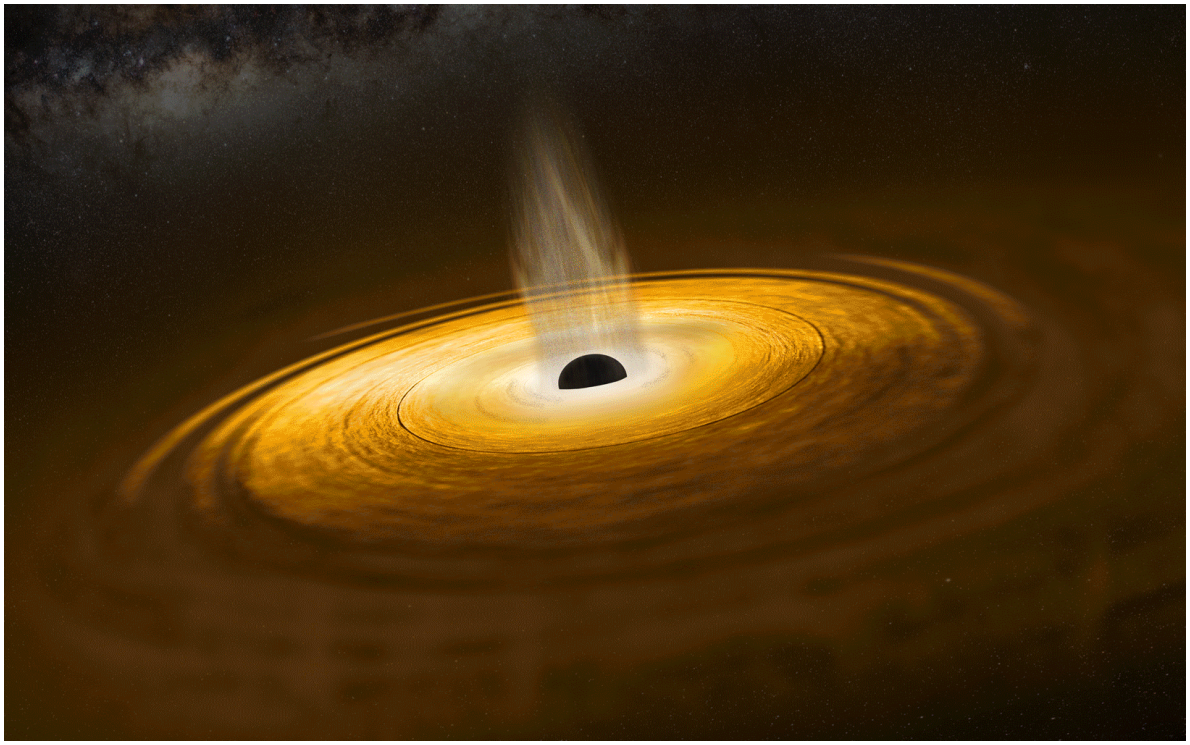
Into the Heart of the AGN IRAS13224-3809

Andy Fabian

Institute of Astronomy, University of Cambridge

With the help of Michael Parker, Will Alston, Jiachen Jiang, Ciro Pinto, Chris Reynolds, Javier Garcia, Thomas Dauser, Erin Kara and others



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IRAS13224-3809

- ROSAT: Boller+93; 97
- z=0.0667; NLS1, RQ (5mJy at 1.4 GHz)

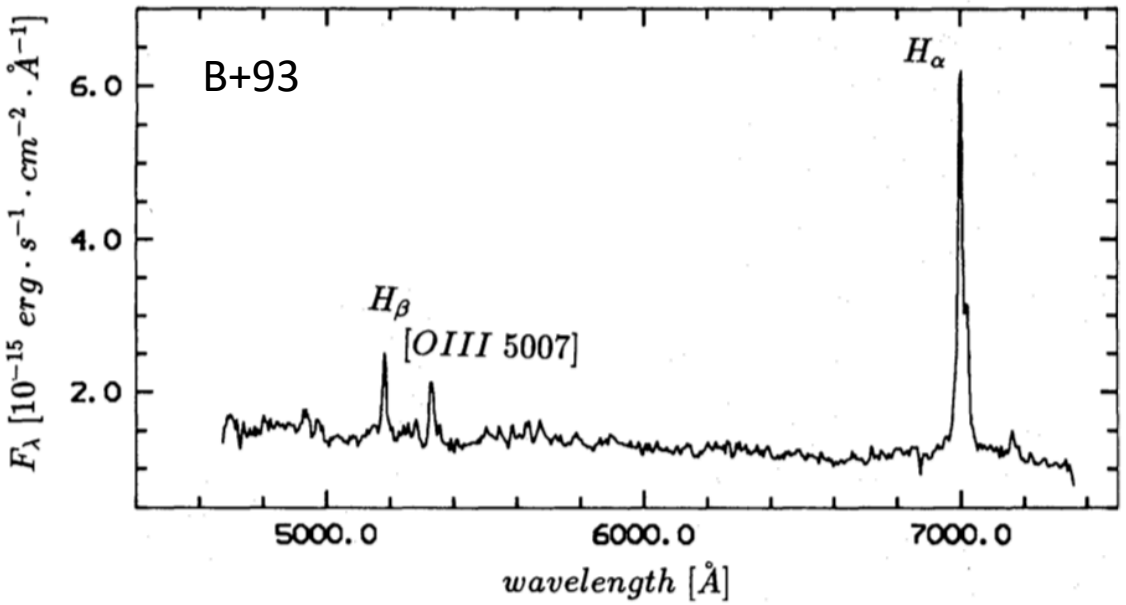
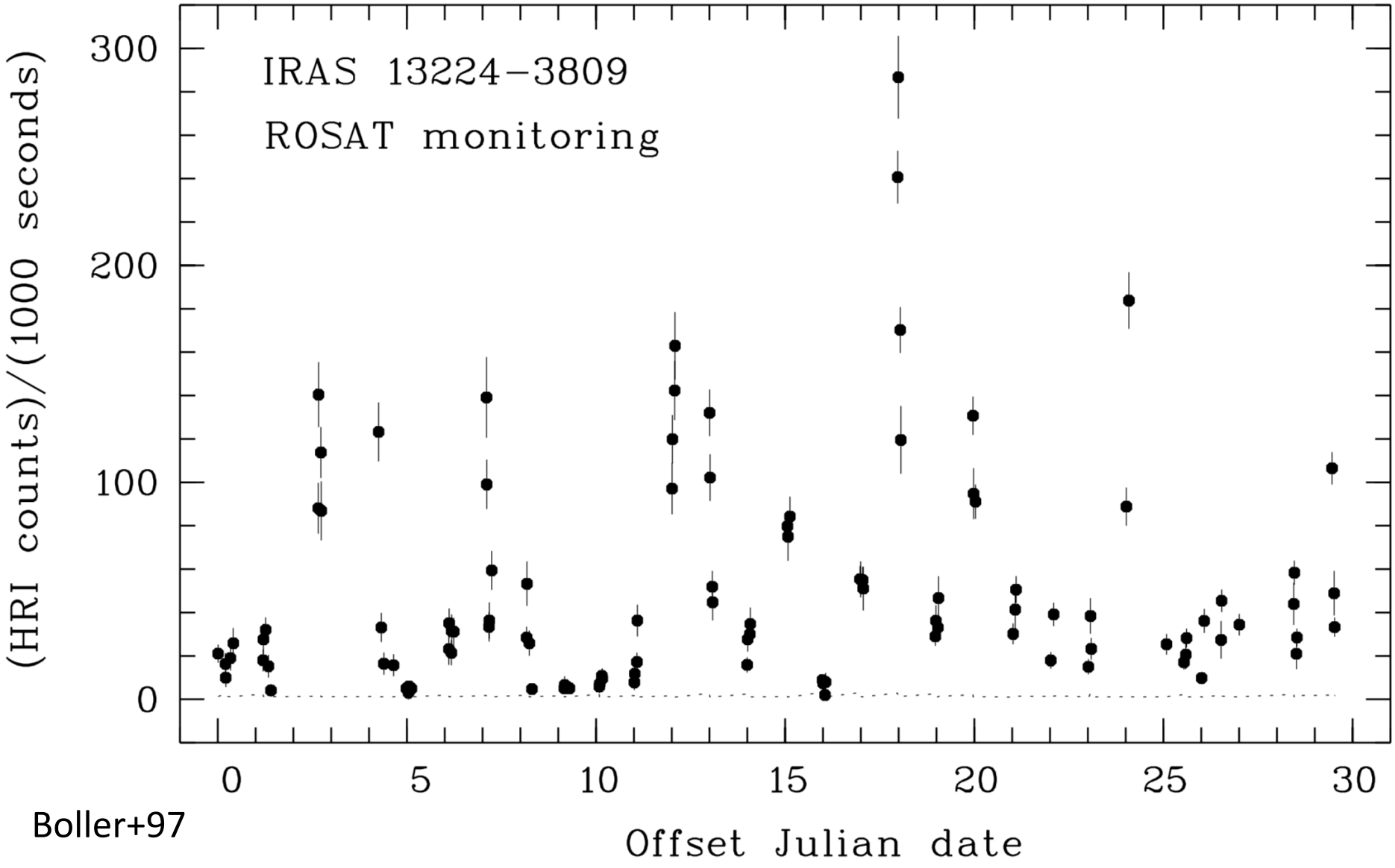


Fig. 4. Optical spectrum of IRAS 13224-3809 obtained at the 2.2 m telescope at La Silla in January, 1993

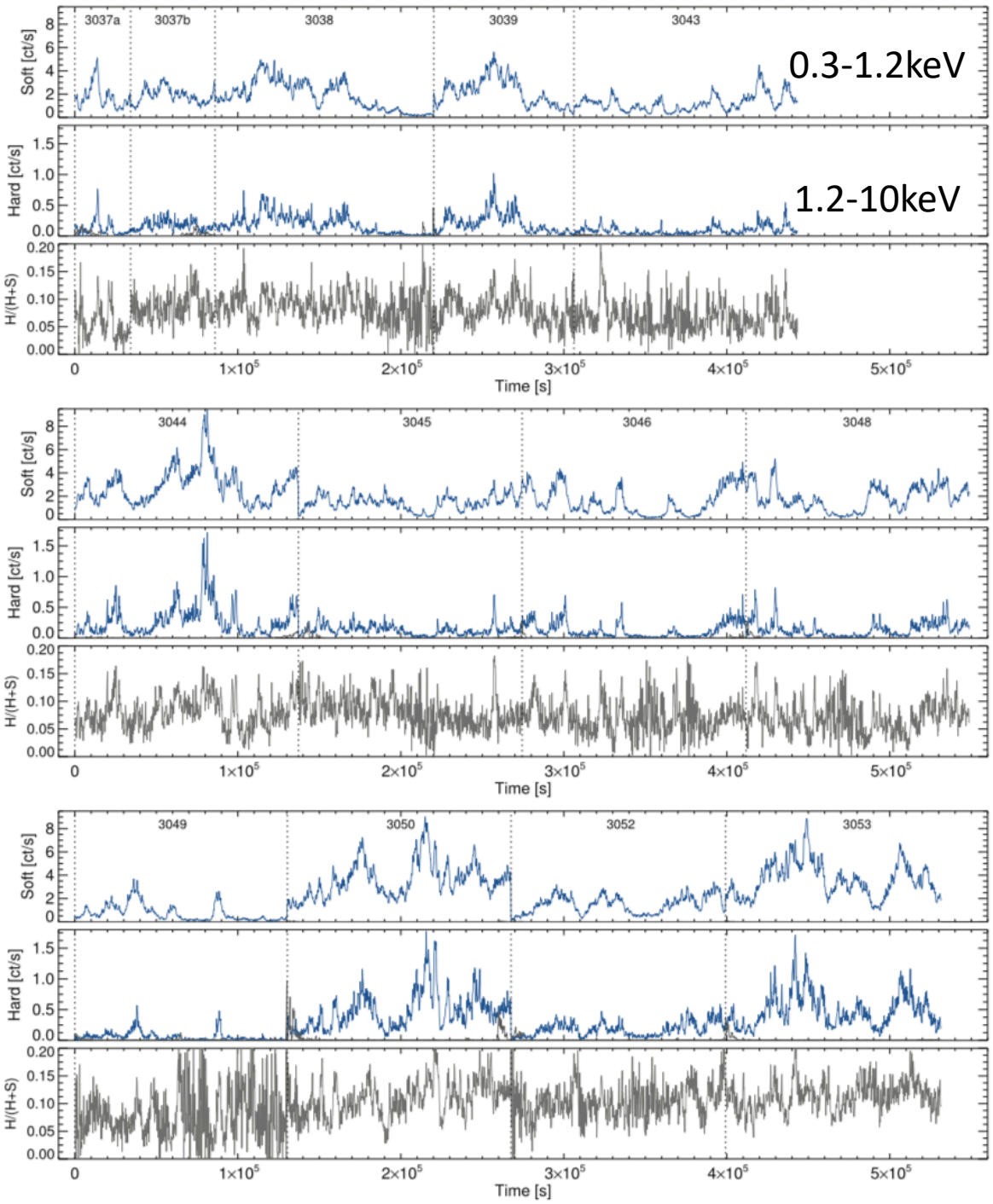
EXTREME VARIABILITY MAKES IRAS13224-3809 INTERESTING



Boller+97

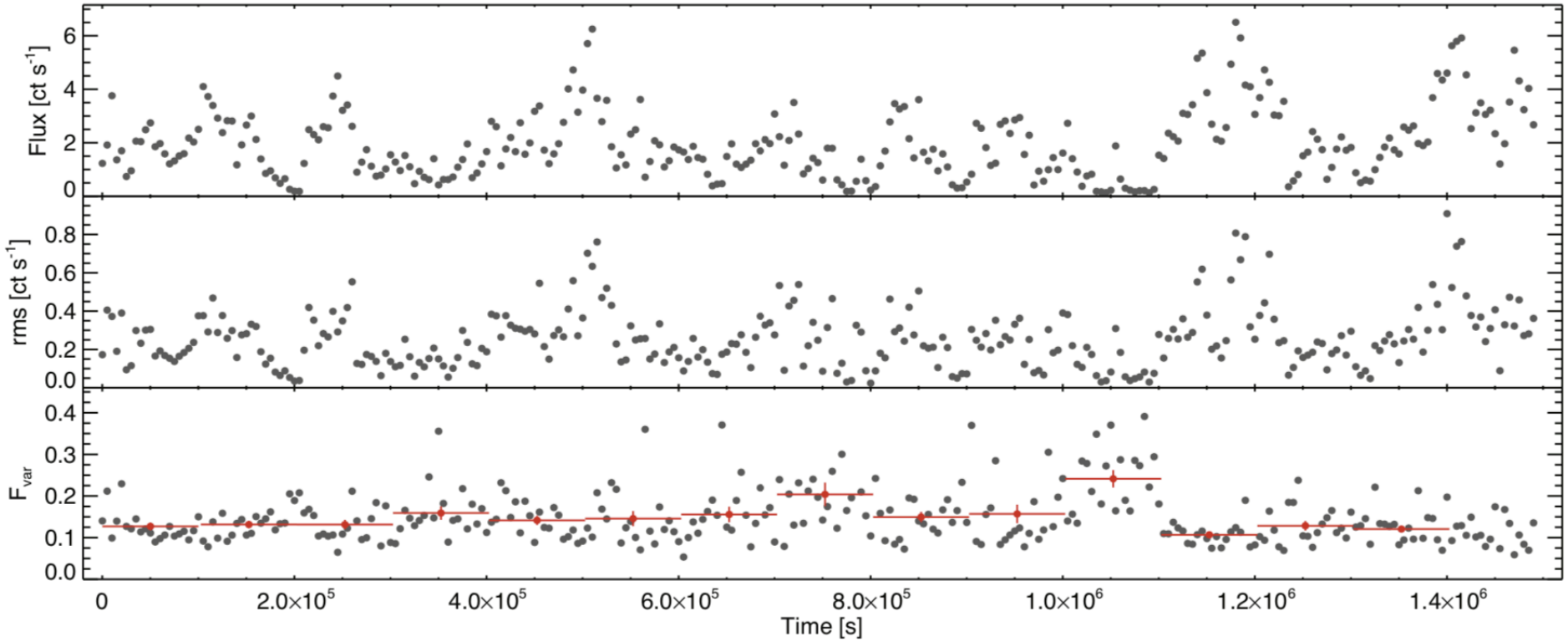
200s bins

IRAS13224-3809
XMM 1.5 Ms
2016

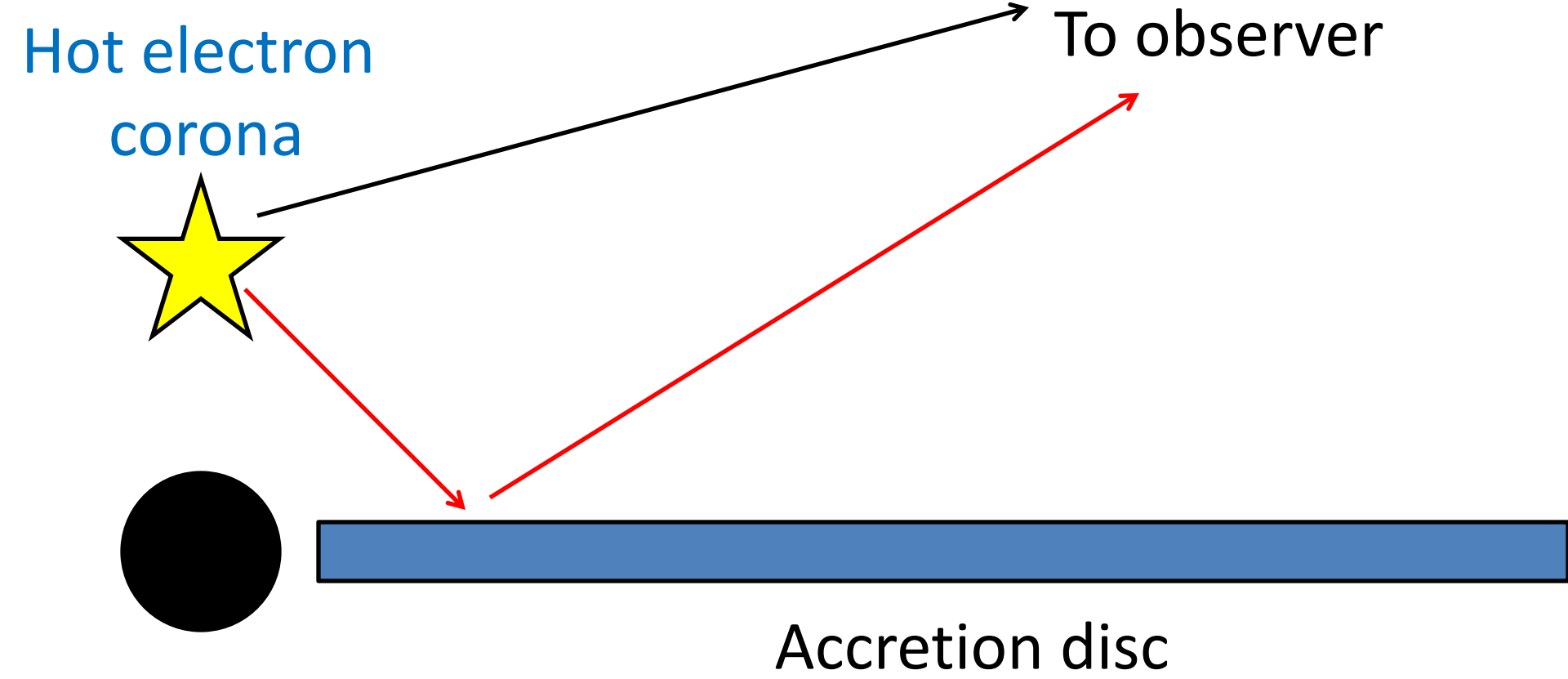


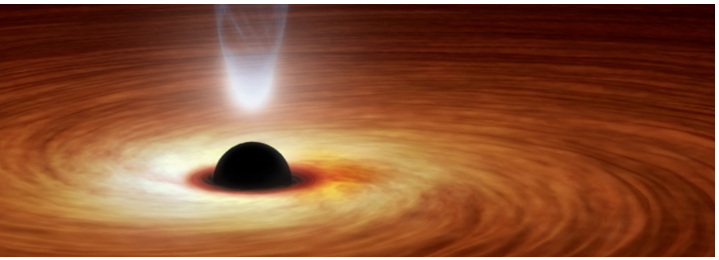
Alston+19

Alston+19 5ks bins 0.3-1.2 keV band

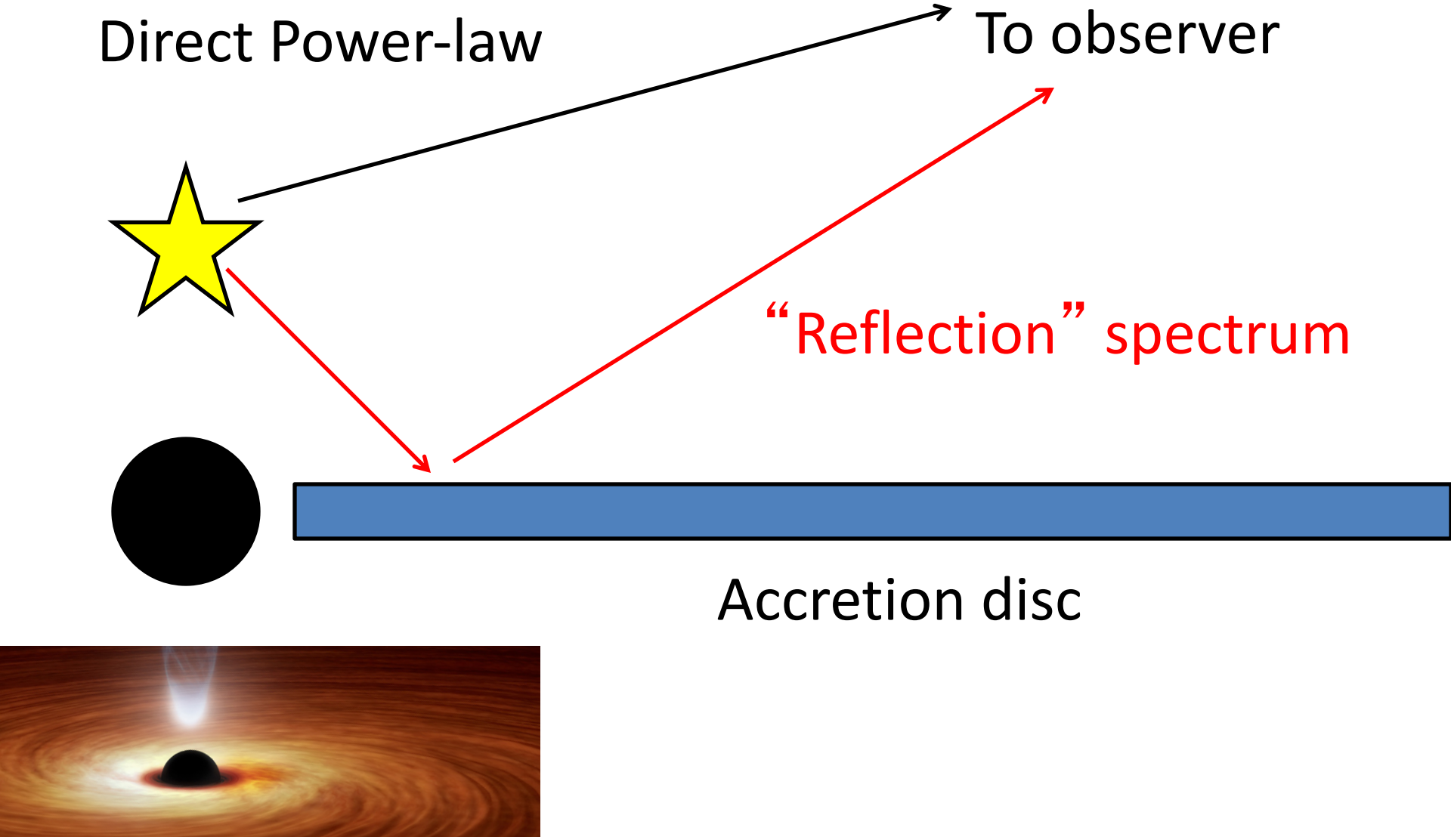


$$Rms \propto flux^{2/3}$$

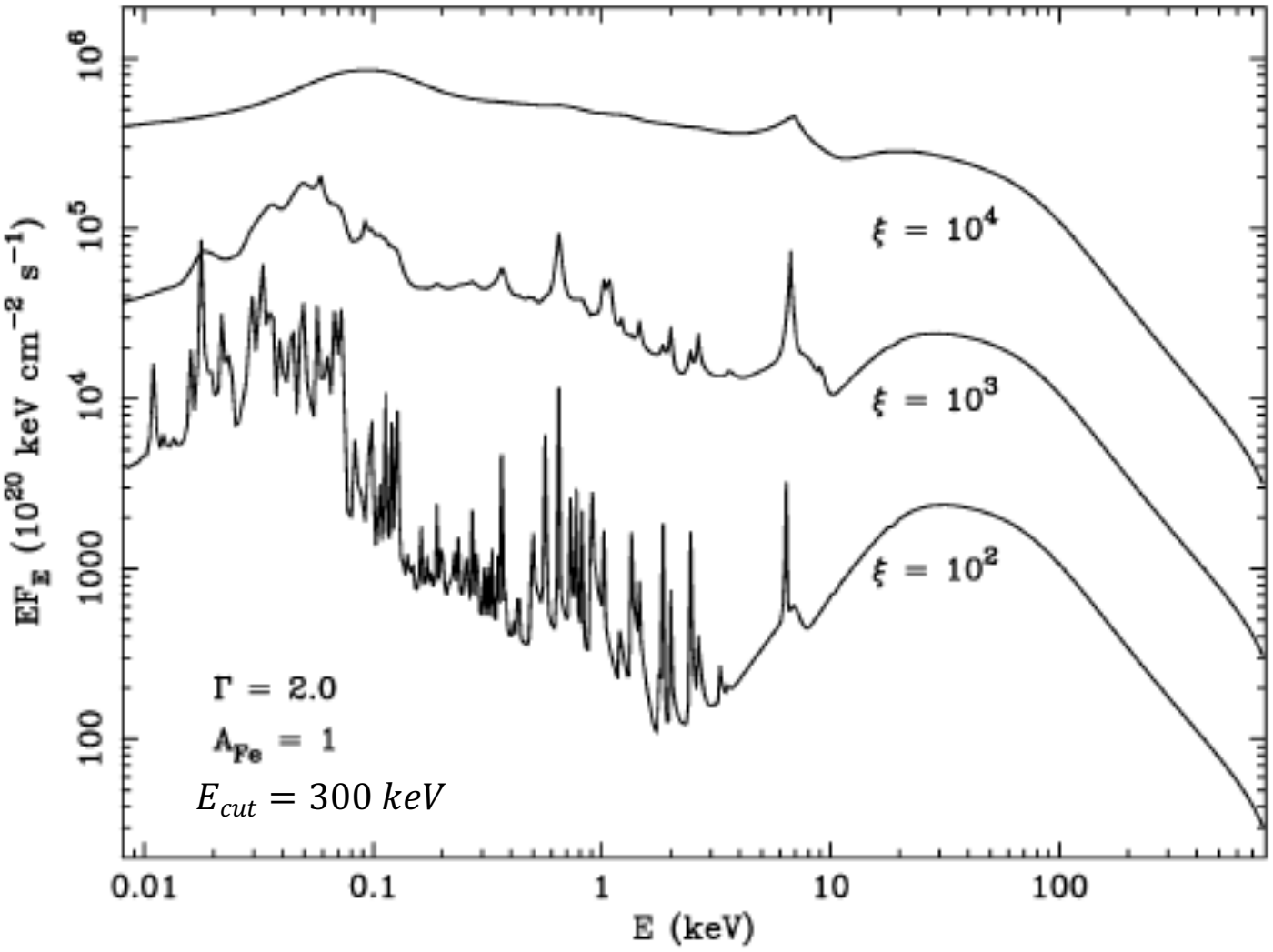




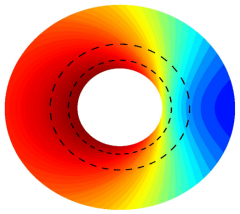
Lamppost model


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

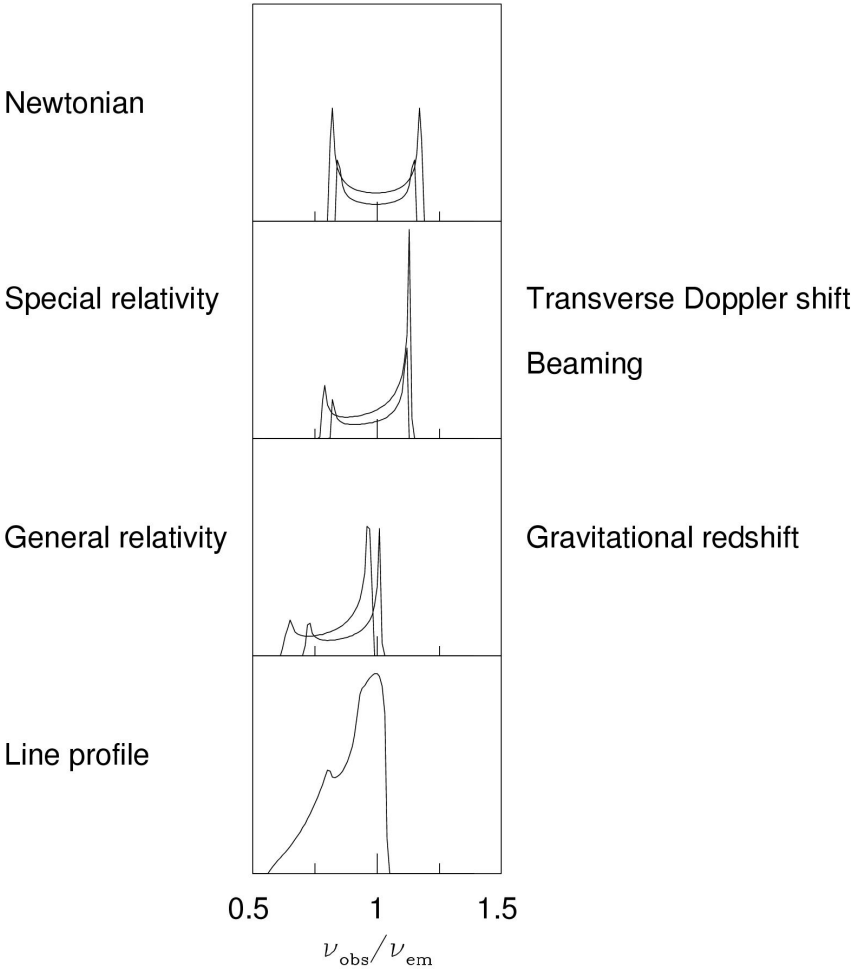
Reflection from ionized gas Ross+Fabian93,05; Garcia+13

