Disc-corona geometry of black-hole binaries

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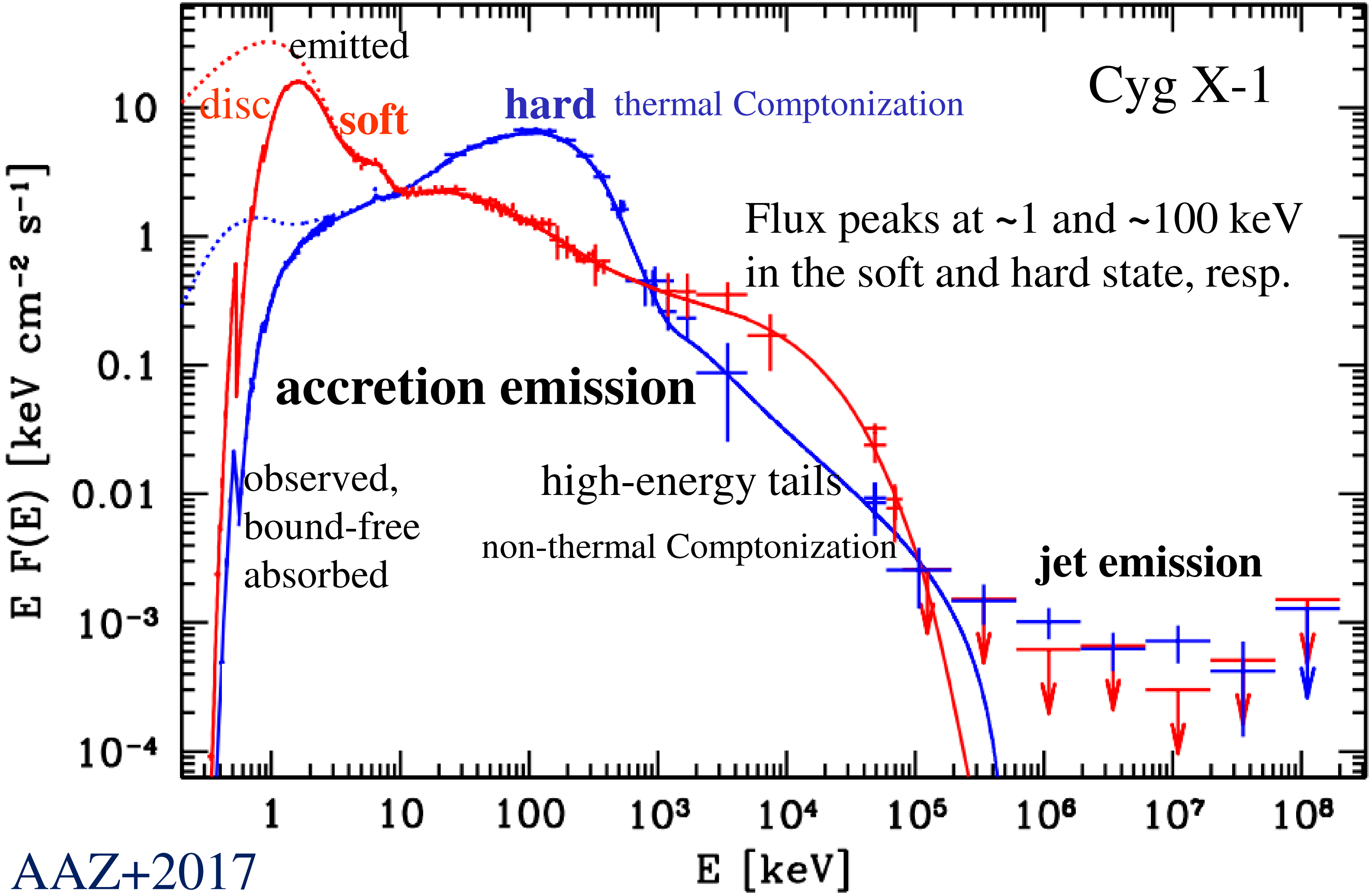
Both transient and persistent black-hole systems show two main luminous states, hard and soft



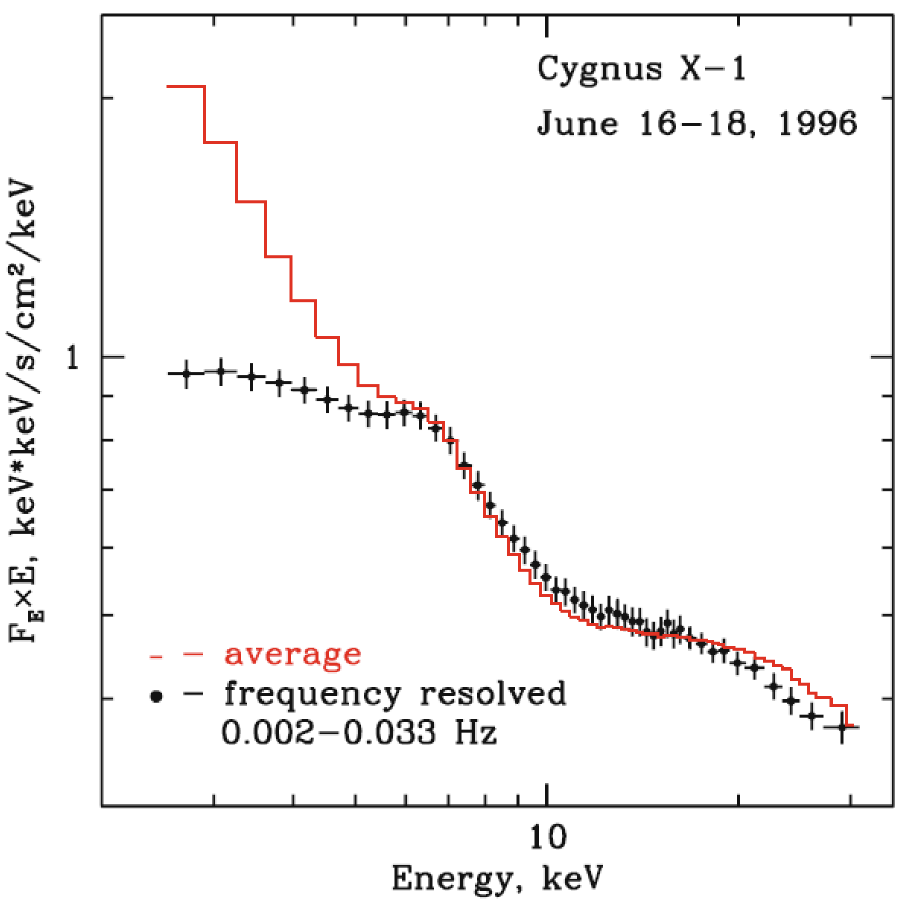
AAZ+2017

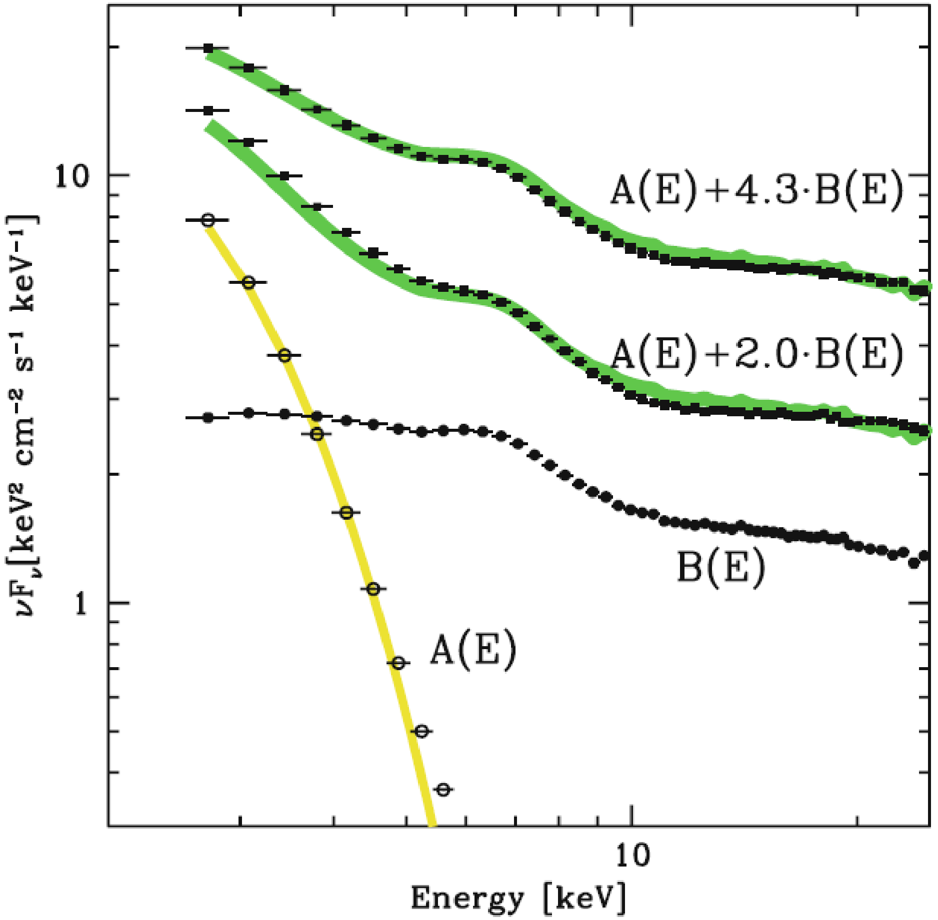
The soft state

- Blackbody (with a colour correction) emission of an optically thick disc extending to the innermost stable circular orbit, ISCO (from the stability of $r_{\rm in}$; Ebisawa+1991,1993; Gierliński & Done 2004; Steiner+2011).
- The blackbody emission is stable, almost no variability. This disagrees with the basic accretion disc theory.
- The emission follows $L \propto T^4$ in most cases.
- The blackbody is often followed by a variable high-energy tail from Compton upscattering of the blackbody photons by relativistic electrons with a hybrid, thermal + non-thermal, distribution, with the spectrum measured up to ~10 MeV.

