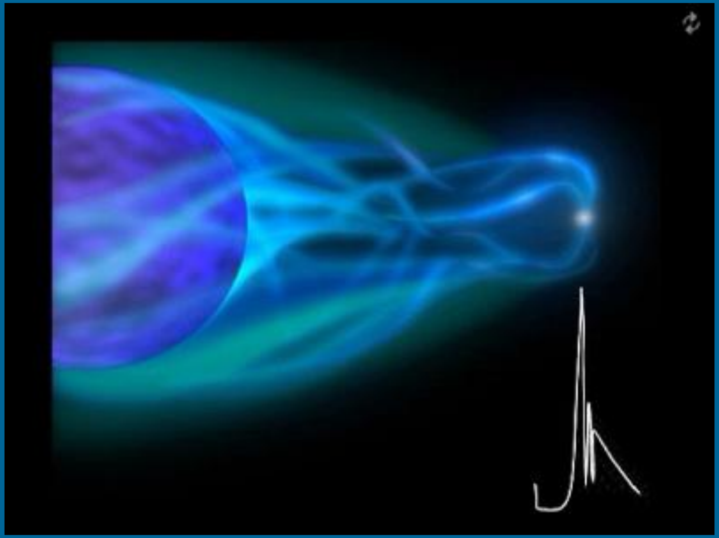
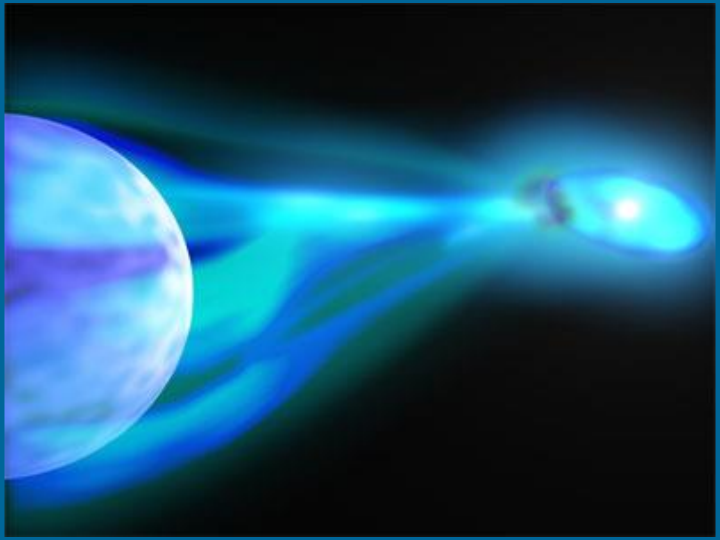
BH binaries



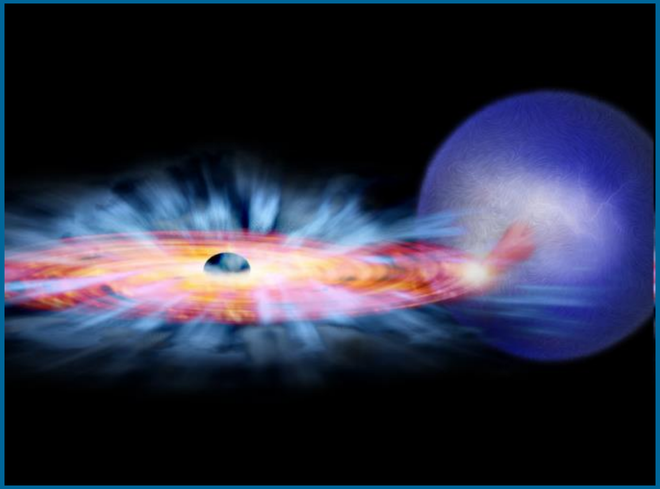


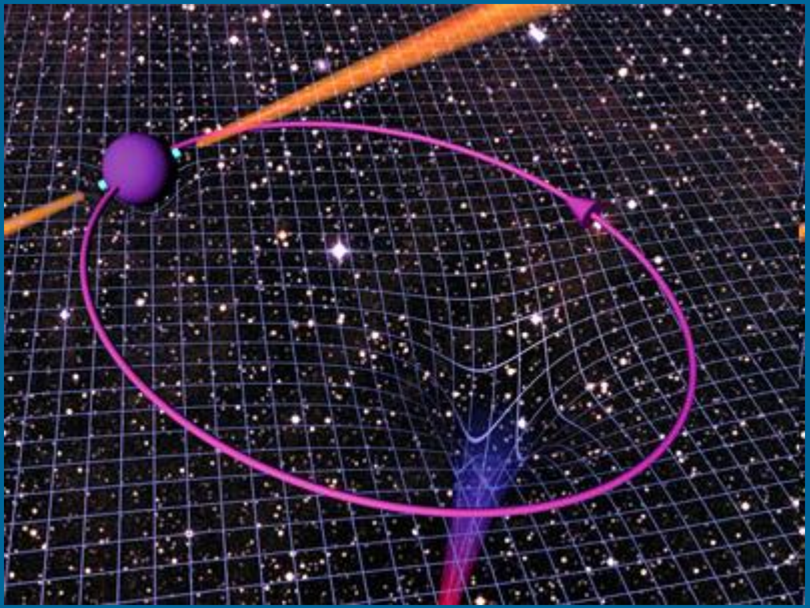
Black hole binaries

• 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)

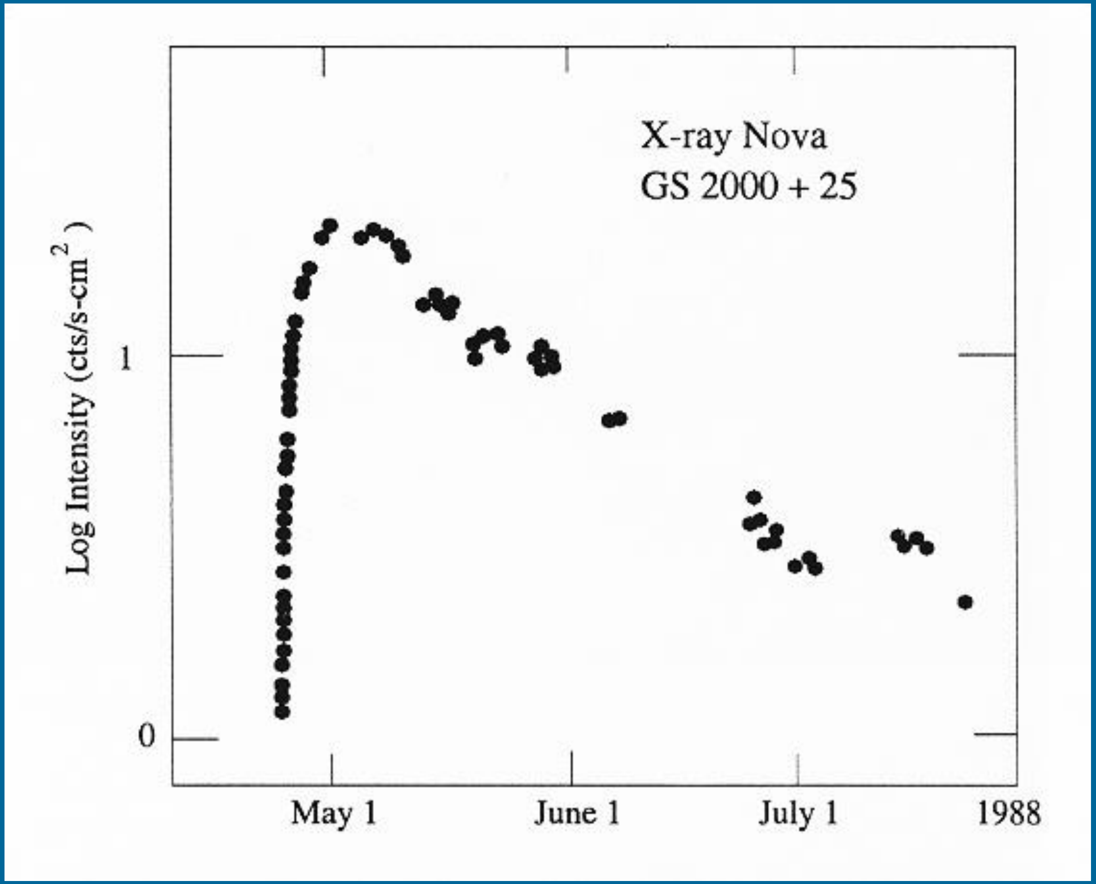
X-ray observations: Cyg X-1

“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

X-ray novae

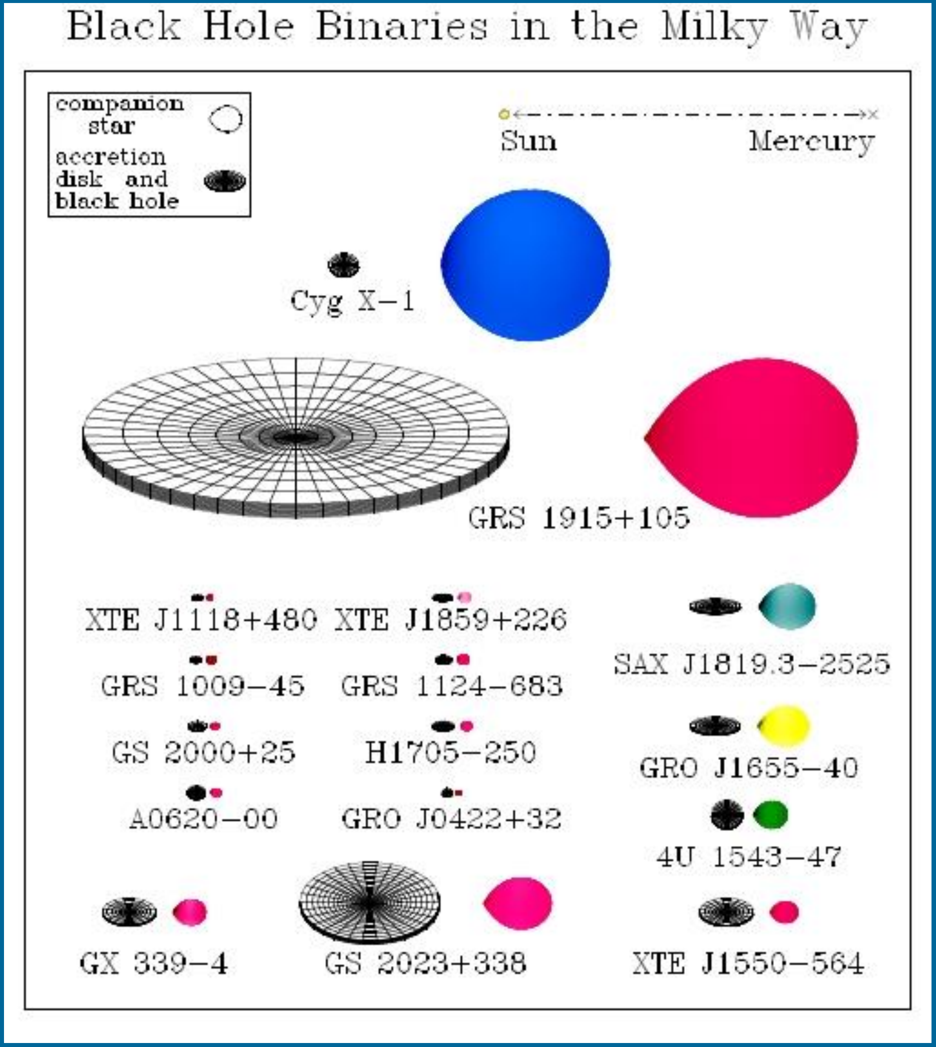


Low-mass binaries with BHs

One of the best candidates

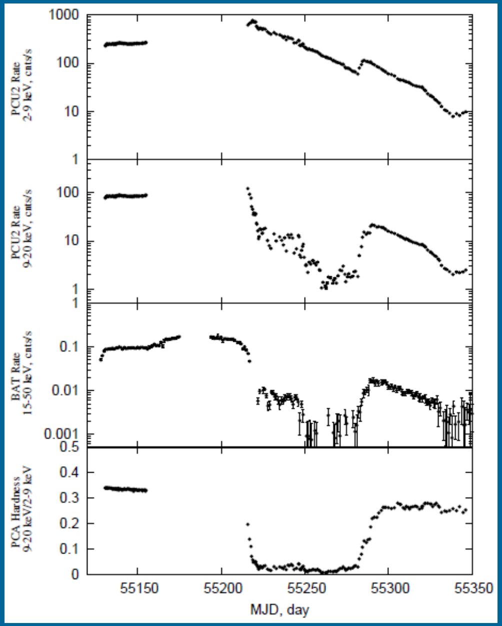
In the minimum it is possible to see the secondary companion, and so to get a good mass estimate for a BH.

BH candidates



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.



J. Orosz, from astro-ph/0606352

Candidates properties

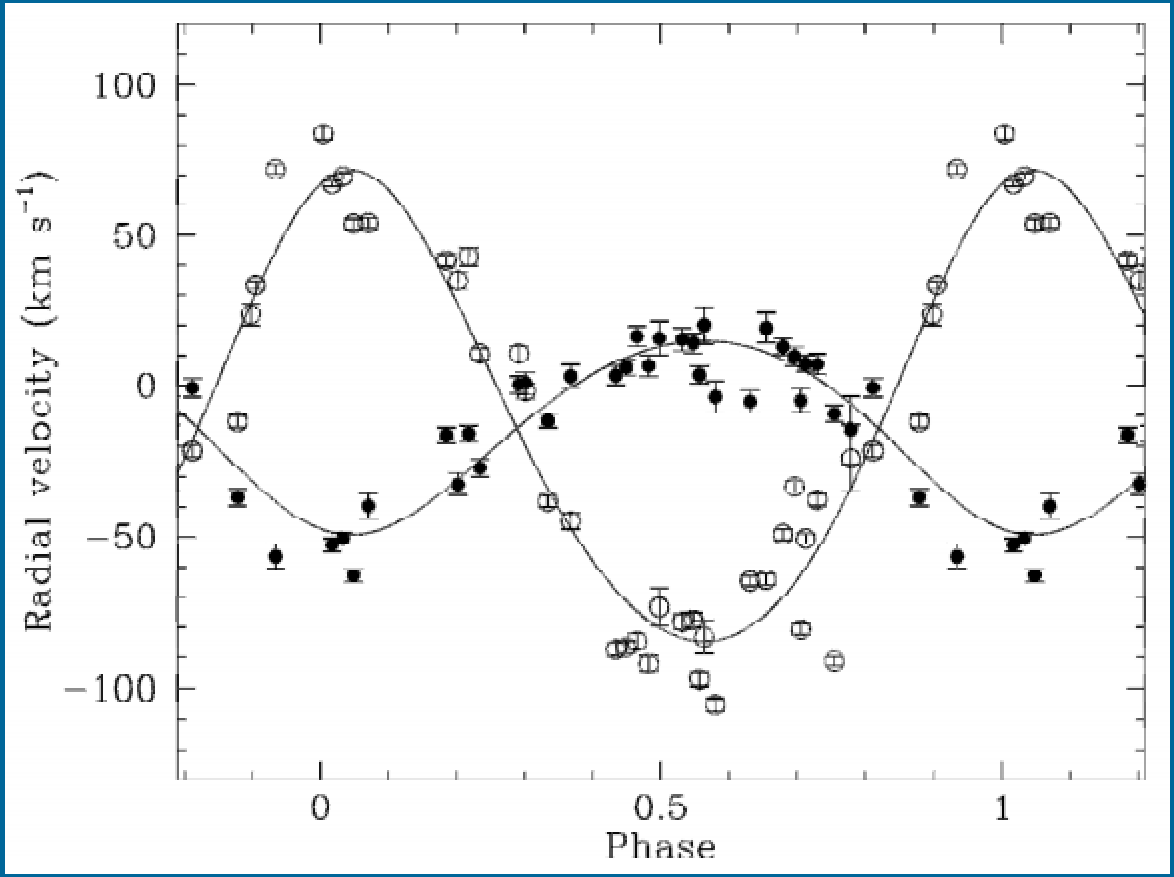
Table 1: Twenty confirmed black holes and twenty black hole candidates[a]

Coordinate Name	Common[b] Name/Prefix	Year[c]	Spec.	P_{orb} (hr)	f(M) ($M_\odot$)	M_1 ($M_\odot$)
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

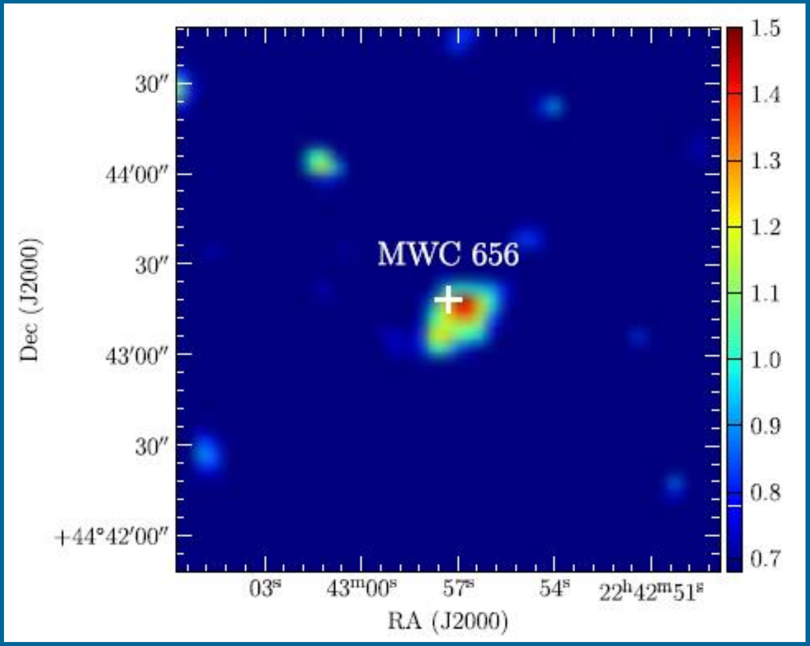


Compact object has a mass 3.8 – 6.9 Msolar.

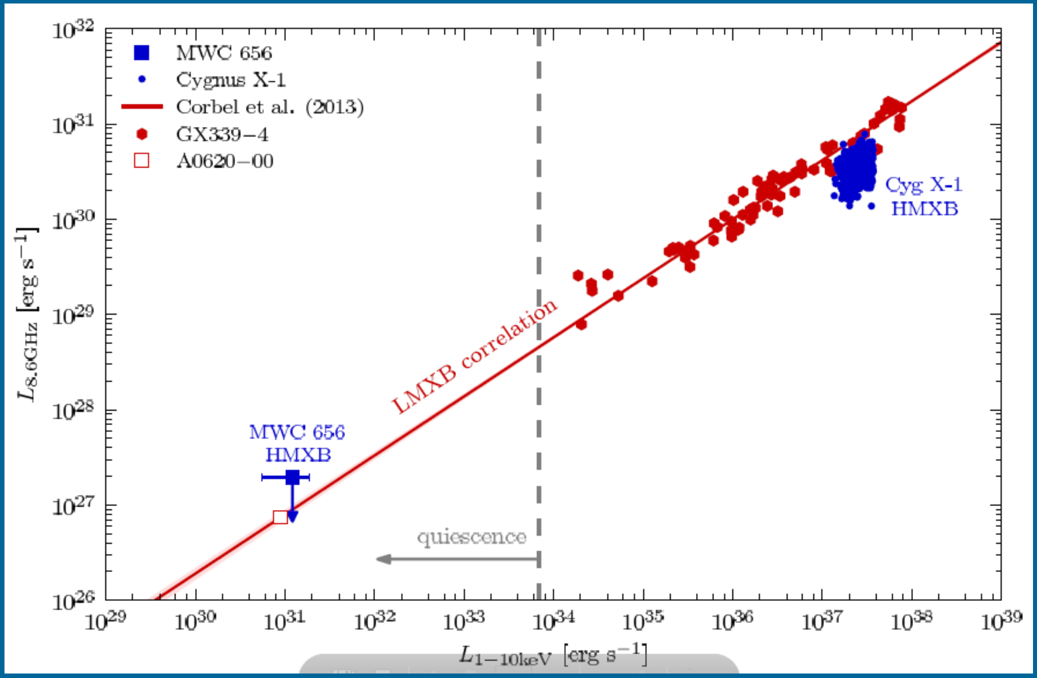
X-ray luminosity is low

1401.3711

X-rays from MWC656



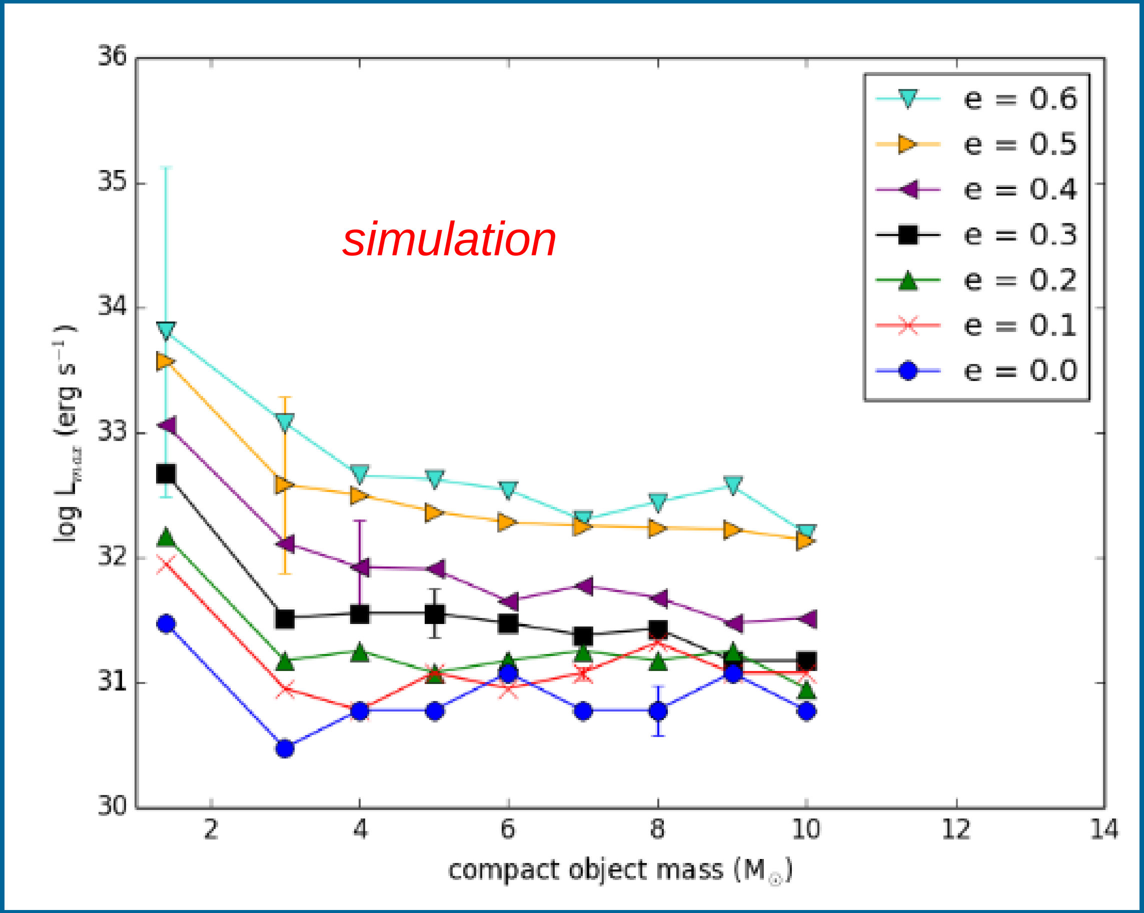
XMM-Newton

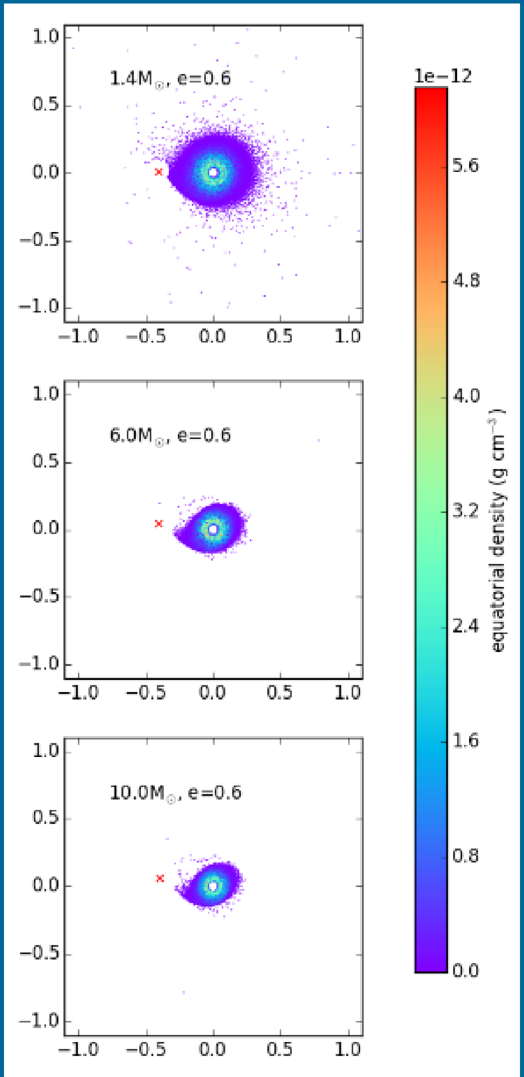


Became fainter since 2014.

1404.0901

BH/Be are fainter than NS/Be

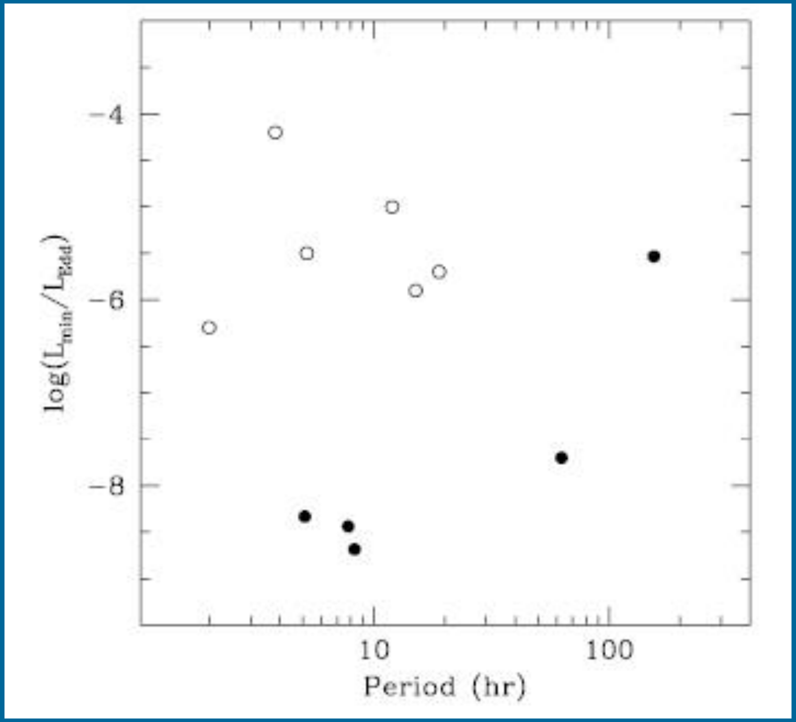


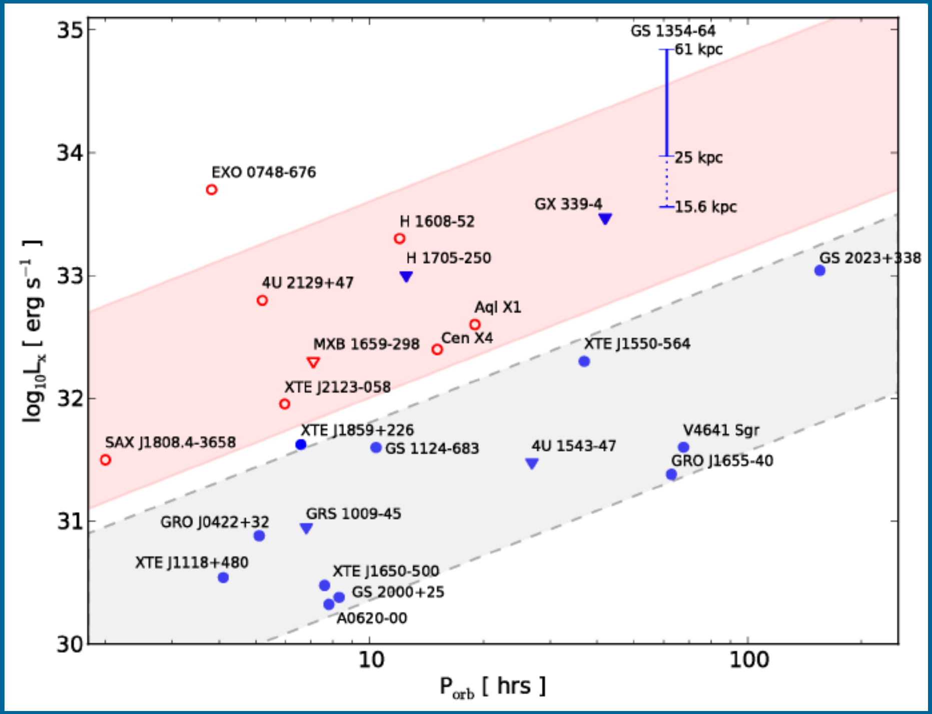


BH systems are fainter even for the same efficiency due to disc truncation. Lower efficiency can help to explain better why BH/Be systems are rarer than NS/Be.

1804.05749

Quescent luminosity vs. Orbital period



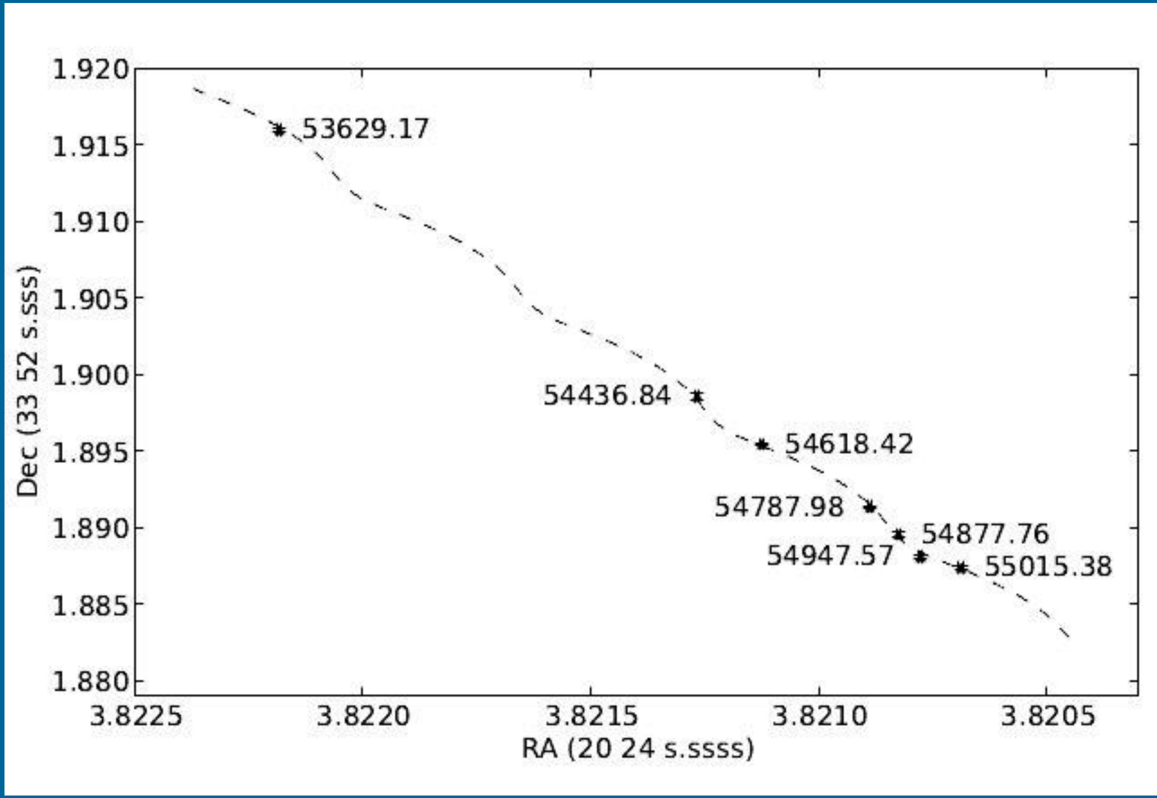


Open symbols – neutron stars
black symbols – black holes.

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

Garcia et al. 2001, see Psaltis astro-ph/0410536

Distance to V404 Cyg



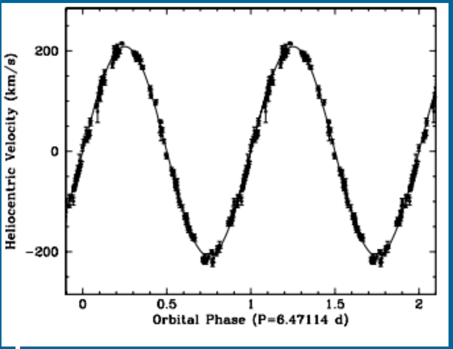
The parallax was measured.
The new distance estimate is 2.25-2.53 kpc.
It is smaller than before.
Correspondently,
flares luminosity is lower,
and so they are subEddington.

arXiv:0910.5253

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

Mass determination

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



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.

