Black Holes: Observations
Lecture 2: BHs in close binaries

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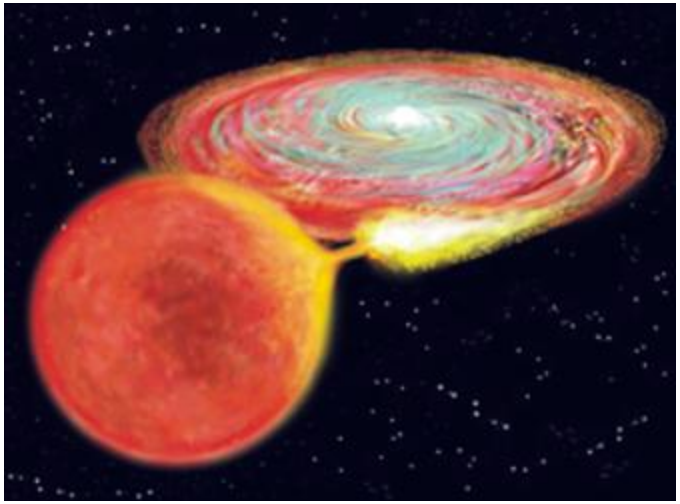
Plan of the lecture

1. Close binaries. Evolution.
2. BH candidates
3. Mass determination
4. Systems BH+PSR – the astrophysical Holy Grail
5. Spectra and states
6. Variability. QPO.
7. ULX – ultraluminous X-ray sources

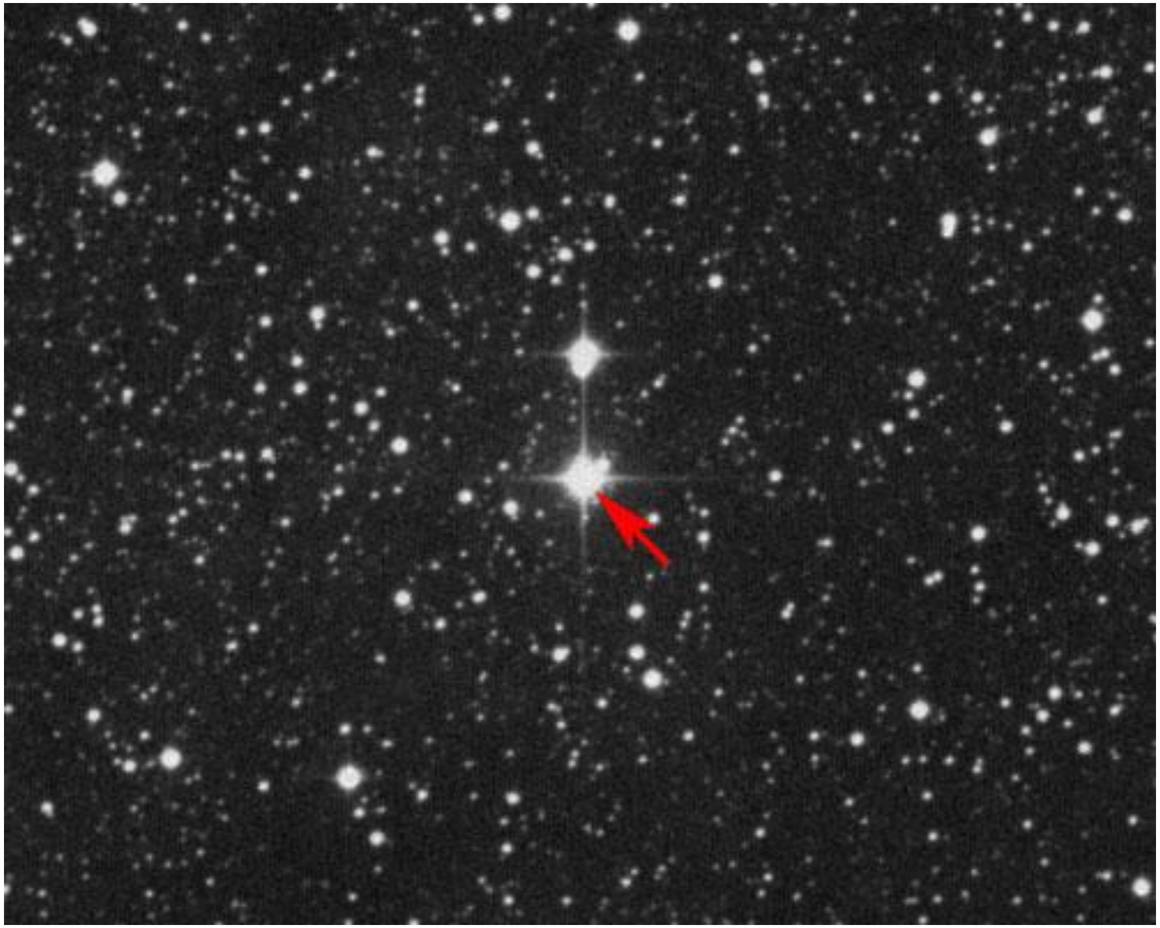


Reviews

astro-ph/0606352 X-ray Properties of Black-Hole Binaries
astro-ph/0306213 Black Hole Binaries
astro-ph/0308402 Intermediate-Mass Black Holes

astro-ph/0410536 Accreting Neutron Stars and Black Holes: A Decade of Discoveries
astro-ph/0410381 What can we learn about black-hole formation from black-hole X-ray binaries?
gr-qc/0506078 Black Holes in Astrophysics
astro-ph/0504185 Black Hole States: Accretion and Jet Ejection
astro-ph/0501298 Class Transitions in Black Holes
astro-ph/0410556 Inclination Effects and Beaming in Black Hole X-ray Binaries
astro-ph/0312033 Evidence for Black Hole Spin in GX 339-4: XMM-Newton EPIC-pn and RXTE Spectroscopy of the Very High State
arxiv:0706.2389 Models for microquasars
arxiv:0706.2562 X-ray observations of ultraluminous X-ray sources

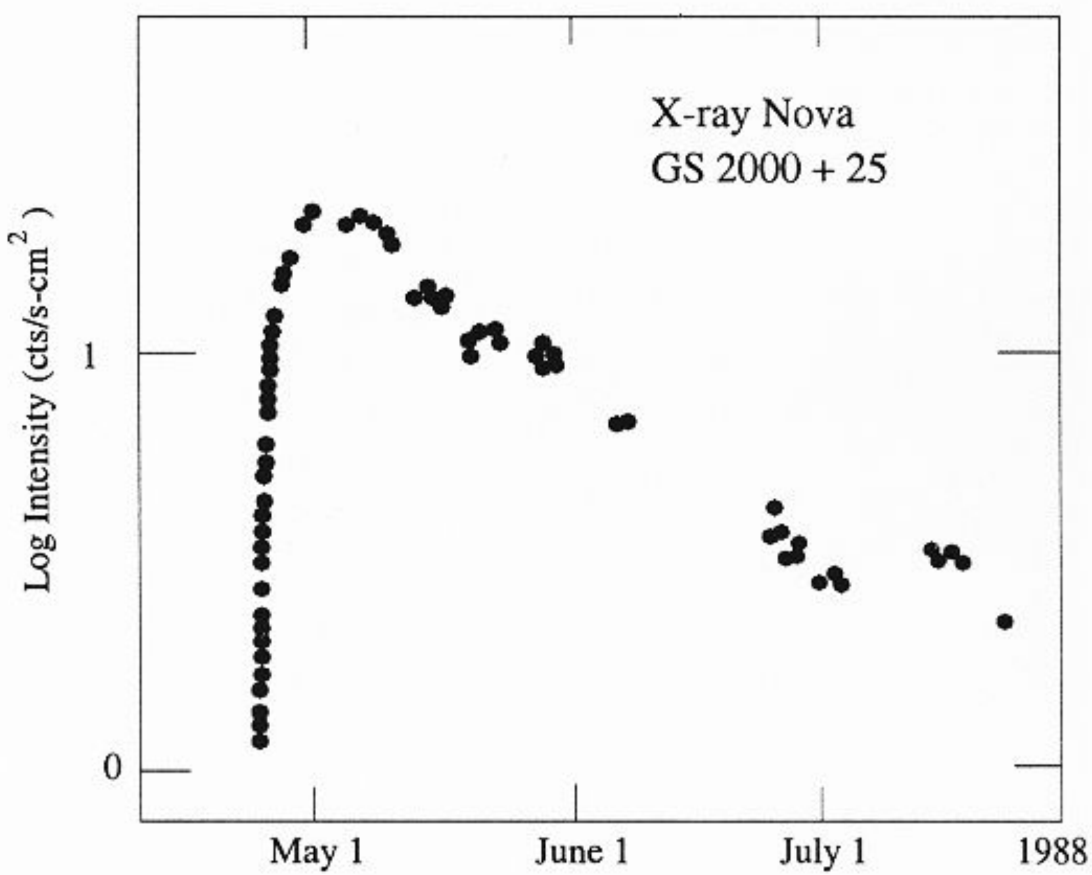
X-ray observations: Cyg X-1



"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 35 years ago...

