

What is the disc truncation
radius in the hard state of
black-hole binaries?

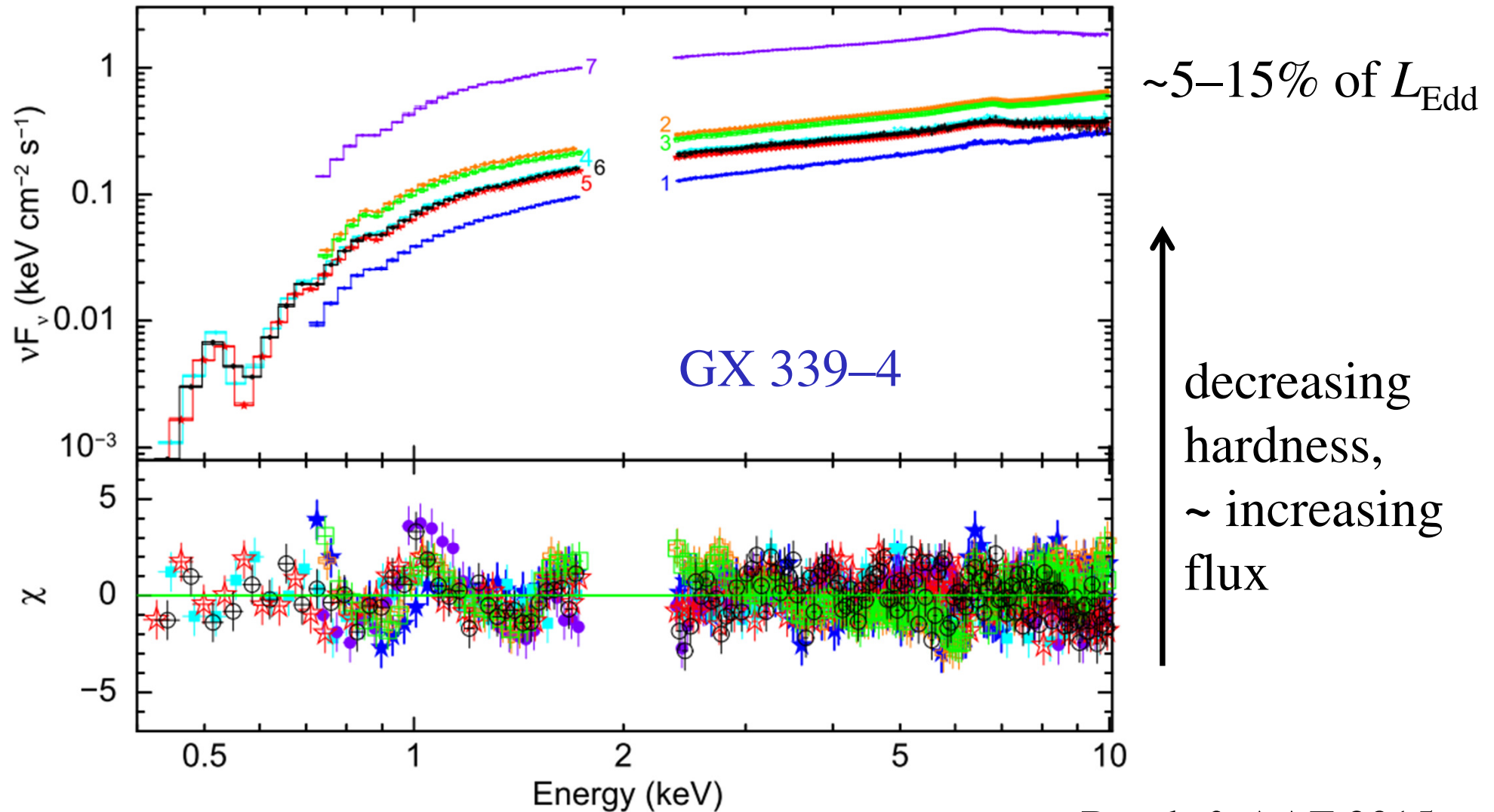
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(1) The black-hole binary GX 339–4