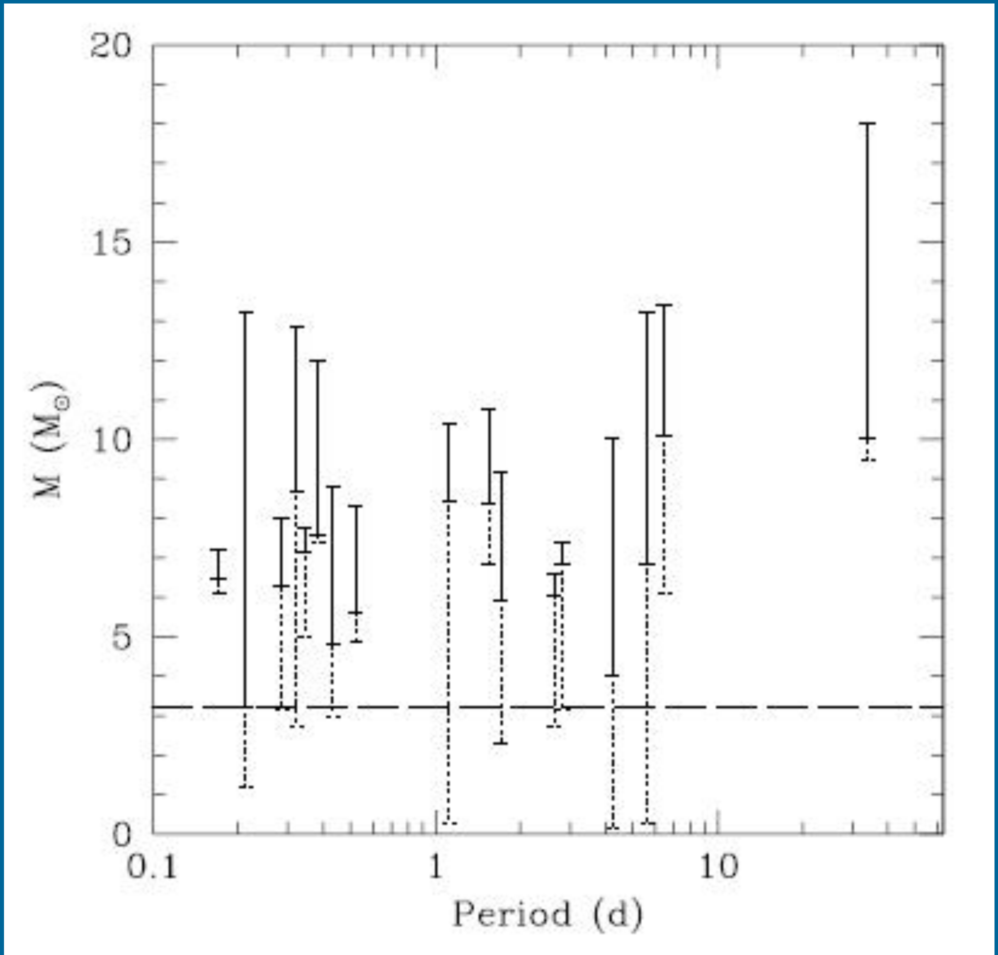
The mass of the compact object can be calculated as:

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

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.

Orosz 2002, see also Psaltis astro-ph/0410536

Some more results on masses

Paredes
arXiv: 0907.3602

System	$P_{\rm orb}$ [days]	$f(M)$ [$M_\odot$]	Donor Spect. Type	Classification	$M_{\rm x}$ [$M_\odot$]
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

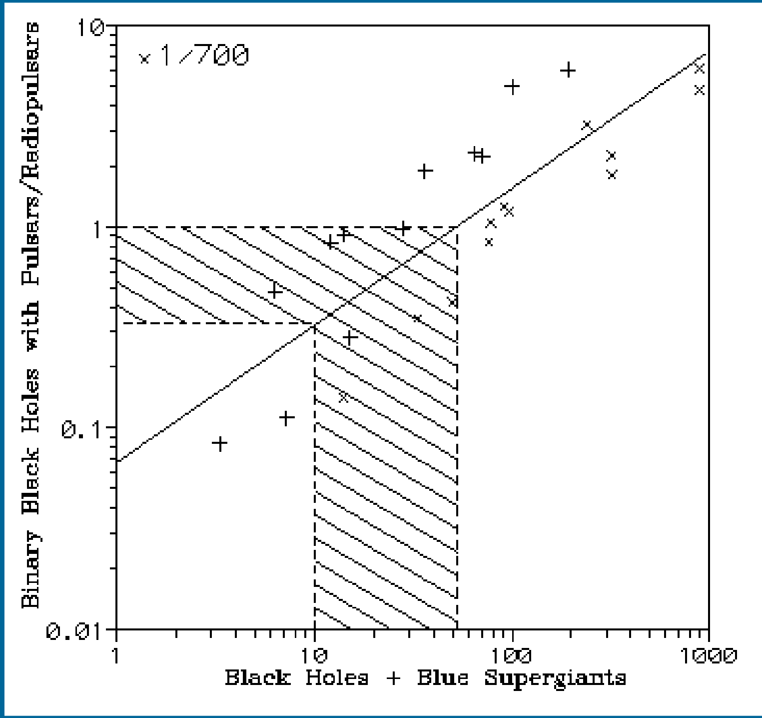
M33 X-7 15.65+/-1.45 M_{solar} (Orosz et al. 2007).
Eclipsing binary IC10 X-1 32+/- 2.6 (Silverman and Filippenko 2008)

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.

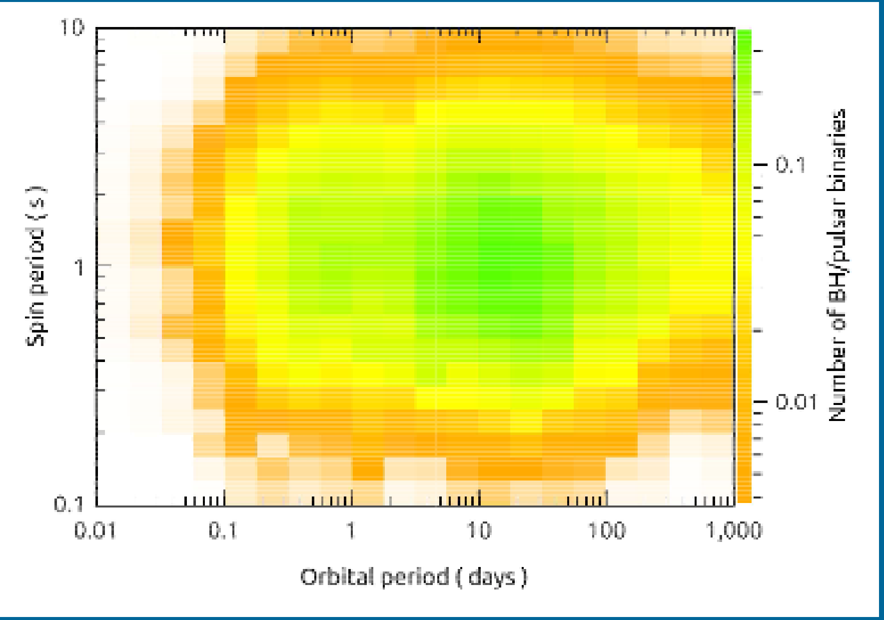
Pfahl et al. (astro-ph/0502122) give much lower estimate for systems BH+mPSR: about 0.1-1% of the number of binary NSs. This is understandable, as a BH should be born by the secondary (i.e. initially less massive) component of a binary system.

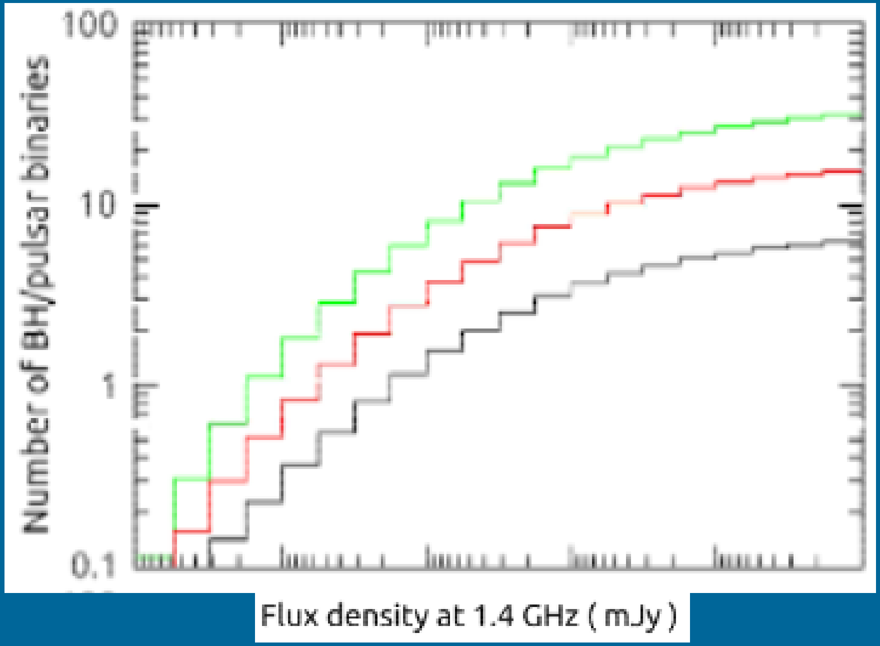


What can be done with such systems if they are detected by SKA was studied recently in 1409.3882. Mainly related to gravity tests.

BH+pulsar binaries and FAST

Birth rate of NS+BH binaries ~0.6-13 Myr^{-1}
Thus, ~10^4 -10^5 in the Galaxy.
Difficult to have a msecPSR.
Thus, typical spin periods ~1 s.
3-80 BH+PSR binaries.
~10% of them can be detected by FAST.

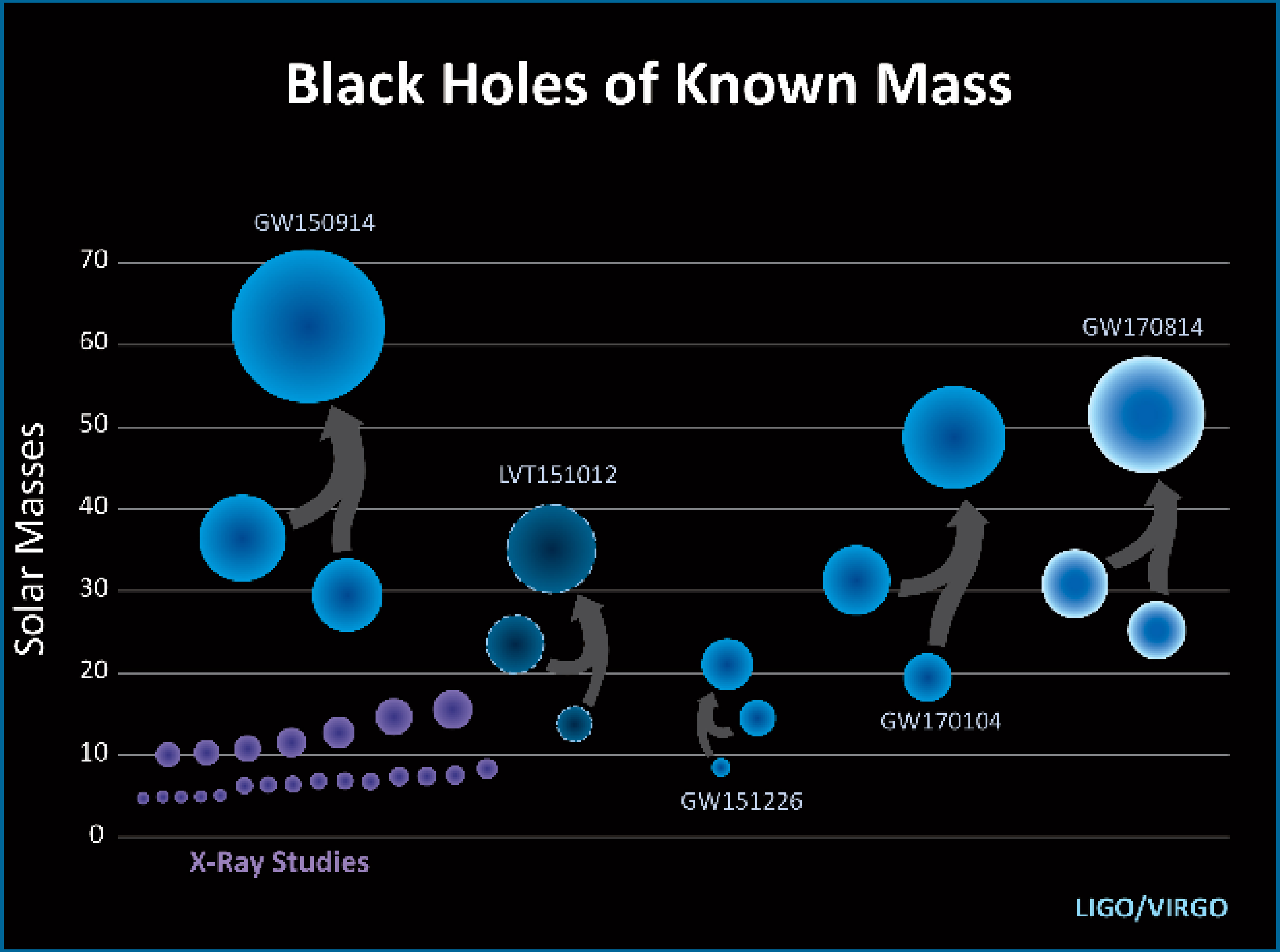




σ_{NS_kick} = 150 km/s

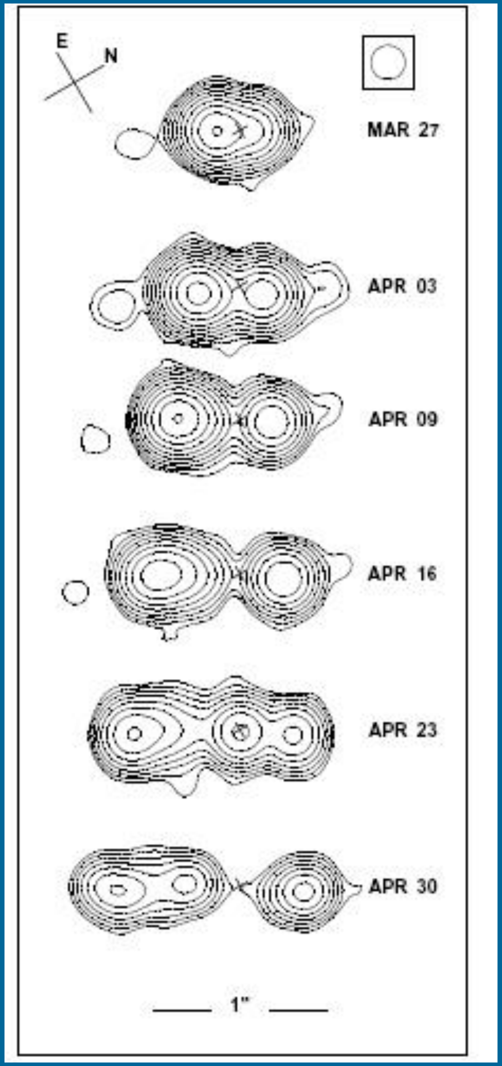
1804.06014

BH+BH. Coalescence.



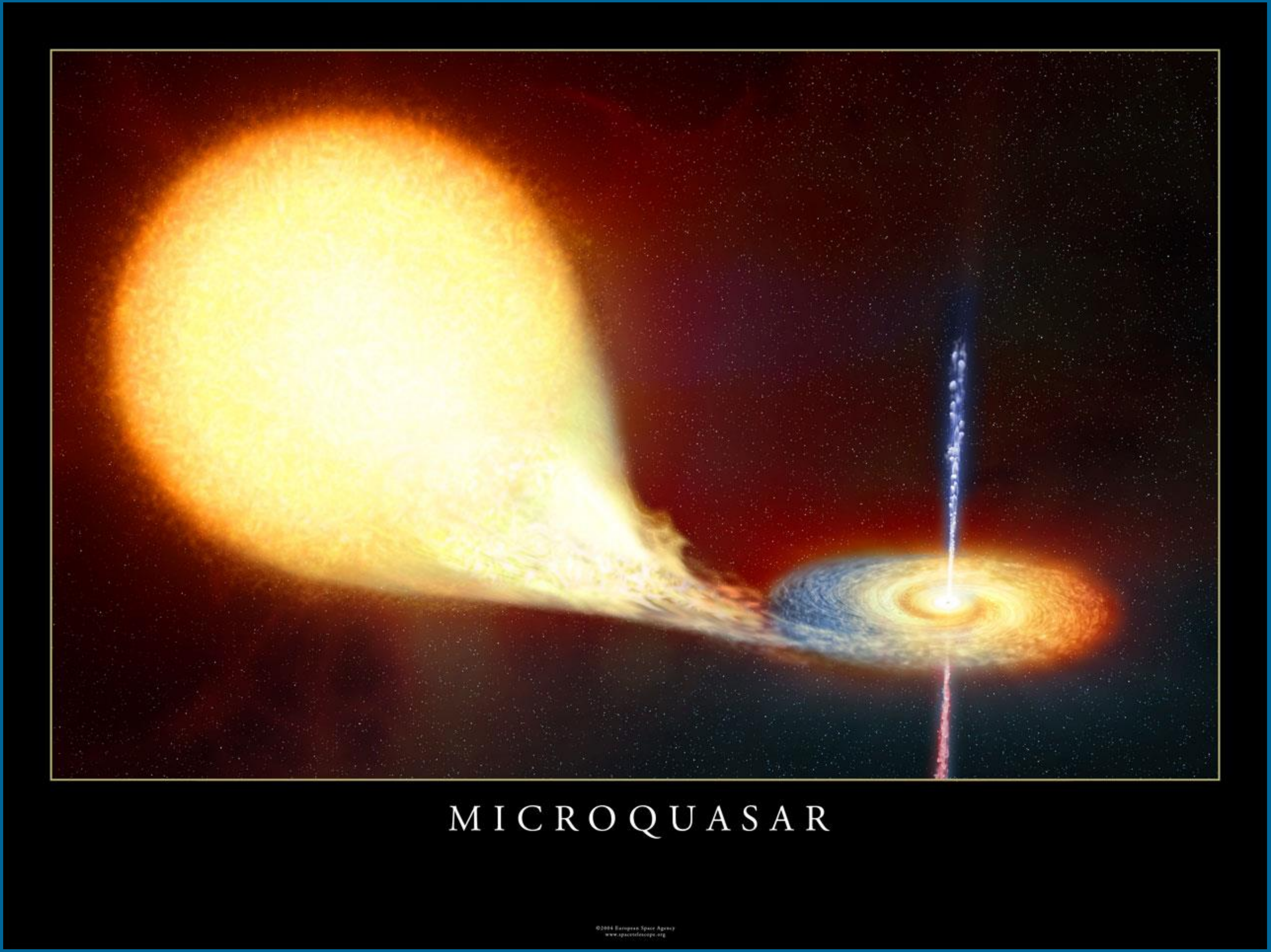
1804.06308

Jet from GRS 1915+105



VLA data. Wavelength 3.5 cm.

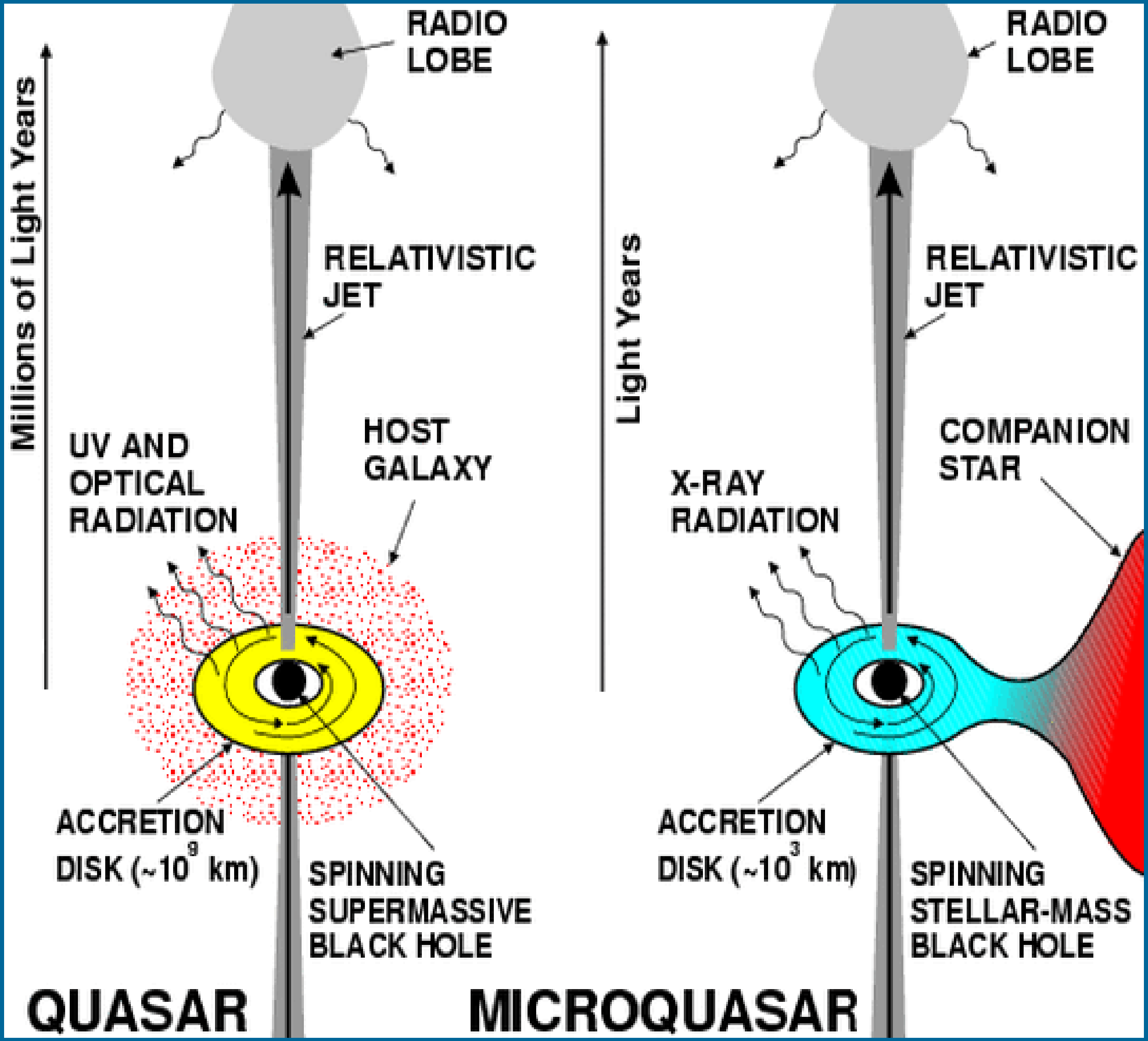
Mirabel, Rodrigez 1994, see Psaltis astro-ph/0410536



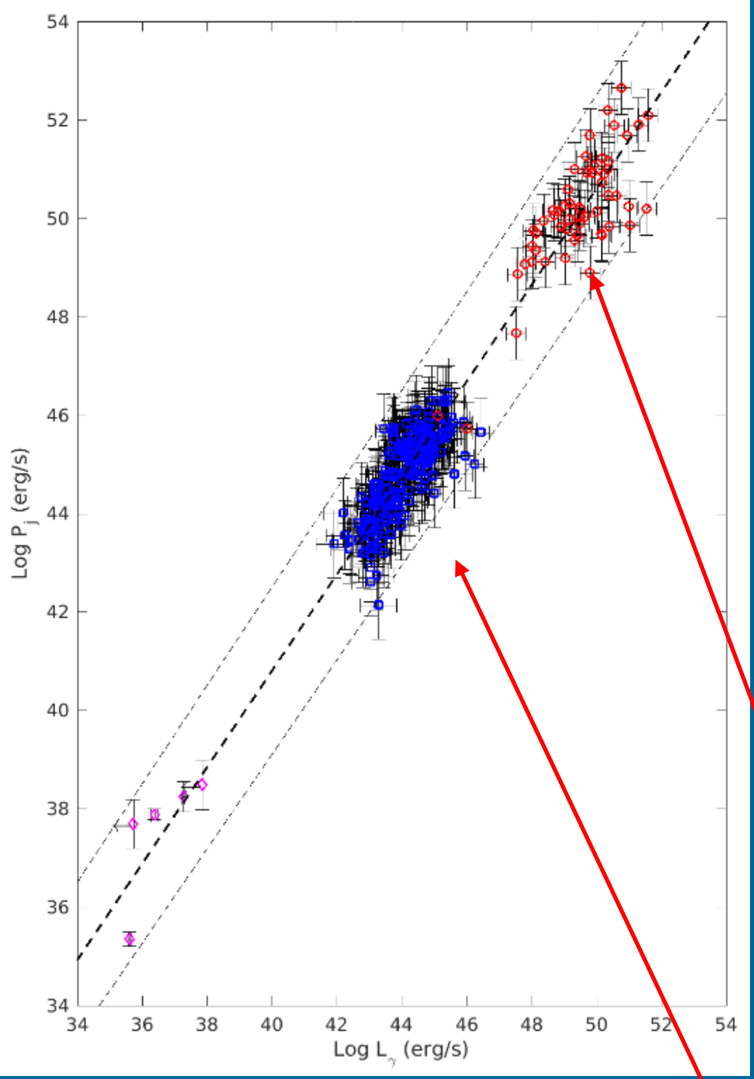
See a brief review in 1106.2059

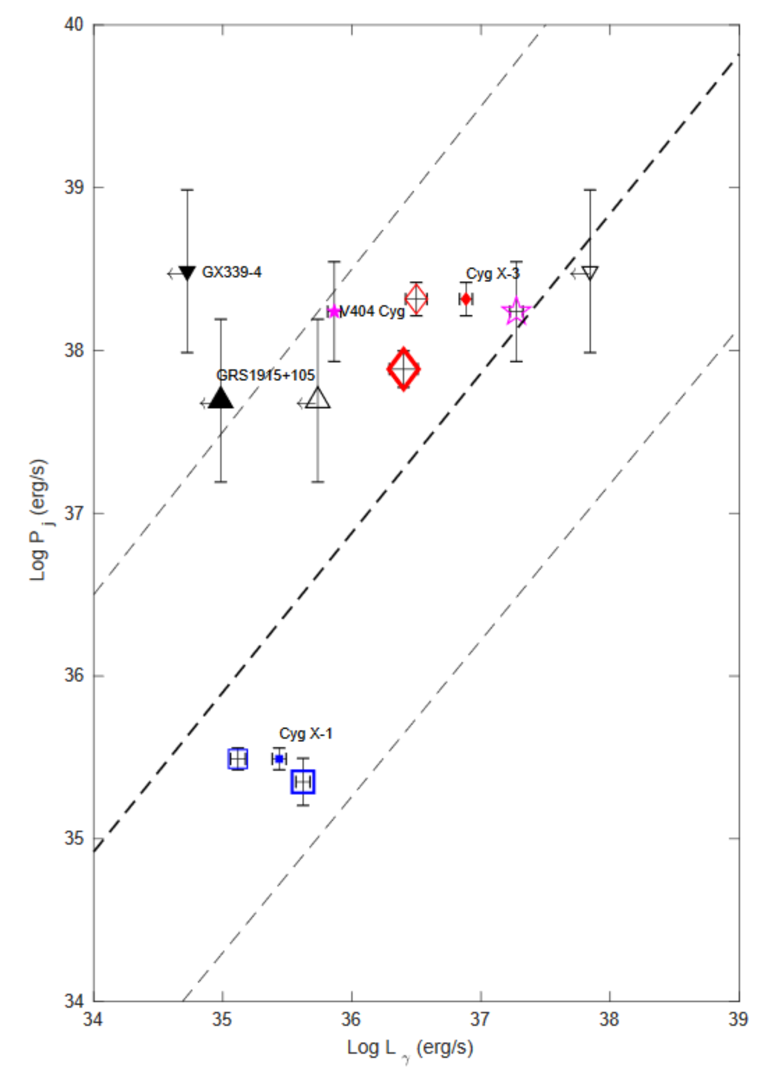
$T \sim 10^7\ K\ M^{-1/4}$ –
last stable orbit temperature at Eddington luminosity

Optics/UV – QSO
X-ray - μQSO



Jet-luminosity relation



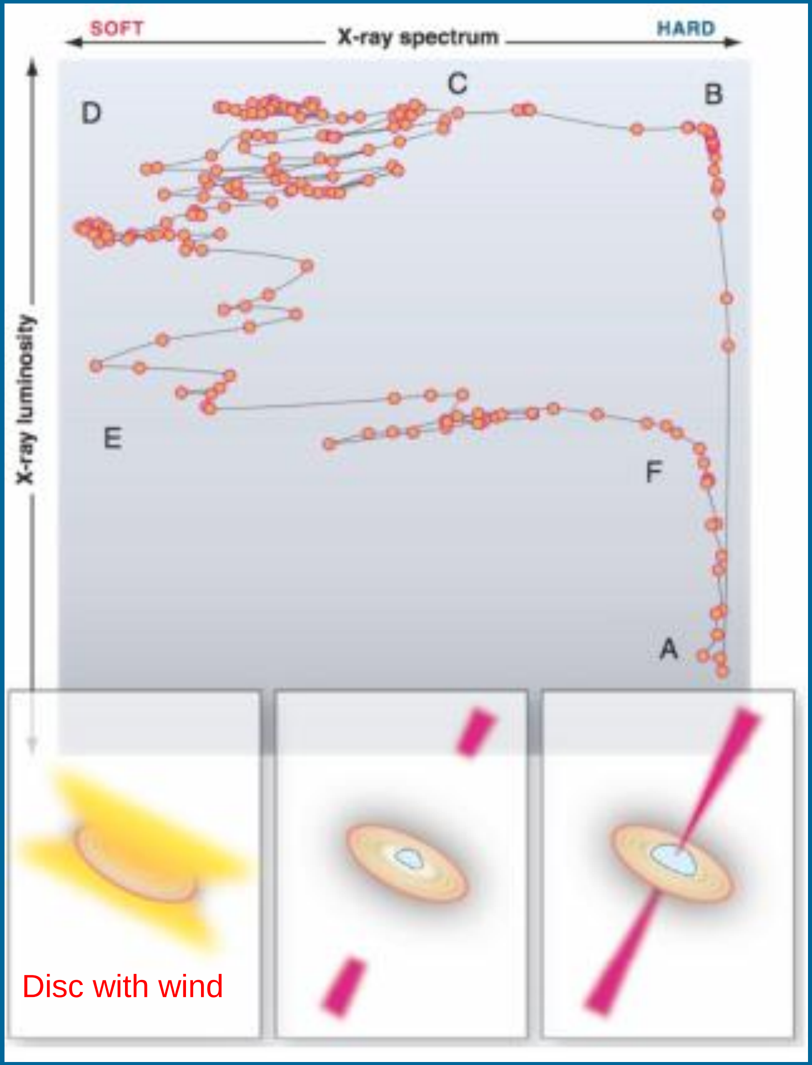


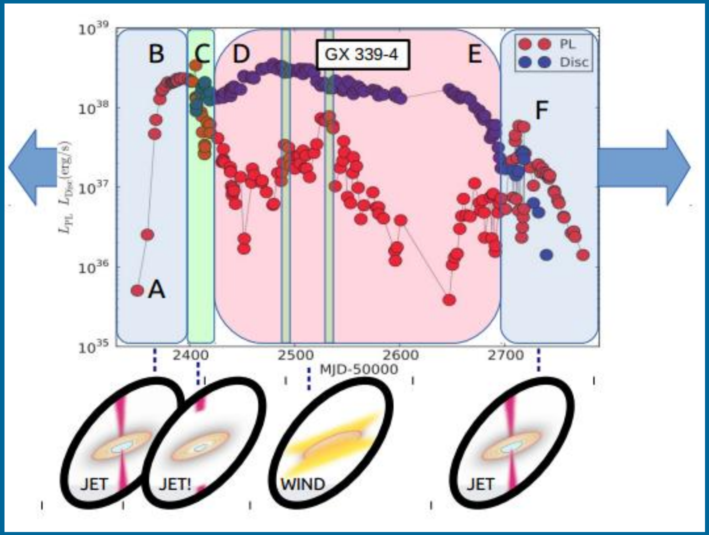
1705.09191

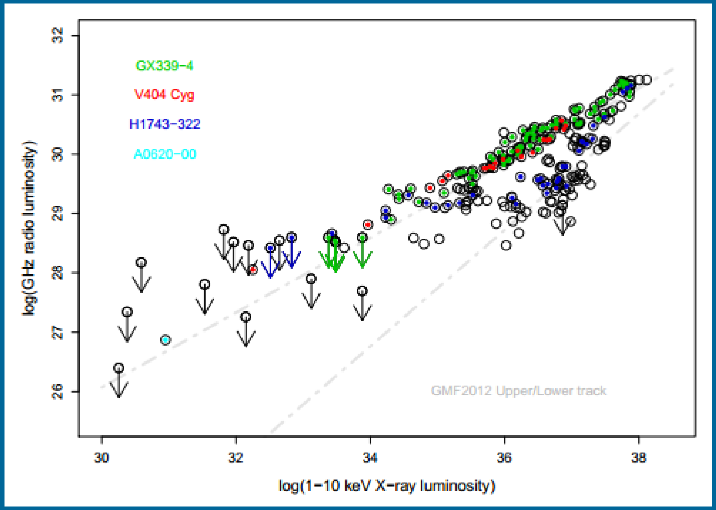
Blazars

GRBs

Large review on jets from binaries

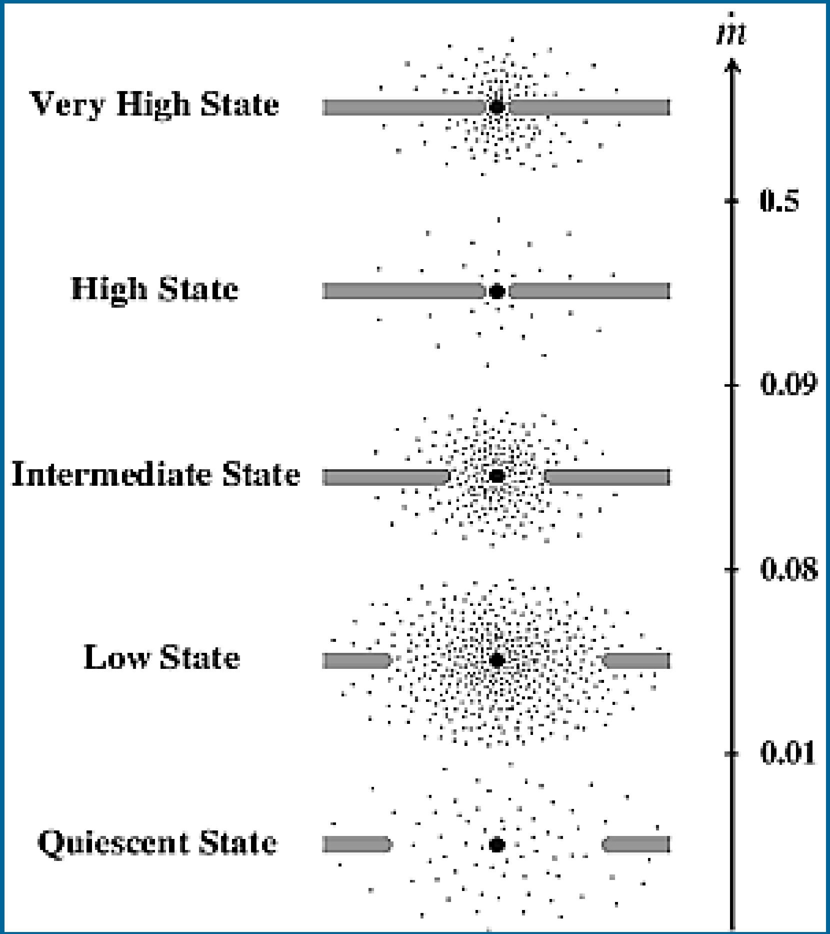






A large recent review can be found in 1407.3674

States (luminosity+spectrum+jet+variability)



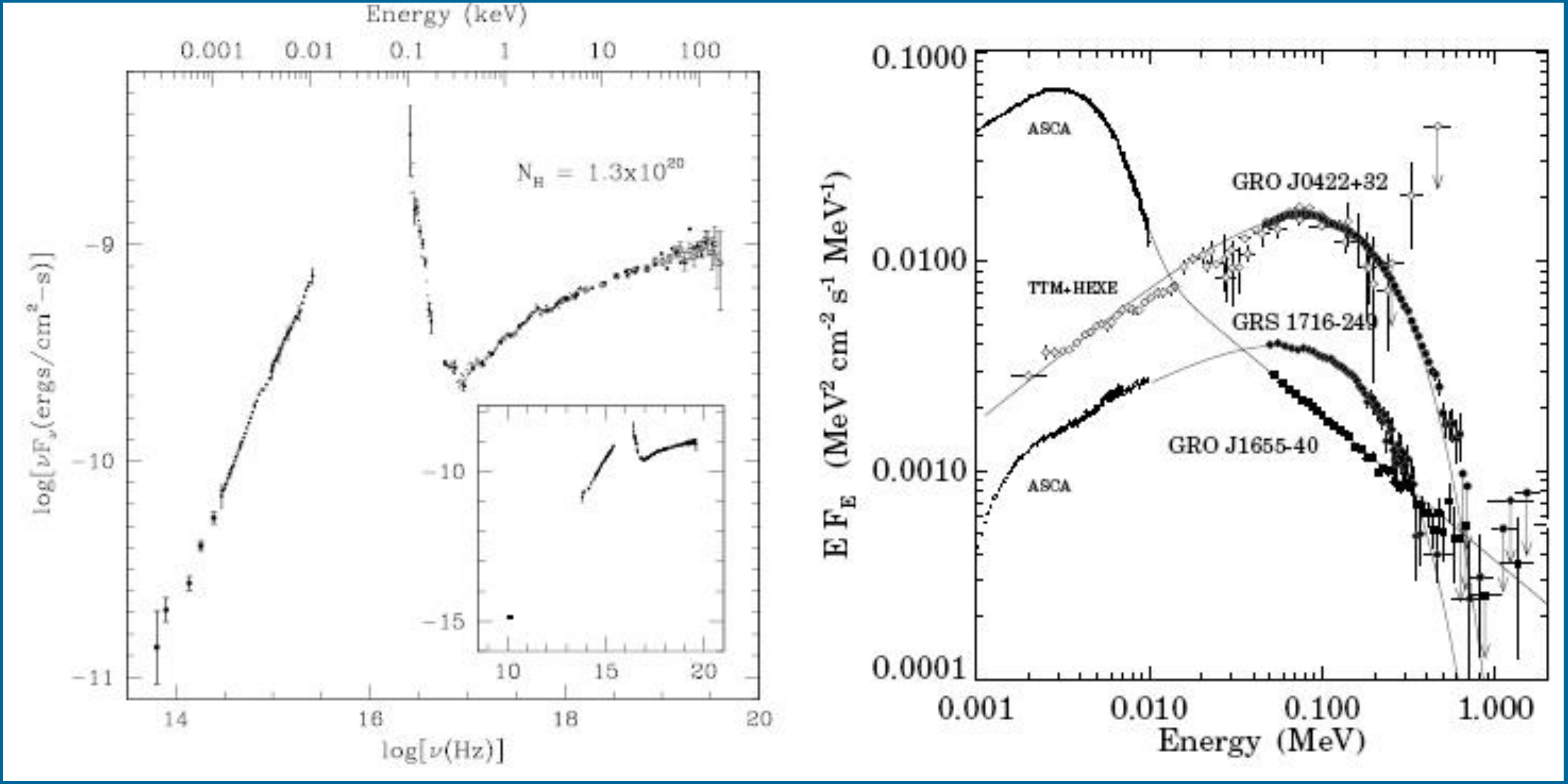
The understanding that BH binaries can pass through different “states” (characterized by luminosity, spectrum, and other features, like radio emission) appeared in 1972 when Cyg X-1 suddenly showed a drop in soft X-ray flux, rise in hard X-ray flux, and the radio source was turned on.

