X-ray Reflection Modeling in the Era of High-Resolution Spectroscopy

Javier A. García
NASA Goddard Space Flight Center

@Cathrinmachin

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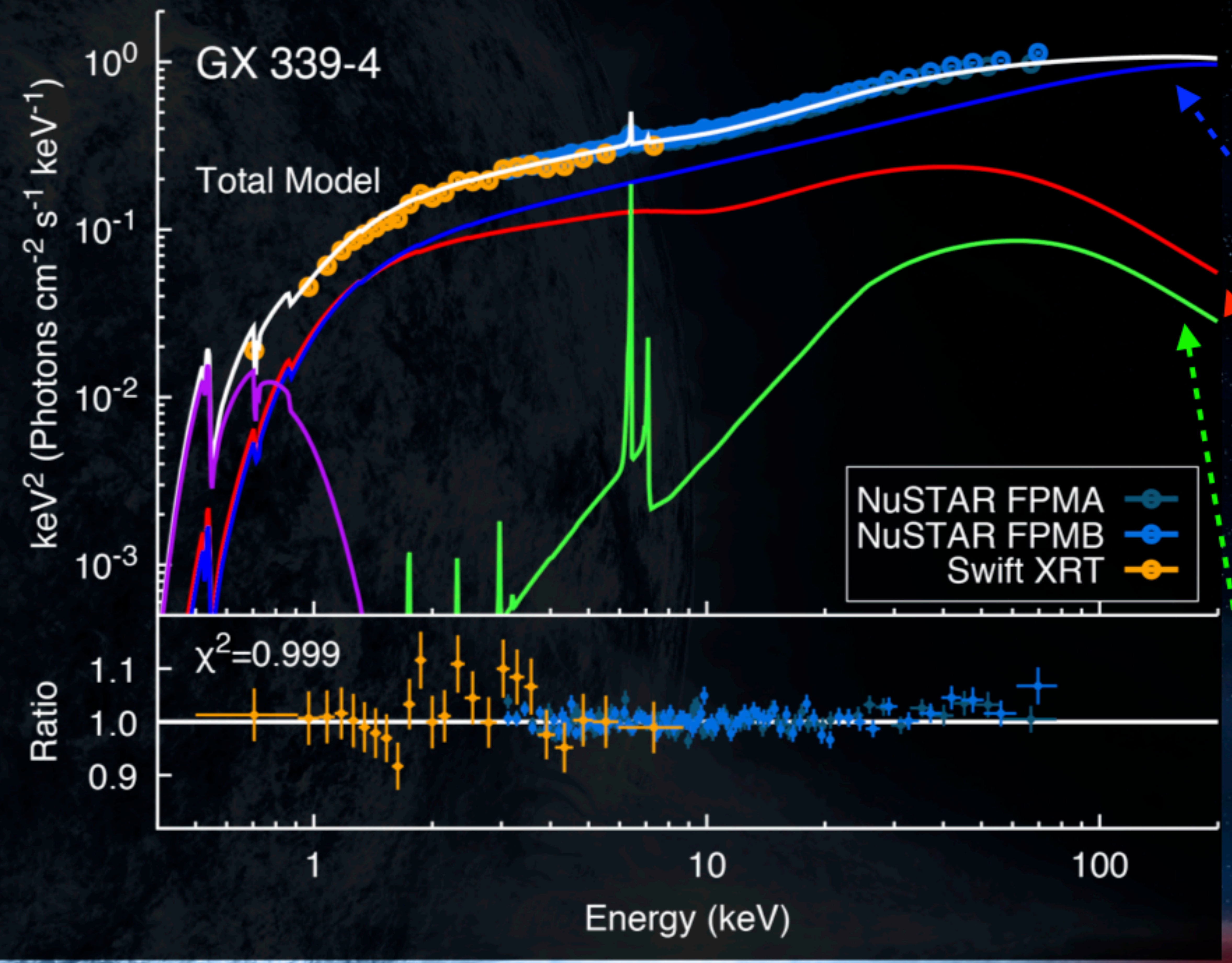
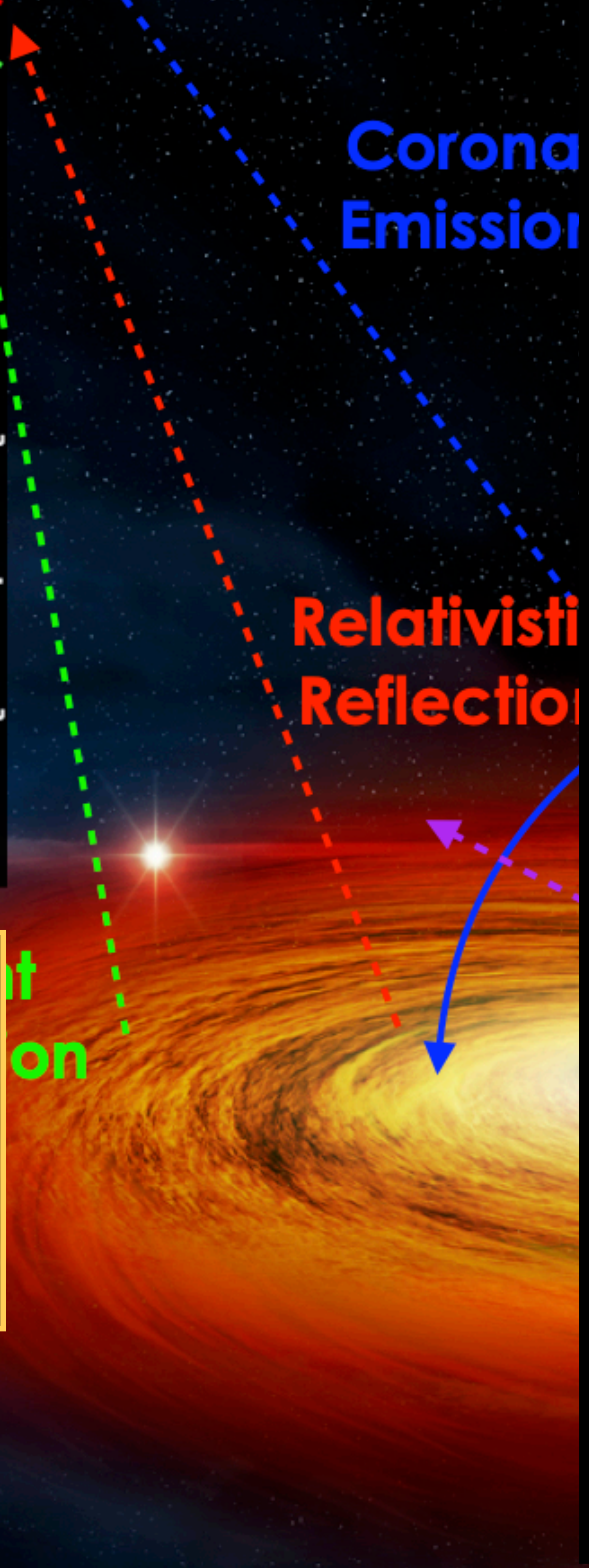
MIT, Cambridge, MA—Aug 1, 2023

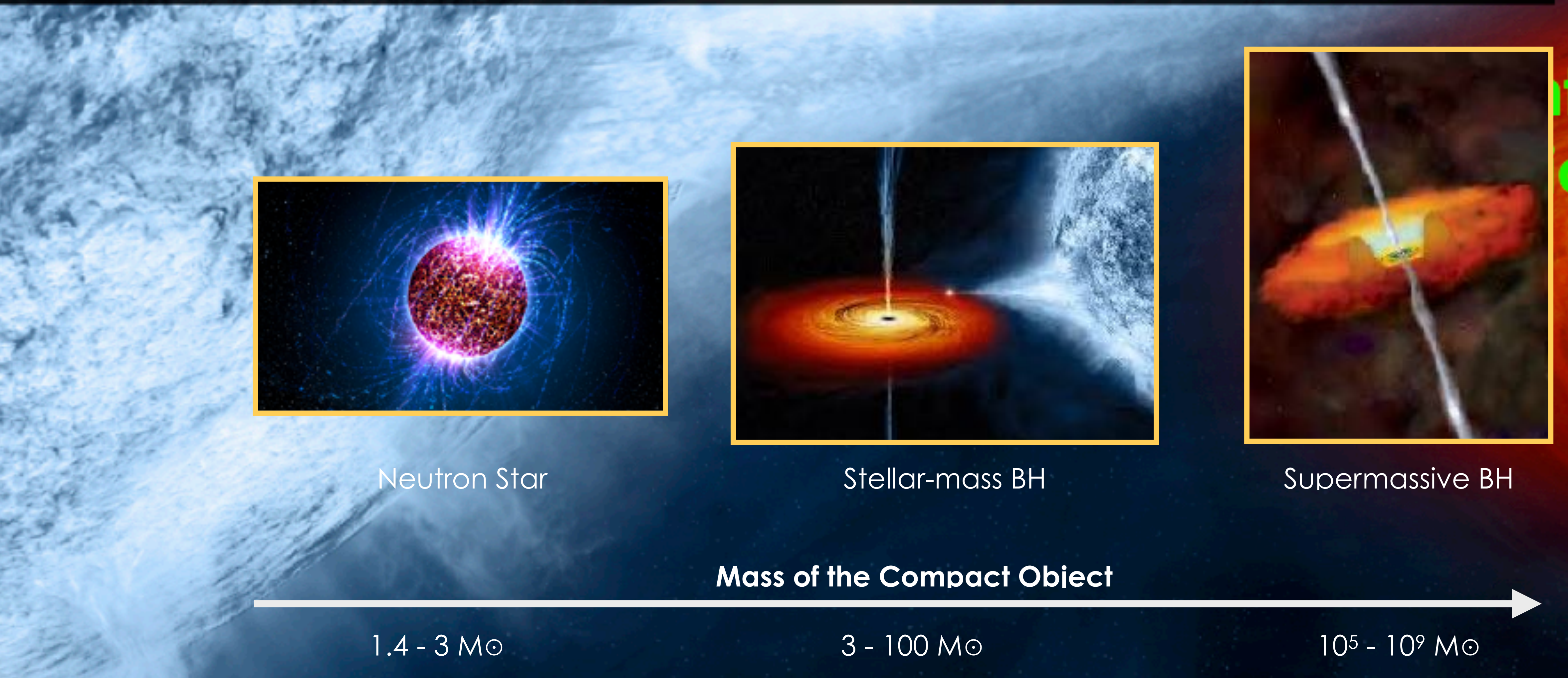
X-ray Reflection Spectroscopy

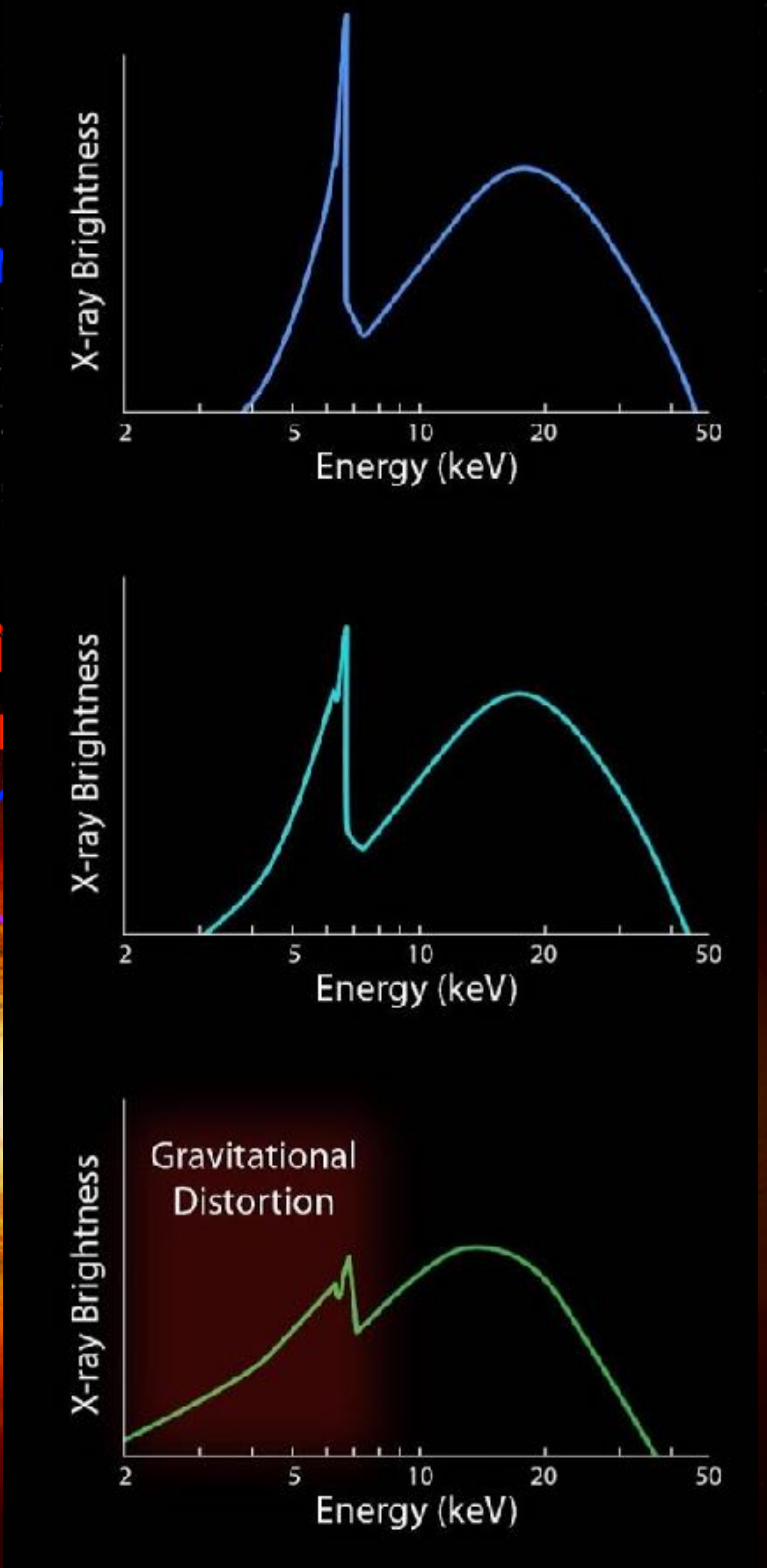

X-ray Reflection Spectroscopy
GX 339-4
Total Model
keV^2 (Photons cm^{-2} s^{-1} keV^{-1})
10^0
10^{-1}
10^{-2}
10^{-3}
NuSTAR FPMA
NuSTAR FPMB
Swift XRT
χ^2=0.999
Ratio
1.1
1.0
0.9
1
10
100
Energy (keV)
Corona
Emissio
Relativisti
Reflectio
Distant
Reflection
X-ray Brightness
2
5
10
20
50
Energy (keV)
Gravitational
Distortion
Faster BH
rotation
Stronger
Relativistic
Distortion

X-ray Reflection Spectroscopy





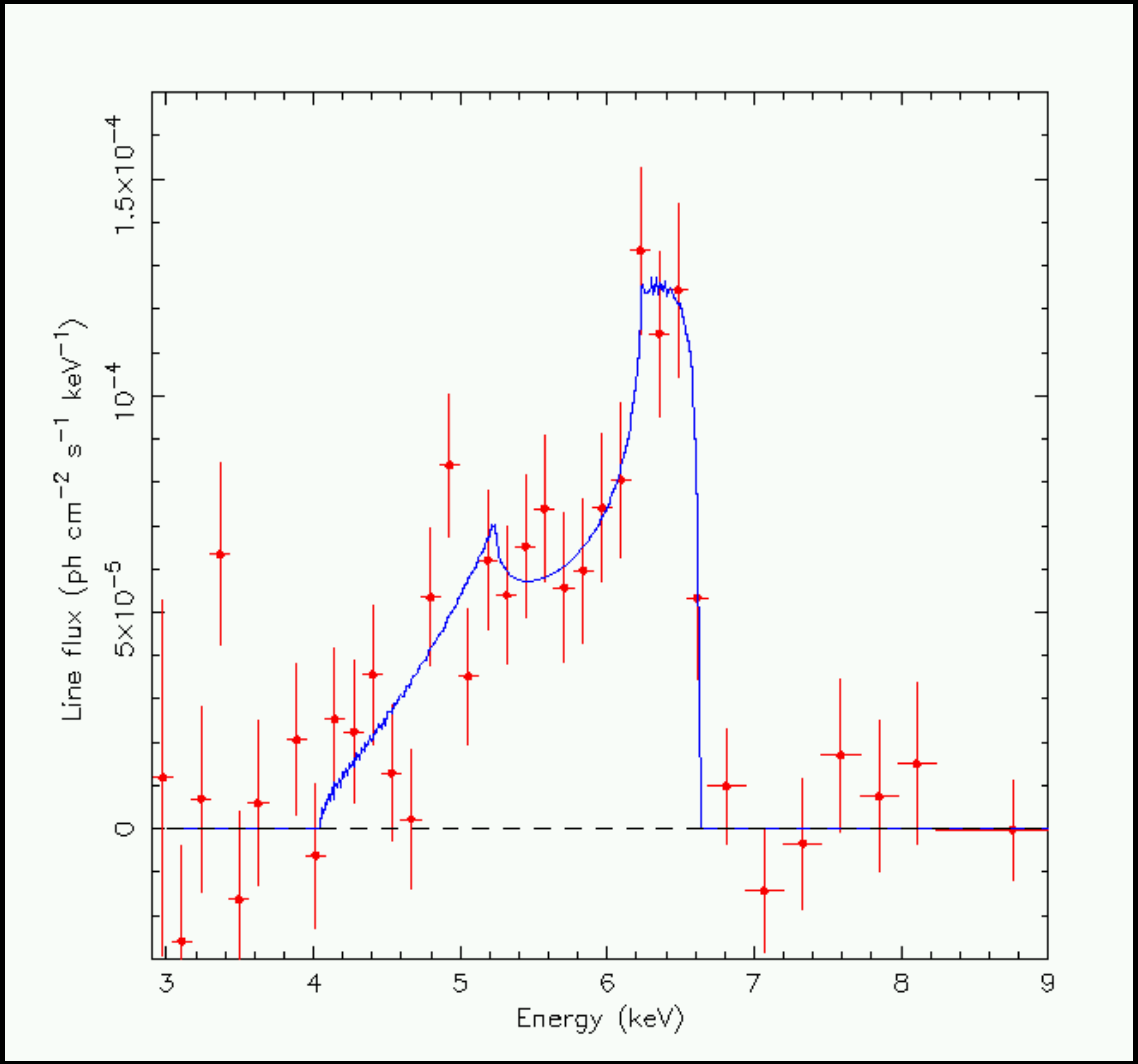




Faster BH rotation

Stronger Relativistic Distortion

First Detections of X-ray Reflection



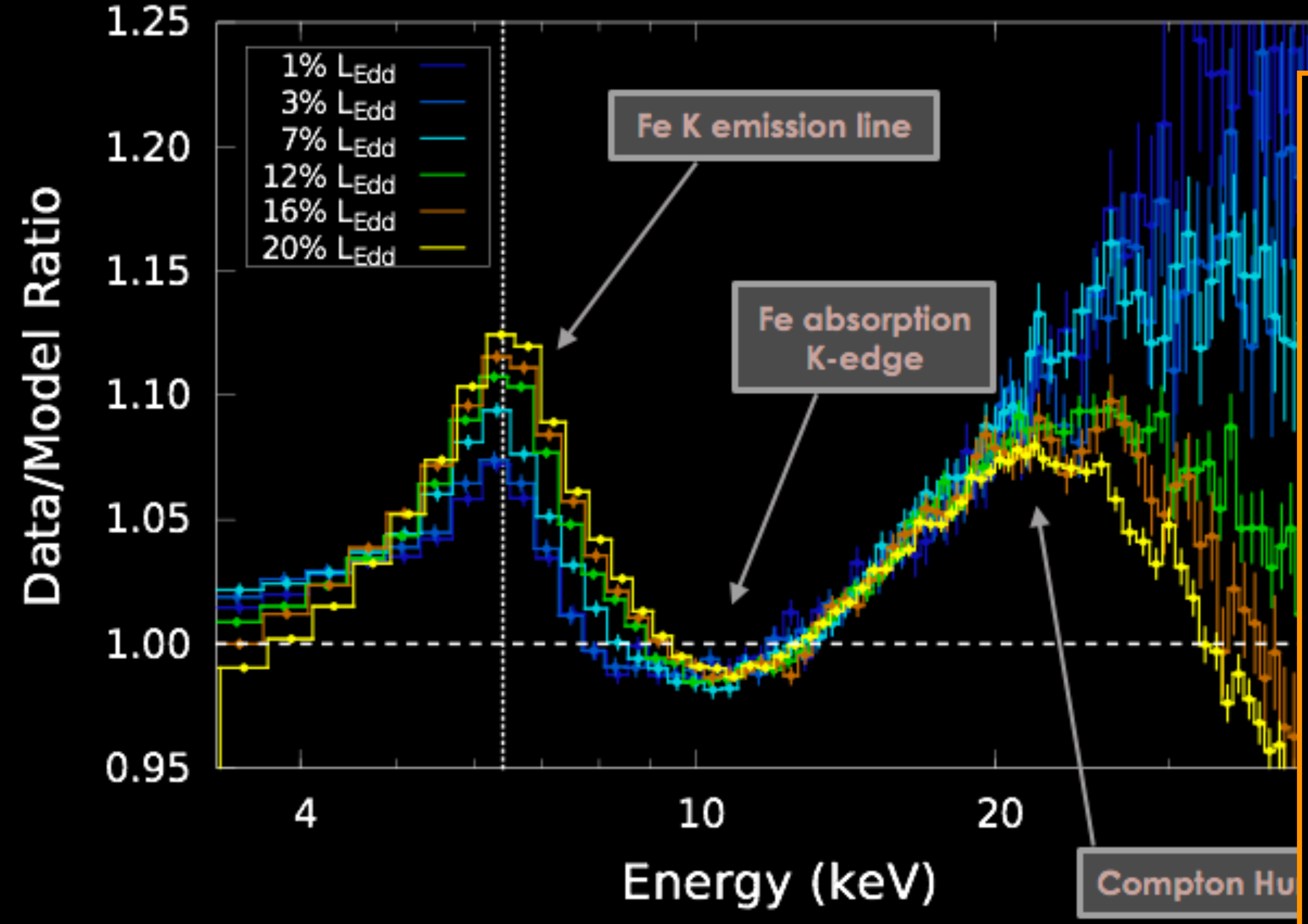
1990's: *ROSAT, ASCA*. First CCDs flying on X-ray observatories. First detections of a distorted Fe K line, which was interpreted as emission affected by relativistic effects near the BH (Tanaka et al. 1995; Nandra et al. 1997; Fabian et al. 2000).

