Introduction to Black Hole Astrophysics II

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CENTRO DE ASTROBIOLOGÍA

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STRONGGRAVITY
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SEVENTH FRAMEWORK PROGRAMME

Outline of the 3 lectures-course

Lecture 1

- The different flavors of astrophysical BHs
- Observational evidence for astrophysical BHs:
  - BHs in binary systems
  - The Milky Way super-massive BH (SMBH): the case of Sgr A^*
  - SMBHs in other galaxies

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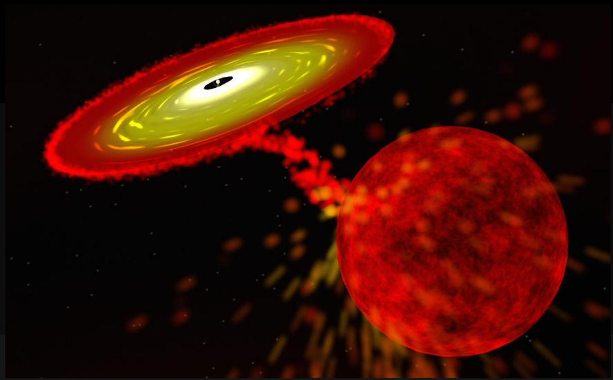
  - SMBHs in other galaxies

Lecture 2

- BH accretion, energy release, efficiency, Eddington limit, BB emission and IC
- BH transients (X-ray binaries): states. BH spin from thermal BB disc
- IMBHs: the special case of HLX-1 in ESO 243-49

Black Holes: observational evidences (some)

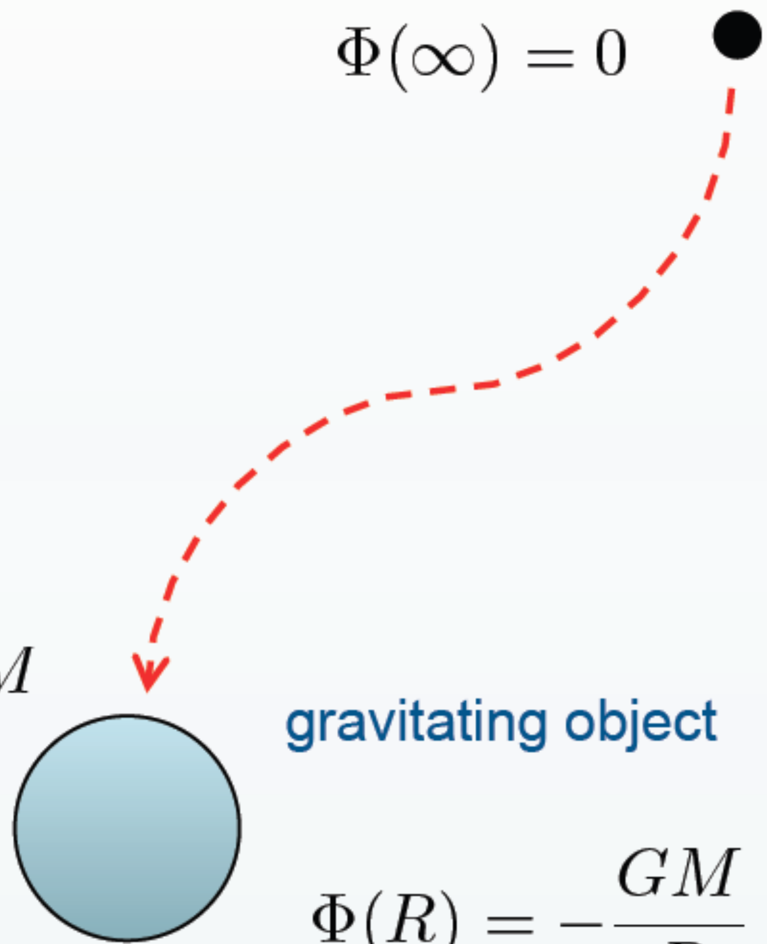


Stellar-mass (~10 solar masses)
The most massive stars end their lives leaving nothing behind their ultra-dense collapsed cores which we can observe when accreting from a companion star [X-ray binary]

Super-massive (10^6-10^9 solar masses)
The centers of galaxies contain giant black holes, which we can observe when accreting the surrounding matter / gas [AGN]

Intermediate-mass (10^2 – 10^4 solar masses)
A new class of recently-discovered black holes could have masses on the order of hundreds or thousands of stars although the debate is open [ULX ?]

Accretion onto compact objects – energy release in accretion



$$
\begin{aligned}
\Delta E &= \Delta m[\Phi(R) - \Phi(\infty)] \\
&= -\Delta m \left(\frac{GM}{R}\right) \\
&= -\Delta m\, c^2 \left(\frac{GM}{R\, c^2}\right) \\
&= -\Delta m\, c^2 \left(\frac{r_{\mathrm{g}}}{R}\right)
\end{aligned}
$$

$$r_{\mathrm{g}} = \left(\frac{GM}{c^2}\right)$$

Accretion onto compact objects – energy release efficiency

efficiency parameter

$$\eta = \left(\frac{r_{\mathrm{g}}}{R}\right)$$

$$\Delta E = -\eta \Delta m\, c^2$$

$$L = \frac{dE}{dt} = -\eta \dot{m} c^2$$

accretion luminosity

accretion rate

	η
Sun	2.1×10^{-6}
white dwarf	$\sim 10^{-4}$
neutron star	~ 0.17
black hole	$?$

nuclear burning

$$\eta_{\mathrm{nuc}} \approx 0.007$$

Accretion onto compact objects – motion of an object under gravity

Newtonian gravity

$$\frac{\dot{\mathbf{r}}^2}{2} - \frac{GM}{r} = E$$

equation of motion

$$\dot{\mathbf{r}}^2 = \dot{r}^2 + r^2\dot{\phi}^2$$

$$l_z = r^2\dot{\phi}$$

specific angular momentum

$$\frac{\dot{r}^2}{2} + V(r) = E$$

KE + PE = total E

$$V(r) = -\frac{GM}{r} + \frac{l_z^2}{2\,r^2}$$

effective potential

Accretion onto compact objects – motion of an object under gravity

Schwarzschild gravity

use the natural units: $c = G = 1$

$$d\tau^2 = -ds^2$$

$$= \left(1 - \frac{2M}{r}\right) dt^2 - \left(1 - \frac{2M}{r}\right)^{-1} dr^2 - r^2 \left(d\theta^2 + \sin^2\theta \, d\phi^2\right)$$

$$\mathcal{L} = \frac{1}{2} g_{\mu\nu} \, \dot{x}_\mu \dot{x}_\nu$$ Lagrangian

$$\text{“}\cdot\text{”} \equiv \frac{d}{d\tau}$$

Euler-Lagrange equation

$$\frac{d}{d\tau}\frac{\partial \mathcal{L}}{\partial \dot{x}^\mu} - \frac{\partial \mathcal{L}}{\partial x^\mu} = 0 \longrightarrow$$ equation of motion

Accretion onto compact objects – motion of an object under gravity

Schwarzschild gravity (cont.)

set $\theta = \pi/2$ and $d\theta = 0$

$$r^2 \dot{\phi} = l_z$$ angular momentum conservation

$$\left(1 - \frac{2M}{r}\right) \dot{t} = E$$ energy conservation

$$\dot{r}^2 + V(r)^2 = E^2$$ equation of motion

$$V(r)^2 = \left(1 - \frac{2M}{r}\right)\left(1 + \frac{l_z^2}{r^2}\right)$$ effective potential

Accretion onto compact objects – energy release in the accretion into a black hole

energy conversion in a Schwarzschild black hole

$$r_{\mathrm{SCO}} = \frac{M}{2}\left[h^2 + (h^4 - 12h^2)^{1/2}\right]$$

stable circular orbit

$$h = l_z = \left[\frac{Mr^2}{r - 3M}\right]^{1/2} \geq 2\sqrt{3}$$

$$E_{\mathrm{SCO}} = \frac{r - 2M}{\sqrt{r(r - 3M)}}$$

orbital binding energy

$$\eta = 1 - E_{\mathrm{SCO}}$$

energy conversion efficiency

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maximum efficiency
for energy conversion

$$h = 2\sqrt{3} \Rightarrow r_{\mathrm{ISCO}} = 6M \Rightarrow \eta_{\max} = 1 - \frac{\sqrt{8}}{3} \approx 0.057$$

innermost stable circular orbit

Accretion onto compact objects – energy release in the accretion into a black hole

energy conversion in a Kerr black hole

$$r_{\rm ISCO} = M\left[3 + B \mp \sqrt{(3-A)(3+A+2B)}\right]$$

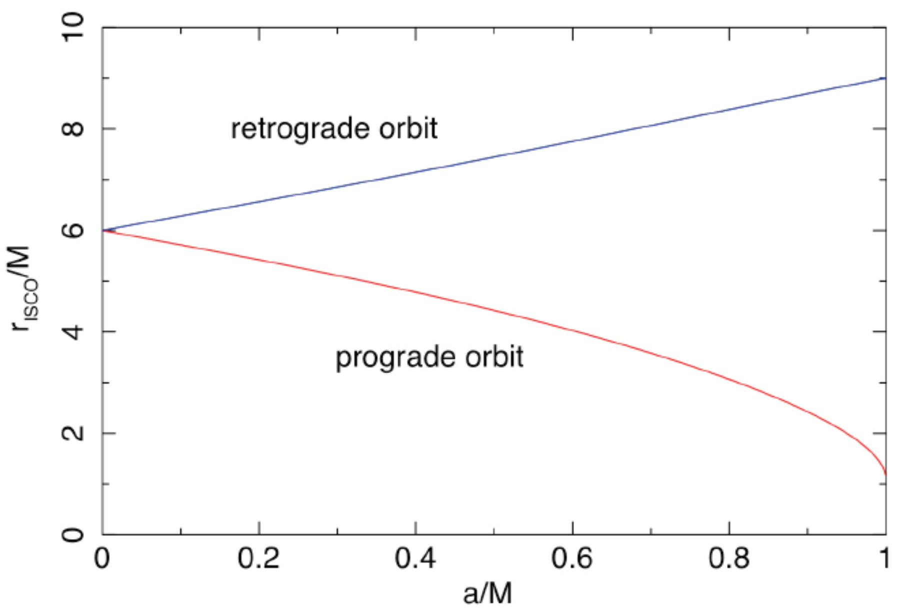
$$A = 1 + (1-x^2)^{1/3}\left[(1+x)^{1/3} + (1-x)^{1/3}\right]$$

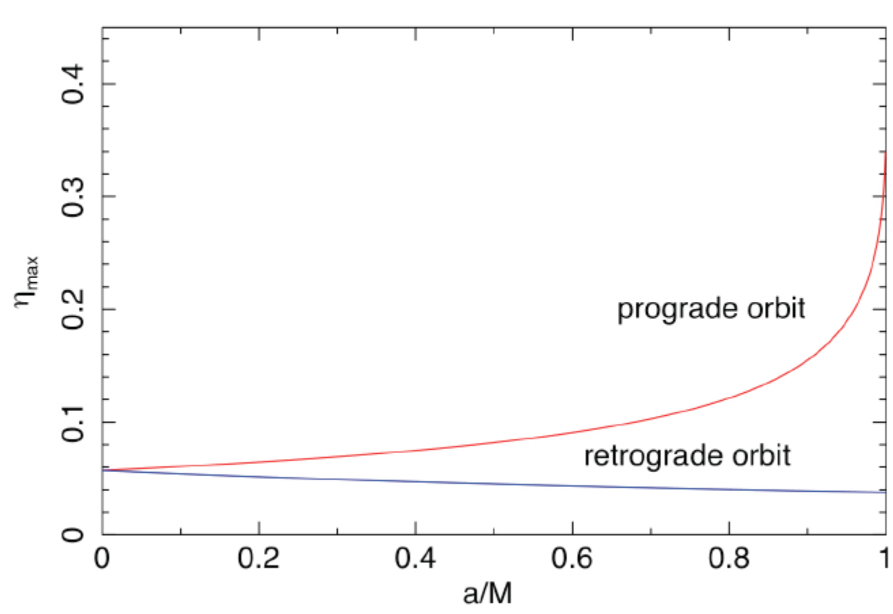
$$B = (3x^2 + A^2)^{1/2}$$

$$x = a/M$$

$$\eta_{\rm max} = 1 - \frac{r_{\rm ISCO} - 2M \pm a\sqrt{M/r_{\rm ISCO}}}{\sqrt{r_{\rm ISCO}\left(r_{\rm ISCO} - 3M \pm 2a\sqrt{M/r_{\rm ISCO}}\right)}}$$

maximum energy conversion efficiency



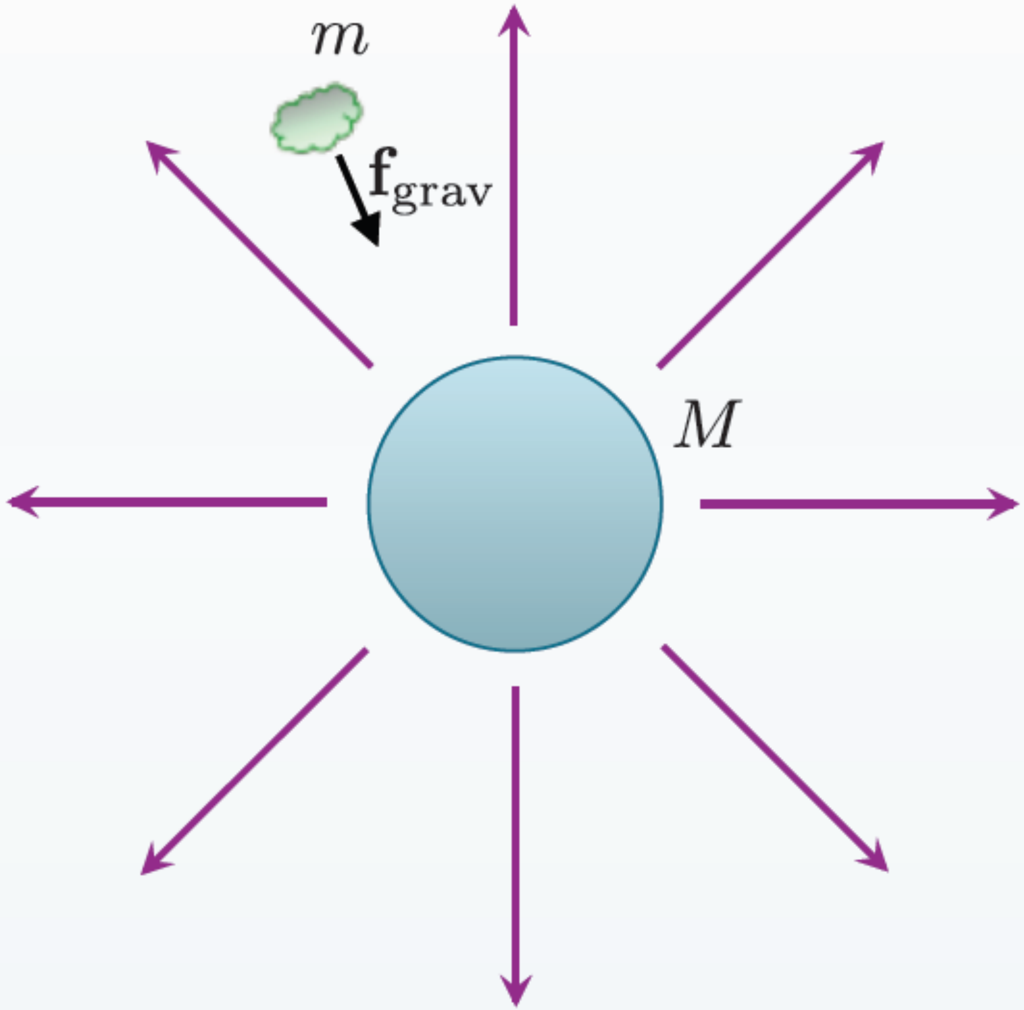


$$L = \frac{GM\dot{M}}{r} \approx 0.1\dot{M}c^2$$

This is the by far the most energy efficient process we know (except annihilation)

The efficiency can vary from 5.7% up to 42% depending on the BH spin
(complete nuclear fusion of H into He only reaches 0.7 %)

Eddington limit – forces on the accreting material



gravitational force on the particles in the accreting material

$$\mathbf{f}_{\mathrm{grav}} = -\frac{GM\,\Delta m}{r^2}\hat{\mathbf{r}}$$

gravitational energy is converted into kinetic and thermal energies and then radiation in the accretion process

$$L = \frac{GM}{r}\frac{\Delta m}{\Delta t}$$

Eddington limit – radiative pressure force

free charged particles experience a force acting upon them in a radiation field because of scattering

cross-section of scattering between a charged particle and a photon

$$\sigma_{\mathrm{sc,e}} = \frac{8\pi}{3}\left(\frac{e^2}{m_{\mathrm{e}}c^2}\right)^2$$ electron

$$\sigma_{\mathrm{sc,p}} = \frac{8\pi}{3}\left(\frac{e^2}{m_{\mathrm{p}}c^2}\right)^2$$ proton

$$\sigma_{\mathrm{sc,p}} \ll \sigma_{\mathrm{sc,e}} \quad (\equiv \sigma_{\mathrm{T}})$$

Thomson cross-section

radiative force experienced by an electron

$$|\mathbf{f}_{\mathrm{rad}}| = \frac{\sigma_{\mathrm{T}} S}{c}$$

radiative energy flux

Eddington limit – Eddington luminosity

Consider a simple case:
a spherical accretion flow where the gravitational force is balanced by the radiative pressure force

$$\mathbf{f}_{\mathrm{rad}} = -\mathbf{f}_{\mathrm{grav}}$$

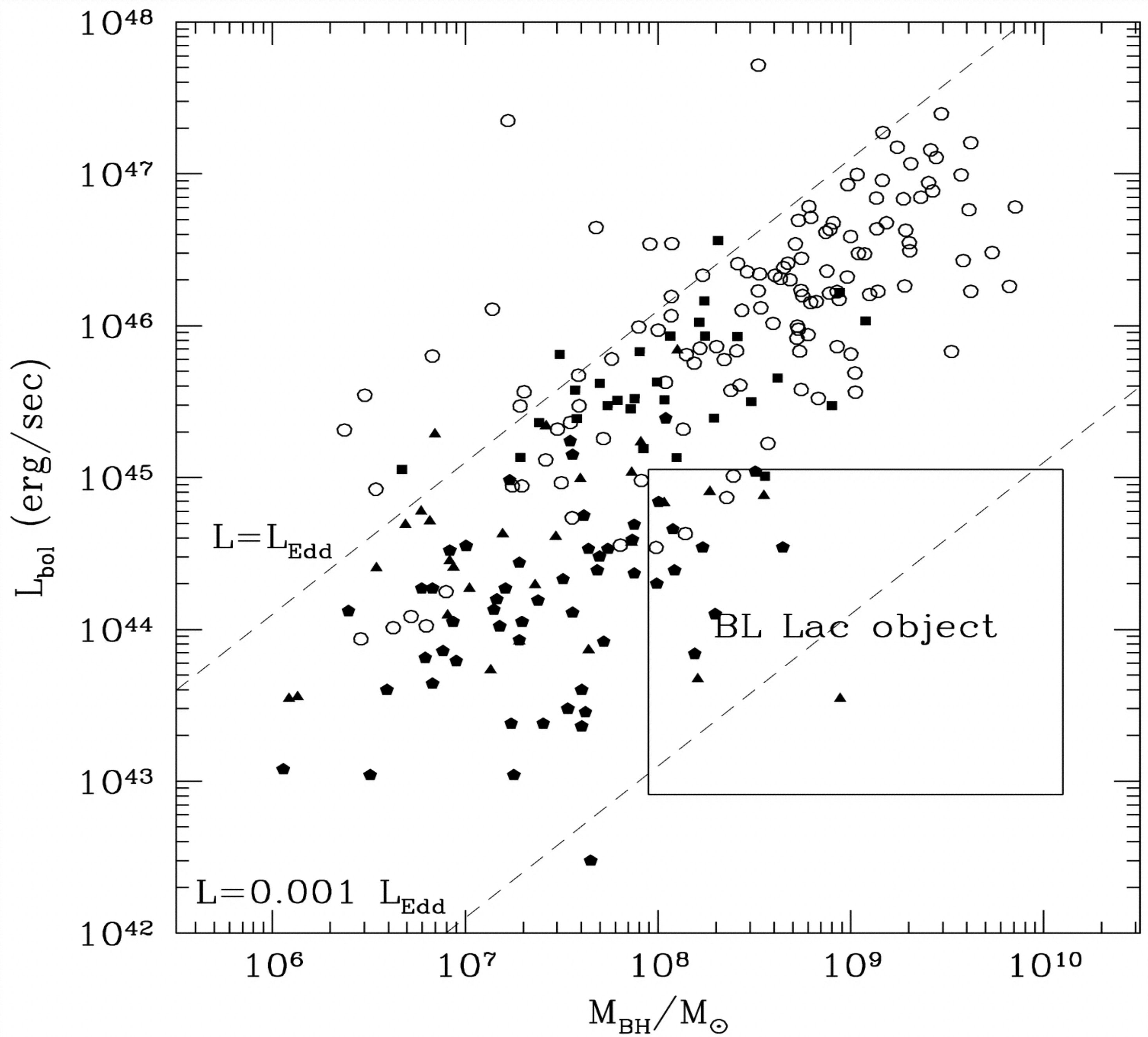
$$\Rightarrow \frac{GM(m_{\mathrm{p}} + m_{\mathrm{e}})}{r^2} = \frac{\sigma_{\mathrm{T}}}{c}\left(\frac{L_{\mathrm{Edd}}}{4\pi r^2}\right)$$

Eddington luminosity of an accreting object

$$L_{\mathrm{Edd}} = \left[\frac{4\pi G(m_{\mathrm{p}} + m_{\mathrm{e}})c}{\sigma_{\mathrm{T}}}\right] M$$

$$\approx 1.3 \times 10^{38}\left(\frac{M}{\mathrm{M}_{\odot}}\right) \mathrm{erg\ s}^{-1}$$

