Accretion-powered X-ray sources

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Accretion: General considerations

Accretion is the accumulation of diffuse gas/matter onto some object under the influence of gravity.

Let us assume a star of mass M and radius R, and an element of gas of mass Δm in free-fall from infinity; the amount of kinetic energy acquired by the element of mass as it falls is equal to the change of its potential energy:

$$\frac{1}{2}\Delta m v_{\mathrm{ff}}^2 = \frac{GM}{r}\Delta m.$$

When $r = R$, the mass element hits the surface of the star and has to dissipate the excess kinetic energy and radiate it away. The rate at which energy is radiated is:

$$L = \frac{1}{2}\dot{m}v_{\mathrm{ff}}^2 = \frac{GM}{R}\dot{m} = \frac{1}{2}\left(\frac{2GM/c^2}{R}\right)\dot{m}c^2 = \frac{1}{2}\left(\frac{r_{\mathrm{g}}}{R}\right)\dot{m}c^2,$$

with $r_{\mathrm{g}} = 2GM/c^2$ the Schwarzschild radius of the star.

$$L = \xi\dot{m}c^2, \quad \textbf{with} \quad \xi = \frac{1}{2}\left(\frac{r_{\mathrm{g}}}{R}\right) = \frac{G}{c^2}\left(\frac{M}{R}\right)$$

M/R is the compactness of the star.

White Dwarf: ($M \sim 1\ M_{\odot}$, and $R \sim 5\times10^3$ km) $\rightarrow$ $\xi \approx 3\times10^{-4}$

Neutron Star: ($M \sim 1\ M_{\odot}$, and $R \sim 15$ km) $\rightarrow$ $\xi \approx 0.1$

Black Hole: ($R = r_g = 2GM/c^2$) $\rightarrow$ $\xi = 0.5$[(1)]

For nuclear reactions, the mass difference between the final and initial products is transformed into energy.

The most effective reaction (the one in which the mass difference is the largest) is the one in which Hydrogen transforms into Helium, $4\ H^1 \rightarrow He^4$ which releases:

$$L_{\rm nuc} = \frac{\Delta E_{\rm nuc}}{\Delta t} \approx 7\times10^{-3}\dot{m}c^2 \Rightarrow \xi \approx 7\times10^{-3}.$$

Accretion is one of the most efficient mechanism to produce energy.

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(1) Actually, a black hole has no surface, and matter could accrete and disappear beyond the horizon, producing no emission.

The Eddington (limiting) luminosity

If $L = \xi \dot{m} c^2,$

the question is: Can L increase arbitrarily if $\dot{m}$ increases?

Since we know that radiation pressure acts upon matter, this should help us to address that question.

Assumptions:

-Accretion is steady and spherically symmetric.

-Accreting material is fully ionized H (plasma consists of protons and electrons).

-Thomson scattering is the principal source of opacity
($\sigma \propto m^{-2} \Rightarrow \sigma_{\mathrm{Proton}}/\sigma_{\mathrm{Electron}} \propto (m_{\mathrm{e}}/m_{\mathrm{p}})^2 \approx 5\times 10^{-4}$).

Gravity acting upon a $H^+ + e^-$ pair:

$$F_{grav} = \frac{GM}{r^2}(m_{\mathrm{p}} + m_{\mathrm{e}}) \approx \frac{GM}{r^2} m_{\mathrm{p}}.$$

The Eddington (limiting) luminosity

Radiation pressure acts upon e^- (as we just saw, H^+ cross section is much lower).
Each photon gives a momentum $p=h\nu/c$ to an electron per collision.
If the photon flux is N_{ph} photons cm^{-2} s^{-1}, the net force transmitted to the electrons is $\sigma_e N_{ph} p$.
But the photon flux at a distance r from the source is $N_{ph} = L/(4\pi r^2 h\nu)$, and hence:

$$F_{rad} = \frac{\sigma_e L}{4\pi r^2 c}.$$

But protons and electrons are linked through Coulomb interactions (the plasma tends to remain neutral), so the net force upon the plasma is:

$$F_{net} = F_{grav} - F_{rad}$$

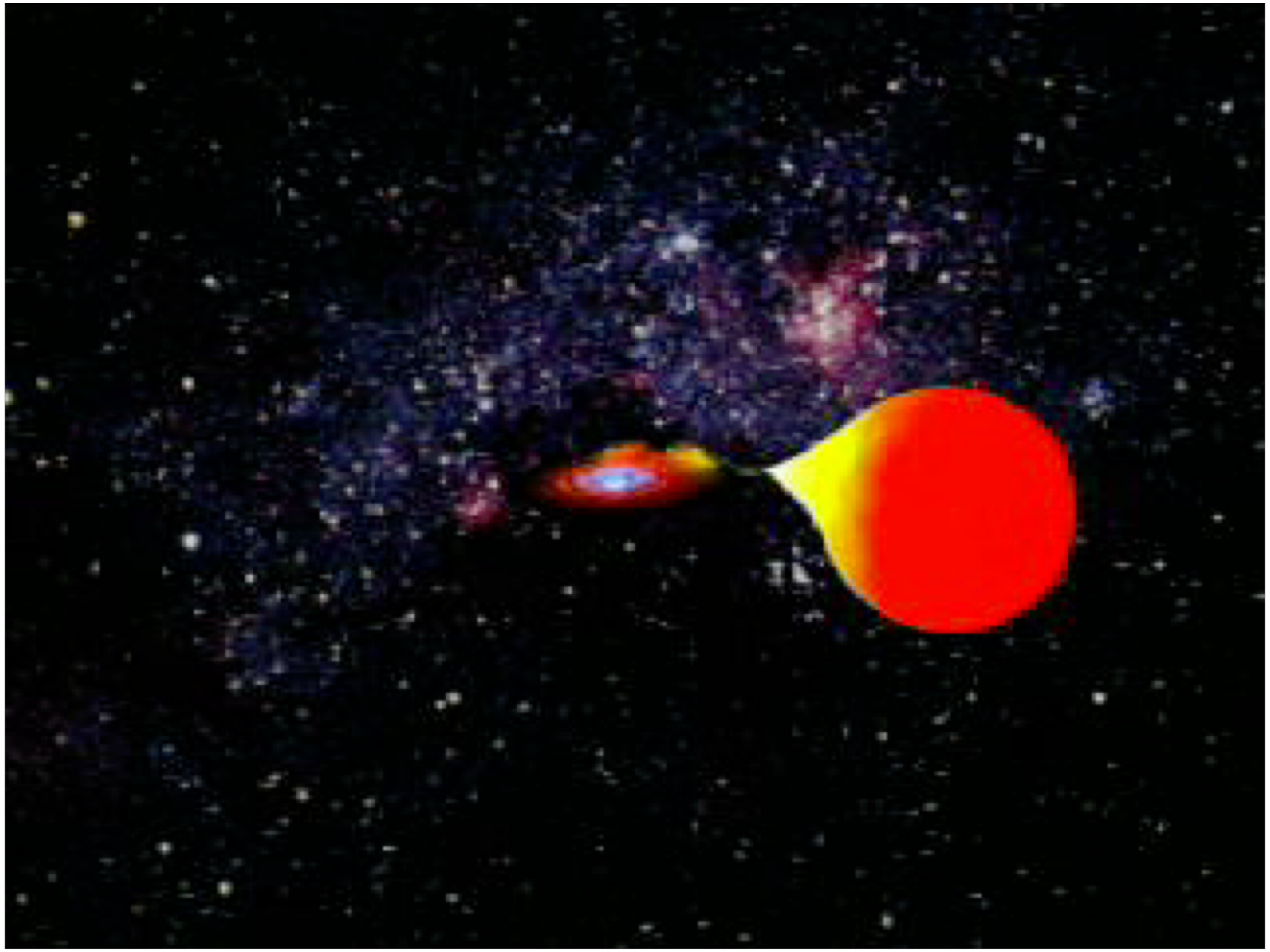
Setting $F_{net} = 0$ yields the condition under which gravitational and radiation forces are *just* balanced:

$$\frac{GMm_p}{r^2} = \frac{\sigma_e L}{4\pi r^2 c},$$

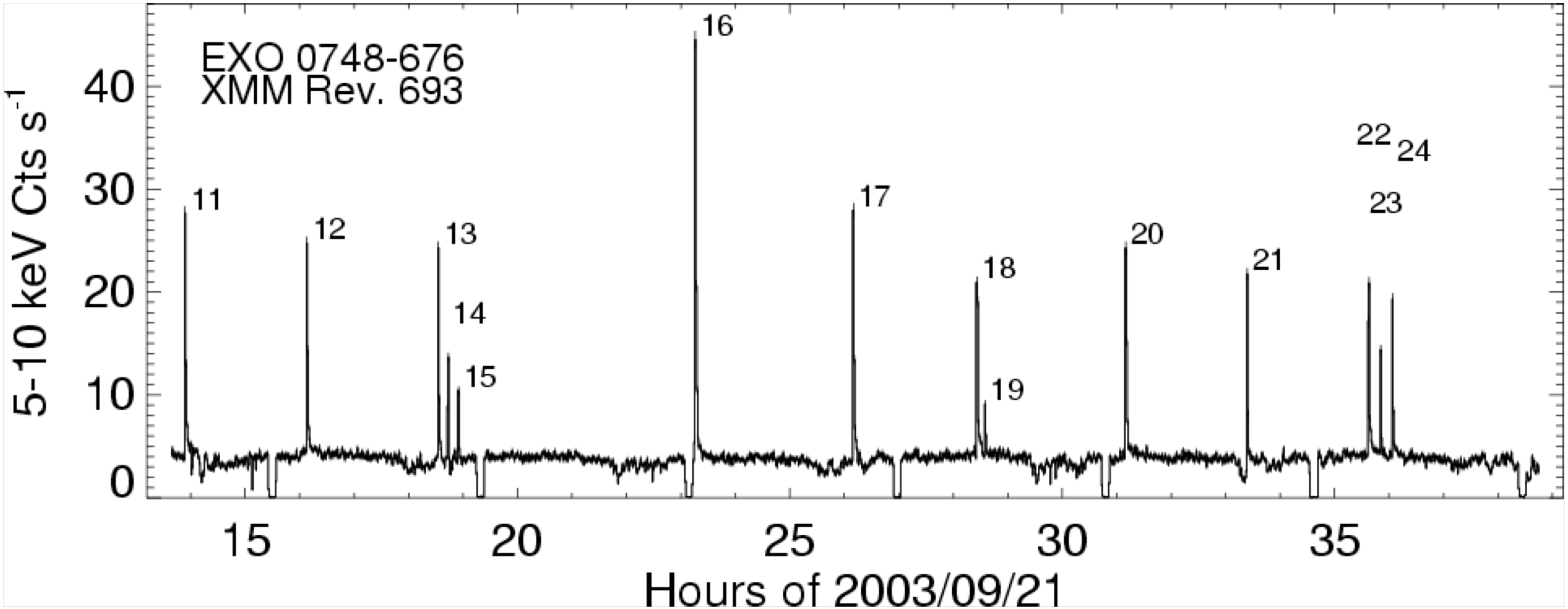
which defines the Eddington Luminosity, the luminosity at which no further accretion is possible:

$$L_{Edd} = 4\pi GMm_p c/\sigma_e \approx 1.3\times10^{38}(M/M_\odot)\ \mathrm{ergs}^{-1}.$$

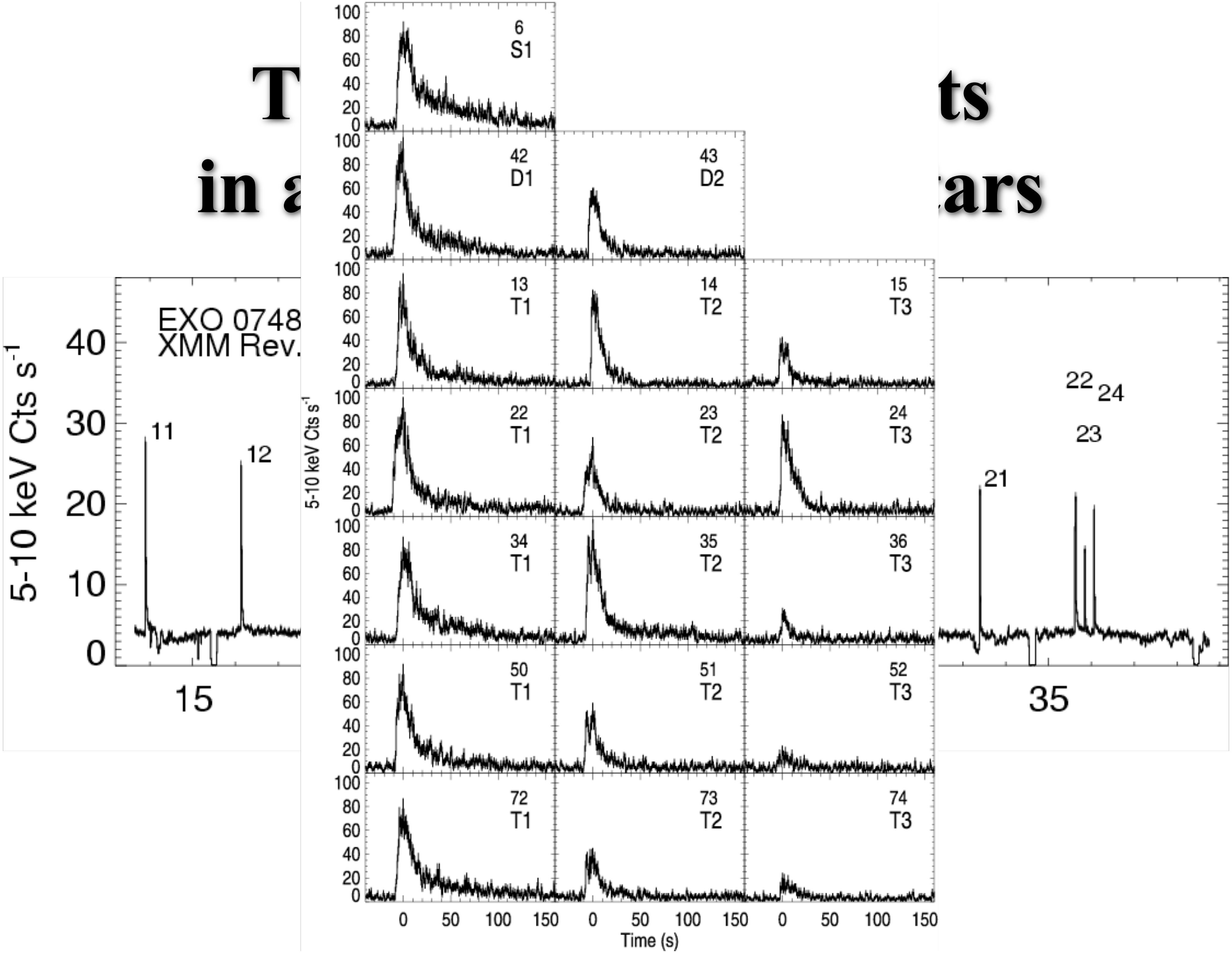
Thermonuclear bursts in accreting neutron stars



Thermonuclear bursts in accreting neutron stars



T ts
in a ars



EXO 0748
XMM Rev.
5-10 keV Cts s-1
0
10
20
30
40
11
12
21
22
24
23
15
35
6 S1
42 D1
43 D2
13 T1
14 T2
15 T3
22 T1
23 T2
24 T3
34 T1
35 T2
36 T3
50 T1
51 T2
52 T3
72 T1
73 T2
74 T3
5-10 keV Cts s-1
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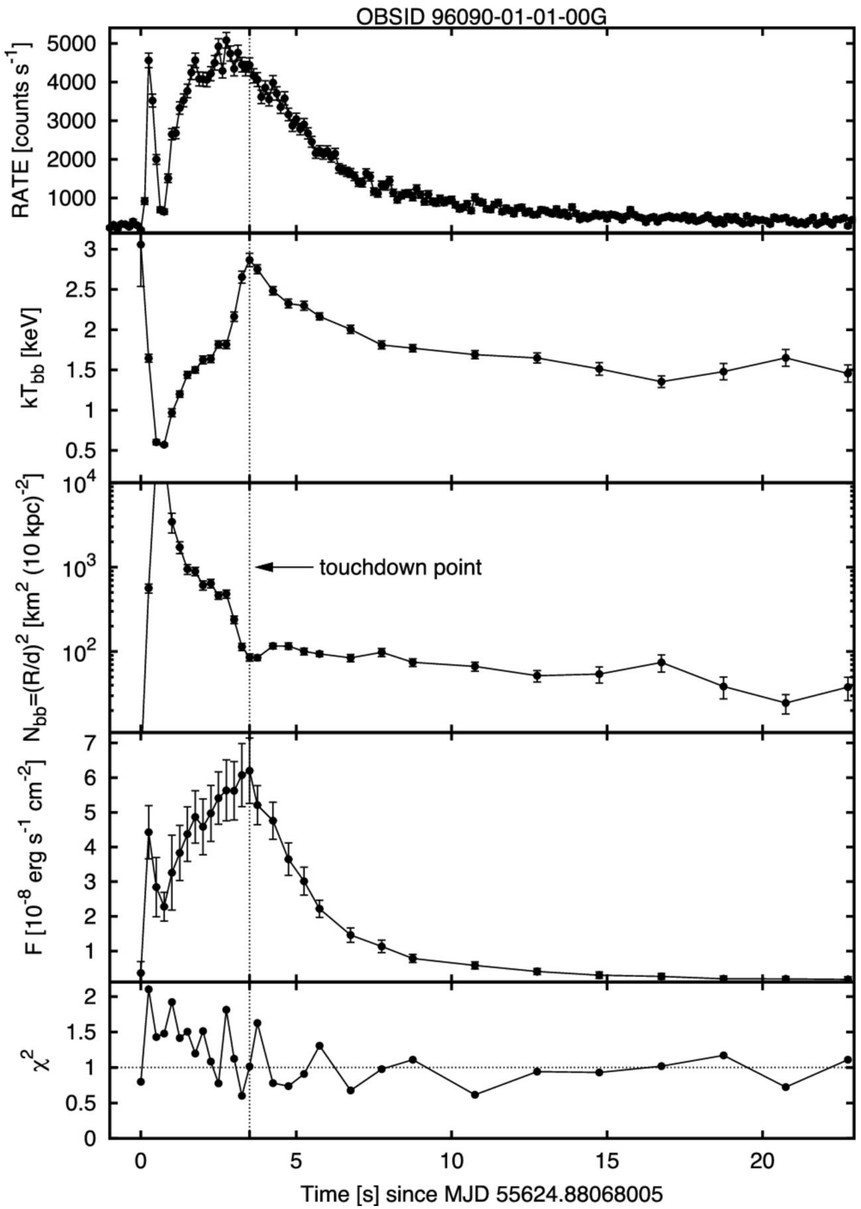
20
40
60
80
100
0
50
100
150
Time (s)

Thermonuclear bursts in neutron stars



When the flux reaches the Eddington limit the atmosphere of the neutron star expands, R_{bb} increases, and its temperature, kT_{bb}, decreases.

Thermonuclear bursts in neutron stars

If one identifies the flux at the peak, f_{peak}, of a burst with the Eddington luminosity of the neutron star, L_{Edd}, one can infer the distance to the source:

$$d = \left[\frac{1}{4\pi} \frac{L_{\mathrm{Edd}}}{f_{\mathrm{peak}}} \right]^{1/2},$$

(actually, this sets an upper limit to the distance).

If we know the temperature as a function of time during the burst, T, assuming the neutron star emits as a blackbody, one can get the neutron-star radius from $L=\pi R^2 \sigma T^4$.

NOTICE THAT THIS IS A VERY CRUDE APPROXIMATION !!!!

Typical temperatures of compact accreting objects

We will now make some order of magnitude estimates of the spectral range of the emission from compact accreting objects. We can characterize the continuum spectrum of the emitted radiation by a temperature T_{rad}. An object of radius R that emits a blackbody spectrum at a luminosity L_{acc} has a temperature T_{bb} given by:

$$T_{\mathrm{bb}} = \left(\frac{L_{\mathrm{acc}}}{4\pi R^2 \sigma}\right)^{1/4}$$

Stefan-Boltzman law.

If all potential energy of the accreted matter would turn entirely into radiation, the material would reach a temperature T_{th}.