The line profile of iron K-alpha from MCG-6-30-15 observed by the ASCA satellite (Tanaka et al. 1995)

Resolution 0.12 keV @ 6 keV

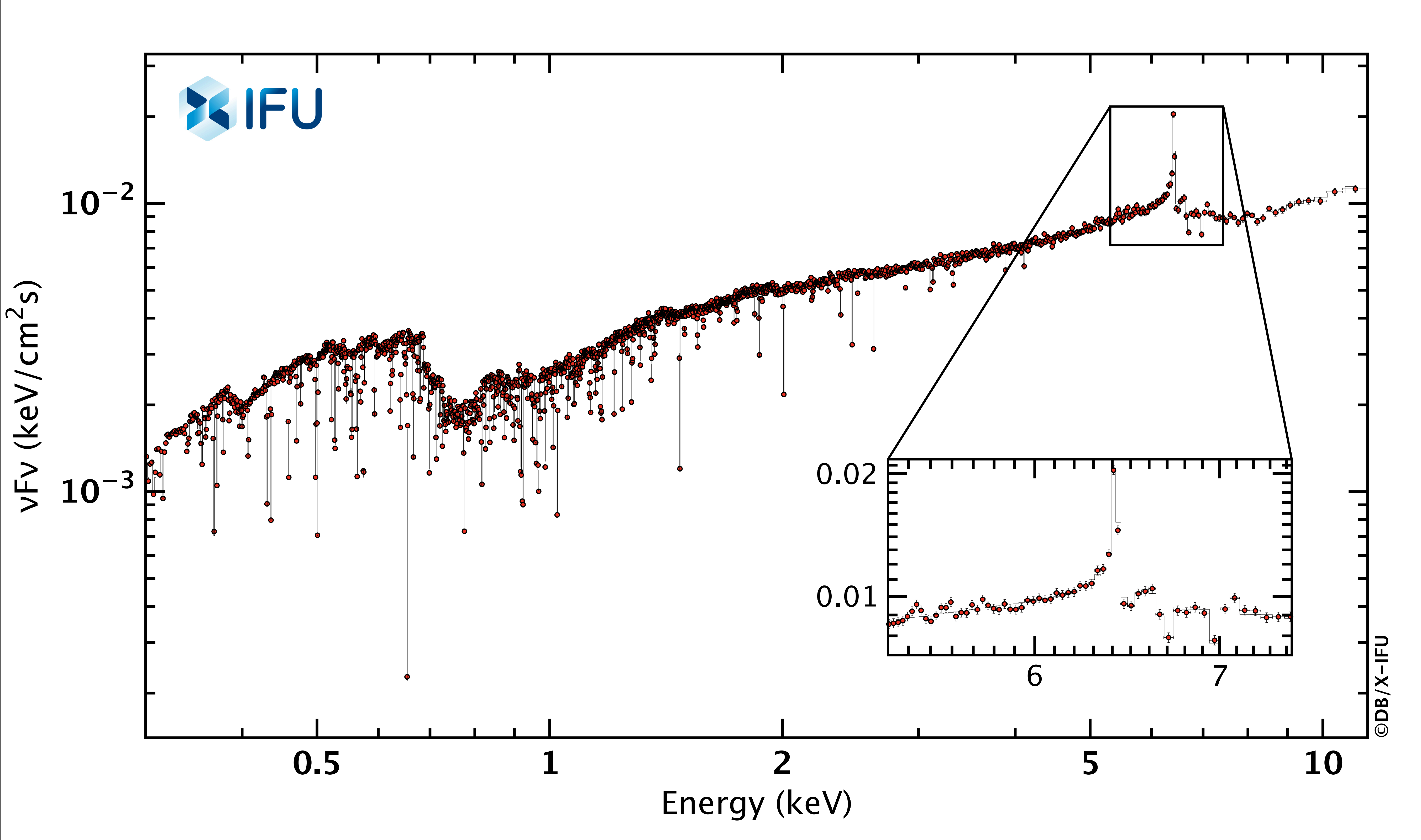
Past, Present, and Future X-ray Detectors

RXTE—Decommissioned in 2012
Resolution 1 keV @ 6 keV



JG+15

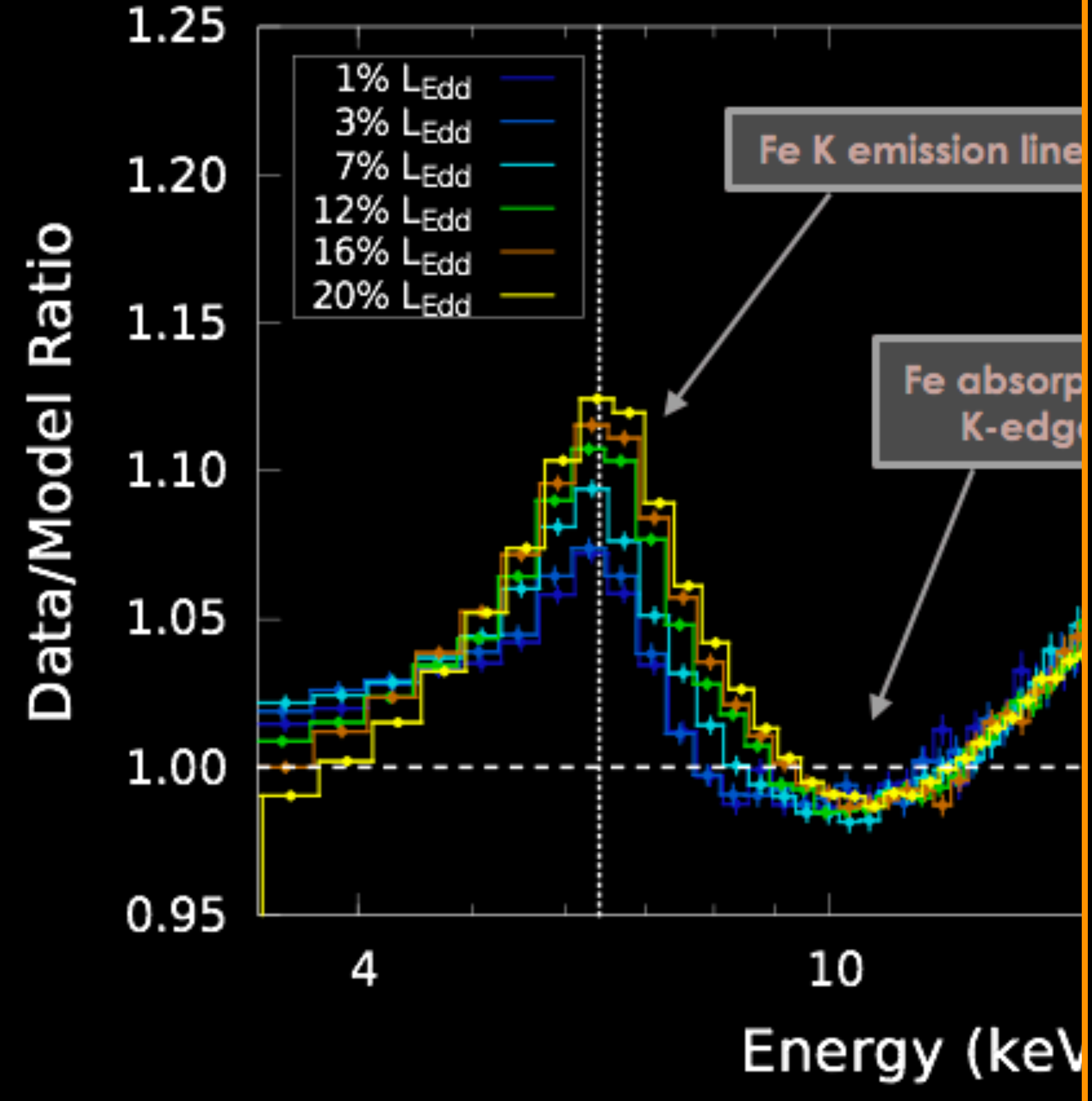
Athena—Expected 2030s
Resolution ~2.5 eV @ 6 keV



Barret & Cappi (2019)

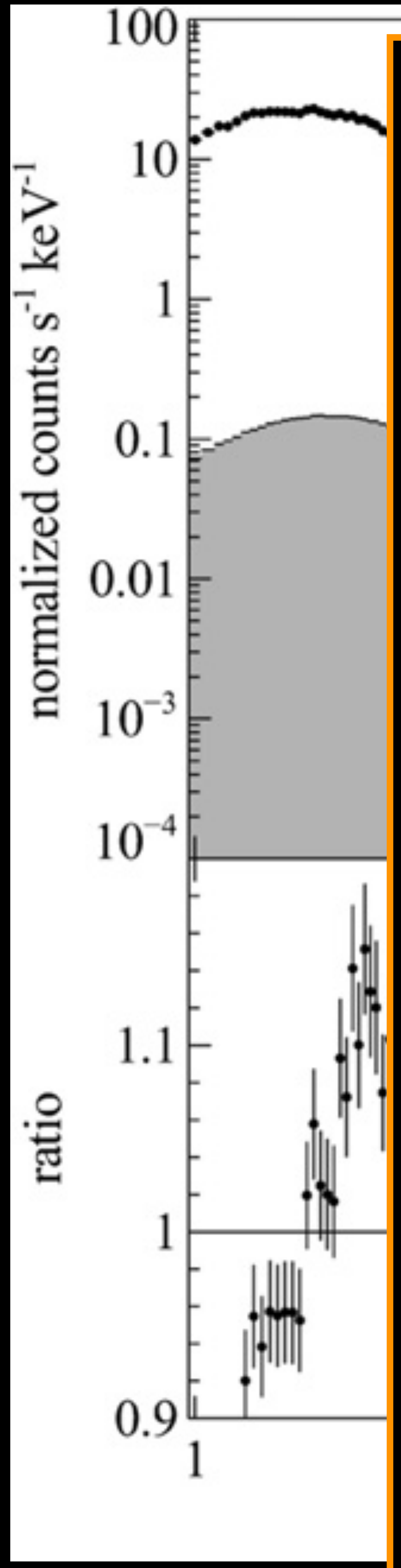
Past, Present, and Future X-ray Detectors

RXTE—Decommission
Resolution 1 keV



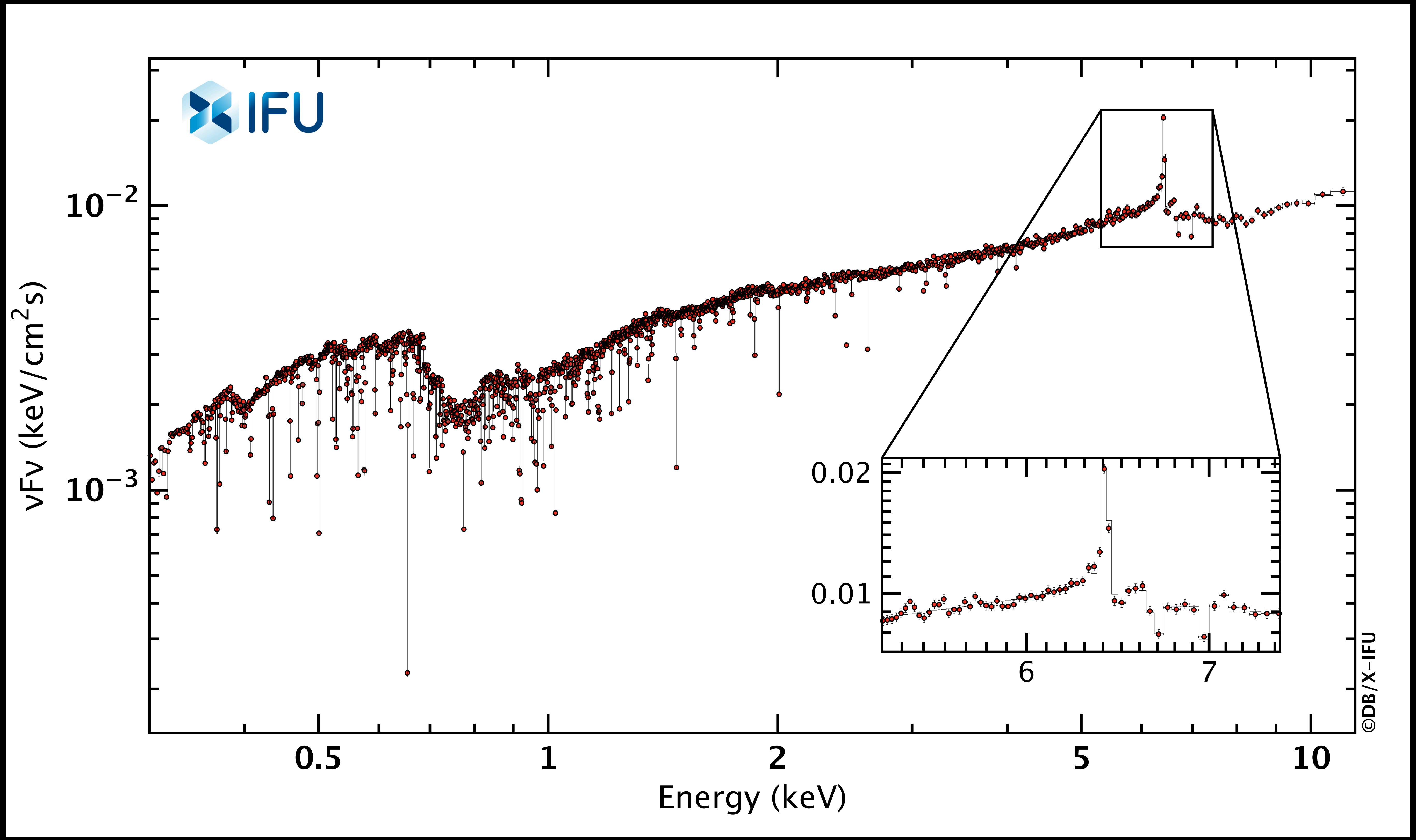
JG+15

NuSTAR—Launched 2012
Resolution 0.4 keV @ 6 keV



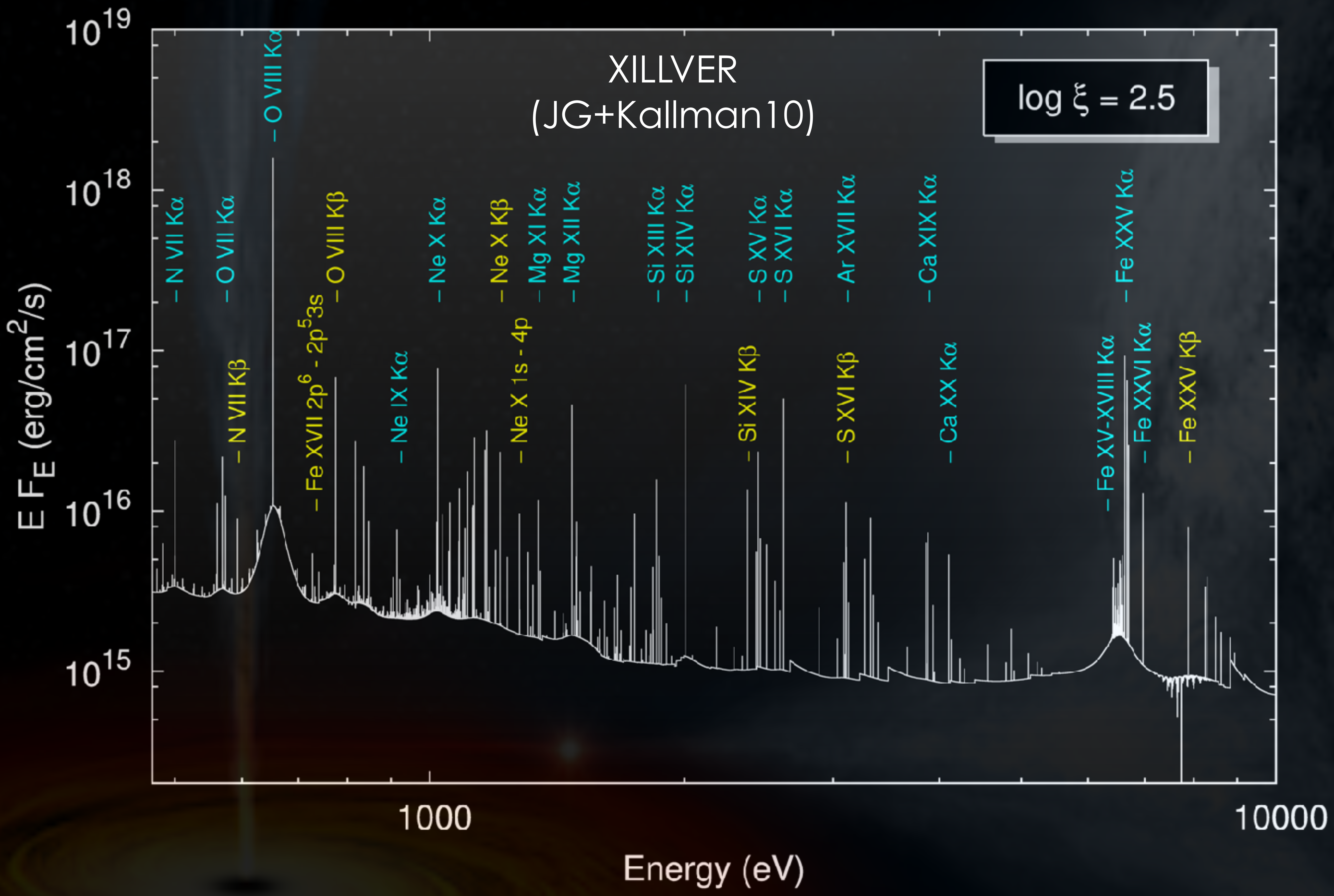
Parker et al.

Athena—Expected 2030s
Resolution ~2.5 eV @ 6 keV



Barret & Cappi (2019)

X-ray Reflection at High-Resolution (~μ-cal)



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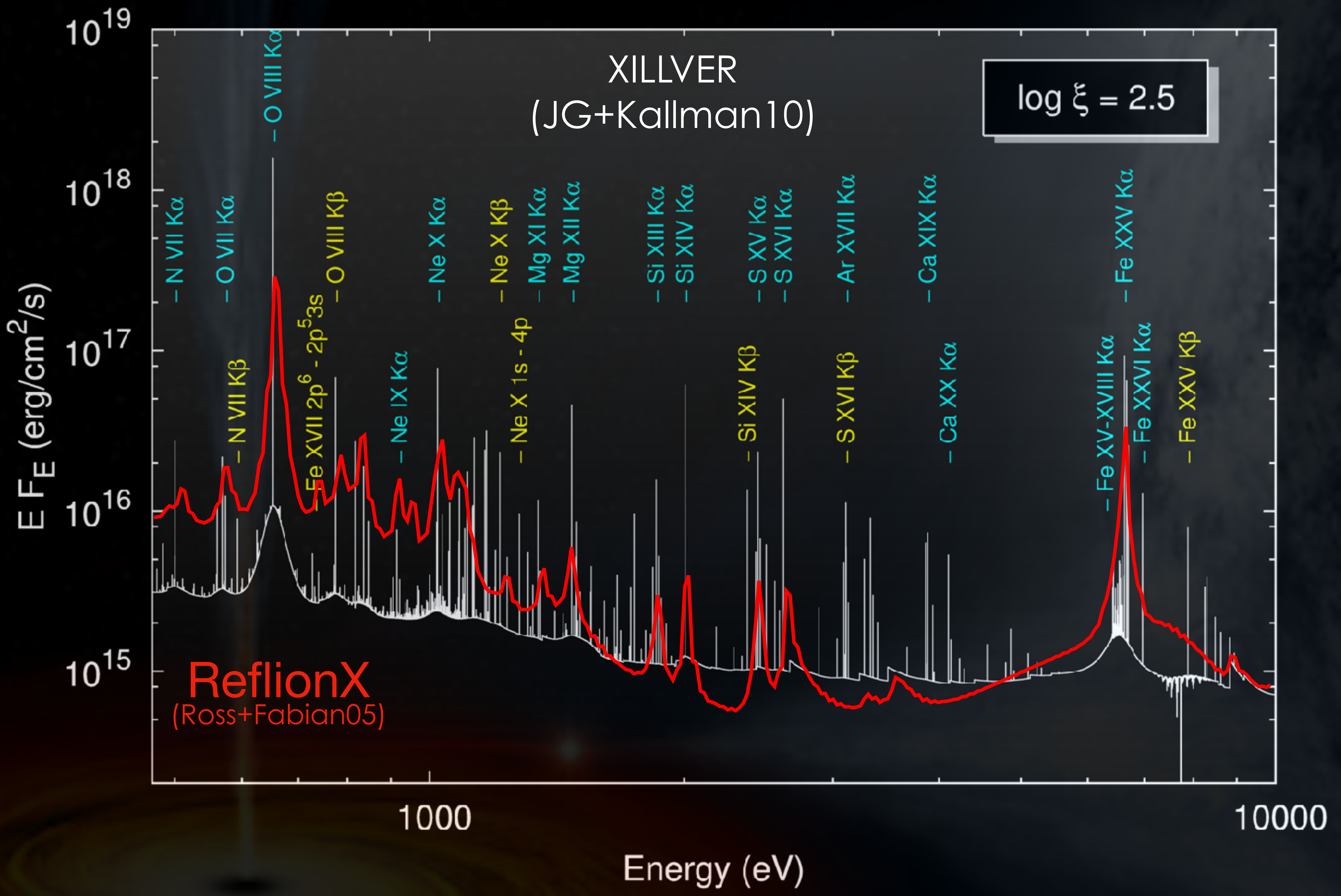
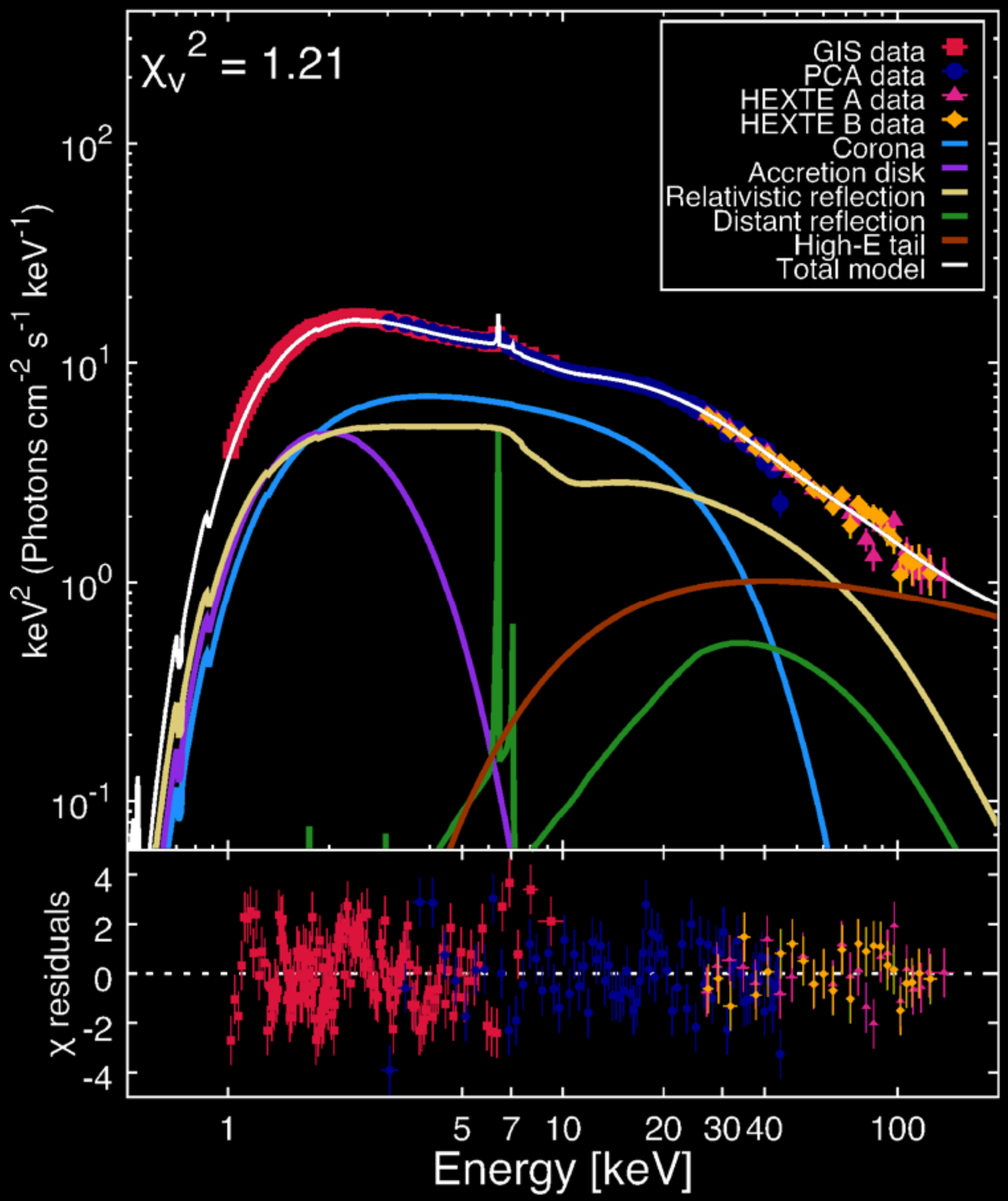
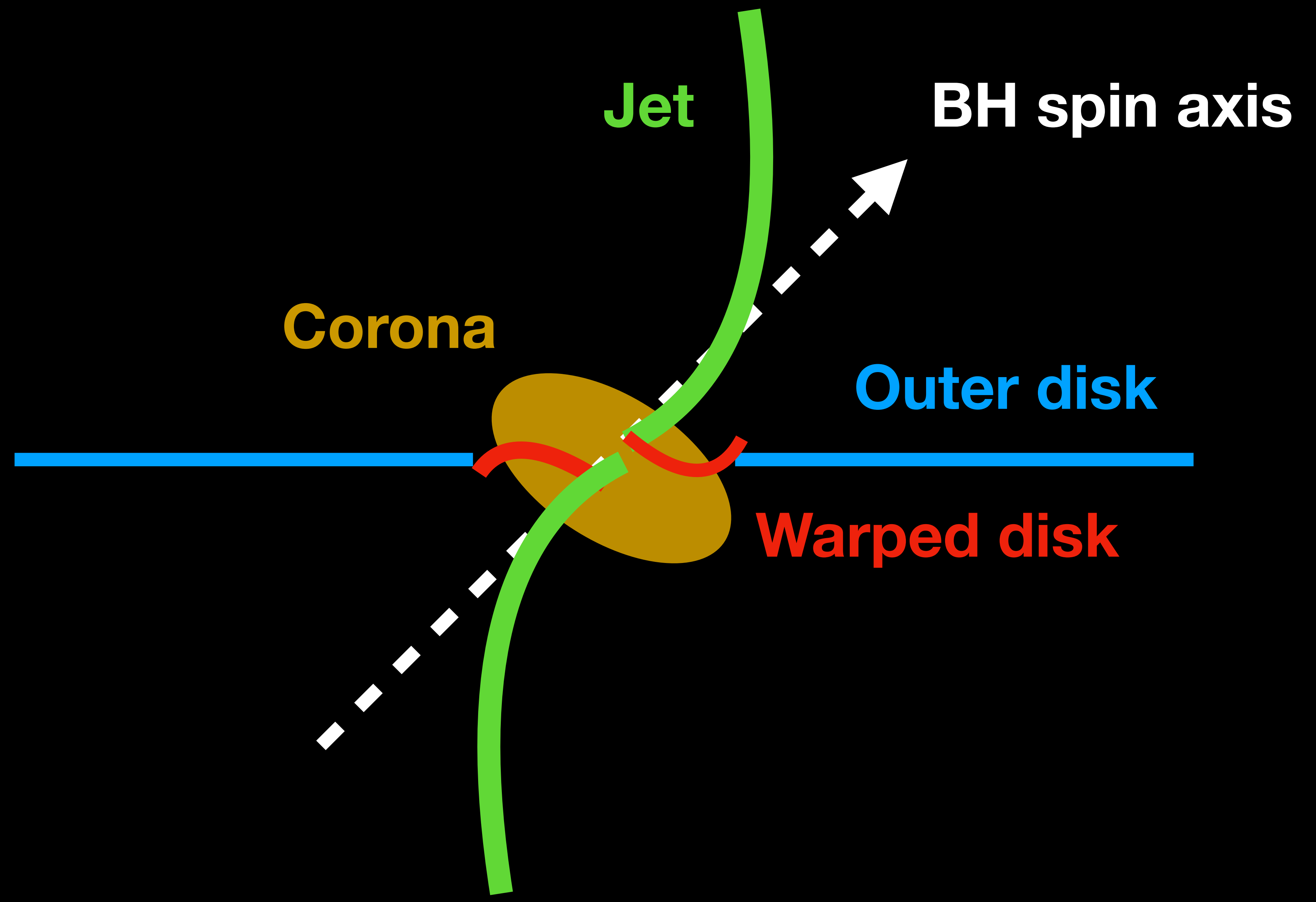