The Eddington limit in practice



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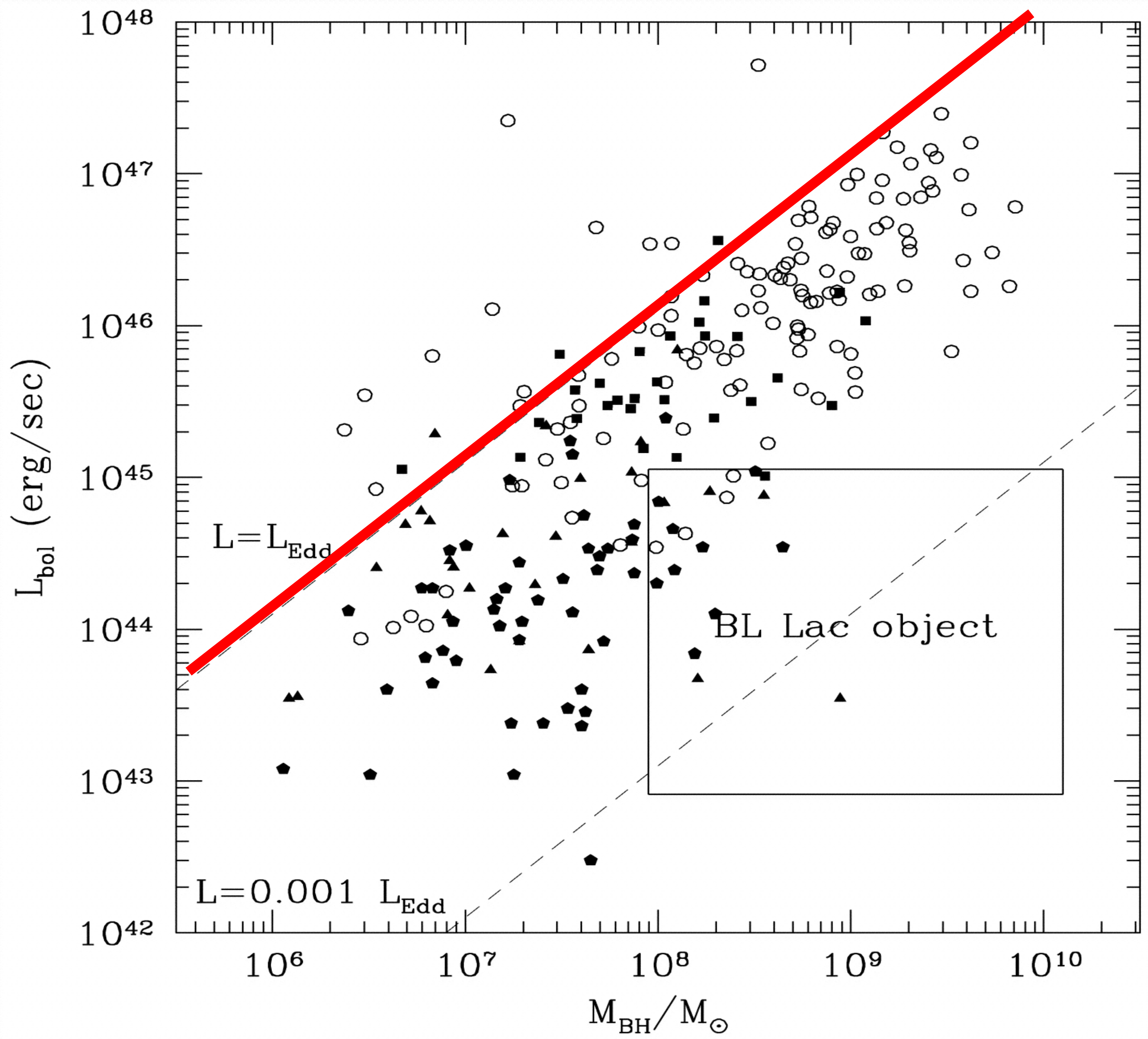

Emission from accreting BH

As mentioned, gas in the accretion disc spirals in via a succession of circular orbits

The orbital angular velocity increase inwards ($\Omega \sim r^{-3/2}$), so that each annulus on the disc is in differential rotation with its neighbours

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$$T_{BB} = \left(\frac{L}{A\sigma} \right)^{1/4}$$

Emission from accreting BH

$$kT_{BB} = k\left(\frac{L}{A\sigma}\right)^{1/4} = k\left(\frac{L}{4\pi R^2\sigma}\right)^{1/4}$$

we can then use the Eddington luminosity derived before

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~ 0.6 keV (X-rays) for a typical BH X-ray binary
~ 0.01 keV (UV) for a tpical AGN

Emission from accreting BH

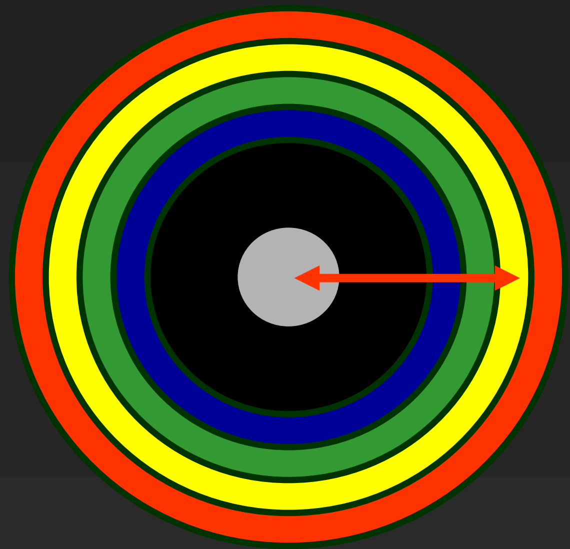
In the real world, the temperature of the accretion disc is a function of radius, i.e. the accretion disc can be though of as an ensable of annuli each emitting its own BB spectrum with temperature increasing inwards

The local dissipation rate due to viscous stresses can be writen as

$$D(r) = \frac{3GM\dot{m}}{8\pi r^3}\left(1 - \left(\frac{r_{in}}{r}\right)^{1/2}\right) = \sigma T^4$$

So that, at each radius r, one has a BB temperature of

$$T(r) = \left[\frac{3GM\dot{m}}{8\pi\sigma r^3}\left(1 - \left(\frac{r_{in}}{r}\right)^{1/2}\right)\right]^{1/4}$$



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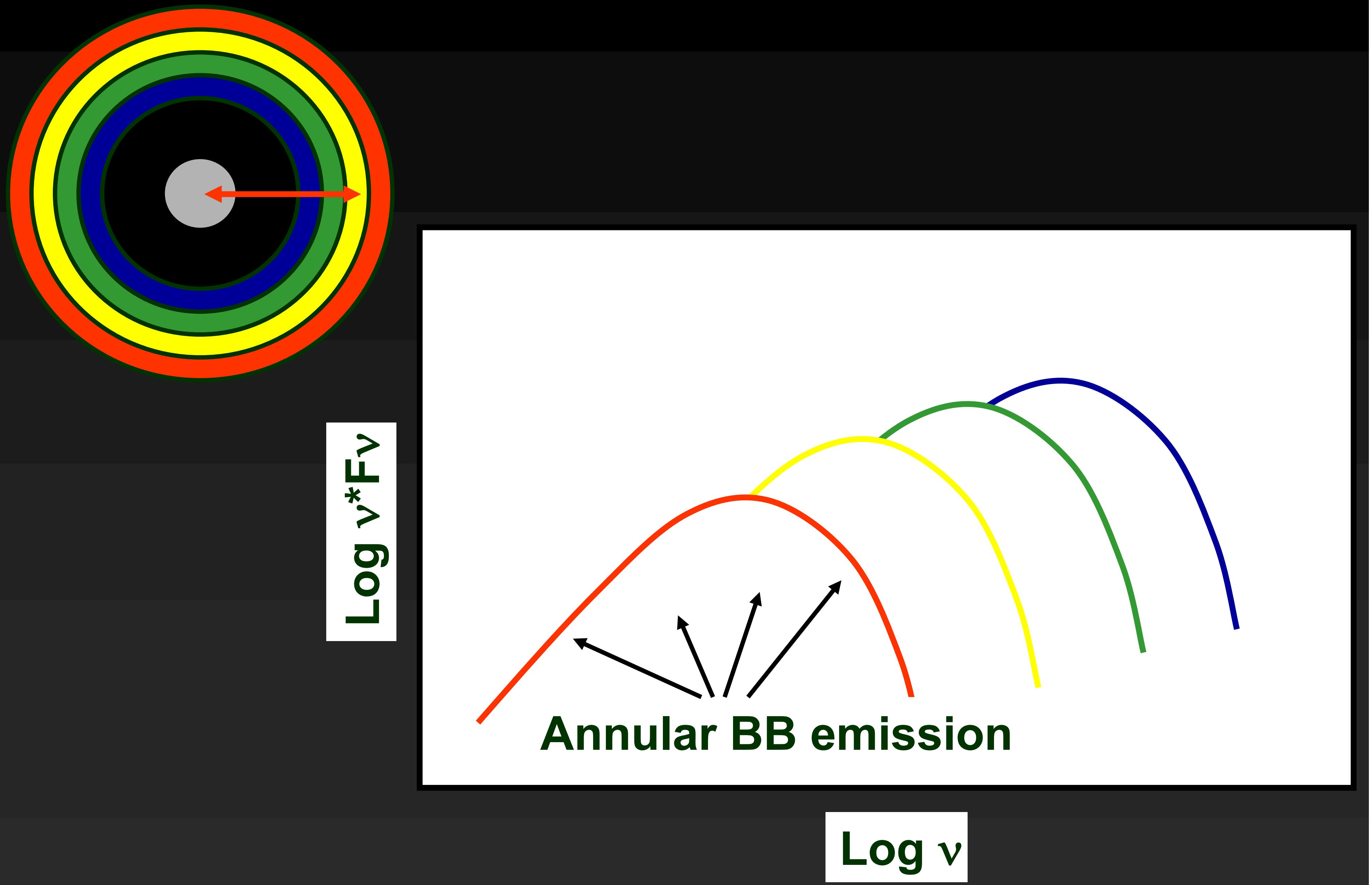

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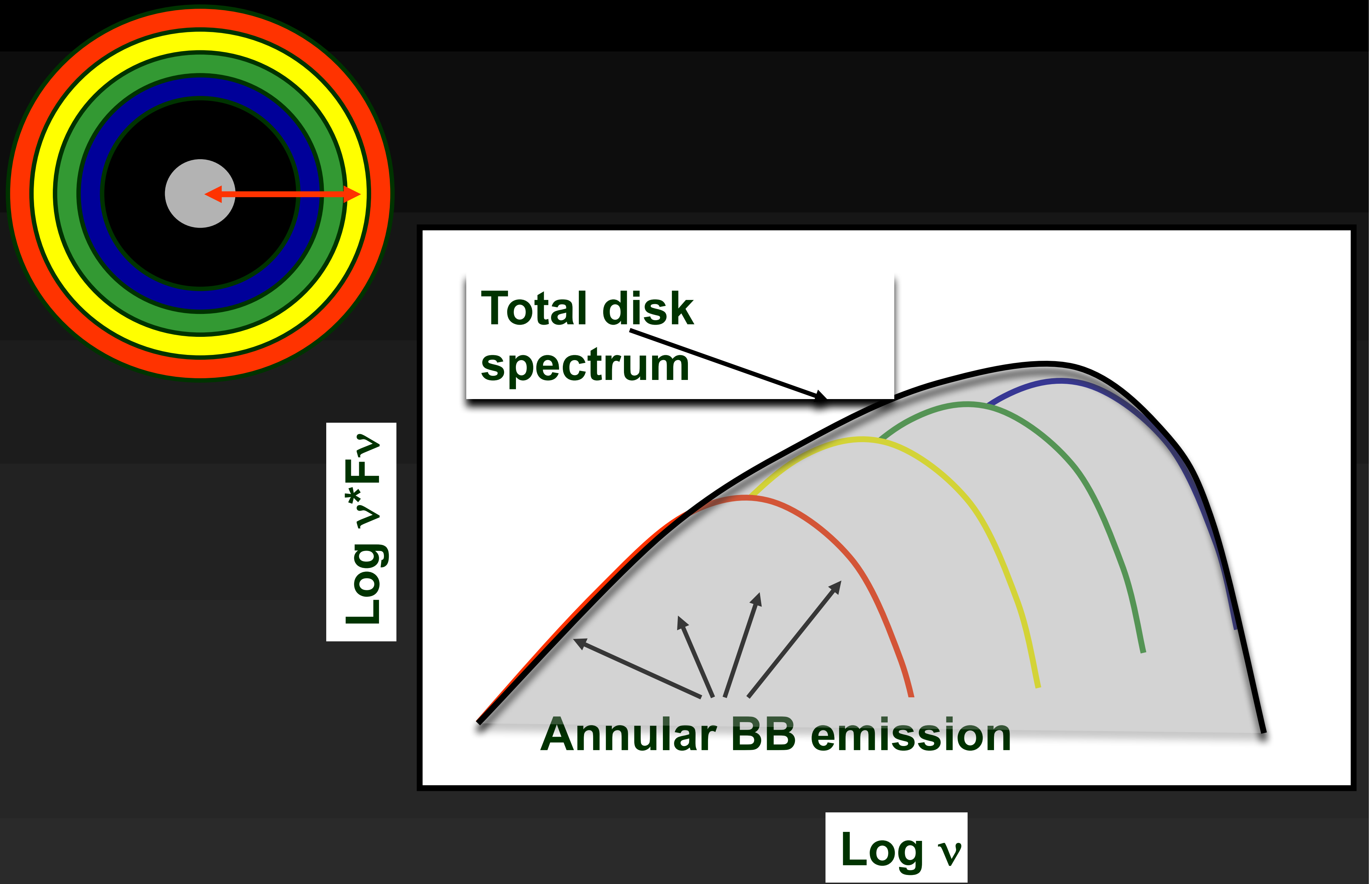
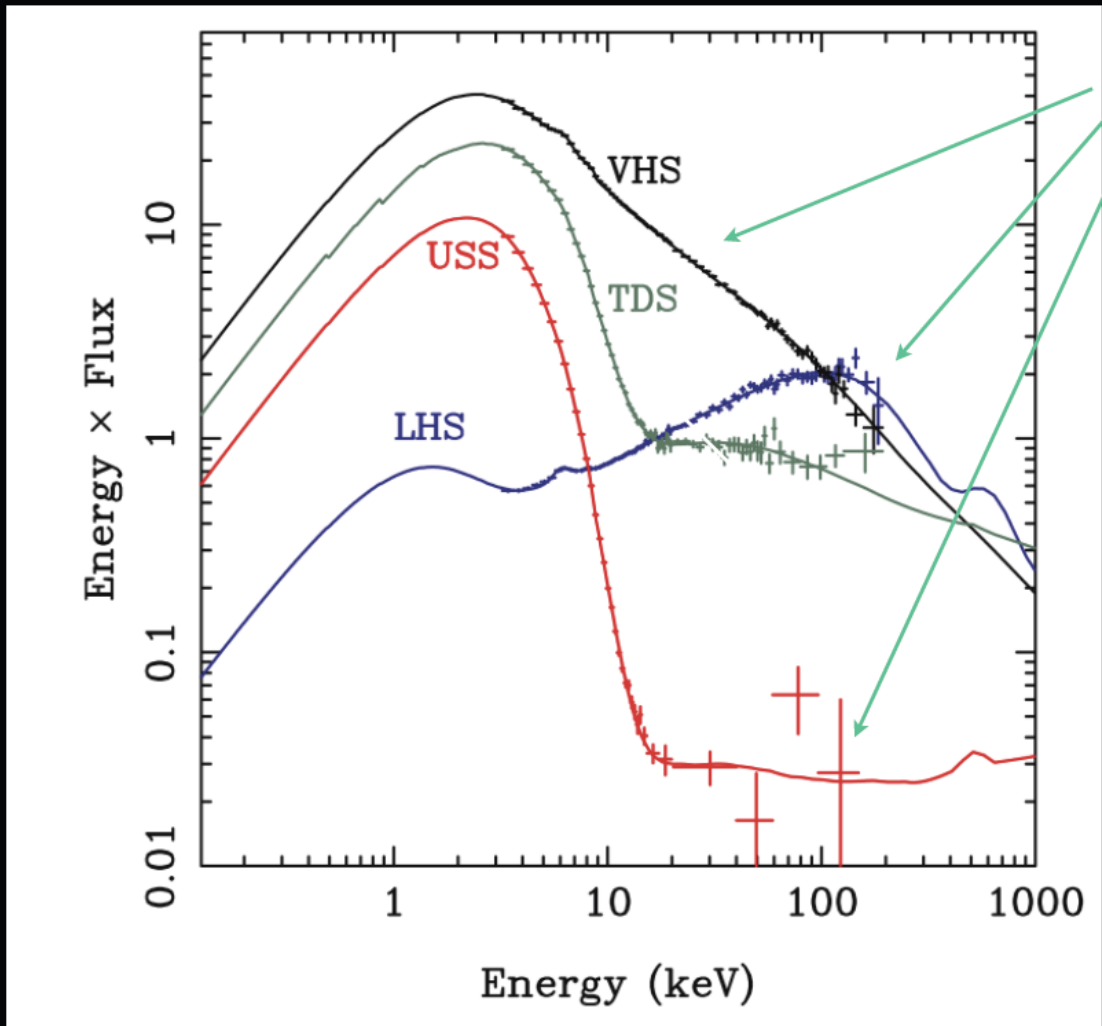
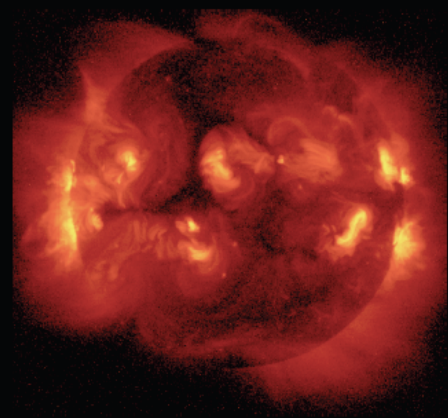


Emission from accreting BH

BB emission from accreting BHs is indeed observed, although this is not the end of the story



Non-thermal emission: 'the corona'



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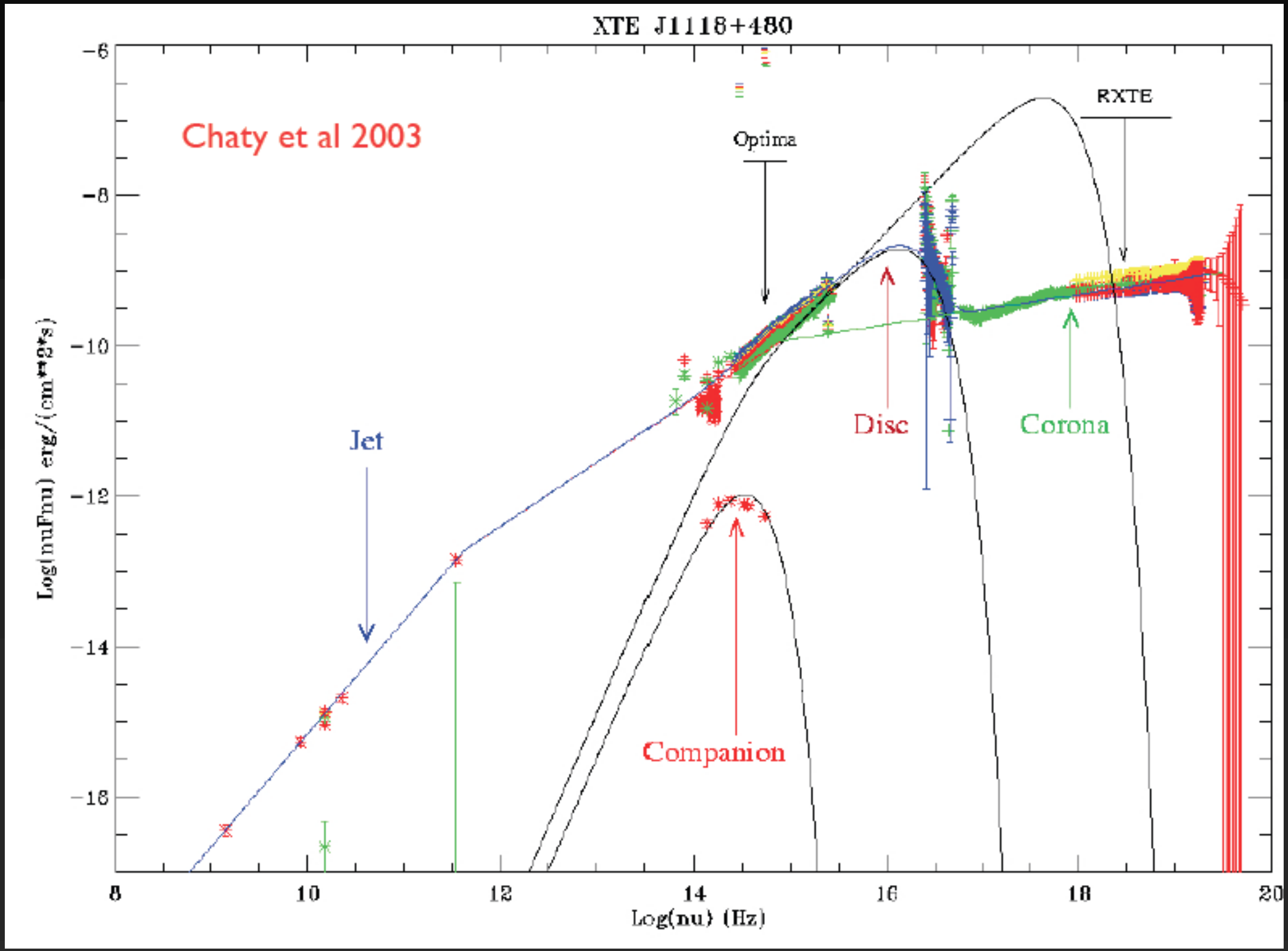

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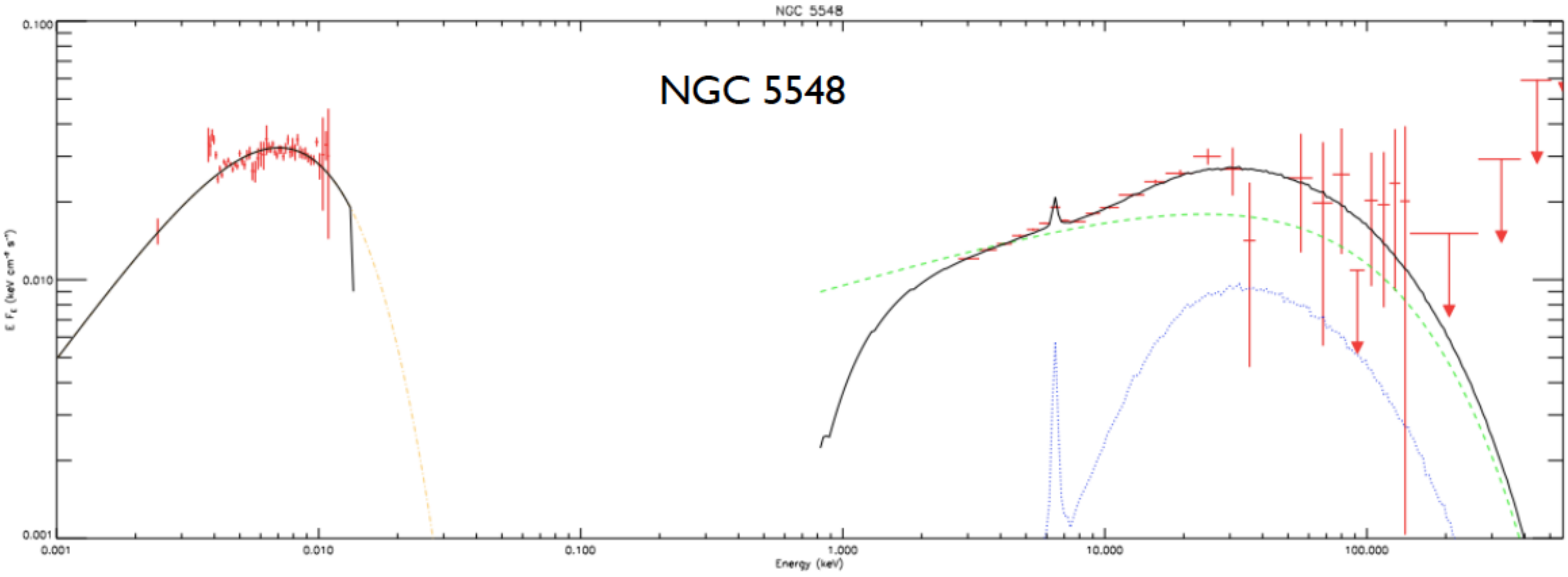

Emission from accreting BH

As seen, BH binaries are often dominated by BB emission peaking (as expected) in the soft X-rays (~ 1keV)

On the other hand, accreting SMBHs (AGN) are characterized by BB emission peaking (again, as expected because of the much higher BH mass) in the UV portion of the EM spectrum

High-energy emission in the form of a ~ power law is however ubiquitously seen in accreting BHs and cannot be explained by BB emission

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This power law like emission extends to hundreds of keV, corresponding to an increase in energy of at least 2 decades even in the case of X-ray binaries

Where does this further high-energy emission come from ?