For each pair $H^+ + e^-$ the potential energy is $G\,M(m_{\mathrm{p}}+m_{\mathrm{e}})/R \approx G\,M\,m_{\mathrm{p}}/R$, and the thermal energy is $2 \times (3/2\,k\,T_{\mathrm{th}})$ ($3/2\,k\,T_{\mathrm{th}}$ per particle); hence:

$$T_{\mathrm{th}} = \frac{GMm_{\mathrm{p}}}{3kR}.$$

Typical temperatures of compact accreting objects

The two extreme situations are:

1. **Accretion flow is optically thick.** **The radiation reaches thermal equilibrium before it escapes, so that the emitted spectrum is blackbody:**

$$T_{\rm rad} = T_{\rm bb} = \left(\frac{L_{\rm acc}}{4\pi R^2 \sigma}\right)^{1/4} .$$

2. **Accretion flow is optically thin.** **The radiation escapes the flow immediately after it is produced:**

$$T_{\rm rad} = T_{\rm th} = \frac{GMm_{\rm p}}{3kR}.$$

In general the properties of the flow will be somewhere in between, and hence the temperature will be somewhere in between. For typical values:

$$T_{\rm bb} \approx \begin{cases} 1 & \text{keV} & \text{NS} & (L_{\rm acc} \approx & 0.1 L_{\rm Edd}) \\ 6 & \text{keV} & \text{WD} & (L_{\rm acc} \approx & 0.01 L_{\rm Edd}) \\ 20 & \text{eV} & \text{AGN} & (L_{\rm acc} \approx & L_{\rm Edd}, M \approx 10^8 M_\odot) \end{cases}$$

$$T_{\rm th} \approx \begin{cases} 50 & \text{MeV} & \text{NS} \\ 100 & \text{keV} & \text{WD} \end{cases}$$

SUMMARY

1. **Accretion is a very efficient process. Up to 10% of the rest mass turns into radiation (in nuclear reactions it is less than 0.7%)**

2. **There is a maximum luminosity, the Eddington luminosity, above which accretion stops. The Eddington limit applies to steady, spherically-symmetric flows. The limit can be violated for short periods of times. The Eddington luminosity can be used to get distances to (and sizes of) some objects.**

3. **Typical temperatures for accreting objects mean that NS/BH should emit mostly in X/γ-rays ($kT \sim$ 0.5 keV – 100 MeV), WD would emit mostly in the UV/X-ray band ($kT \sim$ 6 eV – 100 KeV), while AGN would on average be detected in (soft) X-rays and UV.**

Accretion in binary systems

Mass transfer in Binaries

There are two ways in which matter can be transferred from one star to the other:

1. Wind (outflow) from the secondary

2. Roche lobe overflow

1. Wind accretion:

This mechanism is relevant in systems containing an early-type secondary, of spectral type O or B.

The stellar winds in these stars are intense, and supersonic:

Wind accretion

$$\dot{M}_{\mathsf{W}} \approx 10^{-6} - 10^{-5} M_{\odot}\ \mathsf{yr}^{-1}$$

$$v_{\mathsf{W}} \approx v_{\mathsf{esc}}(R_{\mathsf{E}}) = \left(\frac{2GM_{\mathsf{E}}}{R_{\mathsf{E}}}\right)^{1/2}$$

with R_{E} and M_{E} the radius and mass of the early-type star. For typical radii and masses of O and B stars $v_{\mathsf{W}} \approx 1000$ km s^{-1} ($c_{\mathsf{s}} \approx 10$ km s^{-1}).

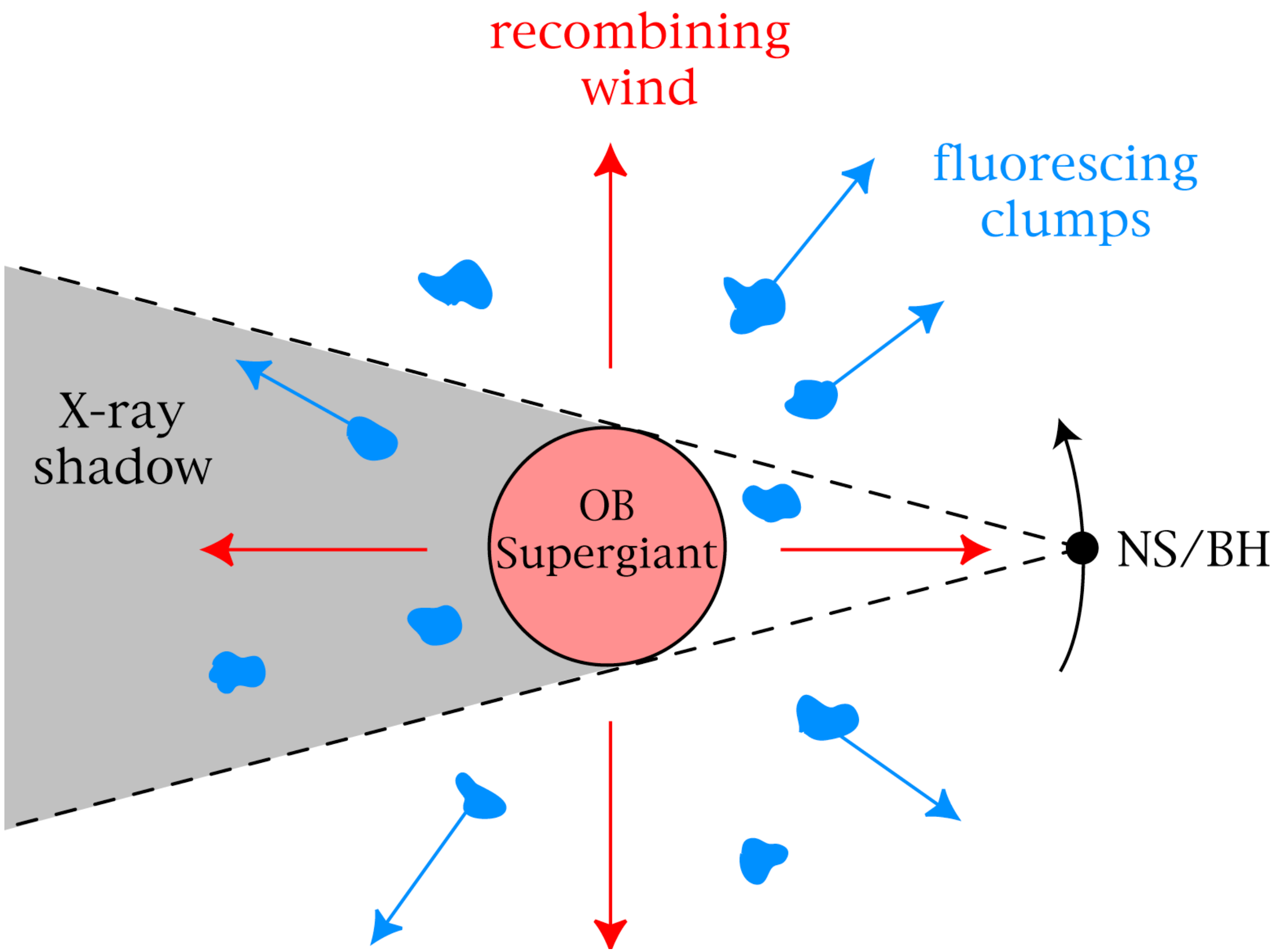
$$L_{\mathsf{acc}} \approx 10^{37} \left(\frac{\dot{M}}{10^{-4}\dot{M}_{\mathsf{W}}}\right) \left(\frac{\dot{M}_{\mathsf{W}}}{10^{-5} M_{\odot}\ \mathsf{yr}^{-1}}\right)\ \mathsf{erg\ s}^{-1}.$$

The mass accreted onto the compact object is $\dot{M} \approx 10^{-4} - 10^{-3}\dot{M}_{\mathsf{W}}$. Clearly this is a very inefficient process. It is important only because in early-type stars $\dot{M}_{\mathsf{W}}$ is so large.

Schematic Picture of Wind-fed system

Some systems have an accretion disk around the compact object.

The clumps could also be highly ionized if the X-ray luminosity is sufficiently high.

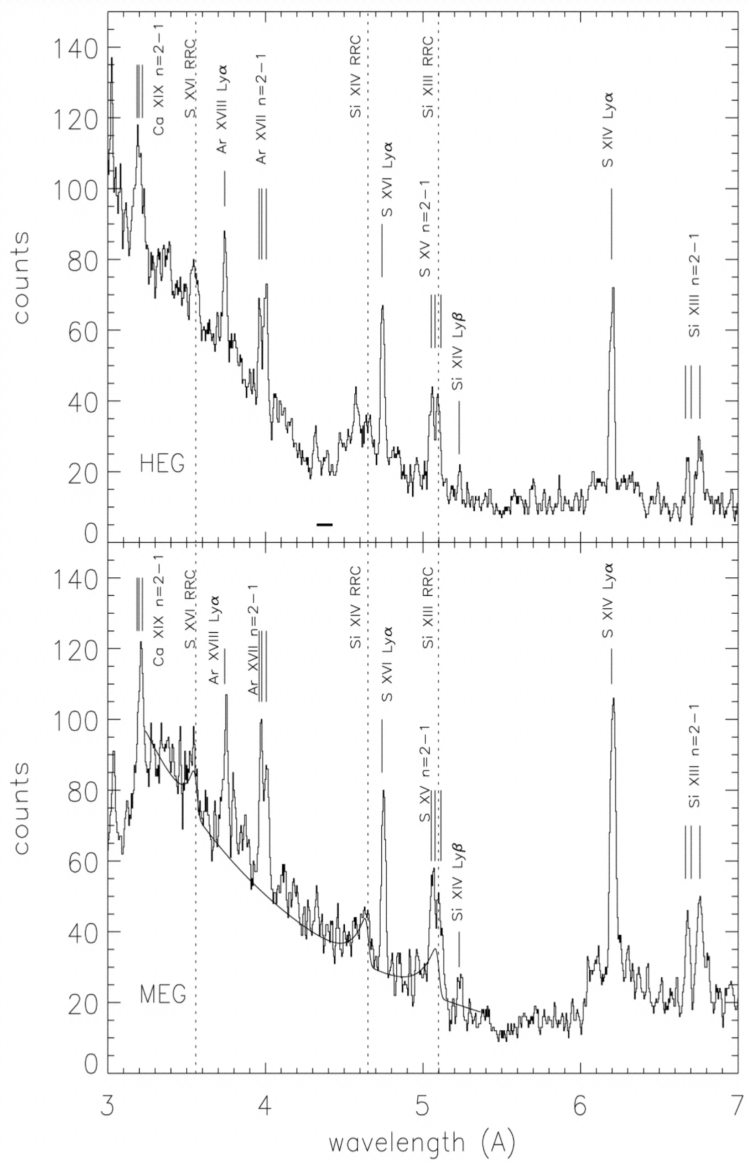


Chandra: Cyg X-3

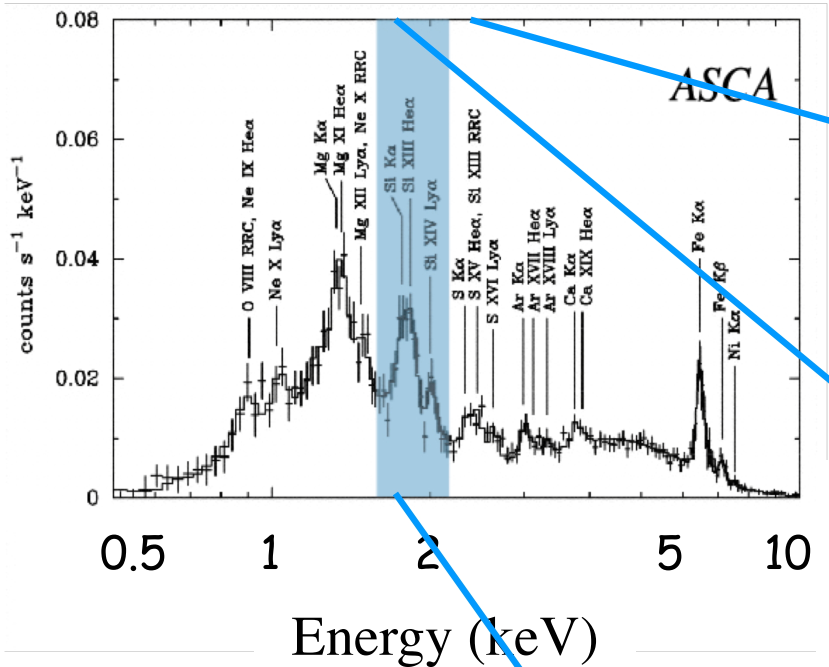
Dominance of recombination line emission from H- and He-like ions of Mg, Si, S, Ar, Ca, and Fe

Narrow radiative recombination continuum (RRC) provides plasma temperature ($kT \sim 50$ eV).
He-like triplet ratio provides density.

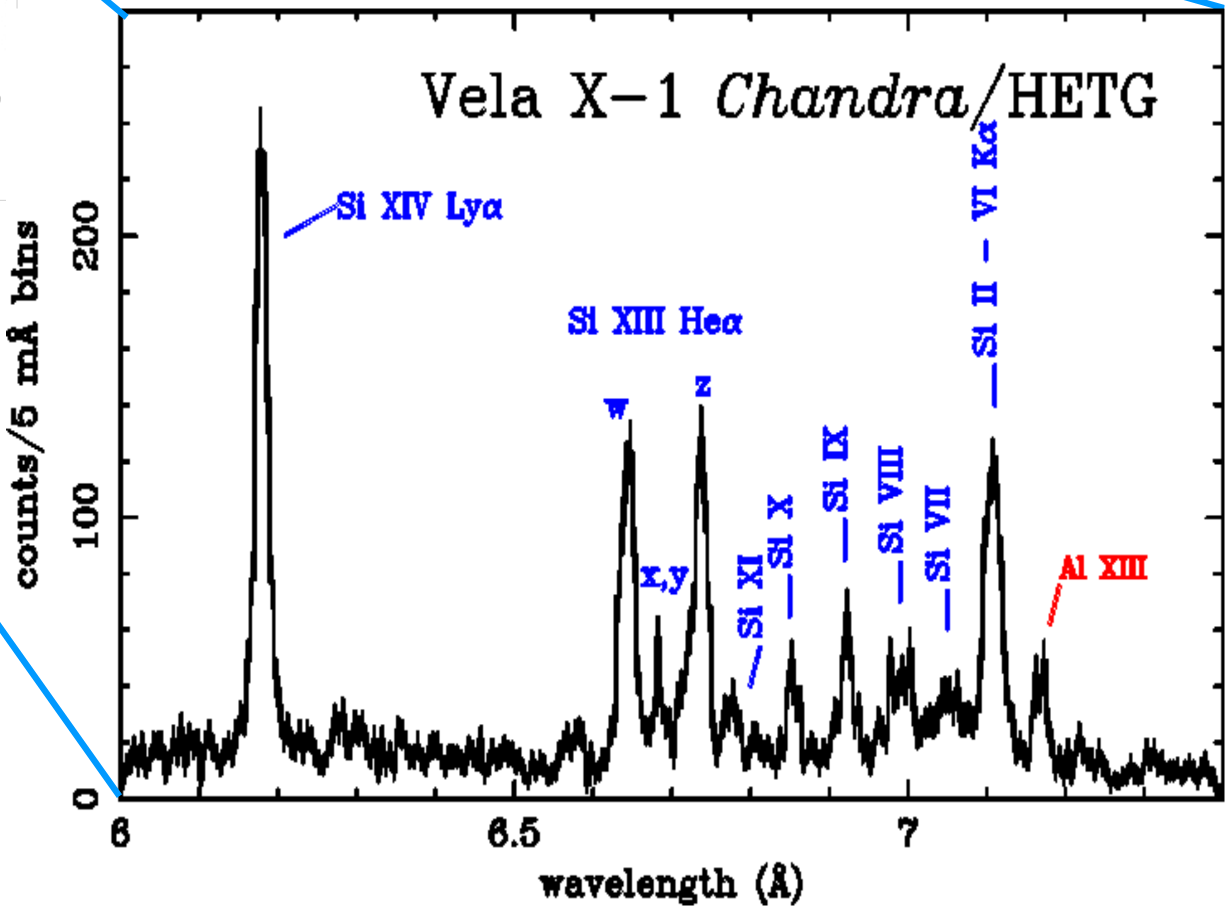
Most of the lines are resolved with characteristic widths of ~ 1000 km/s, which is more or less consistent with that of an isolated WR star



Vela X-1: Silicon Line Complex



The line complex
formerly
known as the "Kα line"



A very wide range of charge states of Si (Si II - XIV) can be probed with the HETG

Mass transfer in Binaries

2. Roche lobe overflow:

Consider the orbit of a test (mass-less) particle in the gravitational potential of two stars orbiting around each other. The orbit of these two stars is assumed to be circular. From Kepler's law:

$$4\pi\, a^3 = G\,(M_1 + M_2)P^2$$

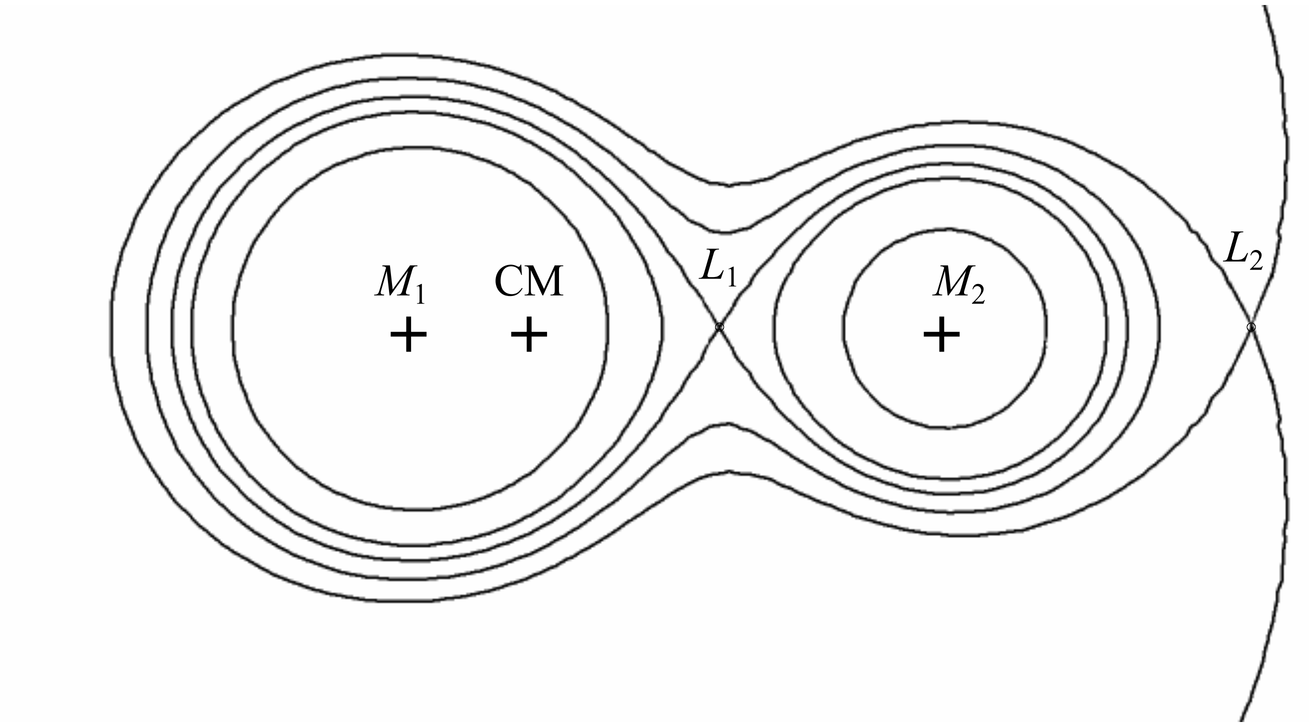
where a is the separation between the 2 stars, M_1 and M_2 are their masses, and P the orbital period (P=2π/ω).