XTE J1550—564: LOW INCLINATION DISK?



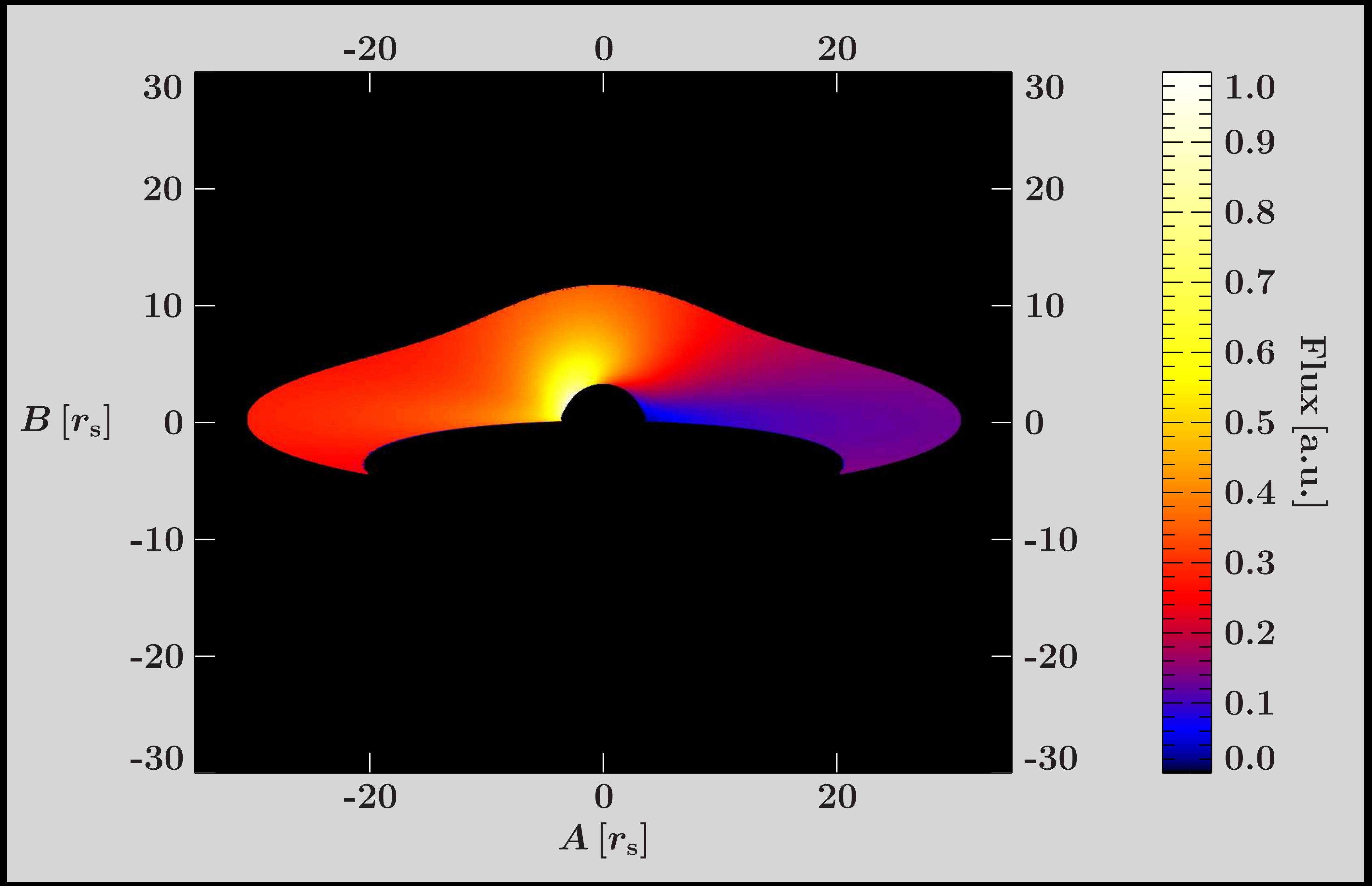
Inclination from reflection modeling inconsistent with radio jet and optical monitoring determinations of the orbital inclination, ***i* ~ 40 deg**, as opposed to ***i* ~ 75 deg** (Orosz et al. 2011, Steiner et al. 2012).



Possible misaligned inner accretion region?

Connors, JG,+19

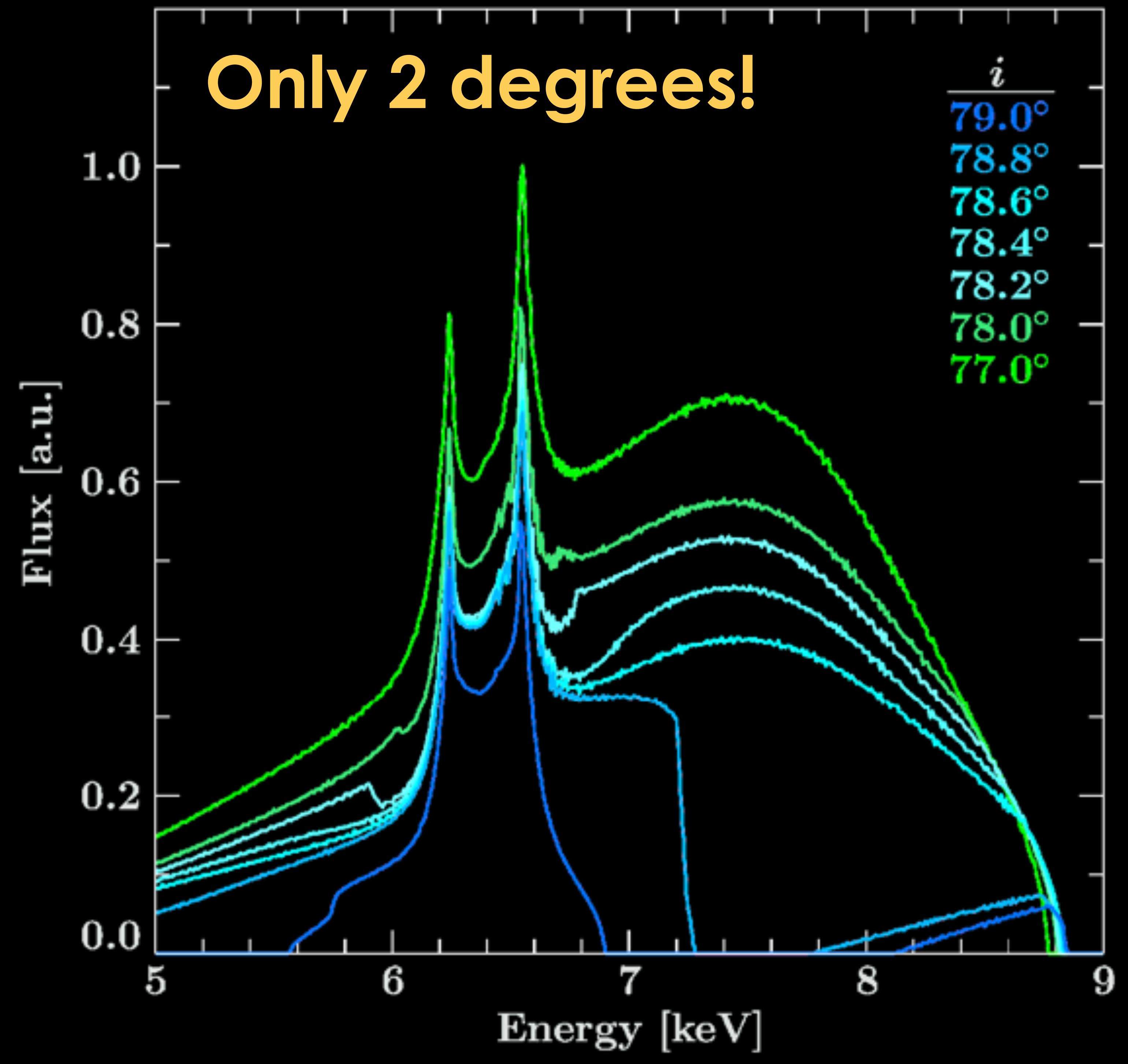
Irradiation of Flared Disks



Brod et al. (2013)

<u>Obscuration effects:</u>

Under an inclination of **78.5°**, part of the disk is covered, affecting both the line profiles and the time lags



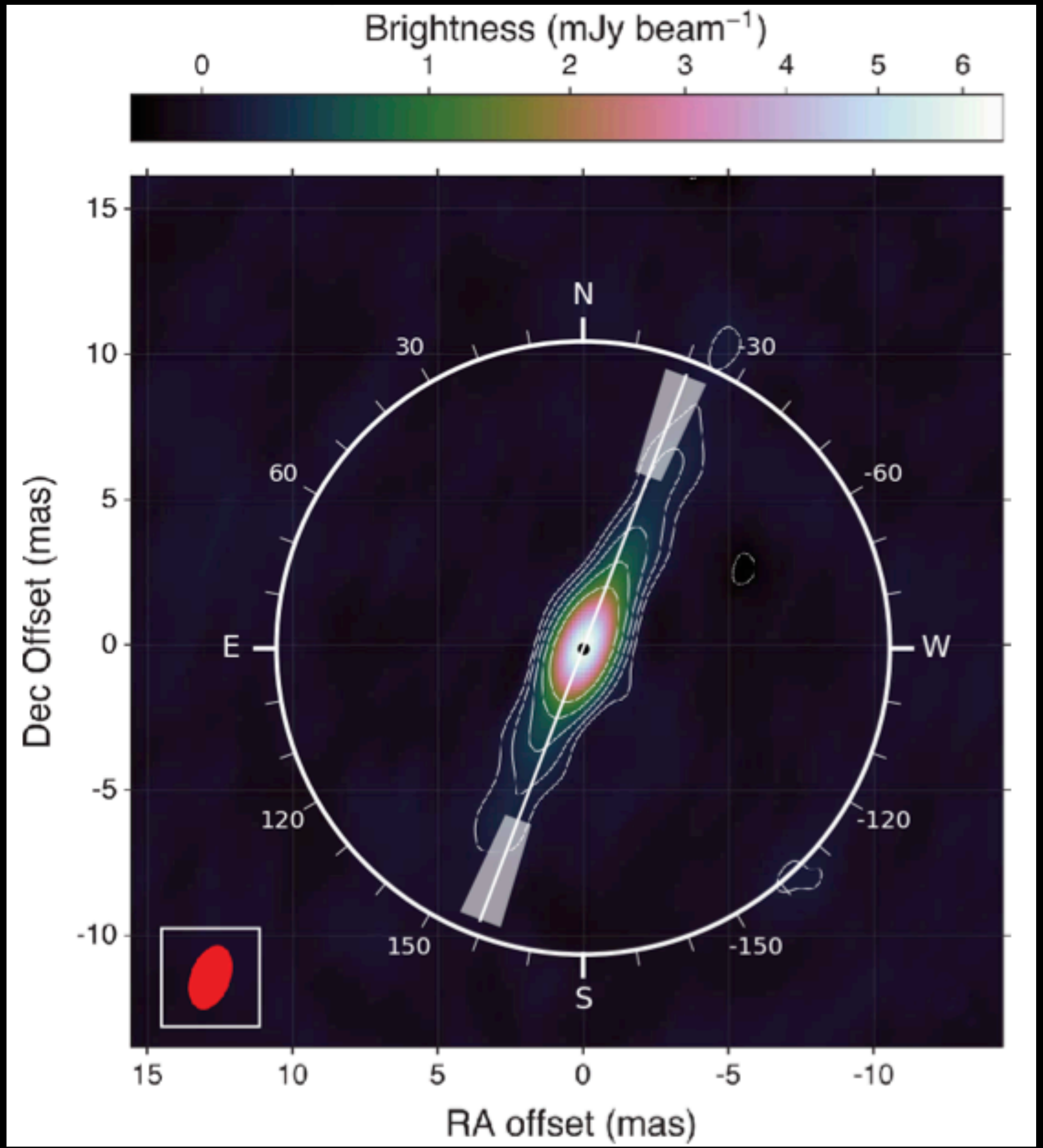
Disk obscuration reduces the blue-wing of the Fe K emission

—> Resembles lower inclination!

X-ray Polarization Measurements: Cyg X-1

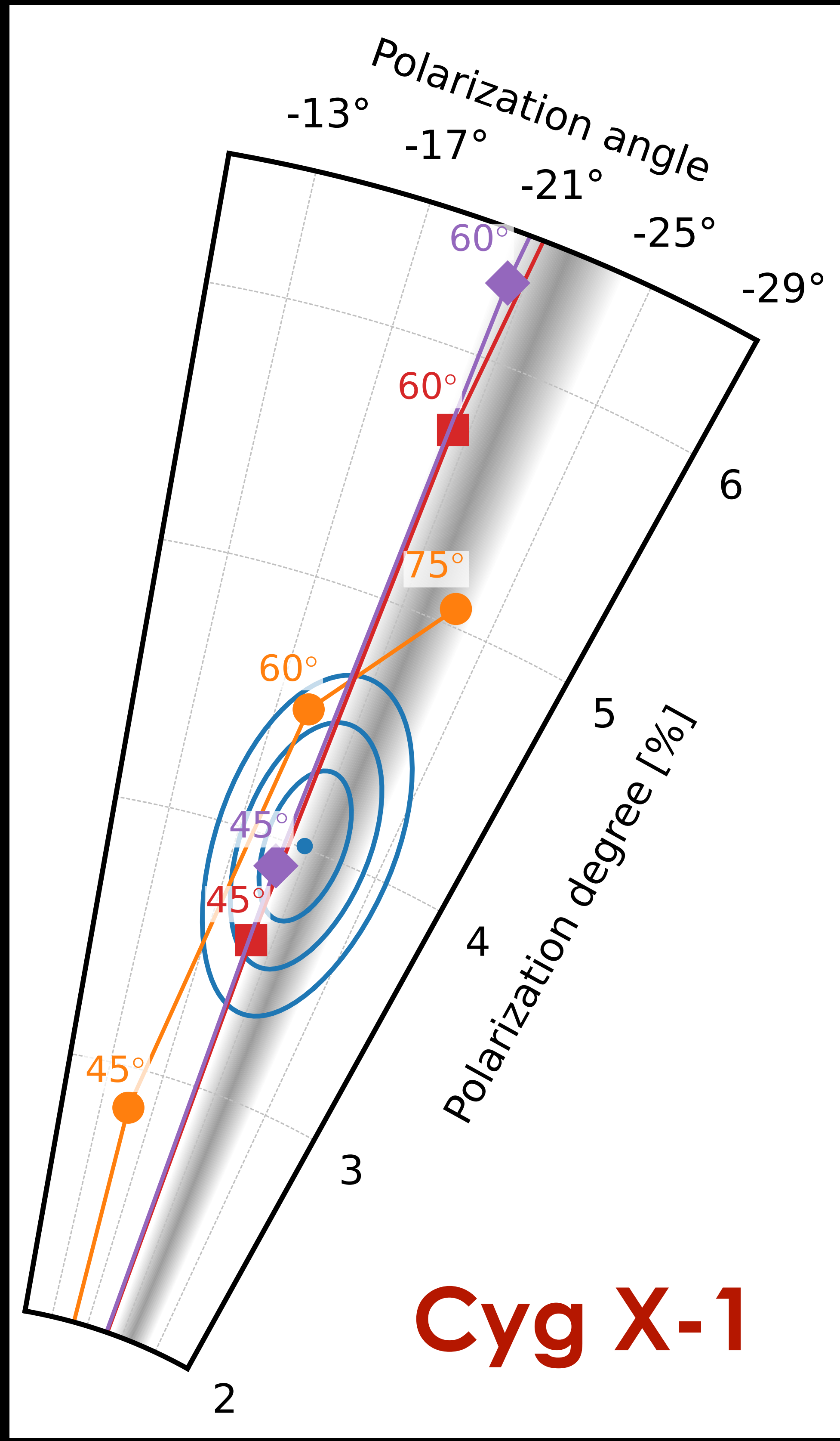
IXPE: The Imaging X-ray Polarimetry Explorer

Polarization angle parallel to the outflowing radio jet



Krawczynski,…,JG+22

Detection of linear polarization degree of 4.0+/- 0.2 % in 2–8 keV (>20 sigma)



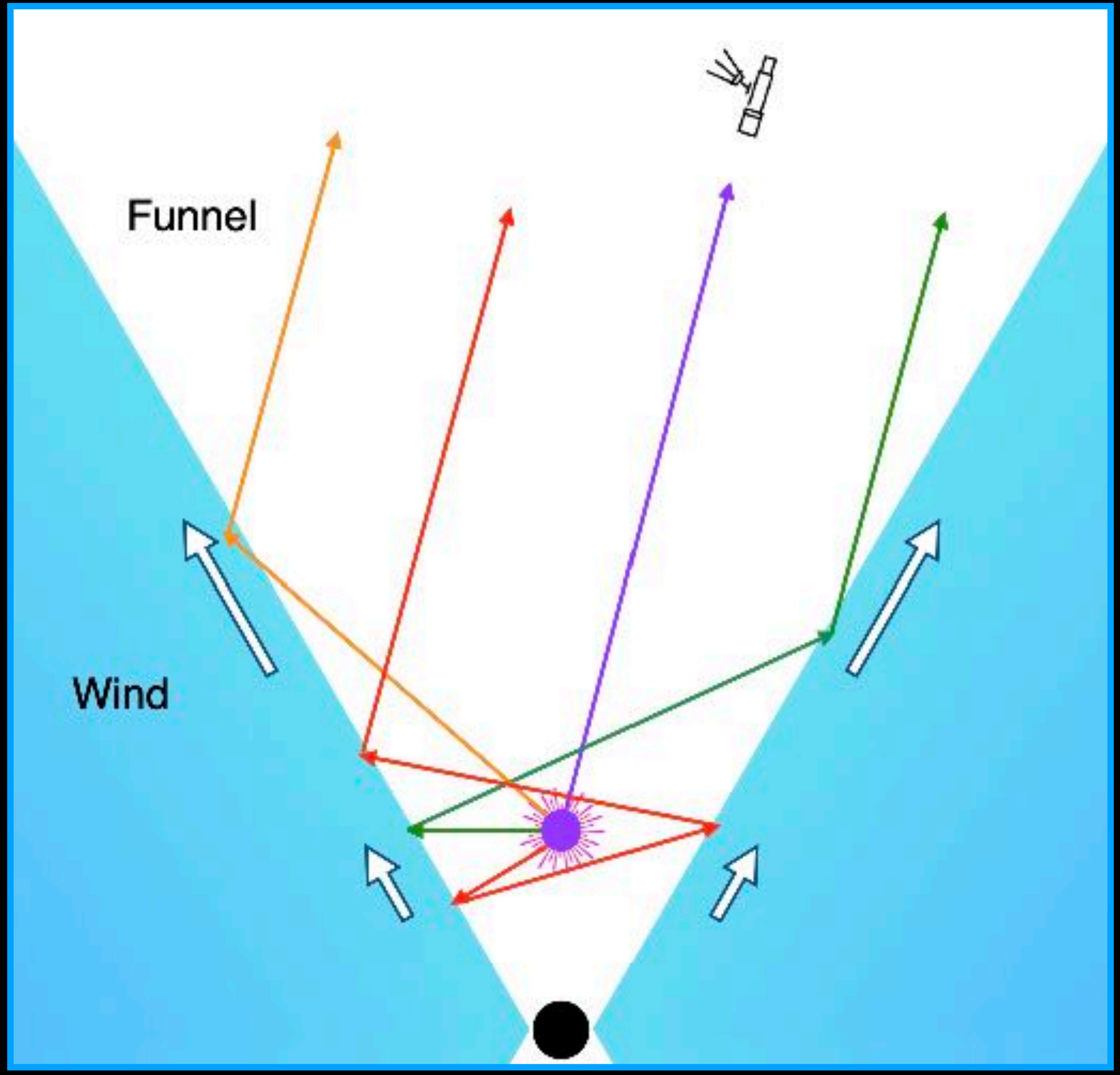
Larger than expected polarization requires a disk inclination larger than the orbit!