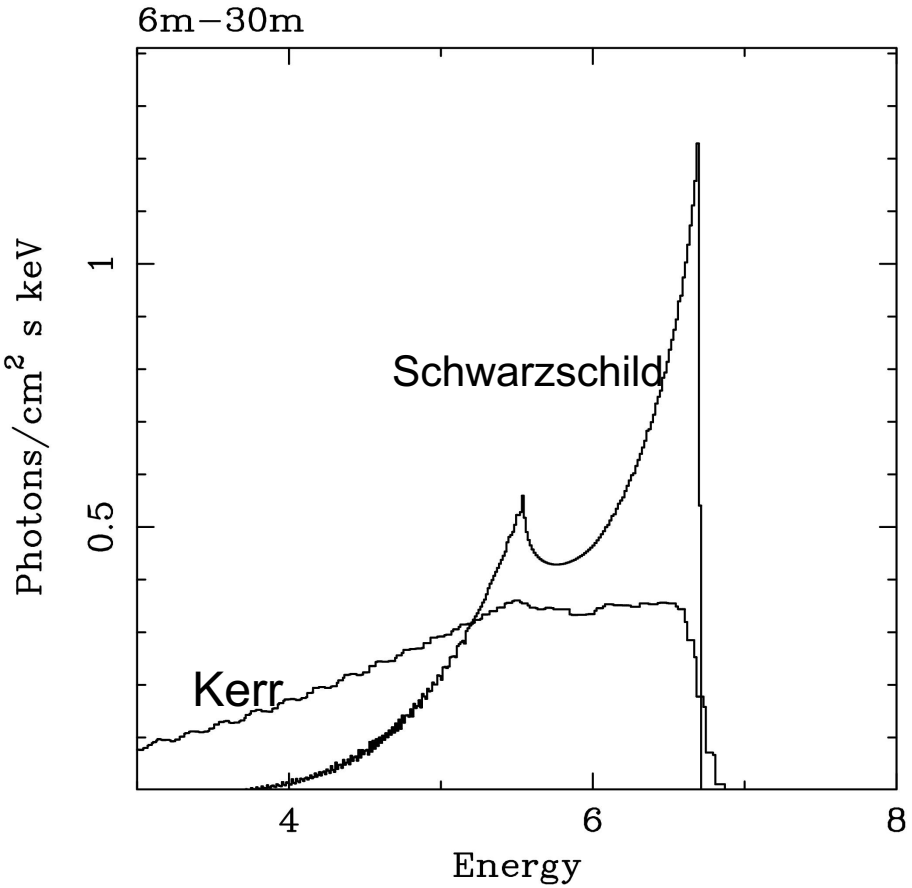


Ionization Parameter $\xi = L/nr^2$



Relativistically Broadened Line



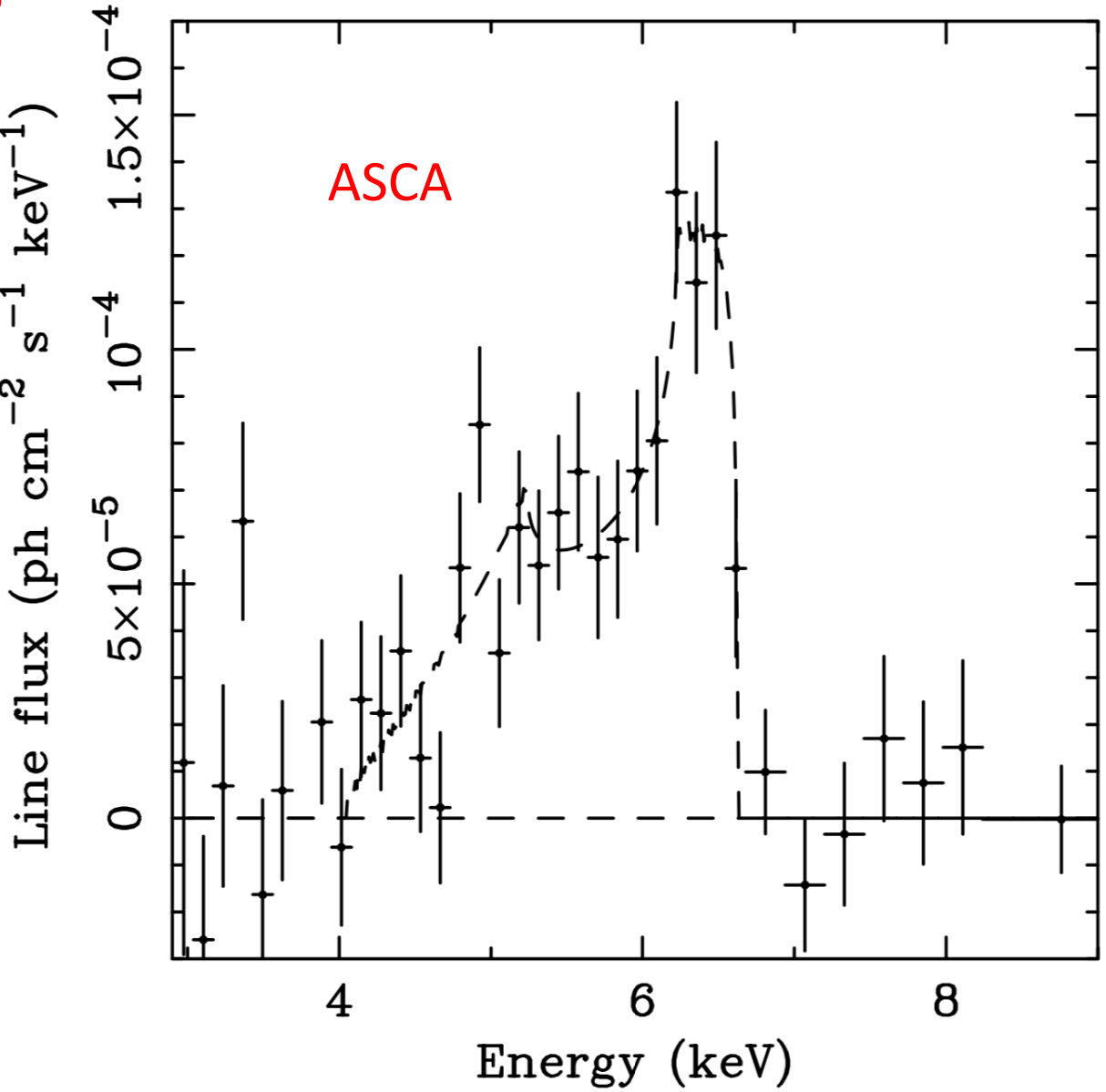


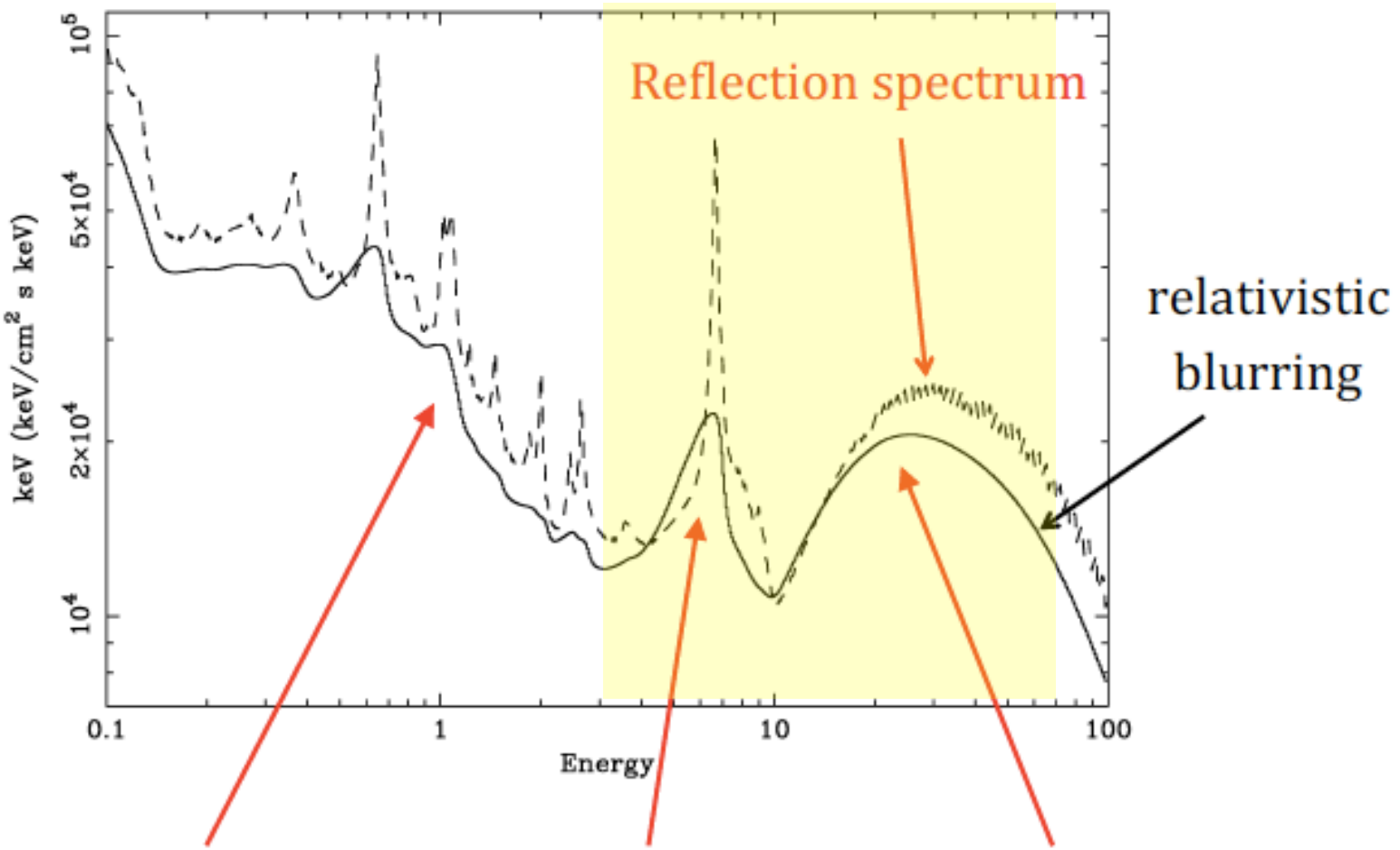
Fabian+89, Laor 91…

Use to measure spin

e.g Brenneman+09

Tanaka+95

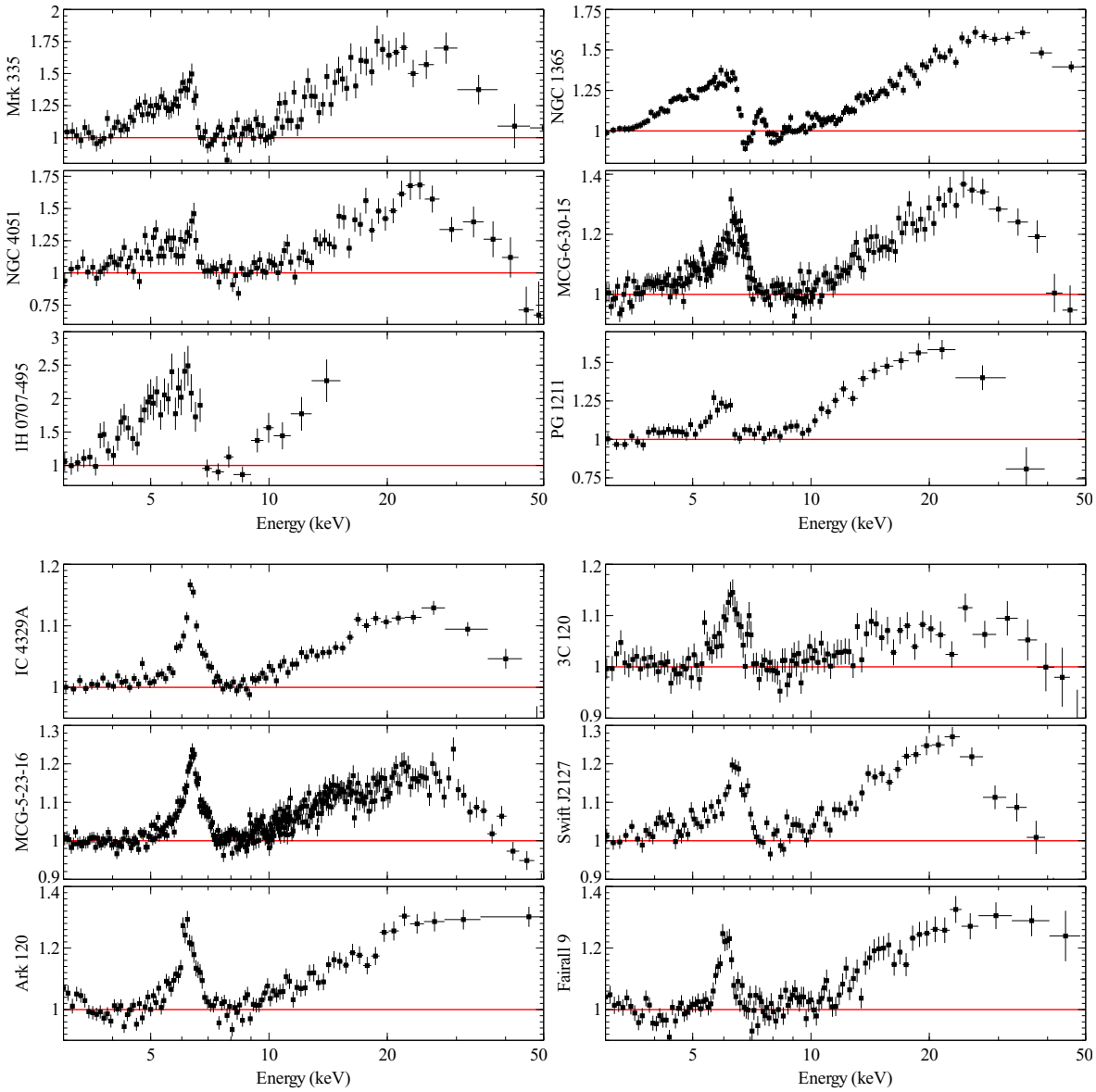




Soft excess – broad iron line – Compton hump

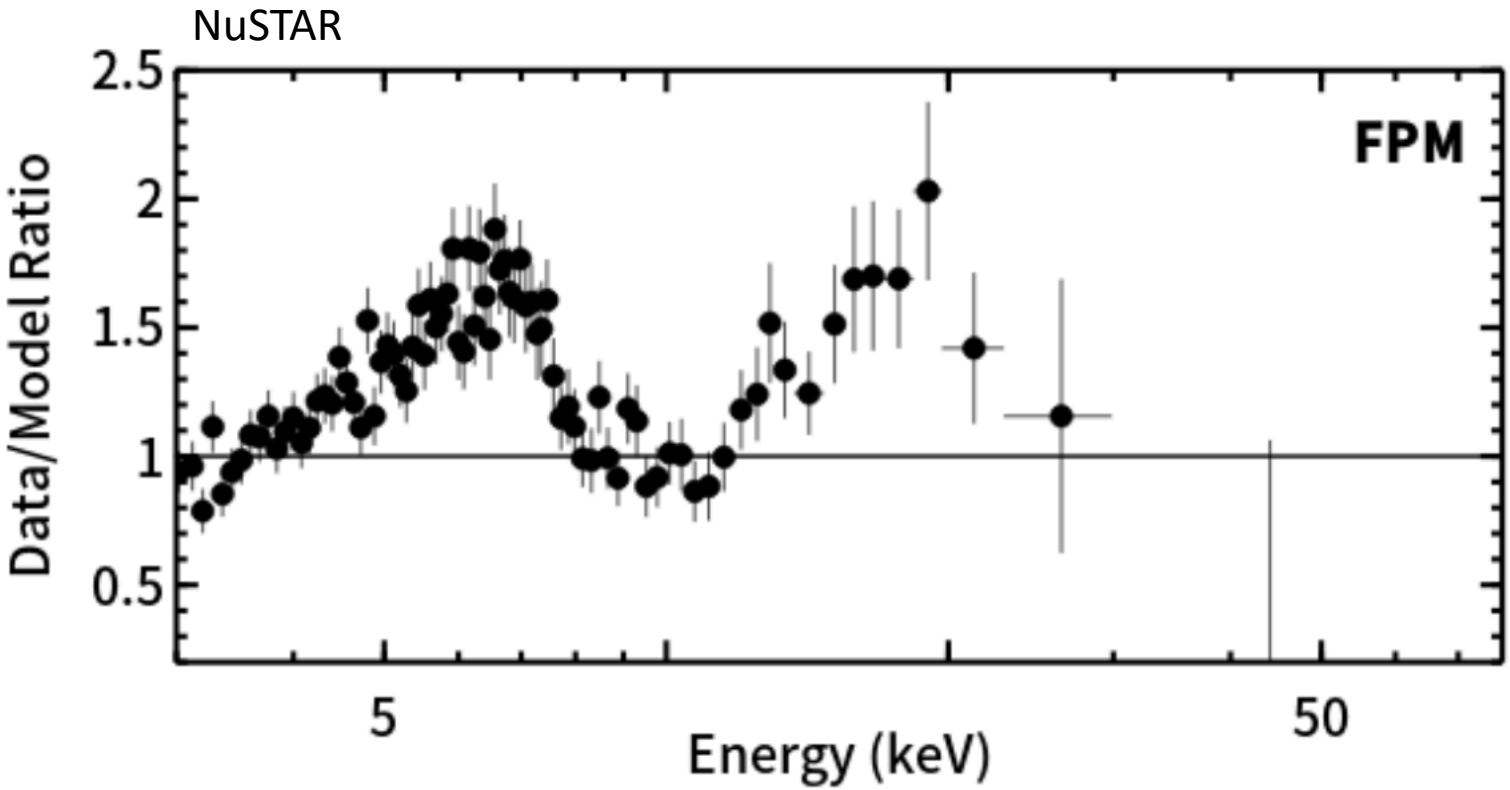
Parker, Matt+

Reflection in AGN with NuSTAR



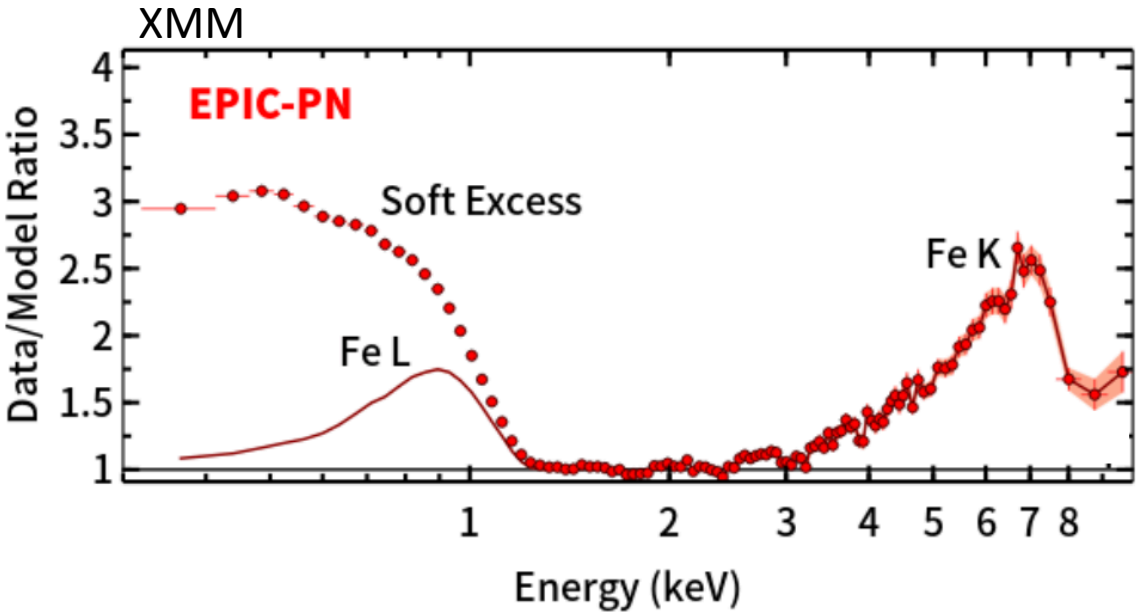
Spectra show ratio of data to model power-law

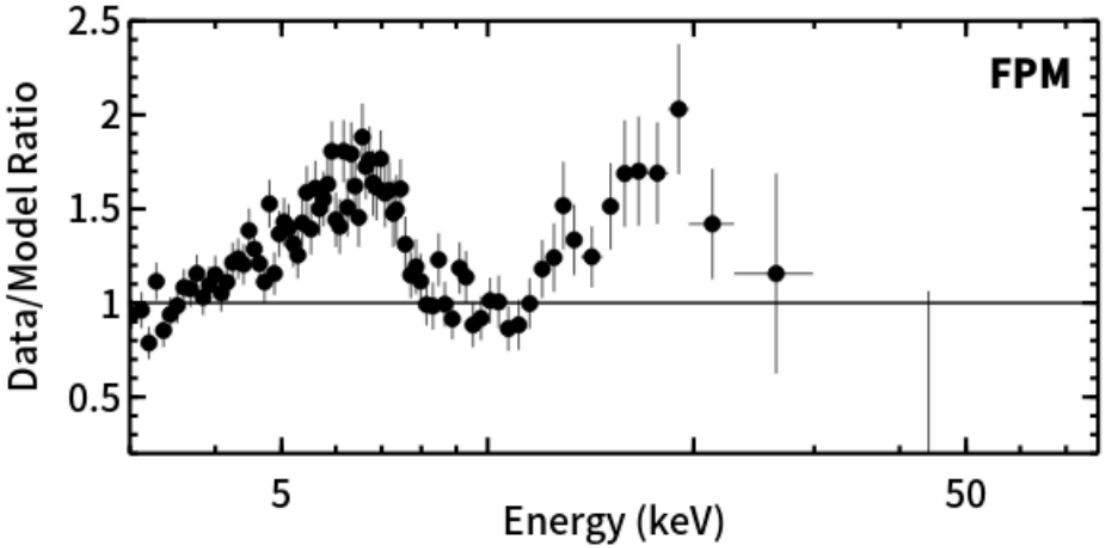
IRAS13224-3809



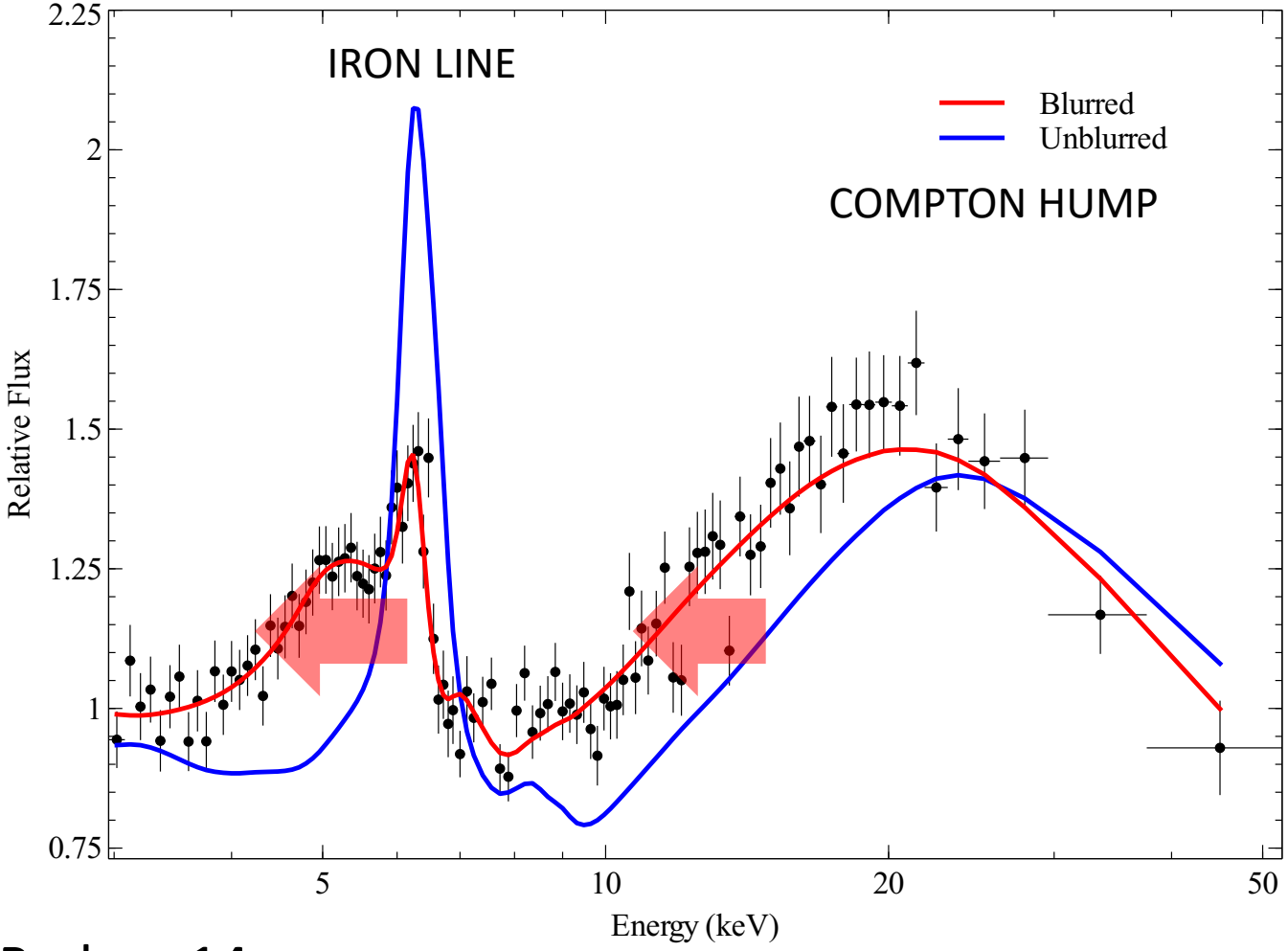
J.Jiang

IRAS13224-3809





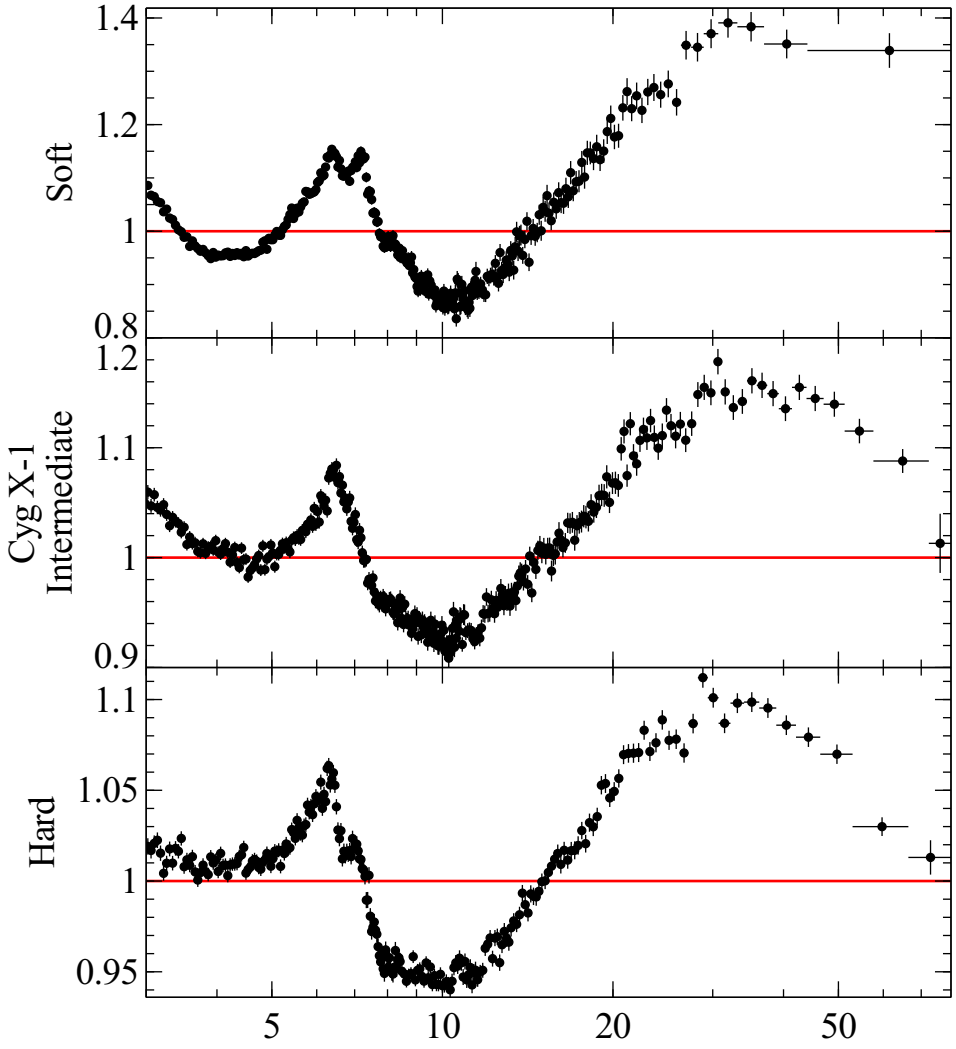
Sometimes most emission from within $2r_g$