Now there are several classifications of states of BH binaries.

astro-ph/0306213 McClintock, Remillard
Black holes on binary systems

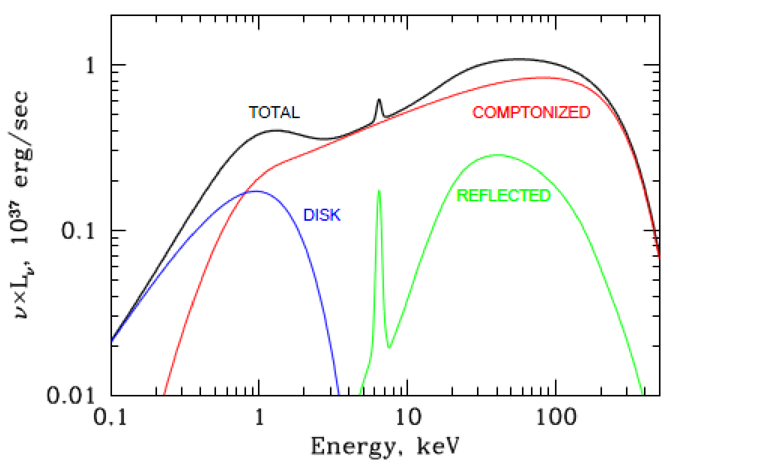
Accretion onto BHs was recently reviewd in 1304.4879

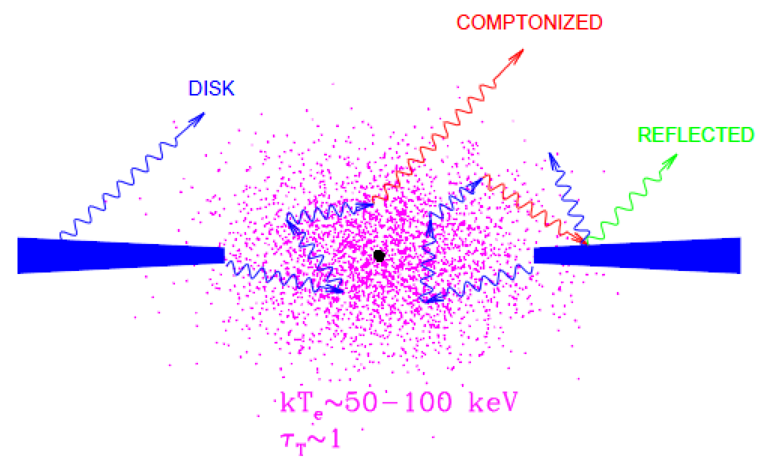
Spectra of BH candidates

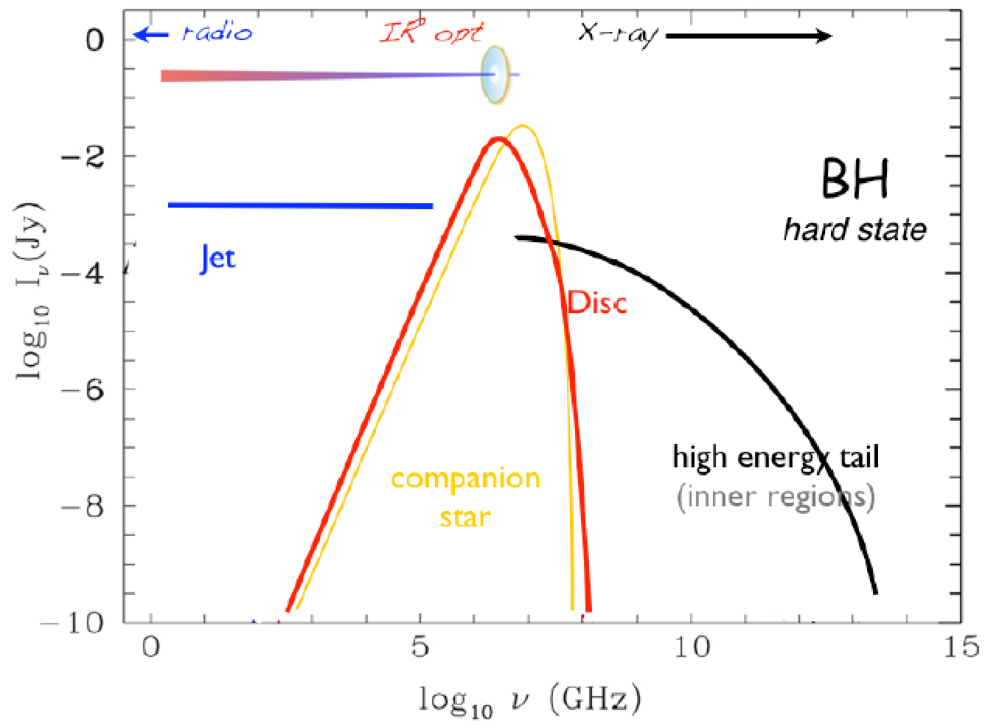


(Psaltis astro-ph/0410536)

Different components of a BH spectrum







1104.0097

Accretion geometry and photon paths at the hard state

0909.2567

Three-state classification

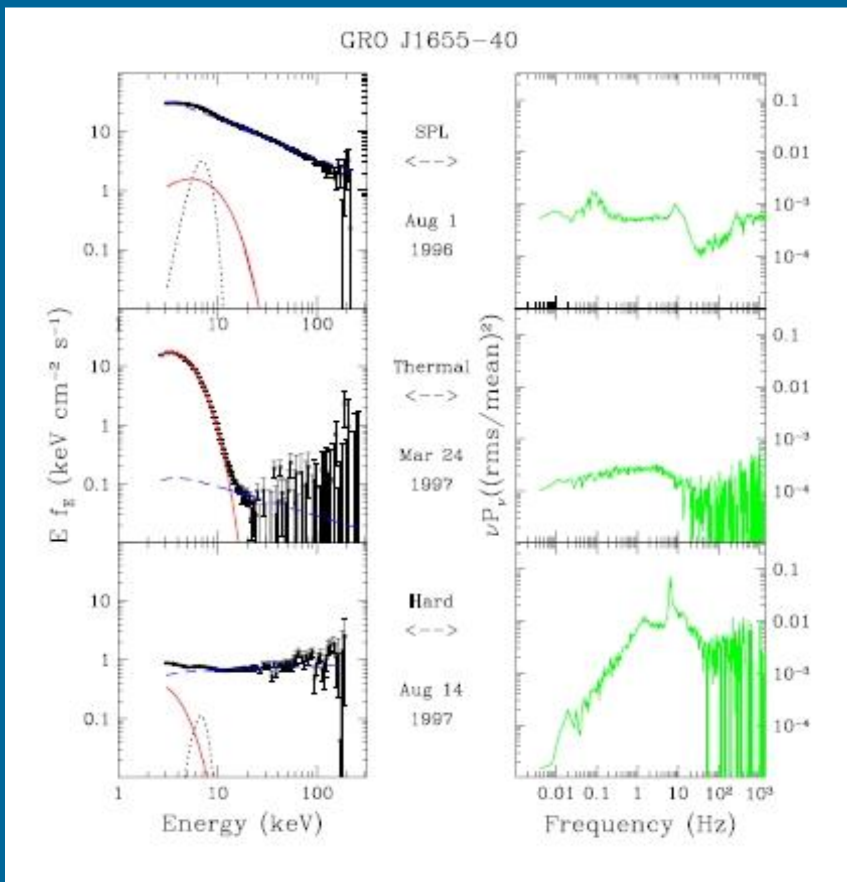


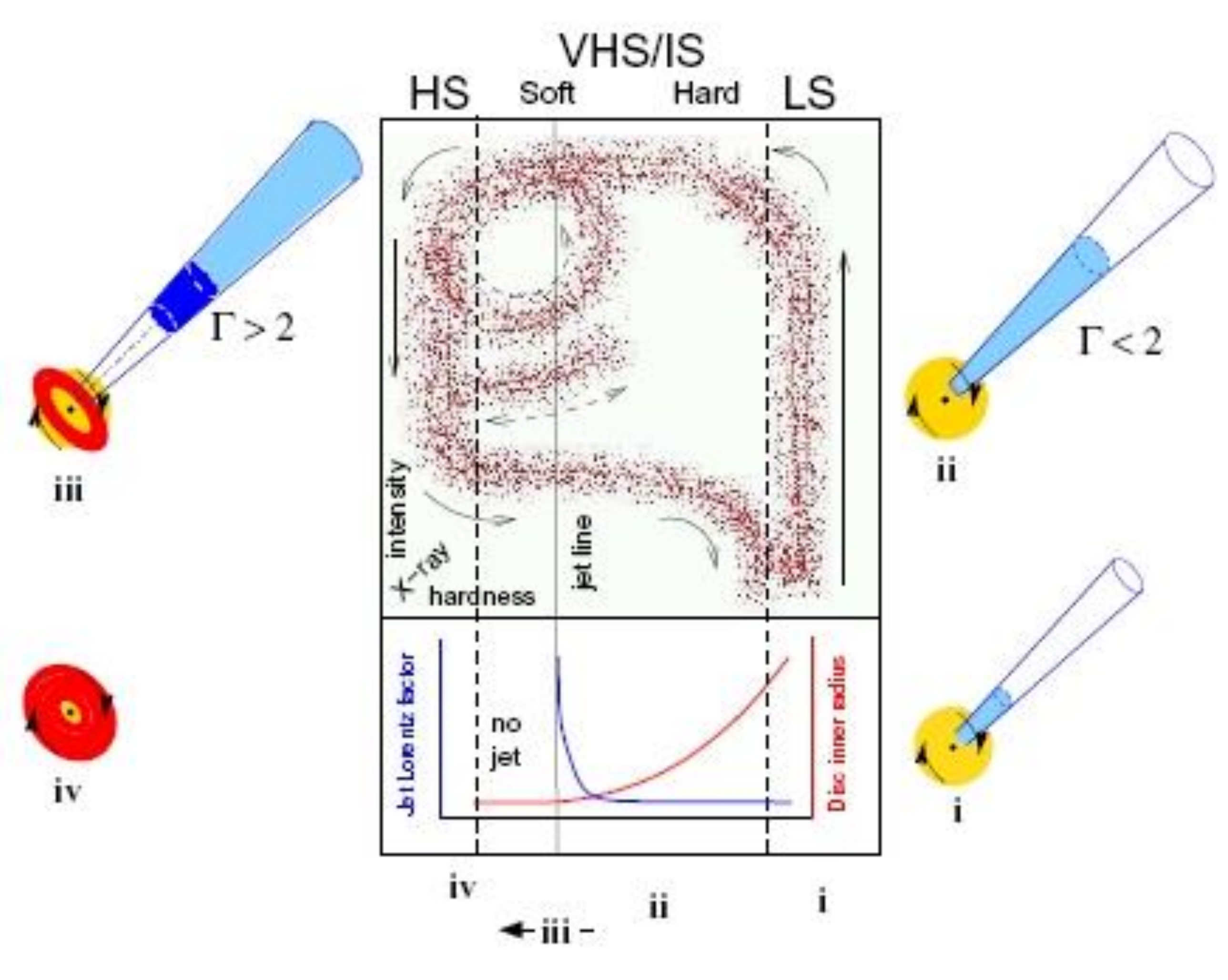
Table 2: Outburst states of black holes: nomenclature and definitions

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: $a^c_{\max} < 0.005$ 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.

(Remillard, McClintock astro-ph/0606352)

Discs and jets



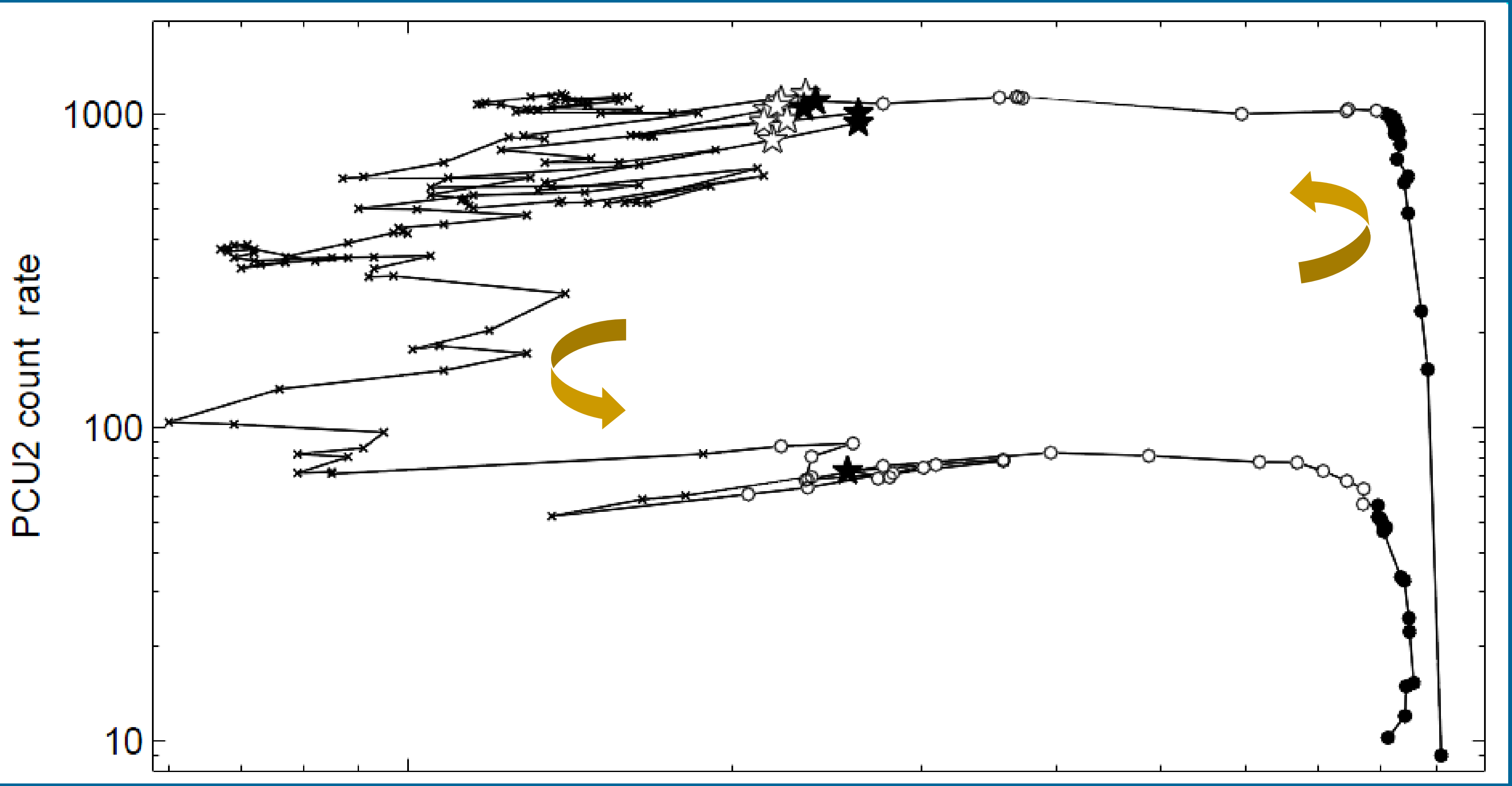
The model for systems with radio jets

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.

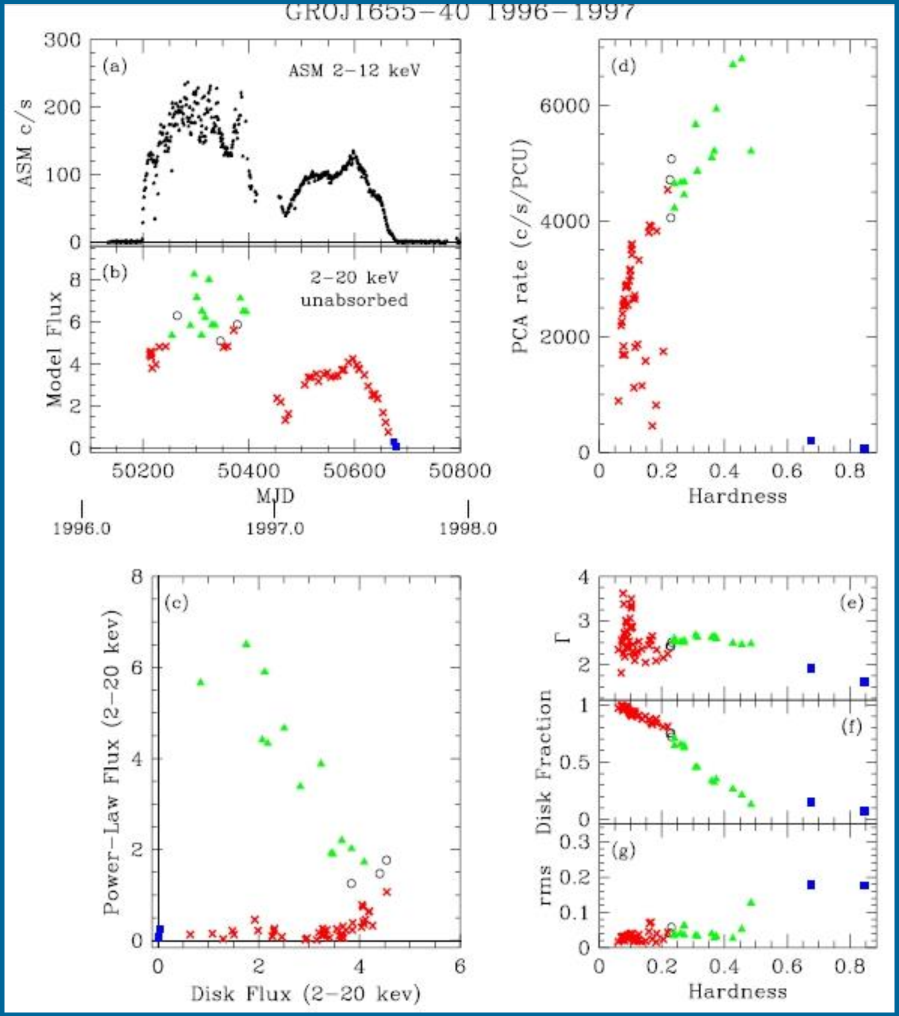
(Fender et al. 2004, Remillard, McClintock astro-ph/0606352)

Hardness vs. flux: state evolution



0909.2474

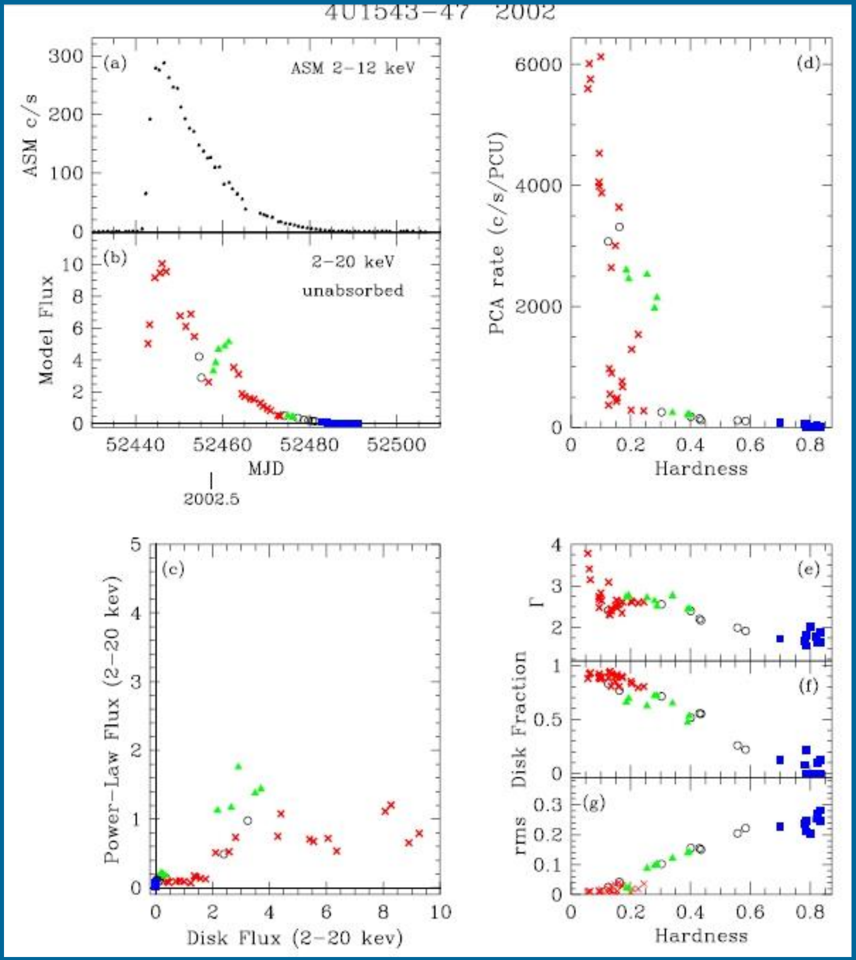
GRO J1655-40 during a burst

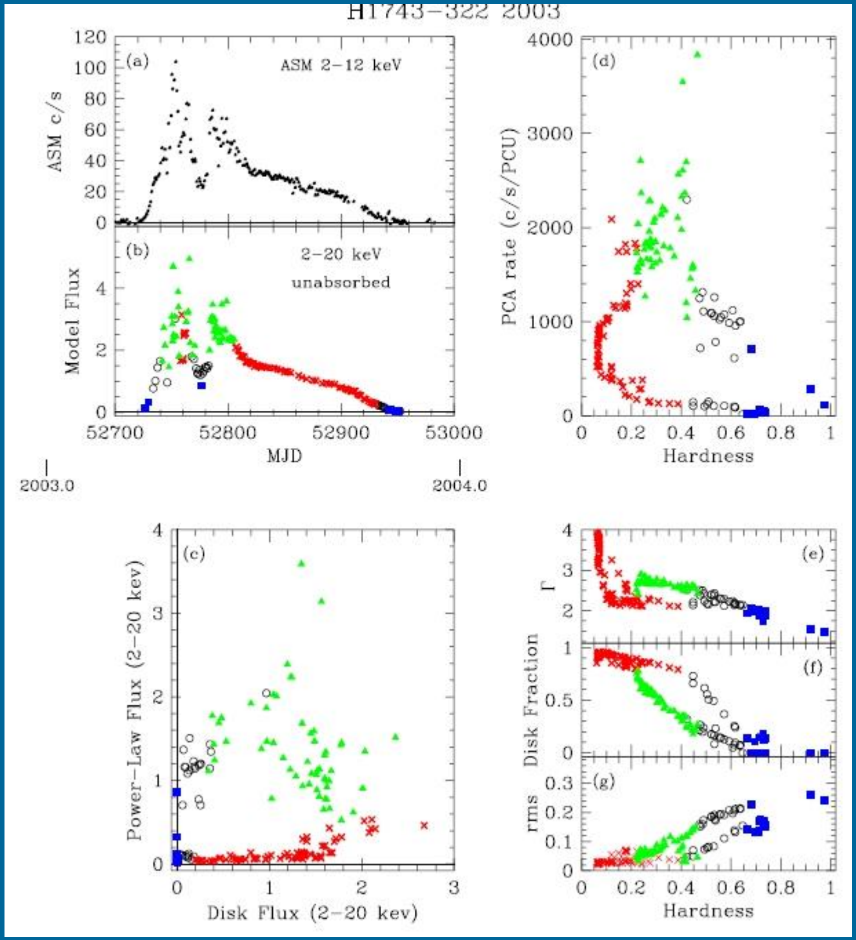


Red crosses – thermal state,
Green triangles – steep power-law (SPL),
Blue squares – hard state.

(Remillard, McClintock astro-ph/0606352)

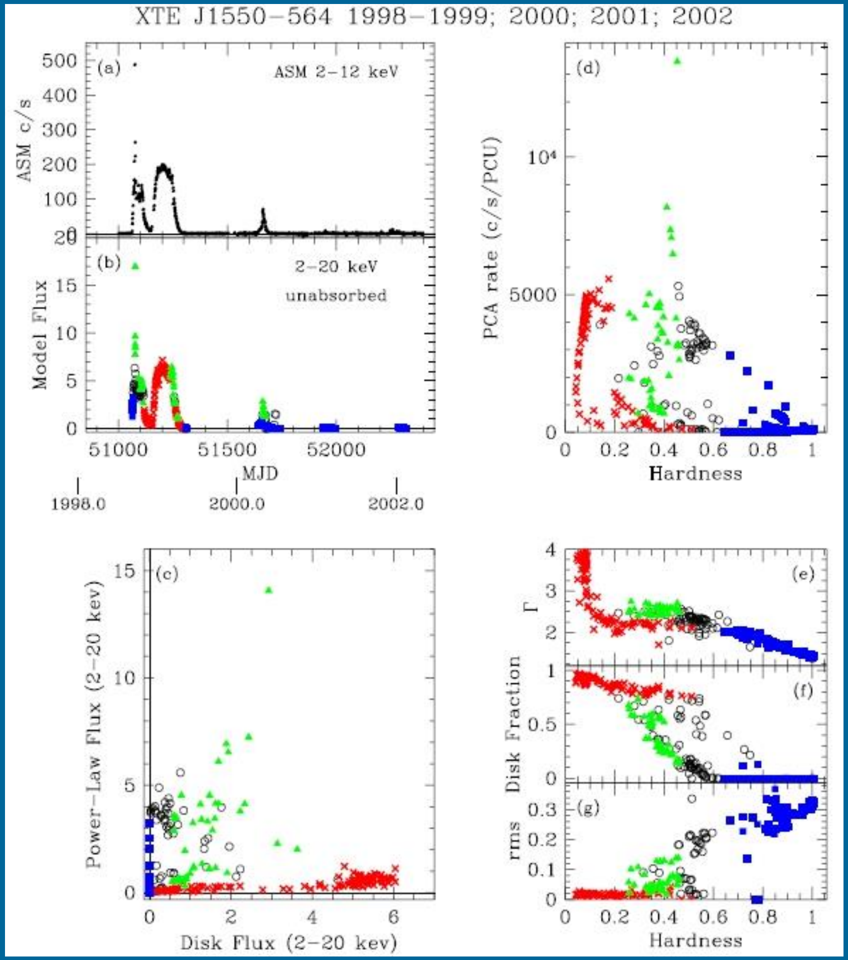
4U 1543-47 and H1743-322

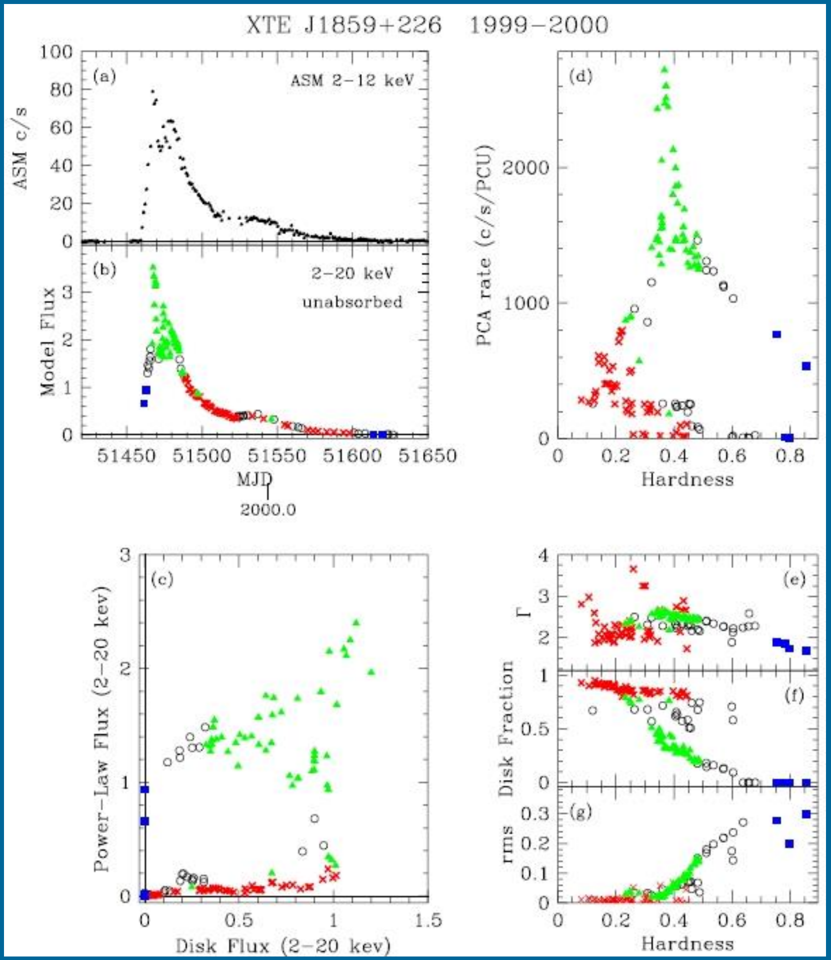




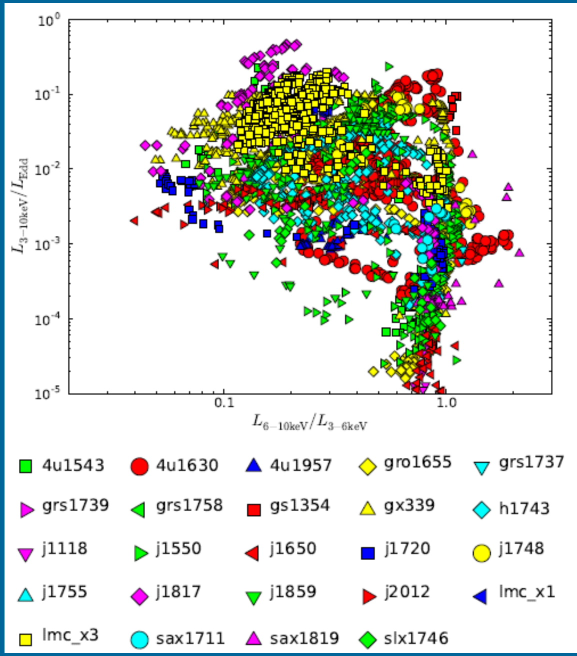
(Remillard, McClintock astro-ph/0606352)