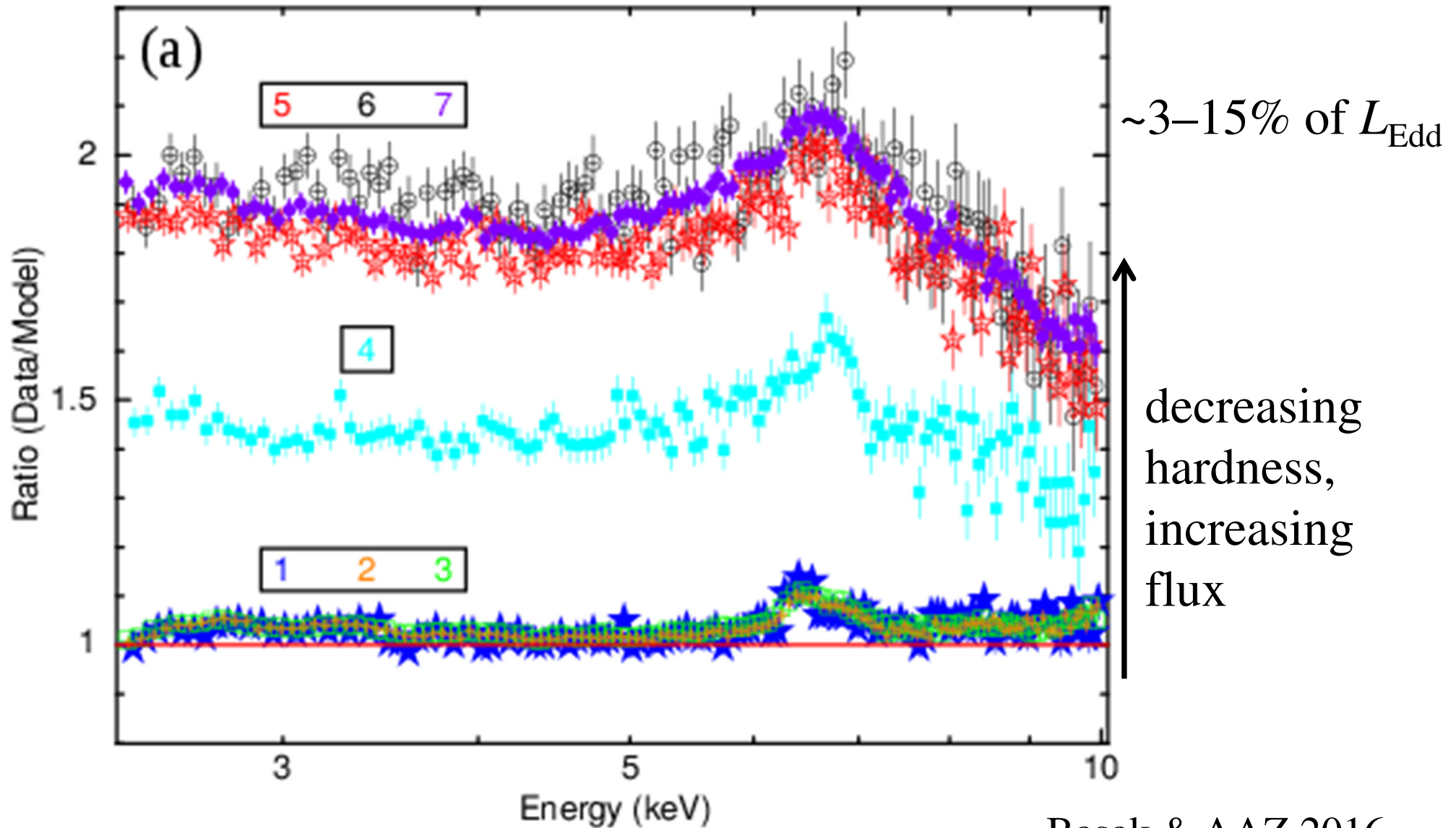
Basak & AAZ (2016), MNRAS

- 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 reanalyze 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*

