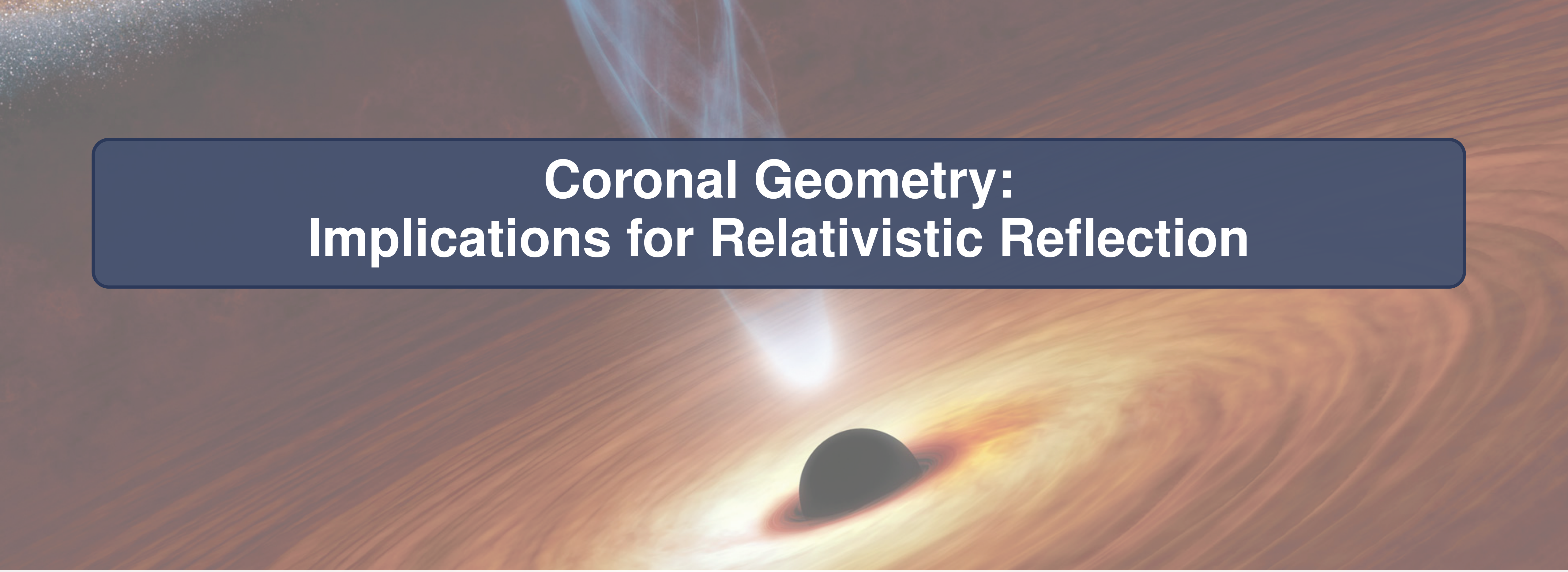


Coronal Geometry: Implications for Relativistic Reflection

Thomas Dauser – Remeis Observatory, FAU Erlangen-Nürnberg

in collaboration with A. Nekrasov (Remeis), J. Wilms (Remeis), J. García (GSFC), P. O. Petrucci (IPAG), and BlackSTAR

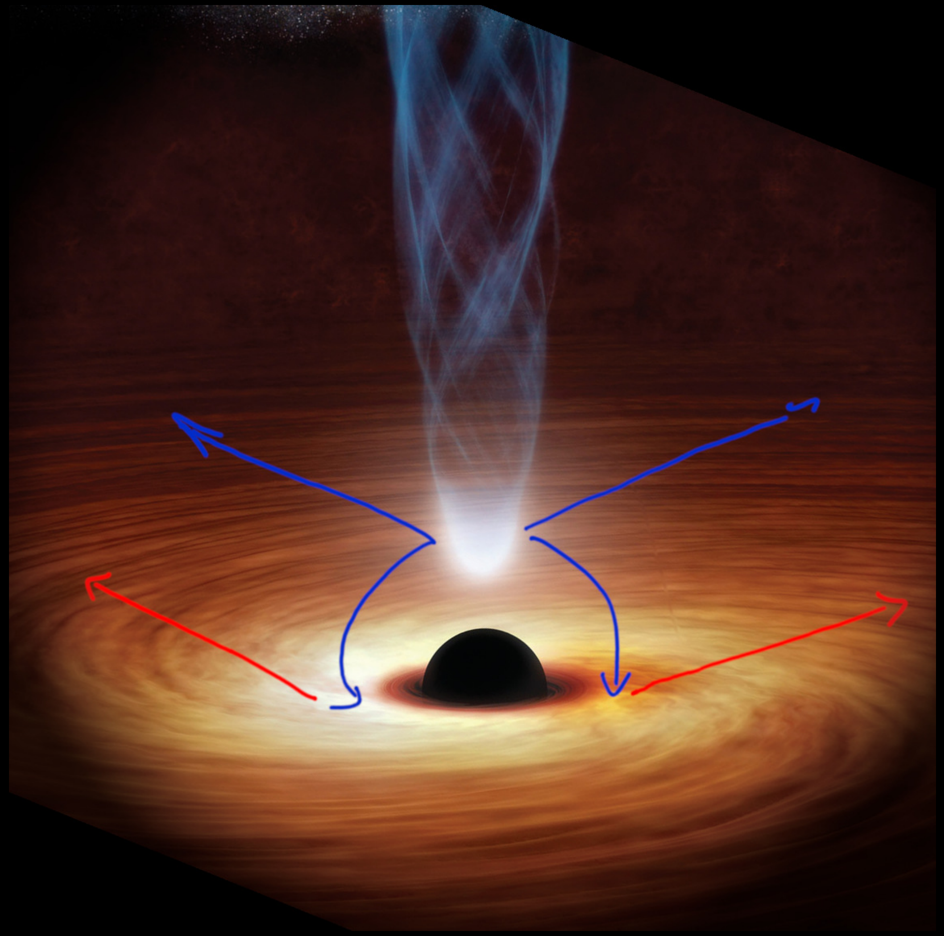
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

ATHENA

BlackSTAR
Black hole Spectral-Timing And Reverberation

The X-ray Corona from a Reflection Perspective



Basic Properties:

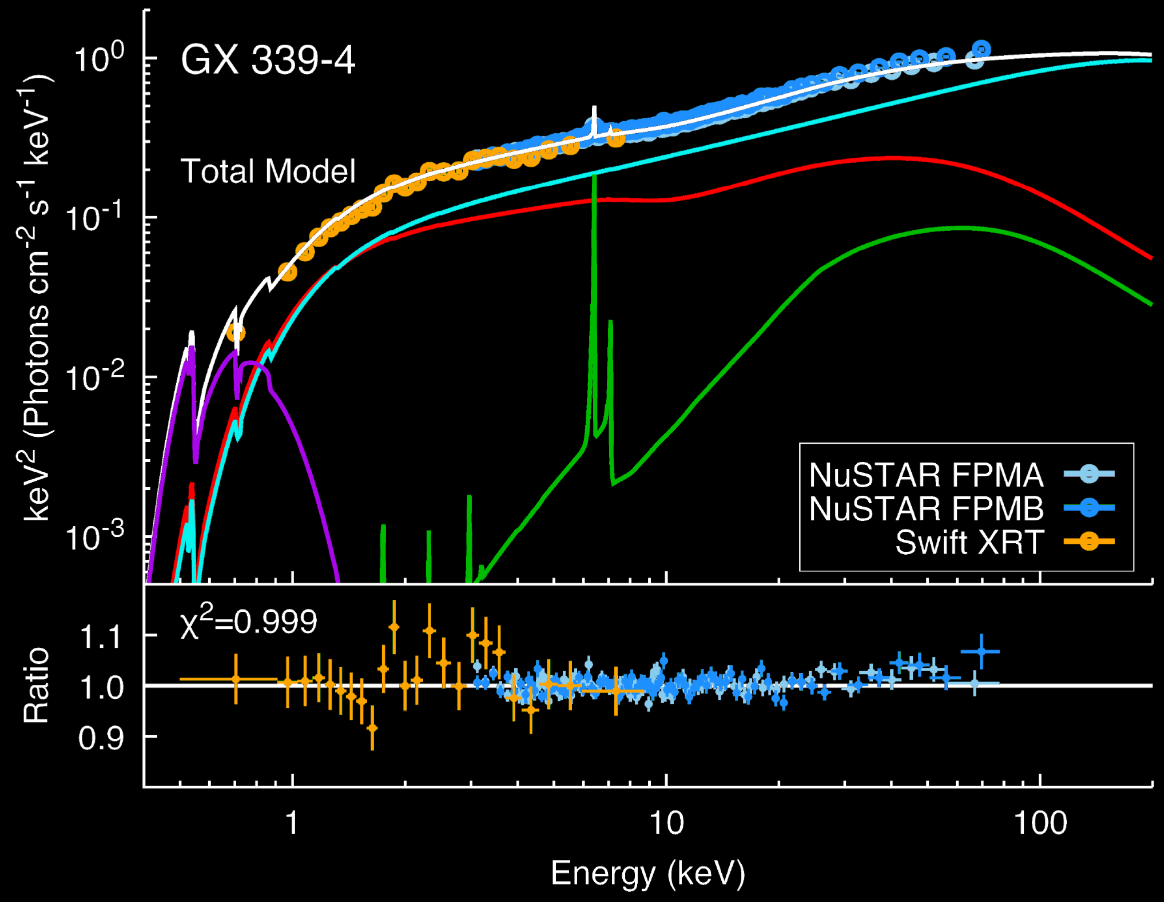
- Comptonized primary X-ray spectrum (cutoff powerlaw) of seed photons from the accretion disk
- irradiates the inner accretion disk
- creates (relativistic) reflection

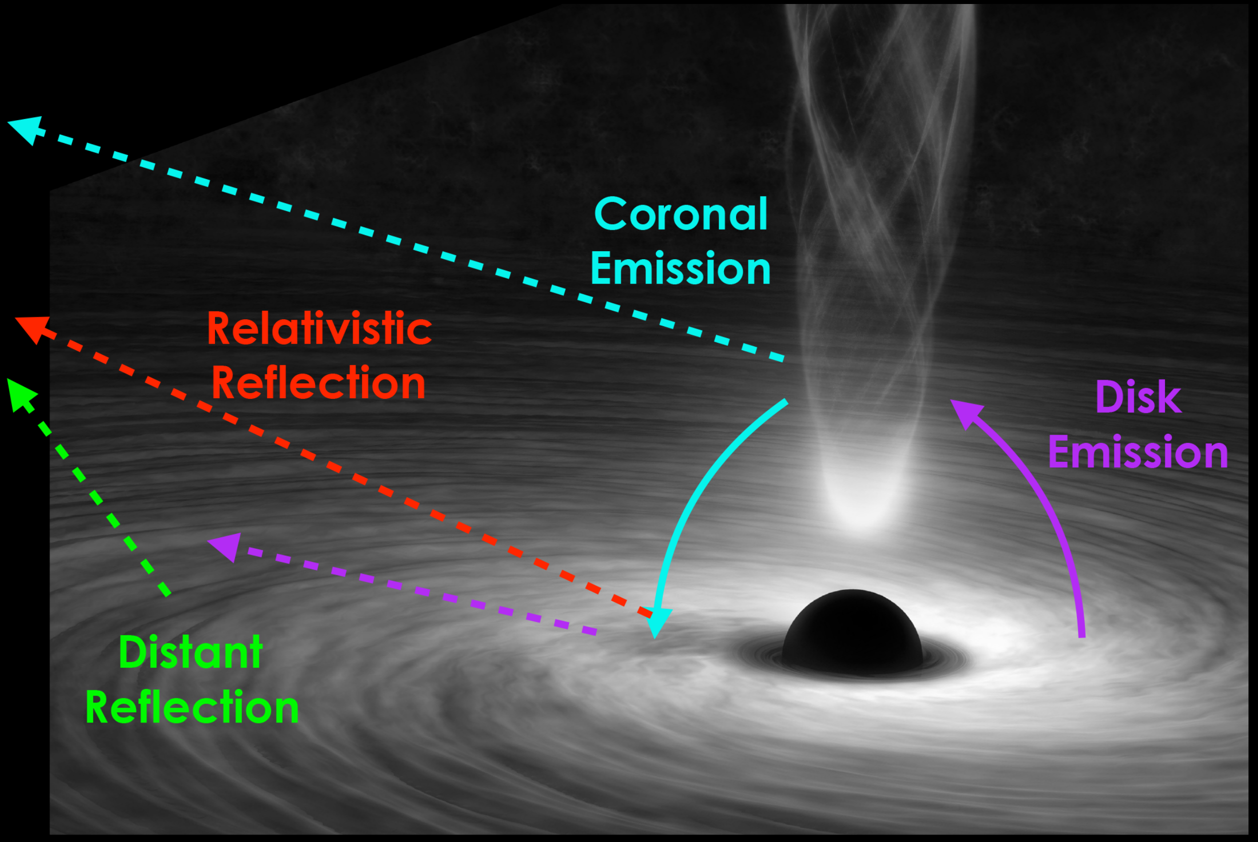
Origins and Connections to Jets?

