Reflection and Iron Lines

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in collaboration with:

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ERLANGEN CENTRE
FOR ASTROPARTICLE
PHYSICS

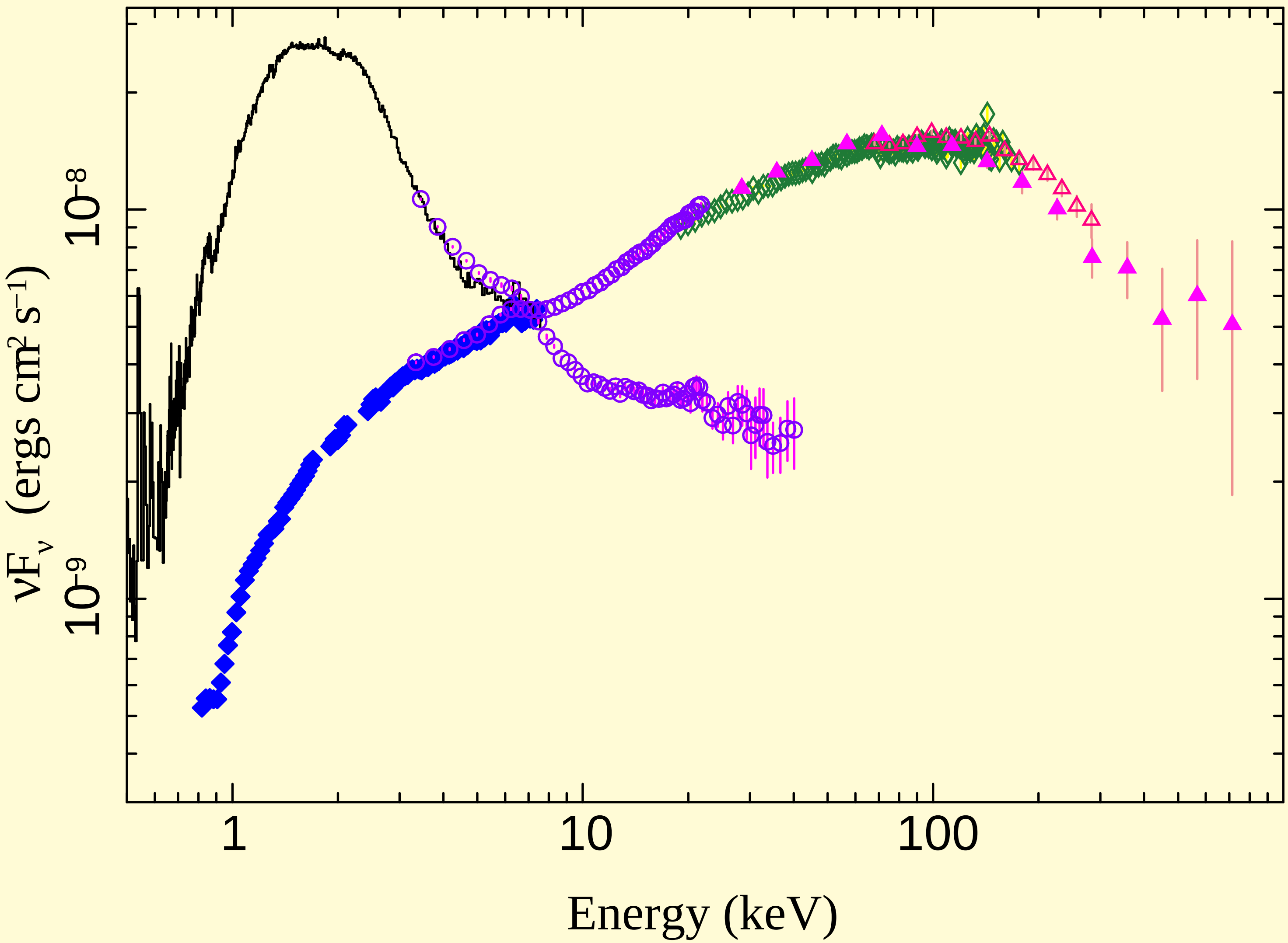
Black Hole Universe

Friedrich-Alexander-Universität
Erlangen-Nürnberg

Structure

- Accretion Geometry, Reflection, and Line Emission (for non-X-ray people)
  - Accretion Geometry
  - Reflection
  - Diagnostic potential of broadened lines
  - Some Caveats
- Observational Results: Lines
  - Broad lines are everywhere!
  - . . . but what can we learn?
  - Caveat: know your instrument. . .
- Summary

Continuum Emission



Typical X-ray spectra of galactic black holes

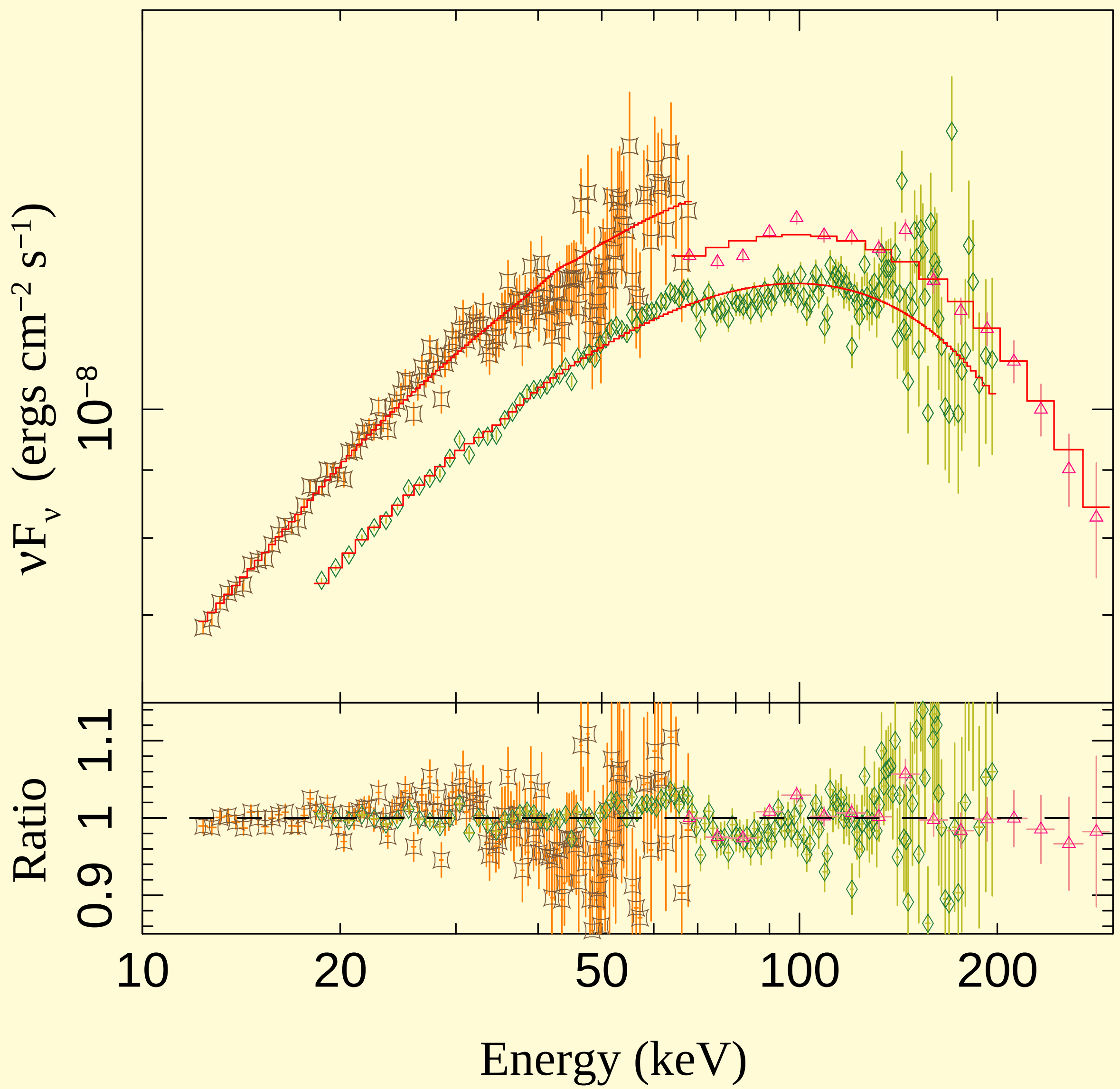
AGN are similar

($L \sim 3\%\, L_{\text{Edd}}$; $L_{\text{Edd}} = 10^{38}\,\text{erg}\,\text{s}^{-1} = 10^5\, L_\odot$)

Cyg X-1 (Nowak, et al., 2011)

See talk by Julien Malzac

Continuum Emission

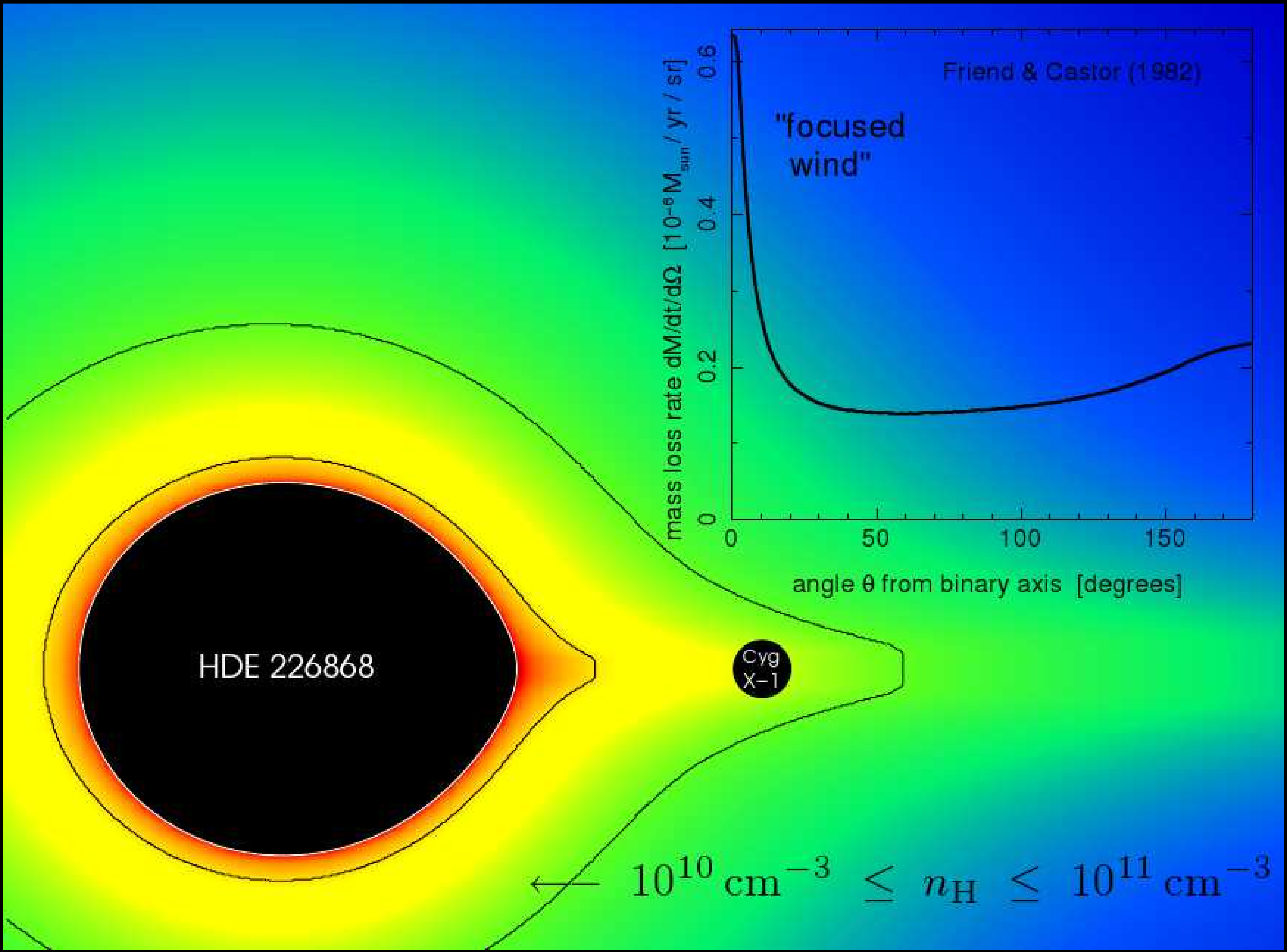


Observational consensus number 1:

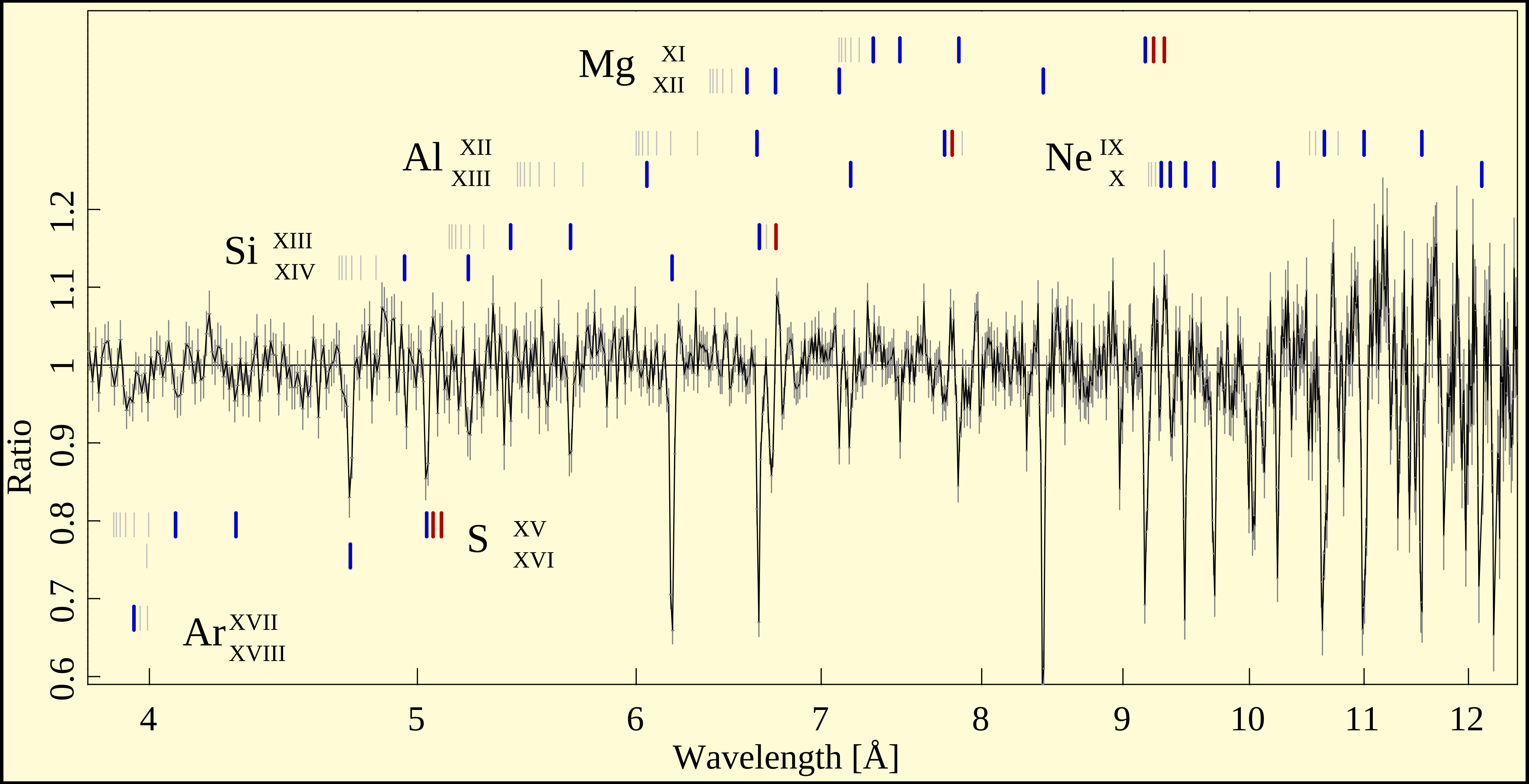
The >10 keV spectrum is an exponentially cutoff power-law,
$F_E \propto E^{-\Gamma} \mathrm{e}^{-E/E_\text{fold}}$.

- Typical folding energies: 50–300 keV
- Some sources also show non-thermal hard tails at >200 keV

Cyg X-1 with Suzaku-PIN and -GSO, and HEXTE (offset: flux normalization), Nowak et al. (2010).



But note: X-rays are affected by environment of black hole

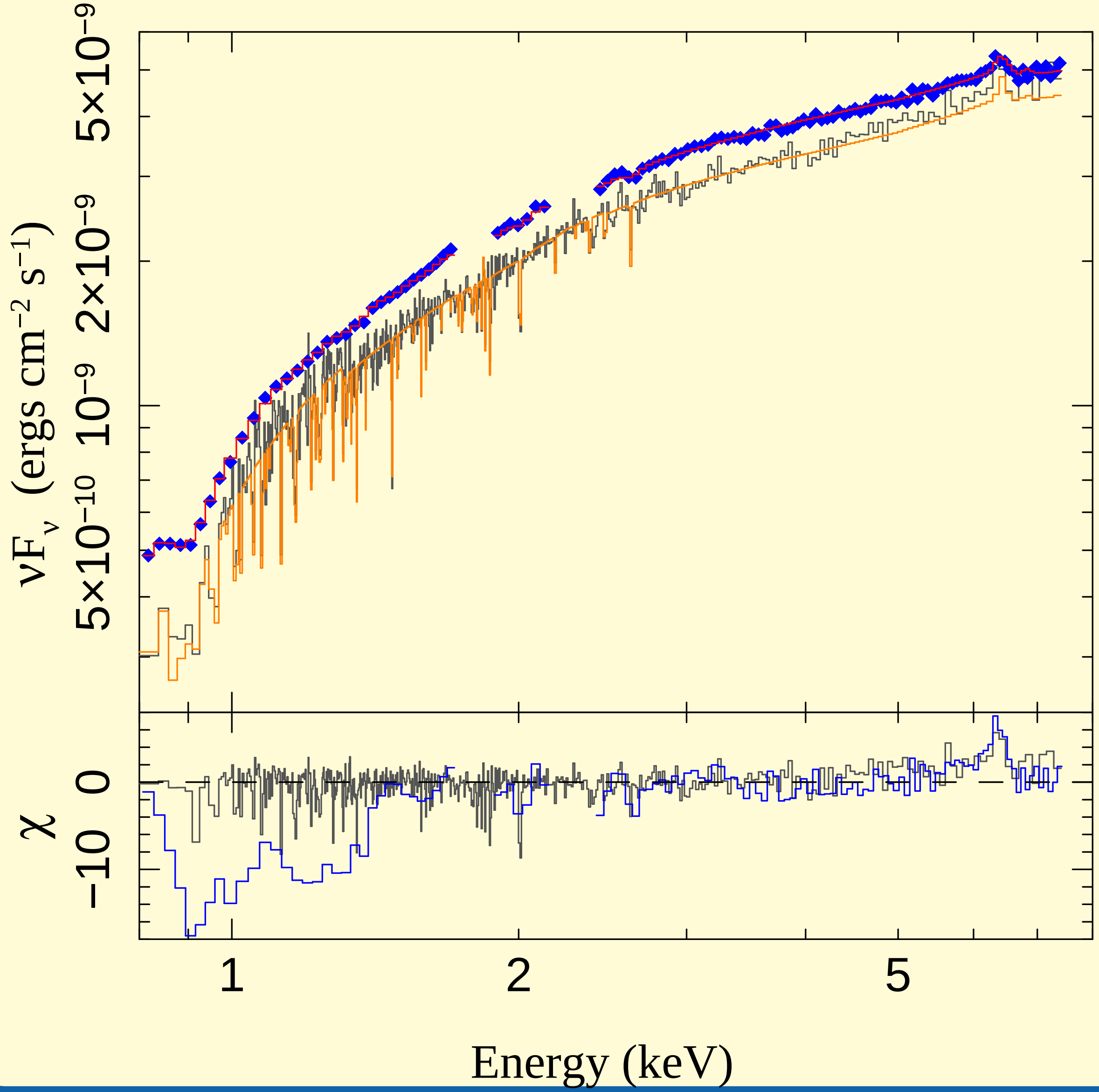


(Hanke et al., 2009)

Even outside absorption dips: For high-mass X-ray binaries Non-dip spectrum shows significant line absorption features from all relevant H- and He-like ions from the stellar wind.

Spectrum during dips shows even more structure.

Continuum Emission



Observational consensus number 2:

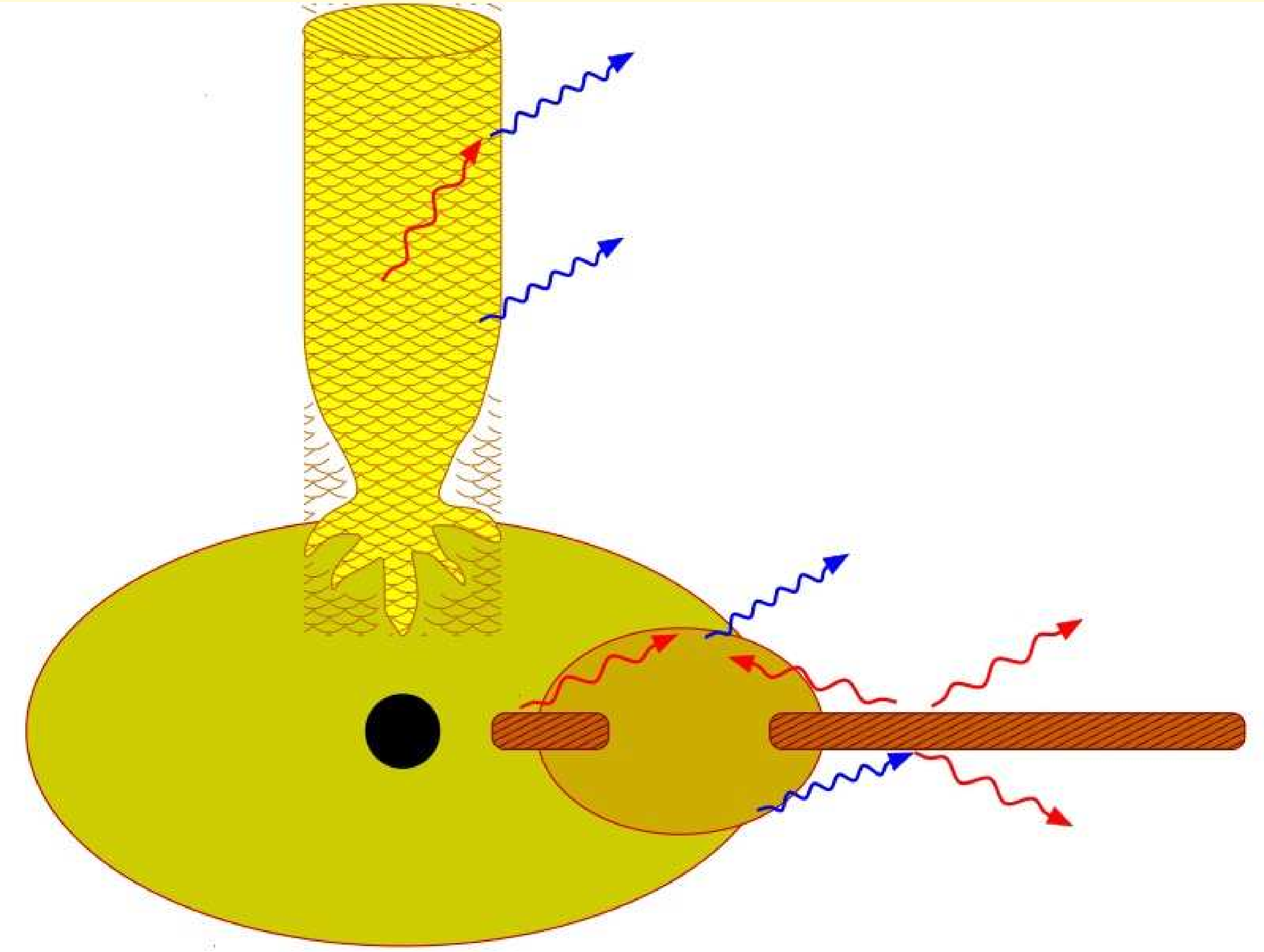
The $<$10 keV spectrum is sum of a power law, disk emission, emission lines, and (ionized) absorption.

- $<$1.5 keV: Ionized absorption *has* significant influence!
- For high spatial resolution: take scattering halo into account!
- Need to use correct abundances in modeling ISM.

Cyg X-1 with Suzaku-XIS and *Chandra*-HETG, lines have been set to zero, Nowak et al. (2010).