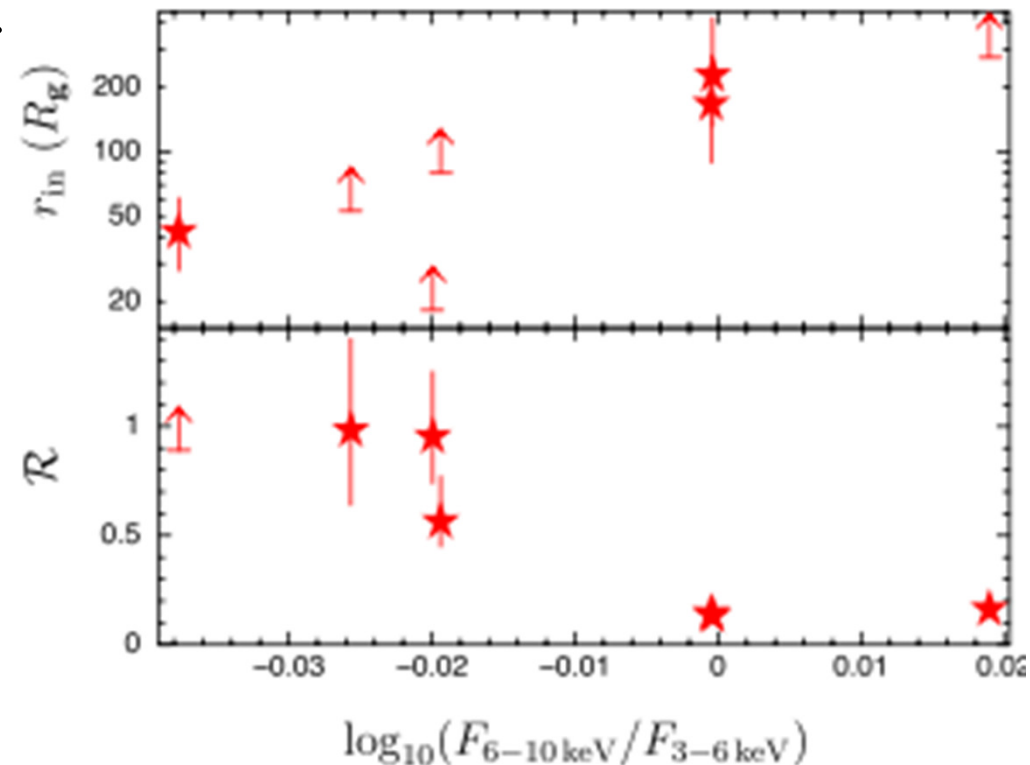


The ratio of the reflection component to the irradiating spectrum



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 $\approx 60 r_g$ as the luminosity increases from 3% to 15% of L_{Edd} .

