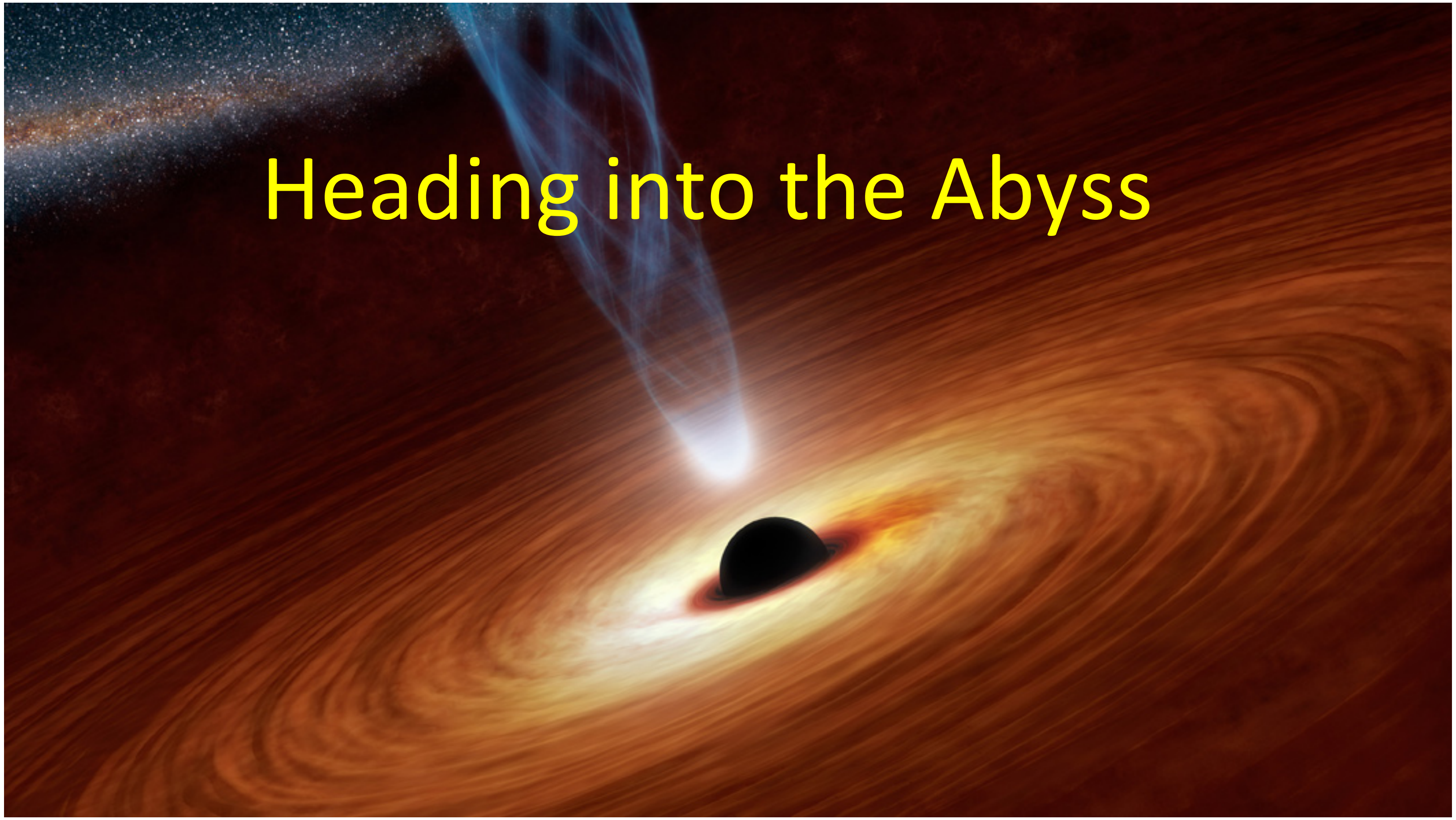
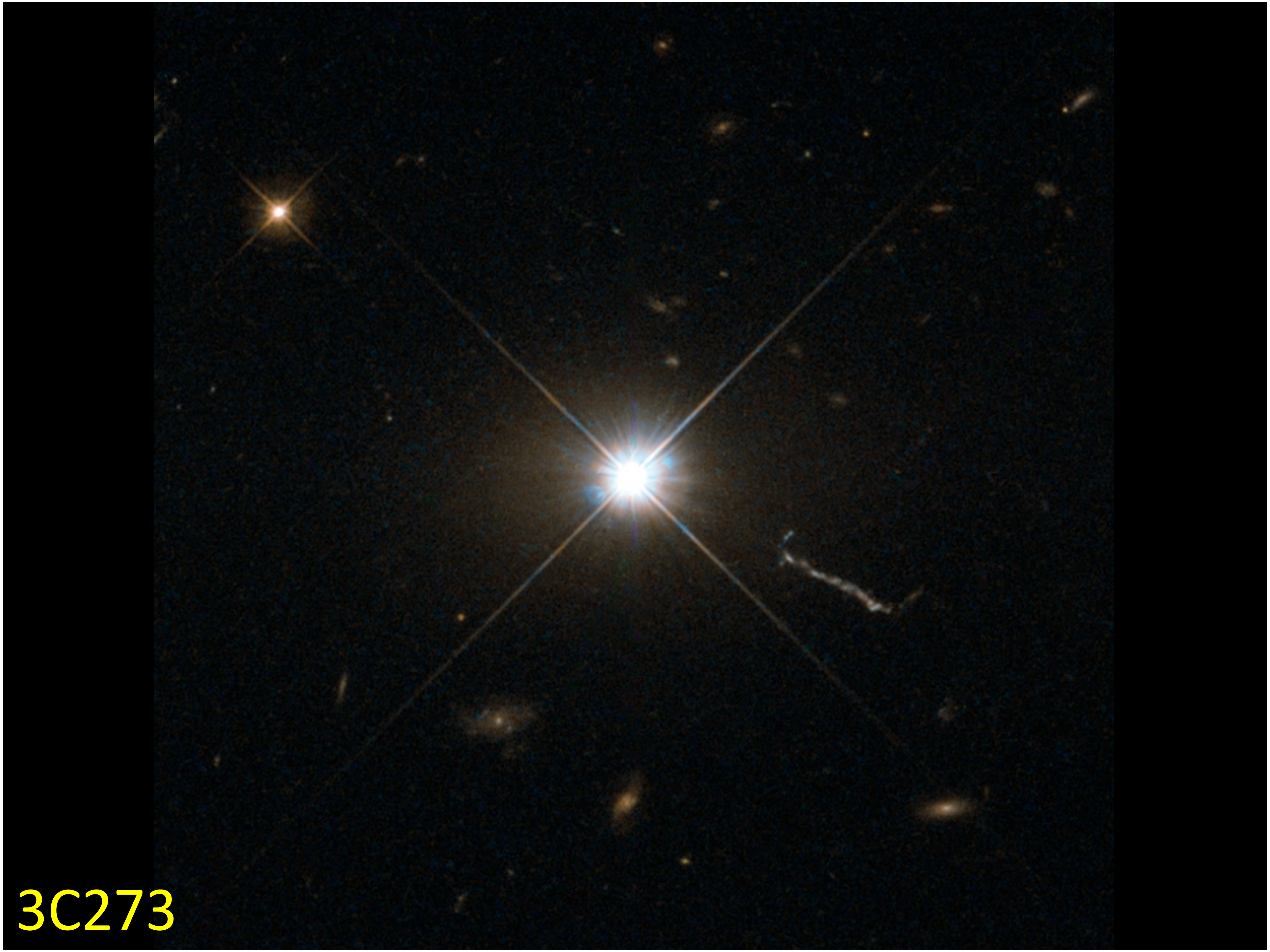


X-ray Spectral timing of Accreting Black Holes

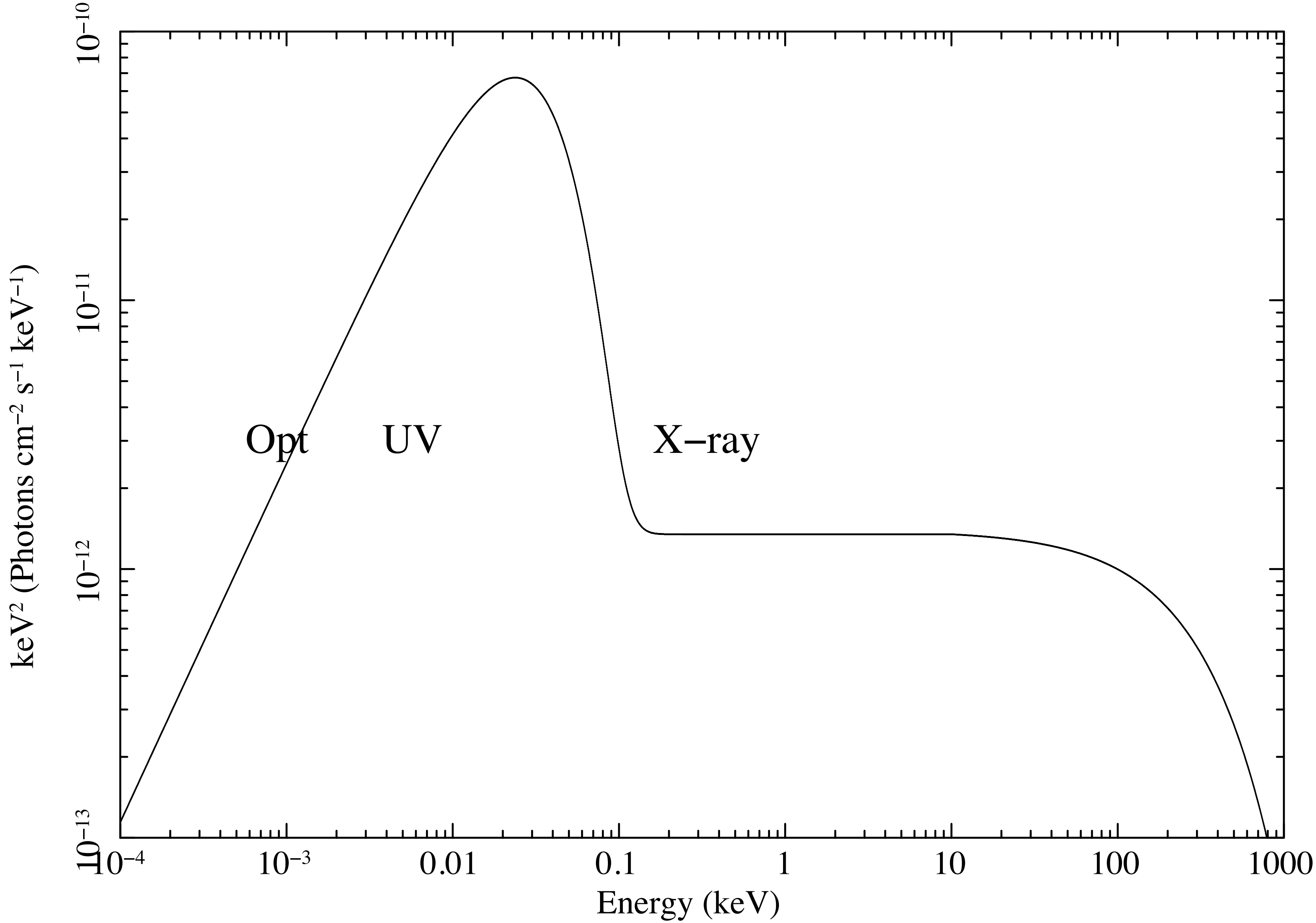
Andy Fabian
Institute of Astronomy
University of Cambridge

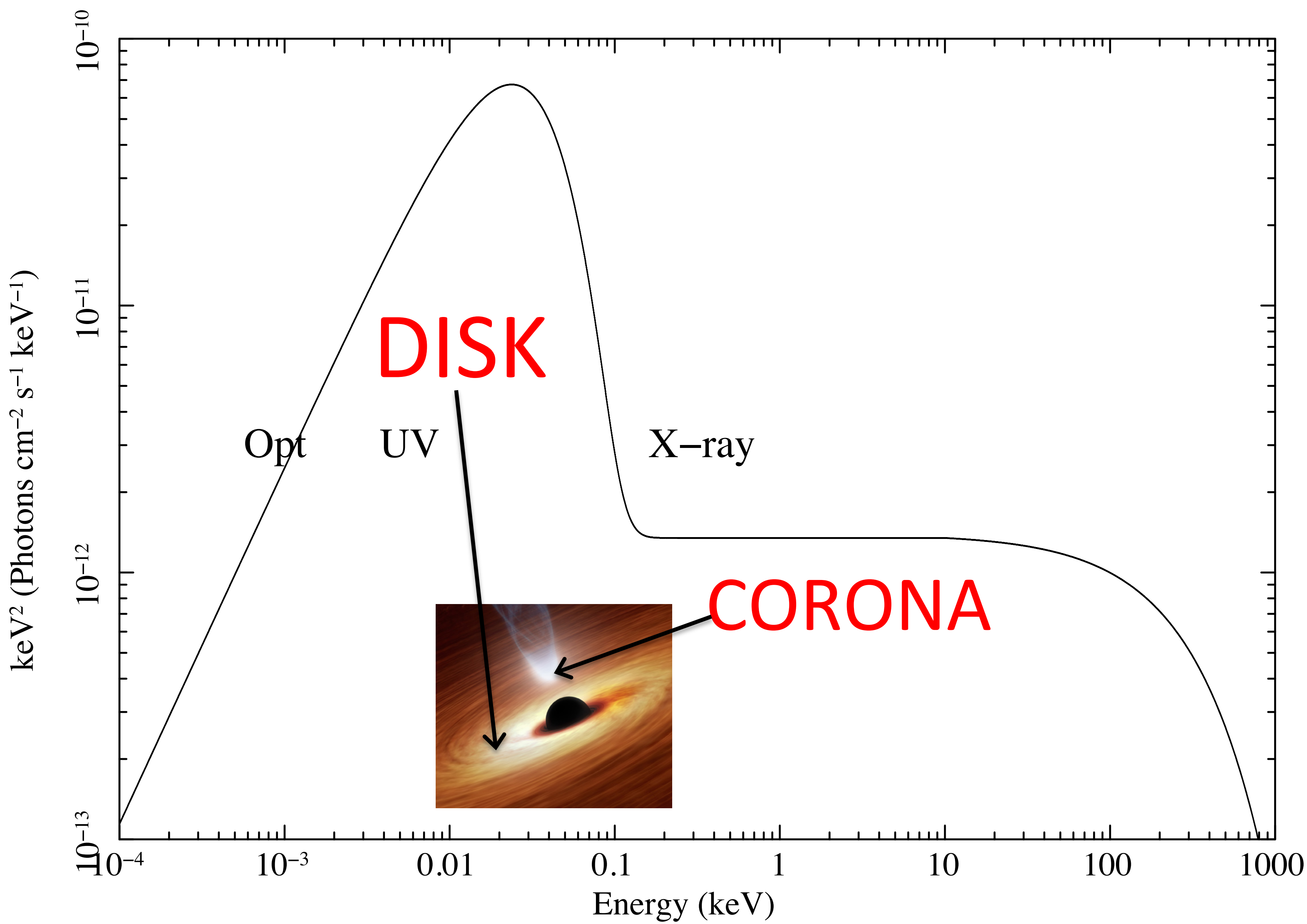

3C273

STRONG GRAVITY

- Gravitational redshift ✔ Red wing
- Strong Light Bending (radian scale) ✔ Reflection Strength
- Shapiro delay ✔ Reverberation
- Dragging of Inertial Frame ✔ High Spin

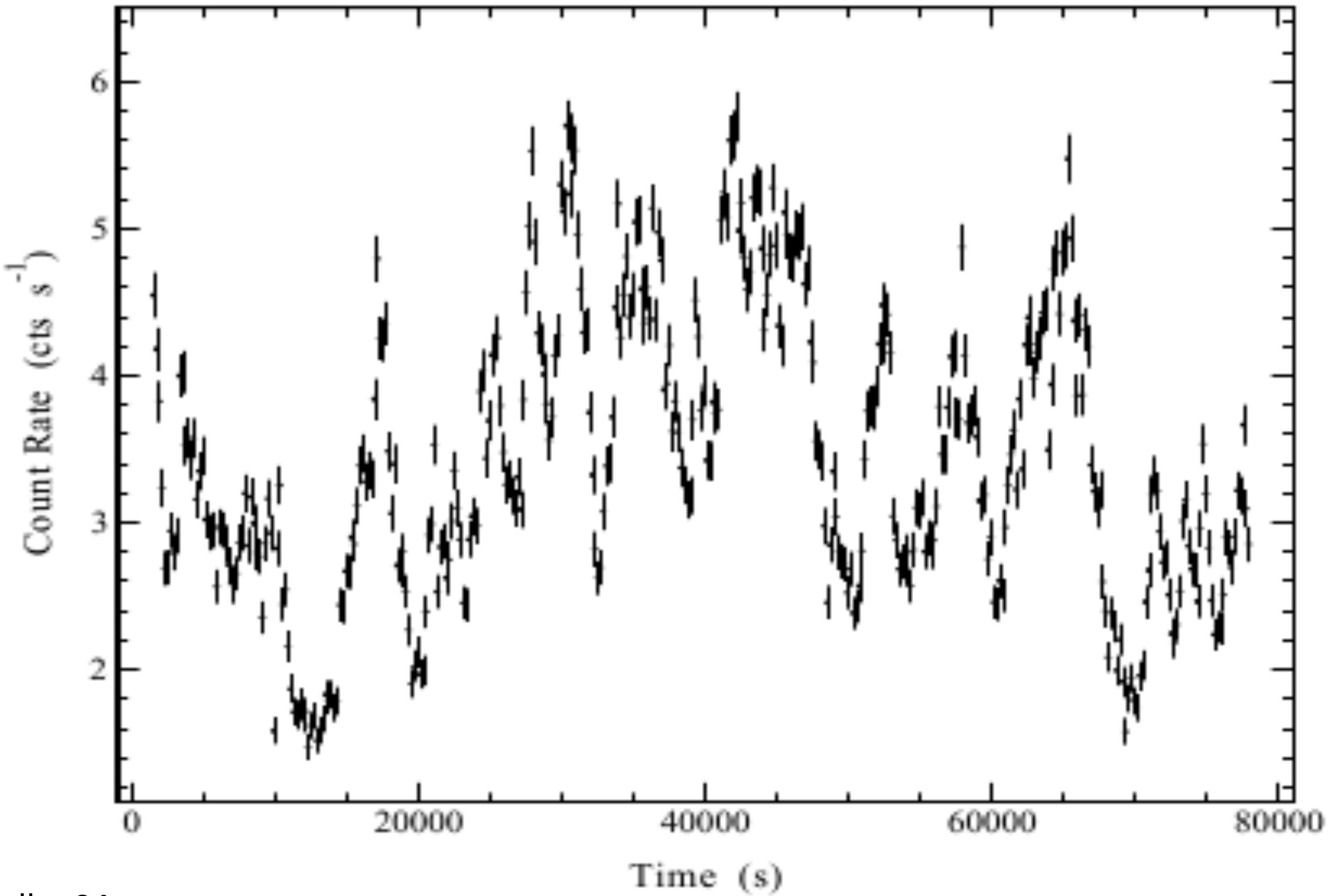
SCHEMATIC SED



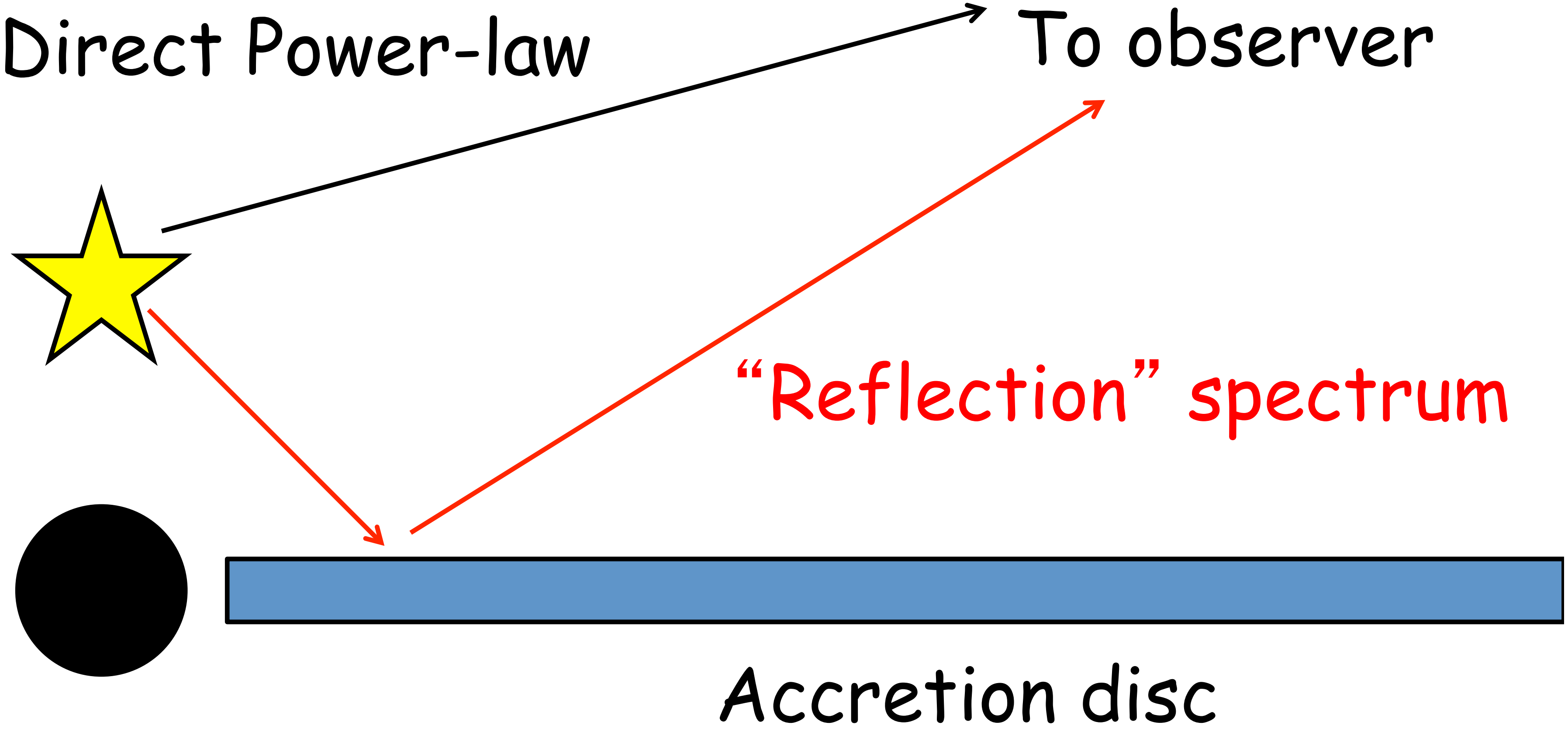


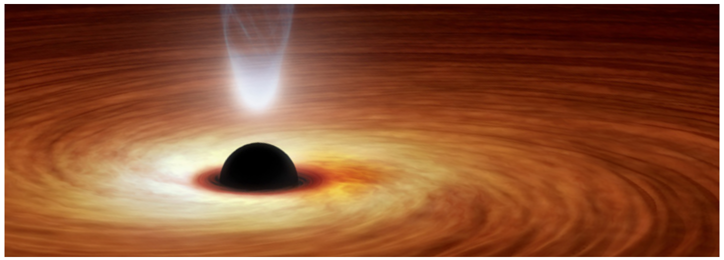
DISK
CORONA
Opt
UV
X−ray
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻⁴
10⁻³
0.01
0.1
1
10
100
1000
Energy (keV)

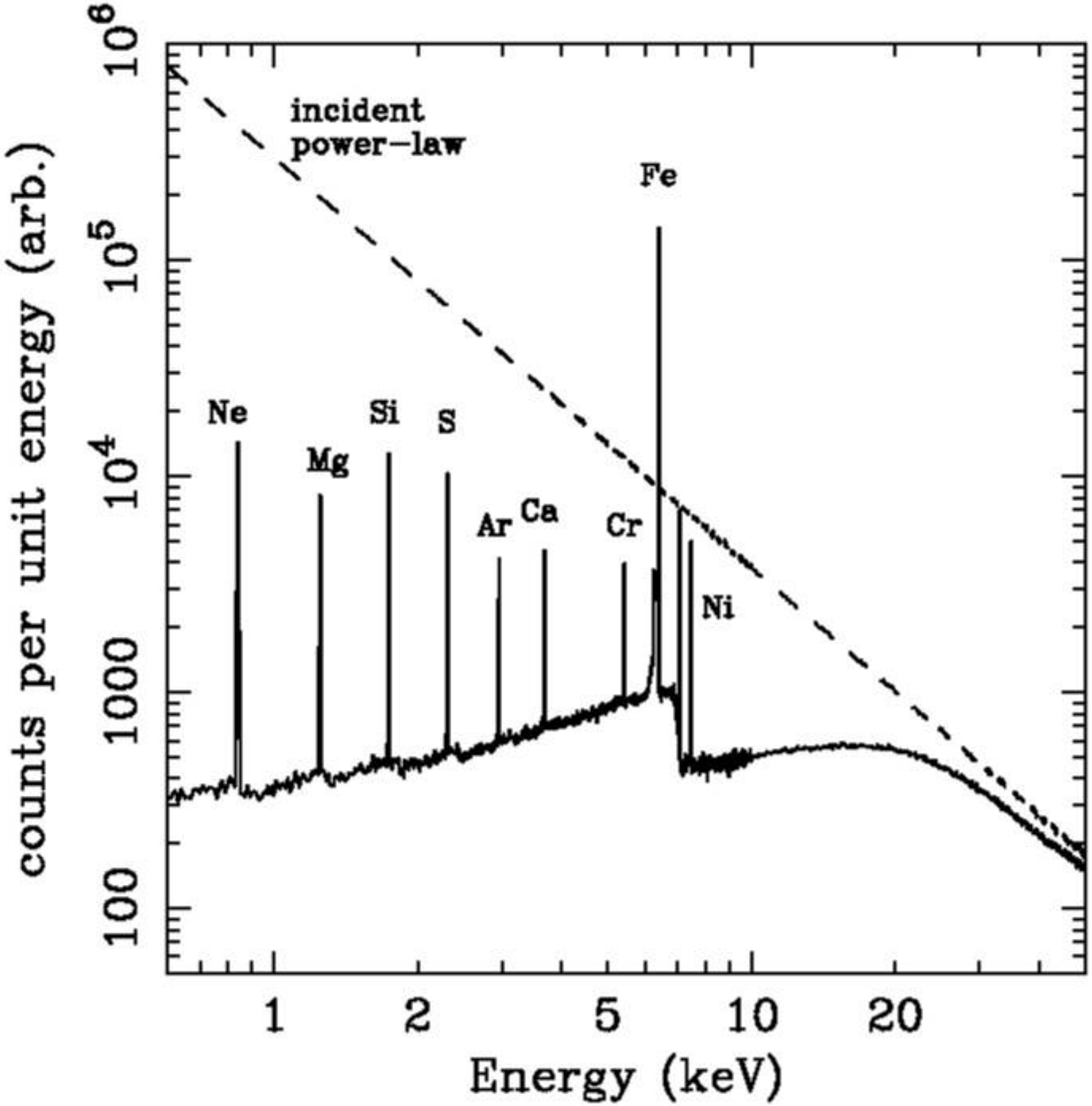
1H0707-495



Gallo+04


Direct Power-law
To observer
"Reflection" spectrum
Accretion disc

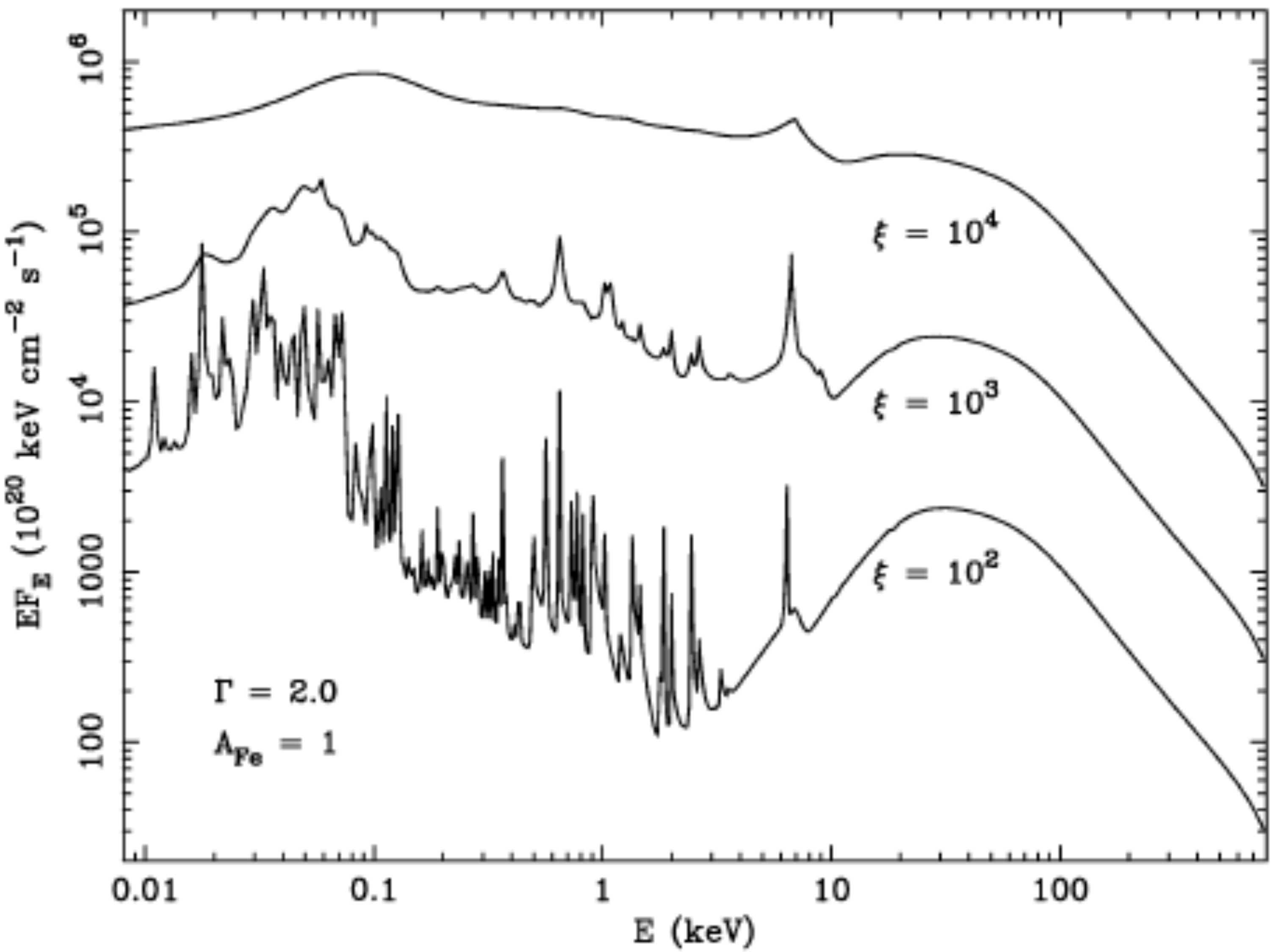




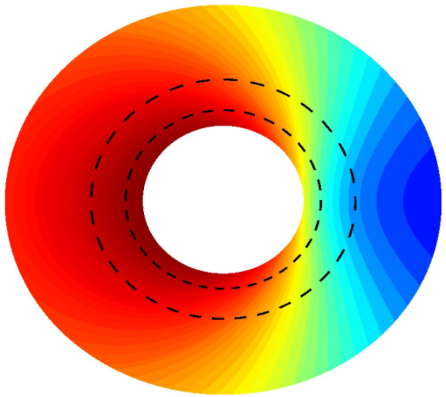
Reflection from cold matter of cosmic abundance

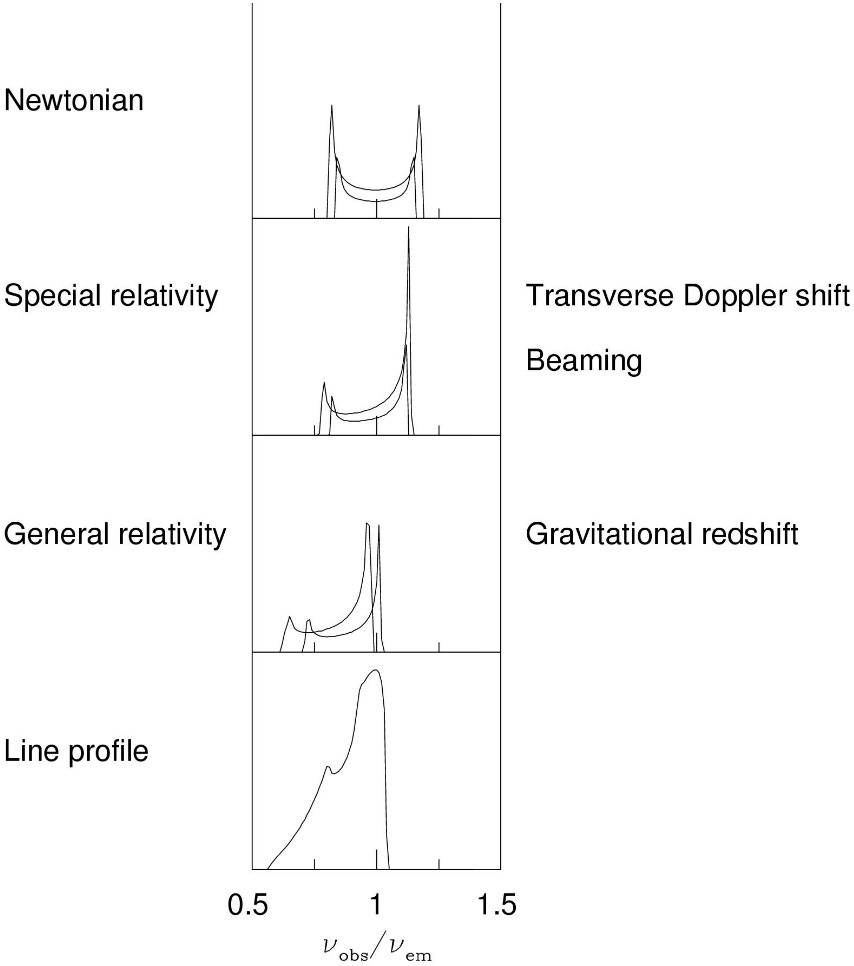
C Reynolds

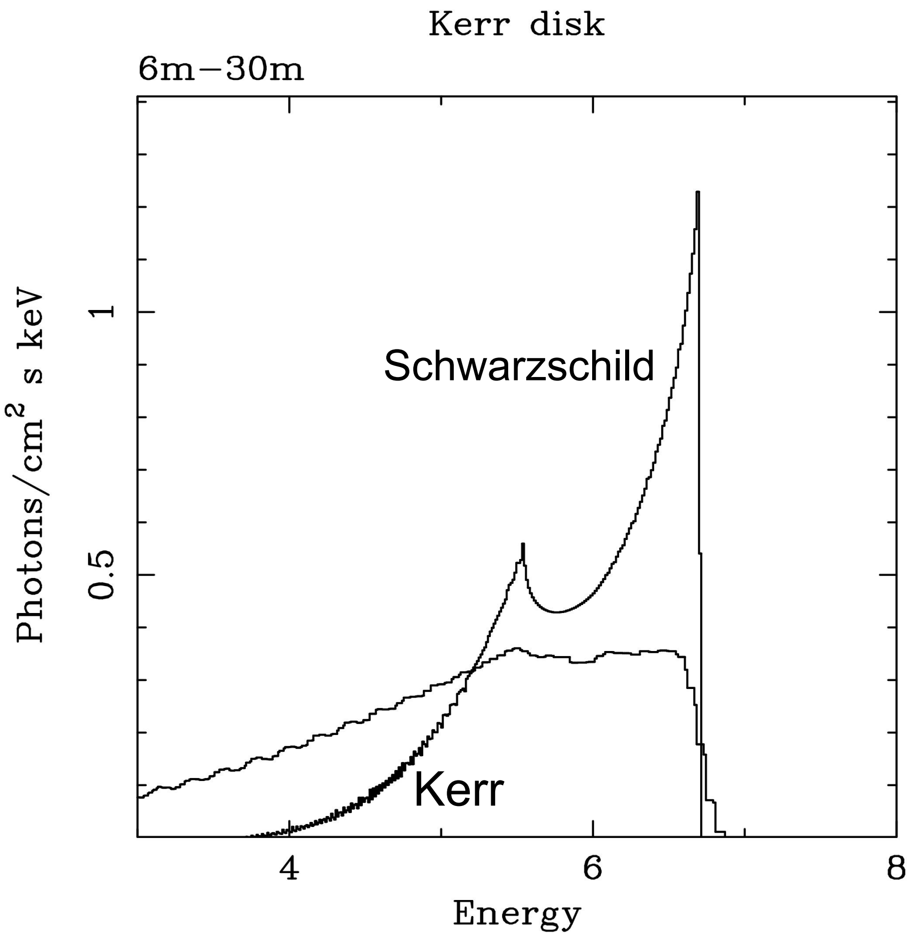
Reflection from ionized gas Ross+Fabian05; Garcia+13



