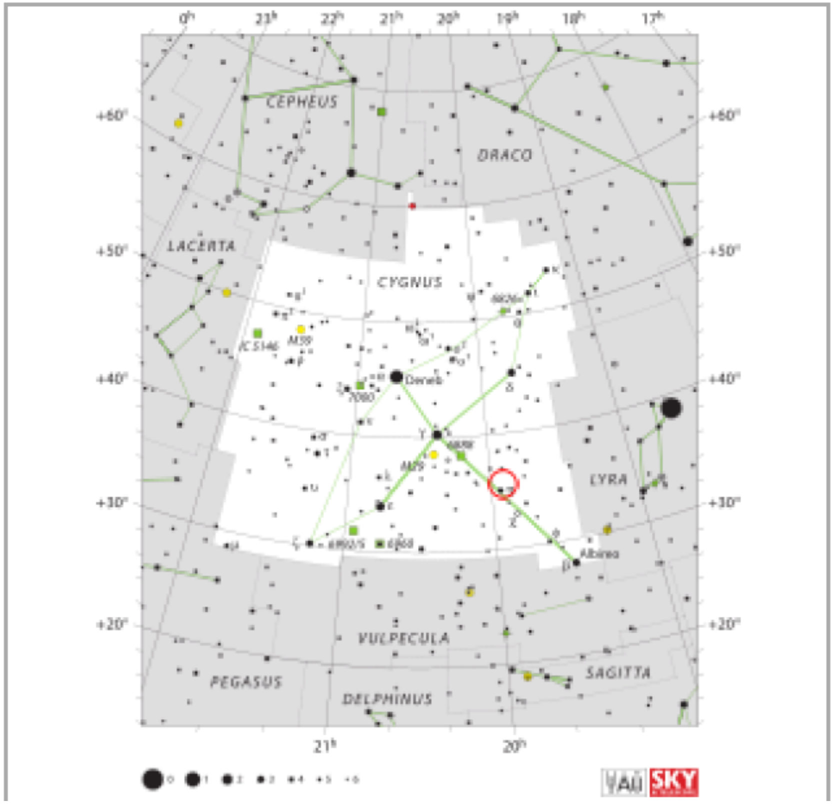
Applications: neutron stars and galactic black holes

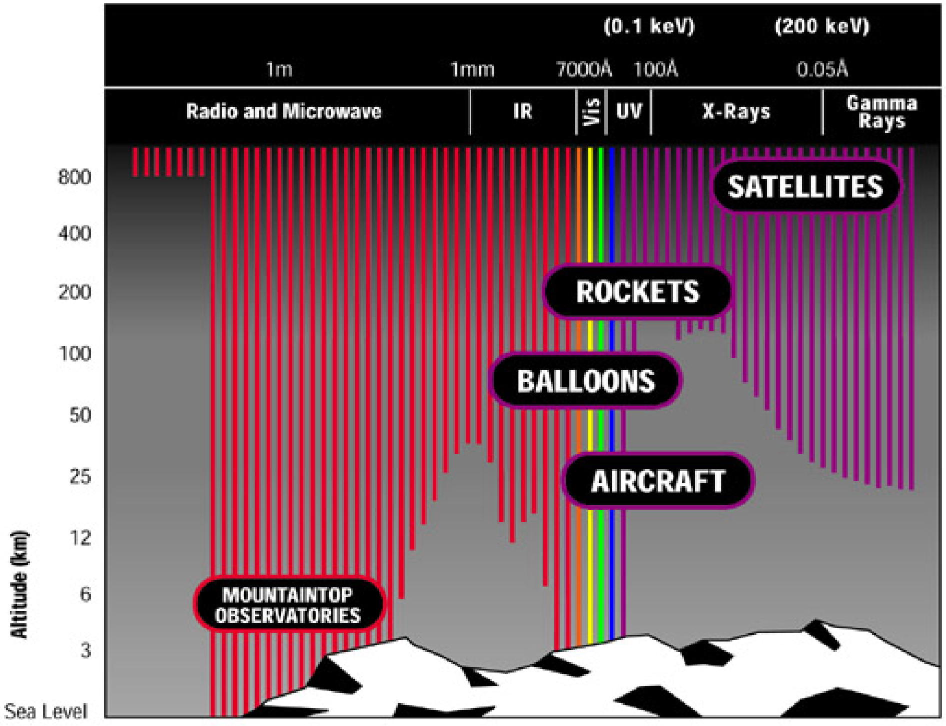
1. Historical comment about the X-ray astronomy

When talking about accreting neutron stars and black holes we will use mostly X-ray data since these sources were discovered in X-rays and emitt most of their energy in X-ray domain. This is reflected in the sources names, like **Cygnus X-1** (the first X-ray source discovered in the Cygnus constellation) or **4U 0614+091** (source contained in 4th Uhuru catalog).

X-rays can be seen only using the satellites located above the Earth atmosphere, as we talked in lecture 1.

Cygnus X-1/HDE 226868





1. Historical comment about the X-ray astronomy

As we also talked in lecture 1, X-ray astronomy started with the space program developed by Riccardo Giacconi (Noble prize laureate in 2002) working in USA, who initially used military rockets for detection of X-ray sources.

Wikipedia

Major steps in X-ray astronomy:

- 1948 – discovery of X-ray emission from the Sun (rocket V2)
- 1962 – discovery of the first extrasolar X-ray source – Scorpius X-1 (rocket Adobee)
- 1966 – optical identification of Sco X-1 (named later V818 Sco) (Sandage et al.)
- 1967 – first X-ray nova
- 1967 – discovery of radio pulsars - confirmation of neutron star existence
- 1970 – beginning of the mission of the first astronomical satellite Uhuru

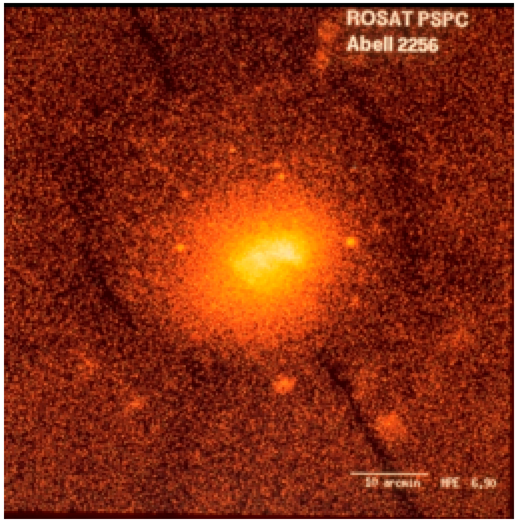
The final catalog – 4th Uhuru catalog, was the first comprehensive X-ray catalog, contains 339 objects and covers the whole sky in the 2–6 keV band.

In 1972 it became clear that the X-ray emission is powered by accretion onto a neutron star or a black hole from the companion (donor star). Lightcurves, emission lines in the companion optical spectra clearly showed the binary star nature of these systems. Theoretical papers followed (Shakura 1972, Shakura i Sunyaev 1973), which brought the accretion disk theory, and implied the role of the radiative processes as well as the role of the magnetic field.

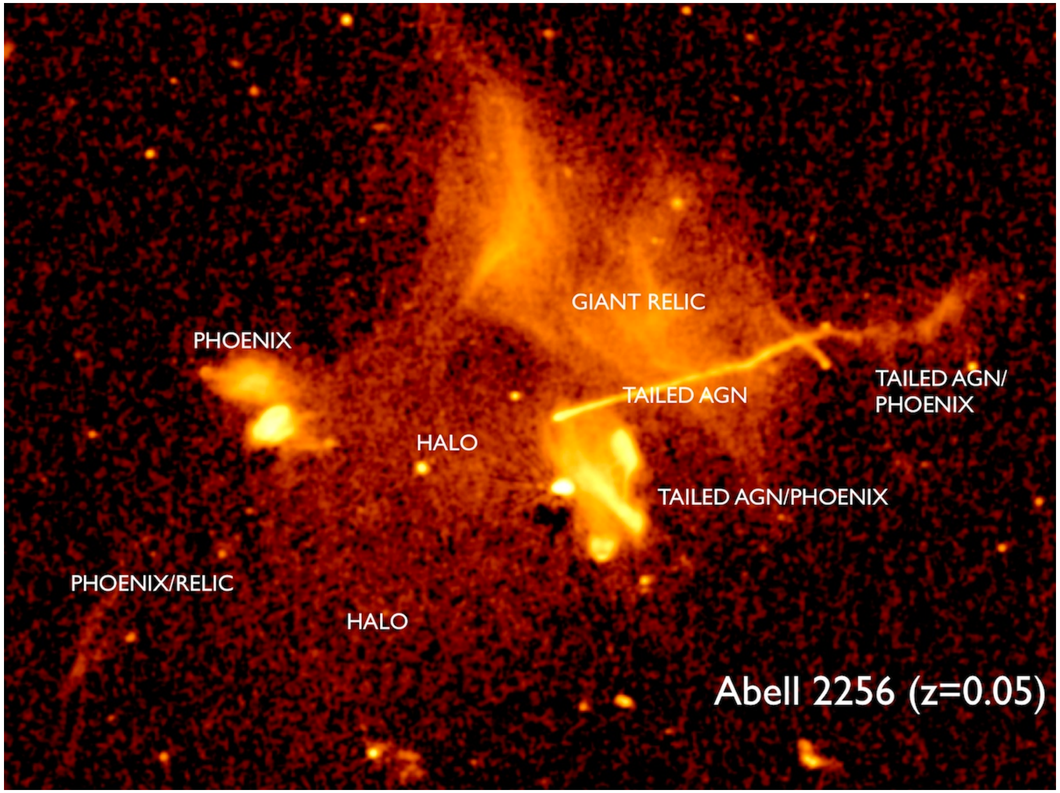
1. Historical comment about the X-ray astronomy

Major steps in X-ray astronomy:

- EINSTEIN (1978-1981) – first high resolution X-ray spectra
- EXOSAT(1983-1986) - first confirmation of strong AGN variability in X-ray band,
- ROSAT all sky survey (1990 – 1999) in soft X-ray band, catalog containing over 150 000 objects
- Chandra (1999 – now!) - high spatial and spectral resolution
- XMM -Newton (1999 – now!) - larger detector area
- Newer smaller satellites – Nustar, eRosita,MAXI,…
- Next major observatory – Athena – expected in 2030 ?



ROSAT image of galaxy cluster Abell 2256



Chandra image of galaxy cluster Abell 2256

As of the present date, there are around 1 to 1.5 million detected unique X-ray sources (Heasarc).

In the optical band, GAIA collected 1.3 billion (10^9) sources.

For majority of known quasars, we do not have detections, apart from upper limits from the ROSAT.

2. X-ray binaries – classification

We know about 200 X-ray binaries in our Galaxy, and several sources in nearby galaxies. It is not a massive statistics because of the sensitivity of the current instruments and lack of all sky survey coverage. Still, there is a complex classification system reflecting different properties.

Mass of the companion:

High-mass X-ray binaries

In high-mass sources the companion (secondary star) is usually of the massive main sequence star of type O, B or Be, while the accreting star can be a neutron star or a black hole. The accretion proceeds through a wind. The formation process is relatively well known, considerable mass exchange took place before the primary star went through the supernova eruption. Sources are young, belong to Population I stars, evolve fast.

In optical band we mostly see the companion.

Example: Cyg X-1

Low-mass X-ray binaries

In low-mass systems the companion is usually a low mass main sequence star, like in cataclysmic variables, and the accreting star is again a neutron star or a black hole. The accretion proceeds through L1 point, the companion fills the Roche lobe. Their formation is more complex, including the common envelope phase. Evolution is slow, the sources are old and belong to population II stars.

In optical band we mostly see an accretion disk, companion can be detected only in quiescence.