X-ray novae

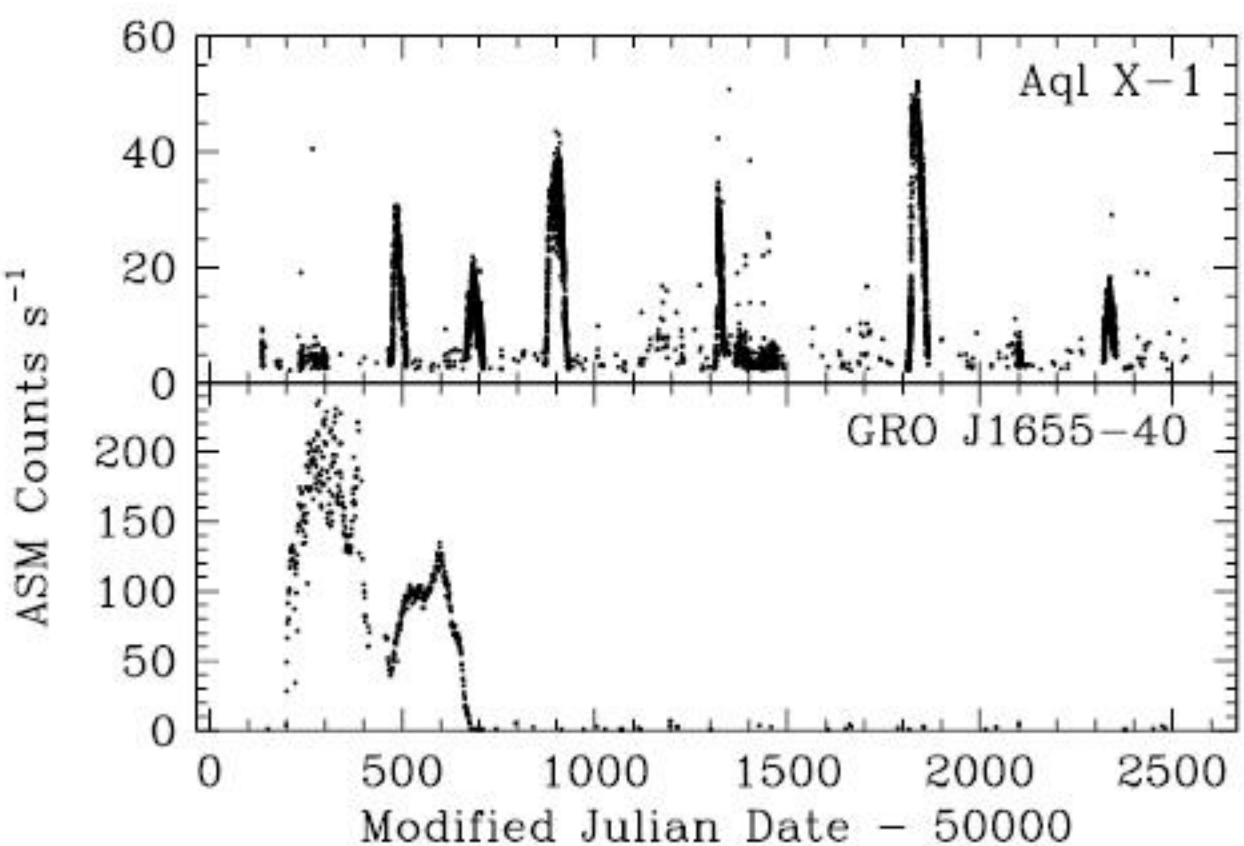


Low-mass binaries with BHs

One of the best candidates

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

X-ray nova light curve

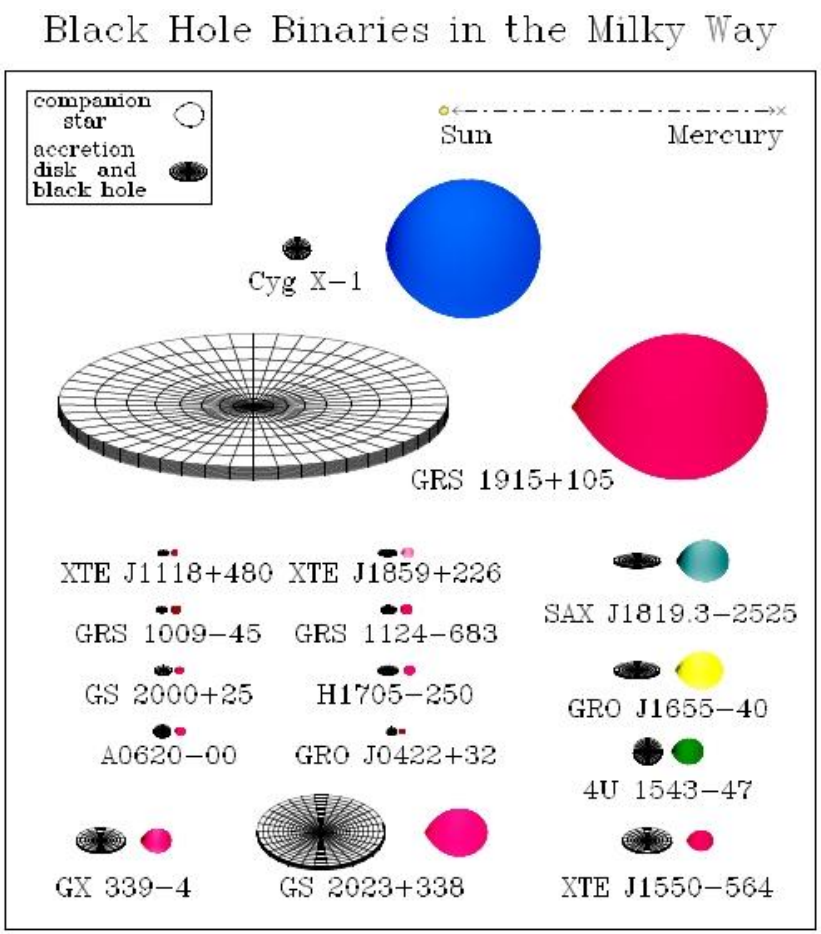


A NS system

A BH system

(Psaltis astro-ph/0410536)

BH candidates



(J. Orosz, from astro-ph/0606352)

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

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 “canditates to candidates”.

Mass determination

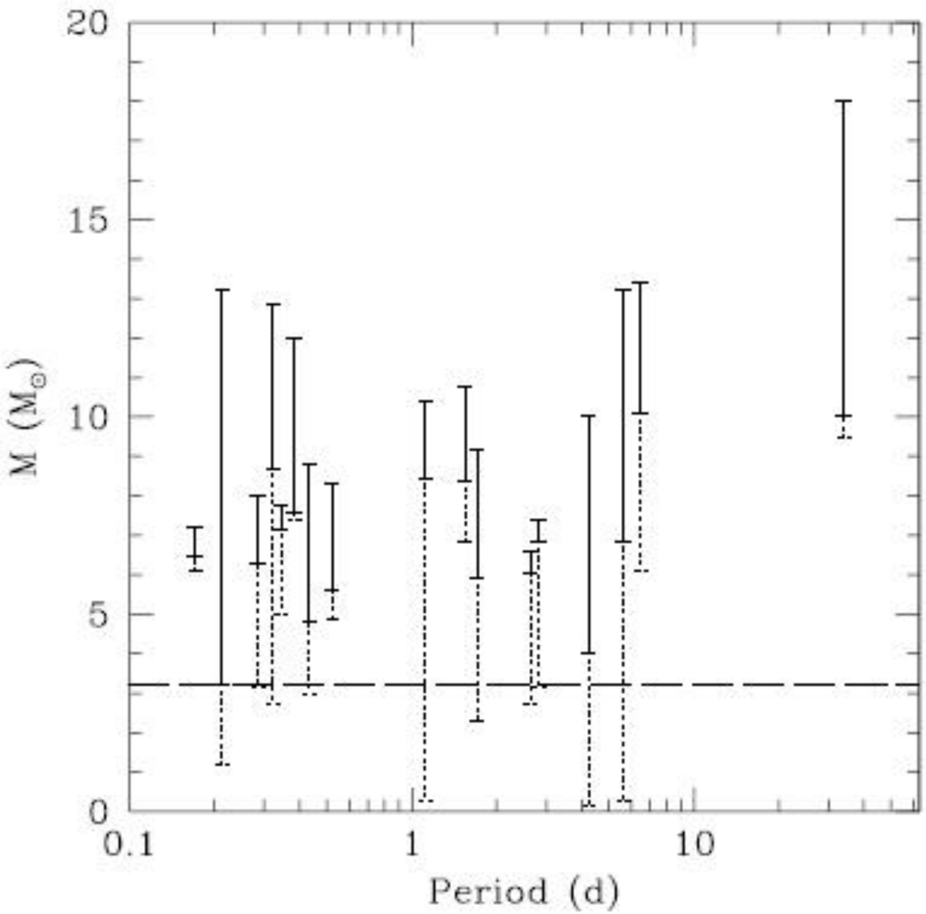
$$f_v(m)\frac{m_x^3 \sin i^3}{(m_x+m_v)^2} = 1,038 \cdot 10^{-7} K_v^3 P (1-e^2)^{3/2} ,$$

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*.

Black hole masses



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

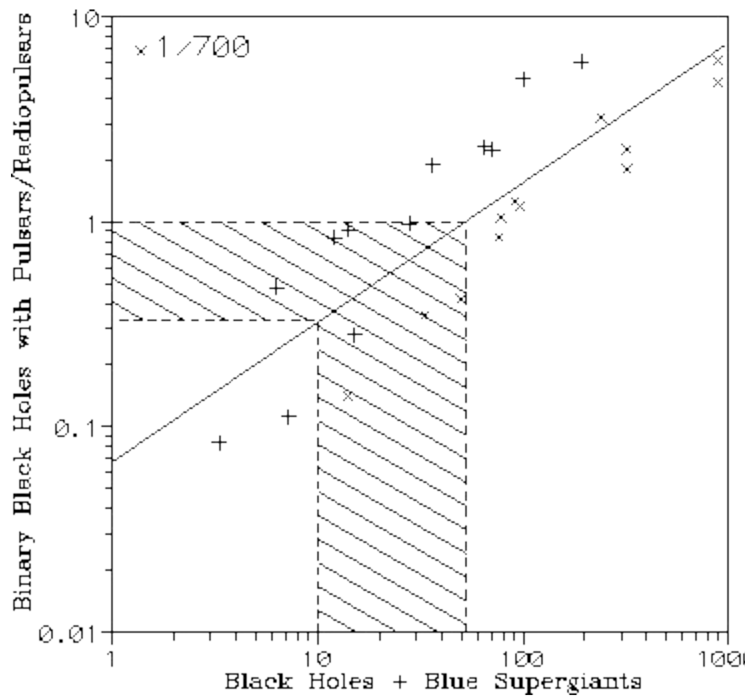
(Orosz 2002, see also
Psaltis astro-ph/0410536)

Systems BH + radio pulsar: a Holy Grail

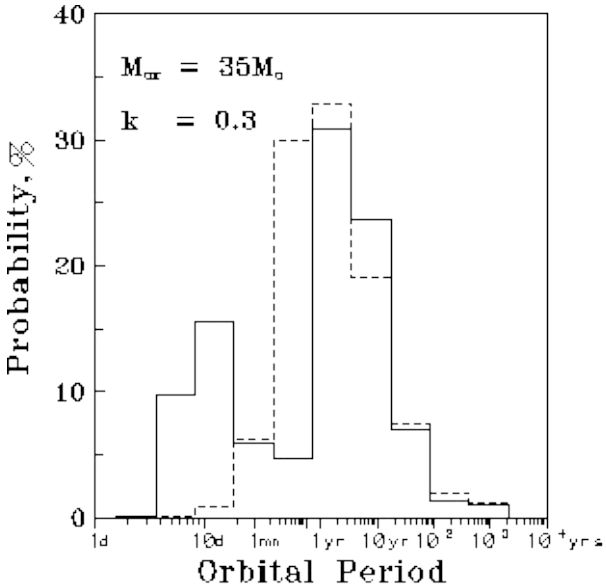
The discovery of a BH in pair with a radio pulsar can provide
the most direct proof of the very existence of BHs.
Especially, it would be great to find a system with a millisecond pulsar observed close to the orbital plane.
Computer models provide different estimates of the abundance of such systems.

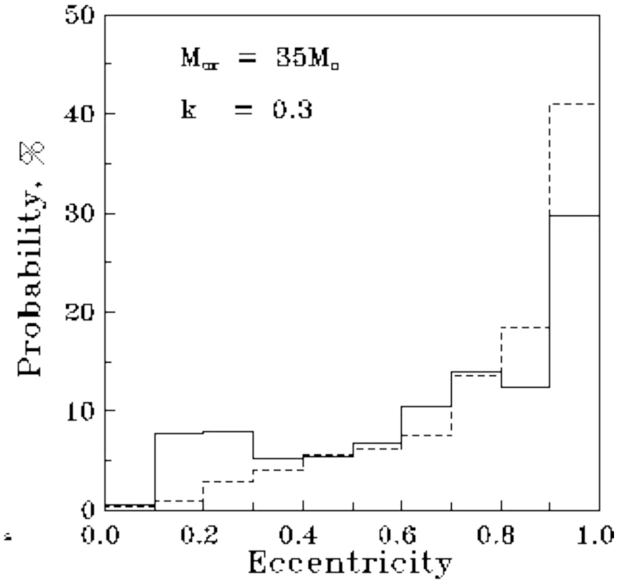
Lipunov et al (1994) give an estimate about one system (with a PSR of any type) per 1000 isolated PSRs.

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.