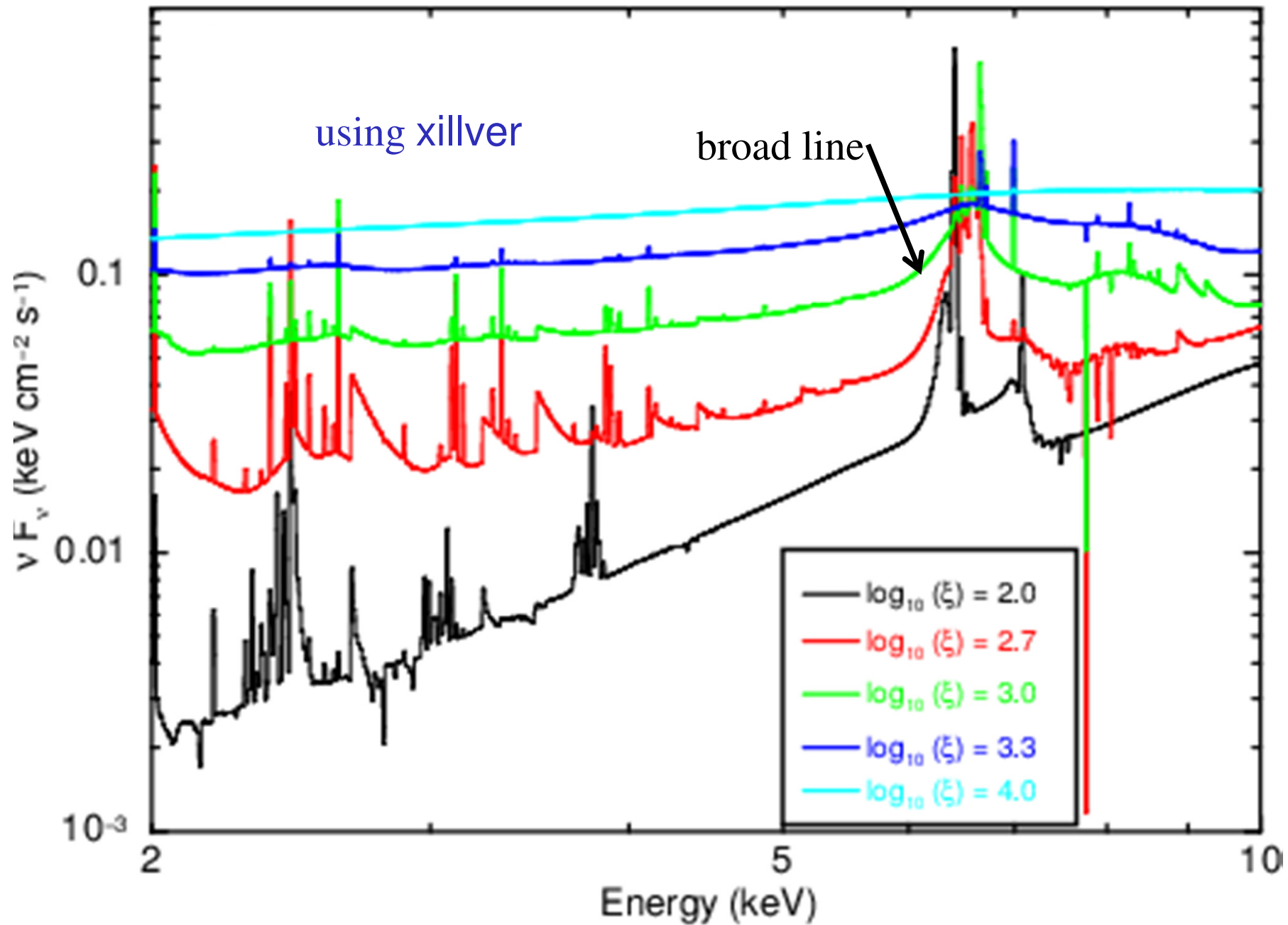
Our results strongly support the truncated disc model and rule out the disc extending down to the ISCO.

- 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.**

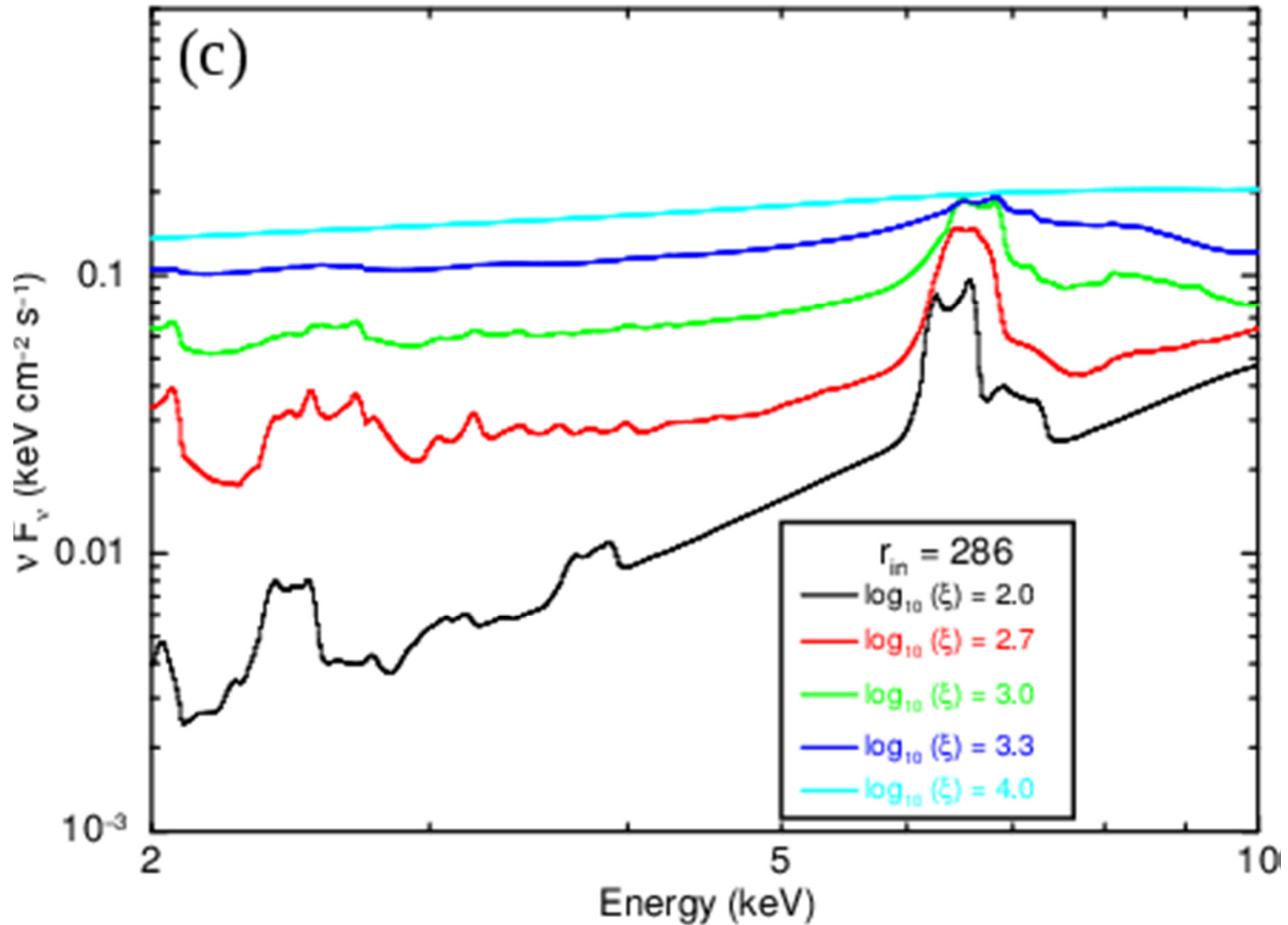
Strong broadening seen in the model spectra for high ionization parameters