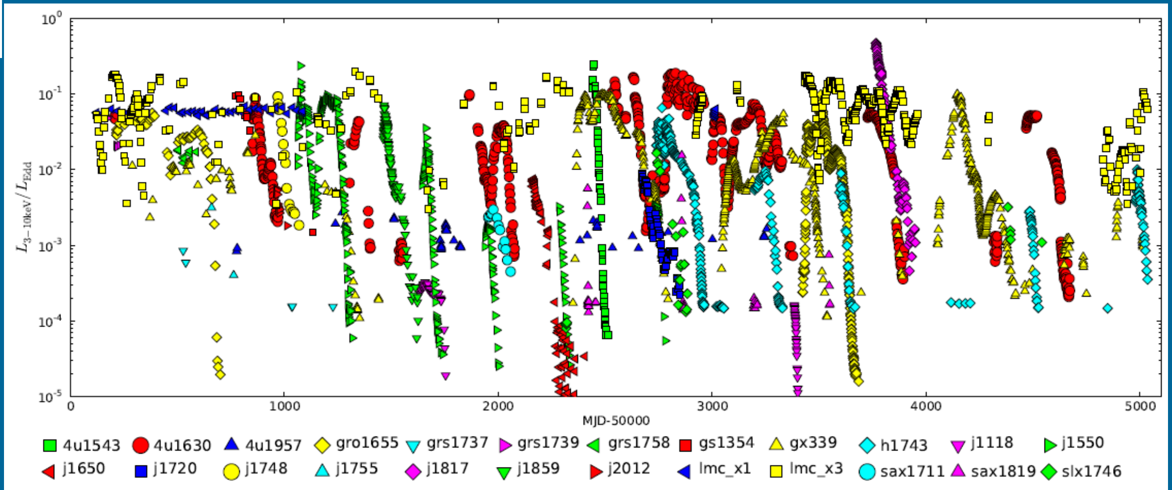
XTE J1550-564 and XTE J1859-226





Recent large set of data

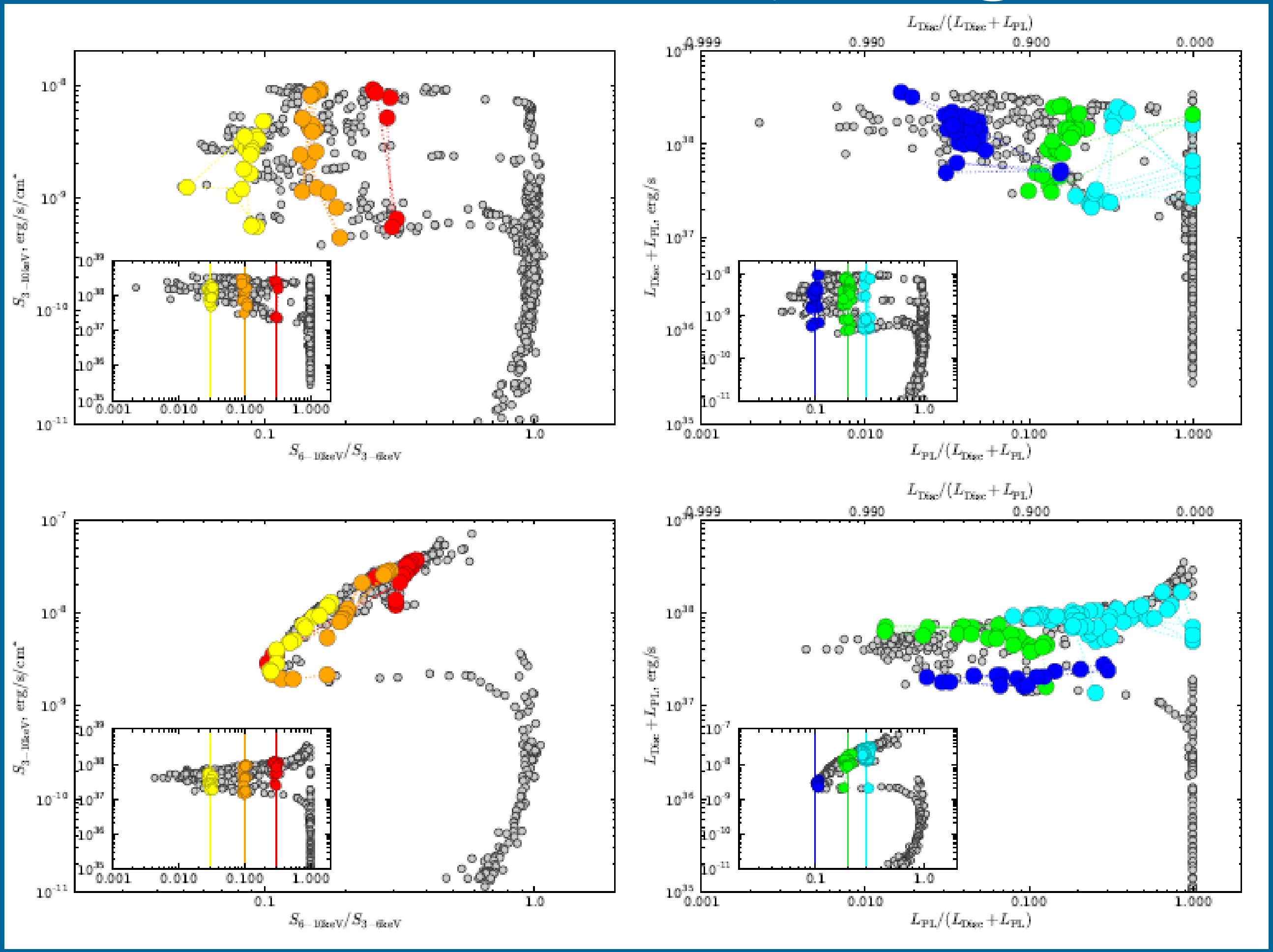




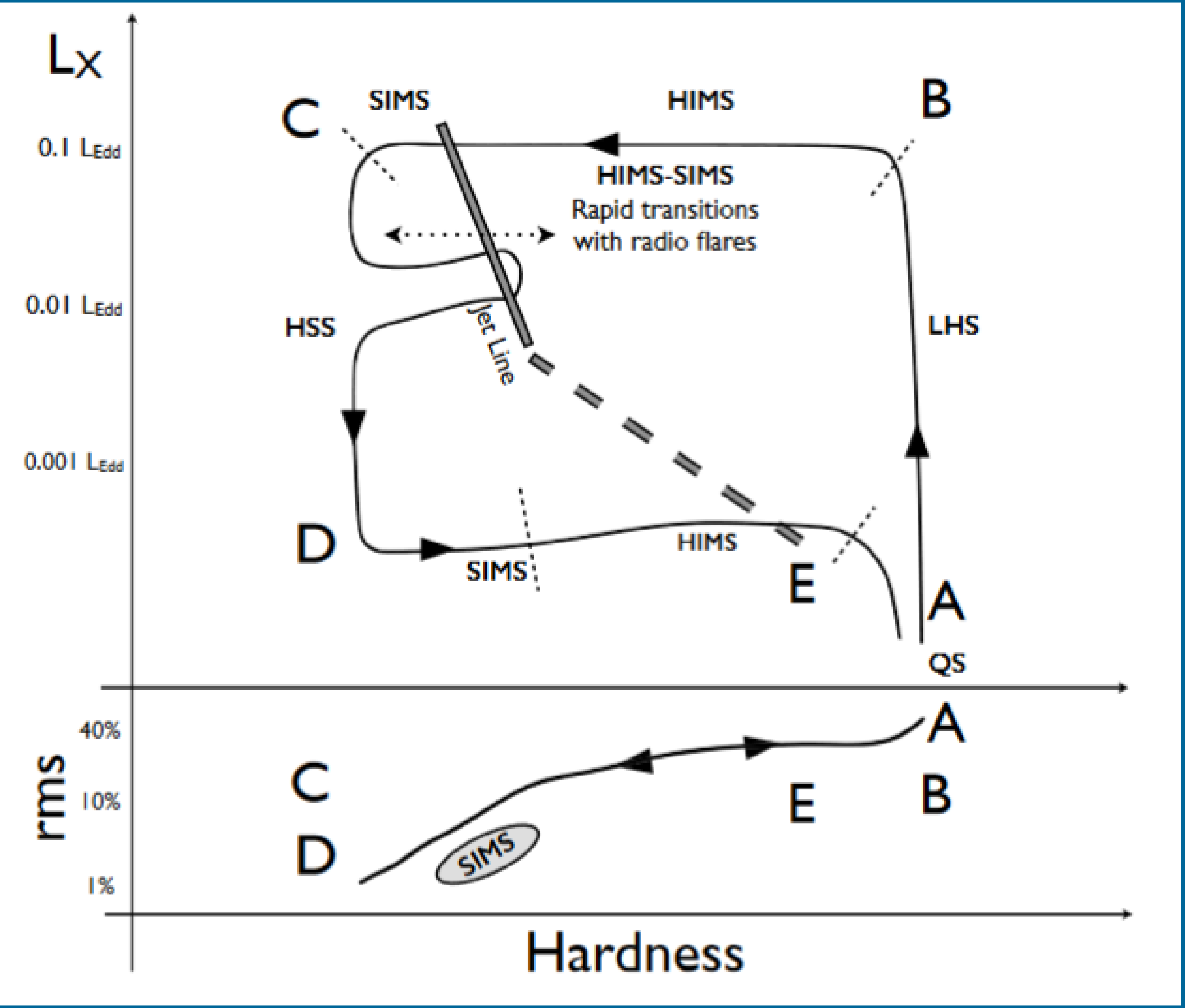
RXTE data
25 LMXBs

0912.0142

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



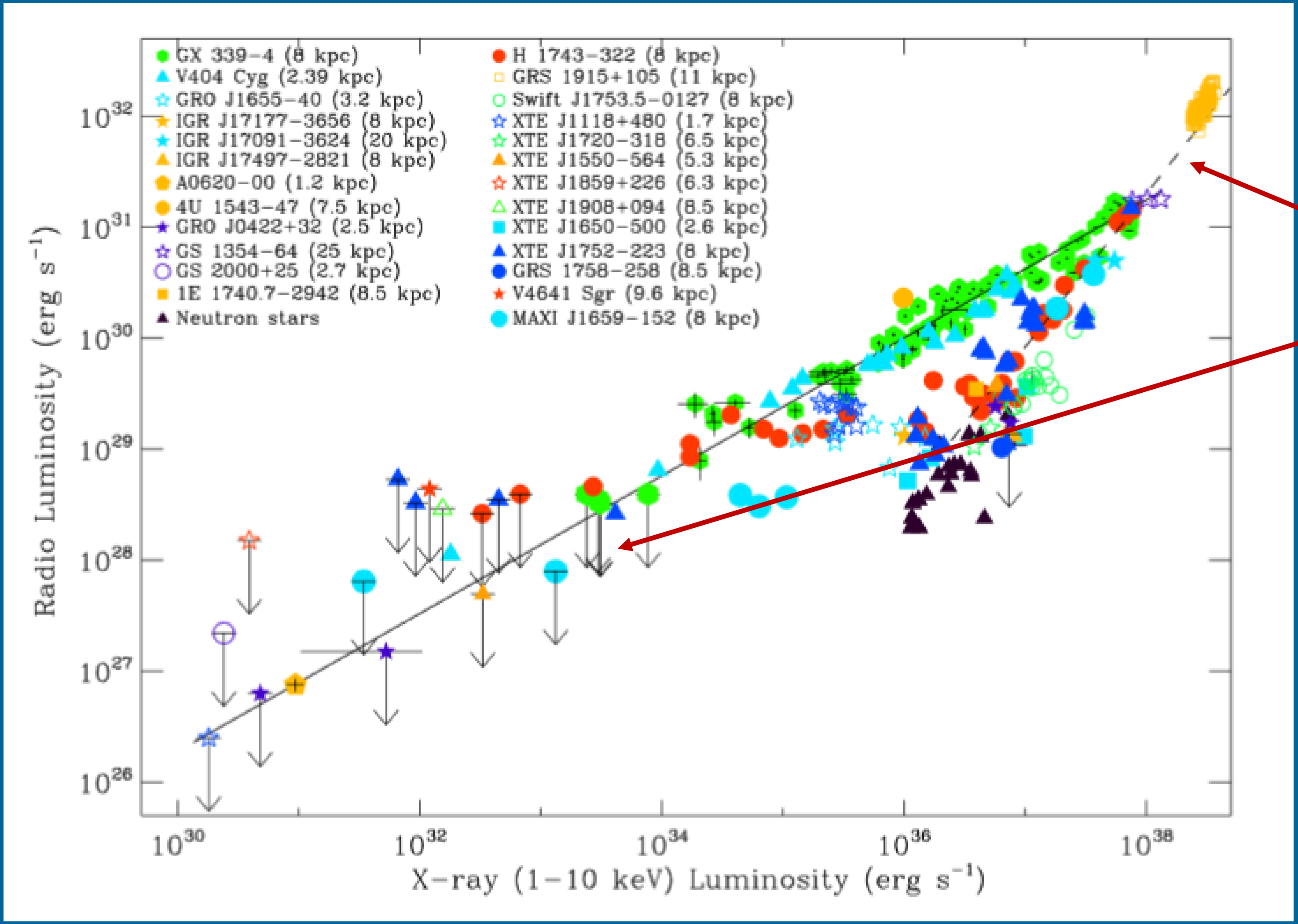
LEFT: HID with specific disc fractions highlighted
RIGHT: DFLD with specific X-ray colours highlighted.
The highlighted disc fractions are red 0.3, orange 0.1, yellow 0.03; and the highlighted X-ray colours are cyan 0.3, green 0.2, blue 0.1.
TOP: GX 339-4,
DOWN: GRO 1655-40



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

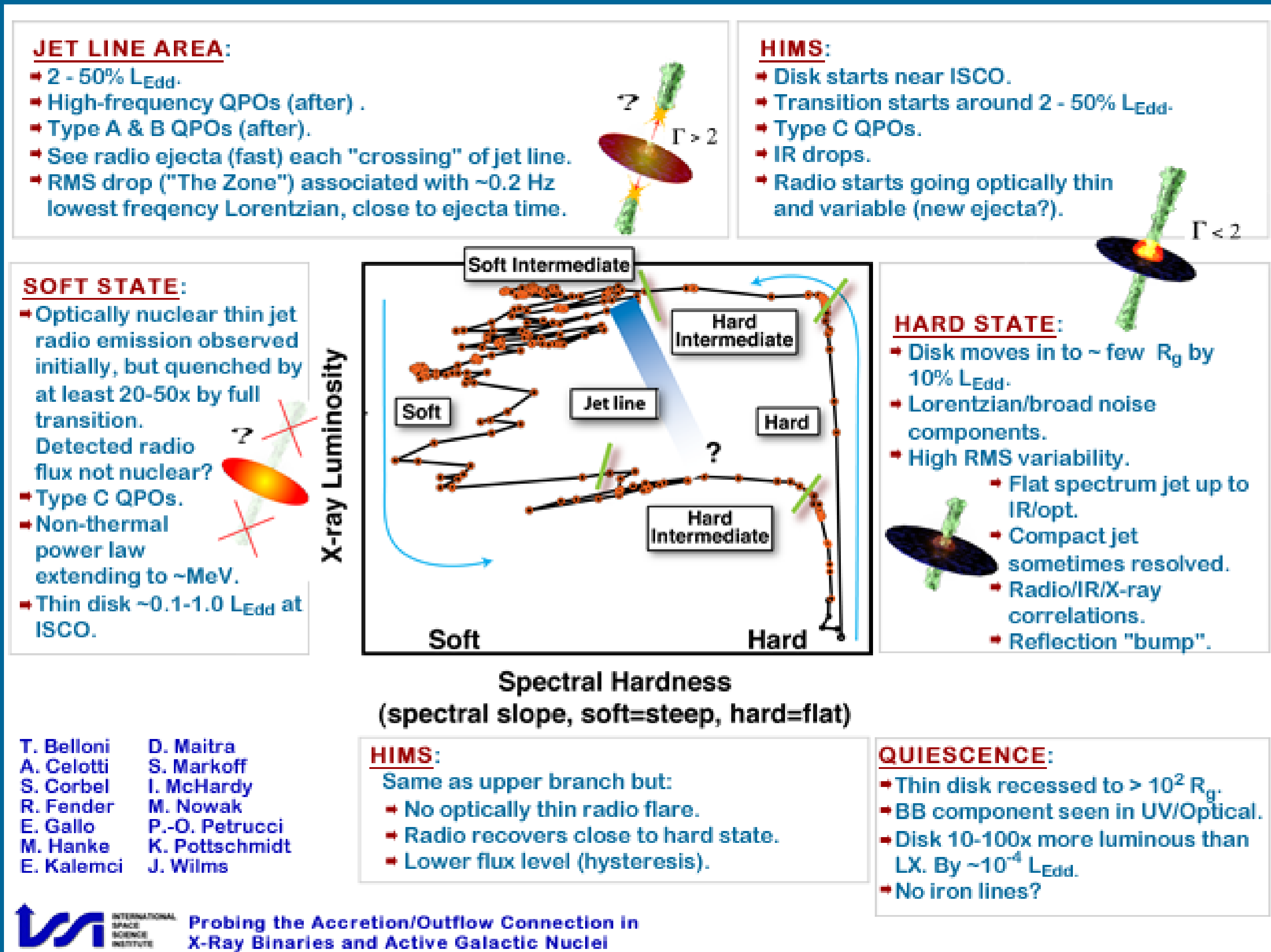
1603.07872

X-ray – radio correlation



1603.07872

Summary of states with jets in BH binaries



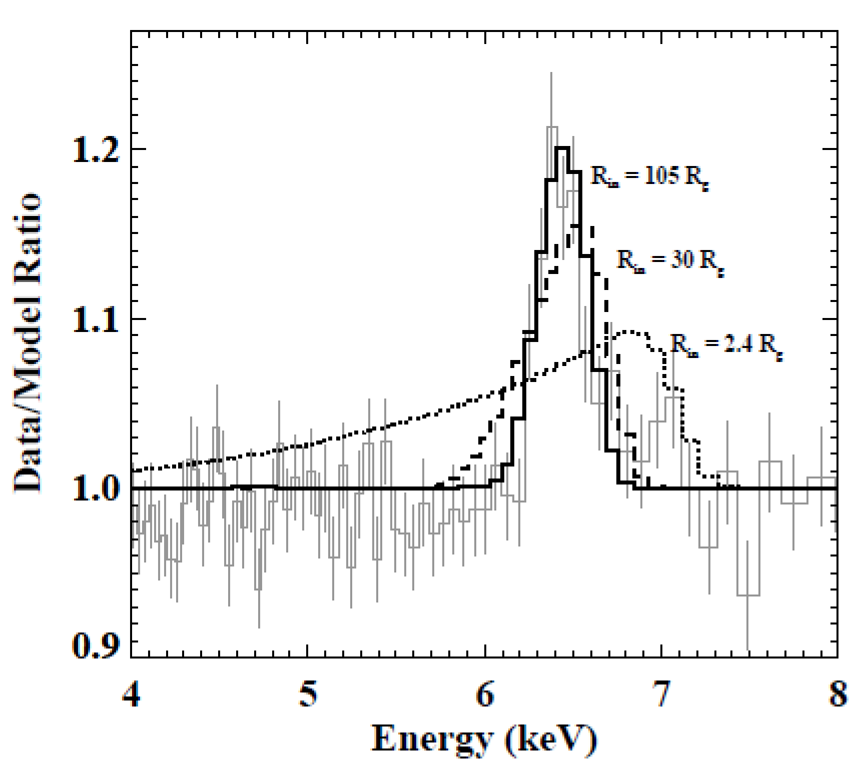
http://www.issibern.ch/teams/proaccretion/Images/newcomplete_72dpi.png

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.

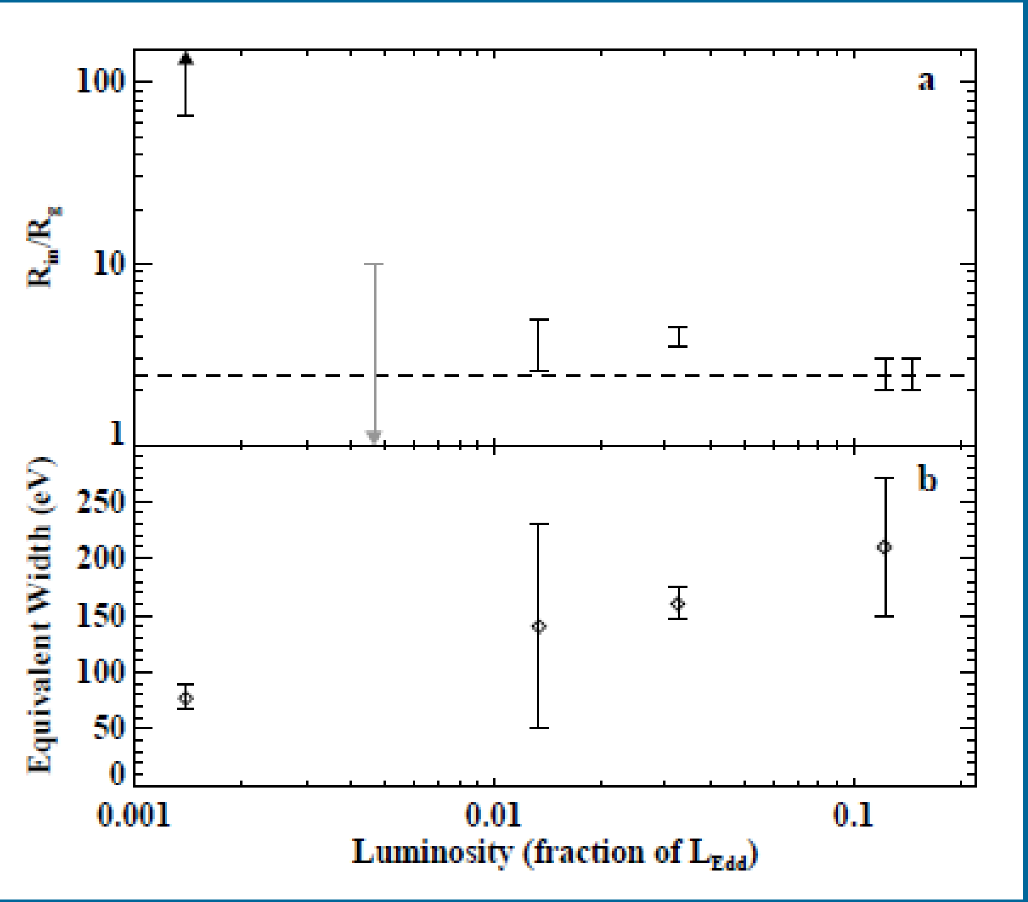


0911.2240

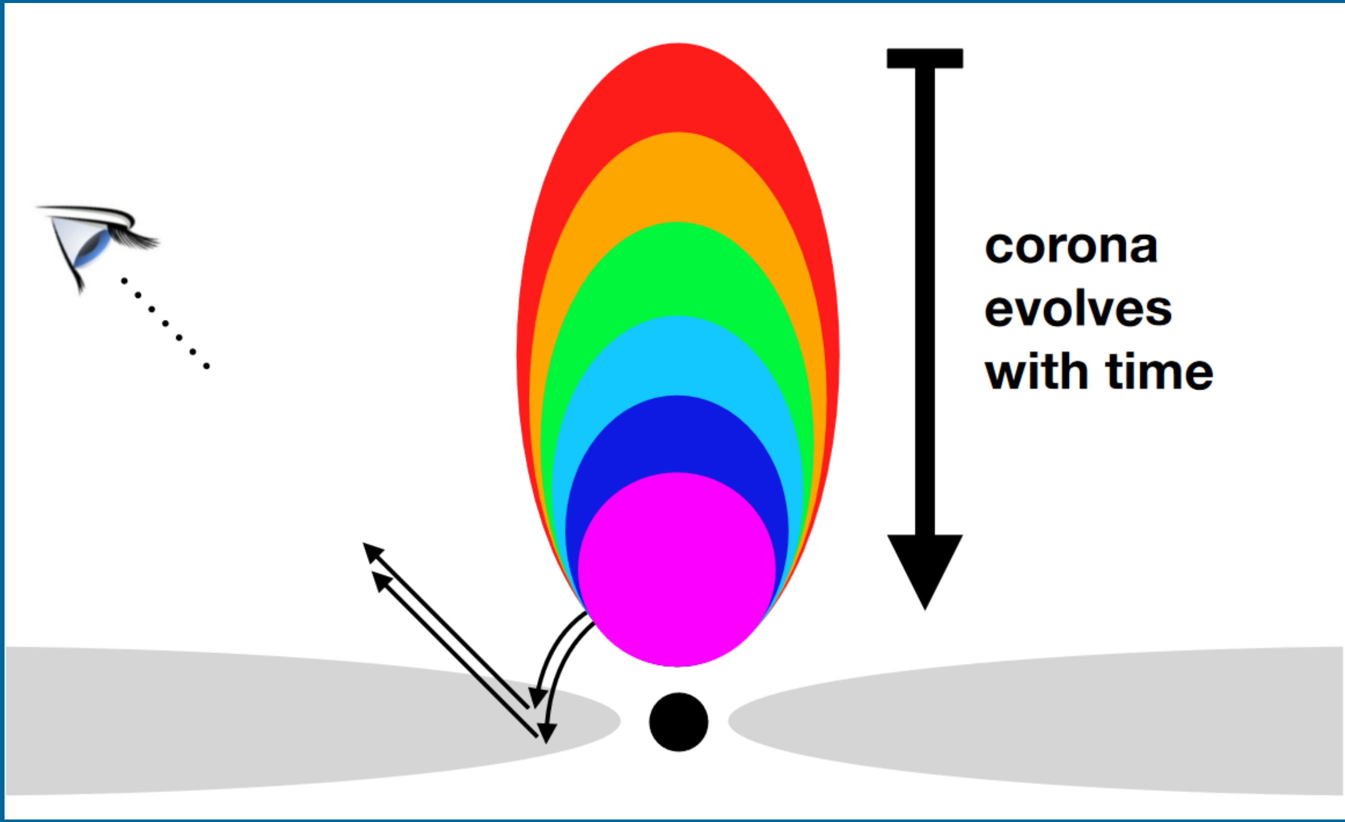
Inner disc boundary

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?

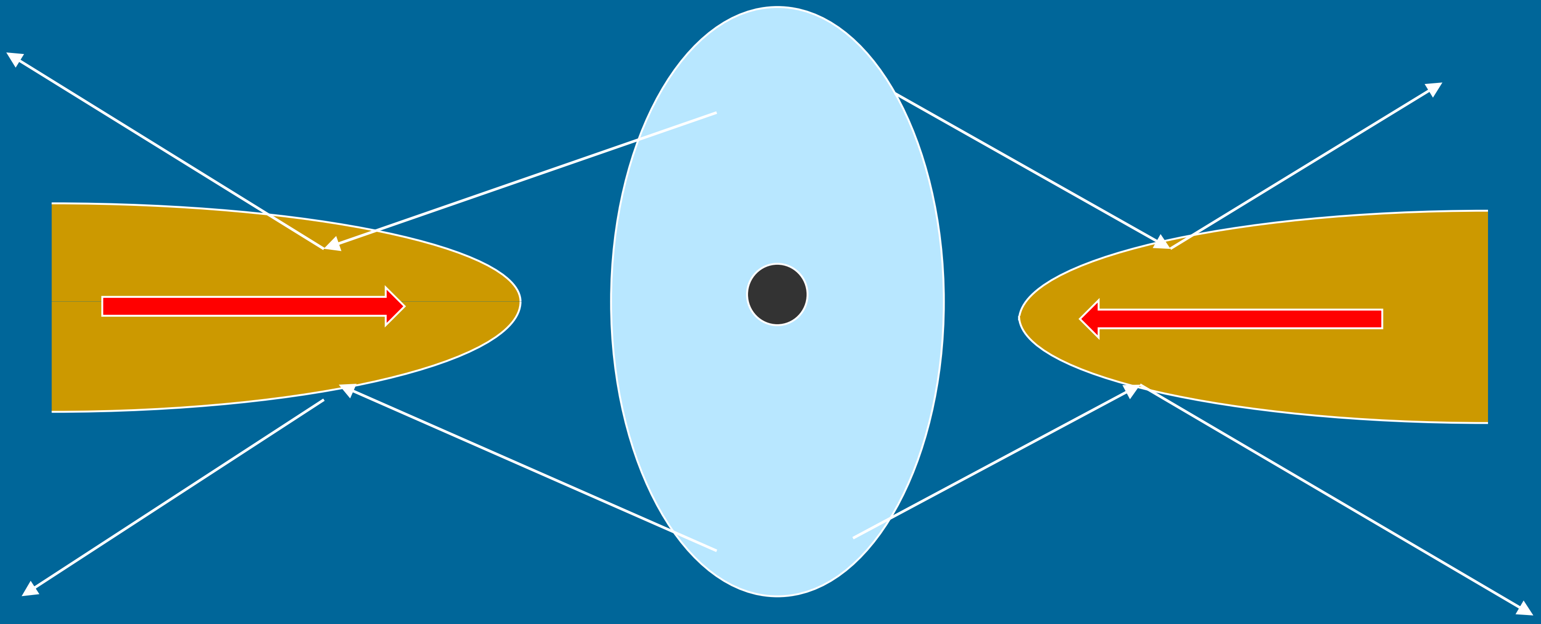


In the case of MAXI J1820+070 observations suggest that changes are mostly not due to modification of the inner disc radius, but due to changes in the hot corona size.
The result is based on time lags between corona and disc emission.

1901.03877

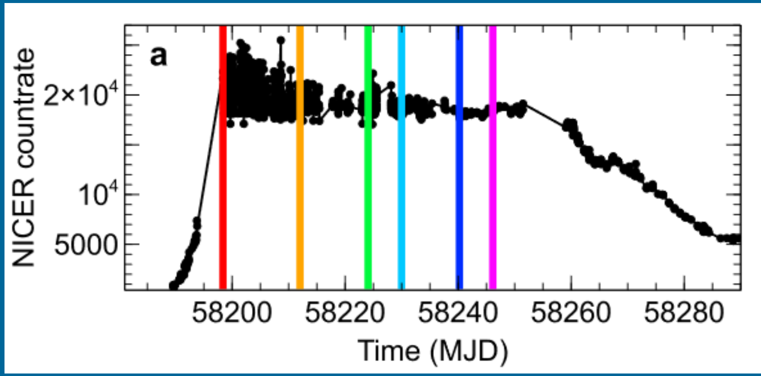
Scheme of time lags

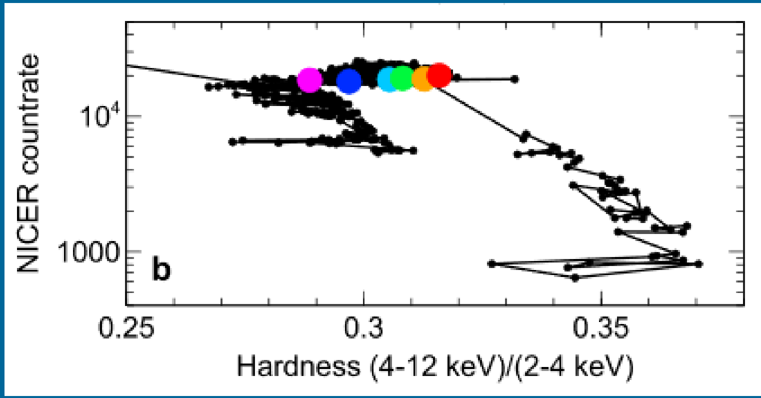
Low-frequency hard lags (soft before hard)
is due to propagation of disturbances in the disc

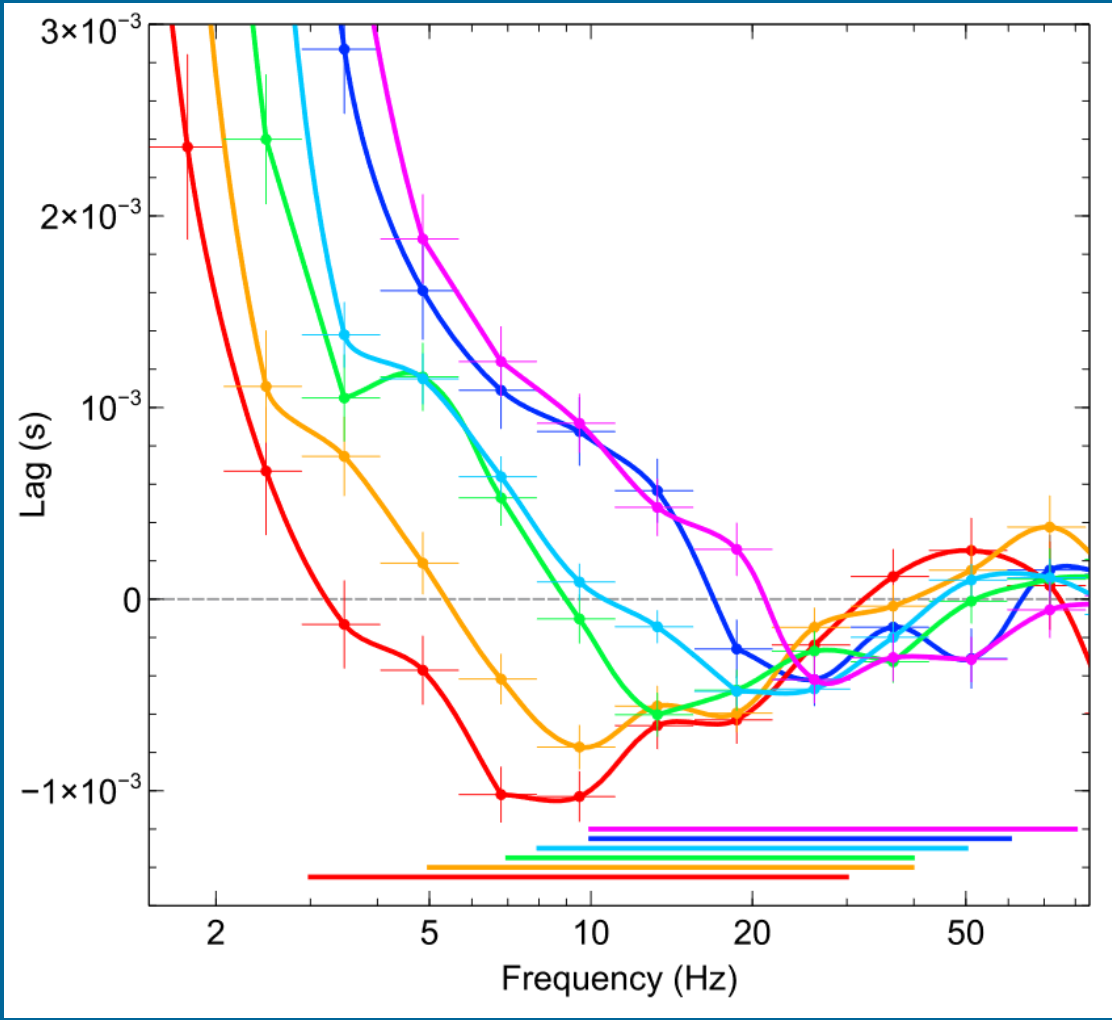


High-frequency soft lag (hard before soft) is due to irradiation of the disc by corona

