RELXILL or: How I Learned to Stop Worrying and Love Reflection Spectroscopy

Javier Garcia
Caltech
javier@caltech.edu

X-Vision School
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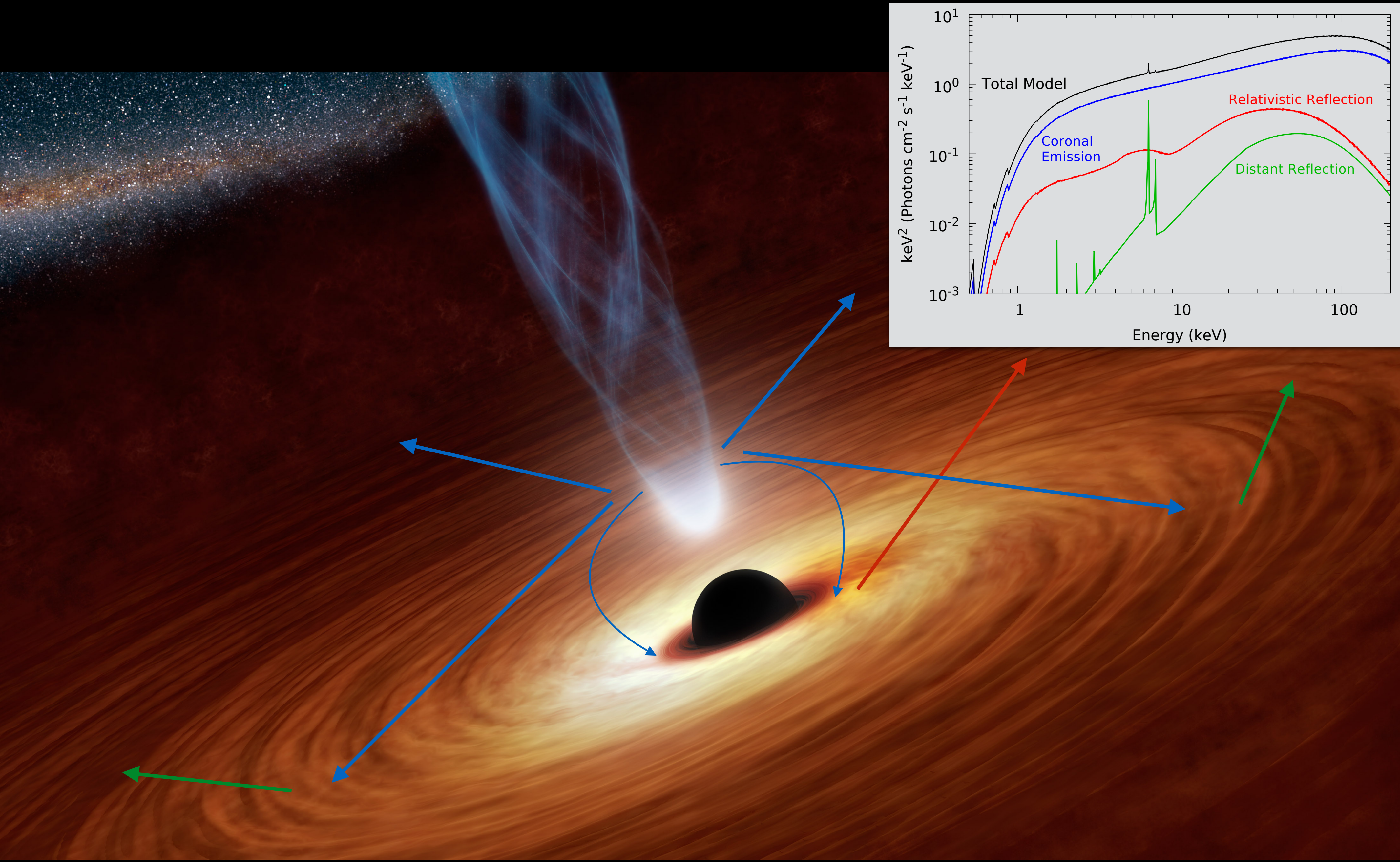
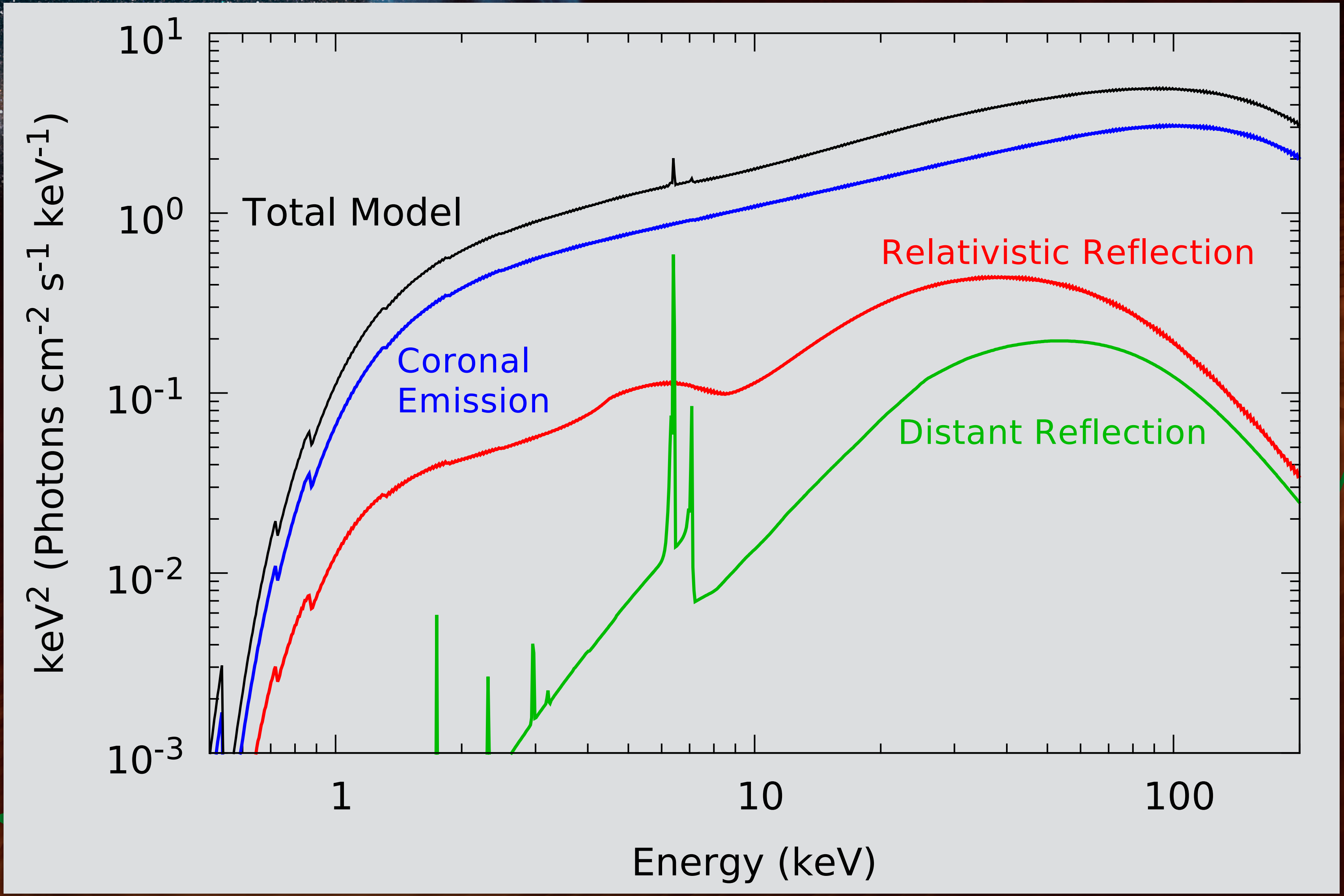
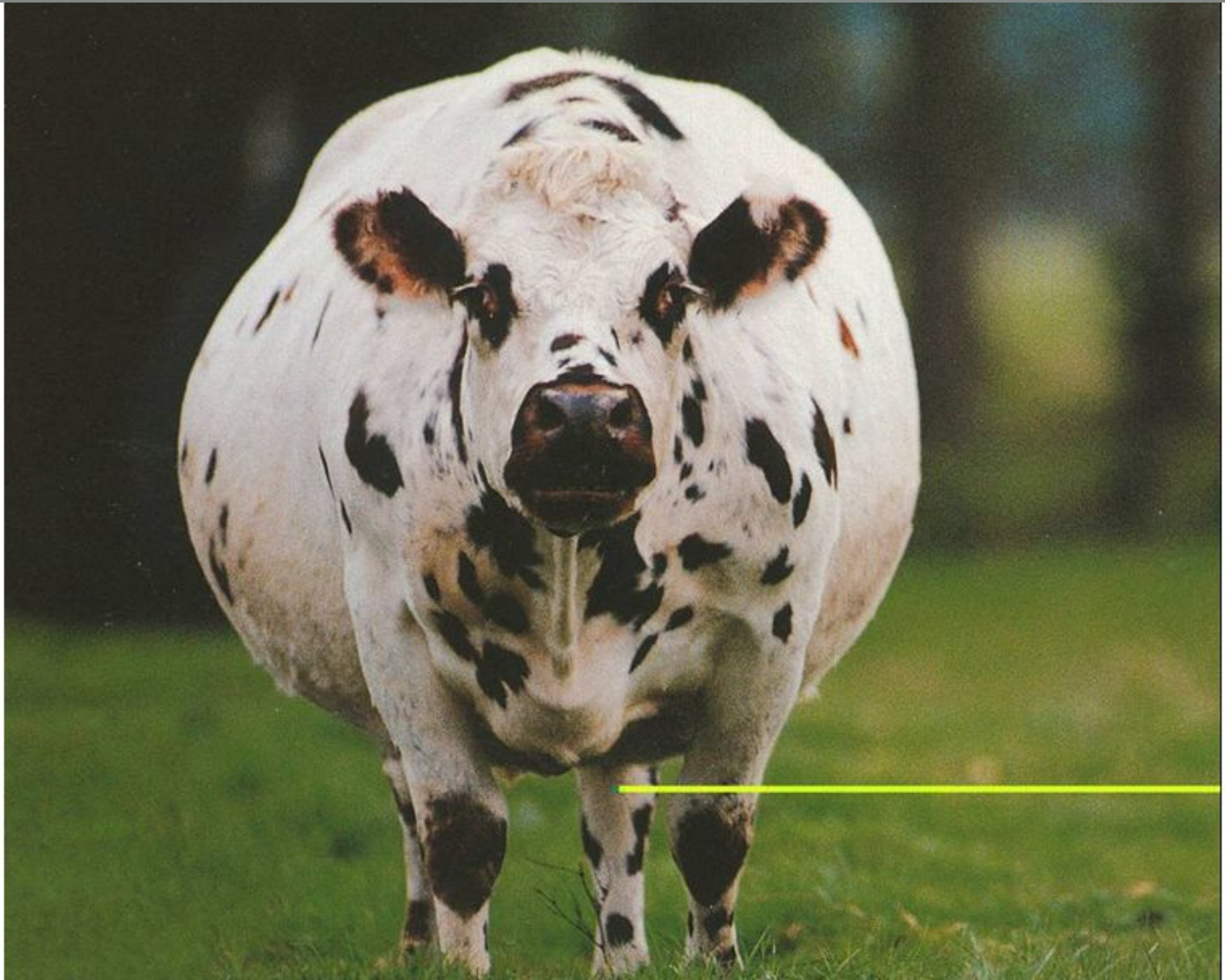


X-ray Reflection from Accretion Disks



X-ray Reflection from Accretion Disks

We work with a few assumptions

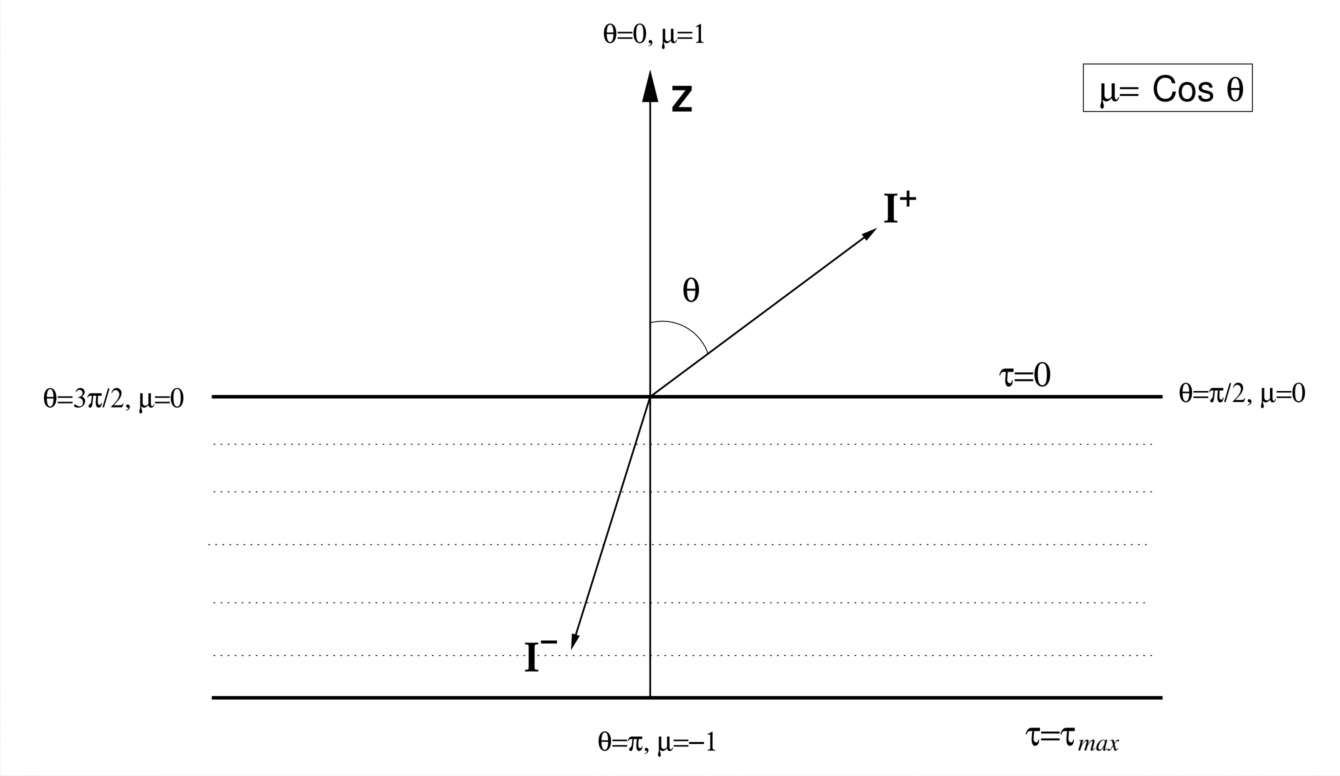


XILLVER: Assumptions & Issues

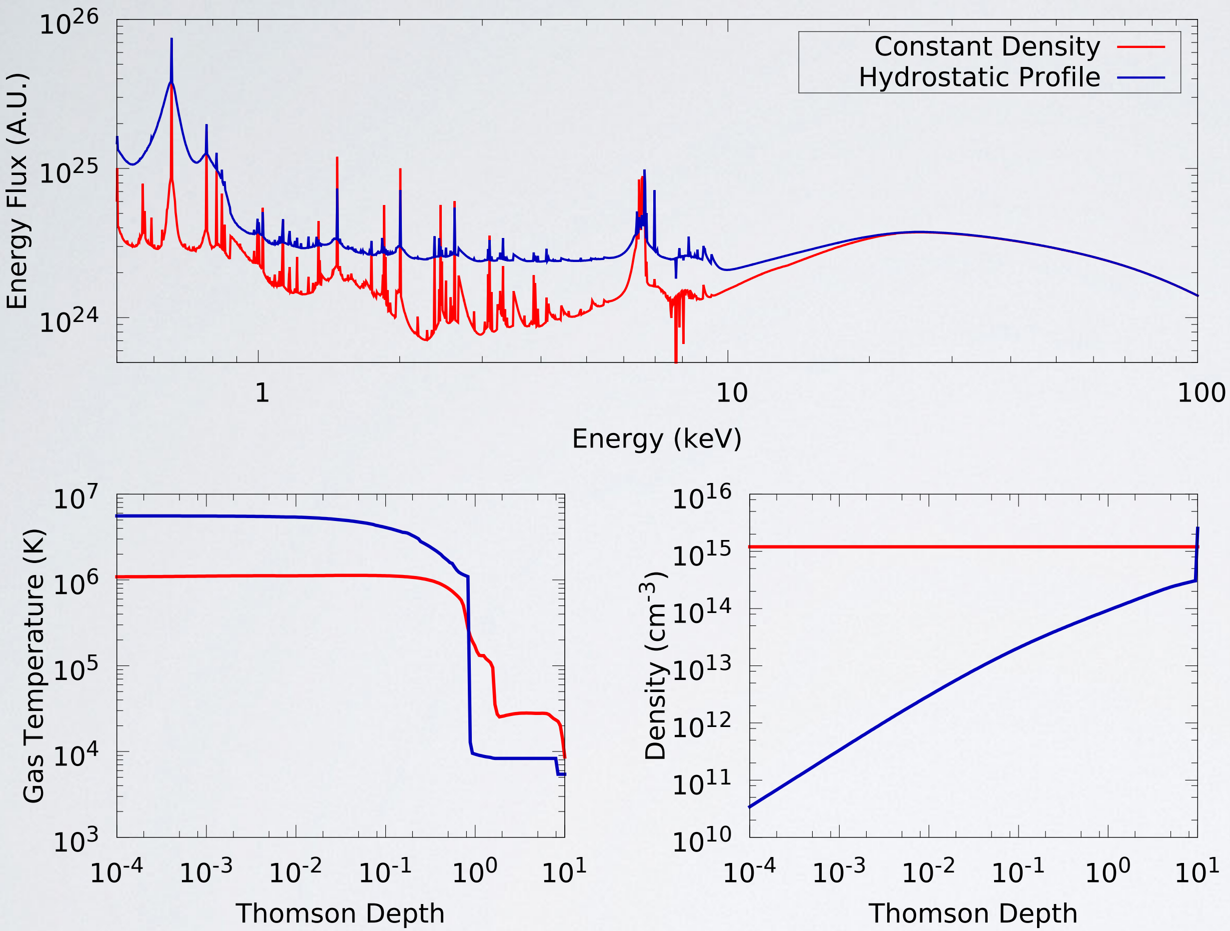
- Simplistic geometry
- Constant density vs. Atmosphere structure
- Super-Solar Fe abundances
- High Density Effects
- Incidence angle for the Illumination
- Time Independent Photo-ioinization

XILLVER: Simplistic Geometry

- Solves the Radiation Transfer equation for every energy, angle, and optical depth
- This requires large number of iterations (~ Tau_max^2)
- Solves the ionization balance using the XSTAR routines —> More iterations!
- Includes the most complete and updated atomic data for inner-shell transitions
- Includes Comptonization within the disk —> CPU intensive



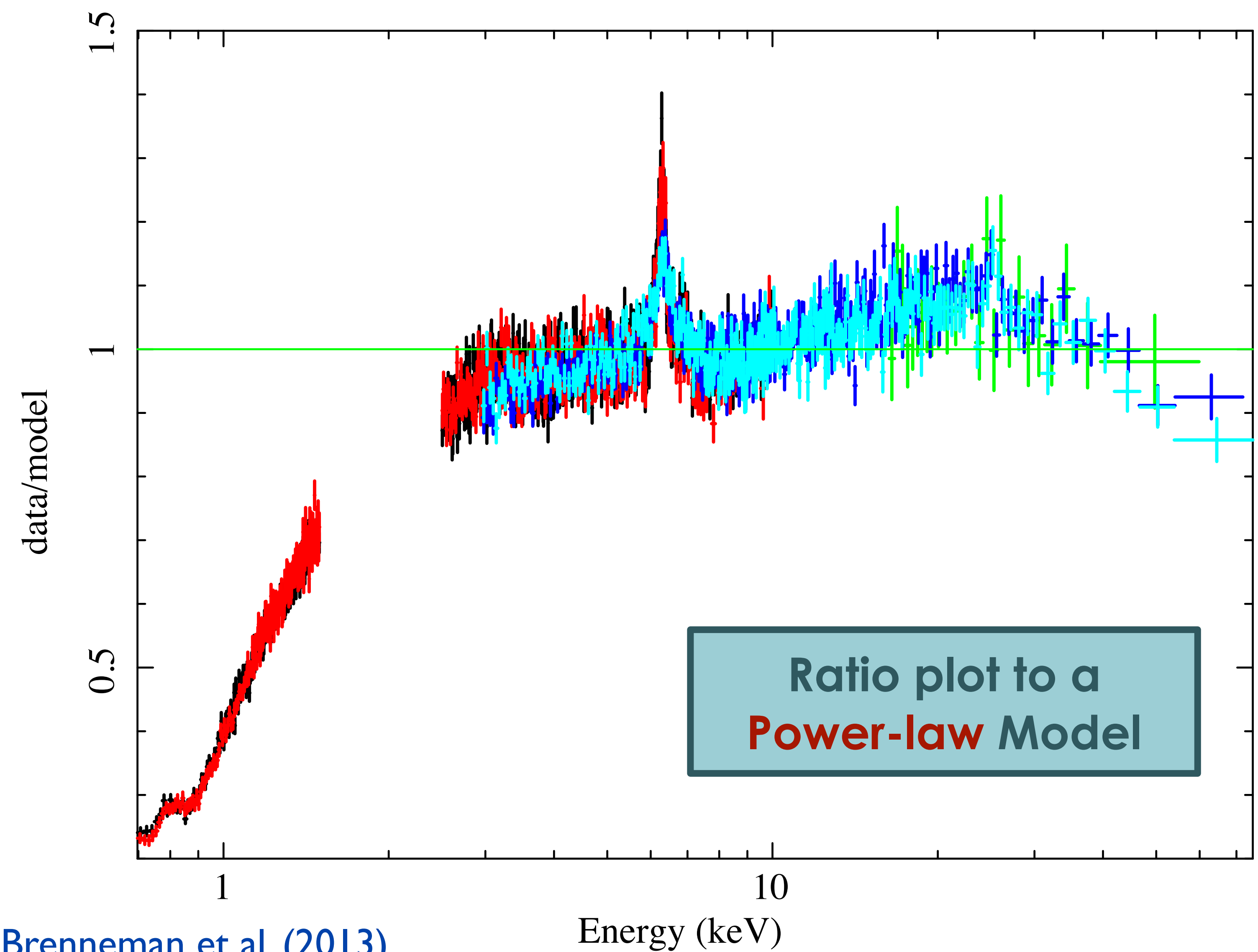
XILLVER: Atmosphere Structure



- Density structure affects the ionization balance
- Temperature transition is sharper and more extreme
- The reflected spectrum is more ionized and Comptonized (Nayakshin & Kallman 2001)
- Reduces the reflection fraction (Ballantyne et al. 2001)
- These models would require even larger Fe abundance!

