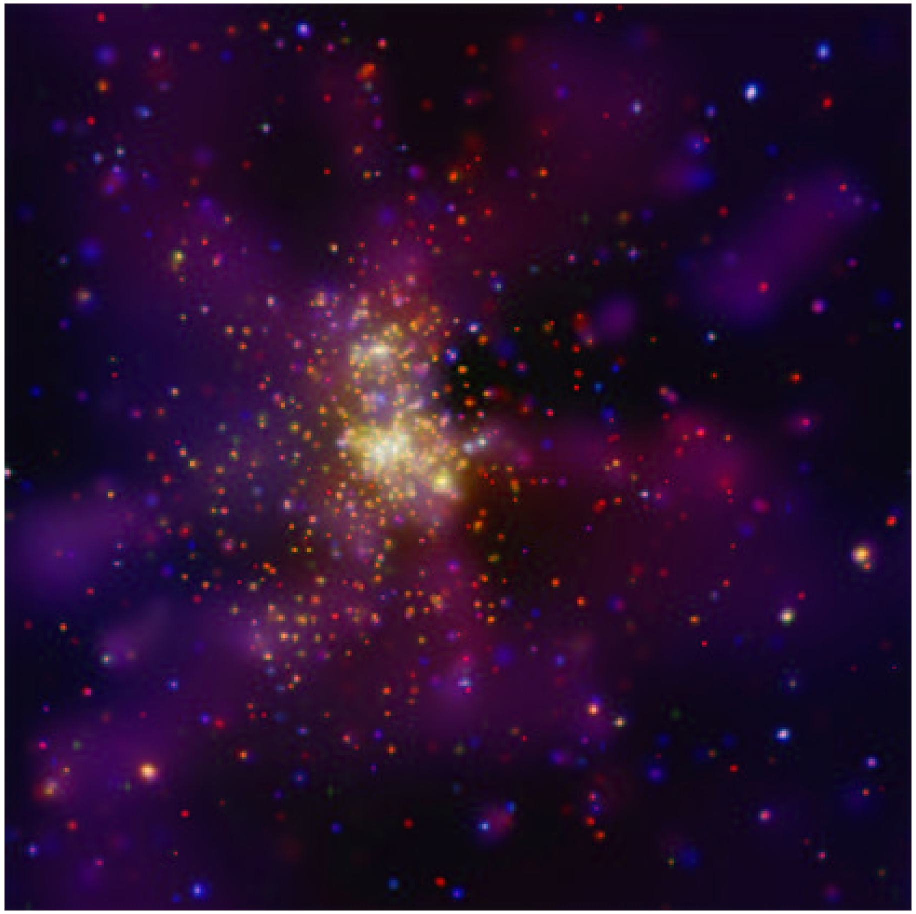
The X-Ray Universe

Potsdam University

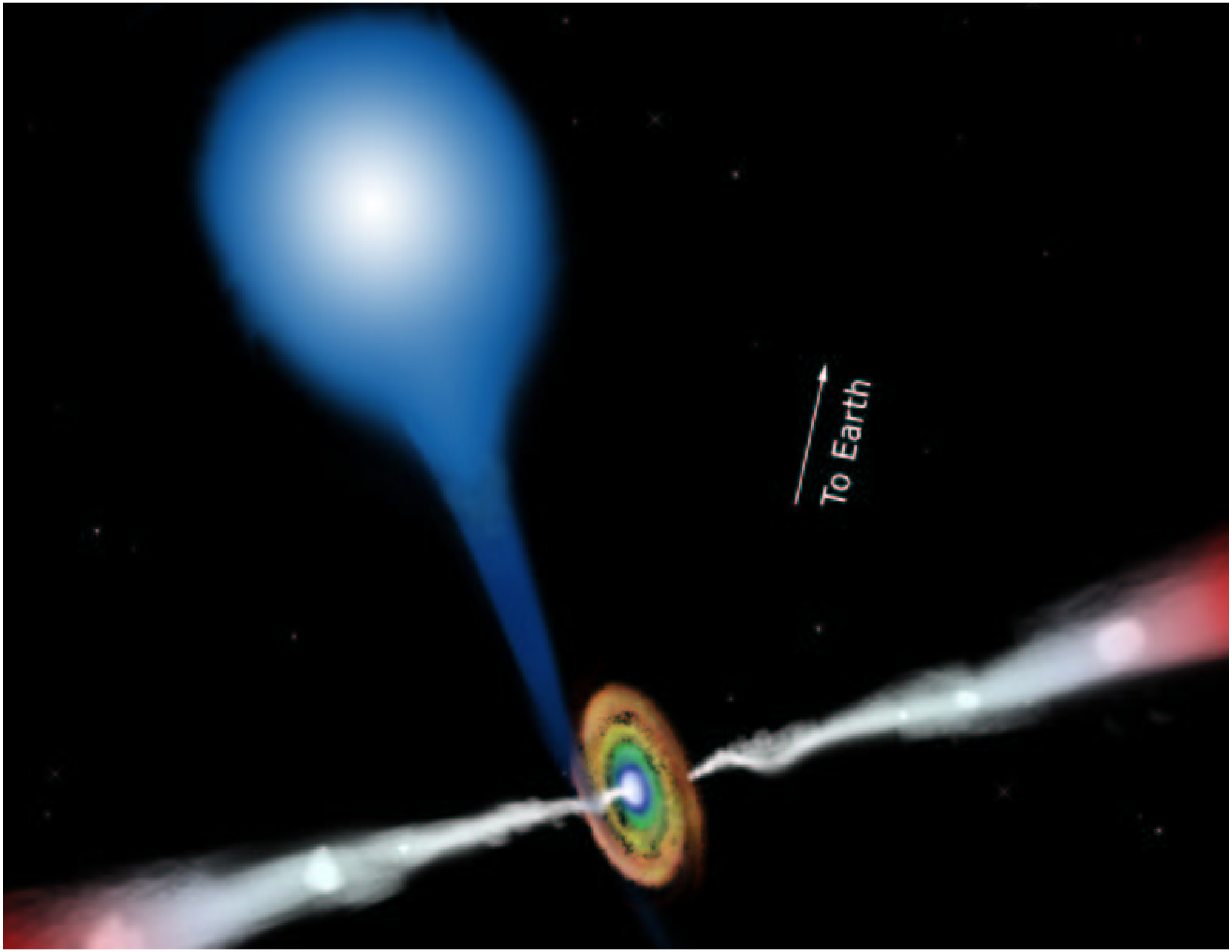


Dr. Lidia Oskinova
Wintersemester 2008/09

lida@astro.physik.uni-potsdam.de
www.astro.physik.uni-potsdam.de/~lida/theormech.html

