X-ray Spectroscopy of Luminous Black Holes

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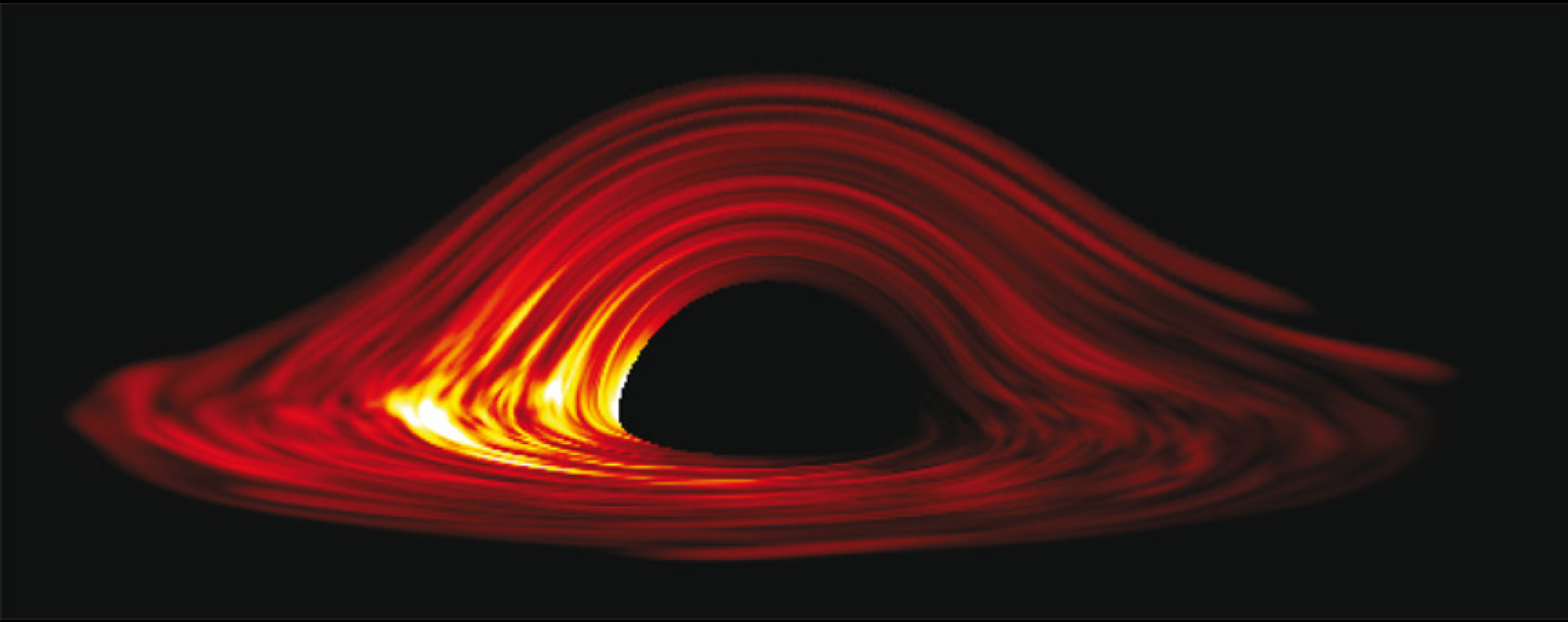
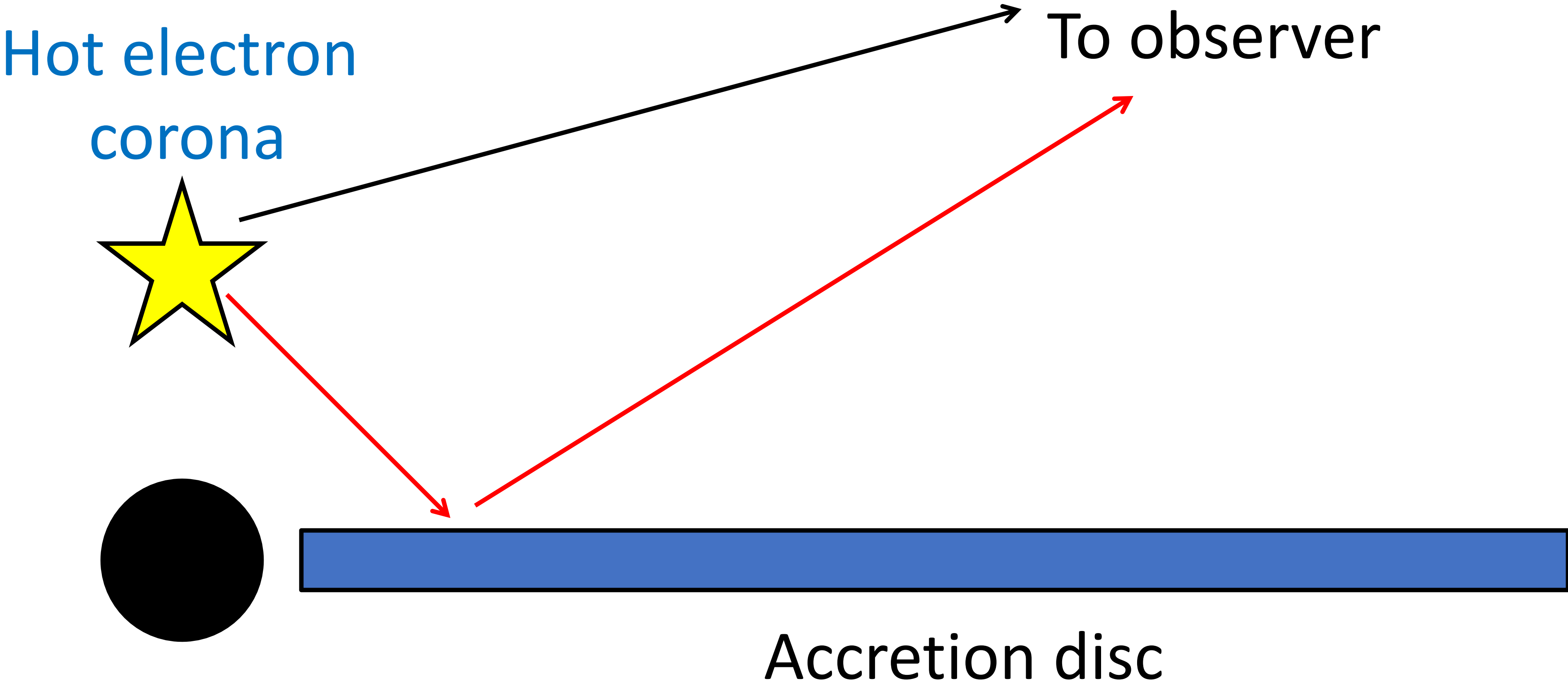
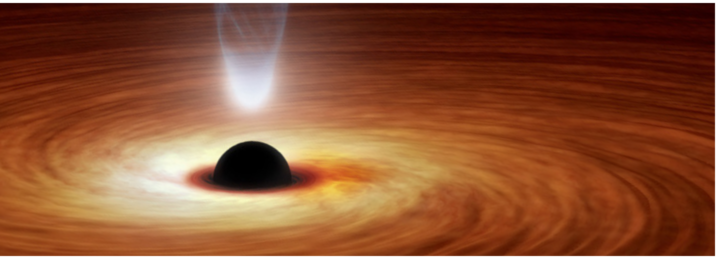




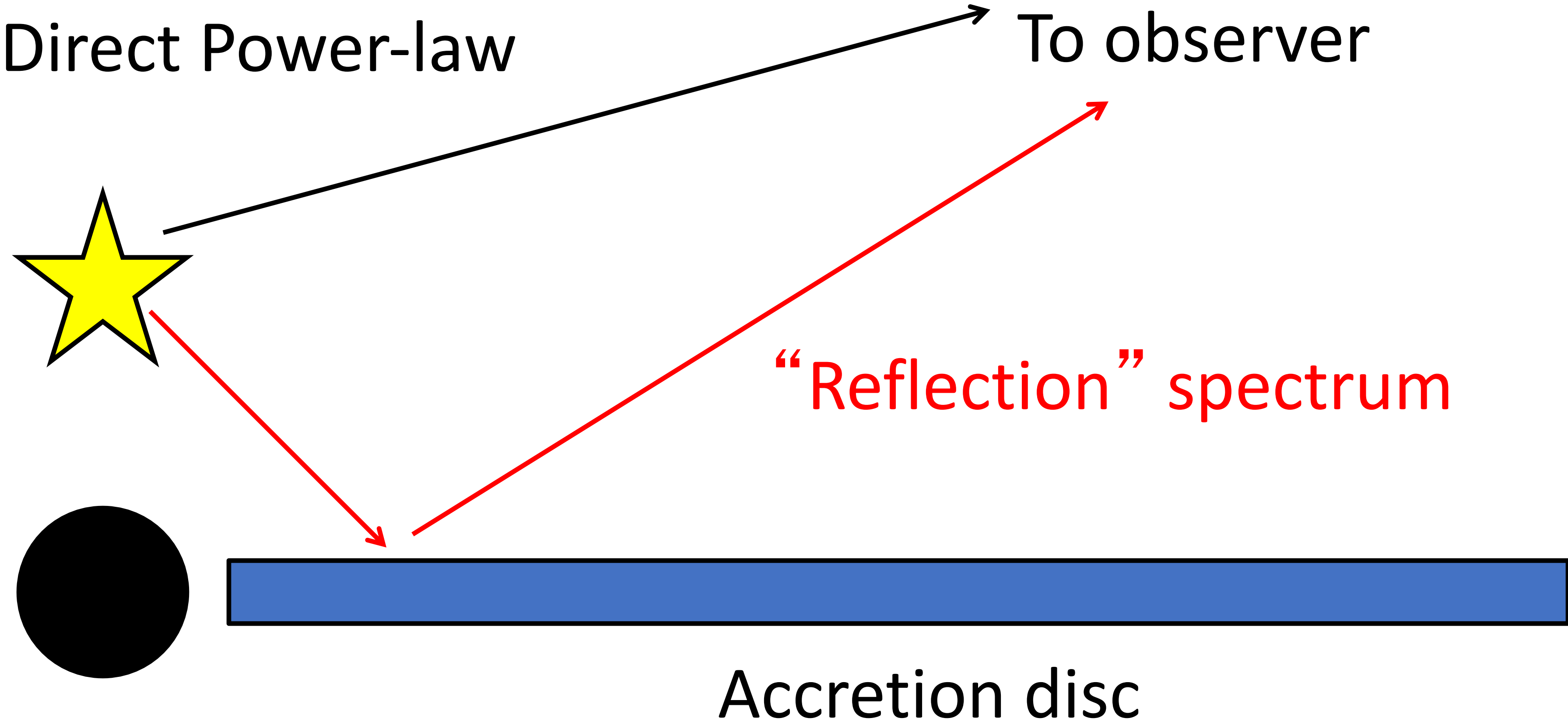
Hot electron corona

To observer

Accretion disc



Lamppost model

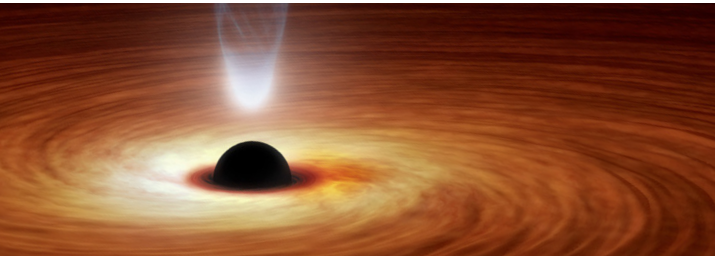


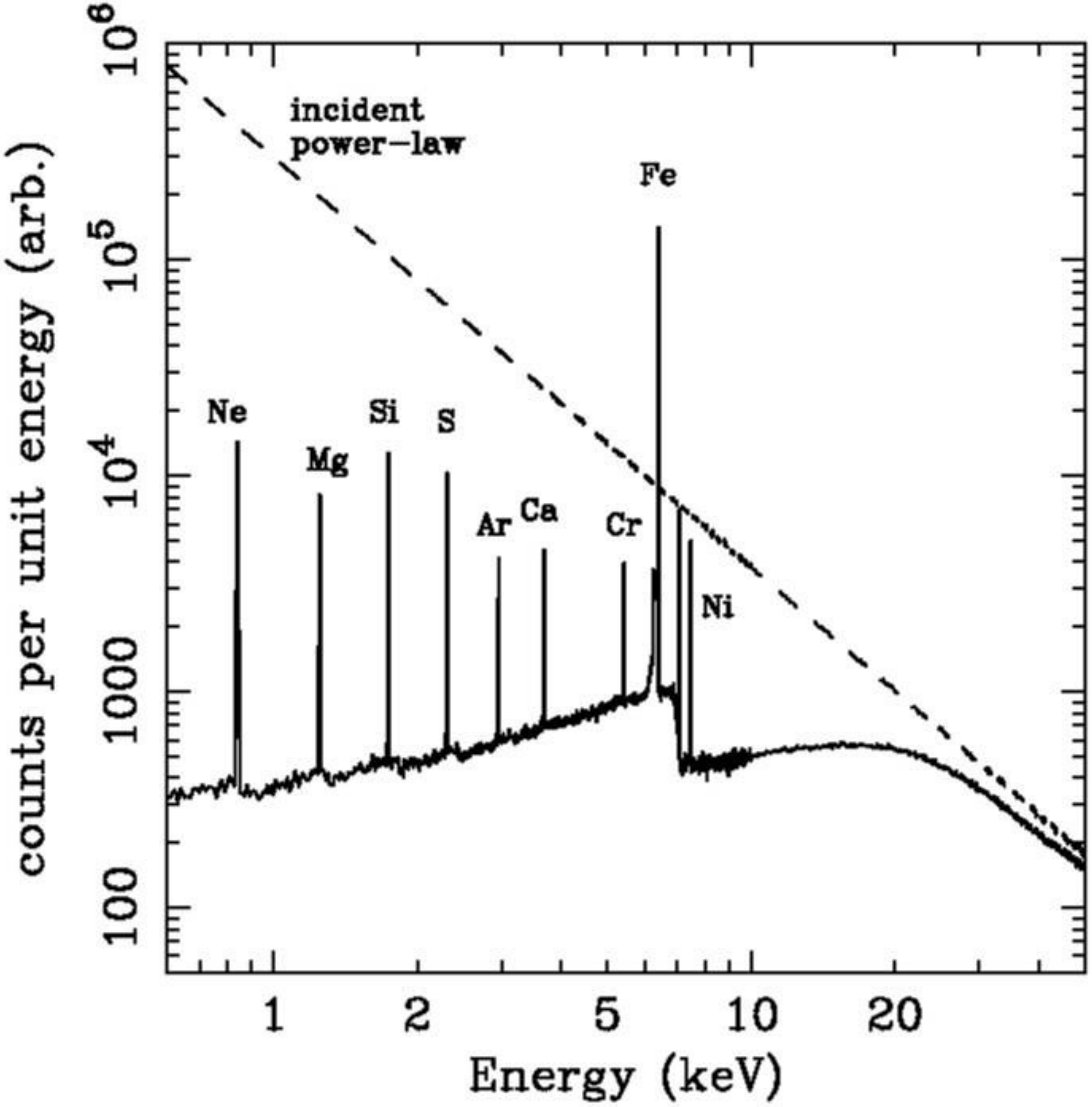
Direct Power-law

To observer

“Reflection” spectrum

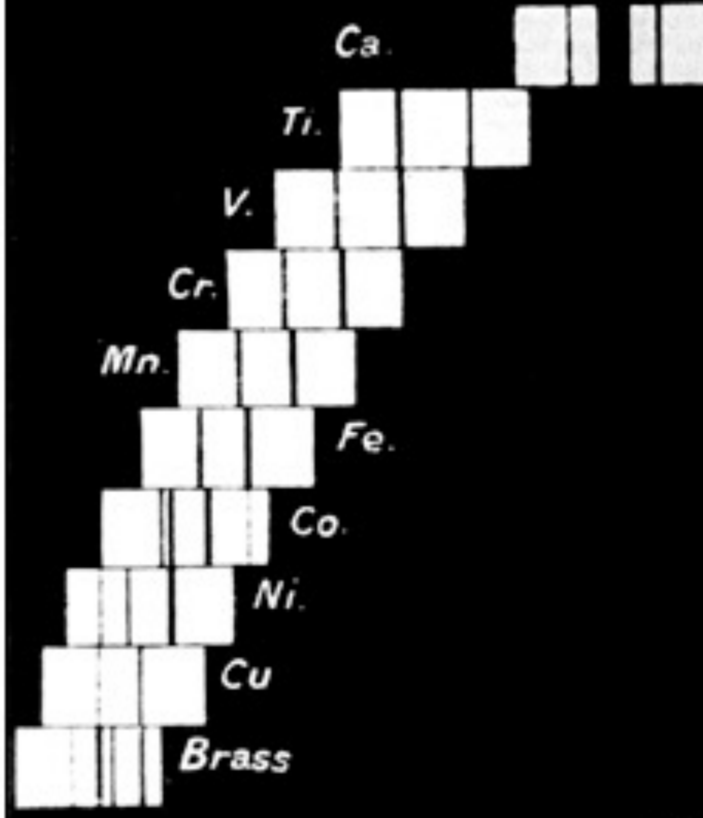
Accretion disc





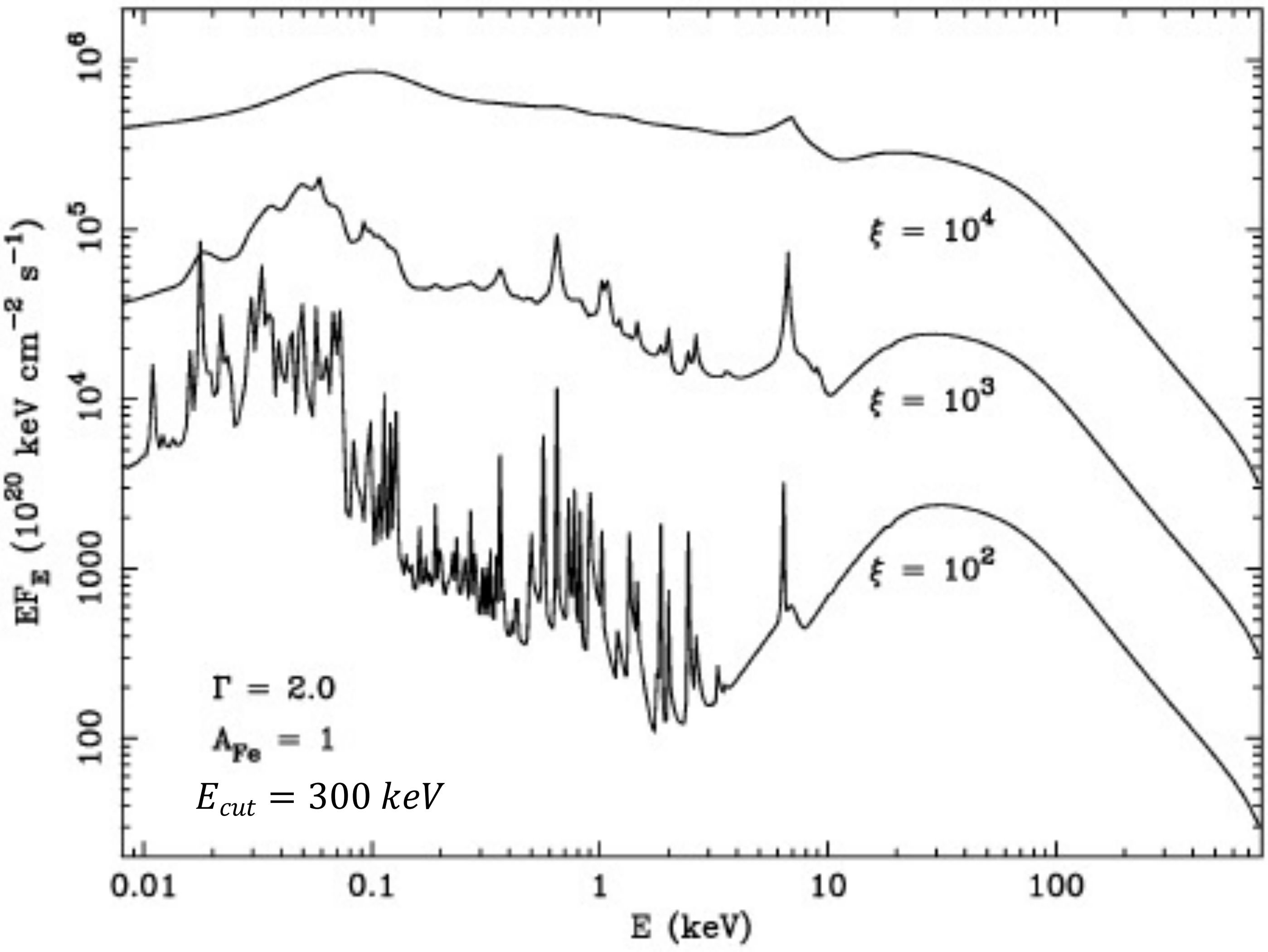
Reflection
from
cold matter
of cosmic
abundance

C Reynolds



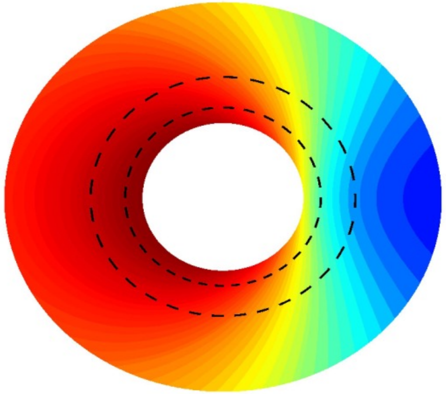
H Moseley

Reflection from ionized gas Ross+Fabian93,05; Garcia+13



$Ionization\ Parameter \quad \xi$ = L/nr^2

Relativistically Broadened Line

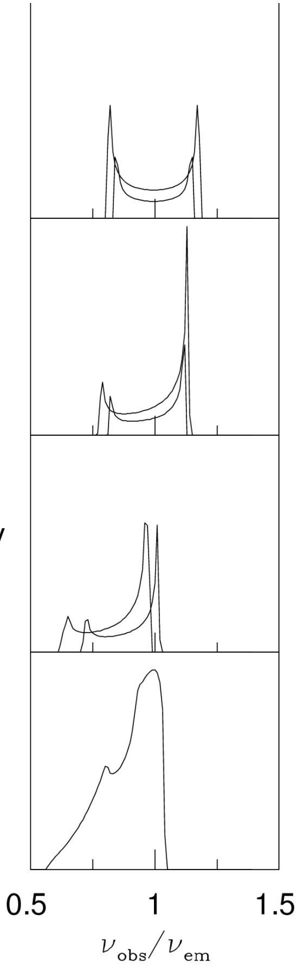


Newtonian

Special relativity

General relativity

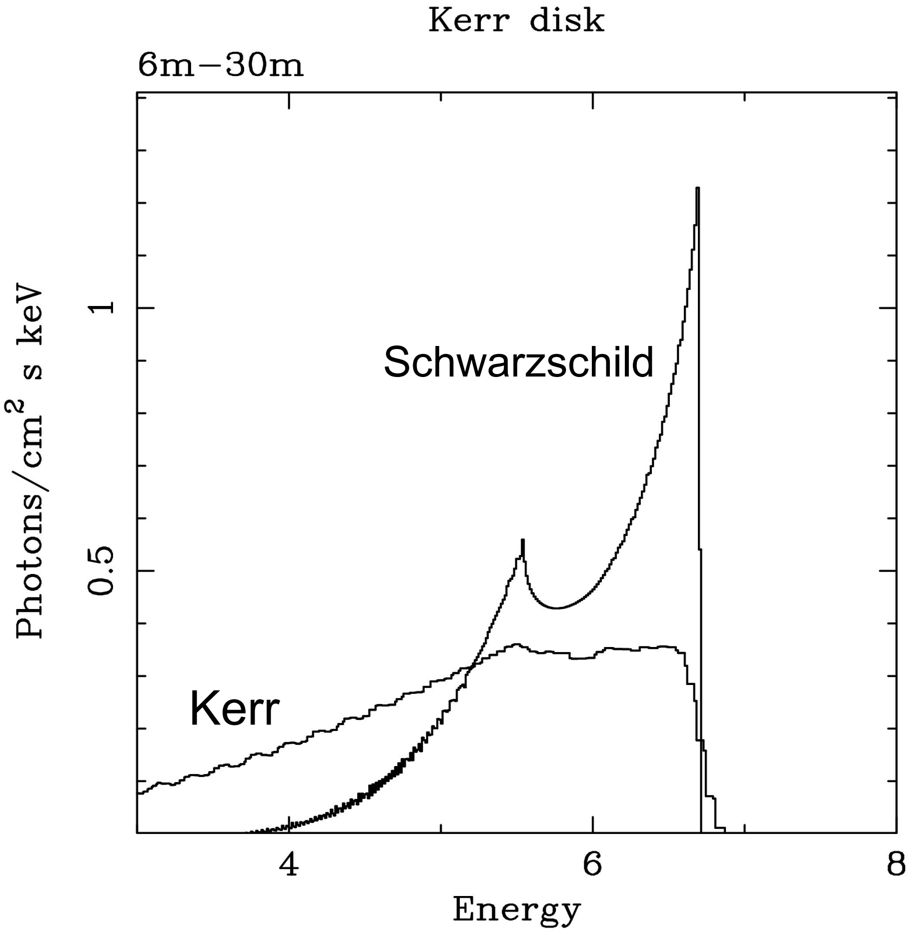
Line profile



Transverse Doppler shift

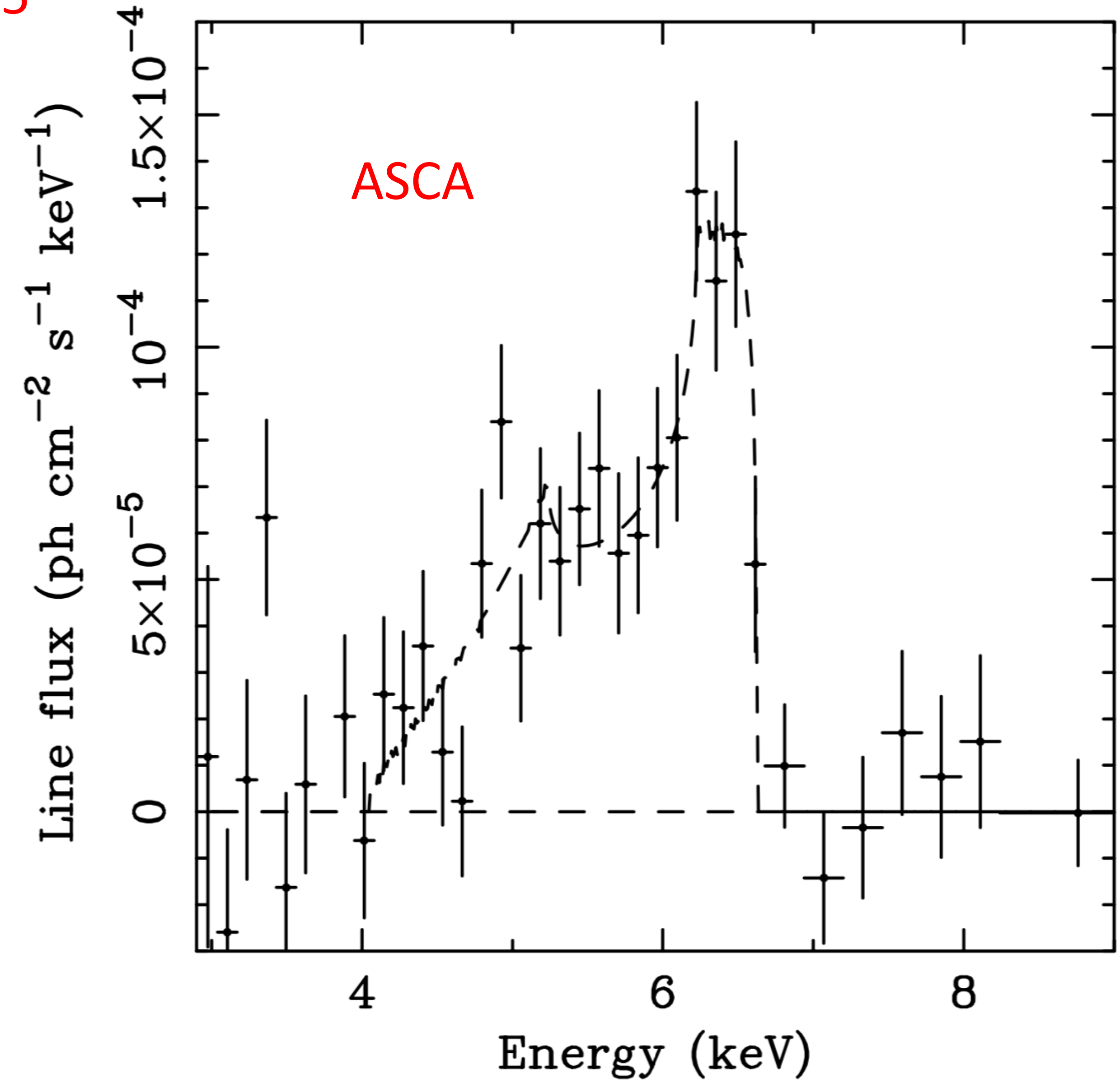
Beaming

Gravitational redshift



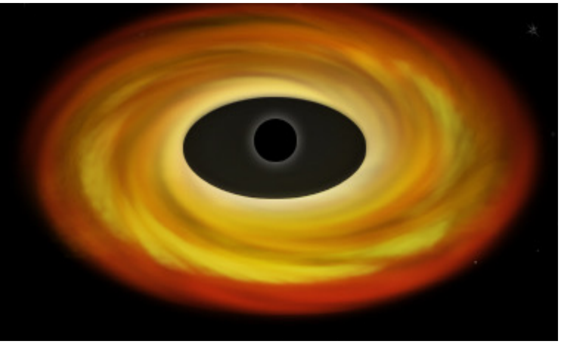
Fabian+89, Laor 91…

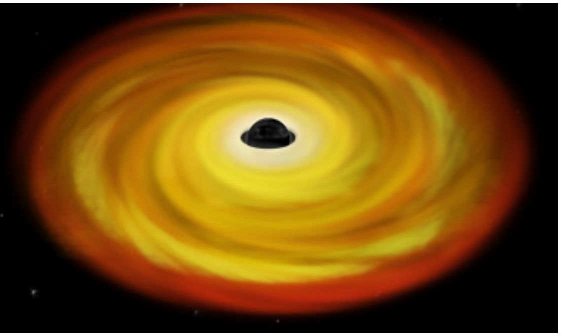
Tanaka+95



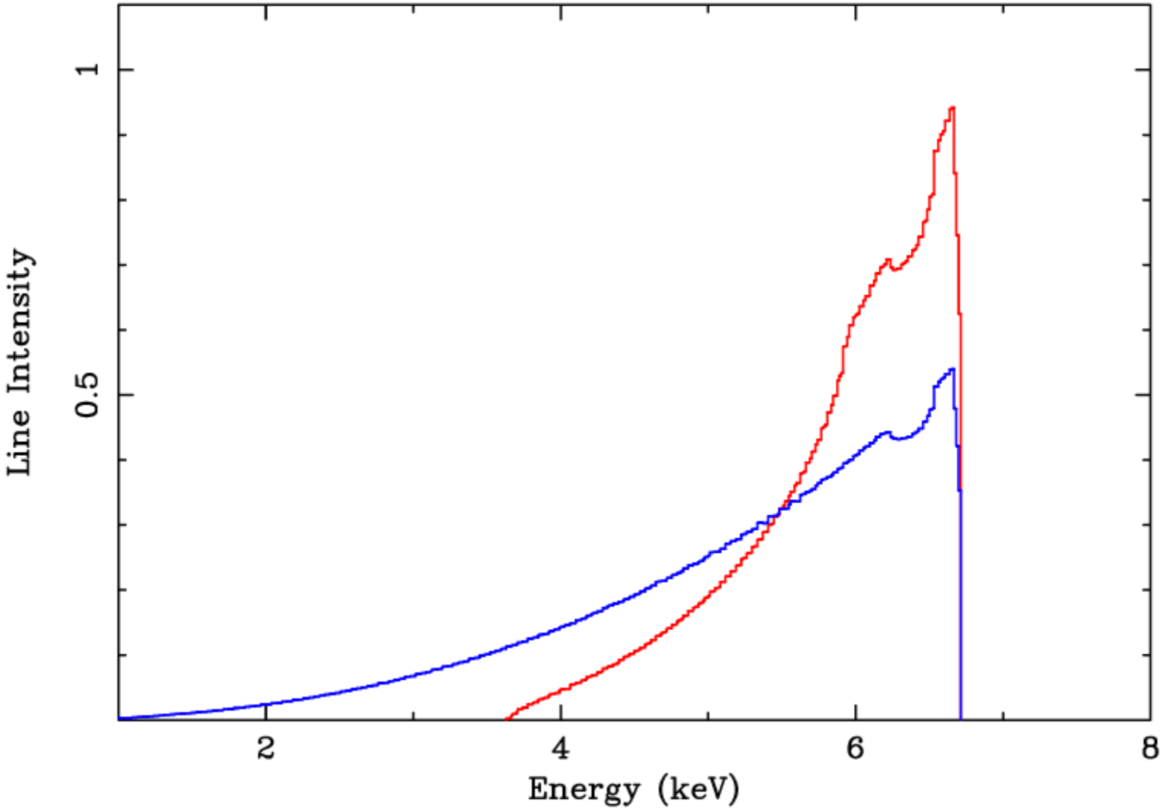
Probing Black Hole Spin

No spin

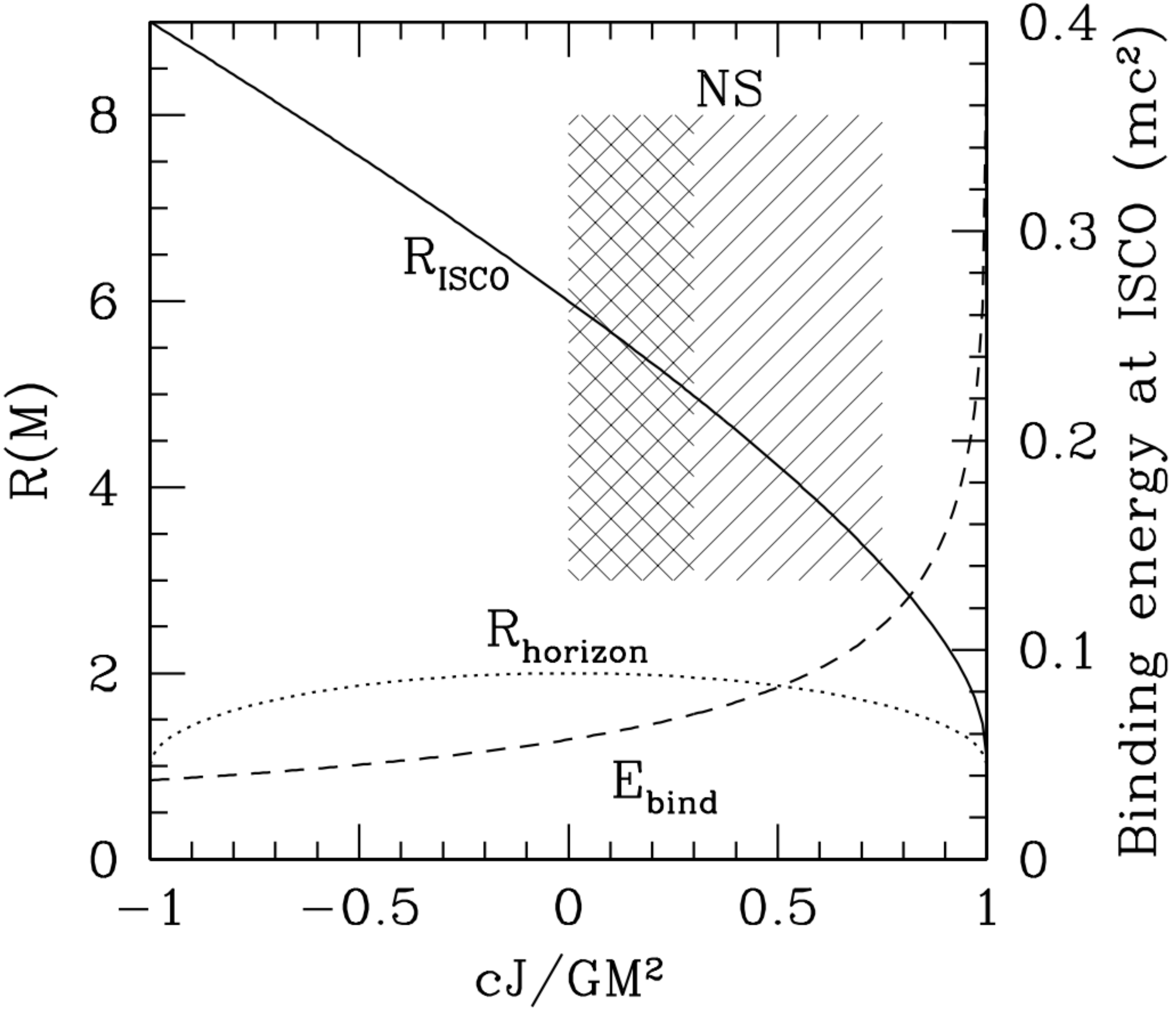




Max spin

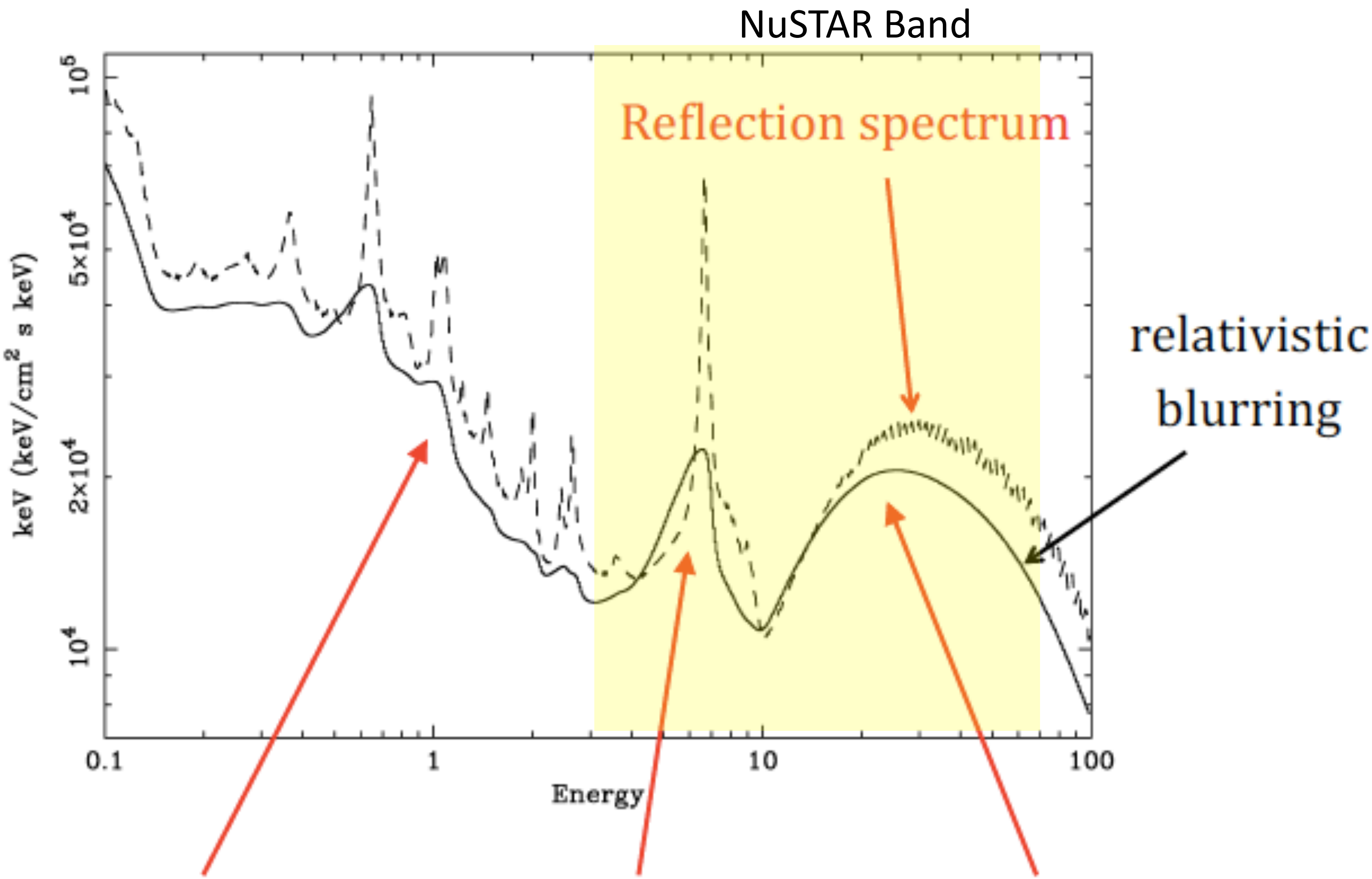


SPIN from Innermost Stable Circular Orbit (ISCO)