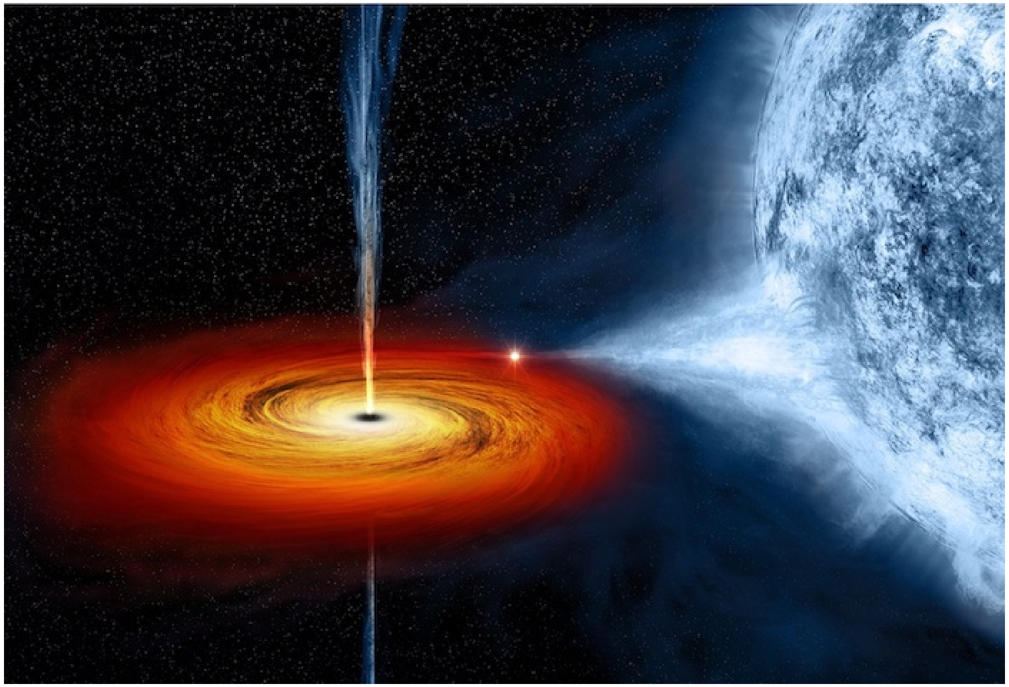
Example: Nova Muscae.

2. X-ray binaries – classification

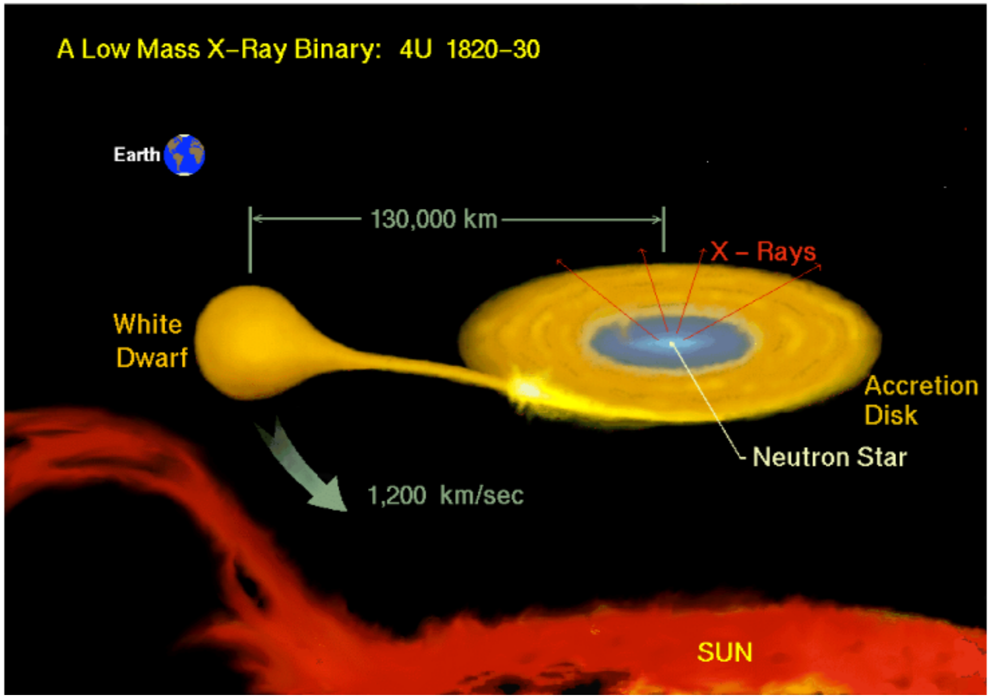
Mass of the companion:

High-mass X-ray binaries

Low-mass X-ray binaries



An artist's impression of a High Mass X-ray Binary. Credit: NASA/CXC/M.Weiss.



Artist's impression of a neutron star LMXB 4U 1820-30. This is a particularly small LMXB with the orbital period of 11 minutes (Sun and Earth are shown for an easy comparison of size). The companion is a white dwarf star, because only such a star can have the size similar to that of companion's Roche lobe in these small systems (figure of Dany P. Page).

2. X-ray binaries – classification

The next division is with respect to the central star

Accreting star:

Neutron star

If the central star is a neutron star, then the strong role can be played by the magnetic field.

LMXB are divided into Z-sources and atol sources (B about 10^{10} G or much smaller than that). In Z-sources the disk does not touch the star.

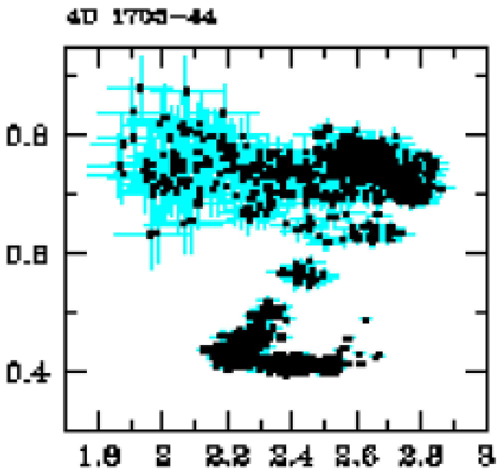


Diagram color-color, in cts/sec and keV: soft (4.0-6.4)/(3-4), hard (9.7-16)/(6.4-9.7) Gierliński & Done (2002)

Black hole

Only LMXB with black holes show the outbursts of the **X-ray novae type**. (?)

Example: Nova Muscae.

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Still higher magnetic fields are in **X-ray pulsars** which are met in HMXB (e.g. Vela X-1). Standard X-ray pulsars are not seen in LMXB.

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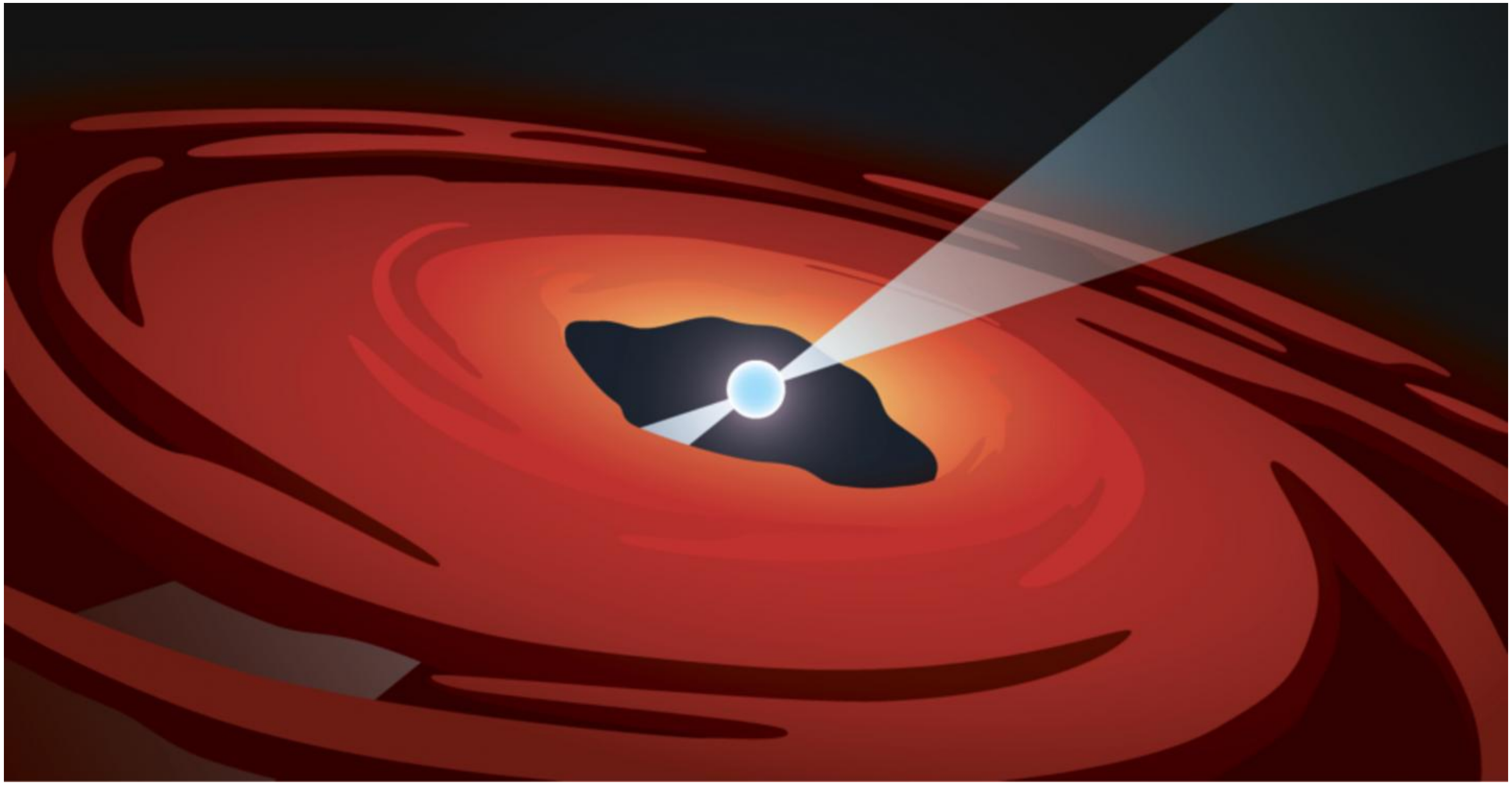
Only LMXB with black holes show the outbursts of the **X-ray novae type**. (?)

Example: Nova Muscae.

2.1 X-ray pulsars

X-ray pulsars have magnetic field of order of 10^{12} G, characteristic for young pulsars. The estimates of the strength of the field is frequently based on detection of cyclotron lines in the X-ray spectra. In this sources accretion proceeds through the accretion column, and the accretion disk does not form.

In some sources, sometimes we see the bright X-ray pulsar, and then later the source enters into a faint state. One of the interpretations is that sometimes the object goes through the propeller state, and the matter is ejected from the system. Thus we must have accretion stages (spining up of the star) and propeller stages (spinning down the neutron star). This conclusion is drawn at the basis of the neutron star rotation and accretion related luminosity. Example: Her X-1 (?). Some authors relate fainter states to jet emission rather than propeller state (J. van den Eijnden et al. 2017). In addition, Her X-1 actually belongs to Intermediate Mass X-ray Binaries (the companion mass is 2 Ms).



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In LMXB we meet **milisecond pulsars**.

