Constraining black-hole accretion flows with X-ray spectral data

Andrzej Niedźwiecki
University of Łódź

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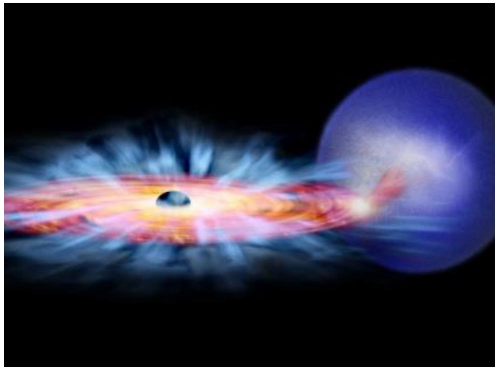
A large part of the energy released by accretion onto black holes emitted in the X-ray range

Black-hole X-ray binaries



discovered in early 1970's as strong X-ray sources, first confirmed BH system – Cyg X-1 (Paczyński, 1974)

Active galactic nuclei (AGN)

strong X-ray emission typical for AGNs and can be treated as their defining property (Elvis et al. 1978)

in both classes the X-ray emission is rapidly variable

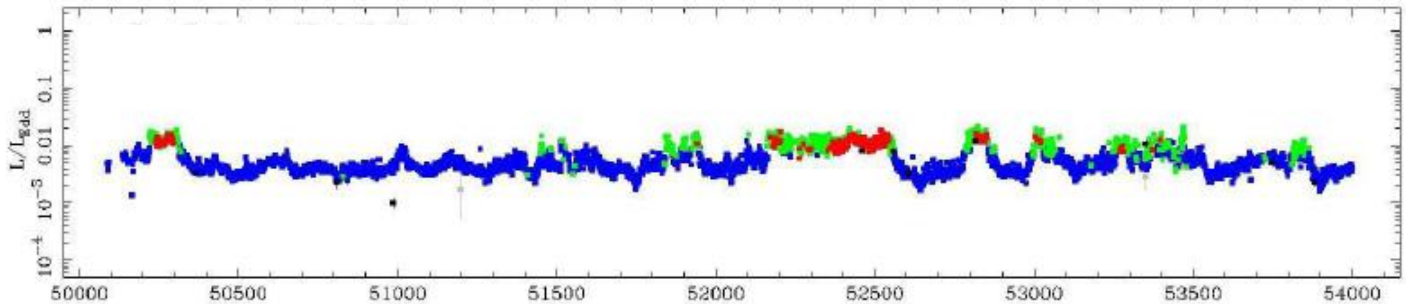
variability time-scale × c $\lesssim$ 100 R_g

$$R_g = \frac{GM_{BH}}{c^2}$$

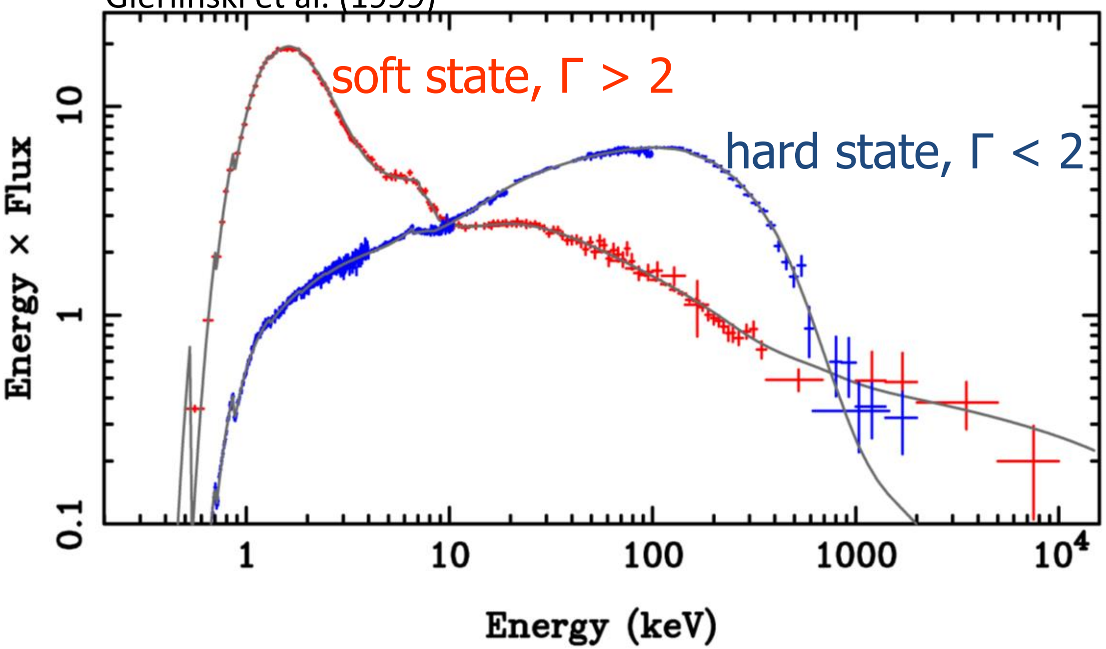
X-ray spectral states

In Cyg X-1: Tananbaum et al. (1972)

Cyg X-1 X-ray light curve (Done, Gierliński, Kubota 2007):

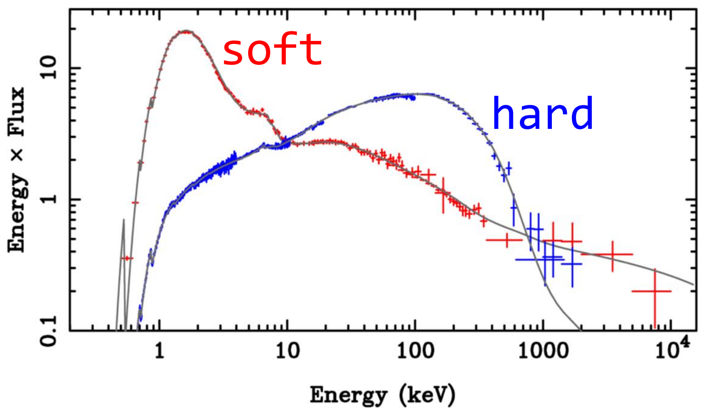


Gierliński et al. (1999)



Γ – photon spectral index: photon flux ∝ $E^{-\Gamma}$

accretion flows



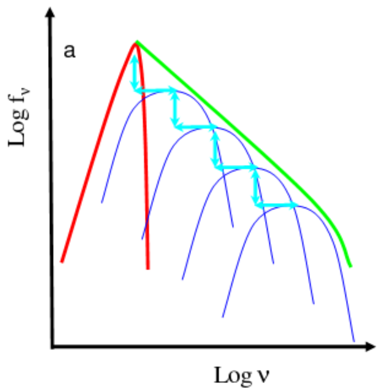
two main solutions, both for the same HD equations for the conservation of mass, radial momentum, angular momentum and energy, but here the energy equations separate for ions and electrons

