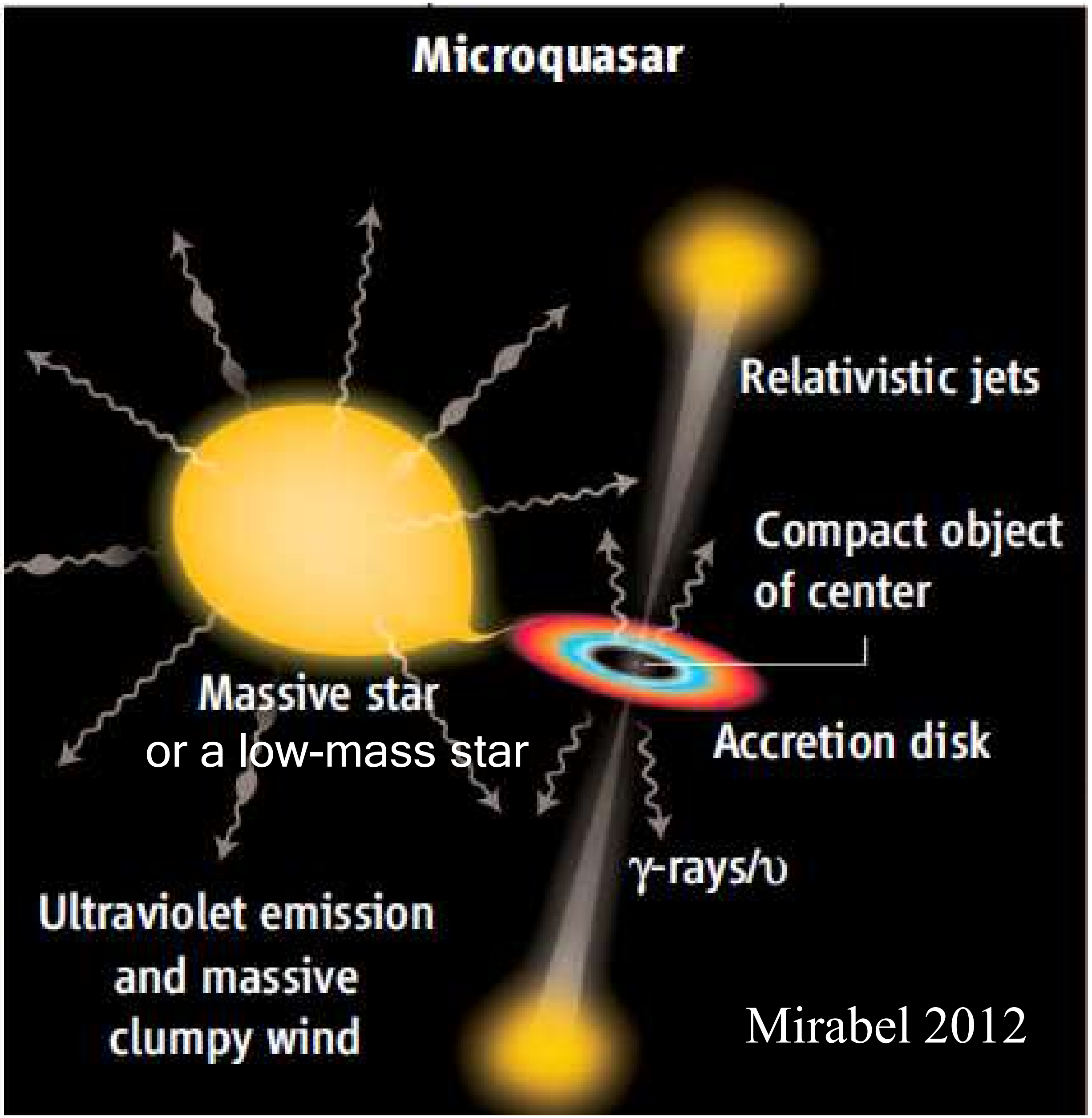
Accretion disc inner radii in black-hole binaries

Andrzej A. Zdziarski
Centrum Astronomiczne im. M. Kopernika
Warszawa, Poland

with R. Basak, B. De Marco, M. Dziełak, A. Niedźwiecki, M. Szanecki, ...

Accreting stellar binary systems with a compact object (black hole or neutron star)



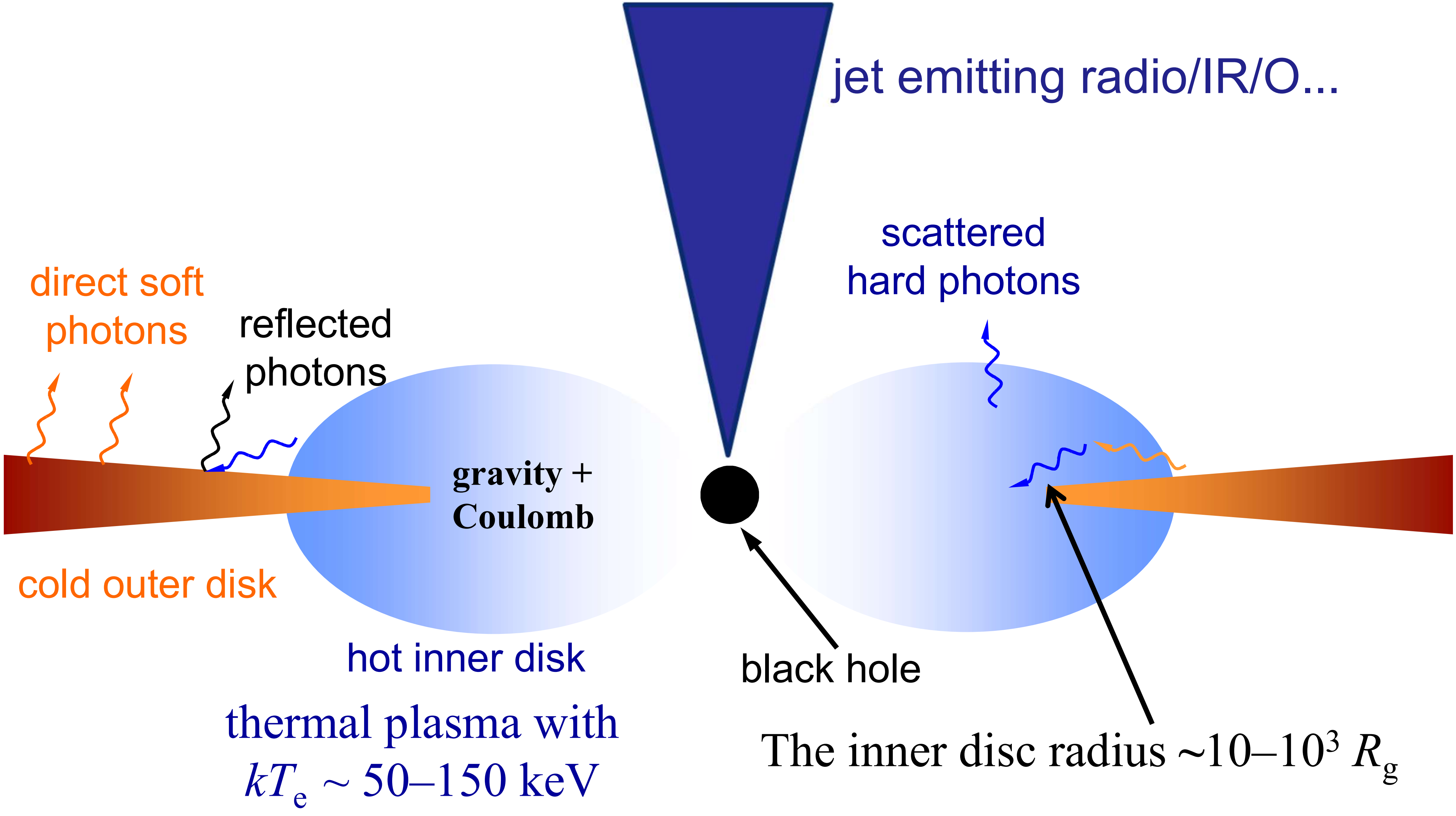
A sketch of an accreting binary. The donor: either a high or a low-mass star.