Black hole

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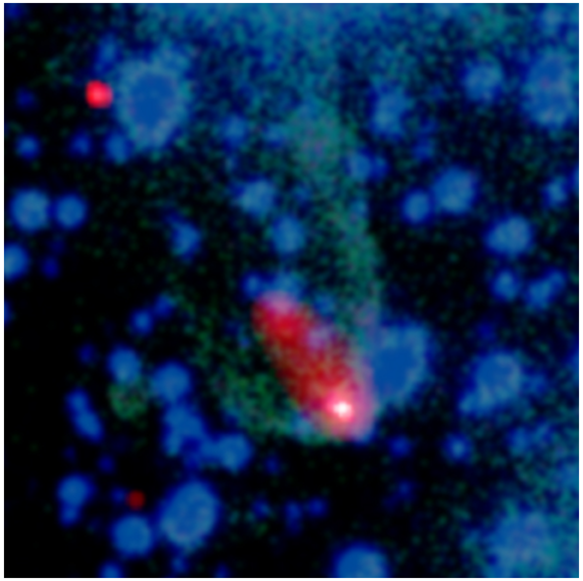
Example: Nova Muscae.

2.2. Milisecond pulsars

Milisecond pulars is a very interesting sub-class. Some of these are seen in X-rays, most are seen in radio, undetected in X-rays. First such object, PSR B1937+21, with period **1.59 ms**, without a companion, was detected in 1982 r., it had a very weak magnetic field so it was an old star. The puzzle was how an old star can rotate so fast. The explanation was that this is a late stage of the evolution of LMXB. Accretion increases the spin of the accreting neutron star, and in the latest stage the companion is slowly evaporated. Since the magnetic field is weak, the loss of rotational energy is slow. One of such object was named ”**Black Widow pulsar**", (PSR B1957+20).



The blue and green are optical images of the field in which the black widow pulsar is found, the green indicating the H-alpha bow shock. The red and white are secondary shock structures discovered in x-ray by the Chandra X-ray Observatory (wikipedia)

Aleksander Wolszczan in Toruń.

Sometimes the companion survives but turns into a neutron star, so the accretion stops. The best example of this class is **PSR 1257+12**, which is the **first ever extraterrestail planetary system** discovered by Aleksander Wolszczan in 1992. Milisecond pulsars also offer a great opportunity to test the effects of GR.

2.2. Milisecond pulsars

Aleksander Wolszczan in Toruń.

First ever discovered extrasolar planet was found by Aleksander Wolszczan and Dave Frail in 1992, three years before Mayor & Queloz.

That planet was found around a milisecond pulsar, using Arecibo telescope. Even three planets, not just one, have been found.

Pulsar is now named **Lich**.

This is a Lich (a figure from computer games).

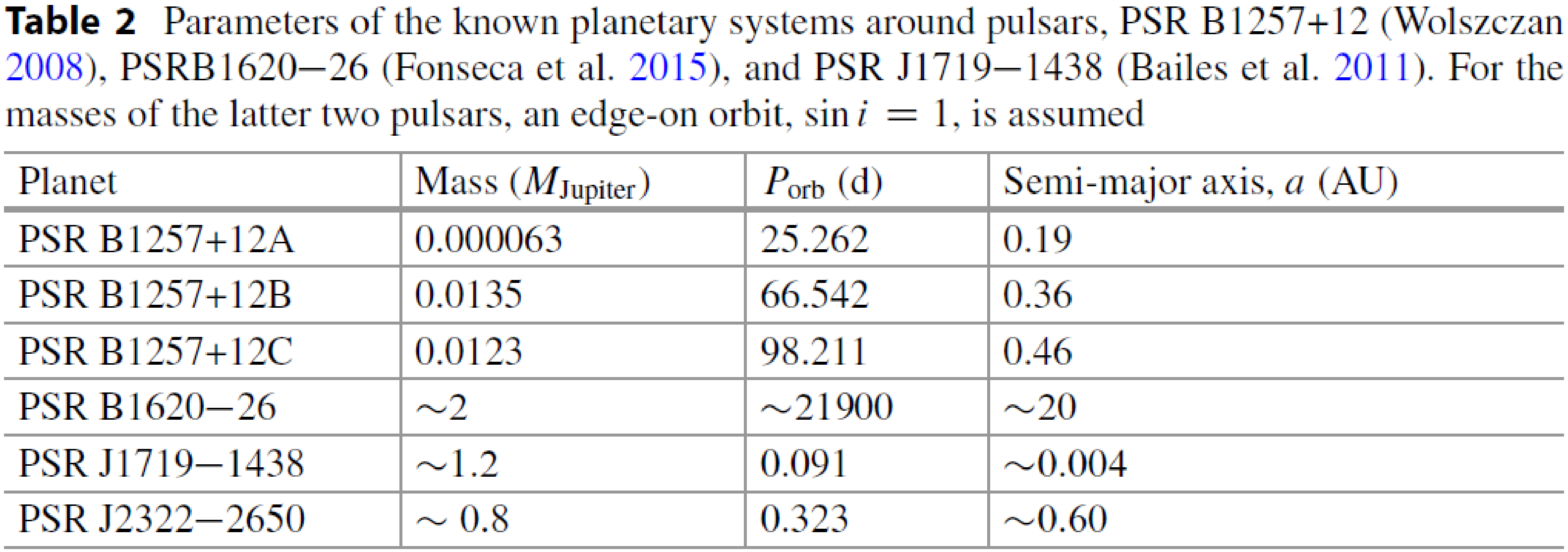


Table 2 Parameters of the known planetary systems around pulsars, PSR B1257+12 (Wolszczan 2008), PSRB1620−26 (Fonseca et al. 2015), and PSR J1719−1438 (Bailes et al. 2011). For the masses of the latter two pulsars, an edge-on orbit, sin $i = 1$, is assumed

Planet	Mass (M_{Jupiter})	P_{orb} (d)	Semi-major axis, a (AU)
PSR B1257+12A	0.000063	25.262	0.19
PSR B1257+12B	0.0135	66.542	0.36
PSR B1257+12C	0.0123	98.211	0.46
PSR B1620−26	∼2	∼21900	∼20
PSR J1719−1438	∼1.2	0.091	∼0.004
PSR J2322−2650	∼ 0.8	0.323	∼0.60

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In LMXB we meet **milisecond pulsars**.

Both in HMXB and LMXB we have **X-ray bursters.**

Black hole

Only LMXB with black holes show the outbursts of the **X-ray novae type**. (?)

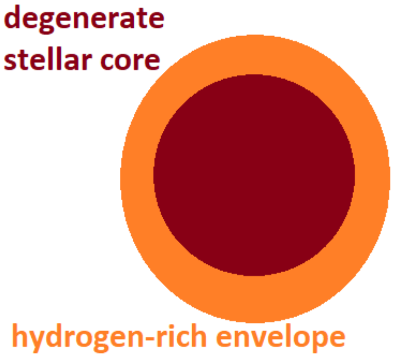
Example: Nova Muscae.

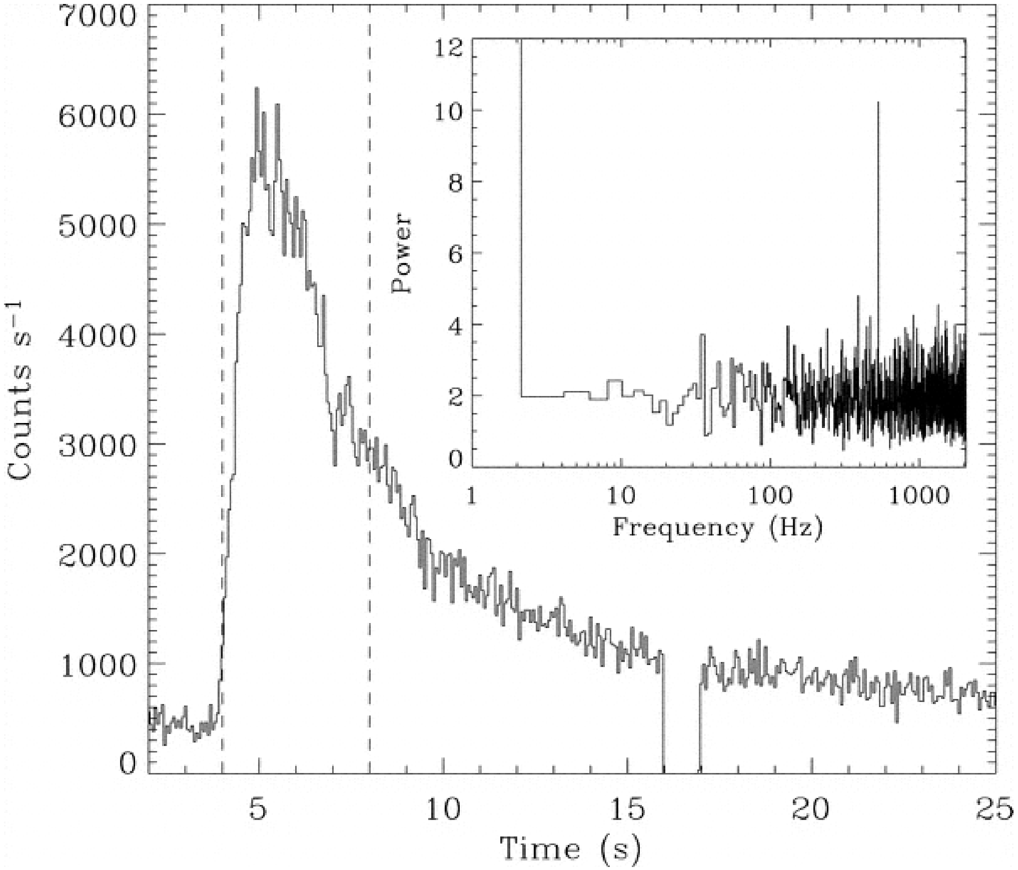
2.3. X-ray bursters

X-ray bursters increase sharply their luminosity by a factor 10 or so in a timescale of a second, and the whole burst lasts several seconds. The mechanism is exactly the same as in the case of the nova in accreting white dwarfs – thermonuclear explosion onto the surface of the accreting star.

Why the timescales and amplitudes are so widely different?

Neutron stars are much more compact:
Radius 10 km – neutron star
Radius 10 000 km – white dwarf
so the dynamical timescale is shorter roughly by a factor of 3 x 10^4, with the characteristic dynamical timescale of miliseconds close to the neutron star surface.





https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect19/lecture19.html

Accretion onto a white dwarf $\eta = 0.000065$
Nuclear burning $\eta = 0.0075$
Accretion onto a neutron star $\eta = 0.15$

In neutron stars nucler burning is actually a small addition to the energy budget, and the outburst causes only a temporary slight expansion of the envelope, without ejection of the material.

2. X-ray binaries – classification

The next division is with respect to the source variability

X-ray source variability:

Persistent sources

The division is somewhat traditional, all accreting systems are strongly variable but persistent sources are those which can be always seen in pre-Chandra type satellites.

Transient sources

Those sources have such high variability amplitude that they are seen only during outbursts in pre-Chandra type satellites. Nowadays we have X-ray detections of some of these sources in quiescent state.