$\Longrightarrow$ See Talk by I. Miskovicova

Continuum Formation

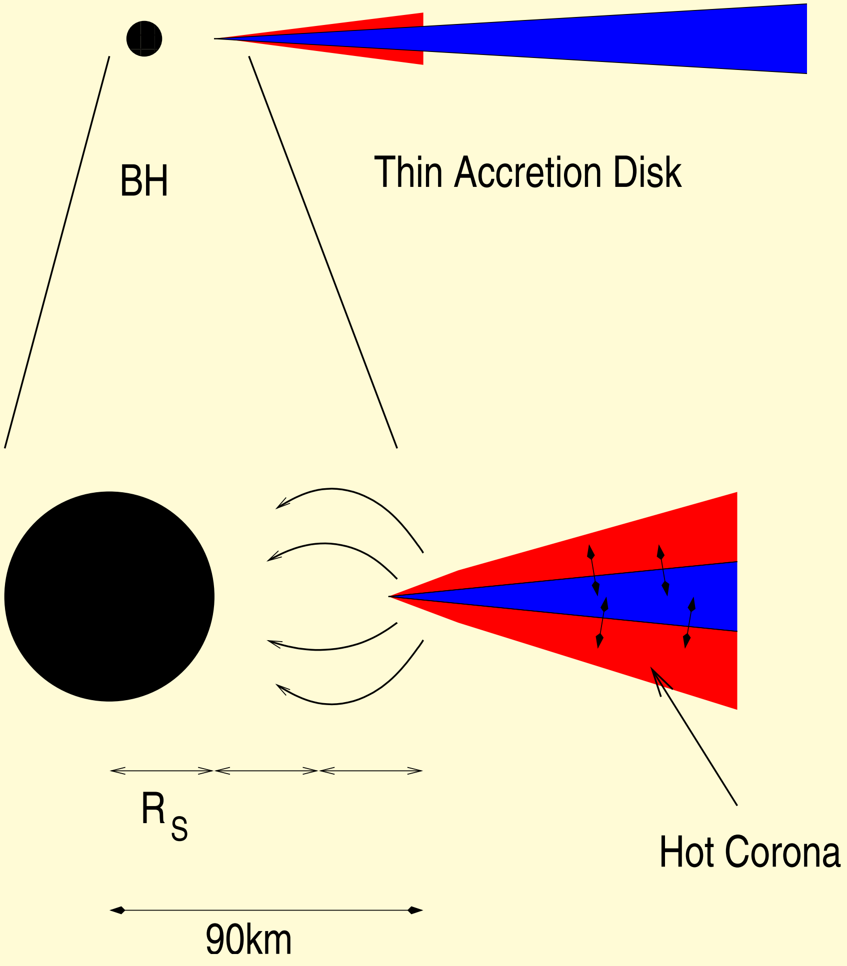


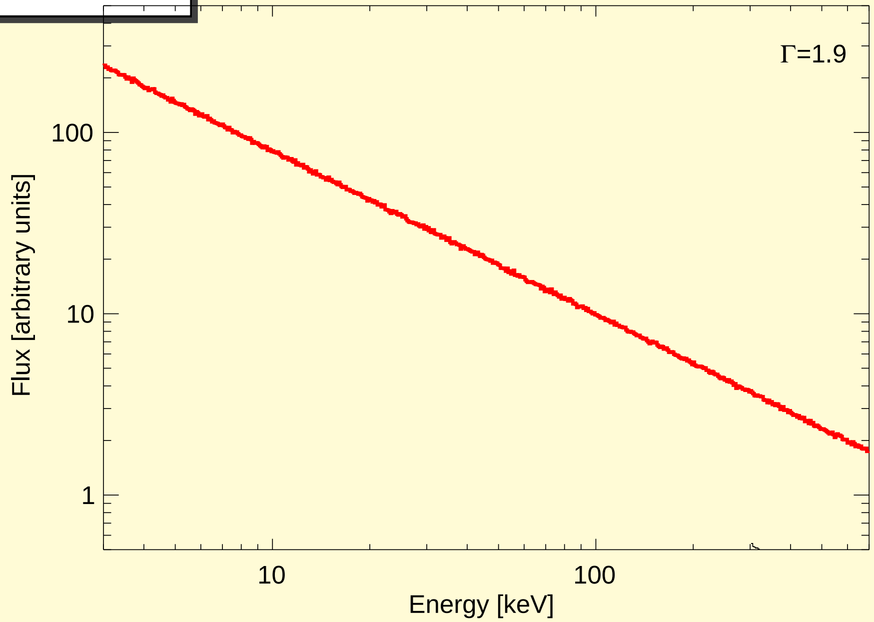
The origin of the Comptonized spectrum is still debated:

- sandwich corona models/sphere+disk: Haardt & Maraschi (1991),Dove et al. (1998),. . .
  $\Longrightarrow$ Comptonization from a hot electron plasma surrounding the disk
- lamppost models: Matt et al. (1992), Markoff et al. (2005), Miniutti et al. (2007),. . .
  $\Longrightarrow$ Comptonization from the base of a jet
  See talks tomorrow

(Nowak et al., 2011)

Simple Reflection





XRB/AGN X-Ray Spectrum:

- Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K): power law continuum.

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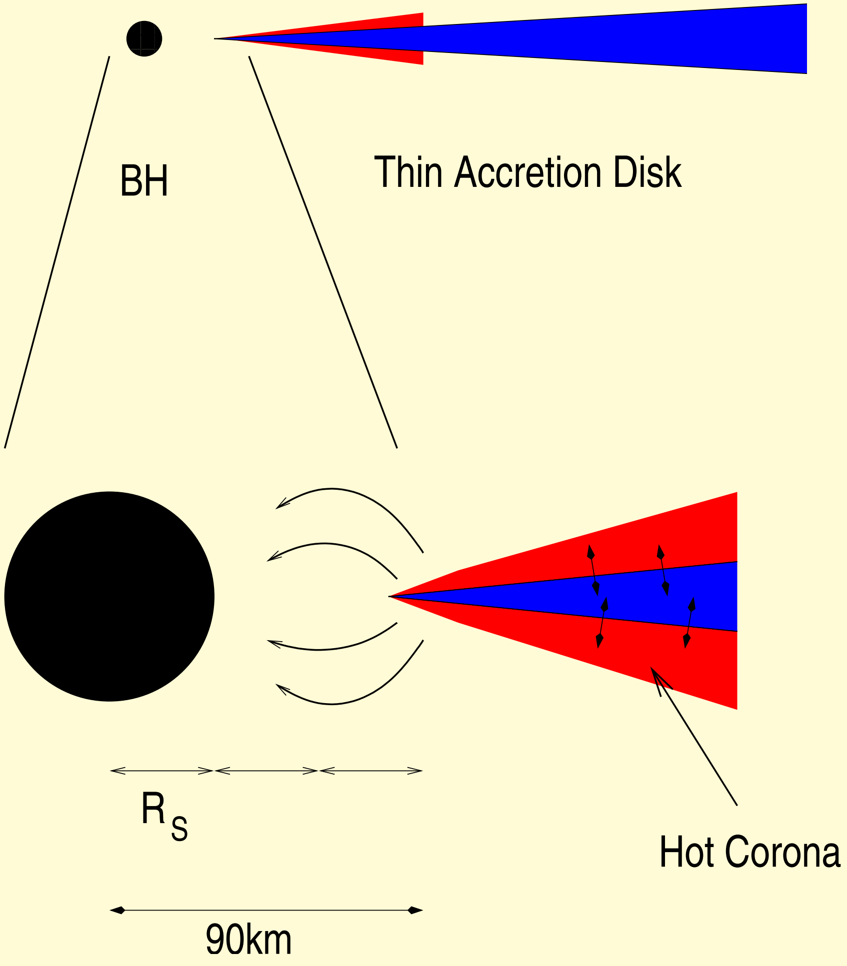

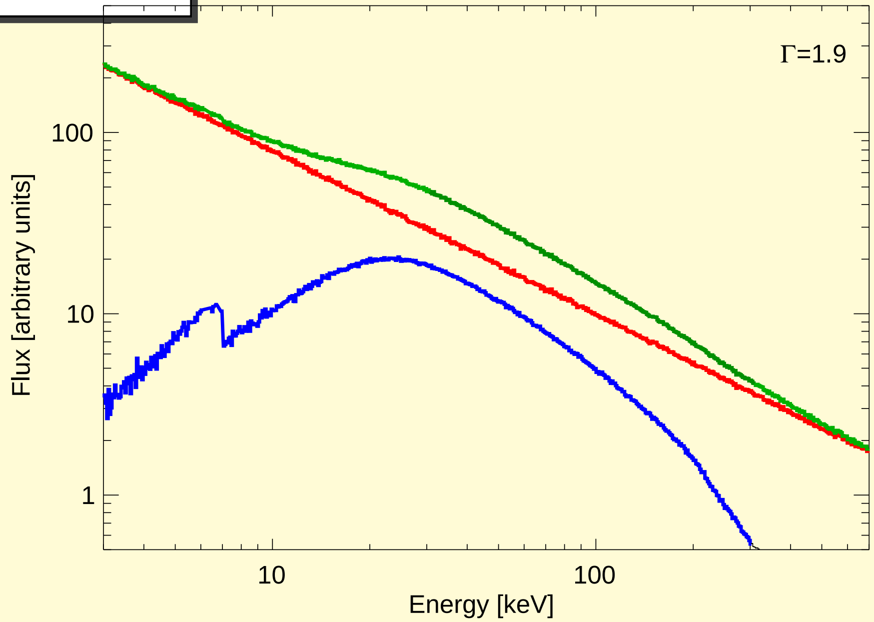

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- Thomson scattering of power law photons in disk: Compton Reflection Hump

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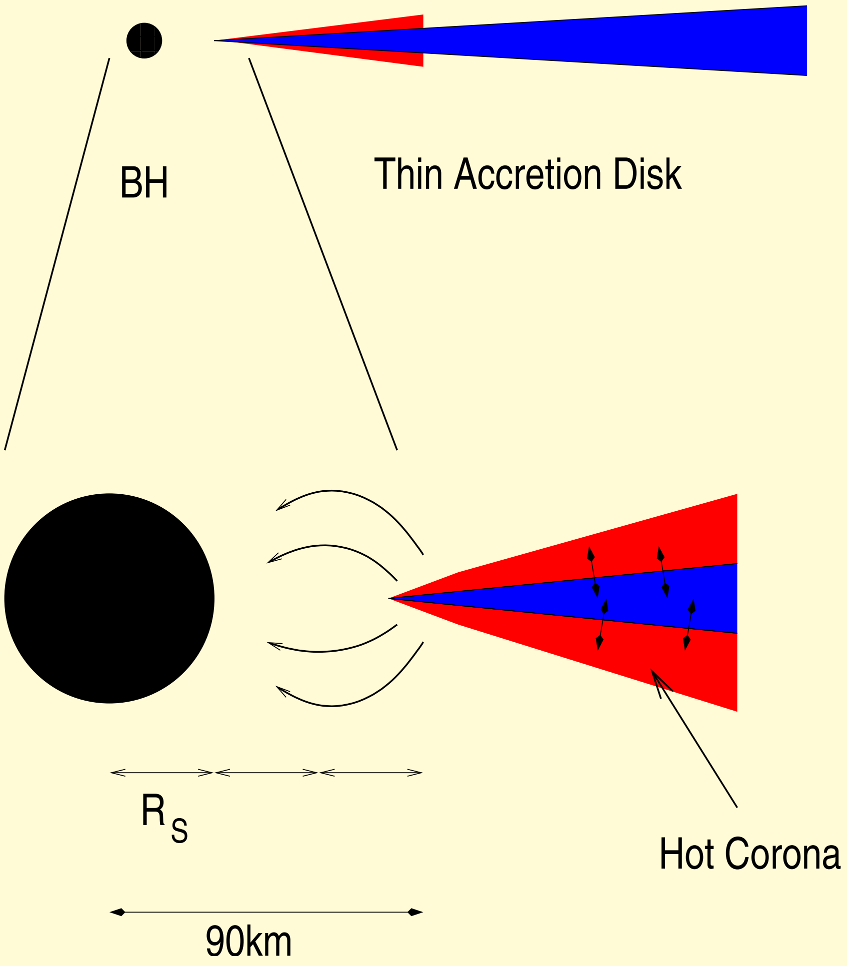
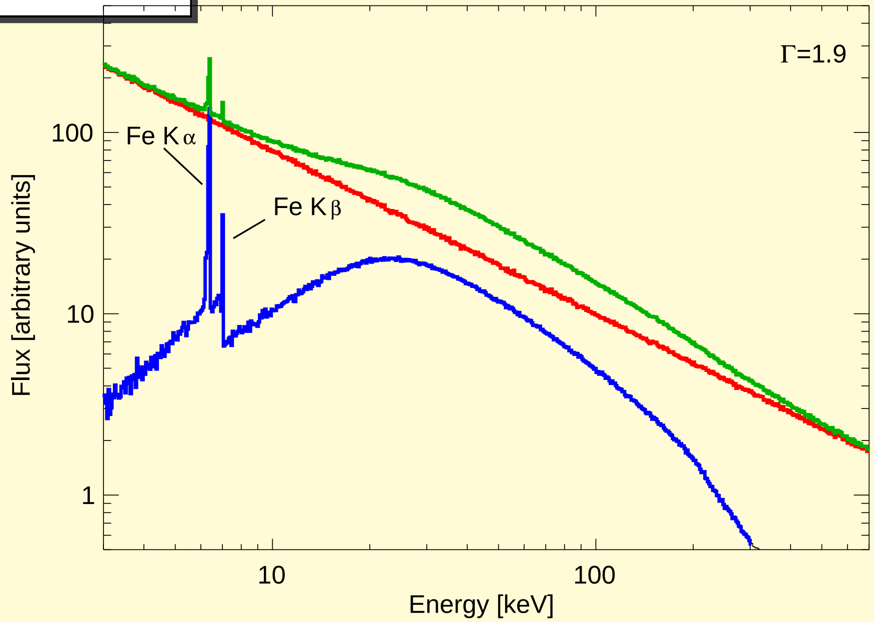


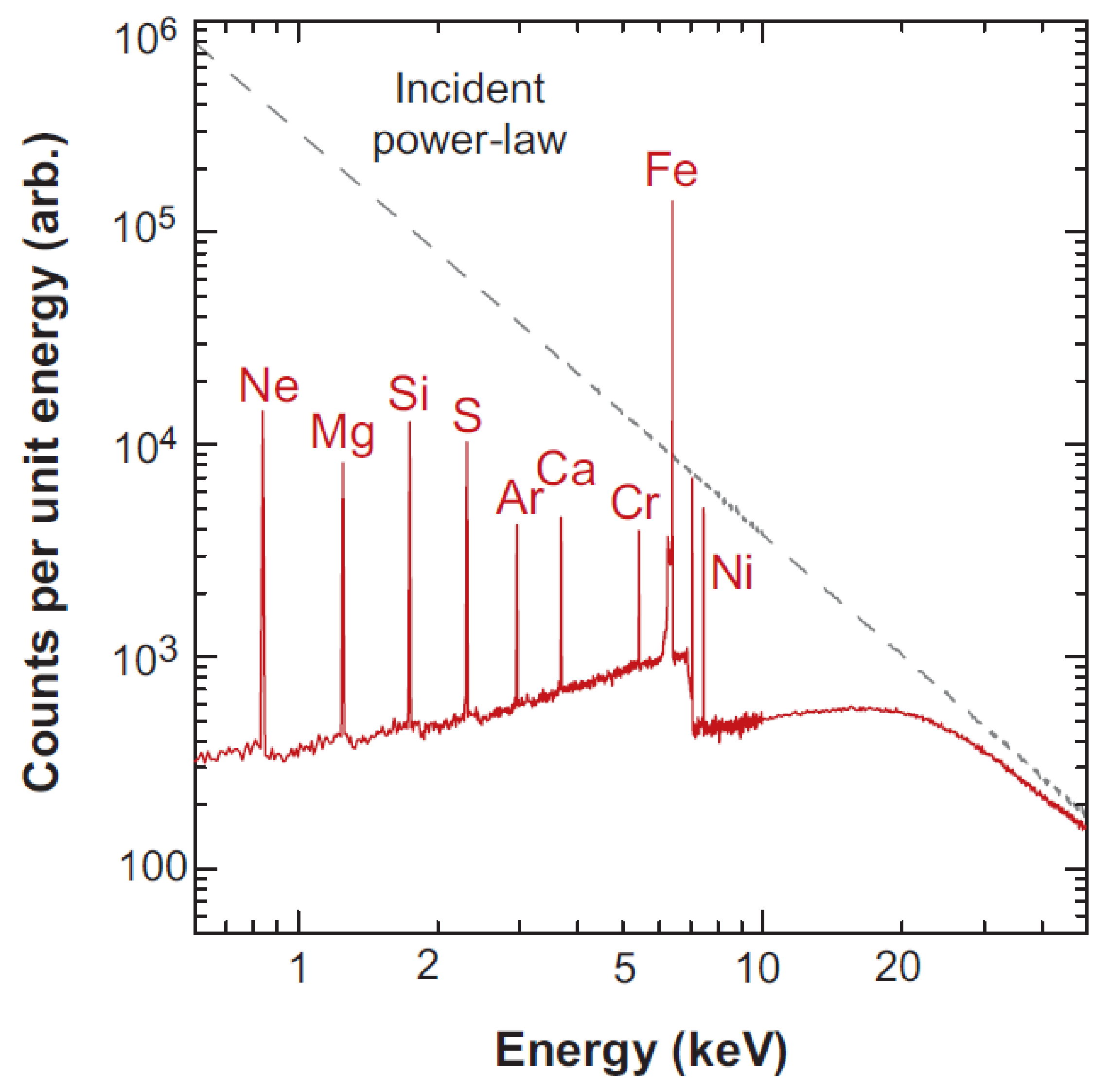


XRB/AGN X-Ray Spectrum:

- Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K): power law continuum.
- Thomson scattering of power law photons in disk: Compton Reflection Hump
- Photoabsorption of power law photons in disk: fluorescent Fe Kα Line at $\sim$6.4 keV

Models: Guilbert & Rees (1988), Lightman & White (1988), Magdziarz & Zdziarski (1995), Ross & Fabian (2007). Reviews: Turner & Miller (2009), Fabian & Ross (2010).

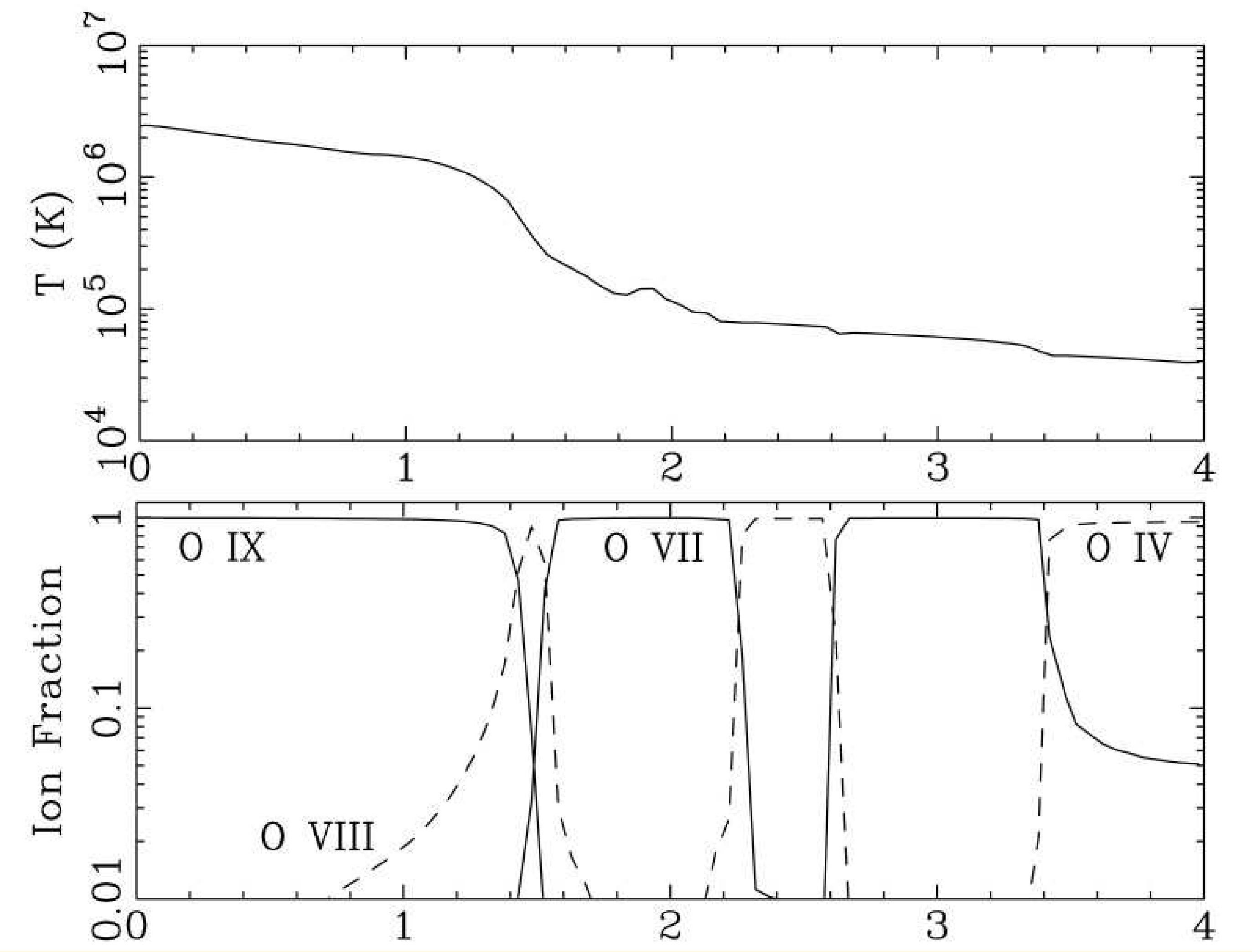
Simple Reflection



Prediction of neutral reflection models: fluorescent emission lines at low energies

(Reynolds, 1996)

Ionized Reflection



So far: neutral medium.

More realistic (Ross et al., 1999; Ross & Fabian, 2007; García & Kallman, 2010): ionized transition layer on disk surface.

(García & Kallman, 2010)

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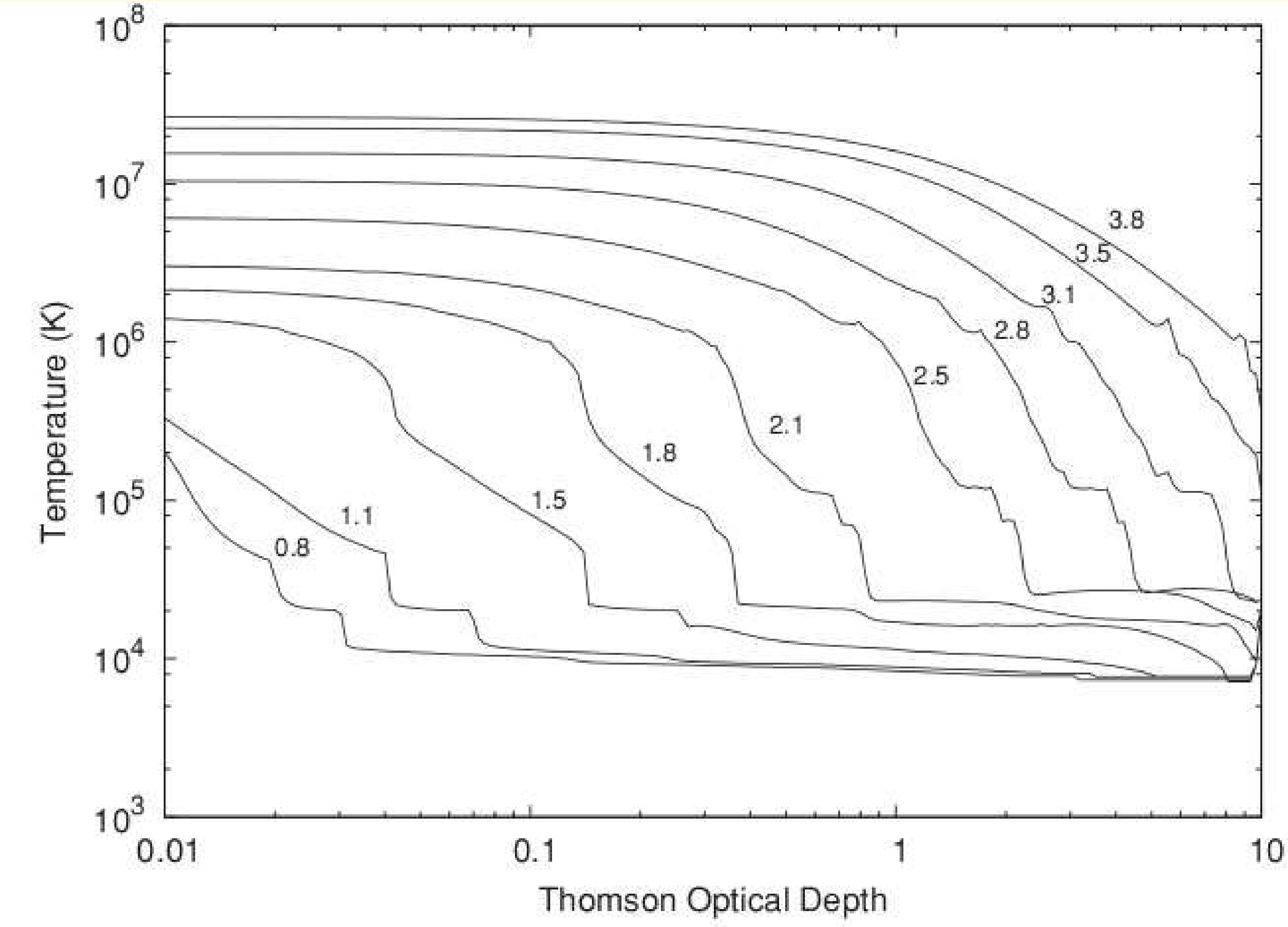