Base of a Jet (Markoff & Nowak, 2004; Dauser et al., 2013), Jet Emitting Disk (Ferreira et al., 2006), . . .

Focus: Geometrical Constraints from Relativistic Reflection

Broad band reflection spectroscopy

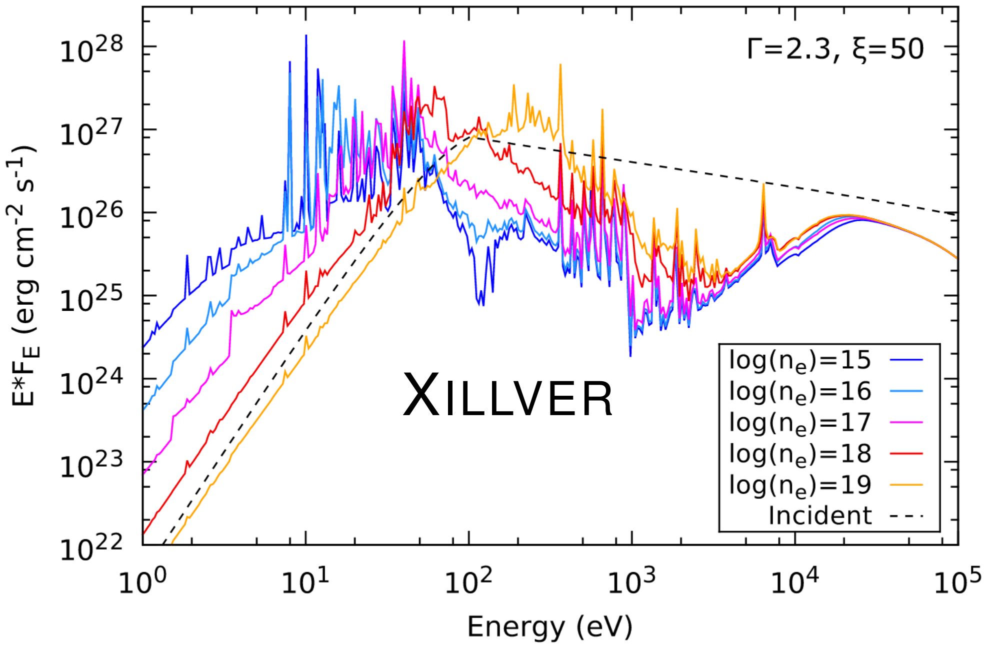


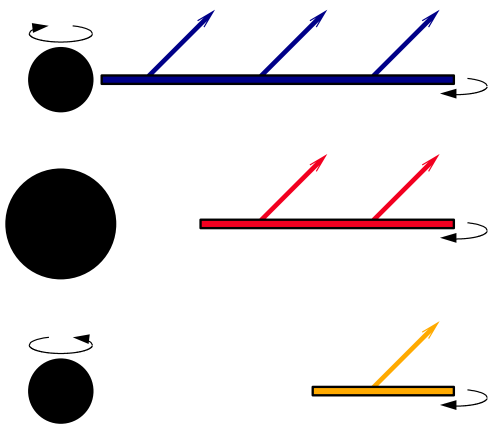


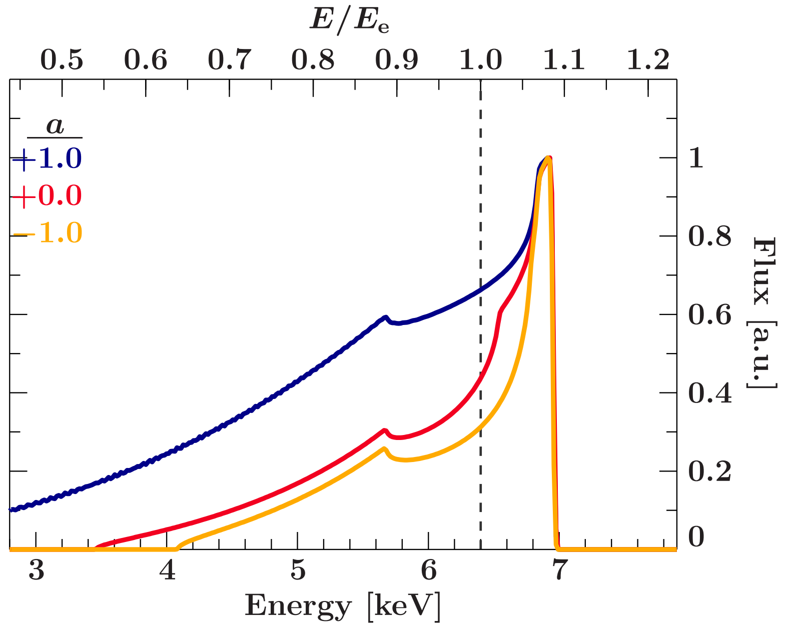
(Garcia et al., 2019)

Relativistic Reflection Modeling

Spectral fitting models: broad band reflection, ionization and density gradient, primary source

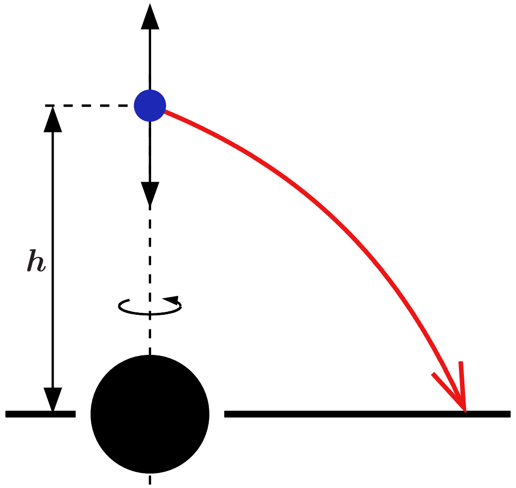


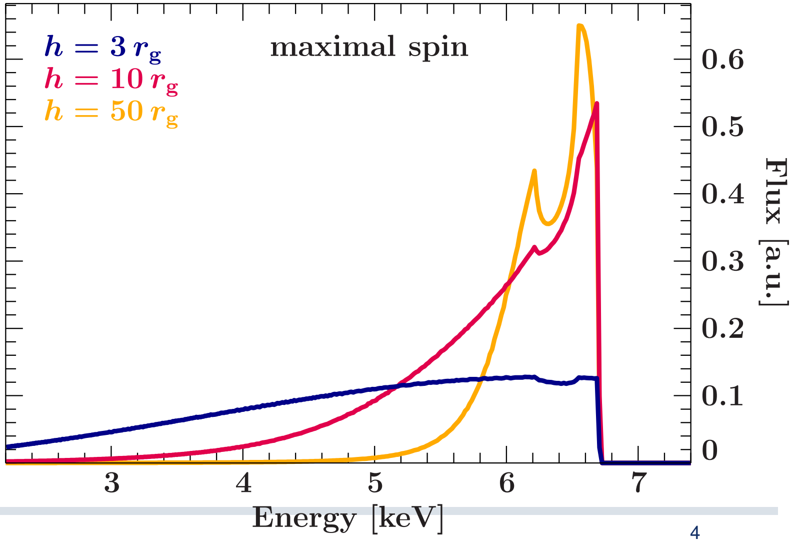




RELXILL *(Dauser et al., 2010, 2013, 2014, 2016, 2022; García et al., 2013, 2014, 2016)*

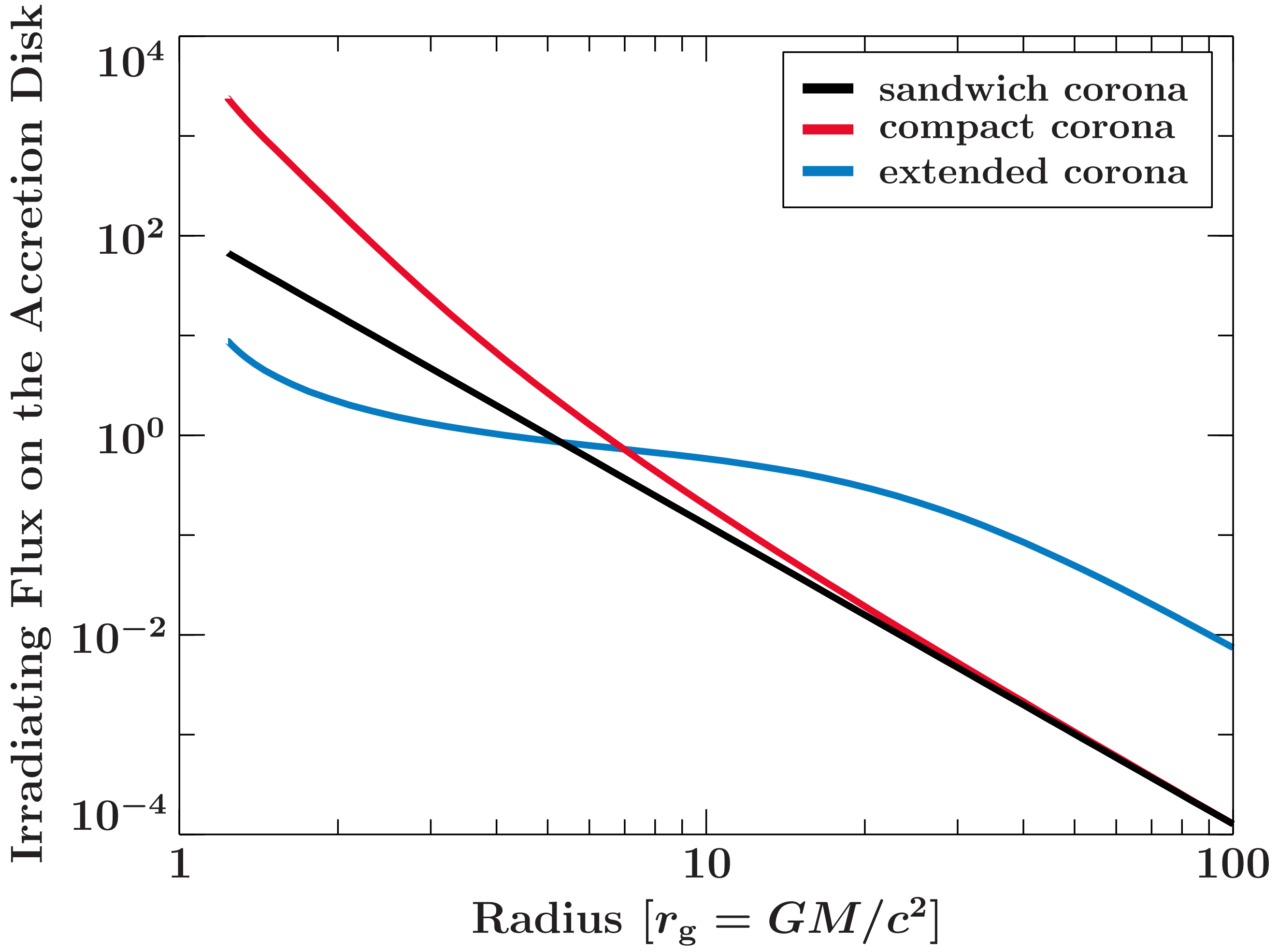
RELTRANS (Ingram et al., 2019), KY-models (Dovciak et al., 2004), REFLKERR (Niedzwiecki et al., 2019), . . .