Spin a

Miller+Miller15



NuSTAR Band

Reflection spectrum

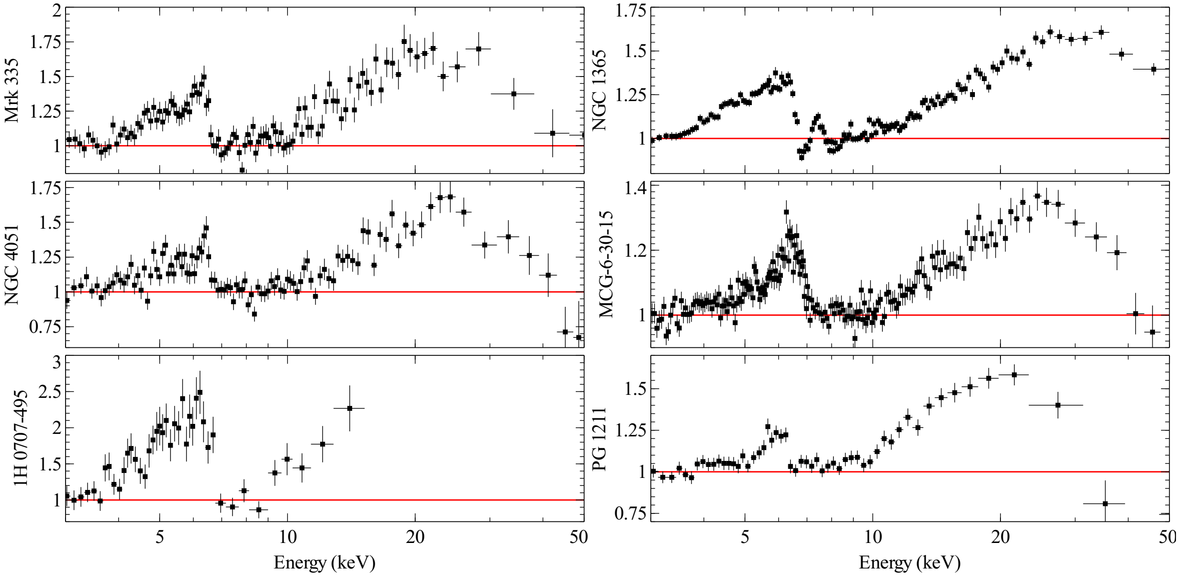
relativistic blurring

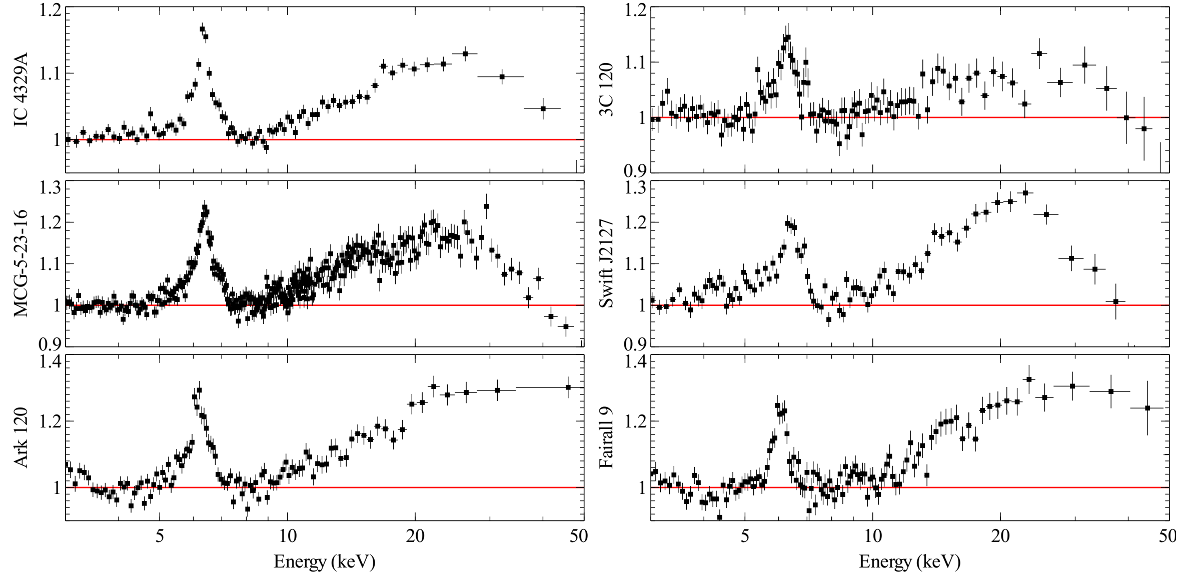
Soft excess – broad iron line – Compton hump

Observer sees blurred reflection spectrum + irradiating power-law
(horizontal line in this plot if photon index=2)
Ratio of components depends on geometry, GR, SR (if corona outflowing)

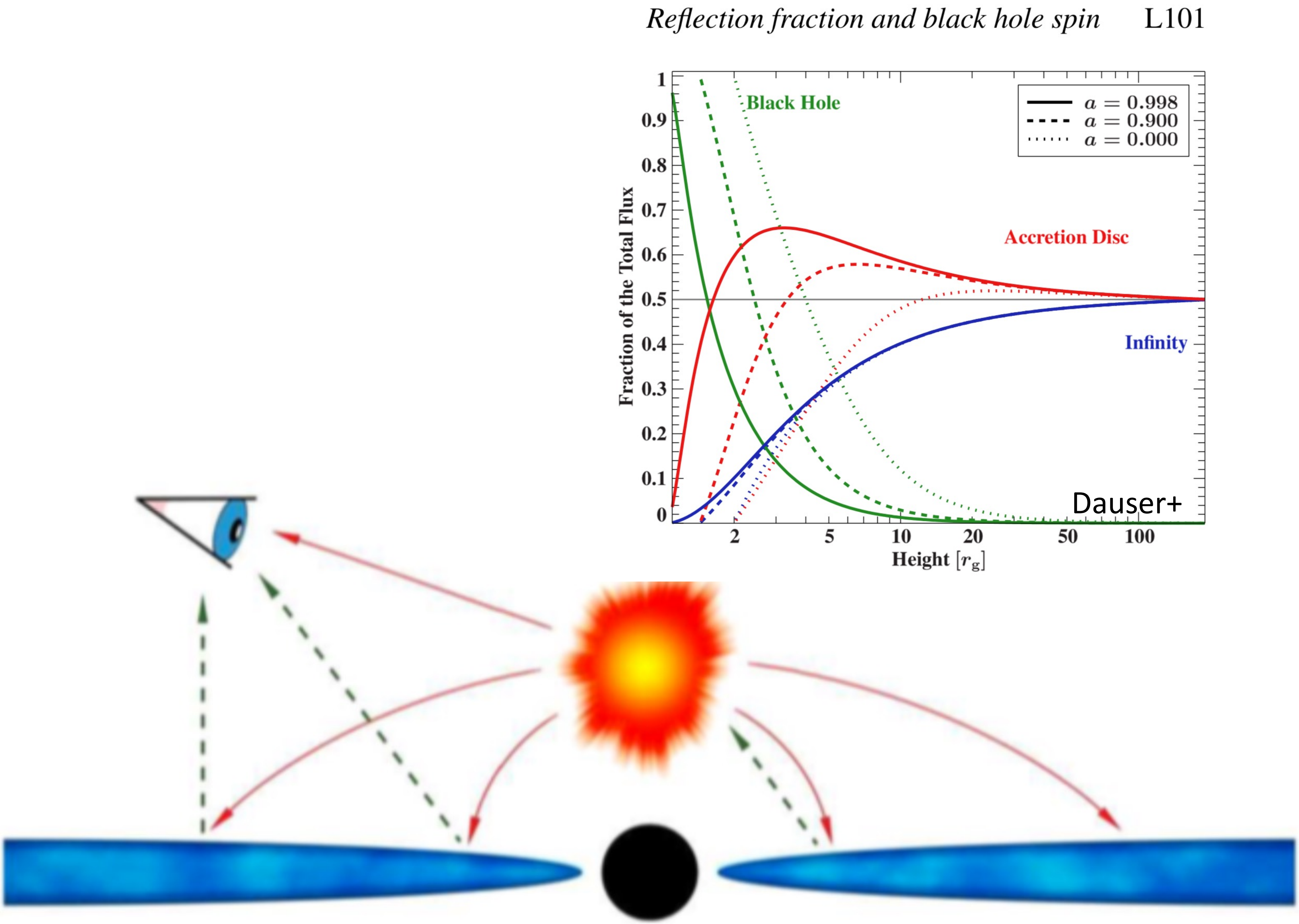
Parker, Matt+

Reflection in AGN with NuSTAR



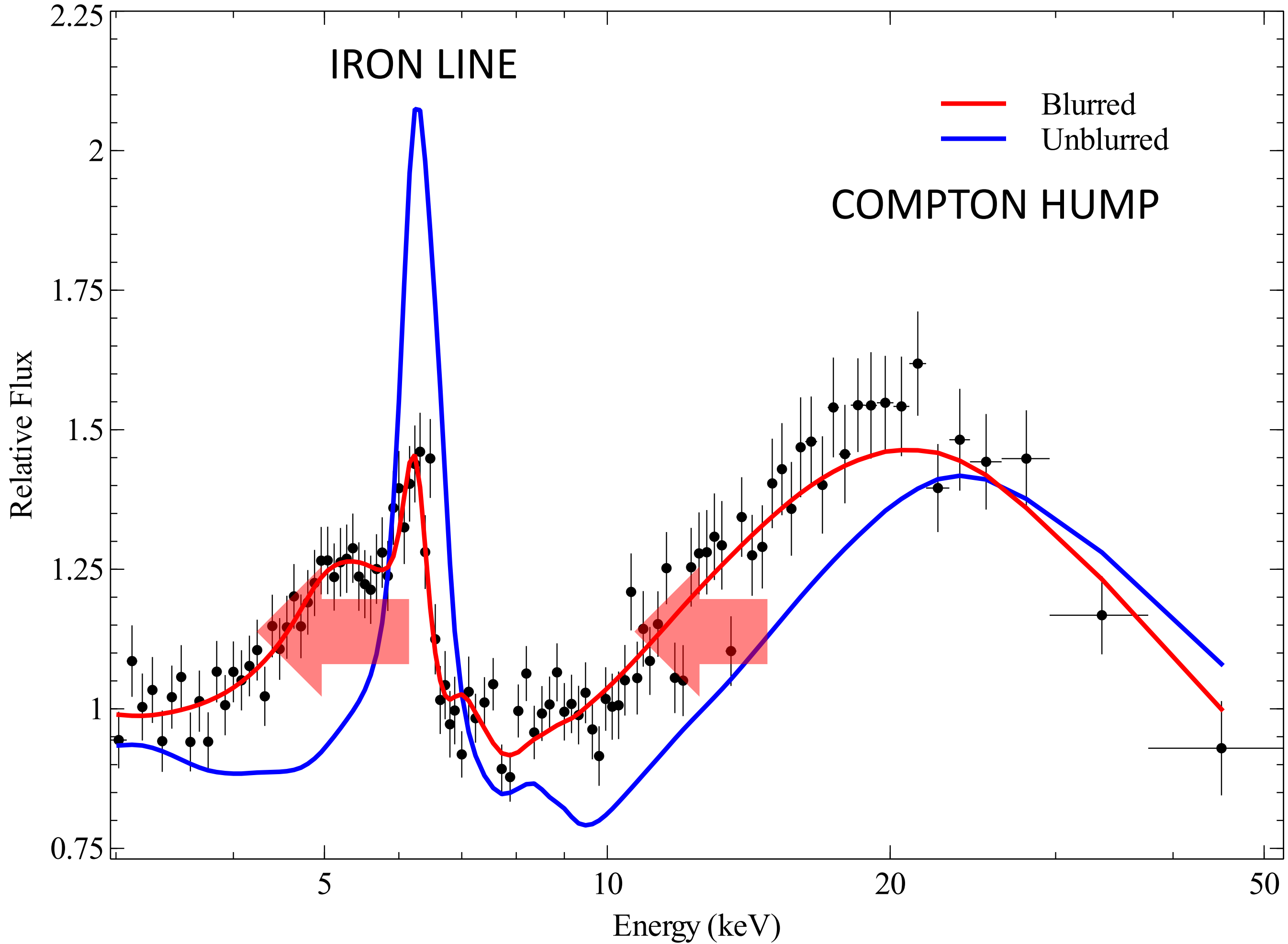


Spectra show ratio of data to model power-law


Reflection fraction and black hole spin L101
Fraction of the Total Flux
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Height $[r_g]$
2
5
10
20
50
100
$a = 0.998$
$a = 0.900$
$a = 0.000$
Black Hole
Accretion Disc
Infinity

Dauser+

Sometimes most emission from within $2r_g$

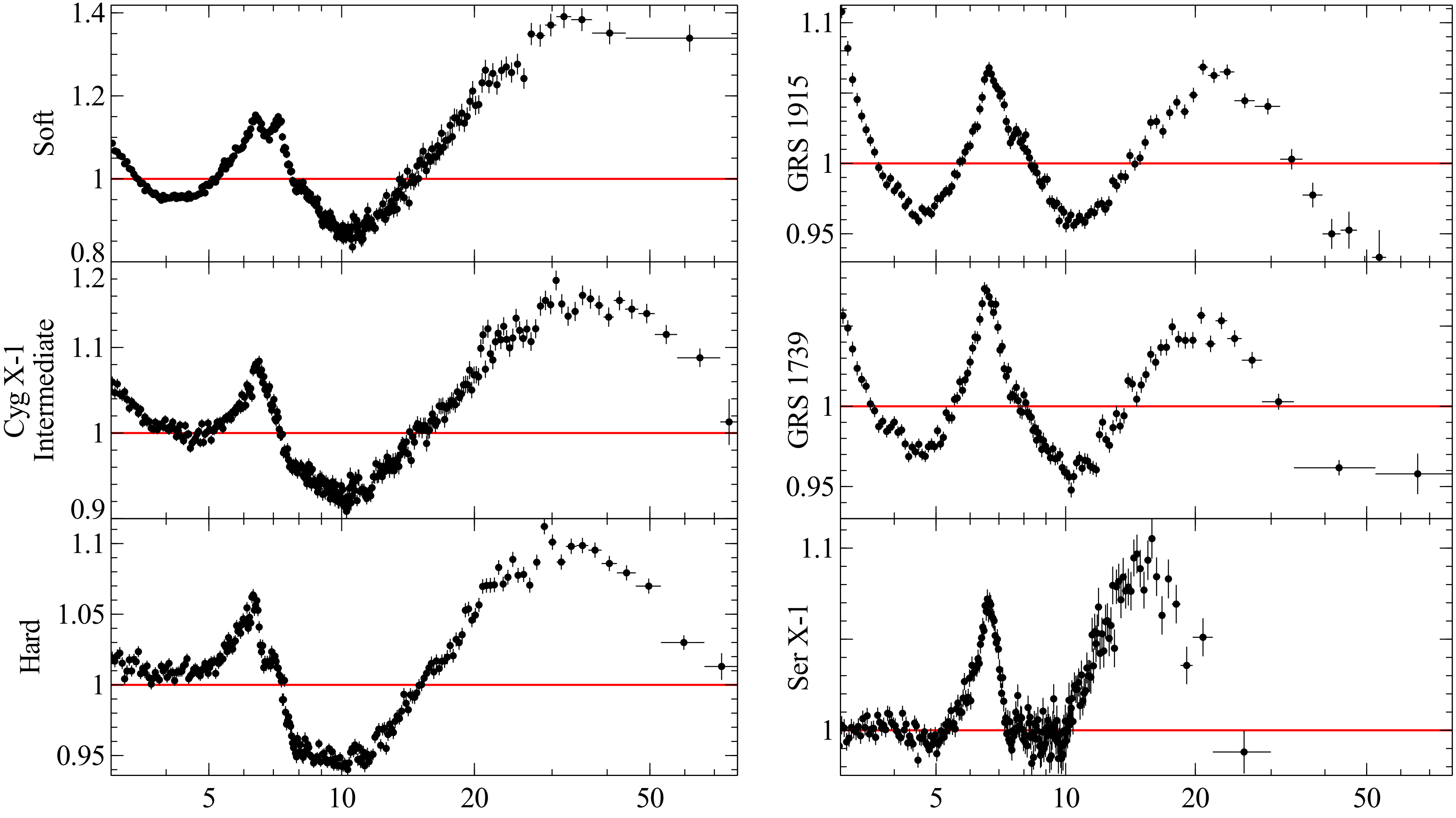


Mkn 335 Parker+14

Reflection-dominated spectrum

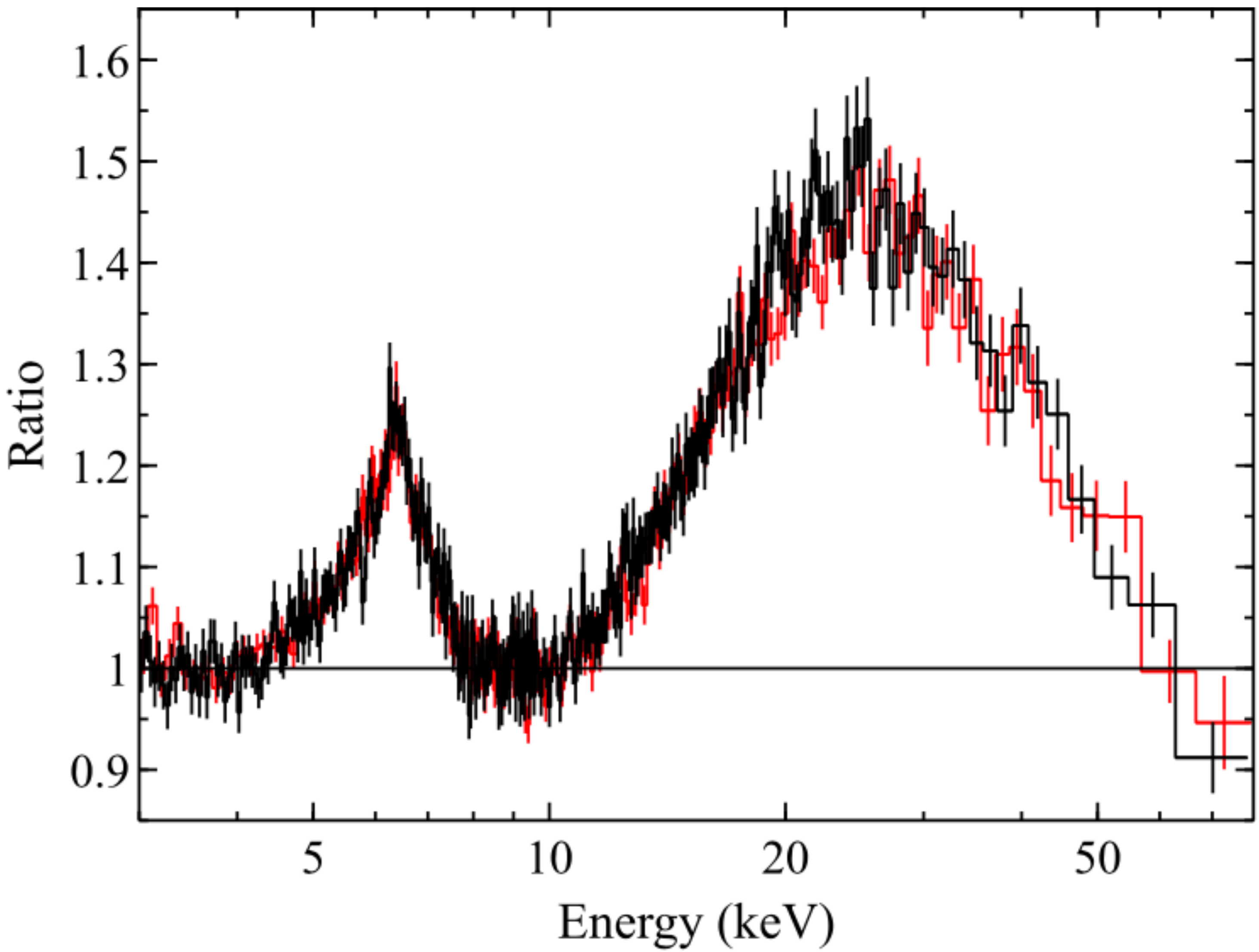
Parker, Tomsick+, JMiller+13,15

and Galactic sources too

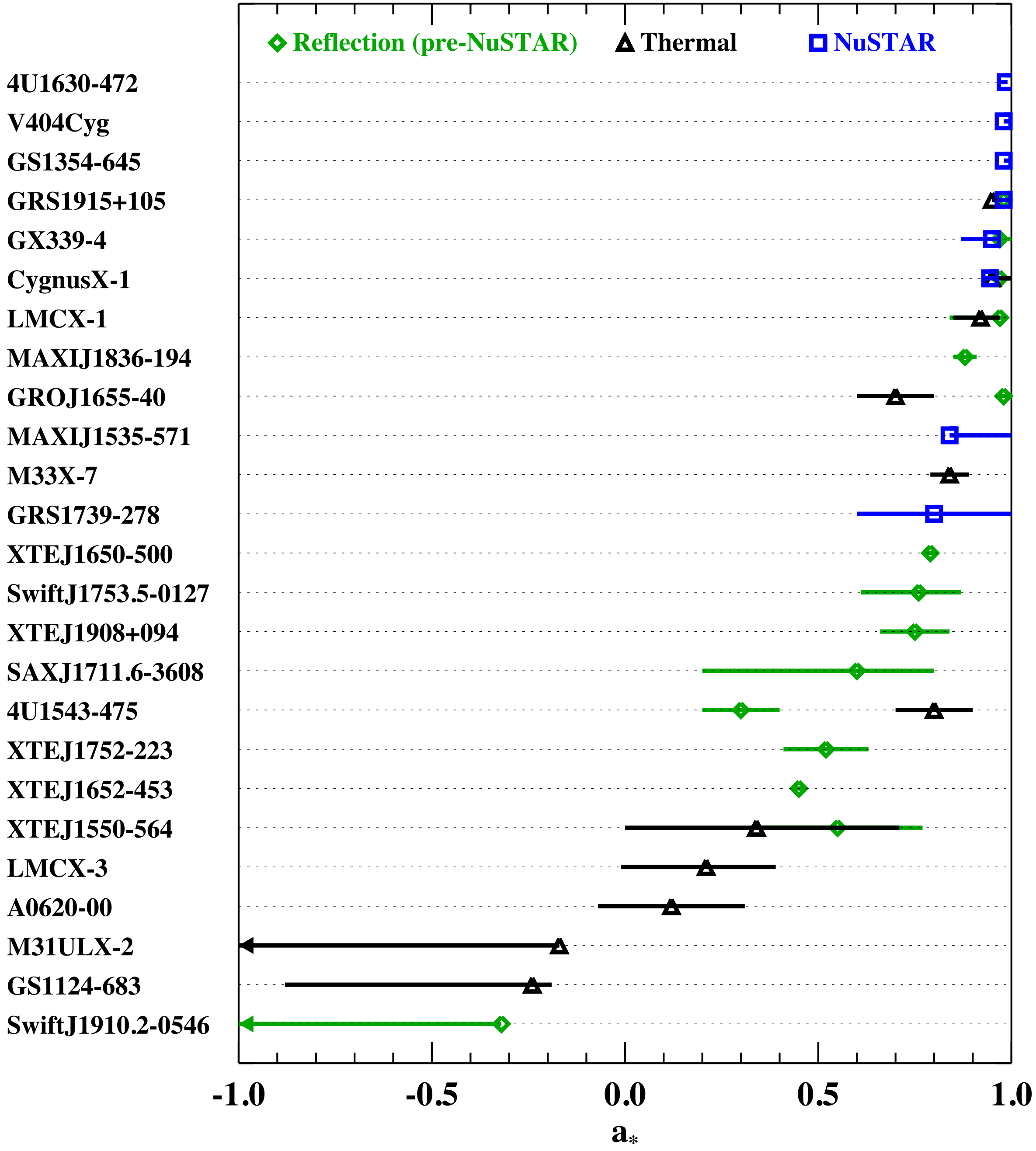


Walton+16

V404 Cyg Flare NuSTAR

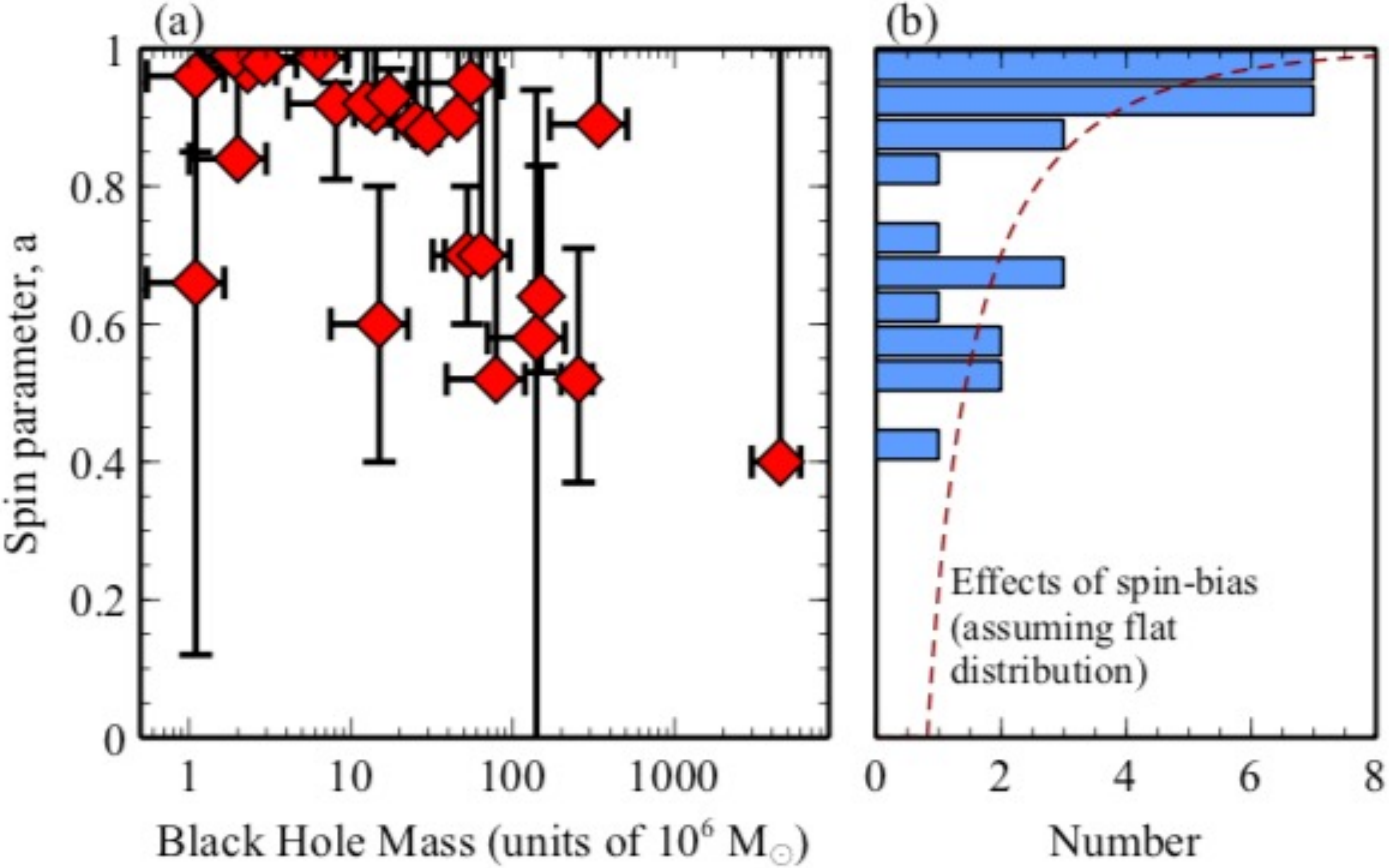


Thermal model relies on blackbody emission from disc in soft state

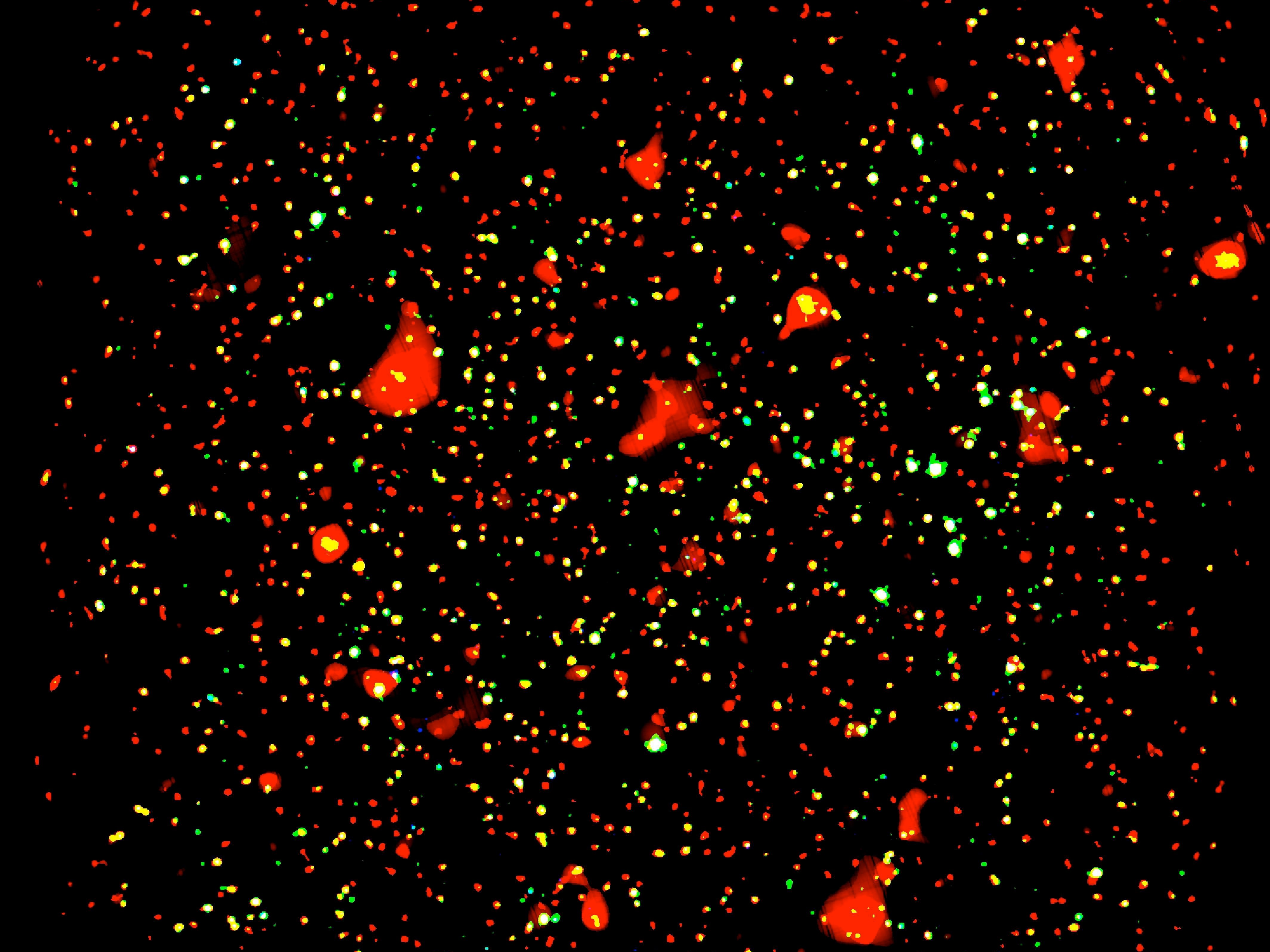


Tomsick19

Active Galactic Nuclei AGN



Vasudevan+16, Reynolds20



Soltan (1982) Argument for radiatively efficient accretion <a> >0.5

- The radiation from accreting black holes leads to an energy density in space of $\mathcal{E}_{\rm acc}$, and a growth in the mean density of black holes of $\frac{\epsilon}{(1-\epsilon)}\rho_{\rm BH}c^2$, where ϵ is the radiative efficiency of the accretion flow.
- With time the Universe expands leading to the same relative drop in density of both factors. However the radiation suffers a loss due to redshift, leading at the present time to

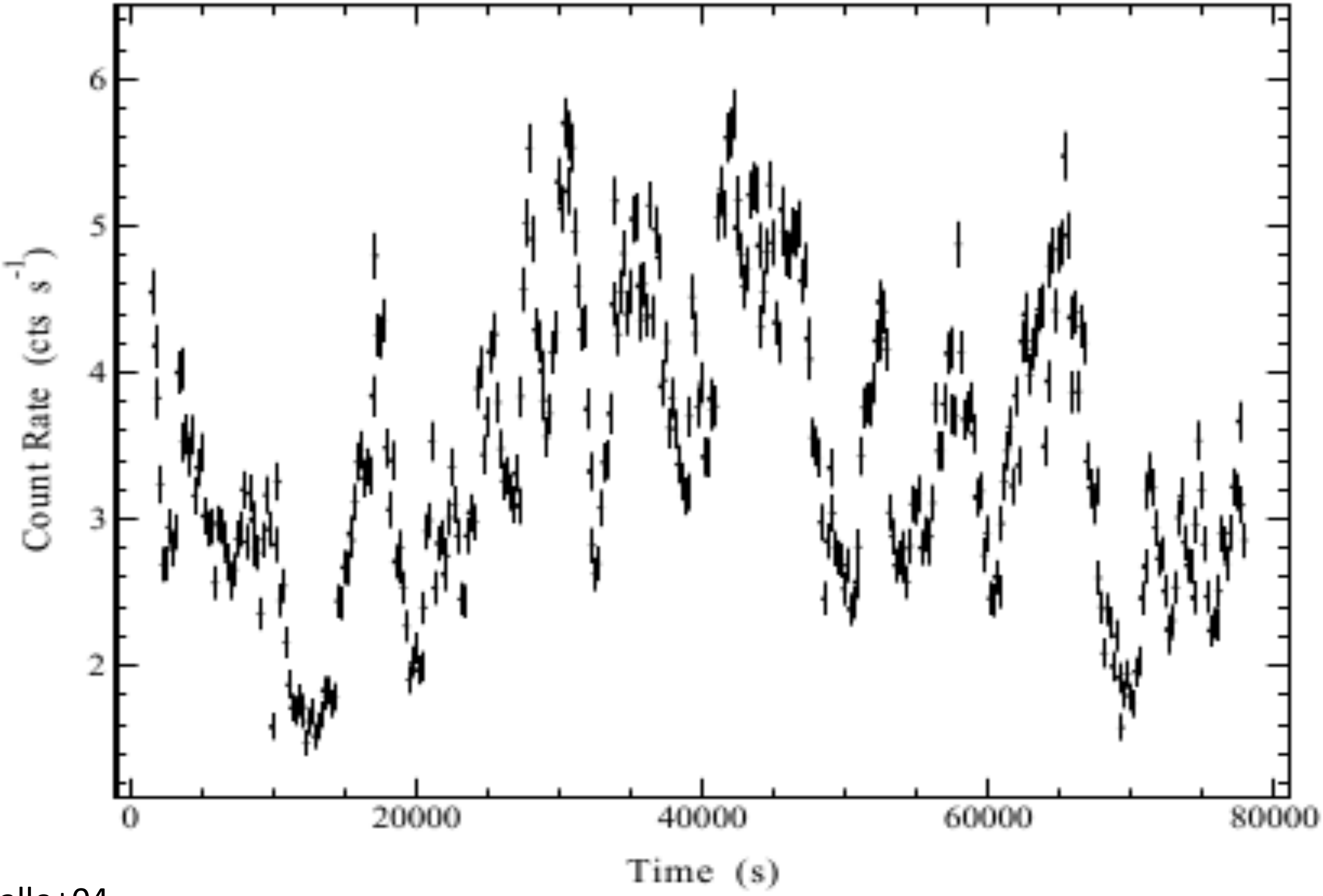
$$\mathcal{E}_{\rm acc}(1+z) = \frac{\epsilon}{(1-\epsilon)}\rho_{\rm BH}c^2,$$

where z is the mean redshift at which the accretion occurs.