Those sources are again divided into:

Periodic sources

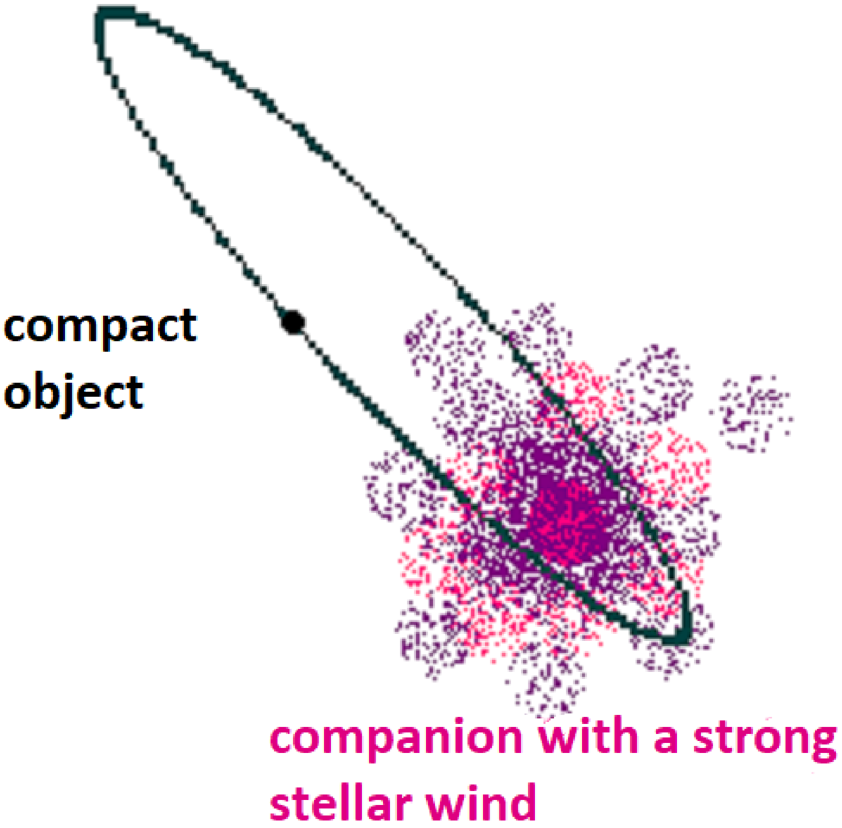
X-ray novae

2.3 X-ray binaries – periodic sources

Some of the HMXB show strong periodic outbursts. The shapes of different outburst show considerable variety but the outbursts themselved repeat regularly.

The phenomenon is related to strongly elliptical orbit. Accretion proceeds through the wind, and only close to the periastron the two stars are close enough that the accretion rate onto compact companion is high.

Those sources are very difficult to model.



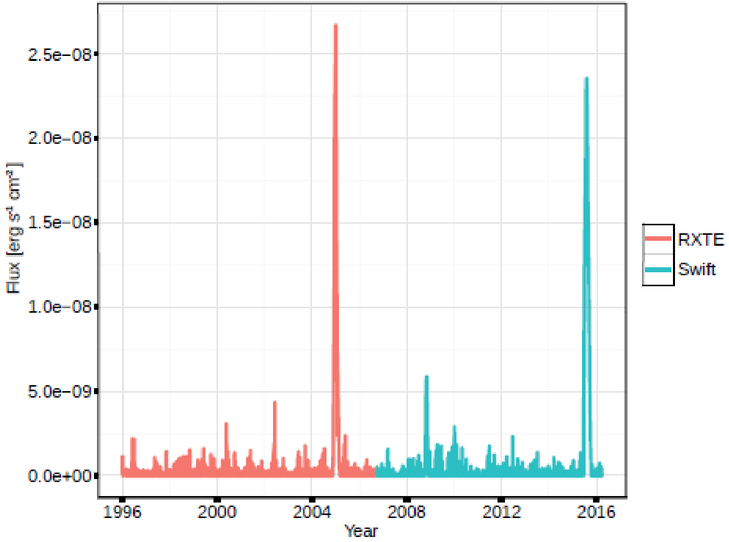


Figure 1. RXTE/ASM and Swift/BAT lightcurves for V0332+53. Daily measurements for both were converted to Crab units, and assuming a power-law spectrum between 0.1 keV - 100 keV, with photon index of 2 converted to bolometric fluxes.

Elshamouty et al. (2016)

The source V0332+53 contains a neutron star, pulsations are seen during outburst. X-ray spectrum seen in quiescence is not consistent with the **propeller state** (ejection of material) but instead suggests a weak column accretion (black body emission with temperature 5 x 10^6 K, emitting radius 0.2 – 0.3 km), providing the luminosity at the level of 10^{33} erg/s.

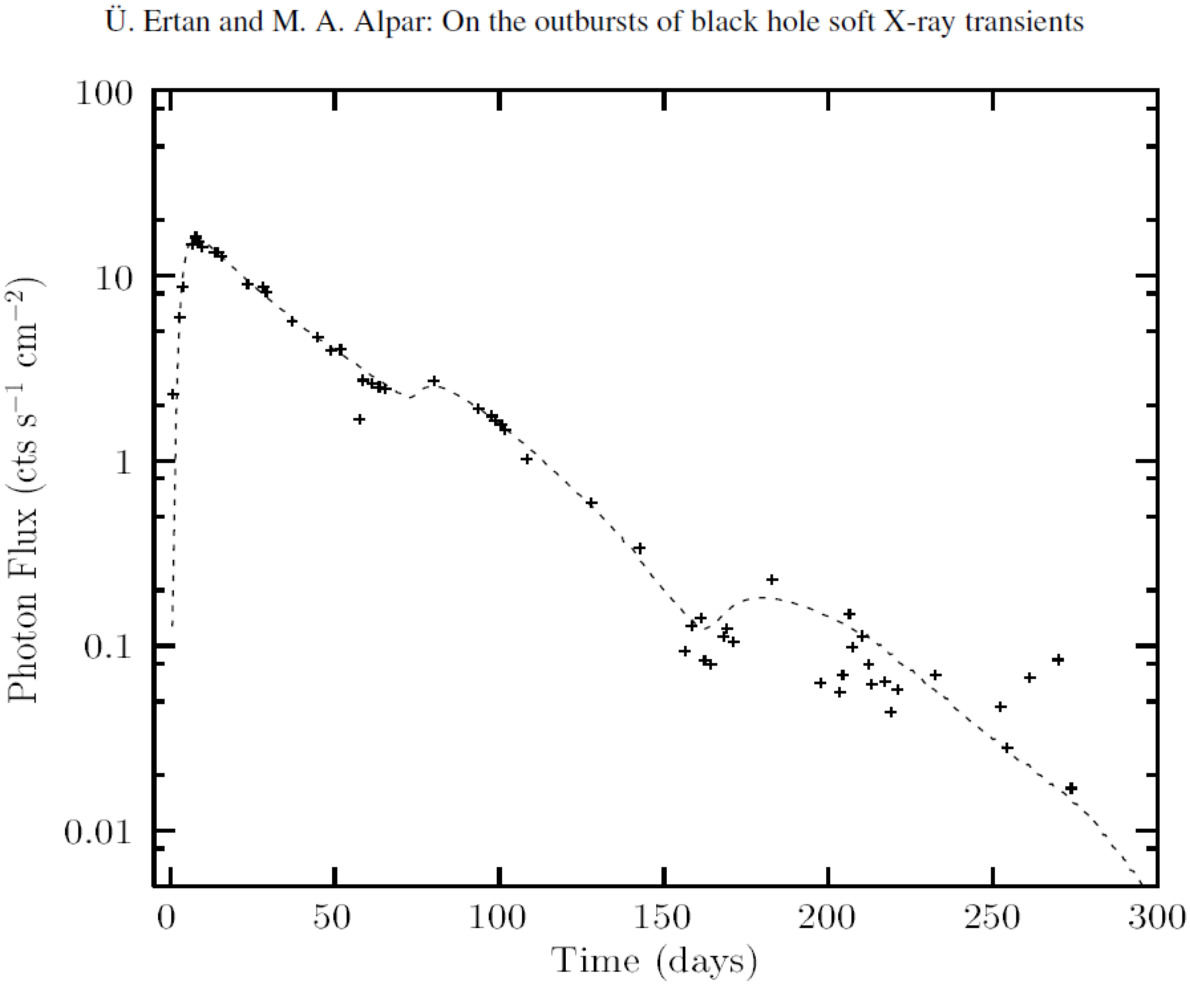
2.4 X-ray binaries – X-ray novae

These sources are alternatively called Soft X-ray Transients.
They always belong to LMXB, and always contain a black hole as a central star.

The outburst mechanism is the same as in cataclysmic variables – ionization instability.

The rise timescale is similar, since the size of the unstable accretion disk is the same as in CV.
The accretion rate in this sources is also similar to CV systems but luminosity is much higher since the overall accretion efficiency is much higher (10^{38} erg/s during outburst, while in CV 10^{33} erg/s during outburst).

However, the decay timescale in some sources is much longer than the rise time.



Outburst of the source GRS 1124-683 known also as Nova Muscae 1991 observed by GINGA, after Ertan and Alpar (2002).

2.4 X-ray binaries – X-ray novae

There is one exceptional source in this family. This is the famous source GRS 1915+105.
The source started the outburst in 1992, when it was discovered, and it is in the outburst state till now.

The system has very high accretion rate, very long orbital period and very large accretion disk. It should last for 20 – 100 years, with the duty cycle 10 000 years (as modeled by Deegan et al. 2009).

Here all the systems are drawn in proportion.

From McClintock & Narayan (2006).

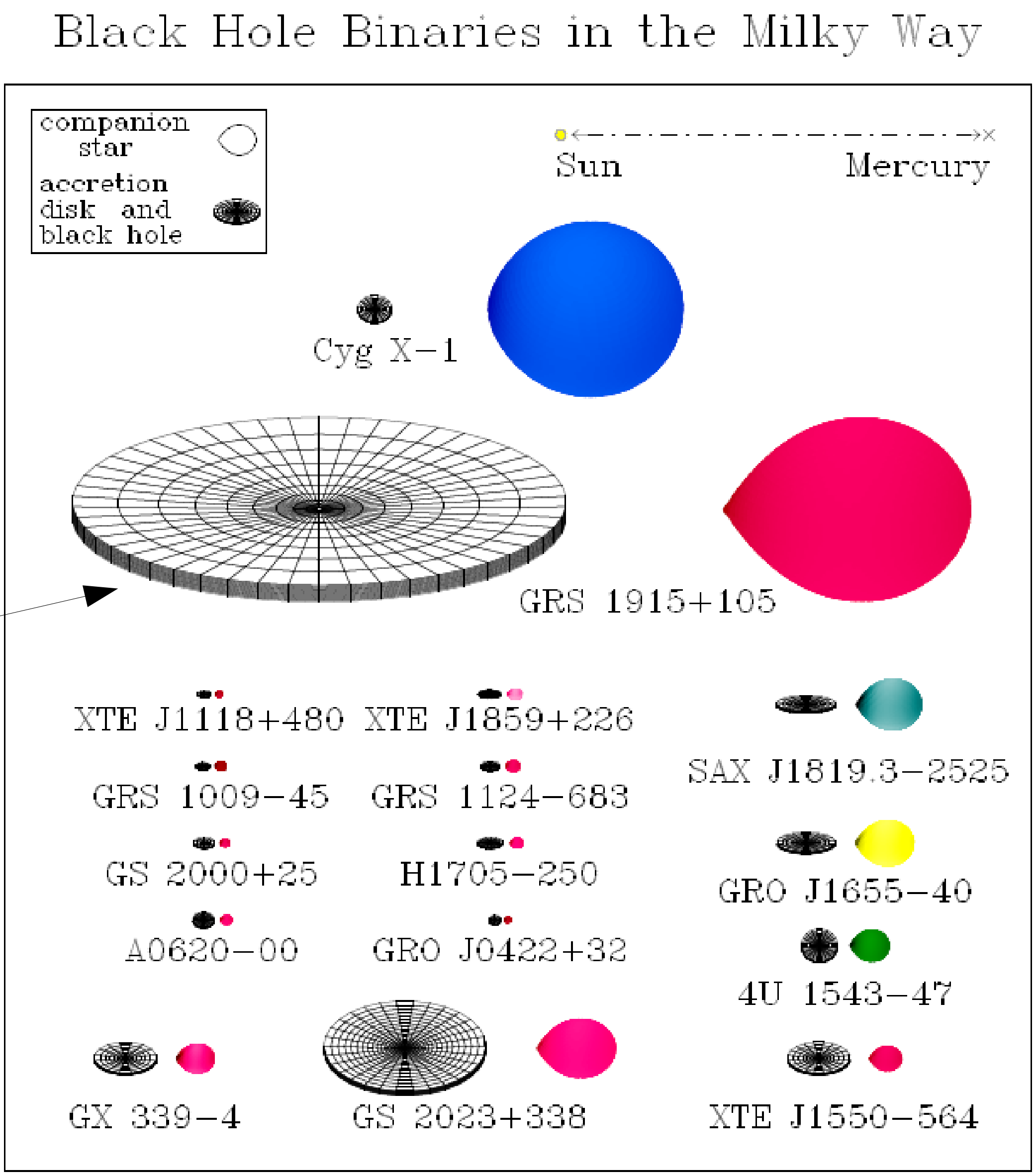
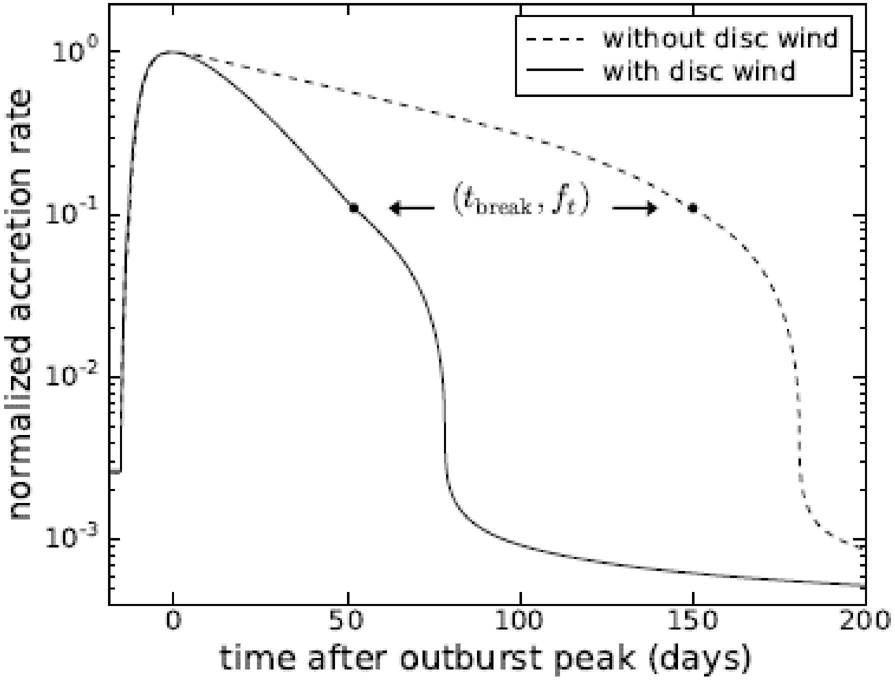