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Where does this further high-energy emission come from ?

Inverse Compton is the answer

Emission from accreting BH

The accretion flow is thought to be surrounded by hot plasma (basically electrons) which we call corona (in analogy with the similar stellar structure)

The hot electrons in the corona interact with the photon field from the accretion flow (mainly soft X-rays for X-ray binaries and UV photons for SMBHs)

Assuming for simplicity a non-relativistic thermal distribution of electrons with temperature T_e the averaged energy exchange in a given scattering event between photon and electron is

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$$\langle \Delta E \rangle = (4kT_e - E)\frac{E}{m_e c^2}$$

If photons are less energetic than electrons, i.e. if $E << kT_e$

Photons gain energy in each scattering, i.e. it gains an energy

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$$\Delta E / E \approx 4kT_e / m_e c^2$$

Emission from accreting BH

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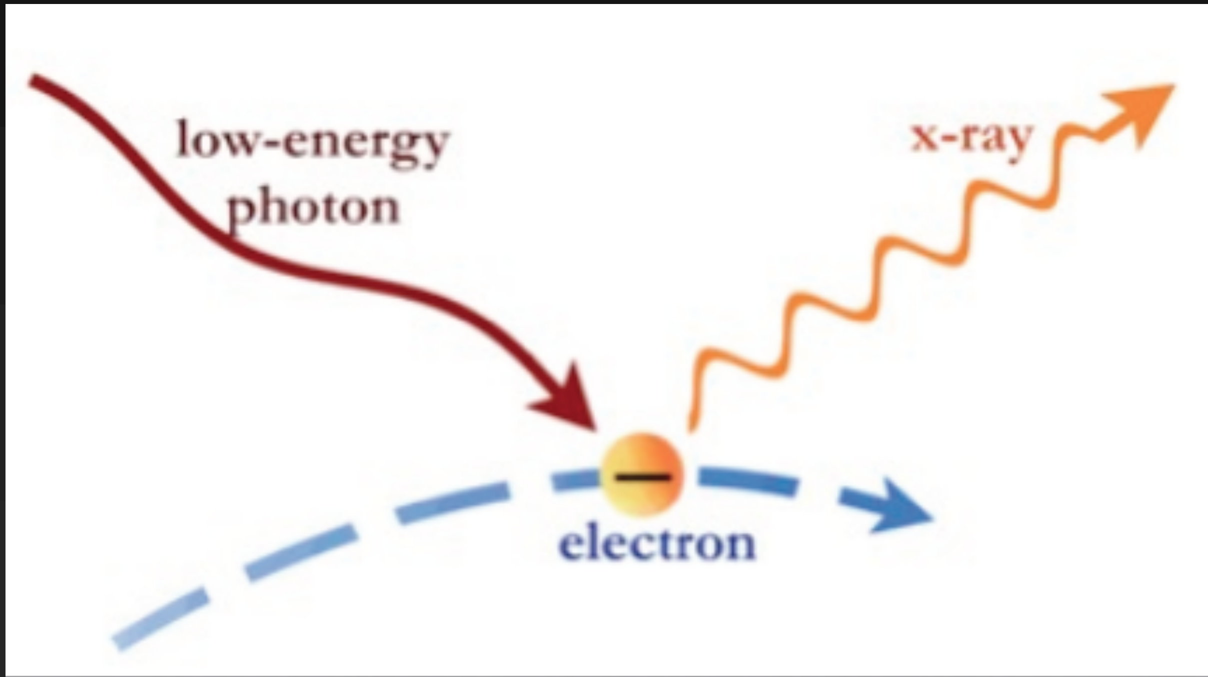

Emission from accreting BH

And, after a series of say N scattering events, the final photon energy will be

$$E_f \approx E_i \exp\left(N \frac{4kT_e}{m_e c^2} \right) \approx E_i \exp(y)$$

Which depends on the initial photon energy, on the electron temperature, and on the number of scattering events (basically function of the optical depth)

Inverse Compton is not effective anymore when the photon energy reaches ~ $4kT_e$ so that a high-energy cutoff is reached for this kind of energies (the electron temperature in the corona has to reach extremely high temperatures of the order of 10^8-10^9 K to explain the observed power law and cutoffs)

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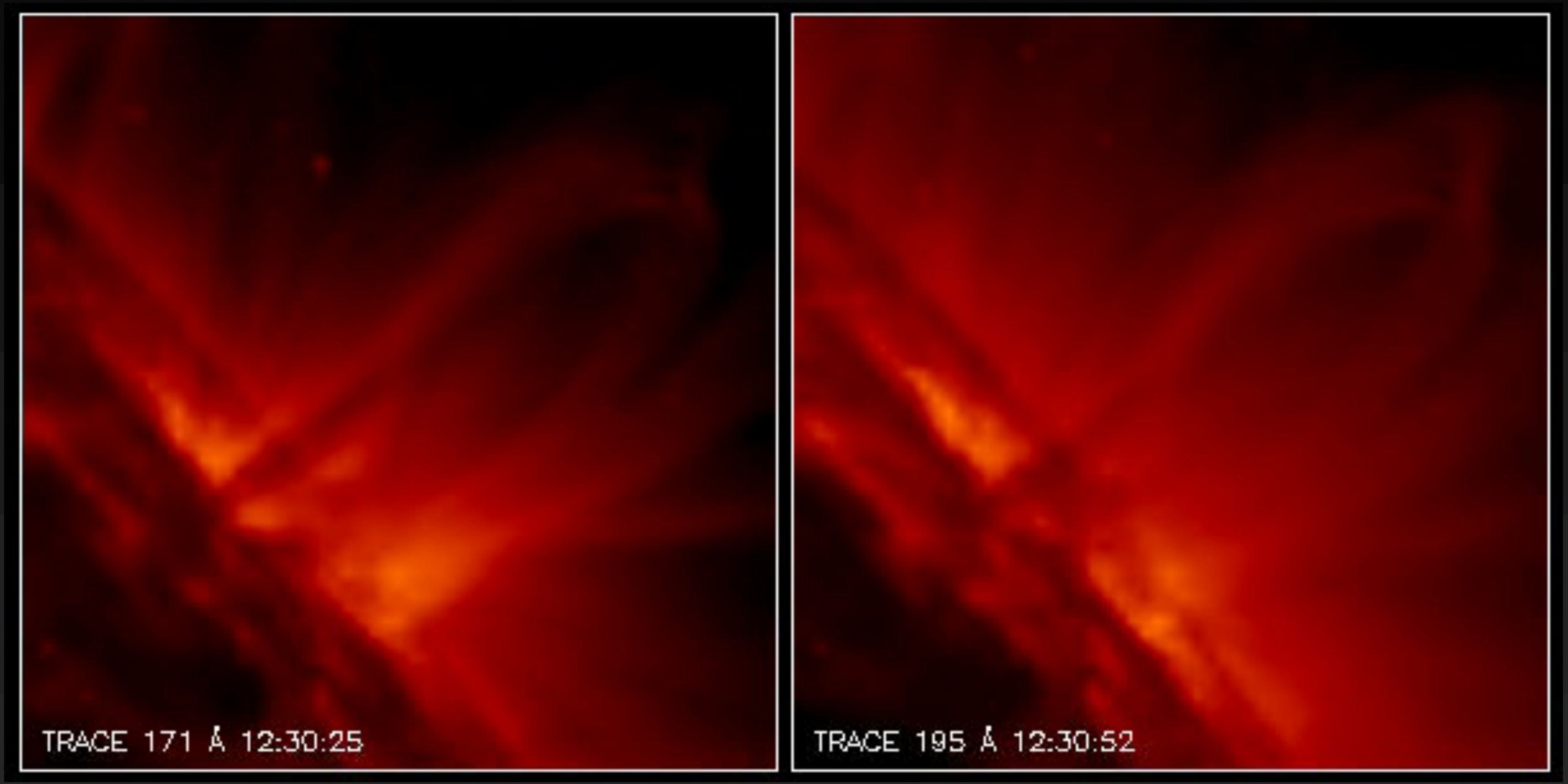
In analogy with the solar corona, magnetic fields are though to play a major role for heating the electron plasma up to such high temperatures

Emission from accreting BH



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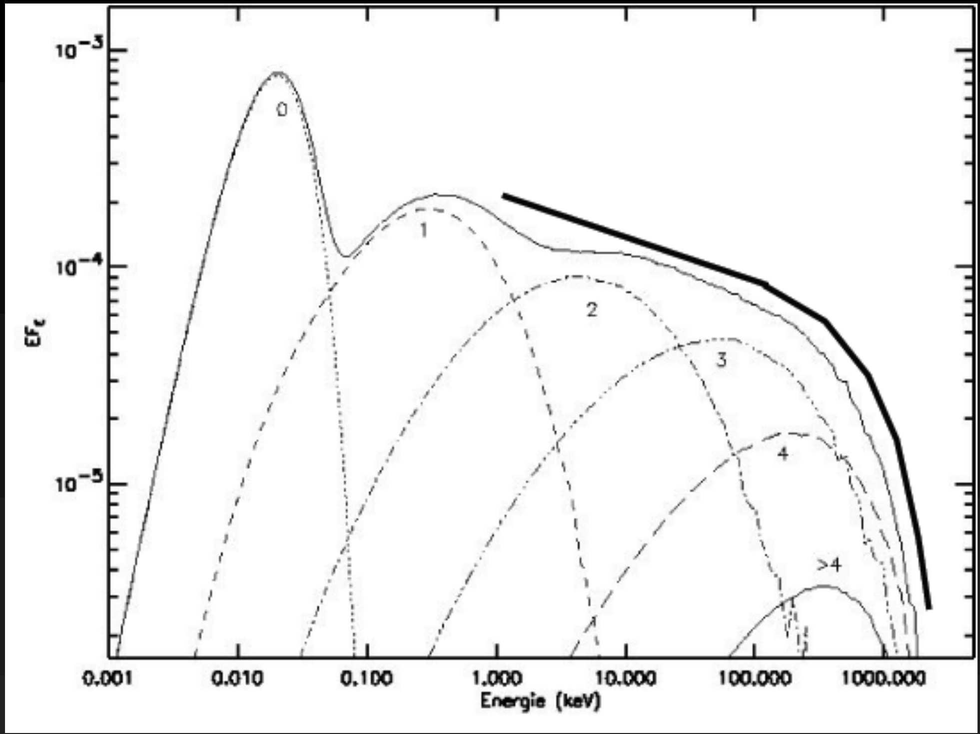

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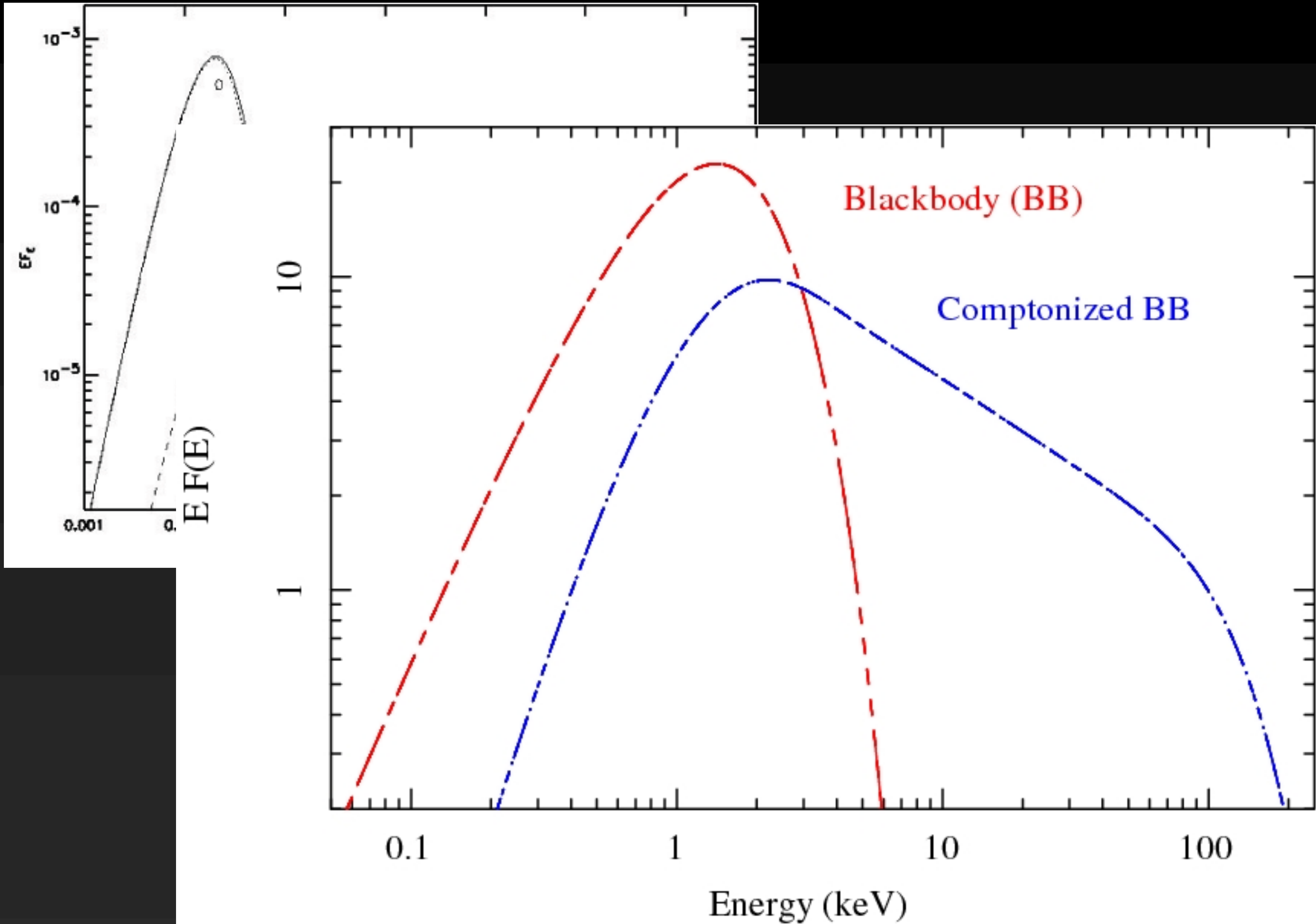
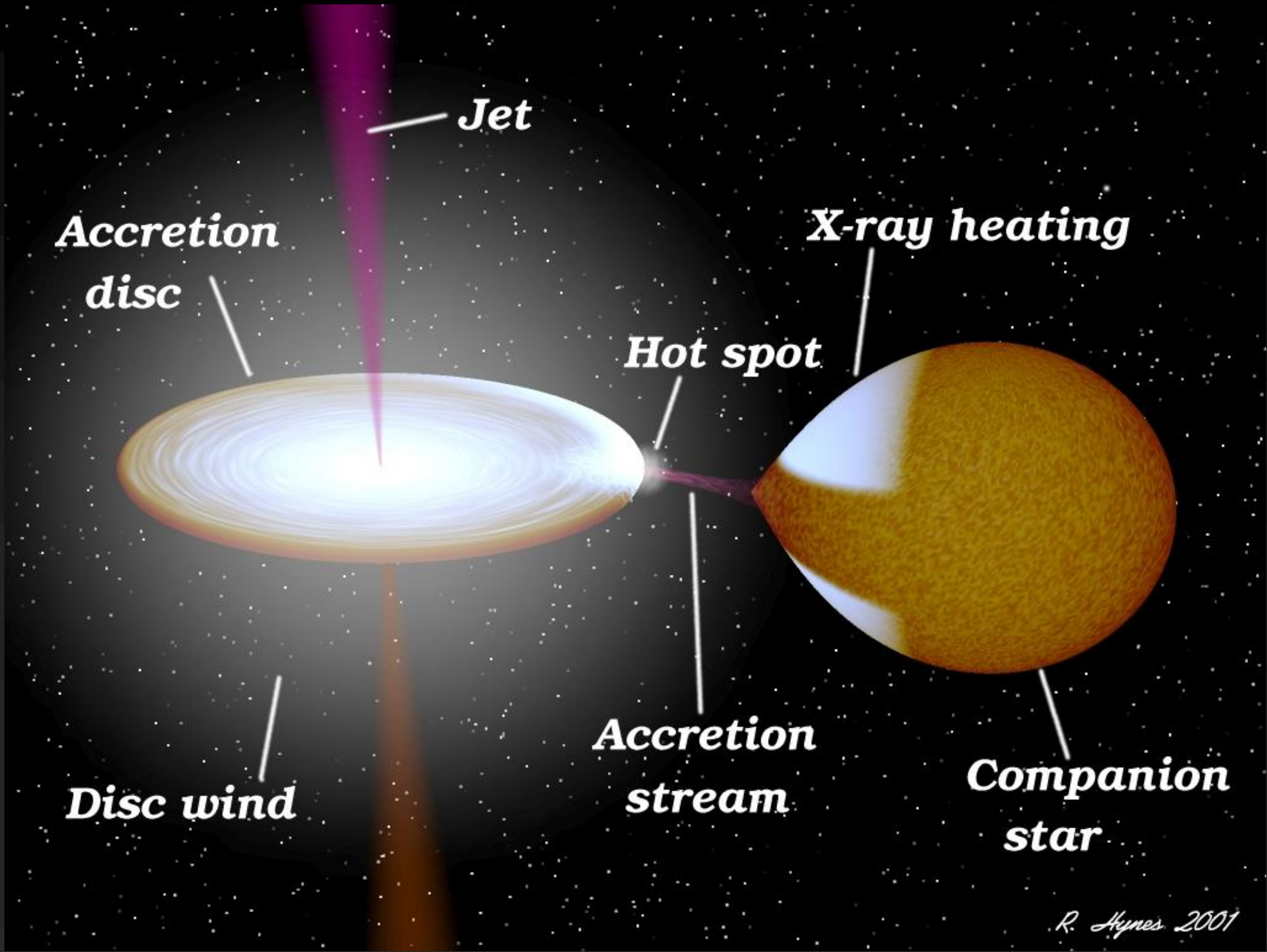


One application: measuring BH spin in BH X-ray binaries



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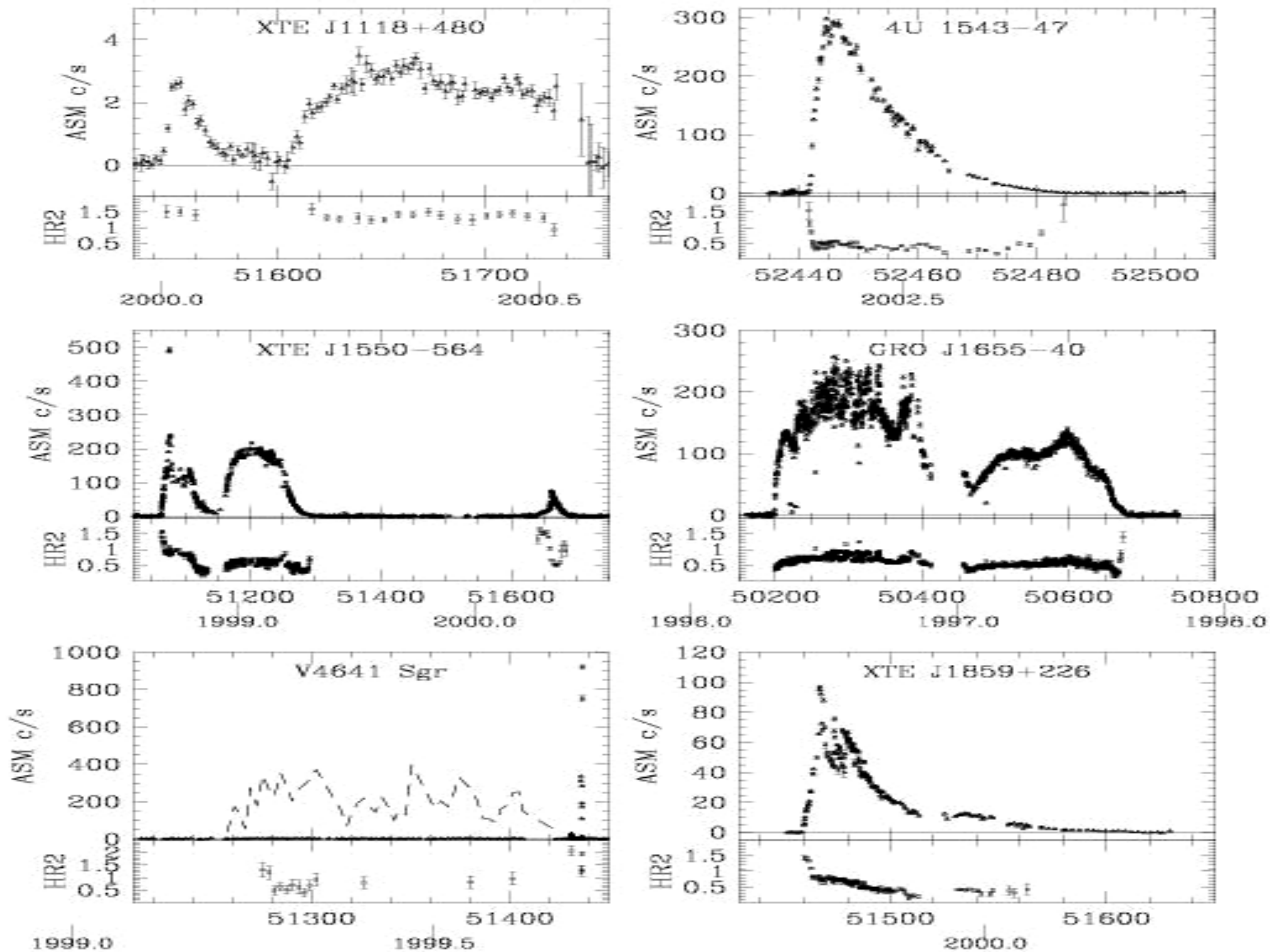
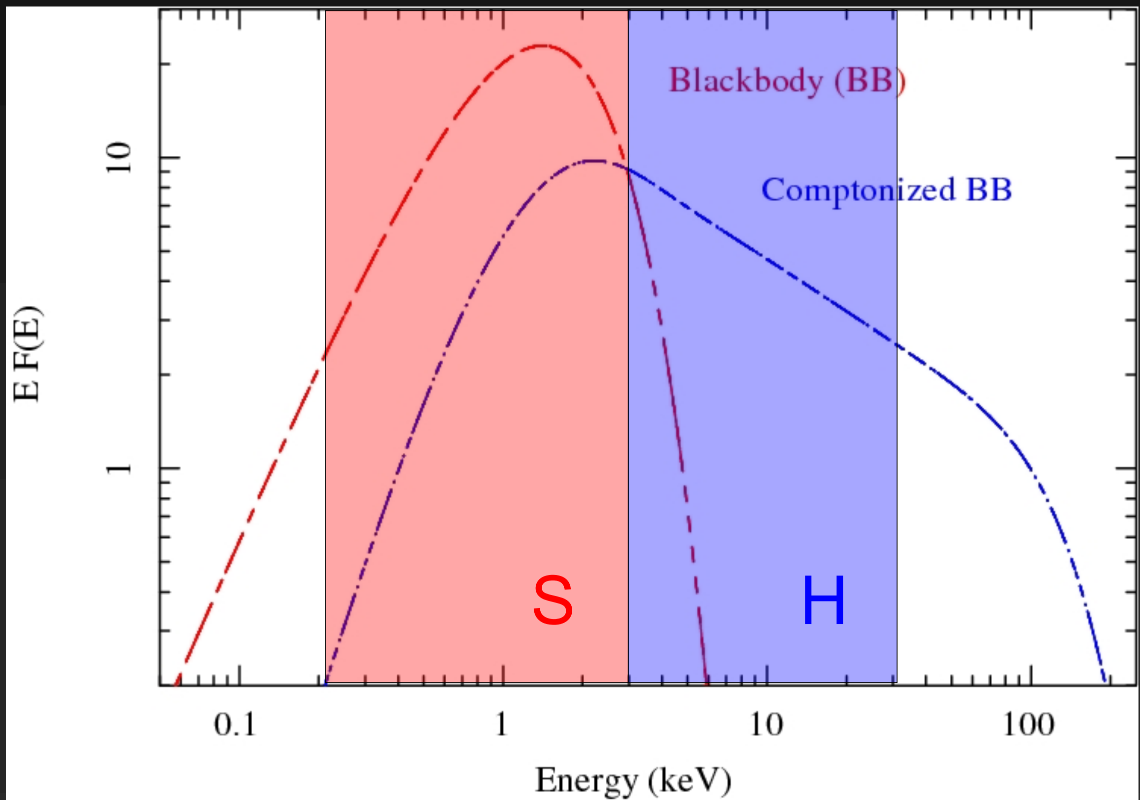