Chandra X-ray Observatory
Westerlund 2 - a young star cluster
d=2×10^4ly

VIII. X-ray Binaries



http://chandra.harvard.edu/photo/2004/ss433/

Integral + A. Melinger

02 What is X-ray binary?

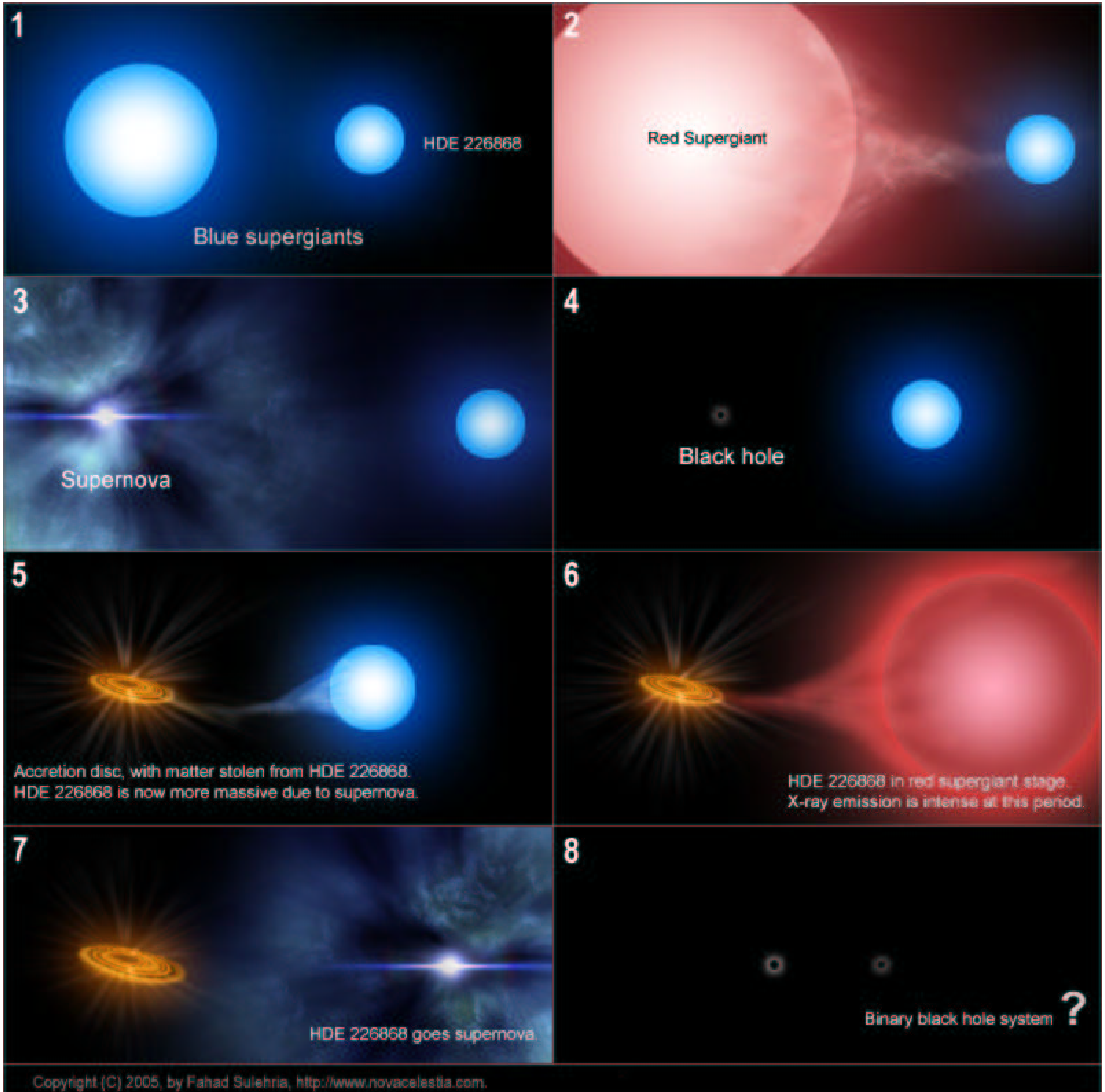
Binary star where one companion is a neutron star or a black hole.
Second companion is non-degenerate star (or WD).
WD companion→ cataclismic variable

The matter is accreted either from the inner Lagrangian point, or from surrounding stellar wind or medium (Bondi accretion)

Gravitational and kinetic energy of matter falling onto the central object is converted by dissipation to heat.

Heat is partially radiated out, partially converted to work on the disc expansion and (in the case of BH accretion) partially lost inside the hole.

02a


1
HDE 226868
Blue supergiants
2
Red Supergiant
3
Supernova
4
Black hole
5
Accretion disc, with matter stolen from HDE 226868.
HDE 226868 is now more massive due to supernova.
6
HDE 226868 in red supergiant stage.
X-ray emission is intense at this period.
7
HDE 226868 goes supernova.
8
Binary black hole system ?
Copyright (C) 2005, by Fahad Sulehria, http://www.novacelestia.com.

03 Accretion

The depth of potential well in compact objects is large → large ammount of energy is liberated in accretion process

The process of accretion at a rate $\dot{M}$ onto an object of mass M and radius R gives a luminosity of

$$L = GM\dot{M}/R$$

Heat is partially radiated out, partially converted to work on the disc expansion and (in the case of BH accretion) partially lost inside the hole.

Mass to energy conversion efficiency $\eta = L/Mc^2 = 0.1$ → **considerably greater than the efficiency of nuclear fusion (**$\eta = 0.07$).

03a Eddington limit

The accretion rate is limited by the Eddington limit. Defined by the balance between outward radiation pressure and inward gravitational force.

Any phenomenon lasting more than a few dynamical scales should have $L<L_{edd}$.

Force of radiation acting on an electron

$$F_{\rm rad} = \frac{L}{4\pi R^2 h\nu}\sigma_{\rm T}\frac{h\nu}{c}$$

Force of gravity on a proton $F_{\rm grav} = \frac{GMm_{\rm p}}{R^2}$

$$L_{\rm edd} = \frac{4\pi GMm_{\rm p}c}{\sigma_{\rm T}} \approx 10^{38}\frac{M}{M_\odot}\ \text{erg/s/}M_\odot$$

Maximum accretion rate

$$\dot{M}^{\rm edd}_{\rm acc} = \frac{L_{\rm edd}}{\eta c^2} \approx 2\times 10^{-8}\frac{M}{M_\odot}\ M_\odot\text{/yr}$$

04 Accretion disks

Matter's angular momentum is > than the Keplerian angular momentum → accreting matter will orbit a compact object.

Dissipation and friction: matter flattens and spreads equatorially into an accretion disk. The angular momentum is transported outward by friction and mass moves inward. Friction is magneto-turbulent is origin (likely) (Balbus & Hawley 1998)

Newtonian gravity: angular momentum at a distance R from a spherical object with the mass M is $(GMR)^{1/2}$ → monotonically increasing → stability of all orbits.

Einstein gravity: angular momentum has a minimum at the radius of the innermost stable circular orbit (ISCO). Orbits above r_{ISCO} are stable, and below are unstable.

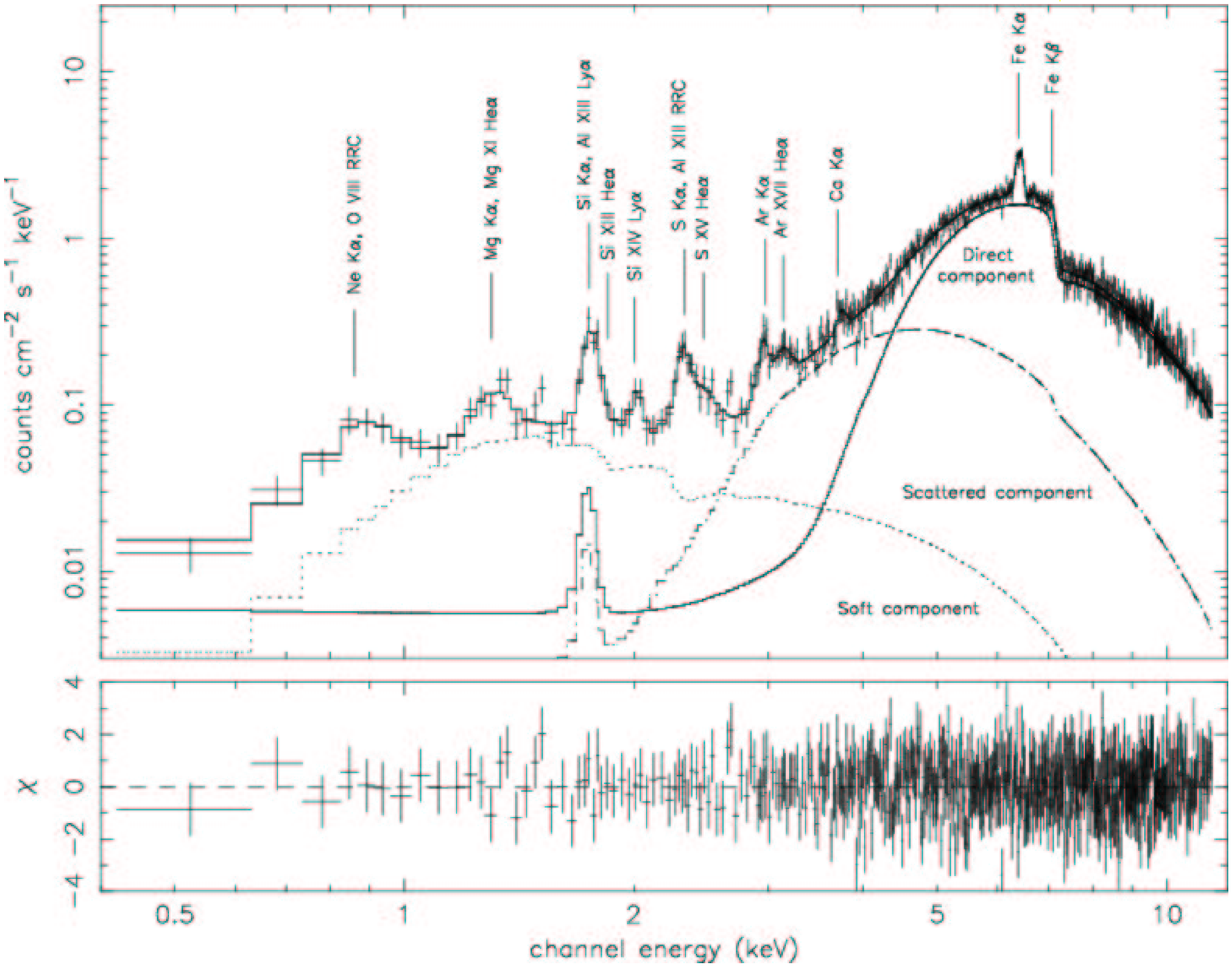
For a non- rotating black hole $r_{ISCO} = 6GM/c^2$