How does the corona influence relativistic reflection?

main effect: determines the **irradiation of the accretion disk**

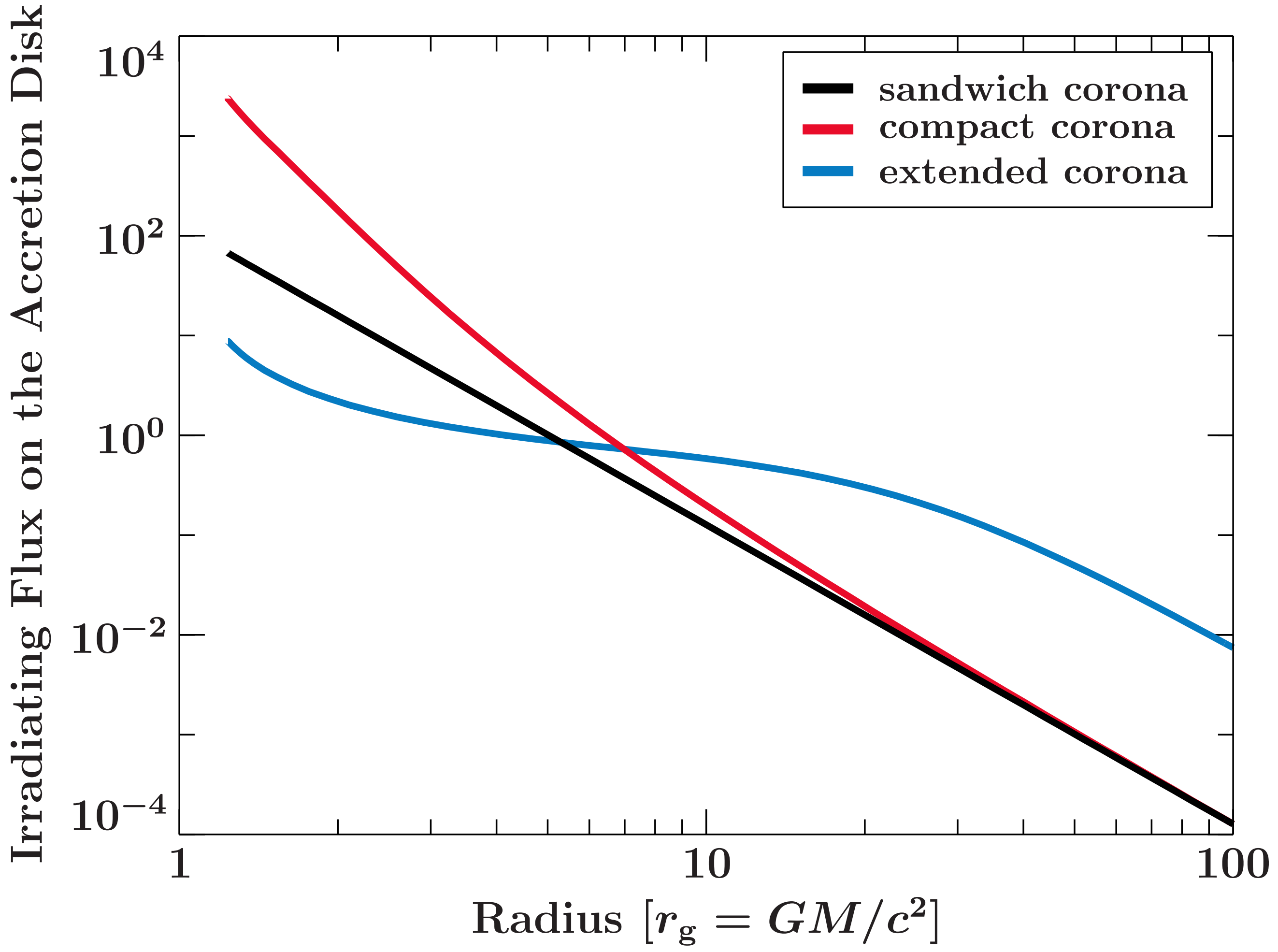


Which part of the disk do we see in reflection?

"broad reflection lines require most photons to be reflected at the inner disk"

How does the corona influence relativistic reflection?

main effect: determines the **irradiation of the accretion disk**



Which part of the disk do we see in reflection?

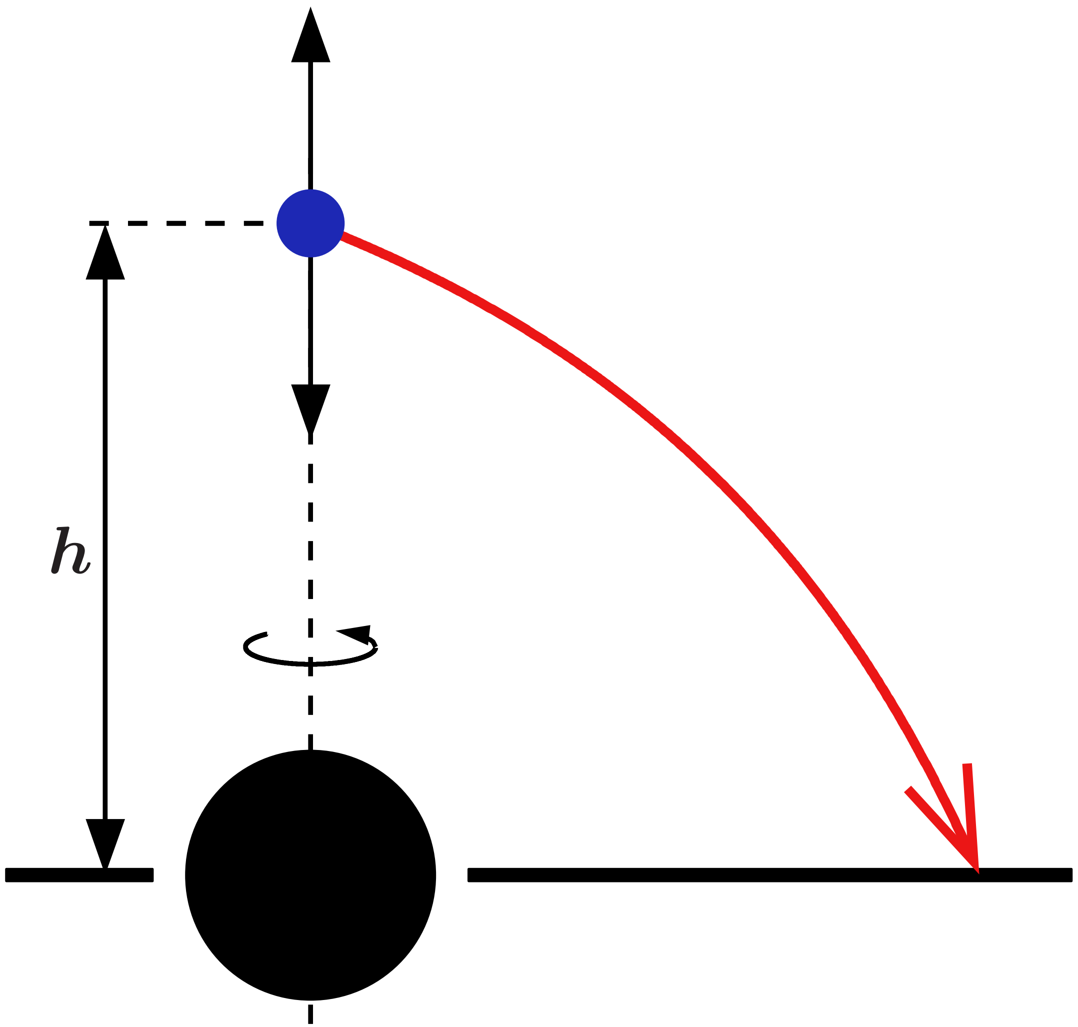
"broad reflection lines require most photons to be reflected at the inner disk"

$\rightarrow$ **strong, broadened relativistic reflection requires steep emissivities**
(Wilms et al., 2001; Dauser et al., 2013; Parker et al., 2014; Duro et al., 2016; Walton et al., 2021, . . .)

$\Rightarrow$ **compact corona close to the BH**
(typically modeled by a lamp post)

Modeling an Extended Corona

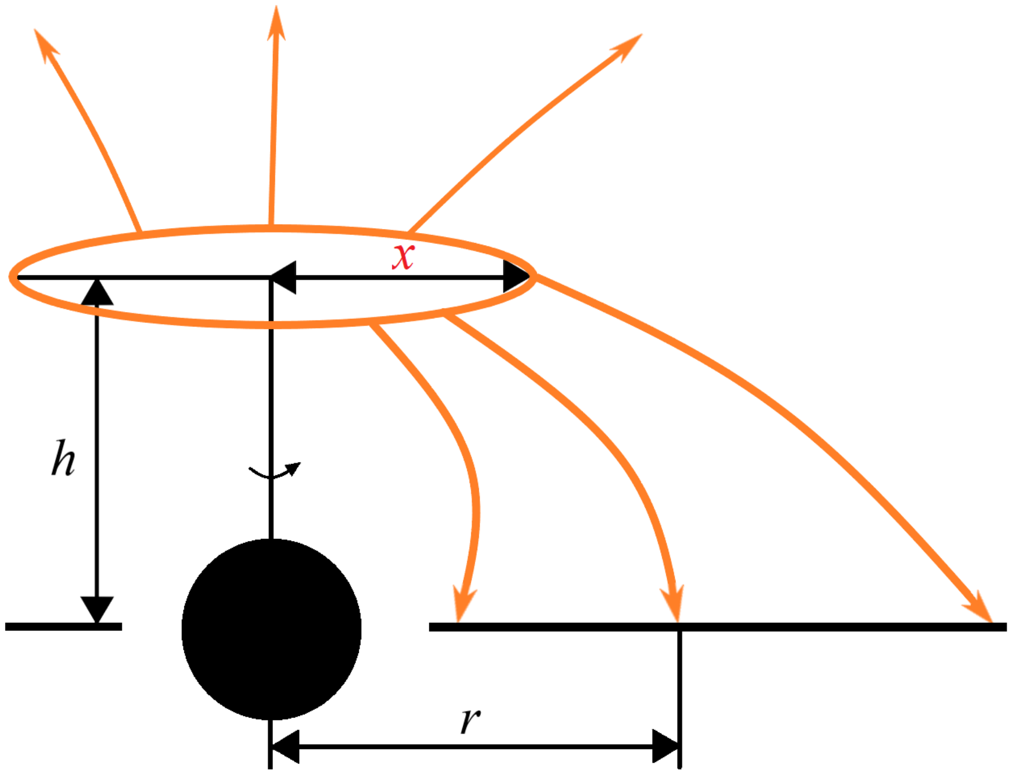
Current status: most observations modeled by a point-like lamp post



Modeling an Extended Corona

Current status: most observations modeled by a point-like lamp post

$\rightarrow$ **RELXILL model for ring-like sources: model any rotationally symmetric source**



(Nekrasov et al., 2025)

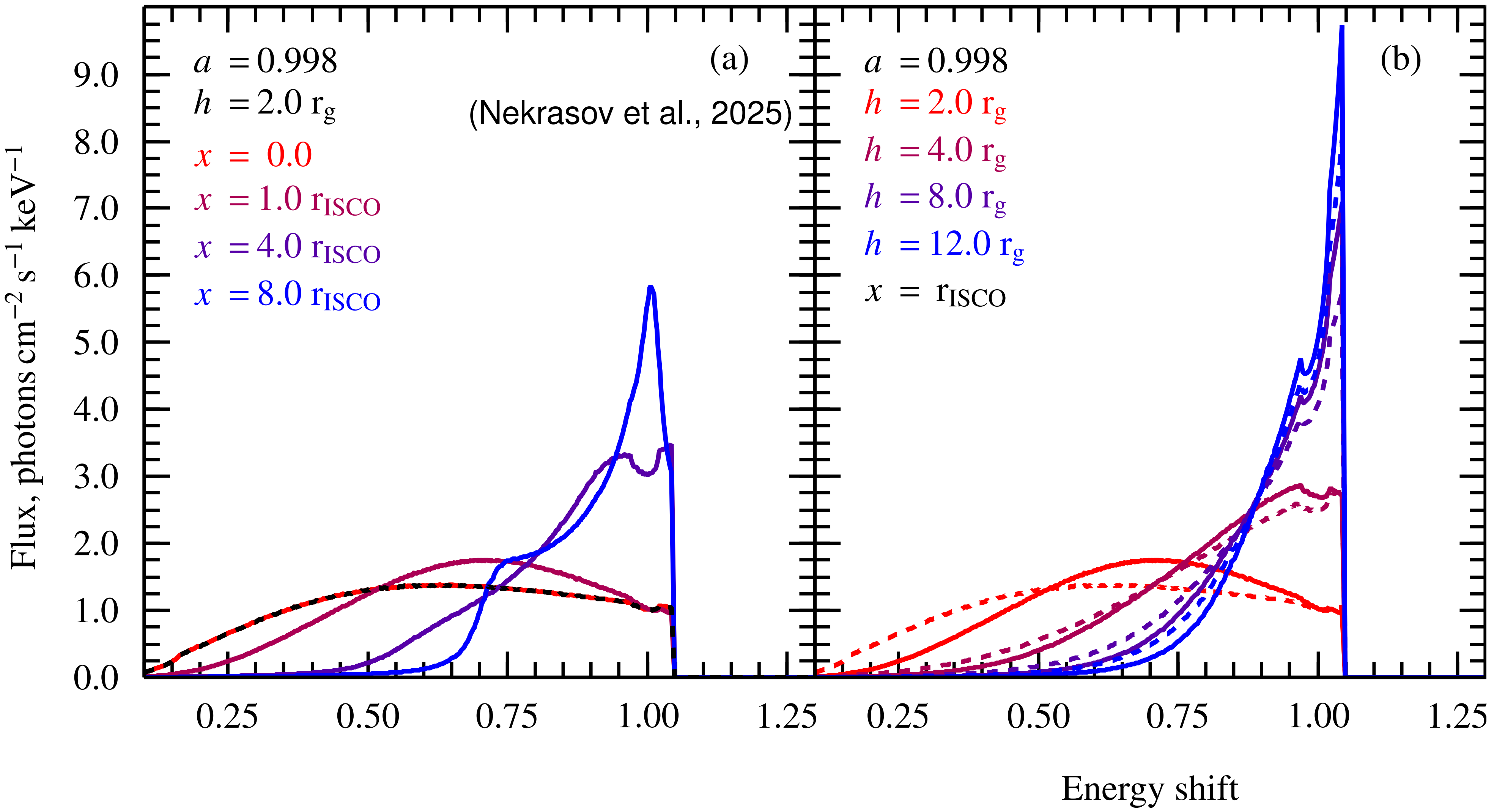
Coronal Geometry and Relativistic Reflection

What are our questions on Corona Geometry for Relativistic Reflection?