One application: measuring BH spin in BH X-ray binaries

During each outburst the X-ray spectra evolve with a rather complex phenomenology

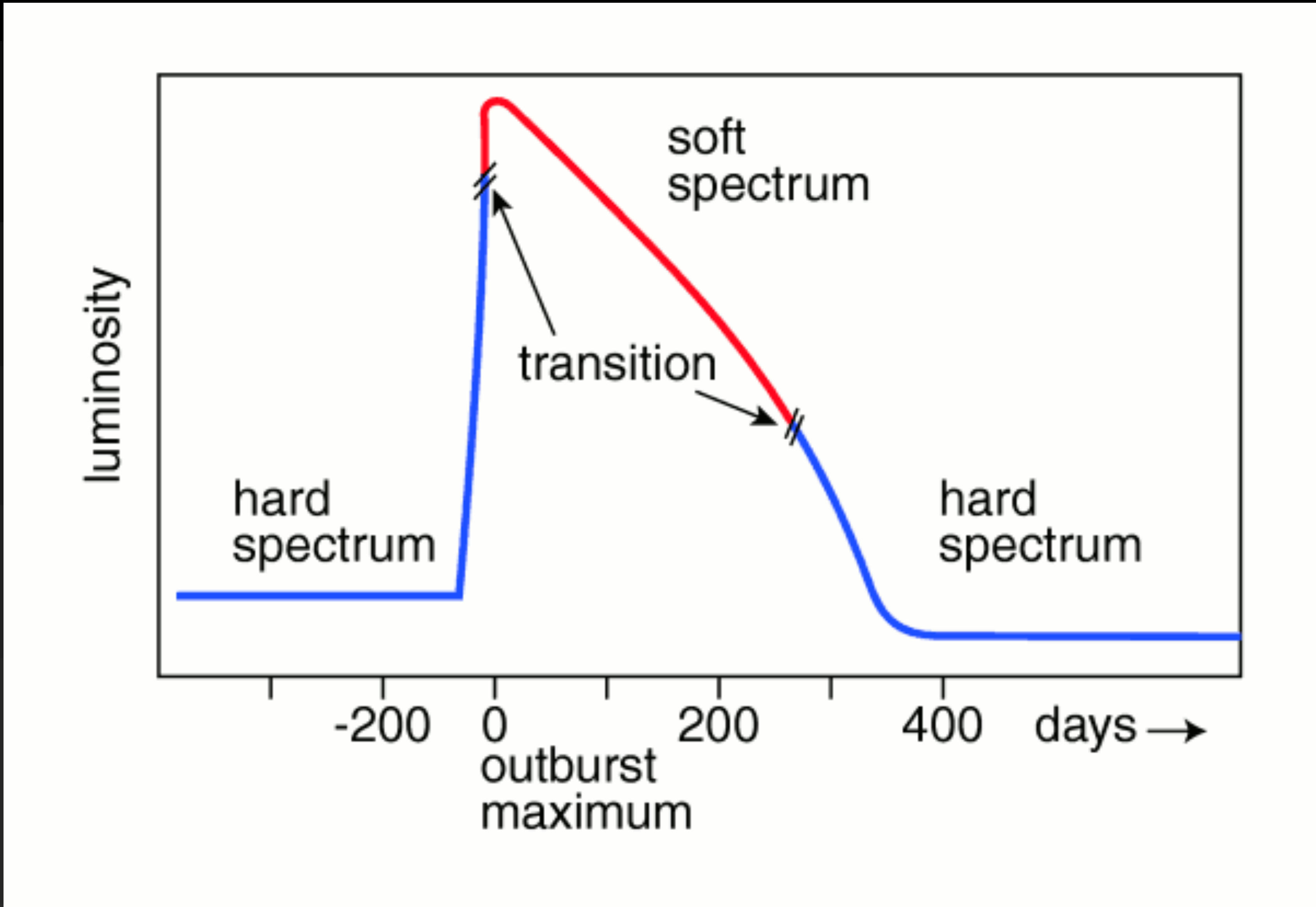
The X-ray spectrum can be roughly described in terms of hardness ratio H/S



Hard spectra are dominated by power law emission from the hot corona

Soft spectra are dominated by accretion disc BB emission

One application: measuring BH spin in BH X-ray binaries



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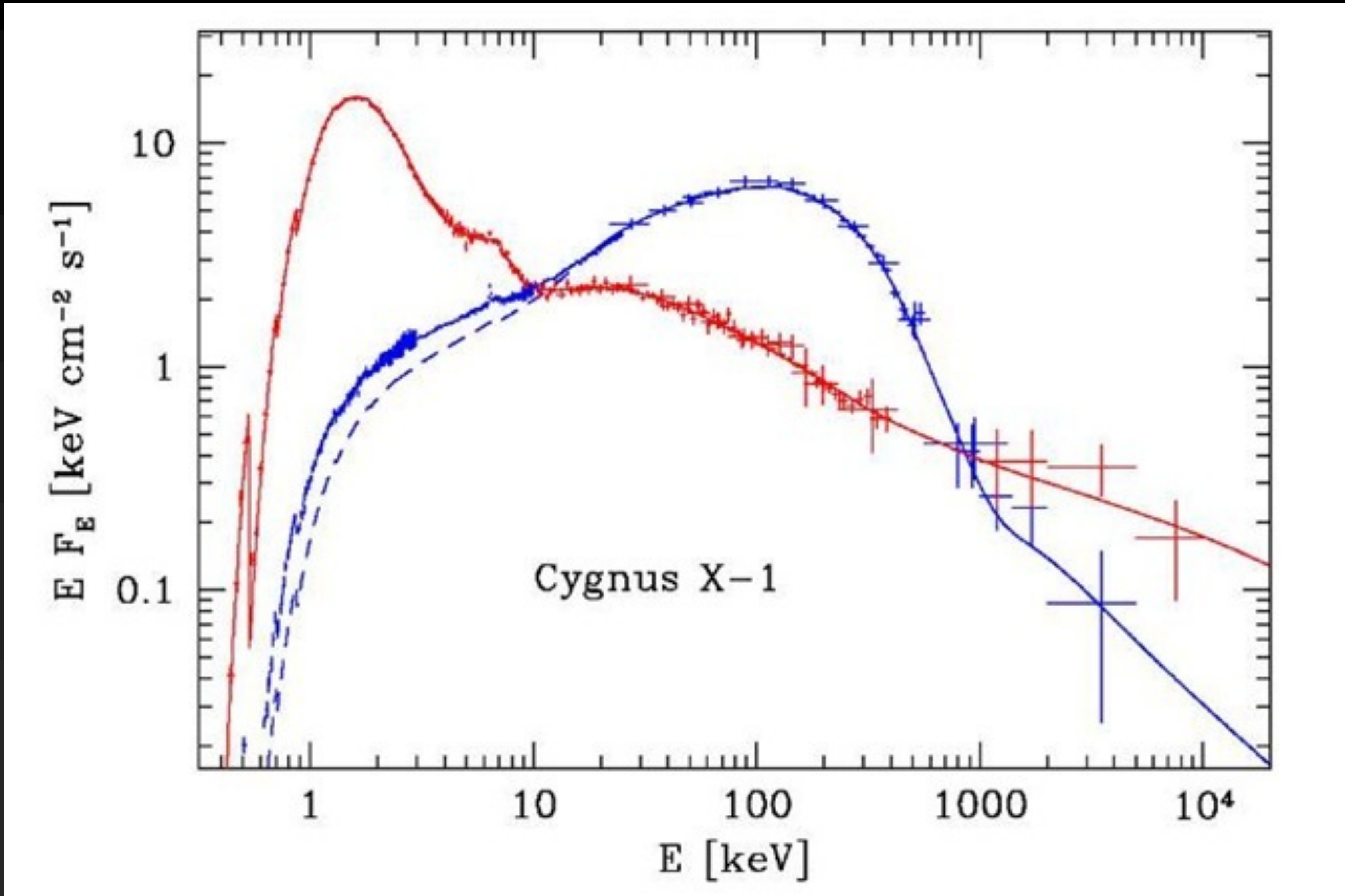

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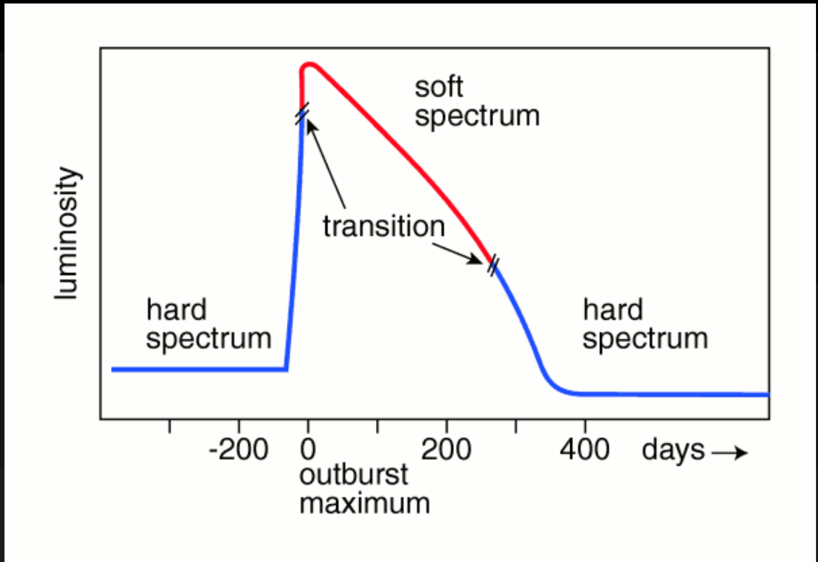
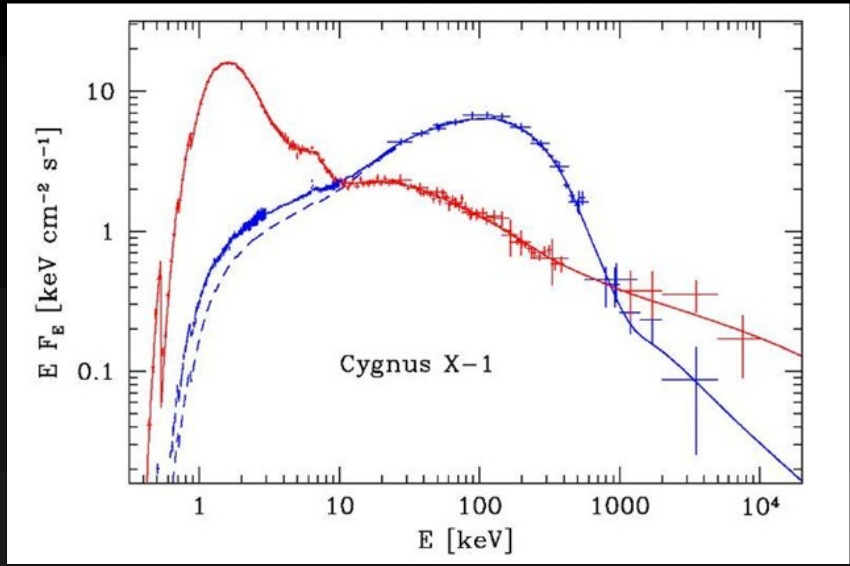
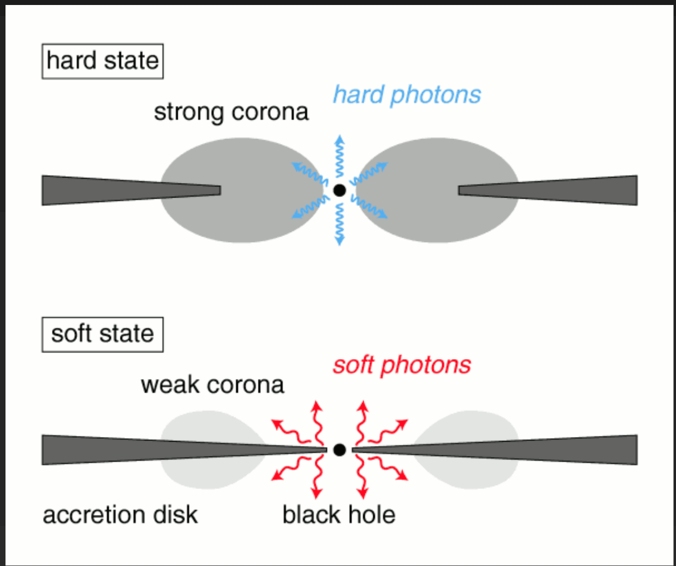
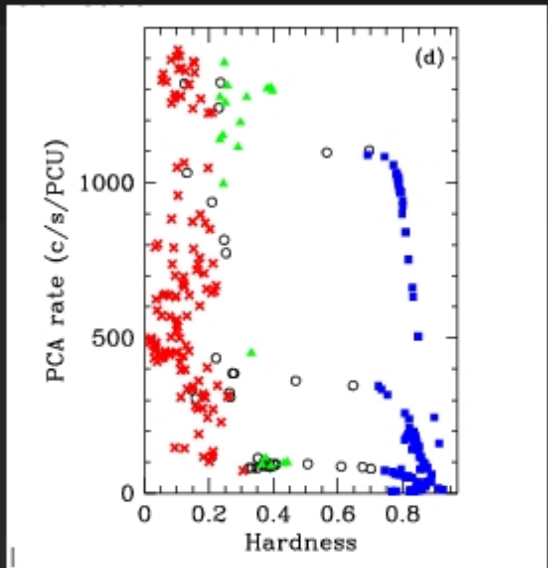


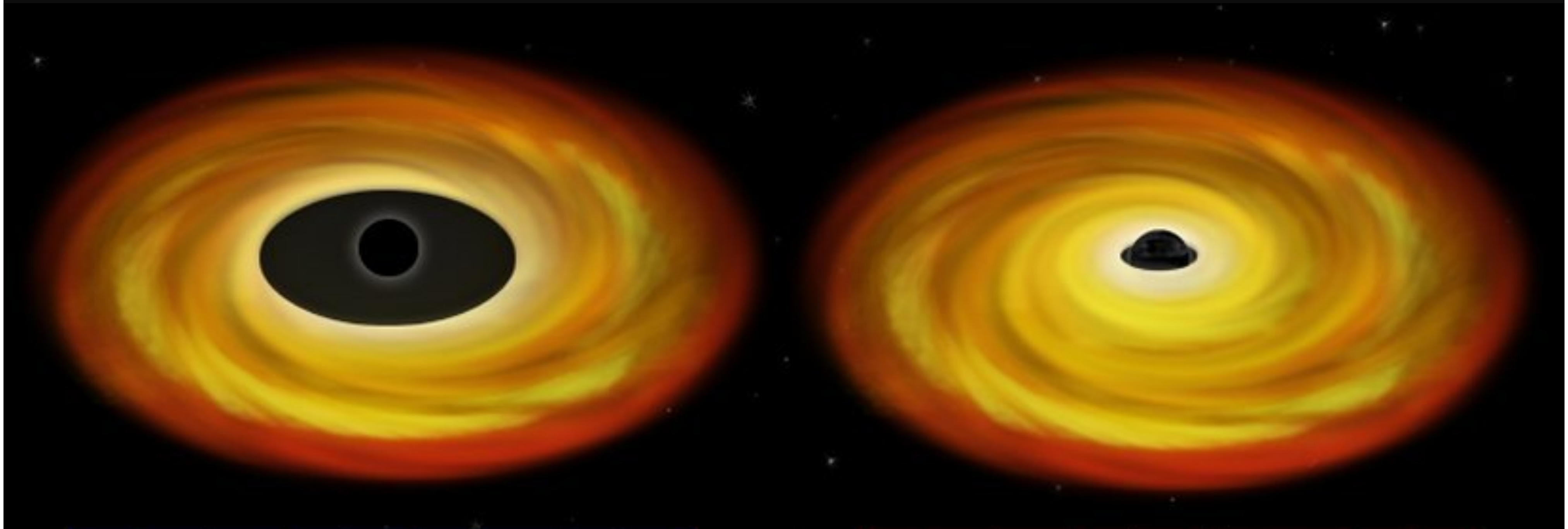






One application: measuring BH spin in BH X-ray binaries

When X-ray spectra are completely dominated by the thermal BB disc emission one can attempt to measure the BB area from the data



But the area depends on how close you can approach the BH along stable circular orbits, namely it depends on the ISCO ($=6r_g$ for a non-rotating Schwarzschild BH and $=1.24\ r_g$ for a maximally rotating Kerr one)

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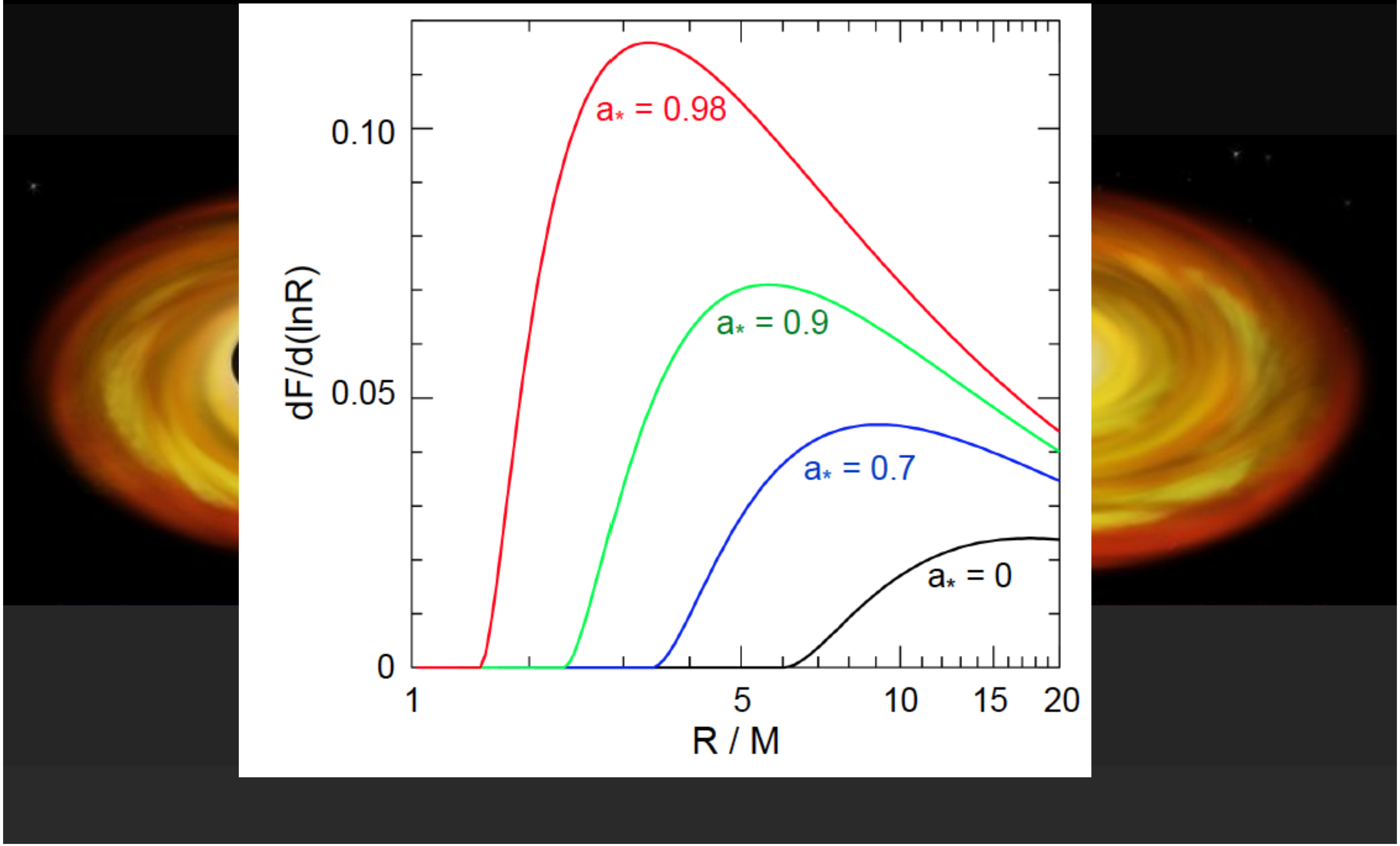

