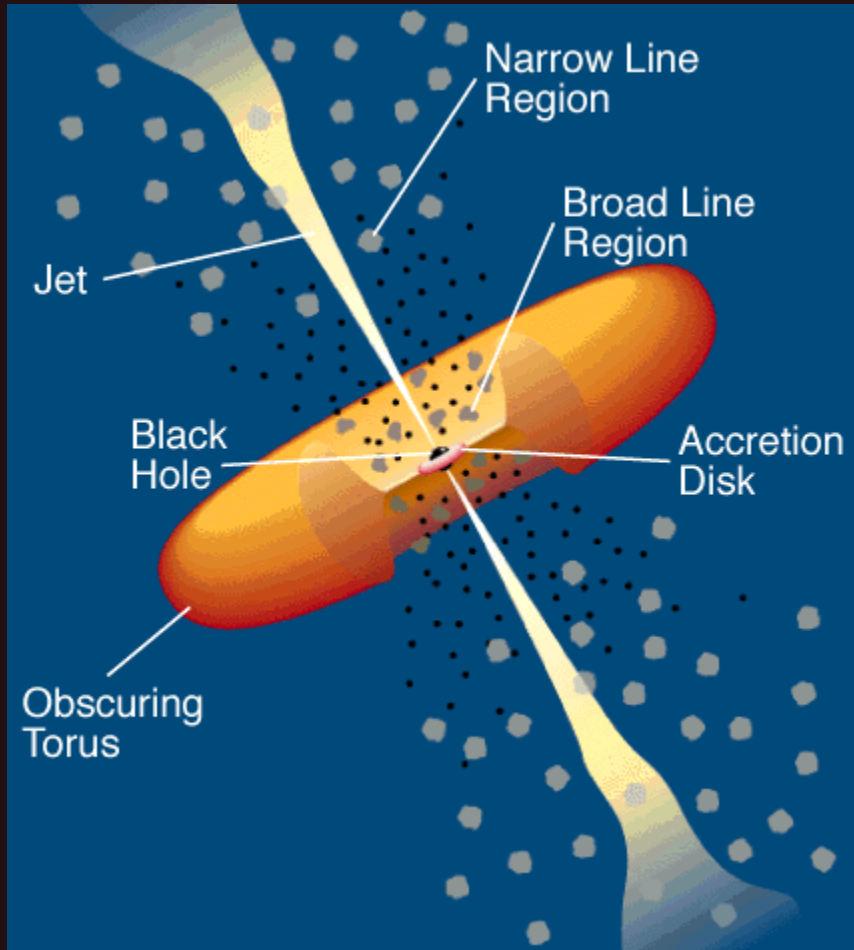
Фоновое излучение



Если у вас есть далекий источник гамма-излучения, то гамма-фотоны по дороге к нам могут взаимодействовать с оптическим и УФ излучением фона, давая электрон-позитронные пары. Соответственно, в спектре далекого гамма-источника мы будем видеть депрессию. Для индивидуального источника увидеть это крайне тяжело. Авторы же использовали данные наблюдений на спутнике Ферми для полутора сотен блазаров, чтобы выделить суммарный эффект.



Unified model

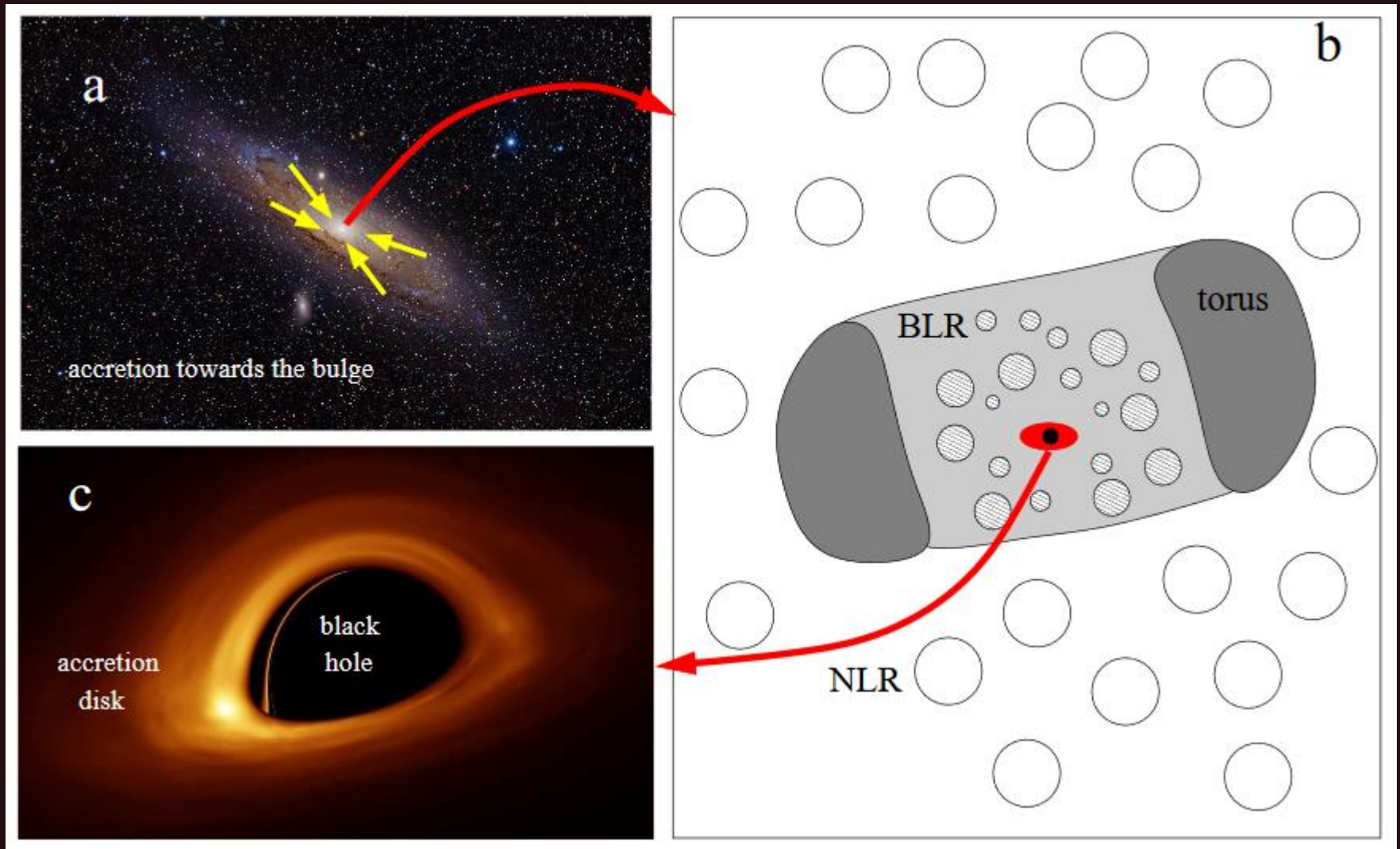


In the framework of the unified model properties of different types of AGNs are explained by properties of a torus around a BH and its orientation with respect to the line of sight.

Antonucci 1993 ARAA 31, 473

The model can be unapplicable to merging systems, see 1505.00811

Accretion on different scales



Unified model and population synthesis

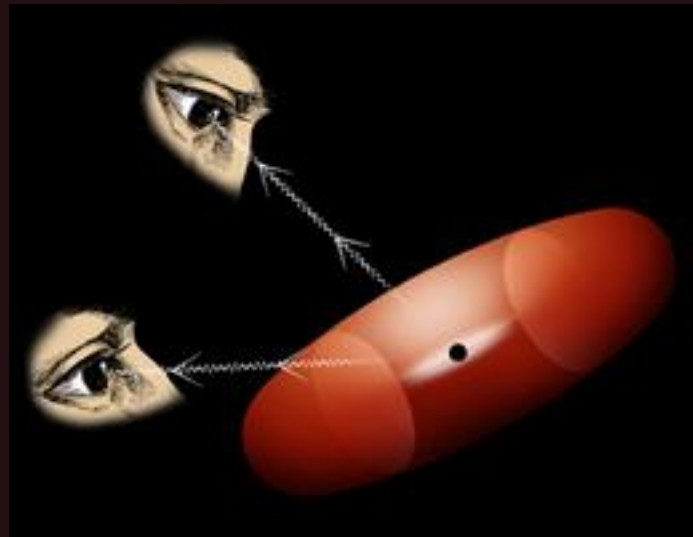
X-ray background is dominated by AGNs.

Discussion of the nature and properties of the background resulted in population synthesis studies of AGNs.

Ueda et al. [astro-ph/0308140](#)

Franceschini et al. [astro-ph/0205529](#)

Ballantyne et al. [astro-ph/0609002](#)



What should be taken into account

- Relative fraction of nuclei obscured by toruses
- Luminosity distribution of nuclei
- Spectral energy distribution
- Evolution of all these parameters

Mass determination in the case of SMBHs

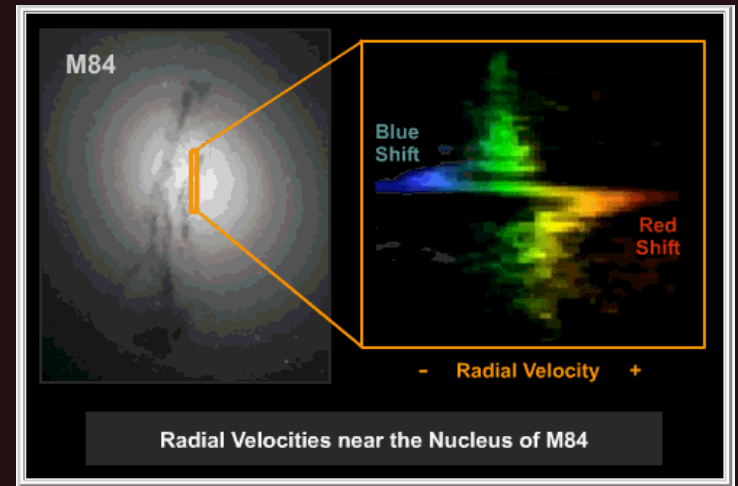
- Relation between a BH mass and a bulge mass (velocity dispersion).
- Measurements of orbits of stars and masers around a BH.
- Gas kinematics.
- Stellar density profile.
- Reverberation mapping.

Also, always a simple upper limit can be put based on the fact that the total luminosity cannot be higher than the Eddington value.

See a short review by [Vestergaard](#)
in astro-ph/0401436

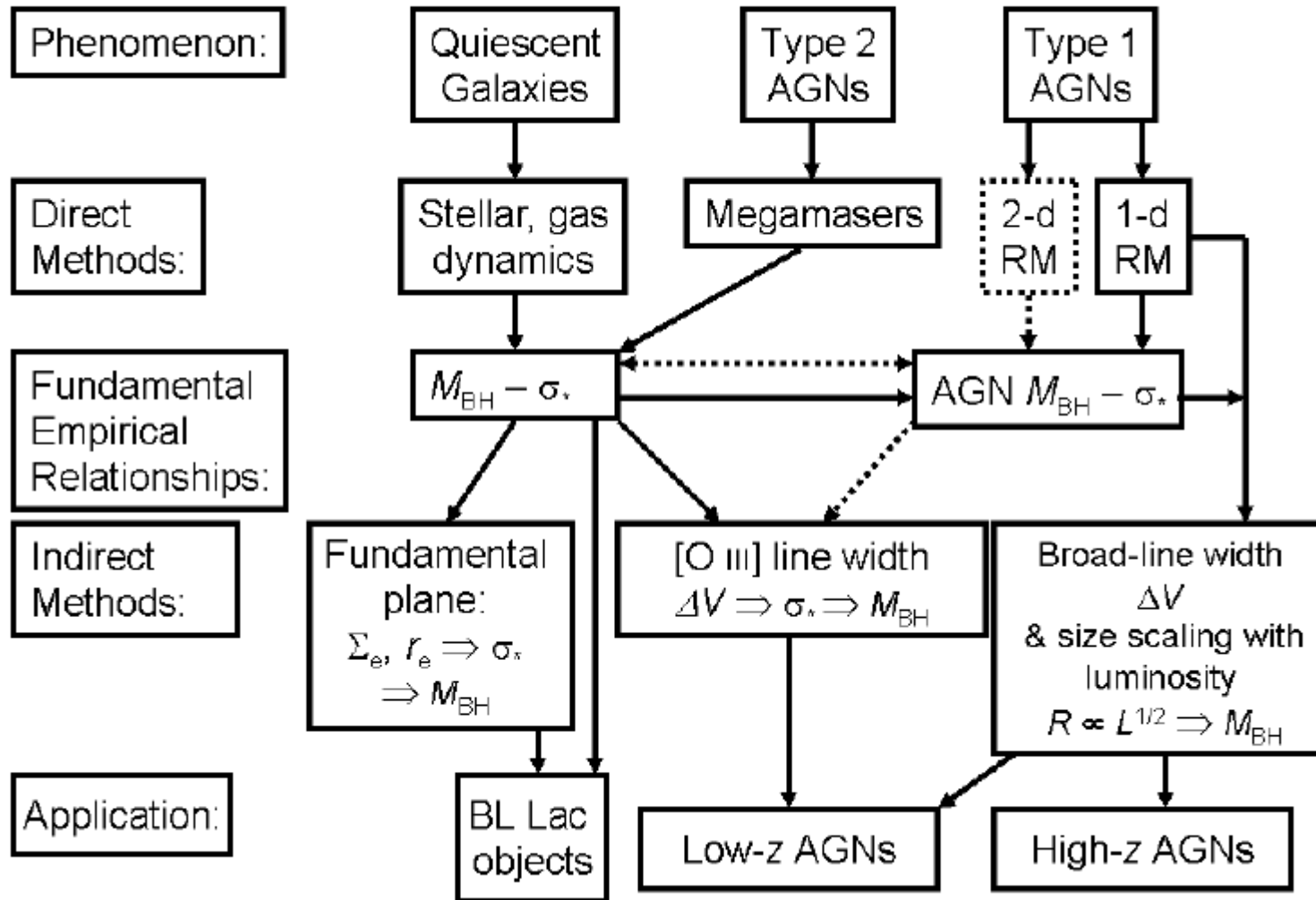
«**Black-Hole Mass Measurements**»

See a more recent reviews in [0904.2615](#),
and [1001.3675](#)



Different methods

Measurement of Central Black Hole Masses

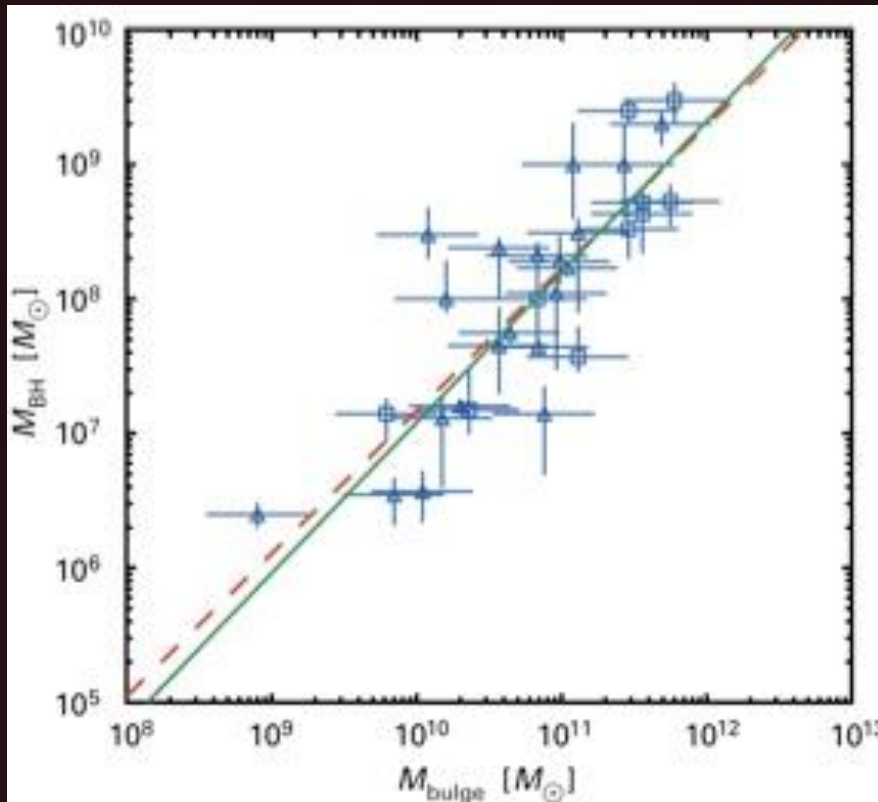


Comparison

Method	NGC 4258	NGC 3227	NGC 4151
	(Units $10^6 M_{\odot}$)		
<u>Direct methods:</u>			
Megamasers	$38.2 \pm 0.1^{[1]}$	N/A	N/A
Stellar dynamics	$33 \pm 2^{[2]}$	$7\text{--}20^{[3]}$	$\leq 70^{[4]}$
Gas dynamics	$25\text{--}260^{[5]}$	$20^{+10}_{-4} [6]$	$30^{+7.5}_{-22} [6]$
Reverberation	N/A	$7.63^{+1.62}_{-1.72} [7]$	$46 \pm 5^{[8]}$
<u>Indirect methods:</u>			
$M_{\text{BH}}\text{--}\sigma_{*}^{[9]}$	13	25	6.1
$R\text{--}L$ scaling ^[10]	N/A	15	29–120

BH mass vs. bulge mass

According to the standard picture every galaxy with a significant bulge has a SMBH in the center.



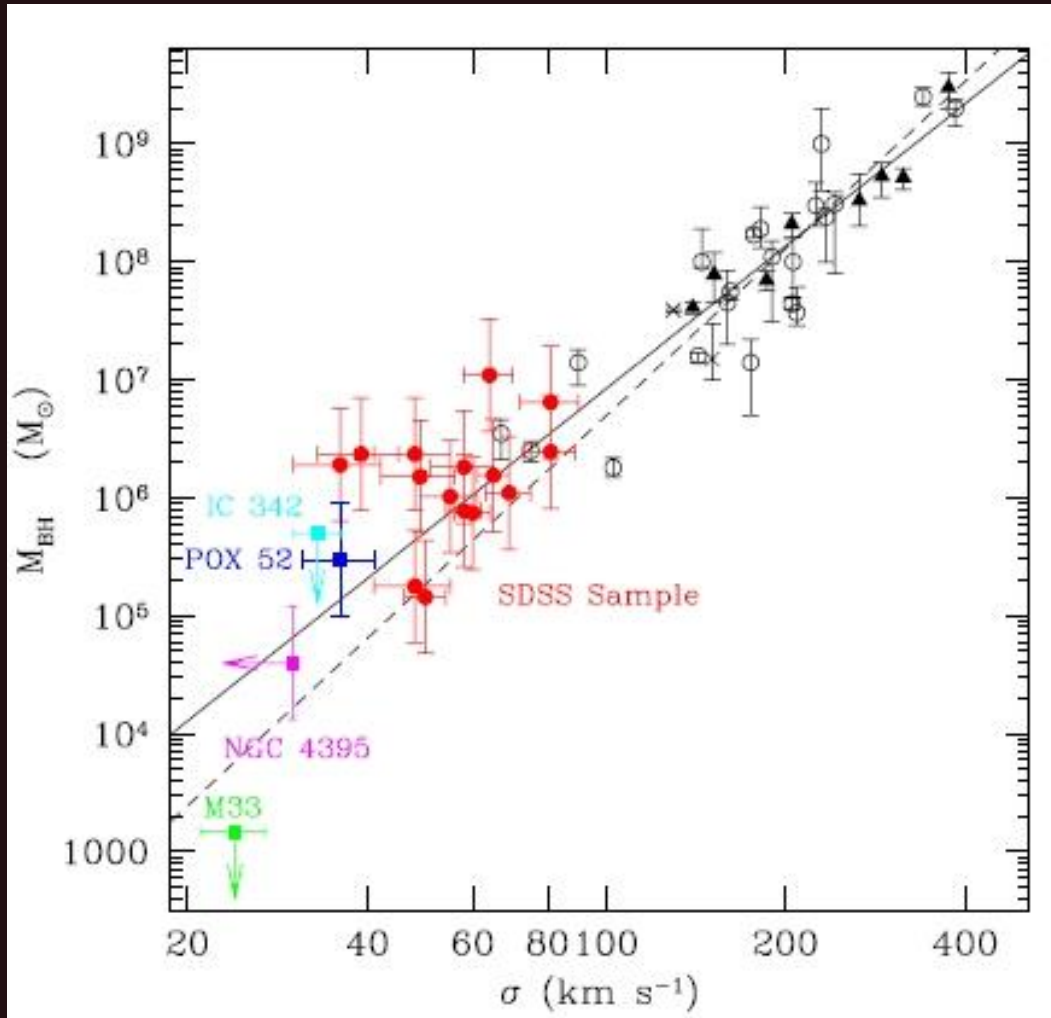
$$M_{\text{BH}} \sim M_{\text{bulge}}^{1.12 \pm 0.06}$$

(Haering, Rix astro-ph/0402376)

BH mass usually is about from 0.1% up to several tenth of percent of the bulge mass.

However, the situation is a little bit more complicated. BH mass correlates differently with different components of a galaxy (see 1304.7762 and 1308.6483).

Exceptions: M33

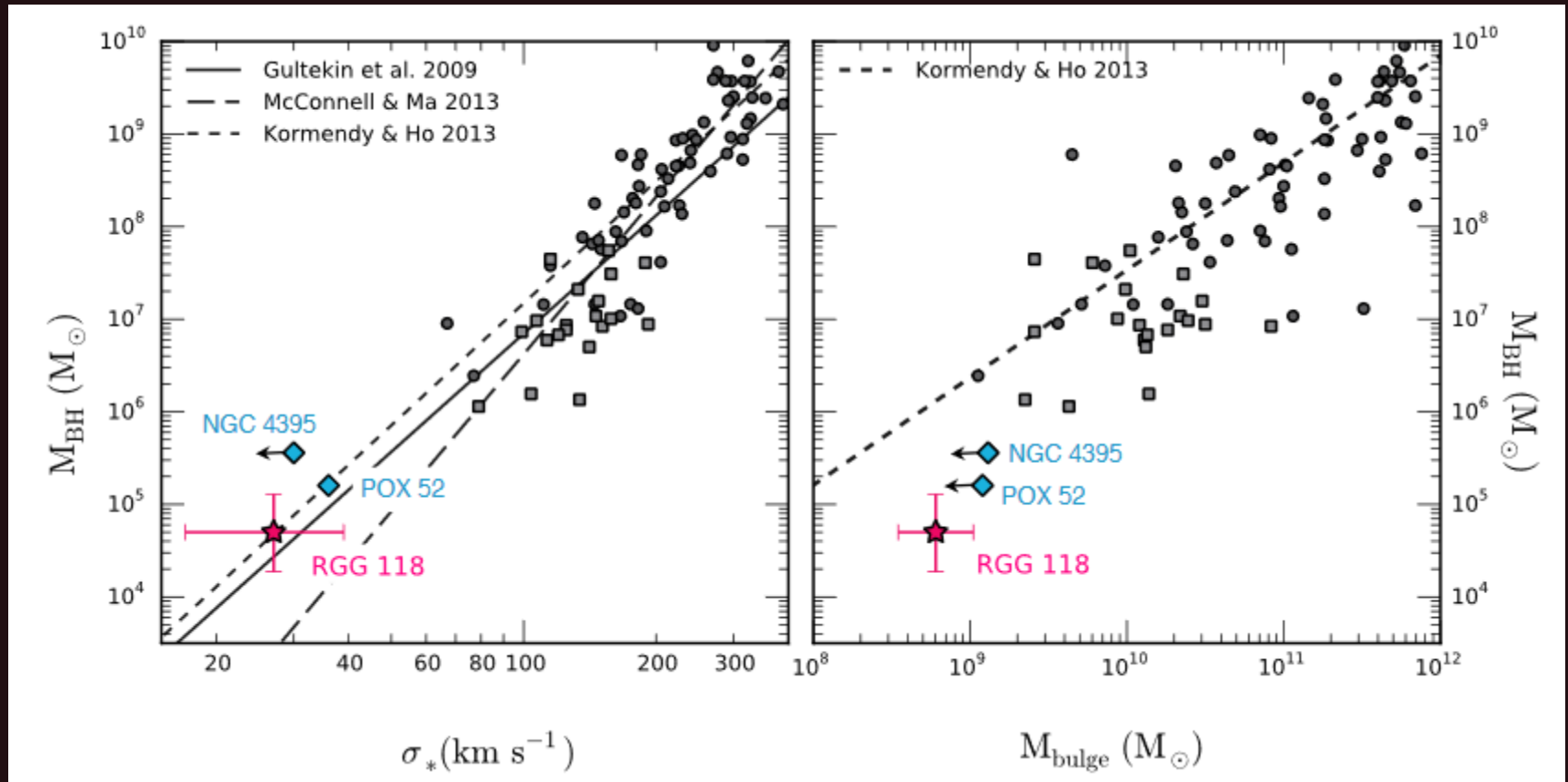


The upper limit on the BH mass in M33 is an order of magnitude lower than it should be according to the standard relation.

Light SMBH

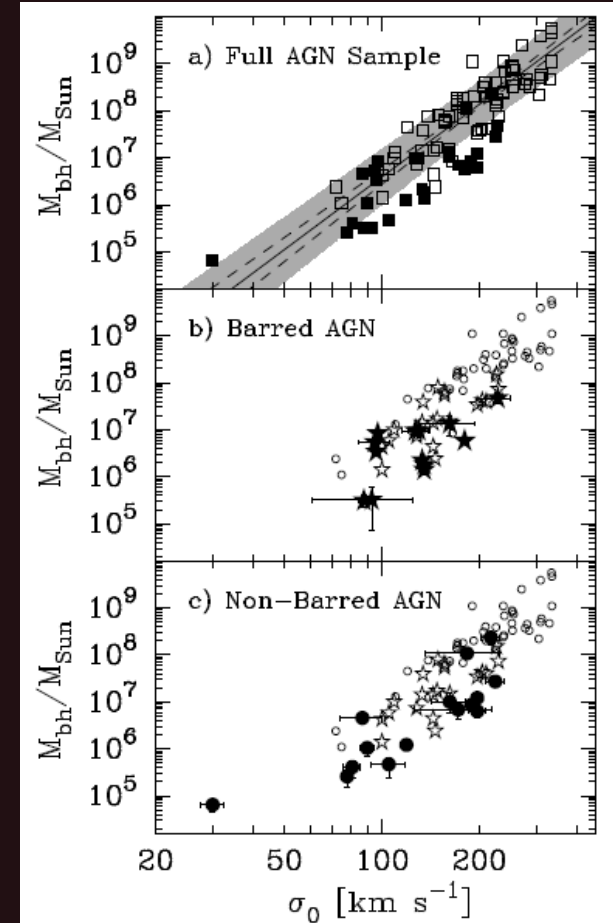
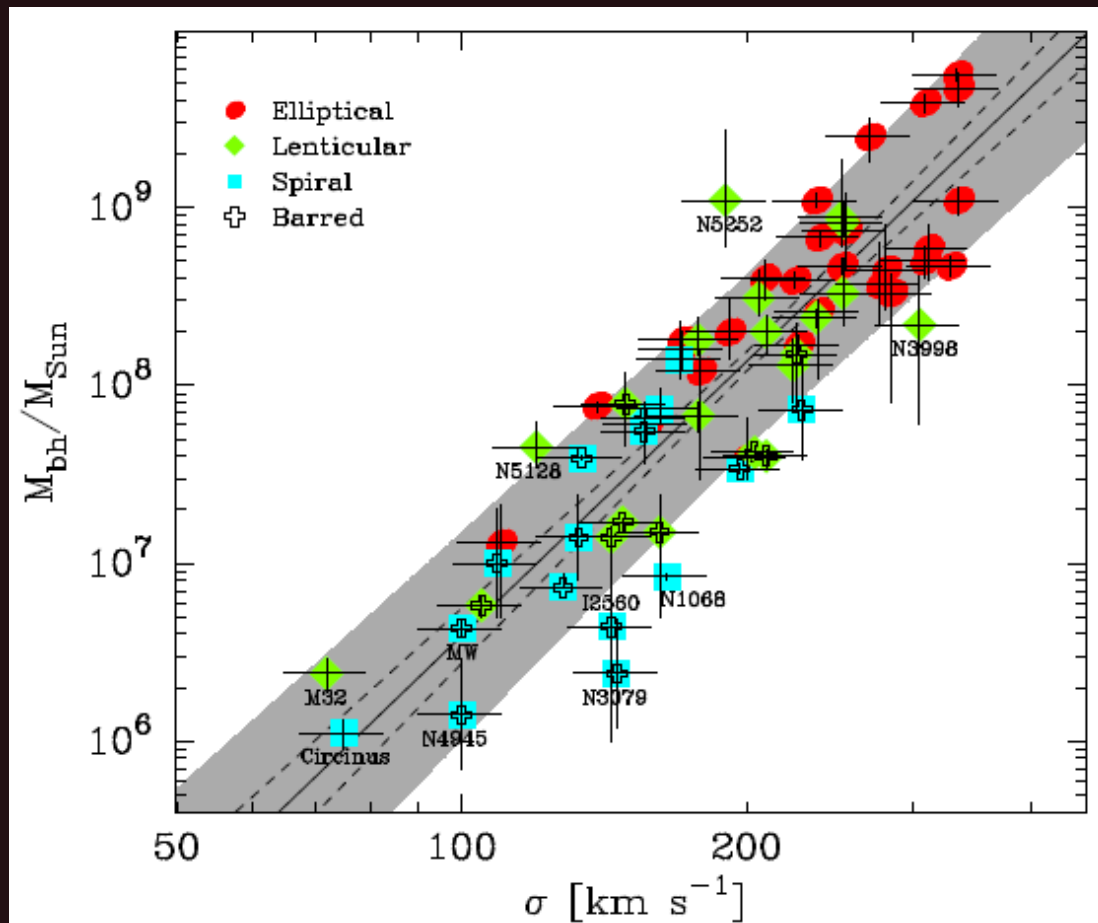
dwarf galaxy RGG 118

BH 50 000 solar masses



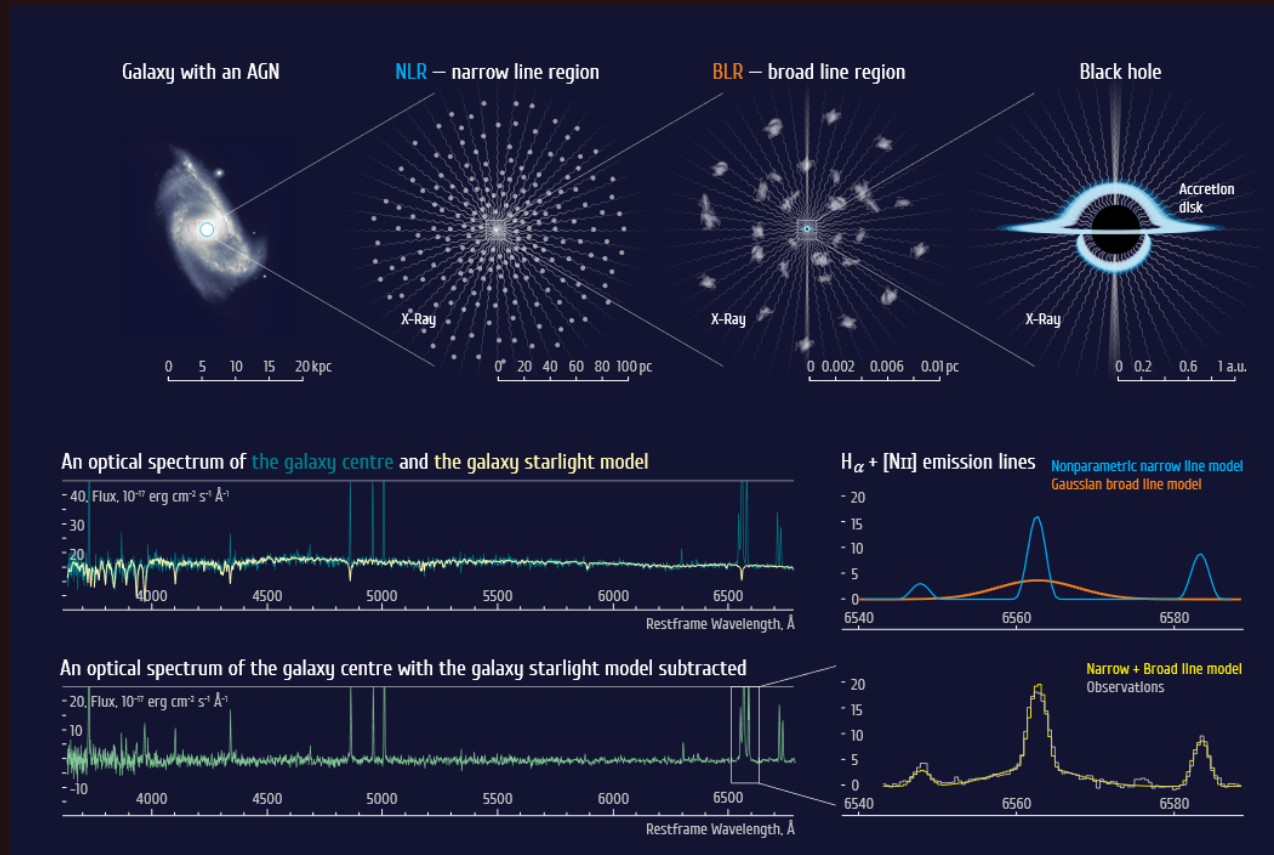
1506.07531

More data

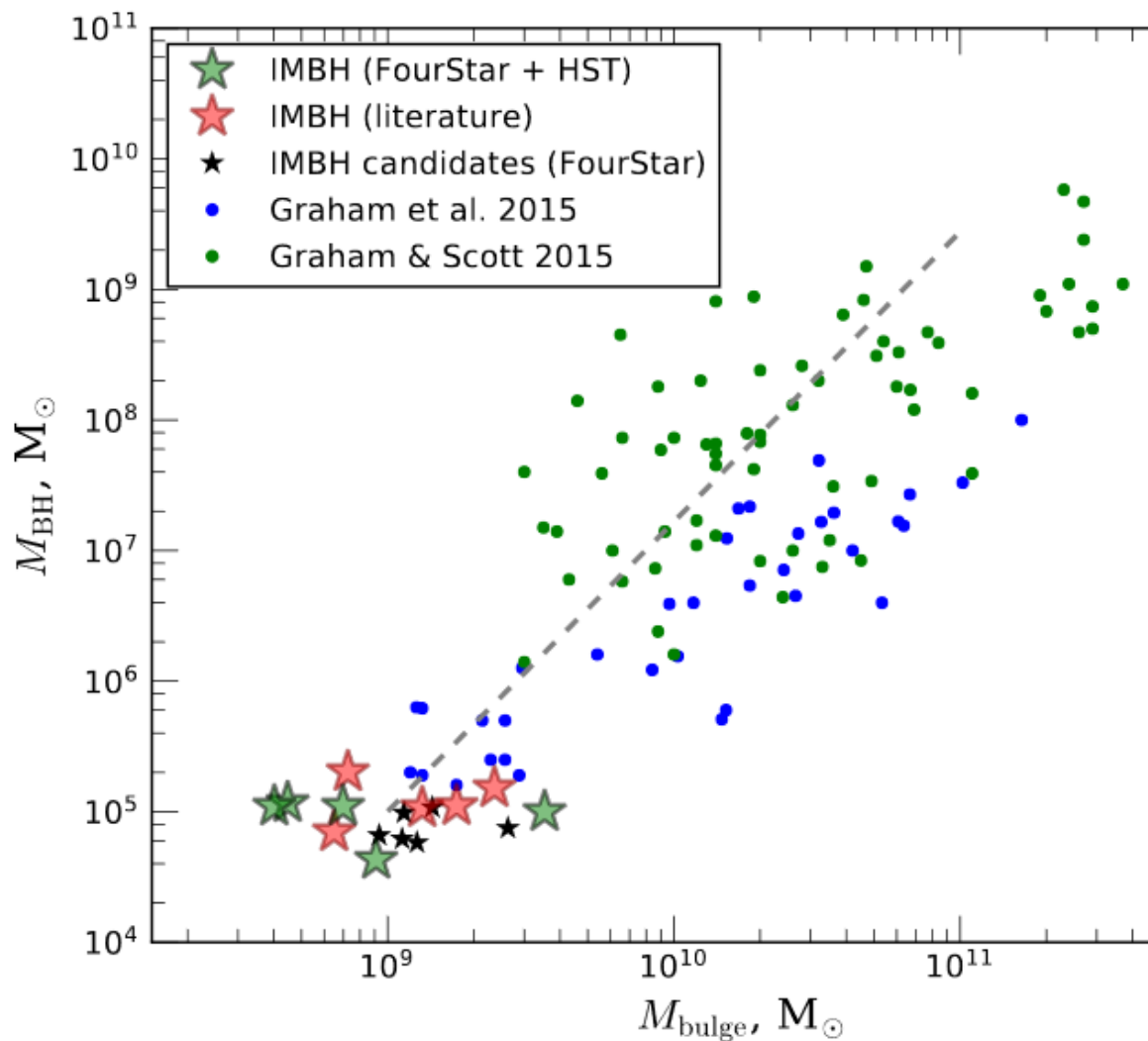


IMBHs in low luminosity AGNs

$$M_{\text{BH}} = 3.72 \times 10^6 (\text{FWHM}_{\text{H}\alpha} / 10^3 \text{ km s}^{-1})^{2.06} \times (L_{\text{H}\alpha} / 10^{42} \text{ erg s}^{-1})^{0.47} M_{\odot}$$



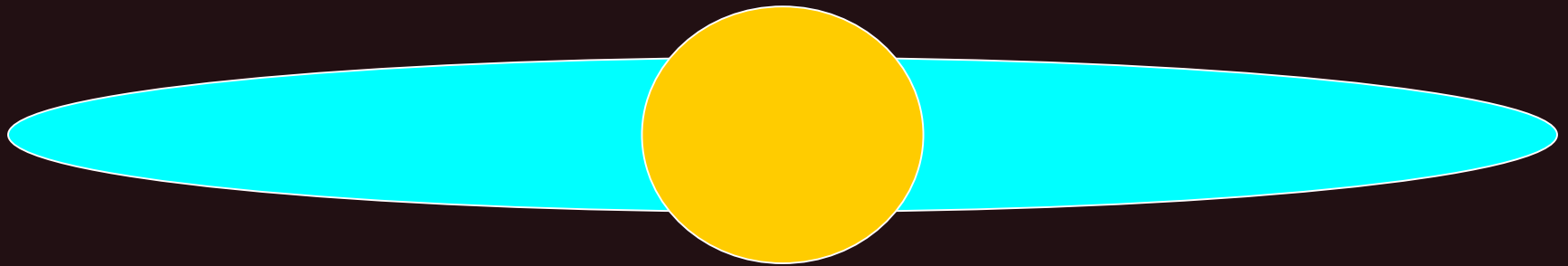
IMBHs in low luminosity AGNs



Object	M_{BH} ($10^3 M_{\odot}$)
J122732.18+075747.7	43 ± 10^1 36 ± 7^2
J134244.41+053056.1	65 ± 7^1 96 ± 13^2
J171409.04+584906.2	115 ± 24^1
J111552.01-000436.1	115 ± 38^1
J110731.23+134712.8	122 ± 18^1 71 ± 10^2
J152304.97+114553.6 ^a	70 ± 20^1
J153425.58+040806.7 ^b	111 ± 7^1
J160531.84+174826.1 ^b	116 ± 11^1
J112333.56+671109.9 ^c	157 ± 36^1
J022849.51-090153.8 ^c	202 ± 13^1 367 ± 27^2

Сверхмассивная черная дыра там, где ее не должно быть

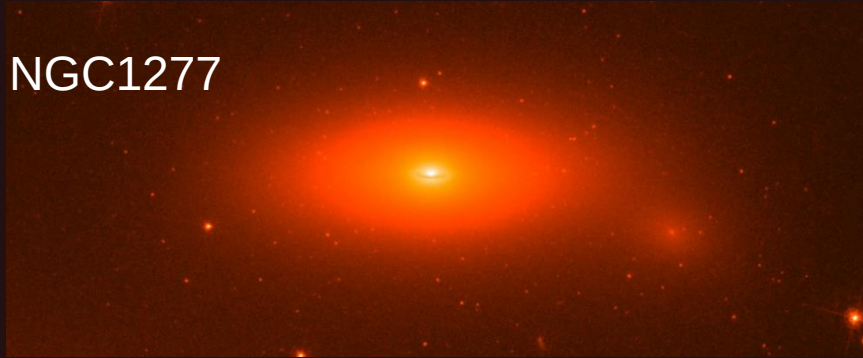
Наблюдения галактики NGC 4561 на спутнике XMM-Newton показали, что в ней есть активное ядро, т.е. – сверхмассивная черная дыра. Но при это быть там этой дыре не положено: у галактики нет балджа.



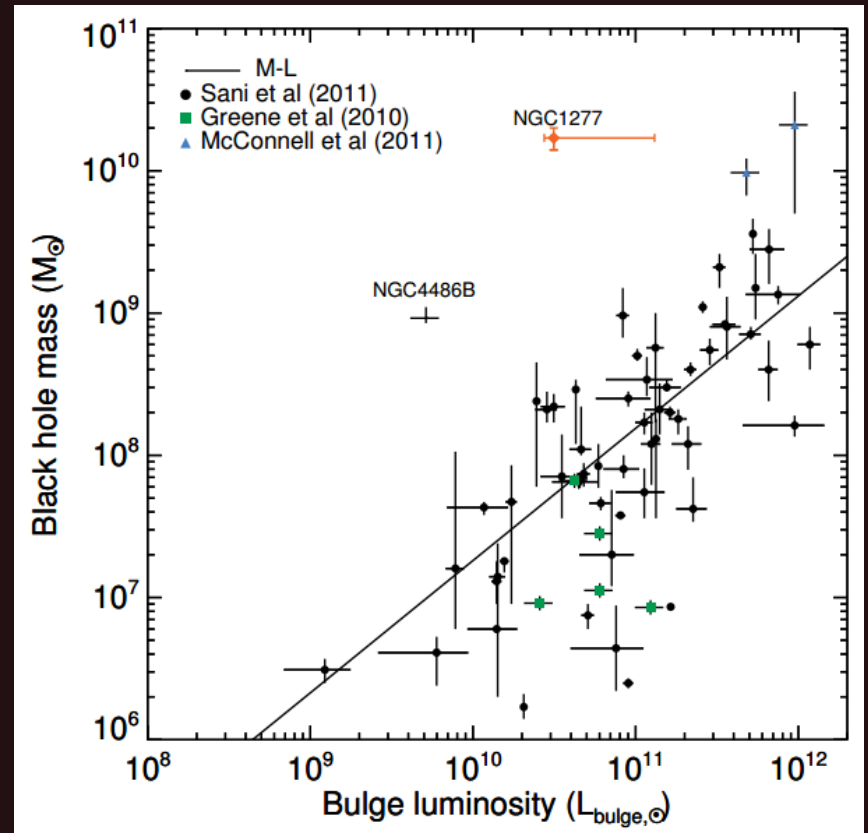
Масса черной дыры $>20000 M_{\odot}$

Слишком массивная черная дыра

NGC1277



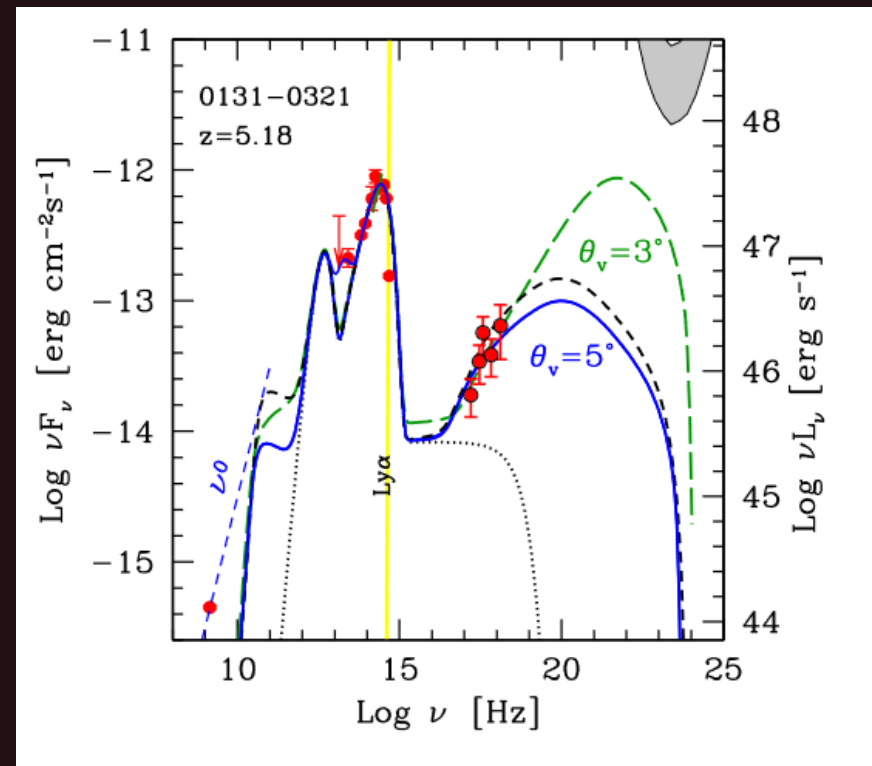
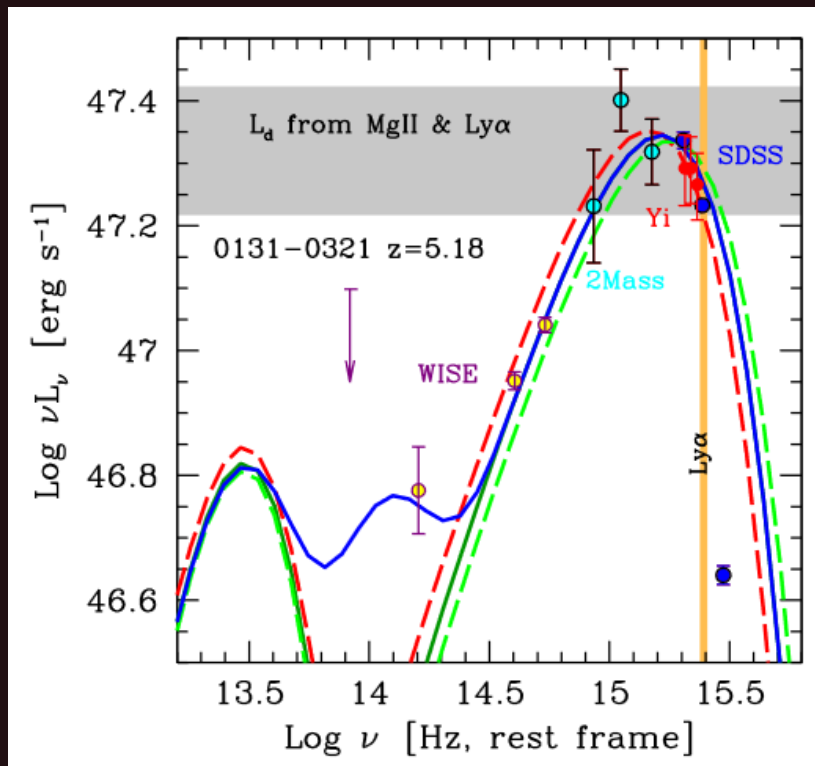
Компактная линзовидная галактика.
«Положено» иметь черную дыру $10^8 M_{\odot}$
А присутствует $>10^{10} M_{\odot}$!



11 billion solar masses BH at $z > 5$

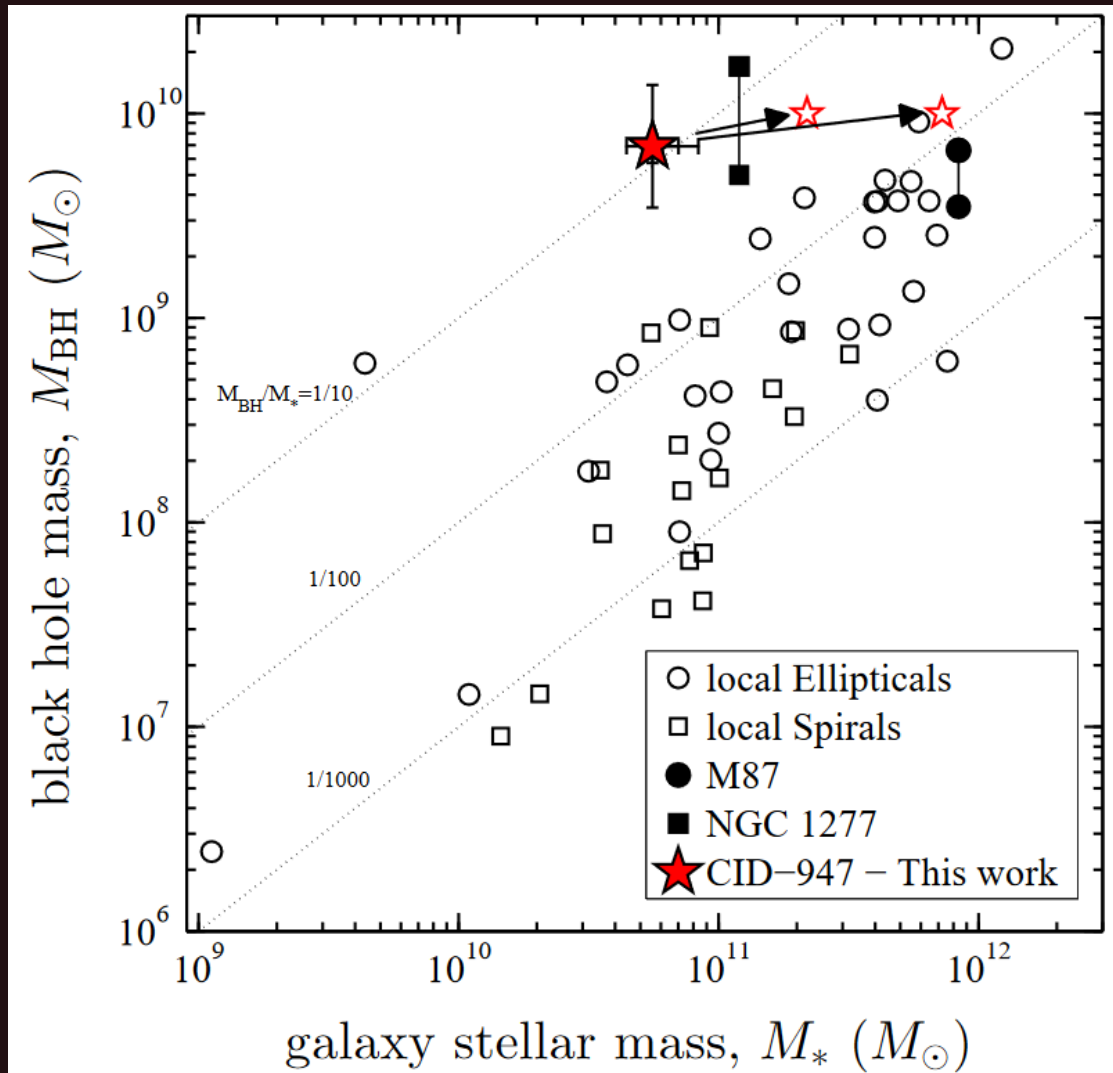
SDSS J013127.34–032100.1

Mass determined via spectral fitting.



1501.07269

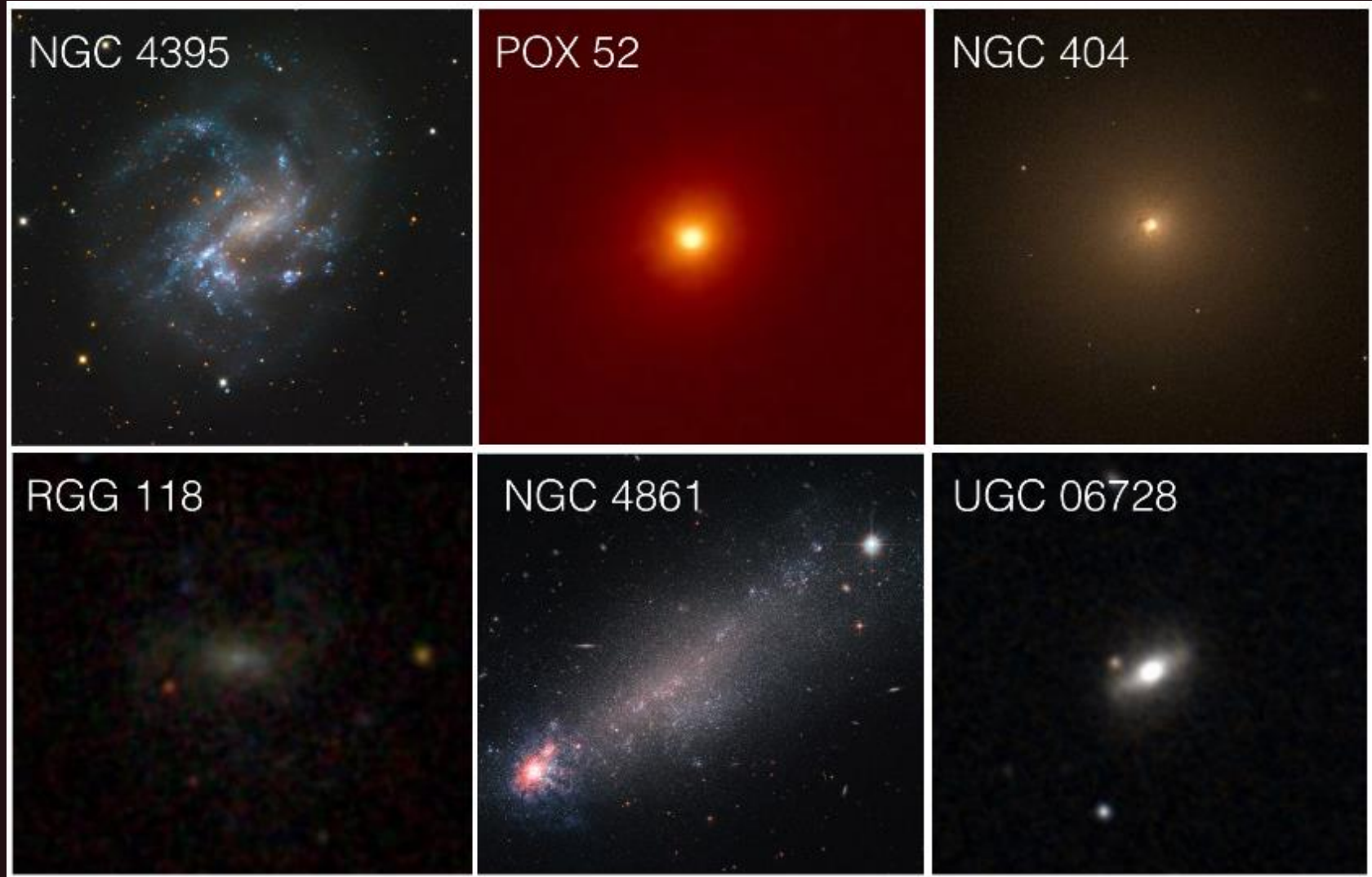
Too massive BH in a starforming galaxy



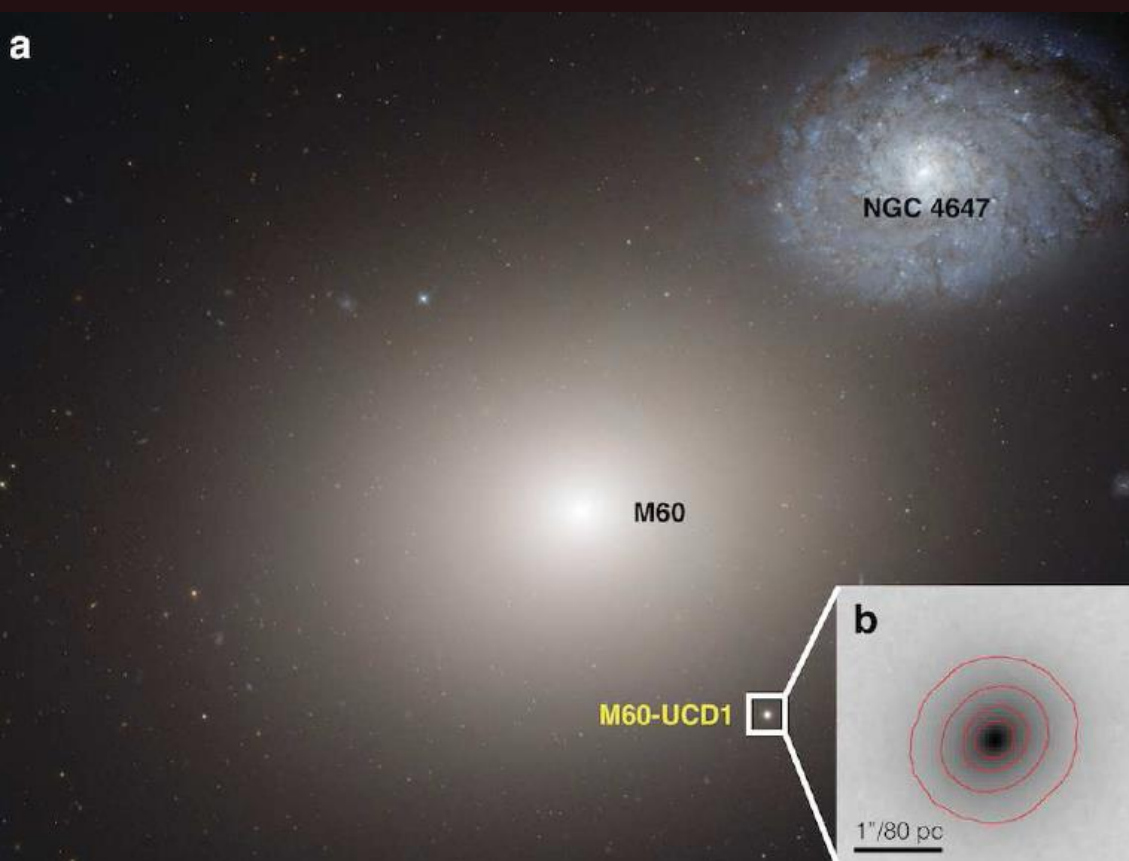
$z=3.3$

Due to large SFR
in a time the BH
might become
“more typical”
respect to the galaxy.

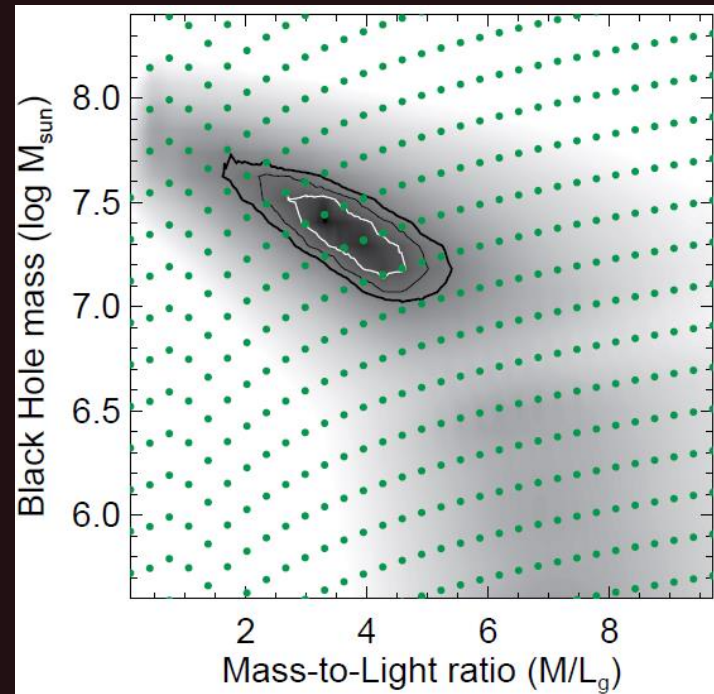
Dwarf galaxies with IMBHs



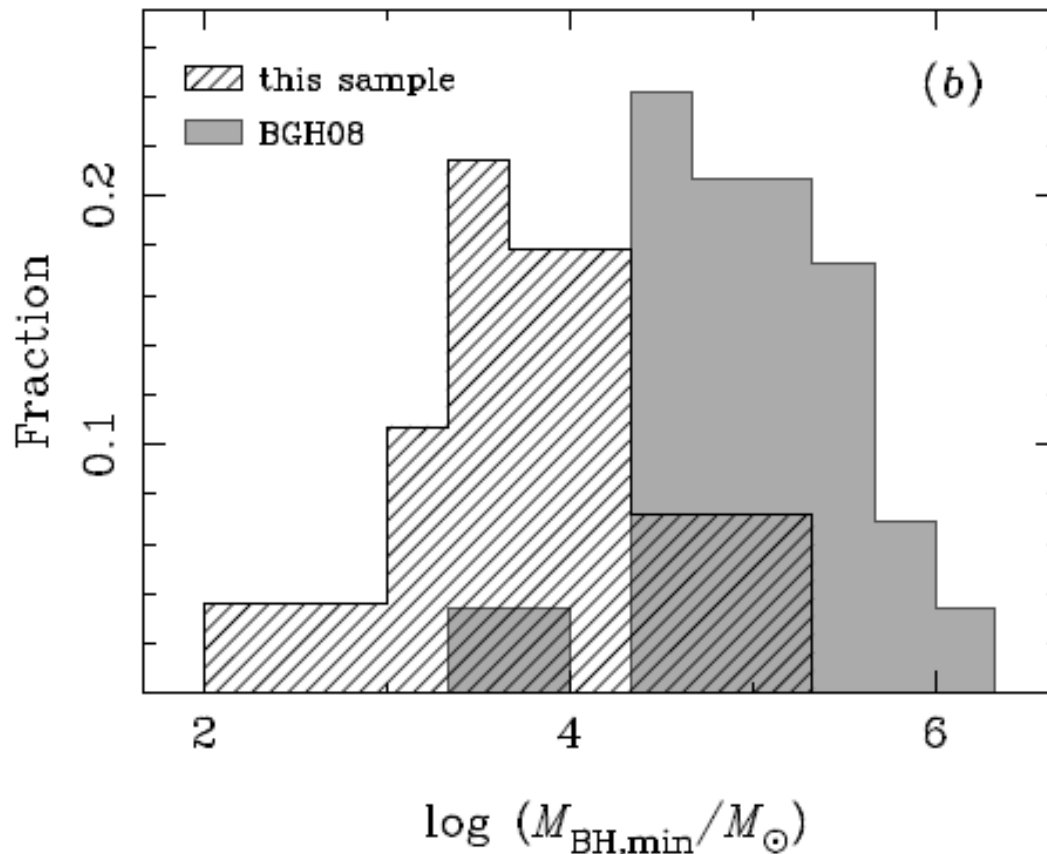
Сверхмассивная черная дыра в карликовой компактной галактике



**Самая легкая
галактика с
черной дырой**

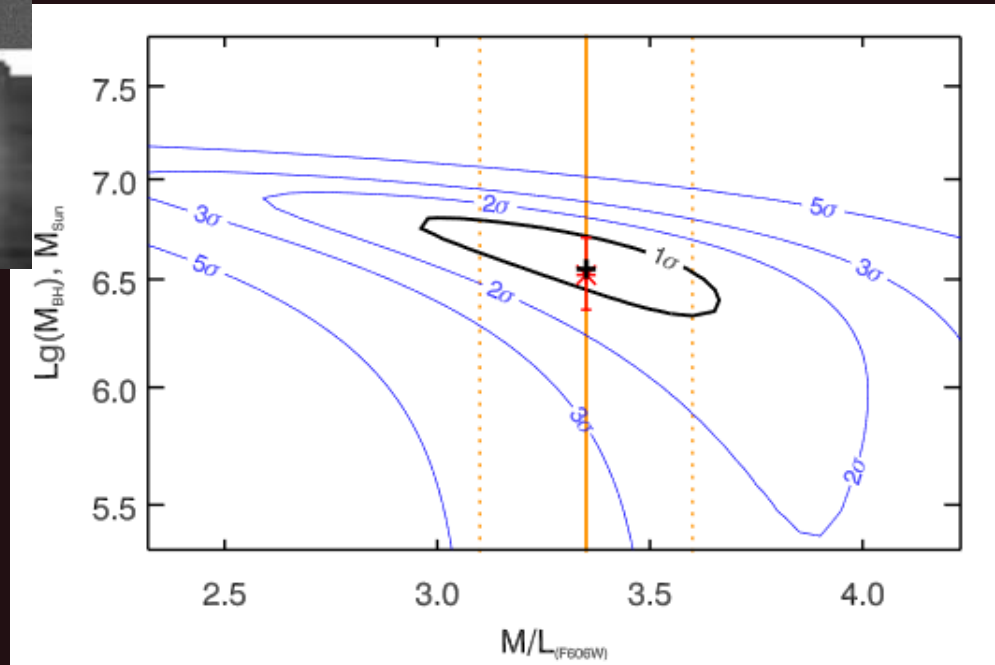
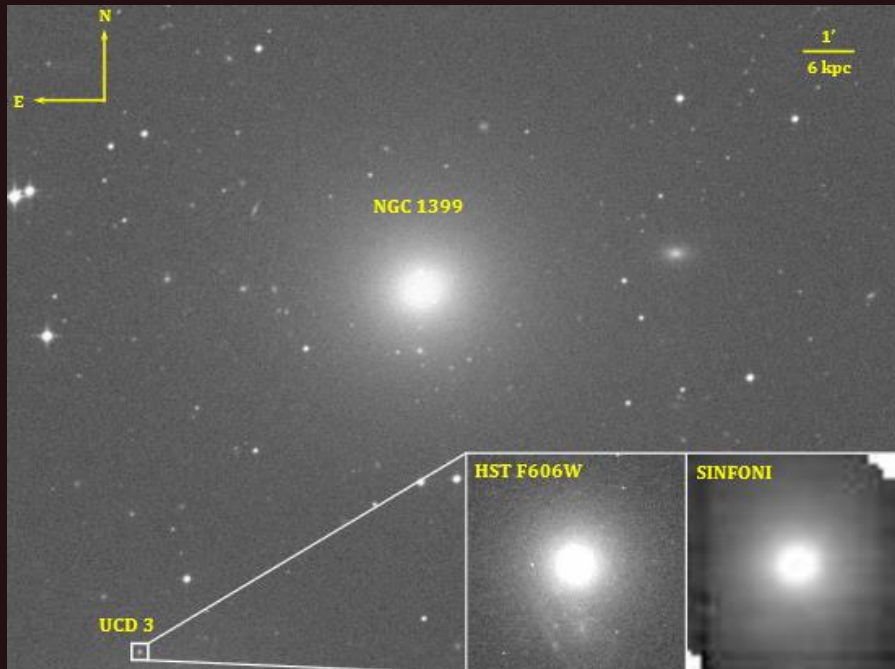


Черные дыры в карликовых галактиках



Сами галактики имеют массы порядка нескольких миллиардов масс Солнца, а размеры порядка нескольких килопарсек.

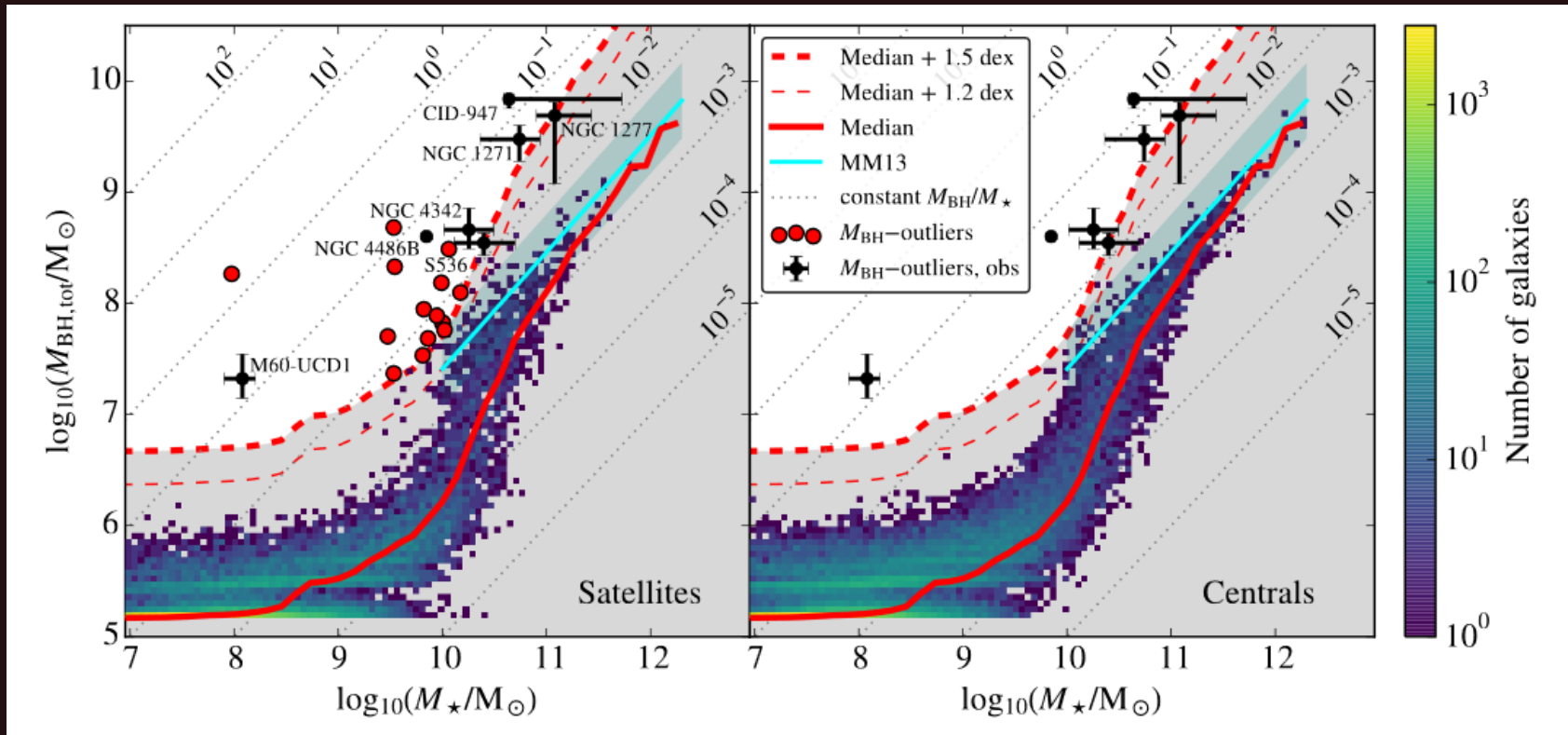
SMBH in Fornax UCD3



3.5 million M_{Solar}

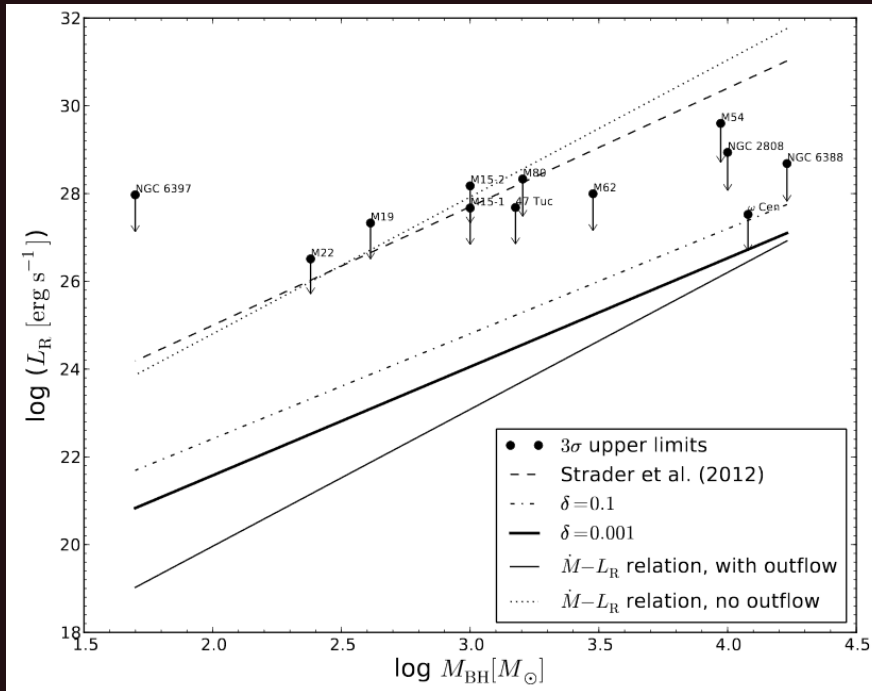
1804.02938

Massive BHs in small galaxies



EAGLE modeling vs. observations.
Outliers are mainly due to tidal stripping.

BHs in globular clusters



Radio pulsar observations in NGC 6624 suggest that there is an IMBH with $M > 7500$ solar masses.

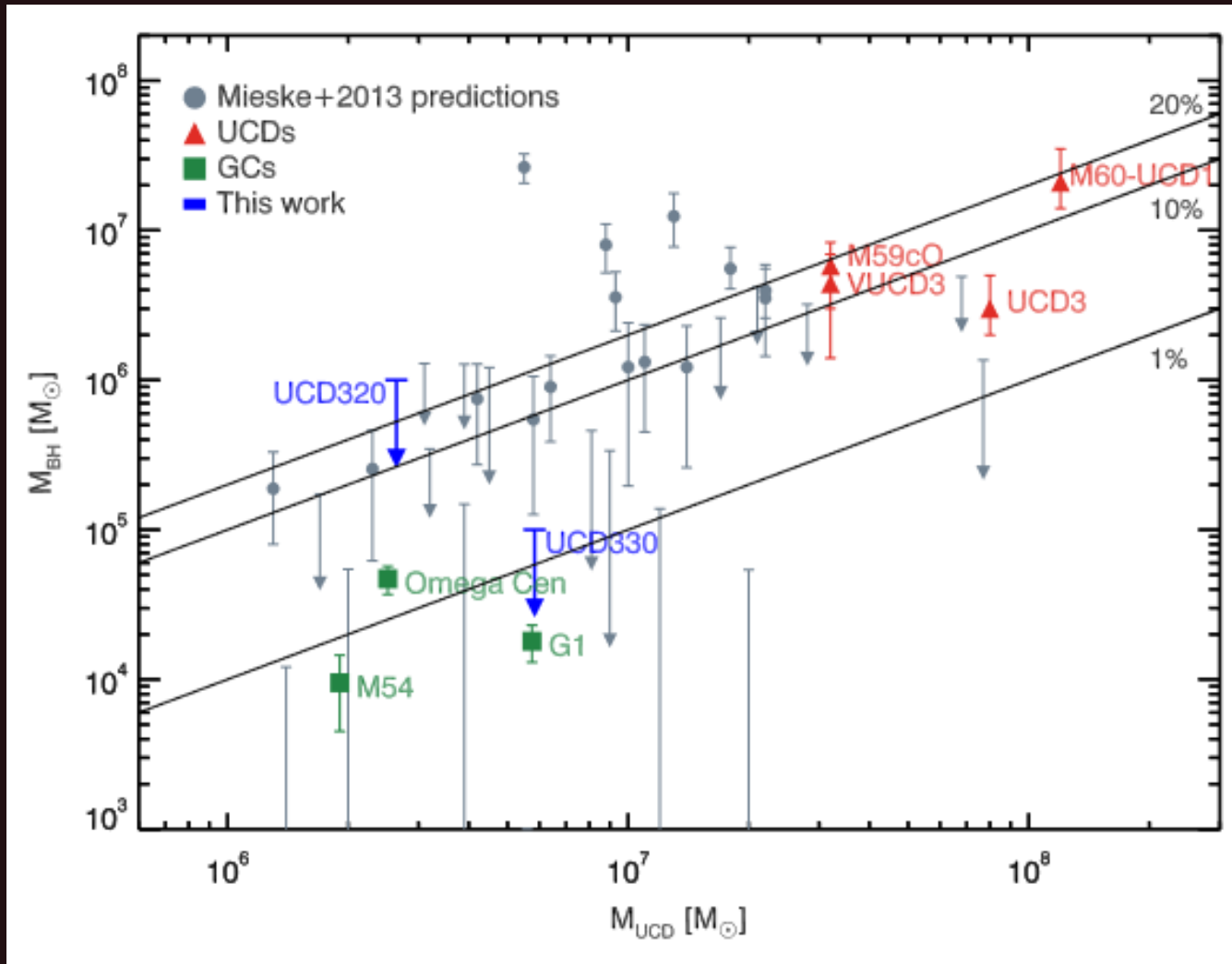
1705.01612

Radio luminosity limits cannot exclude proposed IMBHs in GCs

~15 candidates now (see 1705.09667)

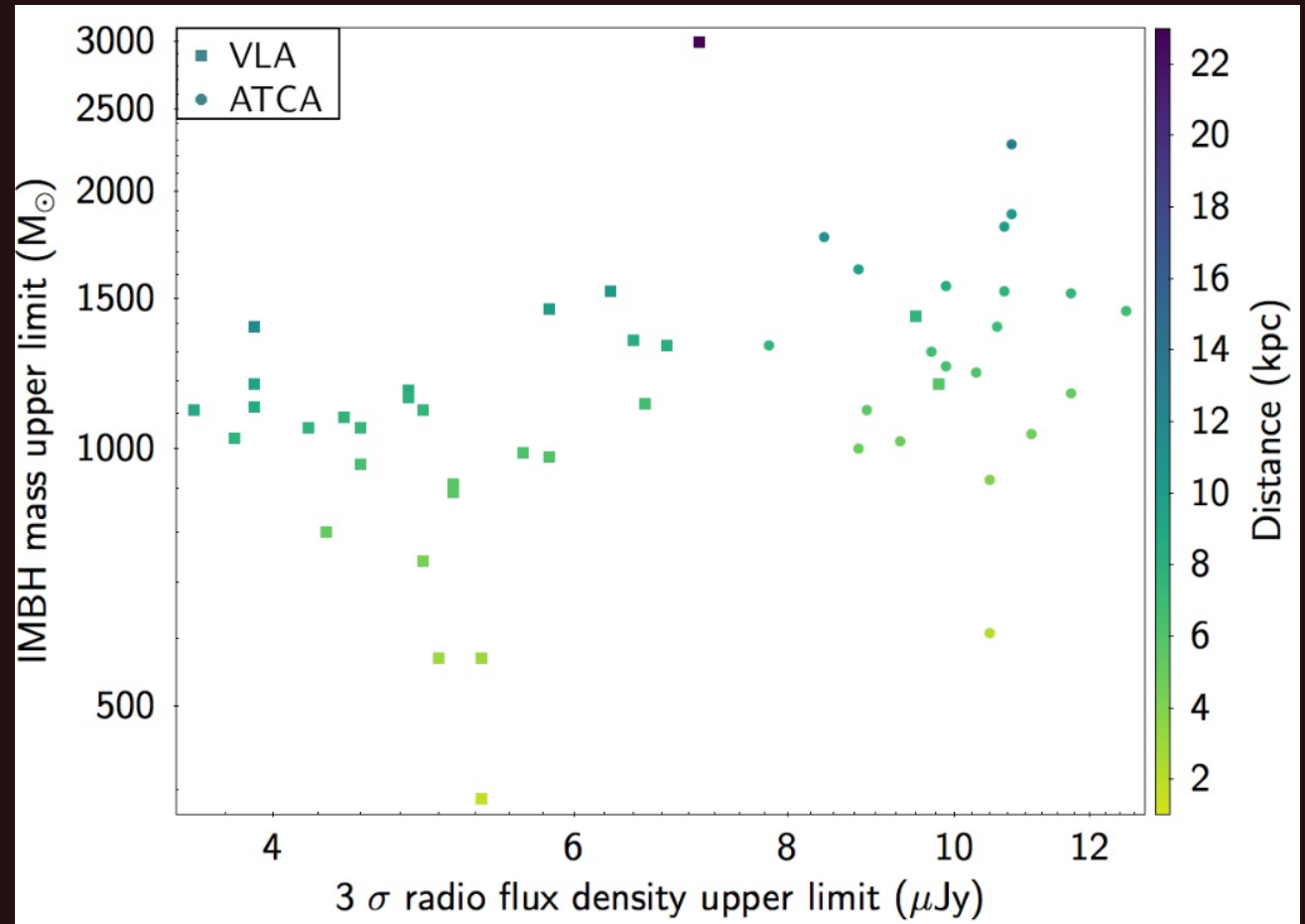
Limits from dynamics: 1404.2781

Ultra compact galaxies vs. globular clusters



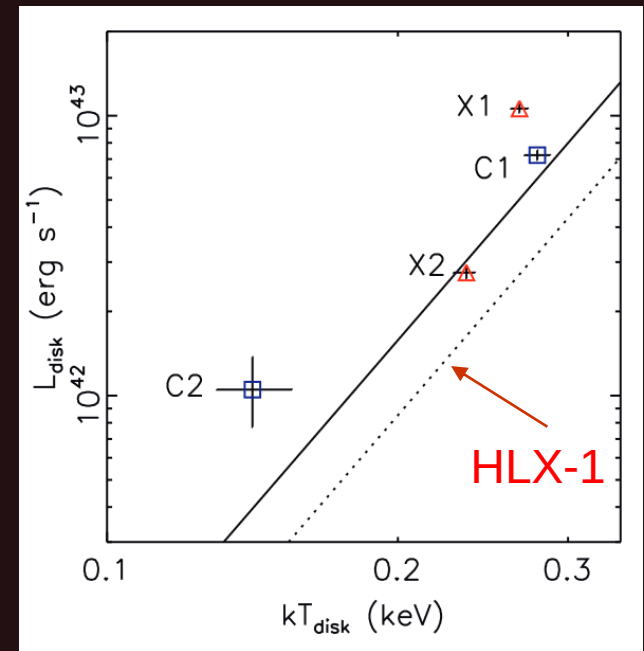
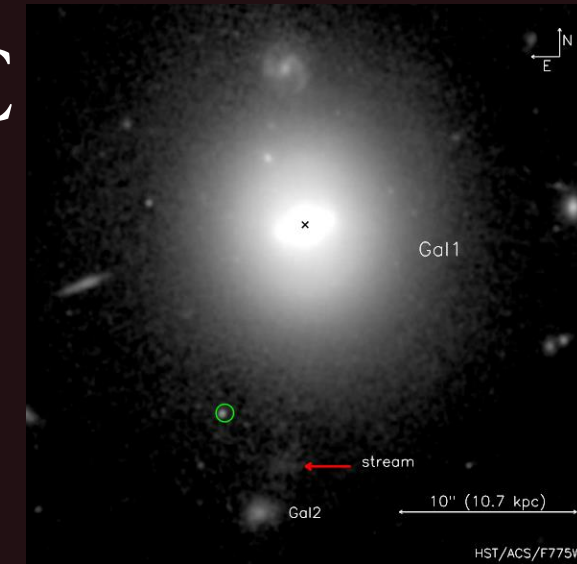
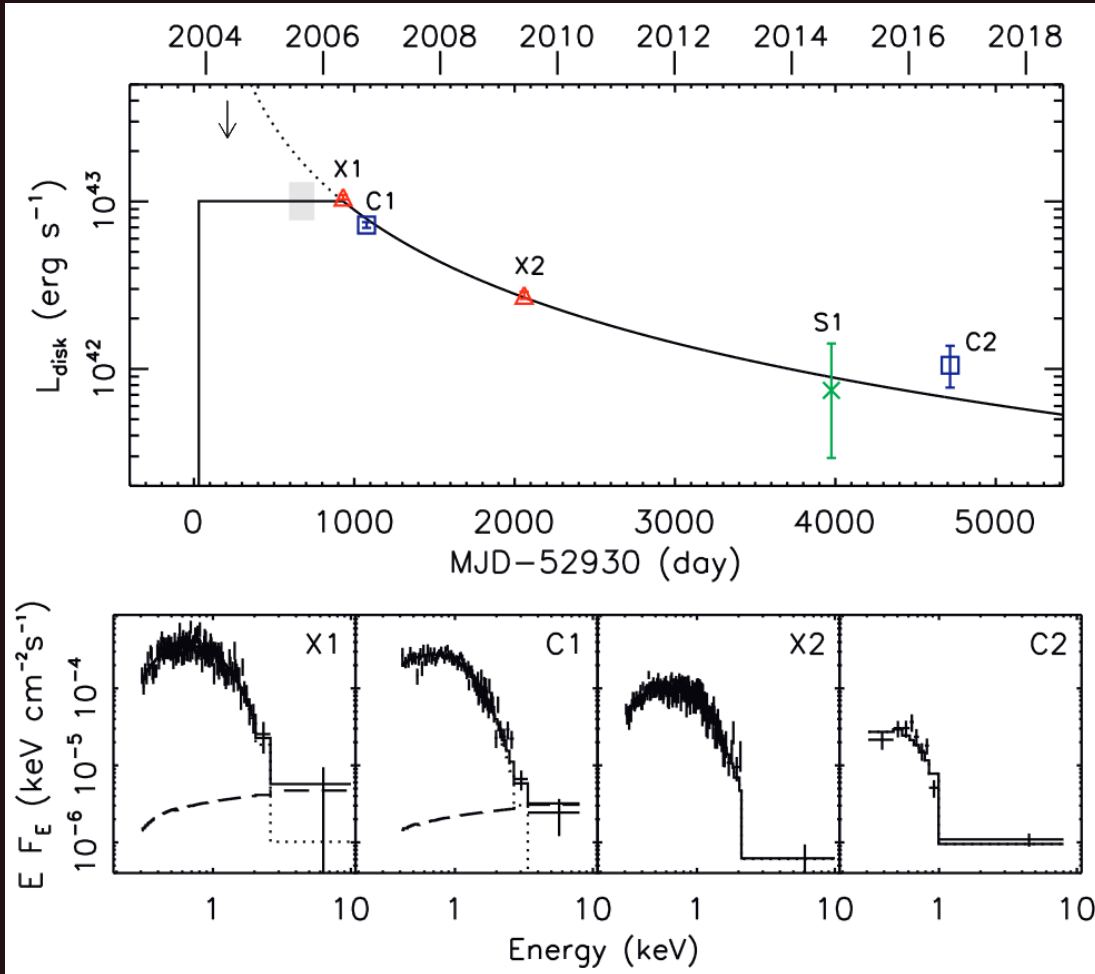
Maveric survey: no accreting IMBHs in GCs

VLA + ATCA
50 globular clusters
No detections.



1806.00259

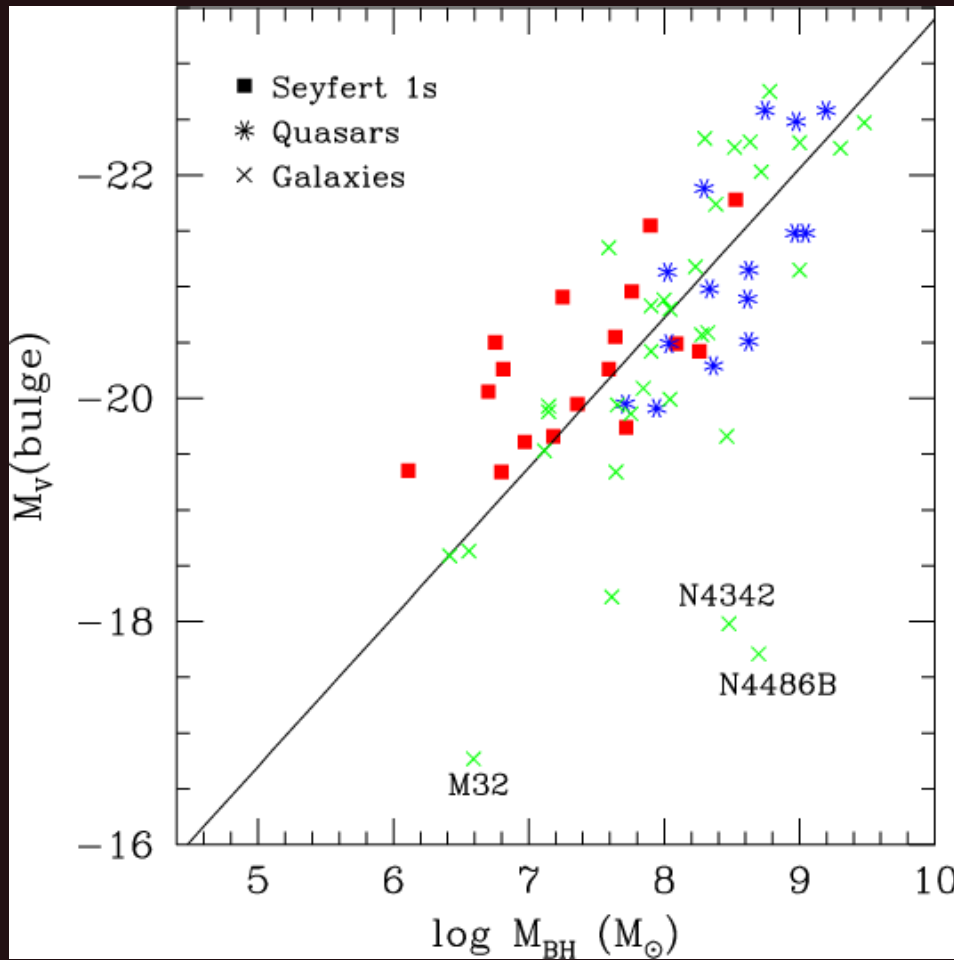
TDE in an extragalactic GC



BH mass ~few 10^4 solar masses

1806.05692, see modeling of such events in 1904.06353

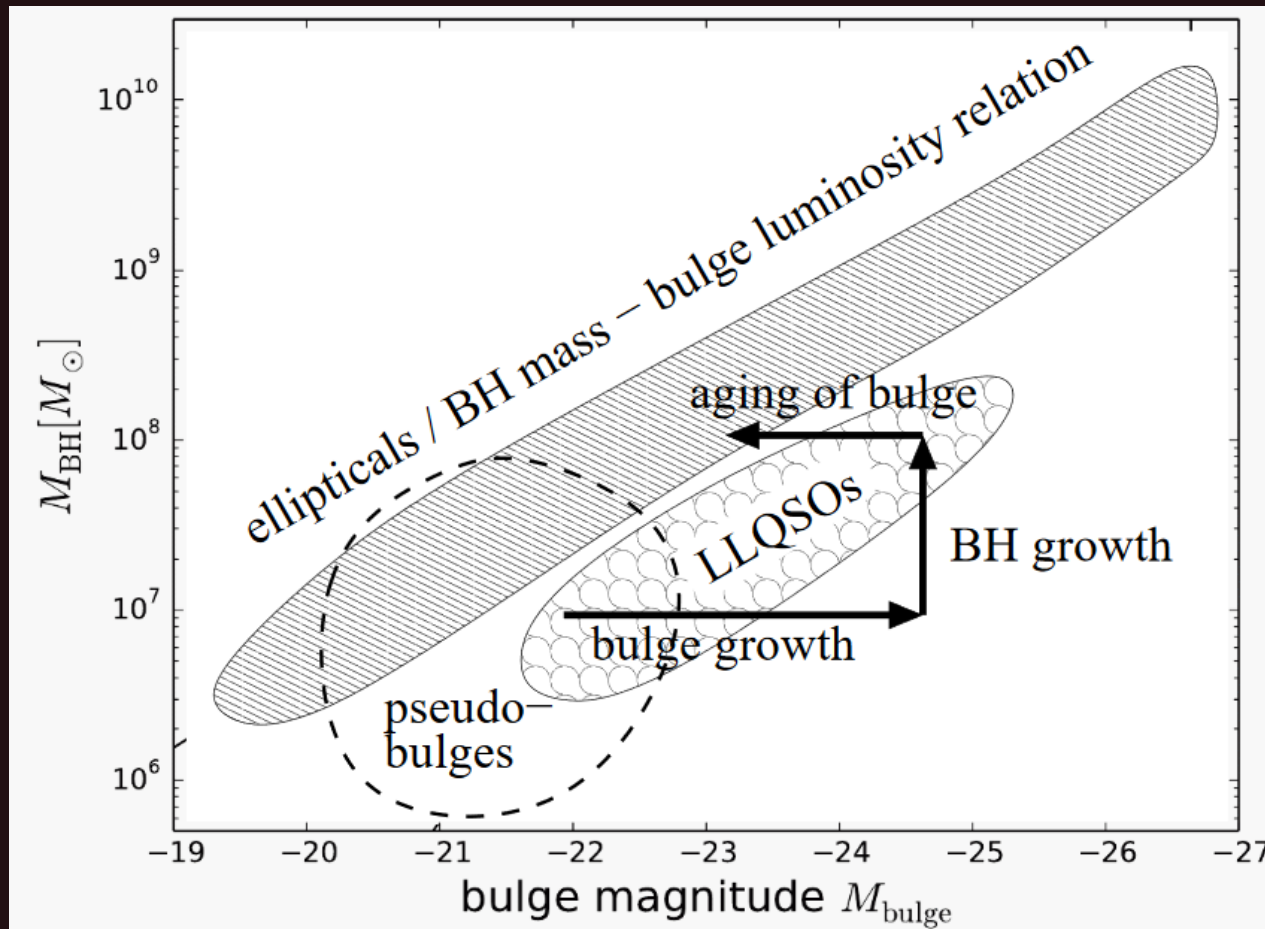
There are other correlations



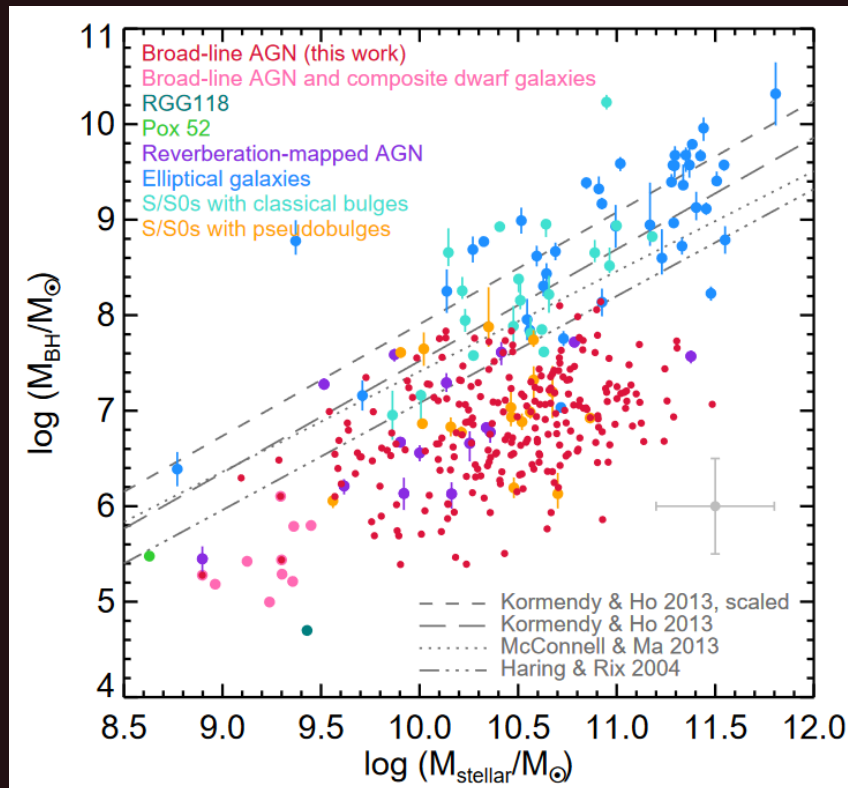
In the figure the following correlation is shown: absolute magnitude of the bulge (in V filter) vs. BH mass. BH masses are obtained by reverberation mapping.

Other correlations are discussed in the literature.

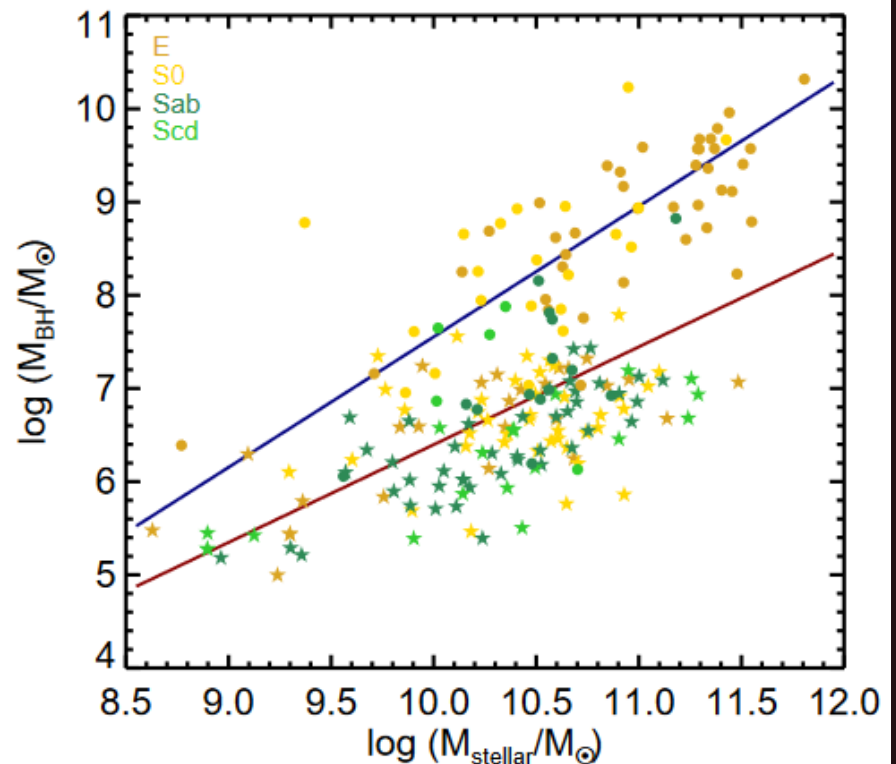
Origin of black hole mass – bulge magnitude correlation



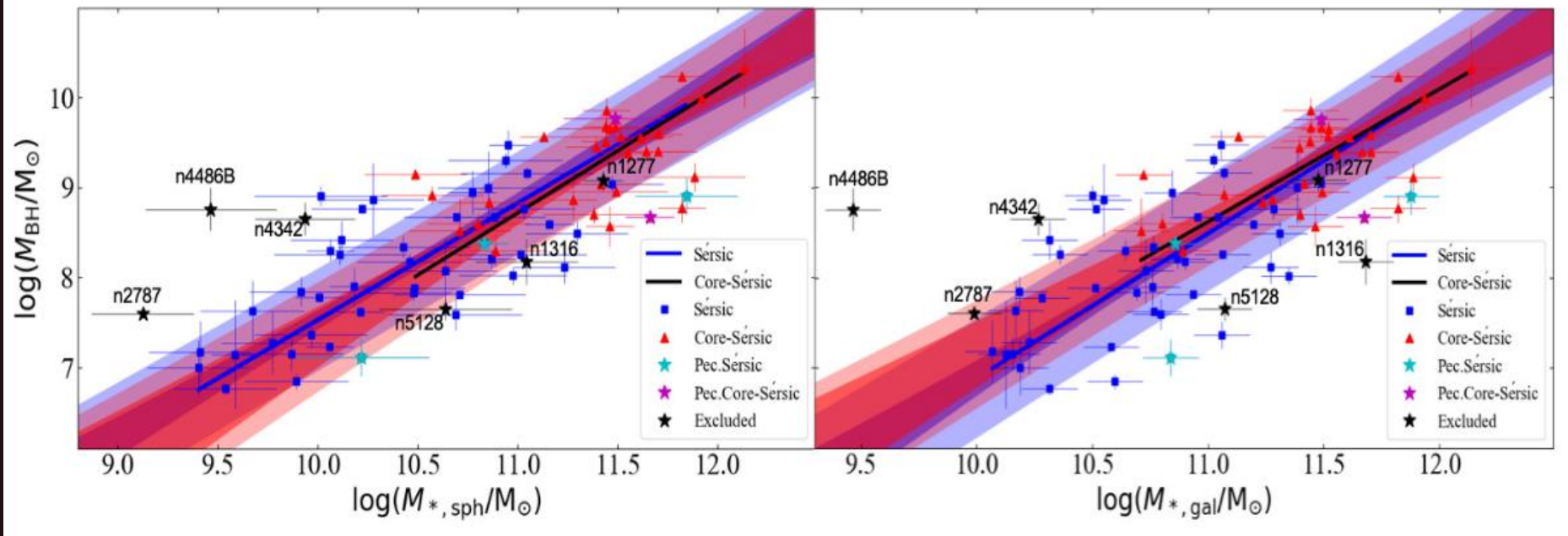
BH mass vs stellar mass



Red points – 244 AGNs.

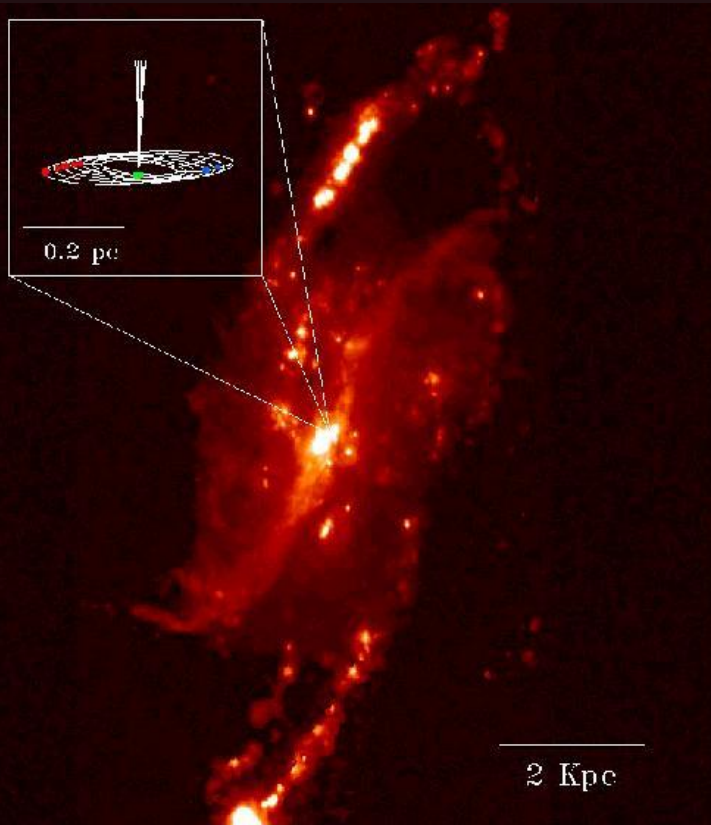


Scaling relations for early type galaxies



The authors studies correlations for different subsamples of early type galaxies.

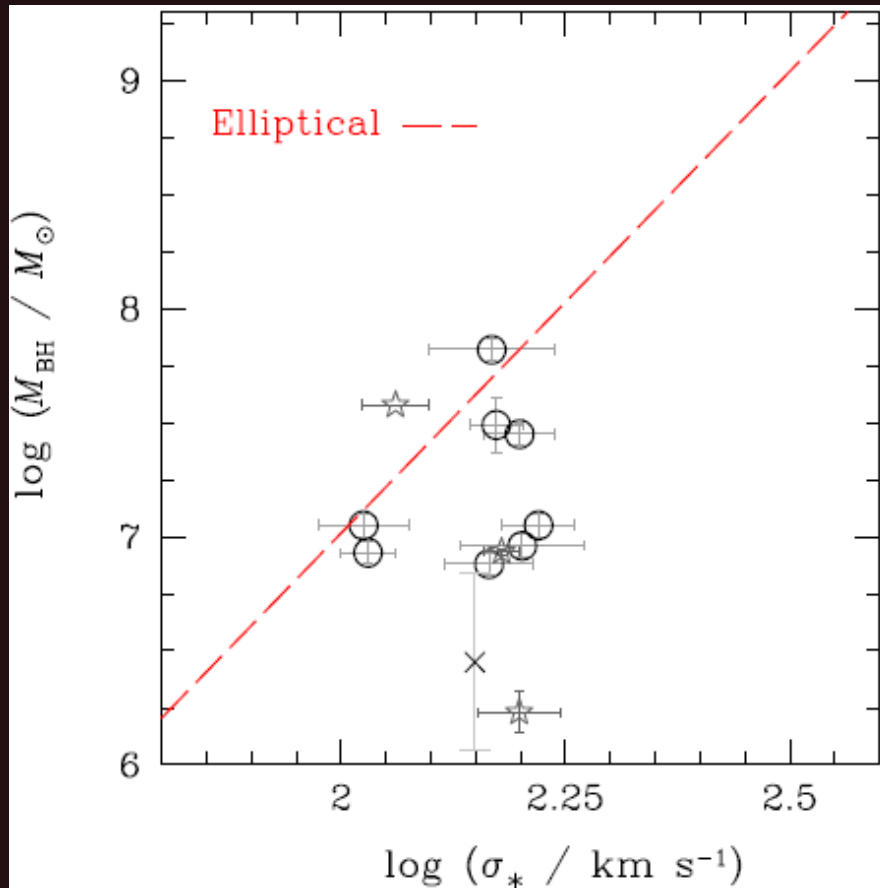
Masers



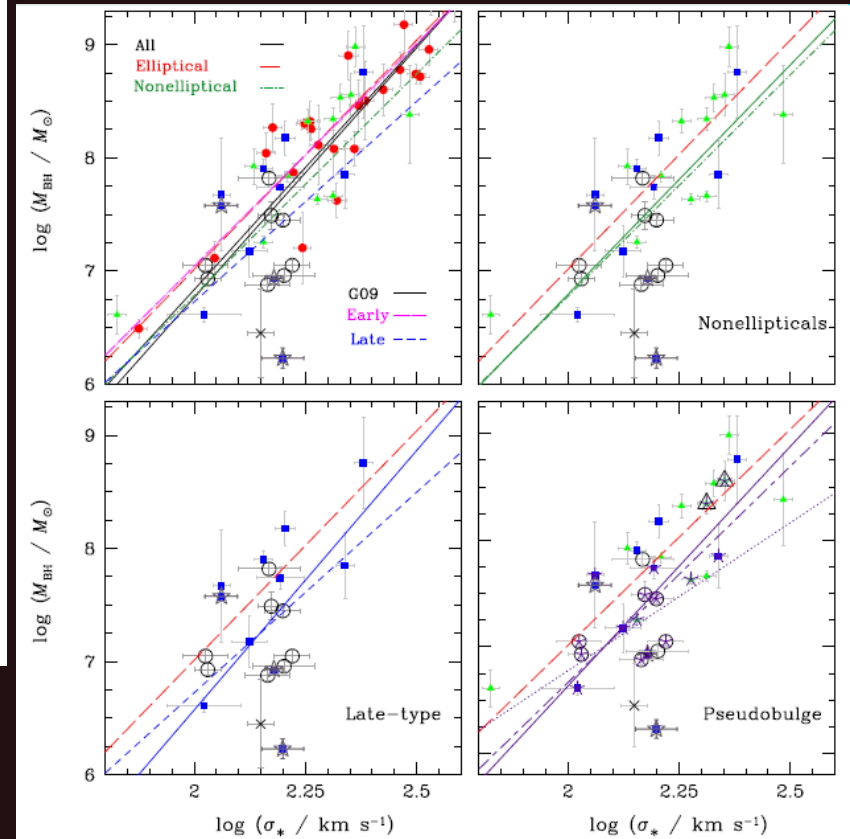
Observing movements of masers in **NGC 4258** it became possible to determine the mass inside 0.2 pc.
The obtained value is 35-40 million solar masses.

This is the most precise method of mass determination.

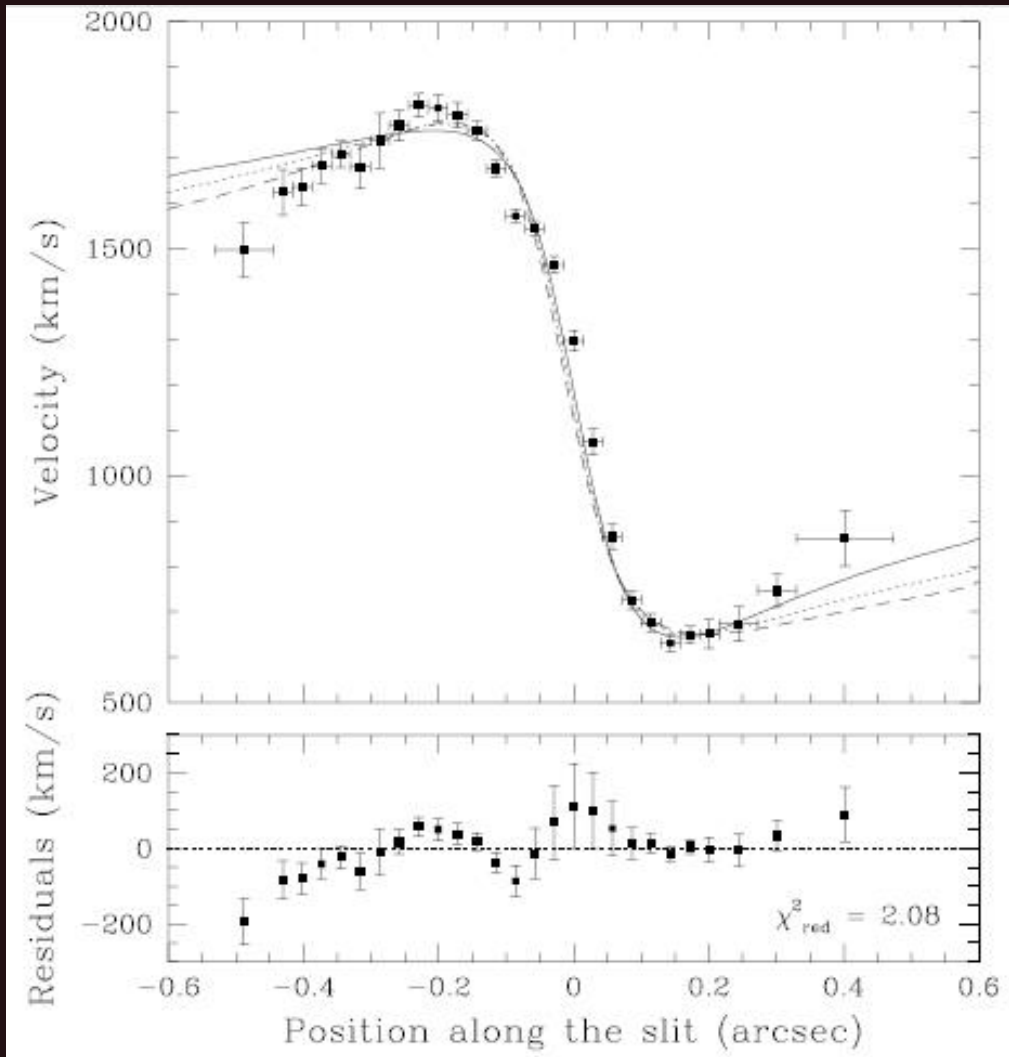
Several more megamaser measurements



Circles – new measurements,
stars – from the literature.



Gas kinematics



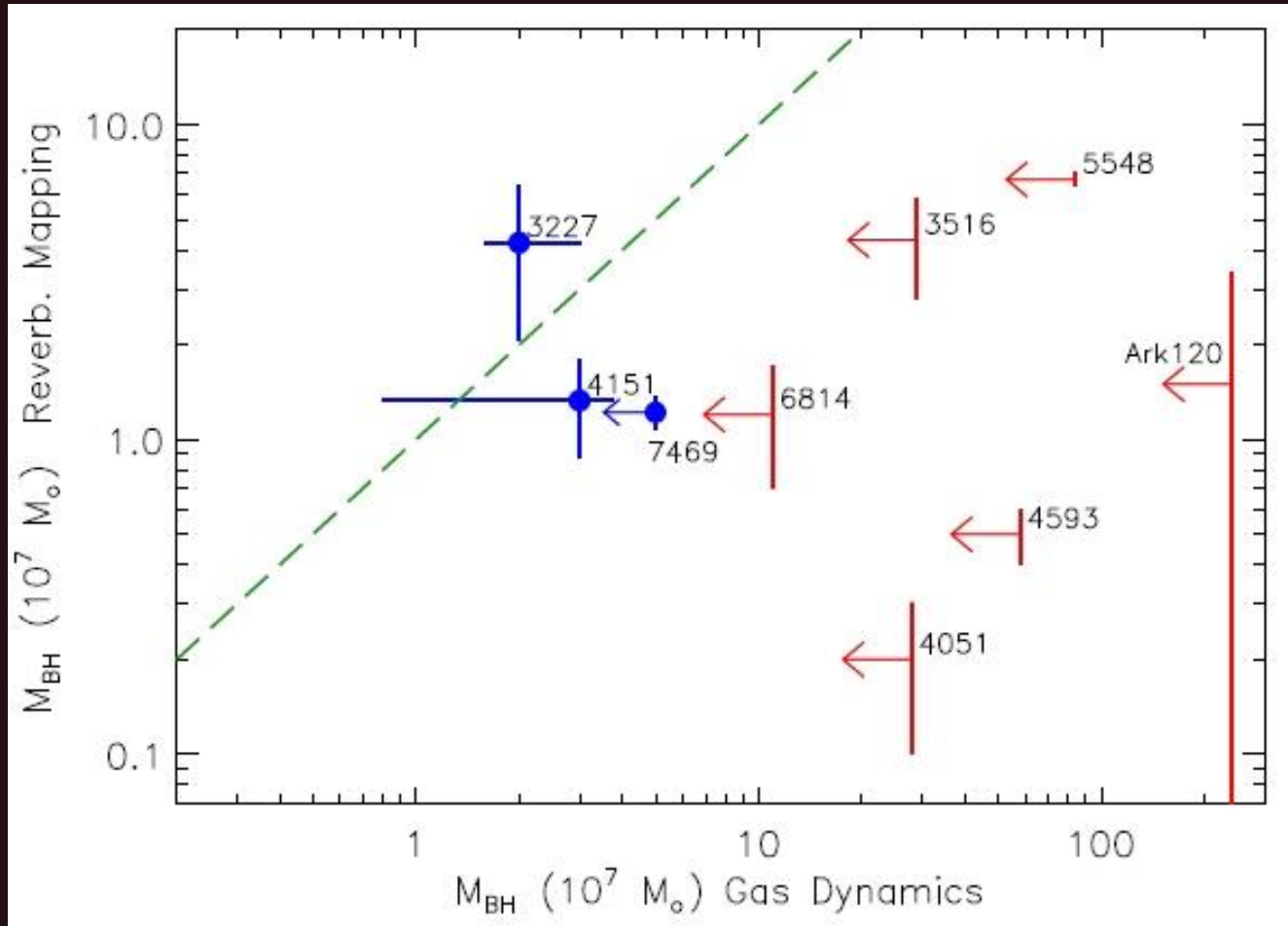
For M87 gas velocities were measured inside one milliarcsecond (5pc).

The mass is $3 \times 10^9 M_{\odot}$.

It is one of the heaviest BHs.