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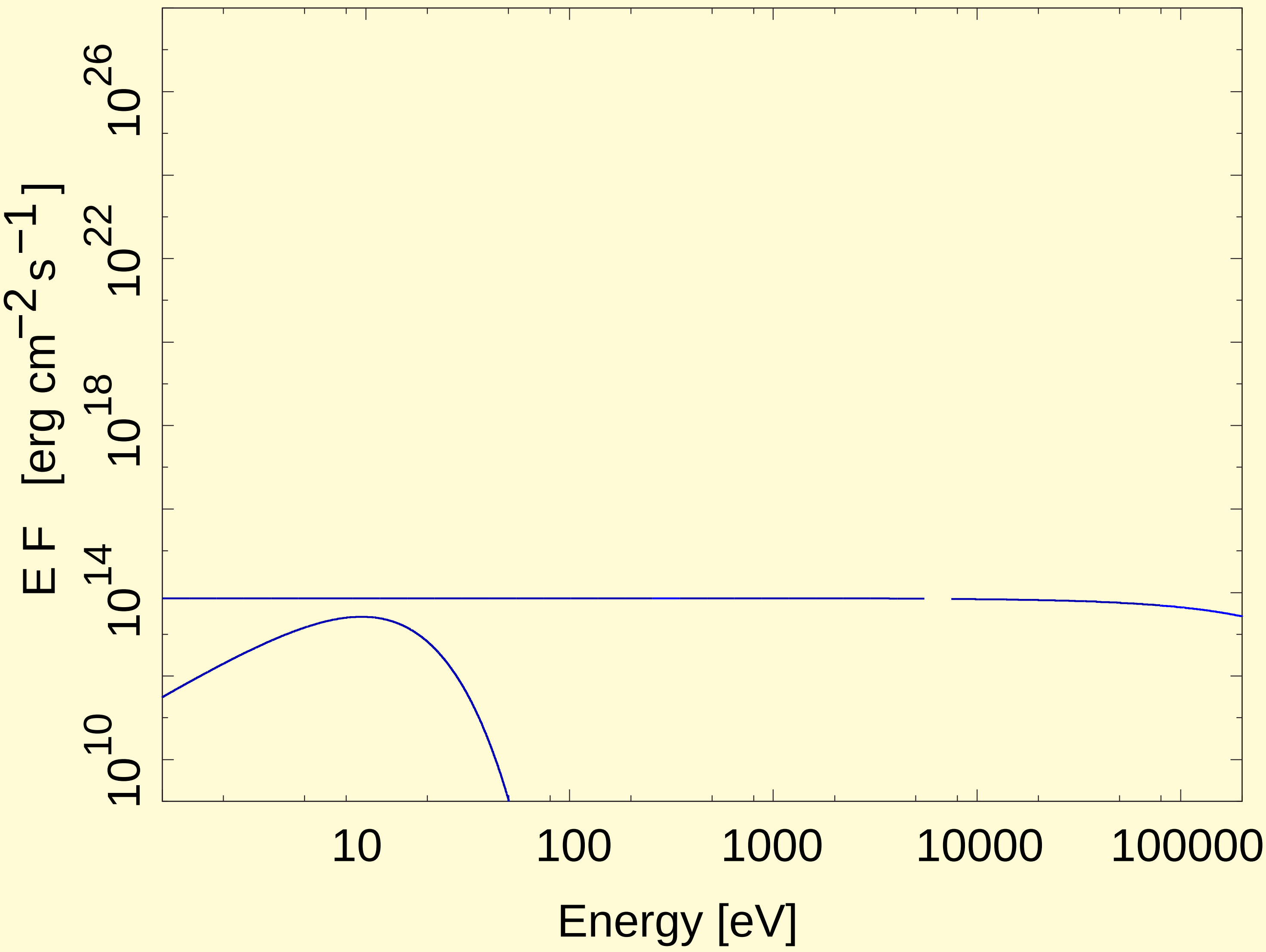


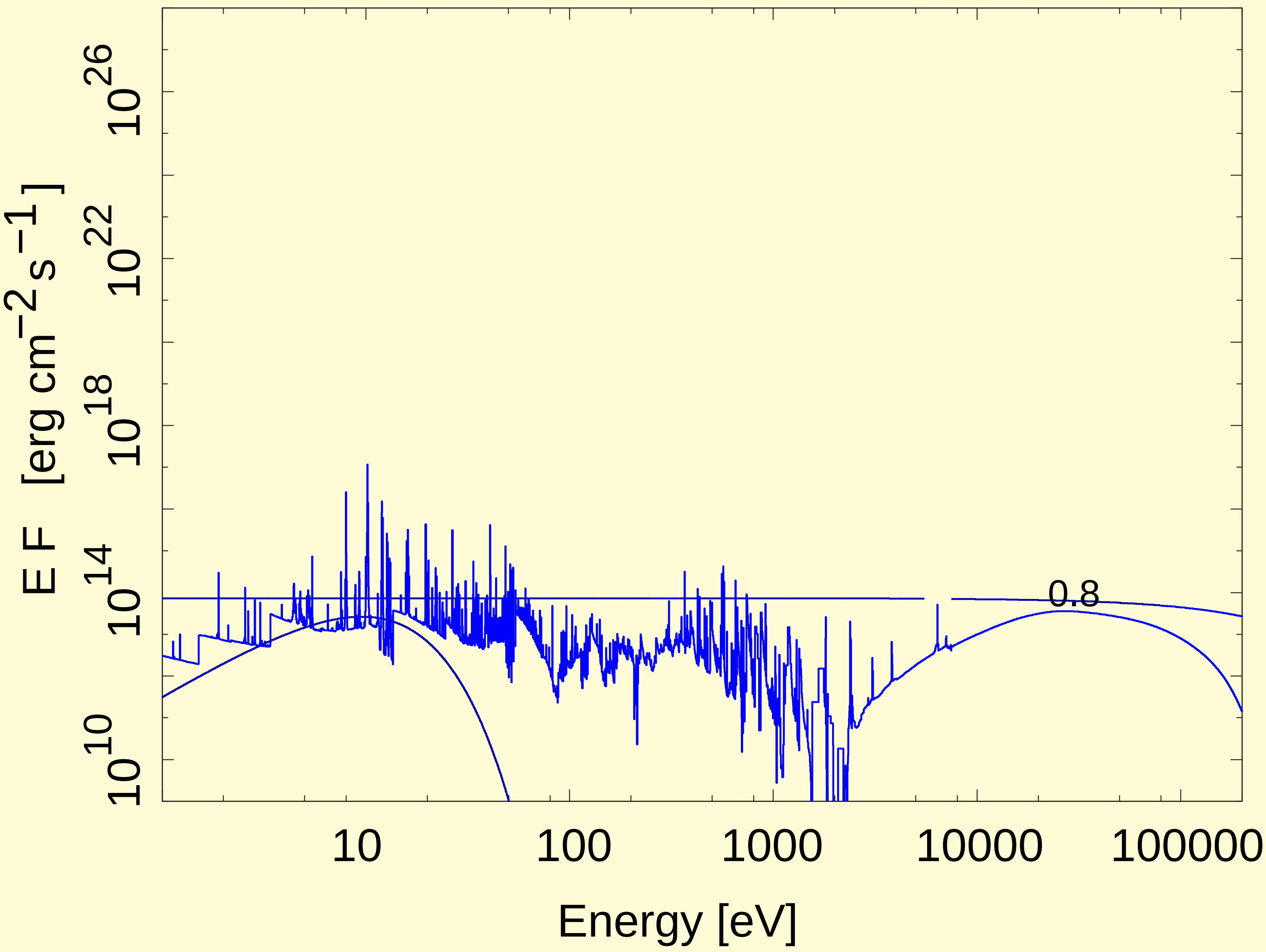
Ross & Fabian (2007, “`reflionx`”): Ionization: less absorption of lower Z elements $\Longrightarrow$ recovery of low energy emission, forest of emission lines

ionization parameter: $\xi = 4\pi F_x/n_\mathrm{e}$

Update with improved atomic physics: García & Kallman (2010), García et al. (2011)

(Fig. after García & Kallman, 2010)

Ionized Reflection



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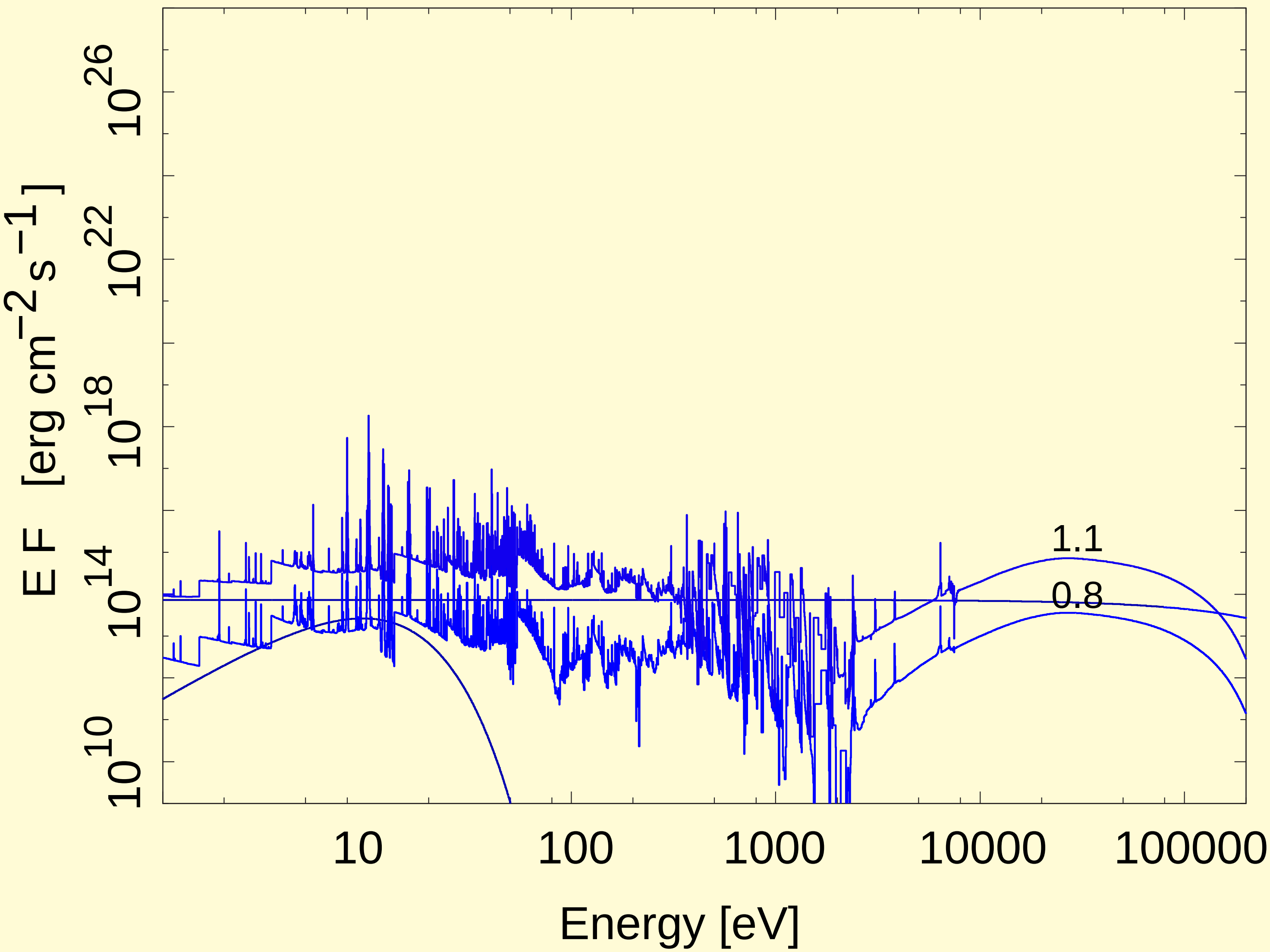

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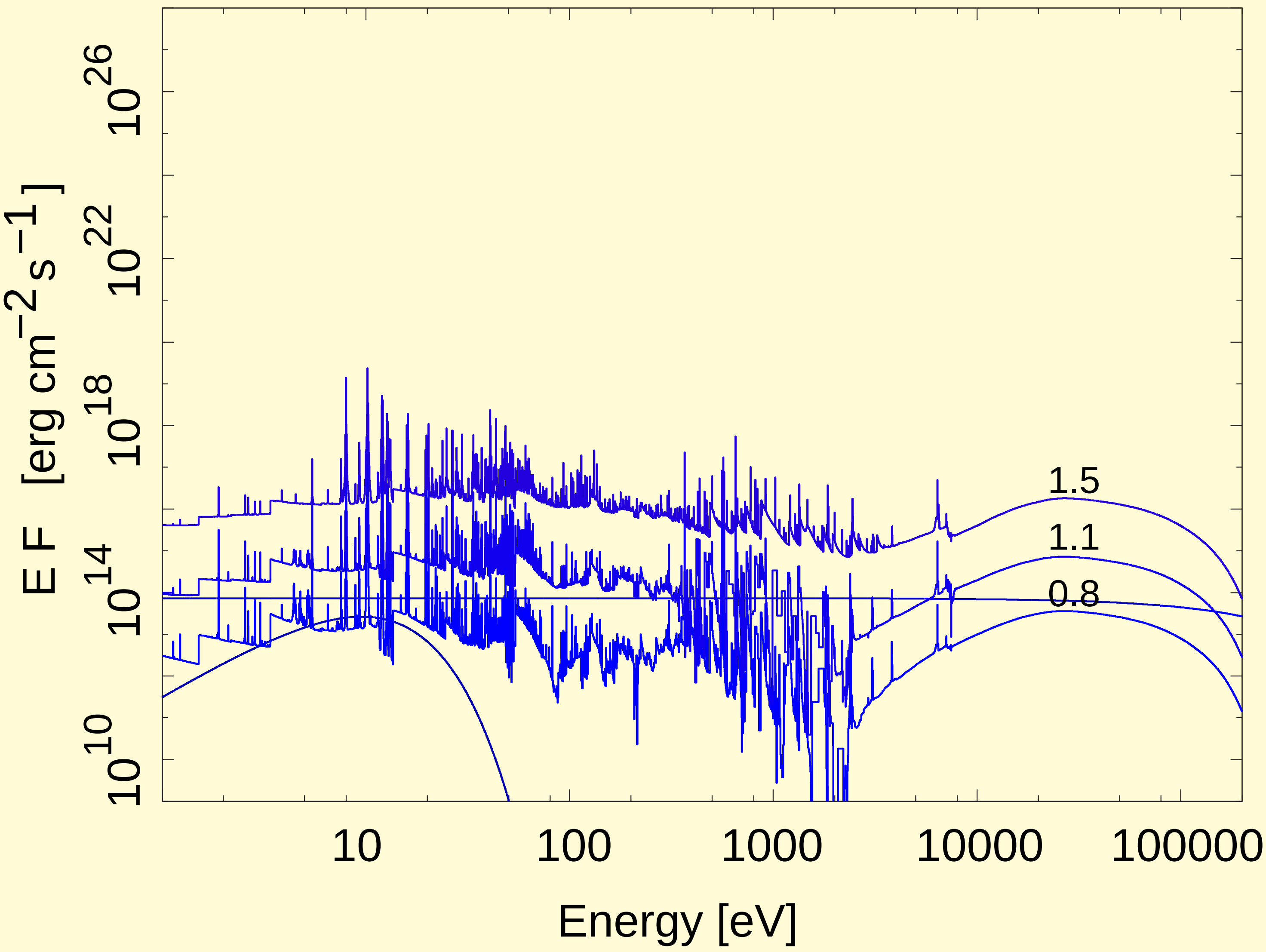

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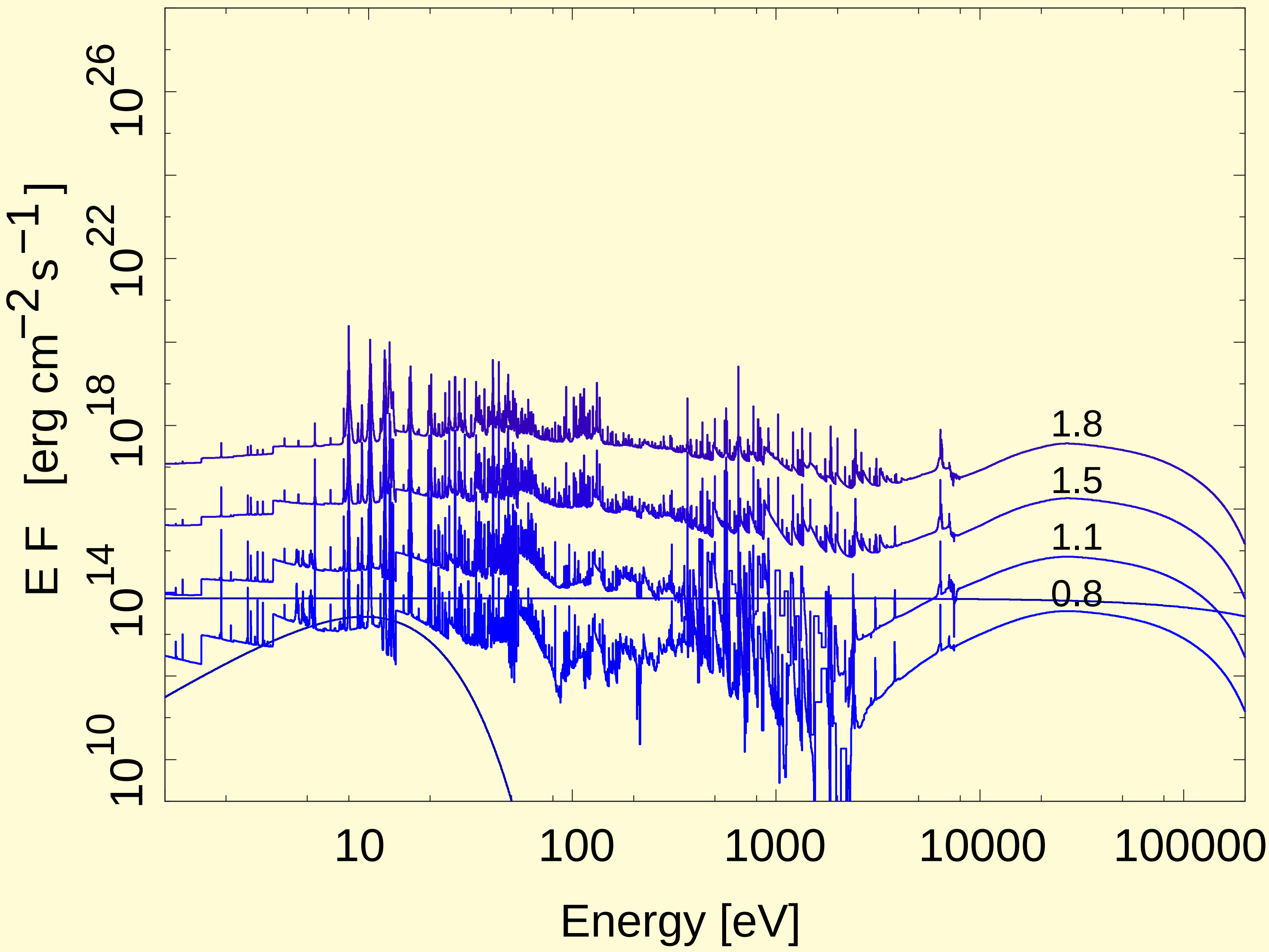

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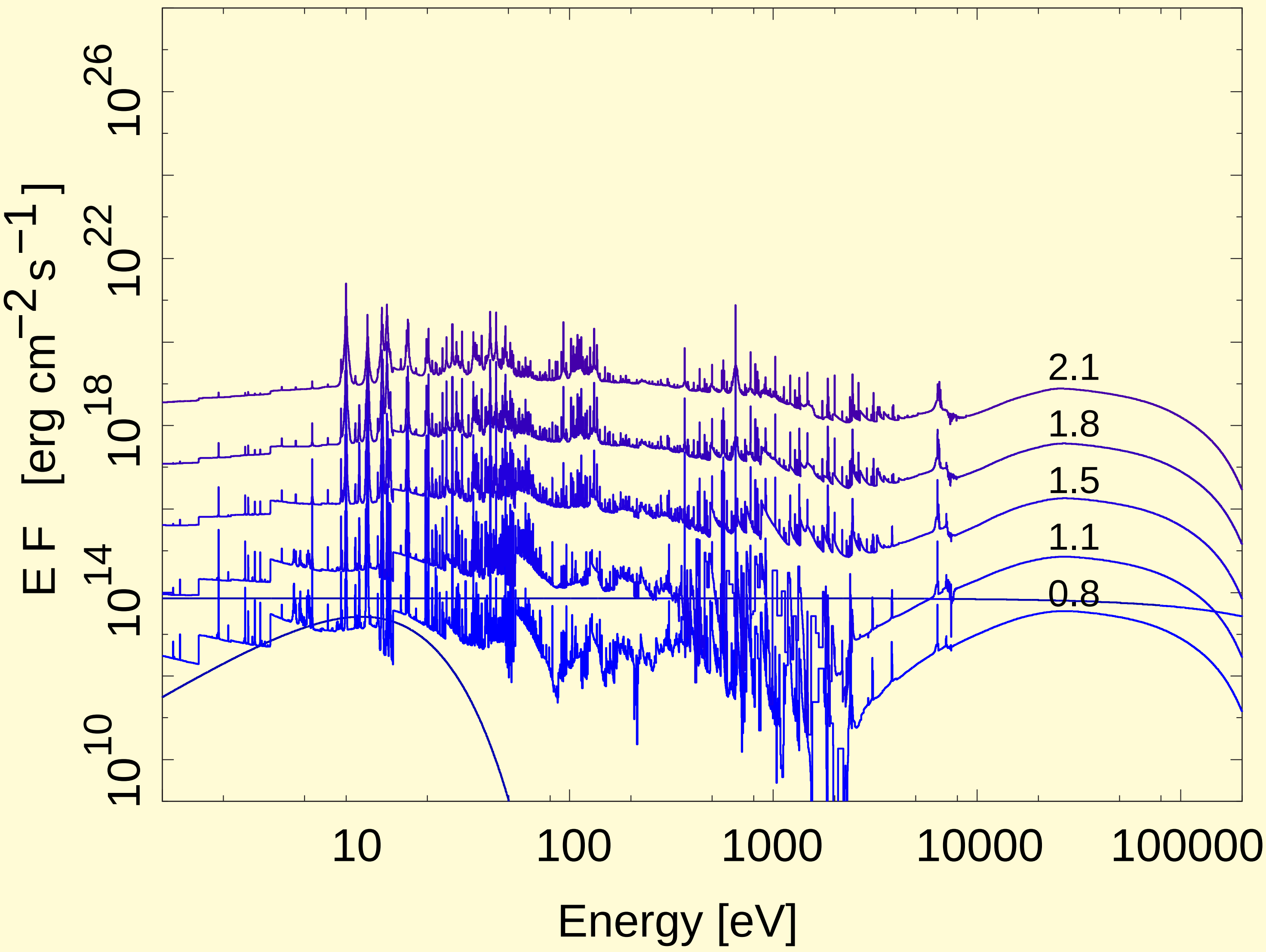

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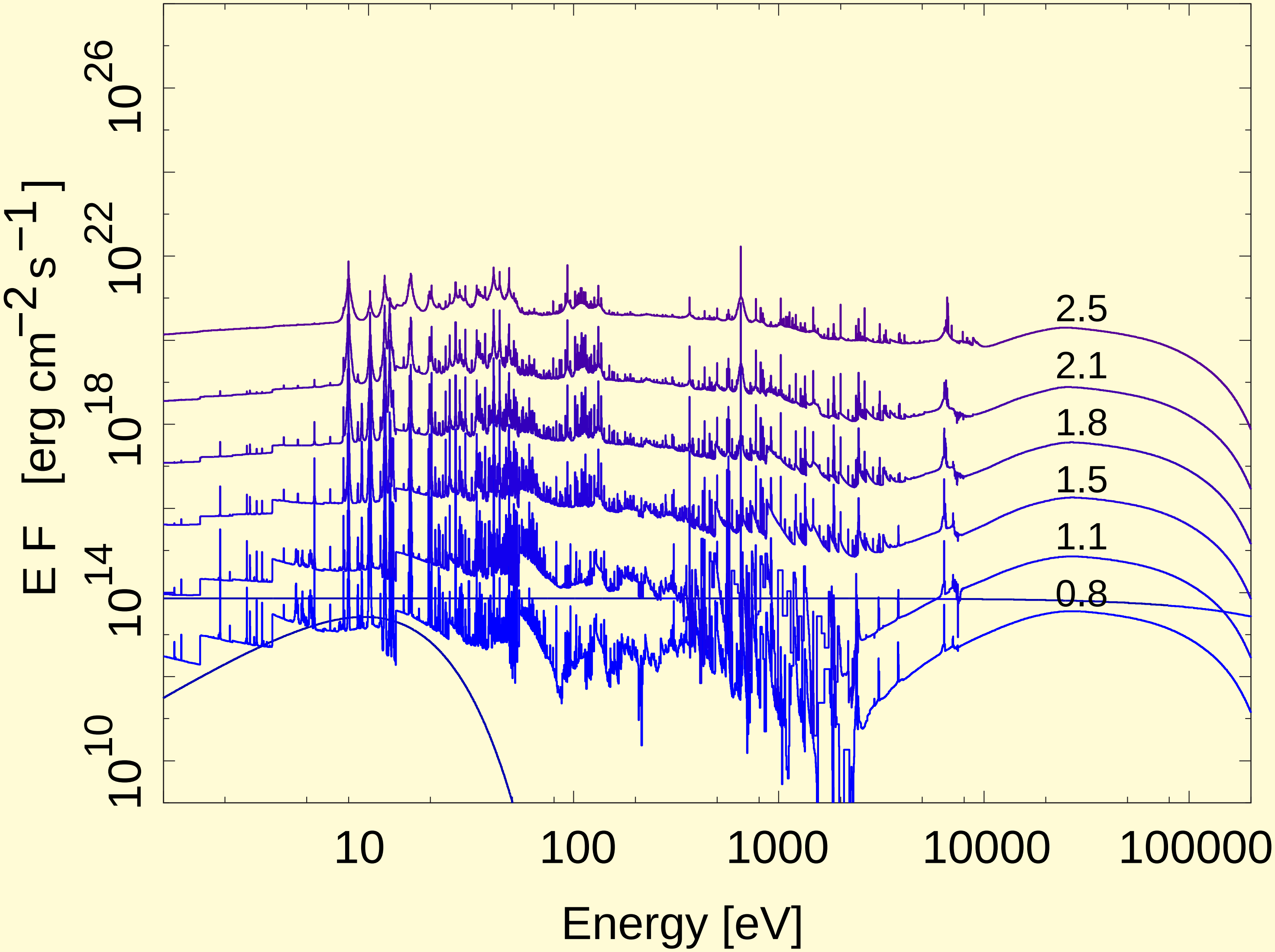