Stable disc and variable corona

using frequency-resolved spectra



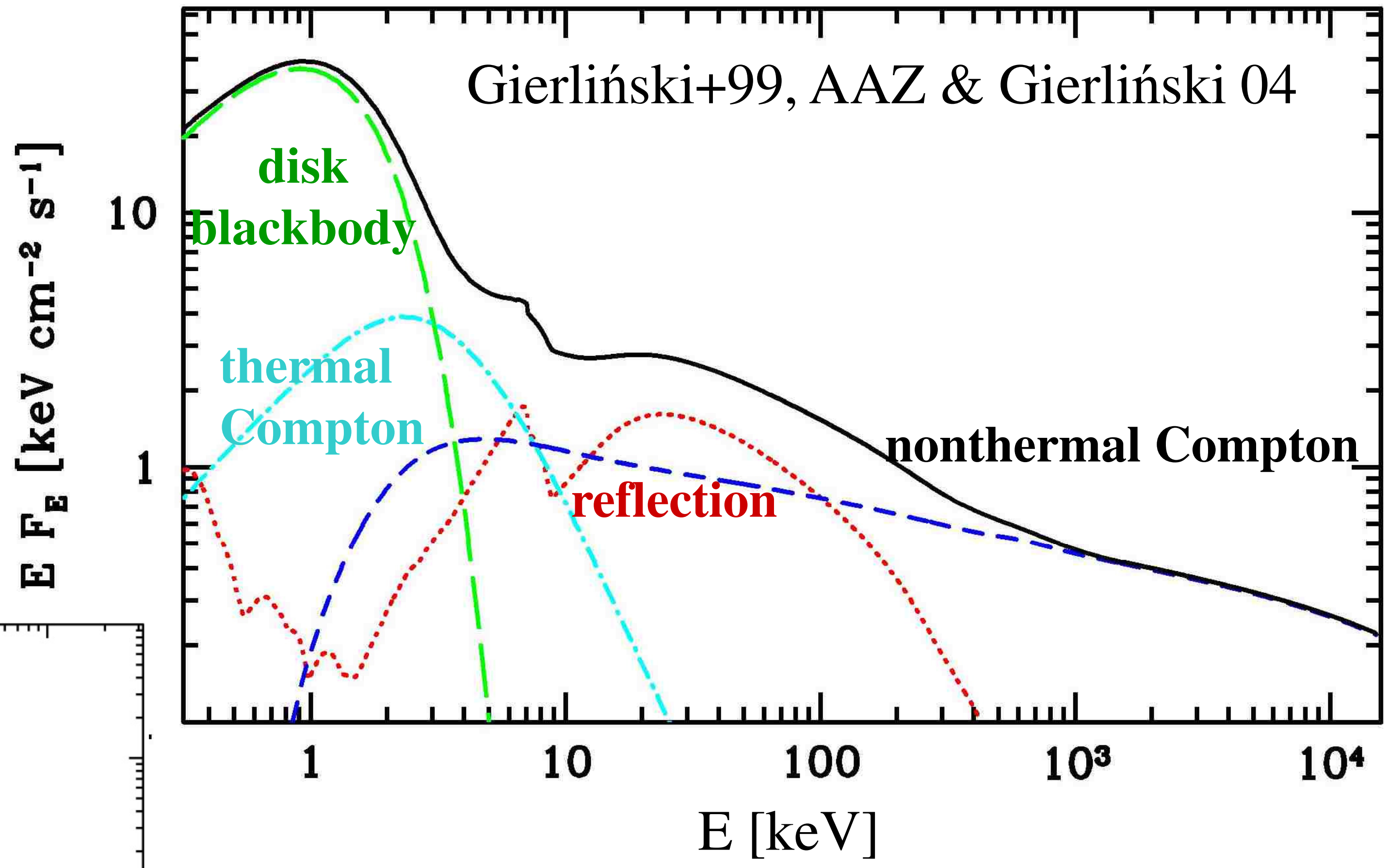


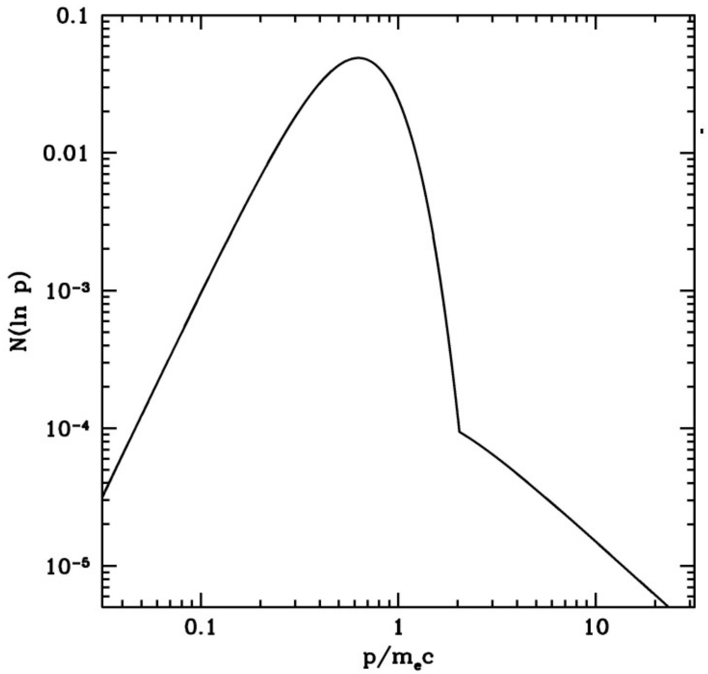
Churazov+ 2001

Cyg X-1: a soft-state spectrum

$\frac{L_{hot}}{L_{disk}} \ll 1$

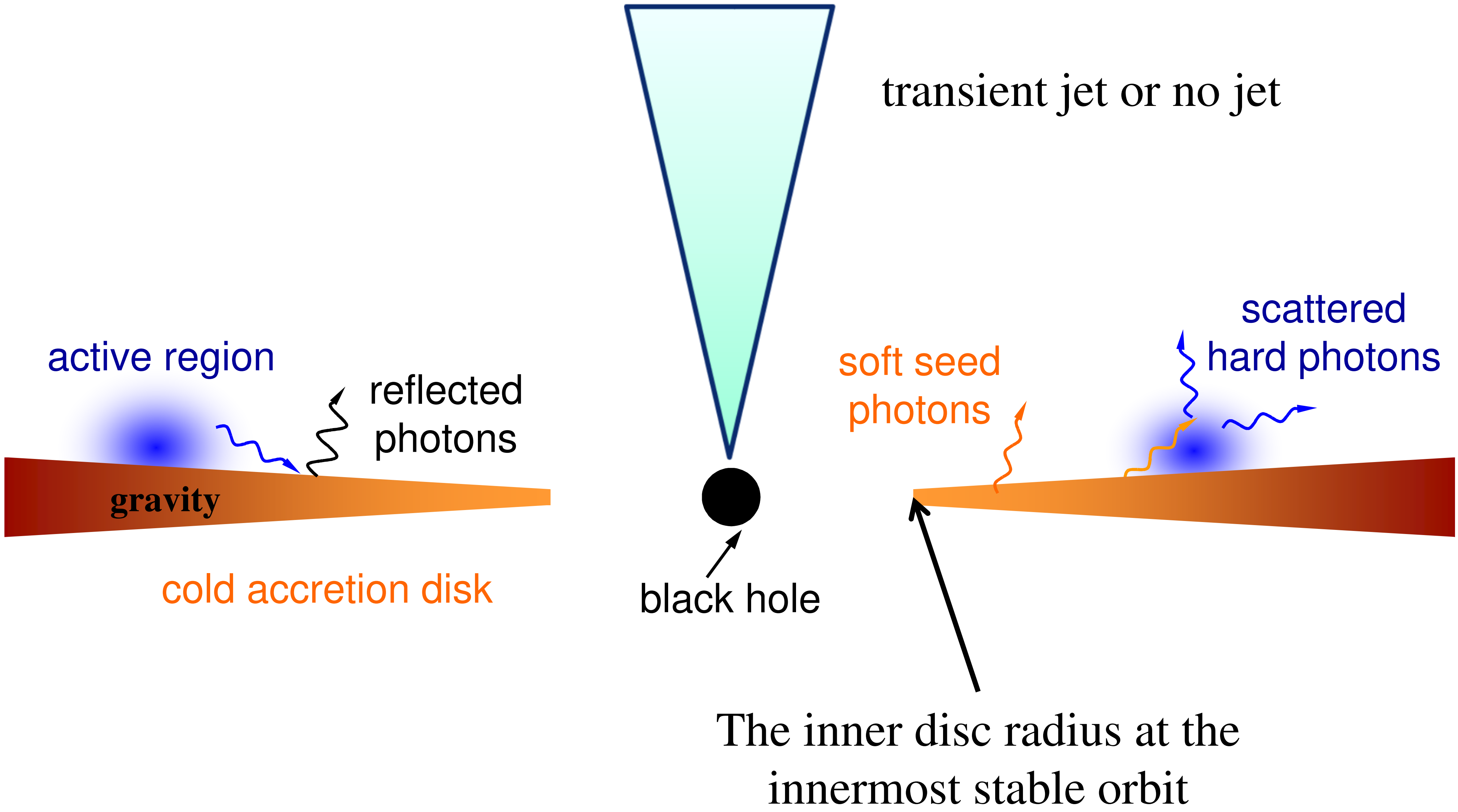
Disk blackbody + hybrid Comptonization





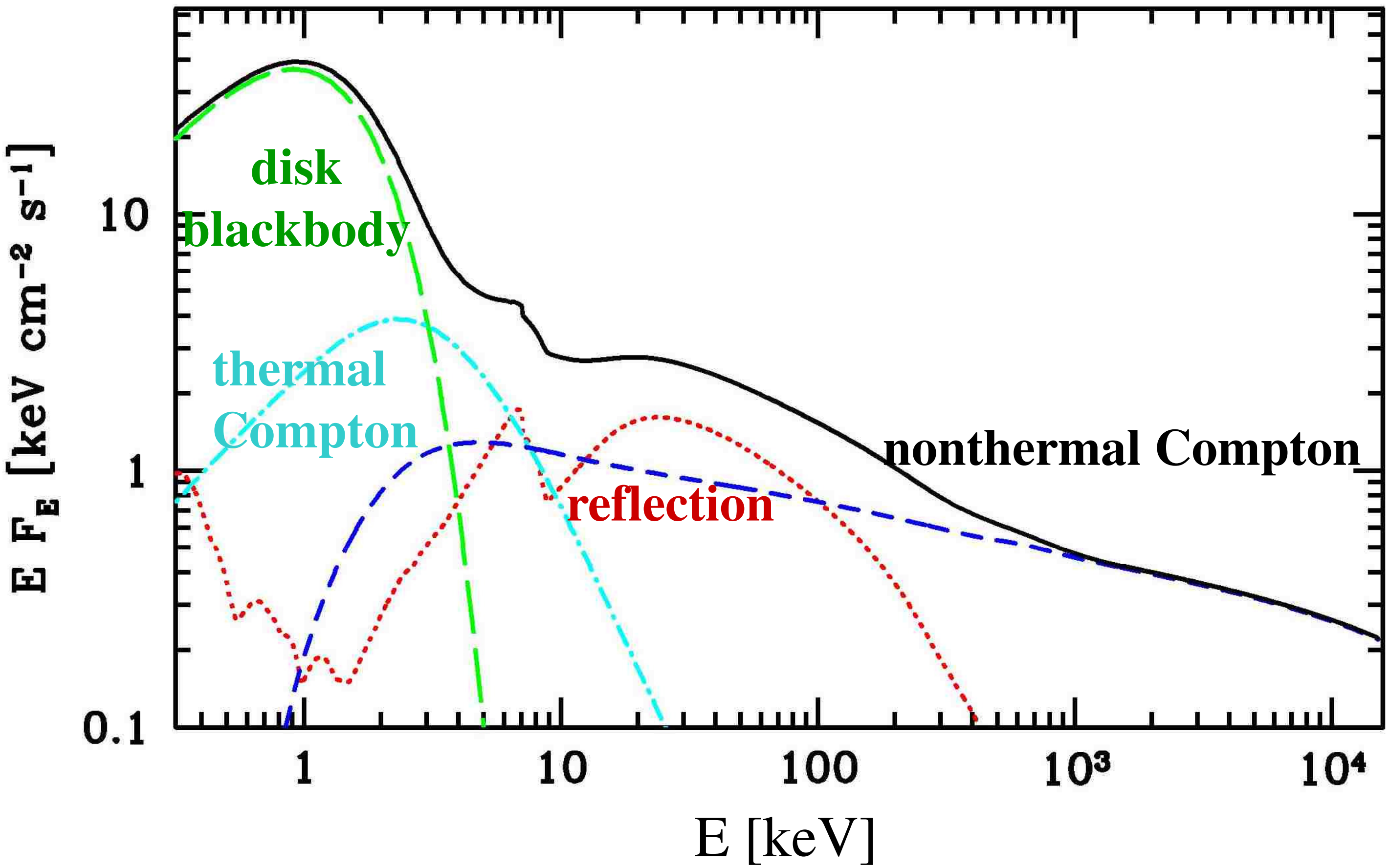
An electron distribution consisting of a Maxwellian and a high-energy (power-law like) tail.

Disc/corona geometry of the soft state:



An important issue:

Disk blackbody + hybrid Comptonization



The high-energy tails in the soft/intermediate states are definitely hybrid, i.e. they contain a part from non-thermal Comptonization. Fitting the tail with thermal Compton is not correct.

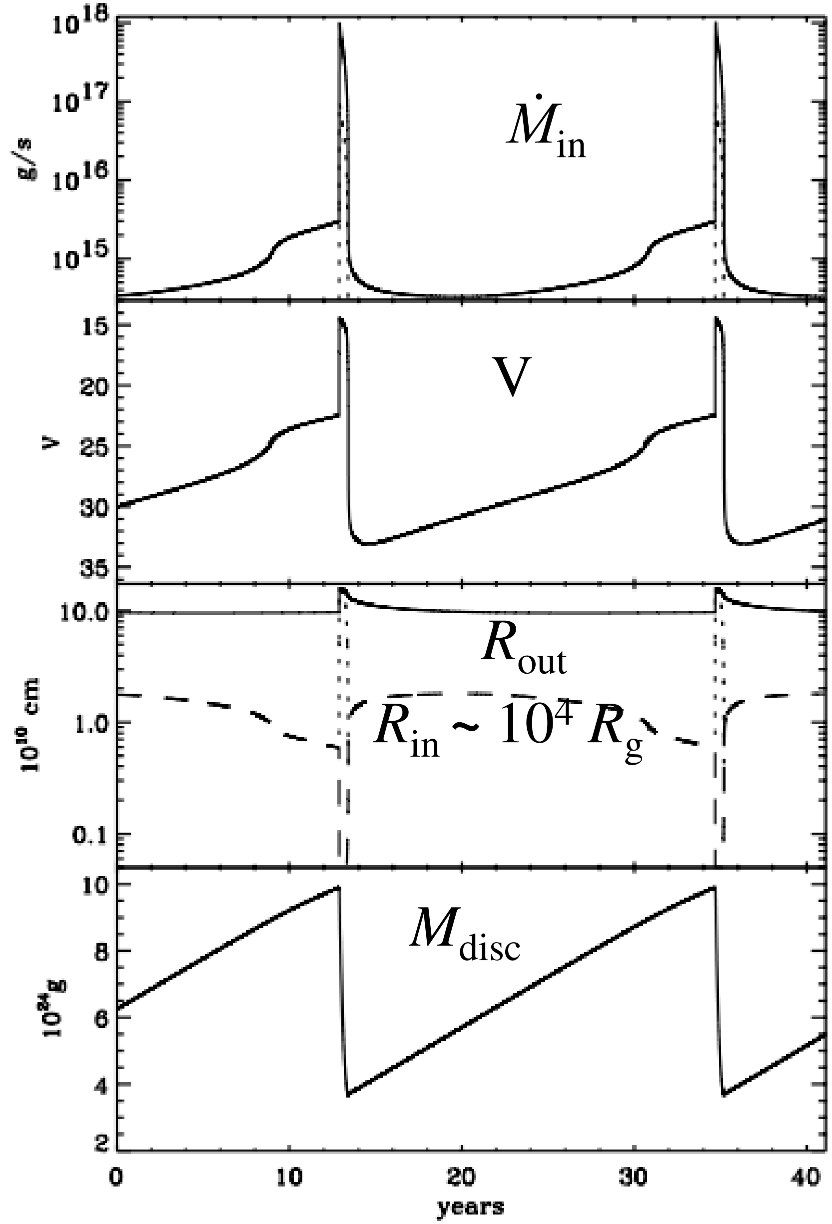
The hard state

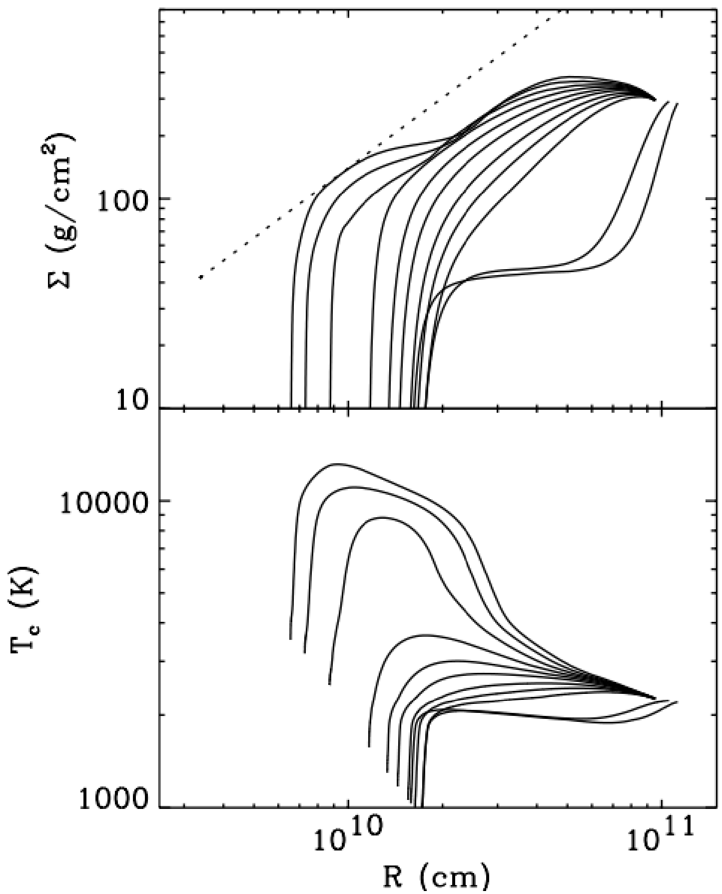
Discs and coronae in quiescence

- Low-mass BH binaries go through cycles of quiescence, lasting years to tens of years, and outbursts, lasting from weeks to years.
- The standard model for this behaviour is the disc instability model (DIM), originally developed for dwarf novae.
- The observed outburst fluences and the quiescent accretion rates are much too low if the quiescent disc extends down to the innermost stable circular orbit (ISCO). Also, a disc extending down to the ISCO cannot explain the observed quiescent X-ray luminosities (Lasota, Narayan & Yi 1996; Dubus, Hameury & Lasota 2001).
- Thus, during quiescence, the disc has to be truncated at a radius of $\sim 10^{10}$ cm ($\sim 10^4\ R_g$; 1 $R_g \approx 10^6$ cm @ $7M_\odot$).