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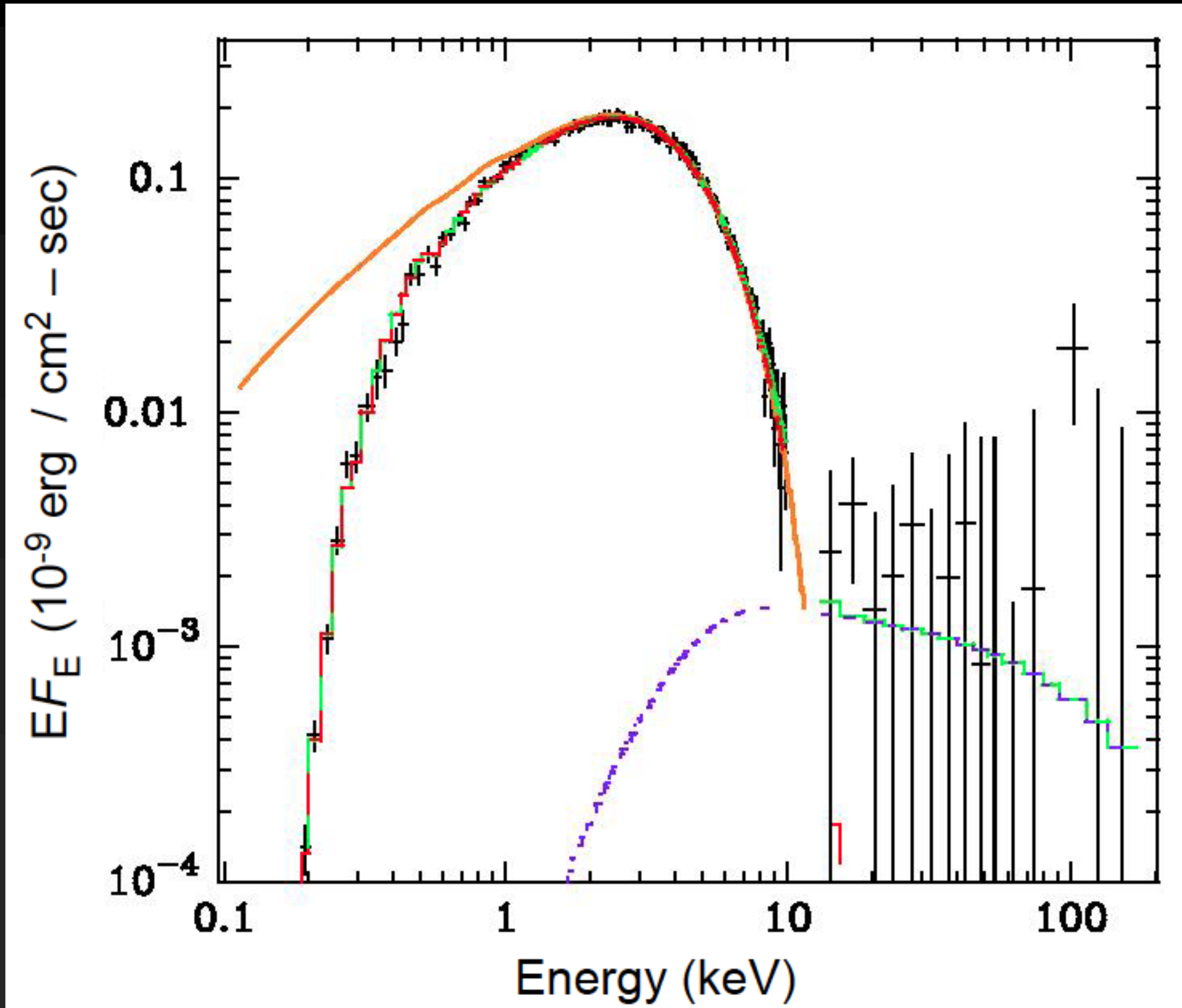
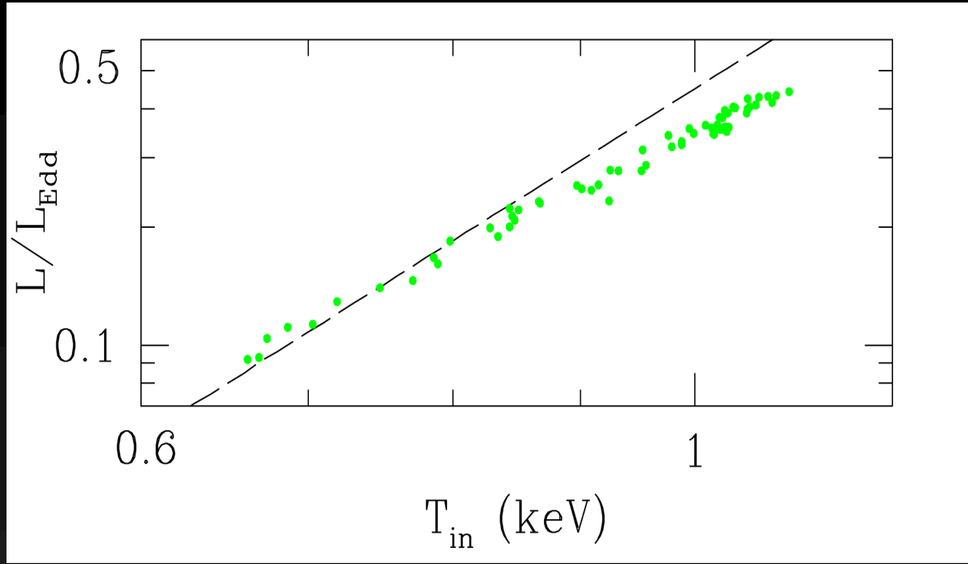


One application: measuring BH spin in BH X-ray binaries

In order to be sure to measure BB, one has to check that the BB luminosity scales as T^4

Well … not really at high T



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In order to be sure to measure BB, one has to check that the BB luminosity scales as T^4

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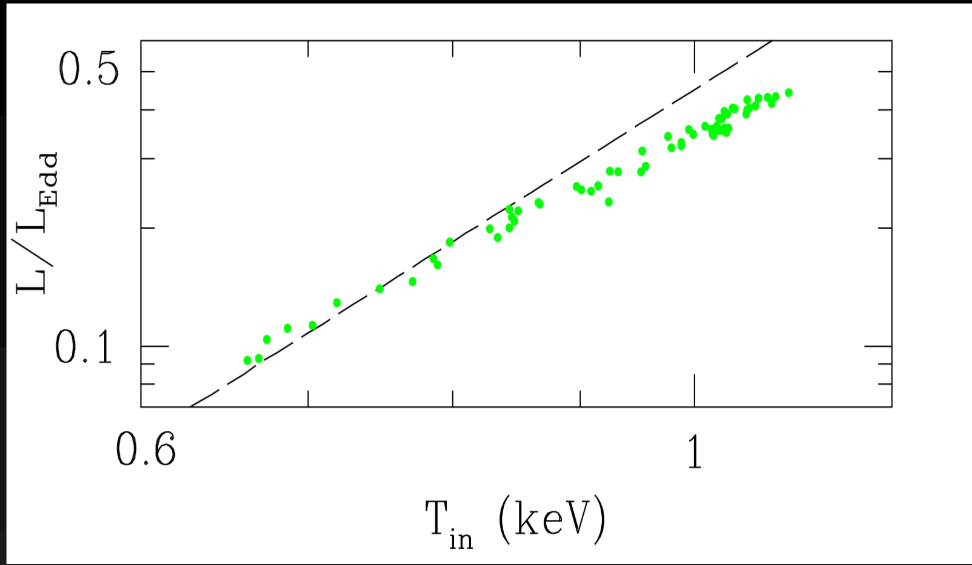
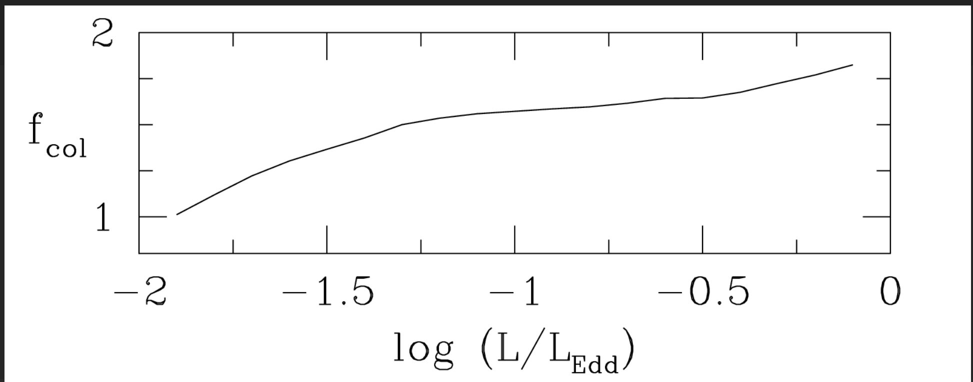
This is however expected and it is the result of electron scattering which can be corrected for by introducing the so-called color correction factor (a corrections that depends on the luminosity)





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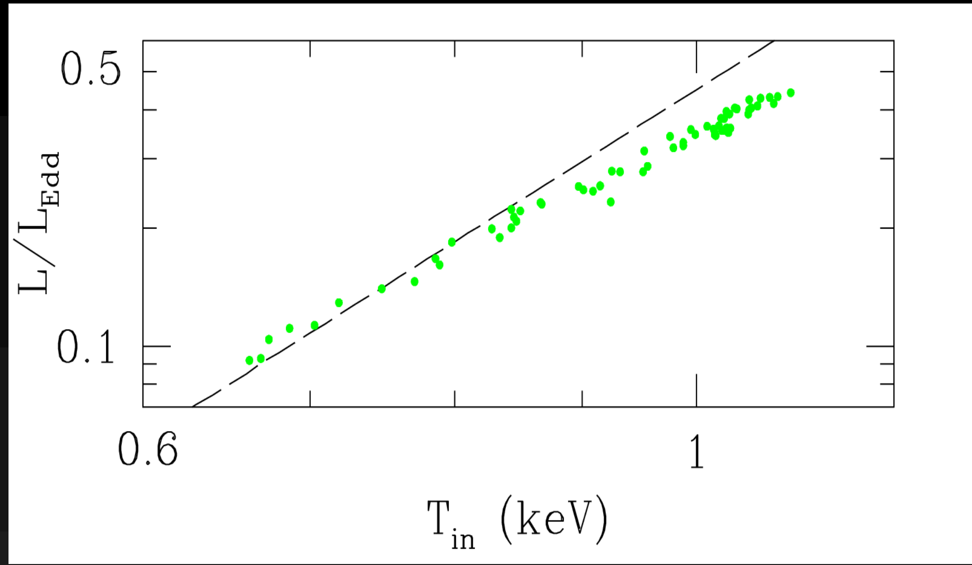

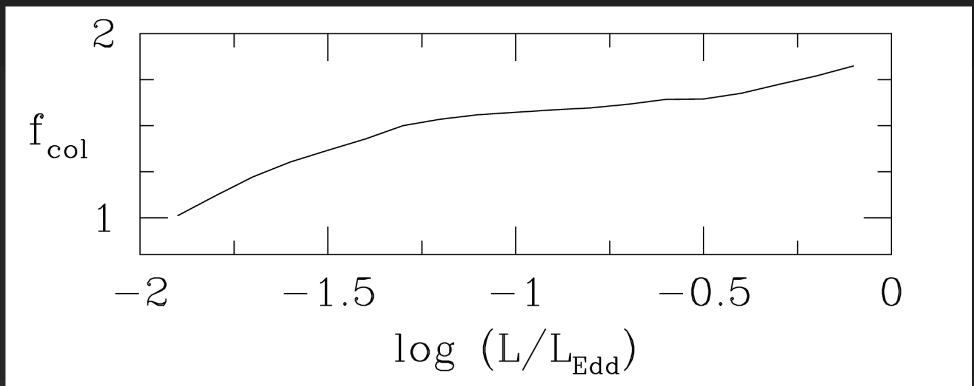

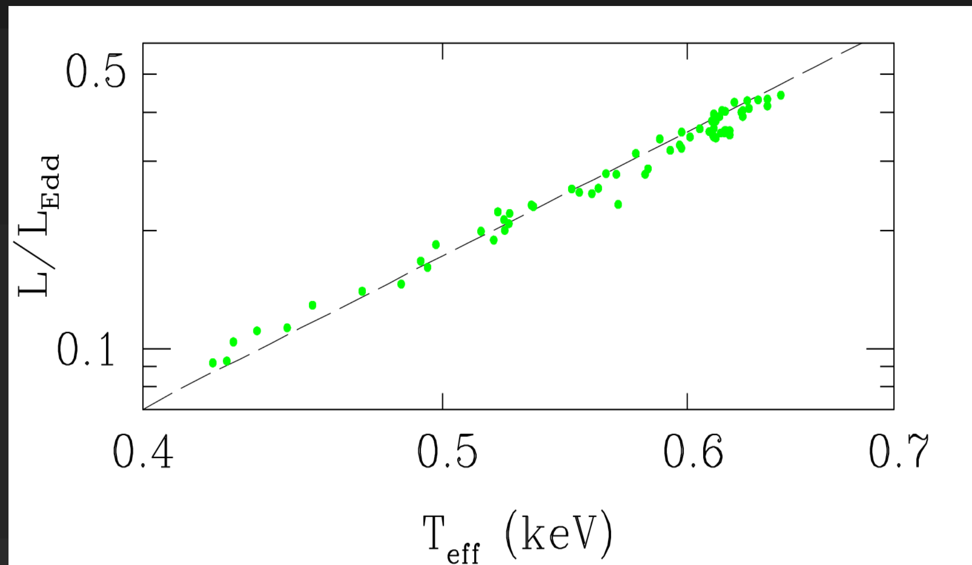

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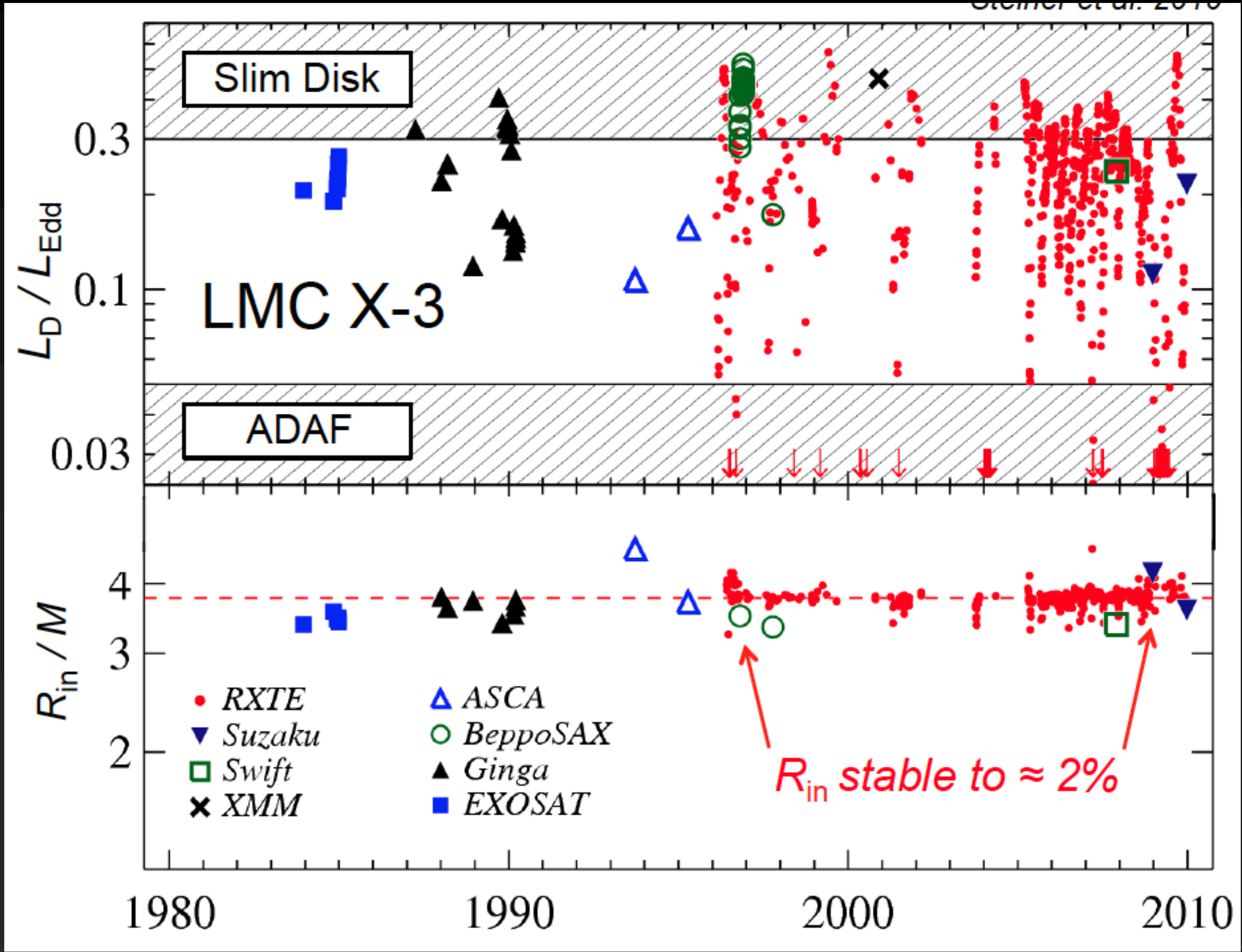

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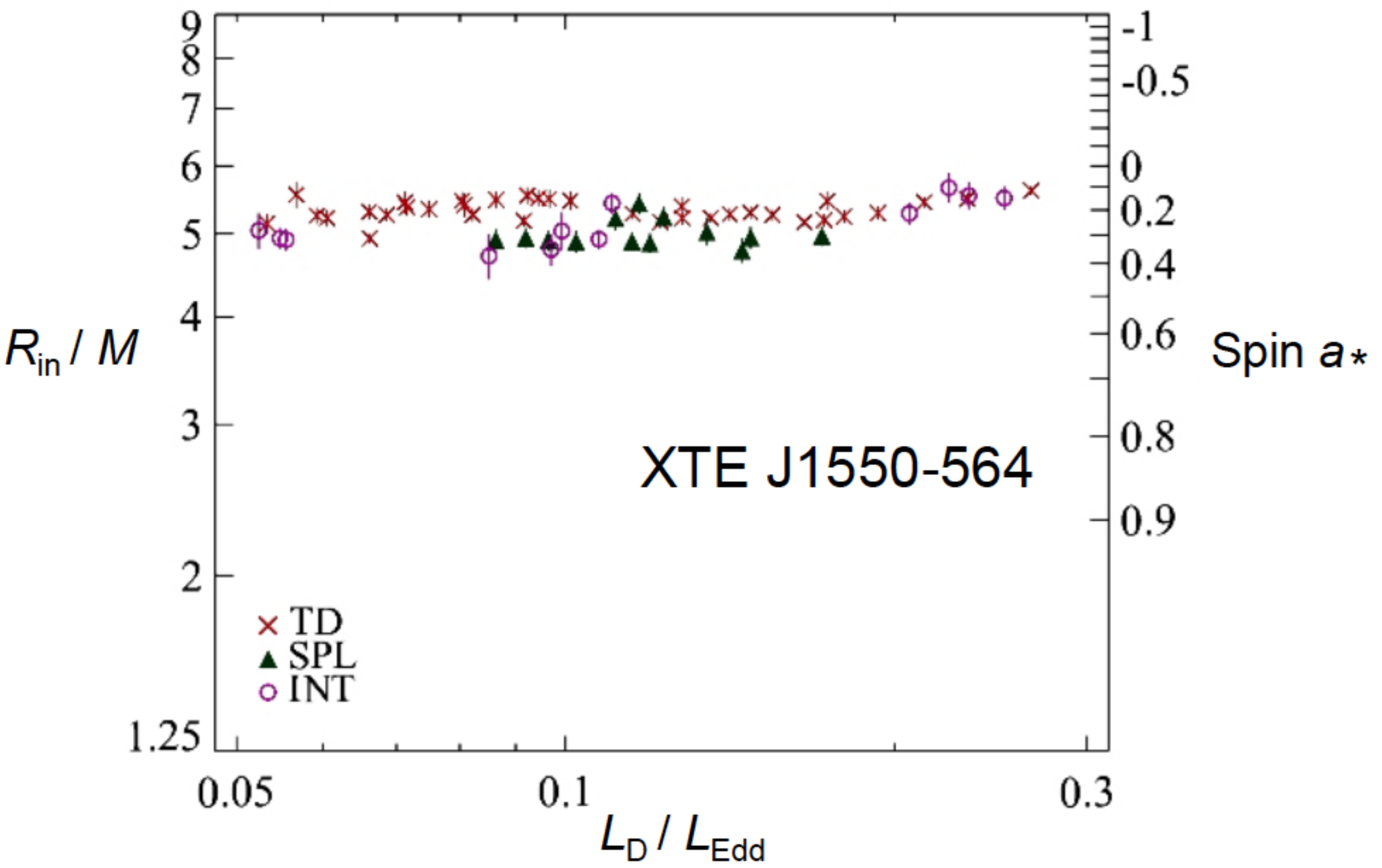
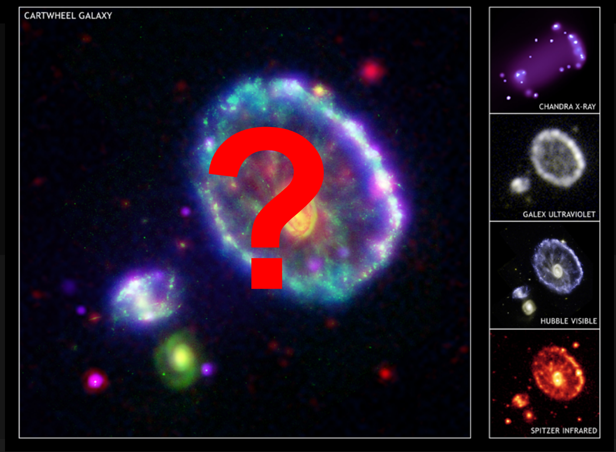


One application: measuring BH spin in BH X-ray binaries

System	Spin a_*	$M/M_\odot$	Reference
Persistent			
Cygnus X-1	> 0.95	15.8 ± 1.0	Gou+ 2011; Orosz+ 2011
LMC X-1	0.92 ± 0.06	10.9 ± 1.4	Gou+ 2009; Orosz+ 2009
M33 X-7	0.84 ± 0.05	15.7 ± 1.5	Liu+ 2008; Orosz+ 2007
Transient			
GRS 1915+105	> 0.95	10.1 ± 0.6	McClintock+ 2006; Steeghs+ 2013
4U 1543-47	0.8 ± 0.1	9.4 ± 1.0	Shafee+ 2006; Orosz+ 2003
GRO J1655-40	0.7 ± 0.1	6.3 ± 0.5	Shafee+ 2006; Greene+ 2001
XTE J1550-564	0.34 ± 0.24	9.1 ± 0.6	Steiner+ 2011; Orosz+ 2011
LMC X-3	< 0.3	7.6 ± 1.6	Davis+ 2006; Cowley+ 1983
H1743-322	0.2 ± 0.3	≈ 8	Steiner+ 2012; Ozel+ 2010
A0620-00	0.12 ± 0.19	6.6 ± 0.3	Gou+ 2010; Cantrell+ 2010

What about IMBHs ? Do they really exist ?



Intermediate-mass ($10^2 – 10^4$ solar masses)
A new class of recently-discovered black holes could have masses on the order of hundreds or thousands of stars although the debate is open [ULX ?]