OPTICALLY THICK
(Skakura & Sunyaev 1973,
Novikov & Thorne 1974,
Page & Thorne 1974,
Cunningham 1975)

- geometrically thin
- Keplerian motion with small radial velocity
- blackbody emission
- the disk temperature $kT_{BB} \lesssim 100$ eV in AGNs (→ UV) and $\lesssim 1$ keV in XRB (→ soft X-rays)

OPTICALLY THIN
(Shapiro, Lightman, Eardley 1976,
Ichimaru 1977, …)

- large geometrical thickness
- supported by proton pressure
- proton temperature close to virial
- radial velocity much larger than in a Keplerian disk
- low optical depth – electrons radiate in hard X-rays
- inefficient proton-electron coupling – exist only at low accretion rates



thermal Comptonization

Spectrum formed by repetitive scatterings

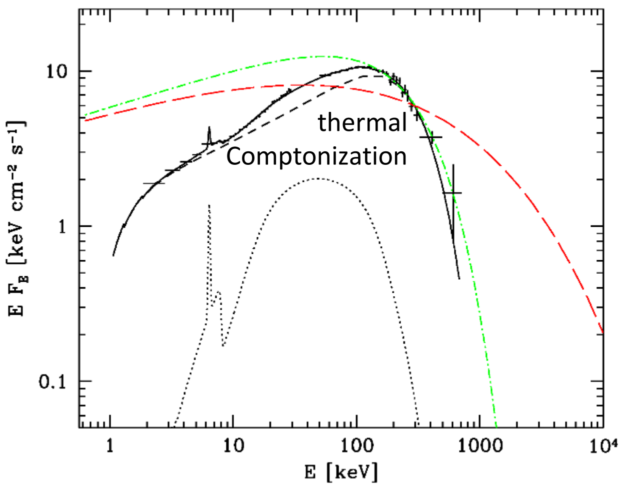
approximately power-law spectrum with a cut-off at hν ≈ kT

accurate models for relativistic temperatures:

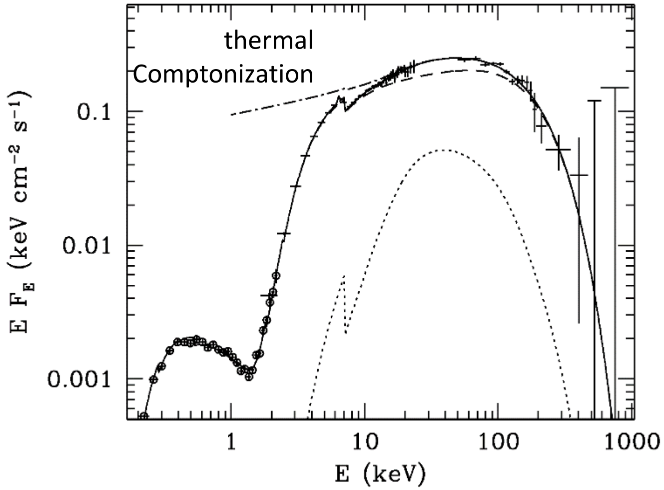
Monte Carlo method (Pozdnyakov, Sobol & Sunyaev 1983, Górecki & Wilczewski 1984) – accurate spectra but not suitable for direct spectral fitting of X-ray spectra

compps (Poutanen & Svensson 1996) – exact solution of kinetic equation by iterative scattering method; requires a large number of iterations which makes it slow

Cyg X-1 (Zdziarski et al. 2003)

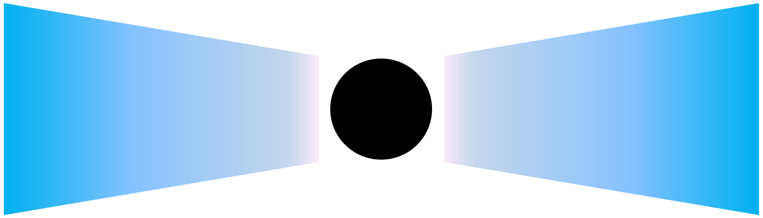


bright Seyfert galaxy – NGC 4151 (Zdziarski et al. 1996)



hot accretion flows

Shapiro, Lightman & Eardley (1976), Ichimaru (1977), Rees et al. (1982), Narayan & Yi (1995), Abramowicz et al. (1996), Esin et al. (1997, 98) ... - advection dominated accretion flows



- key novelty: a two-temperature plasma with protons much hotter than electrons

→ flows supported by proton pressure

theoretical uncertainties on the MHD processes parametrized by

β - plasma magnetization

δ - electron heating efficiency: fraction of accretion power directly heating electrons, (1 – δ) goes to protons

A numer of applications to low luminosity AGNs (Manmoto et al. 1997, Yuan et al. 2003, 2004, Nemmen et al. 2006, 2014, Xu & Cao 2009, Liu & Wu 2013, Xie et al. 2016, Bandyopadhyay et al. 2019, …) and black-hole binaries (Esin et al. 1997, 1998, Yuan et al. 2005, 2007, 2012, Yang et al. 2015, …), however, ALL based on (1) non-GR models (with pseudo-Newtonian potential of Paczyński & Wiita) with (2) local approximation for Comptonization, and (3) neglecting any nonthermal particles

kerrflow: precise, GR hot flow model

xspec version available at wfis.uni.lodz.pl/kerrflow

Niedźwiecki, Szanecki, Zdziarski, Xie (2022)

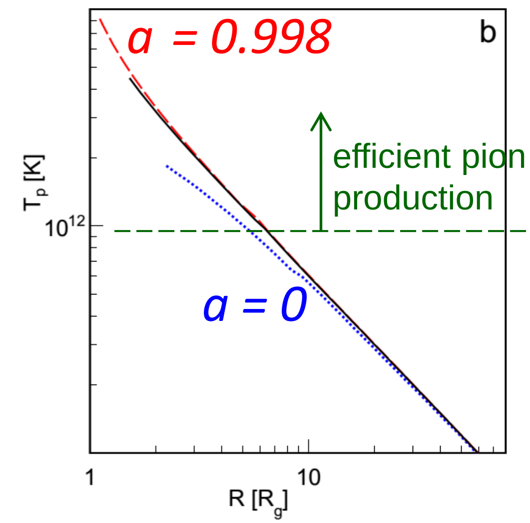
- GR description of hydrodynamics as well as radiative processes,
- exact Monte Carlo computation of global Comptonization (exchange of photons across different radii)
- hadronic processes