Binaries containing a black hole and a massive donor are persistent, and those with a low-mass donor are mostly transient (outbursts separated by years of quiescence).

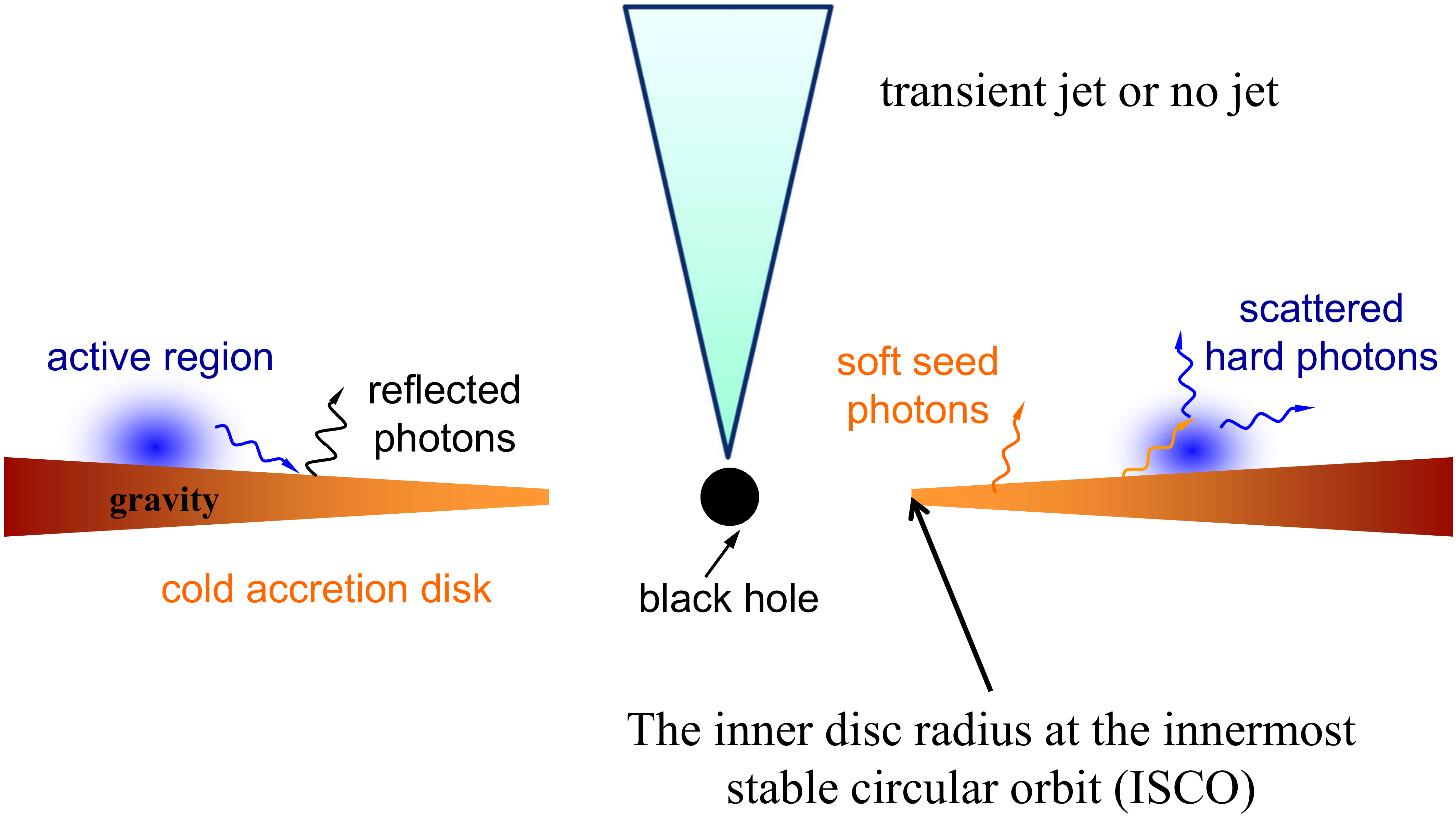
Measurements of disc truncation before outbursts of transient binaries

- The usual sequence is quiescence, hard state, soft state, hard state, quiescence.
- Based on the width of the Hα line, Bernardini+ 2016 find the inner radius $R_{\rm in}\gtrsim 3\times 10^4 R_{\rm g}$ during quiescence, and $R_{\rm in}\lesssim 10^4 R_{\rm g}$ 13h before the 2015 outburst of V404 Cyg.
- Disc truncation in quiescence is required theoretically (e.g. Dubus+2001).
- From the 7-d delay of the X-ray outburst w/r to the optical one, Bernardini+ estimated the radius of the onset of the outburst as $\sim 10^9$ cm or $10^3 R_{\rm g}$.
- A very similar ~7-d delay was found for the black-hole binary ASASSN-18ey by Tucker+ 2018.