(Macchetto et al. astro-ph/9706252)

Masses determined by gas kinematics



Masses determined by observing gas kinematics are in good correspondence with value obtained by reverberation mapping technique.

arXiv: 0707.0611

See a review in 1406.2555

Mass via hot gas observations

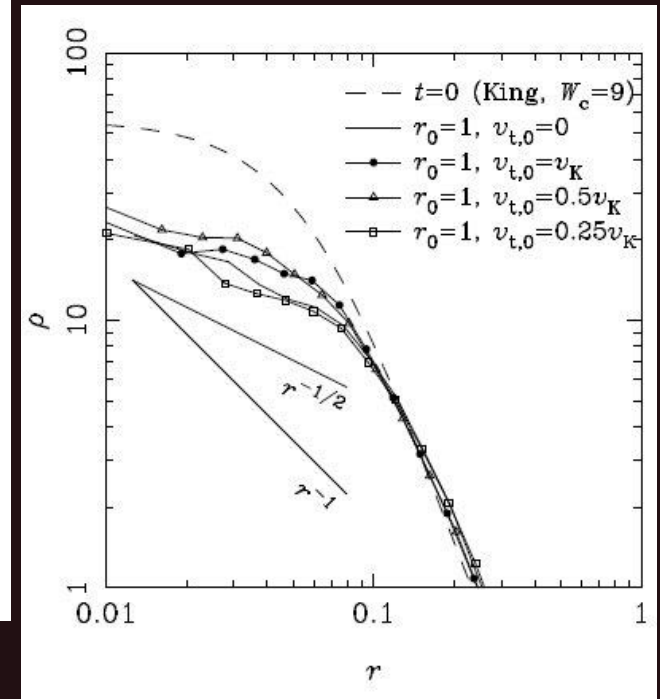
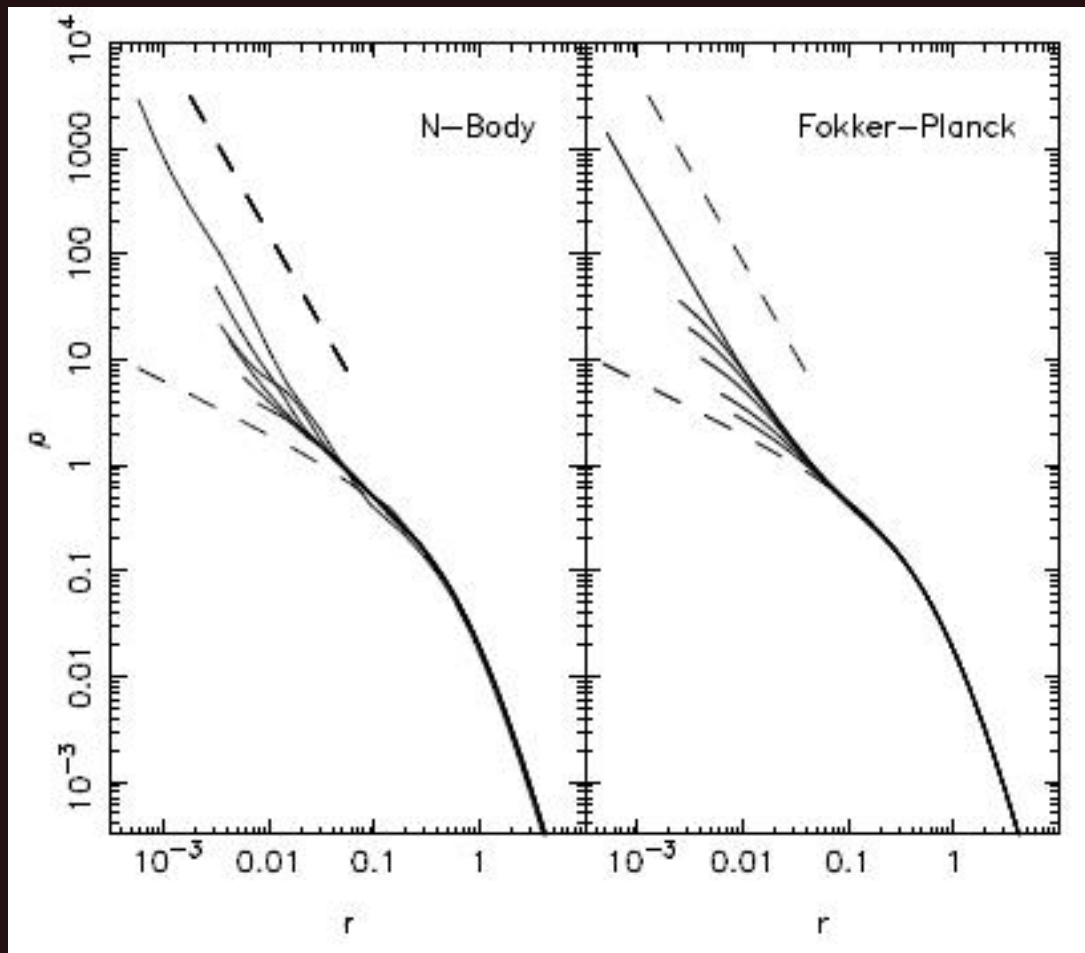
Giant elliptical galaxy NGC4649.

Chandra observations.

Temperature peaks at $\sim 1.1\text{keV}$ within the innermost 200pc.

Under the assumption of hydrostatic equilibrium it is demonstrate that the central temperature spike arises due to the gravitational influence of a quiescent central super-massive black hole.

Stellar density profiles



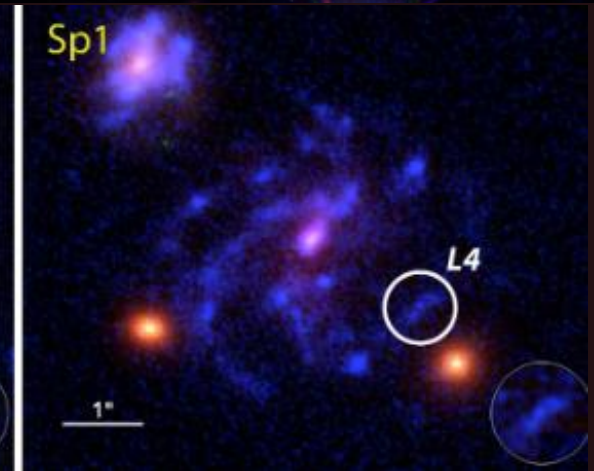
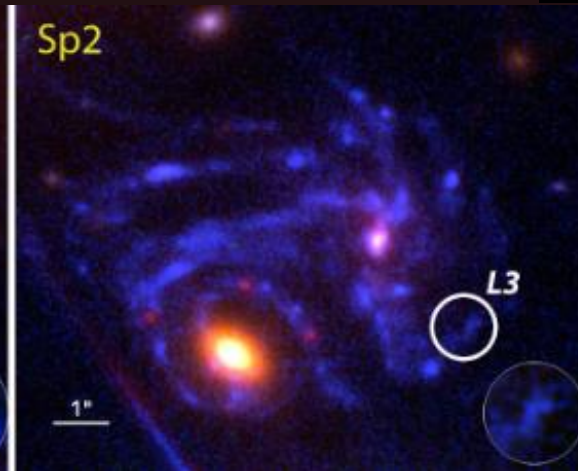
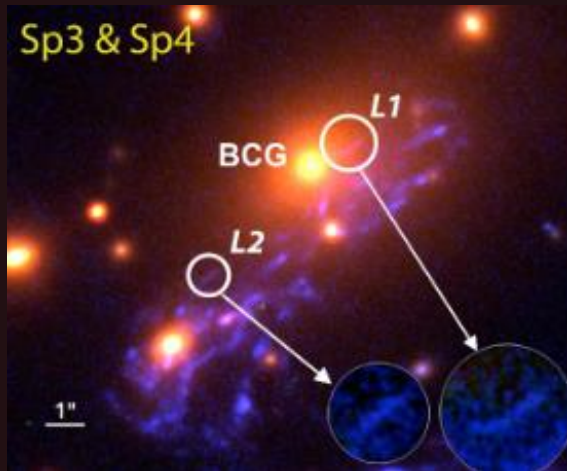
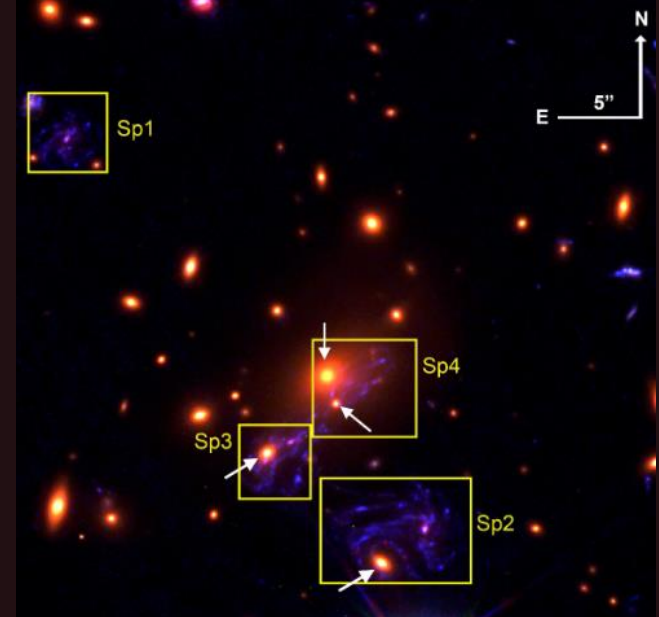
Gravitational lensing on a SMBH

A background galaxy is lensed by a massive galaxy. Analysis of images suggests that some features are generated by a point mass.

Fits with an off-center SMBHs are the best.

Other explanations (a compact galaxy) are still possible.

SMBH mass estimate is $\sim 7\text{-}12$ billion solar masses.



Reverberation mapping

The method is based on measuring the response of irradiated gas to changes in the luminosity of a central sources emitting is continuum.

Initially, the method was proposed and used to study novae and SN Ia.

In the field of AGN was used for the first time in 1972 (Bahcall et al.)

An important early paper: Blandford, McKee 1982.

What is measured is the delay between changes in the light curve in continuum and in spectral lines. From this delay the size of BLR is determined.

To apply this method it is necessary to monitor a source.

$$M_{BH} = f G^{-1} R_{BLR} V^2,$$

dimensionless factor,
depending on the geometry of BLR
and kinematics in BLR

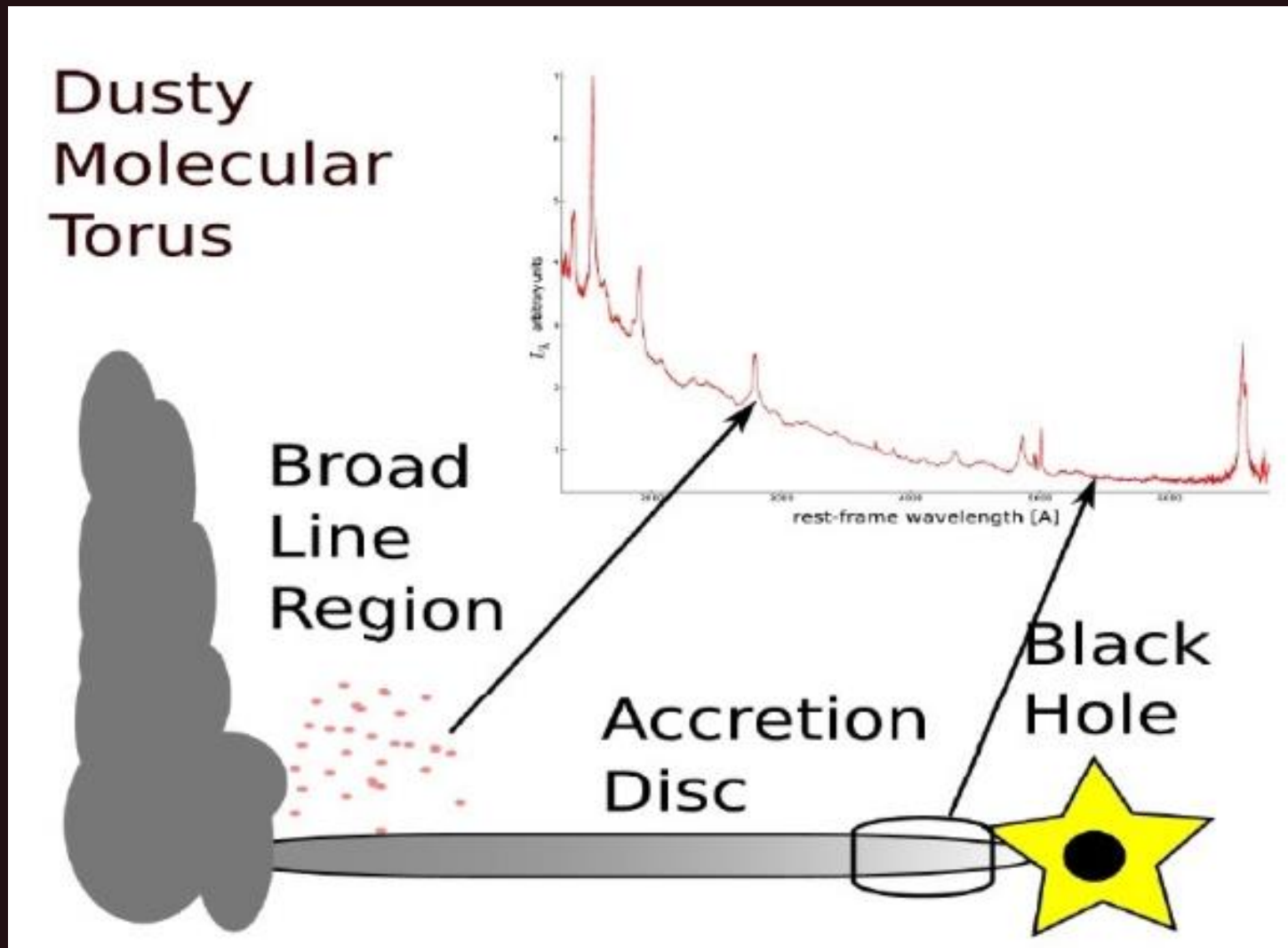
clouds velocities in BLR

The method is not good for very bright and very weak AGNs.

(For details see arxiv:0705.1722)

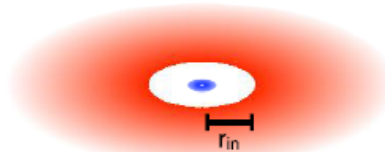
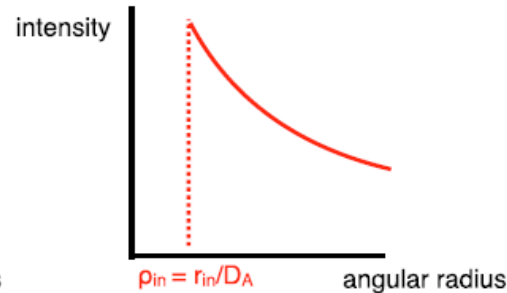
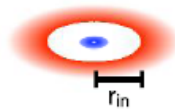
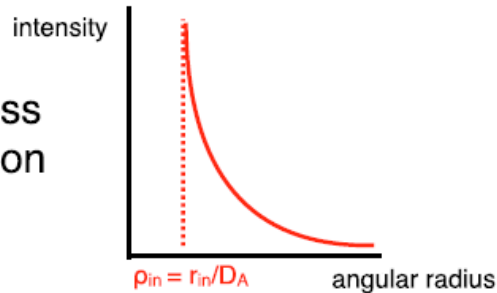
See a detailed recent example in 1104.4794

General scheme

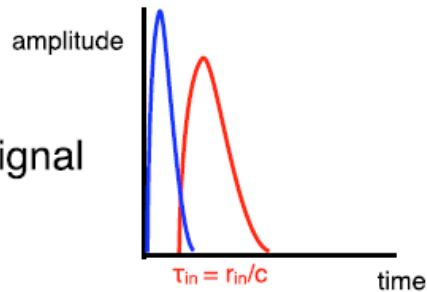


Как расстояние помогает массу измерить

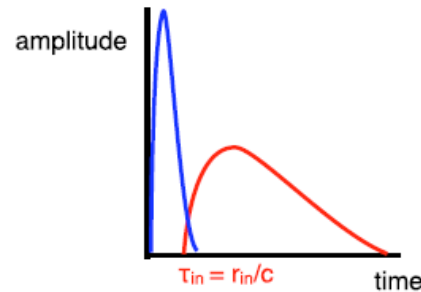
(a) brightness distribution



(b) delay signal



$\alpha = -2.5$ (steep)



$\alpha = -0.5$ (shallow)

Удалось уточнить расстояние до важной галактики NGC 4151 с черной дырой. По ней калибруют массы других черных дыр. В итоге – массы возросли почти в полтора раза.

Population synthesis in astrophysics

A population synthesis is a method of a direct modeling of relatively large populations of weakly interacting objects with non-trivial evolution.

As a rule, the evolution of the objects is followed from their birth up to the present moment.

(see [astro-ph/0411792](#))

Two variants

Evolutionary and Empirical

1. Evolutionary PS.

The evolution is followed from some early stage.

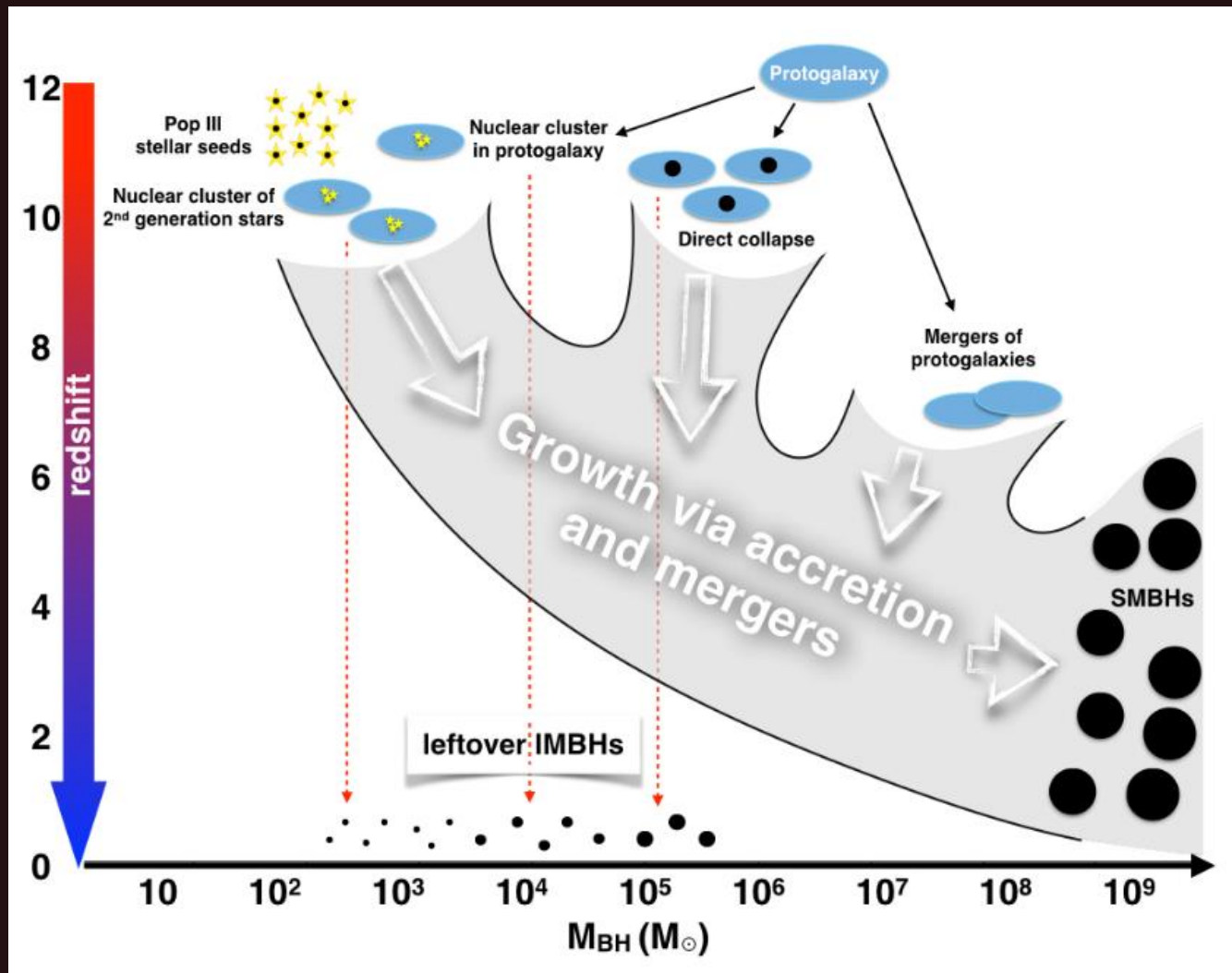
Typically, an artificial population is formed
(especially, in Monte Carlo simulations)

2. Empirical PS.

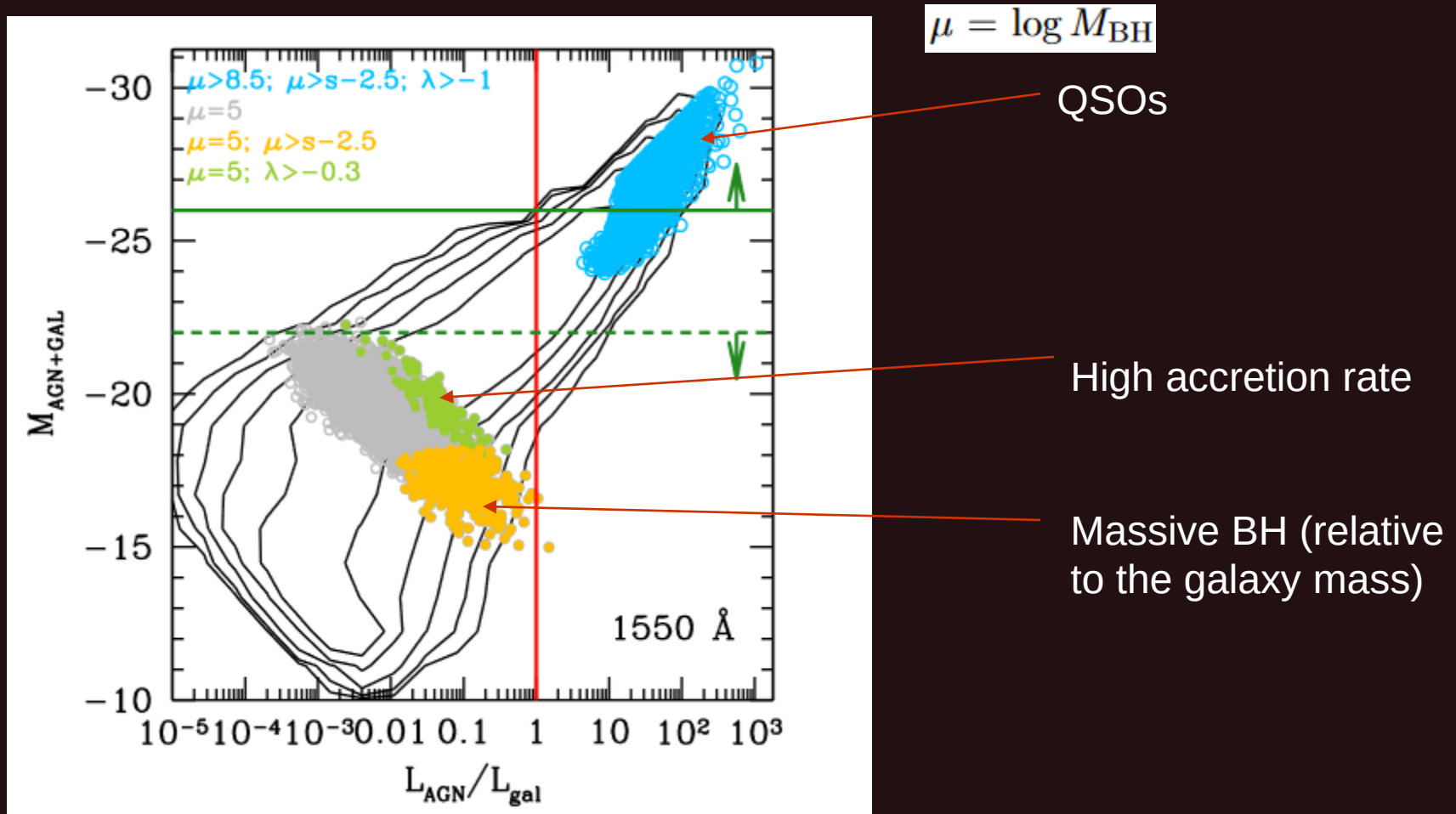
It is used, for example, to study integral properties
(spectra) of unresolved populations.

A library of spectra is used to predict integral properties.

Origin of SMBHs

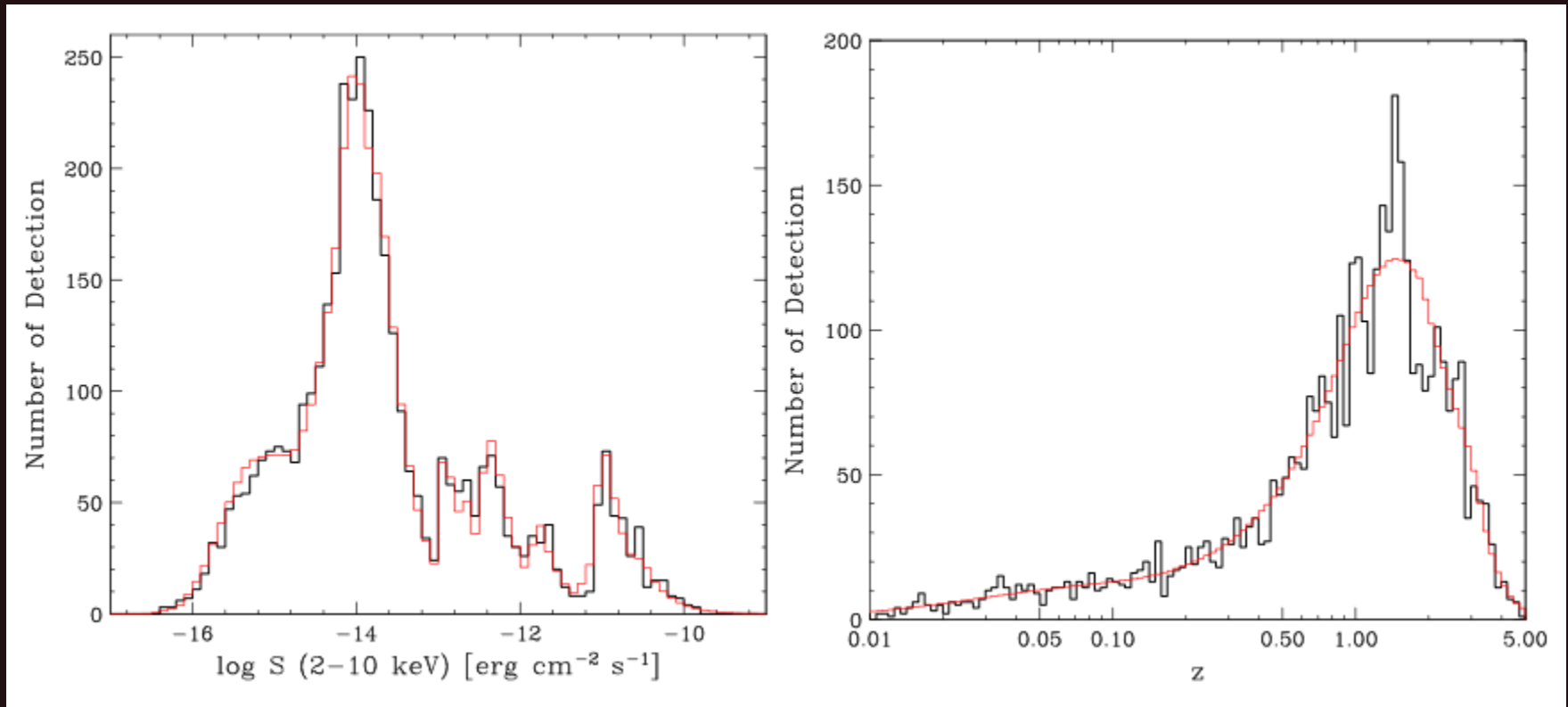


Population synthesis of SMBHs



Predictions for JWST

X-ray background and pop. synthesis

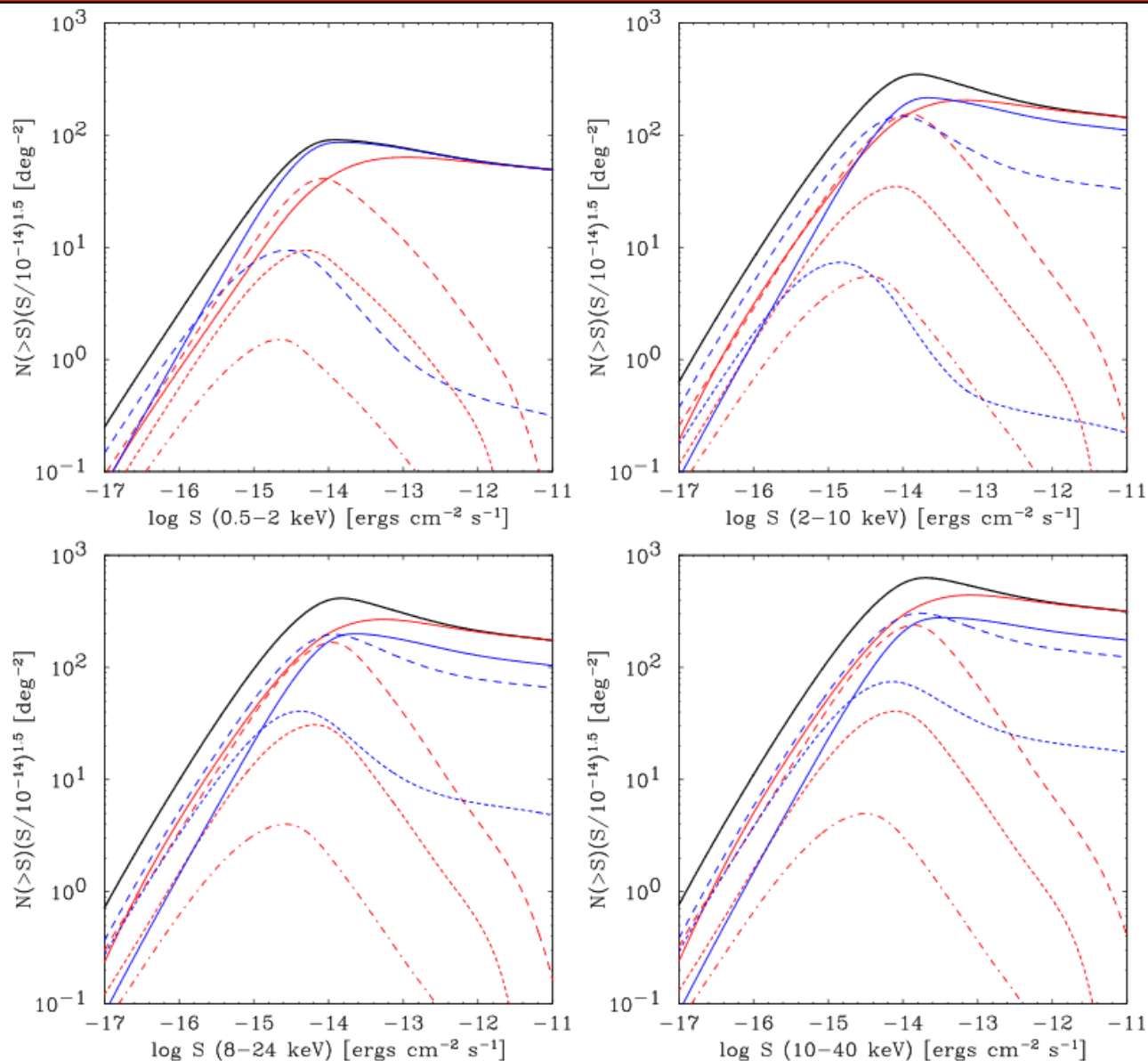


Observed histograms (thick, black) of flux (left) and redshift (right) of the authors sample compared with model predictions (thin, red).

Predicted
Log N – Log S
distributions.

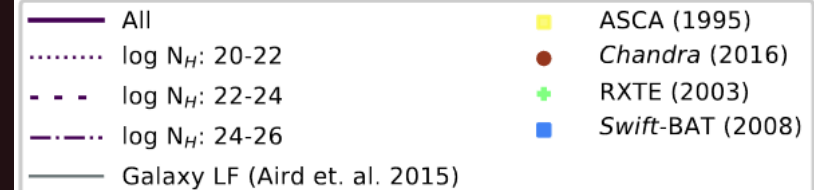
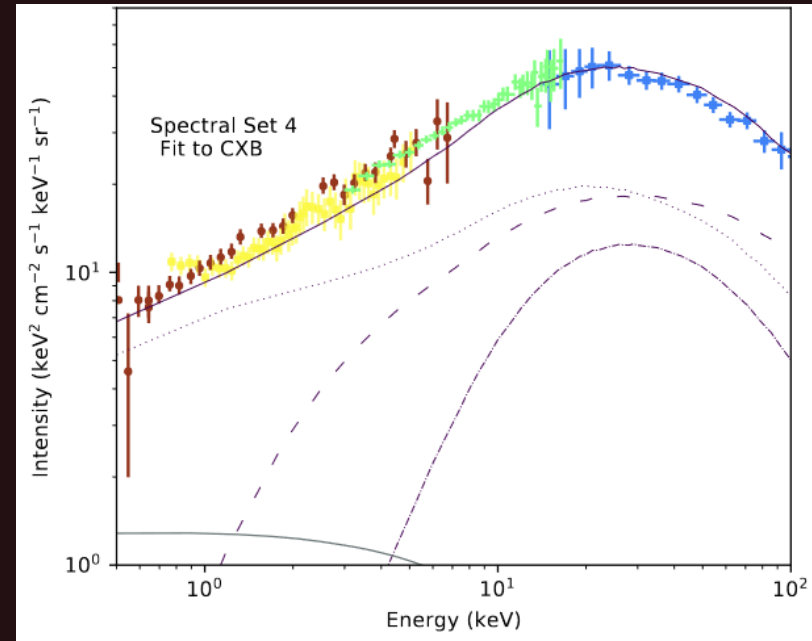
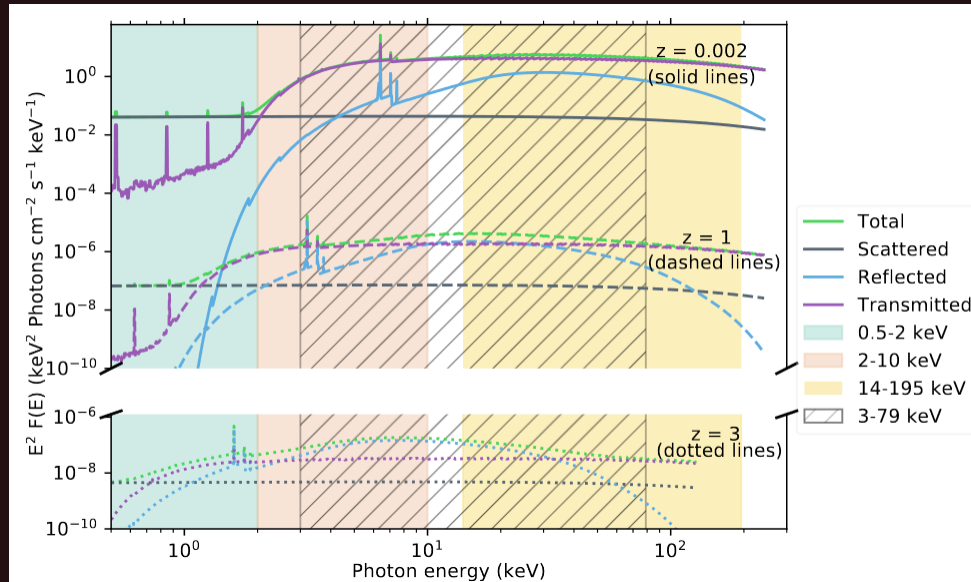
Red: different z :

solid: $z < 1$,
long-dashed: $z = 1-2$,
short-dashed: $z = 2-3$,
dot-dashed: $z = 3-5$

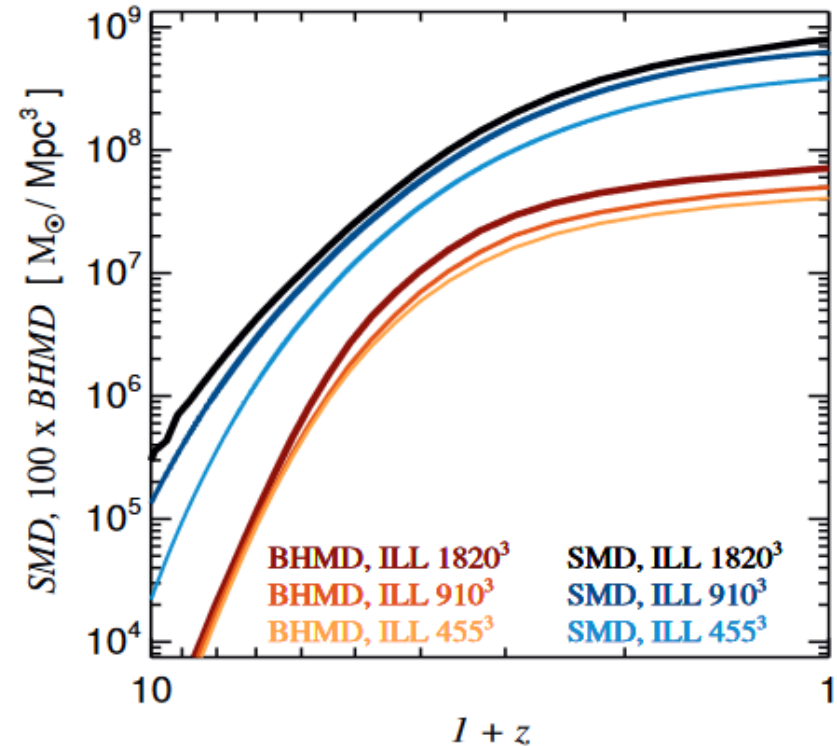
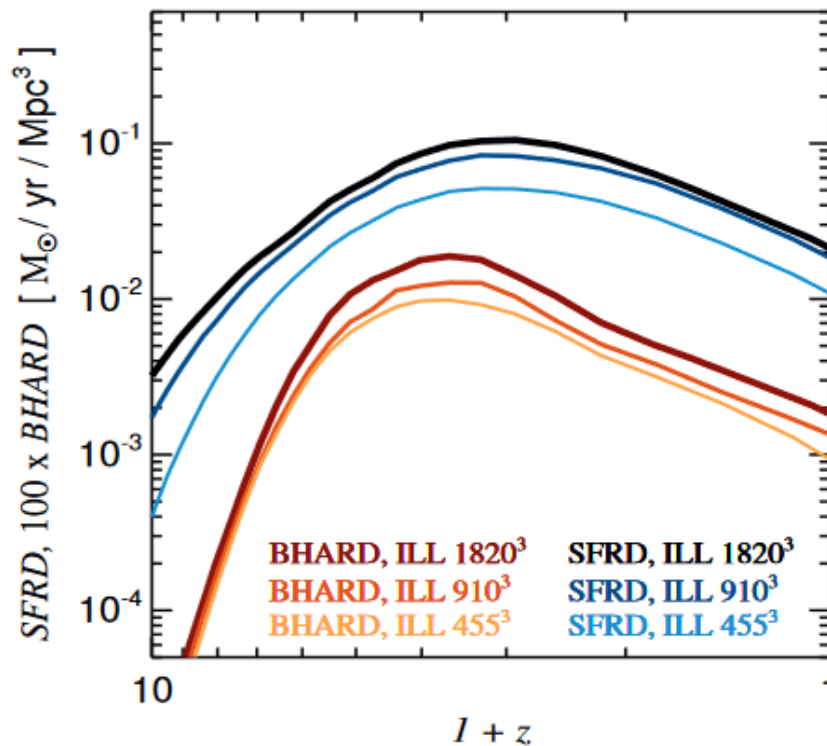


X-ray spectra of AGNs

New population synthesis



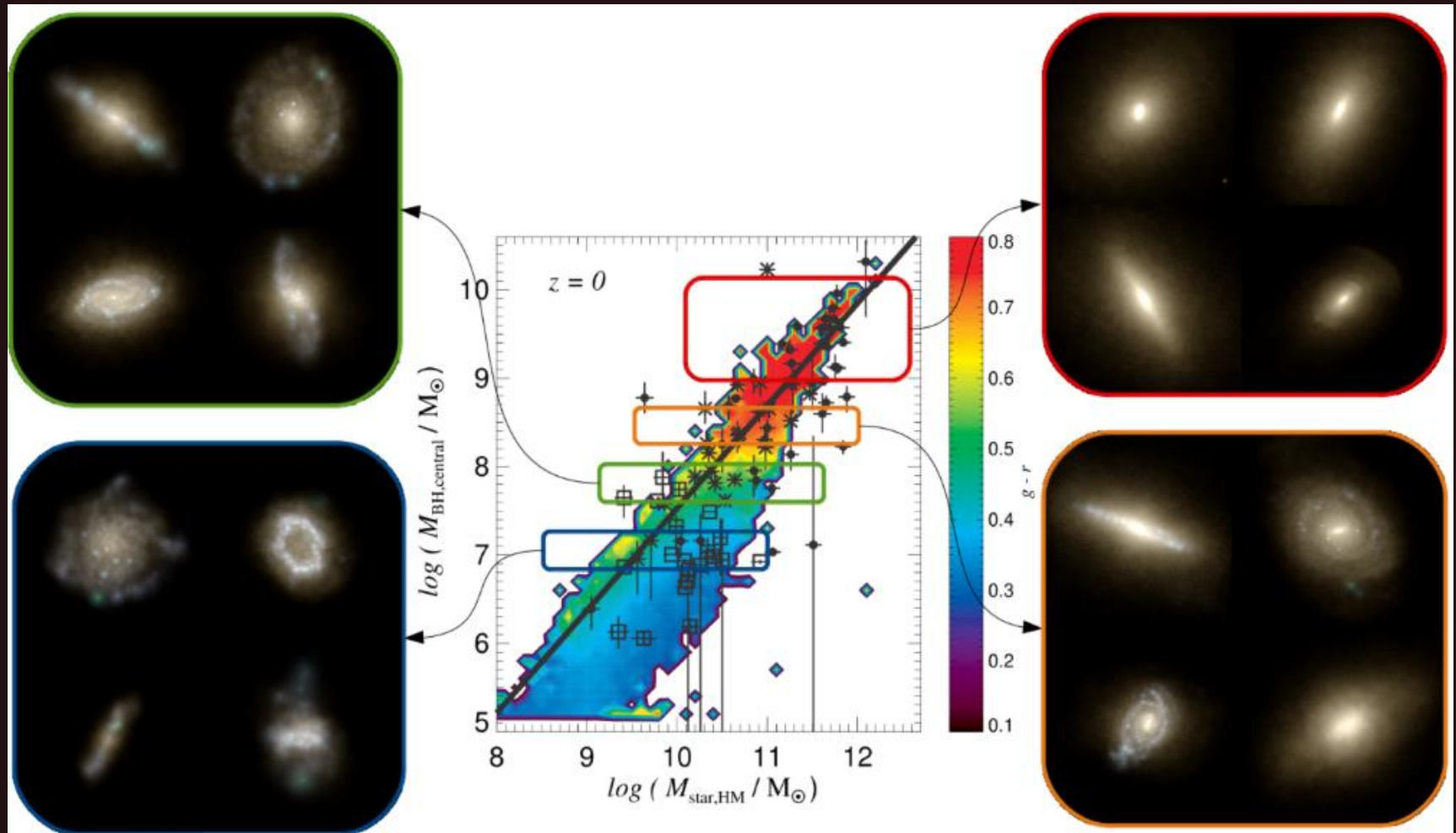
Illustris calculations



Time evolution of the star formation rate density (blue curves) and of the black hole accretion rate density (red curves; rescaled by a factor of a 100) for three different resolutions.

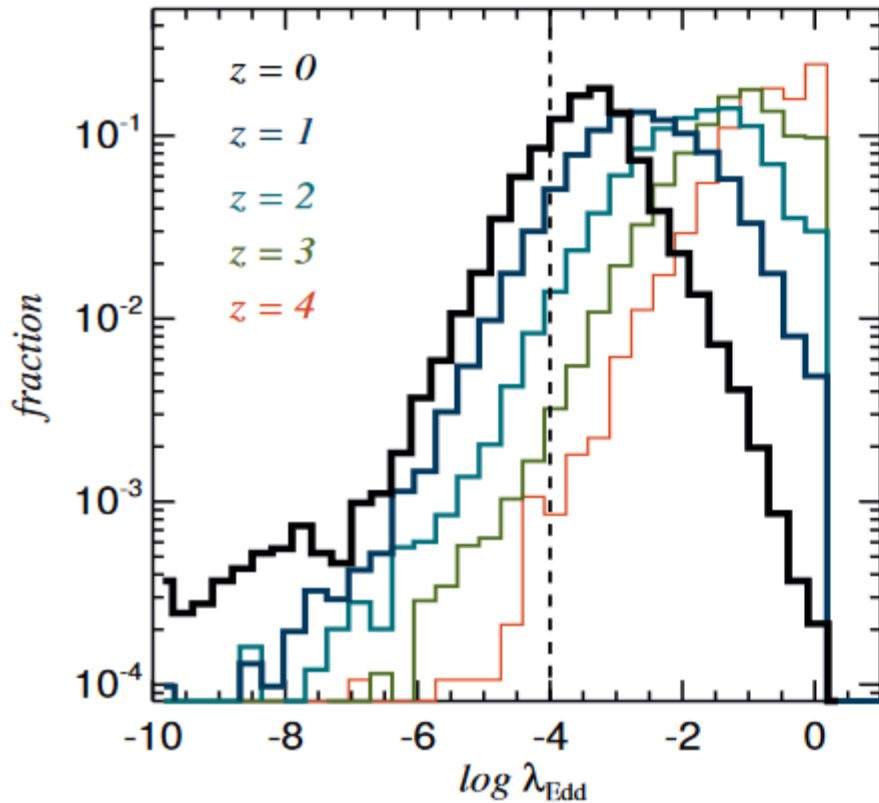
Stellar mass density and black hole mass density as a function of cosmic time

Illustris simulations

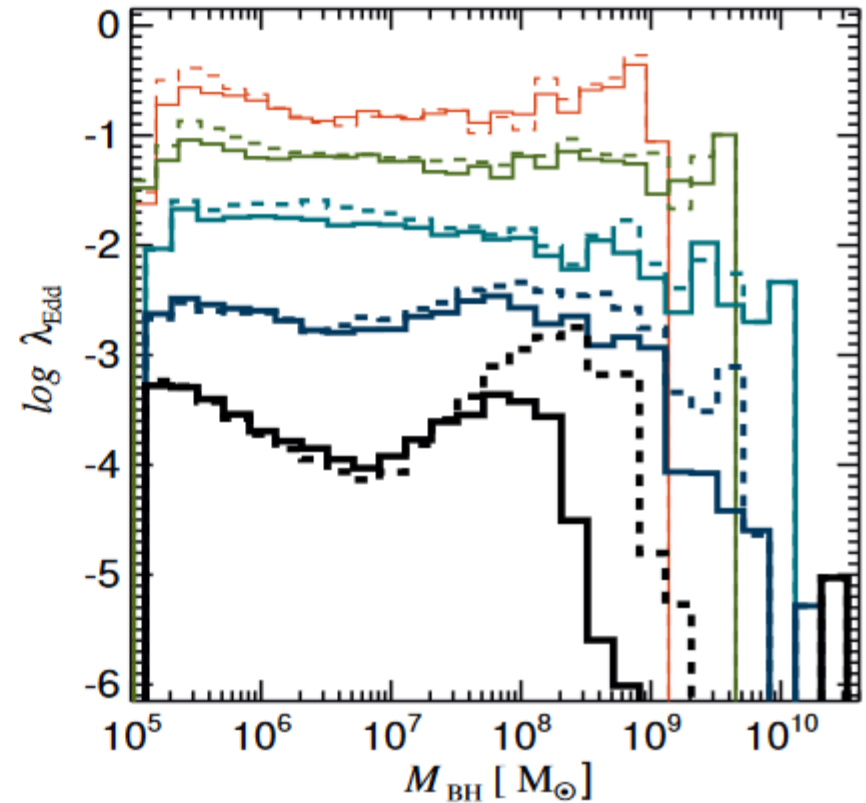


Stellar half-mass of all galaxies at $z=0$ versus their central black hole mass

BH accretion rate evolution



Distribution of black hole Eddington ratios at $z=4, 3, 2, 1$ and 0.

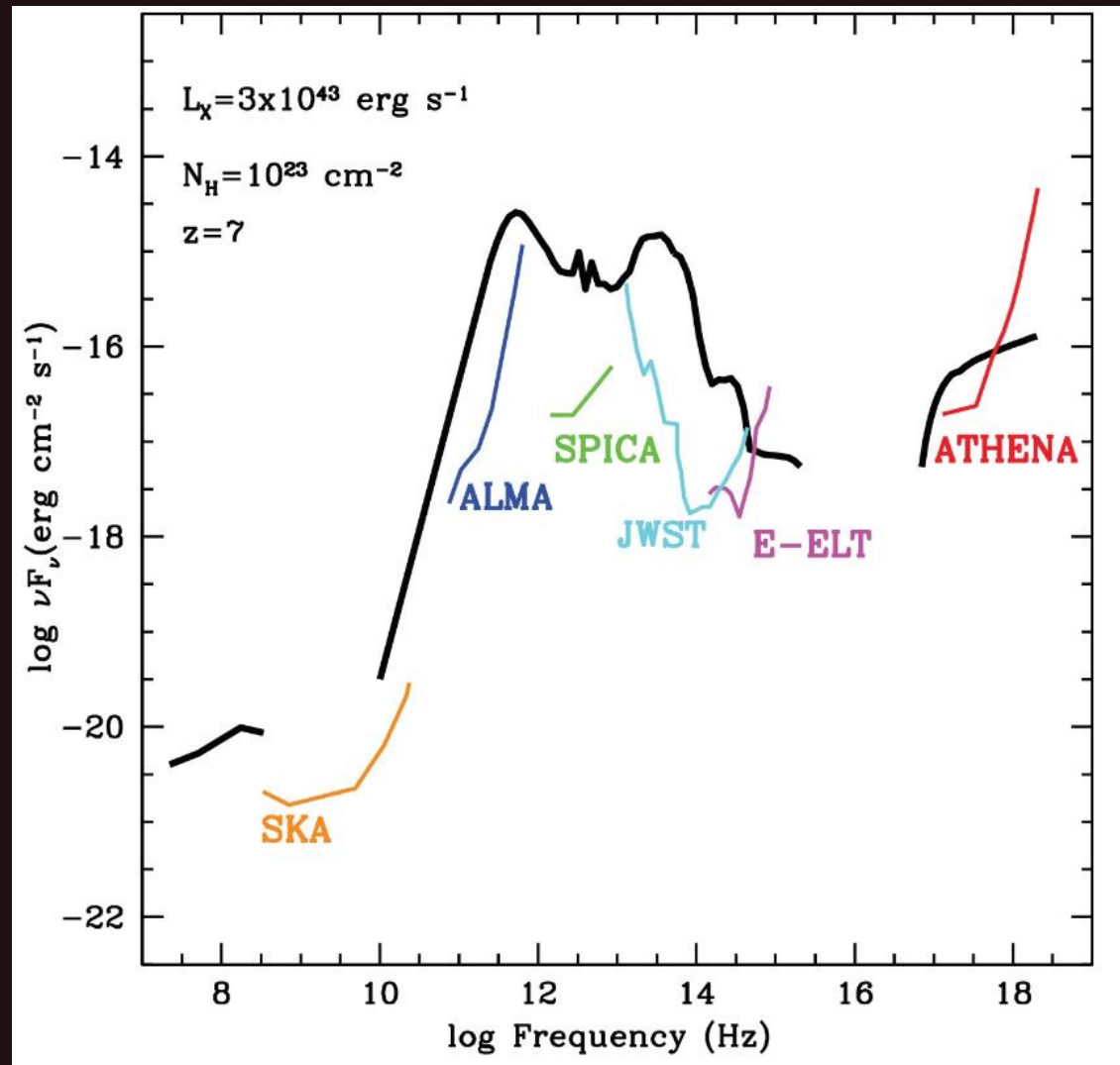


Eddington ratios as a function of black hole mass at $z=4, 3, 2, 1$ and 0.

High redshift AGNs

Future observations might reveal many AGNs with moderate luminosities at high z .

This will allow to probe early evolution of SMBHs.



SMBH mass growth and BH coalescence

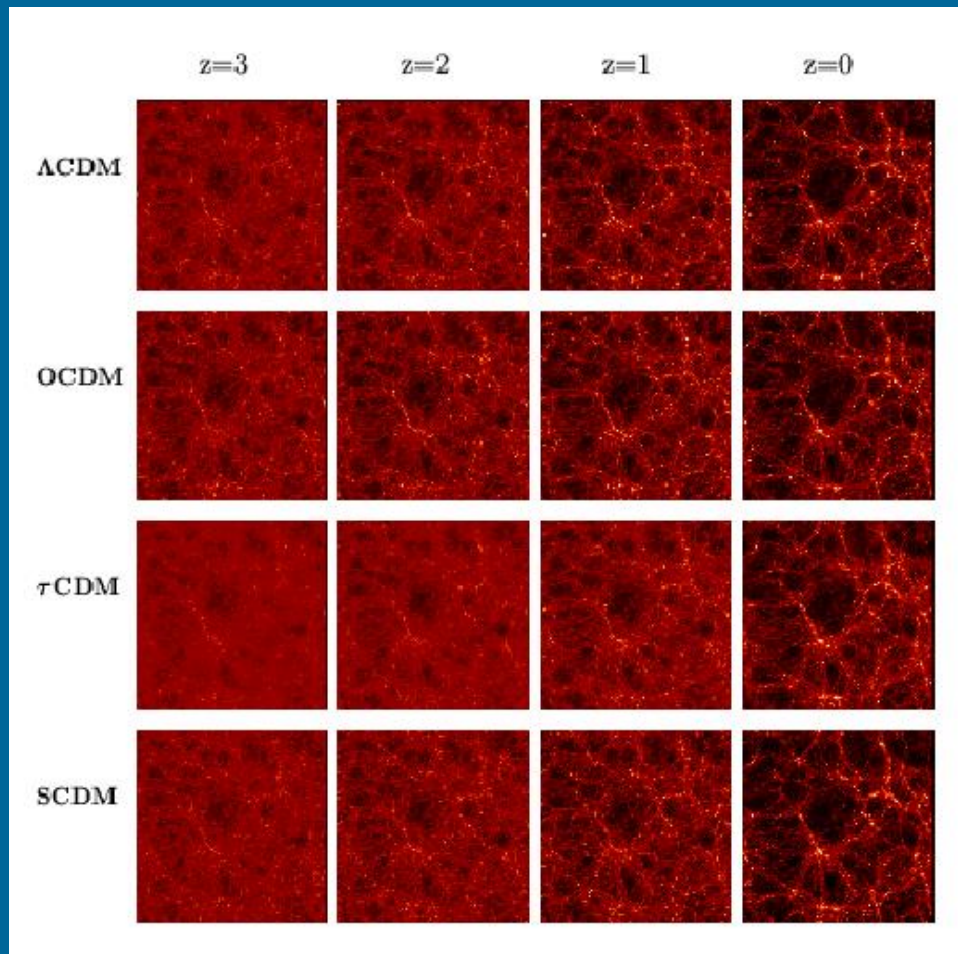
Plan of the lecture

1. Hierarchical model of galaxy formation.
2. Gravitational wave rocket.
3. Black holes at large redshifts.
4. Coalescence of SMBHs.
5. BH coalescence in binaries.

Reviews

- | | |
|--|--|
| <u>arXiv: 1307.3542</u> | Astrophysics of Super-massive Black Hole Mergers |
| <u>arXiv:1103.4404</u> | Formation of Supermassive Black Holes |
| <u>astro-ph/0609741</u> | Supermassive black hole mergers and cosmological structure formation |
| <u>arXiv: 1110.6445</u> | A practical guide to the massive black hole cosmic history |
| <u>arXiv:1112.0320</u> | The Cosmic History of Black Hole Growth from Deep Multiwavelength Surveys |
| <u>arXiv:1203.6075</u> | The Formation of the First Massive Black Holes |
| <u>arXiv: 1407.3102</u> | Massive binary black holes in galactic nuclei and their path to coalescence |
| <u>arXiv: 1307.4086</u> | Gravitational wave emission from binary SMBHs |
| <u>arXiv: 1807.11489</u> | Lectures on Black hole binary astrophysics |

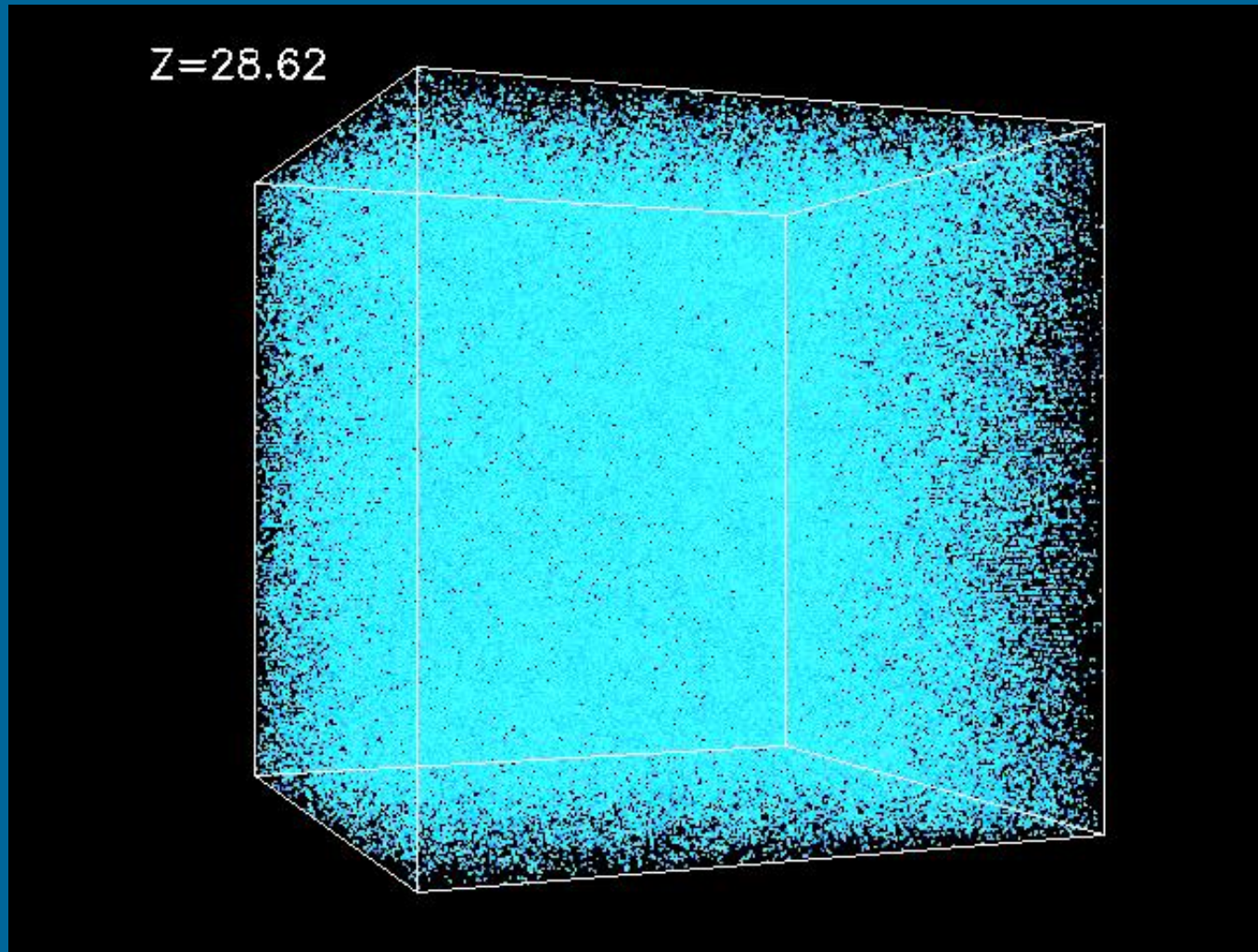
Structure growth in the universe



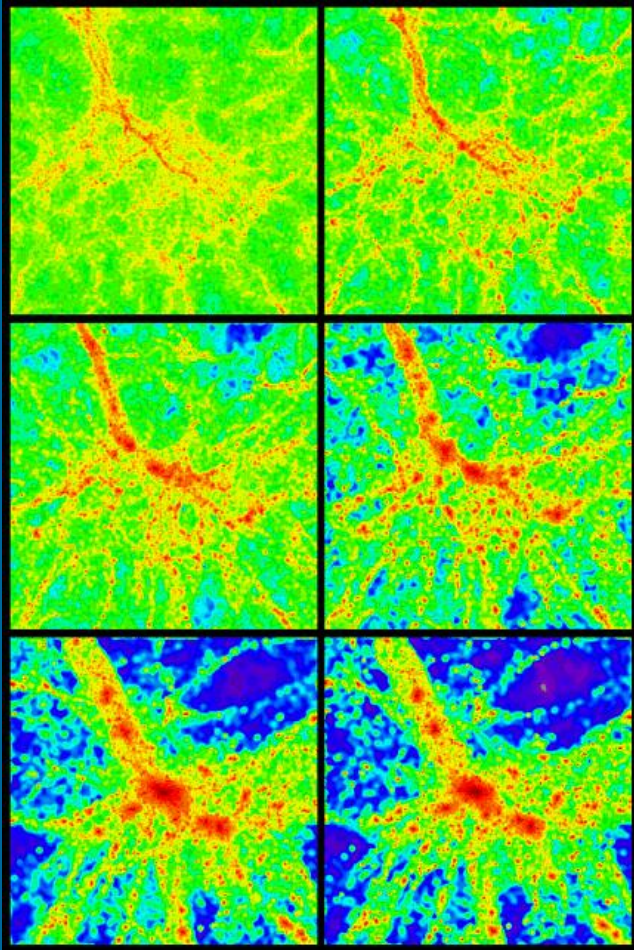
Today the standard model of the structure formation is the *hierarchical* one.

Numerical calculations of the evolution of the large-scale structure and single “blocks” reached a very high level of precision ([arxiv:0706.1270](https://arxiv.org/abs/0706.1270)).

Large scale structure



Formation of clusters of galaxies



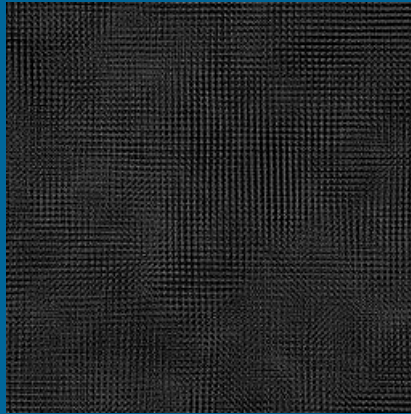
tCDM 21x21 (Mpc/h)³ LCDM 35x35 (Mpc/h)³

In the process of structure growth numerous coalescence of “building blocks” happen, each of these blocks can contain a BH.

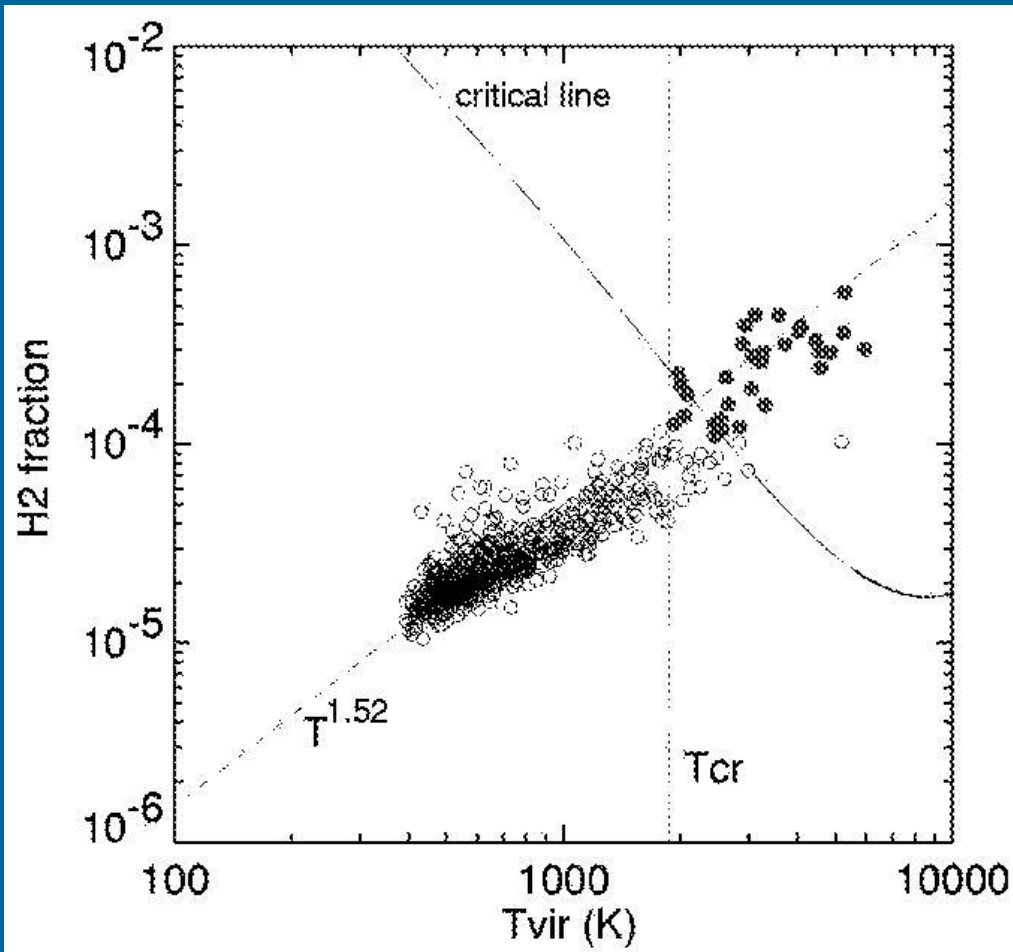
After a coalescence a new-formed BH slowly, due to dynamical friction, moves towards the center of the resulting structure.

Formation of large galaxies is finished as $z \sim 2$, after this no major mergers happen, only small satellites are captured by big galaxies.

Growth of clusters of galaxies



Minihalos and the first stars



Symbols indicate minihalos.

Open symbols –
Cooling is not effective enough.

The critical line corresponds to equality between the cooling time and dynamical evolution time scale of a minihalo (free-fall time).

This line separates dark halos and halos that can produce stars.

In each minihalo a very small number of stars is formed.

The first stars and minihalos

In the standard Λ CDM model the first massive BHs are formed at $z > 15$ in minihalos with $M > 5 \times 10^5 M_{\odot}$.

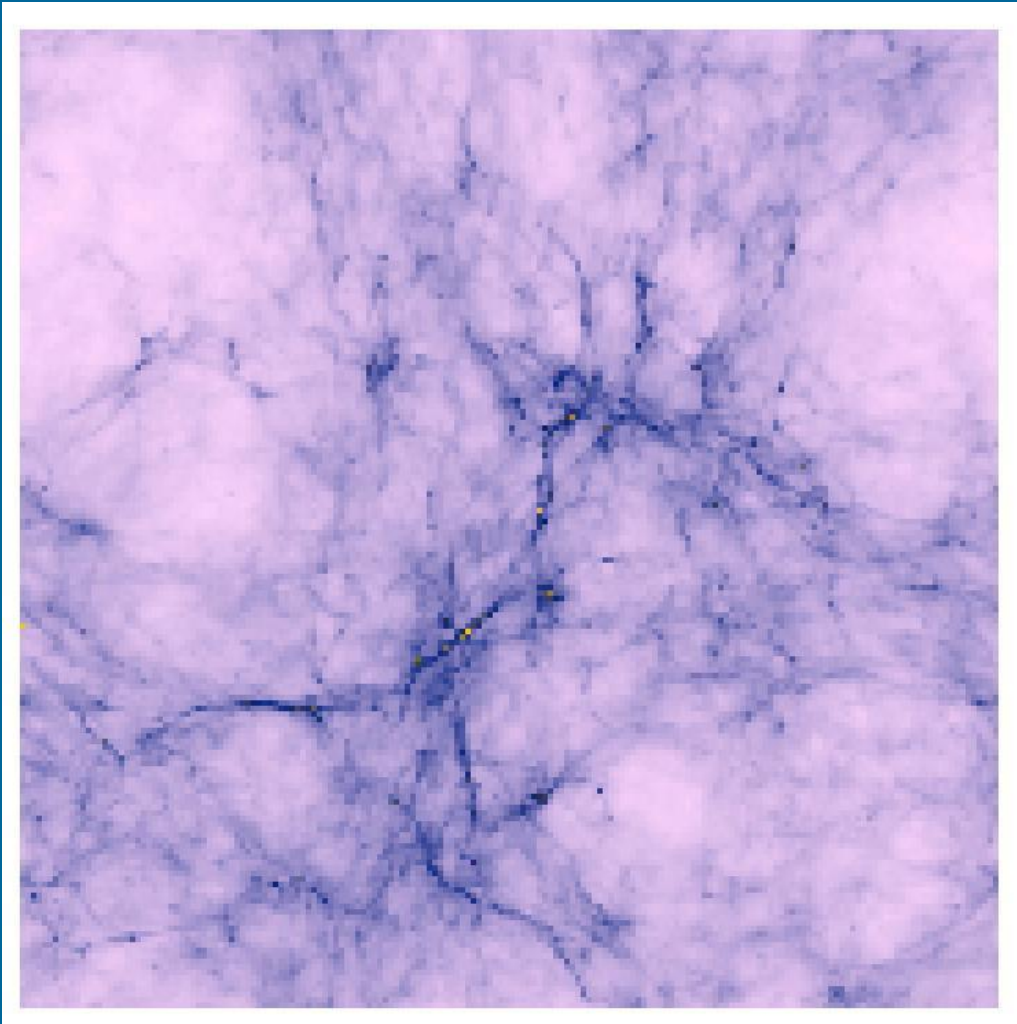
These BHs produce the first miniquasars, which contribute to the reionization at $z \sim 10-12$.

Such low mass of minihalos is explained by the role of molecular hydrogen (Tegmark et al. 1997).

$$5 \times 10^5 [(1+z)/10]^{-3/2} M_{\odot}$$

The first stars with masses 40-140 solar and > 260 solar masses produce BHs. A BH mass (in the case of the first stars) is typically > 0.5 of the mass of a star.

The first stars



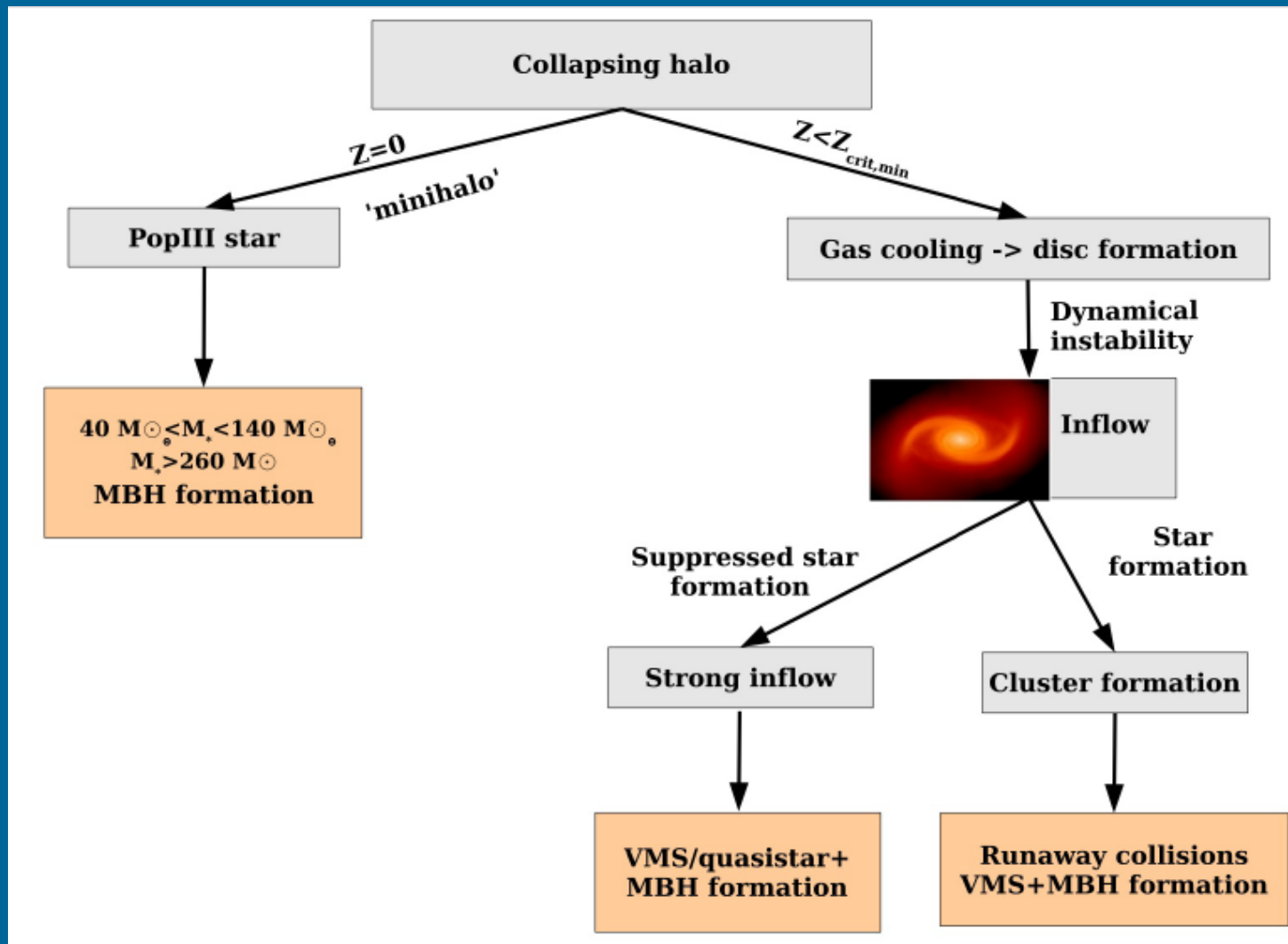
Calculations have been done in the Λ CDM model.

The picture is plotted for $z=17$.

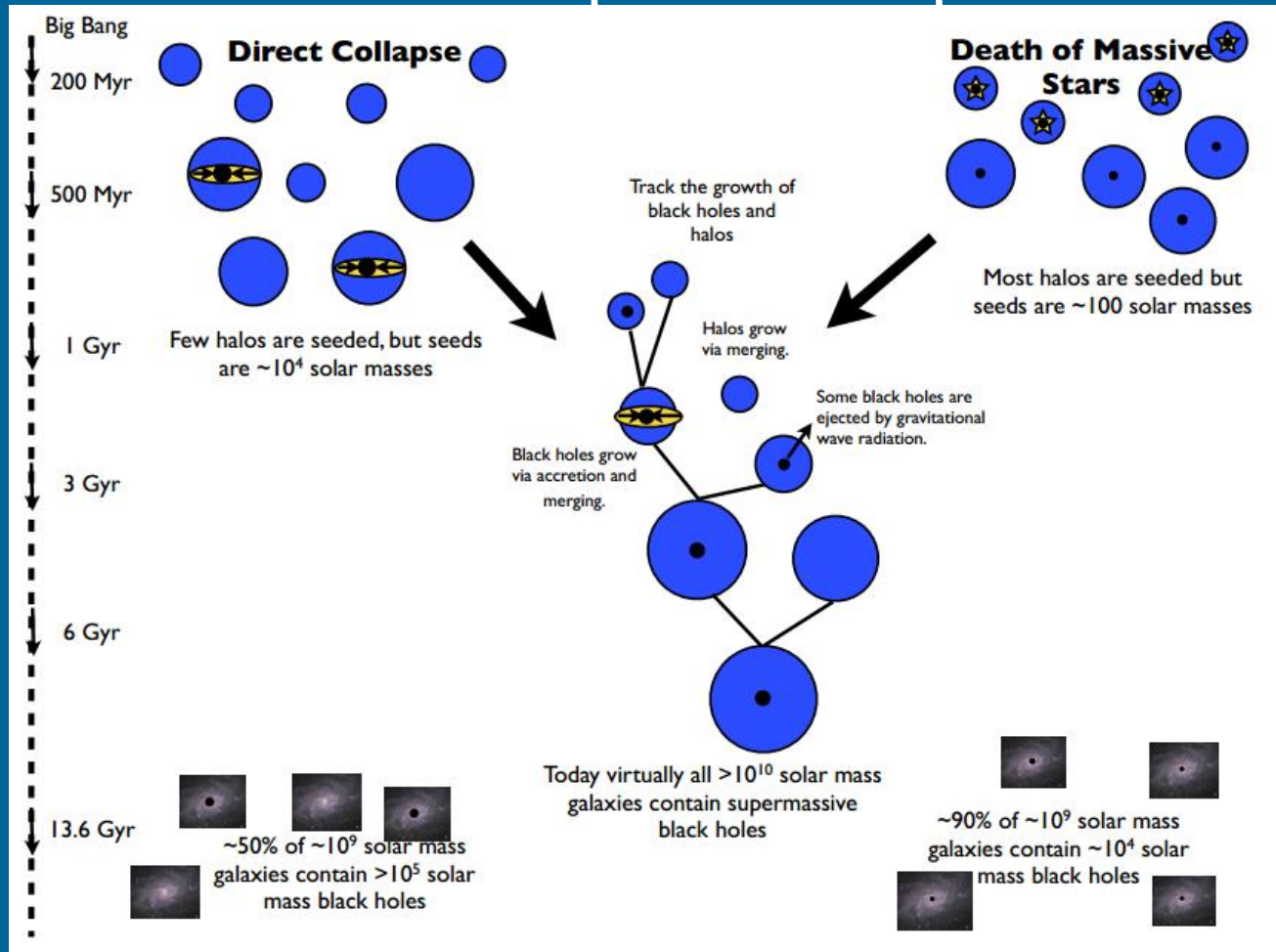
The size is 50 kpc.

Stars are formed on the cross-sections of filaments (bright dots).

A scheme for SMBH formation



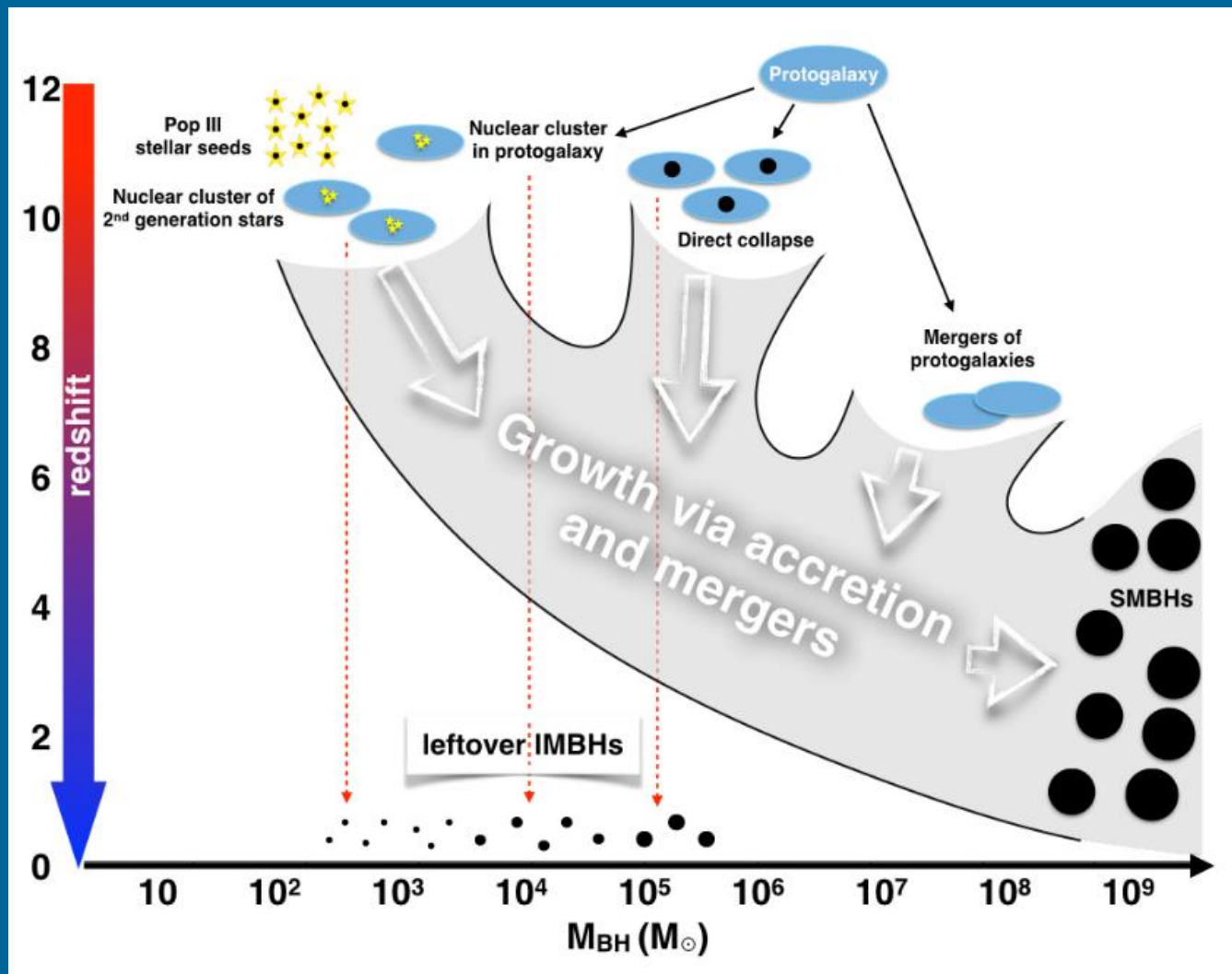
Сценарии образования и эволюции массивных черных дыр



Есть два основных сценария:

- первые звезды
- прямой коллапс

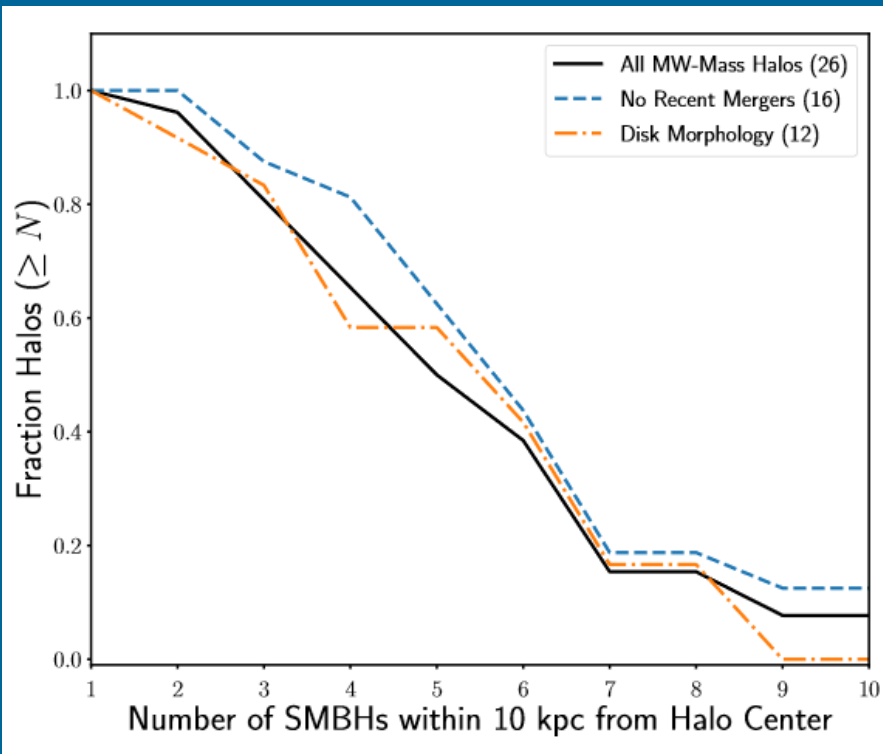
Origin of SMBHs and IMBHs



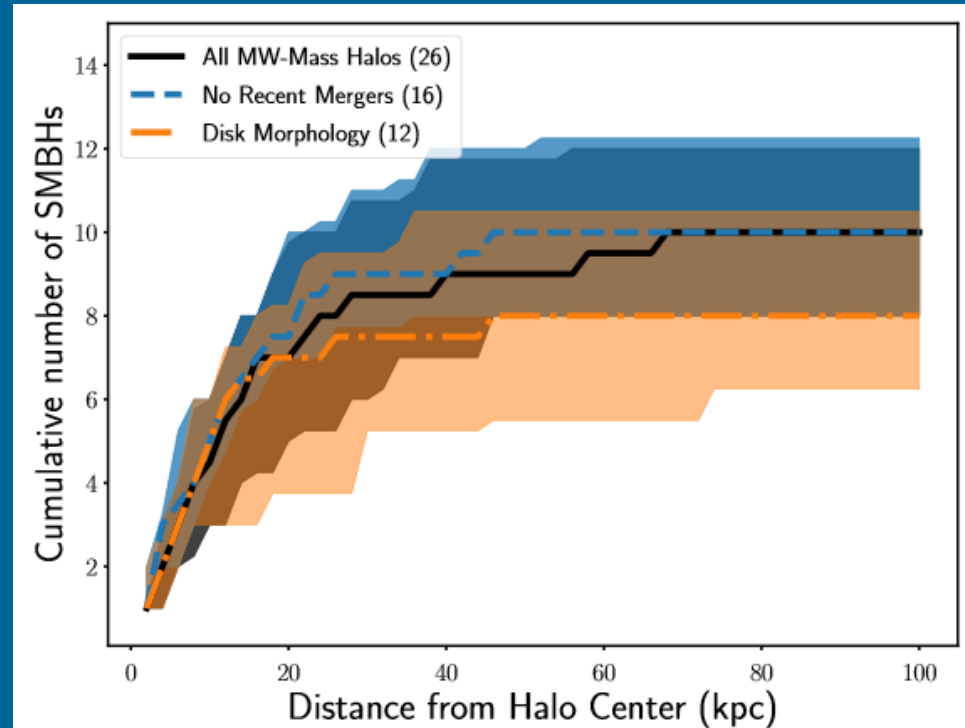
IMBHs:

- Globular clusters
- ULXs
- Dwarf galaxies
- Remaining seed BHs

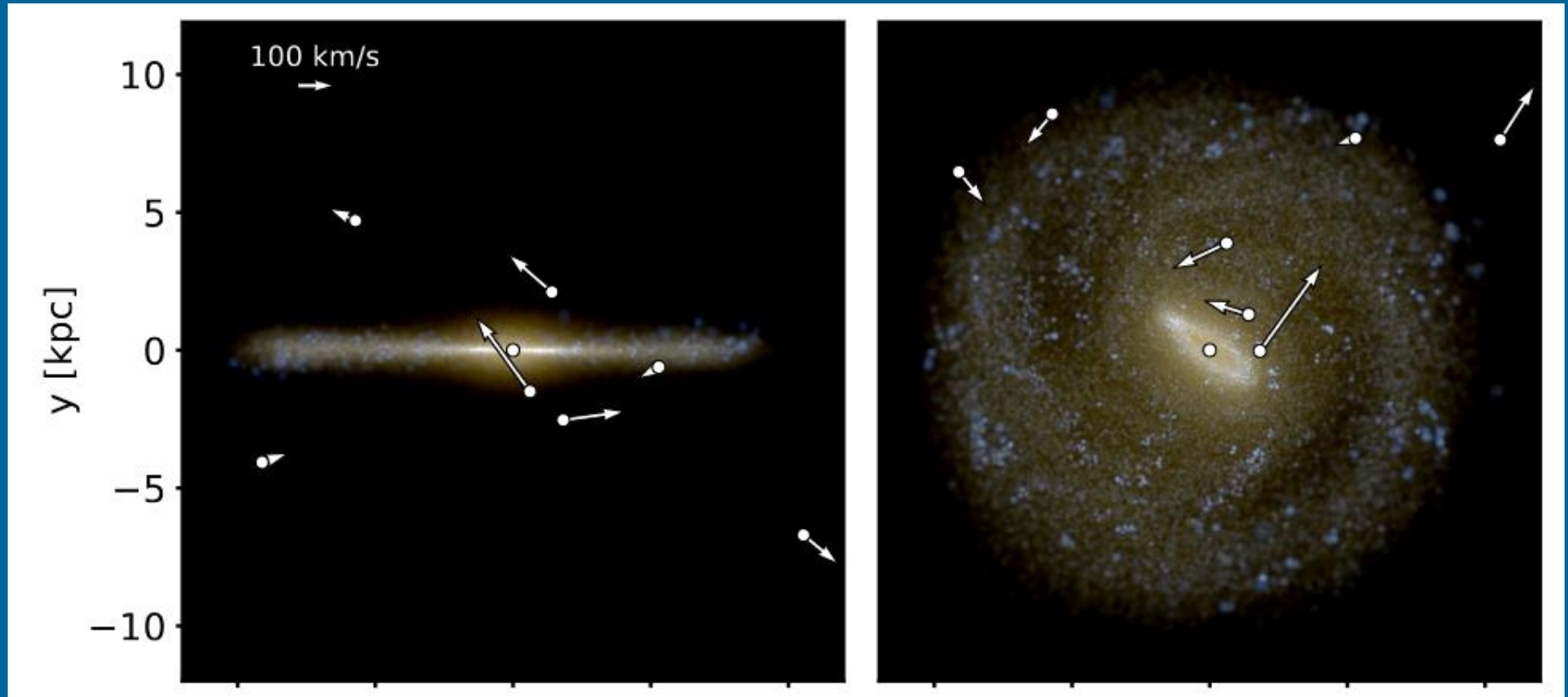
Wandering BHs



Only masses $>10^6$ solar are considered.
Usually 2-8 inside 10 kpc,
and up to ~ 20 inside the virial radius.

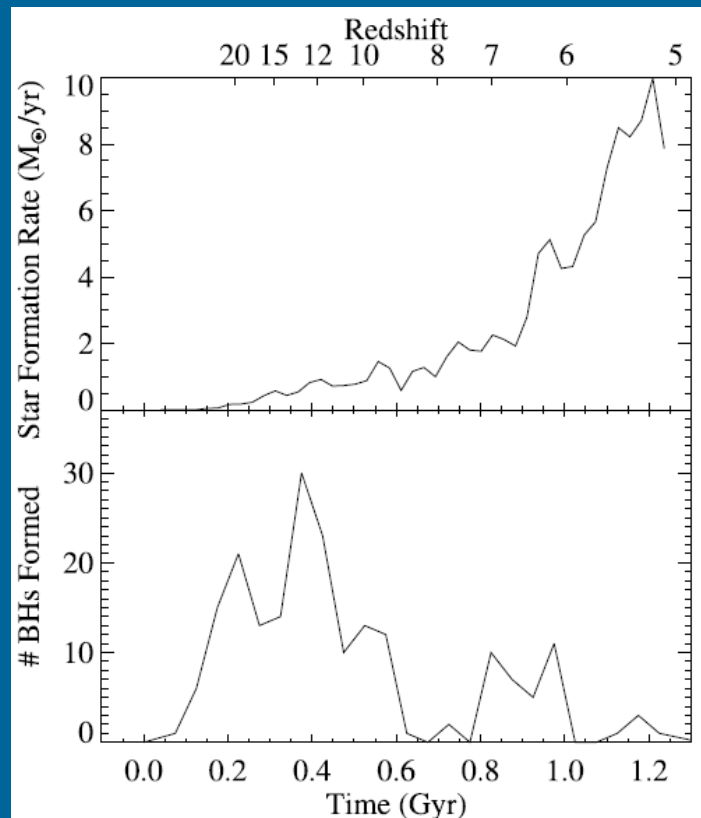


Examples from simulations



Modeling SMBH formation

(SPH+N-body code) + assumptions about BH seeds formation and growth.
Follow-up of three different halos: low-mass disc, MW-like, massive elliptical.



BH mass growth is not followed.

Seeds can appear both:
Due to Pop III massive stars, or
Due to low-metallicity gas cloud collapse.

Gas metallicity is very important

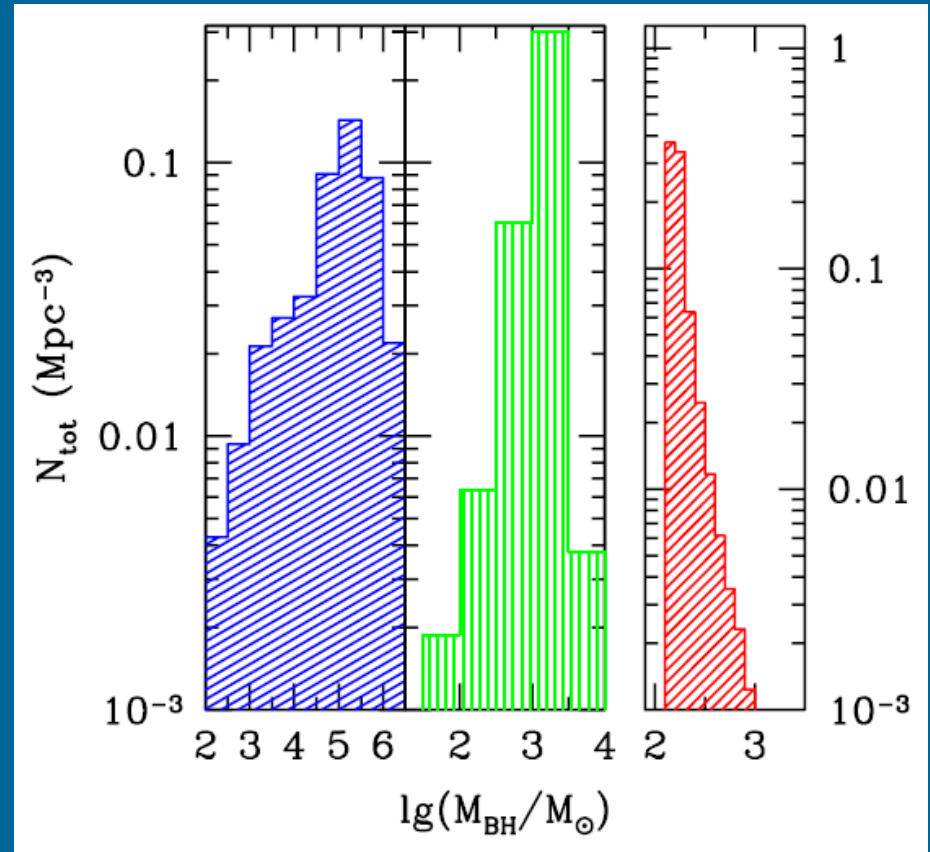
The problem of the existence of very massive BHs at high redshifts

At redshifts ~ 7 already there are SMBHs with masses $\sim 10^9 M_\odot$. These redshifts correspond to the age of the universe $< 10^9$ yrs.

It is necessary to have seed BHs already at $z > 15$ and to provide their rapid growth (note, that the accretion rate is limited by the Eddington rate).

See a brief review of different scenarios of seed formation in arXiv: 0912.0525.

In the figure: seeds mass function for three scenarios. Direct collapse, runaway stellar mergers, Pop III



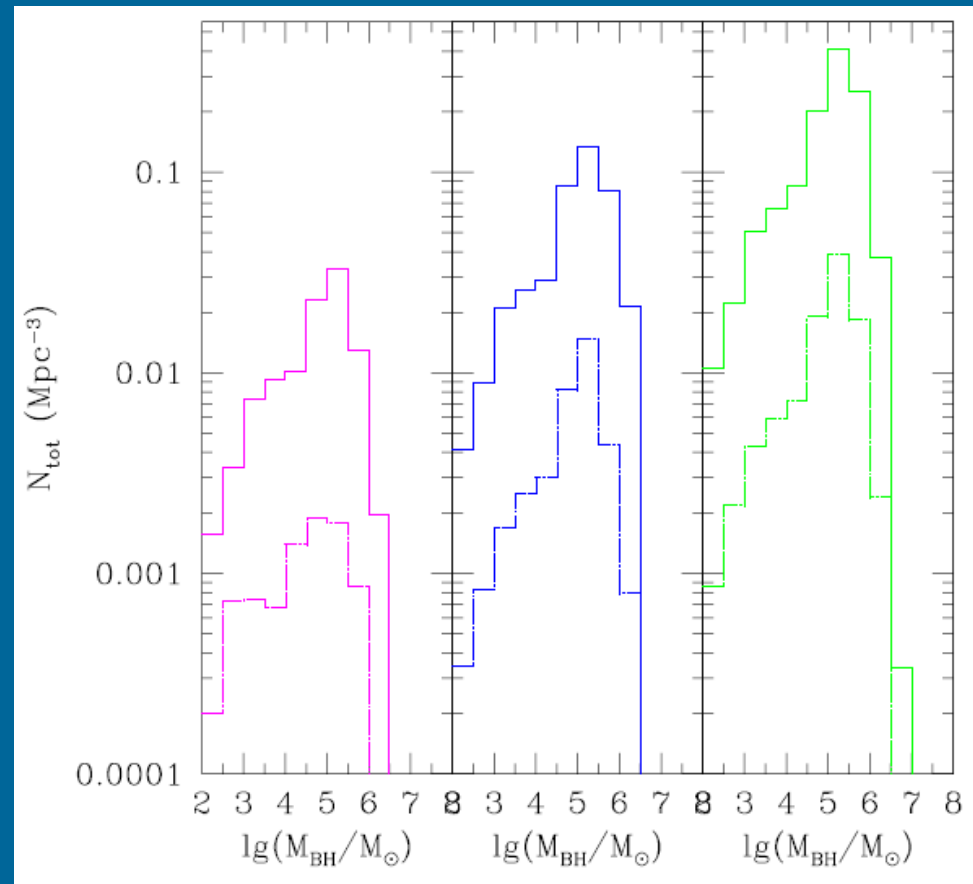
Direct collapse of gas discs

Plots are done for different efficiencies and for two values of the redshift: $z=18$ (dashed) and $z=15$ (solid).

In low-mass halos and in rapidly rotating halos (later on, probably, bulgeless galaxies) there are no SMBHs in this scenario.

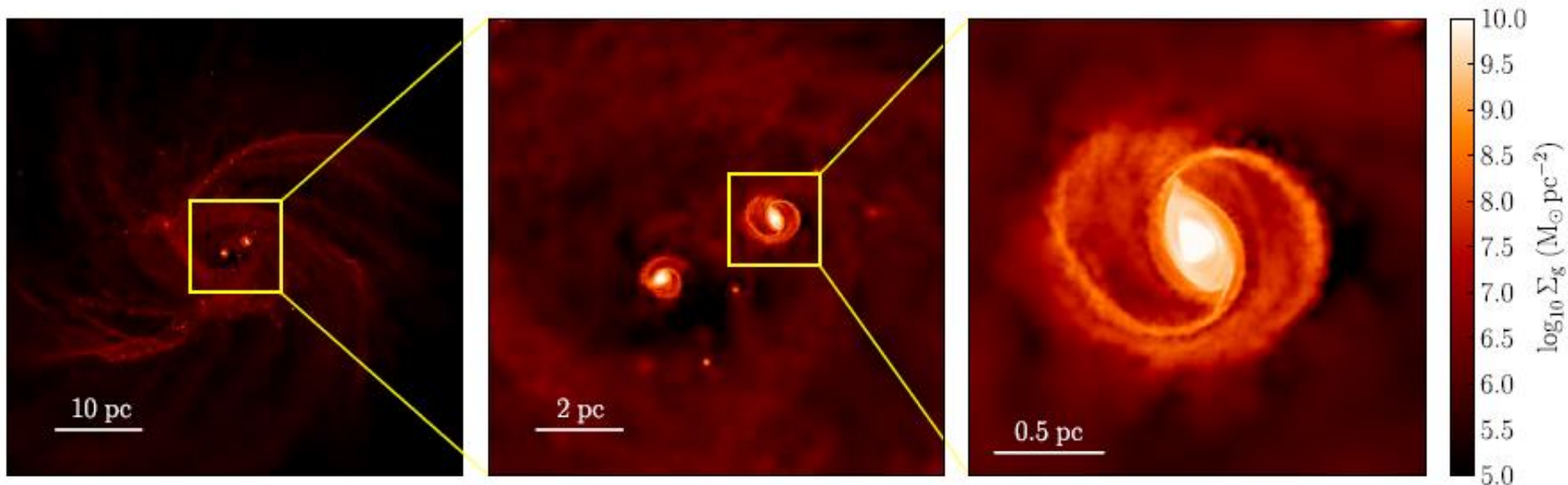
In this model it is possible to explain lack of correlation between dark matter halo mass and SMBH mass for galaxies with small bulges (1103.1644).

Direct collapse of pre-galactic gas discs.
Seeds are already massive at formation:
 $M > 10^5 M_{\text{Solar}}$ (at $z > 15$)



Образование массивных черных дыр

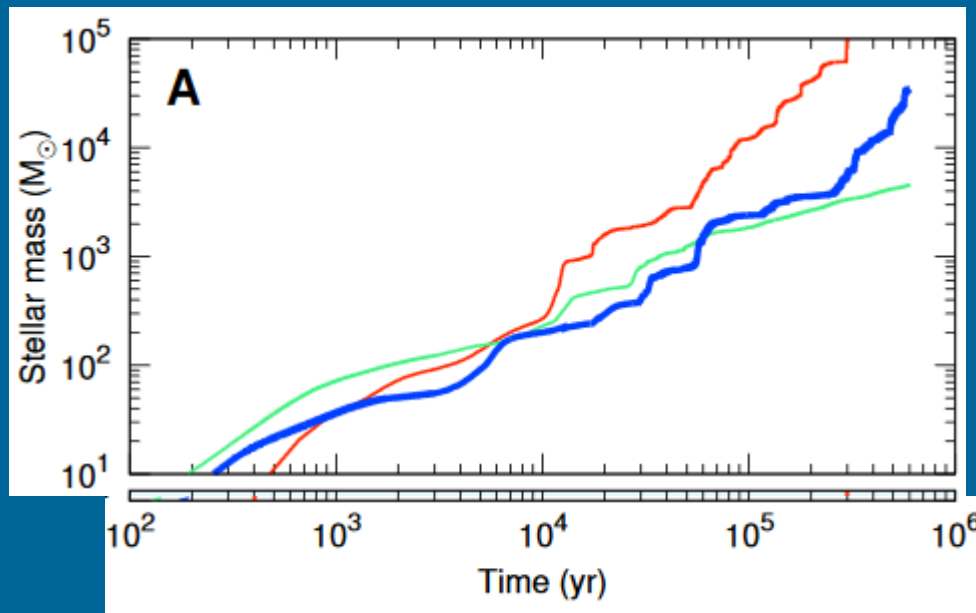
Сверхмассивные черные дыры можно образовать в результате слияния крупных галактик на $z=8-10$.



Formation via a supermassive star

34000 solar mass star $\longrightarrow$ 34000 solar mass BH at $z \sim 30$

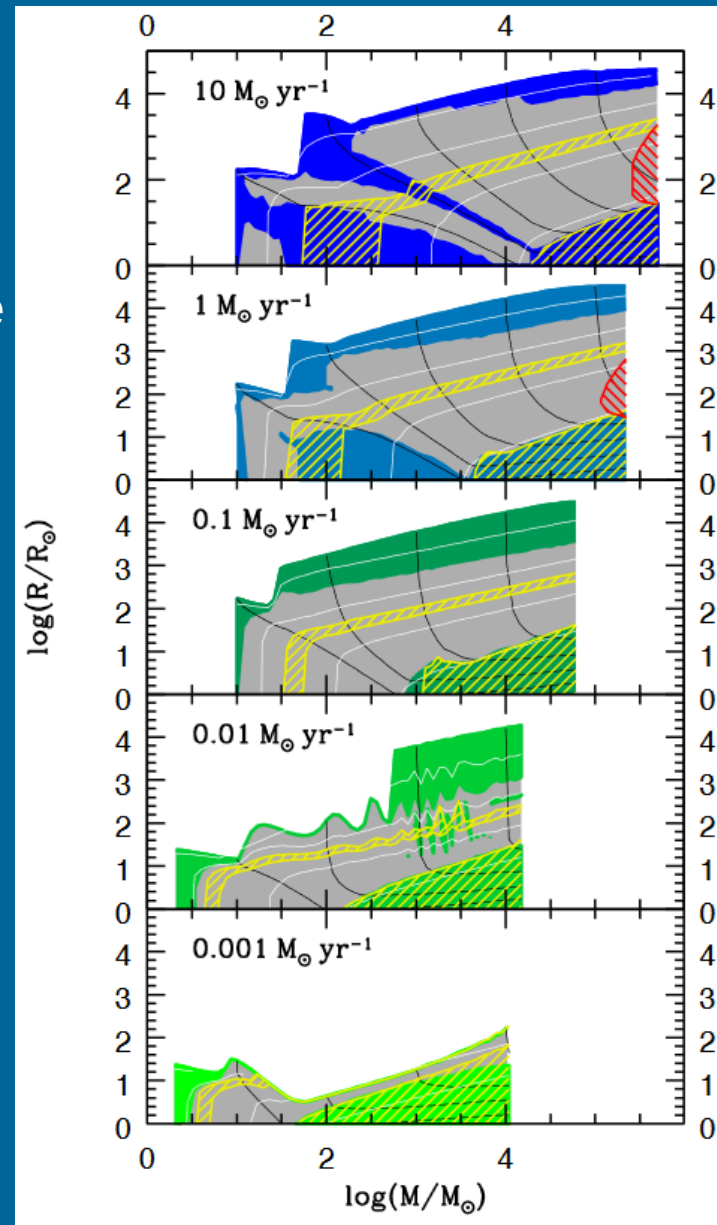
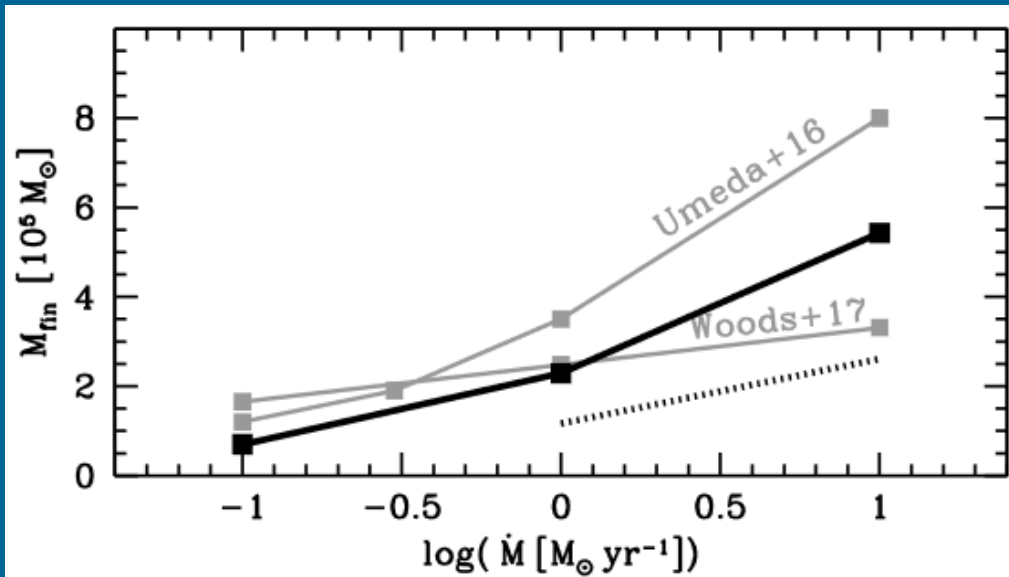
In regions with a large streaming velocity, gas condensation – and hence star formation – is suppressed until a deep gravitational potential is generated by a clump of dark matter with mass 10^7 solar masses.



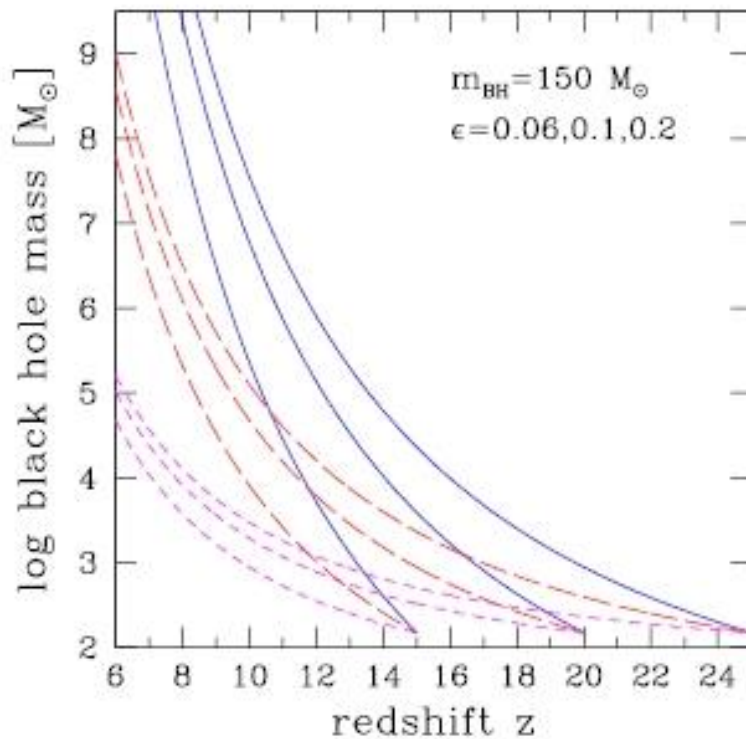
1709.09863, see more recent calculations in 1901.07563

Supermassive primordial stars

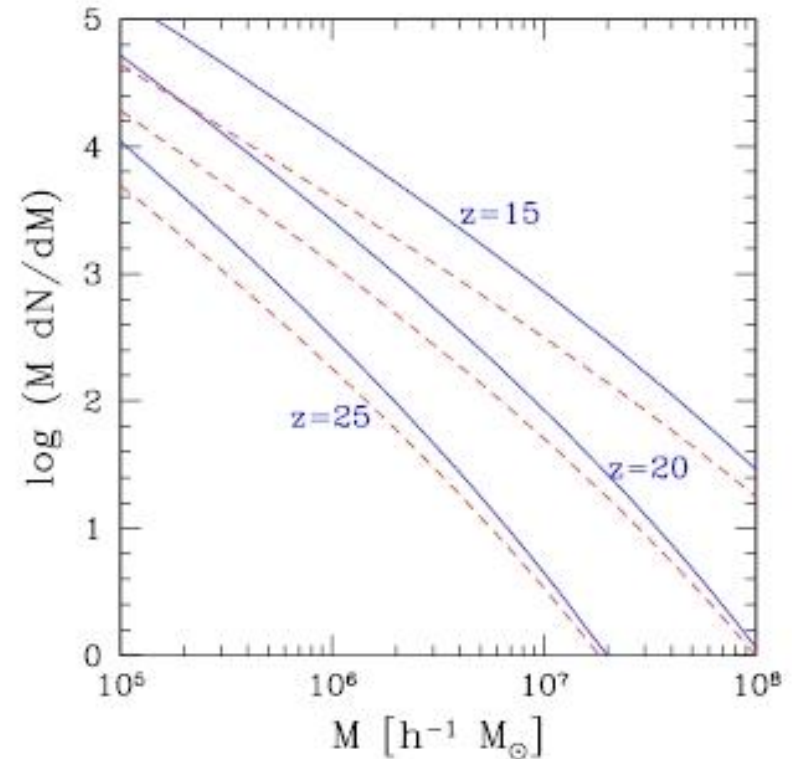
Internal structures of the models for the indicated accretion rates. On each panel, the upper curve is the stellar radius, the blue and green areas indicate convective zones, and the grey areas indicate radiative transport. The yellow hatched areas correspond to D- and H-burning, and the red hatched areas indicate the GR instability according to the polytropic criterion with $n=3$.



BH mass growth

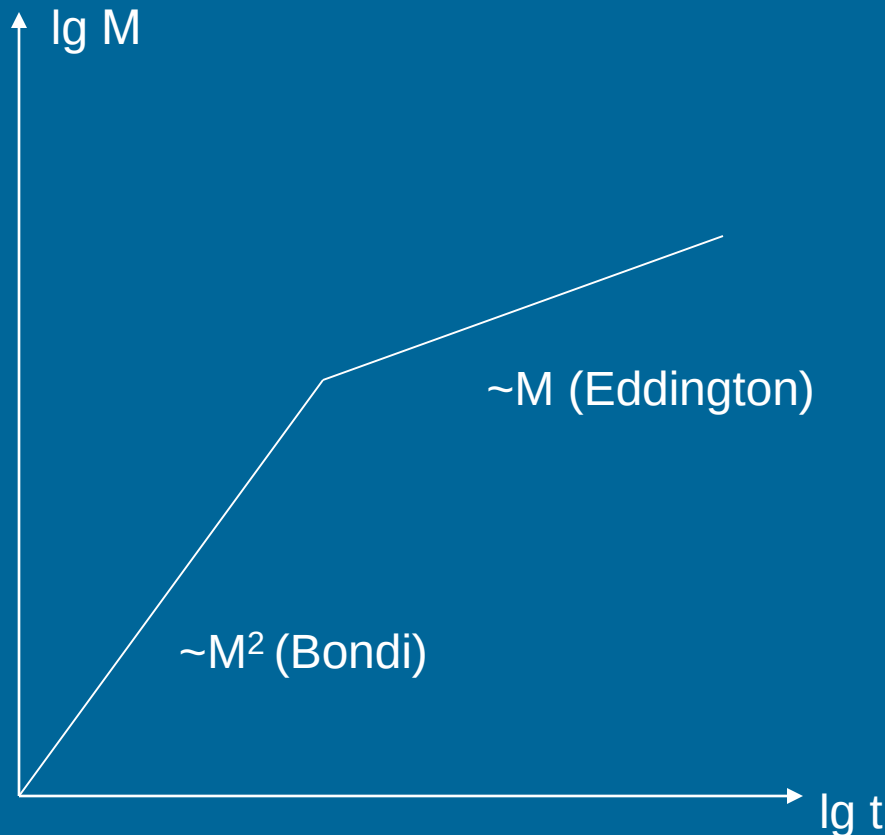


BH mass growth for different accretion efficiency.



Halo mass functions at different z . These galaxies due to coalescence produce at $z_0=0.8$ a Milky Way-like galaxy (10^{12} solar masses, solid curves), or a slightly smaller one at $z_0=3.5$ (2×10^{11} , dashed curves).

Mass growth



At first the mass is growing rapidly according to the Bondi formula. Then, when the Eddington limit is reached, the growth slows down.

The so-called Salpeter time: the time in which the mass is doubled.

Accretion and coalescence are both important for the mass growth.

Now SMBHs in giant elliptical galaxies increase their masses mostly due to coalescence with satellites.

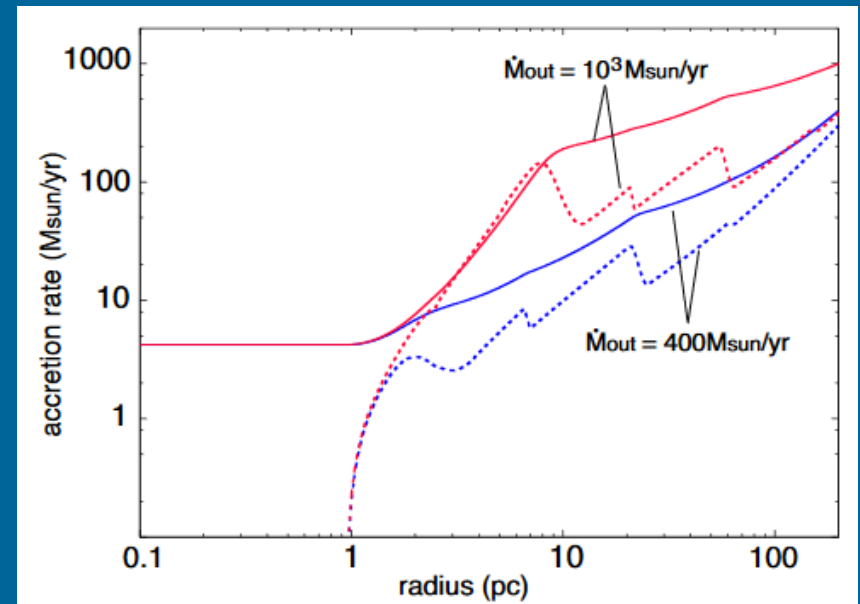
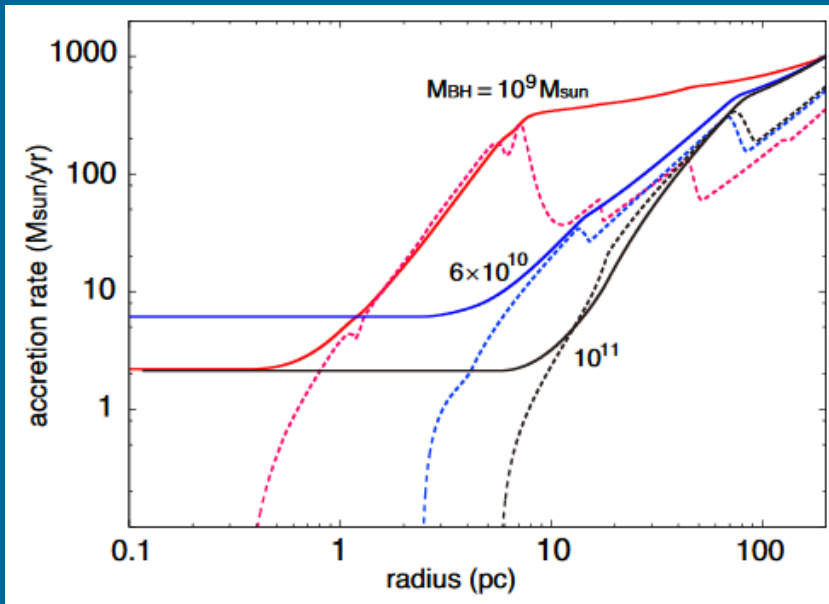
Maximum mass

The most massive BHs are $\sim 10^{10}$ solar masses.