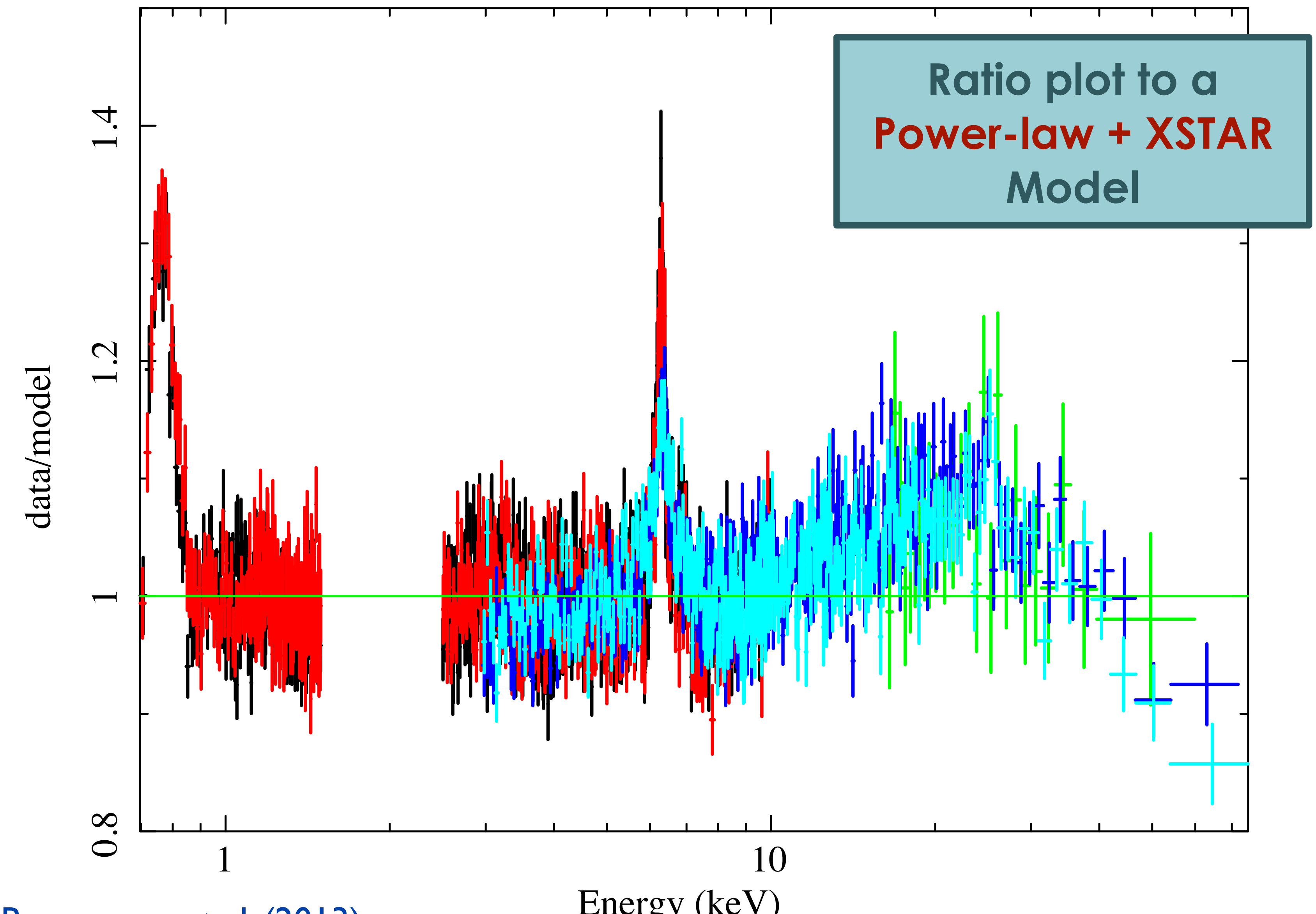
But remember: reflection occurs in a very small layer at the surface (tau~10), so constant density in the vertical direction should be a good approximation.

XILLVER: Cold Reflection in IC 4329A



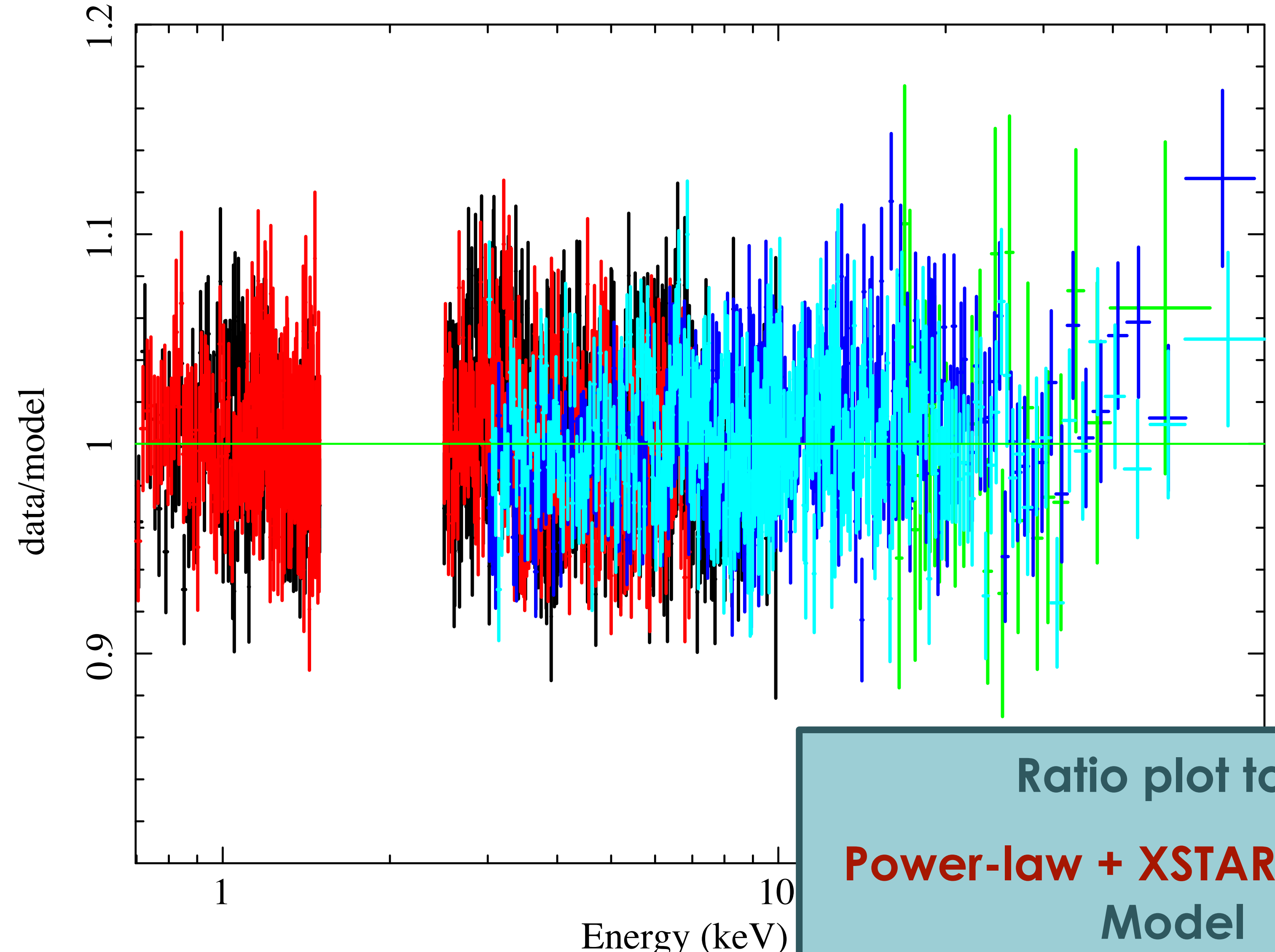
Brenneman et al. (2013)

XILLVER: Cold Reflection in IC 4329A



Brenneman et al. (2013)

XILLVER: Cold Reflection in IC 4329A



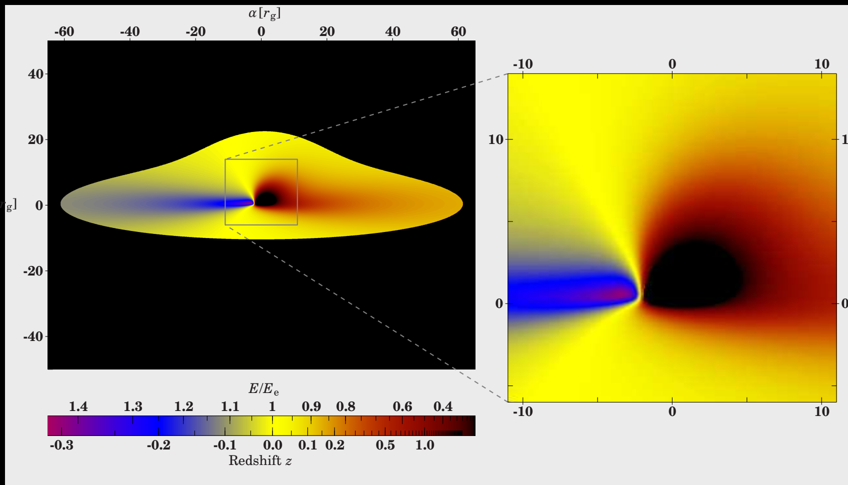
Ratio plot to a

Power-law + XSTAR + XILLVER Model

Brenneman et al. (2013)


Relativistic effects also need to be accounted for!

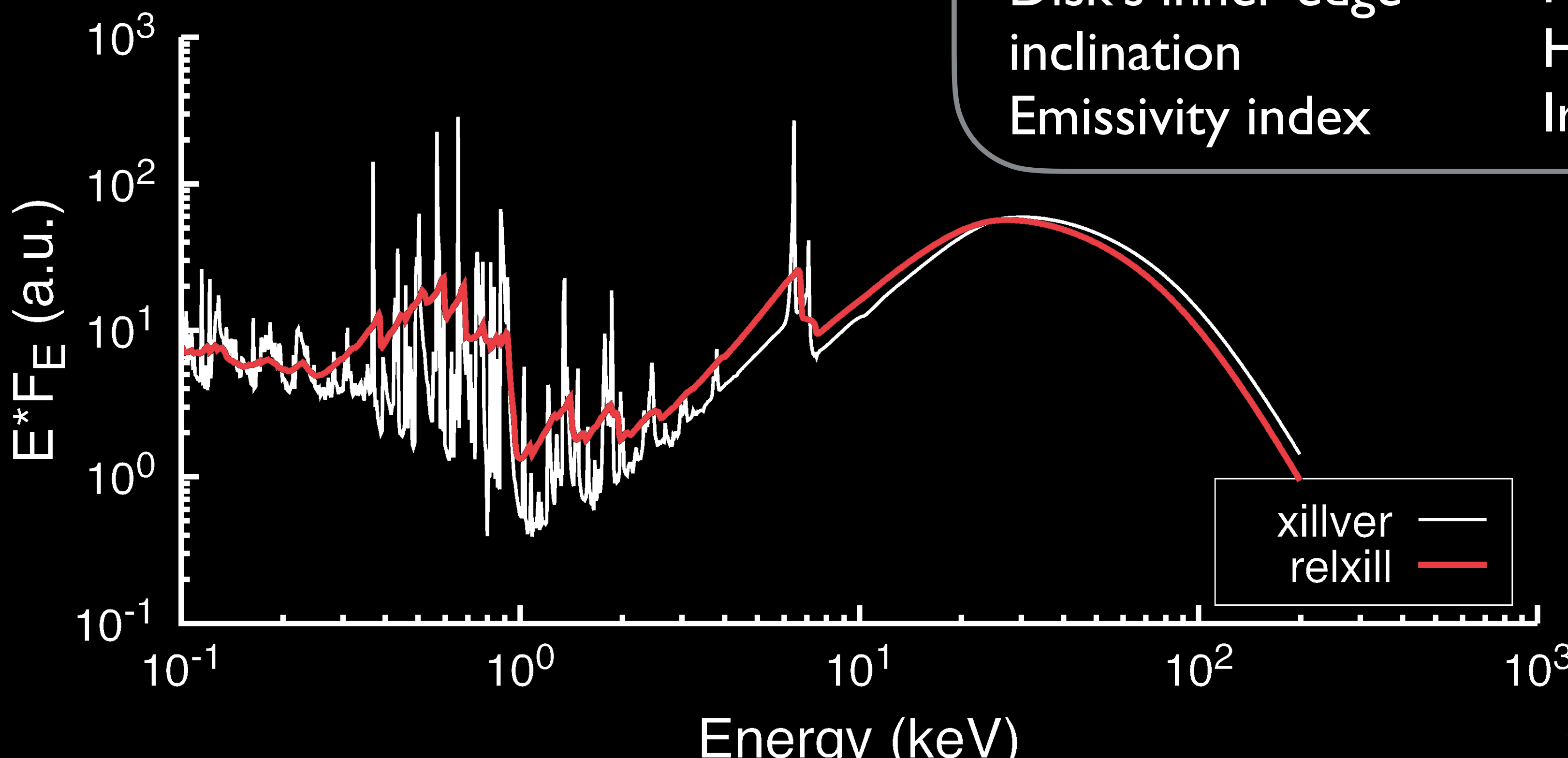
Modeling Relativistic Reflection



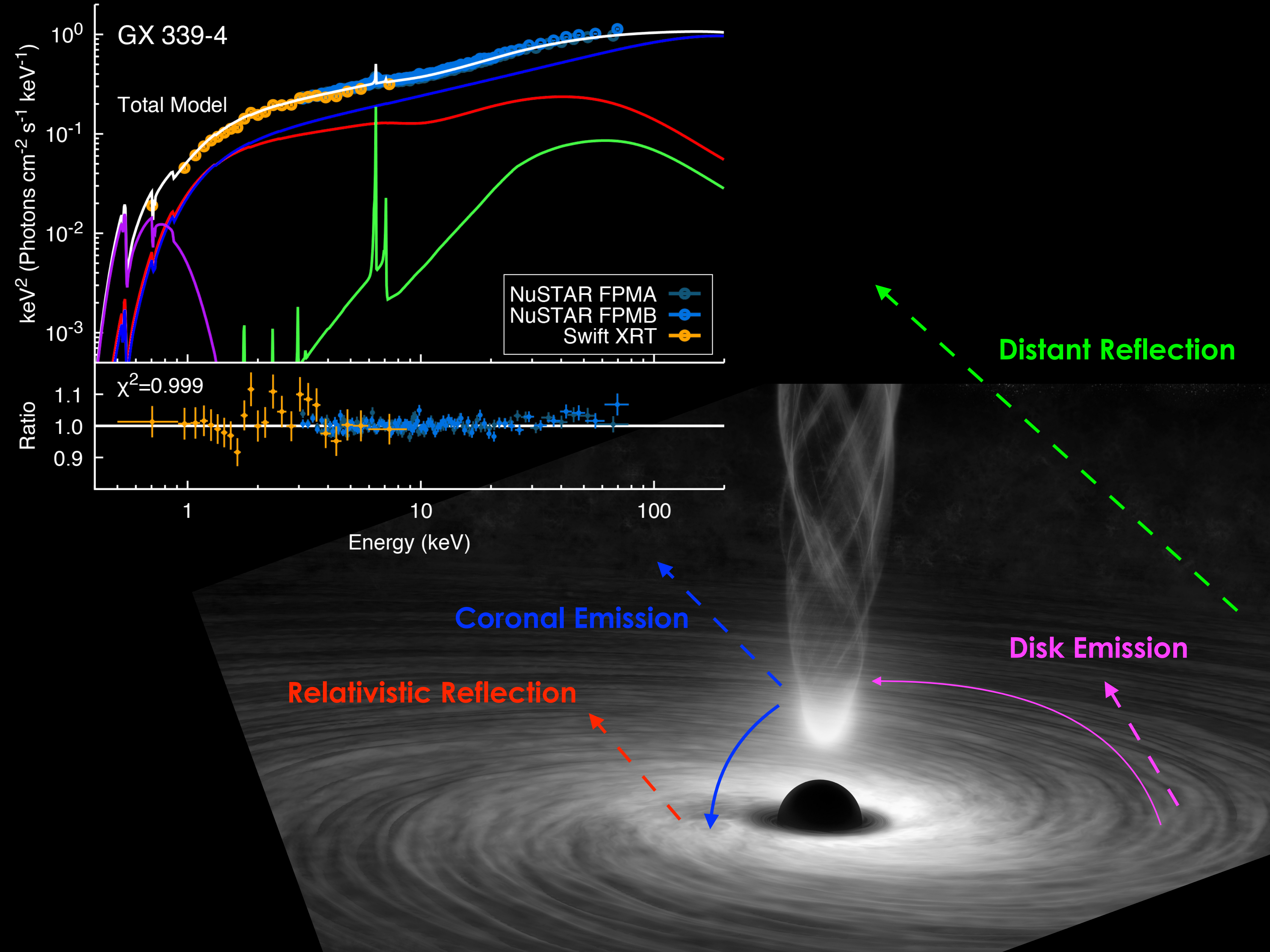
The relxill model: Combines ionized reflection spectra from xillver (Garcia & Kallman 2010), with the relativistic blurring code relline (Dauser et al. 2010)

Model parameters:

- Black hole spin
- Disk's inner edge
- inclination
- Emissivity index
- Reflection fraction
- Photon index
- High energy cutoff
- Iron abundance

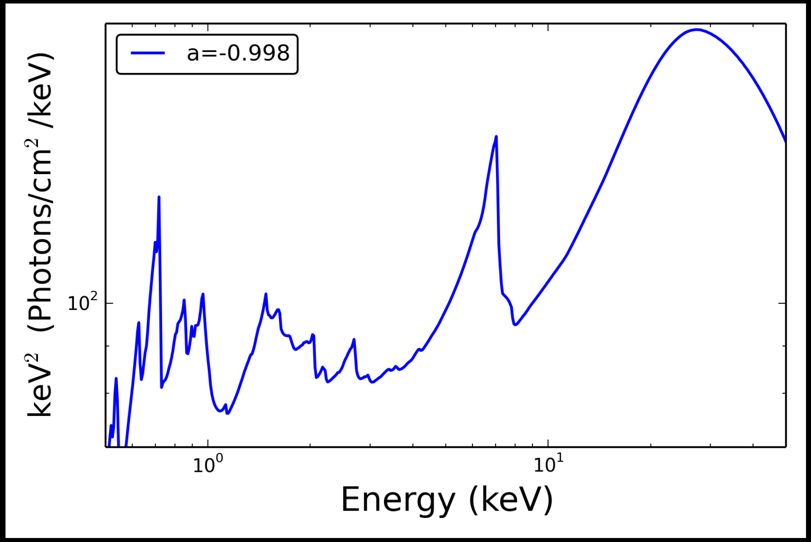


García et al. (2014)

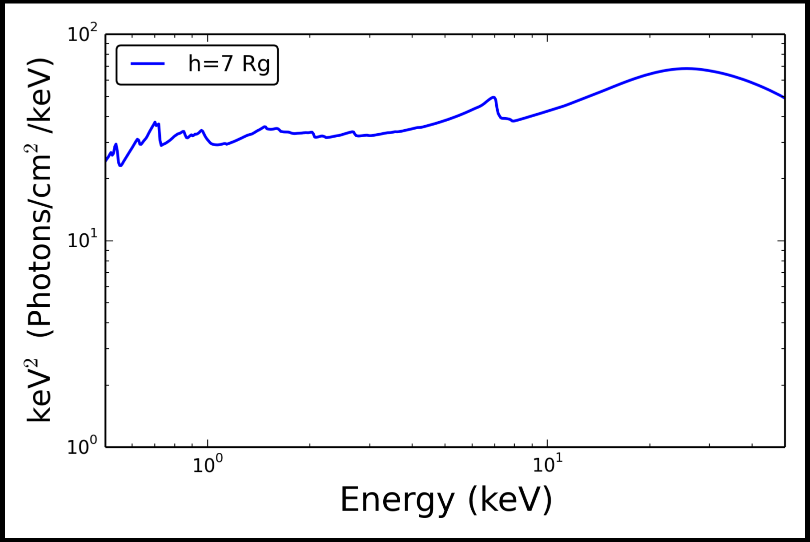

GX 339-4
Total Model
keV^2 (Photons cm^{-2} s^{-1} keV^{-1})
10^0
10^{-1}
10^{-2}
10^{-3}
NuSTAR FPMA
NuSTAR FPMB
Swift XRT
χ^2=0.999
Ratio
1.1
1.0
0.9
1
10
100
Energy (keV)
Distant Reflection
Coronal Emission
Disk Emission
Relativistic Reflection