Relativistically Broadened Line



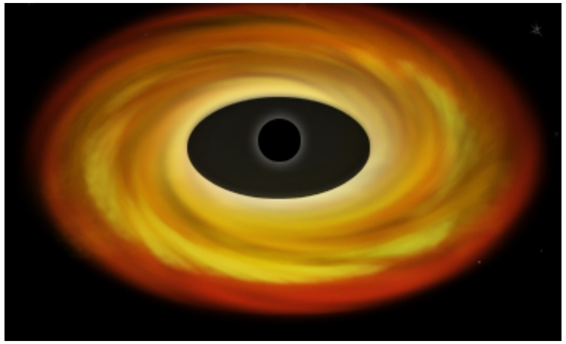


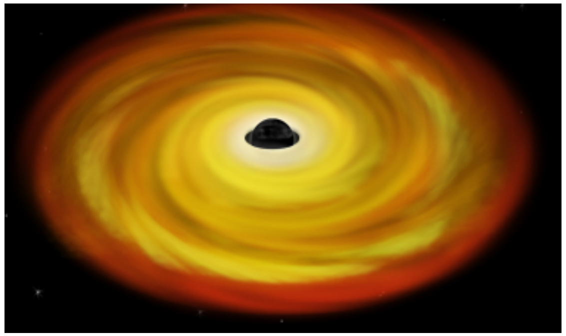


Fabian+89, Laor 90…

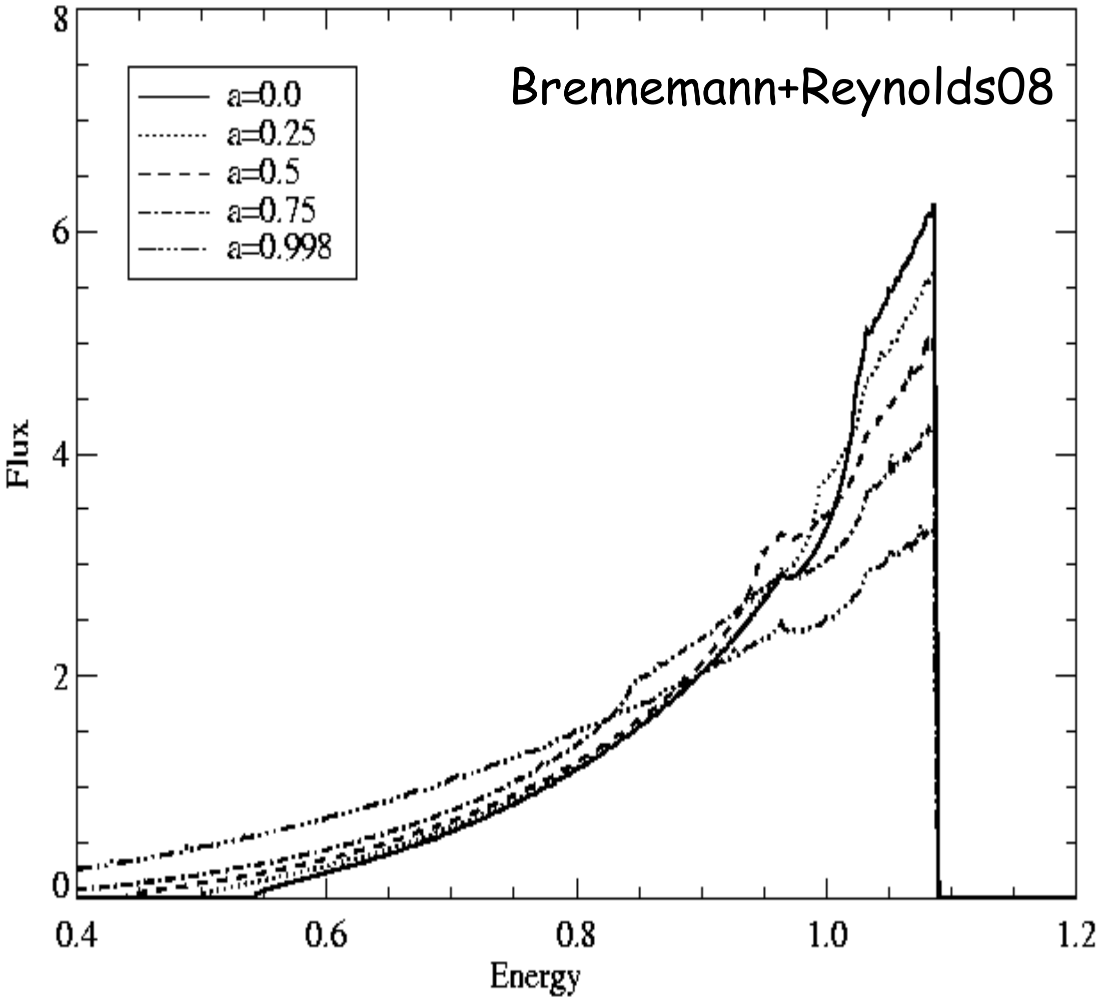
Probing Black Hole Spin

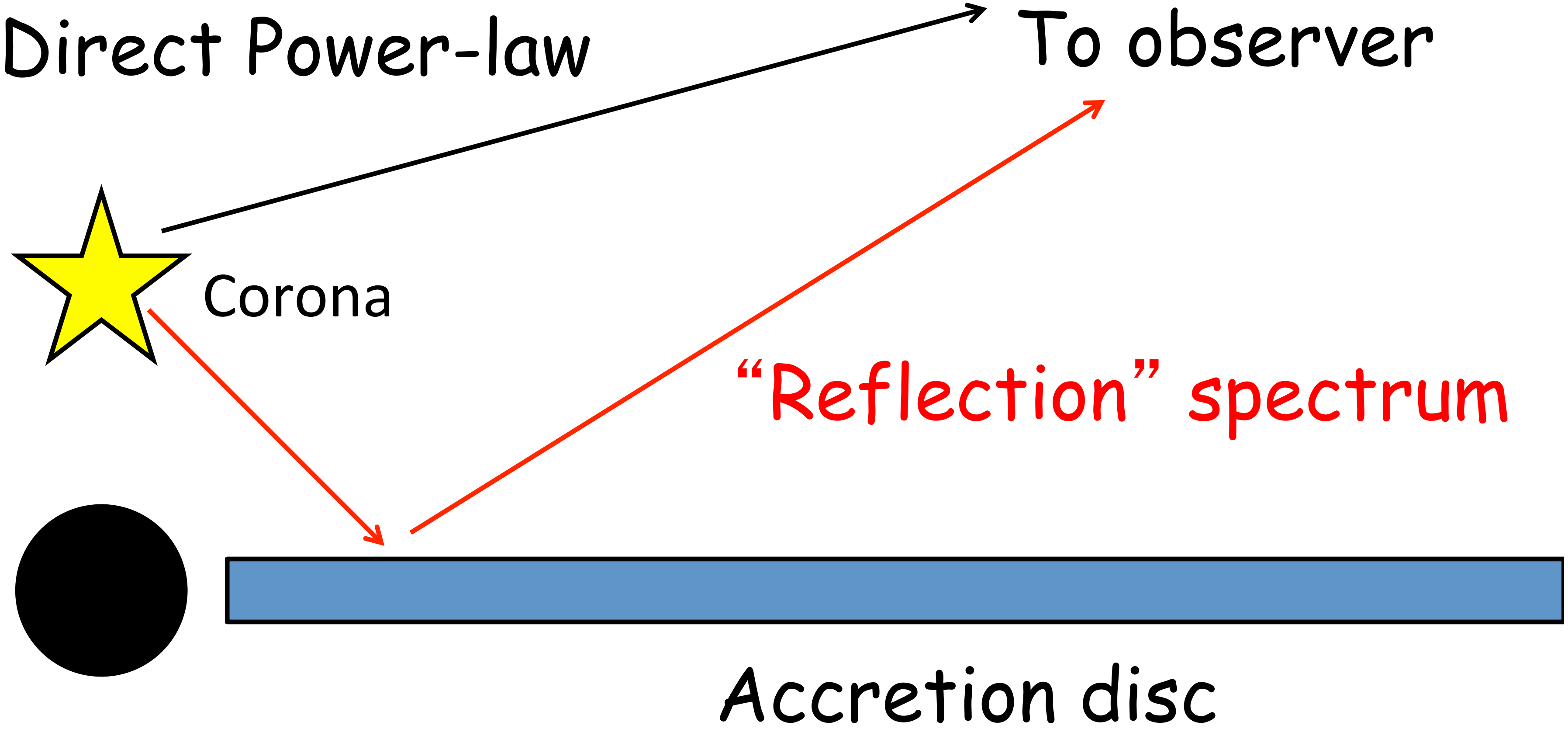
No spin

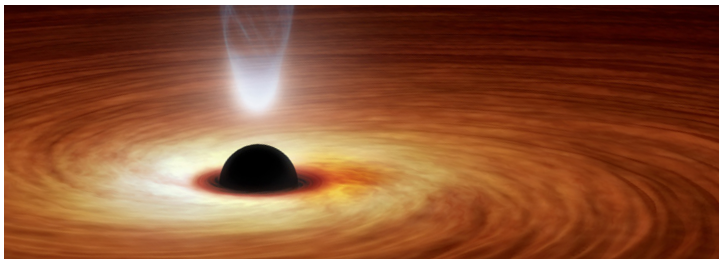


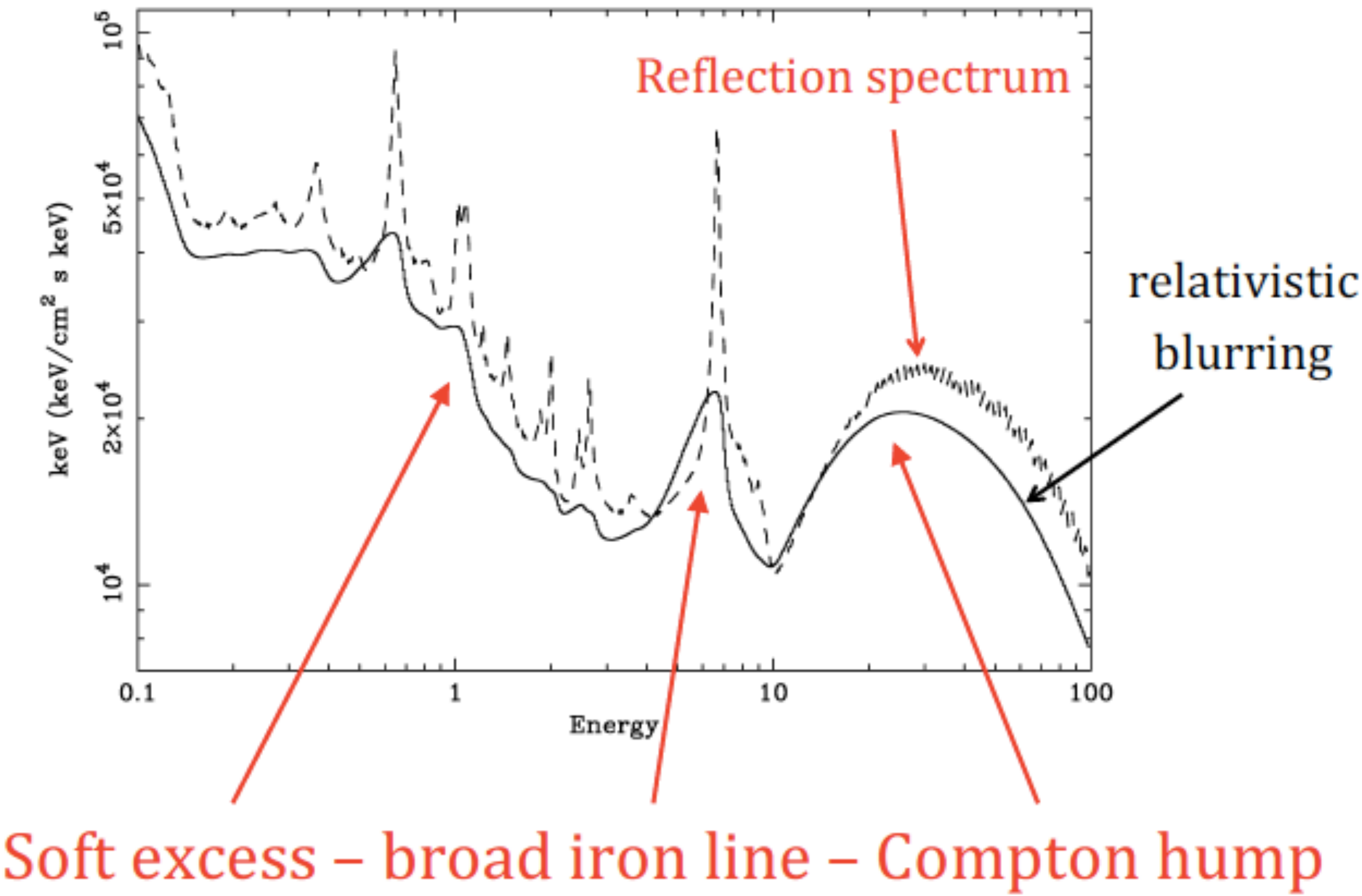


Max spin

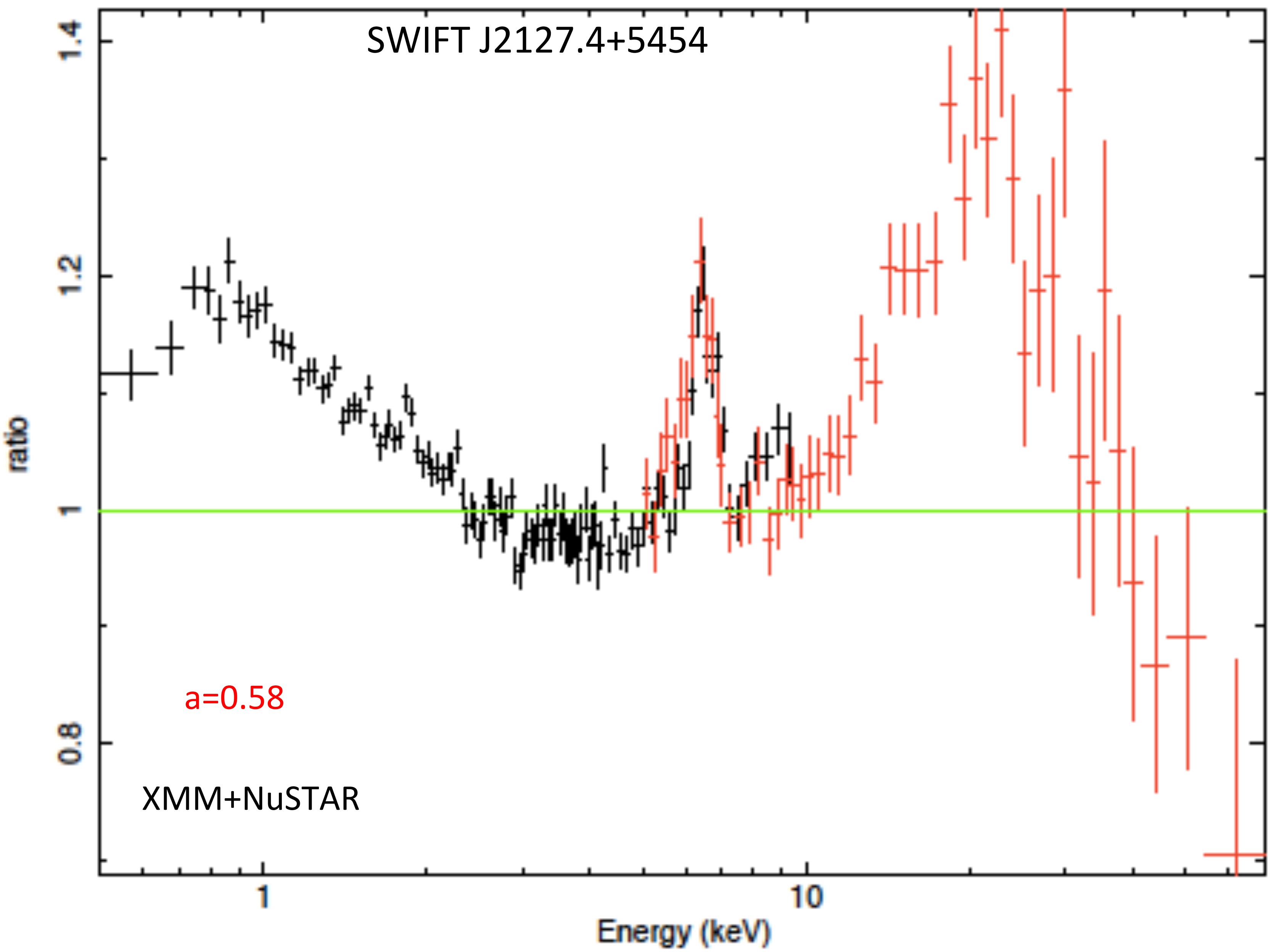



Direct Power-law
To observer
Corona
“Reflection” spectrum
Accretion disc

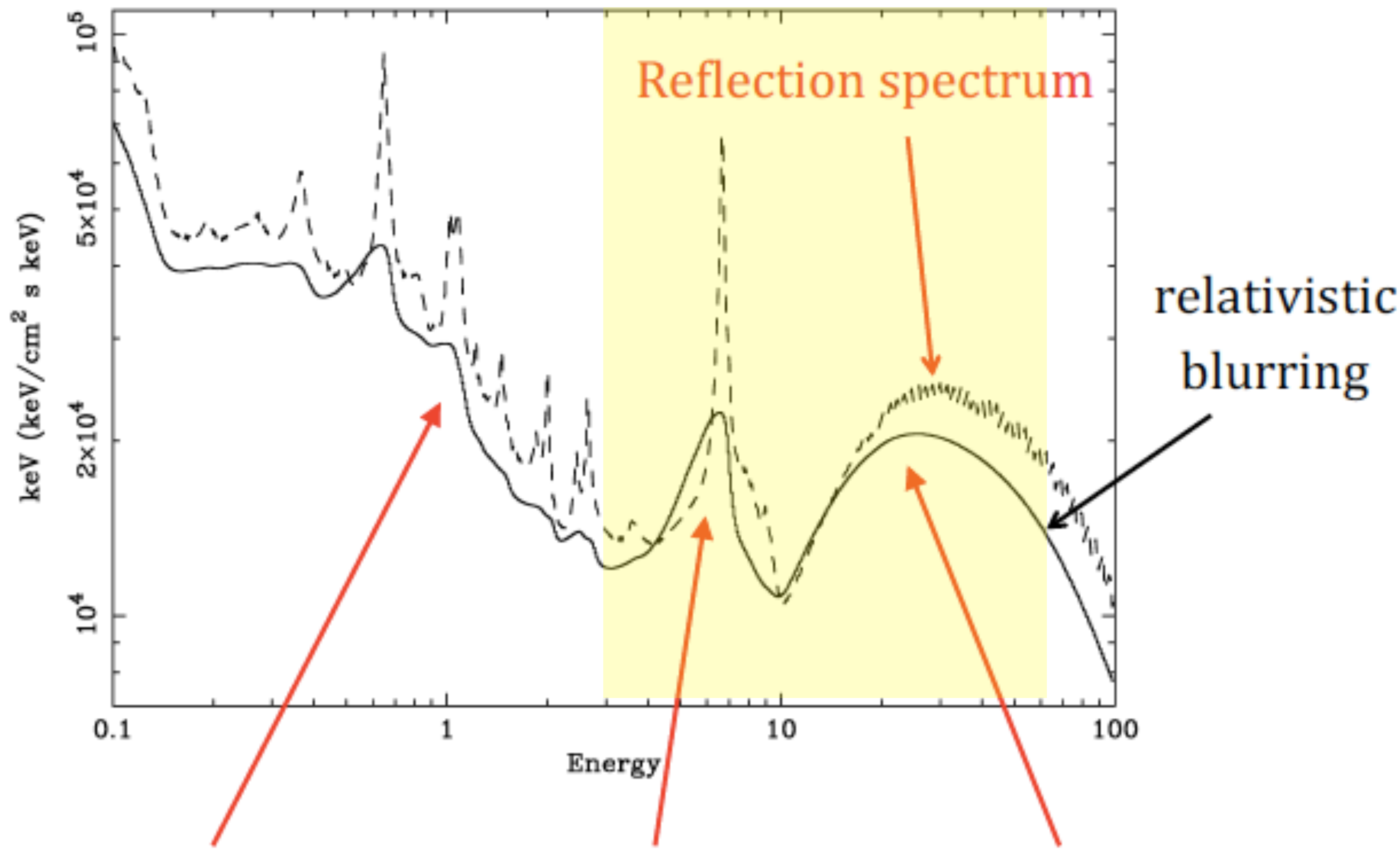




Reflection spectrum
relativistic
blurring
keV (keV/cm^2 s keV)
10^5
5×10^4
2×10^4
10^4
0.1
1
10
100
Energy
Soft excess – broad iron line – Compton hump

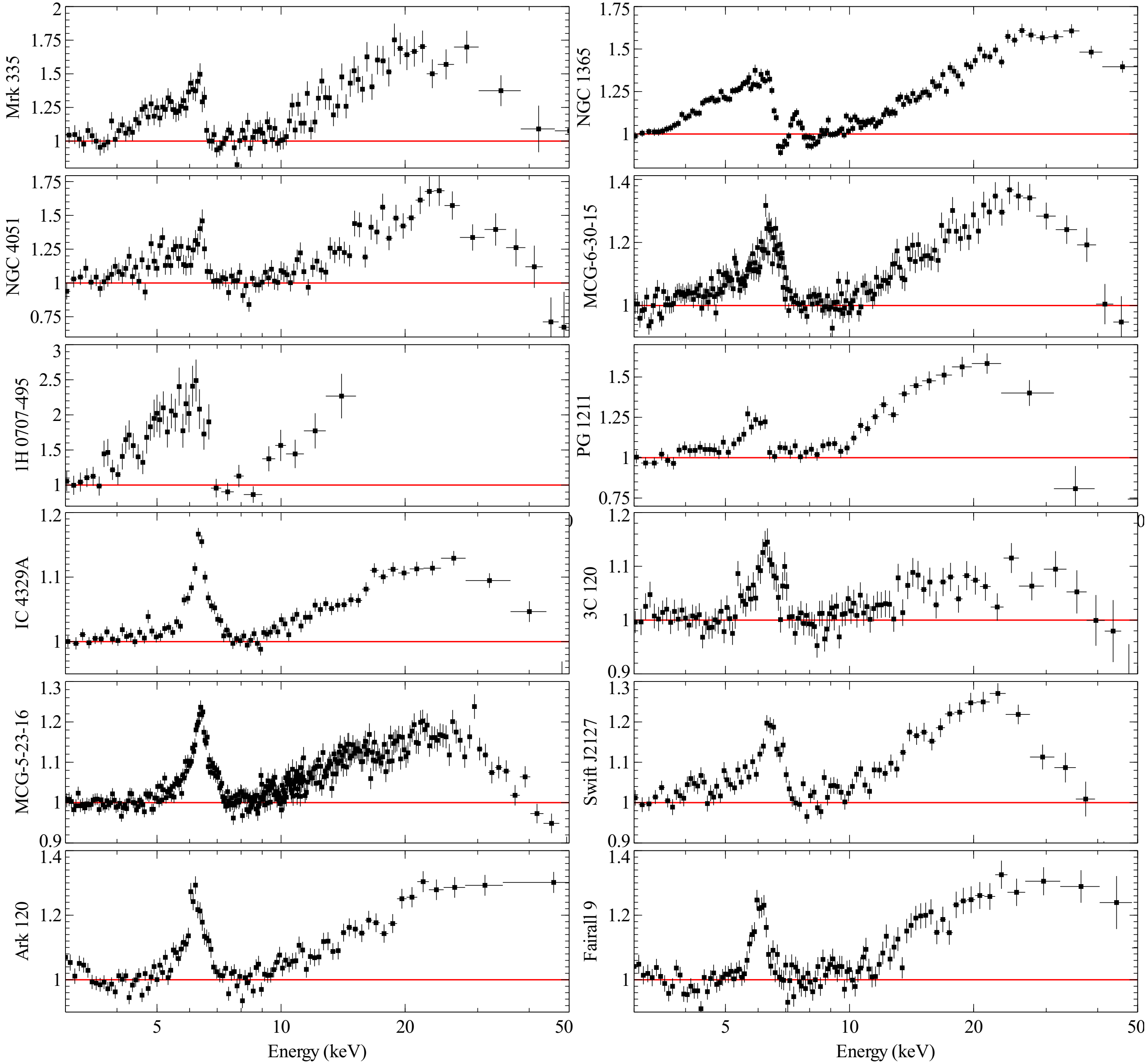


Marinucci+14



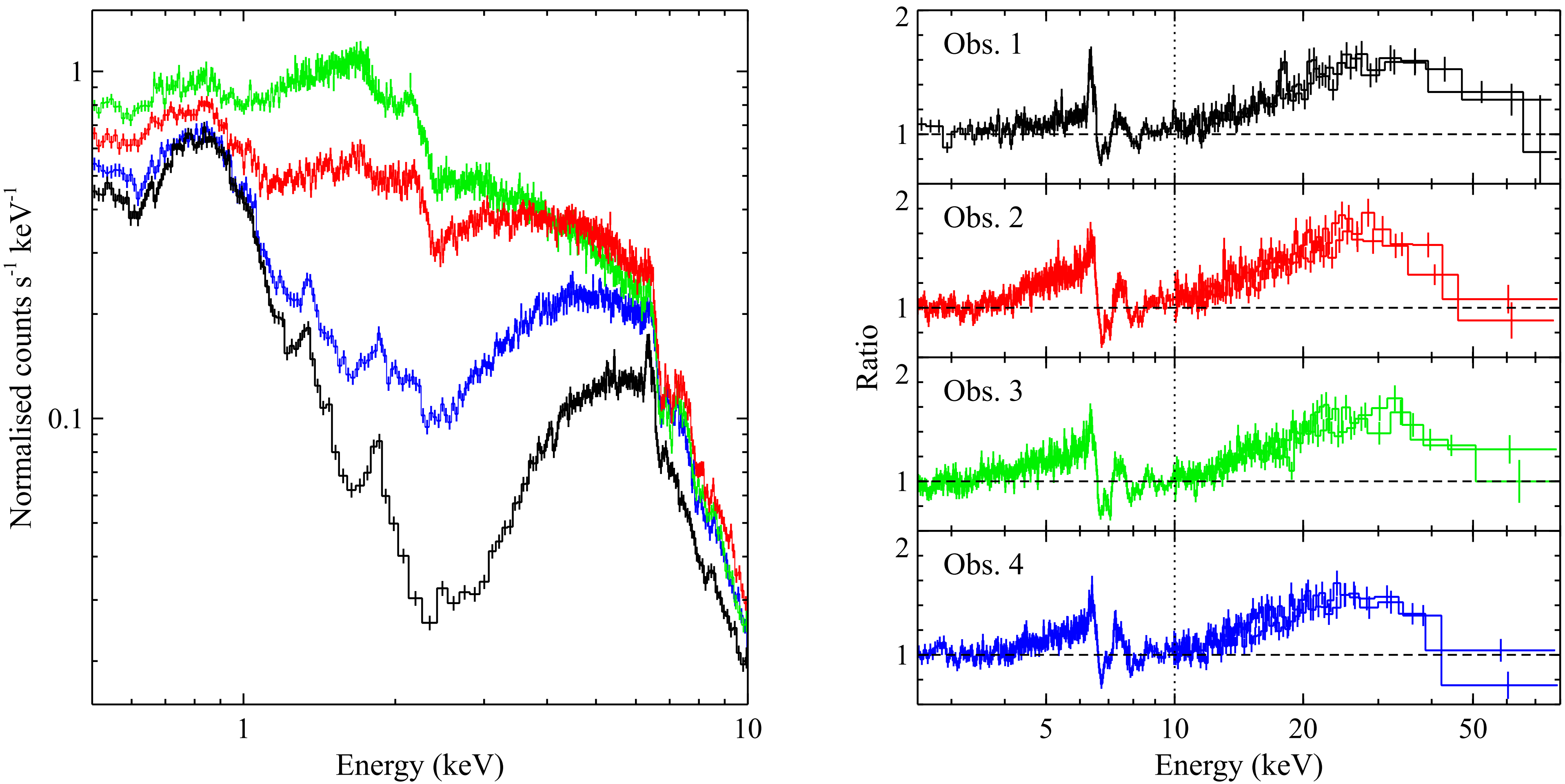
Soft excess – broad iron line – Compton hump