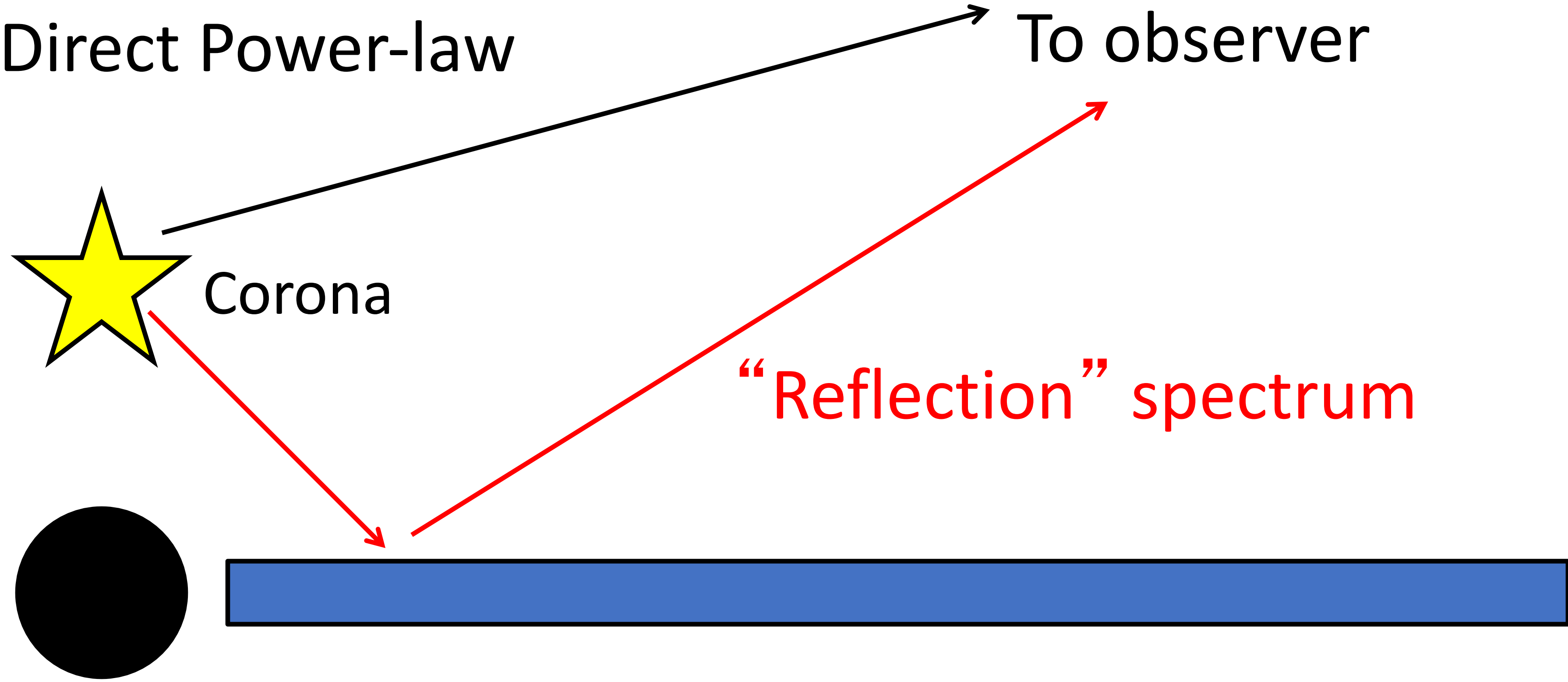
- $\mathcal{E}_{\rm acc}$ can be measured from the summed spectra of AGN and $\rho_{\rm BH}$ can be estimated from the mass function of galaxies together with the $M_{\rm BH} - M_{\rm gal}$ relation.
- Results show agreement if $\epsilon \sim 0.1$, indicating that most black holes have a spin of $a \sim 0.5$ and that massive black holes have grown by accretion.

See e.g. Shankar+20

1H0707-495



Gallo+04

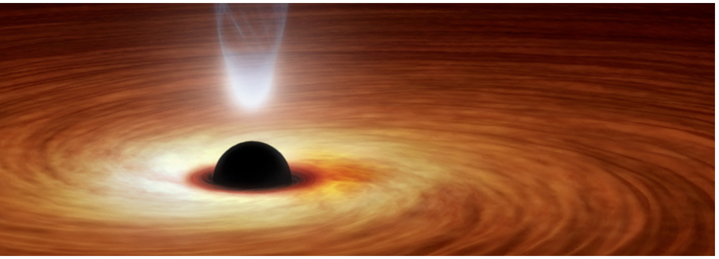


Direct Power-law

To observer

Corona

“Reflection” spectrum



Path difference leads to

Reverberation

(Time lags)

So far all lengthscales are in units of r_g (=GM/c^2), i.e. depend on BH mass.

Time lags give lengths in cm.

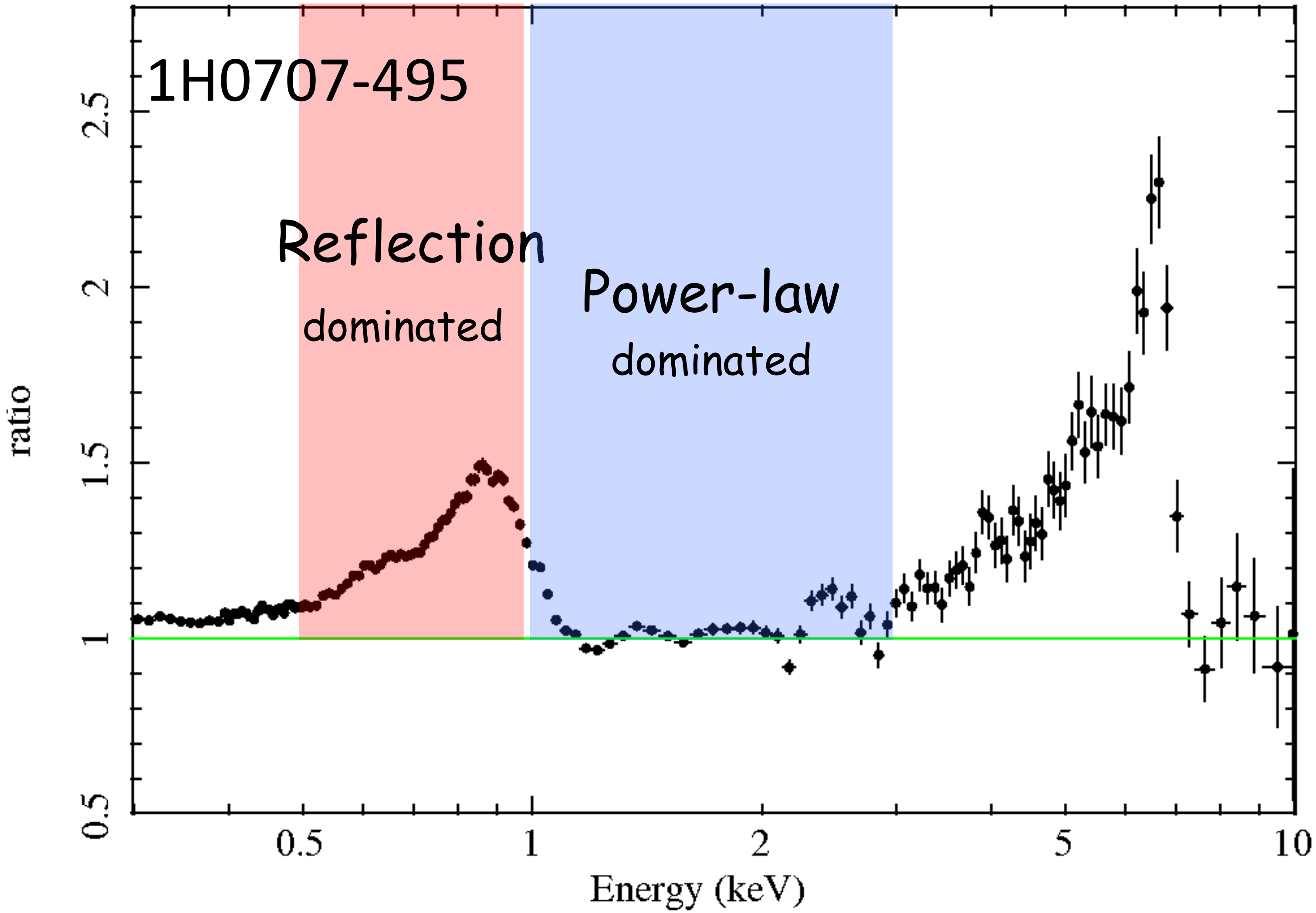
Observations of Reverberation complicated since see both Direct and Reflection components together

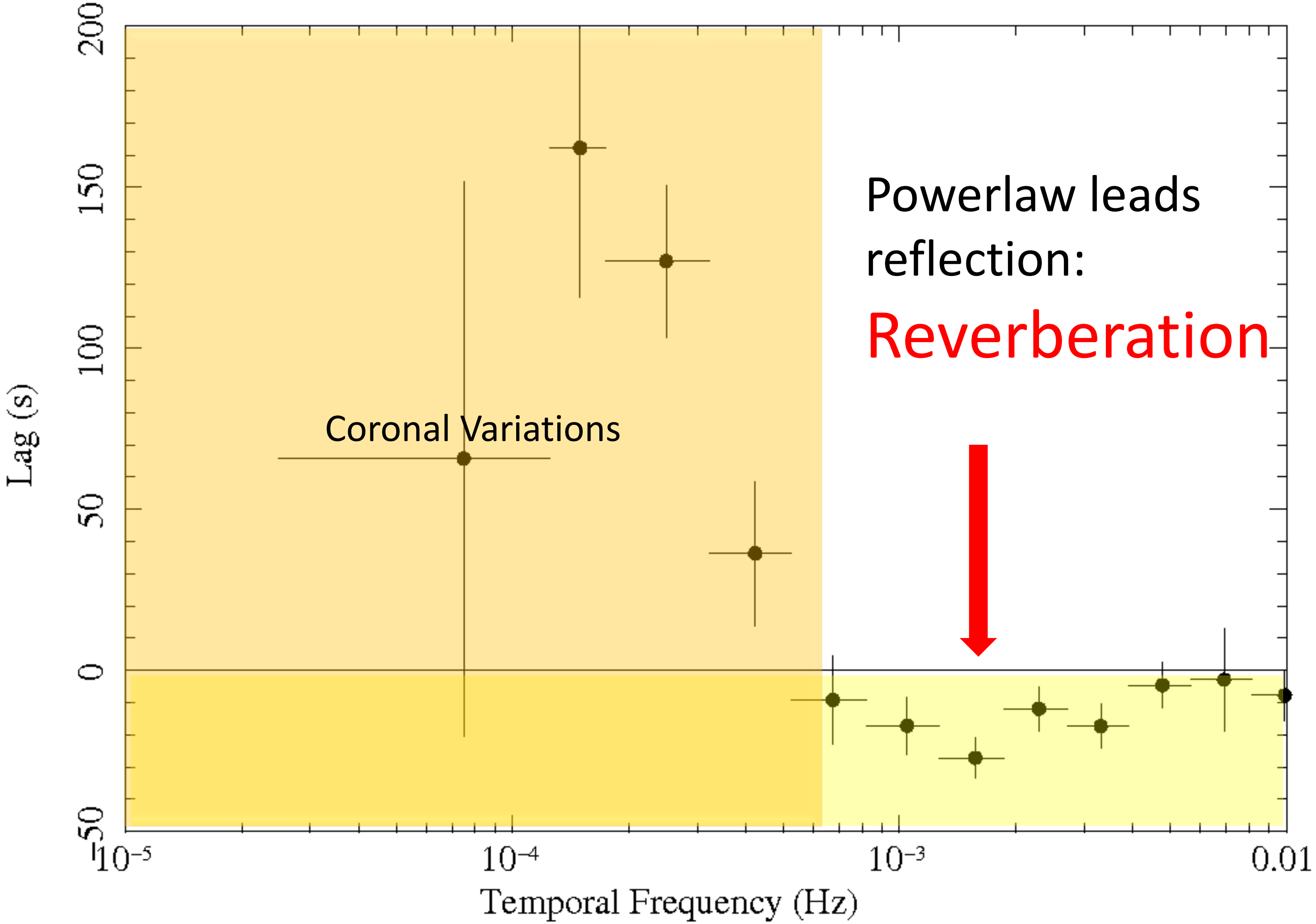
Separate spectrally
(contributions vary with energy)

Need Spectral Timing

Fabian+09

X-ray Reverberation



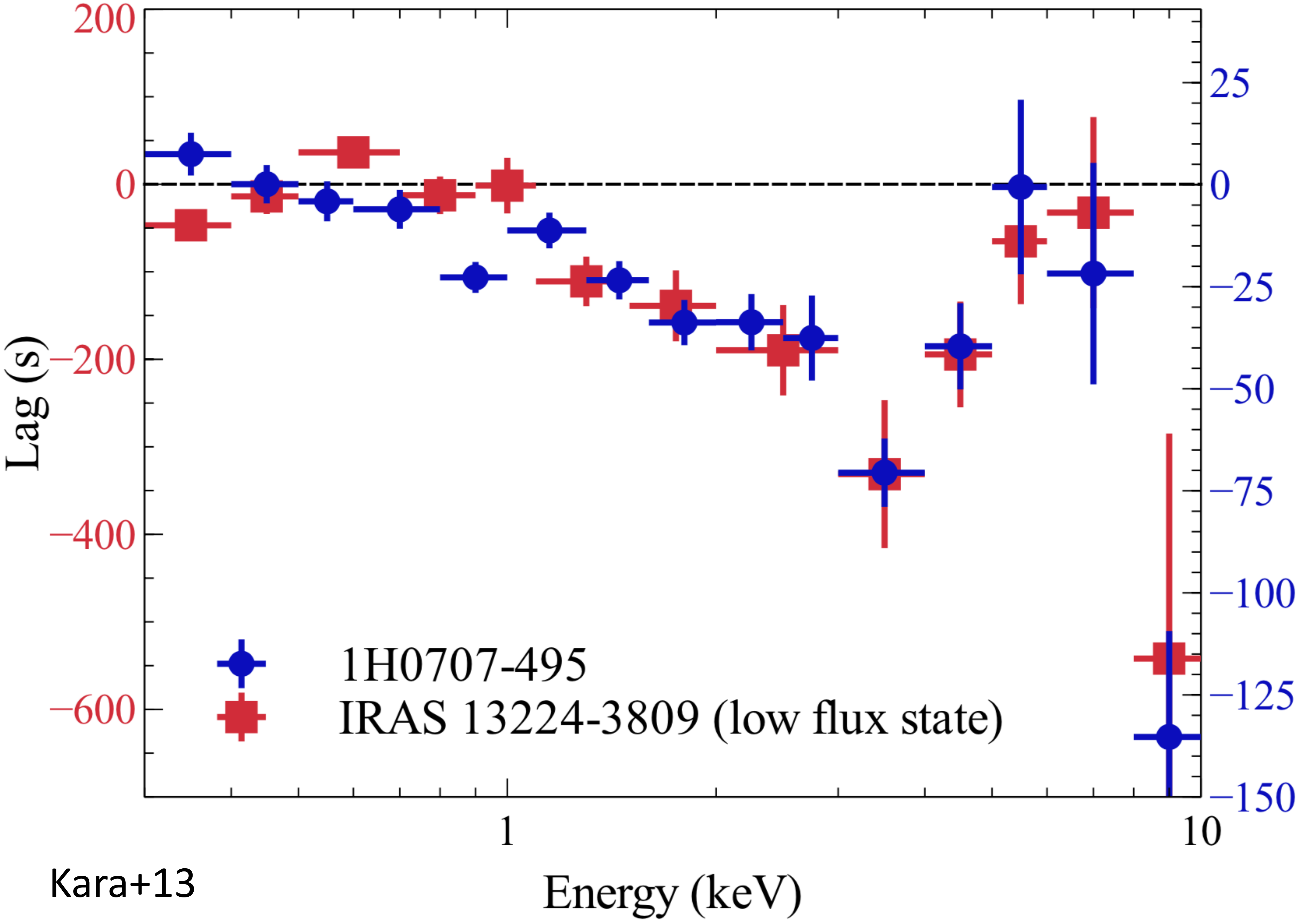


Coronal Variations

Powerlaw leads reflection:

Reverberation

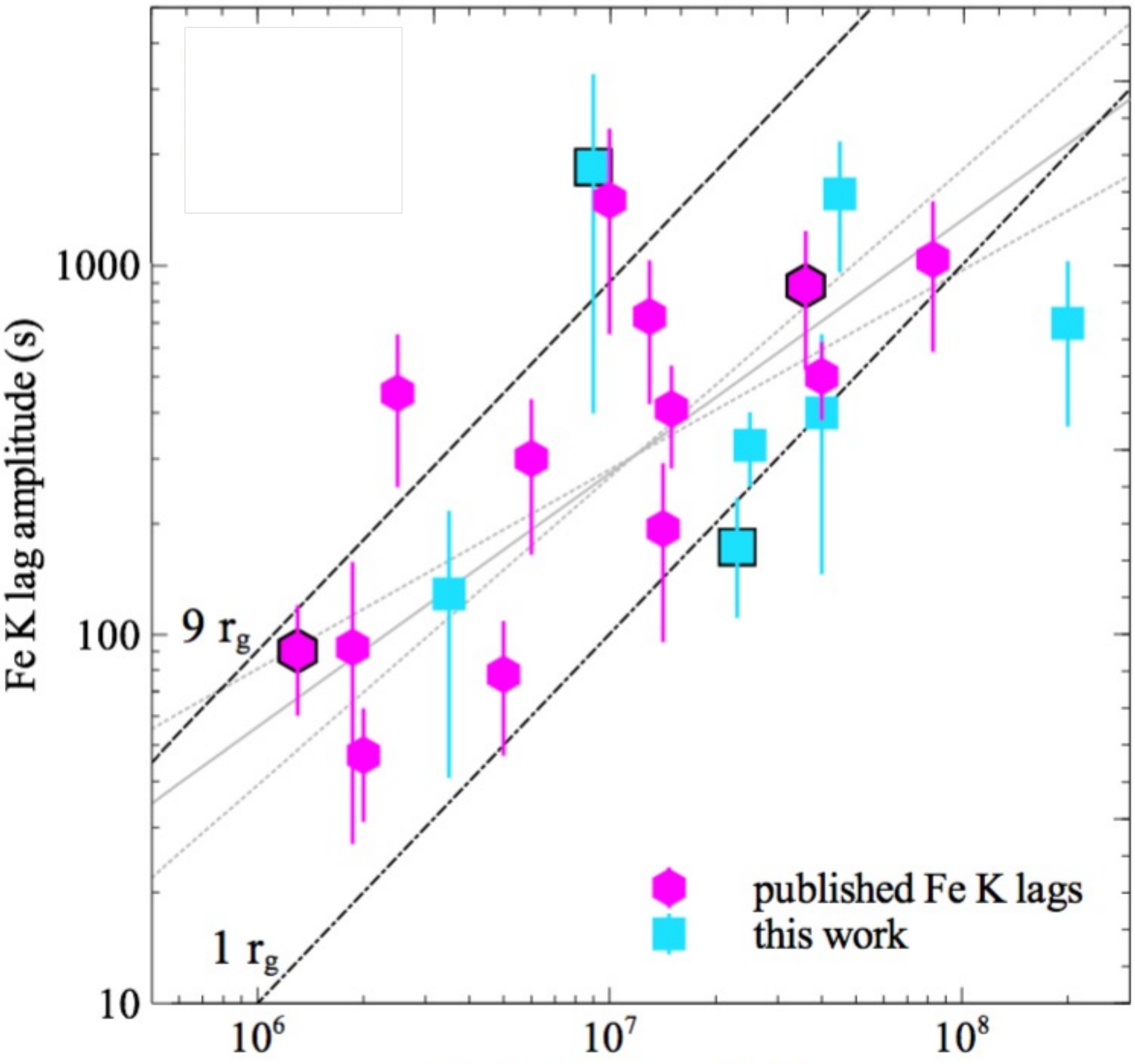
1H0707-495 Fabian+09 TIME LAGS between 0.5-1 and 1-3 keV


200
0
−200
−400
−600
25
0
−25
−50
−75
−100
−125
−150
Lag (s)
Energy (keV)
1
10
1H0707-495
IRAS 13224-3809 (low flux state)

Kara+13

Kara+16

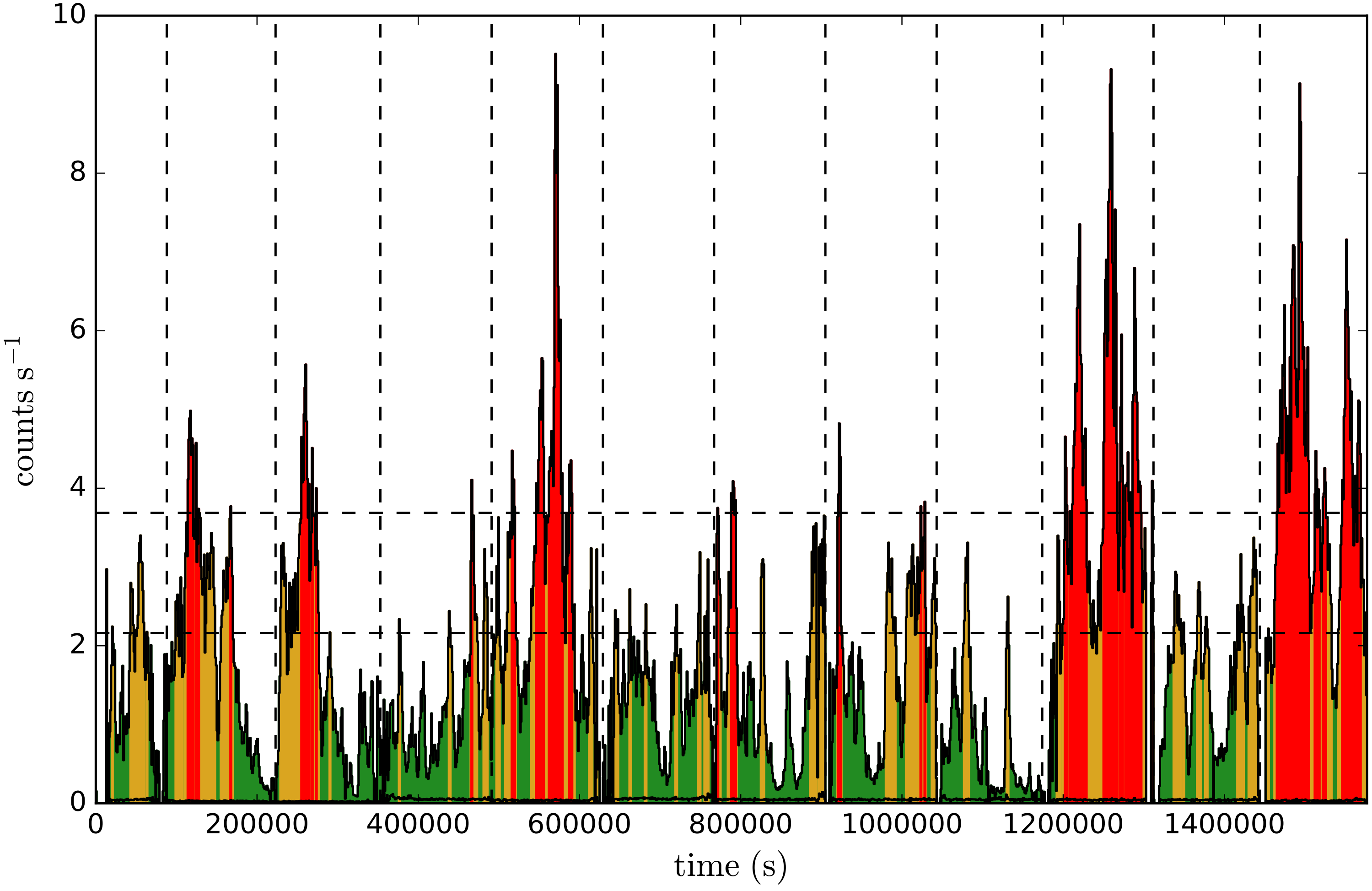
3-4 keV vs 5-7 keV



from e.g. optical

IRAS13224-3809 – MOST VARIABLE AGN IN X-RAYS

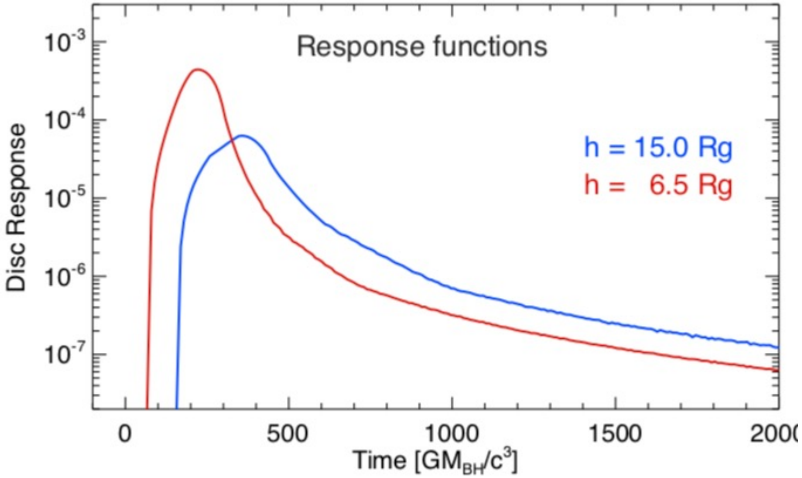
XMM + NuSTAR PROGRAMME 1.5Ms

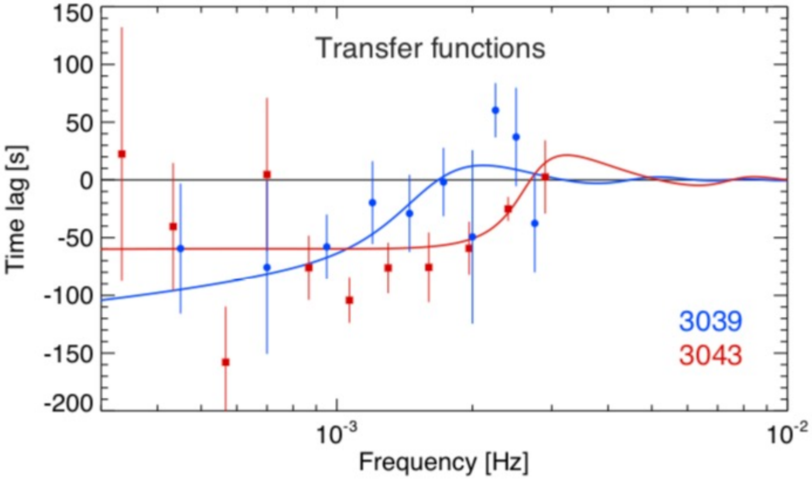


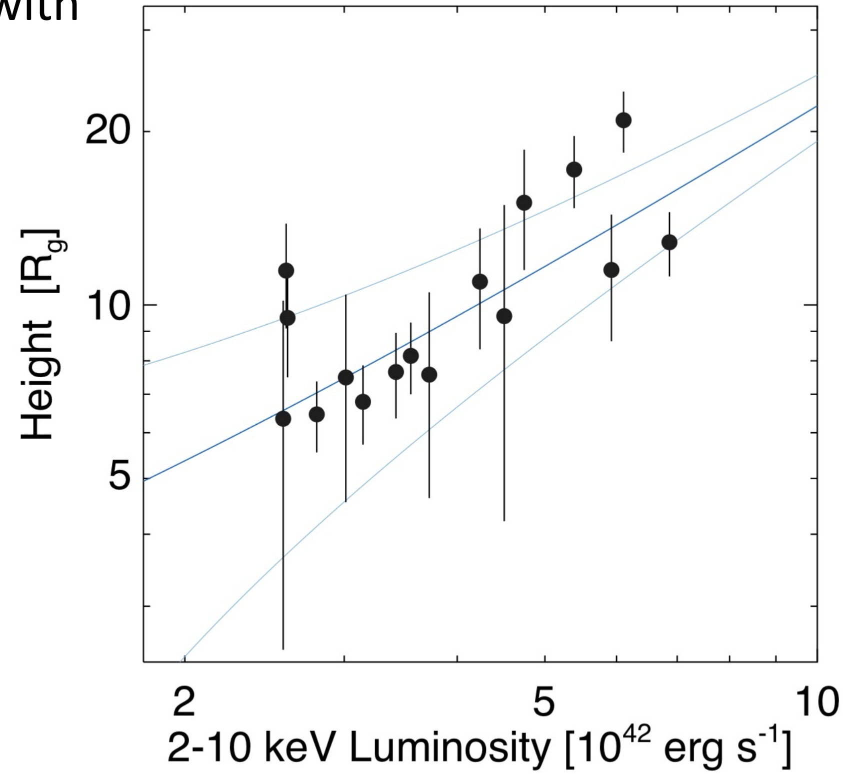
Quantifying the dynamics of the corona with 2 Ms of IRAS 13224-3809

Alston+20

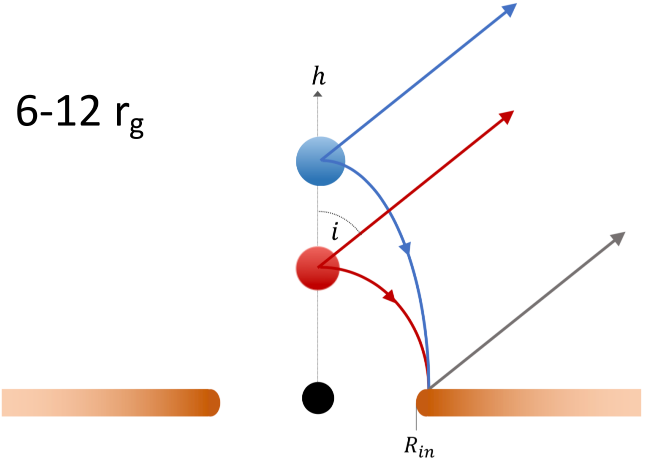
ky models by Michal Dovciak

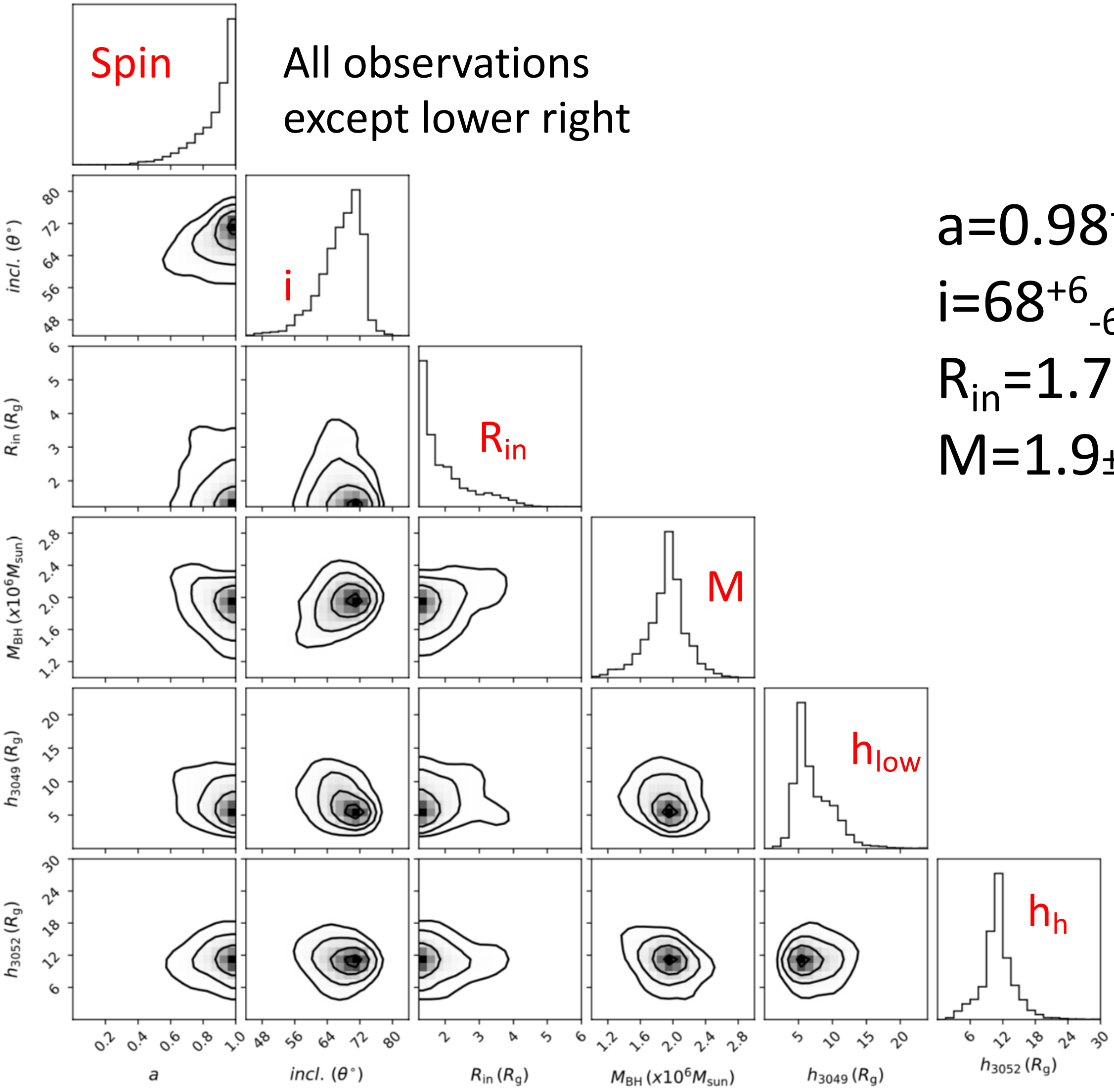






6-12 r_g





All observations
except lower right

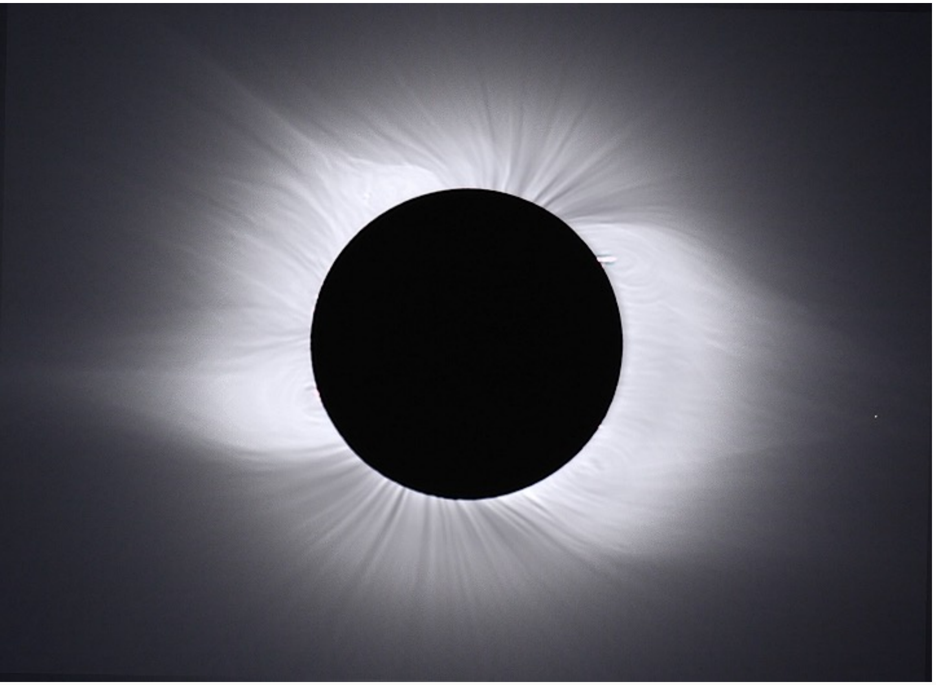
$a=0.98^{+0.01}_{-0.13}$

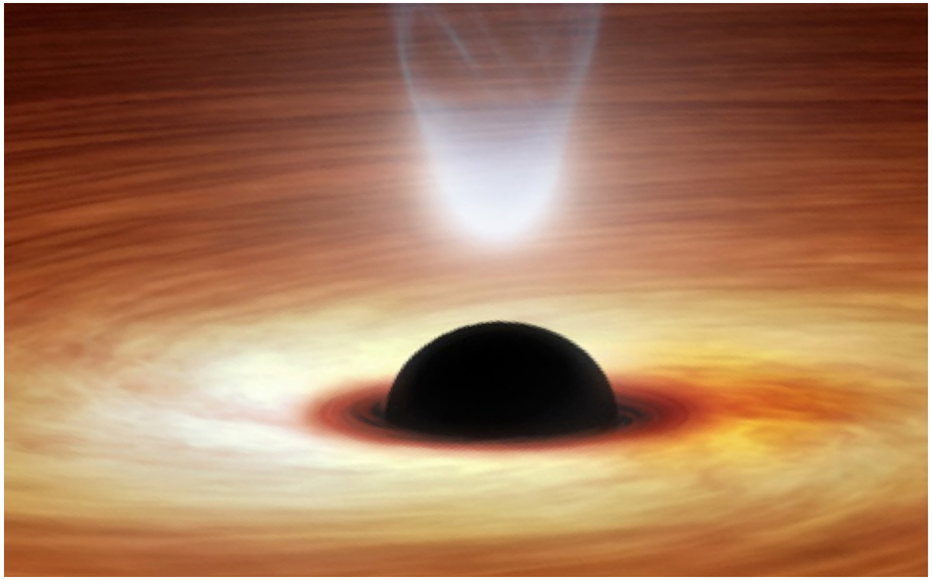
$i=68^{+6}_{-6}$ deg

$R_{in}=1.7^{+1.1}_{-0.4}\ r_g$

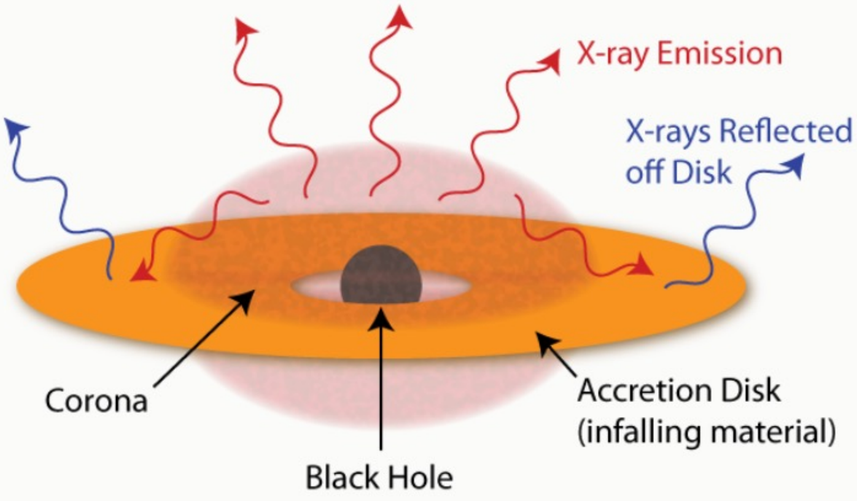
$M=1.9\pm0.2 \times 10^6\ M_{sun}$

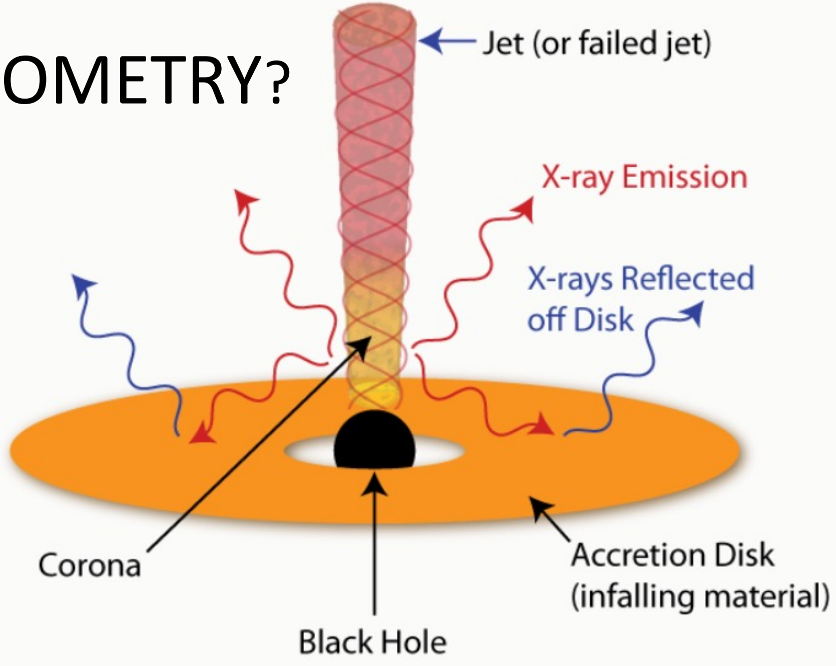
What is the Corona?