Constraining Physical Quantities

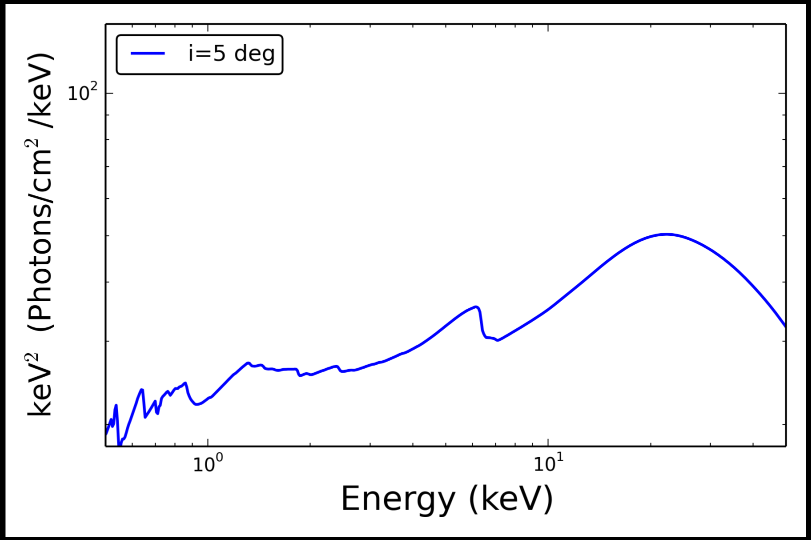
Black Hole Spin



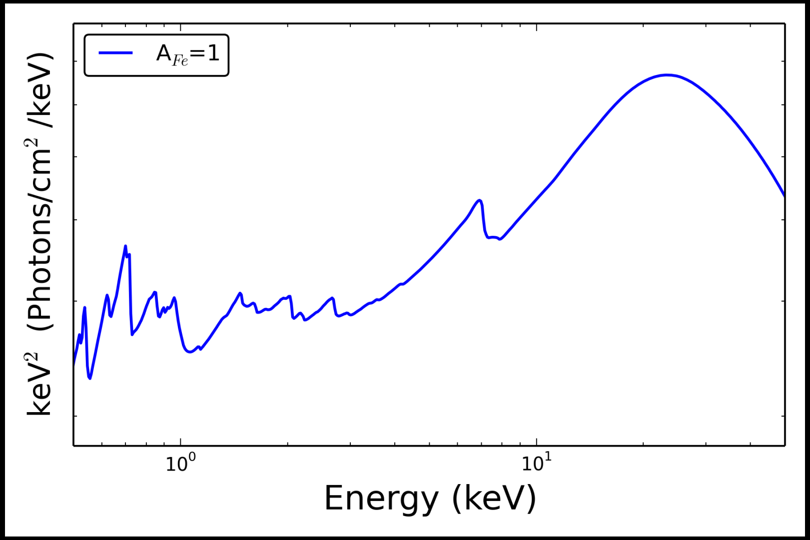
Coronal Height



Inclination

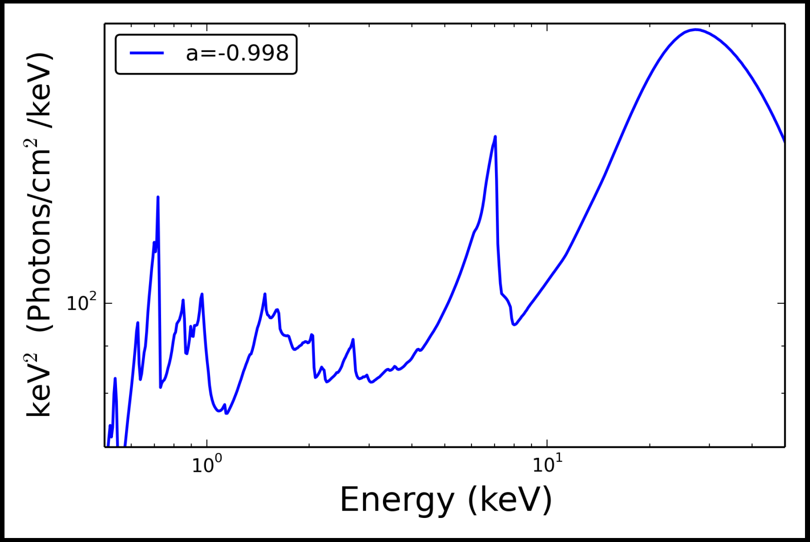


Iron Abundance

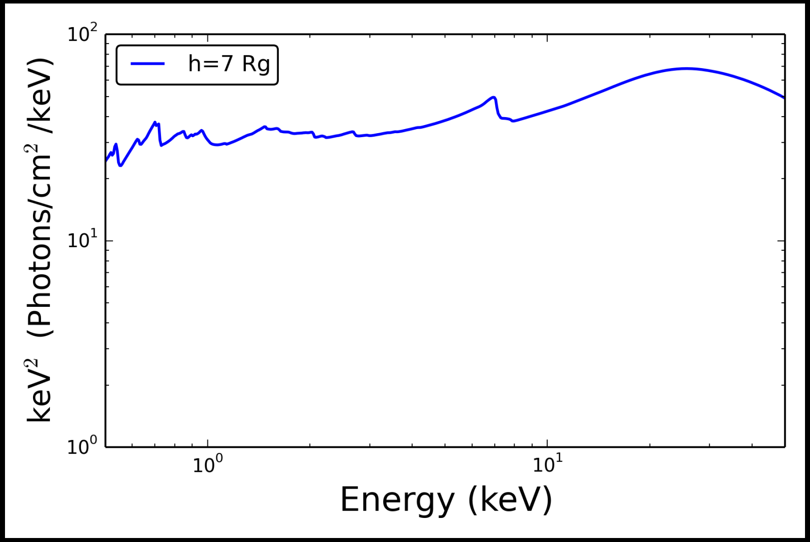


Constraining Physical Quantities

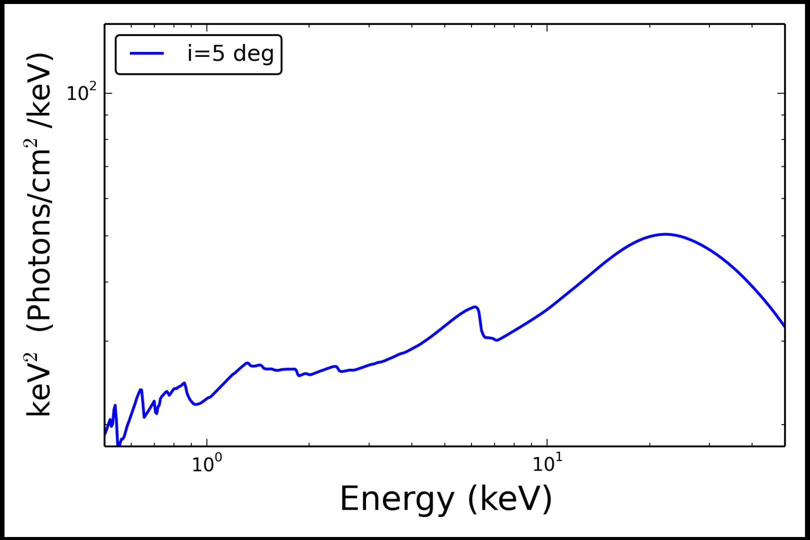
Black Hole Spin



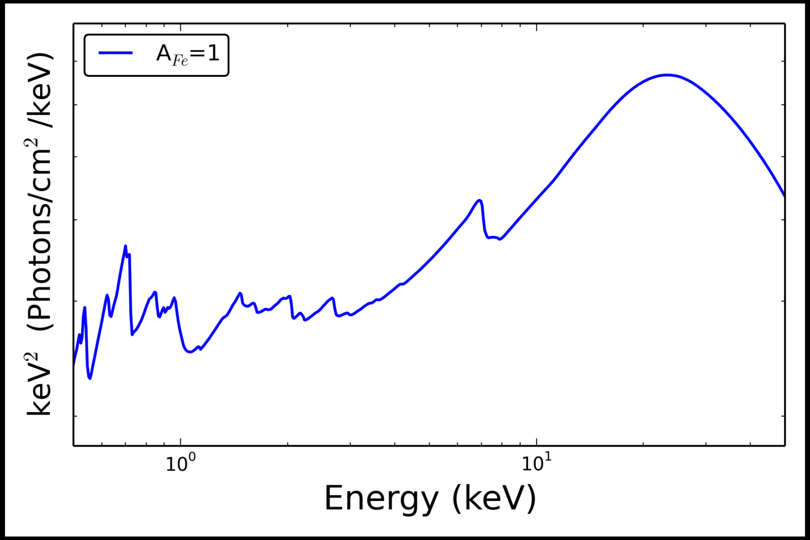
Coronal Height



Inclination



Iron Abundance

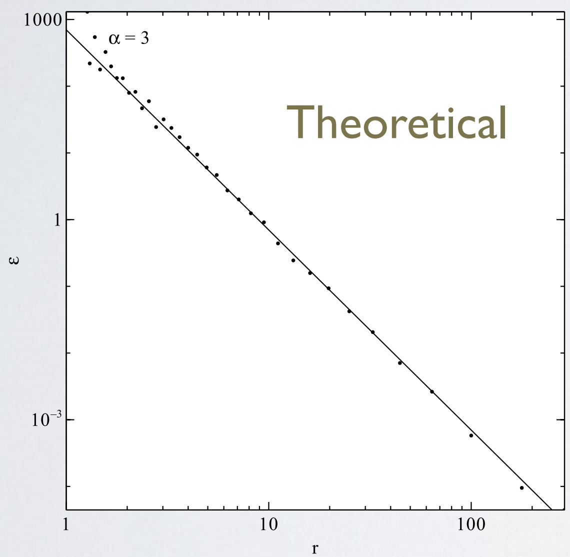


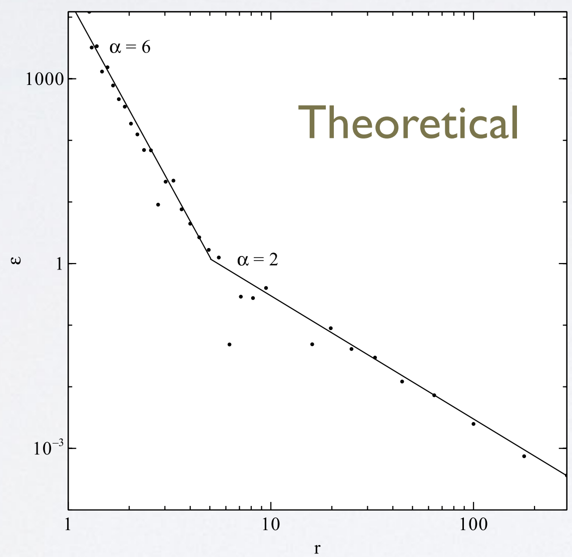
RELXILL: Assumptions & Issues

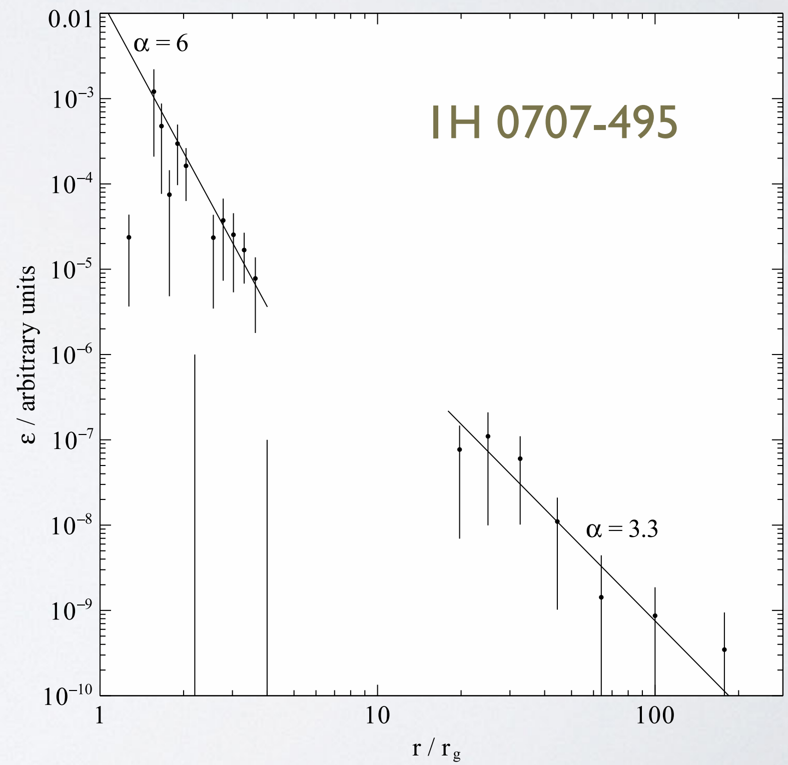
- Assumes Rin = Risco to measure spins.
- Can’t fit both Rin and spin (can we?)
- Emissivity profile: what’s the right shape?
- Lamppost Geometry
- Degeneracies: incl. vs spin, Afe vs spin, etc.
- Single ionization vs. gradients
- Incidence Angle in GR
- Connection with accretion disk models

RELXILL: Emissivity Profile

- What's the right shape?
- Should we be following Wilkins et al? i.e., Measuring the emissivity profile from the observations



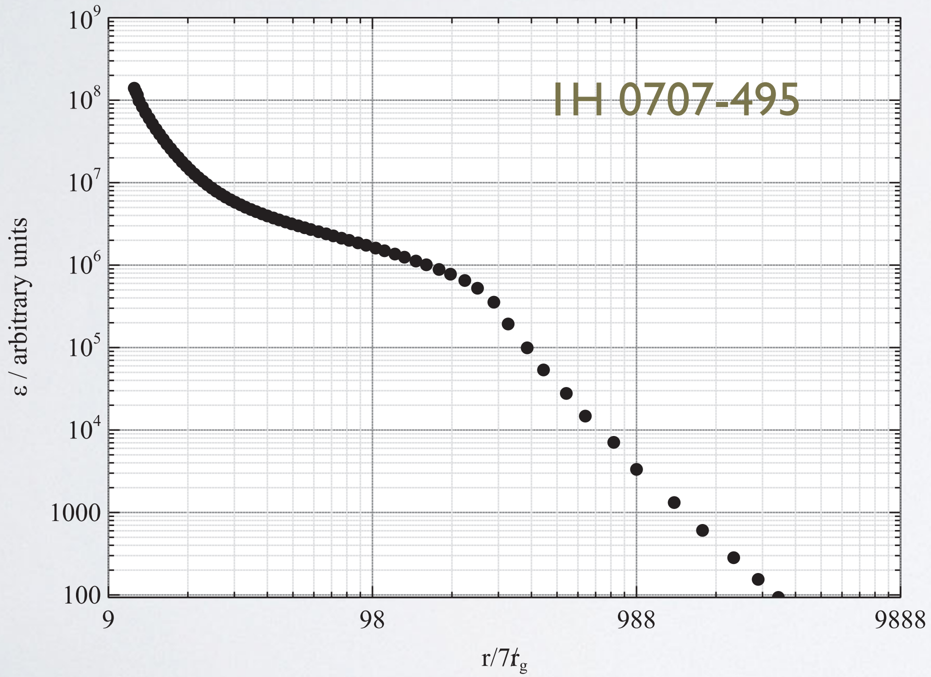




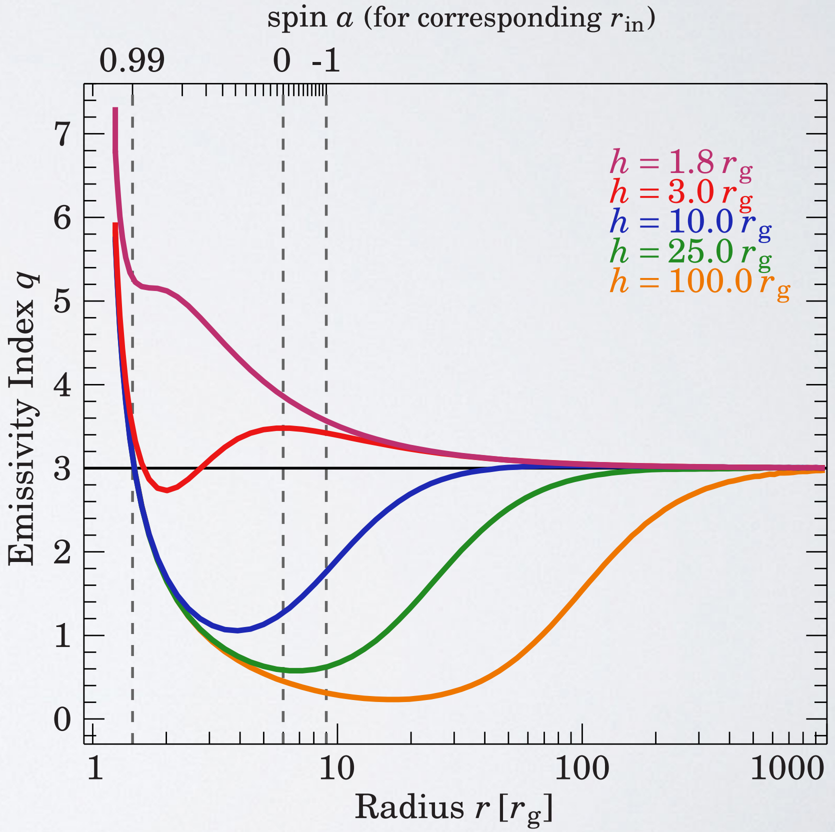
Wilkins & Fabian (2011)

RELXILL: Emissivity Profile

- It can be more complicated:
- Double broken power-law? Lamppost?



Wilkins & Fabian (2012)

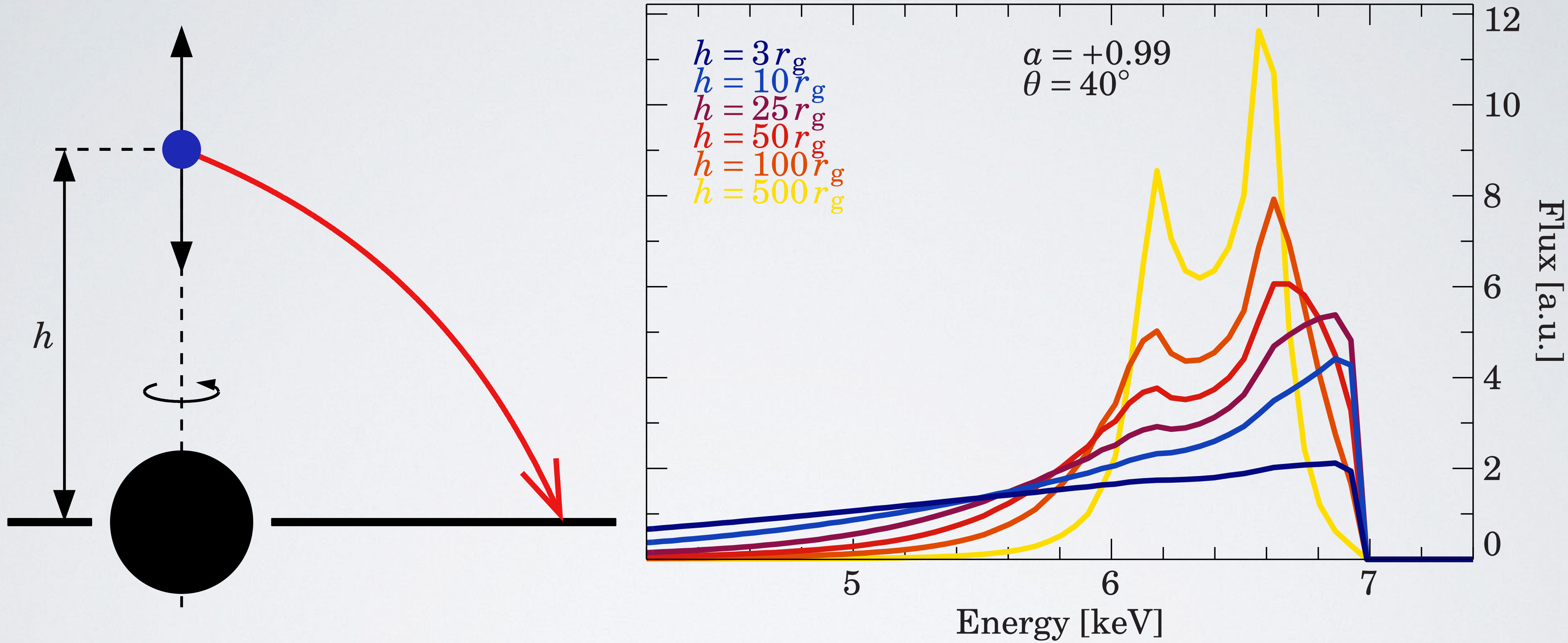


Dauser et al. (2013)

RELXILL: Lamppost Geometry

- Is the lamppost geometry correct? Probably no, but it seems to work very well in many cases!
- In fact, the better the data quality, the best the lamppost outperforms the standard emissivity law… why?
- However, the reflection fraction is typically lower than predicted (but see later about the incidence angles)
- In my opinion, the lamppost provides a much more physical profile for the illumination, but it fails to predict the true reflection fraction because of its simplicity

Diagnostic Tool: Geometry



Probe geometry and location of the primary source

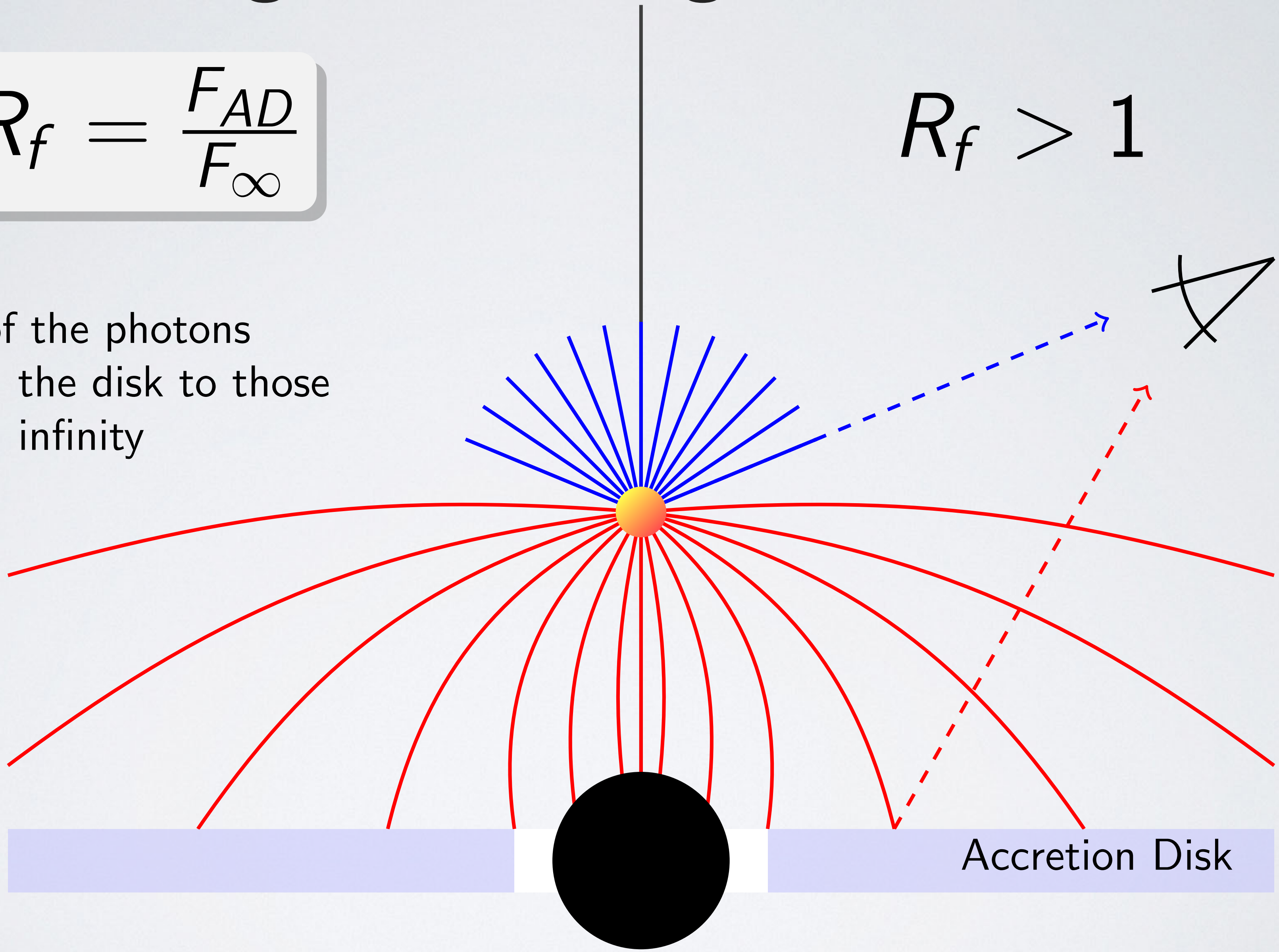
Low high implies enhanced irradiation of the inner regions