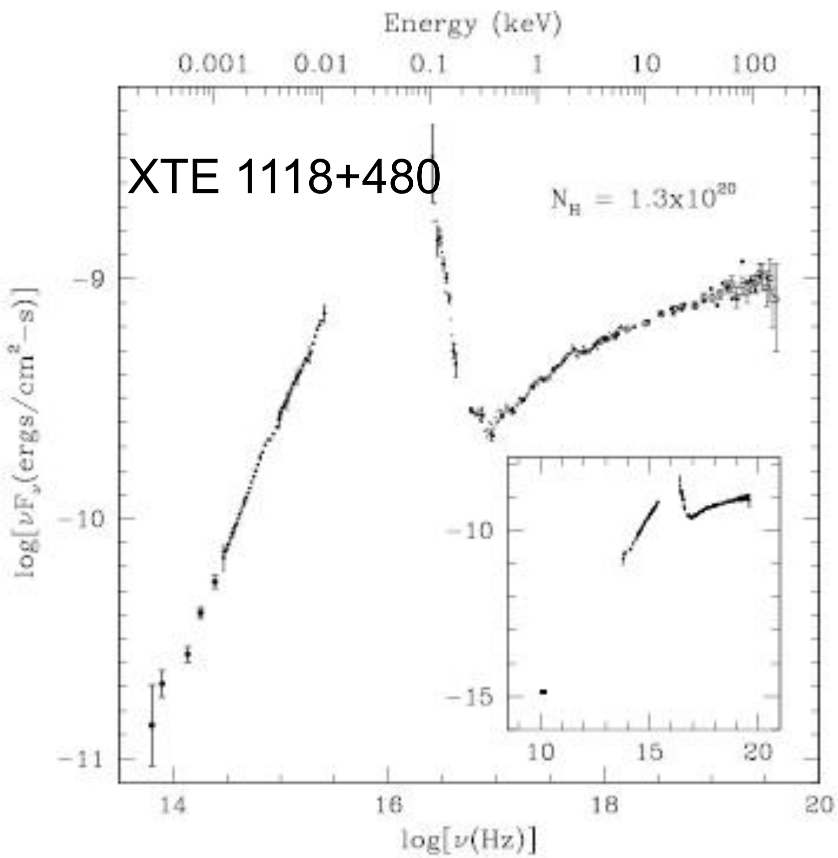
Parameters of systems BH+PSR

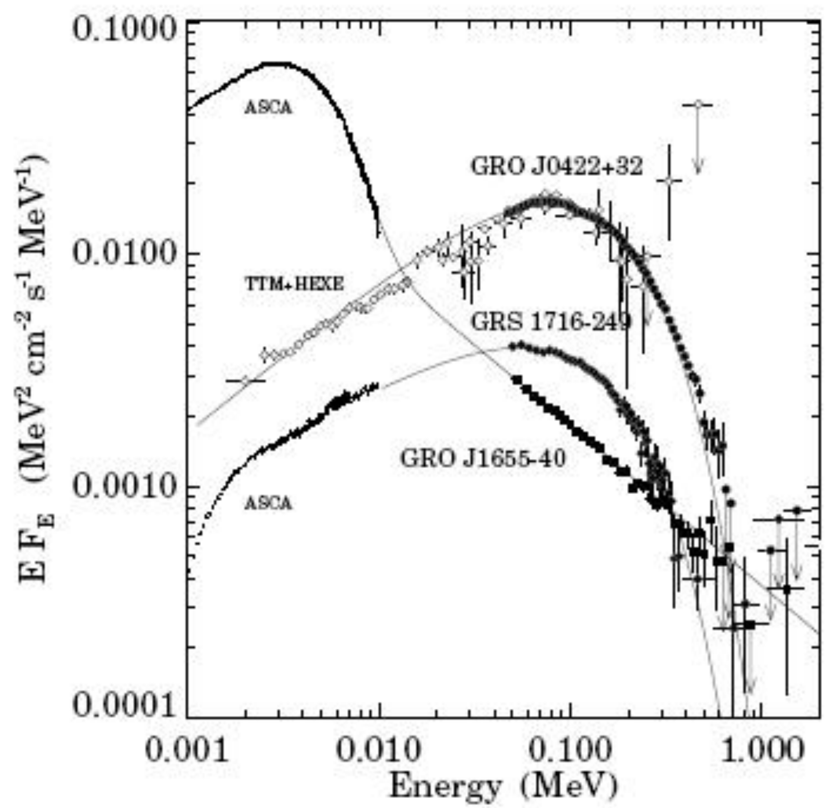




(Lipunov et al. 1994)

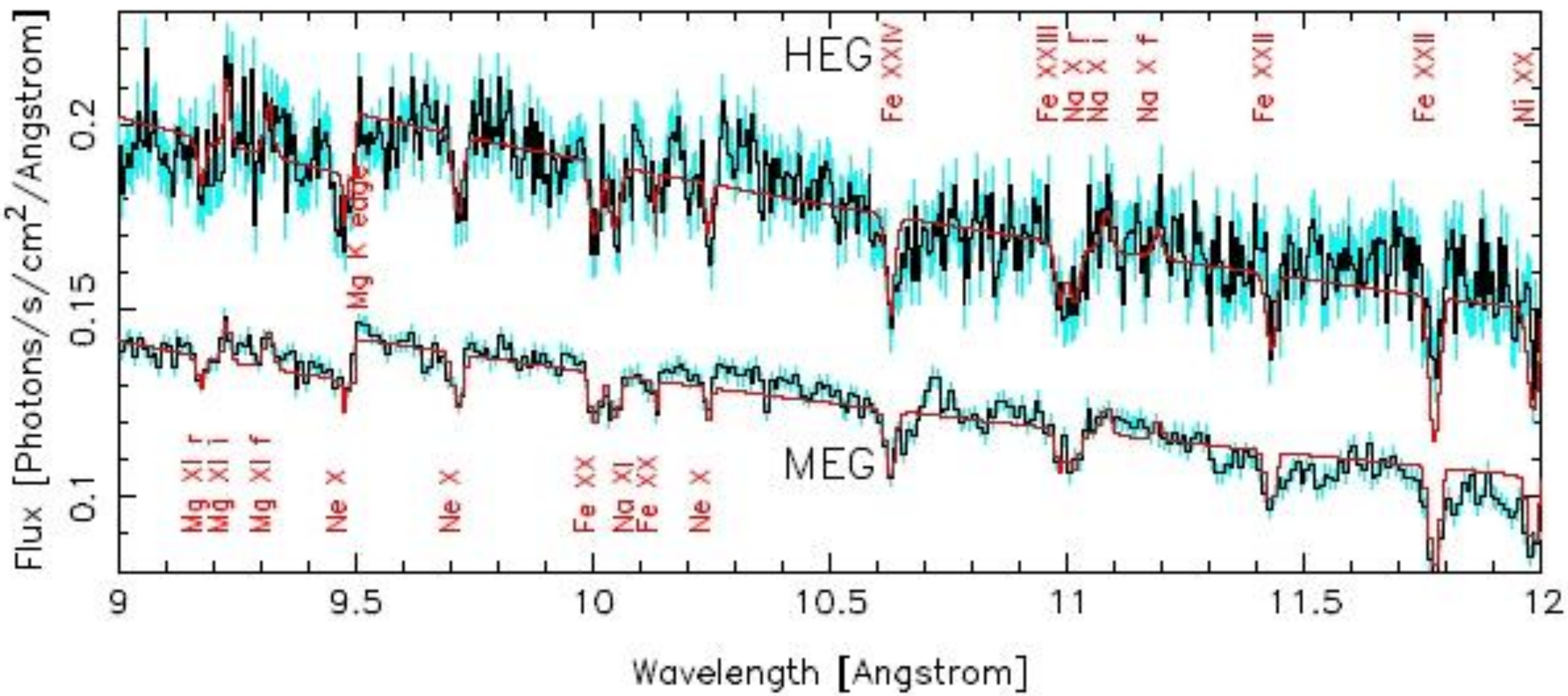
Spectra of BH candidates





(Psaltis astro-ph/0410536)

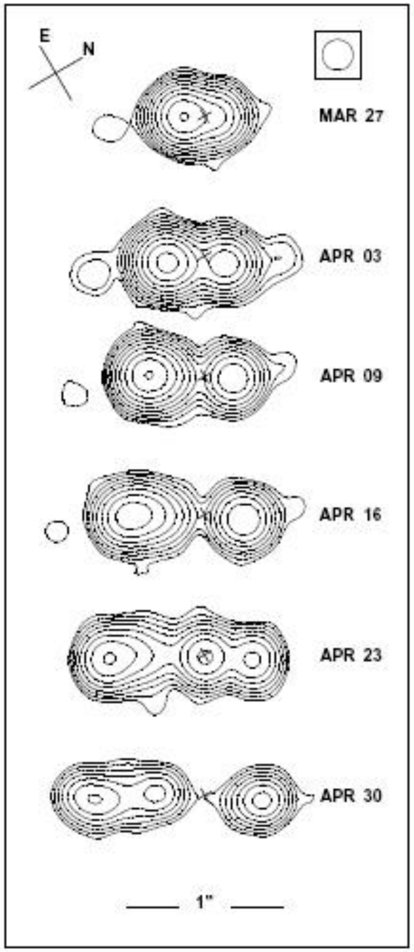
The spectrum of Cyg X-1



Absorption features are formed in the wind of the companion.

(Miller et al. 2002, see Psaltis astro-ph/0410536)

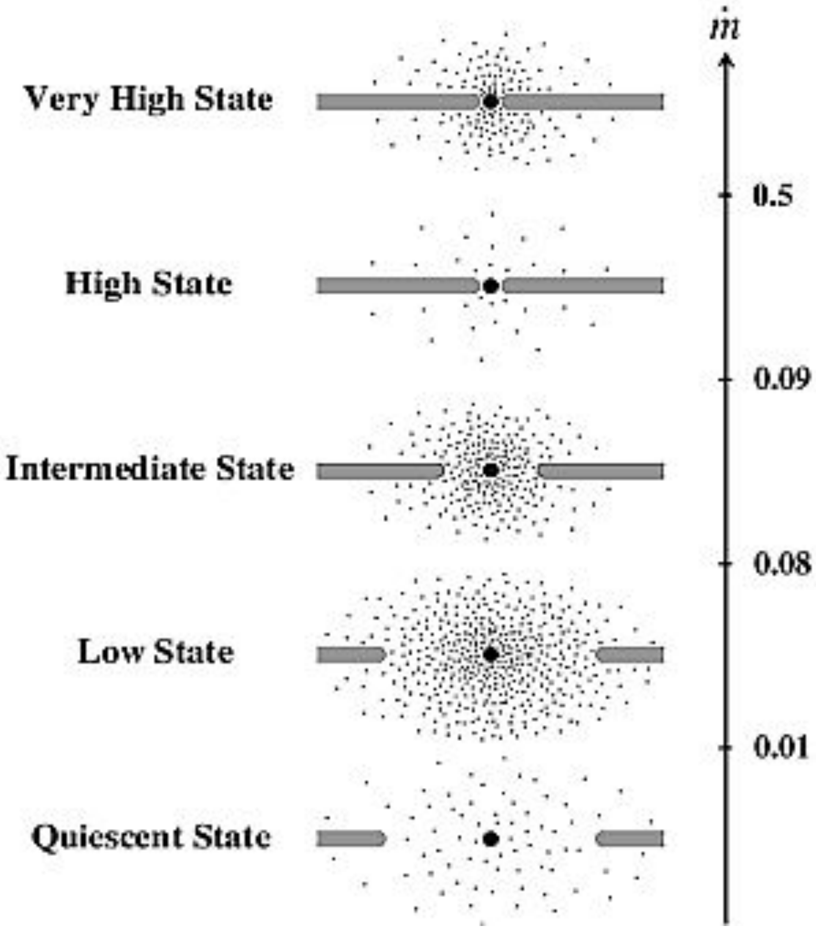
Jet from GRS 1915+105



VLA data. Wavelength 3.5 cm.