05 Spherically symmetrical (Bondi) accretion

- Spherical accretion onto an object occurs e.g. in a star accreting from ISM or in a compact object immersed in stellar wind.
- This happening when angular momentum is not dynamically important
- Accretion rate $\dot{M}_{\rm acc} = 4\pi r_{\rm A}^2 \rho v$, velocity can be either sound speed (c_s) or motion speed of compact object through the medium.
- Accretion $E_{tpt}<0$ → r_A is effective radius such that escape velocity $\sqrt{\frac{2GM}{r_{\rm A}}} = v$
- $$r_{\rm A} = \frac{2GM}{v^2} \rightarrow \dot{M}_{\rm acc} = \frac{8\pi\rho G^2 M^2}{v^3}$$

05a X-ra spectrum

- The gravitational energy of accreted matter is converted to heat.
- In optically thick case, black-body radiation $L_X = 4\pi\sigma_{sb}T^4$ → kT ≈ 1keV
- In optically thin case, mean particle energy $\frac{3}{4}kT = \frac{GMm_p}{R}$ → kT ≈ 50 MeV



Broad range of temperatures. Thermal radiation may be modified by comptonisation, fluorescence, and absorption

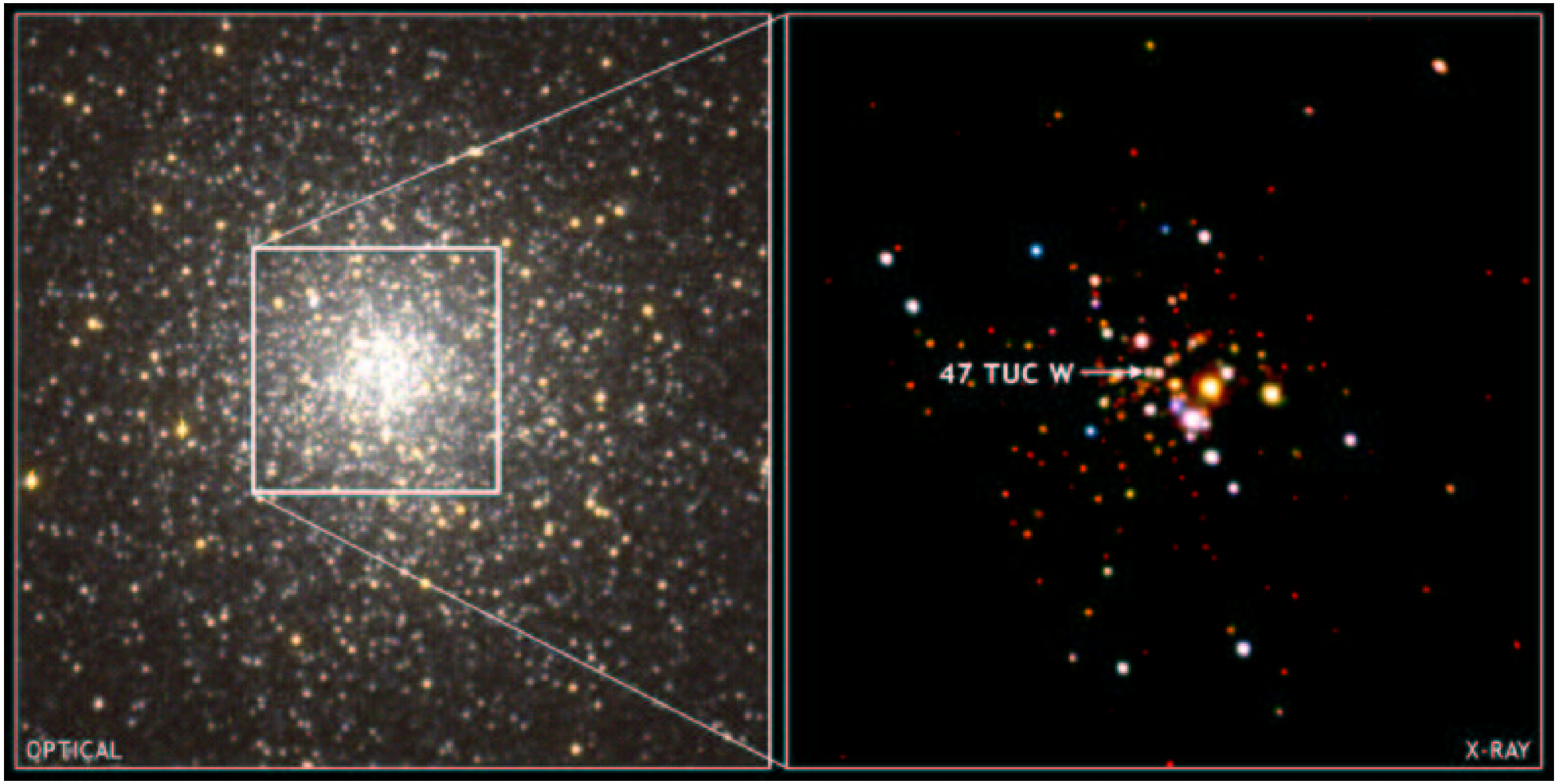
X-ray photoionized surrounding matter → secondary X-ray source