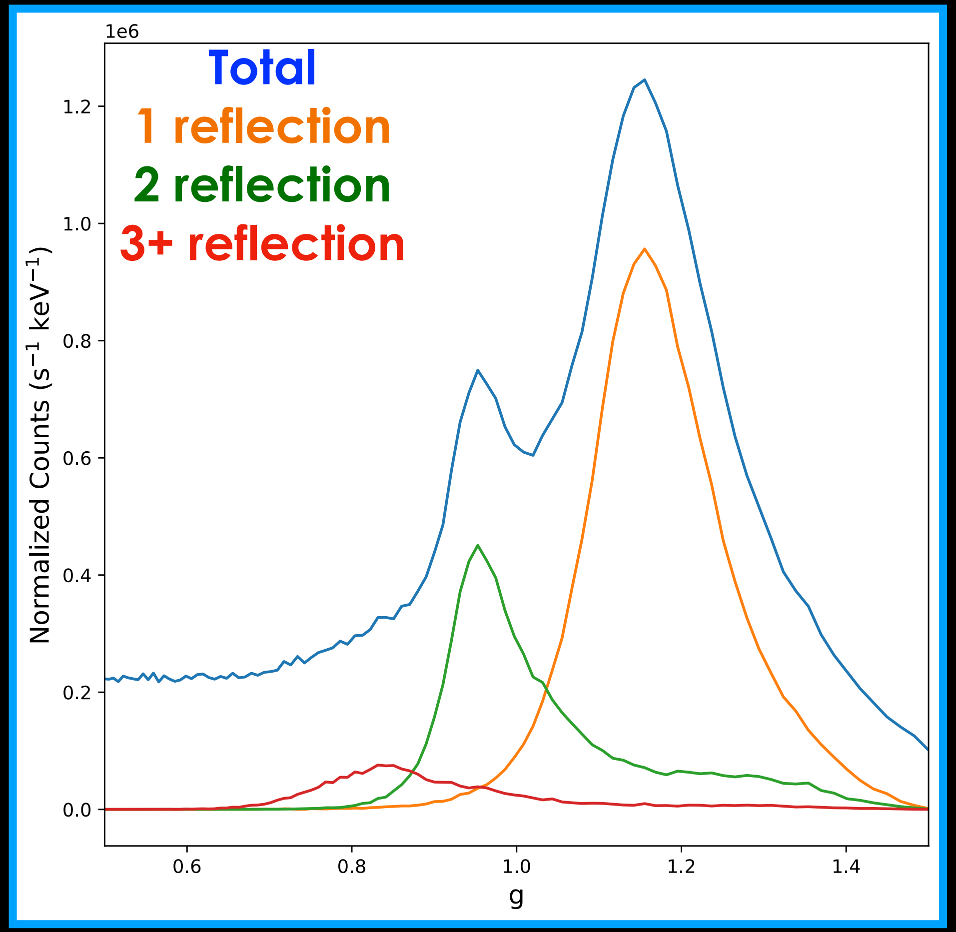
Super-Eddington Accretion

Multiple reflections in a funnel
(simulations by Zijan Zhang and Jane Dai)

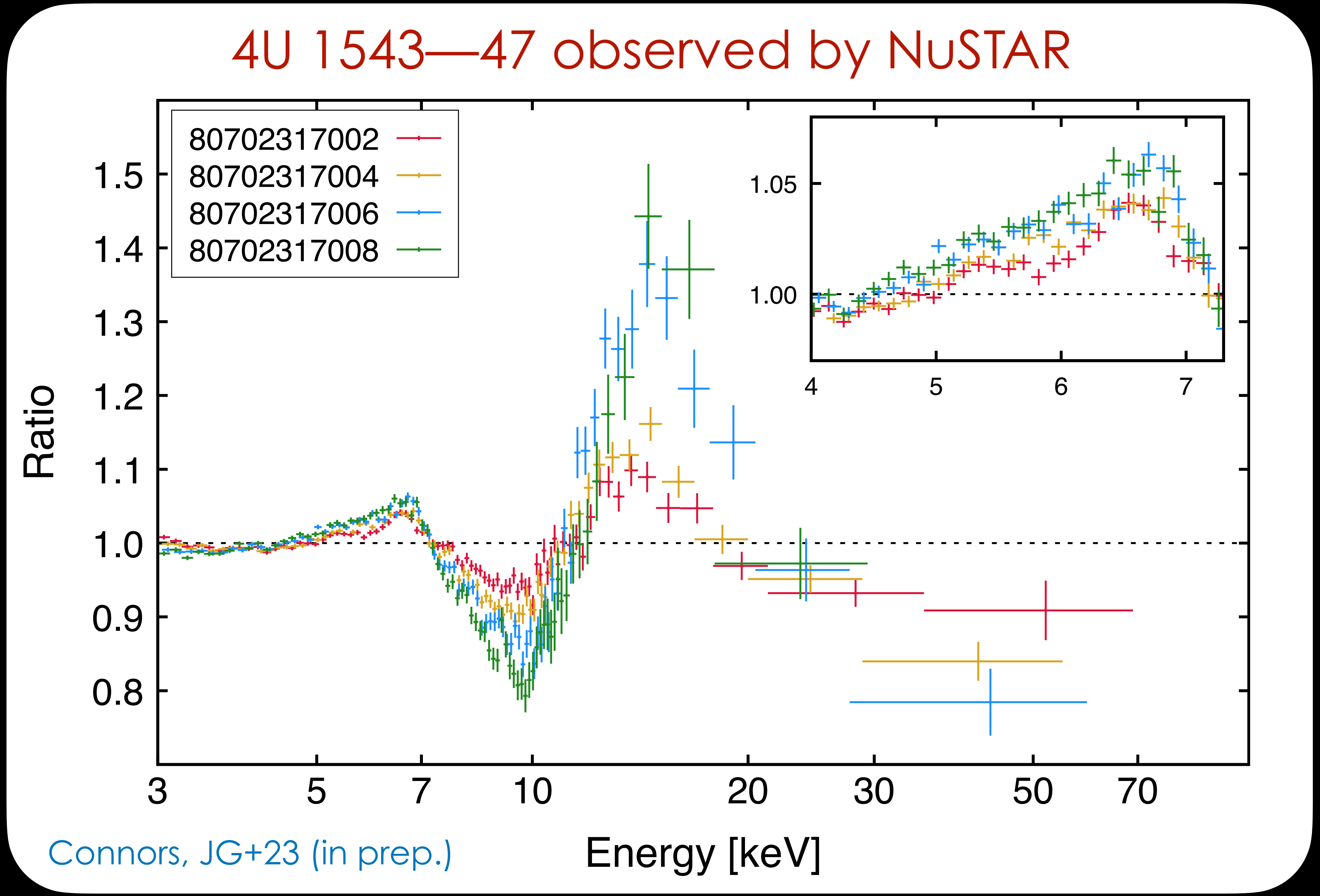
Lamppost corona height: $h_{\rm LP}$
Funnel half open angle: θ

Wind velocity: $v(r) = \left(\frac{r - 6R_g}{r + R_{\rm acc}}\right) v_t$





Monte Carlo
Ray Tracing



$h_{\rm LP} = 30R_g, v_t = 0.5c, R_{\rm acc} = 30R_g, \theta = 30^\circ$

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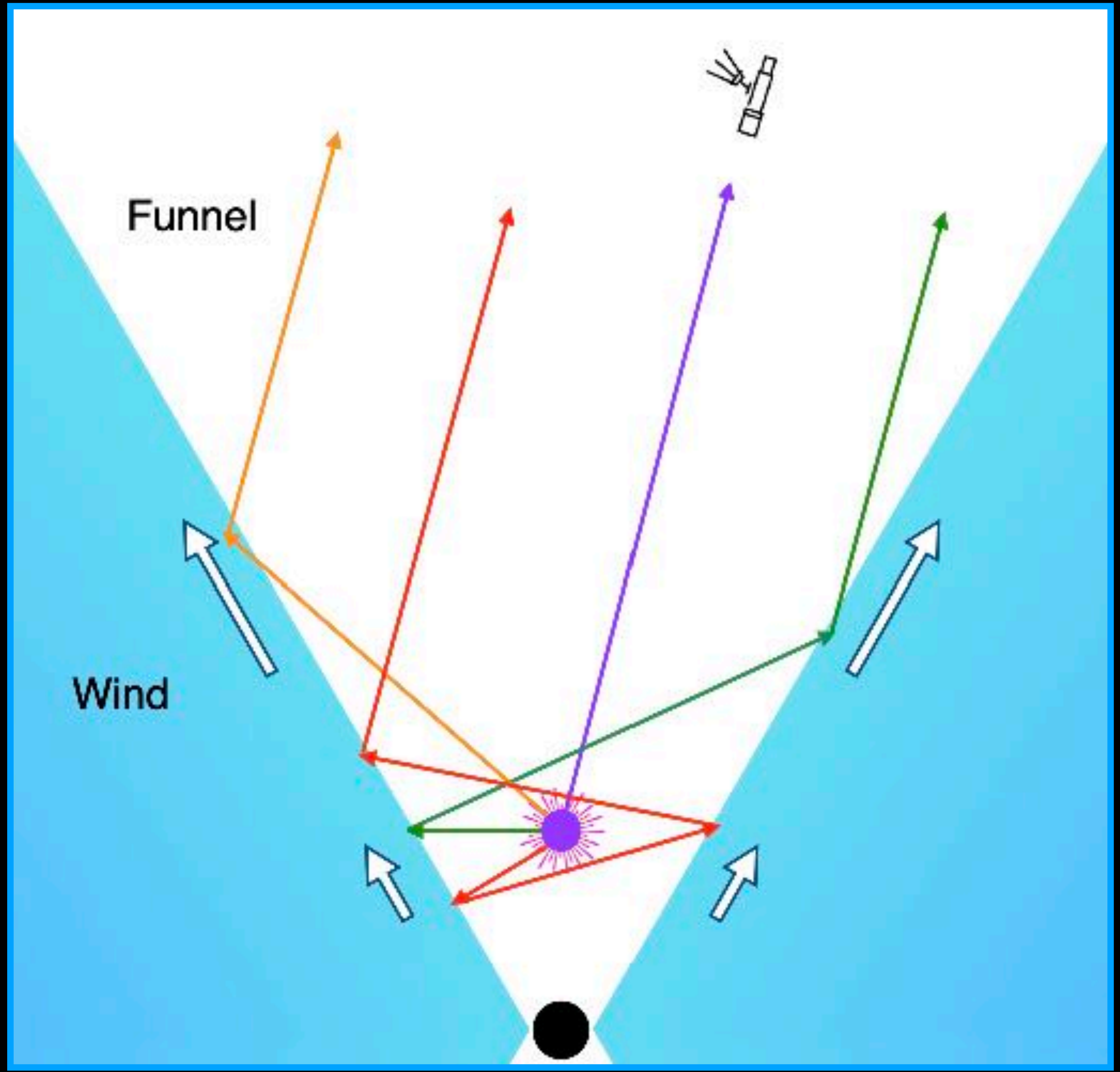

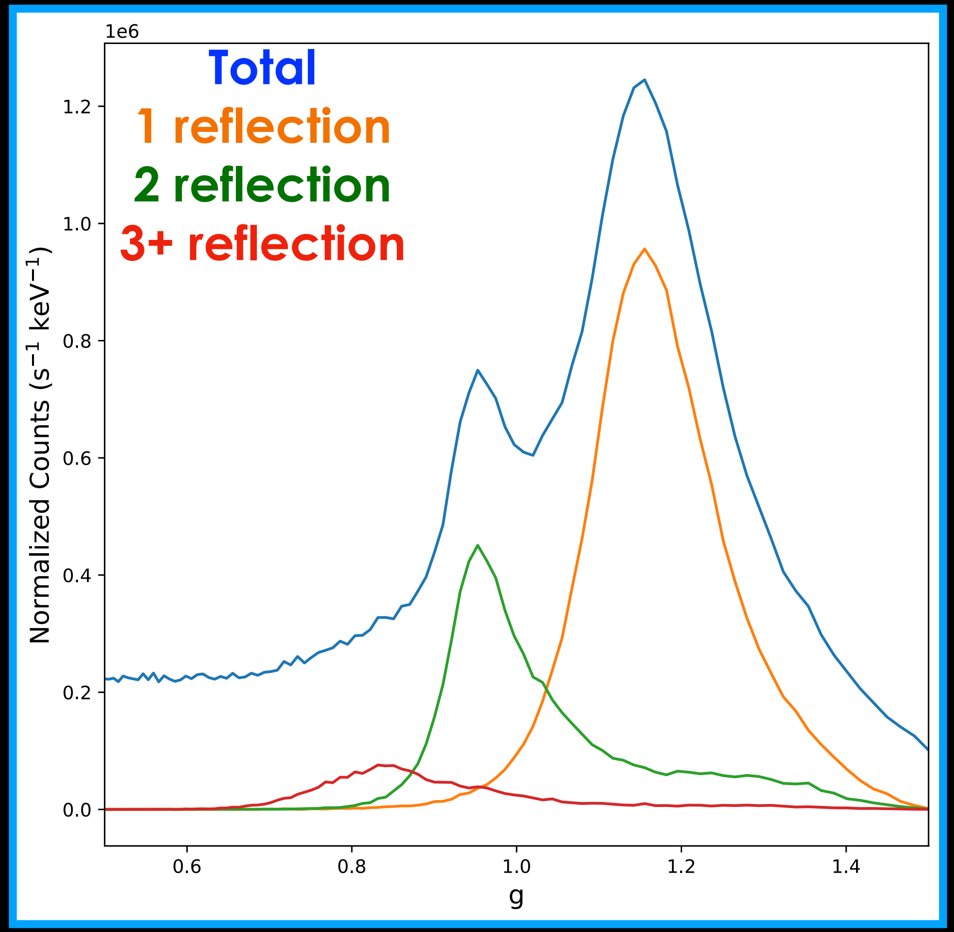

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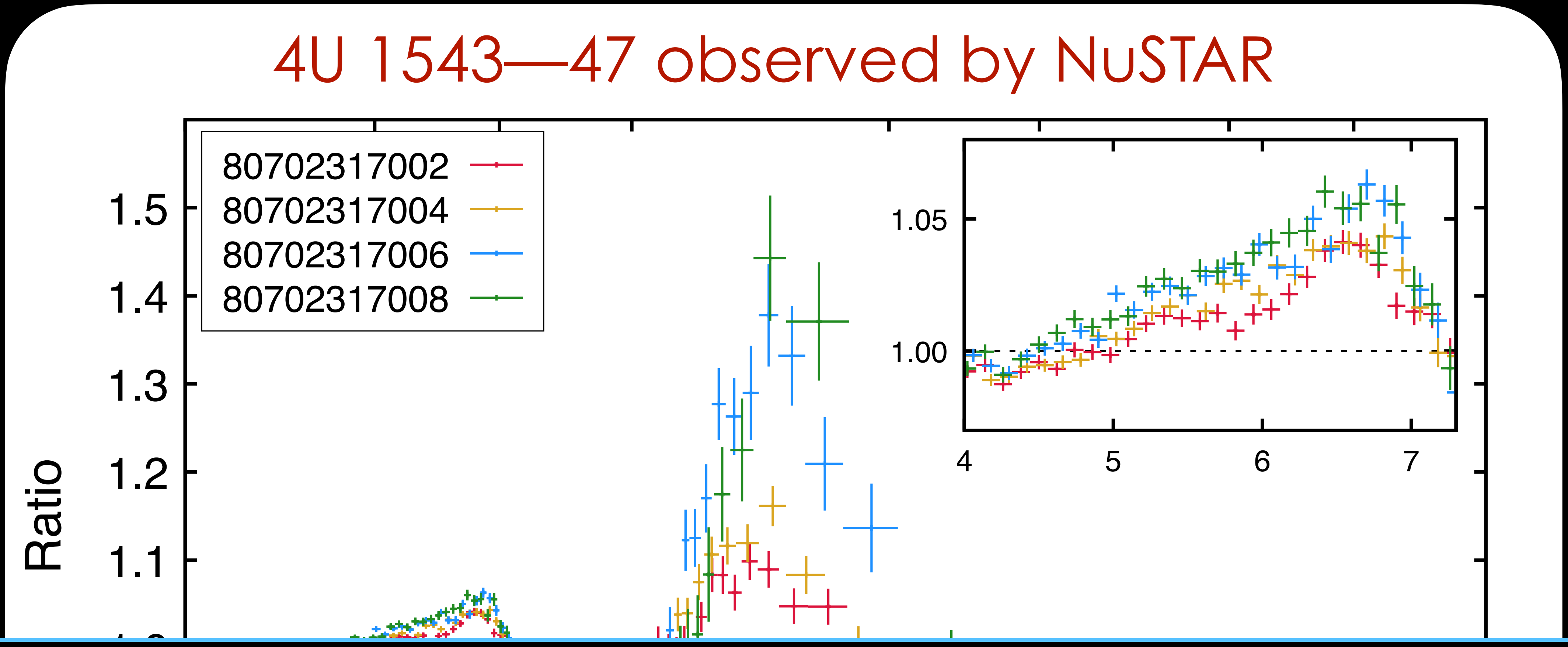
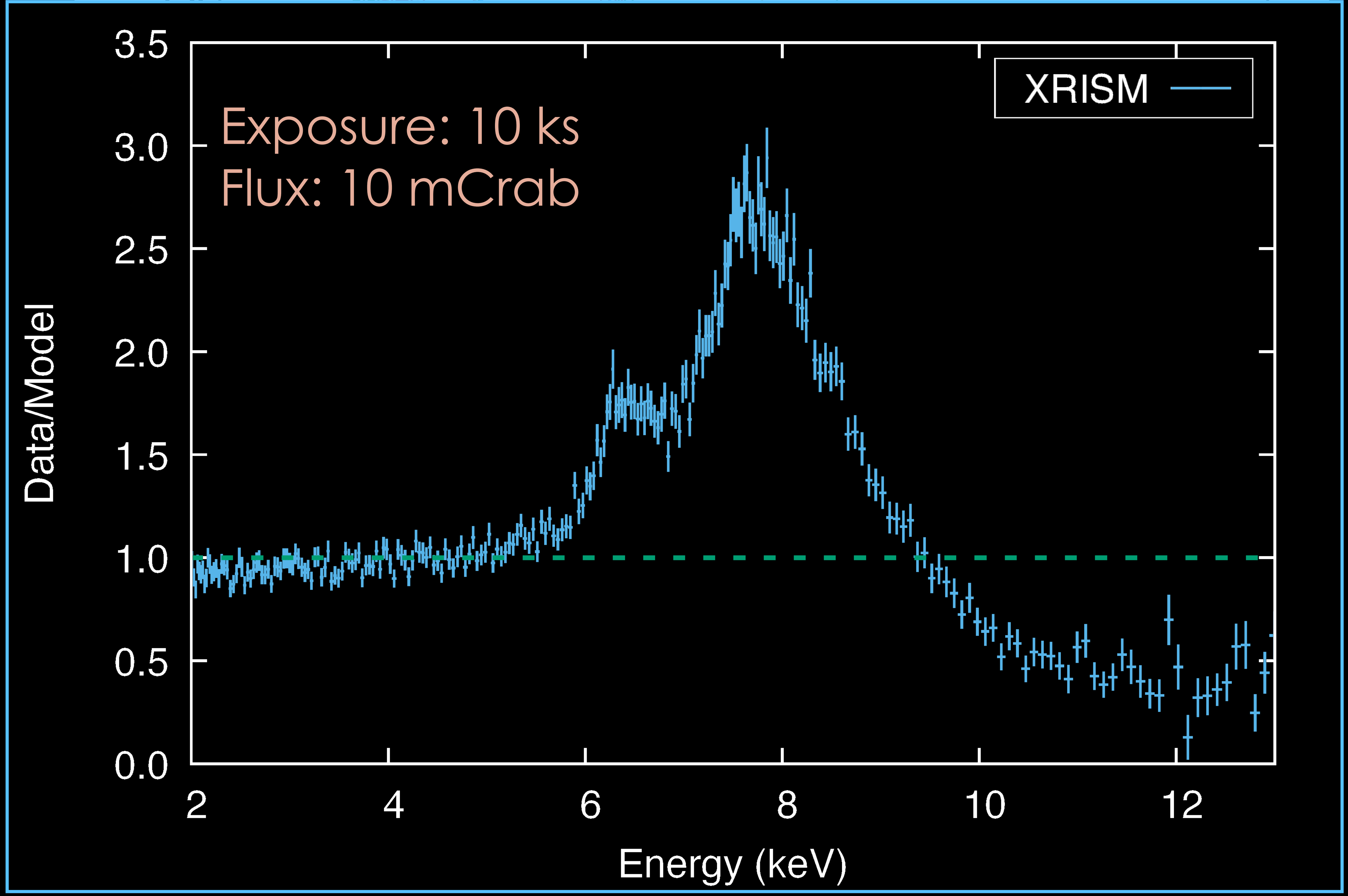