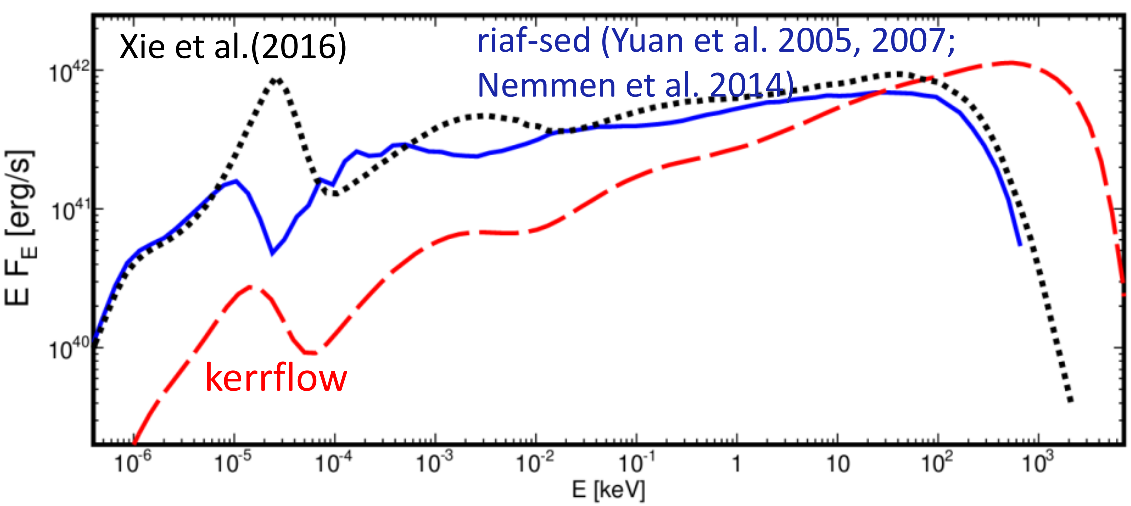
Proton energies above the threshold for pion production

$pp \rightarrow \pi^{\pm} + \ldots$

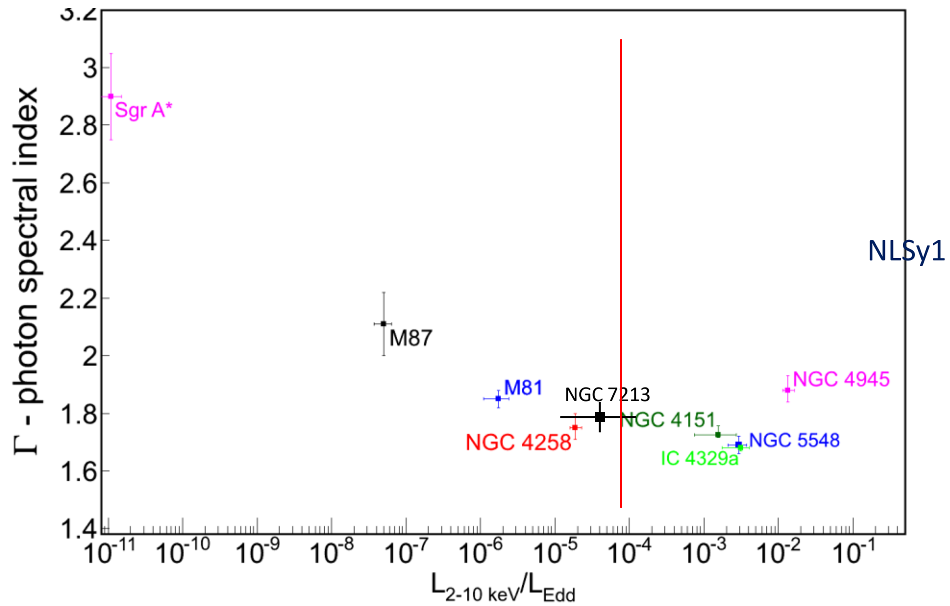
$\downarrow$

$e^{\pm} + \ldots$



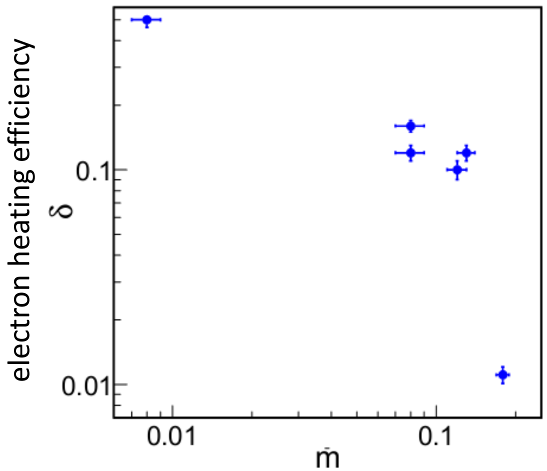


AGNs



$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} \sim 10^{38}\,(M/M_\odot)\ \mathrm{erg/s}$$