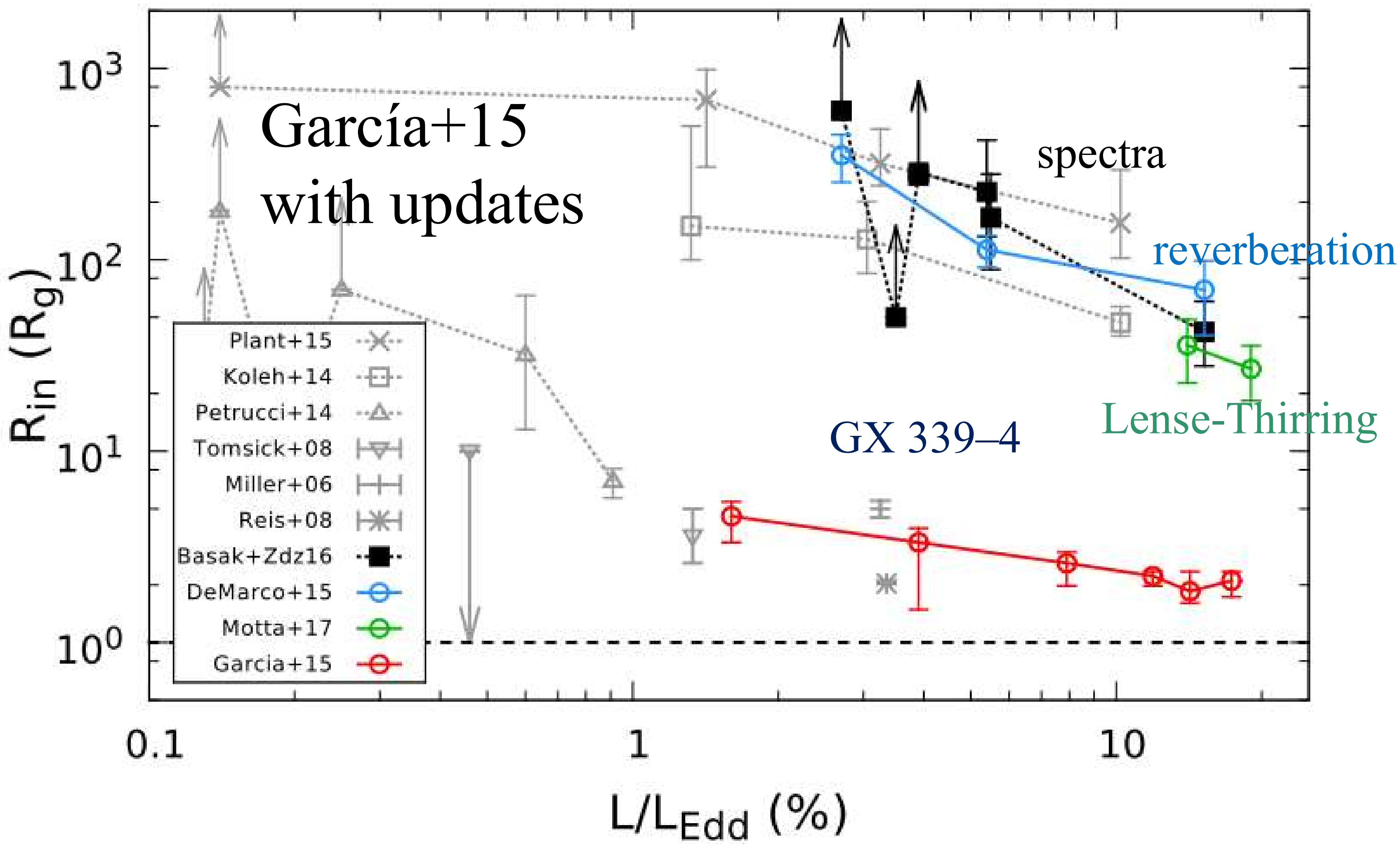
Truncated disc at the beginning of an outuburst (hard state)



Disc/corona geometry in the soft state:



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



The main method: relativistic effects on reflection and reprocessing

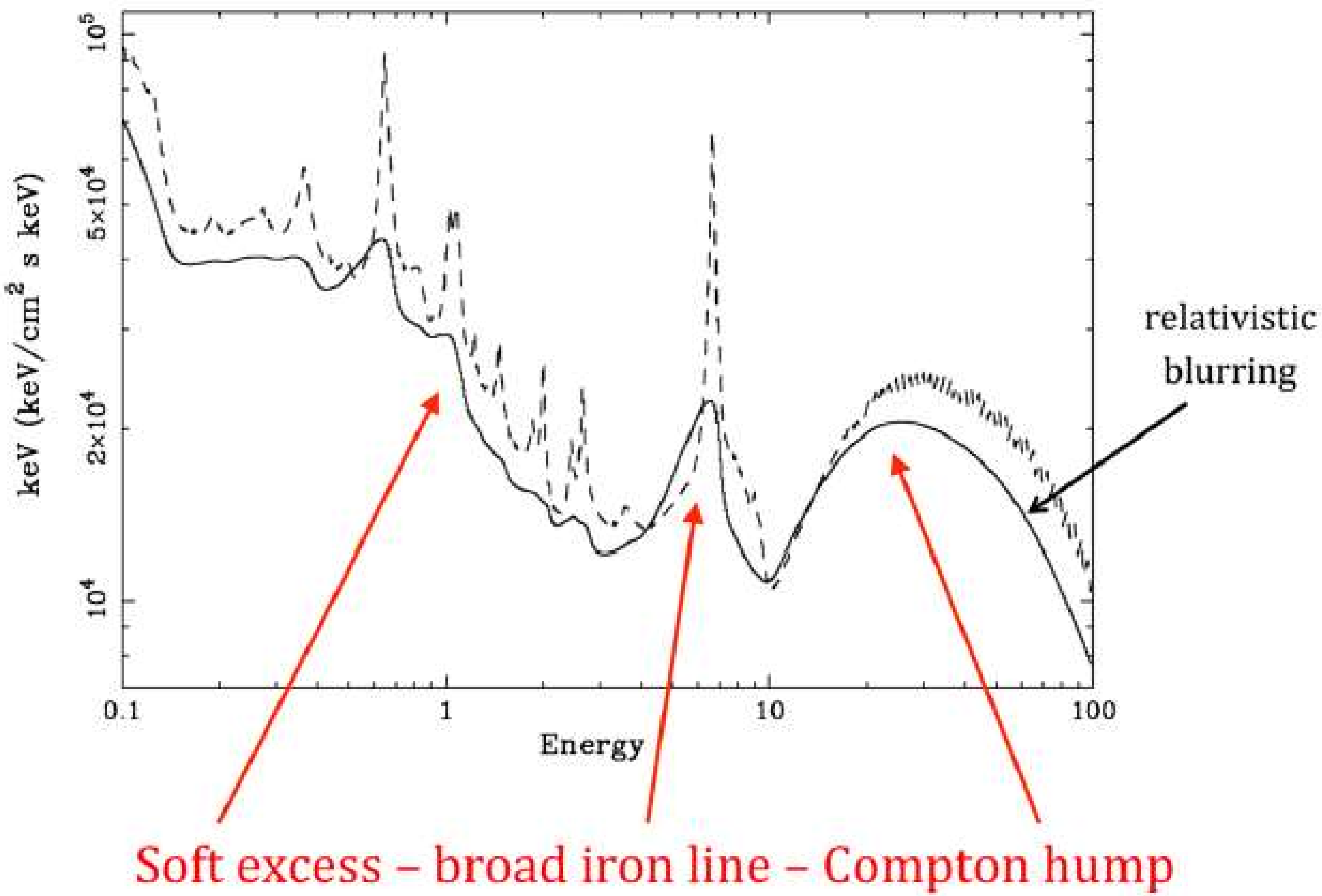


Fig. 2 Relativistically blurred reflection spectrum from an ionized disc compared with its local (unblurred) counterpart, shown as a *dashed line*. The reflection spectrum typically has three characteristic parts: a soft excess, broad iron line and a Compton hump

Uttley+ 2014

What causes the conflicting measurements?

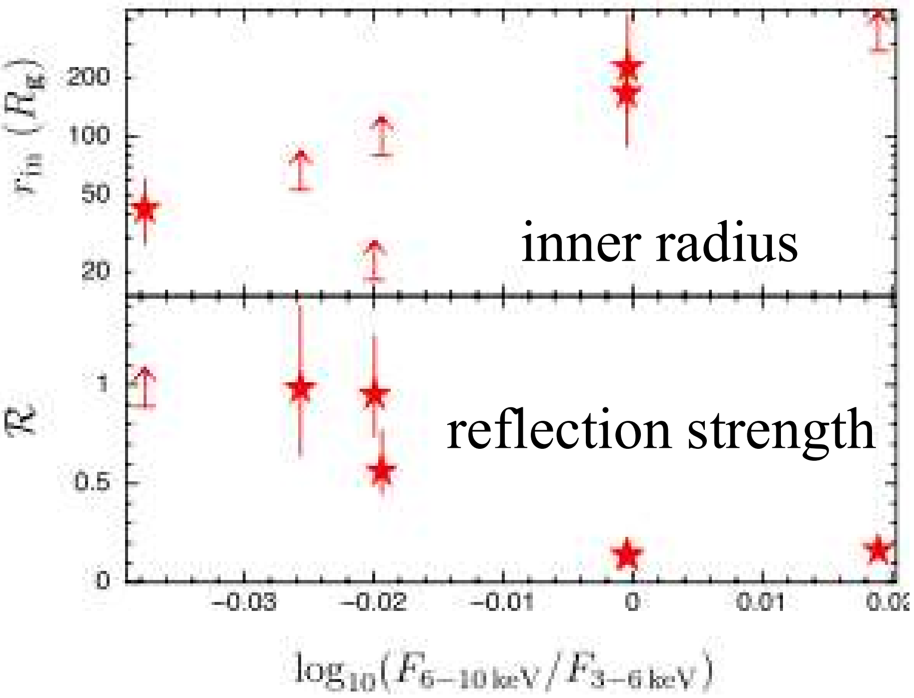
- Possible calibration uncertainties.
- In some cases, pileup in the detector affected the measurements.
- Uncertainty about the underlying continuum. A hard continuum below the Fe K line requires a strong red wing of the line, thus, implying strong relativistic effects. A soft continuum may be compatible with a narrow line. In general, the X-ray continuum is unlikely to be a single power law.
- Questionable reflection models. E.g., one paper assumed strongly different Fe abundances in the two parts of the reflecting medium.

The work of our group to resolve this issue

1. GX 339–4 in the hard state with *XMM* (Basak & AAZ16). Truncated discs in all cases, different from Miller+2006; Tomsick+2008 (detector pileup), agrees with Plant+2015.
2. Cyg X-1 with *Suzaku* and *NuSTAR*. The previous study by Parker+2015 used an unphysical spectrum. A truncated disc found (Basak, AAZ, Parker & Islam 2017).
3. GX 339–4 in the hard state with *RXTE* PCA (Dziełak+2019). A truncated disc found for the same data for which García+2015 found the disc close to ISCO (assuming two different Fe abundances in two disc regions).
4. New codes for relativistic reflection: reflkerr, hreflect, see users.camk.edu.pl/mitsza/reflkerr; Niedźwiecki+ 2016, 2018, 2019.