Mass transfer: Roche overflow

The potential in the rotating frame is

$$\Phi_R(\mathbf{r}) = -\frac{GM_1}{|\mathbf{r}-\mathbf{r}_1|} - \frac{GM_2}{|\mathbf{r}-\mathbf{r}_2|} - \frac{1}{2}(\omega \times \mathbf{r})^2,$$

which is called the Roche potential. Here $\mathbf{r}_1$ and $\mathbf{r}_2$ are the positions of the stars with respect to the center of mass of the system. The equipotential surfaces (in the orbital plane) look like this:



Mass transfer: Roche overflow

There are 5 special points called the ***Lagrangian points***. At those points a test mass experiences zero force.

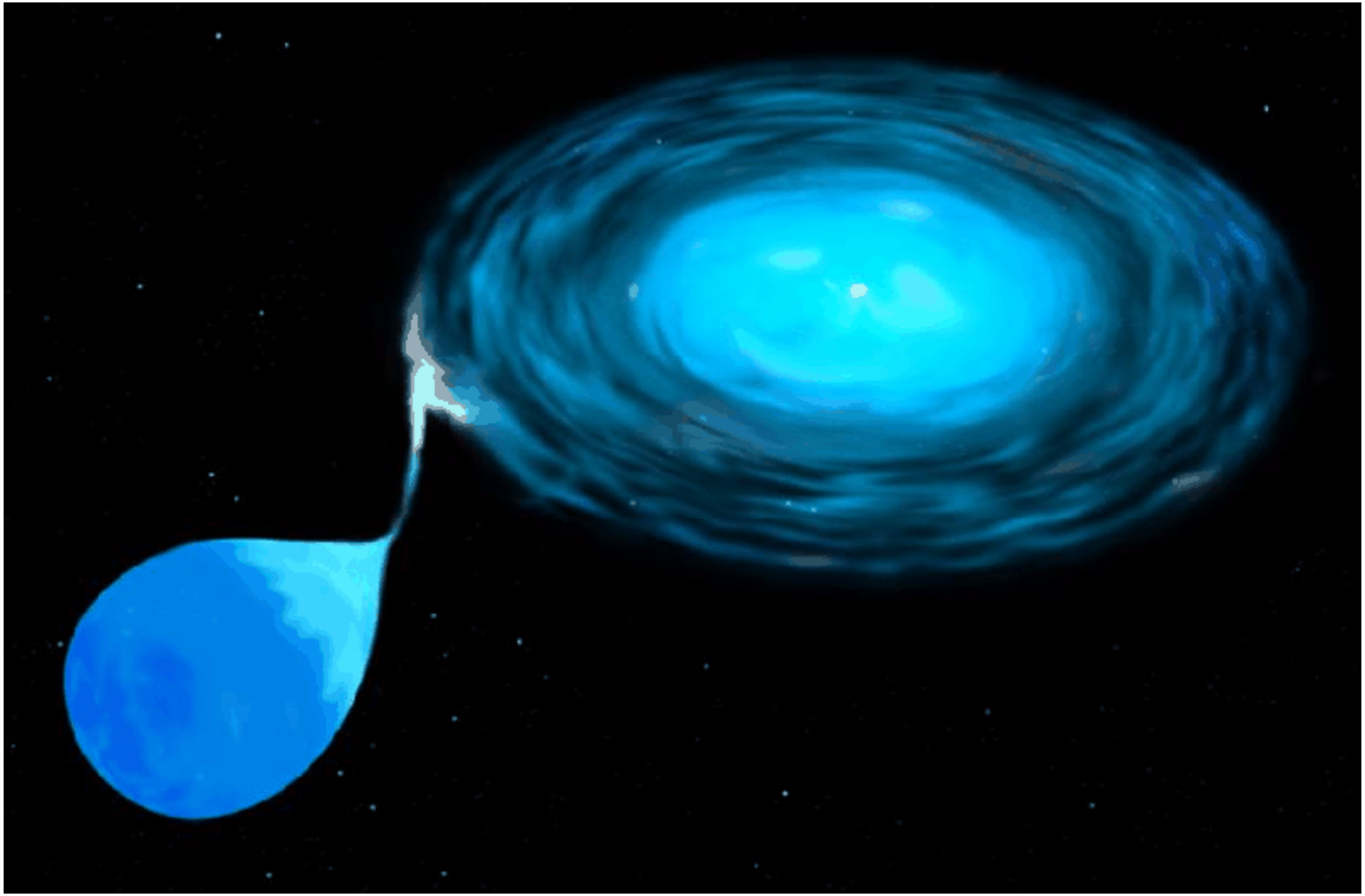
In this case, the most important of the Lagrangian points is L_1, in between both stars, since matter lying at that point finds it very easy to move from one star to the other. When the star M_2 (let's say) fills it Roche lobe, mass flows via L_1 from M_2 to M_1.

Eggleton (1983) found a good approximation to describe the size of the Roche equipotential surfaces. The radius, R_2, of the Roche lobe is:

$$\frac{R_2}{a} \approx \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}$$

with $q = M_2 / M_1$. (To obtain R_1/a replace q by q^{-1}).

Roche Lobe overflow



Accretion disc

As a consequence of Roche overflow mass transfer, an accretion disc is formed around the compact object.

Since the system rotates, from the point of view of M_1 the Lagrangian point L_1 rotates at an angular velocity ω. Hence the matter that crosses L_1 has a specific angular momentum $\omega\, b^2$, where b is the distance from M_1 to L_1.

The mass that crosses L_1 will then form an elliptical ring around M_1. The presence of the secondary makes the elliptical ring to precess slowly, and hence it will intersect itself, resulting in energy dissipation.

Accretion disc

The gas will then loose energy and angular momentum and fall towards M_1, forming a disc around M_1.

The angular velocity at each radius in the disc is very approximately the Keplerian velocity at that radius, $(R) \approx {}_{\mathrm{K}}(R) = (GM/R^3)^{1/2}$.

The fluid rotates differentially, and therefore viscosity makes energy to dissipate in the disc which is then radiated away.

Accretion disc

It can be shown (see "Accretion power in Astrophysics" by Frank, King and Raine for details) that the luminosity produced in a portion of the disc between radii R_1 and R_2 by energy dissipated there, is:

$$L(R_1, R_2) = \frac{3GM\dot{M}}{2} \int_{R_1}^{R_2} \left[1 - \left(\frac{R_{\rm in}}{R}\right)^{1/2}\right] \frac{dR}{R^2},$$

where $R_{\rm in}$ is the inner radius of the disc. Integration of the above yields:

$$L(R_1, R_2) = \frac{3GM\dot{M}}{2} \left\{ \frac{1}{R_1}\left[1 - \frac{2}{3}\left(\frac{R_{\rm in}}{R_1}\right)^{1/2}\right] - \frac{1}{R_2}\left[1 - \frac{2}{3}\left(\frac{R_{\rm in}}{R_2}\right)^{1/2}\right] \right\}.$$

Accretion disc

By making $R_1 \to R_{\text{in}}$ and $R_2 \to \infty$, we obtain the luminosity produced by the whole disc:

$$L_{\text{disk}} = \frac{GM\dot{M}}{2R_{\text{in}}} = L_{\text{acc}}.$$

Hence, half of the accretion energy available is radiated in the disc. The other half of the radiation has to be emitted at the surface of the compact star, or at the inner edge of the disc in the case of a black hole.

If we assume that the disc is optically thick, each annulus radiates as a blackbody and we can calculate the radial temperature profile of the disc. Since each annulus emits as a blackbody, we can use Steffan-Boltzmann law and equate the total dissipation rate per unit face area of the disc to the blackbody flux which yields:

Accretion disc

$$T(R) \approx \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma} \left[1 - \left(\frac{R_{\rm in}}{R} \right) \right] \right\}^{1/4} .$$

We can now calculate the total spectrum emitted by such a disc. This spectrum will be the sum of the contributions of each annulus, but since each annulus emits as a blackbody, this turns out to be:

$$F_\nu = \frac{\cos i}{d^2} \int_{R_{\rm in}}^{R_{\rm out}} B_\nu[T(R)] 2\pi R dR,$$

where d is the distance to the source, i is the angle between the normal to the disc and the line of sight and $B_\nu(T)$ is the spectrum of a blackbody of temperature T.

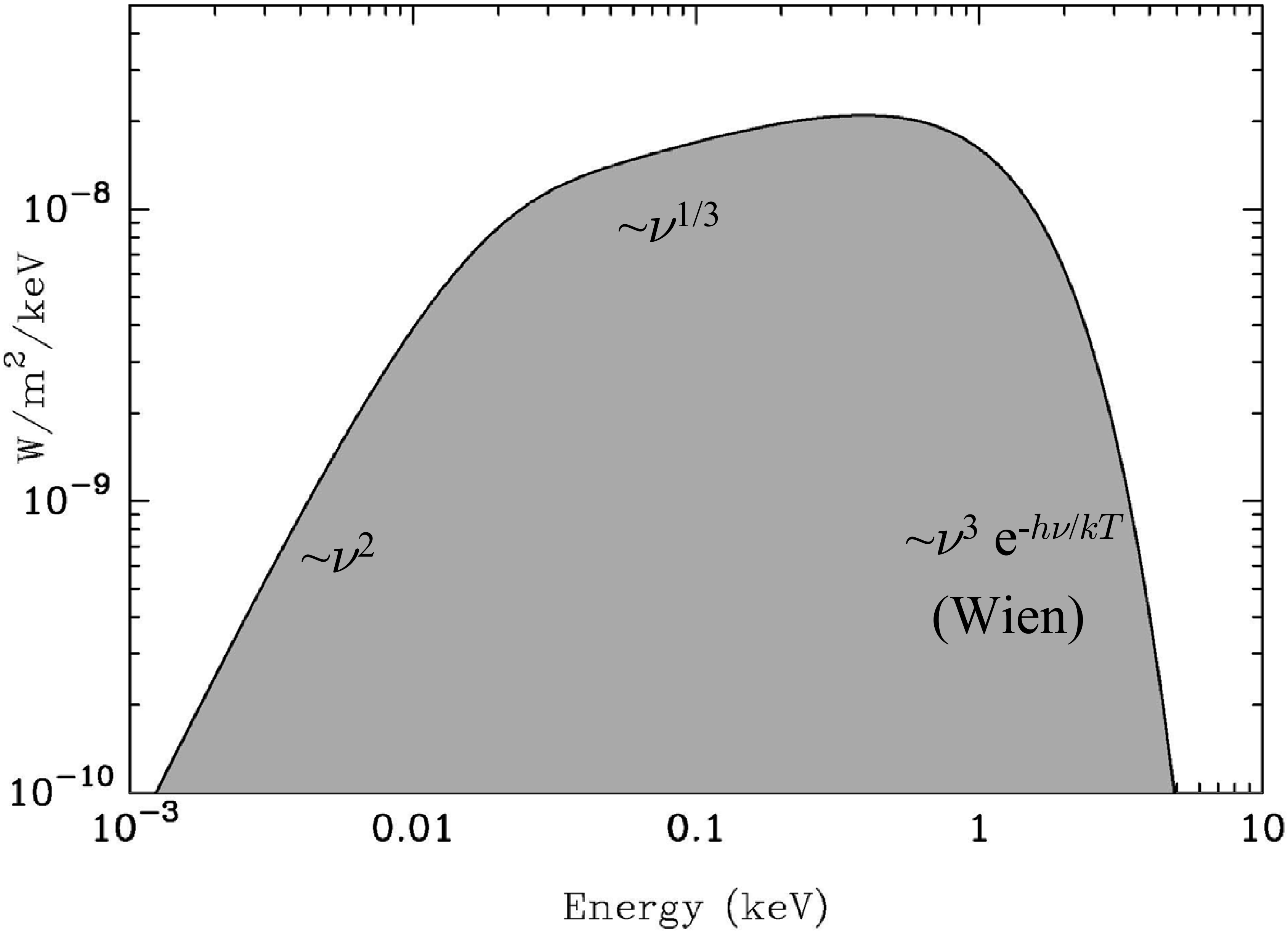
Accretion disc

The previous equation can be (approximately) rewritten as:

$$F_\nu = \frac{8\pi R_{\rm in}^2 \cos i T_{\rm in}^{8/3}}{3d^2} \int_{T_{\rm out}}^{T_{\rm in}} T^{-11/3} B_\nu(T) dT.$$

Hence, by measuring and fitting the spectrum over a given energy (wavelength) range one can estimate $T_{\rm in}$ and $(R_{\rm in}/d)^2 \cos i$.

Accretion-disc spectrum



Hard spectral component

The hard, power-law, component observed in the X-ray spectra of galactic X-ray sources and AGN is interpreted as Compton up-scattering of low-energy photons by very hot electrons in a plasma generally associated to a disc corona. The power-law index, Γ, is given by

$$\Gamma = \left[\frac{9}{4} + \frac{1}{(kT_e/m_e c^2)\tau(1+\tau/3)}\right]^{1/2} - \frac{1}{2}$$

T_e and τ are, respectively, the temperature and optical depth of the hot electron gas.

The nature of the hot corona is not obvious. It may be heated by magnetic processes on the accretion disc surface, analogous to coronal heating in late–type stars and the Sun. In some cases the power law has been seen to extend up to ≈ 1 MeV, which means that non-thermal electrons must be responsible for it.

Black Holes from GR

A few years after Einstein published his paper on the General Theory of Relativity, Karl Schwarzschild found a solution for the space-time metric around a point mass M assuming spherical symmetry:

$$ds^2 = \left(1 - \frac{2GM}{rc^2}\right) dt^2 - \frac{1}{c^2}\left[\frac{dr^2}{\left(1 - \frac{2GM}{rc^2}\right)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right].$$

From this metric one can write the relation between a time interval, $\Delta t'$, of an event that takes place at a distance r from M , and the time interval, Δt, measured by another observer at infinity. The result is:

$$\Delta t' = \left(1 - \frac{2GM}{rc^2}\right)^{1/2} \Delta t.$$

For a periodic phenomenon of period $\Delta t'$, the frequency is $\nu' = 1/\ \Delta t'$, hence for electromagnetic radiation emitted at a frequency ν_e:

$$\nu_\infty = \left(1 - \frac{2GM}{rc^2}\right)^{1/2} \nu_e.$$

Black Holes from GR

In 1916 the next spherically symmetric solution of Einstein's equation, for a point mass M with charge Q was published, the so-called Reissner-Nordstrøm metric.

Finally, in 1962 Kerr discovered the general solution for a black hole with angular momentum J (BH completely described by M, Q and J)

$$ds^2 = \left(1 - \frac{2GM}{\rho c^2}\right) dt^2 - \frac{1}{c^2}\left[\frac{4GMra\sin^2\theta}{\rho c} dt d\phi \right.$$
$$\left. + \frac{\rho}{\Delta} dr^2 + \rho d\theta^2 + \left(r^2 + a^2 + \frac{2GMra^2 \sin^2\theta}{\rho c^2}\right)\sin^2\theta d\phi^2\right].$$

Where $a = J/Mc$, $\Delta = r^2 - (2GMr/c^2) + a^2$, and $\rho = r^2 + a^2 \cos^2\theta$.

Black Holes from GR

Both in the Schwarzschild and the Kerr metric, the coefficient in front of dr^2 becomes singular at a certain radial distance:

$$ds^2 = \left(1 - \frac{2GM}{rc^2}\right) dt^2 - \frac{1}{c^2}\left[\frac{dr^2}{\left(1 - \frac{2GM}{rc^2}\right)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right].$$

$$ds^2 = \left(1 - \frac{2GM}{\rho c^2}\right) dt^2 - \frac{1}{c^2}\left[\frac{4GMra\sin^2\theta}{\rho c} dt d\phi \right.$$

$$\left. + \frac{\rho}{\Delta} dr^2 + \rho d\theta^2 + \left(r^2 + a^2 + \frac{2GMra^2\sin^2\theta}{\rho c^2}\right)\sin^2\theta d\phi^2\right].$$

In the Schwarzschild metric the distance where this happens is $r = 2GM/c^2$, and is called the Schwarzschild radius.
In the Kerr metric it is $r = GM/c^2 + [(GM/c^2)^2 - (J/Mc)^2]^{1/2}$.

Black Holes from GR

In the Kerr metric it is $r = GM/c^2 + [(GM/c^2)^2 - (J/Mc)^2]^{1/2}$.

Notice that $(GM/c^2)^2 - (J/Mc)^2$ must be ≥ 0. That means that:

$GM/c^2 \geq J/Mc$, (remember that $J/Mc = a$).

The spin of the black hole is therefore constrained to:

$a \in [0, G/Mc^2]$,

or $a_* = a/(GM/c^2) \in [0,1]$.

This is the so-called *spin parameter* of the black hole.

Black Holes from GR

In the Schwarzschild metric the distance where this happens is $r = 2GM/c^2$, and is called the Schwarzschild radius.
In the Kerr metric it is $r = GM/c^2 + [(GM/c^2)^2 - (J/Mc)^2]^{1/2}$.

Recalling the relation for gravitational redshift:

$$\nu_\infty = \left(1 - \frac{2GM}{rc^2}\right)^{1/2} \nu_\mathrm{e}.$$

at the Schwarzschild radius, the gravitational redshift is infinite. This defines the horizon of the black hole.

In reality, there is a point in the radial direction around a black hole inside which no stable orbit is possible. At this point a particle can move in a stable orbit around the black hole, the so-called marginally stable orbit (MSO) or innermost stable circular orbit (ISCO).

Black Holes from GR

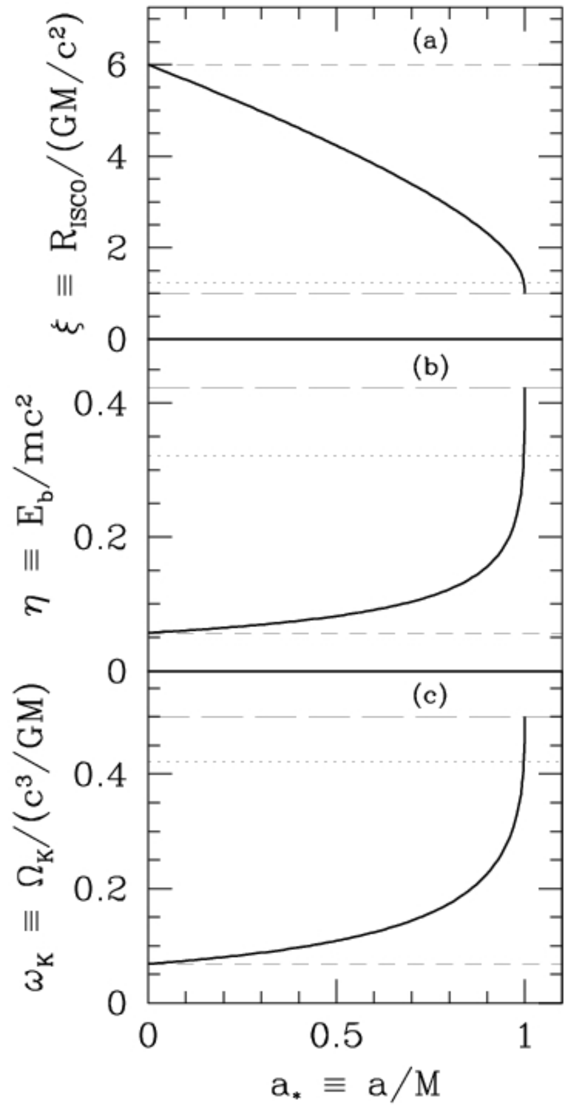
In a Schwarzschild black hole the ISCO is at a distance that is 3 times the Schwarzschild radius:

$R_{\mathrm{ISCO}} = 6GM/c^2$.

In a Kerr black hole the ISCO is at:

$R_{\mathrm{ISCO}} \approx GM/c^2$

Black-hole spin



R_{ISCO}: From $6r_g$ to $1r_g$ as the spin changes from $a_*=0$, ***Schwarzschild*** **BH**, to $a_*=1$, ***Kerr*** **BH** ($r_g = GM/c^2$). (*)

Binding energy: ~7 times larger in a Kerr than in a Schwarzschild BH.

Keplerian frequency at the ISCO:

$\rightarrow \nu_K \sim 10^{-5}$ **Hz** for $M_{BH} \sim 10^8\ M_{[?]}$

$\rightarrow \nu_K \sim 600$ **Hz** for $M_{BH} \sim 10\ M_{[?]}$

(*) In reality the maximum possible spin is $a_*=0.998$, and the minimum radius of the ISCO is $R_{ISCO}=1.23r_g$.