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

States (luminosity+spectrum+jet)



The understading 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

Three-state classification

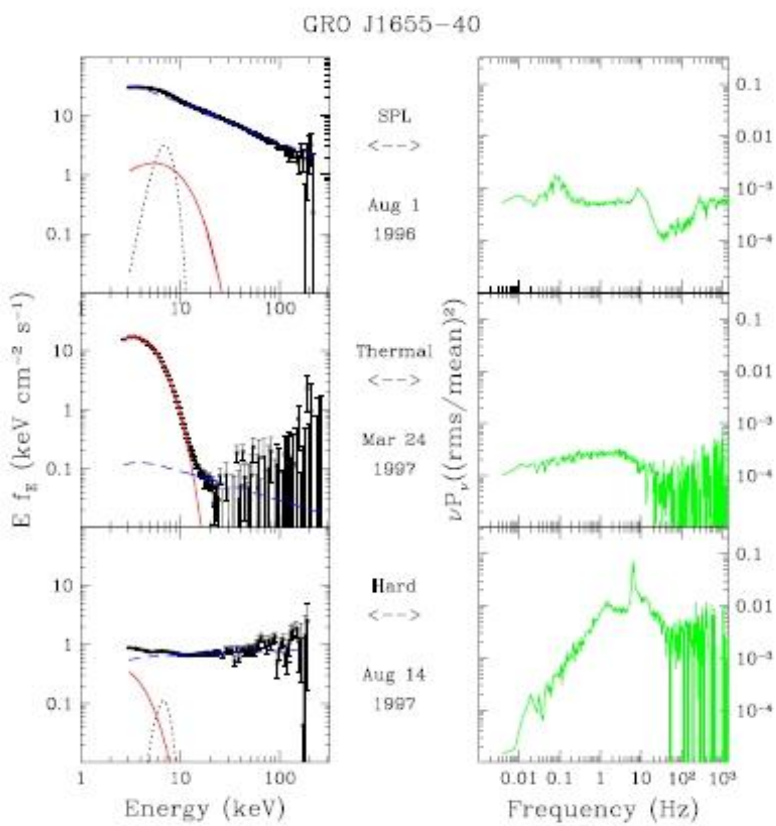


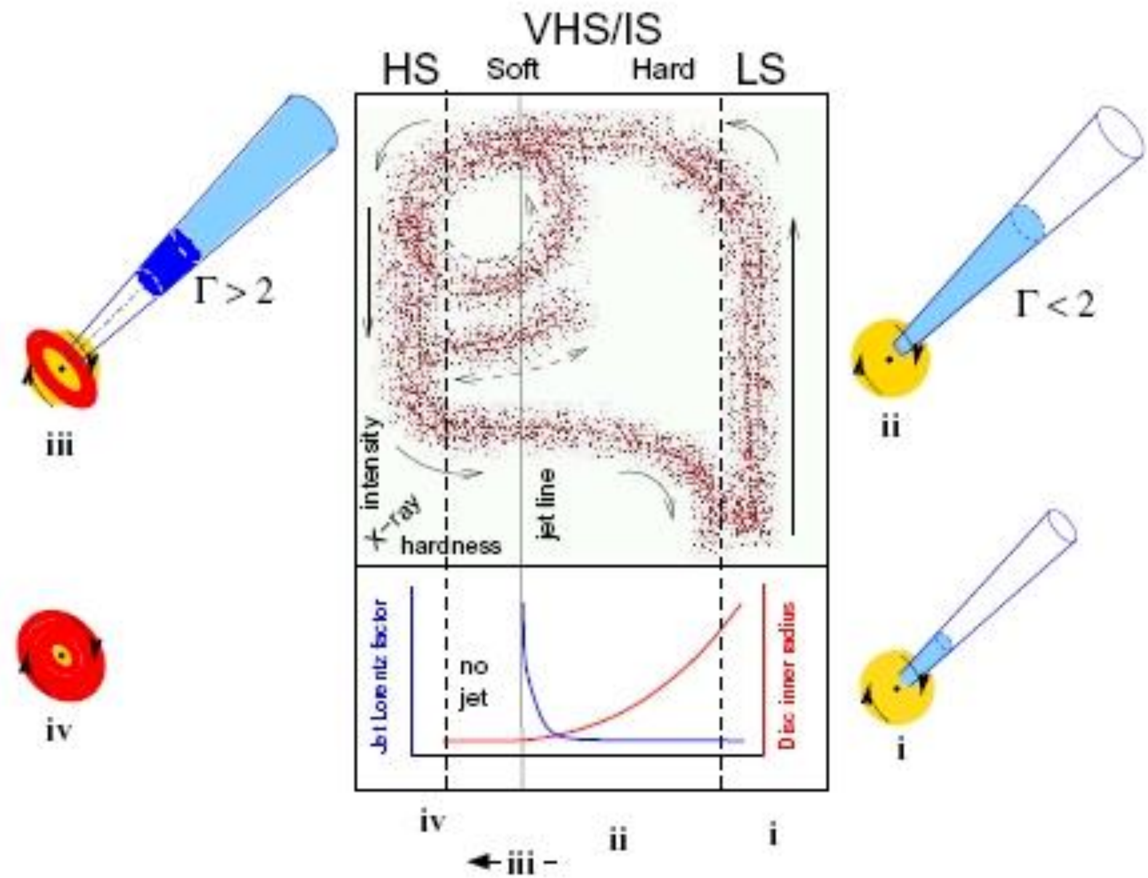
Table 2: Outburst states of black holes: nomenclature and definitions

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



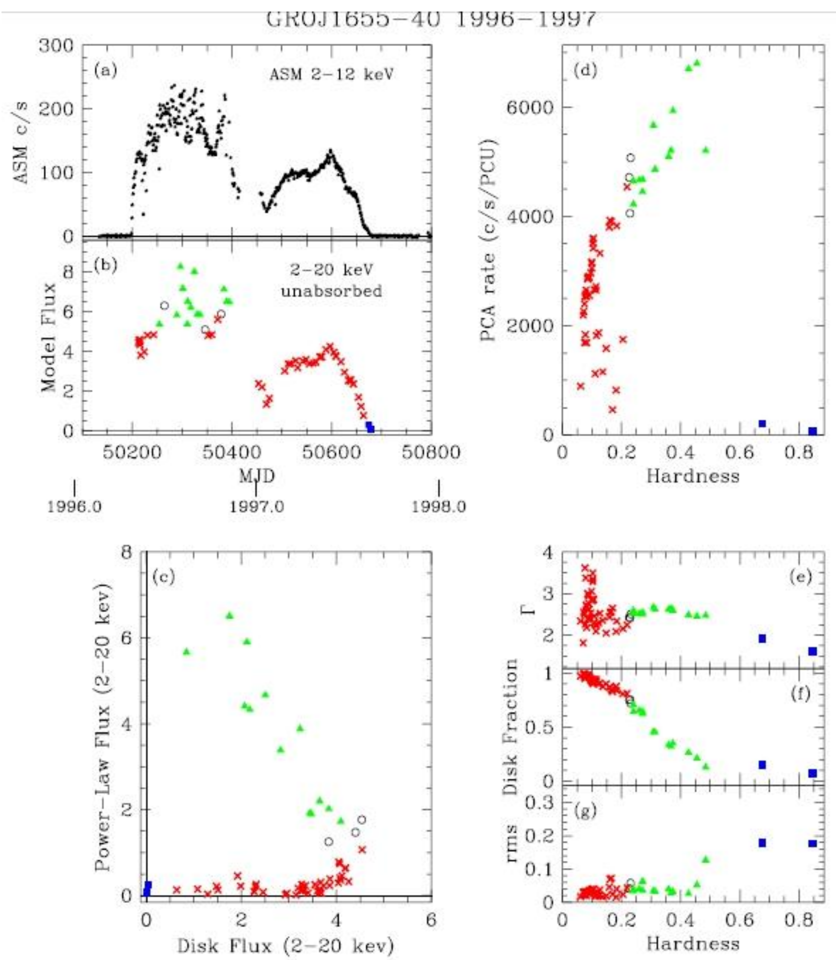
The model for systems with radio jets

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)