ULXs are X-ray sources that are found off the nuclei of other galaxies (i.e. they are not associated with central SMBHs) and exceed the Eddington limit for 10-20 M_{sun} accreting BHs

$$L_{Edd} \cong 1.3 \times 10^{38} \left(\frac{M}{M_{Sun}} \right) erg/s$$

ULXs are off-axis X-ray sources with L > 10^{39}-10^{40} erg/s

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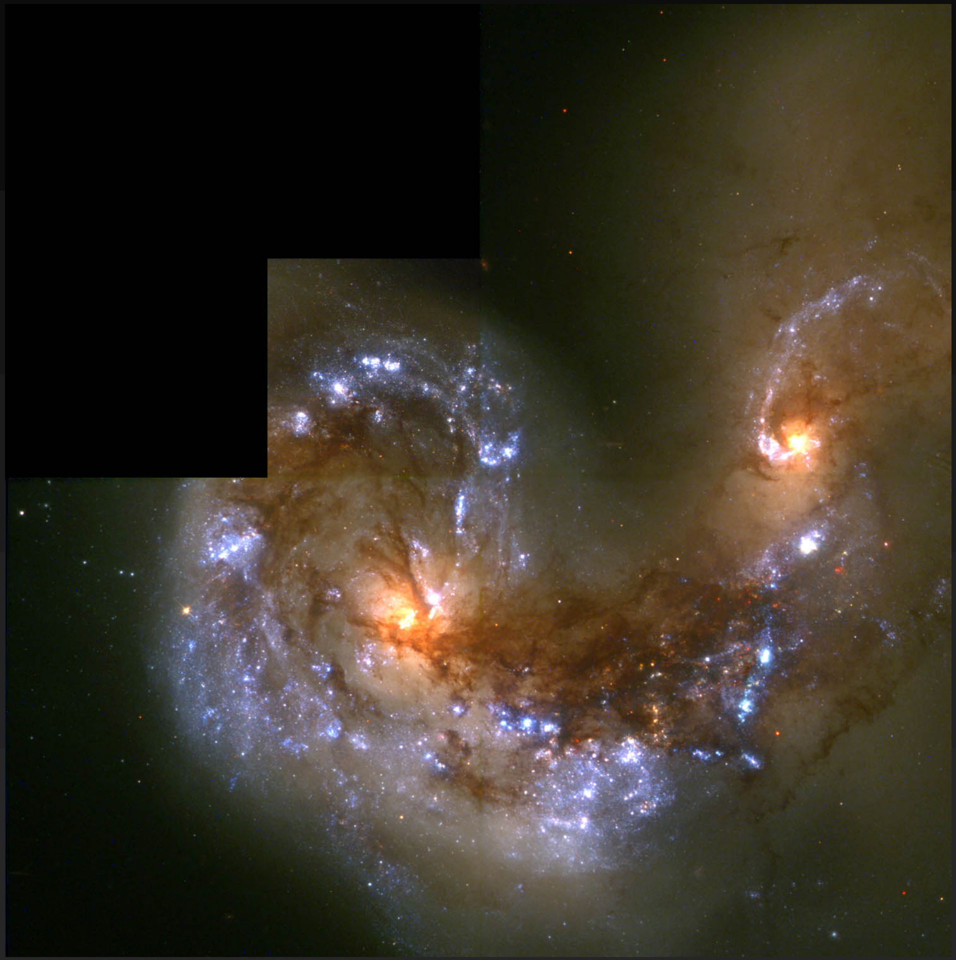

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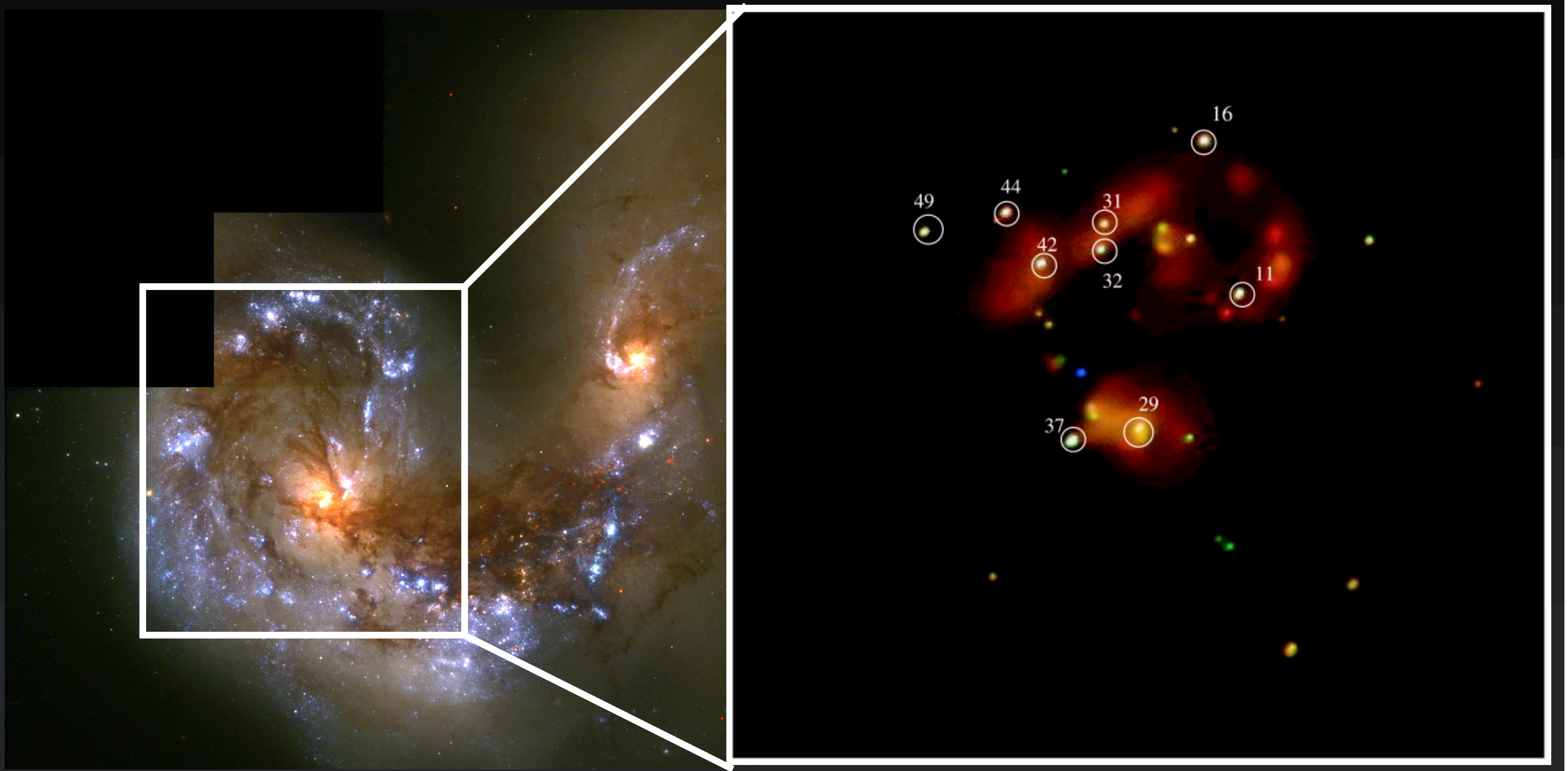

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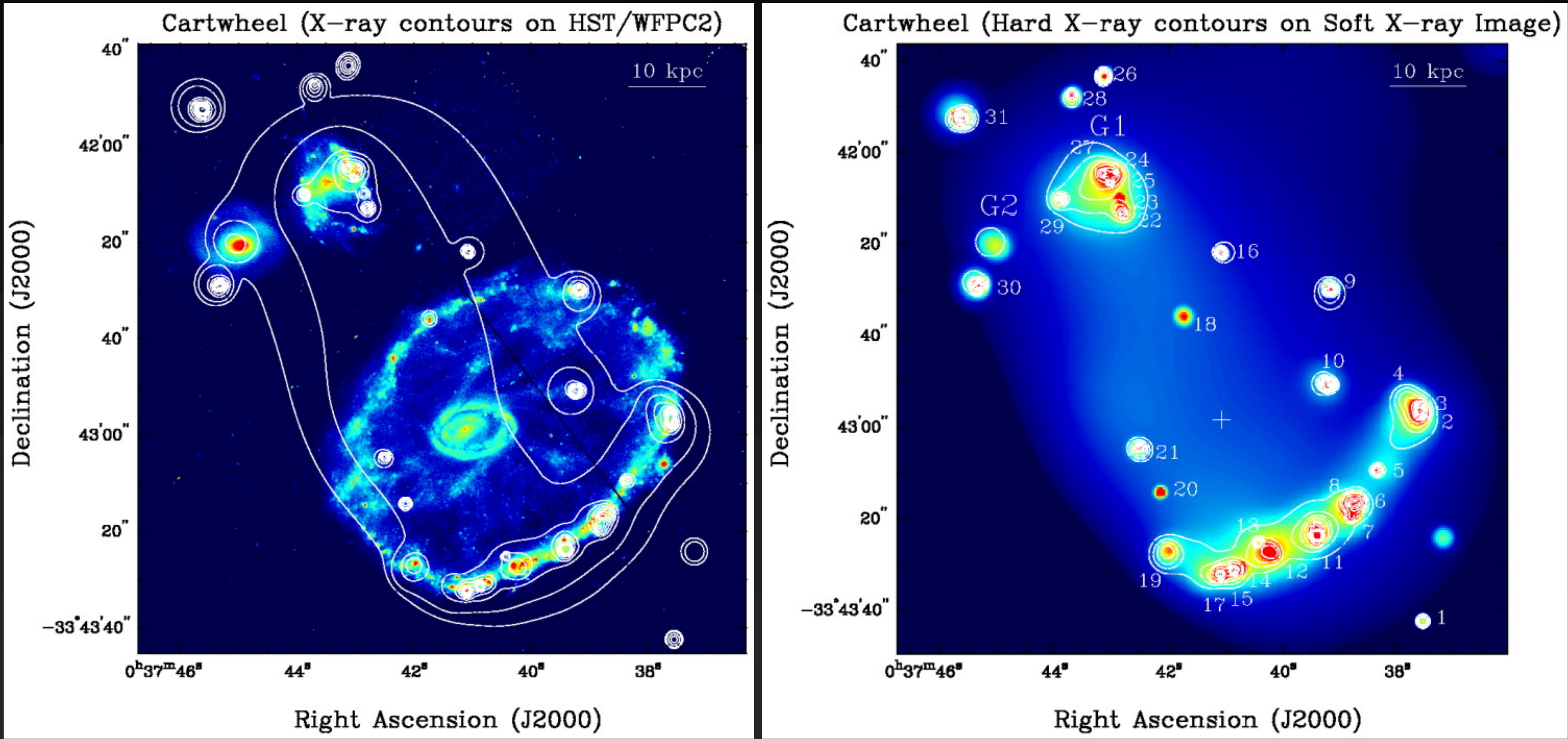

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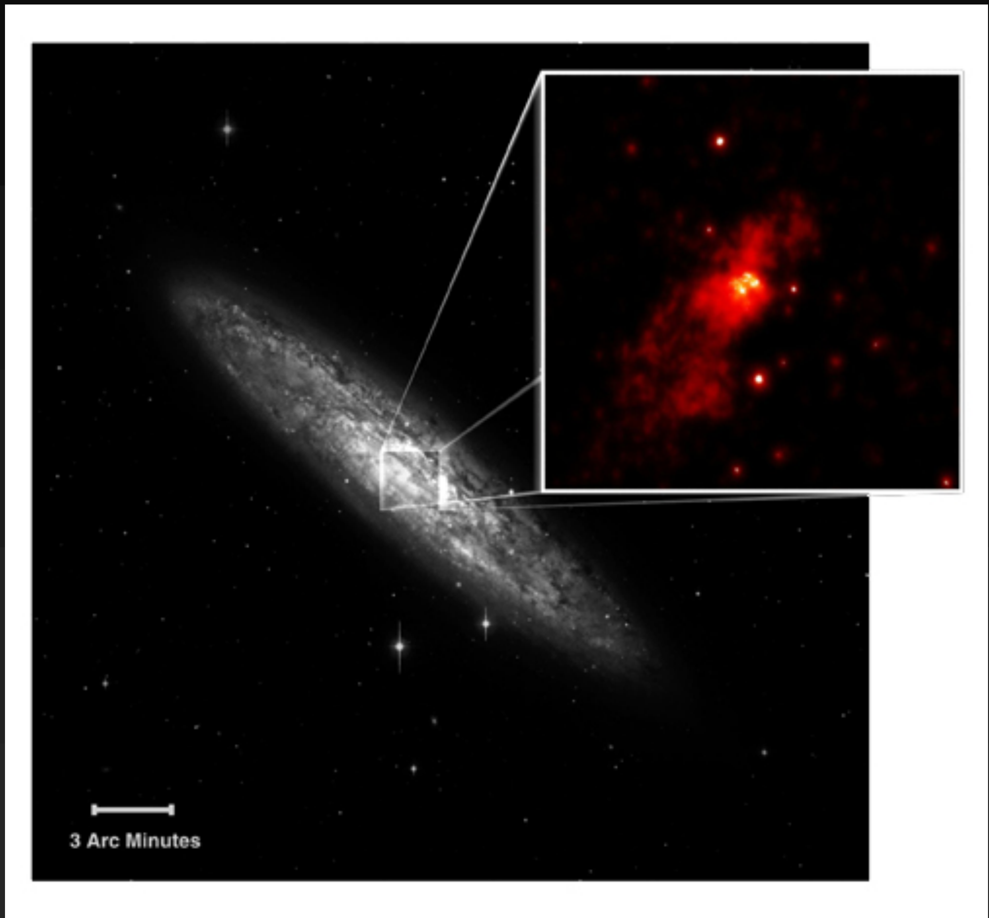
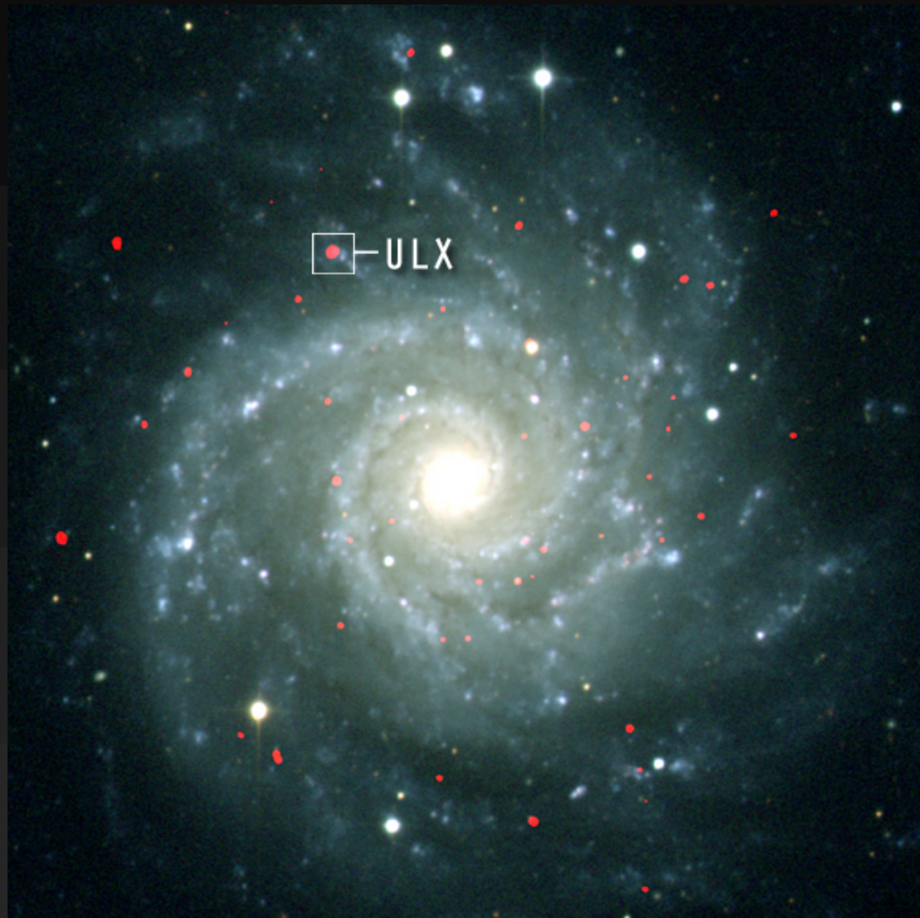
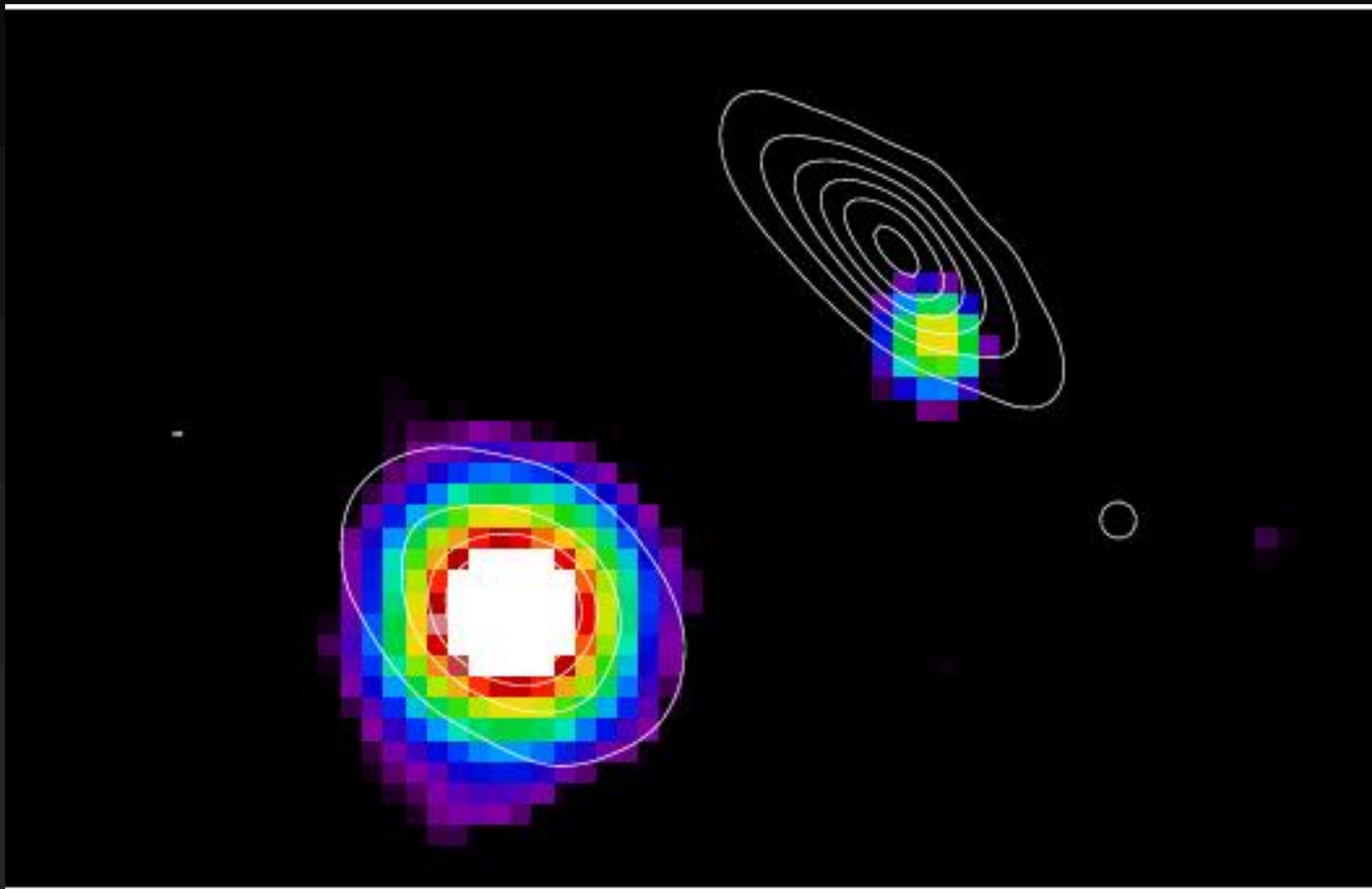




What about IMBHs ? Do they really exist ?

Detection and methods



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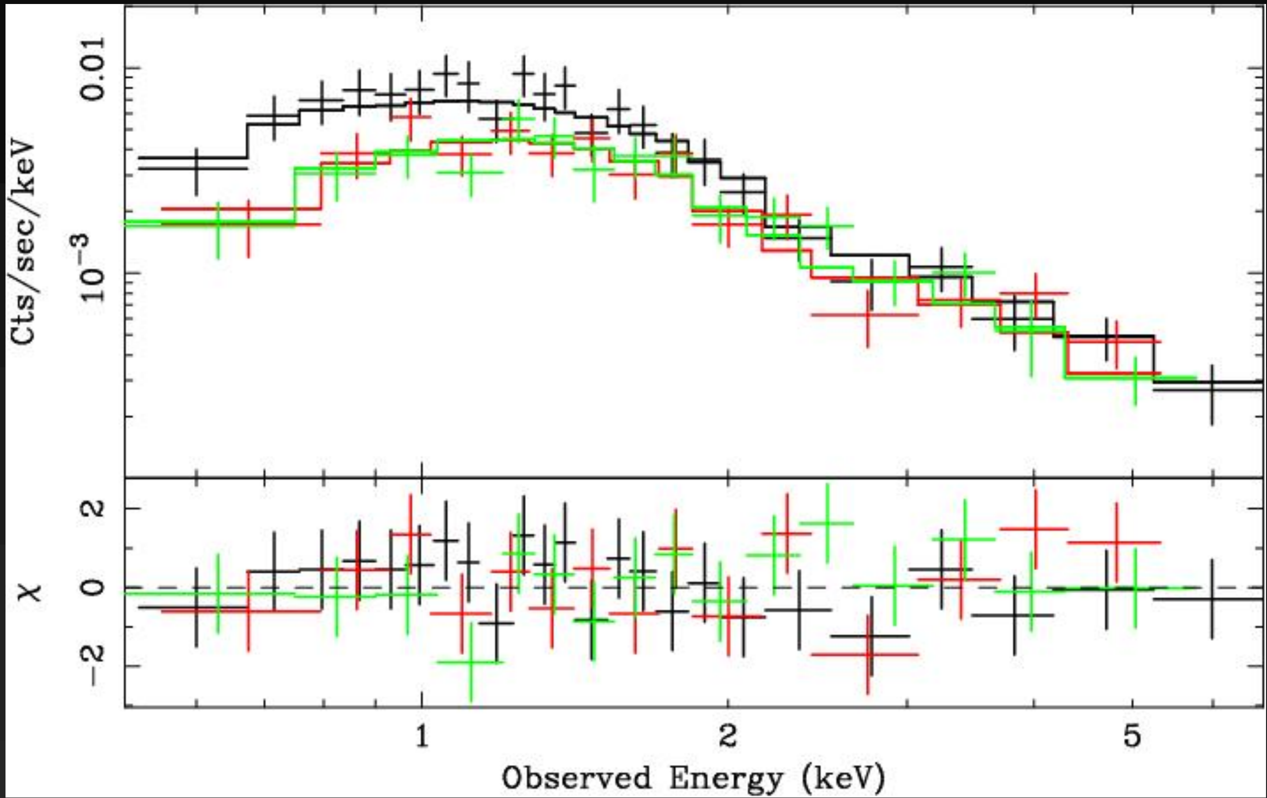
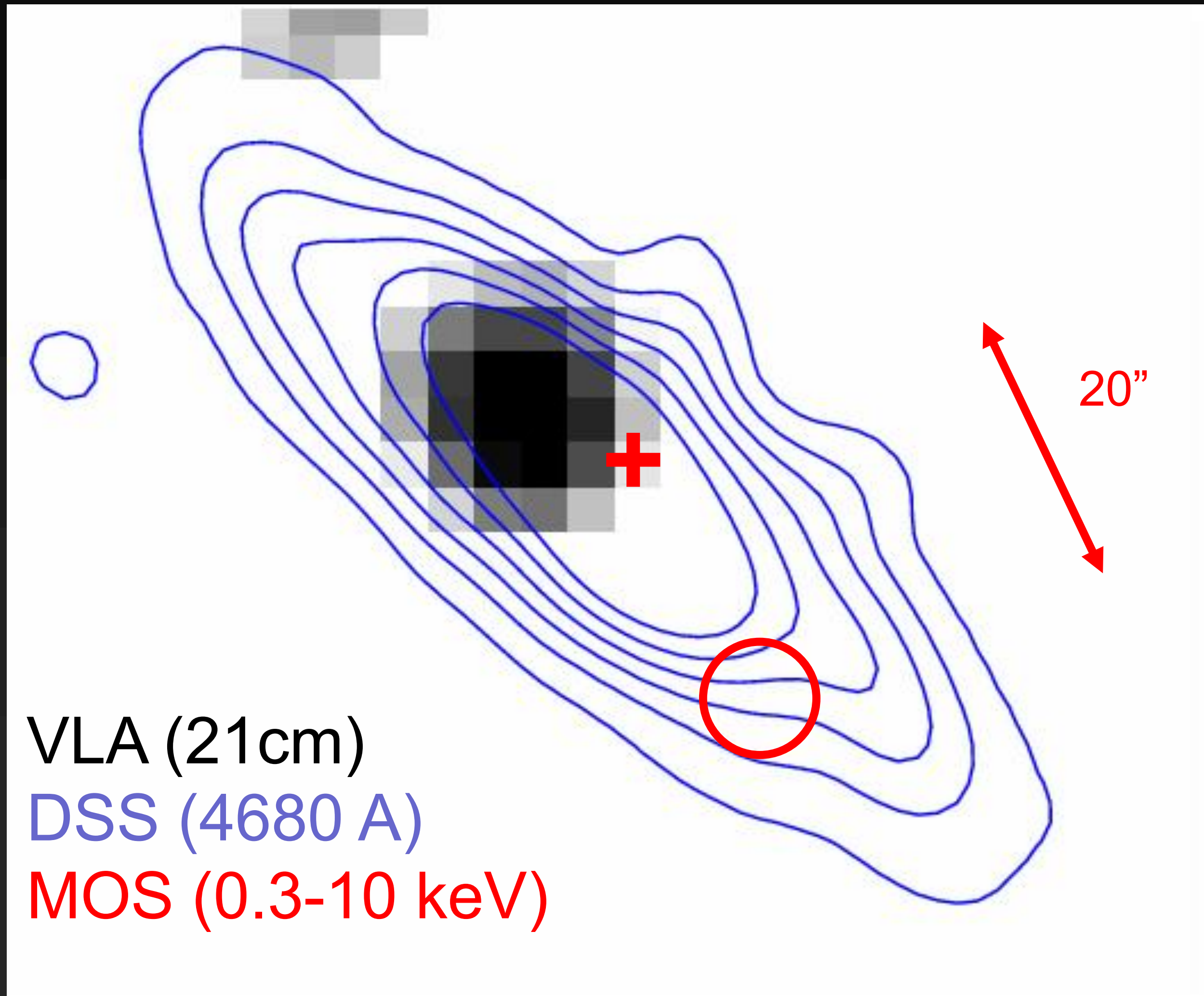