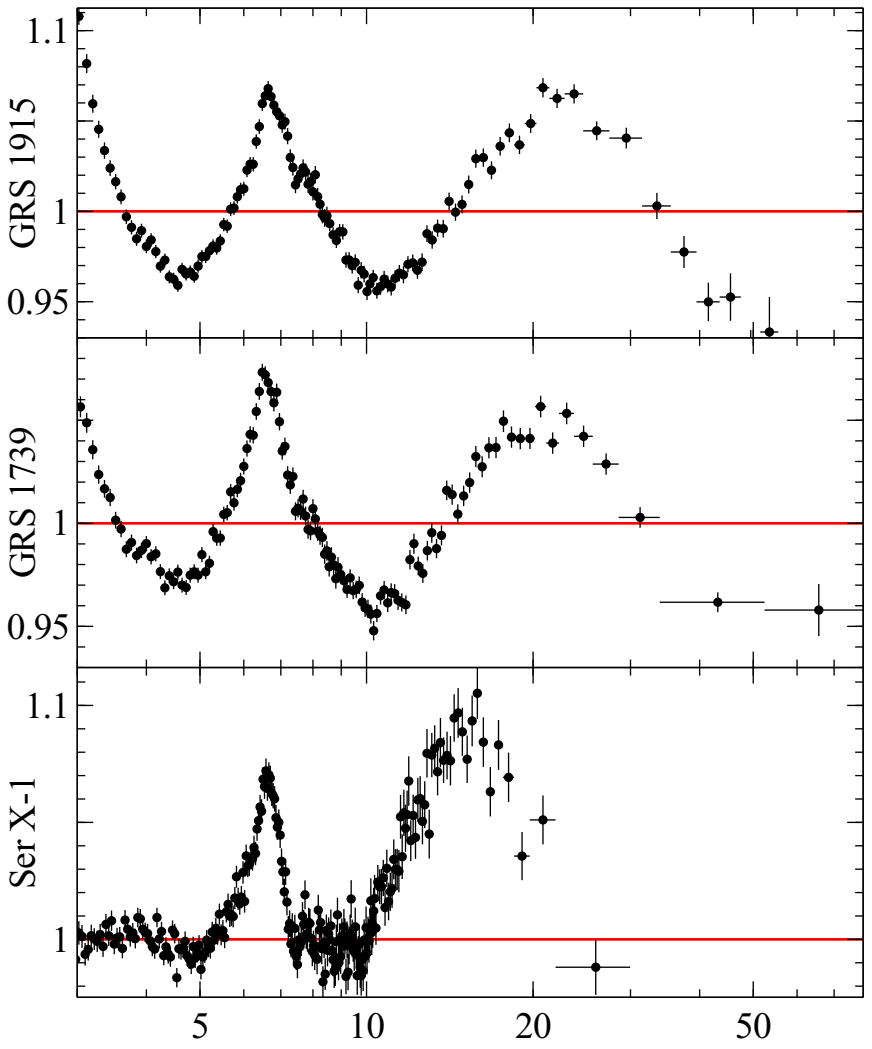


Mkn 335 Parker+14

Parker, Tomsick+, JMiller+13,15

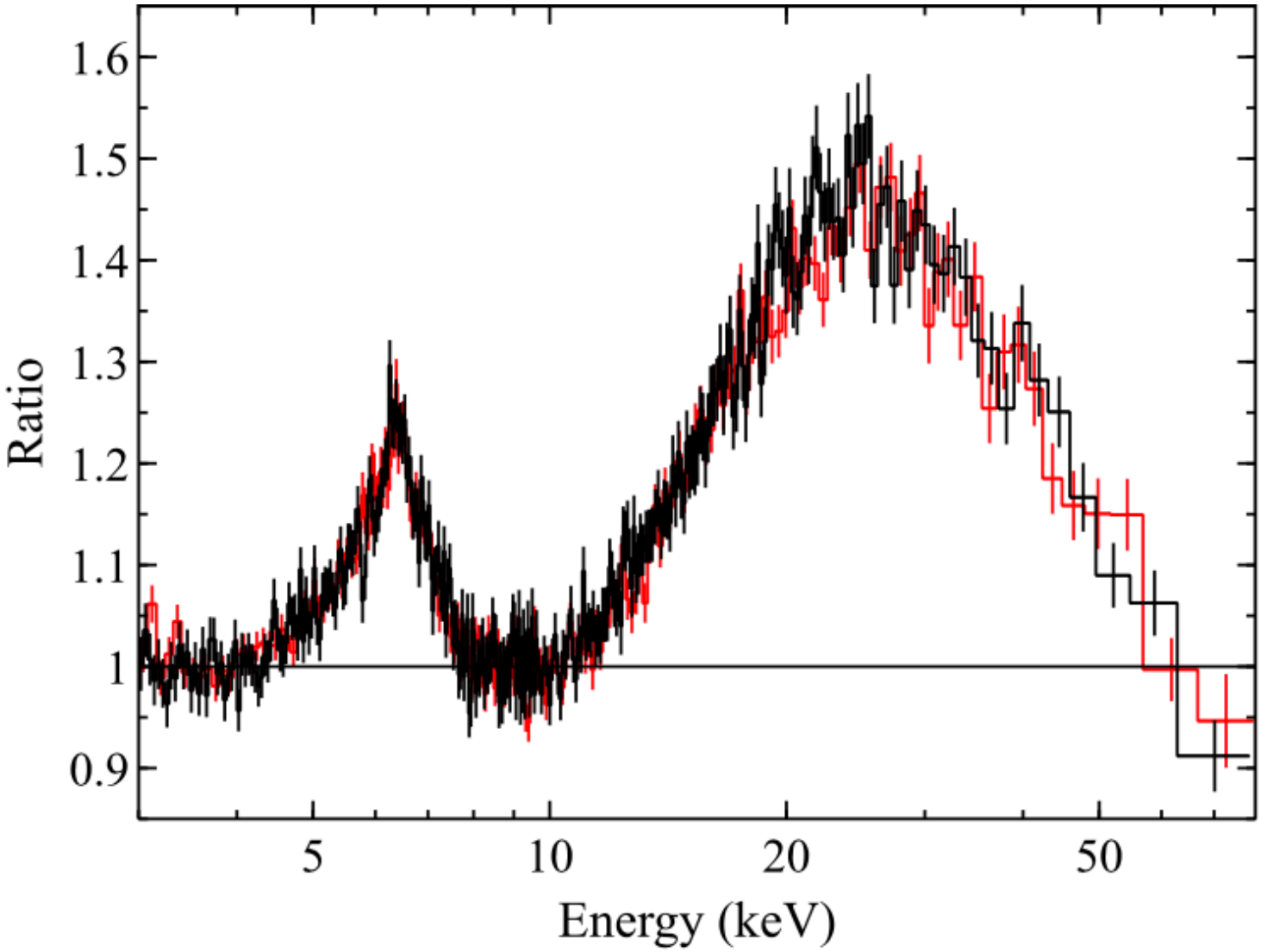
and Galactic sources too





Walton+16

V404 Cyg Flare NuSTAR

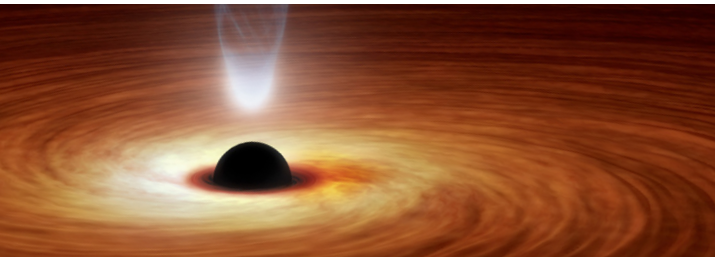


Direct Power-law

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.

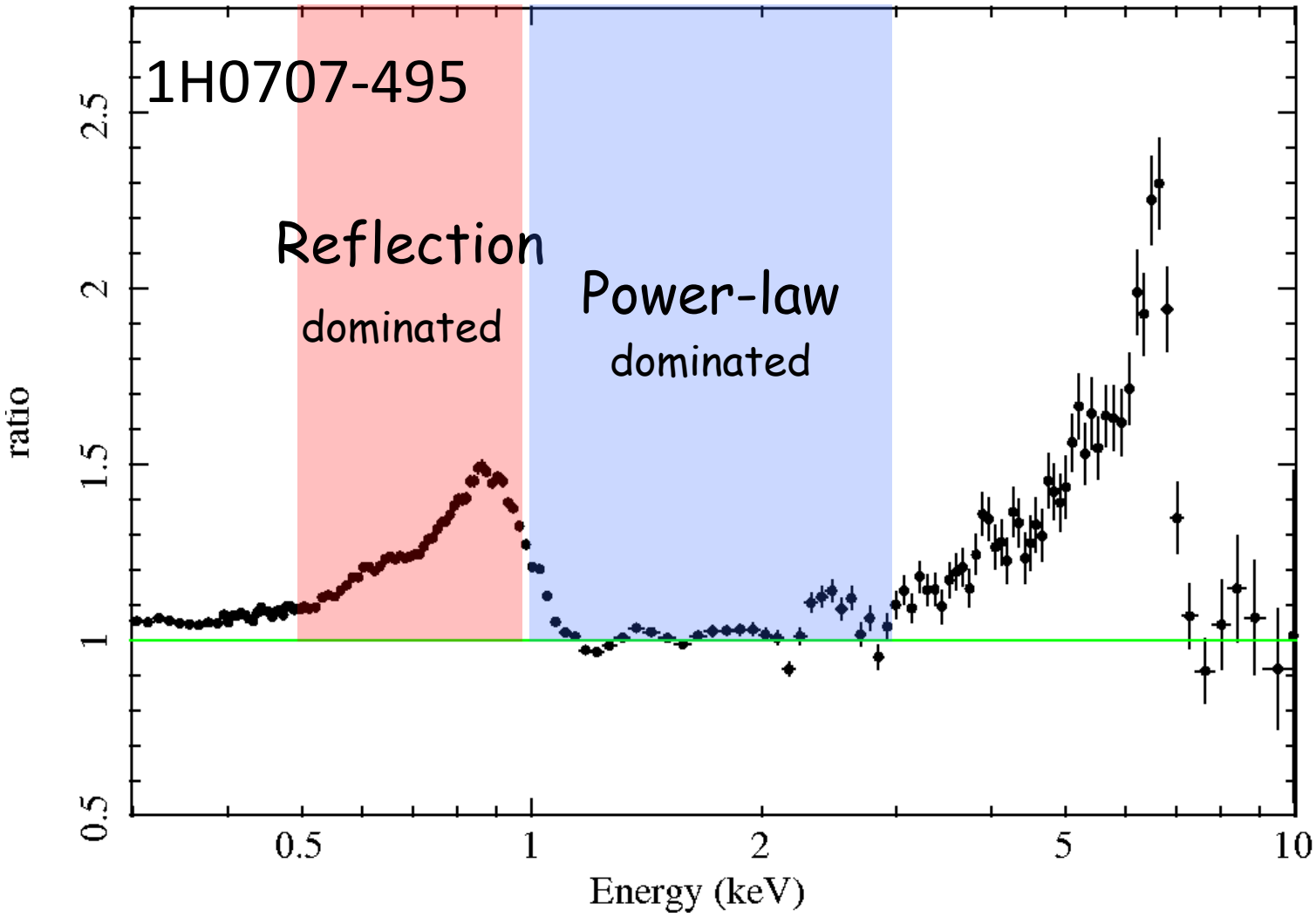
Observations of Reverberation complicated since see both Direct and Reflection components together

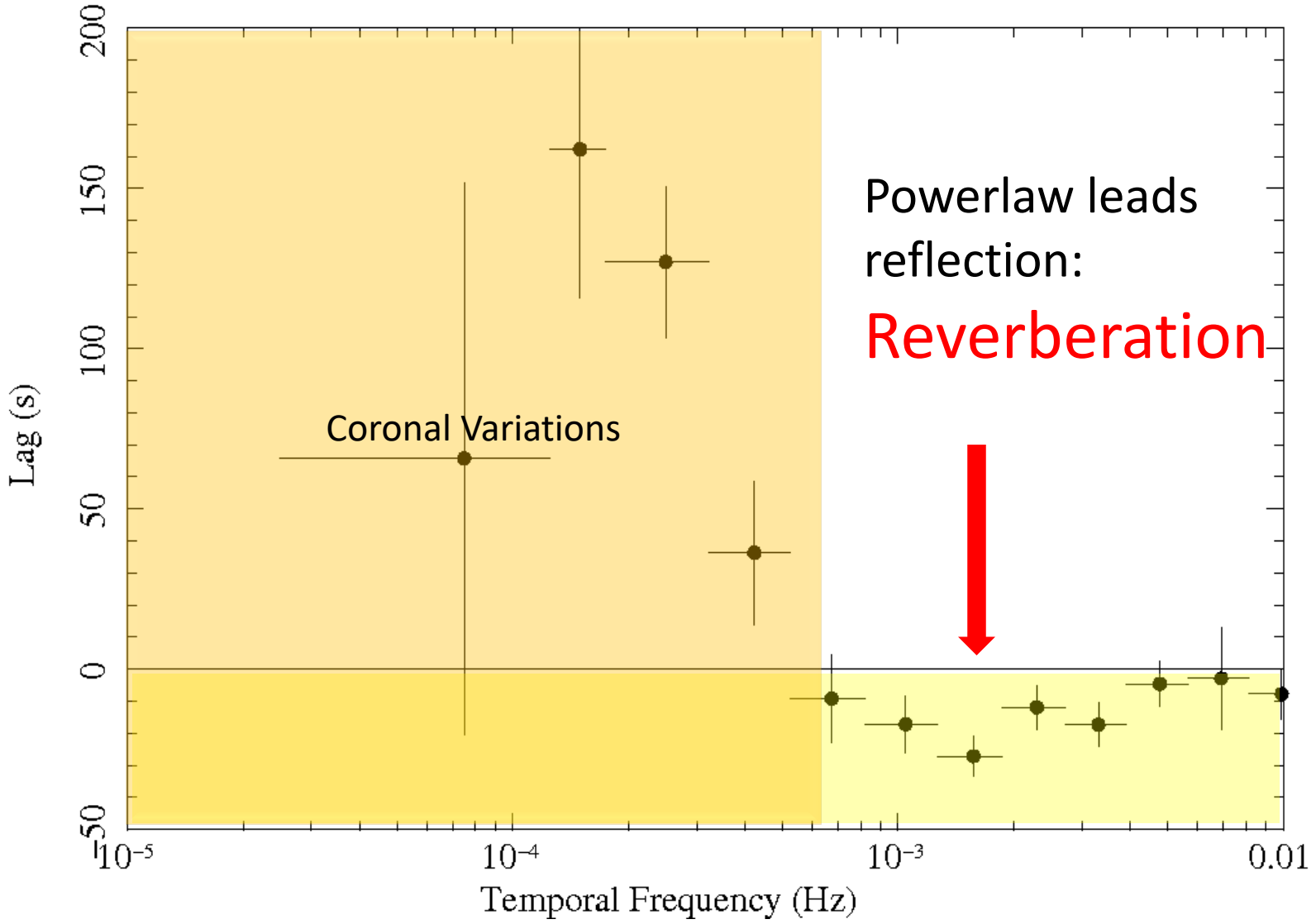
Separate spectrally
(contributions vary with energy)

Need Spectral Timing

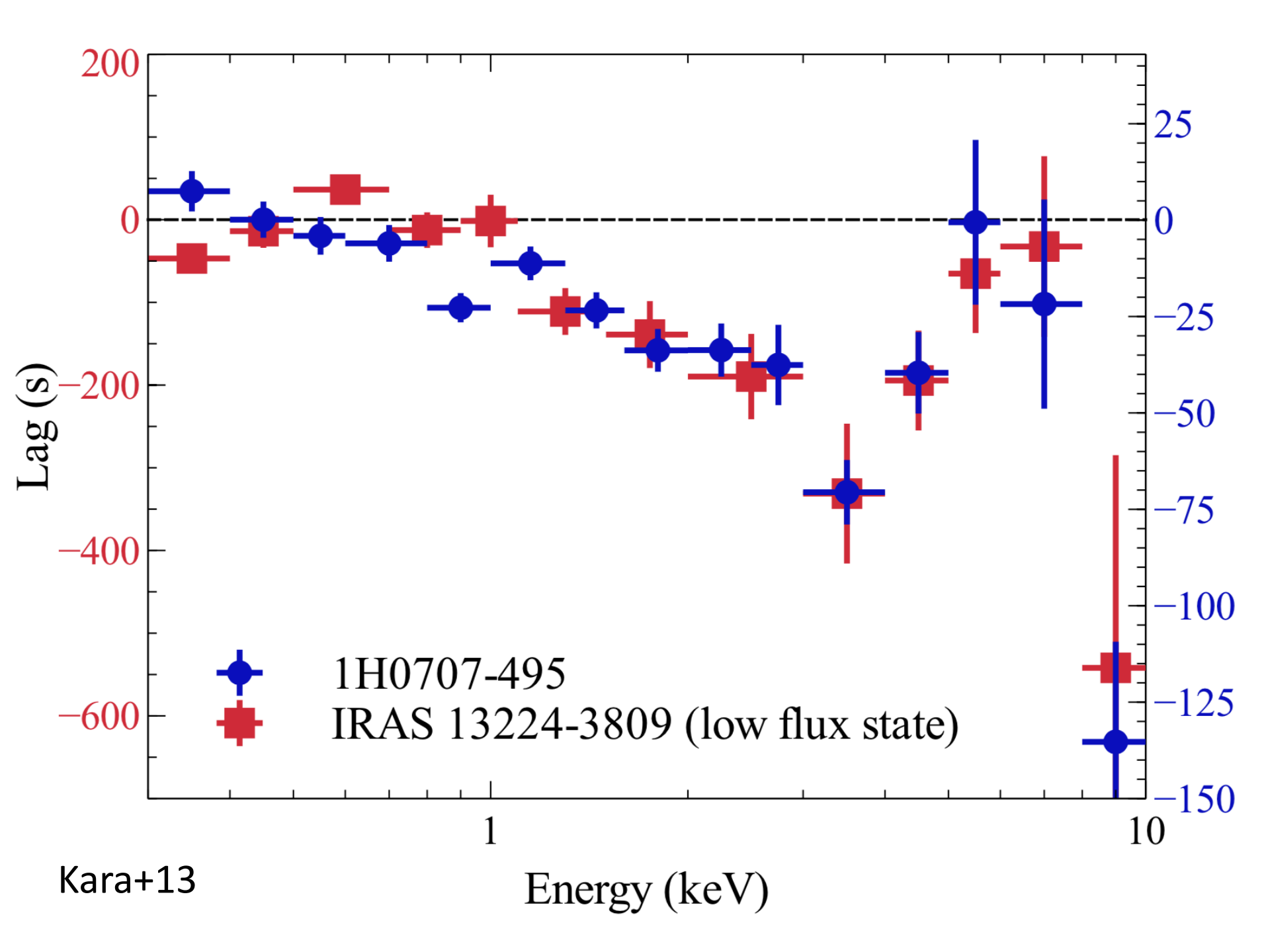
Fabian+09

X-ray Reverberation



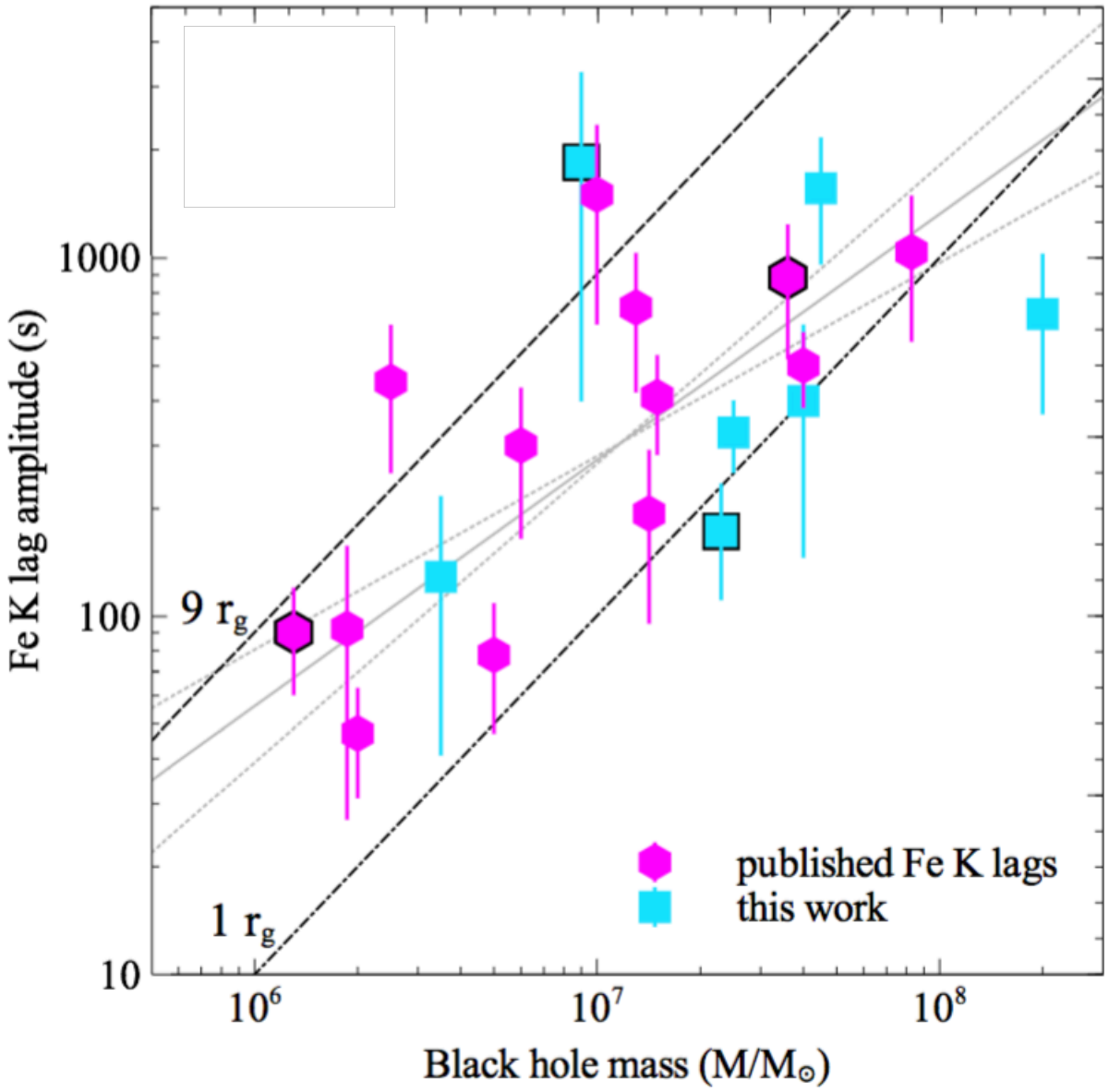


1H0707-495 Fabian+09 TIME LAGS between 0.5-1 and 1-3 keV


200
0
−200
−400
−600
Lag (s)
25
0
−25
−50
−75
−100
−125
−150
1
10
Energy (keV)
1H0707-495
IRAS 13224-3809 (low flux state)
Kara+13

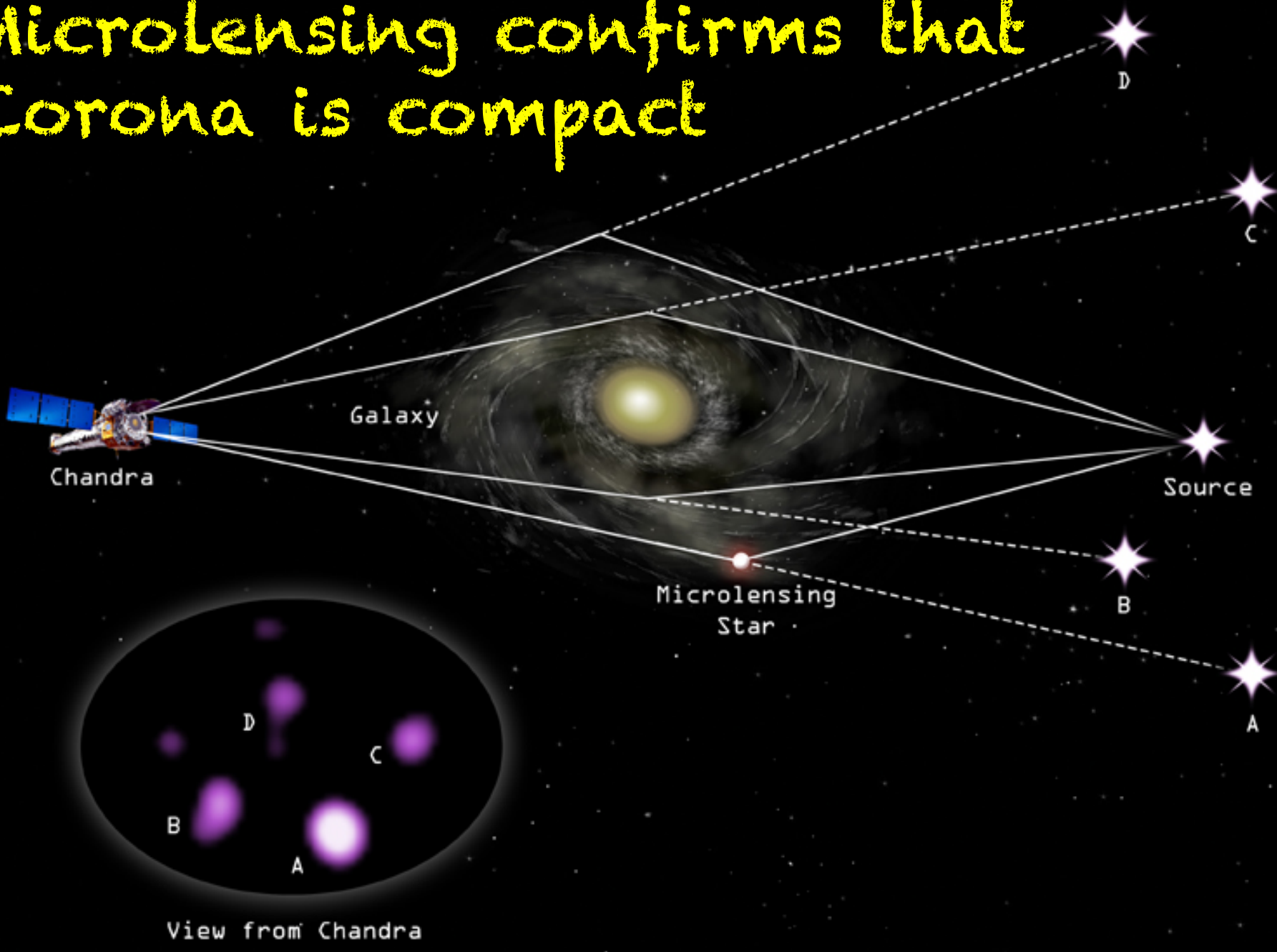
Kara+16

3-4 keV vs 5-7 keV

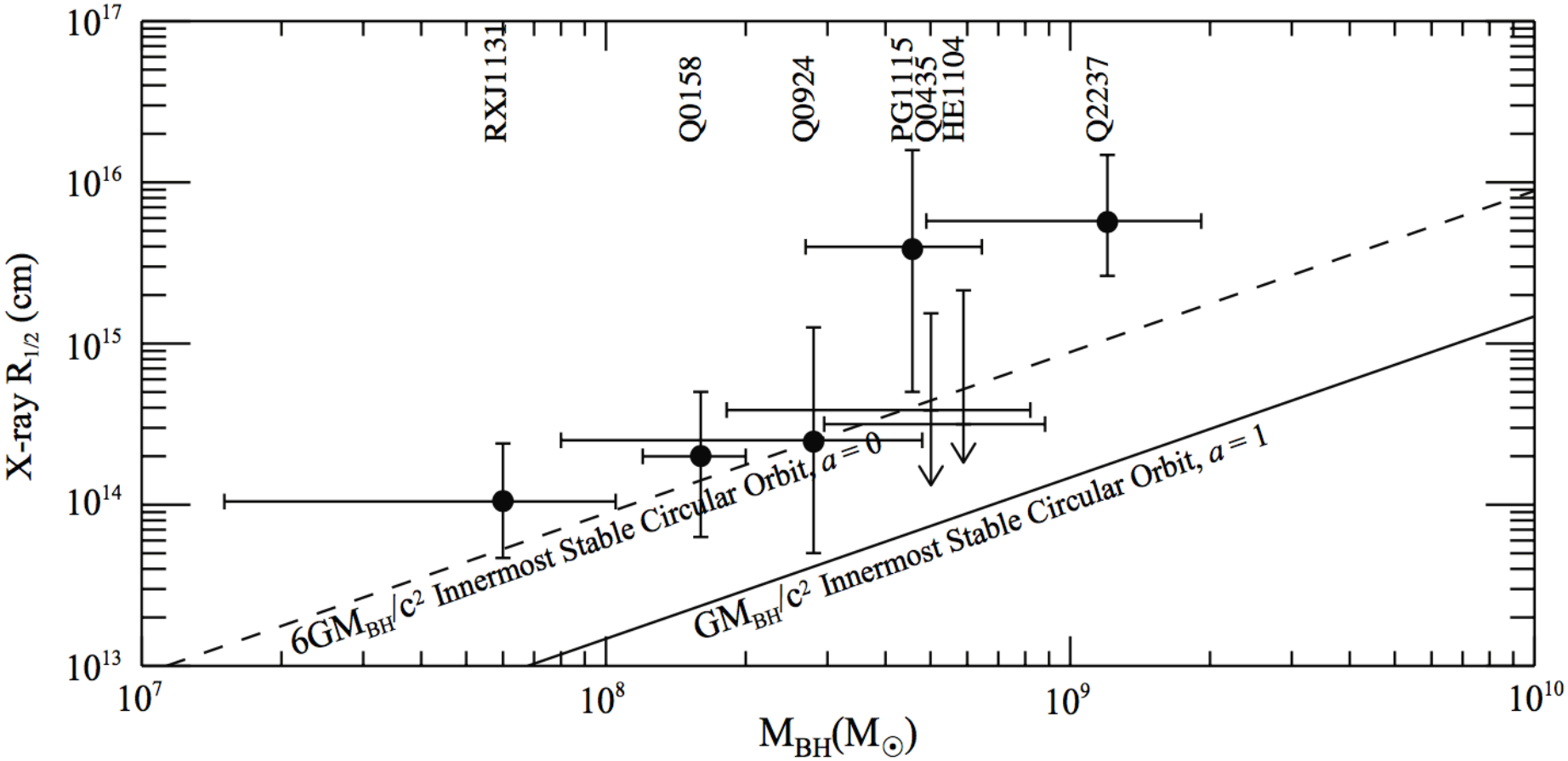


from e.g. optical

Microlensing confirms that Corona is compact



Coronal Size from Microlensing: Coronae are Compact



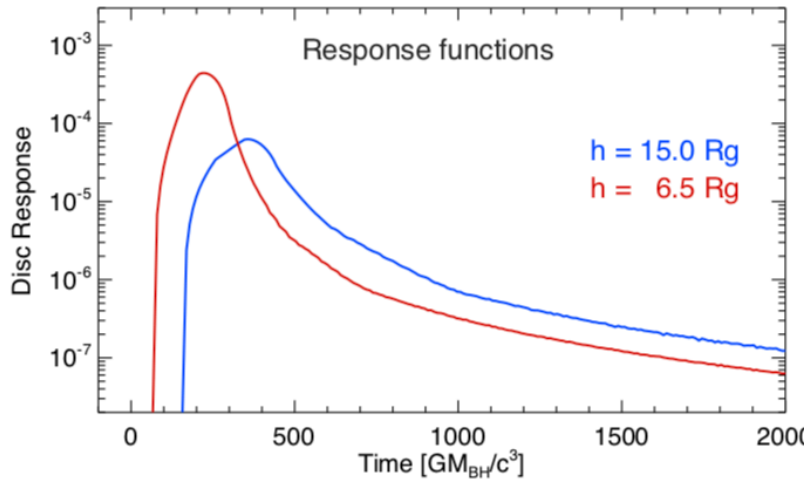
Half-light radius of X-ray emission in quasars is about 5-10 gravitational radii