- 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 $K\alpha$ line is formed.
- The line then undergoes repeated scattering before it leaves the disc, and develops a strong low-energy tail.

Reflection spectra from static ionized medium



The same, including a modest relativistic broadening



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

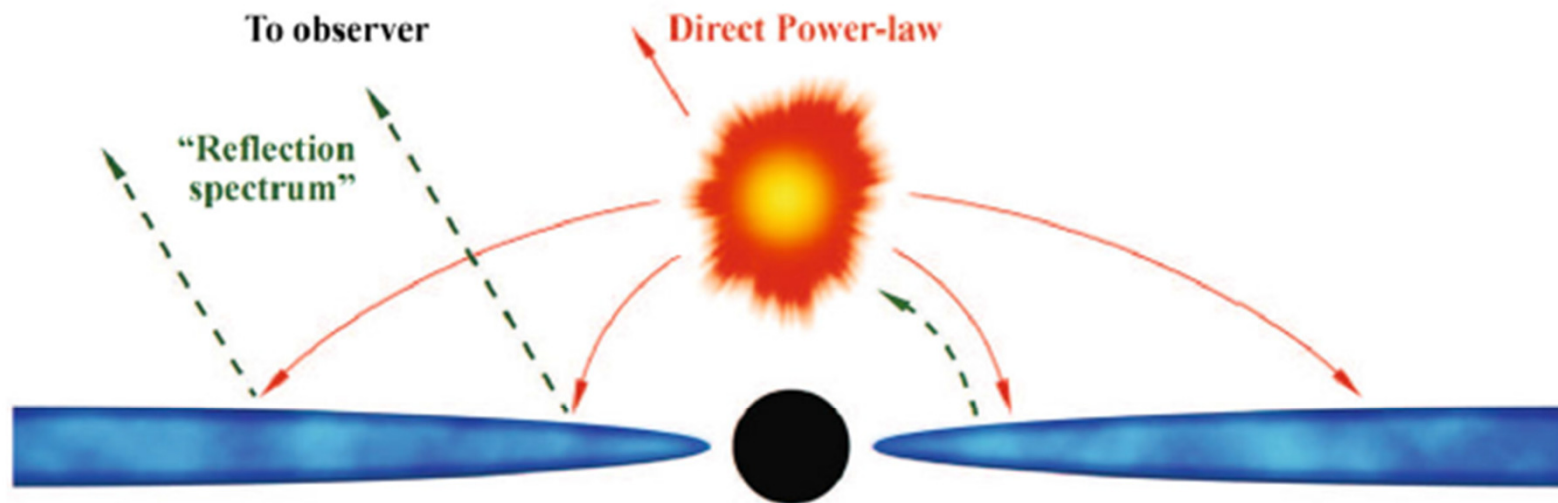
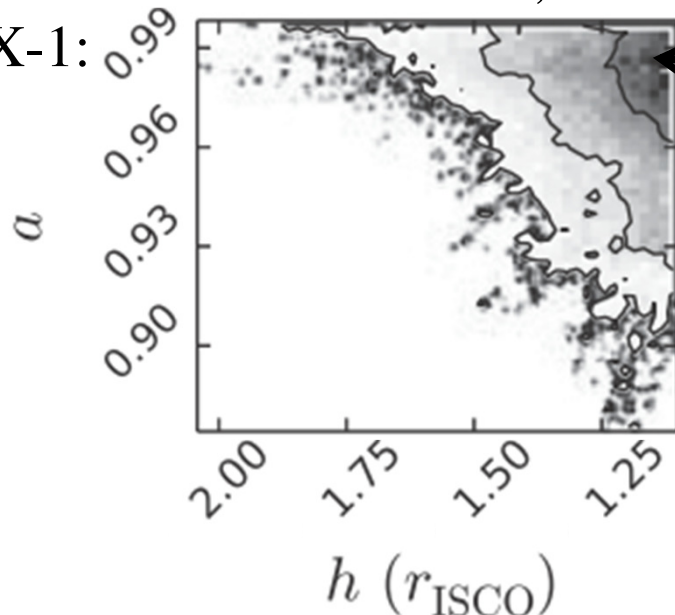


