Accretion in black-hole binaries: how does the inner flow look like?

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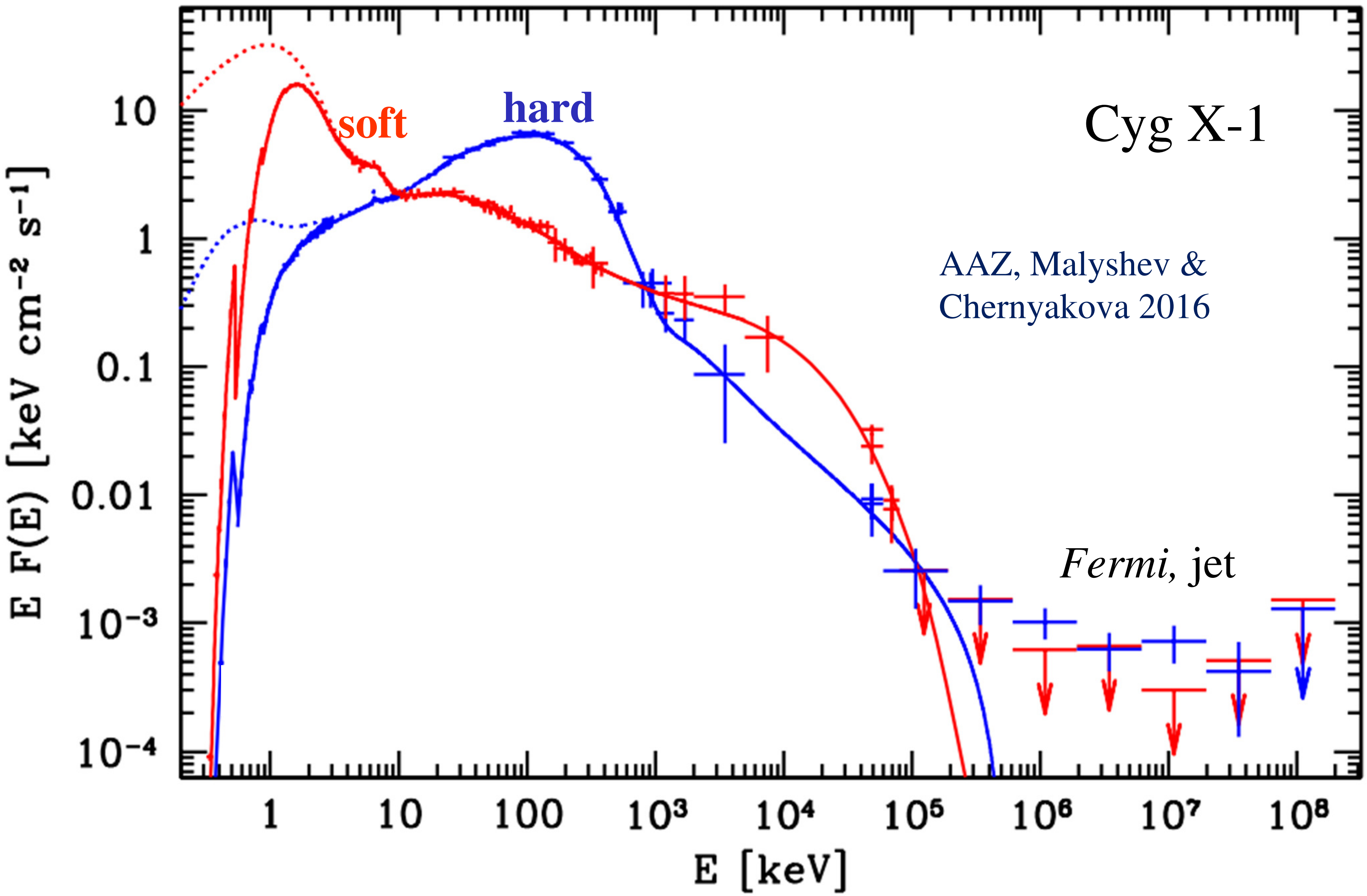
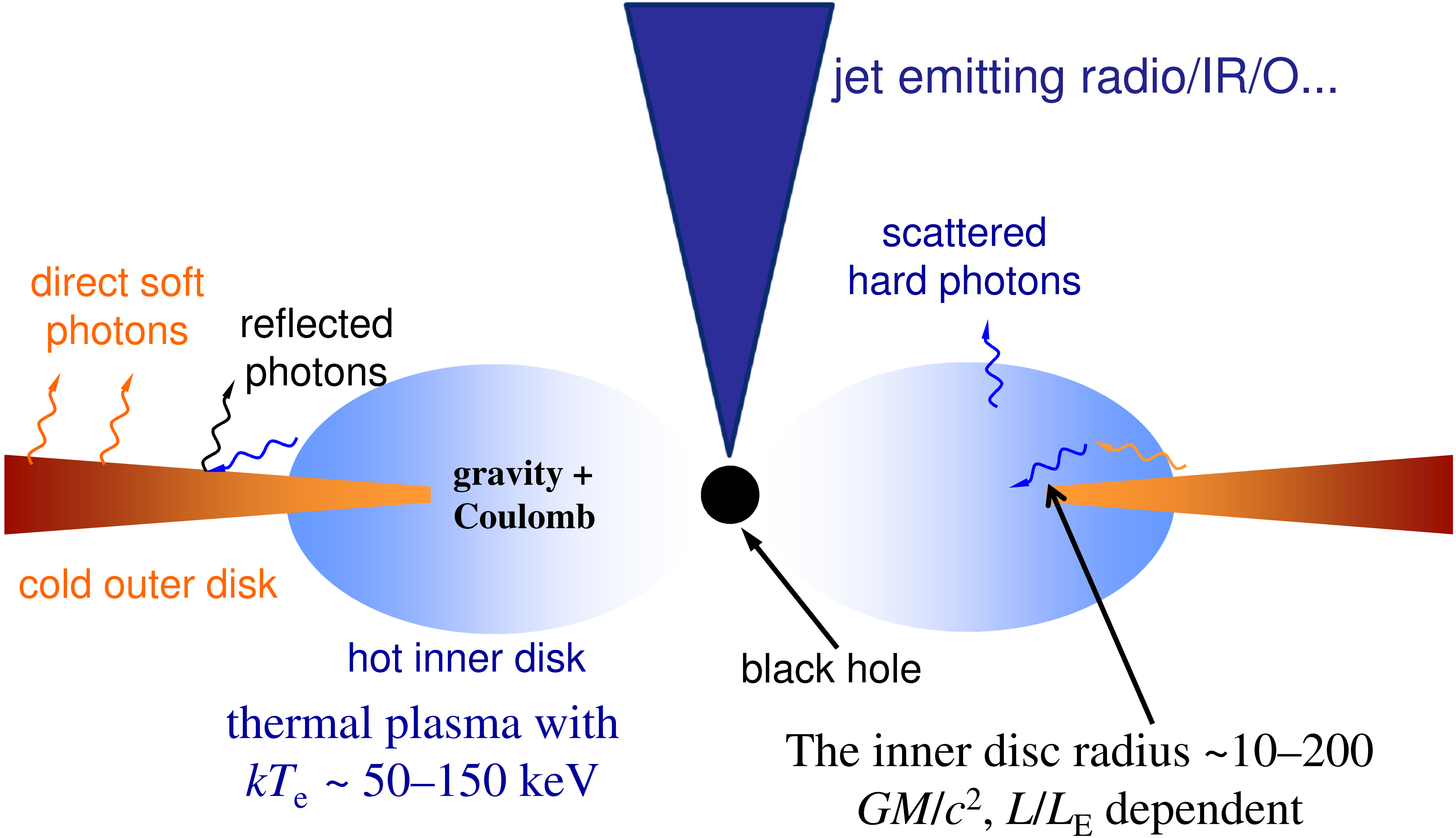
Two main spectral states of black-hole binaries, hard and soft