Relativistic Reflection: relxillNS

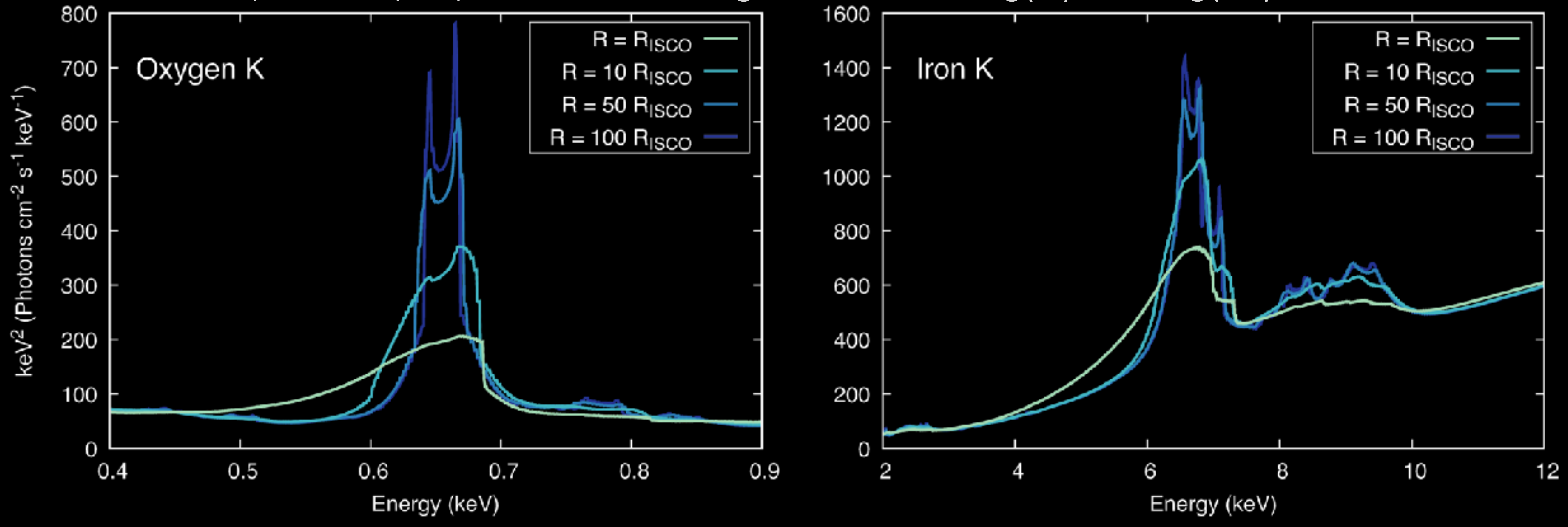
Table 2. List of Parameters for the `relxillNS` Model

Parameter	Symbol (Units)	Range
Inner Emissivity Index	q_1	$[-10, 10]$
Outer Emissivity Index	q_2	$[-10, 10]$
Break Radius	$R_{\rm Br}$ (R_g)	$[1 - 1000]$
Spin Parameter	a_* (cJ/GM^2)	$[-0.998, 0.998]$
Inclination	i (degrees)	$[3, 87]$
Inner Disk Radius	$R_{\rm in}$ $(R_{\rm ISCO})$	$[1, 1000]$
Outer Disk Radius	$R_{\rm out}$ (R_g)	$[1, 1000]$
Blackbody Temperature	$kT_{\rm bb}$ (keV)	$[0.5, 10]$
Ionization Parameter	$\log(\xi/{\rm erg\,cm\,s^{-1}})$	$[1, 4]$
Electron Number Density	$\log(n_e/{\rm cm^{-3}})$	$[15, 19]$
Iron Abundance	$A_{\rm Fe}$ (Solar)	$[0.5, 10]$
Reflection Fraction[a]	$R_{\rm frac}$	$[0, 10]$

[a] If this parameter is set to negative values, the model only outputs the reflection component, without the continuum.

JG, Dauser, Ludlam+22

relxillNS spectra: q1=q2=0, a=0, i=30 deg, kTbb=4 keV, log(Xi)=3.1, log(ne)=15, AFe=5, Rf=1



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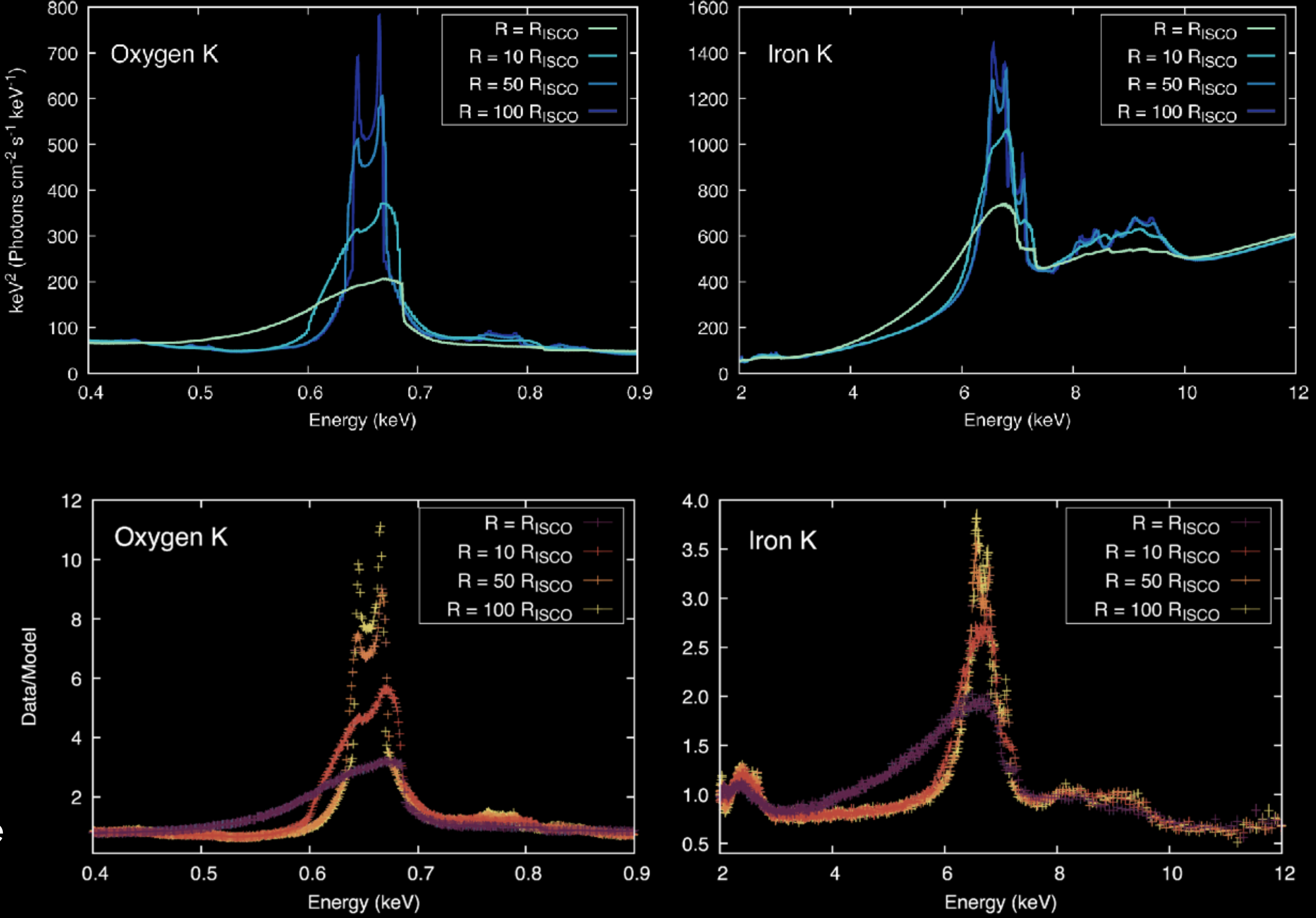
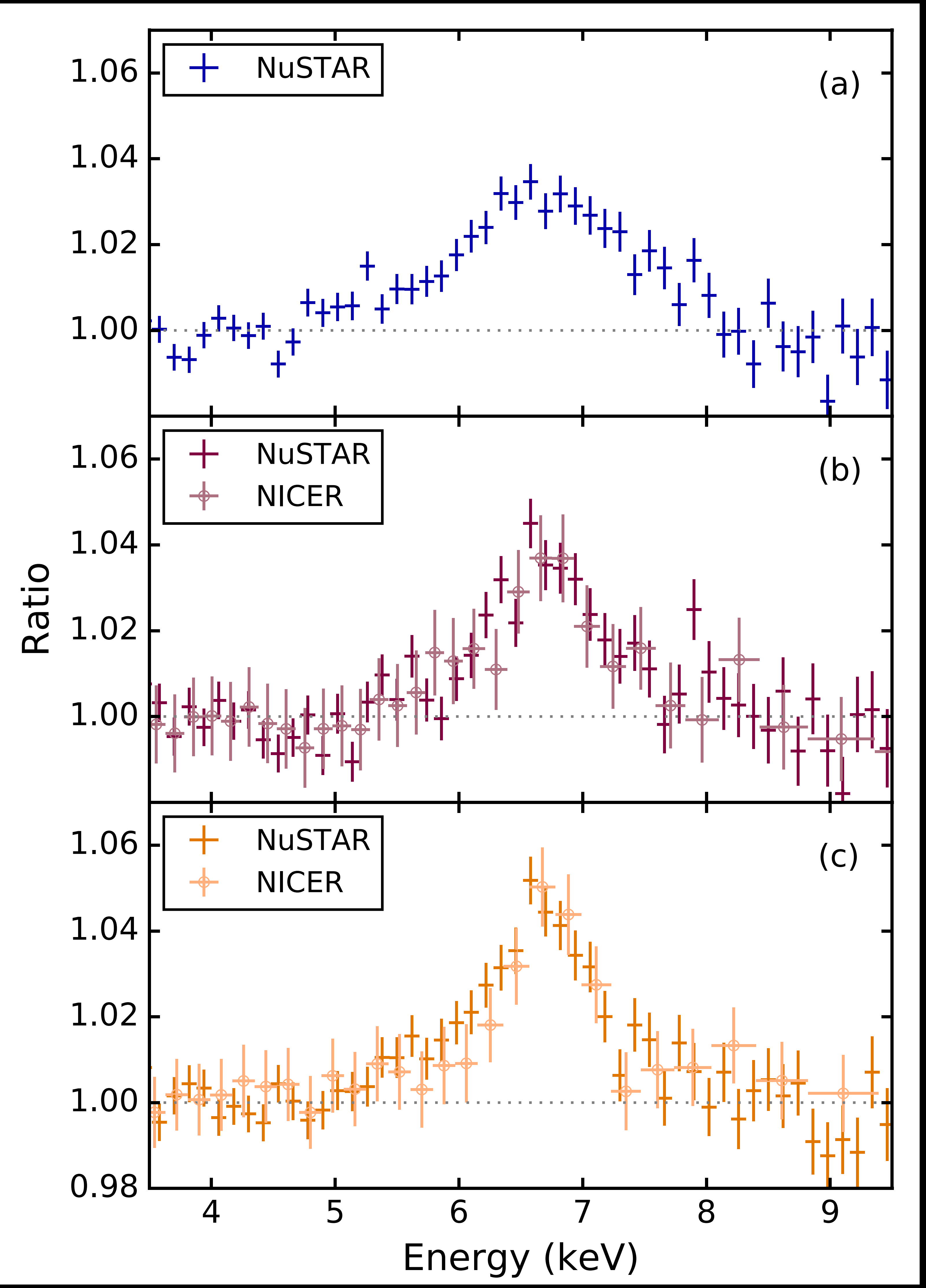
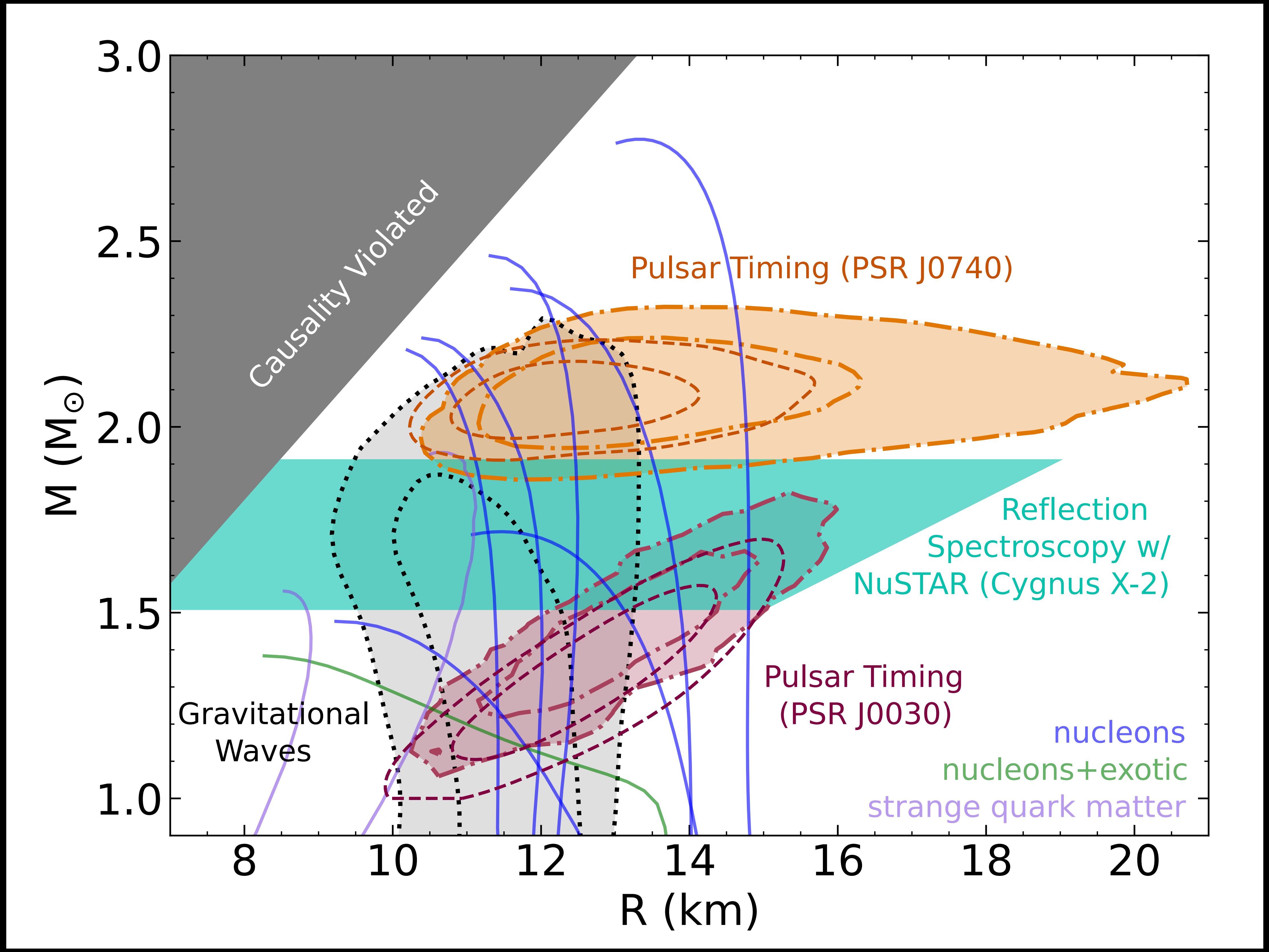


Simulated 10 ks Athena X-IFU observation of a 10 mCrab source

Neutron Star Radii

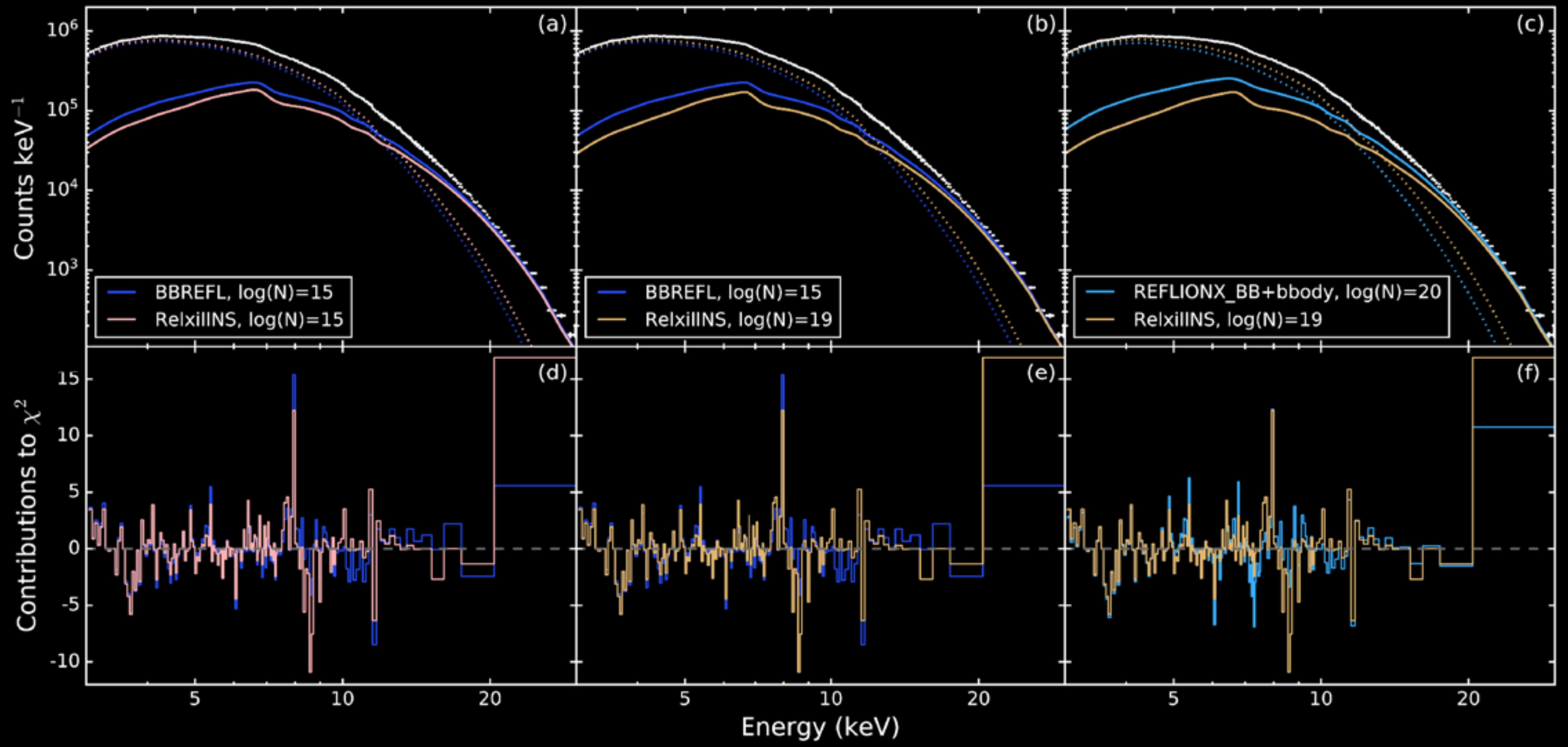
NuSTAR observations of Cygnus X-2 provide radius constraints complementary to other methods, helping to constrain models of the NS equation of state.





Ludlam,...,JG+22

Comparison with Previous Models



Test case 4U 1705—44

Broadly consistent results between relxillNS, BBRefl and ReflionX_BB when fitting NuSTAR data.

Larger discrepancies might be seen at softer energies

JG, Dauser, Ludlam+22

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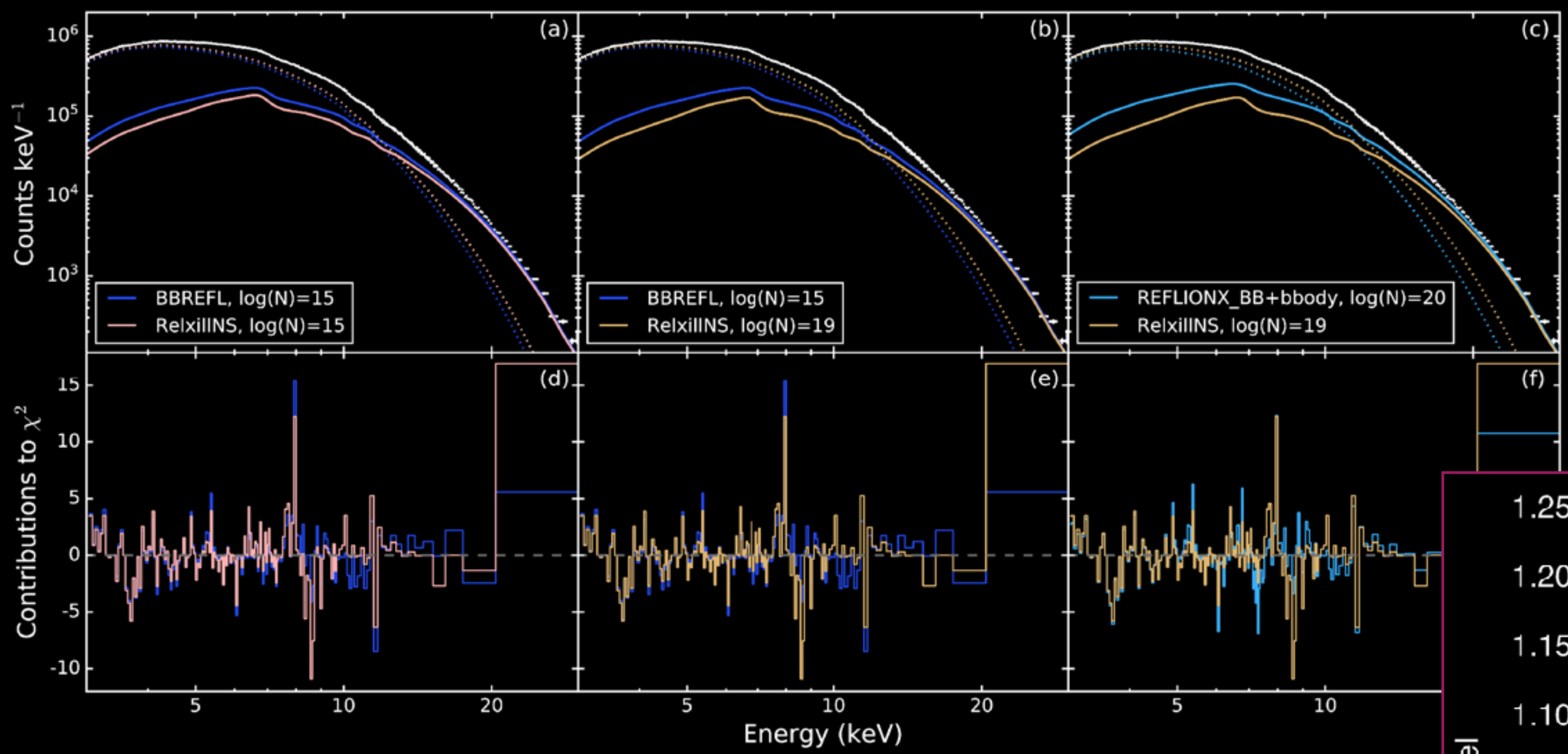