Fig. 1 Schematic diagram showing the power-law emitting corona (*orange*) above the accretion disc (*blue*), orbiting about a central black hole. The observer sees both the direct power-law and its “reflection”, or back-scattered spectrum. The black hole causes strong gravitational light bending of the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

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_{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 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.

Nieźwiecki, AAZ & Szanecki (2016), ApJL

Accretion rates implied by the lamppost model

- The accretion rate of NGC 4151 would then be \sim 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 **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.

Further problems with `relxill` and `relxillp`

- 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.

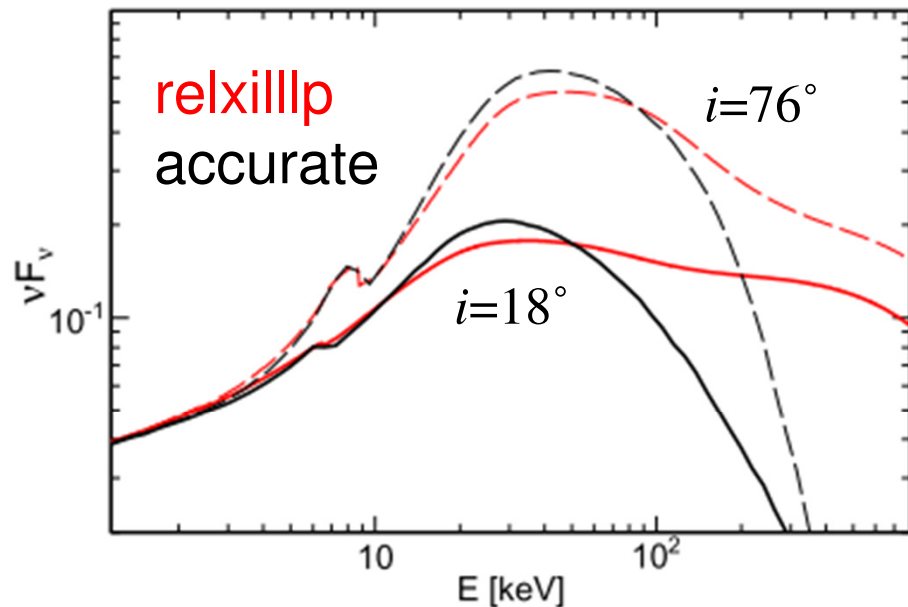


Figure 2. Observed spectra (direct emission+reflection) for the lamppost model with $h=1.3$, $a=0.98$, computed with `relxillp` at `fixReflFrac = 1` (red curves) and with `reflkerr` (black curves). The heavy solid and thin dashed curves are for $i = 18^\circ$ and 76° , respectively. The direct spectrum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