Reflection in AGN with NuSTAR



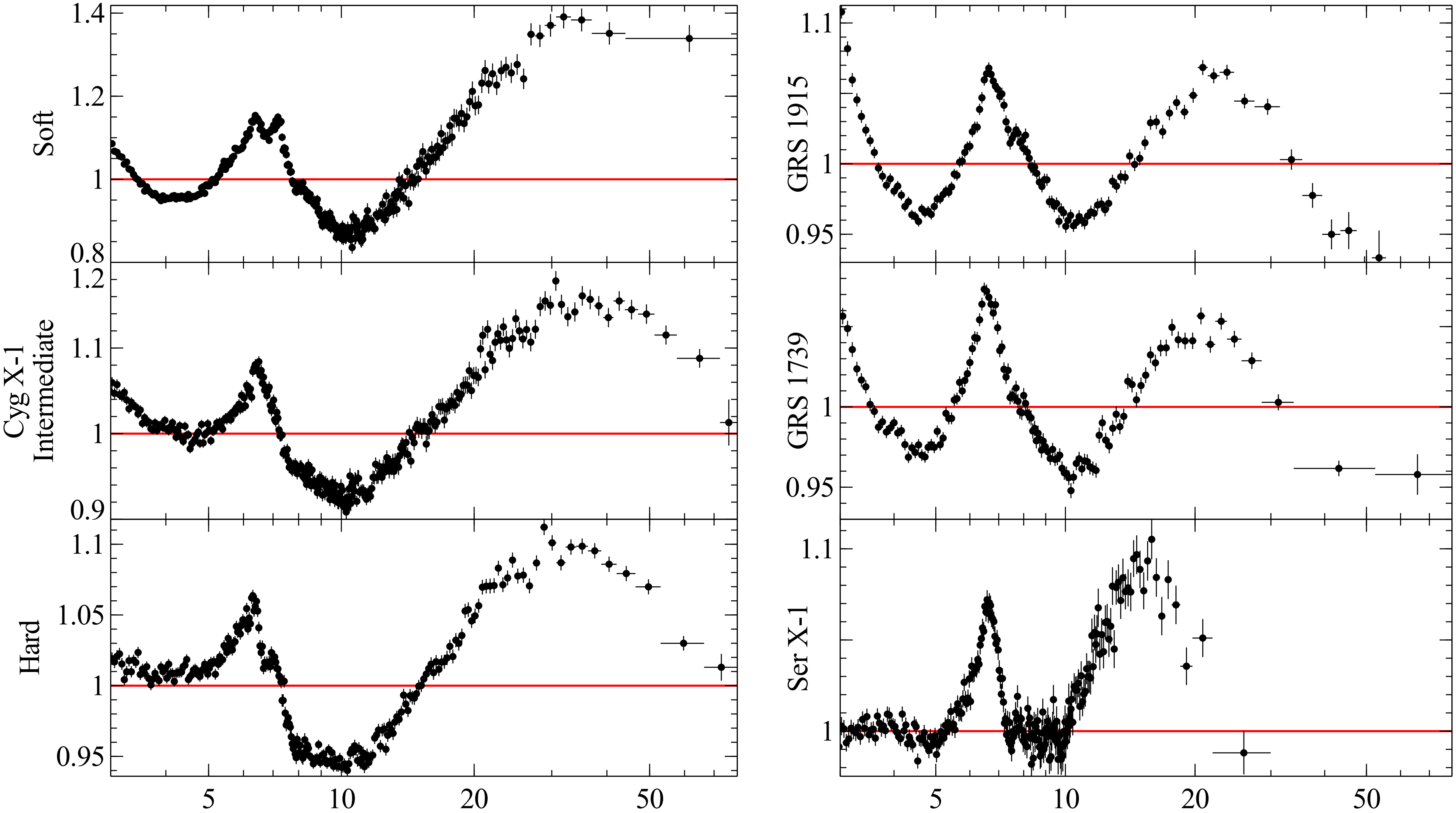
Parker, Matt+

NGC1365 XMM+NuSTAR



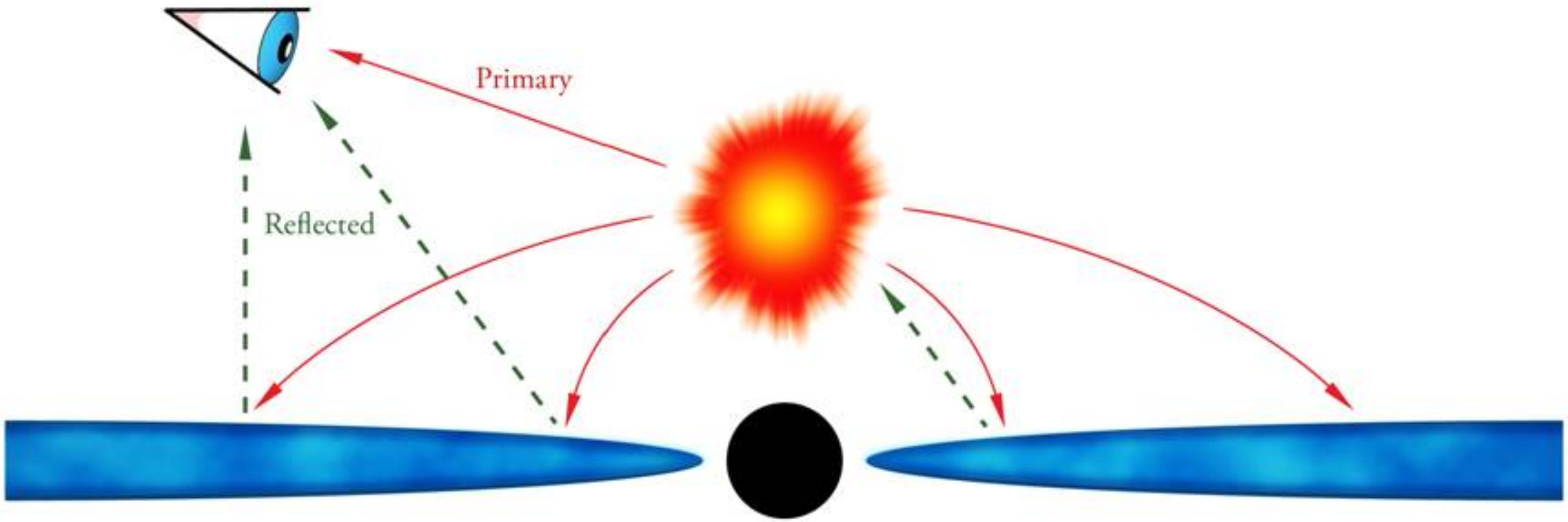
Walton+14

and Galactic sources too



Parker, Tomsick+, JMiller+13,15

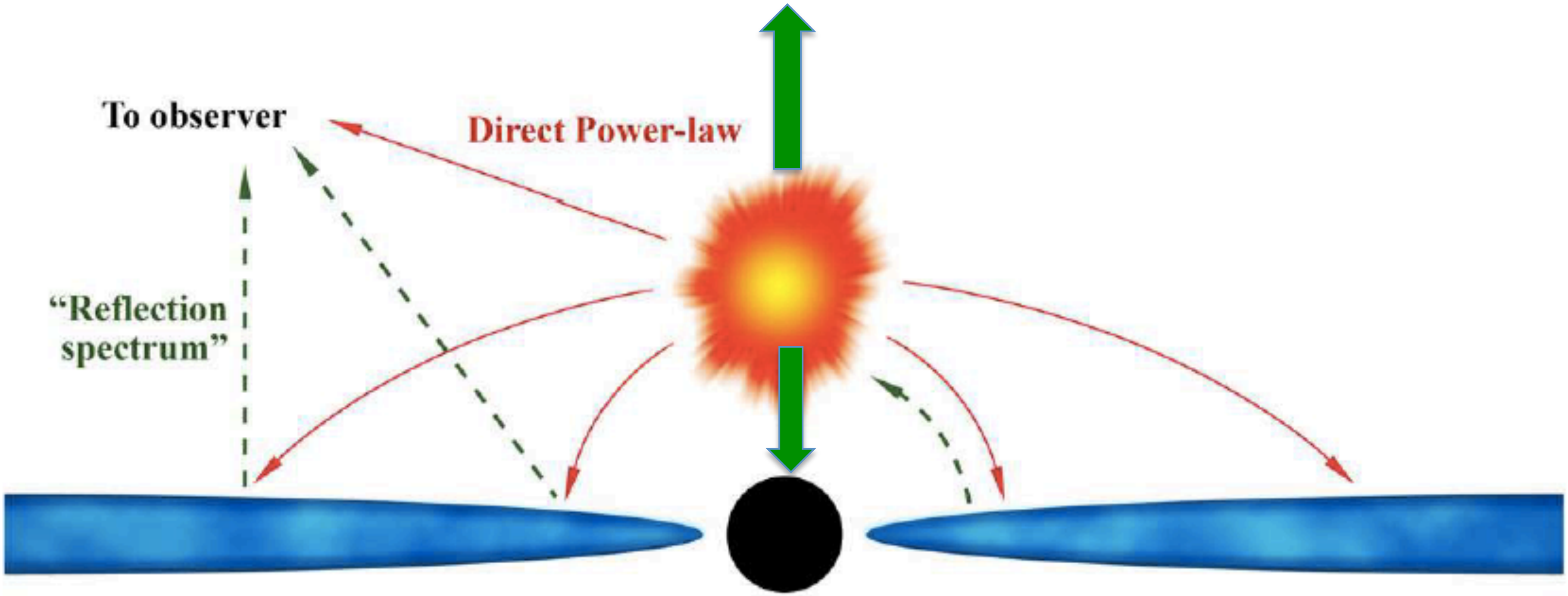
Strong light bending close to BH

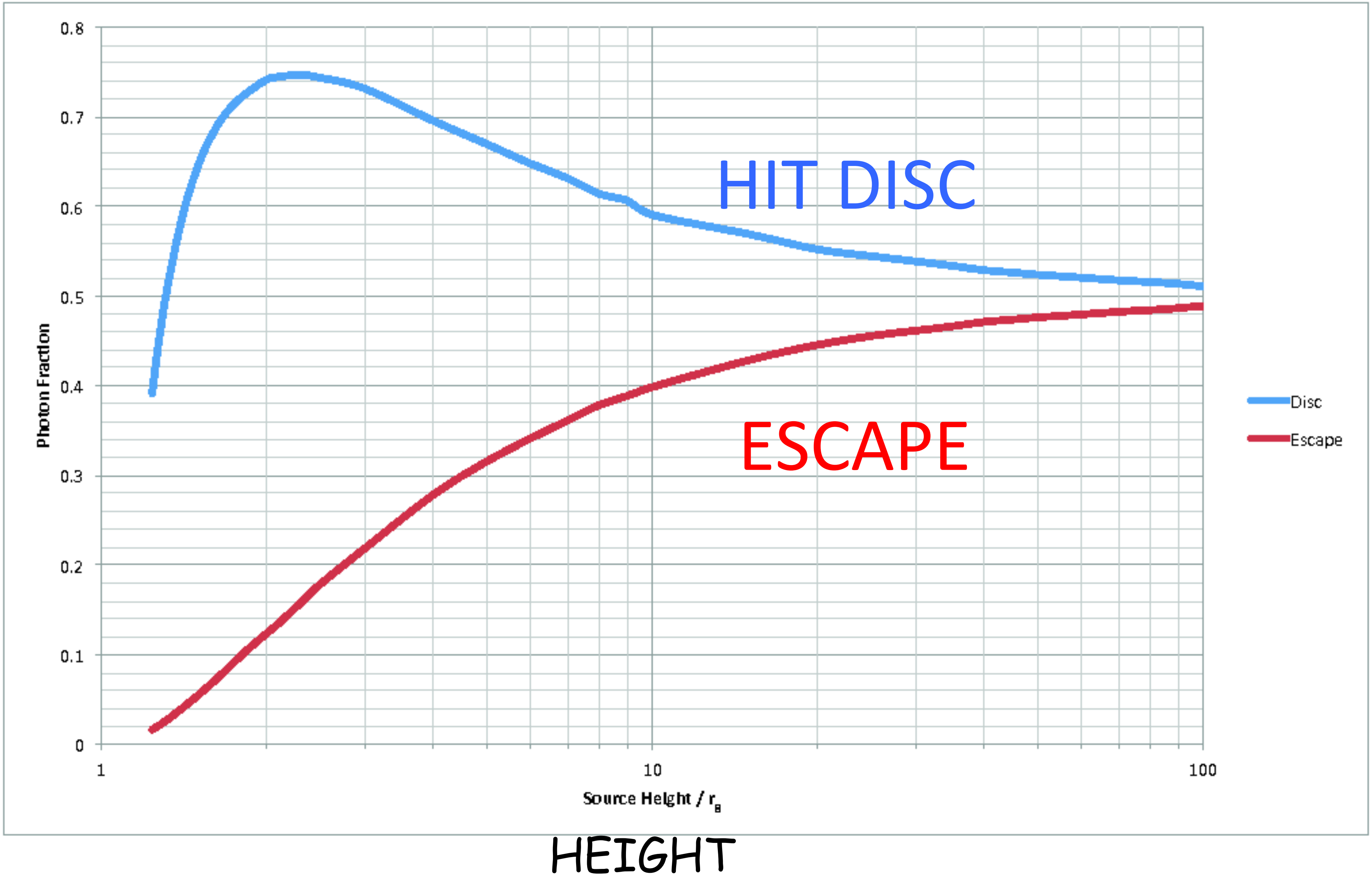


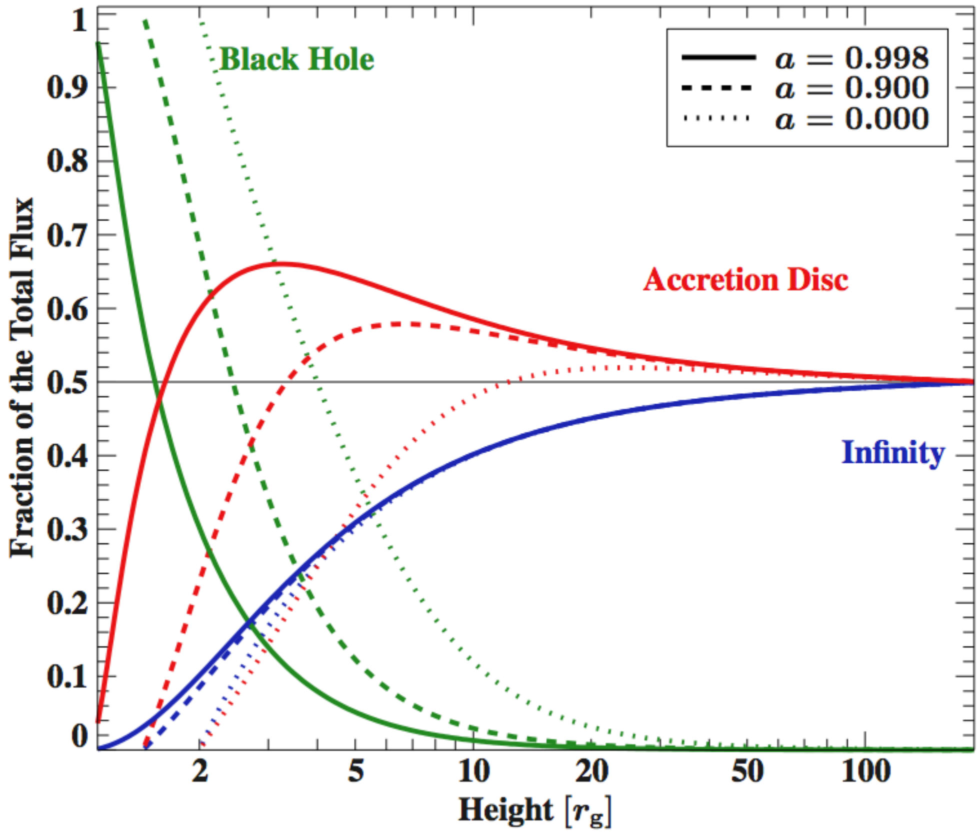
Martocchia&Matt, Miniutti&Fabian

GR + lightbending make emissivity steep

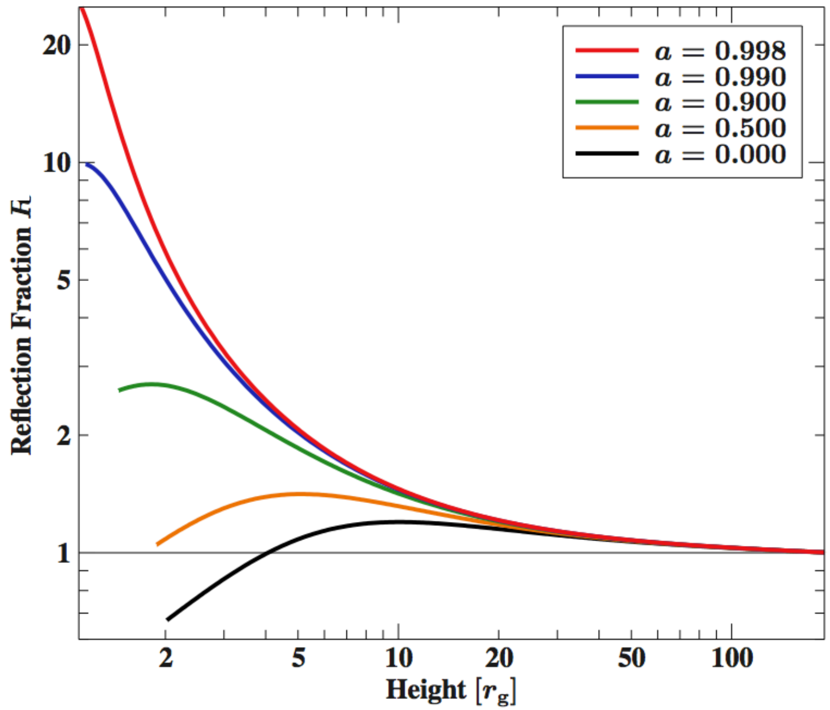
Change in height of corona - more or less light bending




HIT DISC
ESCAPE
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
100
Photon Fraction
Source Height / r_g
Disc
Escape
HEIGHT

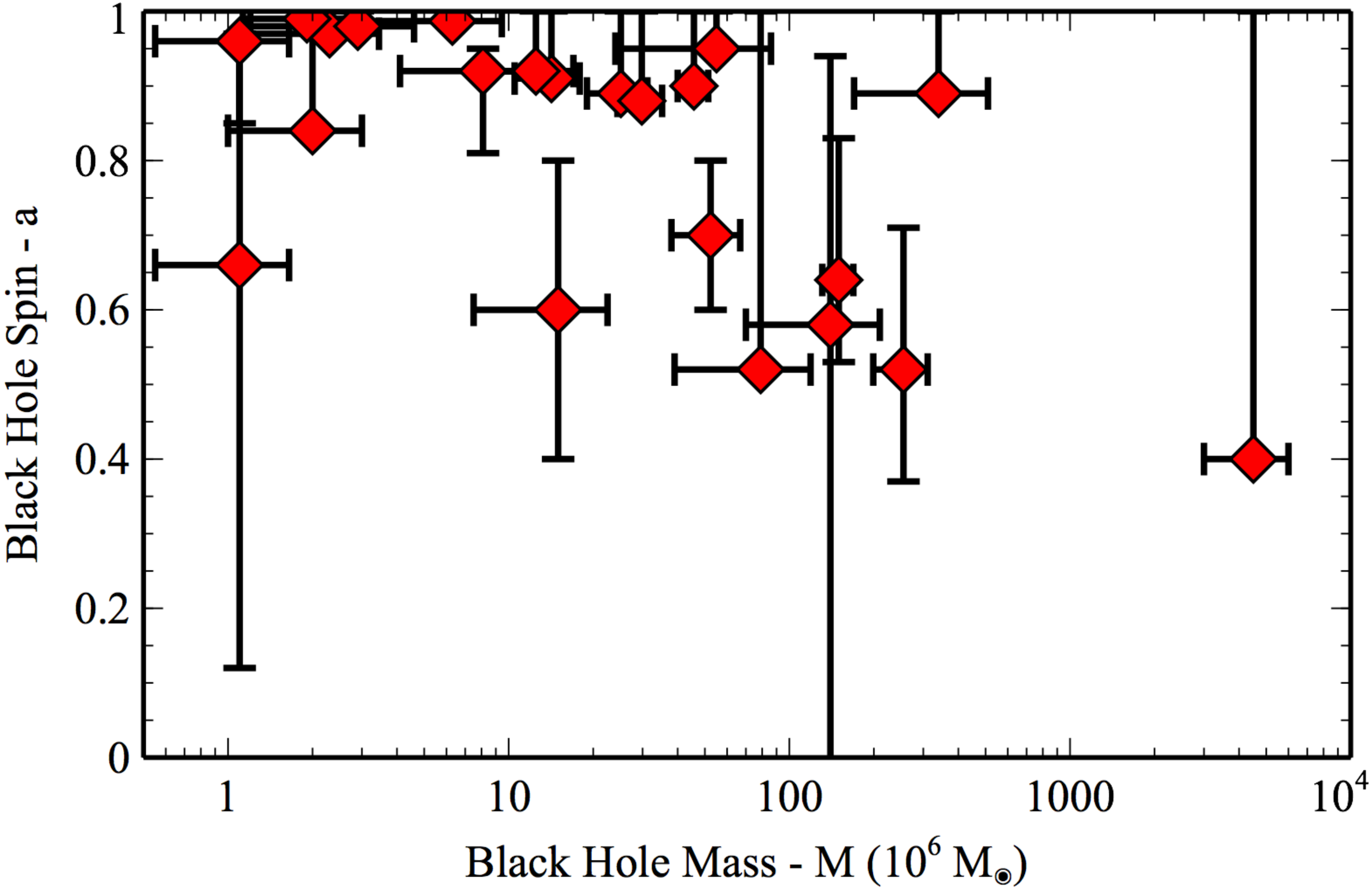


High Reflection Fractions
= Strong Light Bending

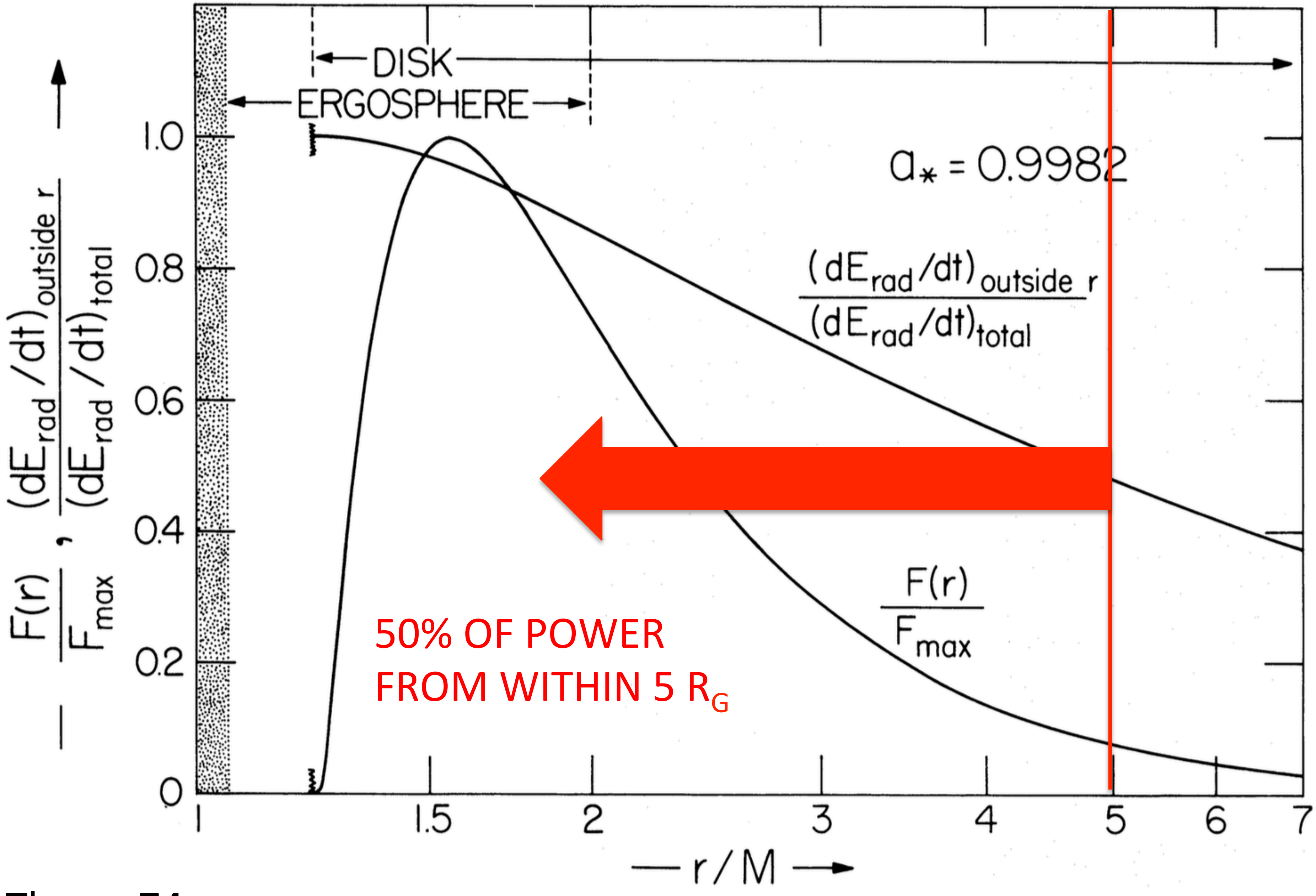


Dauser+14

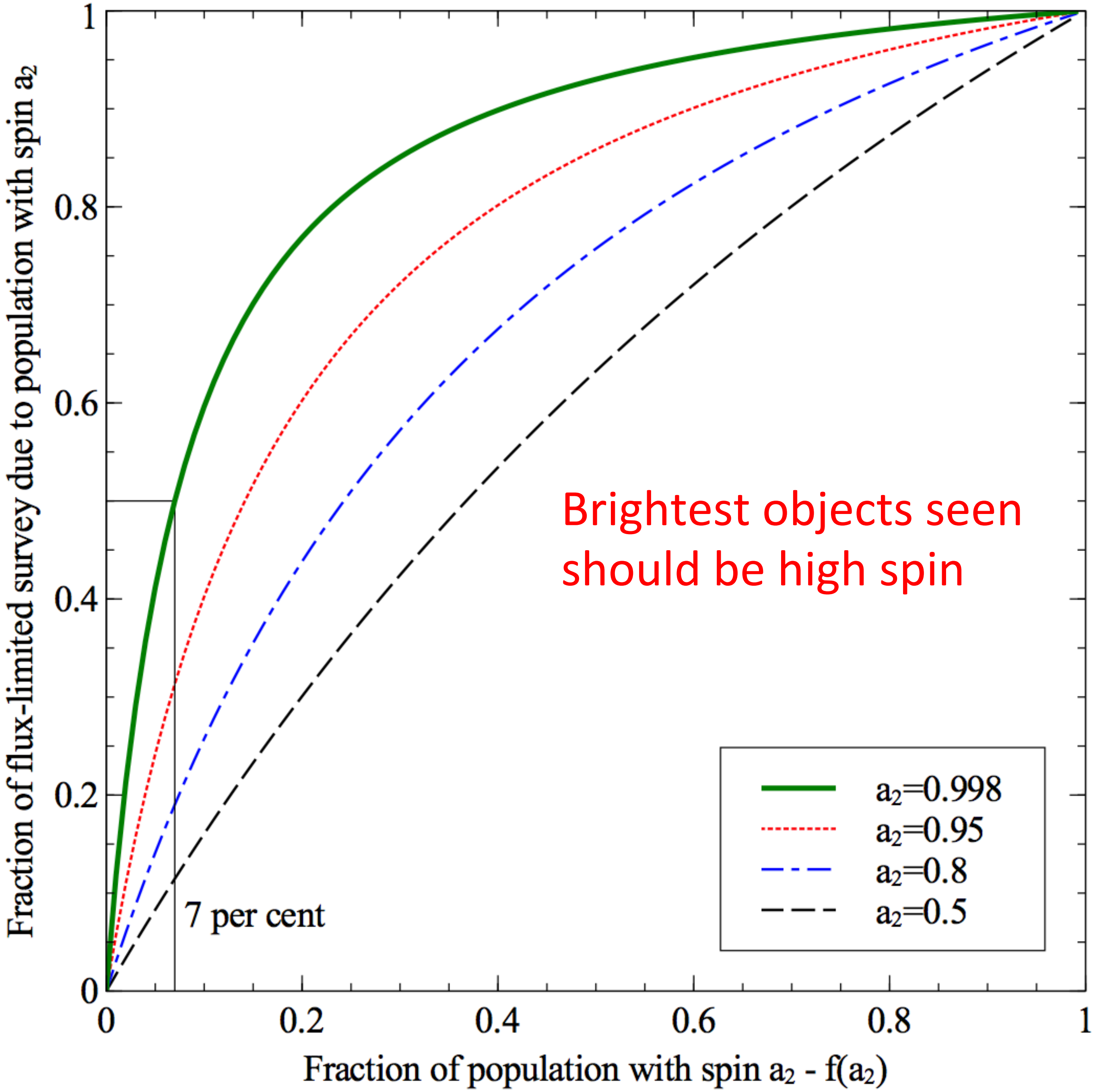
Black Hole Spin from Reflection Spectrum



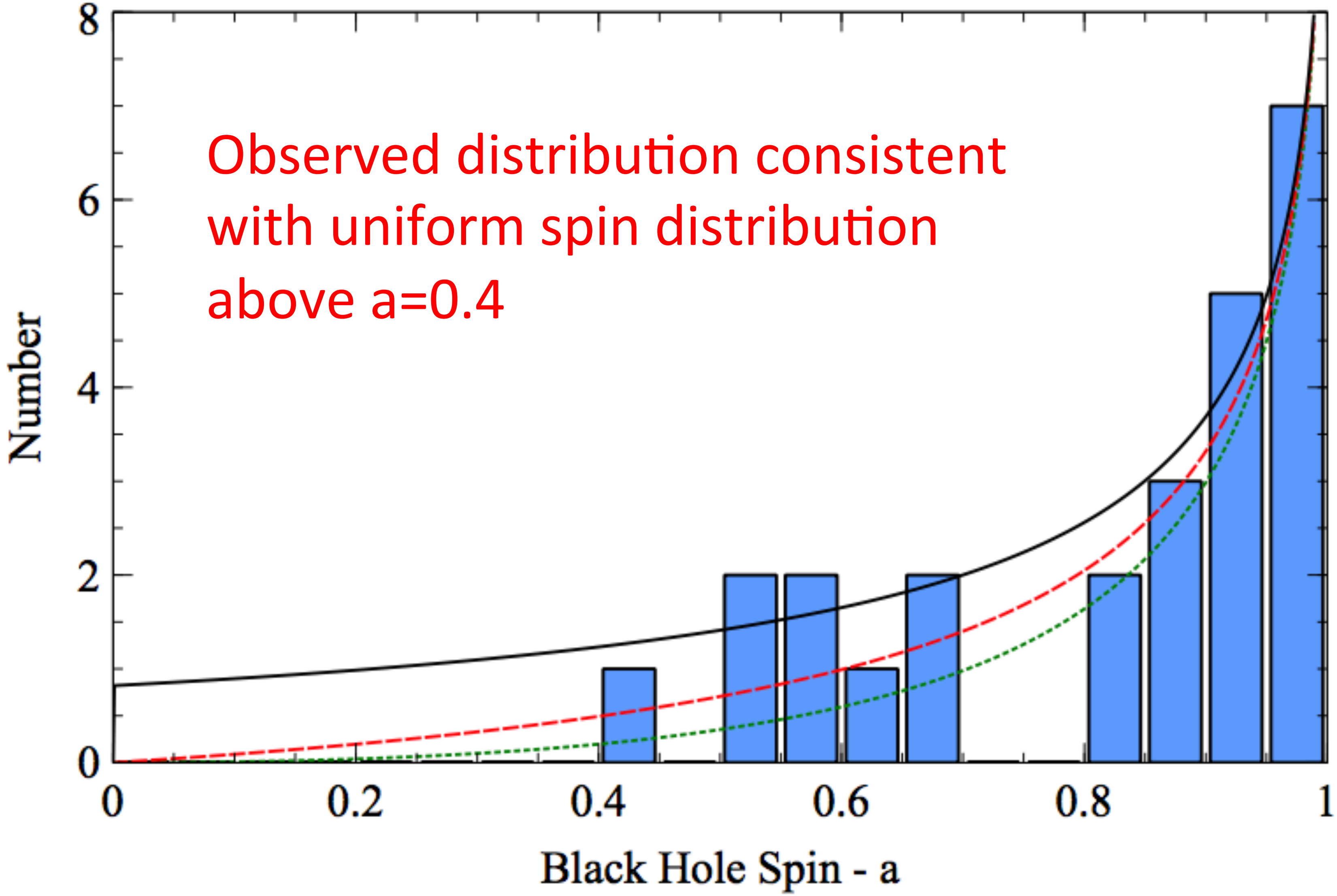
Reynolds14, Vasudevan+15


DISK
ERGOSPHERE
$a_* = 0.9982$
$\frac{(dE_{rad}/dt)_{outside\ r}}{(dE_{rad}/dt)_{total}}$
$\frac{F(r)}{F_{max}}$
$\frac{F(r)}{F_{max}}, \frac{(dE_{rad}/dt)_{outside\ r}}{(dE_{rad}/dt)_{total}}$
1.0
0.8
0.6
0.4
0.2
0
1
1.5
2
3
4
5
6
7
r / M
50% OF POWER
FROM WITHIN 5 R_G

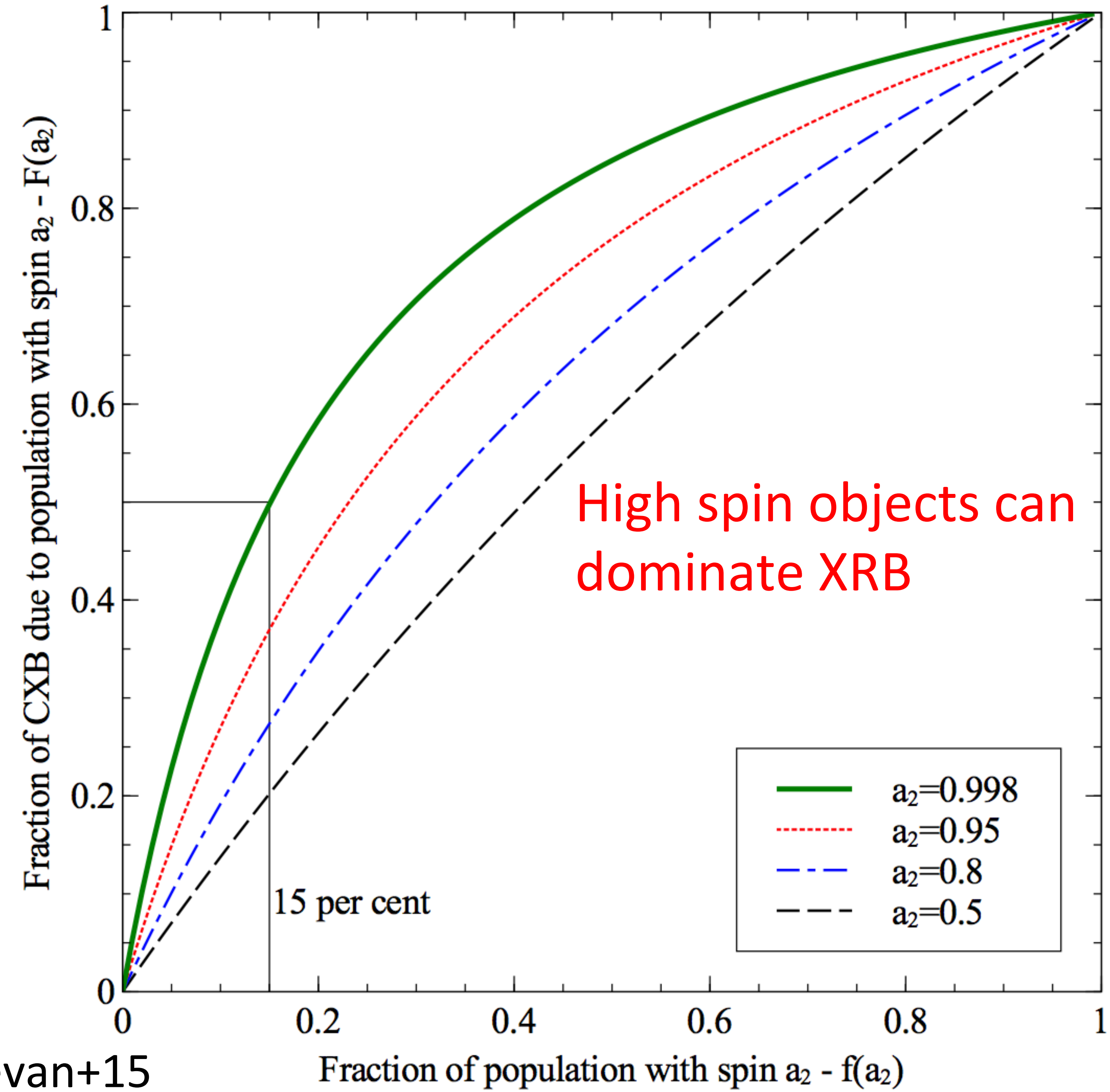
Thorne74



Fraction of flux-limited survey due to population with spin a2
Fraction of population with spin a2 - f(a2)
0
0.2
0.4
0.6
0.8
1
7 per cent
a2=0.998
a2=0.95
a2=0.8
a2=0.5
Brightest objects seen
should be high spin



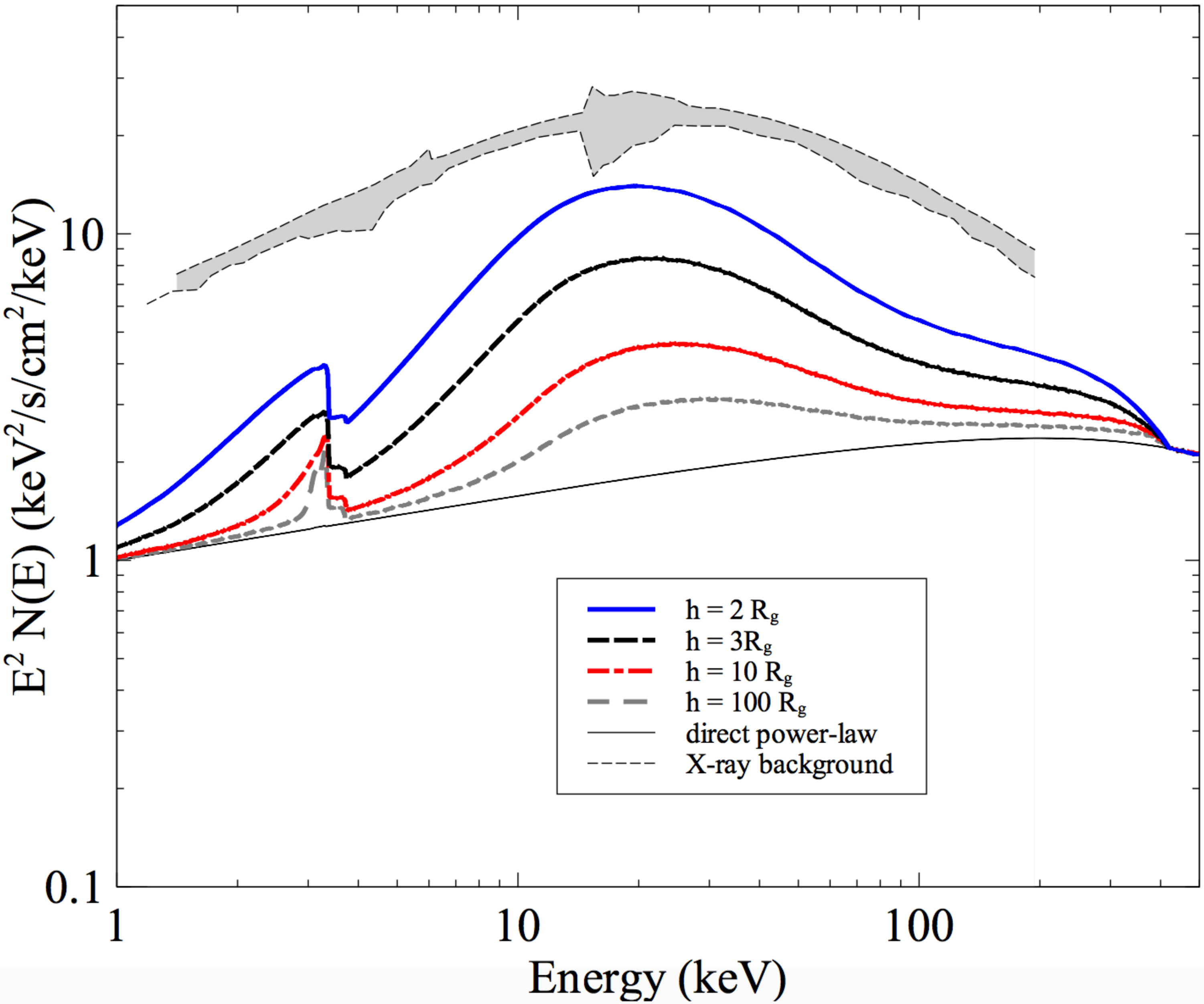
Observed distribution consistent
with uniform spin distribution
above a=0.4
Number
Black Hole Spin - a
0
2
4
6
8
0
0.2
0.4
0.6
0.8
1