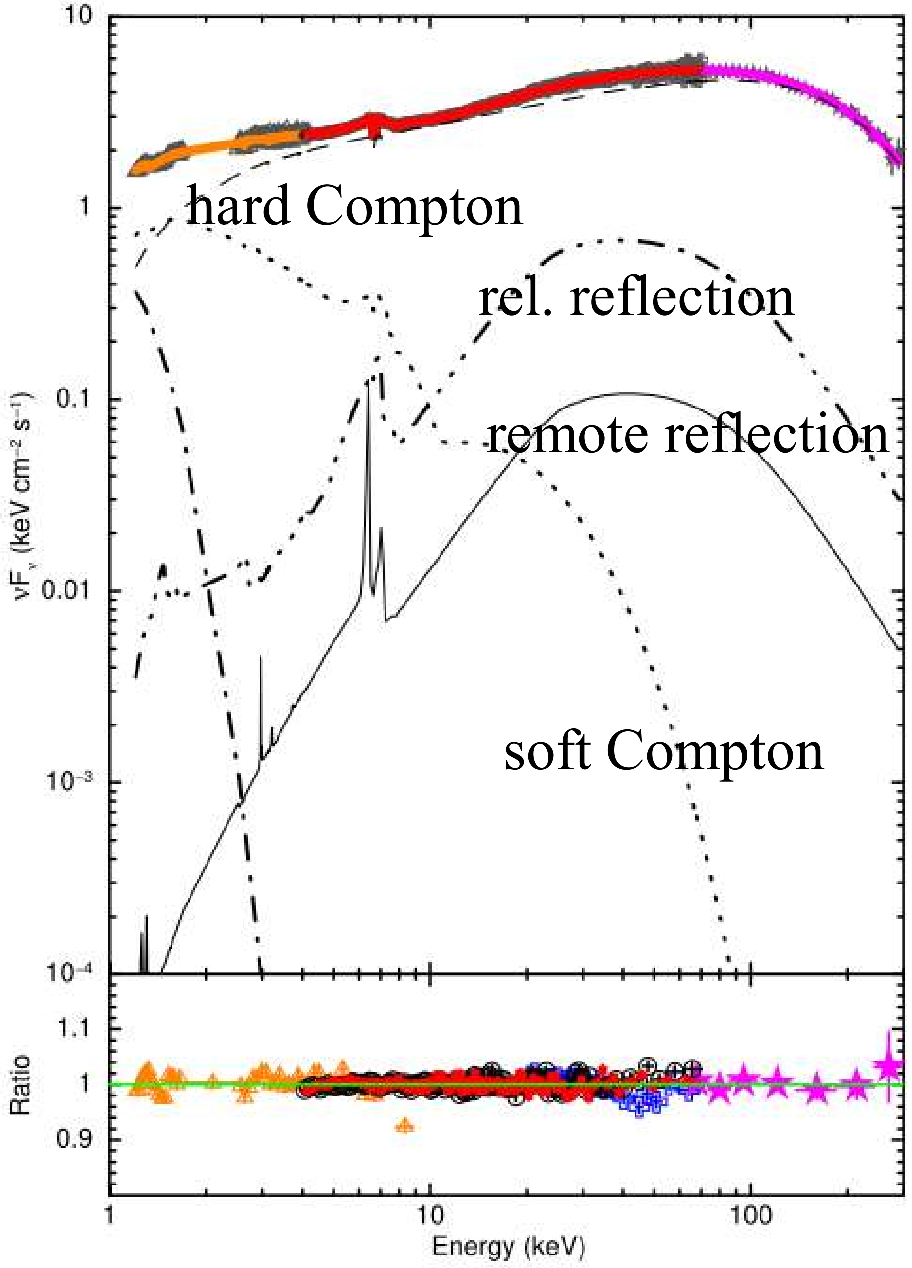
1. Inner disc radius from *XMM* data in GX 339–4, Basak & AAZ 2016

We obtain the values of the inner disc radius between tens and hundreds of the gravitational radius, R_g. The inner radius increases with the increasing hardness, and the reflection fraction decreases. Agreement with Plant+15.



Agreement with De Marco+2015, who found (from thermal reverberation time lags) r_{in} decreasing from ≈280 to ≈60 R_g as L increases from 3% to 15% of L_{Edd}.