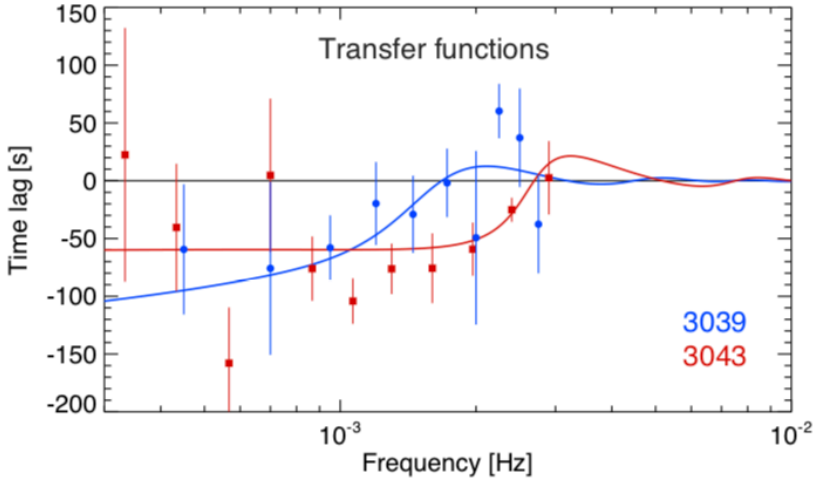
Chartas+16; Kochanek+04

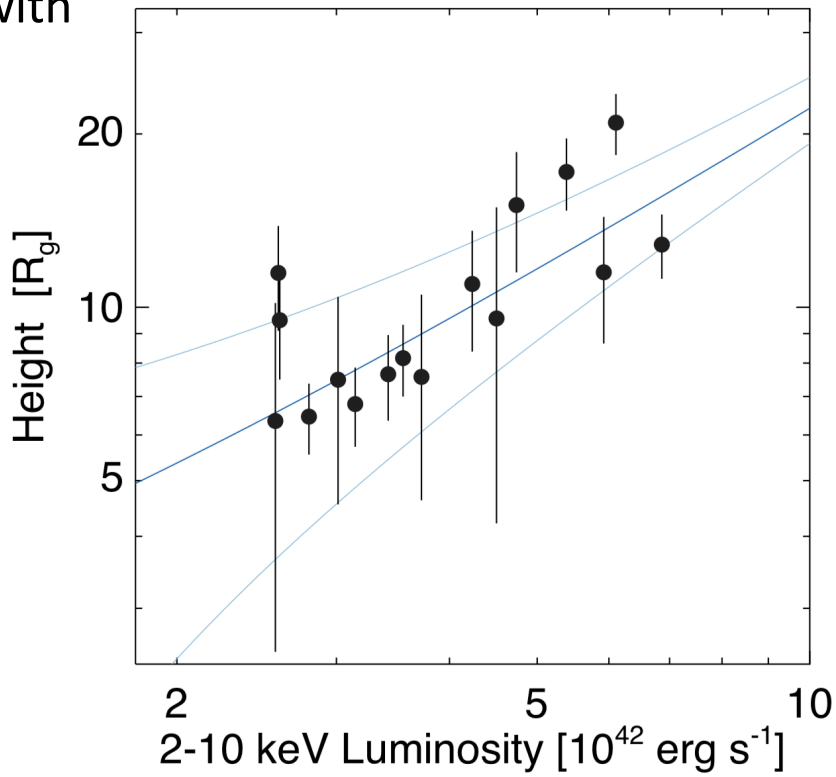
Quantifying the dynamics of the corona with 2 Ms of IRAS 13224-3809

Alston+20

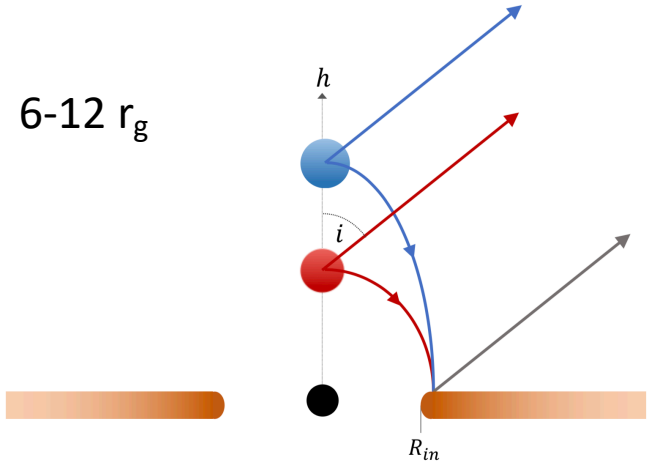
ky models by Michal Dovciak

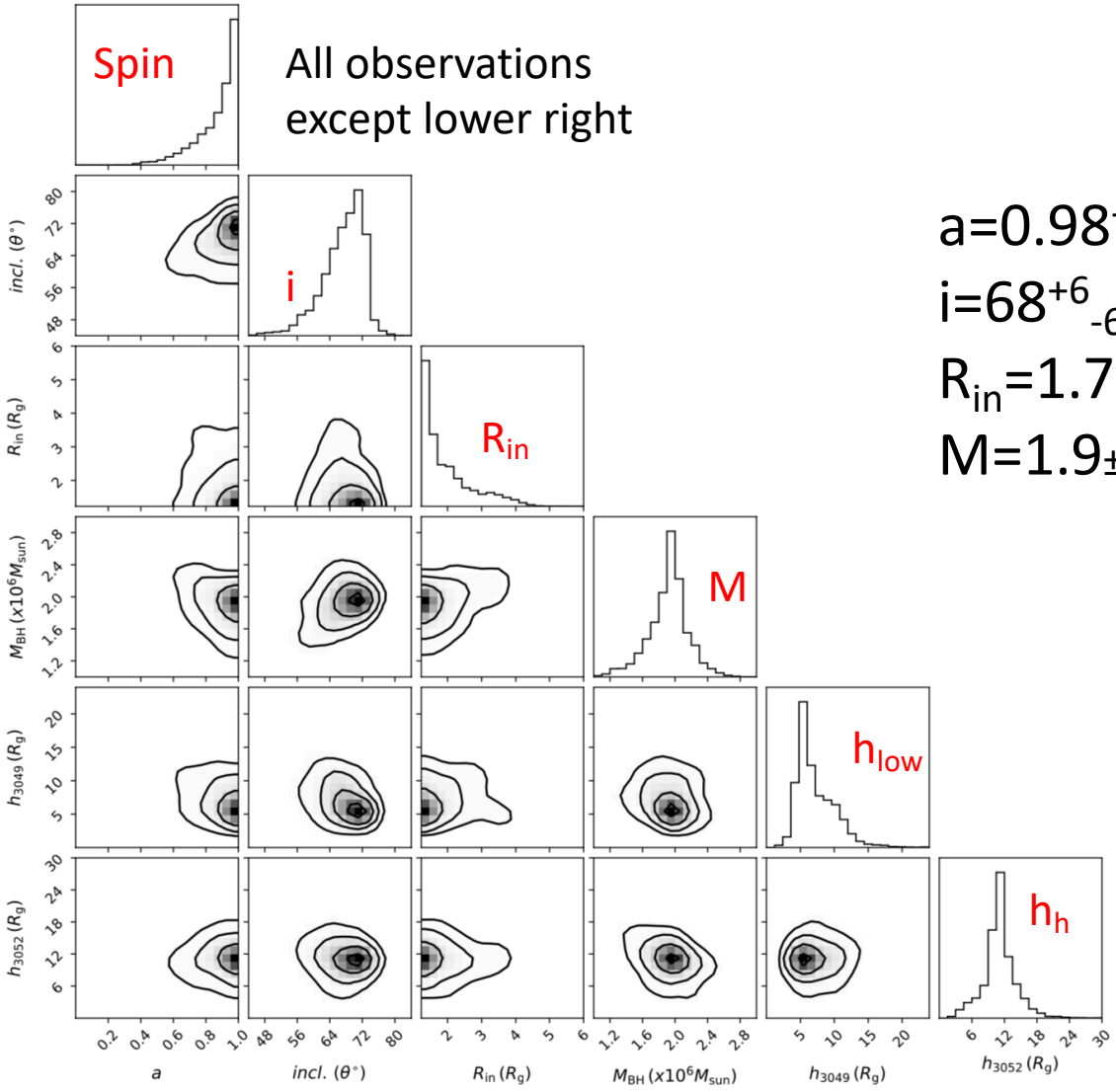






6-12 r_g





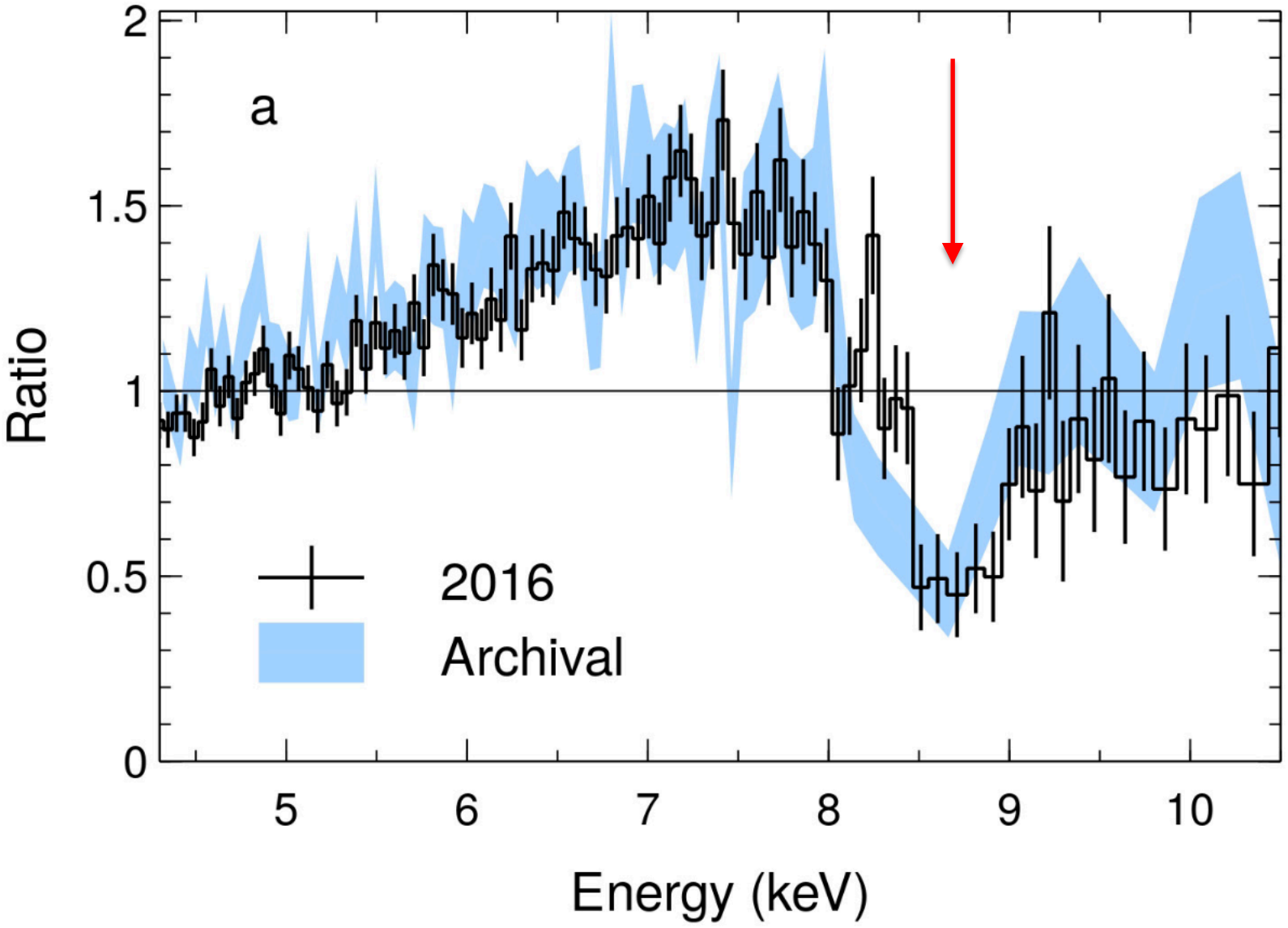
$a=0.98^{+0.01}_{-0.13}$

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

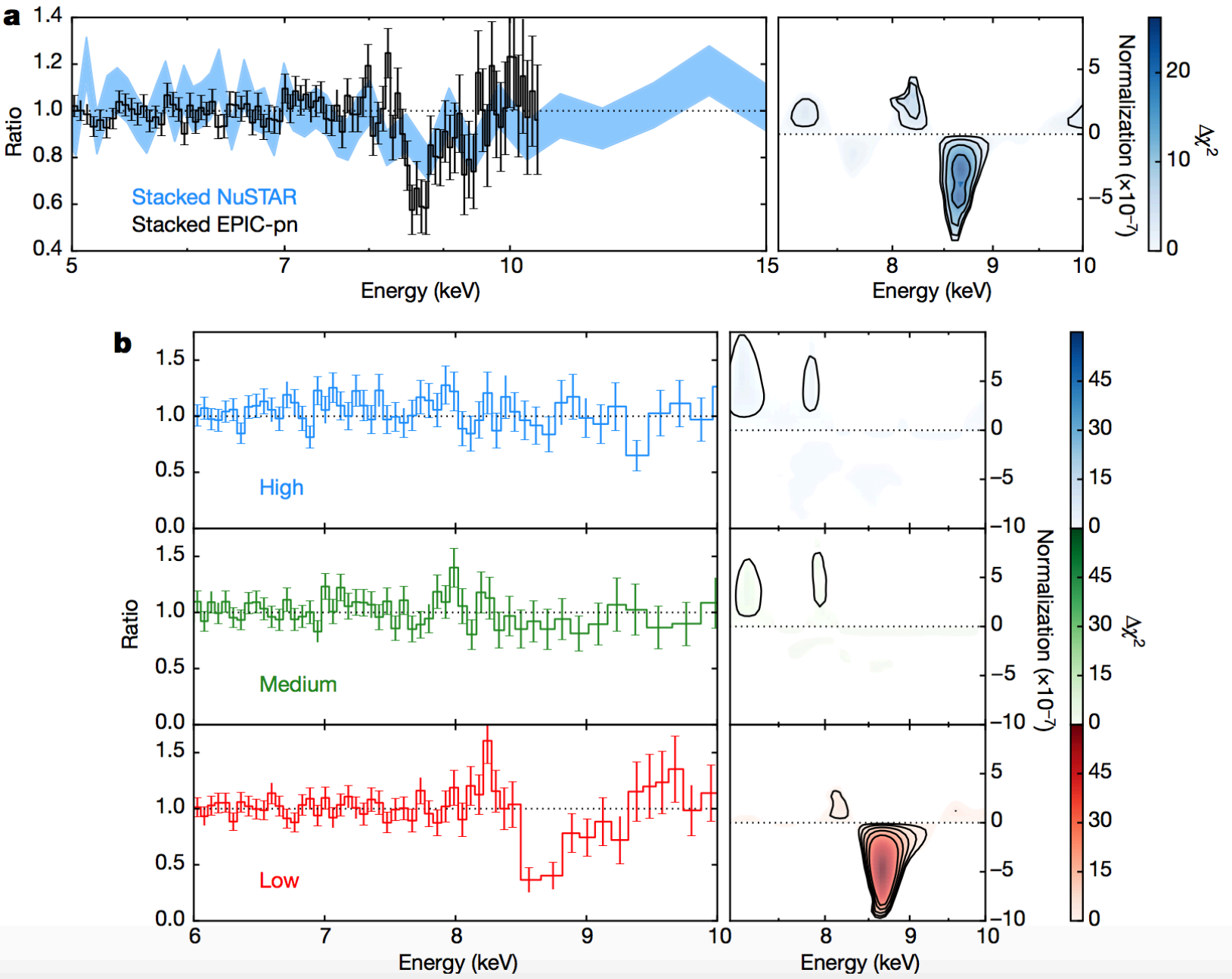
$R_{in}=1.7^{+1.1}_{-0.4}\ r_g$

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

SPECTRA show Fe K absorption



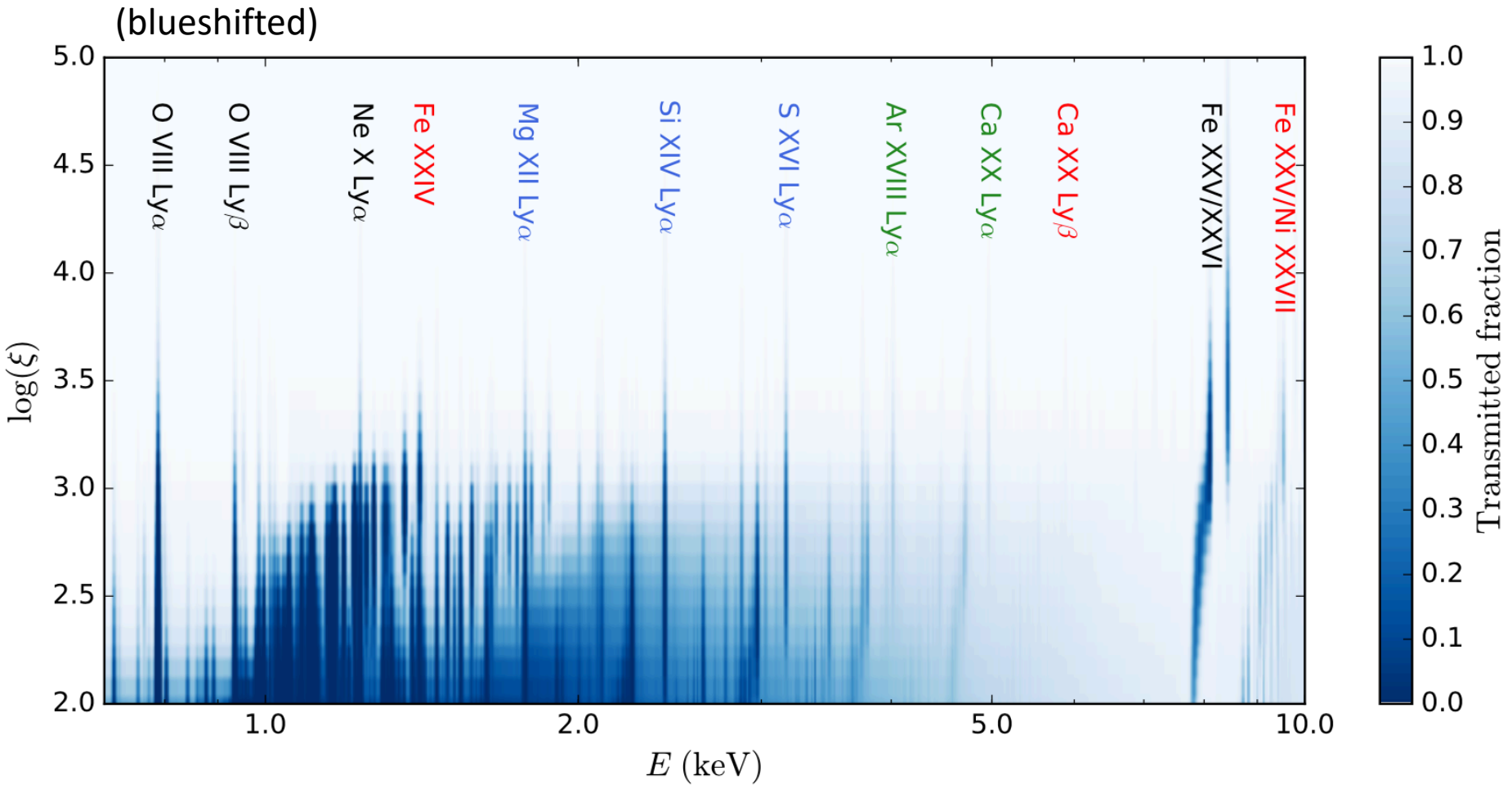
Parker+17



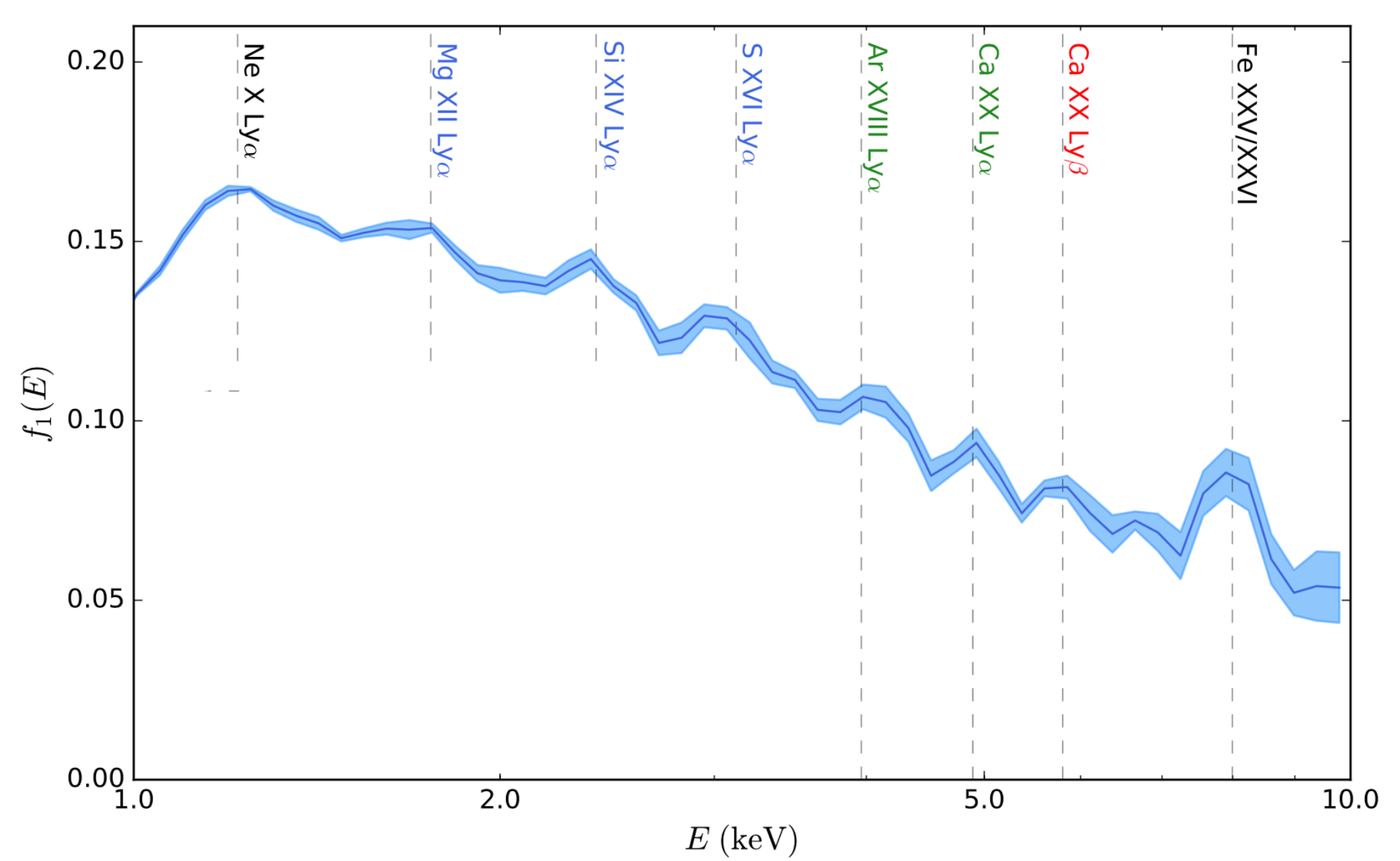
Parker+17a

Variable Blueshifted 0.24c Iron Emission Line

Predicted line spectra

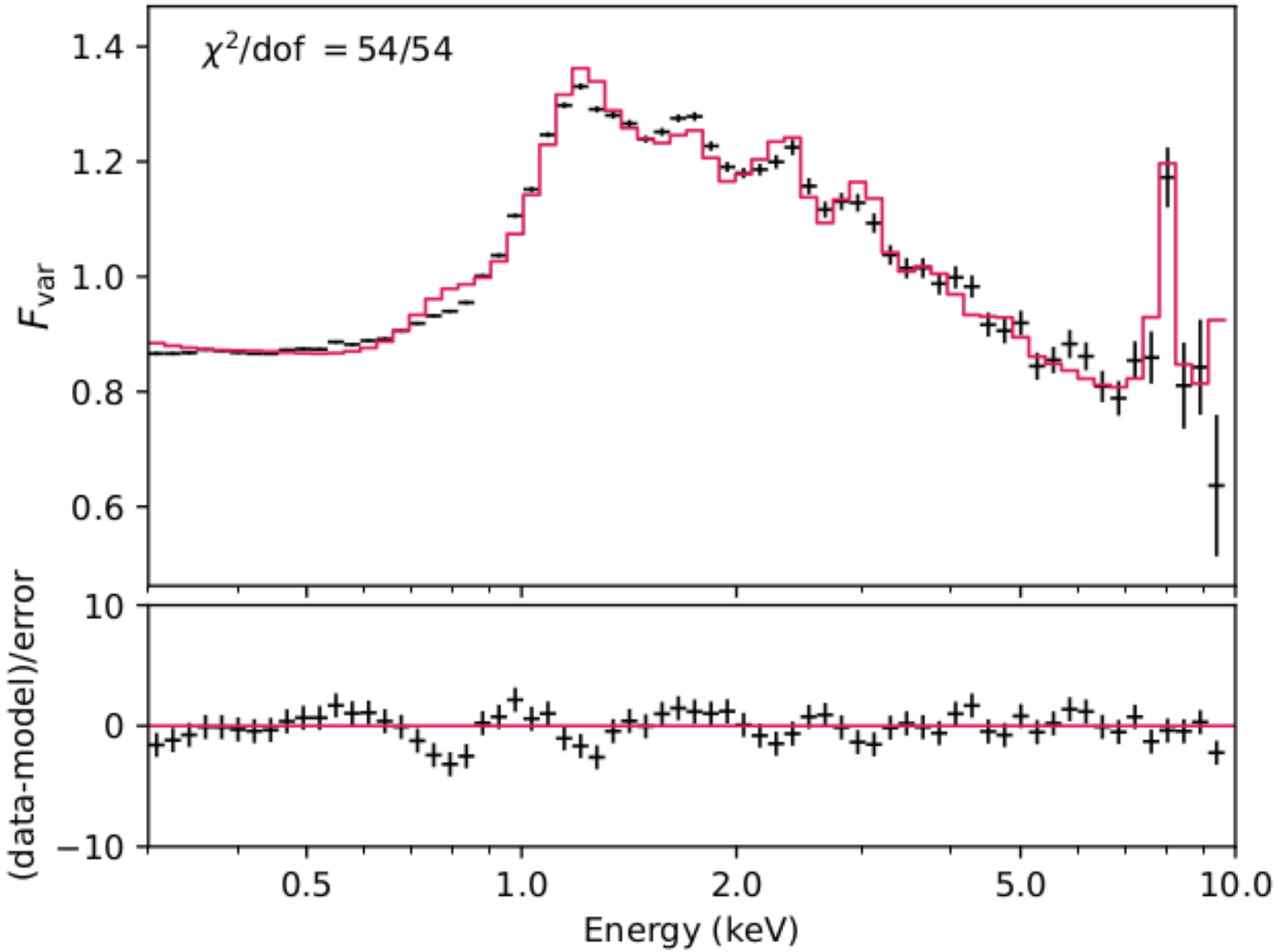


Parker+17, see also Pinto+18



Revealing the ultra-fast outflow in IRAS 13224 through spectral variability (PCA)