Hard lags and soft lags

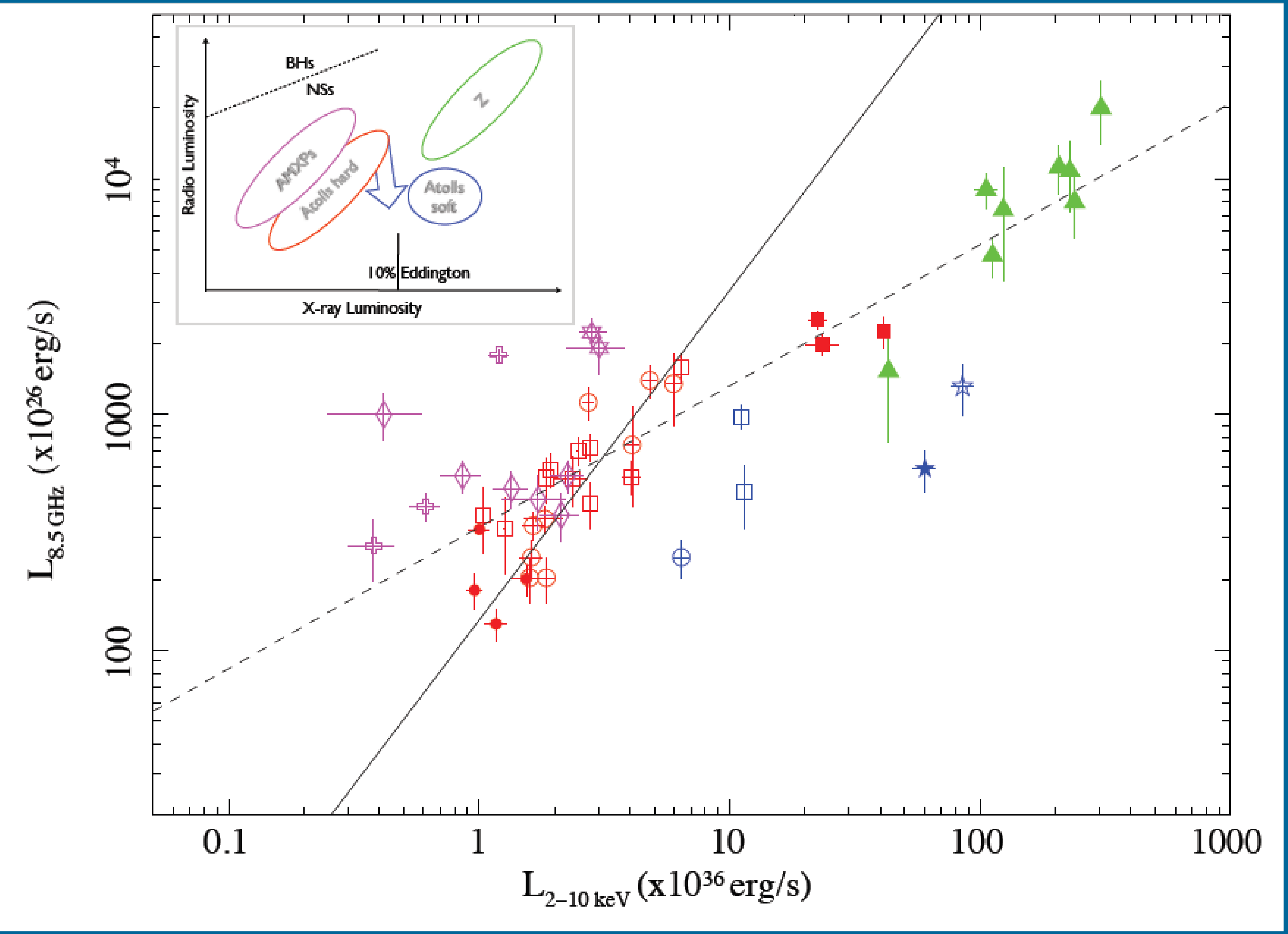






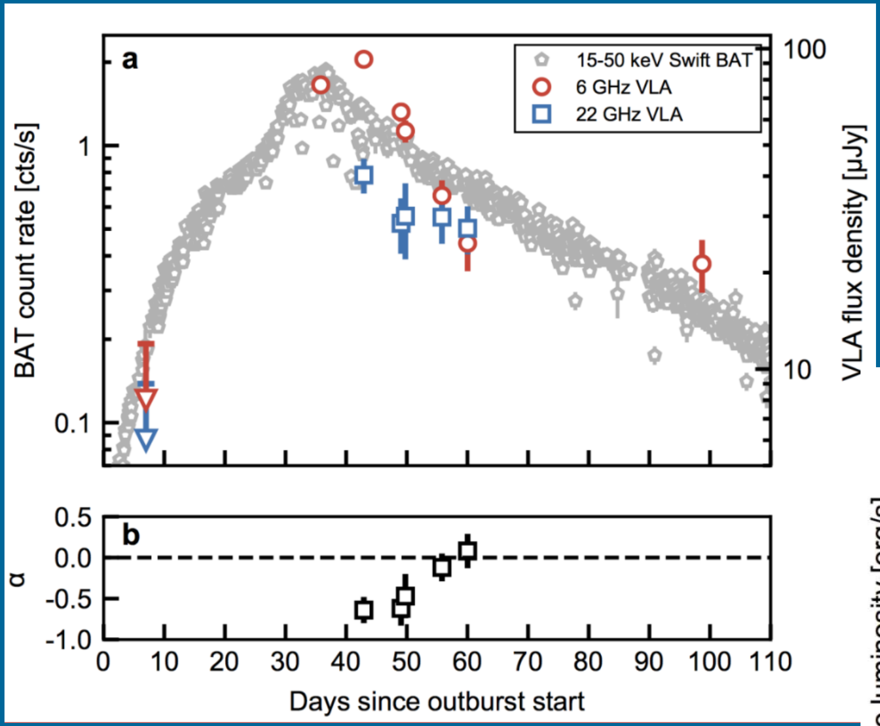
1901.03877

NS jets

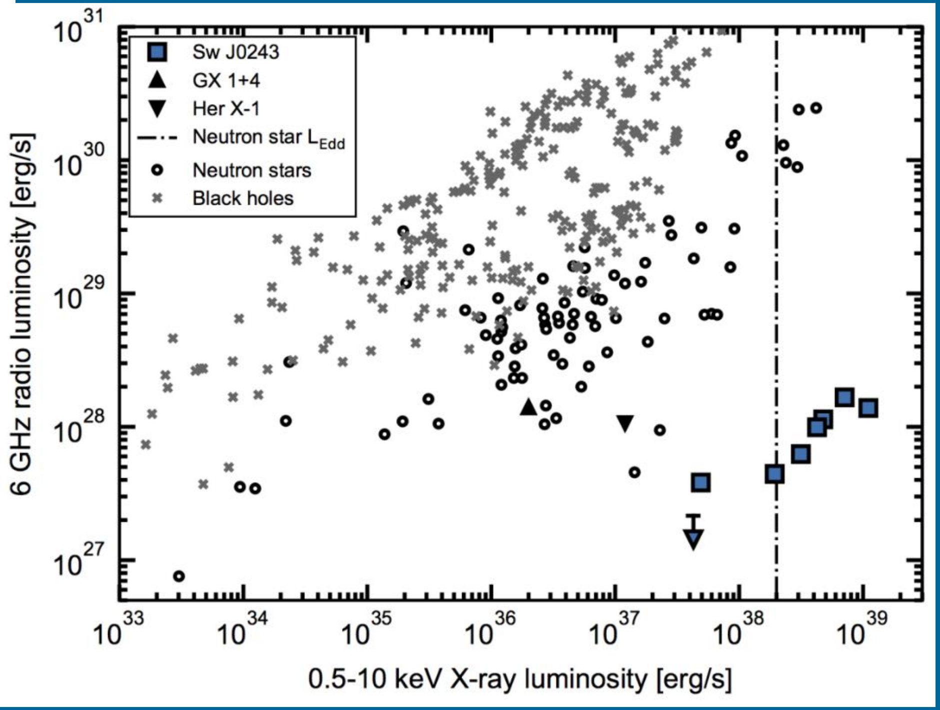


1104.1115

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.



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

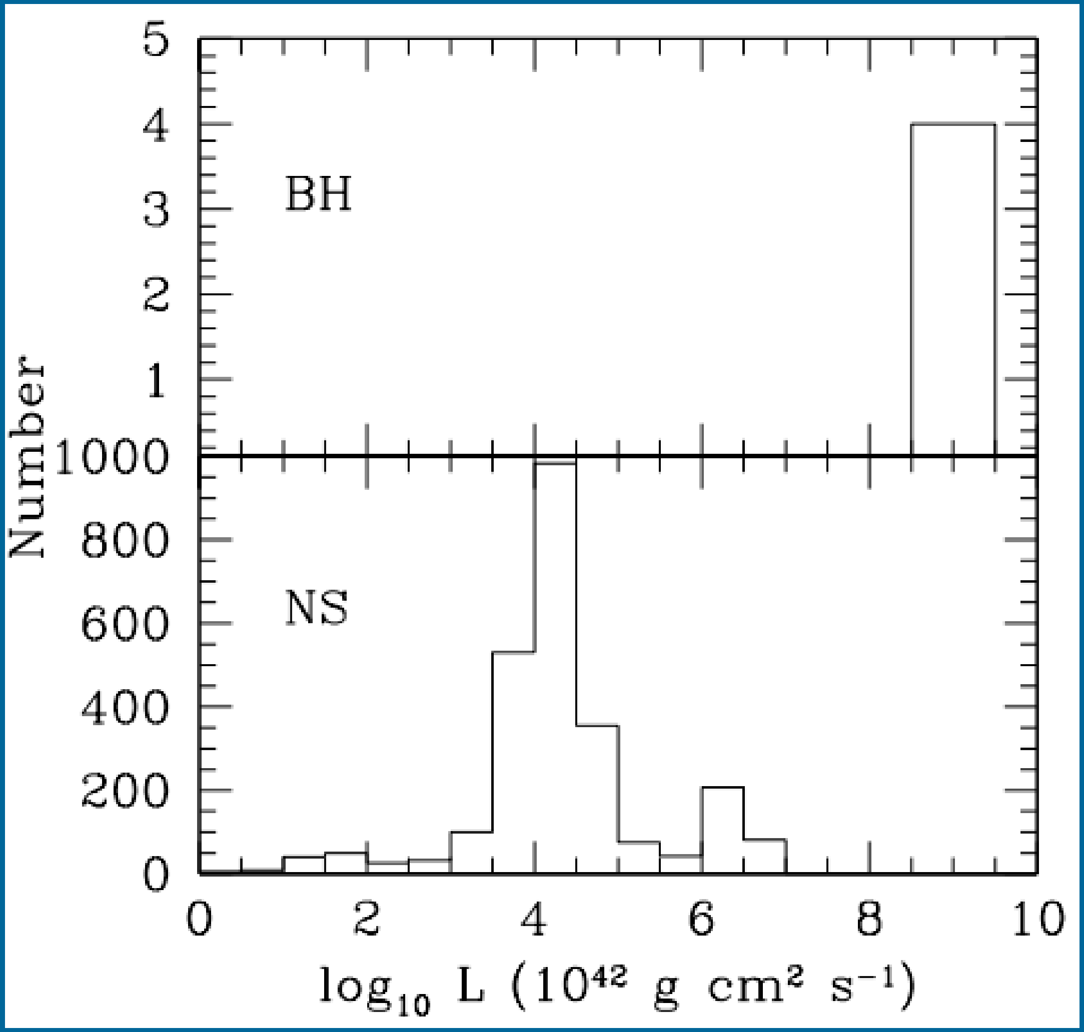
1809.10204

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 Jet
- 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

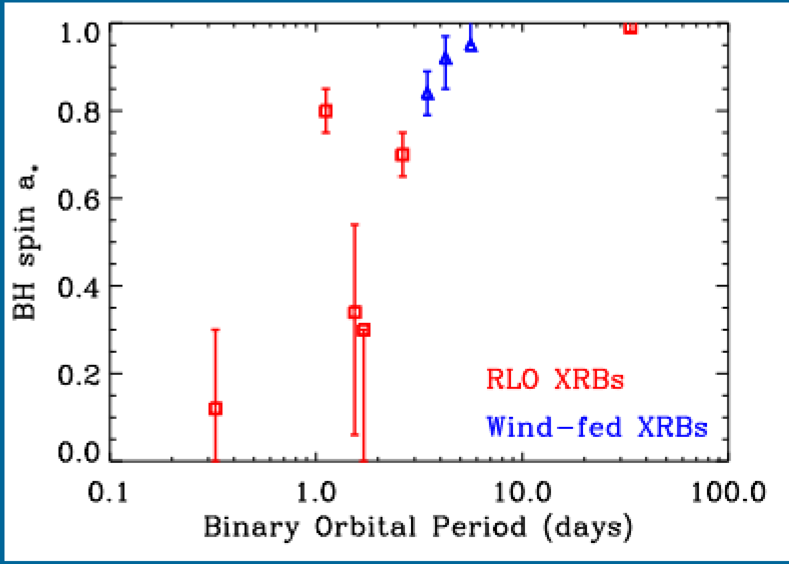
NSs vs. BHs



BHs win!!!!!
They do not loose momentum.

1408.4145

Origin of BH spin



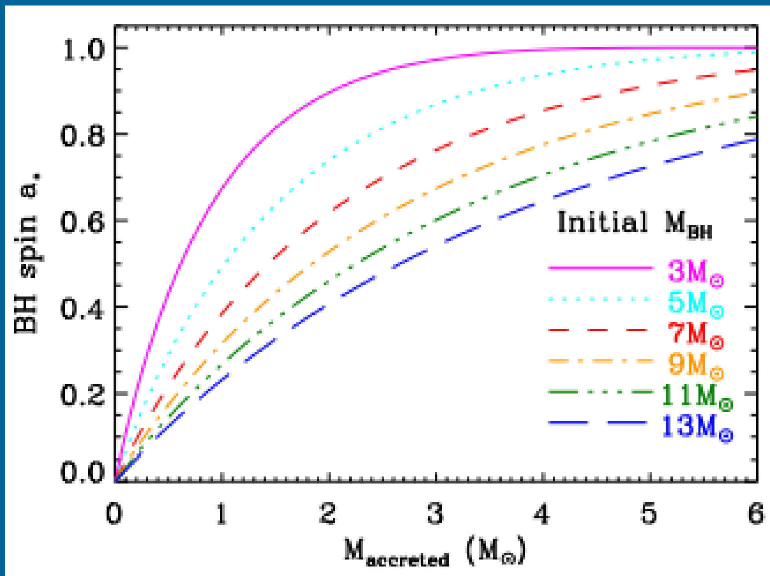
Spin is due to accretion.

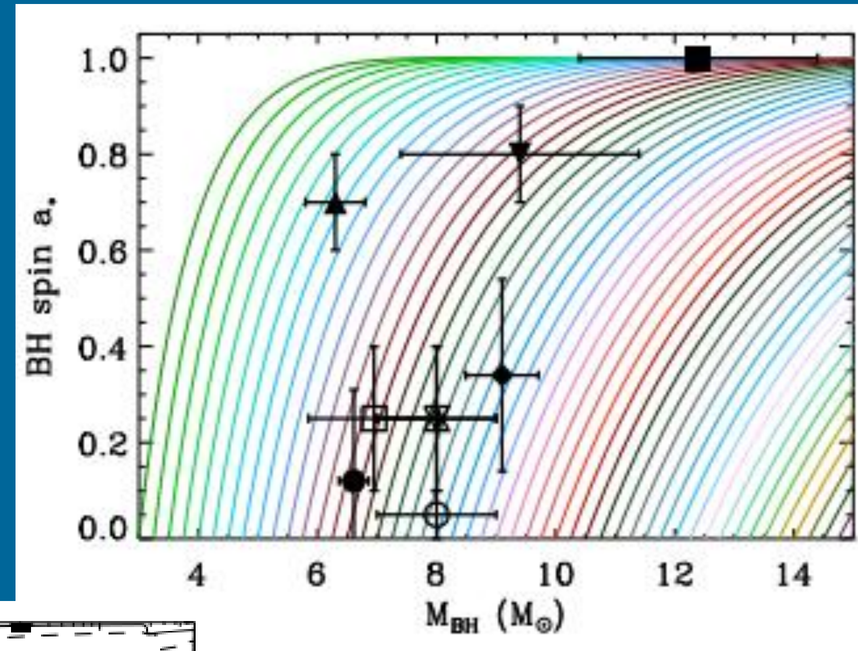
BHs accrete (on average) ~1.5 solar mass

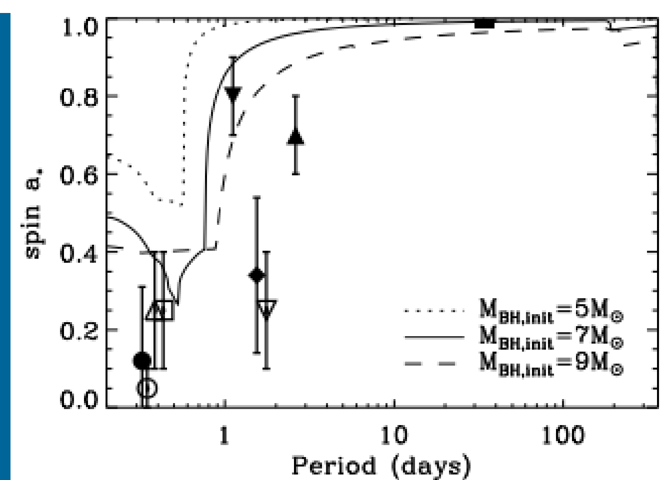
Source	MT Type[b]	P_{orb} (days)[b]	Spin a_*	Reference
GRS 1915+105	RLO	33.5	> 0.98	McClintock et al. (2006)
Cyg X-1	Wind	5.6	> 0.95	Gou et al. (2011)
LMC X–1	Wind	4.23	$0.92^{+0.05}_{-0.07}$	Gou et al. (2009)
M33 X–7	Wind	3.45	0.84 ± 0.05	Liu et al. (2008, 2010)
4U 1543–47	RLO	1.15	0.80 ± 0.05	Shafee 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)

1408.2661

Spin (and mass) growth due to accretion







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

1408.2661

QPO

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

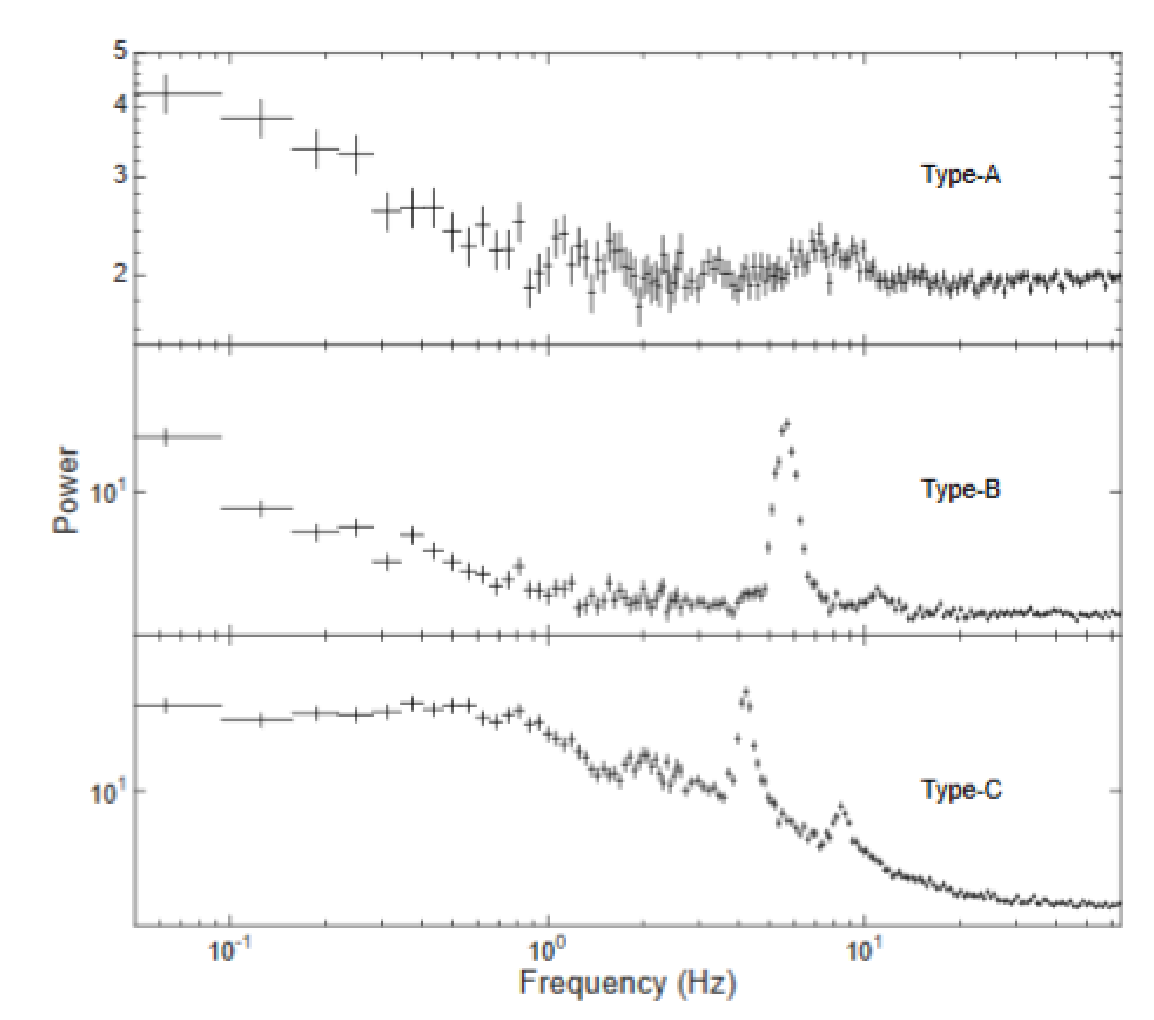
Low-frequency QPOs are found in 14 out of 18 objects.
They are observed during different states of sources.
Probably, in different states different mechanisms of QPO are working.

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



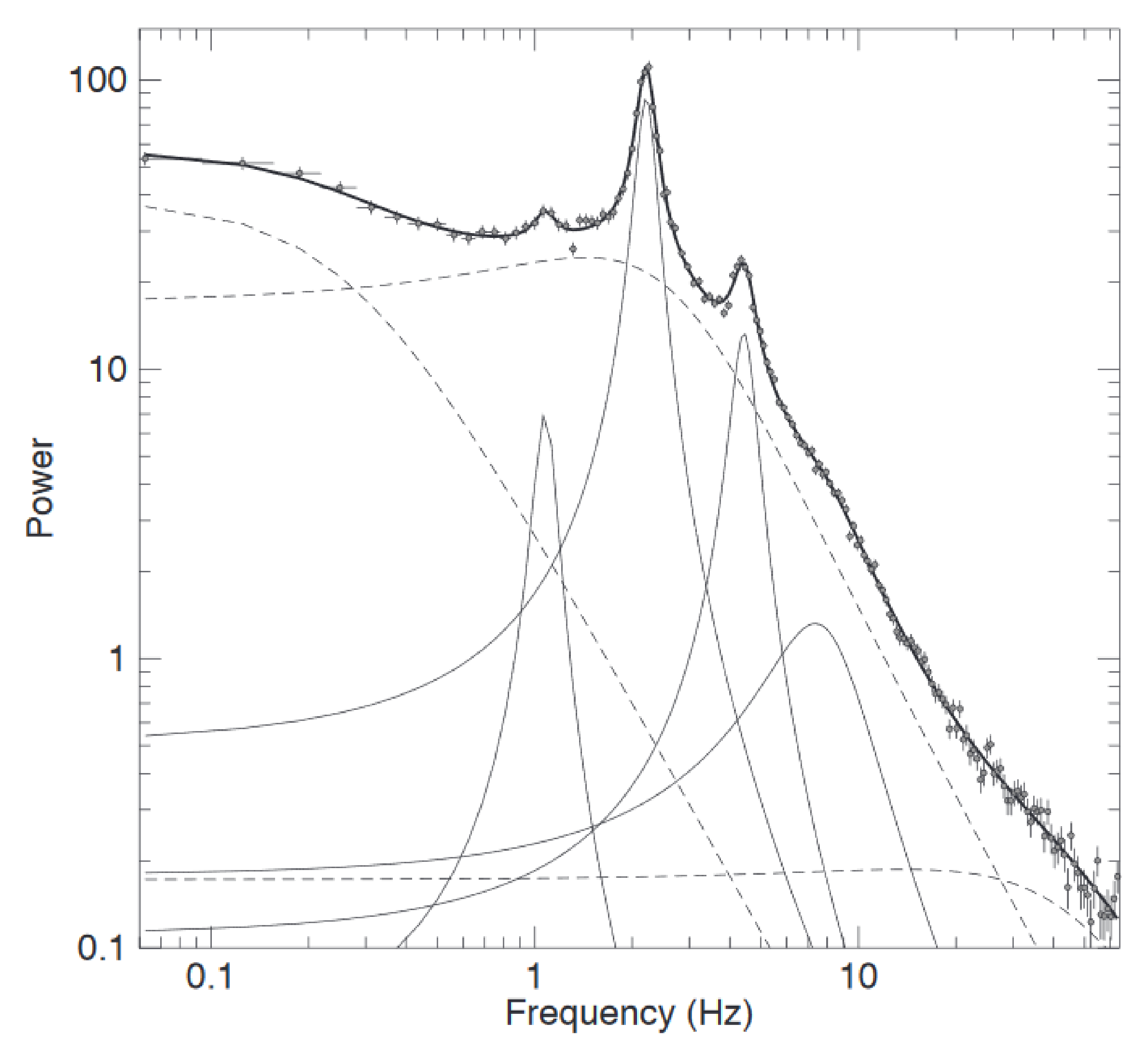
Disc instabilities ?

Jets?

Disc instabilities ?

1603.07885

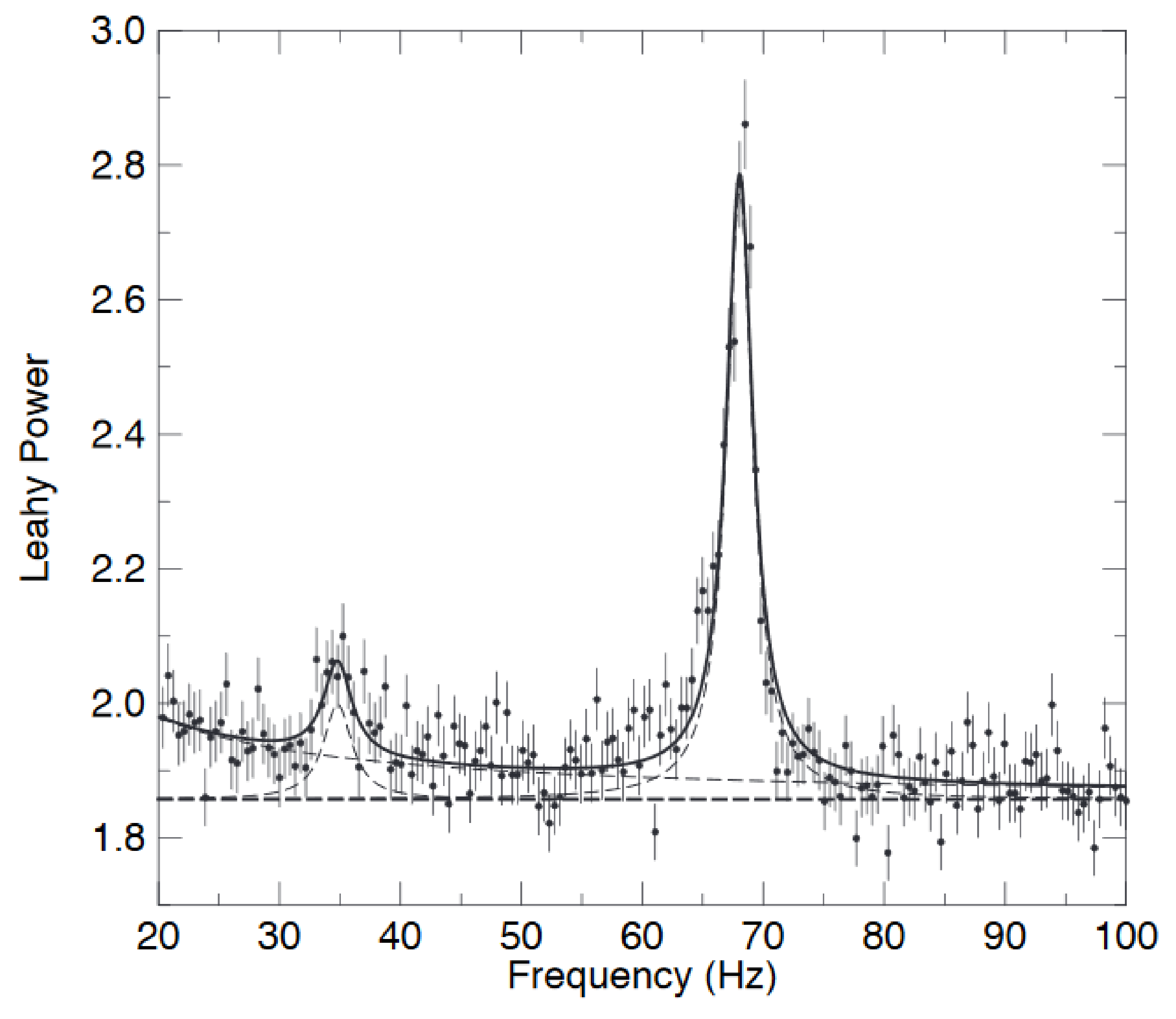
GRS 1915+105



Low-frequency QPO

1902.06586

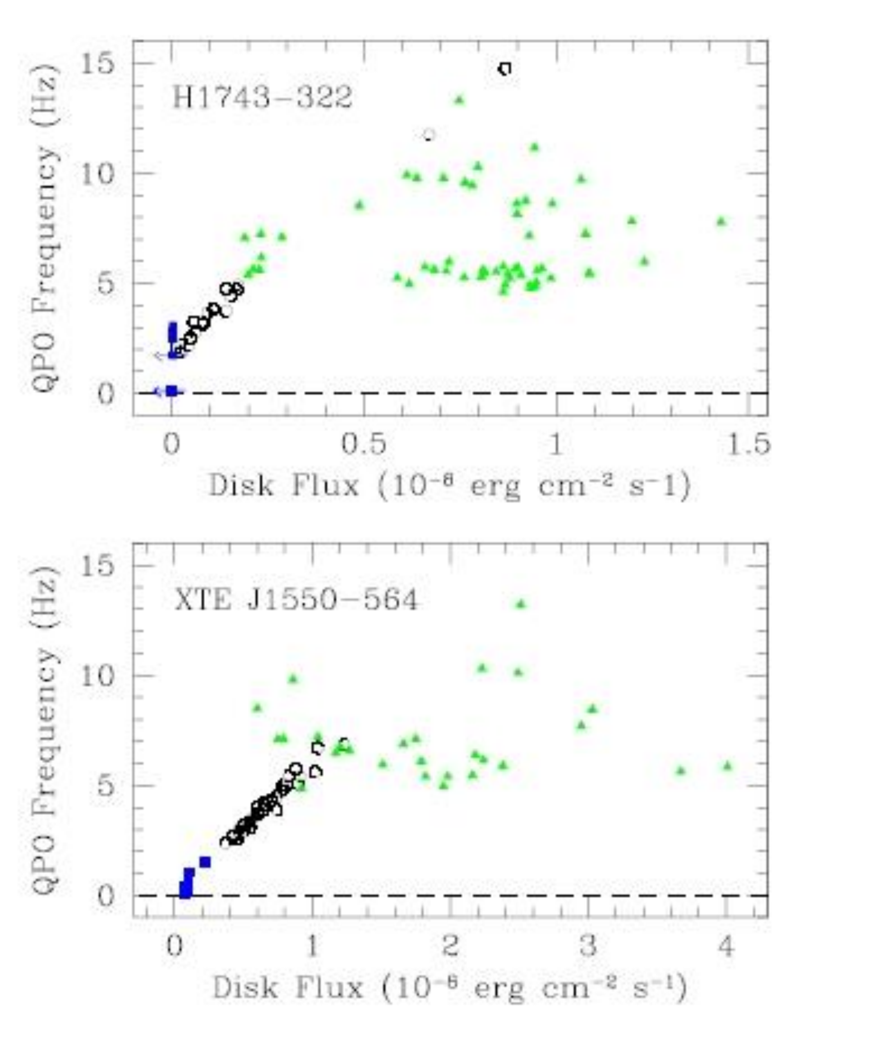
GRS 1915+105



High-frequency QPO

1902.06586

QPO and flux from a disc



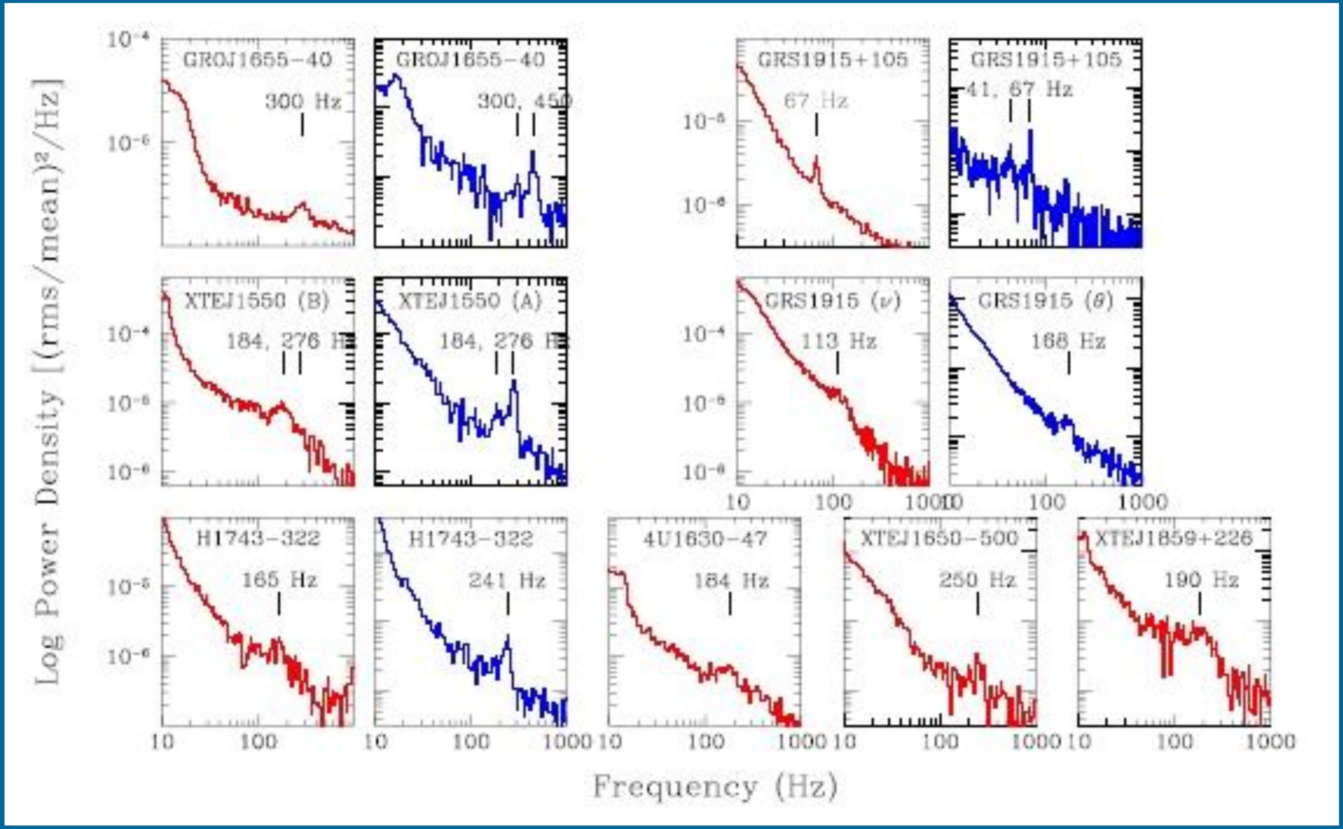
SPL – green triangles
Hard – blue squares
Intermediate states – black circles

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.