Figure 1: Scale drawings of 16 black-hole binaries in the Milky Way (courtesy of J. Orosz). The Sun–Mercury distance (0.4 AU) is shown at the top. The estimated binary inclination is indicated by the tilt of the accretion disk. The color of the companion star roughly indicates its surface temperature.

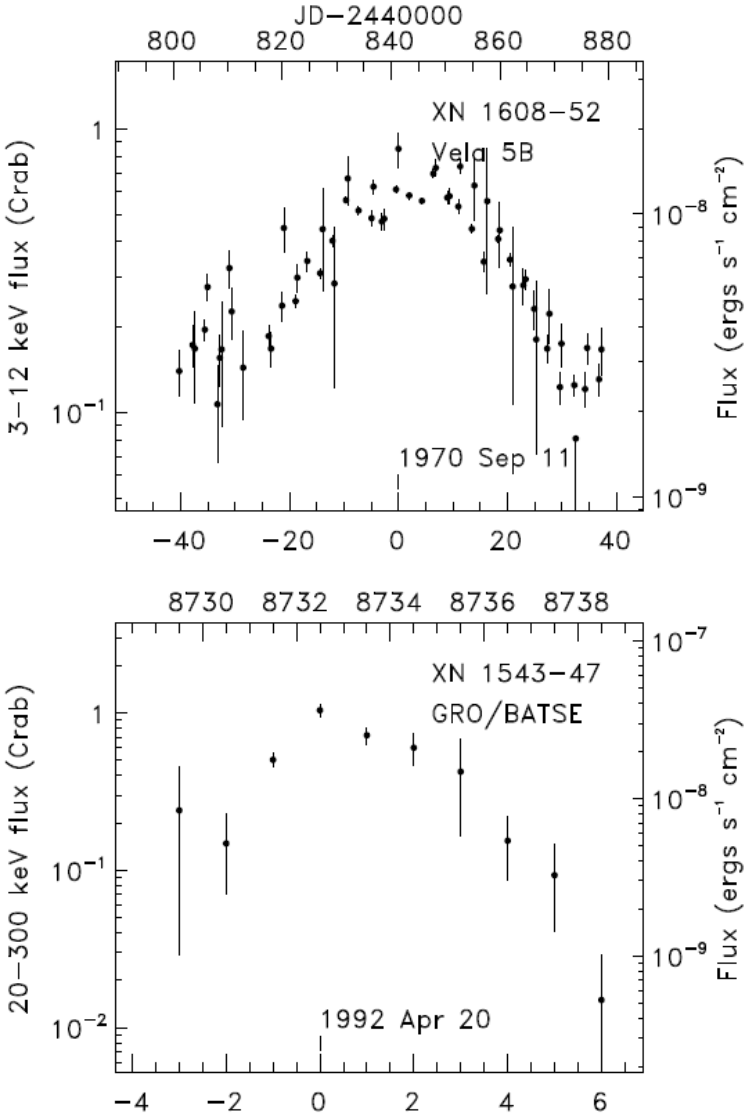
2.4 X-ray binaries – X-ray novae

This happens because the outer disk becomes strongly **irradiated** during outburst, and the radial extension of the instability increases, leading to much longer outbursts.
In CV irradiation is much less important since the dissipated energy close to the central star is much lower.

However, some X-ray novae are almost symmetric and lasts similarly to CV.
This may imply that the disk wind compensates the irradiation effect (model from Tetarenko et al. 2018).



But it may also mean that the irradiation is not always as strong as postulated.



From Chen et al. (1997)

3. How to distinguish a binary with a neutron star from a binary with a black hole ?

3.1 mass function measurement

We know from the theory that a neutron star cannot have a mass much larger than 2 Ms, the exact limit depends on the equation of state and stellar rotation (including its character, whether rigid or differential). For larger mass, the degenerate pressure of neutron stars cannot stop the collapse and the system must become a black hole.

Thus determination of the mass is the basic method. From the orbital motion we actually measure the so called mass function:

$$f(M) = \frac{(M \sin i)^3}{(M + M_{opt})^2} \propto K^3 P$$

Here K is the amplitude of the radial velocity measured from the optical lines and P is the system period.

The final estimate thus depends on the estimate of the viewing angle as well as of the optical companion mass from its spectral type.

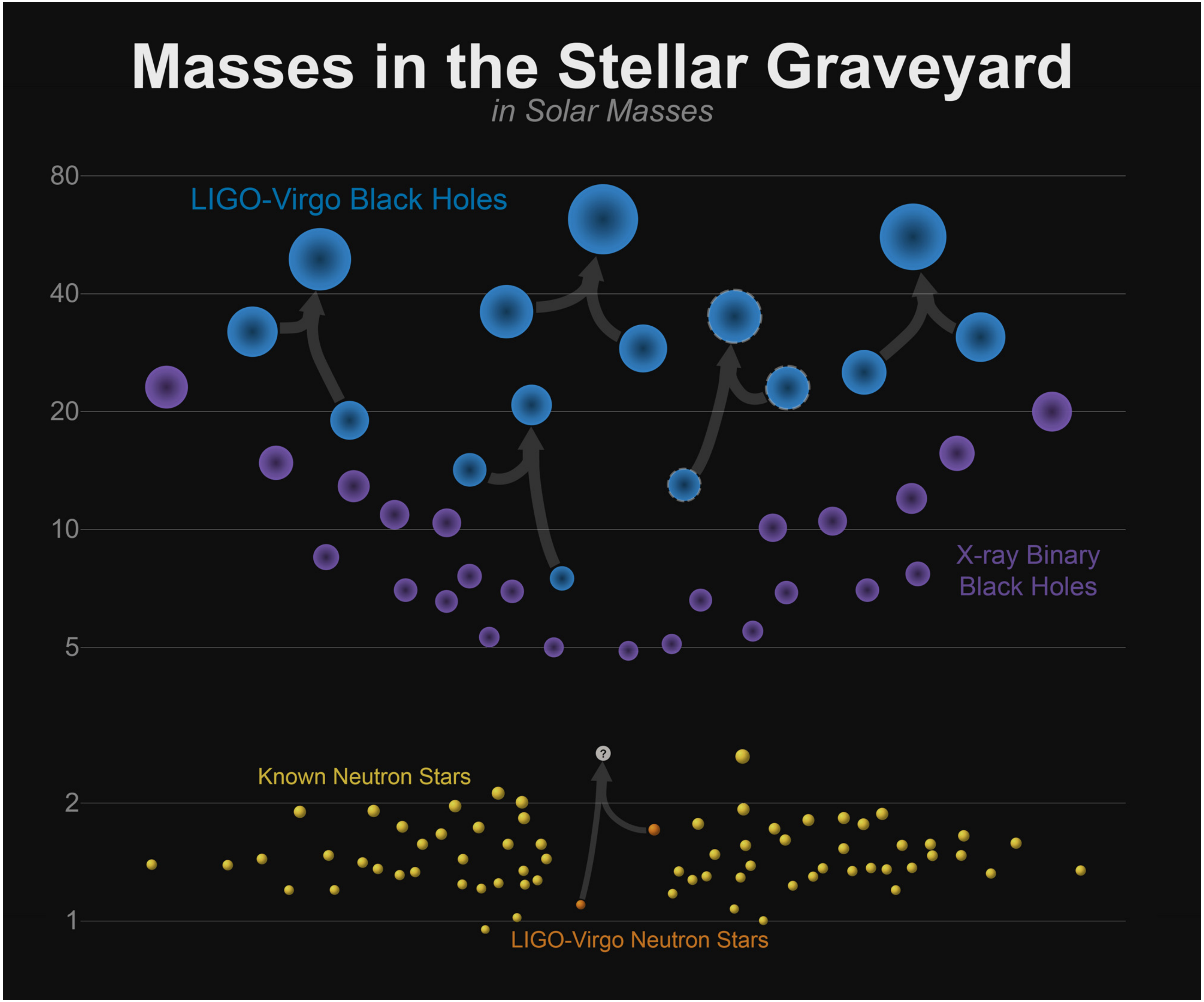
3.1 mass function measurement

Exemplary determinations of black hole masses in binary systems (Orosz 2002, Ziółkowski 2002):

source	f(M)	BH
XTE J1118+480	6.1+/-0.3	6.5 - 7.2
GS 1124-683(NovaMusce)	3.0+/-0.1	6.5 - 8.2
XTE J1550-564	6.9+/-0.7	8.4 - 10.8
SAX J1819.3-2525	3.2+/-0.1	6.8 - 7.4
GRS1915+105	9.5+/-3.0	10.0 - 18.0
LMC X-3	2.3+/-0.3	6.0 - 9.2
LMC X-1	0.14+/-0.05	4.0 - 10.0
SS 433		6.0 - 16.0
Cyg X-1	0.24+/-0.005	6.9 - 13.3 (16+/-5)

Masses of the black holes center around 8 – 10 Ms. This is very much different from the masses of black holes recently derived from the gravitational wave signals. This population of binaries is apparently very much different.