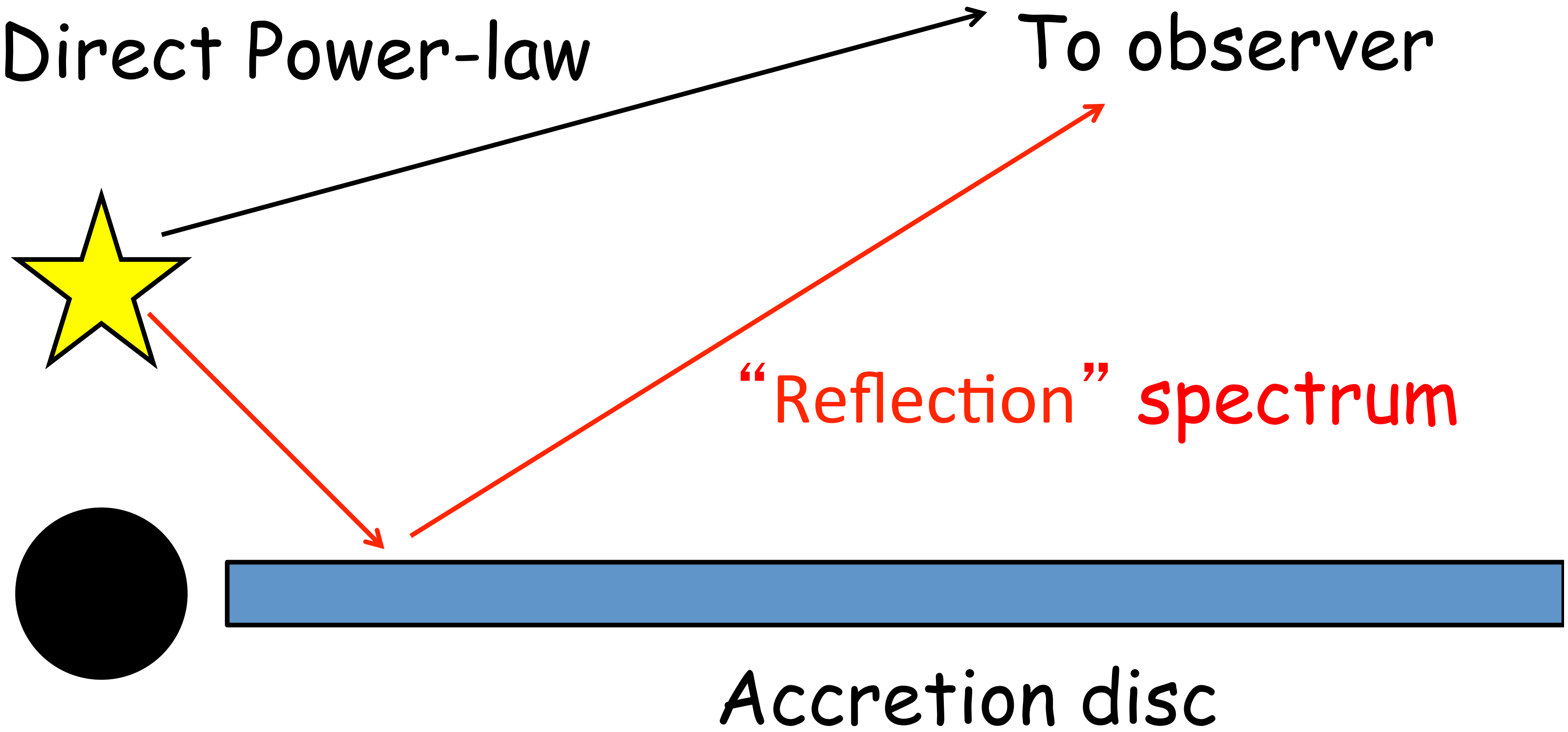


High spin objects can dominate XRB

Vasudevan+15

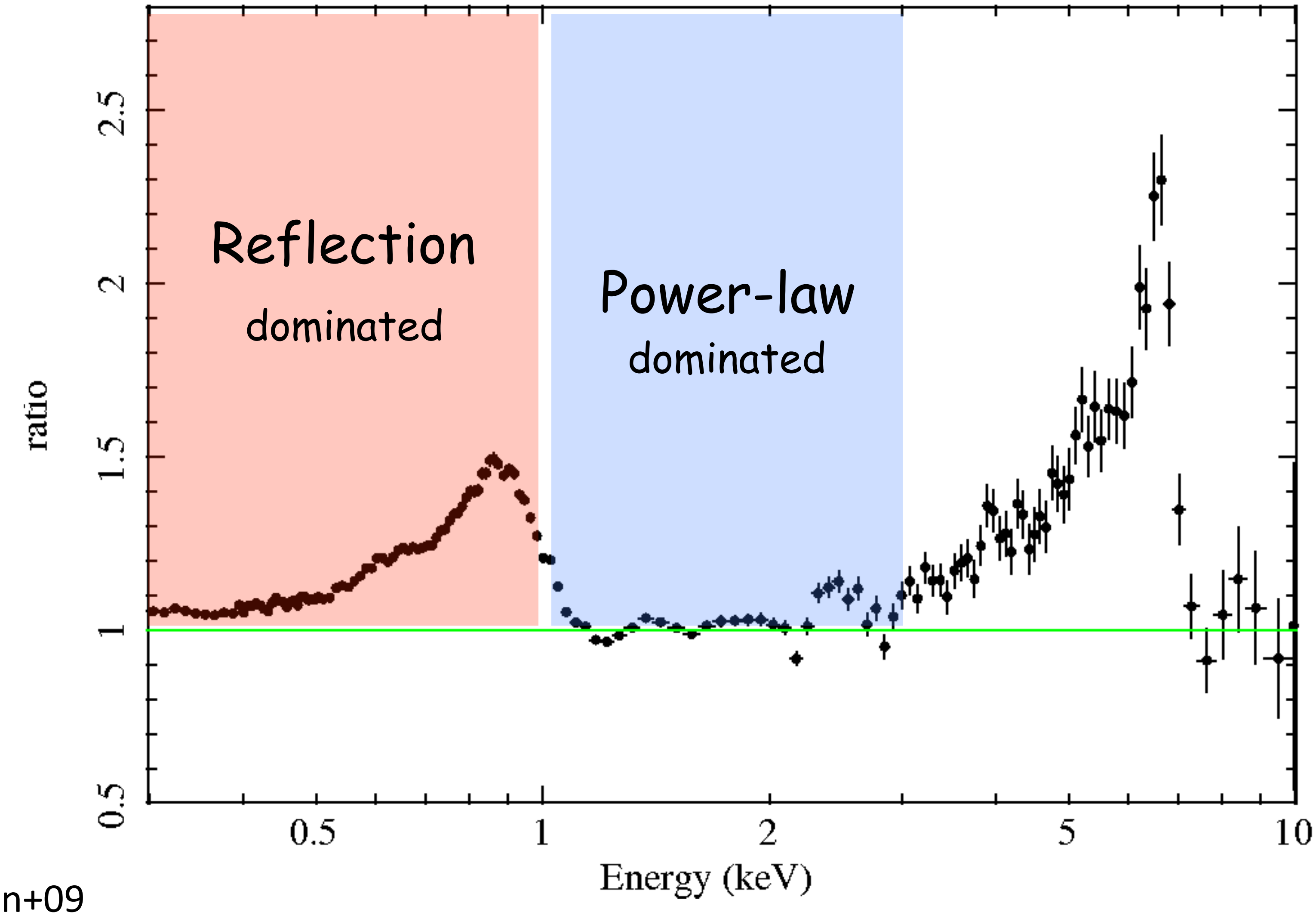
X-ray Background Spectrum



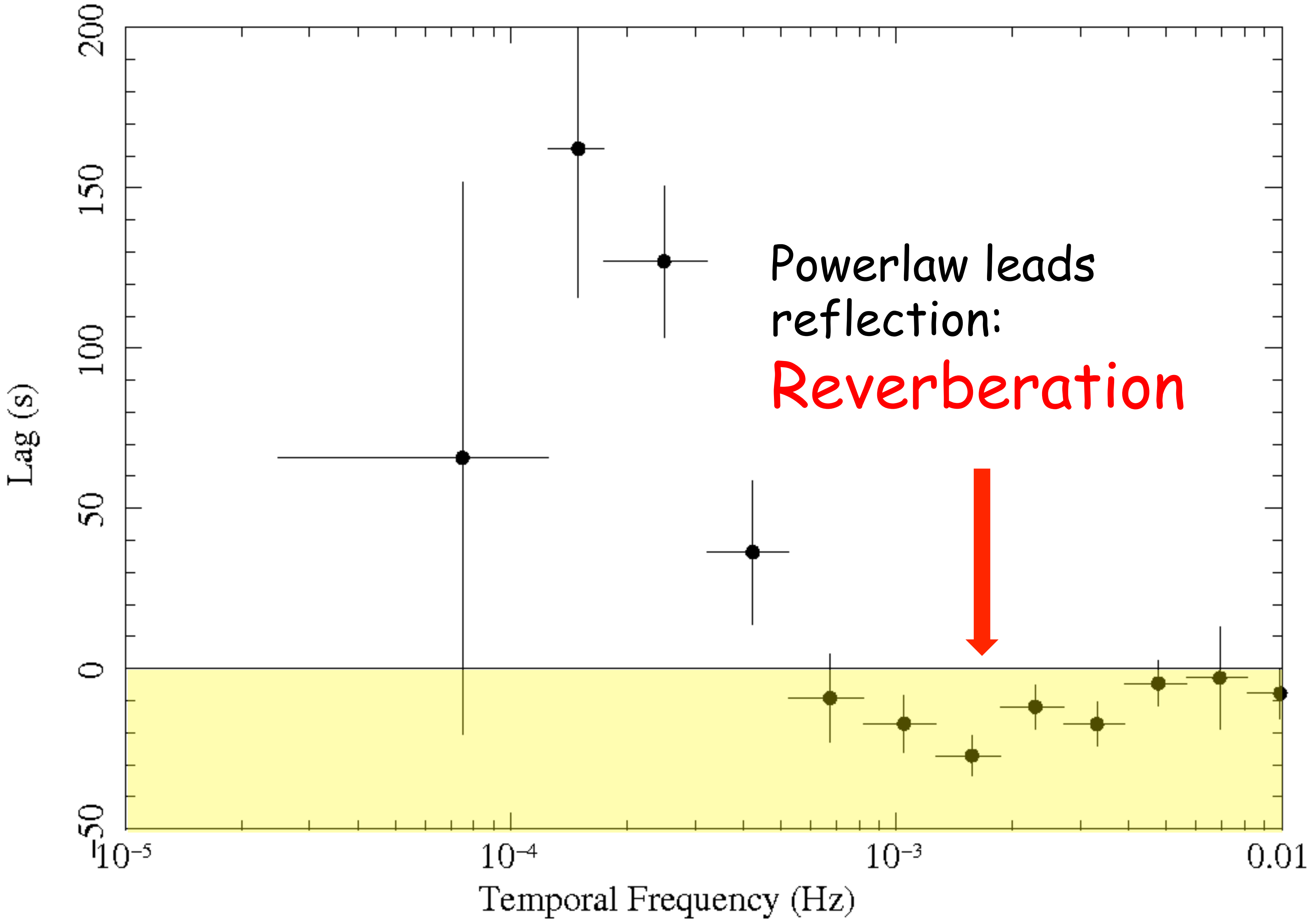


Path difference leads to *reverberation*

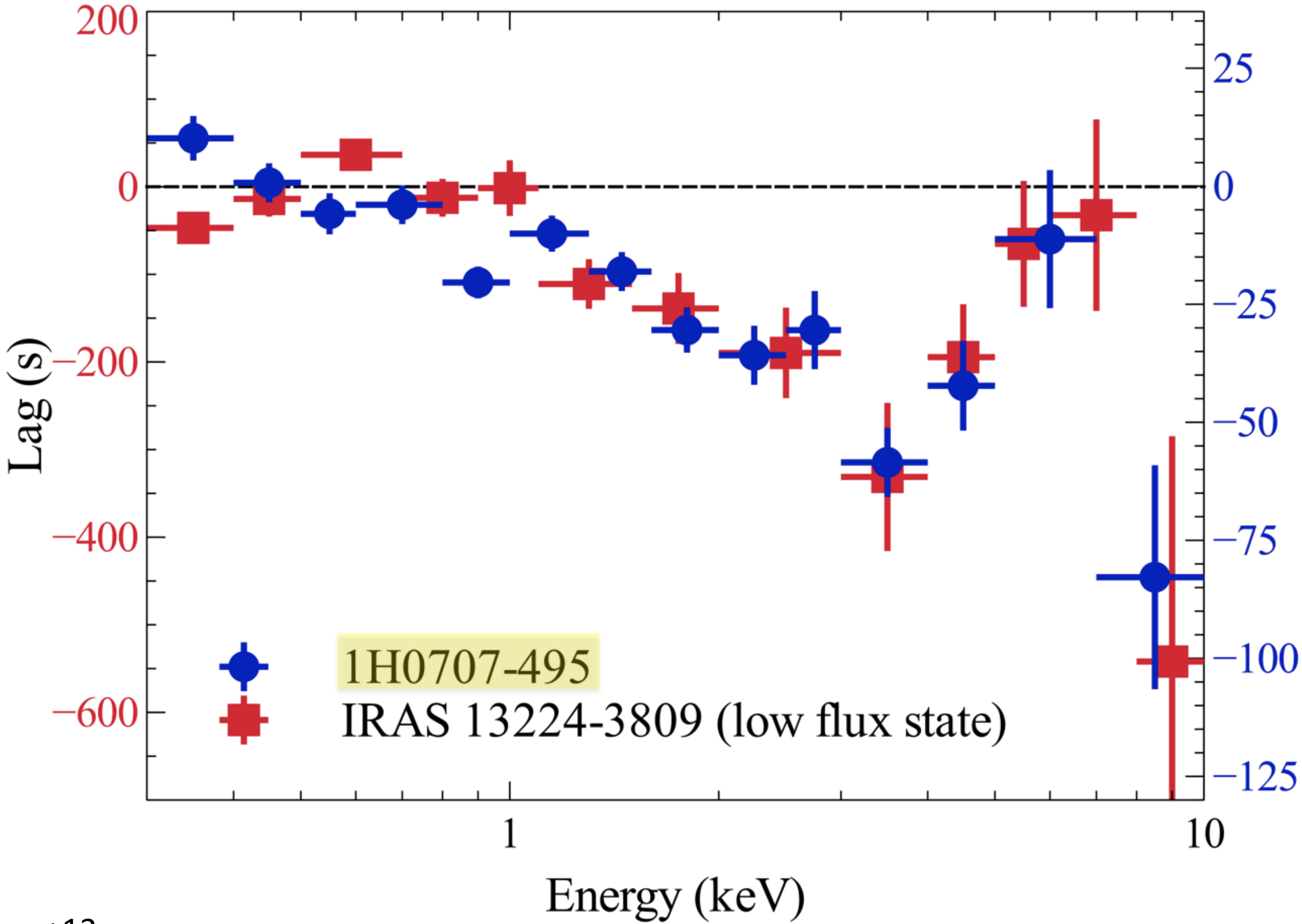
Broad iron-L and iron-K emission lines (XMM)



Fabian+09



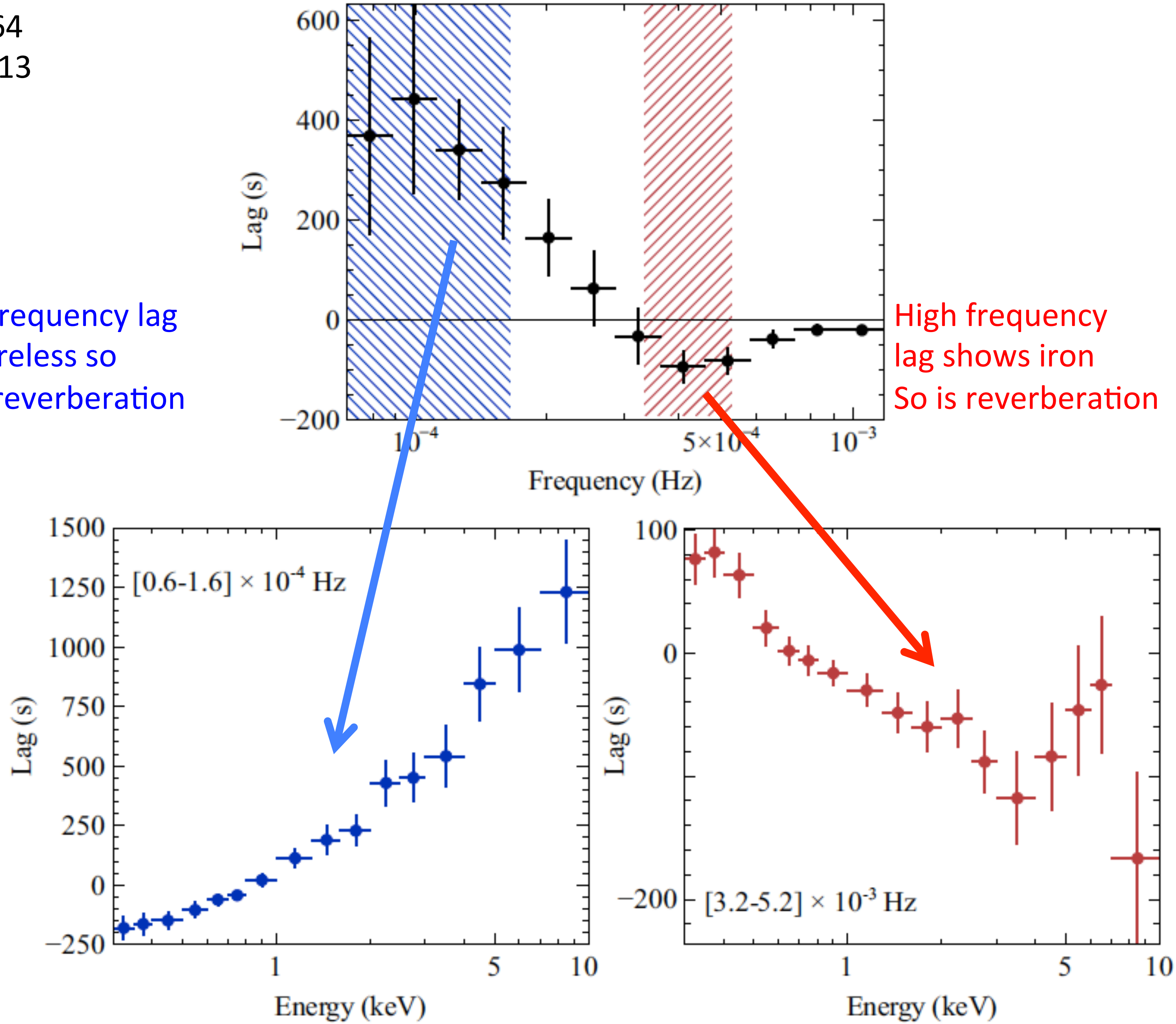
Powerlaw leads reflection:
Reverberation
Lag (s)
200
150
100
50
0
-50
10^{-5}
10^{-4}
10^{-3}
0.01
Temporal Frequency (Hz)


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

Kara+13a

Akn564
Kara+13

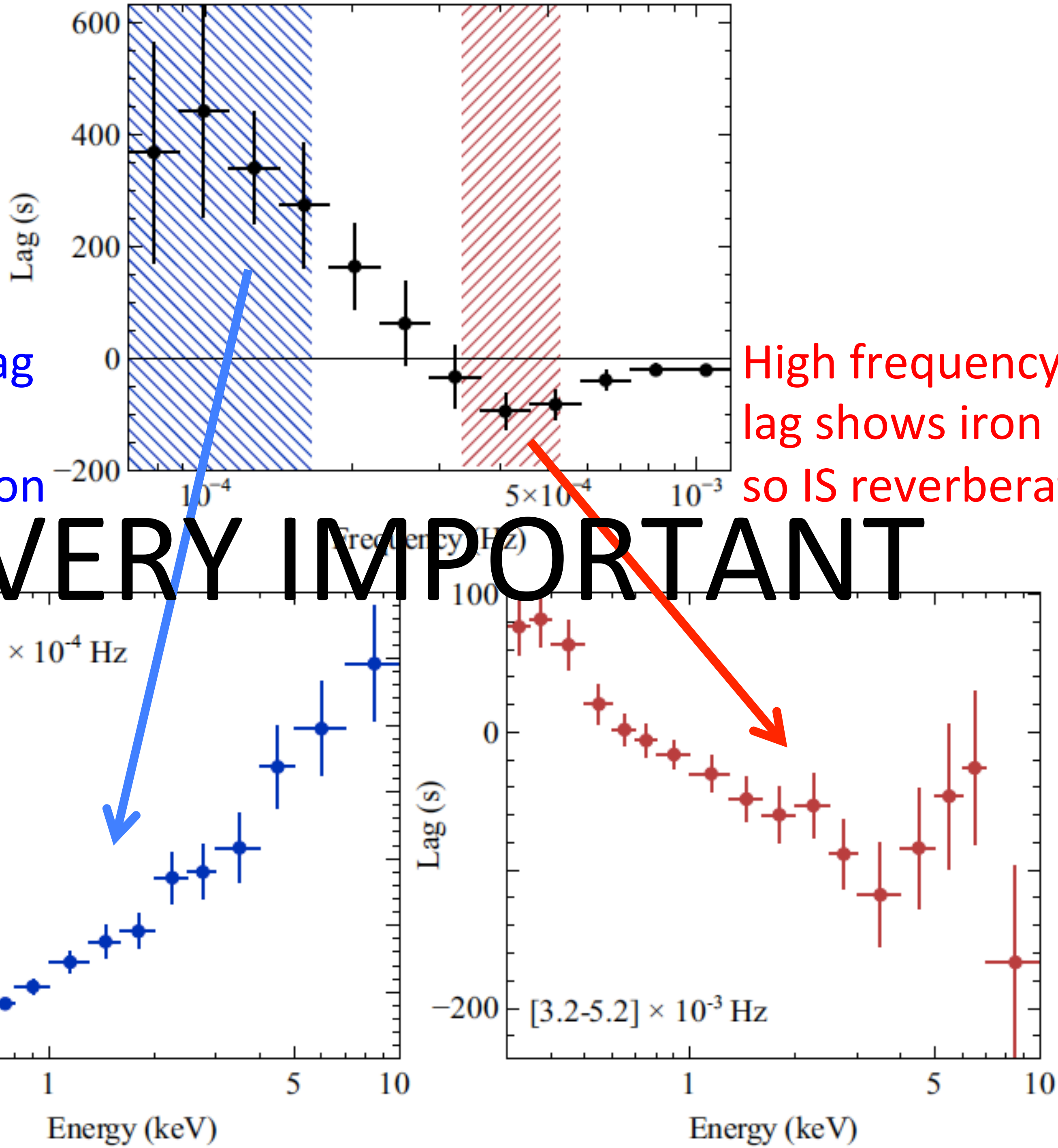
Low frequency lag
featureless so
NOT reverberation



High frequency
lag shows iron
So is reverberation

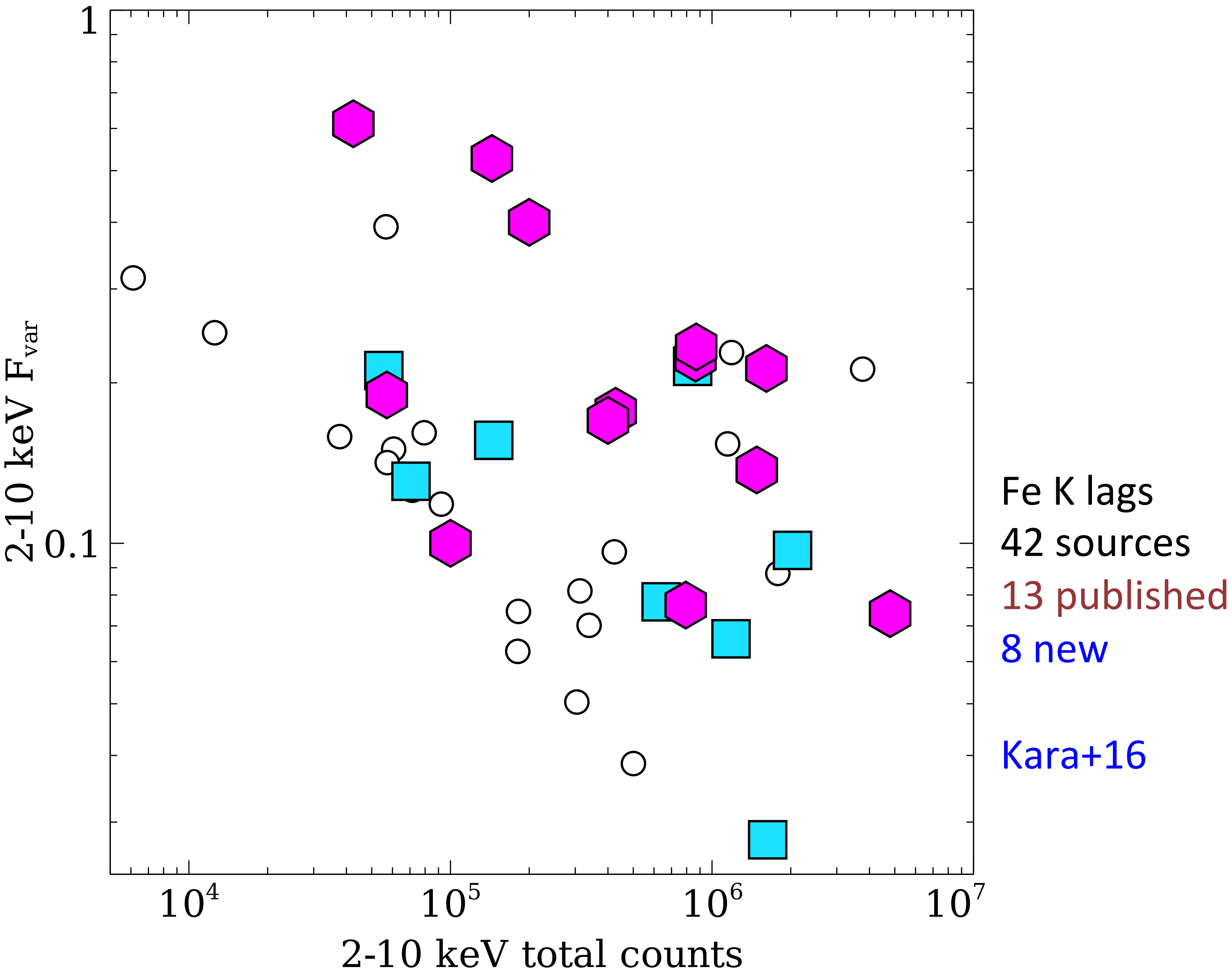
Akn564
Kara+13

Low frequency lag featureless so NOT reverberation



High frequency lag shows iron so IS reverberation

VERY IMPORTANT

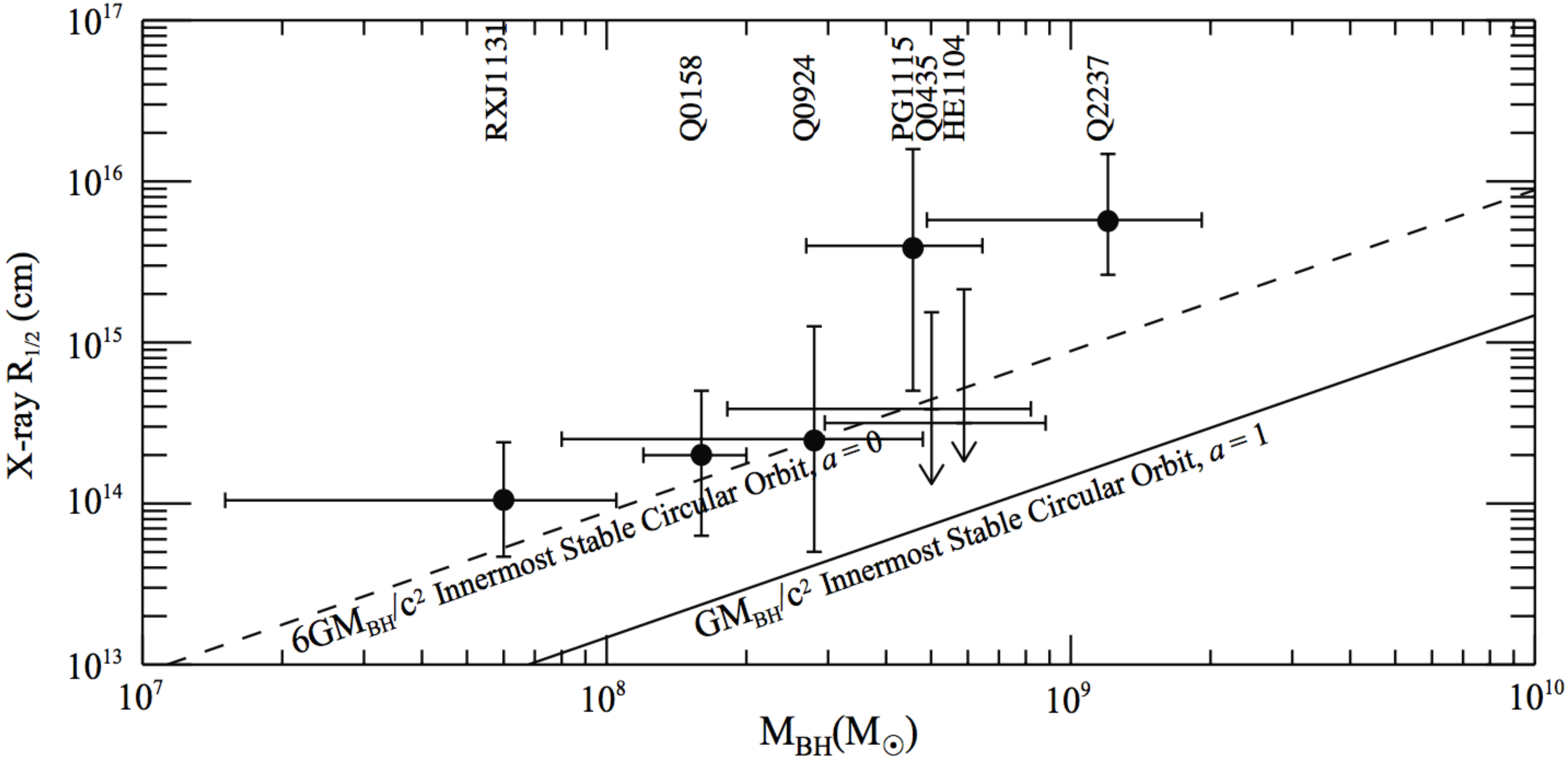


1
0.1
2-10 keV F_{var}
10^4
10^5
10^6
10^7
2-10 keV total counts
Fe K lags
42 sources
13 published
8 new
Kara+16

Corona is compact

Need to understand anisotropy of corona in order to improve precision on strong gravity

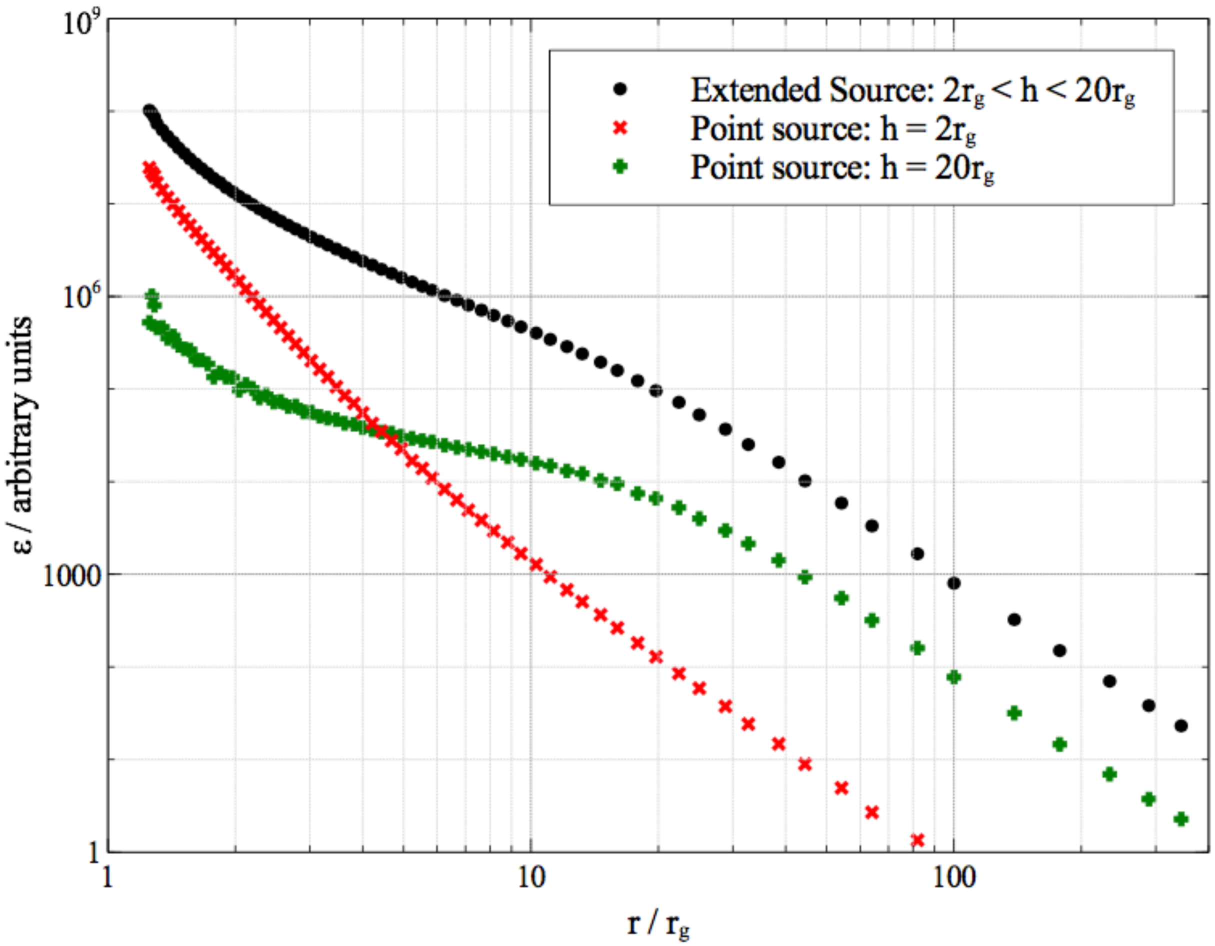
Coronal Size from Microlensing: Coronae are Compact