- Can we find a geometry to fit current observations? Yes, easily!
  (but WHY does the lamp post fit so well?)
- Which parameters of the coronal geometry (location, extent, velocity) can we constrain?
- Do they agree with other measurements? (reverberation, polarization, . . .)

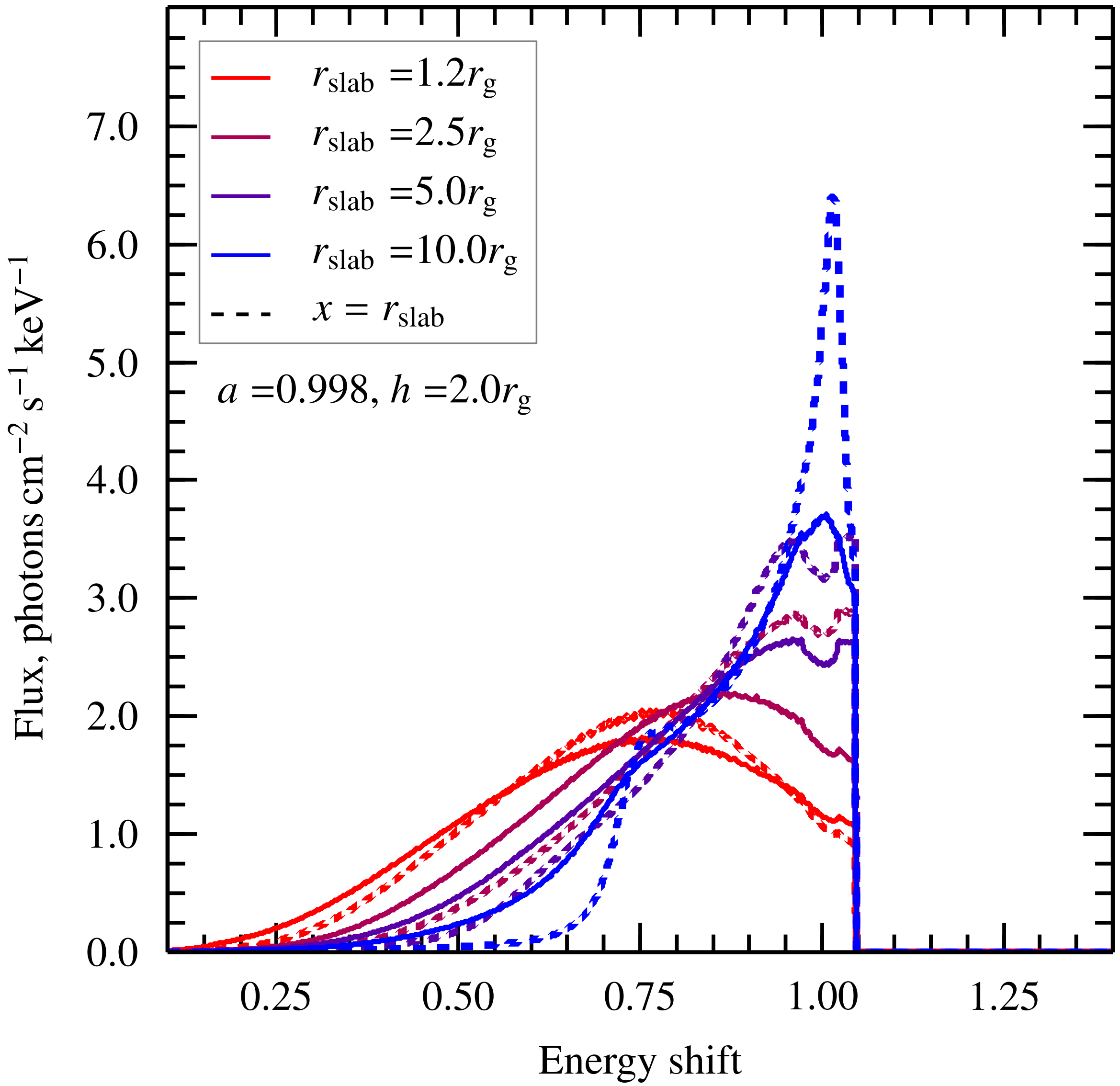
Important: we only probe the part of the corona (strongly) irradiating the disk

Ring-like Extended corona



$x = 0$ to $x = R_{\text{ISCO}}$ has only a minor effect on the line shape

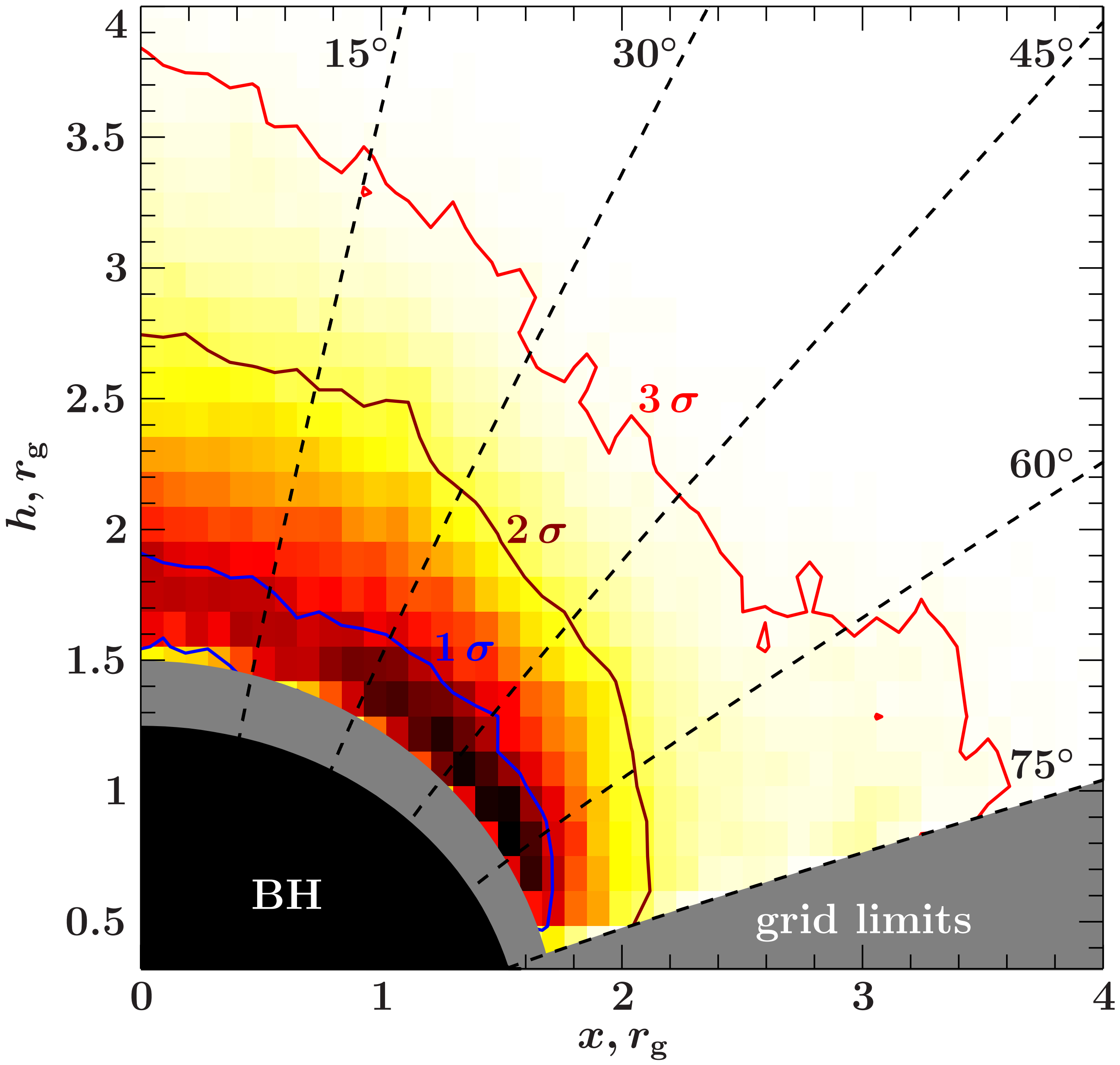
From a ring to a slab



- small slab similar to a LP
- larger slab similar to ring at $0.5 r_{\rm slab}$

(see also other work on extended geometries, e.g., by Niedźwiecki & Życki, 2008; Wilkins & Fabian, 2012; Baker & Young, 2026) and Fergus Baker's Thesis (`https://cosroe.com/thesis.html`)

Testing the Ring: Relativistic Reflection in ESO 033-G002



apply ring-like RELXILL model
(Nekrasov et al., 2025)

- *XMM-Newton* & *NuSTAR* spectra of Seyfert galaxy ESO 033-G002 shows very strong reflection (Walton et al., 2021)
- compact Lamp Post corona ($h < 3\, r_{\rm g}$), high spin ($a > 0.93$)

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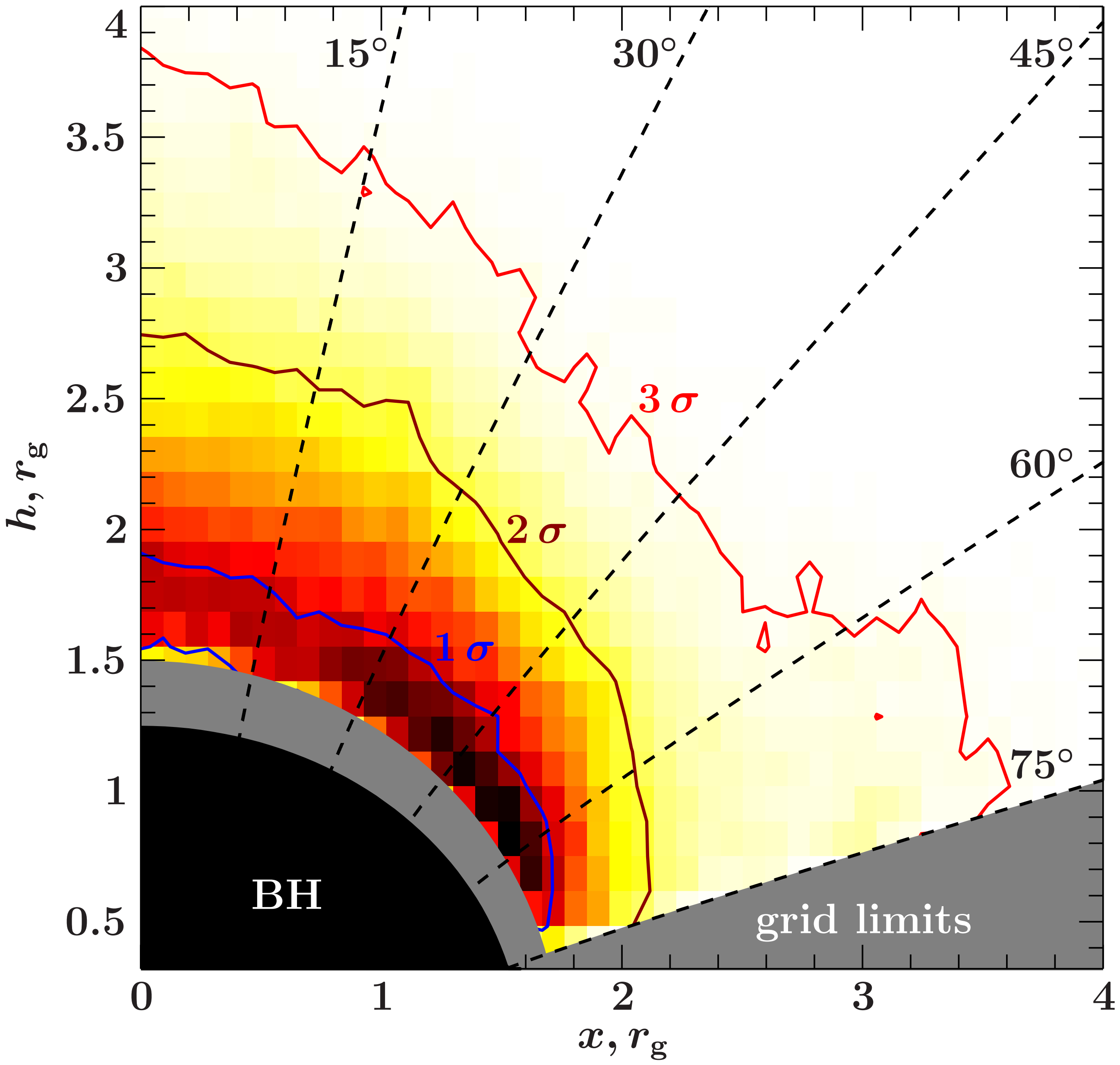