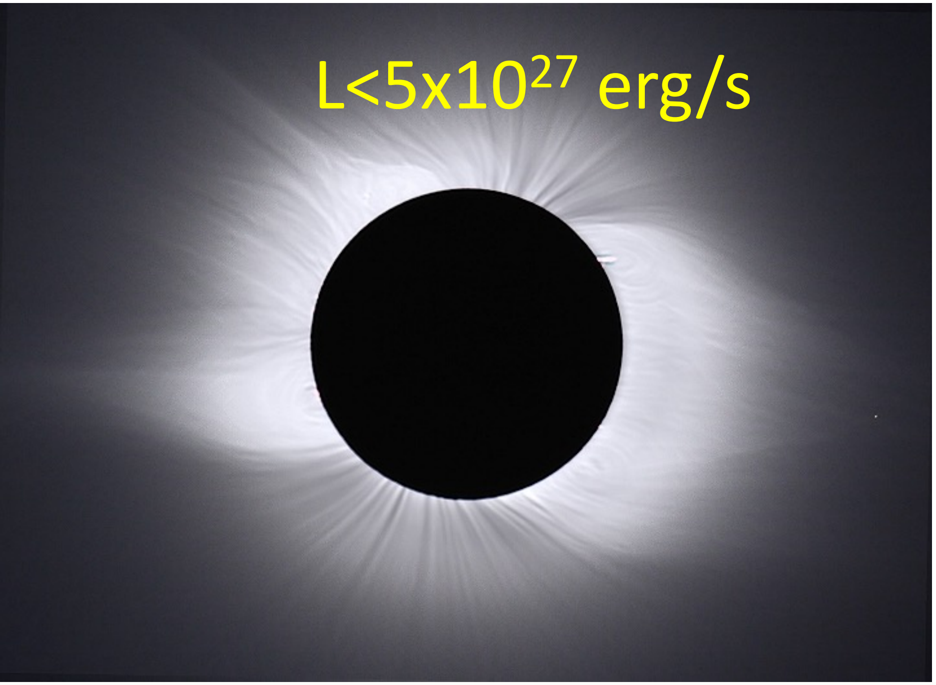


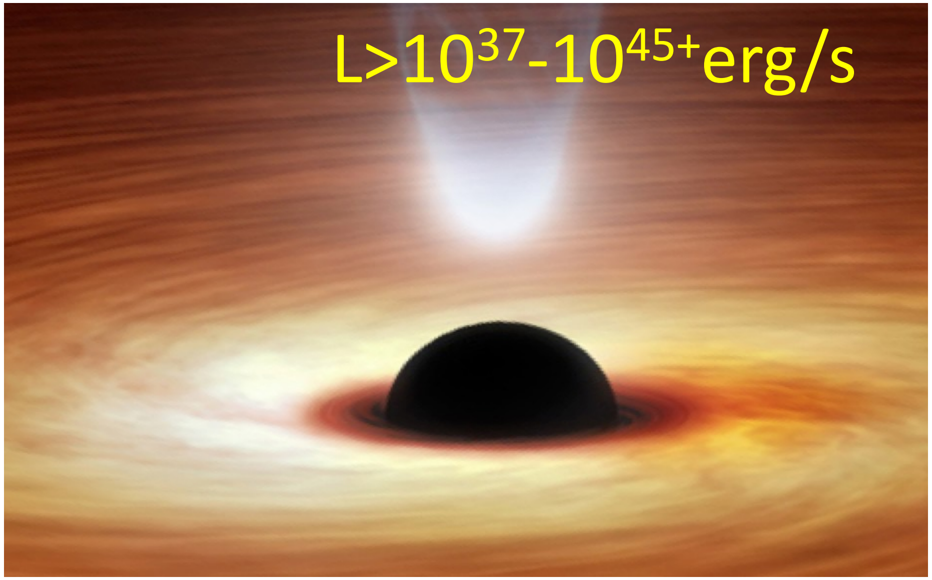


CORONAL GEOMETRY?

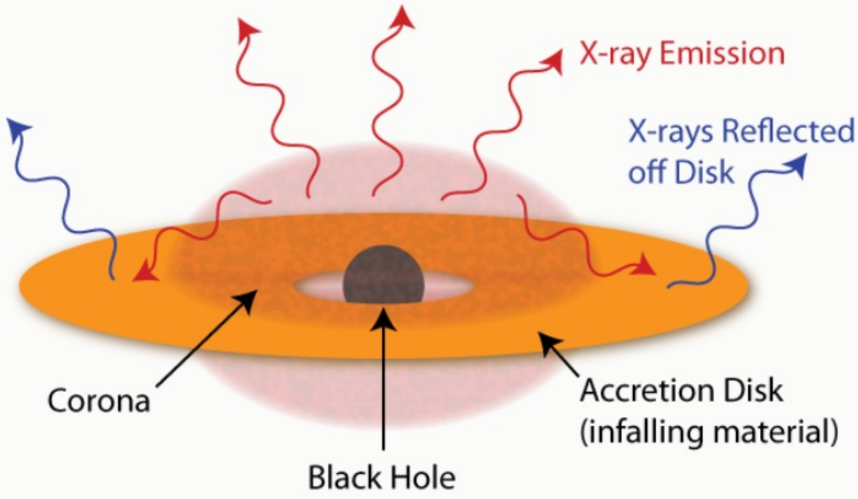


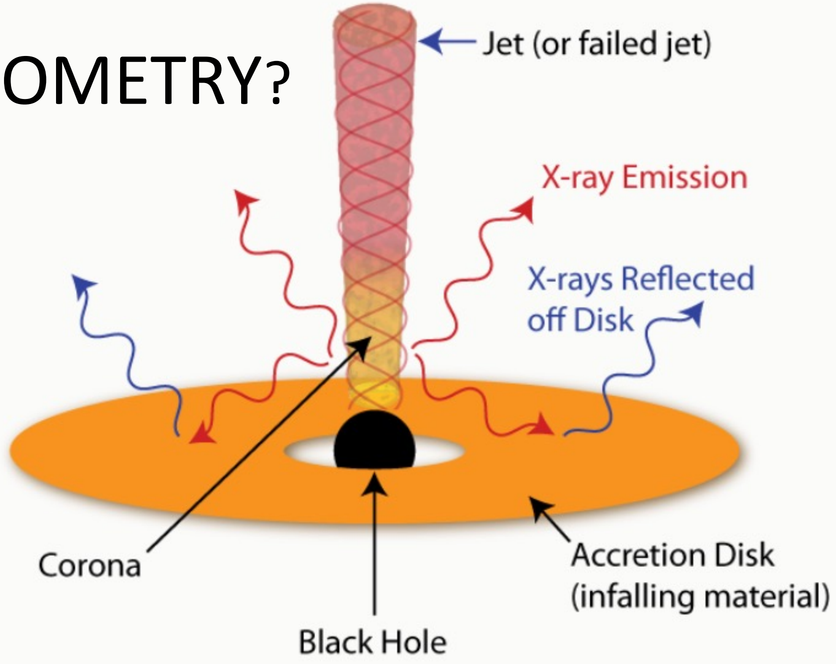






CORONAL GEOMETRY?



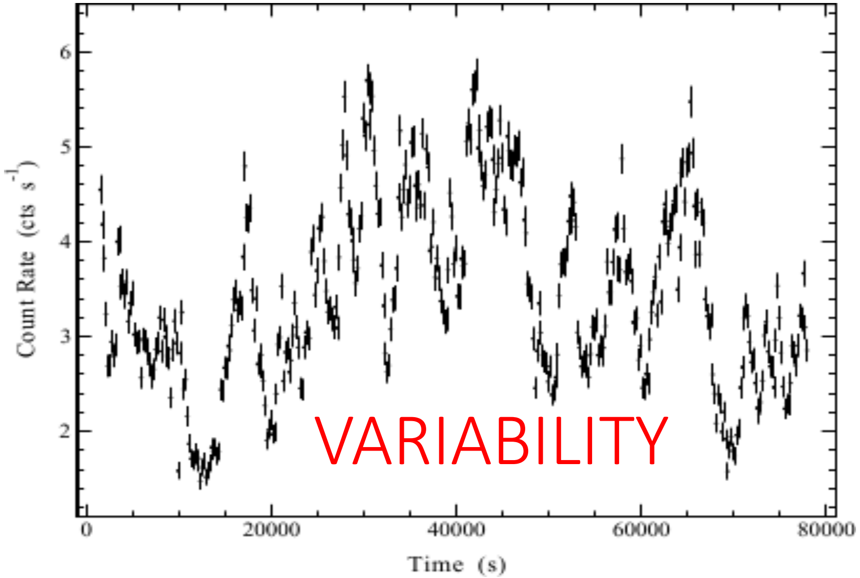


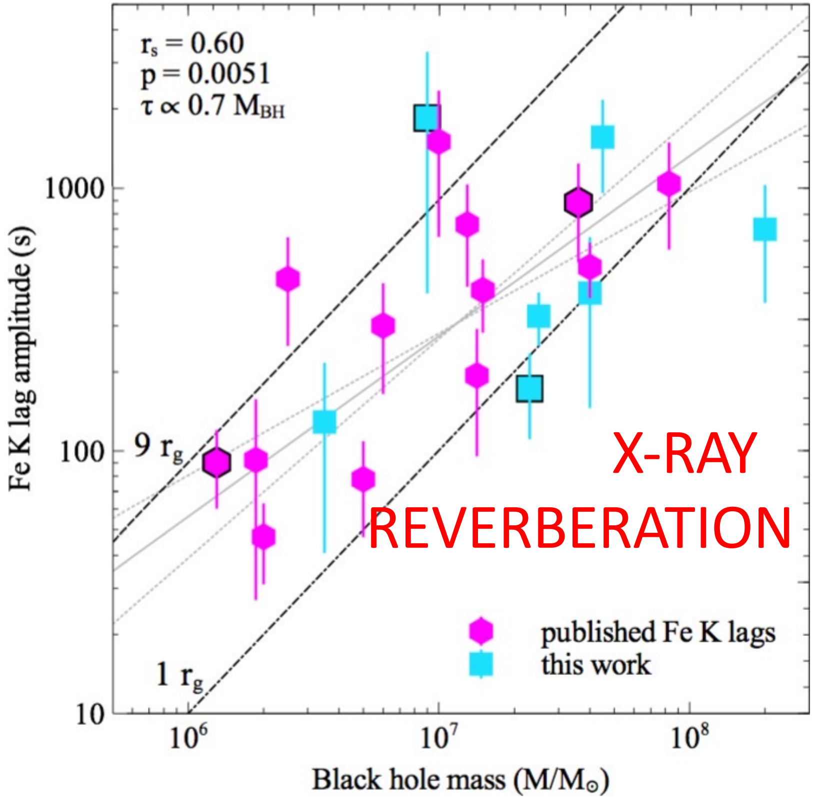
How to constrain geometry of corona

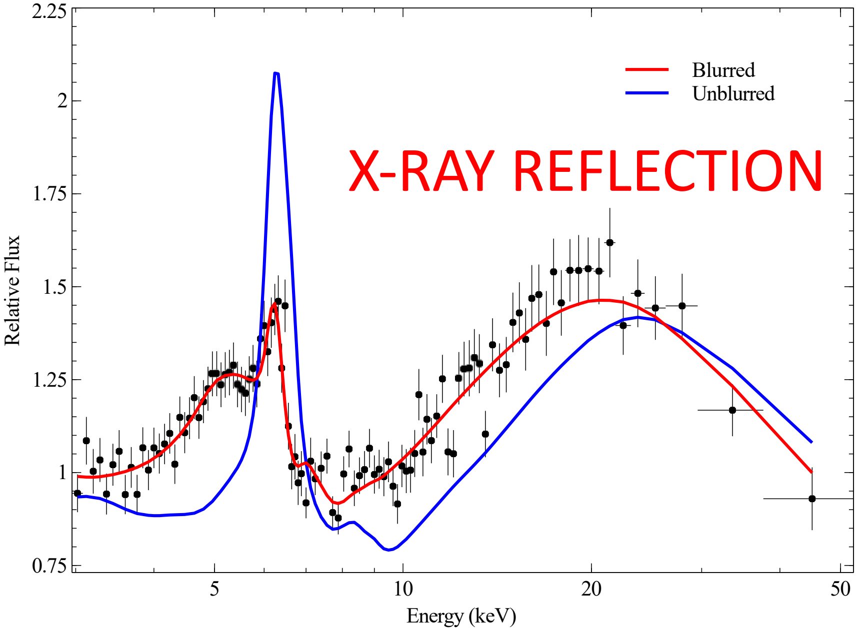
- Variability
- Reflection
- Reverberation
- Emissivity profiles
- Gravitational microlensing
- Occultations
- Soltan argument

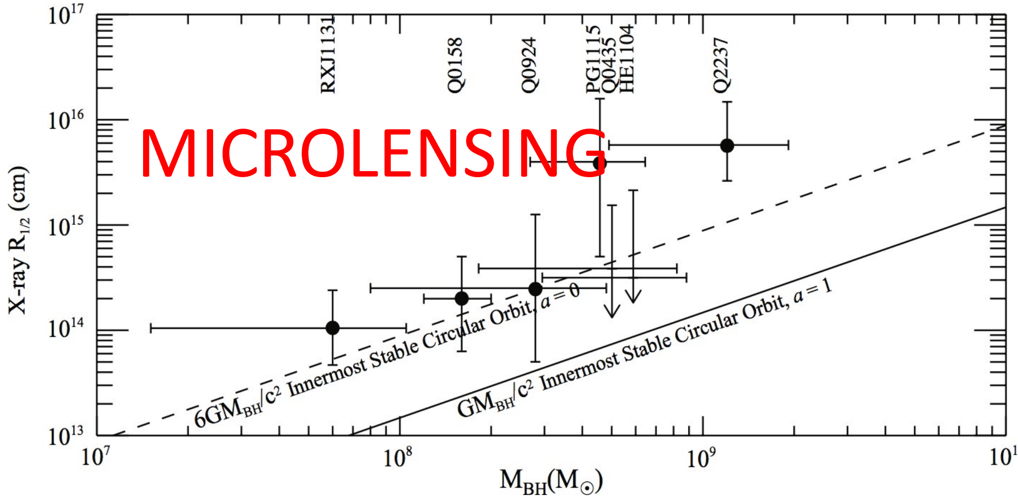
- Brightest parts of the Universe immediately next to the darkest parts

CORONAL SIZE CONSTRAINTS

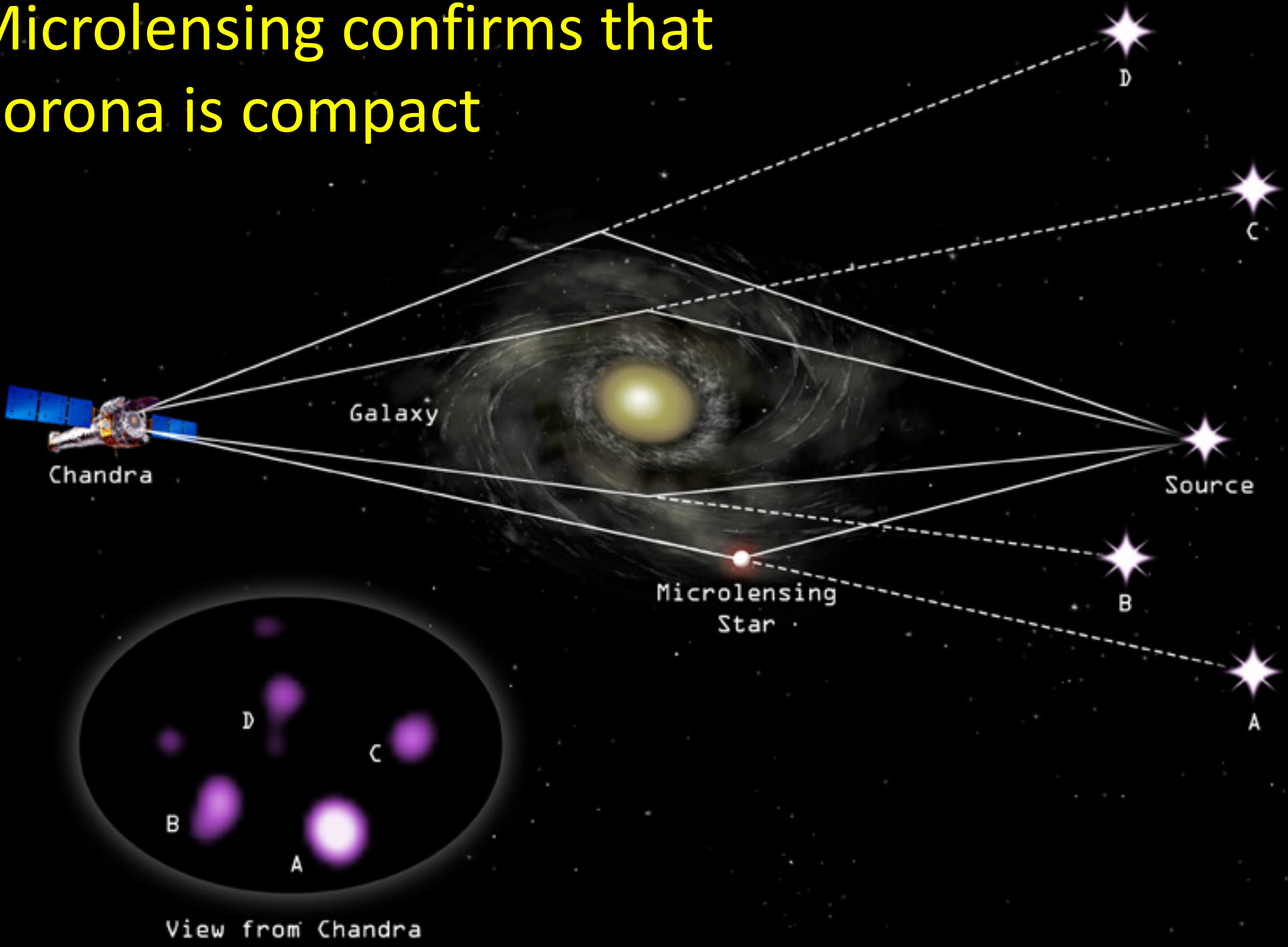








Microlensing confirms that Corona is compact



Chartas+

Coronal properties

- 15<kT<150 keV, most 50-100 keV
- R<10 r_g for much of the power
- Some could be outflowing (Beloborodov99, Malzac+01, Wilkins+14)
- Probably not static!
- Lowest part of corona dominates reflection, outflowing upper part dominates observed powerlaw

WHAT DETERMINES CORONAL TEMPERATURE?

PAIR PRODUCTION: electron-positron pairs form when photons and/or particles collide at energies $> m_e c^2 = 511keV$

From **particle-particle** interaction in a relativistic thermal gas: energy injected goes into the rest mass of new particles (not in kinematics) $\longrightarrow$ limit the temperature at about $\sim 10\mathrm{MeV}$. Pair production outweighs annihilation above that temperature .

From **photon-photon** collisions: $\gamma + \gamma \rightarrow e^{\pm}$ requires $\frac{\epsilon_1}{m_e c^2} \frac{\epsilon_2}{m_e c^2} > 2$

(the ϵ's are the energies of the photons involved)$\longrightarrow$ between two MeV photons or a TeV photon and a infrared photon.

Rieger

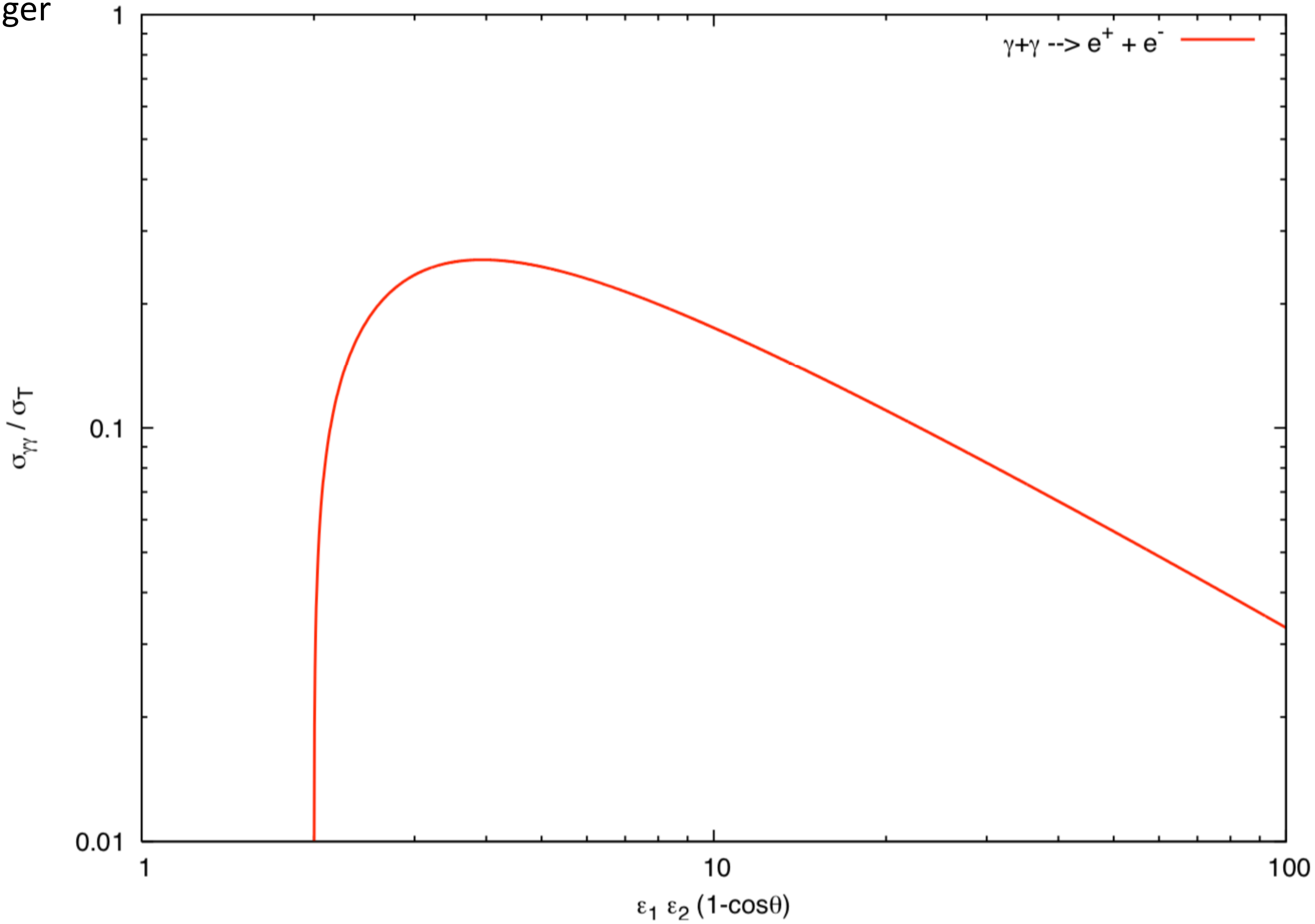


Figure 1: Cross-section for $\gamma\gamma$-pair production in units of the Thomson cross-section σ_T as a function of interacting photon energies (ϵ_1/m_ec^2) (ϵ_2/m_ec^2) $(1-\cos\theta)$. The cross-section rises sharply above the threshold $\epsilon_1\epsilon_2(1-\cos\theta) = 2m_e^2c^4$ and has a peak of $\simeq \sigma_T/4$ at roughly twice this value, i.e. at $\epsilon_1\epsilon_2(1-\cos\theta) = 4m_e^2c^4$.

Compactness Parameter and Pair Production

Consider a spherical source of MeV photons of radius R and luminosity L. The photon density

$$\begin{aligned}
n_\gamma &= \frac{L}{4\pi R^2 c 2 m_\mathrm{e} c^2} \\
\tau_{\gamma\gamma} &= n_\gamma \frac{\sigma_\mathrm{T}}{5} R \\
&= \frac{L}{4\pi R 2 m_\mathrm{e} c^3} \frac{\sigma_\mathrm{T}}{5} \\
&= \frac{\ell}{40\pi} \\
\text{where } \ell &= \frac{L}{R} \frac{\sigma_\mathrm{T}}{m_\mathrm{e} c^3}
\end{aligned}$$

ℓ is the dimensionless Compactness Parameter (Guilbert, Fabian & Rees 1983). Most photons will not escape from the source when $\ell > 100$. If heated, pairs will create and scatter photons leading in a non-linear way to a ball of plasma.

Consider spherical source size R, scattering optical depth τ in which luminosity L is generated:

$$\varepsilon = \frac{L}{4\pi R^2 c}(1+\tau)$$

thus

$$t_C = \frac{3\pi R}{2c\ell(1+\tau)}$$

Compton cooling time

where

$$\ell = \frac{L}{R}\frac{\sigma_T}{m_e c^3}.$$

ℓ is the **compactness parameter** of the source. Measures probability of photons and electrons interacting in the source.

$$\frac{t_C}{t_{cross}} = \frac{3\pi}{2\ell(1+\tau)}$$

t_{cross} is the light crossing time of the source. If $\ell > 2$ then $t_C < t_{cross}$.

CORONAL HEATING

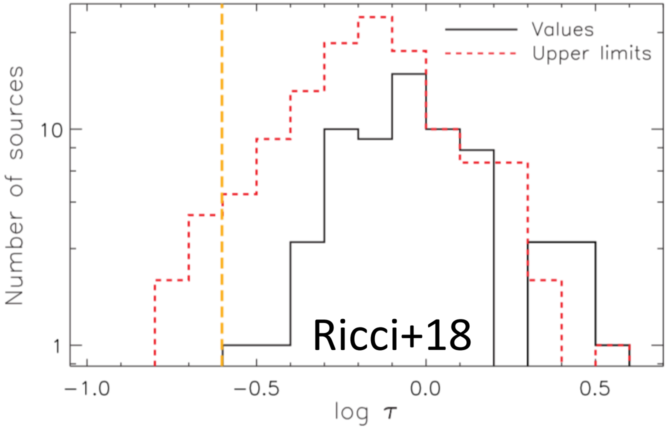
Merloni&Fabian-01)

Consider a spherical corona of radius R, luminosity L, Thomson depth τ and temperature T. Its thermal energy $E_{\rm th} \approx \pi R^3 nkT$ and since $\tau \sim n\sigma_{\rm T}R$ then $E_{\rm th} \approx \frac{\pi R^2 kT\tau}{\sigma_{\rm T}}$.

In order that the corona remains hot we need that the heating time $t_{\rm heat} = E_{\rm th}/L$ exceeds the light crossing time of the corona, $t_{\rm cross} = R/c$.

Thus

$$\begin{aligned} \frac{\pi R^2 kT\tau}{L\sigma_{\rm T}} &> \frac{R}{c} \\ \ell < \frac{\pi kT\tau}{m_e c^2} &= 0.4\tau T \\ R > \frac{L\sigma_{\rm T}}{\pi kT\tau c} &> 10^4 r_g \end{aligned}$$



Ricci+18

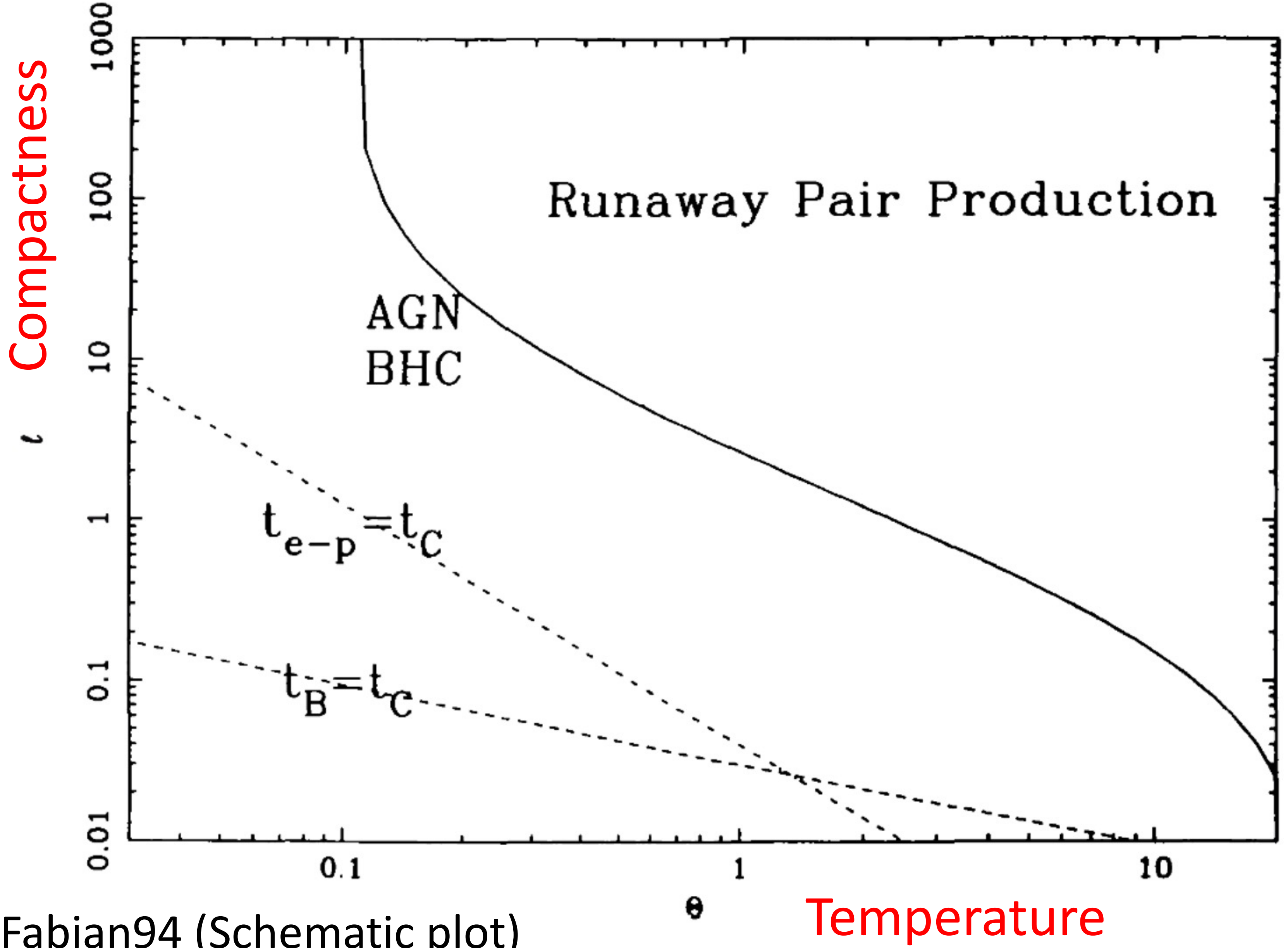
Solution is for the corona to be a small number of magnetically-dominated regions (Merloni & Fabian01).

The heating problem is also present in most "warm coronae".

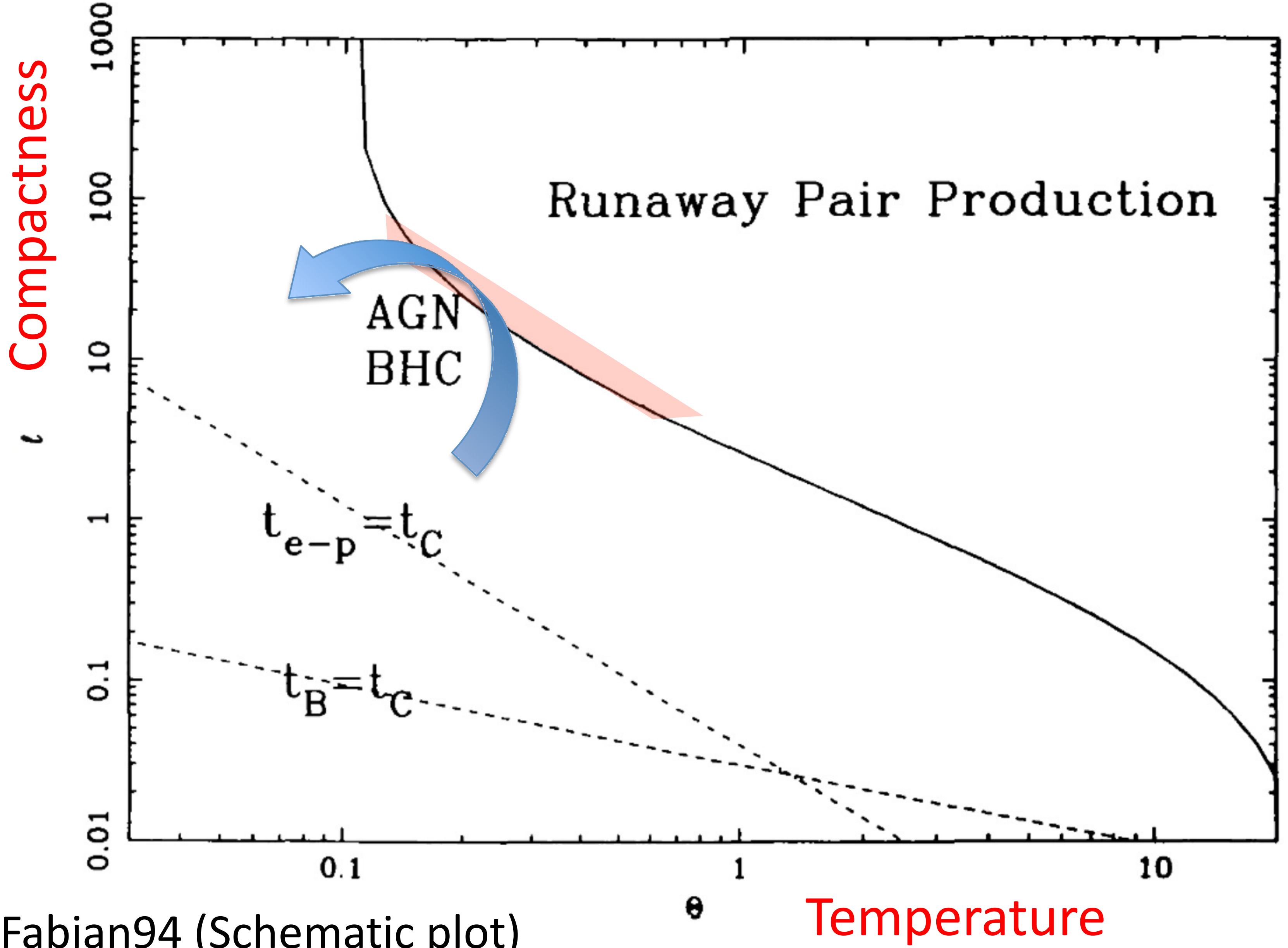
Coronae are magnetically-dominated

Major papers on pair production in compact hot plasmas by Svensson 82,84, Zdziarski 84 and many others in the 80s and 90s.