Chartas15

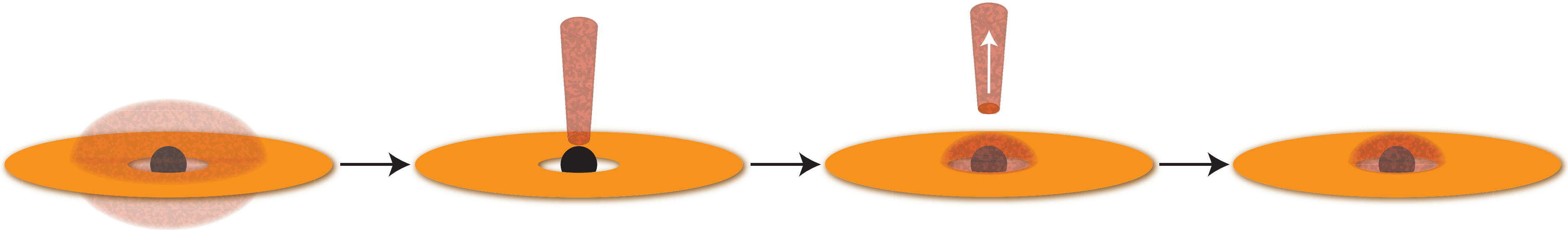
Emissivity profiles enable coronal height and radius to be determined

Wilkins+Fabian12

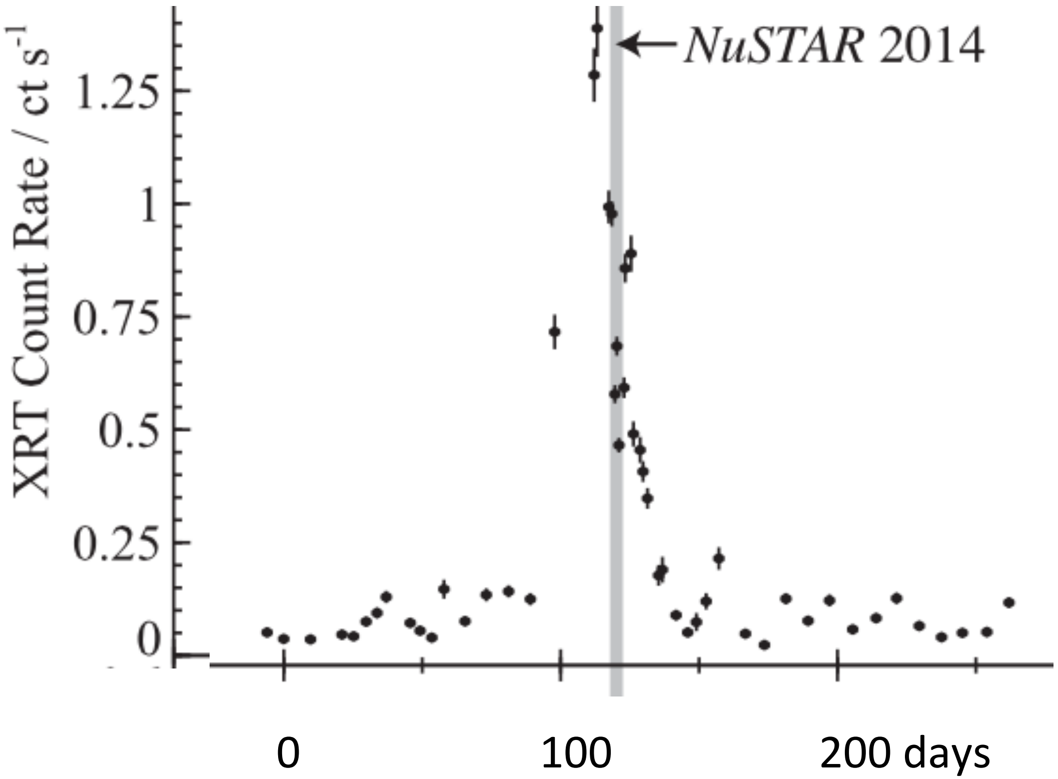


Outflowing Corona

Mild relativistic outflow in corona can beam primary radiation outward

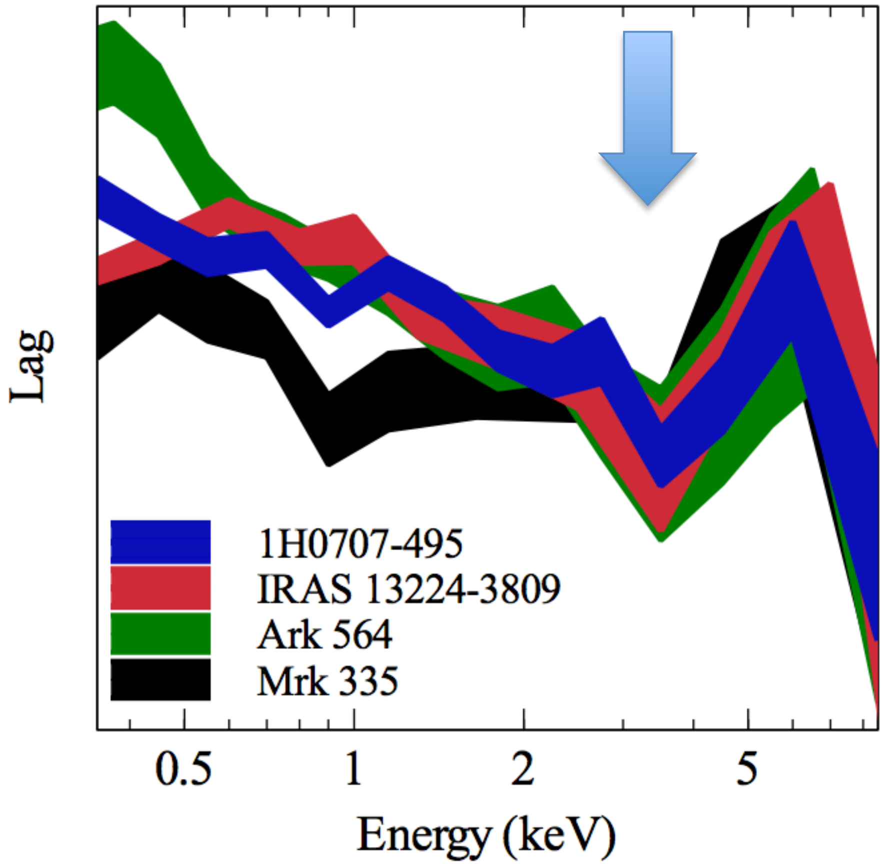


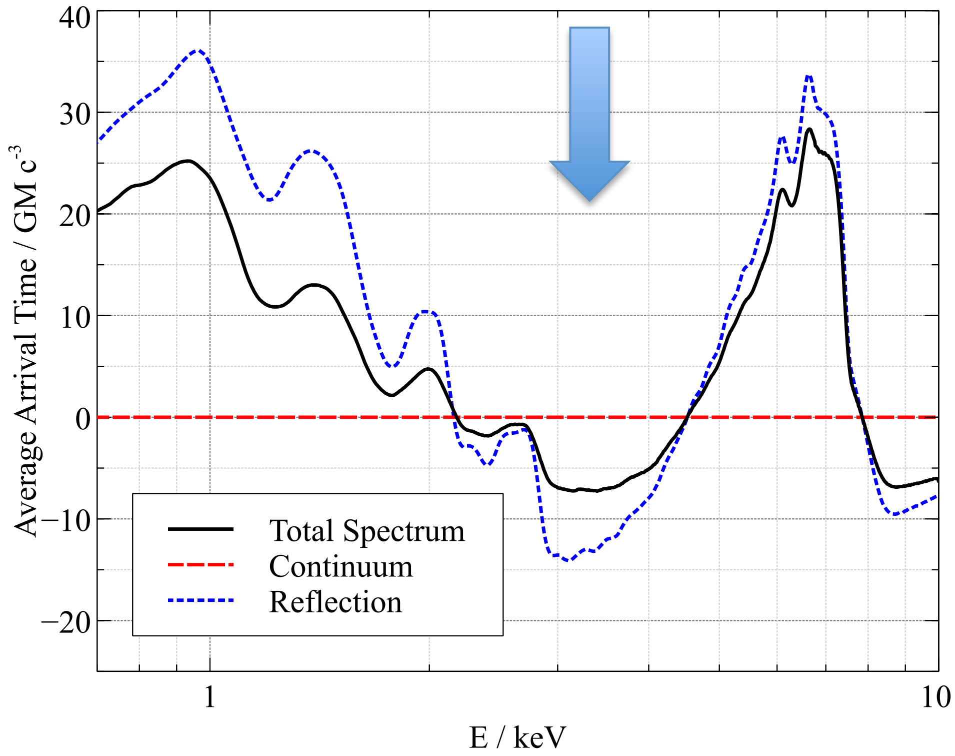
Mkn335



Wilkins+14

Rise of corona can explain 3.5 keV dip



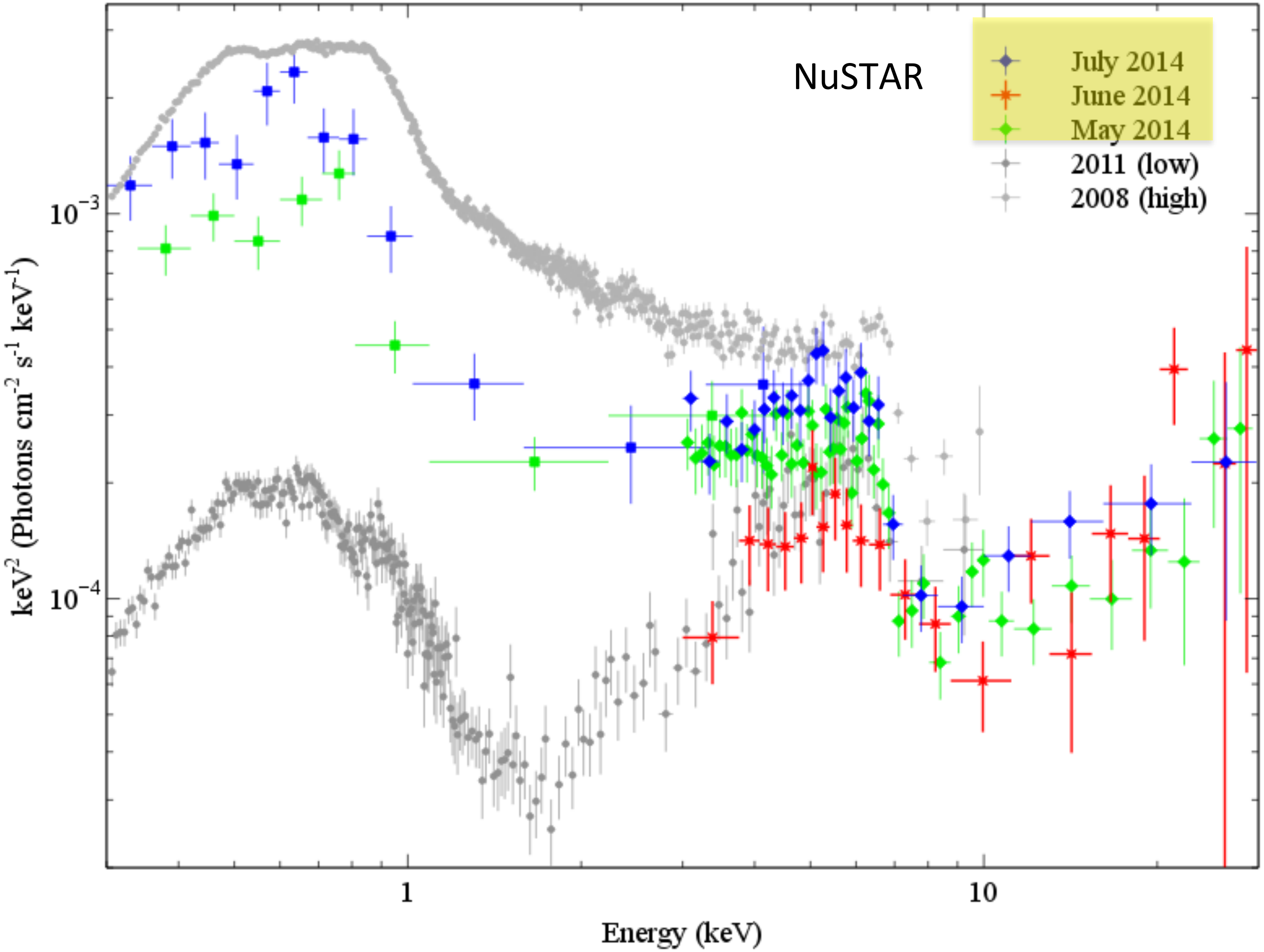


Wilkins+16

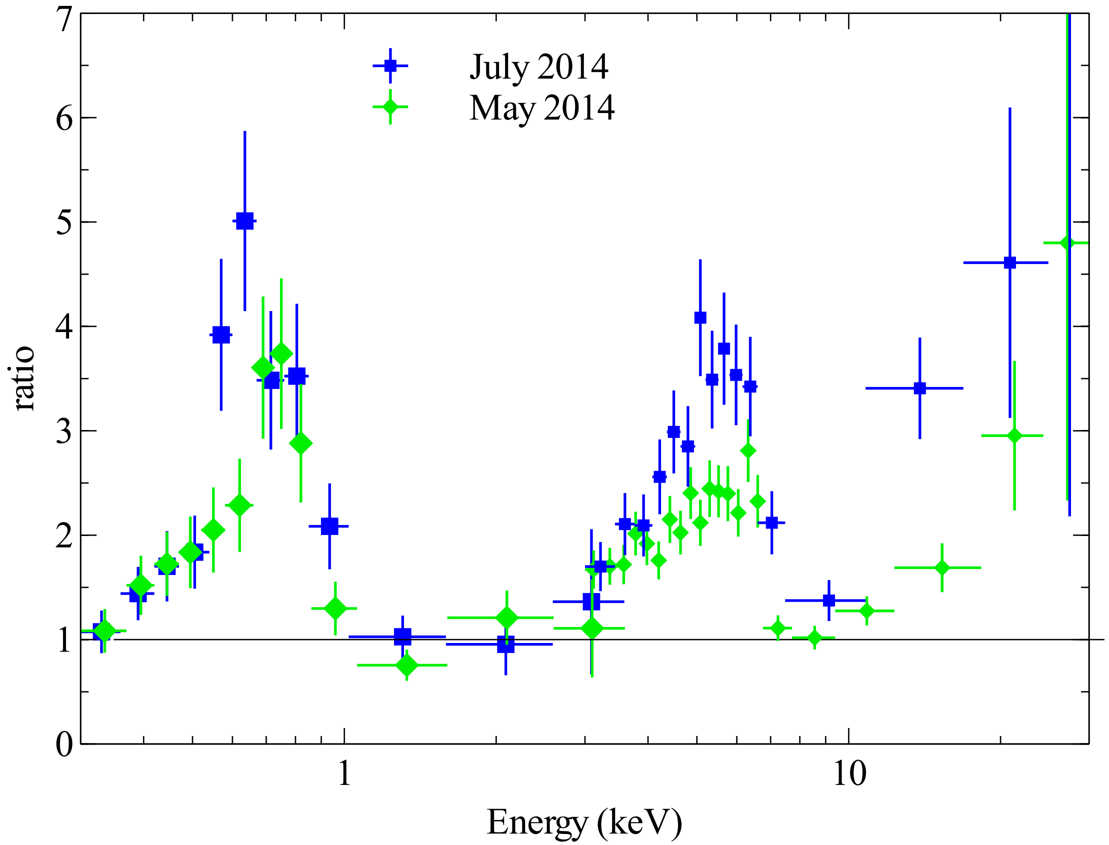
Coronal Collapse

When h drops from 10 to $2r_g$

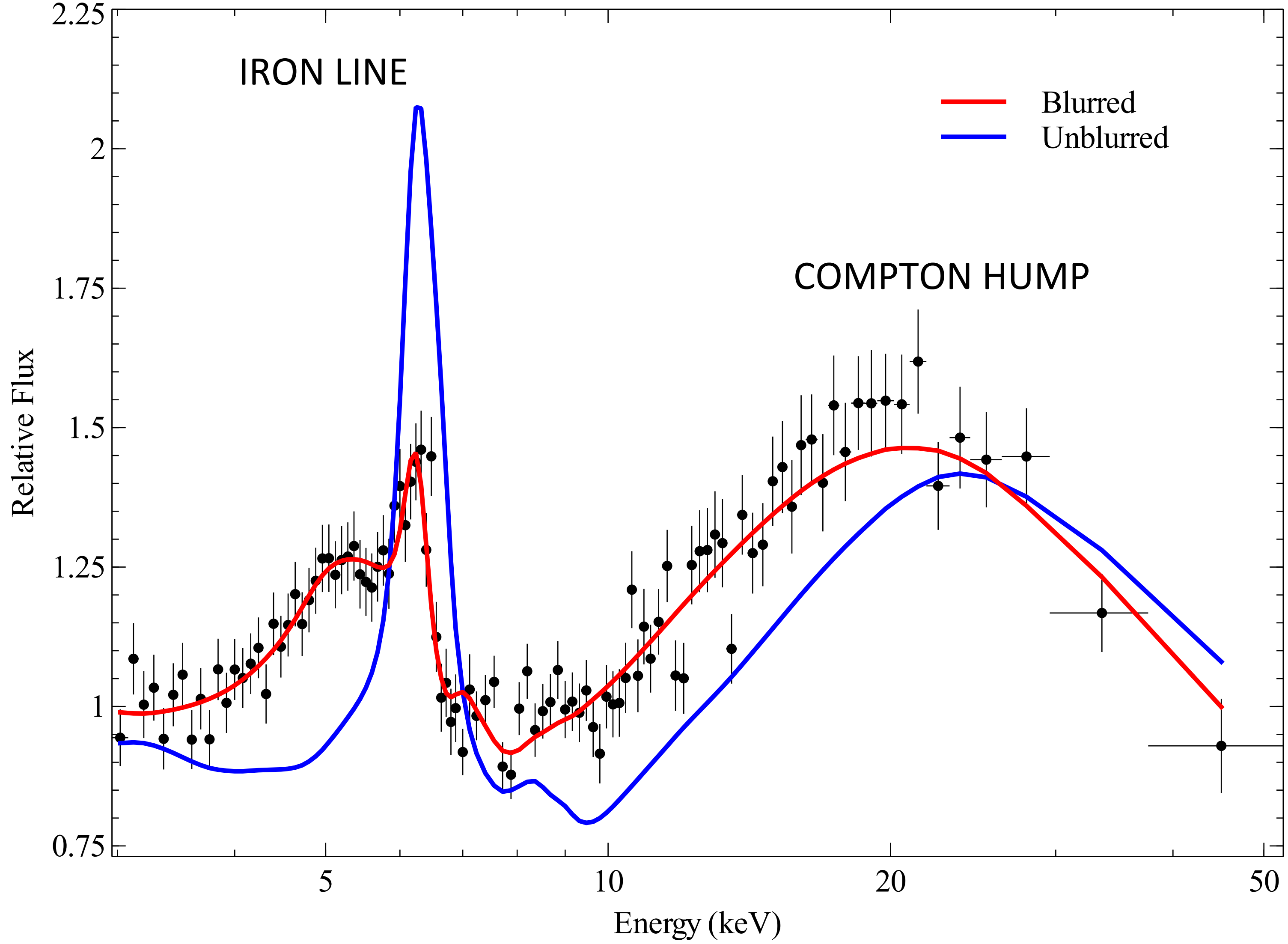
Into the Abyss



1H0707-495 Kara+14

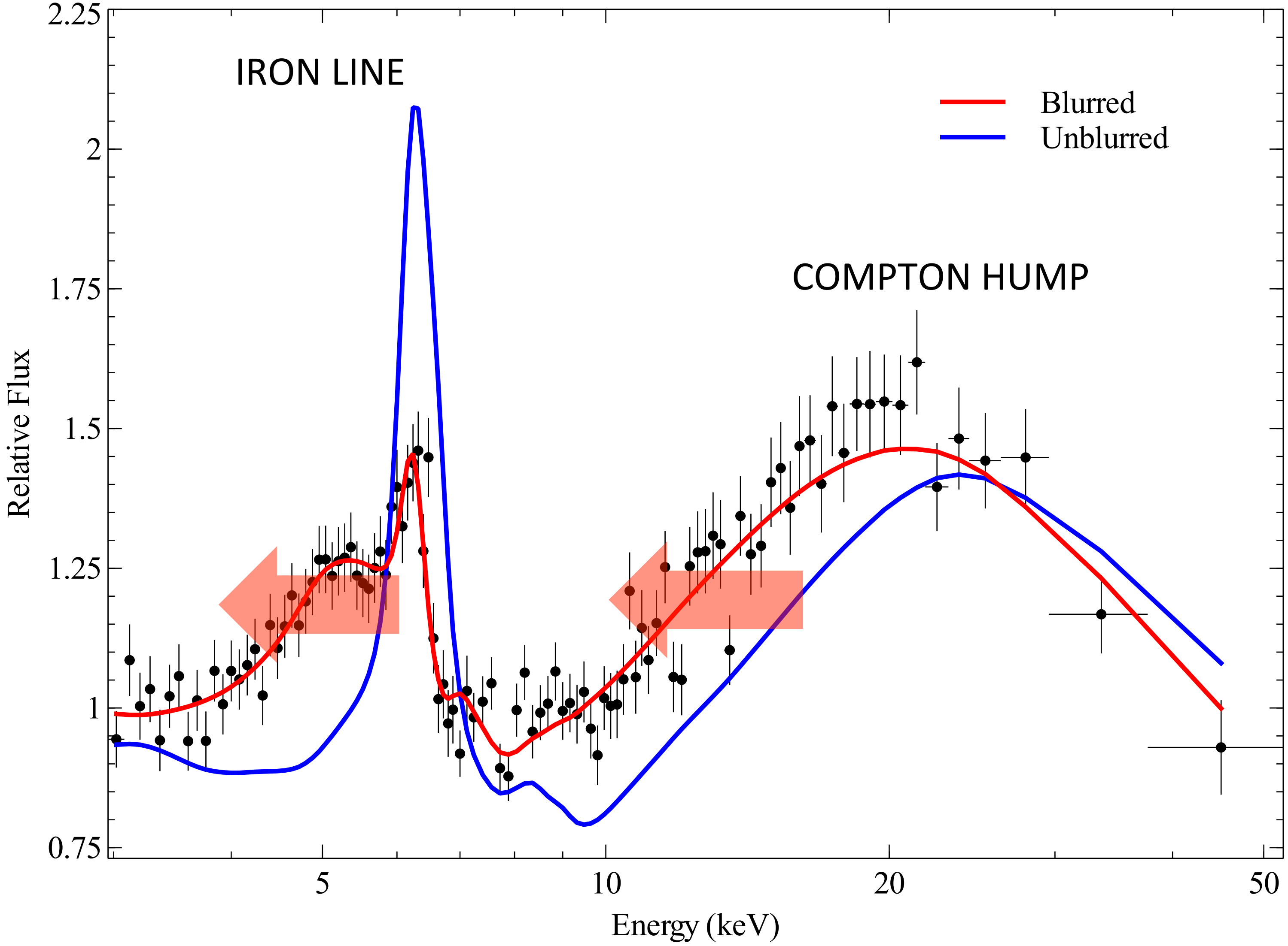


1H0707 Kara+14

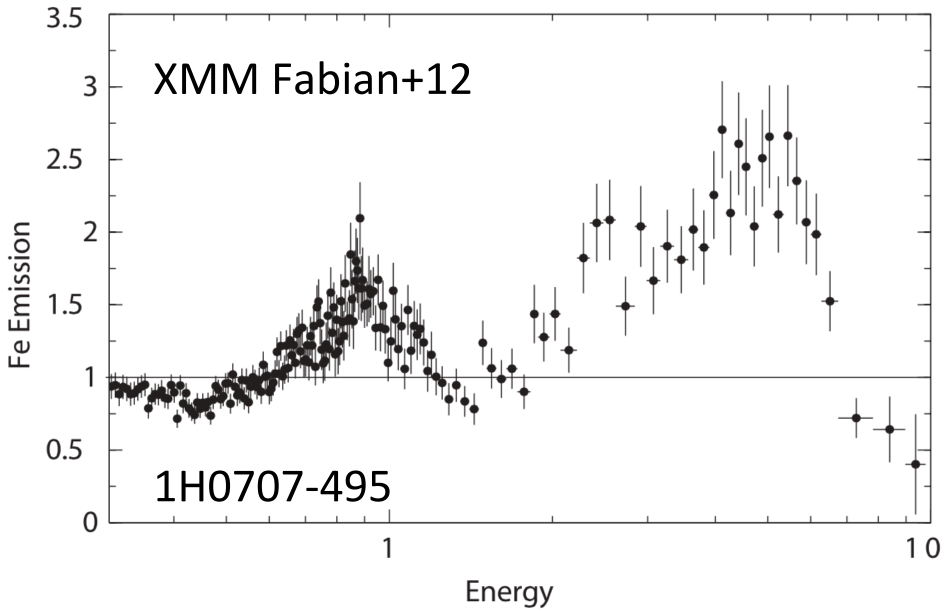


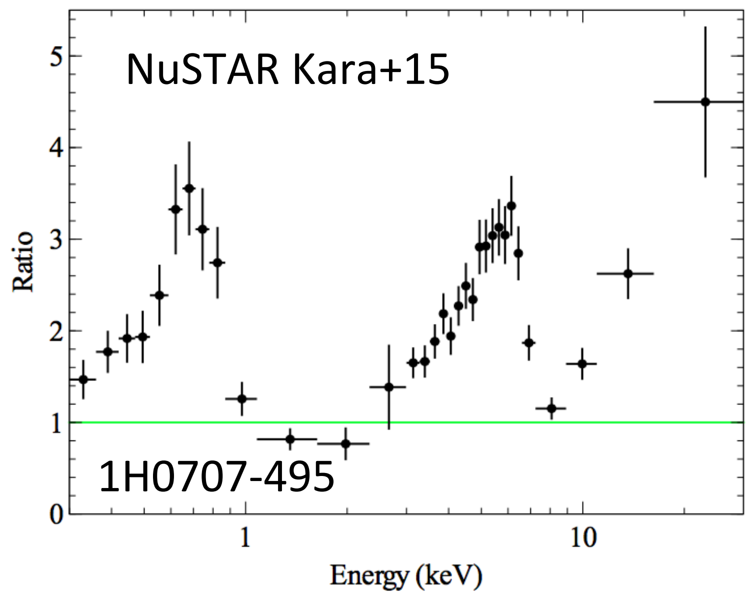
Mkn 335 Parker+14

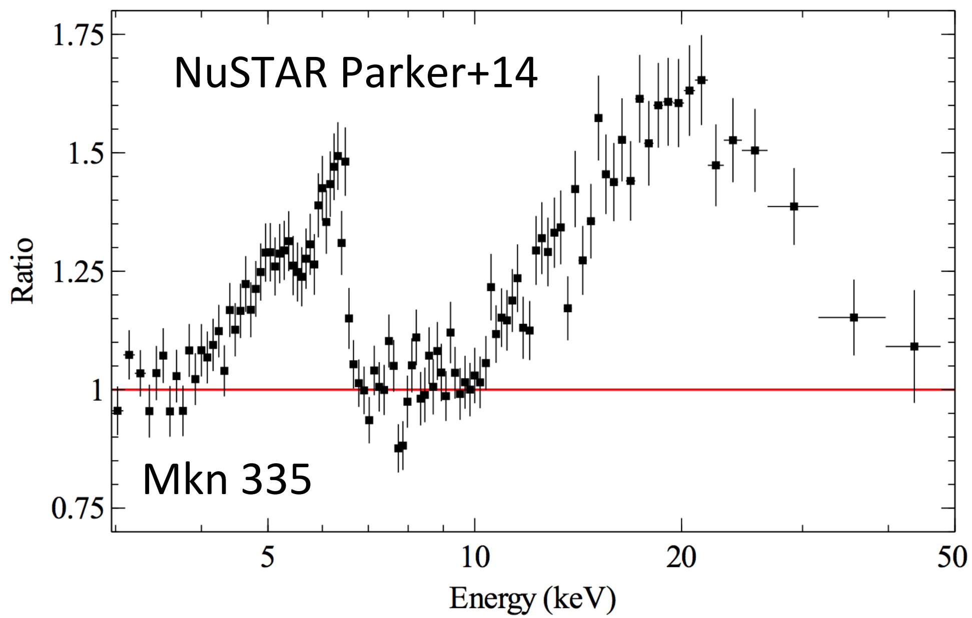
Most emission from 1-2r_g



Mkn 335 Parker+14

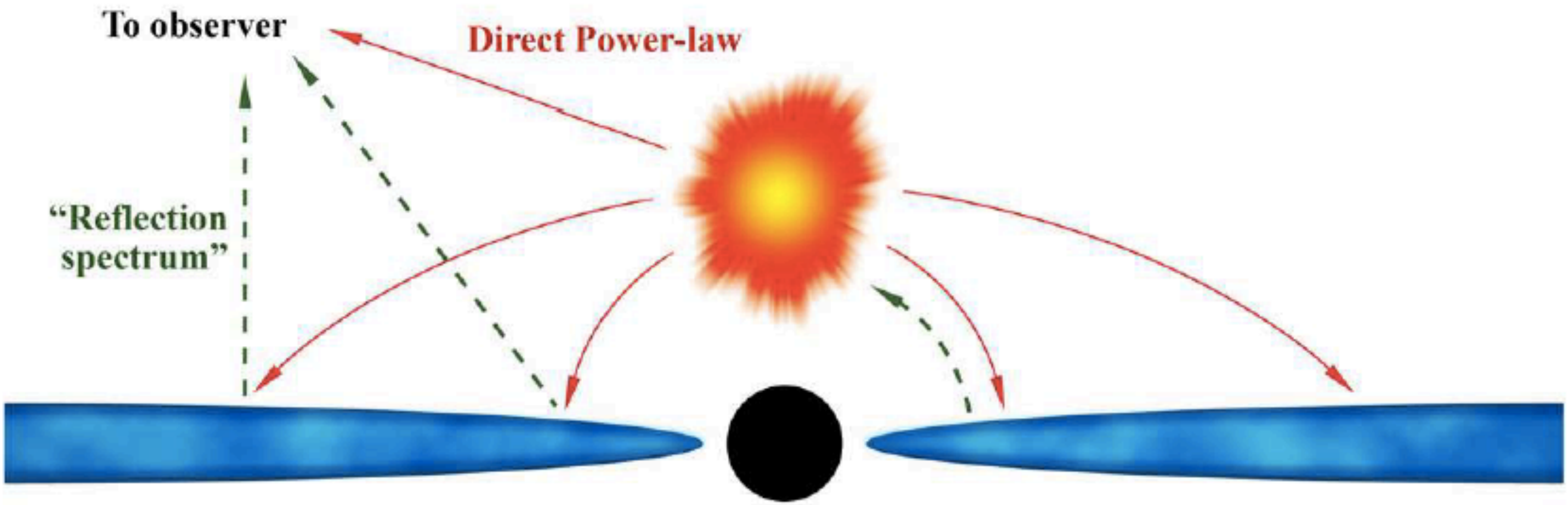






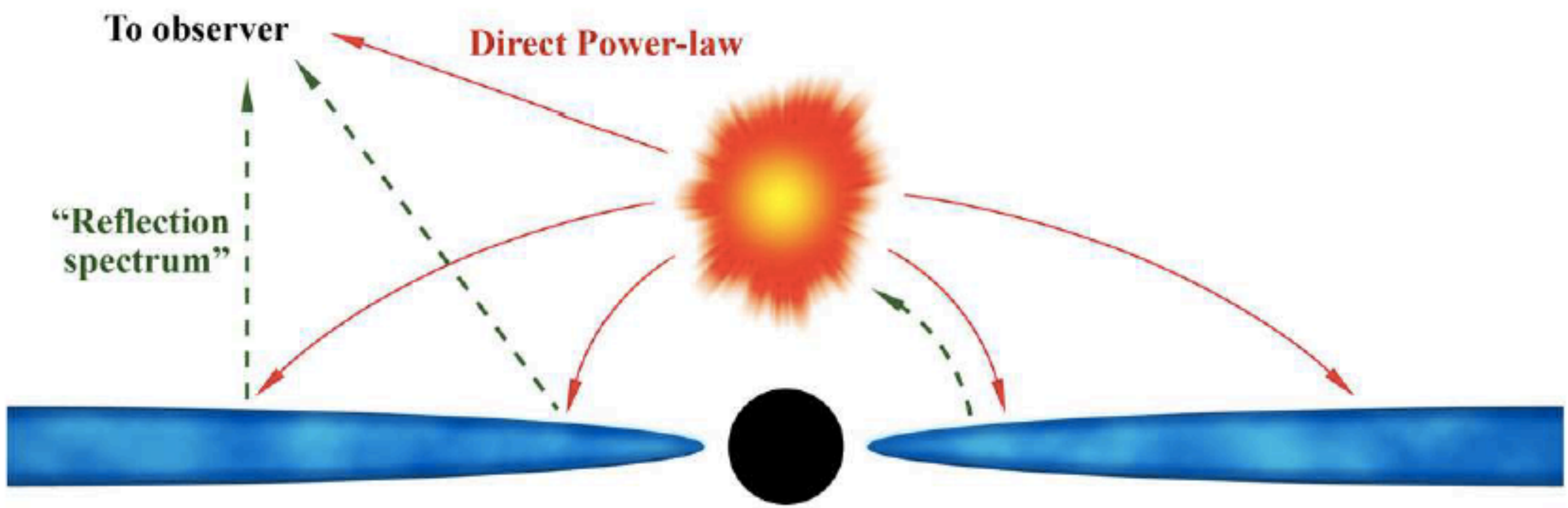
Results from within 2 r_g

Relativistic Reflection is a common feature of luminous accreting black holes



Spectral-timing analyses reveal inner strong gravity regime

Relativistic Reflection is a common feature of luminous accreting black holes

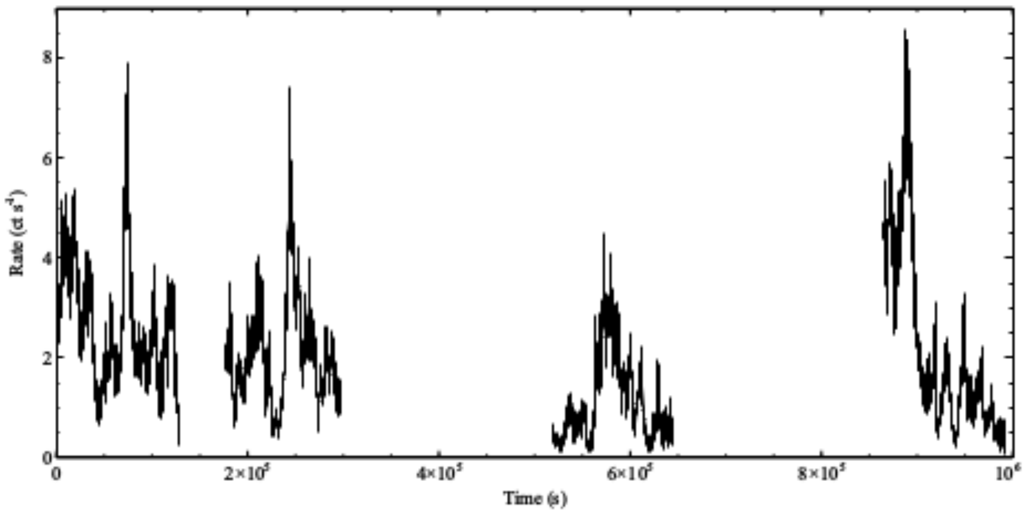


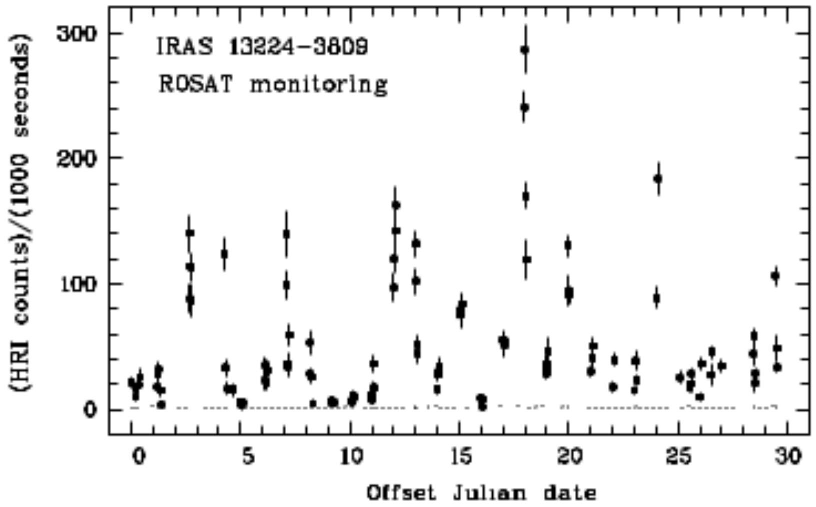
Strong gravitational effects (redshift, light bending etc) are INEVITABLE