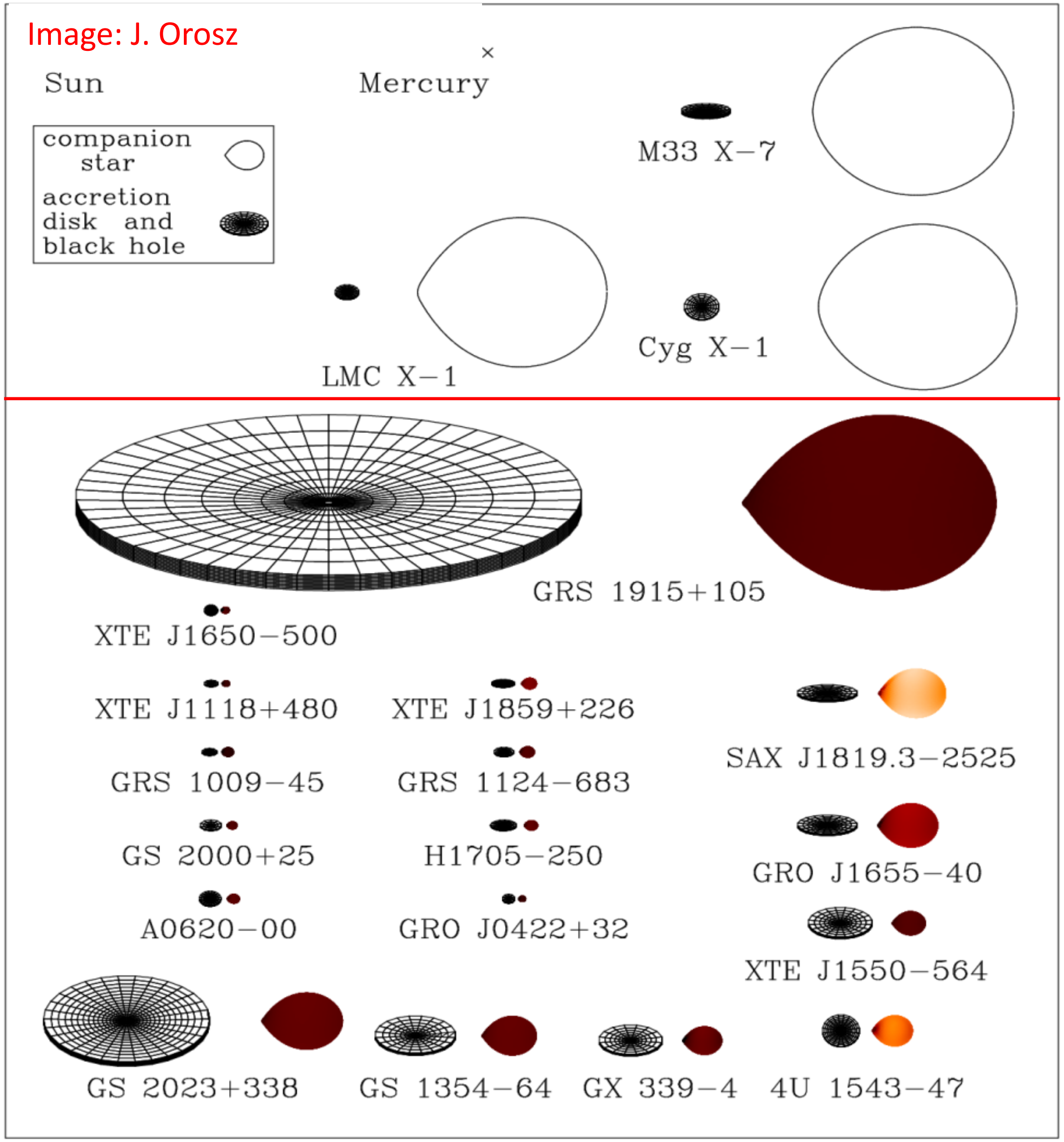
NGC 7213 (Szanecki et al. in prep):