The hard state of BH binaries

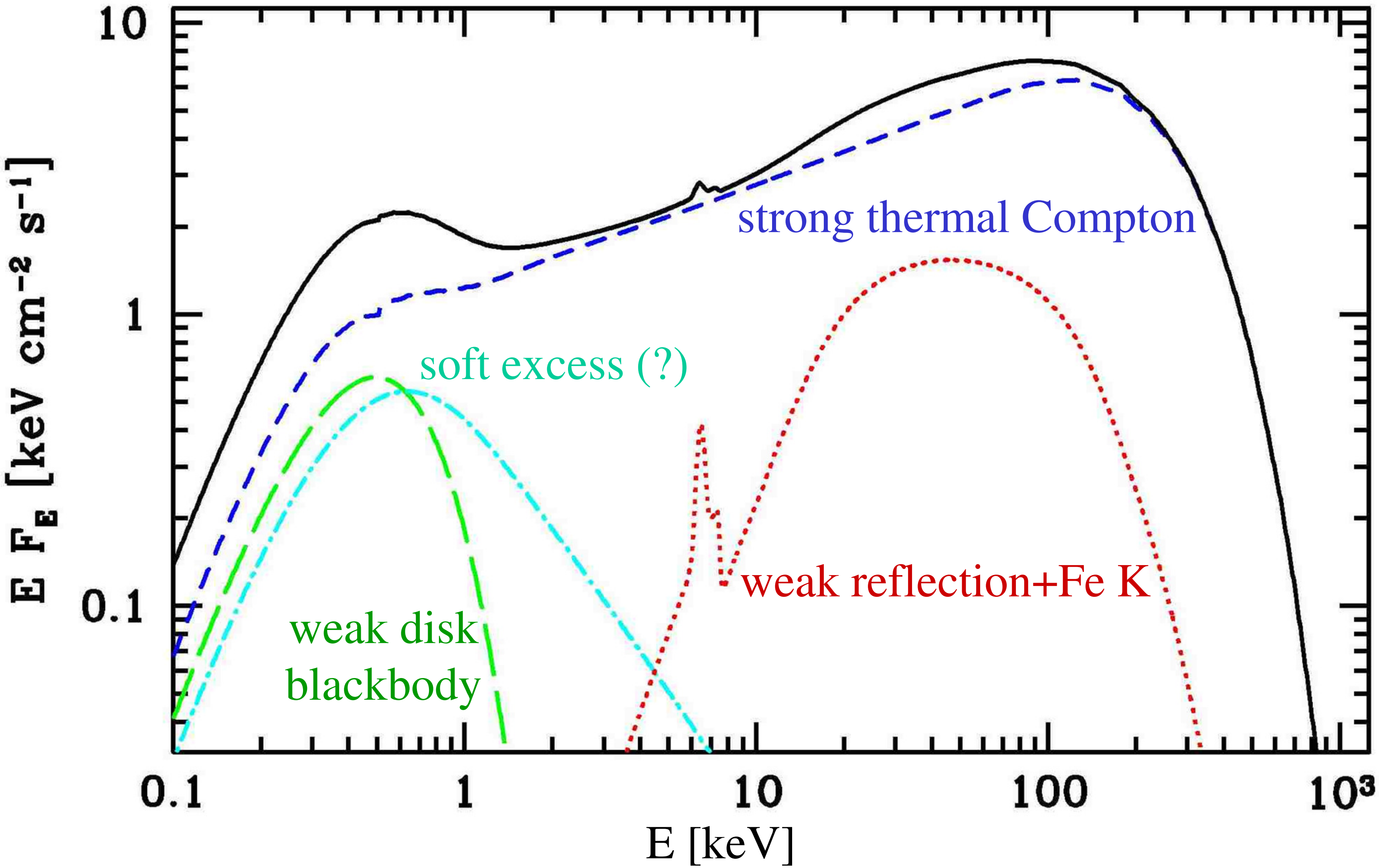
- Disputed geometry and components, either:
  - a hot inner flow overlapping with an outer disc;
  - the same with some blobs of cold matter;
  - a disc extending to ISCO with a corona;
  - the X-ray emission from a jet.
- The main physical process, either:
  - Compton upscattering by thermal electrons;
  - Compton upscattering by hybrid, thermal and non-thermal, electrons;
  - synchrotron emission.
- The main seed photons for Compton scattering, either:
  - disc blackbody photons;
  - synchrotron photons.

The truncated disc model for the hard state:



Cyg X-1: typical hard state spectrum fitted by the truncated disc model

$\frac{L_{\rm hot}}{L_{\rm disk}} \gg 1$



AAZ & Gierliński 2004

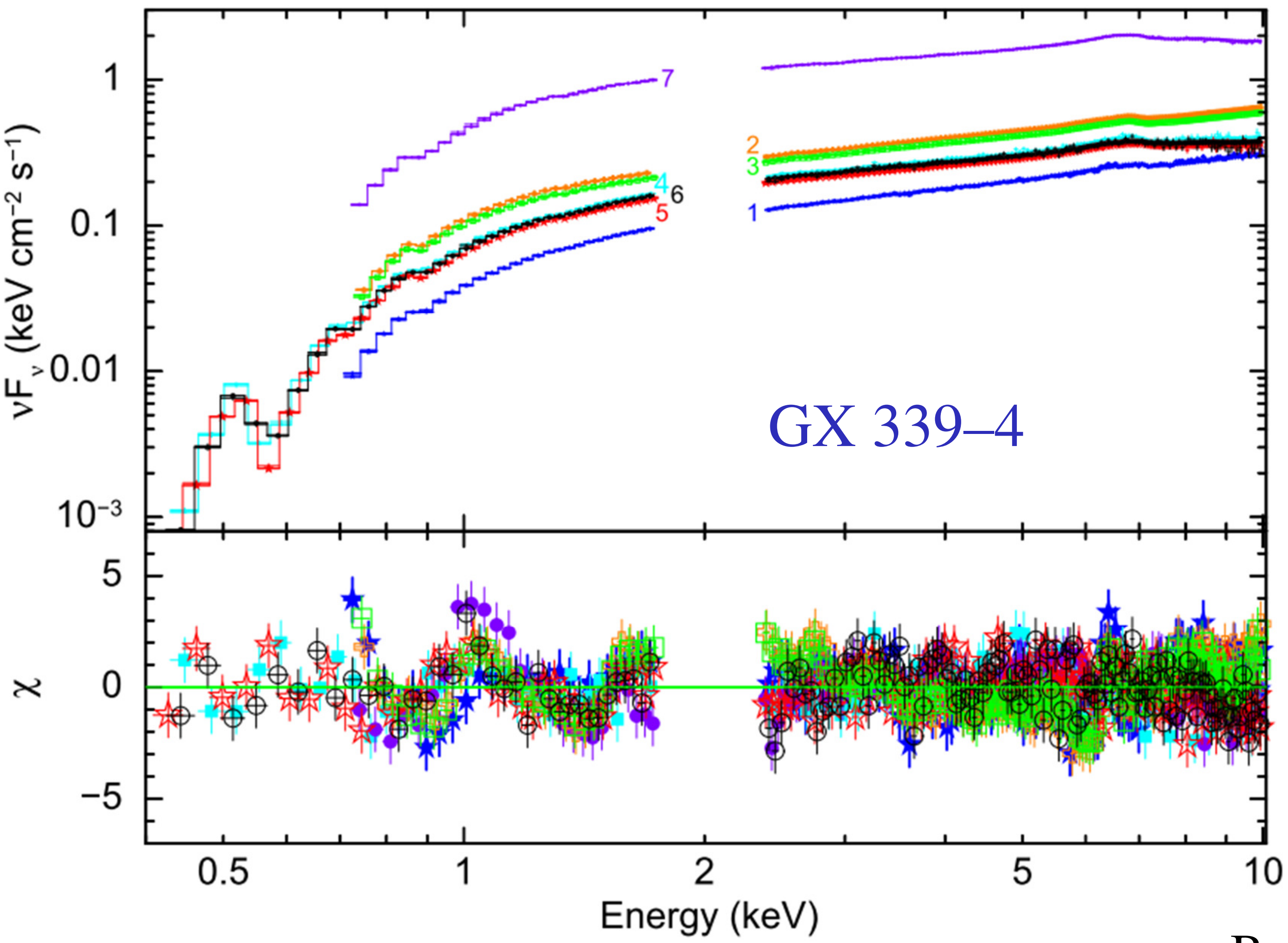
$kT \approx 50$–100 keV, $\tau_T \sim 1$, $\Omega/2\pi \approx 0.3$, $L \approx 1$–2% of L_E

(1) The black-hole binary GX 339–4

Basak & AAZ (2016), MNRAS

- A low-mass black-hole binary, P = 1.76 d, $M > 5.8\ M_\odot$, the distance ~8 kpc; the most-often outbursting transient.
- **The first, and a prime, black-hole binary with an extremely broad Fe K line in the hard state claimed (Miller et al. 2006). Many later claims.**
- We have reanalyzed all (7) of the *XMM-Newton* observations in the hard state, using the EPIC-pn data.
- We use the reflection model of Garcia & Kallman with the treatment of GR effects by Dauser et al. (relxill).
- We include a disc blackbody component and its thermal Comptonization, which provides the photons incident on the disc.