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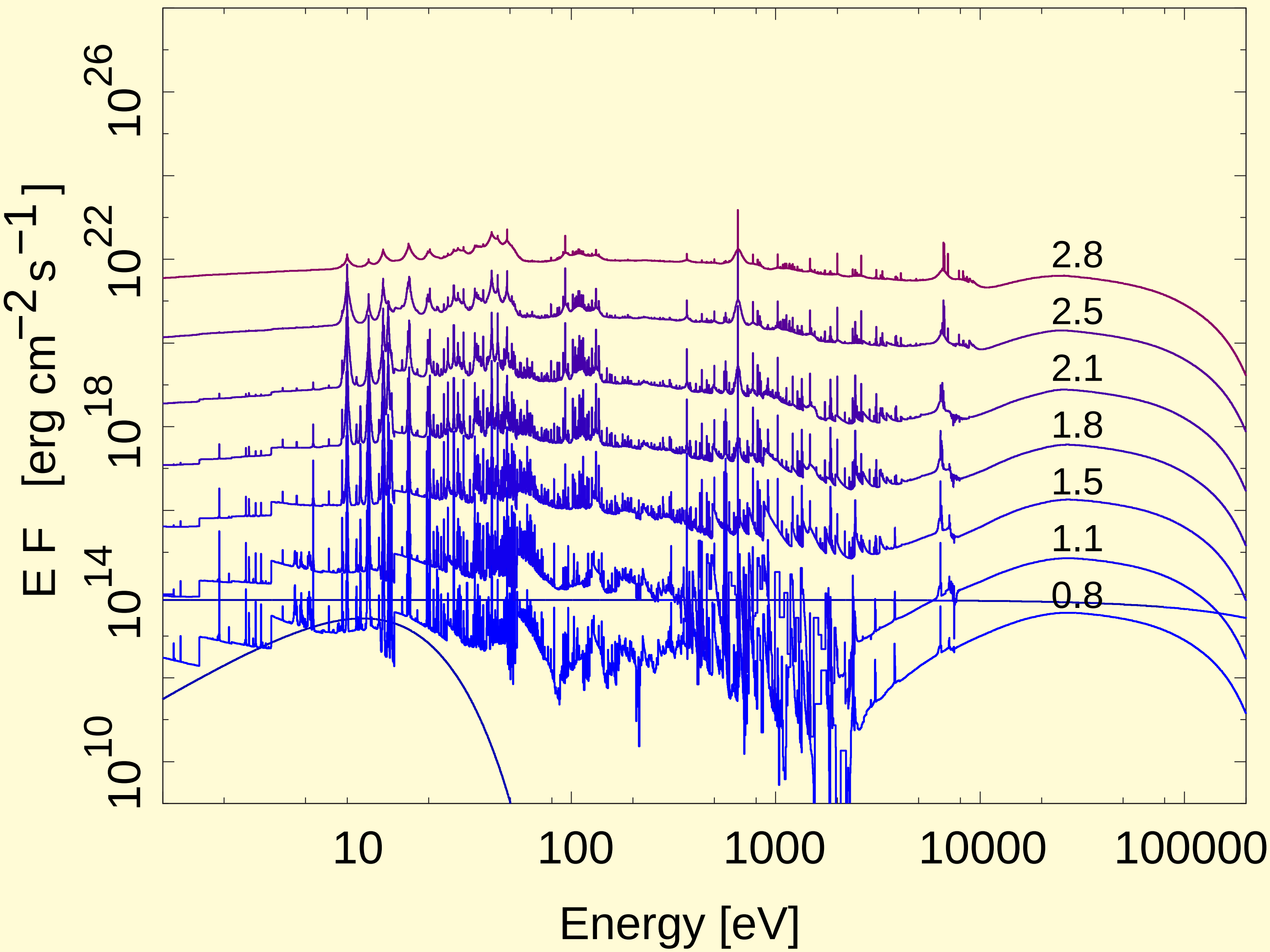

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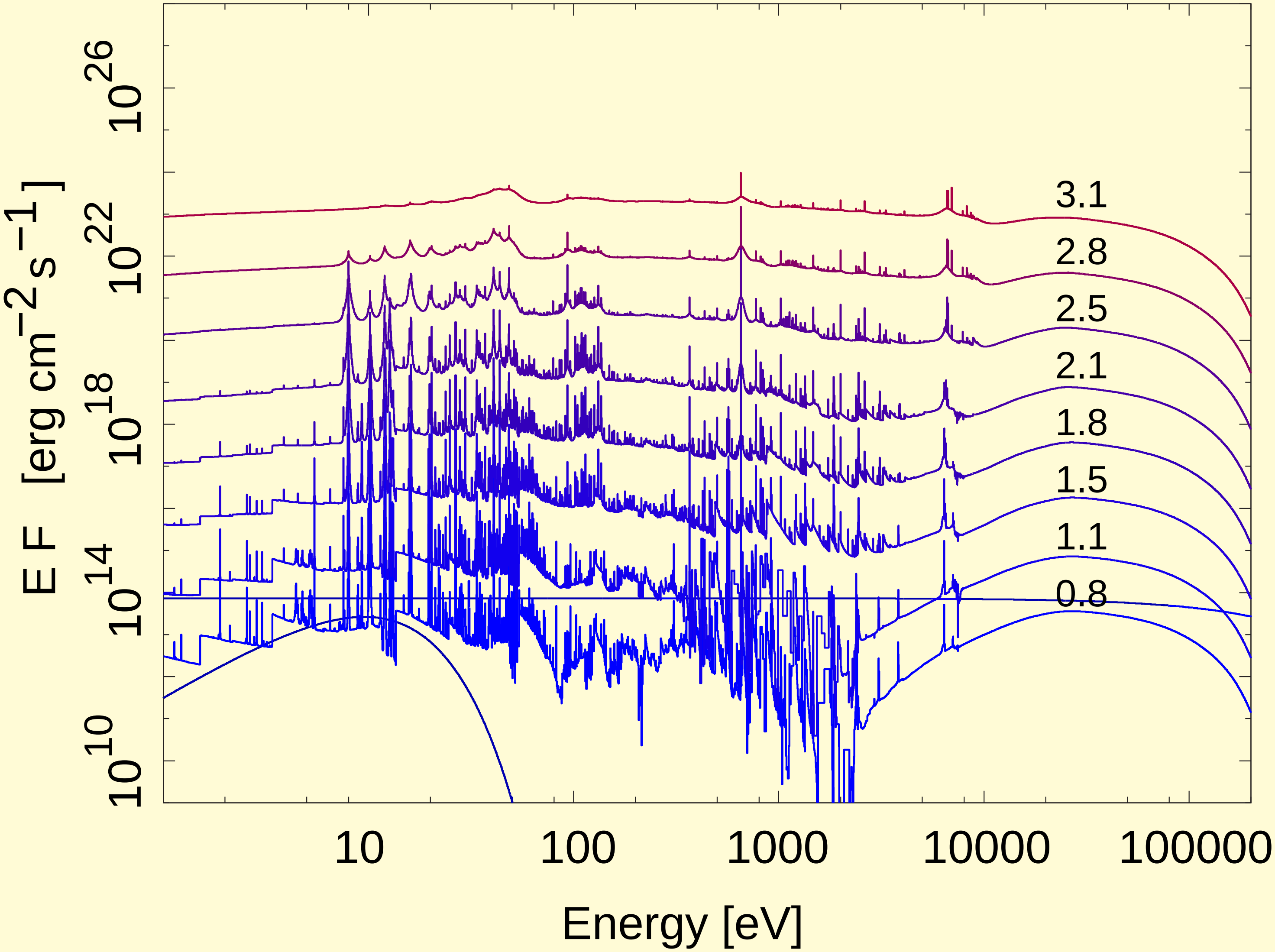

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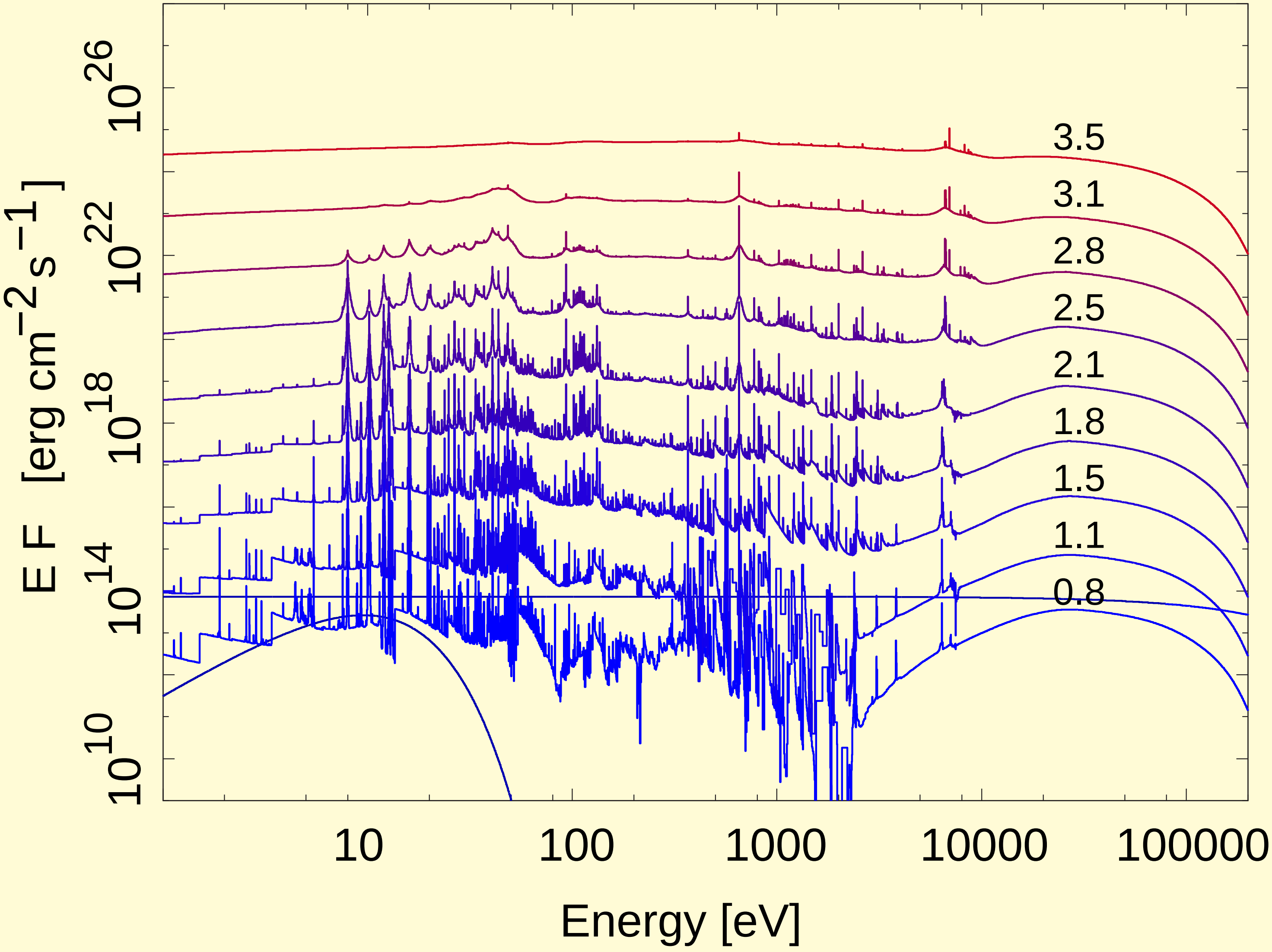

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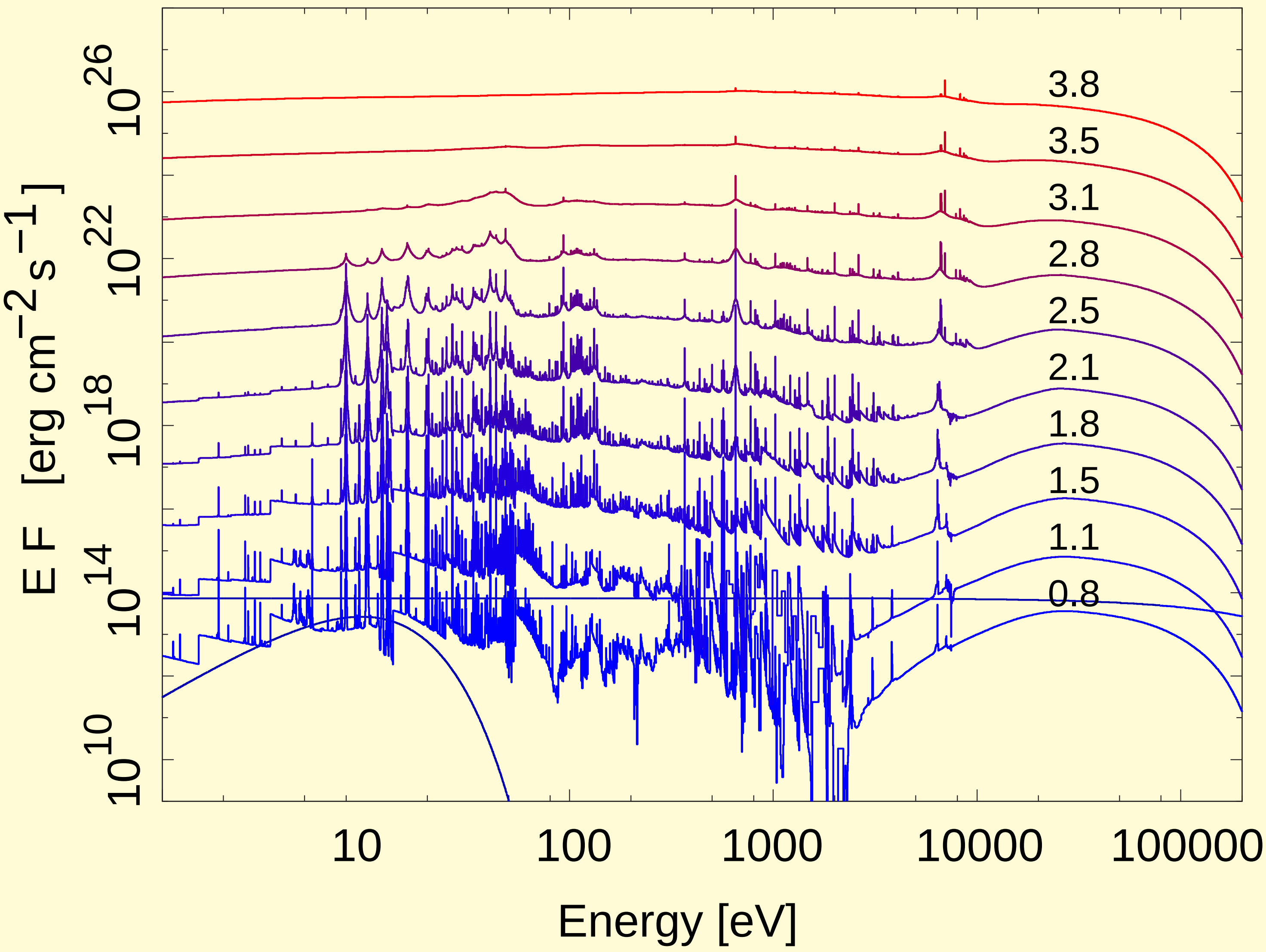

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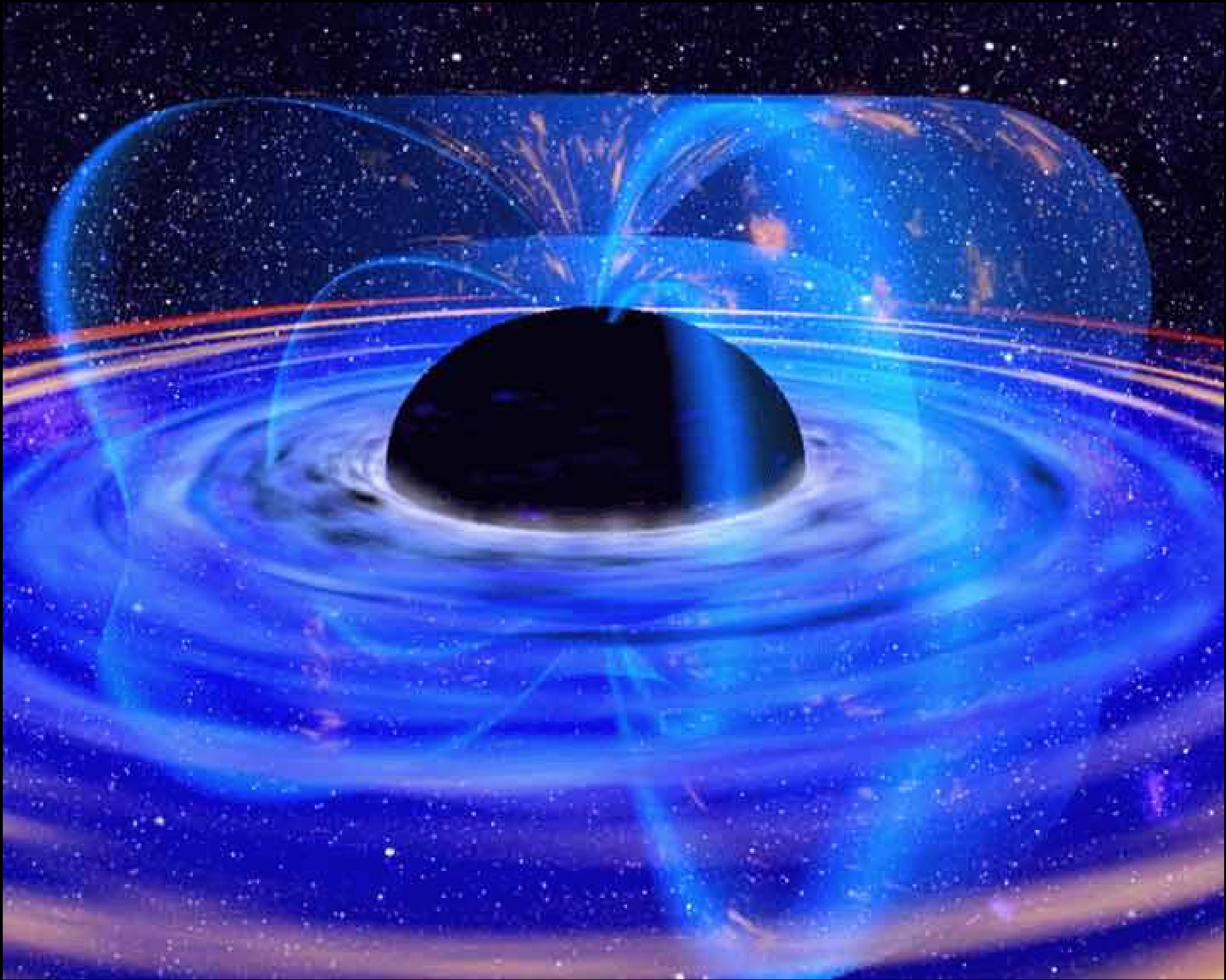
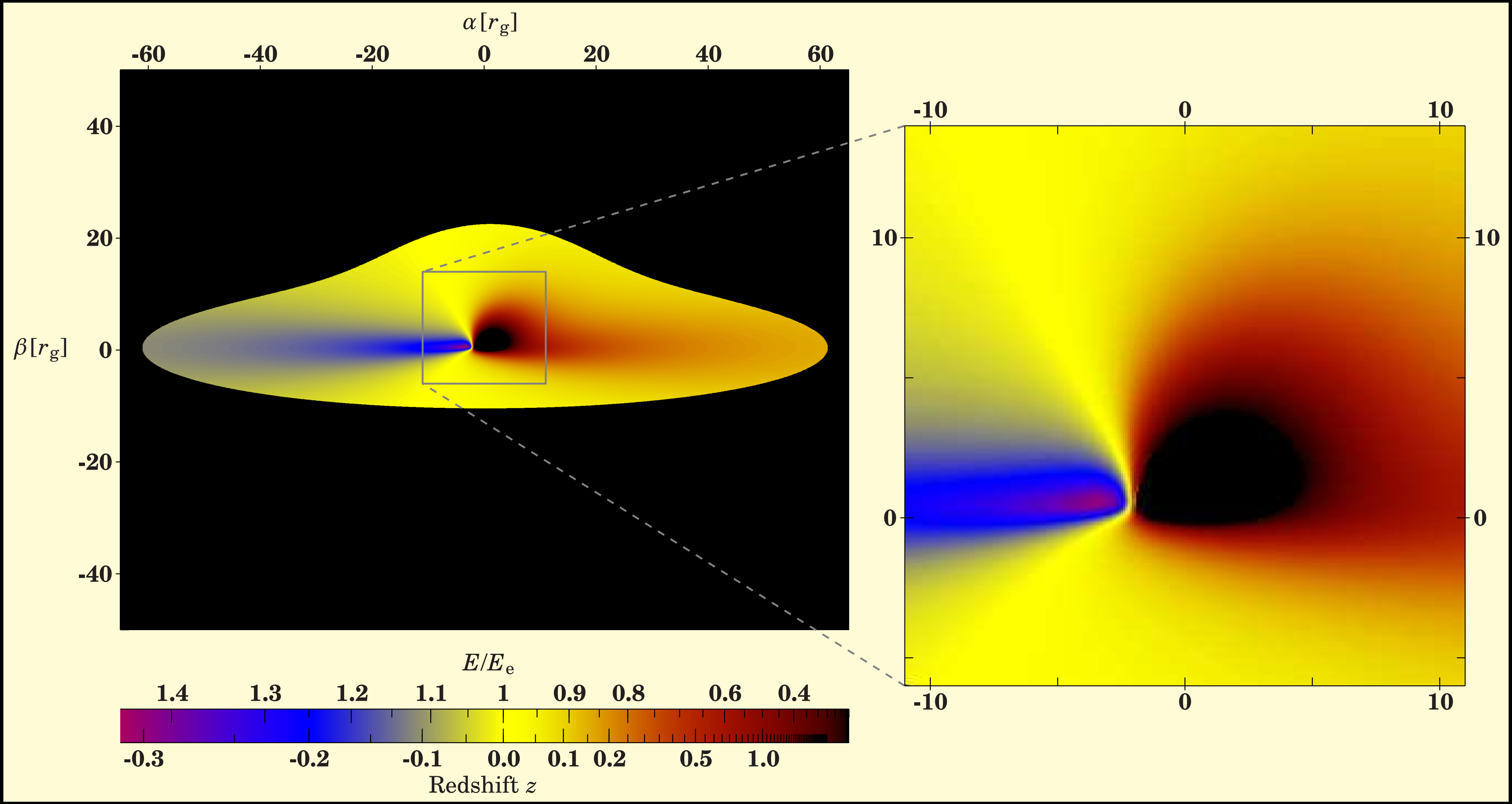
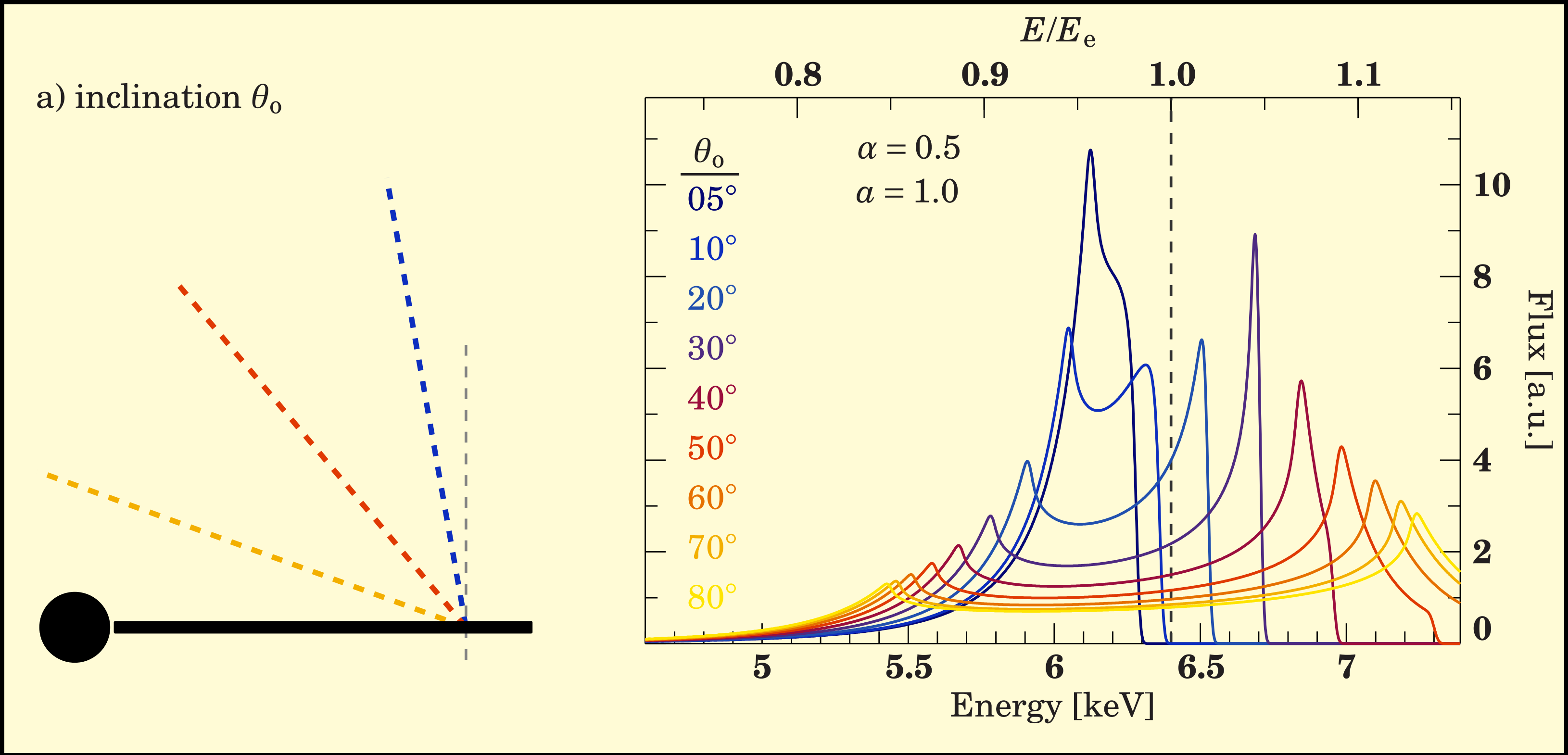




(Dauser, 2010)

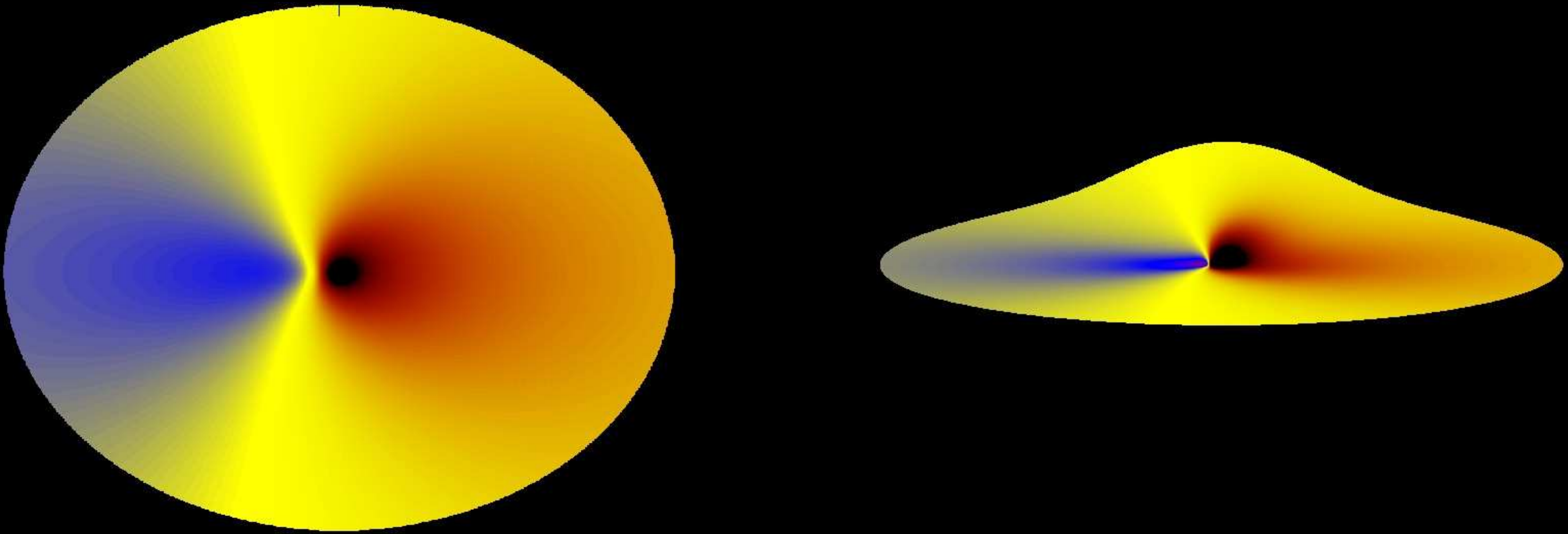
Close to the black hole, we need to include relativistic effects: special relativistic beaming, light bending, and gravitational redshifts.