(Remillard, McClintock astro-ph/0606352)

QPO at high (for BHs) frequency

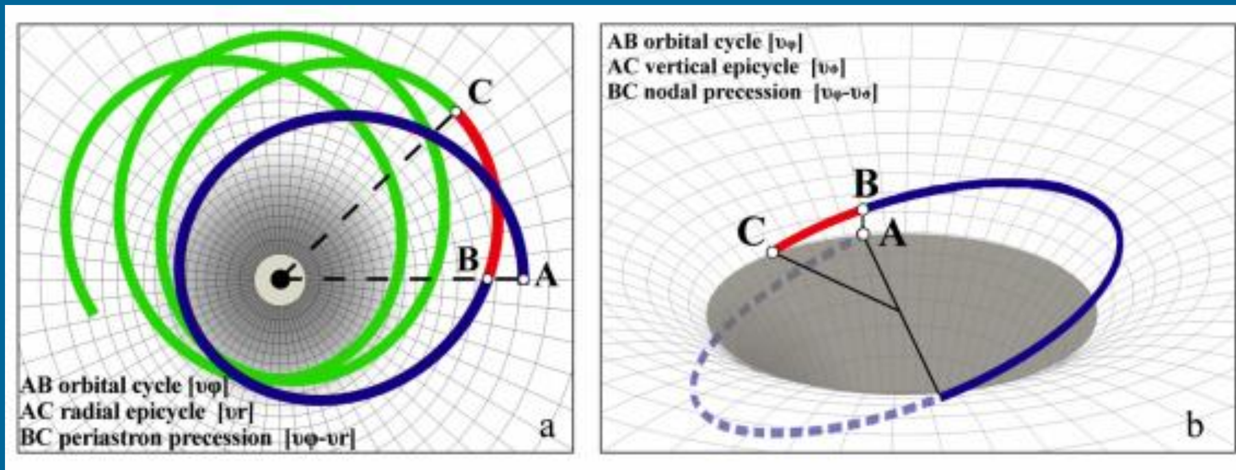


All QPO at >100 Hz are observed only in the SPL state.

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

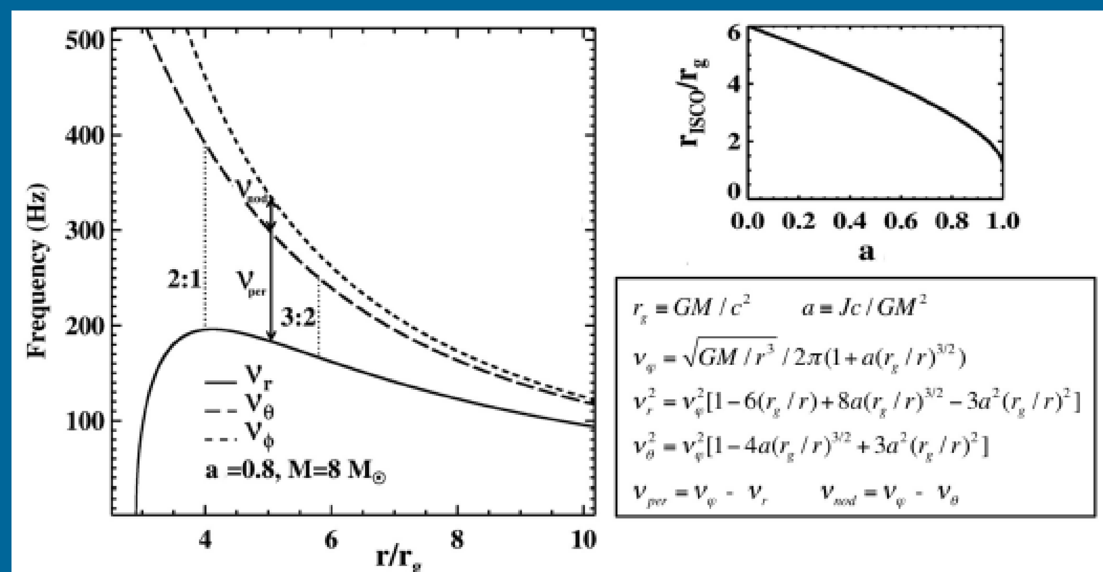
(Remillard, McClintock astro-ph/0606352)

Possible interpretations



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

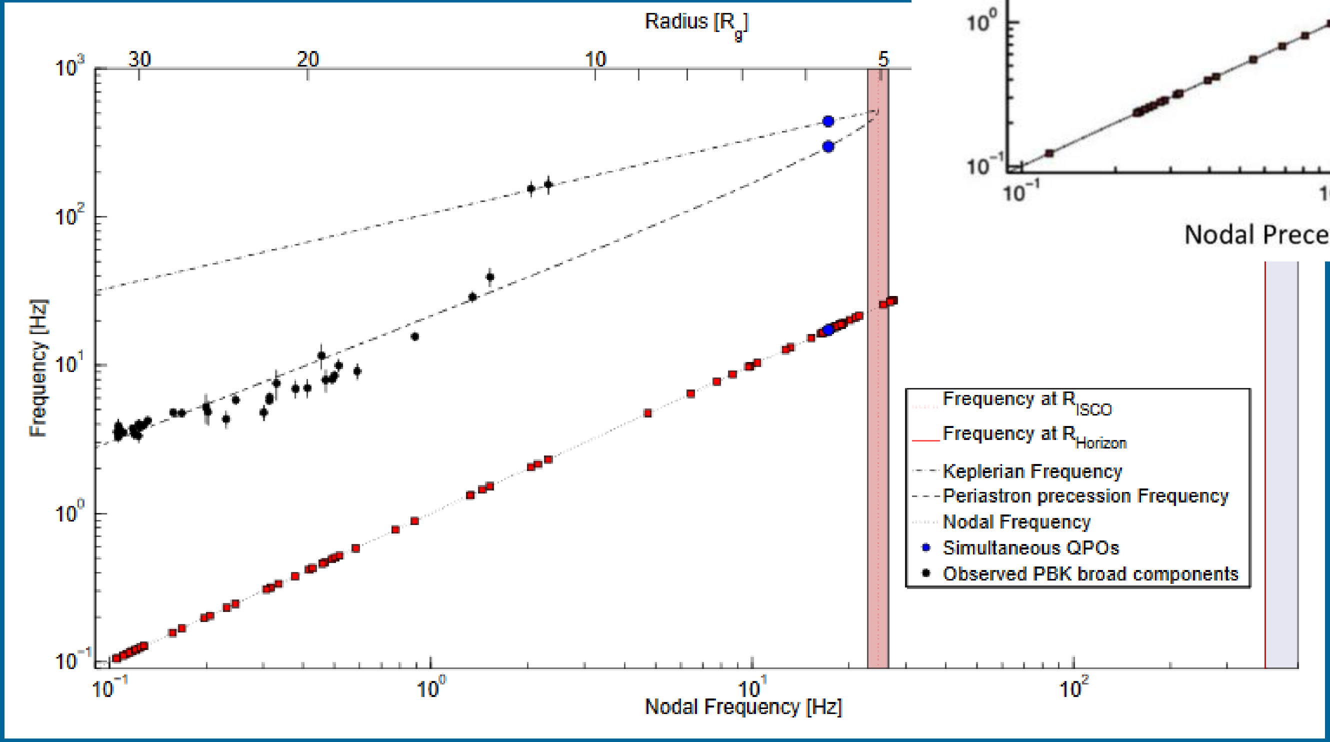
perianstron precession frequency $v_\varphi - v_r$
nodal precession frequency v_φ - v_θ

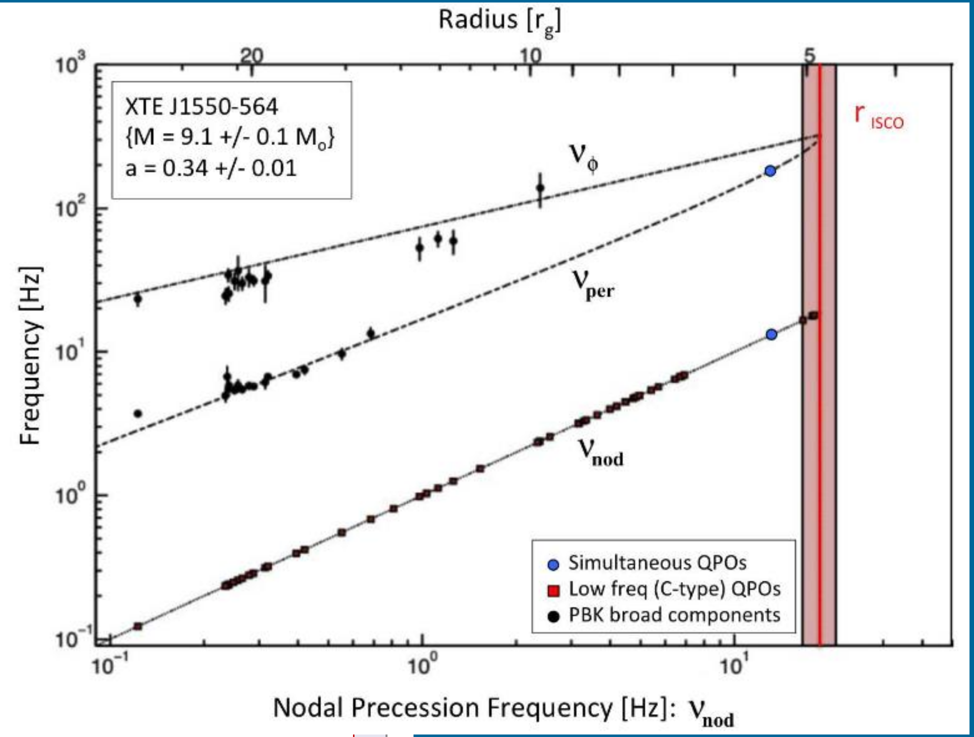


1407.7373

Correlations

GRO J1655-40

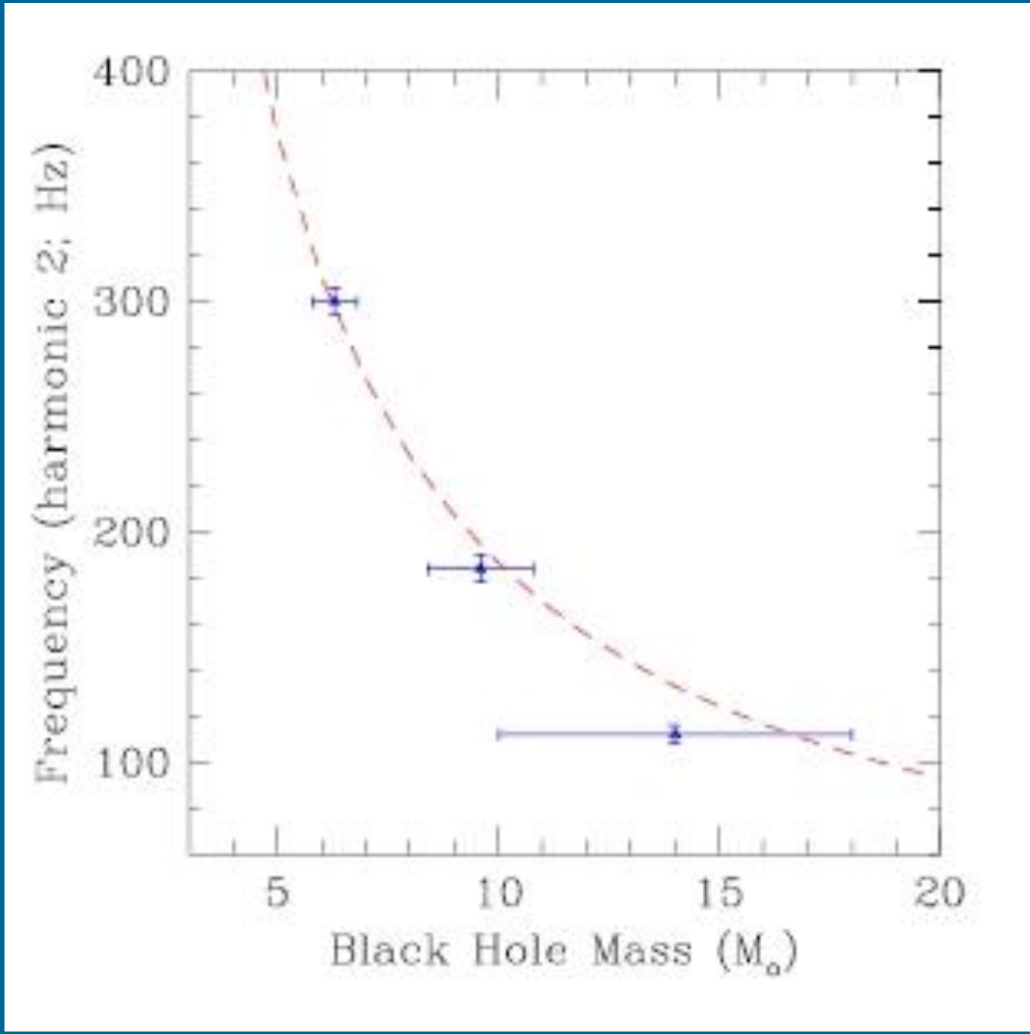




GRO J1550-40

1902.06586

QPOs and BH masses

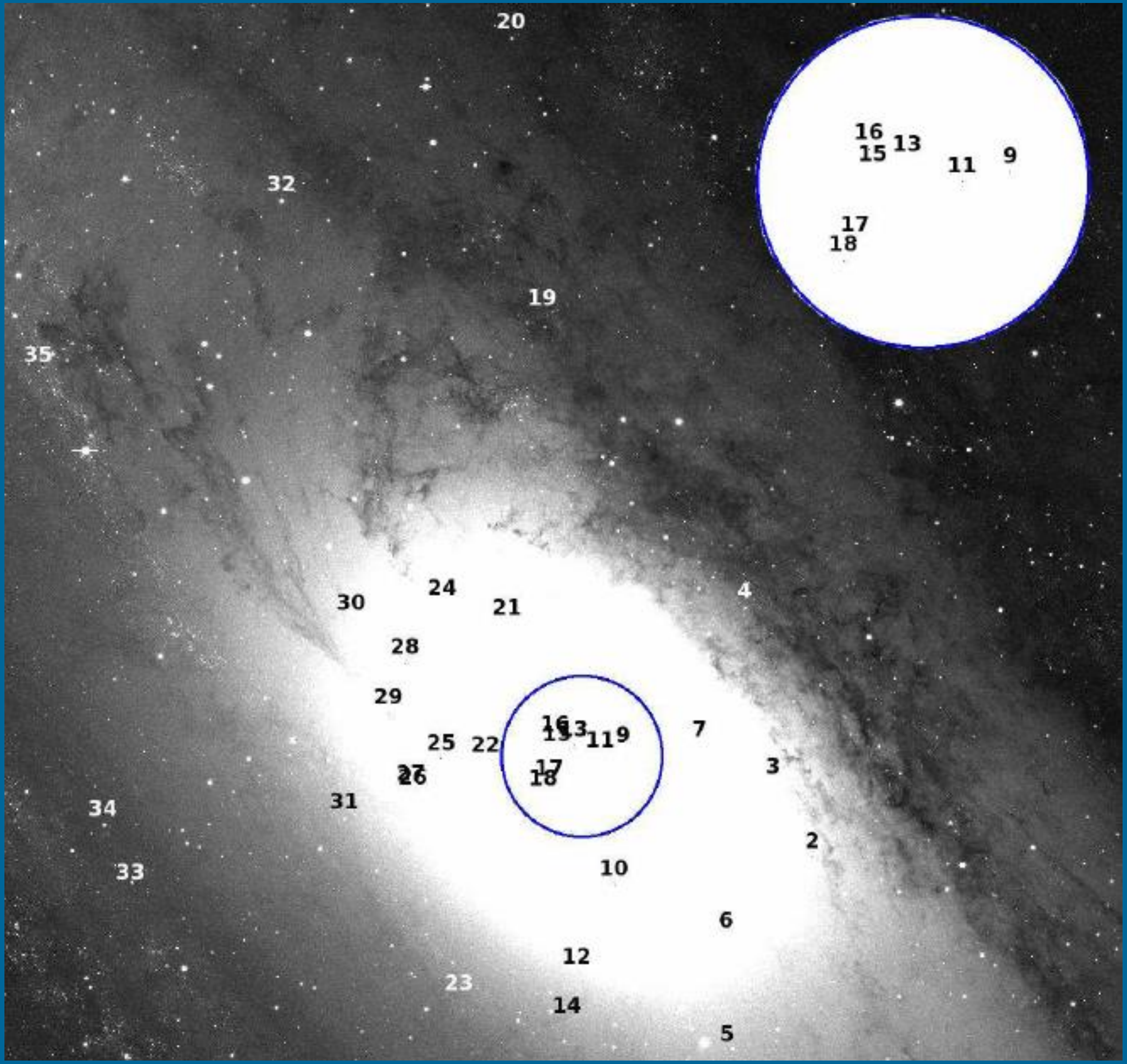


XTE J1550-564,
GRO J1655-40,
GRS 1915+105

Dashed line is plotted for the relation
$\nu_0 = 931 \text{ Hz } (M/M_\odot)^{-1}$
The ordinate shows $2\nu_0$

(Remillard, McClintock astro-ph/0606352)

Extragalactic BHs: the case of M31



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

arXiv:1304.7780

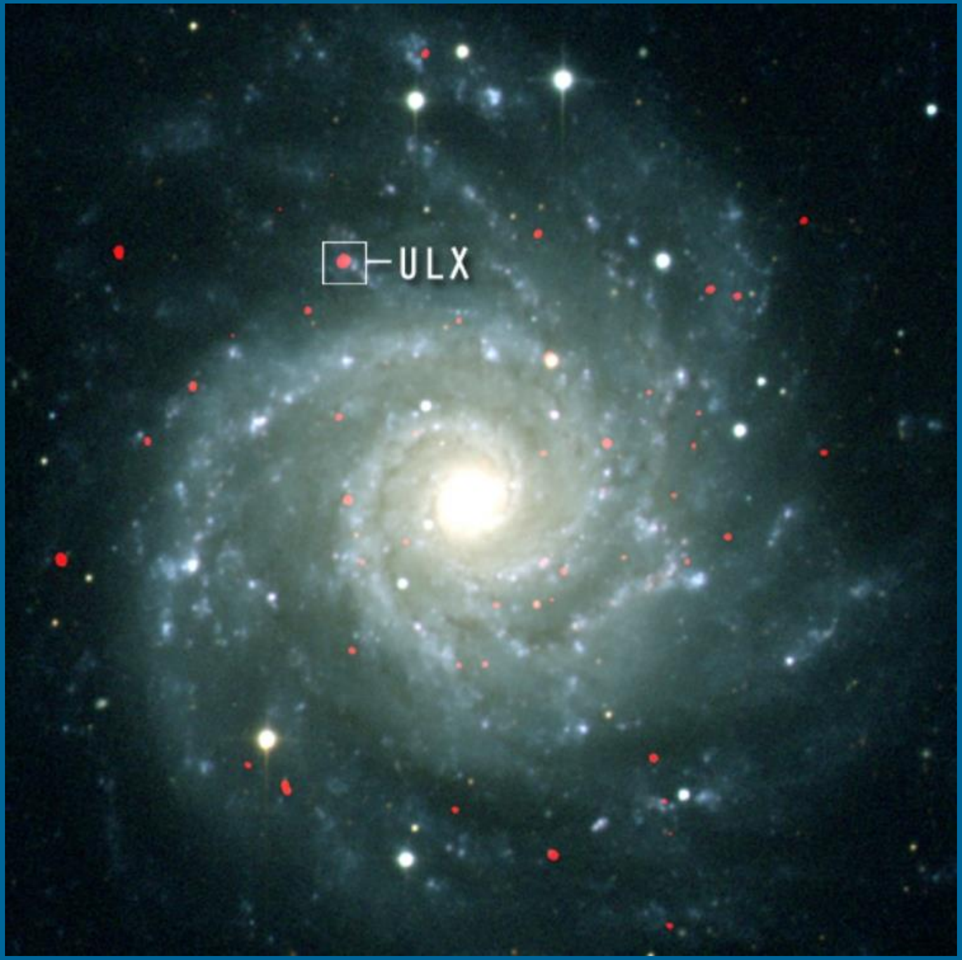
50 BHCs in M31

Src	ID	$D_{M31*}/'$	L^{x}_{Max}	Γ_{Max}	L^{x}_{Min}	Γ_{Min}	N_O	DC 1	DC 2	χ^2_{con}/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

Classification is mainly based on spectral properties.

1406.6091

Ultraluminous X-ray sources

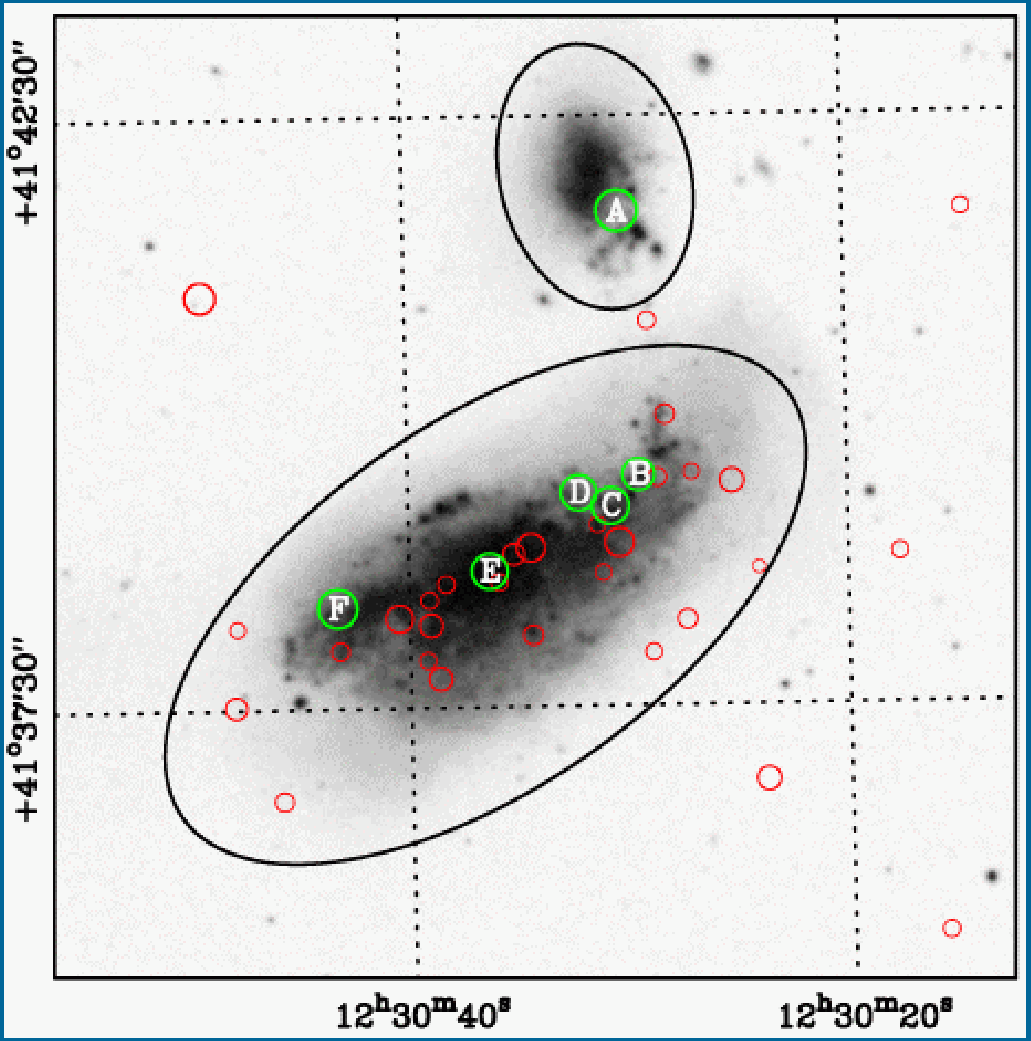


ULXs are sources with fluxes which correspond to an isotropic luminosity larger than the Eddington limit for a 10 solar mass object.

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.

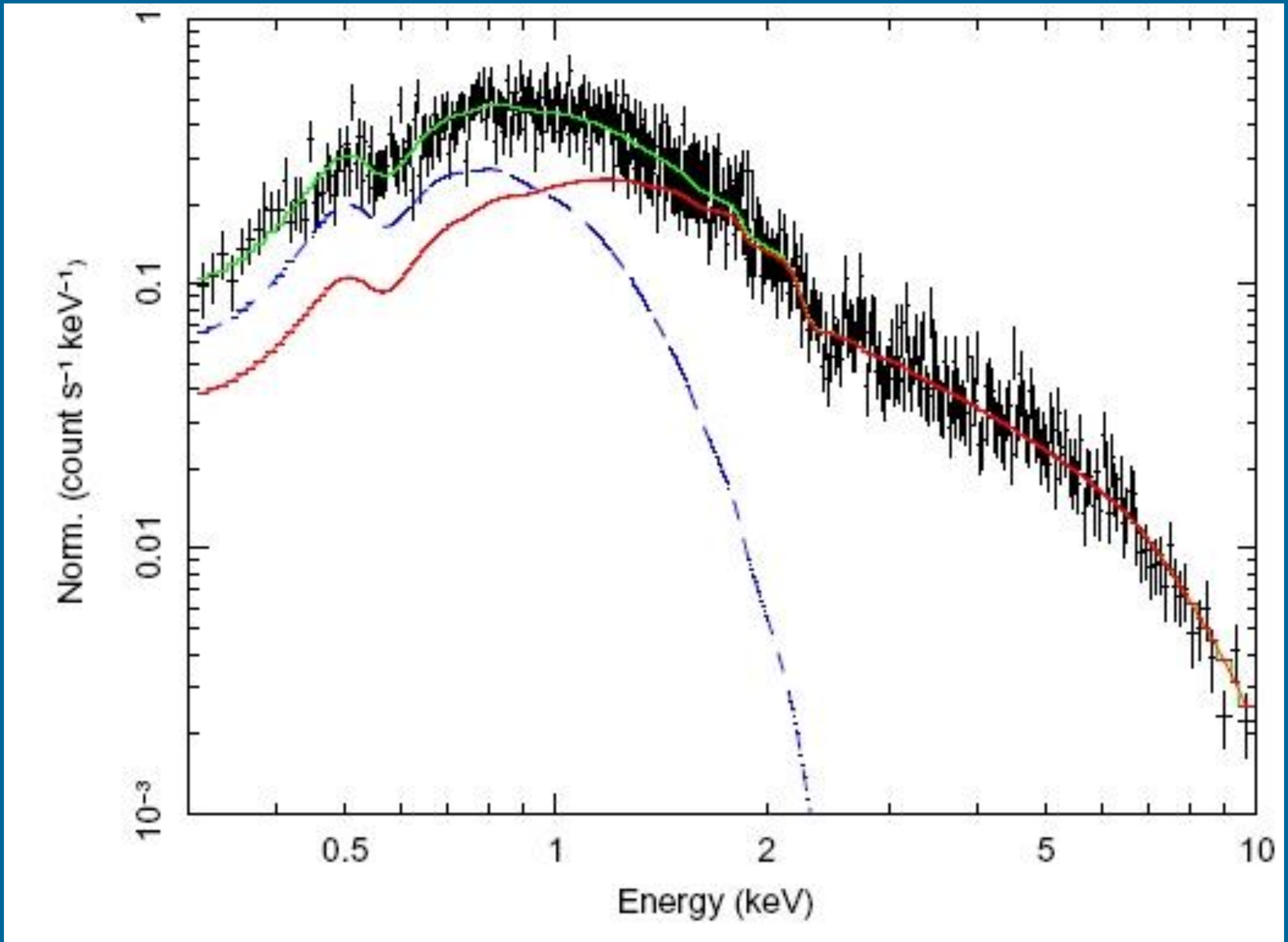
Resent reviews:
1702.05508 - short
1703.10728 - long

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.

(arXiv 0706.2562)

ULX in galaxies of different types

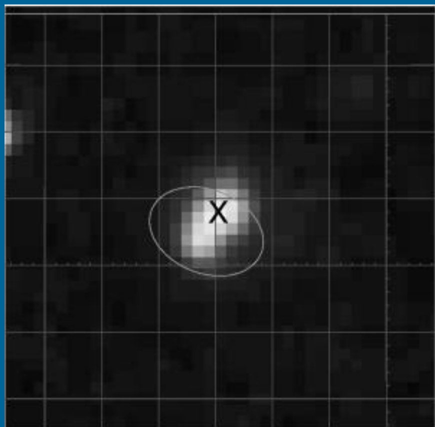
In the following two slides there are images of several galaxies from the SDSS in which positions of ULXs are marked.

Crosses (x) mark sources with luminosities >10^{39} erg/s.
Pluses (+) mark sources with luminosities >5 10^{38} erg/s.

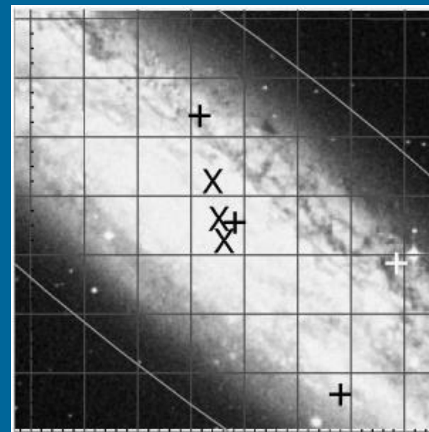
The size of one square element of the grid is 1.2 arcminute (except IZW 18, in which case the size is 0.24 arcminute in right ascension and 0.18 in declination).

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).