The analyzed spectra from *XMM-Newton*

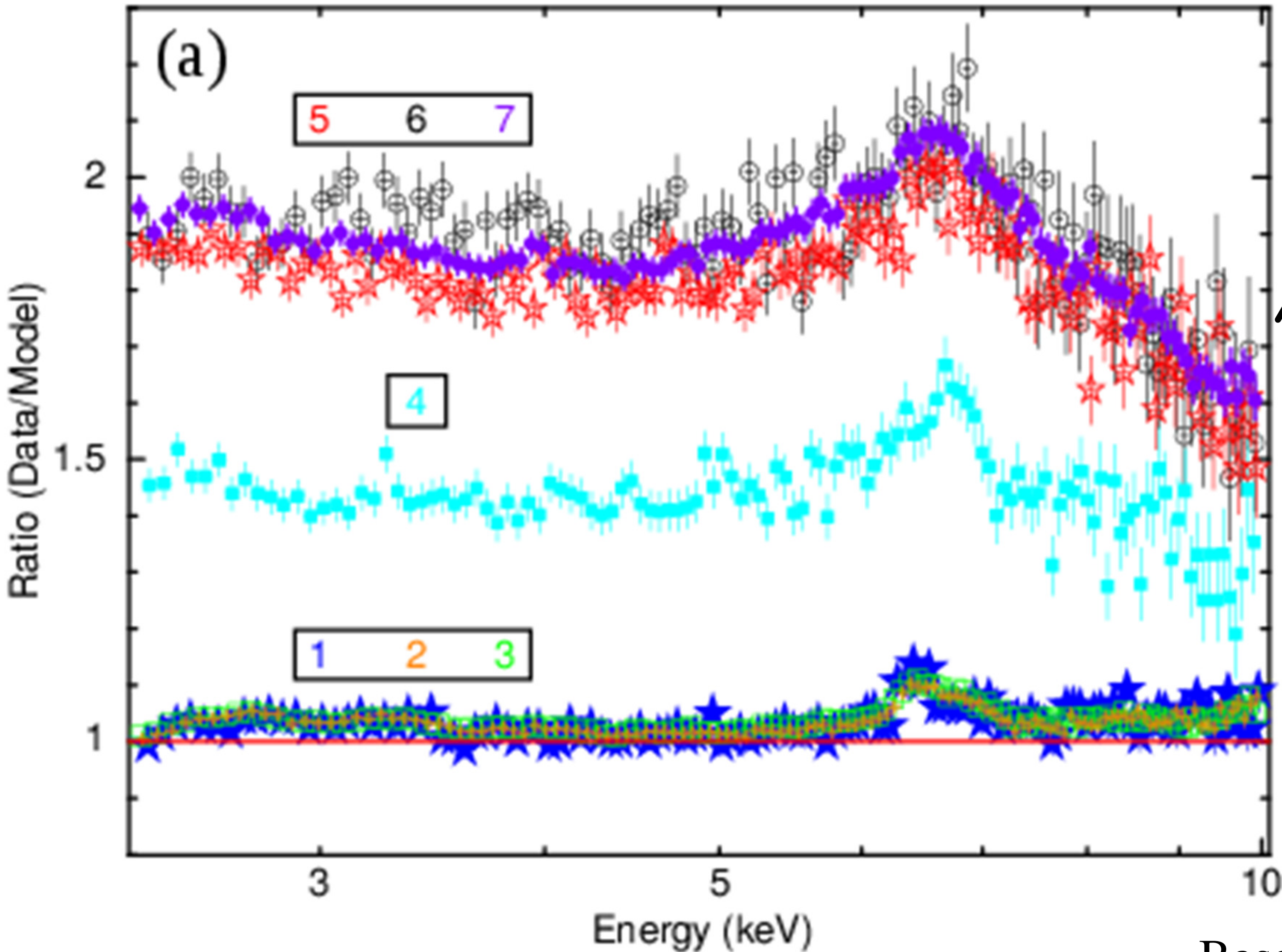


~3–15% of L_{Edd}

decreasing hardness, ~ increasing flux

Basak & AAZ 2015

The ratio of the reflection component to the irradiating spectrum



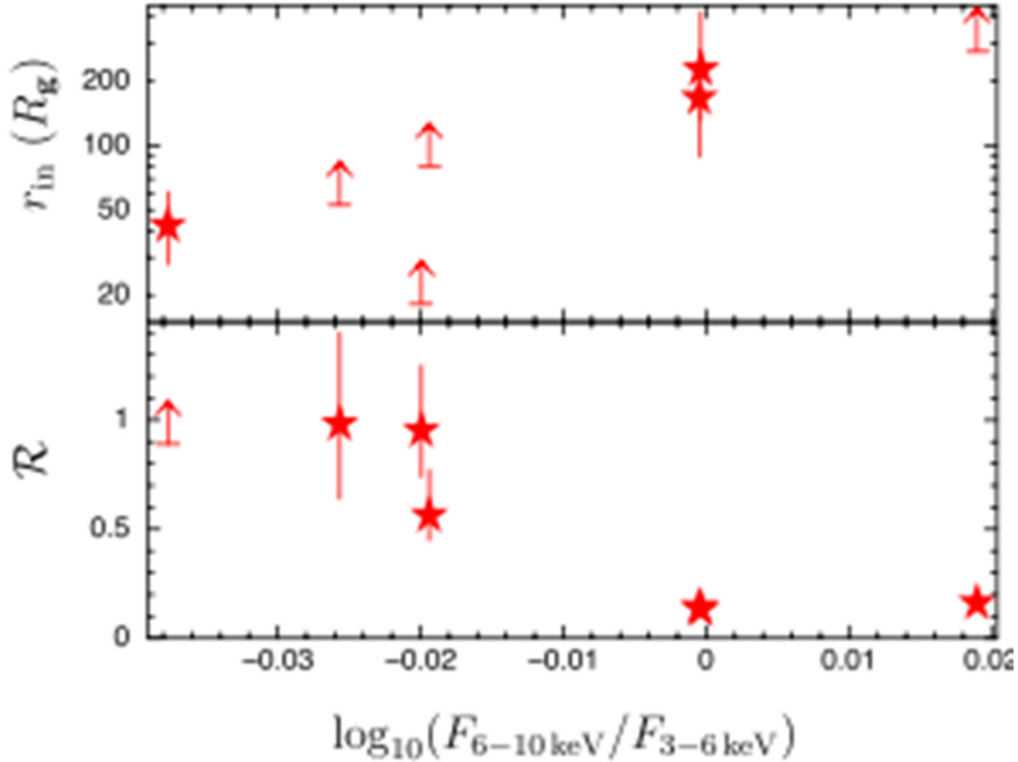
~3–15% of L_{Edd}

decreasing hardness, increasing flux

Basak & AAZ 2016

The fitted inner disc radius and the reflection fraction

We obtain the values of the inner disc radius between tens and hundreds of the gravitational radius, R_g, and the reflection fractions ≤1. The inner radius increases with the increasing hardness, and the reflection fraction decreases.