Parker+17b



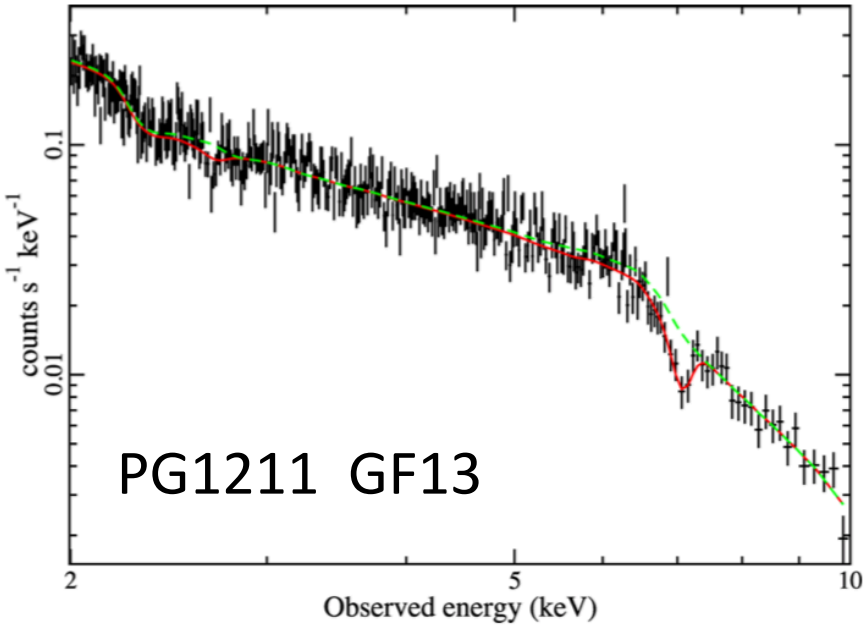
Parker+19 Fractional variability spectrum of IRAS13224

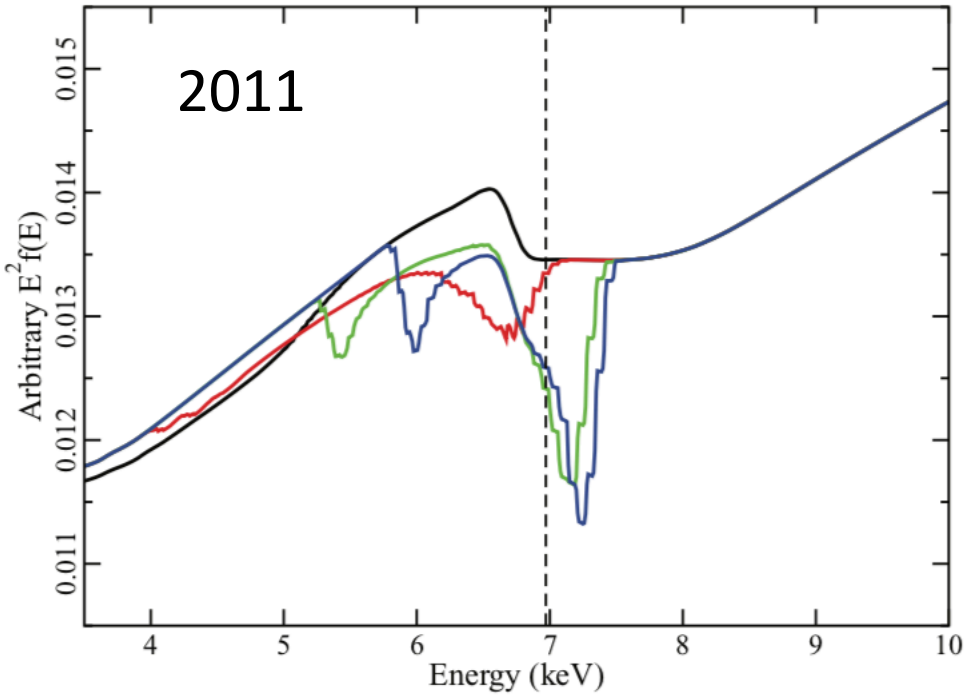
Do High Velocities always mean Outflows?

Orbital velocity rise to c/2 at the ISCO, so:

- Observed UFO velocities are present in the orbital motions of the disc.

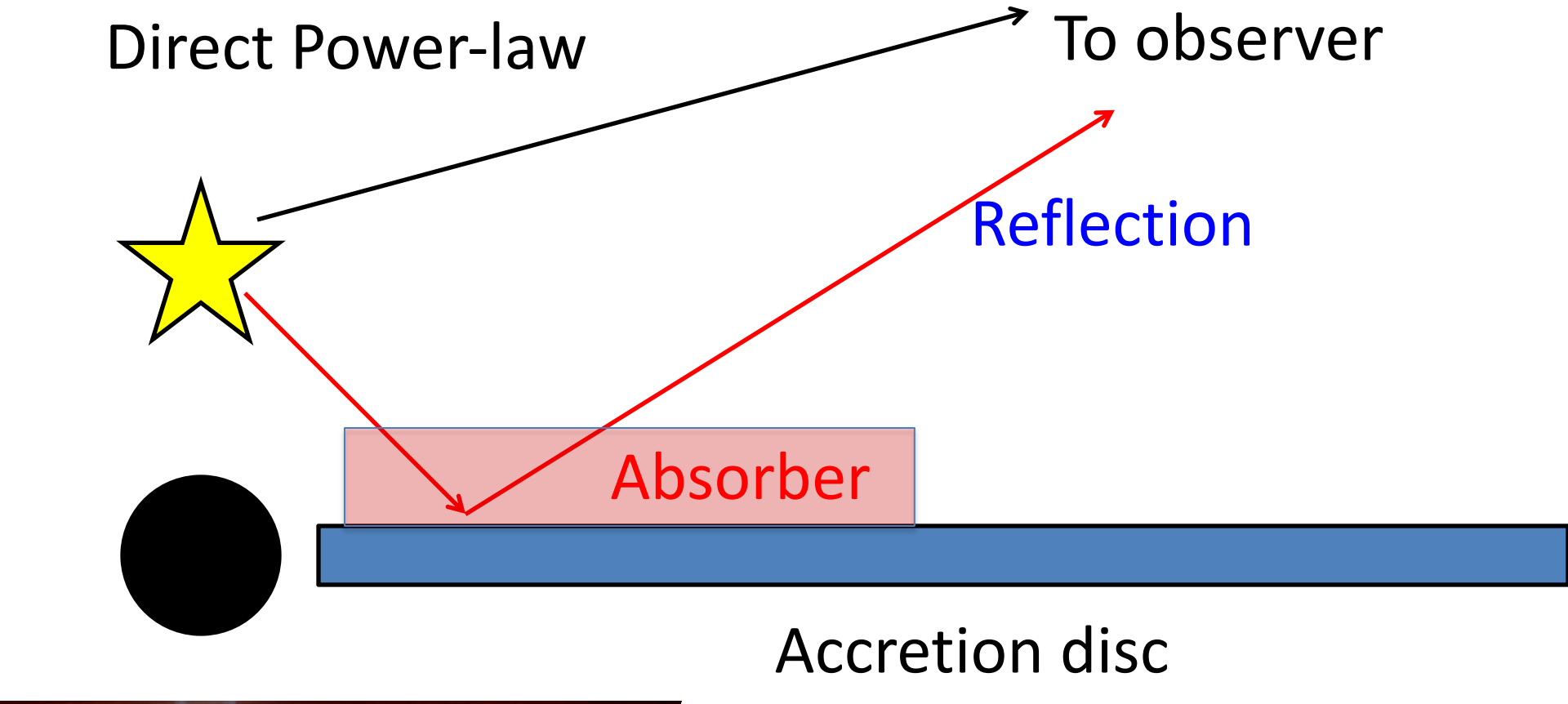
- Our line of sight passes over parts of the disk with $v_{LOS} = -0.24c$
- Can the absorber be located there?

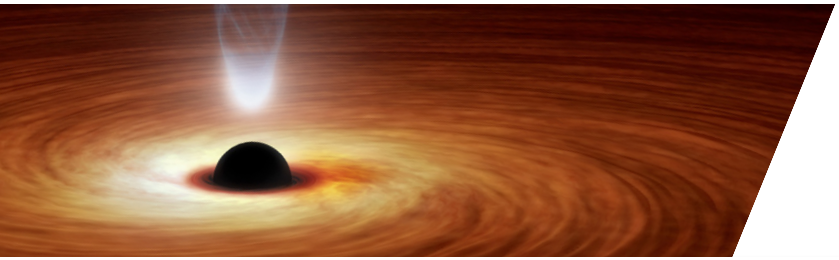


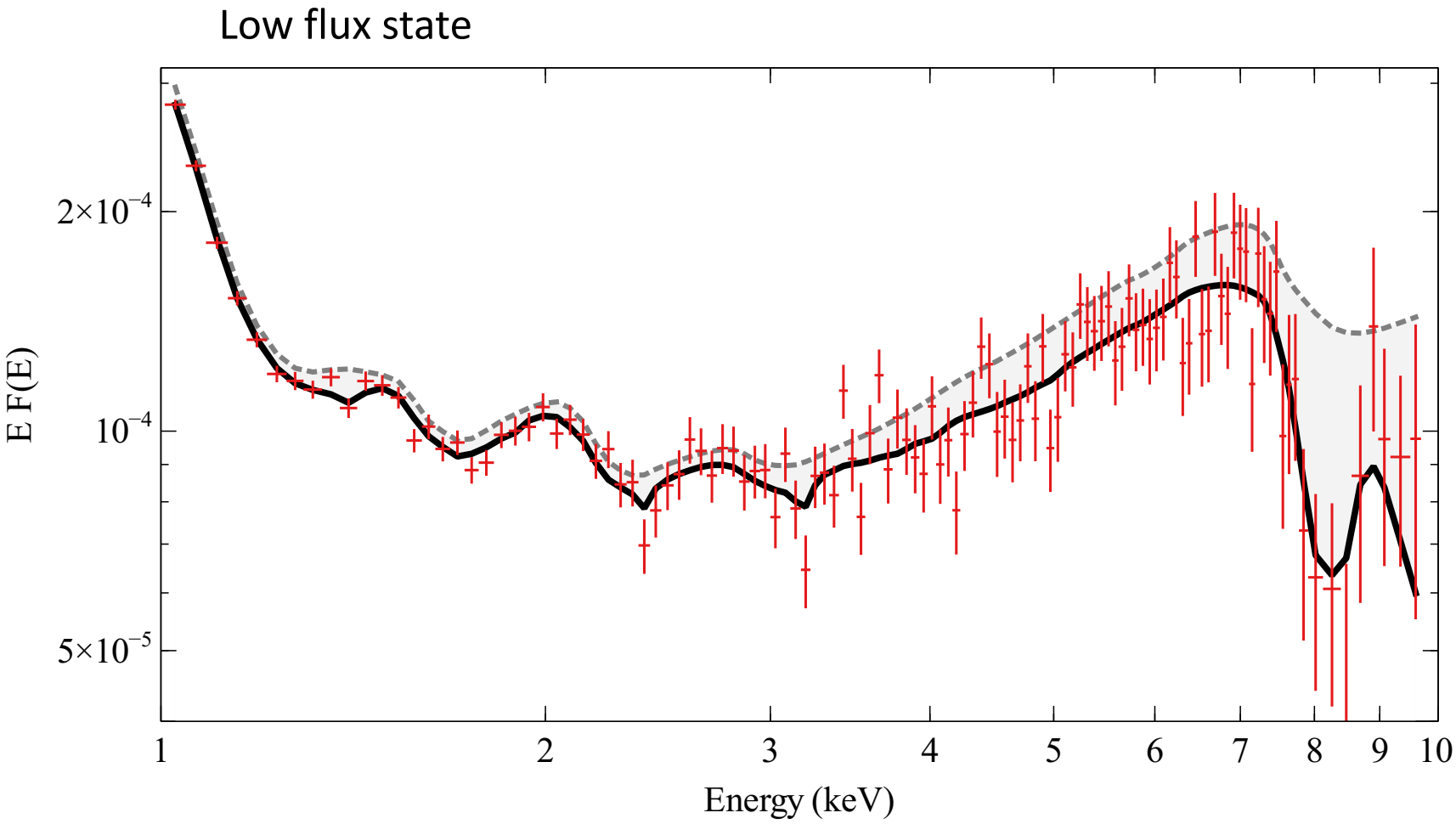


How the effects of resonant absorption on black hole reflection spectra can mimic high-velocity outflows

L. C. Gallo[1★] and A. C. Fabian[2]

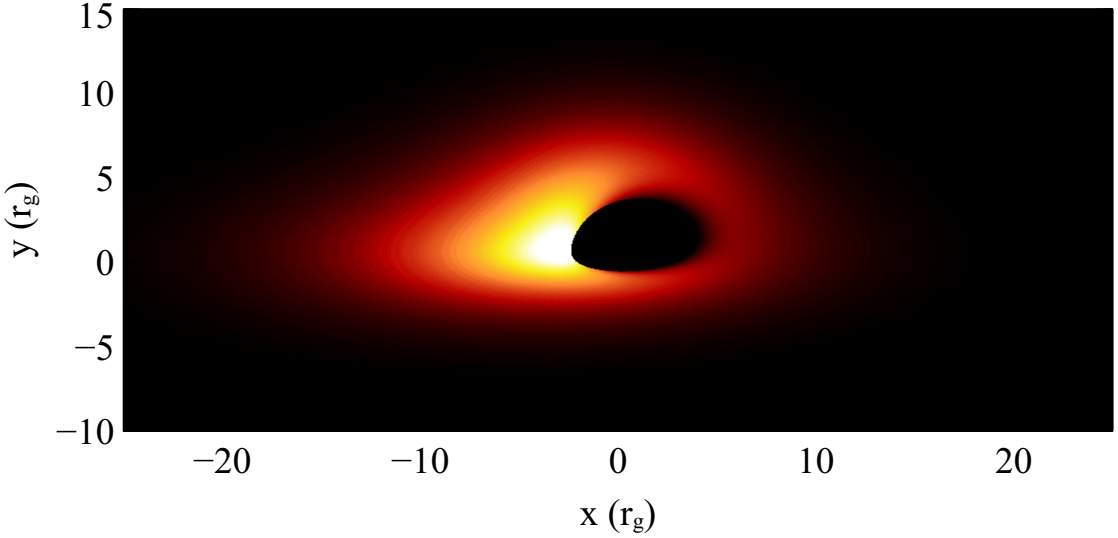

Direct Power-law
To observer
Reflection
Absorber
Accretion disc



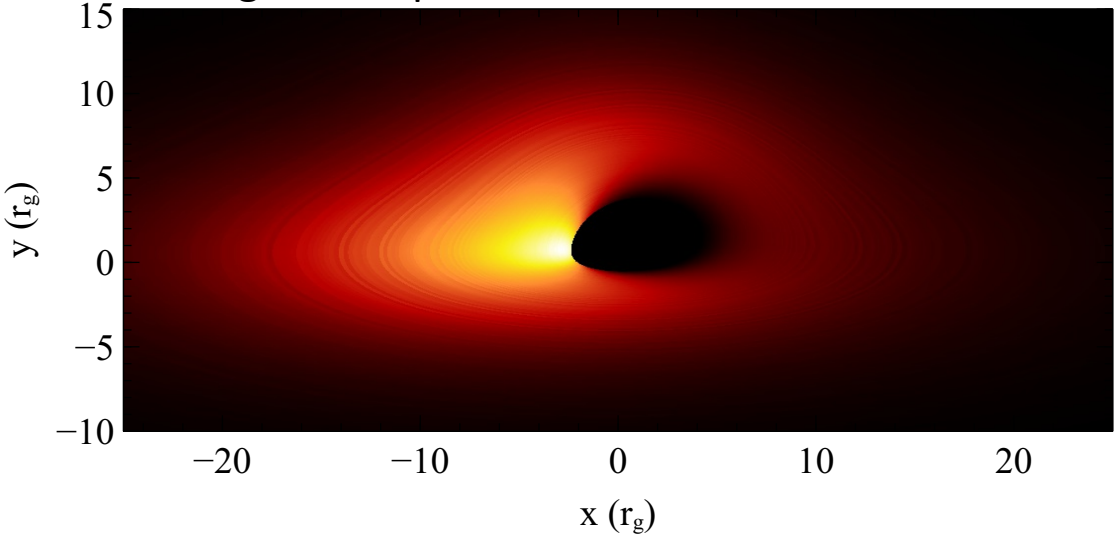


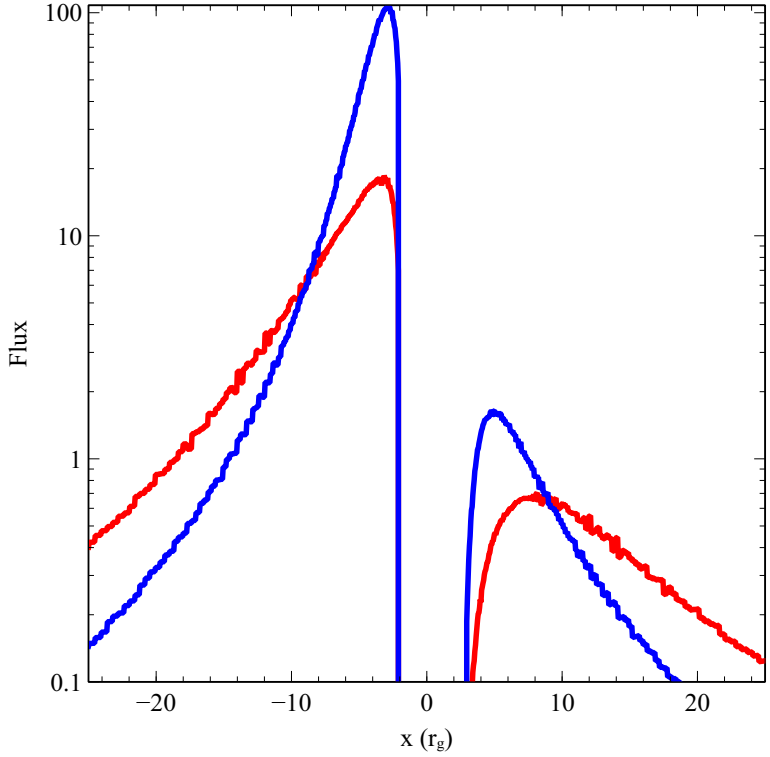
Fabian, Jiang, Reynolds +20

Low flux reflection dominated



High flux power-law dominated





Source frame

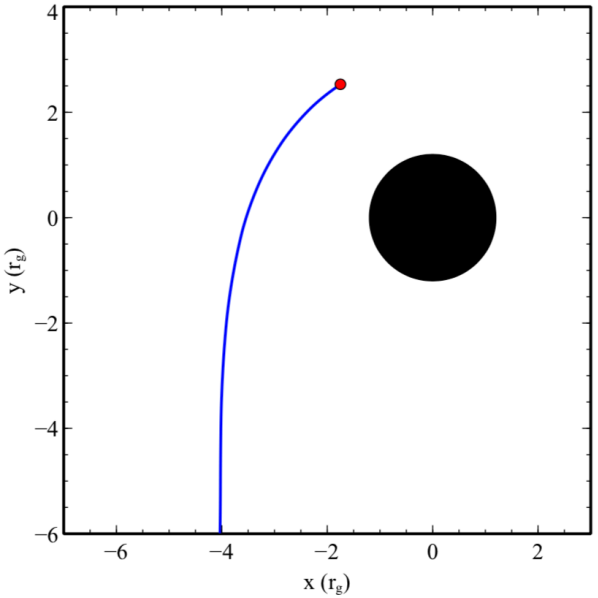
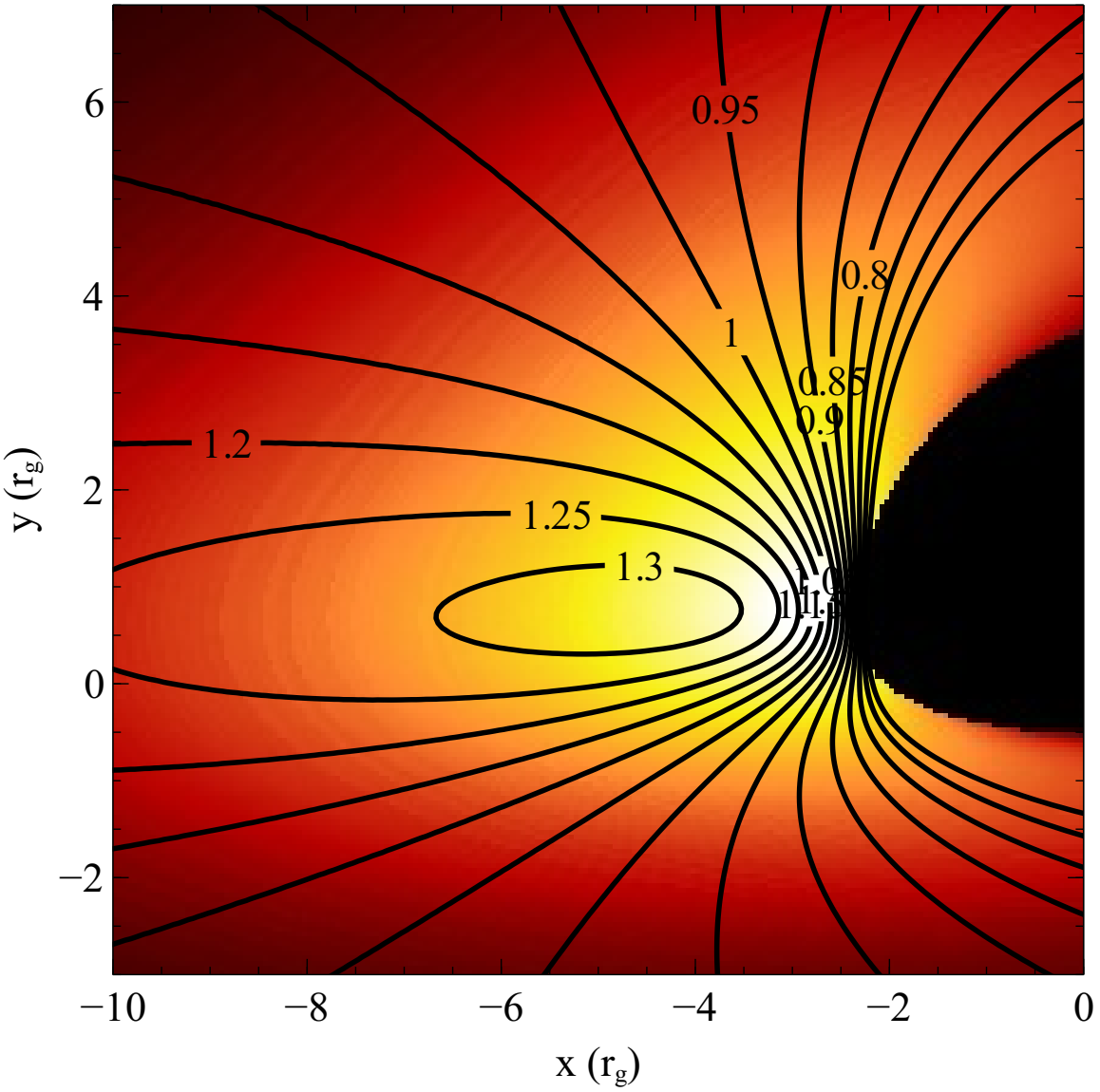


Image frame



$g = E_{obs}/E_{em}$

Depth of absorber ~ 10^{-4} r_g

Further work on blueshifted absorption in IRAS13224 may need new spectra (e.g. XRISM) and/or comparison with other UFO features

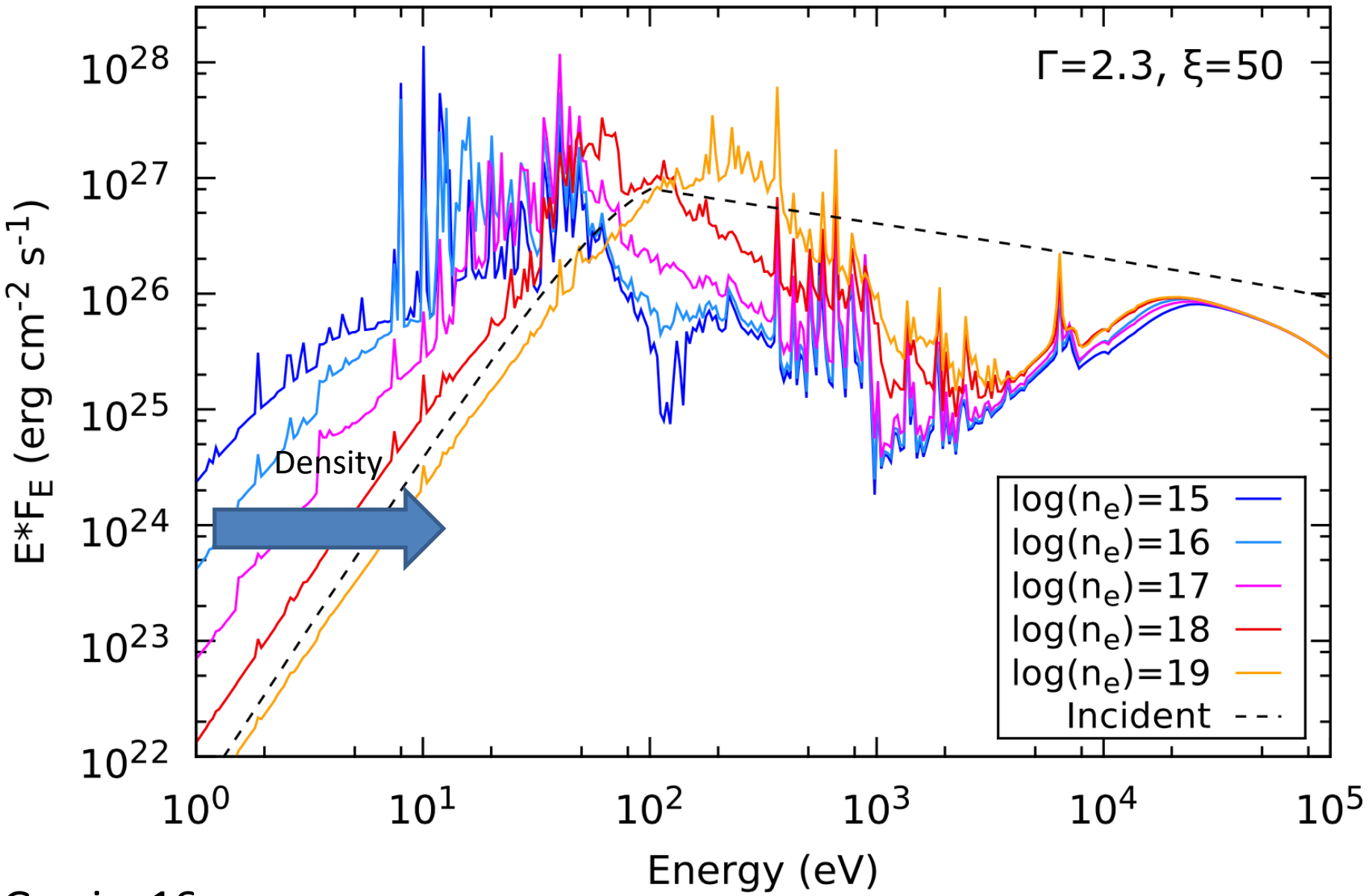
……

Further test of Lamppost model uses measurement of the density of the reflector

This is possible because free-free absorption is energy and density dependent, strongly affecting the soft X-ray spectrum at high densities