van der Meer et al. A&A 432, 999

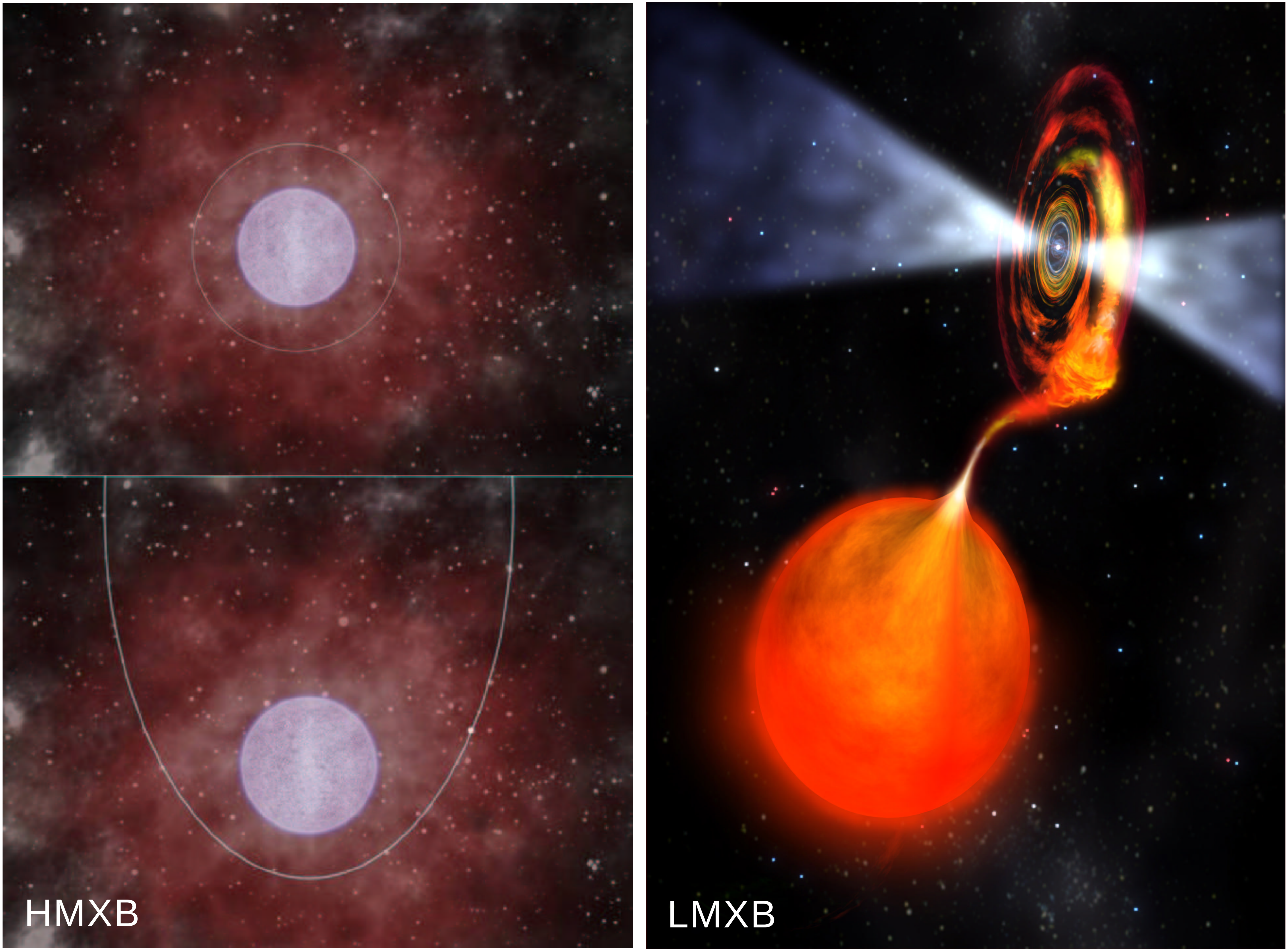
06 X-ray Binary Classification

Classified according to type of non-degenerate star

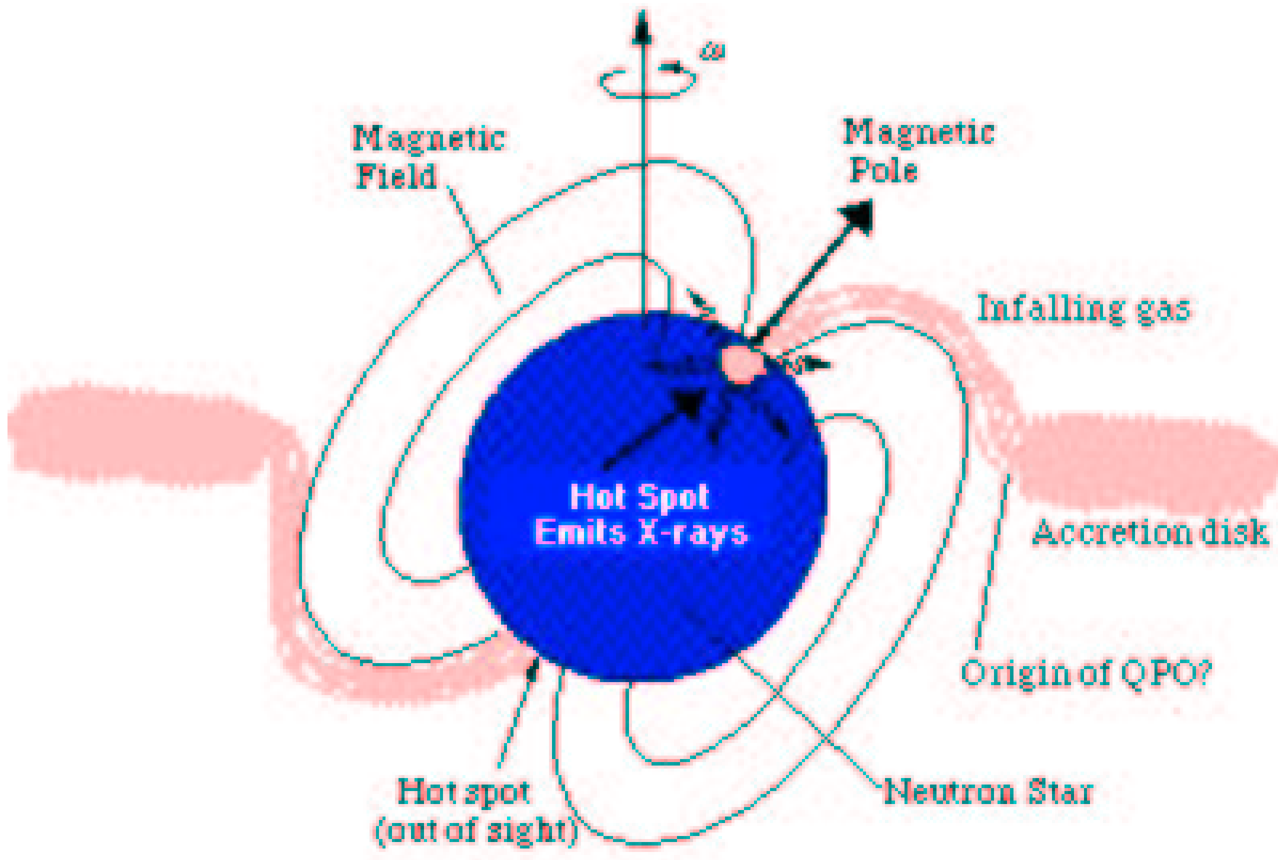
- High-mass X-ray binaries (HMXB): early-type star (A or earlier). Powered by stellar wind accretion. Two categories: Be binaries and the rest. Located in star forming regions, traces of star formation. Cyg X-1, Vela X-1, Her X-1)
- Low-mass X-ray binary (LMXB): late type stars. Powered by mass transfer via L1. Many types. Trace old population, globular clusters. Sco X-1, μQSO



NASA/CXC/CfA/J.Grindlay C.Heinke; ESO/Danish 1.54-m/W.Keel


HMXB
LMXB

06b Schematic view on pulsar accretion (Davidson & Ostriker 1973)



07 X-ray Pulsars (Davidson & Ostriker 1973)

- Observed in HMXBs, P=0.1 ms .. 1 min

- Bondi accretion and dipole magnetic field. Magnetosphere R_M: magnetic pressure equals the ram pressure.

- B_0 magnetic field at surface, B_M at R_M $B_M = \frac{B_0 R_0^3}{R_M^3}$, magnetic pressure is $\frac{B_M^2}{8\pi}$

- Schwarzschild radius $R_G = GM/c^2 \Rightarrow M = c^2 R_G 2G$

- Pressure of the gas $P_{flow} = \rho v_{ff}^2 \propto (\dot{M} R_M^2) \sqrt{M/R_M}$