apply ring-like RELXILL model
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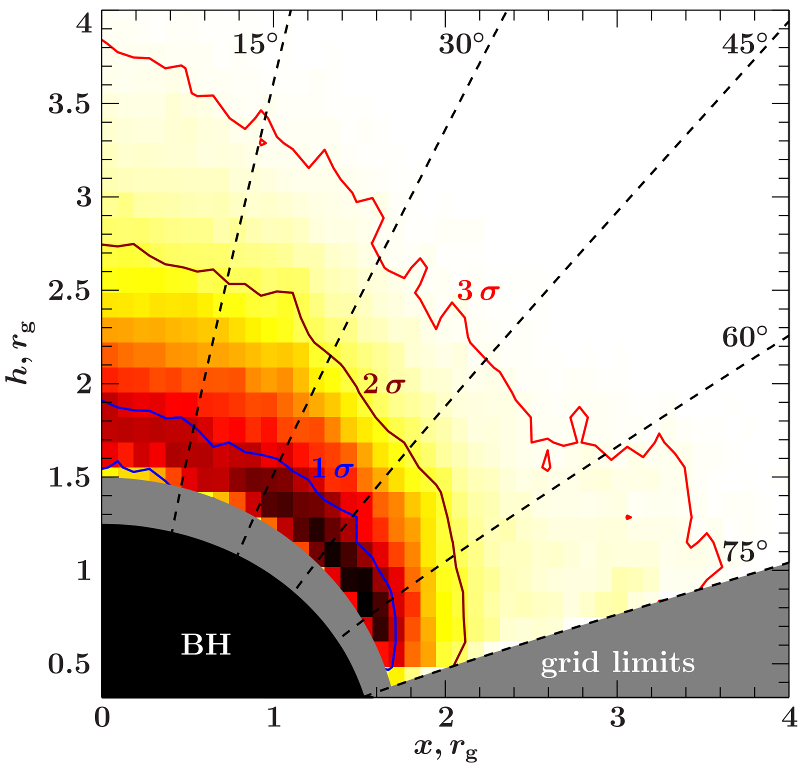
- *XMM-Newton* & *NuSTAR* spectra of Seyfert galaxy ESO 033-G002 shows very strong reflection (Walton et al., 2021)
- compact Lamp Post corona ($h < 3\,r_g$), high spin ($a > 0.93$)

$\Rightarrow$ any ring source at distance $r < 2r_g$ fits the data equally well than a LP with $h = 2r_g$

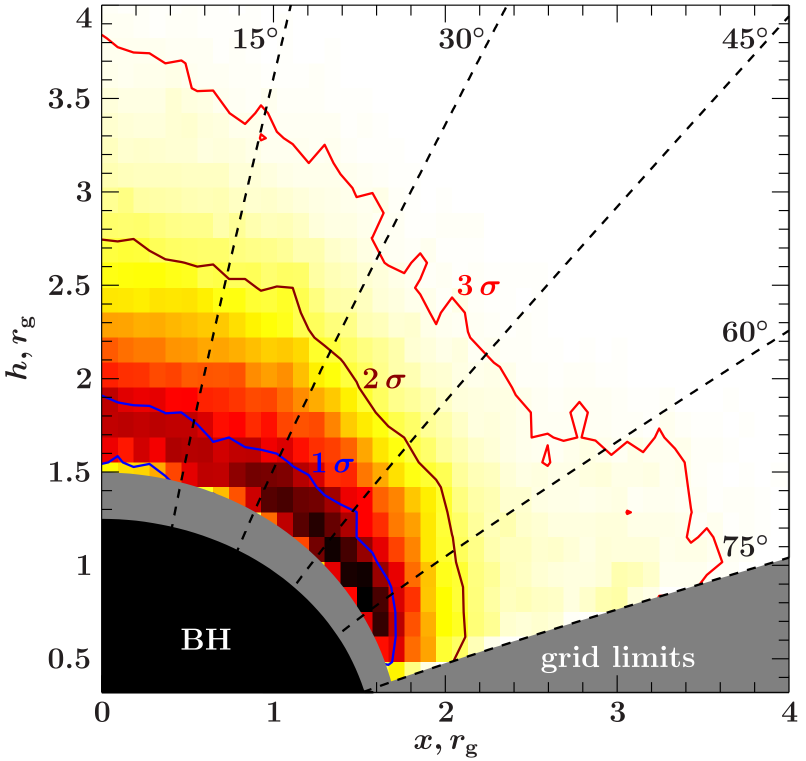
Conclusions: Coronal Geometry

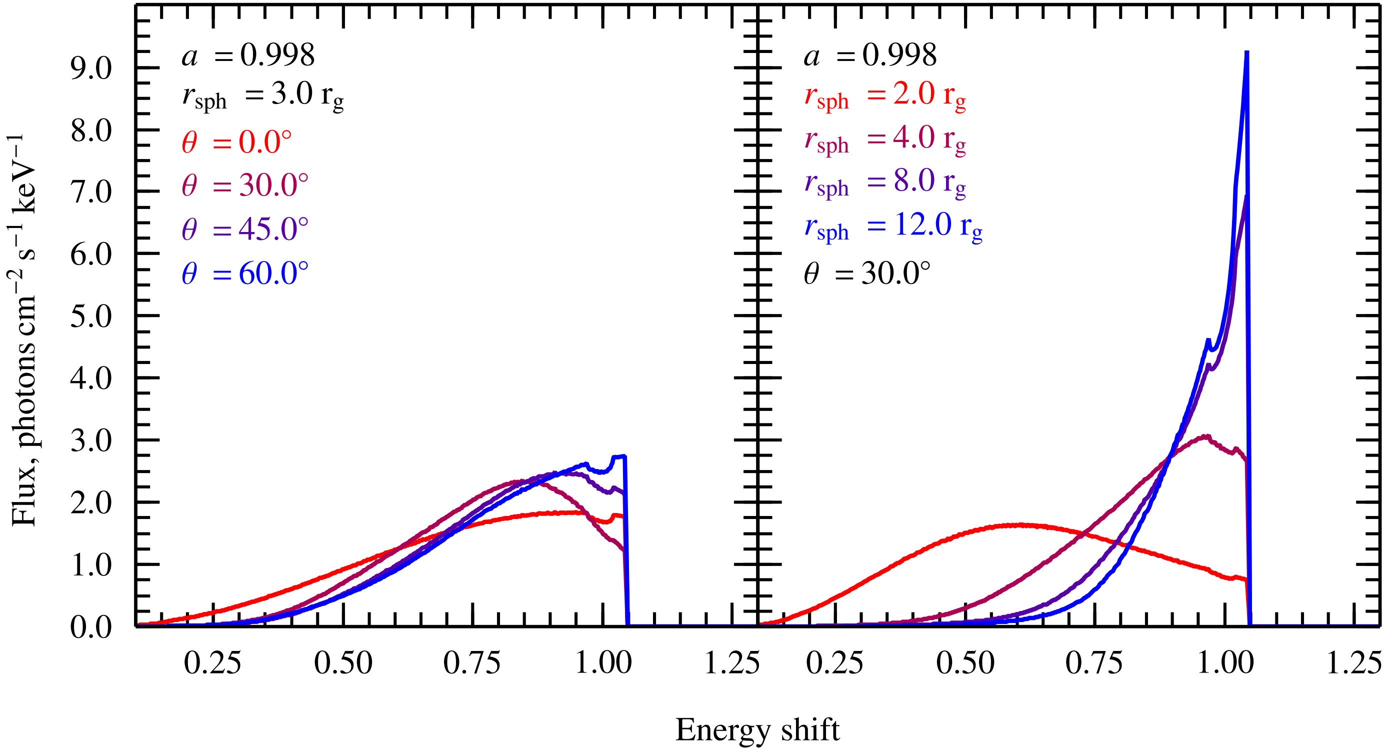


low height LP *likely* equivalent to any compact corona fit

$\rightarrow$ can be extended or point-like

Conclusions: Coronal Geometry



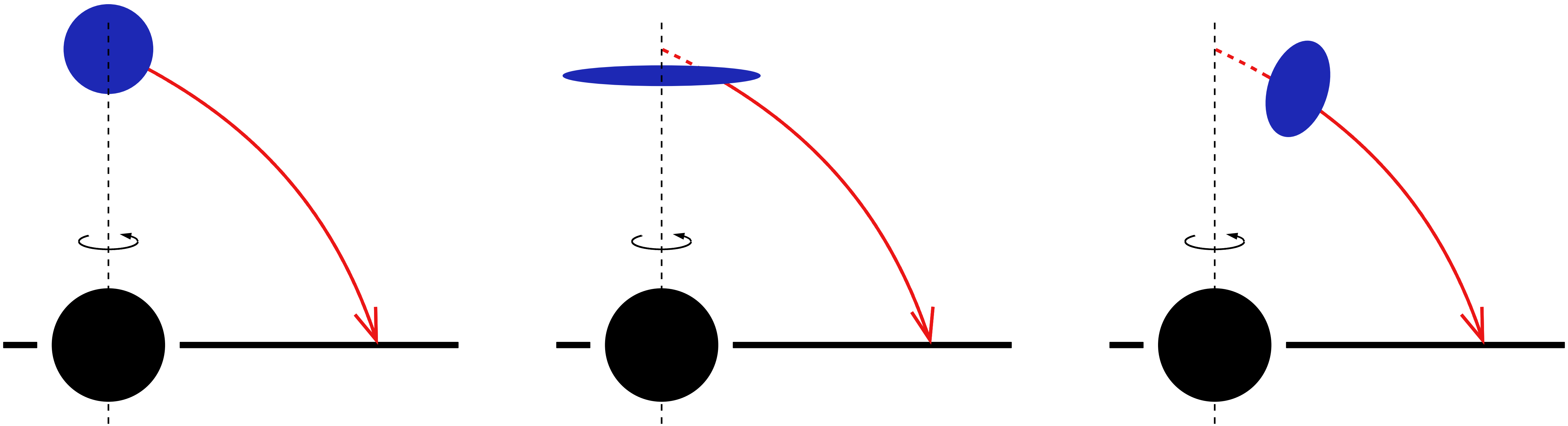


low height LP *likely* equivalent to any compact corona fit
$\rightarrow$ can be extended or point-like

line shape sensitive to:
$\rightarrow$ distance to BH
$\rightarrow$ only weakly on θ

The Lamp Post models a Compact Corona

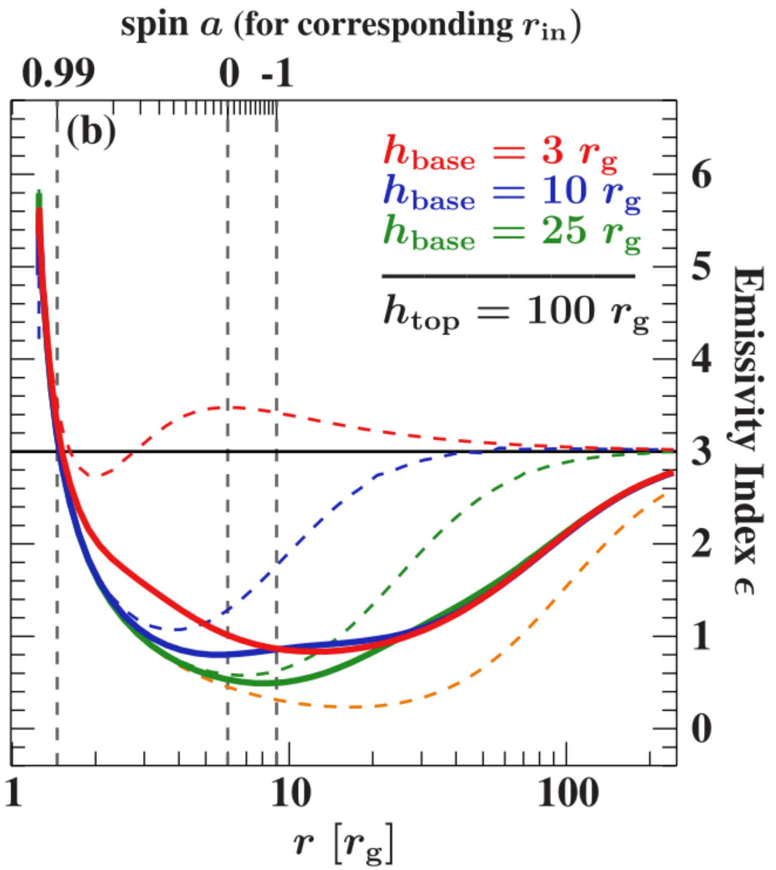
irradiation (and reflection) similar if LP is **extended in radial and vertical direction at $\approx 1 - 2\,R_\mathrm{g}$**