$L_X \sim 2.3\text{x}10^{41}$ erg/s and since $L_{Edd} \sim 1.3\text{x}10^{38}$ erg/s (M/M_{sun})
very simplistic arguments would imply a BH with mass $M_{BH} > 2300\ M_{sun}$

This however assumes the distance of the apparent host: z info is crucial

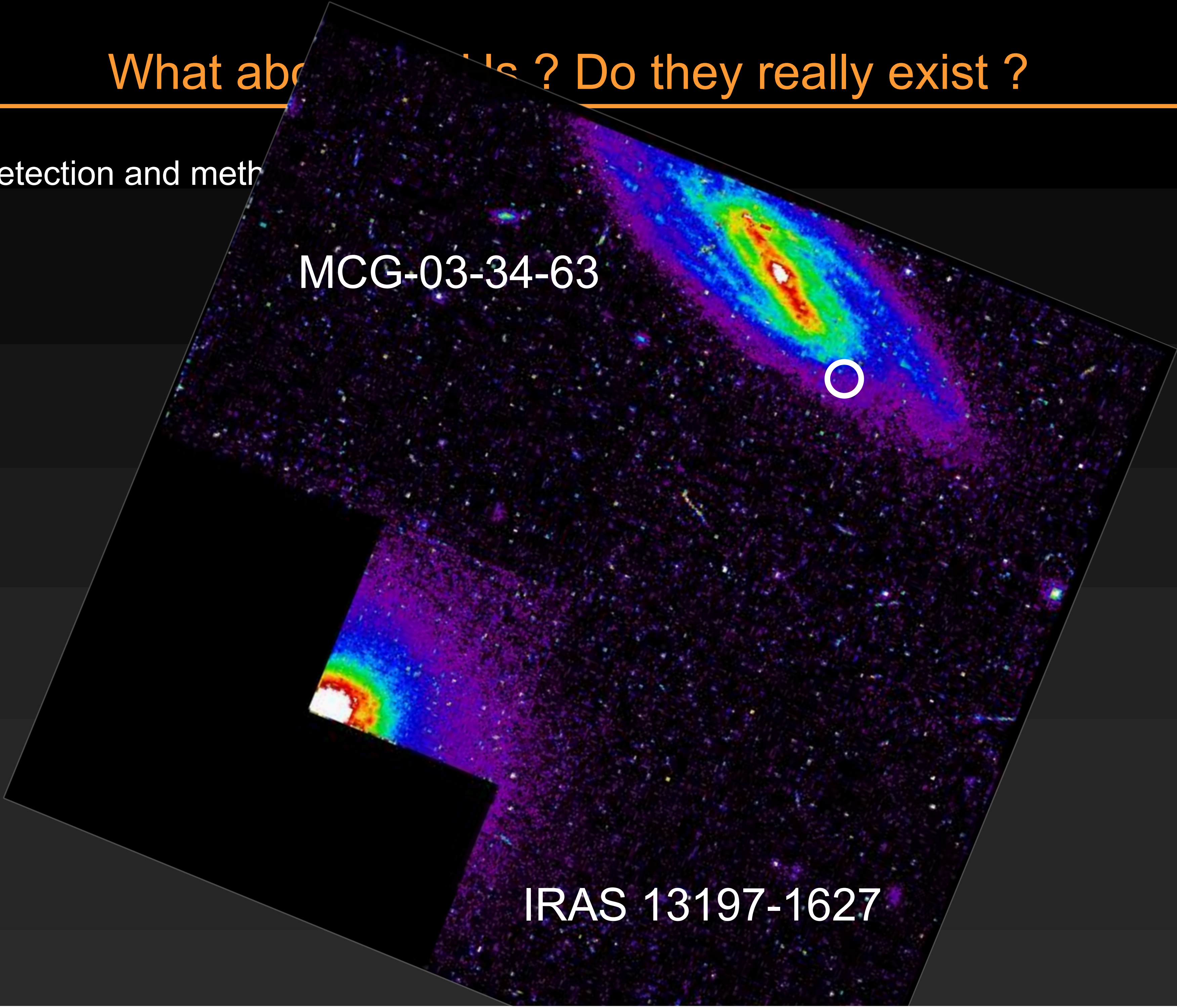
What about IMBHs ? Do they really exist ?

Detection and methods



What abo… ULXs ? Do they really exist ?

Detection and meth…



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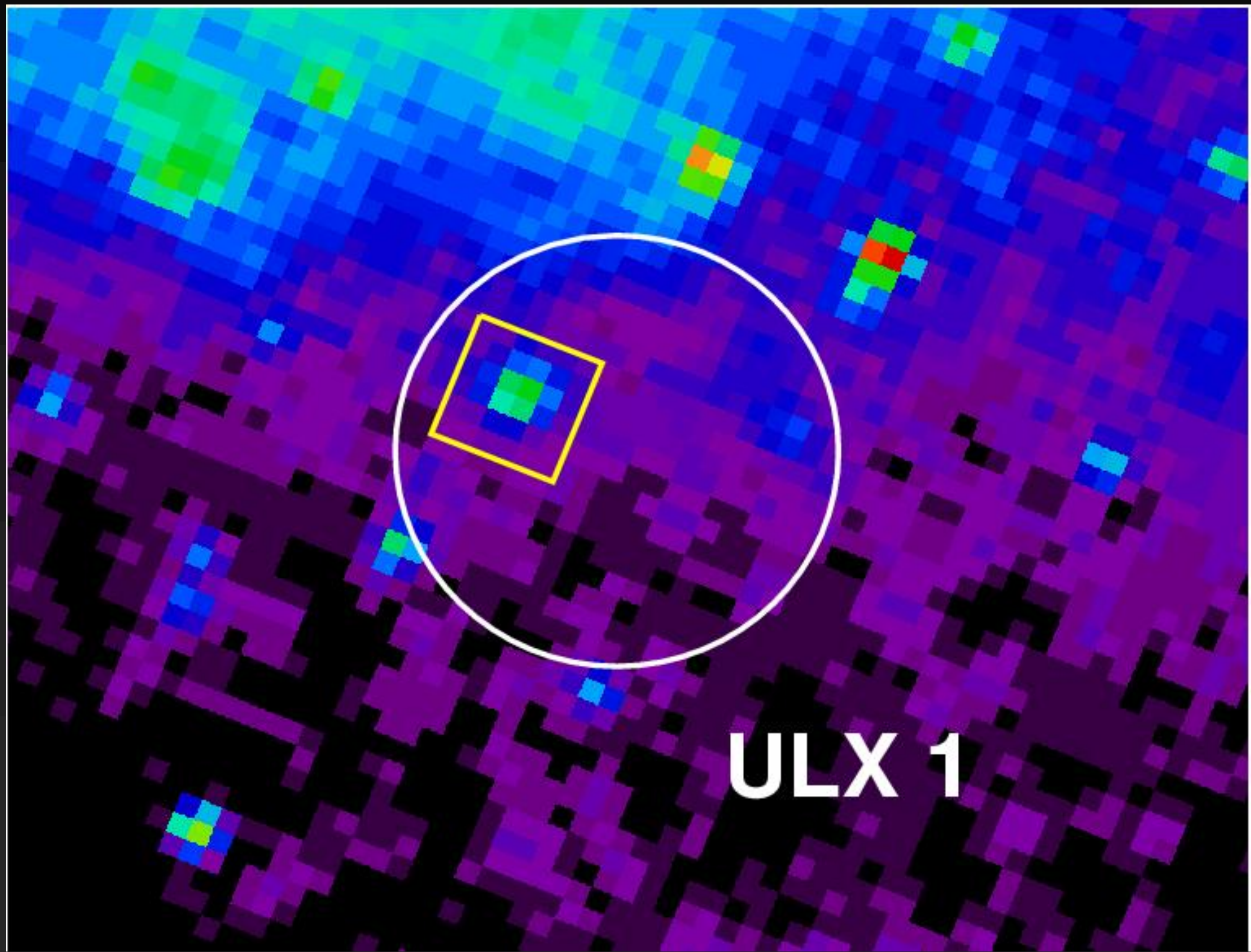
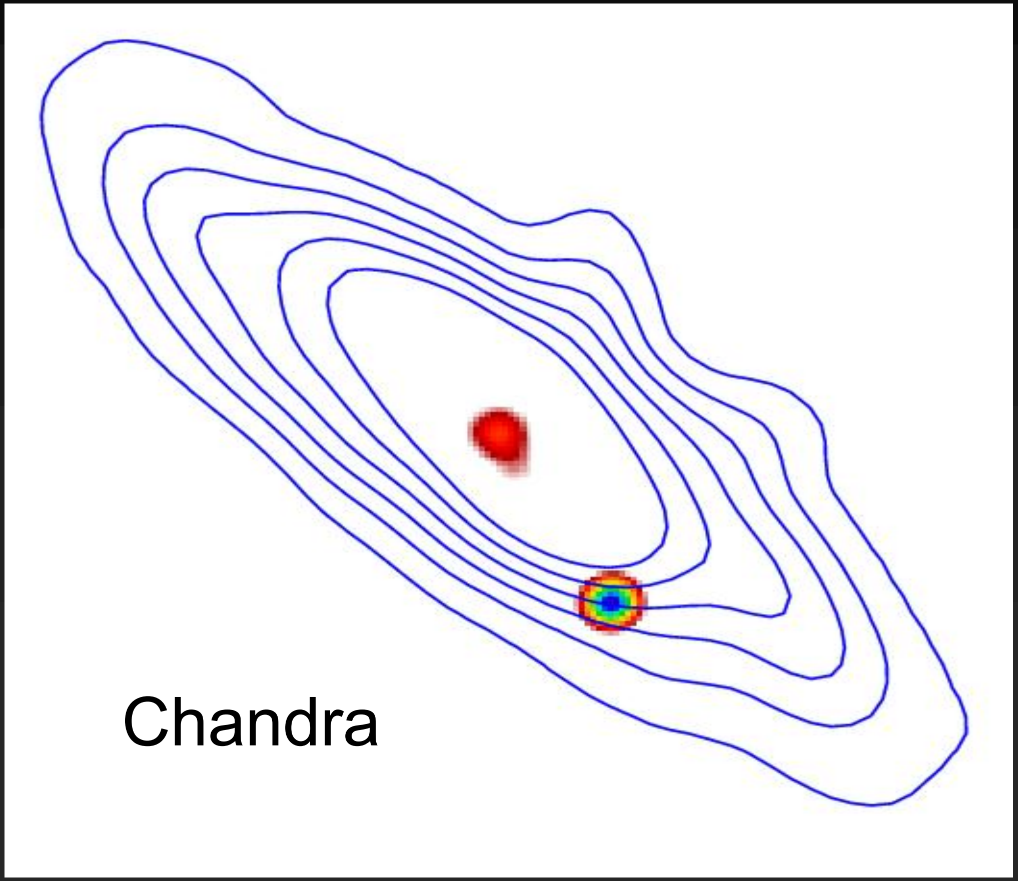
Detection and methods



What about IMBHs ? Do they really exist ?

Detection and methods

a higher angular resolution X-ray position is necessary to be sure of the optical counterpart (which can then be the target of spectroscopic follow-up to derive z)



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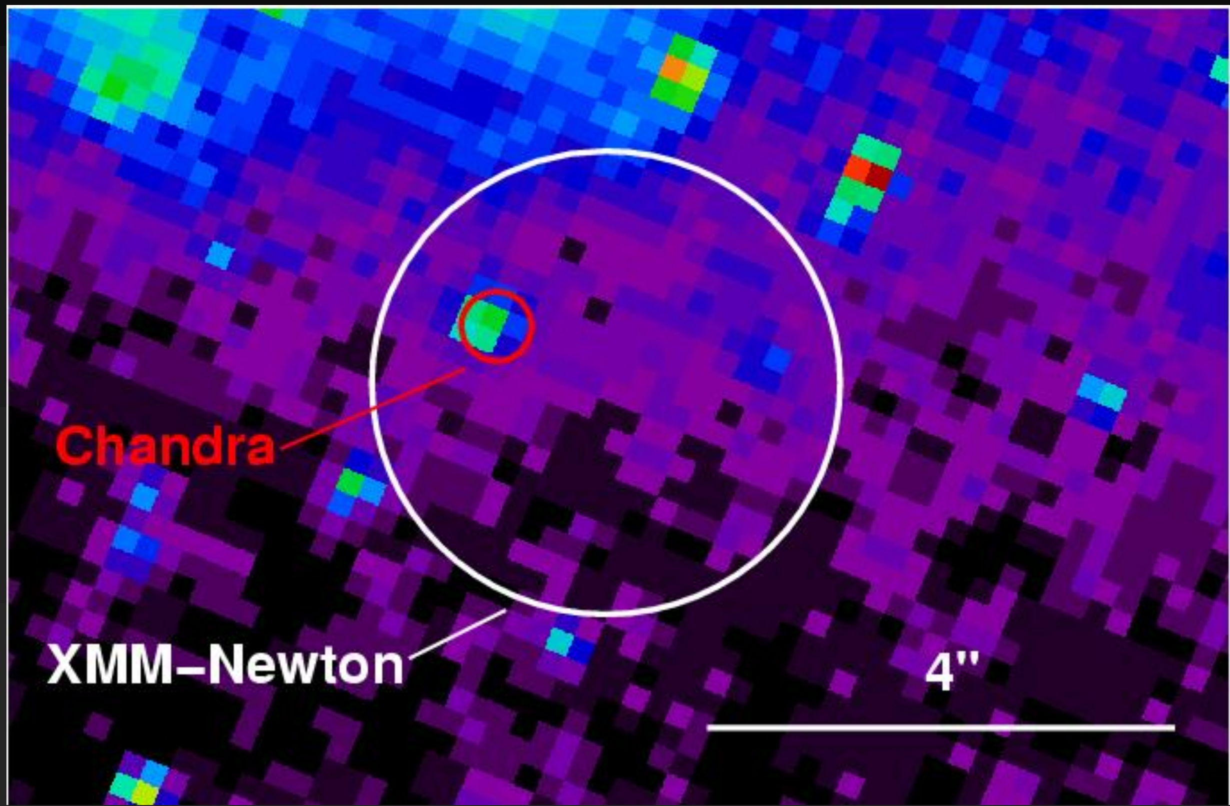
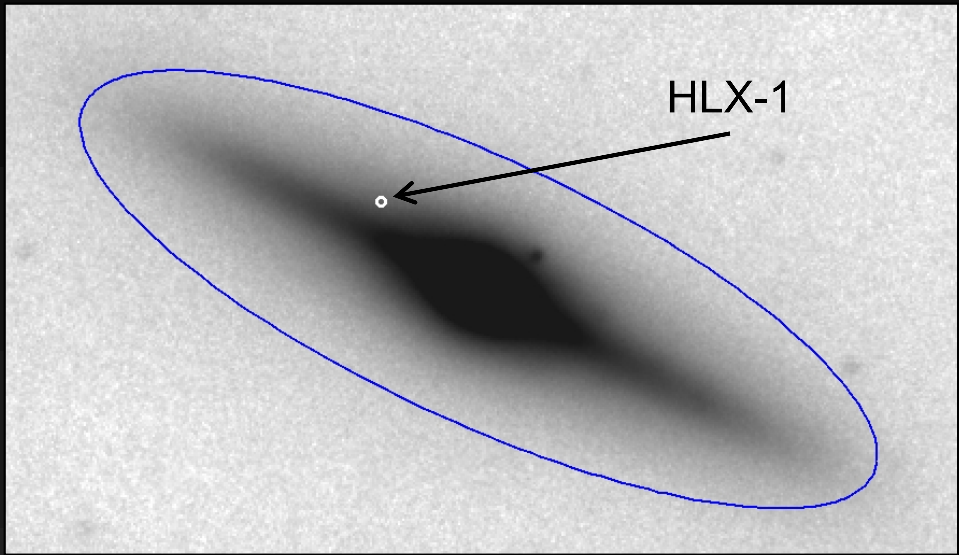


If optical spectroscopy confirms that the source has the same z as the apparent host, the ULX nature is confirmed

What about IMBHs ? Do they really exist ?

One interesting case study: the ULX in ESO 243-49



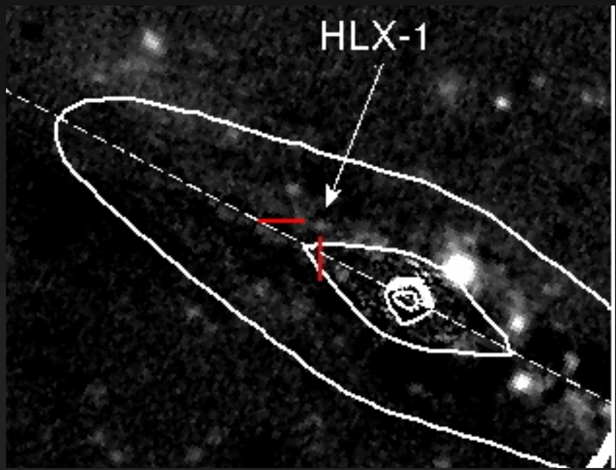
Assuming that the source is associated with the apparent host, an X-ray luminosity of ~ 10^{42} erg/s is observed (1000 times higher than the Eddington limit for a typica ~ 10 M_{sun} accreting BH in a standard X-ray binary)

Large amplitude and short timescale X-ray variability rules out the idea that the large observed luminosity is in fact the result of the emission from multiple distinct X-ray sources

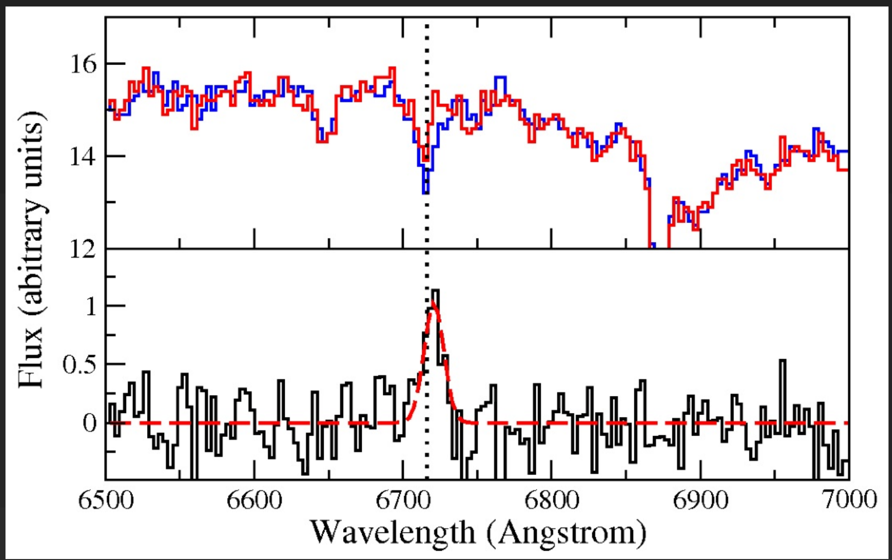
What about IMBHs ? Do they really exist ?

The most important aspect in this game, is to confirm that the source is indeed associated with the apparent host (a distance is necessary to convert fluxes into luminosities)

If this was not the case, HLX-1 could well be a background AGN of higher luminosity with no implications for IMBHs

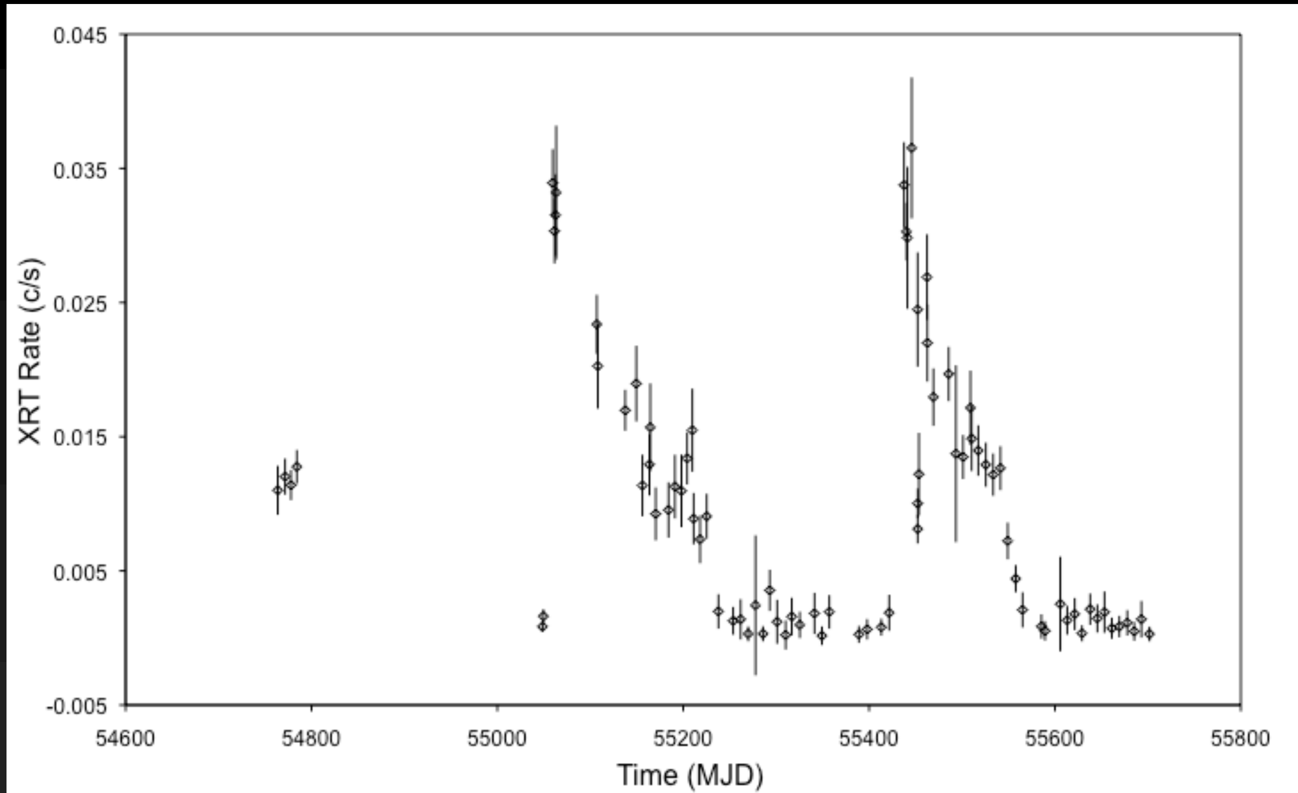


A faint optical counterpart was detected, so that an optical spectrum could be taken



The shift of an Hα emission line is consistent with the redshift of the galaxy → confirmation of the observed large X-ray luminosity

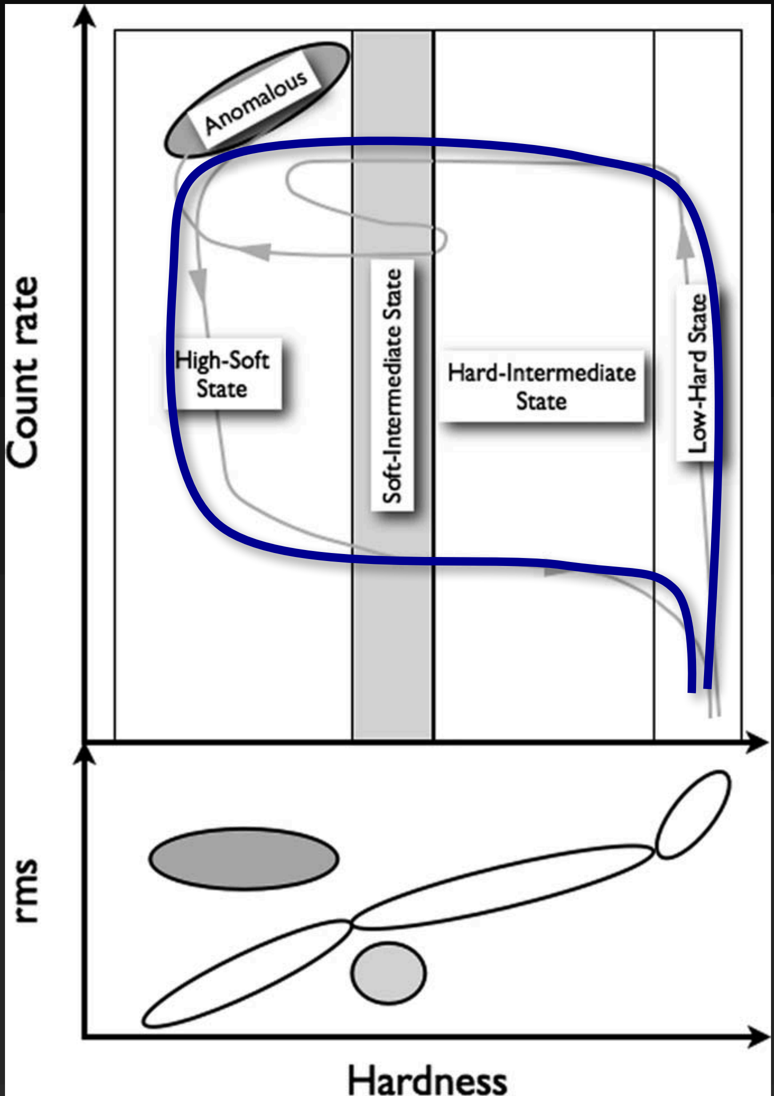
What about IMBHs ? Do they really exist ?