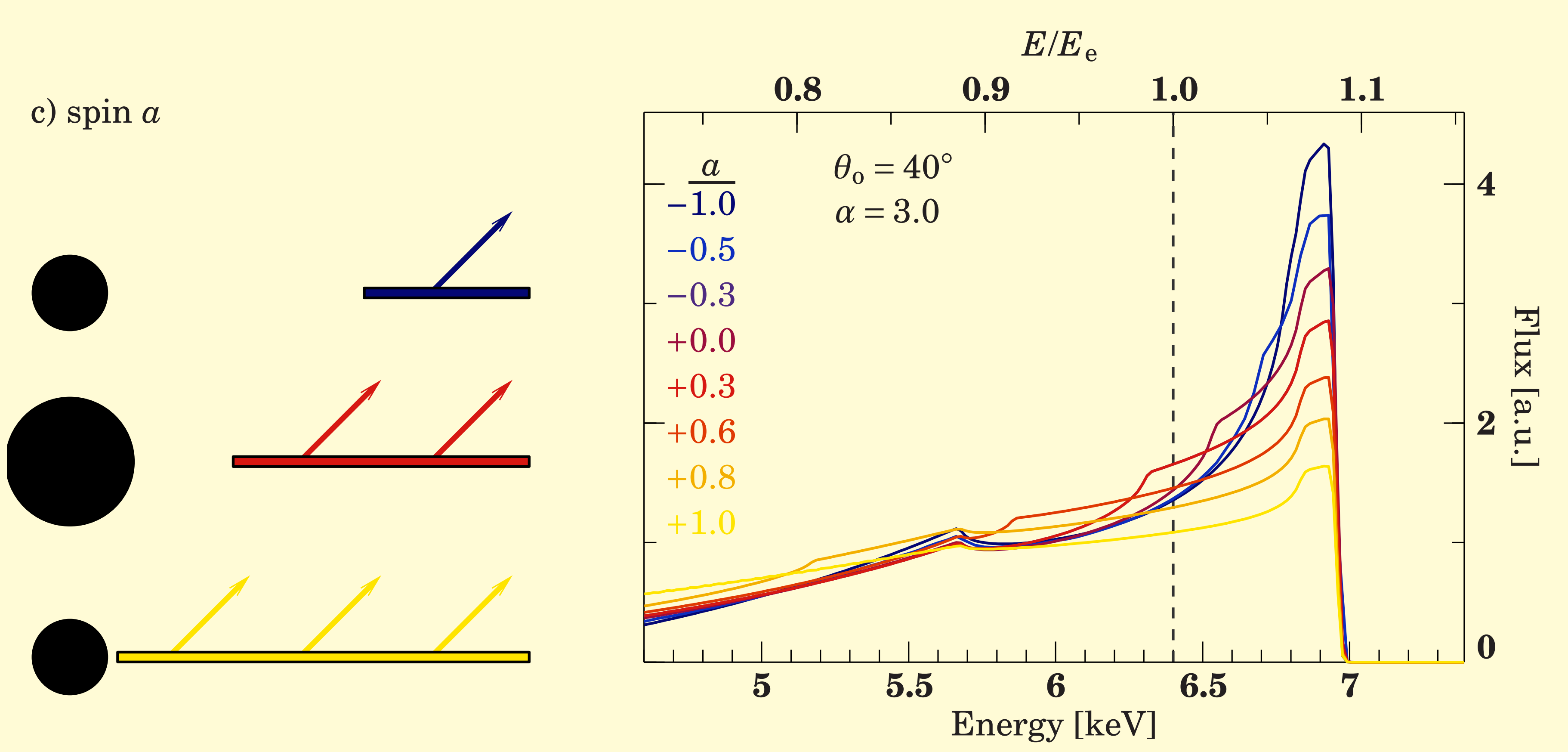
(Cunningham, 1975; Fabian et al., 1989; Laor, 1991; Dovčiak et al., 2004; Dauser et al., 2010)



(Dauser, 2010)

Line profile has strong diagnostic potential: inclination



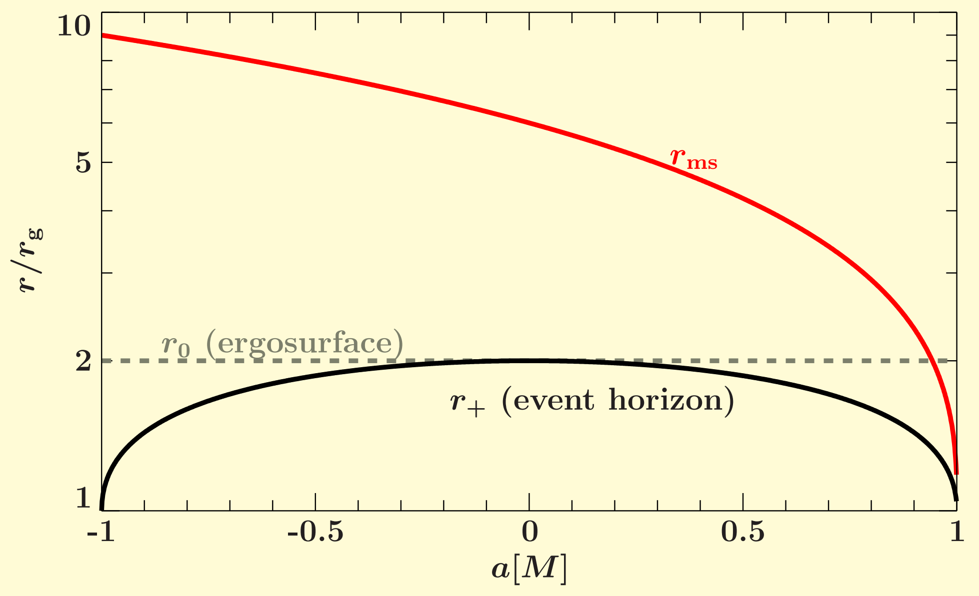


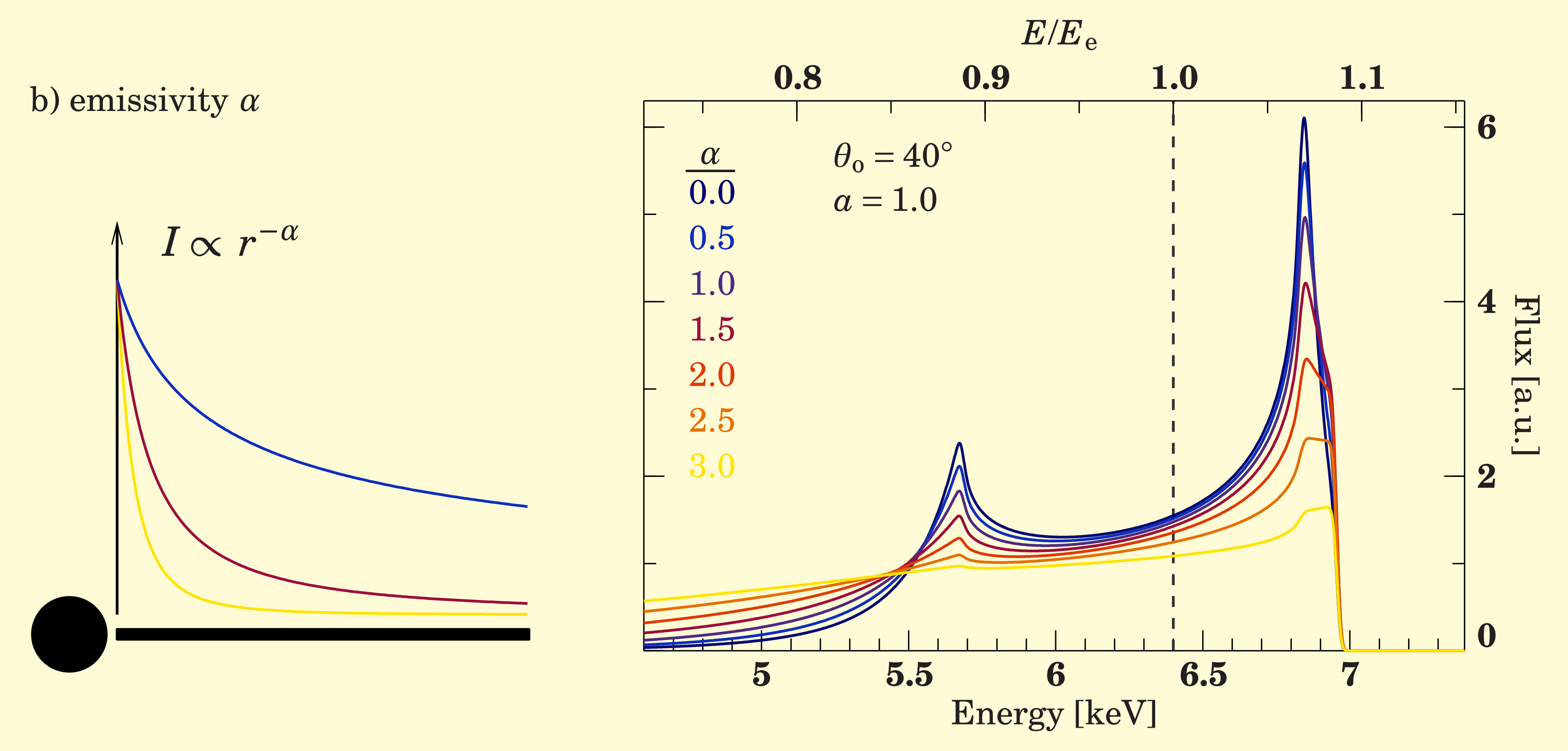
(Dauser, 2010)

Line profile has diagnostic potential:

black hole spin ("holy grail")

"negative spin": angular momenta of disk and BH are antiparallel, also a stable configuration (Andrew King's talk, King et al., 2008)



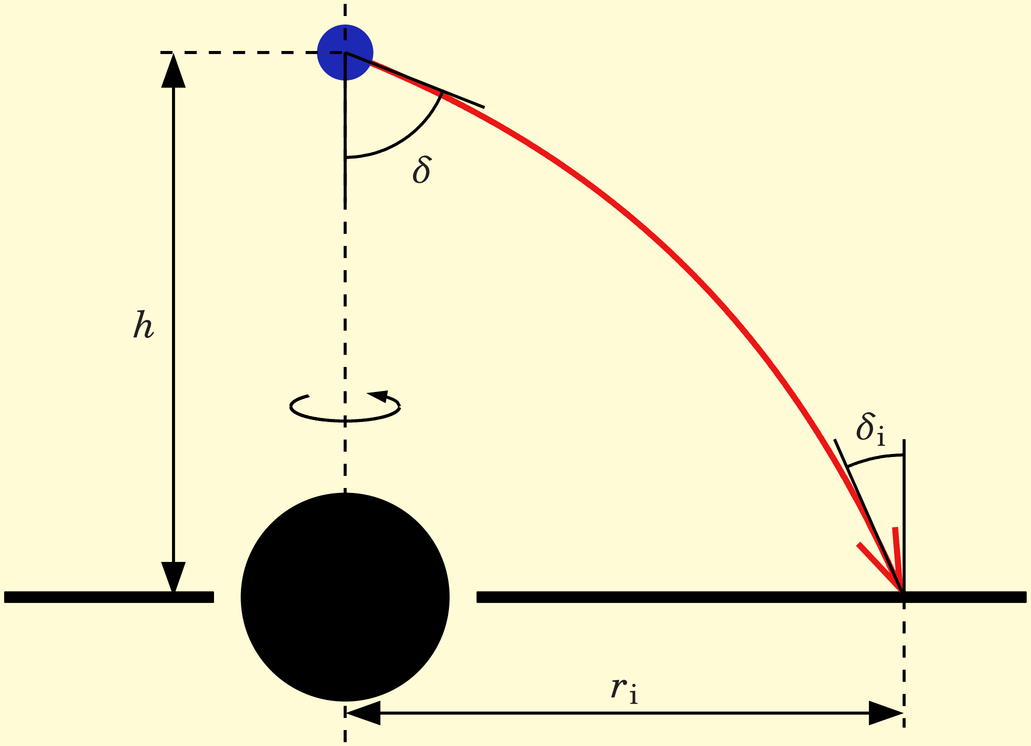


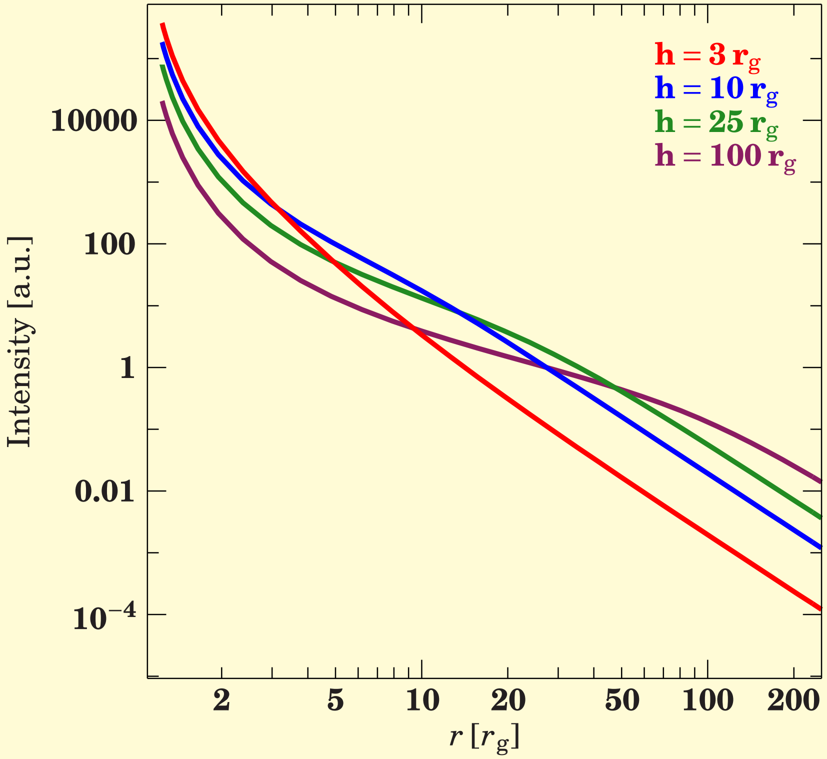
(Dauser, 2010)

Line profile has diagnostic potential: disk emissivity (=energy release per unit area)

for an α-disk: $\alpha \sim 3$

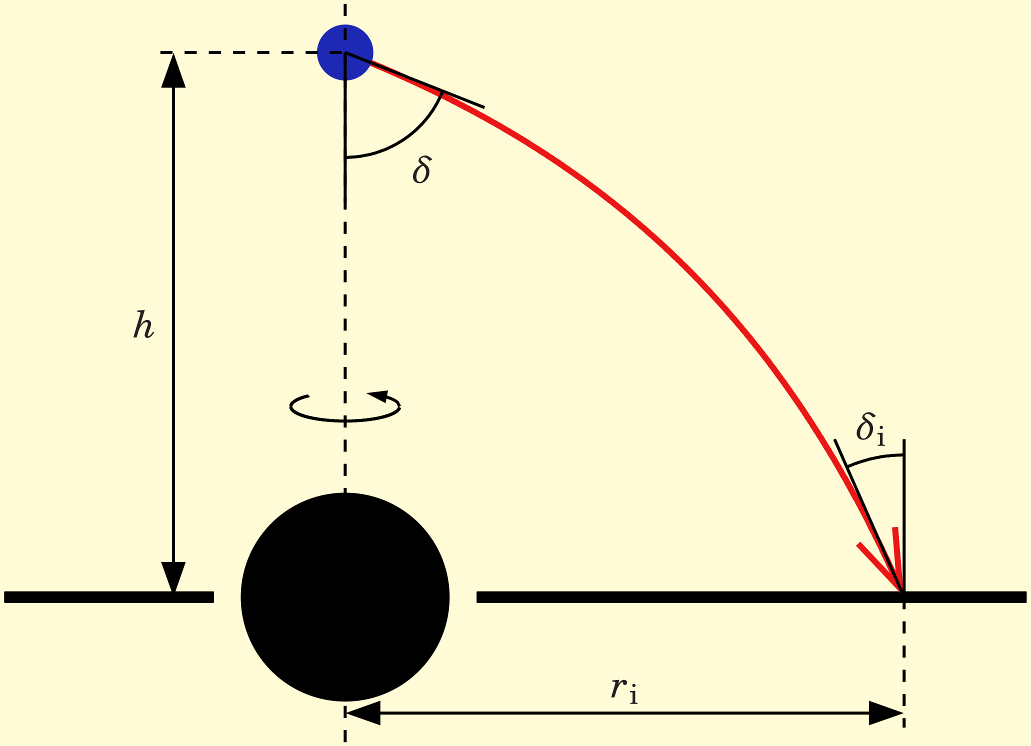
Relativistic Kα Lines

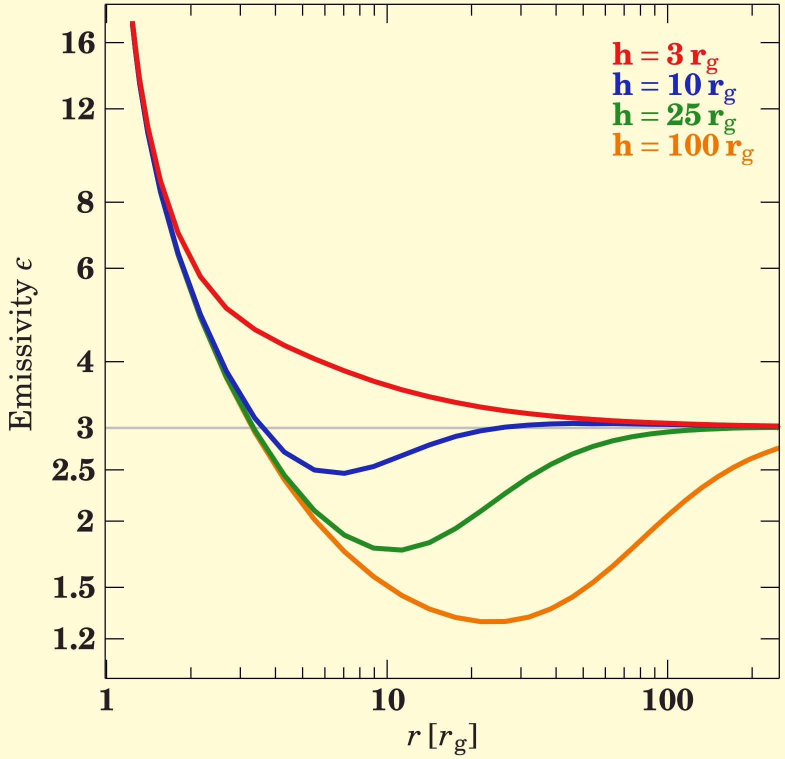




- Disks: emissivity α not well constrained
- Lamppost geometry: emissivity only depends on height above BH

Relativistic Kα Lines





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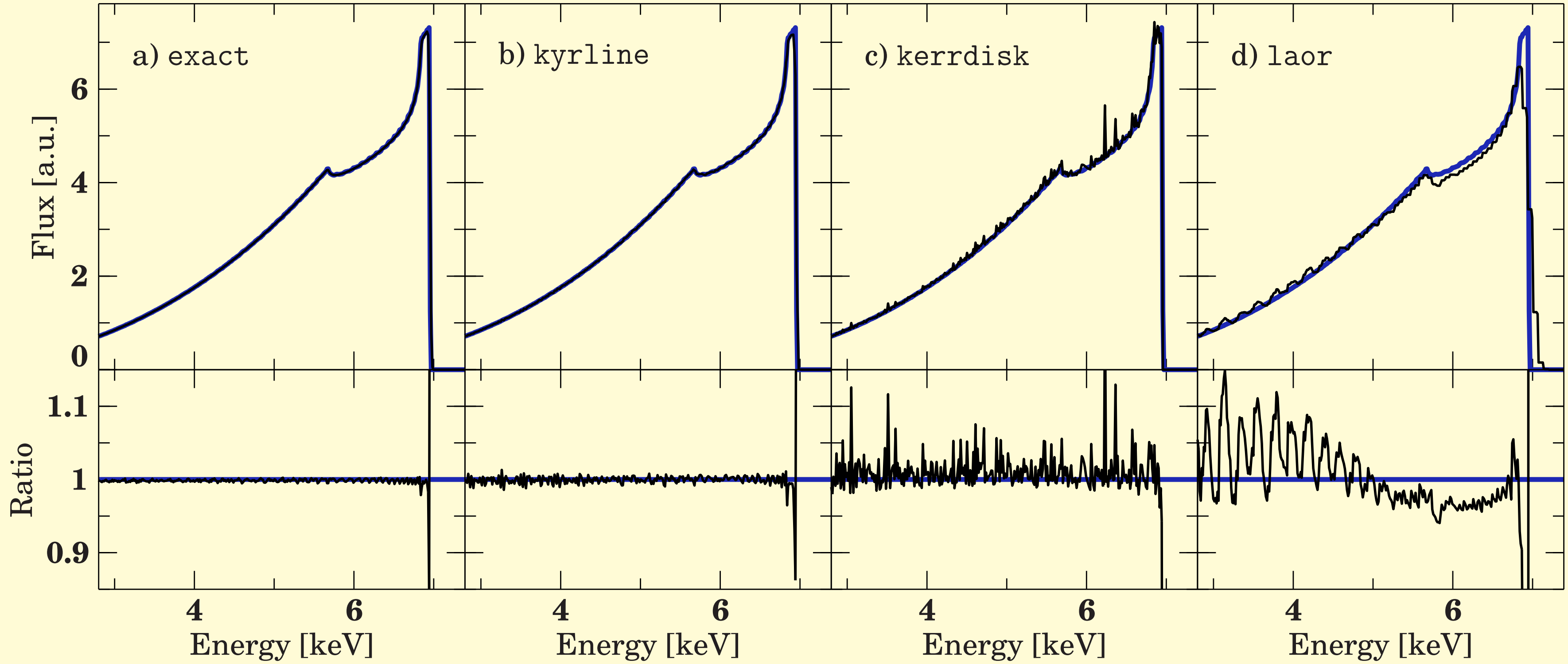
Caveat: Models

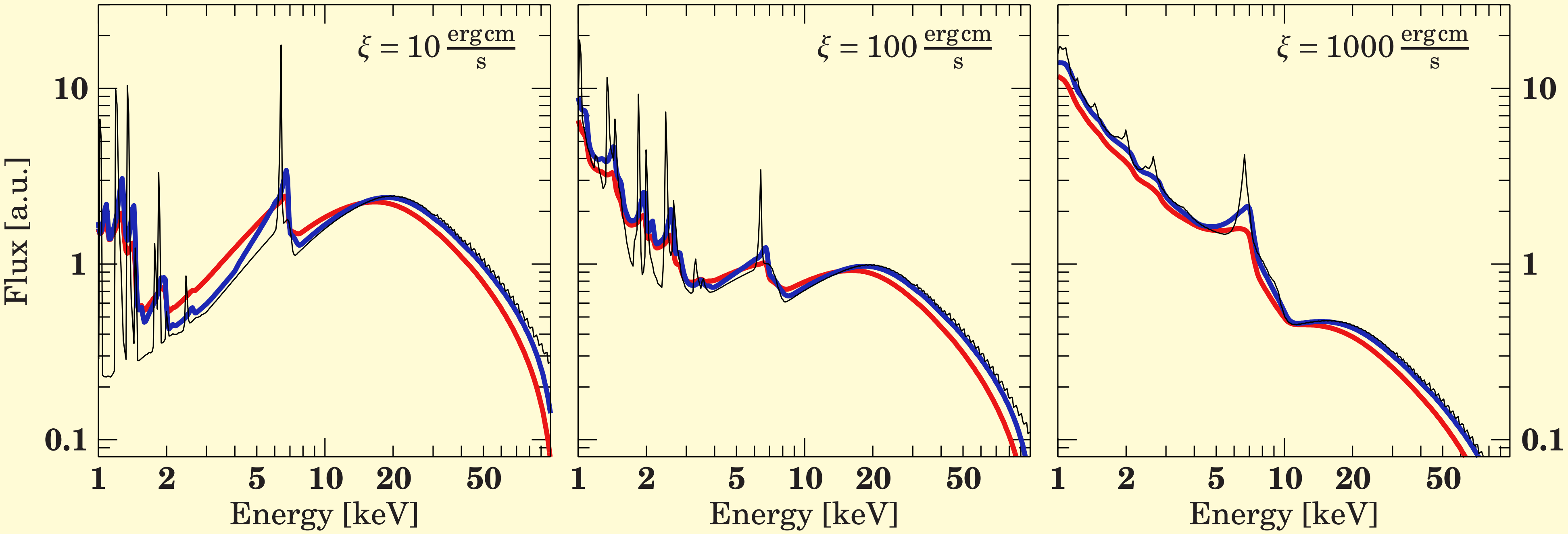


(Dauser, 2010)

Caution: Different line models available have numerical and other issues.