The authors suggest that higher masses require very large accretion rate.

Such a rate requires massive dense accretion discs, and under such conditions most of the gas is transformed into stars.

In addition, outflows can take away matter around very massive BHs.

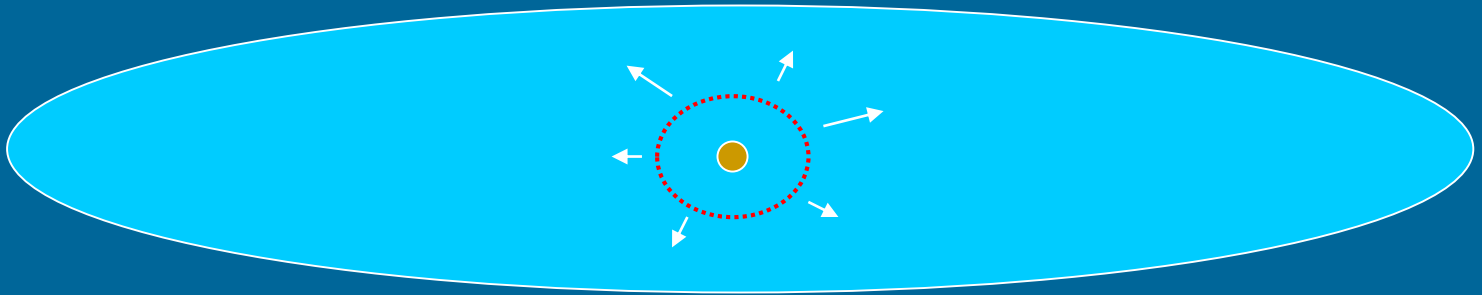


Solid – accretion rate.
Dashed – star formation rate.

$M_{BH} = 10^{10}$

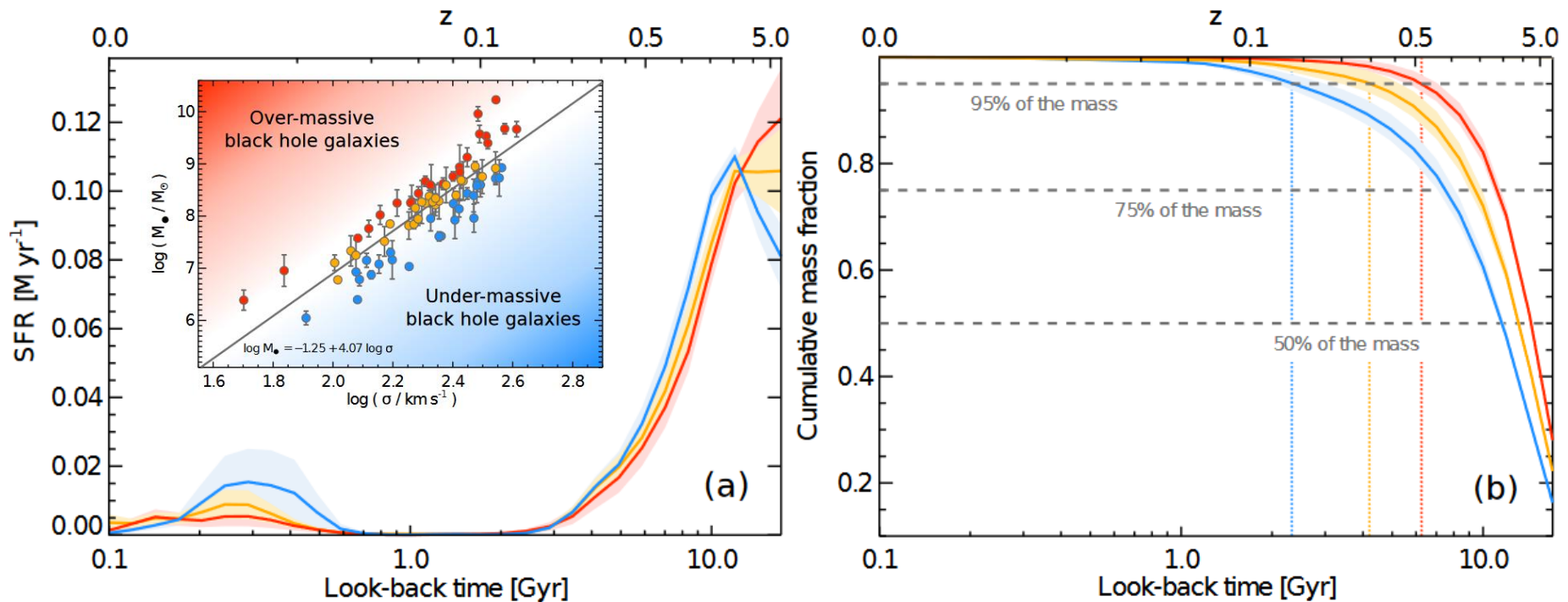
Квазар «задувает» галактику

Активность квазара может привести к мощному оттоку вещества. Этот поток может выметать газ из галактики, что приведет к выключению звездообразования в ней.



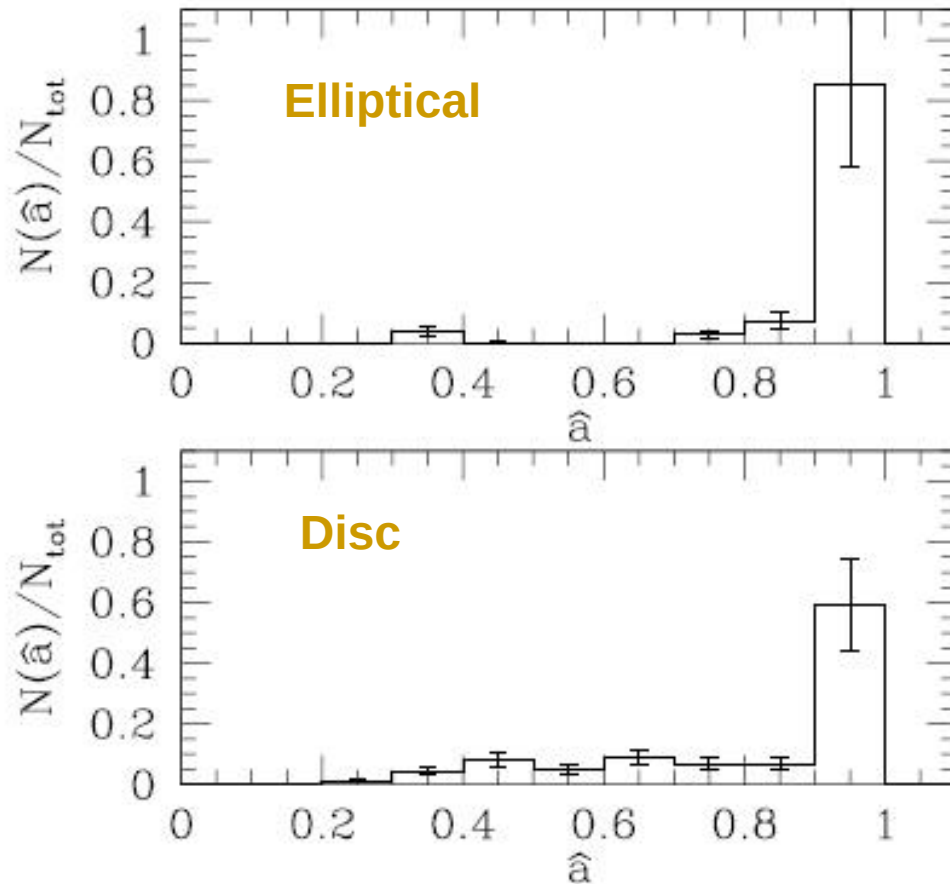
Обнаружен квазар на $z=6.4$
В нем отток вещества составляет
3500 масс Солнца в год.
Этого достаточно, чтобы
воздействовать на всю галактику.

Starformation rate and black hole mass



Galaxies with different BH mass have different star formation histories. Not the absolute BH mass is important, but if it is more or less massive than might be. The authors suggest that more massive BHs form and evolve faster, and then quickly quench star formation in their galaxies.

Mass growth, spin and activity

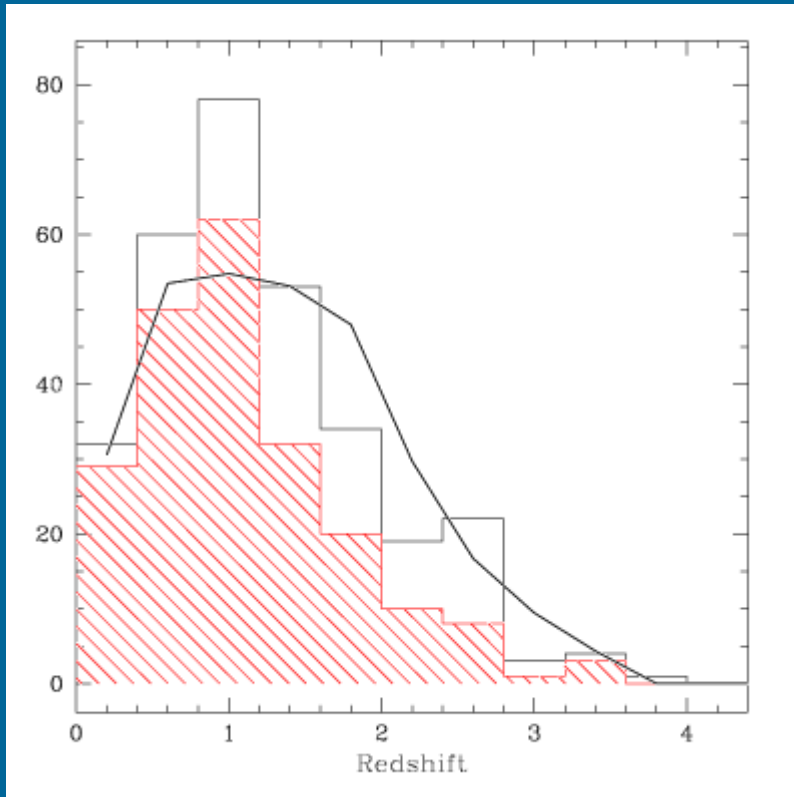


Some time ago it was noticed, that radio emission from elliptical galaxies is stronger, than from disc galaxies.

It was proposed that this can be related to faster rotation of central BHs in elliptical galaxies.

Recent calculations (see the plot) demonstrated that it can be true. The reason is that the mass growth of BHs in ellipticals happen via more powerful episodes of accretion.

Evolution of SMBHs activity



The plot shows the redshift distribution of AGNs detected by Chandra and XMM-Newton.

The top histogram: all sources from the joint sample of Chandra and XMM.

Red hatched region: sources identified in optics.

Solid curve: results of modeling.

The “cutoff” at high redshifts is not an artifact.

Light echo from a dead quasar

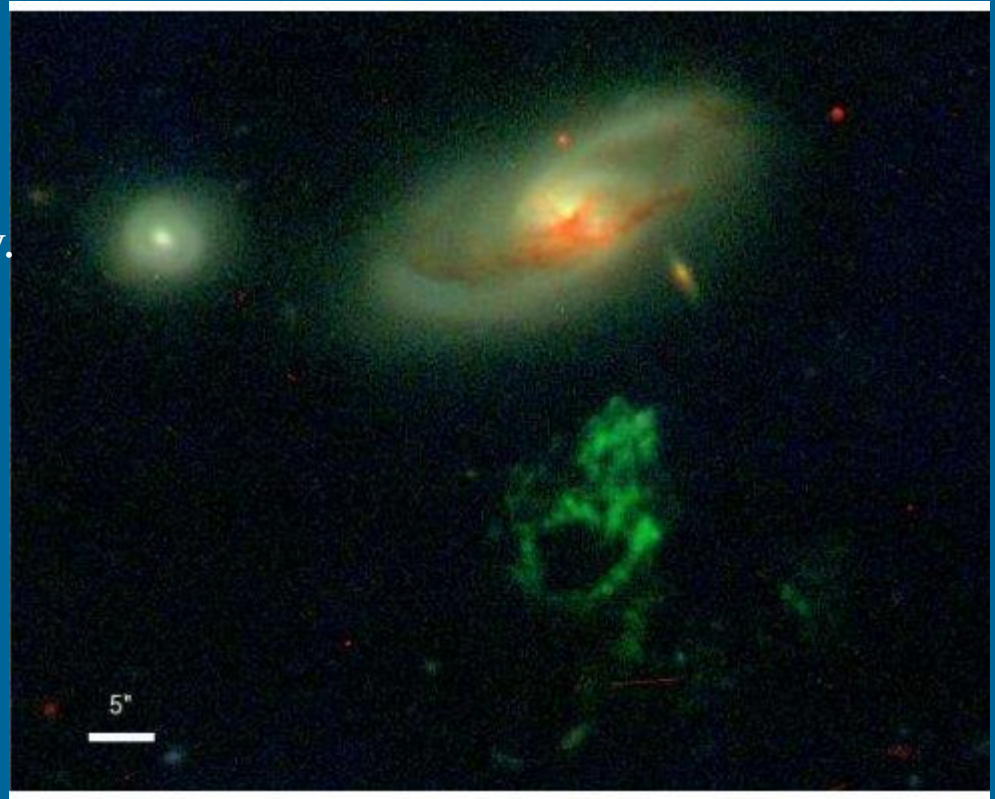
Hanny's Voorwerp.

The source was discovered
by the Galaxy Zoo Project.

This is a gas cloud in 45-70 thousand l.y.
from the galaxy IC 2497

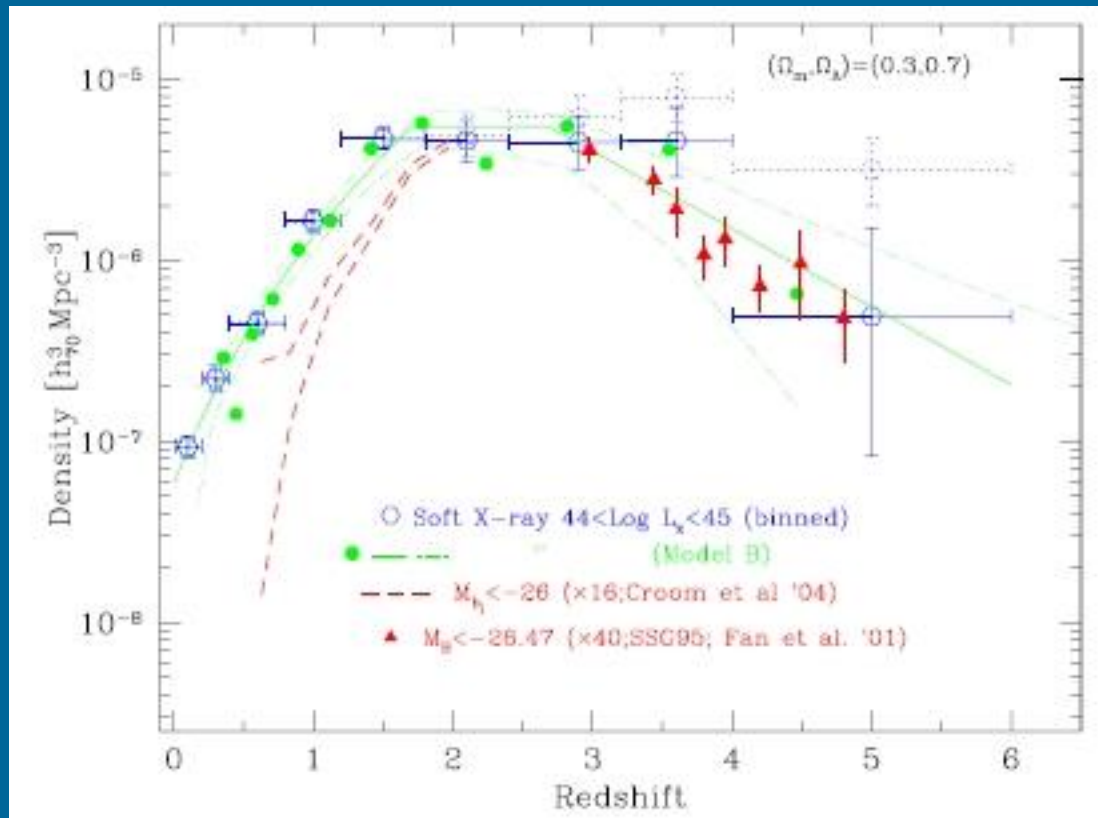
The galaxy is not active now,
but probably <70 000 years ago it was
and powered the gas cloud.

The alternative explanation
(a radiogalaxy with a jet and huge
absorption in the nuclei) was proposed
in arXiv: 1101.2784



This was the closest QSO!

Evolution of quasars number

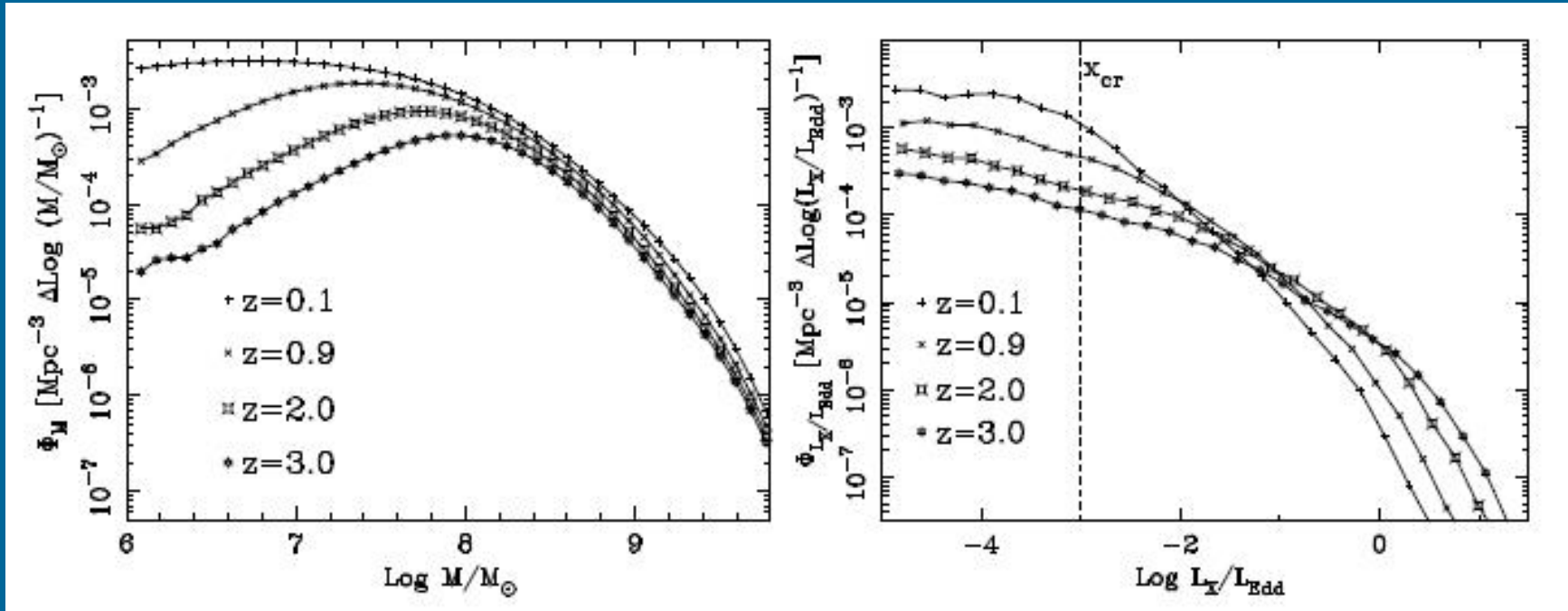


Very bright quasars are formed very early, and then their number is decreasing.

For AGNs with low luminosities the evolution is not so pronounced, but anyway it is evident.

For luminosities 10^{42} - 10^{43} erg/s the maximum is at $z \sim 0.5$ - 0.7 , for 10^{45} - 10^{46} erg/s – at $z \sim 2$.

Mass and luminosity evolution

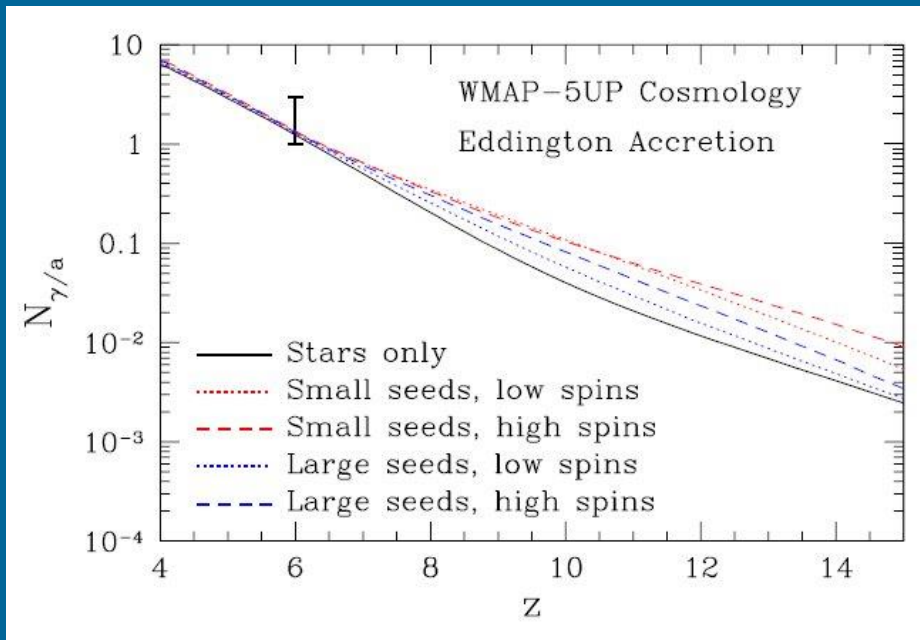


Results of numerical simulations are shown (Merloni 2004).
Lifetime grows with decreasing z .

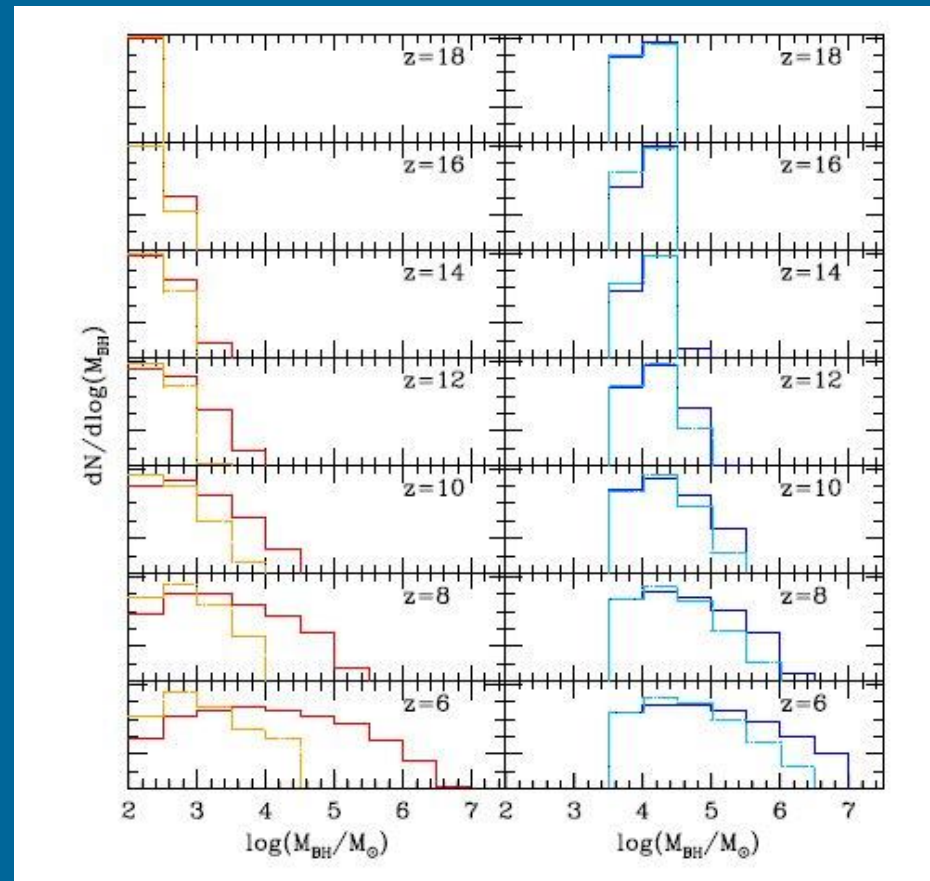
Quasars and reionization

It is important that quasars have harder spectrum.

Quasars dominate till $z \sim 8$.
Then – starforming galaxies dominate.



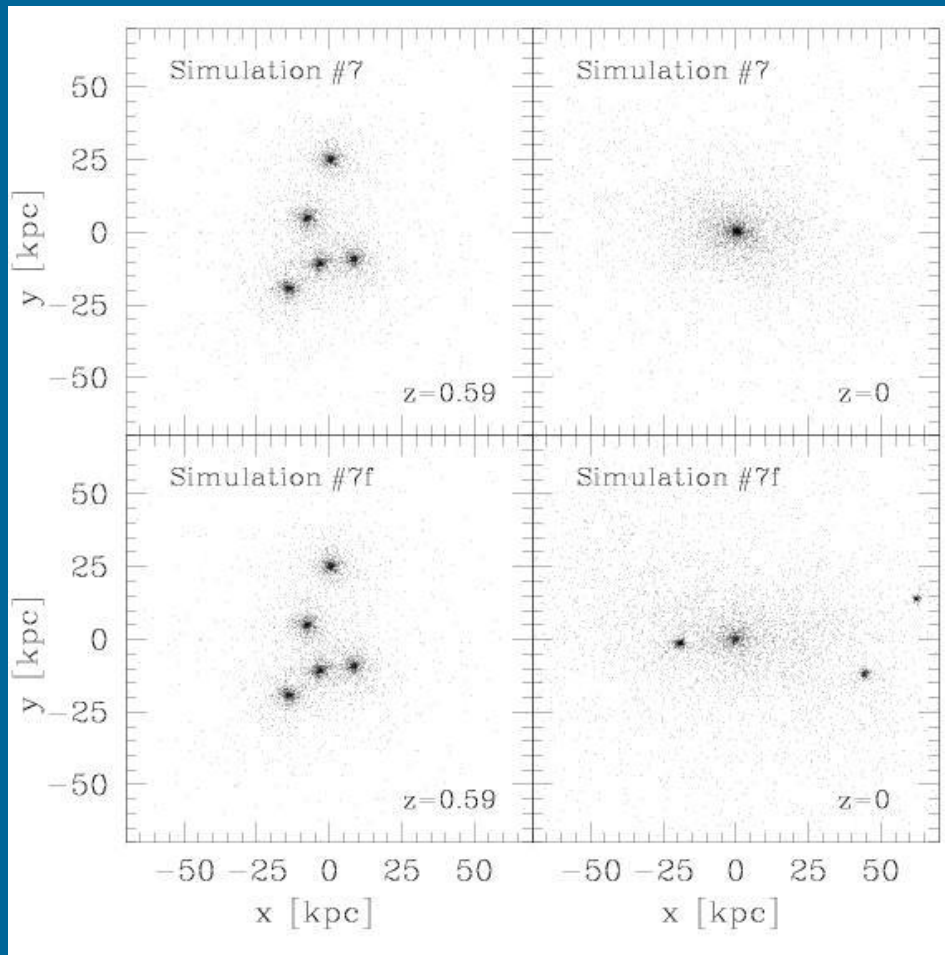
Mass function of MBHs at different cosmic times



Small seeds

Large seeds

Galactic cannibalism



Results of calculations for the evolution of galaxies in the center of the cluster C0337-2522.

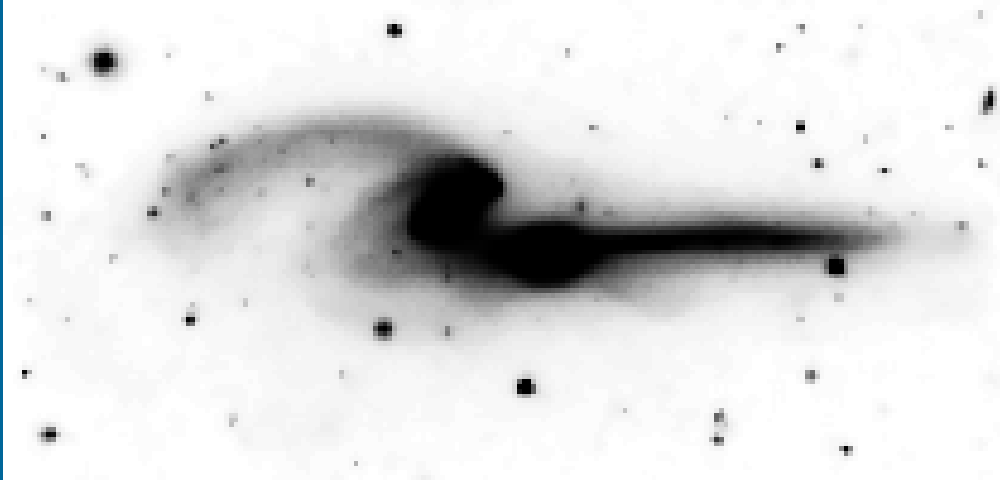
On the left the present day (observed) configuration is shown.

On the right – results of calculations for two models.

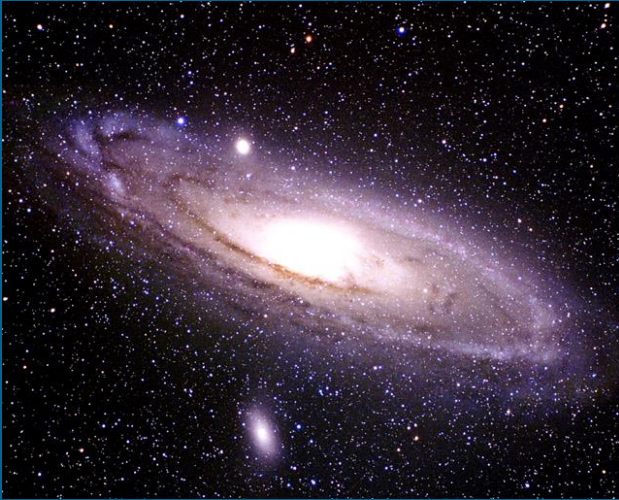
Two variants of calculations differ by the way the DM particles are treated. The upper one seems to be more realistic.

Dynamical friction is important.

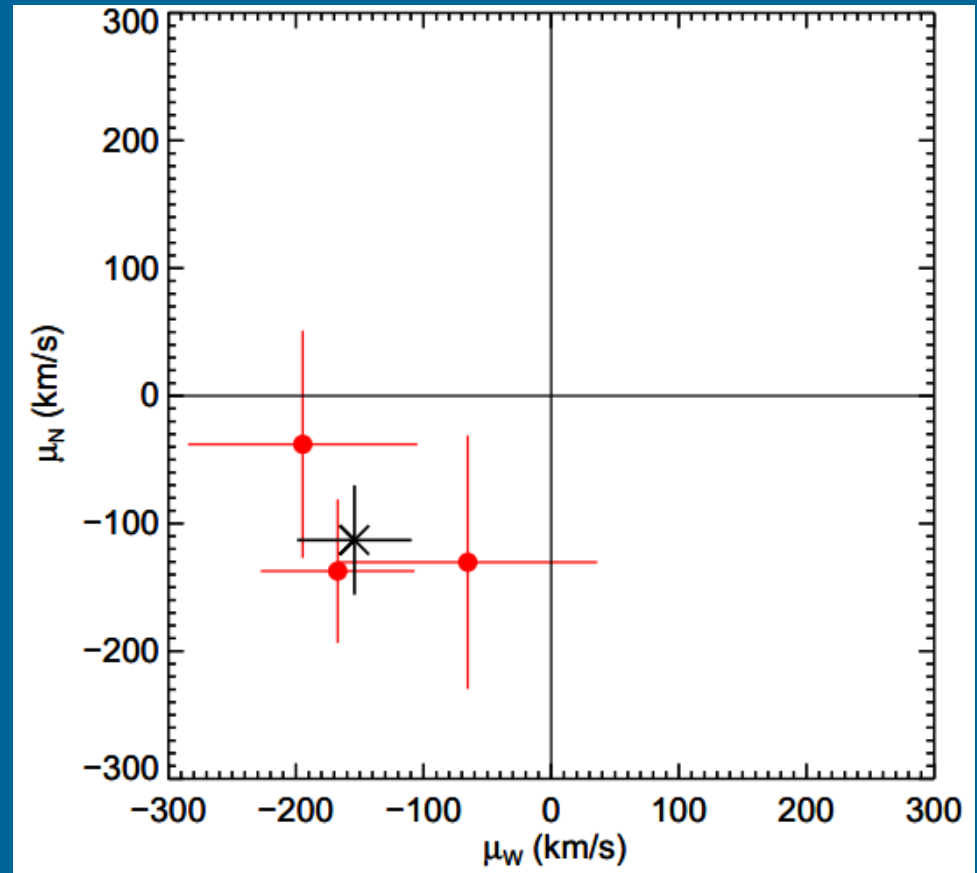
Interacting galaxies



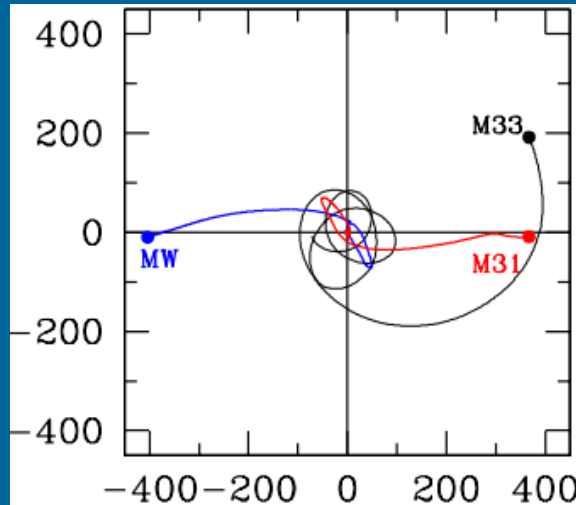
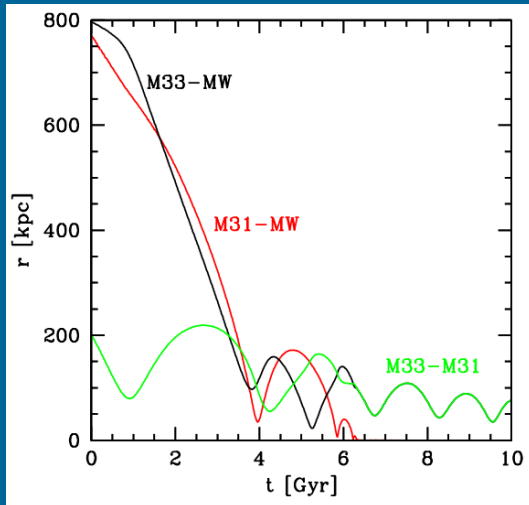
Куда движется туманность Андромеды?



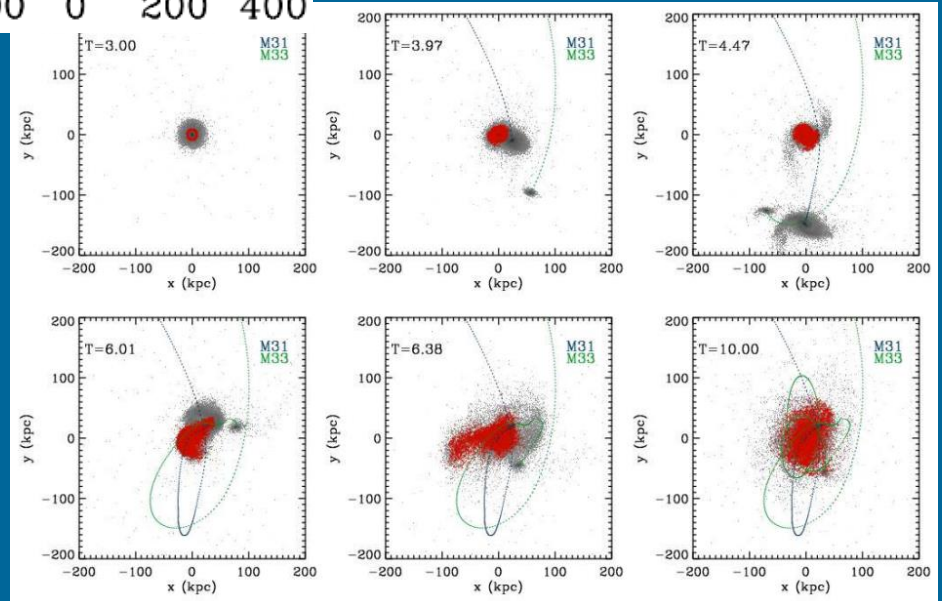
Впервые удалось измерить собственное движение ближайшей крупной галактики – М31. Это позволяет определить ее трехмерную скорость.



Как все сольется

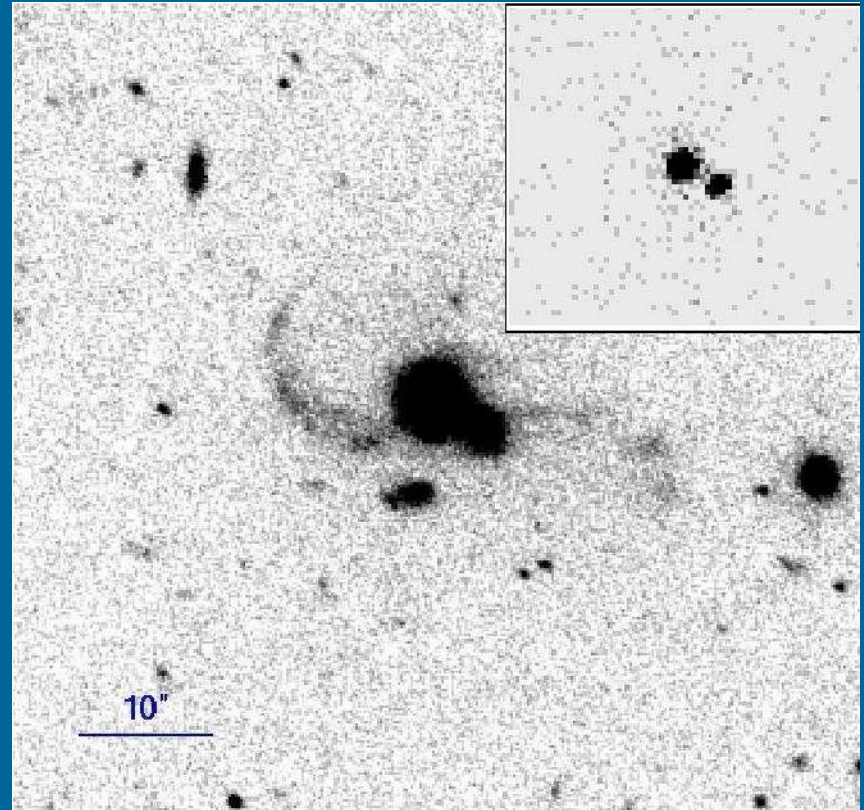
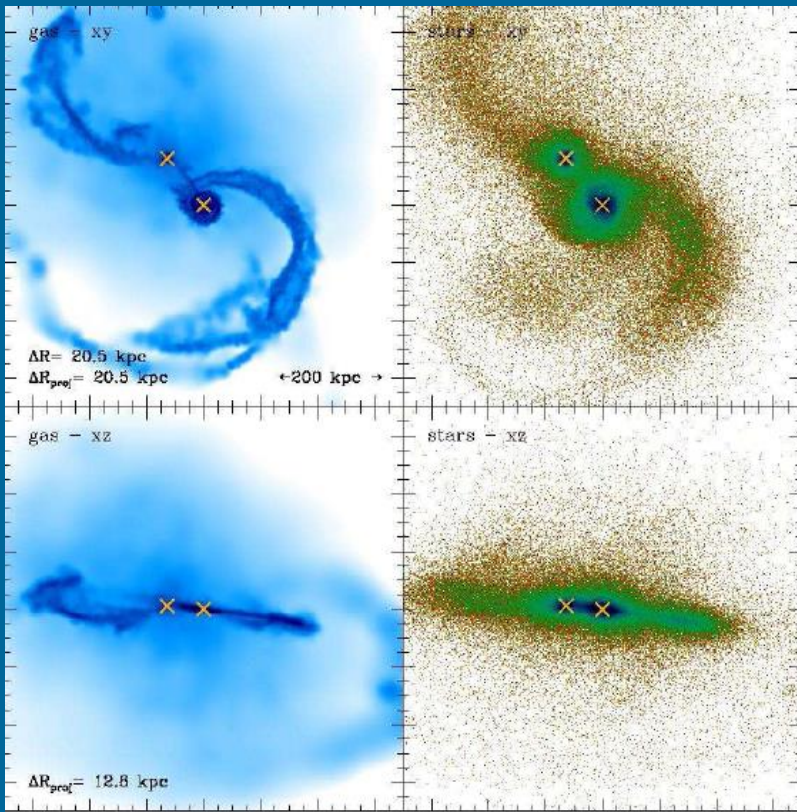


Наша Галактика и М31 сольются через 5-7 млрд. лет. Первое сближение произойдет через 3.5-4 млрд. Скорее всего, М33 также сольется с Милкомедой.

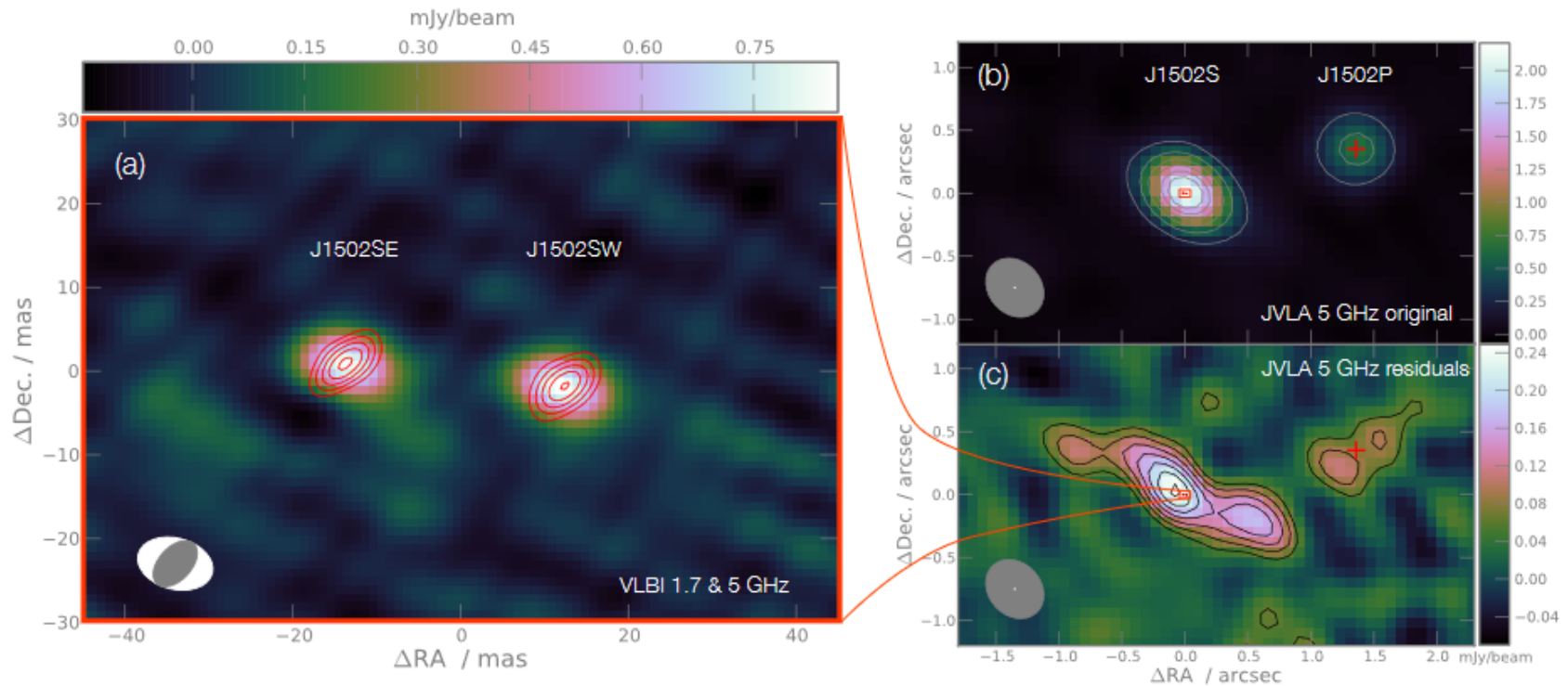


Double quasar in a merger

For the first time a bright binary QSO is found in a clearly merging pair of galaxies. Both QSOs are radioquiet. They form a physically bounded system at $z=0.44$. In projection the separation is 21 kpc.

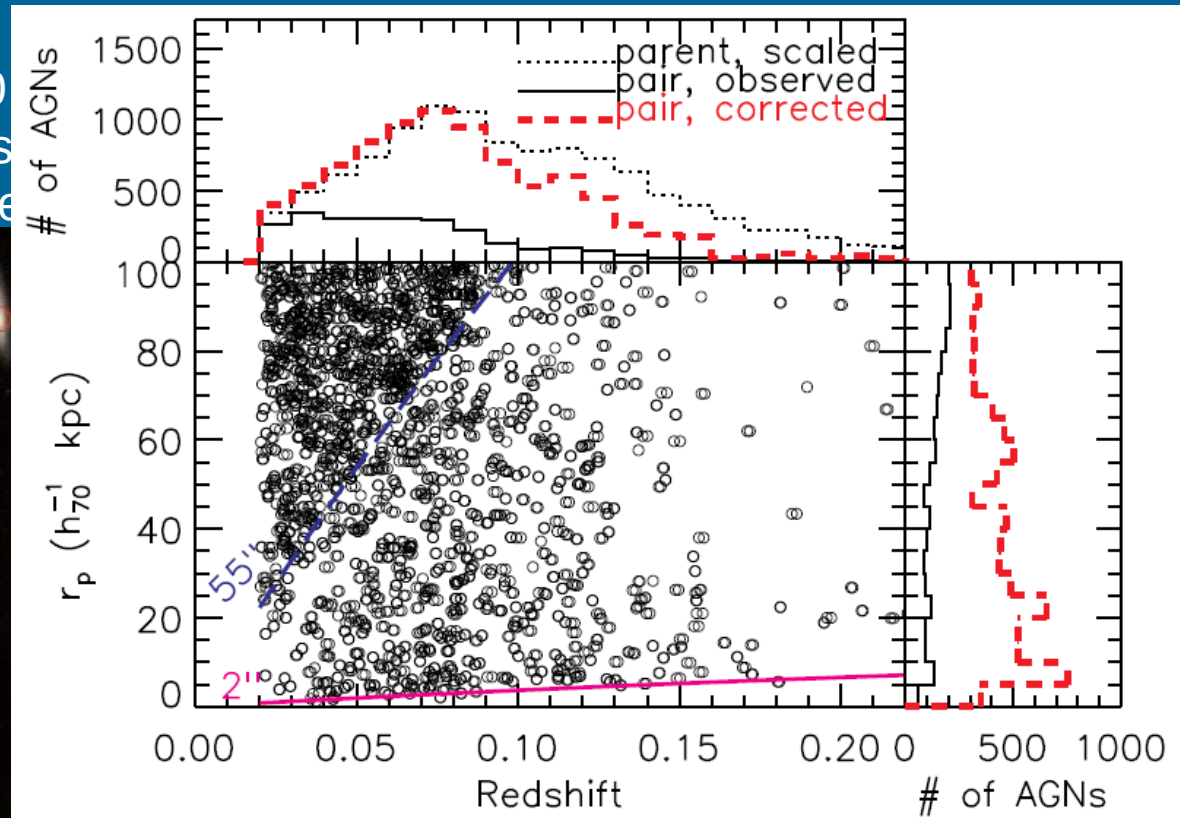
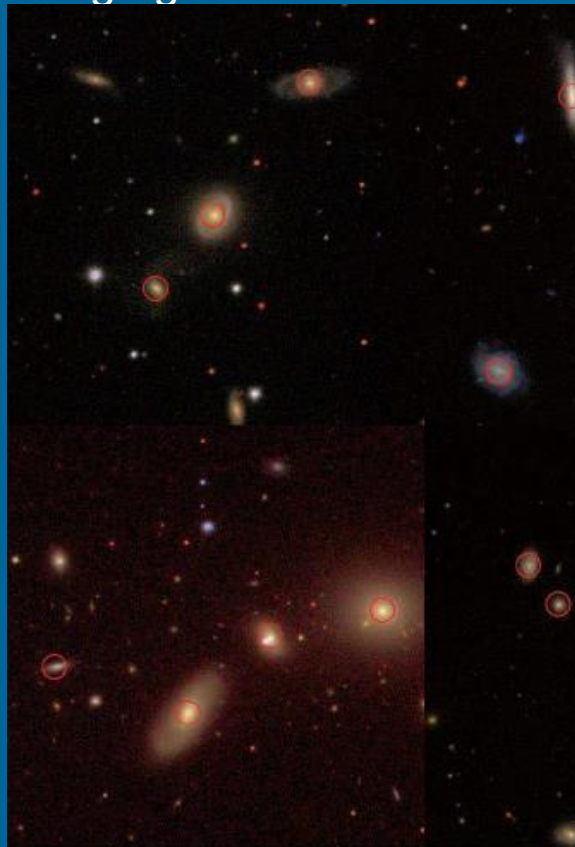


Triple BH system



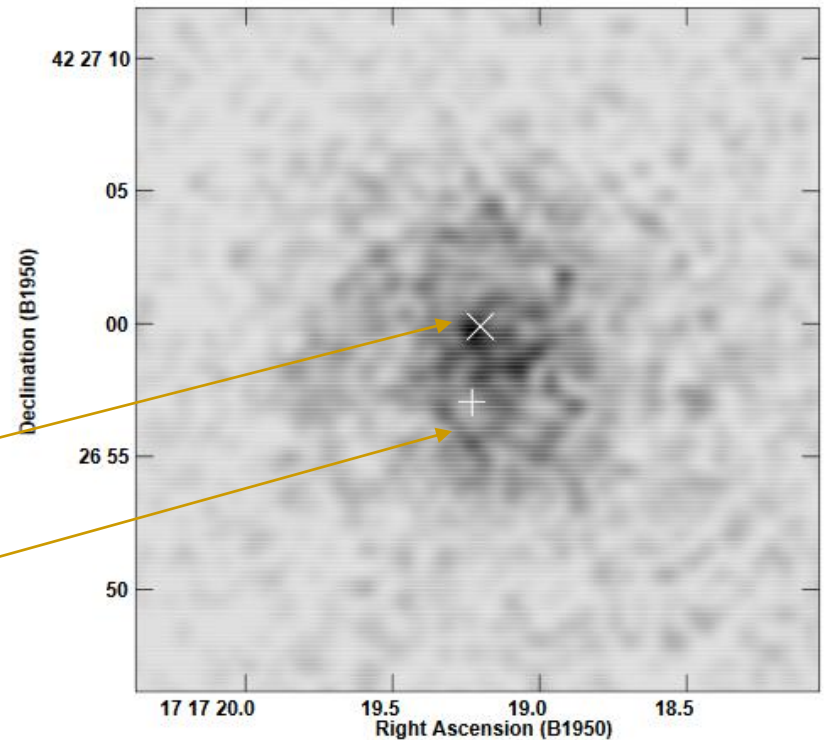
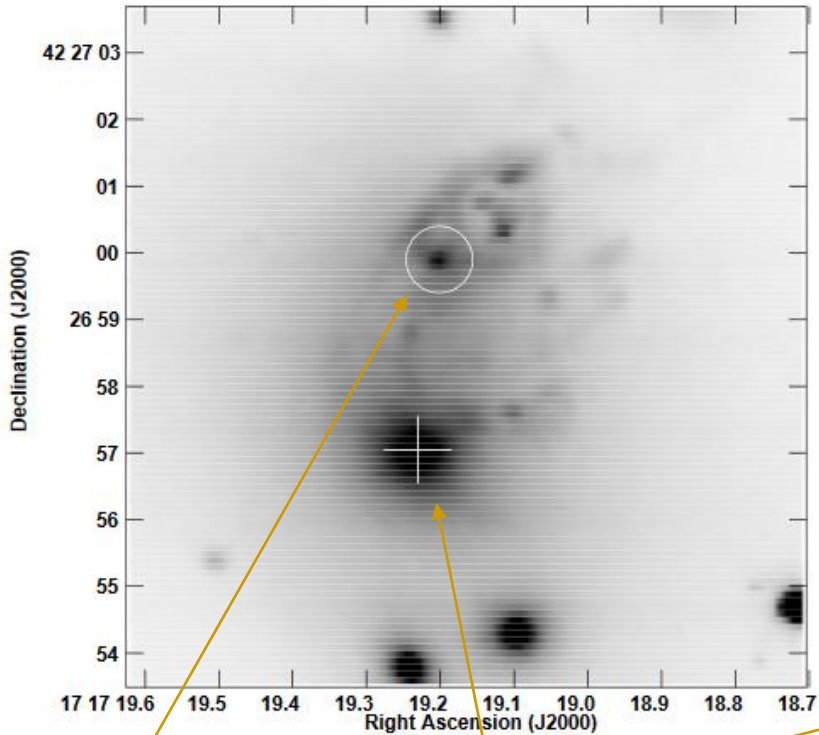
AGN pairs in SDSS

1286 pairs out of >130 000
3.6% of AGNs. In 30% cas
merging features are visible



Nearly naked SMBH

Strong radio source 8.5 kpc from the BCG.
Likely an AGN in a small stripped galaxy.
Traces of interaction.



Radio
source

BCG

1606.04067

Gravitational wave rocket

In addition to energy and angular momentum, gravitational waves also take away the linear momentum. So, the object formed via a coalescence gets a kick. The first estimate of the effect in the case of binaries was obtained in 1983 by Fitchett:

$$V_F \simeq 1480 \text{ km/s} \frac{f(q)}{f_{\text{max}}} \left(\frac{2GM/c^2}{r_{\text{term}}} \right)^4$$

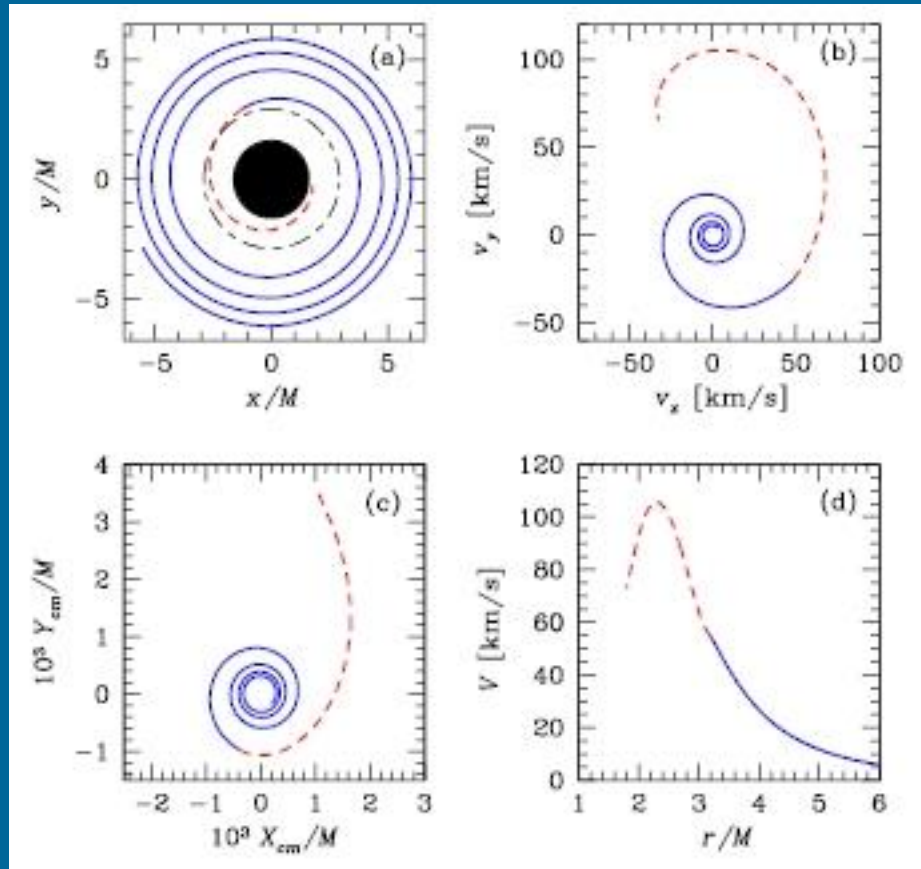
$$f(q) = q^2(1-q)/(1+q)^5, f_{\text{max}} = 0.38$$

Recently, this topic became very hot due to calculations in the framework of the hierarchical model. Continuously new results appear to improve the formula above

One of the first articles in the “new wave” was the paper by Favata et al.

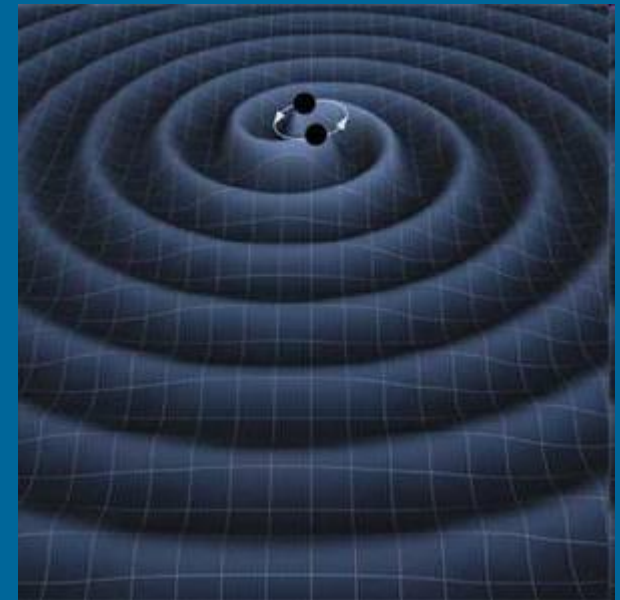
[astro-ph/0402056](#) “How black holes get their kicks?”

Favata et al. (2004)

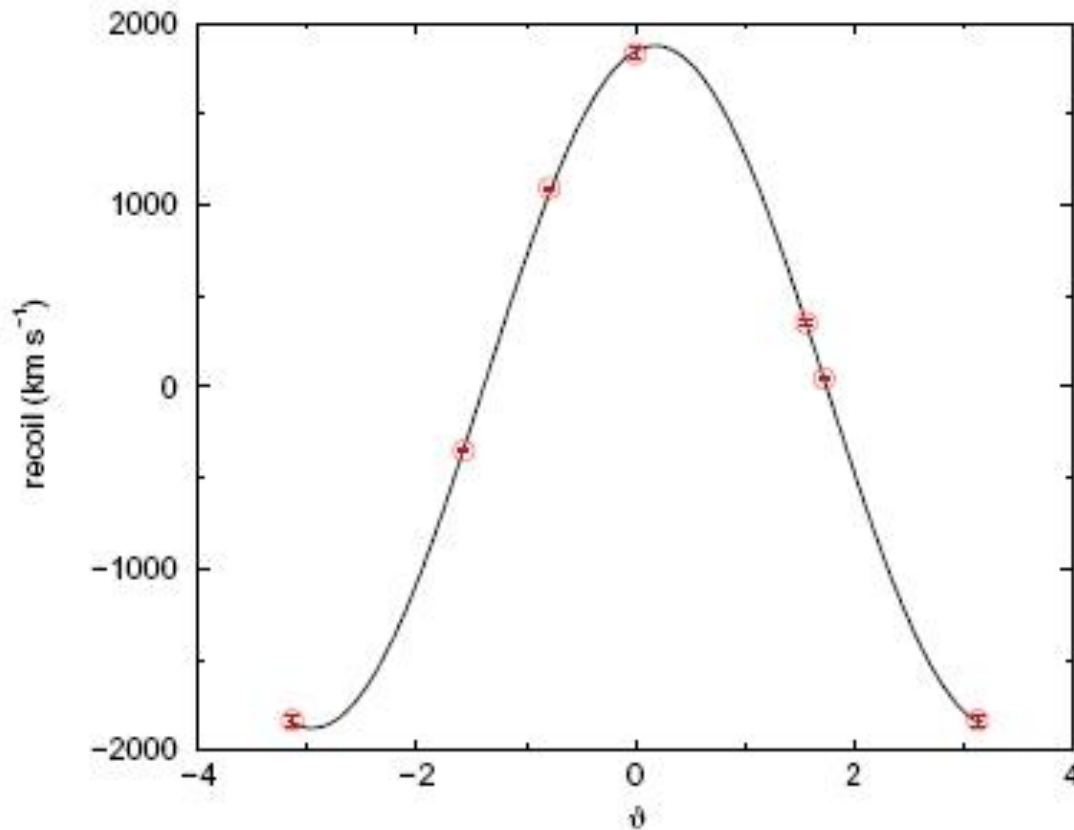


$a/M=0.8$, $q=0.127$
(rotation of the smaller BH
is neglected)

The velocity is high enough to
escape from a not very massive halo,
or to “shake” a central SMBH.



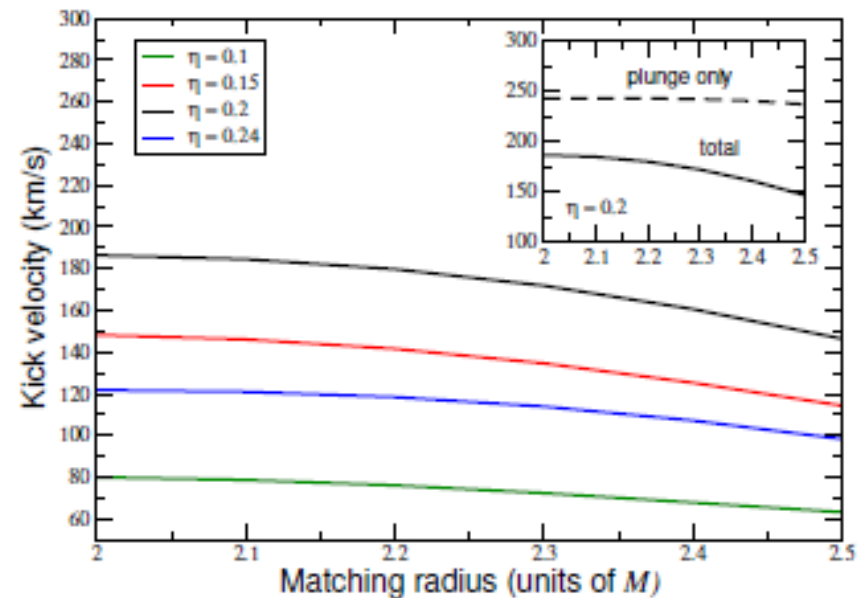
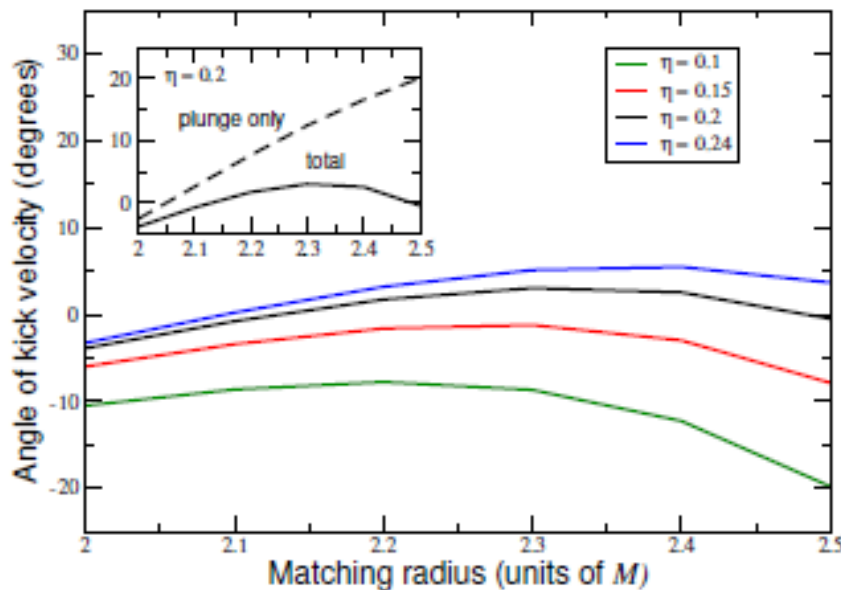
Maximum kick



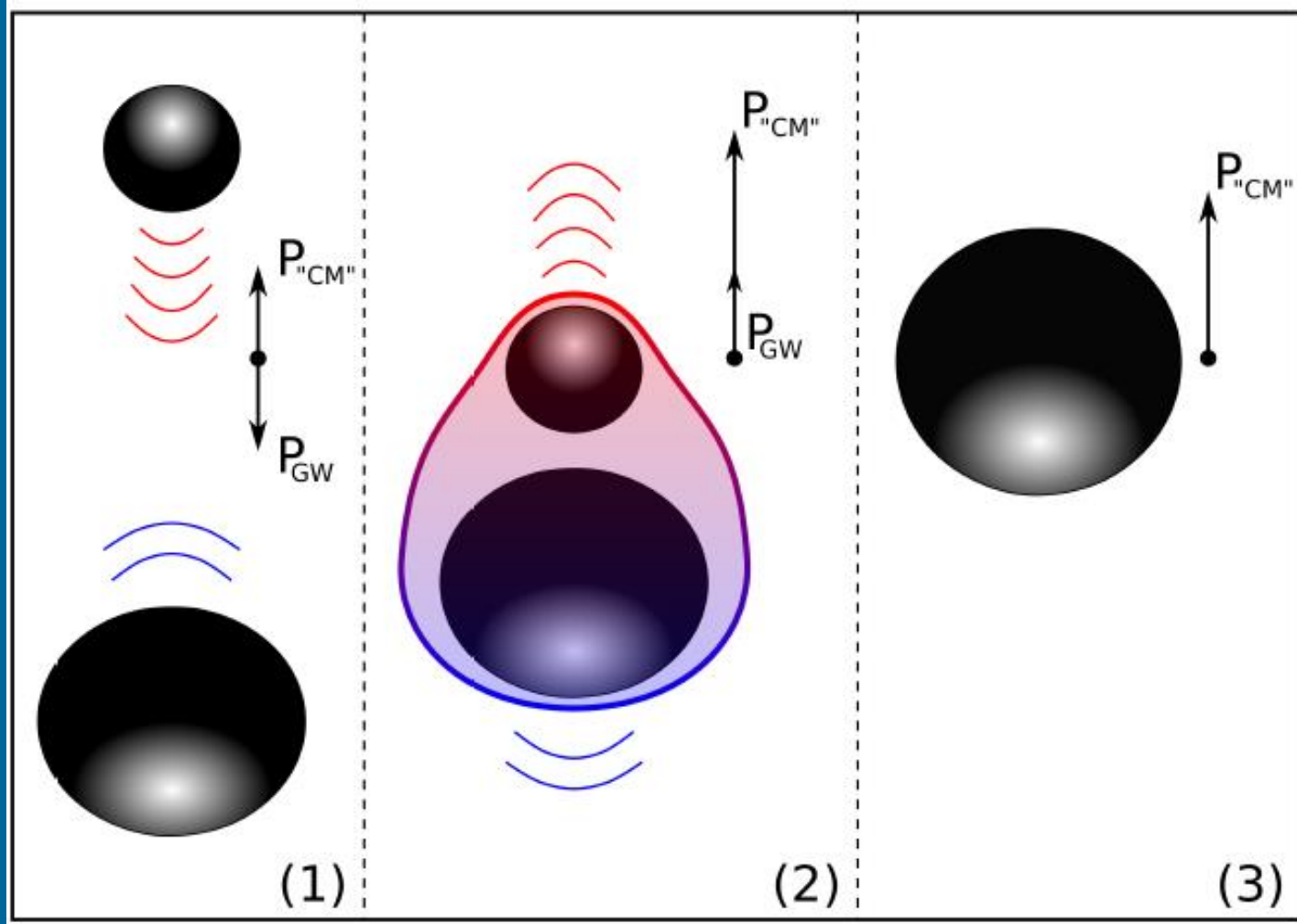
The velocity is strongly dependent on the relative orientation of BHs spins prior to coalescence.

Antikick

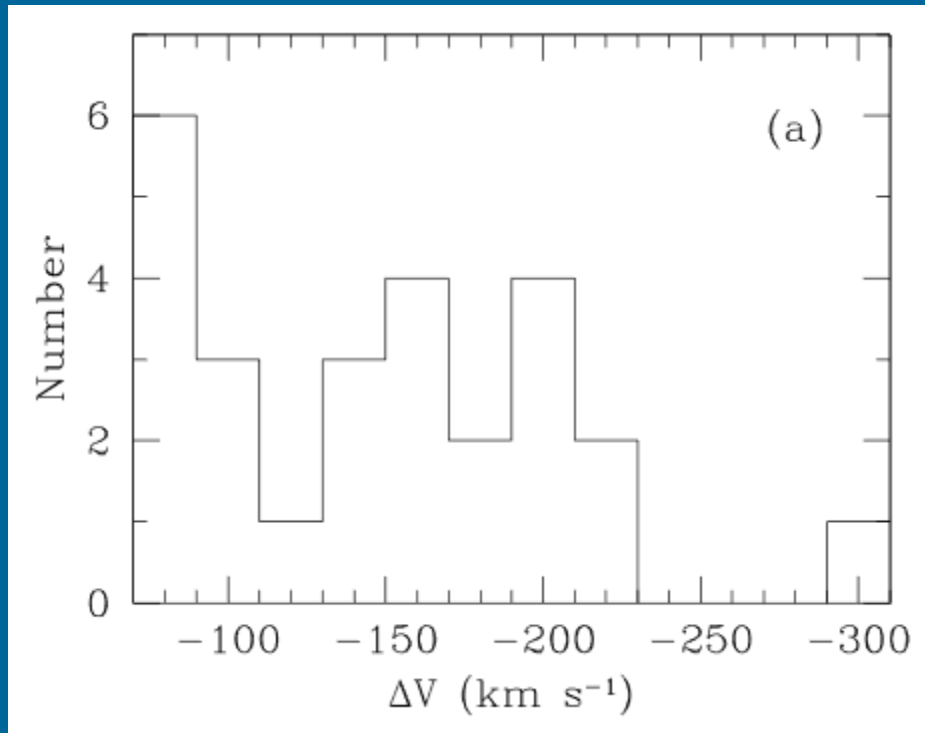
In all cases we found that the direction of the ringdown kick is approximately opposite to that of the accumulated inspiral plus plunge kick. I.e., ringdown radiation produces a significant “anti-kick”.



Antikick



Recoiling BH



Among 1271 SDSS QSOs at $z < 0.25$ the authors selected 26 recoiling SMBH candidates.

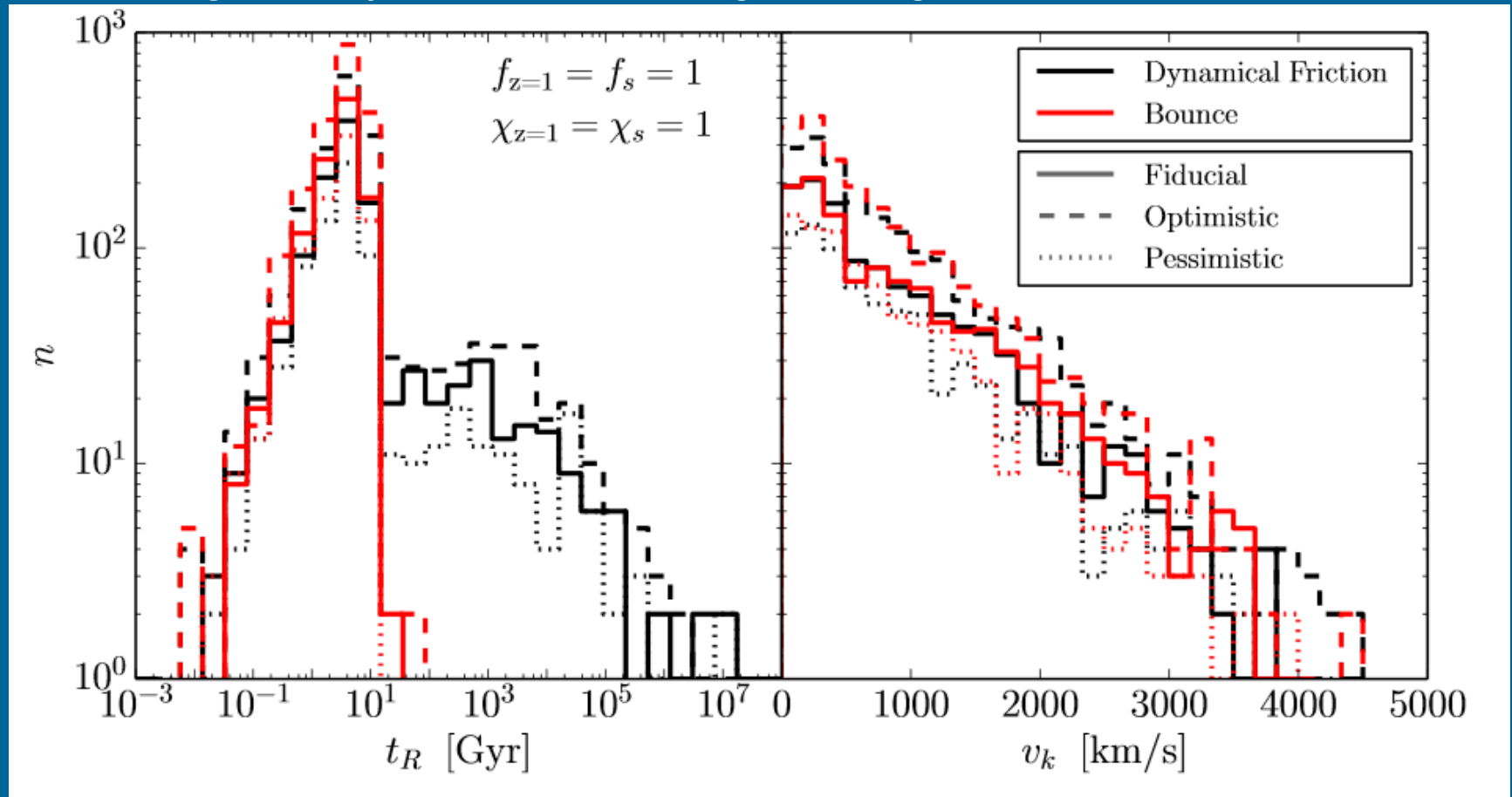
Average velocity $\sim 265 \text{ km/s}$.

See also 1409.3976

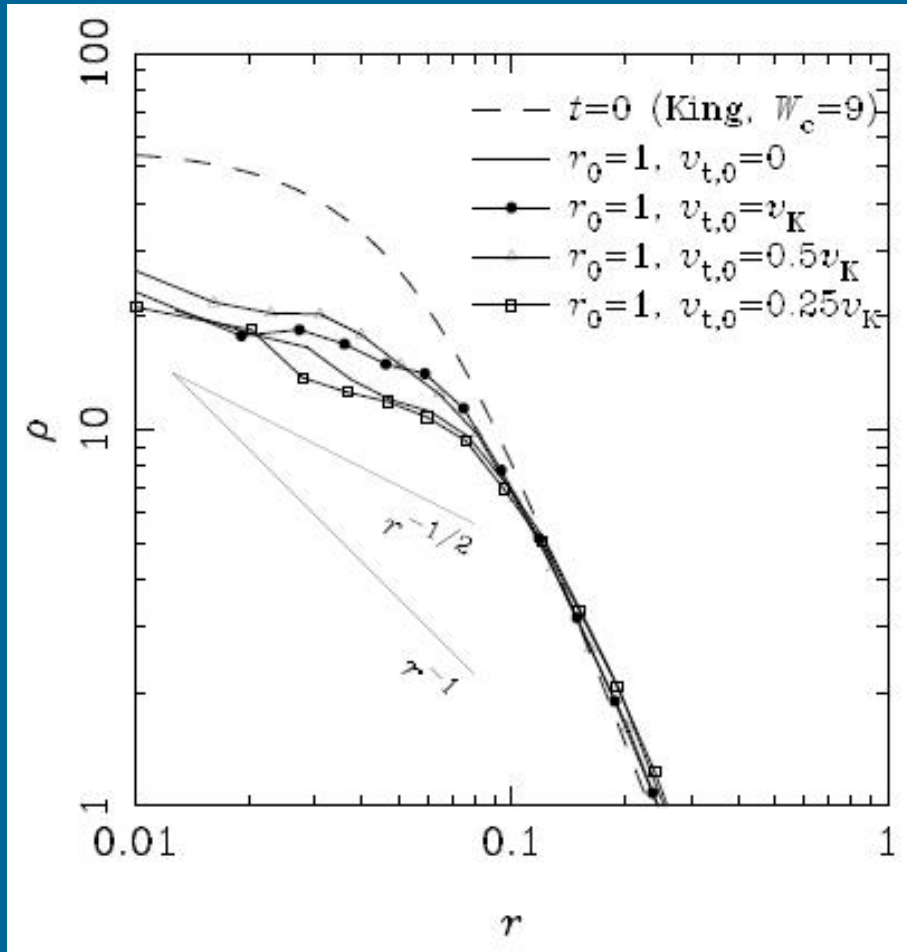
Superkicks?

Large kicks (>2000 km/s) can eject SMBHs even from BCG.

As these galaxies have rich merging history, their SMBHs can be at least significantly shifted, due to long returning time.

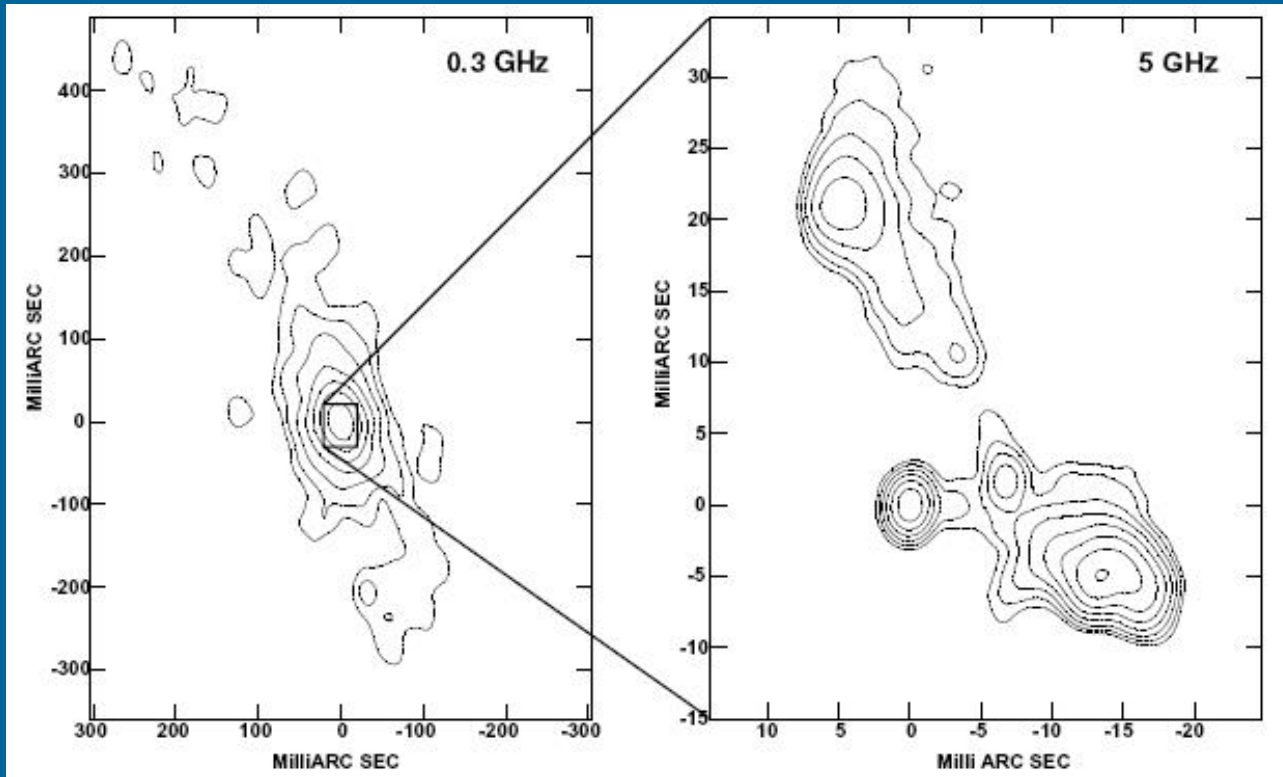


Stellar density profile evolution in the case of two BHs



Flat profiles can be explained by an existence of the second BH.

Binary supermassive BHs

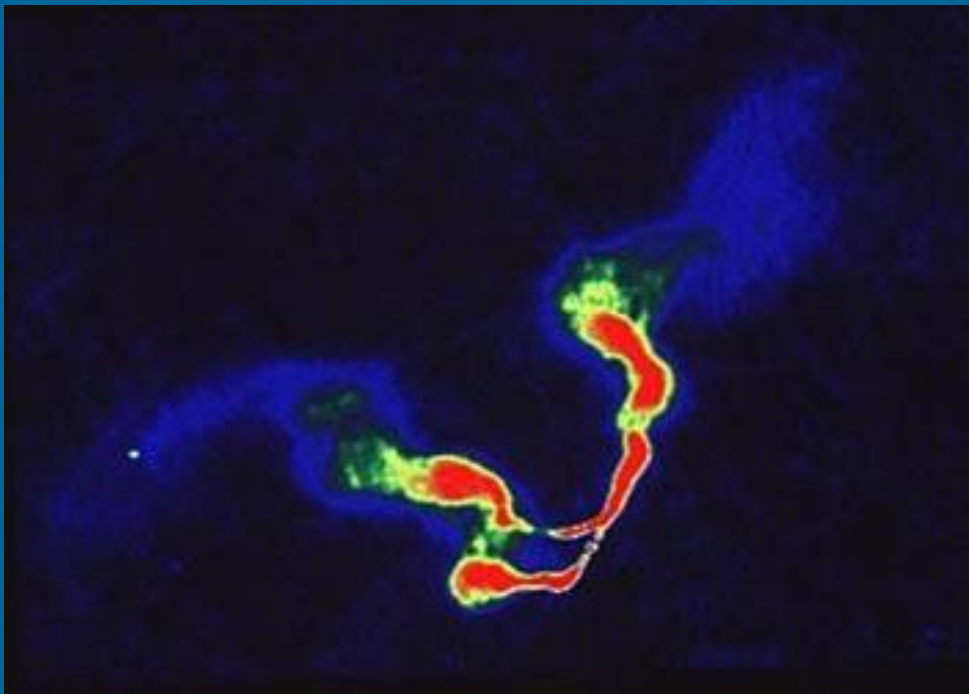


Galaxy 0402+379

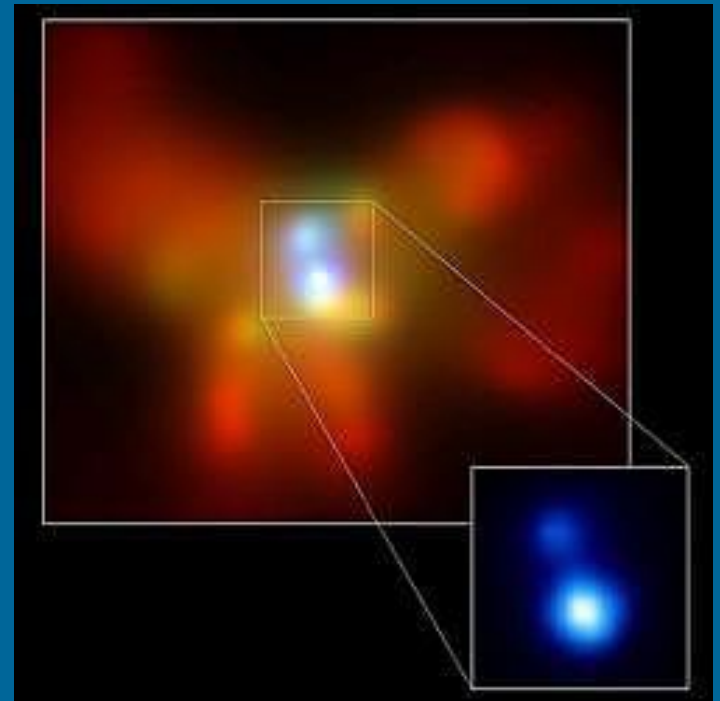
Total mass: $1.5 \cdot 10^8 M_{\odot}$

Distance between
two BHs is 7.3 pc.

Examples of binary SMBHs



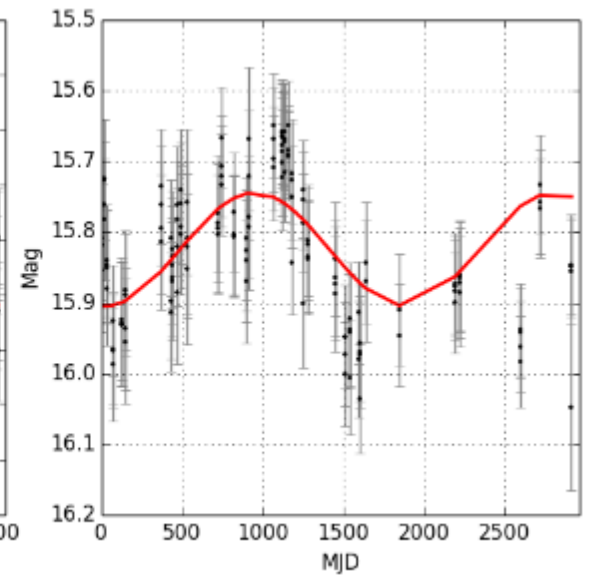
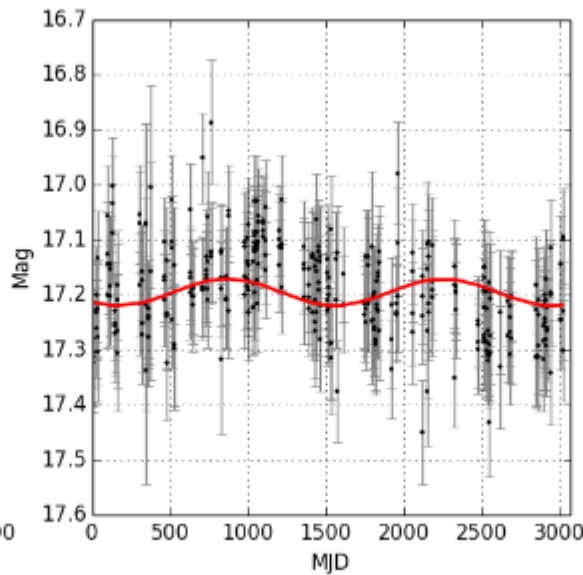
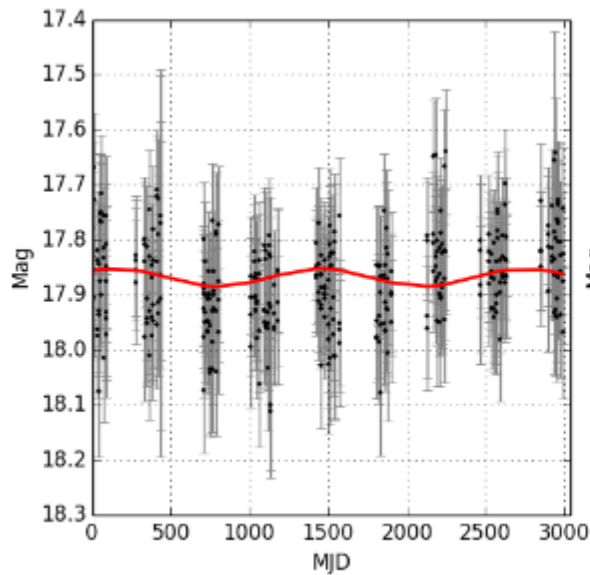
3C75



Abell 400

Search for more binaries

Search for periodicities in AGN light curves.
Dozens of candidates.

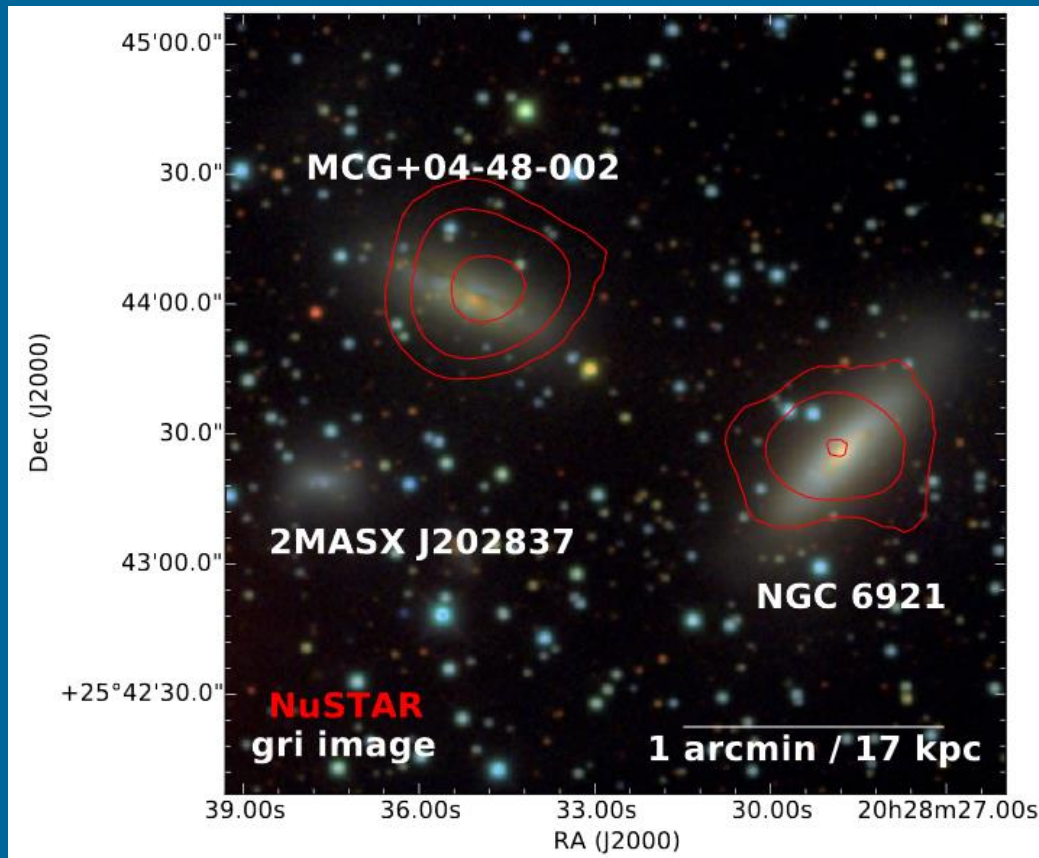


Dual AGN observed by NuStar

SWIFT J2028.5+2543

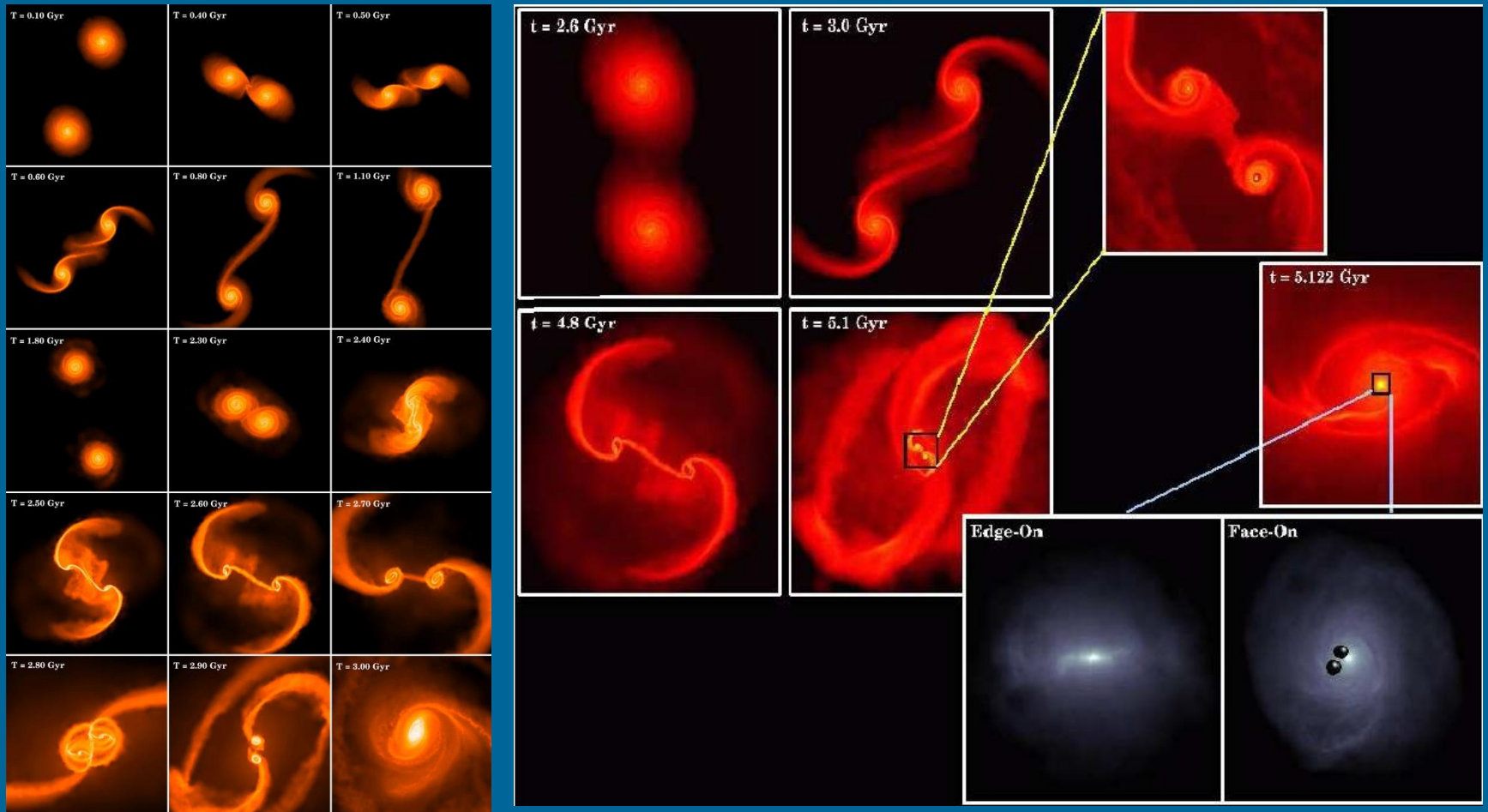
NGC 6921 and MCG+04-48-00

First observations at $E > 10$ keV

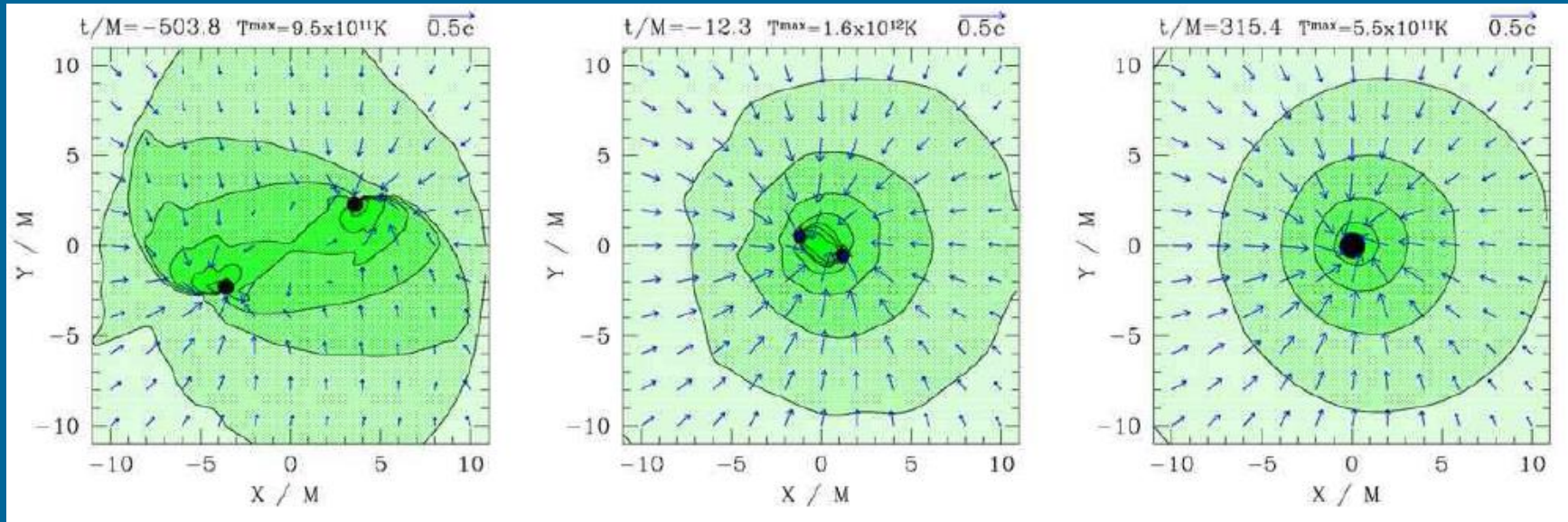


Galaxy merger
triggers AGN activity.
Separation ~ 25 kpc
 4×10^8 and $7 \times 10^7 M_{\text{solar}}$

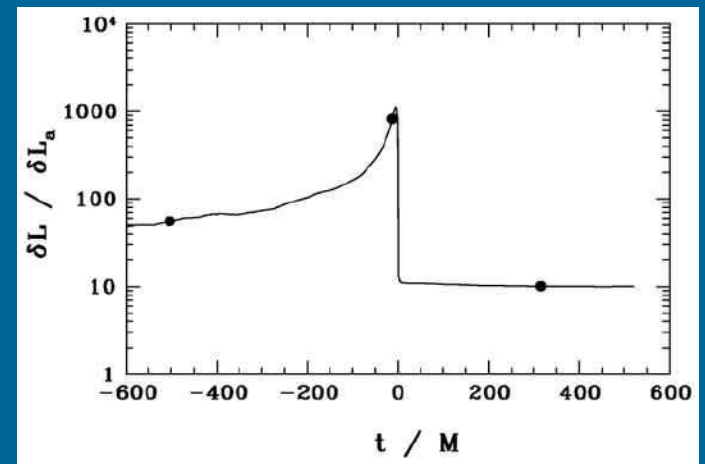
Merging of galaxies with BHs



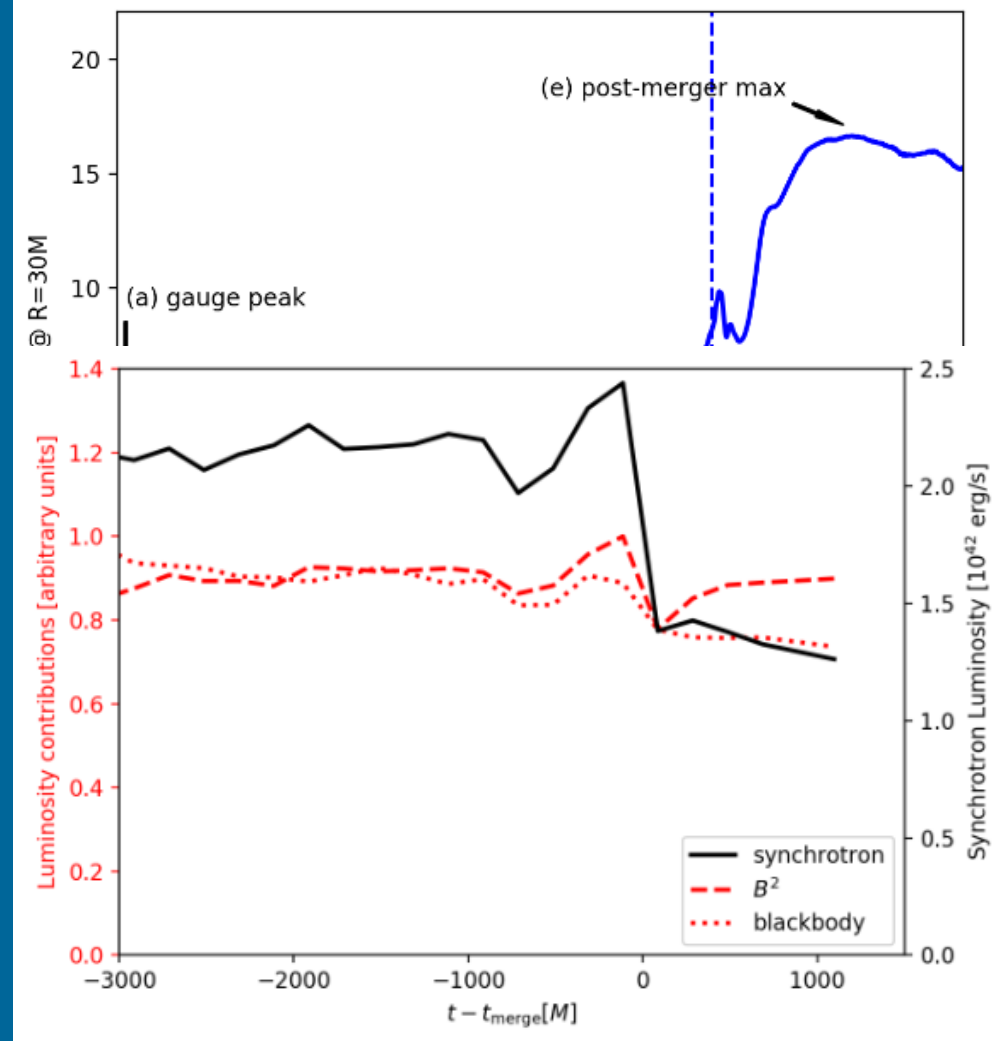
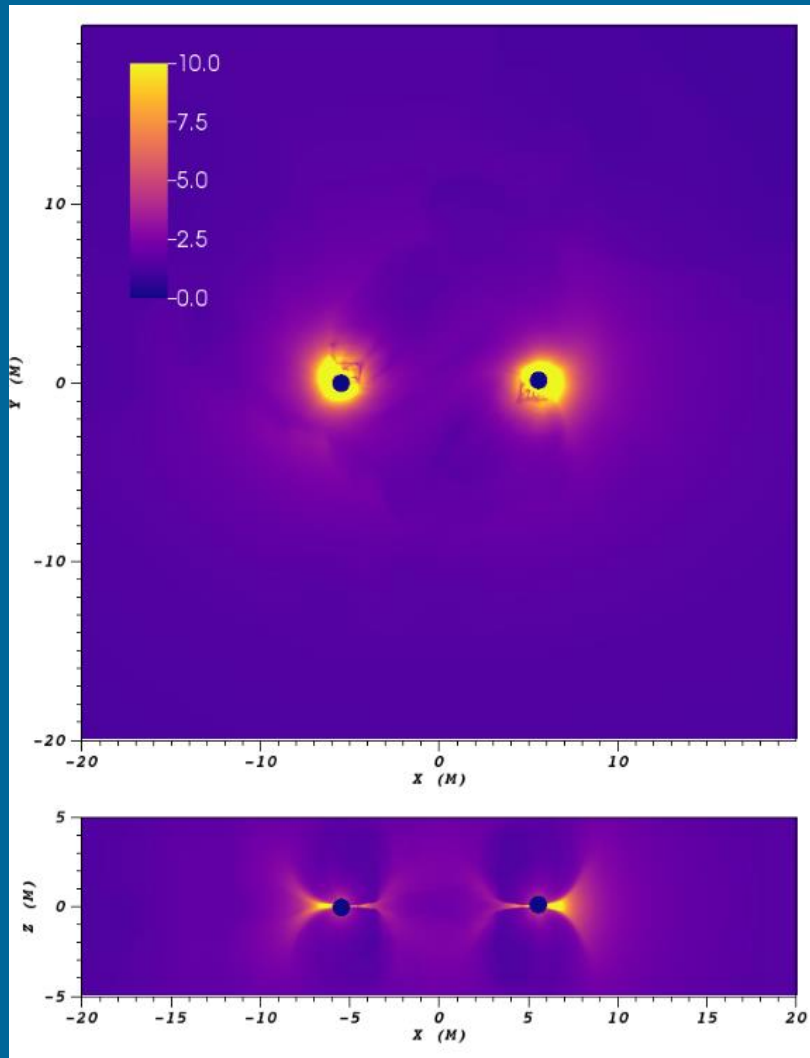
EM signal during coalescence



For $M=10^6$ solar mass binary in $n=10 \text{ cm}^{-3}$ gas
 $\Delta L \sim 3 \cdot 10^{43} \text{ erg/s}$
Detectable by LSST from $z \sim 1$



Electromagnetic signals



1710.02132, see new calculations in 1806.05697

Coalescence of BHs in binary systems

Unfortunately, at the moment we do not know any systems with two compact objects, one of which is a BH.

It is very difficult to identify a system with two BHs. However, models of the stellar evolution show, that such systems are quite natural result of binary evolution.

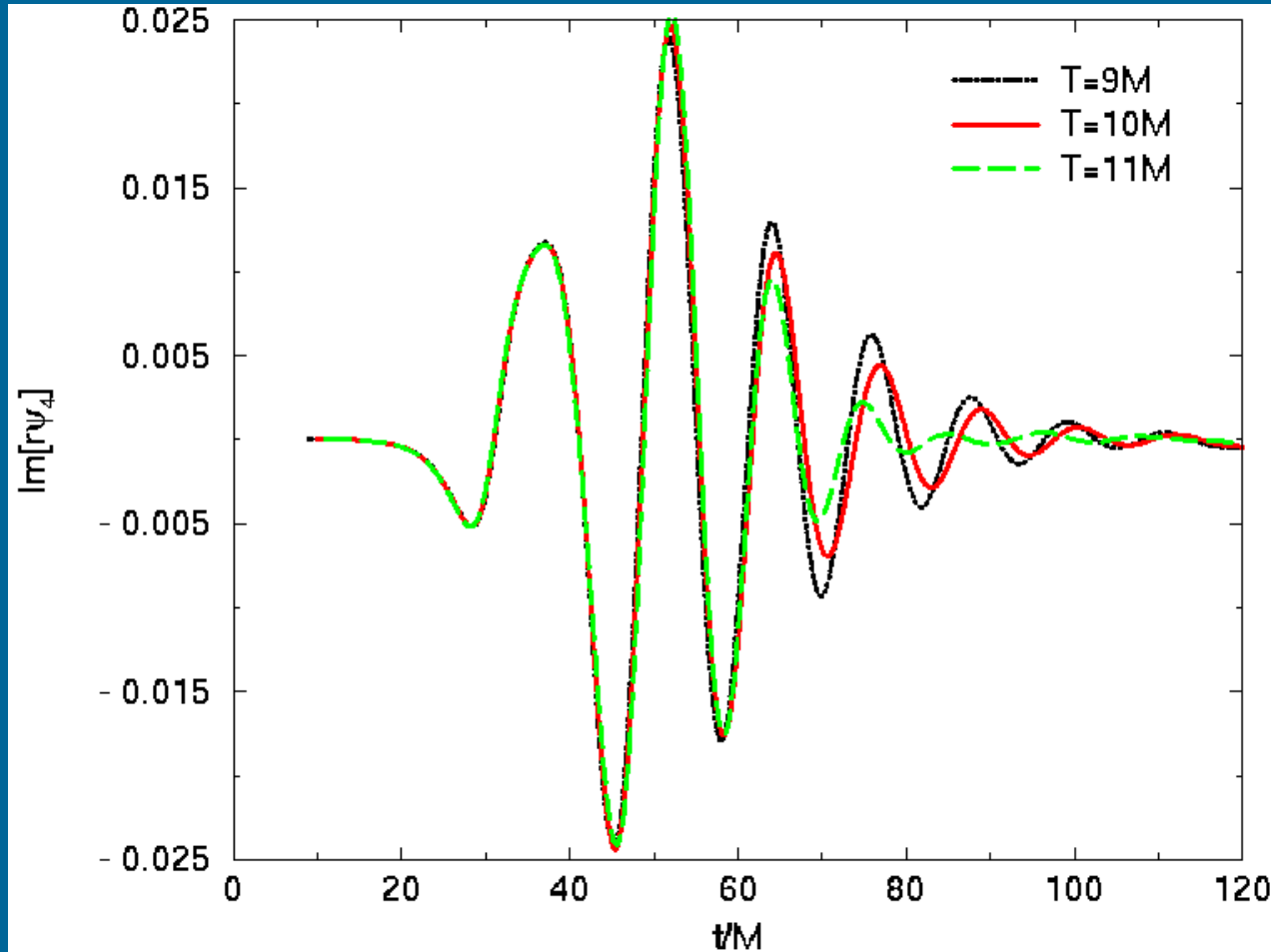
Also, systems BH+NS can exist.

Calculations show that systems BH+PSR should be relatively abundant (one system per several thousand PSRs).

On one hand, systems with BHs are more rare than NS+NS systems, on the other hand, due to larger masses GW signal is much more powerful. So, coalescence of BHs can be observed from much larger distances. Probably, the first events to be registered by GW detectors like VIRGO and LIGO are coalescence in NS+BH systems.
(see, for example, Lipunov et al. 1996 <http://xray.sai.msu.ru/~mystery/articles/review/>)

See 1010.5260 for a review of BH-BH coalescence physics

Last orbits of BHs



It is important to calculate in advance so-called waveforms.

Otherwise, it is very difficult to identify the signal.

Waveforms in the case of BH coalescence should be different from NS+NS coalescence.

[astro-ph/0305287](https://arxiv.org/abs/astro-ph/0305287)

See 1010.5260 for a review

Fall-down of matter onto a BH and GW emission

Accretion of a Quadrupolar Dust Shell onto a
Schwarzschild Black Hole and Emission of
Gravitational Radiation

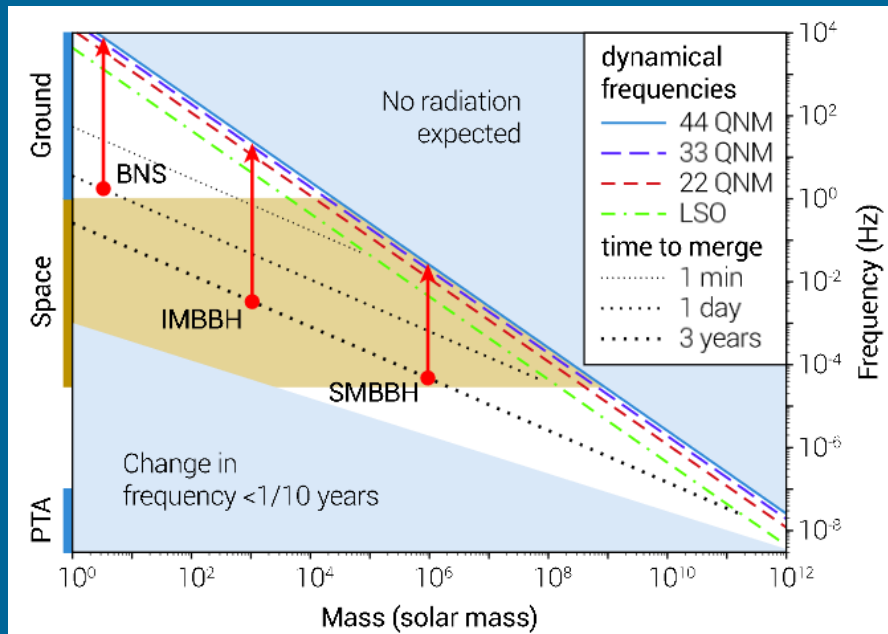
Left: density evolution Right: waveform
Final time: 350M

Authors: Philippos Papadopoulos & Jose A. Font
Reference: Physical Review D, 1999, 59, 044014

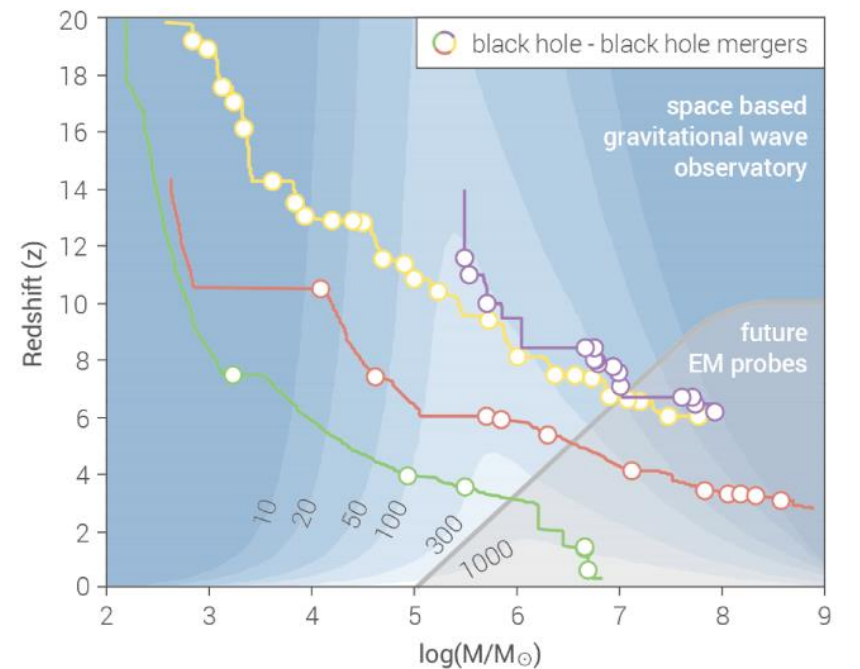
See also [gr-qc/0306082](https://arxiv.org/abs/gr-qc/0306082) **An Effective Search Method for
Gravitational Ringing of Black Holes**

In this paper the authors calculated a family of waveforms
for effective search for gravitational ringing of BHs.

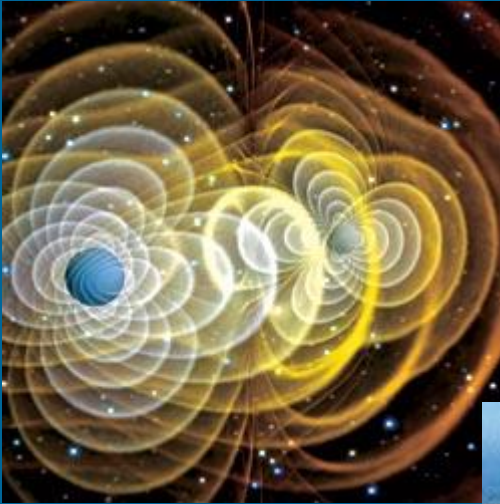
Frequency ranges and instruments



Blue (massive seed) and yellow (PopIII seed):
BH powering a $z \approx 6$ quasar.
Red: typical elliptical.
Green: Milky way-like



Registration of GW



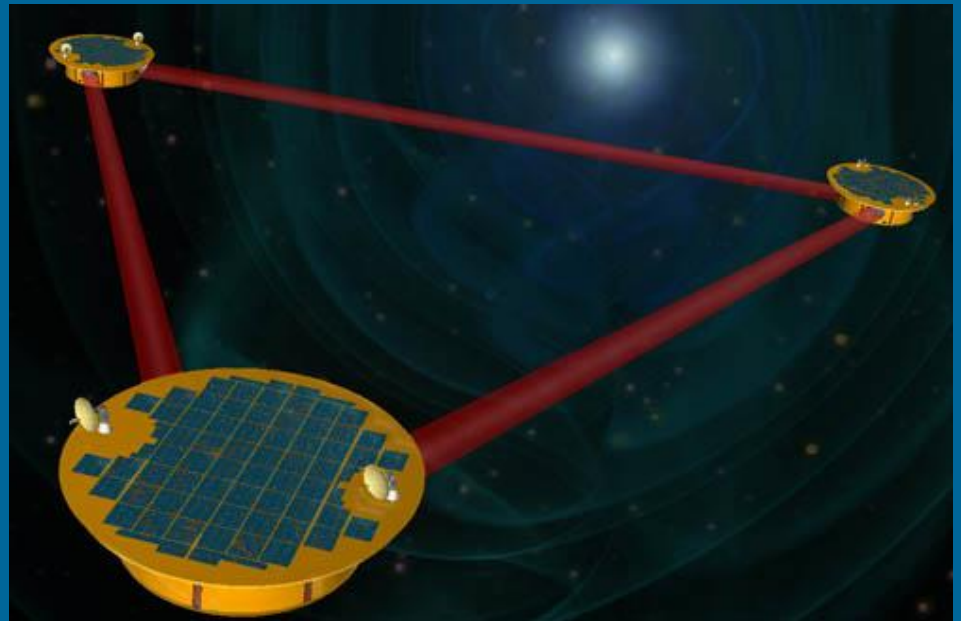
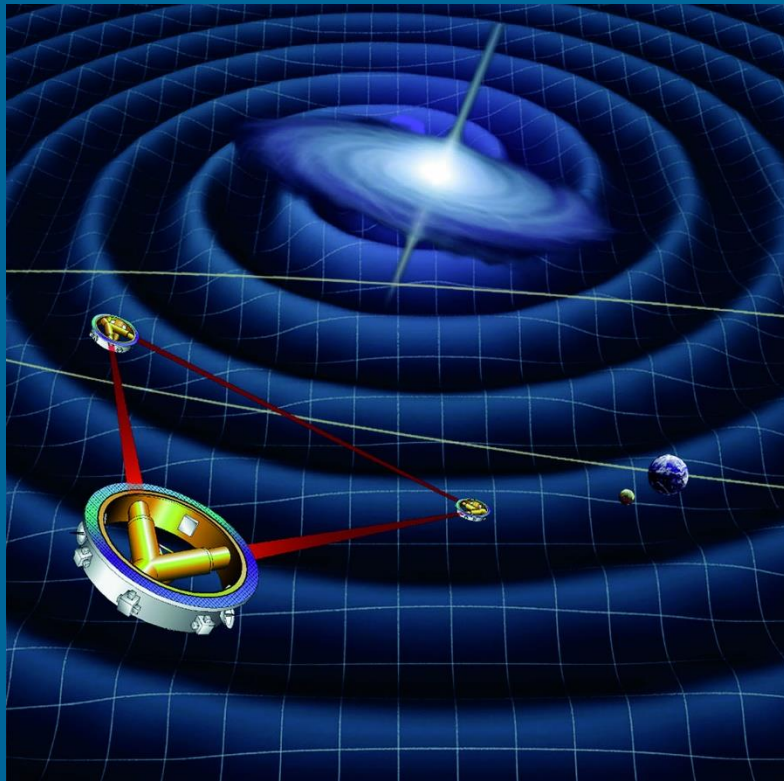
Since 2015 LIGO and VIRGO detect signals from coalescing compact objects.