The disc instability model for BH binaries

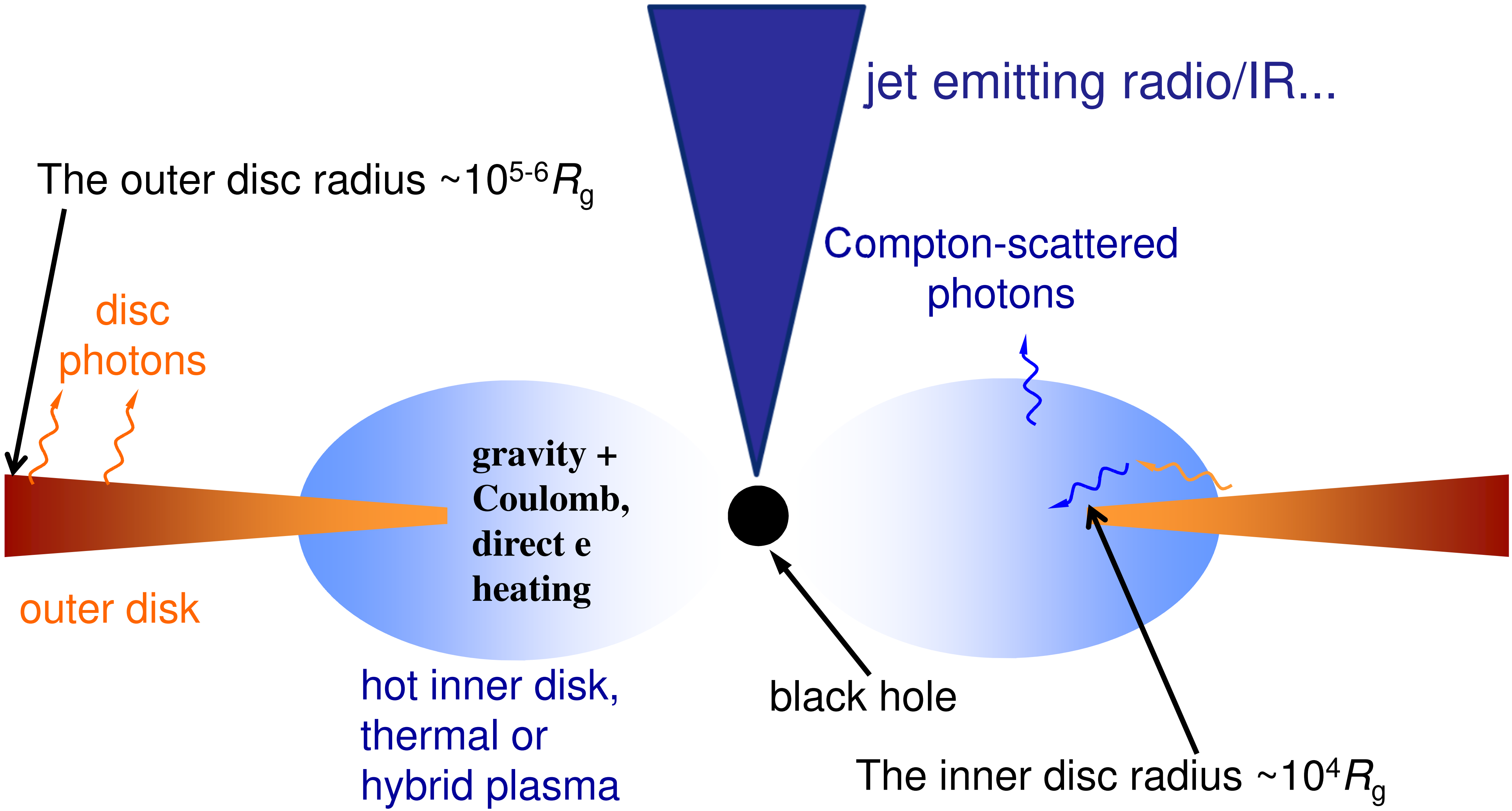
Dubus+2001





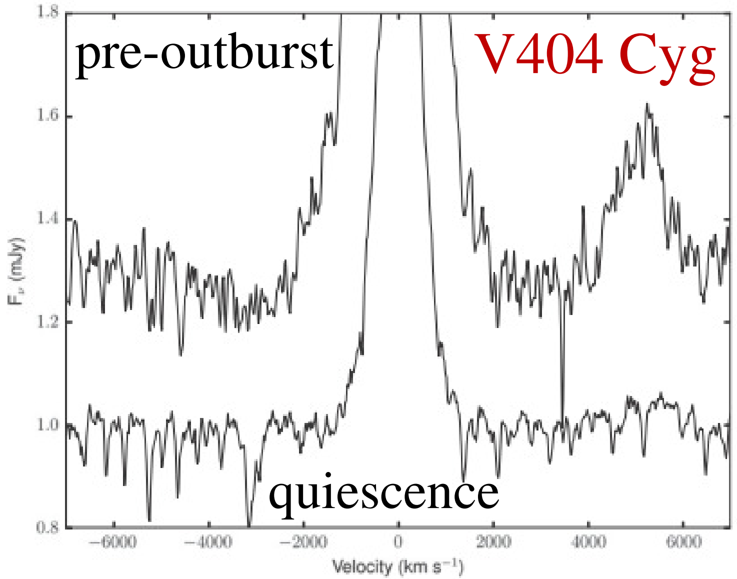
For the chosen parameters, the onset of the (inside-out) outburst is at ~7×10^9 cm, and the maximum truncation radius is ~2×10^{10} cm (~ 2×10^4 R_g).

The geometry in the quiescent state



A measurement of disc truncation in quiescence

- Based on the width of the Hα line, Bernardini+ 2016 found the disc inner radius of $R_{\rm in} \gtrsim 3\times10^4 R_{\rm g}$ as the average during quiescence of V404 Cyg, confirming the theoretical prediction.
- A significantly broader line, $R_{\rm in} \lesssim 10^4 R_{\rm g}$, was found 13h before the 2015 X-ray outburst of V404 Cyg.



- Downstream of $R_{\rm in}$, there is still an accretion flow, but hot, likely a radiatively inefficient accretion flow (RIAF).
- The physical nature of the truncation uncertain.

Measurements of disc truncation

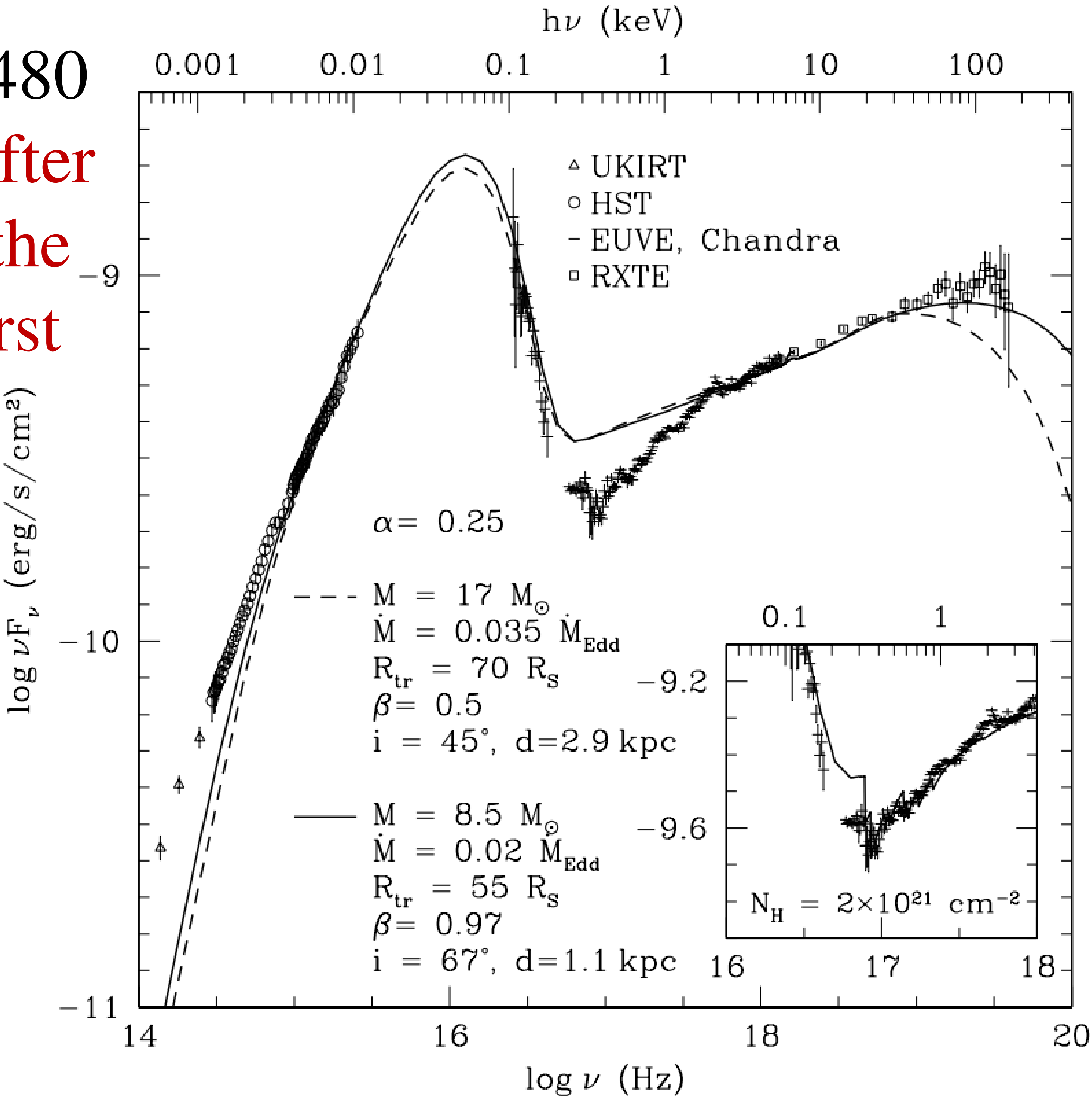
- The X-ray outburst of V404 Cyg started 7 days after the optical outburst. The standard viscous time scale can be written as:
- $\Delta t \approx 15\ \mathrm{d}\ (M/10\mathrm{M}_\odot)^{1/2}(\alpha/0.2)^{-1}(T_c/10^5\mathrm{K})^{-1}(R/10^{10}\mathrm{cm})^{1/2}$.
- From the 7-d delay of the X-ray outburst w/r to the optical one and assuming that the X-ray outburst starts at $R \approx 5\times10^8$ cm, Bernardini+ estimated the radius of the onset of the optical outburst was at ~10^9 cm or ~$10^3 R_g$.
- A very similar ~7-d delay was found for the black-hole binary ASASSN-18ey by Tucker+ 2018.

Disc truncation during an outburst

- Given the observed ~7-d delays, the viscous disc would have reached the ISCO within a few days after the start of the X-ray outburst.
- This is an argument for truncation through most of the hard state.
- But is it really the case?
- E.g., the disc inner radius in XTE J1118+480 was measured to be $\gtrsim 50 R_{\mathrm{g}}$ three weeks after the onset of the outburst (McClintock+2001; Esin+2001).

XTE J1118+480

three weeks after the onset of the X-ray outburst



Esin+2001

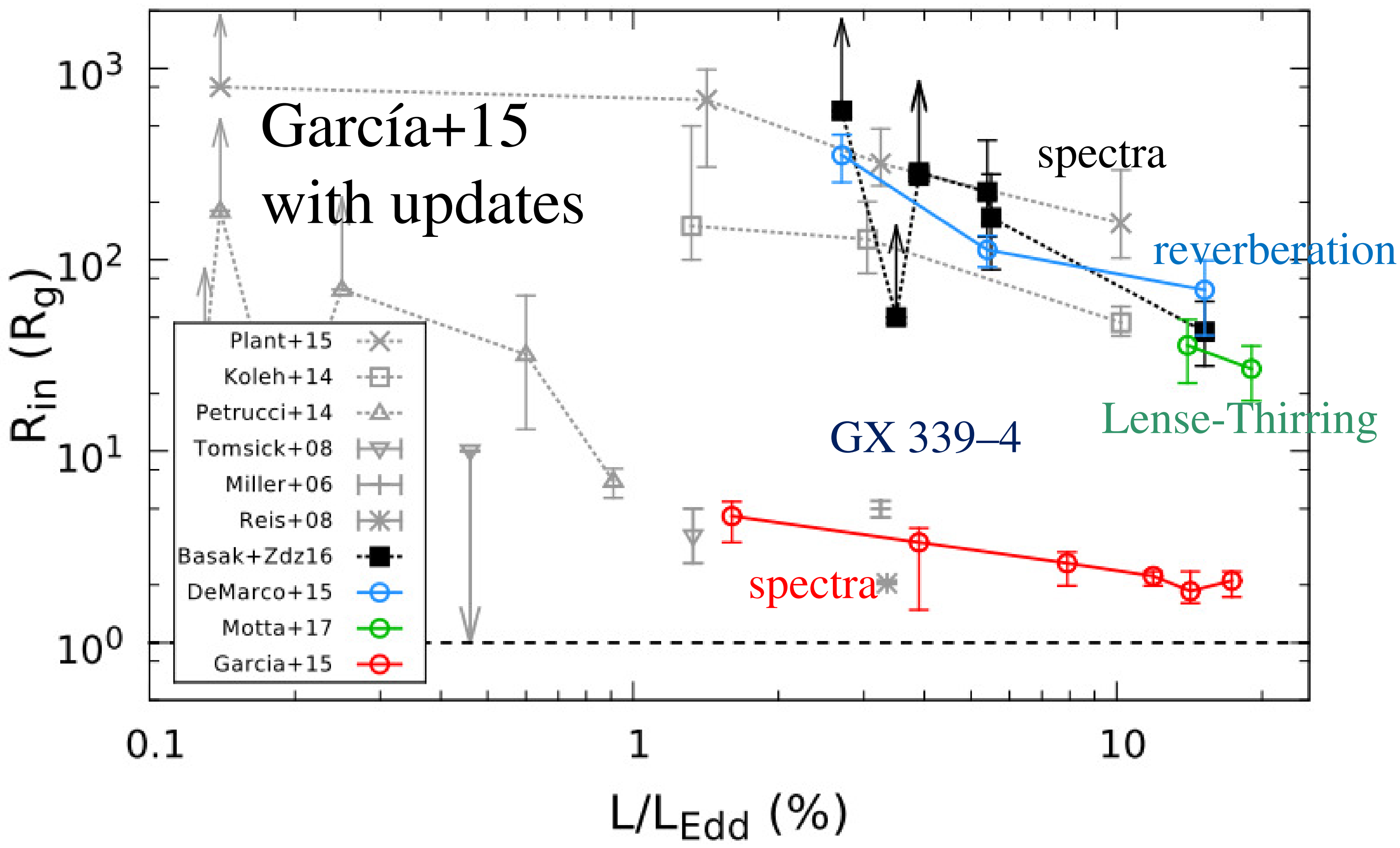
Disc truncation during an outburst

- If the disc remains truncated during the hard state, what can prevent the disc to reach the ISCO?
- We are not sure. It could be emission of a jet through the Blandford-Payne mechanism (Ferreira, Petrucci, Marcel), or formation of a hot corona and disc evaporation (Różańska; Meyer, Meyer-Hofmeister, Liu, ...), or winds.

Accretion models: the luminous hard state

- The main geometries proposed.
  - A hot inner flow:
    - overlapping with a truncated outer disc;
    - with cold clumps inside.
  - A disc extending to ISCO with a corona:
    - covering the disc;
    - as a lamppost.
- The dominant physical process is Compton upscattering by thermal electrons (with a possible weak non-thermal tail).
- The main seed photons for Compton scattering:
  - disc blackbody photons
  - synchrotron photons from:
    - a pure Maxwellian distribution (inefficient at $kT_e<100$ keV);
    - a Maxwellian distribution with a weak high-energy tail (highly efficient).