`relline` (Dauser et al., 2010) and the `ky`-type models (Dovčiak et al., 2004) work well, don't use `diskline` or `laor`.

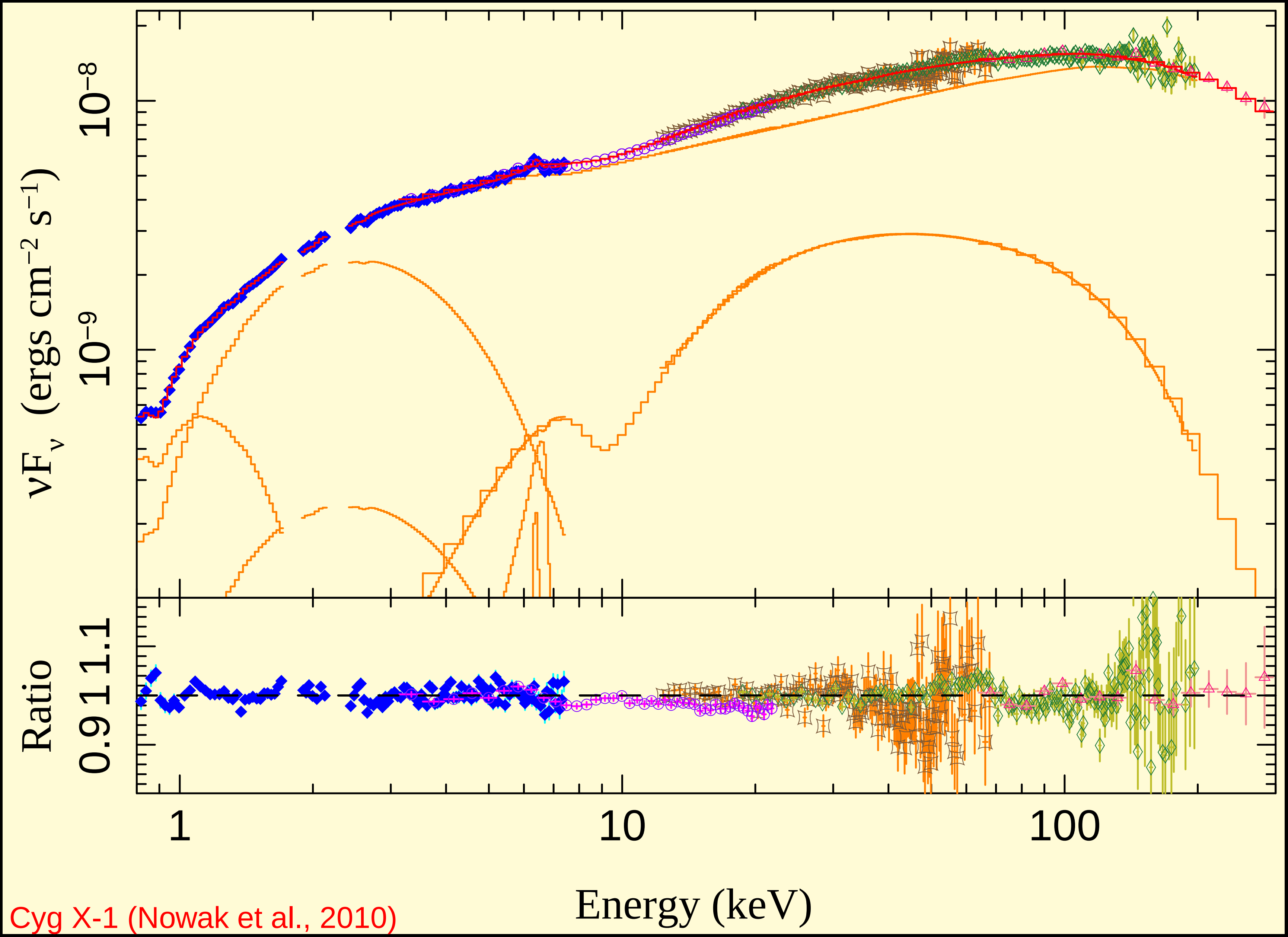
Relativistic Smearing



(Dauser, 2010)

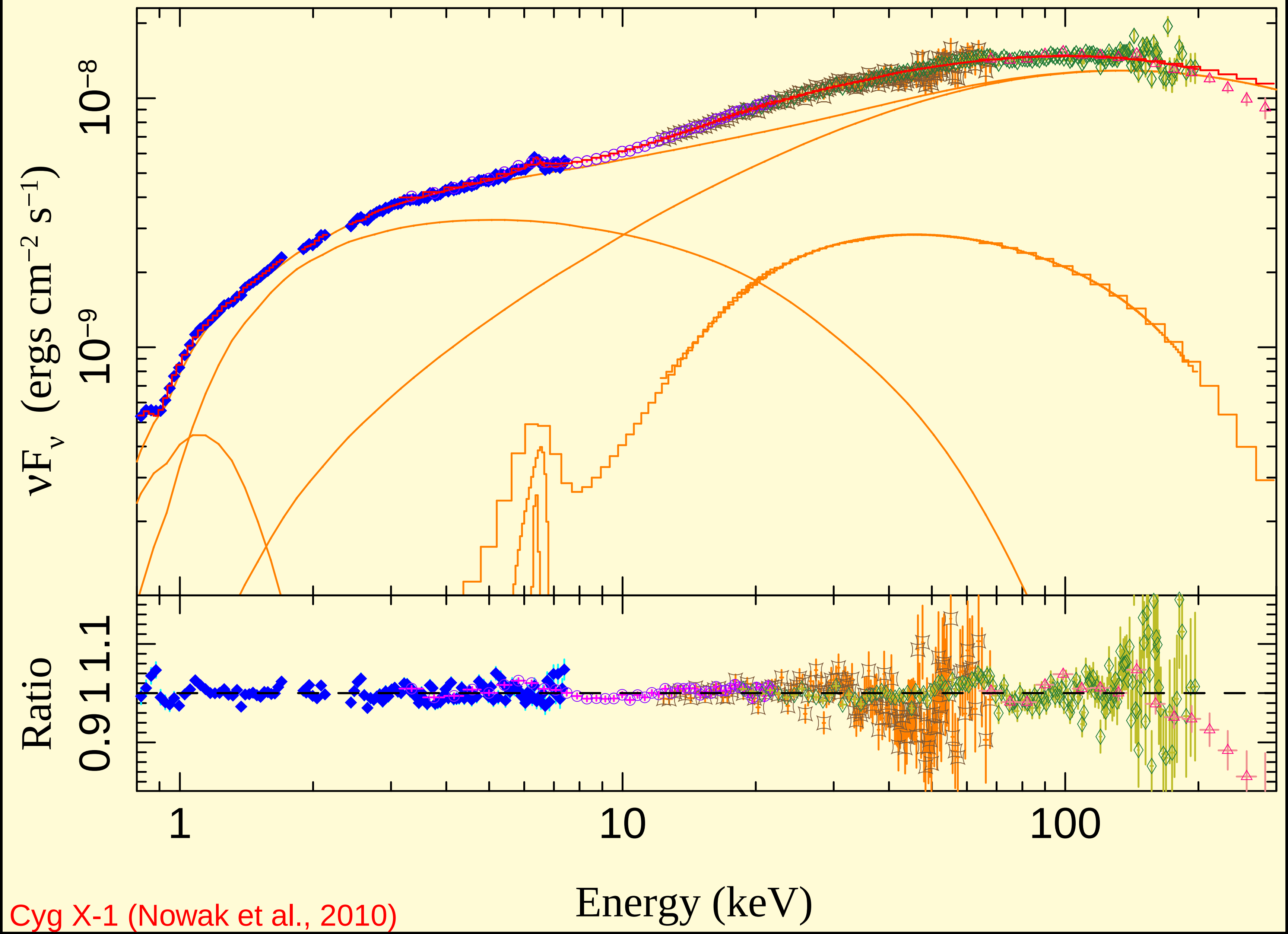
Relativistic smearing affects the whole reflection spectrum

Only modeling a strong emission line with relativistic effects and ignoring the reflection continuum is wrong.



Cyg X-1 (Nowak et al., 2010)

Thermal Comptonization plus reflection explain the broad-band spectrum very well.

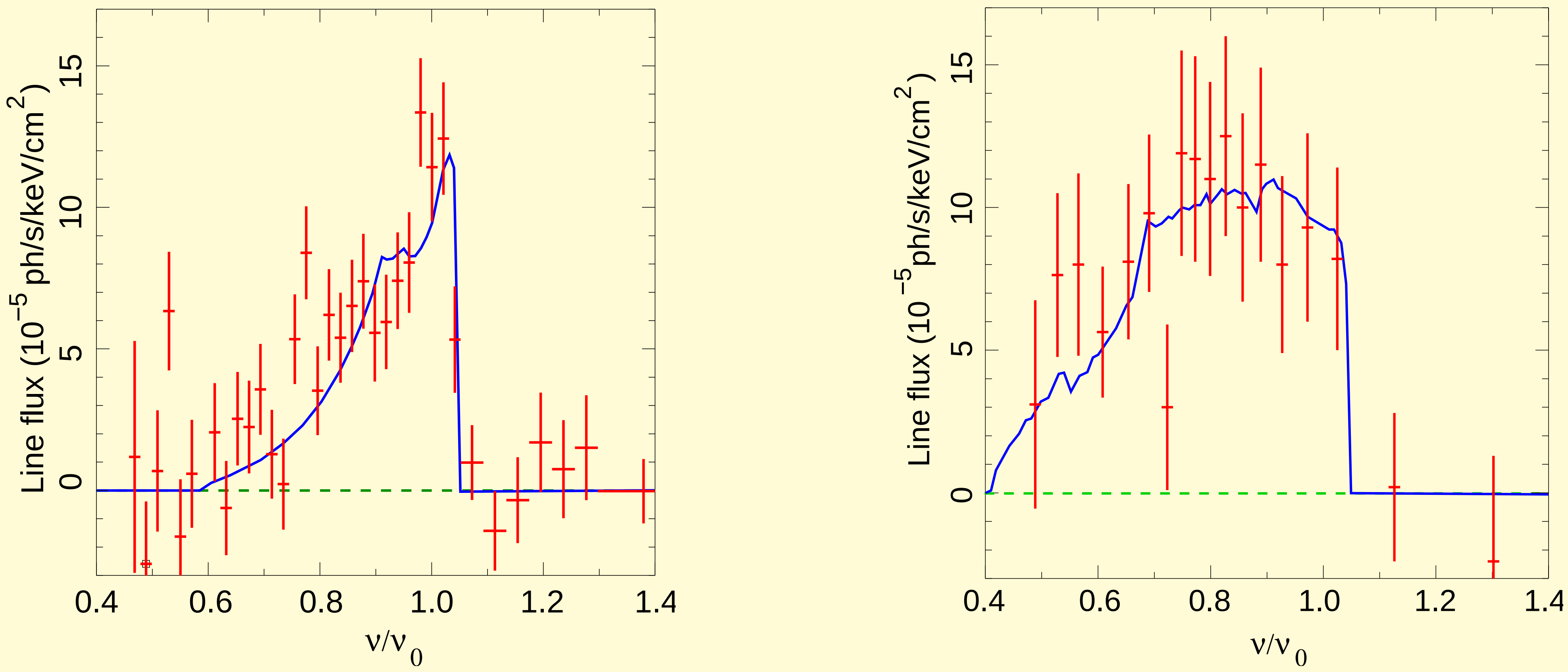


Cyg X-1 (Nowak et al., 2010)

The hard state broad band spectrum can be equally well described with emission from the base of a jet.

Markoff et al. (2005), but see, e.g., Malzac et al. (2009)

Broad Lines in AGN



MCG$-$6-30-15 ($z = 0.008$): first AGN with relativistic disk line

Tanaka et al. (1995): time averaged *ASCA* spectrum: line skew symmetric

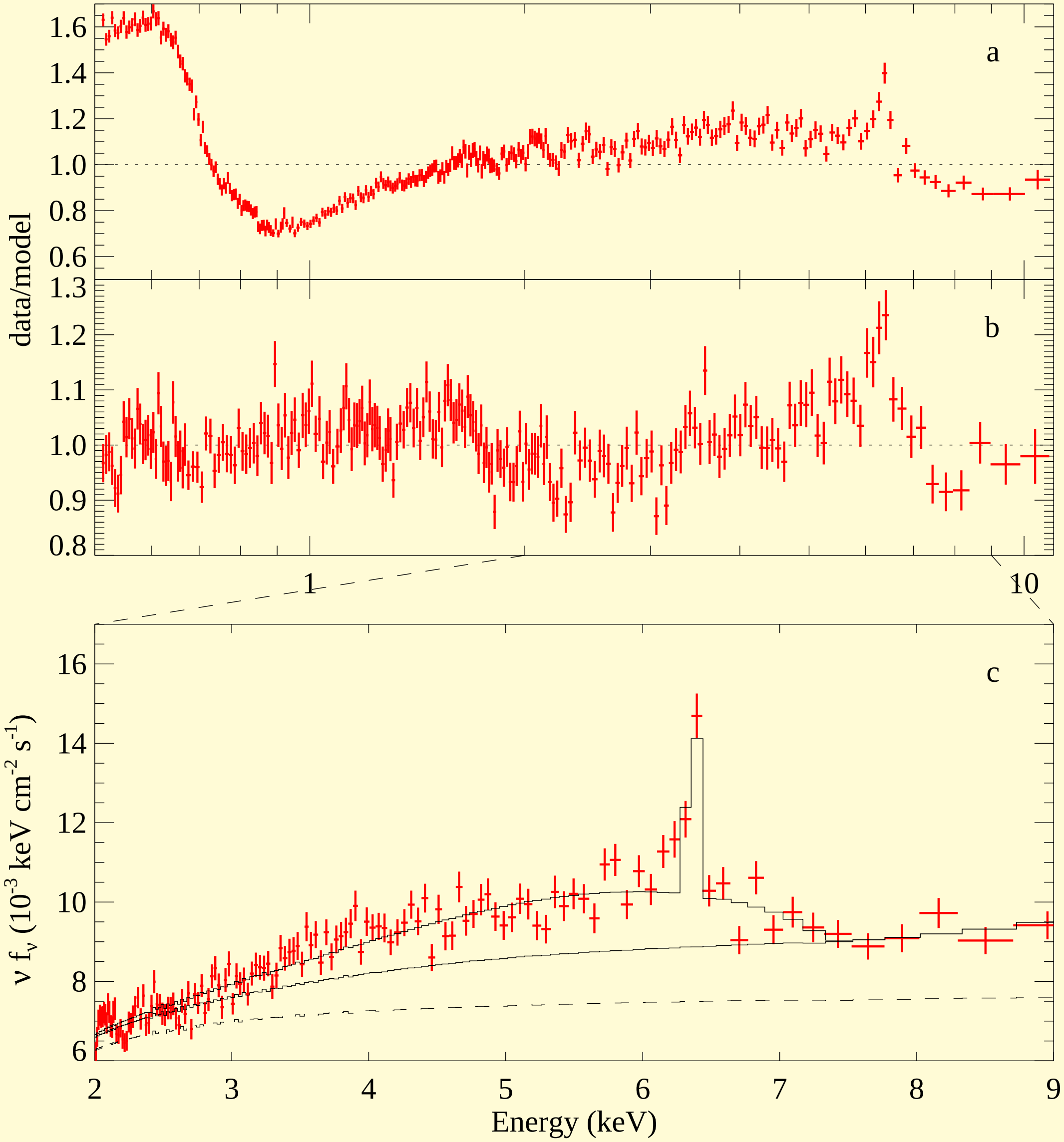
$\Longrightarrow$ Schwarzschild black hole.

Iwasawa et al. (1996): “deep minimum state”: extremely broad line

$\Longrightarrow$ Kerr Black Hole.

Confirmed by all subsequent X-ray missions.

Broad Lines in AGN



pure PL fit

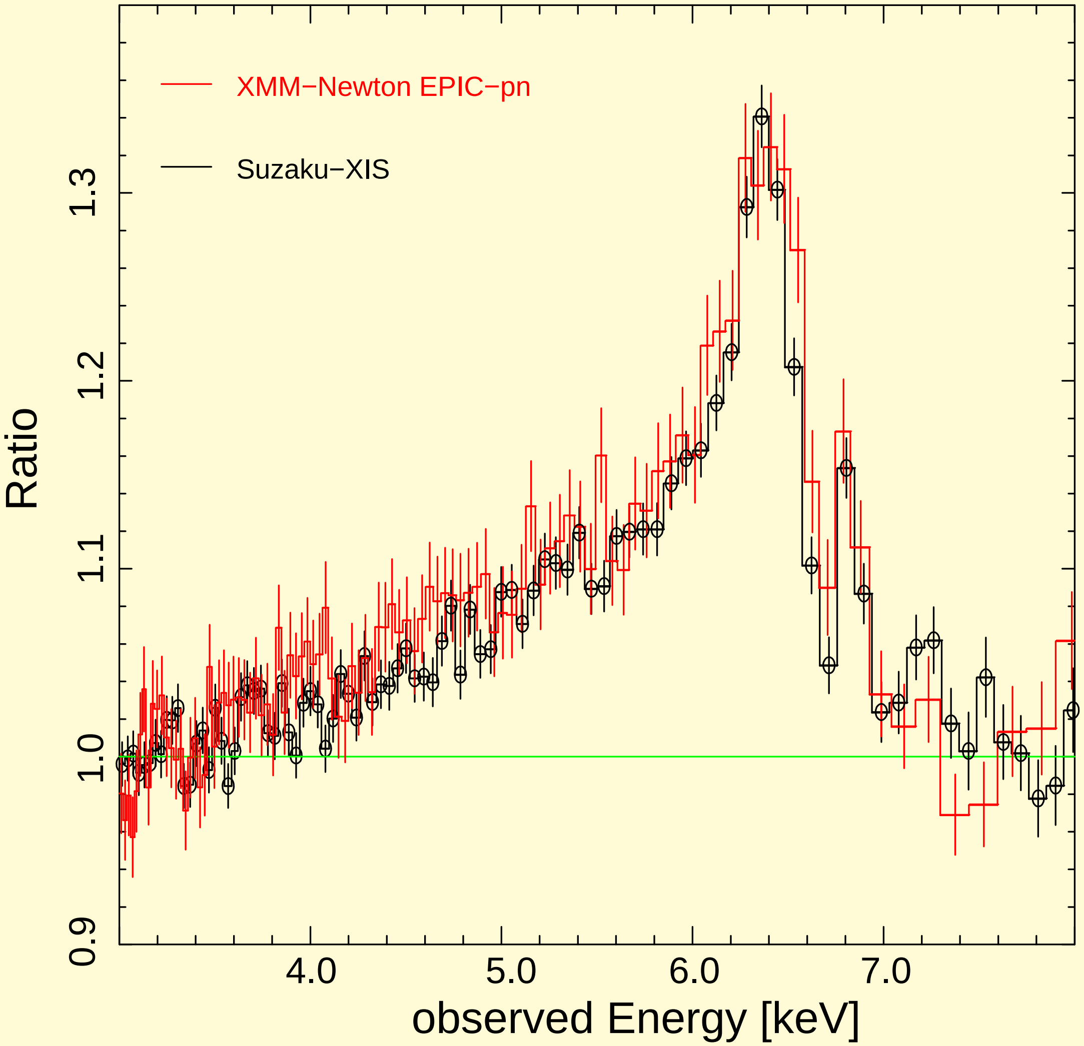
Better modeling of soft excess and reflection $\Longrightarrow$ Fe Kα line has extreme width and skewed profile.

Components of the final fit.

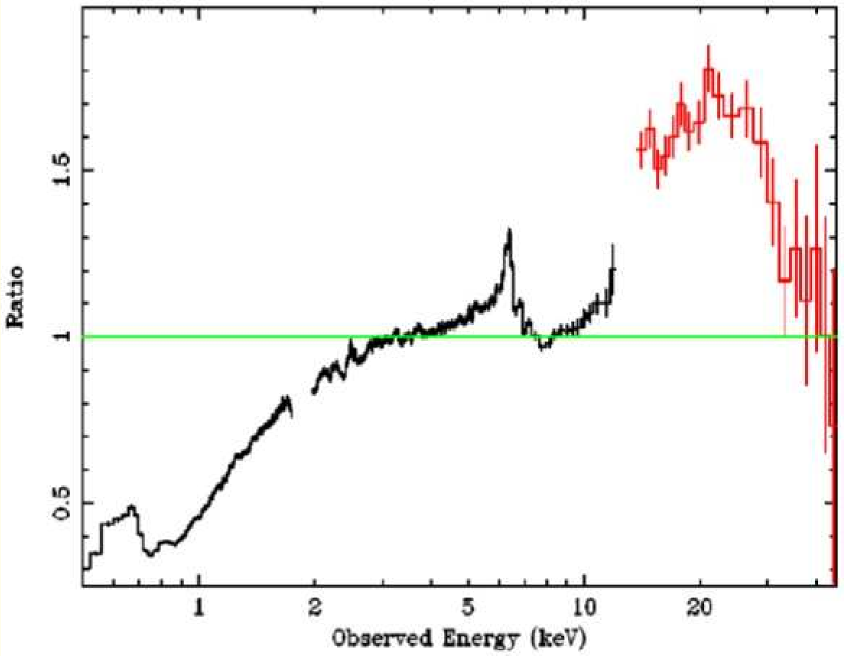
$\Longrightarrow$ Line emissivity is strongly concentrated towards the inner edge of the disk ($\epsilon \propto r^{-4.6}$; cannot be explained with standard α-disk)

(Wilms et al. 2001; 100 ksec *XMM-Newton*, “deep minimum state” of 2000 June)

Broad Lines in AGN



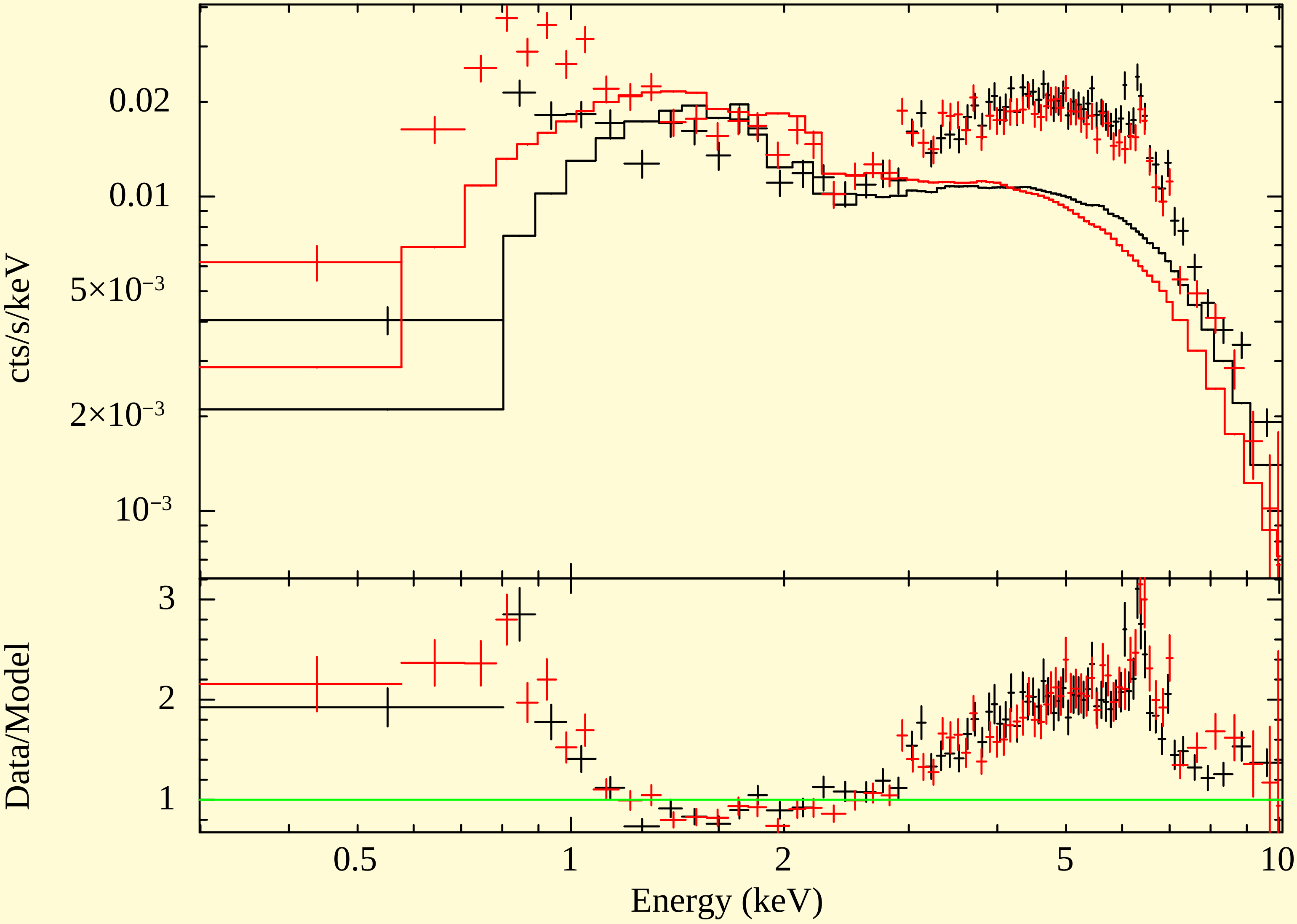
Suzaku (2006 Jan; ∼350 ksec; Miniutti et al. 2007)



Brenneman & Reynolds (2006): Angular momentum of BH in MGC$-$6-30-15: $a = 0.989^{+0.009}_{-0.002}$.