Test case 4U 1705—44

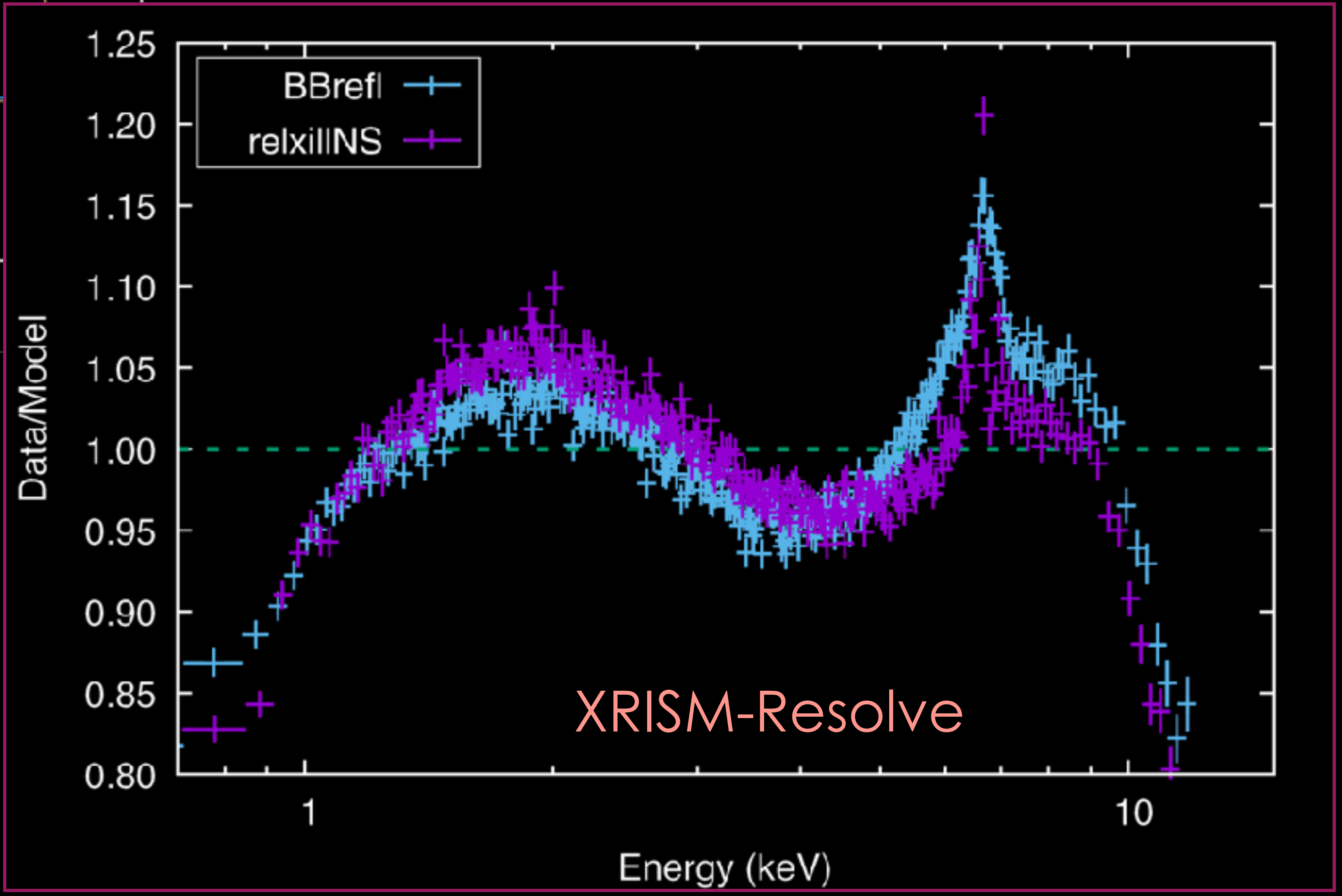
Broadly consistent results between relxillNS, BBRefl and ReflionX_BB when fitting NuSTAR data.

Larger discrepancies might be seen at softer energies

High-resolution spectra (microcal) could distinguish between models

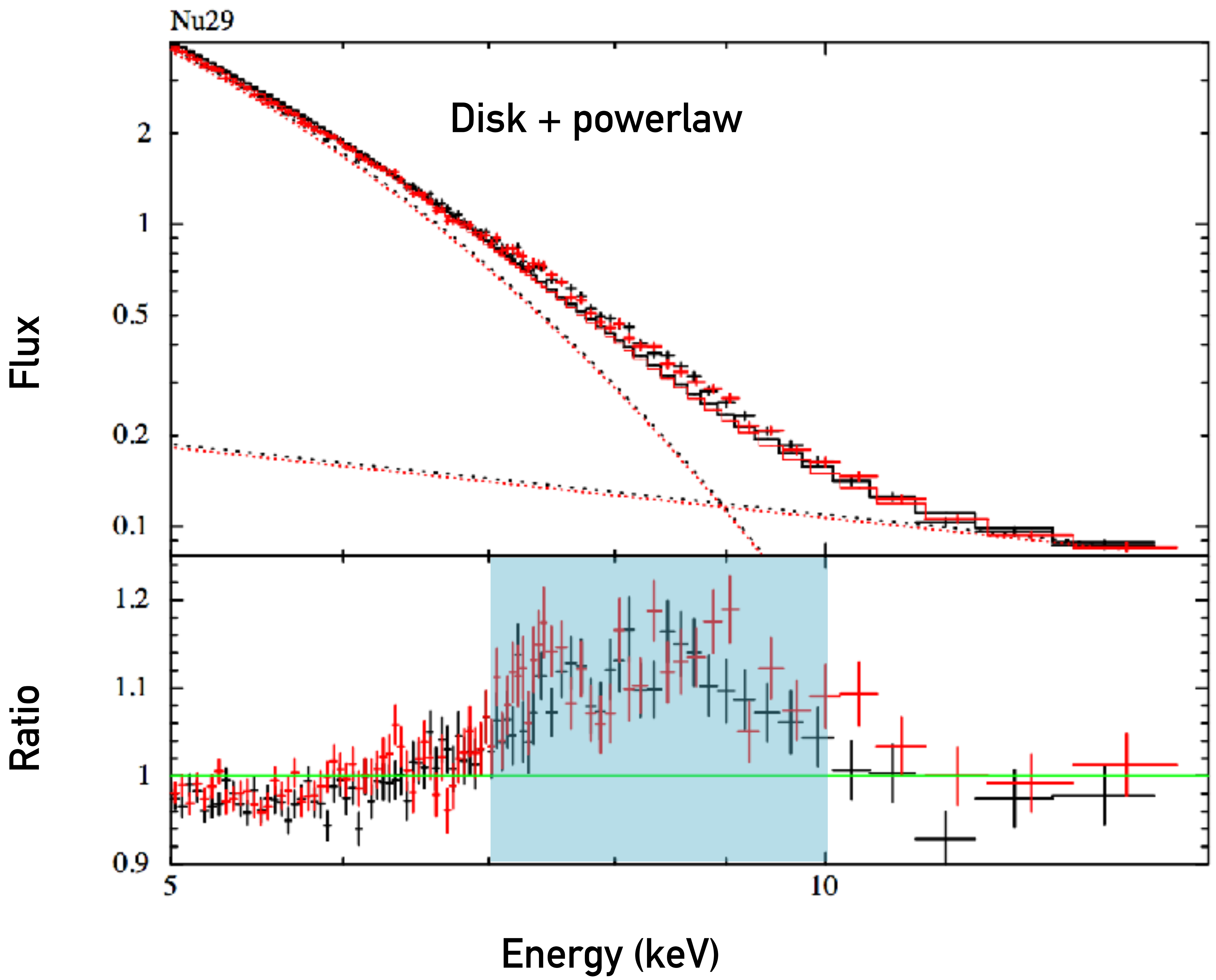
(Simulation for a 20 ks observation of a 100 mCrab source)

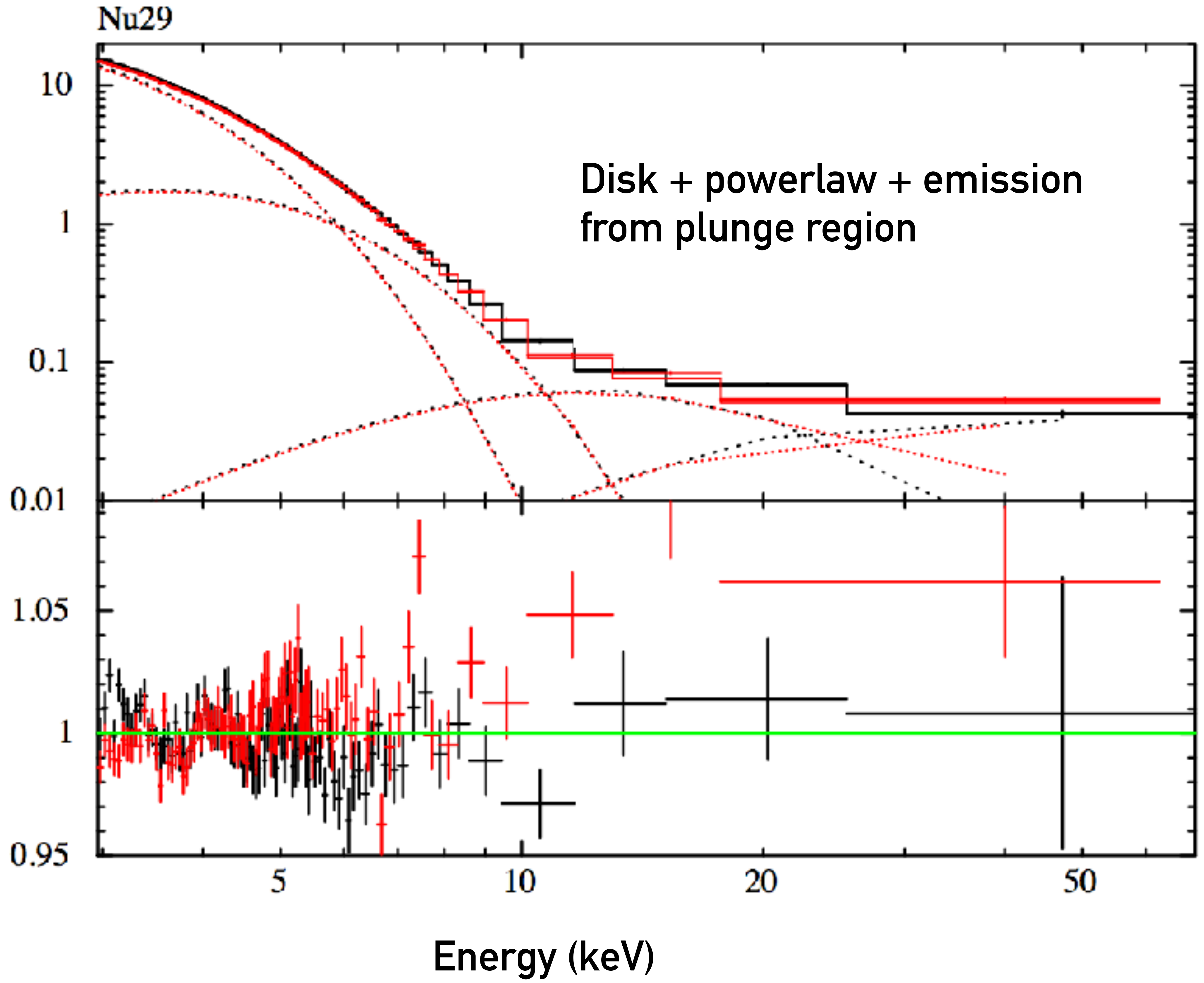
JG, Dauser, Ludlam+22



Emission from the Plunging Region?

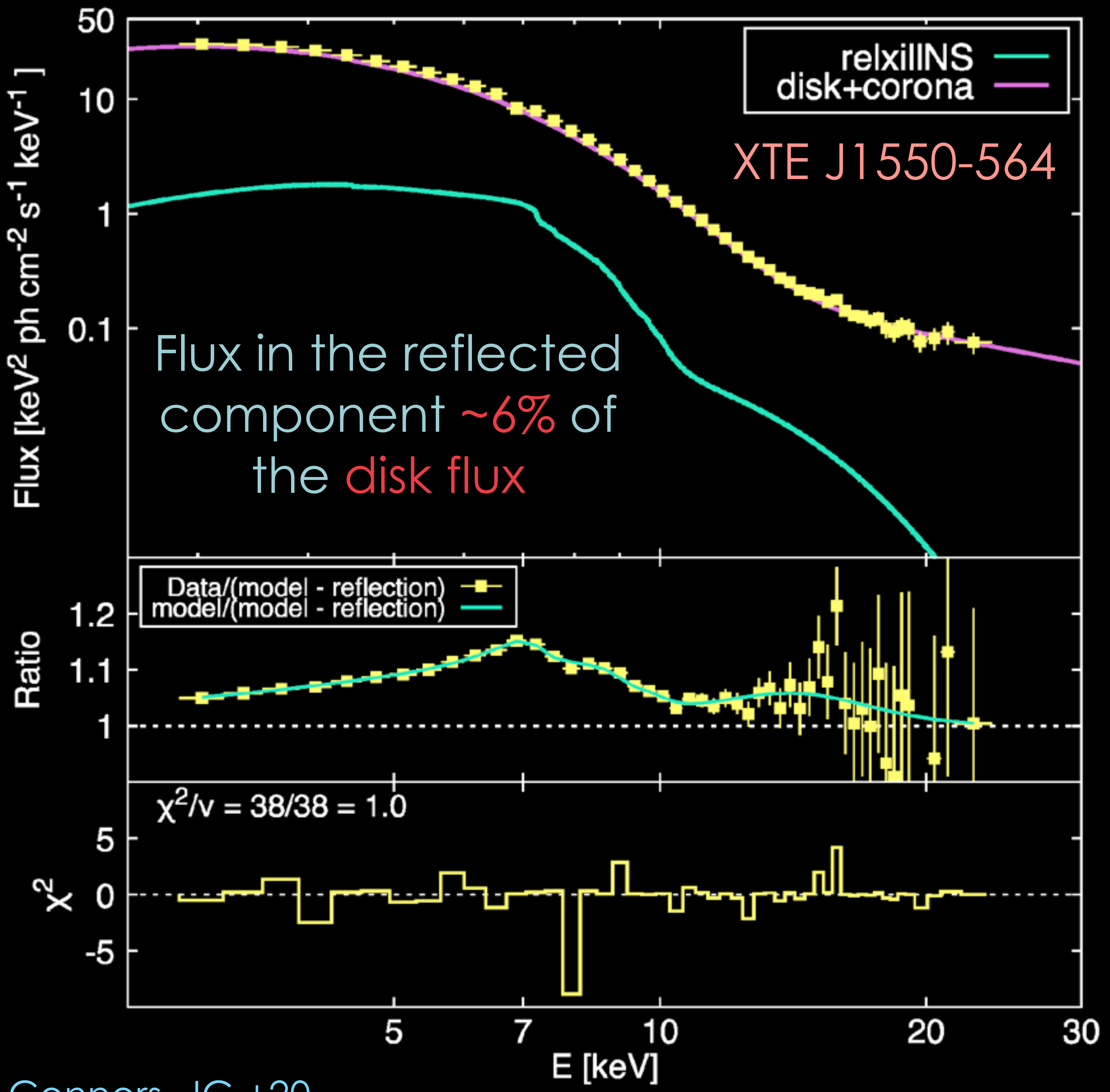
MAXI J1820+070





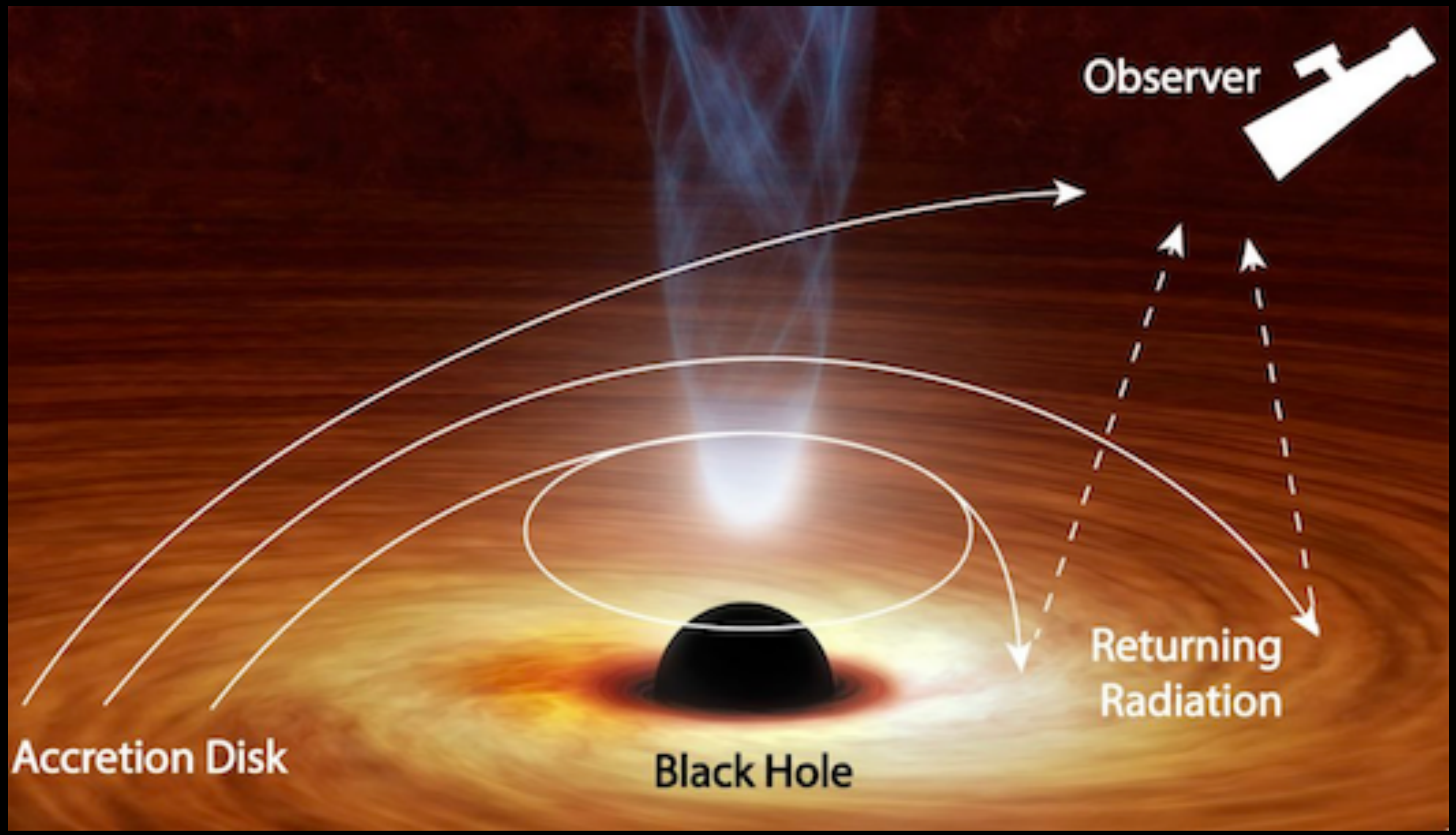
Fabian,…,JG+20

Disk Self Irradiation (Returning Radiation)