Concept of Pair Thermostat introduced



Fabian94 (Schematic plot)

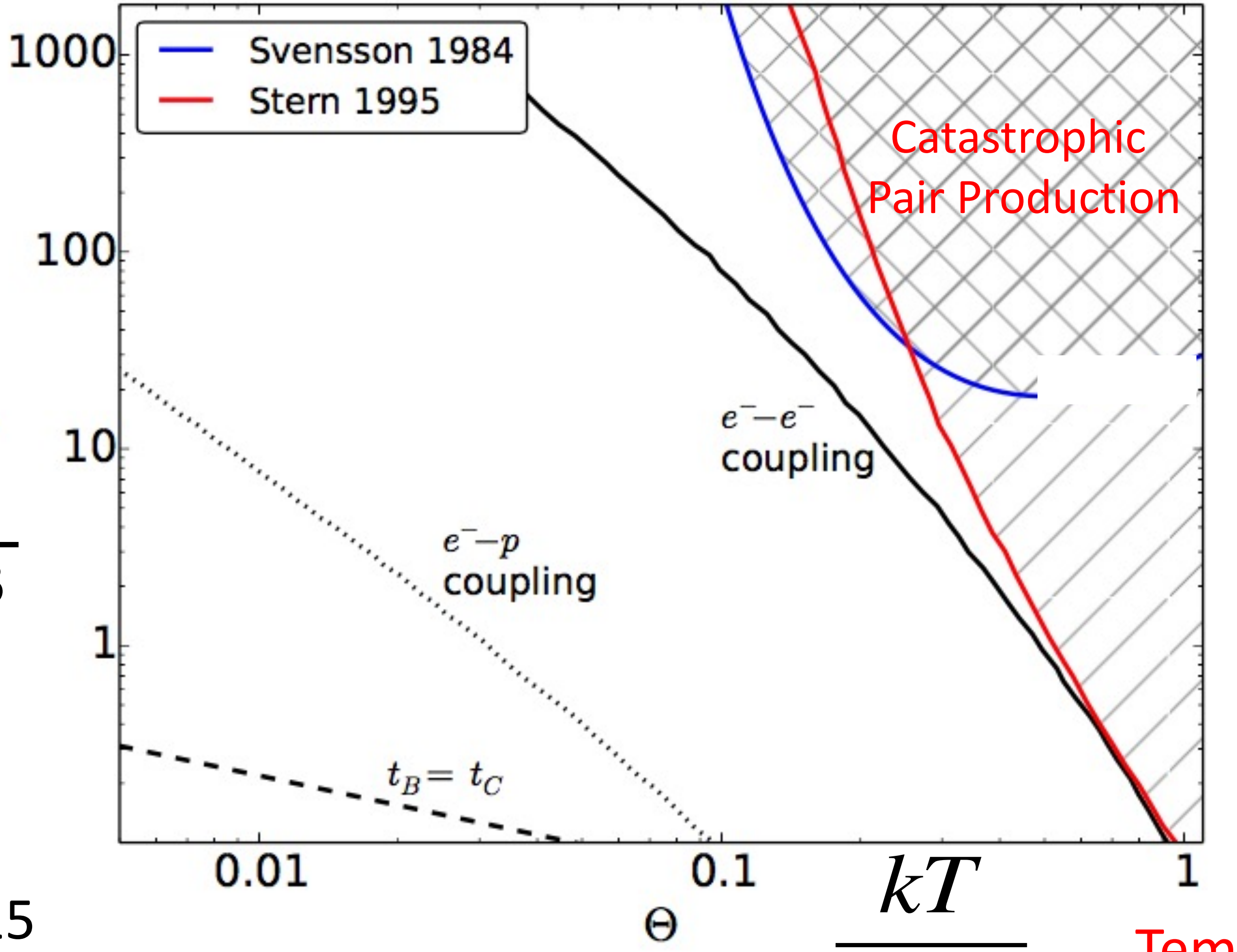


Fabian94 (Schematic plot)

CORONAL PHYSICS

Compactness

$$\frac{L}{R}\frac{\sigma_T}{mc^3} \quad \ell$$



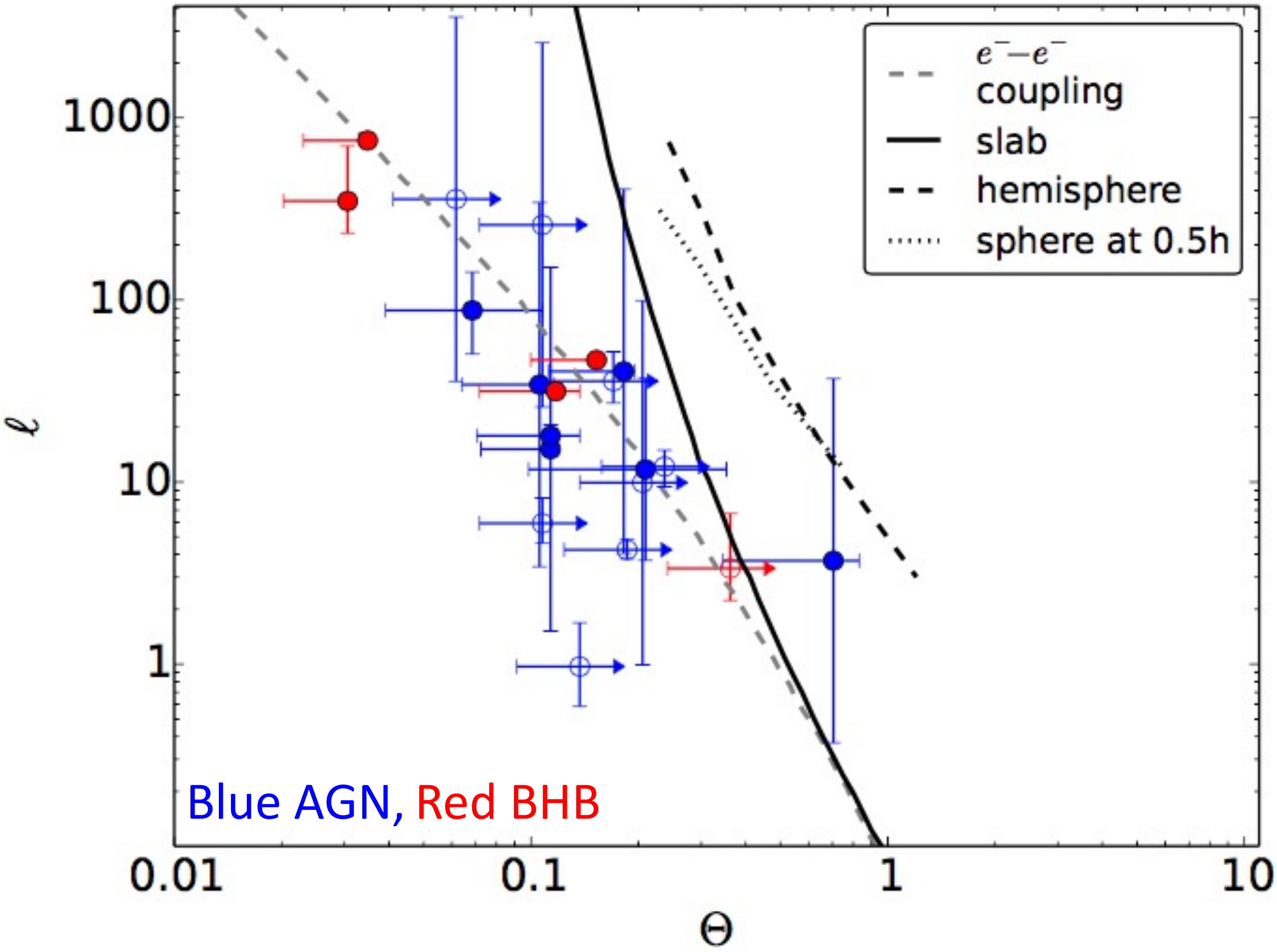
Catastrophic Pair Production

Fabian+15

$$\Theta = \frac{kT}{m_e c^2}$$

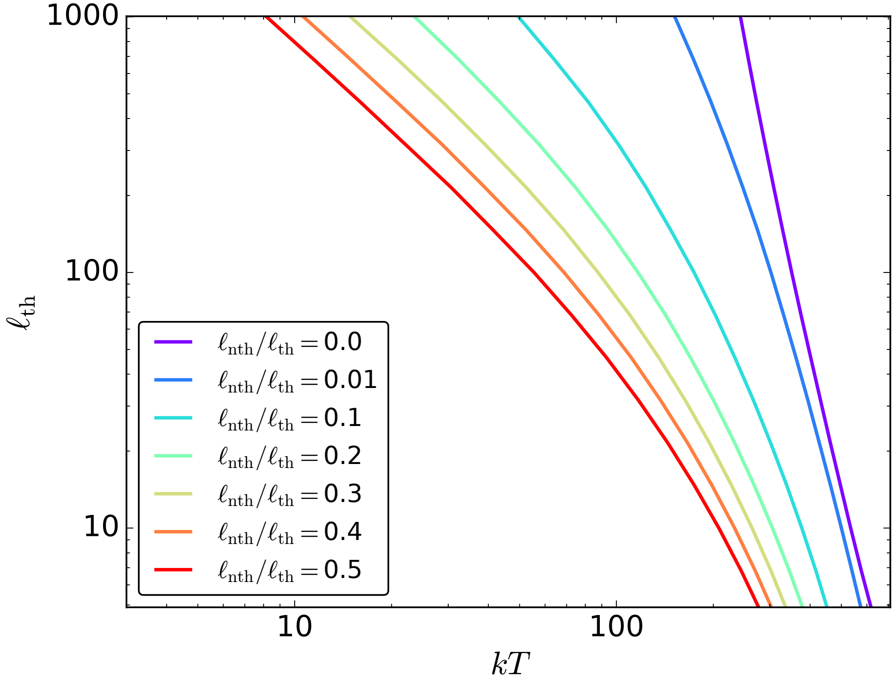
Temperature

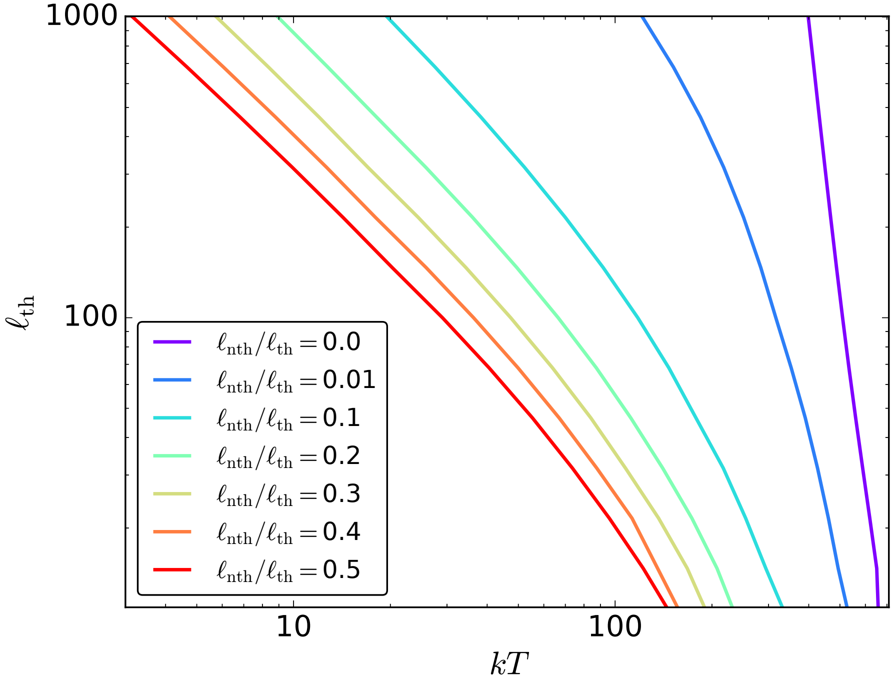
NuSTAR results



Blue AGN, Red BHB

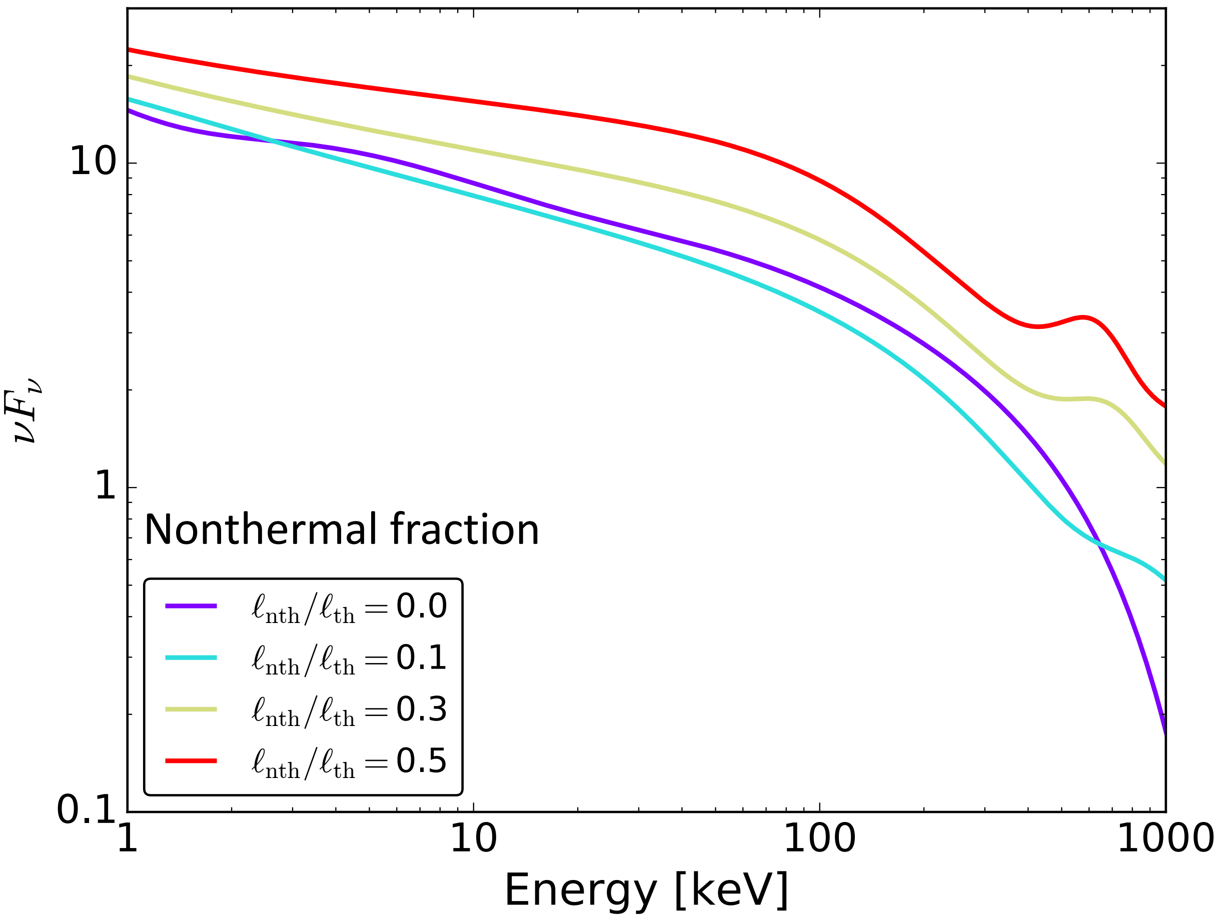
Effect of addition of nonthermal particles - Hybrid Plasma

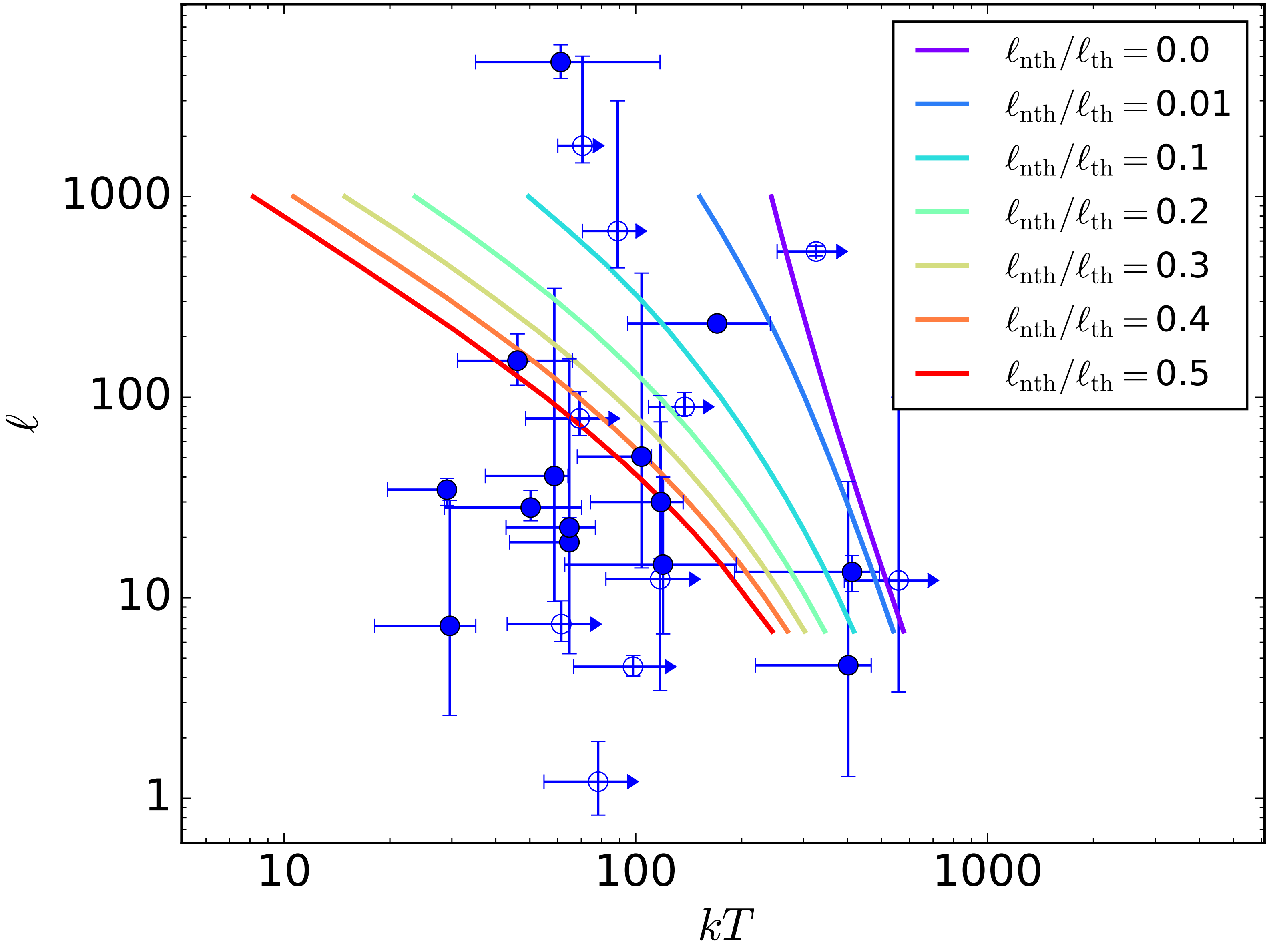

l_h/l_s=1


l_h/l_s=0.1

Uses BELM, similar results for EQPAIR

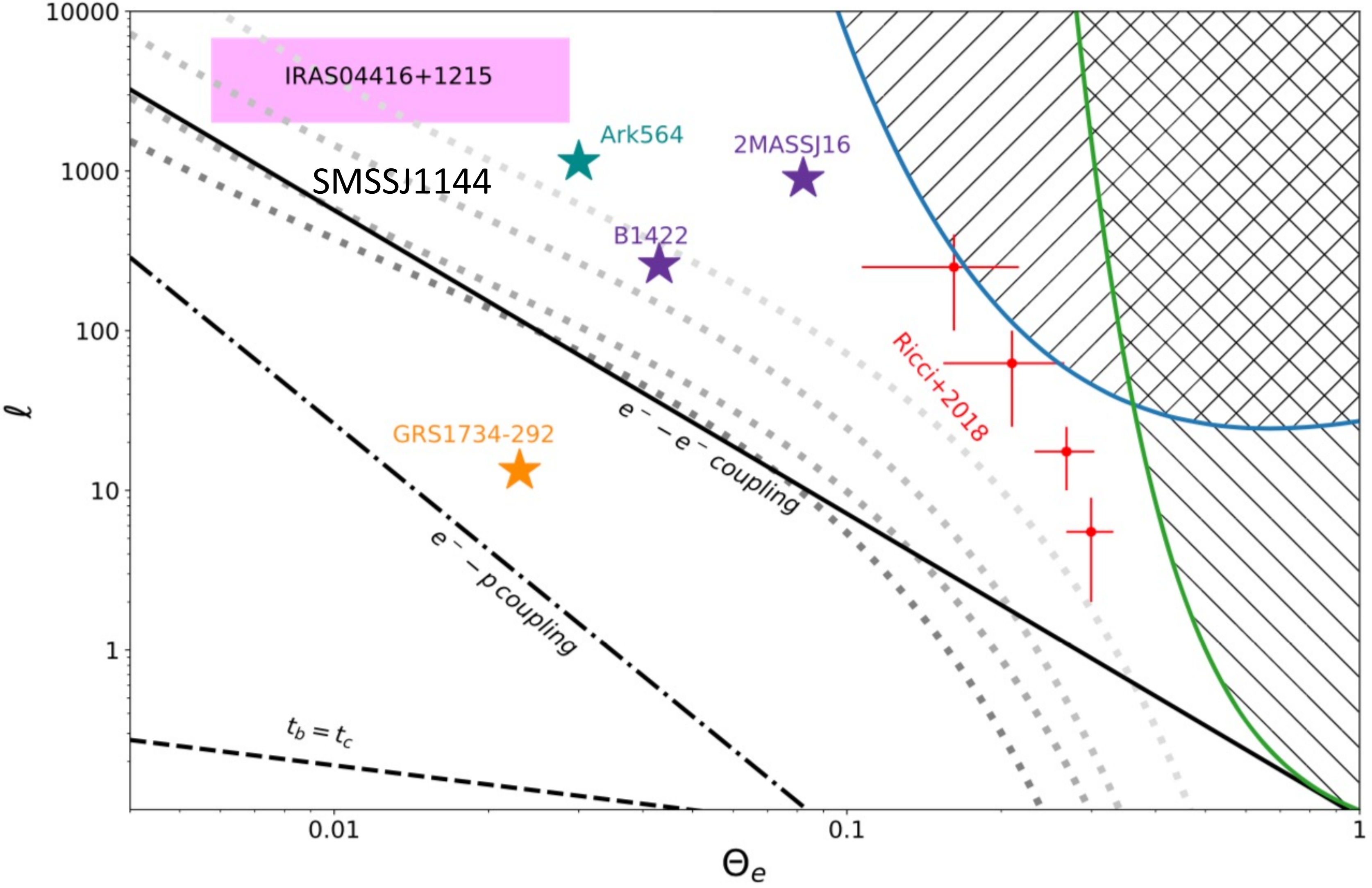
Fabian, Lohfink, Belmont, Malzac, Coppi 2017

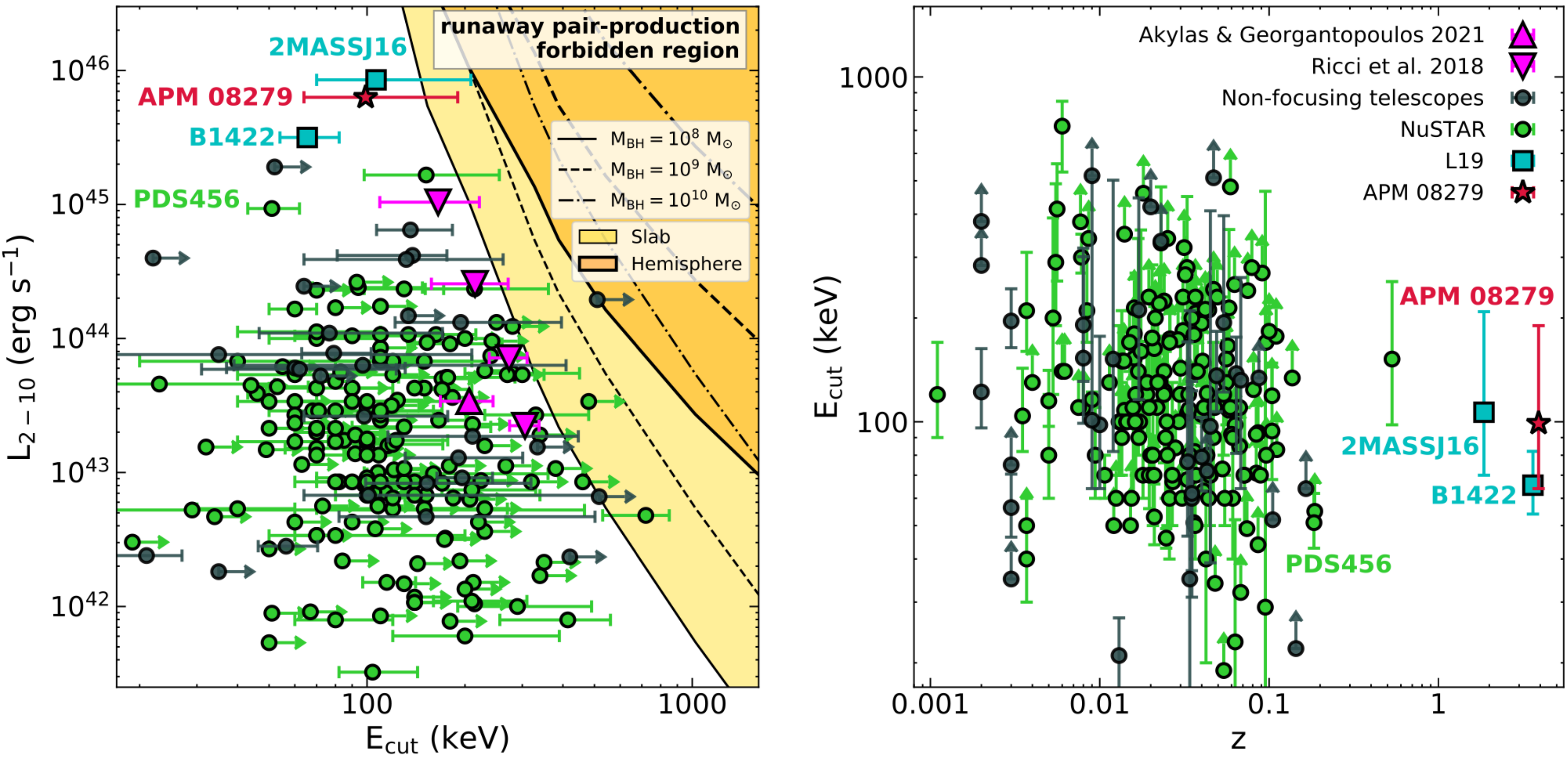

νF_ν
10
1
0.1
1
10
100
1000
Energy [keV]
Nonthermal fraction
$\ell_{\rm nth}/\ell_{\rm th} = 0.0$
$\ell_{\rm nth}/\ell_{\rm th} = 0.1$
$\ell_{\rm nth}/\ell_{\rm th} = 0.3$
$\ell_{\rm nth}/\ell_{\rm th} = 0.5$



ℓ
kT
1
10
100
1000
10
100
1000
$\ell_{\rm nth}/\ell_{\rm th}=0.0$
$\ell_{\rm nth}/\ell_{\rm th}=0.01$
$\ell_{\rm nth}/\ell_{\rm th}=0.1$
$\ell_{\rm nth}/\ell_{\rm th}=0.2$
$\ell_{\rm nth}/\ell_{\rm th}=0.3$
$\ell_{\rm nth}/\ell_{\rm th}=0.4$
$\ell_{\rm nth}/\ell_{\rm th}=0.5$

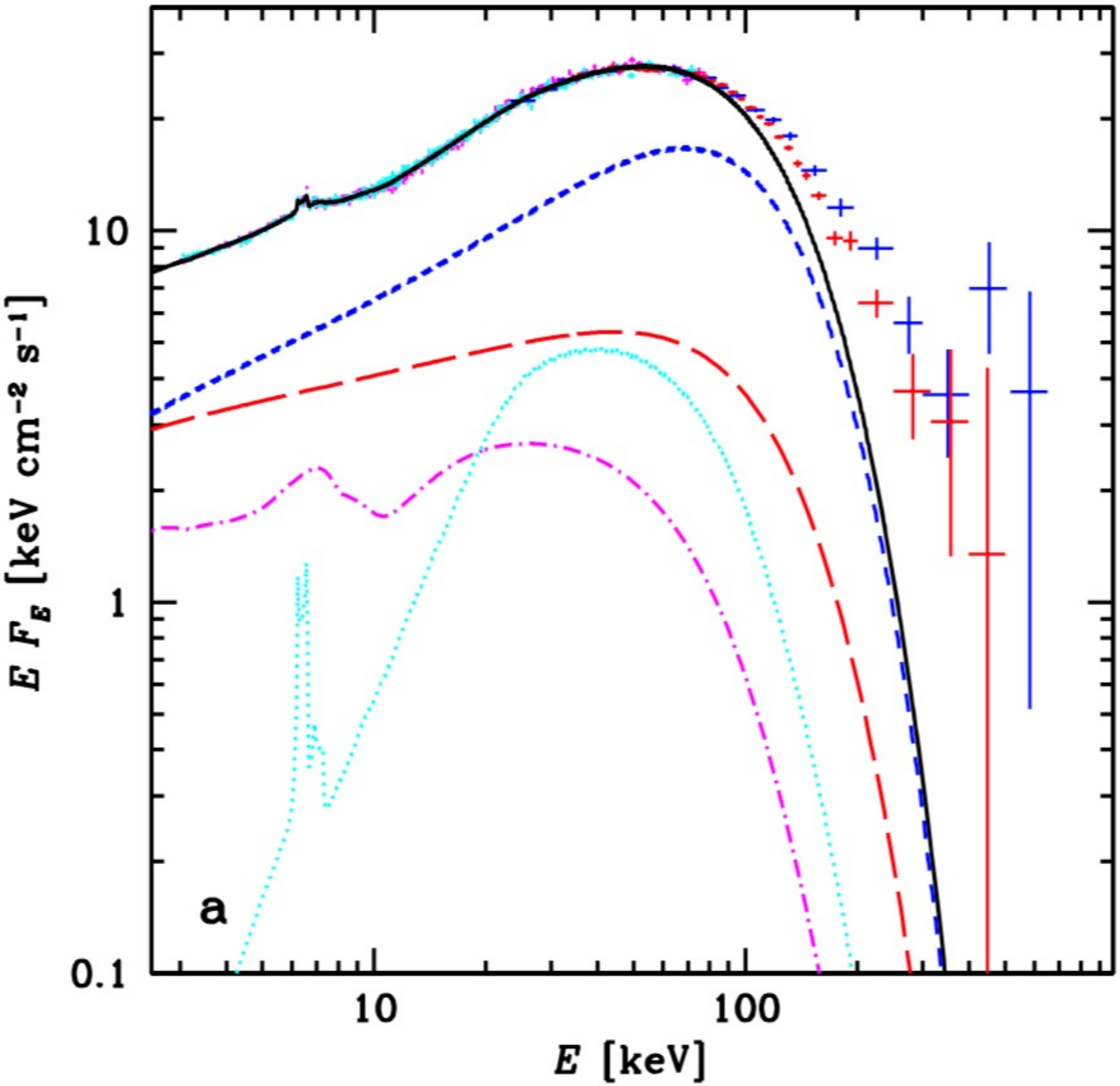
A. Tortosa et al. 2022




runaway pair-production forbidden region
2MASSJ16
APM 08279
B1422
PDS456
$M_{BH} = 10^8\ M_\odot$
$M_{BH} = 10^9\ M_\odot$
$M_{BH} = 10^{10}\ M_\odot$
Slab
Hemisphere
L_{2-10} (erg s^{-1})
10^{42}
10^{43}
10^{44}
10^{45}
10^{46}
E_{cut} (keV)
100
1000
Akylas & Georgantopoulos 2021
Ricci et al. 2018
Non-focusing telescopes
NuSTAR
L19
APM 08279
APM 08279
2MASSJ16
B1422
PDS456
E_{cut} (keV)
100
1000
0.001
0.01
0.1
1
z

MAXI 1820+070 NuSTAR + Integral

Zdziarski et al. 2021



Pair Annihilation and 511 keV line

Purely thermal pair plasmas don't show distinct lines but hybrid plasmas can (see discussion in Zdziarski+21). Luminous coronae are superEddington for pairs, which can create pair wind with v~0.5c (rad. pressure vs Compton drag: Beloborodov99).

What does the Heating? Magnetic Reconnection?

See recent discussions by Beloborov18, Sironi+B..20

THE ASTROPHYSICAL JOURNAL, 850:141 (11pp), 2017 December 1 Beloborodov

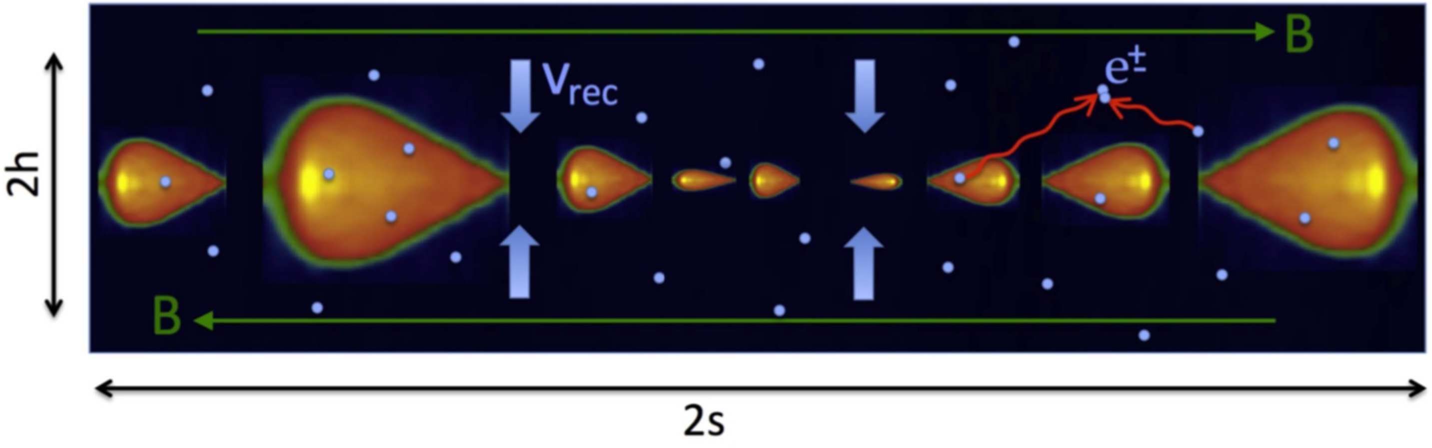
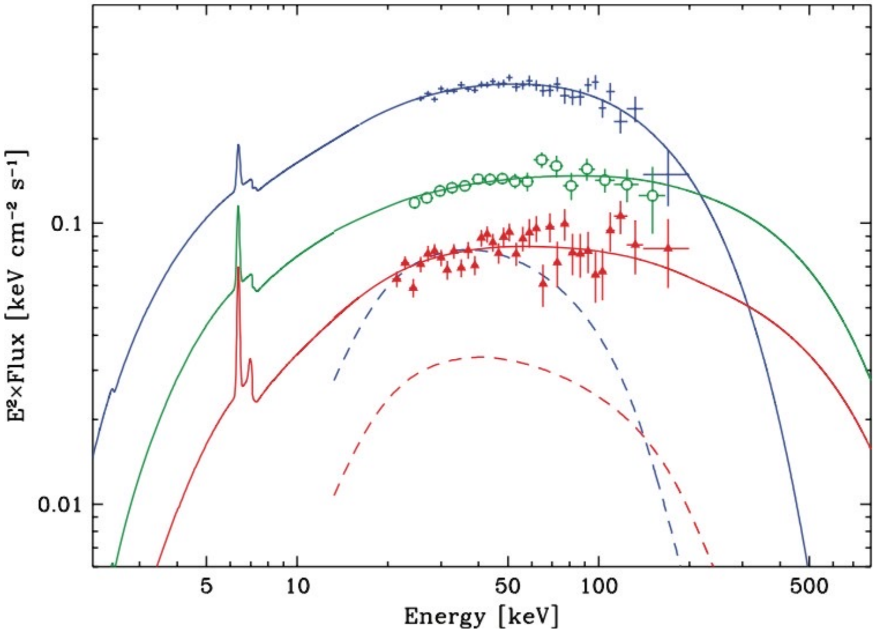


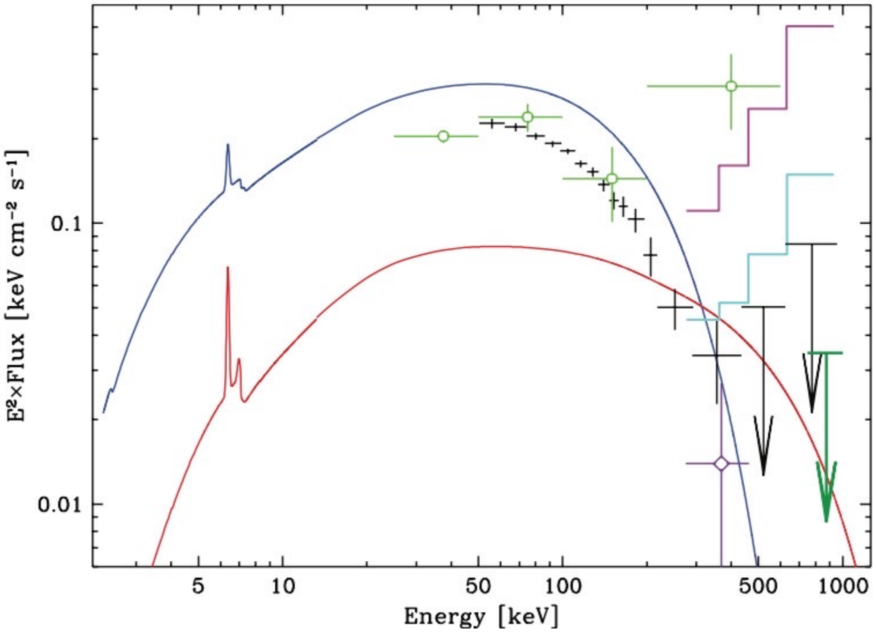
Figure 1. Schematic picture of the reconnection layer. Opposite magnetic fluxes converge toward the midplane of the layer with velocity $v_{\rm rec} \sim 0.1c$. The reconnected magnetic field forms closed islands (plasmoids), which move horizontally with various relativistic speeds. Their Lorentz factors γ reach $\sigma^{1/2}$, where σ is the magnetization parameter defined in Equation (2). The Lorentz factors are controlled by radiative losses and related to the plasmoid size w as discussed in Section 3.3. The plasmoids have a broad distribution of w and γ, and form a self-similar chain. They radiate hard X-rays with a spectrum calculated in Section 4. Photons with energies $E > m_e c^2$ convert to $e^{\pm}$ pairs in photon–photon collisions (shown by the red arrows); this process greatly increases the optical depth of the reconnection layer.