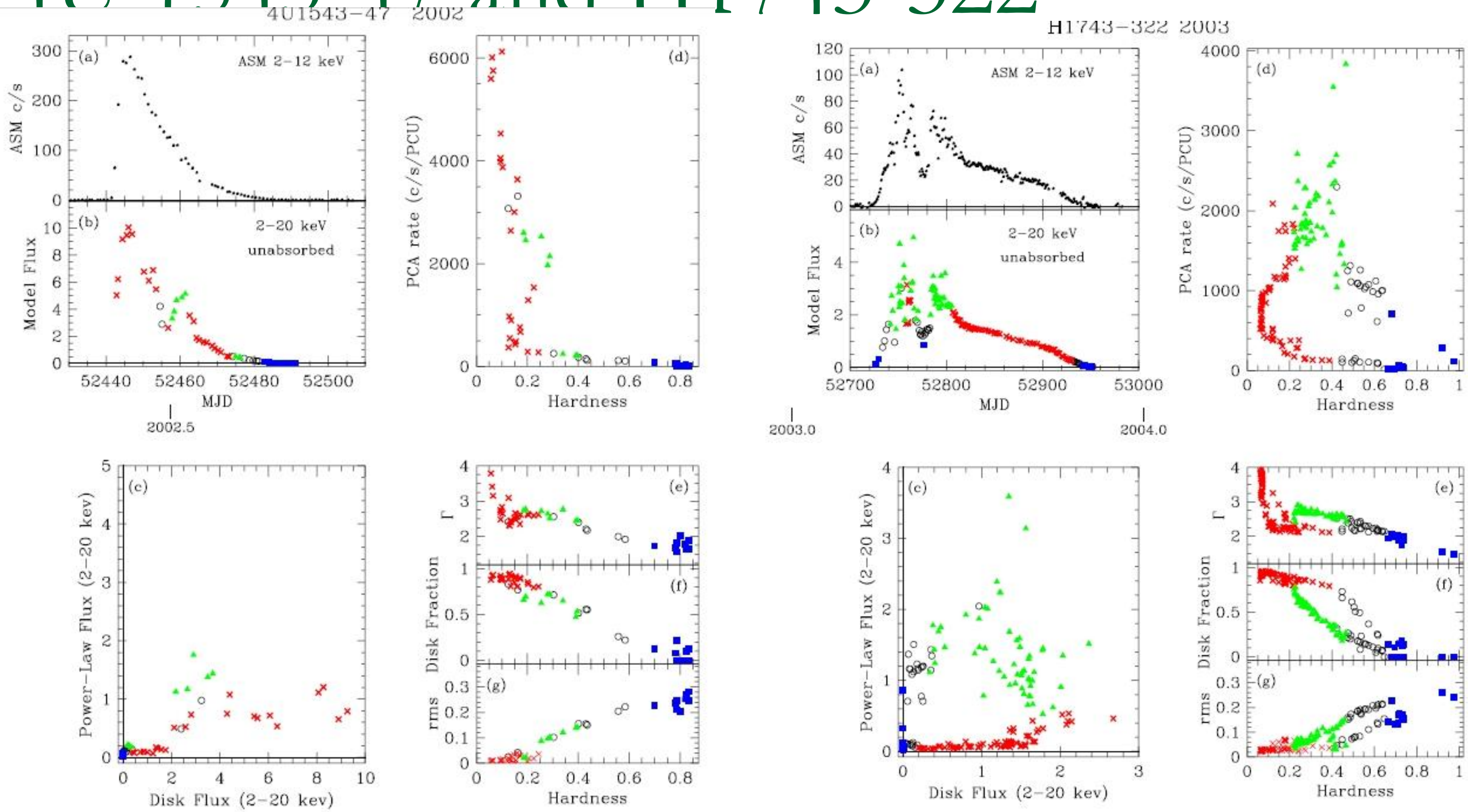
GRO J1655-40 during a burst



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

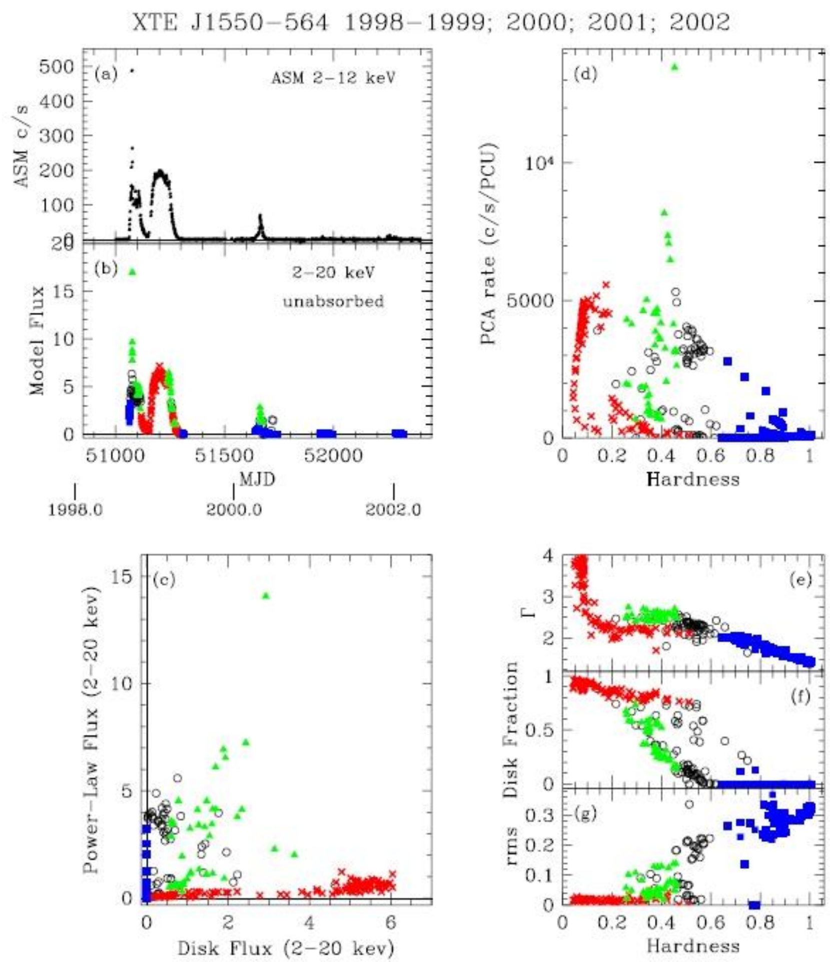
(Remillard, McClintock astro-ph/0606352)

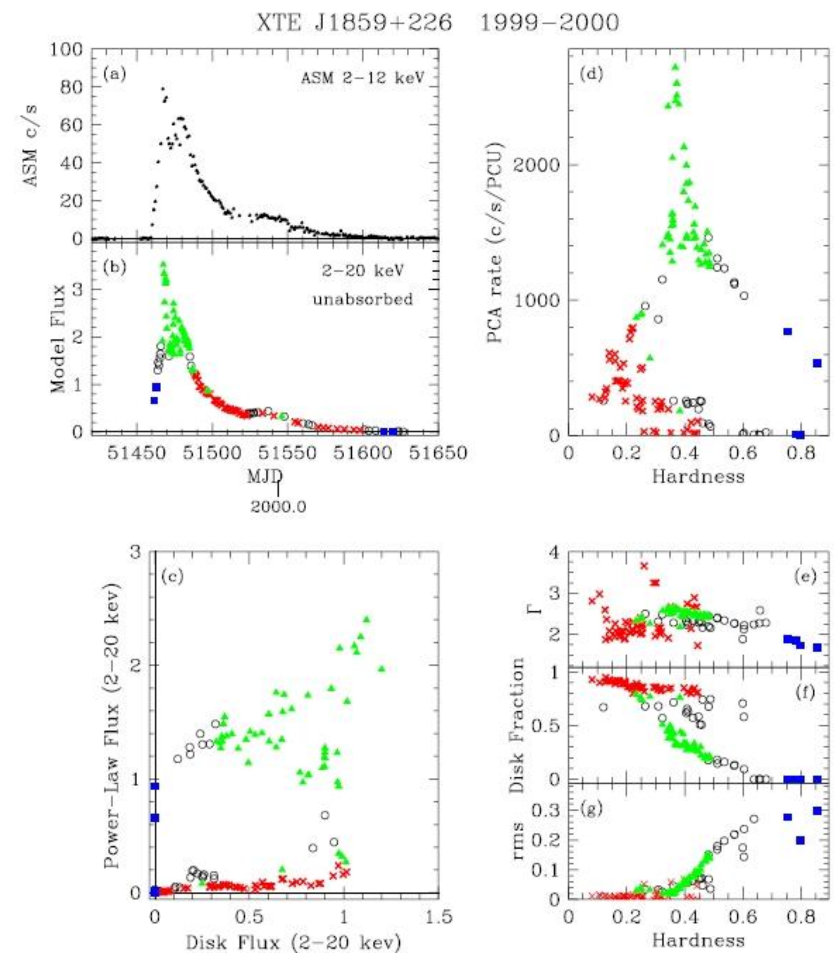
4U 1543-47 and H1743-322



(Remillard, McClintock astro-ph/0606352)

XTE J1550-564 and XTE J1859-226





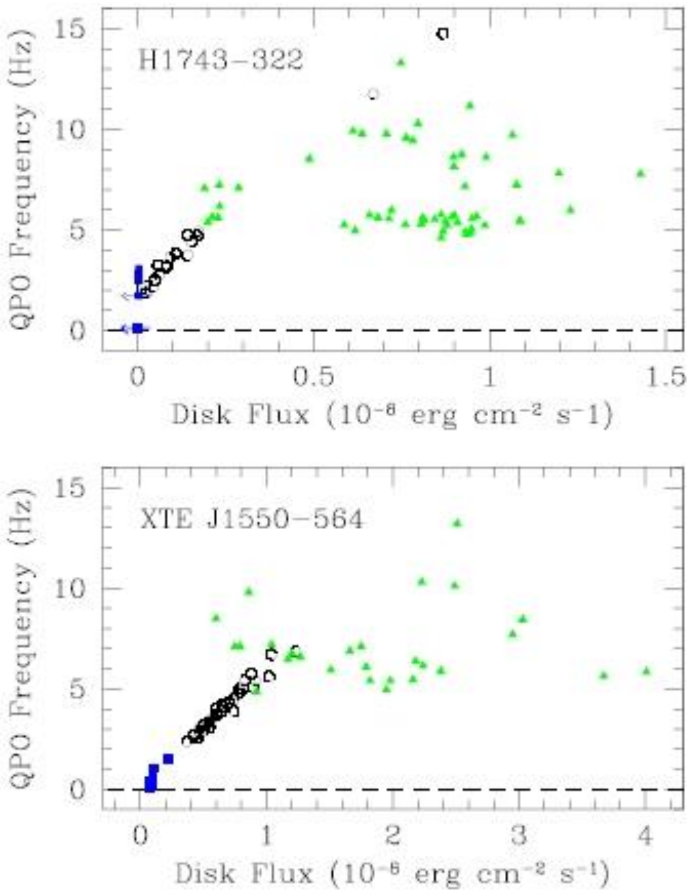
QPO

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 (7).
It is supposed that frequencies of these QPOs correspond to the ISCO.

QPO and flux from a disc



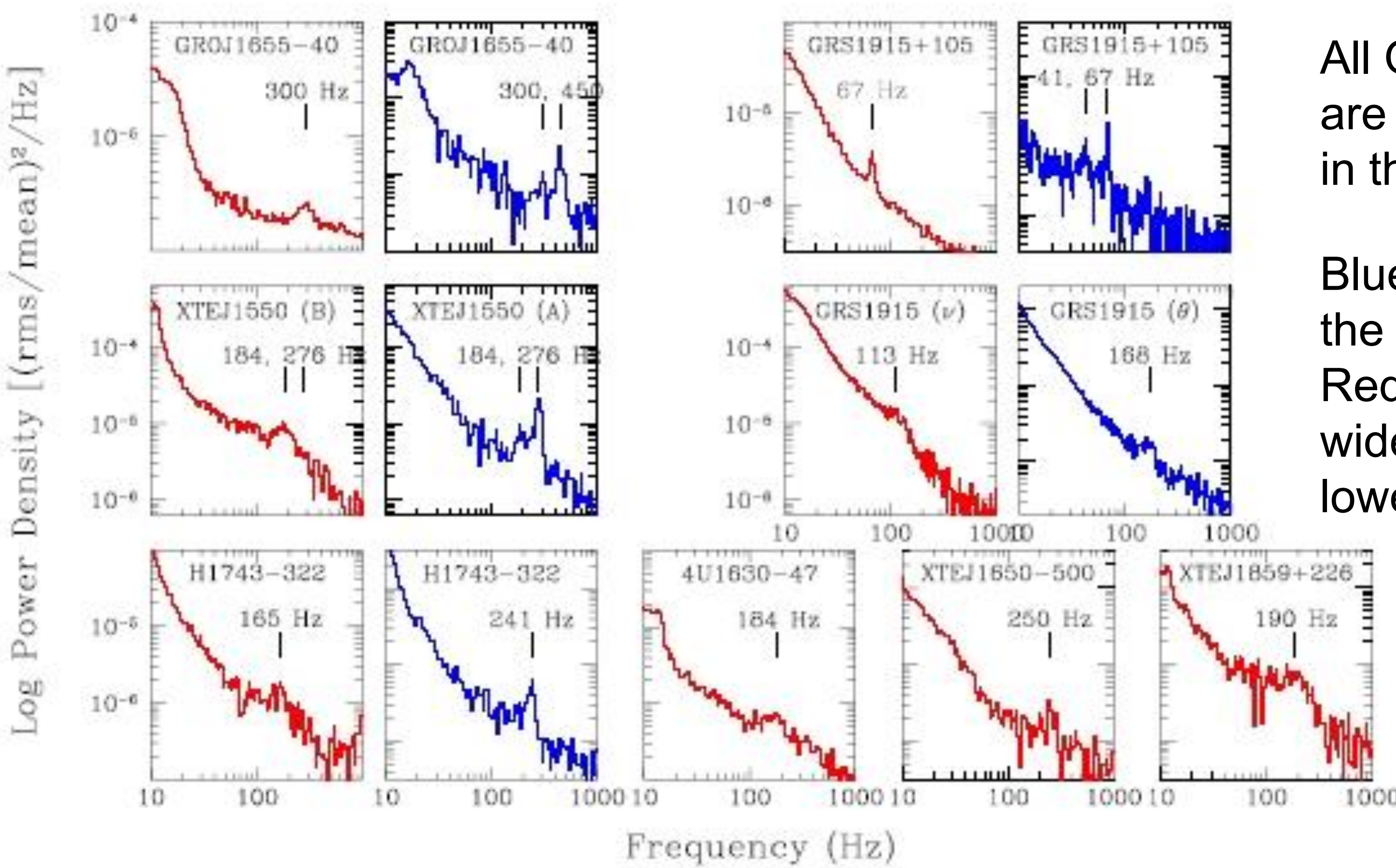
SPL – green triangles
Hard – blue squares
Intermediate states – black circles