$\beta = P_{gas}/P_{mag} = 3$,

BH spin: $a > 0.9$

Black-hole binaries
with dynamically determined BH mass

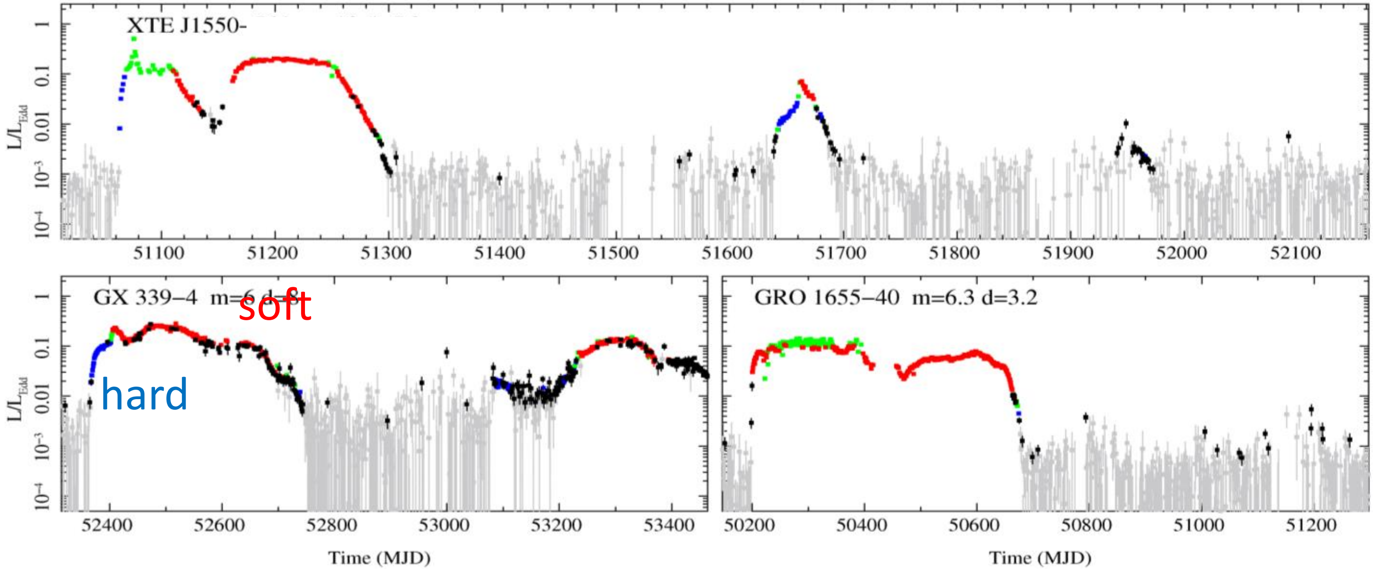


high mass companion: persistent emission

low mass companion: transient emission

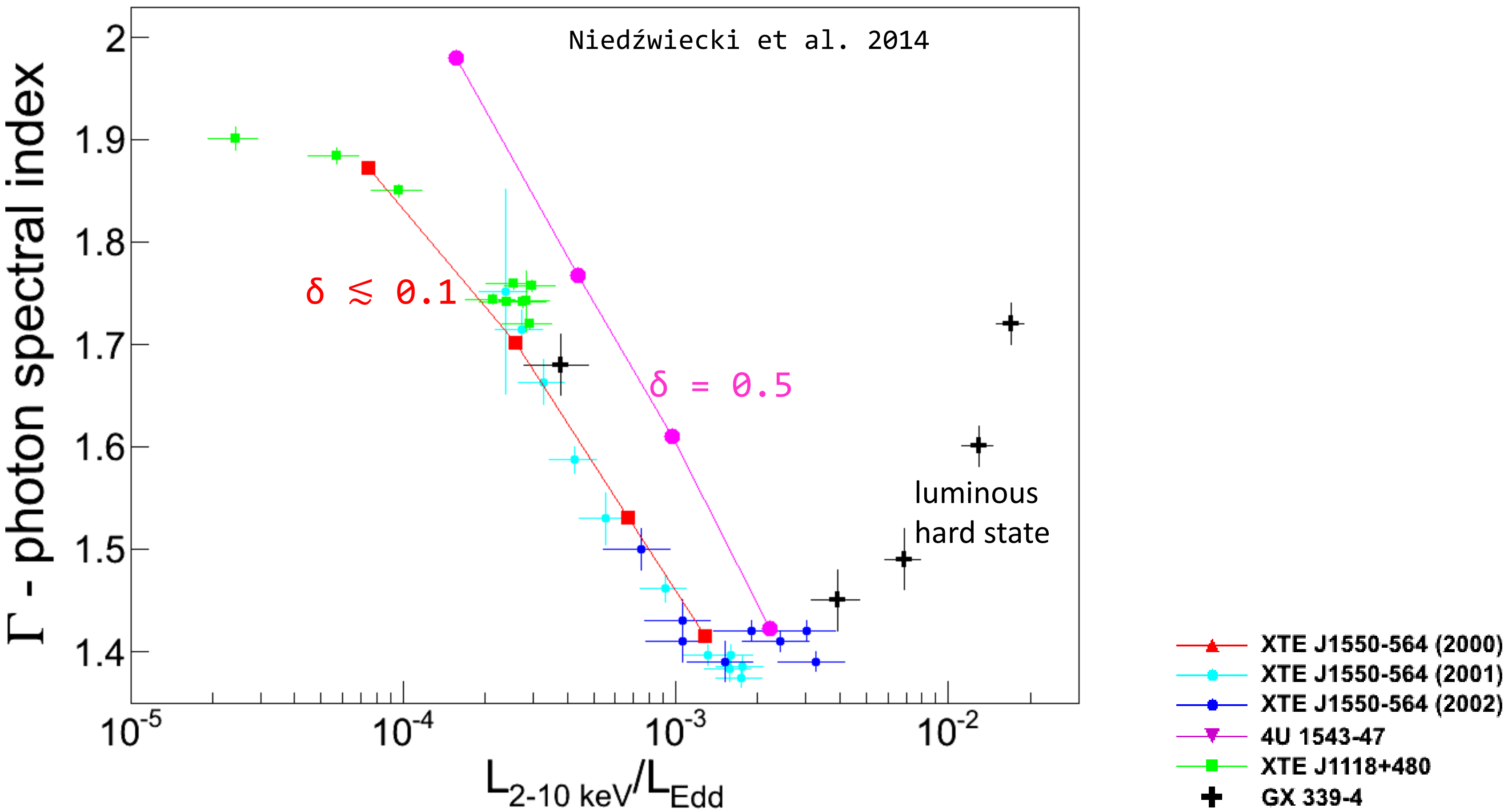
Transient BH binaries

Done, Gierliński, Kubota (2007)

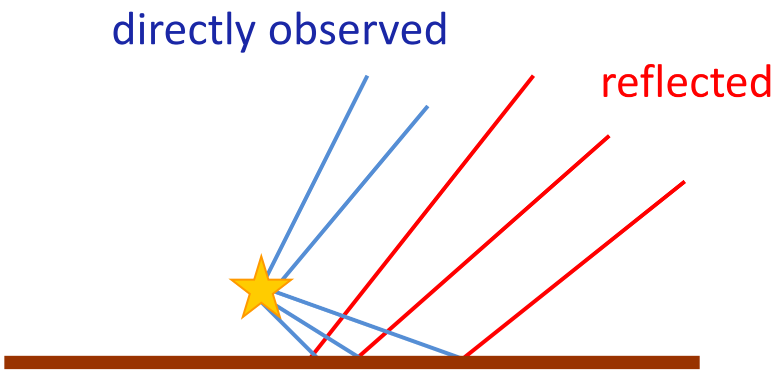


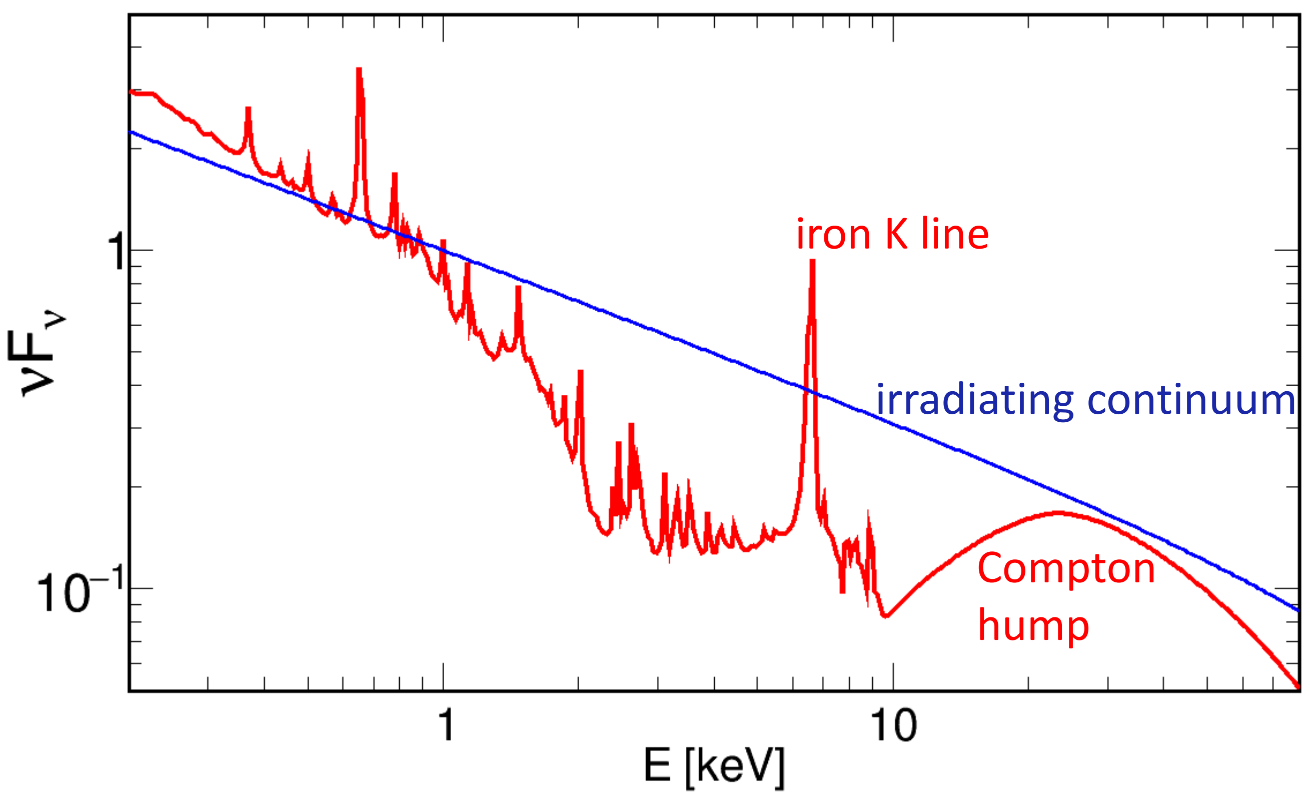
evolution in the hard state
spectral index – Eddington ratio plane

excellent agreement with kerrflow at $L_{bol} \lesssim 0.01\ L_{Edd}$, weakly dependent on model parameters (BH spin, plasma magnetization, ...) except for the electron heating parameter δ