NGC4151



INTEGRAL

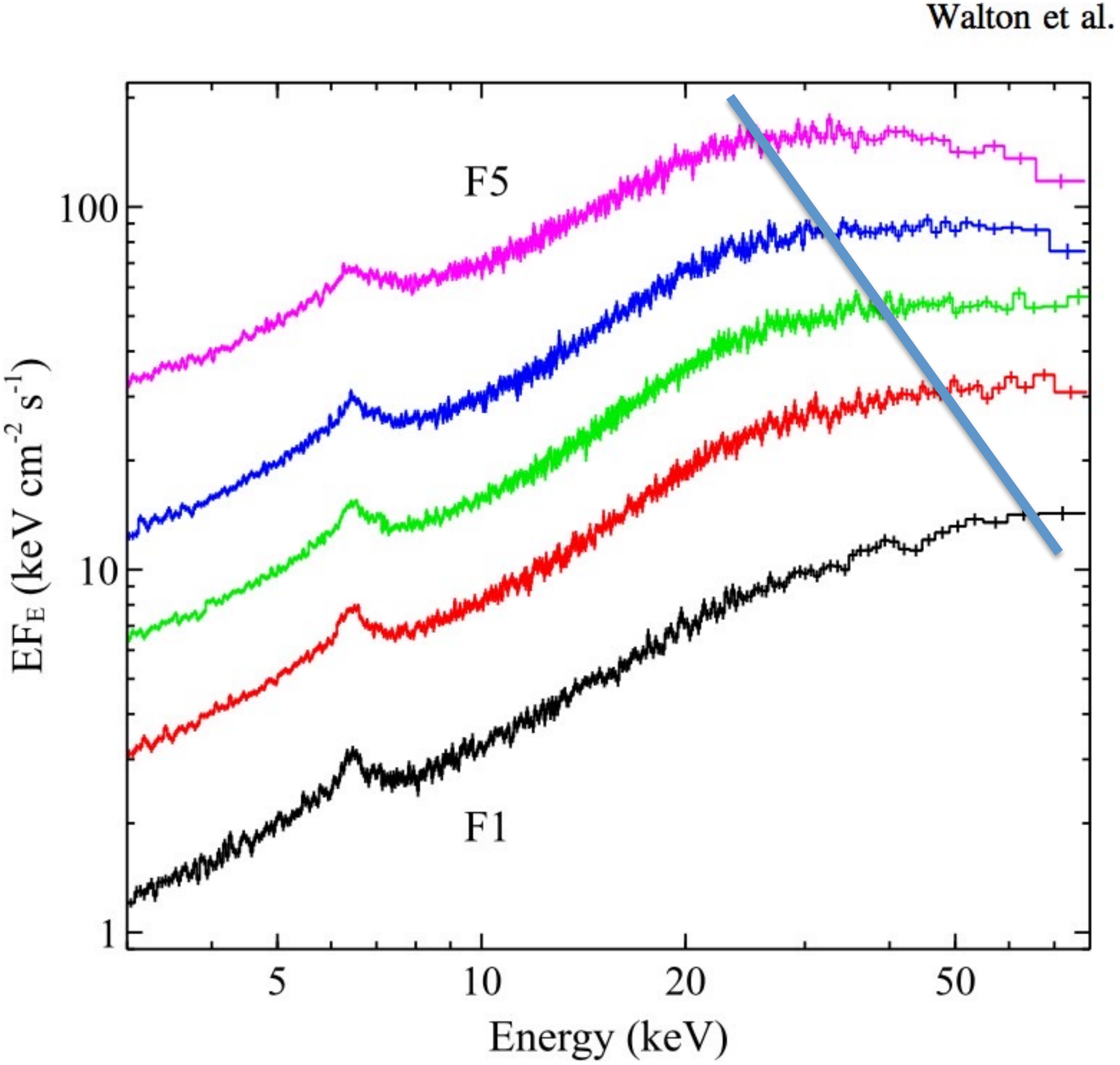
Extreme flux states of NGC 4151 1859



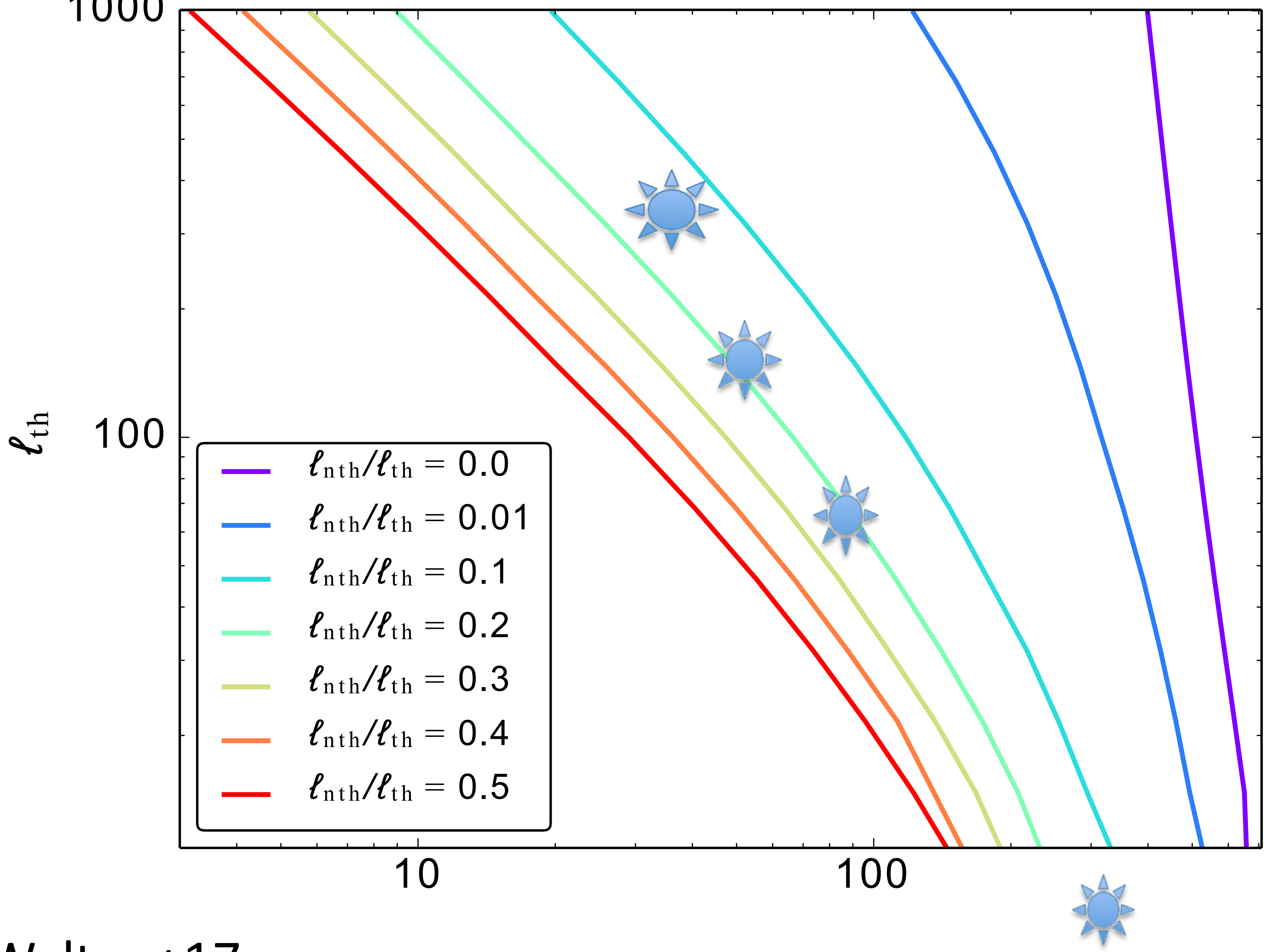
OSSE, Comptel
INTEGRAL/PICsIT SPI

Lubinski+10 see also Keck+15, Beuchert+17

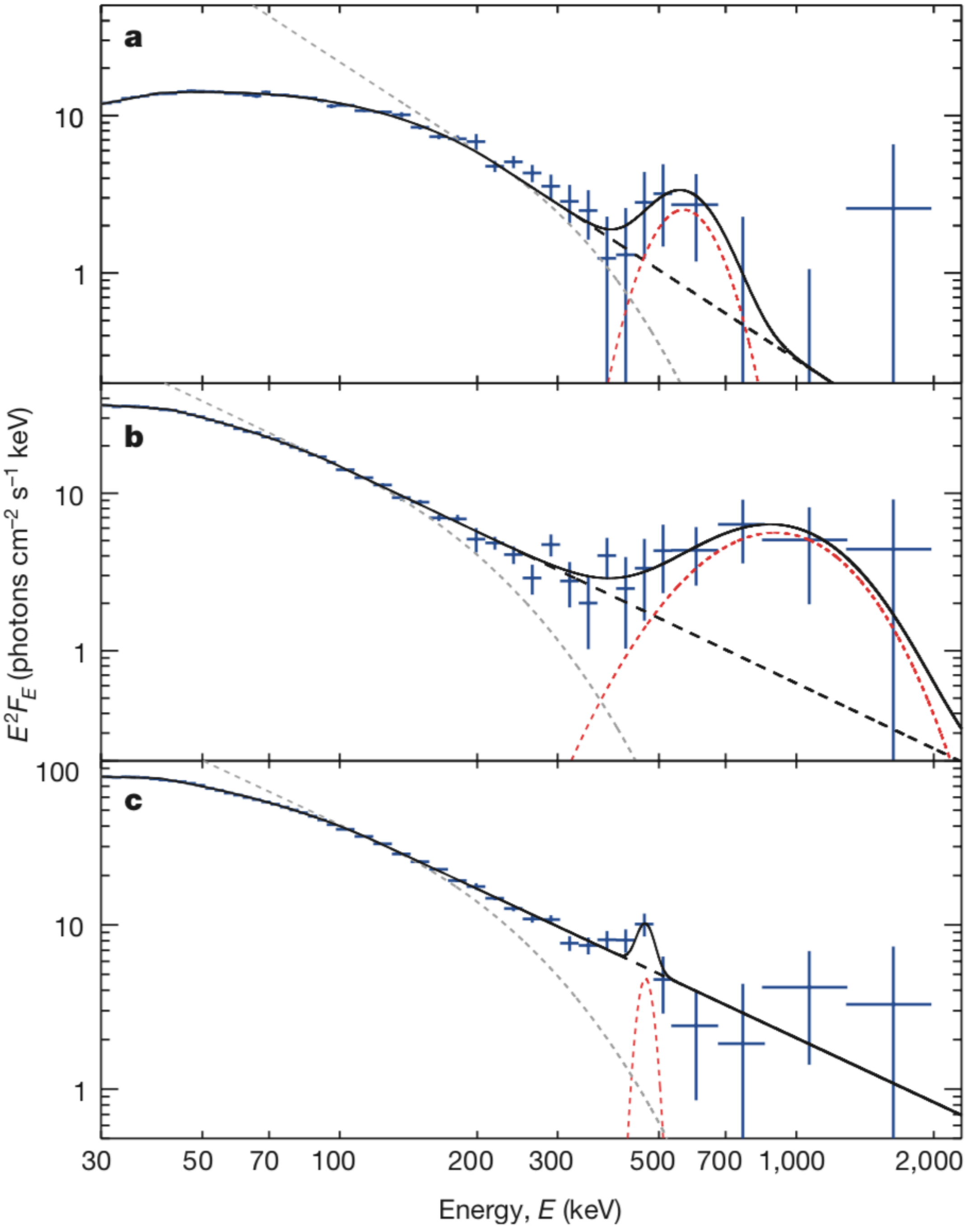
V404 Cyg NuSTAR



V404 Cyg (GR corrections included)

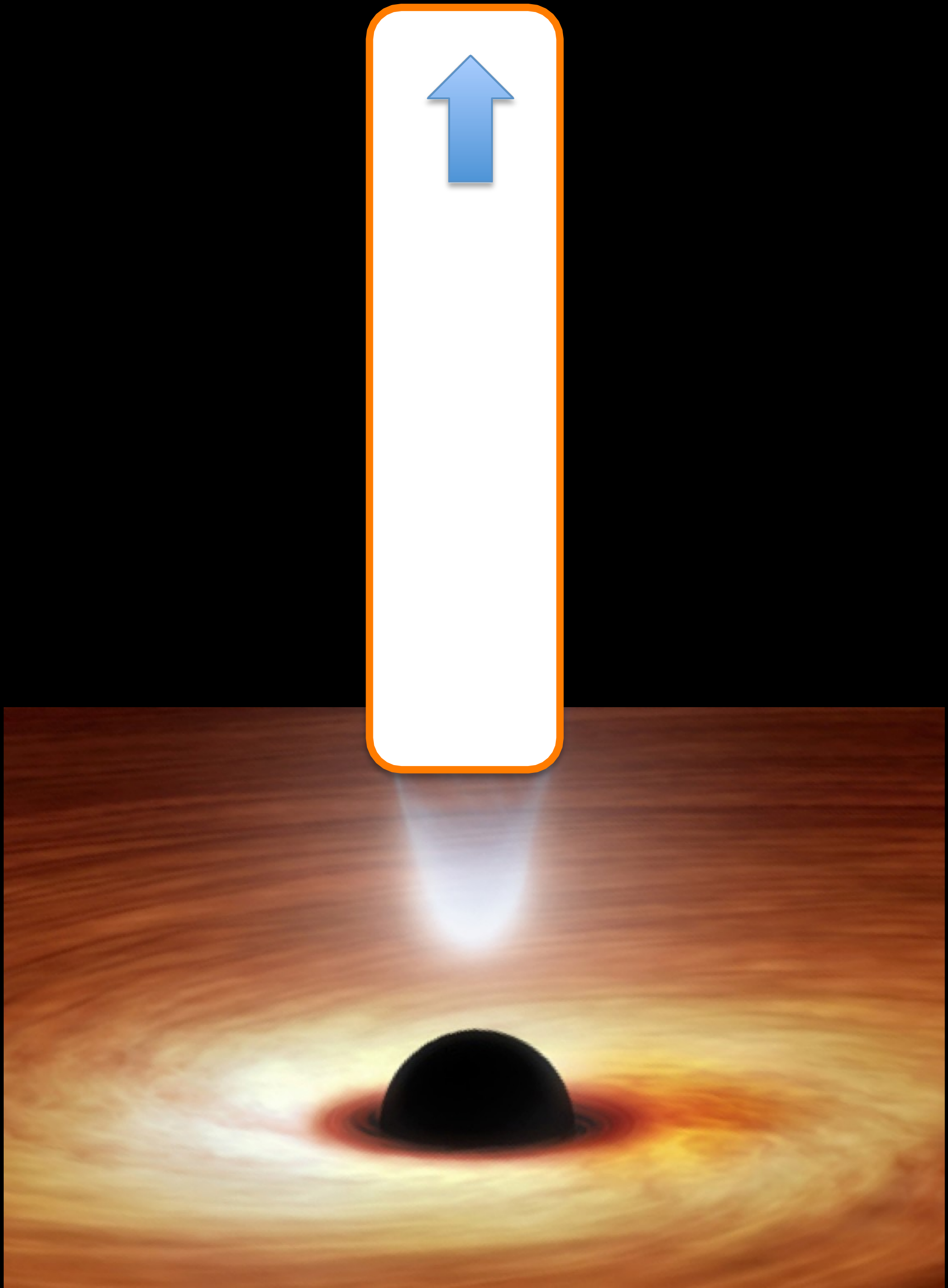


D Walton+17



Siegert+16

Figure 1 | Spectral evolution of V404 Cygni. a–c, Spectra in the soft γ-ray



Cautionary Notes

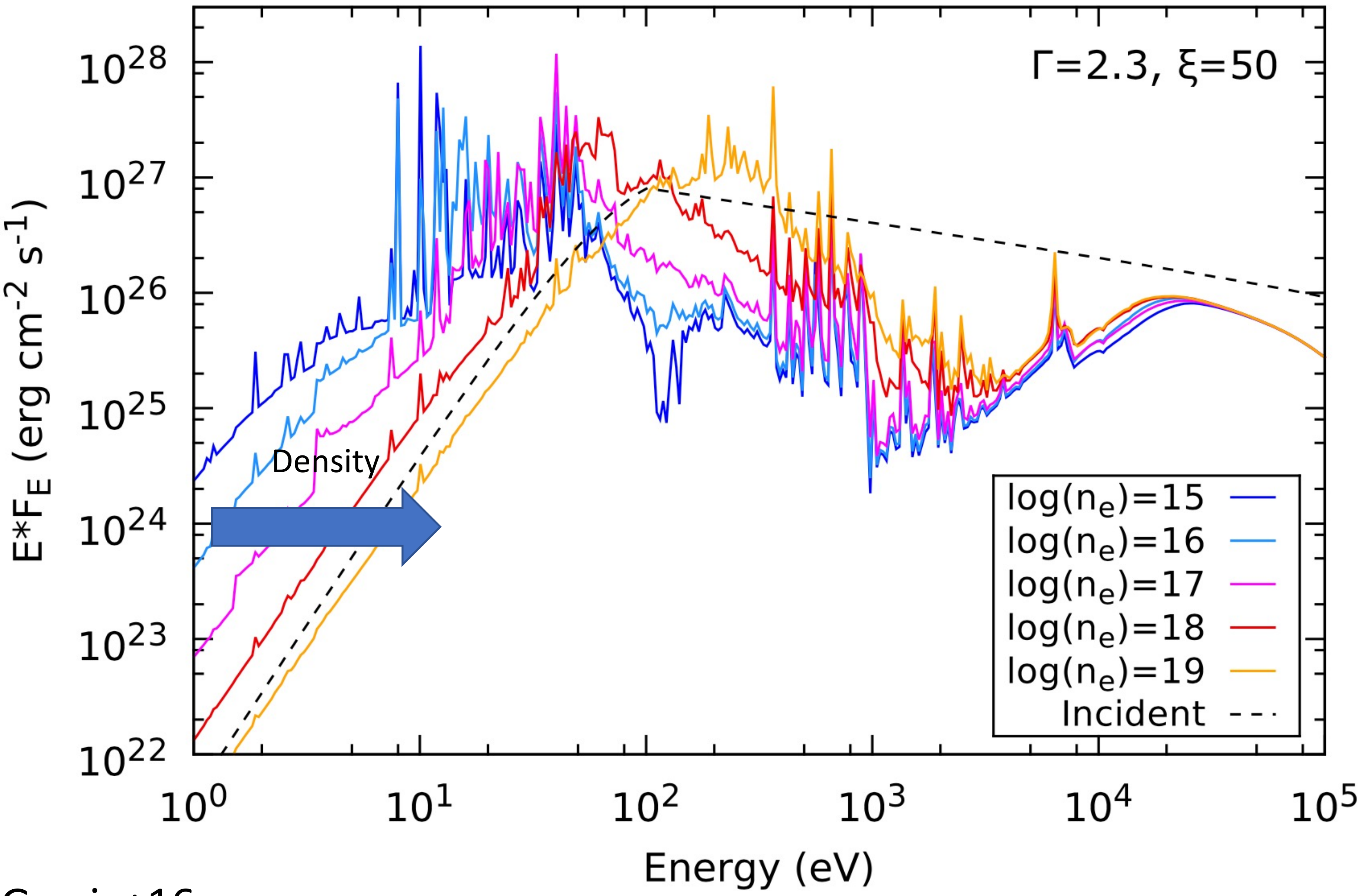
- Most hard X-ray spectra cover many dynamical times and many many cooling times
- Characterizing a corona by a single T, tau etc could be misleading
- Measured compactness values are probably underestimates
- Converting E_{cut} (exponential cutoff) to kT unreliable
- Outflowing corona will have anisotropic emission (Beloborodov99, Malzac+01)
- Some reflection viewed through corona (Petrucci+01, Wilkins+Gallo15, Steiner+17)

Luminous Coronae are

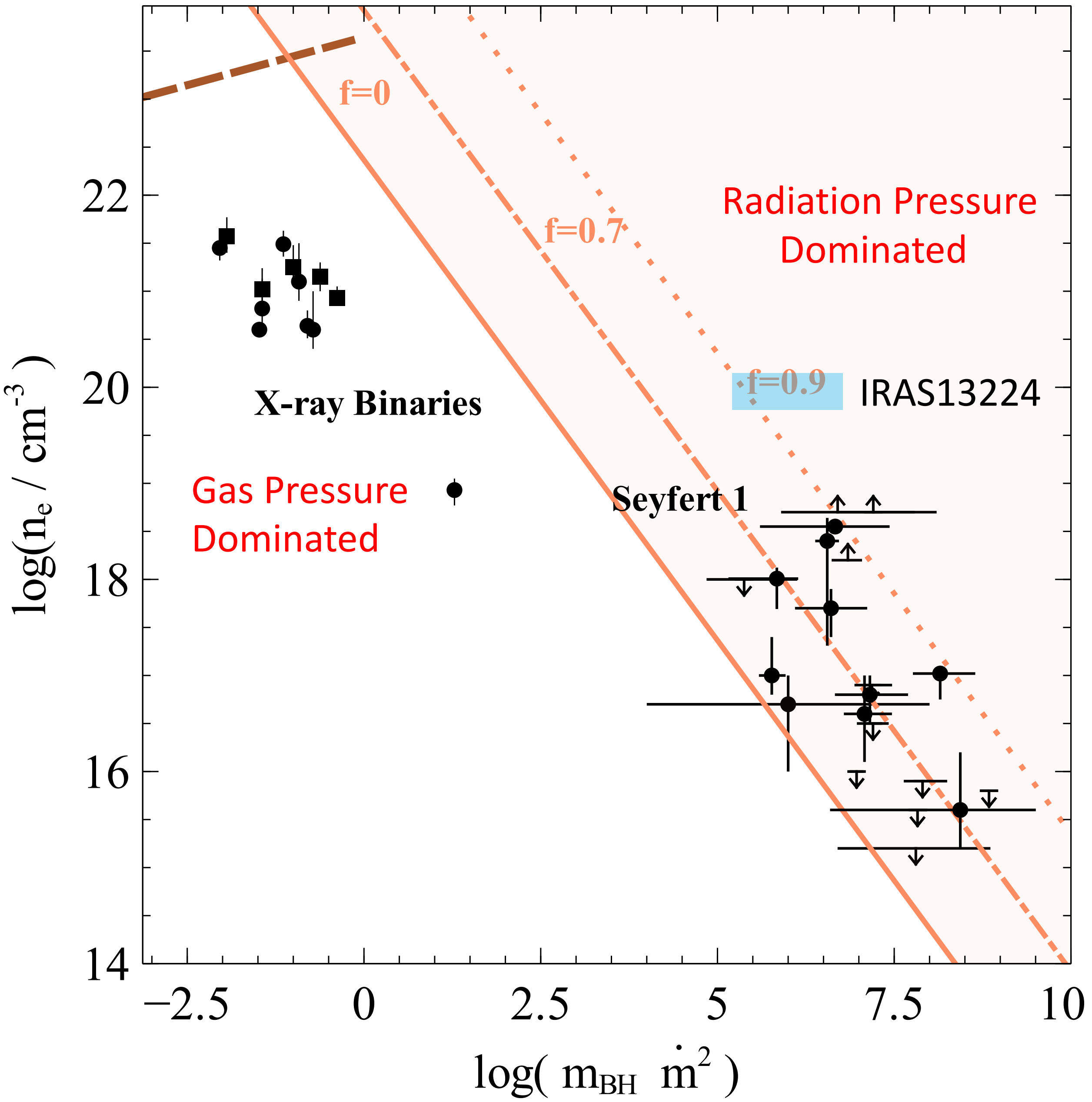
- Compact
- Highly magnetized
- Close to the black hole along spin axis
- Dynamic, possibly outflowing
- Probably contain electron-positron pairs
- Controls ~10-50% of the power
- Related to jets?

- Generate outer optically thin atmosphere which can affect polarization measurements

High Density Reflection Spectra

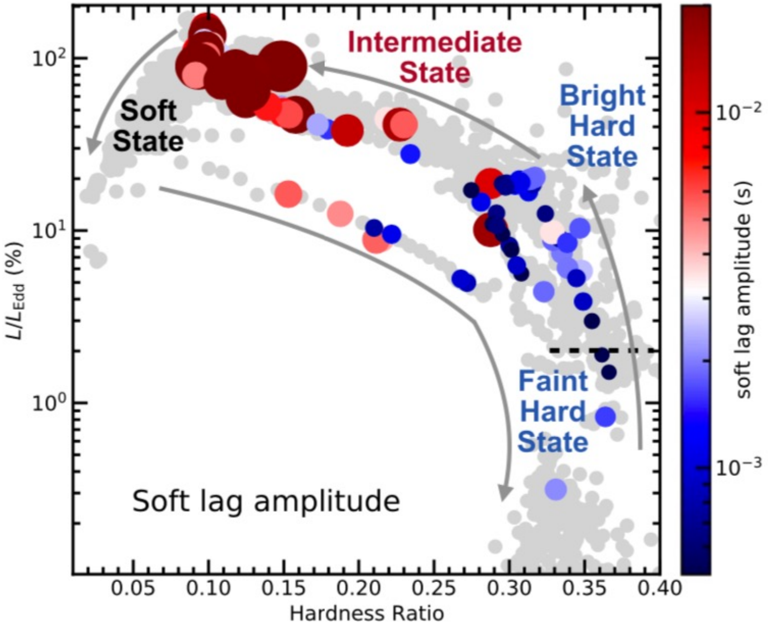


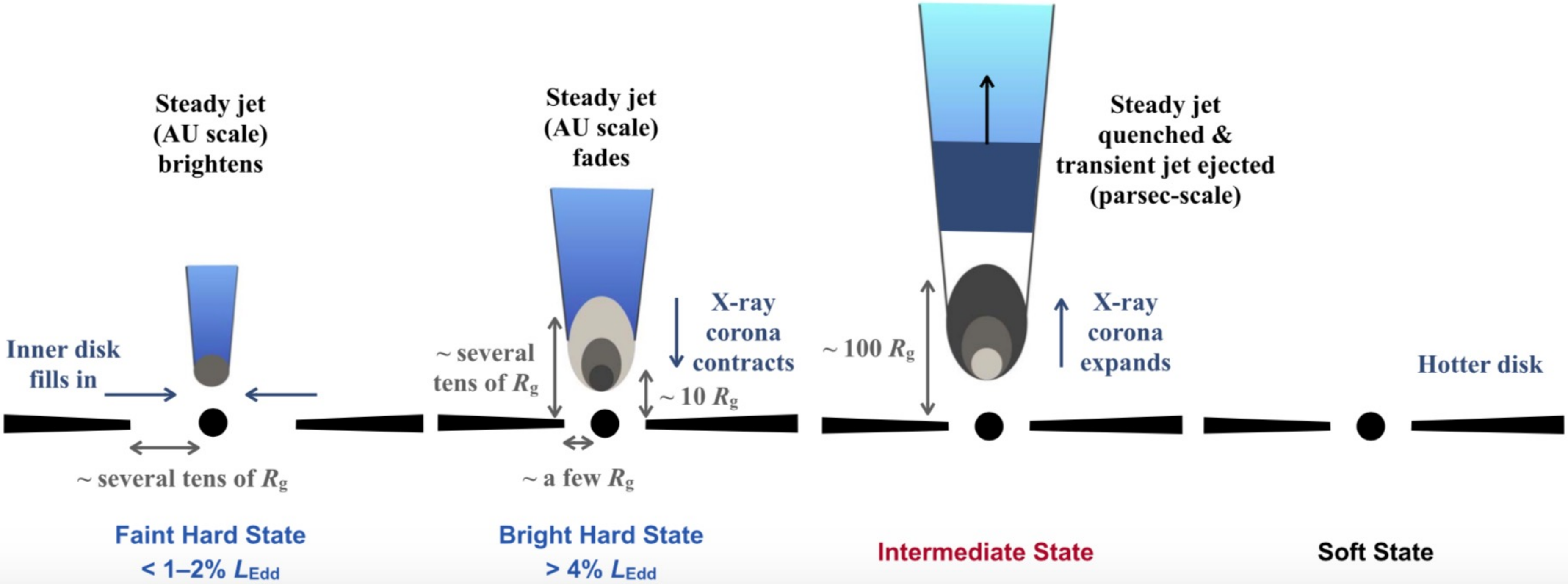
Garcia+16



Jiang+19, 20 in prep using modified SS equations (Svensson&Zdziarski93)

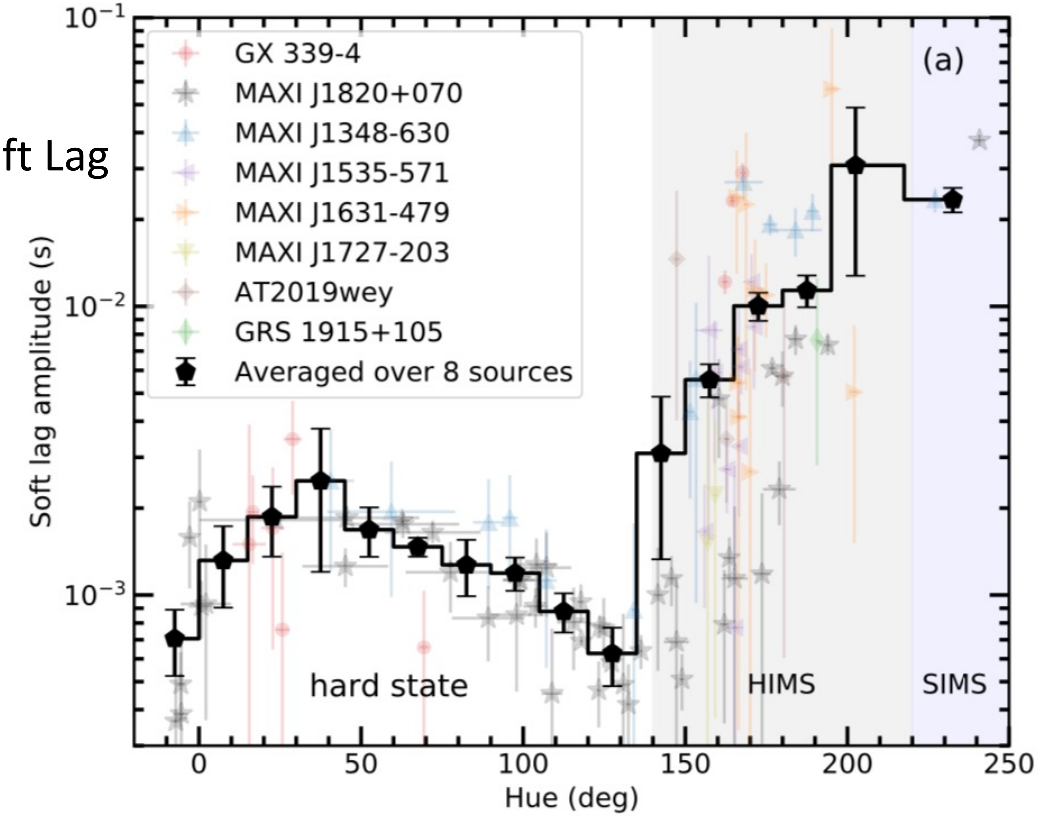
Jingyi Wang+22



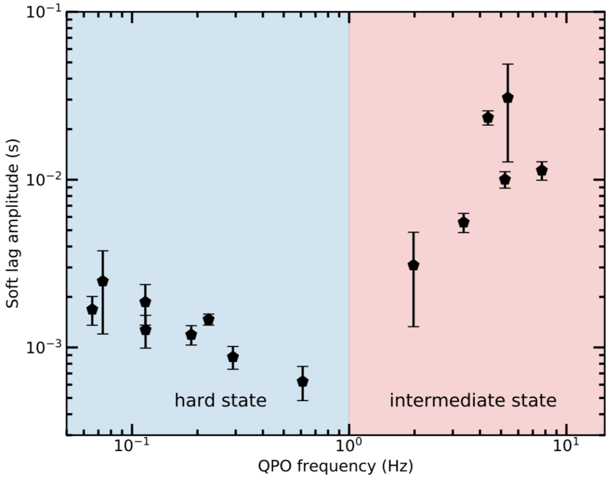


THE ASTROPHYSICAL JOURNAL, 930:18 (24pp), 2022 May 1 Jingyi Wang+

Soft Lag

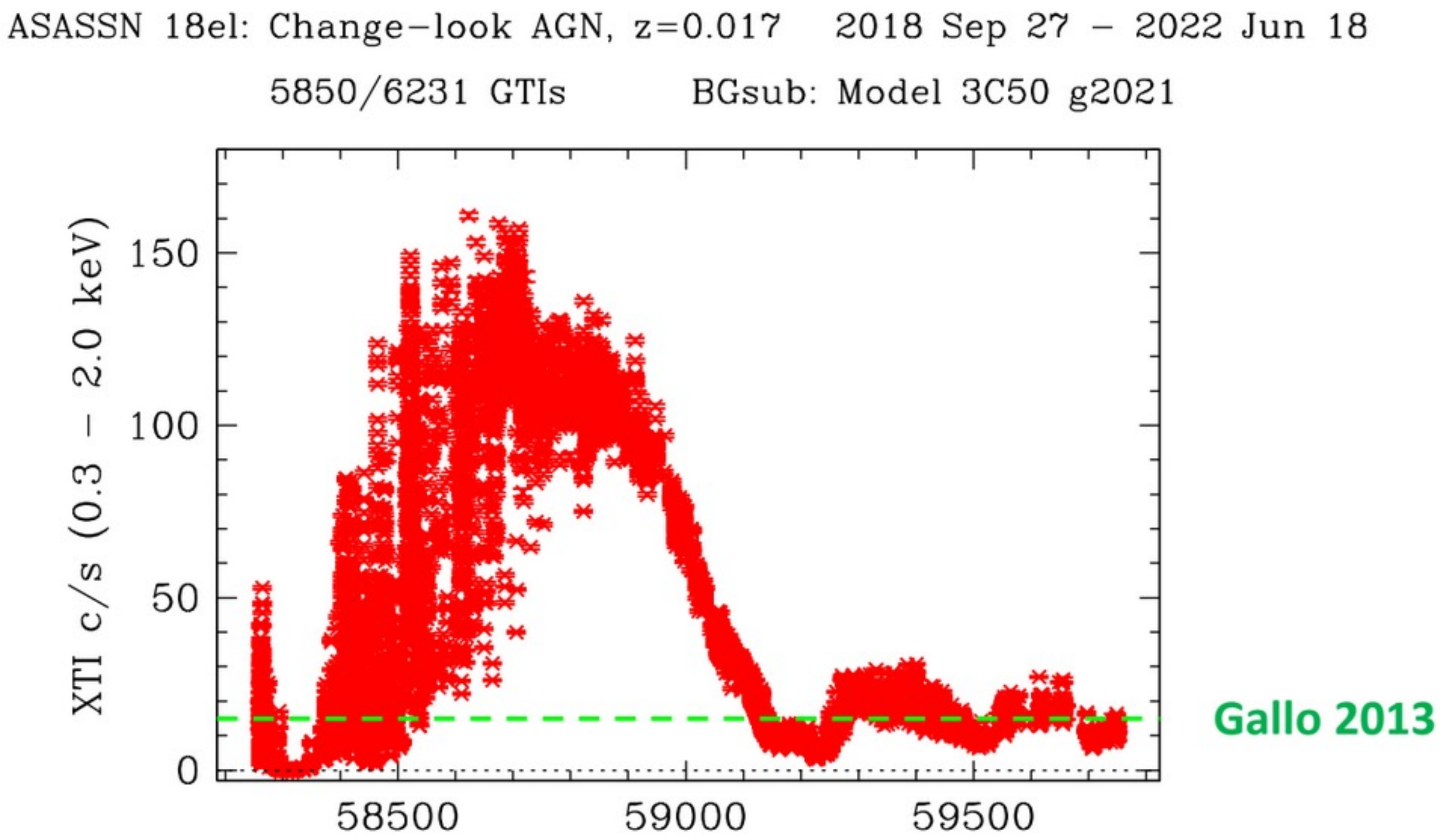


MAXI1820



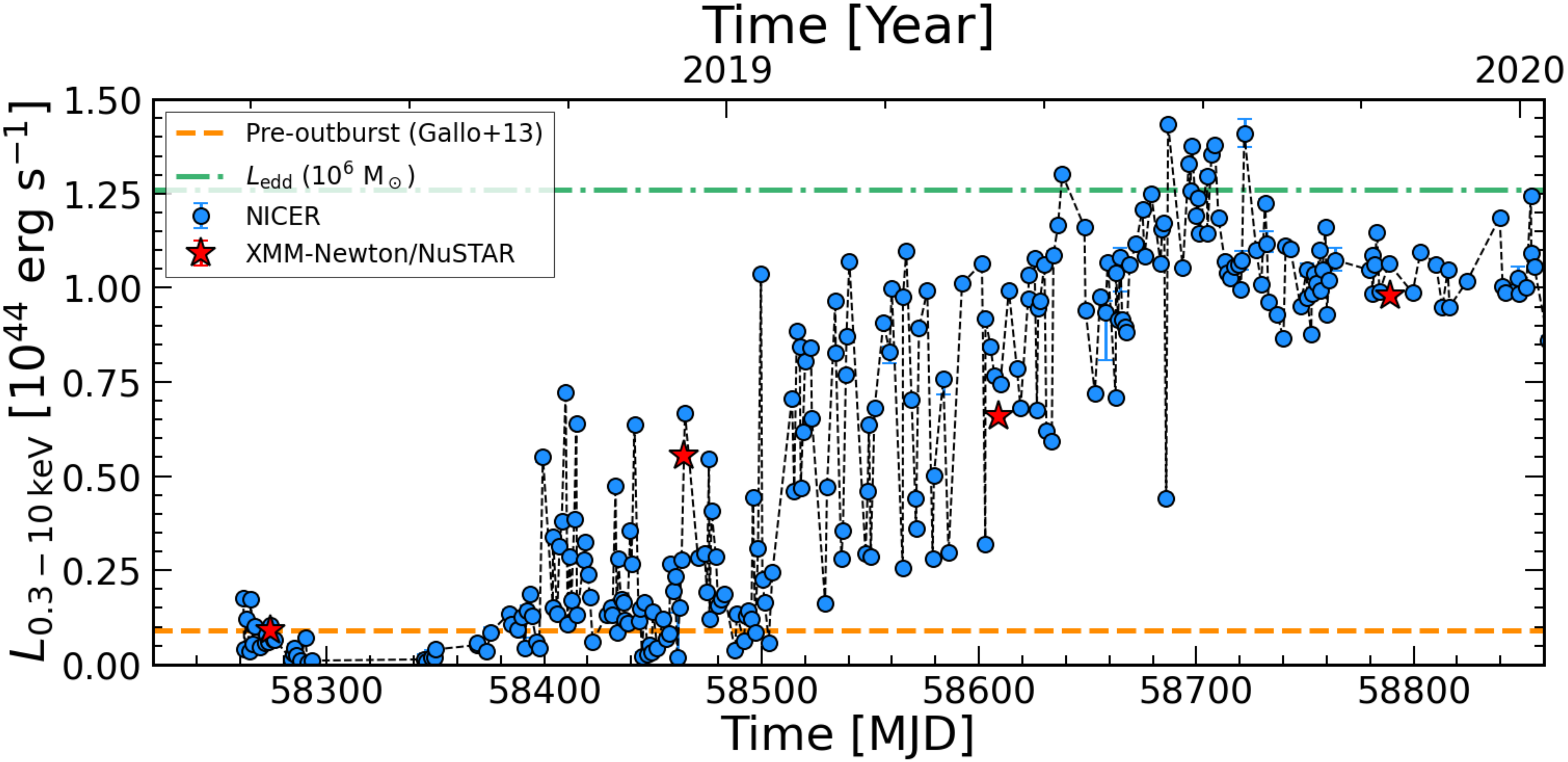
Systematic behaviour seen in Hard State BHB