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

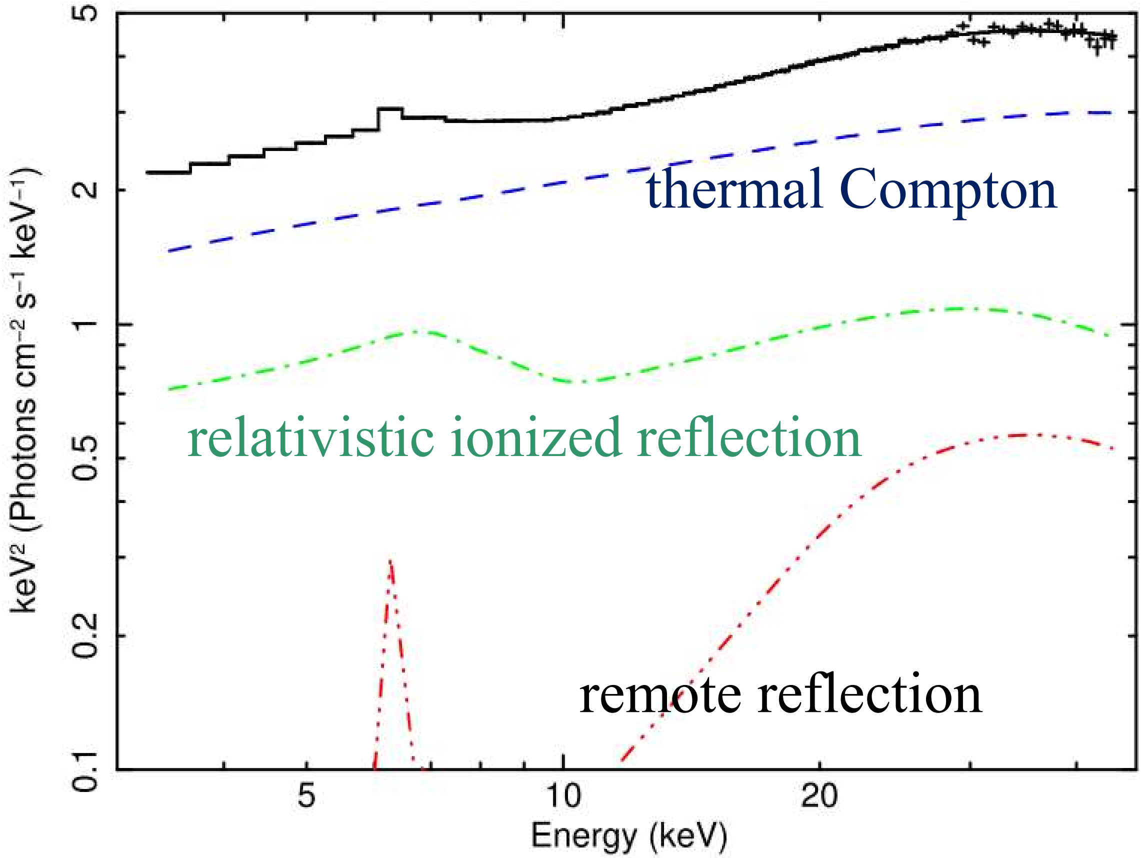


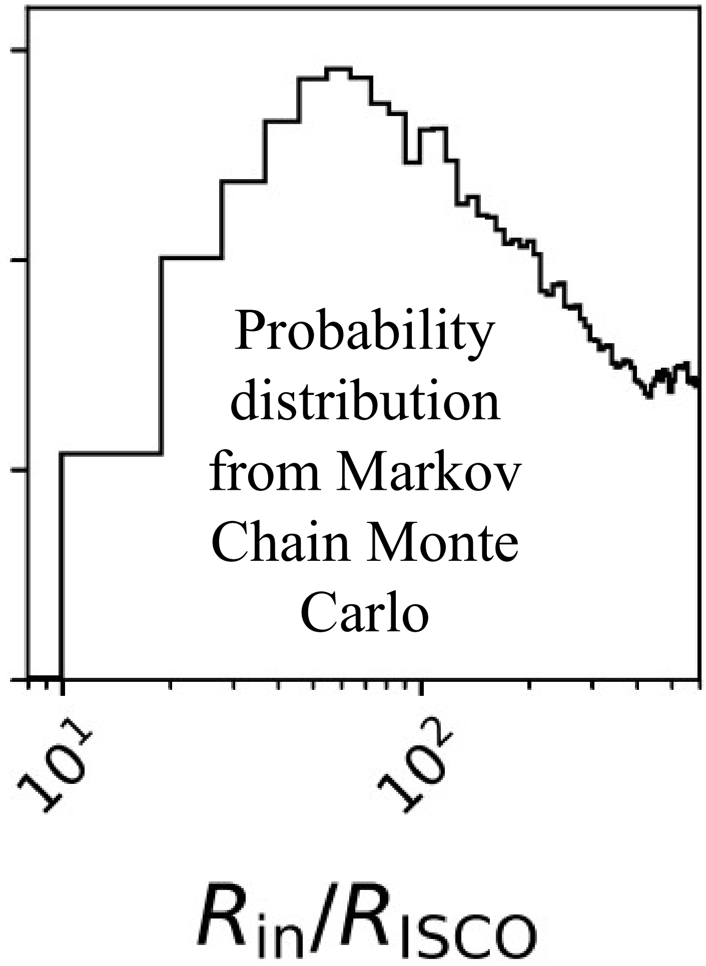
Basak, AAZ, Parker & Islam 2017

The same data set as in Parker+2015, who found $R_{in} \approx 1.5 \pm 0.3\ R_{ISCO}$. We assume two Comptonization components (e.g., Yamada+2013) and find $R_{in} \approx 15 \pm 3\ R_g$, i.e., a significant truncation.

3. Inner disc radia from *RXTE* data in a bright hard state of GX 339–4, Dziełak, AAZ, et al. 2019

- A set of summed spectra with 10^7 counts (following the method of García+2015, who found R_{in}~R_{ISCO}).
- We find $R_{in} \approx 47_{-45}^{+1000} R_{ISCO}$.