Our obtained values agree well with those obtained by De Marco+ 2015, who found (by studying thermal reverberation time lags) r_{in} decreasing from ≈280 to ≈60 r_g as the luminosity increases from 3% to 15% of L_{Edd}.

Our results are compatible with those of Plant+2015, who analyzed some of the observations used by us.

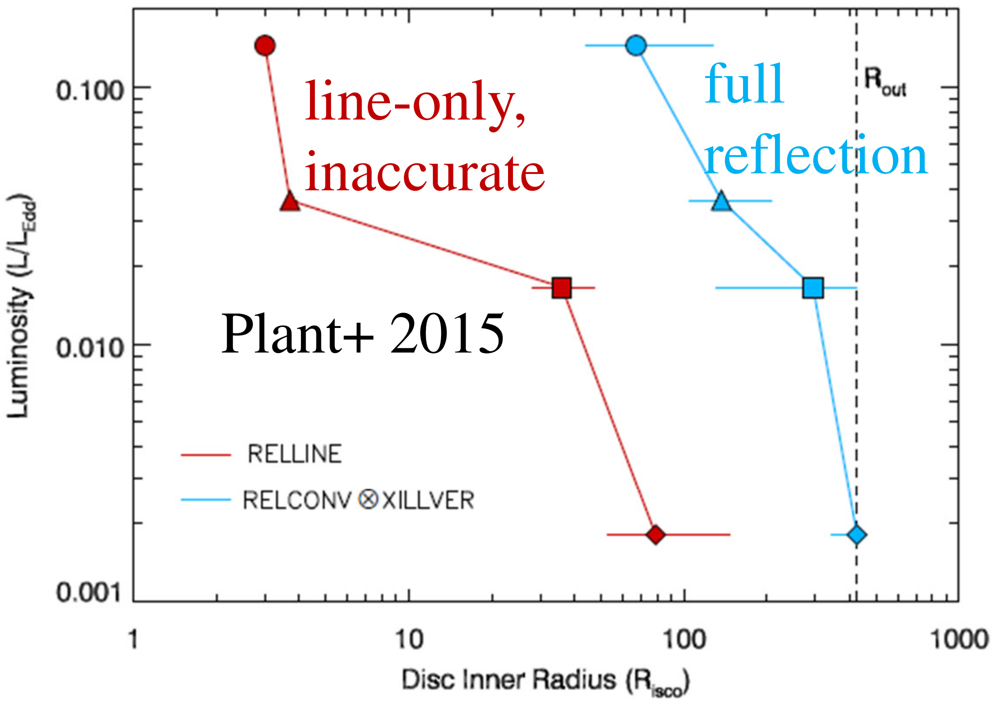


Fig. 3. Evolution of the estimated inner radii (x-axis; Table 3) as a function of luminosity (y-axis; assuming a BH mass and distance of 8 $M_\odot$ and 8 kpc respectively), clearly showing that the inner radius decreases as the source luminosity rises. The red and blue lines refer to fits with RELLINE and RELCONV∗XILLVER respectively. The black dashed line indicates the disc outer radius, which was fixed to be 1000 r_g.

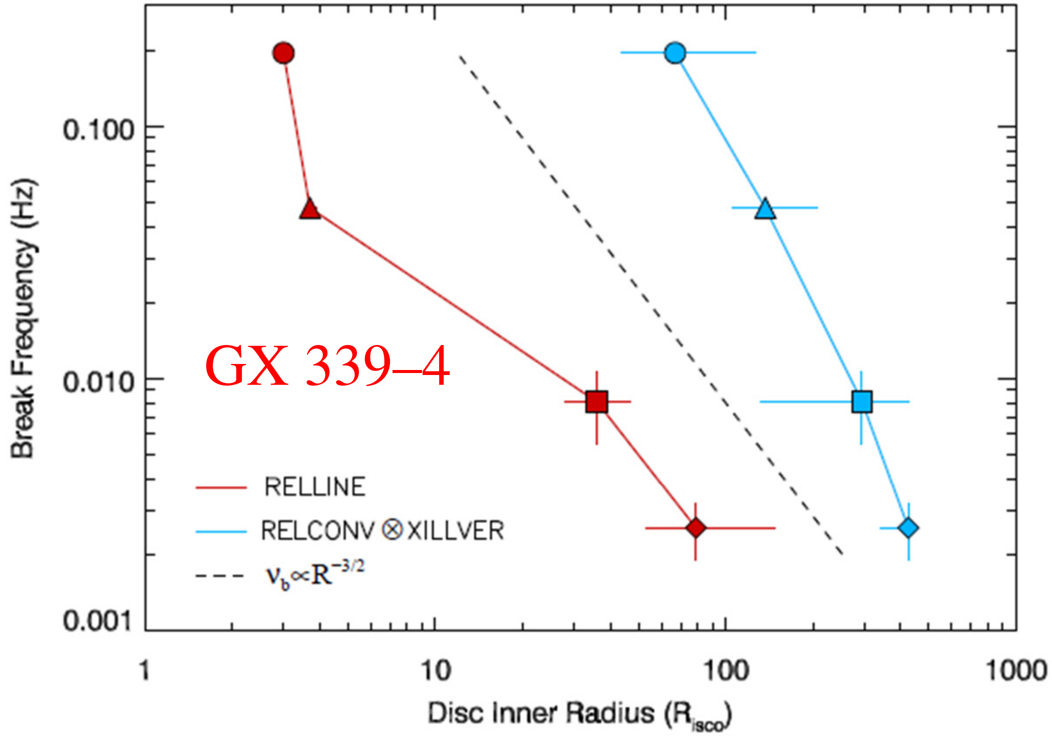


Fig. 9. The estimated disc inner radii (x-axis; Table 3) using RELLINE (red) and RELCONV∗XILLVER (green) versus and the fitted break frequency from simultaneous RXTE observations (y-axis; Table 5). The dotted line represents the relation $\nu \propto R^{-3/2}$, which corresponds to the dynamical and viscous timescales for accretion onto a BH.

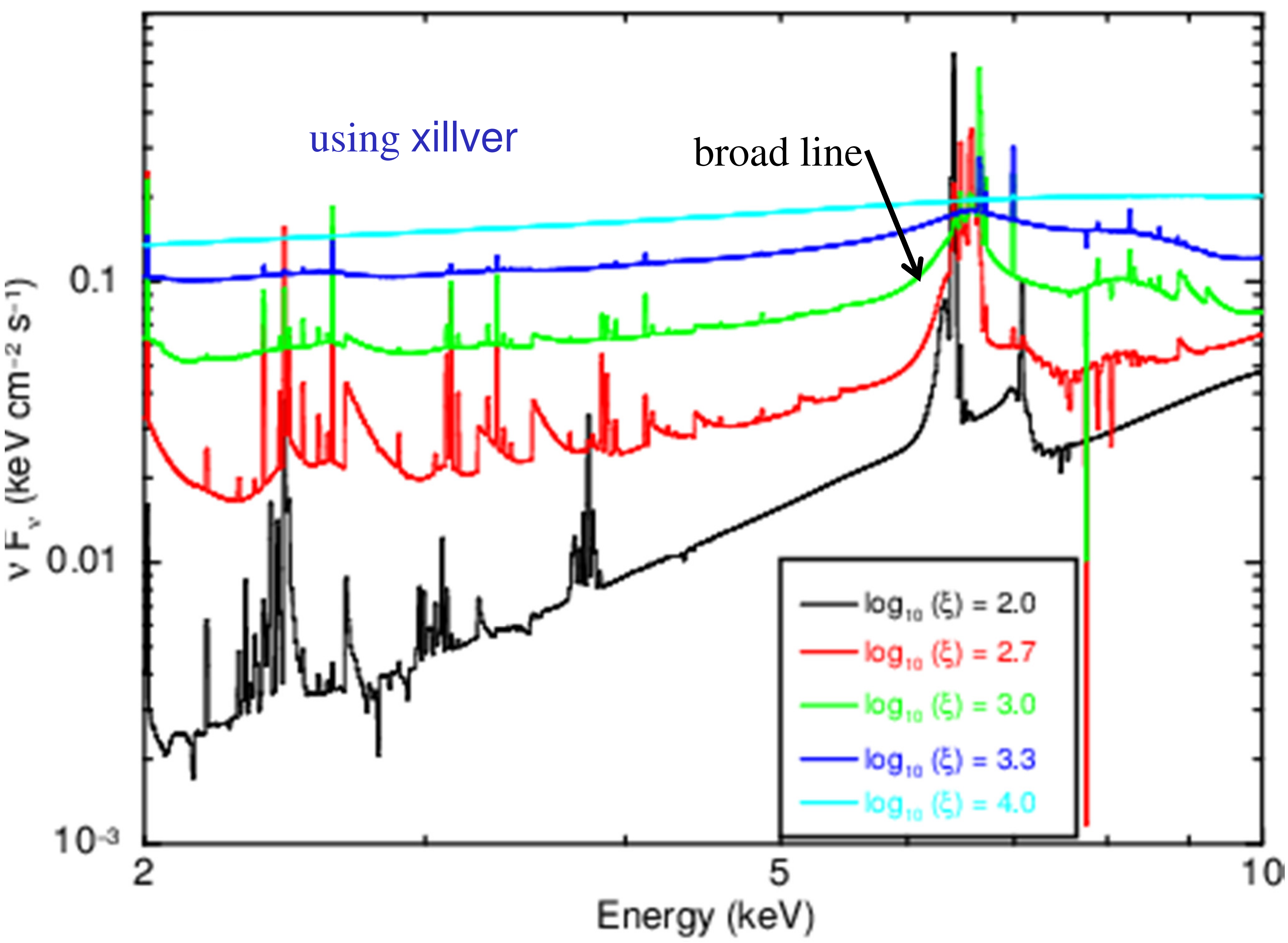
Our results strongly support the truncated disc model and rule out the disc extending down to the ISCO.