A controversy regarding the truncation radii in the hard state: the case of GX 339–4

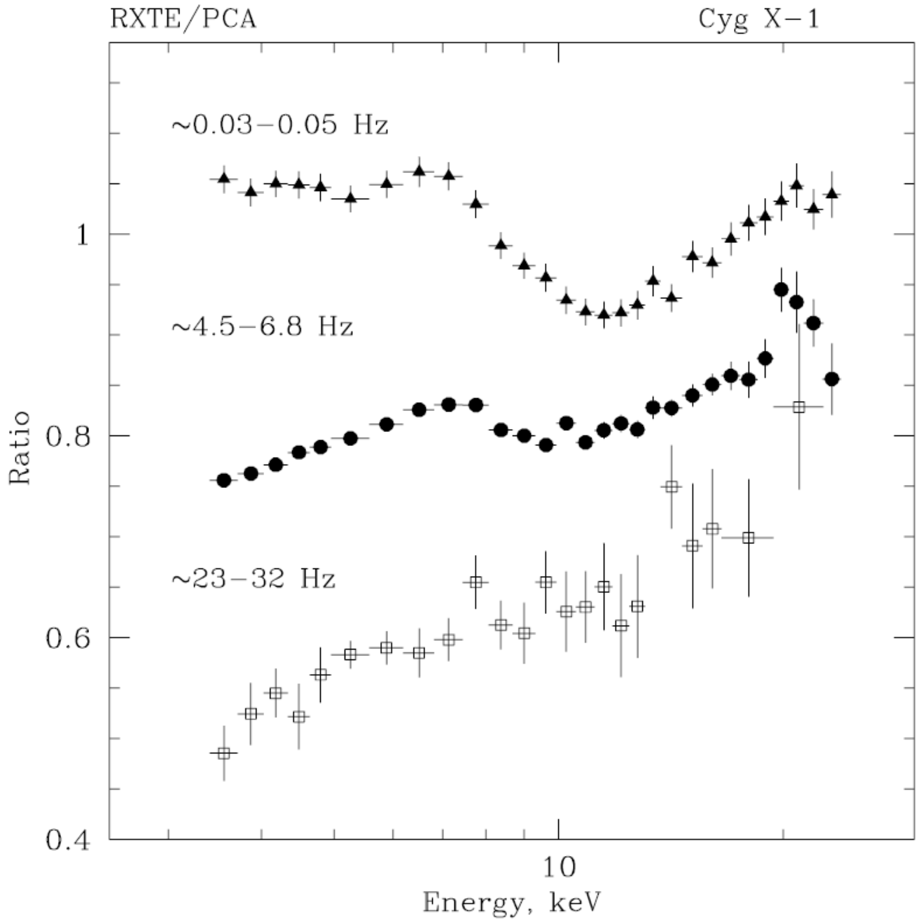


The truncated disc model for the hard state

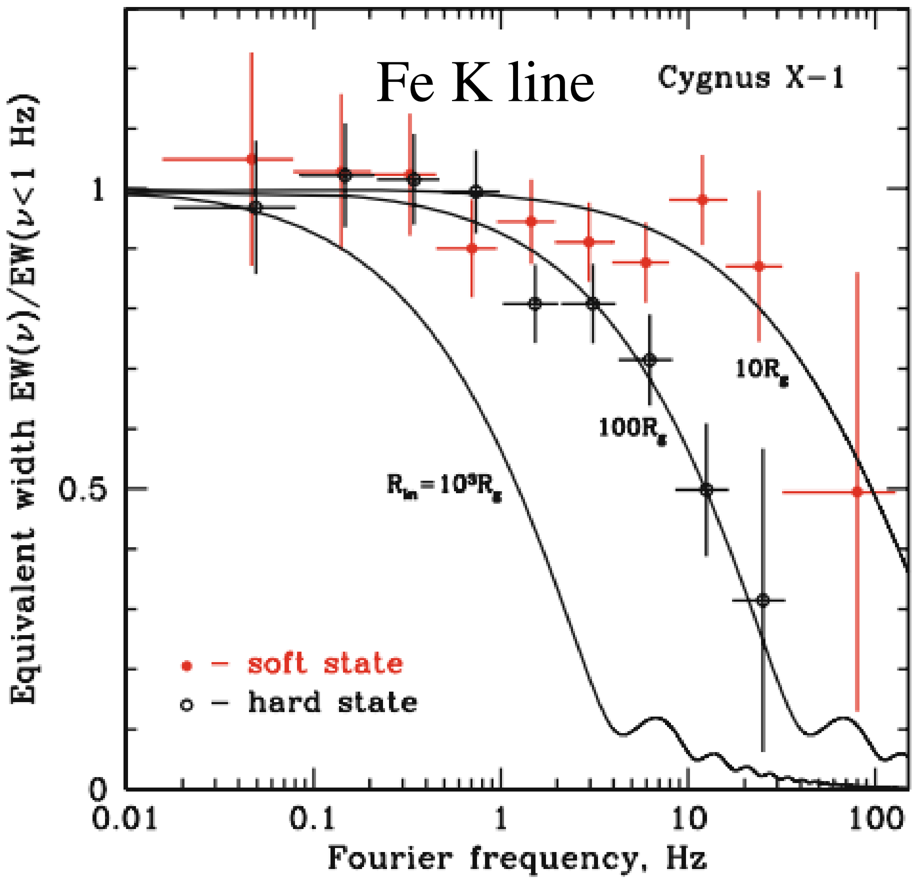
- It explains correlations between the luminosity, hardness, reflection strength, Fe K width and strength, and the characteristic frequencies. It explains results of the frequency-resolved spectroscopy. It gives a physical model for the power spectra and the low-ν QPO.
- It explains the transition to the soft state as due to the flow reaching the innermost stable orbit.
- If the disc is truncated, a crude estimate of the expected of the truncation radius can be obtained comparing powers released in the disc and the hot flow.
- A half power is emitted within $\approx 33 r_g$ for a non-spinning black hole, $a = 0$, and within $\approx 5 r_g$ for a maximally spinning black hole, $a = 1$ (Thorne 1974). In general, the half-power radius is $\sim[5+28(1-a)]r_g$ (Fabian+ 2014).

Fourier-resolved spectroscopy

hard state

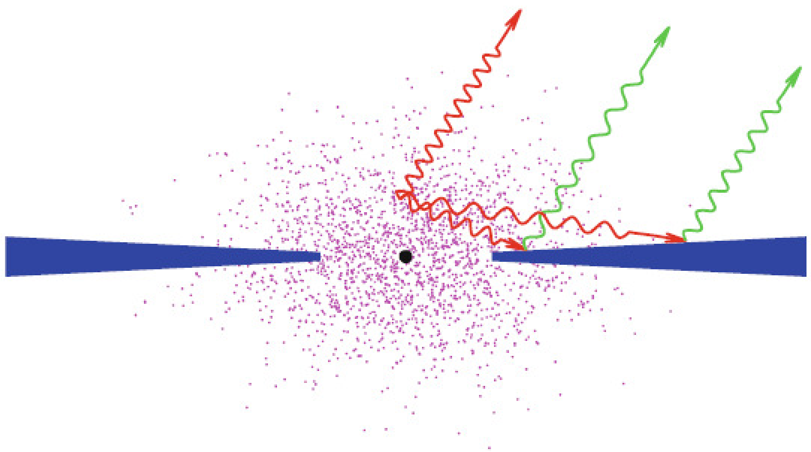


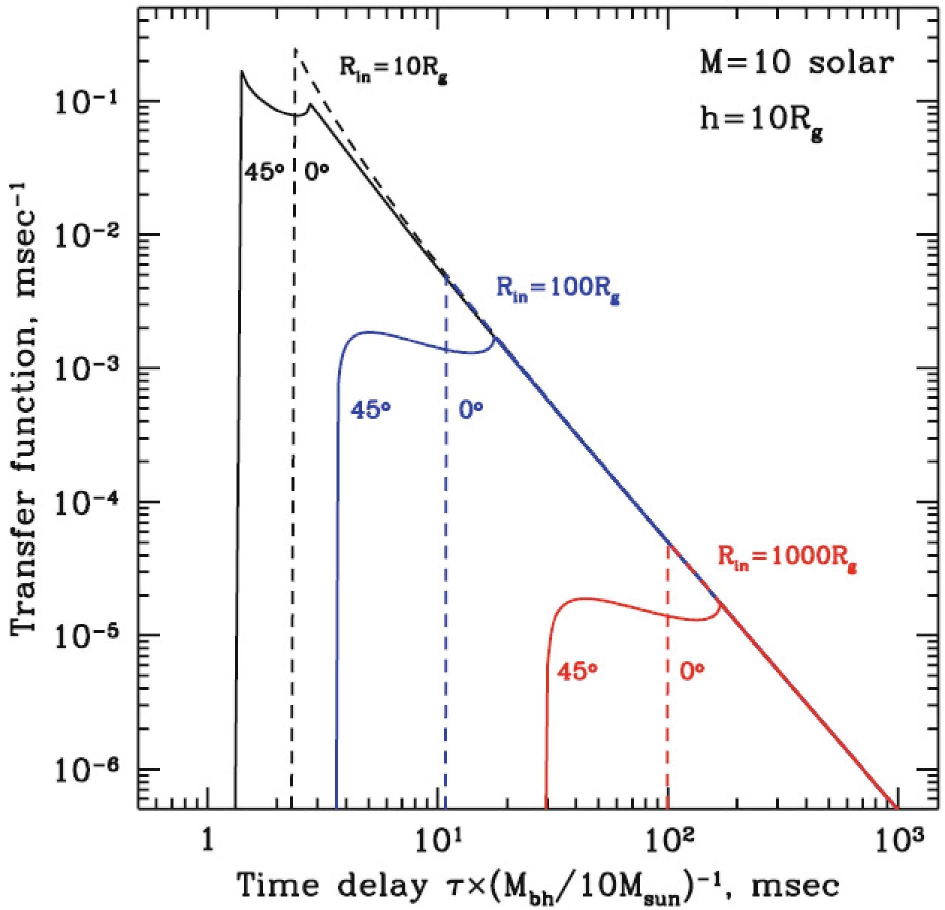
We see the reflection features only at low frequencies, thus at relatively large distances from the black hole, and no such features appear to be emitted near the black hole.