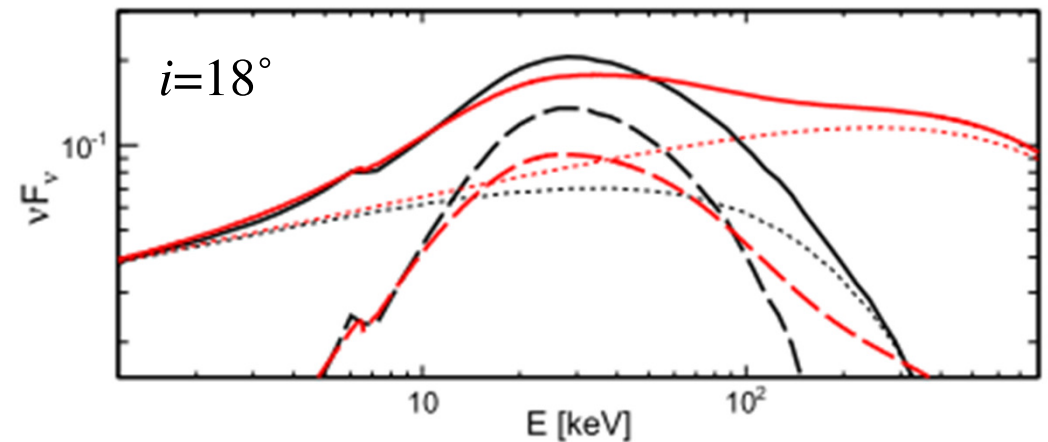


Figure 3. Spectral components for the low-inclination case of Figure 2 ($\Gamma = 1.75$, $E_c = 1$ MeV, $h = 1.3$, $a = 0.98$, $i = 18^\circ$). The solid black curve gives the actual total spectrum (obtained with `reflkerr` including the 2nd-order reflection, same as the solid black curve in Figure 2).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

The direct and reflection components in `relxillp` and `relxillp`

- 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.