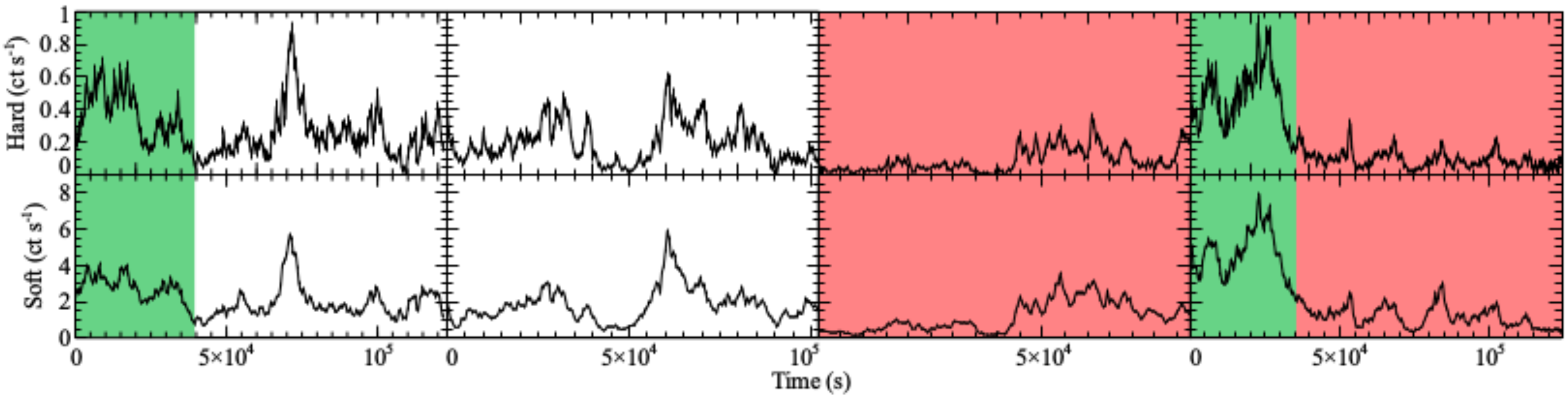
The Near Future

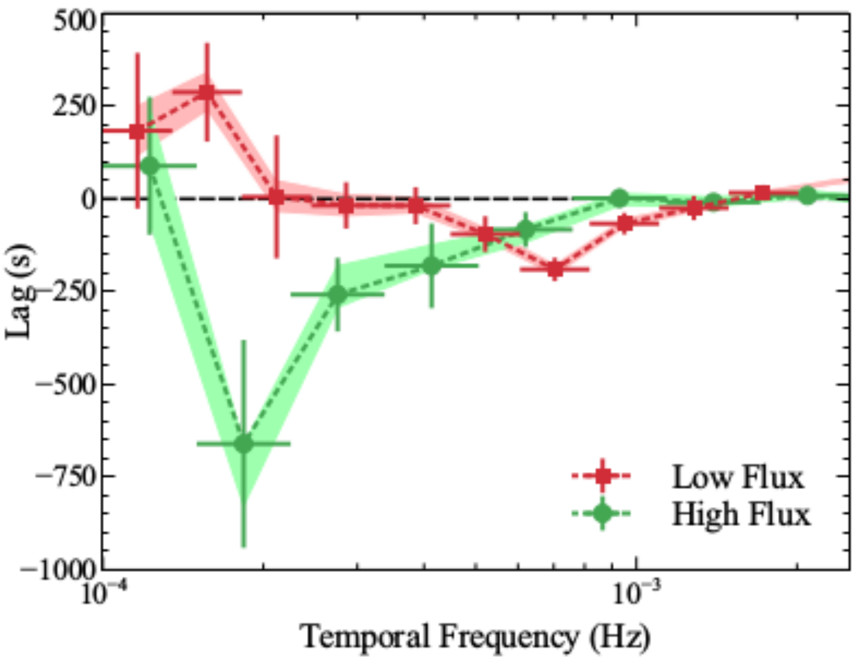
- VERY LONG (Ms) observations of Key Objects will study dynamic behaviour of corona
- Launch of ASTRO-H (scheduled for Feb 12 2016)

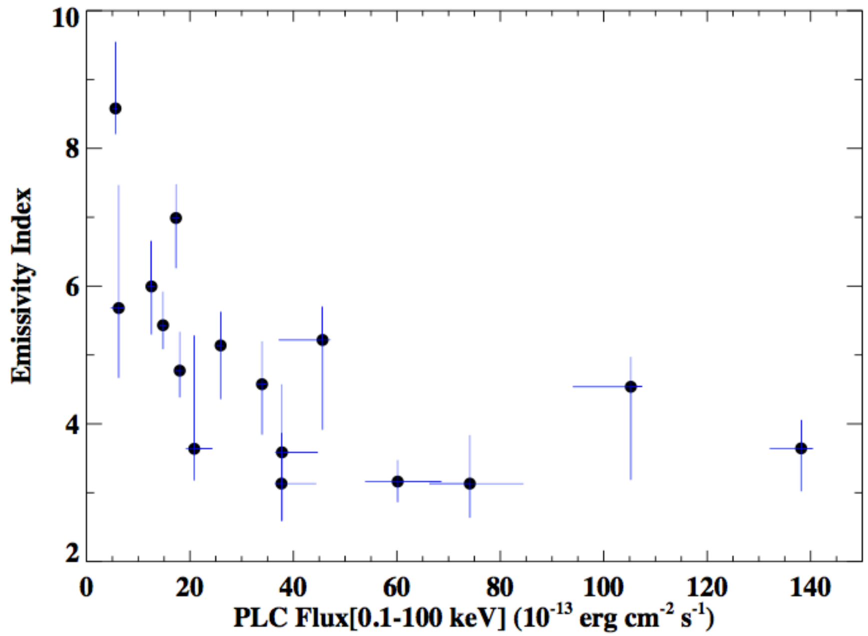
IRAS13224-3809 - Example of a key object






Hard (ct s^{-1})
Soft (ct s^{-1})
Time (s)


Lag (s)
Temporal Frequency (Hz)
Low Flux
High Flux


Emissivity Index
PLC Flux[0.1-100 keV] (10^{-13} erg cm^{-2} s^{-1})

STRONG GRAVITY

- Gravitational redshift ✔ — Red wing
- Strong Light Bending (radian scale) ✔ — Reflection Strength
- Shapiro delay ✔ — Reverberation
- Dragging of Inertial Frame ✔ — High Spin

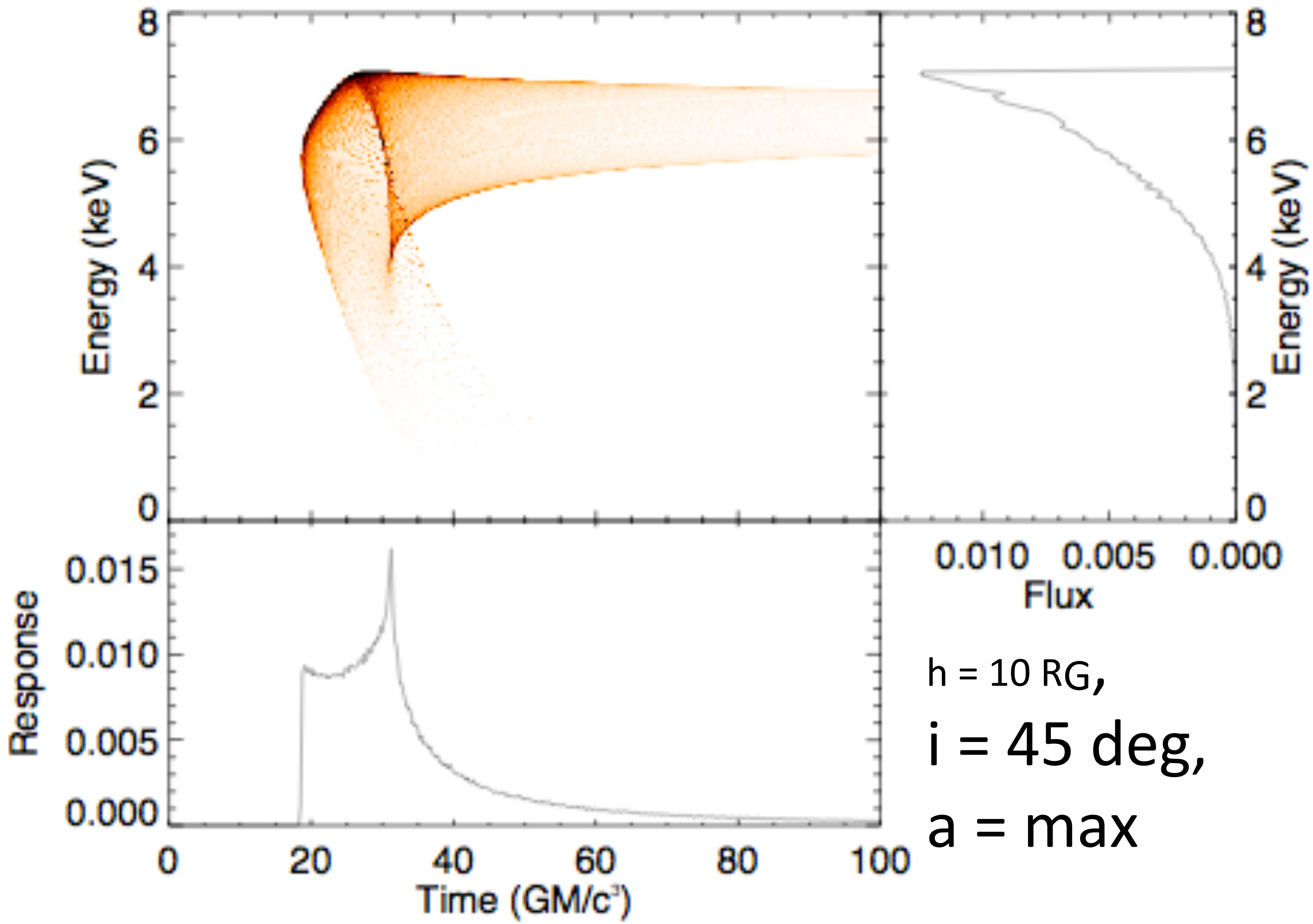
Summary

- We're now doing Relativistic Astrophysics of the immediate region around accreting black holes – the central engine of quasars.

- Quasars are the most luminous persistent sources in the Universe and, through feedback, determine the final stellar mass of galay bulges

Cackett+13

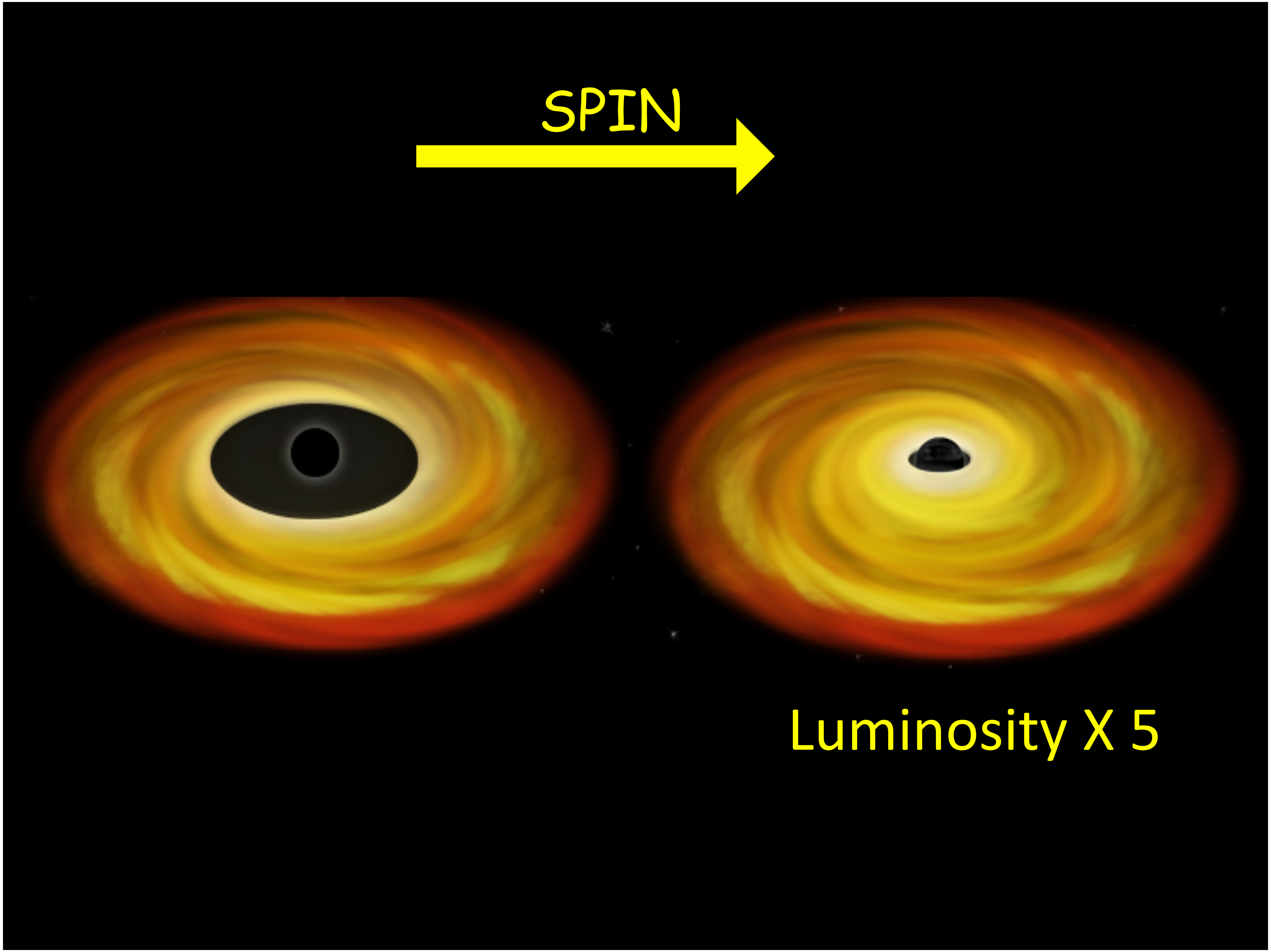
2D transfer function



h = 10 RG,

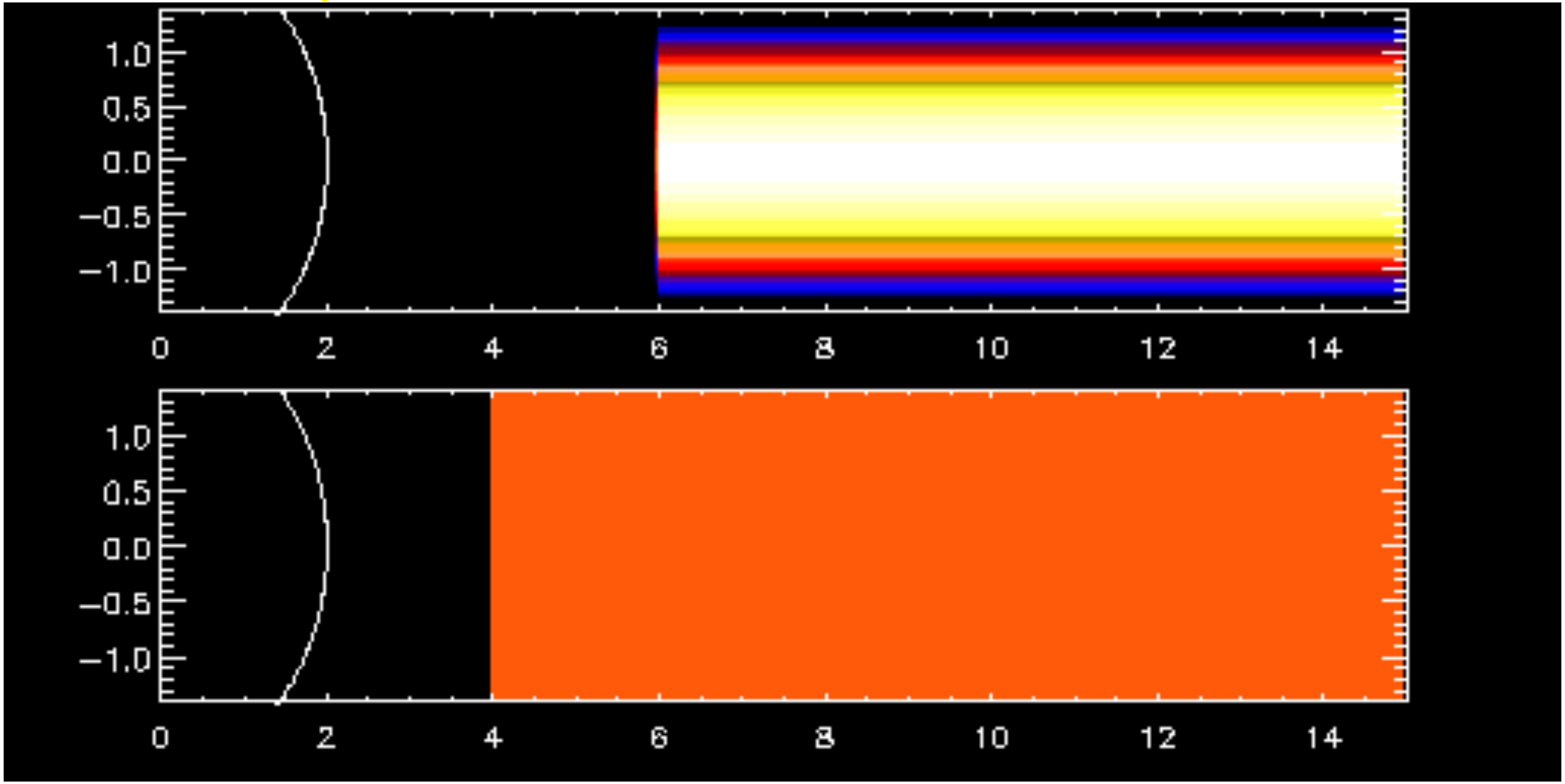
i = 45 deg,

a = max


SPIN
Luminosity X 5

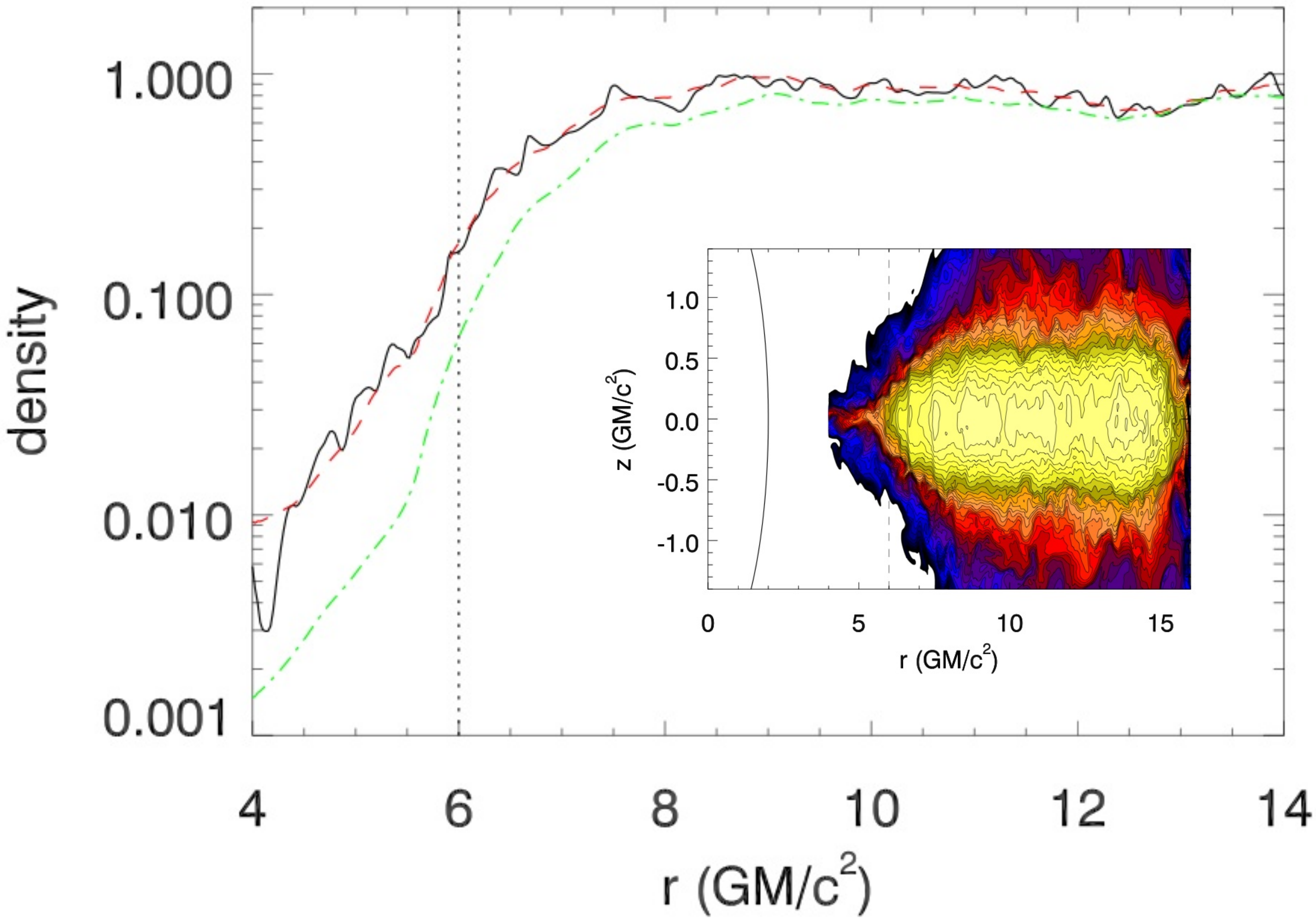

ASTRO-H
ISAS/JAXA
08 May, 2015

Density

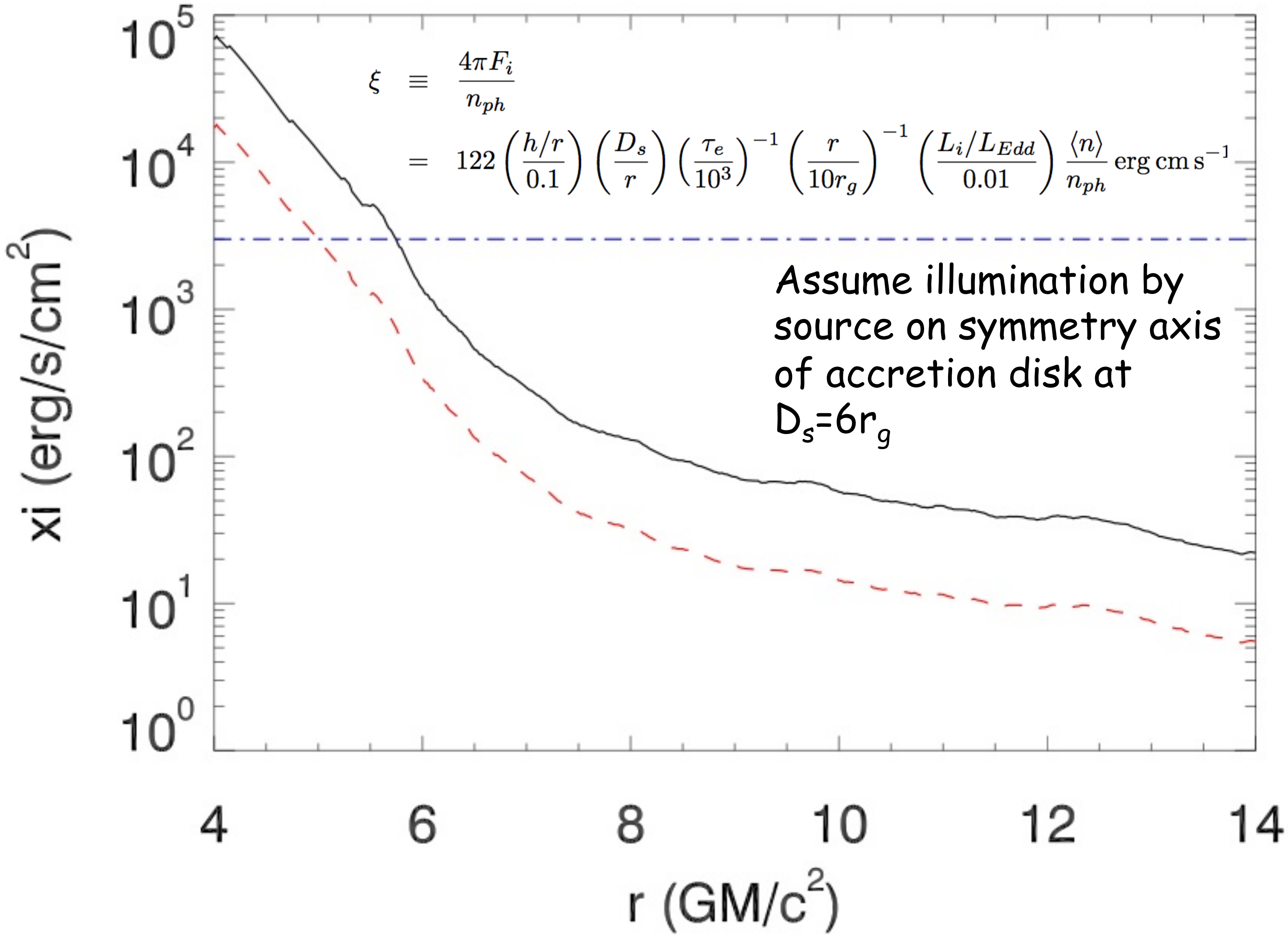


Azimuthal field

Reynolds & Fabian 08

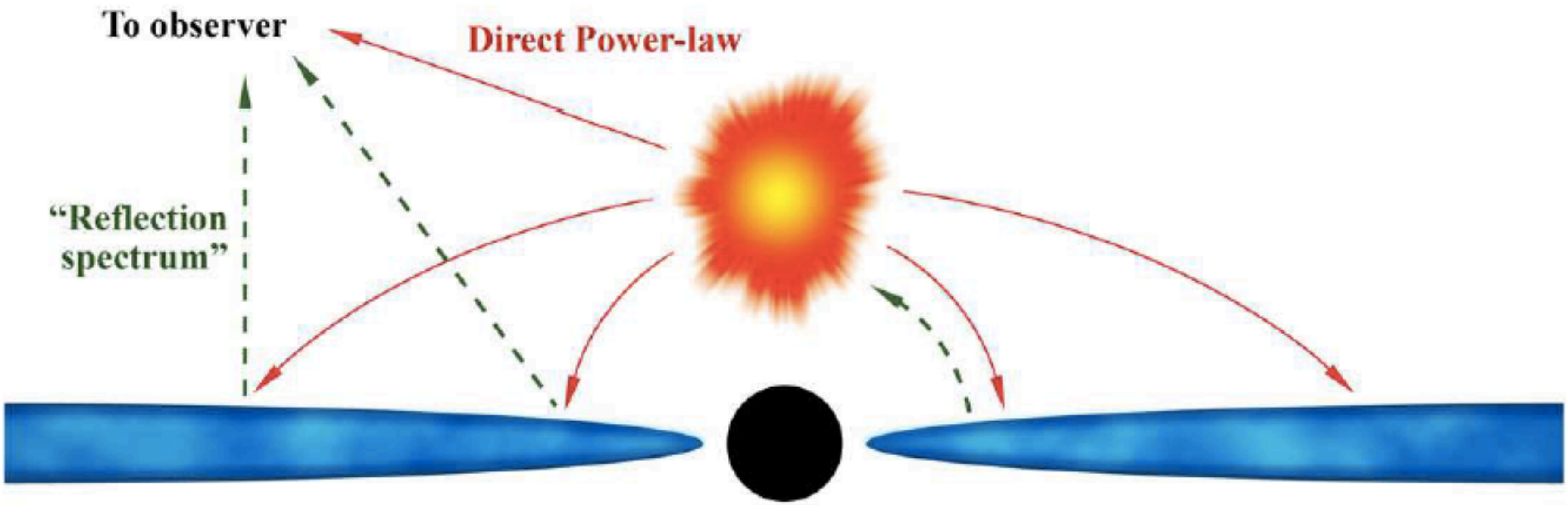


Reynolds & Fabian 08



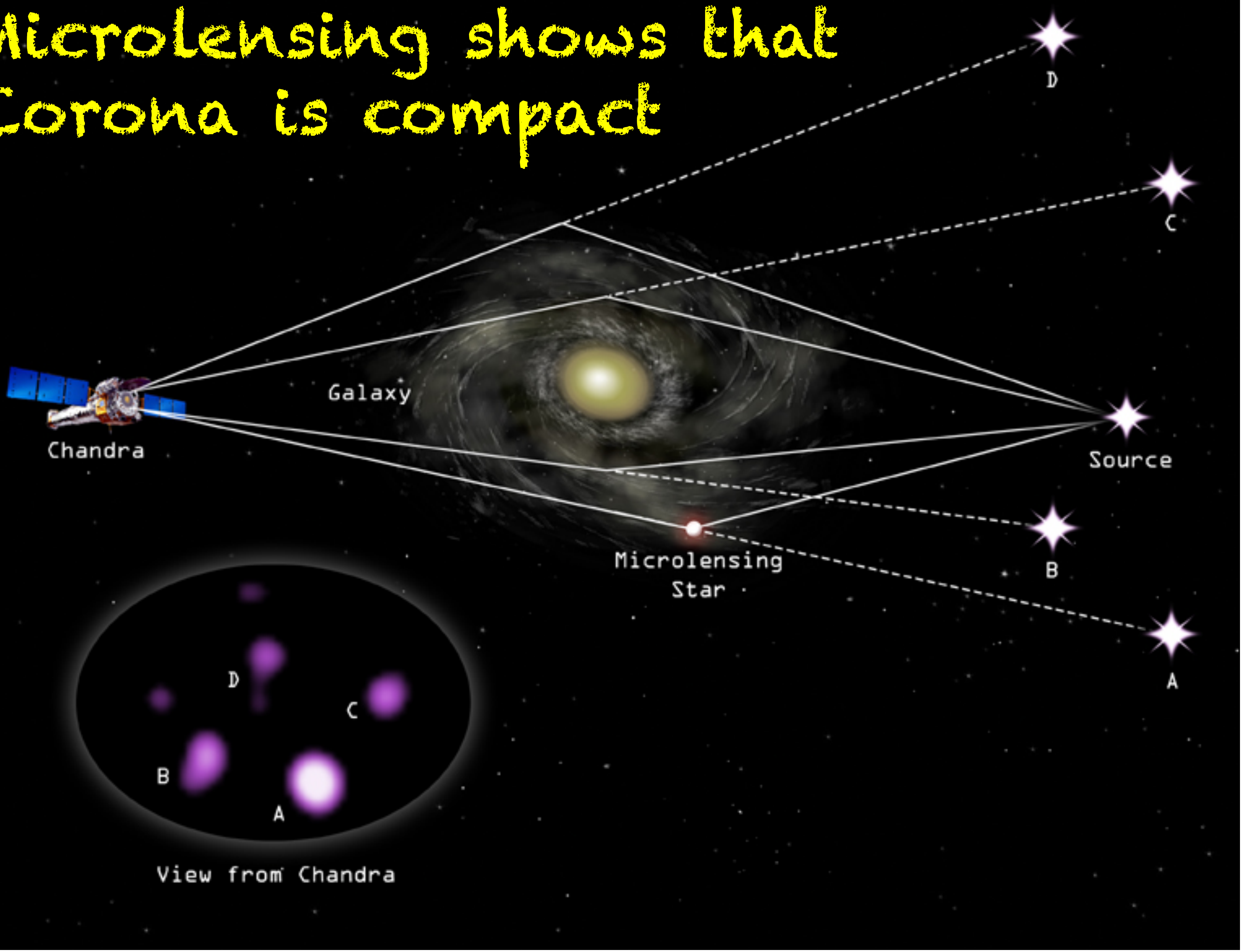
Reynolds & Fabian 08

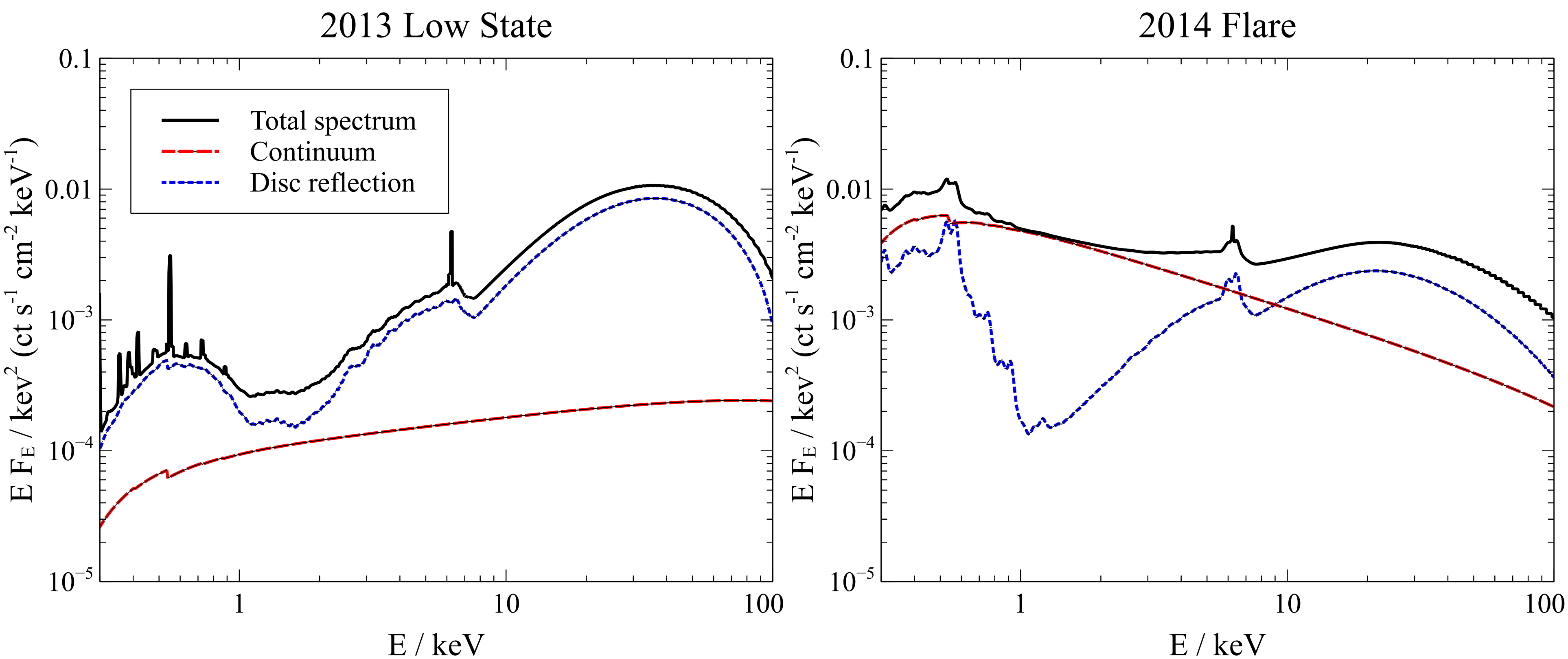
Relativistic Disc Lines are a common feature of luminous accreting black holes