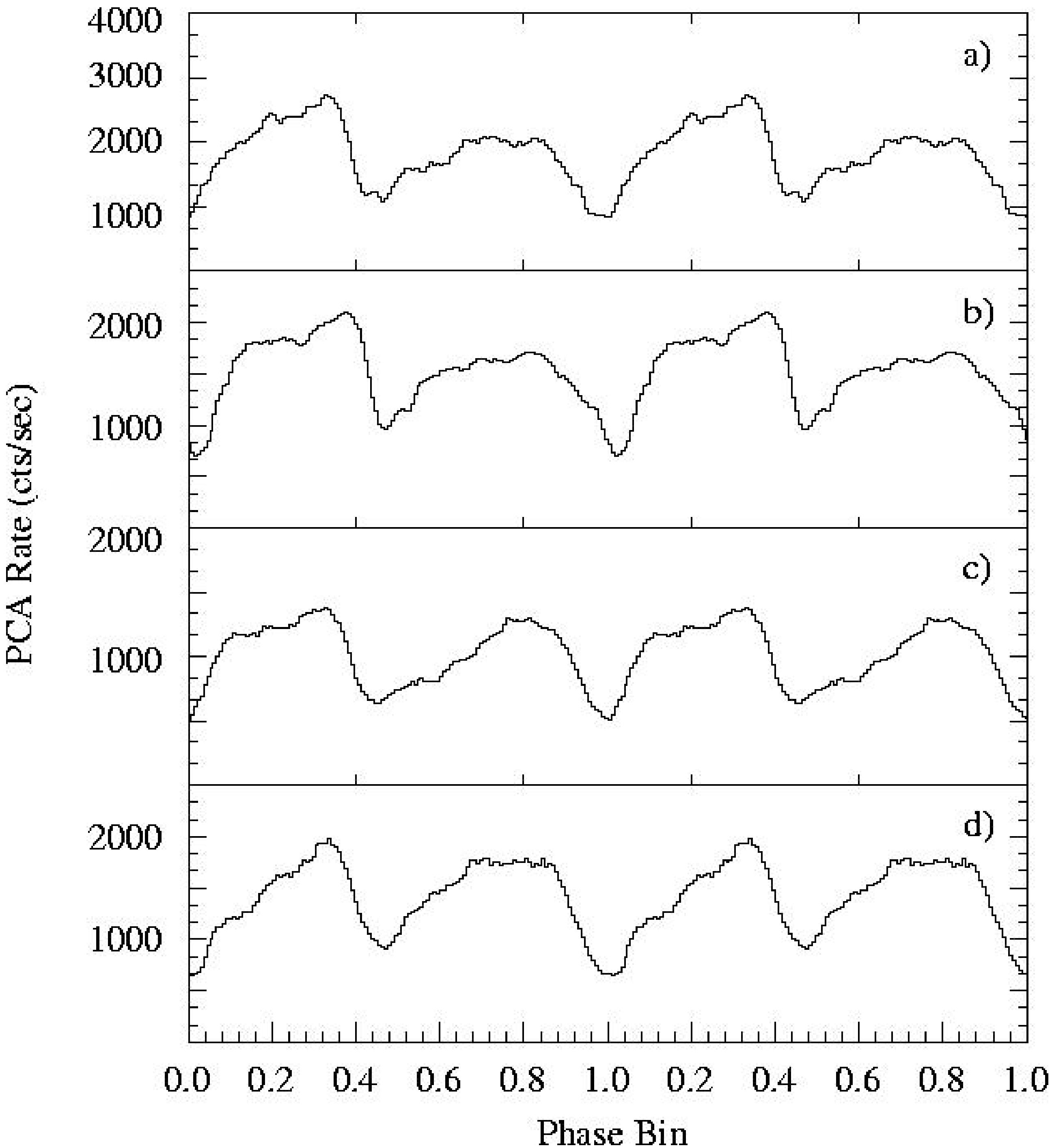
- The energy released $L_X = \frac{GM\dot{M}}{R_*} = \frac{R_G c^2 \dot{M}_{acc}}{R_*} \approx 10^{36}$ erg/s as indeed observed

- Putting all together $R_M \propto L^{-2/7} M^{1/7} R^{10/7} B_0^{4/7}$

- Lets angular rate of pulsar spin Ω and $P=2\pi/\Omega \rightarrow R_c=c/\Omega$

- Synchronisation orbit: gravitational orbital velocity is in corotation with the NS $R_{sy} = R_G^{1/3} R_c^{2/3} = M^{1/3} P^{2/3}$. For typical parameters of NS ($B_0=10^{12}$ G) $R_{sy}=R_M$

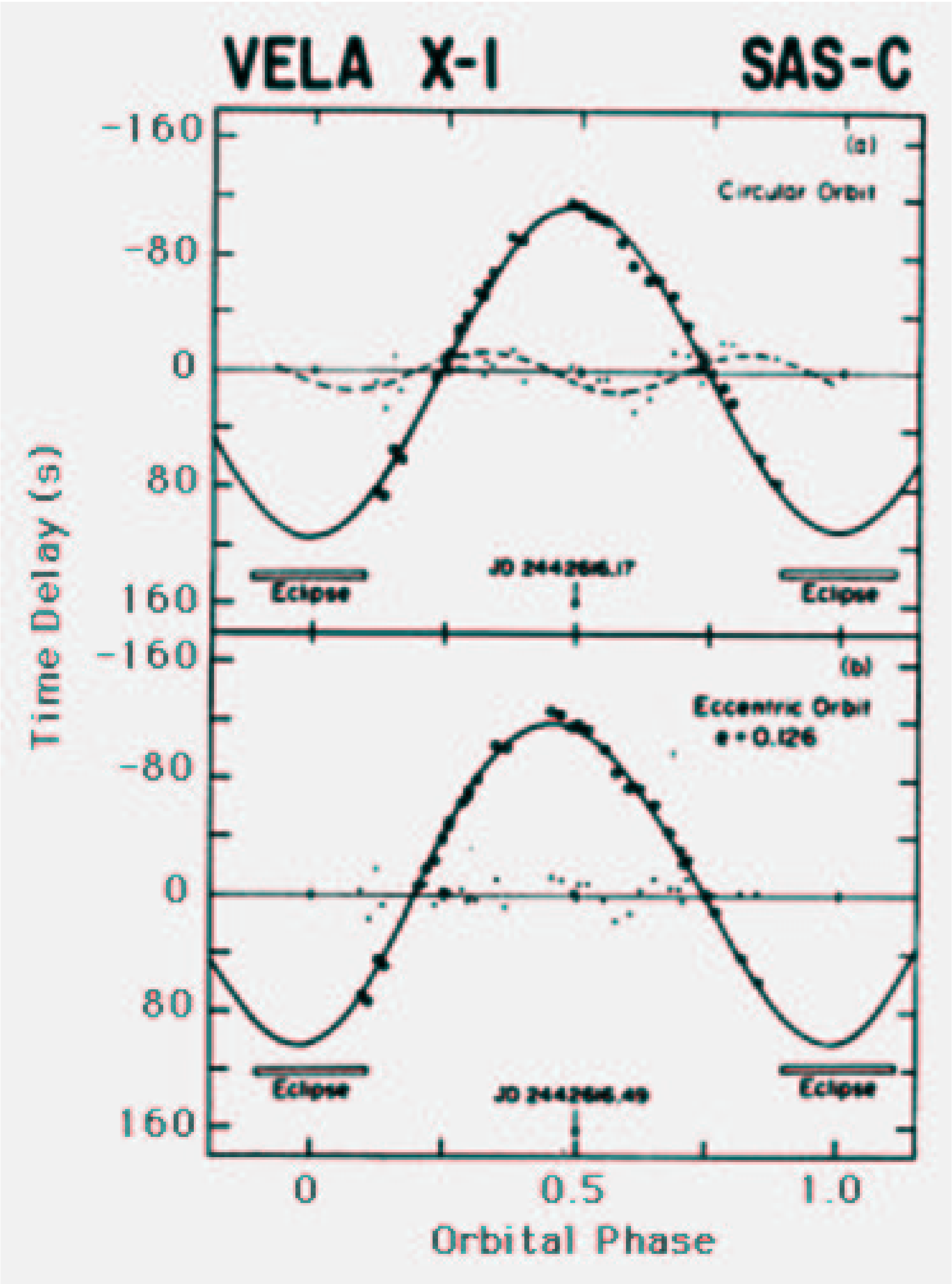
08 X-ray Pulsars (cont.)