Black Holes: observational evidence

The semi-axis of the orbit of a secondary around a primary can be defined in terms of the individual semi-axes around the center of mass:

$$a = a_2 + a_X.$$

On the other hand, the definition of center of mass means that:

$$M_2 a_2 = M_X a_X.$$

Combining the above two equations we get.:

$$a = \frac{M_2 + M_X}{M_X} a_2.$$

Black Holes: observational evidence

On the other hand, the orbital speed of the secondary, which could be measured via Doppler shift of optical spectral lines, is:

$$v_2 = \frac{2\pi}{P_{orb}} a_2 \sin i,$$

where i is the orbital inclination to the line of sight, and $P_{\rm orb}$ is the orbital period of the secondary.

Finally, Kepler's law is:

$$\frac{G(M_2 + M_X)}{a^3} = \left(\frac{2\pi}{P_{orb}}\right)^2 .$$

Black Holes : observational evidence

Summarizing:

$$a = \frac{M_2 + M_X}{M_x} a_2,$$

$$v_2 = \frac{2\pi}{P_{orb}} a_2 \sin i,$$

$$\frac{G(M_2 + M_X)}{a^3} = \left(\frac{2\pi}{P_{orb}}\right)^2,$$

which combined give:

$$f(M_2, M_X, i) = \frac{(M_X \sin i)^3}{(M_C + M_X)^2} = \frac{v_2^3 P_{orb}}{2\pi G}$$

Black Holes : observational evidence

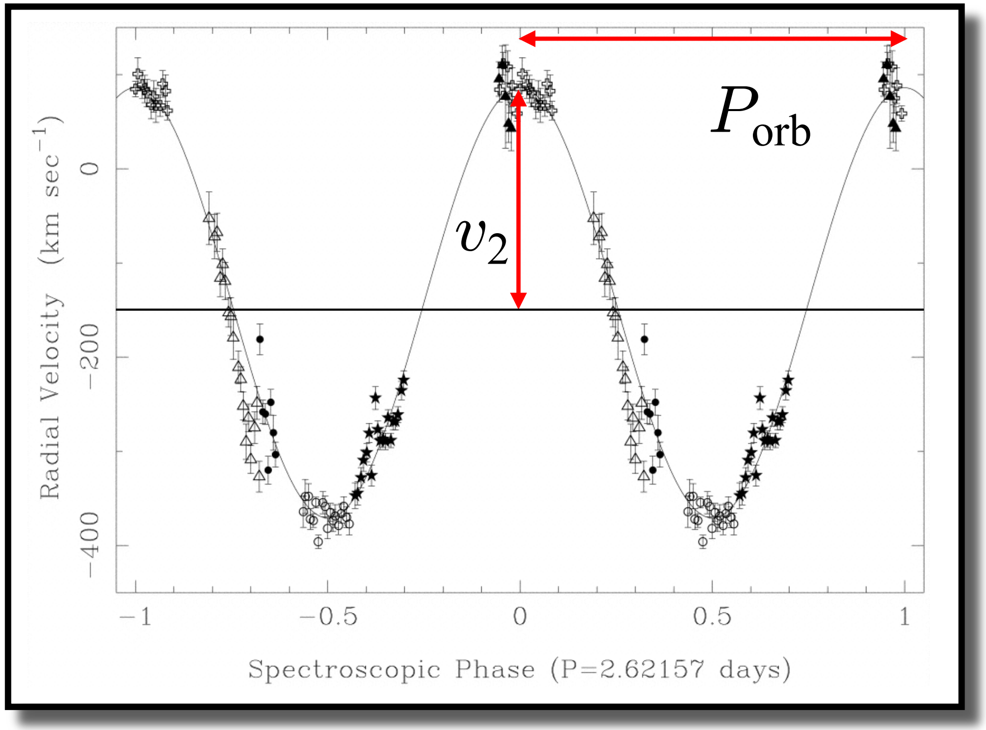
This is the so-called mass function:

$$f(M_2, M_X, i) = \frac{(M_X \sin i)^3}{(M_2 + M_X)^2} = \frac{v_2^3 P_{orb}}{2\pi G}.$$

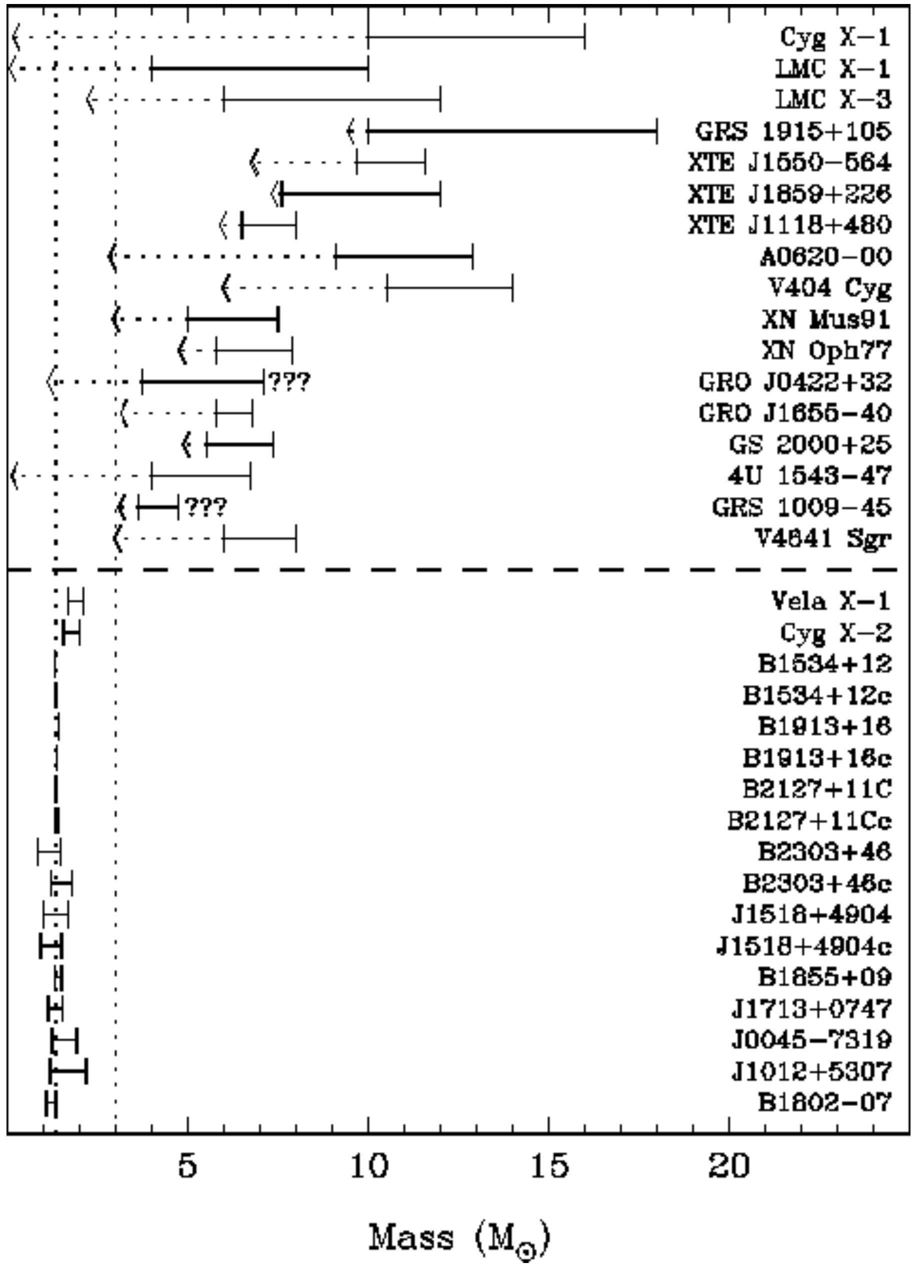
The right-hand side contains only measured quantities. The part in the middle contains only unknown quantities.

It is apparent that M_X will always be:

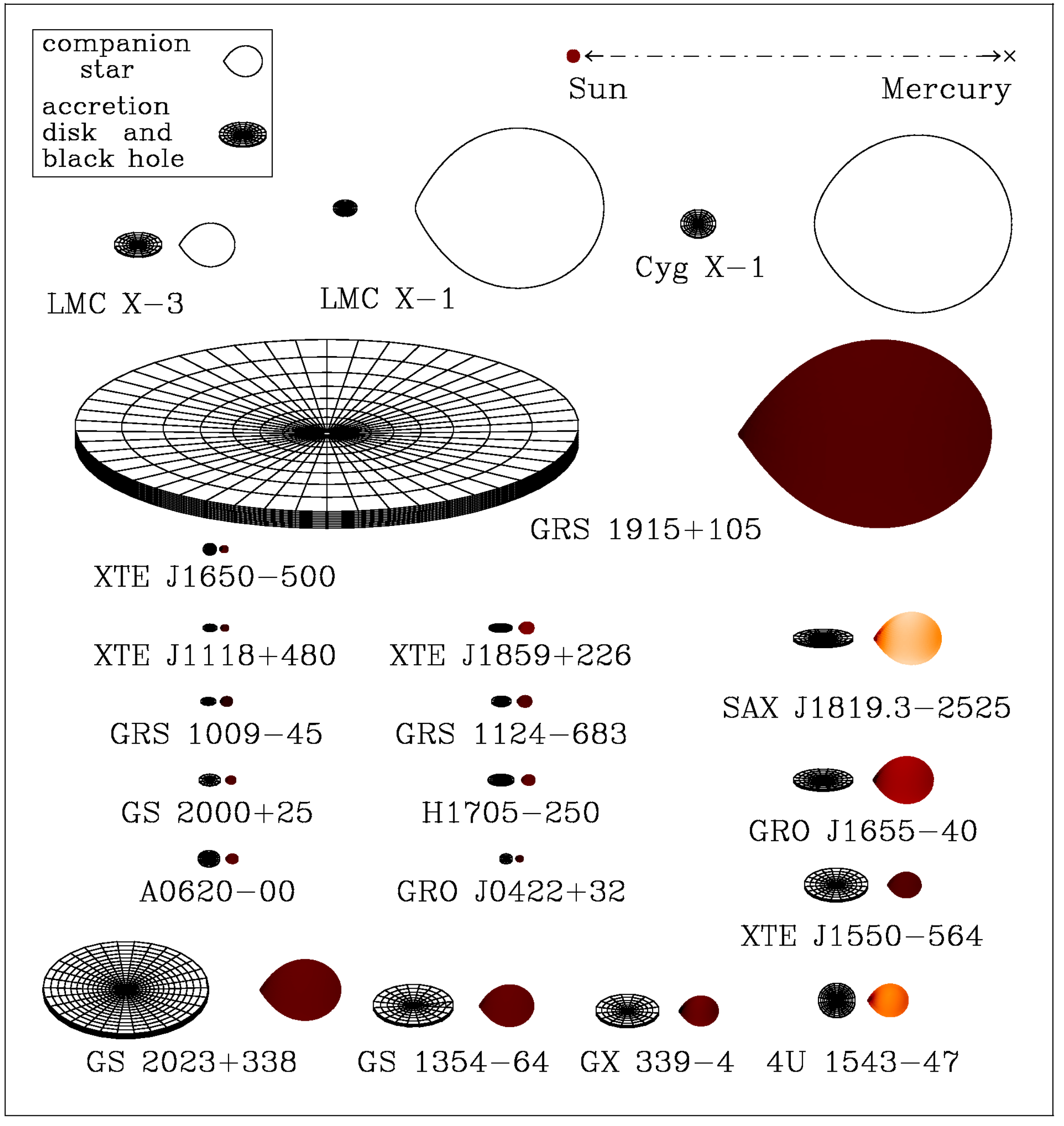
$$M_X \geq f(M_2, M_X, i).$$



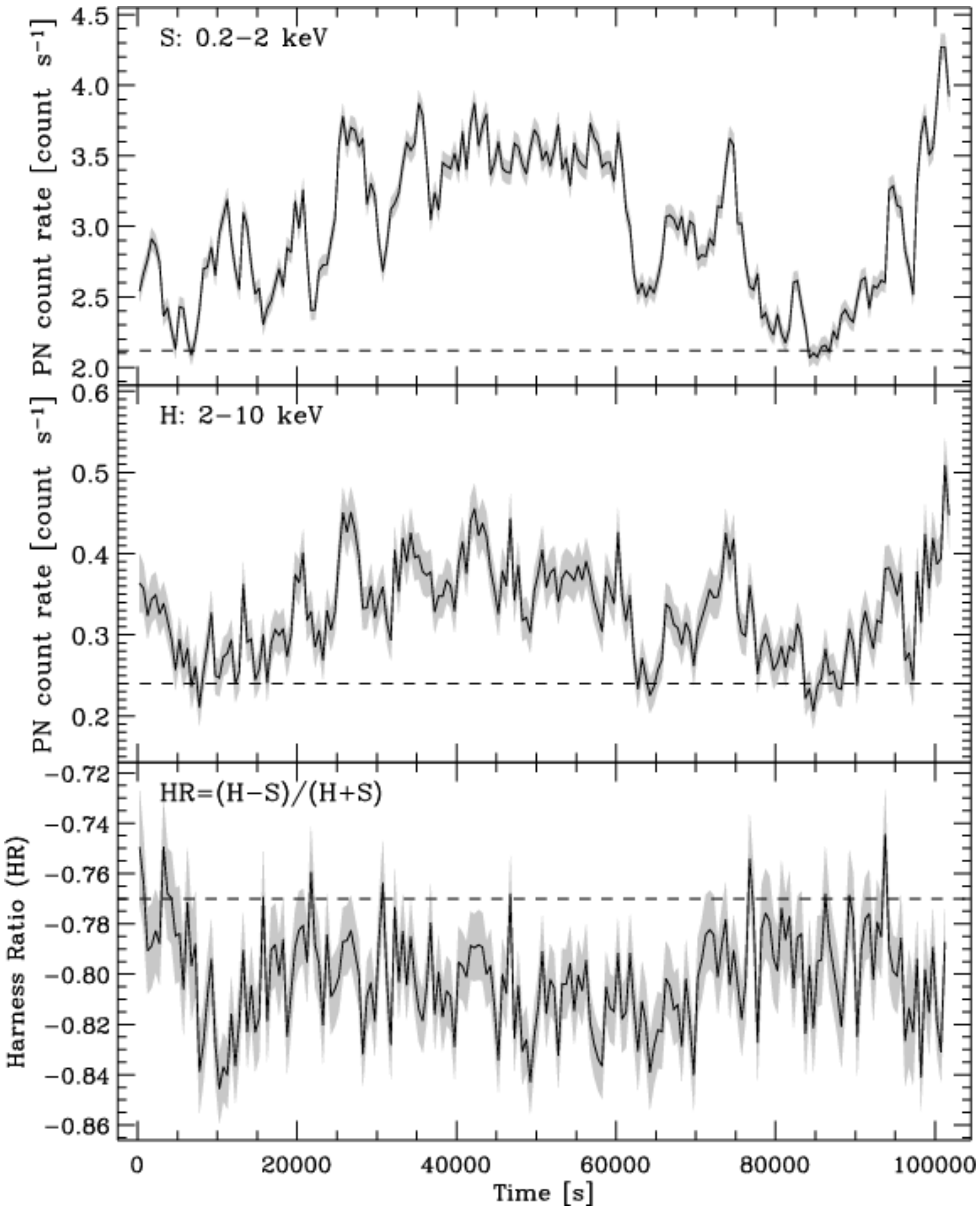
Mass distribution of black holes and neutron stars



Black holes with measured mass at scale

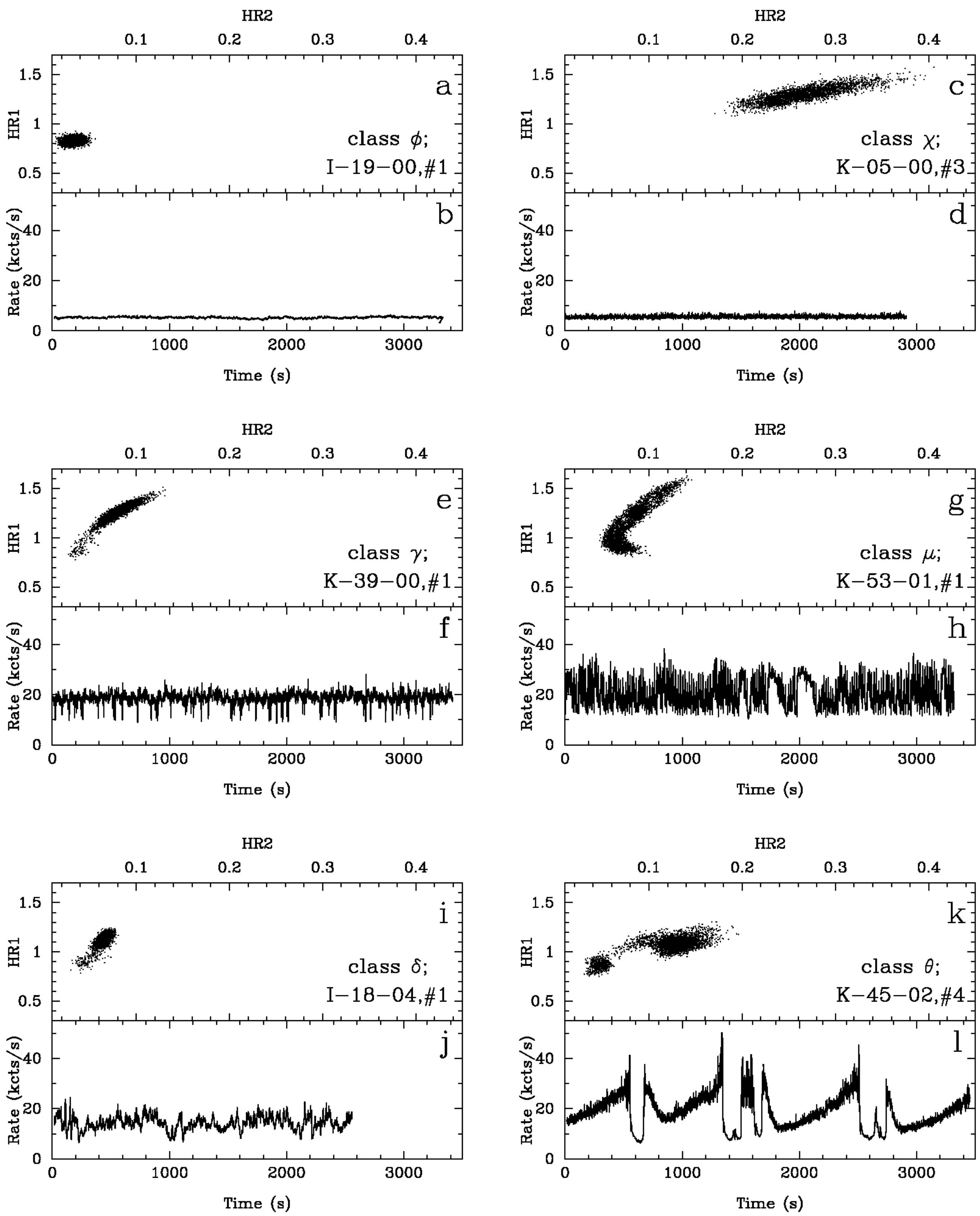


Variability



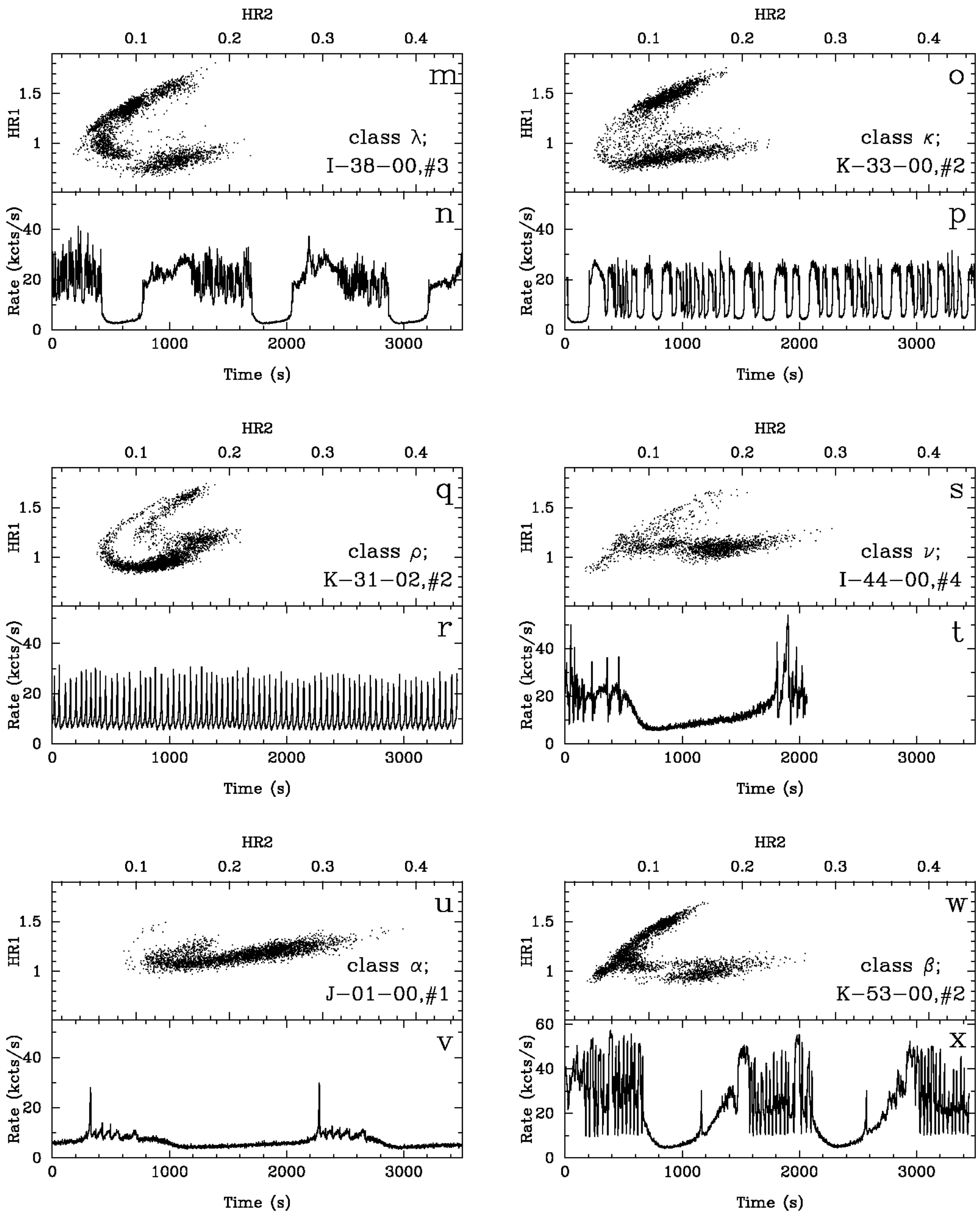
Light curve in 2 X-ray bands and hardness ratio for the black hole at the center of the Active Galaxy NGC 4051.