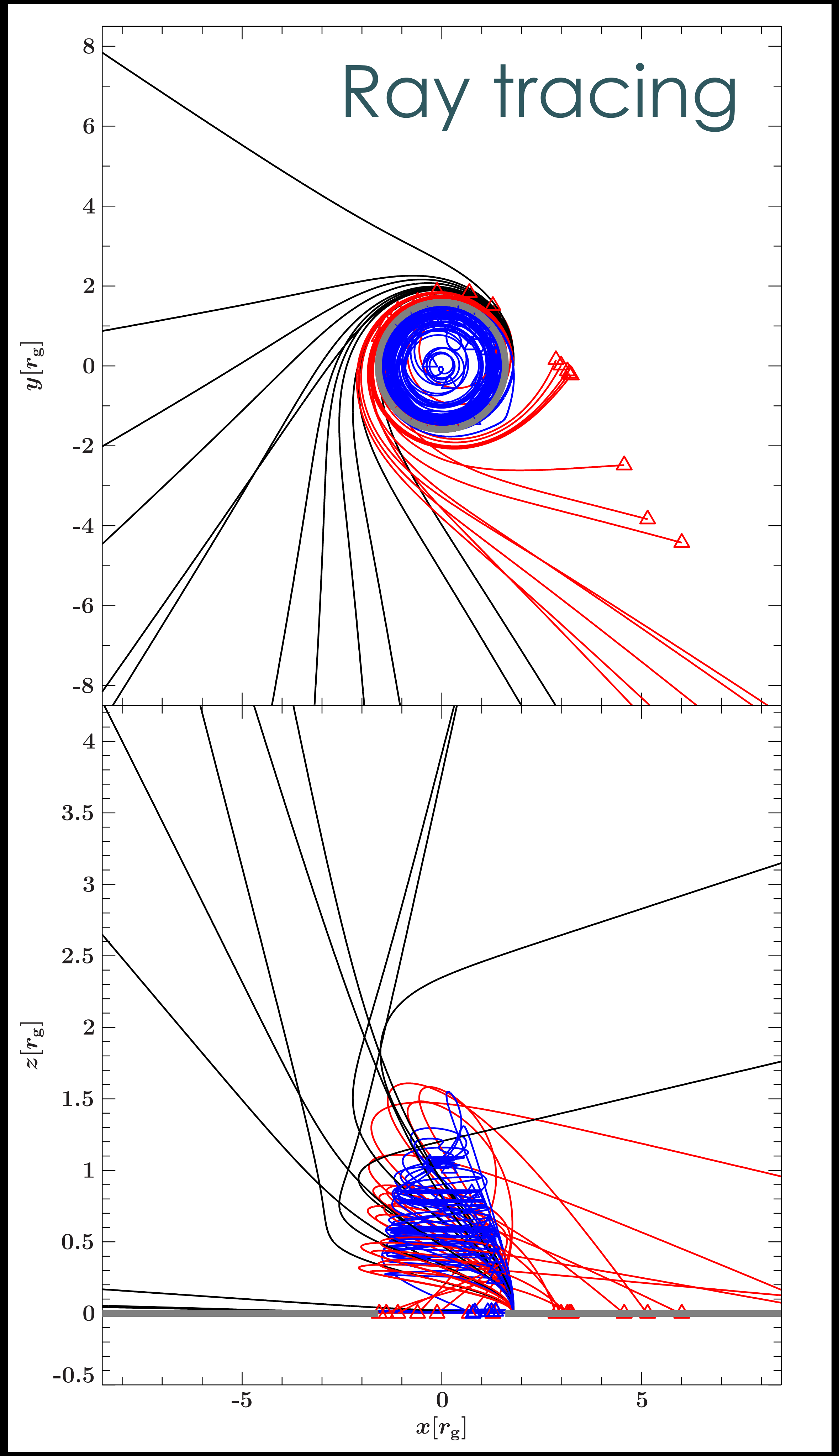
Connors, JG,+20

Radiation Returning to the Disk due to GR light bending



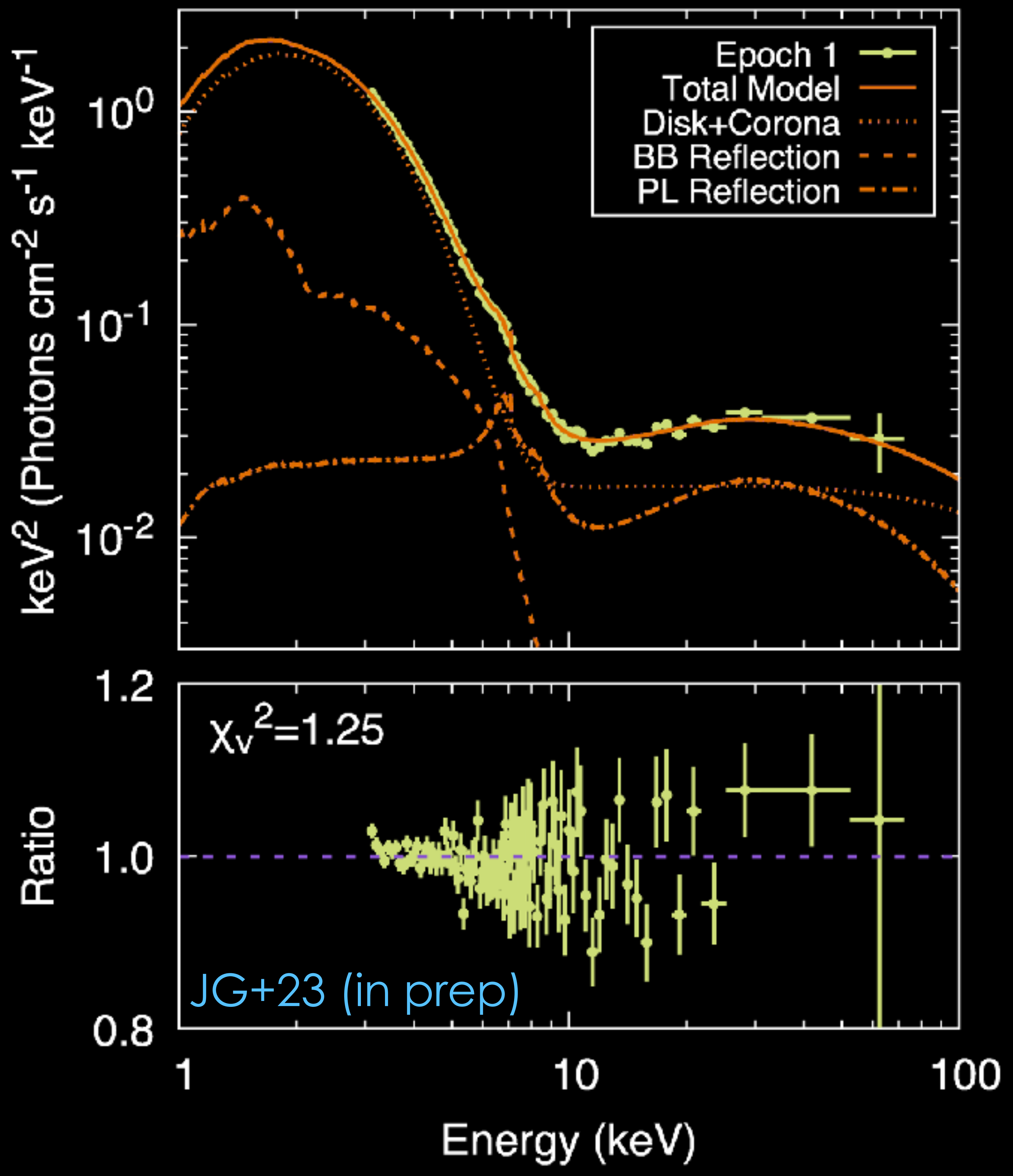
First observational evidence!
—> Predicted by Cunningham (1975), and later by Agol & Krolik (2000)

Thermal Disk Emission



Dauser, JG+22

Soft-State of GX 339-4



Returning radiation detected in several other sources:

- 4U 1630-47 (Connors, JG+21)
- EXO 1846-031 (Wang,…,JG+21)
- MAXI J0637-430 (Lazar,…,JG+21)
- GX 339-4 (JG+23)

New theoretical work:

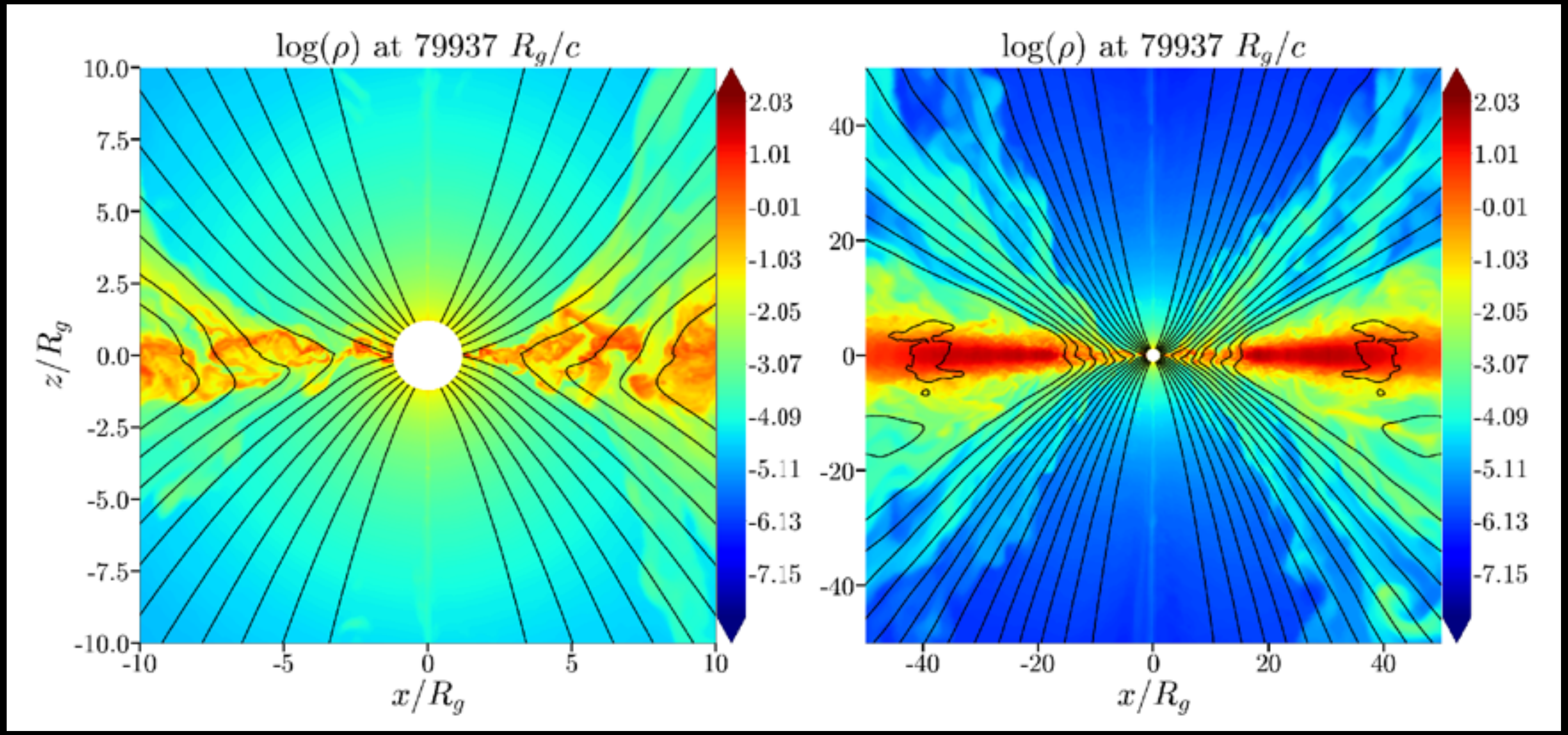
- Effects on timing properties (Wilkins, JG+21)
- Effects on emissivity profiles (Dauser, JG+22)

GRMHD Density Profiles

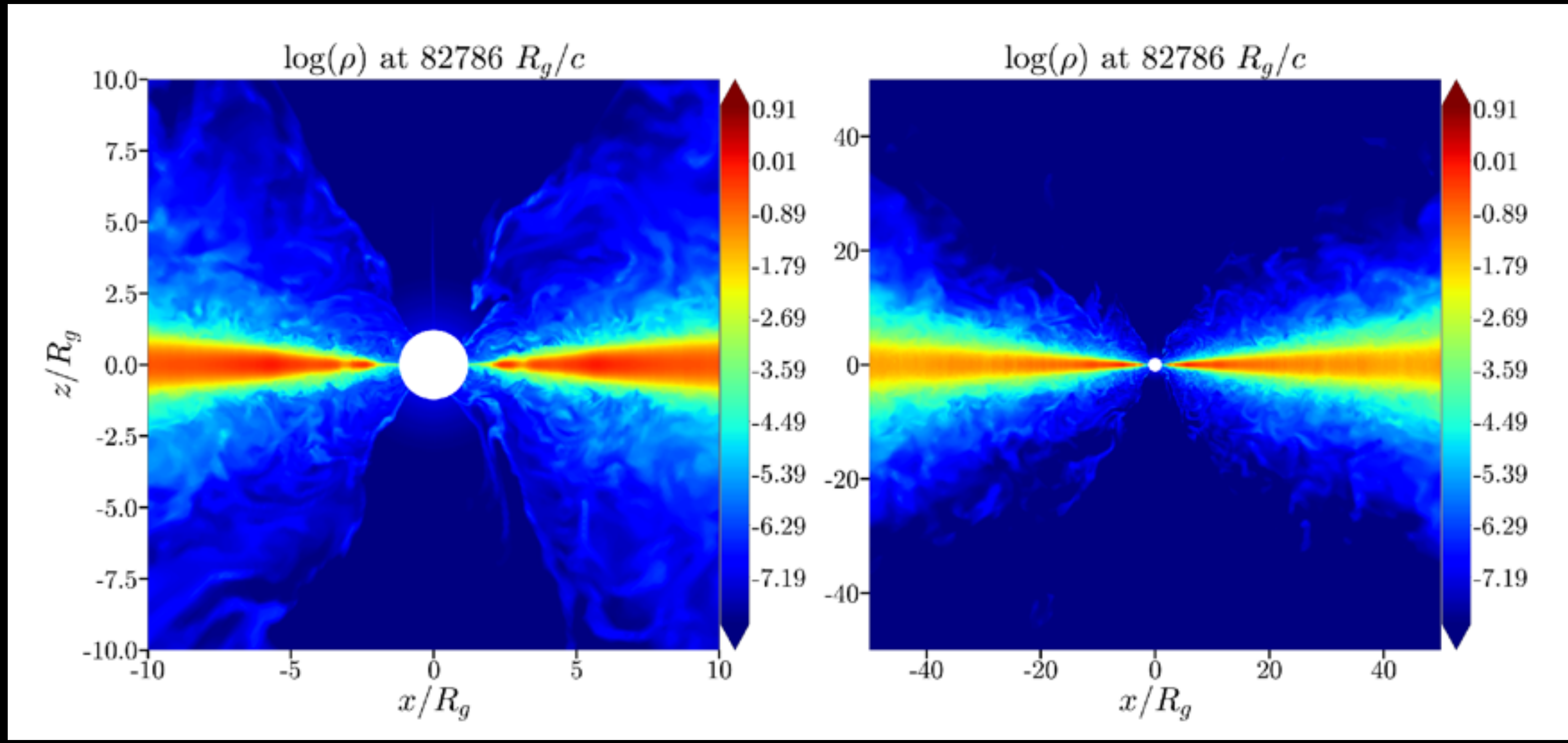
High resolution simulations without radiation.

There is no density drop inside the ISCO for the MAD case

—> Accretion does not proceed via viscous stress



MAD

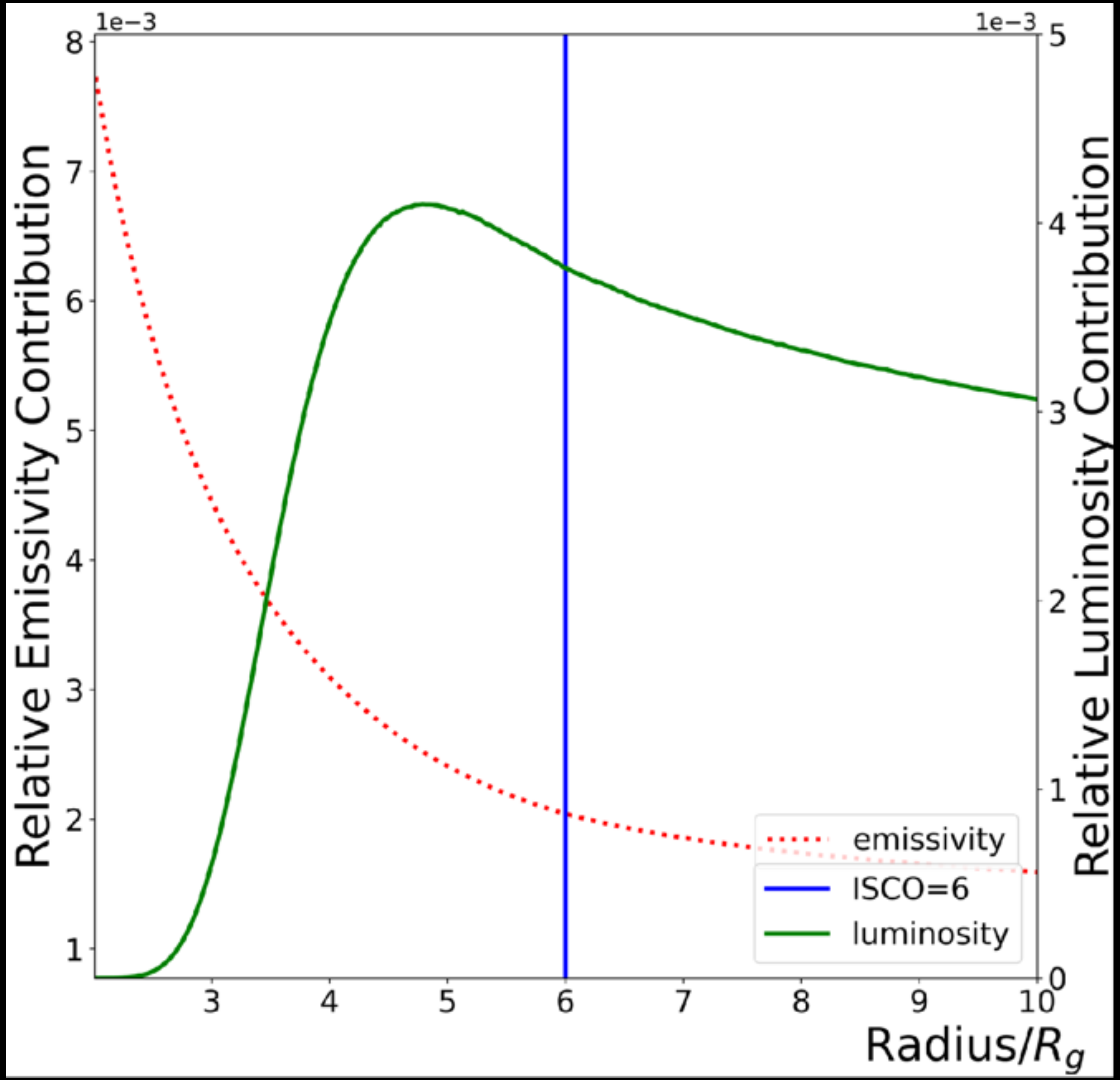


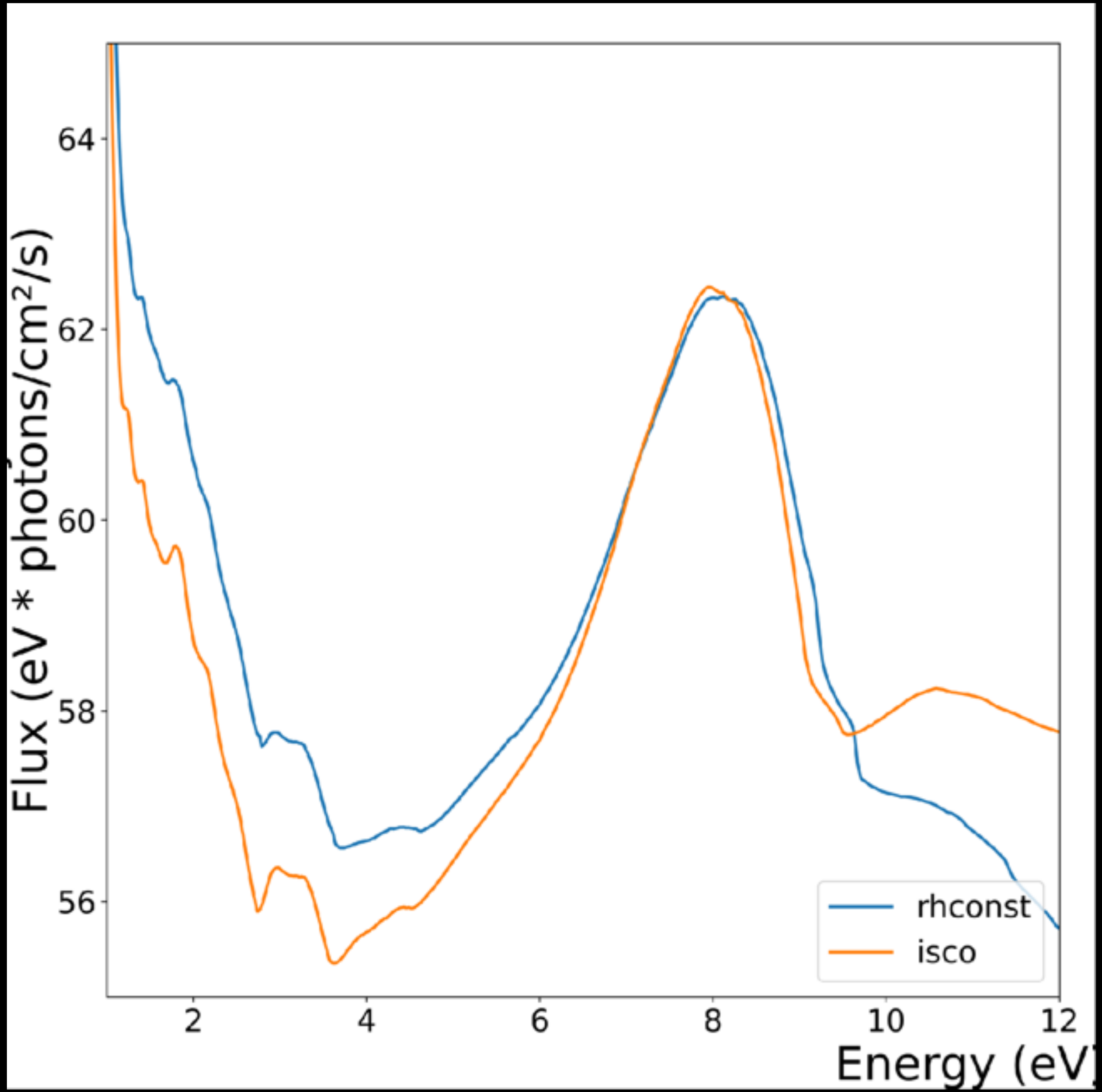
no-MAD

Simulations courtesy of Matthew Liska

Venturing inside the ISCO

Reflection from inside the ISCO assuming a flat density profile





Dong, JG+23 (in prep.)

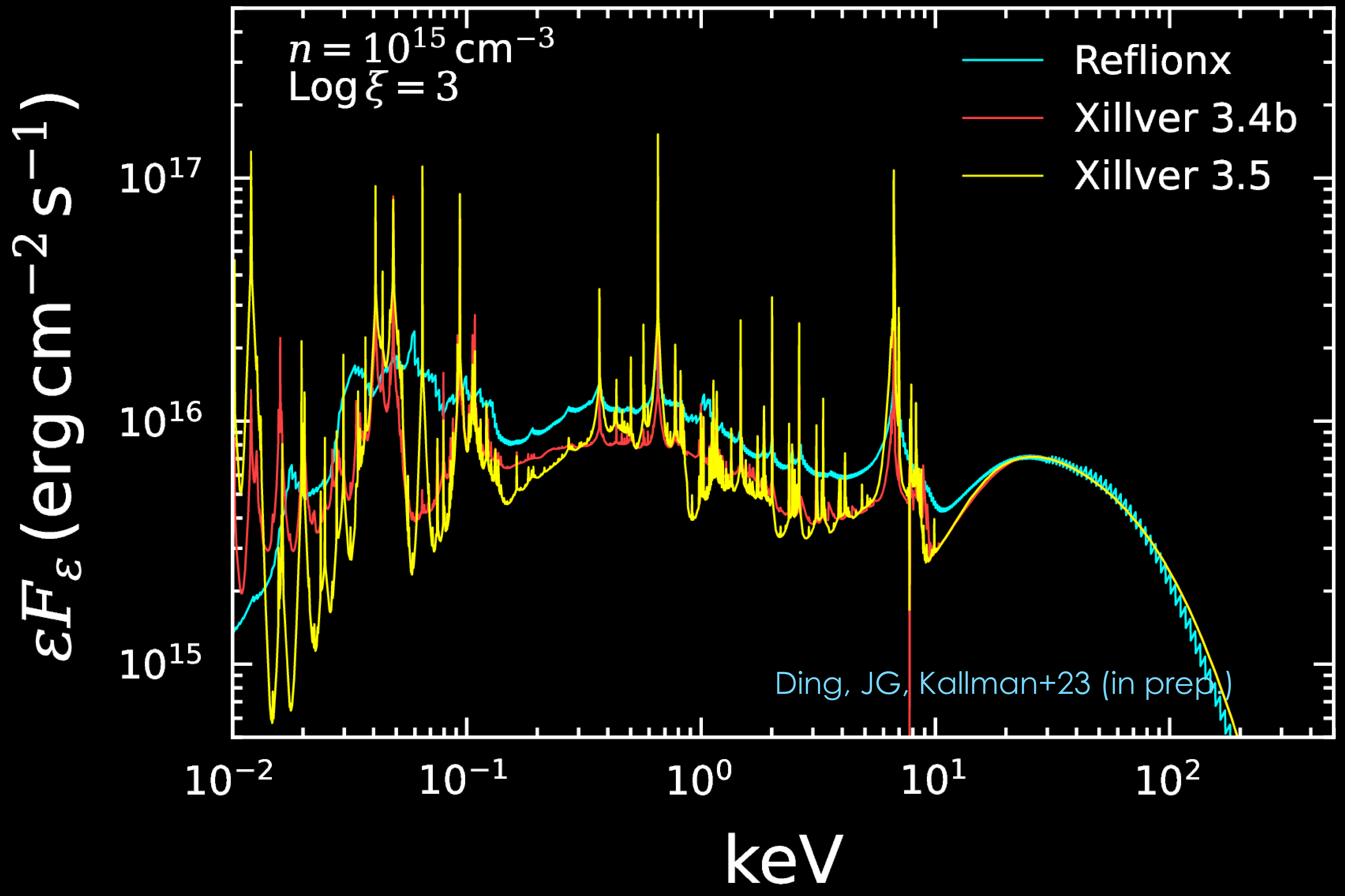
(**Preliminary results**)