See <https://gracedb.ligo.org/>
<https://stellarcollapse.org/>



VIRGO

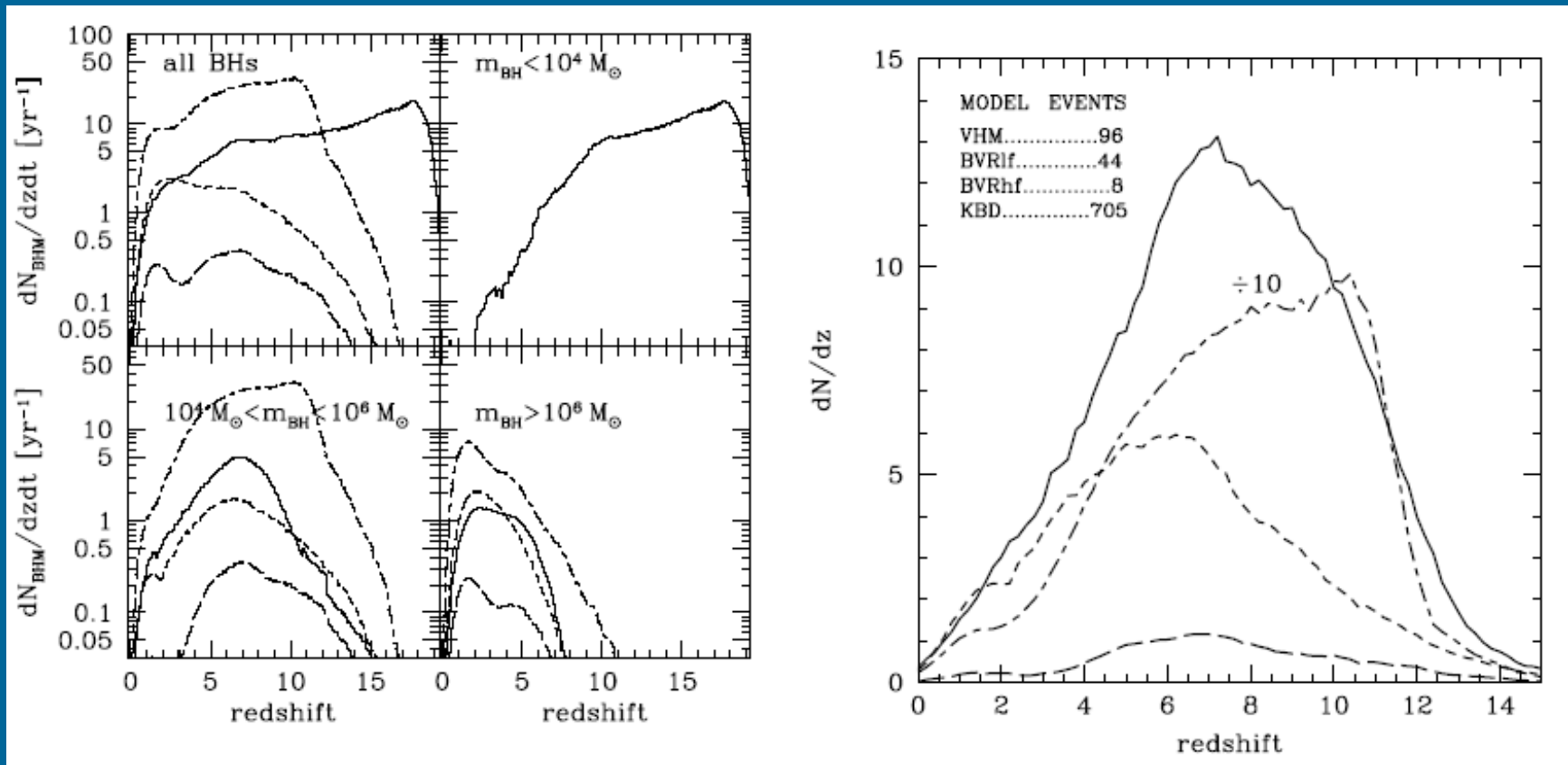
Космический проект LISA



NASA сняла свое финансирование.
Европа в начале не одобрила
даже сокращенный вариант.
Но теперь он поддержан: >2032 г.
Правда, в урезанном виде



Coalescence rate and background



Calculations made aiming to fit the sensitivity of the original LISA proposal. The authors predicted LISA detection rates spanning two order of magnitude, in the range 3-300 events per year, depending on the detail of the assumed massive black hole seed model

0810.5554

Main conclusions

- The first massive BHs are formed from the first massive stars at redshifts >15 in minihalos with masses about $10^6 M_{\odot}$.
- Halos (and BHs inside them) coalesce with each other in the process of hierarchical merging.
- Mass growth of BHs is due to accretion and coalescence.
- Already at $z>6$ there are SMBHs with masses $\sim 10^9 M_{\odot}$.
- The GW rocket effect is important, especially early in the merging history, as at that time potentials were not so deep.
- Observations of GW signals are possible with detectors like VIRGO and LIGO (for stellar mass objects), and with LISA (in the case of SMBHs).

Jets, tidal disruption and lenses

Plan and reviews

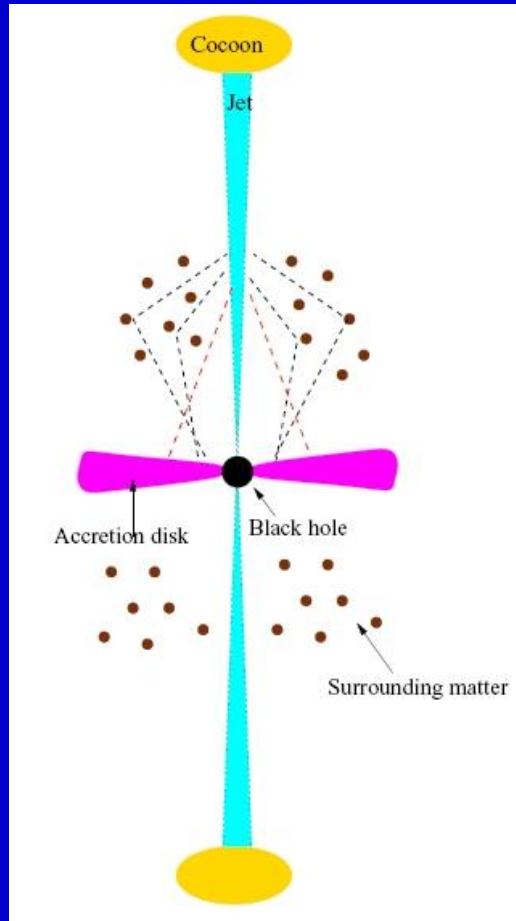
Plan

1. Jets: AGNs and close binary systems
2. Tidal disruption of stars by SMBHs
3. Spectral lines and lensing

Reviews

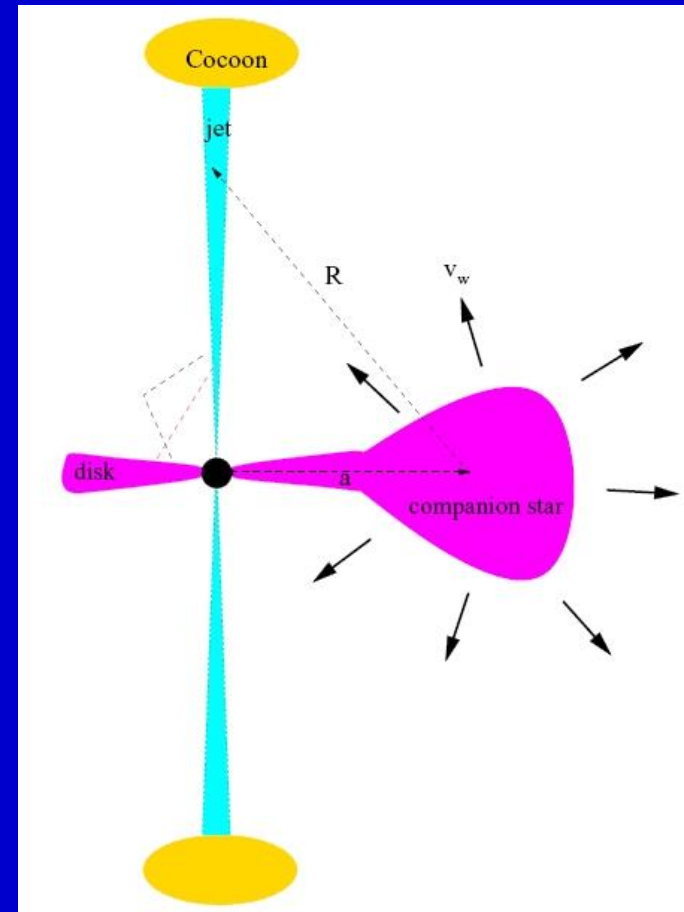
- [astro-ph/0611521](#) **High-Energy Aspects of Astrophysical Jets**
- [astro-ph/0306429](#) **Extreme blazars**
- [astro-ph/0312545](#) **AGN Unification: An Update**
- [astro-ph/0212065](#) **Fluorescent iron lines as a probe of astrophysical black hole systems**
- [arXiv: 1104.0006](#) **AGN jets**
- [astro-ph/0406319](#) **Astrophysical Jets and Outflows**
- [arXiv: 1309.4772](#) **Blazars: jets and discs**
- [arXiv: 1707.07134](#) **AGNs of different types**

Jets in AGNs and close binaries



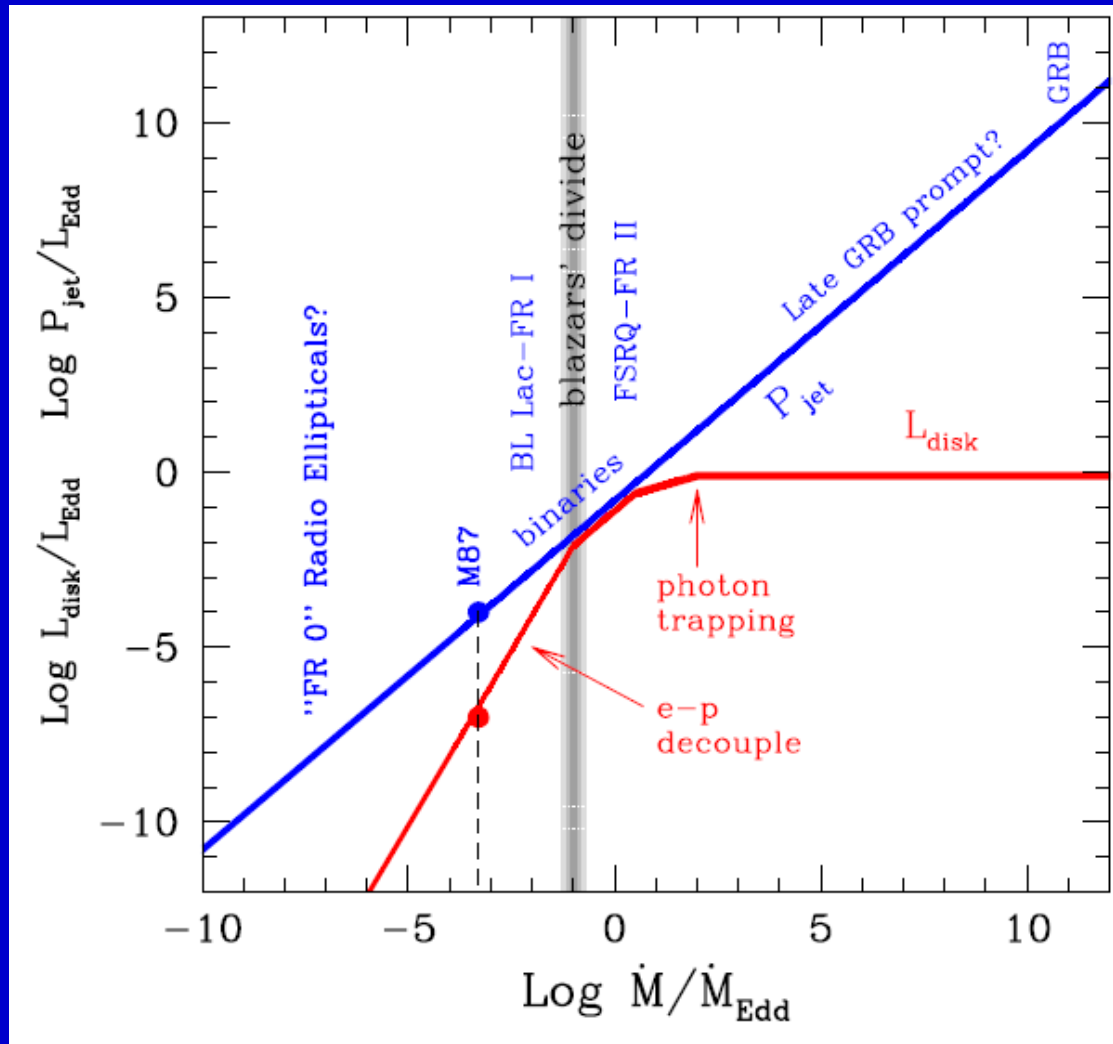
AGN: $M_{\text{BH}} = 10^8 - 10^9 M_{\odot}$
 $L < \sim L_{\text{Edd}} \sim 10^{42} - 10^{47} \text{ erg/s}$
< few Mpc
 $\Gamma \sim 5 - 50$
 $\Delta t \sim \text{hours-years}$

CBS: $M_{\text{BH}} \sim 10 M_{\odot}$
 $L < \sim L_{\text{Edd}} \sim 10^{37} - 10^{40} \text{ erg/s}$
 $\sim \text{pc}$
 $\Gamma \sim 1 - 10$
 $\Delta t \sim \text{days}$



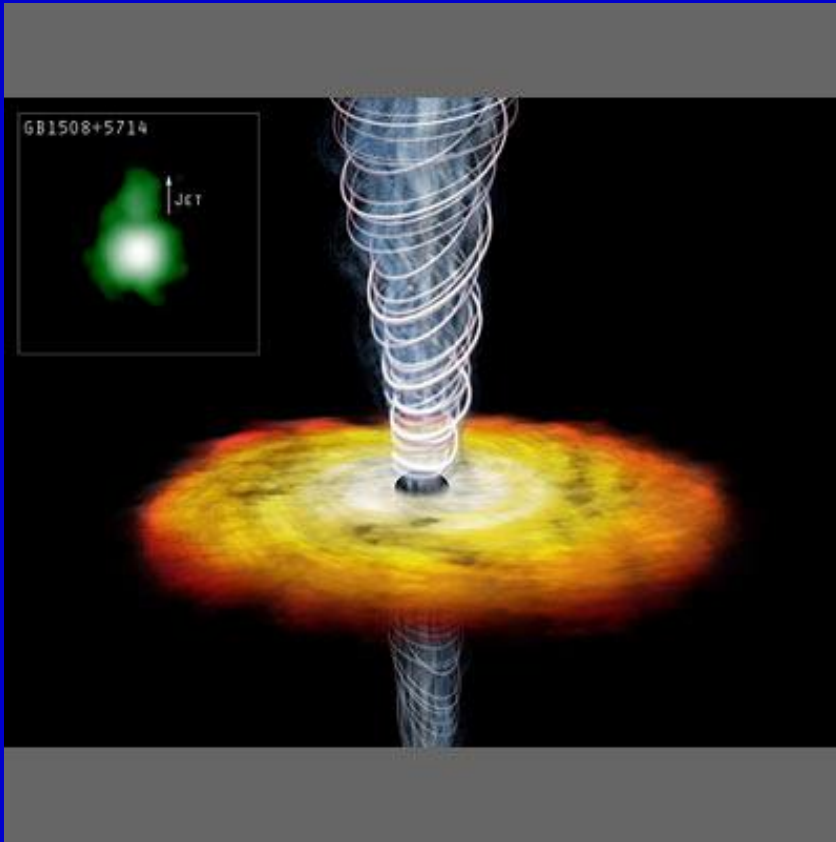
see astro-ph/0611521

All jets in one plot

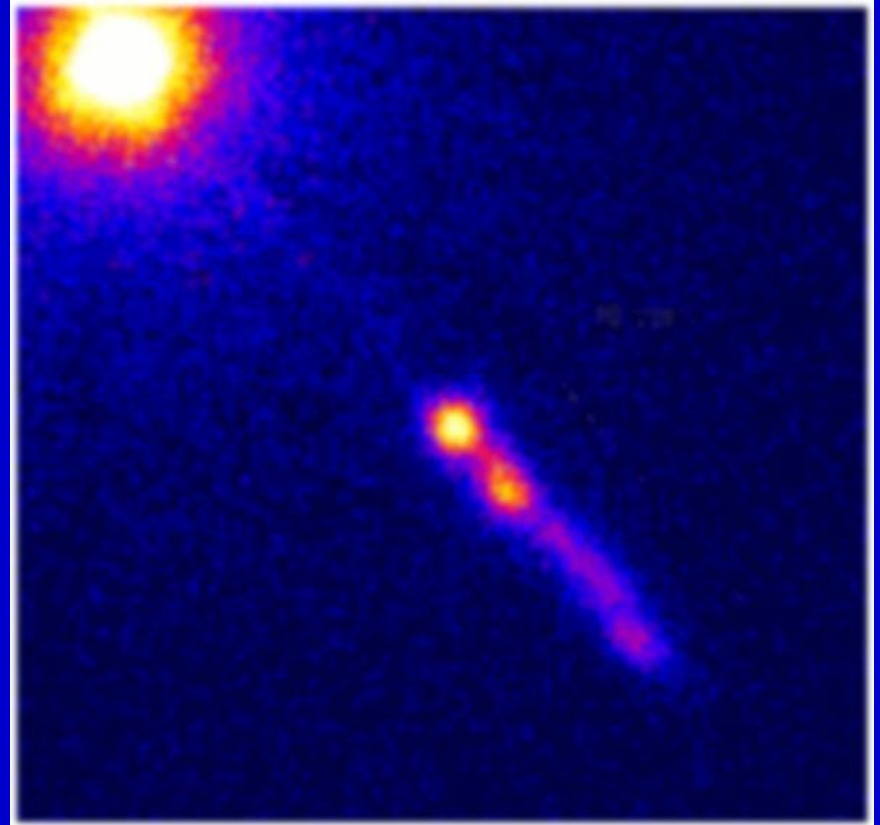


Close-by and far-away jets

1% of SMBH are active. 10% out of them launch relativistic jets.
Jets are not magnetically dominated.



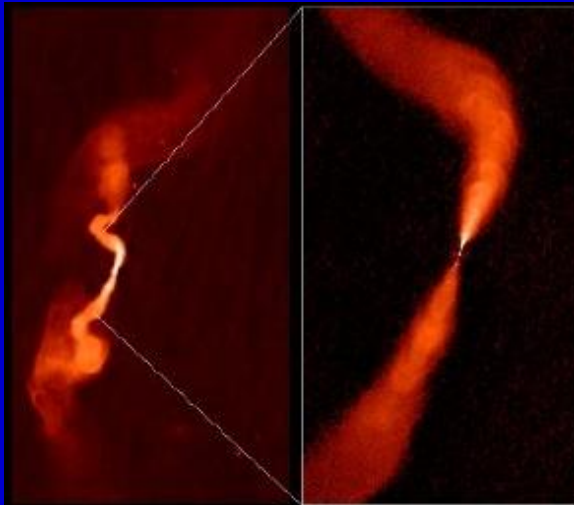
GB1508+5714 $z=4.30$



3C273

See a review in 1104.0006

Classification of AGN radio jets

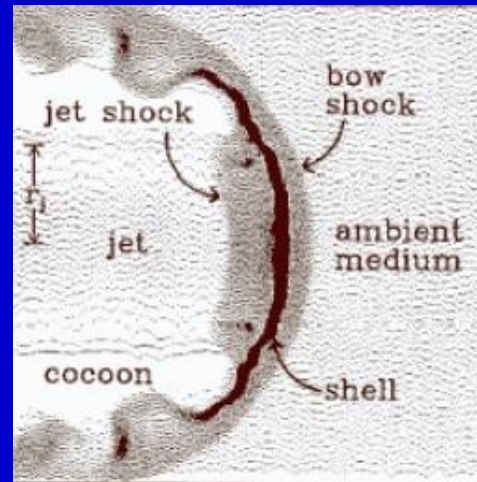


FR Class I source: radio galaxy 3C31



FR Class II source: quasar 3C175

FR I. Two-sided jets.
Jets dominate in the emission.
Usually are found in rich clusters.

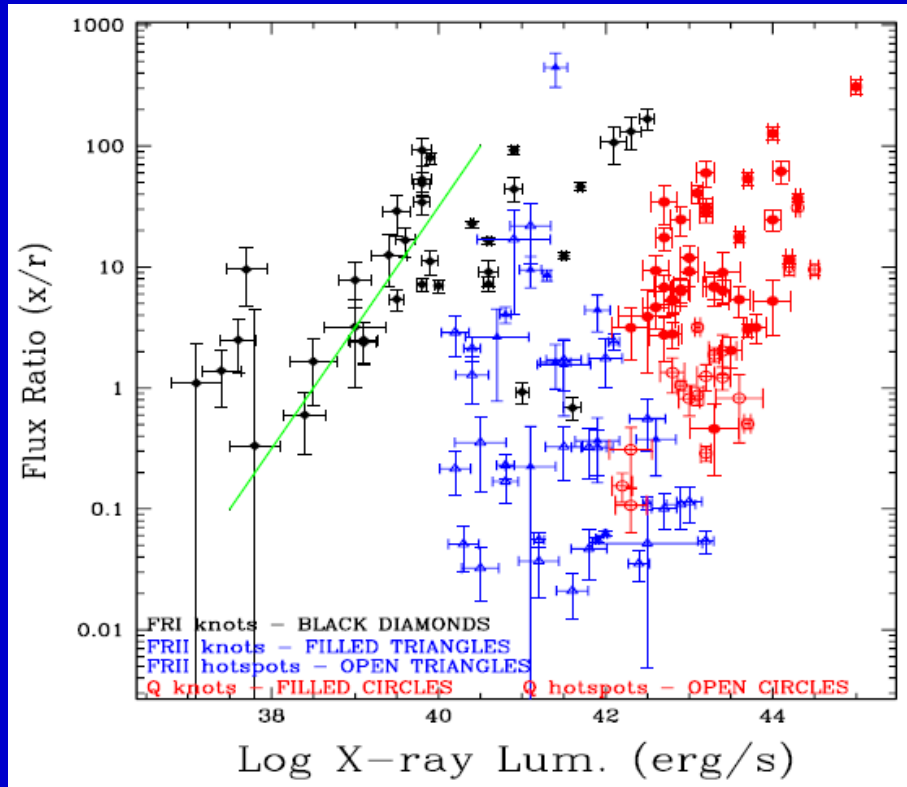


FR II. One-sided jets.
Radio lobes dominate over jets.
Mostly isolated galaxies
or poor groups.

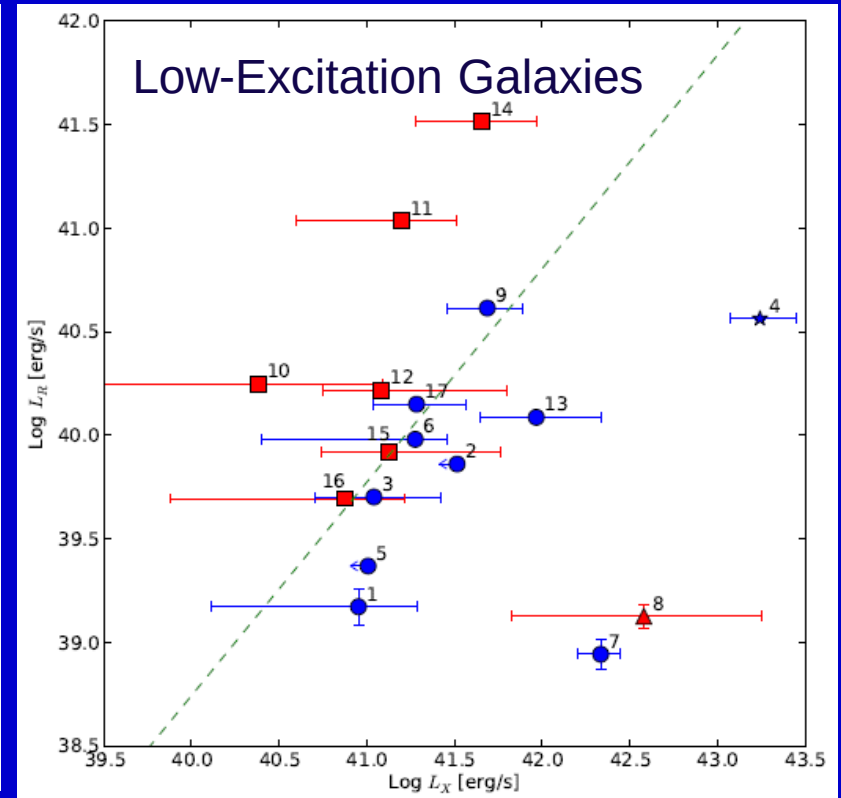
astro-ph/0406319

See a review on radio galaxies in arXiv: 1101.0837

X-ray and radio properties



1003.0976



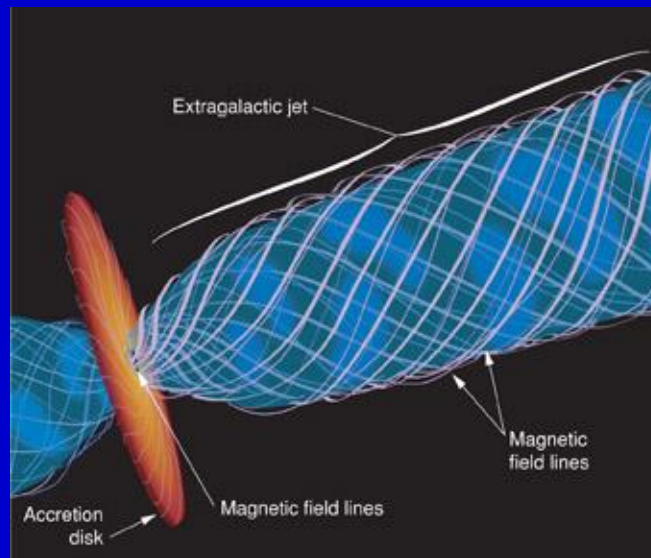
1104.3575

Magnetic field in a jet



Observations of M87 tell us that the magnetic field in the jet is mostly parallel to the jet axis, but in the emission regions (“knots”) it becomes perpendicular (see [astro-ph/0406319](https://arxiv.org/abs/astro-ph/0406319)).

The same structure is observed in several jets with radio lobes.

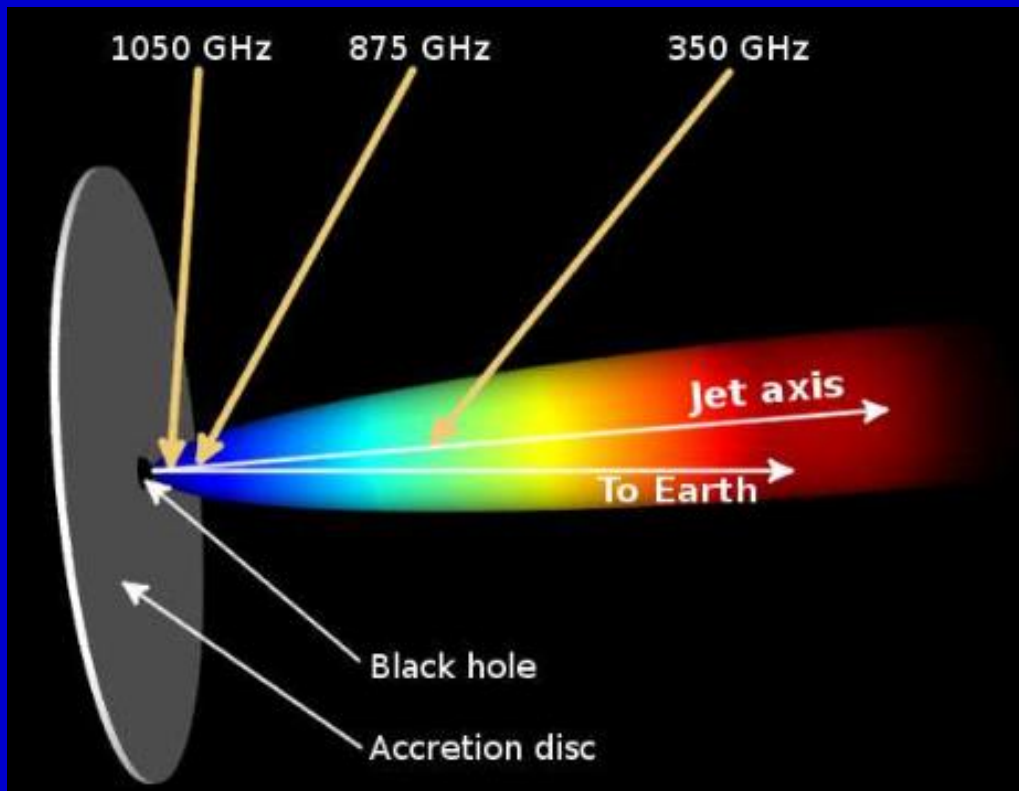


New RadioAstron data give some new insights.

Magnetic field in the jet

Due to modern high resolution observations new important results on the magnetic field in jets are obtained.

ALMA 0.01 pc scale

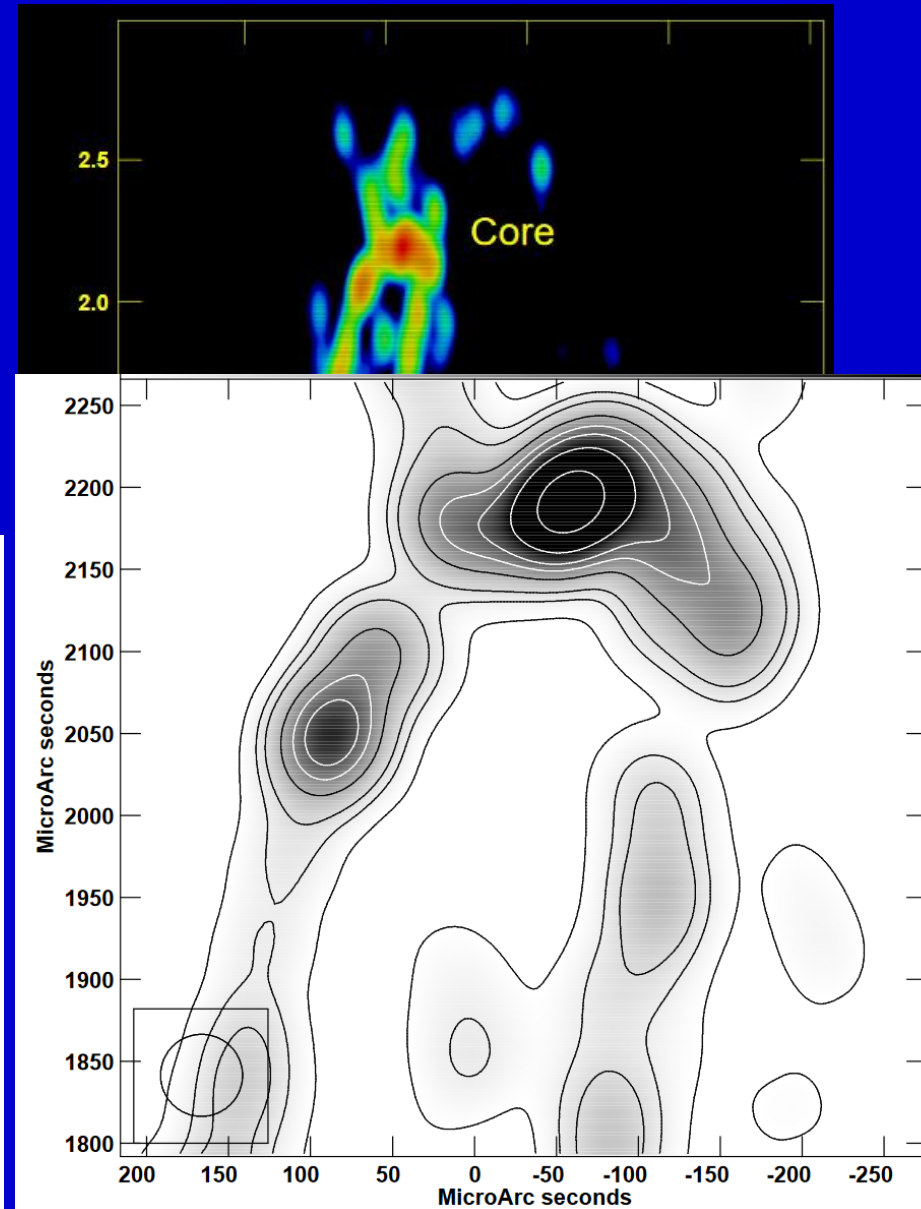
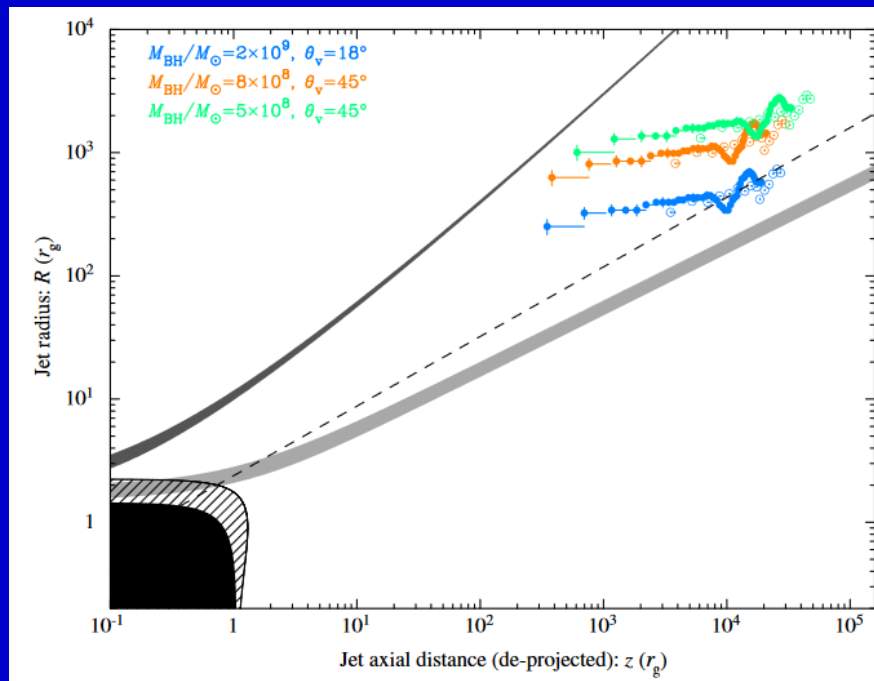


Magnetic fields of at least tens of Gauss (and possibly considerably higher) on scales of the order of light days (0.01 pc) from the black hole.

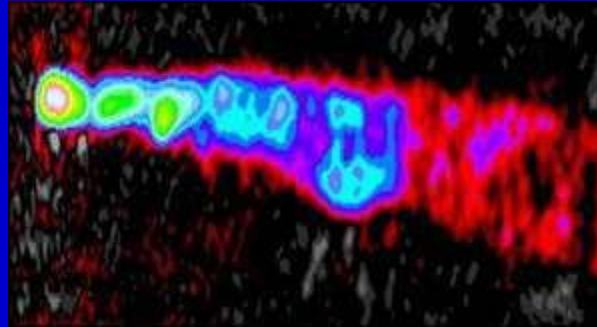
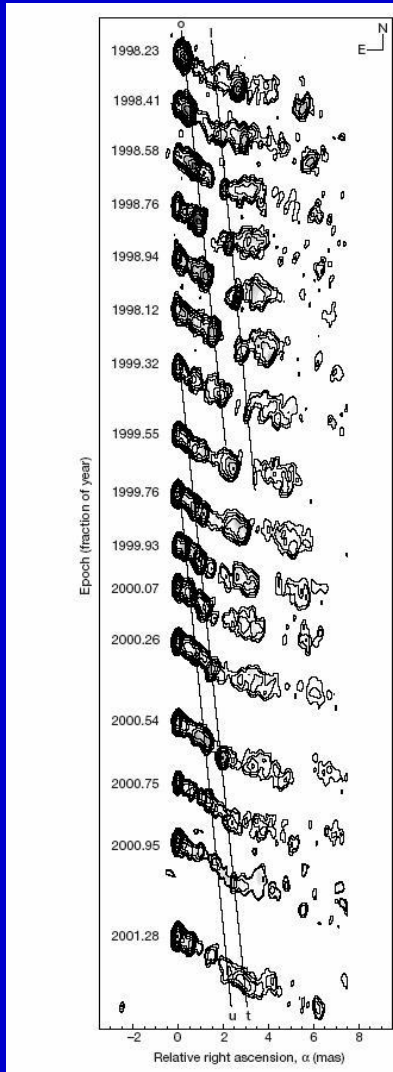
3C84 jet

Jet followed down to $>\sim 100 R_{\text{sh}}$
BH mass $\sim 2 \cdot 10^9$

Jet from the disc, not from ergosphere?



Blobs in jets

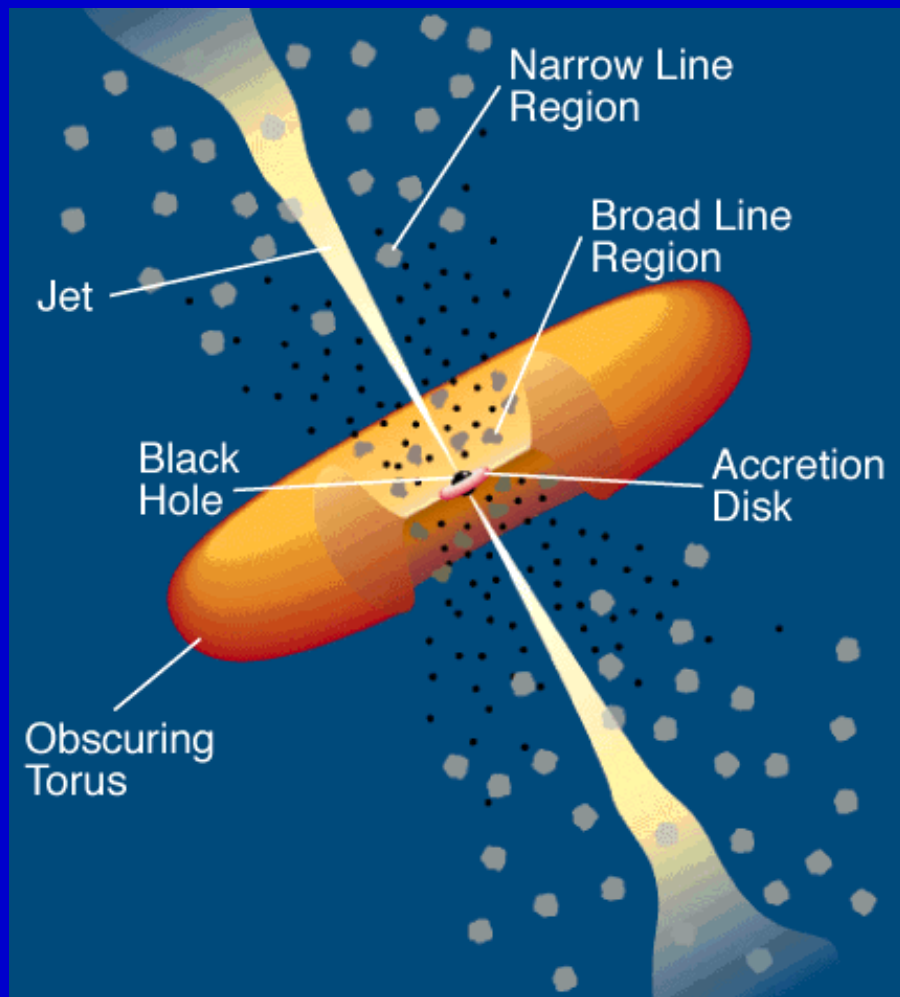


It is believed that bright features in AGN jets can be results of the Kelvin-Helmholtz instability. This instability leads to a spiral structure formation in a jet. (see, for example, astro-ph/0103379).

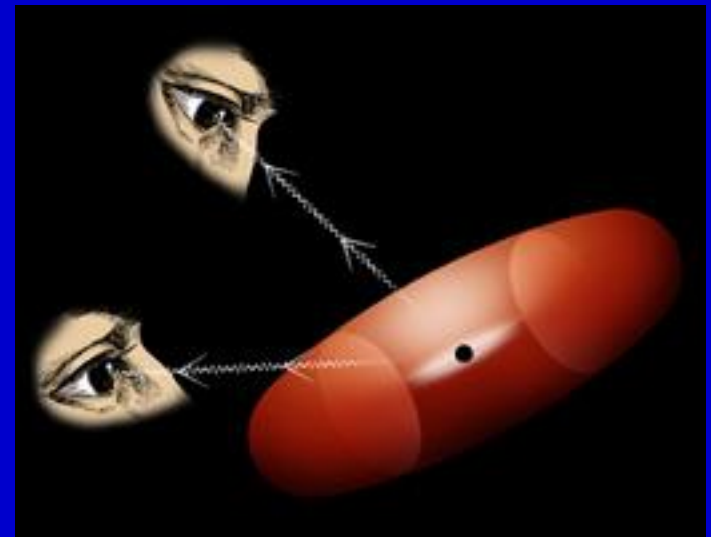
3C 120

However, in the case of 3C 120 the blobs appearance is due to processes in the disc. Dips in X-rays (related to the disc) appear before blobs ejection (Marscher et al. 2002).

Blazars



If a jet is pointing towards us, then we see a *blazar*.



Blazars at very high energies

Blazars are powerful gamma-ray sources. The most powerful of them have equivalent isotropic luminosity 10^{49} erg/s.

Collimation $\theta^2/2 \sim 10^{-2} - 10^{-3}$. θ – jet opening angle.

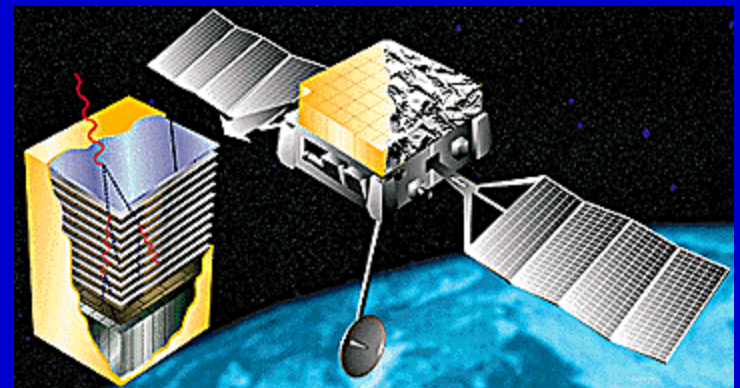
EGRET detected 66 (+27) sources of this type.

New breakthrough is expected after the launch of GLAST.

Several sources have been detected in the TeV range by ground-based gamma-ray telescopes. All of them, except M87, are BL Lacs at $z < 0.2$ (more precisely, to high-frequency-peaked BL Lac – HBL).

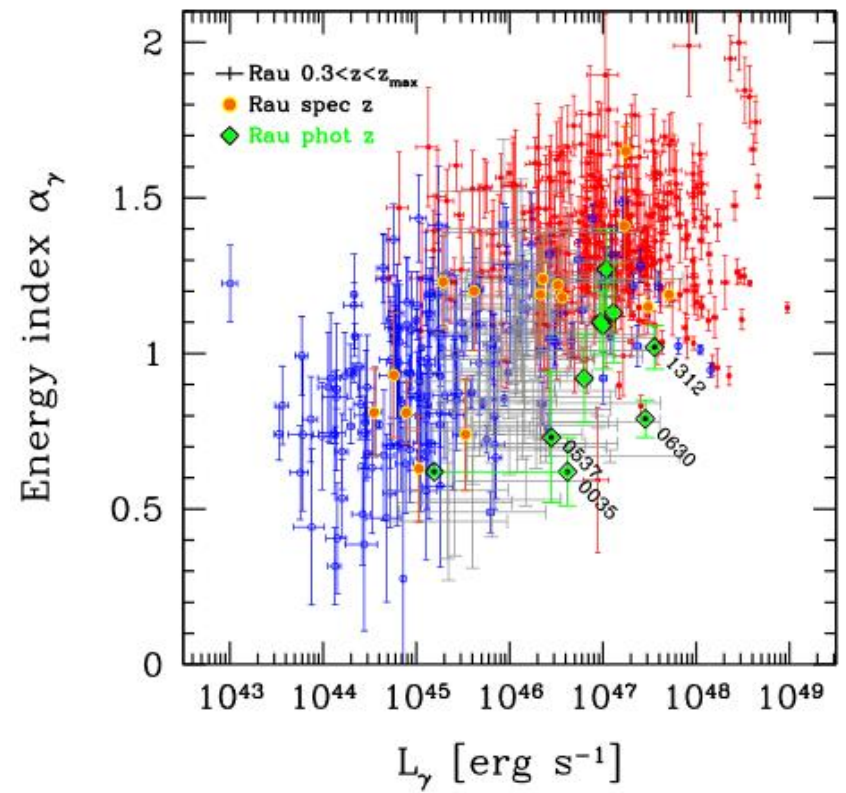
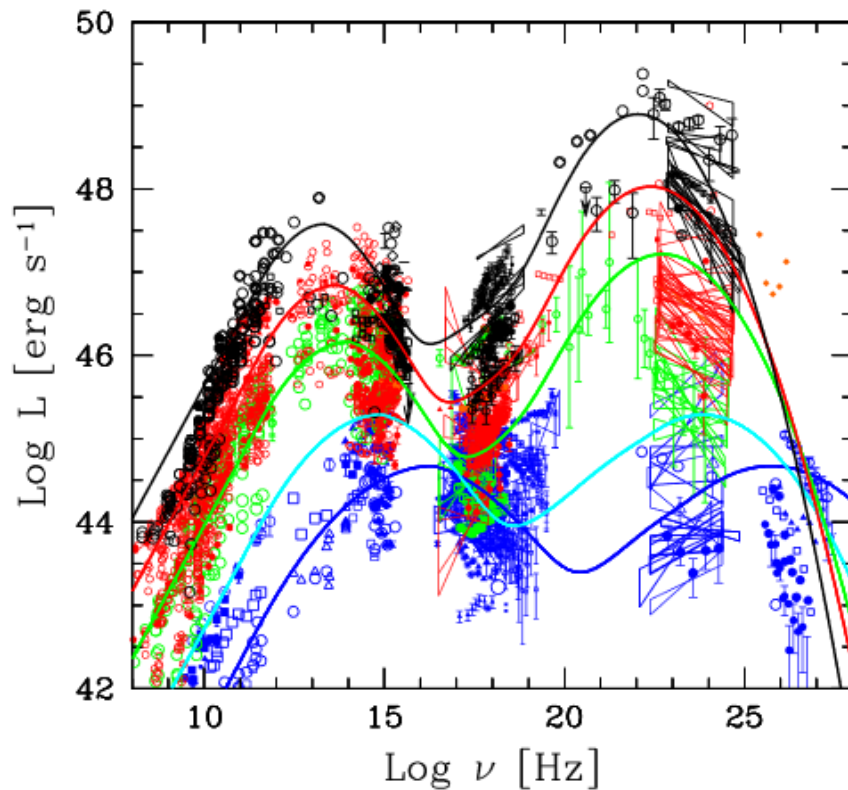
Observations show that often (but not always) after a gamma-ray bursts few weeks or months later a burst happens also in the radio band.

(see astro-ph/0611521)

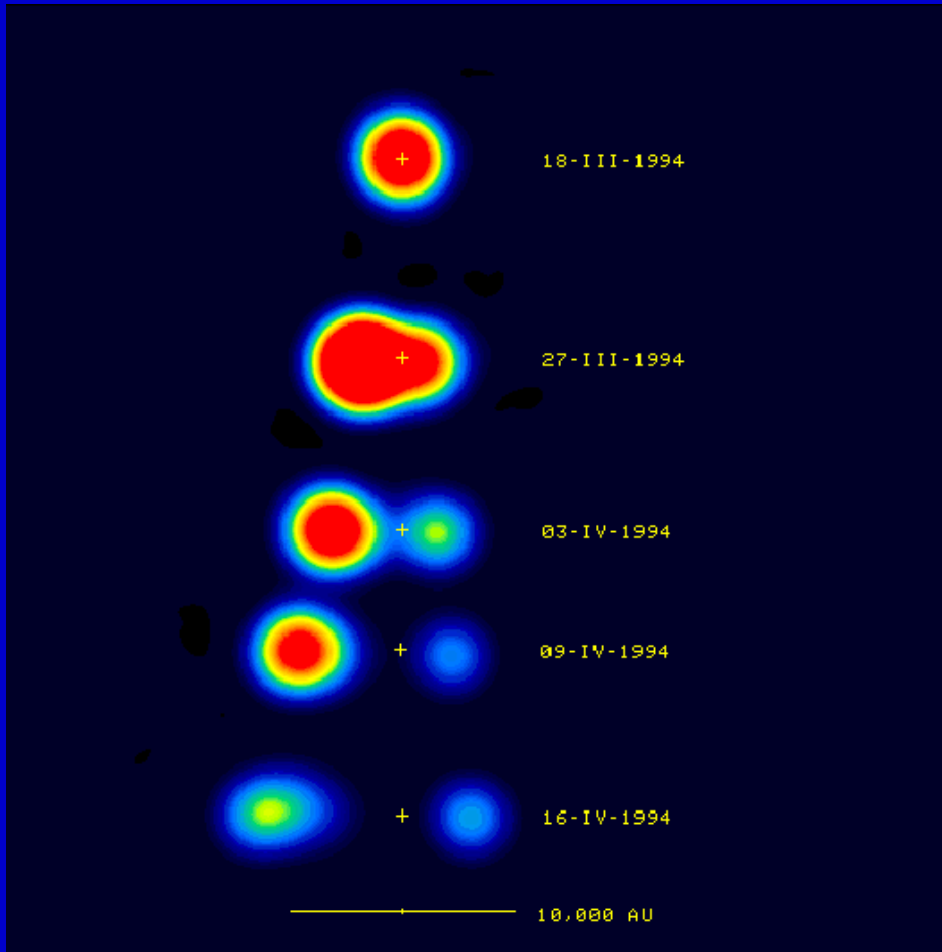


Fermi

Blazar spectra



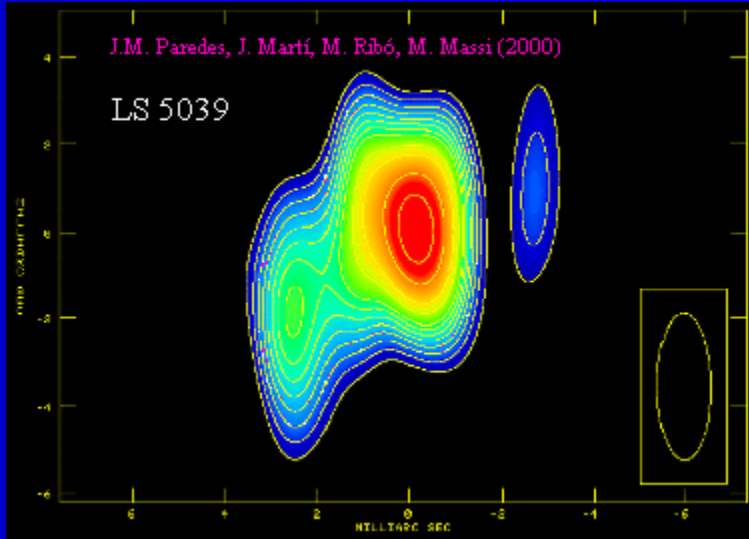
Microquasars



GRS 1915

The correlation between X-ray and synchrotron (i.e. between disc and jet emission) is observed.

Microquasars jets in radio



LS 5039/RX J1826.2-1450 –
is a galactic massive X-ray binary.

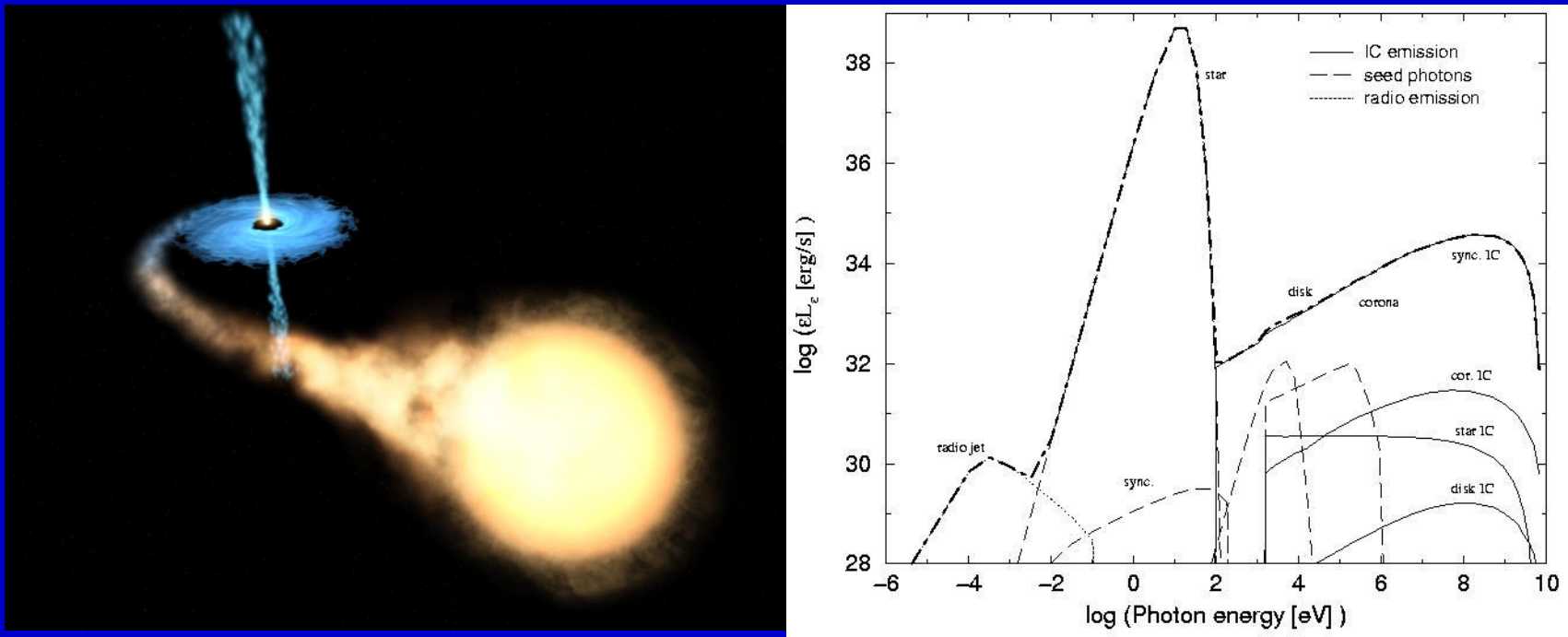
The jet length is ~ 1000 a.e.

Probably, the source was
observed by EGRET
as 3EG J1824-1514.

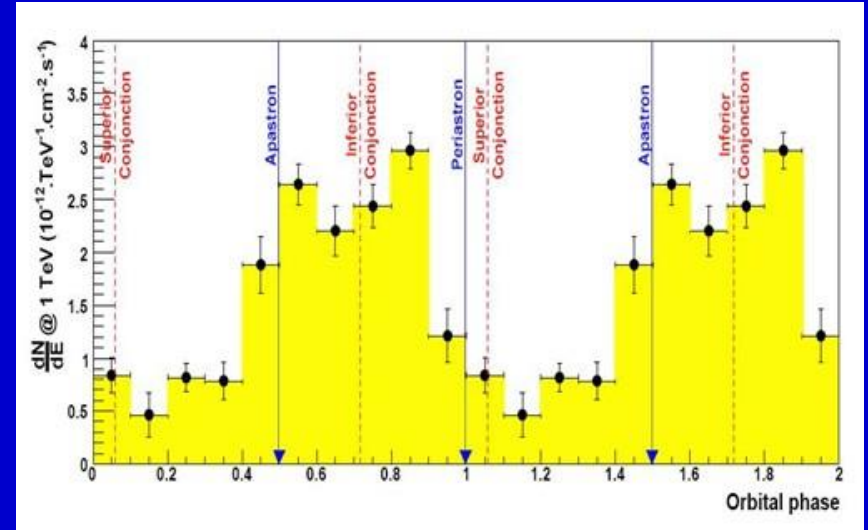
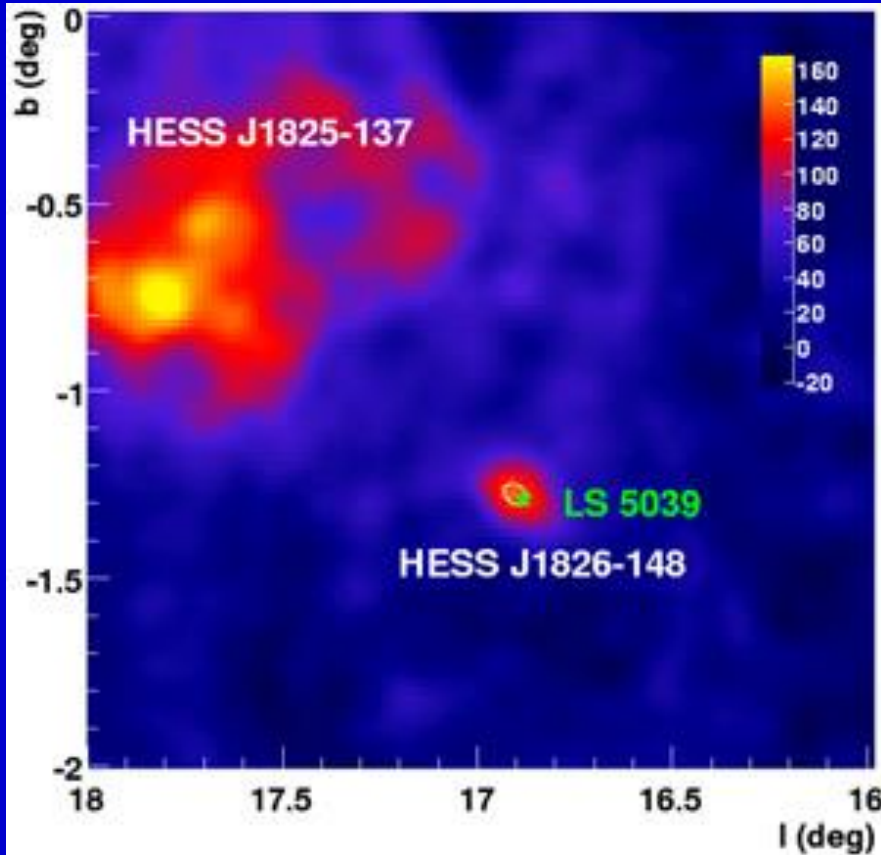
(Many examples of VLBI radio jets from different sources
can be found at the web-site <http://www.evlbi.org/gallery/images.html>)

The role of a donor

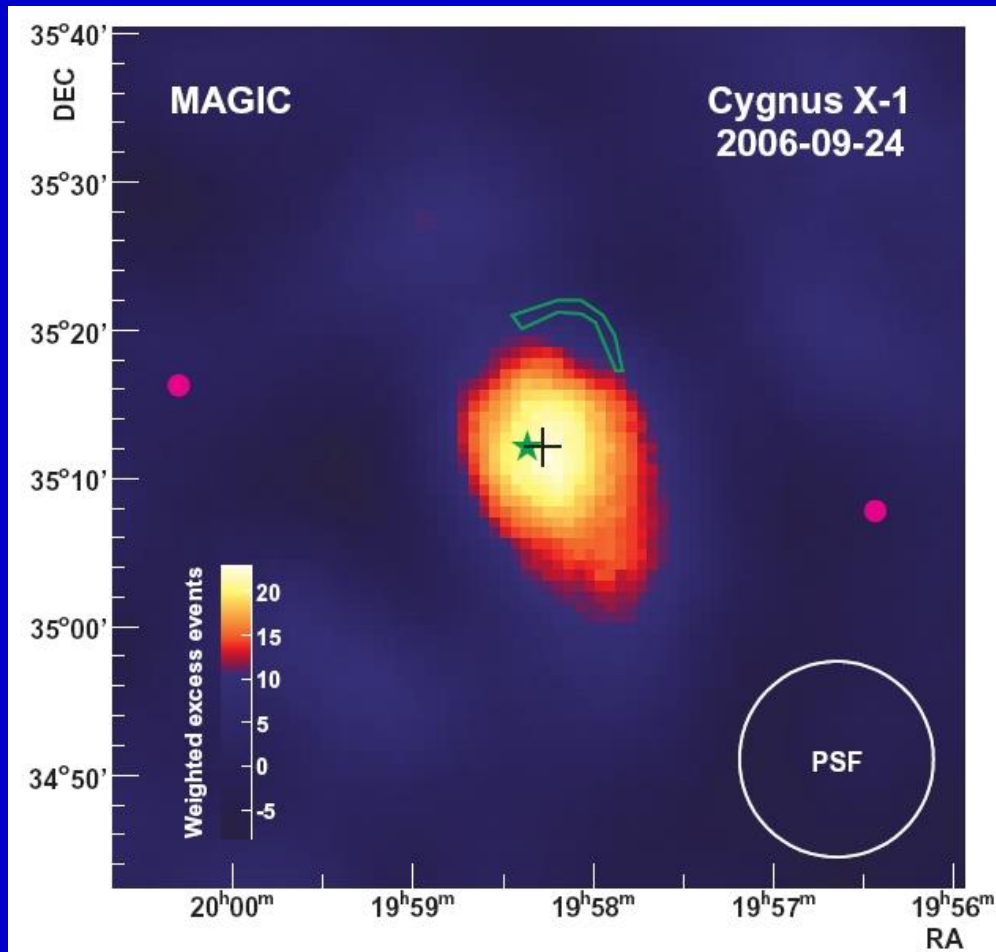
An important difference between the microquasars case and AGNs is related to the existence of a donor-star. Especially, if it is a giant, then the star can inject matter and photons into the jet.



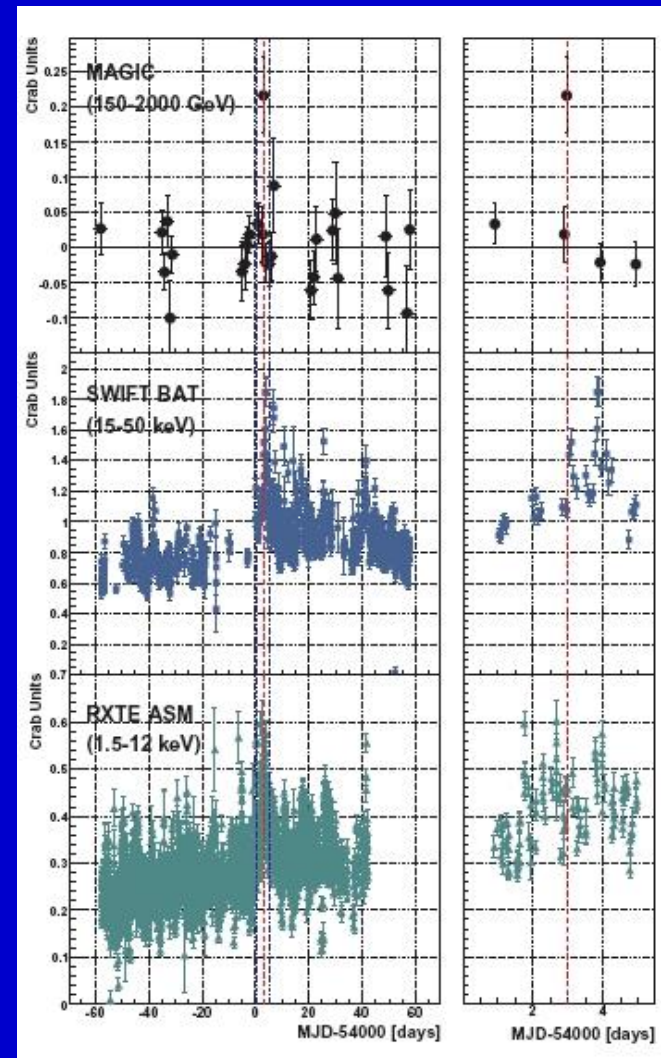
Microquasars in gamma-rays: TeV range



TeV emission from Cyg X-1



arxiv:0706.1505



See a review on jets in binaries in 1407.3674

Jet models

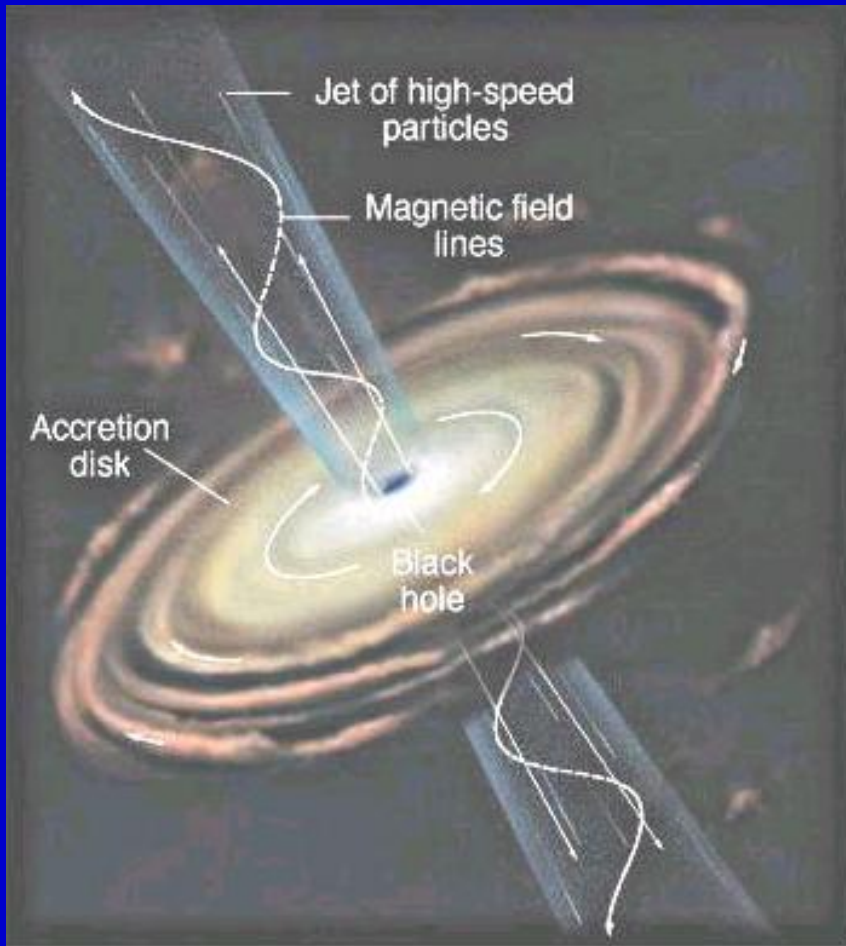


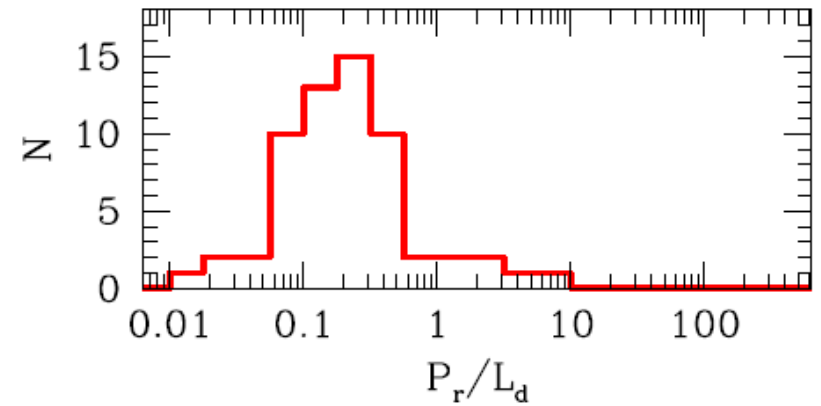
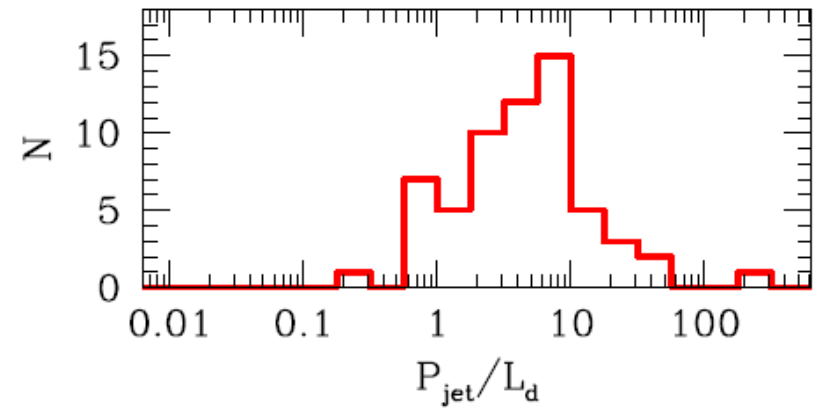
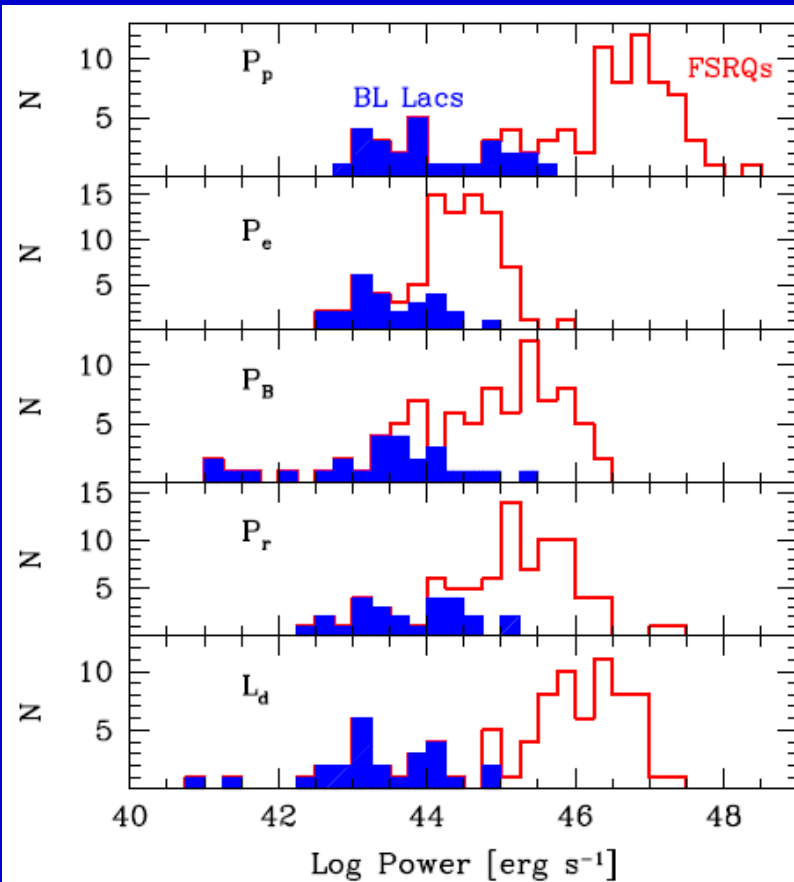
Table 1. Characteristic parameters of relativistic jet sources.

	L_j (erg/s)	Γ	Δt
GRB	10^{47} - 10^{50}	$10^2 - 10^3$	millisec - min.
AGN	10^{42} - 10^{47}	5 - 50	hours - years
MQ	10^{37} - 10^{40}	1 - 10	days
GF	10^{43} - 10^{46}	1	seconds

In all models jets are related to discs. Velocity at the base of a jet is about the parabolic (escape) velocity.

(the table is from astro-ph/0611521)

Jet power



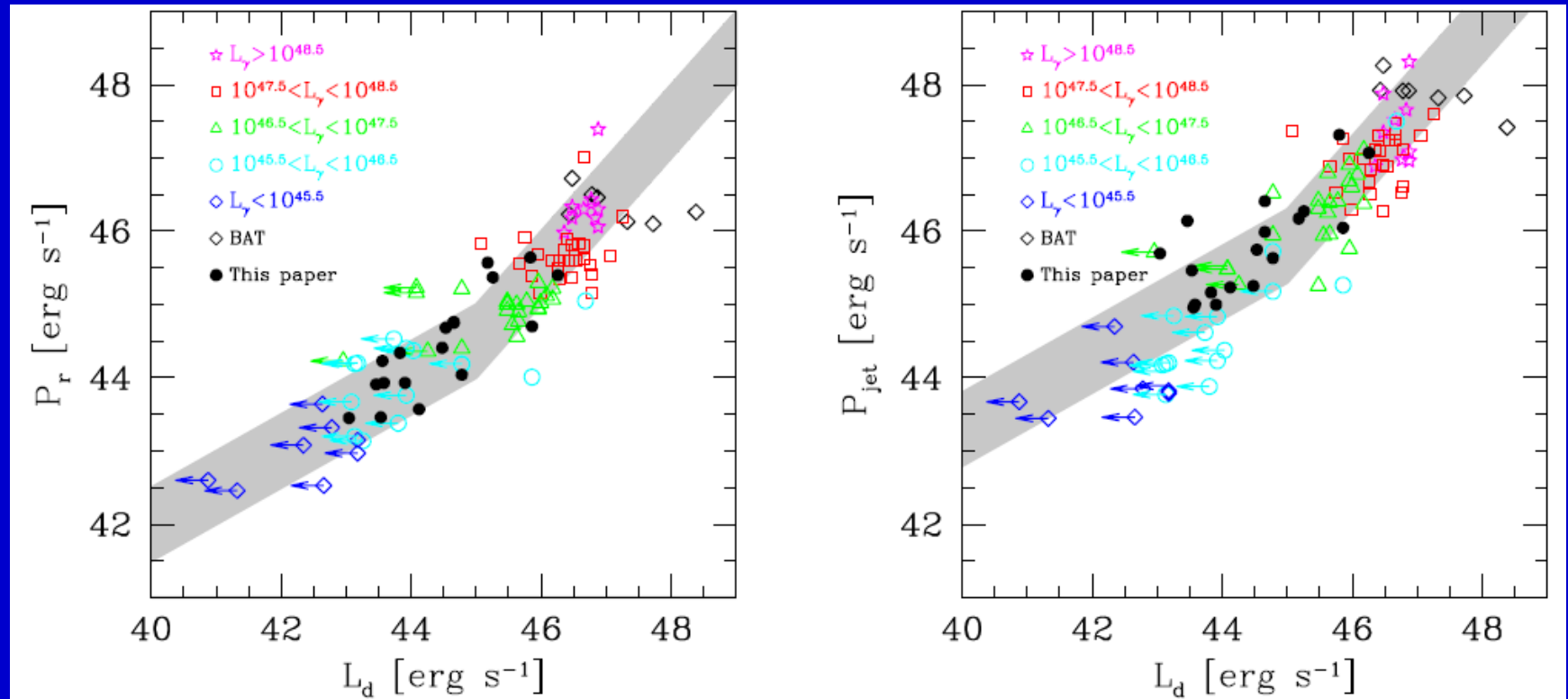
$$P_{\text{jet}} > 2P_r \sim 2L/\Gamma^2$$

Jet and disc

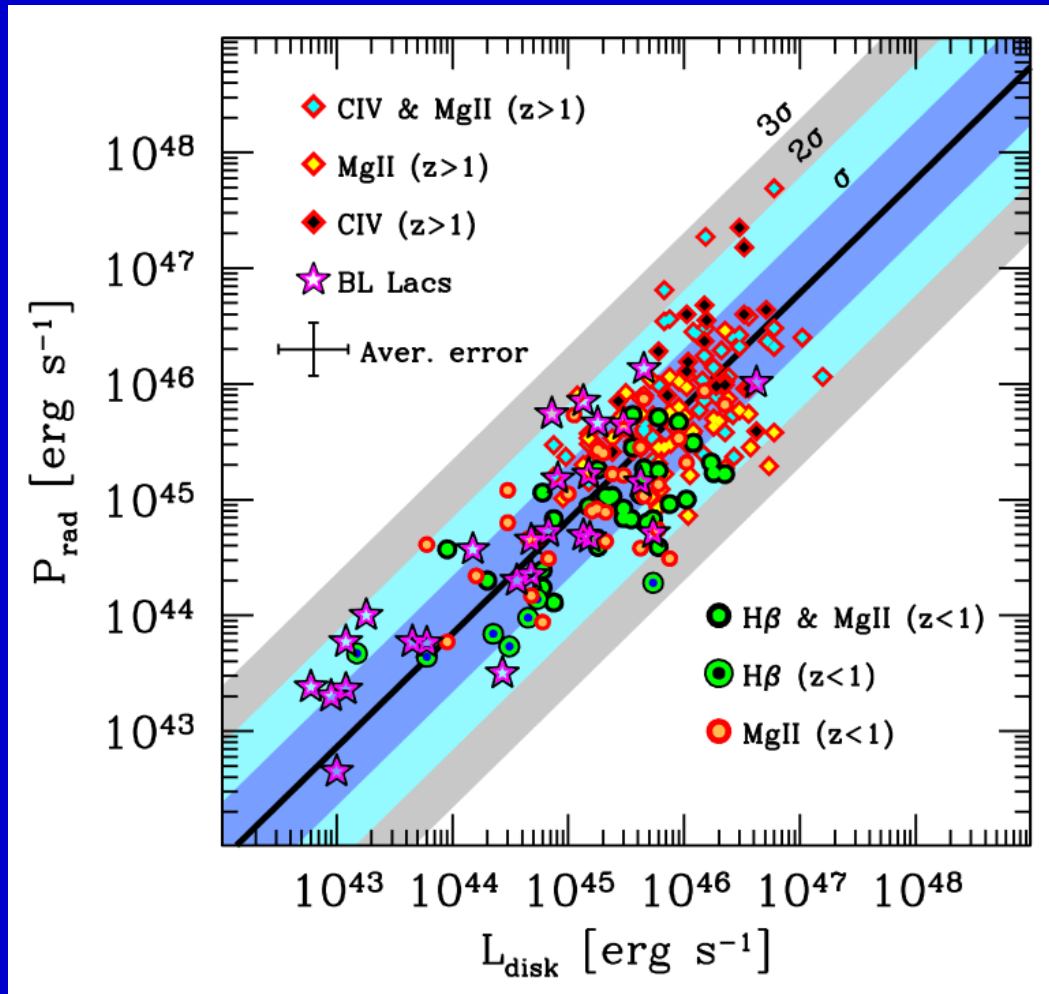
L_d – disc luminosity.

$$P_{\text{jet}} = P_B + P_P + P_e$$

In the gray stripes $P_{\text{jet}} \sim \dot{M}$ and
at low accretion rates $L_d \sim \dot{M}^2$, at large - $L_d \sim \dot{M}$.

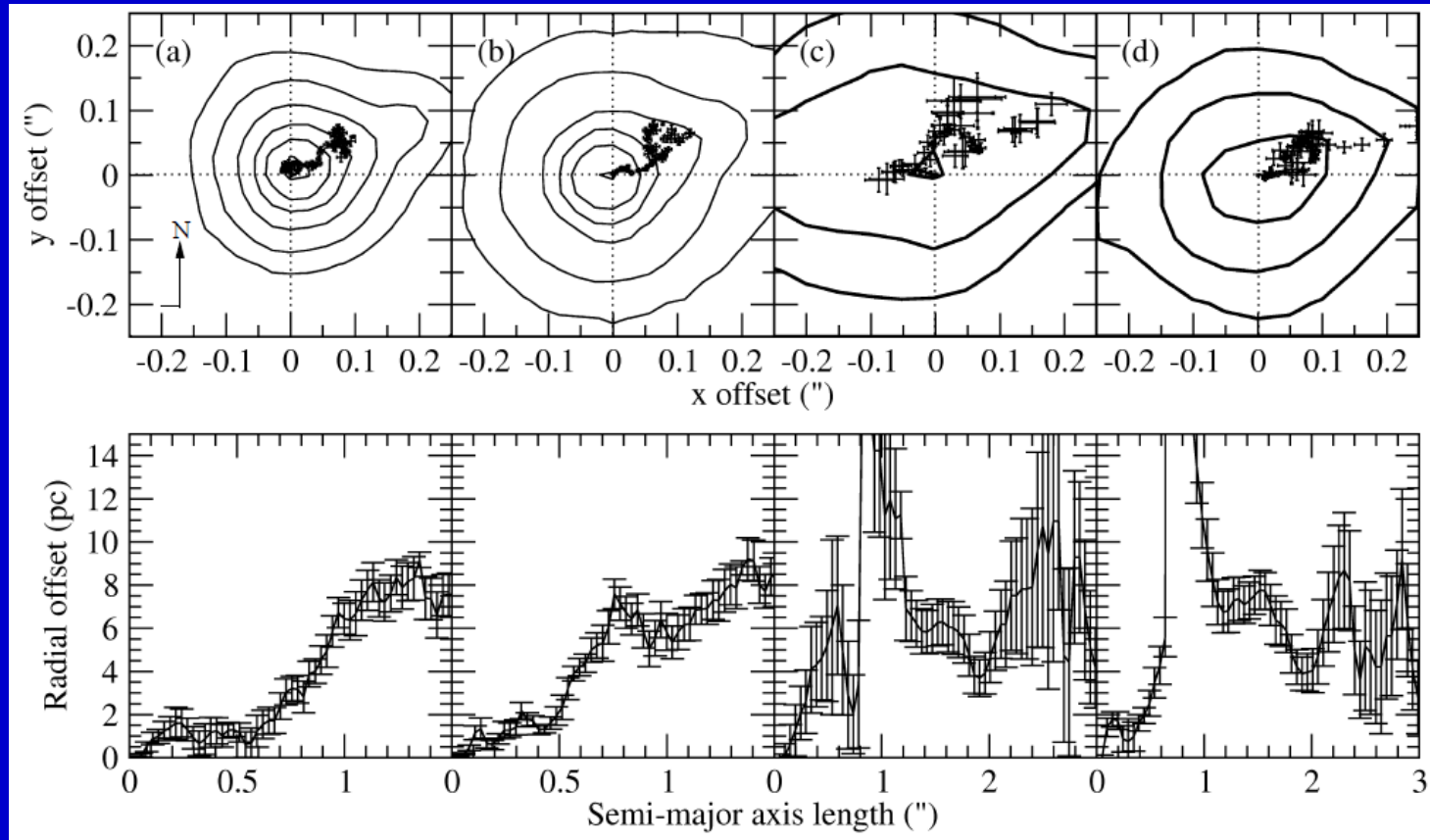


Jets are more powerful than discs

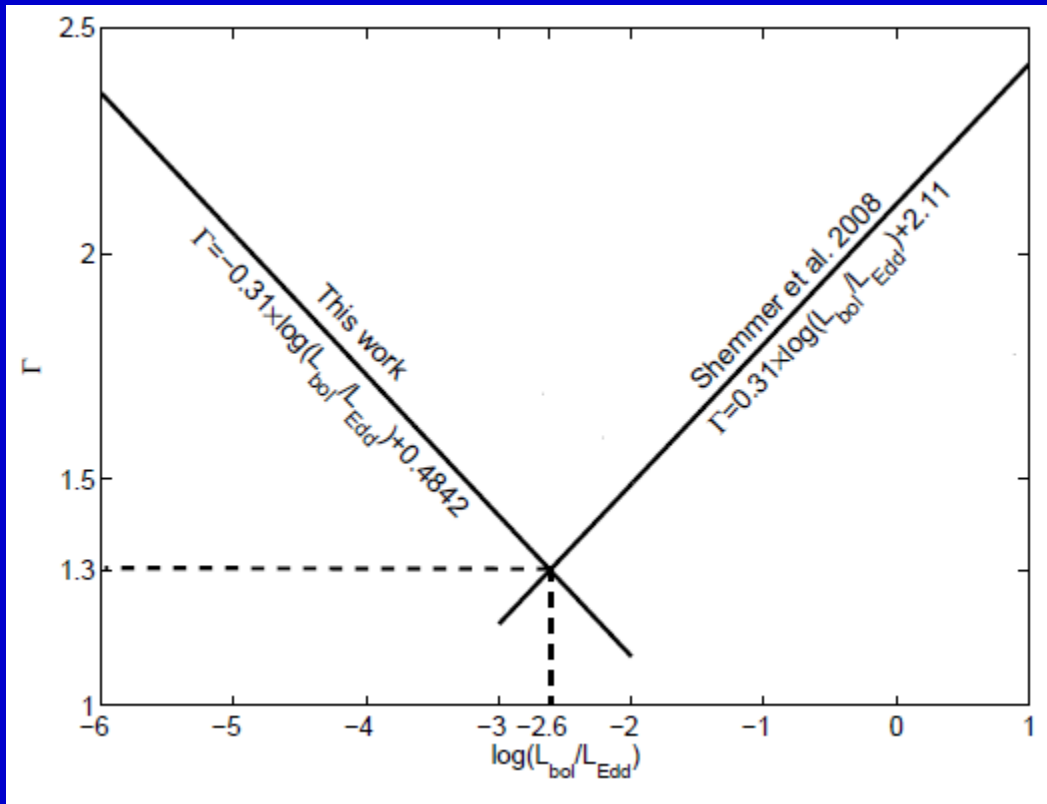


Displaced SMBH in M87

Projected displacement of 6.8 ± 0.8 pc
consistent with the jet axis
displaced in the counter-jet direction



Different accretion regimes in AGNs



Γ - photon index

Anticorrelation for low-luminosity AGNs (LINERS).

Correlation for luminous AGNs.

In the critical point the accretion regime can be changed: from a standard thin accretion disc to RIAF (radiatively inefficient accretion flow).

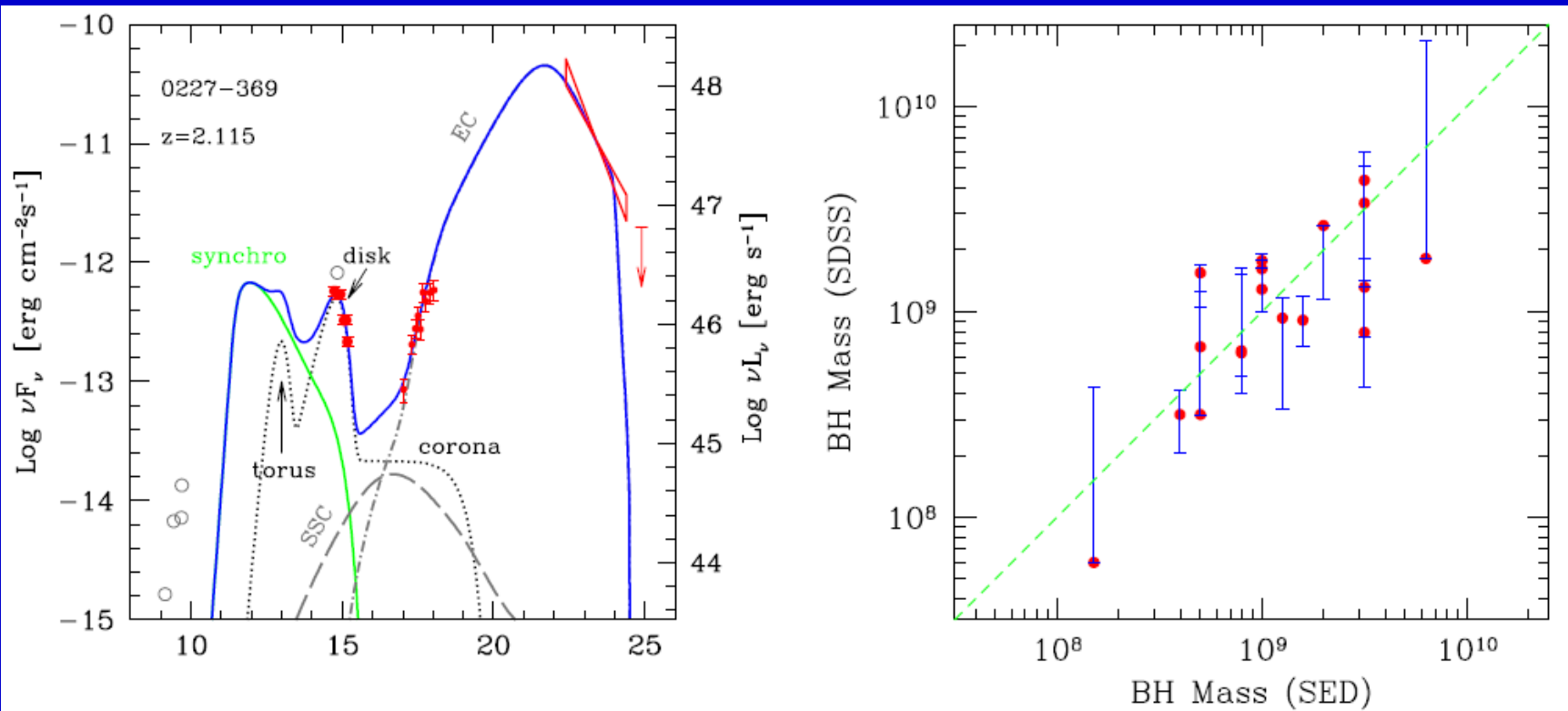
BH mass determination

Accretion disc contribution is visible in opt-UV.

It allows to estimate the BH mass.

It can be compared with emission lines estimates.

Bars correspond to different lines used.



BH mass and jet properties in M87

Table 3. Predicted jet and BH parameters for $M = 6.5 \times 10^9 M_{\odot}$.

σ_M	$\Gamma\theta_j$	ϕ	a_*	W_j (10^{42} erg/s)
(1)	(2)	(3)	(4)	(5)
10	0.062	3.2	0.093	1.9
20	0.063	3.3	0.144	4.7

Estimates are in correspondence with the EHT data on the BH mass.

If the mass is assumed to be known,
then the initial magnetization σ_M can be determined.

Tidal disruption

The Hills limit: 3×10^8 solar masses. A BH disrupts stars.

After a disruption in

$$(t_0 - t_D) \sim 1.1 M_8^{1/2} \text{ yr}$$

happens a burst with
the temperature

$$T_{\text{eff}} \approx (L_{\text{Edd}}/4\pi\sigma R_T^2)^{1/4} = 3.7 \times 10^5 M_8^{1/12} \text{ K}$$

The maximum accretion rate

$$\dot{M}_{\text{max}} \sim 0.14 M_8^{1/2} M_{\odot} \text{ yr}^{-1}$$

This rate corresponds to the moment

$$(t_{\text{max}} - t_D) \sim 1.5 (t_0 - t_D)$$

Then the rate can be described as

$$\dot{M}(t) = 0.3 M_8 [(t - t_D)/(t_0 - t_D)]^{-5/3} M_{\odot}$$

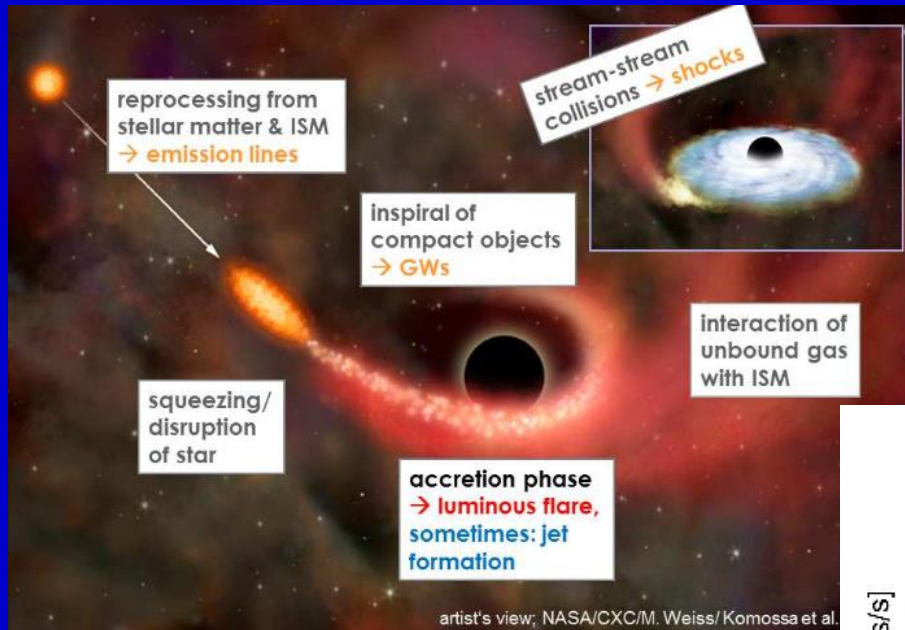
For a BH with $M < 10^7 M_{\odot}$ the luminosity at maximum is:

$$L_{\text{flare}} \geq \eta \dot{M}_{\text{Edd}} c^2 > 1.3 \times 10^{45} M_7 \text{ ergs s}^{-1}$$

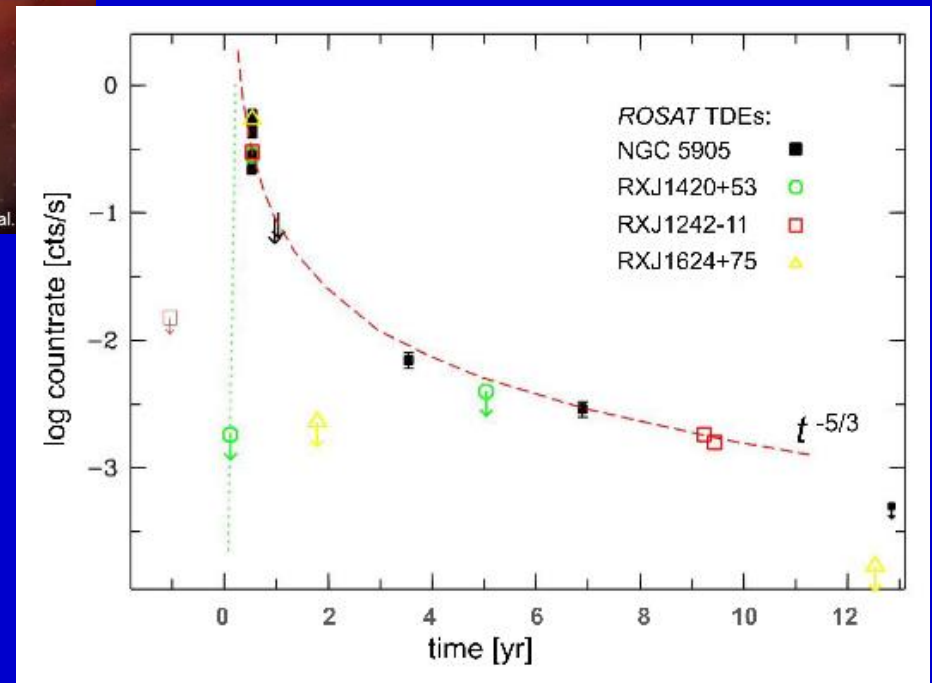
(astro-ph/0402497)

See a review in 1505.01093

General picture

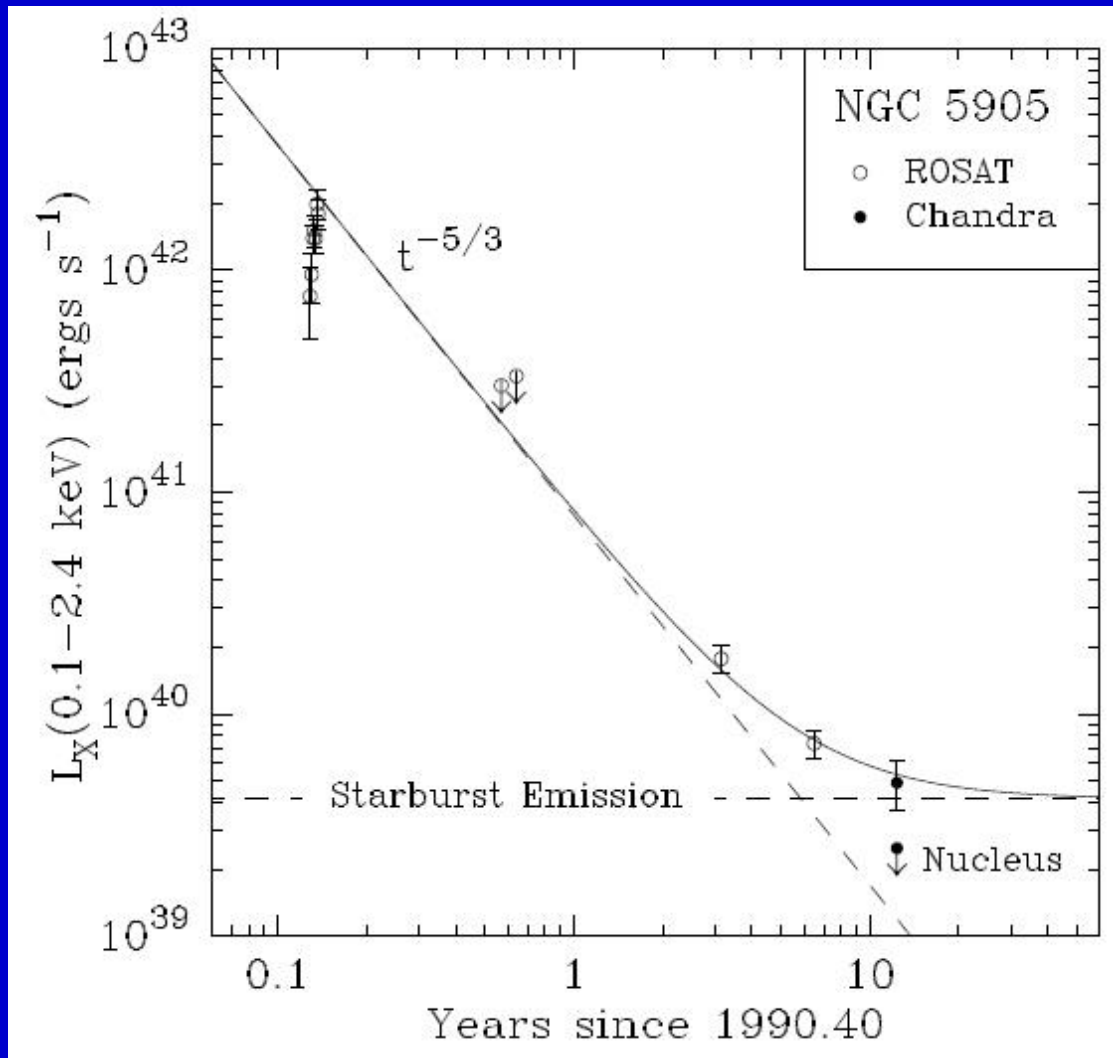


Rate of TDE is $\sim 1/100000$ yrs per galaxy (1407.6425).



See a review in 1505.01093

A burst in NGC 5905



The decay was well described by the relation:

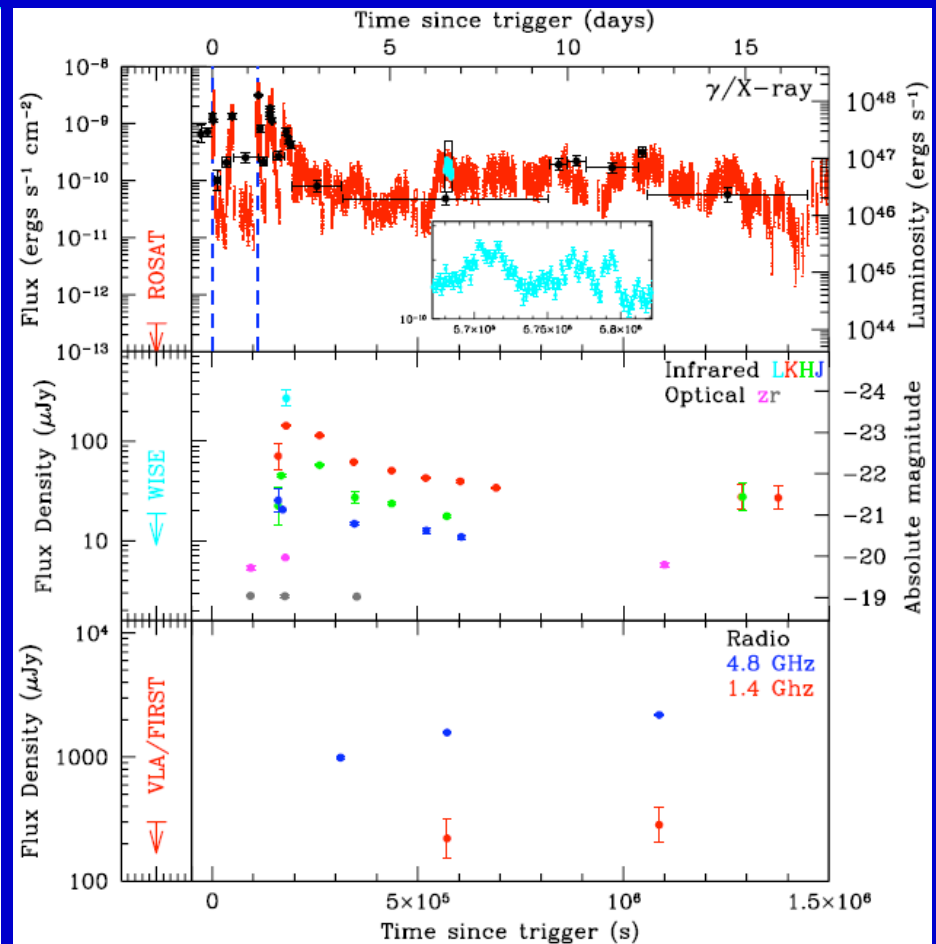
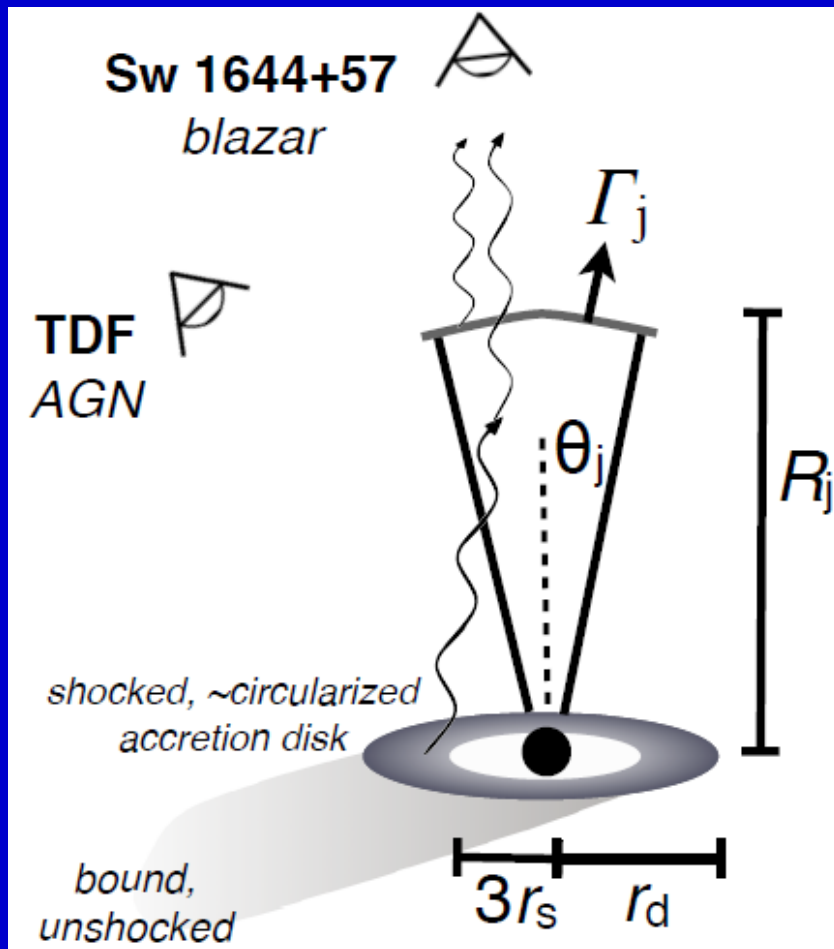
$$(t - t_D)^{-5/3}$$

Two other bursts discovered by ROSAT and observed by HST and Chandra:

RX J1624.9+7554

RX J1242.6-1119A

High-energy transient Swift J164449.3+573451

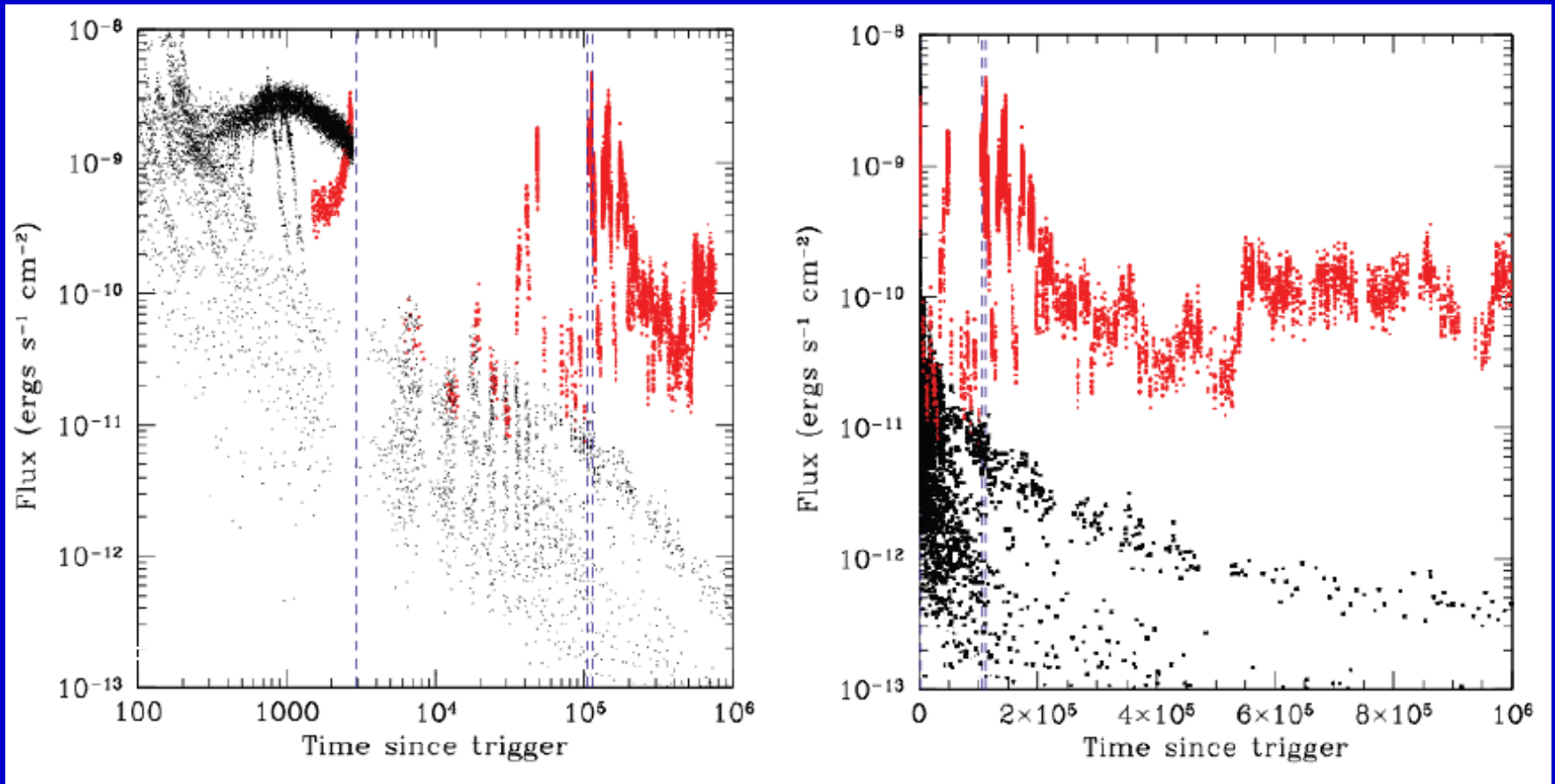


1104.3257

1104.3356

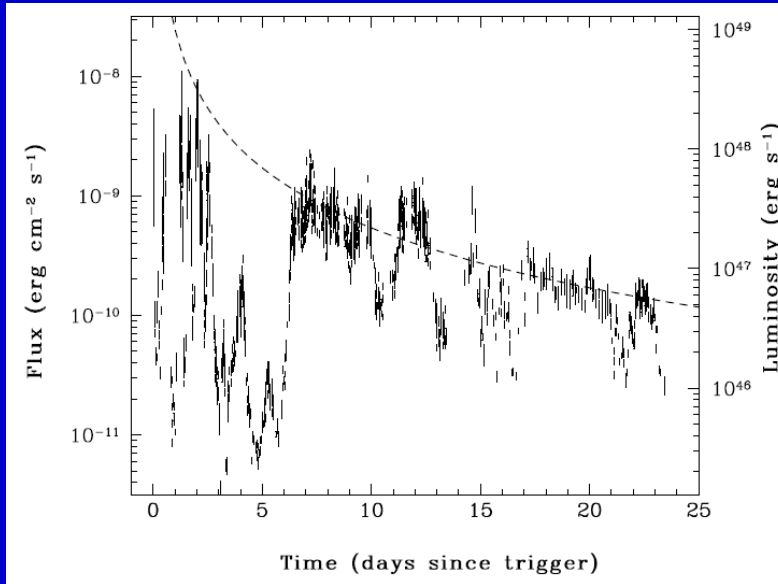
Also known as GRB 110328A

A unique event

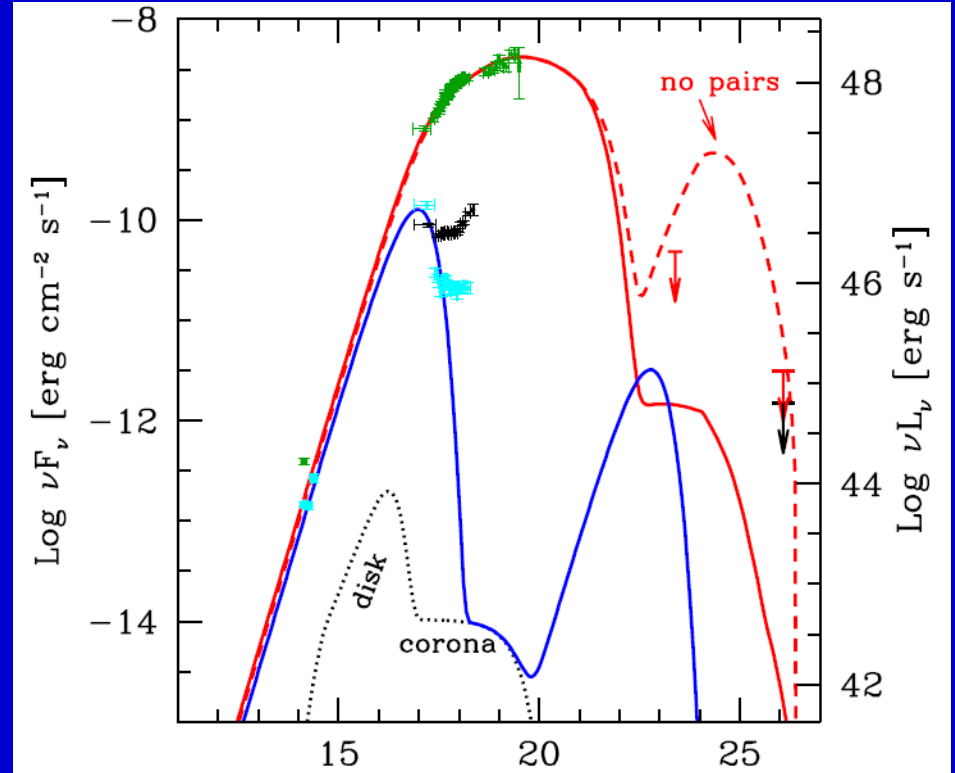


The transient does not look similar to GRBs, SN or any other type of event

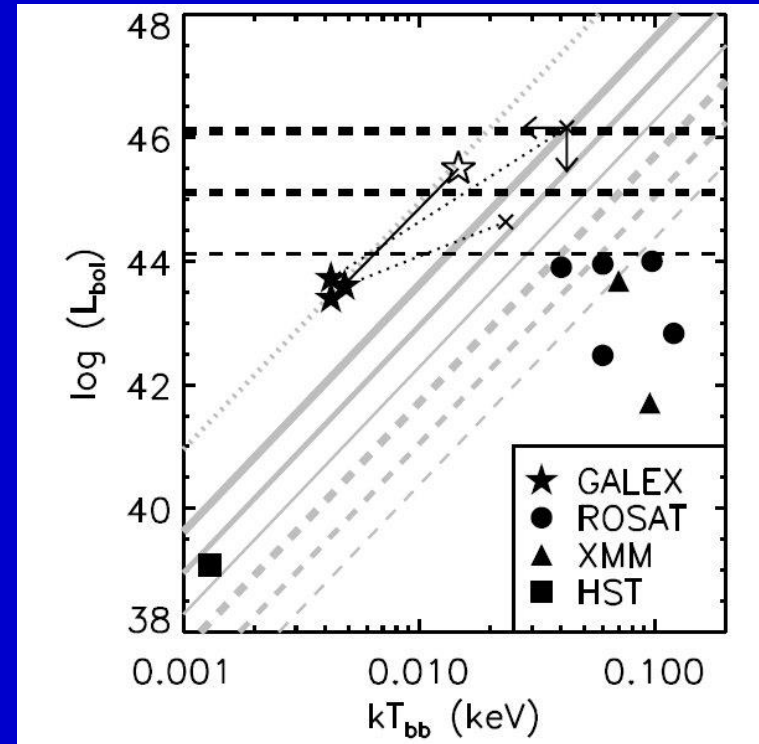
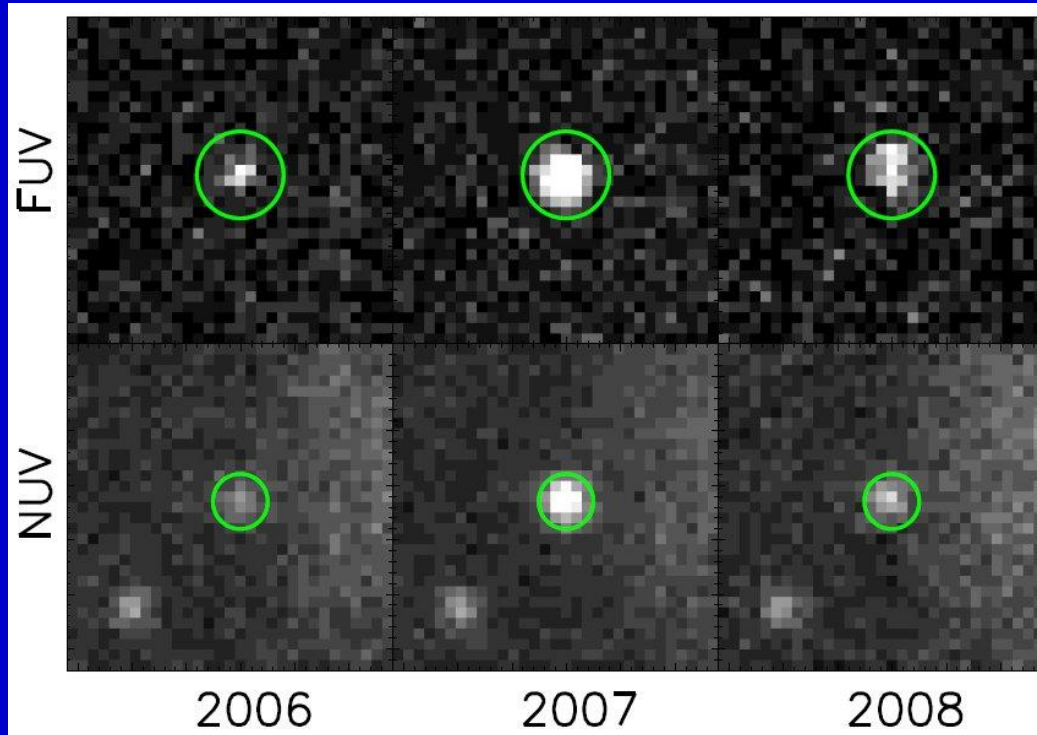
A tidal disruption event



Light curve fits the prediction
for a tidal event.
The spectrum is blazar-like.