Variability



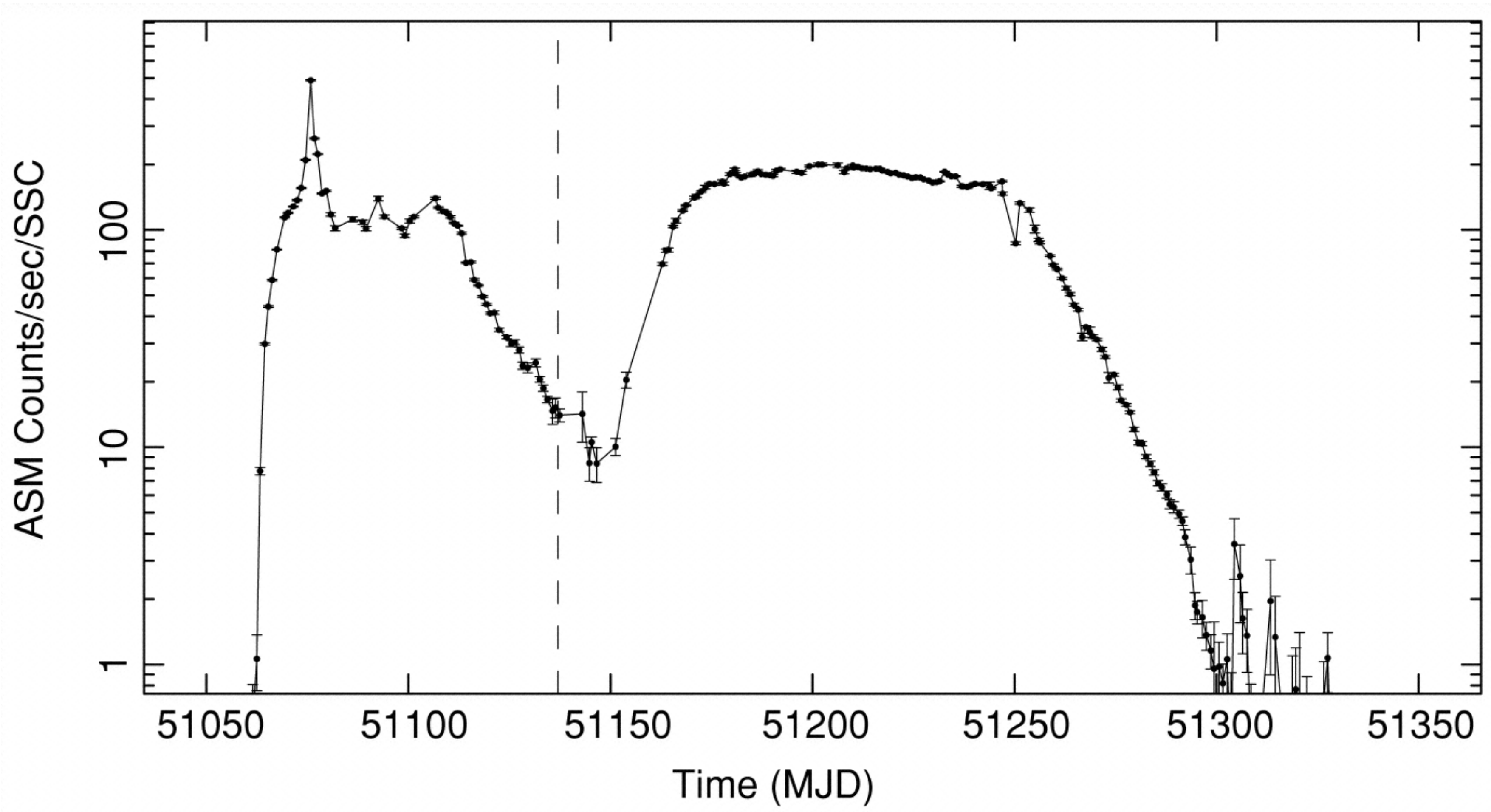
Light curves and color-color diagrams for the galactic black hole GRS 1915+105.

Variability



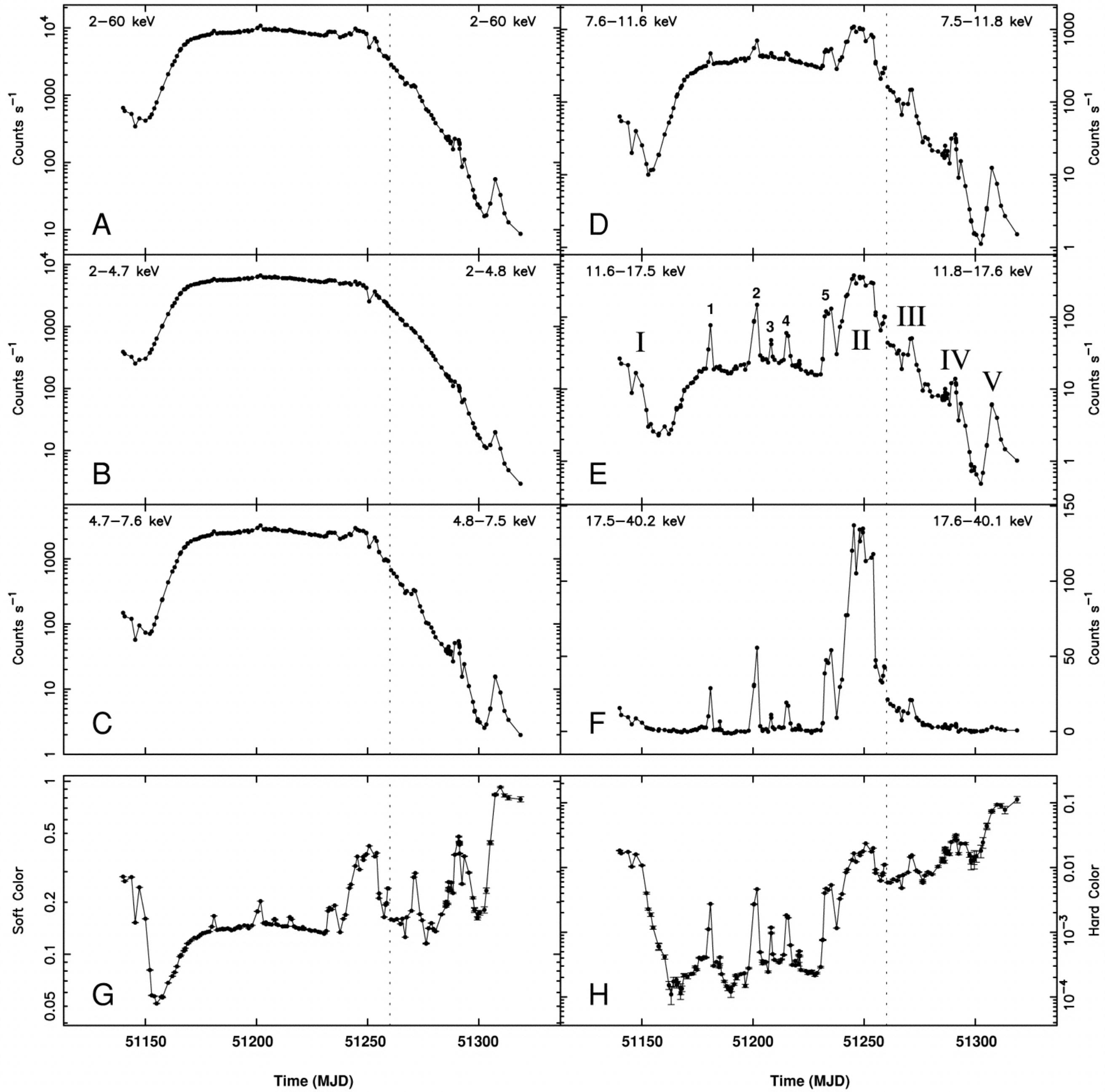
Light curves and color-color diagrams for the galactic black hole GRS 1915+105.

State transitions – Spectra and Timing



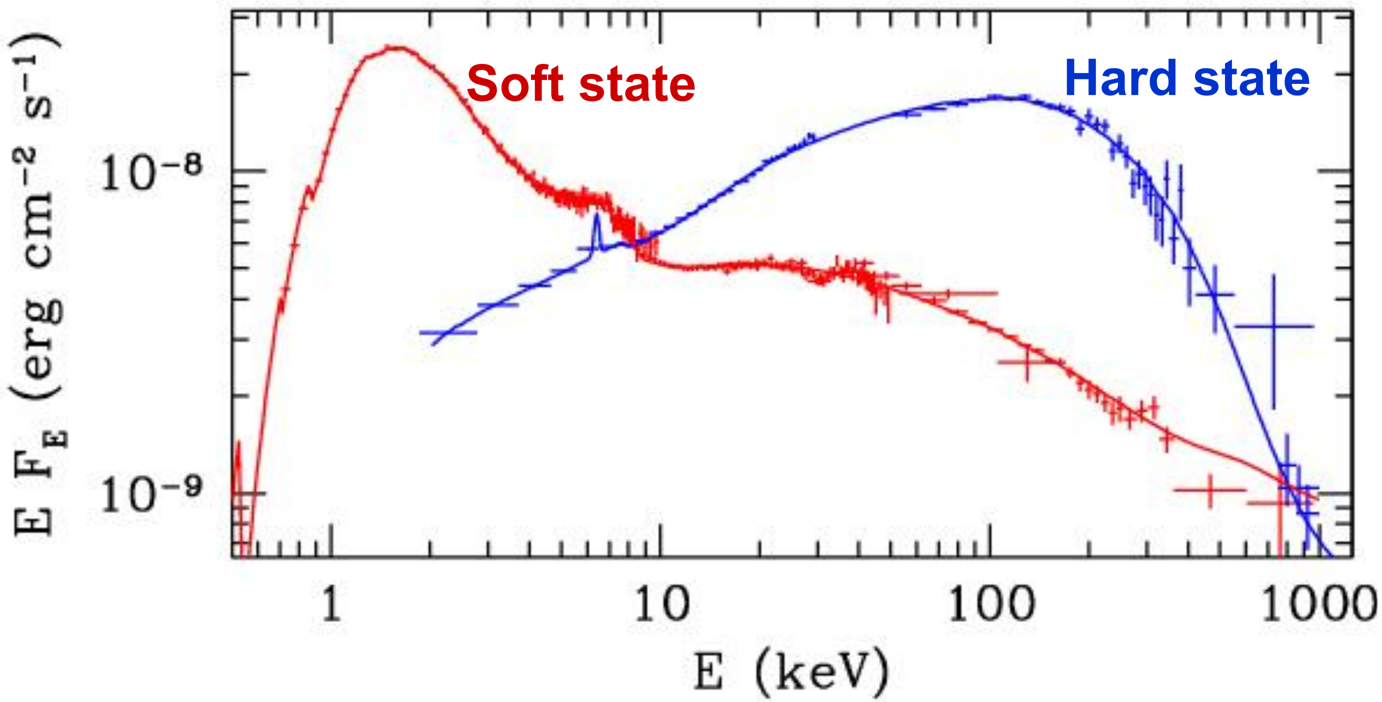
Outburst of the galactic black-hole candidate: XTE J1550–564

State transitions – Spectra and Timing



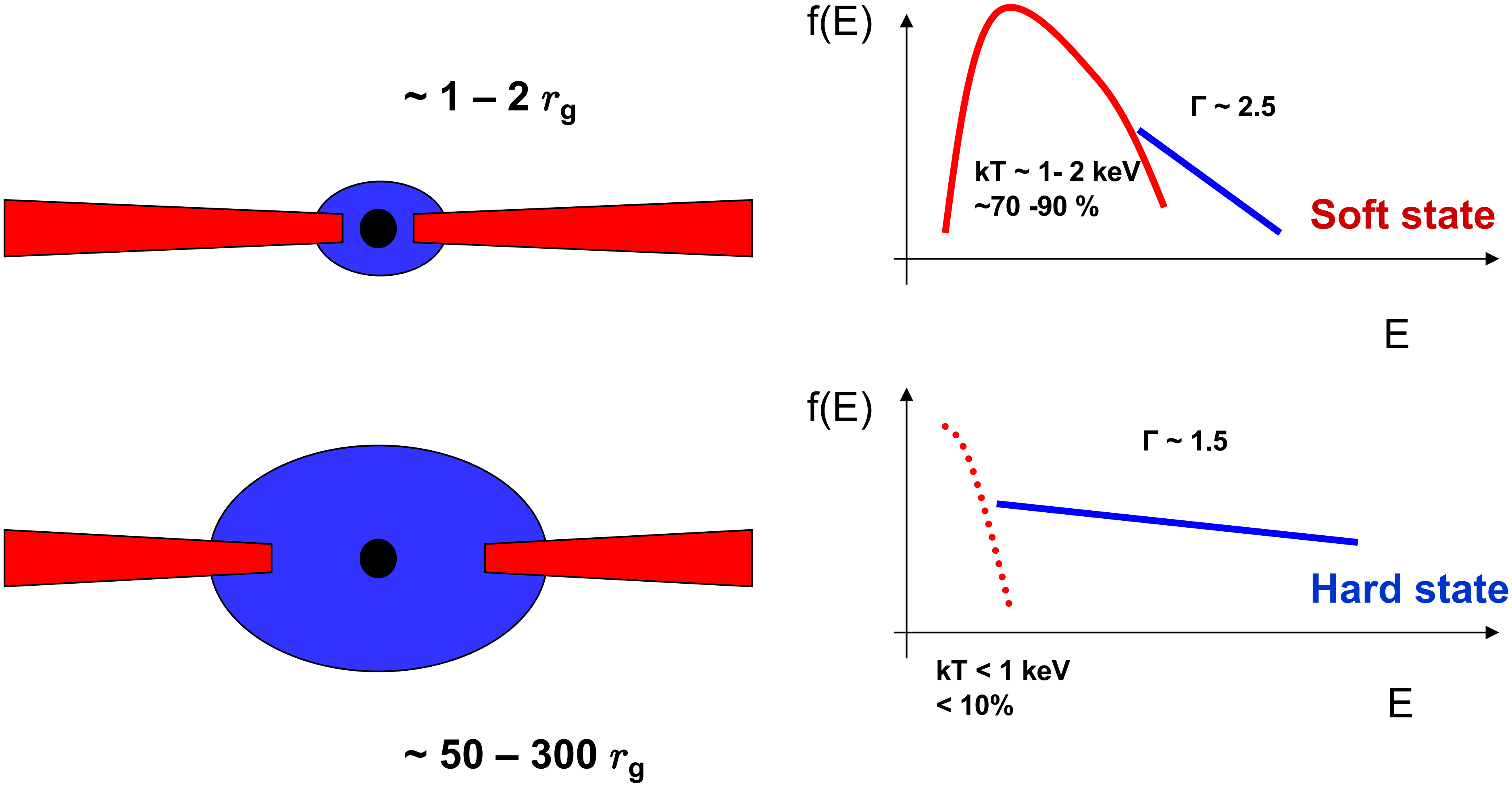
Light curves of the second half of the outburst in 6 different X-ray bands, and two colors.

Black-holes states: Continuum spectrum



Gierlinski et al. 1999

BH states: Accretion-flow geometry



State transitions – Spectra and Timing

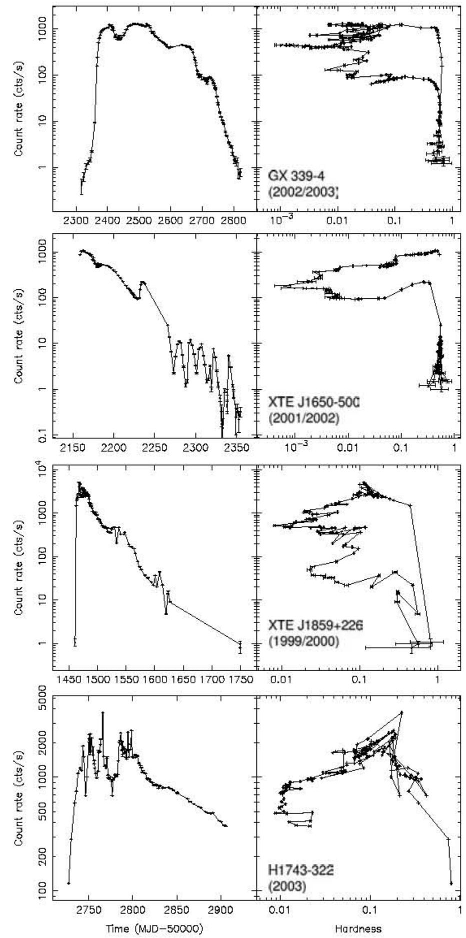


Figure 1. Light curves and hardness–intensity diagrams of four recent transients observed with the *RXTE*/PCA. Count rates are in the ~3–21 keV band and hardness is defined as the ratio of count rates in the ~6–19 and ~3–6 keV bands. For GX 339–4, XTE J1859+226, and H1743–322, the outbursts were observed to start in the upper-right corner, with the sources moving through the diagram in a counter-clockwise direction. For XTE J1650–500 the initial rise was not observed with the PCA, but ASM observations suggest it started in the upper-right corner as well, following a vertical path to the lower-right corner, where the PCA coverage started.

Outburst of 4 galactic black-hole candidates.