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

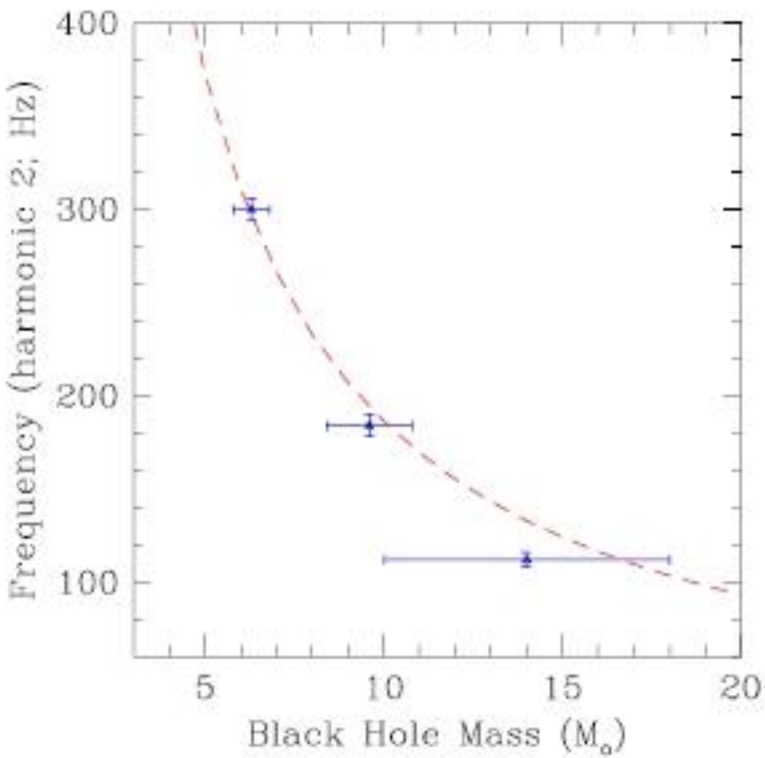


All QPO at >100 Hz are observed only in the SPL state.

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

(Remillard, McClintock astro-ph/0606352)

QPOs and BH masses

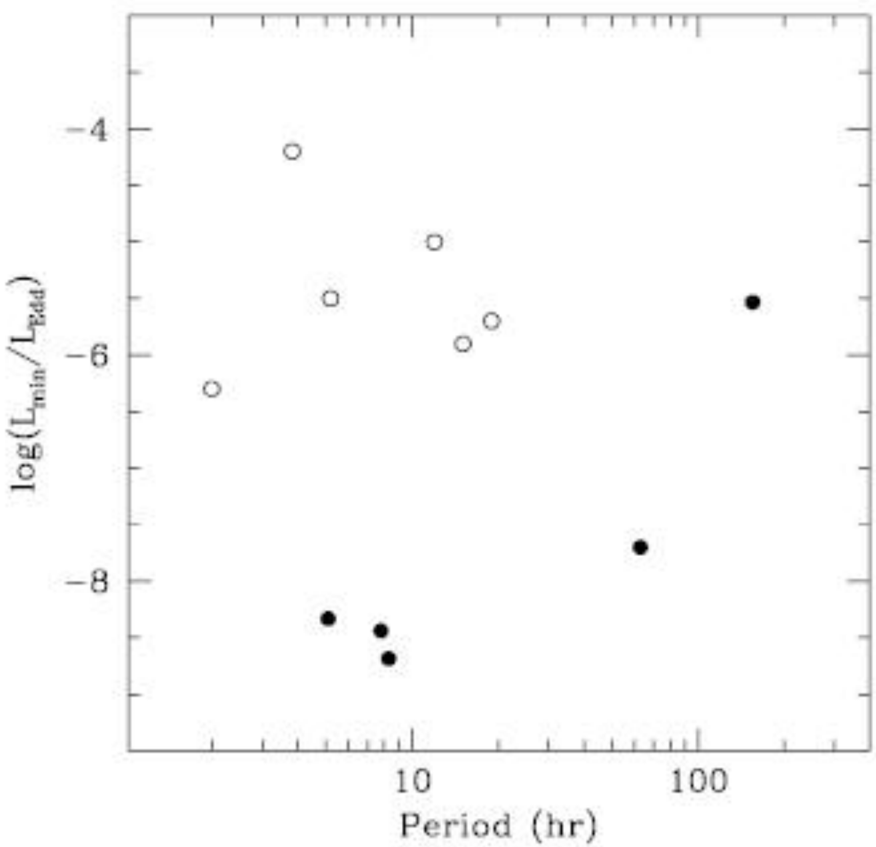


XTE J1550-564,
GRO J1655-40,
GRS 1915+105

Dashed line is plotted for the relation
$v_0 = 931\ \mathrm{Hz}\ (M/M_O)^{-1}$

(Remillard, McClintock astro-ph/0606352)

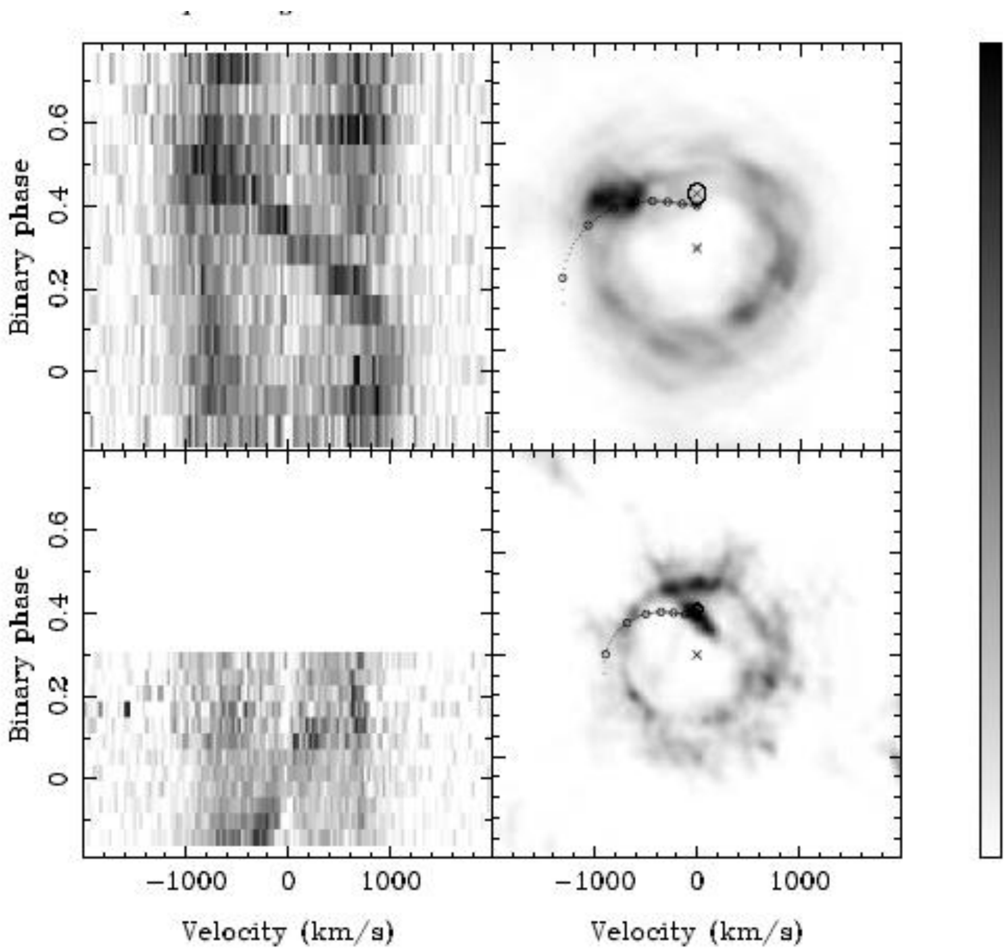
Quescent luminosity vs. Orbital period



Open symbols – neutron stars
black symbols – black holes.

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

GS 2000+25 and Nova Oph 1997



On the left – Hα spectrum,
On the right – the Dopler image

GS 2000+25

Nova Oph 1997

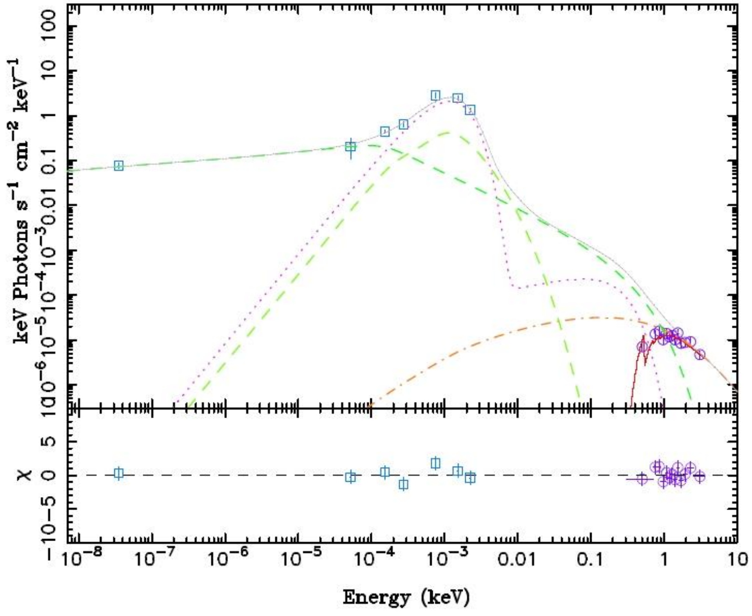
See a review in Harlaftis 2001 (astro-ph/0012513)

(Psaltis astro-ph/0410536)

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

IR observ. of sources in quescent state

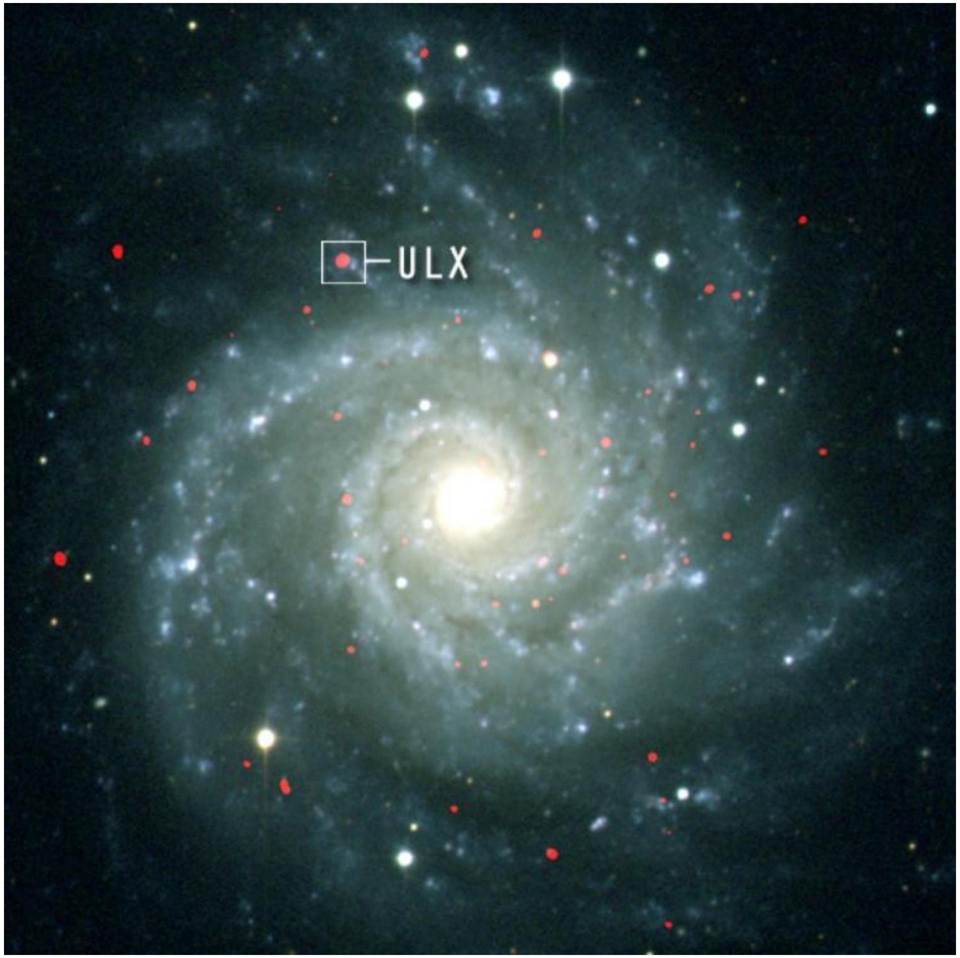
arXiv:0707.0028 E. Gallo et al.
“The spectral energy distribution of quiescent black hole X-ray binaries: new constraints from Spitzer”



Excess at 8-24 microns.