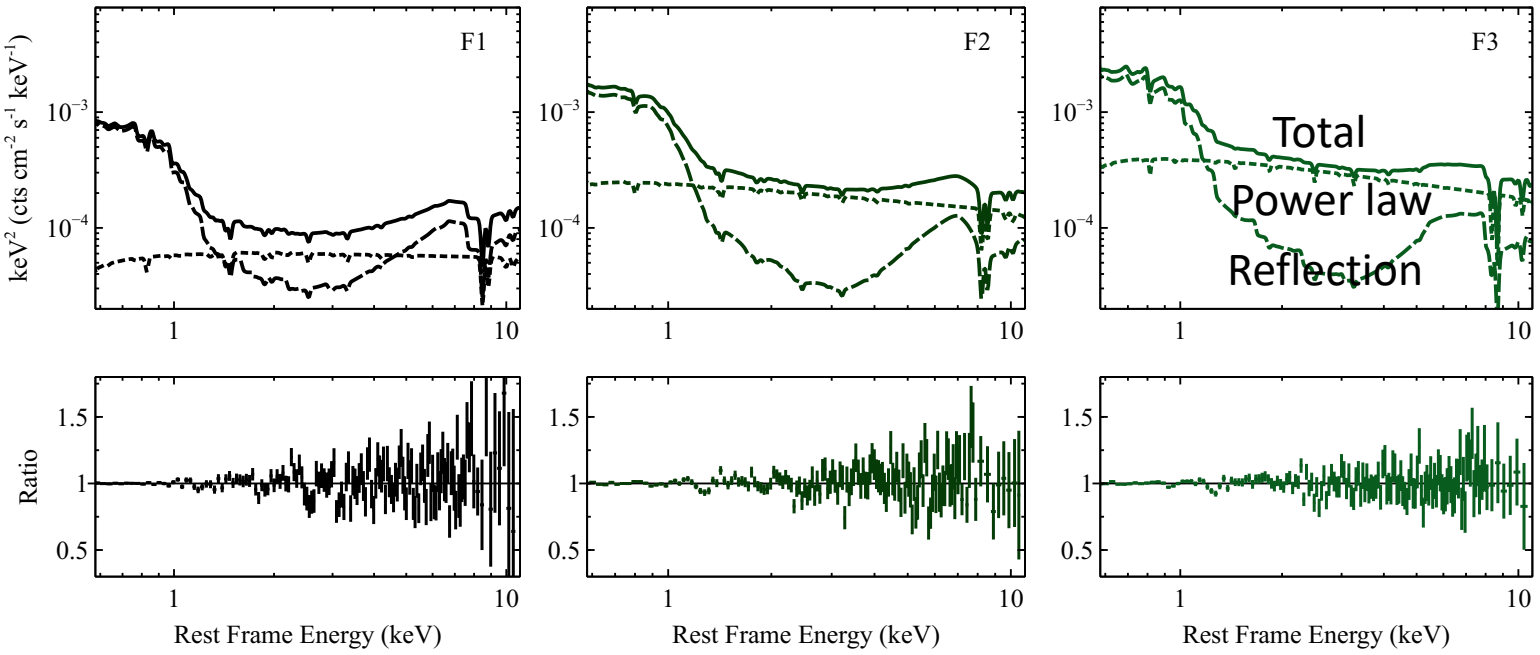
Energy at which free-free opacity equals Thomson opacity

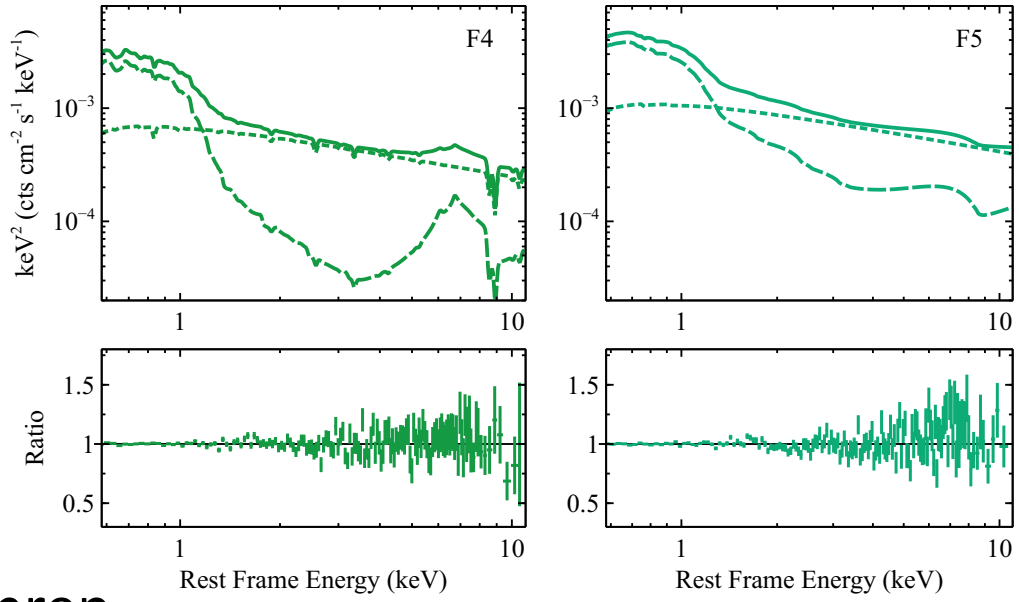
$$E \propto \sqrt{n}$$


High Density Reflection Spectra
1 keV
Γ=2.3, ξ=50
Density
log(ne)=15
log(ne)=16
log(ne)=17
log(ne)=18
log(ne)=19
Incident
E*FE (erg cm-2 s-1)
Energy (eV)
10^28
10^27
10^26
10^25
10^24
10^23
10^22
10^0
10^1
10^2
10^3
10^4
10^5

Garcia+16

IRAS13224-3809 XMM spectra in 5 flux states





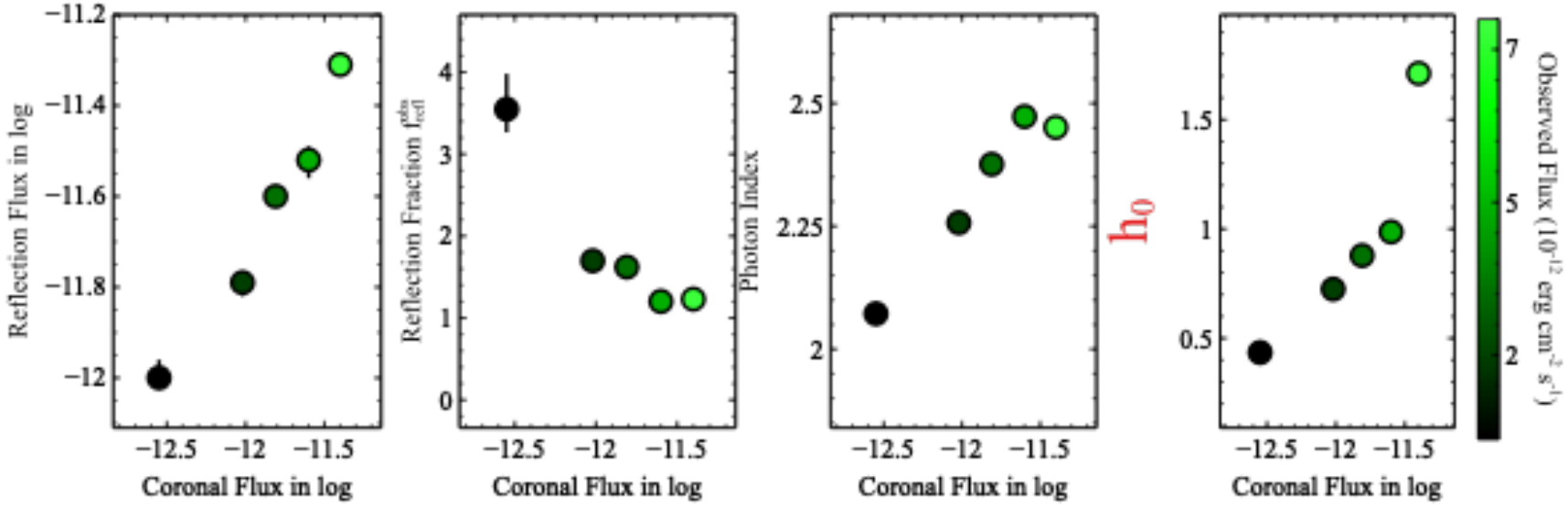
Density of reflector (disc surface)

$n \sim 10^{20}$ cm^{-3}

A(Fe)~3

$\xi \sim 10$

J. Jiang in prep

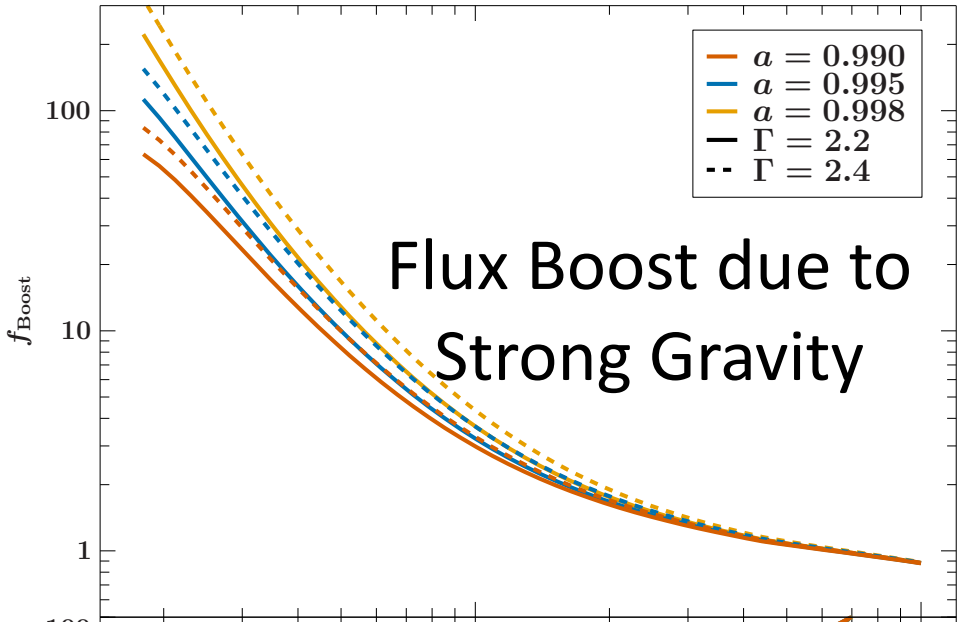


Use Ionization Parameter to infer "Euclidean" coronal height h_0

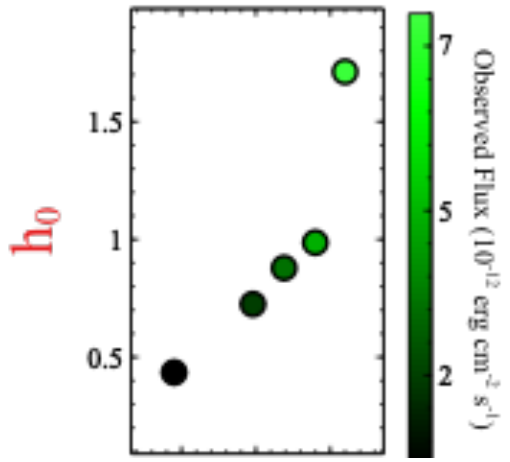
$$\xi = L/nh_0^2$$

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

T. Dauser

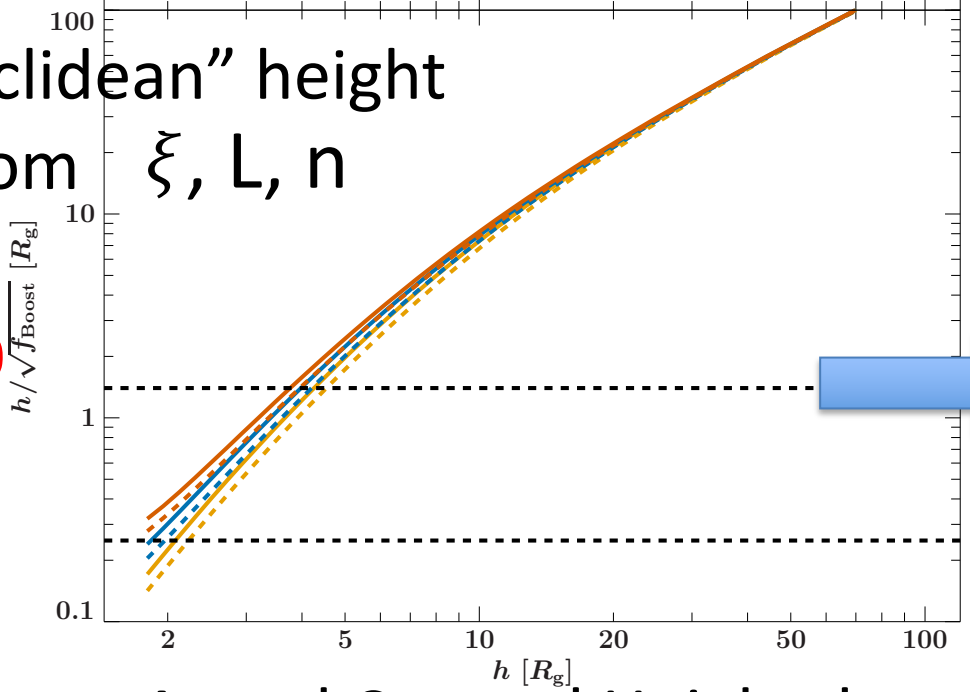


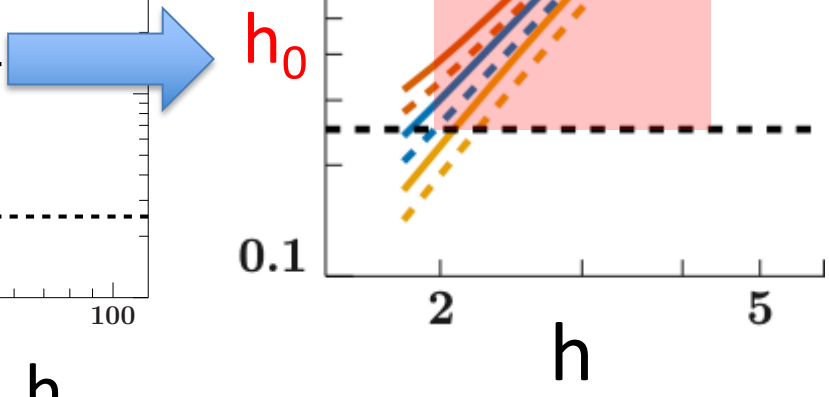
Flux Boost due to Strong Gravity



"Euclidean" height from ξ, L, n

$h_0\sqrt{f_{\rm Boost}}$





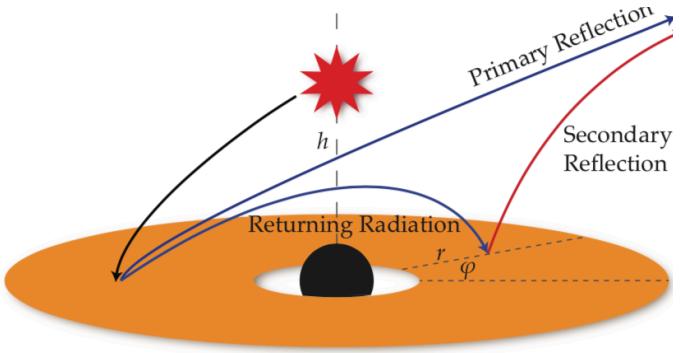
Actual Coronal Height, h

Coronal Height Measurement

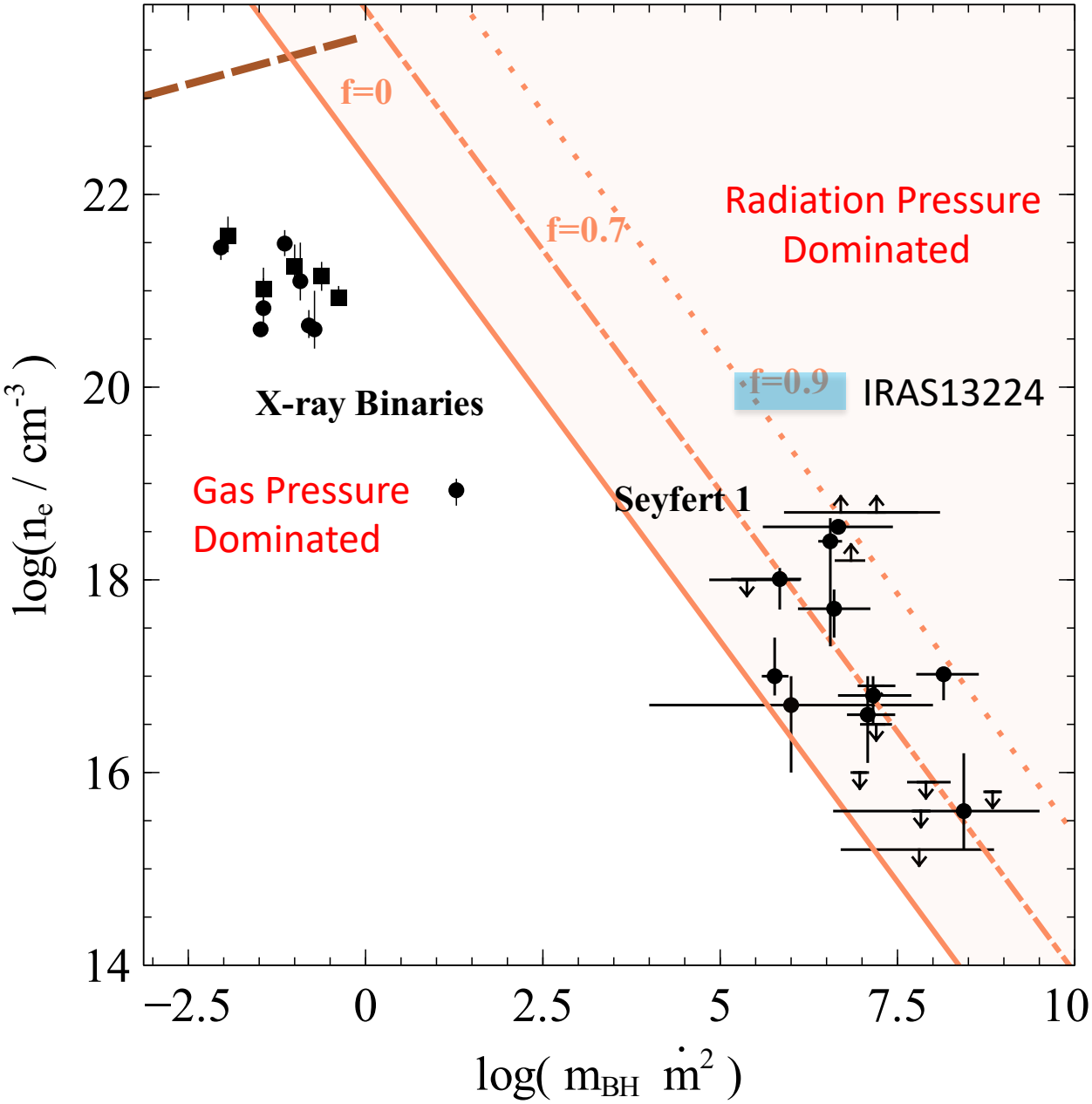
- Euclidean estimate $h_0 \sim 0.4 - 1.7\ r_g$
- Flux boosted height $h \sim 2 – 5\ r_g$
- Reverberation height $h \sim 6 – 12\ r_g$

Other Considerations

- Returning radiation?
- Size of corona



Wilkins+20



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

Summary of New Results

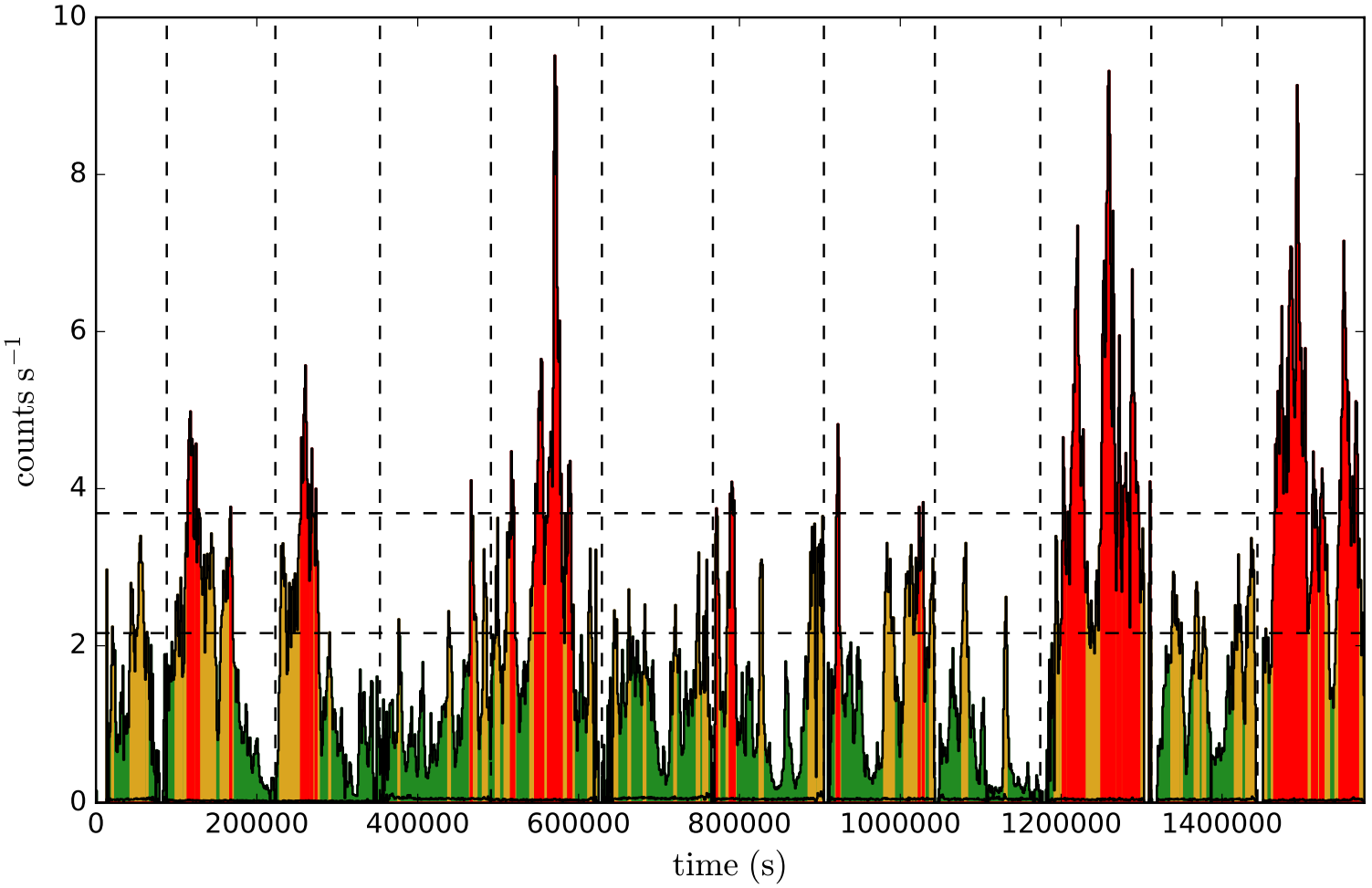
- Relativistic reflection and reverberation common in luminous accreting BH
- First X-ray reverberation AGN BH mass from IRAS13224 (10% uncertainty; Alston+20)
- Possible absorption lines from disc surface
- Measuring surface disc density for objects with BH mass < 2 x 10^7 M_{sun} (Jiang+19a,b,c,20)
- 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

Some implications for other objects

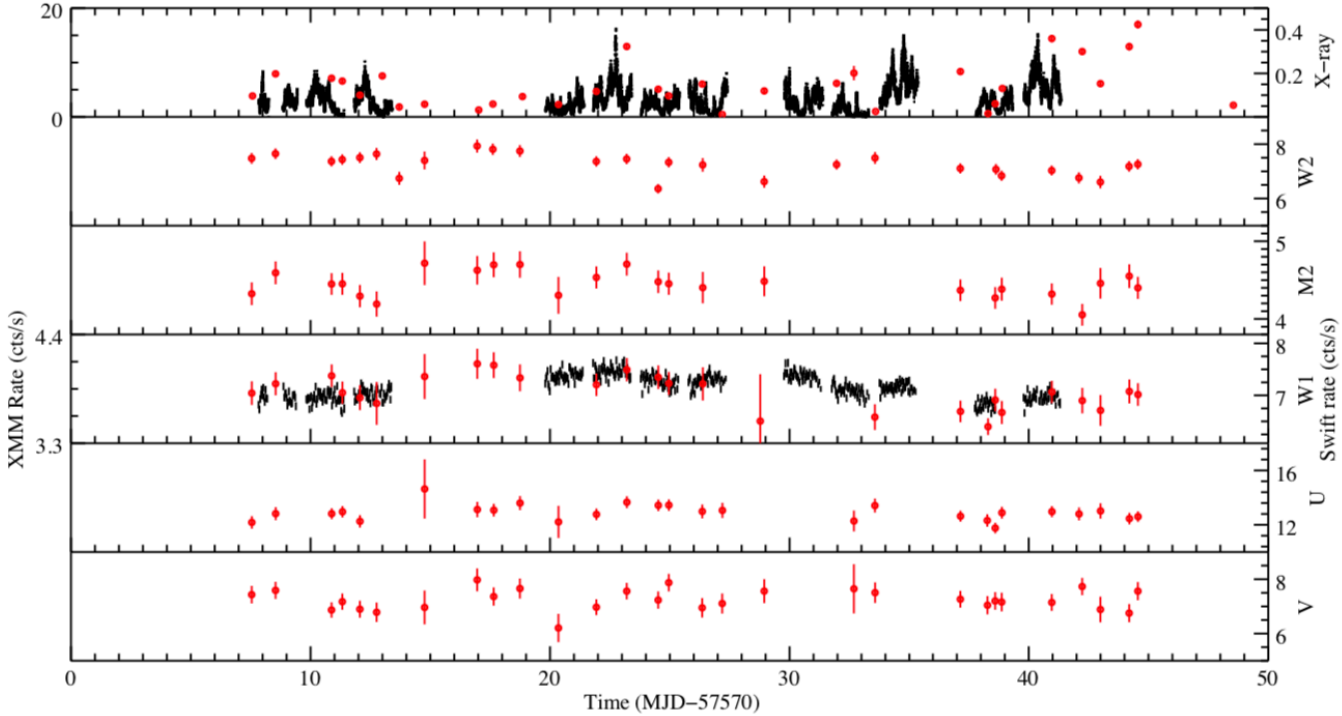
- There are dozens of bright AGN which could be observed to this depth with long exposures
  (need high f_{var} * Countrate).
- Many more with eXTP, Athena, Lynx…
- High density reflection models open new observational approach to accretion discs
- Since BHB discs more ionized, then surface absorption unlikely to be observable
- Accretion disc models may need to be revised to account for powerful coronae.
- Implications for Super-Eddington behaviour

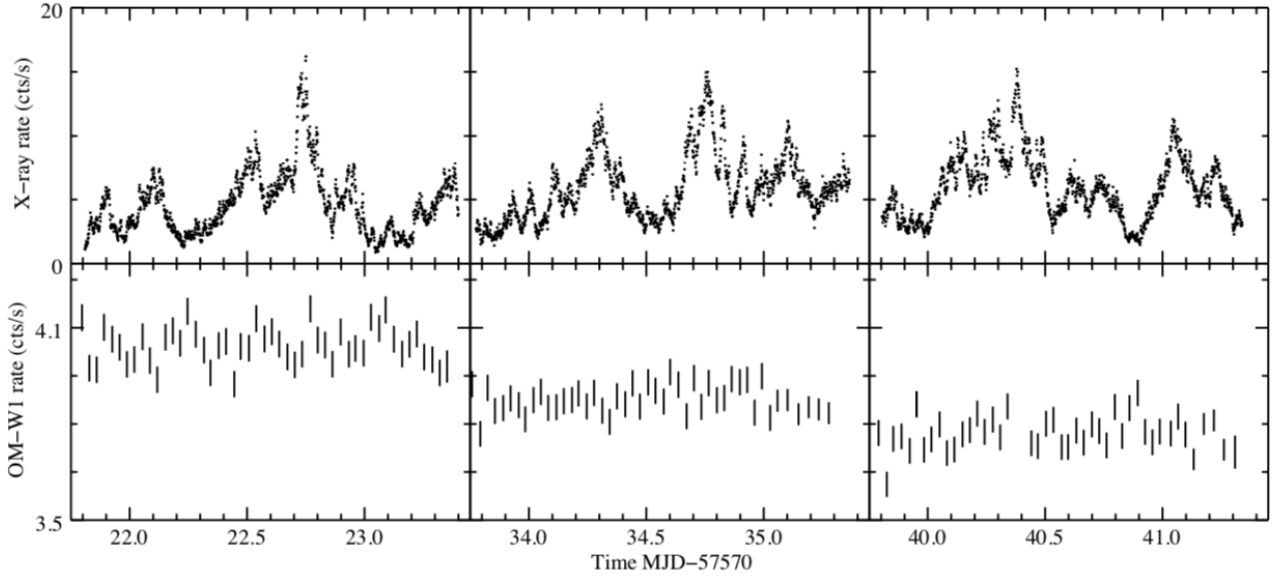
IRAS13224-3809 – MOST VARIABLE AGN IN X-RAYS