Light Bending Effects

$$R_f = \frac{F_{AD}}{F_\infty}$$

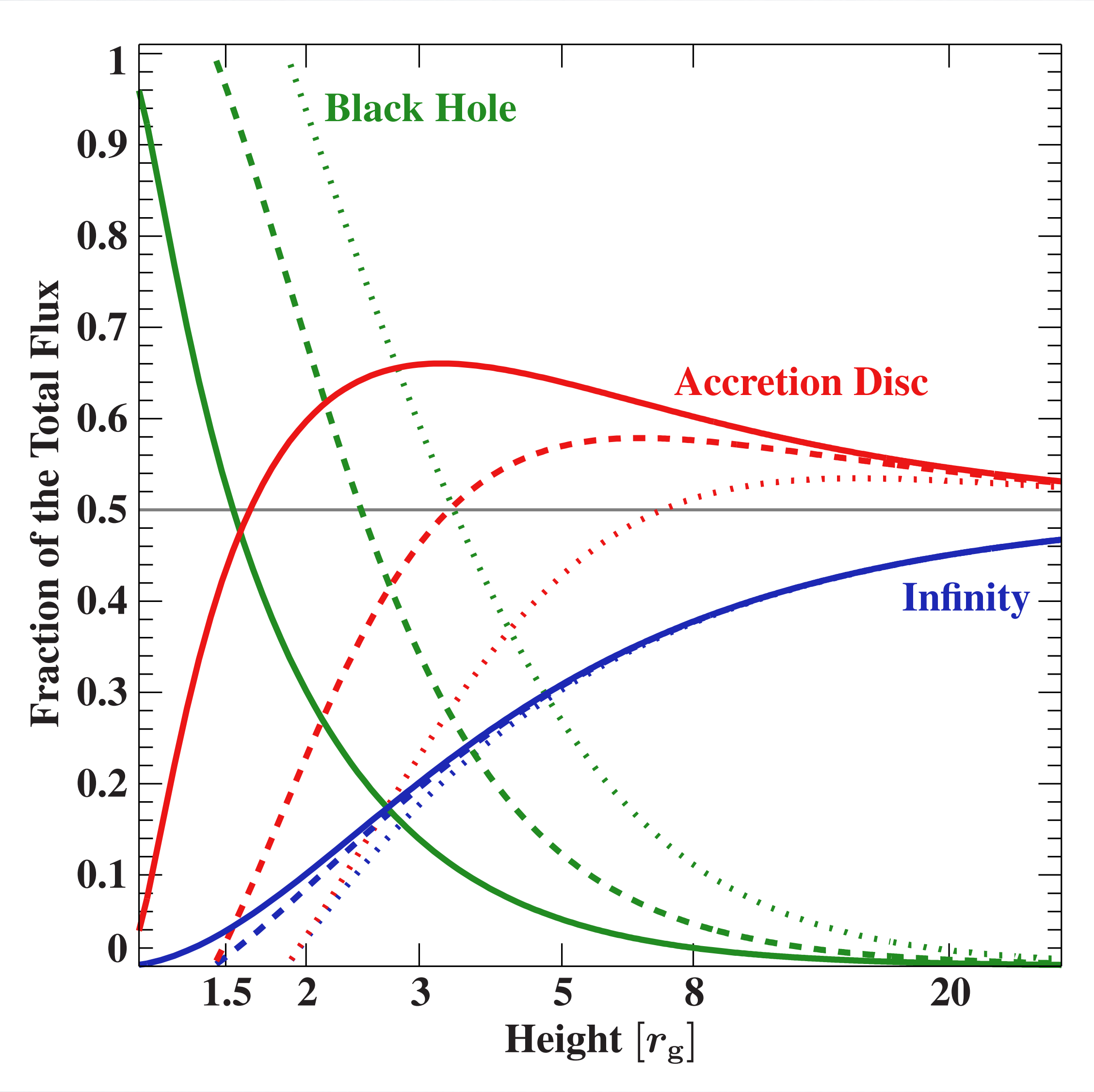
$$R_f > 1$$

Fraction of the photons that reach the disk to those that reach infinity



Dauser, Garcia et al. (2014)

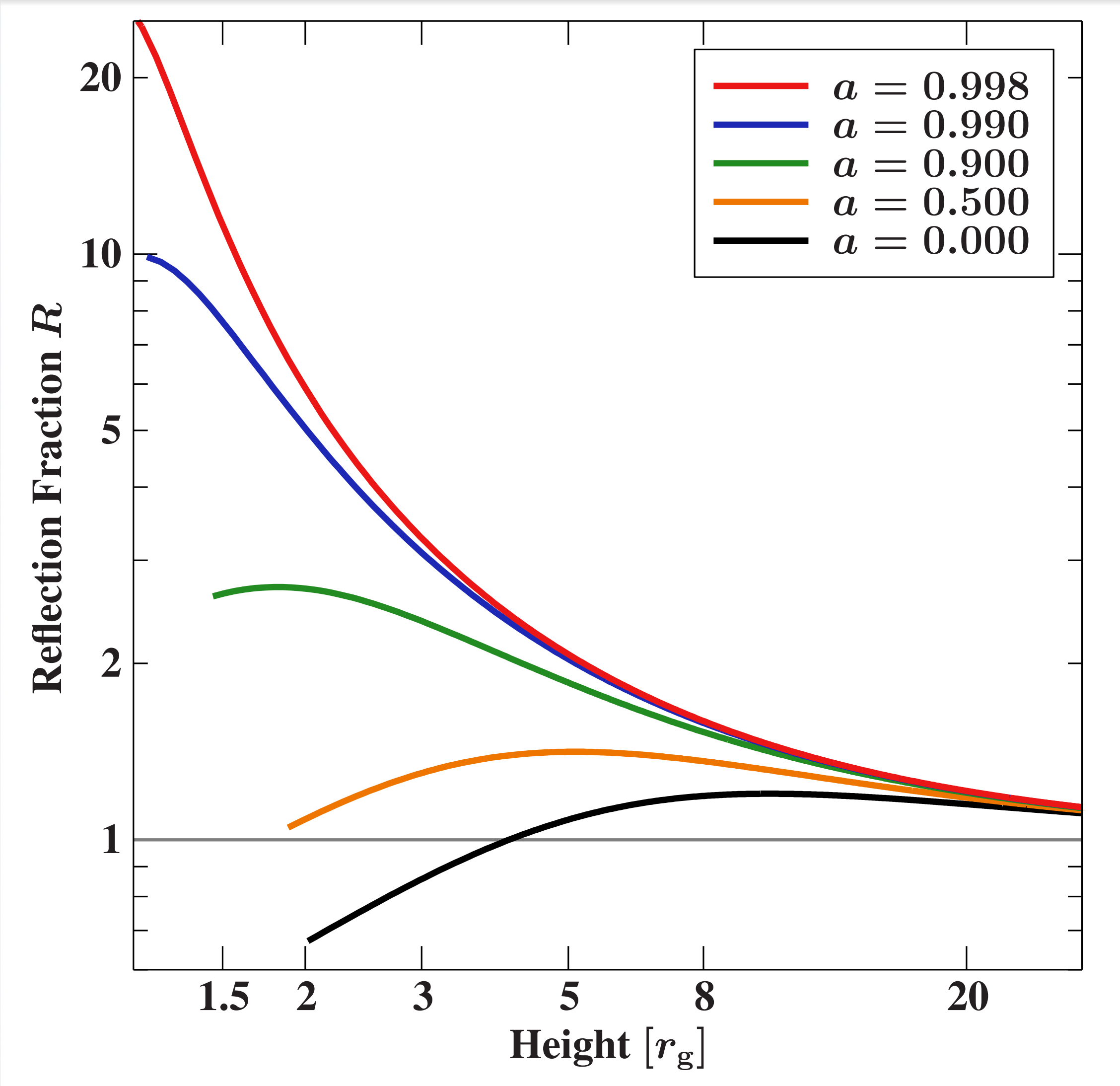
The Reflection Fraction



Photons from the corona can reach the observer, hit the accretion disk, or get lost in the black hole

Dauser, Garcia et al. (2014)

The Reflection Fraction

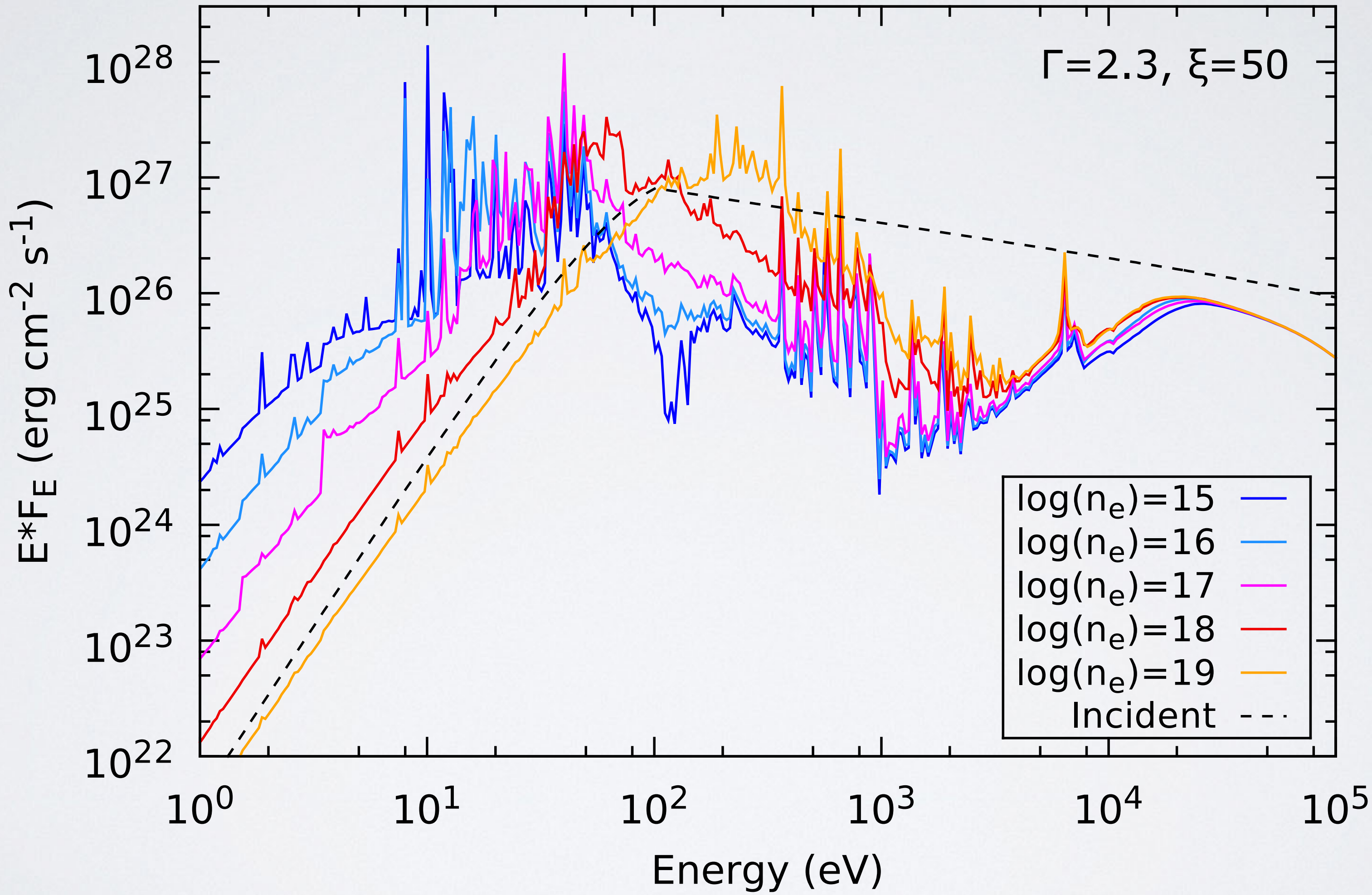


The reflection fraction is controlled by the spin, inner radius, and the height of the X-ray source

Dauser, Garcia et al. (2014)

High-Density Effects

Models with high gas density ($n_e >> 10^{15}$ cm^{-3}) produce a remarkable flux excess at soft energies as free-free emission becomes important.



García et al. (2016a)

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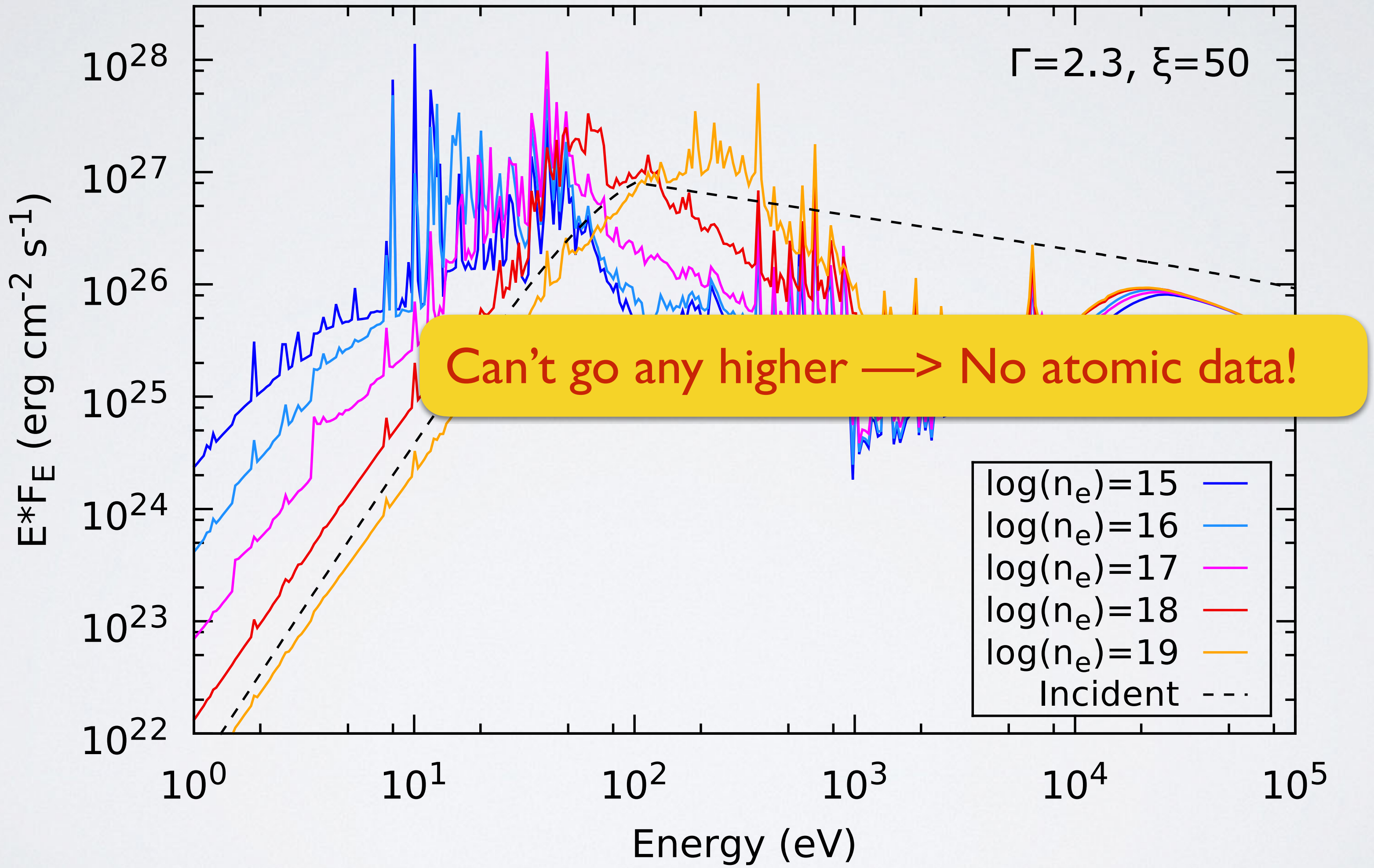
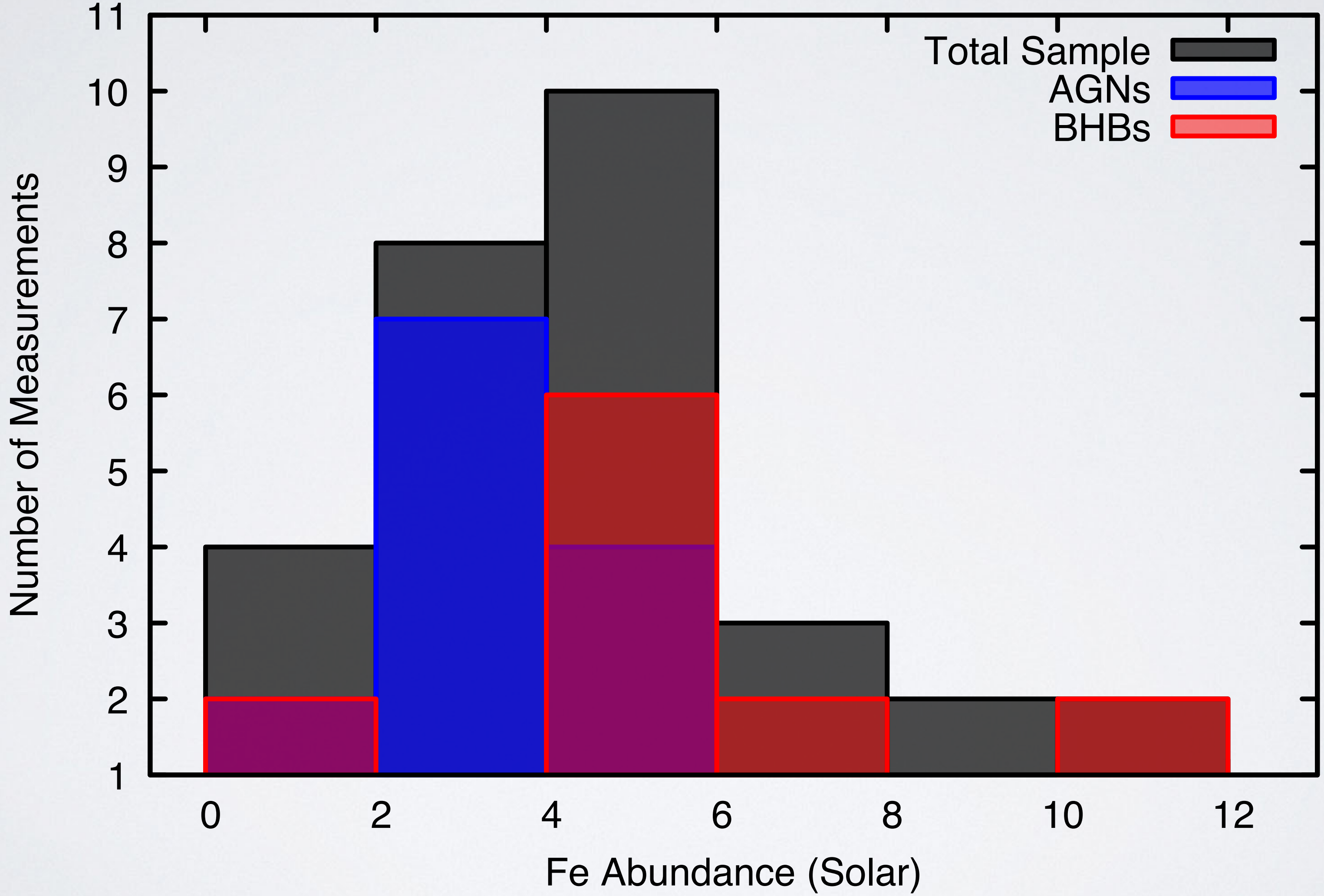


García et al. (2016a)

The Problem of the Fe Abundance

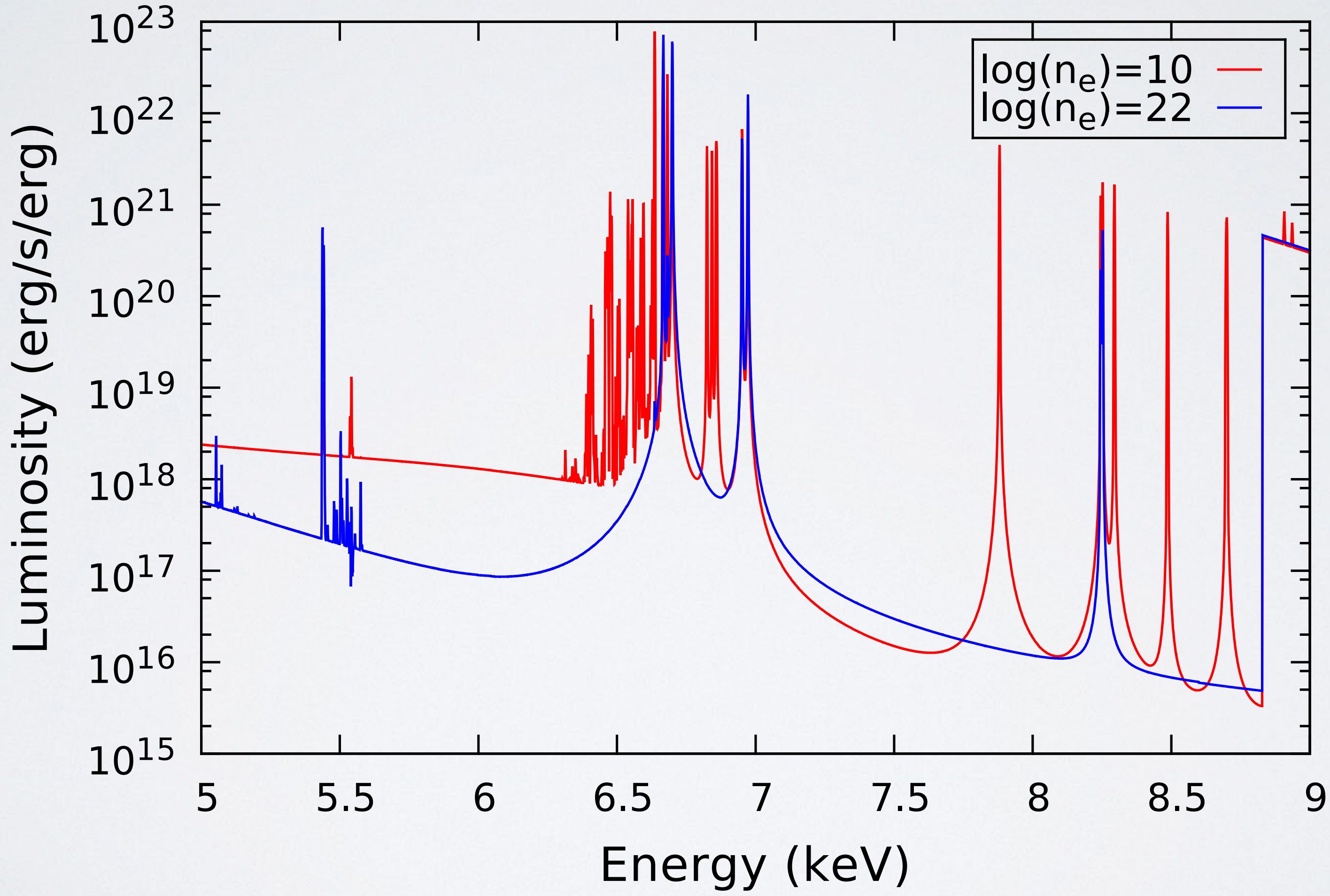
Iron abundance determinations using reflection spectroscopy from publications since 2014 tend to find a few times the Solar value! WTF? (Why The Fe?)