With NuSTAR now considering second order effects

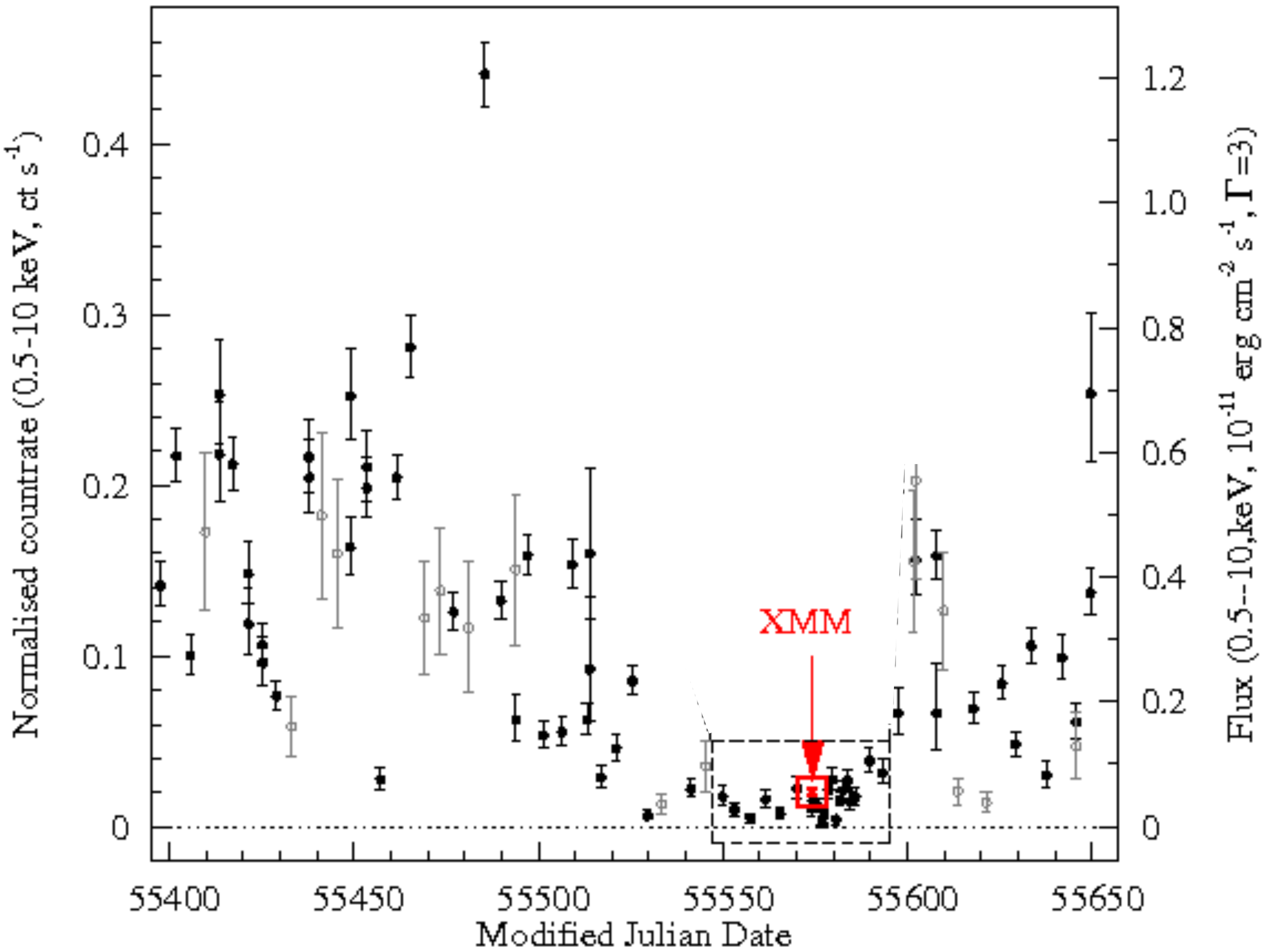
Microlensing shows that Corona is compact



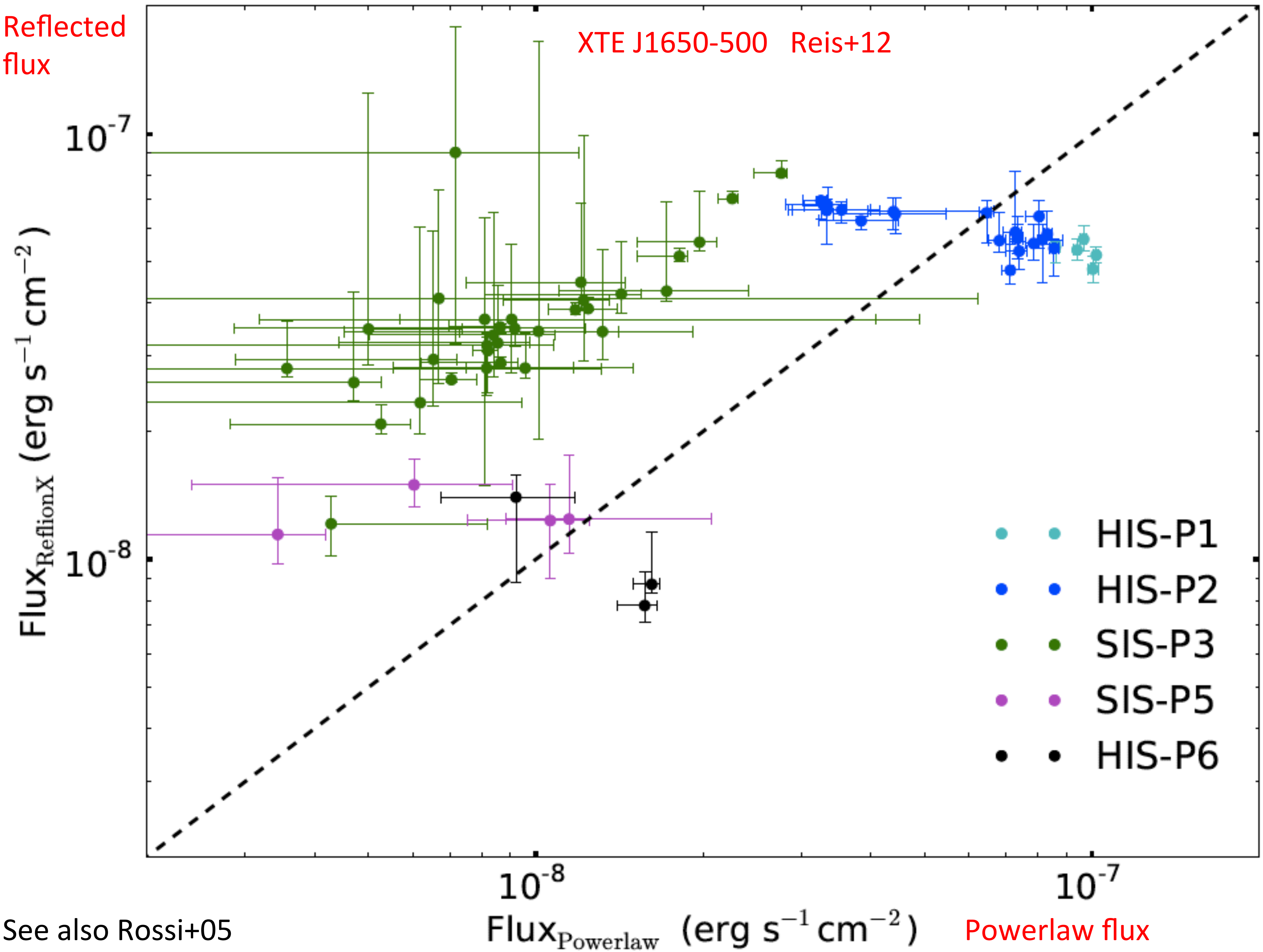


2013 Low State
2014 Flare
Total spectrum
Continuum
Disc reflection
E F_E / kev^2 (ct s^-1 cm^-2 keV^-1)
E / keV
0.1
0.01
10^-3
10^-4
10^-5
1
10
100

1H0707-495 Fabian+12

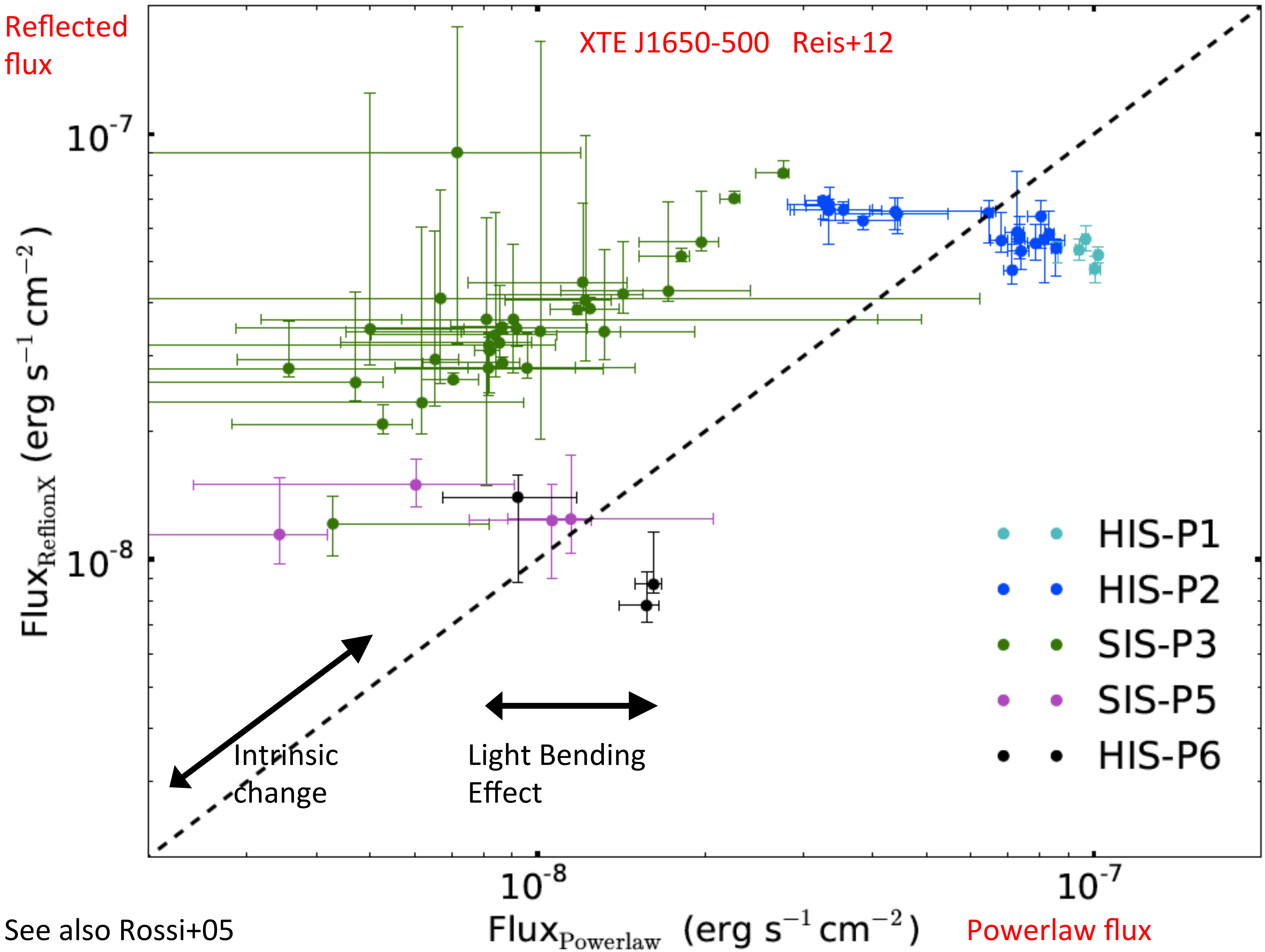


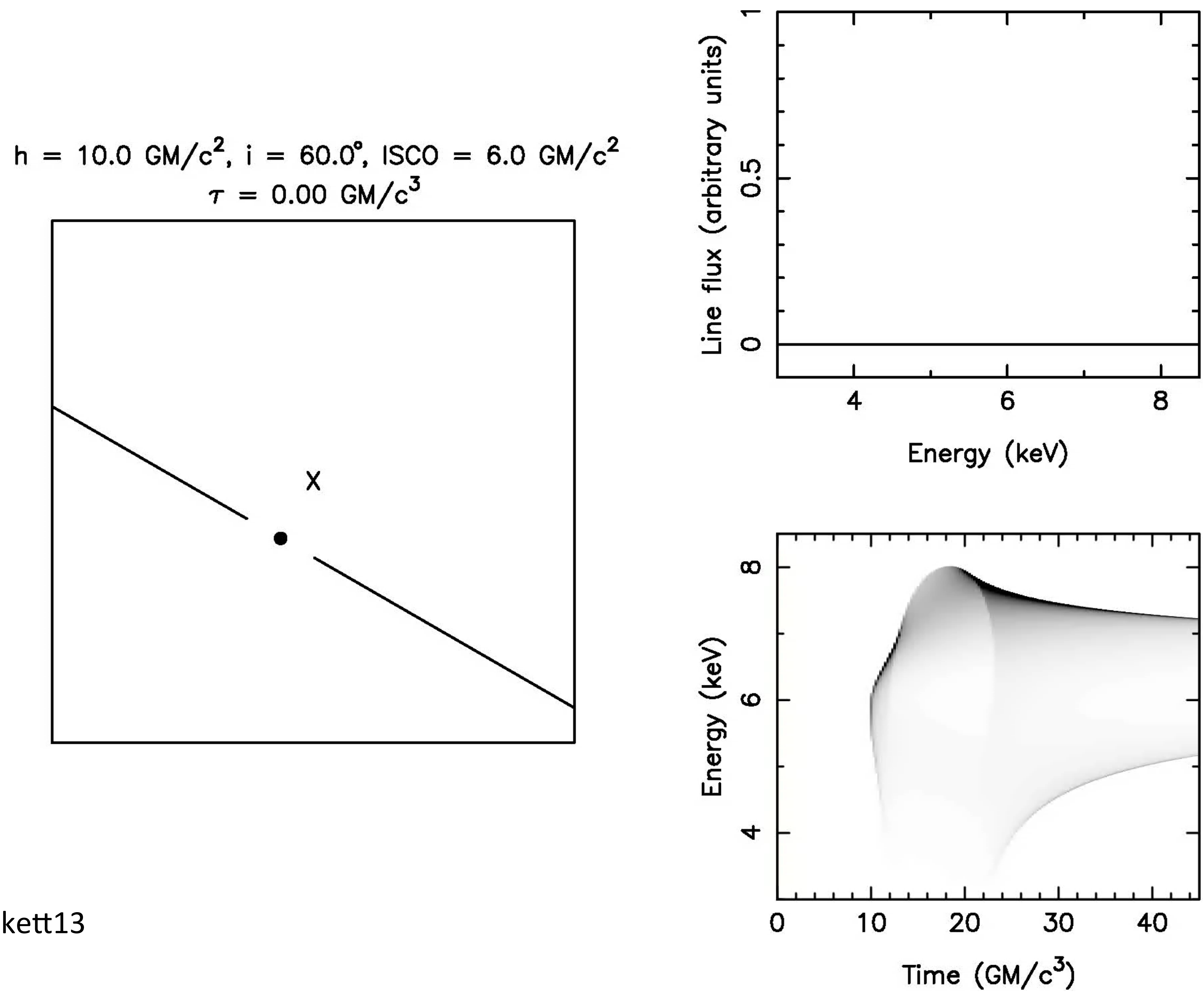
Reflected flux



See also Rossi+05

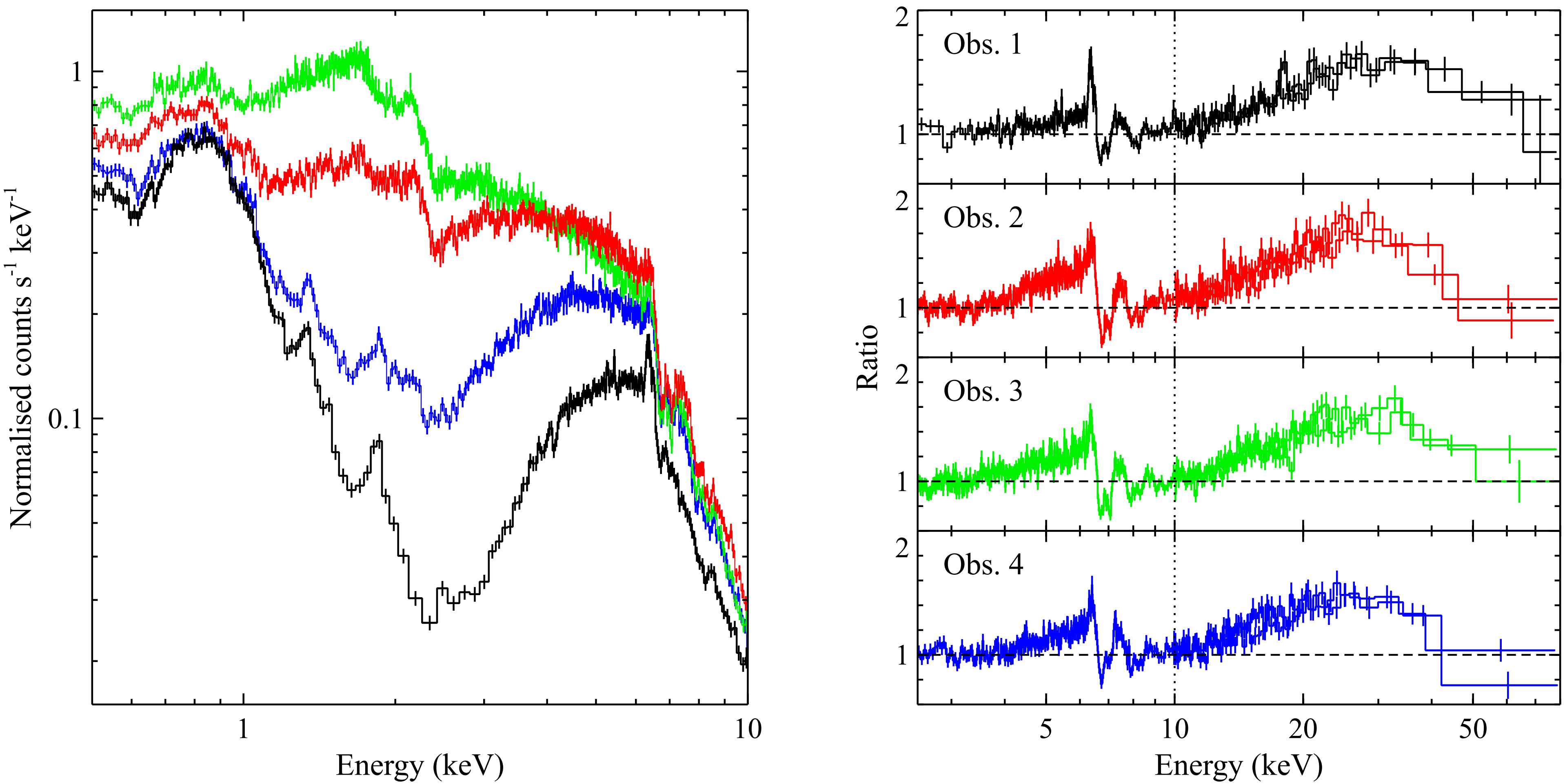
Powerlaw flux


Reflected flux
XTE J1650-500 Reis+12
10^{-7}
10^{-8}
$\mathrm{Flux}_{\mathrm{ReflionX}}$ (erg s^{-1} cm^{-2})
HIS-P1
HIS-P2
SIS-P3
SIS-P5
HIS-P6
Intrinsic change
Light Bending Effect
10^{-8}
10^{-7}
$\mathrm{Flux}_{\mathrm{Powerlaw}}$ (erg s^{-1} cm^{-2})
Powerlaw flux
See also Rossi+05

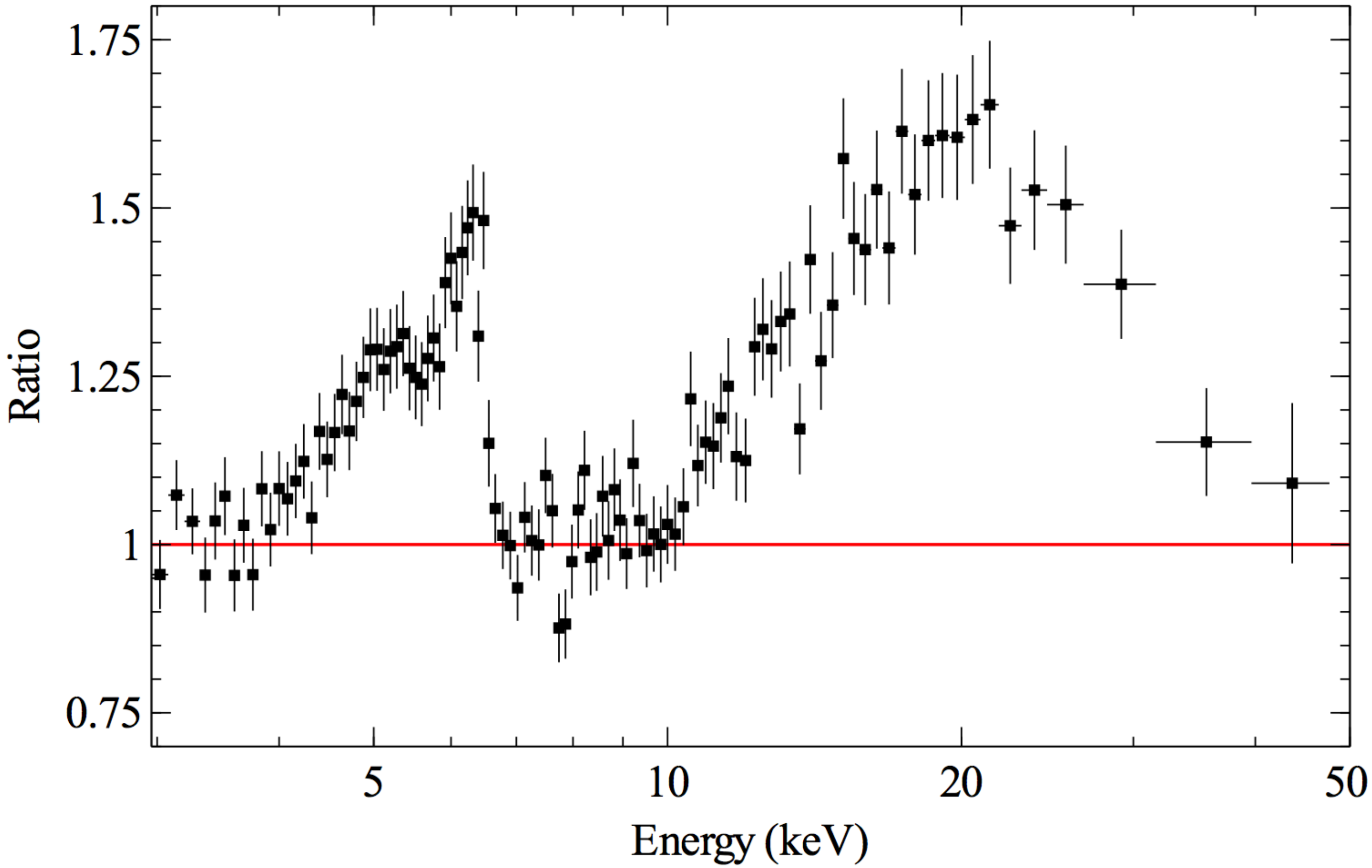

h = 10.0 GM/c^2, i = 60.0°, ISCO = 6.0 GM/c^2
τ = 0.00 GM/c^3
X
Line flux (arbitrary units)
0
0.5
1
4
6
8
Energy (keV)
Energy (keV)
4
6
8
0
10
20
30
40
Time (GM/c^3)

Cackett13

NGC1365 XMM+NuSTAR



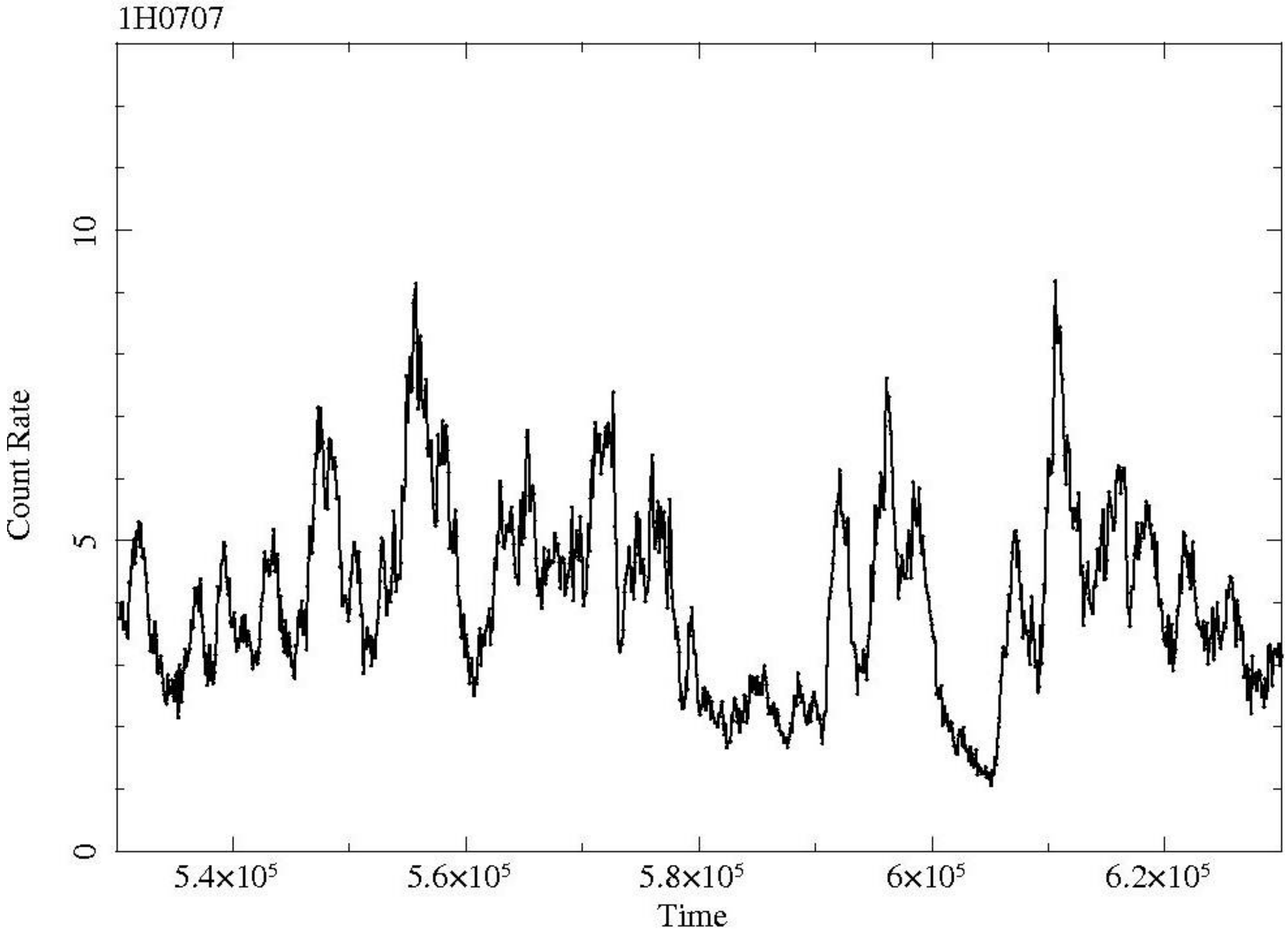
Walton+14

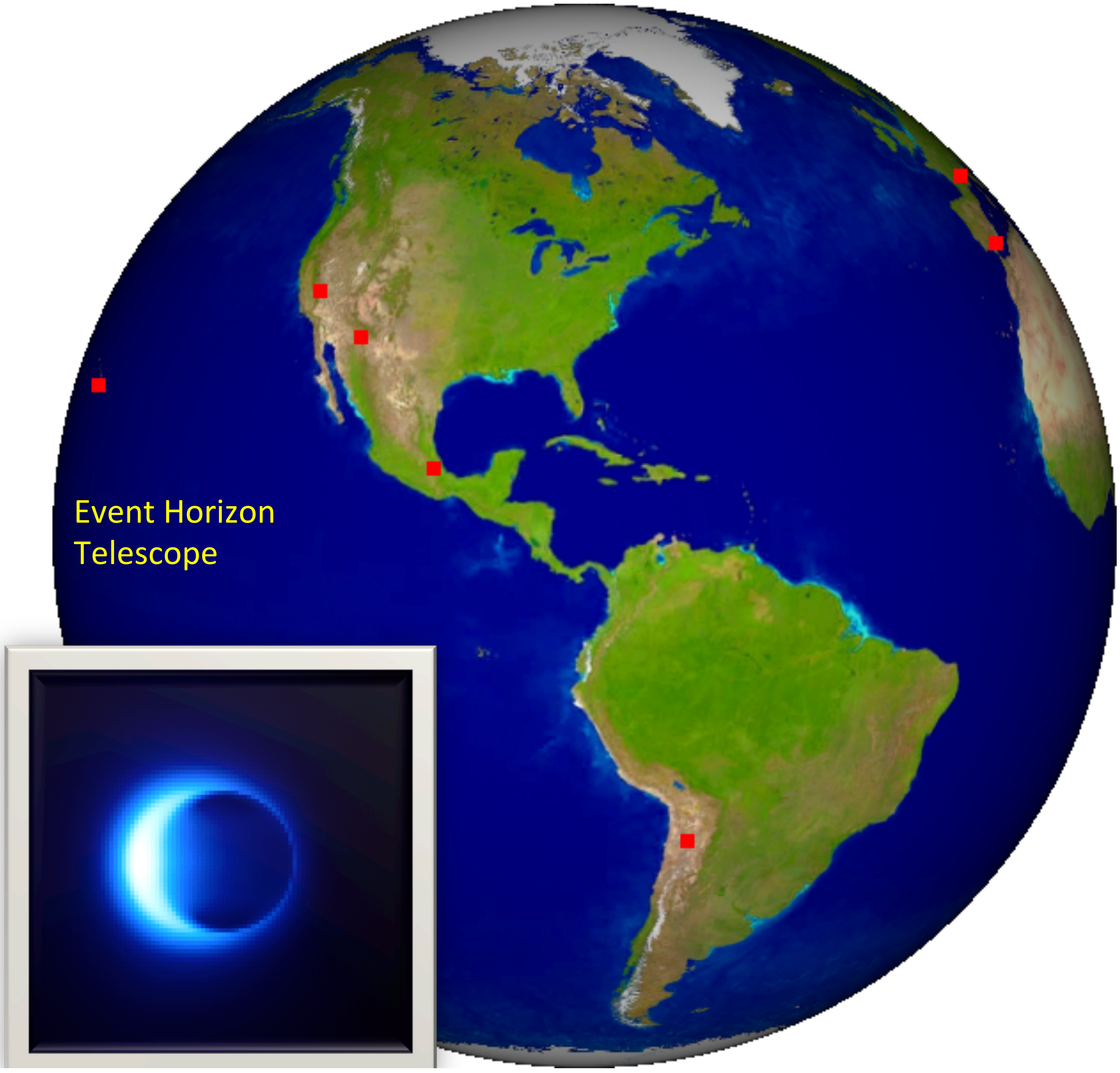


The *NuSTAR* spectrum of Mrk 335: Extreme relativistic effects within 2 gravitational radii of the event horizon?