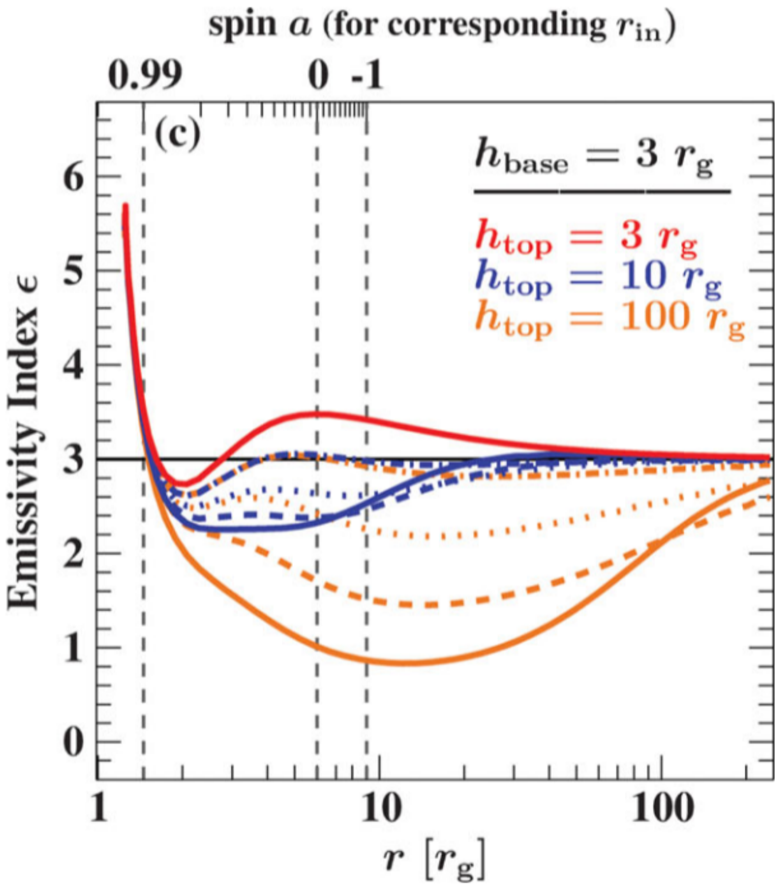
⇒ **no principle disagreement with polarization measurements**
(favoring a horizontally extended corona, see, e.g., Krawczynski et al., 2022; Gianolli et al., 2023; Ingram et al., 2023, ...)

Vertically Extended Corona

Vertical Static Corona



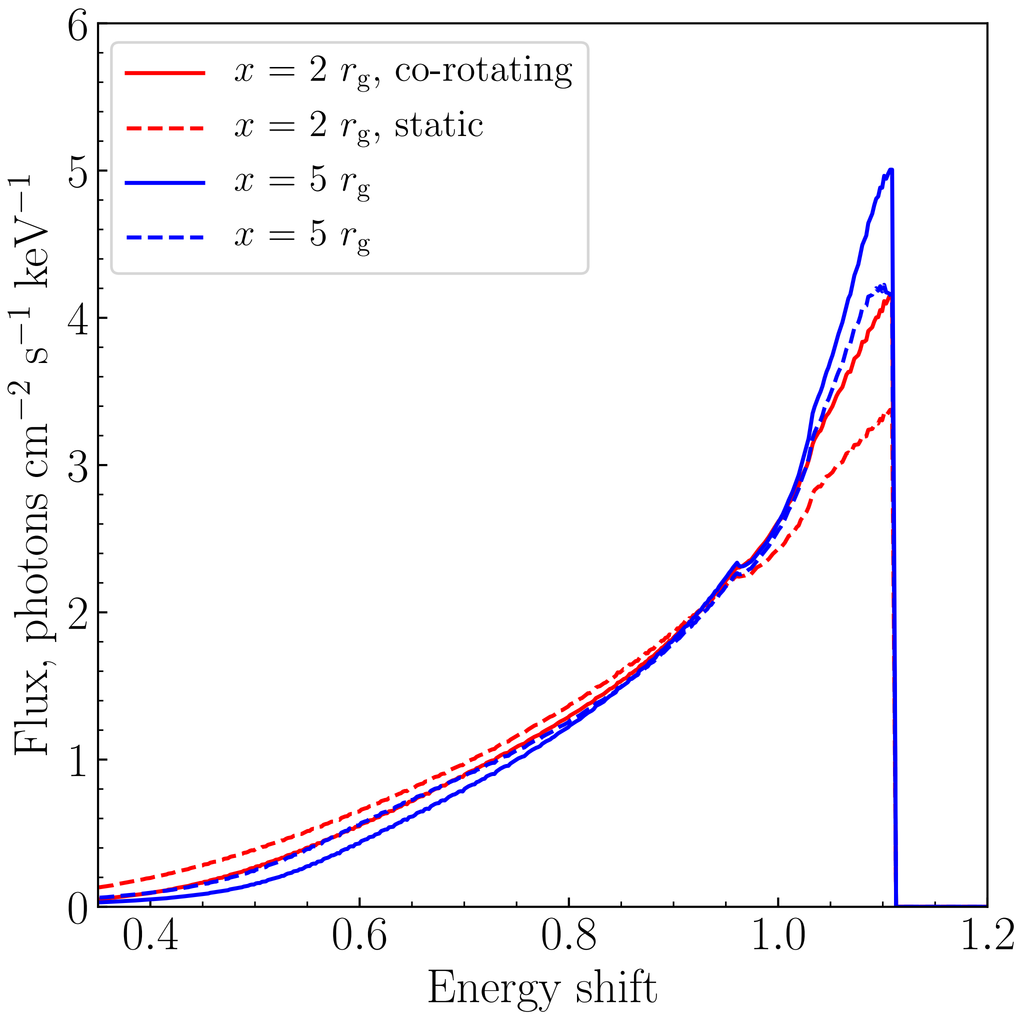
Constant acceleration



(Dauser et al., 2013)

- vertically extended corona $\rightarrow$ similar to a lamp post
- adding a acceleration $\rightarrow$ compact lamp post

Rotational Velocity of the Corona



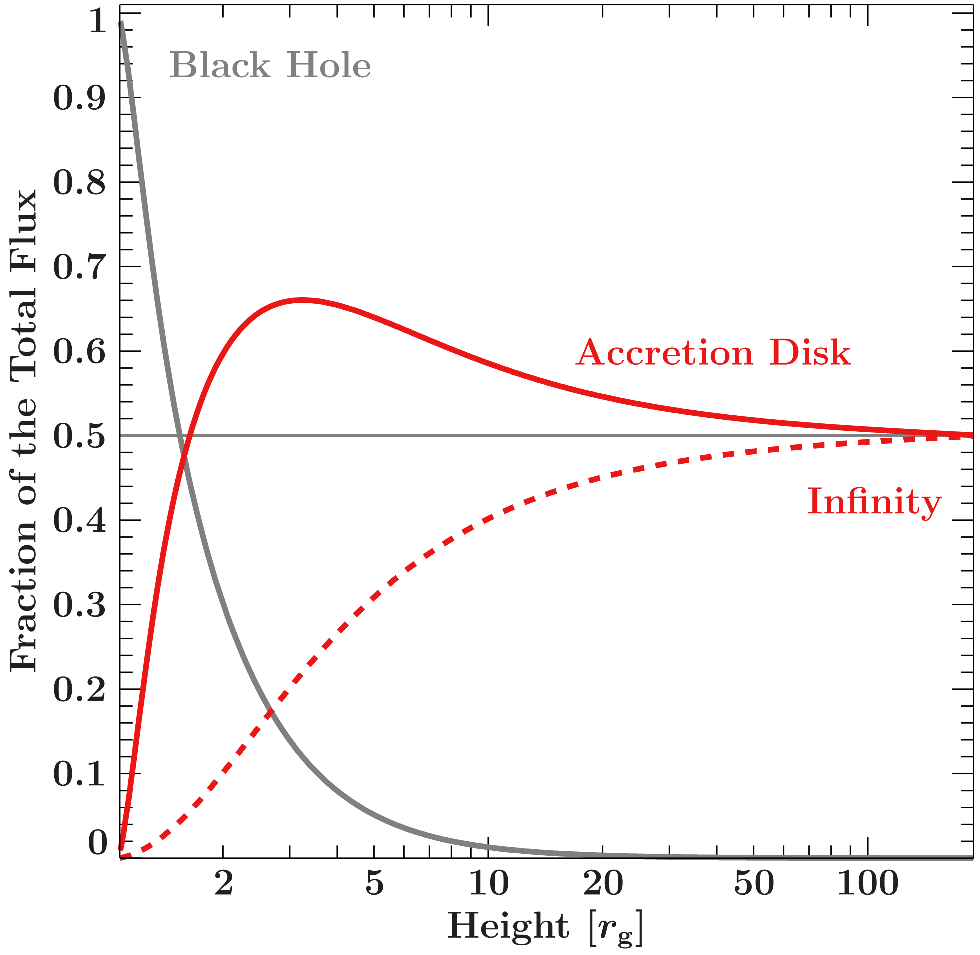
Rotational Velocity

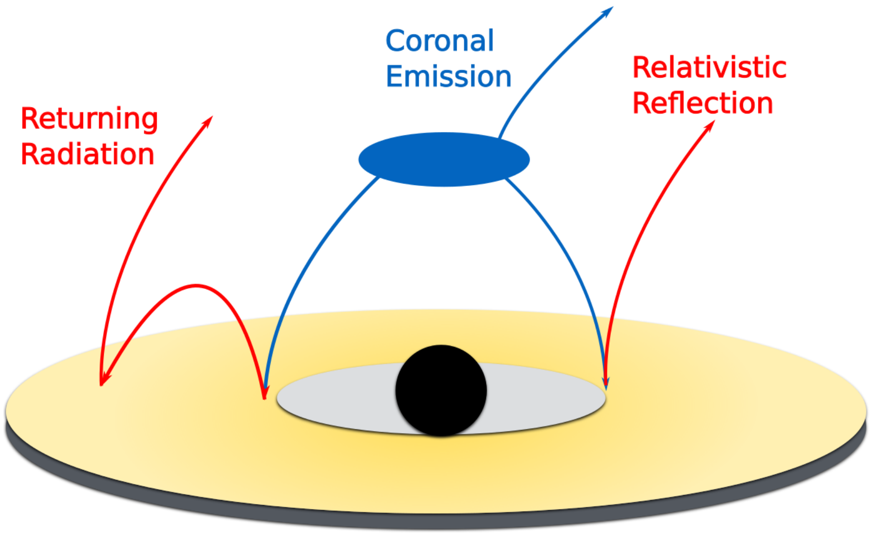
- moderately affects irradiation through energy shifts and beaming towards the disk (see also Niedźwiecki & Życki, 2008)
- current assumption: co-rotation with the disk (seems reasonable)

- similar spectral shape for v_φ with different extent *x* (or height *h*)
  $\Rightarrow$ narrower line for **co-rotating corona**, means **lower limit on size**