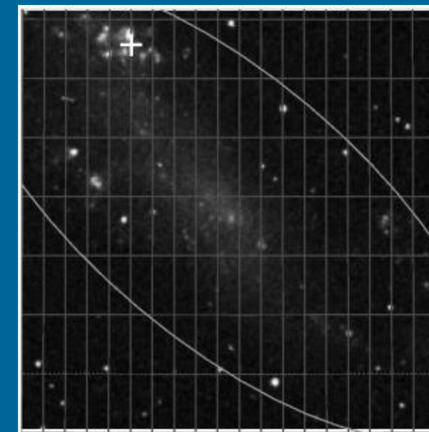
ULX in galaxies of different types



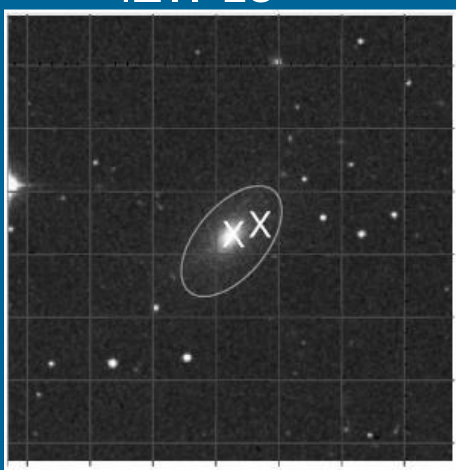
IZW 18



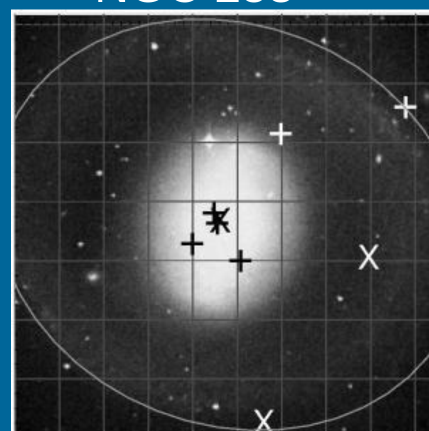
NGC 253



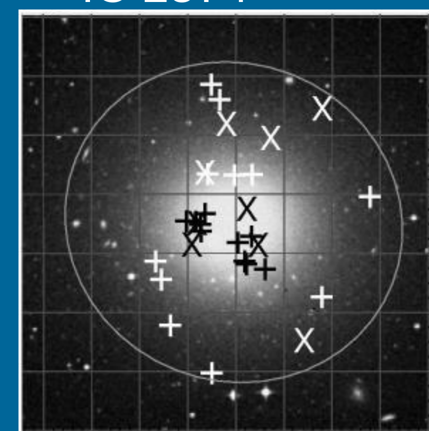
IC 2574



NGC 1132

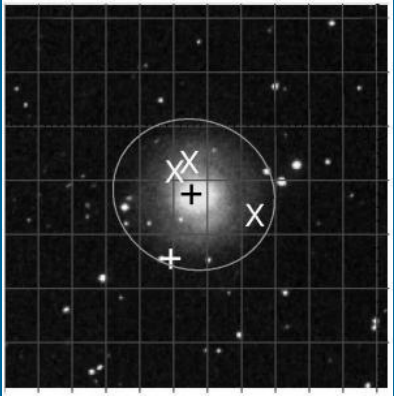


NGC 1291

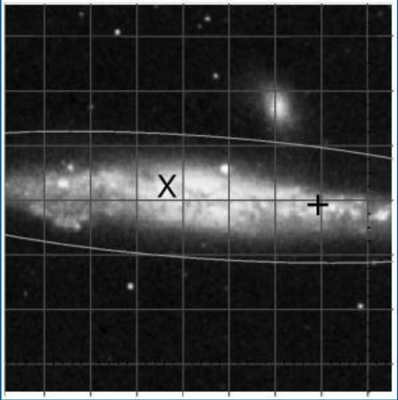


NGC 1399

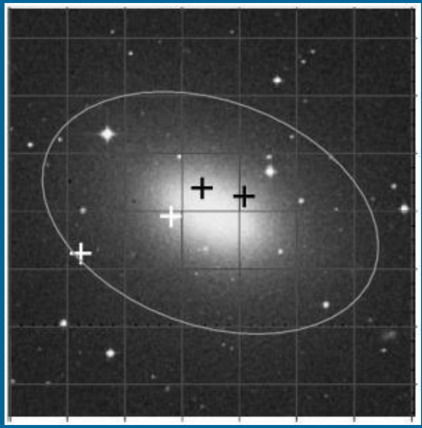
ULX in galaxies of different types



NGC 2681

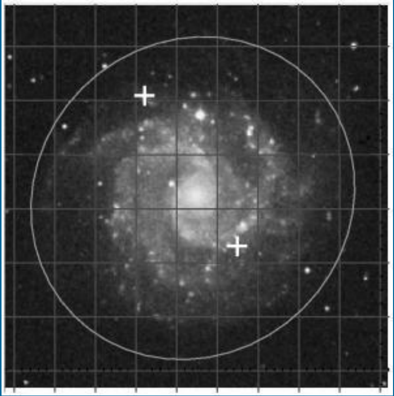


NGC 4631

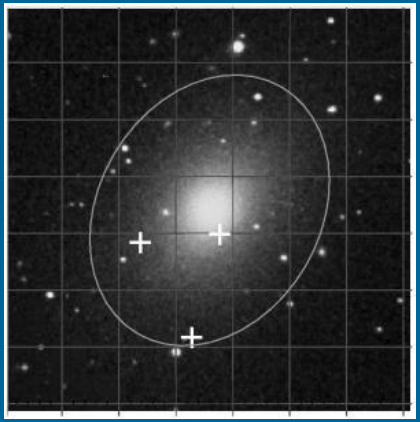


NGC 4697

Large sample of
host galaxies for ULX:
1108.1372

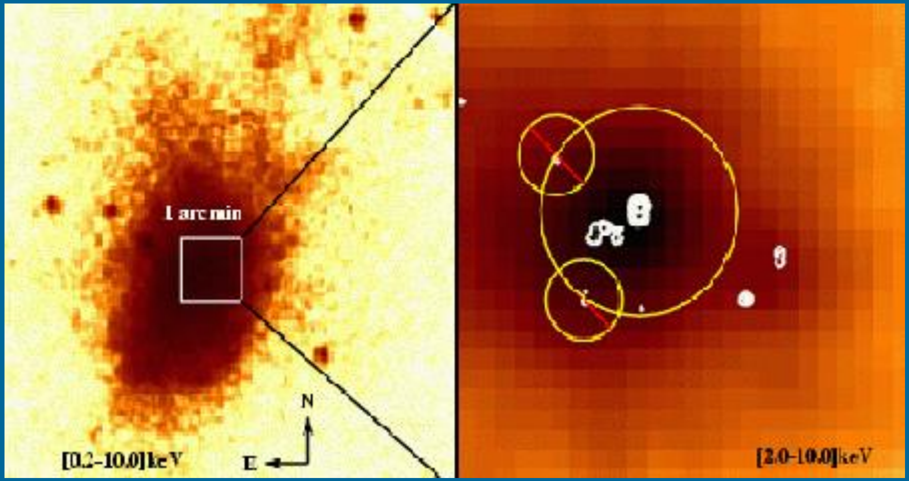


NGC 3184



NGC 4636

The source X-1 in M82



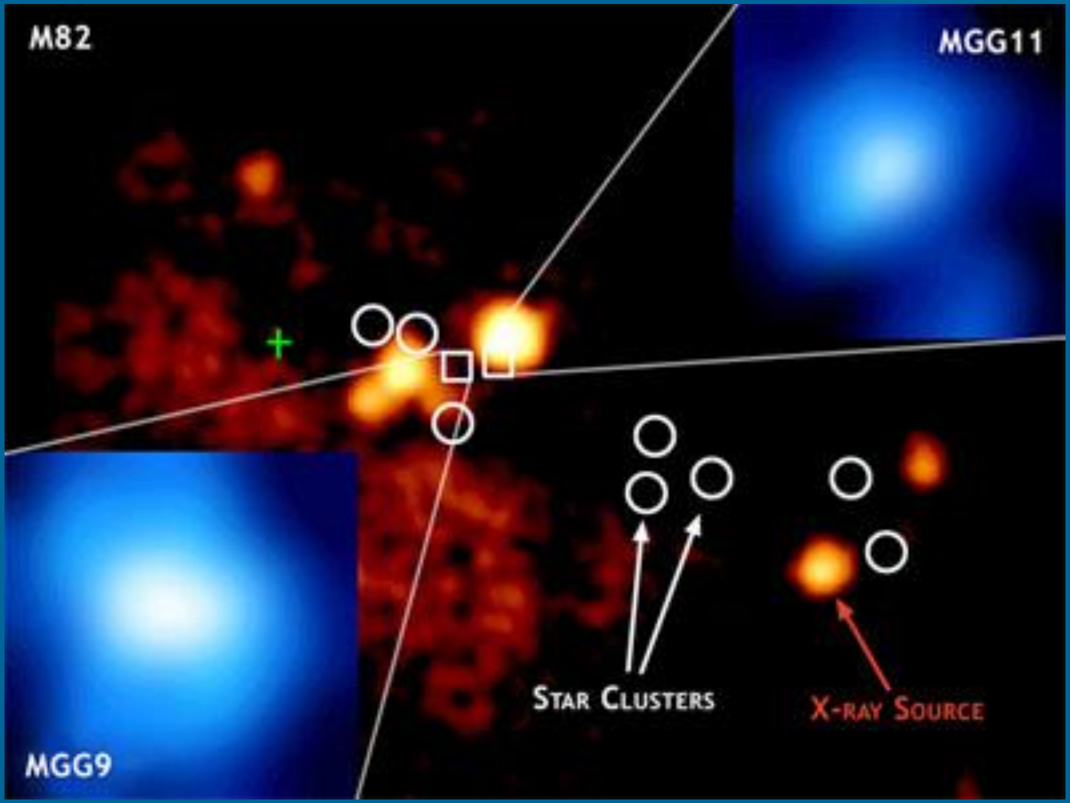
The source M82 X-1 is one of the most luminous, and so it is the best candidate to be an intermediate mass BH.

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

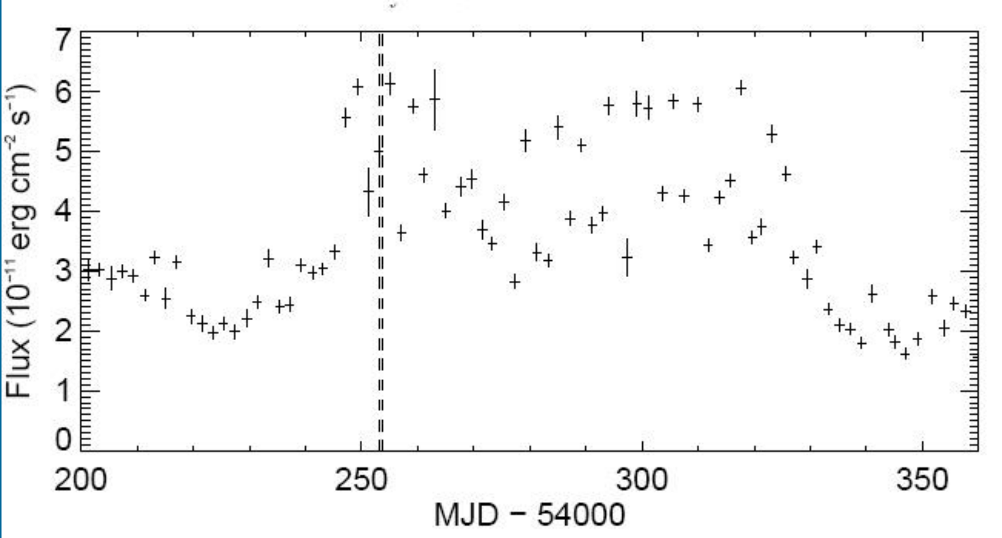
X41.4+60 in M82

79-day burst. Isotropic luminosity ~5 10^{40} erg/s
Hard state. Usually L~0.3 L_{edd}, here there are indications (photon index Γ= 1.6) that it is even ~0.1 L_{edd}.

QPOs.

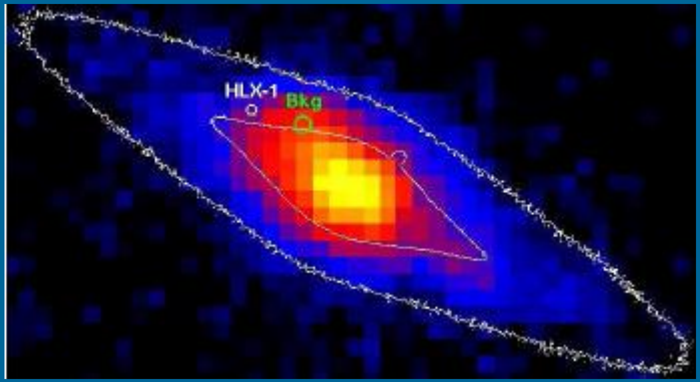
Altogether: mass ~ few 1000 Solar.

RXTE + Chandra observations



(Kaaret et al. 0810.5134)

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

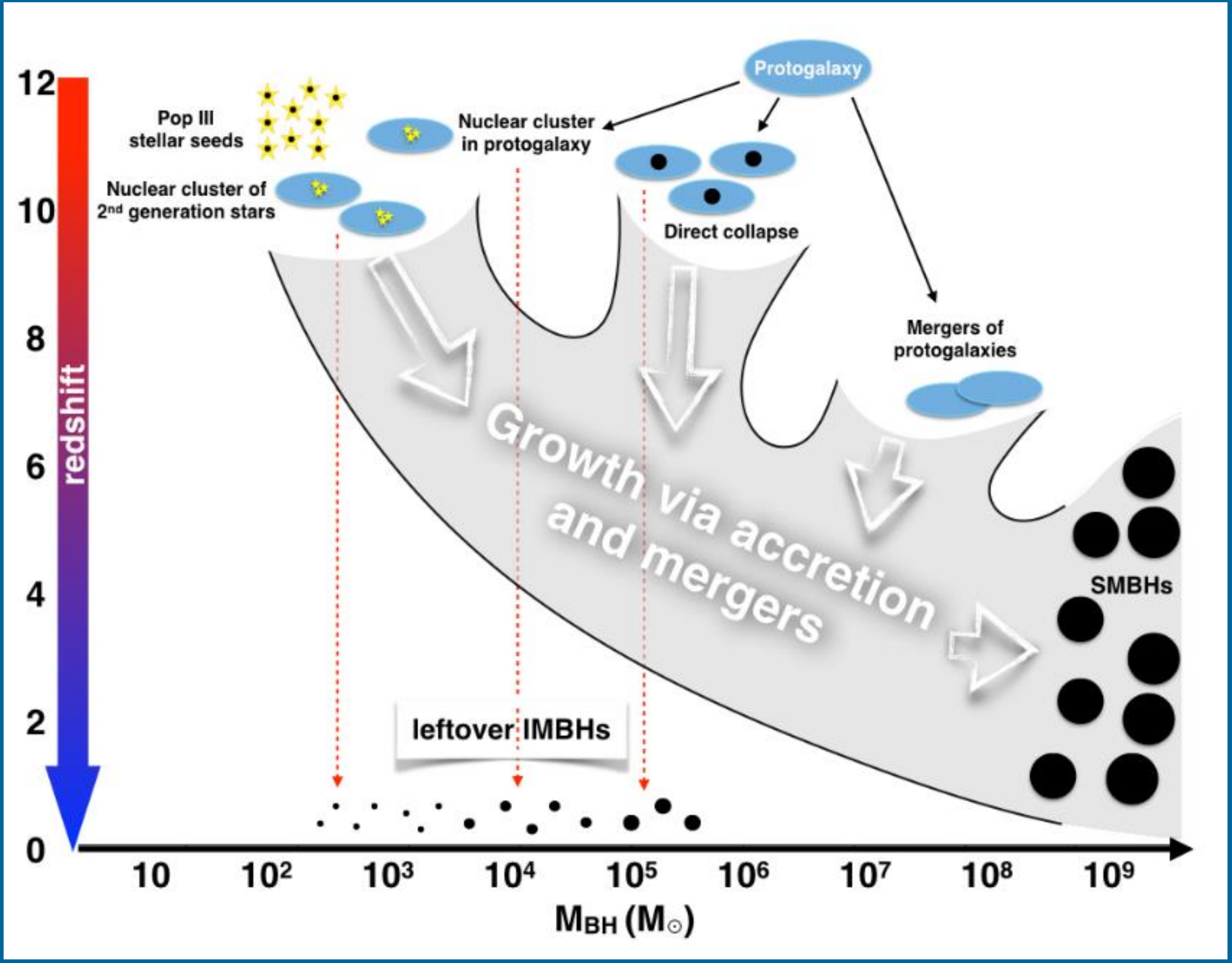


$L > 10^{42}$ erg/s
$M \sim 500 M_{\odot}$

1011.1254, 1104.2614

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

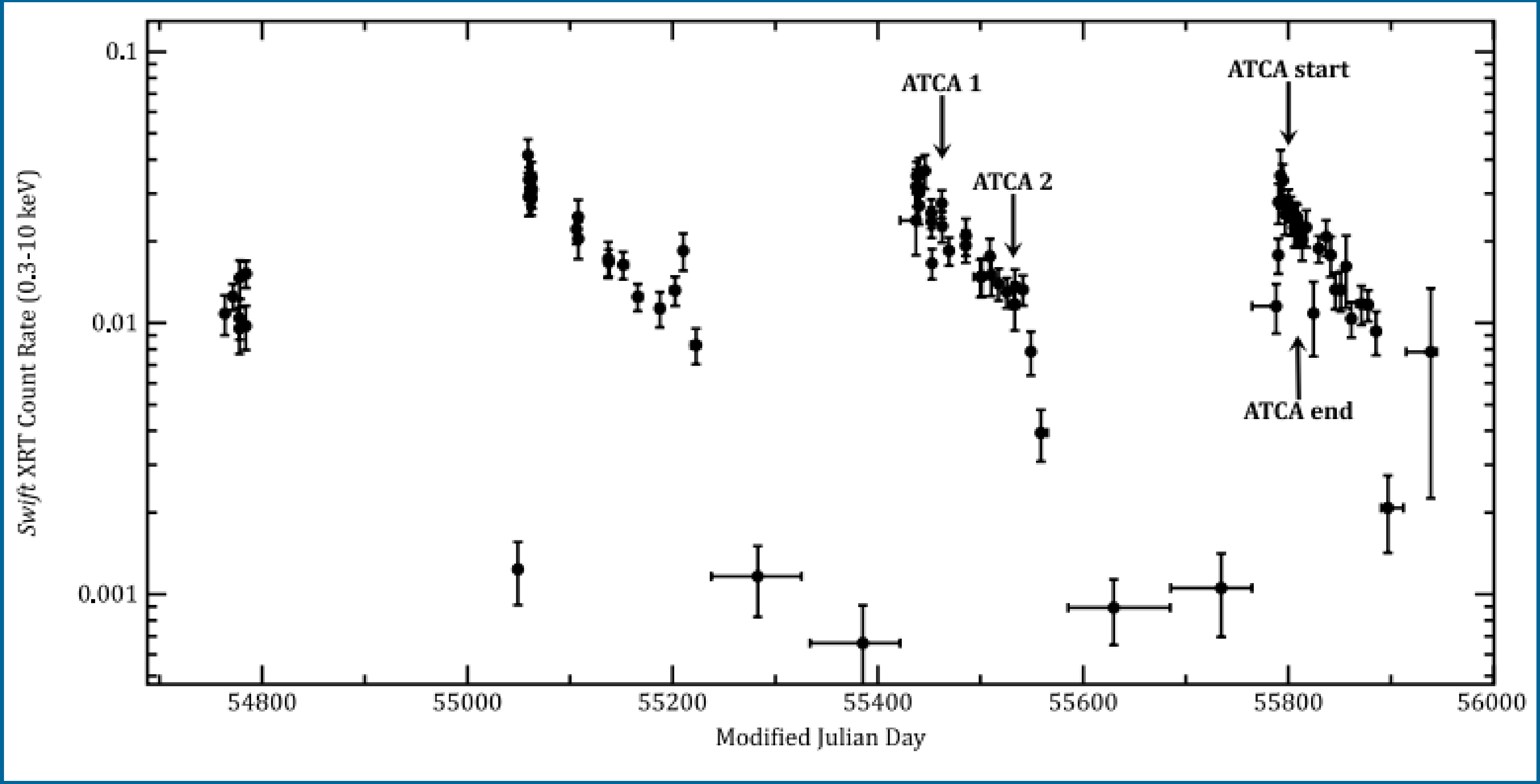
Origin of IMBHs



1705.09667 See also a review in 1801.01095

State transitions in ESO 243-49 HLX-1

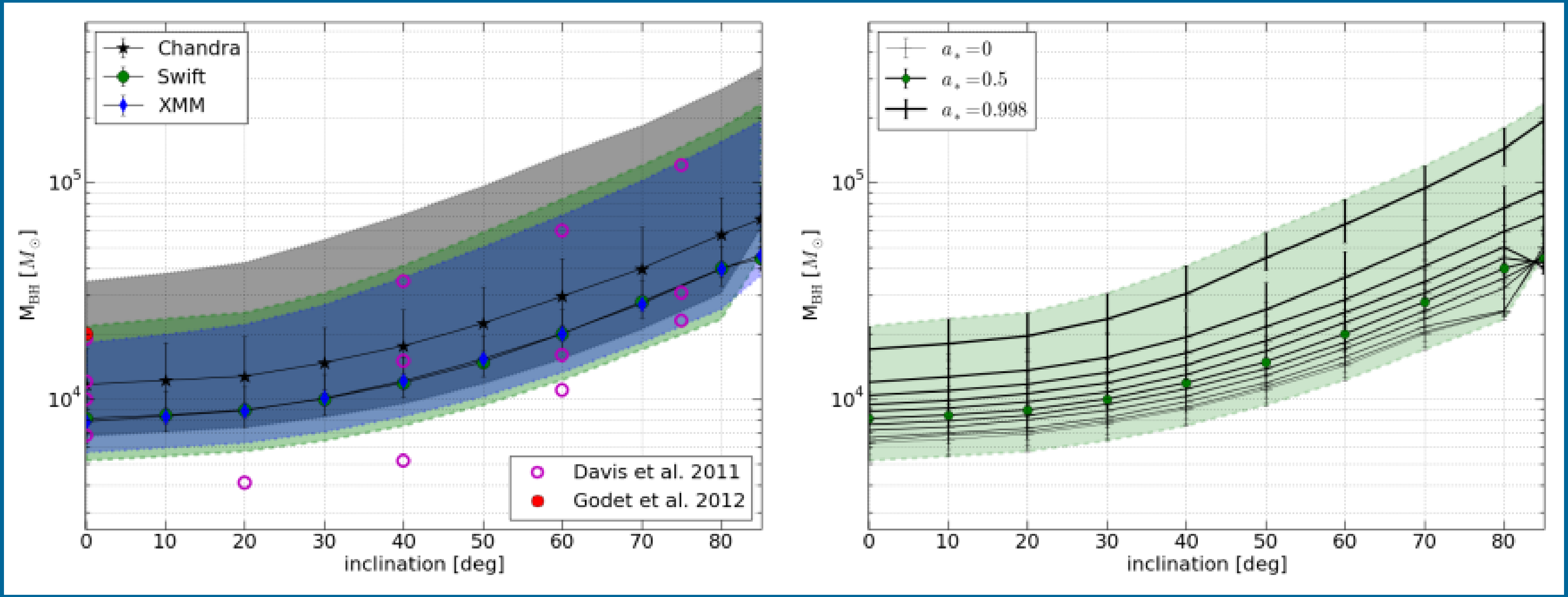
Mass is estimated to be 10^4-10^5 Msolar



1311.6918

More mass estimates for HLX-1

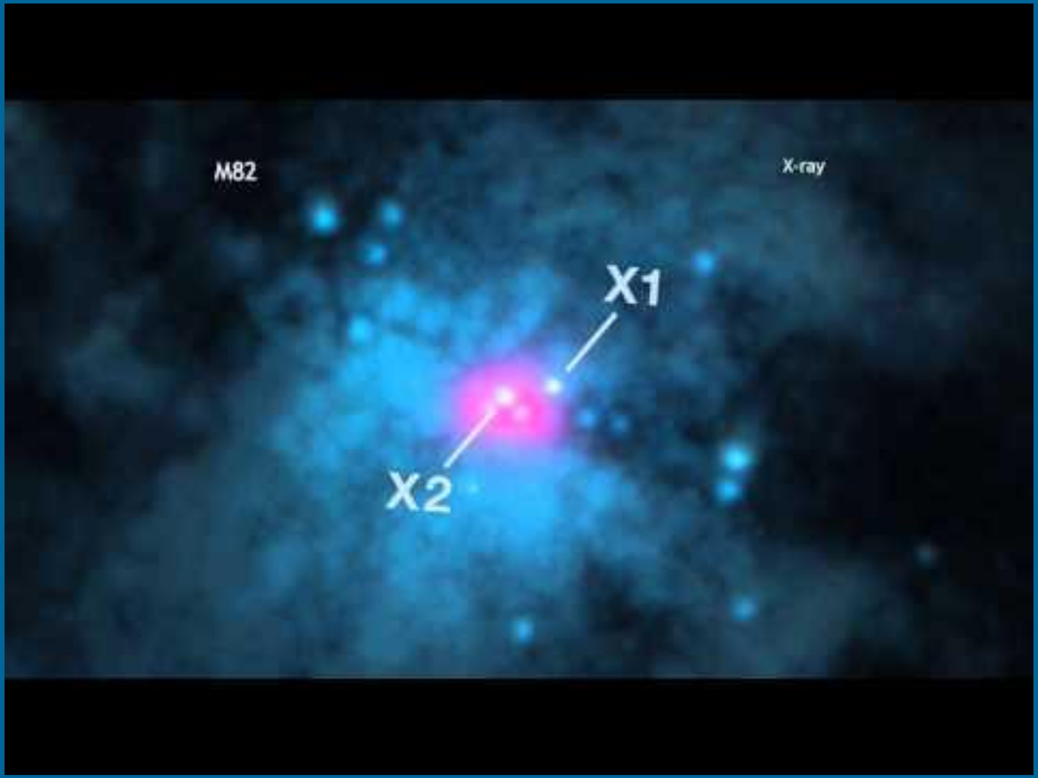
Taking into account all uncertainties the mass is still large

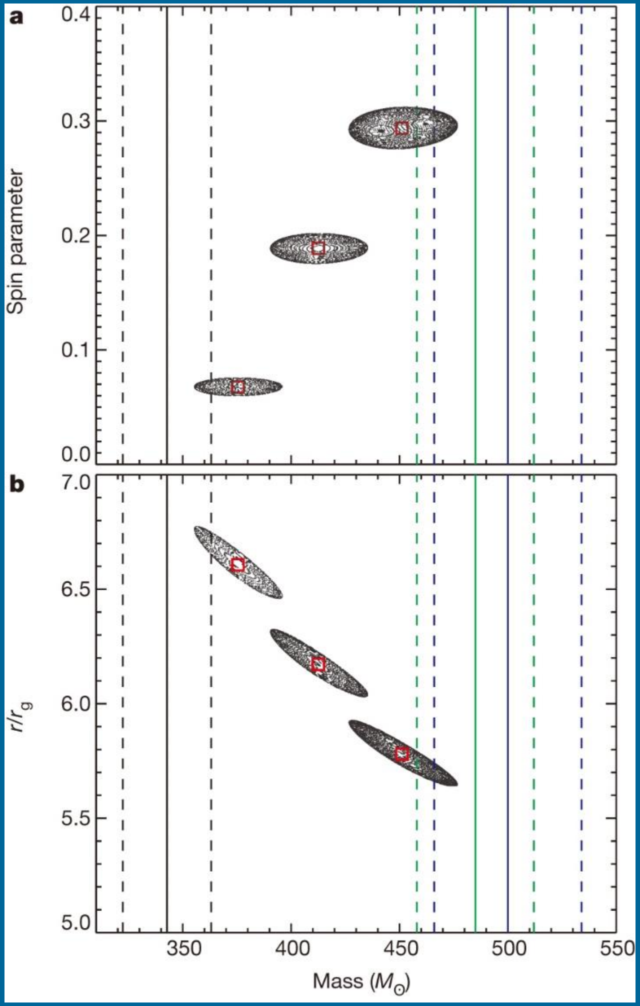


Accretion model for this source was presented in 1402.4863

Heavy BH in M82

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





1501.03180

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.

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

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

Tod E. Strohmayer[1] & Richard F. Mushotzky[1]

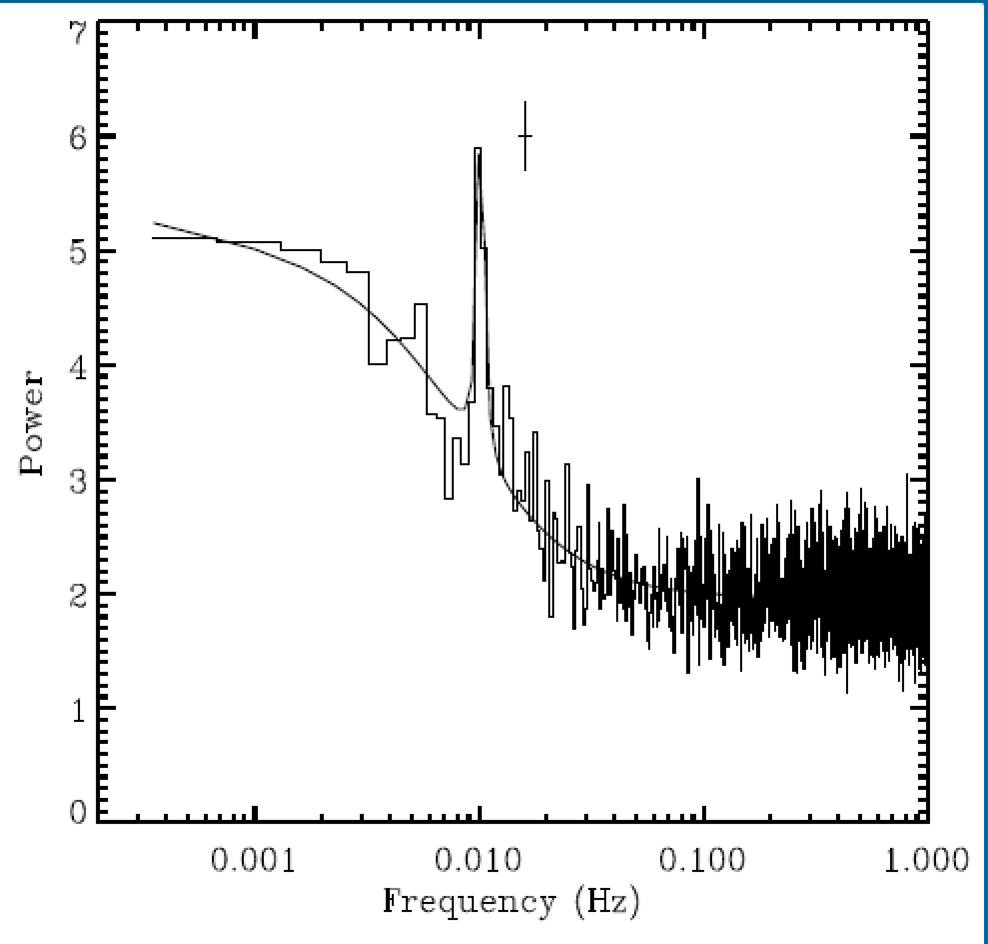
ABSTRACT

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.

0911.1076

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.

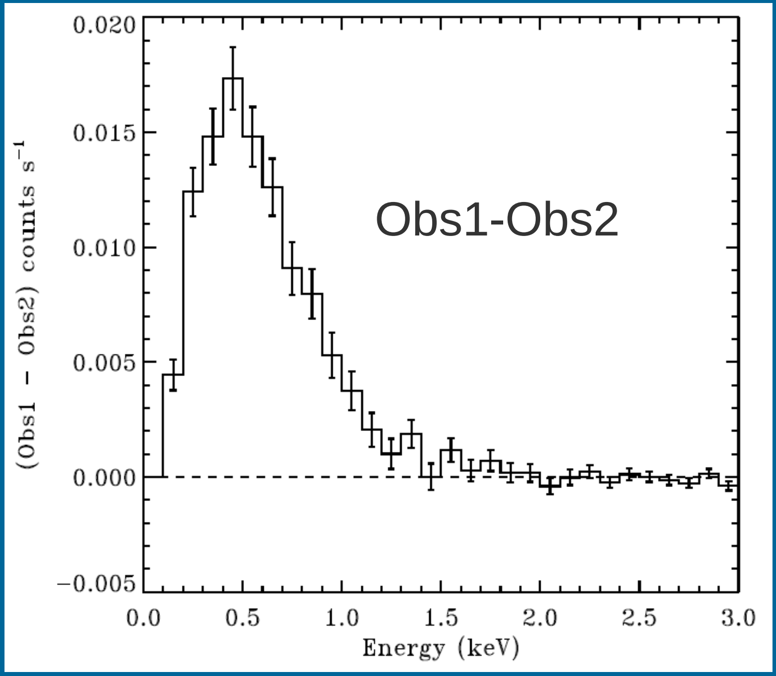


E>1 keV

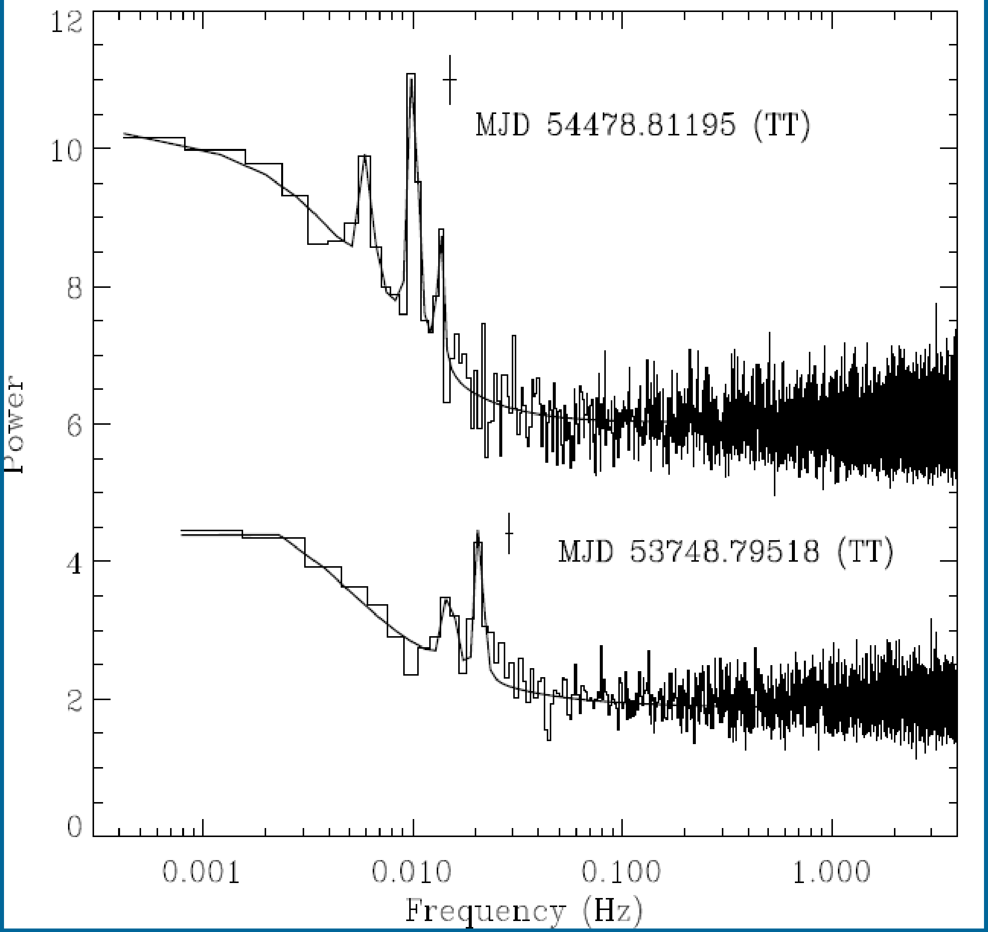
0911.1076

Comparison of two observations

Obs1 – 2006
Obs2 – 2008

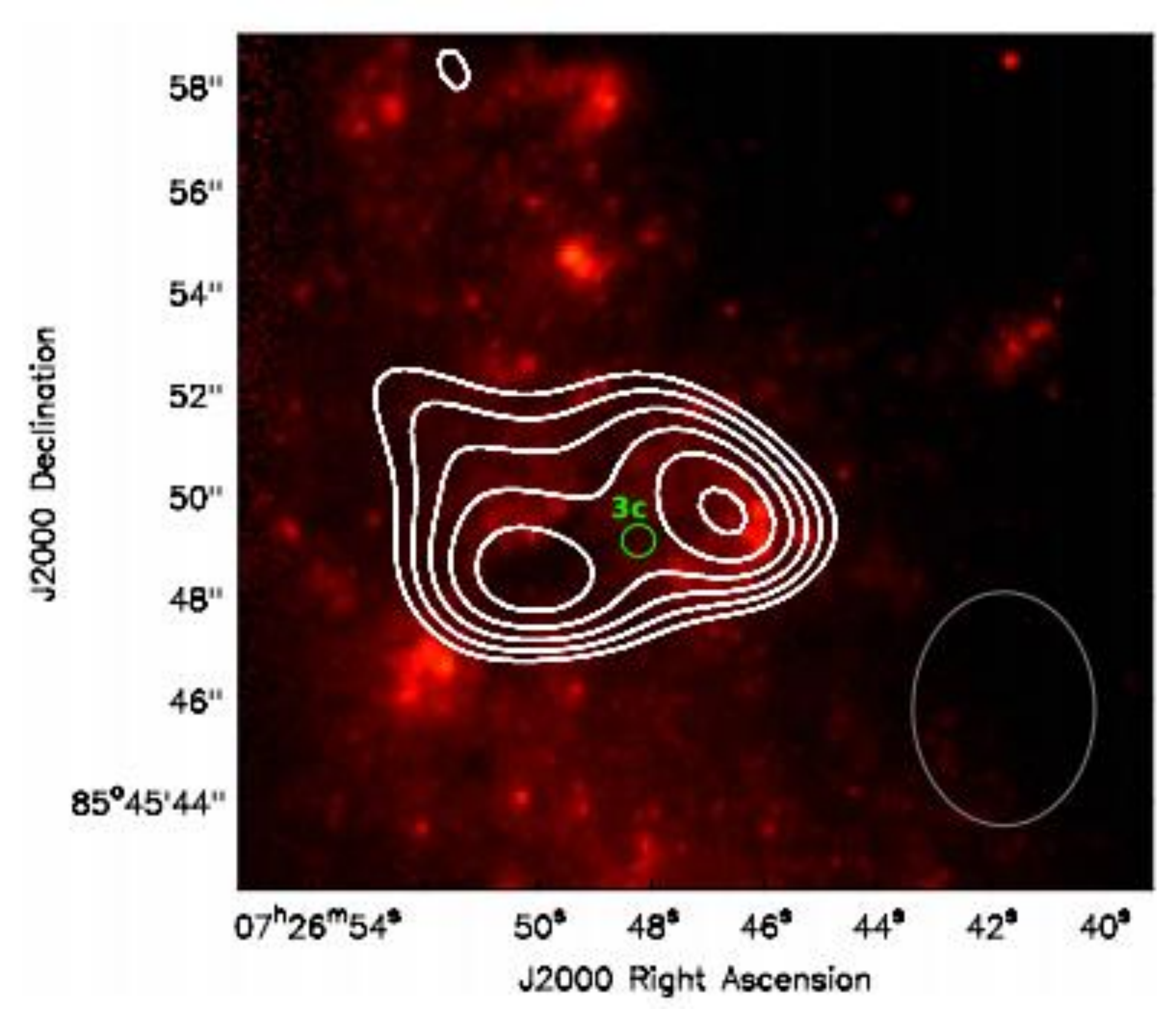


Obs1 was brighter, but all difference is due to soft (disc) component.