XMM + NuSTAR PROGRAMME 1.5Ms

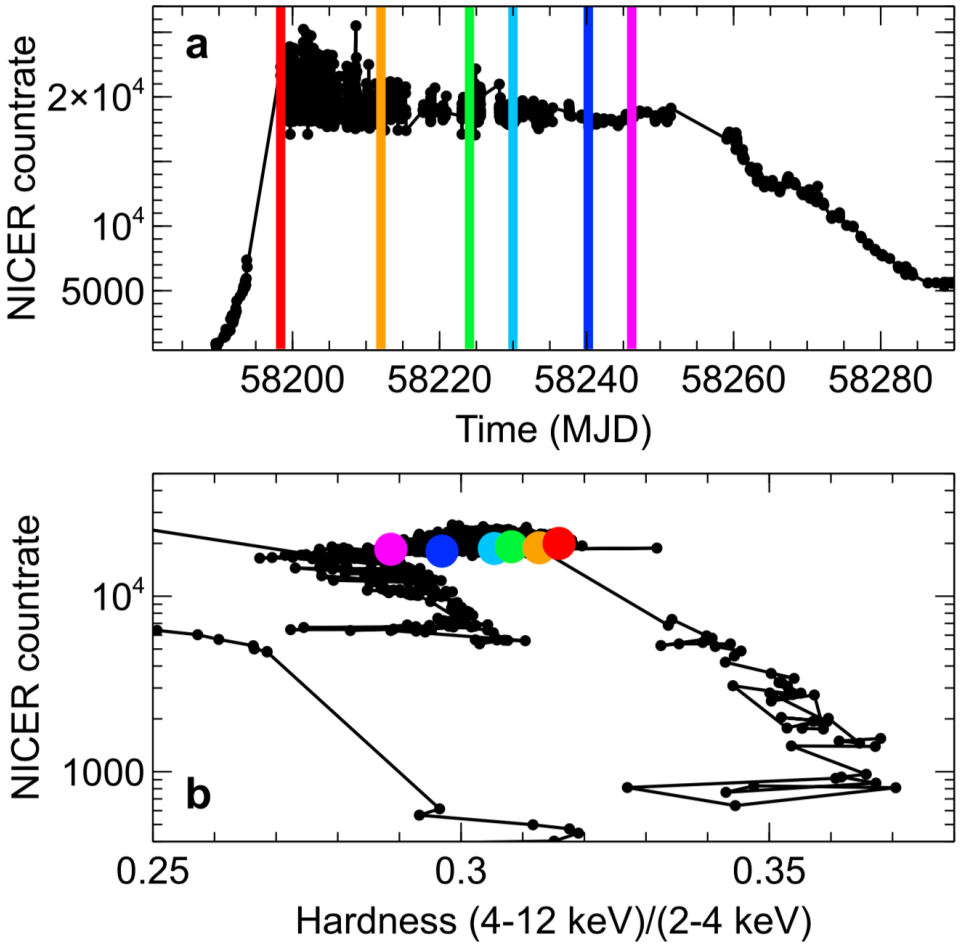


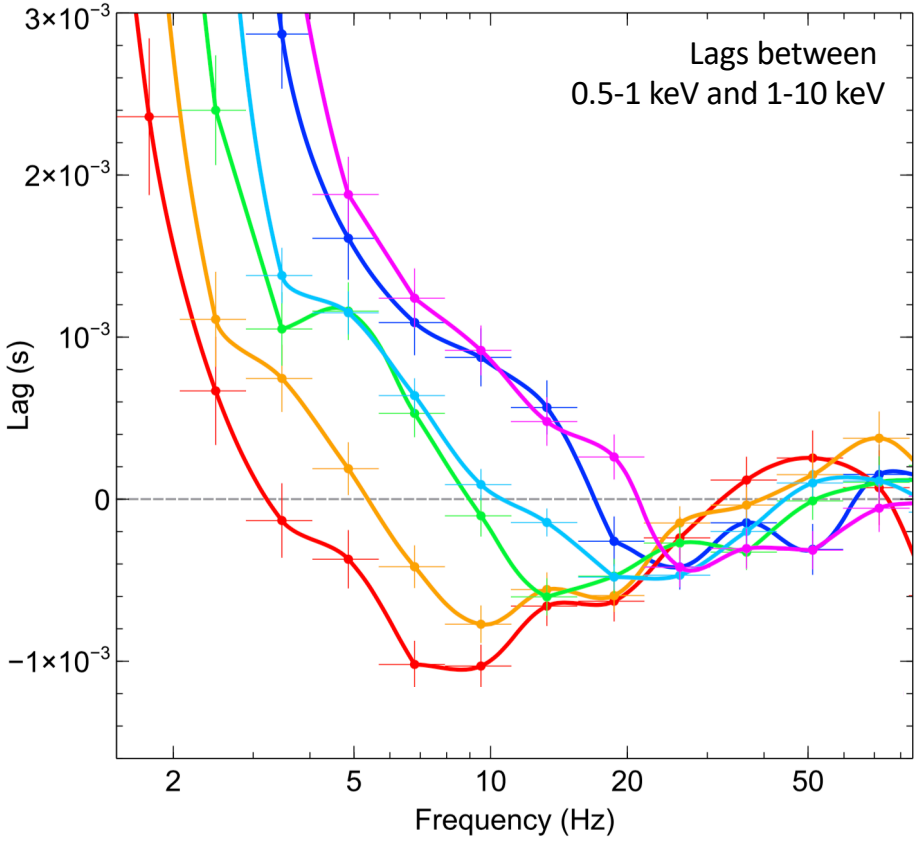
Buisson+18


XMM Rate (cts/s)
Swift rate (cts/s)
X−ray
W2
M2
W1
U
V
Time (MJD−57570)


X−ray rate (cts/s)
OM−W1 rate (cts/s)
Time MJD−57570

NICER measures short reverberation lags

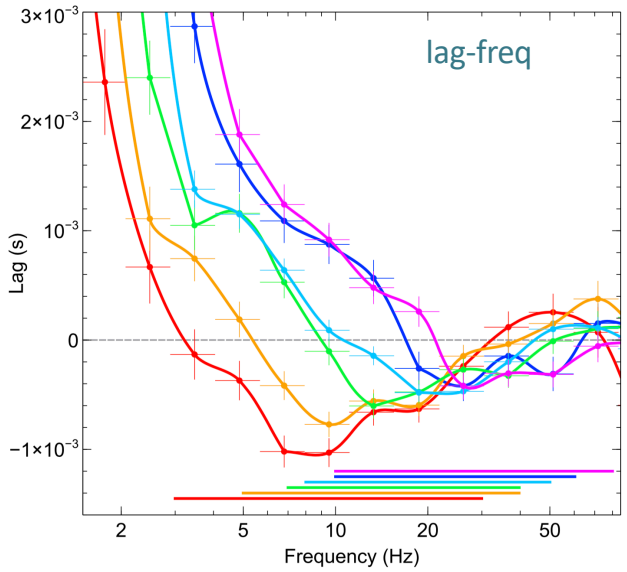


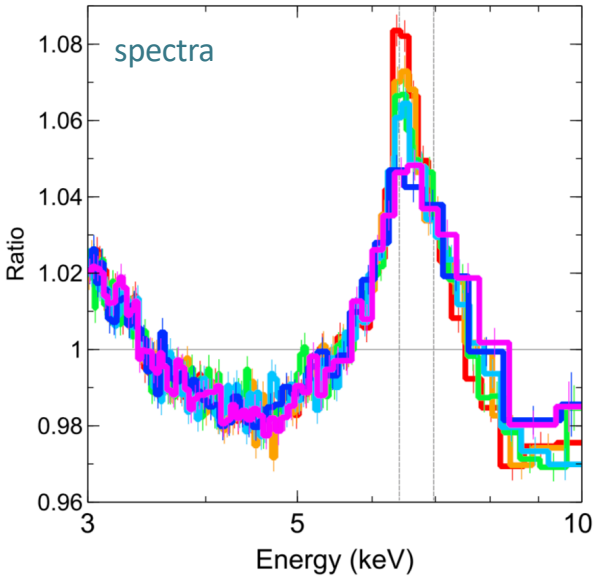


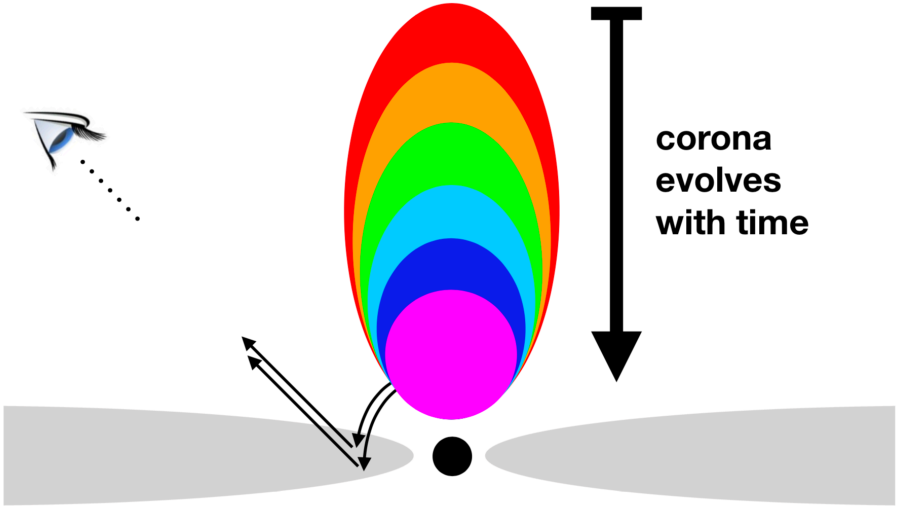
volve to higher frequencies

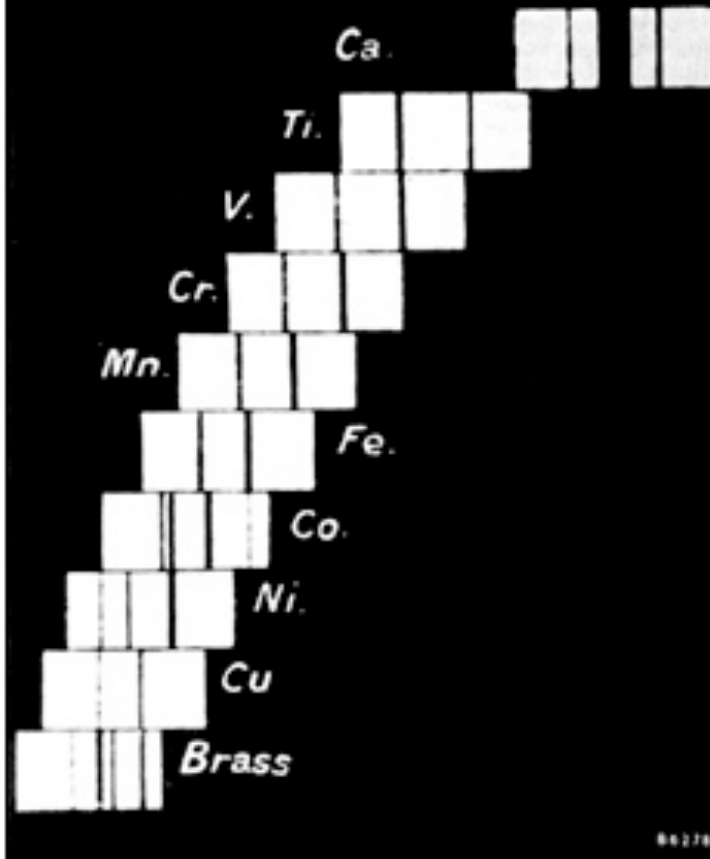
Reverberation in XRBs: Uttley et al., 2011, De Marco et al., 2017

Consistent picture between spectra and timing analyses!





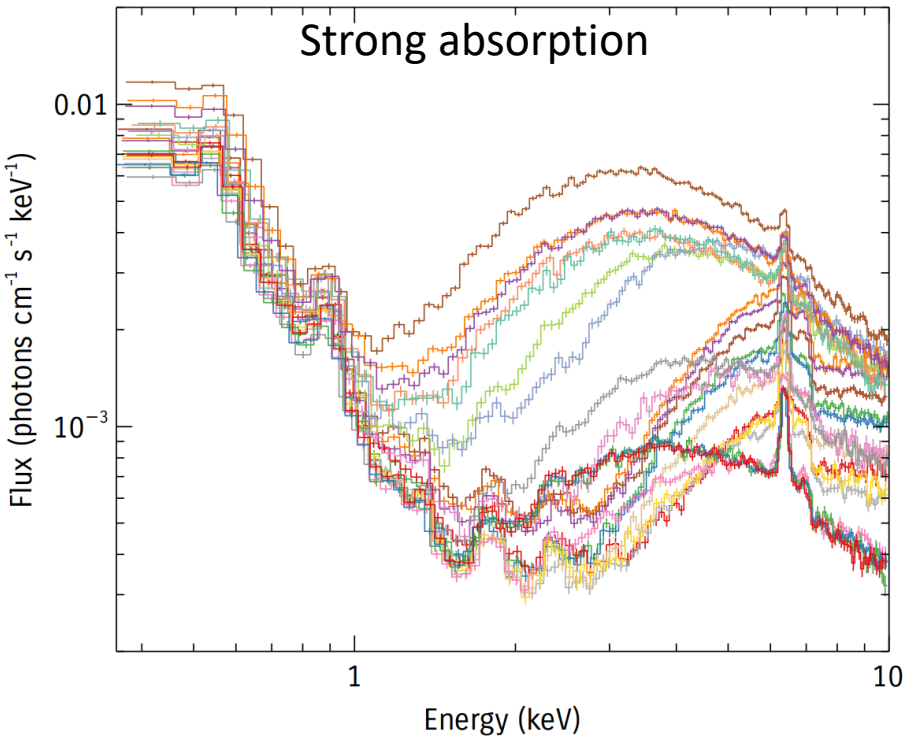




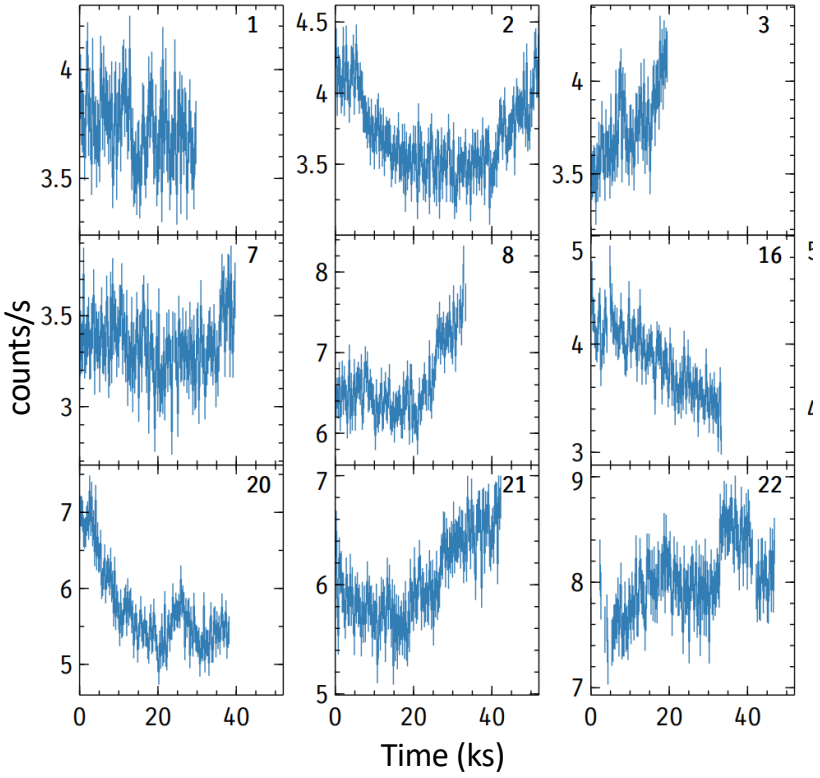
H Moseley

X-ray Fluorescent Spectroscopy / X-ray Reflection

But is there relativistic reflection in NGC 4151?



Spectra are complex,
doesn't require broad line



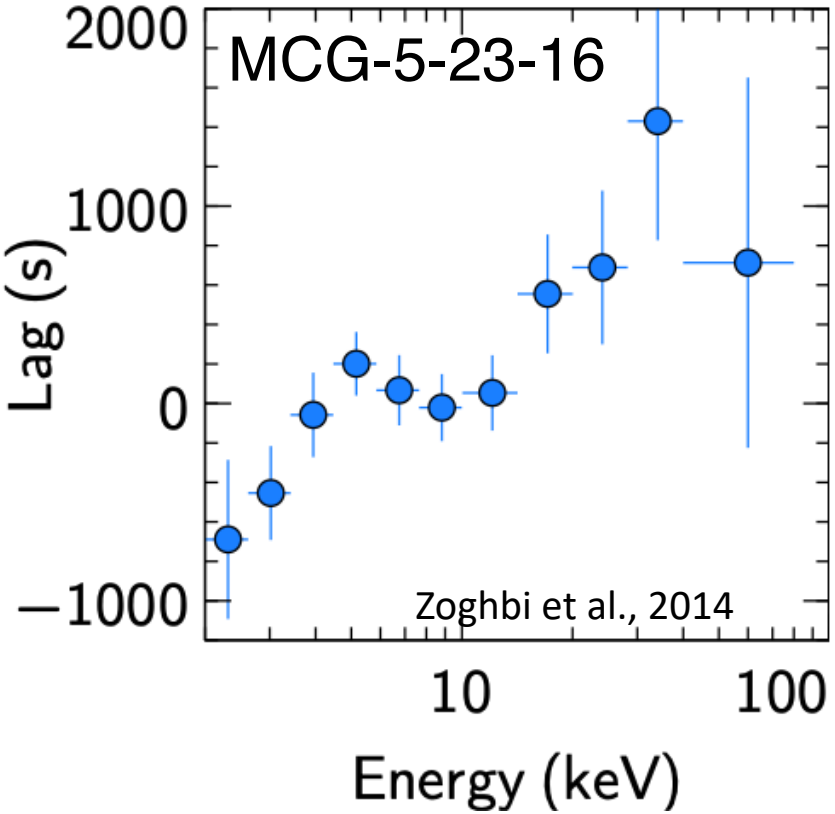
No signatures of reverberation

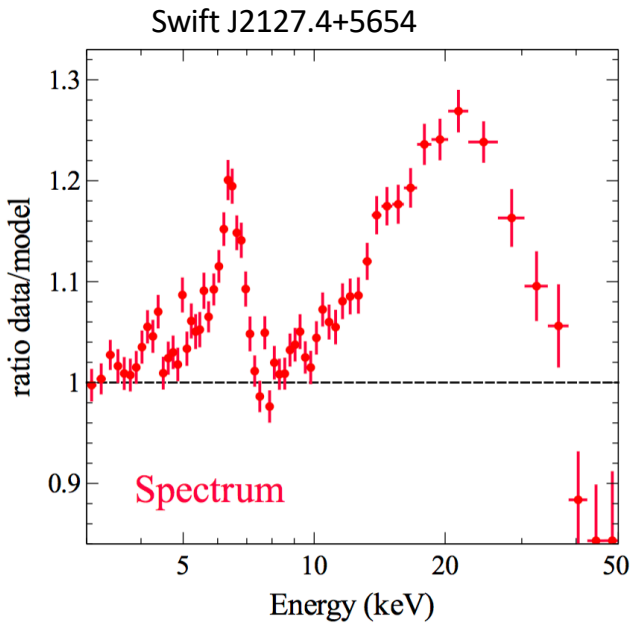
High mass black hole, short observations → Are we probing long enough timescales?

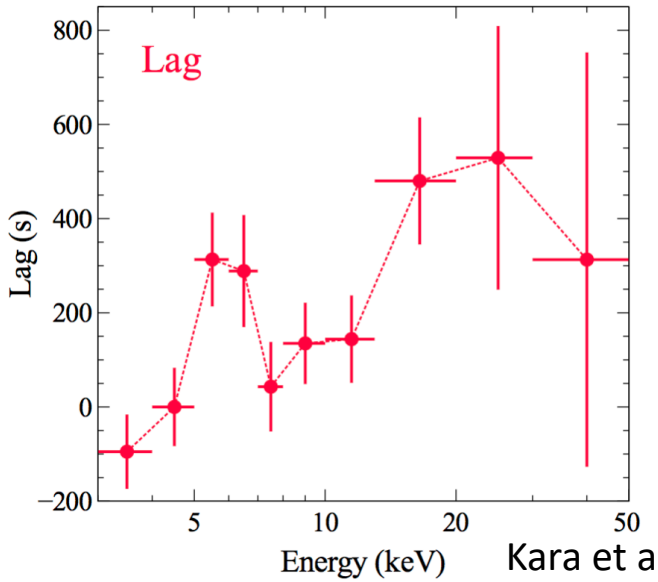
Zoghbi, Miller & Cackett 2019

NuSTAR

Zoghbi et al., 2013 - Lags can be measured through time domain techniques, allowing for reverberation measurements even from data with gaps