Destruction followed by formation of AGN Corona in 1ES 1927+654



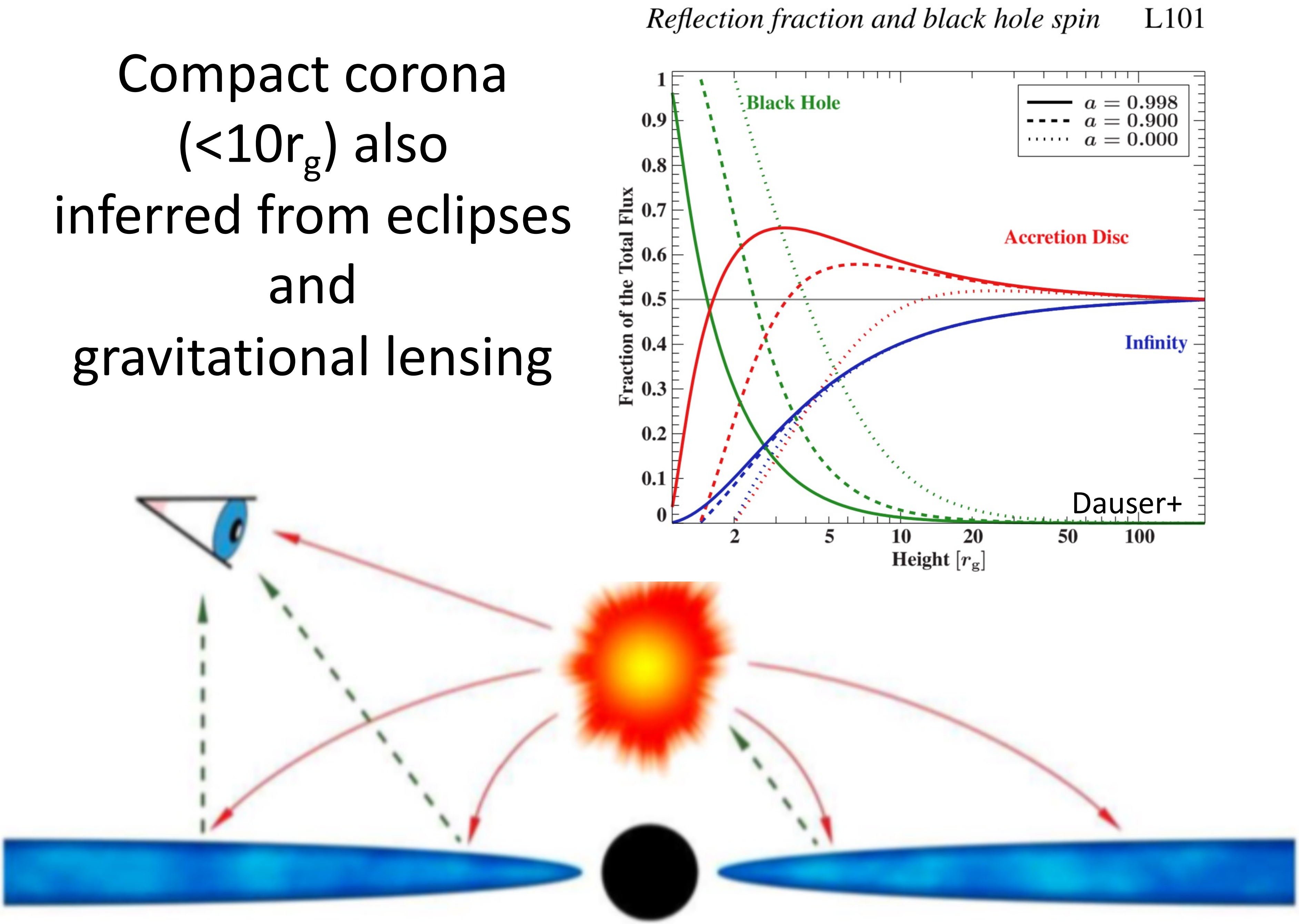
Ricci+21, Masterson+22

1ES 1927



M.Masterson

Compact corona ($<10r_g$) also inferred from eclipses and gravitational lensing



Dauser+

On re-acceleration, pairs and the high-energy spectrum of AGN and Galactic black hole candidates

G. Ghisellini,[1] F. Haardt[2] and A. C. Fabian[3] 1993

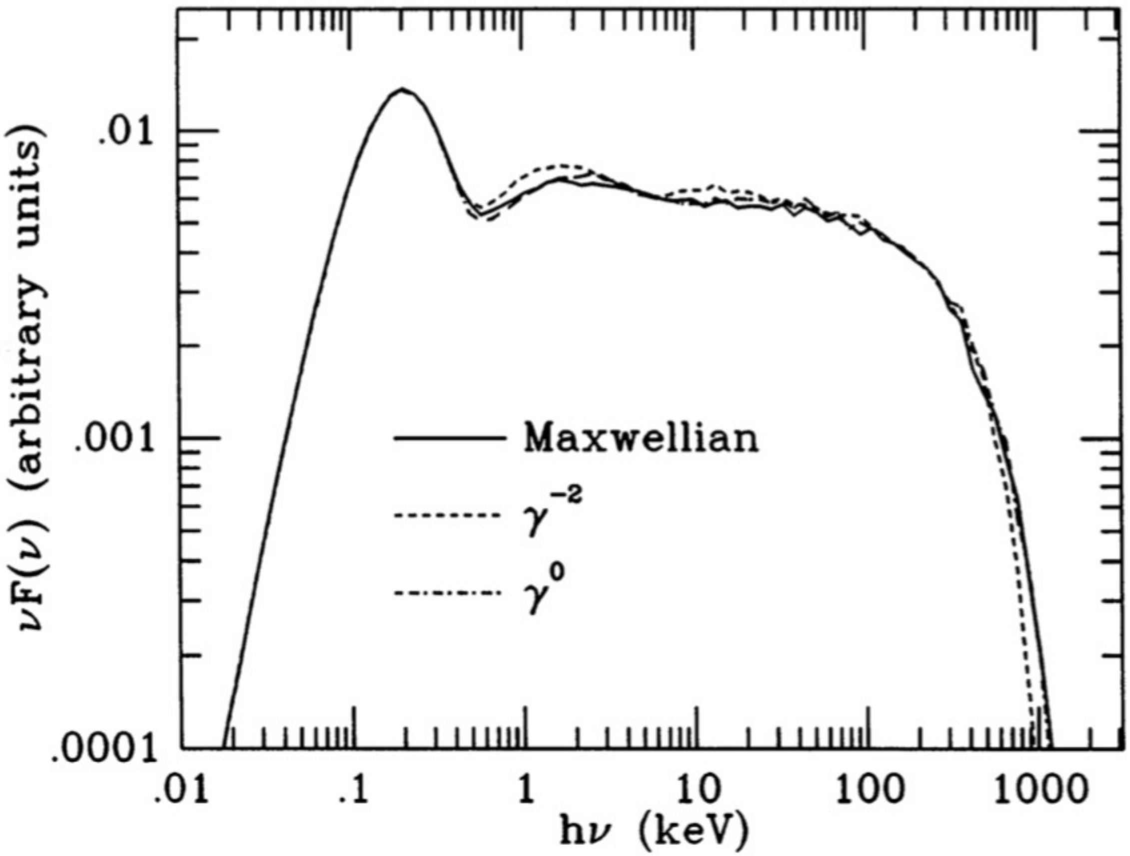
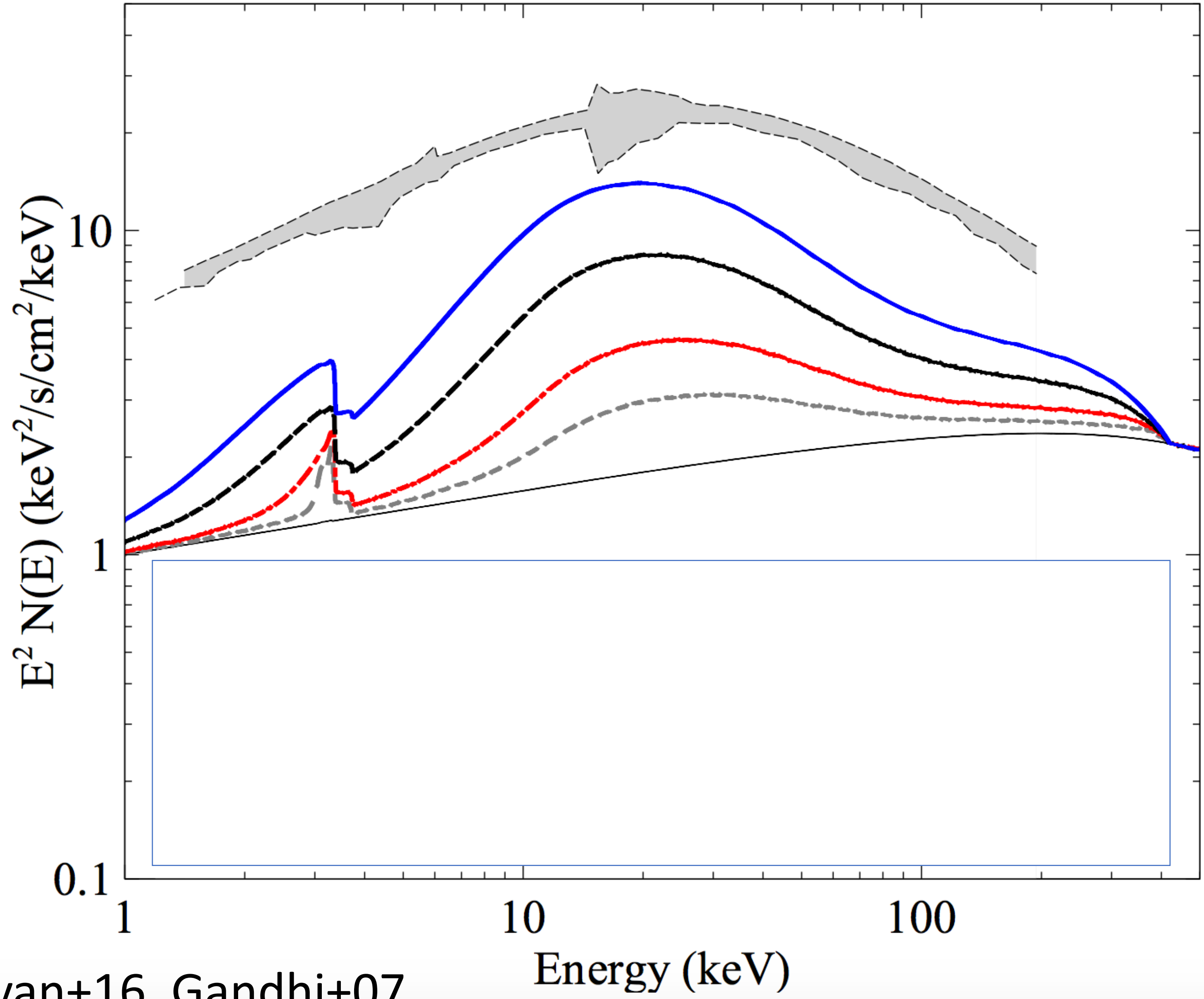
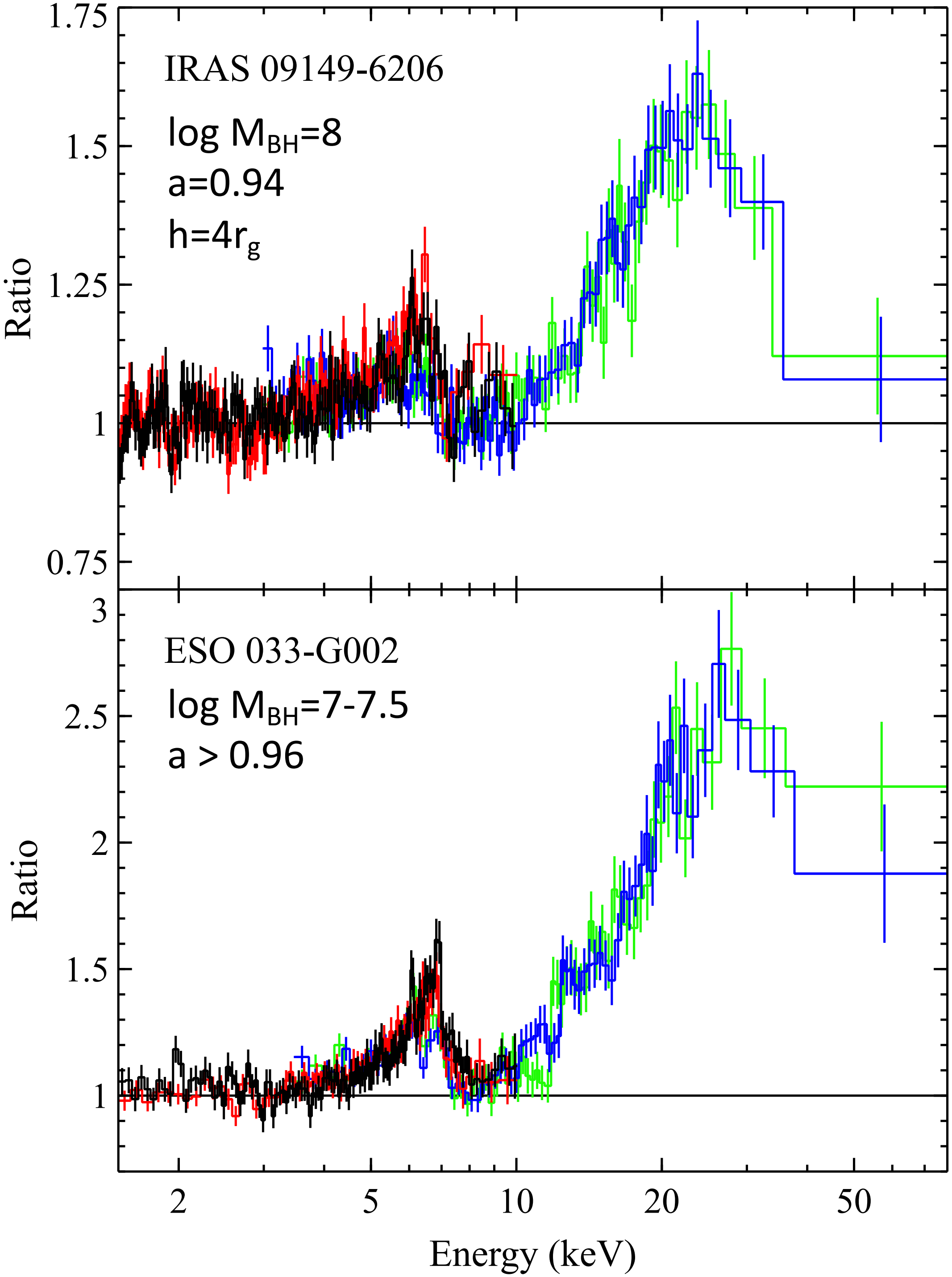


Figure 2. Comptonization spectra calculated with a Monte Carlo code for different electron distributions. Solid line: thermal distribution, with $kT = 171$ keV; short-dashed line: power-law distribution, $N(\gamma) \propto \gamma^{-2}$, with $1 < \gamma < 3$; long–dashed line: $N(\gamma) = $ constant, with $1 < \gamma < 2.37$. All models have the same $\tau_T = 0.35$.

X-ray Background Spectrum



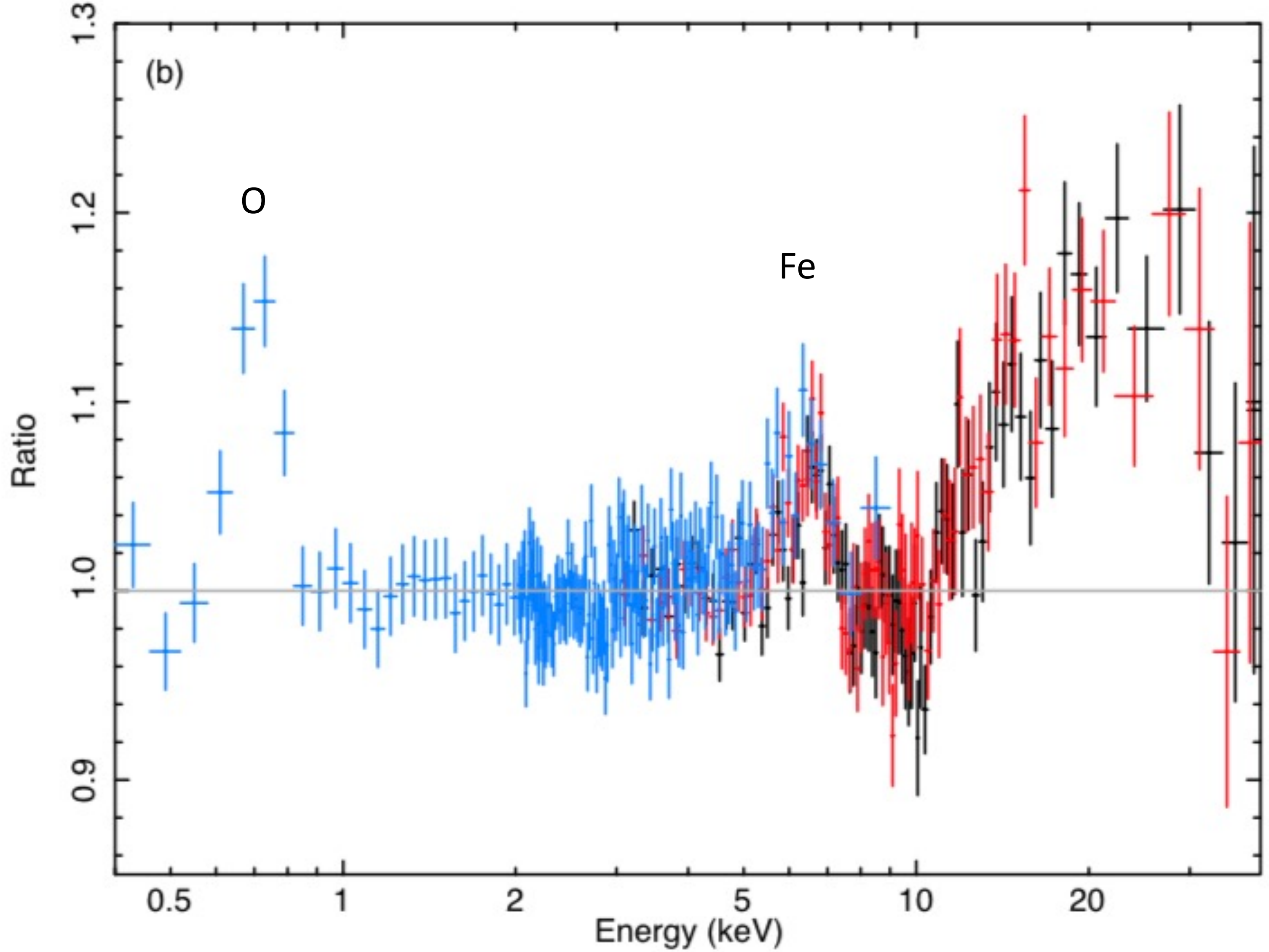
Vasudevan+16, Gandhi+07



IRAS 09149-6206
log M_BH=8
a=0.94
h=4r_g
ESO 033-G002
log M_BH=7-7.5
a > 0.96
Ratio
1.75
1.5
1.25
1
0.75
3
2.5
2
1.5
1
2
5
10
20
50
Energy (keV)

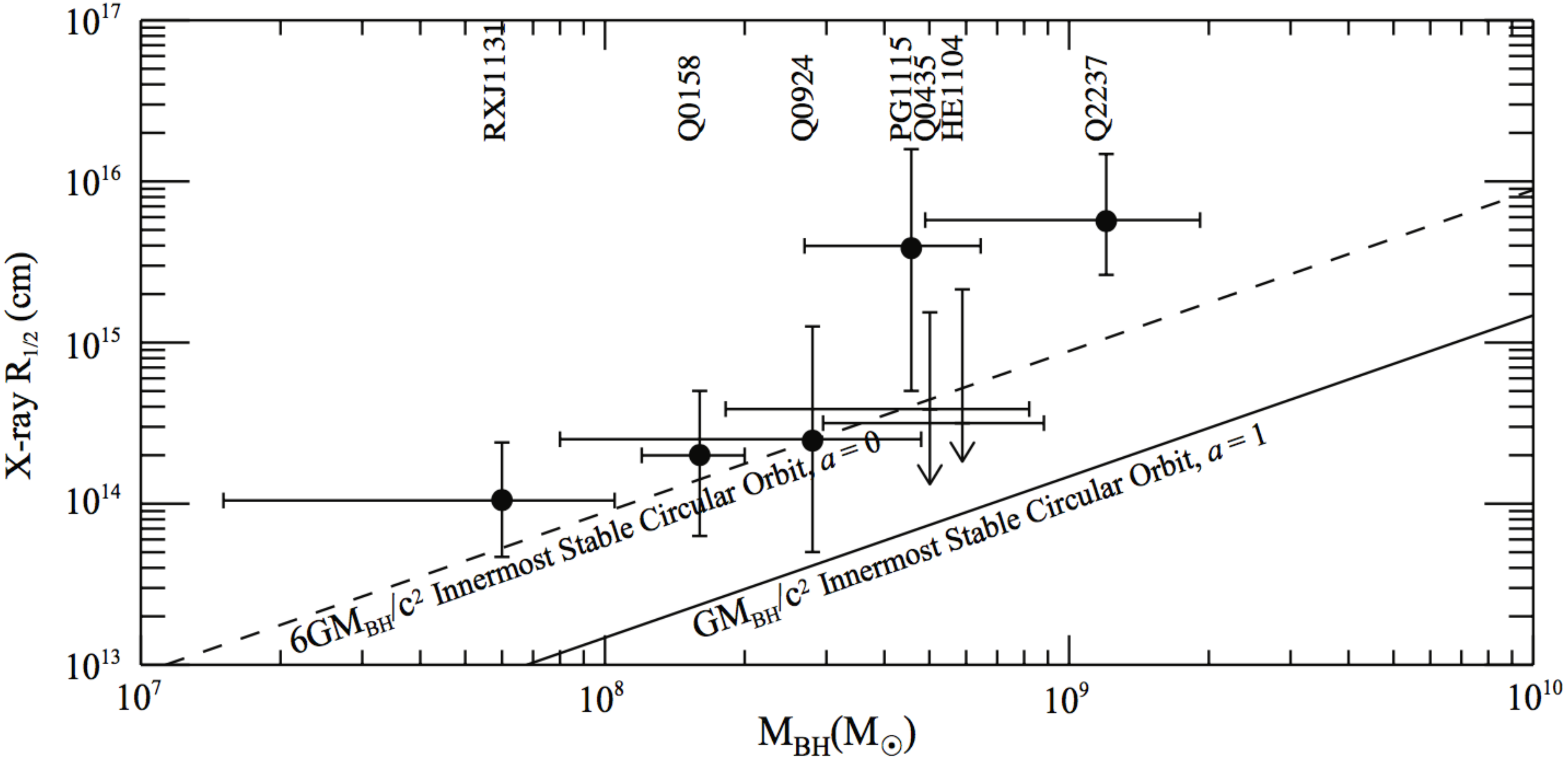
Walton+20,21

4U1543-624 Ludlam+20

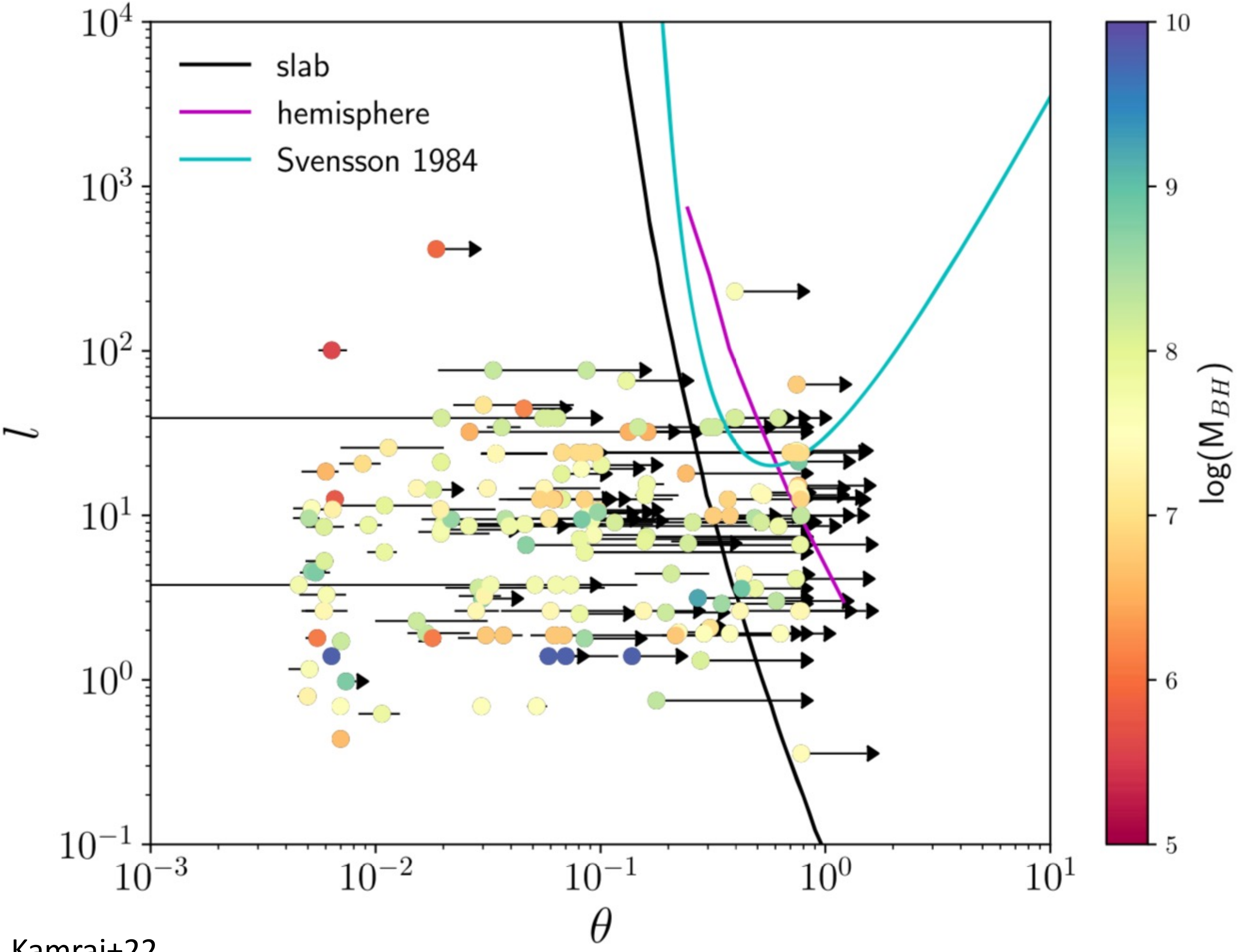


18 min binary composed of CO WD + NS

Coronal Size from Microlensing: Coronae are Compact



Chartas15

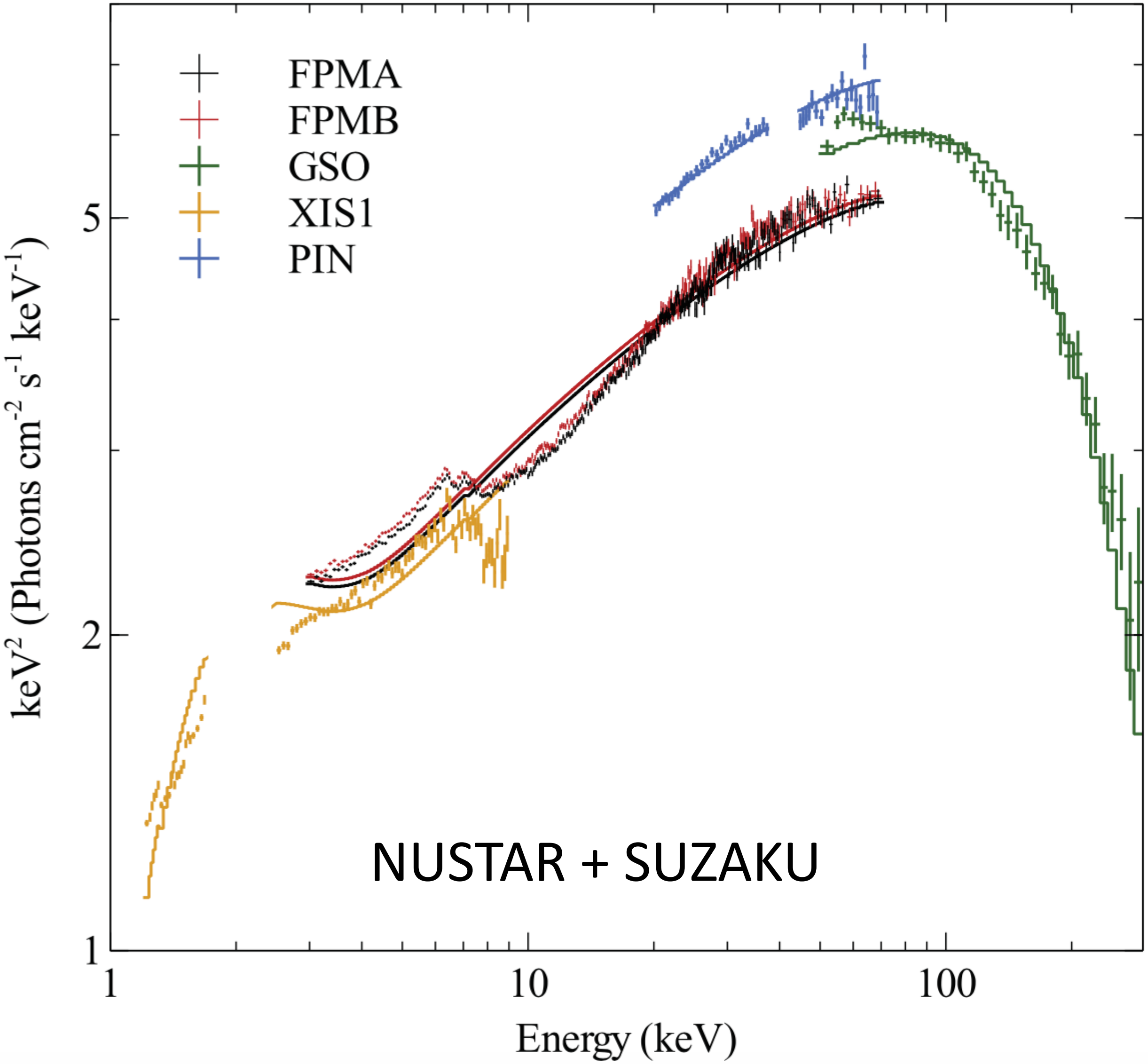

slab
hemisphere
Svensson 1984
l
θ
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
$\log(\mathrm{M}_{BH})$
5
6
7
8
9
10