High-Density Plasma Effects

New XSTAR routines and Atomic Data including:

- Screening of the atomic potential (Debey—Hückel approximation)
- Continuum lowering (truncation of the high-*n* states)
- Suppression of Dielectronic Recombination (Nikolik+20 formulae)

Kallman,..,JG+21
Mendoza,...,JG+21



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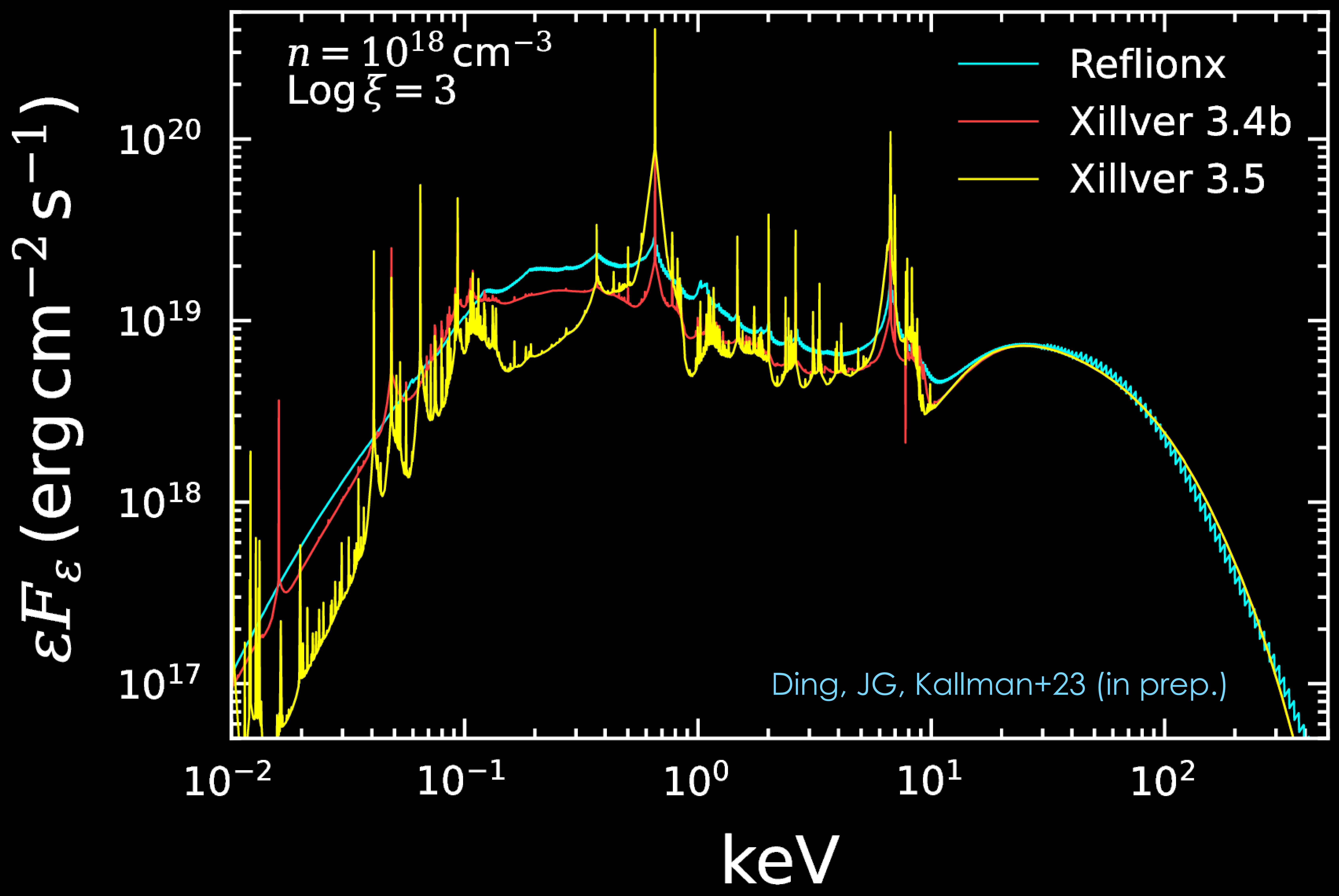

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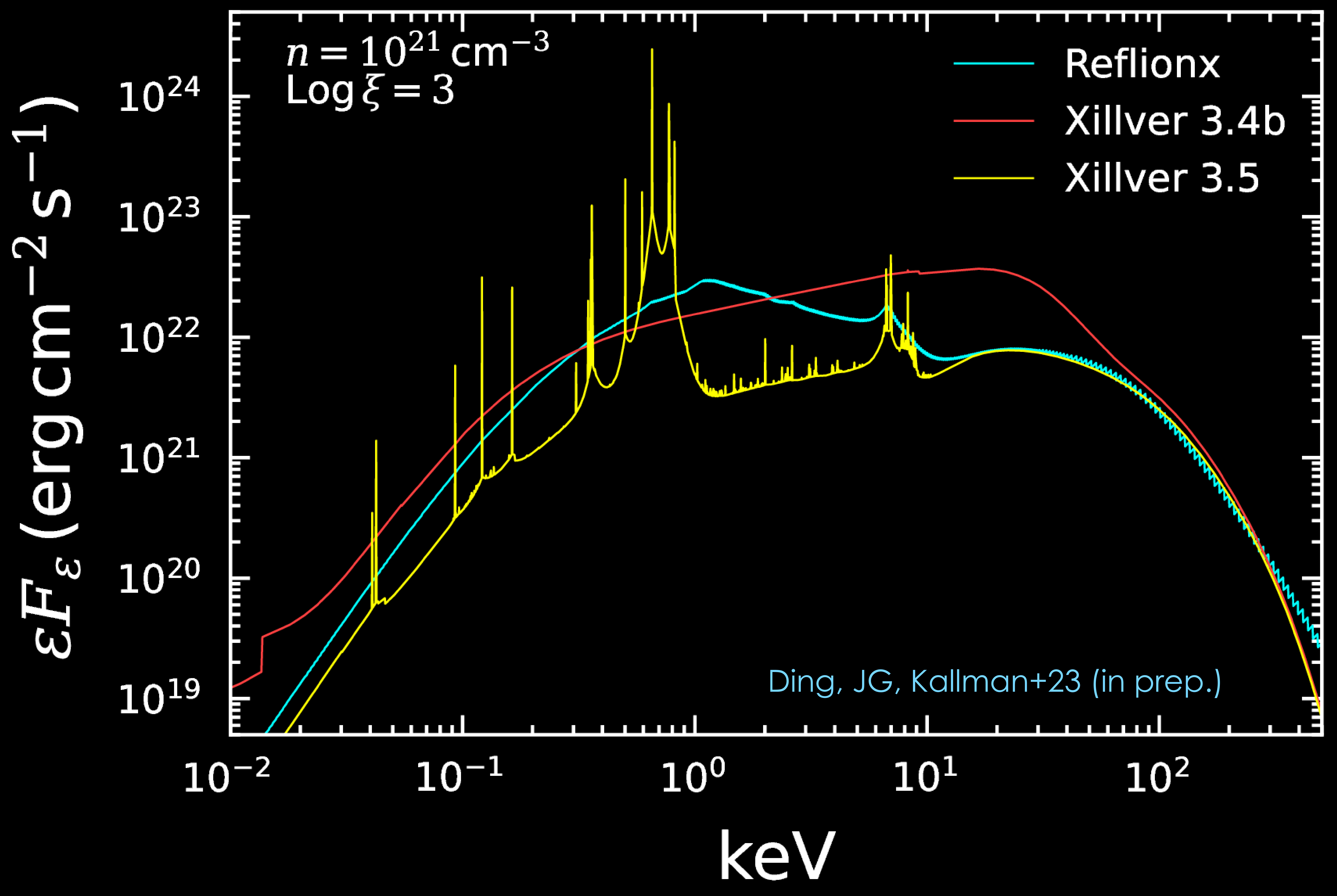

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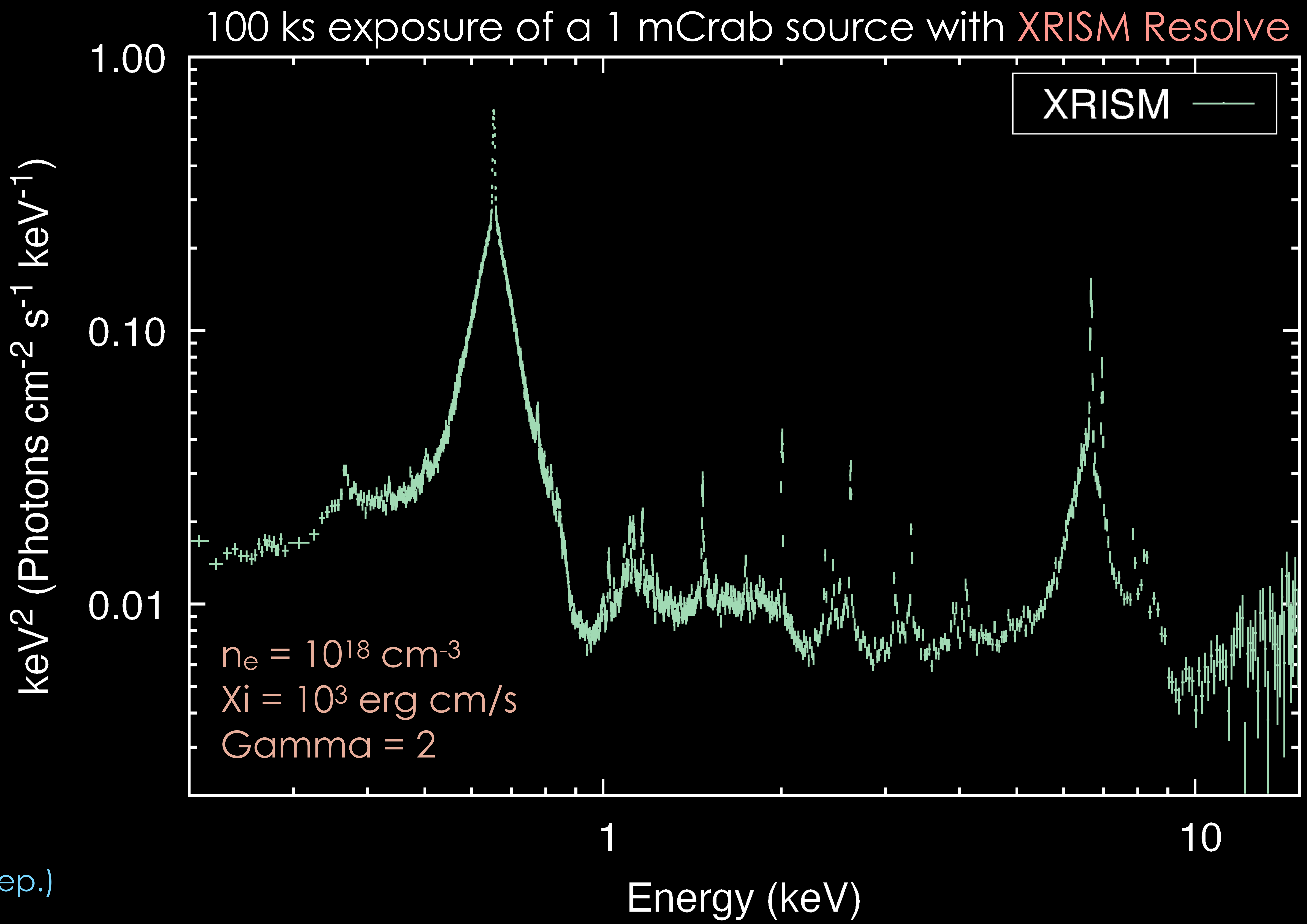

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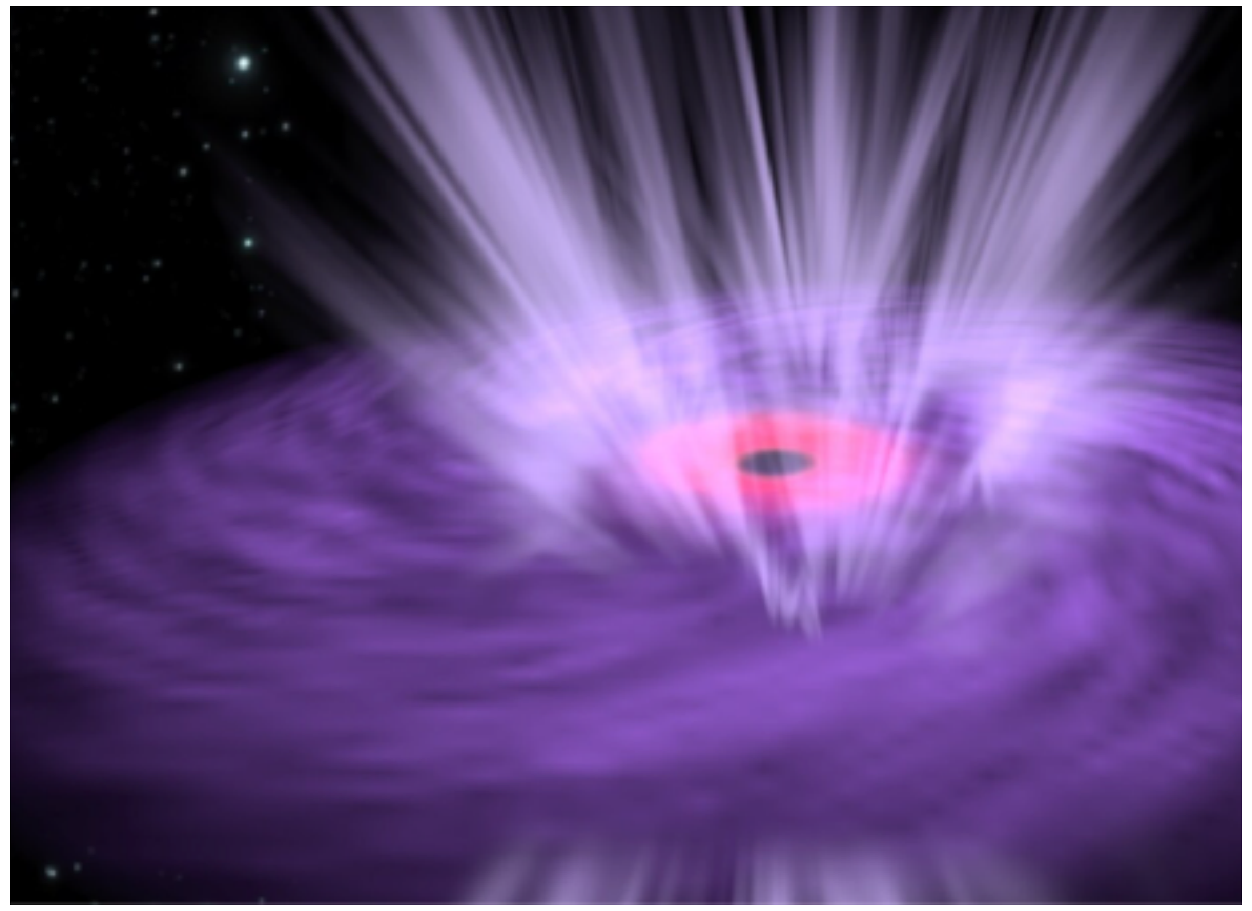
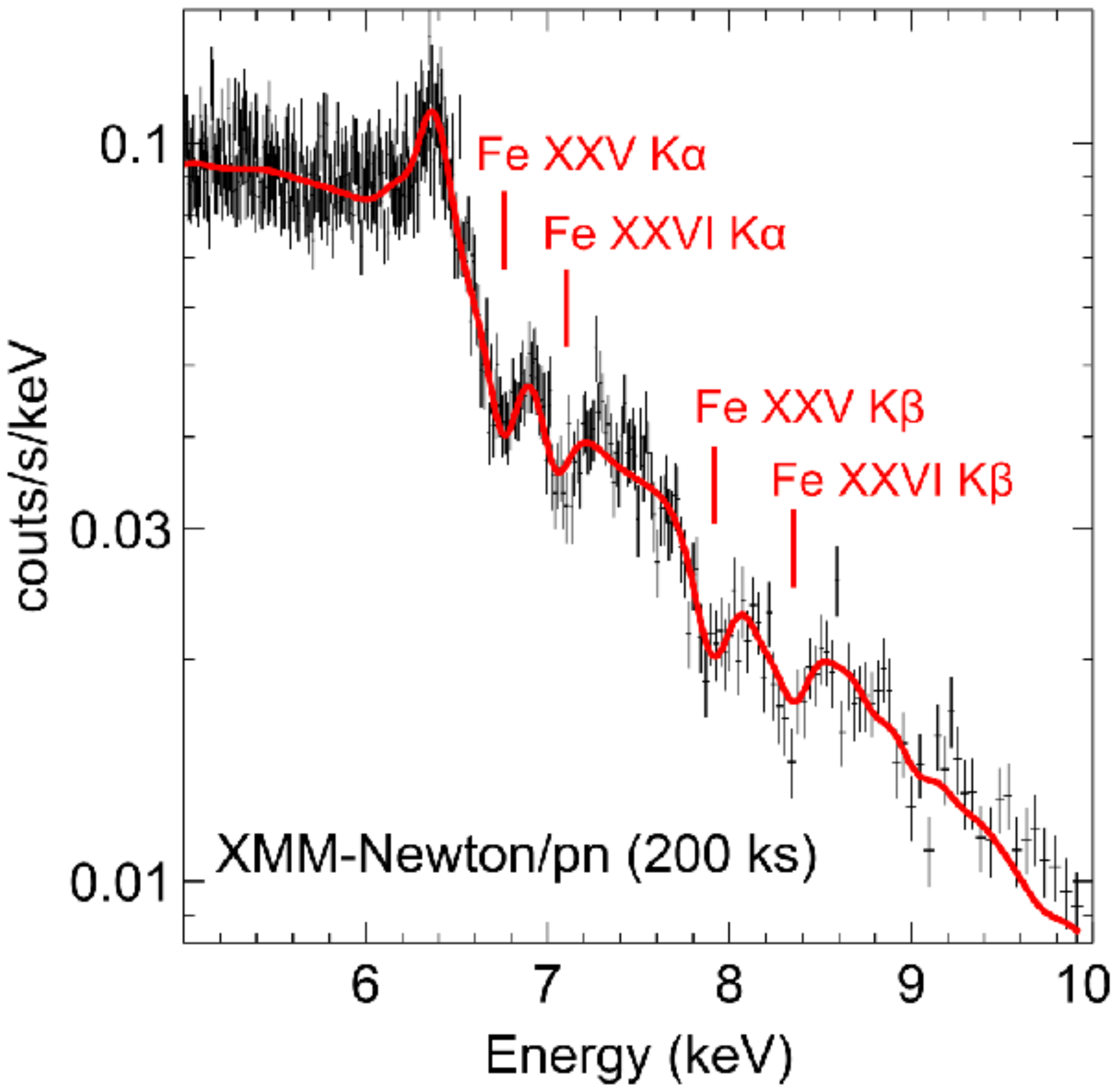
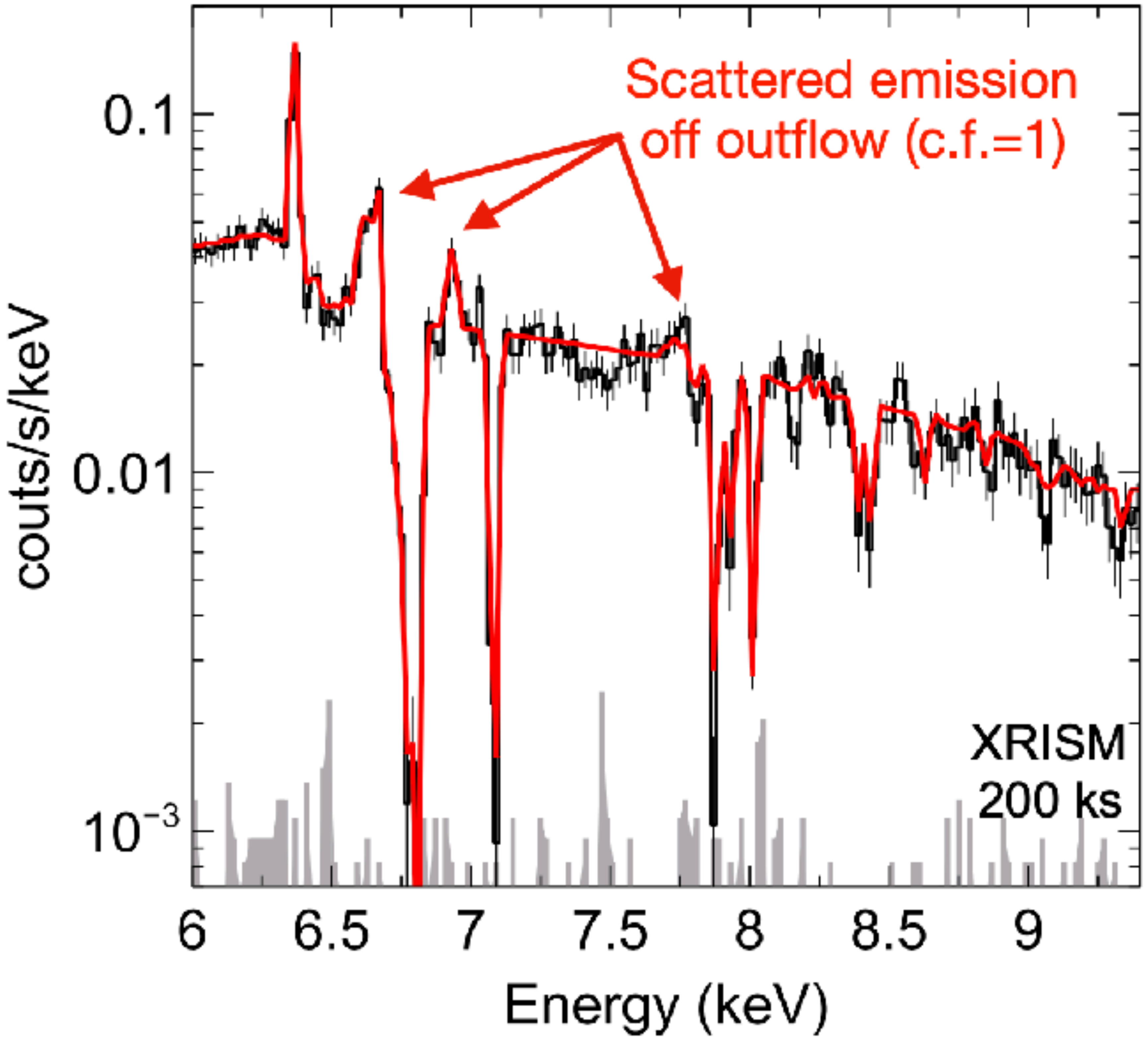
The Present



Launching in 2023!

NGC 1365





Adapted from Risaliti+05

Slide courtesy of E. Kara

The Future

HEX-P
HIGH ENERGY X-RAY PROBE
https://hexp.org/