Kreykenbohm et al. A&A 341, 141

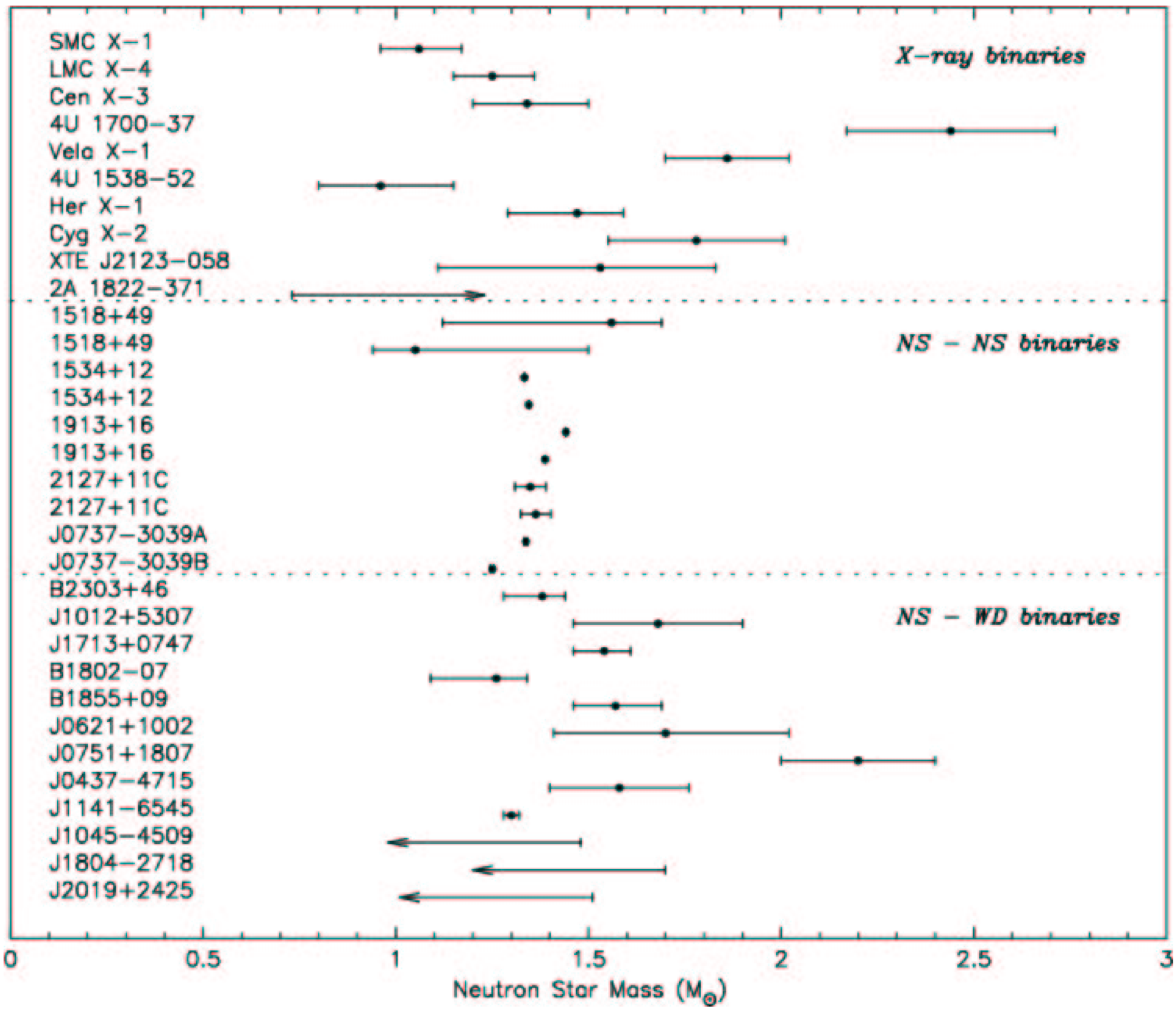
- The rotation rate of the NS is held near equilibrium, depending on the B_0 and rotation rate
- If NS is spinning too fast $R_M > R_{sy}$, matter cannot fall through the magnetosphere
- Material is flung out of the system, inducing a braking torque. Spin-down for 10^3 yr but stopped aferwards
- If is spinning too slow $R_M < R_{sy}$. Density gradient in stellar winds → a side closer to the star accrets more → a torque → spin up.
- The centrifugal barrier acts as a valve regulating the transfer of angular momentum

09 Mass of Neutron stars



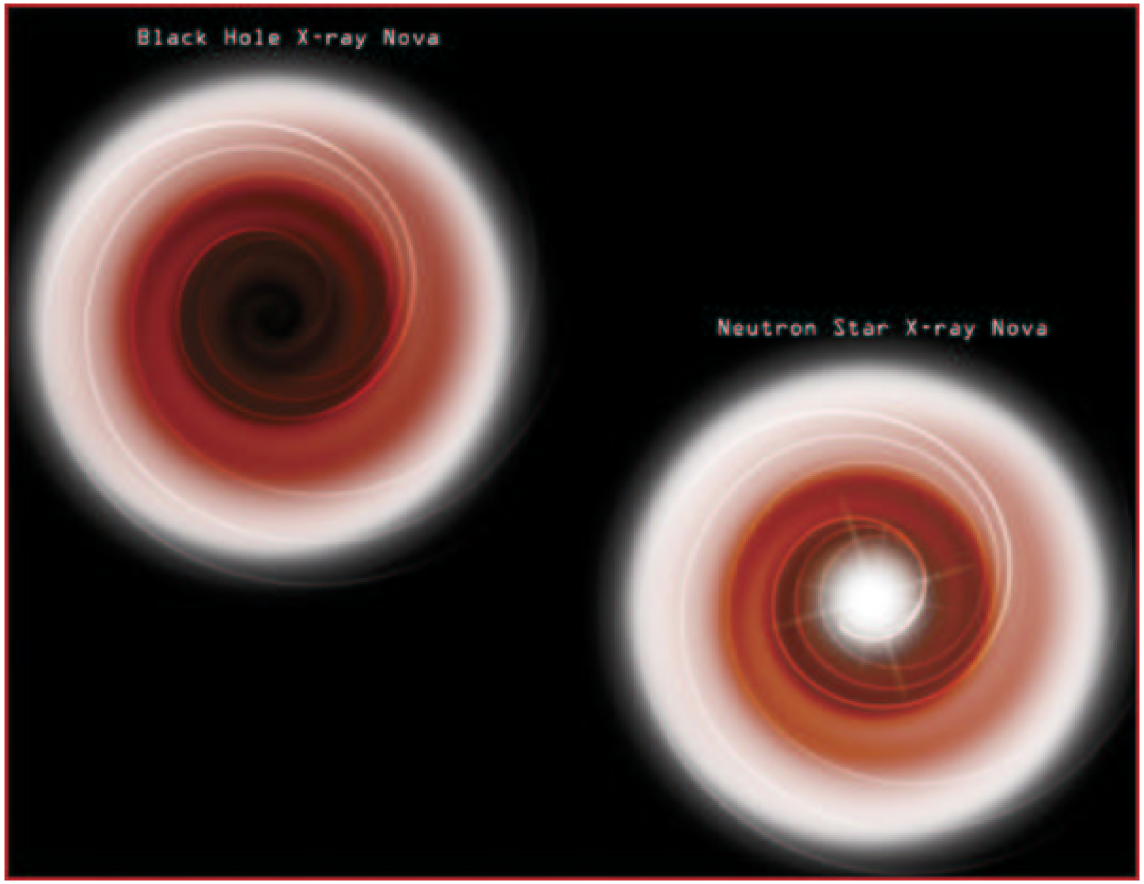
- Equation of state for neutron star matter is poorly established (X-ray observations help)
- Tolman-Oppenheimer-Volkoff upper limit on NS mass: 1.5-3? Msun
- Binary radio pulsars have well-defined mass around 1.4 M_{sun}. What about accreting systems?
- Needed eclipsing X-ray pulsars: RV of donor from optical, RV of NS from pulse measurments, inclination from eclipse duration → mass
- So far only 7 eclipsing X-ray pulsars are known, incl. Vela X-1