Coronal Geometry and the Reflection Strength

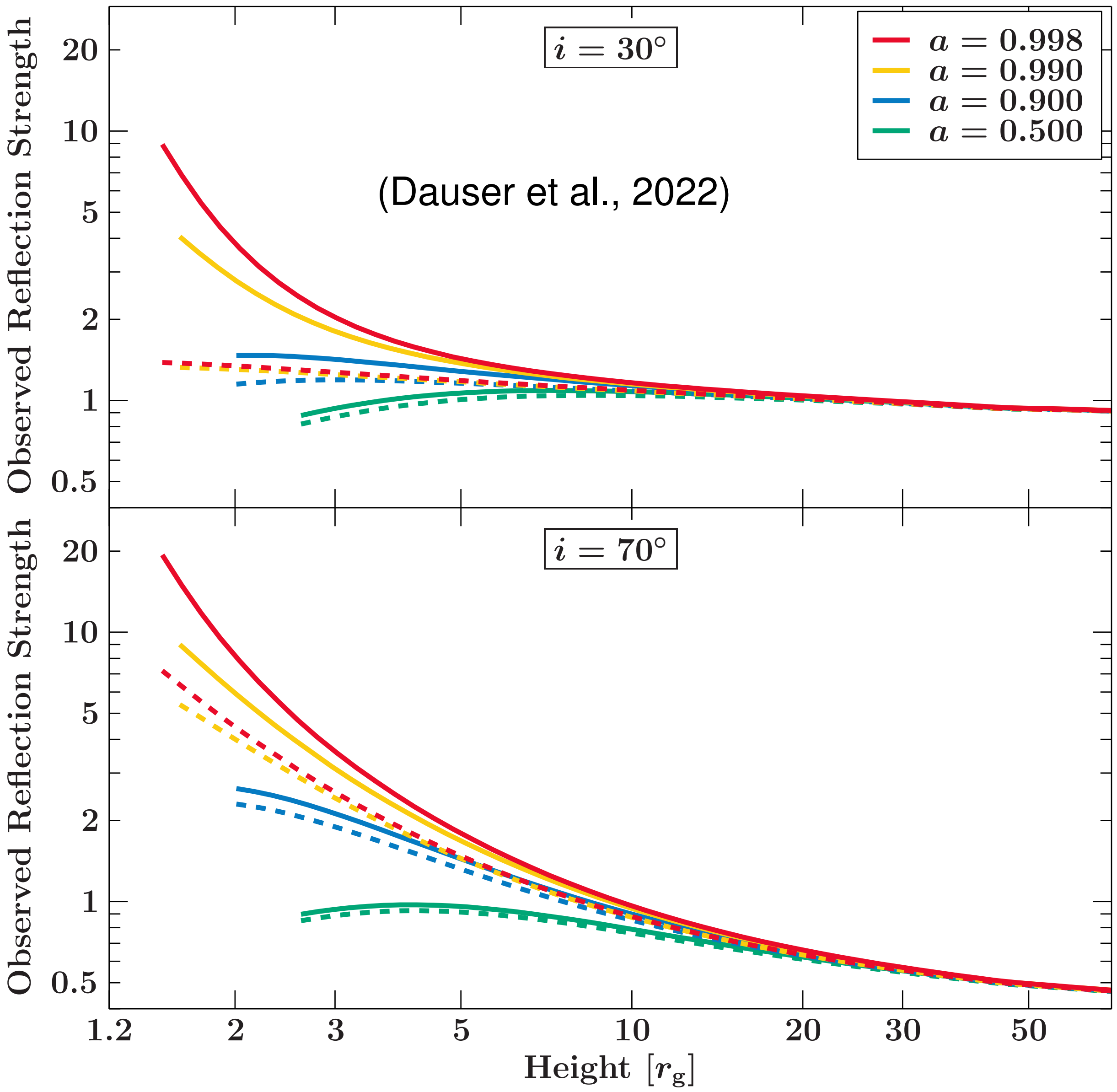
What fraction of primary photons are incident on the accretion disk?





strong reflection (only) for a compact source

Coronal Geometry and the Reflection Strength



Reflection Strength $= \frac{\text{Observed reflected flux}}{\text{Observed coronal flux}}$

(typically in 20–40 keV band)

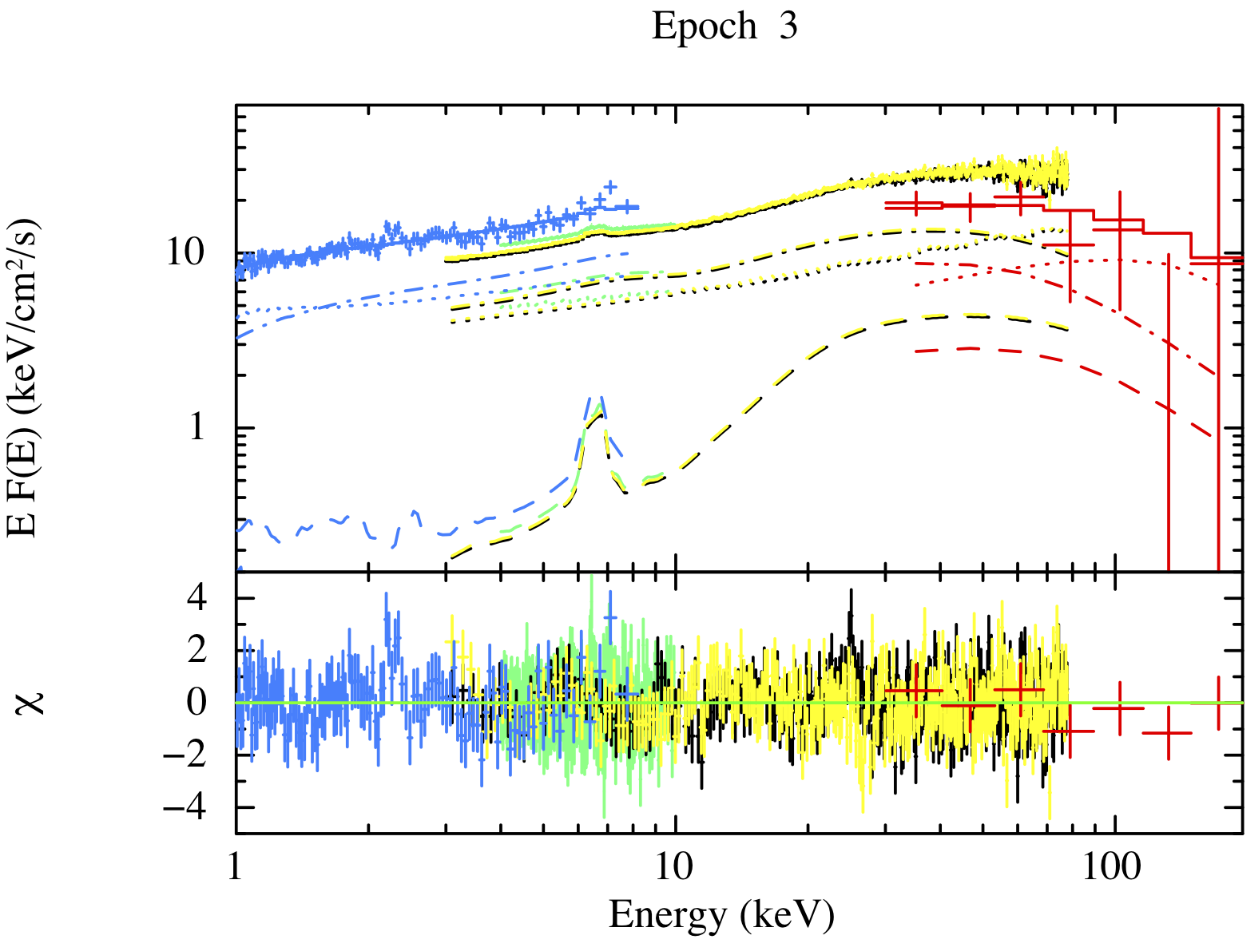
dashed: only direct refl., solid: incl. returning refl

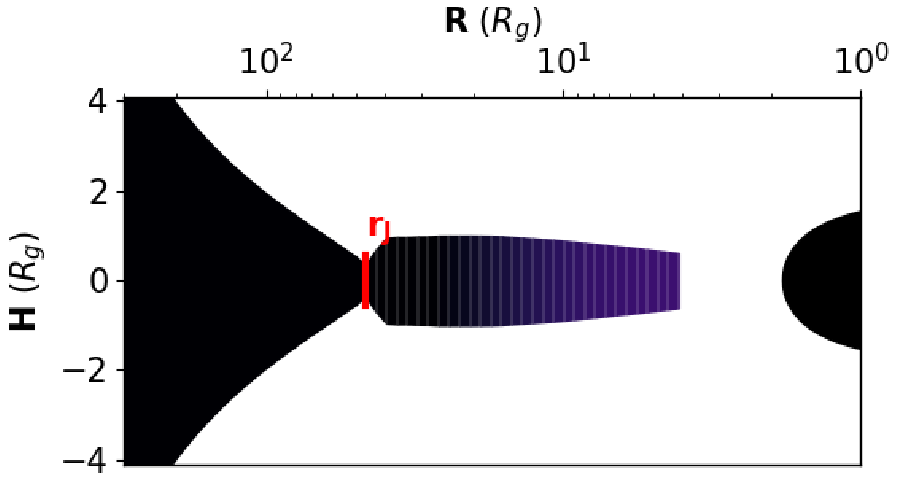
Returning Radiation is important: strong boost for low inclinations (Dauser et al., 2022)

Reflection strength constrains the Coronal Geometry

typically assuming isotropic coronal emission + velocity; RTDIST can fit angular profile (Ingram et al., 2022)