13 AGNs
9 BHBs

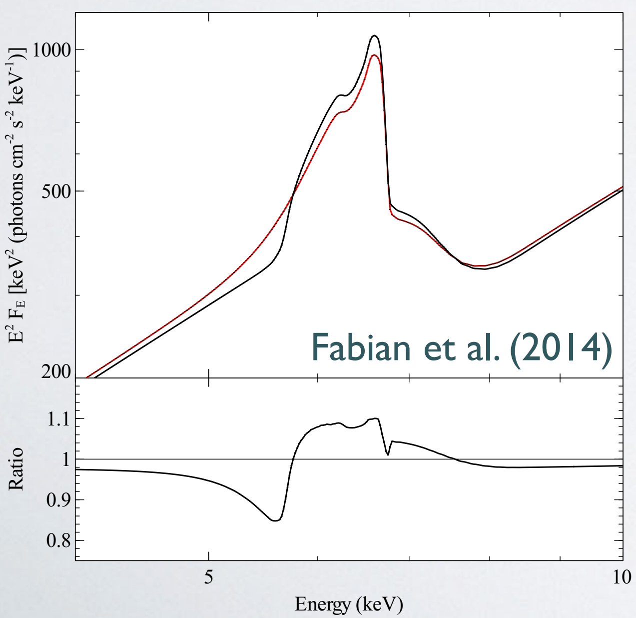
Possible Link with Density Effects?

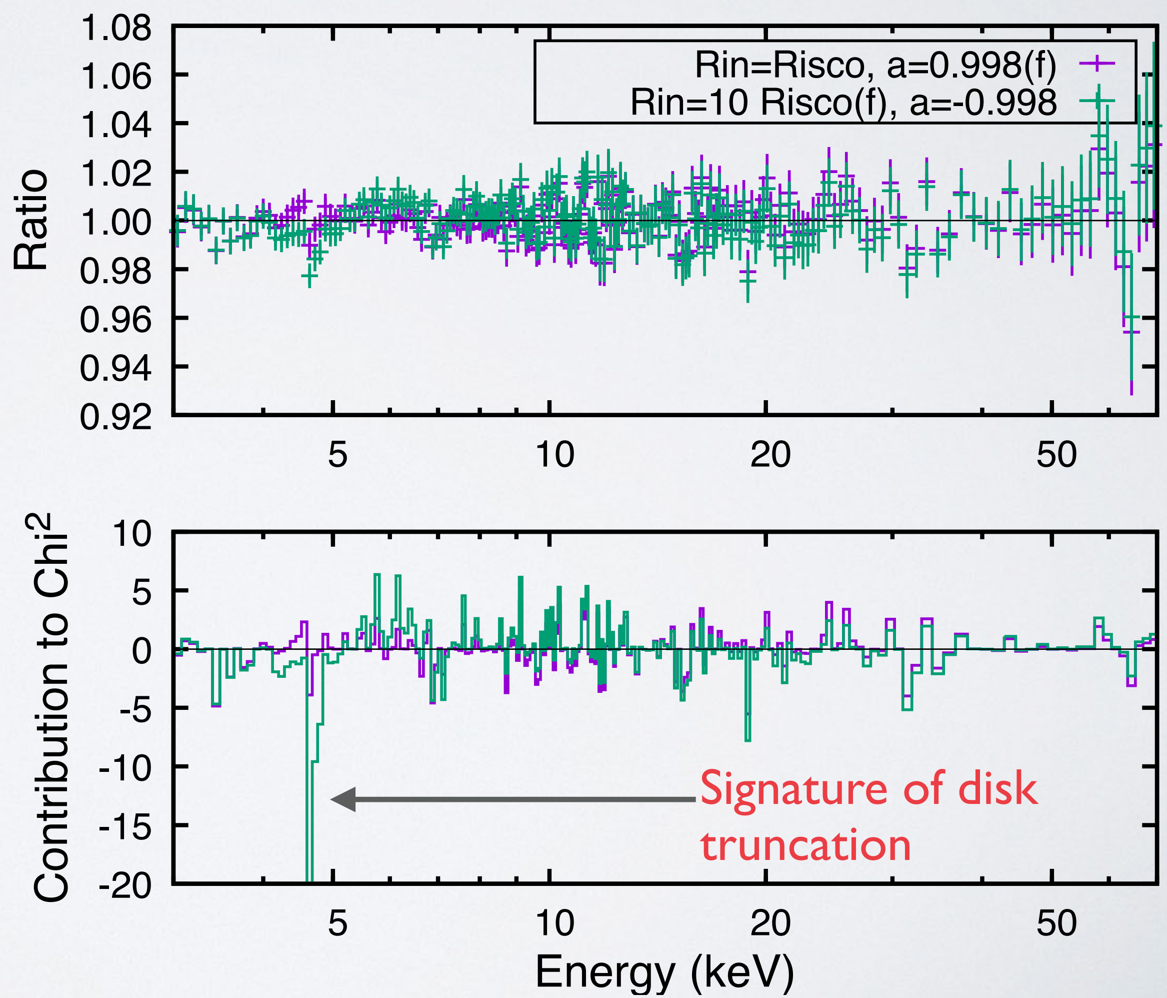
High-density effects such as continuum lowering could have an impact in the Fe abundance. However, new atomic data for high density plasmas is required!



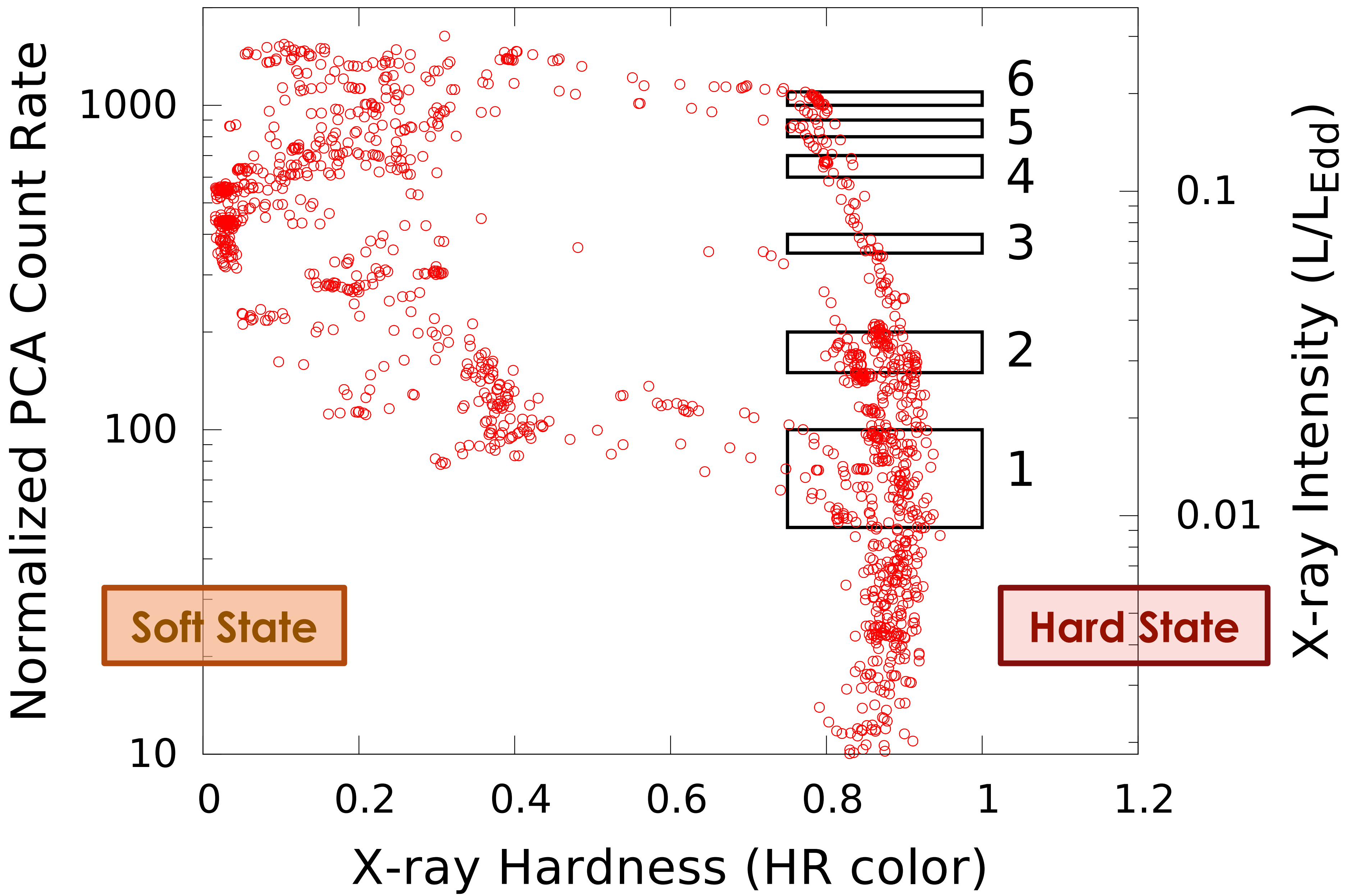
RELXILL: Spin and Inner Radius

- If the disk is truncated (Rin > Risco), then fitting with Rin=Risco will under predict the spin
- Conversely, if Rin is desired, fixing spin to max (a=0.998) will estimate largest possible truncation
- We can't measure both spin and Rin, can we?
- Typically very loose constraints



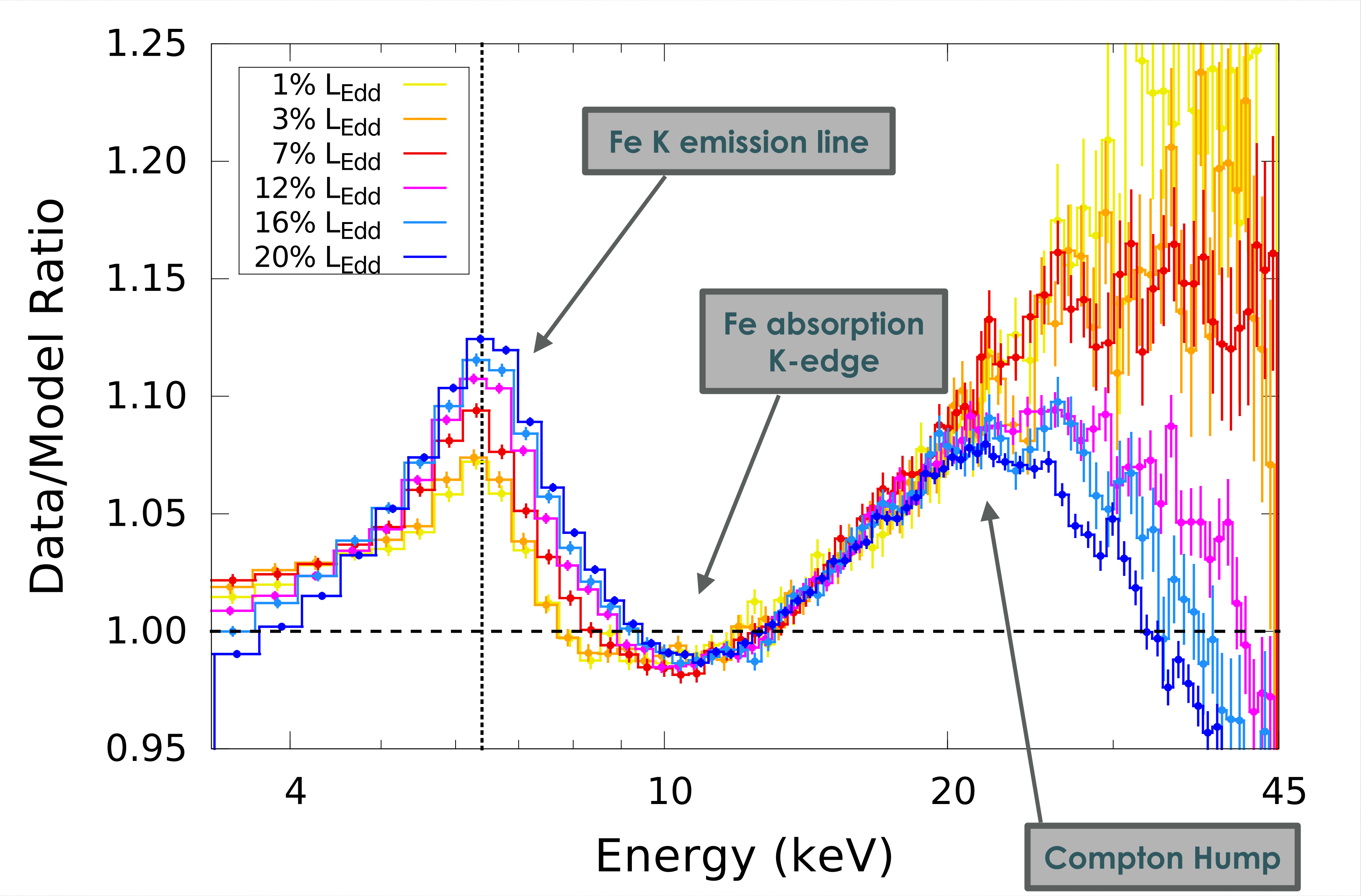


The HID of GX 339-4



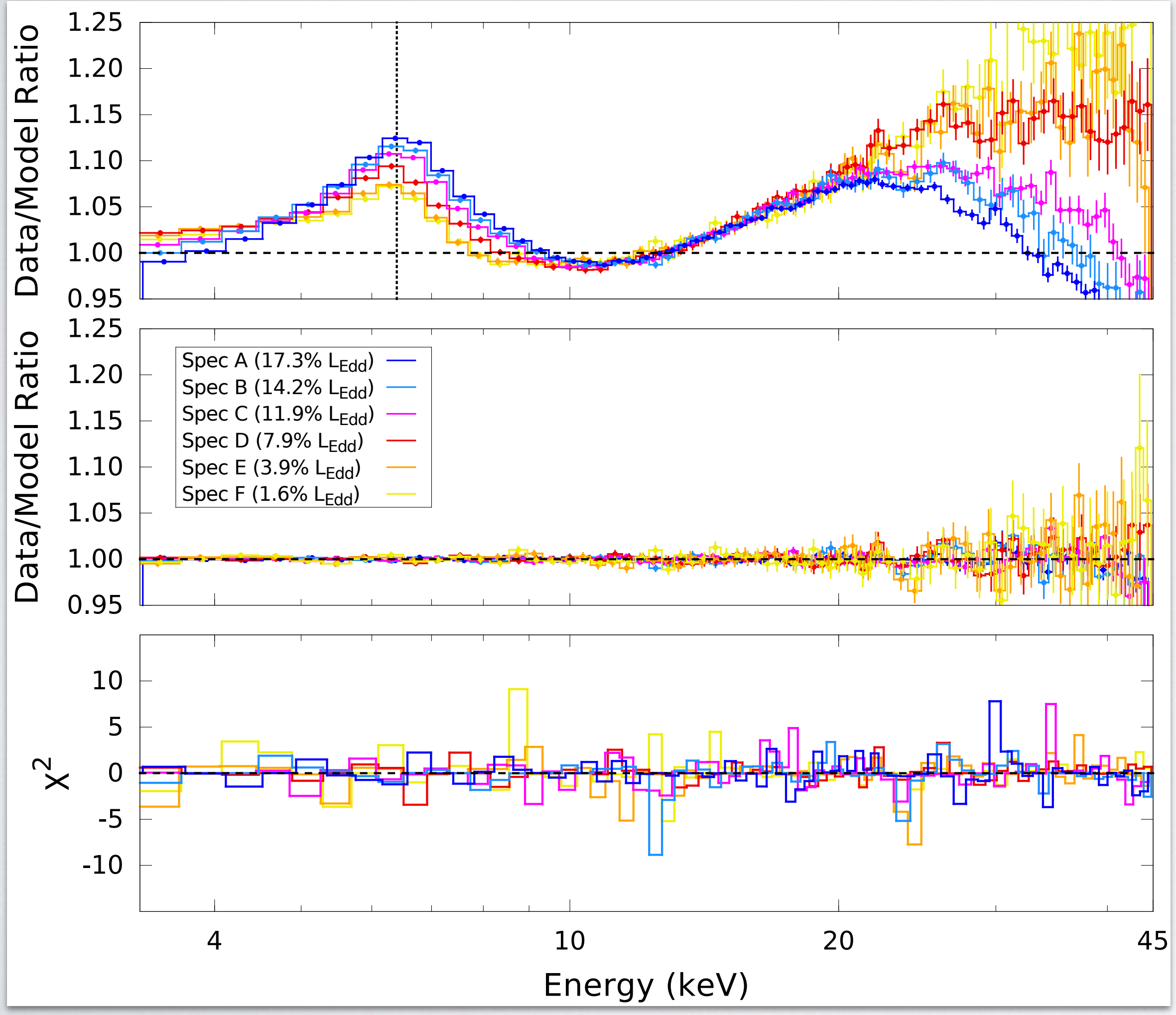
GX 339-4: Reflection Signatures

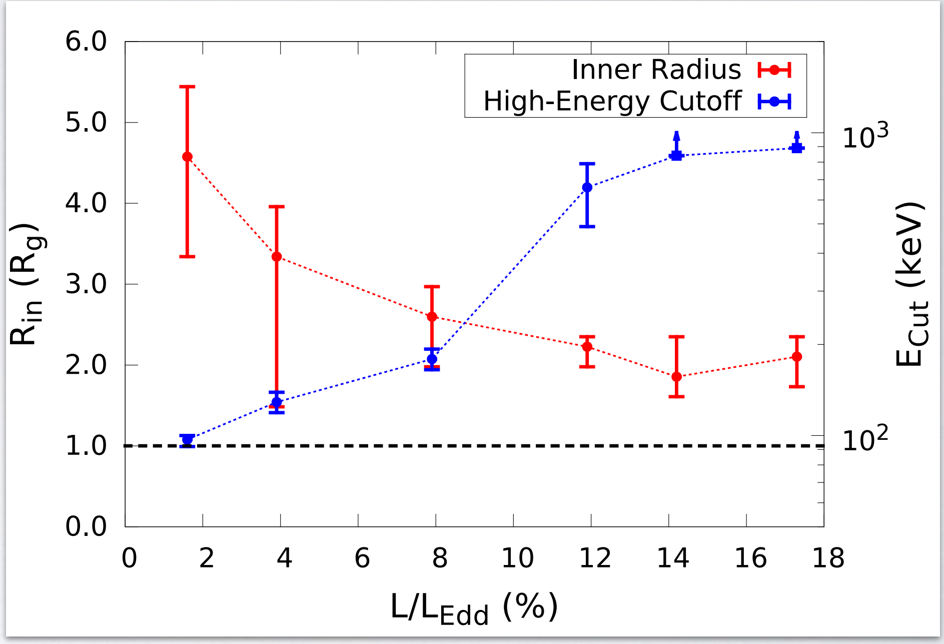
Ratio to a power-law model shows the signatures of reflection



Disk and Corona Evolution in GX 339-4

Simultaneous fit of the RELXILL model to a 77 million count RXTE spectra revealed changes in disk and corona.



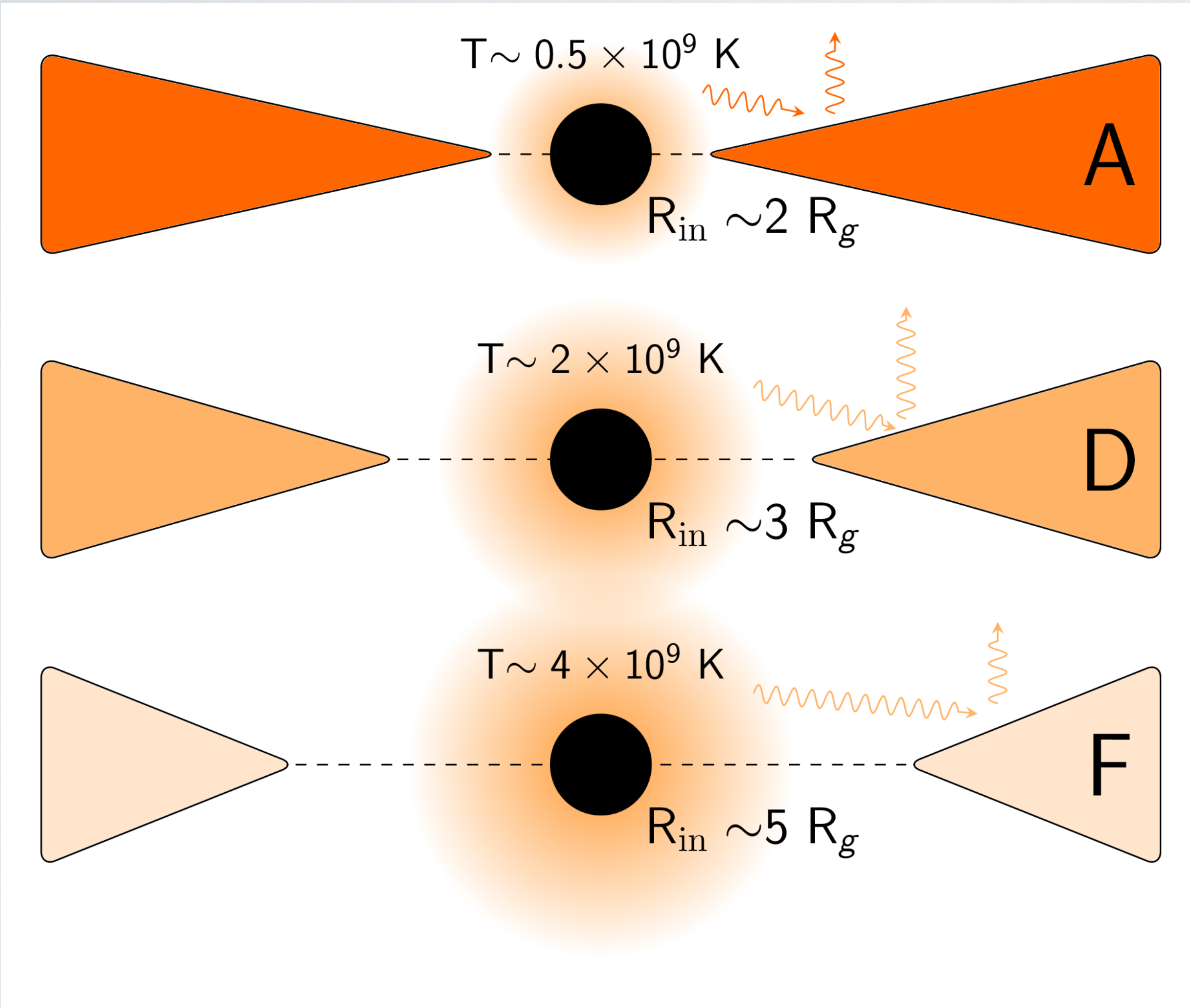


a = 0.95 +/- 0.04 (90% conf)
i = 48 +/- 1 deg
Fe abundance 5x Solar
Reduced χ^2 = 1.06
0.1% systematics

García et al. (2015)

GX 339-4: Detecting Geometrical Changes

These changes seem to be correlated…



For increasing luminosity, the disk moves inward and the corona cools down.