10 Neutron Star (NS) masses (van der Meer et al. 2007, A&A, 473, 523)

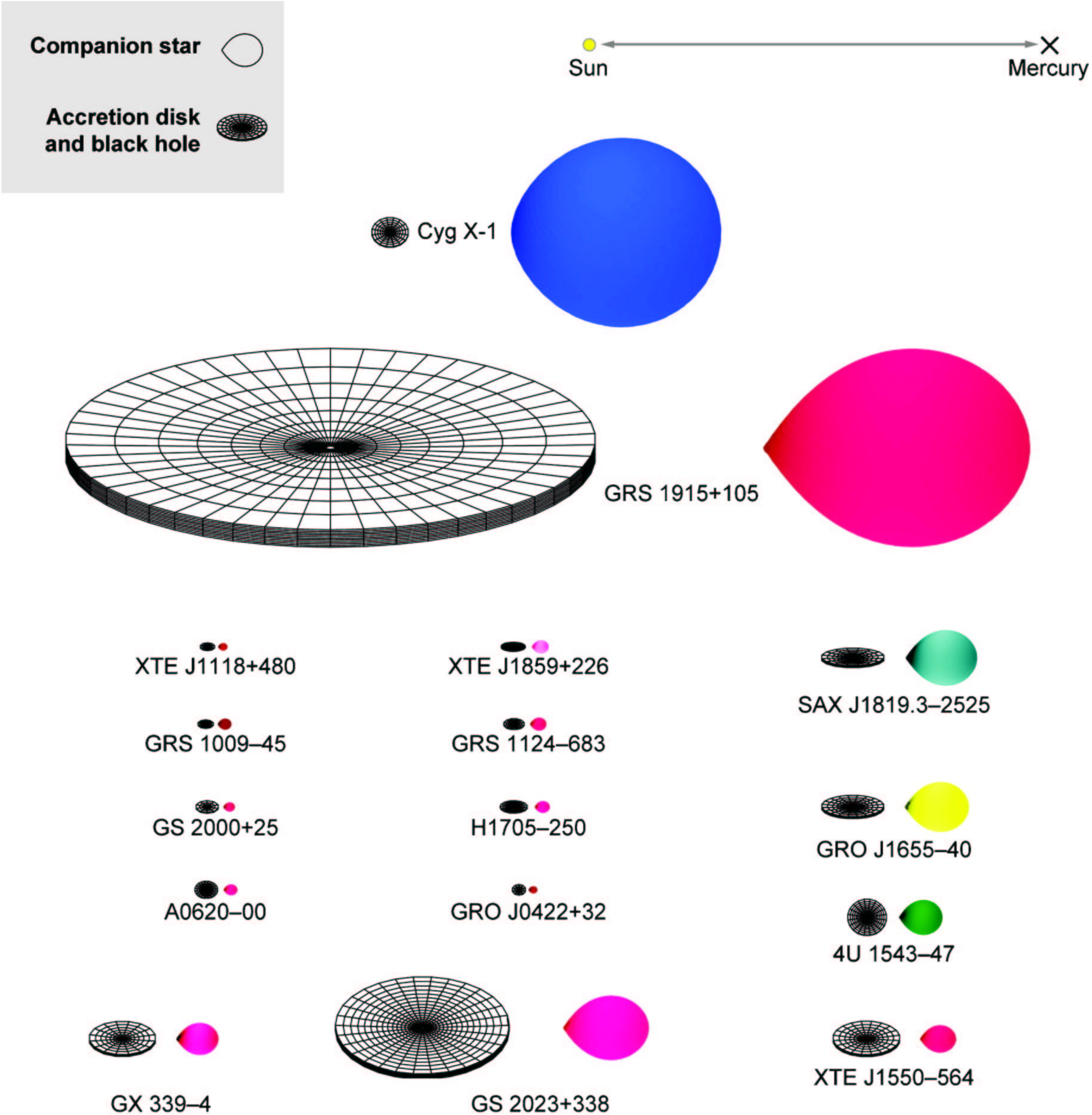


11 Black Hole X-ray Binaries

Oppenheimer & Snyder (1939): formation of a black hole.



- 20 XRBs contain a compact object with $M > 3M_\odot$. In the Galaxy 10^{8-9}.
- A BH is specified by M (scale) and spin a=J/c M (geometry), where J is angular momentum. Or $a^* = a/R_G$. Schwarzschild BH: $a^* = 0$; Kerr BH: $a^* = 1$.
- Event horizon of a Schwarzschild BH $R_S = 2R_G = 30\text{km}\ (M/10M_\odot)$, the ISCO lies at $R_{ISCO} = 6R_G$, and the maximum orbital frequency is $\nu_{ISCO} = 220\text{Hz}(M/10M)^{-1}$. For Kerr BH (a* = 1), the $R_S = R_{ISCO}$ and $\nu_{ISCO} = 1615\text{Hz}(M/10M)^{-1}$.
- Radiating gas orbiting a compact object is the steady-state, thin accretion disk model (Shakura & Sunyaev 1973) → $T(R) \propto R^{-3/4}$. Luminosity of an annulus $L_X \propto R dR \sigma_{sb} T^4 \propto R^{-2}$. X-rays are the best window to the horizon of a BH.



Remillard RA, McClintock JE. 2006. Annu. Rev. Astron. Astrophys. 44:49–92

12 Census

LMC X-3 B3V

M_{BH} =5.9-9.2$M_{\odot}$

LMC X-1 O7III

M_{BH} =4.0-10.0$M_{\odot}$

GRS1915+105 MIII

M_{BH} =10.0-18.0$M_{\odot}$

Cyg X--1 O9.7I

M_{BH} =6.8-13.3$M_{\odot}$

V404 Cyg K0III

M_{BH} =10.1-13.4$M_{\odot}$

XTE1118 M0V

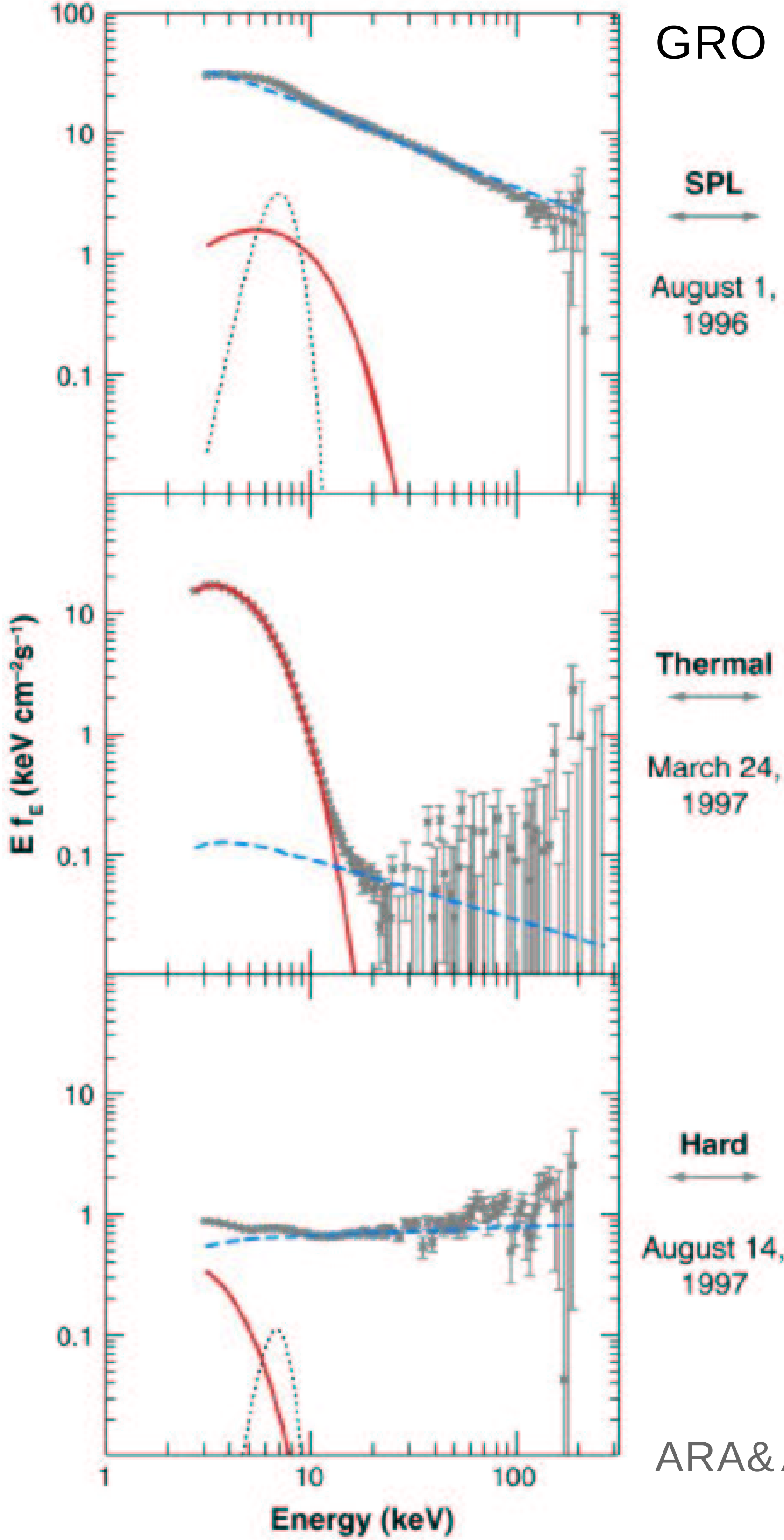
M_{BH} =6.5-7.2$M_{\odot}$

steady X-ray bright

transient X-ray novae

GRO J1655-40

13 Emission states of BH binaries



Steep Power Law

"The physical origin of the SPL state remains one of the outstanding problems in high-energy astrophysics. "