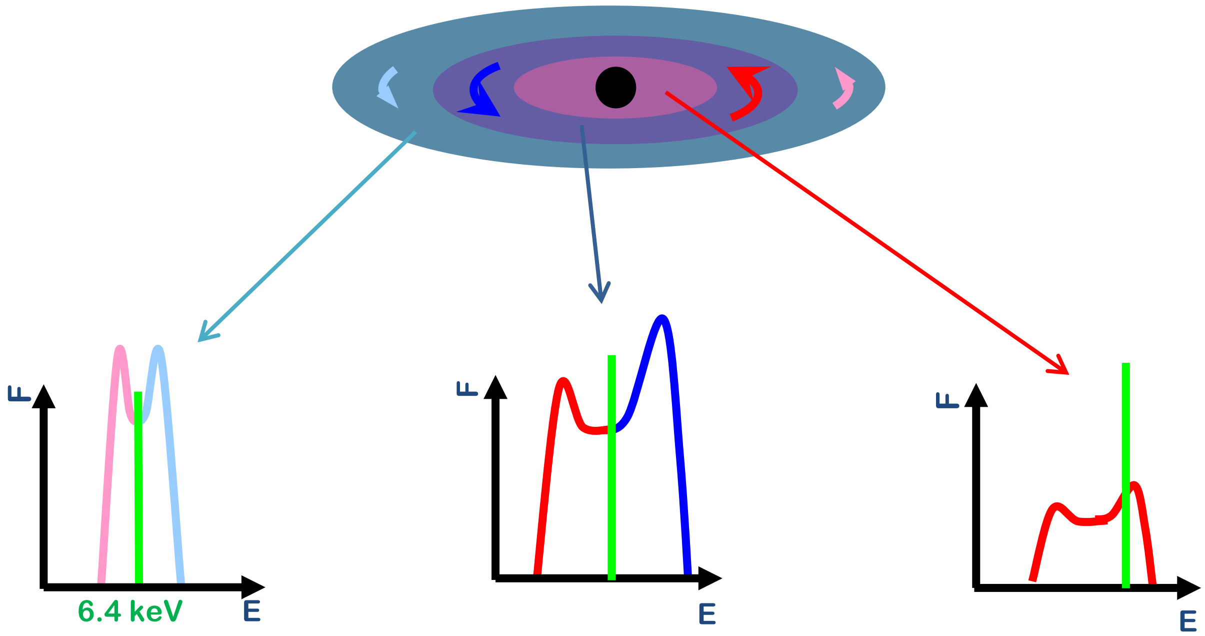


X-ray reflection





Reflection from disc: relativistic distortion

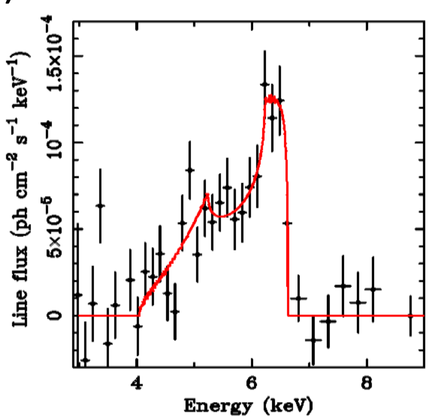


Doppler shift

relativistic beaming

gravitational redshift

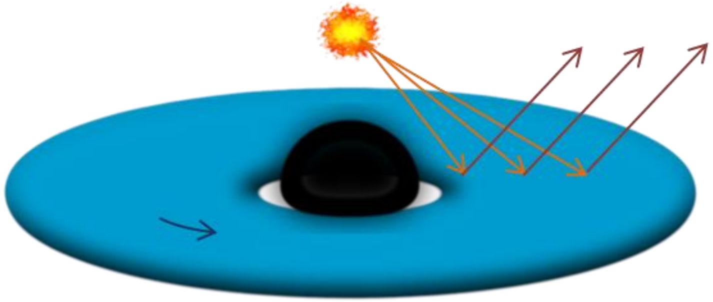
Observed (Tanaka et al. 1995):



relativistic reflection spectroscopy

Spectrum depends on the radial emissivity profile of reflection, fitting theoretical reflection spectra to the data allows to constrain:

- Inner truncation radius of the disk
- Geometry of the X-ray source
- Black-hole spin

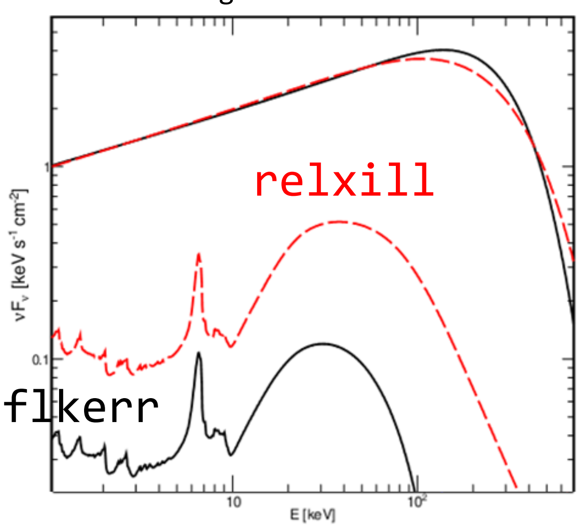


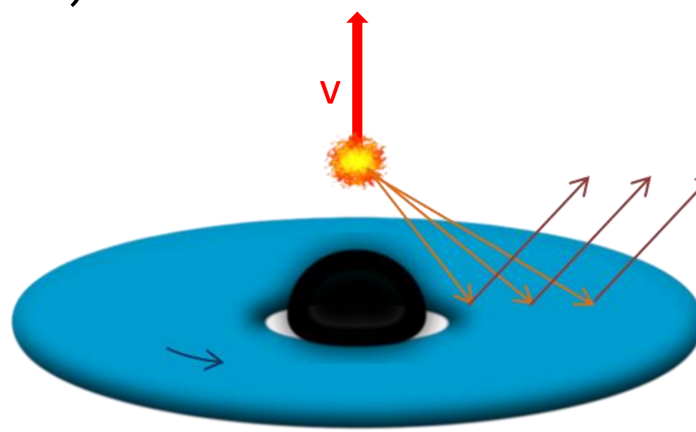
relativistic reflection models

relxill (Dauser et al. 2010, 2013)
kyn (Dovciak et al. 2004)
reltrans (Ingram et al. 2019)
reflkerr (Niedźwiecki, Szanecki, Zdziarski 2019) – the most accurate (compps) model for primary emission. Using other models likely yields nonphysical results if data above 10 keV (e.g. from NuSTAR) are used (see Szanecki et al. 2021 for NGC 4151)