- We have used the same observations as those used in the papers claiming the extreme line broadening.
- Still, we see substantial line broadening in the observations with the softest continua and highest fluxes.
- The best fits of those spectra yield a part of the broadening as an ionization effect.
- We have also fitted an extensive range of other models, including the lamppost. The models with the disc extending close to the ISCO yield substantially worse fits than those with a truncated disc and a corona.
- **All models with satisfactorily fits show disc truncation.**

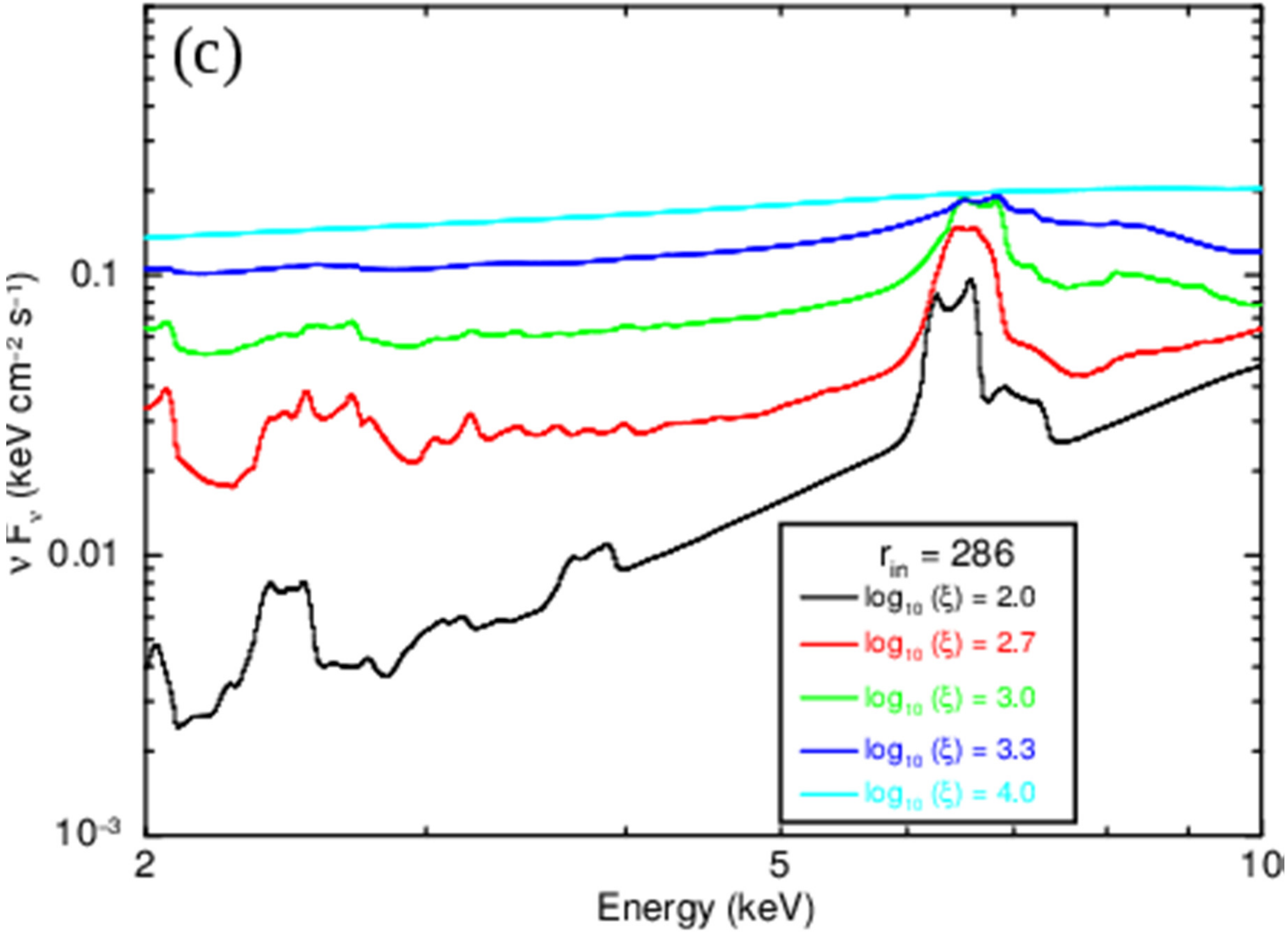
Strong broadening seen in the model spectra for high ionization parameters

- This is obviously a non-relativistic effect.
- It is due to a reduced absorption cross section at a sufficiently high ionization level.
- Incoming photons can penetrate deep in the medium before they ionize a K shell of a Fe atom, and a Fe Kα line is formed.
- The line then undergoes repeated scattering in warm upper layers before it leaves the disc, and becomes broad.