Revnivtsev+ 1999, Gilfanov 2010

Reflection/reprocessing delays

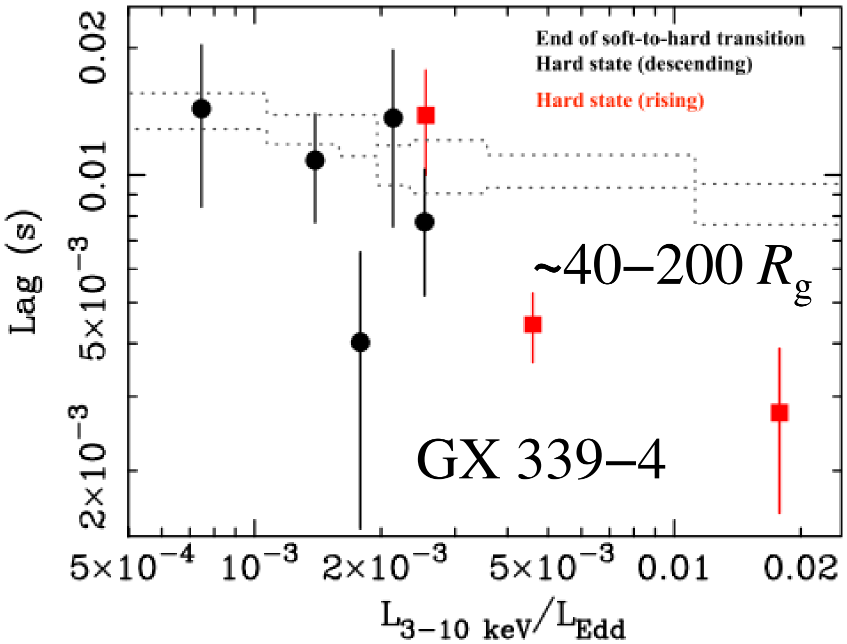




Gilfanov+ 2000

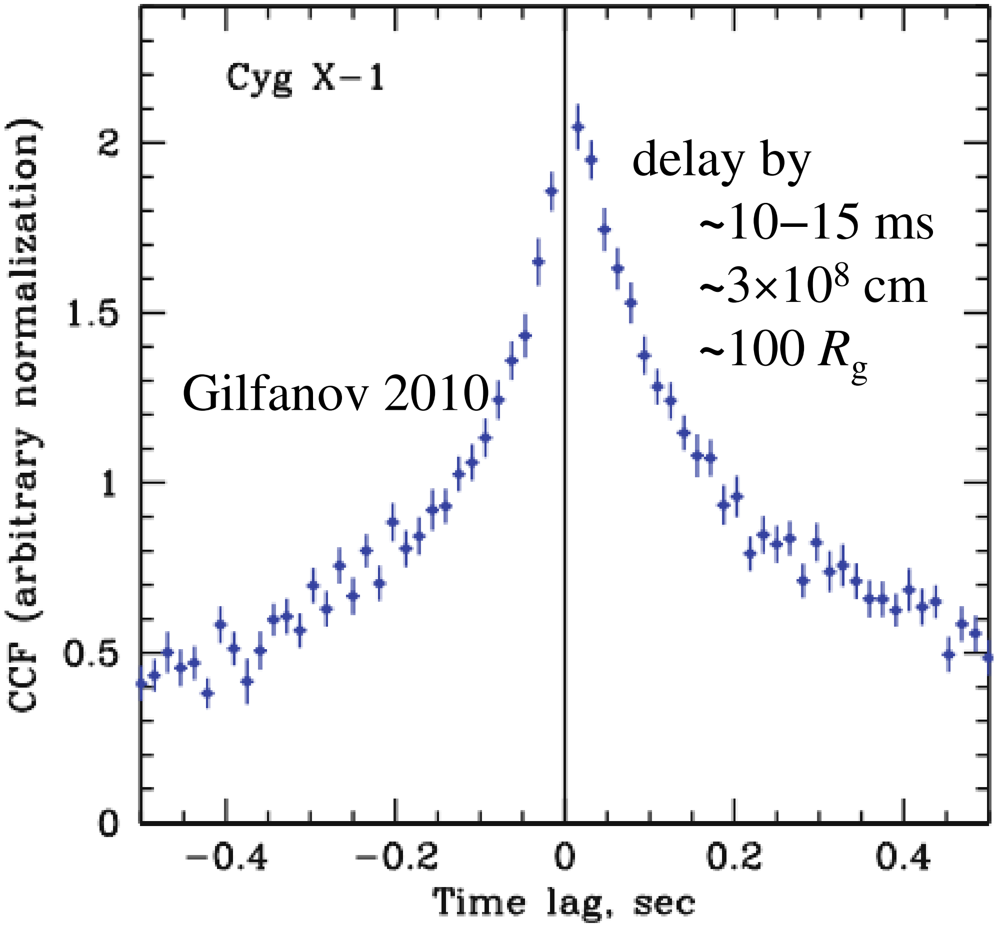
Reprocessing/reflection delays

soft X-rays, blackbody-like response

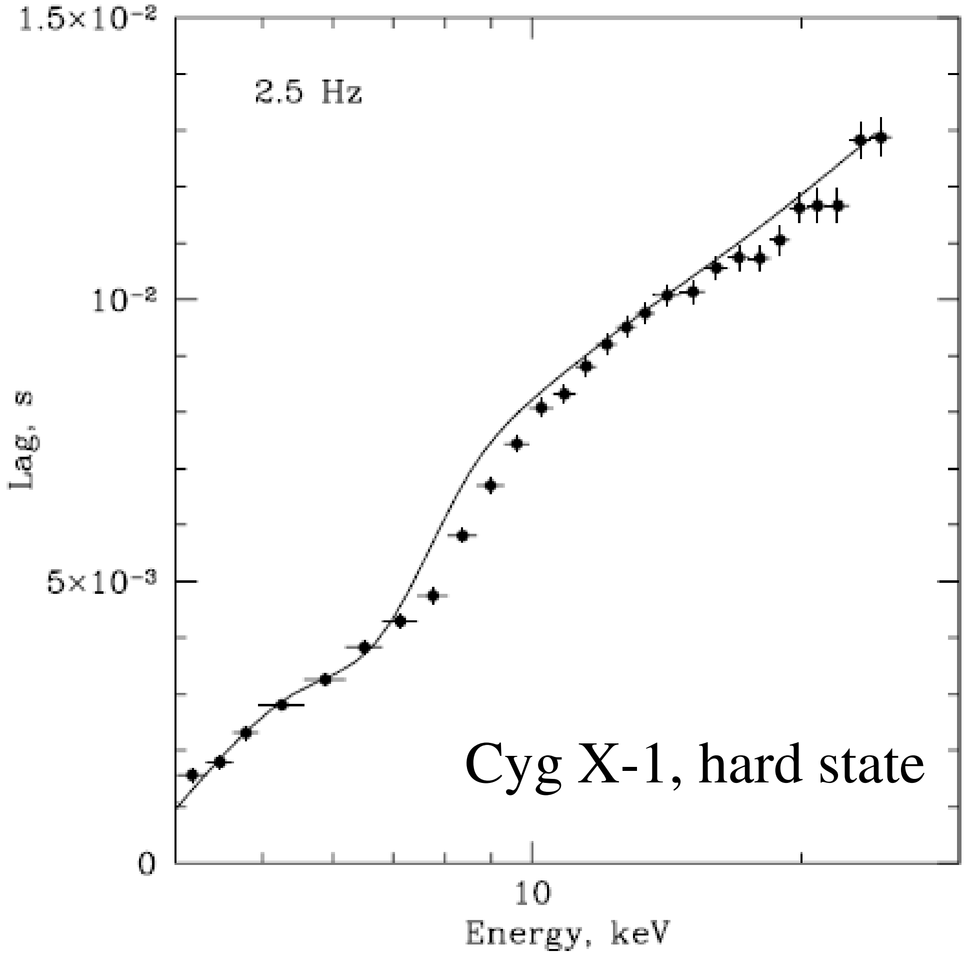


De Marco+17

Fe Kα



The X-ray hard lags



The observed lags are usually explained by fluctuations propagating with the accretion flow (Lyubarsky 1997; Arevalo & Uttley 2006, Ingram & Done 2012), and the local spectrum hardening with the decreasing radius.

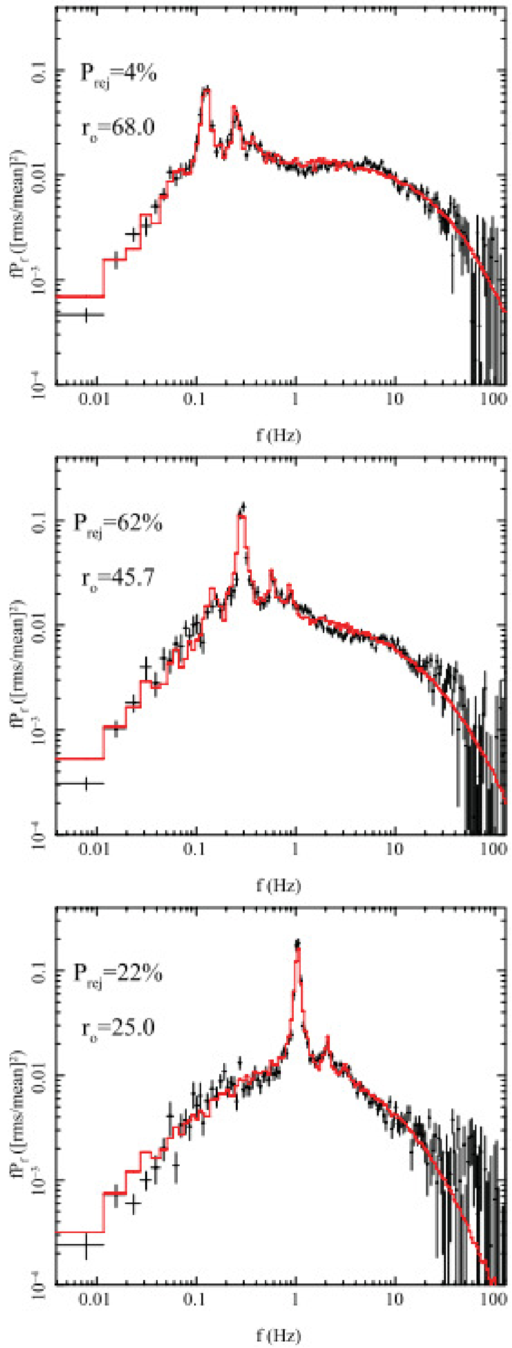
These lags imply the X-ray source is extended, and not confined to the immediate vicinity of the black hole.

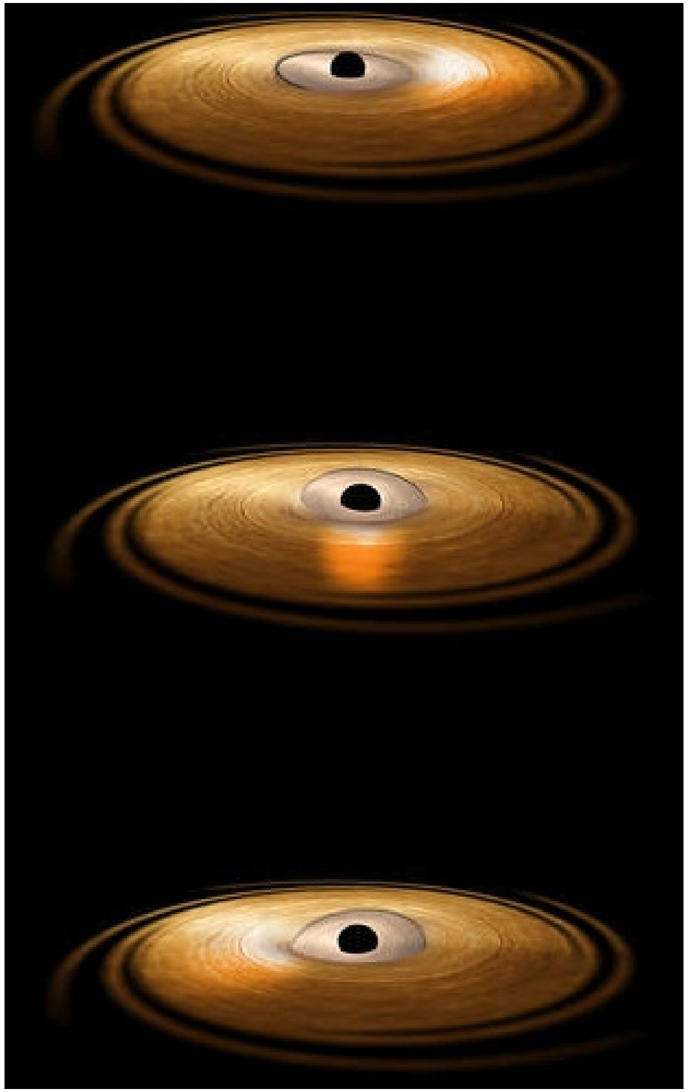
Kotov+ 2001

Inner disc precession: origin of low-frequency QPOs:

A physical model for power spectra in the hard state, based on propagating fluctuations in a precessing inner hot disc.

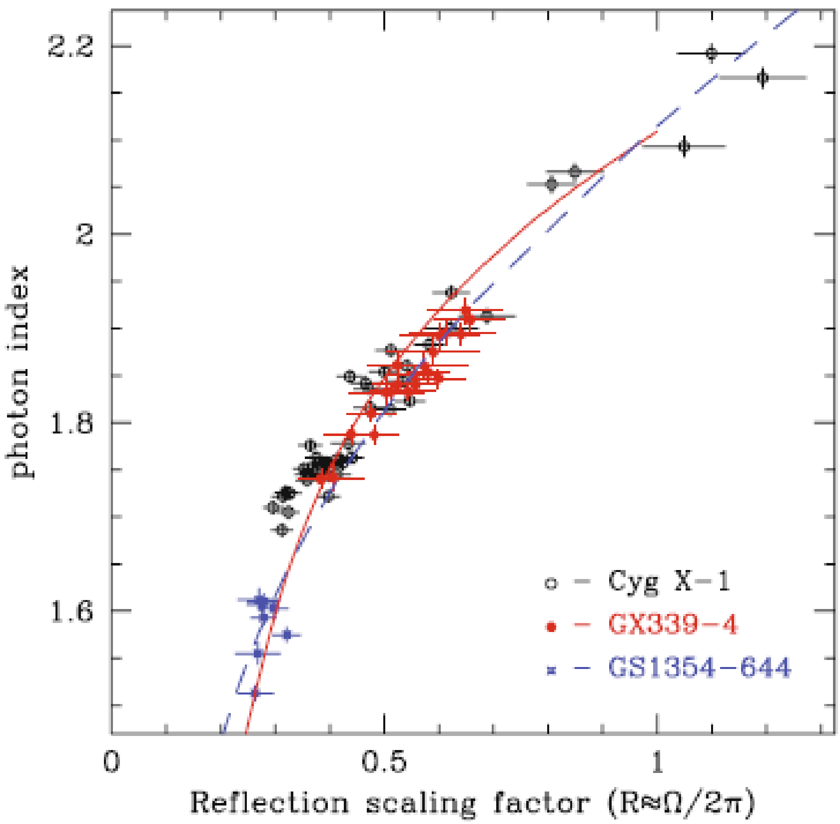
Ingram & Done 12

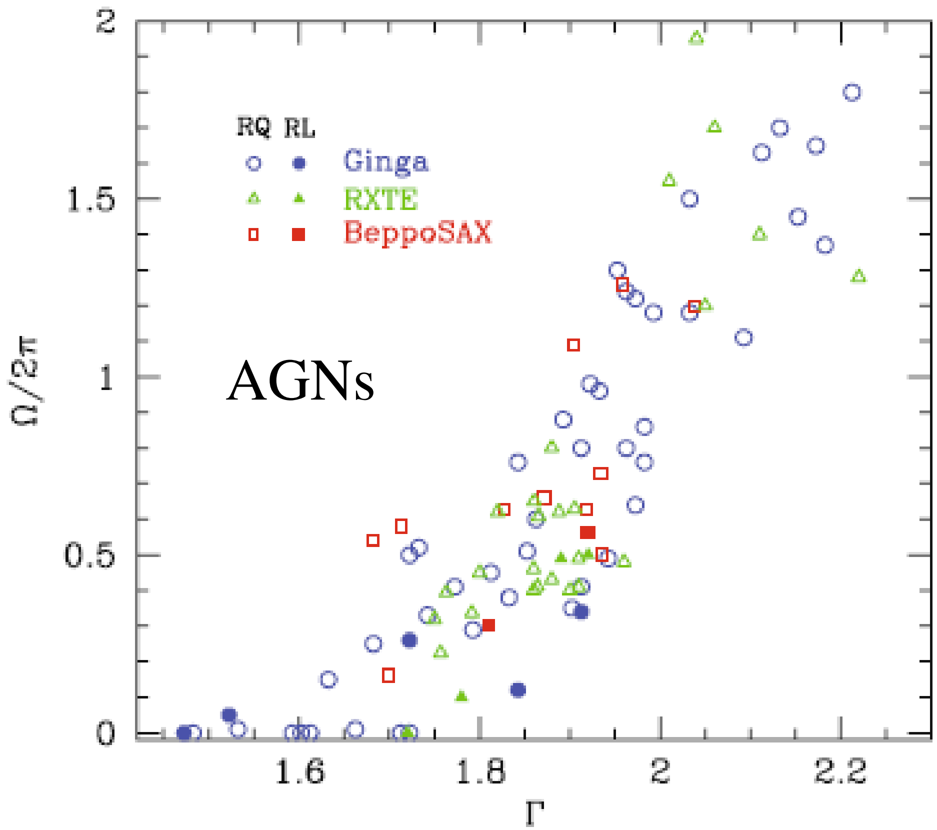




Many papers by C. Fragile, A. Ingram, C. Done etc. Currently a very popular model.

Reflection-index correlation

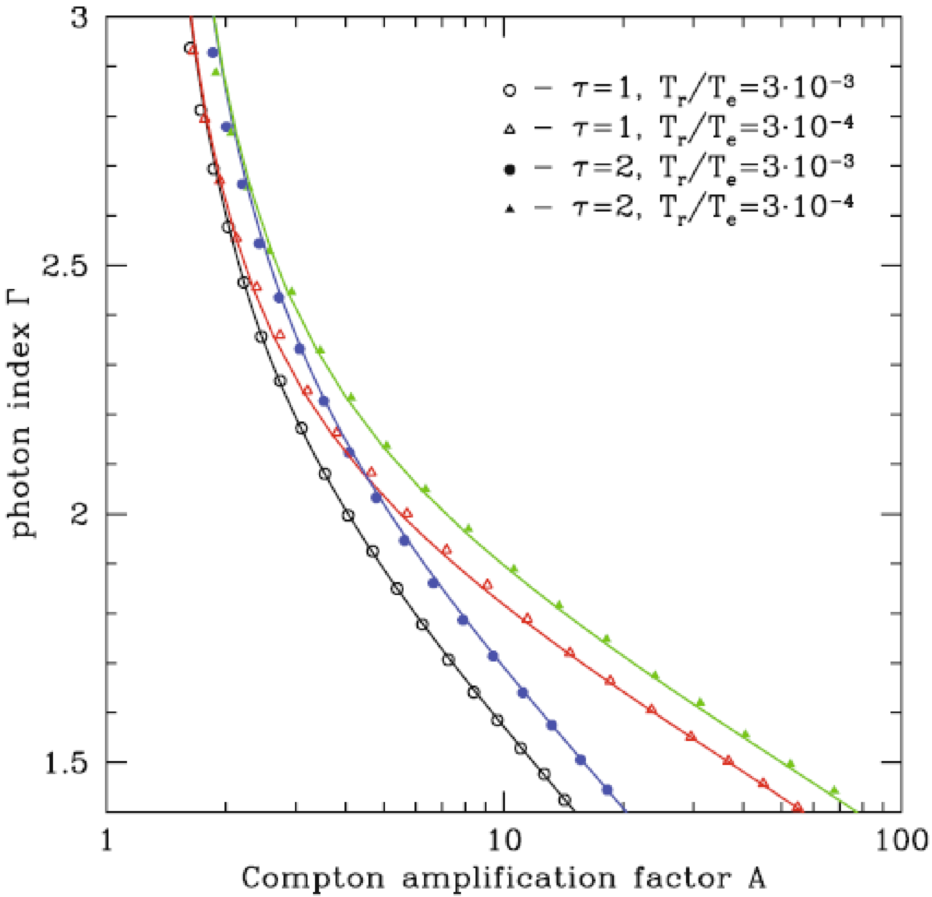


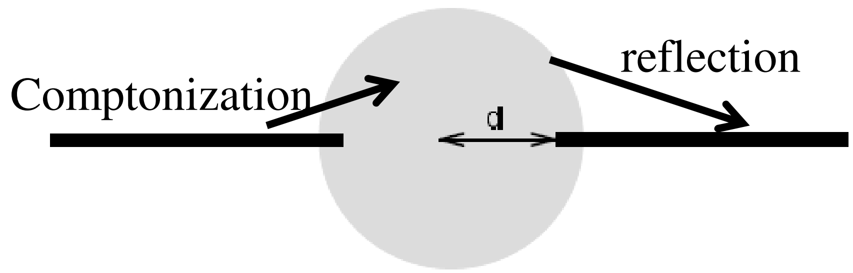


Gilfanov+ 1999; AAZ+ 1999, 2003

The dependence of the spectral hardness on the fraction of seed photons (Compton amplification factor)

Fewer seed photons from the disc → harder spectrum; less disc area seen from the hot source → less reflection.