X-ray source moving away from the disk (Klepczarek et al. in prep):

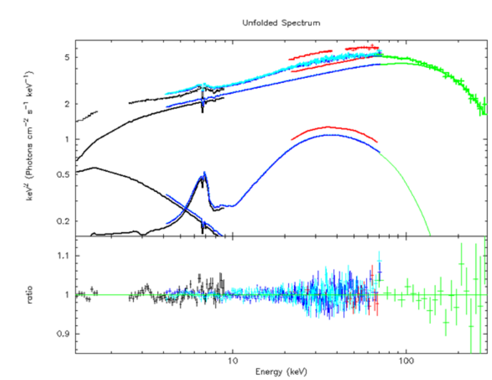
$h = 30\ R_g$, $v = 0.6\ c$





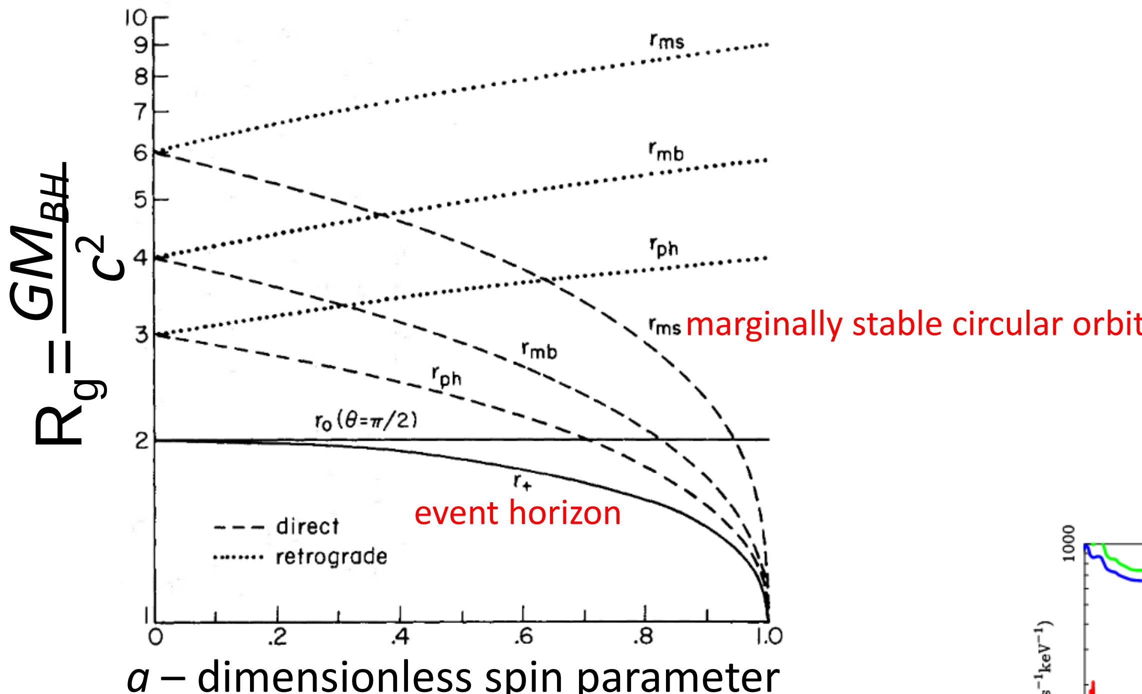
hard state of Cyg X-1:

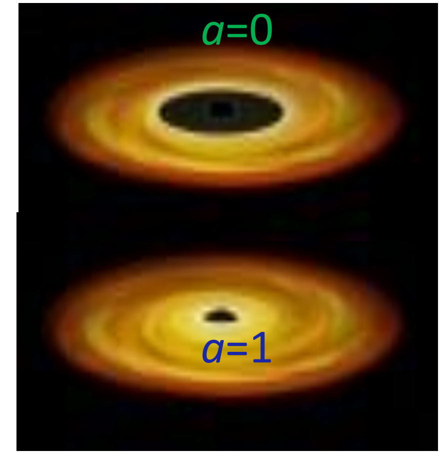
relxill: 0.8 c
reflkerr: 0.3 c

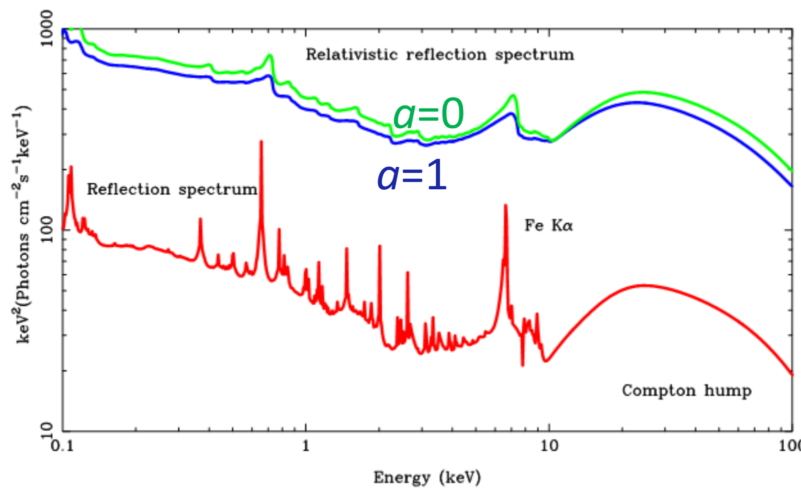


Black hole spin

Bardeen, Press, Teukolsky (1972):