Left: 2-60 keV light curve

Right: Hardness-intensity diagrams

State transitions – Spectra and Timing

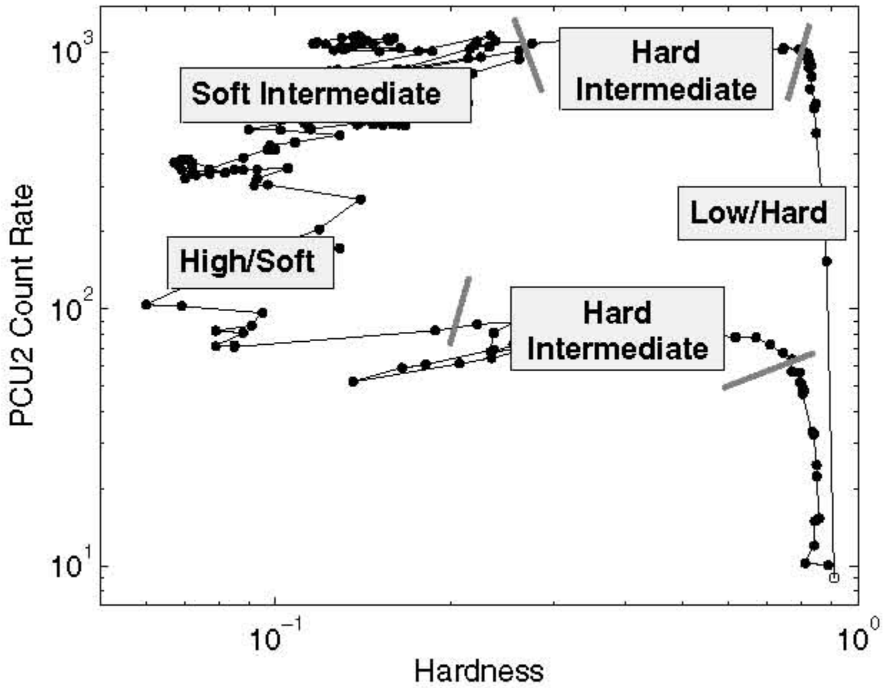


Figure 5. The HID of the 2002/2003 outburst of GX 339–4. Clear transitions are marked by gray segments. The branches corresponding to the four basic states in the q-track are labeled (Belloni et al., 2005).

The 2002/2003 outburst of GX 339–4 with schematic states

State transitions – Spectra and Timing

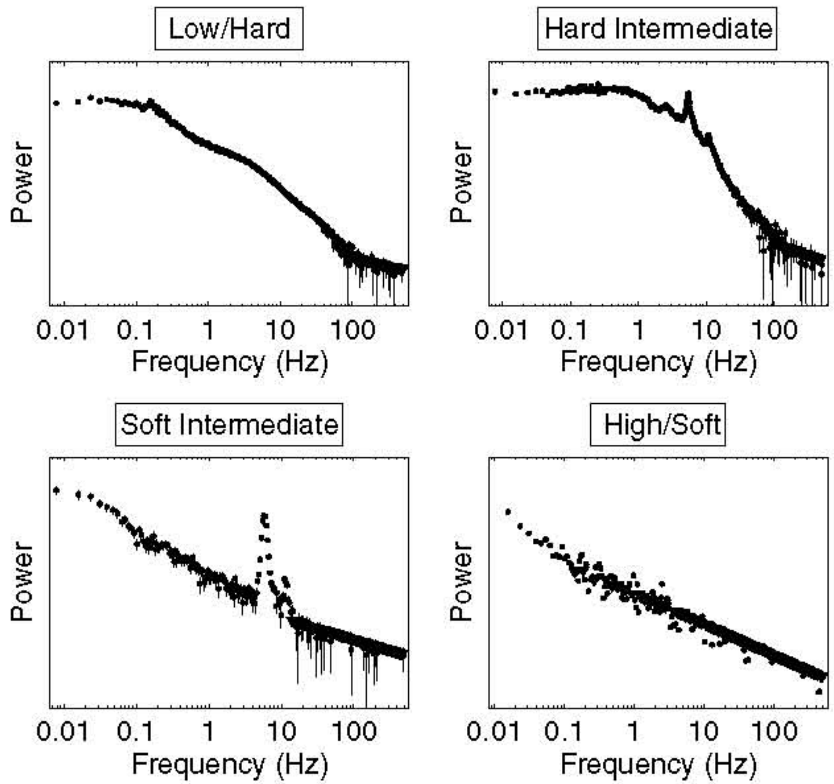
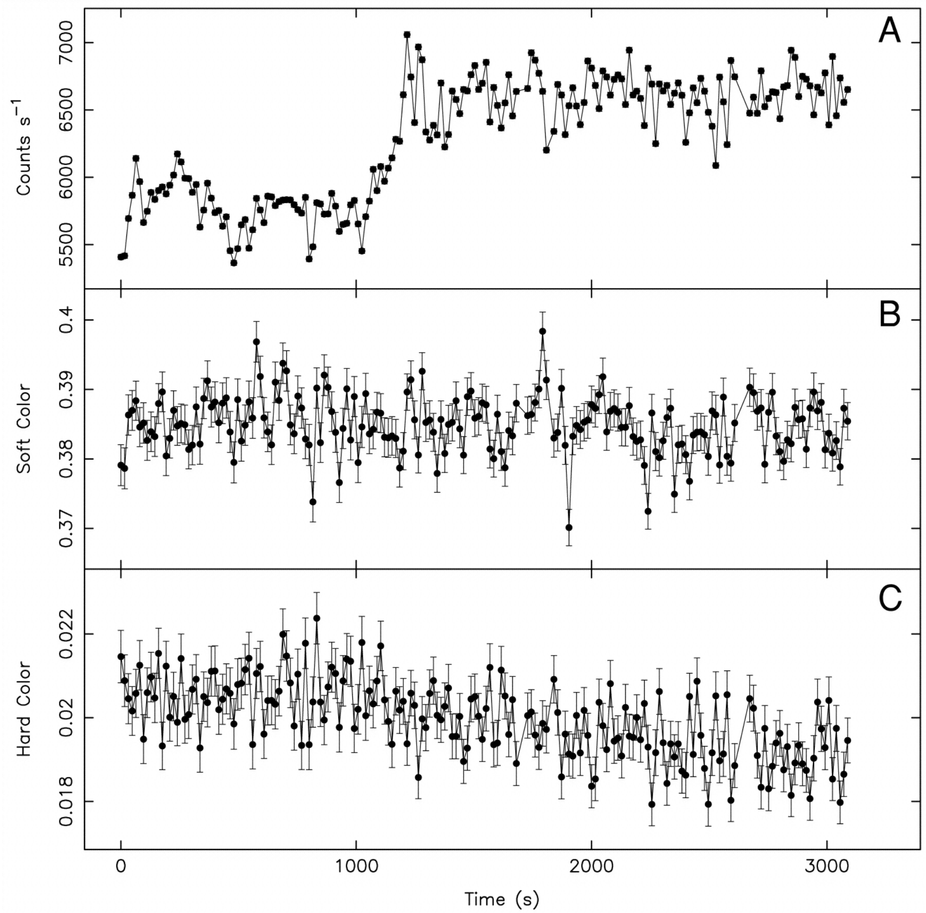
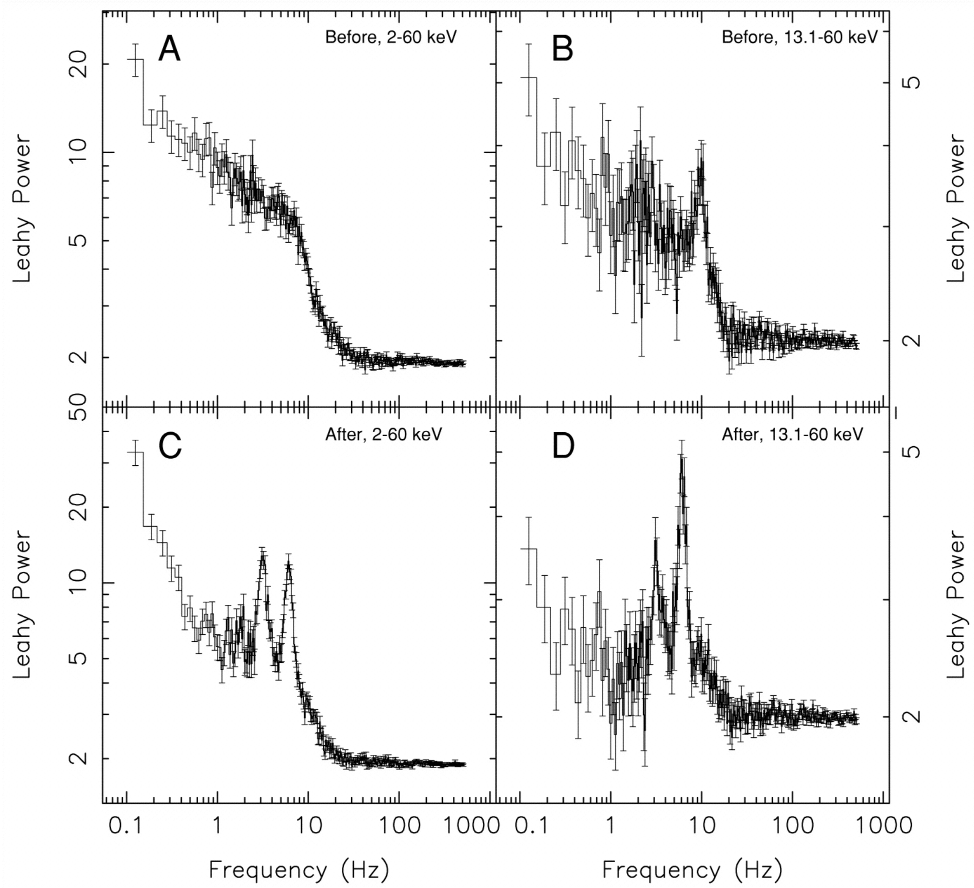


Figure 3. Examples of power-density spectra of GX 339–4 from the four states discussed in the text.

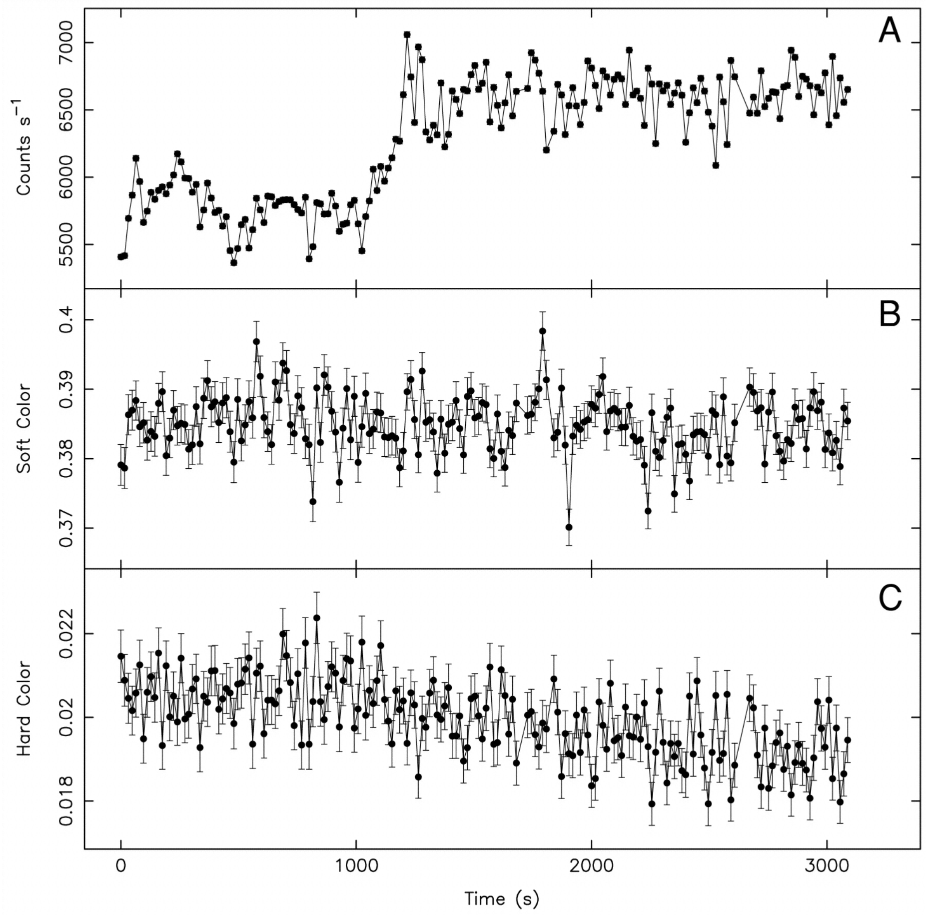
Power density spectra in the basic four states of the galactic black-hole candidate GX 339–4