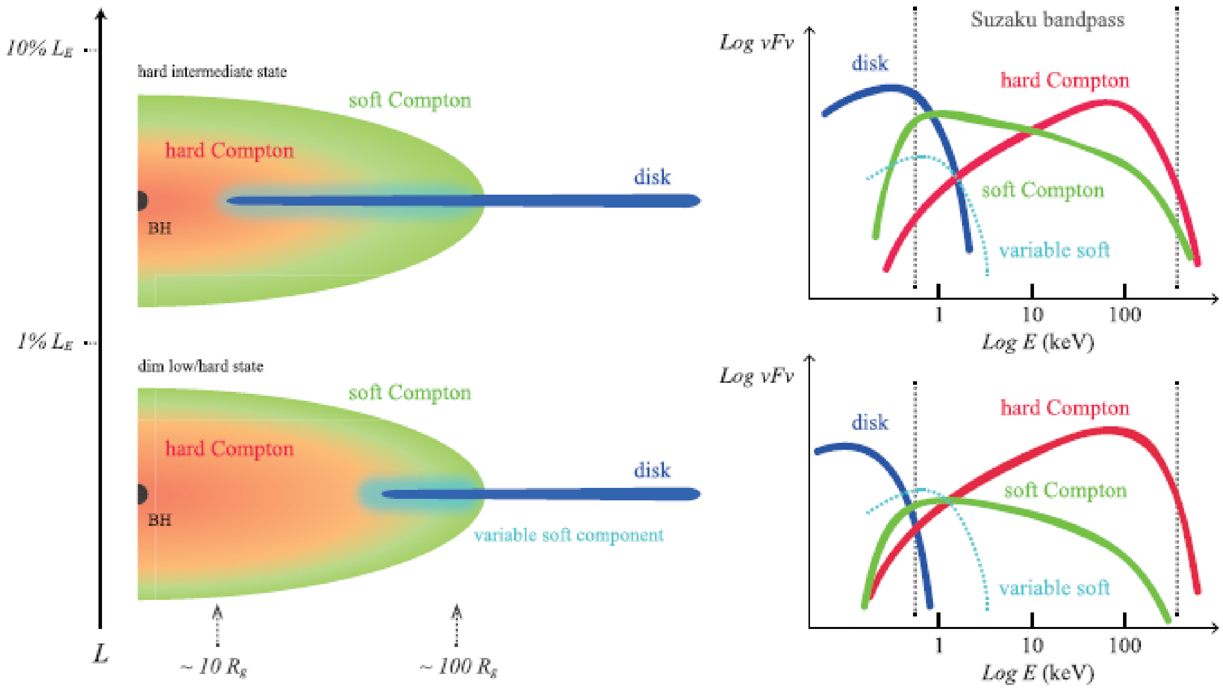




Gilfanov+ 1999; AAZ+ 1999

Suzaku implications for geometry of Cyg X-1

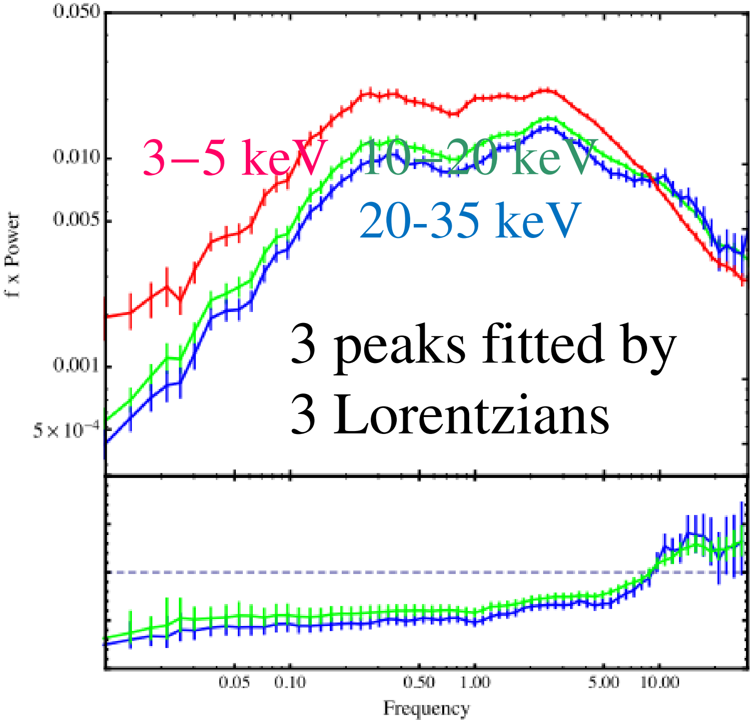
- Yamada+2013 studied broad-band variability of Cyg X-1 in the hard state based on *Suzaku* data.
- They found a number of components have to present. Two Compton clouds are required, hard and soft, confirming a number of previous findings (e.g., Frontera et al. 2001; Di Salvo et aol. 2001). They they found a disc component as well as a variable soft excess.
- Their results are *not* compatible with the disc corona model, and require an overlapping disc/hot flow geometry.
- Fe K fit results strongly depend on the underlying continuum, which is shown to be concave, which in turn decreases the red wing of the line.

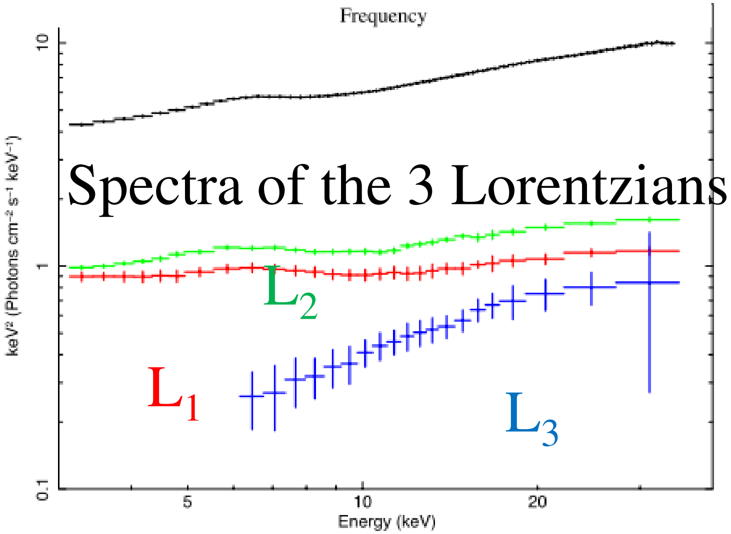


Thus, the disc component claimed by Reis+ 2008, 2009 can be the soft Comptonization component instead.

A continuum complexity:

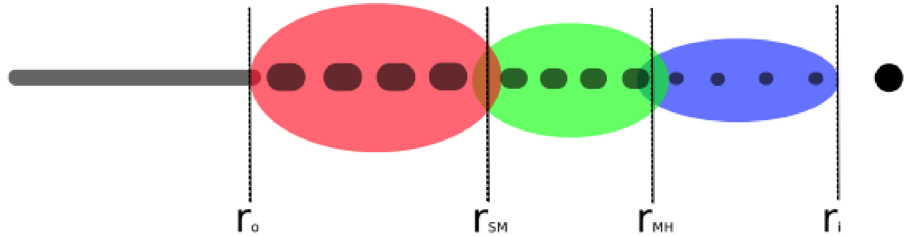
Power spectra in three energy ranges:



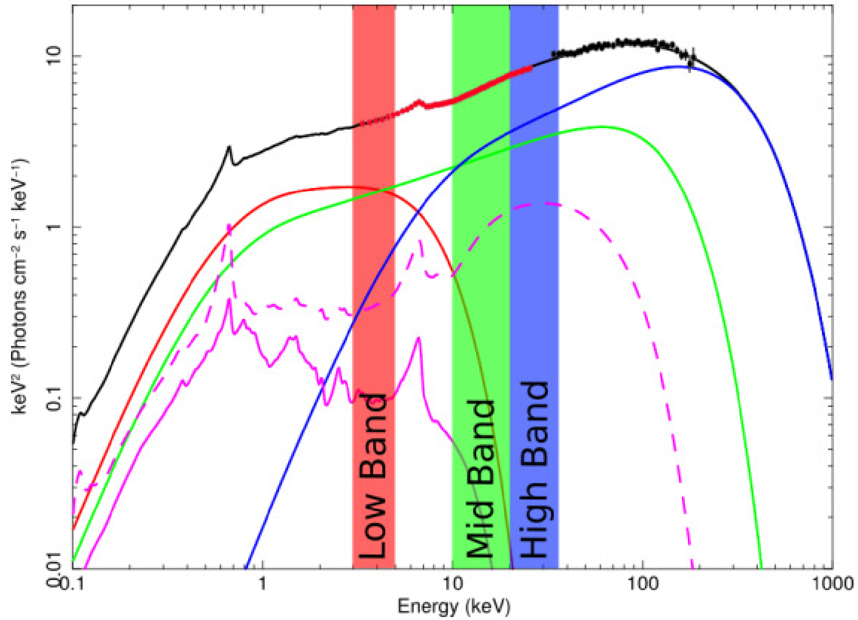


Axelsson & Done 2018

Detailed spectro-timing modelling of Cyg X-1 by Mahmoud & Done 2018, 19 imply a flow with three hot zones:

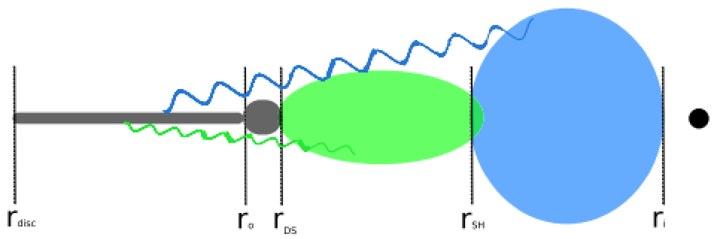


Cyg X-1



The continuum complexity:

- Spectro-timing modelling of GX 339–4 by Mahmoud, Done & De Marco 2019 yield a flows with two cold and two hot zones:

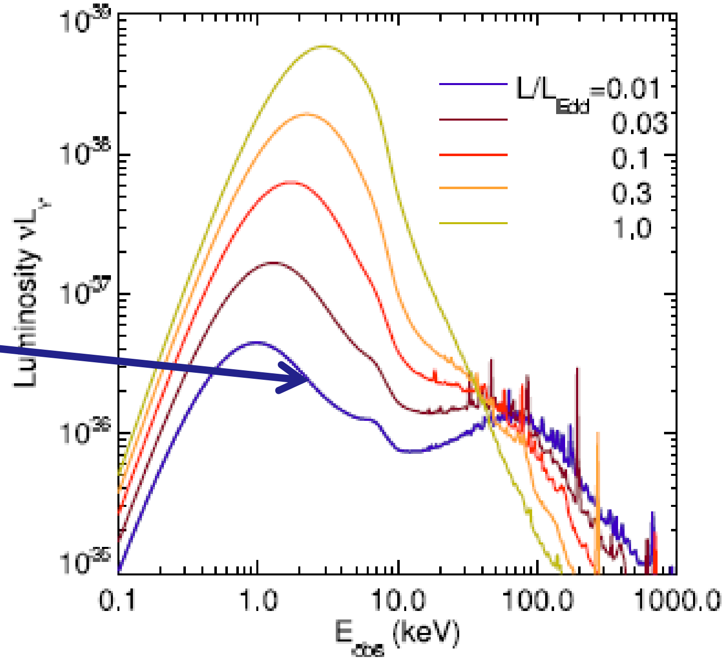


- They have been able to fit with their model the spectrum, the power spectrum and the lags between different energy bands in different frequency ranges.

A disc corona model for the hard state

A claim of explaining the X-ray data by a corona above the disc by Schnittman+2013. They used results of GRMHD simulations to which they added radiative transfer. They stated their spectra at low luminosities are consistent with the hard state, comparing it to the power-law index fitted at 10–100 keV. However, their figure shows very soft spectra at $E \approx 1$–10 keV, with $\Gamma \sim 3$. Thus, their results confirm that the static disc corona model is unable to explain the hard state.

the claimed hard-state model



Different possible disc-corona geometries and energy balance

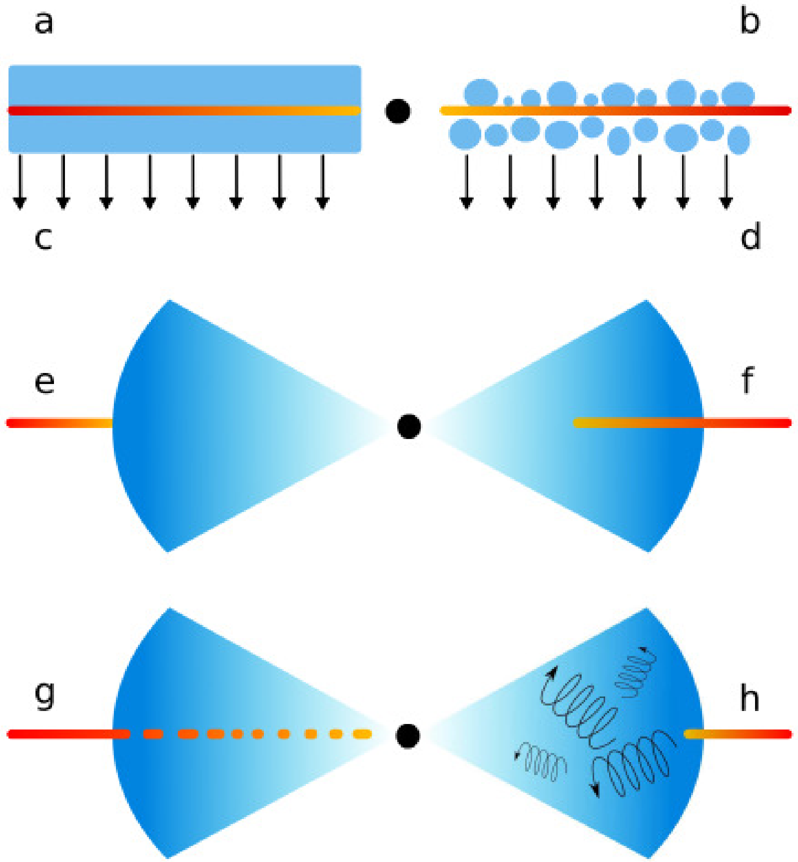
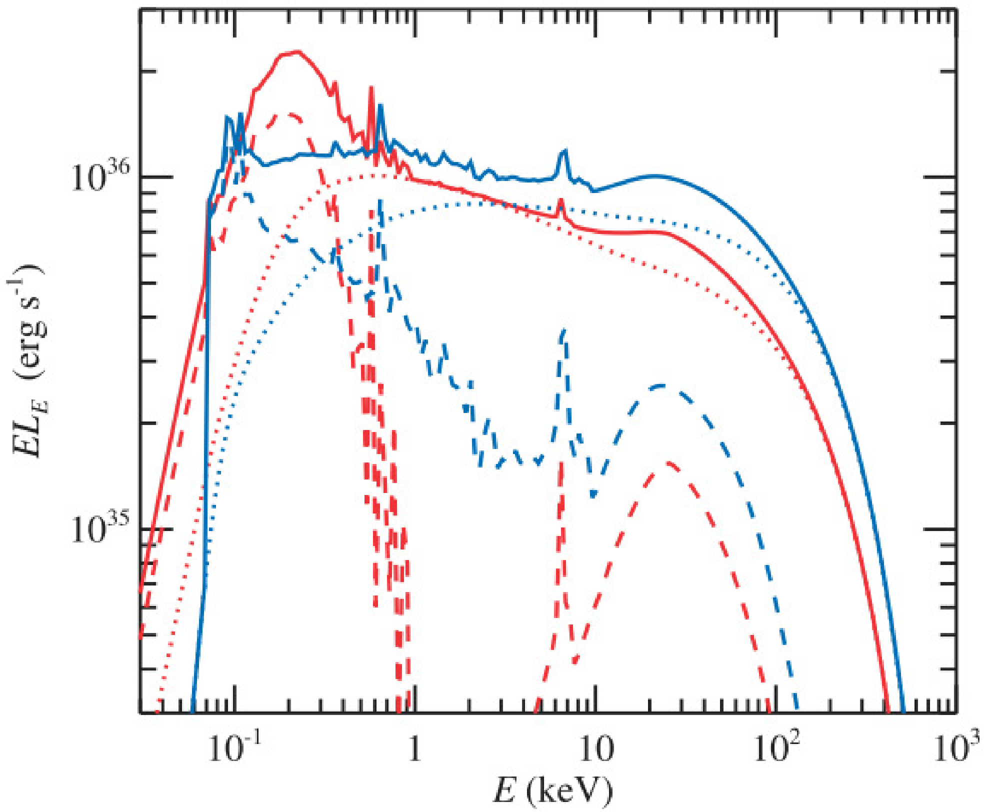