Revealing the effect of BH rotation requires an extremely strong contribution from the innermost few R_g

for emissivity ∝ r^{-q}, typically q ~ 5 – 10

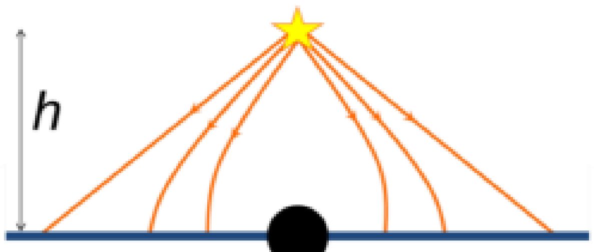
lamppost

allows to explain emissivities which are strongly centrally peaked

but requires a compact source situated <u>extremely</u> close to the black hole

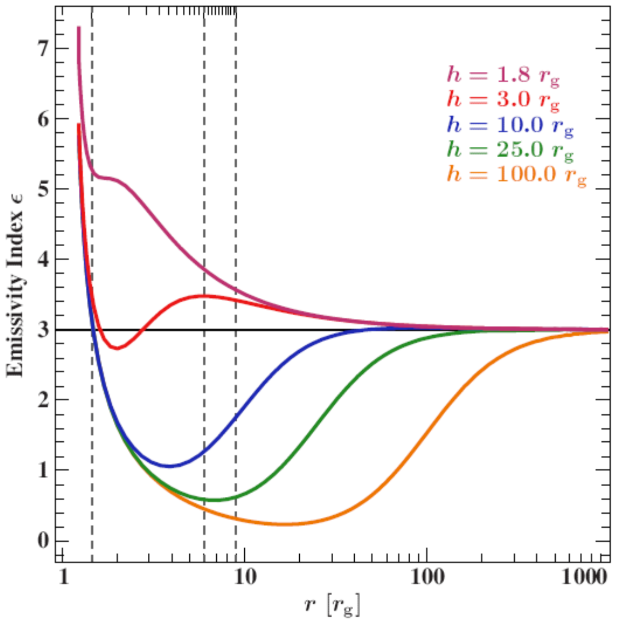
Some fitted lamppost heights:

Cyg X-1: $h < 1.5\ R_g$ (Parker et al. 2015)
GX 339-4: $h = 1.7\ R_g$ (Garcia et al. 2019)
XTE J1752-223: $h = 1.17\ R_g$ (Garcia et al. 2018)
NGC 4151: $h = 1.17\ R_g$ (Beuchert et al. 2017)
NGC 4151: $h = 1.3\ R_g$ (Keck et al. 2015)



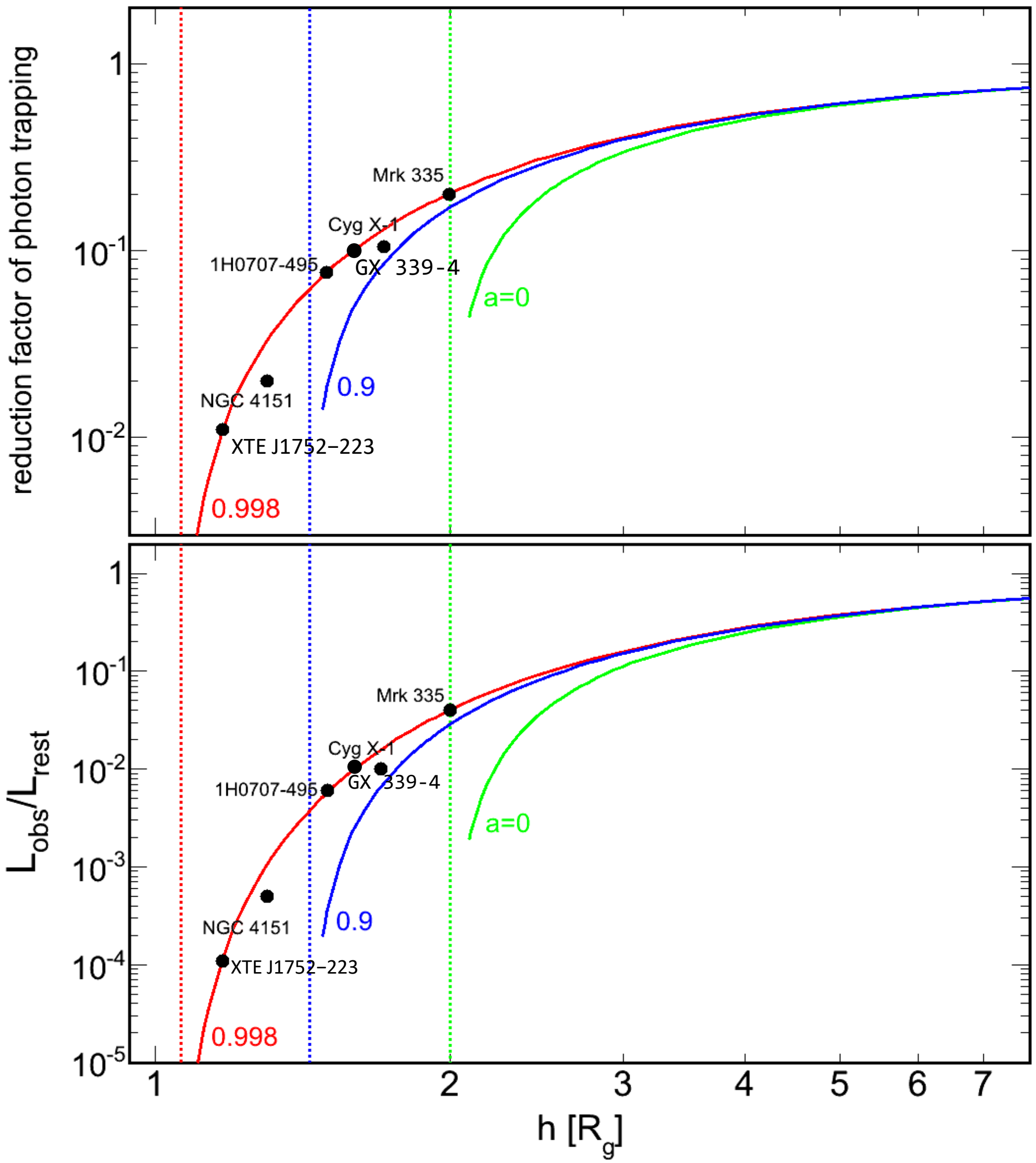
Martocchia & Matt (1996)

radius dependent emissivity index



lamppost - caveats

Niedźwiecki, Zdziarski, Szanecki 2016



most of the emitted photons trapped by the BH → strong reduction of the radiative efficiency

rest-frame luminosity L_{rest} much higher than L_{obs} due to photon trapping, time dilation and redshift, which gives very large compactness parameters $\ell > 10^4$, implying that the fitted sources are out of $e^{\pm}$ pair equilibrium

summary

hot flow model represents the most physically complete explanation of the hard states; good agreement with the data

problems with physical consistency in the most extreme lamp-post fits

new GR models for X-ray emission:

kerrflow – improvements in modeling the emission from hot flows

reflkerr – improvemets in sefl-consistent modeling of the relativistic reflection