Consistency Check: Reflection Strength in MAXI J1820

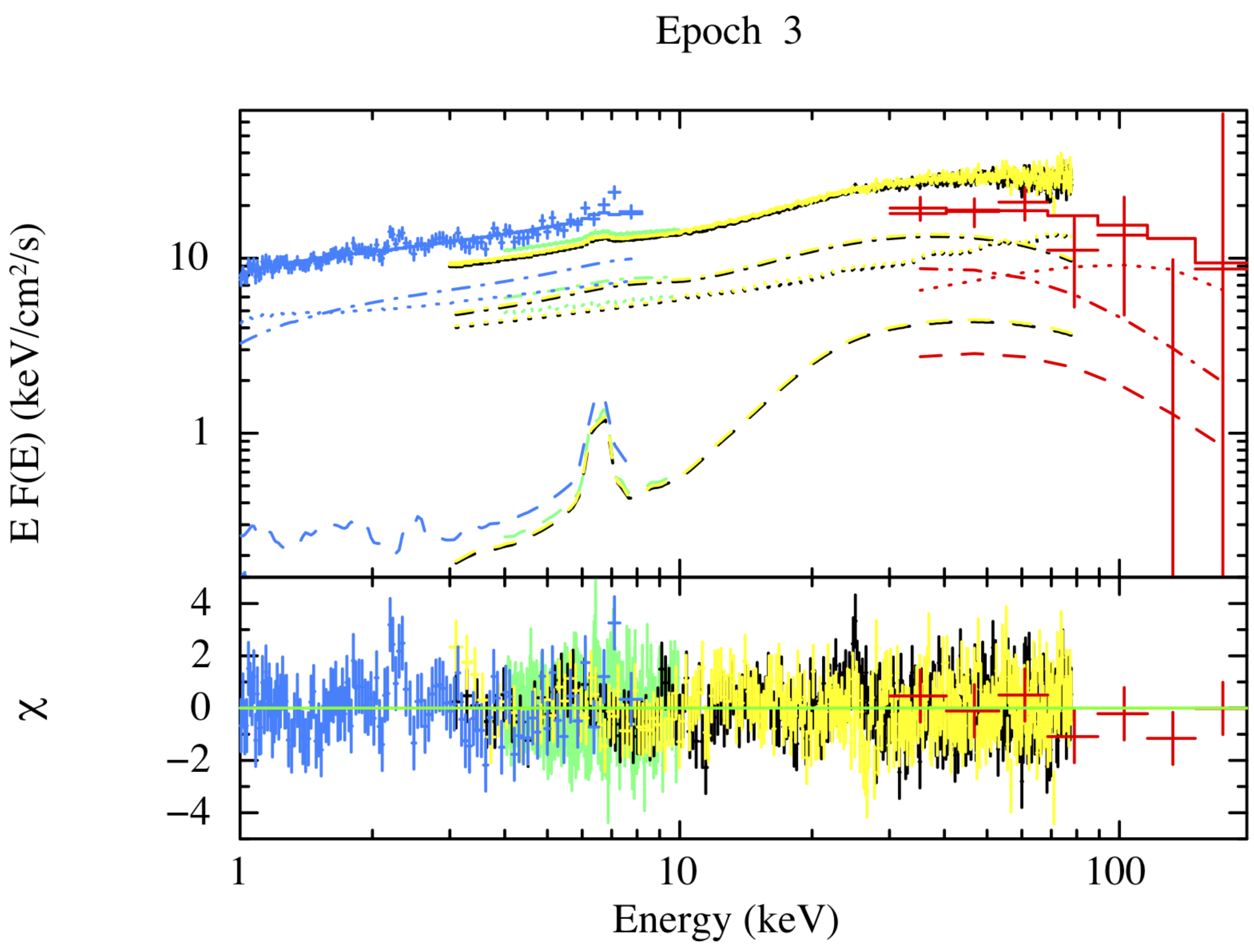


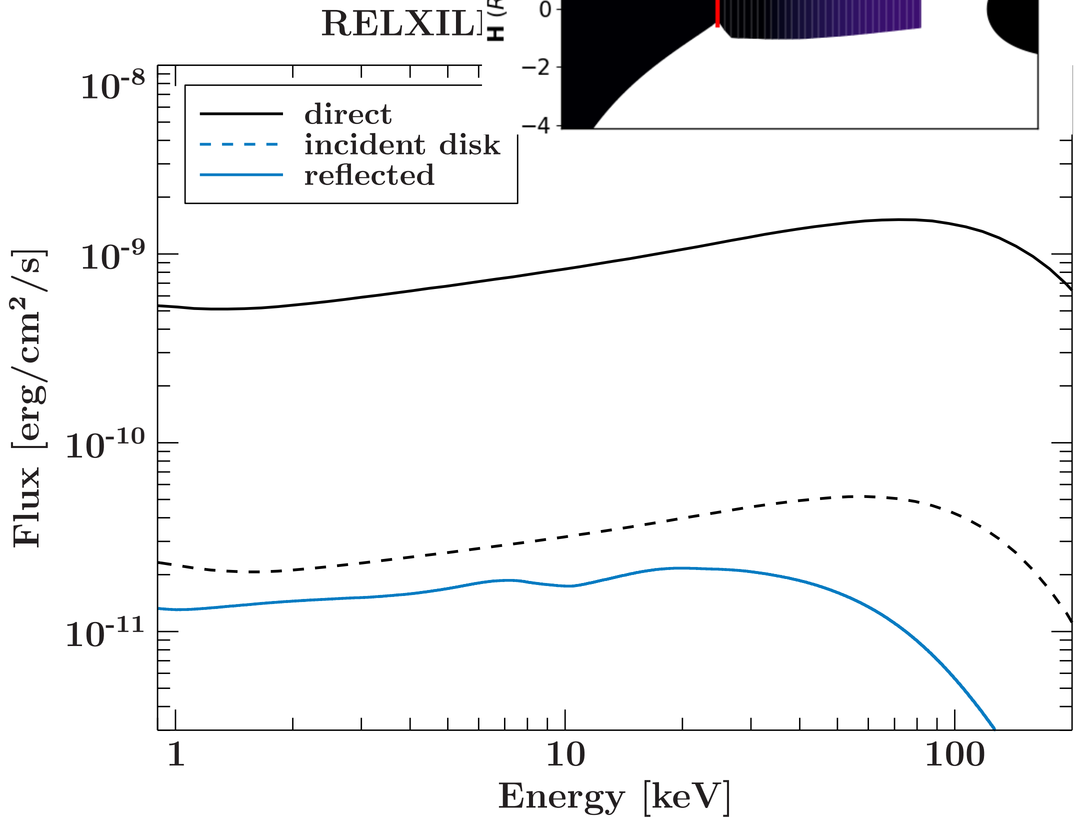


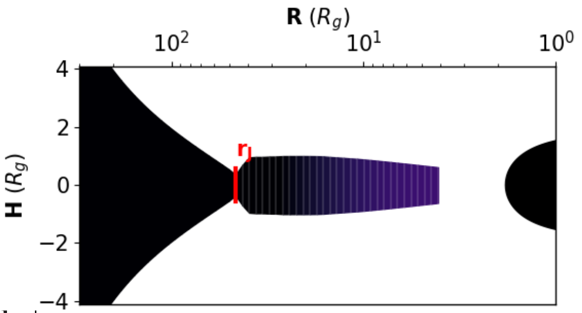
Marino et al. (2021): Using the JED-SAD model linked to RELXILL describes all epochs well

→ **strong relativistic reflection** in some observations but find $R_{\mathrm{in}} \approx r_{\mathrm{J}} \approx 20 - 40\, R_{\mathrm{g}}$

Consistency Check: Reflection Strength in MAXI J1820



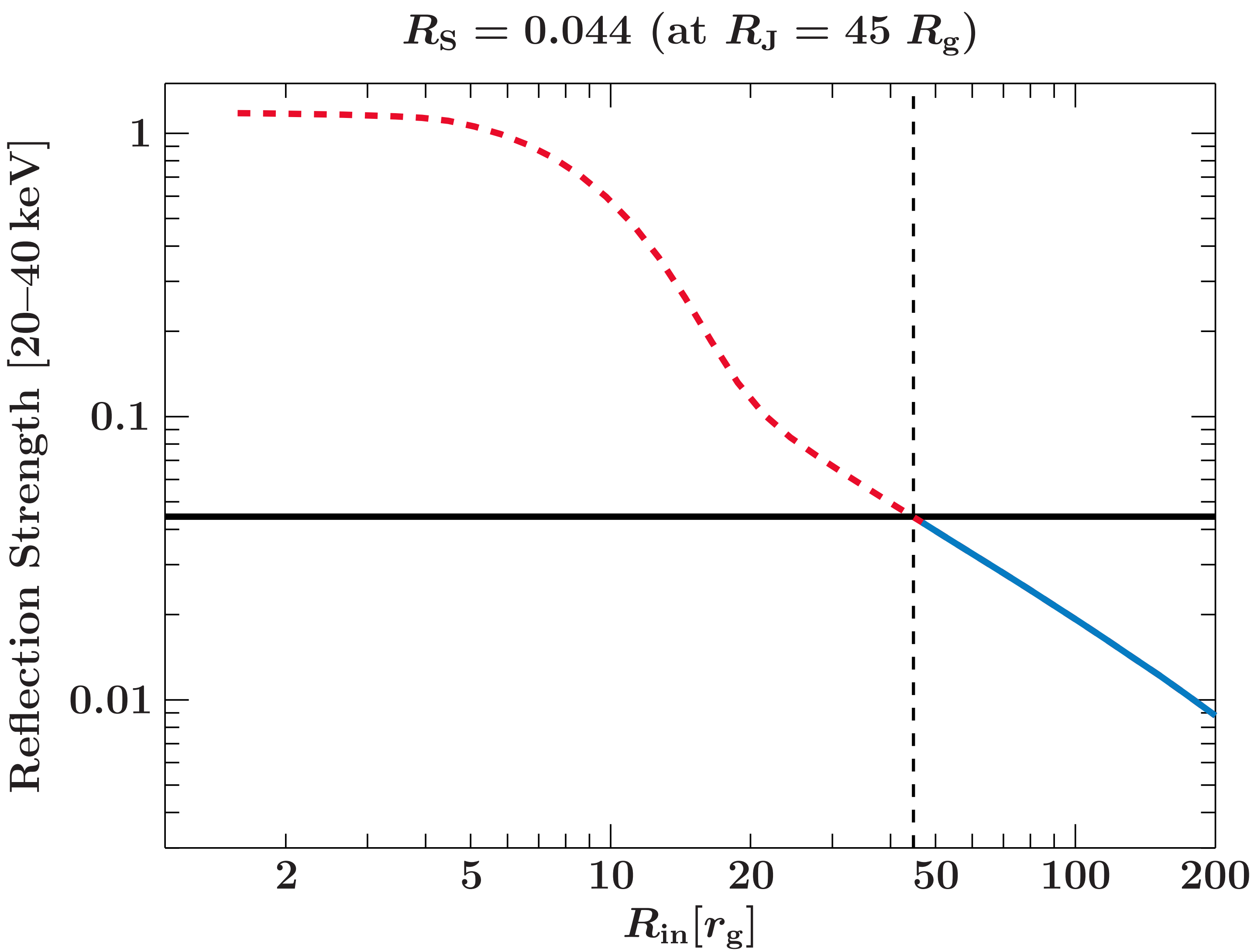




⇒ **ray-tracing: JEDSAD geometry under-predicts reflection strength by factor > 10**

Caveats: using vertically integrated solutions and using ray-tracing from disk scale height *H* instead of photosphere (Marcel et al., 2018)

Reflection Strength constrains the Geometry

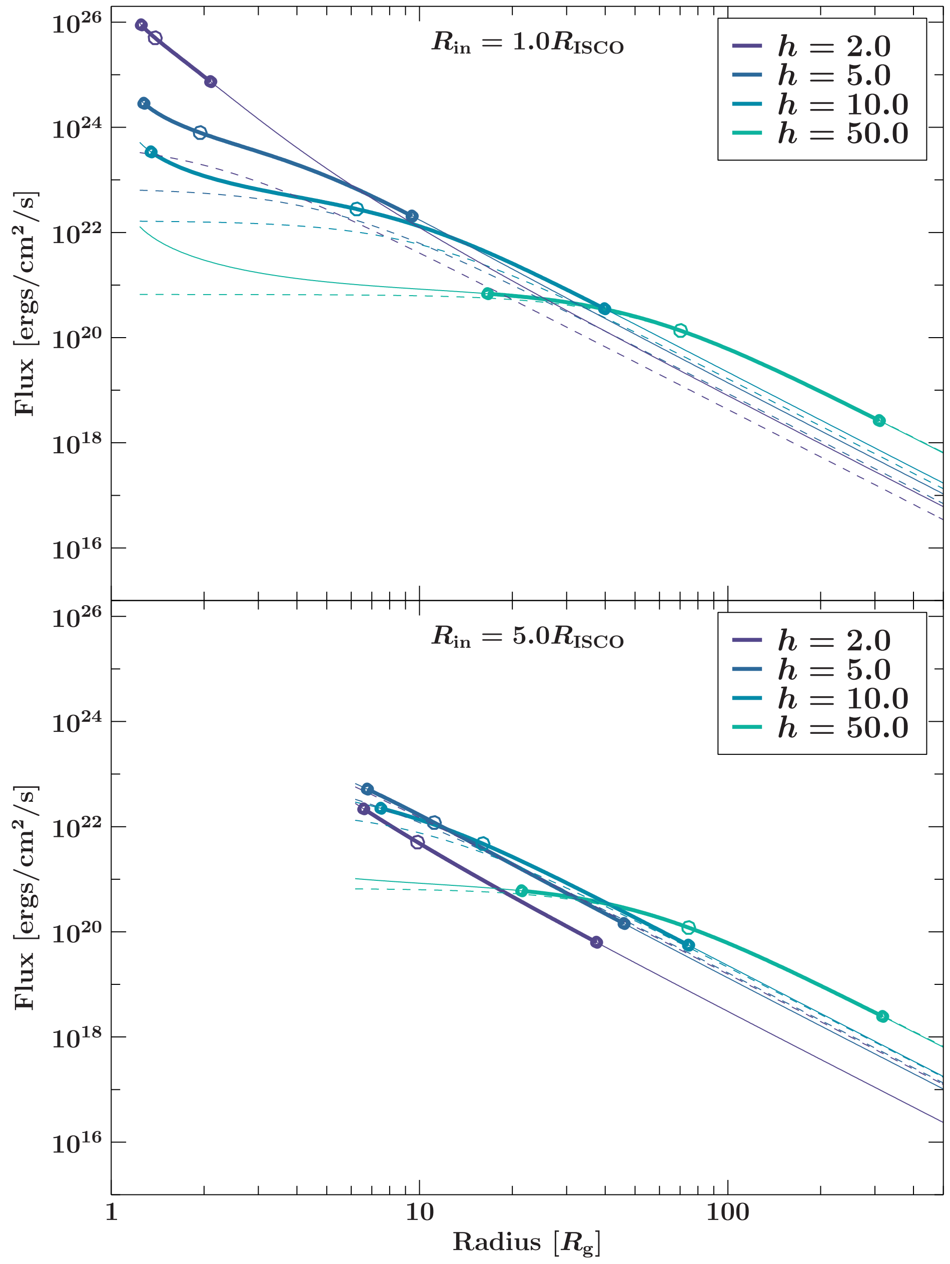


Reflection strength is very sensitive to the inner disk radius and coronal geometry

→ investigate possible ways to increase the reflection strength: disk enters the JED, SAD has a larger H/R, . . . ?

⇒ **ray-tracing as self-consistency check of accretion geometry**

A step further: self-consistent irradiation of the Accretion Disk



parameters based on Cyg X-1 (J. Tomsick, priv. com.; solid lines: 90% interval of incident flux)

- 5 orders of magnitude difference in incident flux for different heights and truncation radii
- incident flux can be used to calculate the ionization $\xi = 4\pi F_{inc}/n_e$ for a given density n_e

implemented in RELTRANS (Ingram et al., 2022, RTDIST) and RELXILL (public soon)

⇒ primary source geometry determines **location on the reflector** (i.e. which part of the disk sees the majority of flux)

Summary & Conclusions

1. Relativistic Reflection strongly depends on the Coronal Geometry
   $\rightarrow$ determines **irradiation** and **reflection strength**
   $\rightarrow$ only probes the part irradiating the disk

2. point and ring-like geometries are similar to extended geometries
   $\rightarrow$ just because the data is fit by a point/ring geometry does NOT mean the corona IS a point/ring
   $\Rightarrow$ **degeneracies** with respect to extent and velocity of the corona

3. implemented flexible extended corona RELXILL model (based on rings)
   $\rightarrow$ applied to ESO 033-G002: **lamp post similar to 2r_g radially extended corona**
   $\rightarrow$ **line broadening depends on distance to the BH and not on θ** (for compact sources)
   $\Rightarrow$ **Question which geometries should be provided?**

Conclusions: Coronal Geometry in the 3D Approach

X-ray reverberation and X-ray polarimetry also strongly depend on the Coronal Geometry

(see talks by Adam, Michal, Gullo)

1. Ideal (statistical) approach: Combined data analysis
2. Consistency check
   $\rightarrow$ is the coronal geometry in agreement with polarization/reverberation?
   $\rightarrow$ how many seed photons intercept the corona? (see, e.g., Dovciak & Done, 2016)
   $\Rightarrow$ test geometries (e.g., using GRADUS.JL, a flexible spectro-timing ray-tracing code; Baker & Young, 2026)

caveat: different assumptions between the models

- which time lag is reverberation probing?
- where is the polarization coming from?
- what region are we probing with relativistic reflection?

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