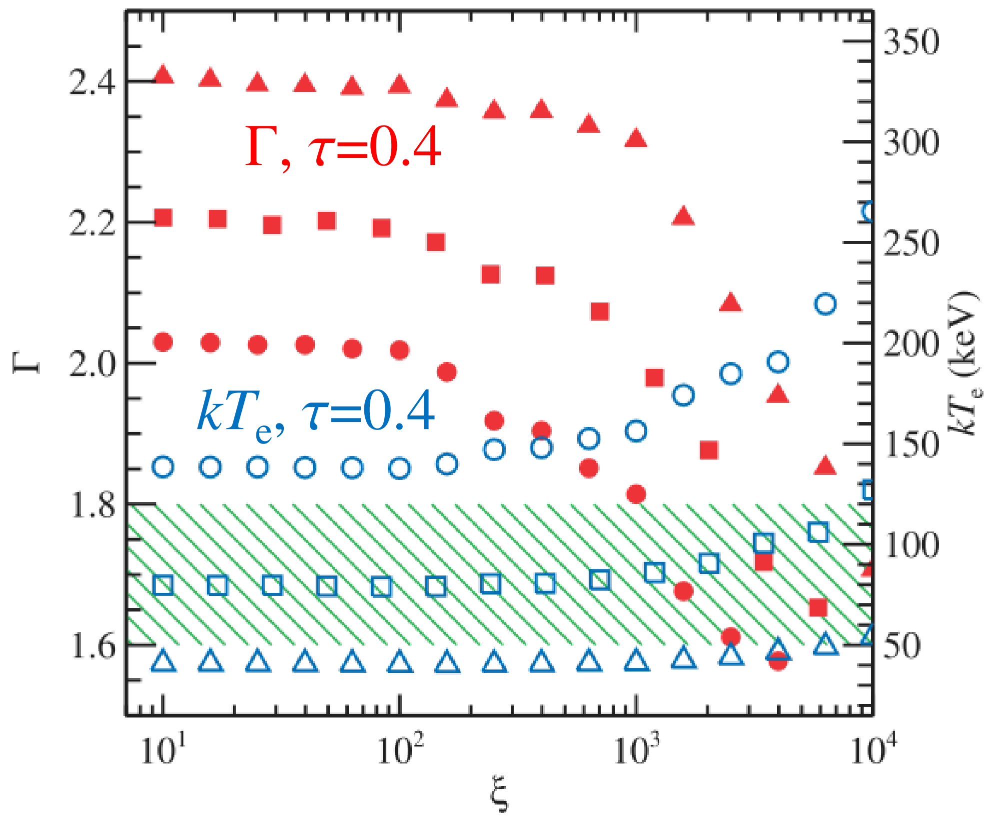
Fig. 1. Geometries of the central parts of the accretion flow proposed over time. (a) Static sandwiching corona, (b) static patchy corona, (c) outflowing sandwiching corona, (d) outflowing patchy corona, (e) cold accretion disc detached form the hot flow and (f) intersecting with it, (g) hot flow with cold condensed regions, (h) truncated disc and hot flow with substantial cyclo-synchrotron radiation.

- The cold medium is irradiated by the emission of the hot plasma. It partly back-scatters the irradiating photons (Compton reflection), and partly absorbs them and re-emits.
- The reprocessed radiation cools the plasma.
- We use the current best reflection/reprocessing code (by J. García).
- We calculate the self-consistent X-ray spectra.
- **We find only the cases f, g, h to be compatible with the observational data.**

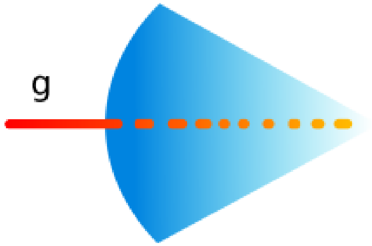
Poutanen, Veledina & AAZ 2018

• A homogeneous corona above a disc

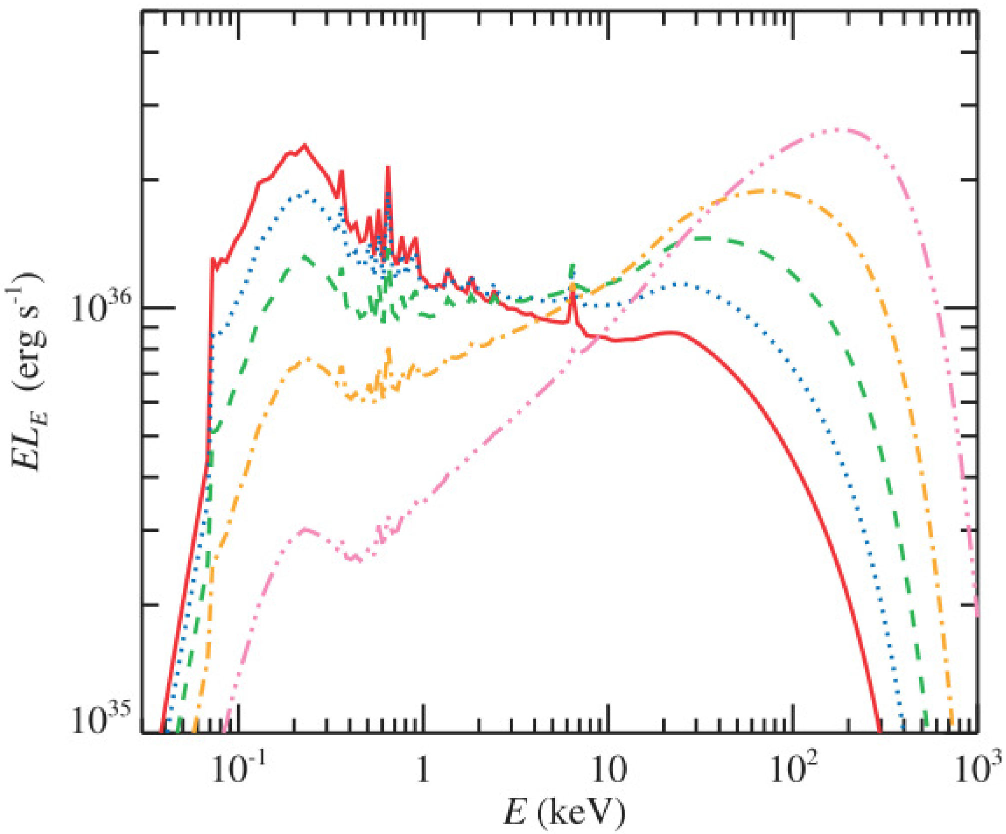


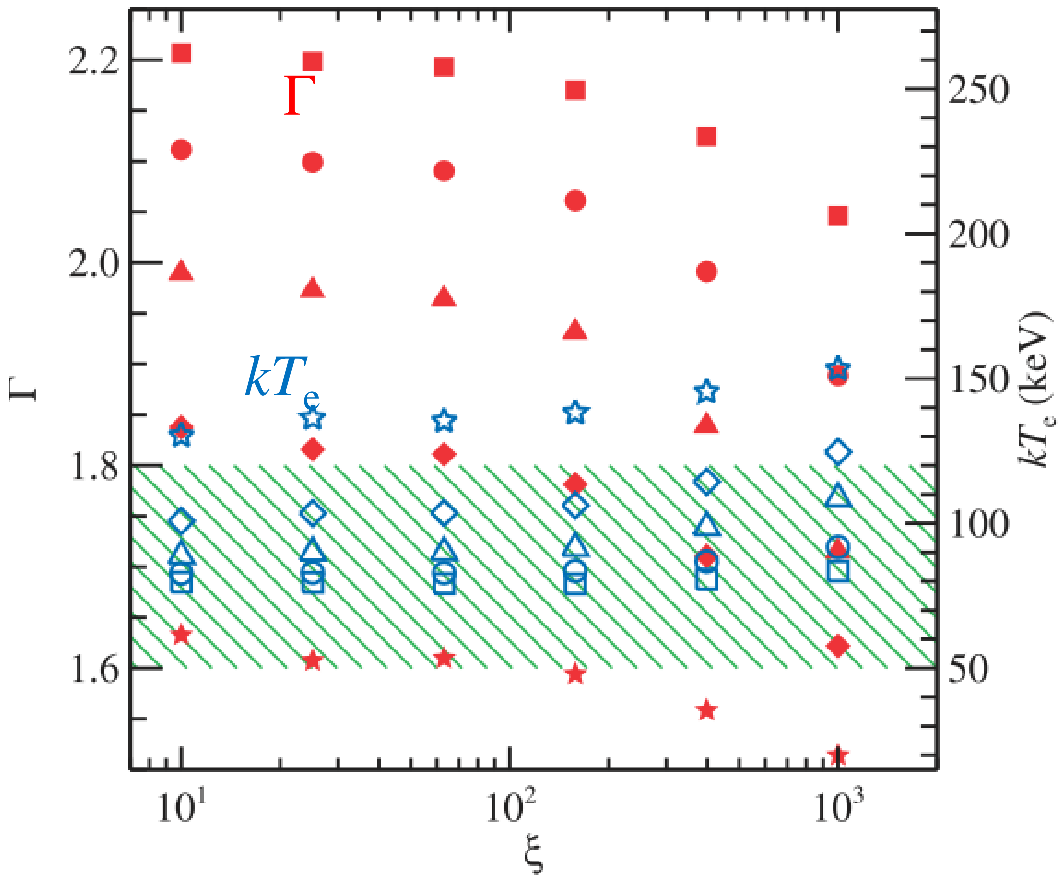


Spectra in this geometry are too soft. In order to match the observations, the spectral index $\Gamma \approx 1.6$–1.9 and the electron temperature of $kT_e \approx 50$–100 keV are required. Thus, this geometry is ***not*** compatible with the hard-state data.



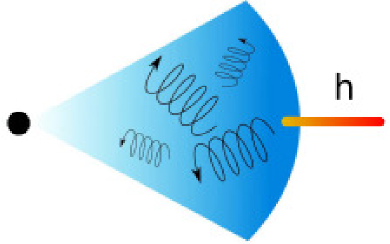
• Cold clumps within the hot flow





Spectra in this geometry can be compatible with the observations (Γ≈1.6–1.9, kT_e≈100 keV). The cold clouds cover a fraction, f_{cl}, of the plane of the flow. Other geometries with a partial overlap of the hot and cold phases remain also possible.

Synchrotron emission within the hot flow surrounded by a truncated disc



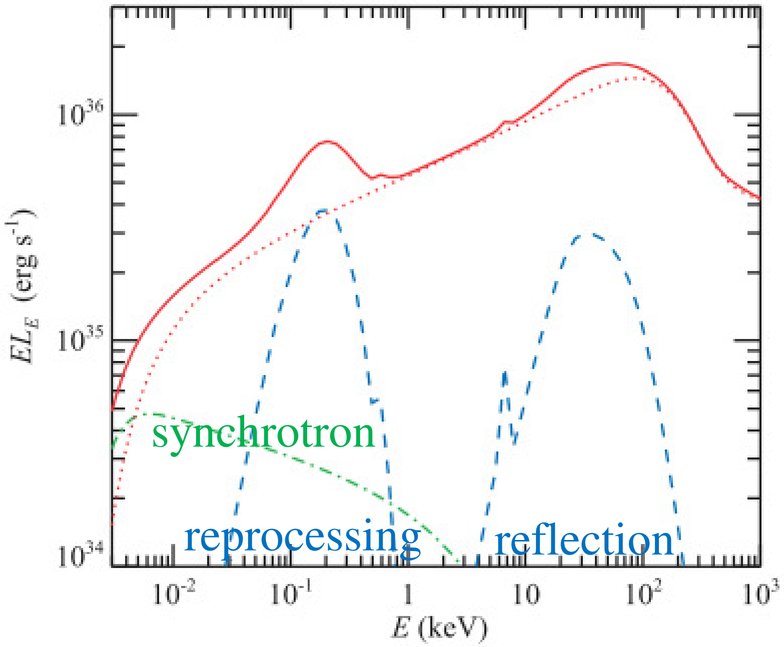


Fig. 6. An example of a synchrotron self-Compton spectrum from a hot plasma with a hybrid electron distribution. The components due to reflection/reprocessing with the reflection fraction of 0.3 and the ionization parameter of ξ = 10 and the blackbody of the temperature of 50 eV due to the reprocesses emission are shown together by the dashed curve. The Comptonization spectrum is shown by the dotted curve, and the total spectrum is given by the solid curve.

In order for the synchrotron emission to be efficient at the observed $kT_e \approx 50\text{–}100$ keV, the electron distribution is hybrid, Maxwellian with a high-energy tail. The model is compatible with observations.

Is the disc fully passive?

- No.