Kamraj+22

Cyg X-1

REMINDER

Parker et al. 2015



also Gilfanov+00, Wilms+06, Novak+11

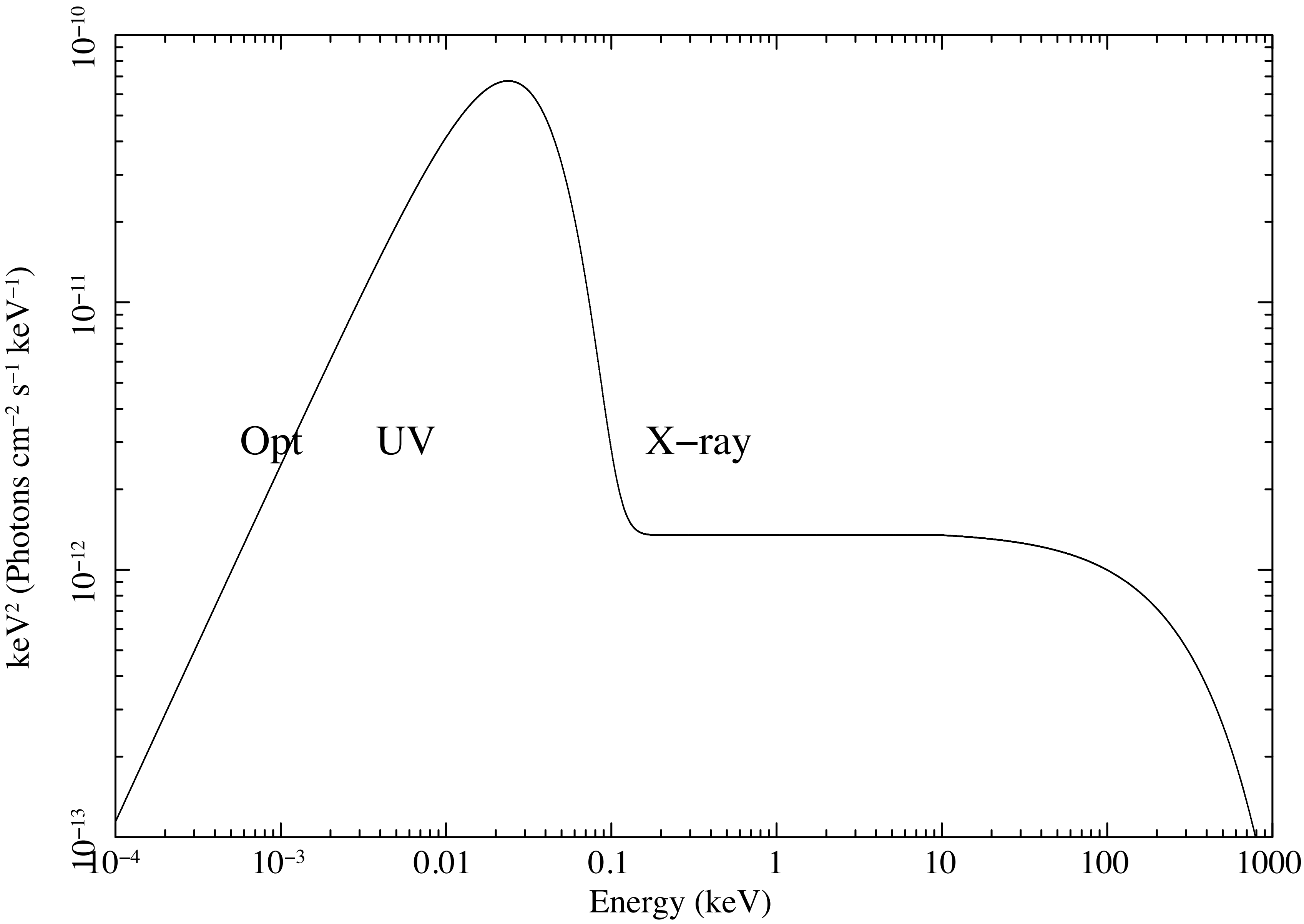
Summary of New Results

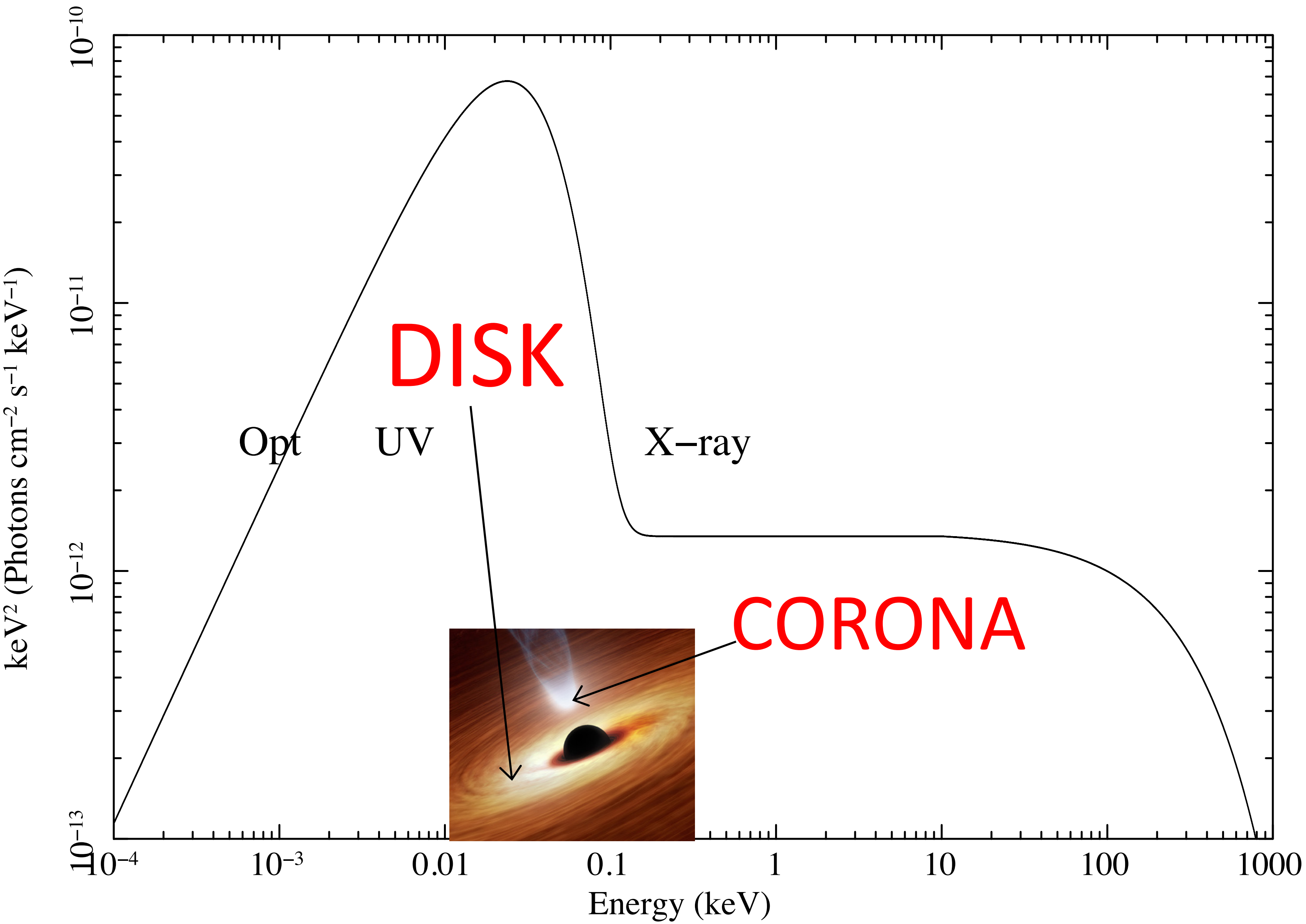
- Relativistic reflection and reverberation common in luminous accreting BH
- First X-ray reverberation AGN BH mass from IRAS13224 (10% uncertainty; Alston+20)
- Possible absorption lines from disc surface
- Measuring surface disc density for objects with BH mass < 2×10^7 M_{sun} (Jiang+19a,b,c,20)
- Approximate agreement between height as measured by reverberation and through the ionization parameter
- Obtaining geometry of innermost $5r_g$ around BH – the heart of the AGN

The Future

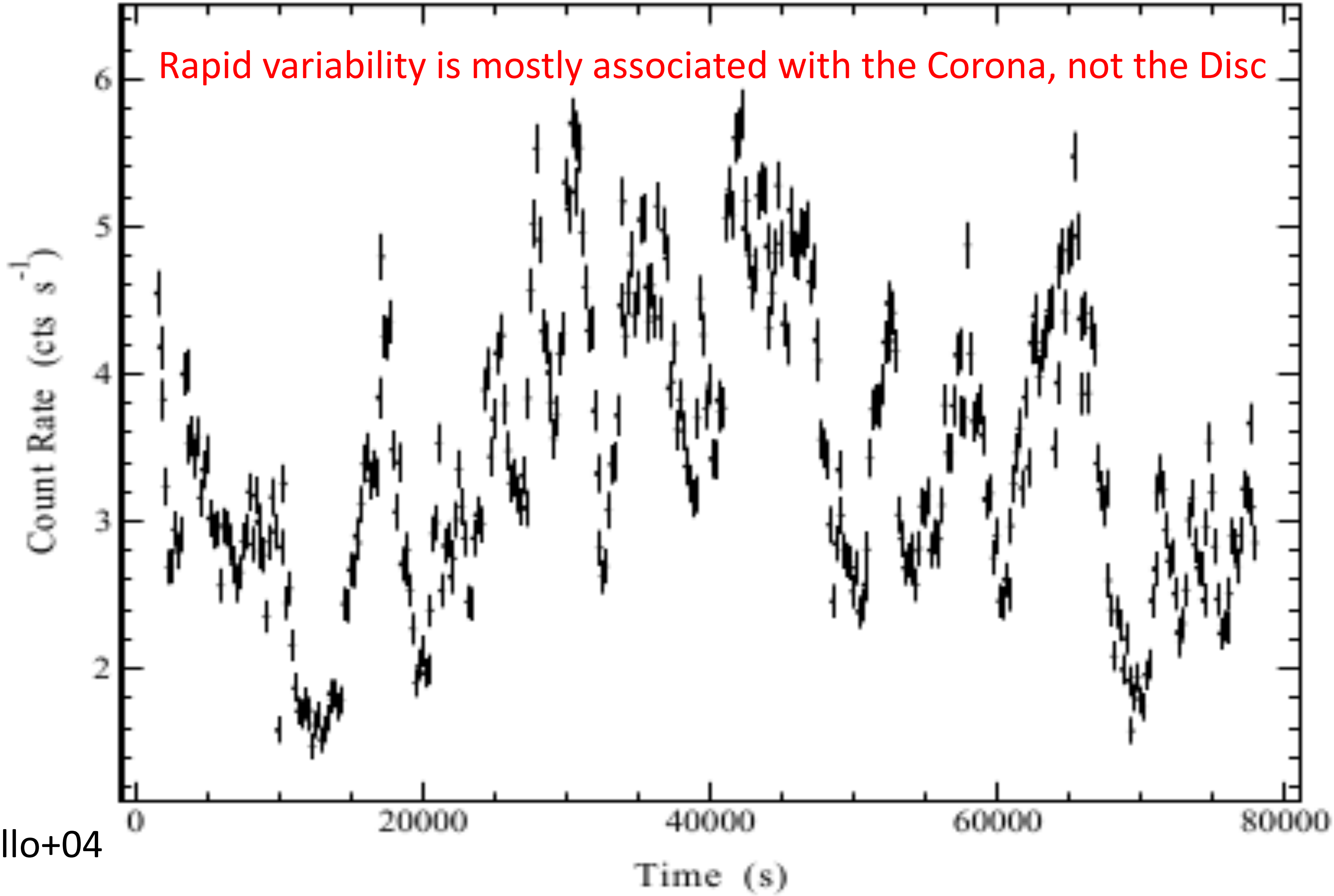
- More objects and outbursts followed more closely
- eROSITA, XRISM, eXTP, ATHENA
- Polarization (IXPE)
- Understand the corona
- Links to jets?
- Links to optical, UV etc
- Evolution of AGN BH spin with redshift
- ….

SCHEMATIC AGN SED, shifted up in E but similar shape in BHB




DISK
CORONA
Opt
UV
X–ray
10^{-10}
10^{-11}
10^{-12}
10^{-13}
keV^2 (Photons cm^{-2} s^{-1} keV^{-1})
10^{-4}
10^{-3}
0.01
0.1
1
10
100
1000
Energy (keV)

1H0707-495

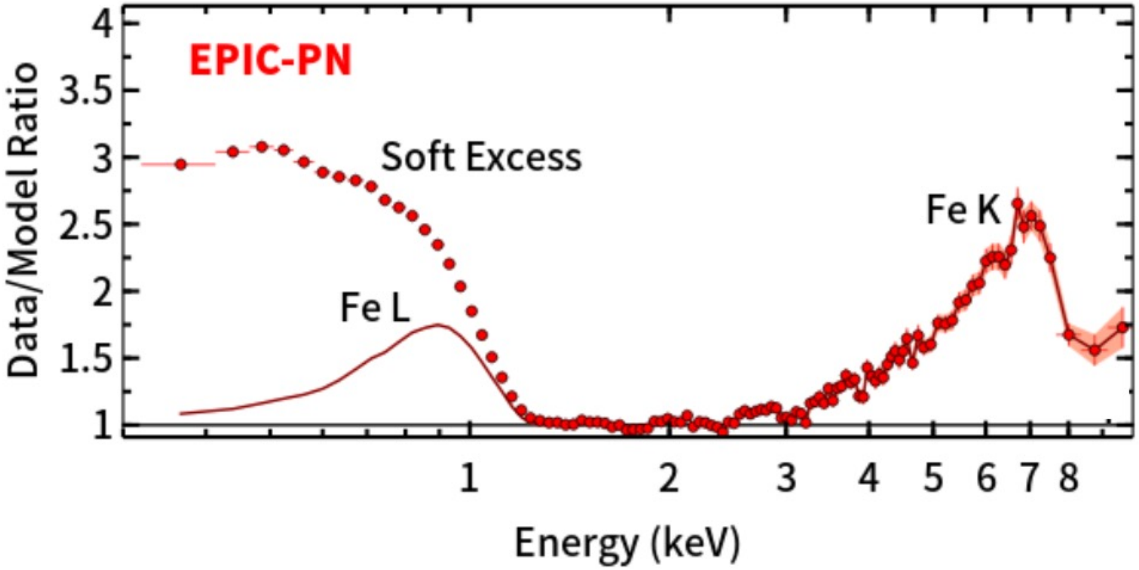


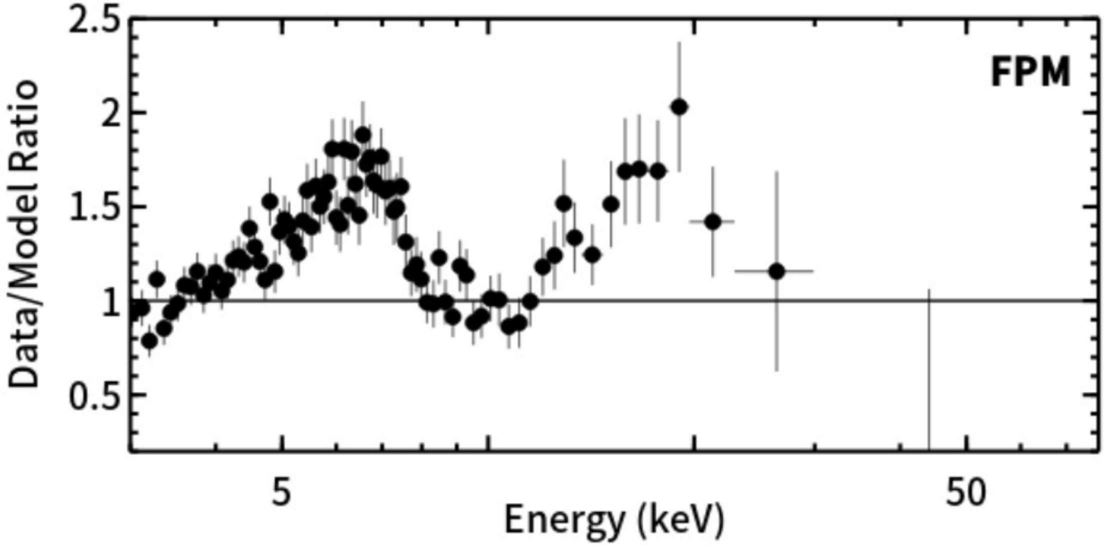
Rapid variability is mostly associated with the Corona, not the Disc

Gallo+04

IRAS13224-3809

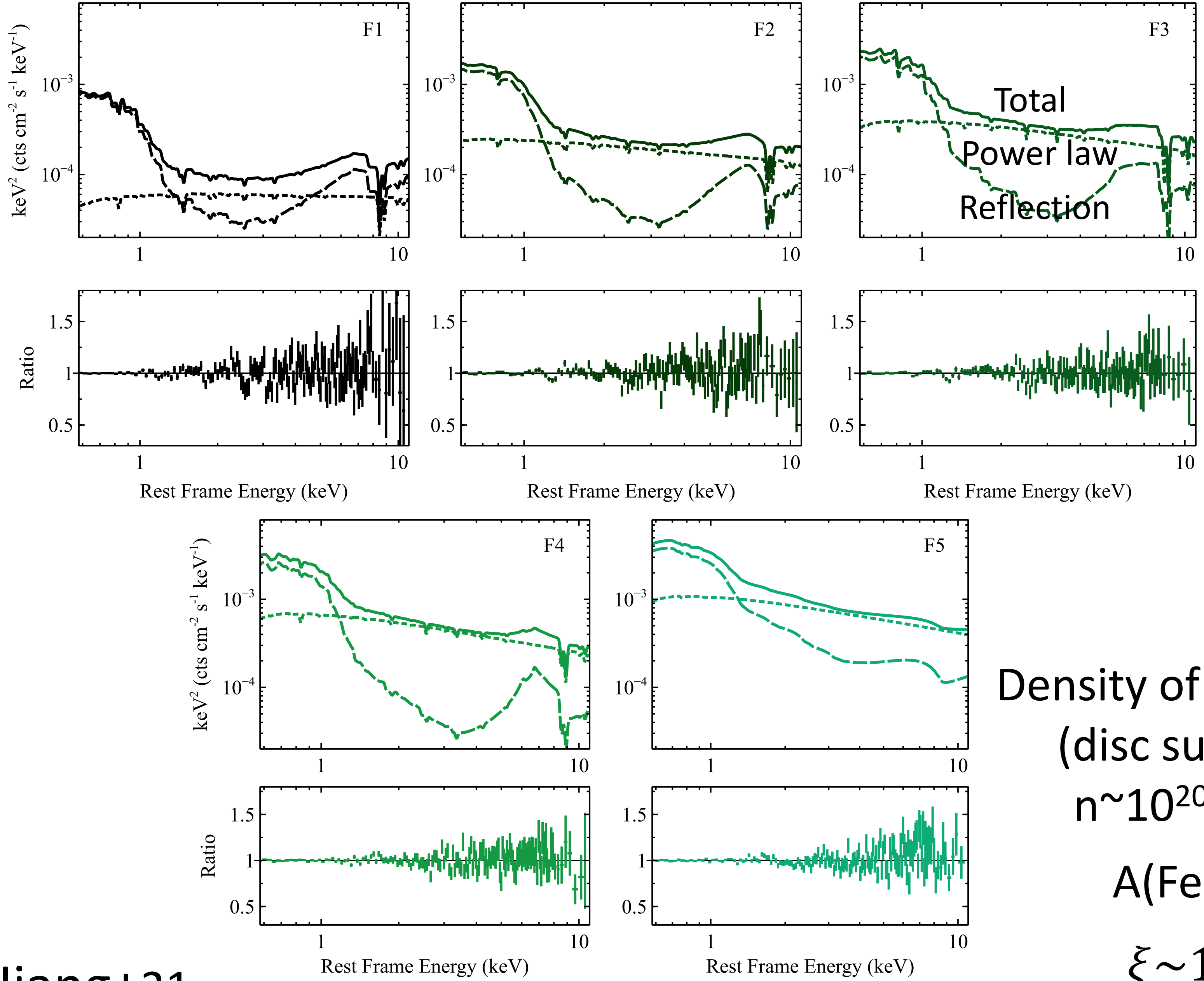
XMM





J. Jiang

IRAS13224-3809 XMM spectra in 5 flux states

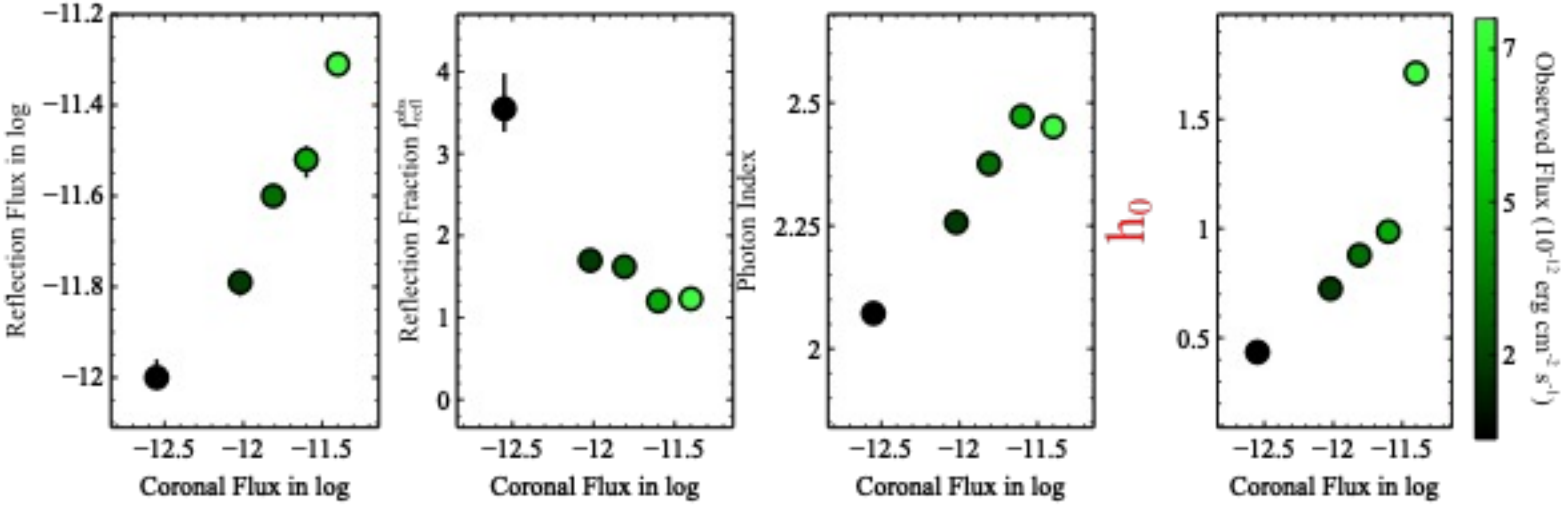


Density of reflector
(disc surface)
$n \sim 10^{20}$ cm^{-3}

A(Fe)~3

$\xi \sim 10$

J. Jiang+21

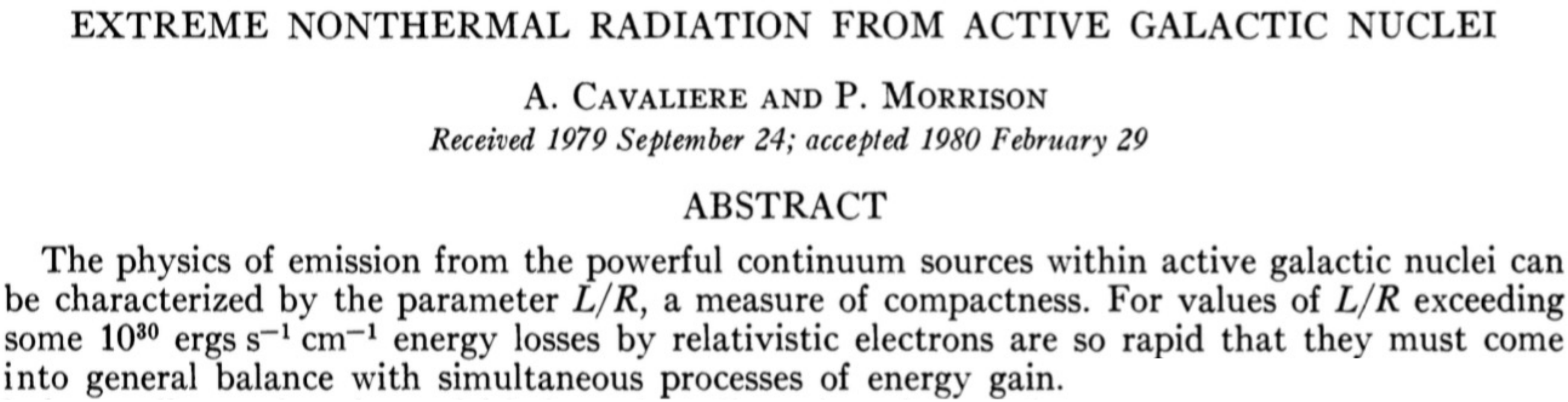


Use Ionization Parameter to infer "Euclidean" coronal height h_0

$$\xi = L/nh_0^2$$

BUT need to include effects of strong gravity (light bending, blueshifts etc)

Concept of Compactness (L/R) introduced in 1980



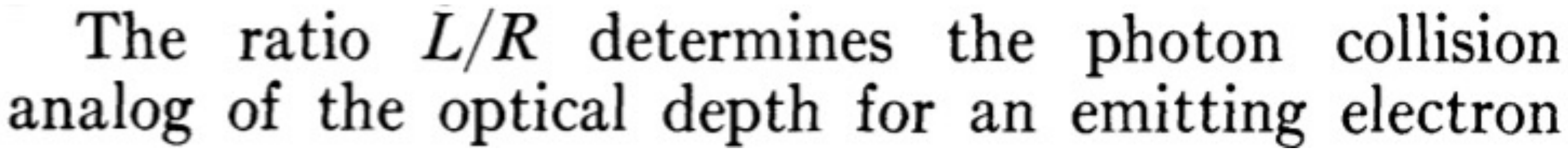
EXTREME NONTHERMAL RADIATION FROM ACTIVE GALACTIC NUCLEI

A. CAVALIERE AND P. MORRISON

Received 1979 September 24; accepted 1980 February 29

ABSTRACT

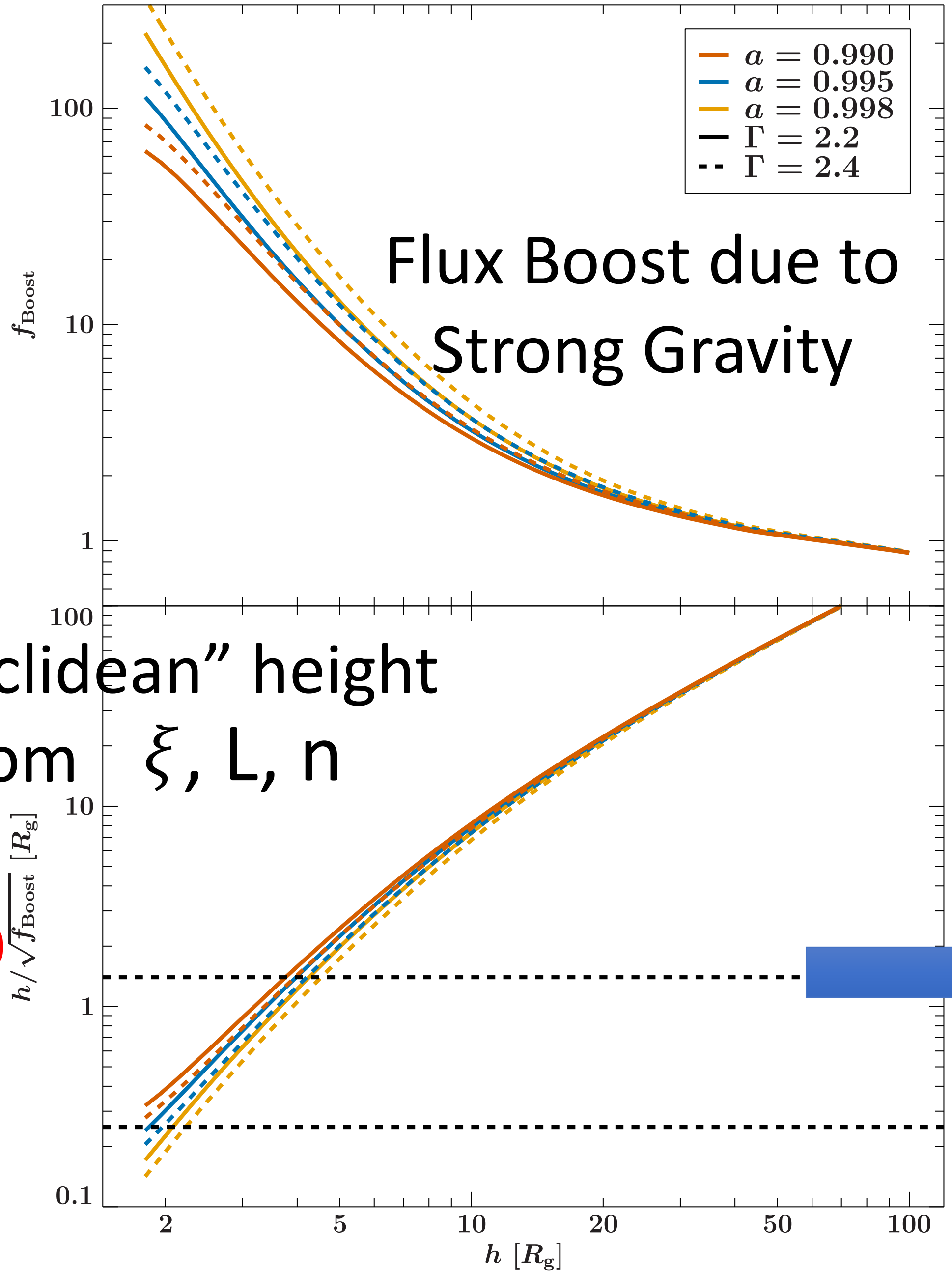
The physics of emission from the powerful continuum sources within active galactic nuclei can be characterized by the parameter L/R, a measure of compactness. For values of L/R exceeding some 10^{30} ergs s^{-1} cm^{-1} energy losses by relativistic electrons are so rapid that they must come into general balance with simultaneous processes of energy gain.



The ratio L/R determines the photon collision analog of the optical depth for an emitting electron

L/R is proportional to the column density of photons in the source

T. Dauser

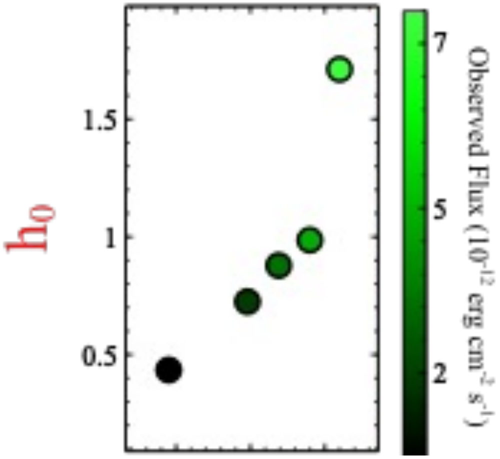


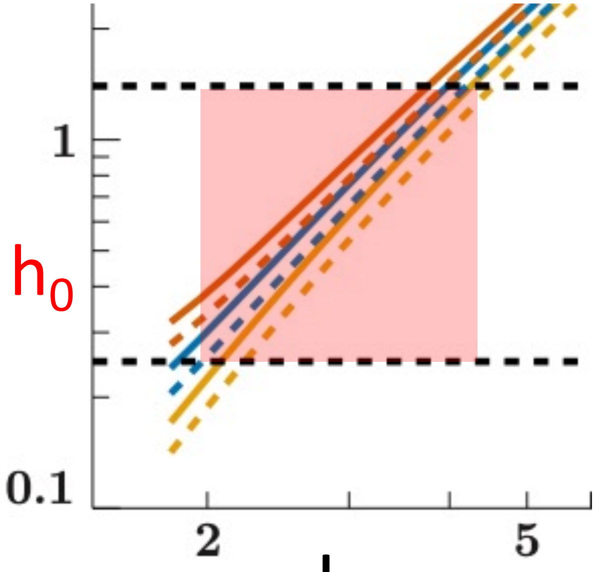
Flux Boost due to Strong Gravity

“Euclidean” height from ξ, L, n

h_0

Actual Coronal Height, h





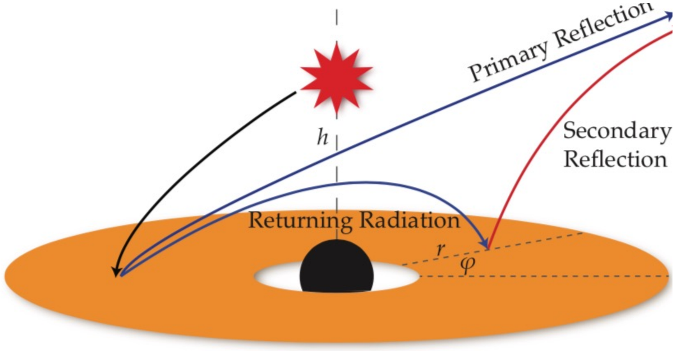
h

Coronal Height Measurement

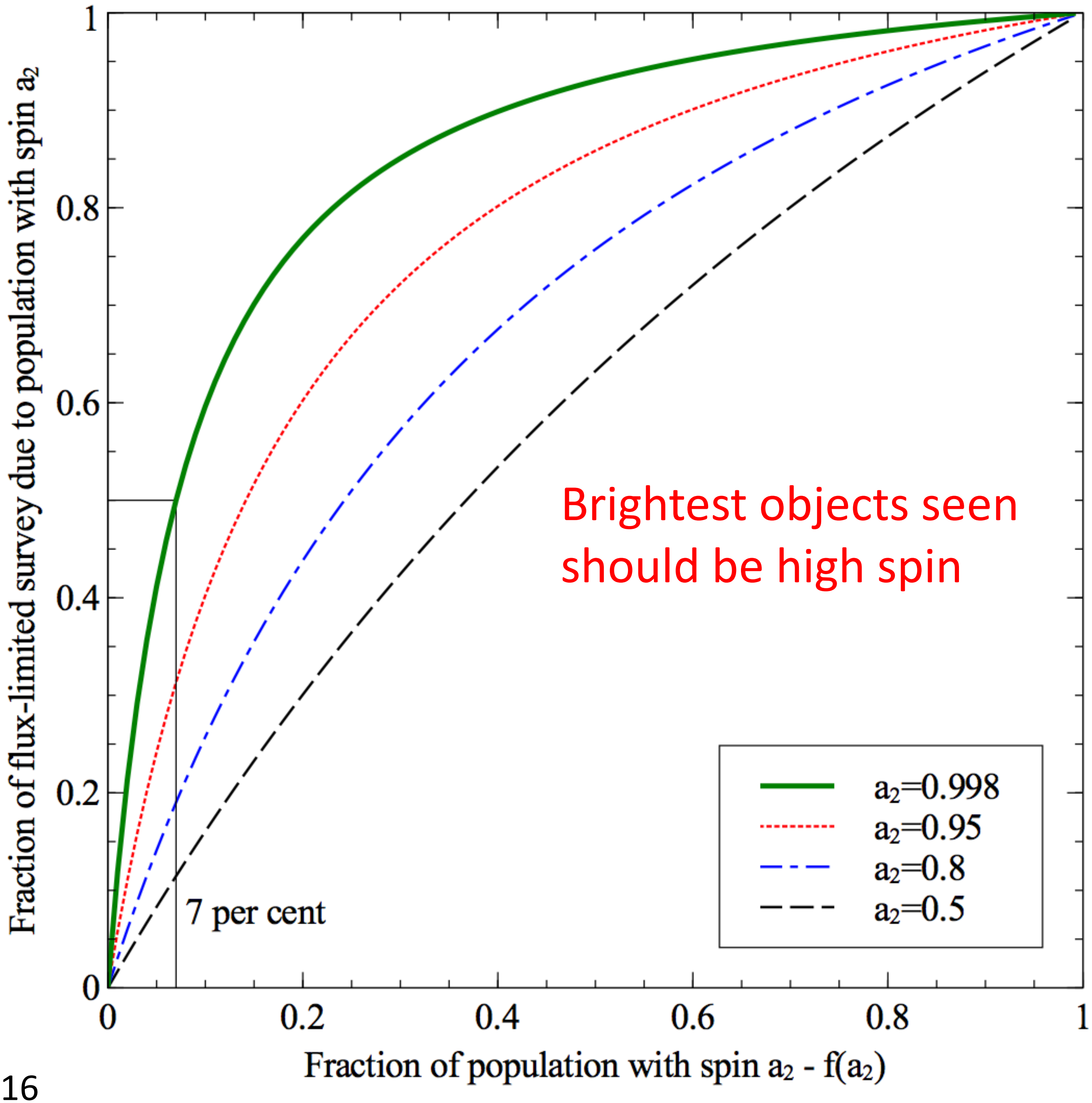
- Euclidean estimate $h_0 \sim 0.4 - 1.7\ r_g$
- Flux boosted height $h \sim 2 – 5\ r_g$
- Reverberation height $h \sim 6 – 12\ r_g$

Other Considerations

- Returning radiation?
- Size of corona

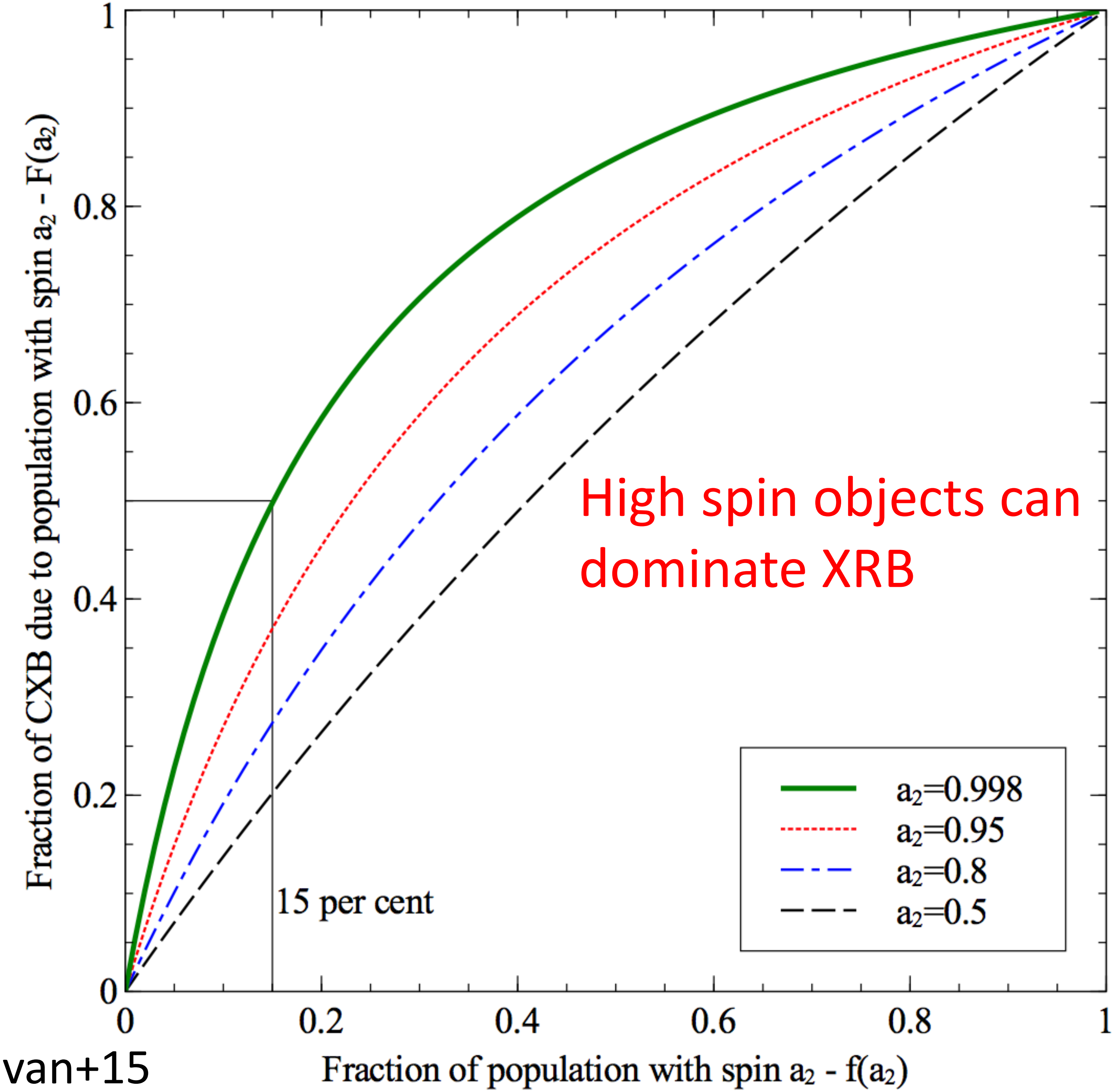


Wilkins+20



Brightest objects seen should be high spin

Vasudevan+16



High spin objects can dominate XRB

Vasudevan+15

Further selection effect

- ISCO needs to be well-illuminated to be measured.
- Implies that coronal height less than about $12r_g$.
- More difficult to measure in objects of low spin.
- Analysis of 199 AGN X-ray spectra from deep fields shows broad FeK line in 2/3 with preference for high spin (Baronchelli+18,20)