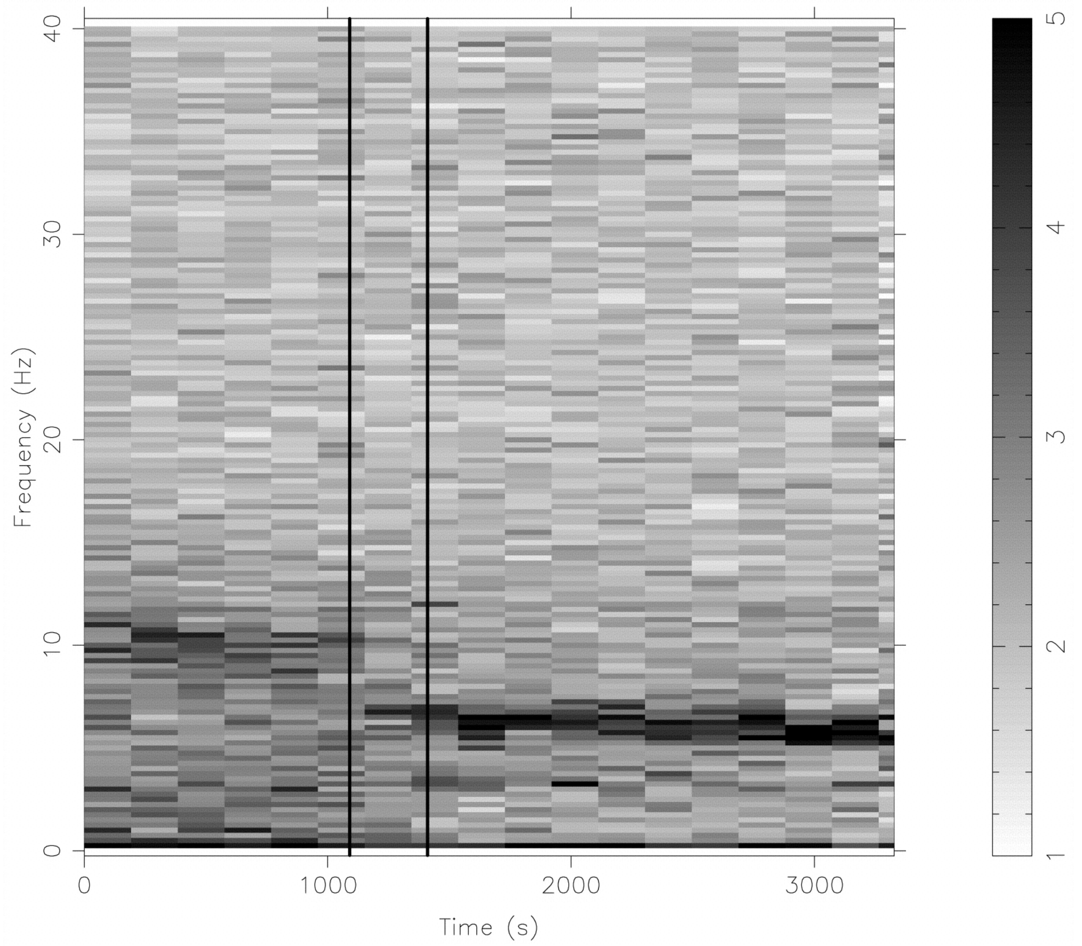
State transitions – Spectra and Timing



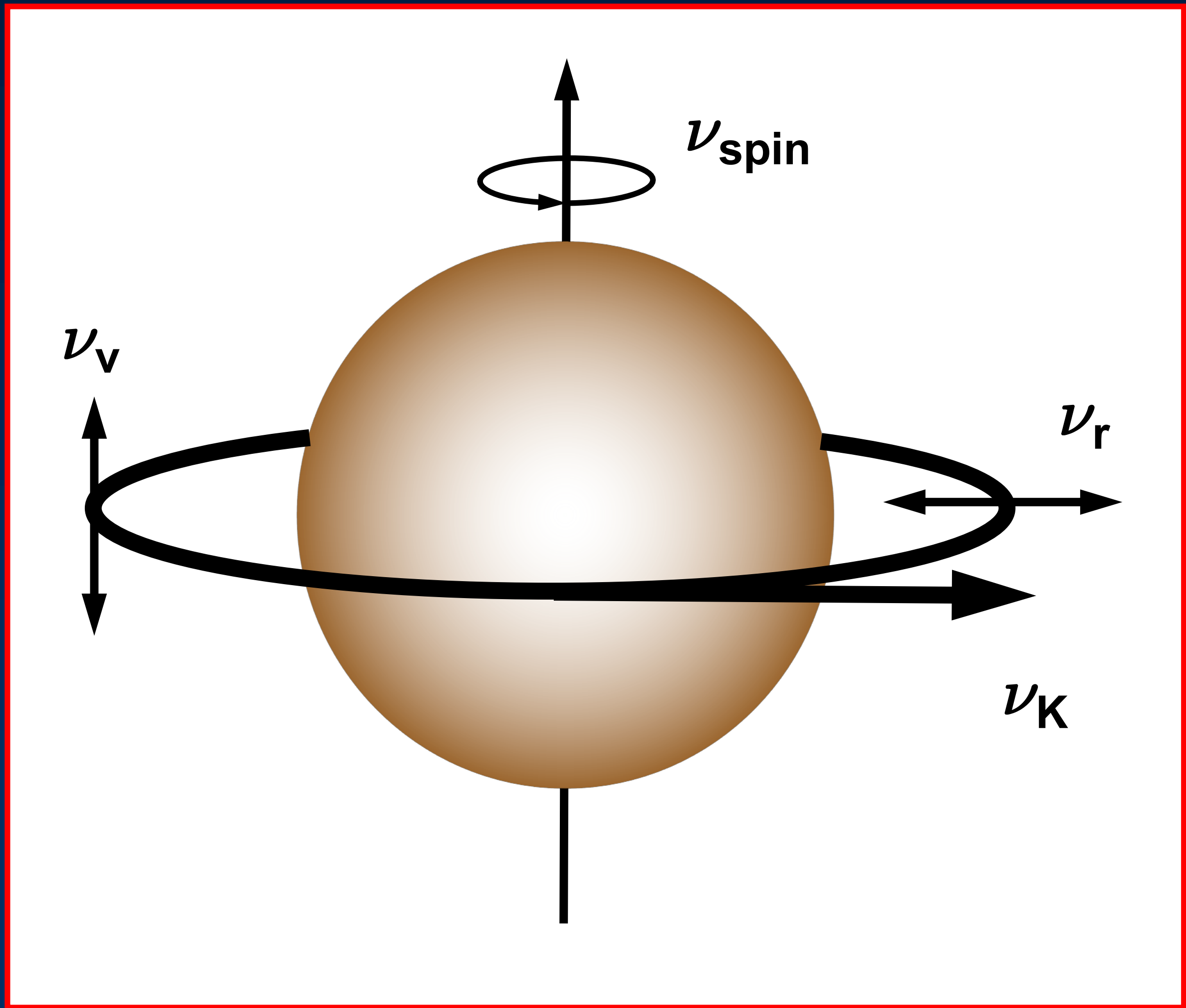


State transitions – Spectra and Timing

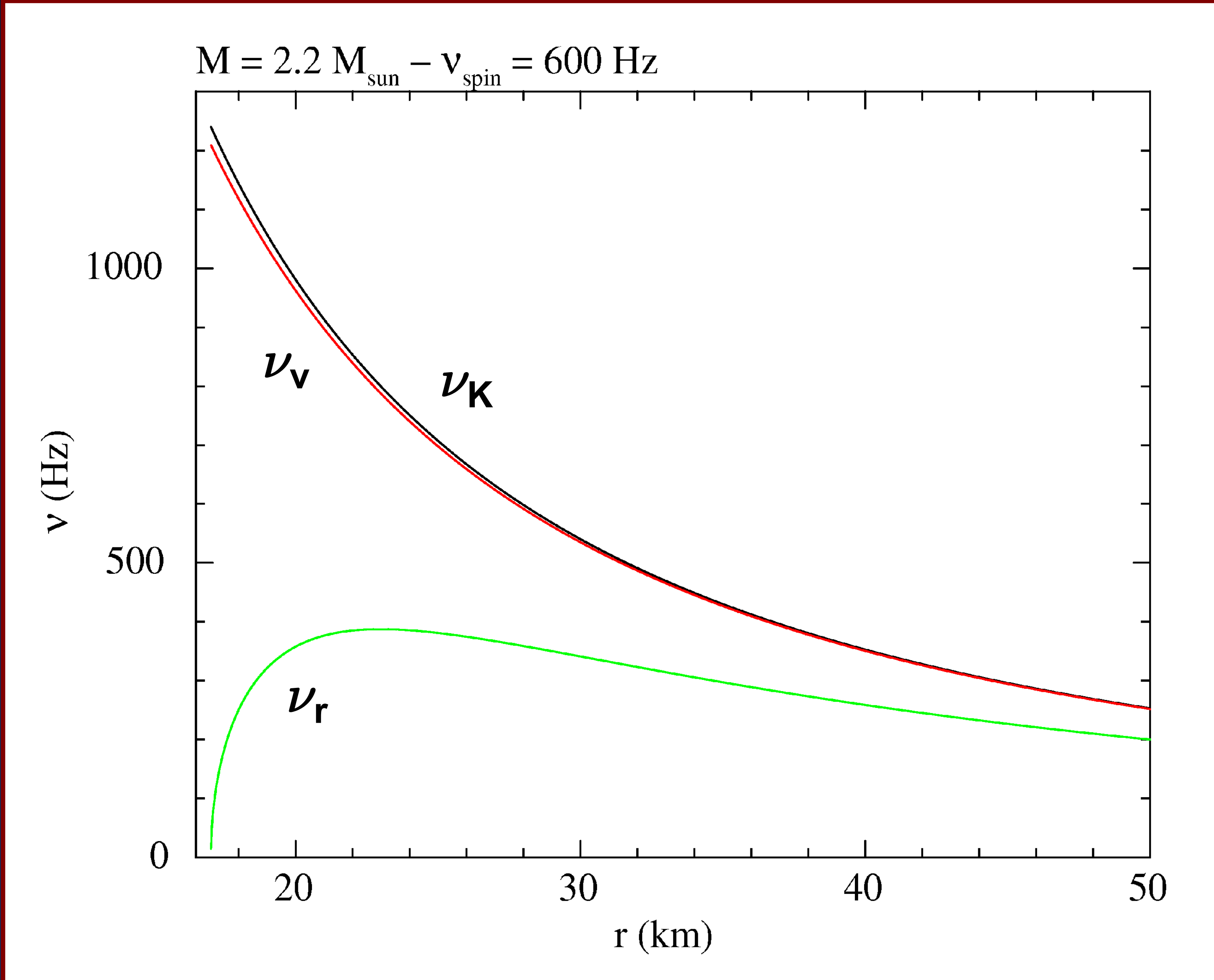




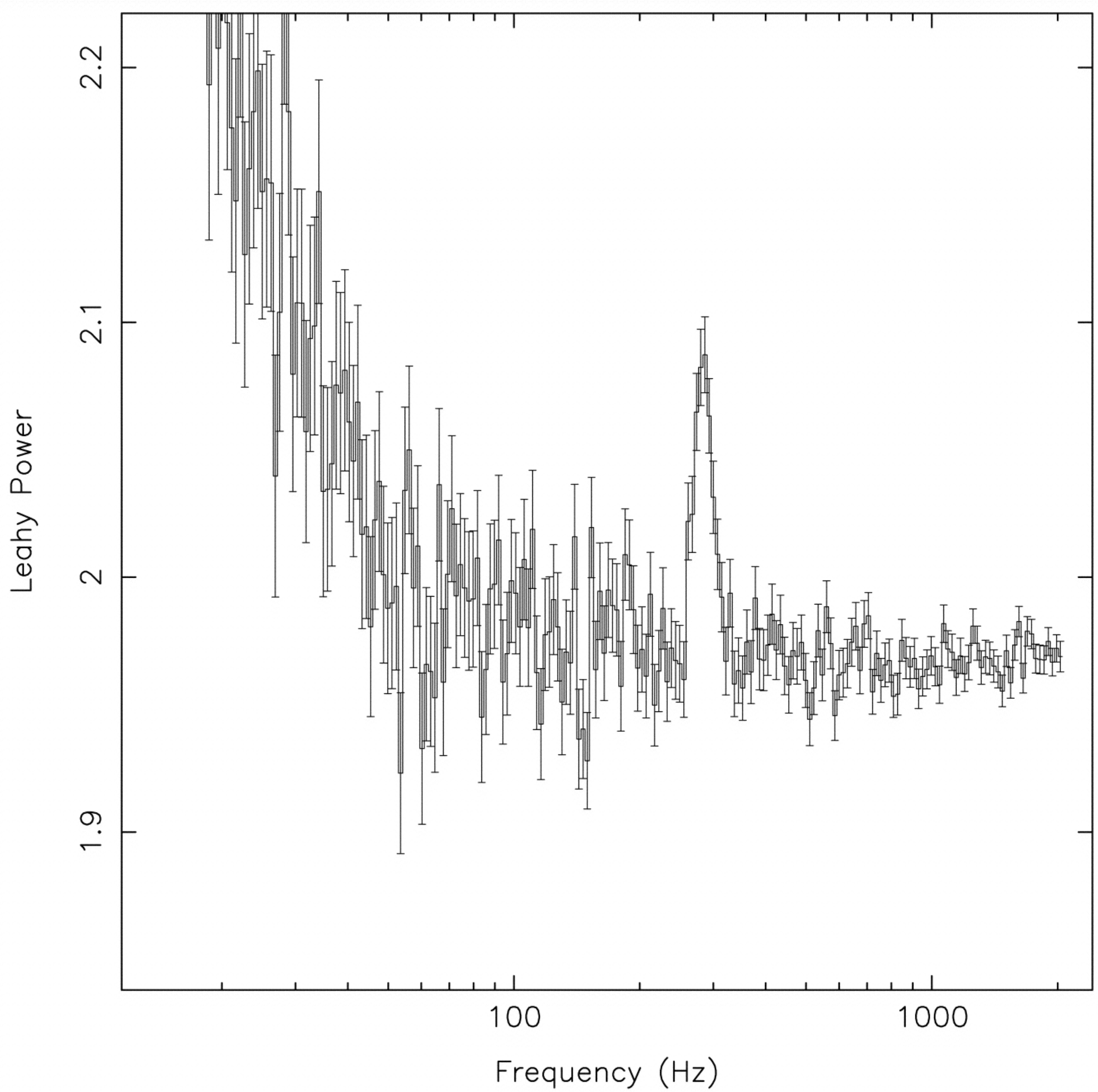
Basic frequencies in General relativity



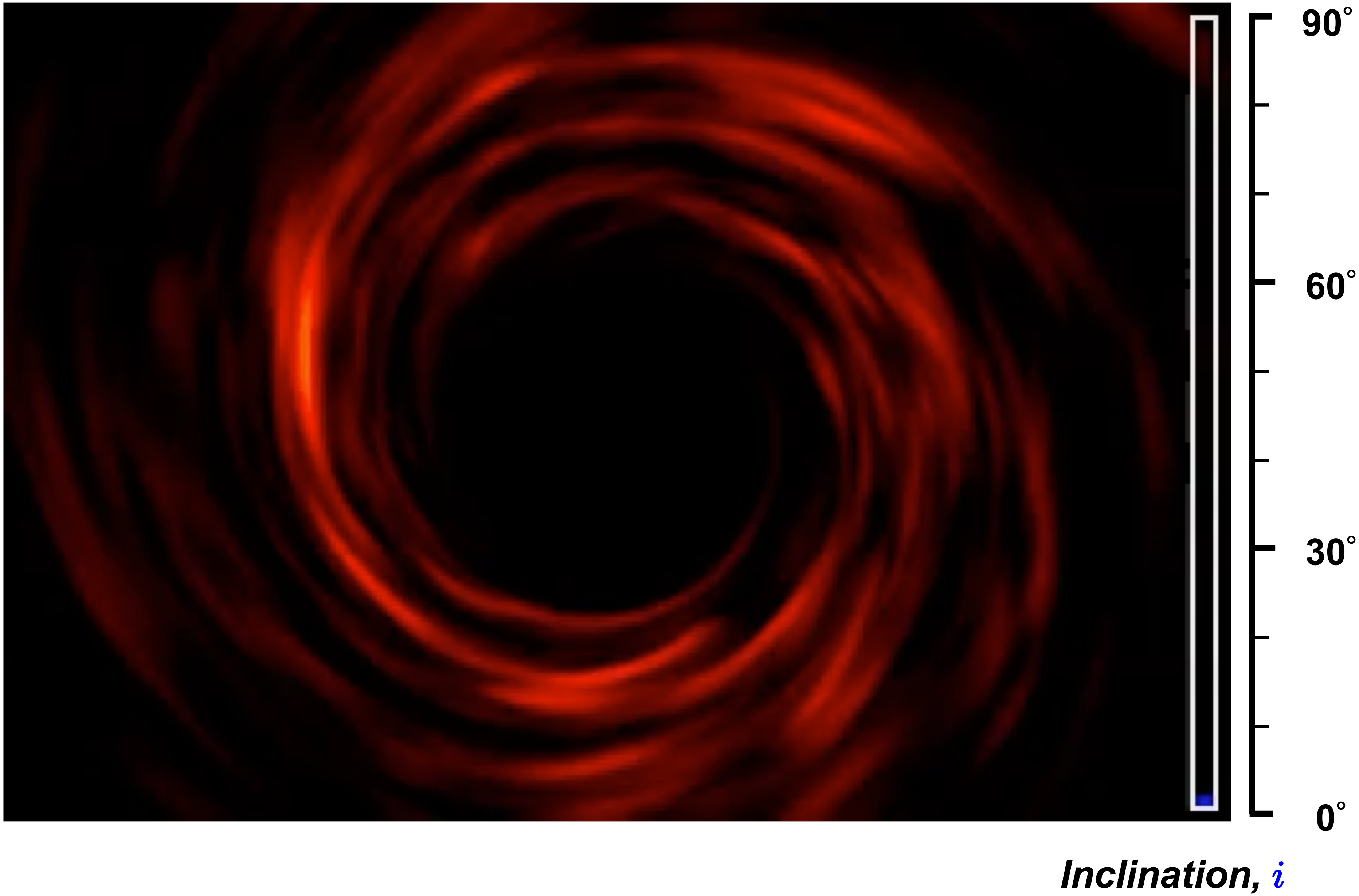
Basic frequencies in General relativity



State transitions – Spectra and Timing



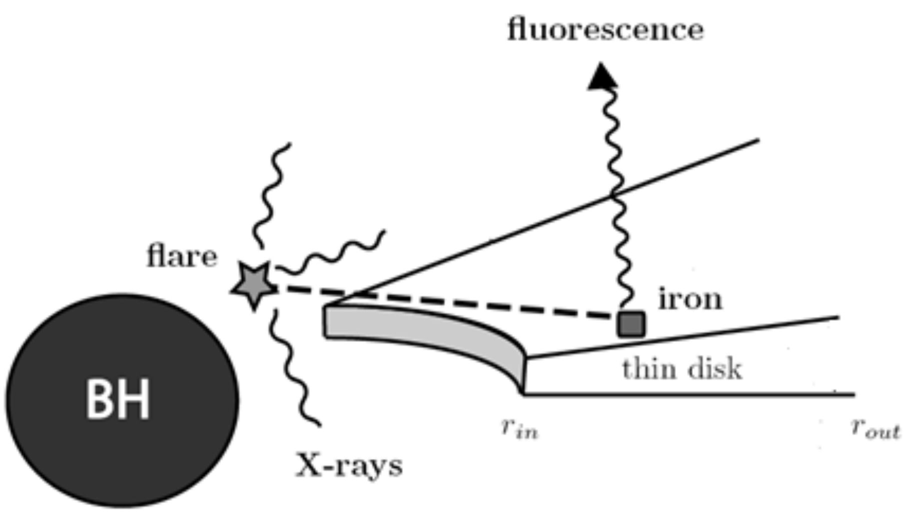
Accretion discs and General Relativity

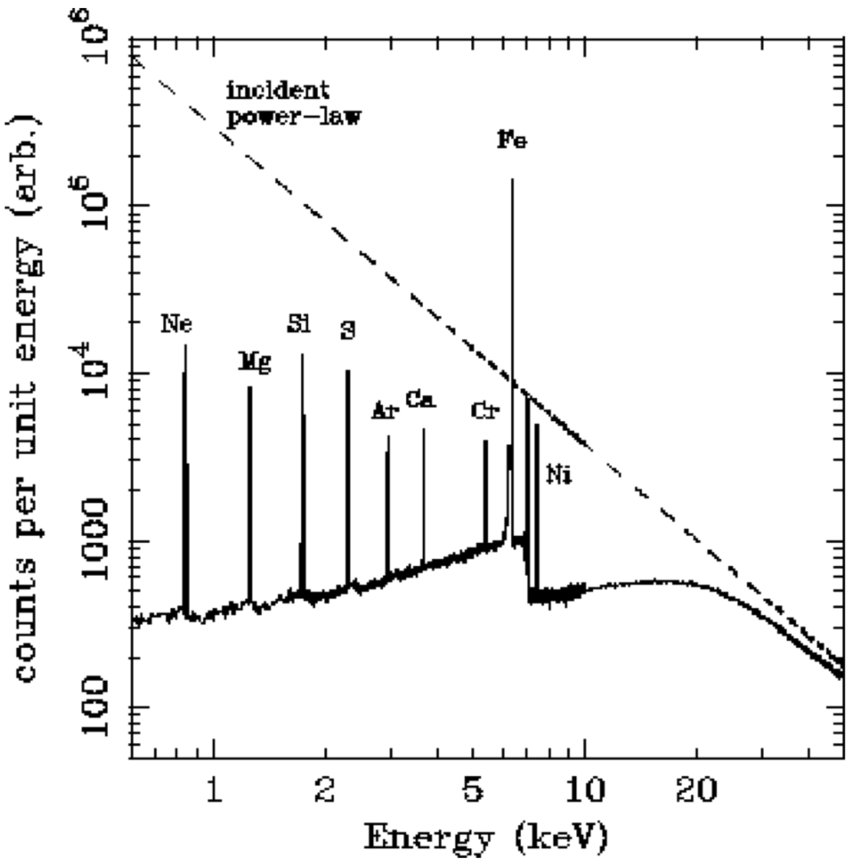


Armitage & Reynolds 2003

Accretion disc: Discrete (line) spectrum

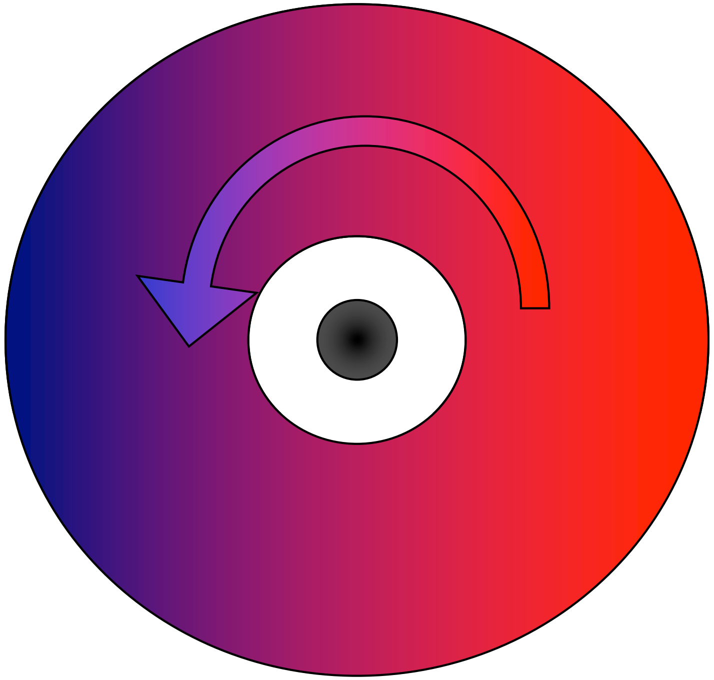
- **Incident spectrum: power-law shape**
- **Photoelectric absorption in the disc → fluorescence line spectrum with Fe producing the most prominent line due to the high Fe abundance and the large Fe Kα yield (Kα line is the transition from energy level 2 → level 1).**

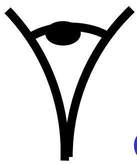




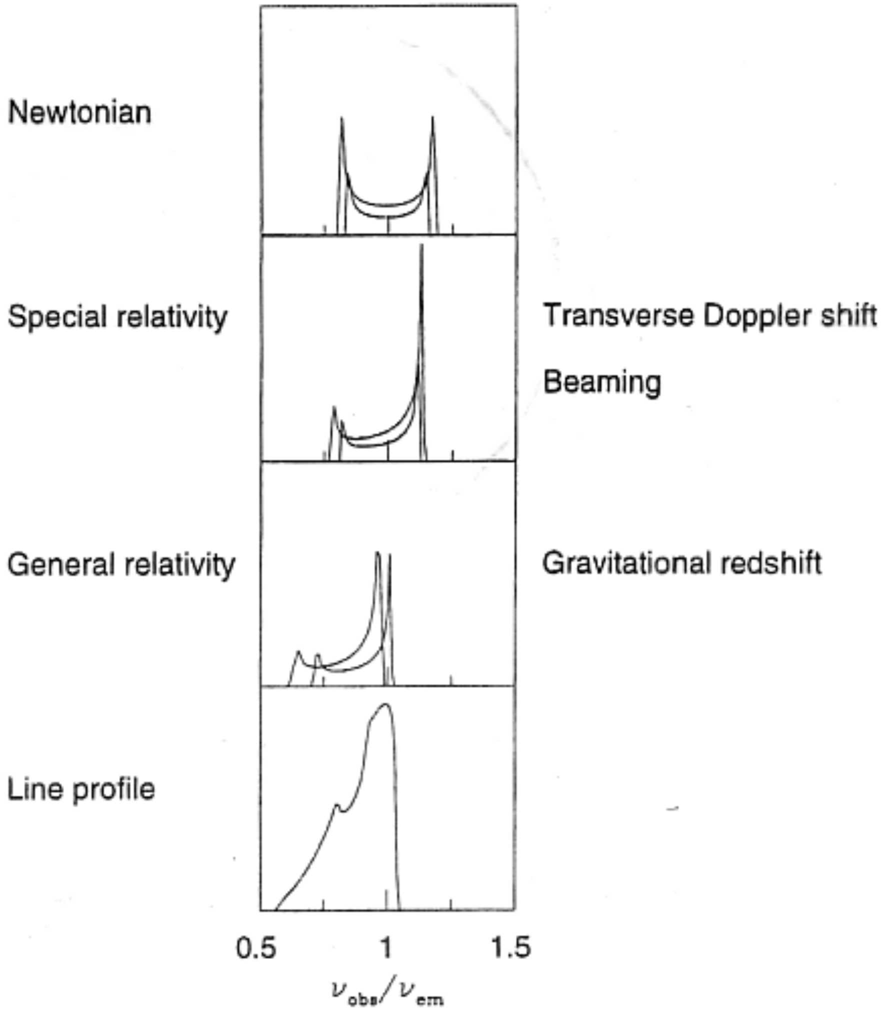
Relativistic Disc Lines

Accretion disc around a black hole (or neutron star)