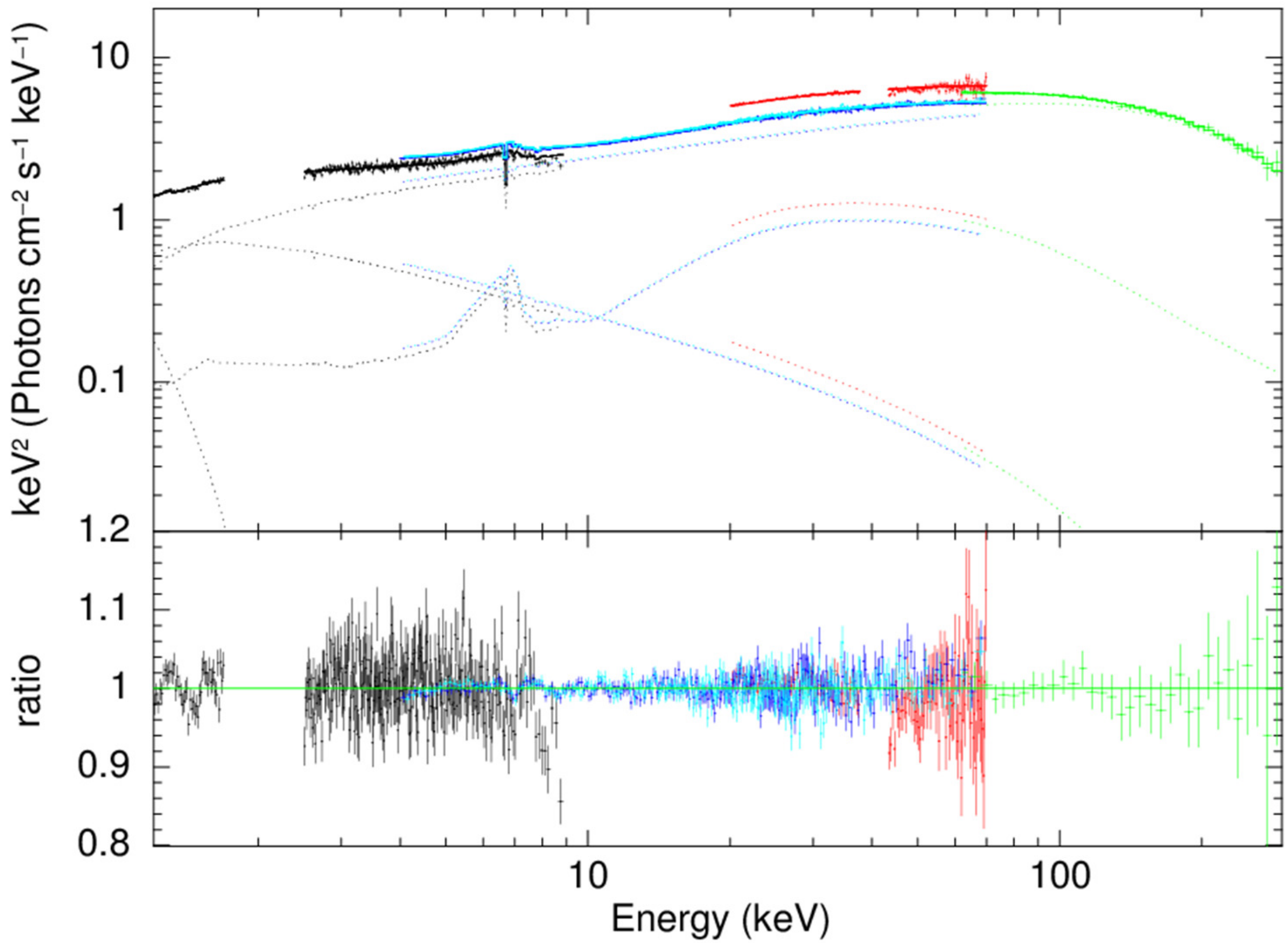
Reflection spectra from static ionized medium



The same, including a modest relativistic broadening



A reanalysis of *NuSTAR-Suzaku* data for Cyg X-1 in the hard state



Basak & AAZ 2017

The same data set as in Parker+2015, who found $r_{\rm in} \approx 1.5 \pm 0.3\ r_{\rm ISCO}$ (a>0.97) and weak reflection. We include a 2nd soft Comptonization component (e.g., Yamada+2013) and also find weak reflection, but $r_{\rm in} \approx 17 \pm 2\ r_{\rm g}$ (truncated disc).

(2) The lamppost model for the hard state: a point-like X-ray source close to the horizon on the BH rotation axis

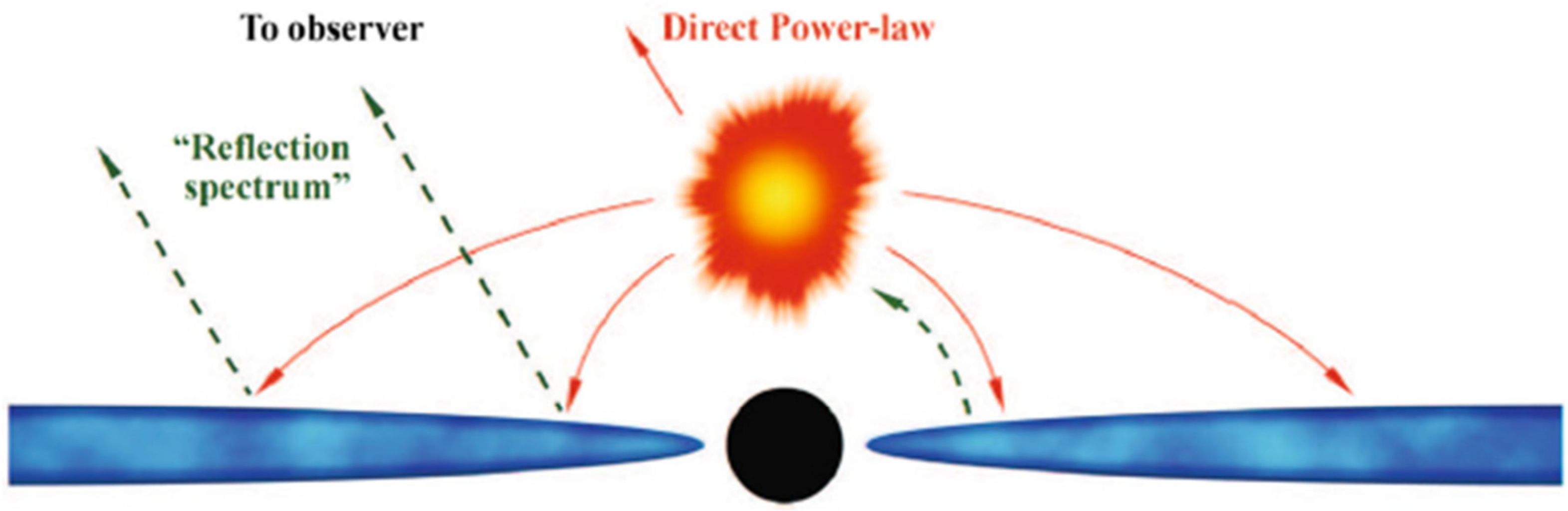


Fig. 1 Schematic diagram showing the power–law emitting corona (*orange*) above the accretion disc (*blue*), orbiting about a central black hole. The observer sees both the direct power–law and its "reflection", or back-scattered spectrum. The black hole causes strong gravitational light bending of the 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

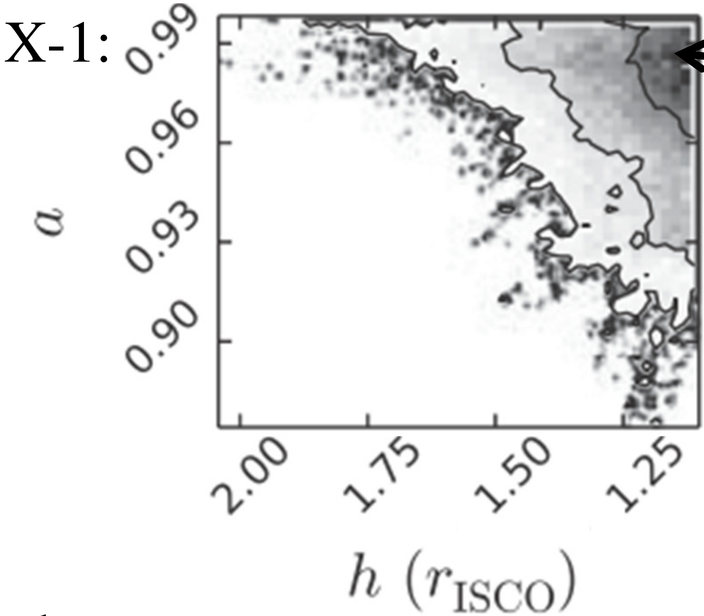
Uttley+ 2014

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?
- The lamppost assumed to be compact in spite of the observed X-ray time lags $\rightarrow$ the source is extended (which was earlier modelled as propagation of fluctuations in the accretion flow). The same implied if X-rays from Comptonization (for enough seed photons).
- Most of the direct radiation is trapped by the black hole, which requires a very large increase of the inferred $\dot{M}$.