Optical observations of tidal disruptions



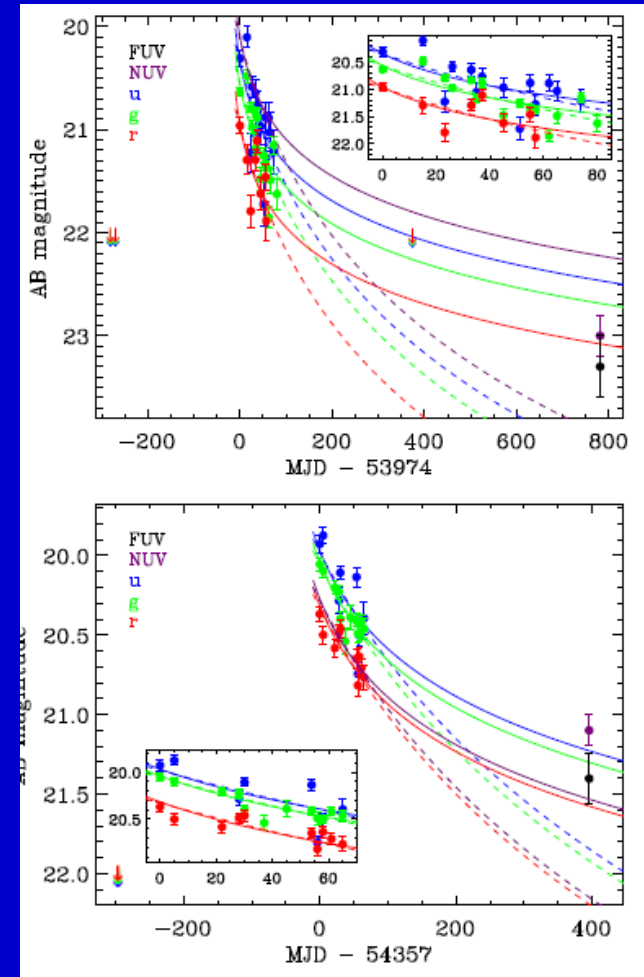
In optics one can observe events far from the horizon.
Future surveys (like Pan-STARRS)
can discover 20-30 events per year.

Two more examples of optical flares due to tidal disruption events

SDSS data

Atypical flares

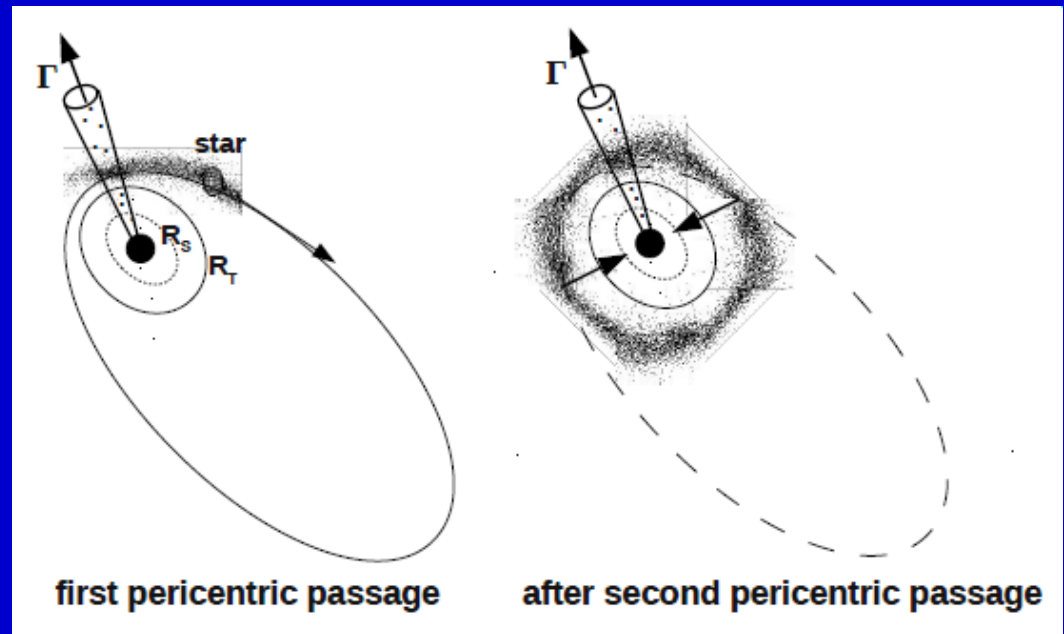
Rate estimates:
 $\sim 10^{-5}$ per year per galaxy
or slightly more



Theoretical models

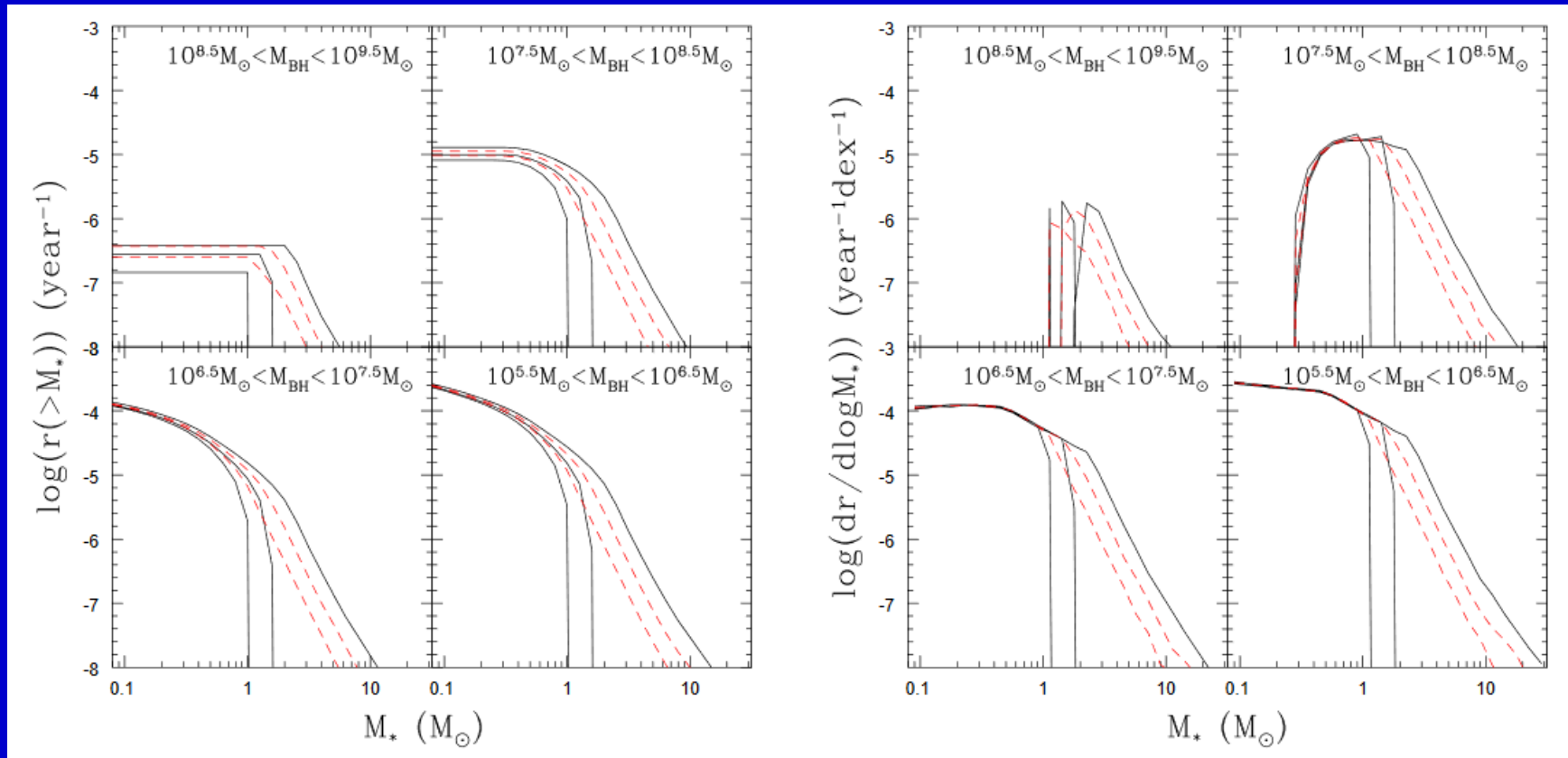
- X-rays. 1105.2060
- Radio. 1104.4105

Flows of hot X-ray emitting gas have been identified after one of tidal disruption events.
1510.06348



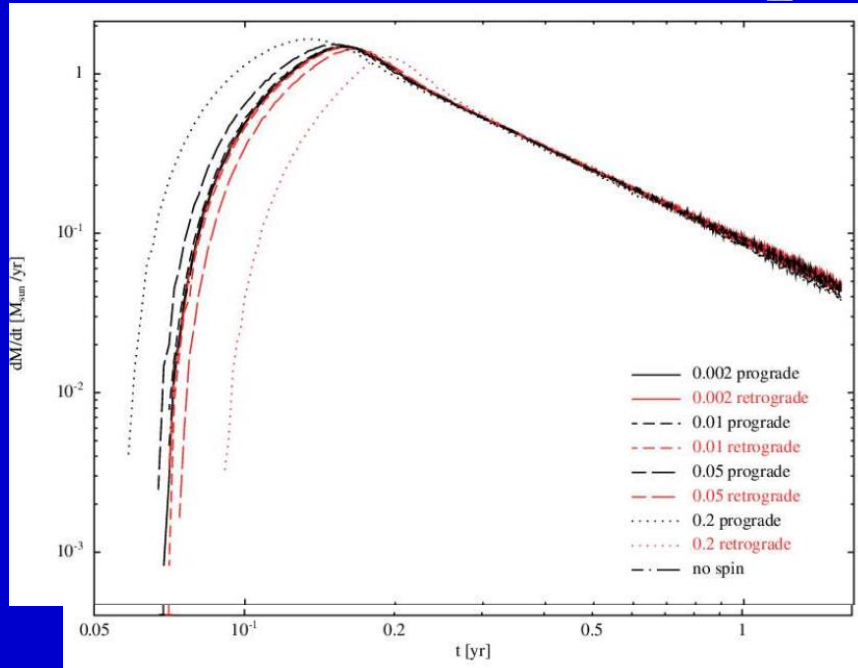
1104.2528

Stellar masses

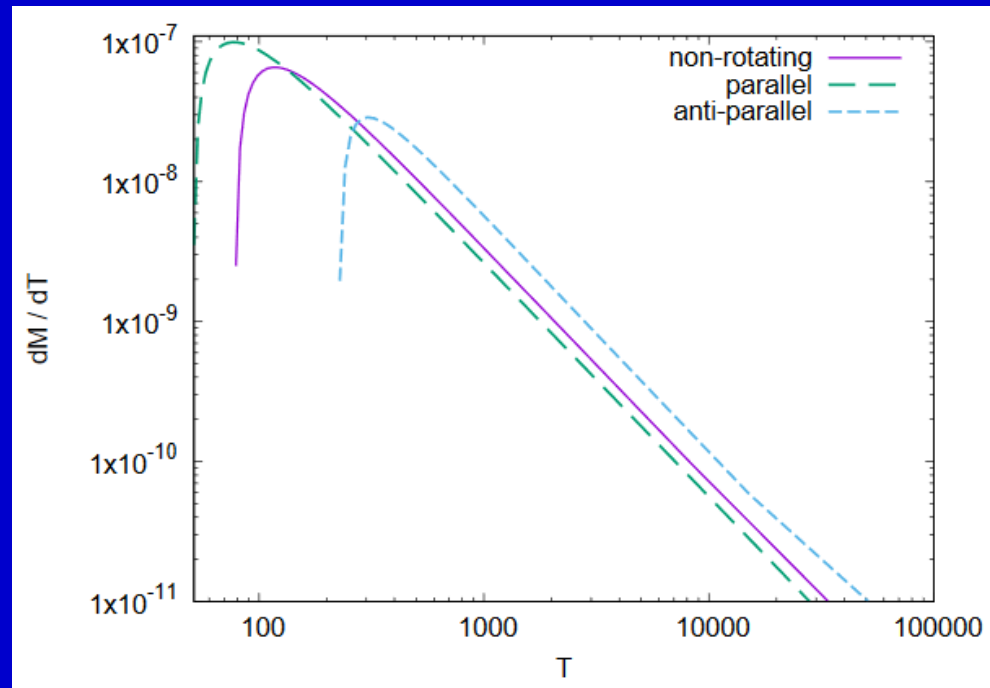


For not too massive BHs the main contribution is due to M-dwarfs ($0.3 M_\odot$). For massive BHs contribution from massive and evolved stars grows.

Role of stellar spin



1901.03717



1901.05644

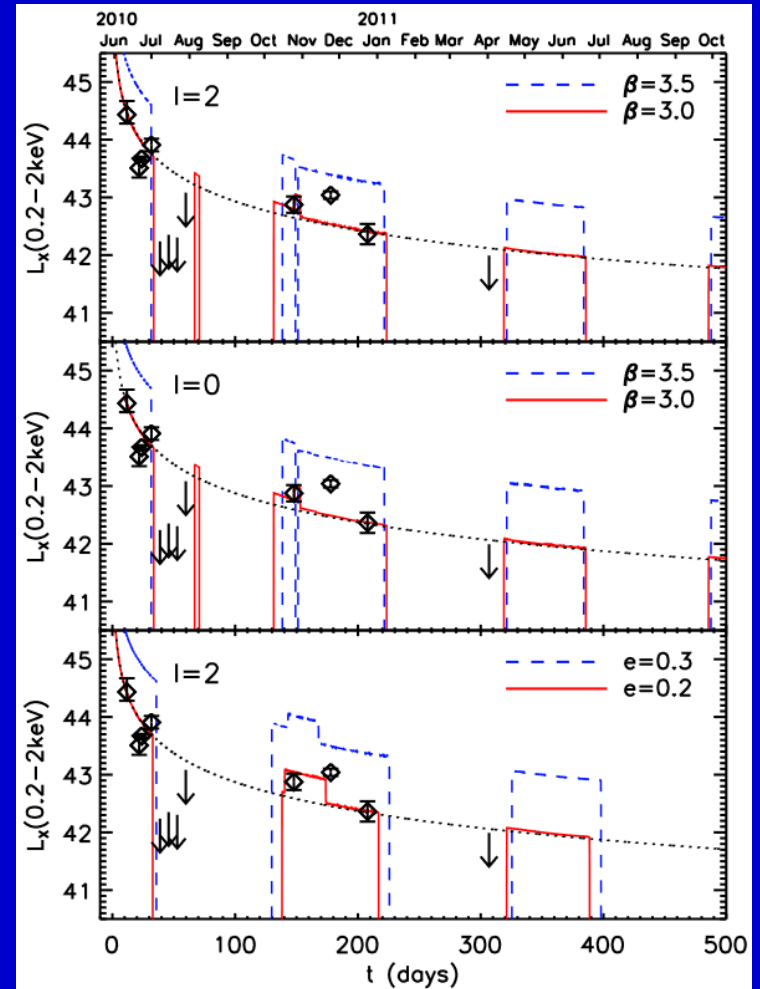
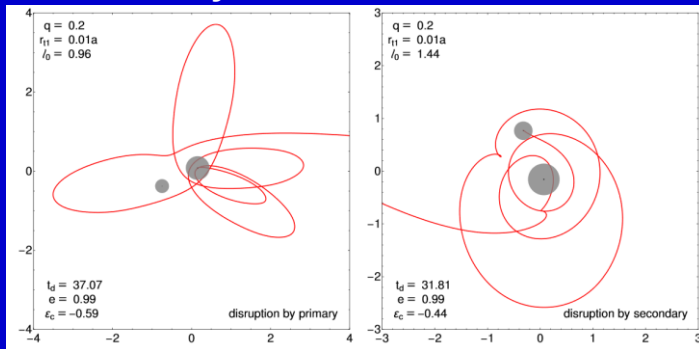
TDE and binary SMBHs

It has been predicted that after a TDE in a system of close SMBH binary there might be particular drops in the light curve. Such phenomena was observed.

SDSS J120136.02+300305.5
XMM-Newton observations

Masses $\sim 10^7$ and 10^6 solar masses,
orbital separation $\sim 10^{-3}$ pc
Eccentricity ~ 0.3

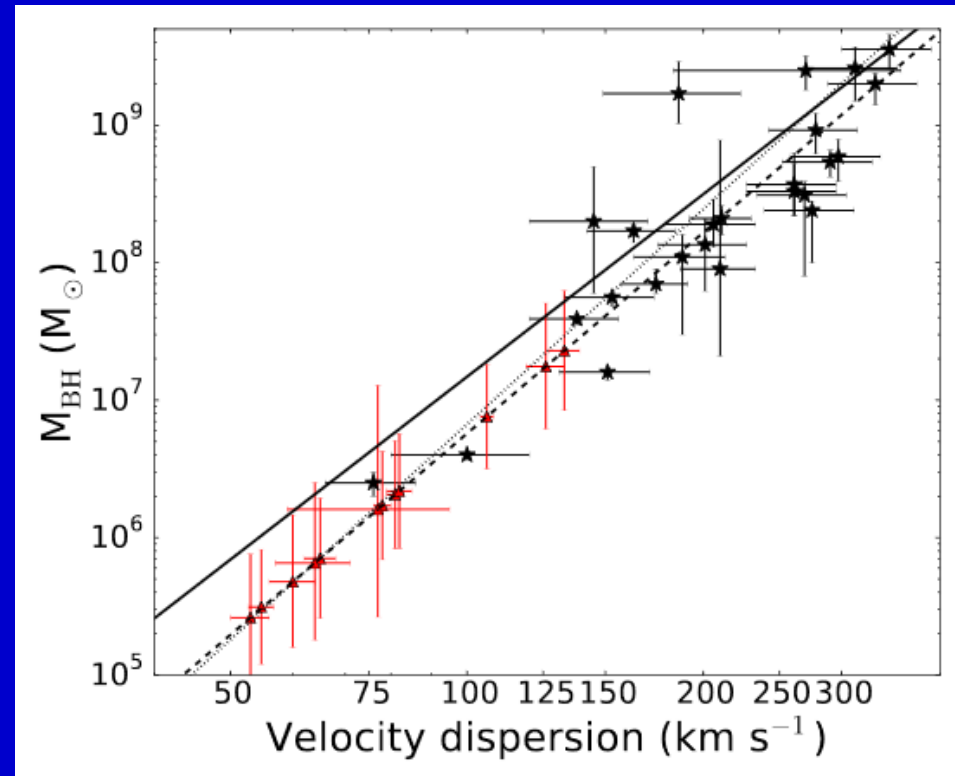
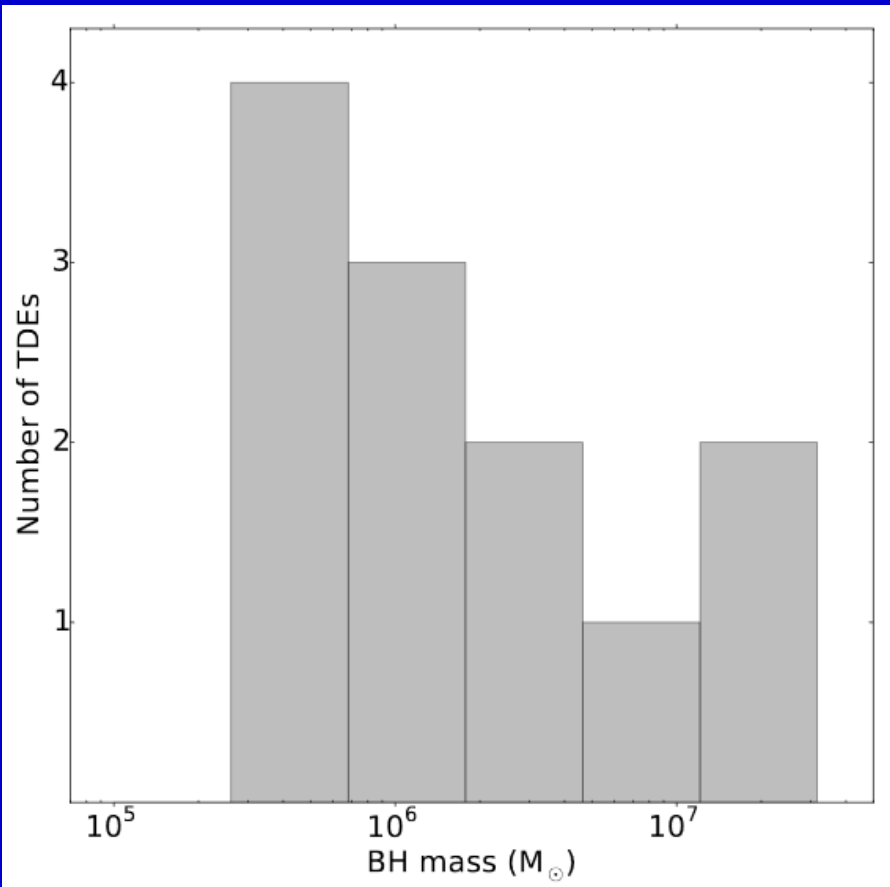
TDEs in supermassive BH binaries
were recently modeled in 1802.07850.



1404.4933

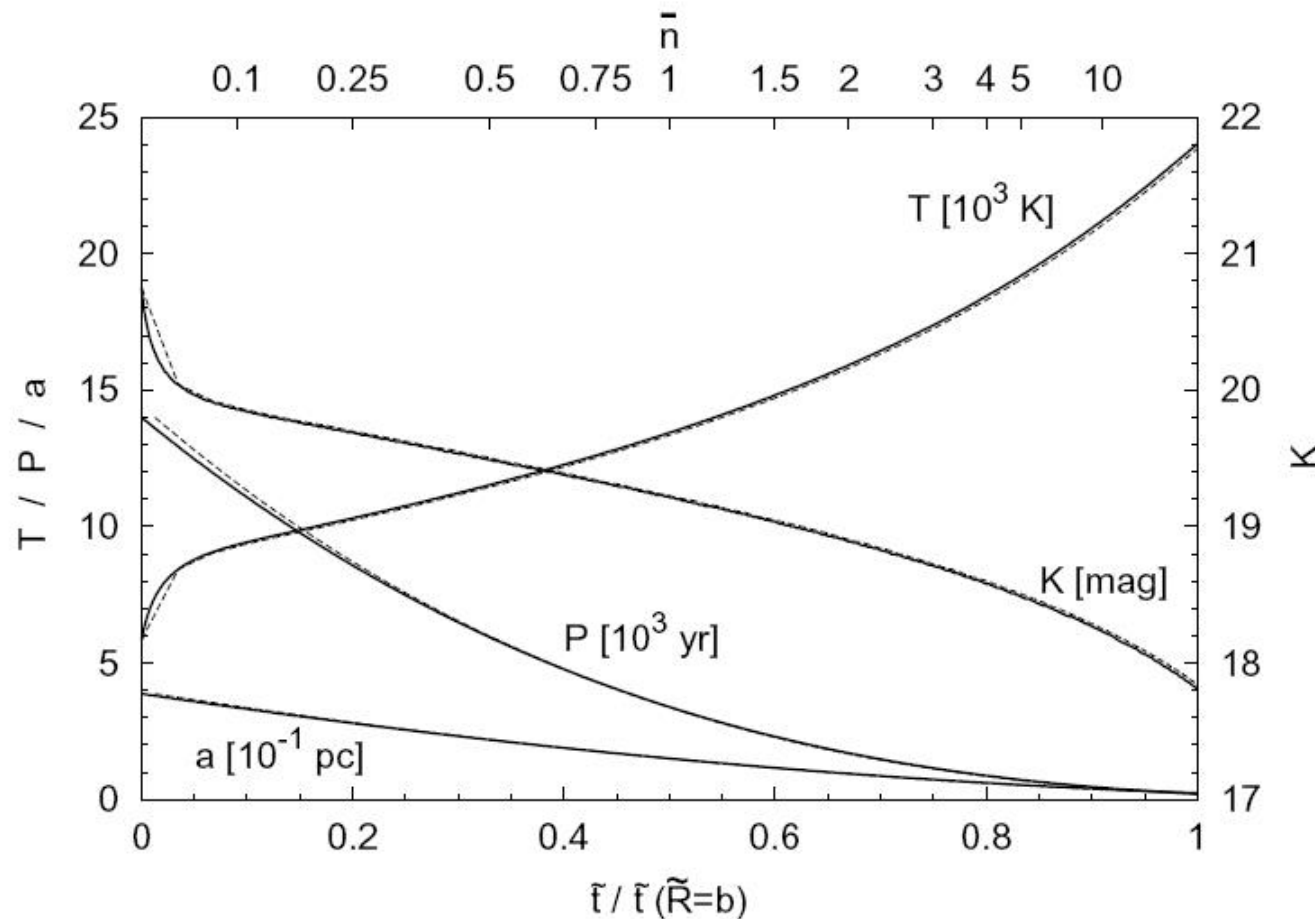
Mass determination from TDE

12 optically/UV selected TDE host galaxies



Red- new data, lines – best fits,
black – Ferrarese, Ford (2005).

Squeezars



The rate of formation is lower than the rate of tidal disruption events, but the observable time is longer.

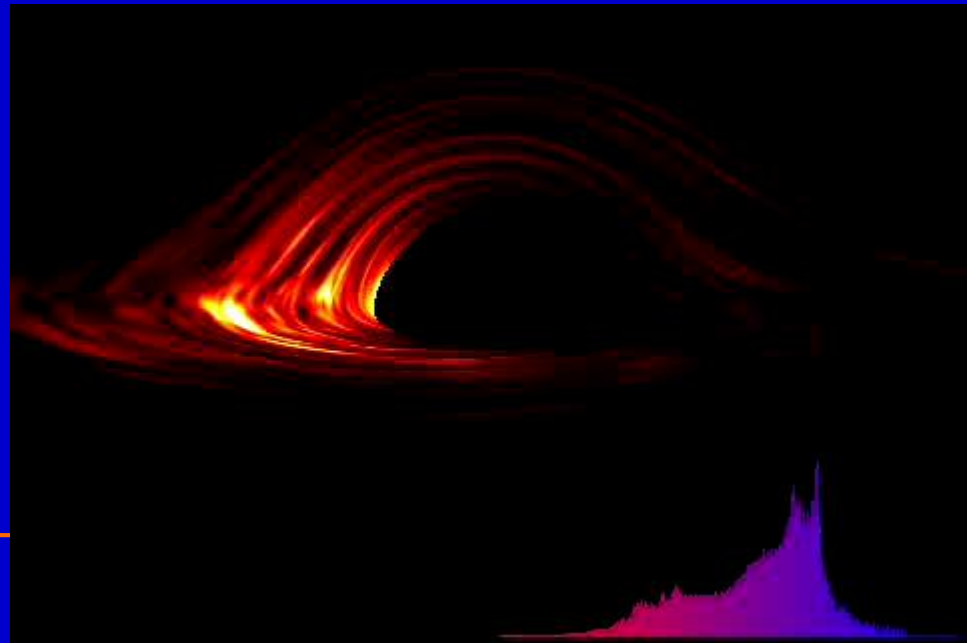
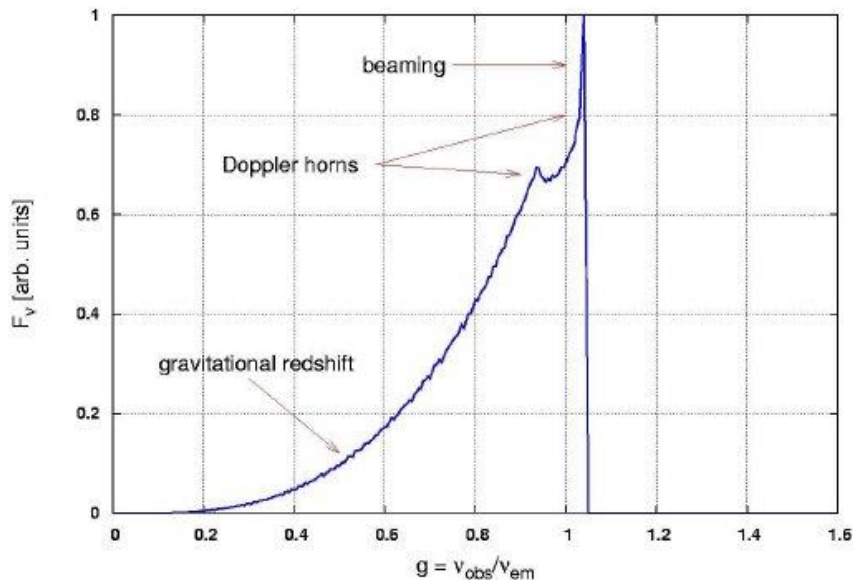
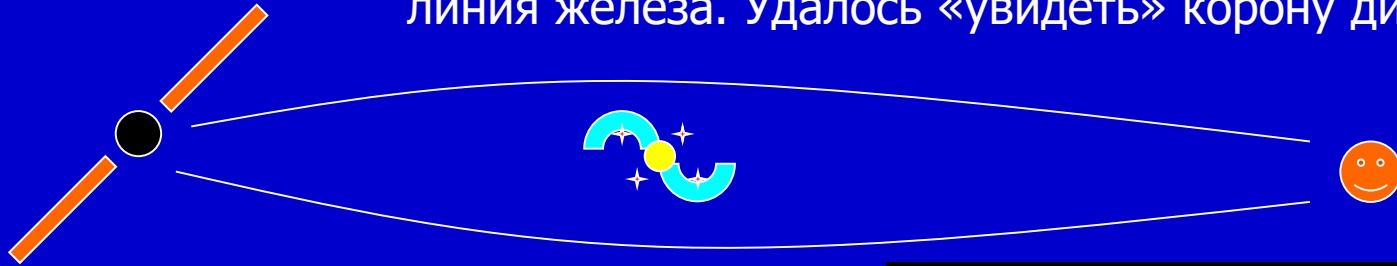
Graphs are plotted for a solar-type star orbiting the BH in the center of our Galaxy.

(astro-ph/0305061)

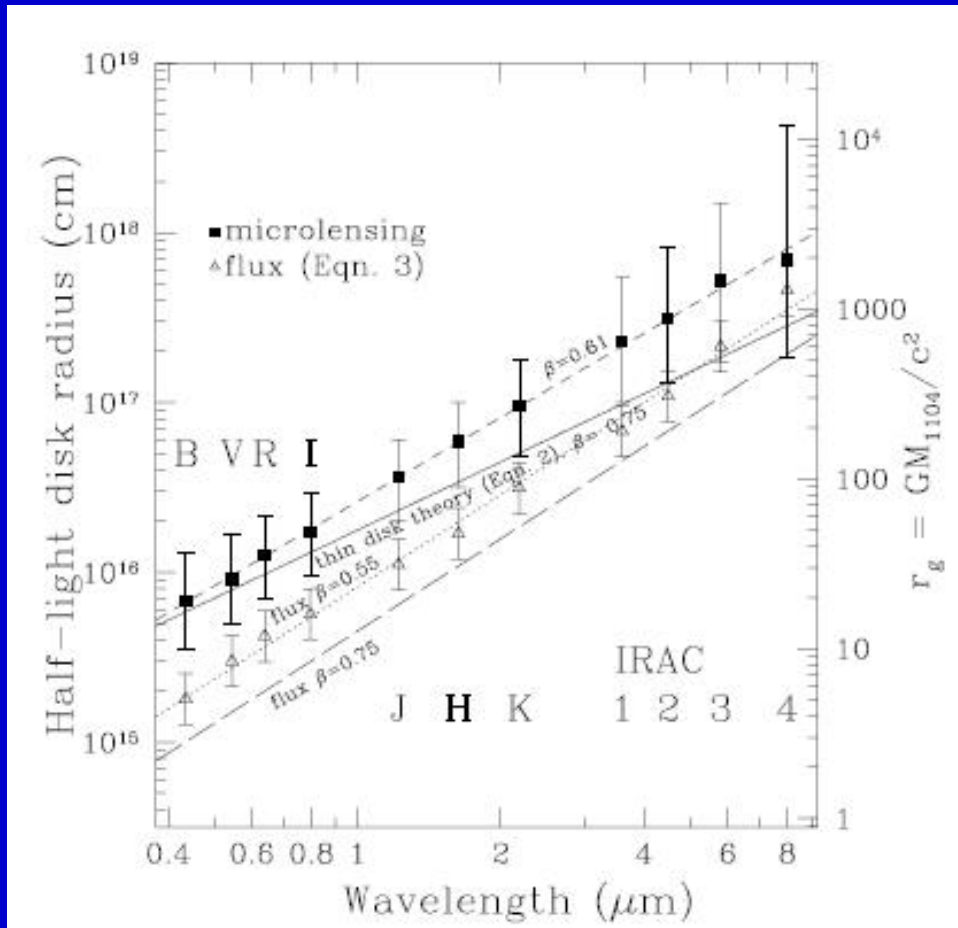
Структура диска вокруг сверхмассивной черной дыры

Наблюдение микролинзирования позволяет
выявлять структуру аккреционного диска.
Кроме этого, наблюдалась линзированная
линия железа. Удалось «увидеть» корону диска.

1204.4480

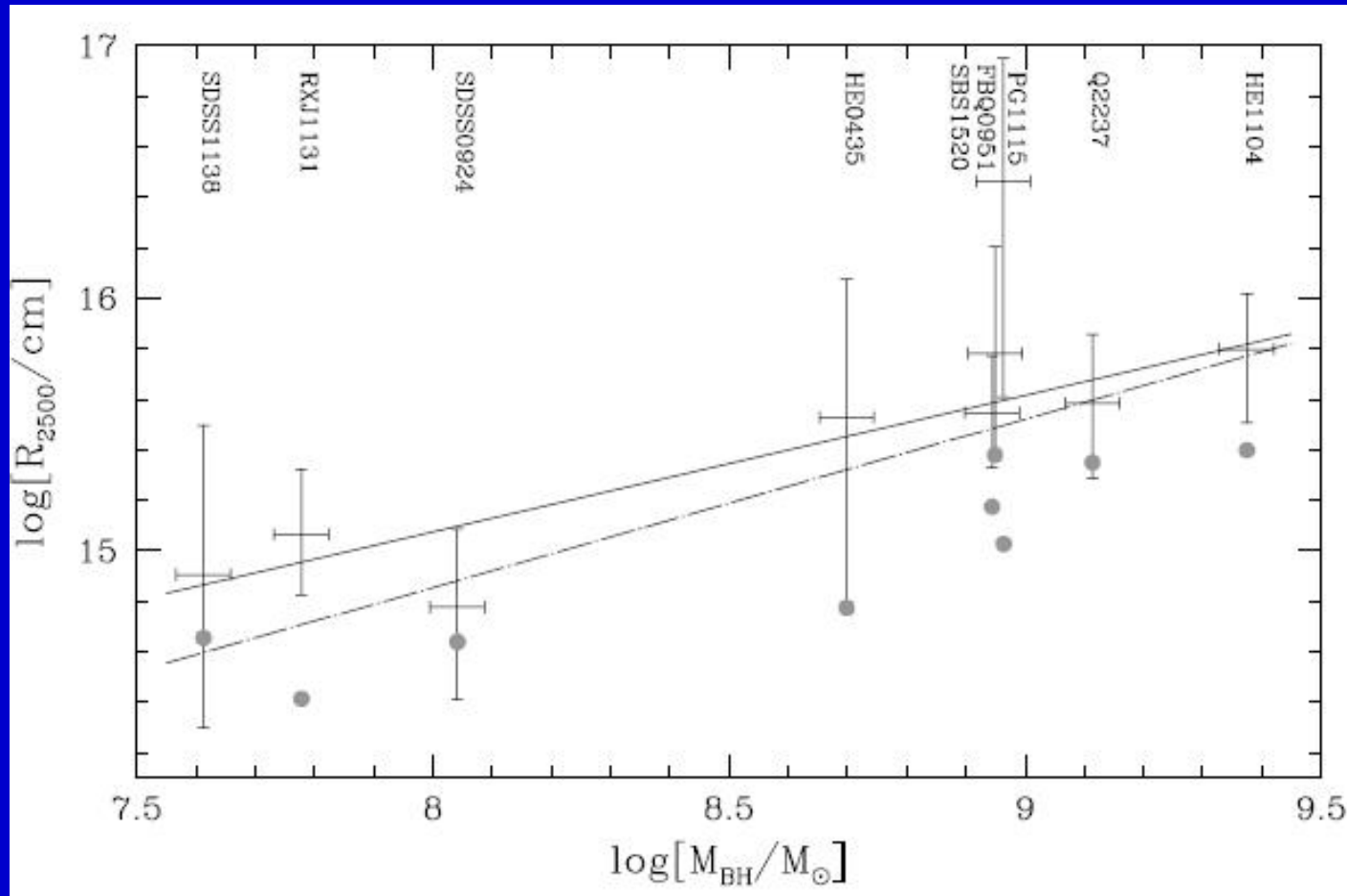


Disc structure from microlensing



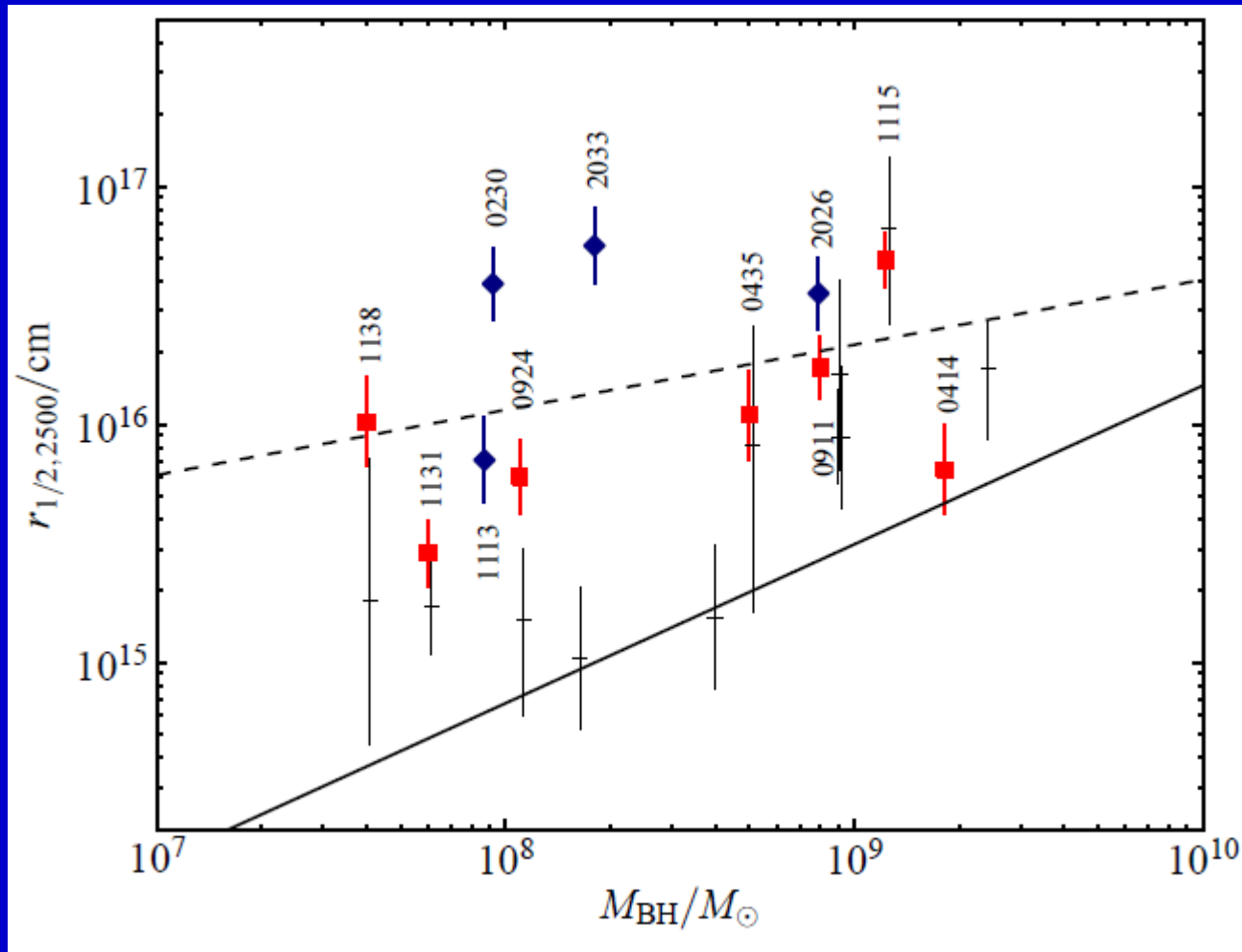
Using the data on microlensing at wavelengths 0.4-8 microns it was possible to derive the size of the disc in the quasar HE1104-1805 at different wavelengths.

Disc size – BH mass



Disc size can be determined from microlensing.

New data



IR and optics.

Chromatic microlensing:
blue light from
the inner regions
is more strongly
microlensed than
red light from farther out

Solid line is
the prediction
of the thin disk model.

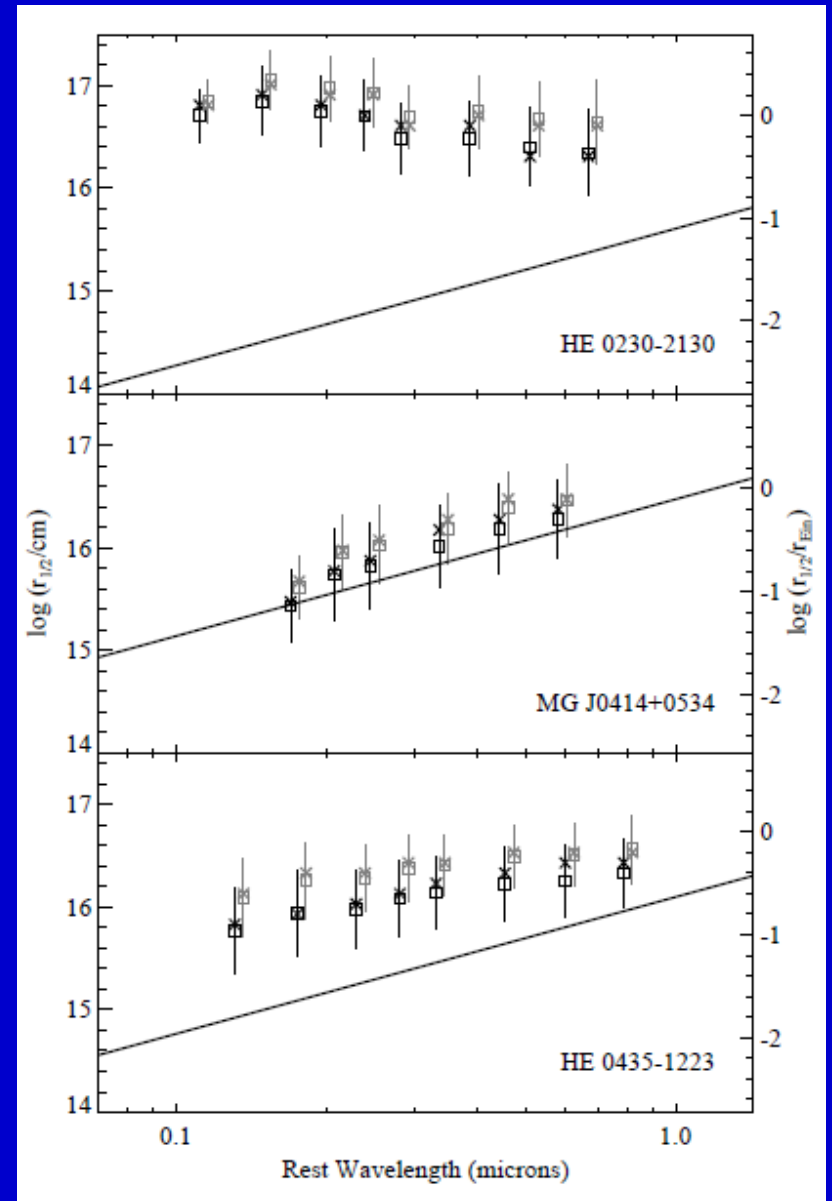
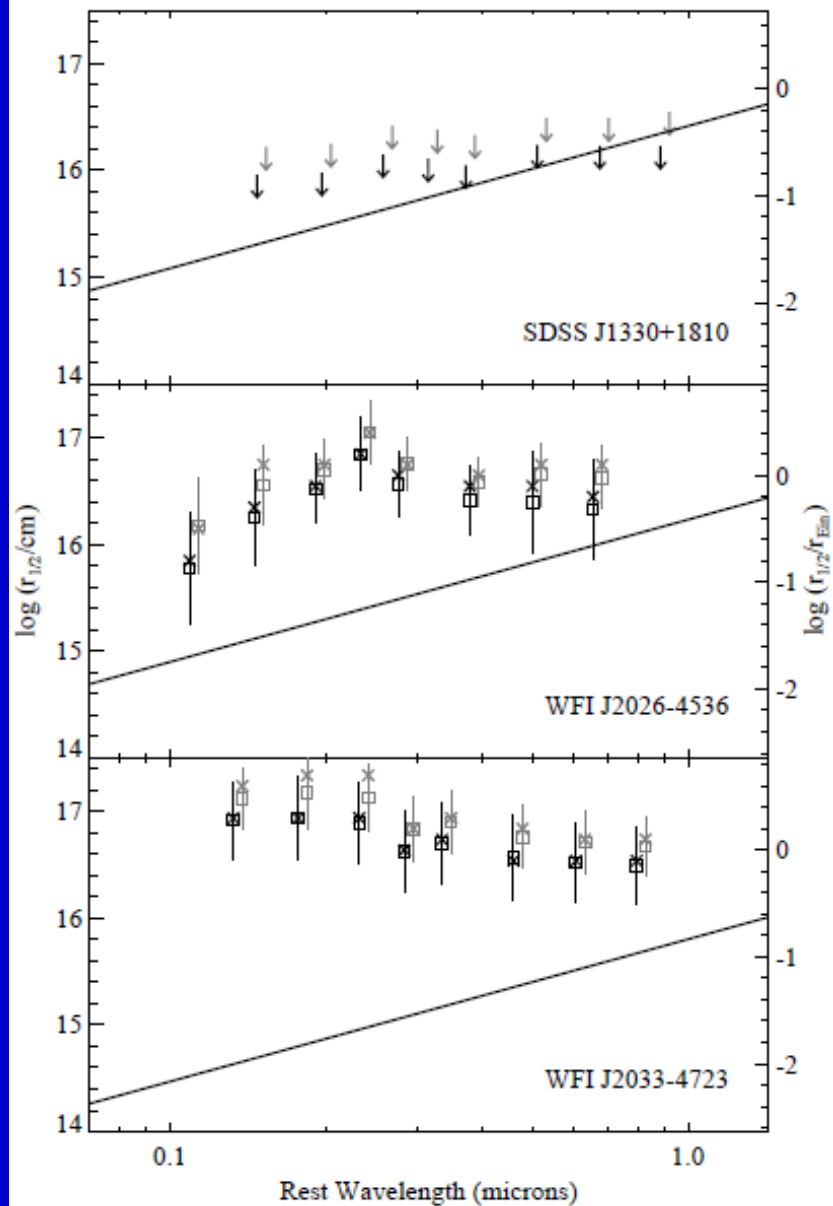
Standard disc properties

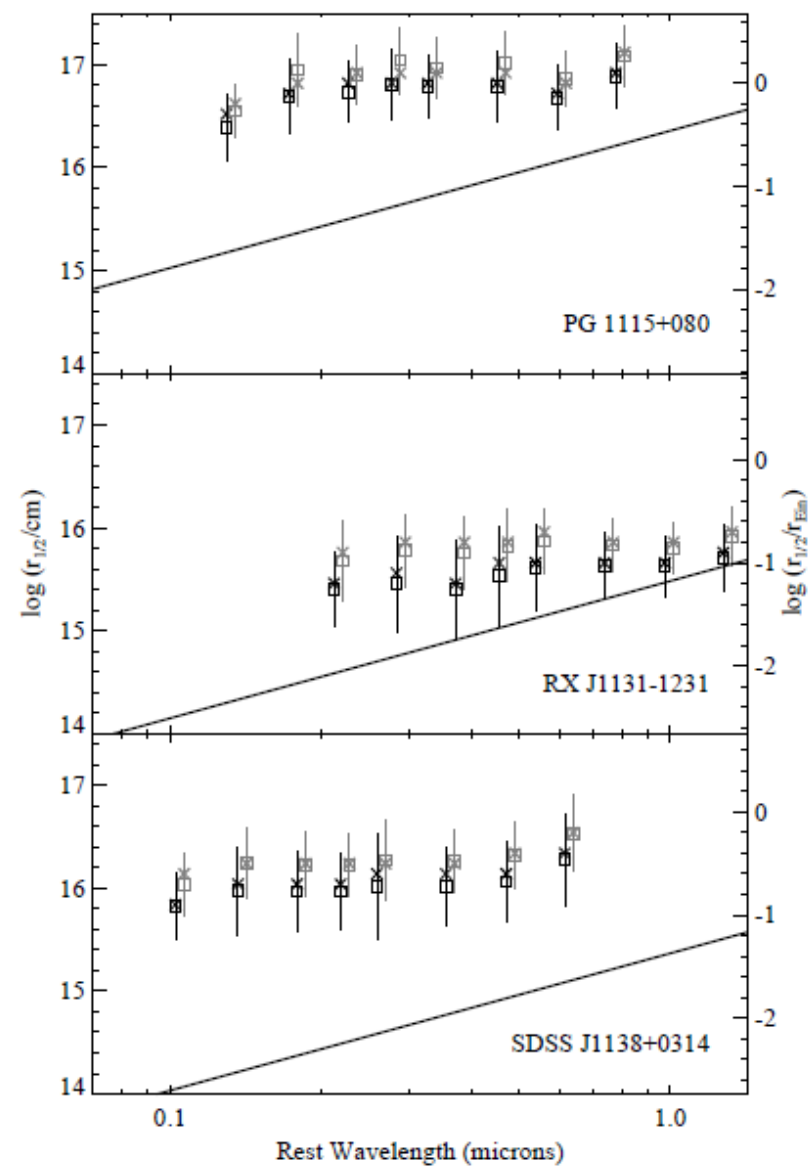
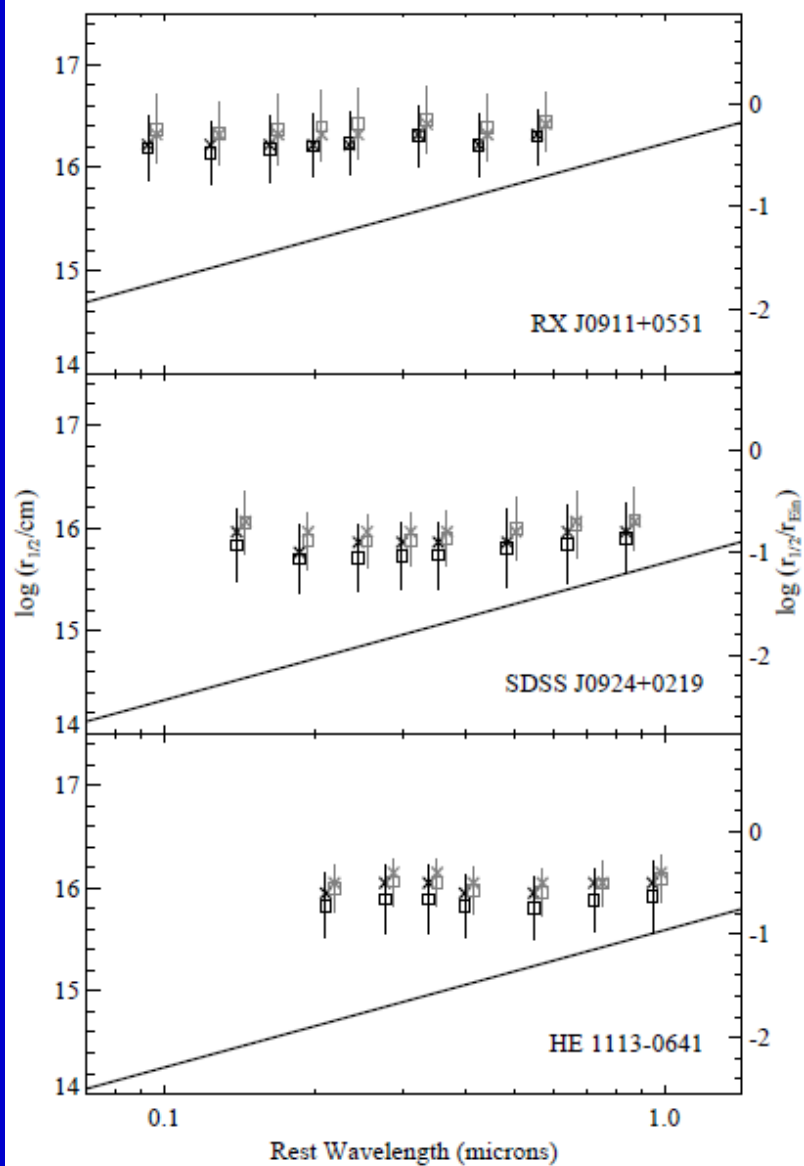
$$T_{\text{eff}}(r) = \left(\frac{3G^2 M_{\text{BH}}^2 m_p f_{\text{Edd}}}{2c\sigma_B \sigma_T \eta r^3} \right)^{1/4} g(r_{\text{in}}/r)^{1/4}$$

Standard disc model

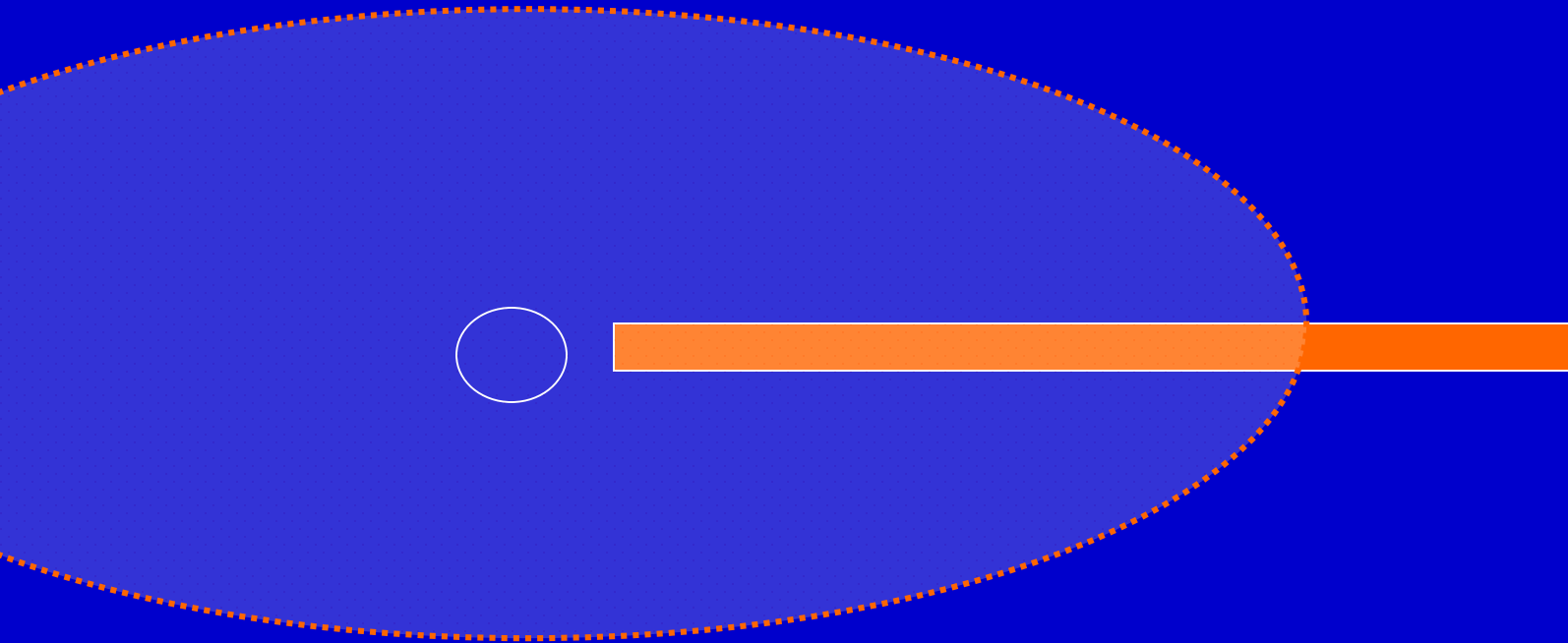
$$\begin{aligned} r_{1/2} &= 2.44 \left[\frac{45G^2 M_{\text{BH}}^2 m_p f_{\text{Edd}} \lambda^4}{4\pi^5 h_P c^3 \sigma_T \eta} \right]^{1/3} \sqrt{\cos i} \\ &= 1.68 \times 10^{16} \text{cm} \left(\frac{M_{\text{BH}}}{10^9 M_{\odot}} \right)^{2/3} \left(\frac{f_{\text{Edd}}}{\eta} \right)^{1/3} \left(\frac{\lambda}{\mu\text{m}} \right)^{4/3} \end{aligned}$$

$$r_{1/2} \sim \lambda^{4/3}$$





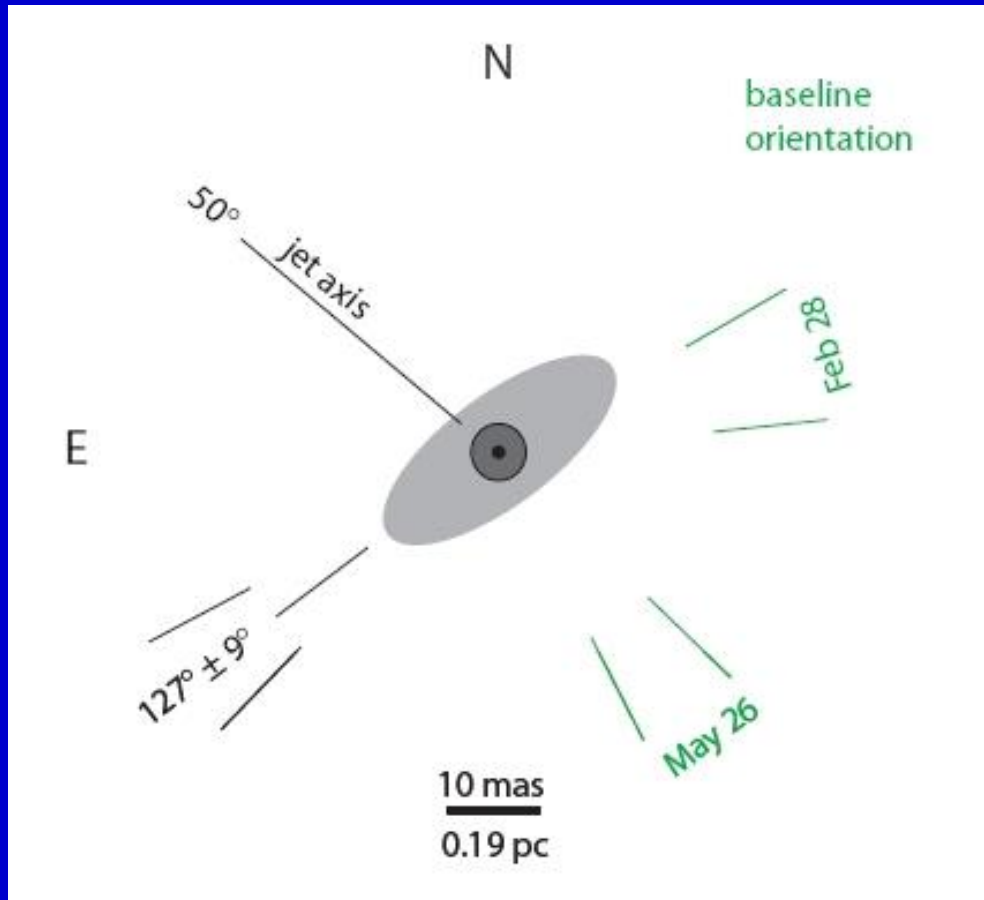
Super-Eddington discs



Super-Eddington accretion leads to formation of an optically-thick envelope scattering the radiation formed in the disc.

This makes the apparent disc size larger and practically independent of wavelength

Discs observed by VLTI



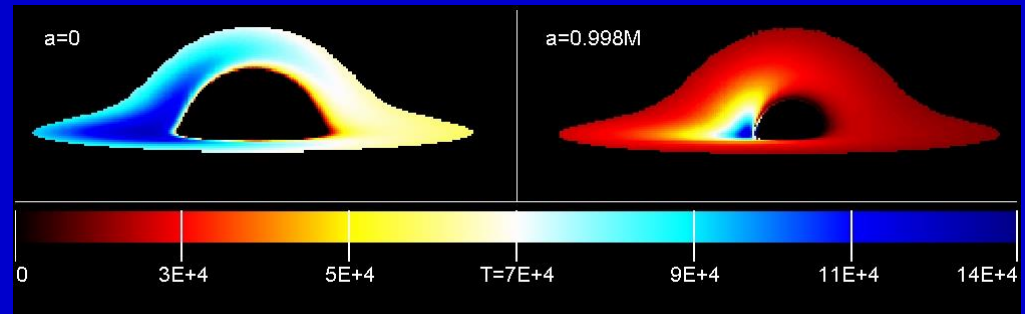
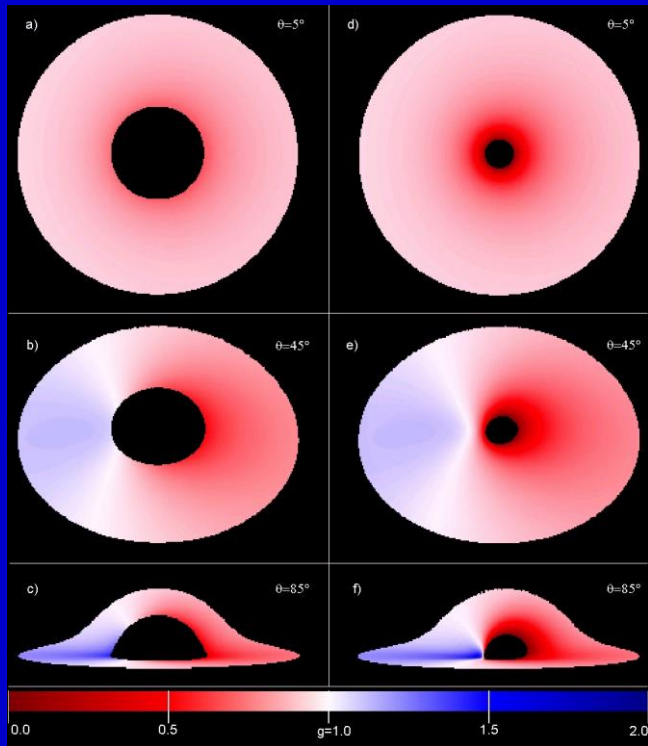
The structure of the disc in Cen A was studied in IR for scales $<1 \text{ pc}$.

The data is consistent with a geometrically thin disc with diameter 0.6 pc .

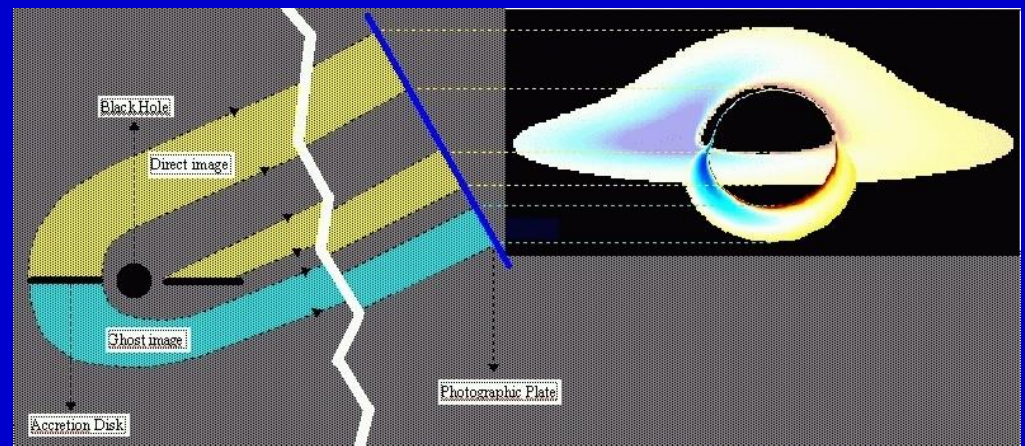
Observations on VLTI.

arXiv:0707.0177 K. Meisenheimer et al.
«Resolving the innermost parsec of Centaurus A at mid-infrared wavelengths»

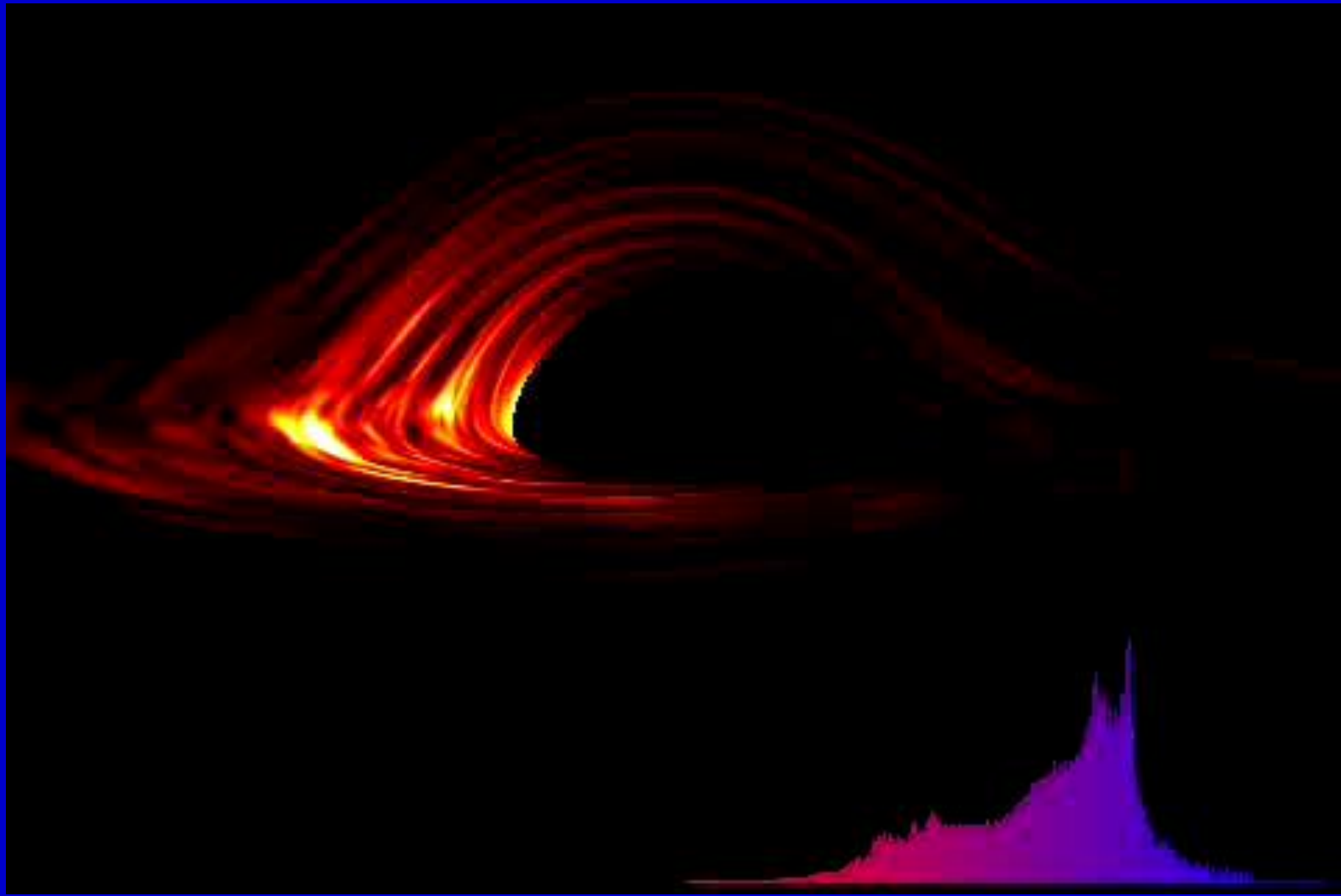
Discs around black holes: a look from aside



Disc temperature

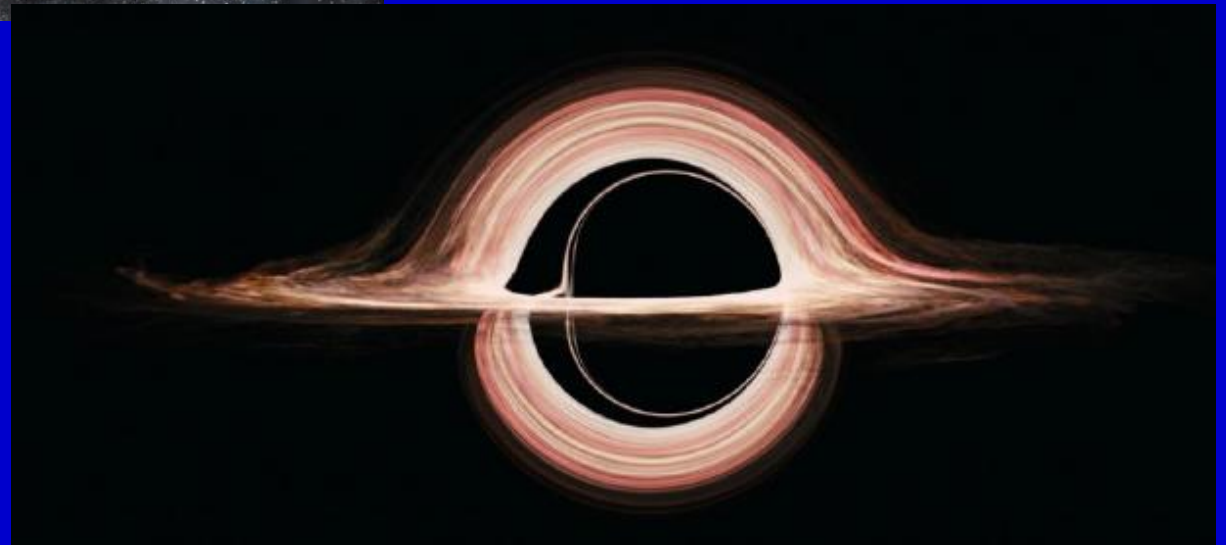
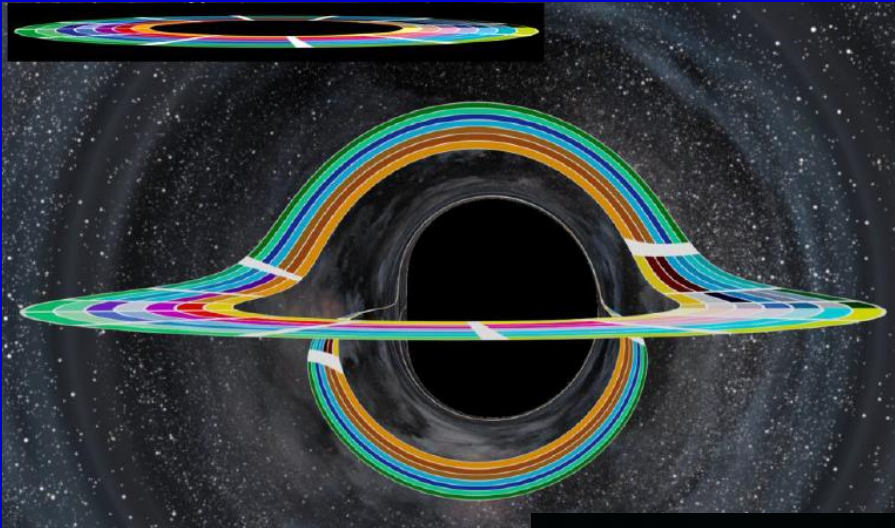


Discs observed from infinity.
Left: non-rotating BH,
Right: rotating.



from gr-qc/0506078

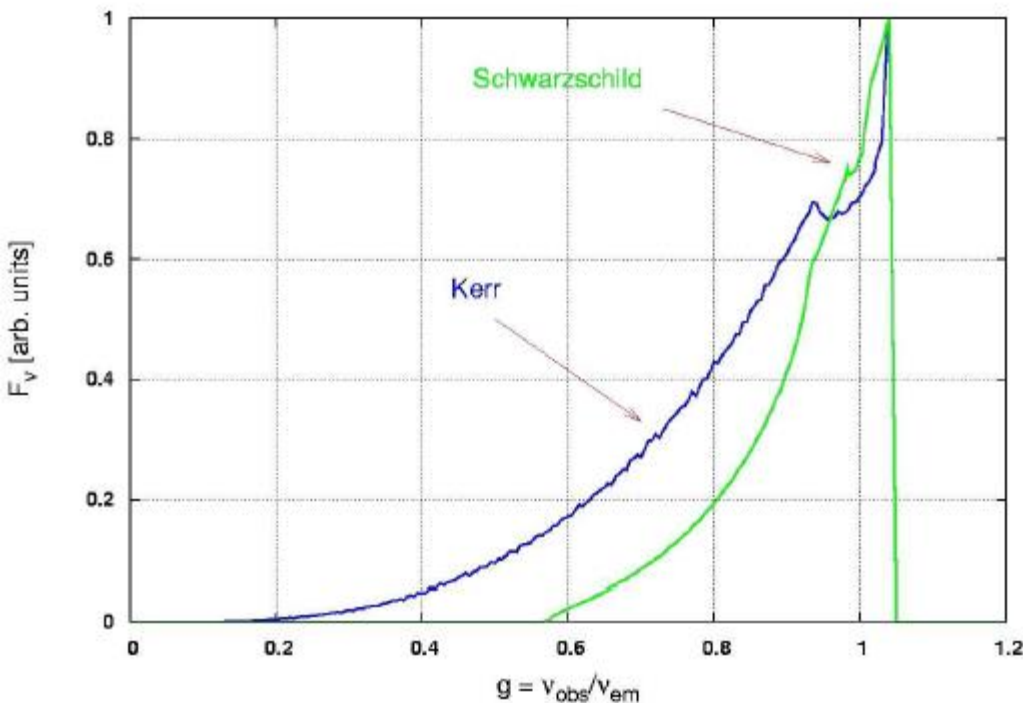
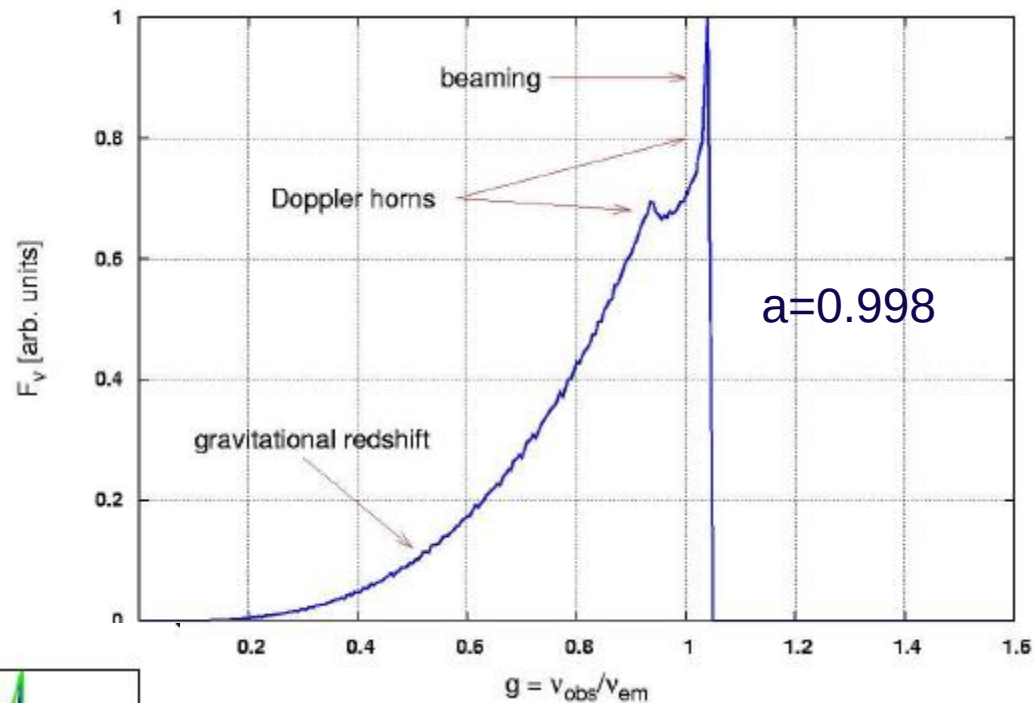
Discs from Interstellar movie



Different effects

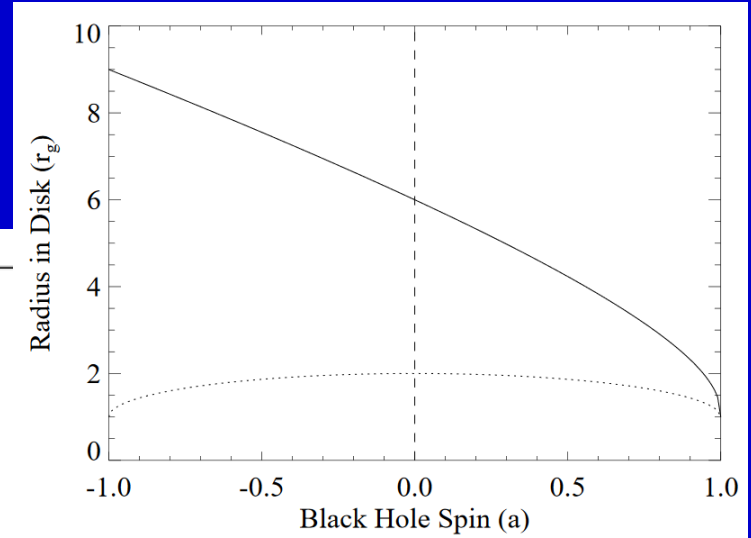
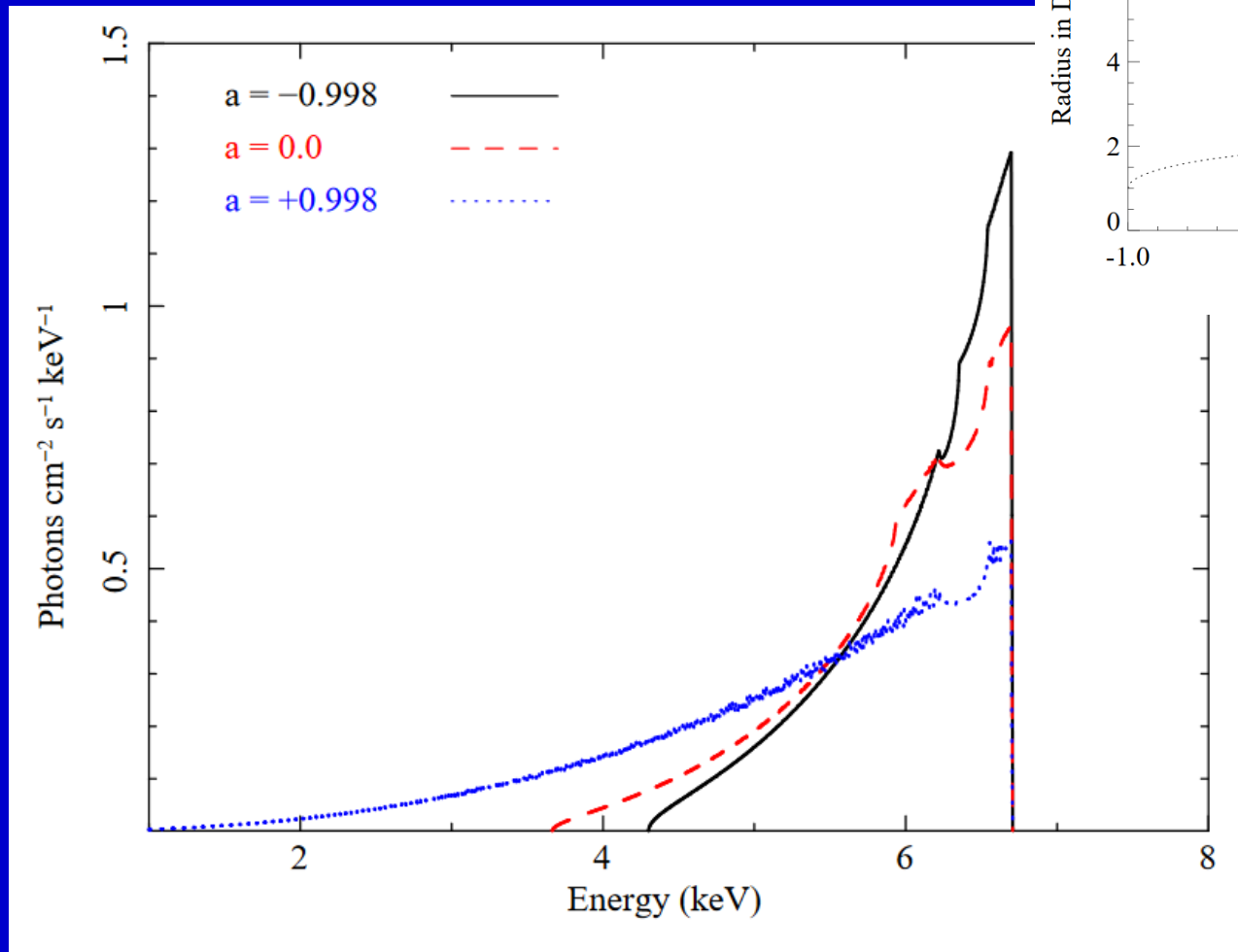
$$r_+ = \frac{GM}{c^2} + \left[\left(\frac{GM}{c^2} \right)^2 - \left(\frac{J}{Mc} \right)^2 \right]^{\frac{1}{2}}$$

For maximal rotation $r_{\text{ISCO}} = r_+$

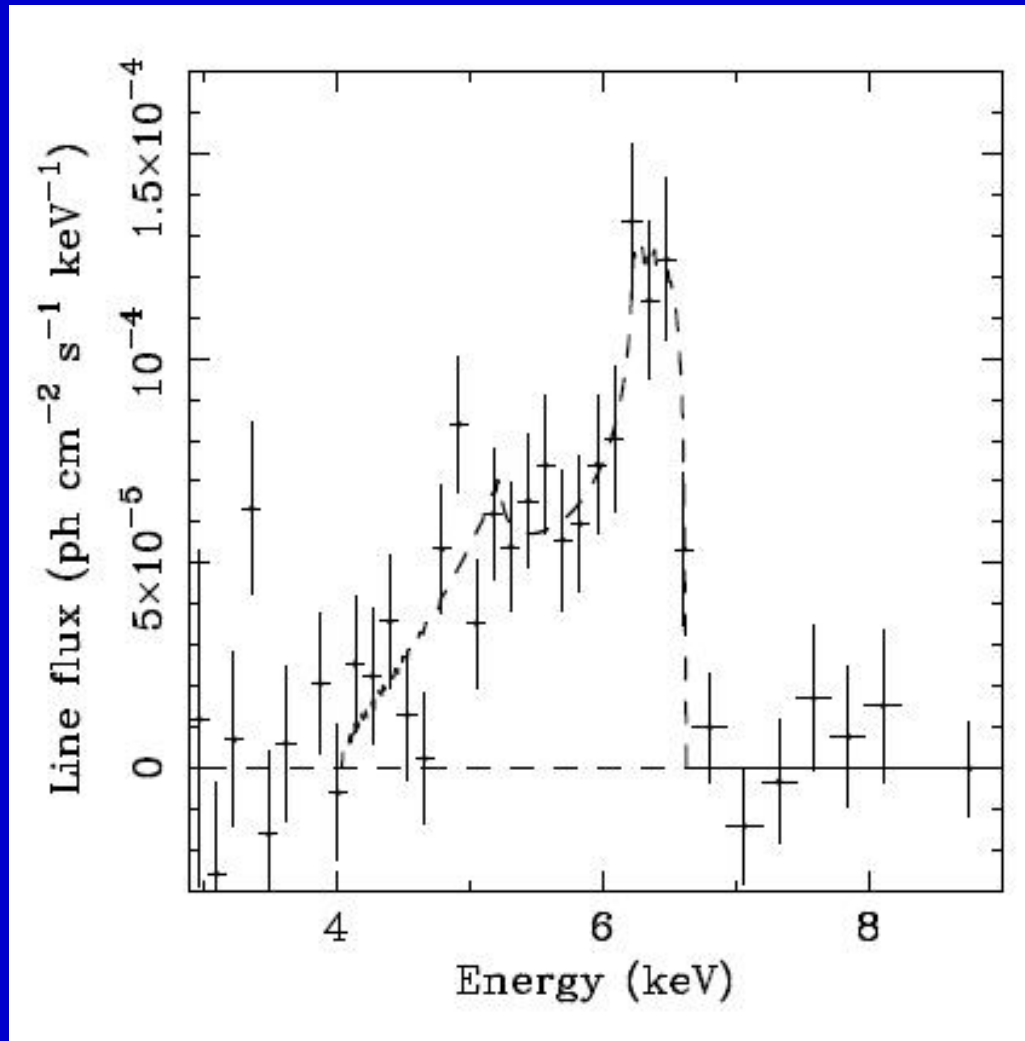


- Doppler effect
- Relativistic beaming
- GR light bending
- GR grav. redshift

Rotation direction



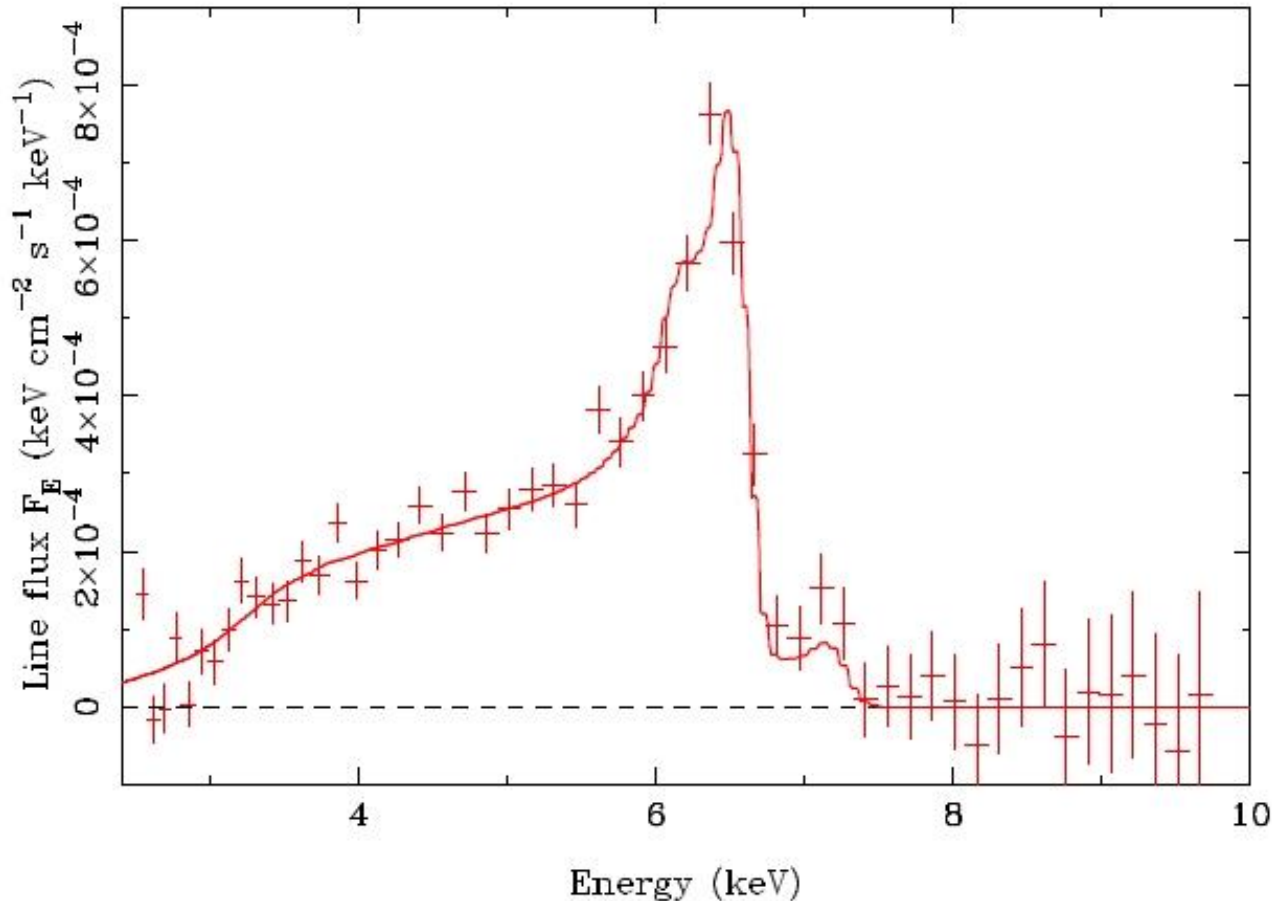
Fluorescent lines



The K α iron line observed by
ASCA (1994 r.).
Seyfert galaxy MCG-6-30-15

Dashed line: the model with
non-rotating BH,
disc inclination 30 degrees.

Lines and rotation of BHs



XMM-Newton data
(astro-ph/0206095)

The fact that the line extends to the red side below 4 keV is interpreted as the sign of rapid rotation (the disc extends inside $3R_g$).

see astro-ph/0212065

Suzaku spin measurements program

NGC 3783 $z = 0.00973$

A very complicated model.

$a > 0.93$ (90% confidence)

AGN	a
MCG-6-30-15 ^a	≥ 0.98
Fairall 9 ^b	$0.65^{+0.05}_{-0.05}$
SWIFT J2127.4+5654 ^c	$0.6^{+0.2}_{-0.2}$
1H0707-495 ^d	≥ 0.98
Mrk 79 ^e	$0.7^{+0.1}_{-0.1}$
Mrk 335 ^f	$0.70^{+0.12}_{-0.01}$
NGC 7469 ^f	$0.69^{+0.09}_{-0.09}$
NGC 3783 ^g	≥ 0.98

A little bit more data

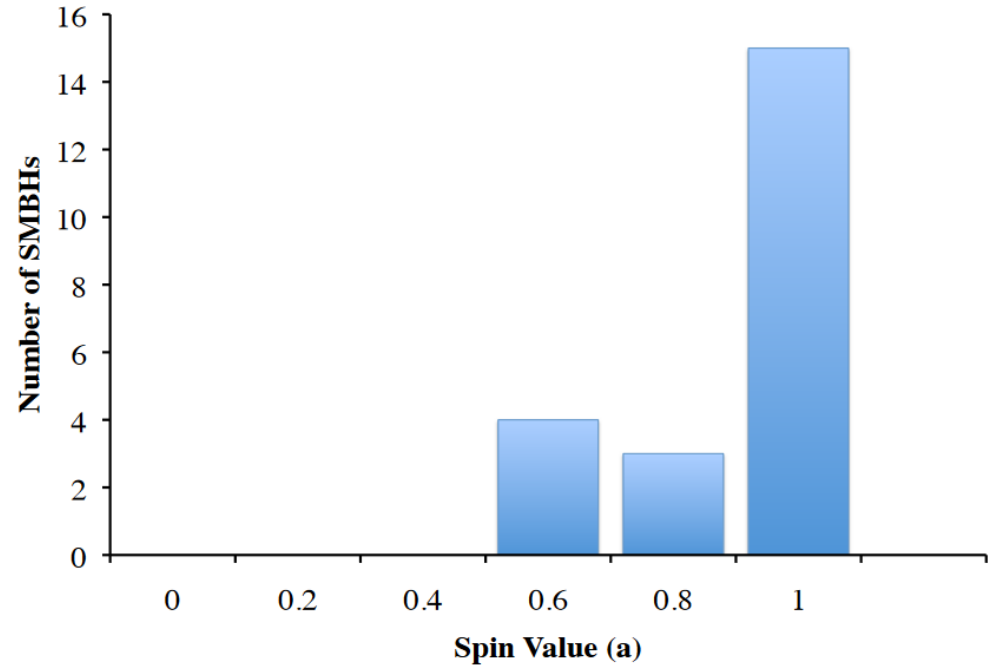
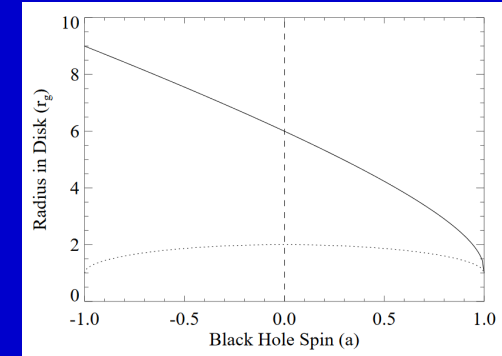
in 1307.3246

and a big review in 1309.6334

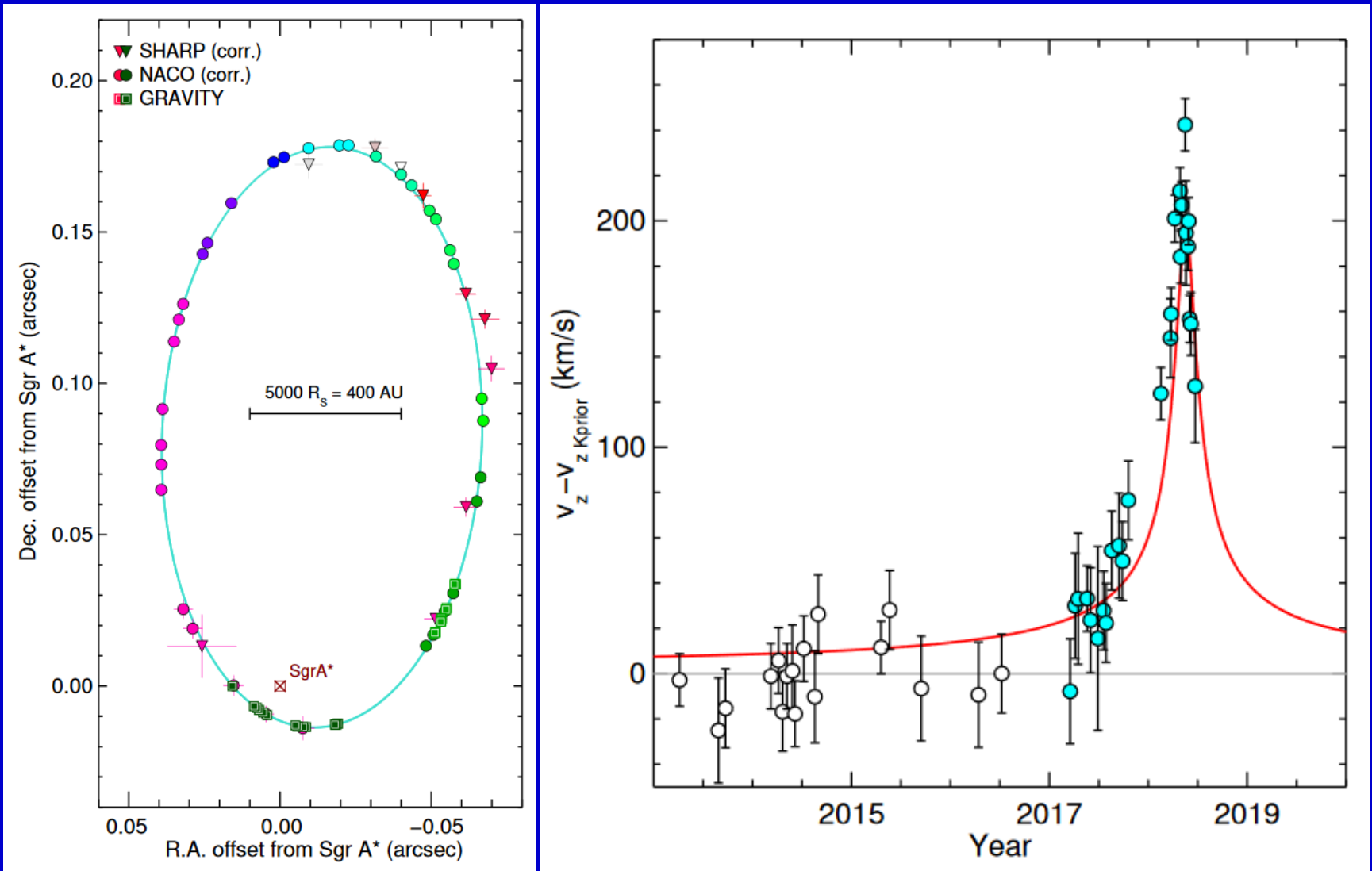


Relativistic reflection fitting of spectra

AGN	a	log M	$L_{\text{bol}}/L_{\text{Edd}}$	Host
MCG 6-30-15 ^a	$\geq +0.98$	$6.65^{+0.17}_{-0.17}$	$0.40^{+0.13}_{-0.13}$	E/S0
Fairall 9 ^b	$+0.52^{+0.19}_{-0.15}$	$8.41^{+0.11}_{-0.11}$	$0.05^{+0.01}_{-0.01}$	Sc
SWIFT J2127.4+5654 ^c	$+0.6^{+0.2}_{-0.2}$	$7.18^{+0.07}_{-0.07}$	$0.18^{+0.03}_{-0.03}$	—
1 H0707-495 ^d	$\geq +0.98$	$6.70^{+0.40}_{-0.40}$	$\sim 1.0_{-0.6}$	—
Mrk 79 ^e	$+0.7^{+0.1}_{-0.1}$	$7.72^{+0.14}_{-0.14}$	$0.05^{+0.01}_{-0.01}$	SBb
Mrk 335 ^f	$+0.70^{+0.12}_{-0.01}$	$7.15^{+0.13}_{-0.13}$	$0.25^{+0.07}_{-0.07}$	S0a
NGC 3783 ^g	$\geq +0.98$	$7.47^{+0.08}_{-0.08}$	$0.06^{+0.01}_{-0.01}$	SB(r)ab
Ark 120 ^h	$+0.94^{+0.1}_{-0.1}$	$8.18^{+0.05}_{-0.05}$	$0.04^{+0.01}_{-0.01}$	Sb/pec
3C 120 ⁱ	≥ 0.95	$7.74^{+0.20}_{-0.22}$	$0.31^{+0.20}_{-0.19}$	S0
1 H0419-577 ^j	$\geq +0.88$	$8.18^{+0.12}_{-0.12}$	$1.27^{+0.42}_{-0.42}$	—
Ark 564 ^j	$+0.96^{+0.01}_{-0.06}$	≤ 6.90	≥ 0.11	SB
Mrk 110 ^j	$\geq +0.99$	$7.40^{+0.09}_{-0.09}$	$0.16^{+0.04}_{-0.04}$	—
SWIFT J0501.9-3239 ^j	$\geq +0.96$	—	—	SB0/a(s) pec
Ton S180 ^j	$+0.91^{+0.02}_{-0.09}$	$7.30^{+0.60}_{-0.40}$	$2.15^{+3.21}_{-1.61}$	—
RBS 1124 ^j	$\geq +0.98$	8.26	0.15	—
Mrk 359 ^j	$+0.66^{+0.30}_{-0.54}$	6.04	0.25	pec
Mrk 841 ^j	$\geq +0.52$	7.90	0.44	E
IRAS 13224-3809 ^j	$\geq +0.995$	7.00	0.71	—
Mrk 1018 ^j	$+0.58^{+0.36}_{-0.74}$	8.15	0.01	S0
IRAS 00521-7054 ^l	$\geq +0.84$	—	—	—
NGC 4051 ^m	$\geq +0.99$	6.28	0.03	SAB(rs)bc
NGC 1365 ^k	$+0.97^{+0.01}_{-0.04}$	$6.60^{+1.40}_{-0.30}$	$0.06^{+0.06}_{-0.04}$	SB(s)b



Gravitational redshift of the S2 star

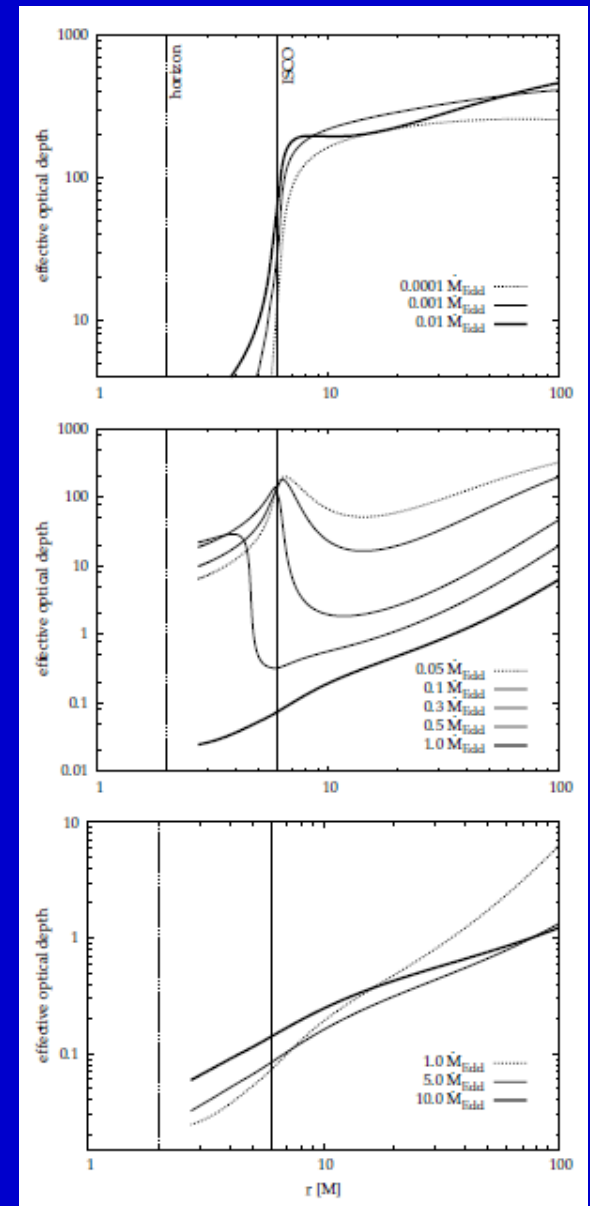
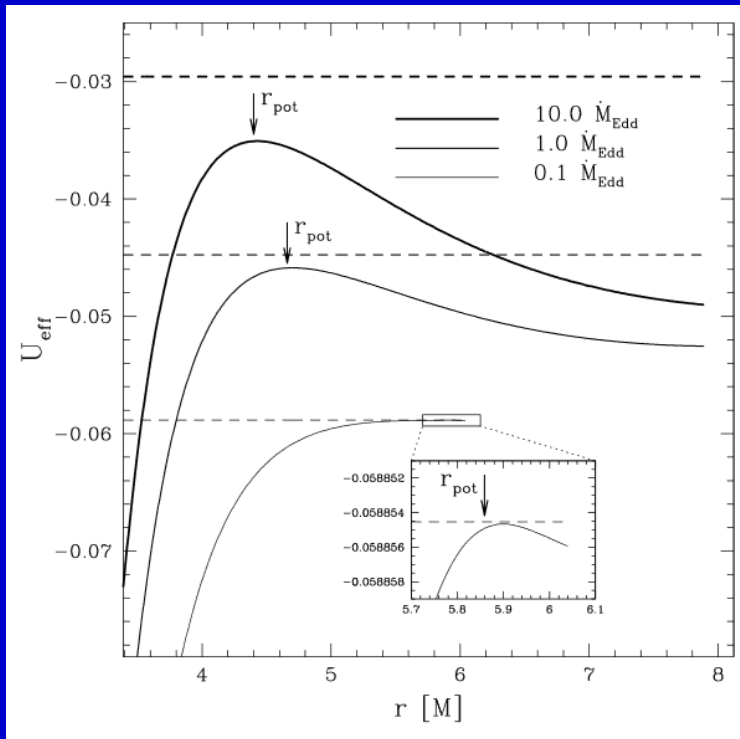


1807.09409

The inner edge

The place where the fluorescent line is formed is not necessarily the standard ISCO.

Especially for large accretion rates the situation is complicated.



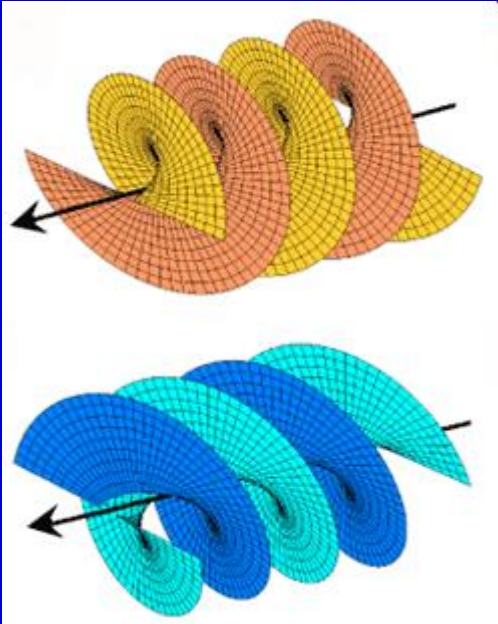
Measuring spins of stellar-mass BHs

Source	Spin a_*
GRS 1915+105	> 0.98
LMC X-1	$0.92^{+0.05}_{-0.07}$
M33 X-7	0.84 ± 0.05
4U 1543-47	0.80 ± 0.05
GRO J1655-40	0.70 ± 0.05
XTE J1550-564	$0.34^{+0.20}_{-0.28}$
LMC X-3	$< 0.3^b$
A0620-00	0.12 ± 0.18

Different methods used
1101.0811

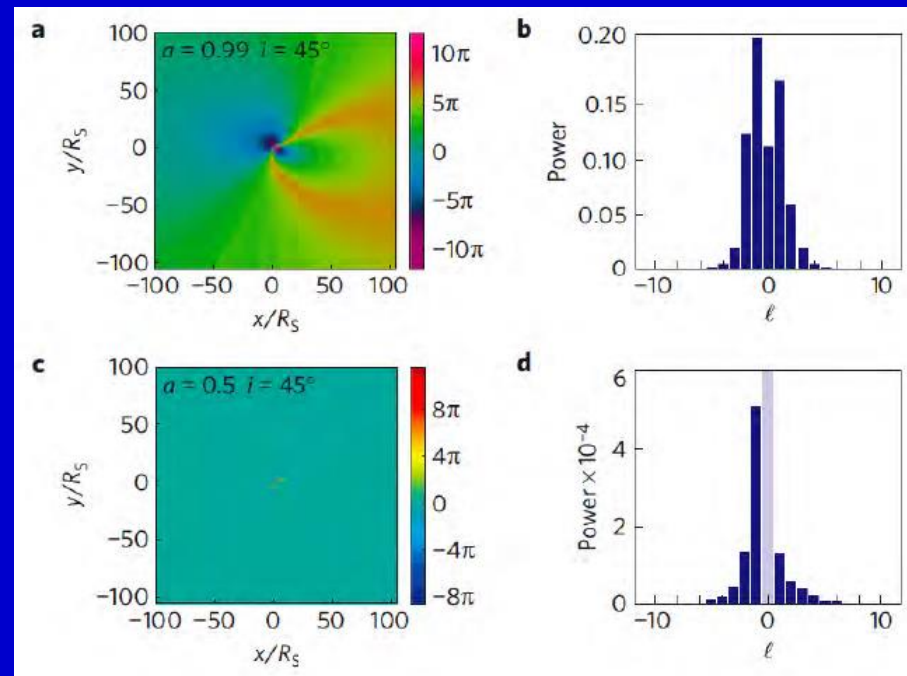
See a review on BH spin
(both XRB and AGN) in
1507.06153

Twisted light



This effect can be used to learn about spin of accreting BHs.

If the source of the gravitational field also rotates, it drags space-time with it. Because of the rotation of the central mass, each photon of a light beam propagating along a null geodesic will experience a well-defined phase variation.



1104.3099

See <http://www.physics.gla.ac.uk/Optics/play/photonOAM/> and astro-ph/0307430 about orbital angular momentum of photons

Horizon and exotics

Main reviews and articles

- gr-qc/0506078 **Black Holes in Astrophysics**
- astro-ph/0207270 **No observational proof of the black-hole event-horizon**
- gr-qc/0507101 **Black holes and fundamental physics**
- astro-ph/0401549 **Constraining Alternate Models of Black Holes:
Type I X-ray Bursts on Accreting Fermion-Fermion and
Boson-Fermion Stars**
- arXiv: 0903.1105 **The Event Horizon of Sagittarius A***
- arXiv: 1312.6698 **Observational evidence (review)**
- arXiv: 1904.05363 **Testing the nature of dark compact objects: a status report**

The horizon problem

What can be a 100% proof that we observe a BH?

Of course, only a direct evidence for the horizon existence!

But it is very difficult to prove it!

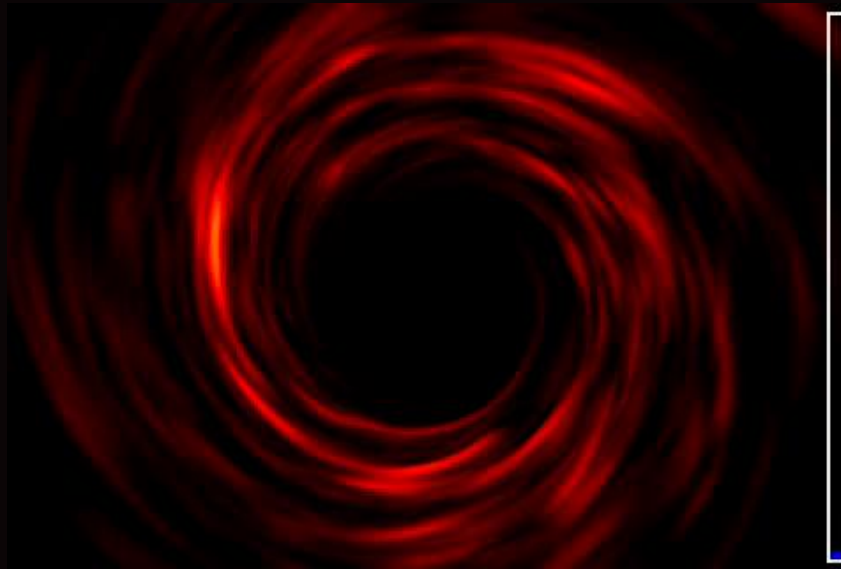
One can try to follow three routes:

1. To look for direct evidence for the horizon.
2. To try to prove the absence of a surface.
3. To falsify the alternative models.

The first approach is not very realistic ([astro-ph/0207270](https://arxiv.org/abs/astro-ph/0207270) Abramowicz et al.)

We can hope to have direct images from the horizon vicinity (for example, for Sgr A* the corresponding size is 0.02 milliarcseconds), or to have data from BH coalescence via GW detection. (see Narayan [gr-qc/0506078](https://arxiv.org/abs/gr-qc/0506078))

Dreams about direct images



(Narayan 2005)



The MAXIM Project (Cash 2002)
<http://beyondeinstein.nasa.gov/press/images/maxim/>

Prototype: 100 microarcsecs
MAXIM: 100 nanoarcsecs
33 satellites with X-ray optics
and a detector in 500 km away.

Absence of surface

Here we mostly discuss close binaries with accretion

- Lack of pulsations
- No burster-like bursts
Nowhere to collect matter.
(however, see below about some alternatives)
- Low accretion efficiency (also for Sgr A*)
ADAF. Energy is taken under horizon.
- No boundary layer (Sunyaev, Revnivtsev 2000)
Analysis of power spectra.
Cut-off in BH candidates above 50 Hz.

The case of Sgr A*

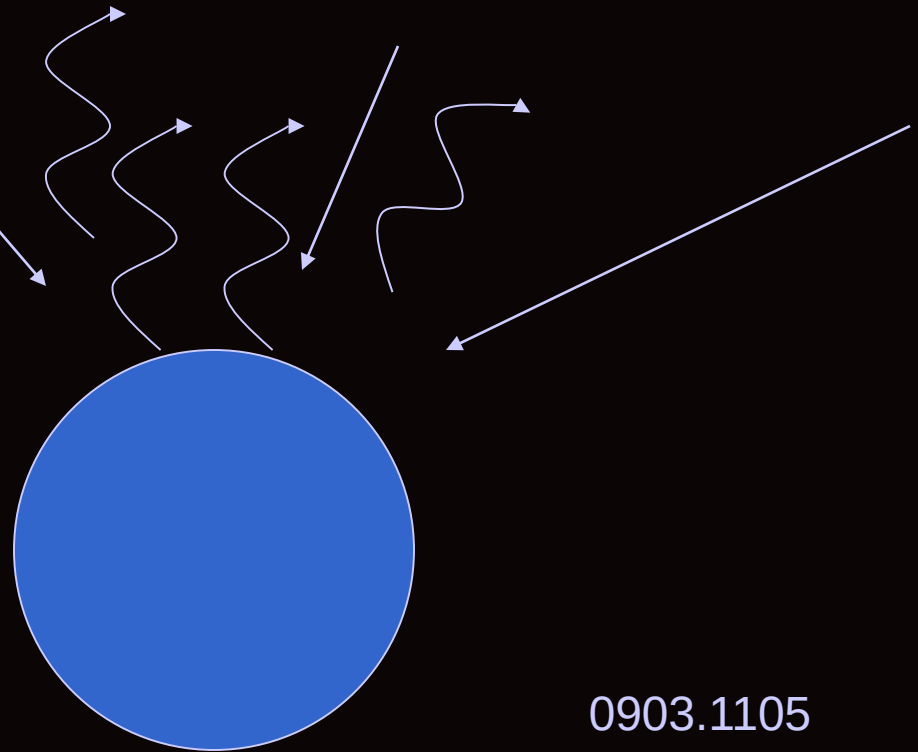
Recent millimeter and infrared observations of Sagittarius A* (Sgr A*), the supermassive black hole at the center of the Milky Way, all require the existence of a horizon.

Magnetic field observed around Sgr A* due to faraday rotation of the radio pulsar emission can explain the energy release in the flow:

1308.3147.

Now fields are observed directly:

1512.01220.