Large amplitude X-ray variability suggests cycles of activity similar to those seen in BH X-ray binary transients in the Milky Way (but with orders of magnitude more luminosity released at X-ray emergies)

In fact, the source appears to cycle through the same spectral states as stellar-mass BH transients in X-ray binaries

What about IMBHs ? Do they really exist ?



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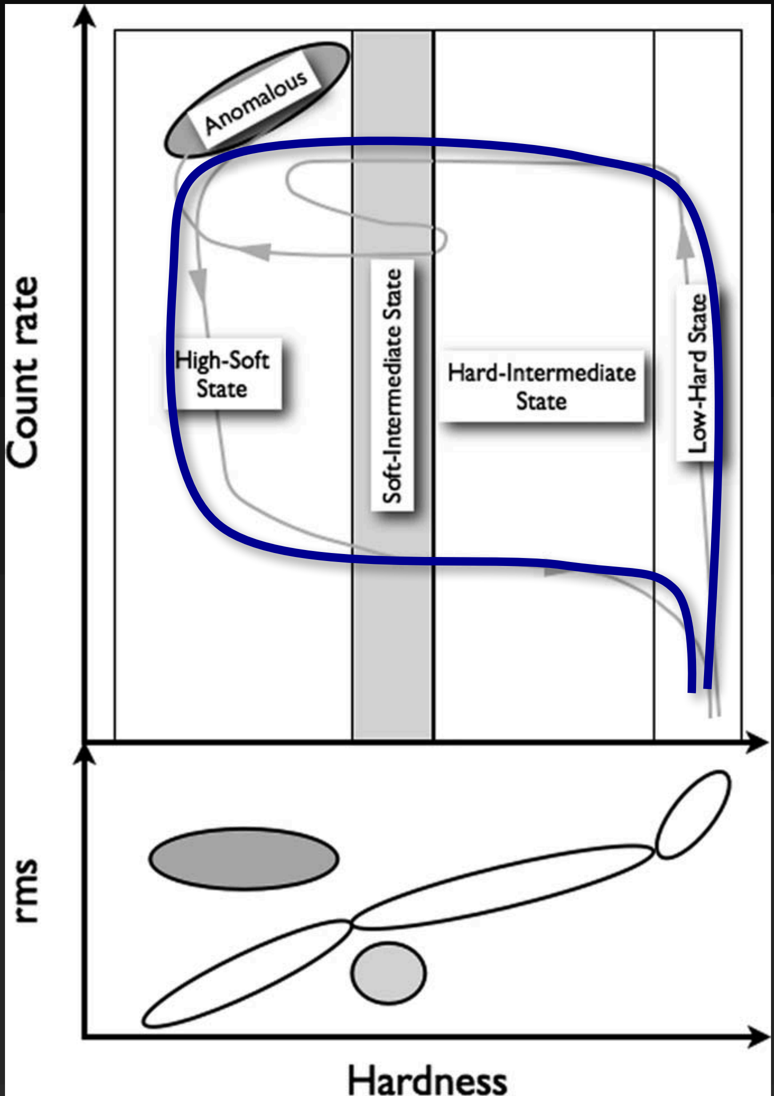
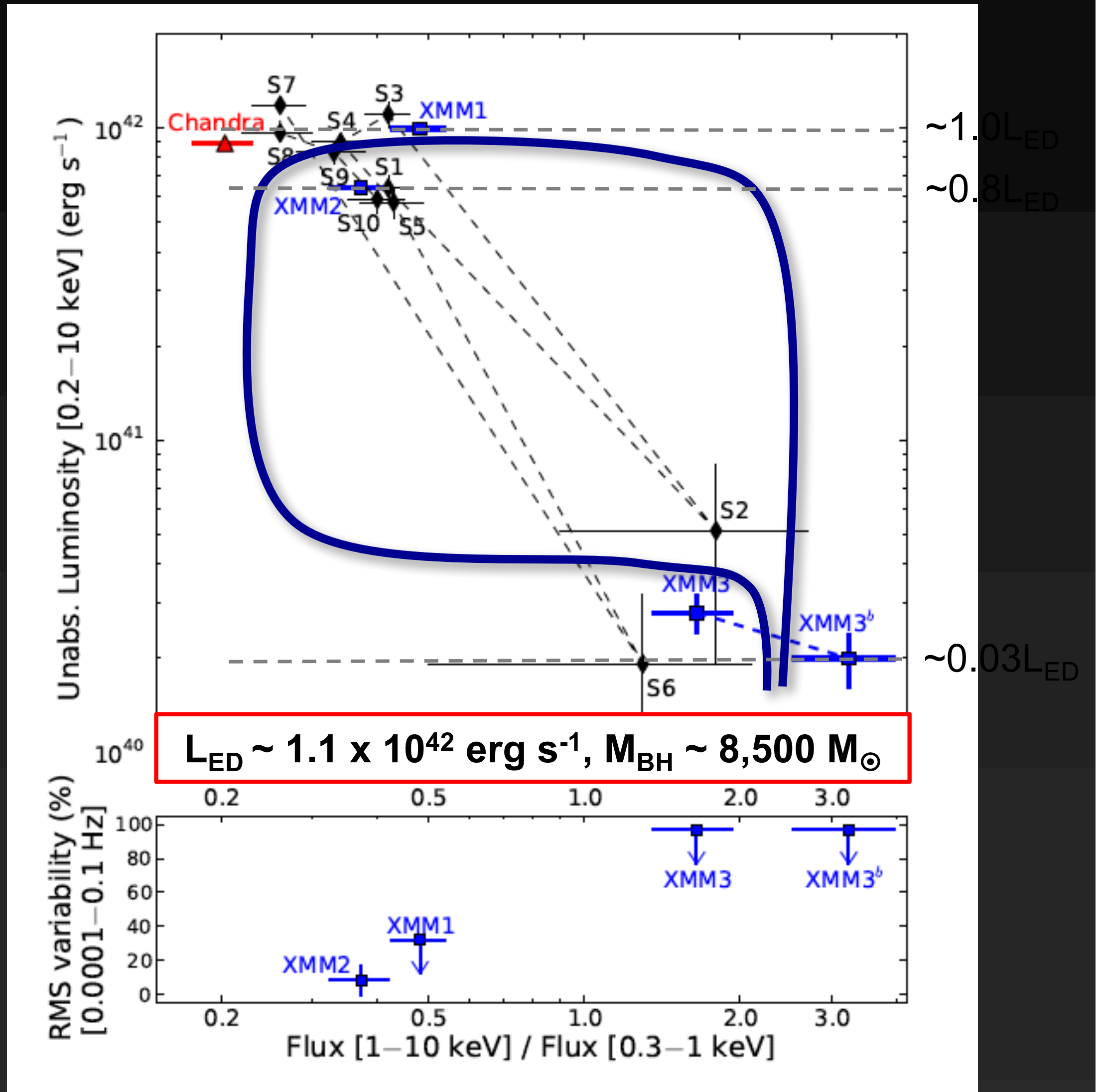
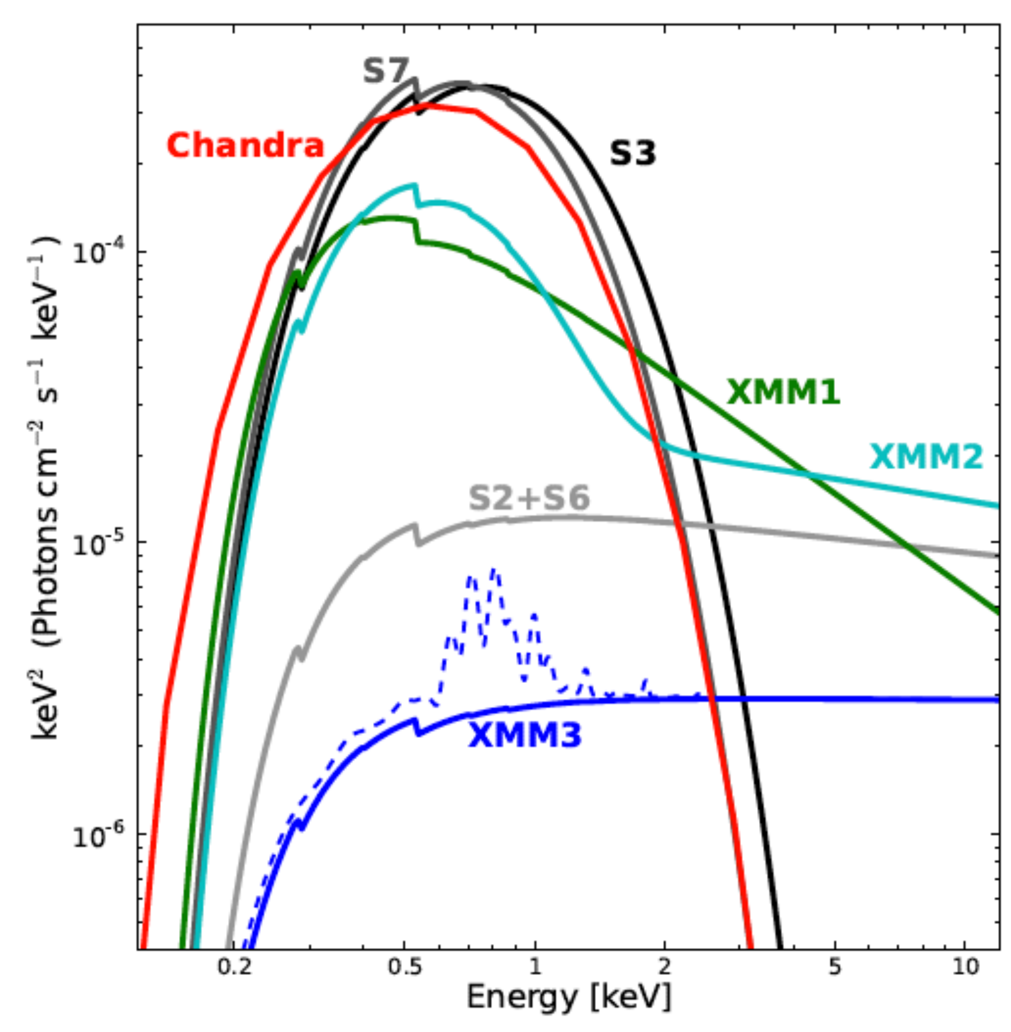


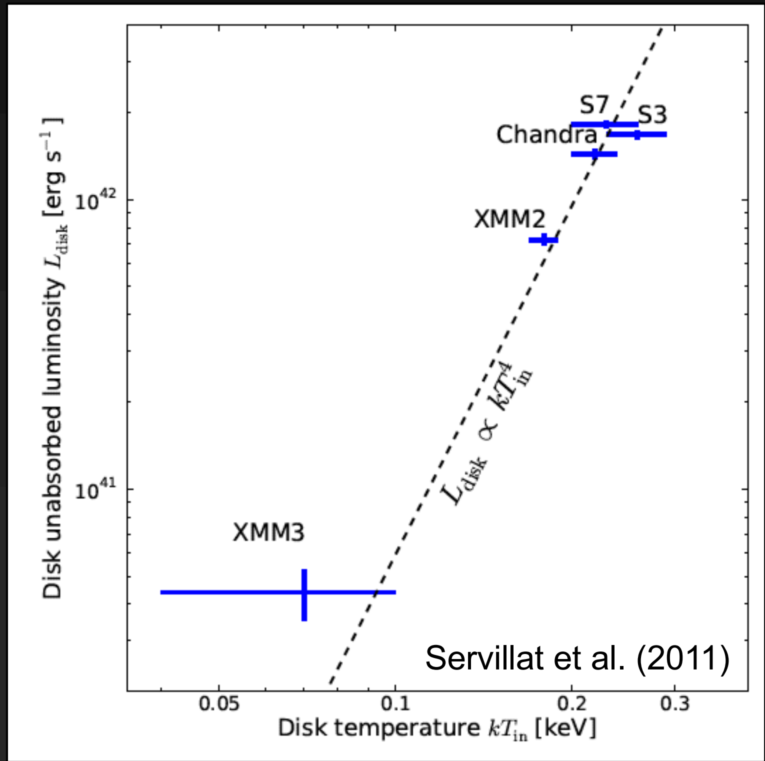


$L_{ED} \sim 1.1 \times 10^{42}$ erg s^{-1}, $M_{BH} \sim 8{,}500\ M_{\odot}$

What about IMBHs ? Do they really exist ?



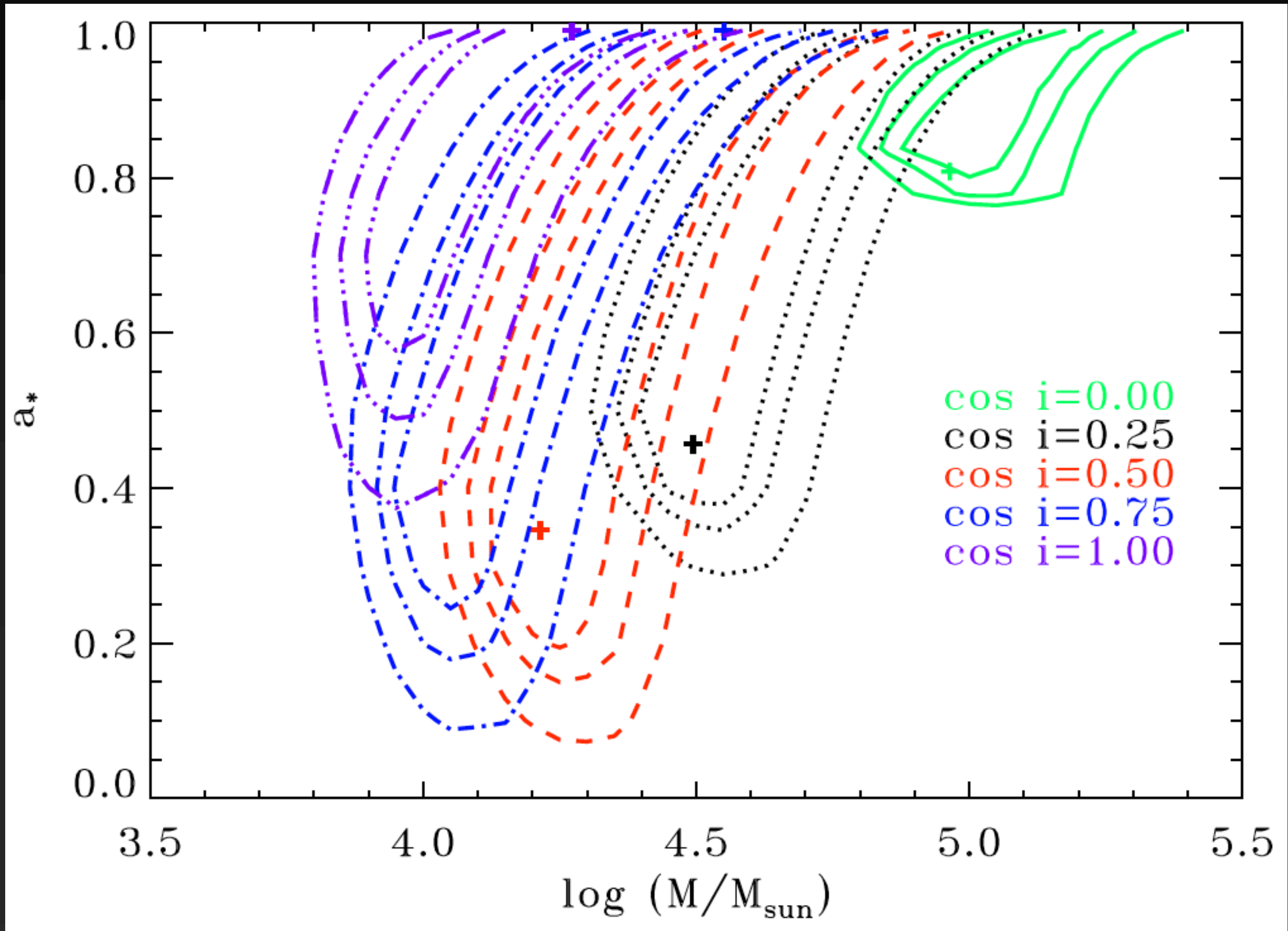
The spectral evolution allows to select some representative states that are completely dominated by thermal BB-like emission from the accretion disc



Servillat et al. (2011)

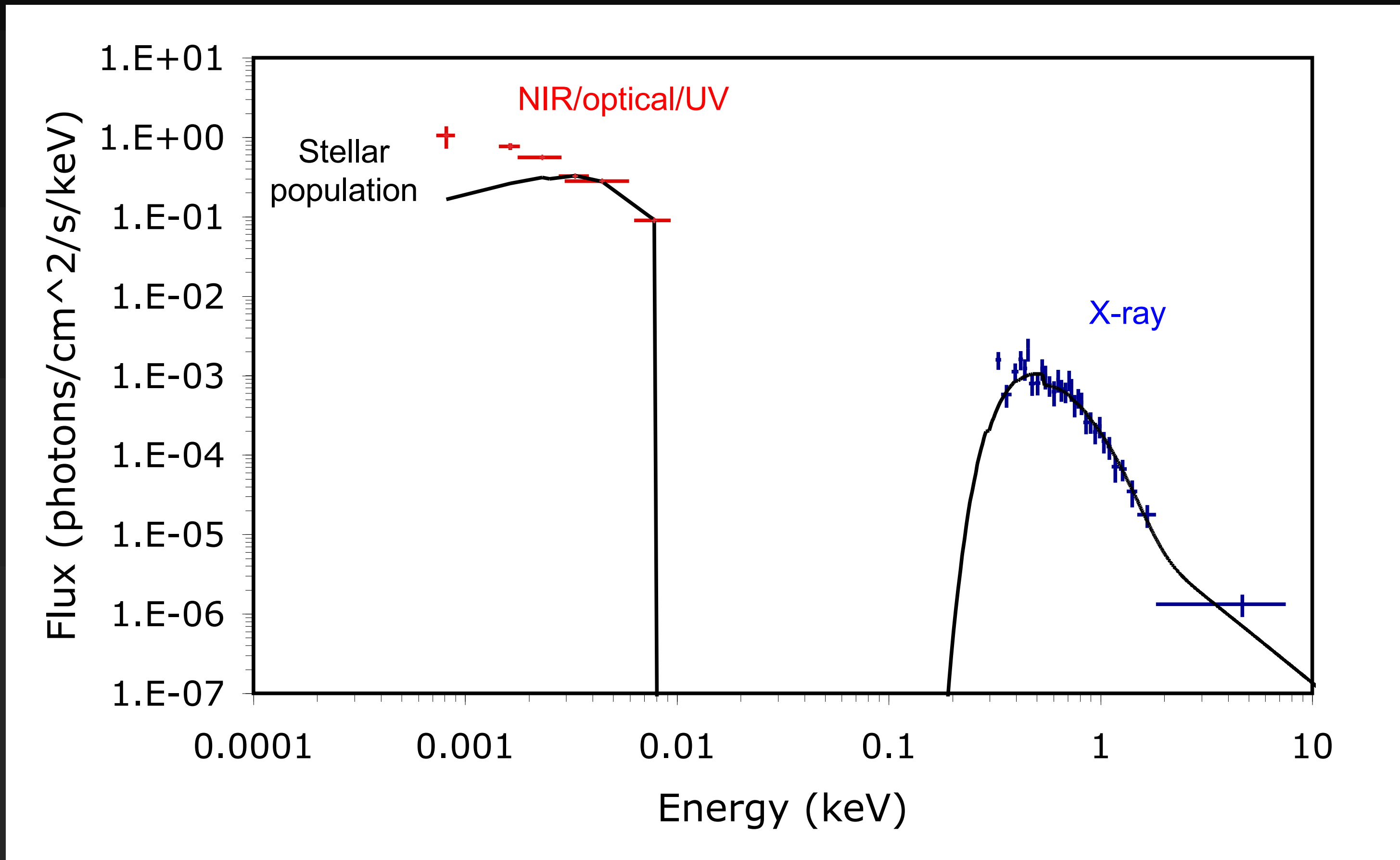
What about IMBHs ? Do they really exist ?

As done for BH binaries one can fit these spectra looking for constraints on both BH spin and, most importantly in this case, BH mass



What about IMBHs ? Do they really exist ?

Adding the IR/optical/UV data to the X-ray ones increases robustness and suggests an IMBH of ~ 10^4 M_{sun} in this ULX → an IMBH population may well exist, although only very few cases appear to be robust enough to be really trusted



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