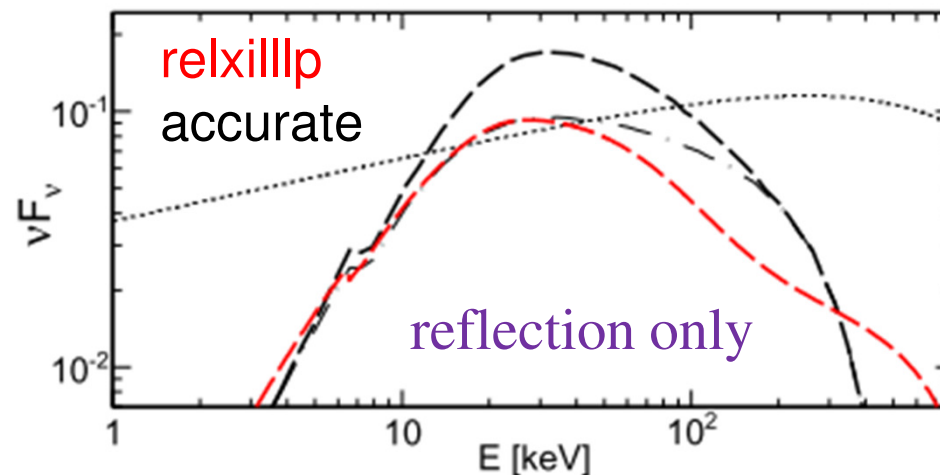


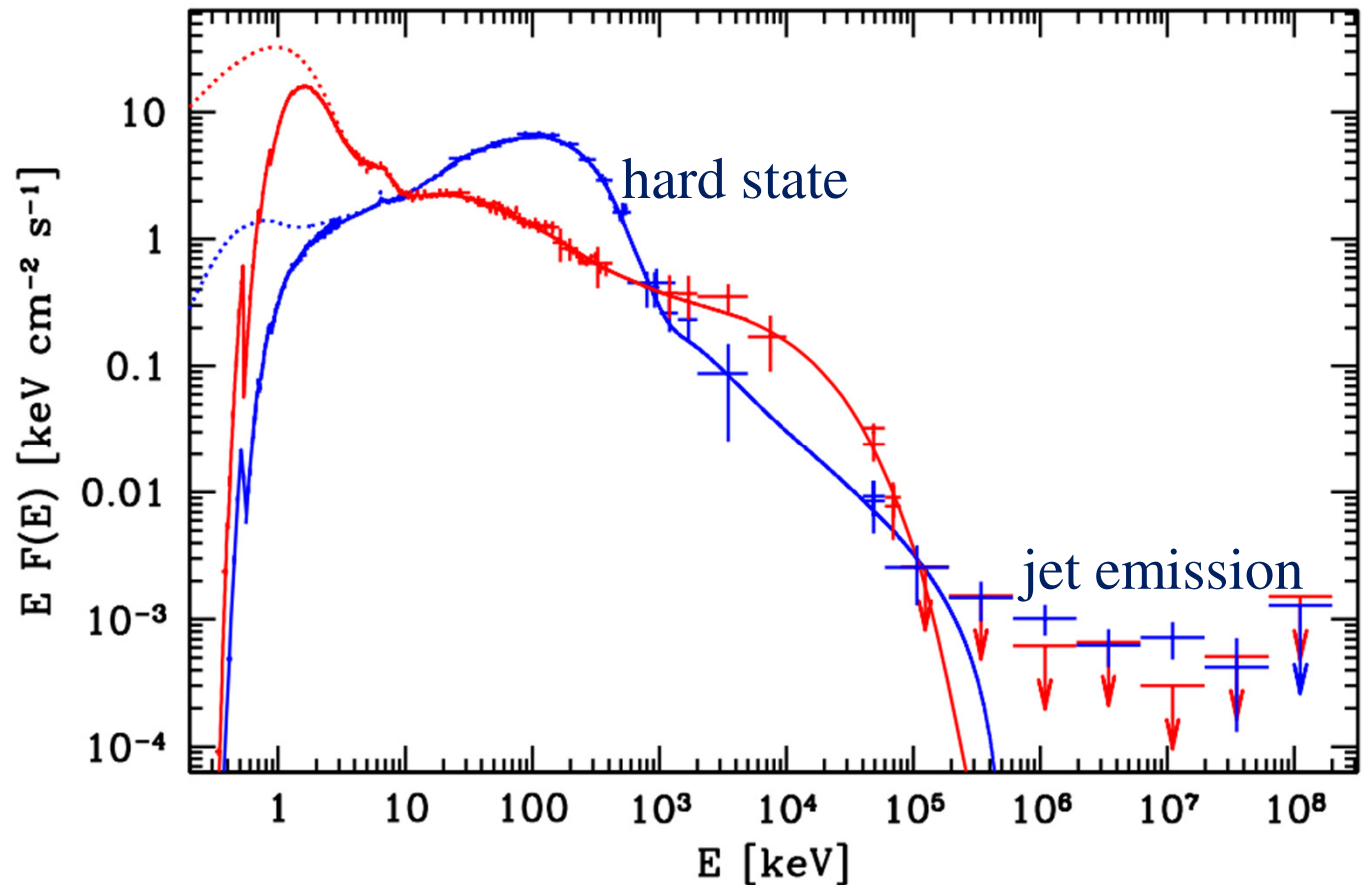
Figure 4. Spectral components for the same case as in Figure 3 ($i = 18^\circ$), but now with compensation of the neglect of redshift in `relxillp` by using E_c in `reflkerr` higher by $(1 + z)$. The observed $E_c = 1$ MeV then corresponds to the intrinsic value of 7 MeV. The black dotted curve shows the observed intrinsic spectra (identical for `reflkerr` and `relxillp`) and the black and red dashed curves show the reflected components for `reflkerr` and `relxillp` with `fixRefFrac` = 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.

(3) The size of the X-ray source from pair absorption

- $R \gtrsim 6R_g$ in the hard state of Cyg X-1 from the flux measurement at ~ 50 MeV by the *Fermi* LAT.



AAZ, Malyshev,
Chernyakova & Pooley
(2016)

Conclusions

- Our calculations for GX 339–4 in the hard state find the inner disc radius \gg 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 `relxillp` 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.
- $R \gtrsim 6R_g$ in the hard state of Cyg X-1 from pair absorption.