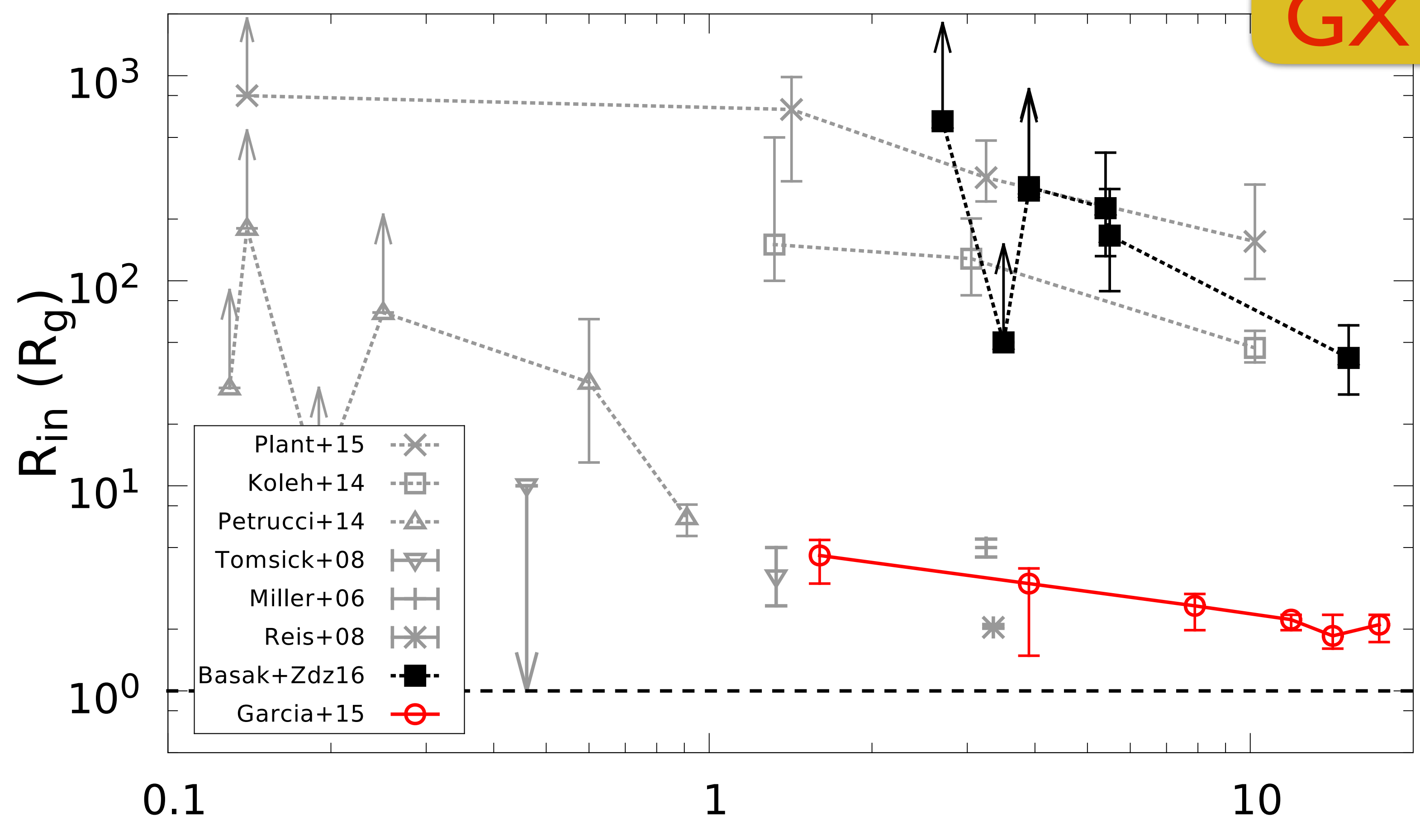
For a 10 solar-mass BH, these changes correspond to a differential of ~45 km!

García et al. (2015)

Controversy on the Disk Truncation

Fits of the inner-disk radius disagreement up to ~2 orders of magnitude between different simultaneous observations

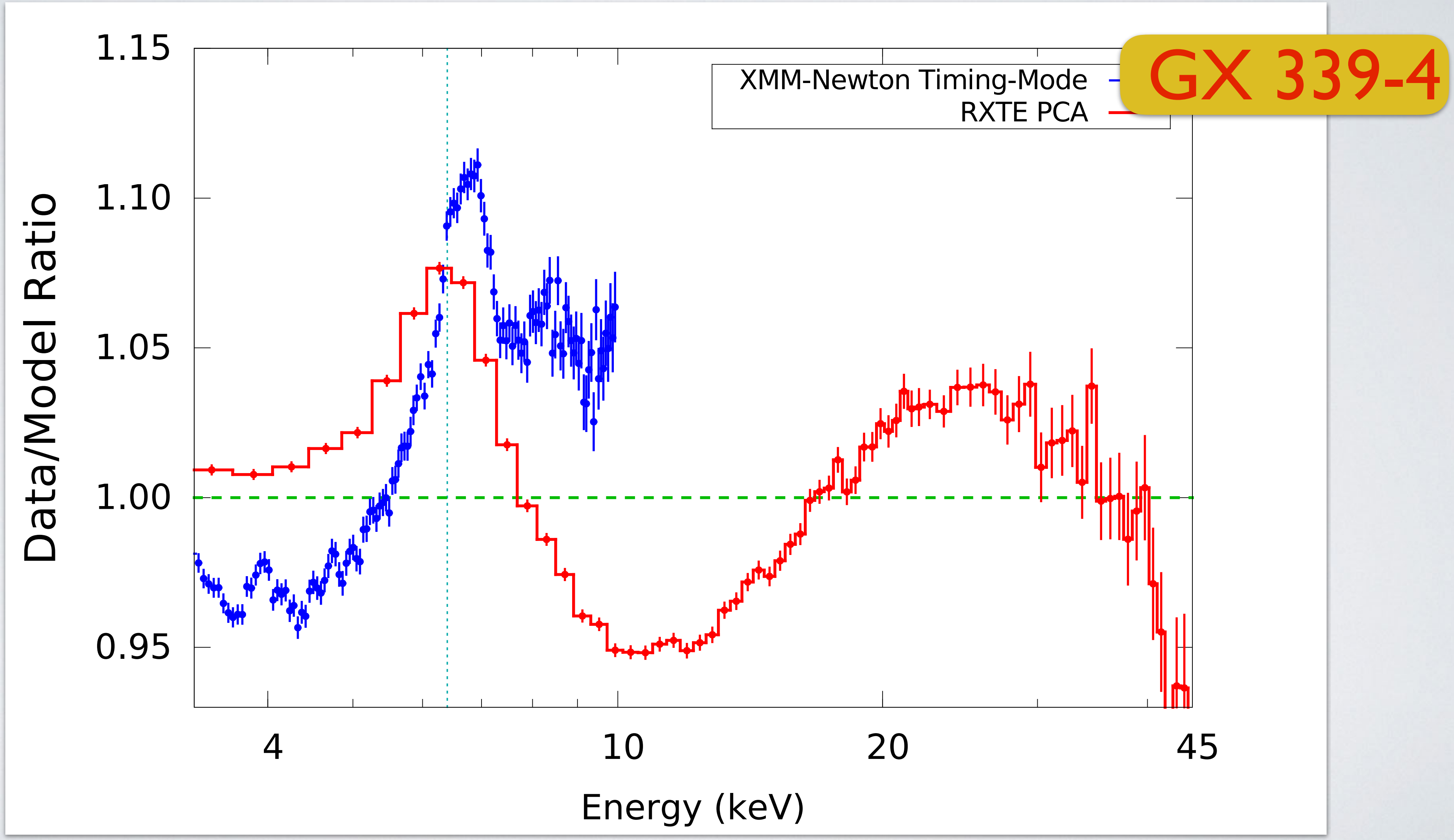
GX 339-4



García et al. (2015)

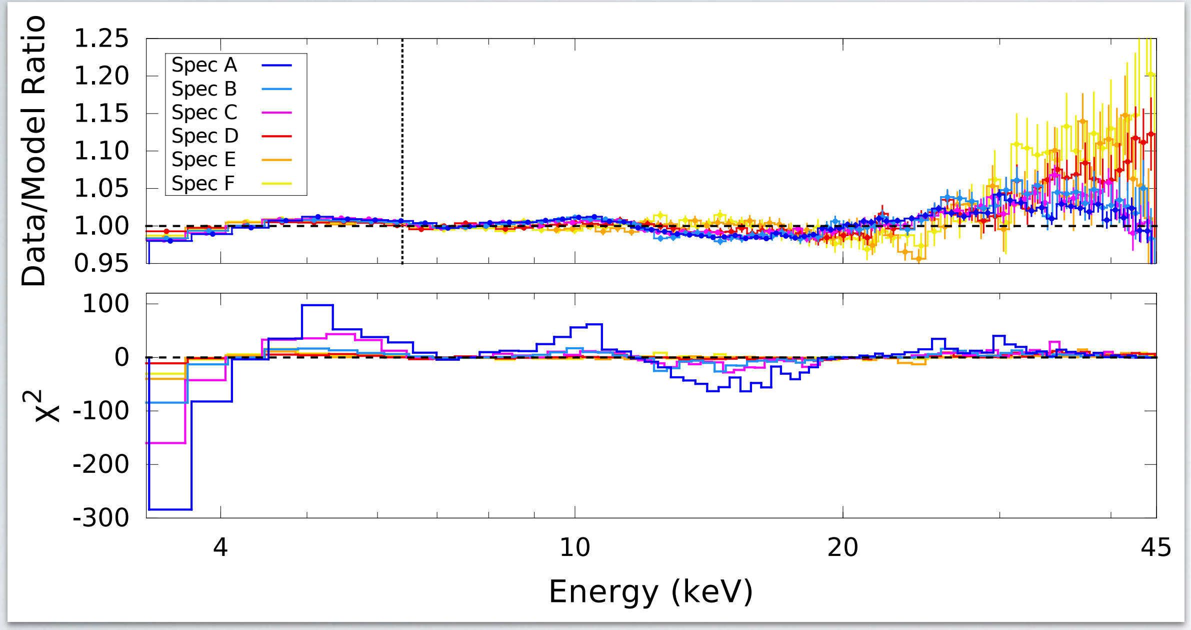
XMM Timing Mode Vs. RXTE PCA

The XMM timing mode data shows a much narrower Fe K emission profile than the simultaneous RXTE data

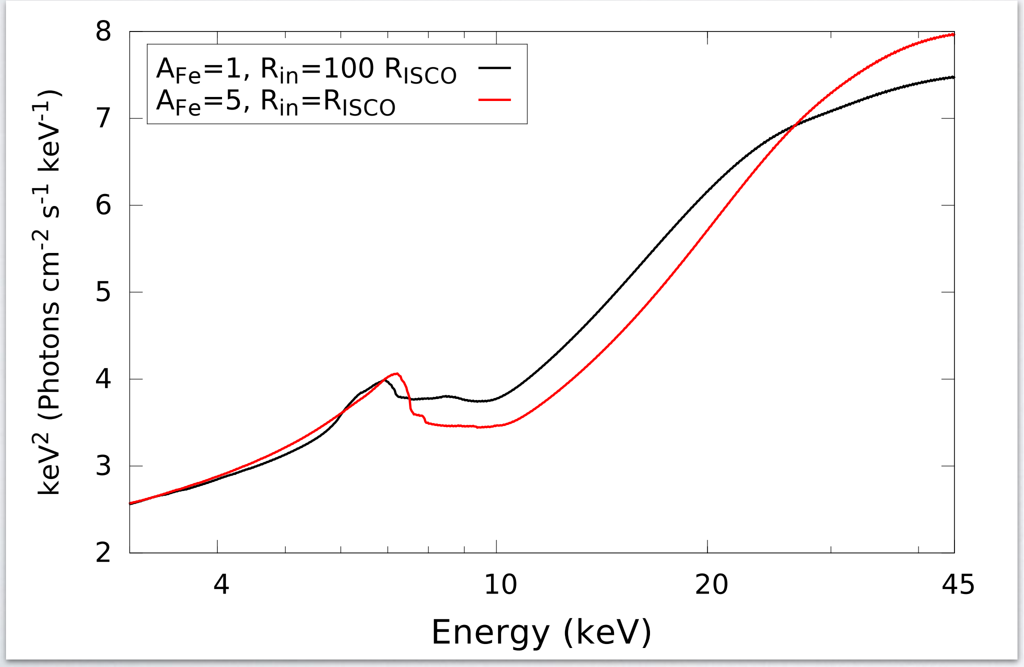


Possibly due to calibration issues in this particular mode

Connection between R_{in} and A_{Fe}



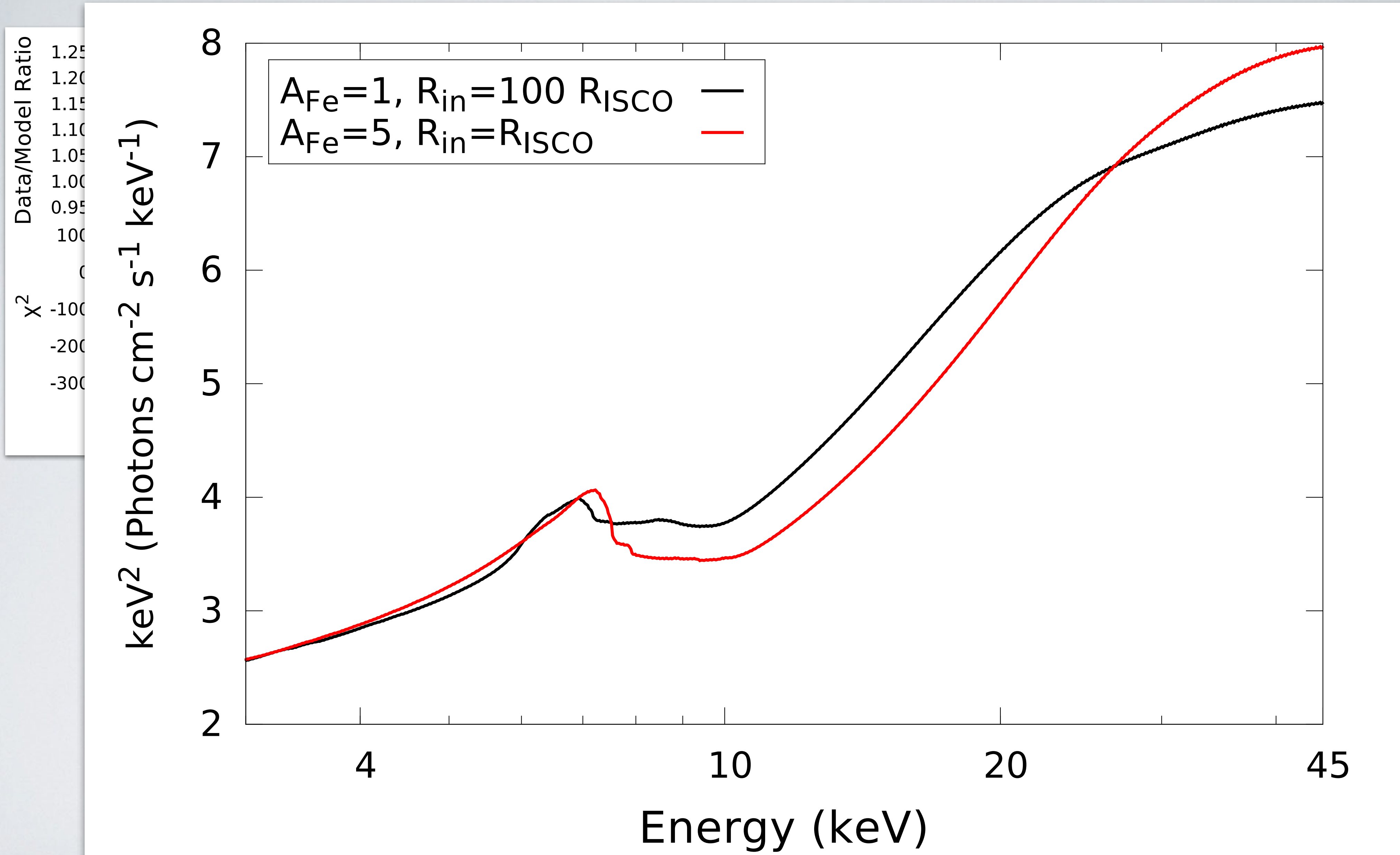
Fixing the Fe abundance to its Solar value resulted in poor fits with $\chi^2 \sim 10$



A truncated disk with Solar abundance produces an Fe K line similar to an over-abundant disk reaching the ISCO

García et al. (2015)

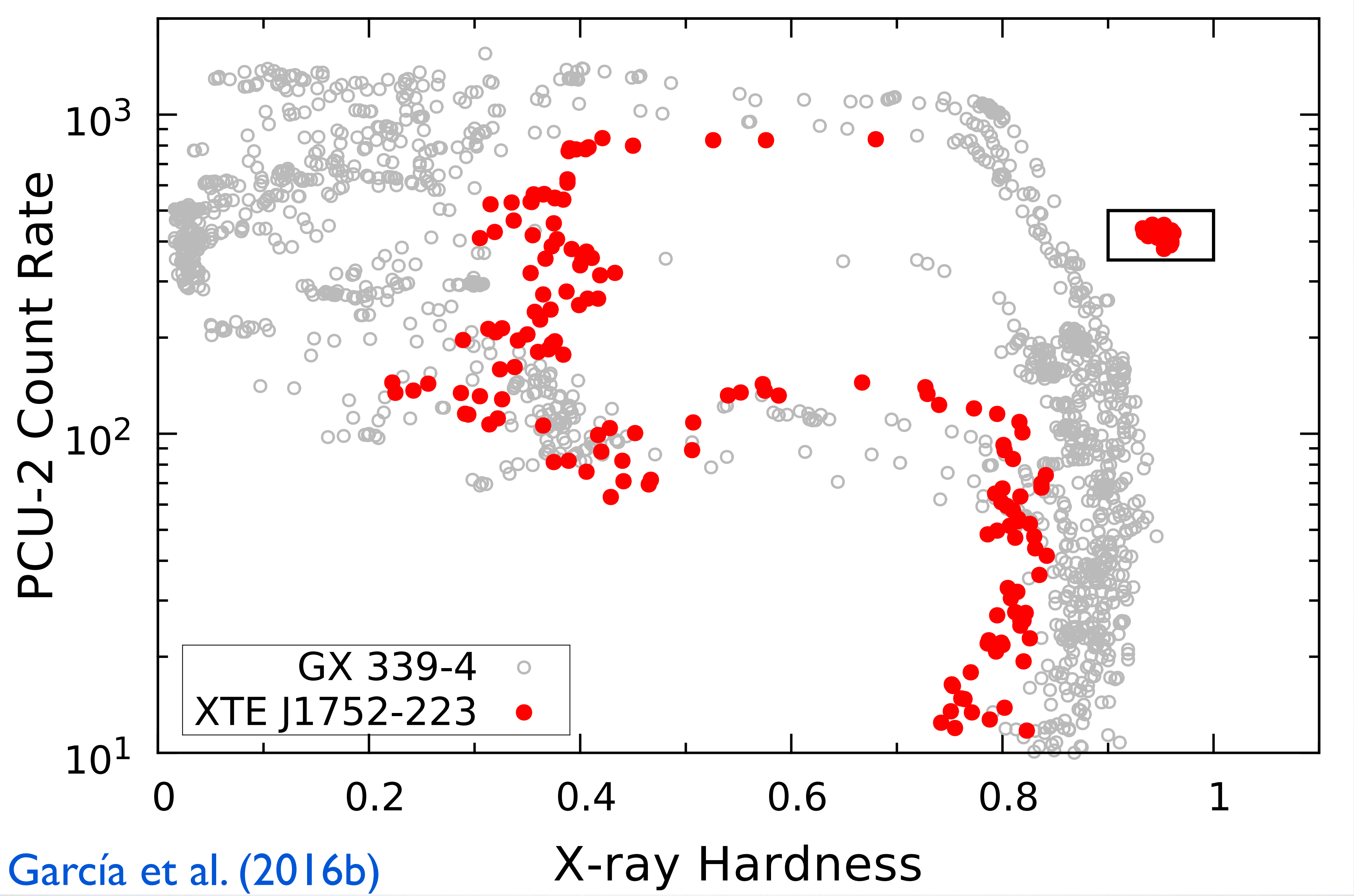
Connection between R_{in} and A_{Fe}



García et al. (2015)

The Peculiar Hard State of XTE J1752-223

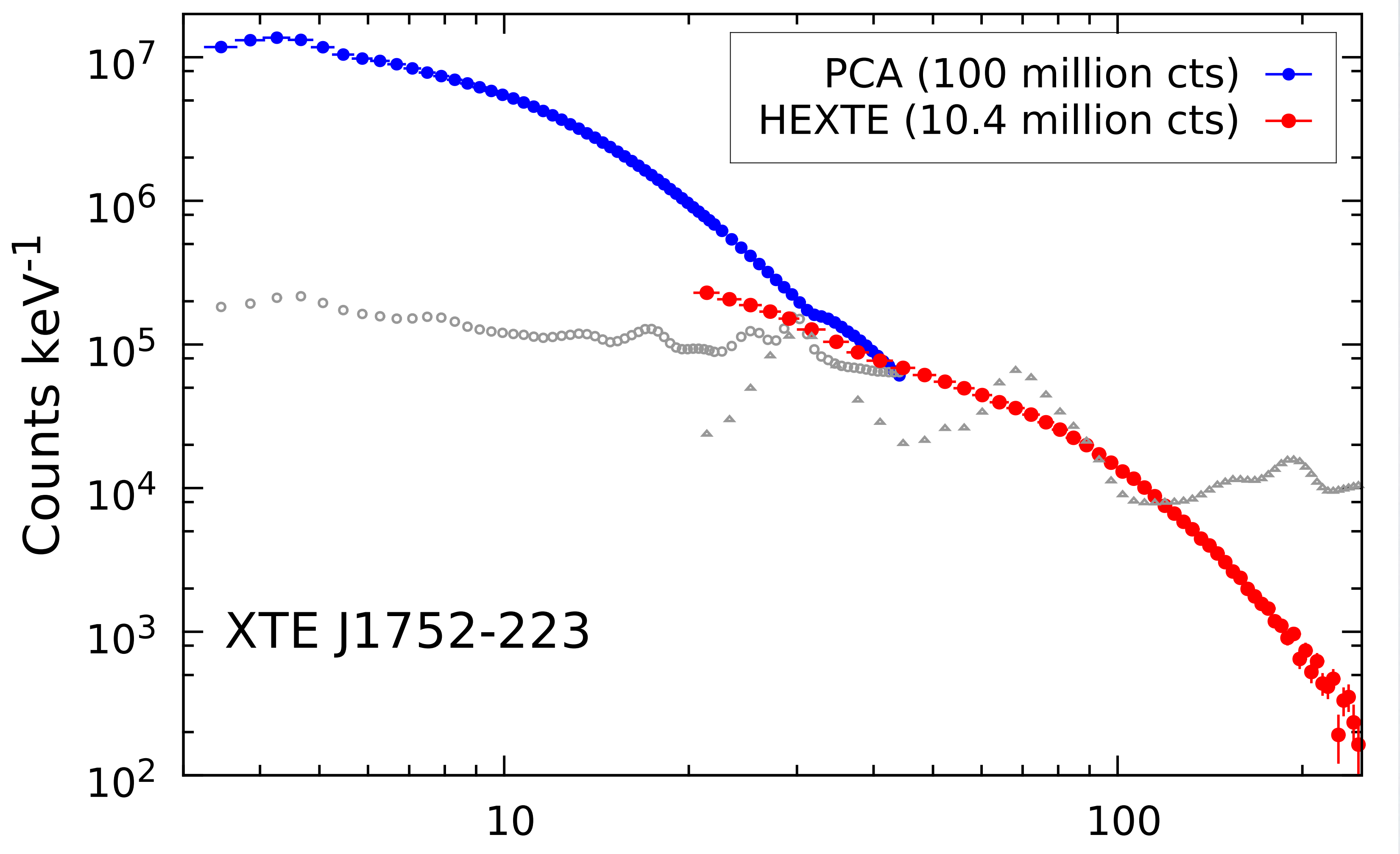
A total of 60 RXTE observations spanning ~1 month for ~300 ks of exposure.