Possible explanation: jet synchrotron emission.

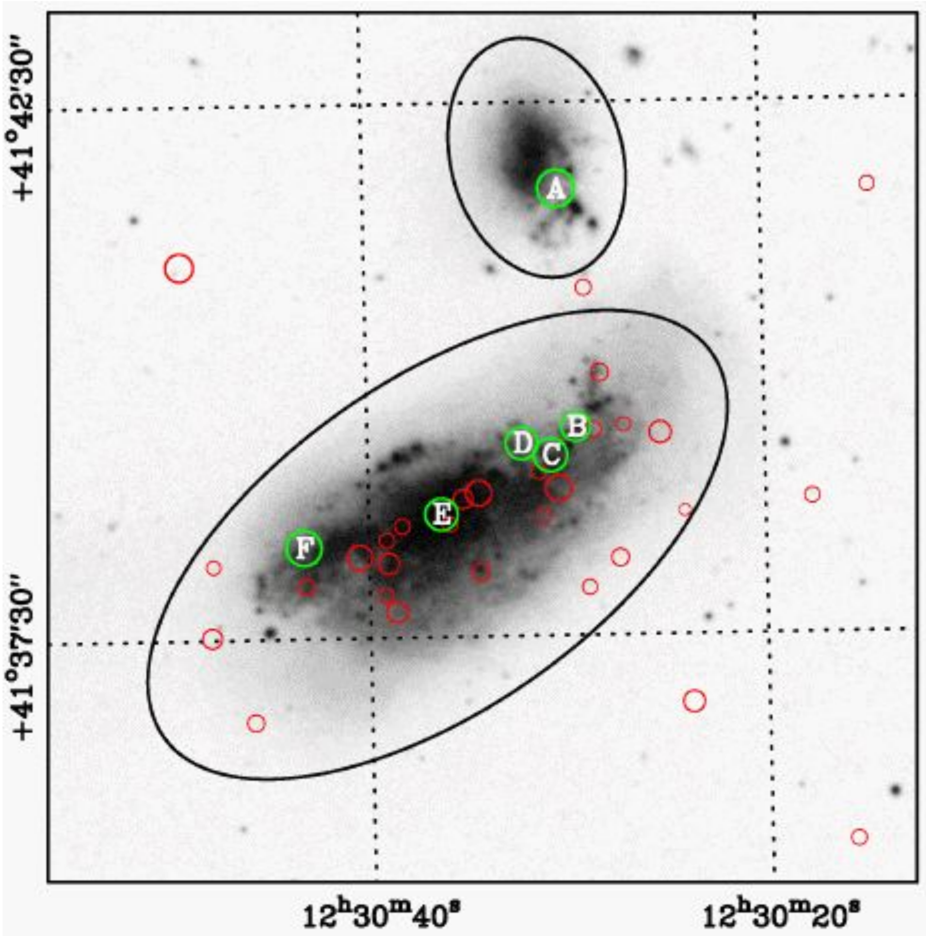
Ultraluminous X-ray sources



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

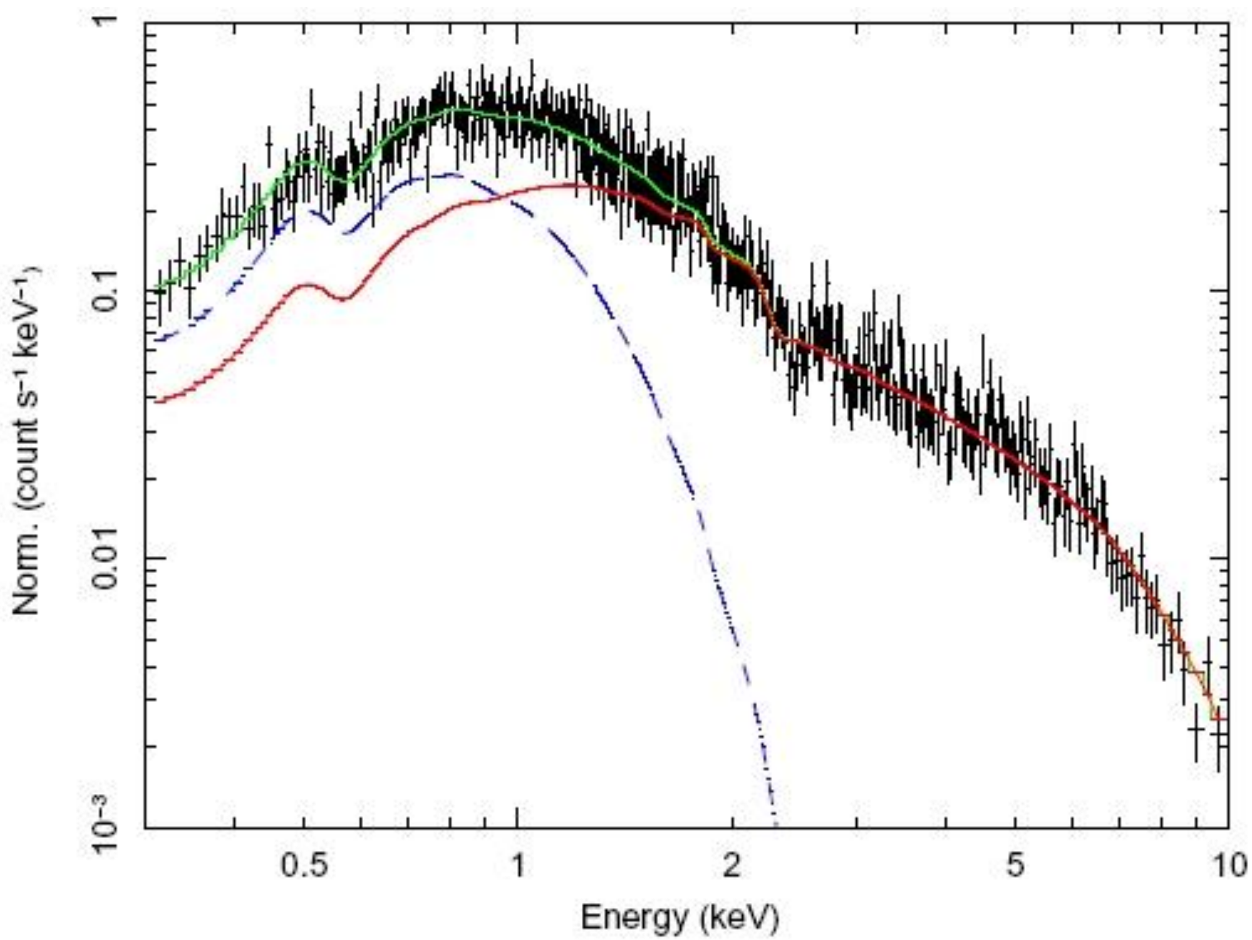
Now many sources of this type are known. Their nature is unclear. Probably, the population contains both: stellar mass BHs with anisotropic emission and intermediate mass BHs.

ULXs in NGC 4490 and 4485



Six marked sources are ULXs

Spectrum of the ULX in NGC 1313



NGC 1313 X-1

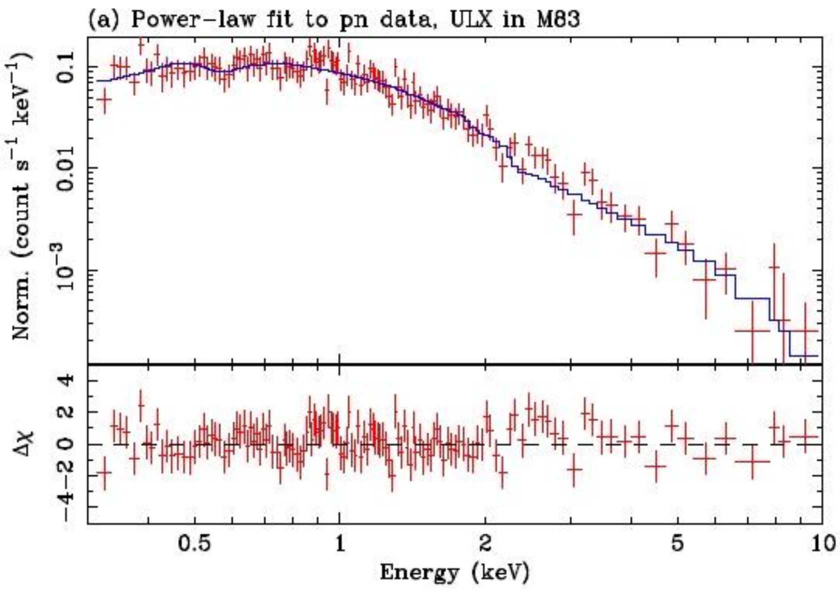
Green line –
the IMBH model.

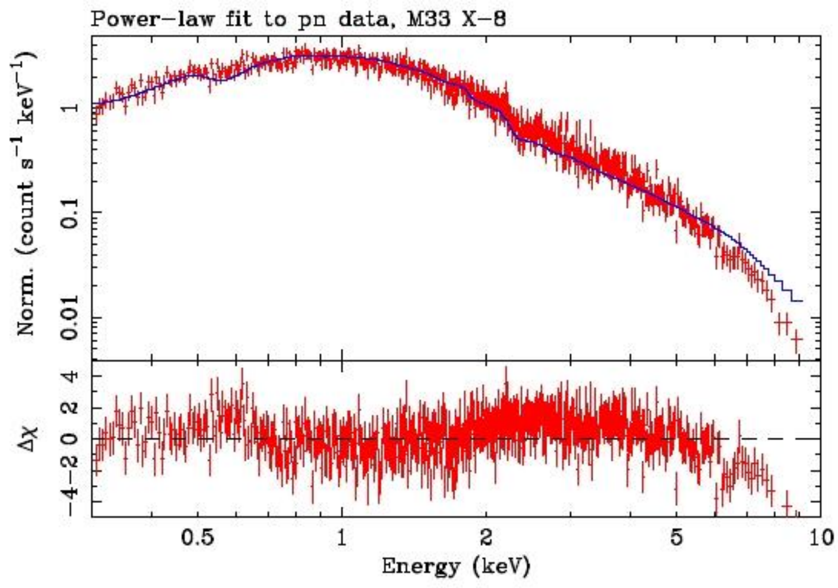
Red – thermal component.

Blue – power-law.