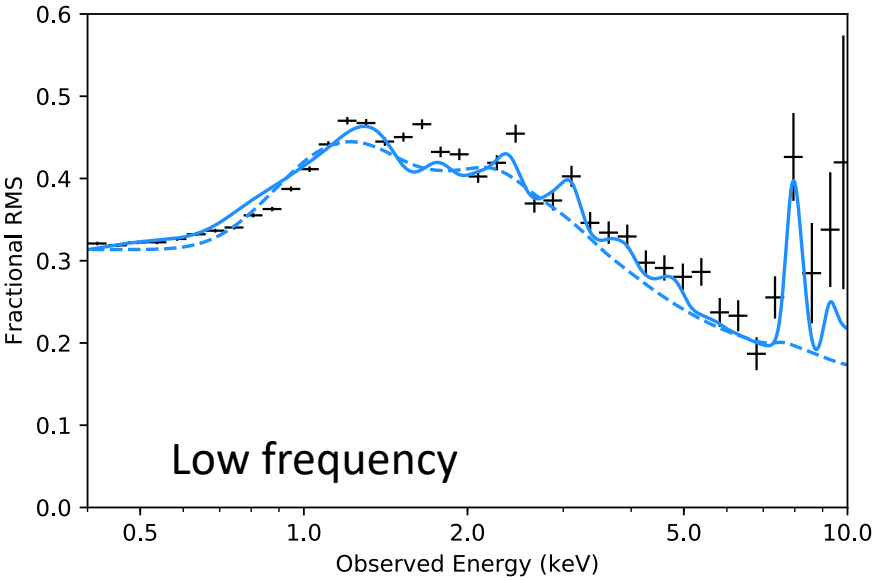


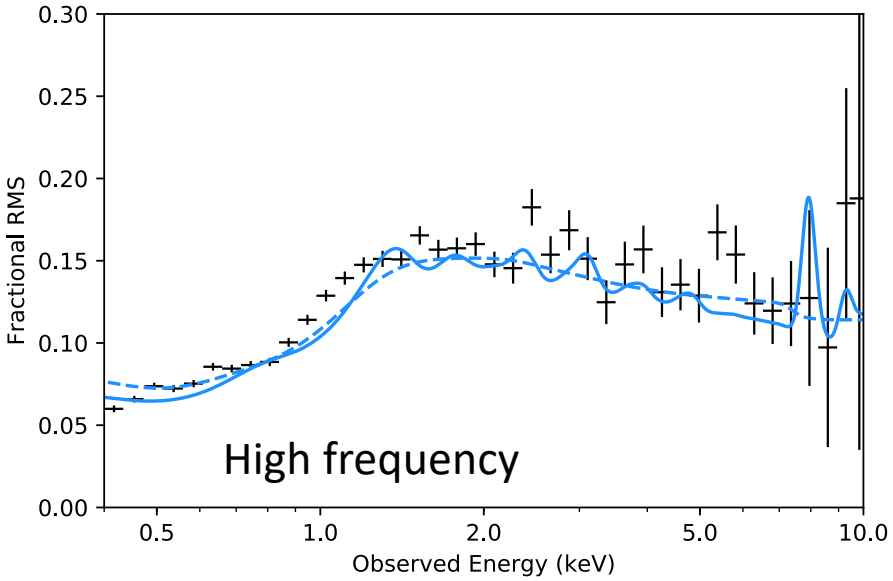




Kara et al., 2015

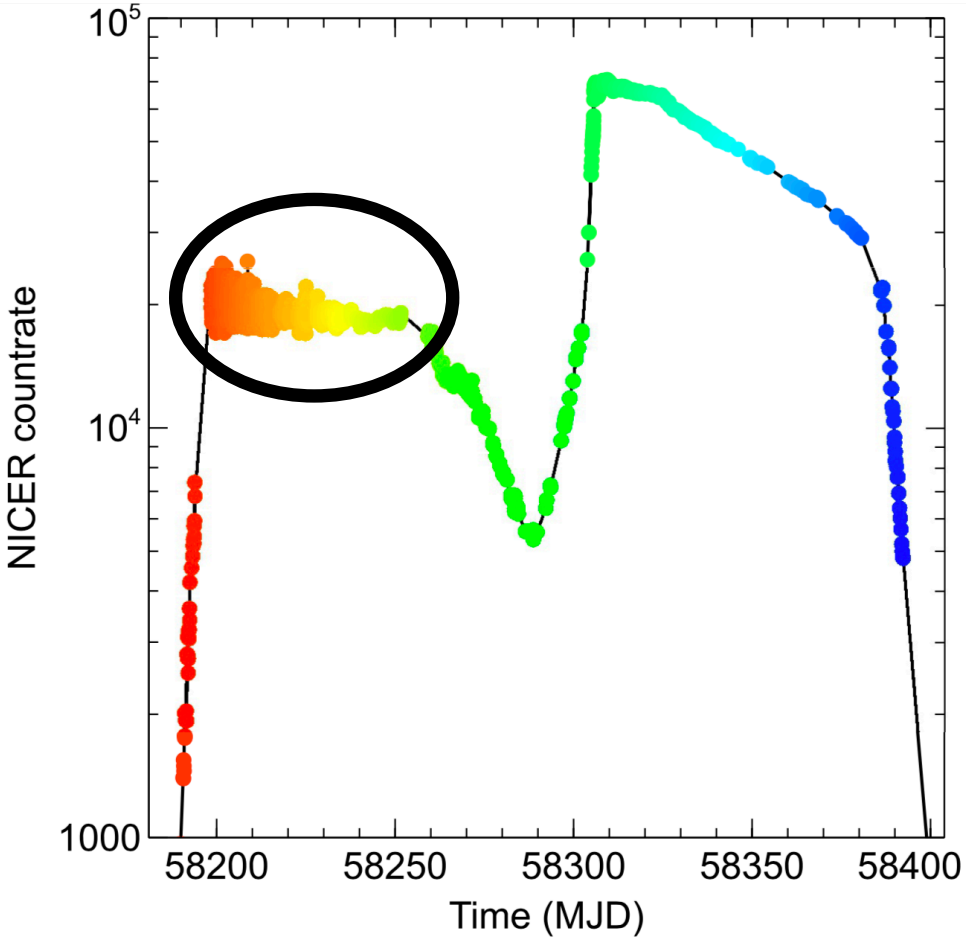
IRAS13224 RMS –Energy spectra

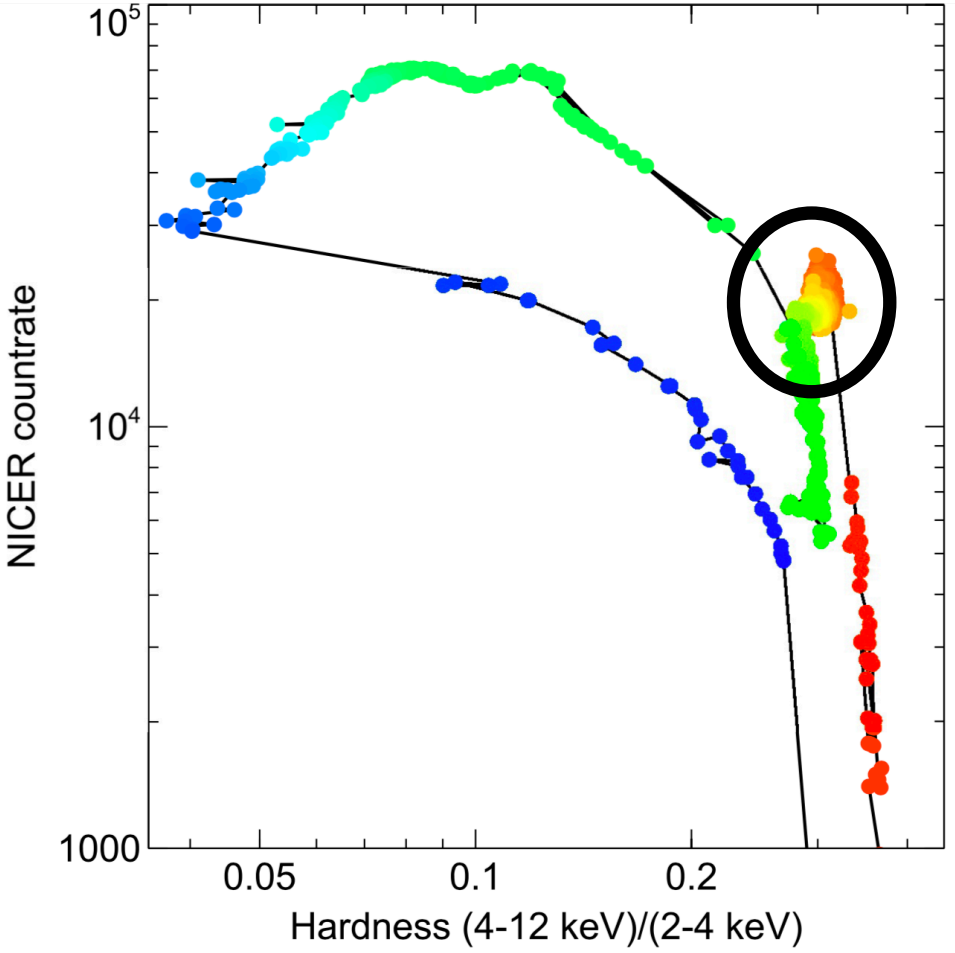


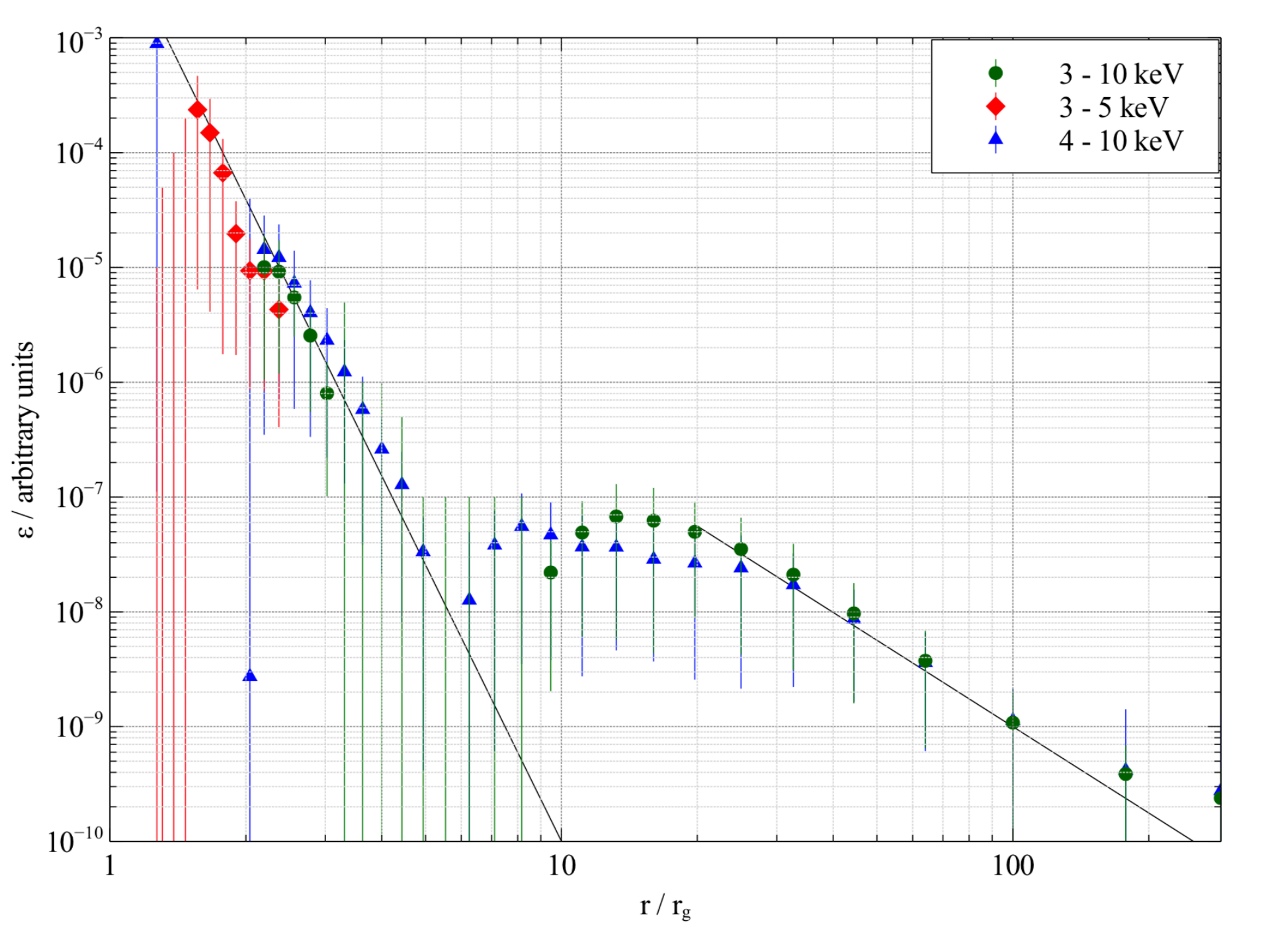


Alston, Parker+19

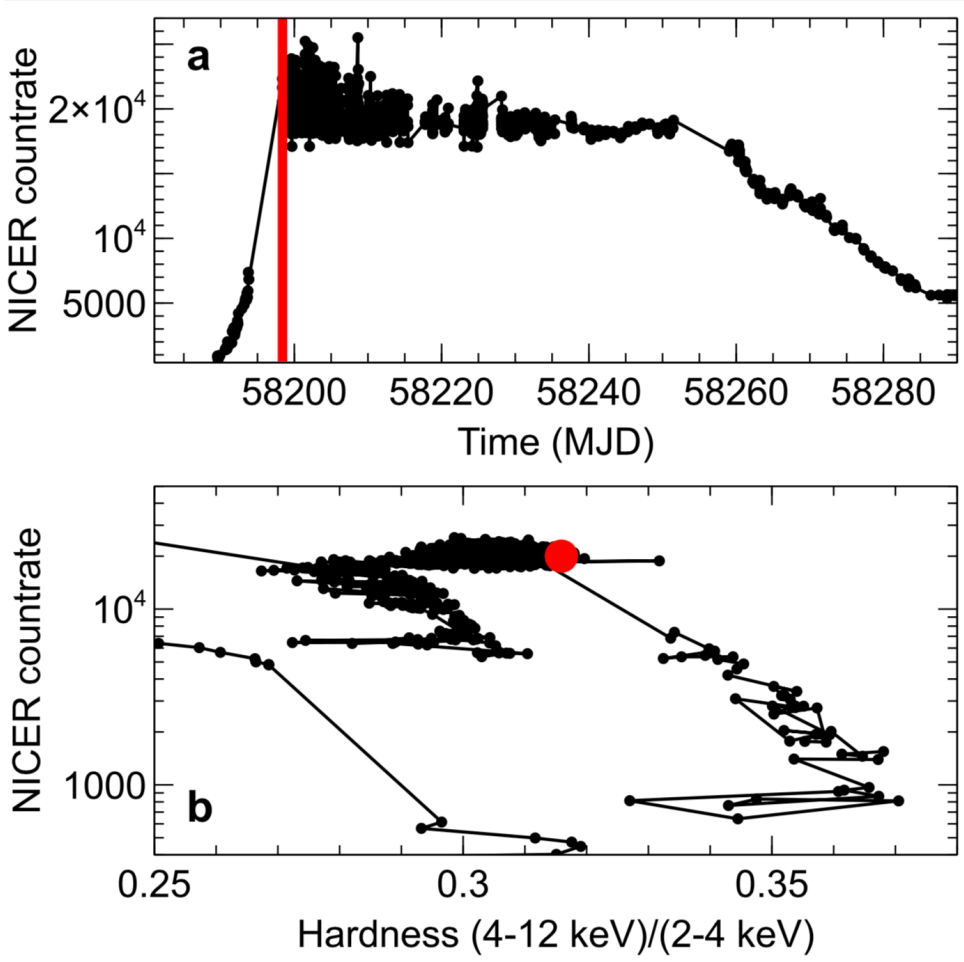
NICER observations of MAXIJ1820+070

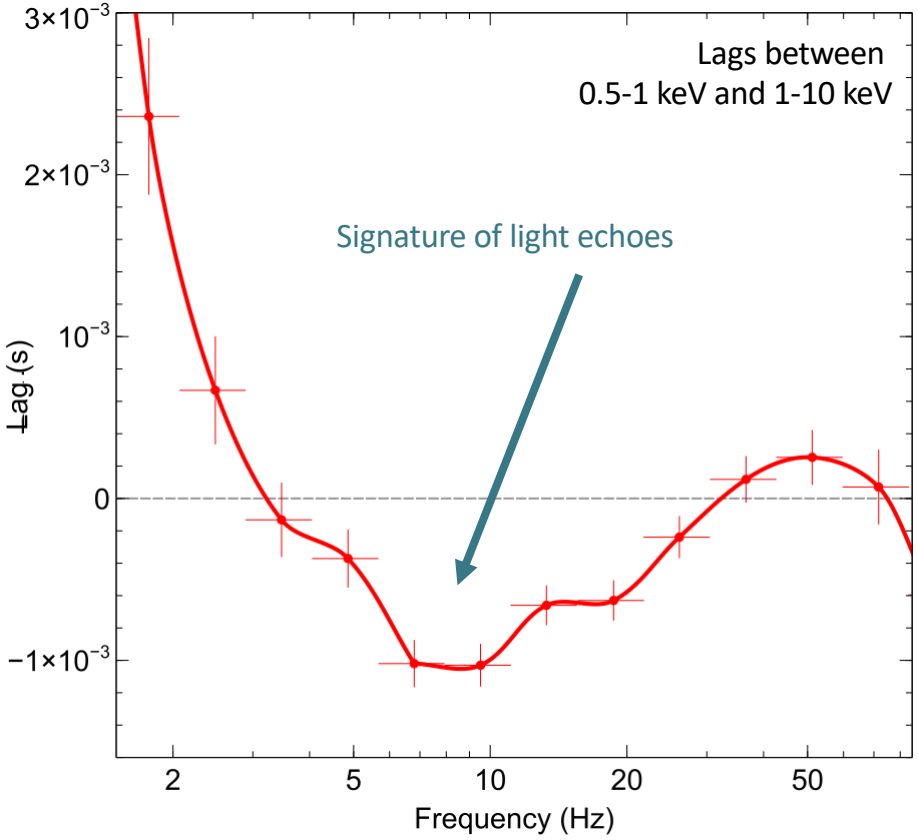





3 - 10 keV
3 - 5 keV
4 - 10 keV
ε / arbitrary units
r / r_g
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
1
10
100

NICER measures short reverberation lags

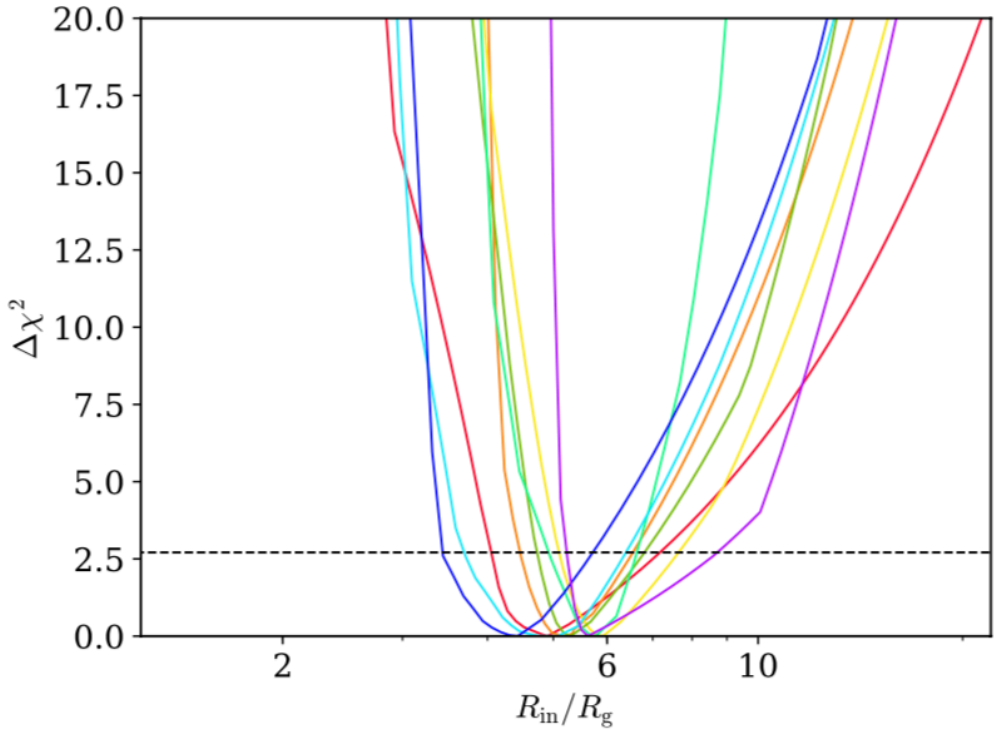




(Temporal Frequency —
how rapidly light curve varies)

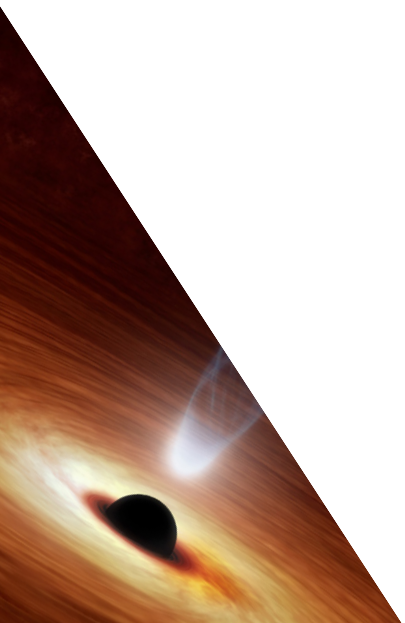
Reverberation in XRBs: Uttley et al., 2011, De Marco et al., 2017

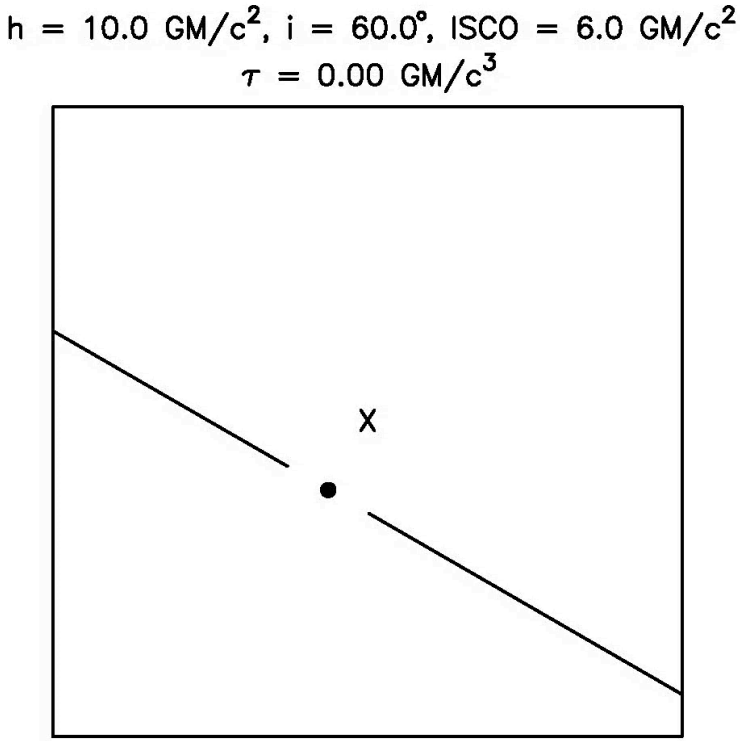
MAXI J1820+070

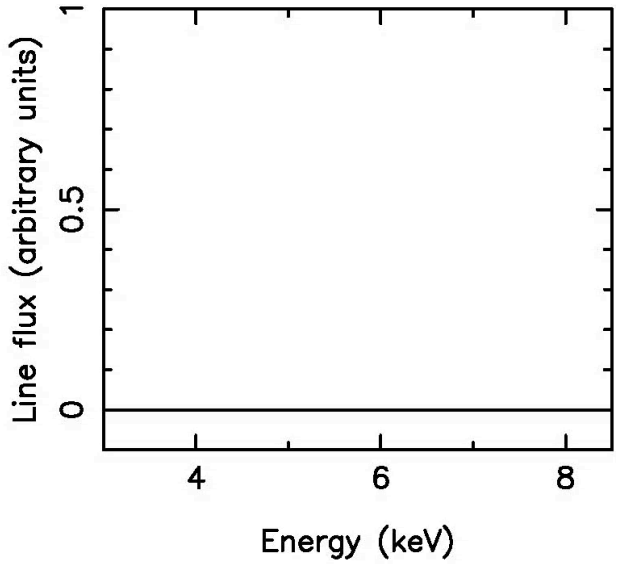


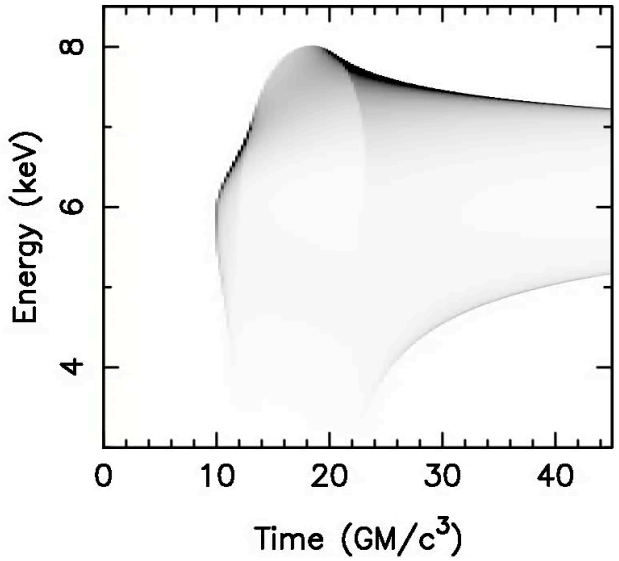
Disc is NOT truncated

Cackett13



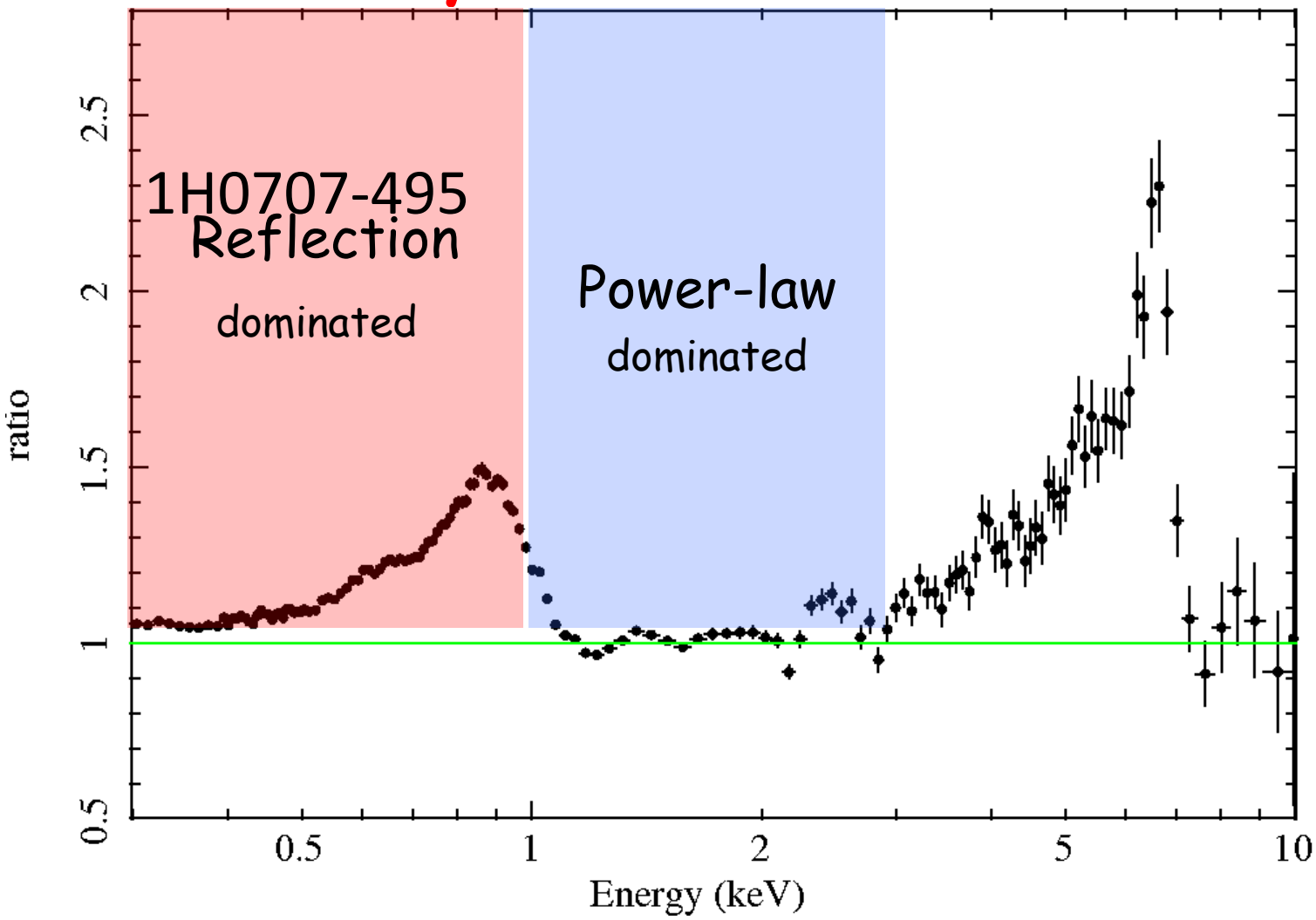

h = 10.0 GM/c^2, i = 60.0°, ISCO = 6.0 GM/c^2
τ = 0.00 GM/c^3
X


Line flux (arbitrary units)
0
0.5
1
4
6
8
Energy (keV)

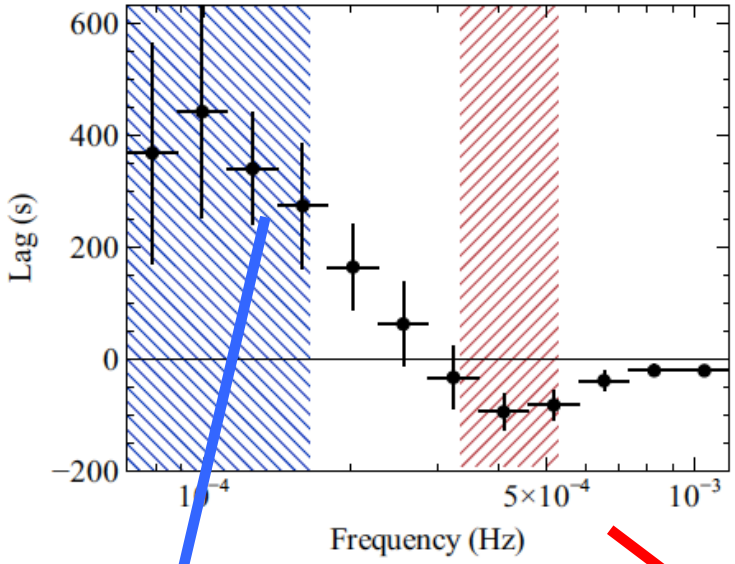

Energy (keV)
4
6
8
0
10
20
30
40
Time (GM/c^3)

Fabian+09

X-ray Reverberation

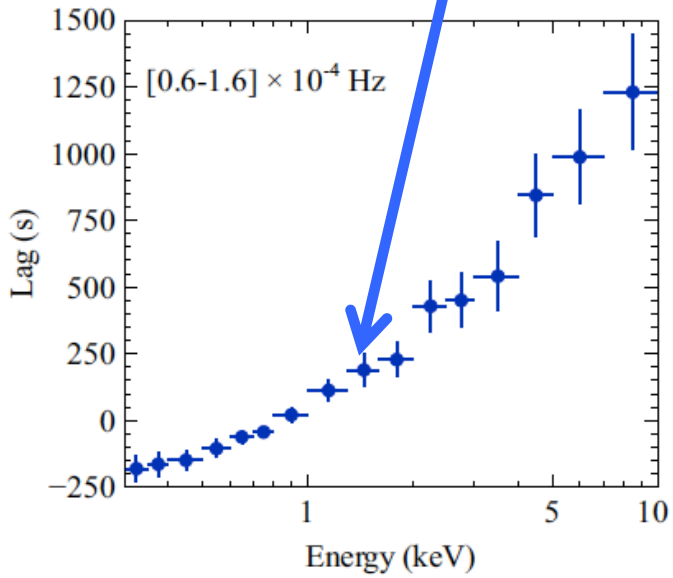


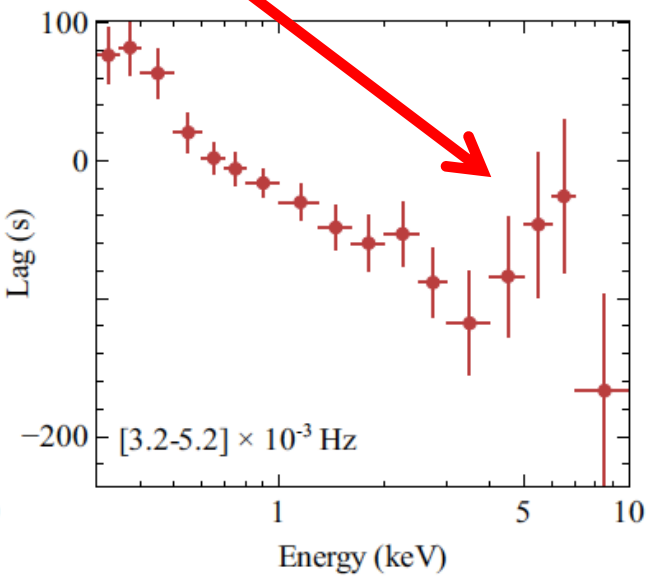
Akn564
Kara+13



Low frequency lag
featureless so
NOT reverberation

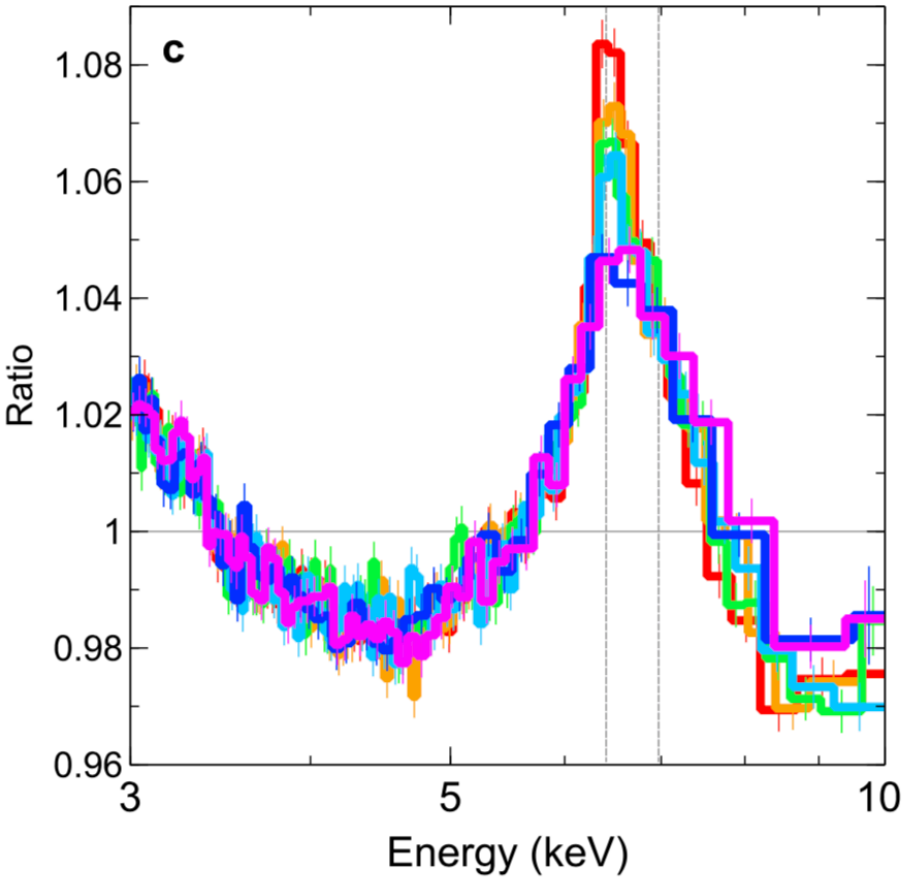
High frequency
lag shows iron
So is reverberation



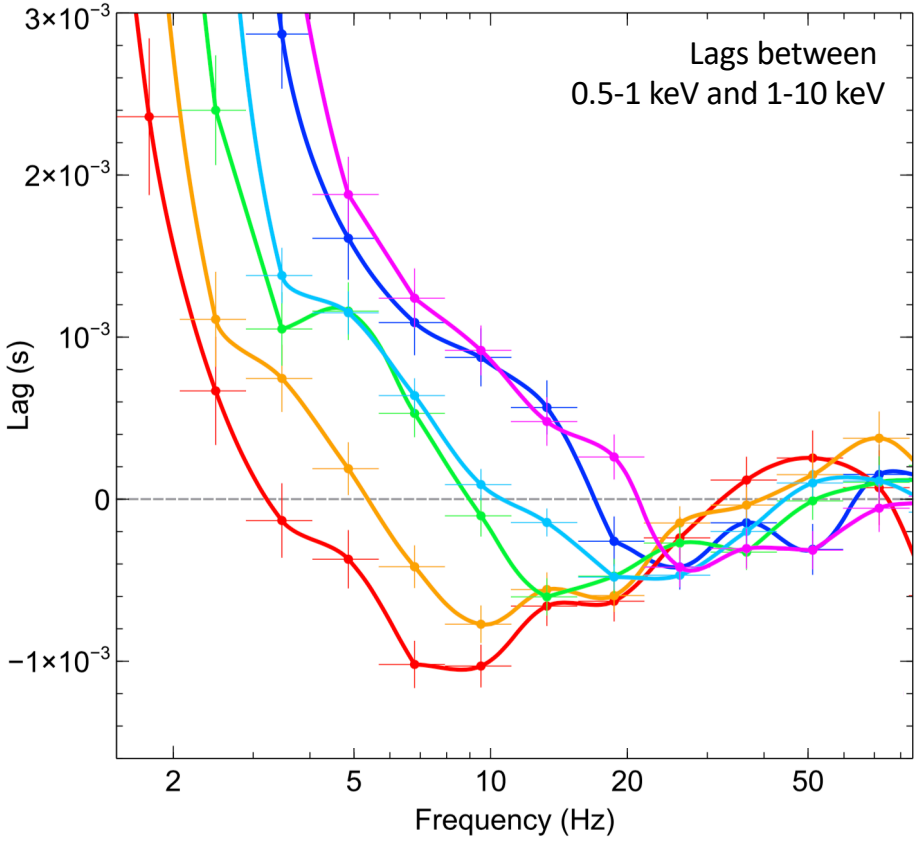


relativistic reflection and reverberation

Kara et al., *Nature*, 2019



Broad line is constant over time



Lags evolve to higher frequencies

Gallo+04

1H0707-495