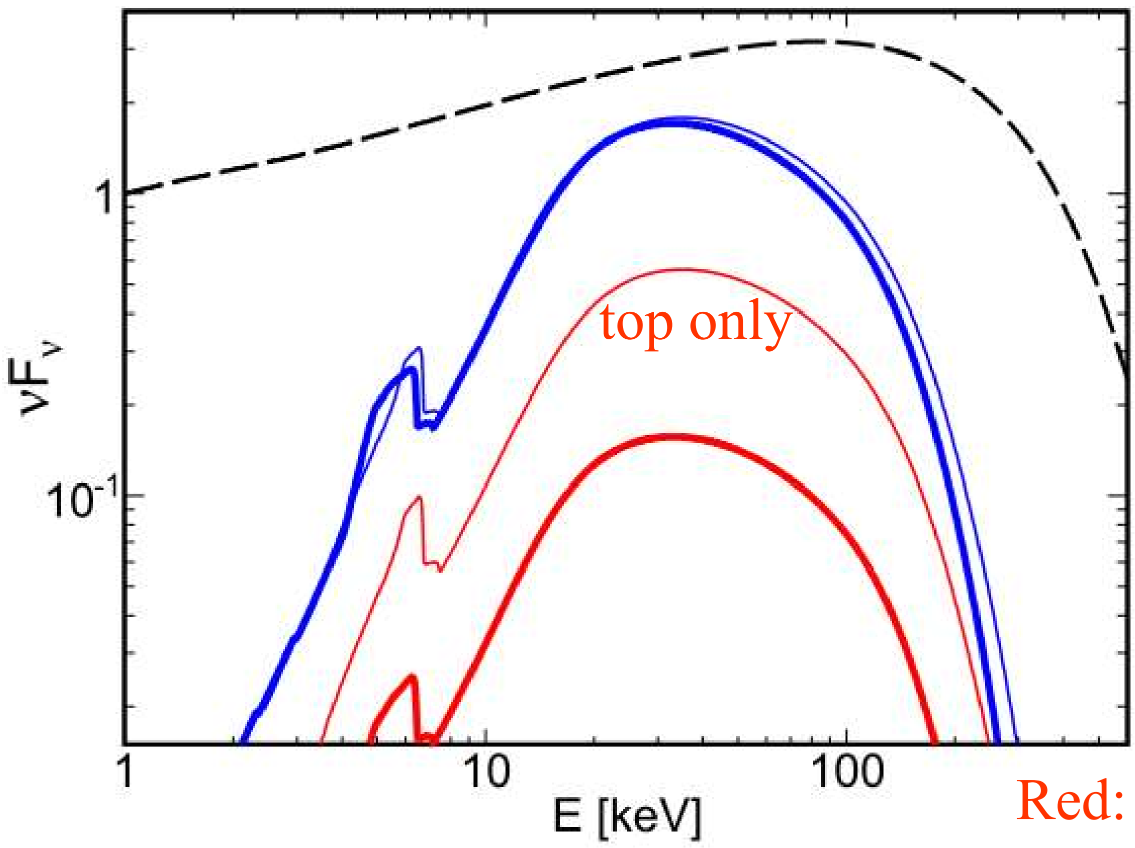


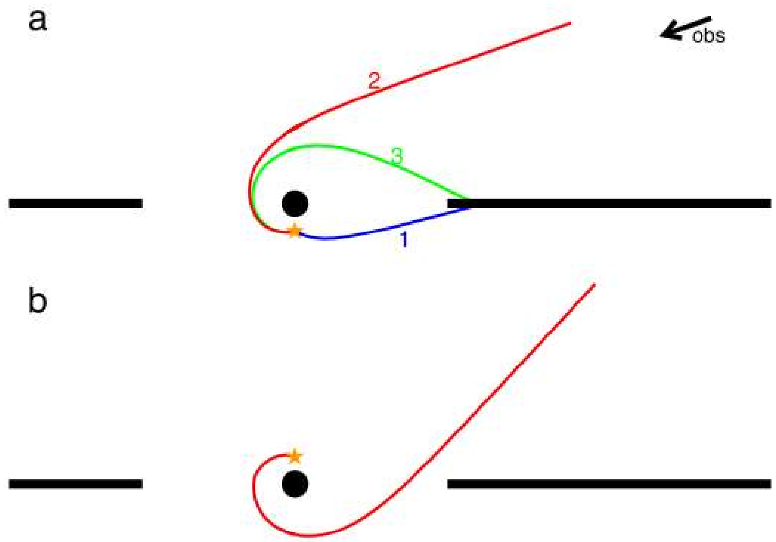


4. New improved codes for relativistic reflection

- reflkerr – coronal geometry, reflkerr_lp – lampost, + a version of reflection of neutron-star boundary layer emission.
- Improvements with respect to the popular relxill codes (many papers by Dauser et al. and García et al.):
- The incident continuum: thermal Comptonization valid at most temperatures of interest (Poutanen & Svensson 1996).
- Reflection including Klein-Nishina.
- The atomic physics: xillver of García & Kallman 2010.
- Lamppost, both sources treated.
- Full agreement with kynrefrev (Dovčiak +2004), but some differences with respect to relxill.
- See Niedźwiecki, Szanecki & AAZ 2019, Niedźwiecki & AAZ 2018, Niedźwiecki, AAZ & Szanecki 2016 for details.

The effect of the bottom source in the lamppost model



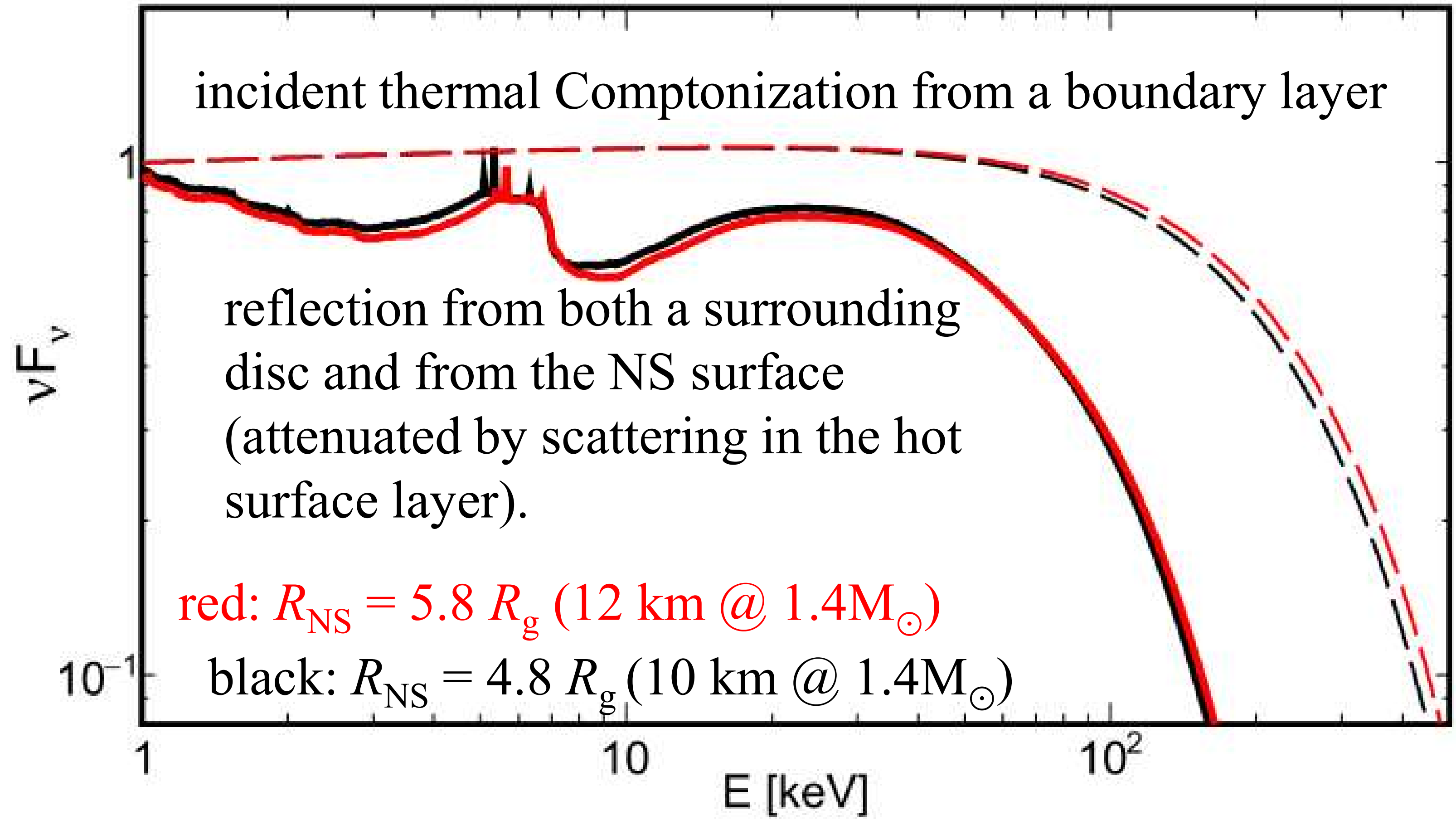


Red: θ=9°, blue: θ=30°. h=2, r_{in}=4.9 [R_g]