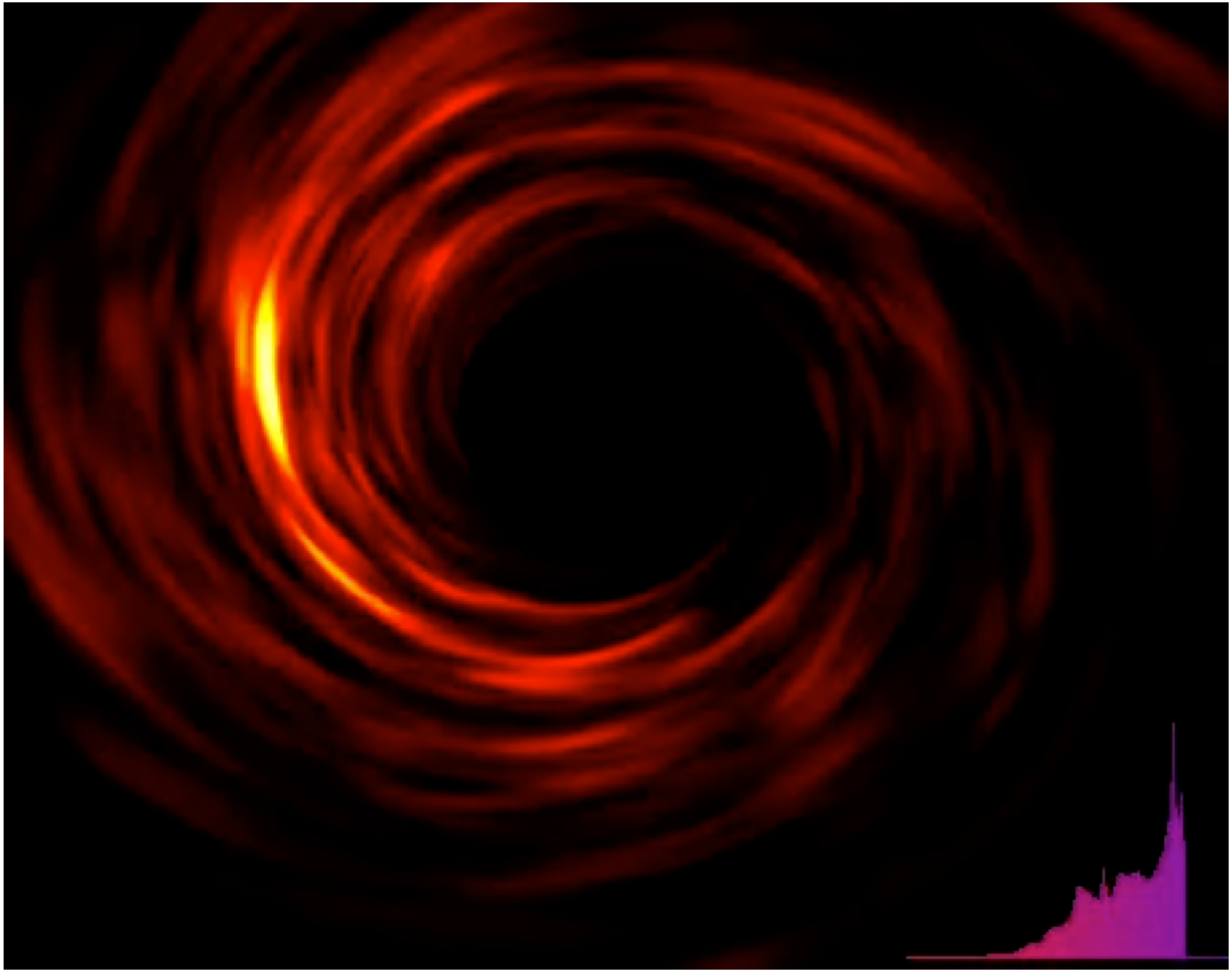


observer



Line profile

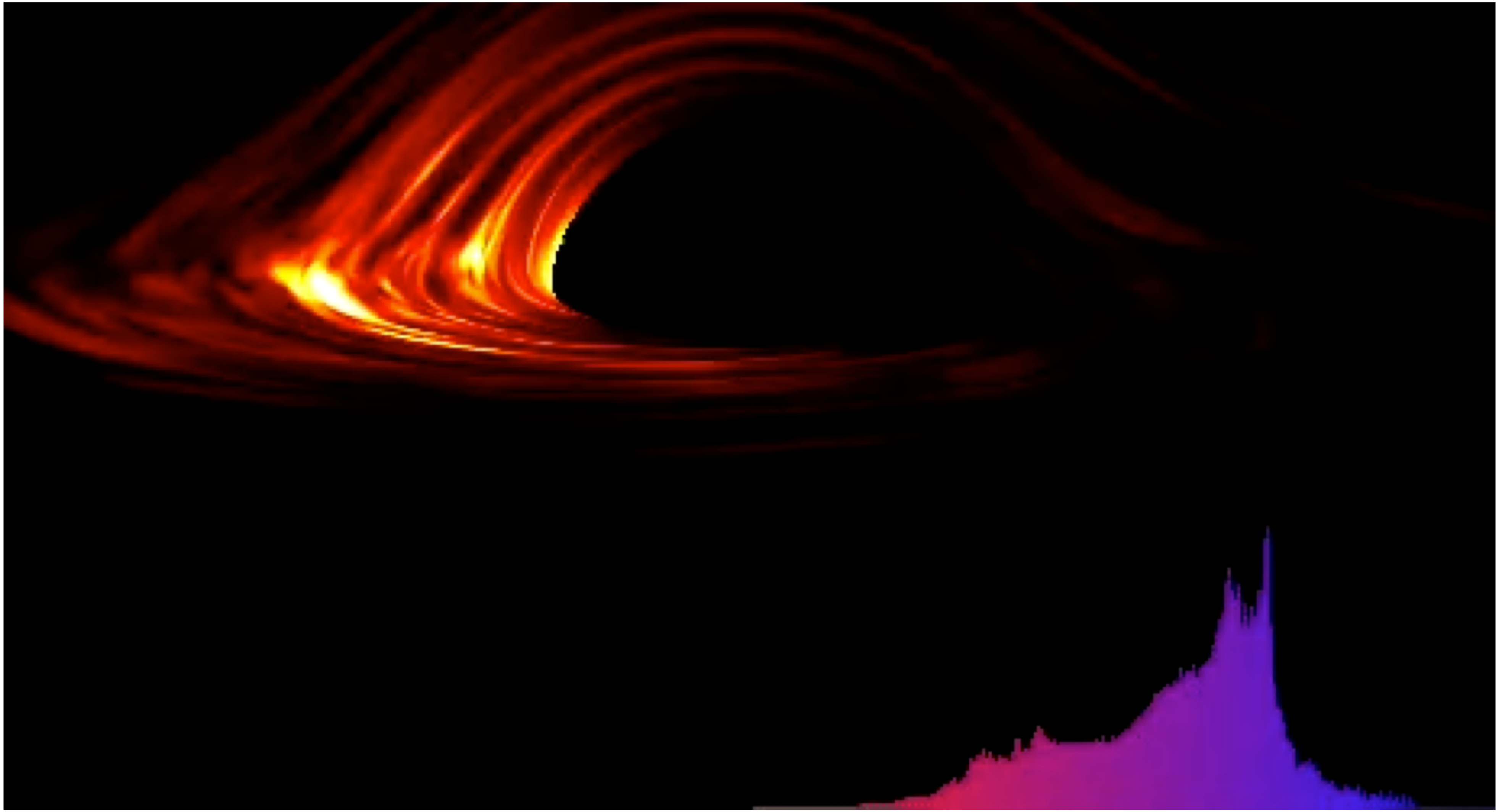
Relativistic Disc Lines



$i = \mathbf{30°}$

Armitage & Reynolds 2003

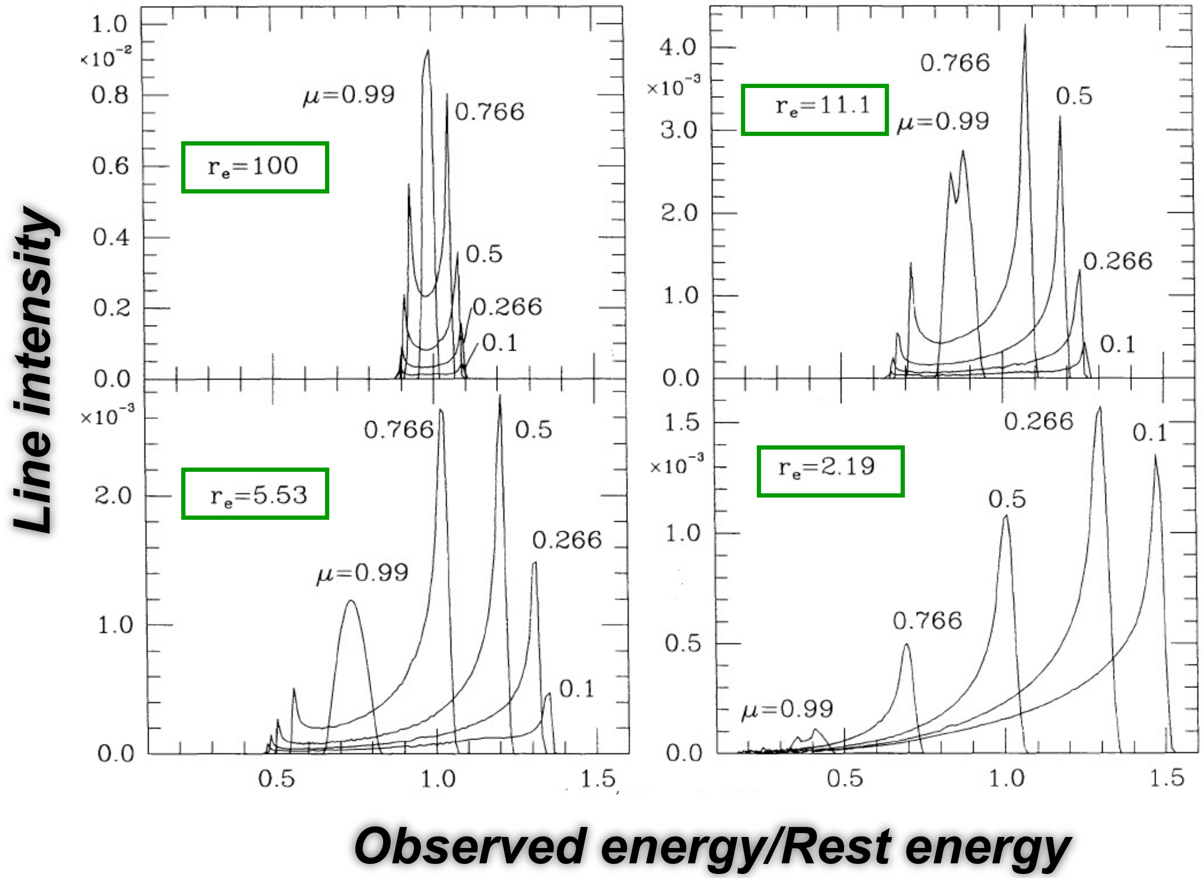
Relativistic Disc Lines



Armitage & Reynolds 2003

$i = 80°$

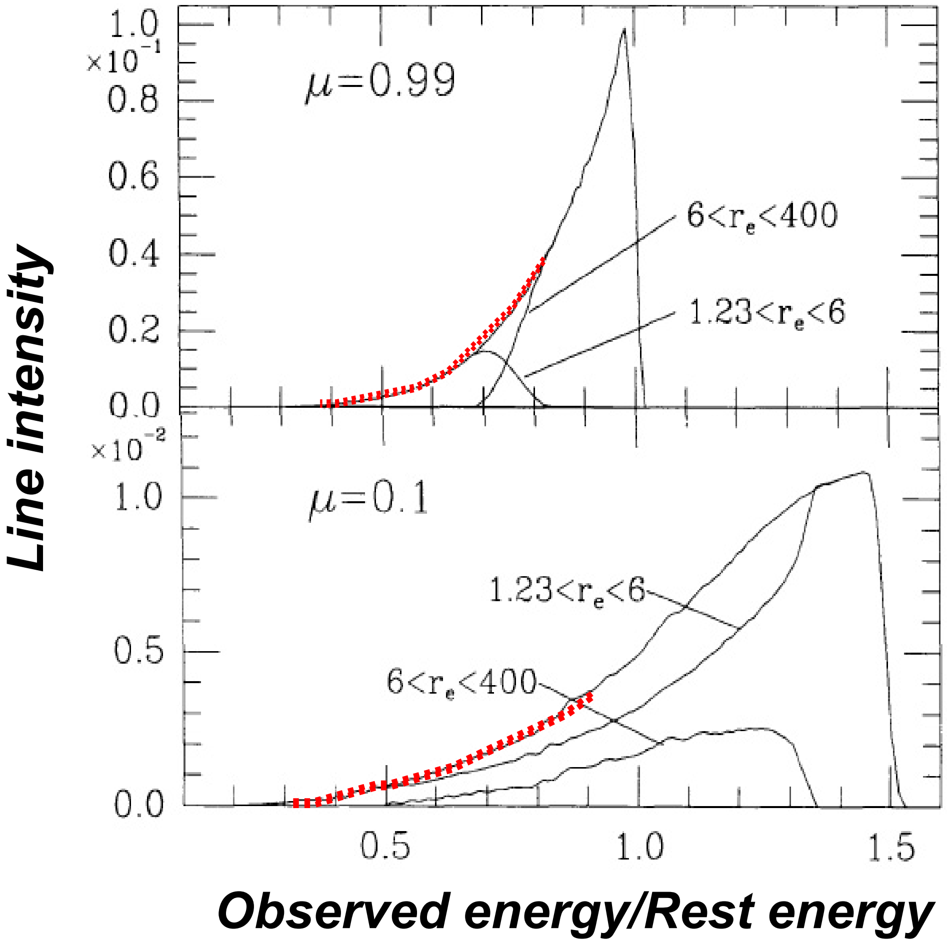
Relativistic Disc Lines: Models



- $\mu = \cos i$
- r_e = radius of the ring, in units of $r_g = GM/c^2$, at which the line is produced.
- For a *non-rotating* black hole/neutron star $r_e \geq 6\ r_g$. (This is the so-called *innermost stable circular orbit,* ISCO.)
- Rotation makes it possible to have lower r_e.

Laor 1991

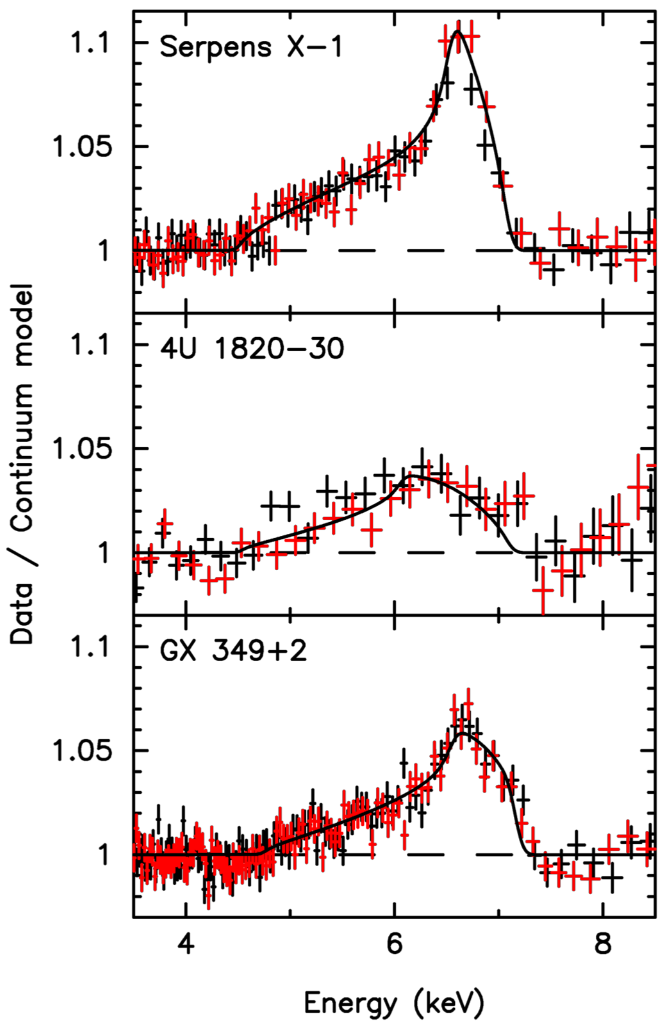
Relativistic Disc Lines: Models

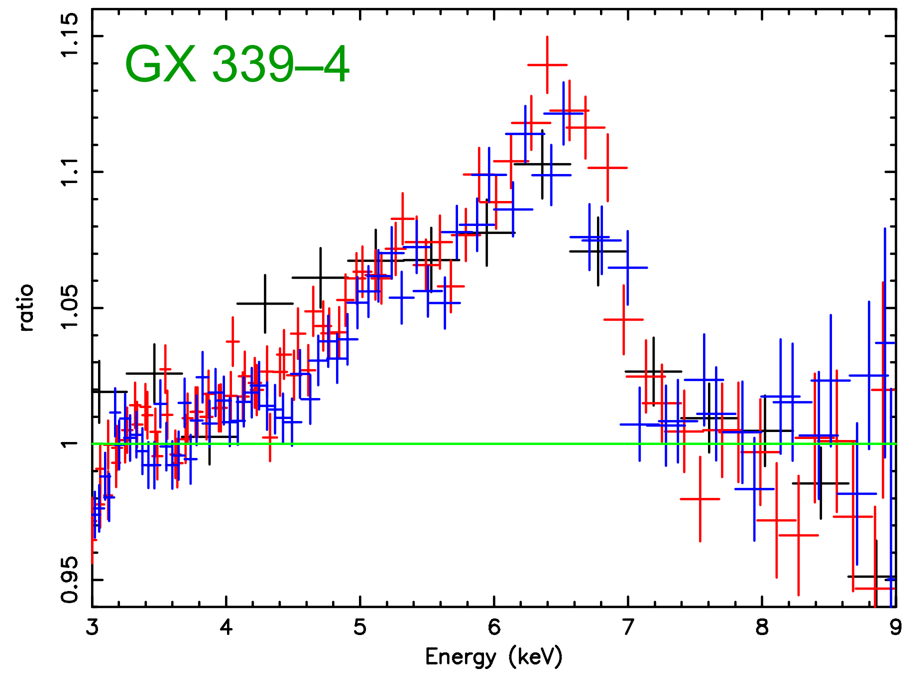


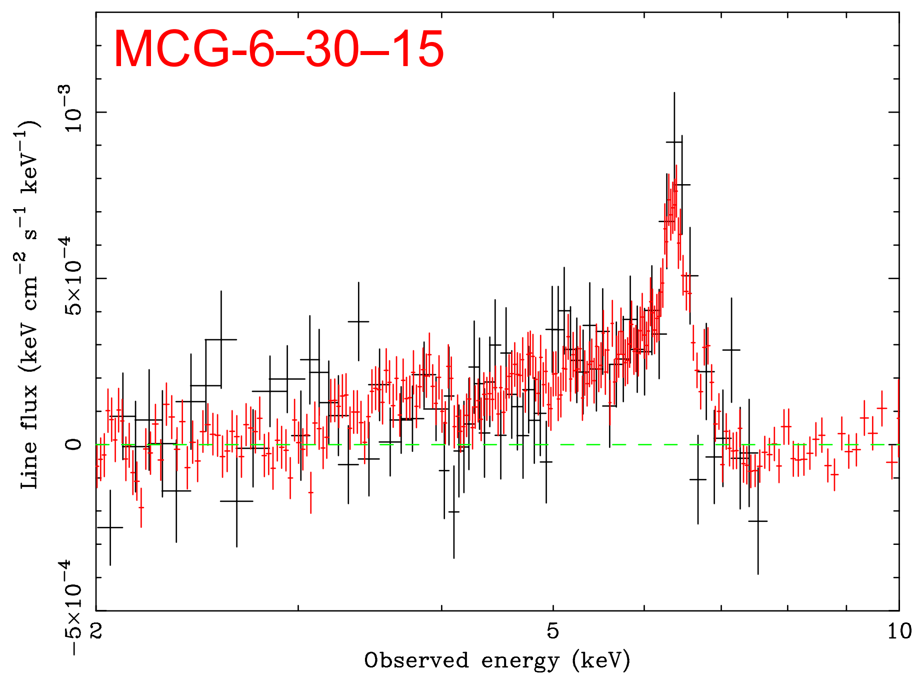
- **The *red wing of the line* is mostly emitted from very close to the black hole/neutron star.**

Laor 1991

Relativistic Disc Lines: Observations







- **Broad (*doubled peaked*), line detected between 6 and 7 keV in *neutron-star* and *black-hole* binaries, and *AGN*.**

Miller et al. 2002,; Young et al. 2006; Cackett et al. 2007