Assuming no emission from within innermost stable circular orbit, (too) tightly constrained geometry.

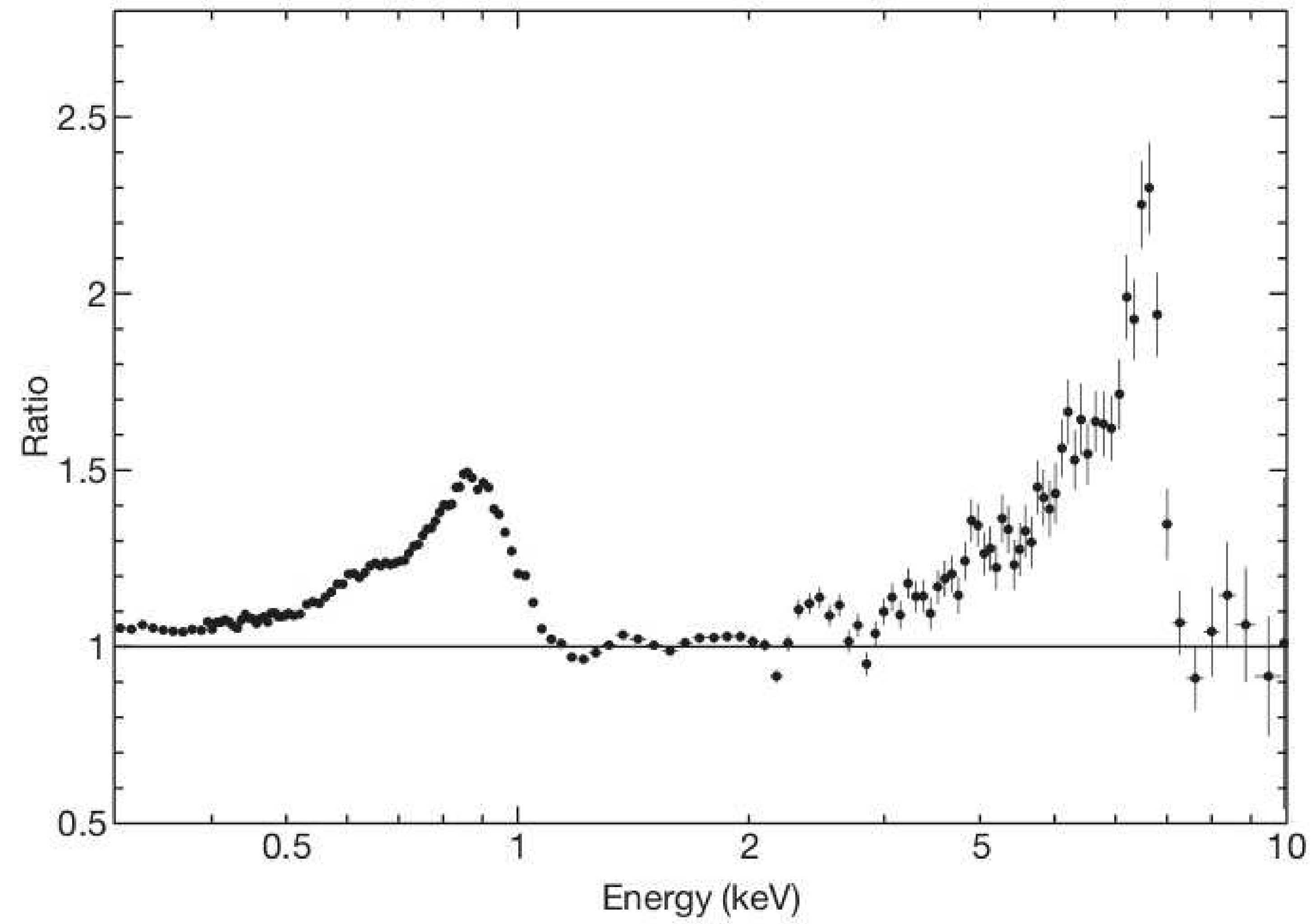
Broad Lines in AGN



Clear broadening, consistent with $a = 0.998$, but no clear reflection component seen. Jet?

Suzaku, NGC 1052 (Brenneman et al., 2009)

Broad Lines in AGN

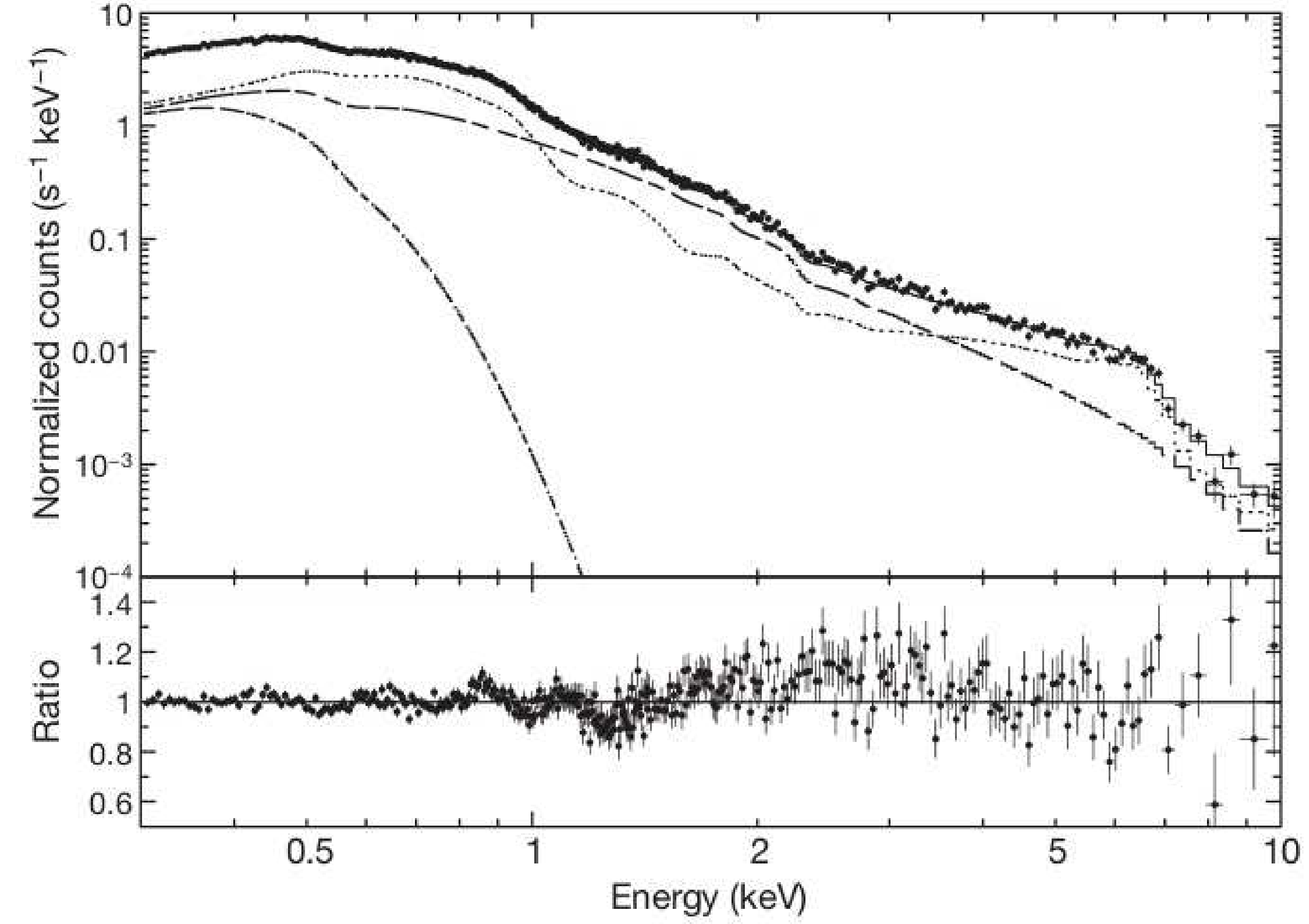


(Fabian et al., 2009)

1H0707$-$495 (NL Sy1): relativistically broadened Fe Kα *and* Lα lines; $a > 0.98$

See poster by T. Dauser

Broad Lines in AGN

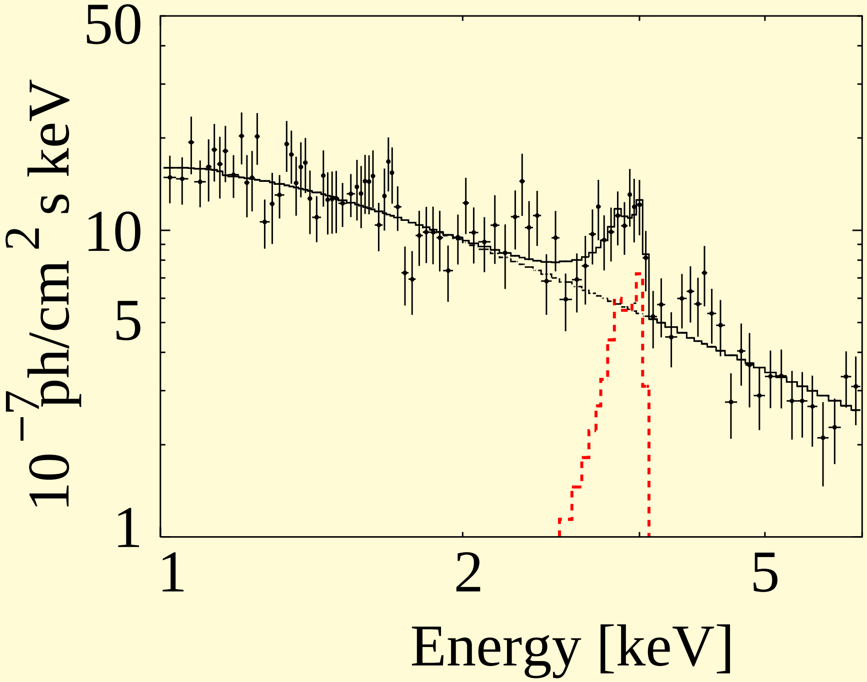


(Fabian et al., 2009)

1H0707$-$495 (NL Sy1): relativistically broadened Fe Kα *and* Lα lines; $a > 0.98$

Similar results also for IRAS13224$-$3809 (Ponti et al., 2010)

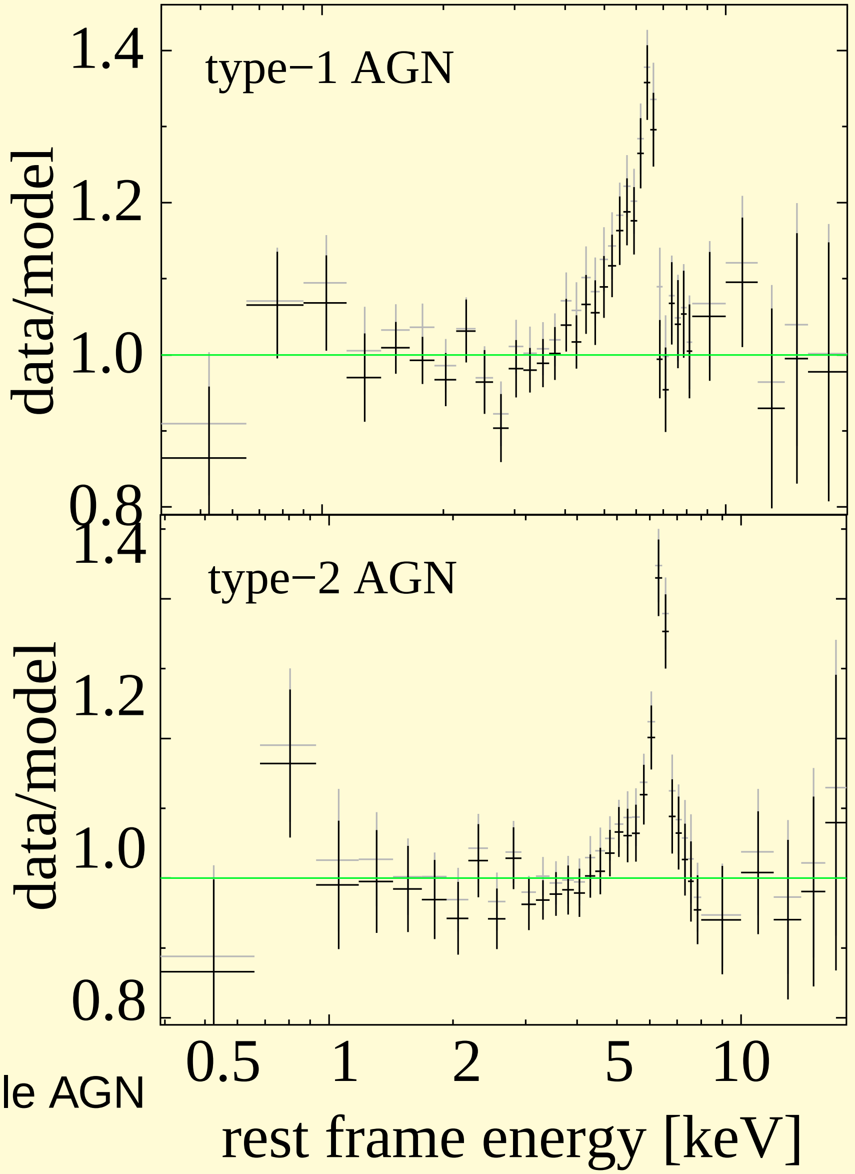
Broad Lines in AGN



(Comastri et al. 2004; *Chandra*)

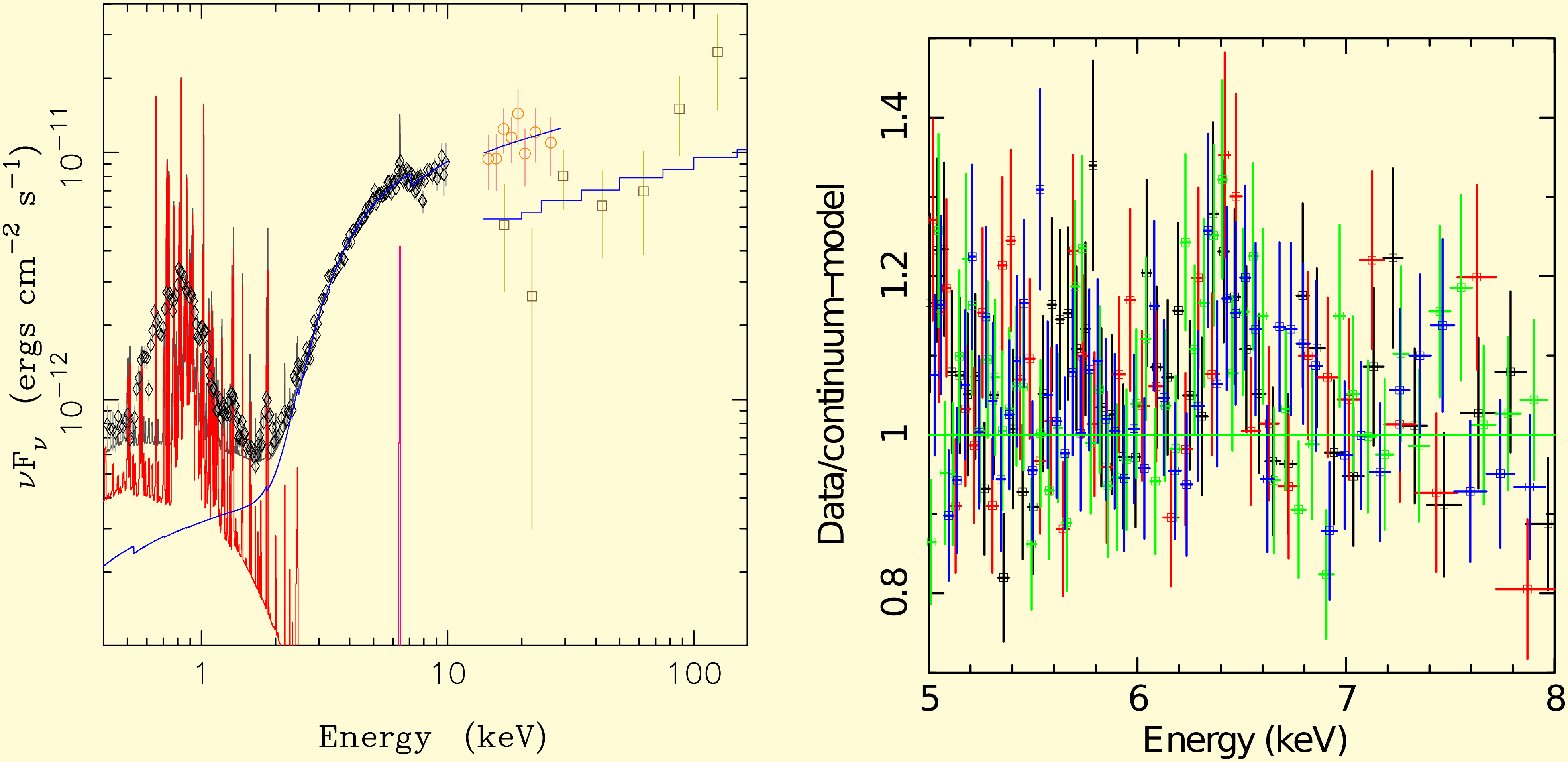
CXO J123716.7+621733 (CDF-N; $z = 1.146$)

Broad Fe Kα lines already present in high-z universe!



Average Fe line for the Lockman hole AGN (Streblyanska et al., 2005)

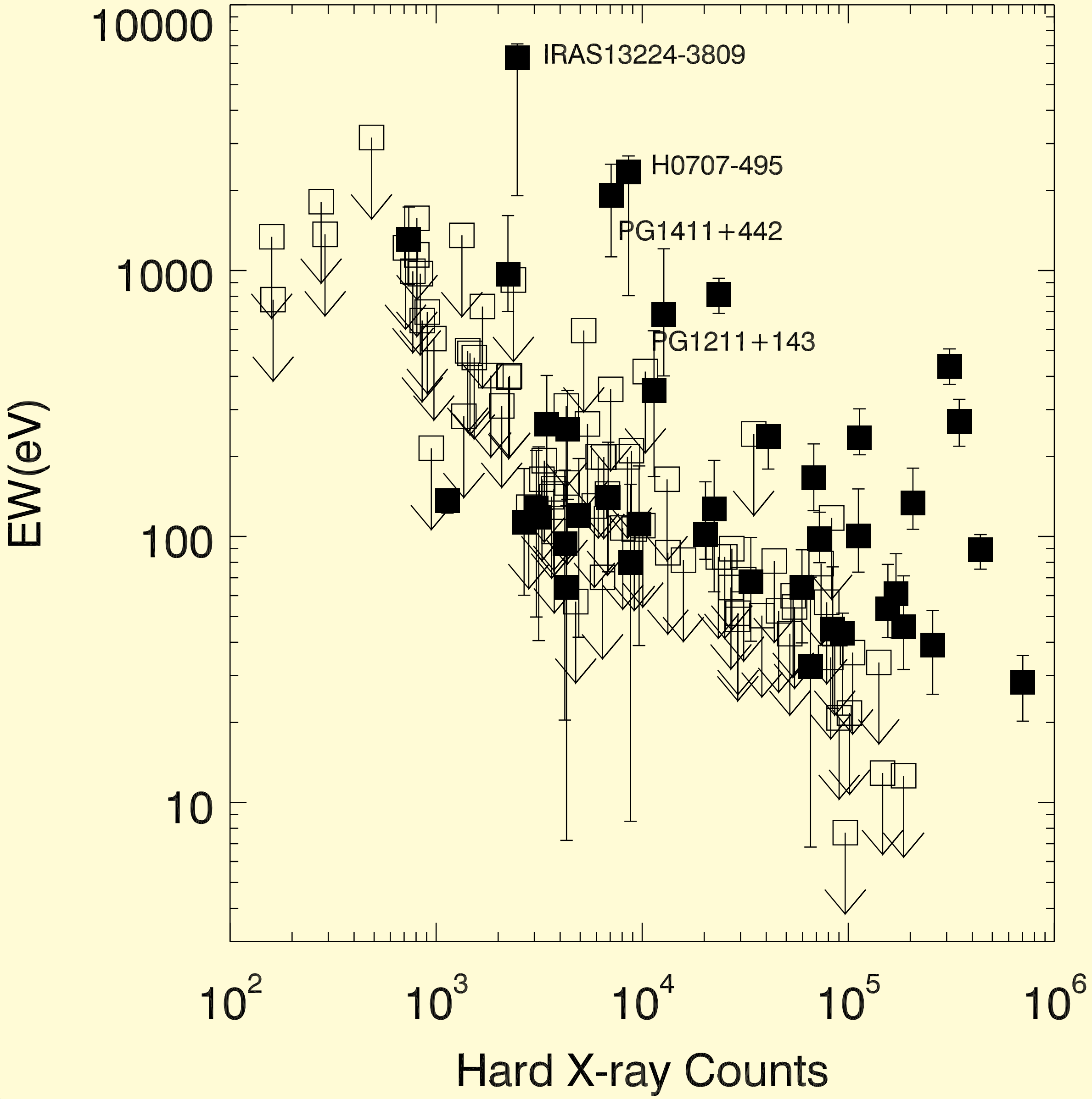
non detections



NGC 4258 (Reynolds, et al., 2008; Suzaku, Swift)

But: Some AGN do *not* show relativistic lines!

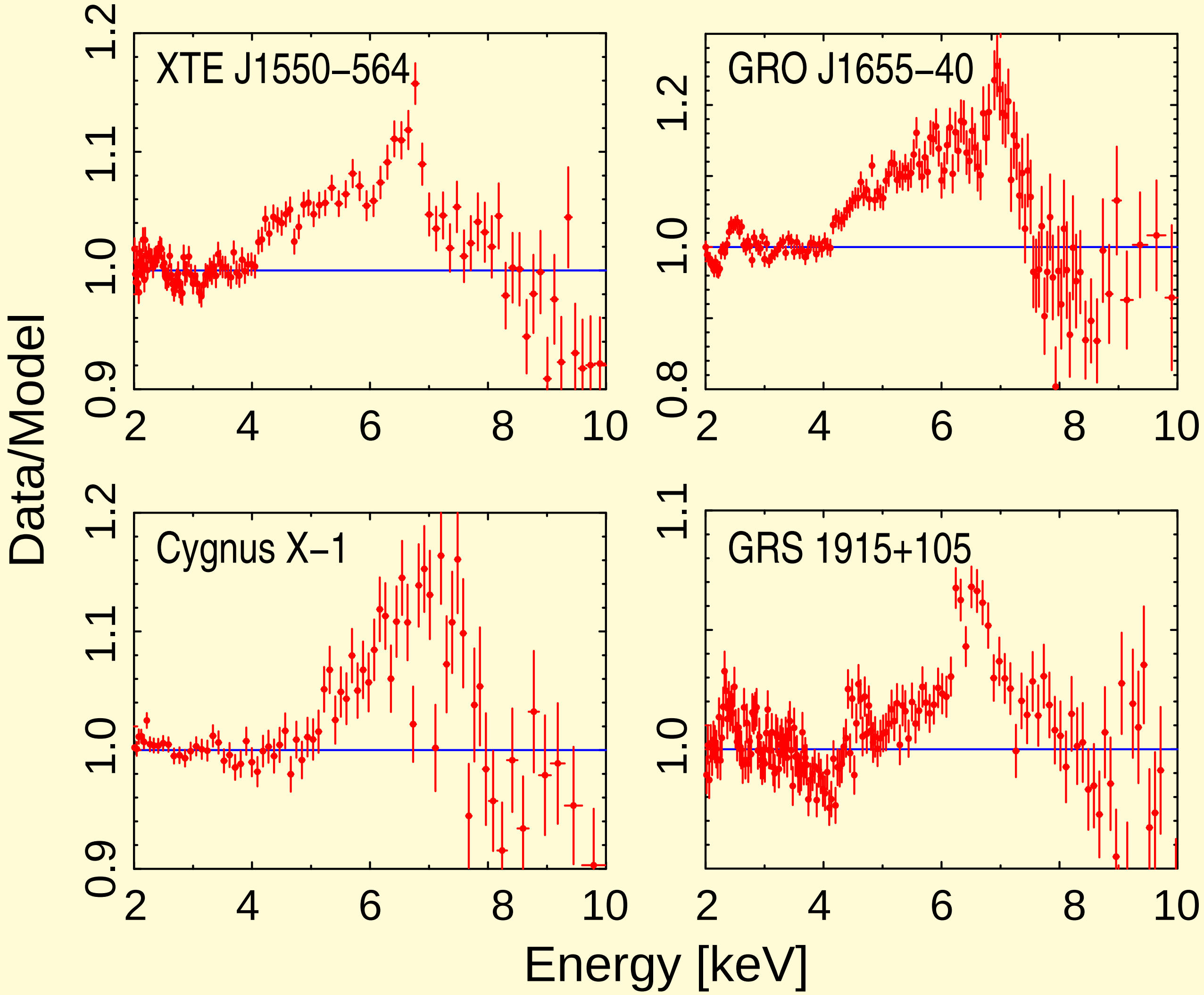
non detections



Guainazzi et al. (2006): non-detections due to ionization and detection significance

200000 photons are needed to unequivocally detect broad line in an AGN.