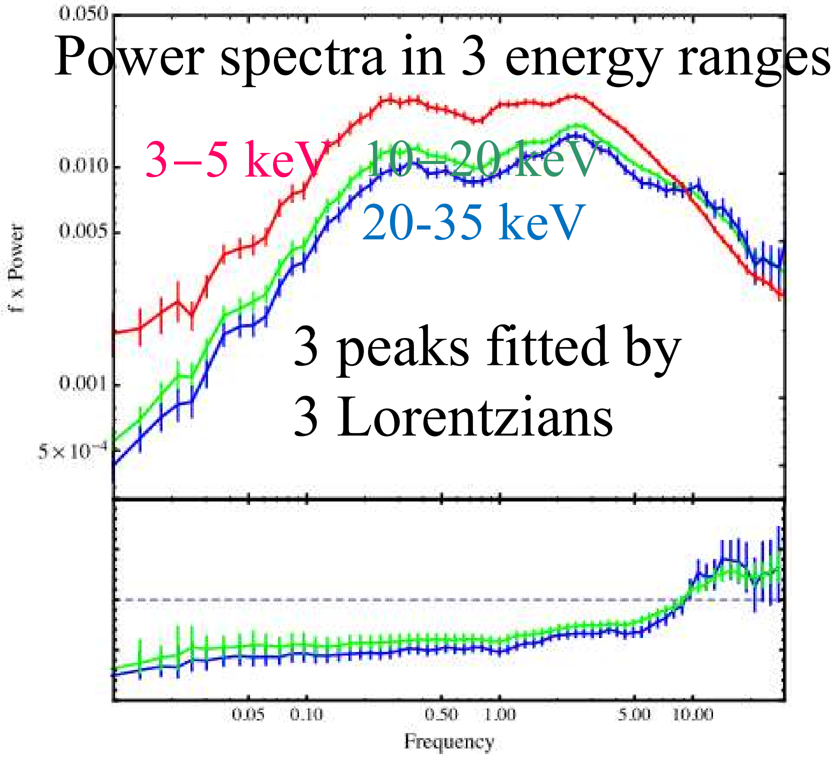
The BH is a gravitaional lense, enhancing the direct emission of the bottom source. Here, we normalize the spectra to the incident one. Thus, that enhancement is seen as a reduction in the reflection amplitude.

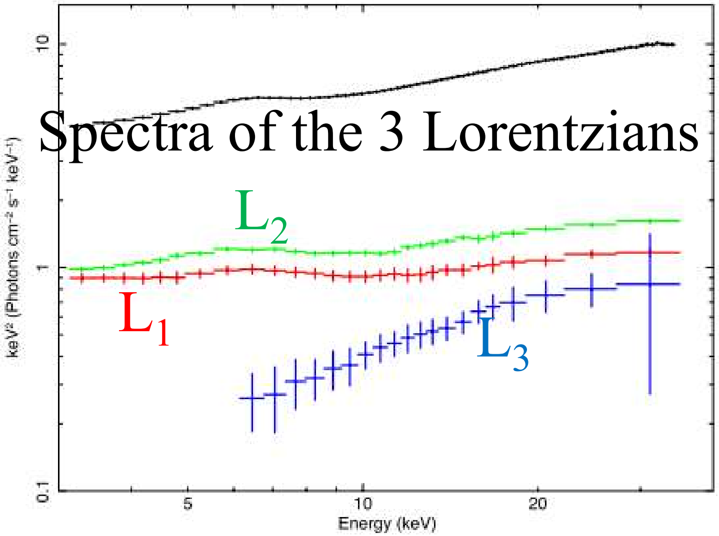
An example of reflection of emission of the boundary layer of a neutron star

Observed spectra

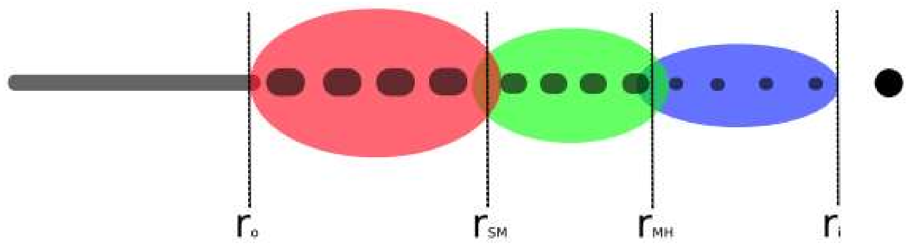


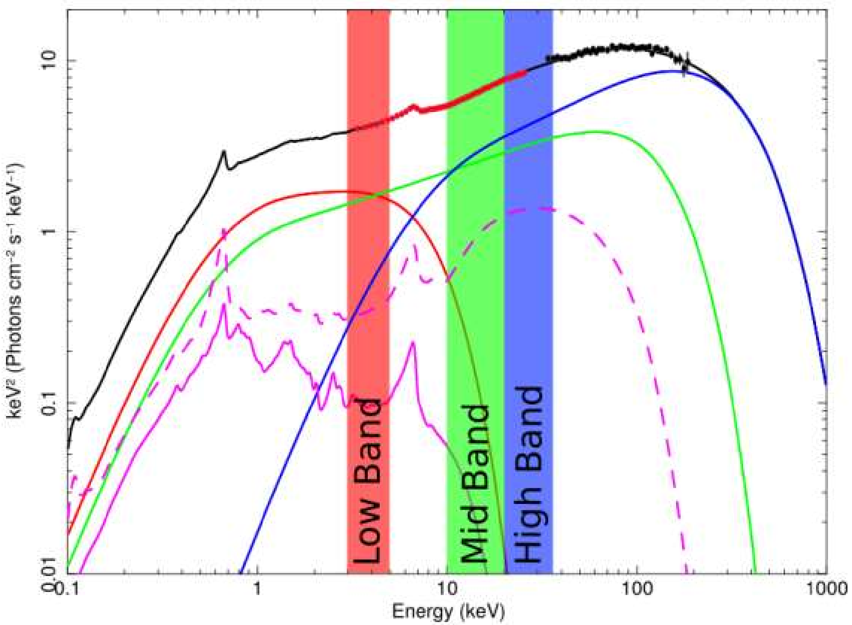
The existing models are too simple; e.g. the irradiating spectrum is not a power law





Fourier-resolved spectroscopy and models (Axelsson & Done 2018; Mahmoud & Done 2018, Mahmoud+2019)





Conclusions

- The discs in transient X-ray binaries are truncated during the quiescence, but it is unclear when they reach the ISCO during outbursts. The disc is certainly at ISCO in the soft state.
- Our spectral fitting results provide evidence for disc truncation during the entire hard state.
- New improved models for relativistic reflection, including a model for accreting neutron stars.
- More complex and more realistic models needed.