See also 1503.03873 about M87

Surface emission limits

$$E_{\infty} = \Delta\epsilon_g \dot{m} c^2$$

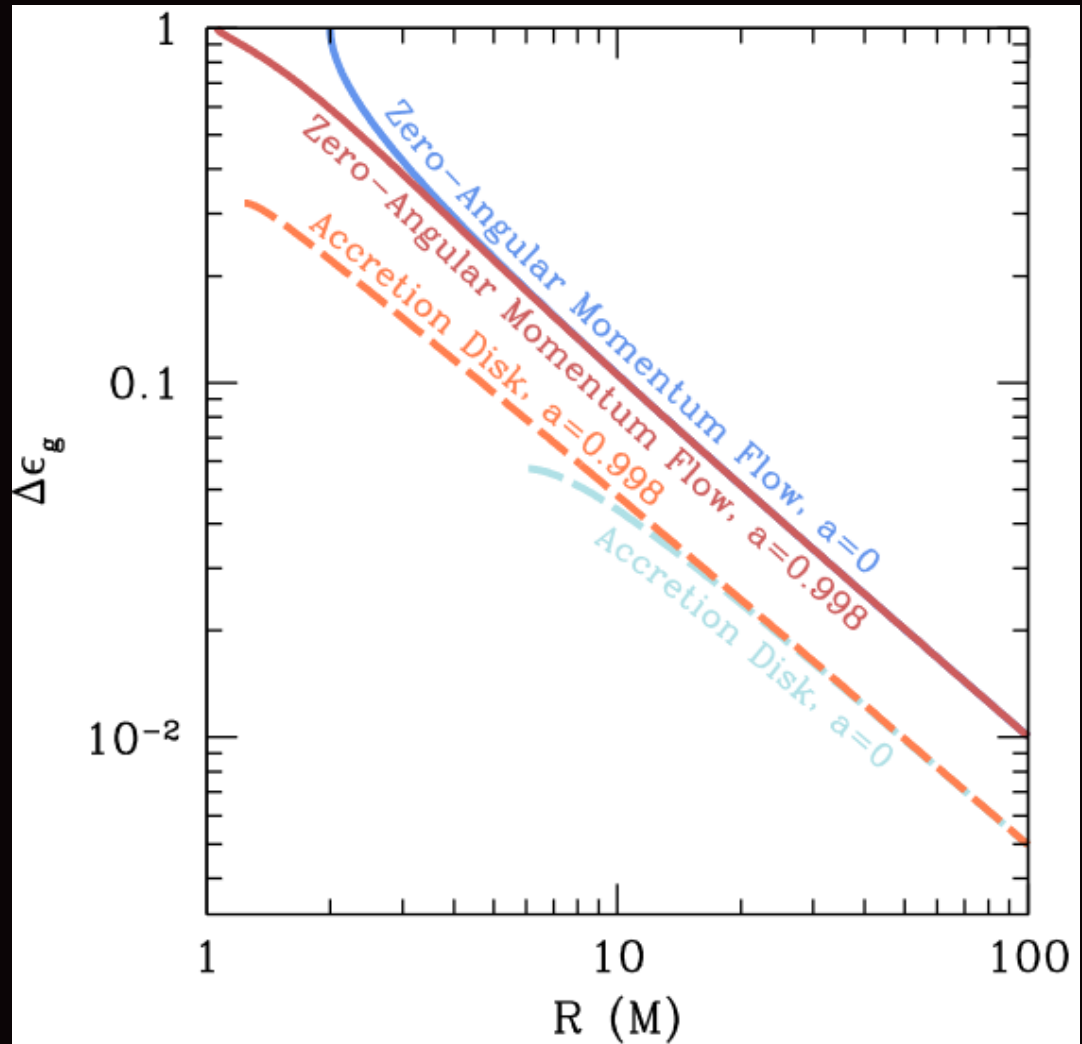
$$L_{\infty} = \Delta\epsilon_g \dot{M} c^2$$

$$L_{\text{obs}} = \eta_r L_{\infty}$$

$$L_{\text{out}} = \eta_k L_{\infty}$$

$$L_{\text{surf}} = L_{\infty} - L_{\text{obs}} - L_{\text{out}}$$

$$= \frac{1 - \eta_r - \eta_k}{\eta_r} L_{\text{obs}}$$



Limits

$$L_{\text{surf}} = 4\pi\sigma R_a^2 T_\infty^4$$

$$T_\infty = \left(\frac{1 - \eta_r - \eta_k}{\eta_k} \frac{L_{\text{obs}}}{4\pi\sigma R_a^2} \right)^{1/4}$$

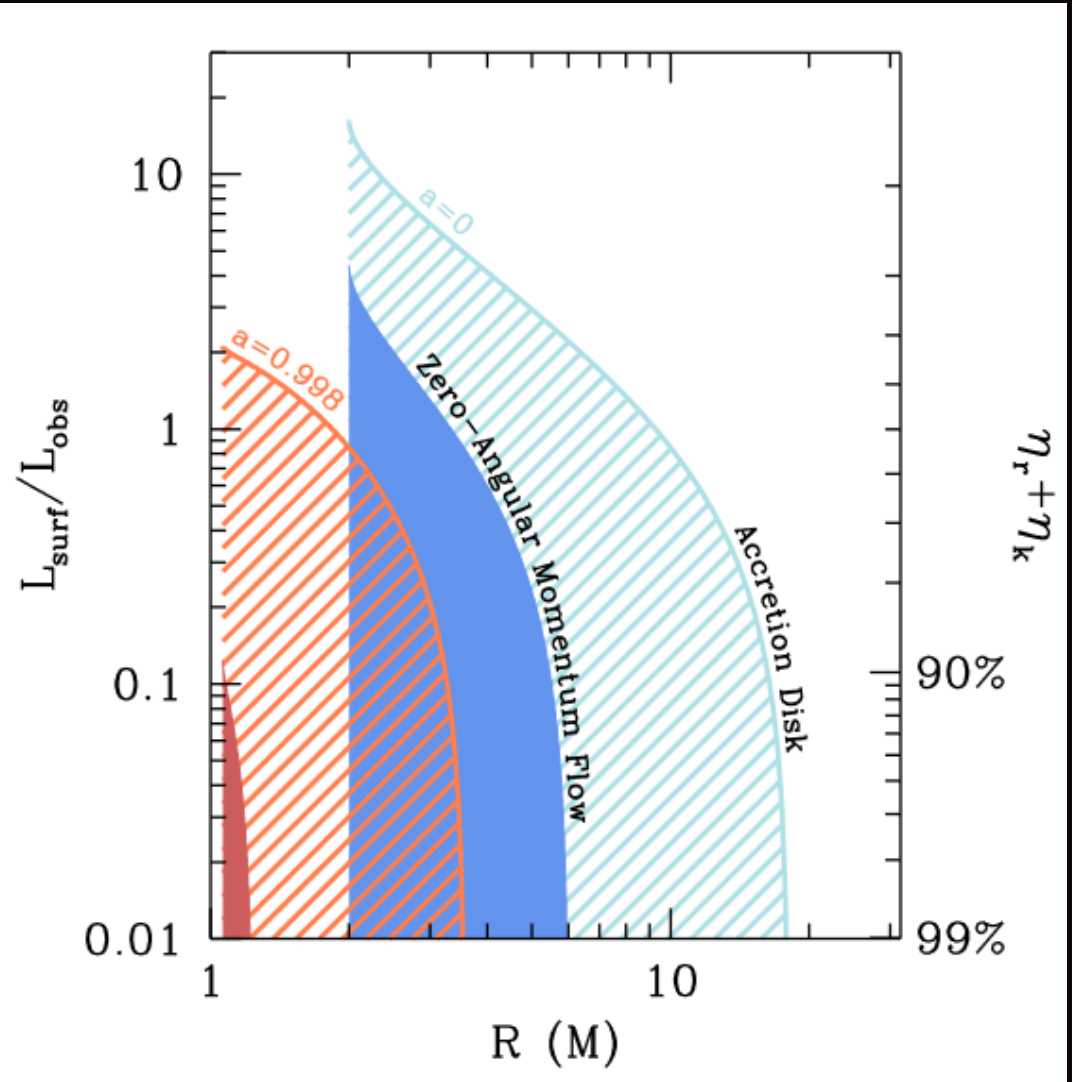
$$F_\nu = \pi \left(\frac{R_a}{D} \right)^2 B_\nu(T_\infty)$$

$$T_{\text{max}} = h\nu / k \ln \left(1 + \frac{2\pi h\nu^3 R_a^2}{c^2 F_\nu^{\text{obs}} D^2} \right)$$

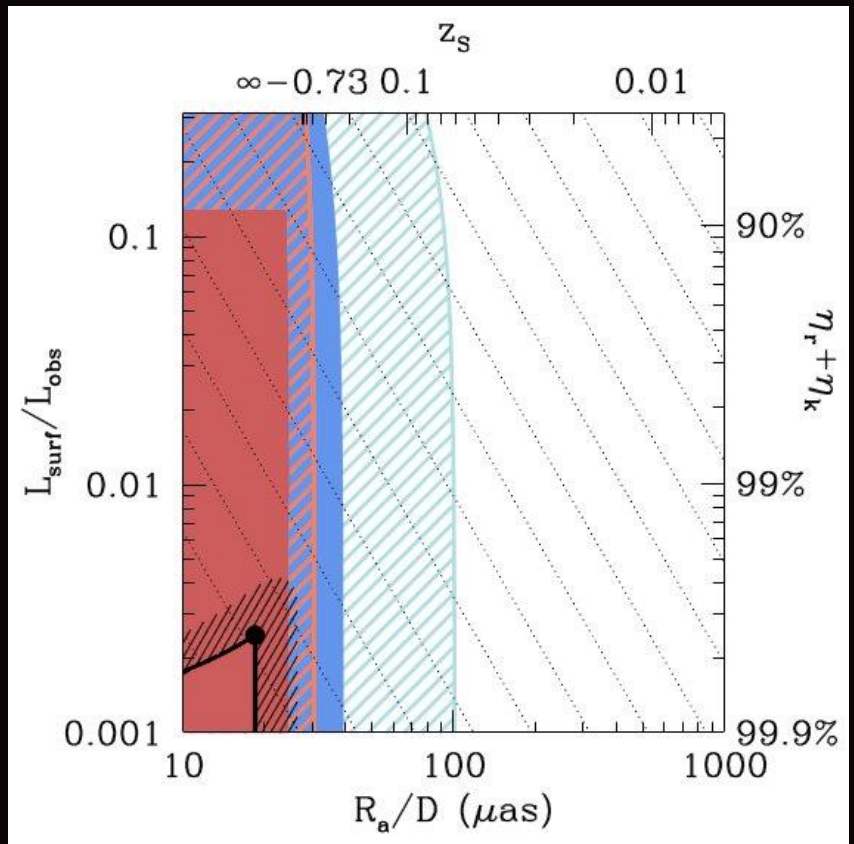
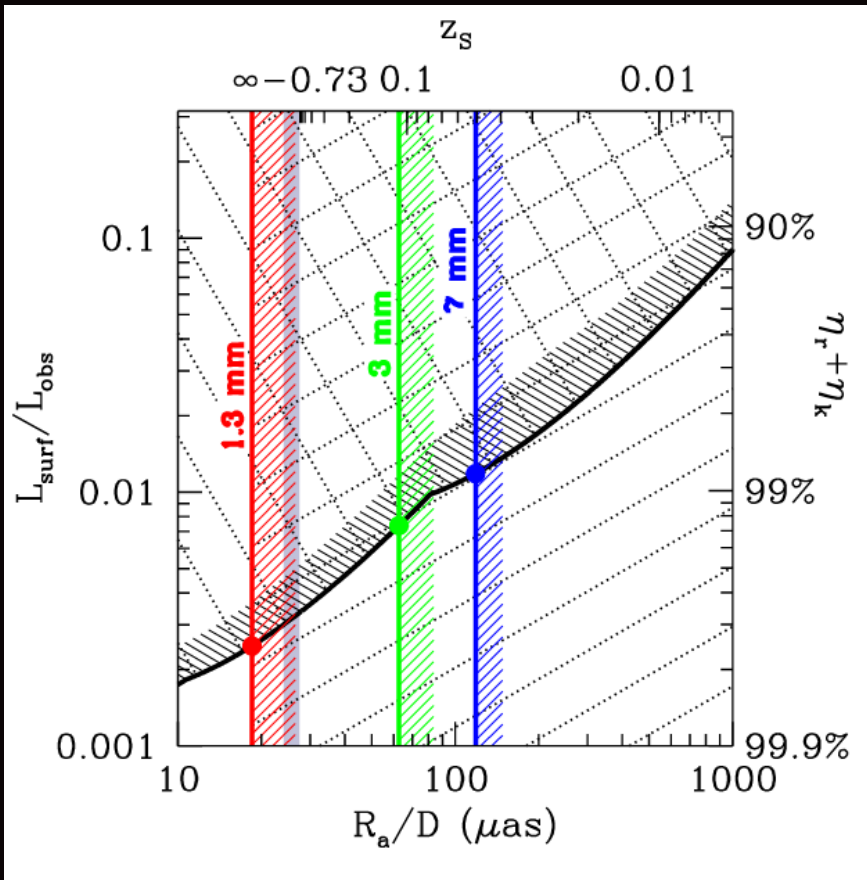
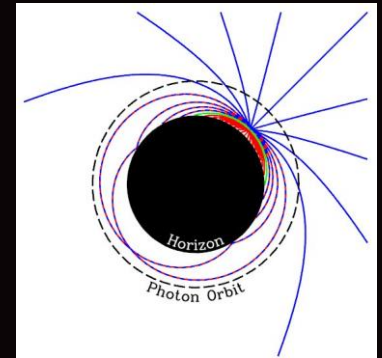
$$\frac{L_{\text{surf}}}{L_{\text{obs}}} \leq \frac{L_{\text{surf,max}}}{L_{\text{obs}}}$$

$$\equiv \frac{\sigma R_a^2}{D^2 F_{\text{obs}}} T_{\text{max}}^4 \left(\nu, F_\nu^{\text{obs}}, \frac{R_a}{D} \right)$$

$$\eta_r + \eta_k \geq \frac{1}{1 + L_{\text{surf,max}}/L_{\text{acc}}}$$



Sgr A*

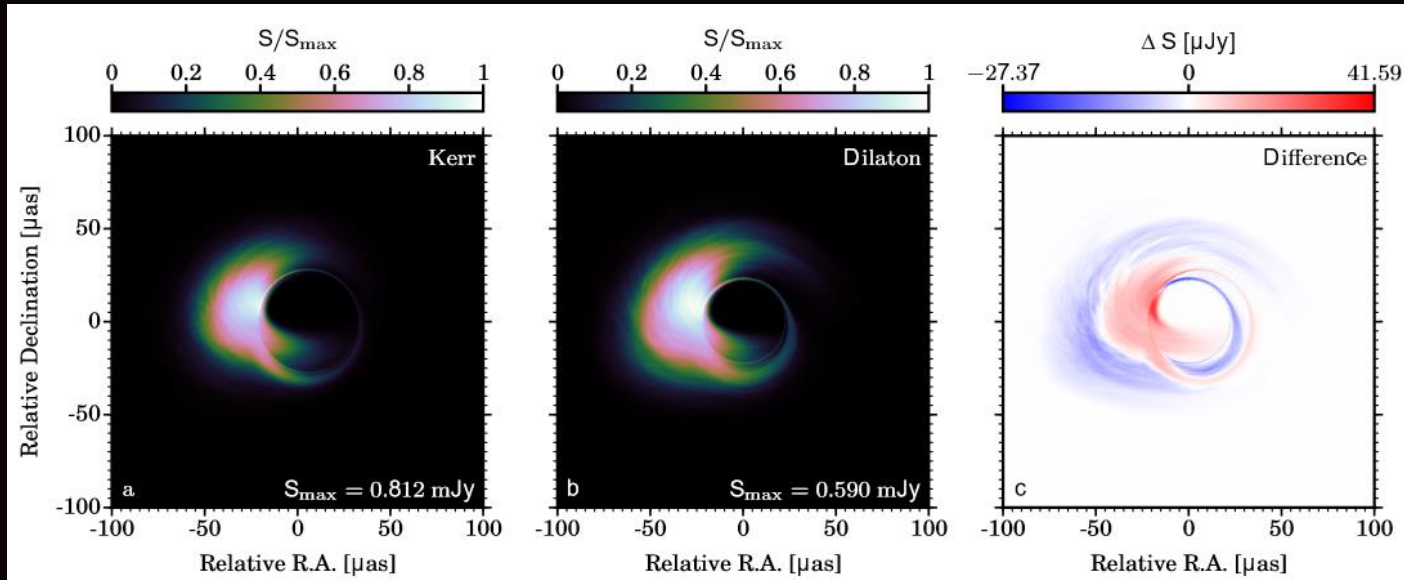


BH shadow and alternative theories

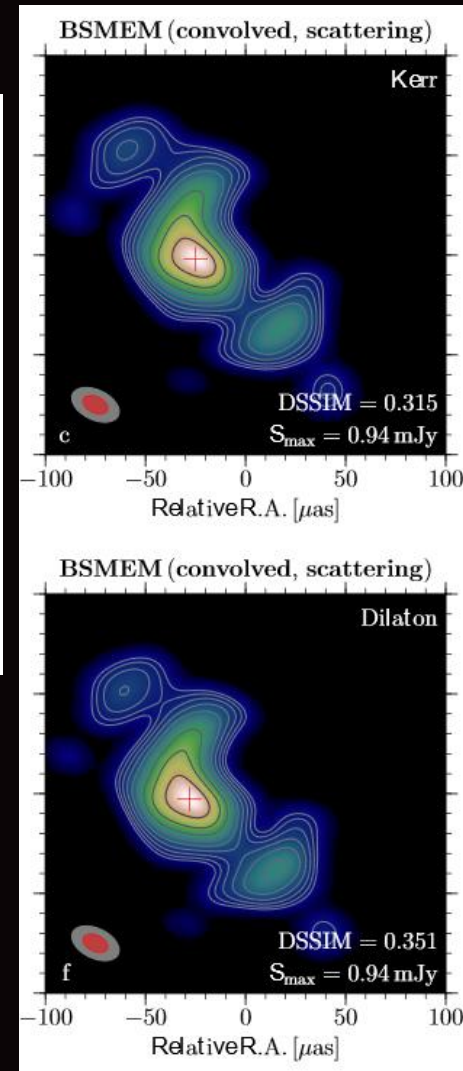
Kerr BH

Dilaton non-rotating

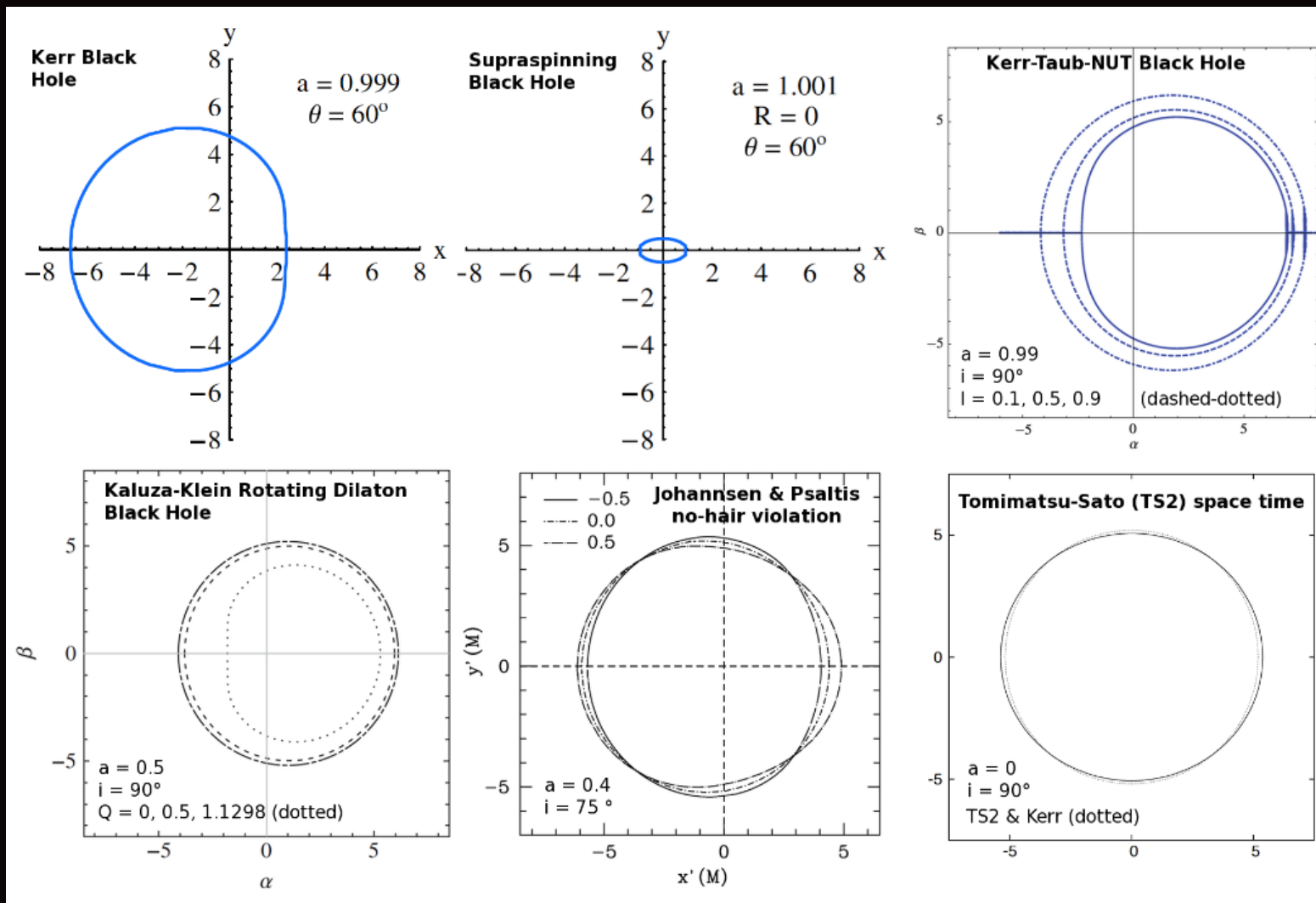
Difference



Impossible to distinguish with present day technique.



BH shadow in different models



Parameters of different models

Fermion stars:

$M_f = 223 \text{ MeV}$ (non-interacting)

$M_{\text{max}} = 12.61 M_0$

$R(M=10M_0) = 252 \text{ km} = 8.6 R_{\text{sh}}$

Collapse after adding $0.782 M_0$ of gas.

Bozon stars:

$M_b = 2.4 \cdot 10^{-17} \text{ MeV}$, $\lambda = 100$

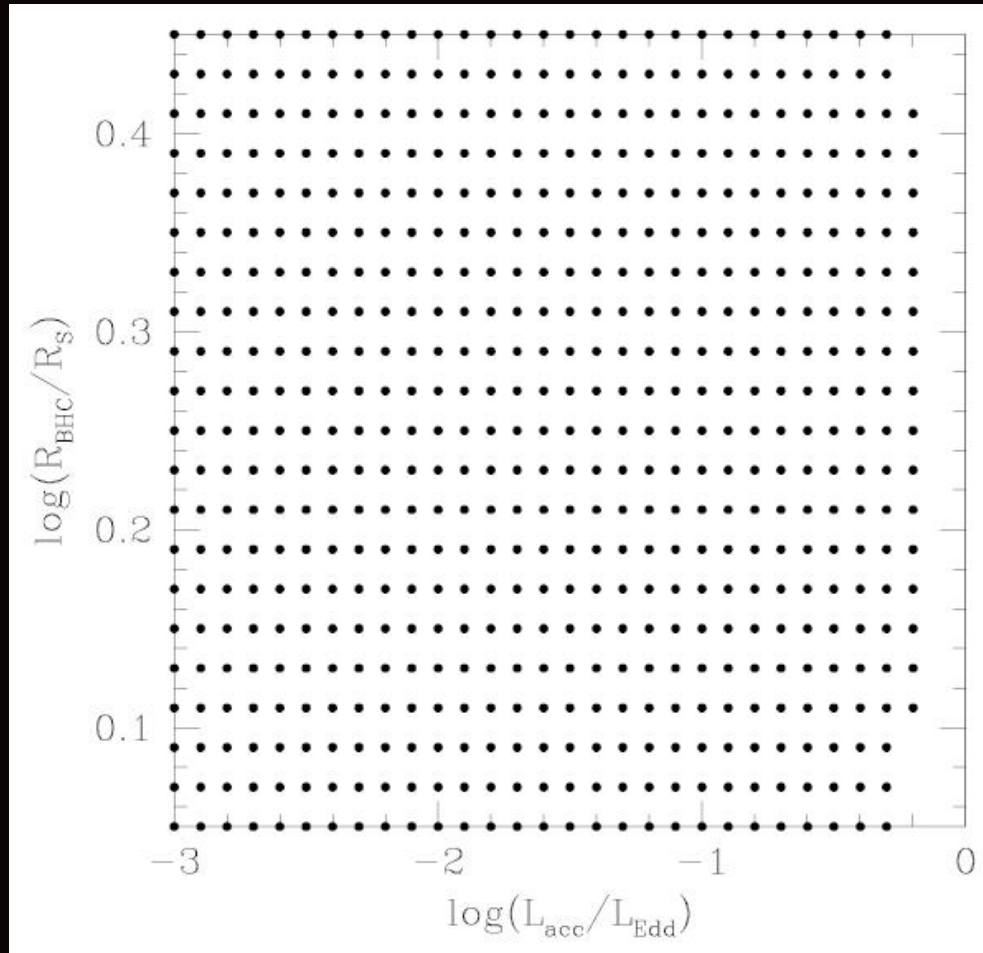
$M_{\text{max}} = 12.57 M_0$

$R(M=10M_0) = 153 \text{ km}$ (99.9% of mass)

Collapse after adding $0.863 M_0$ of gas.

Model parameters are constrained by limits on the maximum size of an object derived from QPOs at 450 Hz

Stability respect to flares on a surface



$$R_{\min} = 9/8 R_{\text{sh}}$$

Potentially, smaller radii are possible, but such objects should be unstable in GR.

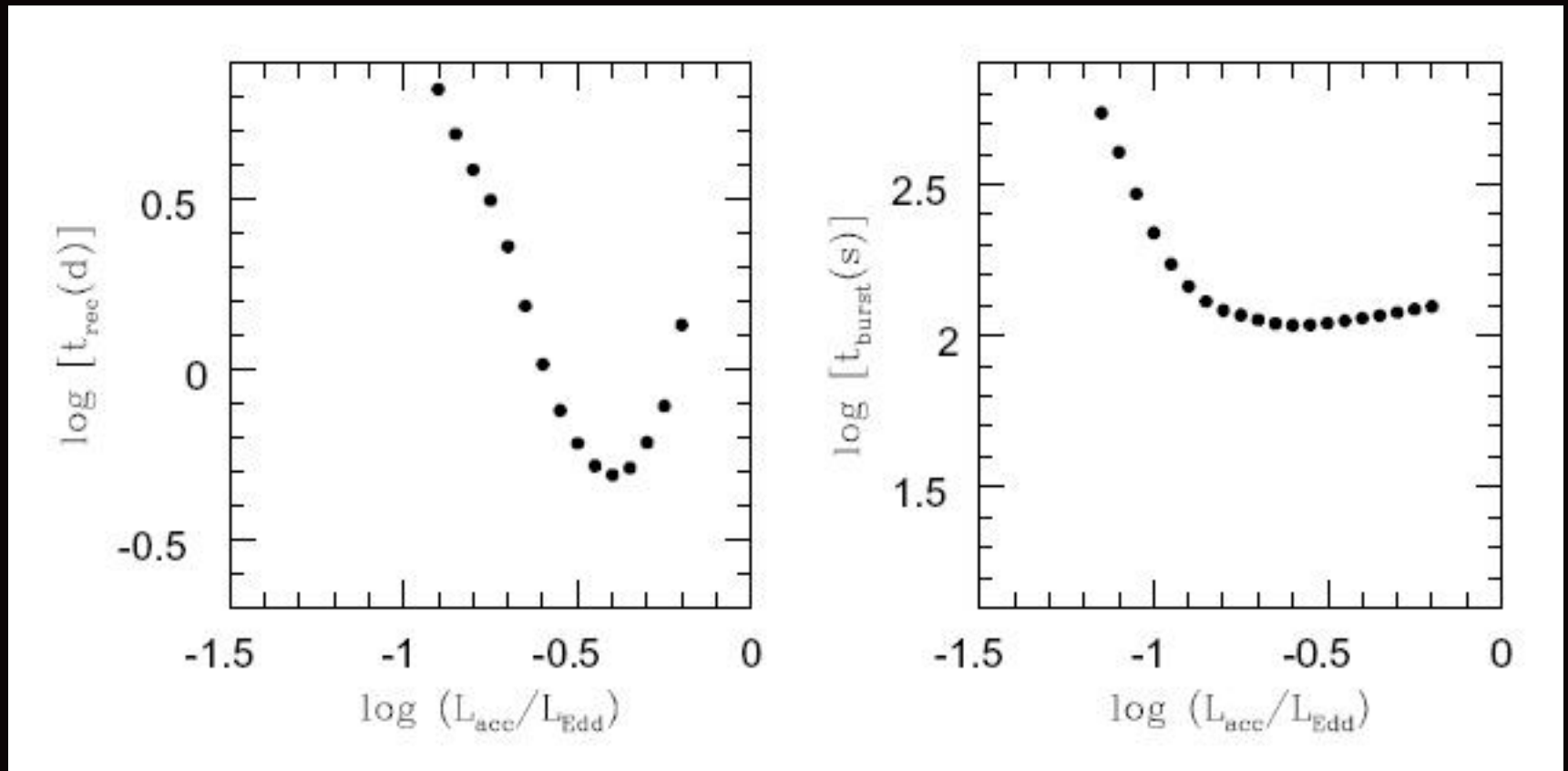
Still, if they are possible, then one can “hide” bursts due to high redshift.

Solid dots – bursts.

Blank field – stable burning.

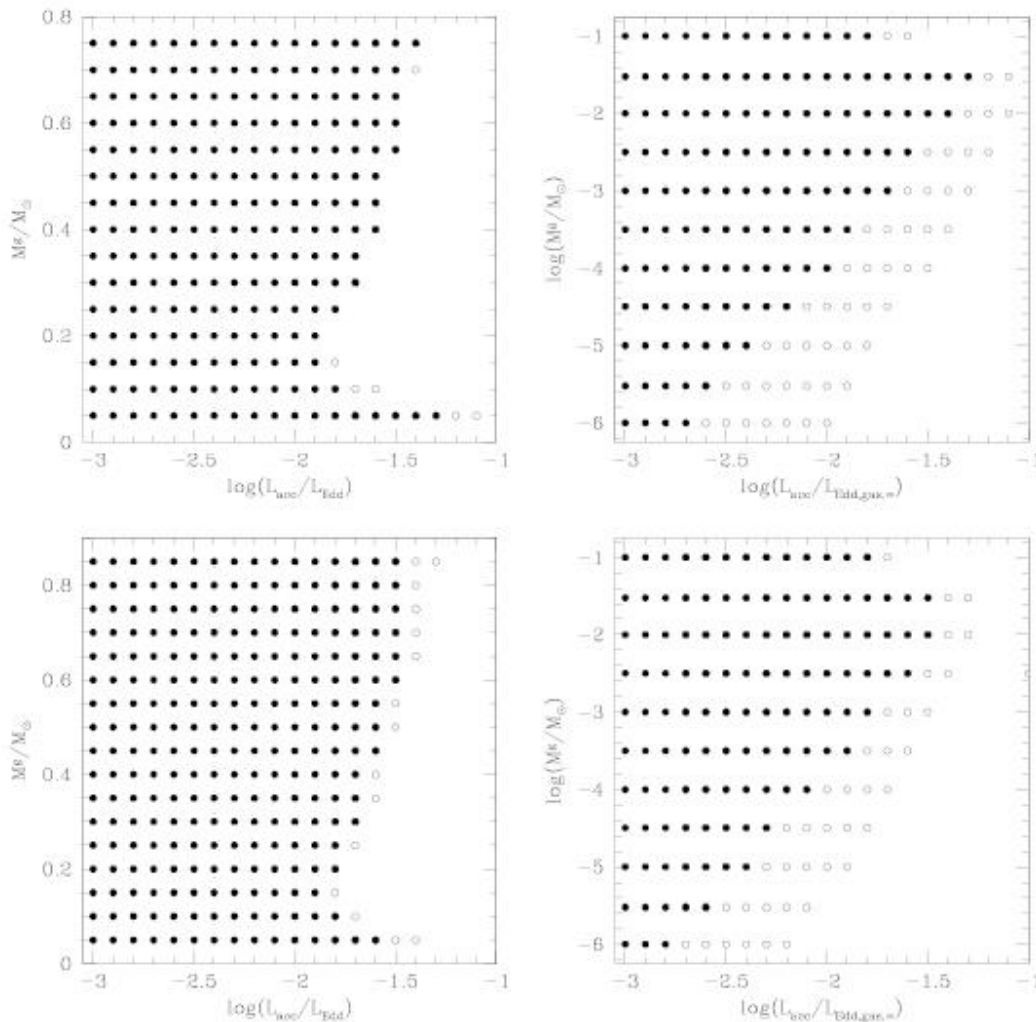
For a 10 solar mass object with hard surface

Timing characteristics of surface bursts



For a 10 solar mass object with hard surface for $R=2R_{\text{sh}}$

Stability respect to flares inside an object

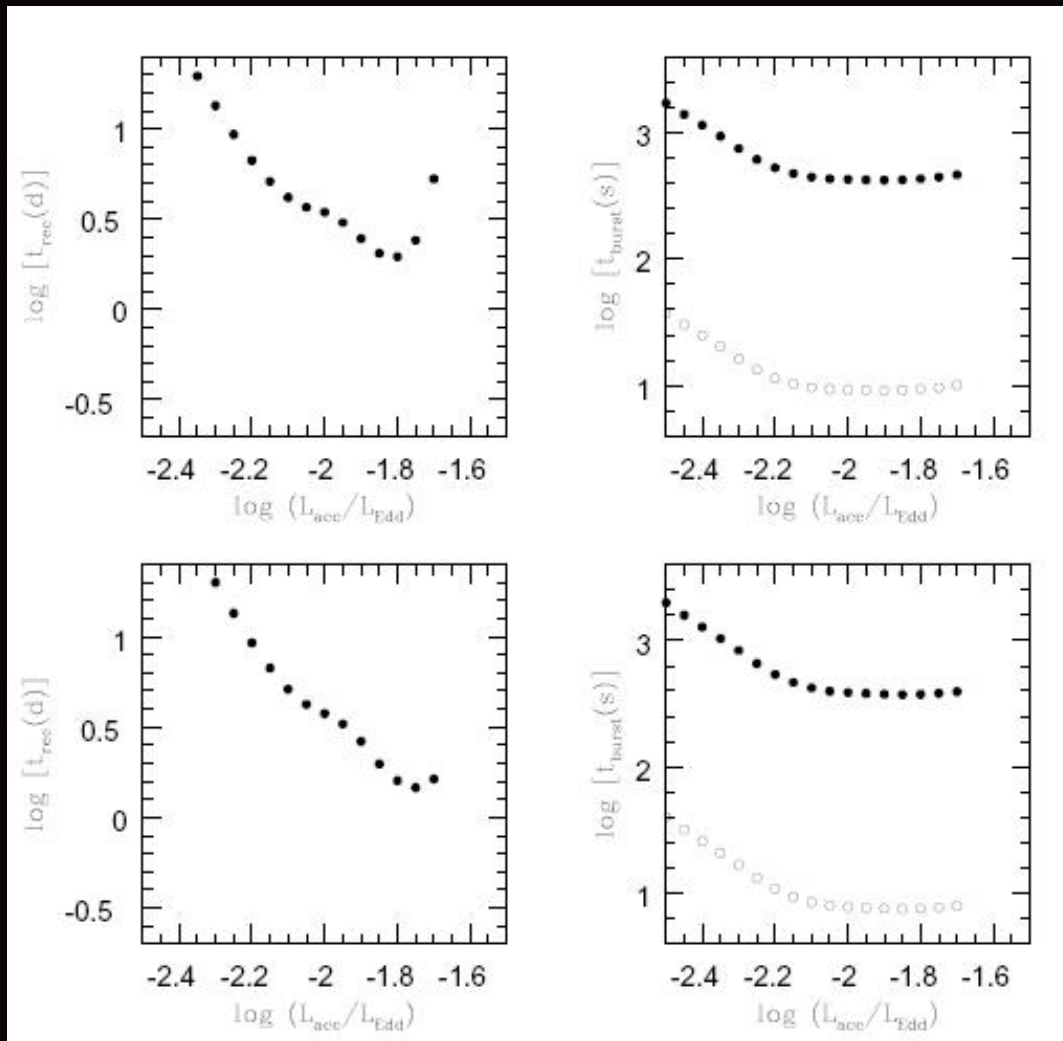


Fermion stars



Bozon stars

Timing characteristics of internal bursts



Fermion stars



Bozon stars

$M_{\text{gas}}=0.3$ solar mass

BHs and fundamental theories

1. Thermodynamics of BHs and Hawking radiation.
2. Testing alternative theories of gravity.
3. Black holes and extra dimensions
4. Accelerator experiments

**Under some reasonable assumptions
astrophysical data can provide
strong and important constraints
on parameters of fundamental theories.**

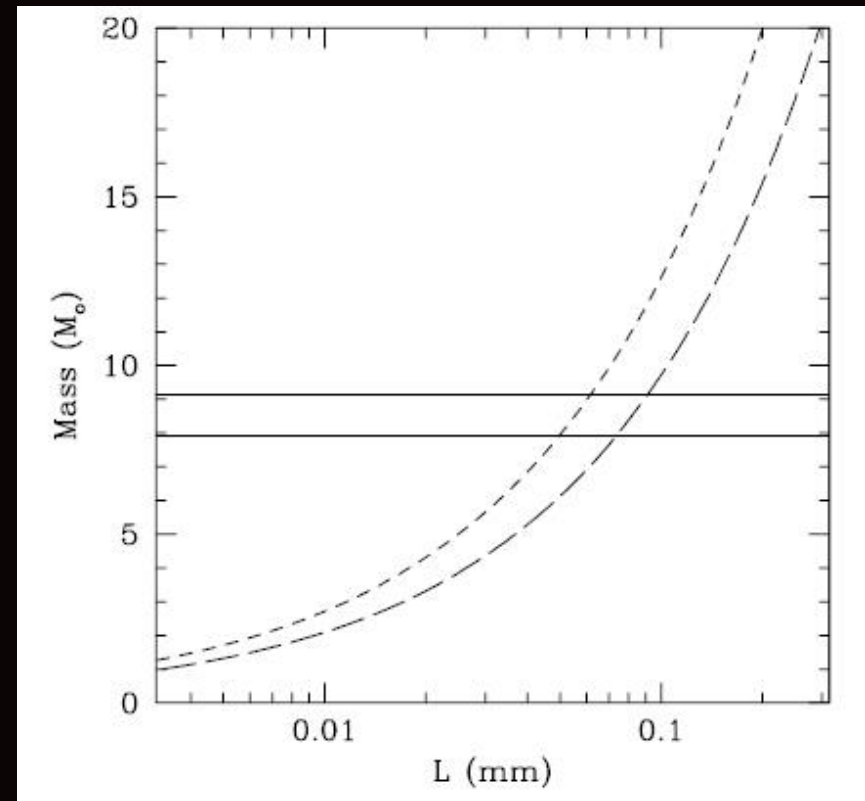
Brane worlds and black holes

In astro-ph/0612611 the author discuss constraints on parameters of world on brane basing on observations of XTE J1118+408. The idea is the following. In many scenarios of brane world BHs lifetimes are short. An estimated of a lower limit on the age of a BH can provide a stronger limit than laboratory experiments.

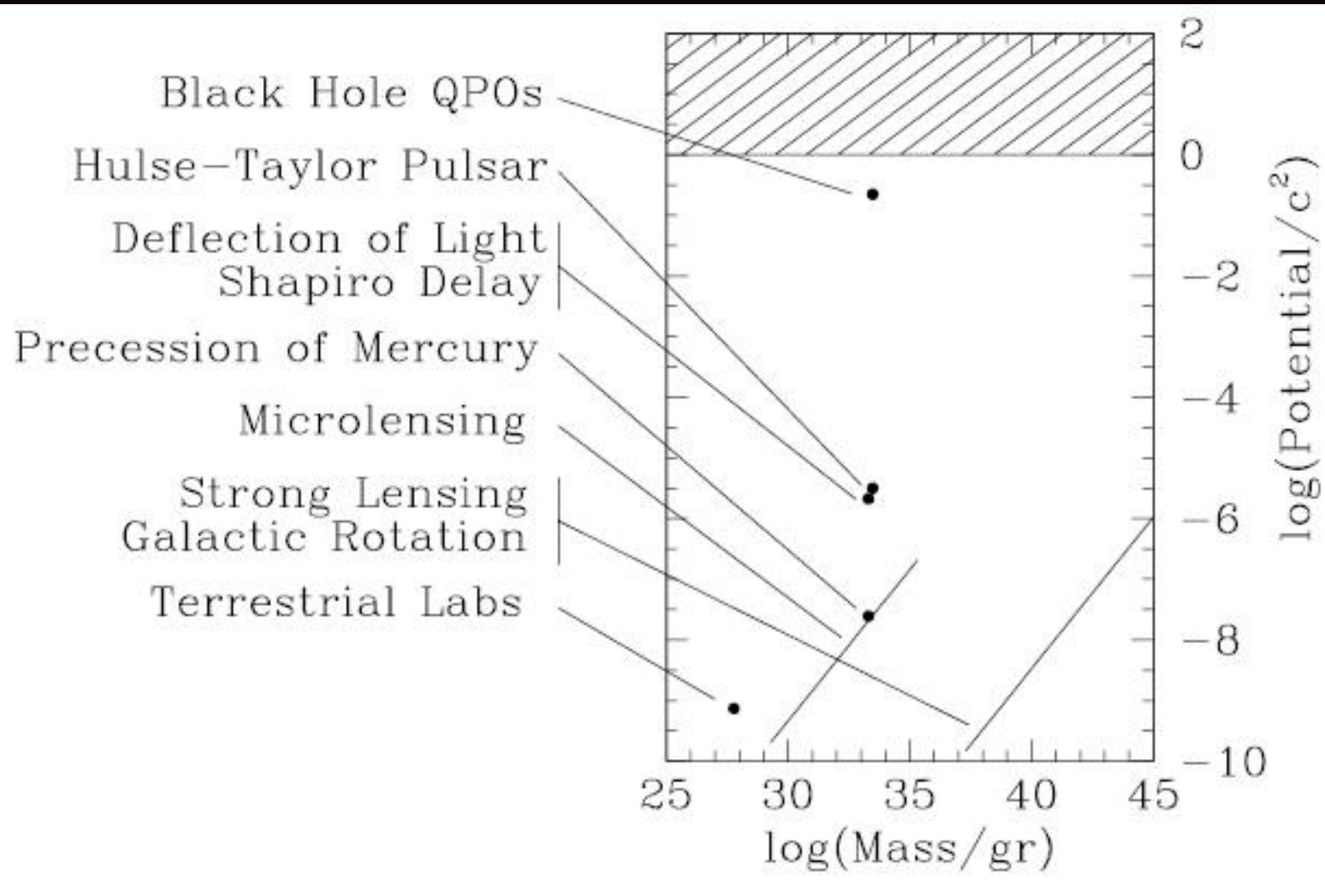
Age estimated by the time of the last galactic crossing.

$$\tau \simeq 1.2 \times 10^2 \left(\frac{M}{M_{\odot}} \right)^3 \left(\frac{L}{1 \text{ mm}} \right)^{-2} \text{ yr}$$

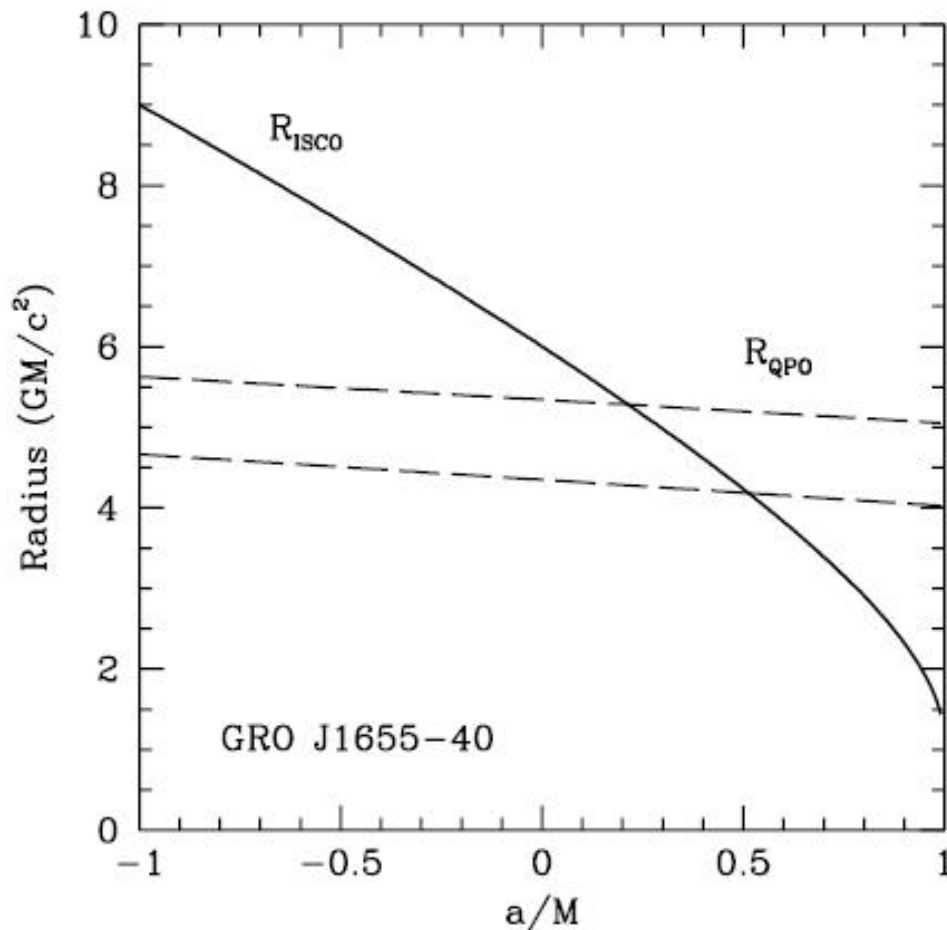
(see also astro-ph/0401466)



BH spin and testing the GR



QPO in GRO 1655-40



If the interpretation of QPOs in this source is correct, then we can “look inside” $3R_g$.

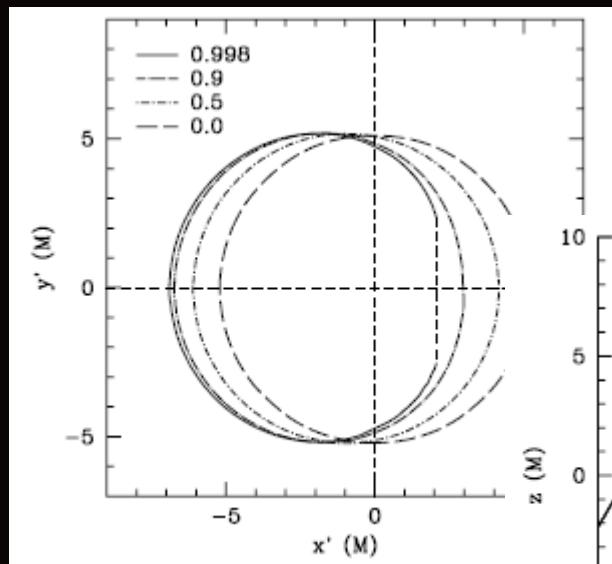
The observed frequency is 450 Hz. Uncertainties (dashed lines) are due to uncertainty in the mass: 5.8-7.9 solar masses.

However, this conclusion crucially depends on our understanding of the QPO phenomenon.

Here it is assumed that $f_{\text{QPO}} < f_{\text{AZIM}} = (GM)^{1/2} / 2\pi R^{3/2}$

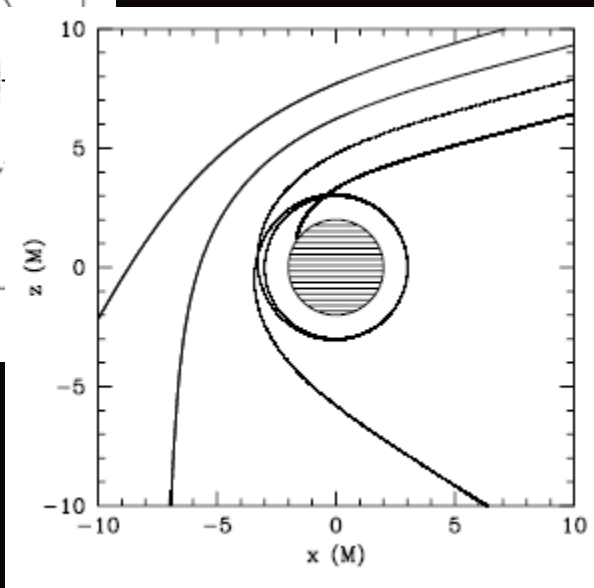
Testing no-hair theorem

It is possible to study and put limits for the existence of quadrupole moments.

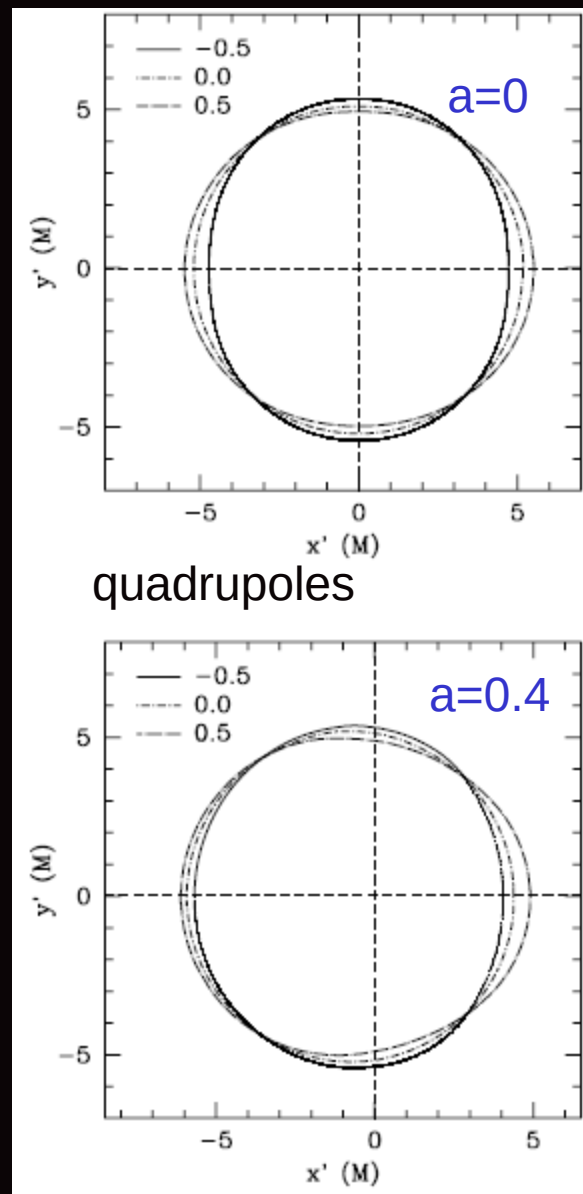


Spinning BHs

$$Q = -M (a^2 + \epsilon M^2)$$

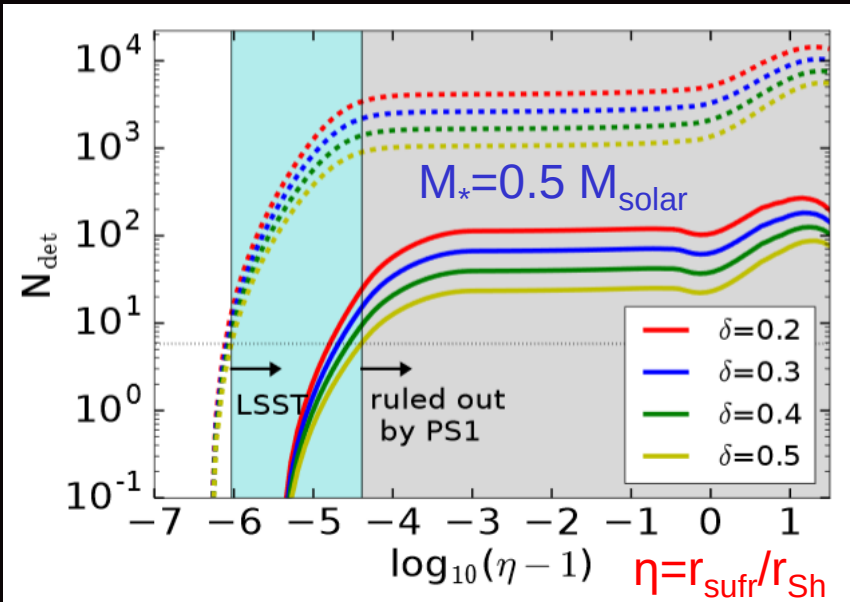
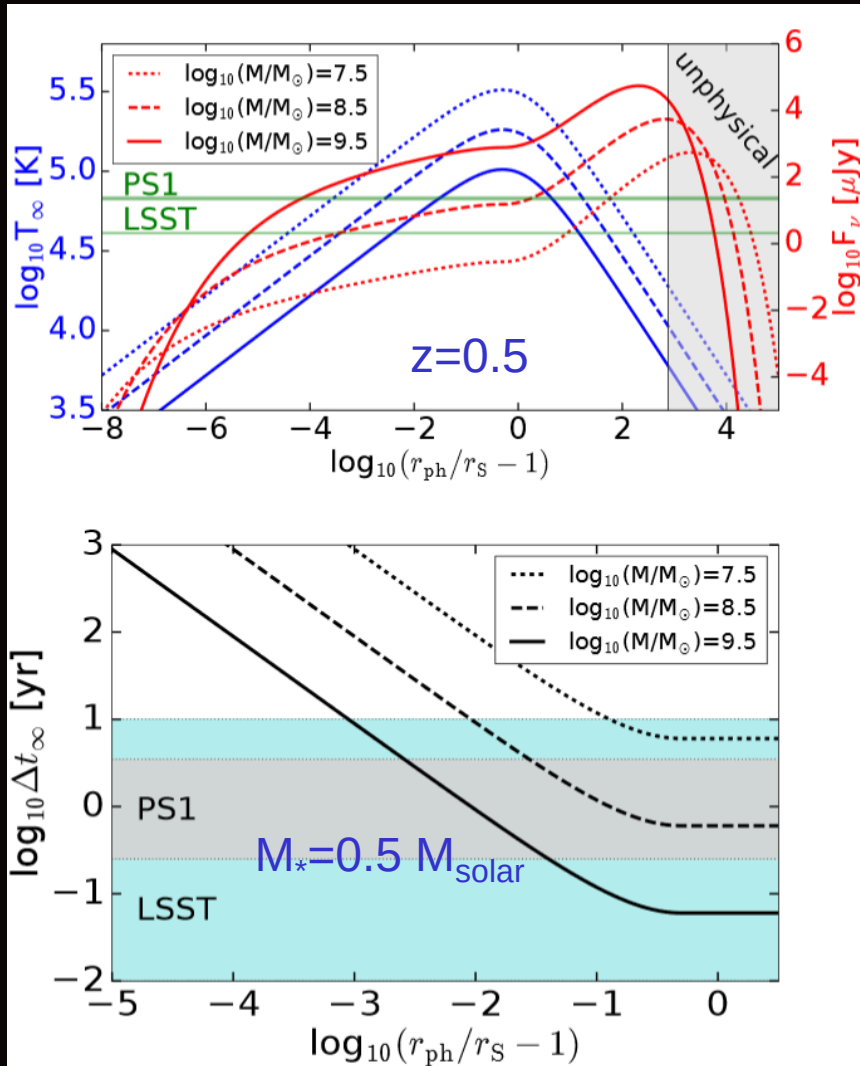


Photon ring formation



quadrupoles

Tidal disruption and horizons



If there is a hard surface, then a kind of a photosphere might be formed above it.

No surface emission after tidal events.
Limit $1+10^{-4.4}$ of the Schwarzschild radius.

Alternatives

1. Gravastar - GRAvitational VAcuum STAR (Mazur, Mottola gr-qc/0109035)
2. Dark energy stars (Chaplin astro-ph/0503200)
3. Boson stars (see, for example, Colpi et al. 1986 Phys. Rev. Lett.)
4. Fermion balls (see discussion in Yuan et al. astro-ph/0401549)
5. Evaporation before horizon formation (Vachaspati et al. gr-qc/0609024)

Except general theoretical criticism, some models are closed by absence of burster-like flares (Yuan et al. astro-ph/0401549).

This is not the case for models like those proposed by Vachaspati et al. However, they are actively criticized by theorists.

Problems with formation mechanisms and stability.

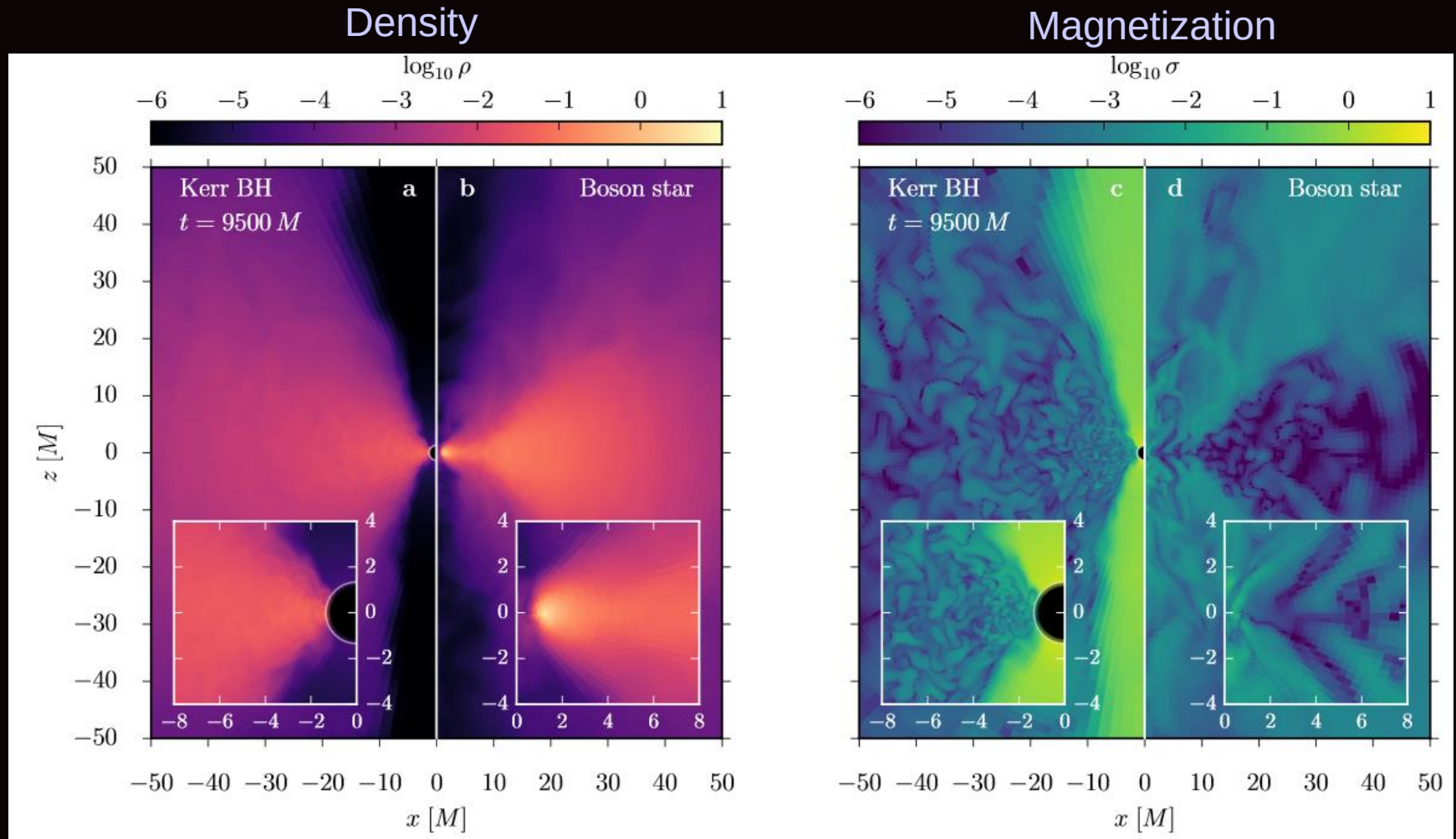
Taking all together, black hole – is the most conservative hypothesis!

Model	Taxonomy	Formation	Stability	EM signatures	GWs
Fluid stars	UCOs	✗	✓ [18, 25, 33, 56–58]	✓	✓ [18, 25, 30, 56]
Anisotropic stars	ClePhOs [59–61]	✗	✓ [62, 63]	✓ [35, 61, 64]	✓ [35, 64]
Boson stars & oscillatons	UCOs, (ClePhOs?) [65–72]	✓ [68, 71, 73–75]	✓ [70, 76–80]	✓ [81–83]	✓ [24, 50, 55, 84–88]
Gravastars	COs – ClePhOs [4, 89]	✗	✓ [79]	✓ [90–92]	~ [23, 25, 33, 50, 55, 92, 97]
AdS bubbles	UCOs – ClePhOs [98]	✗	✓ [98]	~ [98]	✗
Wormholes	ClePhOs [99–103]	✗	✓ [104, 105]	✓ [106–109]	~ [23, 50, 55]
Fuzzballs	ClePhOs [5, 6]	✗	✗ (but see [110–113])	✗	~ (but see [23, 24, 114])
Superspinars	COs – ClePhOs [115]	✗	✓ [37, 116]	✗ (but see [117])	~ [23, 24]
2 – 2 holes	ClePhOs [118]	✗	✗ (but see [118])	✗ (but see [118])	~ [23, 24]
Collapsed polymers	ClePhOs [119, 120]	✗	✗ (but see [119, 121])	✗	~ [121]
Quantum bounces / black stars	ECO – ClePhOs [7, 8, 122–125]	✗ (but see [123, 126])	✗	✗	~ [125]
Quantum stars*	UCOs – ClePhOs [127, 128]	✗	✗	✗	✗
Fire-walls*	ClePhOs [129–131]	✗	✗	✗	~ [24, 132]

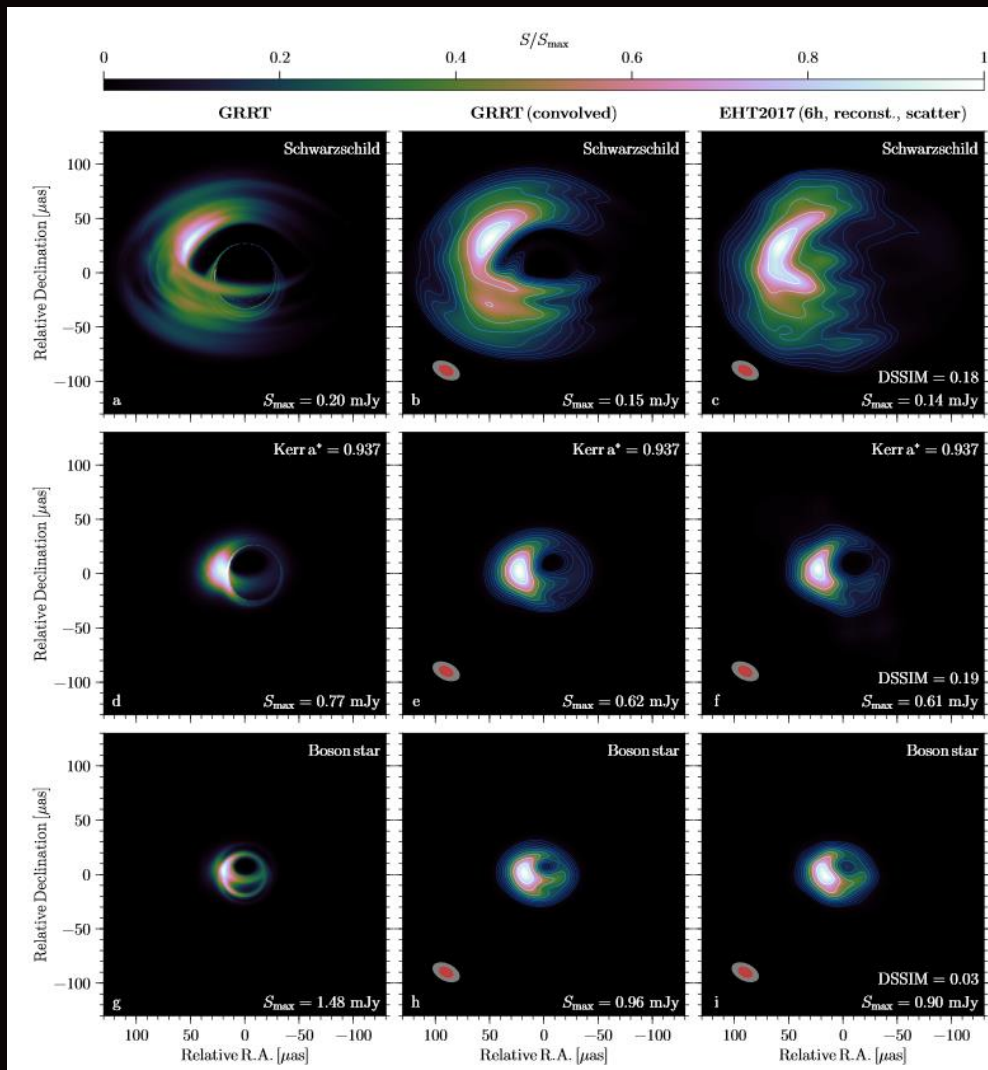
Buchdahl limit in GR:
 $r > 9/8 R_{\text{sh}}$

Valid for ordinary fluids.

BHs vs. boson stars



230 GHz images of BHs and boson stars



Potentially, future imaging (most probably with space based millimeter range interferometers) can distinguish between SMBHs and boson stars due to differences in the appearance of the “shadow”.

GRAvitational VAcuum STAR

- I. Interior : $0 \leq r < r_1$, $\rho = -p$,
- II. Shell : $r_1 < r < r_2$, $\rho = +p$,
- III. Exterior : $r_2 < r$, $\rho = p = 0$.

Vacuum outside,
Vacuum inside

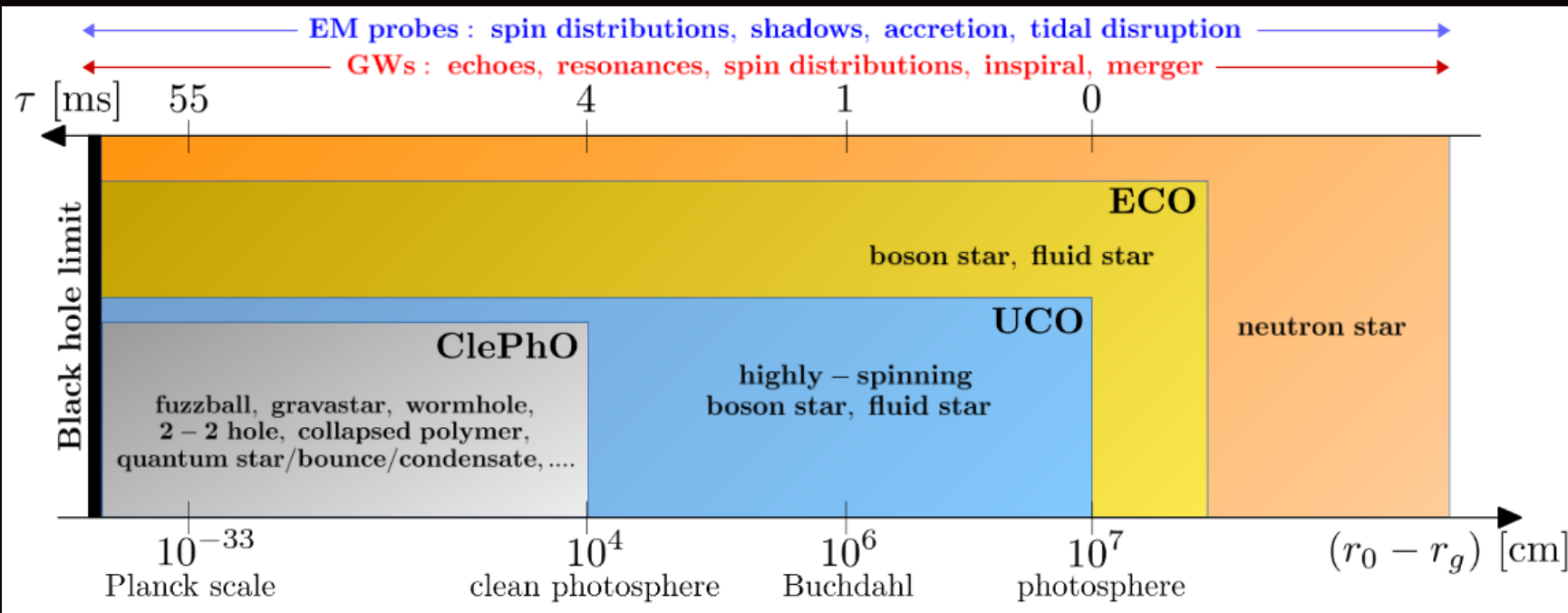
Do not produce
Hawking radiation.

Can be distinguished
in coalescence.

See recent developments
in 1512.07659



Probing vicinity of a horizon



ECO – more massive than a NS

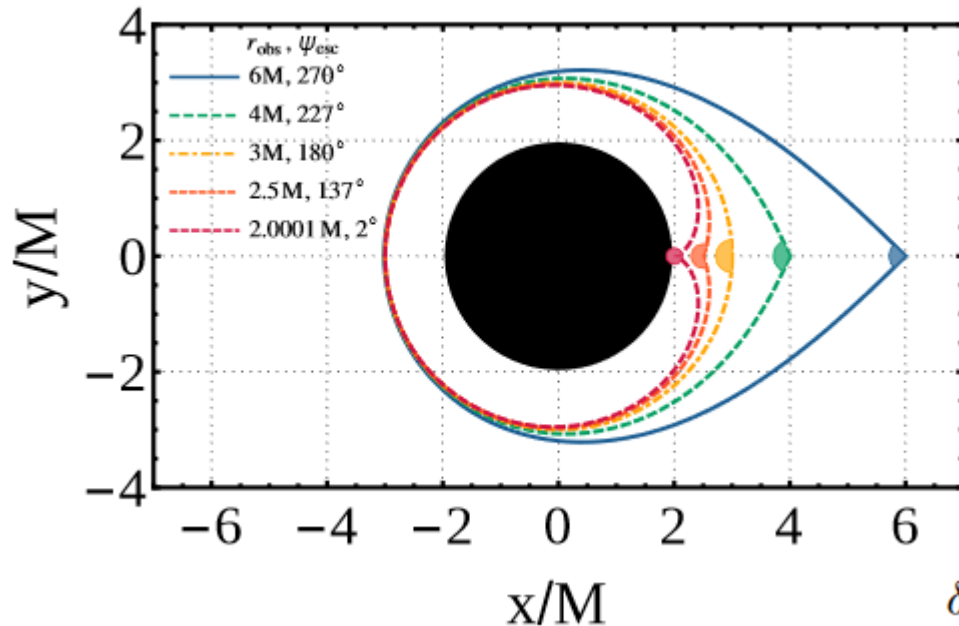
UCO – have a photosphere (radius < photon sphere)

ClePhOs – have surface too close to the horizon

$$r_0 = 2M(1 + \epsilon)$$

$$\epsilon \lesssim \epsilon_{\text{crit}} \sim 0.0165$$

Emission propagation in the vicinity of a BH horizon



$$\delta(t) \sim \delta_0 e^{\lambda t}, \quad \lambda = \sqrt{\frac{-f^2 V_r''}{2E^2}} = \frac{1}{3\sqrt{3}M}$$

$$\Delta\Omega_{\text{esc}} = 2\pi \left(1 - \sqrt{1 - \frac{27M^2(r_0 - 2M)}{r_0^3}} \right) \sim 27\pi \left(\frac{r_0 - 2M}{8M} \right)$$

What can low luminosity rule out?

$$t_{\text{roundtrip}} \sim 8M \log(\cot(\psi/2)) \approx 9.33M$$

$$N = T/t_{\text{roundtrip}}$$

$$\Delta E \sim [1 - (1 - \epsilon)^N] \delta M$$

$$r_0 = 2M(1 + \epsilon)$$

$$\Delta E \sim \epsilon N \delta M \text{ if } \epsilon N \ll 1.$$

$$\epsilon \ll 10^{-16} \left(\frac{M}{10^6 M_\odot} \right) \left(\frac{t_{\text{Hubble}}}{T} \right)$$

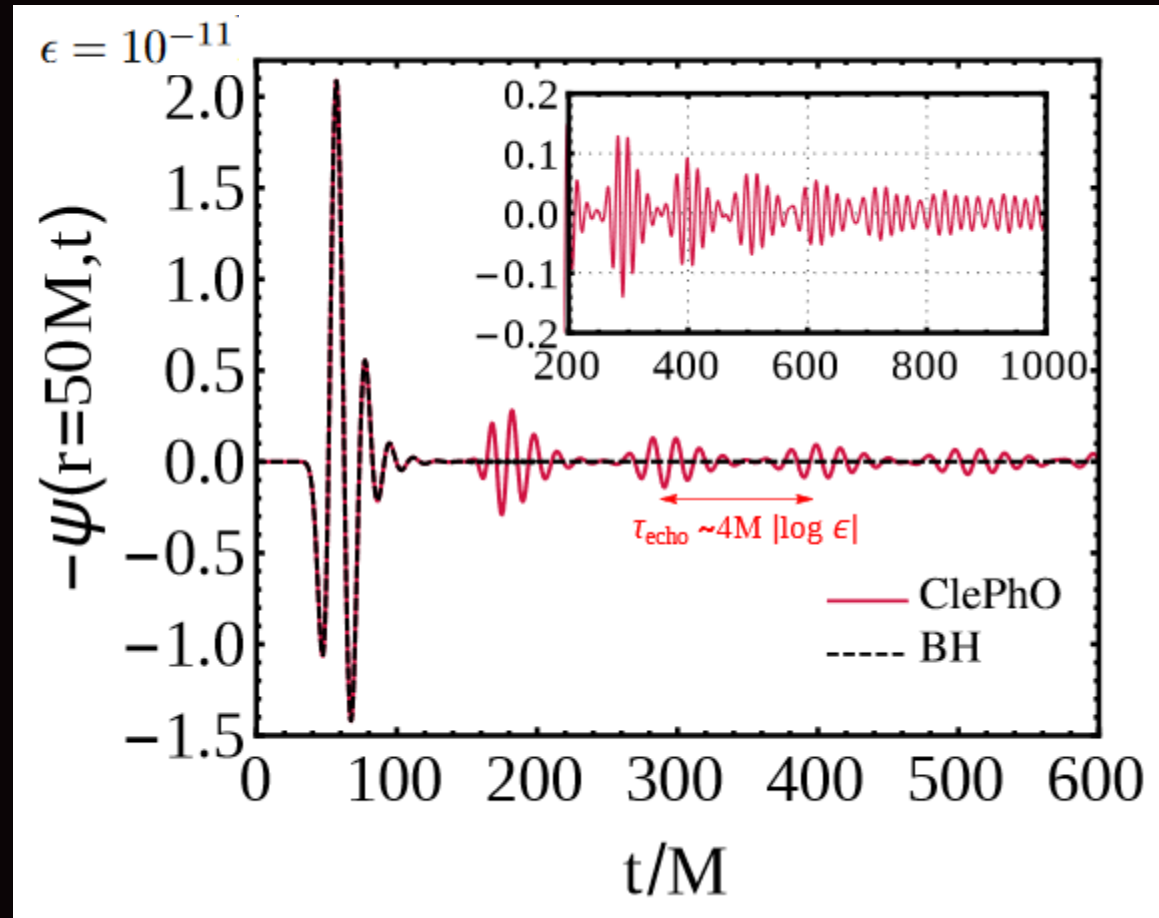
$$\dot{E} \sim 10^{-17} \left(\frac{\epsilon}{10^{-16}} \right) \left(\frac{\delta M}{M} \right)$$

Thus, it is difficult to rule out $\epsilon \ll 10^{-16}$

with electromagnetic observations.

Echos in CLePhOs

$$\tau_{\text{echo}} \sim 4M |\log \epsilon|$$



$$\tau_{\text{echo}} \sim 2M [1 + (1 - \chi^2)^{-1/2}] \log \epsilon, \quad \tau_{\text{echo}} \sim (\omega_R - m\Omega)^{-1}$$

GWs: BHs vs. ECOs

		BH	ECO	ClePhO
ringdown	GW echoes	$\times$	$\checkmark$ (only UCOs)	$\checkmark (\tau_{\text{echo}} \sim M \log \epsilon)$
	Modified prompt ringdown	$\times$	$\checkmark$	$\times$
	Extra modes	$\times$	$\checkmark$	$\checkmark$
inspiral	Multipolar structure (2PN)	$\delta M_l = \delta S_l = 0$	$\delta M_l \neq 0, \delta S_l \neq 0$	$\delta M_l \simeq 0, \delta S_l \simeq 0$
	Tidal heating (2.5 – 4PN)	$\checkmark$	$\times$	$\times$
	Tidal Love number (5PN)	$k = 0$	$k \lesssim \mathcal{O}(k_{\text{NS}})$	$k \sim [\log \epsilon]^{-1}$
	Resonances	$\times$	$[80, 96]$	$\omega M \sim [\log \epsilon]^{-1}$

$$\tau_{\text{echo}} \sim M |\log \epsilon|$$

Conclusions

It is very difficult to prove that a given object is a real BH with horizon, or may be even impossible (see 1904.05363).

Primordial BHs

Main reviews and articles

- • astro-ph/0504034 **Primordial Black Holes - Recent Developments**
- astro-ph/0304478 **Gamma Rays from Primordial Black Holes in Supersymmetric Scenarios**
- gr-qc/0304042 **Do black holes radiate?**
- gr-qc/0506078 **Black Holes in Astrophysics**
- arXiv: 0709.2380 **Do evaporating BHs form magnetospheres?**
- arXiv: 0912. 5297 **New cosmological constraints on primordial black holes**
- arXiv: 1403.1198 **PBHs (review)**
- arXiv:1503.01166 **PBHs (review)**
- • arXiv:1510.04372 **PBHs (very large review)**

Introduction

The idea was proposed by Hawking (1971)
[however, some discussion appeared also before, see,
for example, Zeldovich & Novikov, 1966].

The idea is that at early times large-amplitude overdensities would overcome internal pressure forces and collapse to form black holes. The mass of a PBH is close to the Hubble horizon mass.

Of course, we are interested only in PBH formed after inflation.

PBHs may also form at the phase transitions expected in the early universe, in particular, PBH formation can be related to topological defects.

PBH contribute not only to γ -ray, but also to CR and ν background.

Masses from 10^{-5} g up to 10^5 solar masses.

See introductions in arXiv: 0709. 2380, 0910.1876, astro-ph/0304478

Primordial black holes

$$M_H(t) \approx \frac{c^3 t}{G} \approx 10^{15} \left(\frac{t}{10^{-23} \text{ s}} \right) g.$$

Primordial black holes (PBH) are formed with masses about the mass inside a horizon at the given moment (particle horizon).

$$T = \frac{\hbar c^3}{8\pi G M k} \approx 10^{-7} \left(\frac{M}{M_\odot} \right)^{-1} \text{ K},$$

Hawking radiation

BHs with $M > 10^{26} \text{ g}$ have temperatures lower than the CMB radiation now.

The time for complete evaporation

$$\tau(M) \approx \frac{\hbar c^4}{G^2 M^3} \approx 10^{64} \left(\frac{M}{M_\odot} \right)^3 \text{ y}.$$

Mass-spectrum

$$\frac{dn_{KL}}{dM_i} = \frac{n+3}{4} \sqrt{\frac{2}{\pi}} \gamma^{7/4} \rho_i M_{H,i}^{1/2} M_i^{-5/2} \sigma_H^{-1} \times \exp\left(-\frac{\gamma^2}{2\sigma_H^2}\right)$$

Mass function in the standard model
(Kim-Lee)

The case $n = 1$ corresponds to a scale-invariant (Harrison-Zel'dovich) spectrum which yields a Carr initial mass function, $dn/dM_i \sim M_i^{-5/2}$.

As some authors realized, the $n = 1$ spectrum does not yield a significant PBH abundance when normalized to COBE observations (astro-ph/0304478).

Evaporating PBH can be considered non-charged, non-rotating as both (spin and charge) are rapidly emitted due to particle creating (Hawking radiation).

In different models of PBHs formation the spectrum can have different shape (power law, log-normal, etc.).

Hawking spectrum

$$\frac{d^2 N}{dQ dt} = \frac{\Gamma_s}{2\pi\hbar \left(\exp\left(\frac{Q}{kT}\right) - (-1)^{2s} \right)}.$$

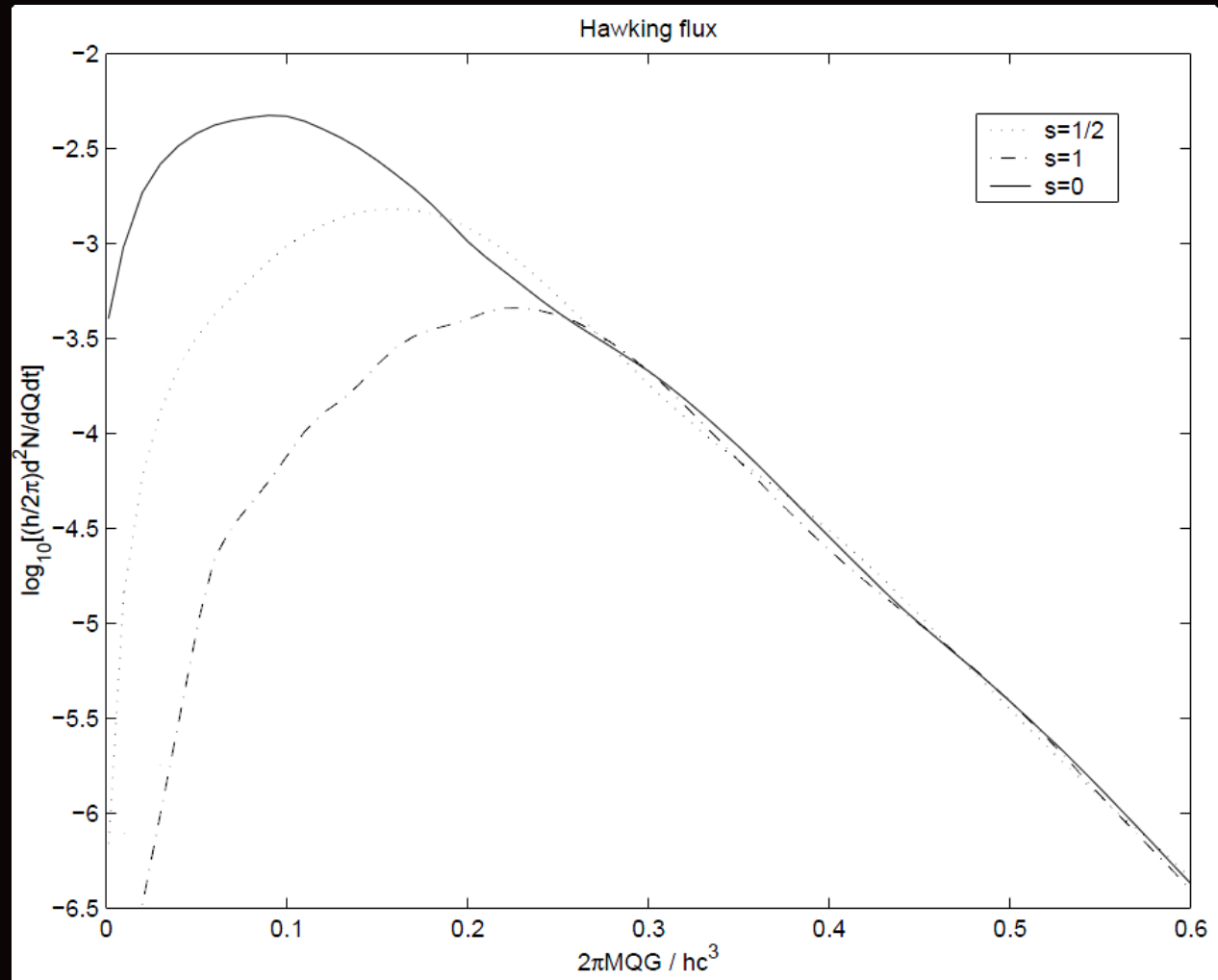
For non-rotating,
non-charged BH.

Horizontal axis $\sim Q/kT$

$T=T(M)$

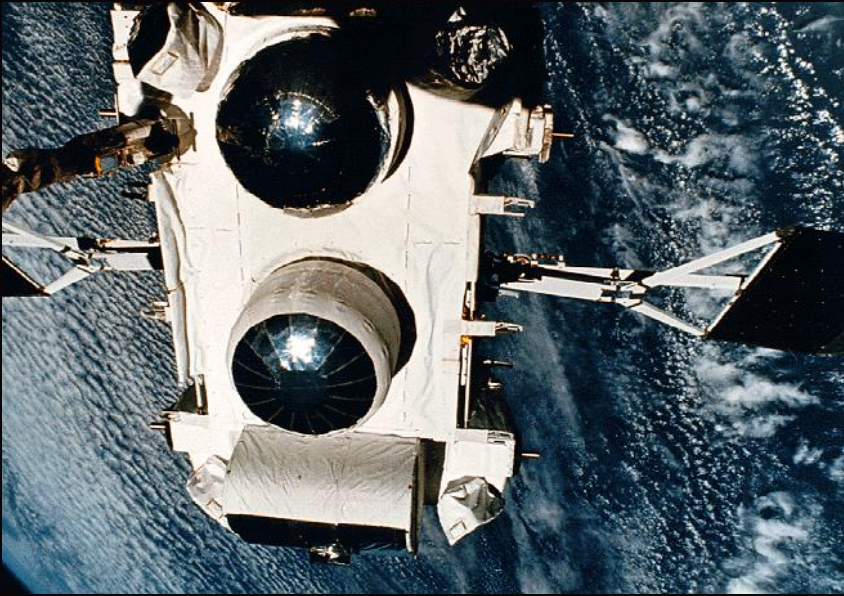
Vertical – $d^2 N/dQ dt$

Rem: Spectrum is different in other models of gravity. For example, about BH evaporation in loop quantum gravity see 1808.08857.



astro-ph/0304478

EGRET and constraints on PBH



$$\frac{dF_{\gamma}}{dE} = 7.3 \times 10^{-14} \left(\frac{E}{100 \text{ MeV}} \right)^{-2.10} \text{ cm}^{-3} \text{ GeV}^{-1}$$

Background radiation at energies:
30 MeV – 120 GeV.

The upper limit on the density of PBHs

$$\Omega_{\text{PBH}} \leq (5.1 \pm 1.3) \times 10^{-9} h^{-2},$$

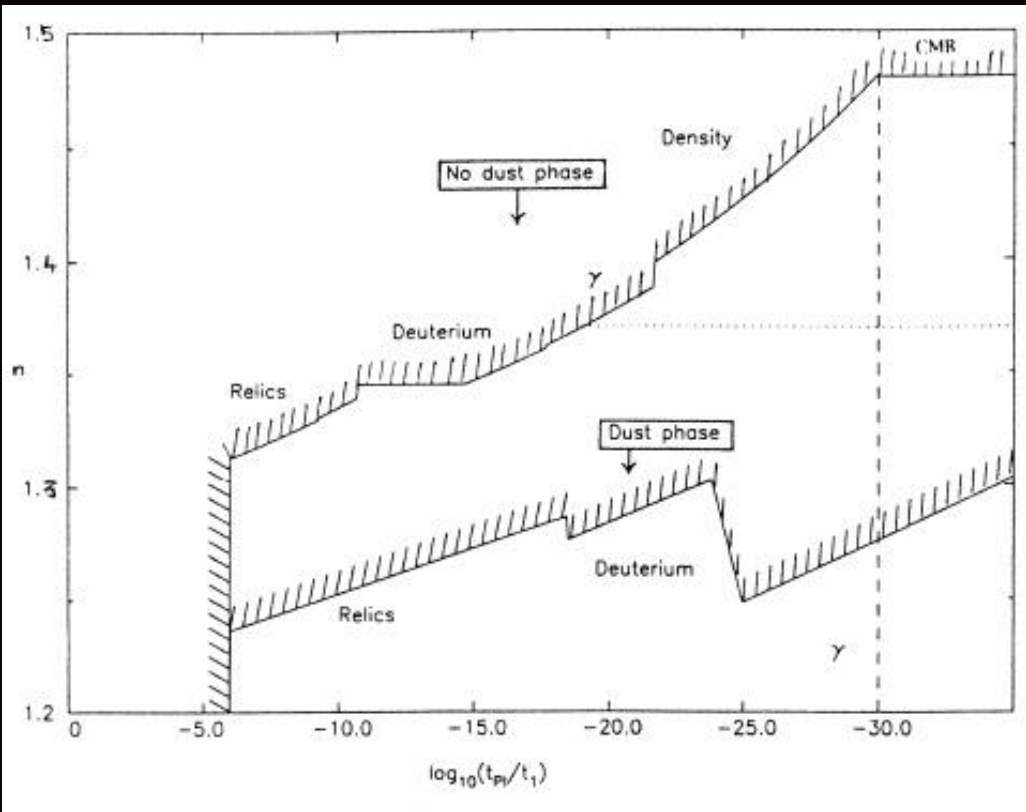
Constraints on cosmological parameters from data on PBH

Data on PBHs in principle can provide constraints on different cosmological parameters related to the density fluctuations.

$$M > M_{\min} = M_P (T_{RH}/T_{Pl})^{-2}$$

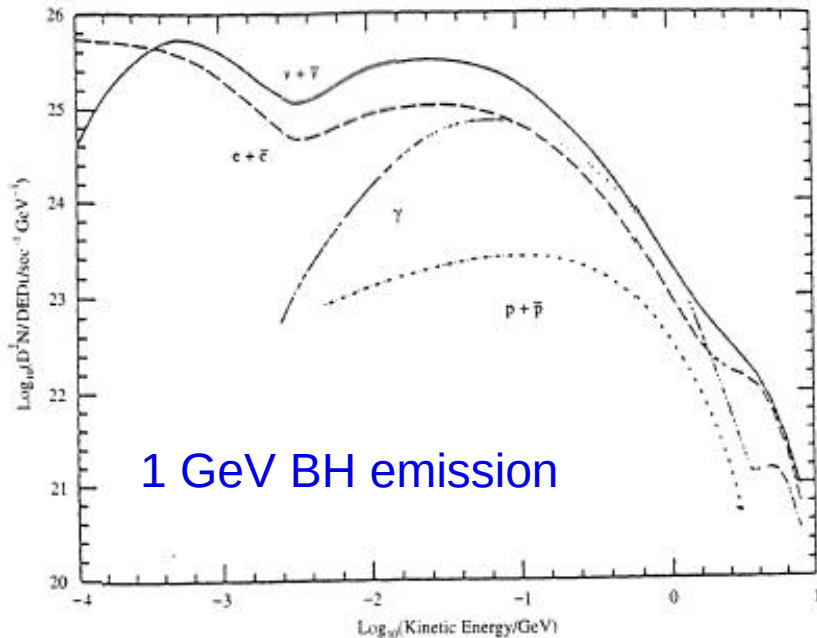
For example, on the parameter n , characterizing the power spectrum of fluctuations.

$$|\delta_k|^2 \approx k^n$$



About other constraints see Carr (2005) astro-ph/0504034

Particle emission during PBH evaporation



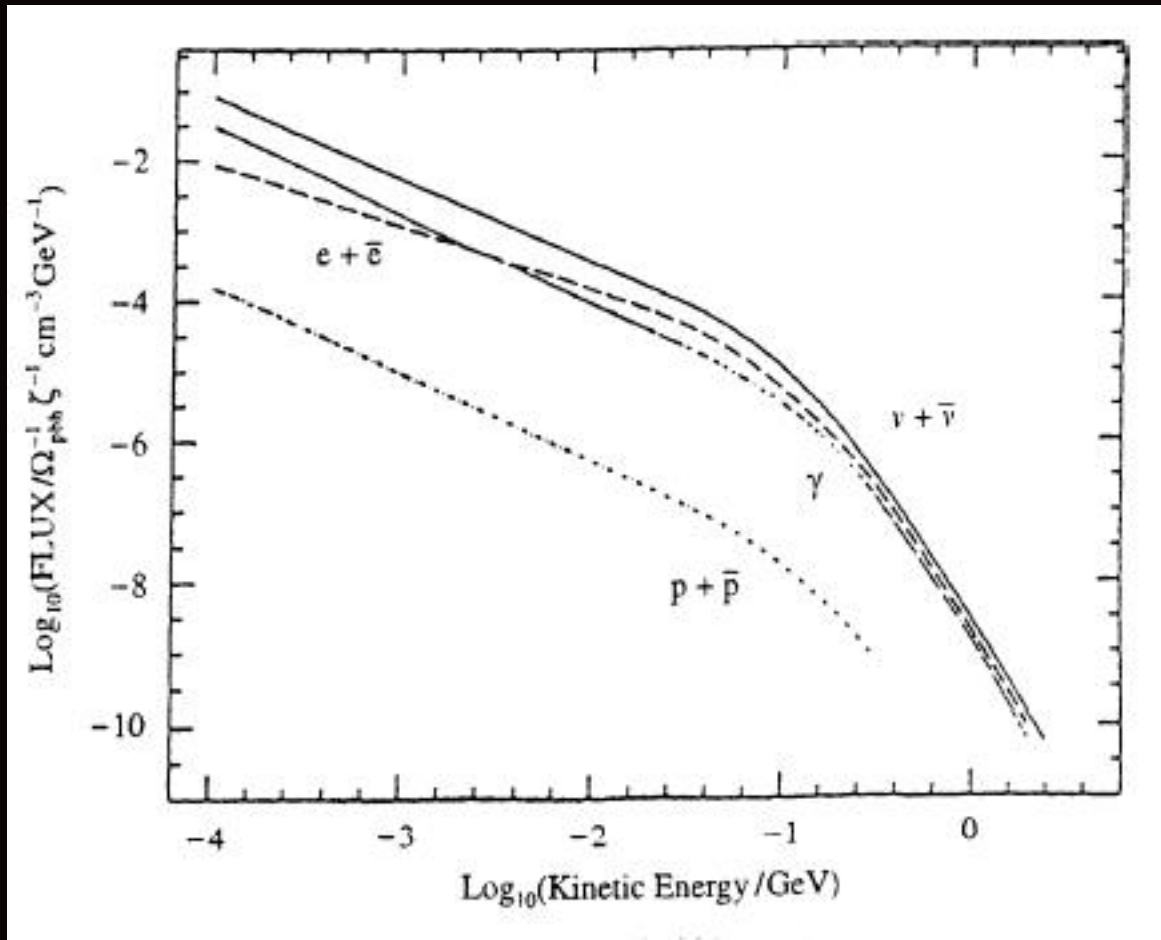
$$T \approx 10^{26} \left(\frac{M}{g} \right)^{-1} \text{ K} \approx \left(\frac{M}{10^{13} g} \right)^{-1} \text{ GeV.}$$

$$\dot{M} = -5 \times 10^{25} (M/g)^{-2} f(M) \text{ g s}^{-1}$$

$$\tau(M) = 6 \times 10^{-27} f(M)^{-1} (M/g)^3 \text{ s.}$$

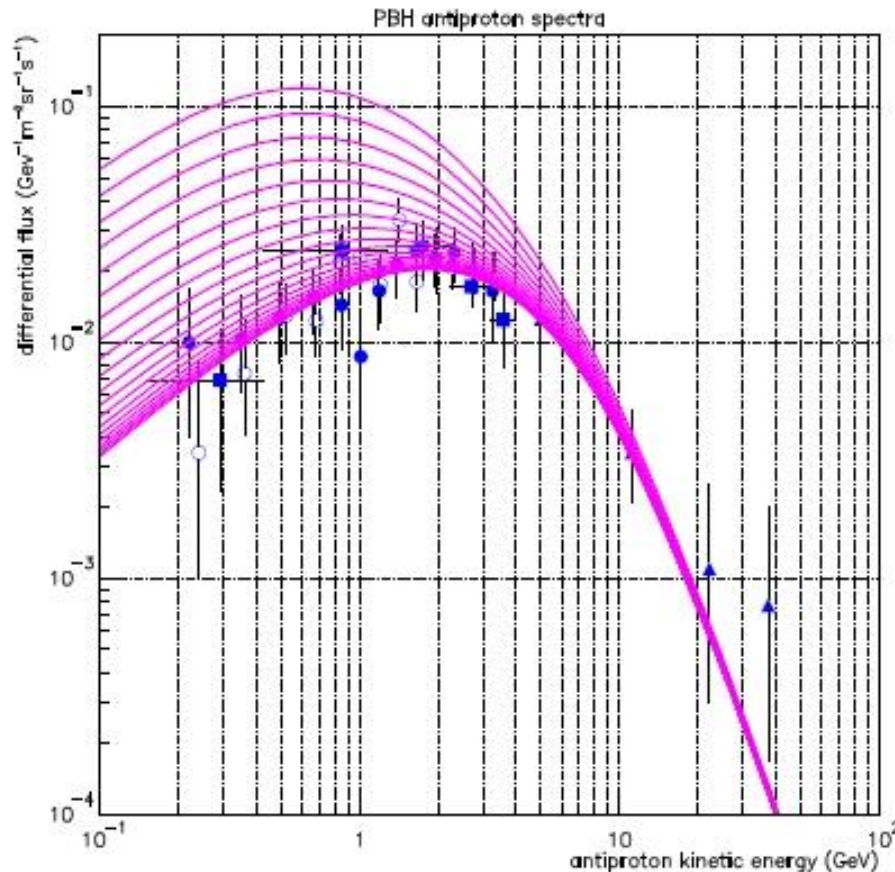
When a BH mass is below 10^{14} g , it starts to emit hadrons.

Particle spectrum for uniform distribution of PBHs



BHs uniformly distributed in the Universe.

PBH and antiprotons



Antiprotons are detected in cosmic rays. They are secondary particles. Properties of these secondary antiprotons should be different from properties of antiprotons generated during PBH evaporation at energies 0.1-1 GeV.

Comparison between calculations and the observed spectrum of antiprotons provides a limit on the spatial density of PBHs.

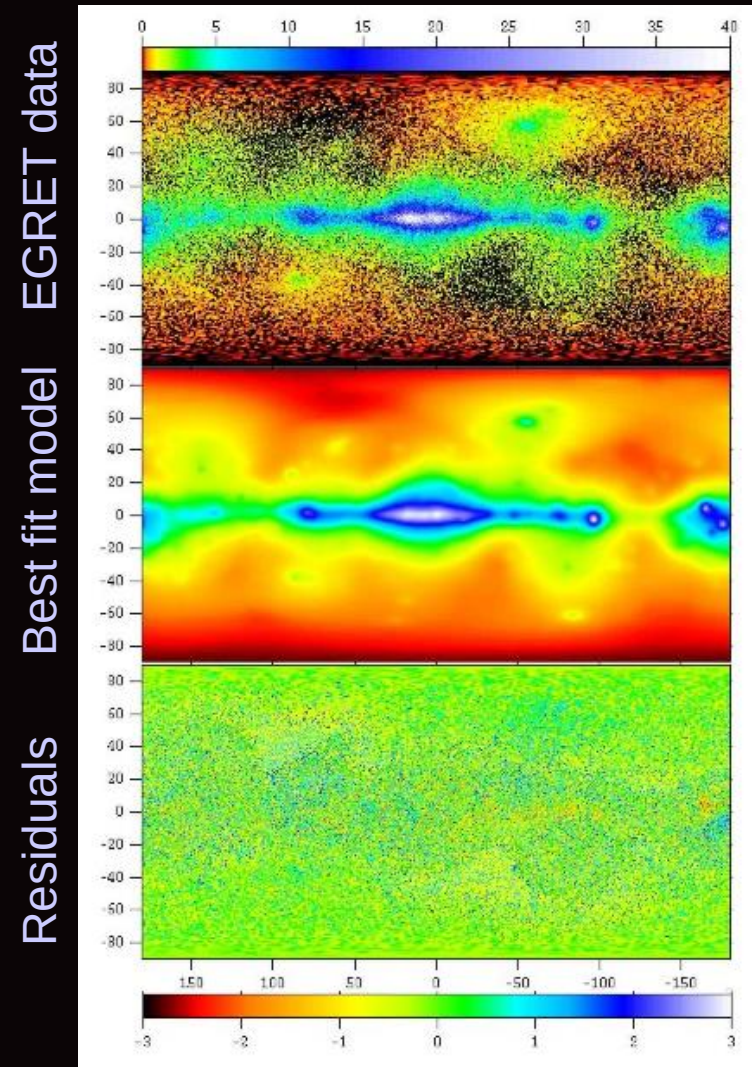
Recently, positron spectrum measured by Voyager-1 was used to put constraints on the PBH number (1807.03075).

Constraints from galactic γ -ray background

The authors assume that PBHs are broadly distributed like dark matter in the halo of our Galaxy.
EGRET data

1. spacetime is 4D;
2. PBHs form through a cosmological scenario;
3. most PBHs are presently neutral and non-rotating;
4. being part of the dark matter, PBHs are distributed alike.

The flux peaks at higher energy (around $5 kT$) than for a pure blackbody at the same temperature (which flux is maximum at $1.59 kT$)



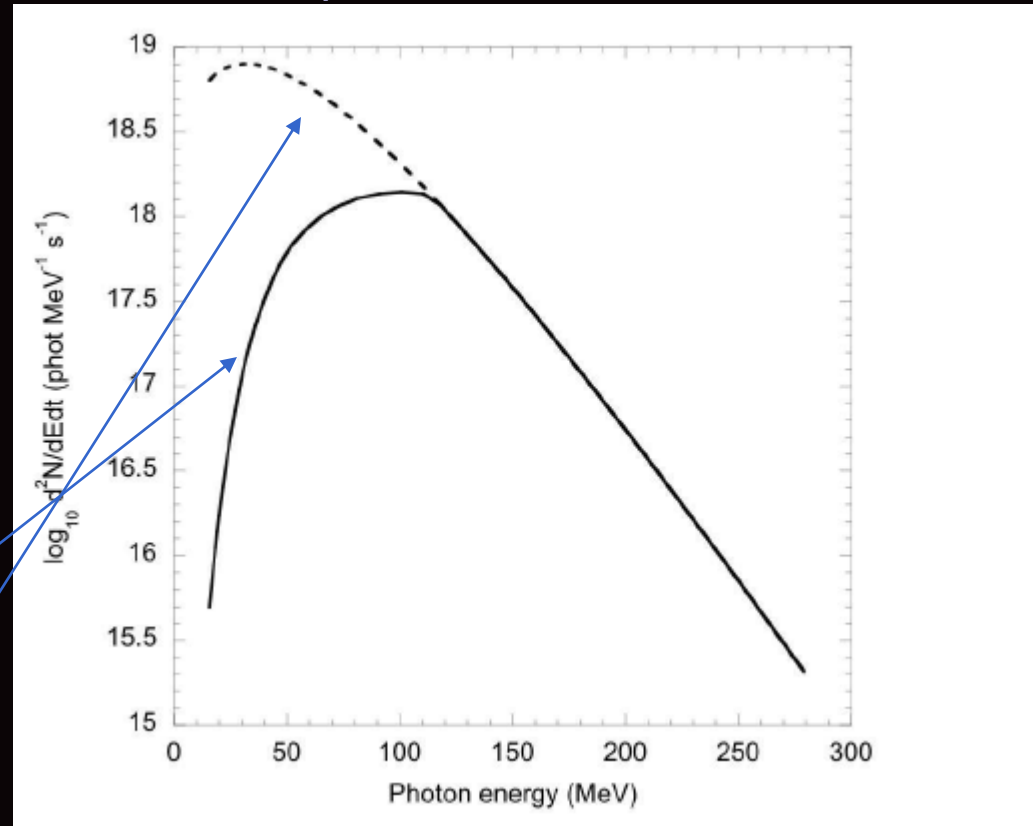
The spectrum

Since the typical temperature of PBHs born in the early Universe and that end its life at present time is about 20 MeV, a distinctive signature of quantum black holes would be a quasilplanckian spectrum at unexpectedly high energy, peaking at about 100 MeV

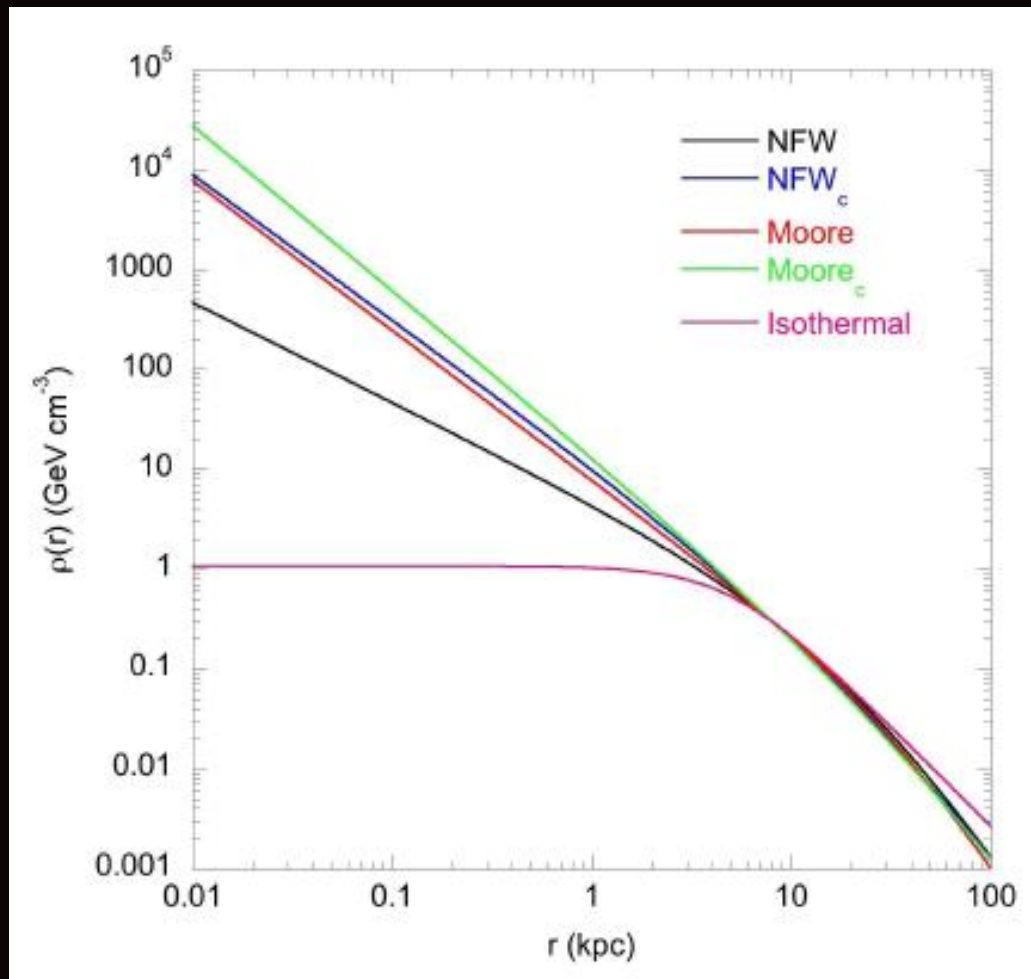
BH spectrum
(MacGibbon&Webber 1990)

Blackbody spectrum
with the same temperature

Spectrum of a $kT=20$ MeV BH



Density distribution



It was assumed that PBH follow the DM distribution. Several different variants have been used.

Results and limits

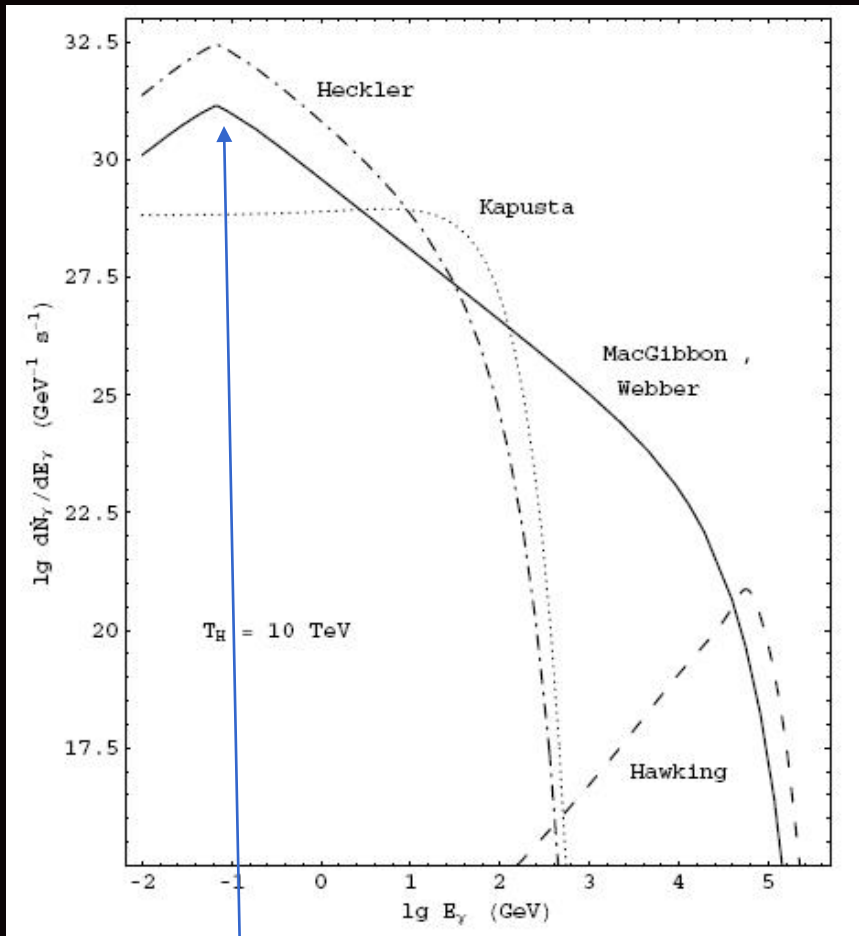
DM distribution	$f(M_\star)$	$\Omega_{PBH}(M_\star)$	$\beta(M_\star)$
Moore	$6.04 \pm 0.05 \cdot 10^{-9}$	$1.38 \cdot 10^{-9}$	$0.98 \cdot 10^{-27}$
Moore _c	$1.07 \pm 0.07 \cdot 10^{-9}$	$0.24 \cdot 10^{-9}$	$0.17 \cdot 10^{-27}$
NFW	$6.70 \pm 0.05 \cdot 10^{-9}$	$1.53 \cdot 10^{-9}$	$1.08 \cdot 10^{-27}$
NFW _c	$1.93 \pm 0.08 \cdot 10^{-9}$	$0.44 \cdot 10^{-9}$	$0.31 \cdot 10^{-27}$
isothermal	$11.62 \pm 0.04 \cdot 10^{-9}$	$2.65 \cdot 10^{-9}$	$1.87 \cdot 10^{-27}$

Upper limits for the local PBH density are:

$3.3 \cdot 10^7 - 2.1 \cdot 10^8$ per pc^3 .

Explosion rate $\sim 0.06 \text{ pc}^{-3} \text{ yr}^{-1}$.

Spectra in different models



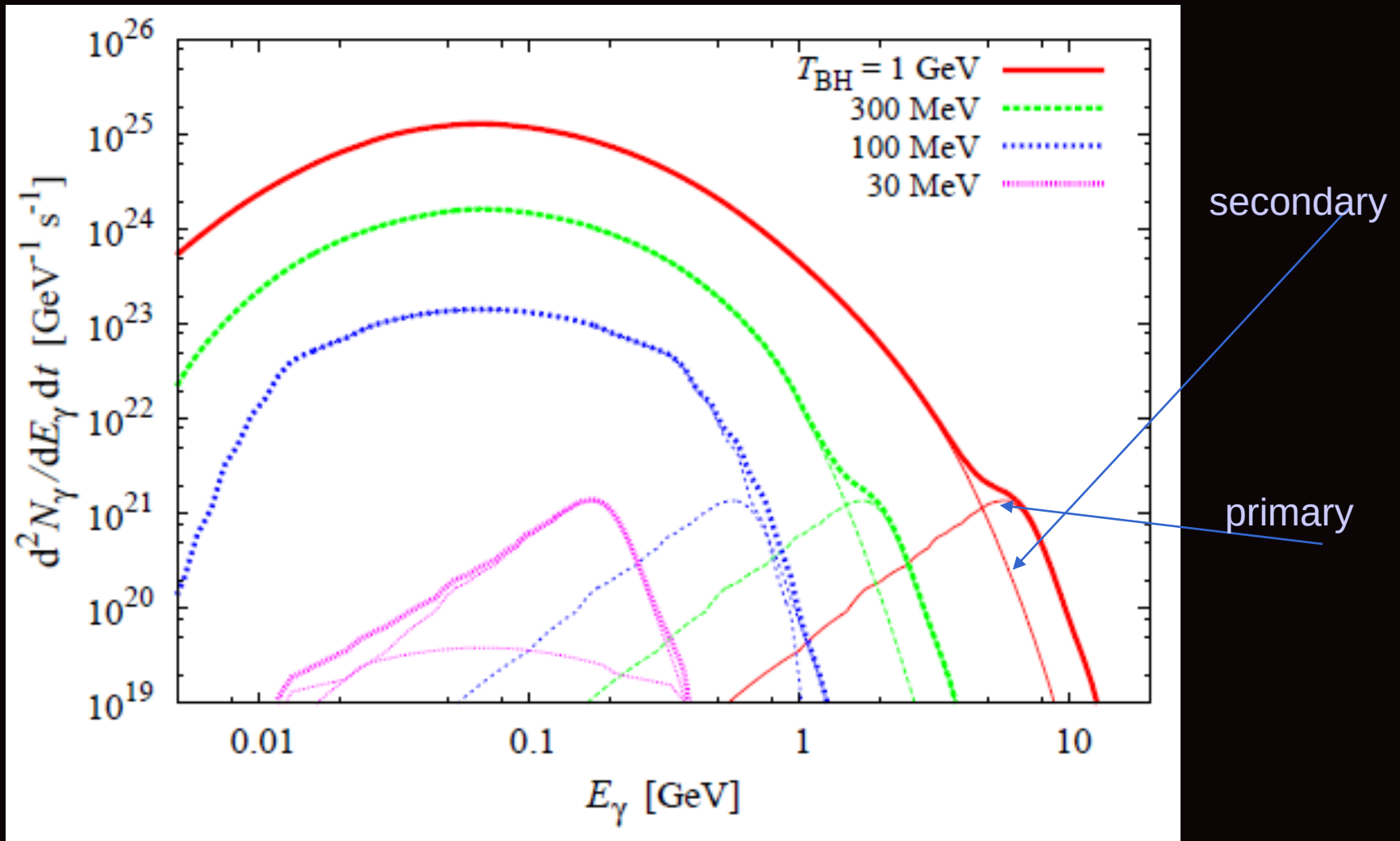
$$E_\gamma \simeq m_{\pi^0}/2 \approx 68 \text{ MeV}$$

The spectrum can be non-thermal. This is due to creation of particles which then demonstrate series of transformations (decays) and interactions; only at the very end we have photons. And their spectrum is different from the thermal (i.e. from the blackbody).