0911.1076

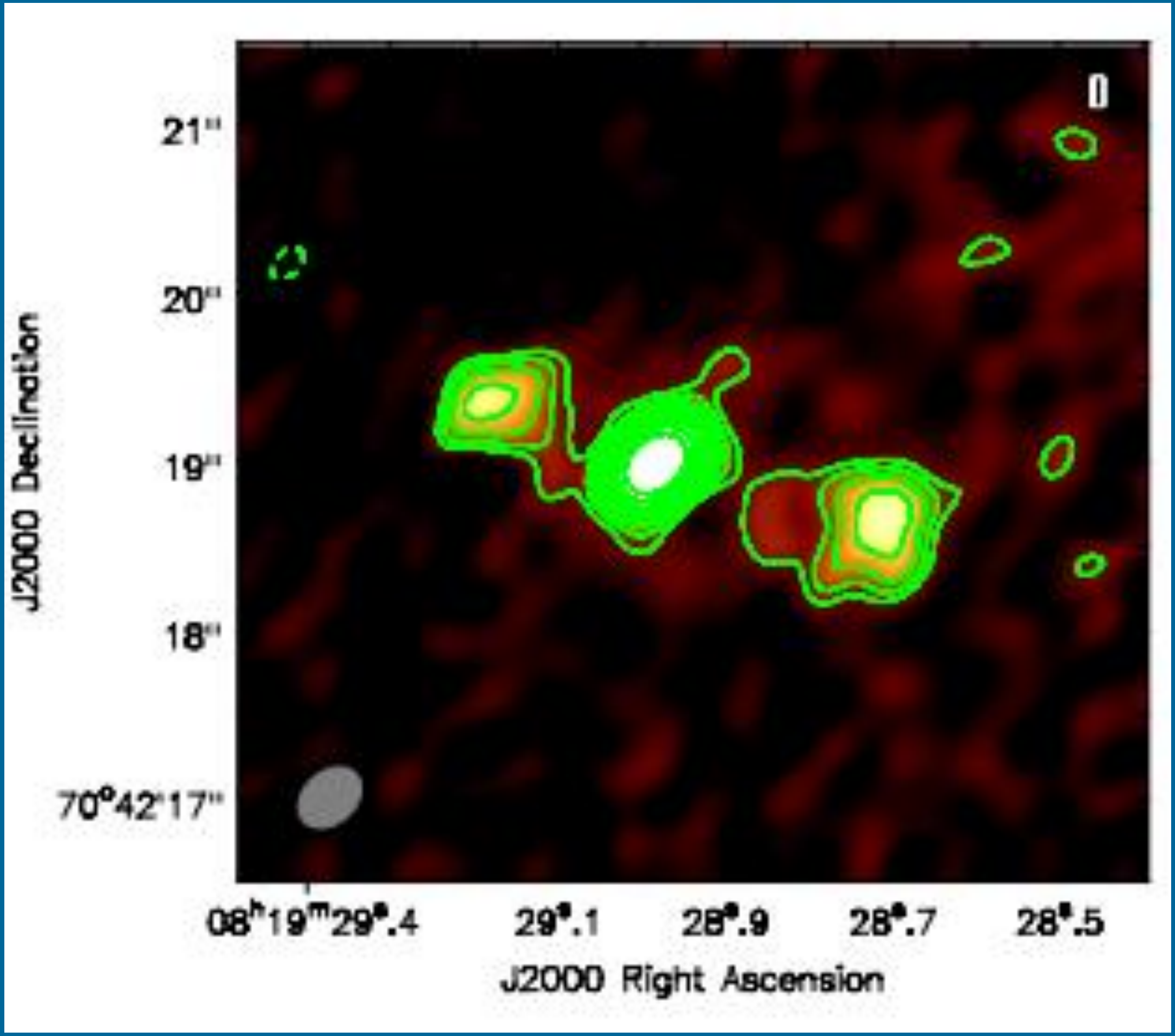
Jet from an ULX in NGC 2276



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

1309.5721

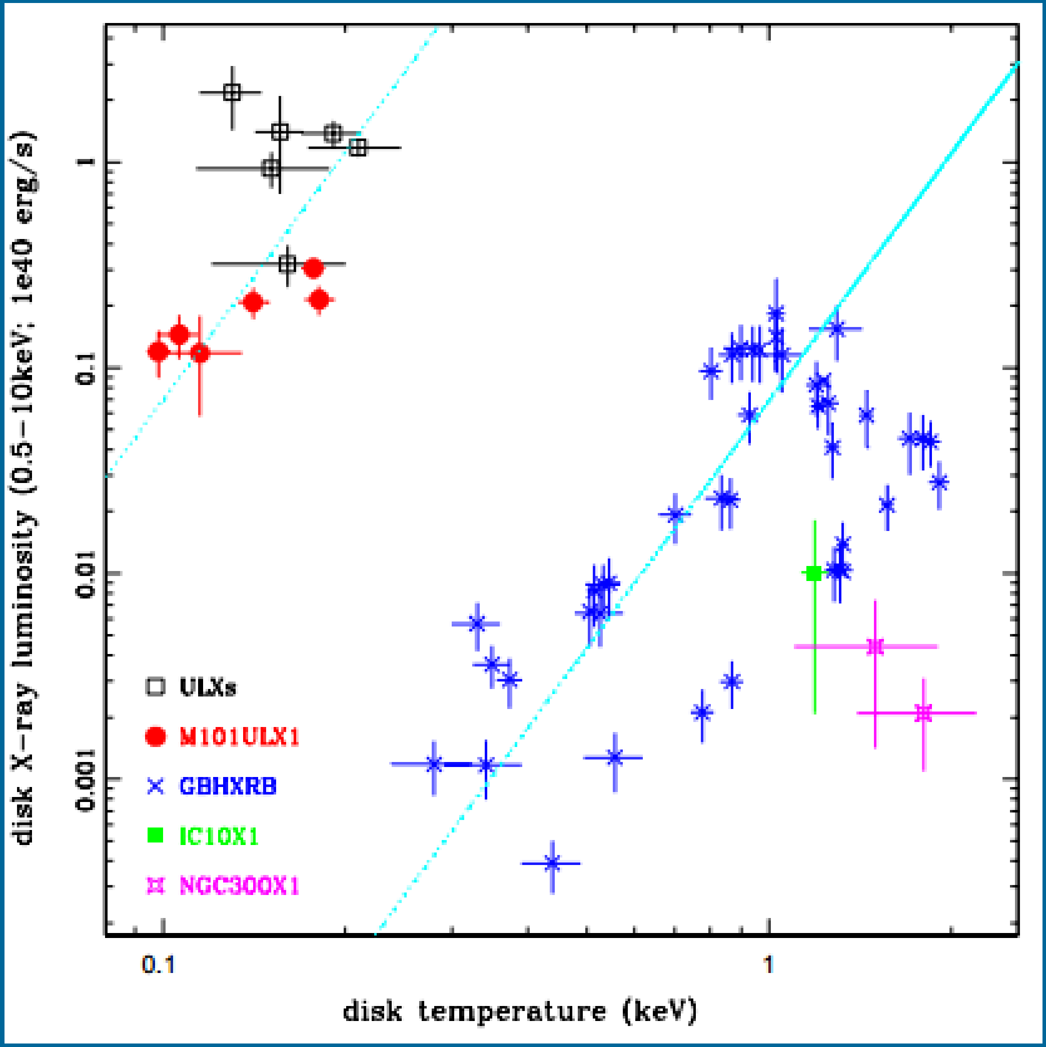
Jet from ULX Holmberg II X-1



Mass limits are poor:
M> 25 Msolar

1311.4867

Strange accretion in the ULX in M101



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

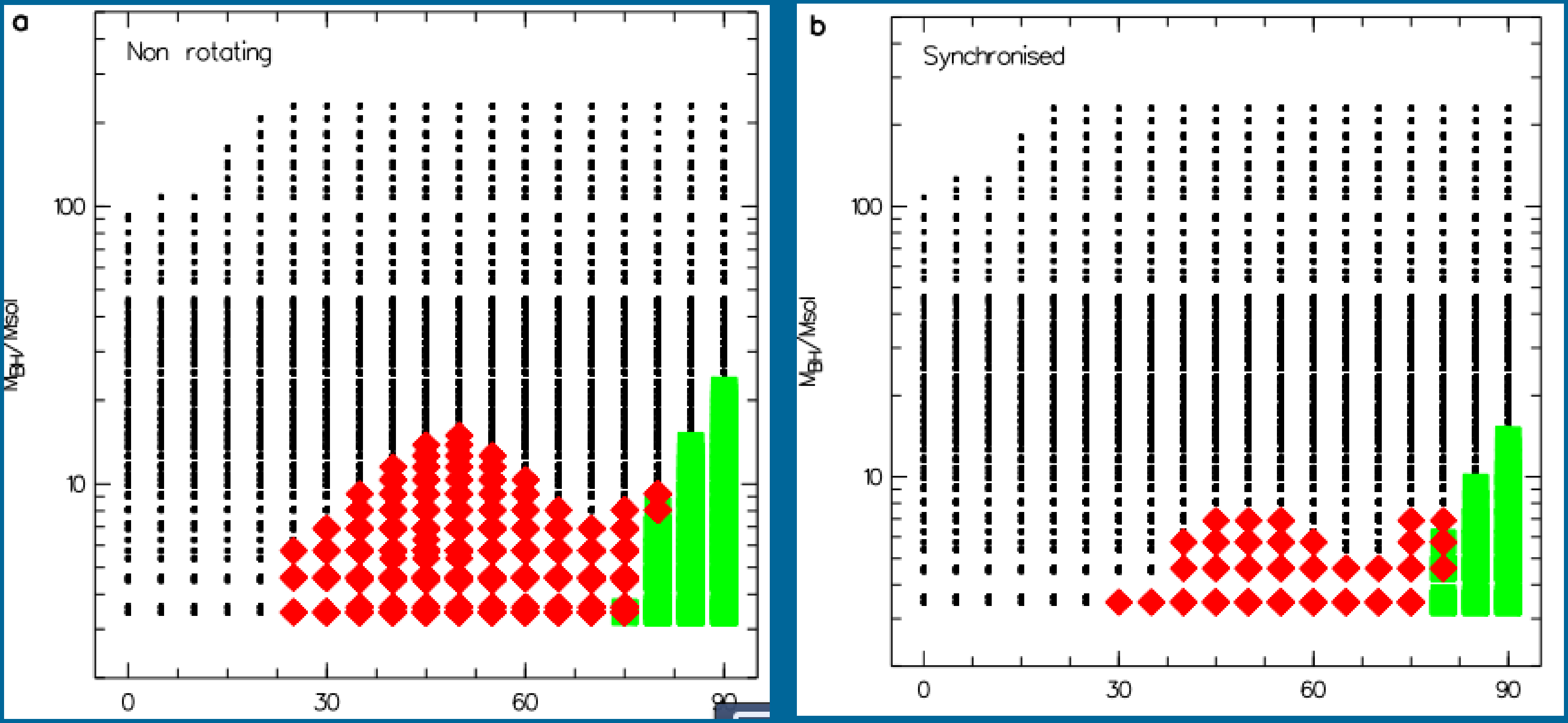
The BH mass is estimated to be ~20-30 Msolar.

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

1312.0337

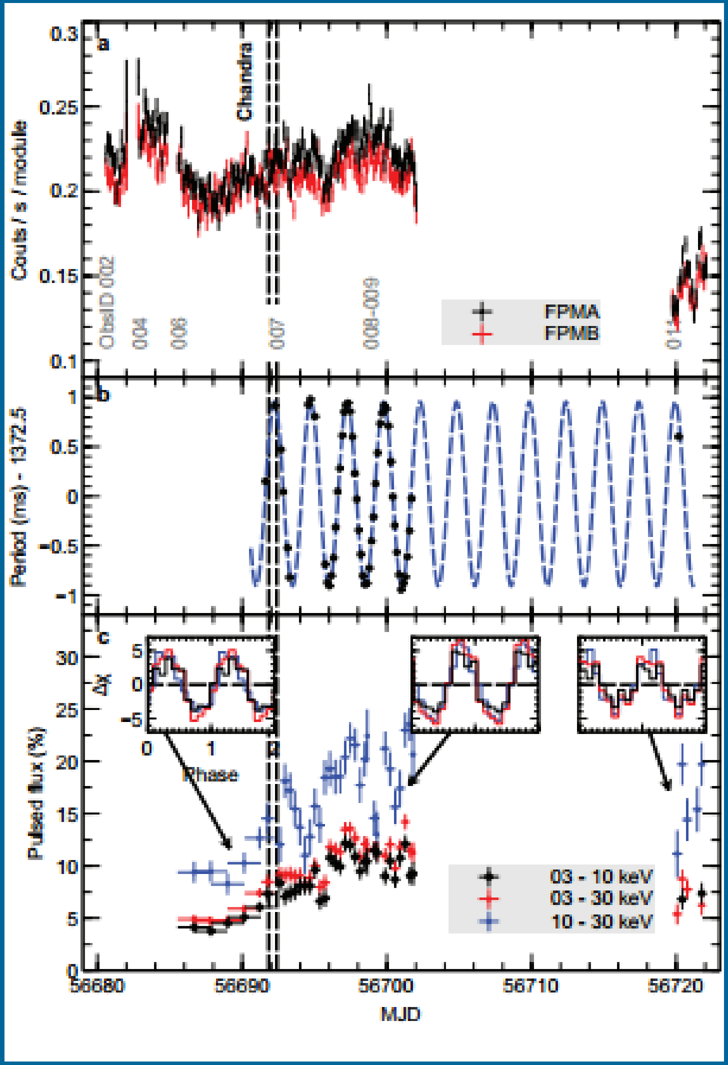
Normal BH in an ULX

P13 in the galaxy NGC 7793
BH mass 7-15 Msolar
(depending on rotation)

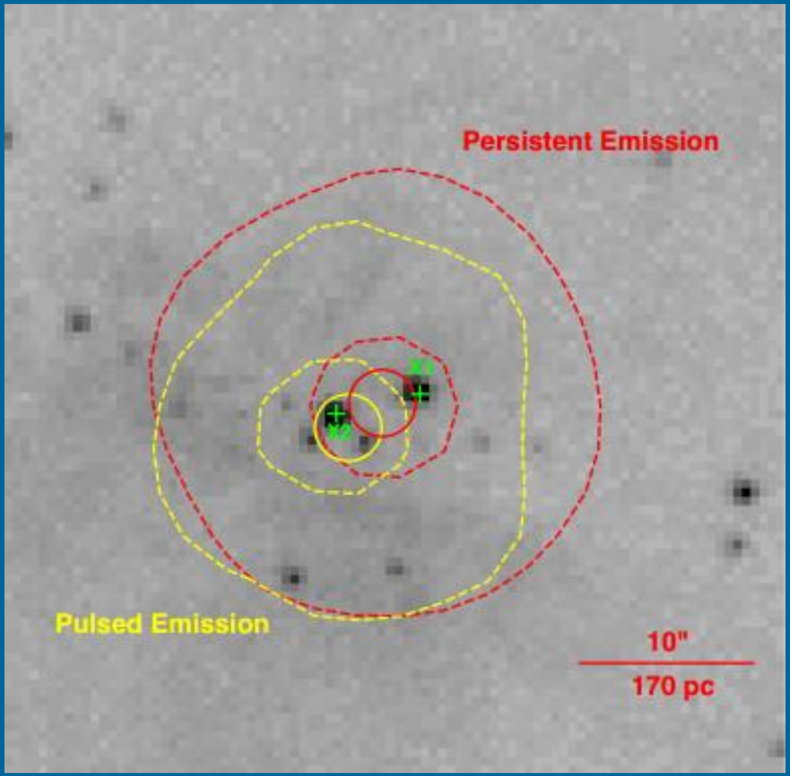


1410.4250

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.

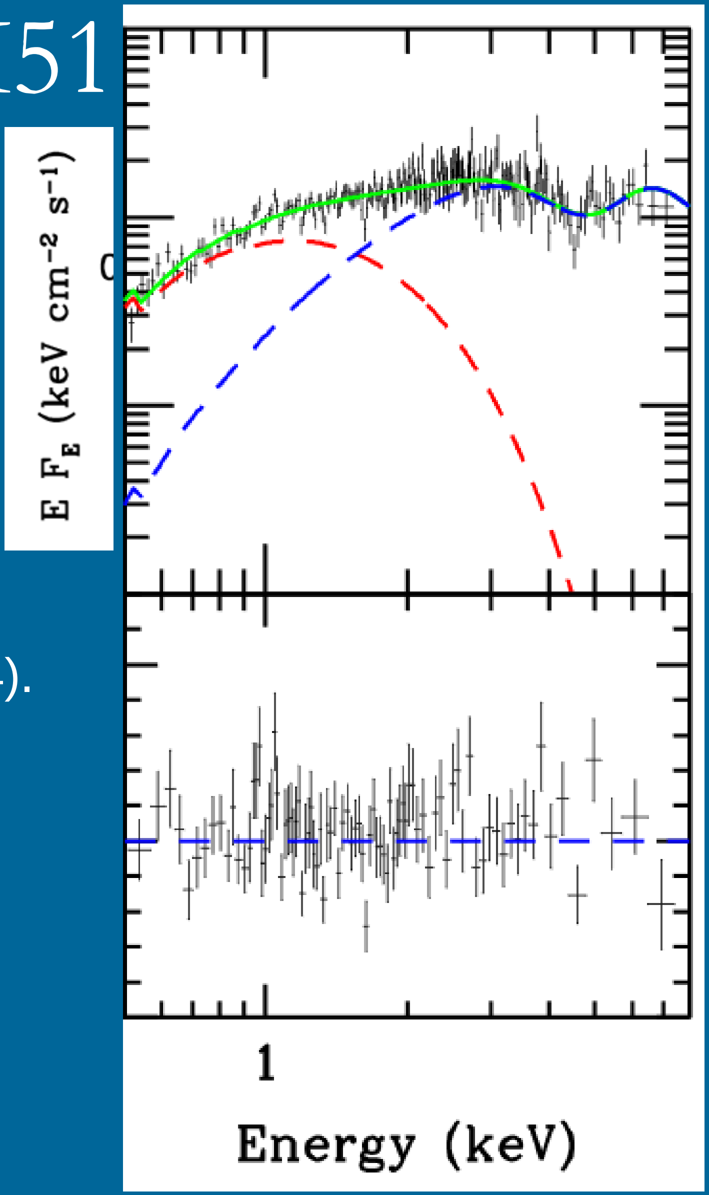
- Outflow (0.24c) in ULX NGC300. 1803.02367
- Cyclotron resonance line in ULX NGC300. 1803.07571
- Cyclotron line in ULX M51. 1803.02376
- New indirect arguments in favour of NSs in ULXs. 1803.04424

Cyclotron line in ULX M51

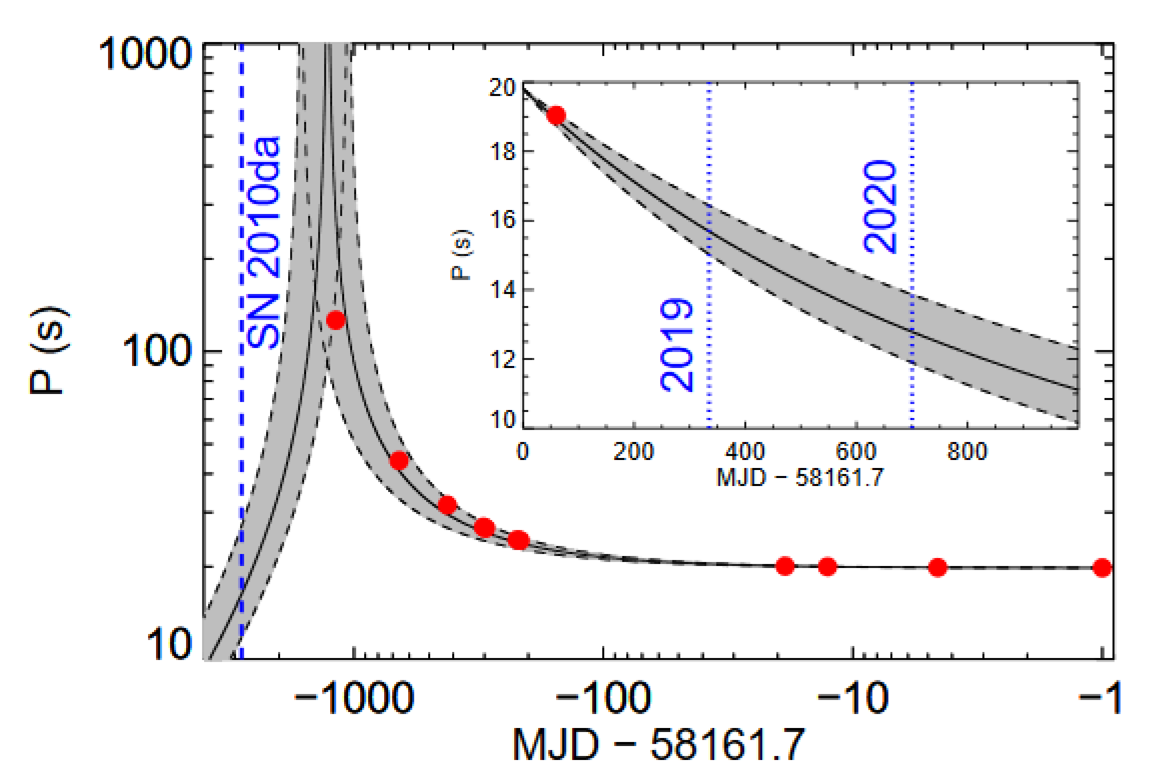
~10^{12} G dipolar field.
Strong dipole field is excluded,
but strong multipoles are still possible.

<u>*A big question: are there magnetars in ULX?*</u>

Recent studies suggest that – no (see 1903.03624).



Fantastic spin evolution of the ULX in NGC 300



Torque reversal in 2014?

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

1811.11907

The population of ULXs

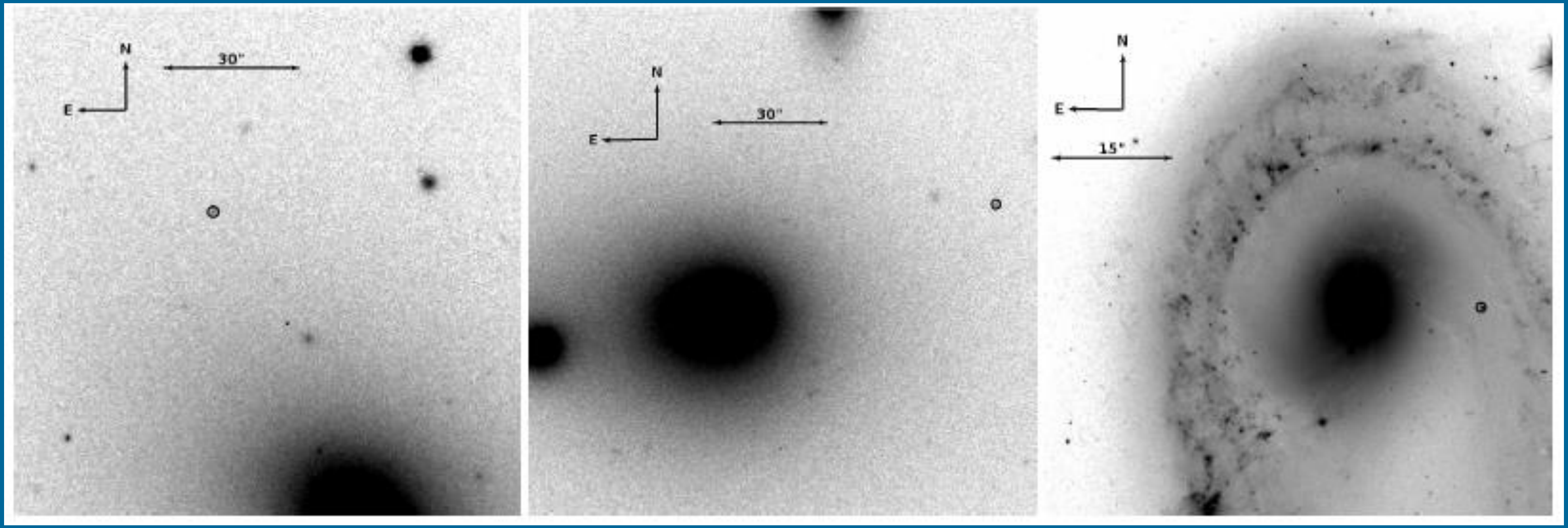
Most probably, the population of ULXs in not uniform.

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

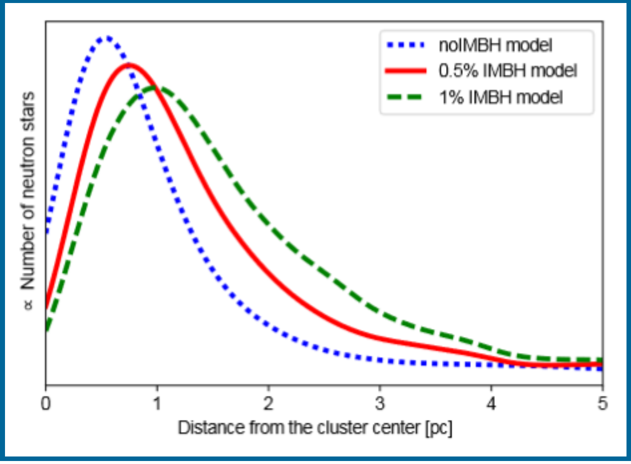
Background sources

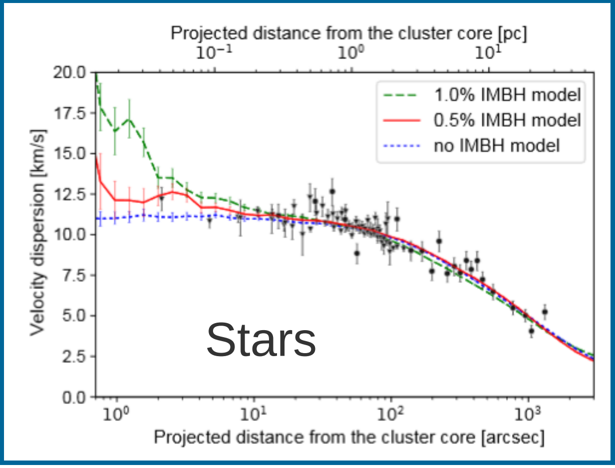


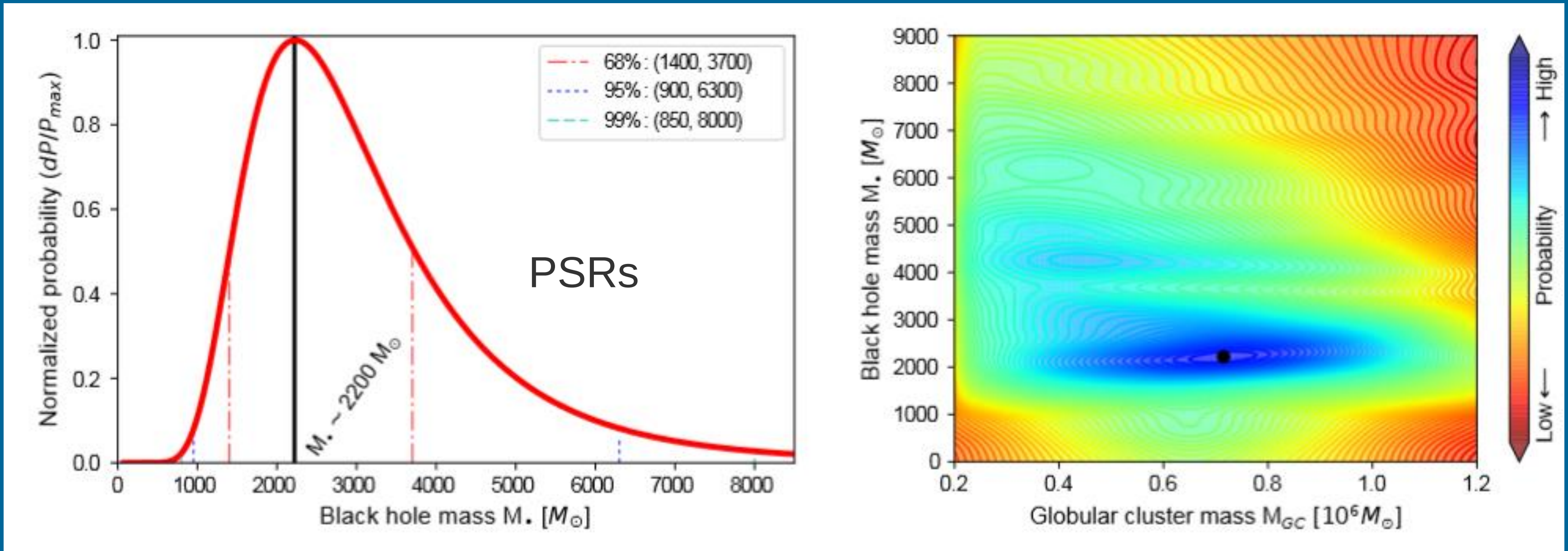
Three out of four studied objects appeared to be background AGNs.
The only true ULX is in a spiral galaxy. Two out of false – in ellipticals.

IMBH in 47 Tuc?

Cluster dynamics was probed with radio pulsars.







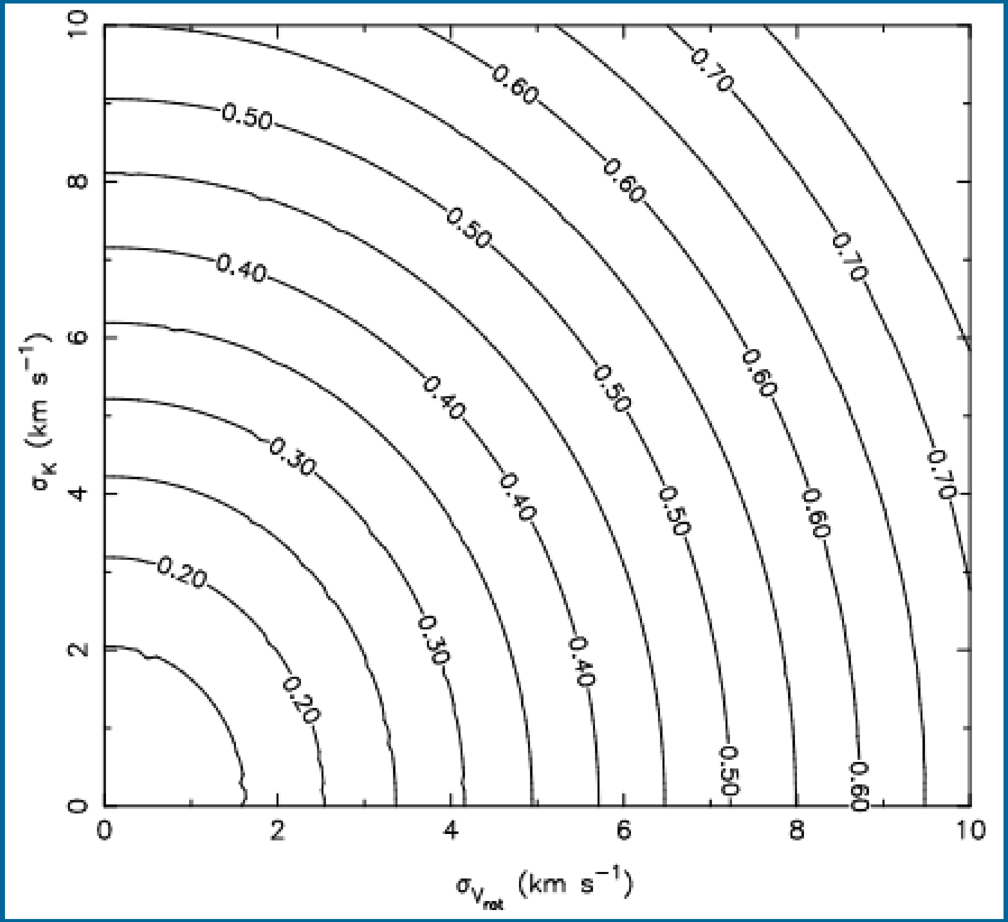
1702.02149

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+/-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+/-0.2.