García et al. (2016b)

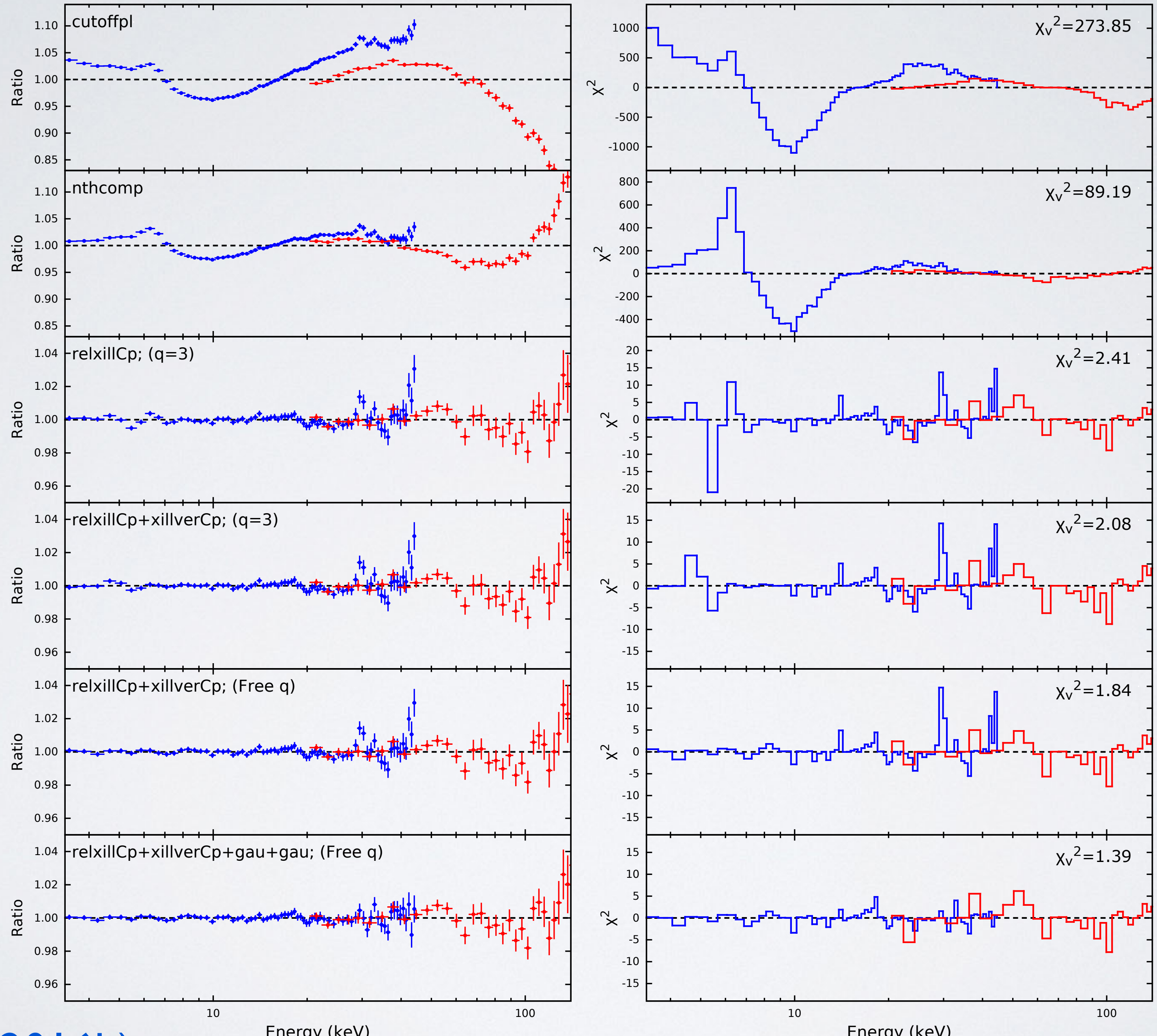
XTE J1752-223: An Outstanding Hard-State Spectrum

In this case we also include higher energy data provided by HEXTE



García et al. (2016b)

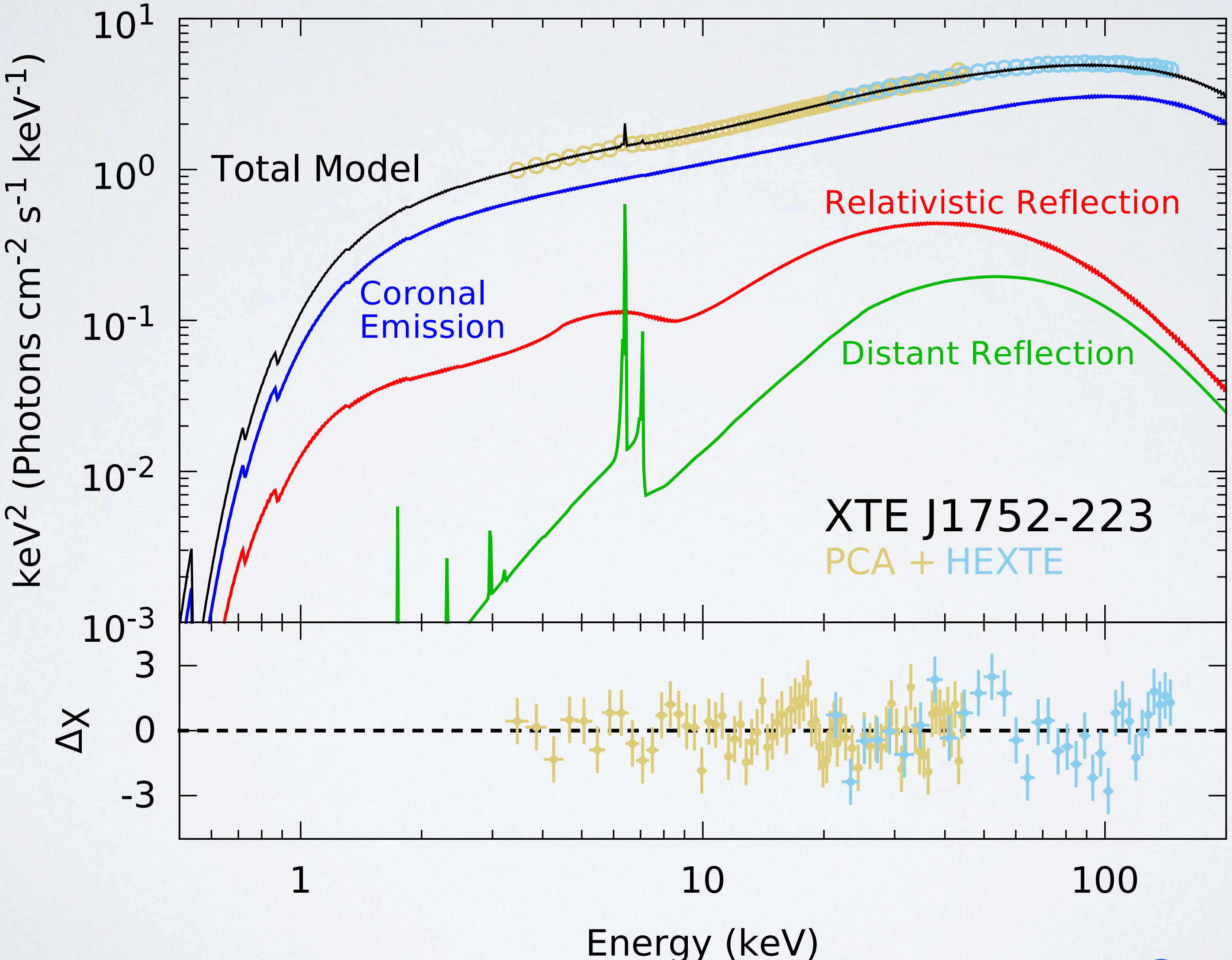
XTE J1752-223: An Outstanding Hard-State Spectrum



García et al. (2016b)

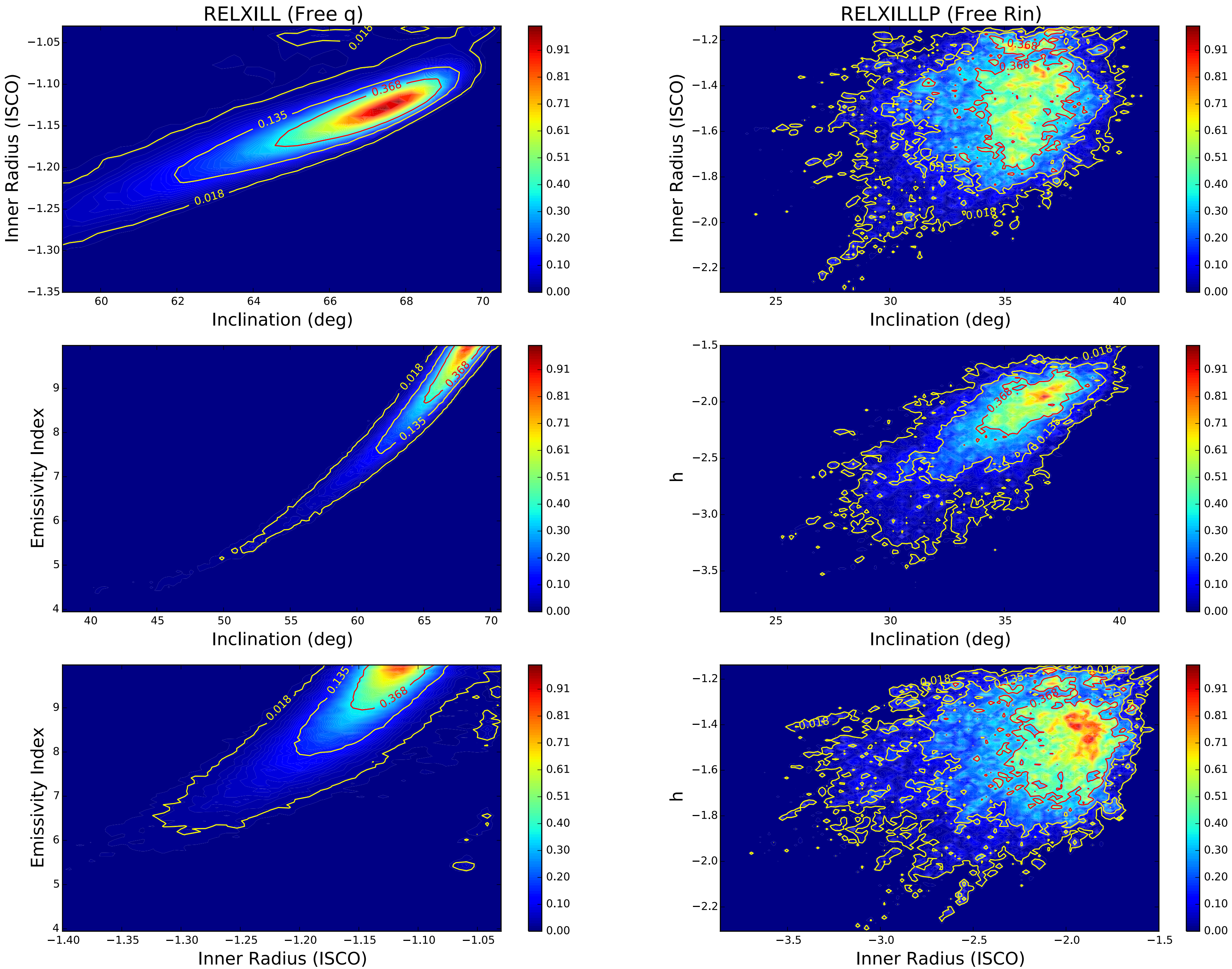
Fits to XTE J1752-223

Similarly to GX 339-4, we find a rapidly spinning black hole (a*~0.992), also with super-solar iron abundance (Afe~4)



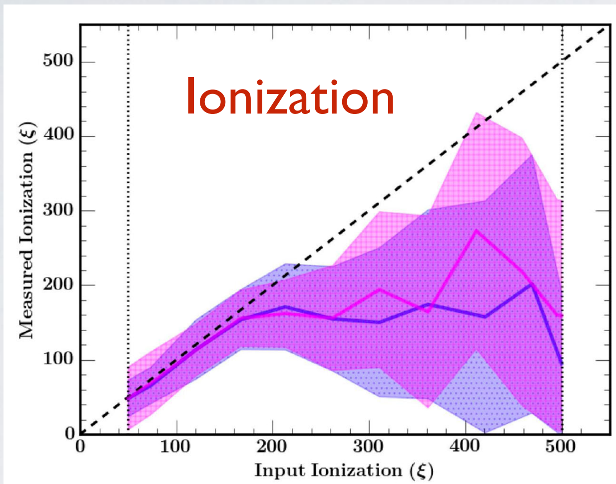
García et al. (2016b)

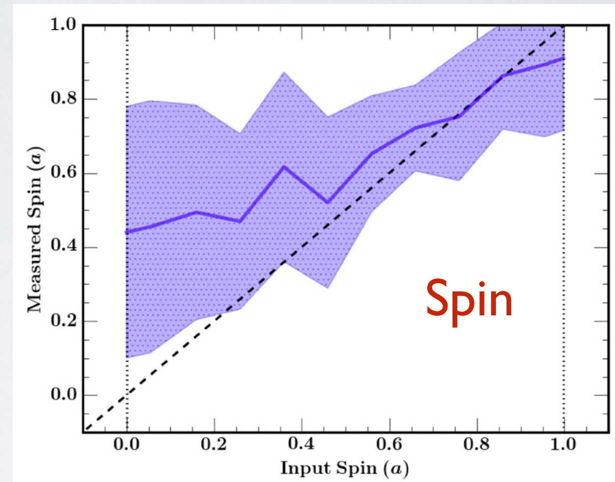
RELXILL: Degeneracies



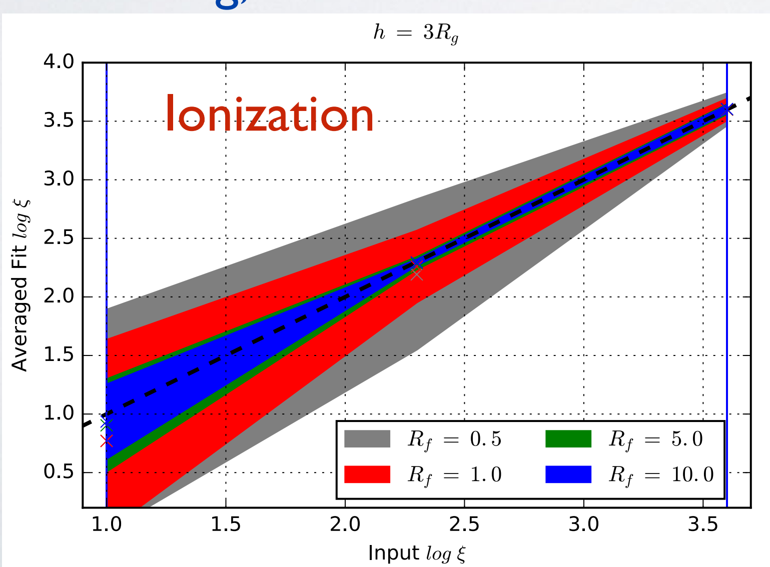
Understanding the Model Systematics

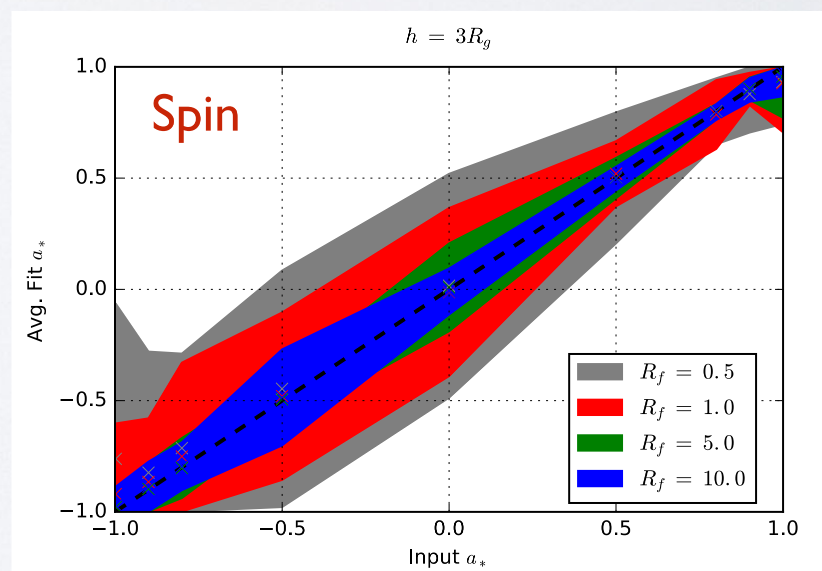
Bonson & Gallo (2016): Relatively large uncertainties in recovering fundamental parameters





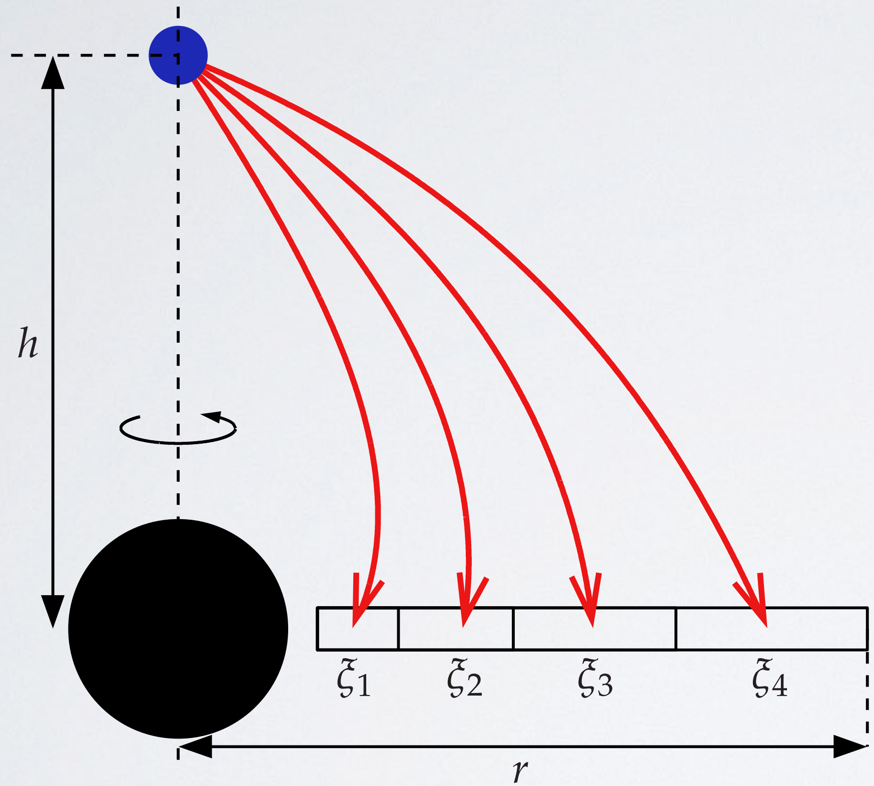
Choudhury et al. (in prep.): Uncertainties are highly dependent on the initial values, proper spectral binning, and minimization methods!

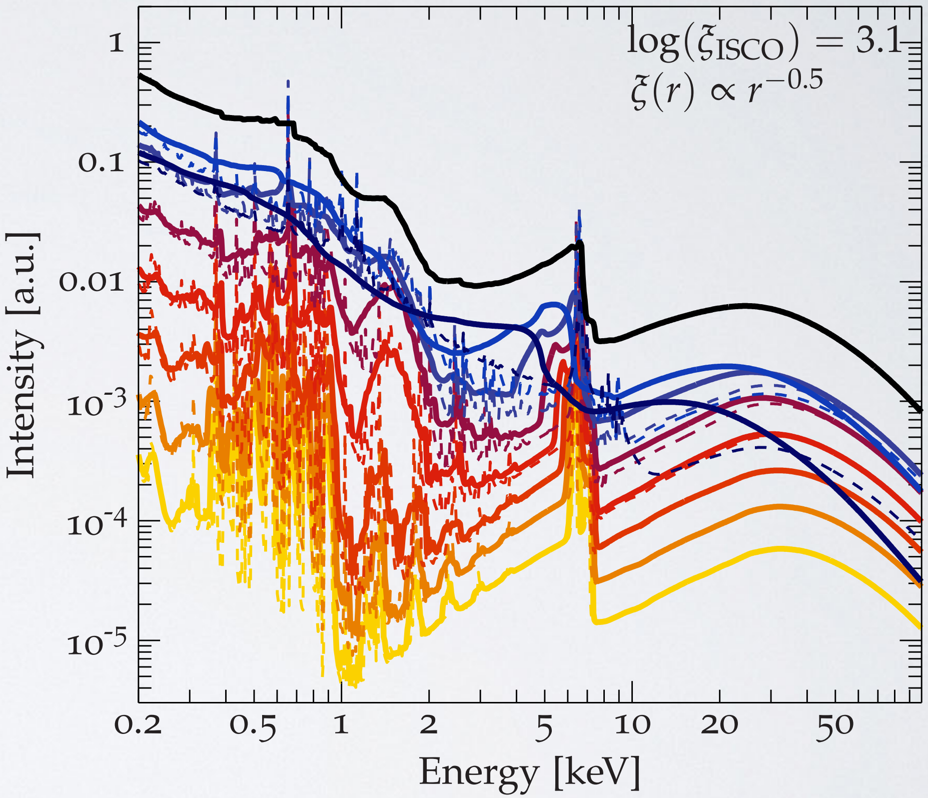




RELXILL: Radial Ionization Gradients

If the lamppost model is accepted, we must then consider the possibility of large ionization gradients in the radial direction.