Problems with physical self-consistency of 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 $R_{\rm ISCO}$

- 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), ApJL

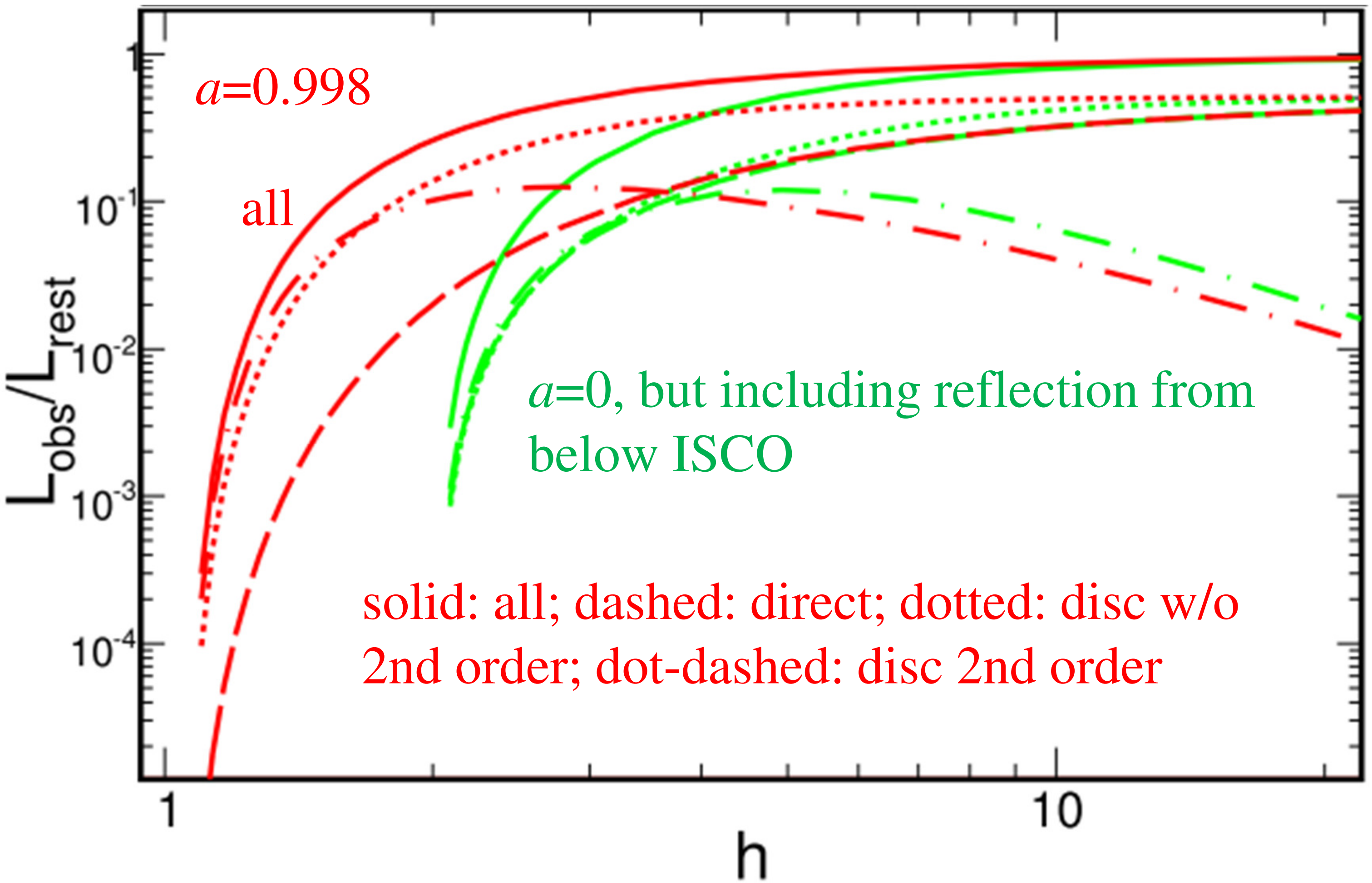
Accretion rates implied by the lamppost model

- The accretion rate of NGC 4151 would then be ~Eddington, and its radiative efficiency would be ~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

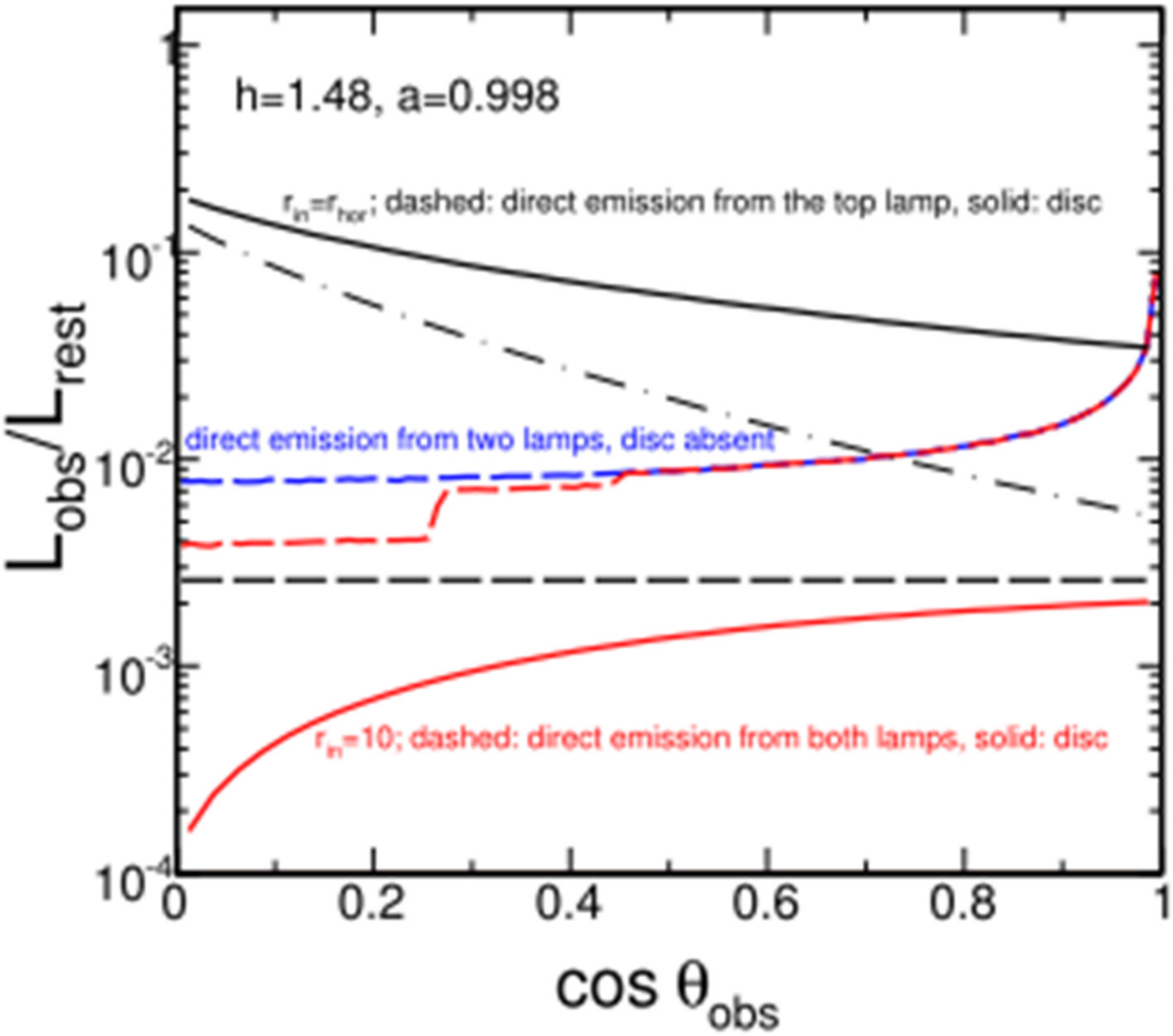
- The parameters in the source frame are even more extreme. Photons in the local frame have (1+z) higher energies than those observed; e.g., $z = 6$ for the model of Keck+ 2015. The redshift, time dilation and light bending increase the locally-measured luminosity with respect to that observed (e.g., by **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.