M. L. Parker,[1*] D. R. Wilkins,[1,2] A. C. Fabian,[1] D. Grupe,[3] T. Dauser,[4] G. Matt,[5] F. A. Harrison,[6] L. Brenneman,[7] S. E. Boggs,[8] F. E. Christensen,[9] W. W. Craig,[10,11] L. C. Gallo,[2] C. J. Hailey,[11] E. Kara,[1] S. Komossa,[12] A. Marinucci,[5] J. M. Miller,[13] G. Risaliti,[7,14] D. Stern,[15] D. J. Walton[6] and W. W. Zhang[16]

Rapid variability in AGN

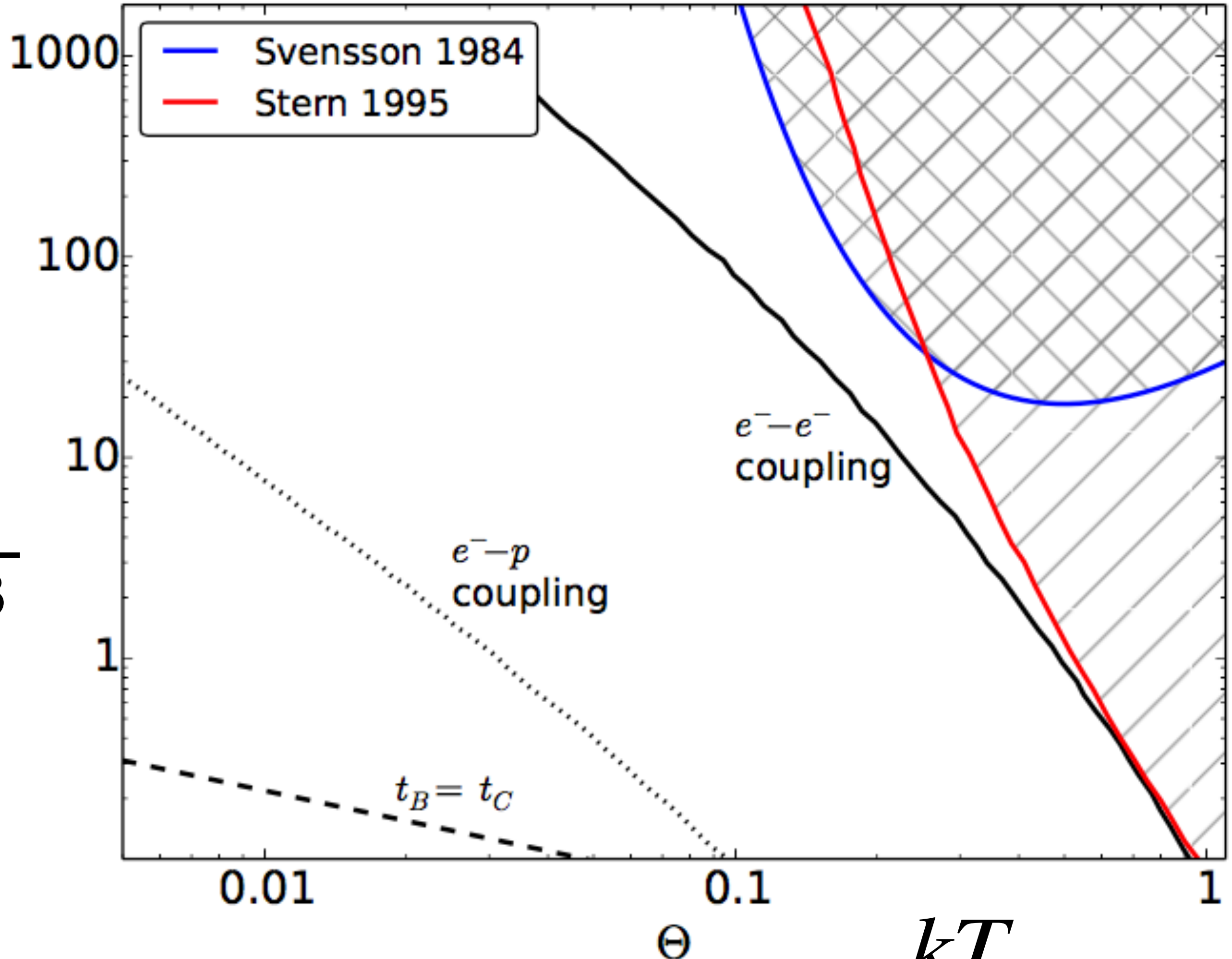



Event Horizon
Telescope

CORONAL PHYSICS

compactness

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

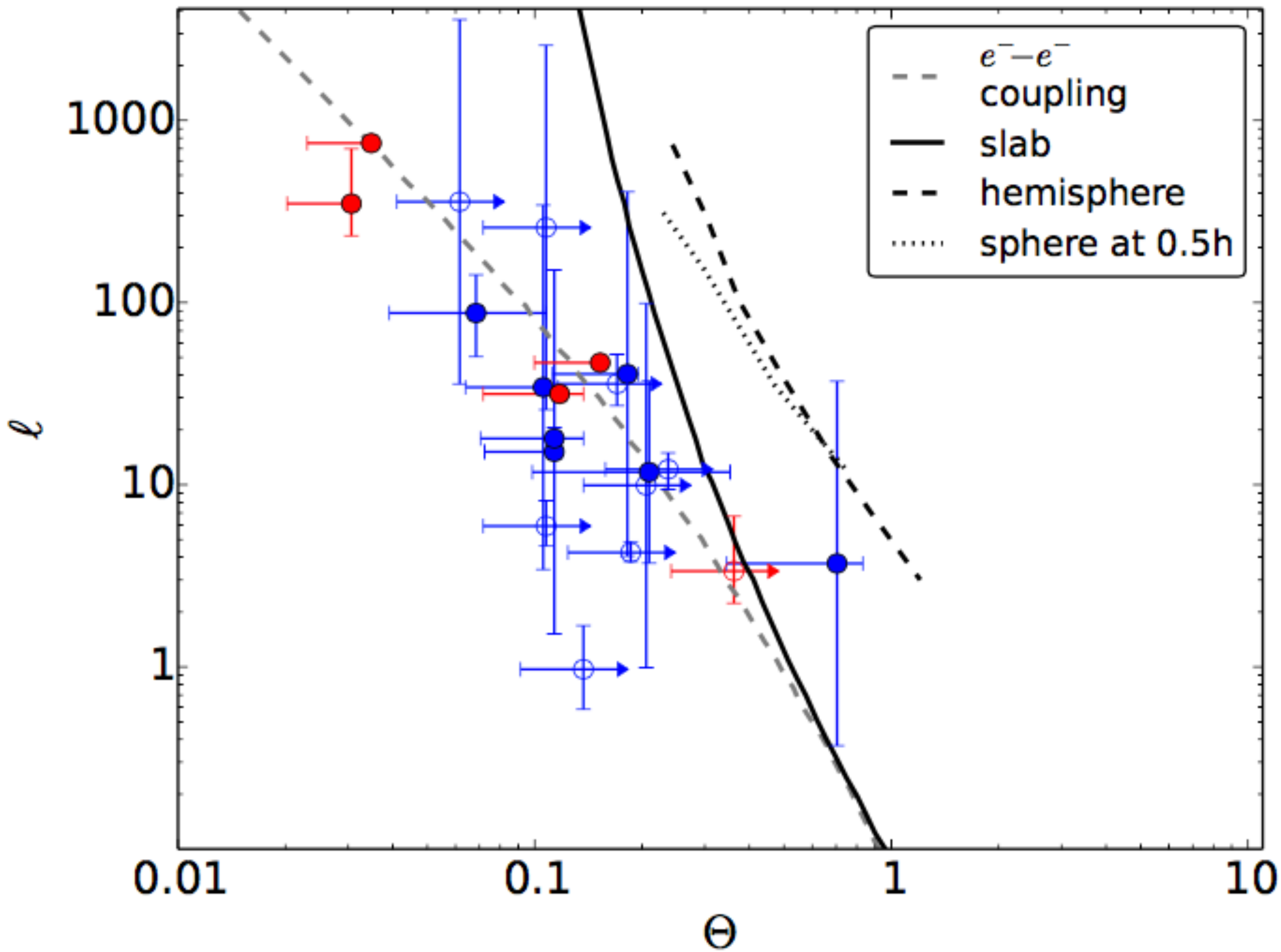


$$\frac{kT}{m_e c^2}$$

temperature

Fabian+15

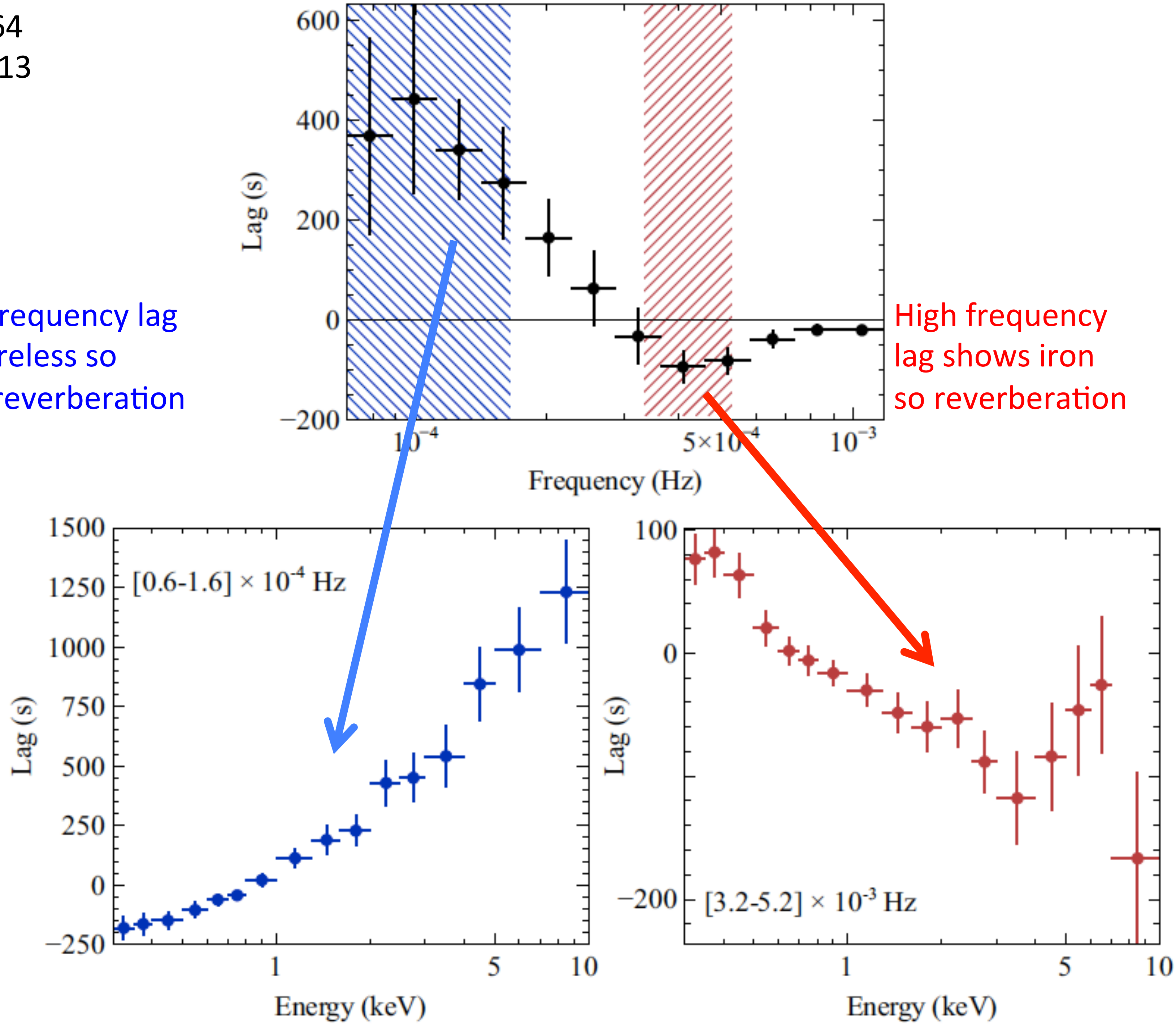
NuSTAR results



Corona lies a few r_g above the disc

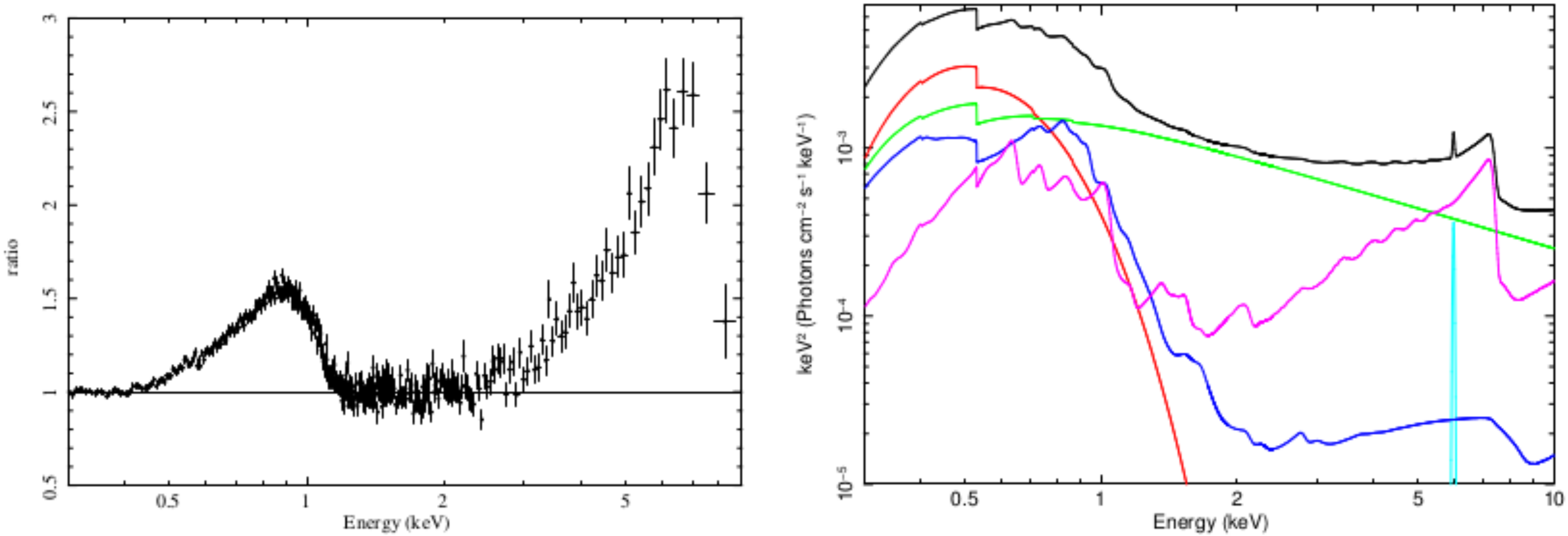
Wilkins&Fabian13

Akn564
Kara+13

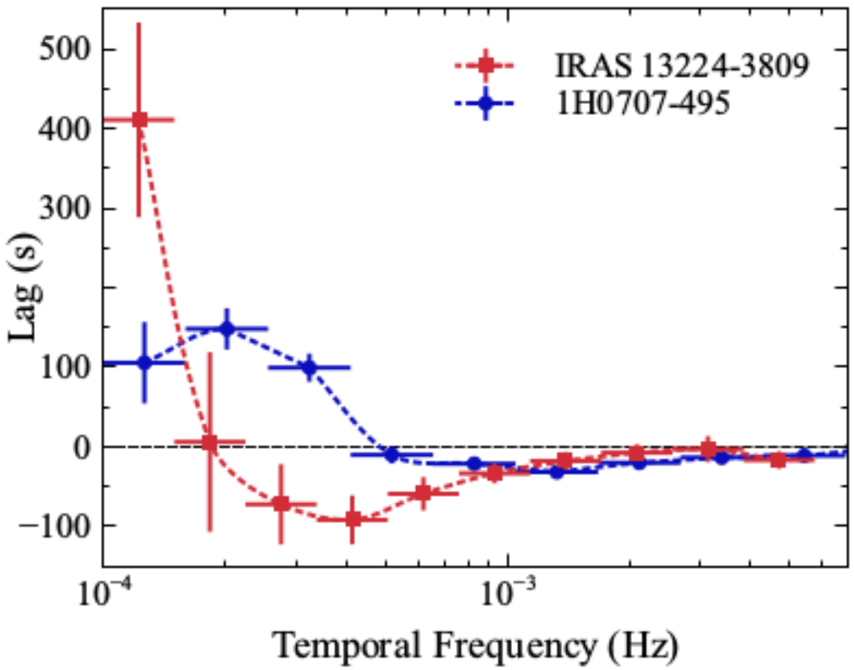


Low frequency lag featureless so NOT reverberation

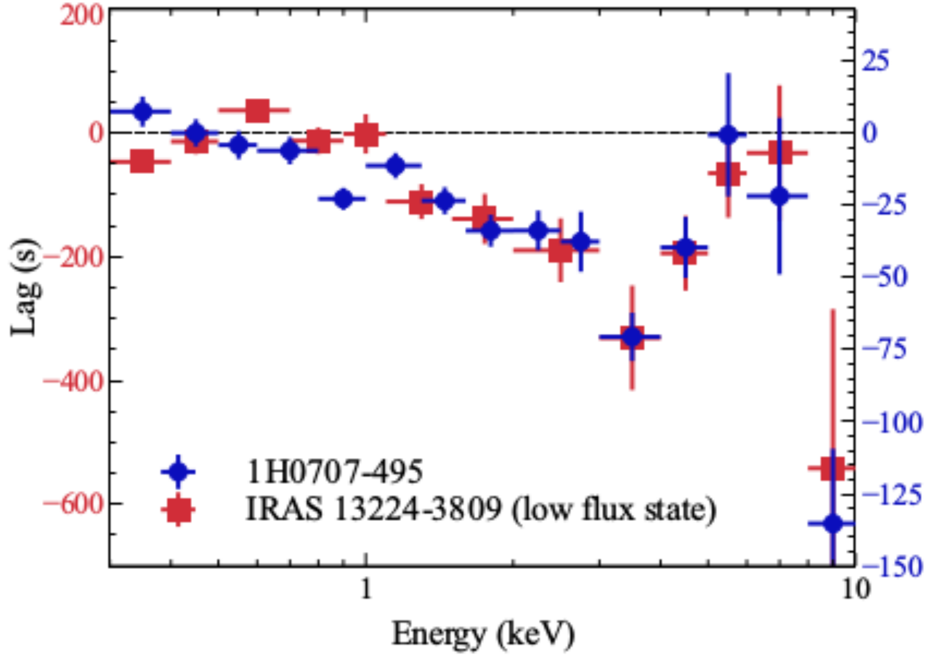
High frequency lag shows iron so reverberation



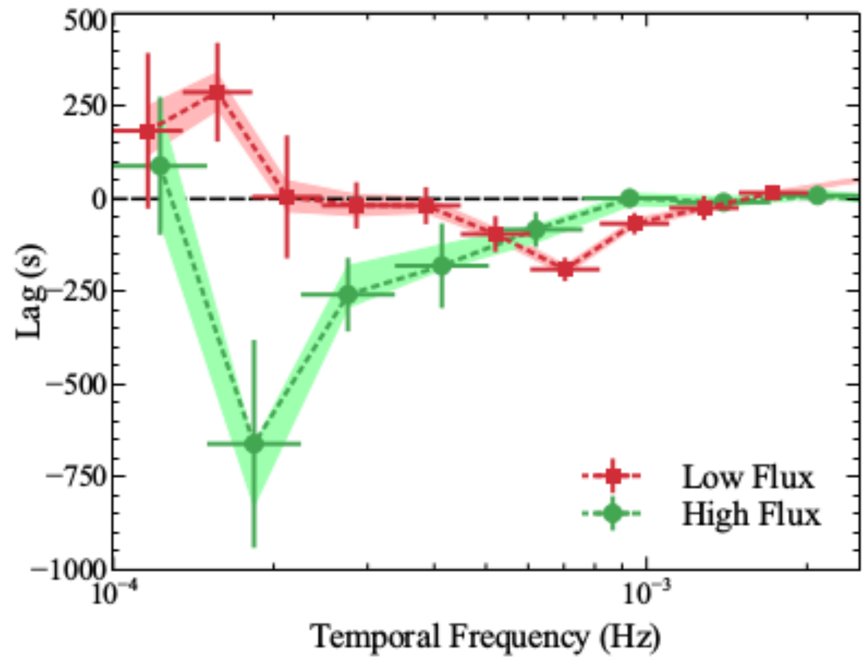
ratio
Energy (keV)
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
Energy (keV)



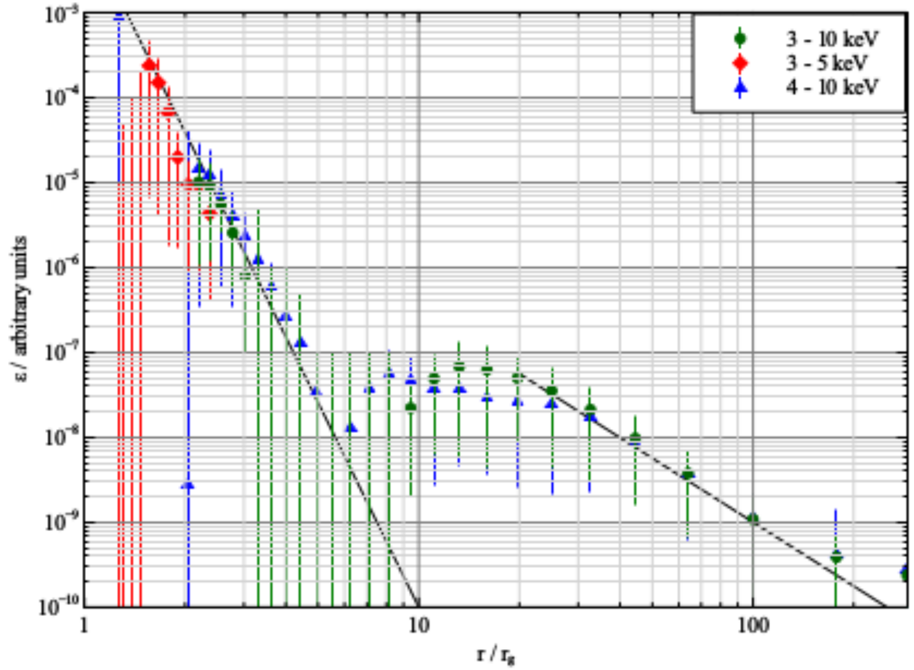
IRAS 13224-3809
1H0707-495
Lag (s)
Temporal Frequency (Hz)



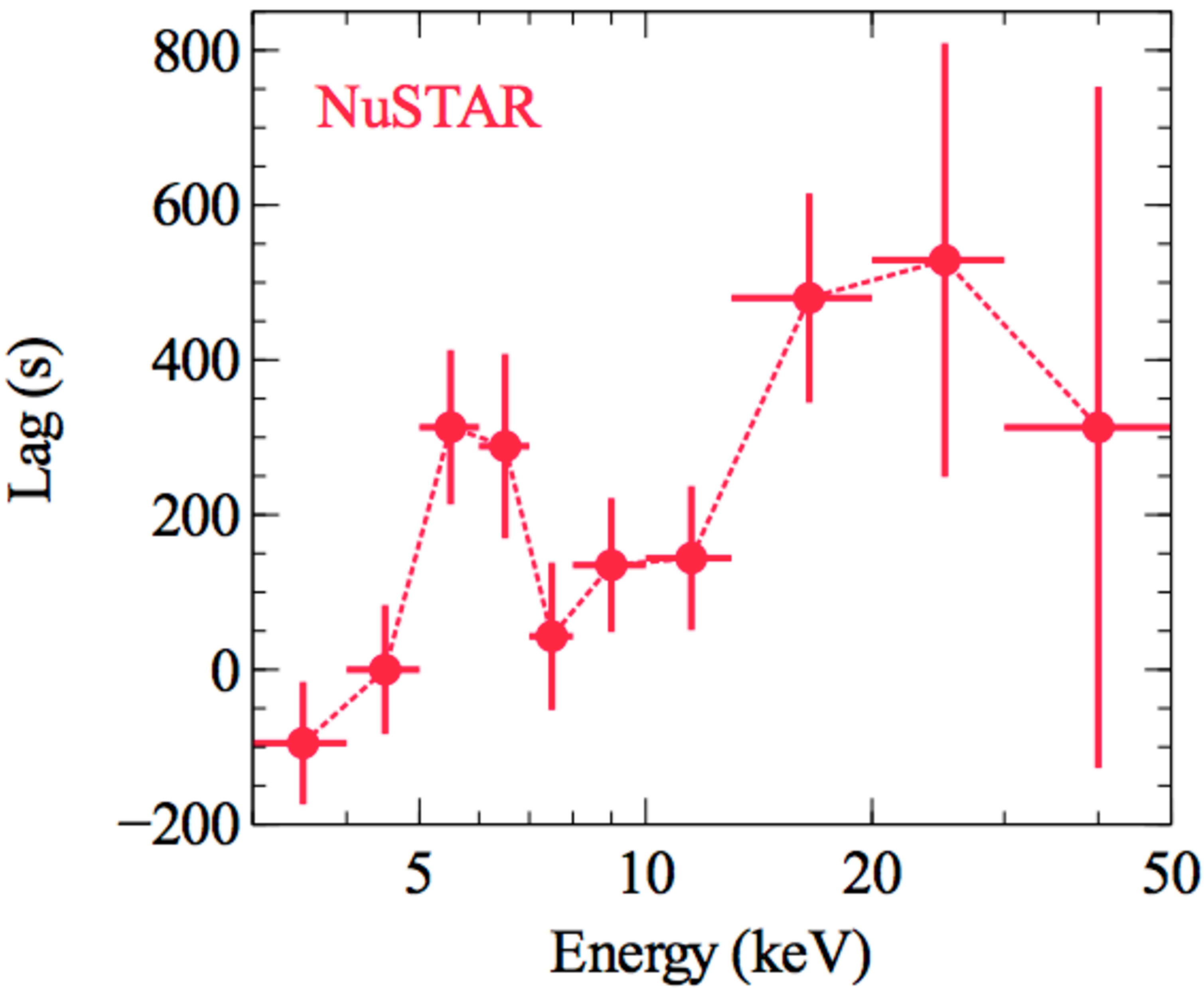
1H0707-495
IRAS 13224-3809 (low flux state)
Lag (s)
Energy (keV)



Low Flux
High Flux
Lag (s)
Temporal Frequency (Hz)

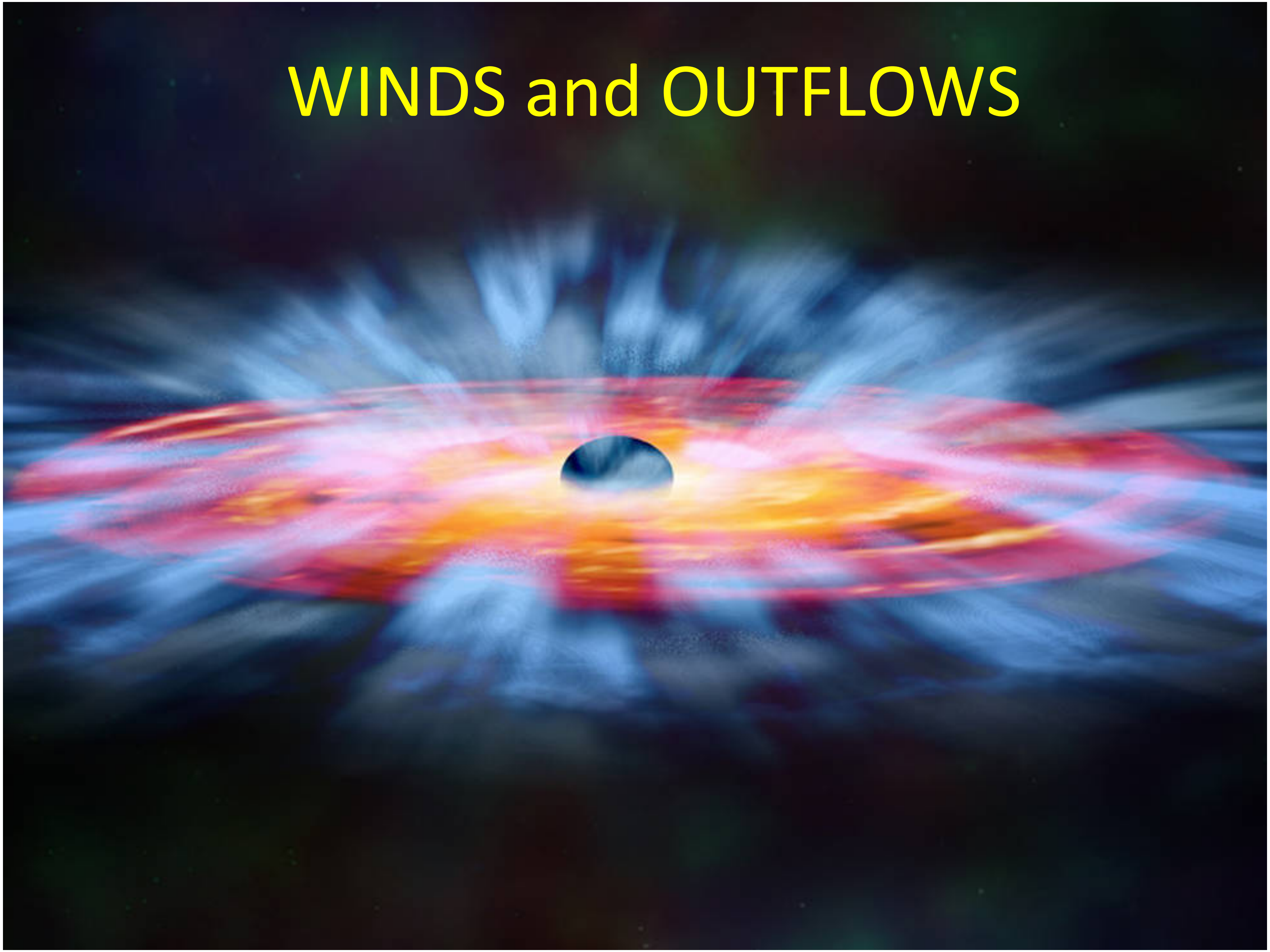


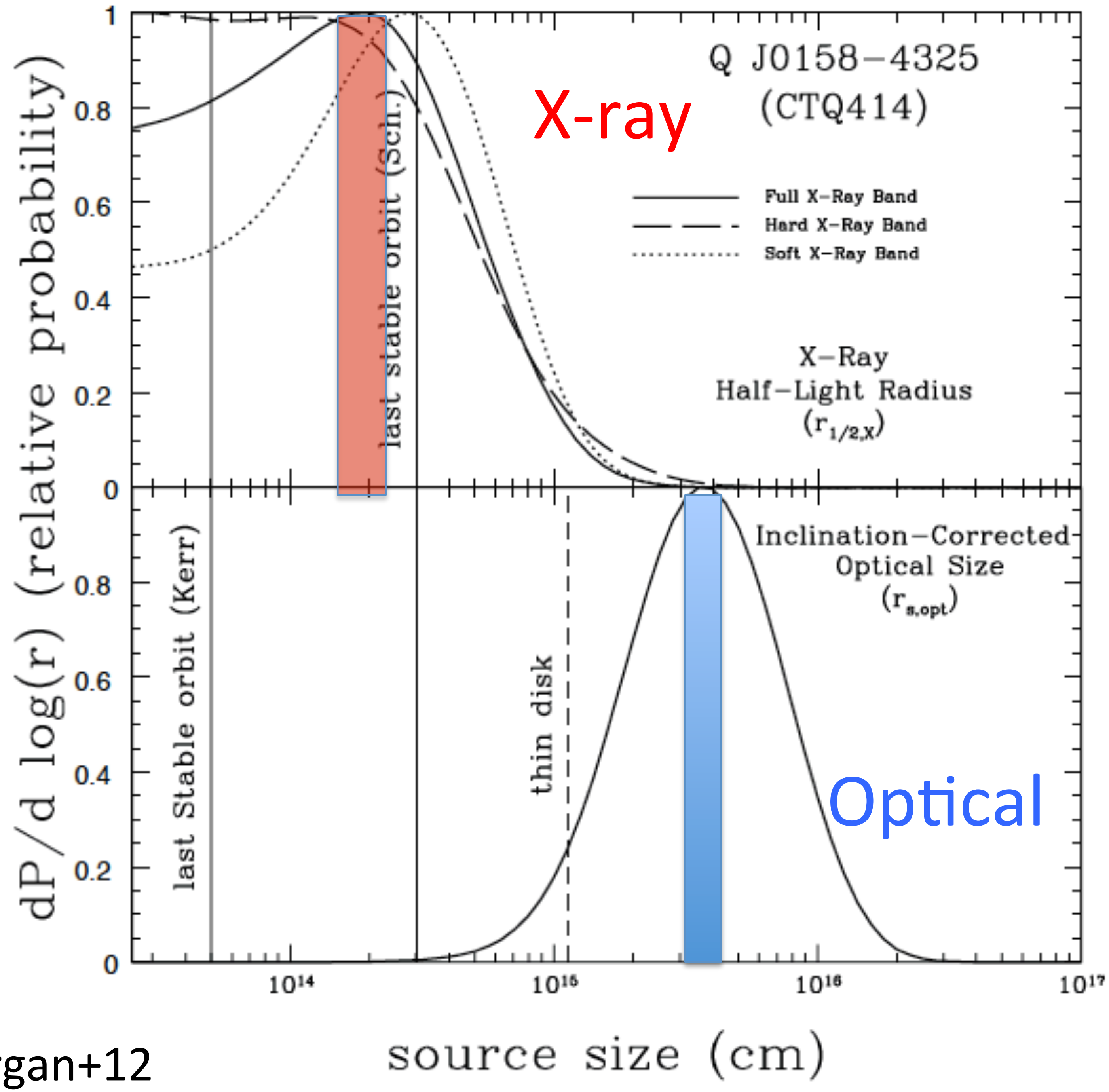
3 - 10 keV
3 - 5 keV
4 - 10 keV
ε / arbitrary units
r / r_g



Kara+14   SWIFT J2127

WINDS and OUTFLOWS

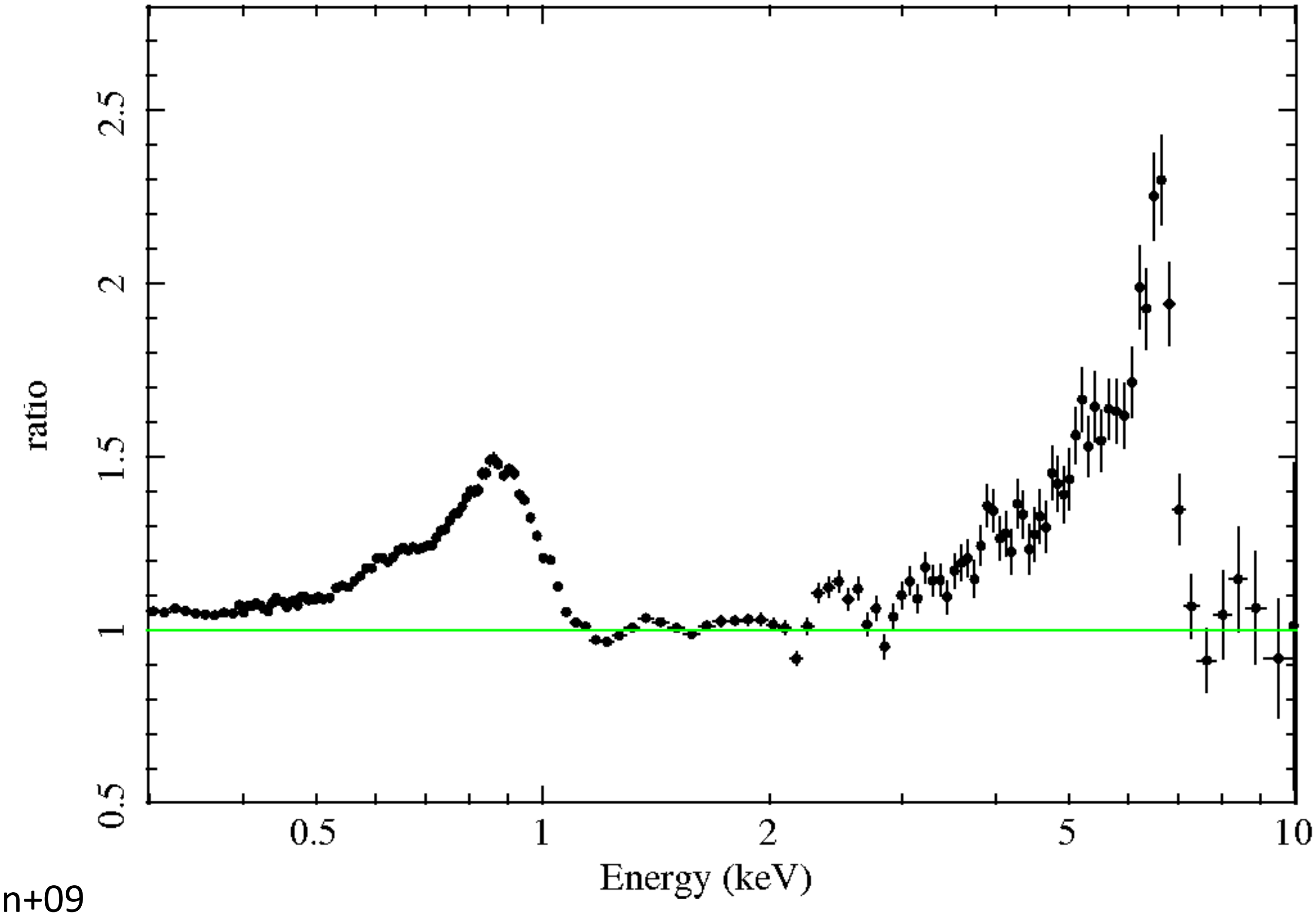




Q J0158−4325
(CTQ414)
X-ray
Full X−Ray Band
Hard X−Ray Band
Soft X−Ray Band
X−Ray
Half−Light Radius
($r_{1/2,X}$)
last stable orbit (Sch.)
last Stable orbit (Kerr)
thin disk
Inclination−Corrected
Optical Size
($r_{s,opt}$)
Optical
dP/d log(r) (relative probability)
source size (cm)
0
0.2
0.4
0.6
0.8
1
10^{14}
10^{15}
10^{16}
10^{17}

Morgan+12

Broad iron-L and iron-K emission lines (XMM)



Fabian+09