Broad Lines in BHC

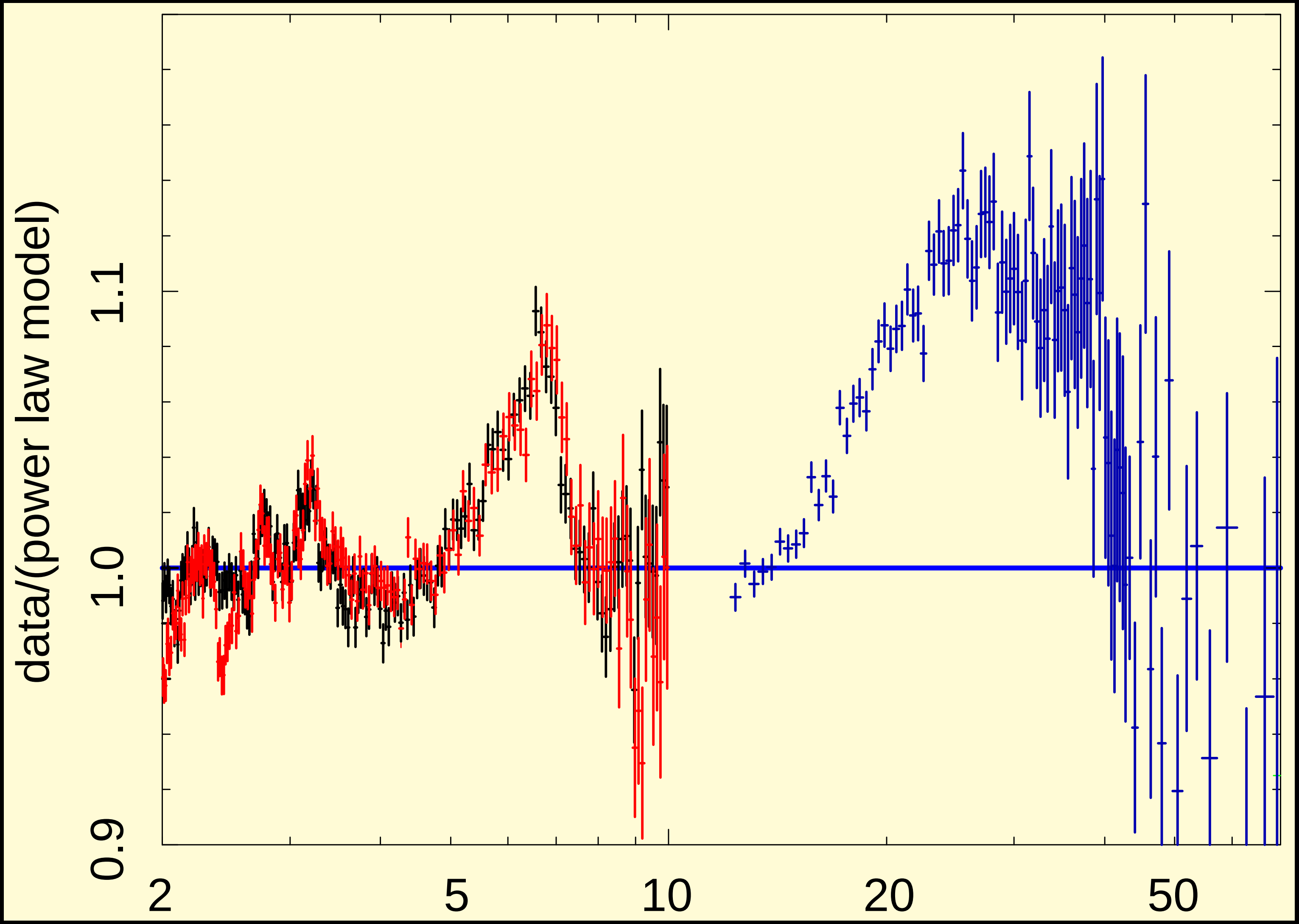


Relativistic lines are also seen in many Galactic Black Holes

- GX 339−4: Nowak et al. (2002); Miller et al. (2004); Caballero-García et al. (2009)
- GRO J1655−40: Bałucińska-Church & Church (2000)
- Cyg X-1: Miller et al. (2002); Fritz et al. (2006)
- XTE J1650−500: Miller et al. (2002)

. . . and many more more (see Miller et al. 2009)

(after Miller 2007)



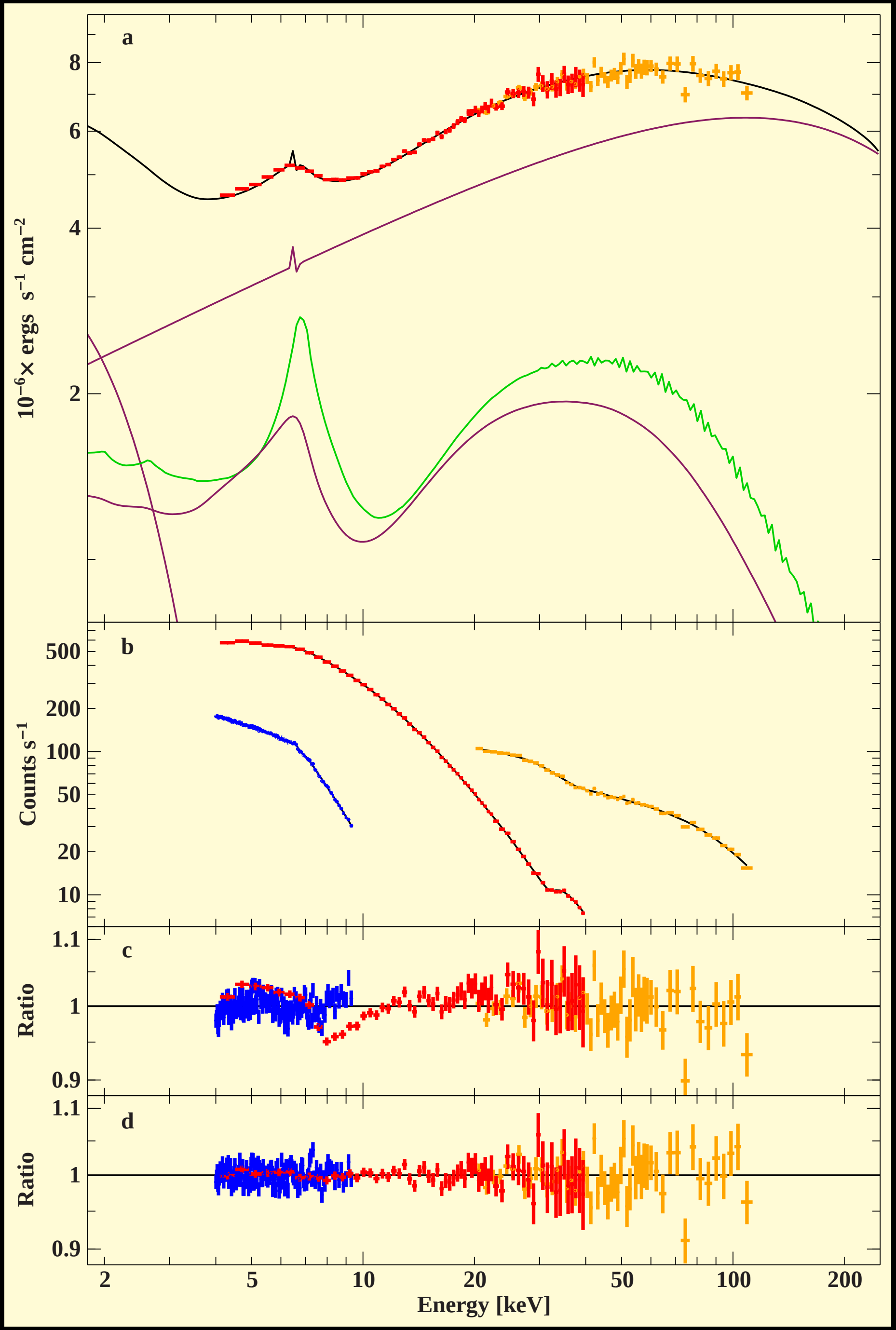
(GX 339−4; Suzaku Miller et al., 2008)

Broad-band data $\Longrightarrow$ can try to measure black hole angular momentum.

E.g., GX 339−4: Suzaku: $a = 0.89 \pm 0.04$ (Miller et al., 2008),

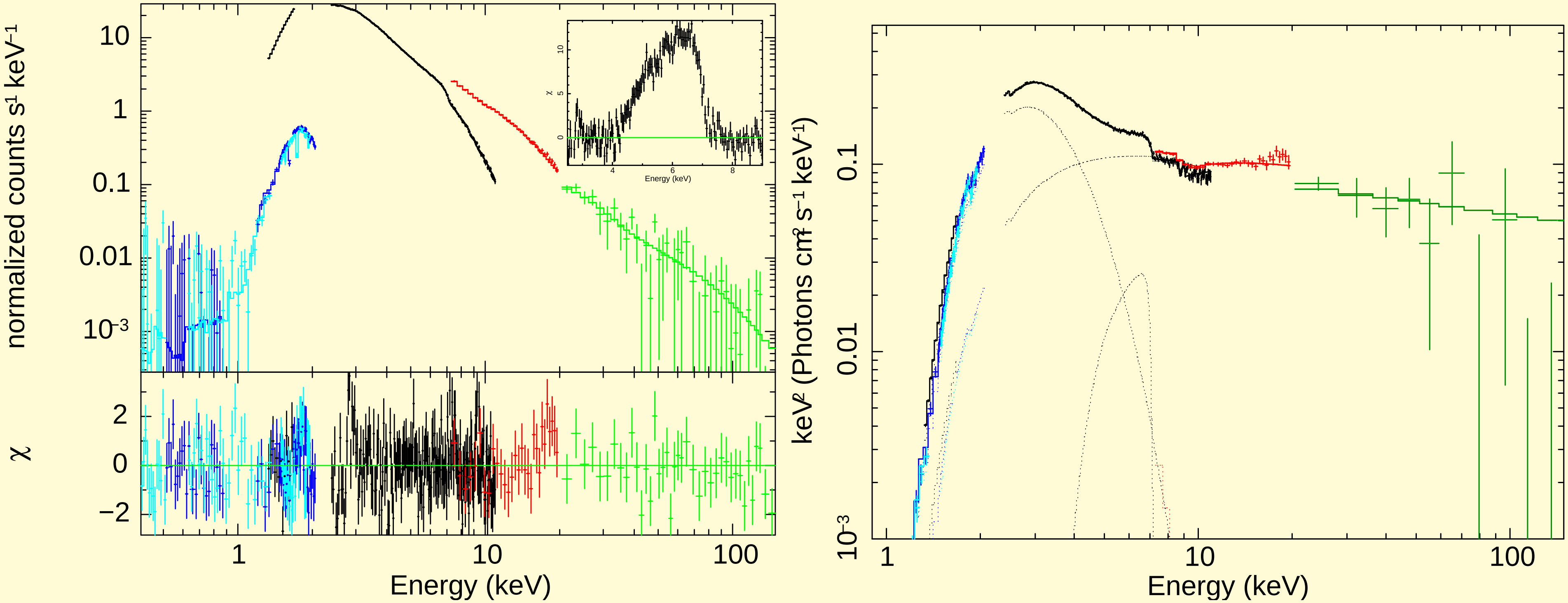
XMM-Newton: $a = 0.93 \pm 0.01$ (Miller et al., 2004)

Warning: Uncertainties do not take into account systematic uncertainty in continuum modeling or detector effects!



Cygnus X-1: $a > 0.9$; see R. Duro’s talk

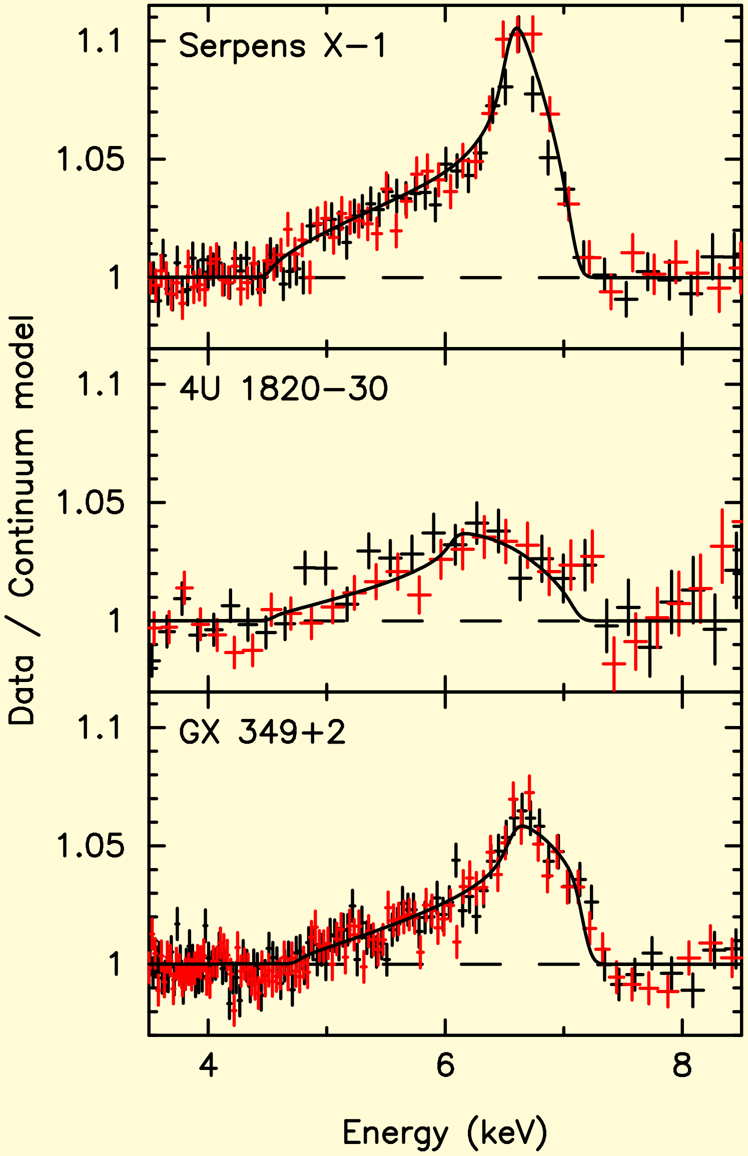
Broad Lines in BHC

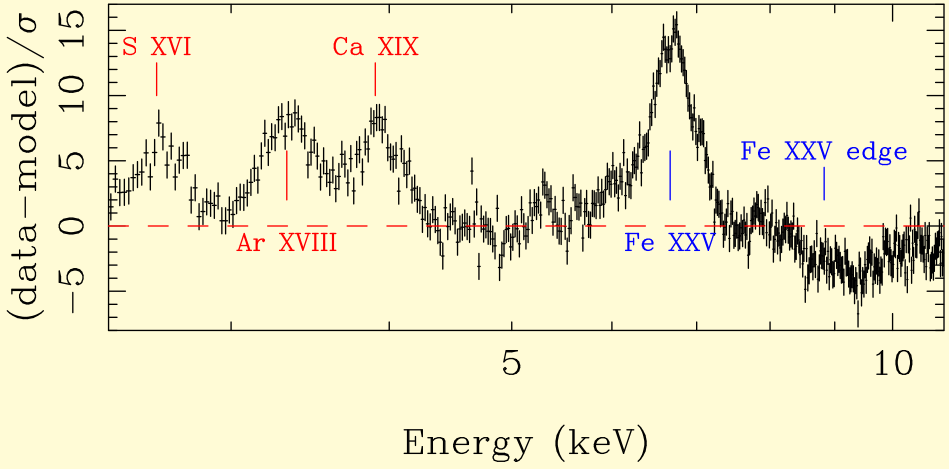


(Hiemstra et al., 2011, XTE J1652−453)

XTE J1652−453: 450 eV EW Fe line, $a \sim 0.5$

Broad Lines in Neutron Stars





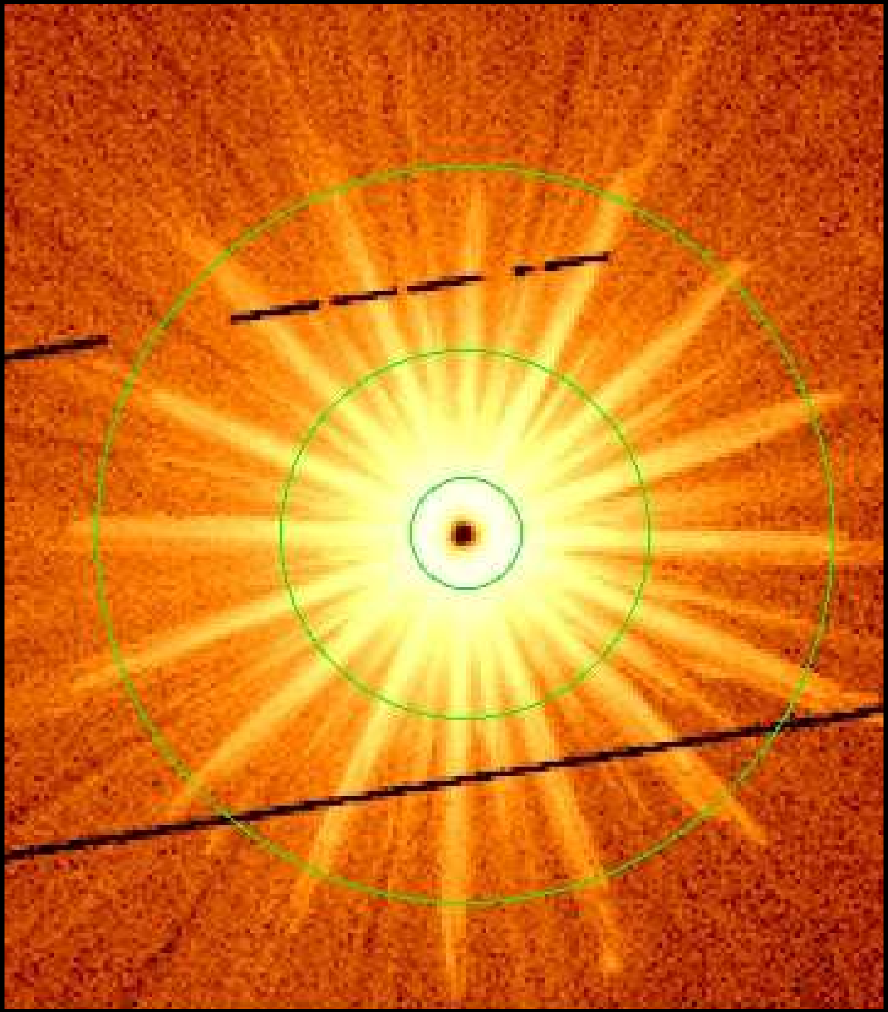
(4U 1705−44, *XMM-Newton*; di Salvo et al., 2009)

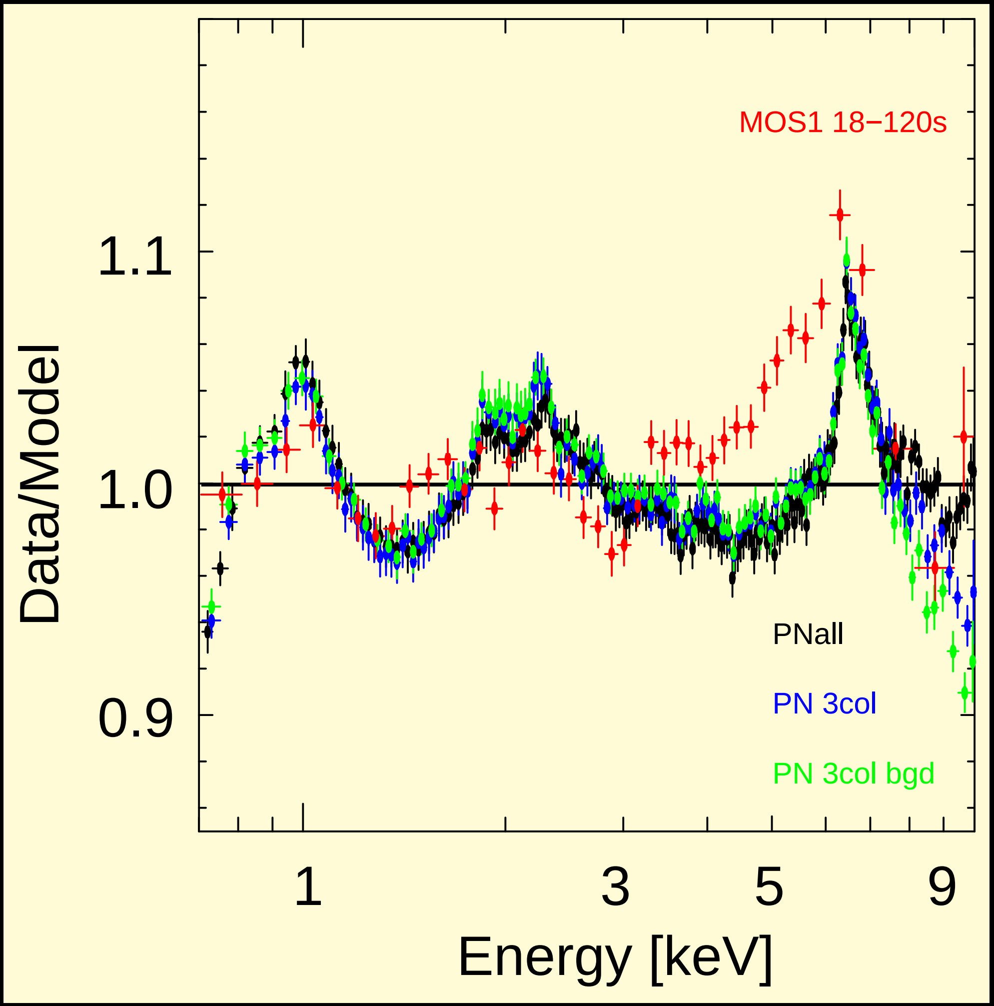
Neutron Star X-ray Binaries also seem to have broad lines

Inner radii can be used to constrain neutron star radius to <14.5 km (Cackett et al., 2008) $\Longrightarrow$ Equation of state!

But not all NSs show broad lines (2 out of 6 in sample of Cackett et al. 2009) – ionization effect?

(Suzaku; Cackett et al., 2008)





(Done & Díaz Trigo, 2009)

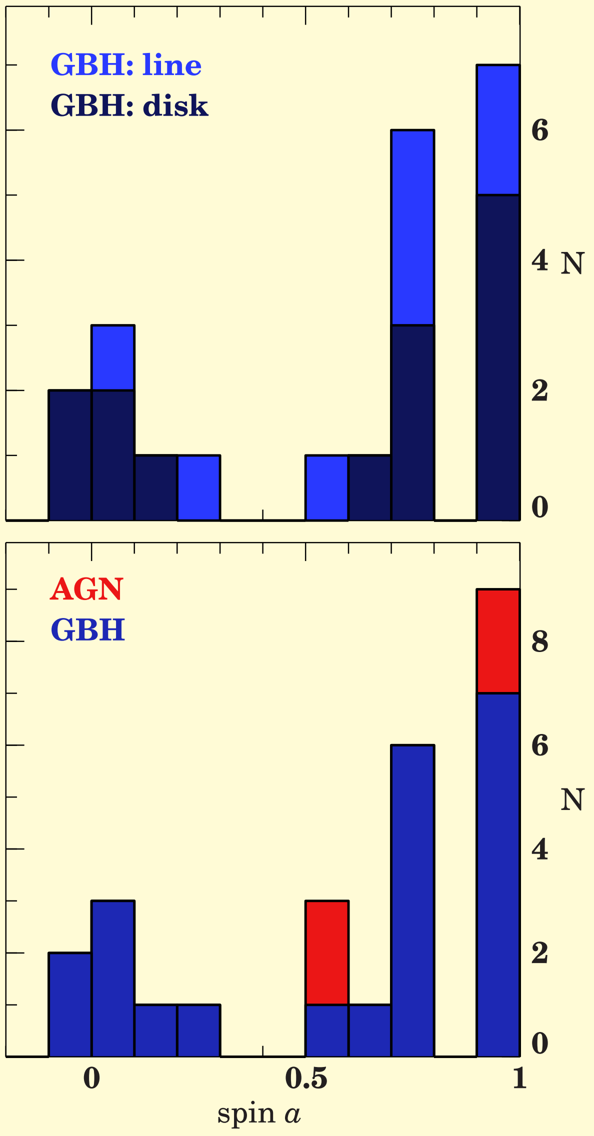
But beware: bright source effects in detectors can affect the line shape!

(Yamada et al., 2009; Done & Díaz Trigo, 2009)

Pileup effects, CTE, background subtraction,. . . $\Longrightarrow$ see R. Duro's talk

Conclusions

Source	Spin (disk)	Spin (line)
M33 X-7	0.77 ± 0.05	
LMC X-1	$0.90^{+0.04}_{-0.09}$	
LMC X-3	< 0.8	
	-0.03	
GS 2000+25	0.03	
GS 1124−68	-0.04	
4U 1543−47	0.7–0.85	0.3 ± 0.1
GRO J1655−40	0.65–0.8	0.98 ± 0.01
	0.93	
GRS 1915+105	0.98–1.0	
	0–0.15	
	~ 0.7	
	0.998	
XTE J1550−564	< 0.8	0.76 ± 0.01
XTE J1650−500		0.79 ± 0.01
GX 339-4		0.94 ± 0.02
SAX J1711.6−3808		$0.6^{+0.2}_{-0.4}$
XTE J1908+094		0.75 ± 0.09
Cygnus X-1	≥ 0.98	≥ 0.9
4U 1957+11	0.8–1.0	
A 0620−00	$0.12^{+0.18}_{-0.20}$	
MCG−6-30-15		$0.989^{+0.009}_{-0.002}$
Swift J2127.4		0.6 ± 0.2
Fairall 9		0.60 ± 0.07
1H 0707−495		≥ 0.98



(after Fender et al., 2010)

Conclusions

Personal summary of where we stand scientifically:

- Good broad band data start are now available!
  - there is a major degeneracy between different emission models,

    But, yes, Comptonization *is* the dominant physical effect.
  - geometry of accretion flow is unclear from spectra alone

    $\Longrightarrow$ jet vs. disk; S. Markoff's talk
  - we need other diagnostics to break degeneracy (timing!)

    $\Longrightarrow$ Tomaso Belloni's talk
- Broad lines do exist
  - lines are of good quality, we can start attempting to measure a.
  - lines are seen in Galactic black holes *and* in neutron star systems.

Major methodological comments:

- Use the `relline`- or `ky`-models!
- soft absorption can have major effect on modeling
- need to improve on calibration (don't we all. . .)
- need to improve signal to noise $\Longrightarrow$ Athena

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