(arXiv 0726.2562)

Spectra of ULXs





(arXiv 0706.2562)

ULX in galaxies of different types

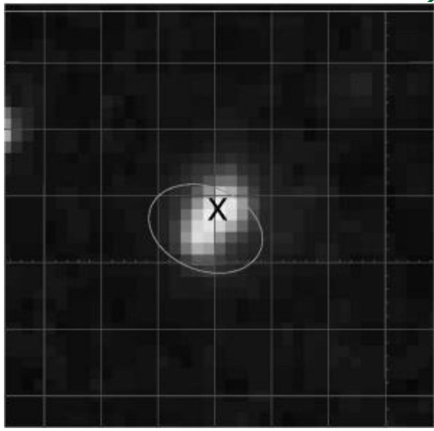
In the following two slides there are images of several galaxies from the SDSS in which positions of ULXs are marked.

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

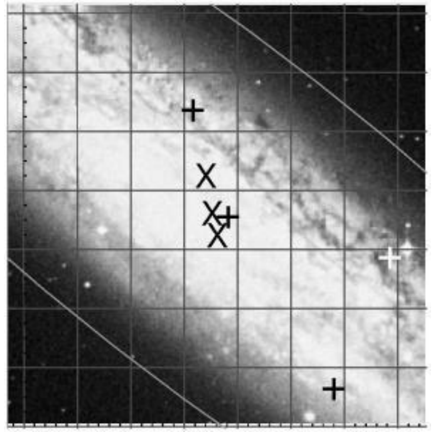
The size of one square element of the grid is 1.2 arcminute (except IZW 18, in which case the size is 0.24 arcminute in right ascension and 0.18 in declination).

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).

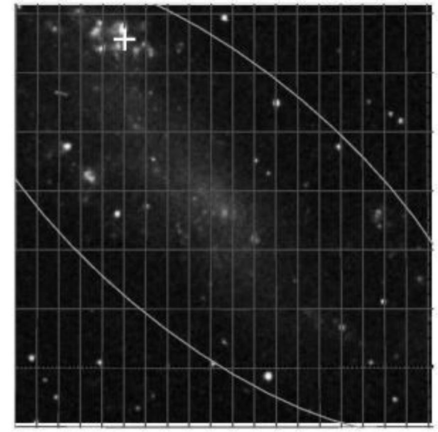
ULX in galaxies of different types



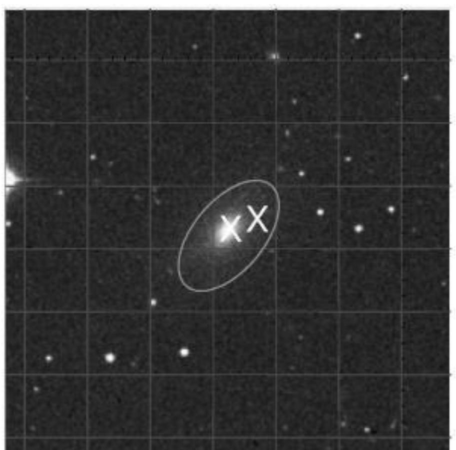
IZW 18



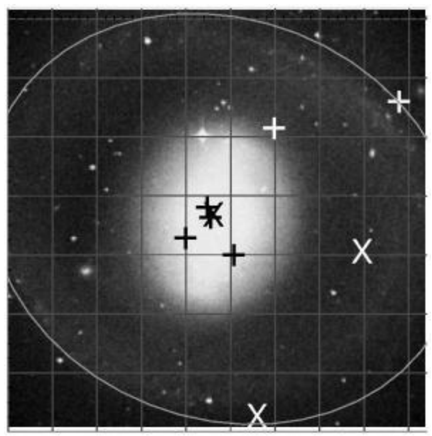
NGC 253



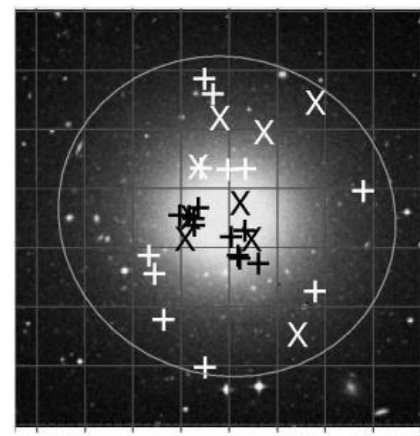
IC 2574



NGC 1132

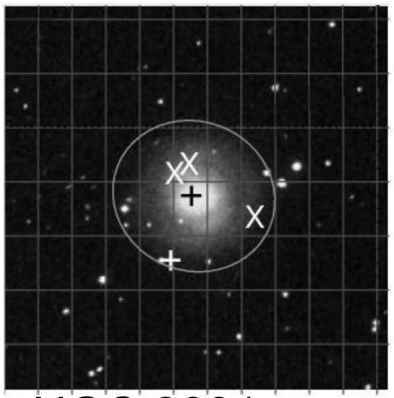


NGC 1291

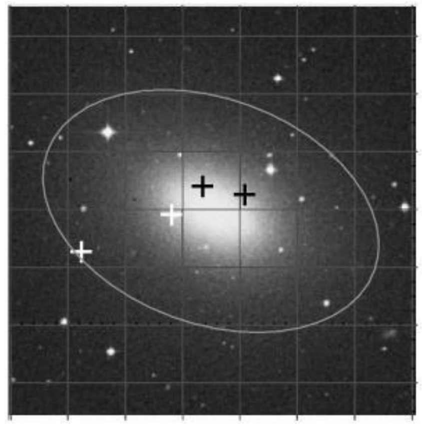


NGC 1399

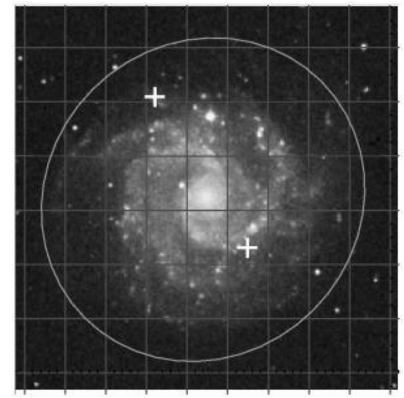
ULX in galaxies of different types



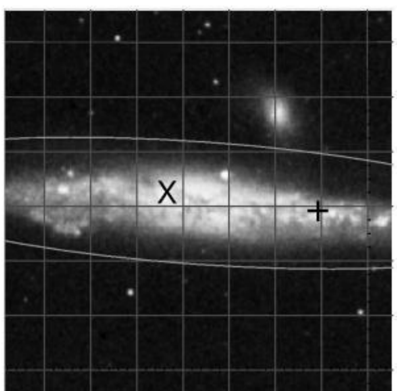
NGC 2681



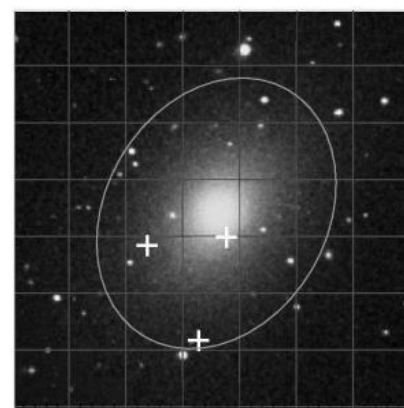
NGC 4697



NGC 3184

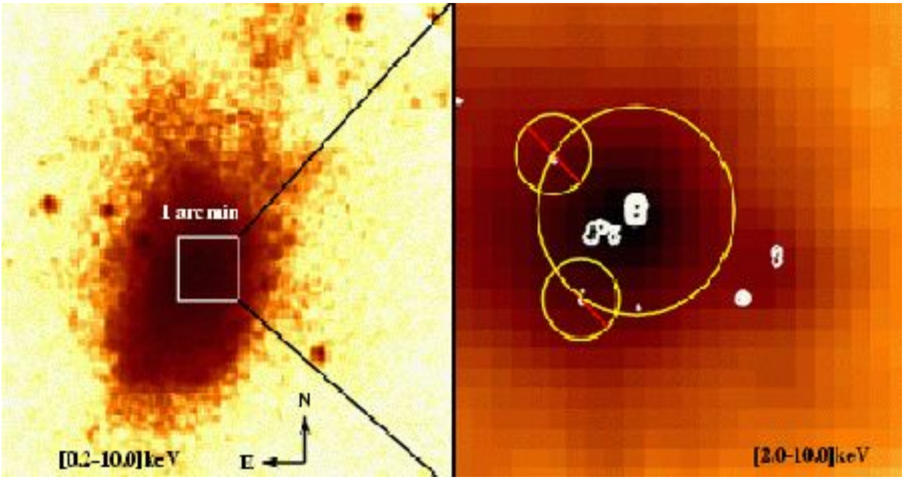


NGC 4631



NGC 4636

The source X-1 in M82

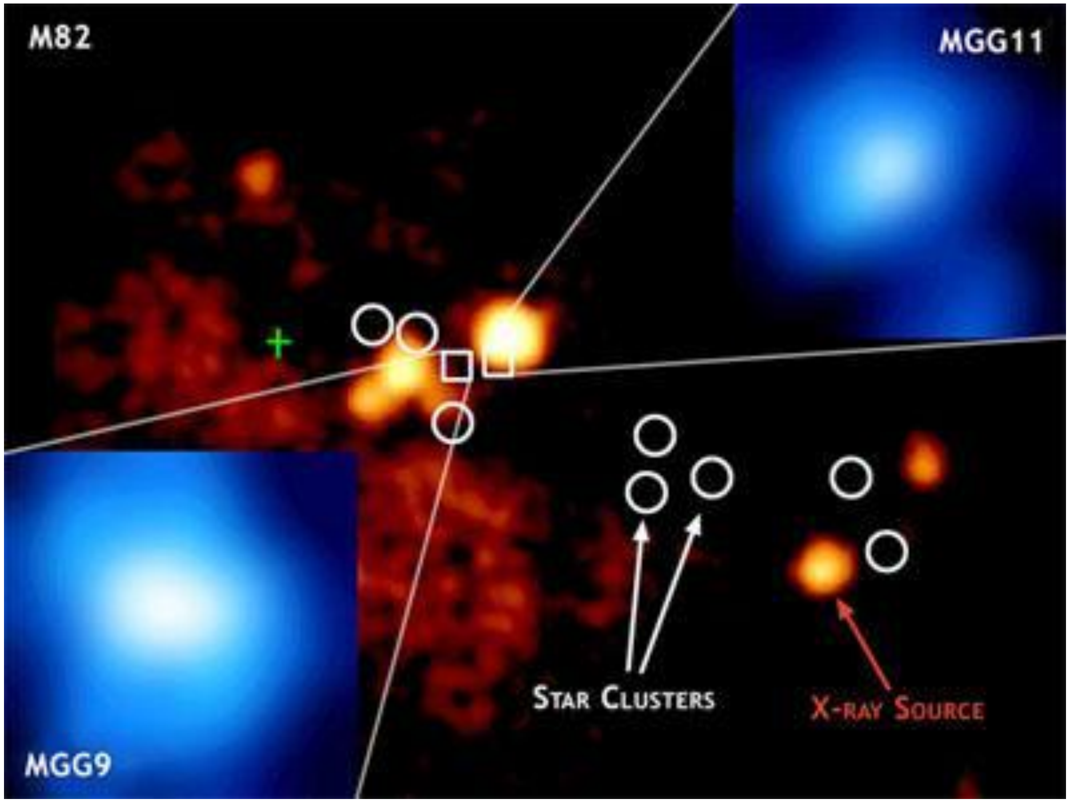


The source M82 X-1 is one of the most luminous, and so it is the best candidate to be an intermediate mass BH.

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

(http://www.pd.astro.it/oapd/2/2_1/2_1_5/2_1_5_1.html)

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)

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. Different types of sources (pulsars, SNR, contamination)
4. Background sources.