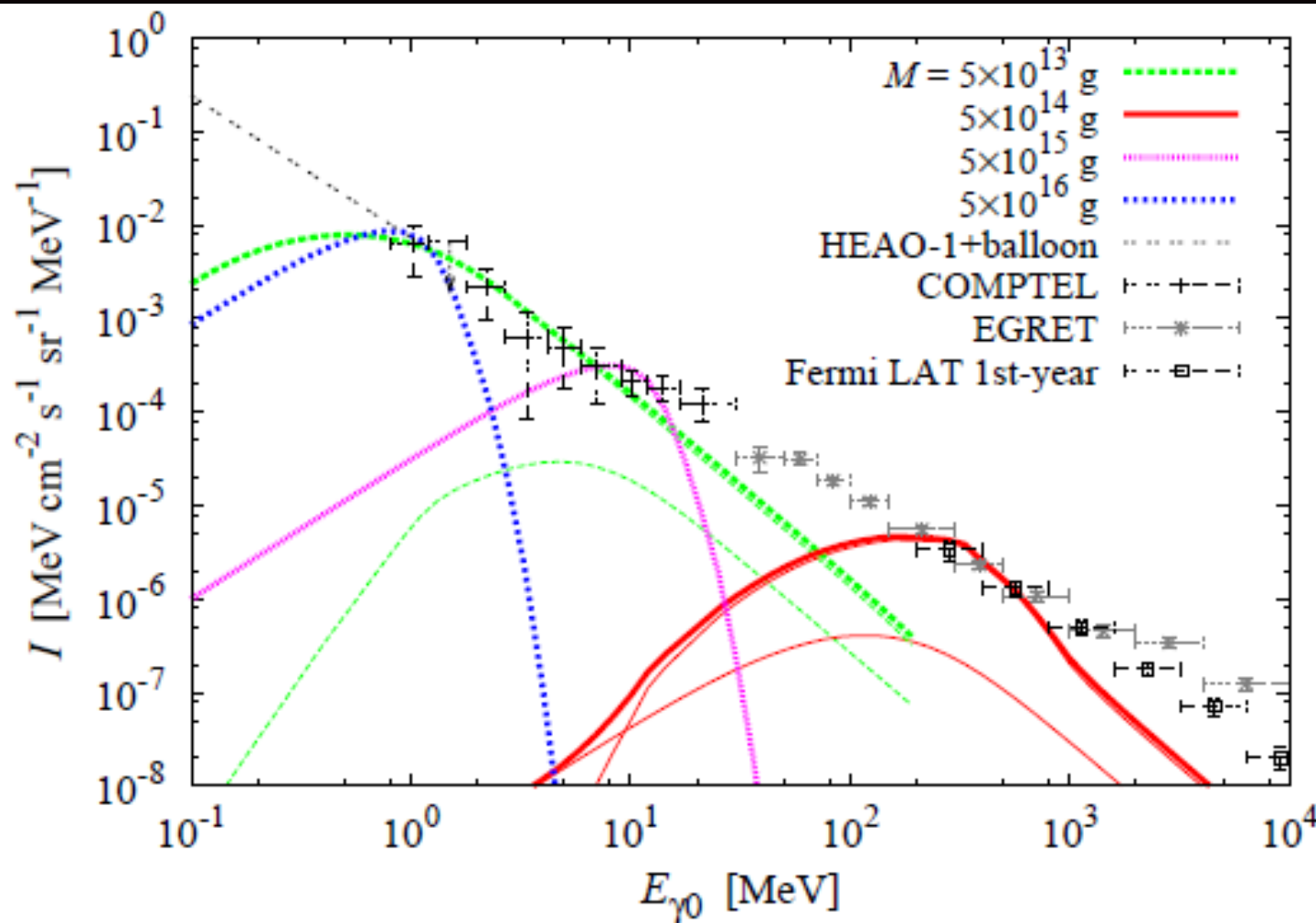
However, the situation is not that clear (see recent criticism in arXiv: 0709.2380).

Note, that γ -ray limits are made for PBH with $T \sim 20 \text{ MeV}$, so effects of photospheres are not important. But they can be important for UHECRs. Effects can be strong at $T_{\text{BH}} \sim \Lambda_{\text{QCD}} \sim 300 \text{ MeV}$

Emission rate of photons

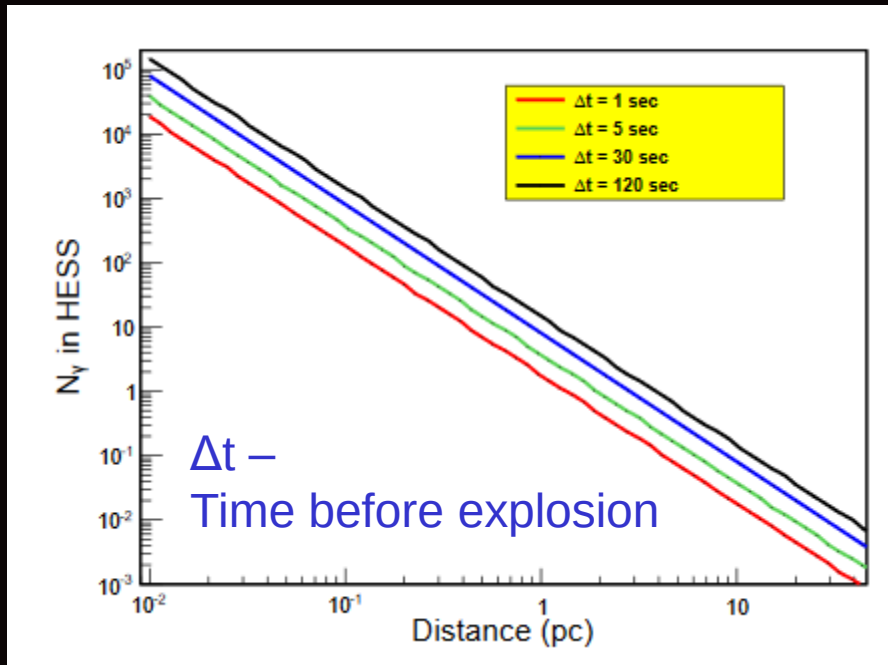


Gamma-ray background



$$\Omega_{\text{PBH}} < 5 \cdot 10^{-10}$$

Constraints from H.E.S.S.



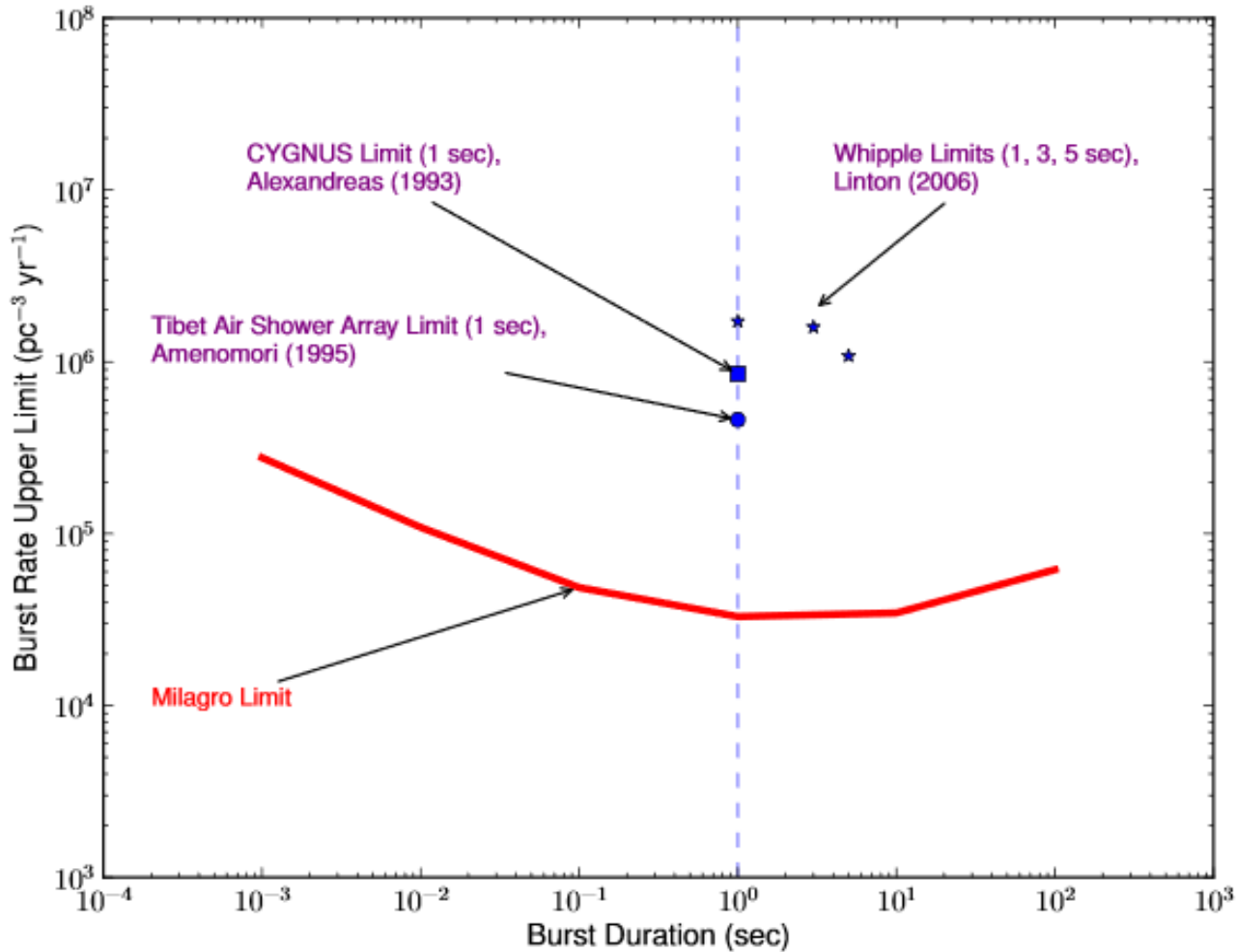
Nothing detected.

Upper limits can be derived.

At the moment these limits are not very constraining. However, with HESS-2 it will be possible to obtain more interesting limits.

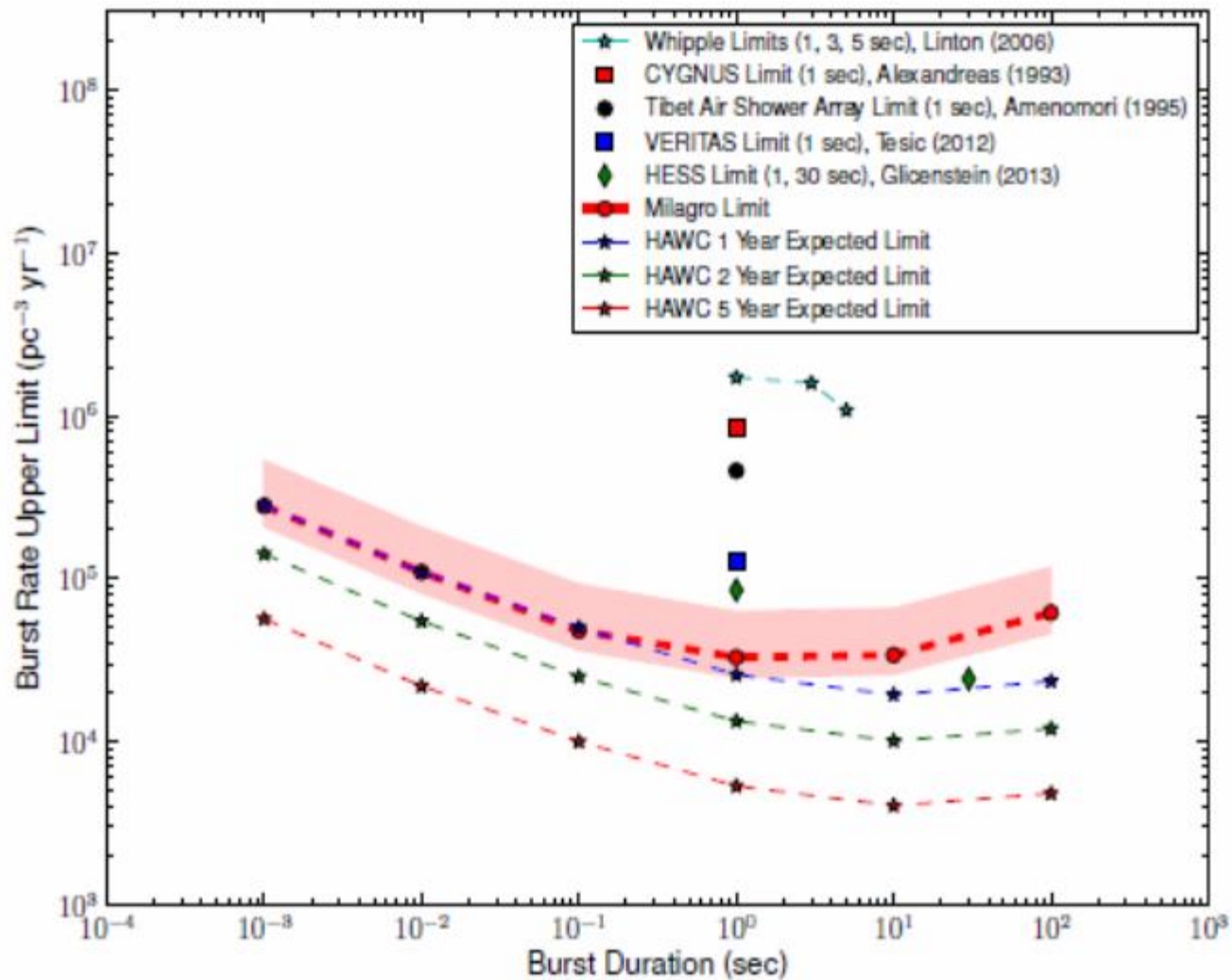
The preliminary upper limit on the explosion rate is $\dot{\rho}_{\text{PBH}} < 1.4 \times 10^4 \text{ pc}^{-3} \text{ yr}^{-1}$ at the 95% CL for $\tau = 30 \text{ s}$. The sensitivity limit, defined in section 5.3 is $1.7 \times 10^4 \text{ pc}^{-3} \text{ yr}^{-1}$. By comparison, the preliminary upper limit obtained with the $\tau = 1 \text{ s}$ search time-window is $\dot{\rho}_{\text{PBH}} < 4.9 \times 10^4 \text{ pc}^{-3} \text{ yr}^{-1}$ (95% CL).

Milagro limits



See also
1507.01648
about future
limits from HAWC.

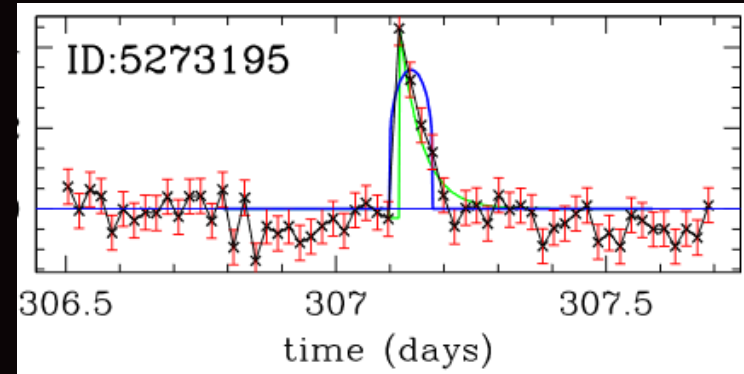
Joint limits



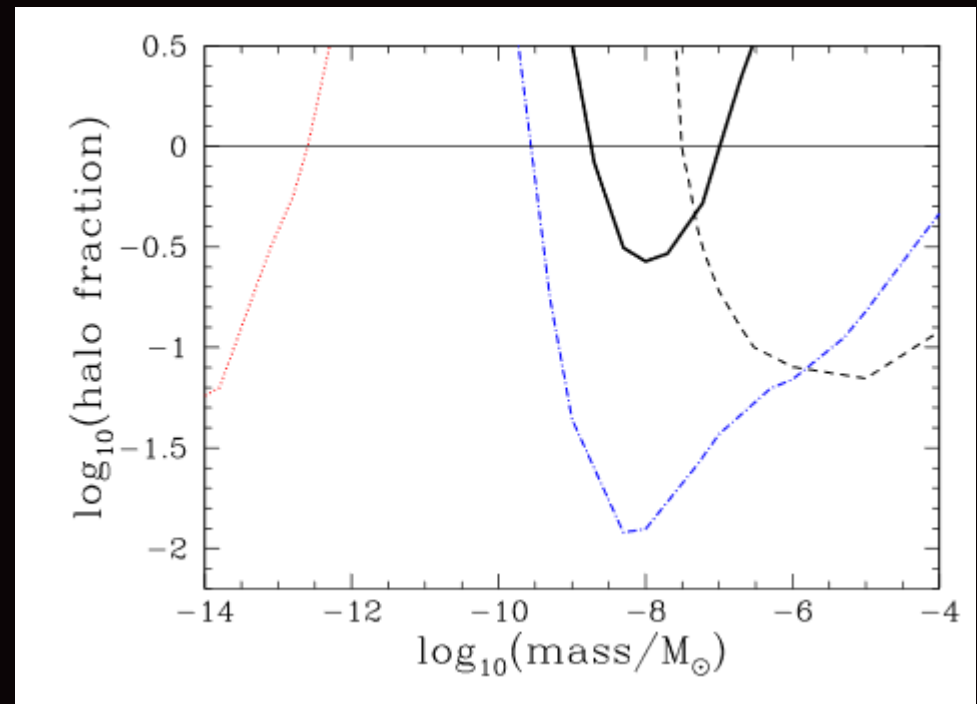
Limits from the Kepler data

Limits are based on lensing searches.
The idea was to put new limits on PBHs
as dark matter candidates looking for MACHOs.

Kepler is sensitive to PBHs in the mass range
 $2 \cdot 10^{-10} M_{\text{solar}} < M_{\text{BH}} < 2 \cdot 10^{-6} M_{\text{solar}}$

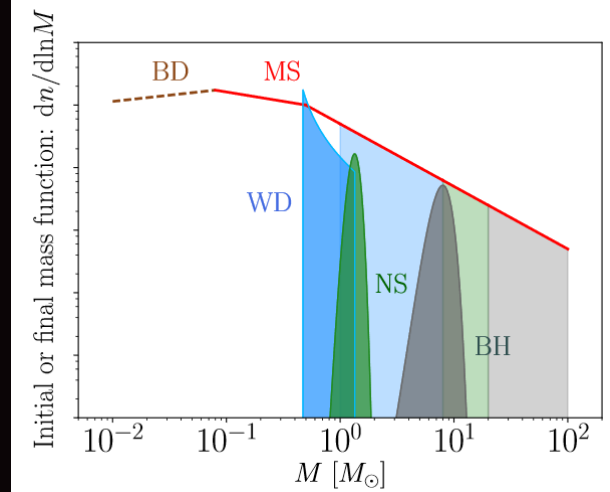


Solid black is the new limit.
It excludes the mass range
 $10^{-9} M_{\text{solar}} < M_{\text{BH}} < 10^{-7} M_{\text{solar}}$
I.e., PBHs from this range
cannot explain halo DM.
The allowed range is
 $10^{-13} M_{\text{solar}} < M_{\text{BH}} < 10^{-9} M_{\text{solar}}$



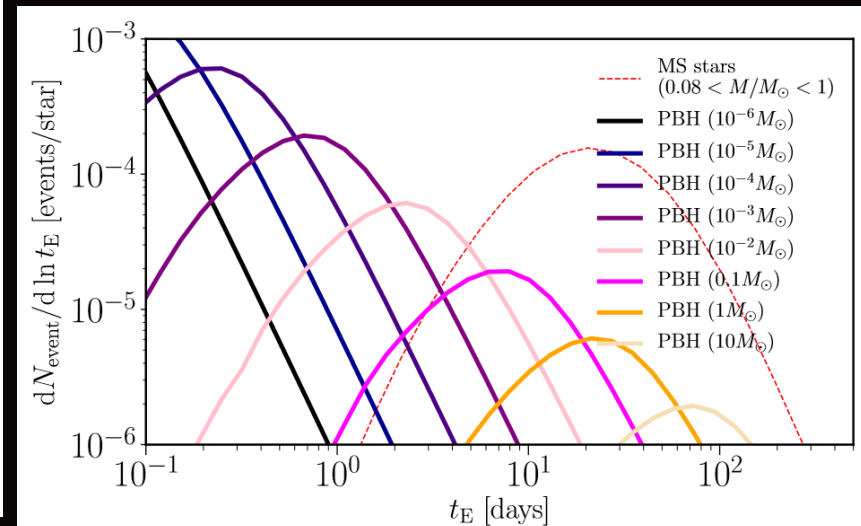
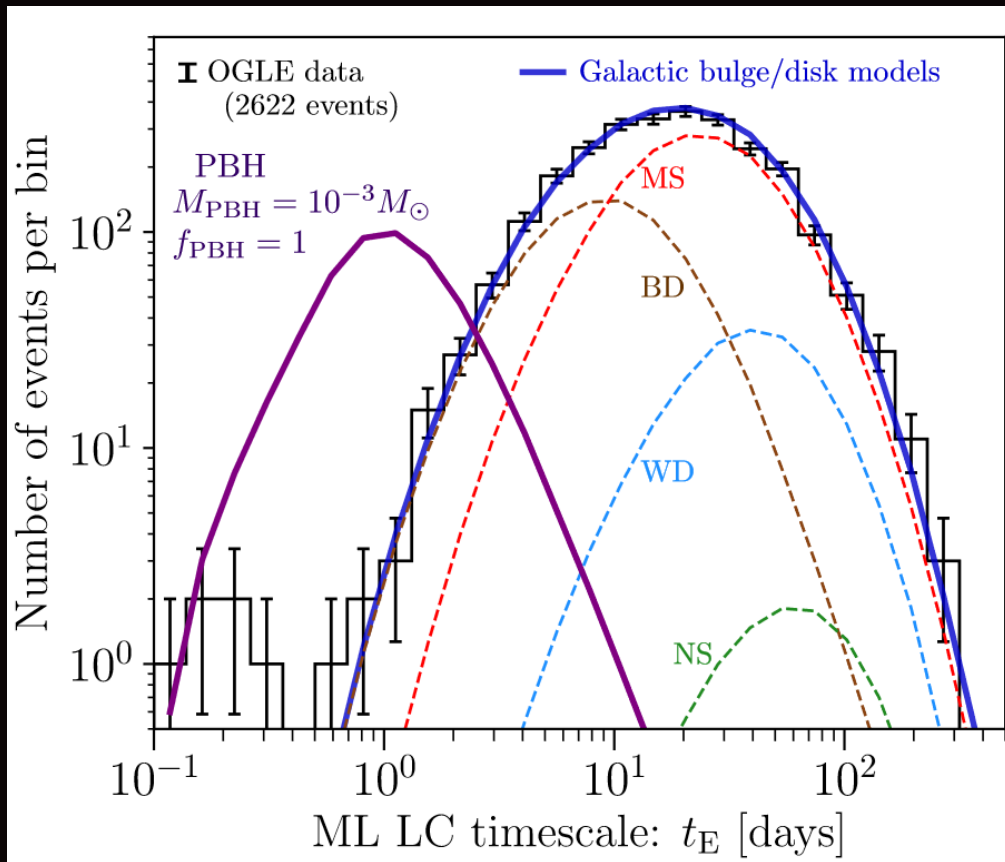
OGLE limits from lensing

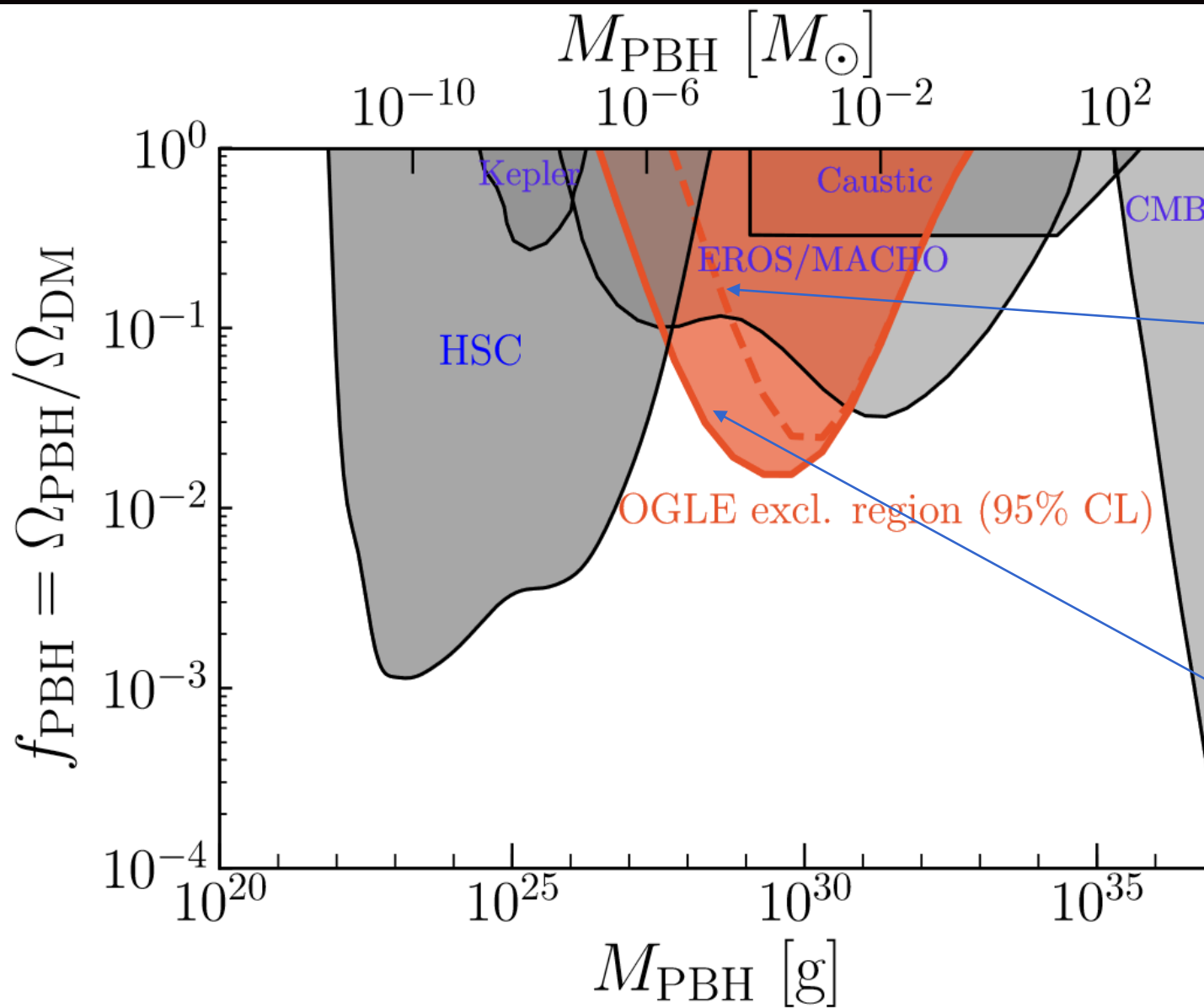
Six “suspicious” ultrashort (few hours) events are detected. They correspond to masses about an earth-like planet. Potentially, they can be PBHs.



MS : WD : NS : BH = 1 : 0.15 : 0.013 : 0.0068

+~0.1 free-floating Jupiter-mass planet per MS star

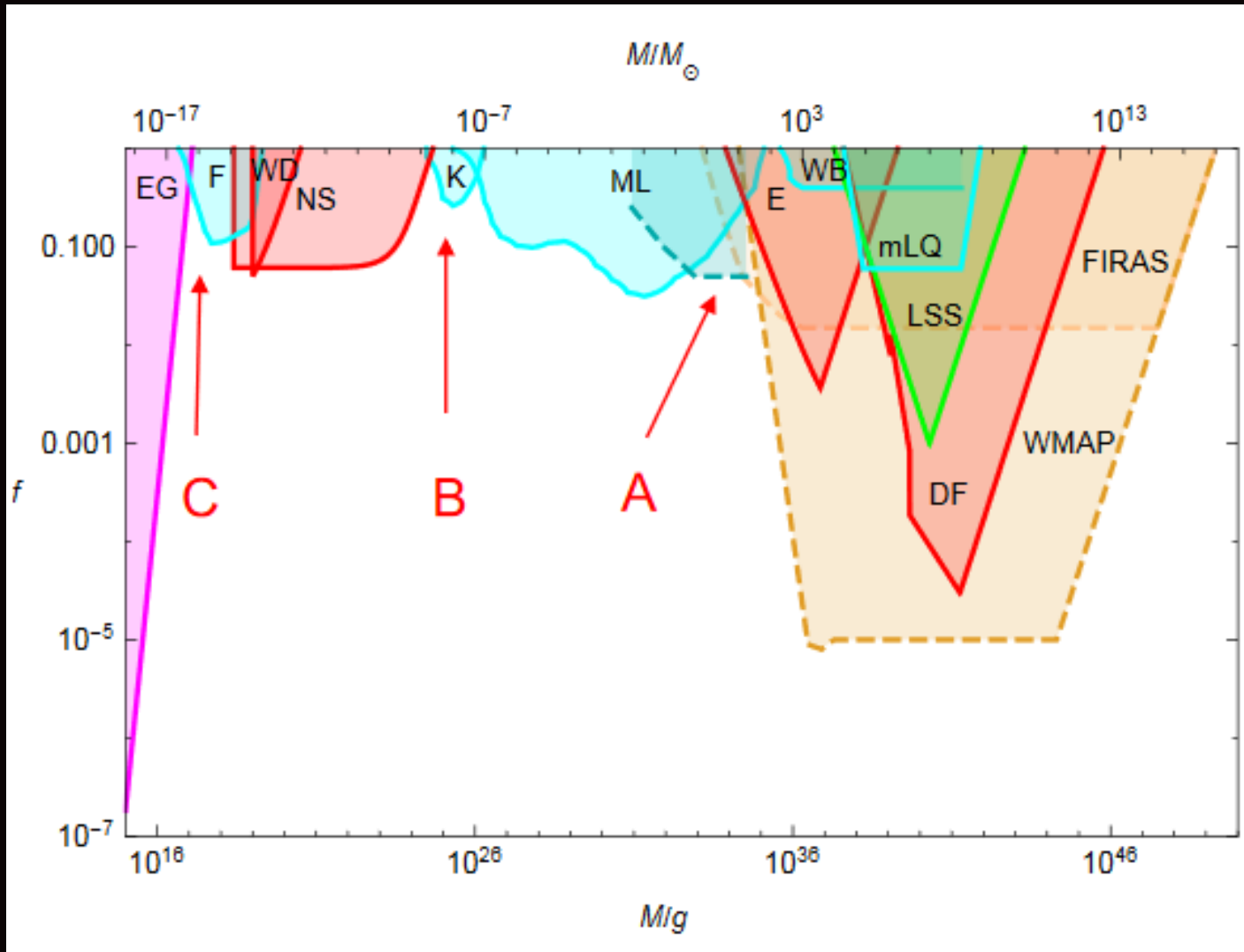




If 4 shortest OGLE events are excluded from the analysis.

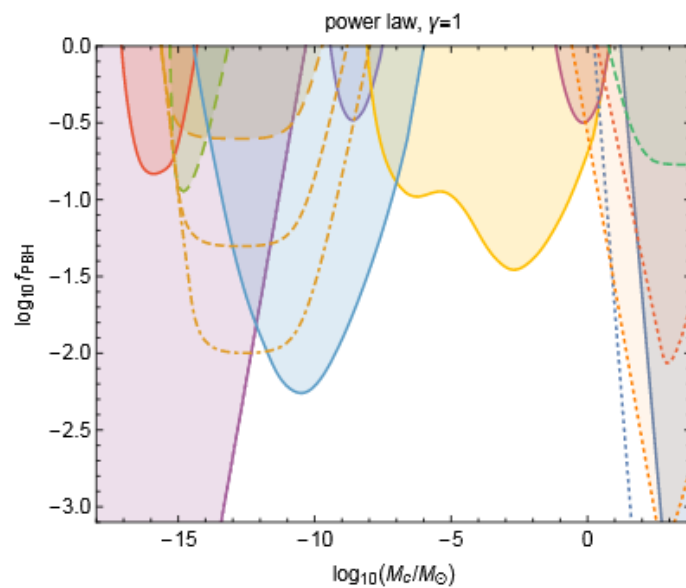
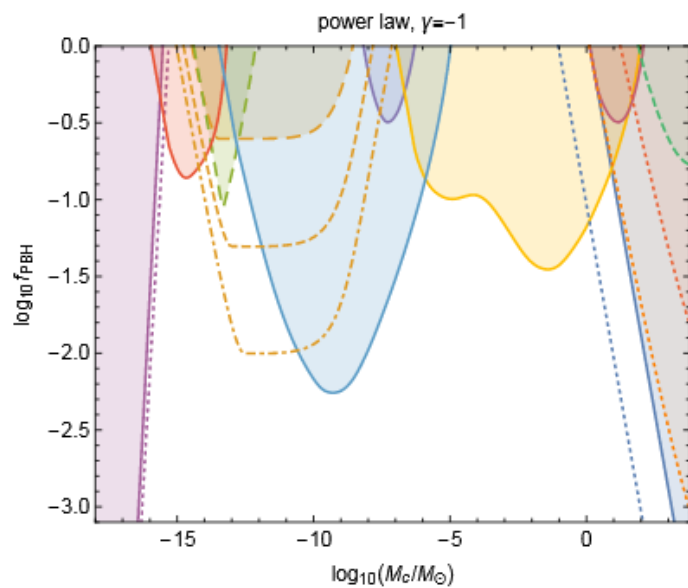
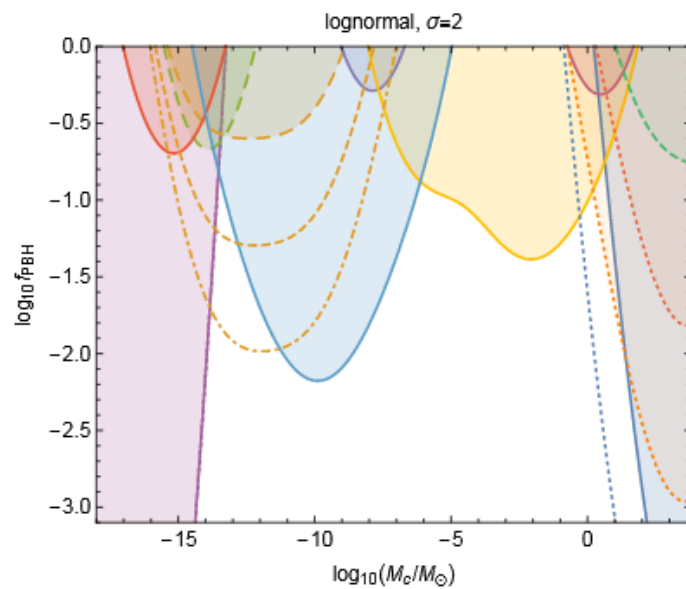
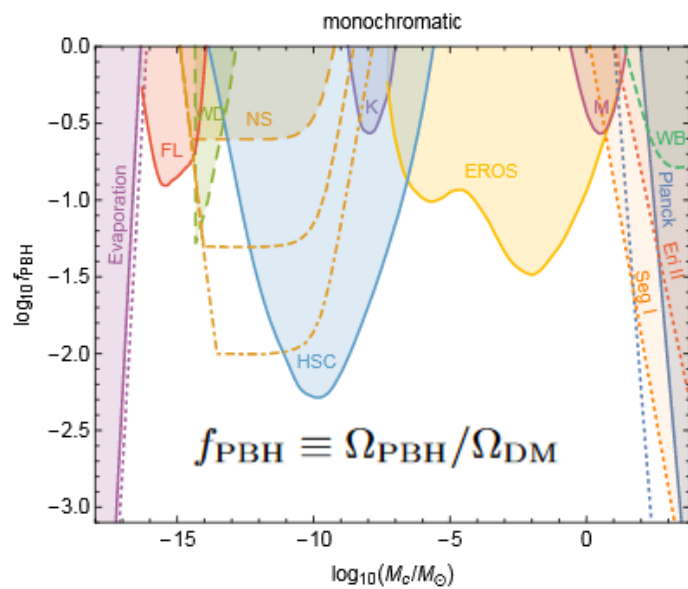
Assuming that no PBHs were detected by OGLE

Limits on PBHs of different masses



Three
“windows”
are marked.

All constraints
are for
monochromatic
mass functions
 $\Delta M \sim M$.



Legend to the previous plot

The purple region on the left is excluded by evaporations, the red region by femtolensing of gamma-ray bursts (FL), the brown region by neutron star capture (NS) for different values of the dark matter density in the cores of globular clusters, the green region by white dwarf explosions (WD), the blue, violet, yellow and purple regions by the microlensing results from Subaru (HSC), Kepler (K), EROS and MACHO (M), respectively. The dark blue, orange, red and green regions on the right are excluded by Planck data, survival of stars in Segue I (Seg I) and Eridanus II (Eri II), and the distribution of wide binaries (WB), respectively. The black dashed and solid lines show, respectively, the combined constraint with and without the constraints depicted by the colored dashed lines.

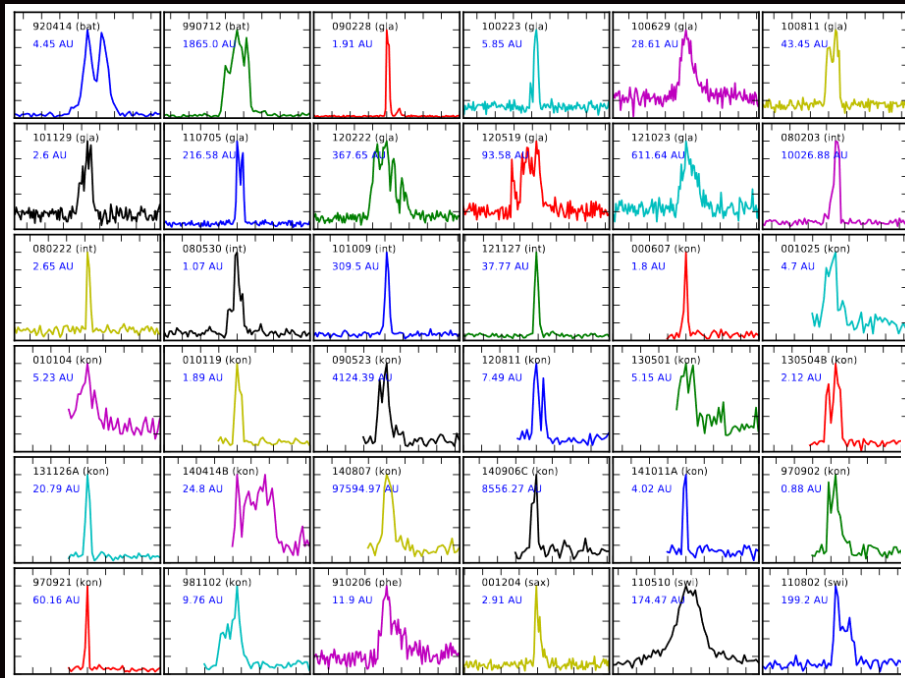
$$f_{\text{PBH}} \equiv \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} = \int dM \psi(M)$$

$$\psi(M) = \frac{f_{\text{PBH}}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

$$\psi(M) \propto M \frac{dn}{dM}$$

$$\psi(M) \propto M^{\gamma-1}$$

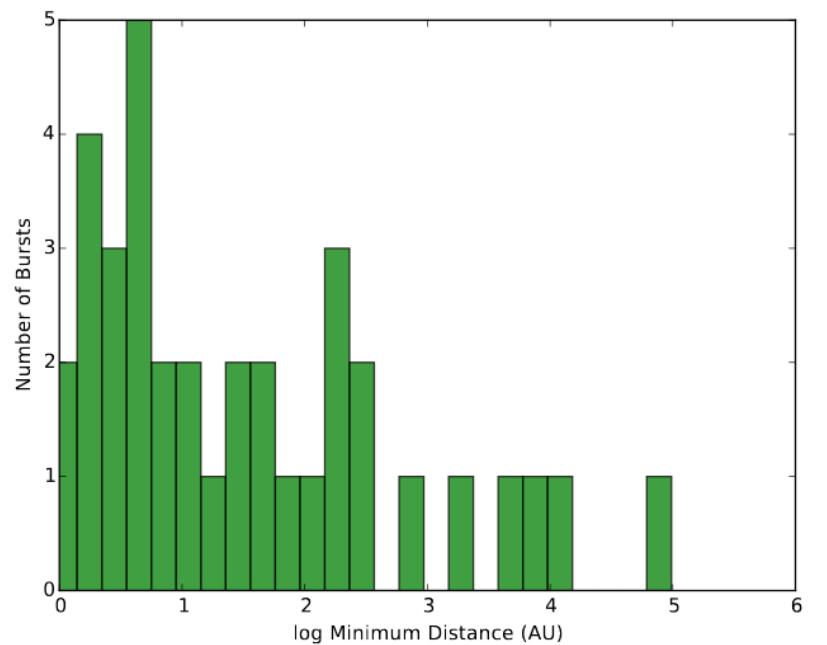
Searches with GRB network of detectors



With IPN the authors try to put limits on the distance to short gamma-ray bursts.

It is expected that PBHs evaporation is visible from short distances.

There are some (36) candidates with possibly small distances (<1 pc). But these are LOW limits. I.e., it is still very uncertain if these bursts are related to PBHs.



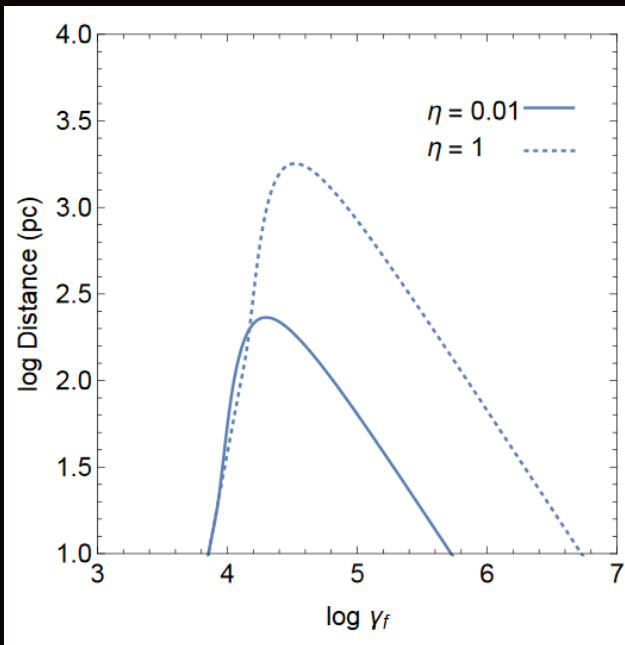
Radio transients. BHs and extra dimensions

Low-frequency (8-meter wavelength) antenna – ETA.

According to Blandford (1977) low-frequency radio observations can provide a limit much better than gamma-ray observations.

The limit strongly depends on the Lorentz factor of the fireball.

Depending on parameters a burst ~0.1s long can be detected from the distance ~hundreds parsec.



The limit is $4.2 \times 10^{-7} \text{ pc}^{-3} \text{ yr}^{-1}$

for Lorentz factor of $10^{4.5}$

L- size of an extra dimension

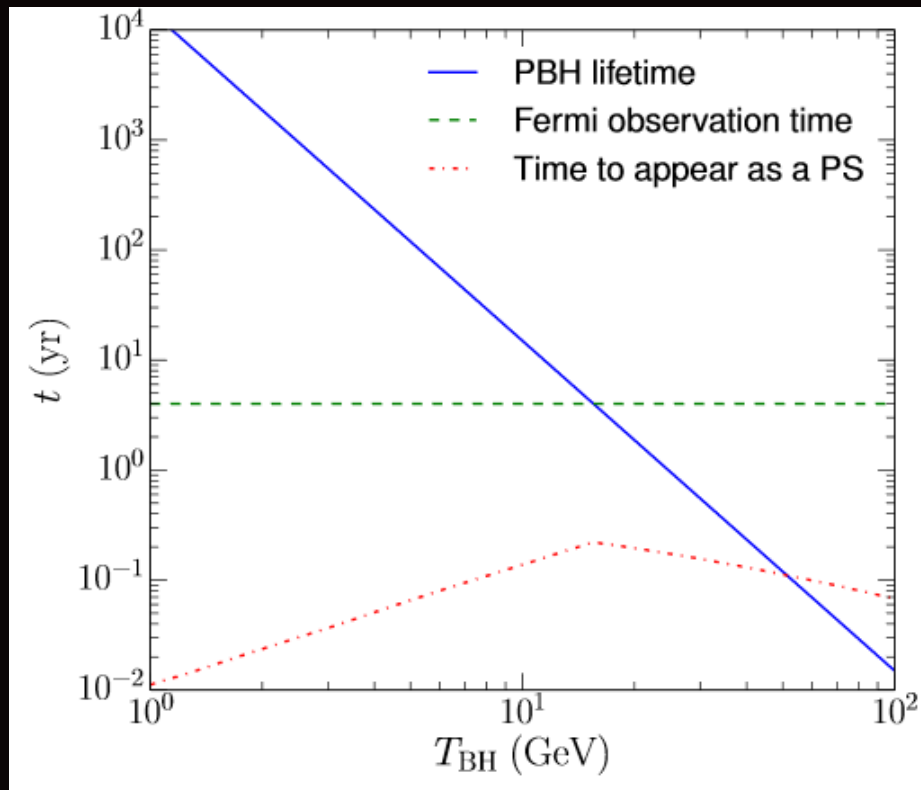
$$\eta M c^2 = \eta \mu L c^4 / G$$

$$\mu = G M / L c^2$$

$$\gamma_f = \frac{\frac{1}{2} k T}{m_e c^2} = \frac{\hbar c}{16 \pi G m_e} \frac{1}{M} \approx 10^5 \left(\frac{10^{11} \text{ g}}{M} \right)$$

Fermi limits

LAT is sensitive to evaporating BHs within 0.03 pc with $T \sim 16$ GeV (mass 6×10^{11} g). Life time is months-years. Some must already disappear during Fermi observations. Sources might show spectral and brightness evolution. And they must move (as they are close)!



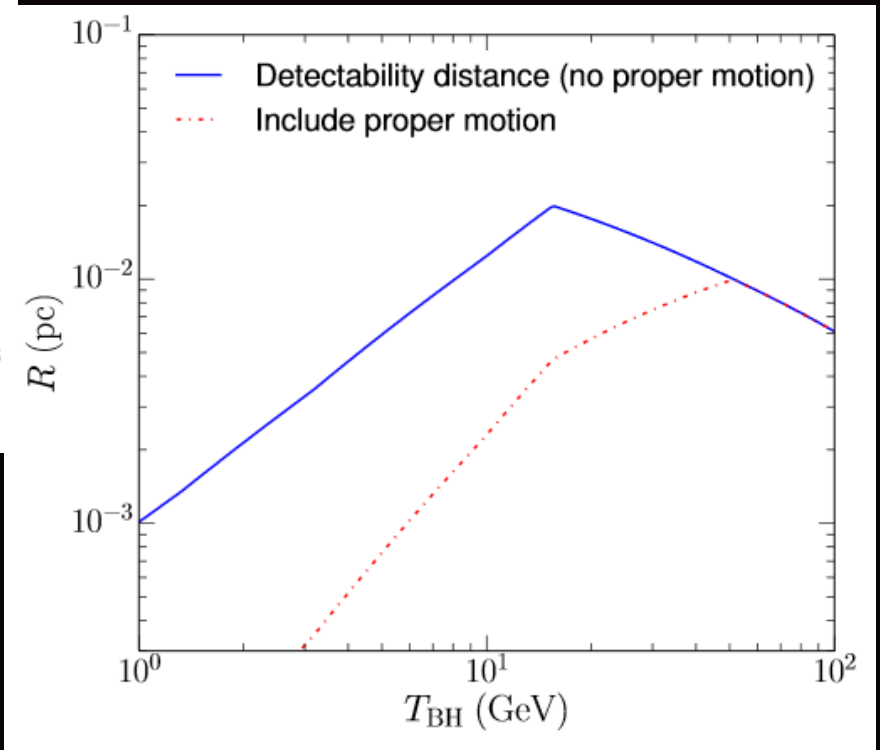
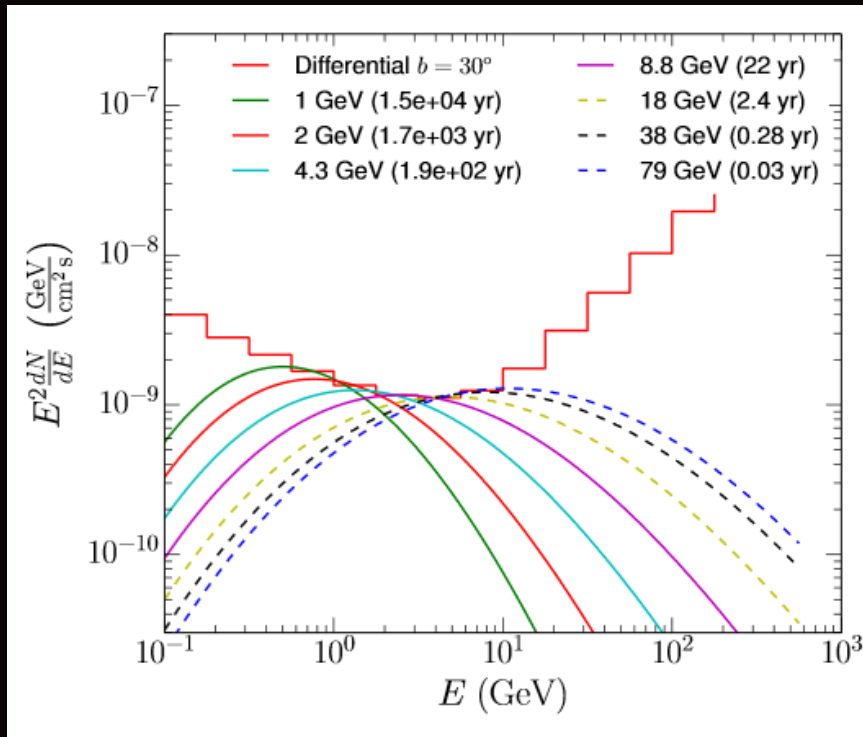
$$< 7.2 \times 10^3 \text{ pc}^{-3} \text{ yr}^{-1}$$

$$T_{\text{BH}} = \frac{\hbar c^3}{8\pi G M k} \approx 10^{-7} \left(\frac{M}{M_{\odot}} \right)^{-1} K$$

$$M(t) \approx 10^{15} \left(\frac{t}{10^{-23} \text{ s}} \right) \text{ g.}$$

$$\tau \approx 400 \left(\frac{M}{10^{10} \text{ g}} \right)^3 \text{ s.}$$

Sensitivity of Fermi to PBHs



Calculations of the limit

$$\dot{\rho}_{\text{PBH}} = \text{const.}$$

$$\frac{d\rho_{\text{PBH}}}{dT} \propto T^{-4}.$$

$$f = \frac{\int_{16.4 \text{ GeV}}^{60 \text{ GeV}} T^{-4} dT}{\int_{5 \text{ GeV}}^{60 \text{ GeV}} T^{-4} dT}.$$

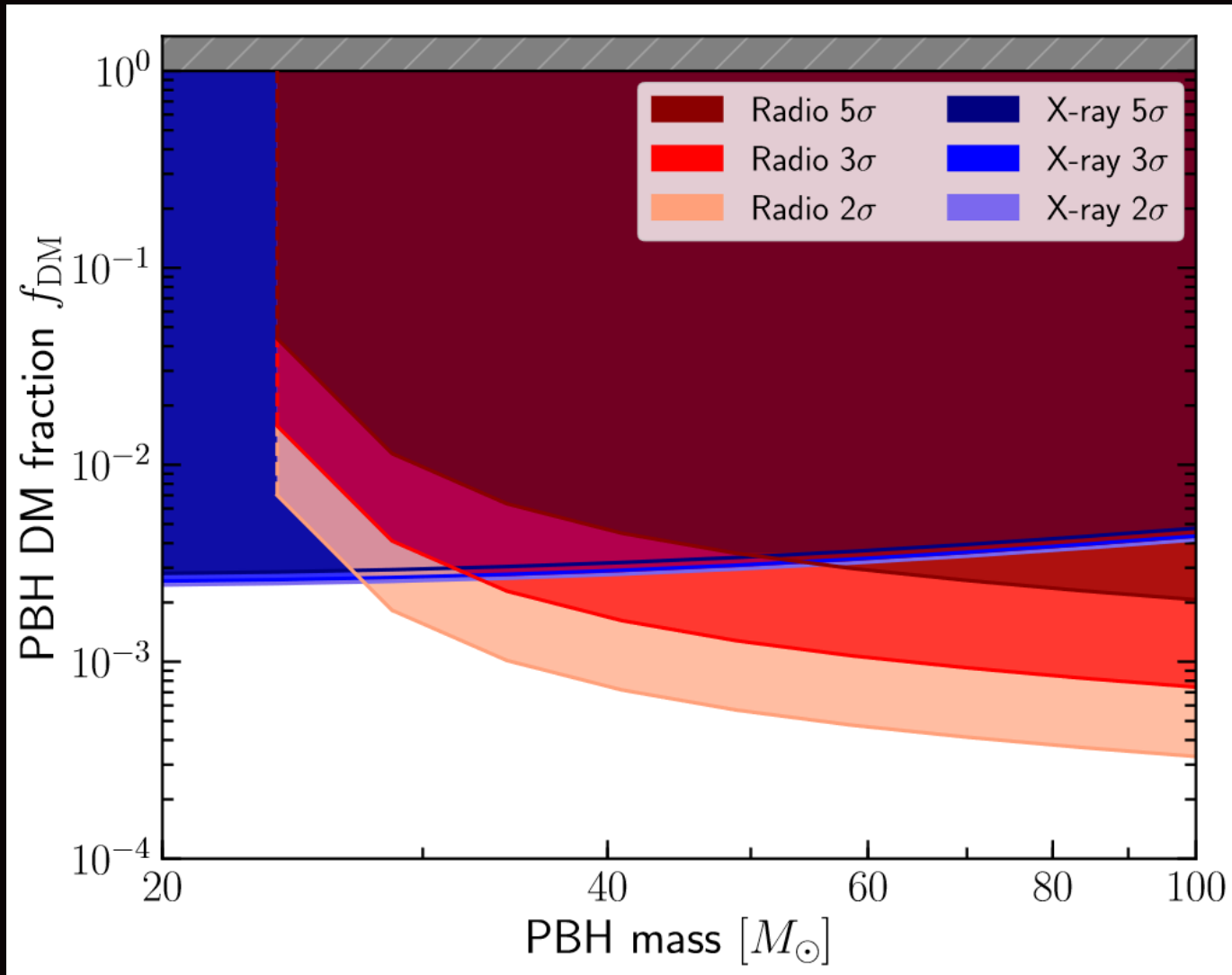
$$N = \rho \epsilon V,$$

$$\epsilon = \frac{\iint \epsilon(R, T) \frac{R^2}{T^4} dR dT}{\iint \frac{R^2}{T^4} dR dT},$$

$$\dot{\rho}_{\text{PBH}} < f \frac{6.64}{\epsilon V t} = 7.2 \times 10^3 \text{ pc}^{-3} \text{ year}^{-1}.$$

$$\dot{\rho}_{\text{PBH}} < (7.2^{+8.1}_{-2.4}) \times 10^3 \text{ pc}^{-3} \text{ yr}^{-1}.$$

Limits from accretion

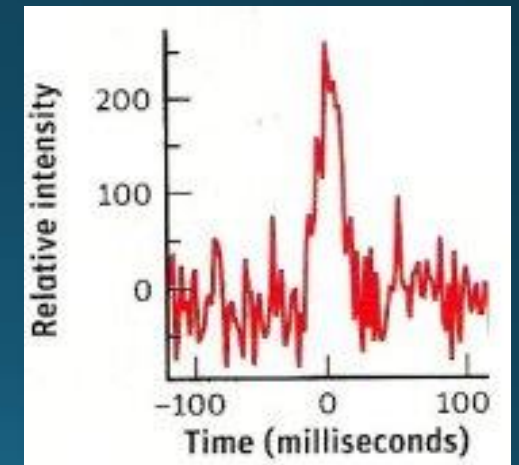
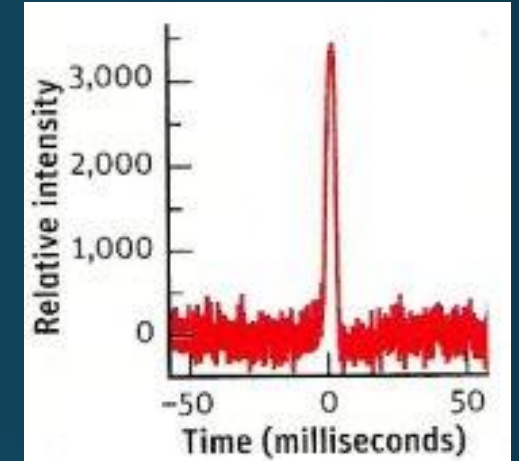
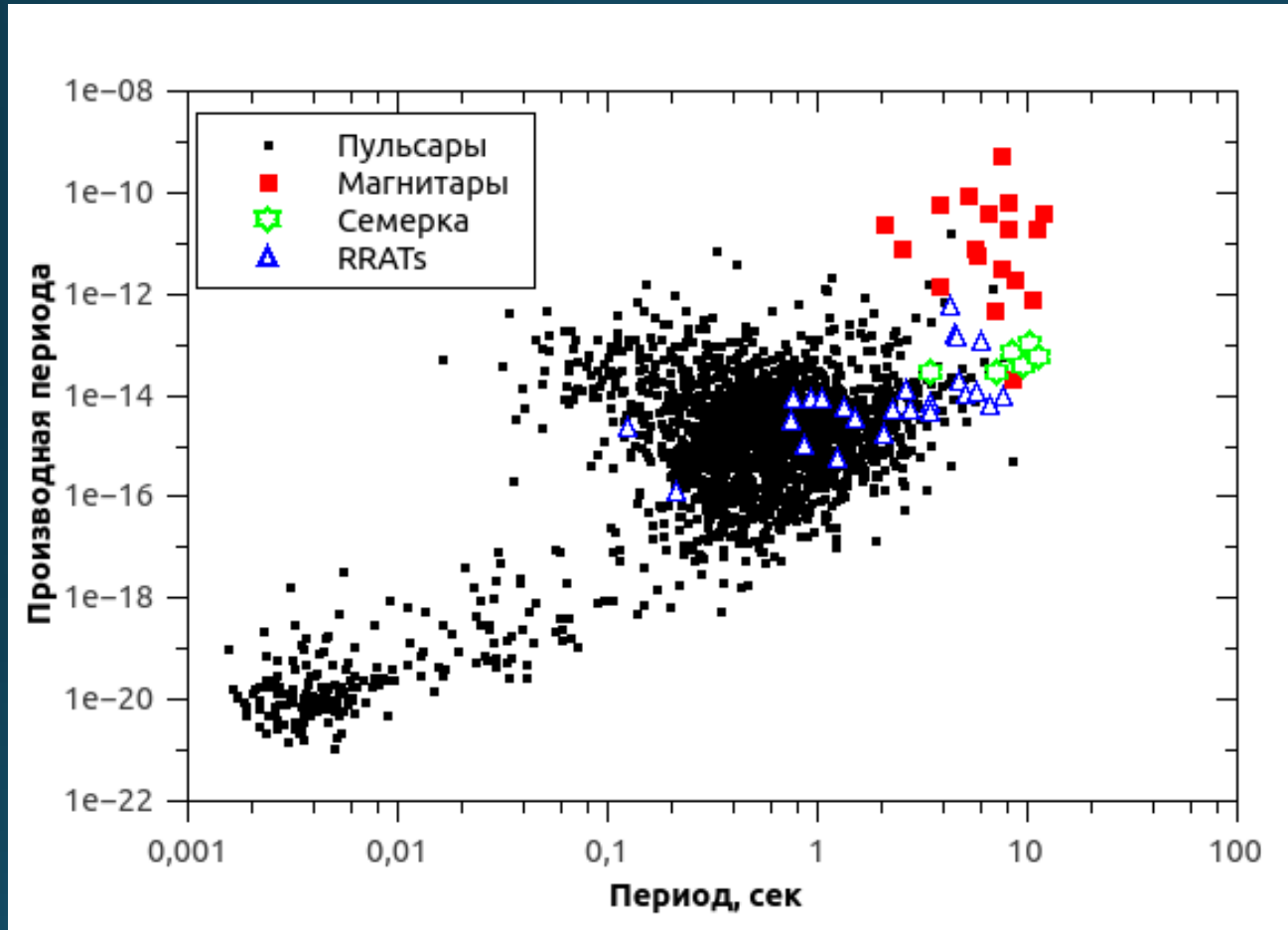


1812.07967, see also 1805.06513

Быстрые радиовсплески

С.Б. Попов

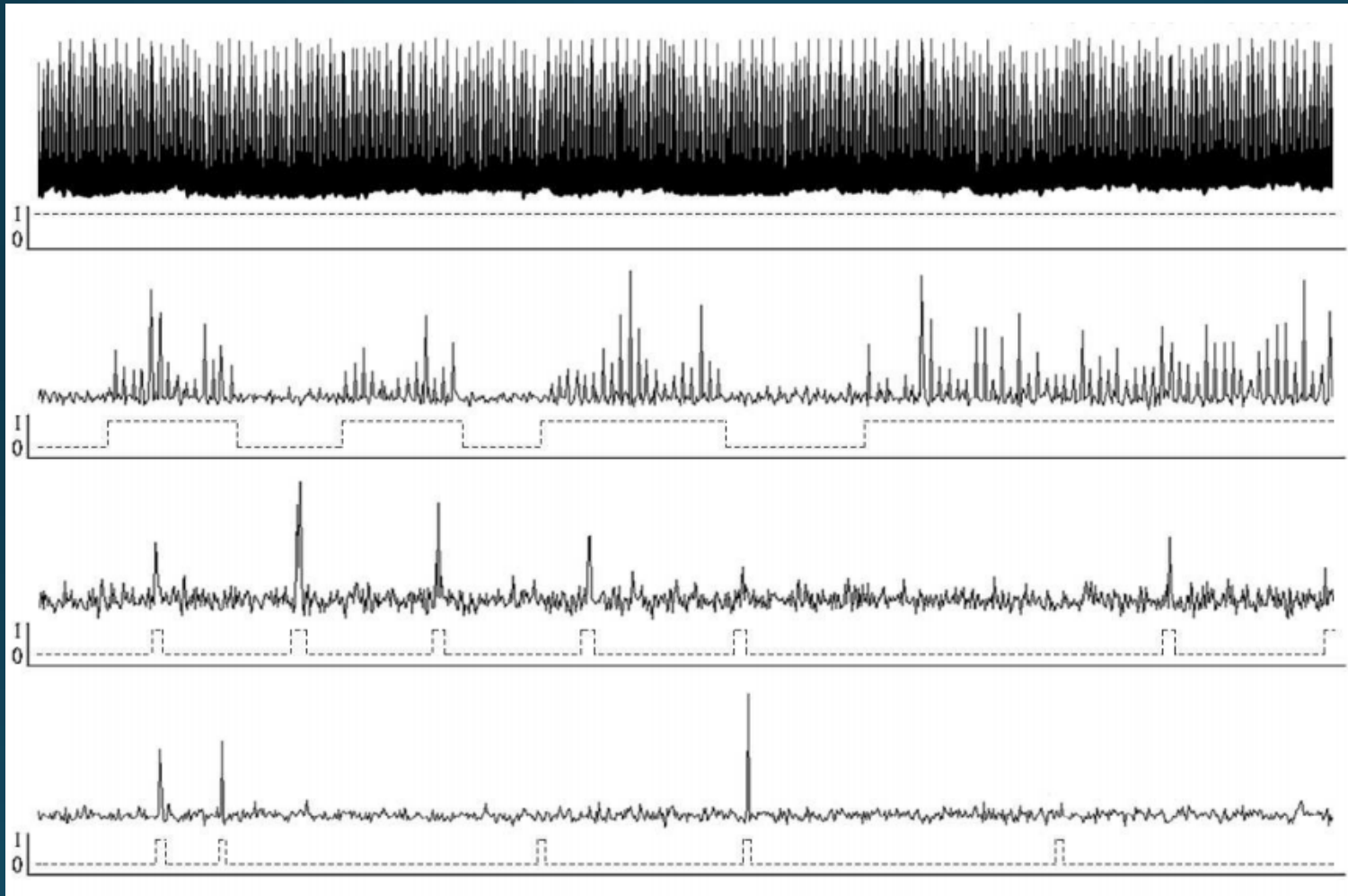
RRATs – Вращающиеся радиотранзиенты



Миллисекундные радиовсплески нейтронных звезд.
Удалось измерить период вращения и его производную.
Причины всплесков не известны до сих пор.

Открыты в 2006 году,
см. [astro-ph/0511587](https://arxiv.org/abs/astro-ph/0511587).

RRAT – это пульсары?



Vela

PSR
J1646–6831

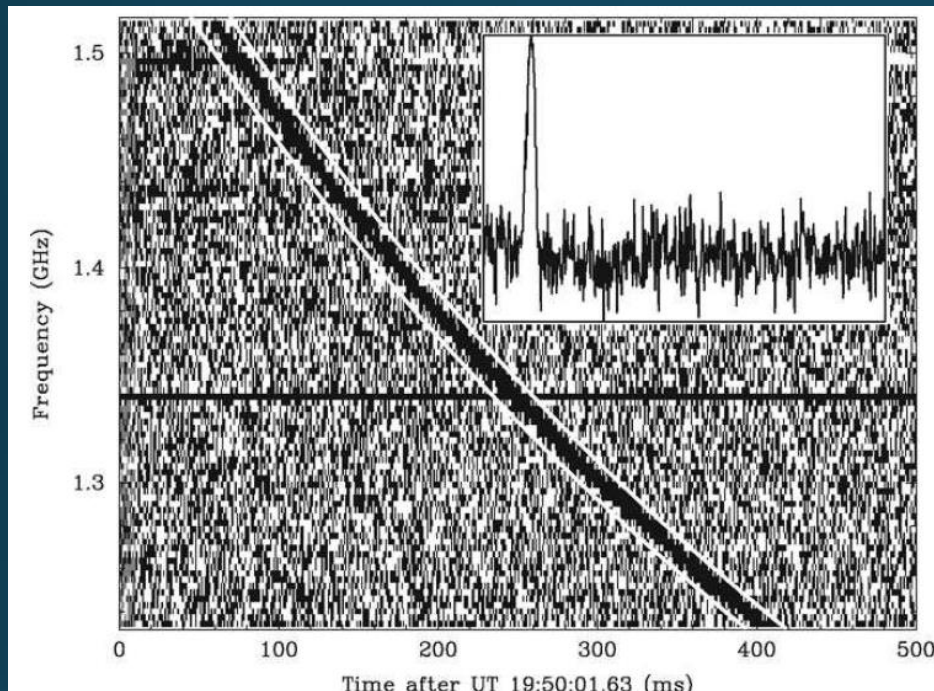
J1647–36

J1226–32

Сейчас считается, что всплески RRATs – это форма магнитосферной активности. Похожие всплески есть у радиопульсаров, и провести резкую границу между ними очень трудно.

Миллисекундные радиовсплески

Science 318, 777 (2007)



Одно из самых интересных открытий 2007 г.

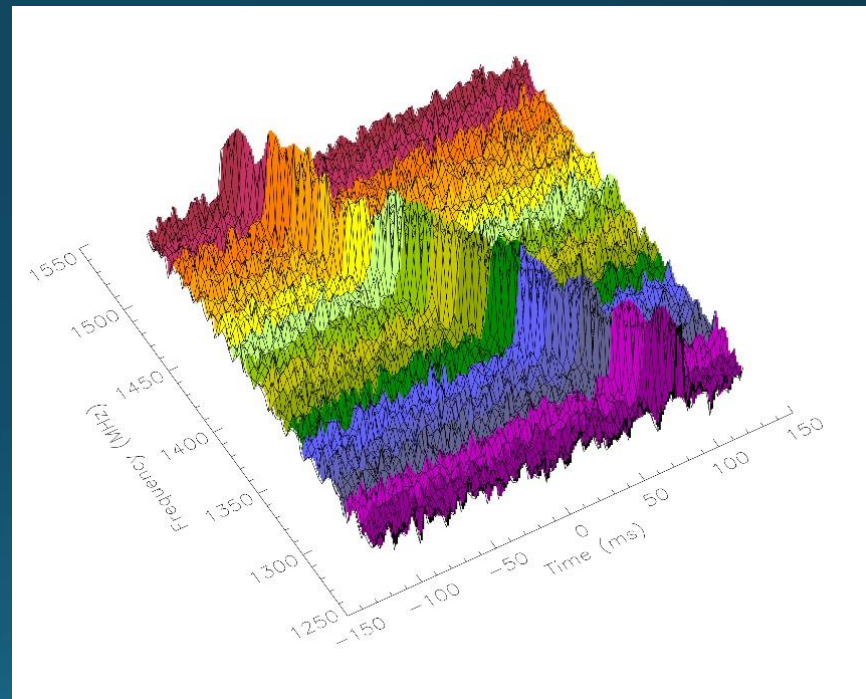
В направлении всплеска не были видно вспышек в других диапазонах.

Идентифицировать источник не удалось.

[О том, как не перепутать RRAT и FRB, см. 1512.02513]

Открыты в 2007 году.

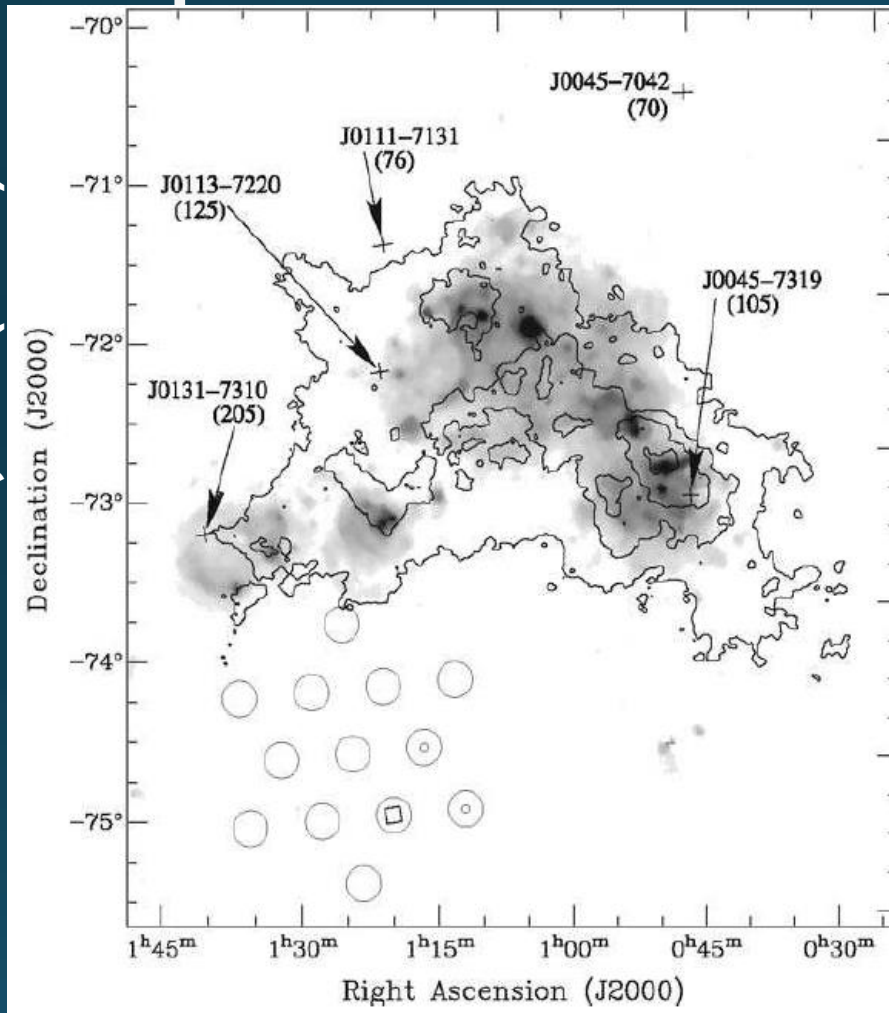
Происхождение неизвестно.



Большая мера дисперсии.
Если дисперсия набирается на межгалактической среде, то светимость в радио $\sim 10^{43}$ эрг/с

Первый всплеск

Science 318, 777 (2007)



Открыт в Парксе
Дунканом Лоримером и др.

~30-40 Ян, < 5 мсек.

3 градуса от Малого
Магелланового Облака



$$\mathcal{L} = 1.3 \times 10^{41} \text{ erg/s} \left(\frac{S_\nu}{1 \text{ Jy}} \right) \left(\frac{\Delta\nu}{1.4 \text{ GHz}} \right) \left(\frac{\Omega}{1 \text{ sr}} \right) \left(\frac{D}{1 \text{ Gpc}} \right)^2.$$

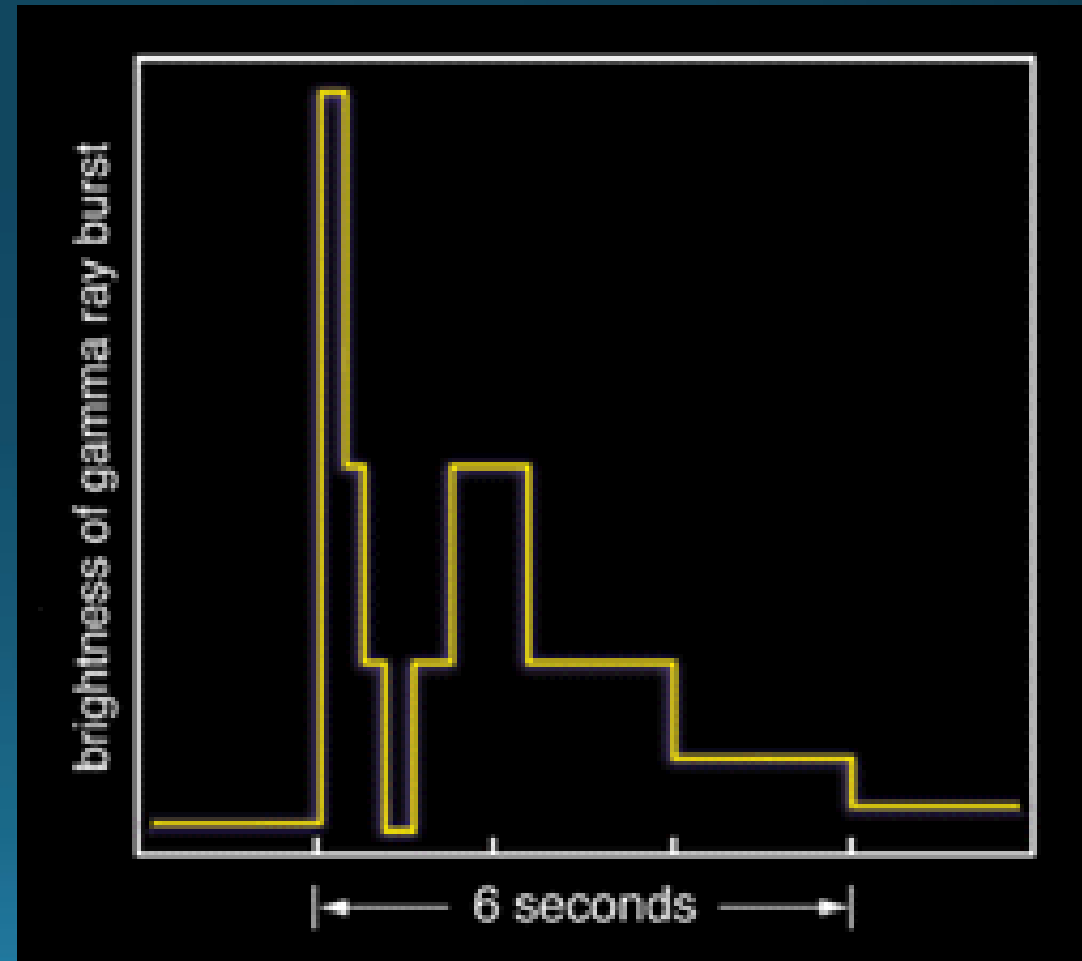
История повторяется? GRB2.0?

<http://www.lanl.gov/about/history-innovation/innovation-timeline.php>



Только в конце 90-х гг. удалось одновременно увидеть всплески и в рентгеновском диапазоне. Это позволило наконец-то идентифицировать их.

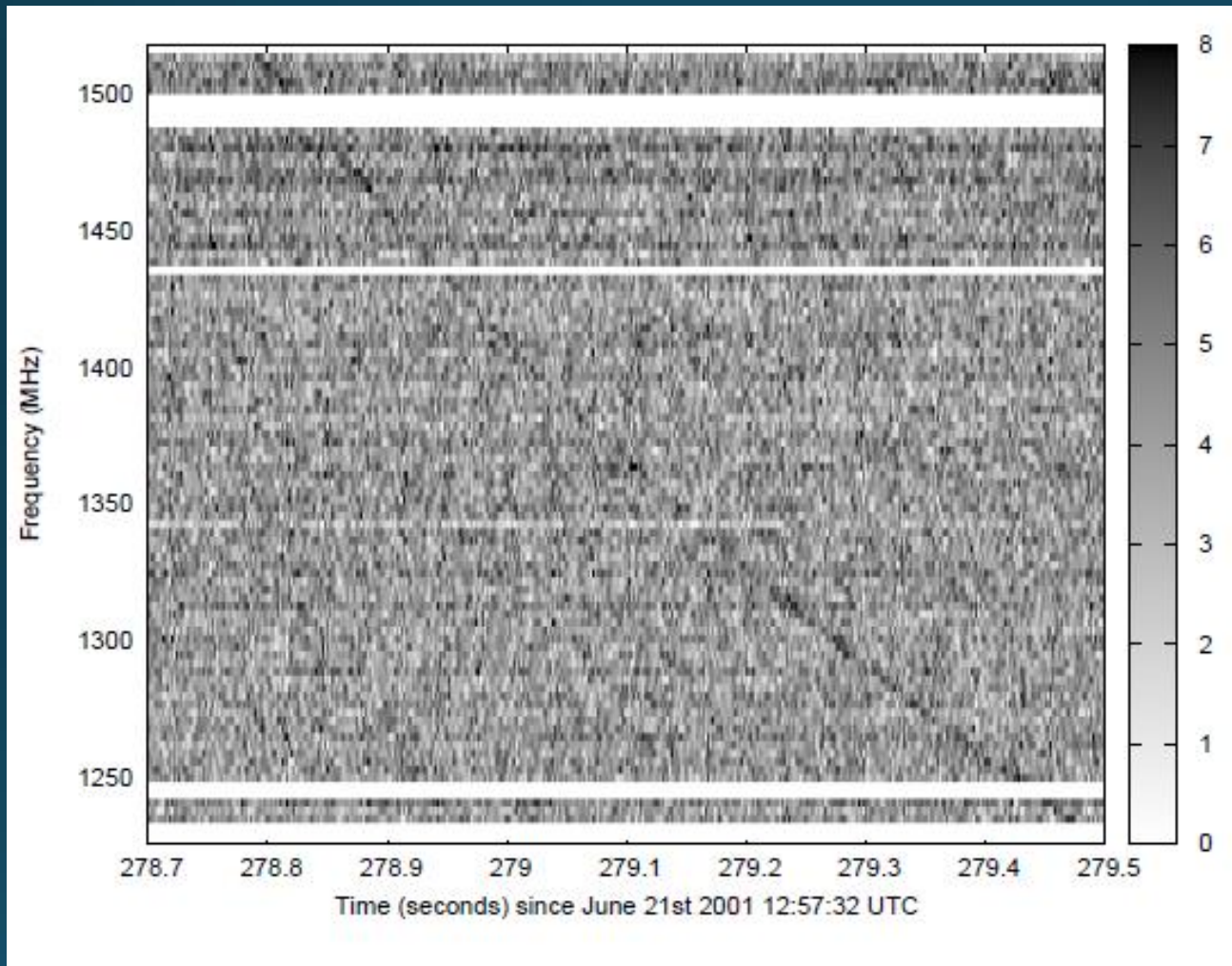
В конце 60 гг. были открыты космические гамма-всплески. 30 лет они оставались загадкой, т.к. в направлении всплеска не удавалось увидеть сигнал в другом спектральном диапазоне.



<https://heasarc.gsfc.nasa.gov/docs/cgro/epo/vu/overview/bursts/firstbst/firstbst.html>

Второй случай?

1206.4135



В плоскости Галактики.

Гипотеза:
испарение
черной дыры!

Радиовсплески
от испаряющихся
черных дыр
были предсказаны
уже давно.
Более того,
одной из мотиваций
ученого, создавшего
ключевую технологию
Wi-Fi, было открыть
в радио такие вспышки.

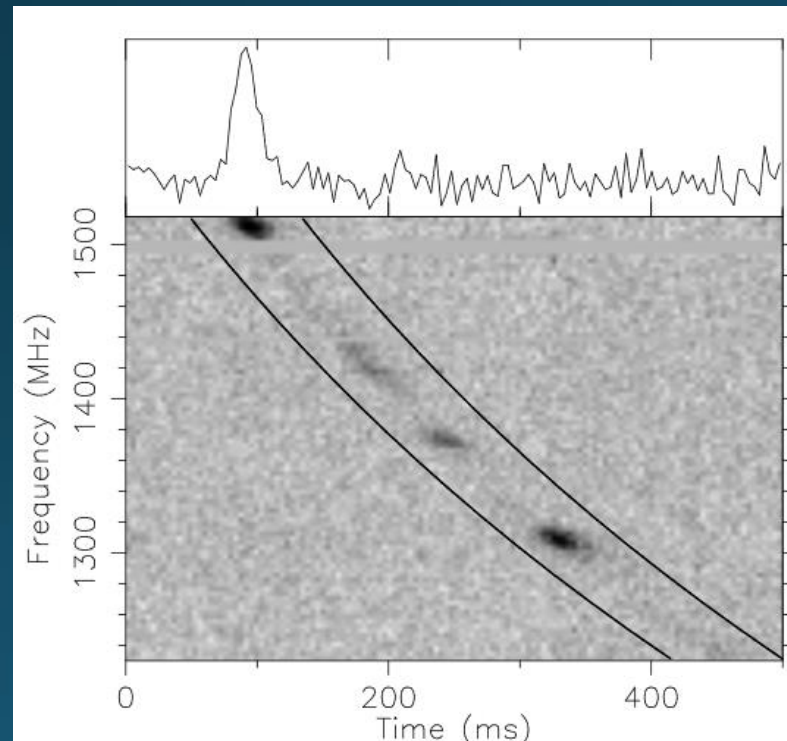
Т.к. всплеск отличался от лоримеровского, то ясности
в ситуацию с быстрыми радиовсплесками это не внесло.

Perytons

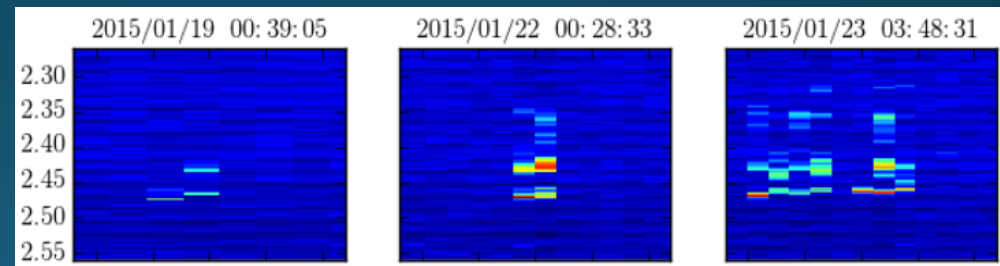
Перитоны начали активно обсуждать несколько лет назад. Их свойства сразу говорили о том, что это должны быть всплески где-то вблизи (максимум – земная атмосфера).

Однако по некоторым параметрам они похожи на БРВ.

Появлялись они только в рабочие часы или по выходным, что указывало на искусственное происхождение.



Всего на 2015 год было зарегистрировано около полусотни таких событий. Все на телескопе Parkes.



Решение проблемы перитонов оказалось довольно неожиданным. Здесь помогла установка новой Системы мониторинга помех.

Сомнения

Открытие перитонов заставило усомниться в реальности события Лоримера.

Быстрые радиовсплески открывались только по архивным данным.

Поиск в разных архивах в течение нескольких лет не давал результатов – новых примеров быстрых радиовсплесков не было.

Даже теоретики притихли



<http://www.onex.in/images/doubts.jpg>

Миллисекундные радиовсплески

В 2007 г. был обнаружен первый всплеск.
Но пока он был один – были сомнения.
В 2012 – еще один, но сомнения остались.

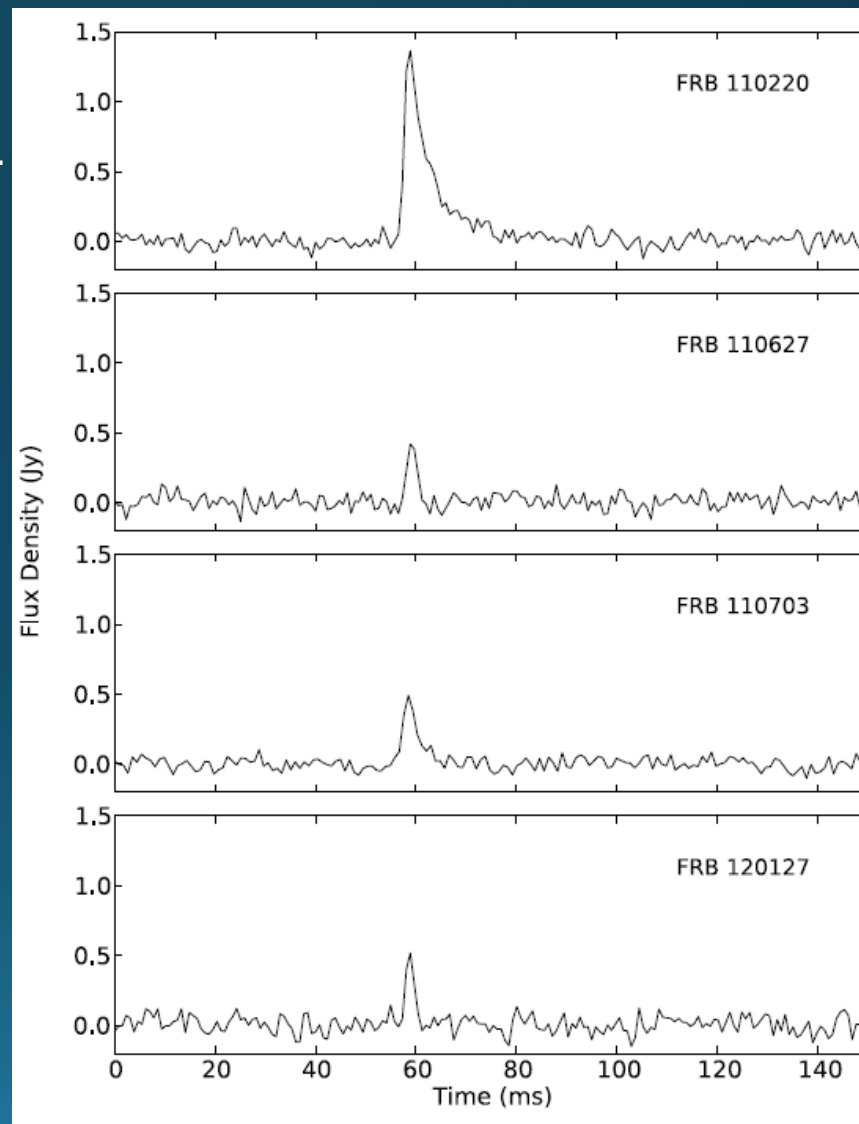
В 2013 – сомнения долой! Еще четыре!

Темп ~ неск. тысяч в день на всем небе.

Это явно новый класс событий,
происхождение которых неизвестно:

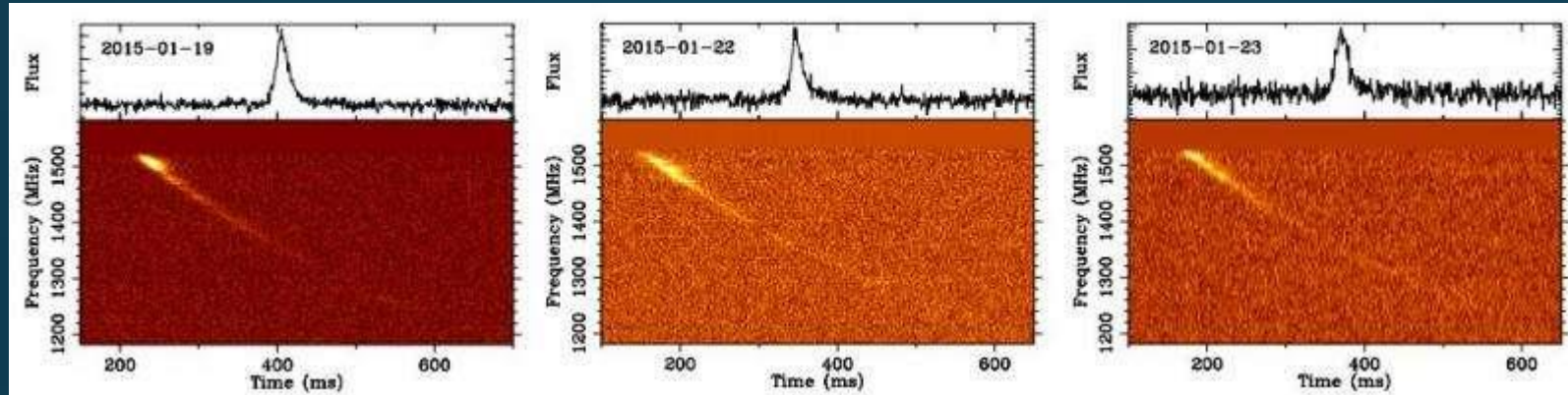
- магнитары
- гамма-всплески
- слияния нейтронных звезд
- сверхновые
- слияния белых карликов
- массивные нейтронные звезды
- вспышки на обычных звездах (?)

Появилось устоявшееся название
Fast Radio Bursts



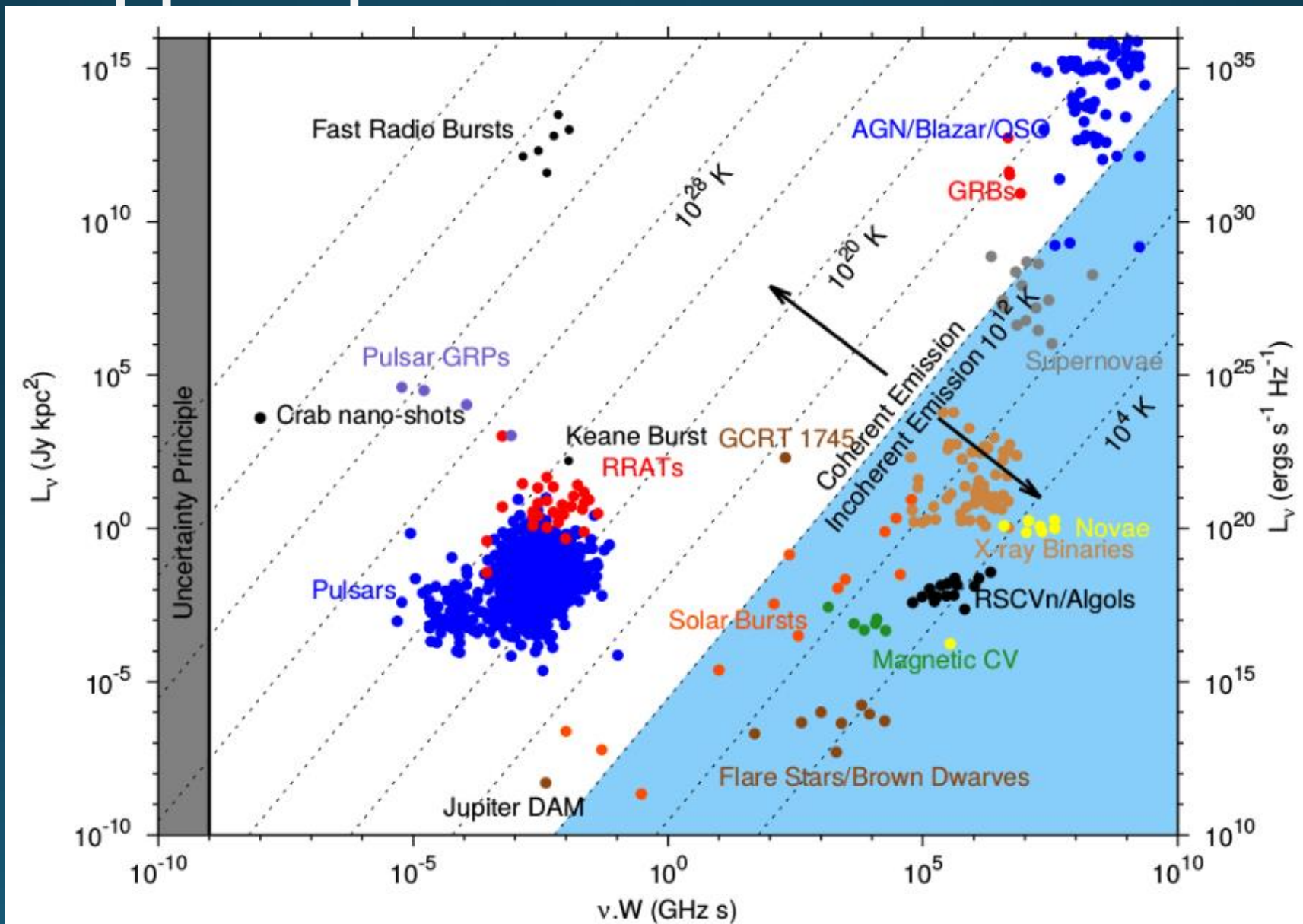
Перитоны – микроволновки!

1504.02165



Исследование показало, что перитоны возникают при преждевременном открытии дверцы микроволновки, если телескоп находится в некотором особом положении. Идентификация источника этих помех сделала еще более надежным представление о том, что сами быстрые радиовсплески – это реальный астрономический феномен.

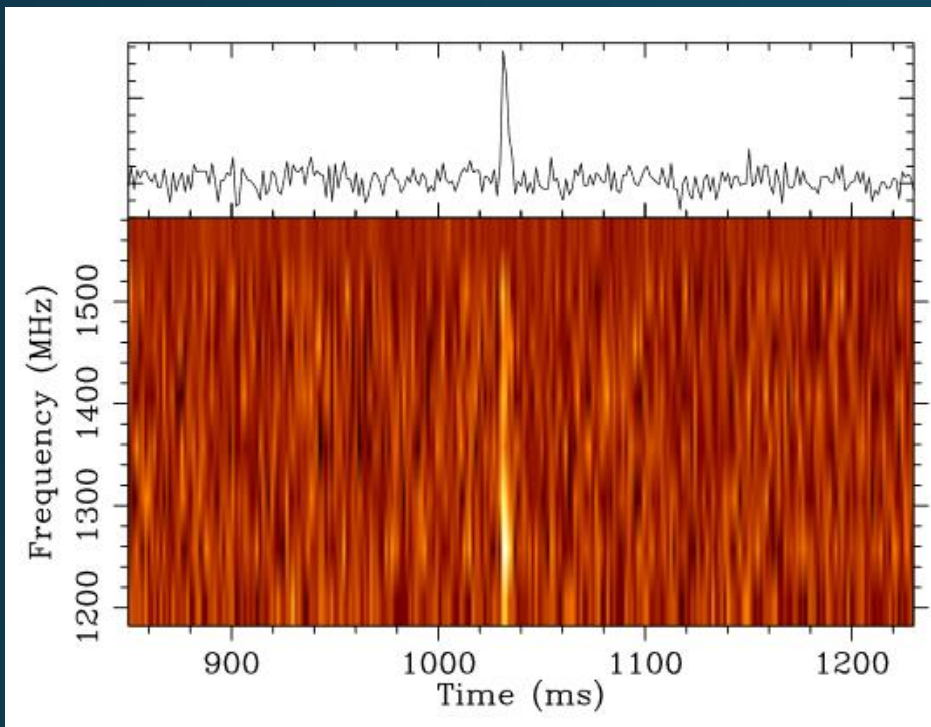
Радиотранзиенты



1507.00729, 1411.1067

Первый всплеск в реальном времени

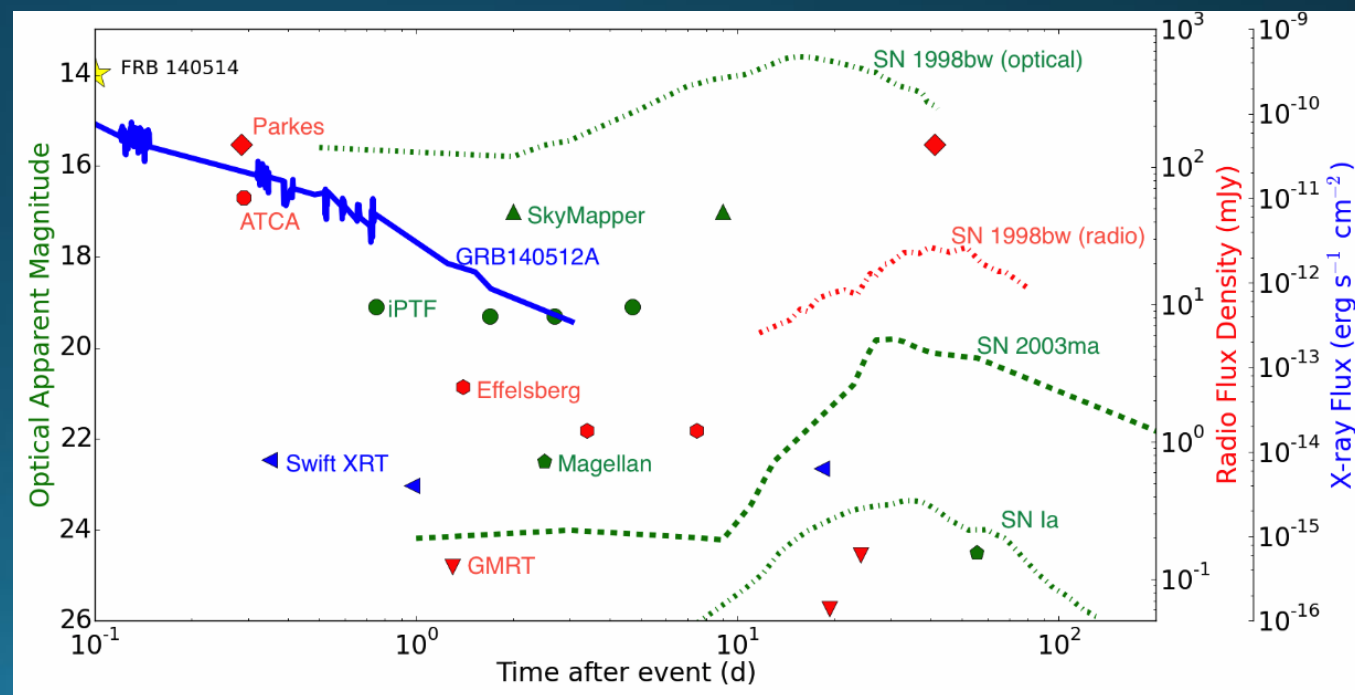
1412.0342



Отсутствие данные
в других диапазонах
закрывает модель
с близкой сверхновой
и с длинным
гамма-всплеском.

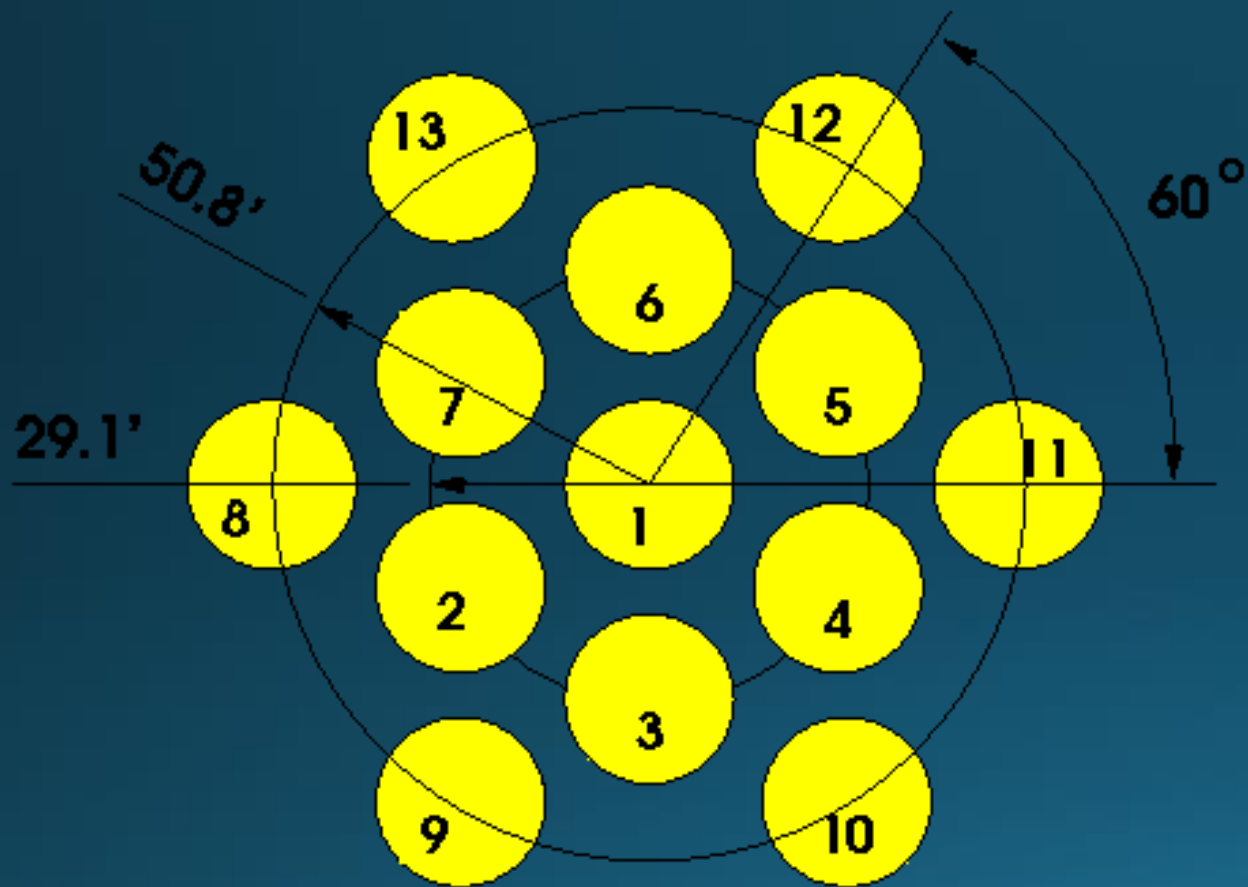
В мае 2014 года впервые удалось увидеть
быстрый радиовсплеск в реальном времени.
Т.е., он был обнаружен непосредственно
при наблюдениях, а не найден в архиве.

Это позволило запустить программу наблюдений
в других диапазонах спектра.
К сожалению, ничего не было найдено.

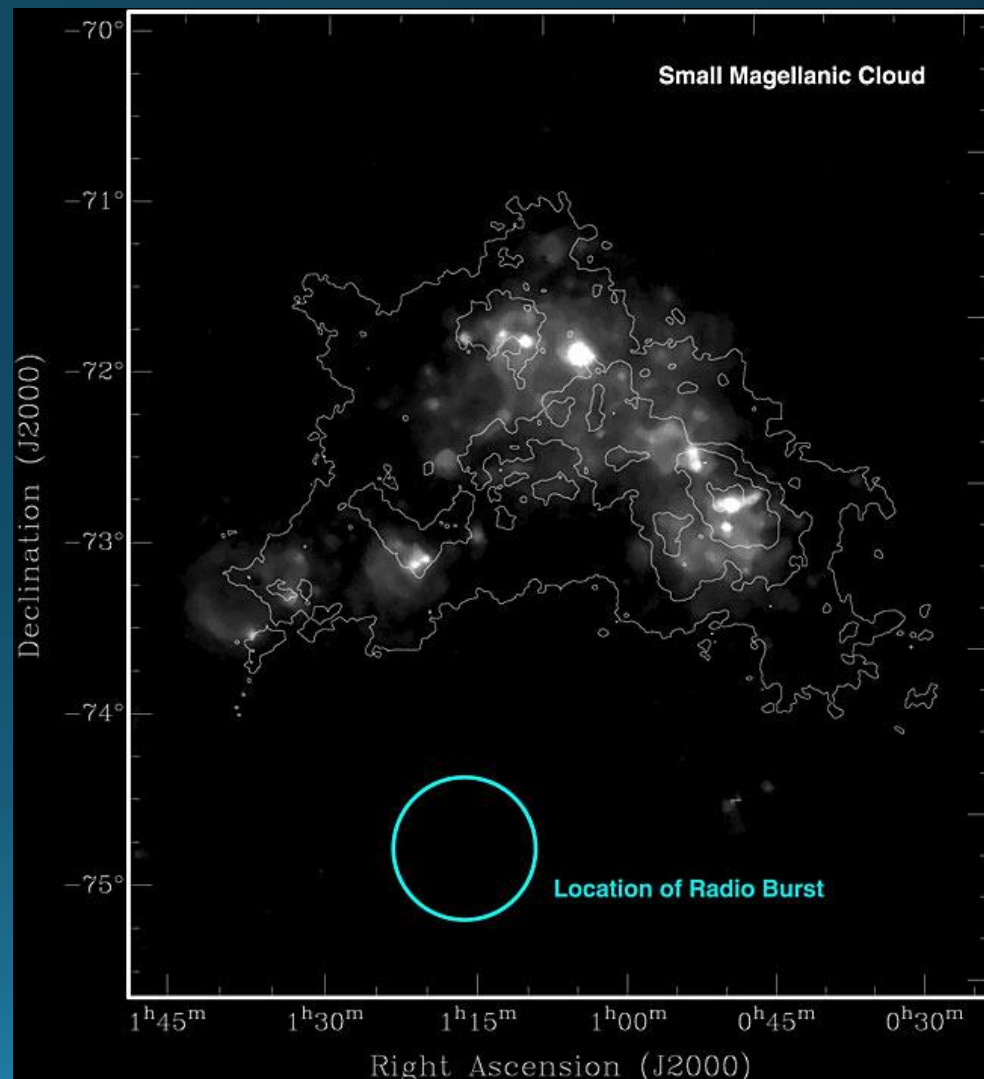


Локализация

Радиус области неопределенности ~ 10 угловых минут



Обычно БРВ виден только в одном биме.



Повторные всплески

Впервые удалось увидеть
повторные всплески от FRB 121102.

Наблюдения на Арэсибо.

10 событий.

Темп ~ 3/час

Всплески слабые (<0.02-0.3 Ян)

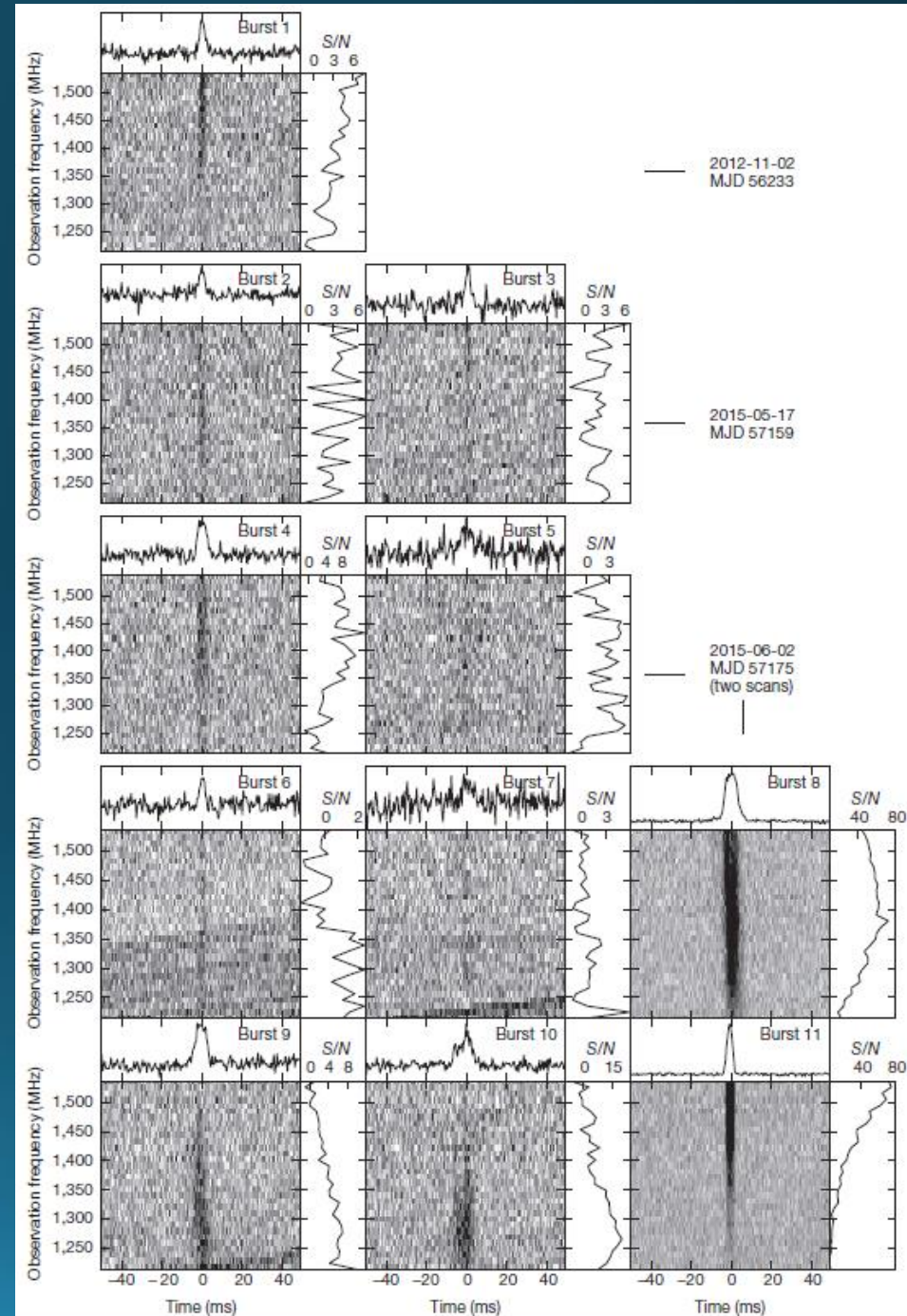
Некоторые из всплесков имеют
двойную структуру.

Переменный спектр.

Это может быть уникальный источник,
т.е. он может не быть типичным
представителем популяции FRBs.

$$dN/dF \propto F^{-1.78 \pm 0.16}$$

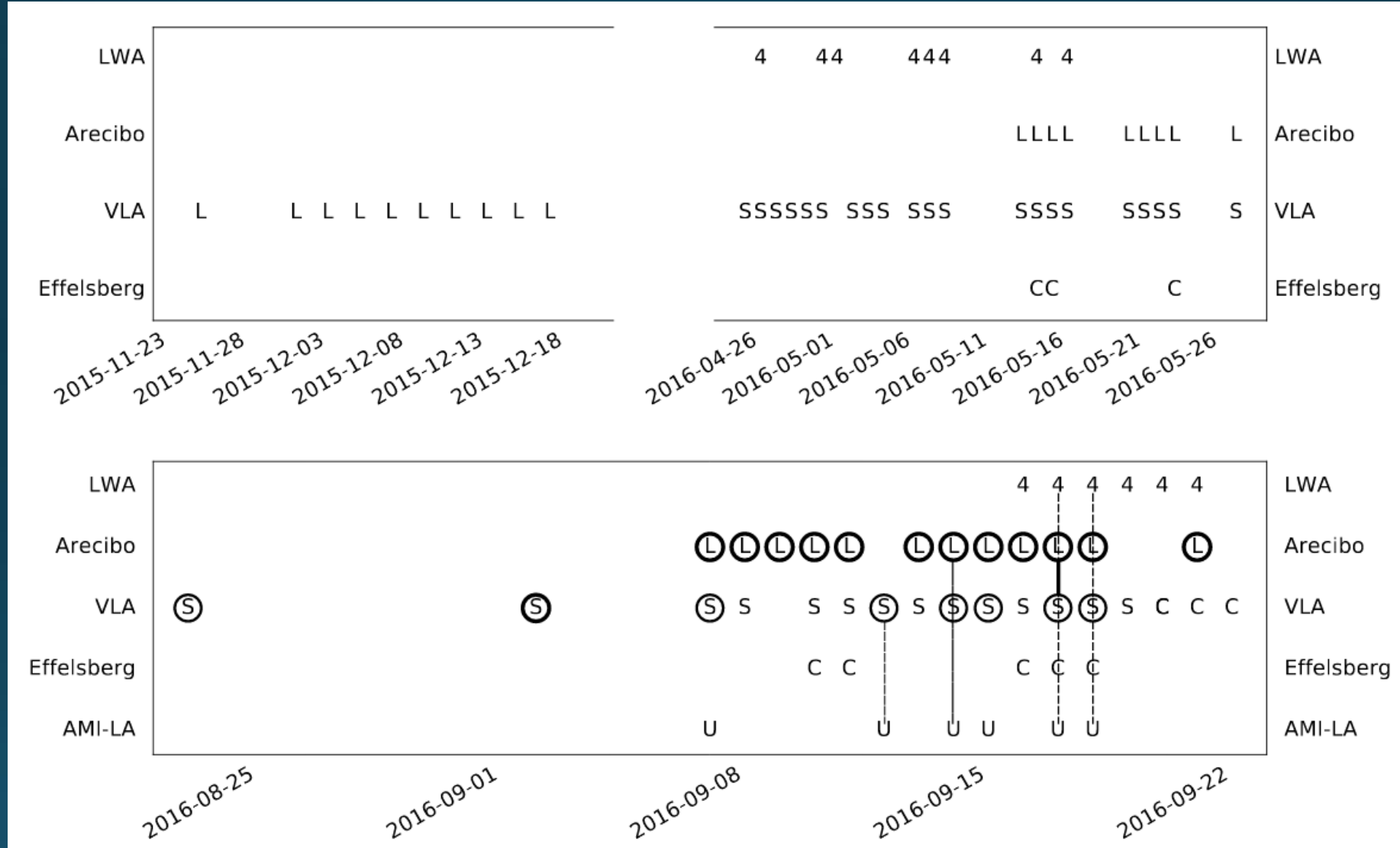
(Wang & Yu 2016)



1603.00581

VLA, Arecibo и все-все-все

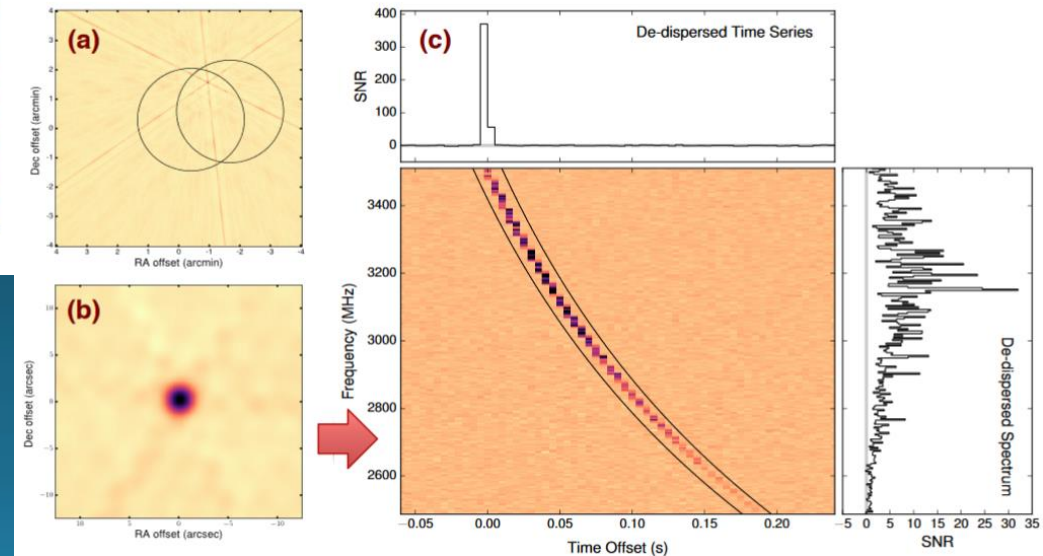
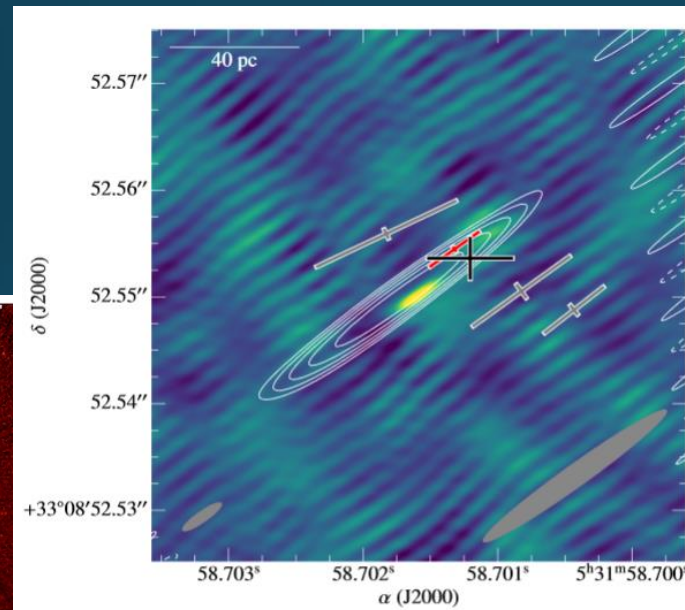
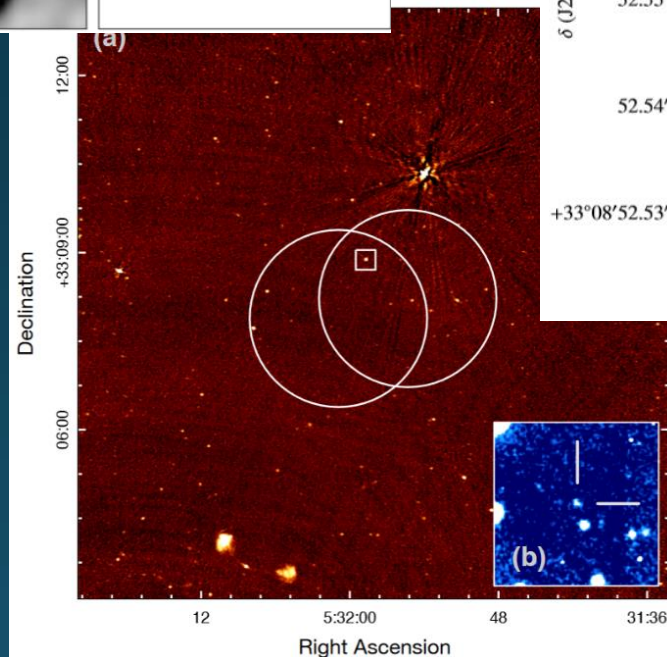
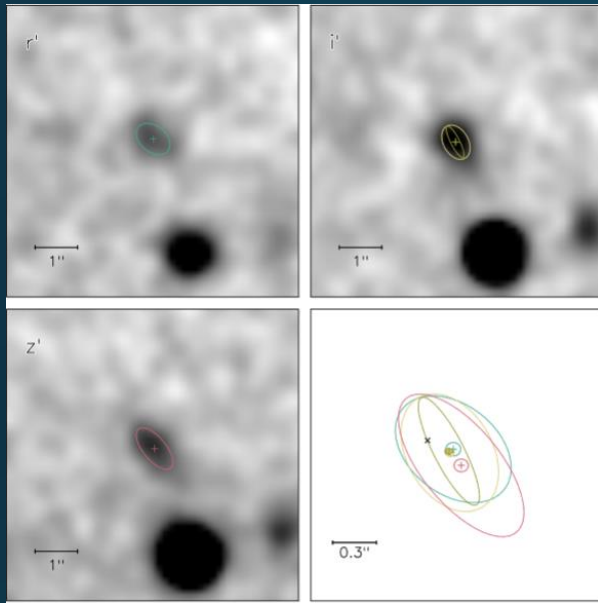
1705.07553



Темп всплесков – раз в несколько часов. Но они могут идти пачками. Одновременная регистрация на VLA и Аресибо.