Flux reduction of the lamppost radiation – can be extreme for small heights



Niedźwiecki & AAZ 2017

Comparison of the direct and reflected components in the lamppost model



Reflection very strongly dominates at low heights, while usually weak in the lamppost fits (e.g. Parker+2015).

Niedźwiecki & AAZ 2017

Further problems with relxill and rexlilllp

- The redshift of the primary radiation and that irradiating the disc, light bending of the primary emission, return of the reflected photons to the disc and their photon trapping by the BH are not taken into account in these models.

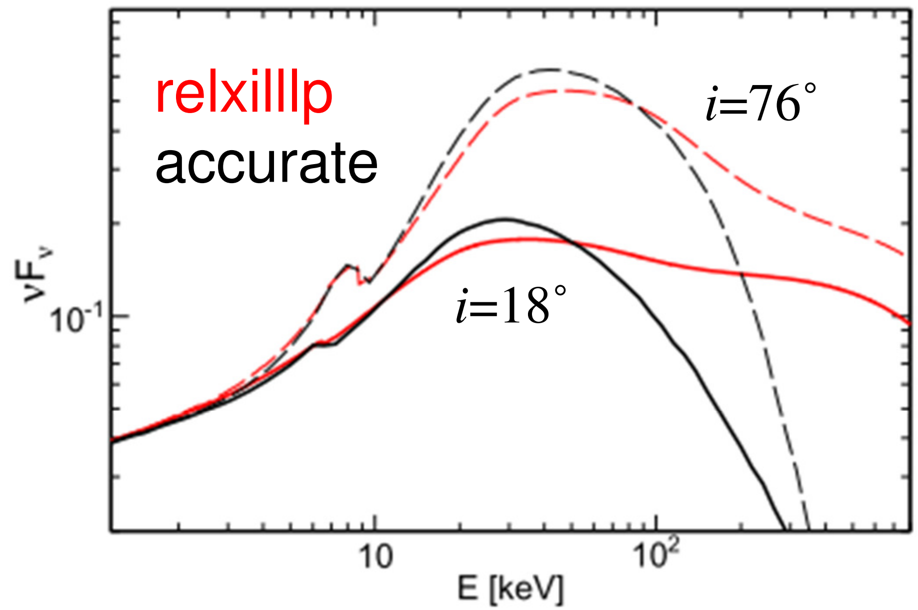


Figure 2. Observed spectra (direct emission+reflection) for the lamppost model with $h = 1.3$, $a = 0.98$, computed with `relxilllp` at `fixReflFrac` = 1 (red curves) and with `reflkerr` (black curves). The heavy solid and thin dashed curves are for $i = 18^\circ$ and 76°, respectively. The direct spectrum has $\Gamma = 1.75$ and $E_c = 1$ MeV. The spectra are normalized to the 1 keV flux.

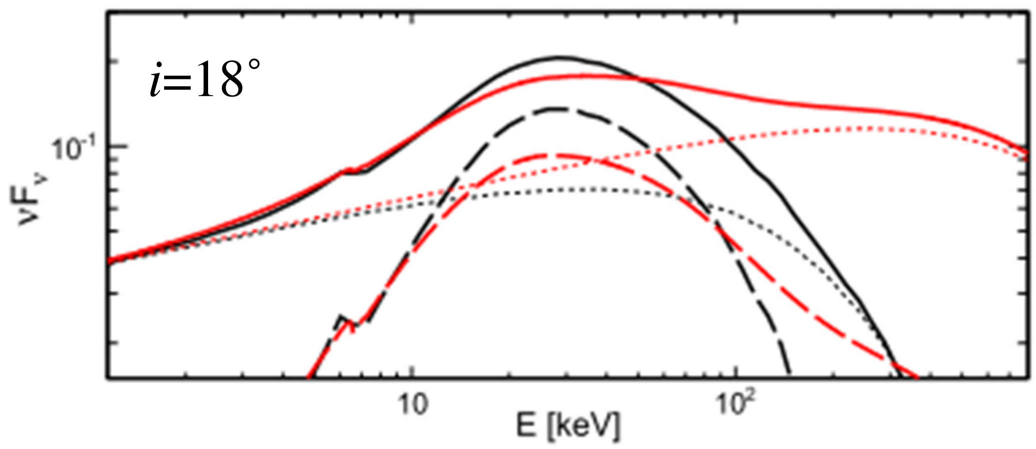


Figure 3. Spectral components for the low-inclination case of Figure 2 ($\Gamma = 1.75$, $E_c = 1$ MeV, $h = 1.3$, $a = 0.98$, $i = 18^\circ$). The solid black curve gives the actual total spectrum (obtained with `reflkerr` including the 2nd-order reflection, same as the solid black curve in Figure 2). The red solid curve is the result of `relxilllp` with `fixReflFrac` = 1. The dotted and dashed curves give, in both cases, the direct and reflected components, respectively.

Niedźwiecki, AAZ & Szanecki (2016)

The direct and reflection components in relxill and rexlilllp

- The lack of the redshift of the direct lamppost emission can be compensated for by manual adjustment. But the lack of redshift of the radiation irradiating the disc (different from that of the lamppost and redshift-dependent) is still not compensated for, and the large differences remain.

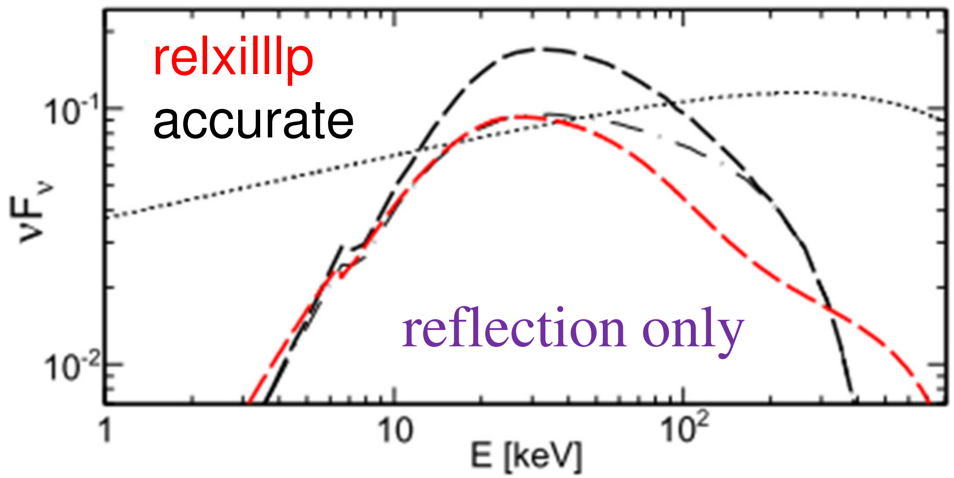


Figure 4. Spectral components for the same case as in Figure 3 ($i = 18°$), but now with compensation of the neglect of redshift in `relxilllp` by using E_c in `reflkerr` higher by $(1 + z)$. The observed $E_c = 1$ MeV then corresponds to the intrinsic value of 7 MeV. The black dotted curve shows the observed intrinsic spectra (identical for `reflkerr` and `relxilllp`) and the black and red dashed curves show the reflected components for `reflkerr` and `relxilllp` with fixReflFrac = 1. The dotted–dashed black curve shows the reflection of `reflkerr` without the second-order component.

A new corrected code

- reflkerr, soon to be public,
- by Niedźwiecki, Szanecki & AAZ.

Conclusions

- Our calculations for GX 339–4 in the hard state find the inner disc radius ≫ ISCO, supporting the truncated disc model.
- Spectral fitting results for black-hole binaries and AGNs with the primary X-ray source very close to the horizon (a lamppost on the rotation axis) and reflection from the disc extending to the ISCO imply very high accretion rates and violate the $e^{\pm}$ pair equilibrium.
- Results obtained with relxill and relxilllp for cases with strong gravity effects appear not reliable due to problems with the treatment of a number of relativity effects.
- A corrected code, reflkerr, available soon.