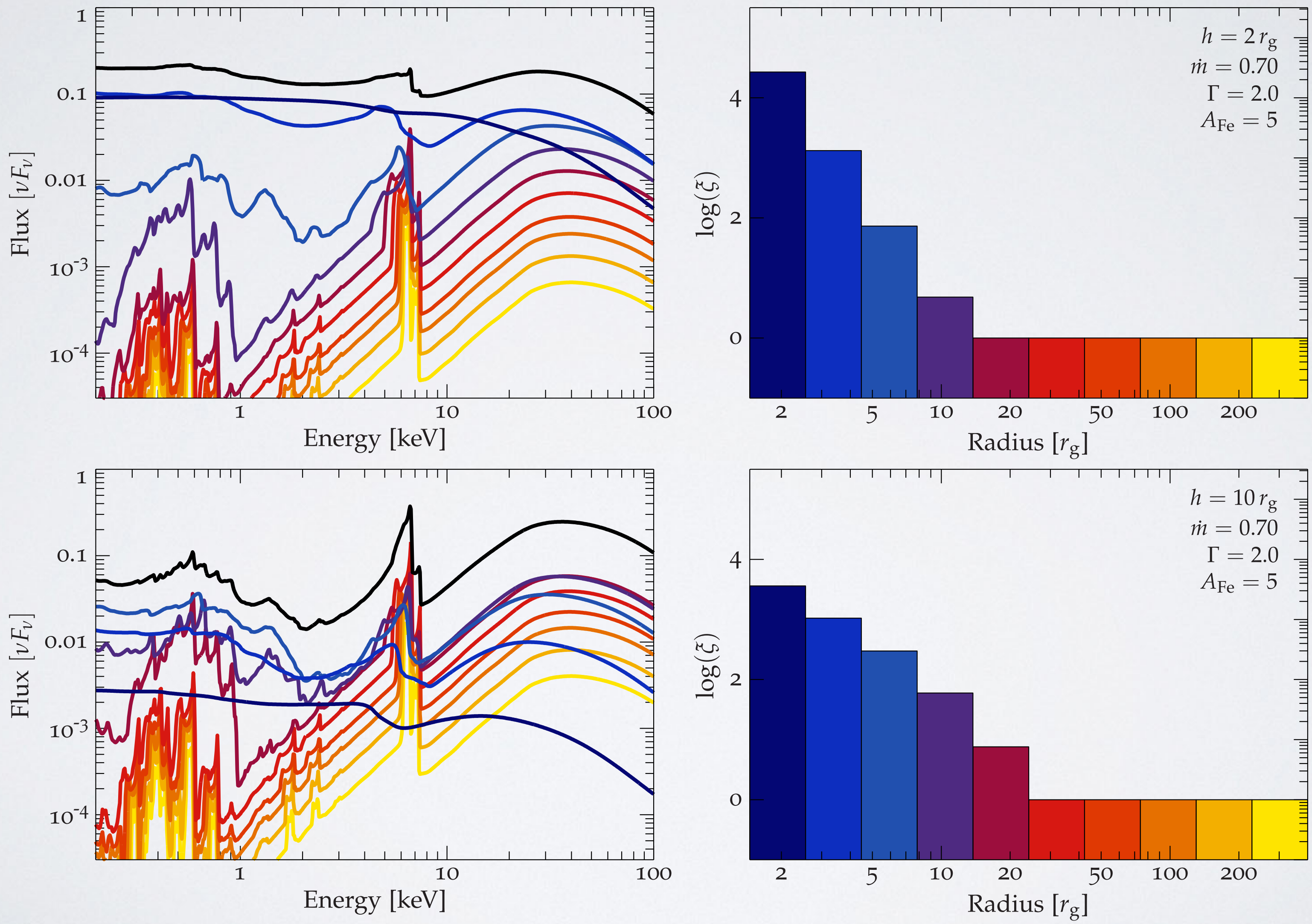




The profile of the gradient will depend not only on the illumination (prescribed by the lamppost) but also on the density profile, which is not well known.

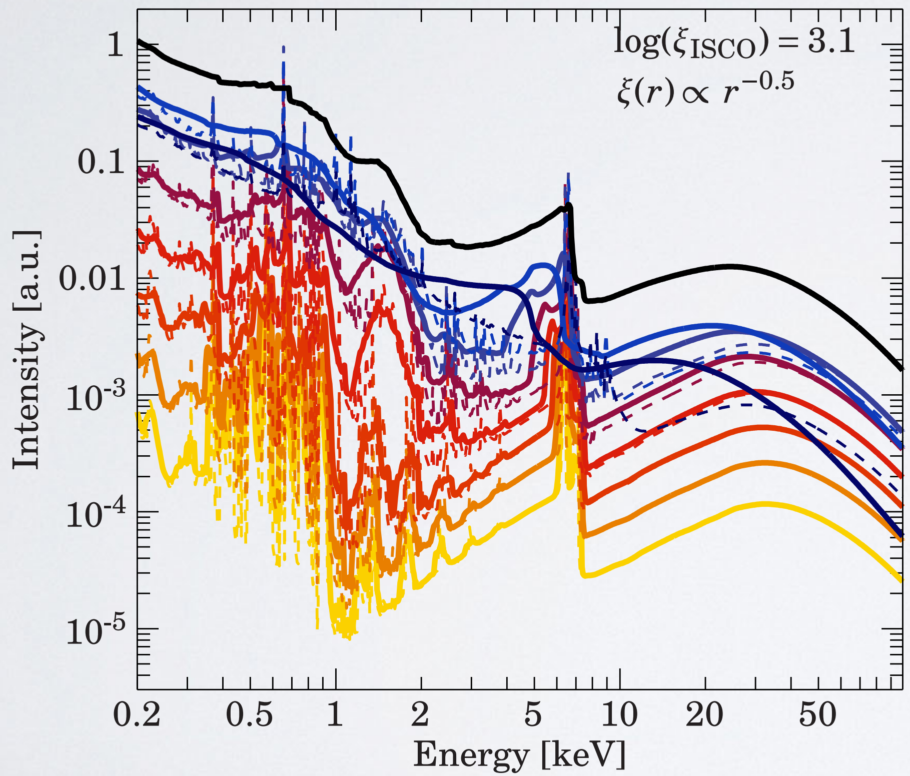
RELXILL: Radial Ionization Gradients

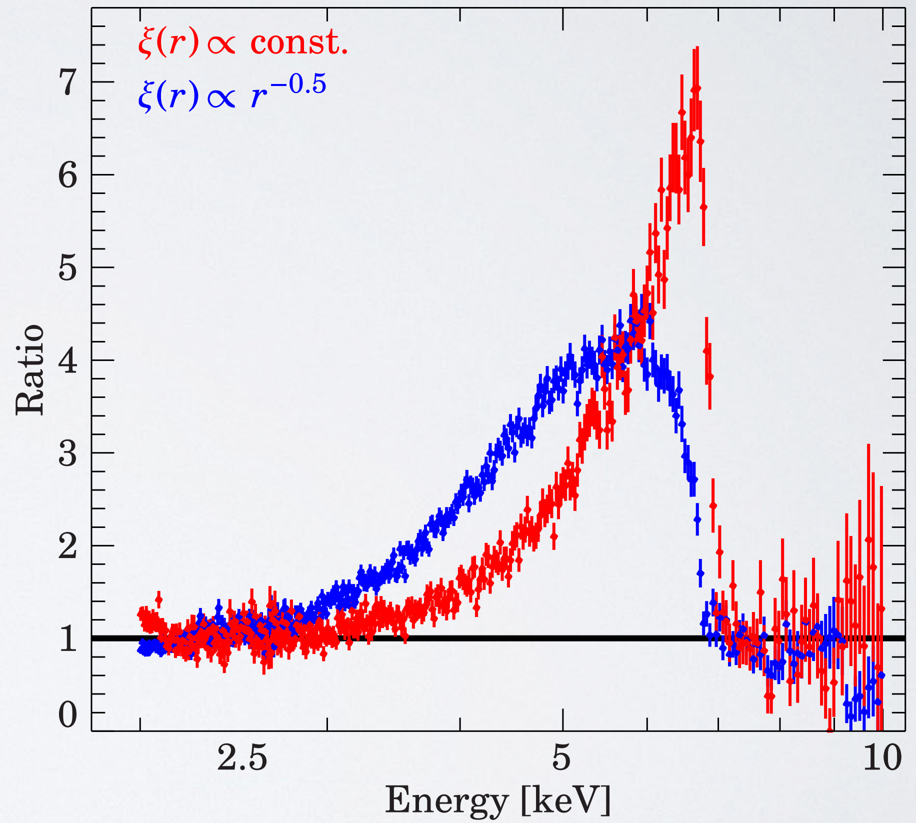
A much more complex Fe K emission profile is expected —> Soft energies are also affected



RELXILL: Radial Ionization Gradients

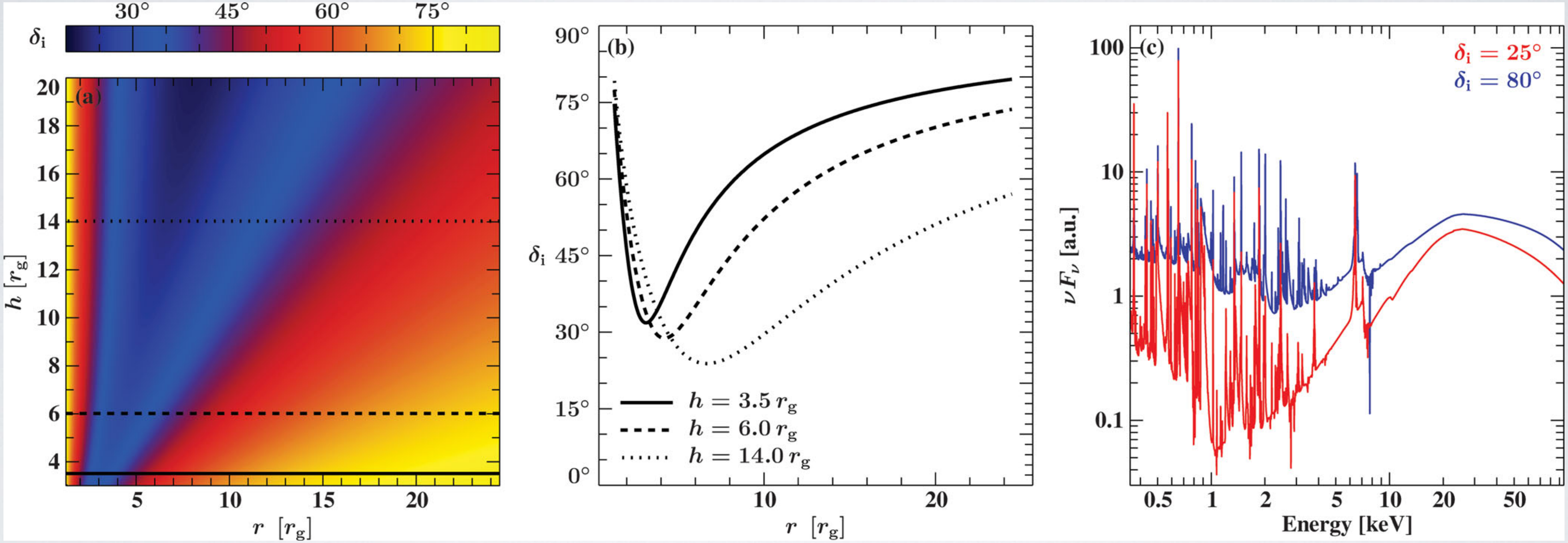
But so far, no real observations have been fitted with this model (relxill_ion). It appears that most sources agree with a single ionization zone, which points to a very concentrated and focused illumination —> Extreme cases are the brightest!





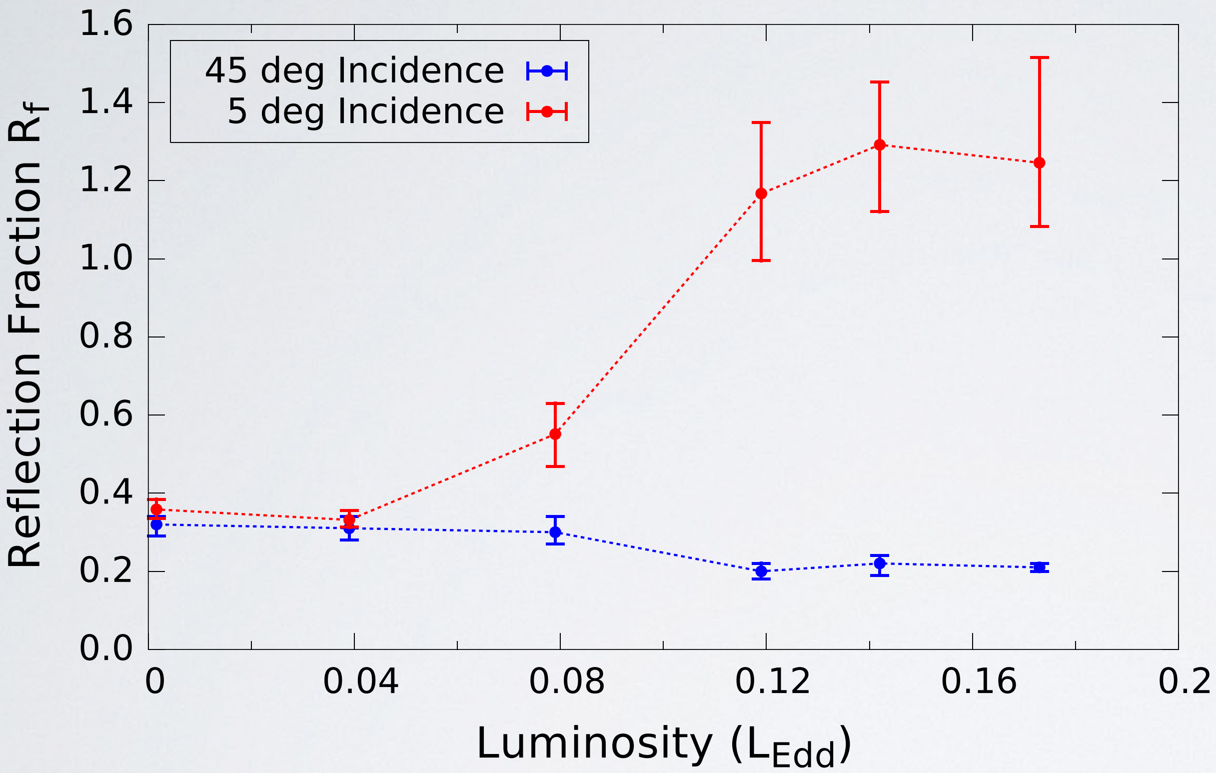
RELXILL: Incidence Angle

Almost any reflection code available today assumes 45 deg incidence for the illuminating photons. This typically OK except when strong GR effects!



Including the incidence angle as a free parameter is expensive in terms of memory, i.e., XILLVER tables can grow 10 times or more… new coding is required.

RELXILL: Incidence Angle



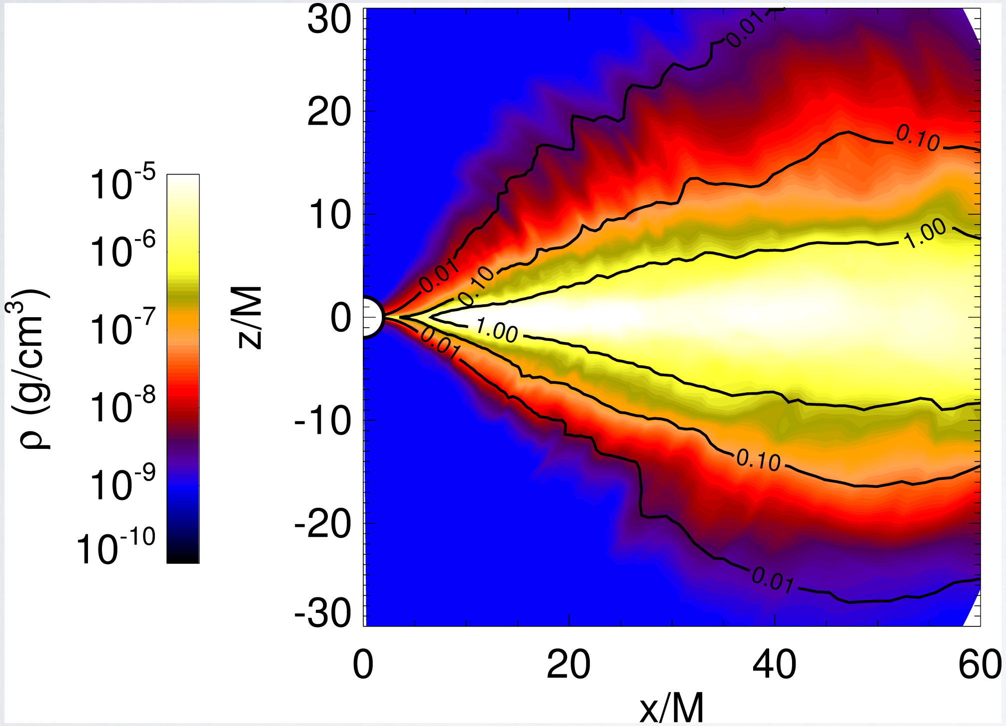
It could have important implications in predicting the right reflection fraction, which is typically much lower than excepted (particularly in BHBs)

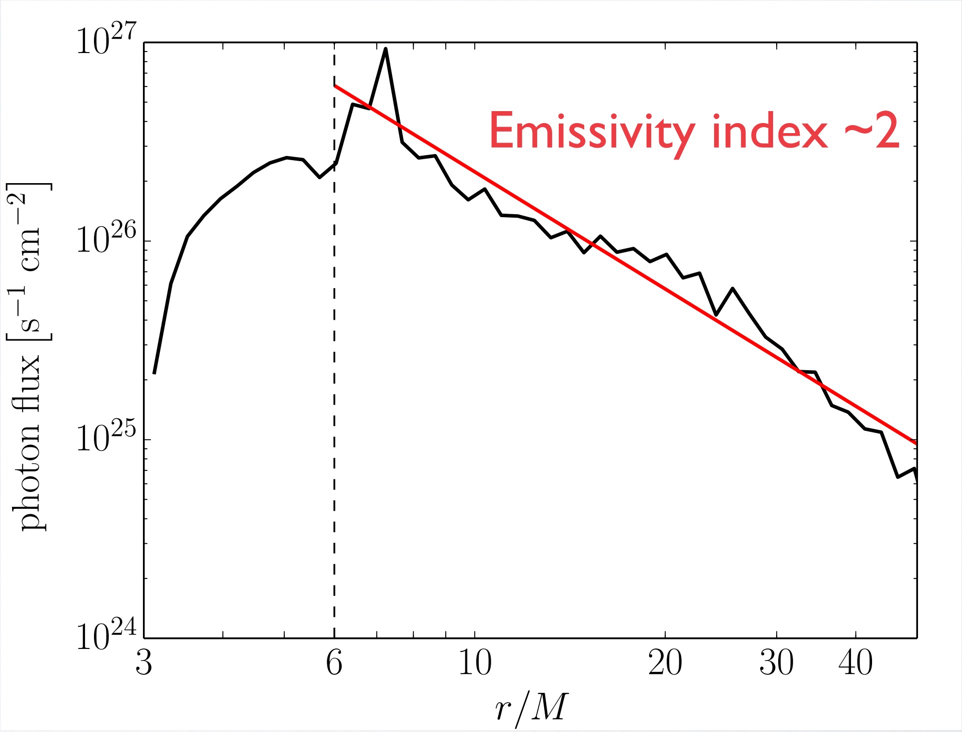
But low Rf can also be due to complex geometry, outflowing corona, disk structure, or extra Comptonization

In the case of GX 339-4, by simply changing from 45deg to 5deg incidence in the models, the reflection fraction increased to more expected values (Rf ~ 1) and it shows a more sensible trend with luminosity! (Garcia et al. 2015)

RELXILL: Connection with AD models

Connecting reflection calculations with GR-MHD models is very challenging but possible —> provides a physically consistent picture for accreting Ohs

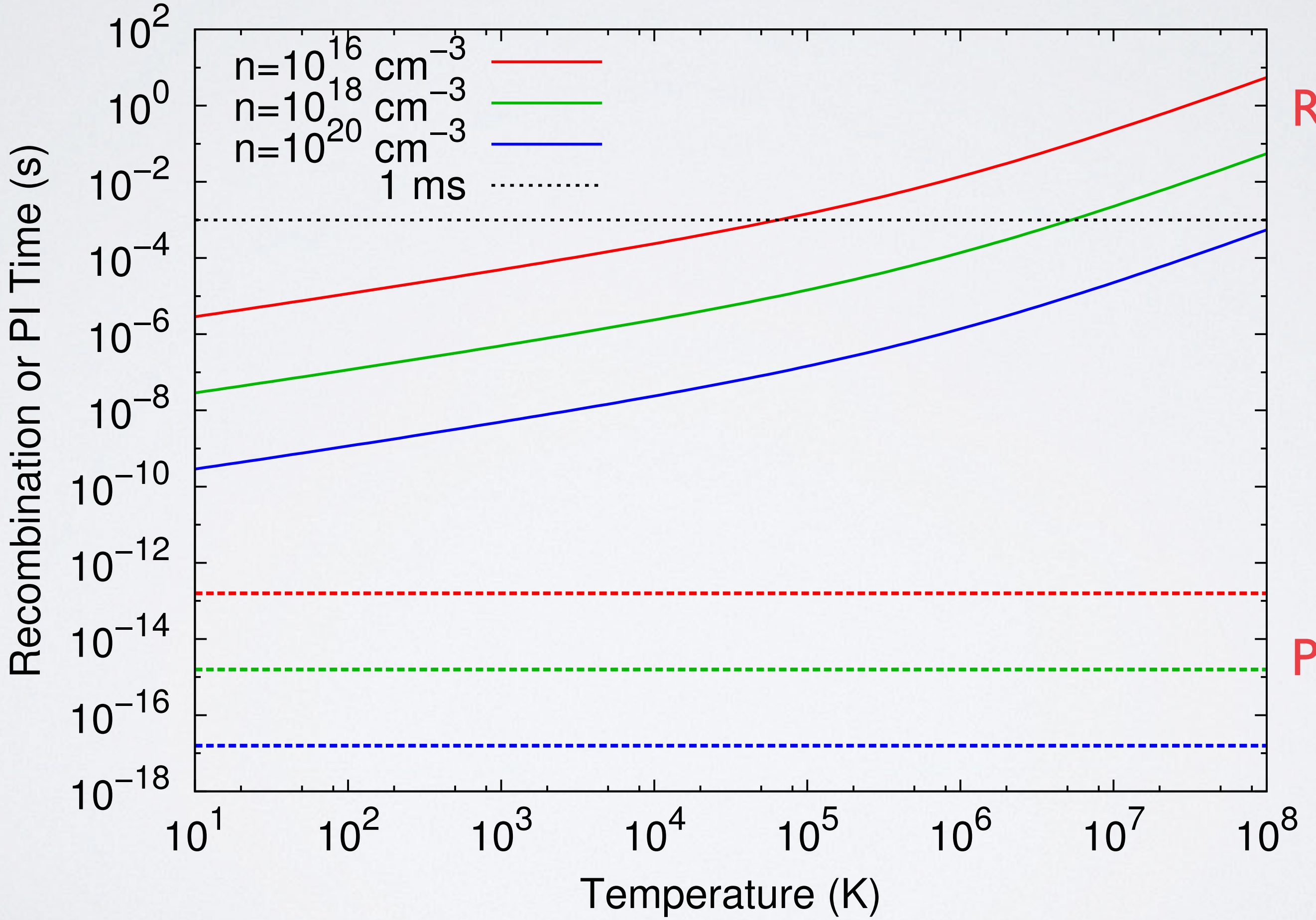




Kinch et al. (2016)

Time-Dependent Photoionization

Typically TDP is neglected at high-densities. However, for sufficiently short times it is possible to see some of the effects. Any current reflection model neglects TDP.



Garcia et al. (2013)