3.1 mass function measurement



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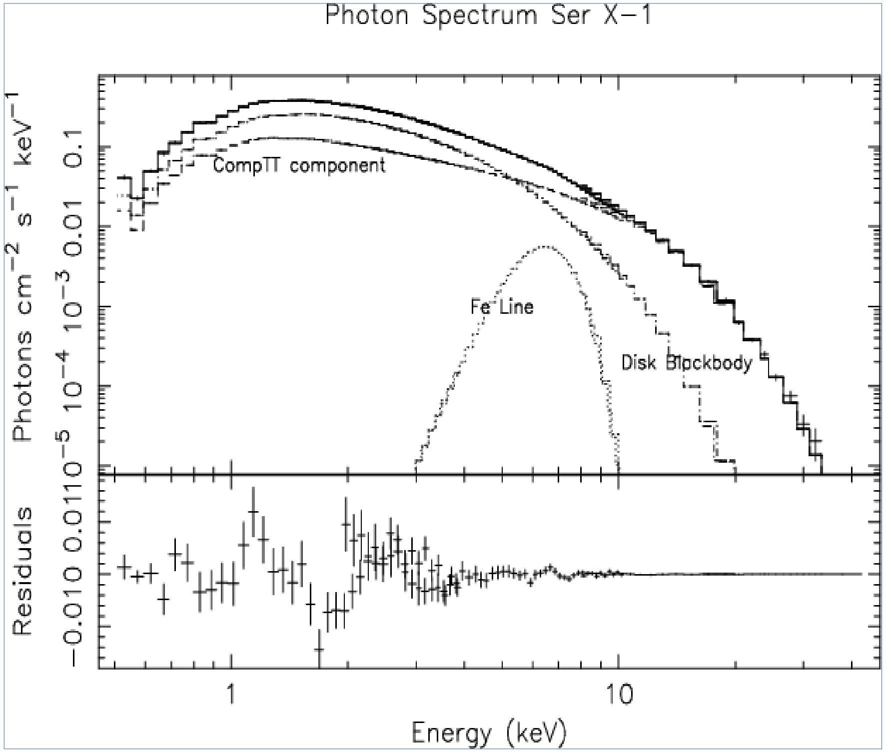
3. How to distinguish a binary with a neutron star from a binary with a black hole ?

3.2 detection of a rotational period of a neutron star or detection of the X-ray bursts

These phenomena are characteristic for systems with neutron stars. System with black holes can show Quasi-Periodic signals (QPO), but never a strictly periodic signal, and of course cannot show thermonuclear flashes from the star surface.

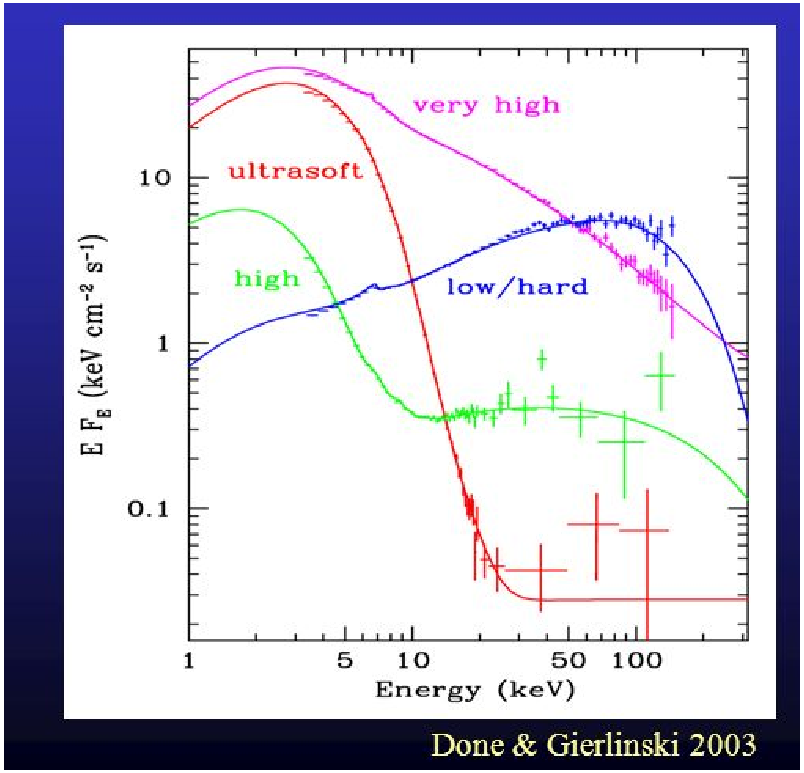
Other methods can only have indicative character, but never strongly reliable.

3.3 X-ray spectral shape



System with a neutron star, Ser X-1, Osterbroeck i in. 2001)

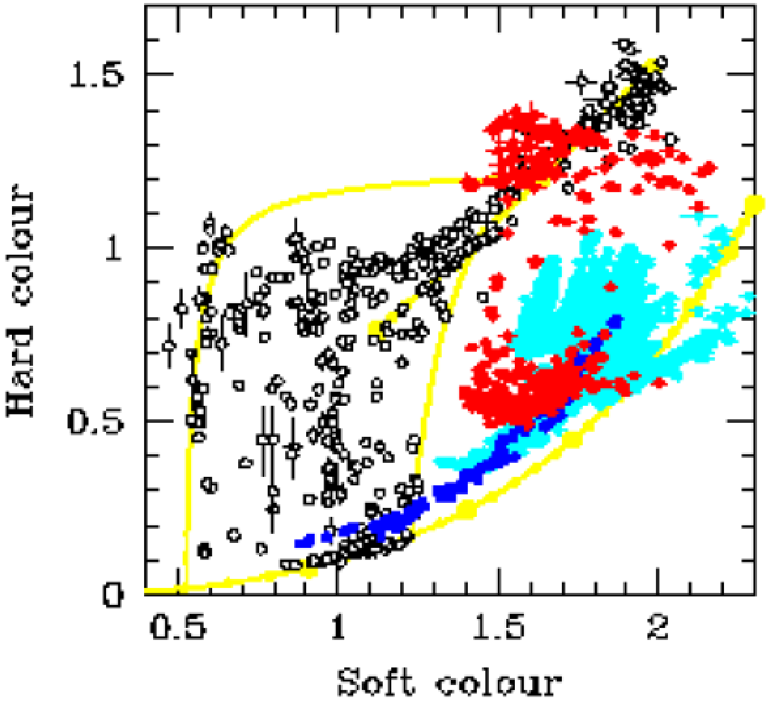
CompTT component represents the emission from the **boundary layer** between the neutron star and a disk.



Done & Gierlinski 2003

3. How to distinguish a binary with a neutron star from a binary with a black hole ?

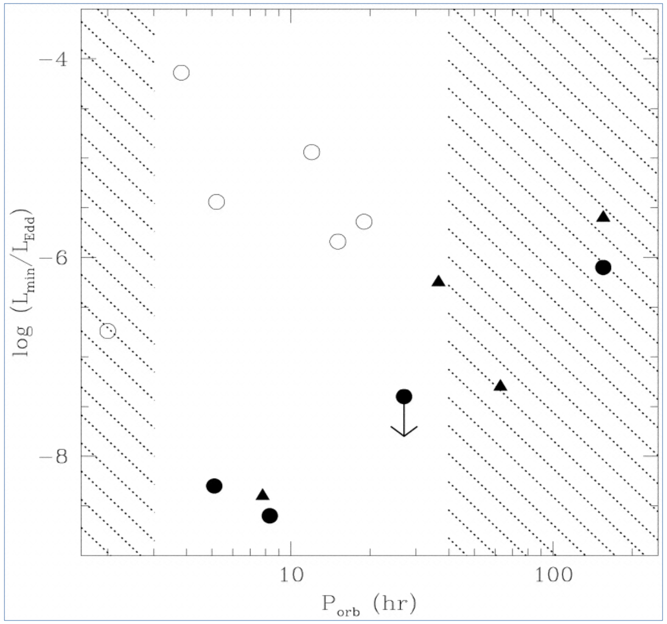
However, in some systems at low accretion rate (e.g. Atoll sources) the star surface is not visible in X-rays (too cool), and the spectrum is dominated by a power law, like in hard states of the black holes and AGN.



Color-color diagram from Gierlinski & Done (2002), open circles are for black holes.

3.4 emission level in quiescence

The emission in quiescence is always higher in the case of neutron stars. Extra emission from neutron star cooling? Pycnonuclear reations? Evolution (no outbursts of the X-ray nova type) ?



3. How to distinguish a binary with a neutron star from a binary with a black hole ?

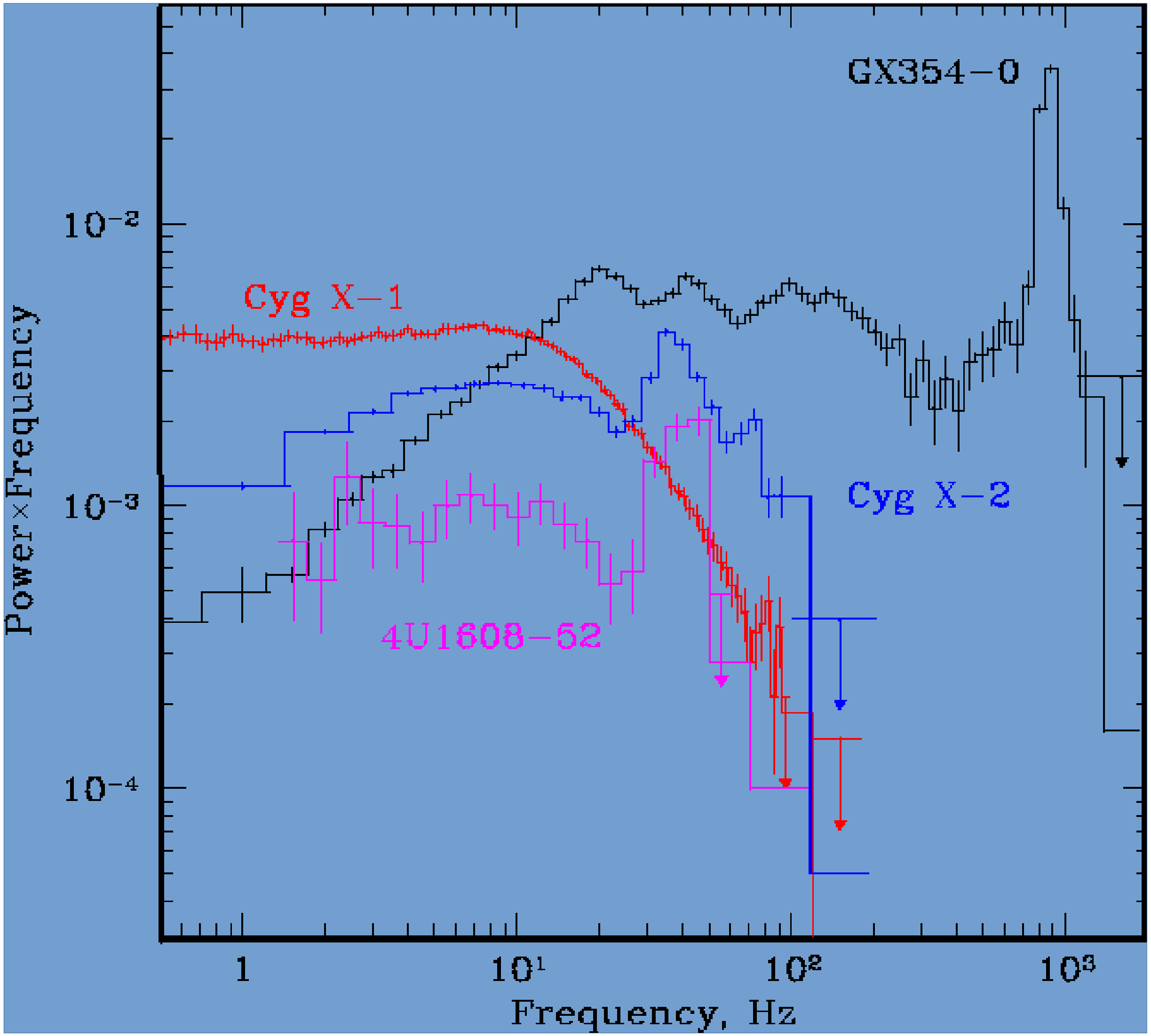
3.5 power spectra

We discussed the power spectra in lecture 10. Generally, both sources with neutron stars and black holes are strongly variable.