Wilkinson & Uttley 2009:

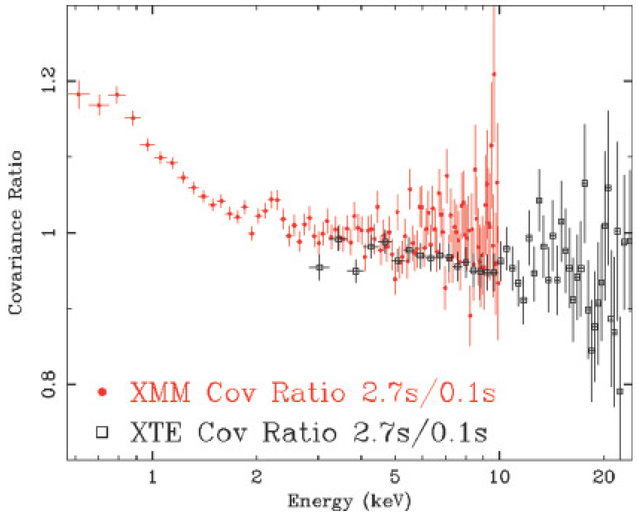
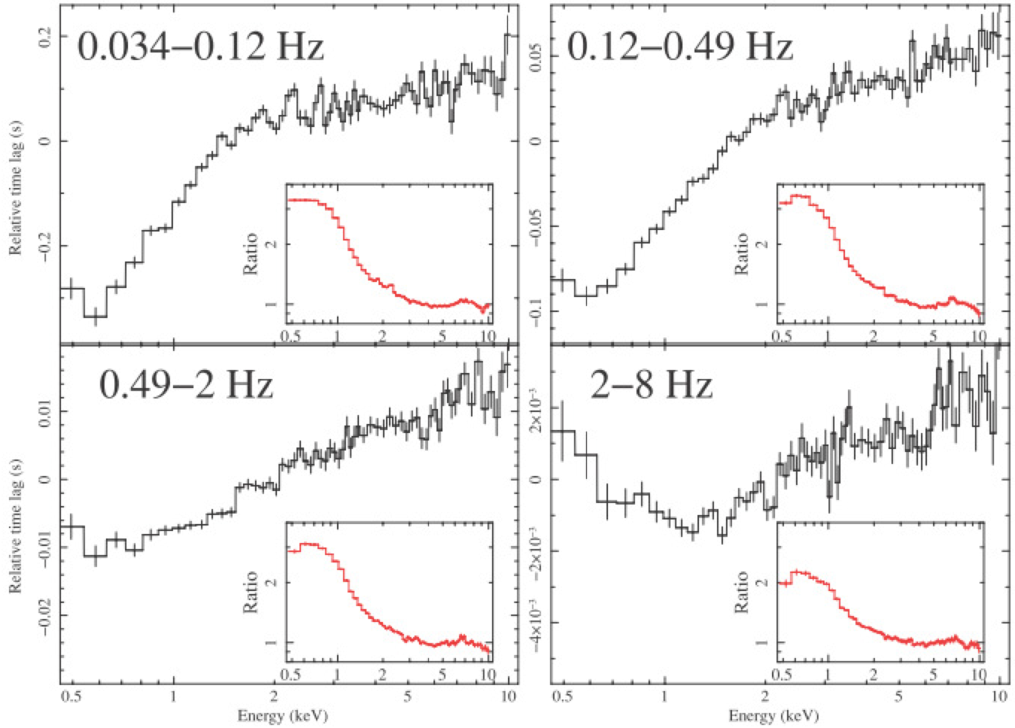


Figure 6. Covariance ratios for GX 339−4 showing the extra thermal component on longer time-scales.

Uttley+2011 GX 339–4



The disc variability leads that of the harder X-rays on long time scales. Thus, there is an intrinsic (variable) dissipation in the disc.

The lamppost geometry

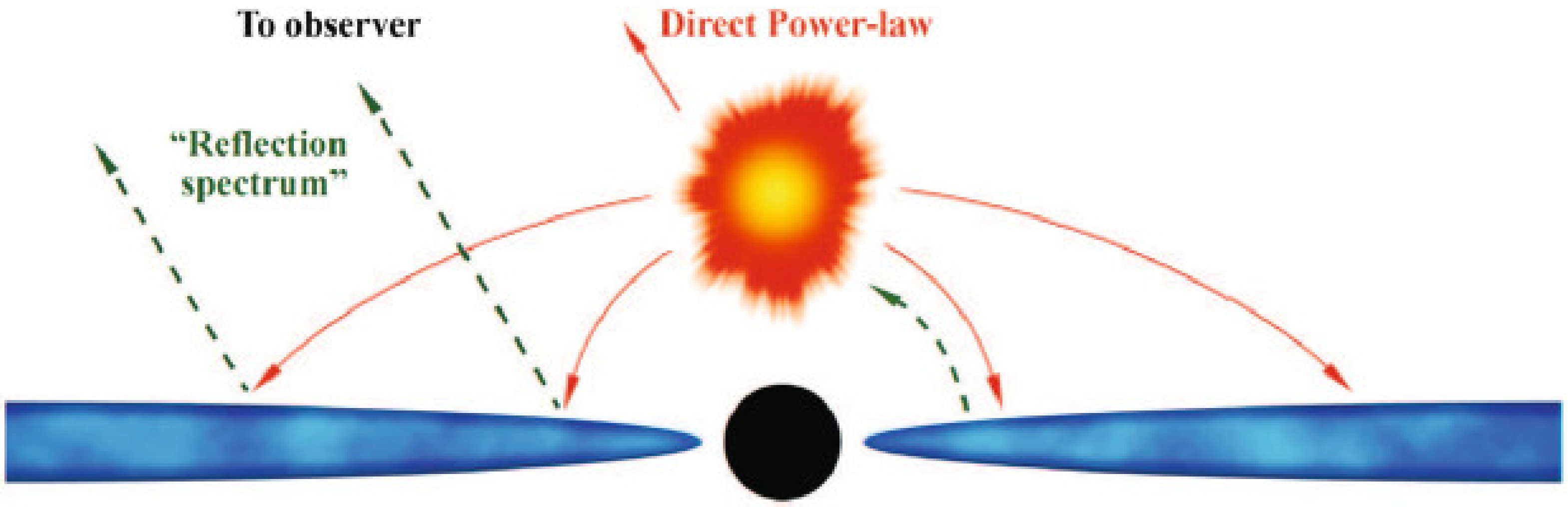


Fig. 1 Schematic diagram showing the power–law emitting corona (*orange*) above the accretion disc (*blue*), orbiting about a central black hole. The observer sees both the direct power–law and its "reflection", or back-scattered spectrum. The black hole causes strong gravitational light bending of the innermost rays. The reverberation signal is the time lag introduced by light-travel time differences between observed variations in the direct power–law and the corresponding changes in the reflection spectrum

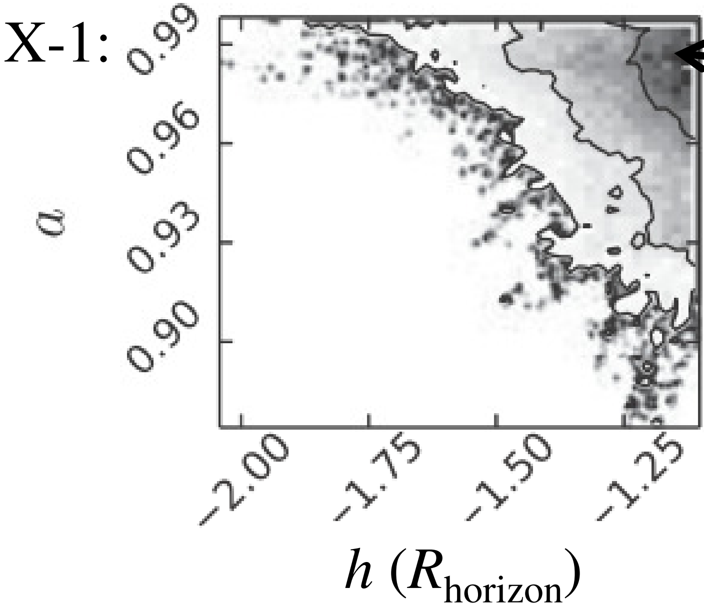
Uttley+ 2014

The lamppost model

- Originally, this model was adopted to describe Compton reflection only due to its mathematical simplicity.
- In recent years, it has been taken literally and claimed to describe the real geometry of the hard state.
- ~100% of the Comptonized emission in the lamppost; dissipation in the blackbody disc at a small fraction of the actual $\dot{M}$.
- How is the energy released gravitationally in the disc transferred to the lamppost without dissipation on the way? What is the efficiency of its energy dissipation?

Problems with physical self-consistency of some lamppost fit results

- The fitted parameters are often extreme, e.g., Keck+ 2015 for the active galaxy NGC 4151 find $a \approx 0.98$, $h \approx 1.3$. Parker+ 2015 find similar values for Cyg X-1:



best fit very close to $a \approx 1$, $h \approx 1$.

h is the source height in units of $R_{\rm horizon}$

- Most of photons produced in such lampposts are light-bent and cross the horizon of the BH. For $a \approx 0.98$, $h \approx 1.3$, 50 times more direct photons cross the horizon than escape to large distances. Then we need to increase the accretion rate by this factor to account for this effect.

Niedźwiecki, AAZ & Szanecki (2016)

Accretion rates implied by the lamppost model

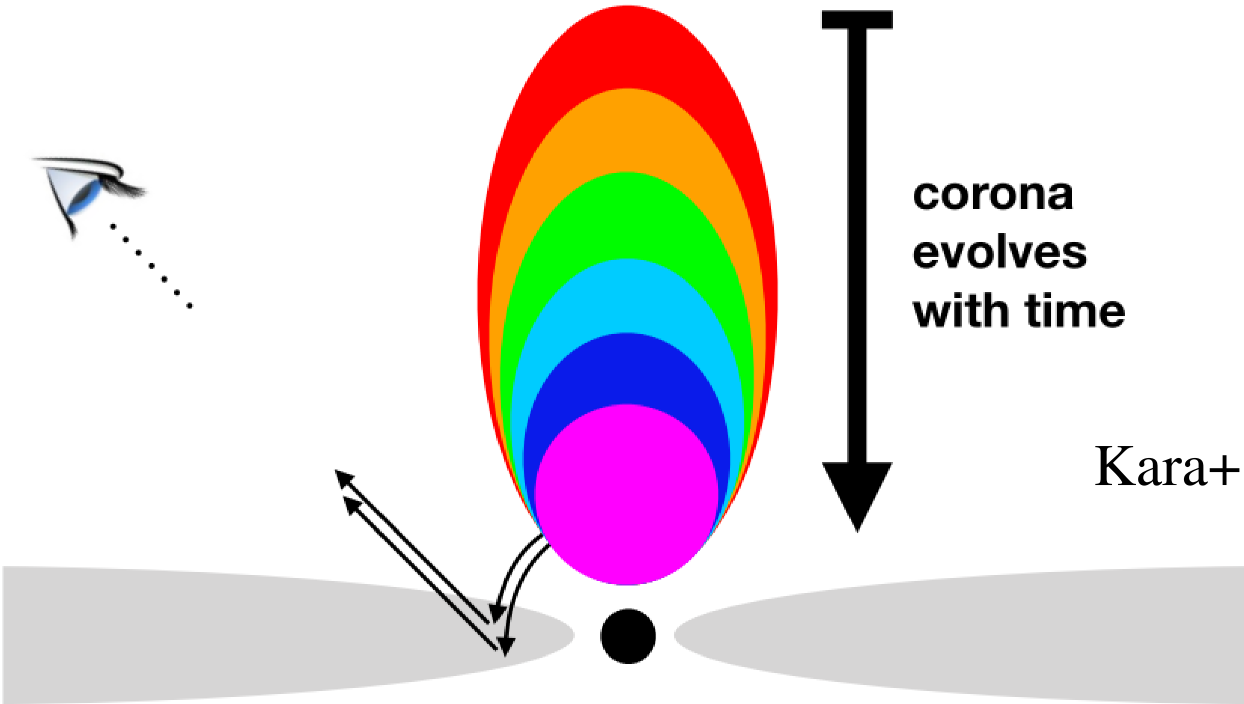
- The accretion rate of NGC 4151 would then be ~Eddington, and its radiative efficiency would be $\sim 10^{-3}$. This is in principle possible, but if common, it would create a problem for the measured average AGN accretion efficiency of $\gtrsim 0.1$.
- In the soft state of BH binaries, there is a large body of evidence that it corresponds to an optically thick accretion disc extending to the ISCO. Even for a maximum Kerr BH, 50% of the emission comes from $>5\ R_g$. Consequently, the effect of photon trapping by the BH is weak in that state. Also, the radiative efficiency of the optically disc is well-known and high. Furthermore, observations show that the increase of the luminosity when transiting from the hard state to the soft one is small, by a factor of ~2.
- Thus, the very strong photon trapping by the BH in the hard state would imply that ***the accretion rate in the hard state were higher*** (or even much higher) ***than that in the soft state***, contrary to a large body of observational and theoretical results.

Electron-positron pair production in the lamppost

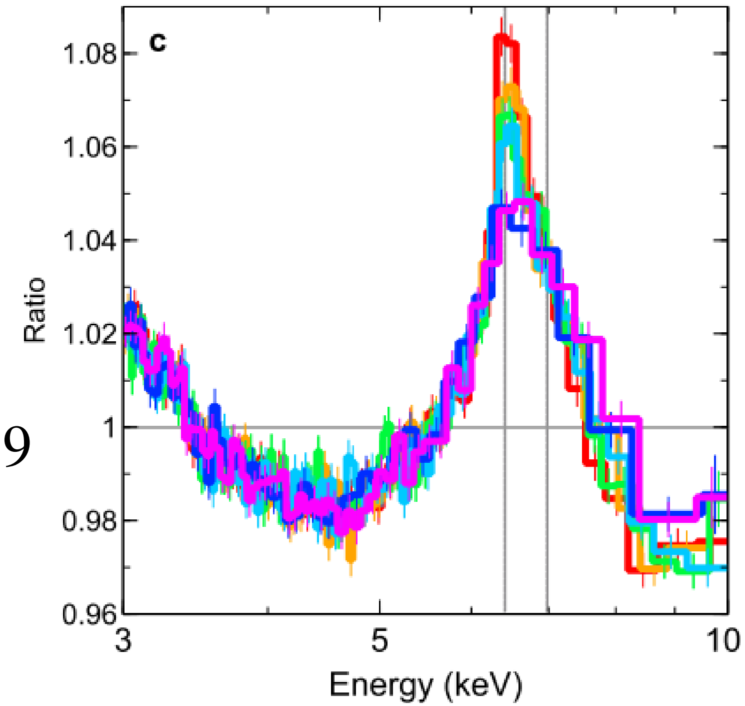
- The parameters in the source frame are even more extreme. Photons in the local frame have (1+z) higher energies than those observed; e.g., $z = 6$ for the model of Keck+ 2015. The redshift, time dilation and light bending increase the locally-measured luminosity with respect to that observed (e.g., by a factor of 2000 for the model of Keck+ 2015).
- The observed high-energy cutoffs in the hard state of BH binaries and in Seyferts are at ~100 keV. Thus, they would be at several hundred keV in the lamppost frame, with a lot of photons above the threshold for $e^{\pm}$ pair production. The local luminosity would be also very high.
- Our calculations show that such sources would be much above the pair equilibrium limit, with the pair production rate exceeding the annihilation rate by orders of magnitude.

The origin of the Fe K line in MAXI J1820+070

The moving-lamppost model appears to contradict the apparently constant broad Fe Kα component observed. The lamppost corona close to the disc would produce a much broader line than that far above it. Thus, this model has the same problem as that of a truncated disc with a variable truncation radius.



Kara+19



Conclusions

- The disc is truncated during the quiescence and it is at the ISCO in the soft state.
- The controversy regarding the disc evolution during the hard state.
- The truncated disc/hot inner flow model explains a lot of observables by now.
- The main argument for the disc extending to ISCO is the presence of apparently broad Fe Kα lines.