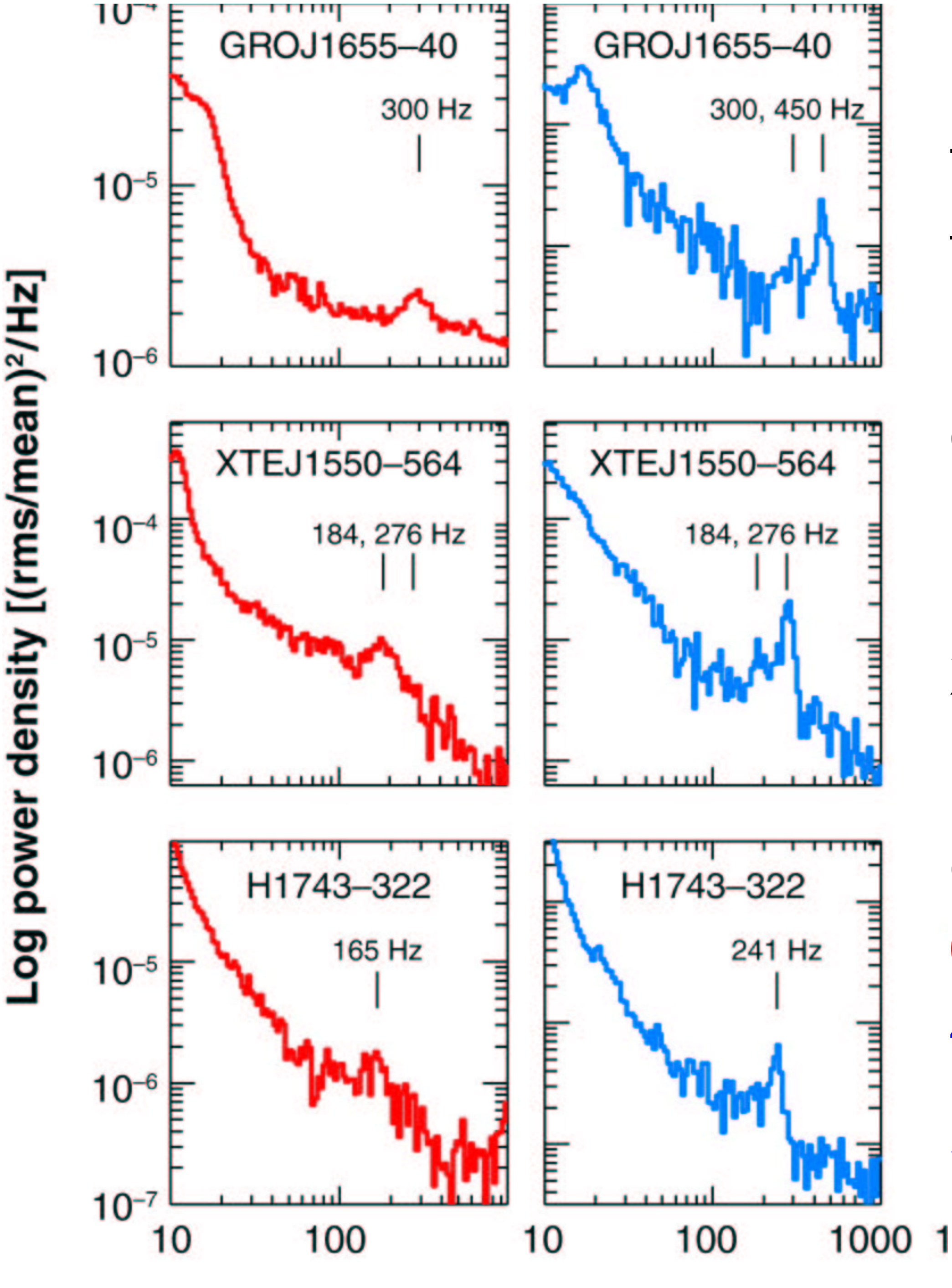
Thermal state

Thermal emission from the inner regions of an accretion disk. Well advance MHD modeling of multitemperature accretion discs, and perhaps, explanation of viscosity.

Hard state

Associated with the presence of a steady radio jet. Synchrotron and Compton components; the Compton emission is presumed to originate at the base of the jet.

ARA&A 44, 49



Remillard RA, McClintock JE. 2006. Annu. Rev. Astron. Astrophys. 44:49–92

14 Quasi-Periodic Oscillations (QPOs)

The pulse period is exactly the same as the spin period of the pulsar. QPO are modulations in the puls.

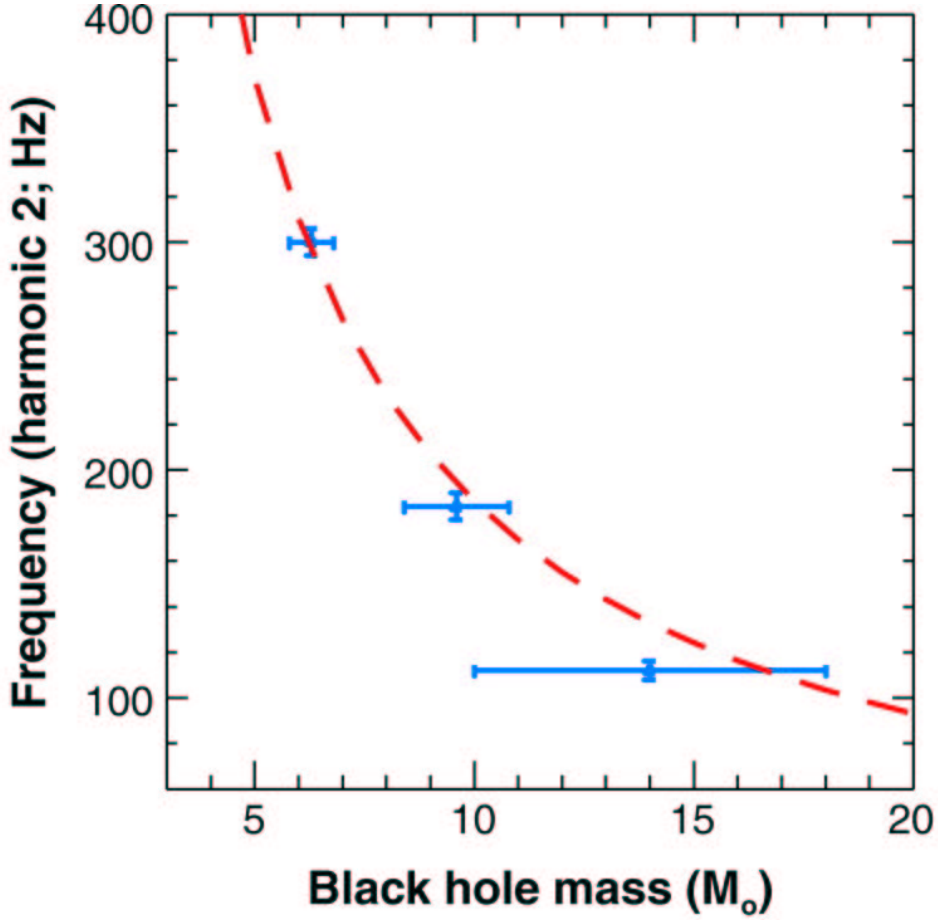
QPOs are observed as broad bump in the Fourier power spectra of X-ray light curves. Frequiency depends on energy. The higher X-ray luminosity, the shorter is the QPO period.

Come in two flavors: Low-frequency QPO (0.1-30 Hz) and High-frequency QPO (40-450 Hz).

Some proposed mechanisms for **LFQPOs**

- Global disk oscillations
- Radial shock fronts in accretion flow
- Accretion-ejection instability model: spiral waves in a magnetized disk

15 High Frequency QPOs



Remillard RA, McClintock JE. 2006. Annu. Rev. Astron. Astrophys. 44:49–92

Offer the most reliable measurement of BH spin once the correct model is known

HFQPOs, 150-450 Hz, correspond respectively to the frequency at the ISCO for Schwarzschild BHs with masses of 15-5 $M_{\odot}$, which in turn closely matches the range of observed masses.

HFQPO frequencies do not vary significantly with L_X. → Frequency dependends on the mass and spin of the BH.

Proposed models invoke orbital resonances in GR.

However only three sources where HFQPOs measured and BH masses are known.