In general, the power spectrum of sources with neutron star is shifted more to the high frequency (lower mass of the central object).

However, in some cases (e.g. pink source) this is not true.

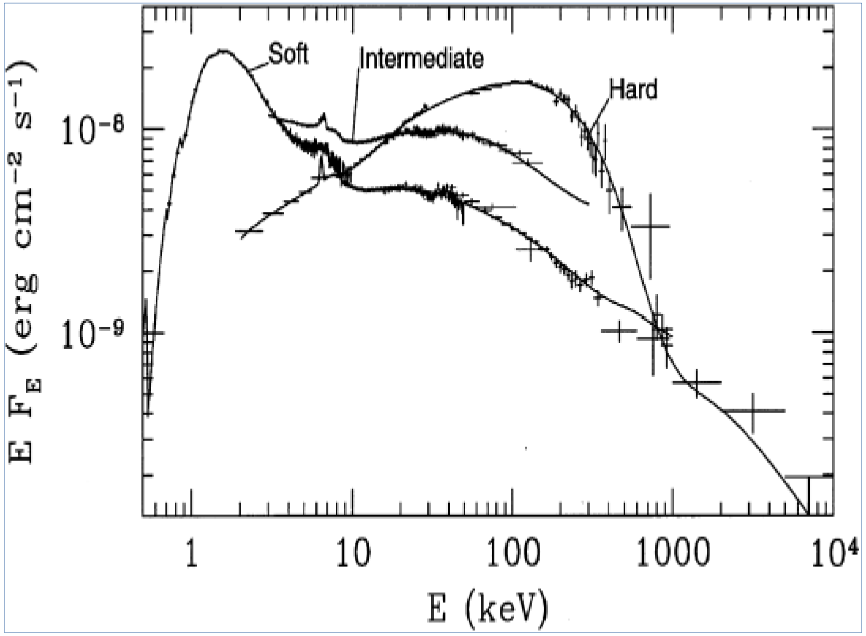
Also neutron star sources show more frequently – and stronger – QPO.



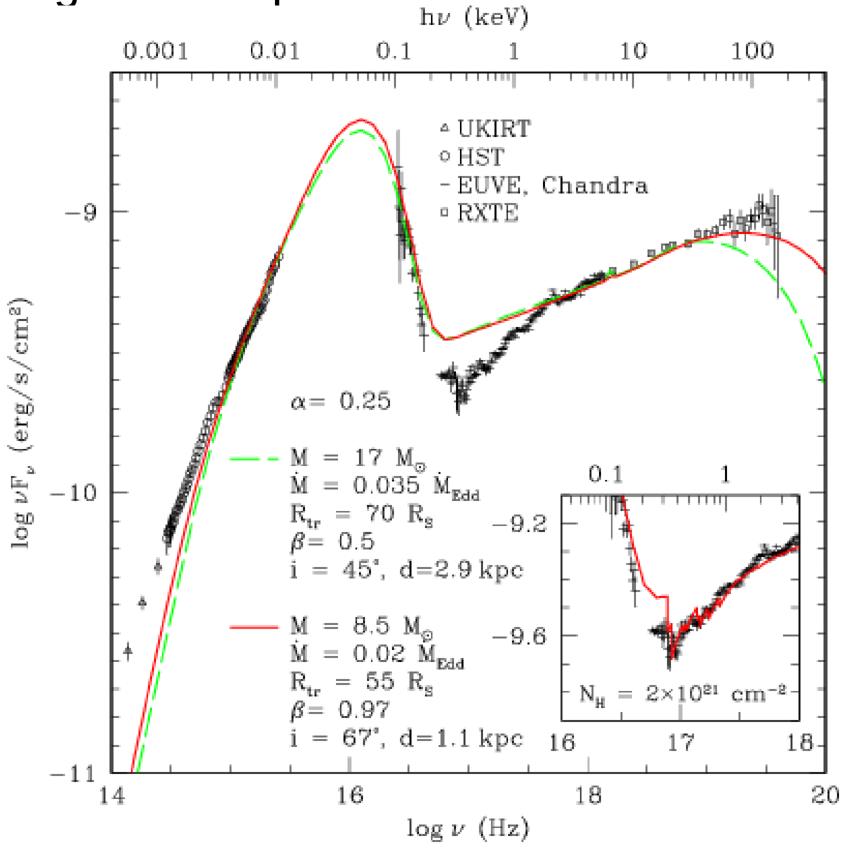
Plot from Sunyaev & Revnivtsev (2000). Cyg X-1 is a black hole source, others ate neutron star sources.

4. Spectral states of galactic black holes

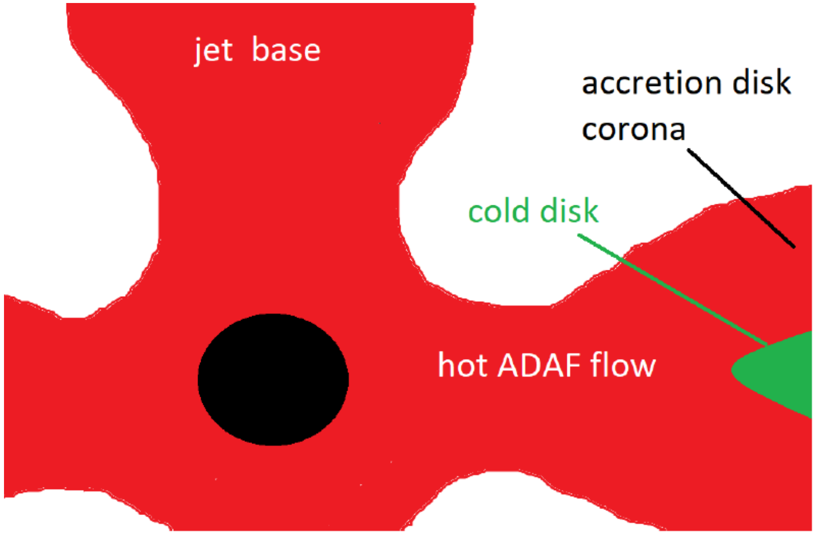
We talked already several times about the different spectral states. Soft state is dominated by the accretion disk extending to ISCO, while in hard state we do not see the disk but we see the hot optically thin plasma emitting Comptonized radiation.
The disk is still there, at much larger radius, so cooler, and should be visible in UV but in majority of sources Galactic extinction prevents us from seeing this component.



From Gierliński et al. (1999)



X-Ray Nova XTE J1118+480, after Done (2002).



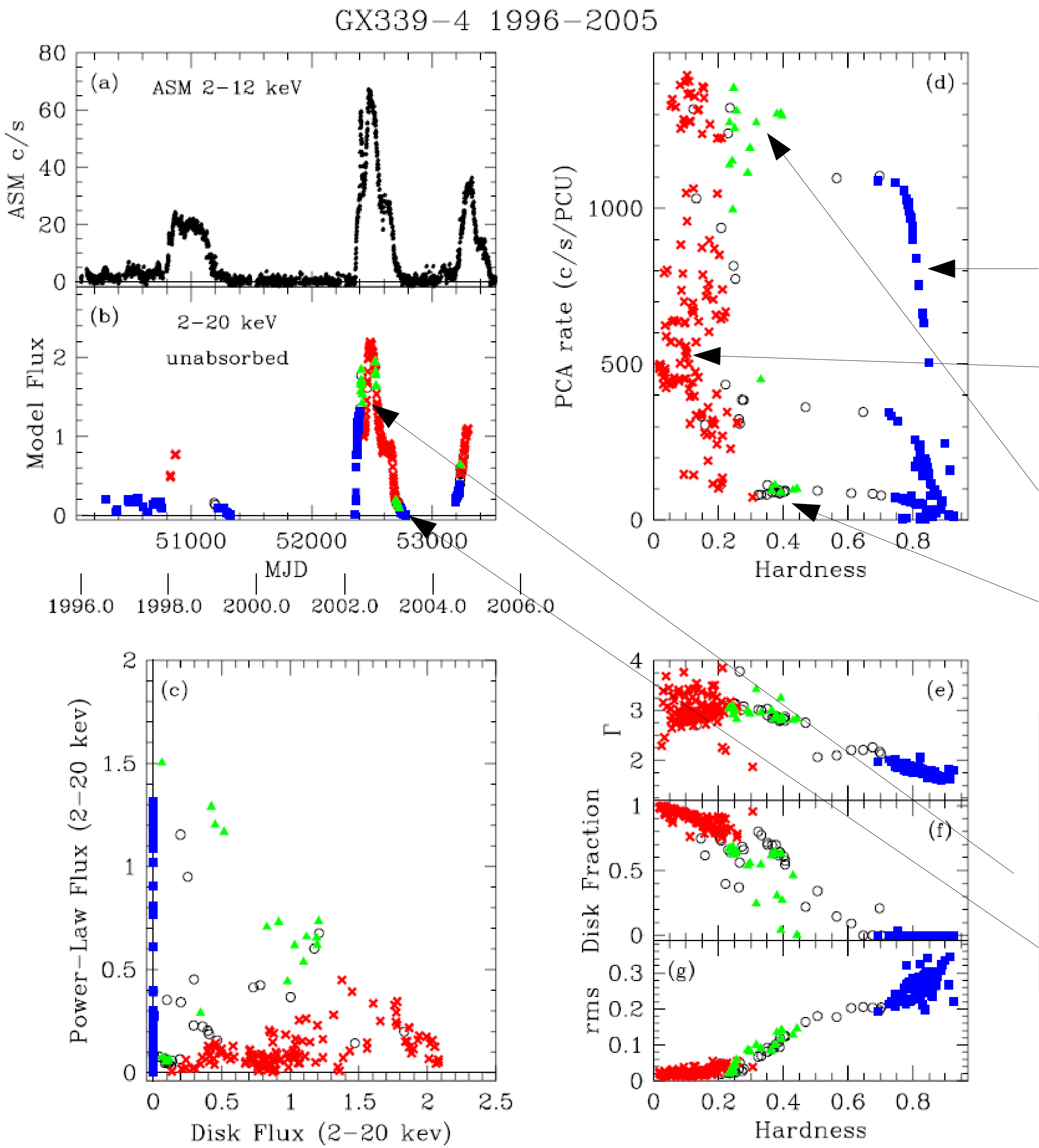
4. Spectral states of galactic black holes

The spectral states are classified according to the general shape, and there were frequent misunderstanding about the identity – or not – of the Very High State and Intermediate State, so sometimes they were both named Soft Steep State to stress the dominance of Comptonization (as in Hard State) but softness of the slope (steep instead of hard).

	Very High	*High/Soft*	*Intermediate*	*Low/Hard*	*Quiescence*
L/Ledd	0.5	0.1	0.05	0.03	1e-6
Disk	yes	yes	yes	no	no
Tin [keV]	1.1	1	0.3	0.1	
Rin [Rschw]	5	5	5	10 - 50	
Disk Compt.	Yes	weak	yes	yes	
ξ	1e4		1e4	<100	
$\Omega/4\pi$	0.5		0.5	0.3	
Γ	2 - 3		2.0	1.7	
PL/Disk	0.2	0.01	0.3	0.4 - 10	

The clear meaning of these states are best seen in the context of X-ray novae, where the source comes (not always !) through all the states.