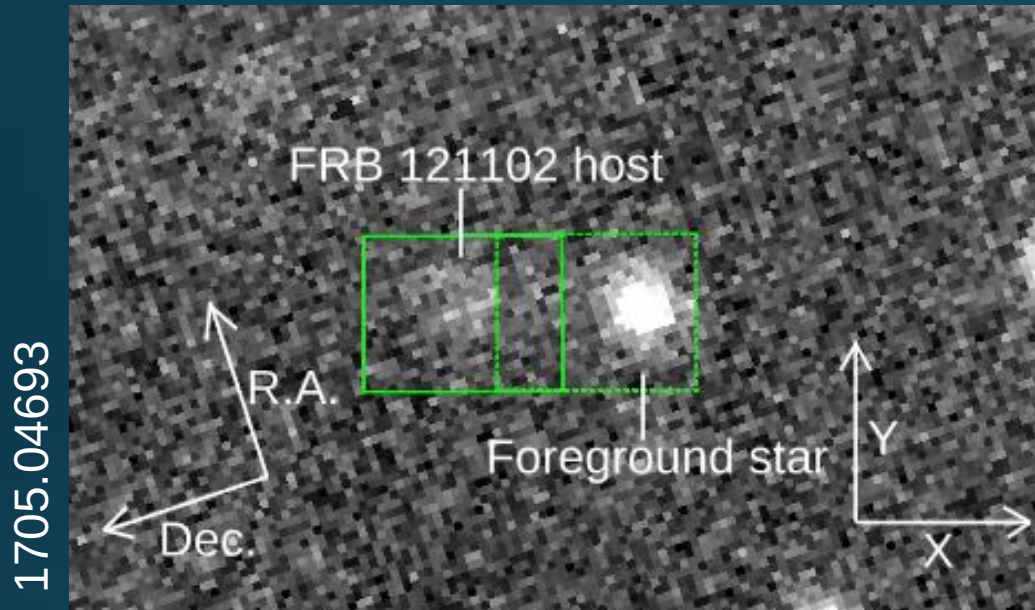
Галактика FRB

Для повторного источника FRB 121102 удалось отождествить материнскую галактику. Это карликовая галактика с высоким темпом звездообразования на $z \sim 0.2$ (1 Гпк).



1701.01098, 1701.01099, 1701.01100

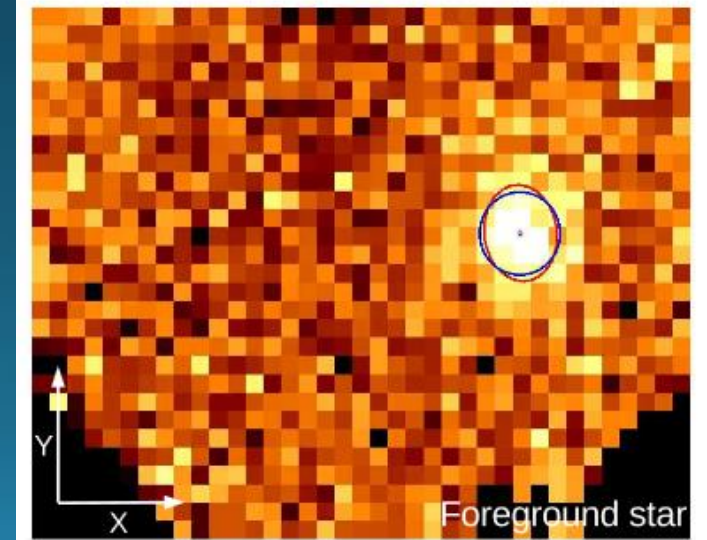
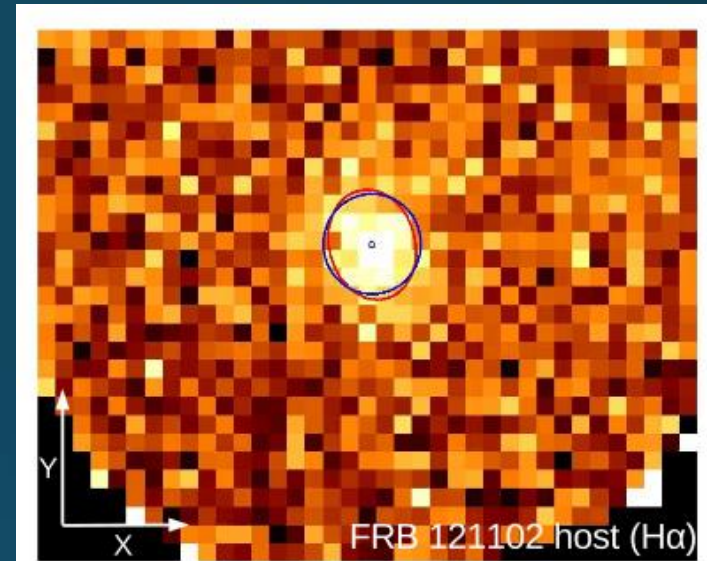
Излучения H-alpha в галактике FRB 121102



Изображение на Кеке.
Прямоугольники показывают области,
наблюдавшиеся на Субару.

Совпадение положения FRB с
областью H-alpha говорит в пользу
моделей с молодыми нейтронными звездами.

Область H-alpha может давать большой вклад
в наблюдаемую меру дисперсии источника.



Каталог быстрых радиовсплесков



FRB Catalogue

This catalogue contains up to date information for the published population of Fast Radio Bursts (FRBs). This site is maintained by the FRBCAT team and is updated as new sources are published or refined numbers become available. Sources can now be added to the FRBCAT automatically via the VOEvent Network, details of this process are given in [Petroff et al., 2017](#). FRBs confirmed via publication, or received with a high importance score over the VOEvent Network, are given 'Verified' status and are shown on the default homepage; to see all events (including unverified candidates received via the VOEvent Network) toggle the "Verified events/All events" button below.

Information for each burst is divided into two categories: observed parameters from the available data, and derived parameters produced using a model. Cosmological values are obtained using the Cosmology Calculator ([Wright, 2006](#)). The observed parameters are sometimes either lower or upper limits, due to the limitations of the data acquisition systems. Where multiple fits or measurements of a burst have been made each one is provided as a separate sub-entry for the FRB.

You may use the data presented in this catalogue for publications; however, we ask that you cite the paper ([Petroff et al., 2016](#)) and provide the url (<http://www.frbcat.org>). Any issues relating to the use of the catalogue should be addressed to FRBCAT team (primary contact: Emily Petroff).

An up-to-date CSV file containing all parameters for all FRBs is available at the following stable link: <http://www.frbcat.org/frbcats.csv>

Visible columns

Verified events

 Export to CSV

Search

Clear

	FRB ▾	UTC ▾	Telescope ▾	RAJ ▾	DECJ ▾	gl ▾	gb ▾	DM ▾	Width ▾	S/N ▾
+	FRB180817.J...	2018/08/17 01:49:20.202	CHIME/FRB	15:33	+42:12	68	54	1006.84±0.002	0.37	69.9
+	FRB180814.J...	2018/08/14 14:20:14.440	CHIME/FRB	15:54	+74:01	108	37	238.32±0.01	0.18	29.7
+	FRB180814.J...	2018/08/14 14:49:48.022	CHIME/FRB	04:22	+73:44	136	16	189.38±0.09	2.6	24
+	FRB180812.J...	2018/08/12 11:45:32.872	CHIME/FRB	01:12	+80:47	123	18	802.57±0.04	1.25	19.8
+	FRB180810.J1...	2018/08/10 22:40:42.493	CHIME/FRB	11:59	+83:07	125	34	169.134±0.002	0.28	56.7

<http://frbcats.org/>

Гипотезы, гипотезы ...

Сейчас известно более 20 всплесков.

Для их объяснения придумано около 20 существенно разных моделей!

- | | |
|-------------------------------------|--|
| 1. Магнитары | 10. Батарея черной дыры |
| 2. Космические струны | 11. МГД процессы на компаньоне
в тесной двойной системе |
| 3. Первичные черные дыры | 12. Белые дыры |
| 4. Сверхновая в системе с пульсаром | 13. Сверхгигантские импульсы пульсаров |
| 5. Слияние нейтронных звезд | 14. Аксионные звезды и тп. |
| 6. Слияние белых карликов | 15. Деконфайнмент |
| 7. Супрамассивные нейтрон. звезды | 16. Падение астероидов и тп. на нейтр.зв. |
| 8. Вспышки обычных звезд | 17. Миллисекундный магнитар |
| 9. Коллапс нейтронной звезды в дыру | 18. Джеты |
| | 19. Заряженные черные дыры |

При этом многие упомянутые гипотезы имеют разные варианты, существенно отличающиеся друг от друга.

Сейчас публикуется примерно 1-2 статьи в неделю на тему БРВ.

Нейтронные звезды и экзотика



У нейтронной звезды масса порядка солнечной и радиус порядка 10 км.

Это дает скорость падения $v=(2GM/R)^{1/2} \sim 0.5$ с

Время падения $t=R/v < 0.1$ msec

Поэтому легко получать короткие события.

То же самое для черных дыр.

Кроме того, отсутствие сопутствующих вспышек в других диапазонах, и вообще недостаток данных, позволяет привлекать весьма необычные сценарии космических транзиентов.



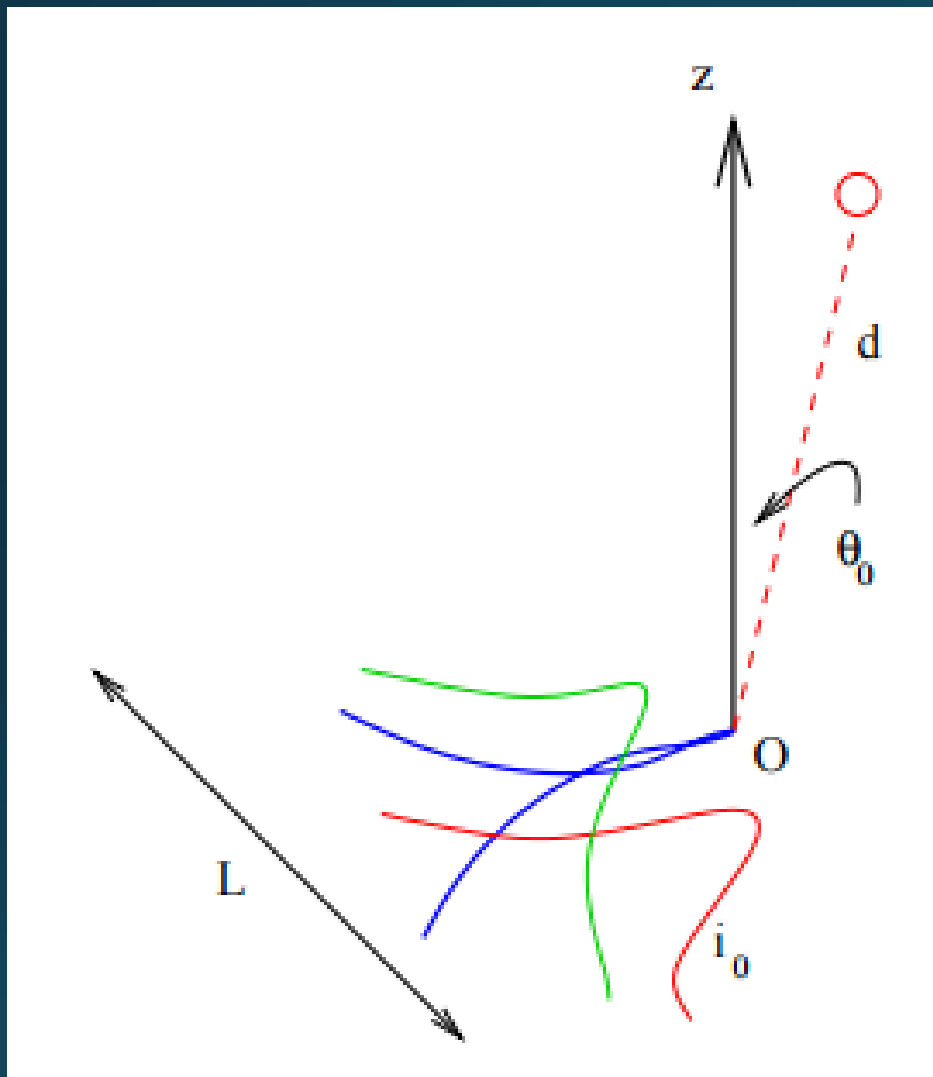
<http://bestiary.ca/>

Кроме того, у нейтронных звезд есть сильное магнитное поле, и они известны как вспыхивающие радиоисточники.

Поэтому модели FRB легко свести к формуле:
компактные объекты или экзотика.



Космические струны

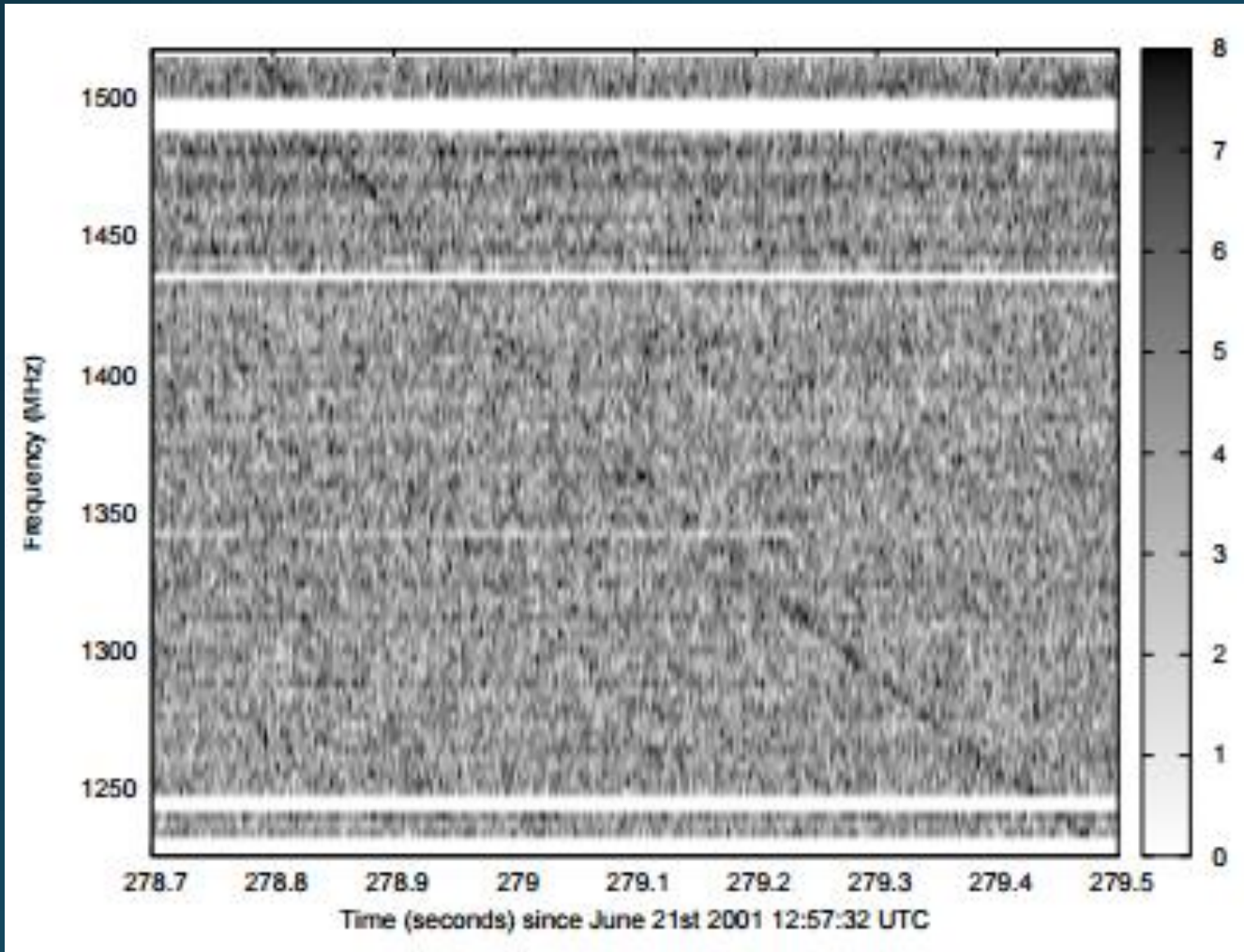


Сверхпроводящие струны
Vachaspati 0802.0711

Струны могут вести себя довольно причудливым образом. В частности, могут возникать точки струны – каспы, - которые разгоняются до околосветовой скорости. Каспы становятся мощными источниками электромагнитного излучения. Именно это и лежит в основе модели.

Также гипотеза космических струн в приложении к FRB рассматривалась в ряде других работ: 1110.1631, 1409.5516,

Первичные черные дыры



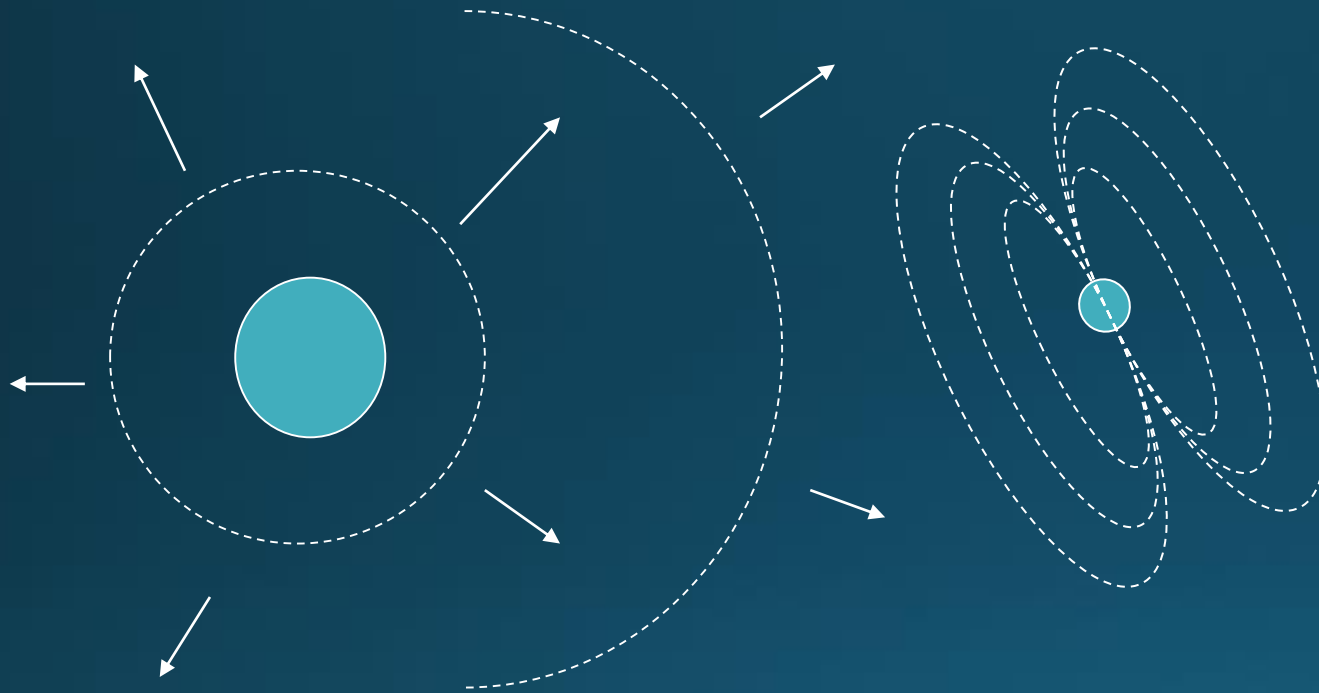
Не подходит в качестве внегалактического источника, т.к. полная светимость мала. Должны быть видны с <200 пк.

Давно предсказывались (Rees 1977).

Эффекты дополнительных измерений могут привести к более высокому энерговыделению, но все равно речь идет о расстояниях порядка 300 пк.

Могут сопровождаться всплеском жесткого излучения (если всплеск происходит достаточно близко).

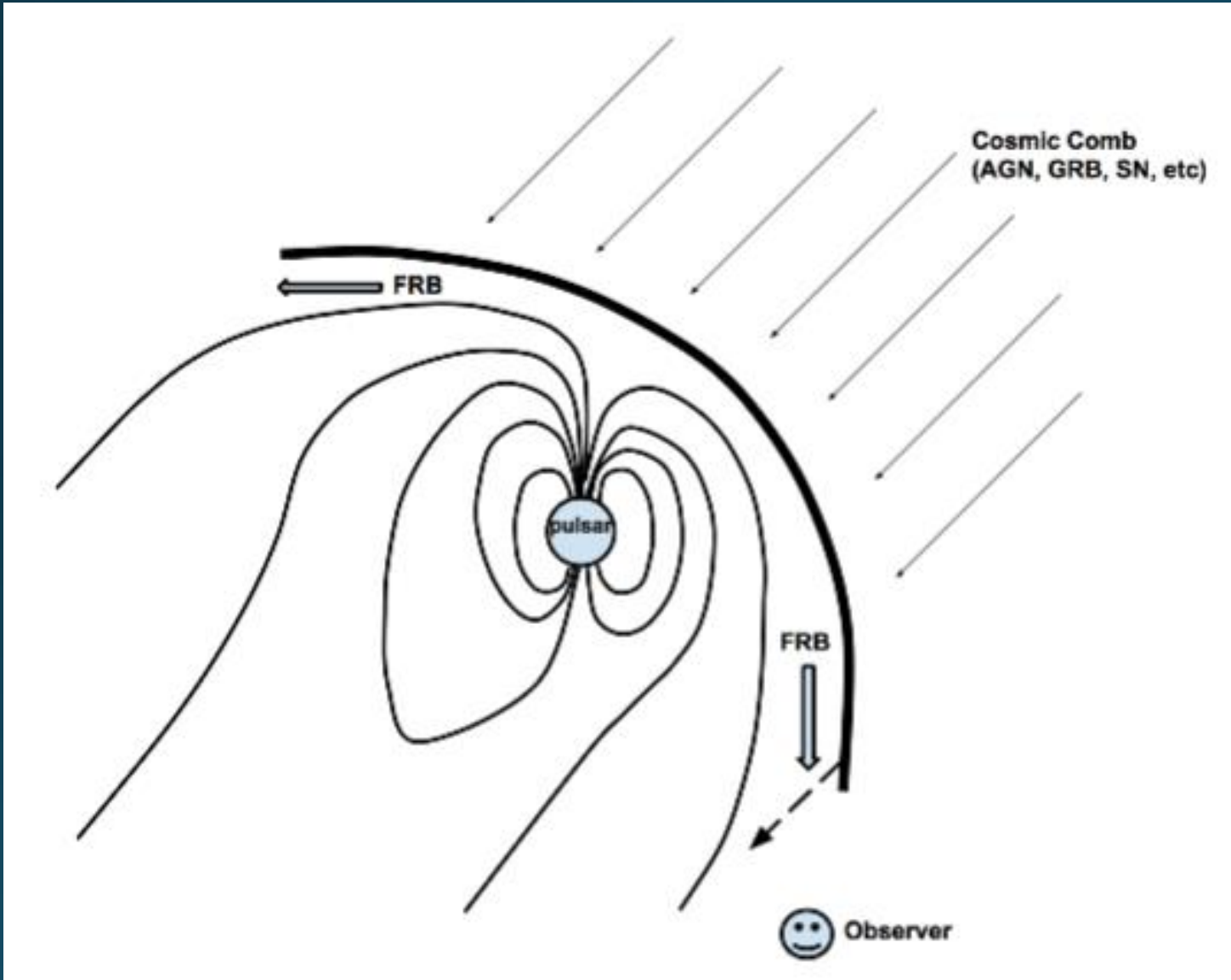
Сверхновая и пульсар



Ударная волна сверхновой в массивной тесной двойной системе может провзаимодействовать с магнитосферой нейтронной звезды, создав магнитосферный хвост. Пересоединение в хвосте может привести к появлению всплеска. (Егоров, Постнов 0810.2219)

Т.о., радиовсплеск ВСЕГДА должен сопровождаться вспышкой сверхновой.

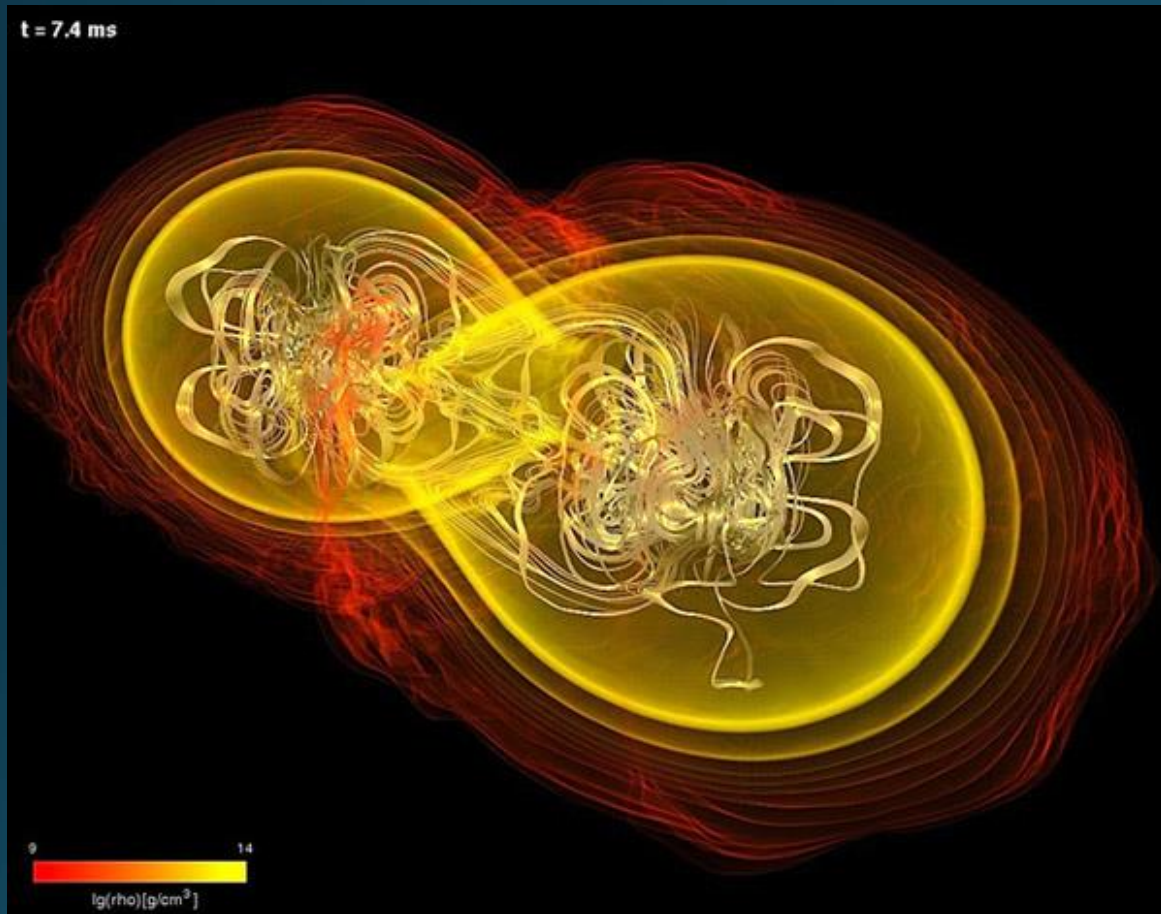
Срыв магнитосферы



Модель позволяет сделать всплеск совпадающим с другим мощным транзиентом (АЯГ, гамма-всплеском).

Слияния нейтронных звезд

<http://www.int.washington.edu/PROGRAMS/14-2a/>



Придумано несколько сценариев, в которых в результате слияния нейтронных звезд возникает радиоисточник (Липунов, Панченко; Hansen, Lyutikov; Постнов, Пширков).

Но в приложении к FRBs основной является работа Totani (1307.4985).

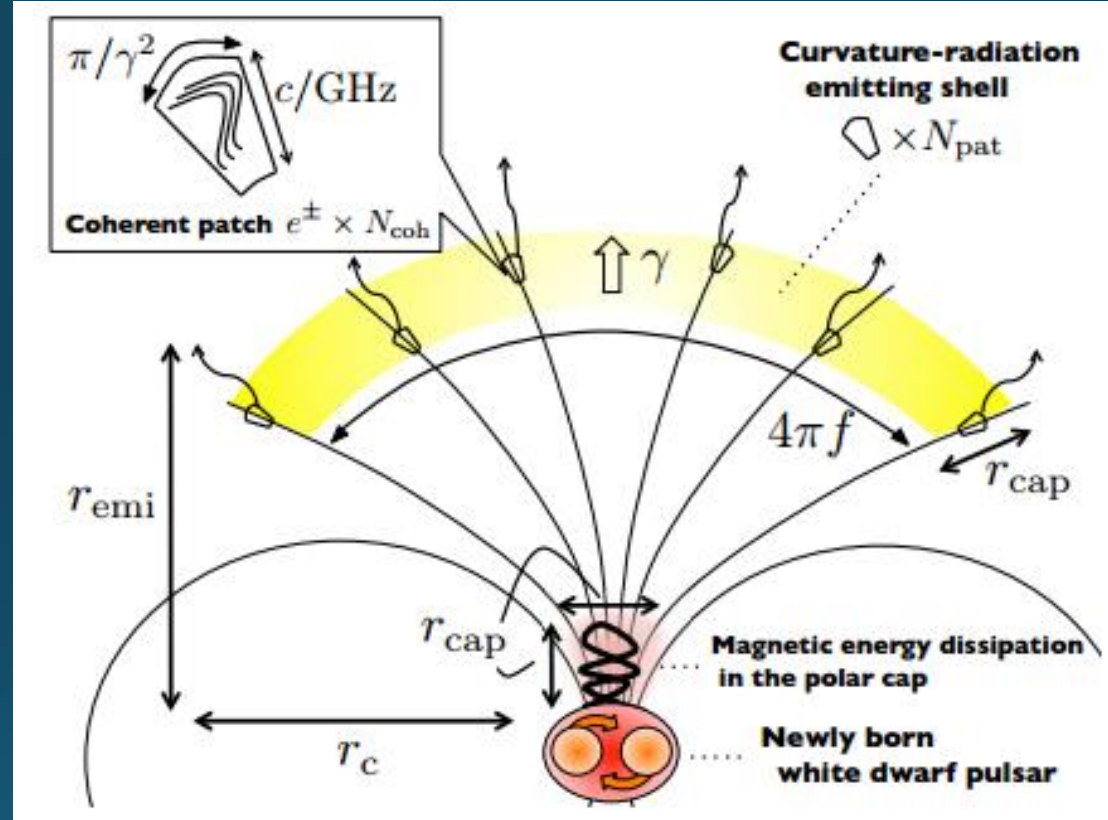
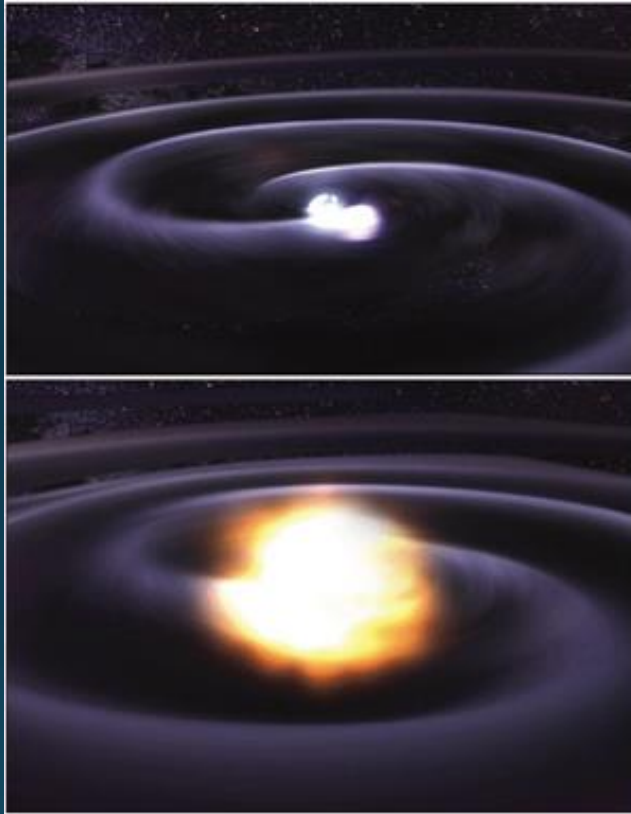
$$\dot{E} = -6.2 \times 10^{45} \left(\frac{B}{10^{12.5} \text{ G}} \right)^2 \left(\frac{R}{10 \text{ km}} \right)^6 \times \left(\frac{P}{0.5 \text{ msec}} \right)^{-4} \text{ erg s}^{-1}.$$

Довольно легко получить быстрое вращение и сильное магнитное поле. Но по физике есть много вопросов, т.к. ситуация очень нестационарная и плохо изученная.

Должны сопровождаться гравитационно-волновым всплеском

Слияния белых карликов

<http://cerncourier.com/cws/article/cern/31855>



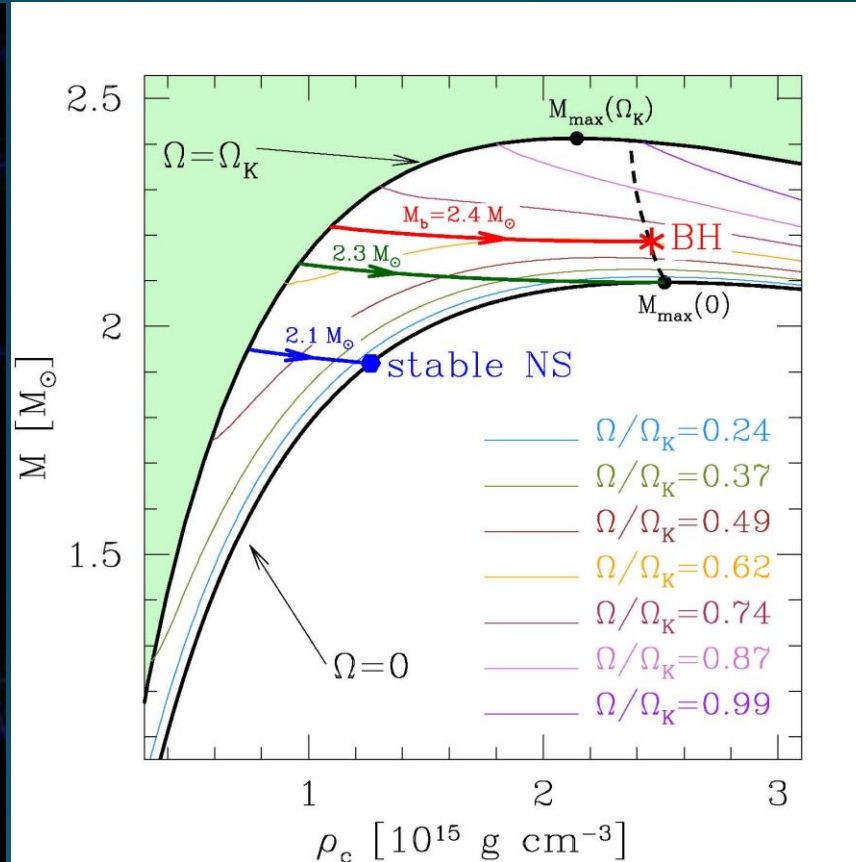
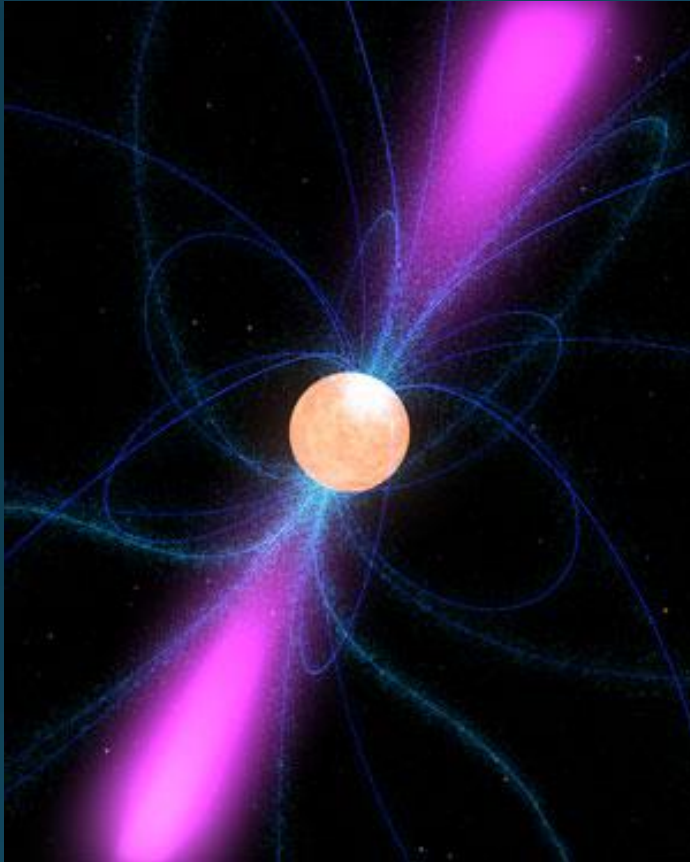
Kashiyama et al. 1307.7708

Основные события разыгрываются на полярной шапке, что необходимо для согласования характерной длительности всплеска с временами процессов.

Сопровождается сверхновой Ia и, возможно, рентгеновским излучением за счет возвратной аккреции (fall-back).

Супрамассивные нейтронные звезды

<http://www.astro.ru.nl/~falcke/PR/blitzar/>



"blitzar"

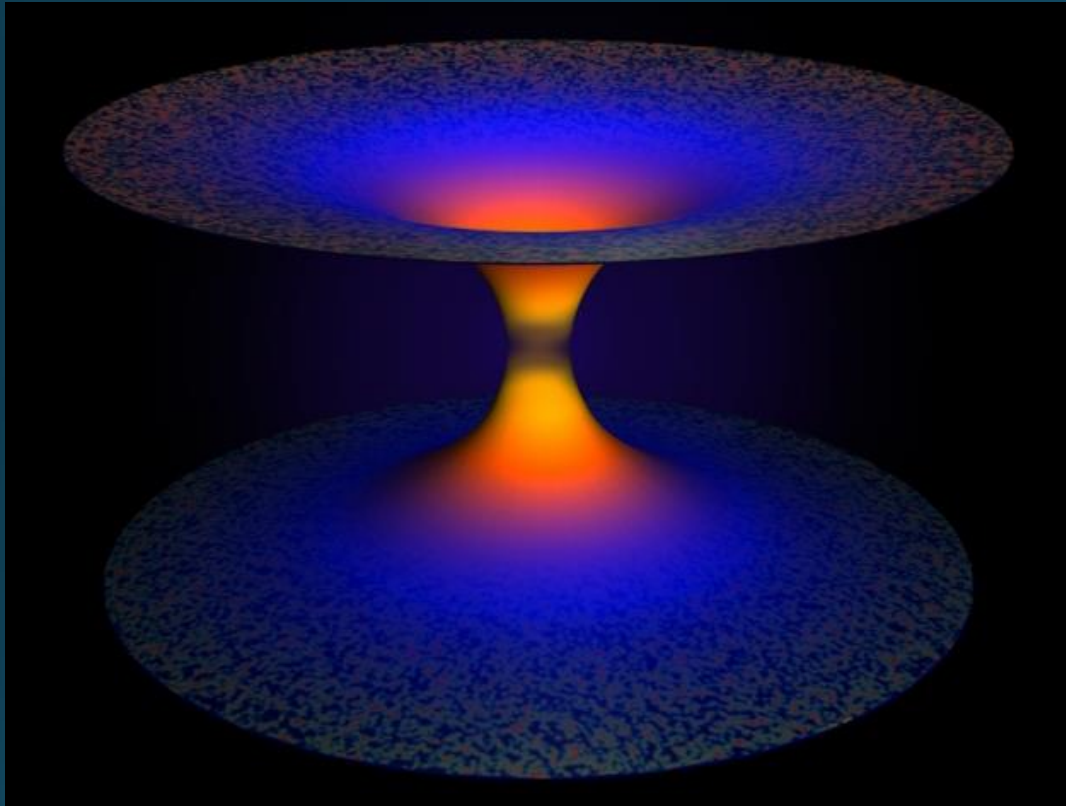
Falcke, Rezzola 1307.1409

Нейтронная звезда может быть устойчивой относительно коллапса из-за очень быстрого вращения. Такая ситуация может возникнуть при слияниях, при аккреции в двойной или же прямо при рождении.

Коллапс может произойти спустя тысячи лет после образования НЗ.

Могут сопровождаться сверхновой, коротким гамма всплеском или всплеском гравволн. Могут давать двойные всплески.

Белые дыры (из черных)



Изначальные расчеты не предсказывали появление радиоизлучения. Но авторы 1409.4031 полагают, что в модели достаточно неопределенностей, чтобы предполагать и появление радиоволн. Длина волны соответствует размеру взрывающейся дыры.

Мы плохо знаем, как испаряются черные дыры. В некоторых моделях это сопровождается появлением белой дыры (при коллапсе квантовые петли нельзя упаковать бесконечно плотно).

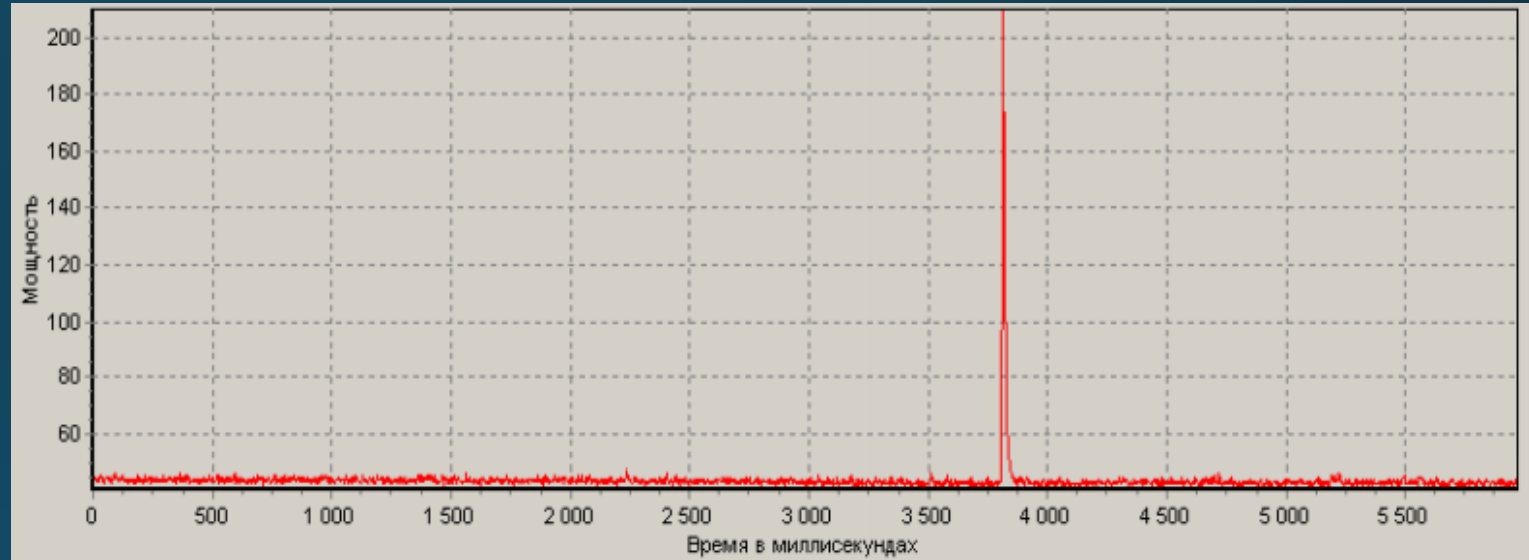
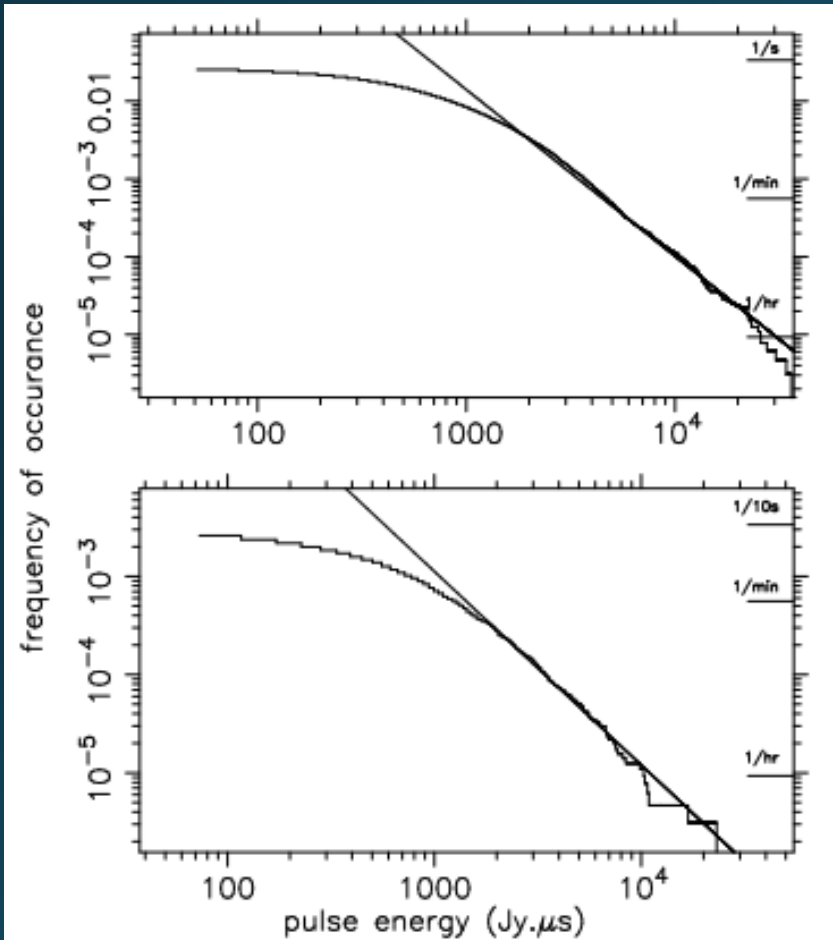
Испарением черных дыр уже было названо как возможная причина FRBs. В этом случае ударная волна взаимодействует с внешним магнитным полем.

Но излучение в случае появления белых дыр имеет совсем другую природу — это уже эффект квантовой гравитации.

1409.4031

Сверхгигантские импульсы внегалактических радиопульсаров

<http://www2011.mpe.mpg.de/363-heraeus-seminar/Contributions/0Poster/p6.pdf>



Известны гигантские импульсы пульсаров. Возможно, распределение тянется дальше, и есть супергигантские импульсы. Они могут быть видны и с внегалактических расстояний.

В некоторых моделях вспыхивающие пульсары находятся в достаточно молодых и плотных остатках сверхновых, что помогает объяснить некоторые из свойств всплесков.

1501.00753, 1505.05535

Аксионы



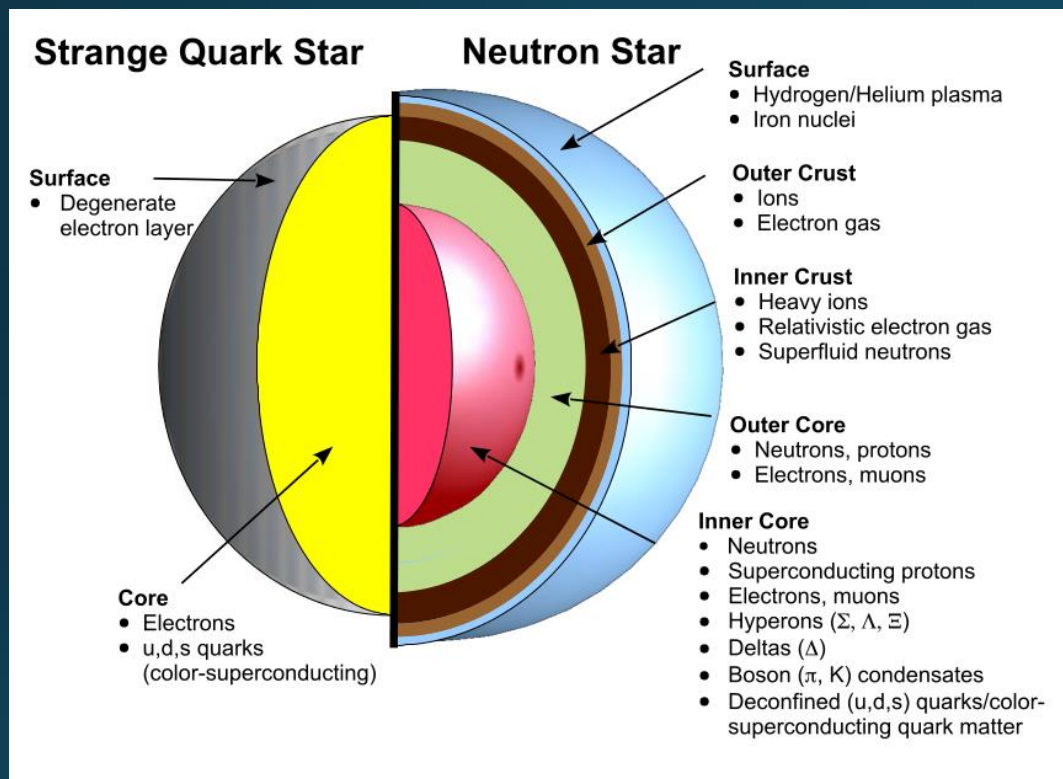
Аксионы – кандидаты в частицы темного вещества.
Аксионные миникластеры.
Возникают в молодой вселенной.
Масса – как у крупного астероида.
Размер – как у звезды.

Кластер может становиться более компактным из-за образования бозе-конденсата.
Размер может быть порядка сотен км, что соответствует ожидаемой области излучения быстрого радиовсплеска (длительность $\times$ скорость света).
Масса компактного кластера может составлять примерно массу Земли!

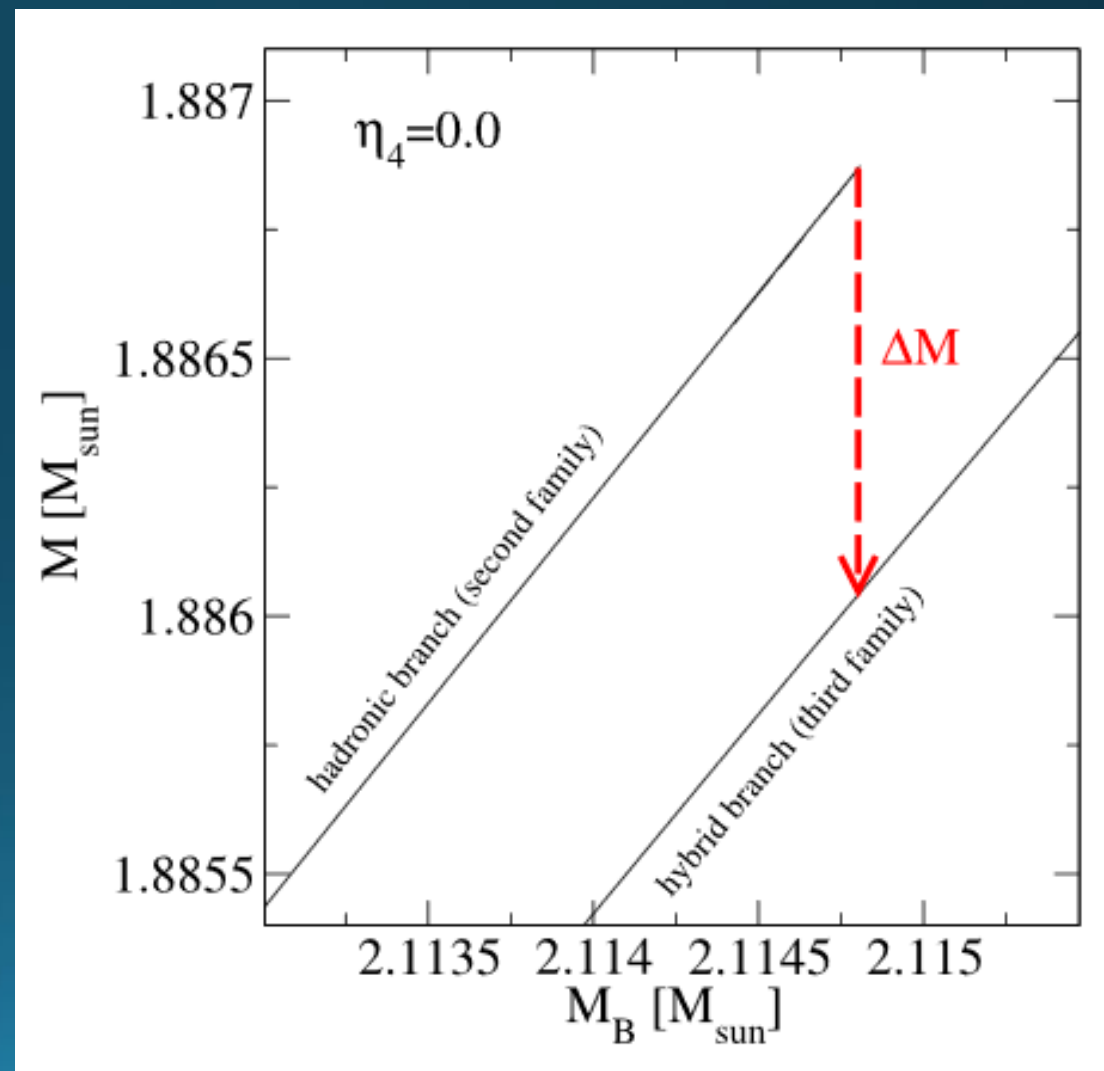
Влетание аксионного кластера в магнитосферу нейтронной звезды должно приводить к конверсии аксионов в фотоны, а значит – к вспышке электромагнитного излучения.

1411.3900, 1410.4323, 1512.06245, 1707.04827

Деконфайнмент – рождение кварковой звезды

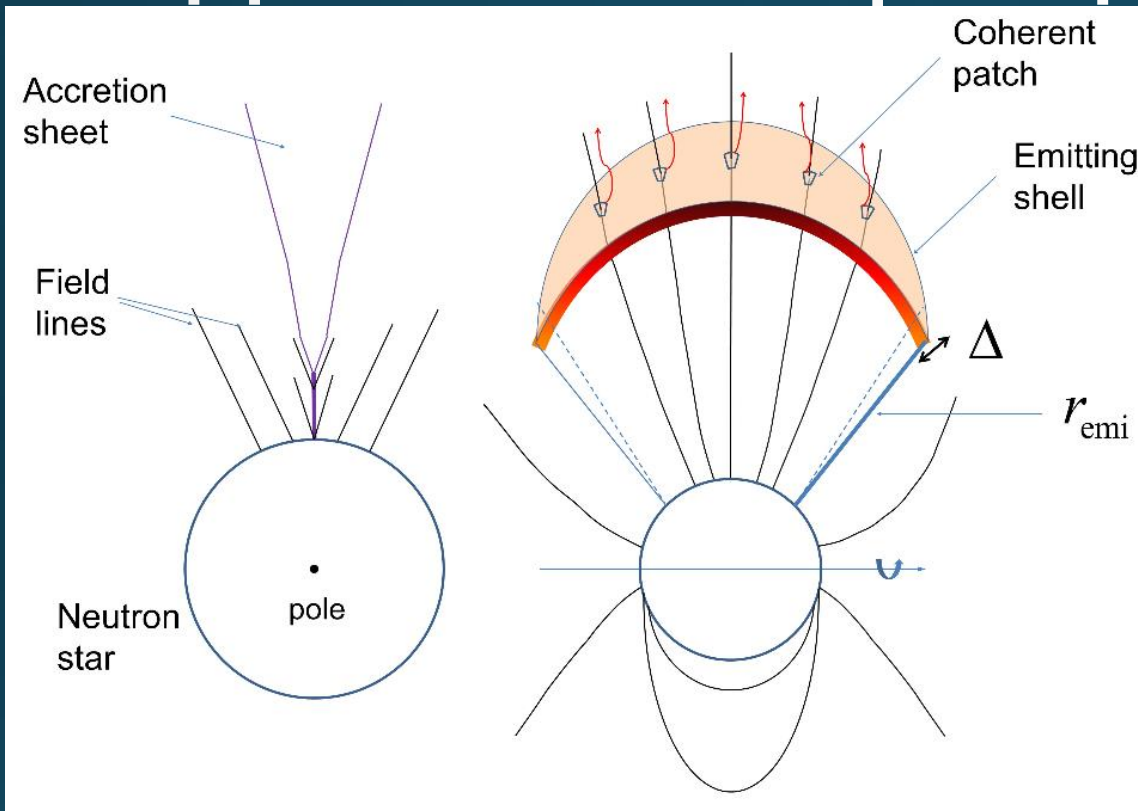


В процессе своей эволюции нейтронная звезда или ее часть могут испытать деконфайнмент: обычное вещество превратится в кварковое. Это сопровождается энергovyделением.



Падение астероидов

1502.05171, см. также 1512.06519



Для FRB активно предлагают механизмы, которые ранее предлагались (лет 30 назад) для объяснения гамма-всплесков. Вот один из них.

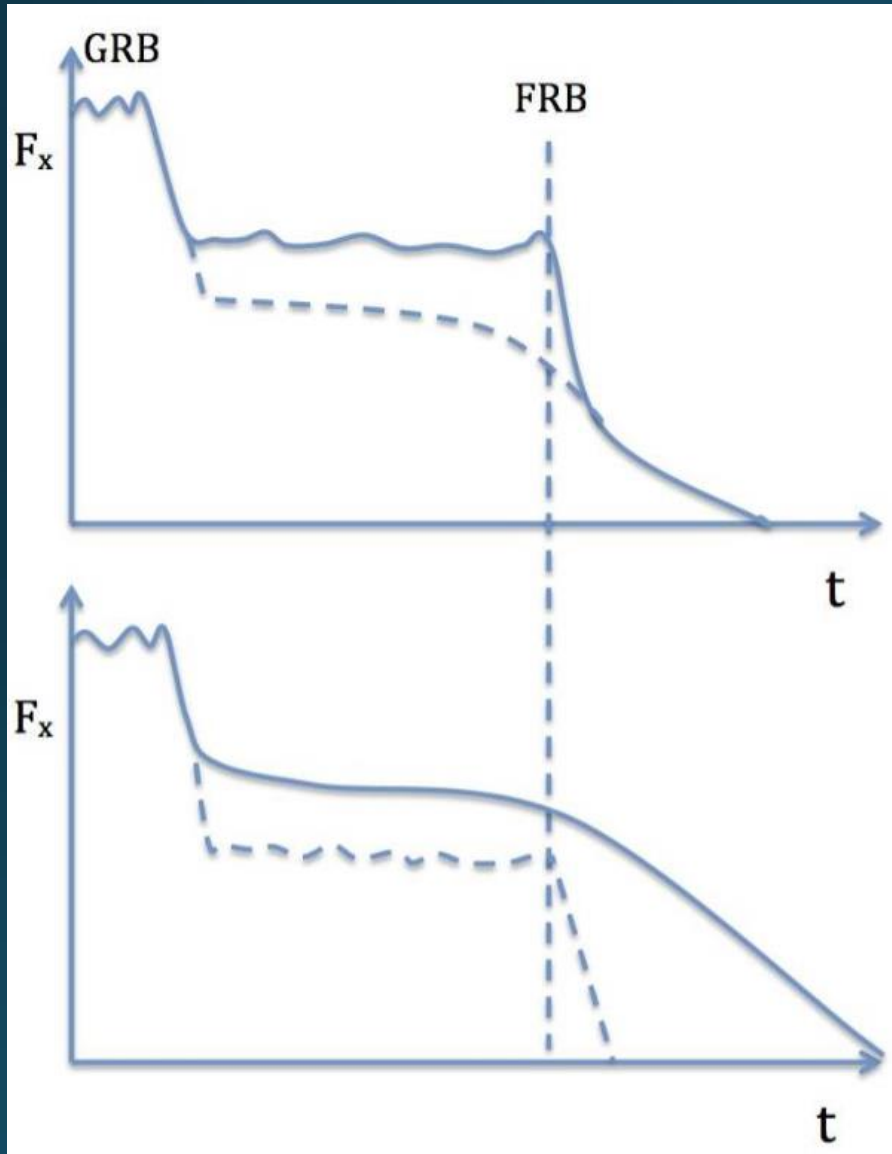
Дело в том, что для НЗ характерное время падения вблизи поверхности составляет миллисекунды. Поэтому любой феномен с такой длительностью соблазнительно объяснить так.

После падения массивного астероида возникает отекающая оболочка. Затем часть вещества разгоняется, и в результате генерируется радио излучение. Механизм радиоизлучения не слишком очевиден. Должна быть слабая рентгеновская вспышка.

О модификации модели с повторными всплесками см. 1603.08207

Об испарении астероидов пульсарами см. 1605.05746.

Супрамаассивные НЗ и гамма-всплески

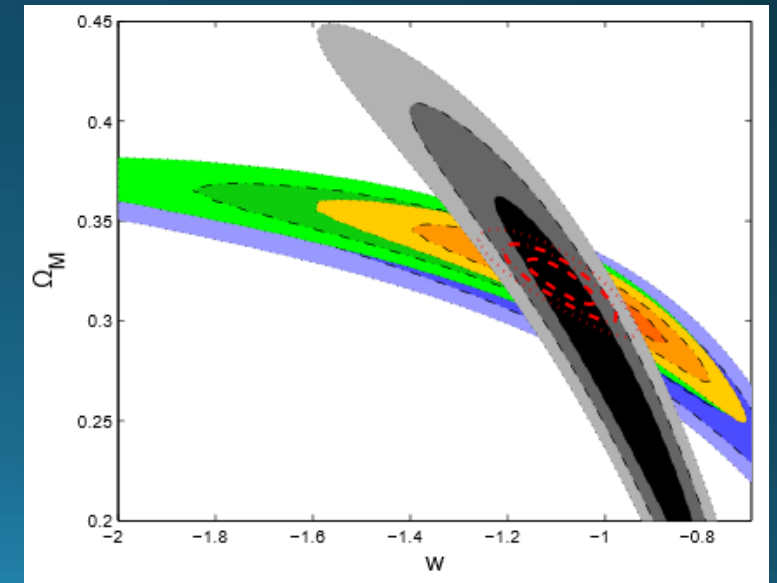


Модель включает в себя образование миллисекундного магнитара (Усов 1992).

При этом не все FRB должны сопровождаться GRB, и наоборот.

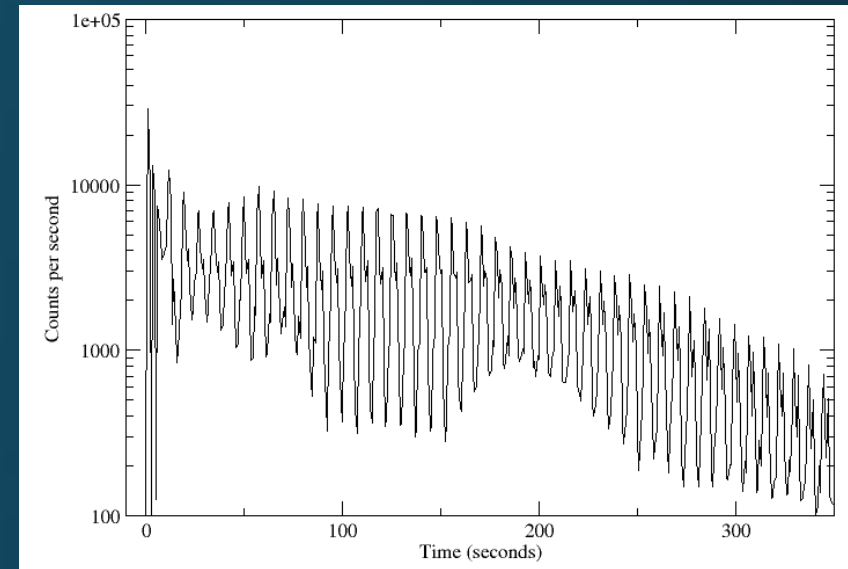
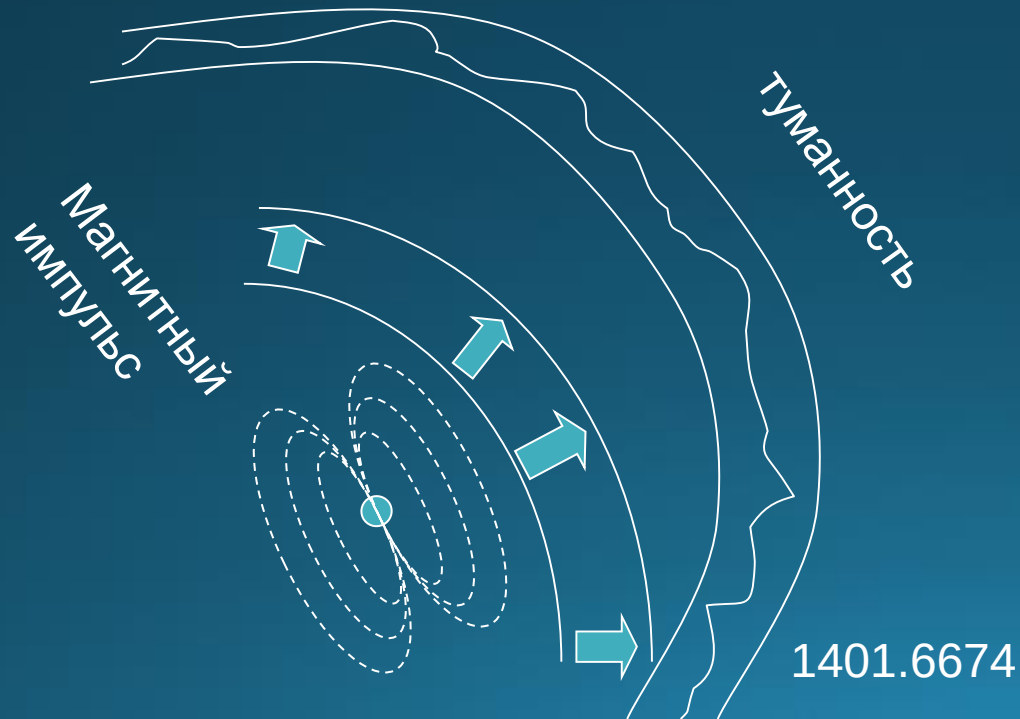
Тогда возникают проблемы с темпом FRB.

Статистика совместных данных по FRB и GRB (если эта модель верна) даст важные данные для космологии.



Гипервспышки магнитаров?

Сразу же после публикации Lorimer et al. (2007) мы предложили модель (0710.2006, 1307.4924), в которой вспышки связаны с гипервсплесками магнитаров. Темп, временные характеристики и отсутствие всплеска в других диапазонах находят прекрасное объяснение. Энергетика также соответствует.



Юрий Любарский в 2014 году построил теоретическую модель, которая позволяет объяснить радиовсплески в рамках магнитарной модели. Пока модель не опровергнута наблюдениями. Для подтверждения необходимо обнаружить магнитарную вспышку. Или, что следует из расчетов Любарского, излучение на очень высоких энергиях.

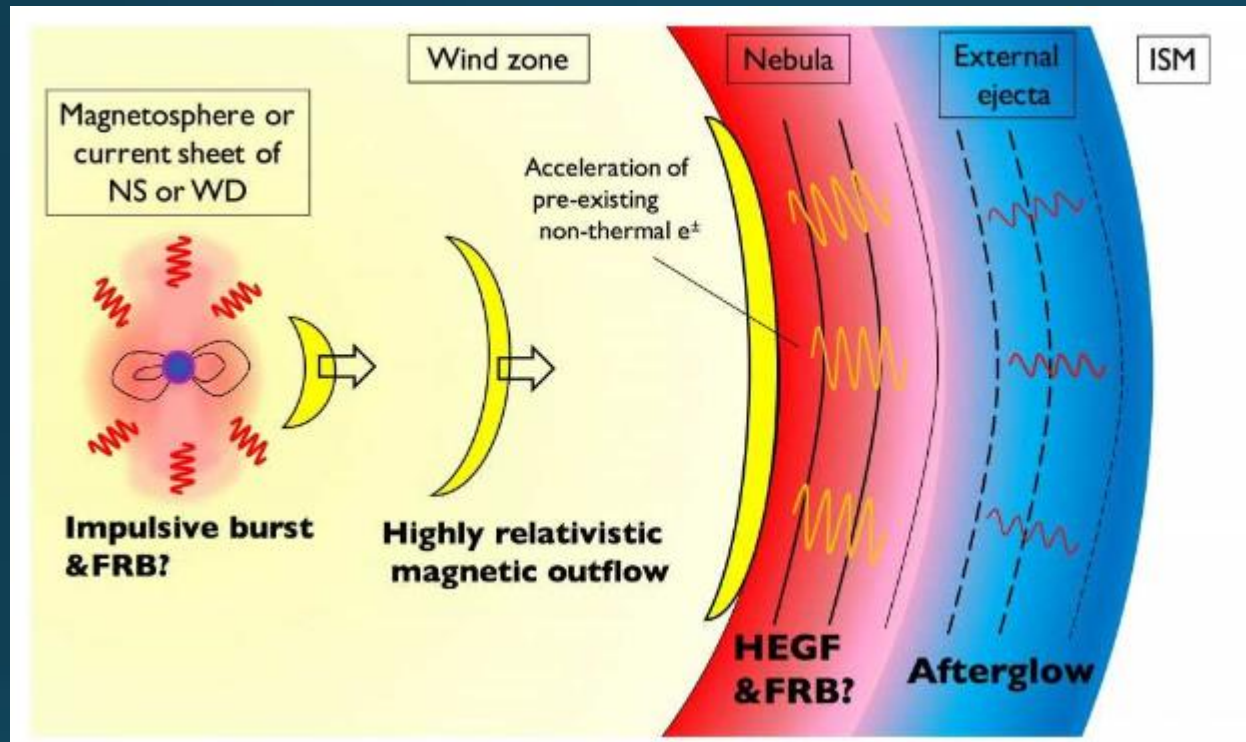
Модель надо развивать

Магнитар в плотной туманности



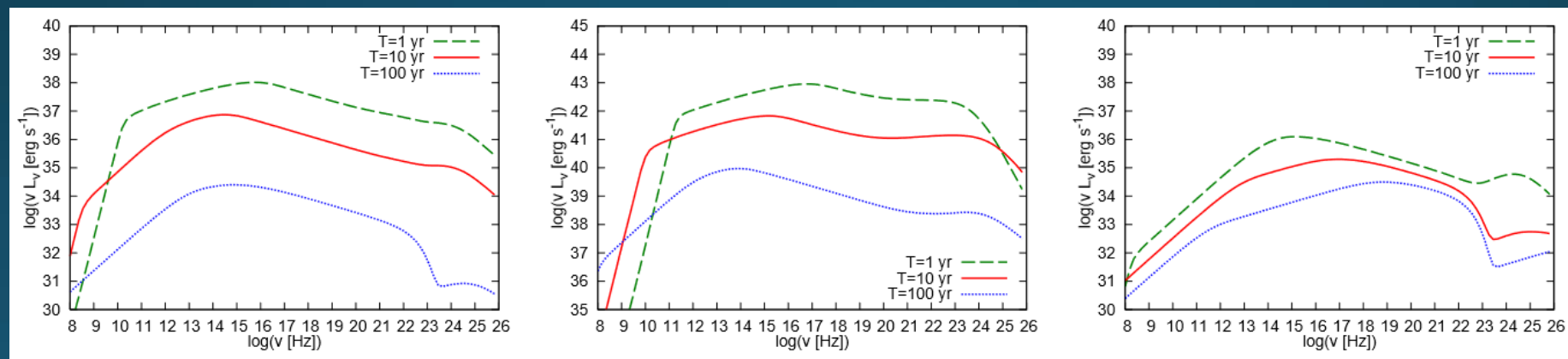
Анимация Алексея Кудаква

Излучение туманности



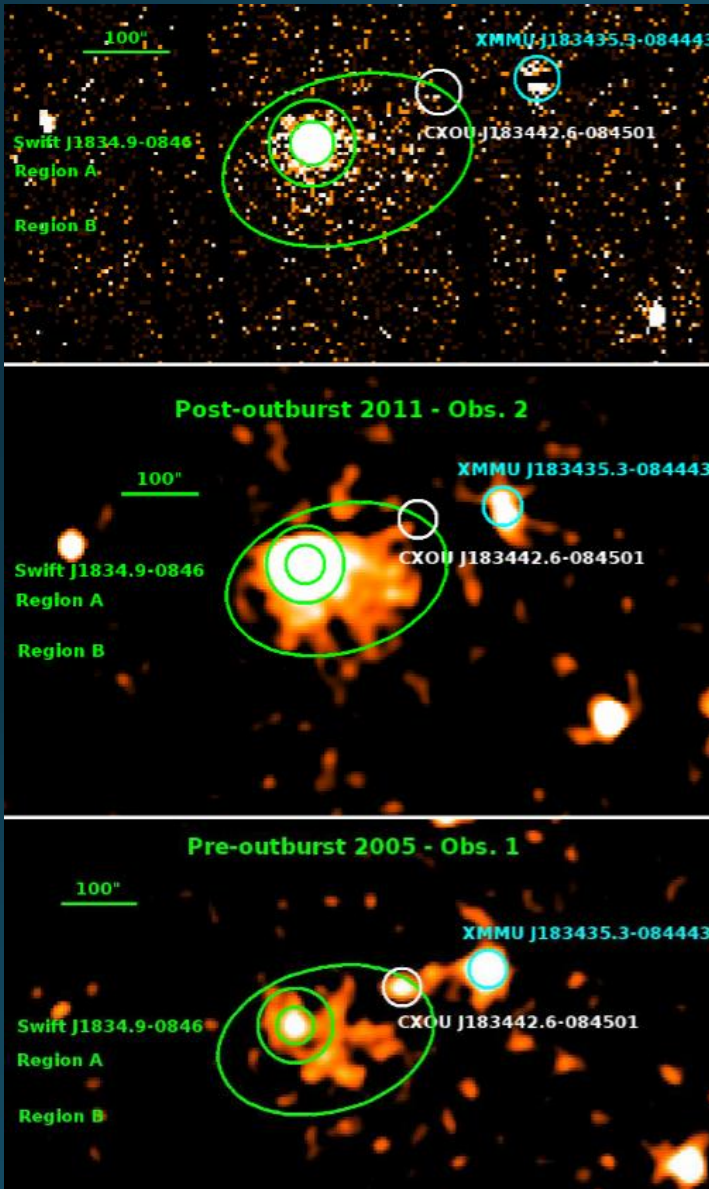
Рассмотрени модели с излучением туманности получило развитие.

Рассмотрены туманности вокруг магнитаров, быстро вращающихся НЗ и белых карликов.

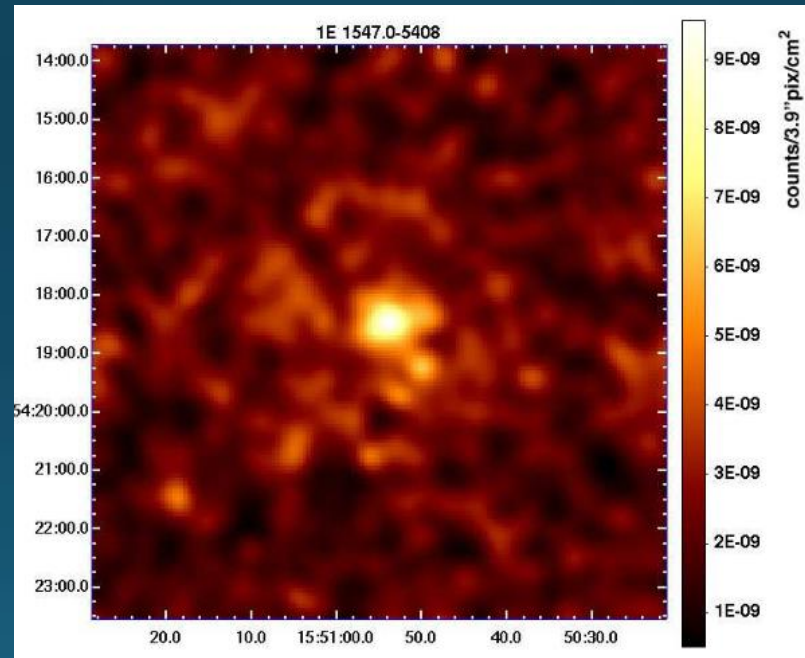


Туманности вокруг магнитаров

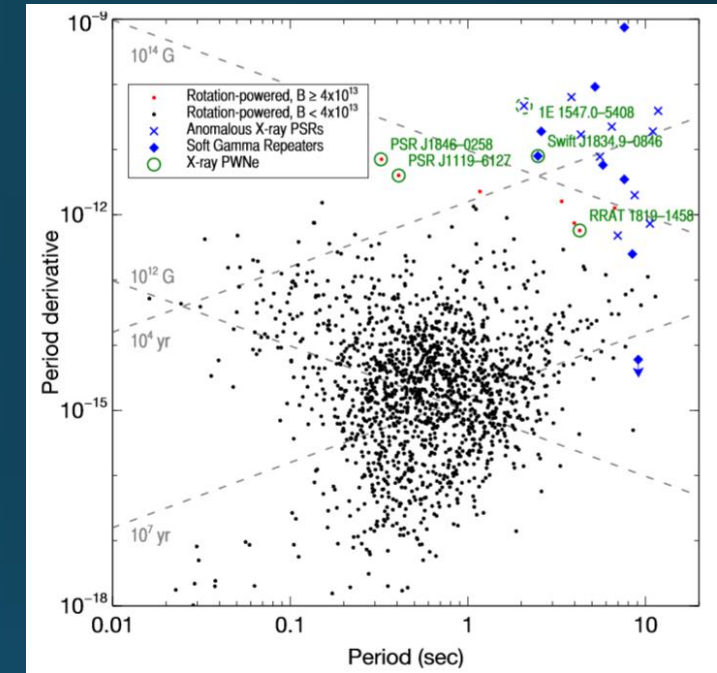
1206.3330. Новые результаты в 1604.06472



О генерации
пульсарных
туманностей
вокруг магнитаров
см. 1606.01391



У нейтронных звезд с сильными магнитными полями
(включая нормальные магнитары)
наблюдают т.н. пульсарные туманности.



1211.0852

0909.3843

Текущий рейтинг гипотез

- Обнаружение повторных всплесков с высоким темпом дает аргументы в пользу супергигантских импульсов пульсаров или активности молодого магнитара
- Идентификация материнской карликовой галактики с высоким темпом звездообразования дает аргументы в пользу молодых НЗ
- Повторный всплеск может быть нетипичным
- Комплекс данных дает несколько косвенных аргументов в пользу магнитарной гипотезы.

Выводы:

- На сегодняшний день есть две хорошие рабочие гипотезы.
- Возможно, популяция БРВ не однородна, т.е. обе гипотезы могут быть верны.

Будущие наблюдения

FAST



FAST —
всплеск за неделю
1602.06099

В недалеком будущем заработают новые крупные инструменты. Возможно, они помогут внести ясность. Кроме того, работающие системы, такие как LOFAR и другие, также могут сыграть свою роль. Хотя наблюдать лучше на высоких частотах (порядка 1 ГГц), а не на низких (LOFAR).

SKA



SKA —
всплеск за час
1602.05165,
1501.07535

По всей видимости, как и случае гамма-всплесков, понадобится одновременное обнаружение быстрого радиовсплеска и сопутствующего излучения в другом диапазоне.

Ближайшее будущее



Продолжаются наблюдения
на радиотелескопе Parkes
с новой системой
мониторинга помех.

Работает новая система ALFABURST
в Аресибо (1511.04132)

Идет поиски по архивам
разных радиотелескопов.

Ключевые моменты:

- Повторяемость
- Обнаружение в другом диапазоне



Специальные проекты



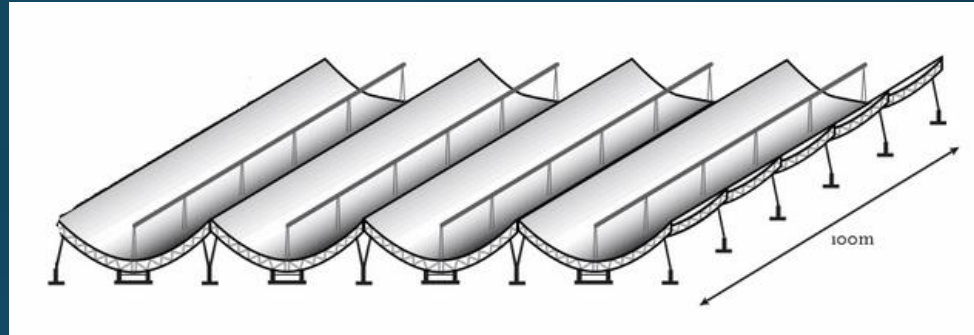
<https://sites.google.com/site/publicsuperb/>



<http://astronomy.swin.edu.au/research/utmost/>
всплеск раз в неделю 1601.02444

CHIME

The Canadian Hydrogen Intensity Mapping Experiment



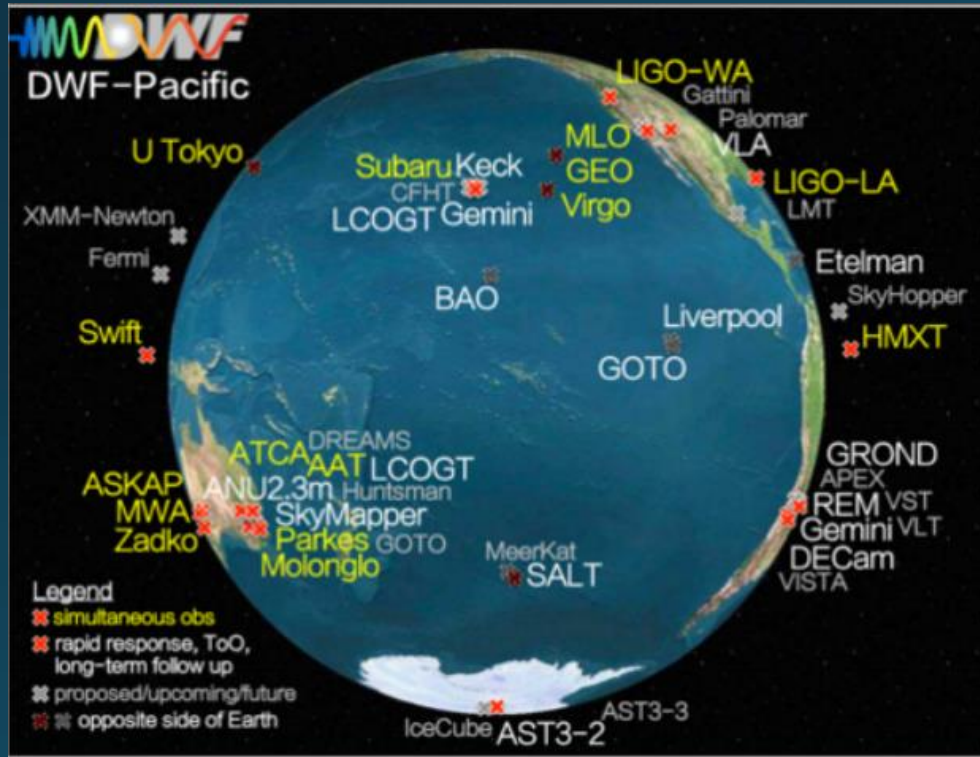
<http://chime.phas.ubc.ca/>

CHIME – всплеск раз в день!

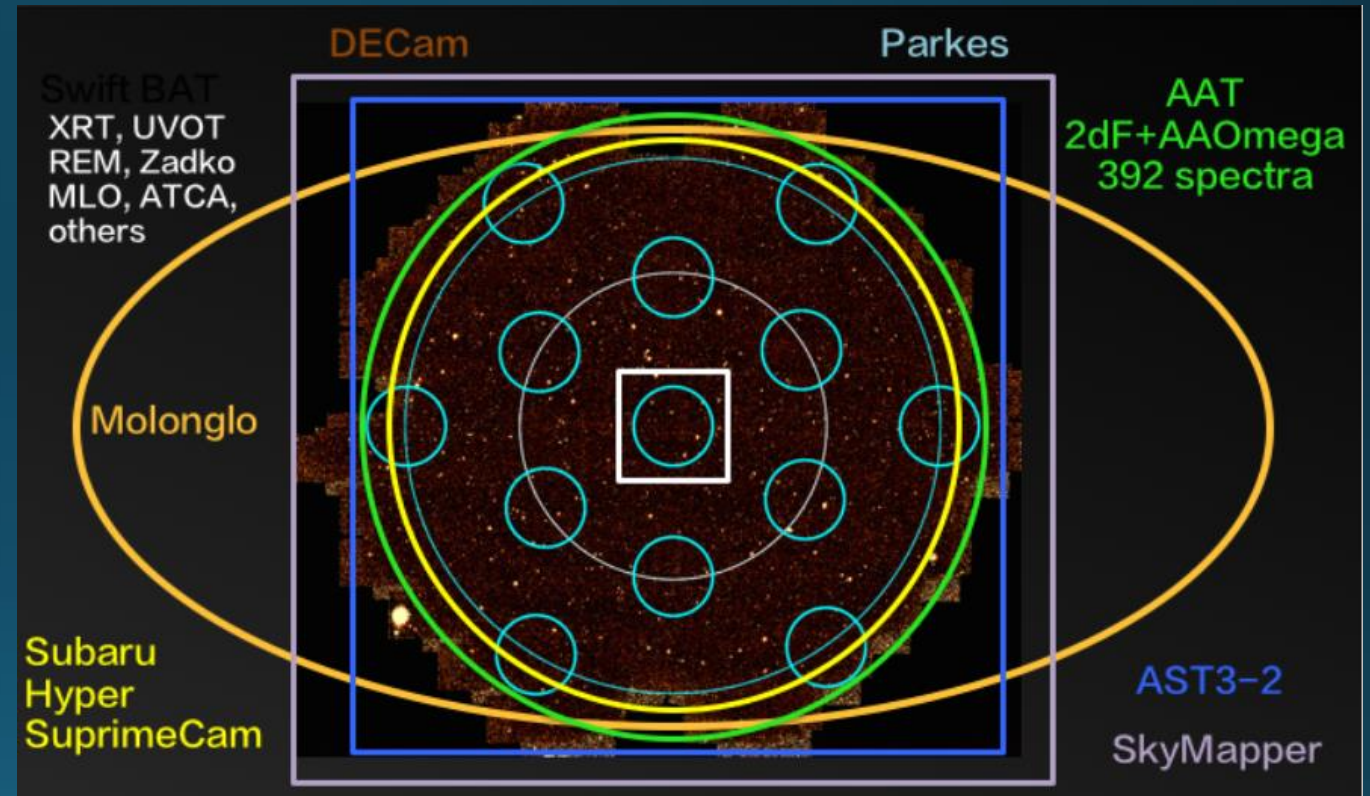


HIRAX. Строится прототип
Южный вариант CHIME
1607.02059

Multi-messenger searches



Deeper Wider Faster



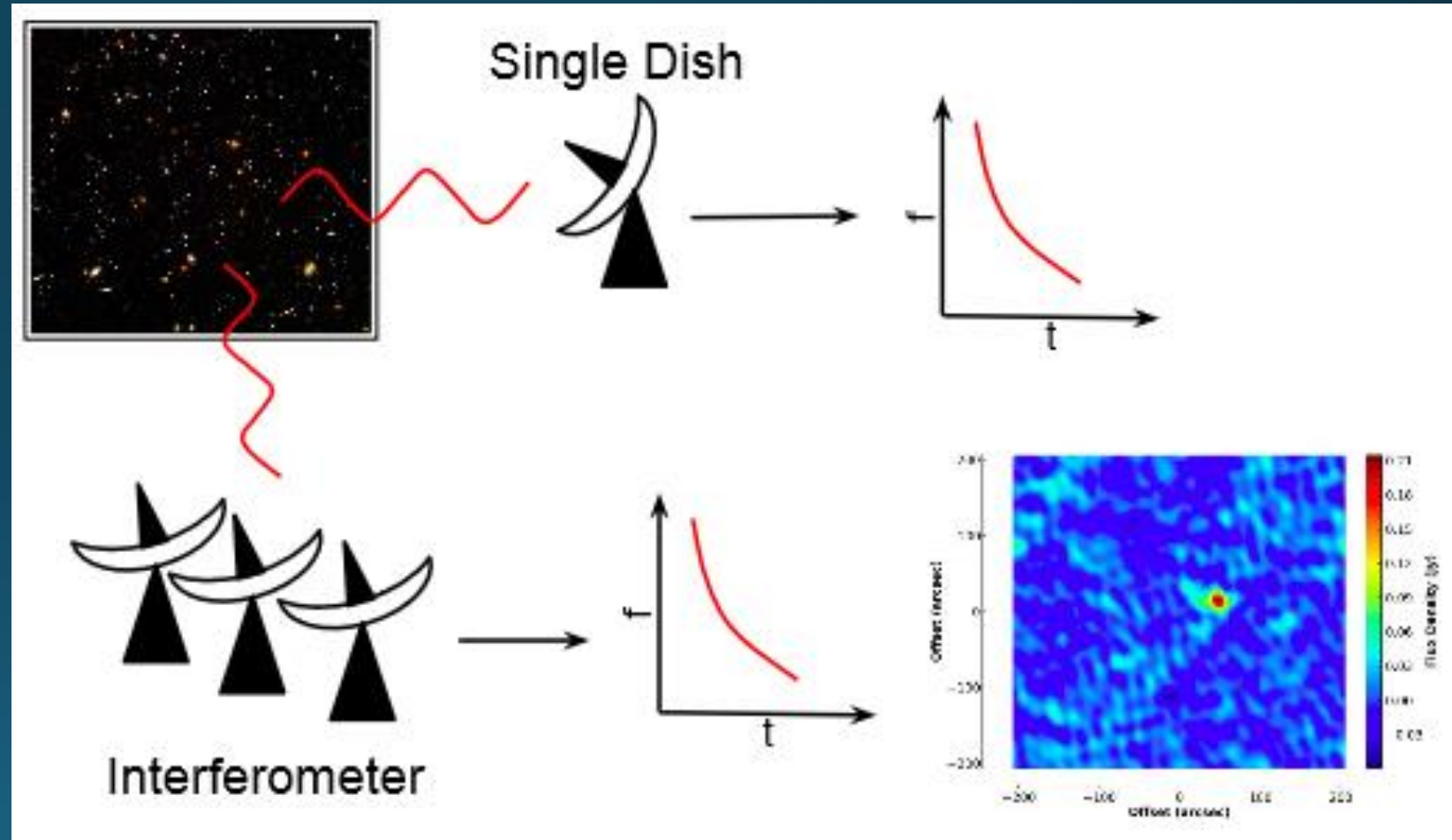
<http://dwfprogram.altervista.org/>

Realfast: new system on VLA

New system for rapid analysis
of fast transients (not only FRBs).

Installed in 2018.

Rapid localization.

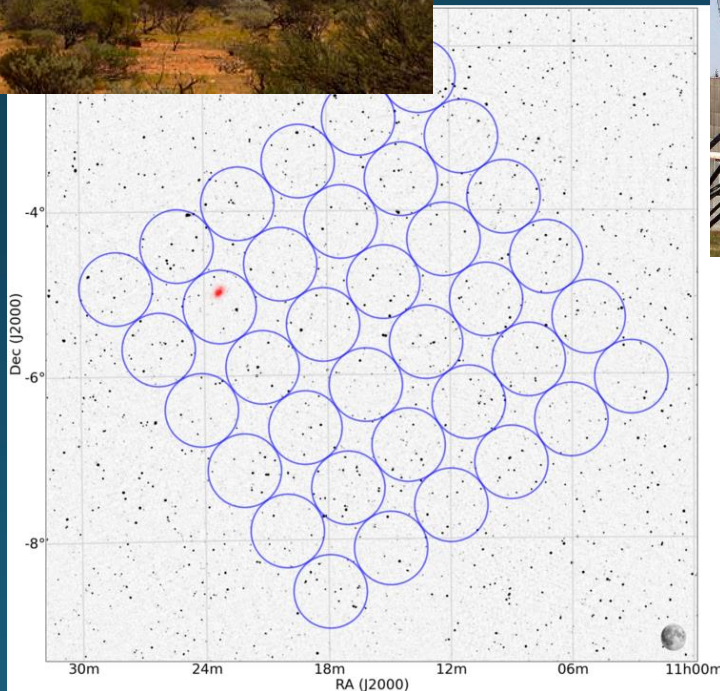


ASKAP and Apertif

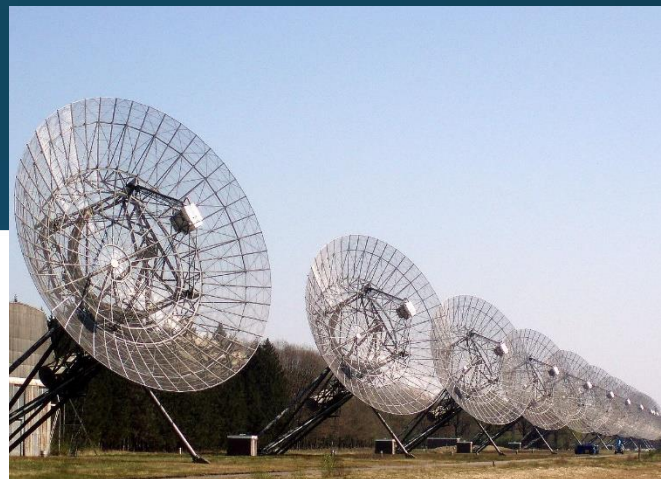
ASKAP



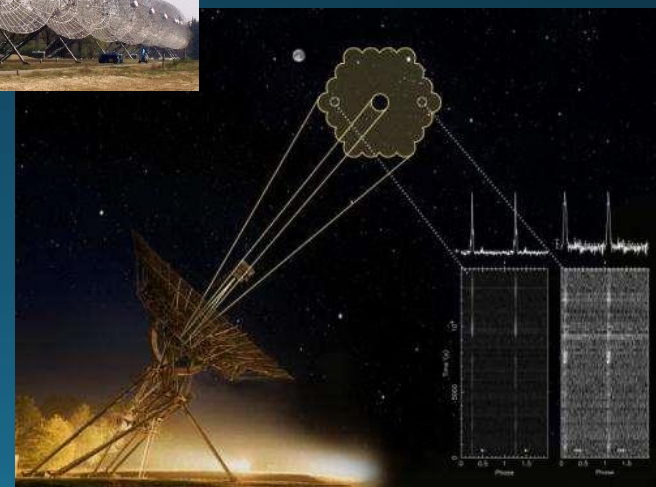
Few bursts per week.
1709.02189



Northern sky.
Doubling the number?
Rapid on-line
identification – follow-up.
FRB per week.



Westerbork

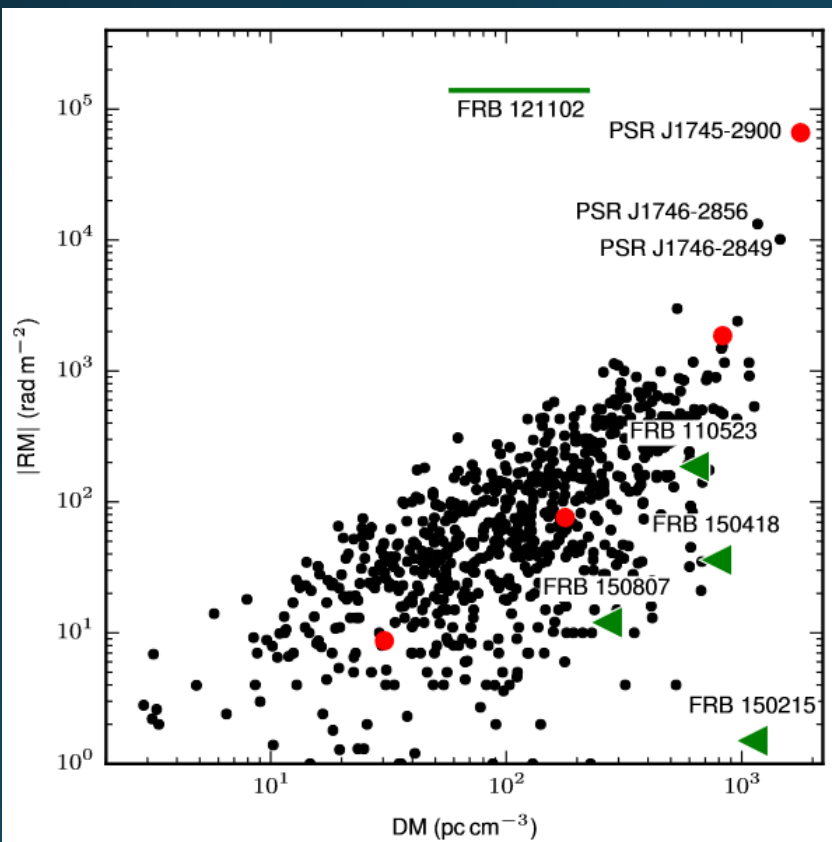


1709.06104

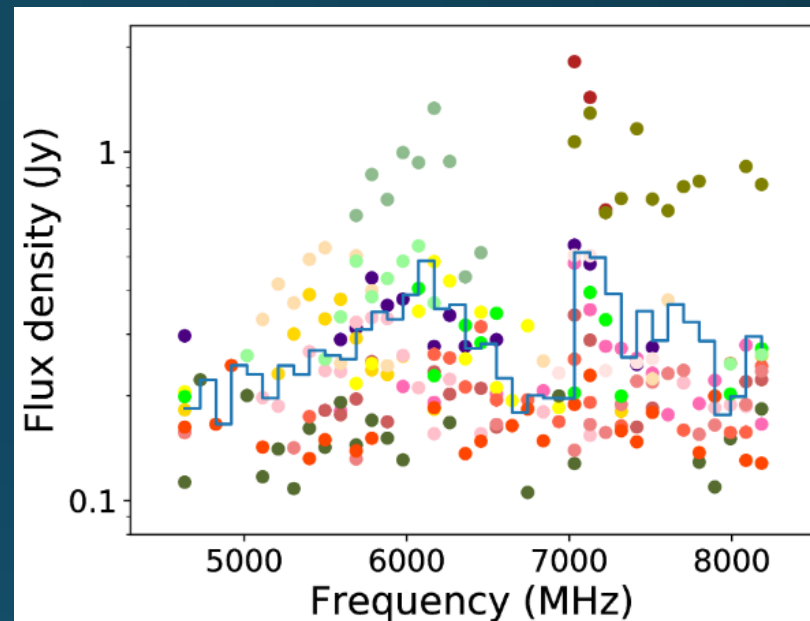
Новые данные по FRB

I. Данные по повторному источнику

Экстремальная среда вокруг.
Определено по большой и
переменной мере вращения.



Впервые всплески
удалось зафиксировать
на высокой частоте:
от 5 до 8 ГГц.



II. Много новых всплесков от ASKAP



1801.03965

1804.04101

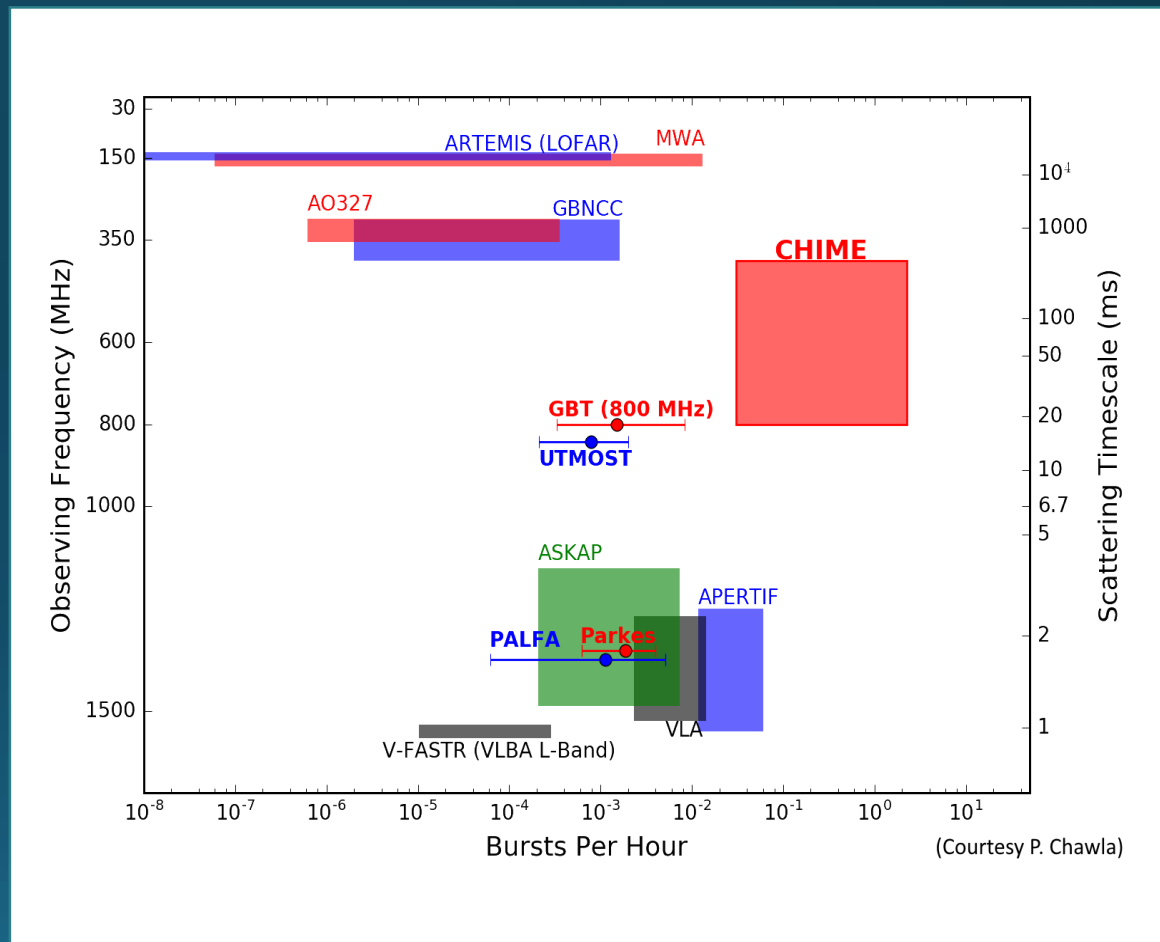
1810.04356

Новые данные по FRB

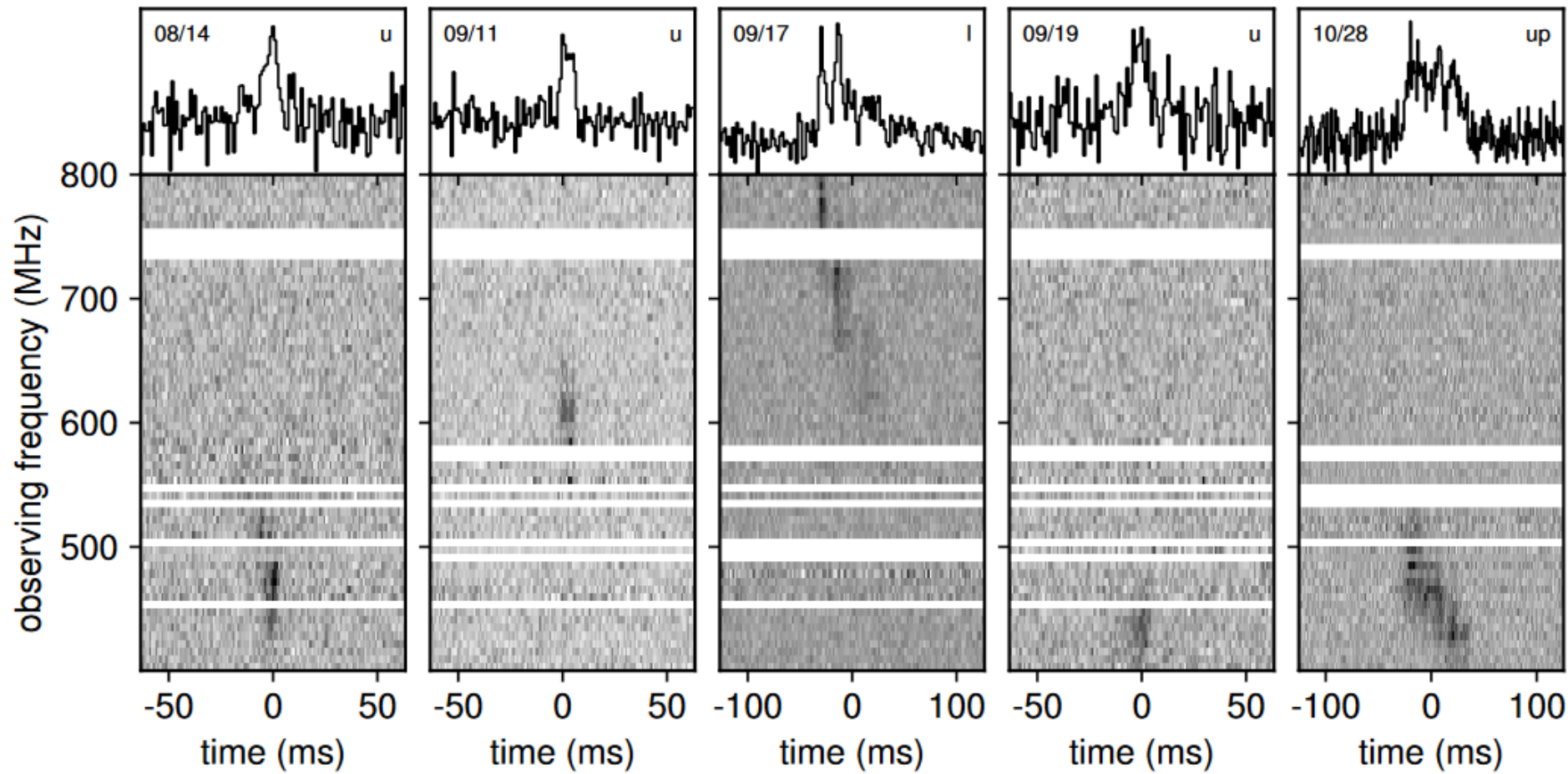


В 2018 г. уже были зарегистрированы первые FRB на CHIME.

Должна заработать система Apertif на радиотелескопах WSRT в Нидерландах.



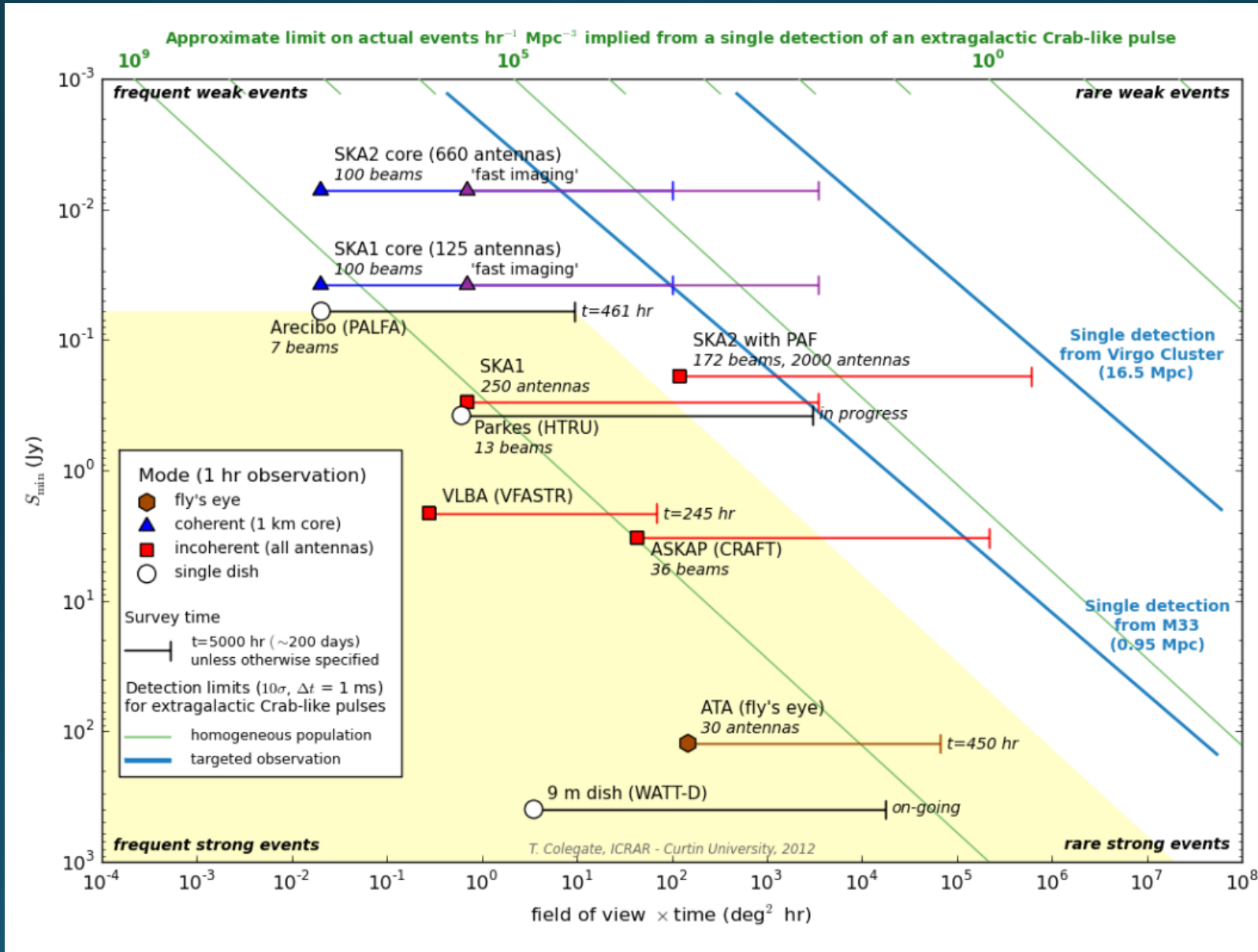
Первый урожай CHIME



12 новых FRB + источник повторных всплесков.
Регистрация на низких частотах: вплоть до 400 МГц.

Регистрация всплесков разными инструментами

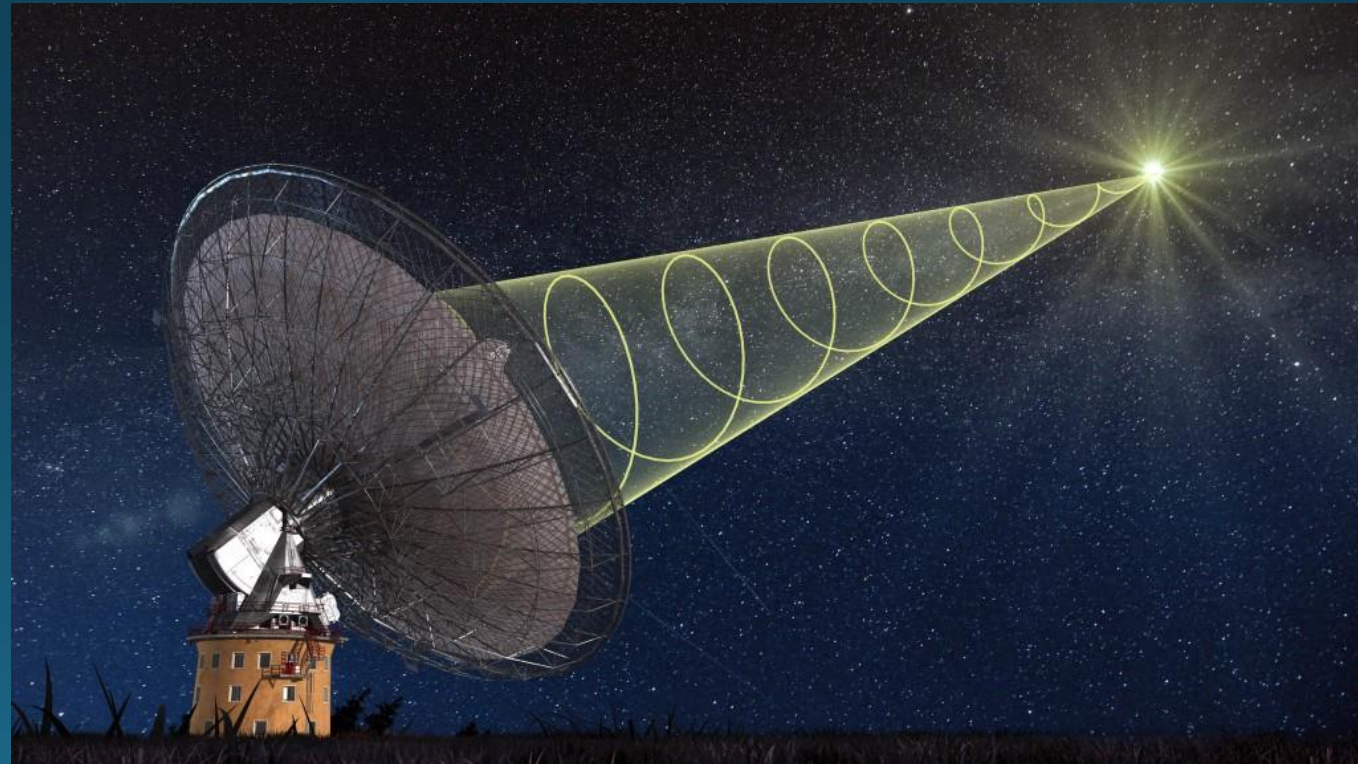
Hall et al. (2012)



Итого

- В 2007 г. был открыт новый класс транзиечных объектов
- Всплески (пока?) видны только в радио
- Известно менее 20 вспышек
- Число моделей превосходит число известных всплесков
- Сейчас есть три хорошие модели, поддерживаемые данными
- Ситуация похожа на проблему гамма-всплесков лет 40 назад
- Ждем, что новые наблюдения позволят выбрать верную модель

См. обзор
Попов, Постнов, Пширков
УФН N10 (2018)
www.ufn.ru



Swinburne Astronomy Productions