4. Spectral states of galactic black holes



Evolution of GX339-4, perhaps the best example of the X-ray Nova limit cycle.

Hard state

Soft State

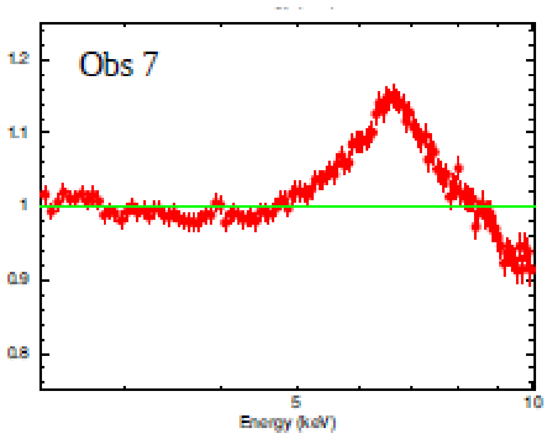
Very High State

Intermediate state

We also see an important effect of the hysteresis: the transition hard/soft state happend at much higher luminosity than the transition from soft/hard state.

From McClintock & Narayan (2006)

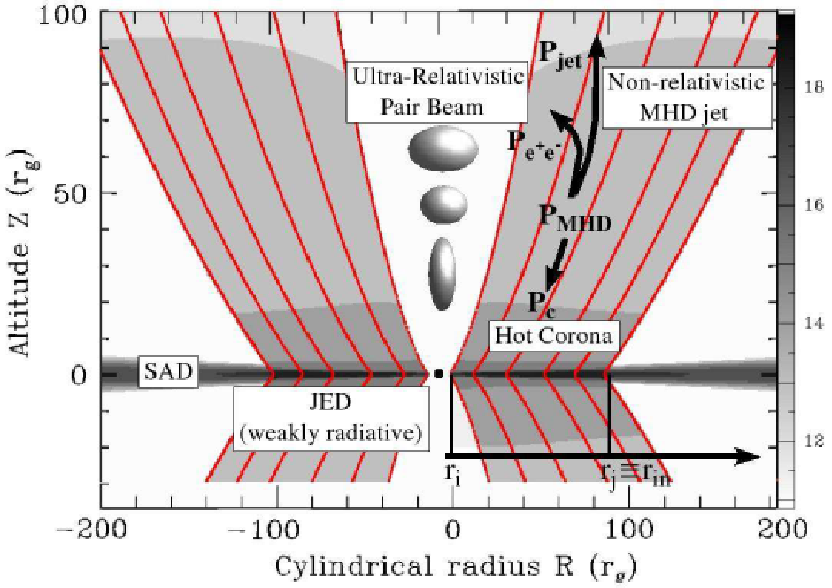
4. Spectral states of galactic black holes



The detailed analysis of the spectrum of GX 339-4 reveils the presence of the truncated disks – the authors (Basak & Zdziarski 2016) modeled the X-ray reflectio from the outer disk and its contribution to producing Fe Kα line.

More difficult is modelling of the Very High State and Intermediate State. Warm corona ?

There are complex models which can **reproduce** the whole limit cycle. For example Marcel et al. (2019) with their jet/disk model of Ferreira et al. (2006) can follow the evolution.



Model (Ferreira et al. (2006)

JED – Jet emitting disk (supersonic accretion !)

Parameters: r_J, r_{tr}, etc.

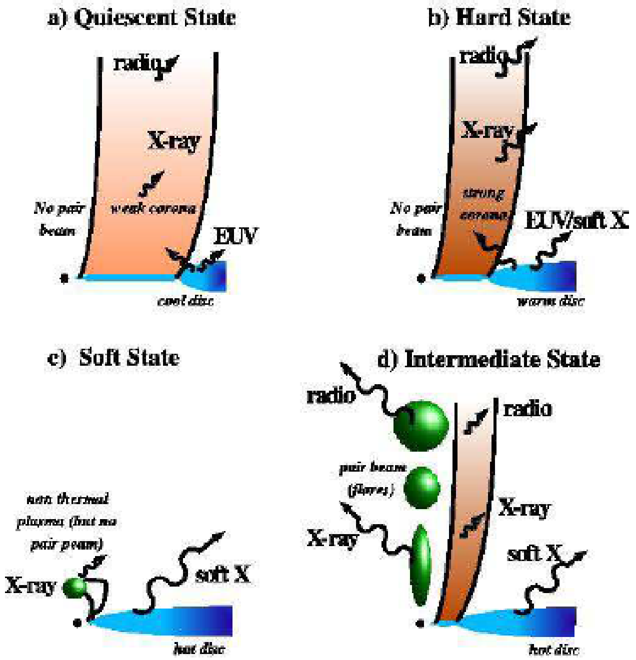
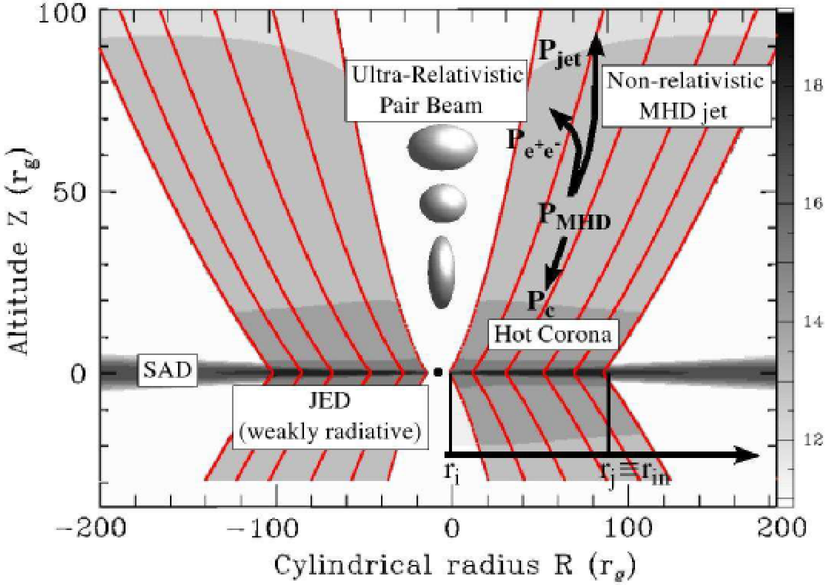


Fig. 2. The canonical spectral states of BH X-ray binaries. **(a)** Quiescent state obtained with a low $\dot{m}$ and a large r_J: the Jet Emitting Disc (JED) occupies a large zone in the accretion disc. **(b)** Hard state with much larger $\dot{m}$ and smaller r_J: the pair creation threshold is still not reached. **(c)** Soft state when $\dot{m}$ is such that there is no zone anymore within the disc where an equipartition field is present: no JED, hence neither MHD jet nor pair beam. **(d)** Luminous Intermediate state between the Hard and the Soft states: the high disc luminosity (SAD) combined with the presence of a MHD jet allows pair creation and acceleration along the axis, giving birth to flares and superluminal ejection events.

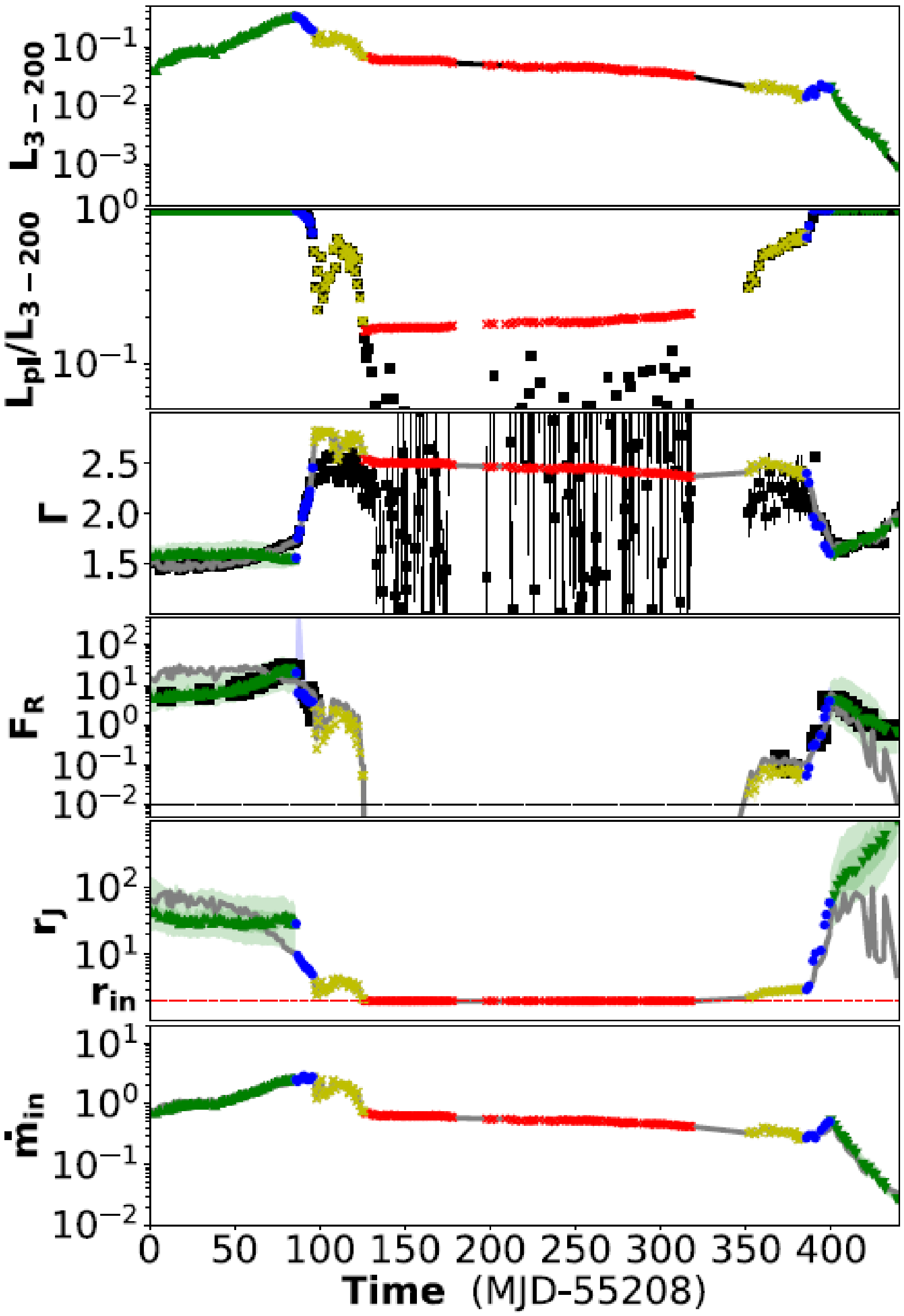
4. Spectral states of galactic black holes

There are complex models which can **reproduce** the whole limit cycle. For example Marcel et al. (2019) with their jet/disk model can follow the evolution: green points are for hard state, blue for hard/intermediate, yellow for soft/intermediate and red for soft. F_R is radio flux, and r_J is the transition radius.



Model (Ferreira et al. (2006))

None of such models predict when/where the transition happens.



5. Summary

A number of issues are not well explained:

- Global evolution of the X-ray binaries (e.g. common envelope stage), source statistics (quiescence periods, hibernations ?)
- Accretion and propeller stages in neutron star binaries with strong magnetic field
- QPO (they may represent the cold disk frequencies, but are seen in hard X-ray part of the spectrum, mostly during transition states
- Exact physics of state transitions
- Jet formation, jet power
- Winds/outflows
- ?

Homework

- Explain why LMXB never contain a standard X-ray pulsar, only eventually a milisecond pulsar
- Why X-ray novae phenomenon is never seen in sources with neutron stars