30 years of Relativistic Reflection and Reverberation around Luminous Accreting Black Holes

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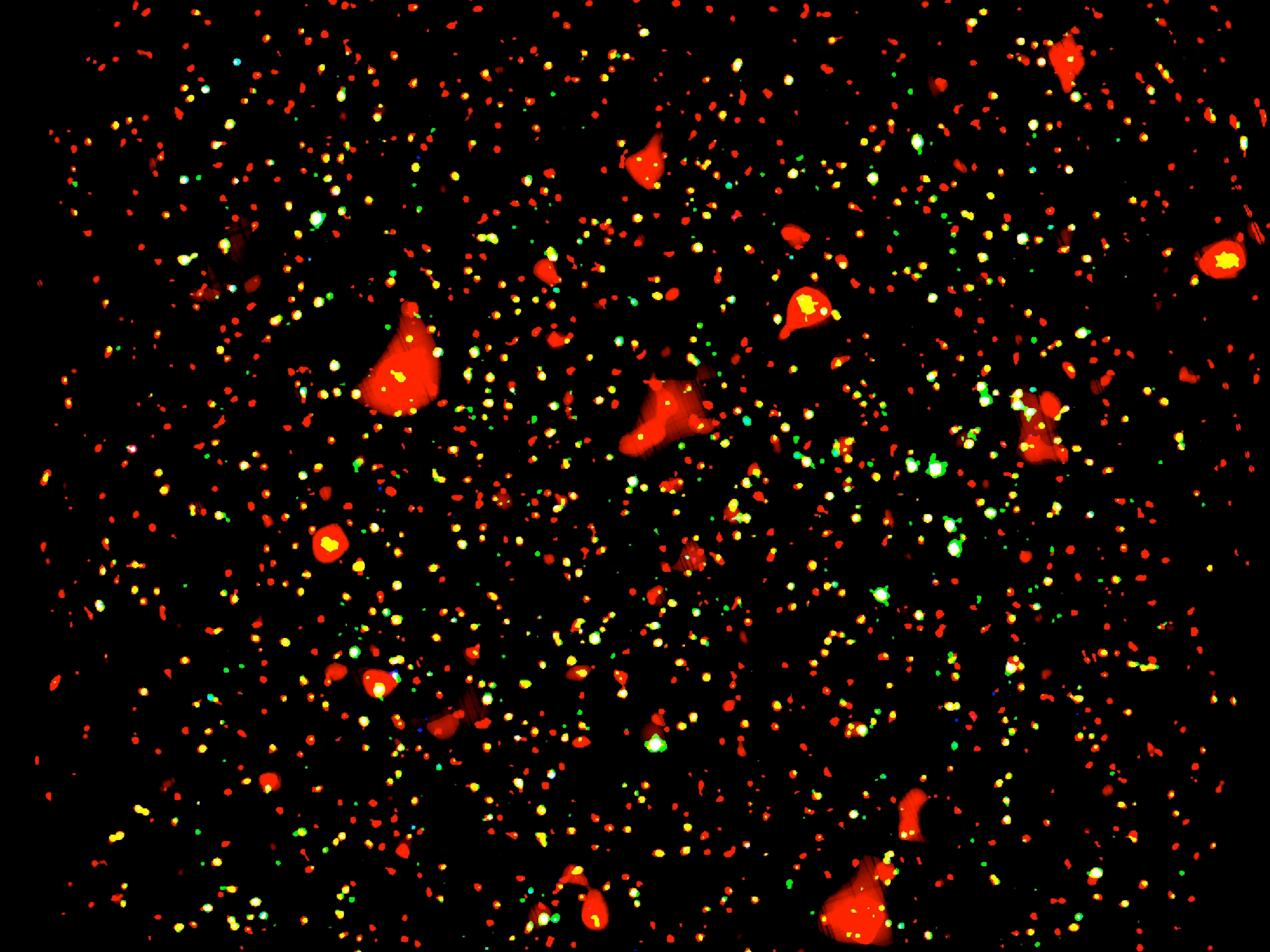
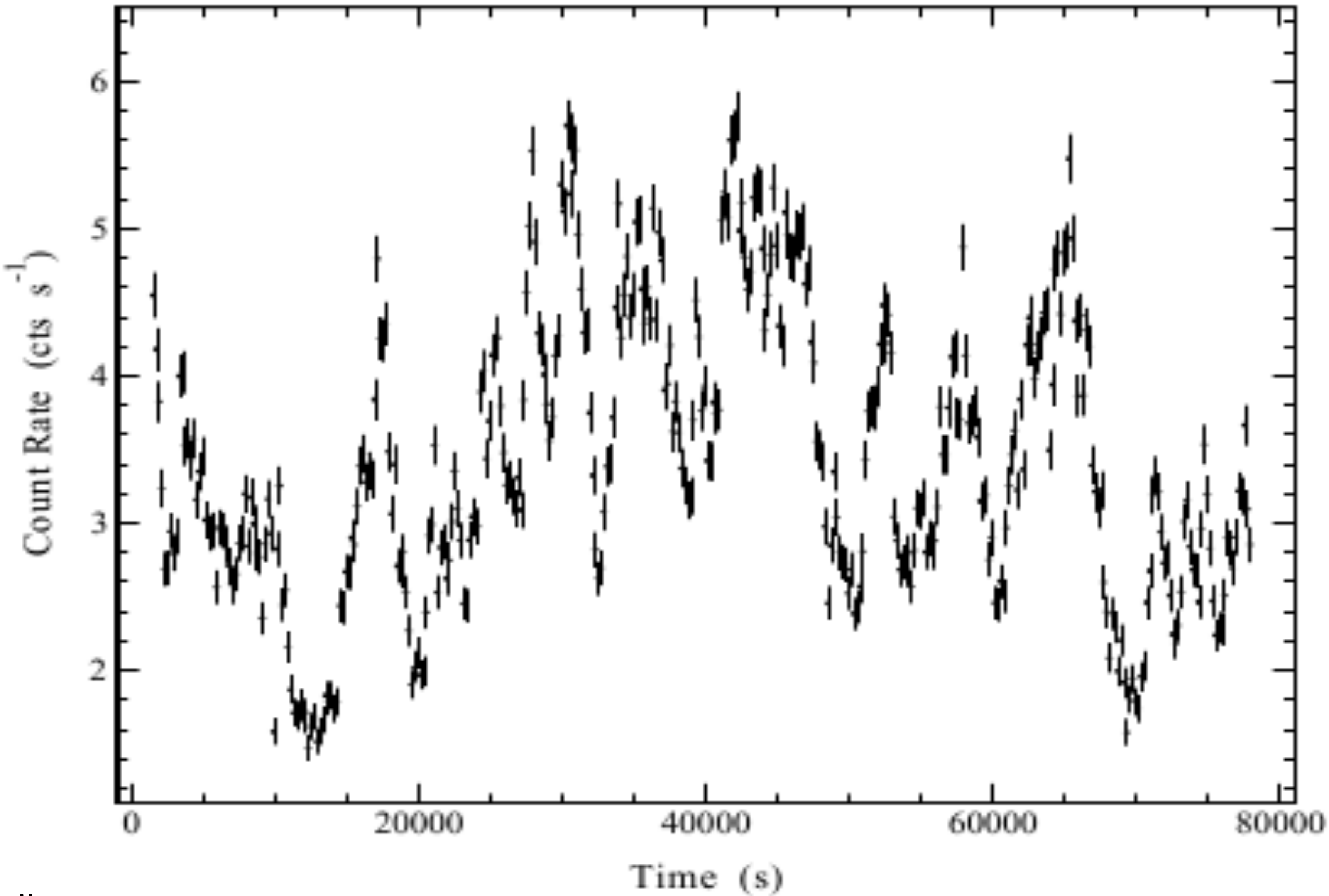
European Research Council

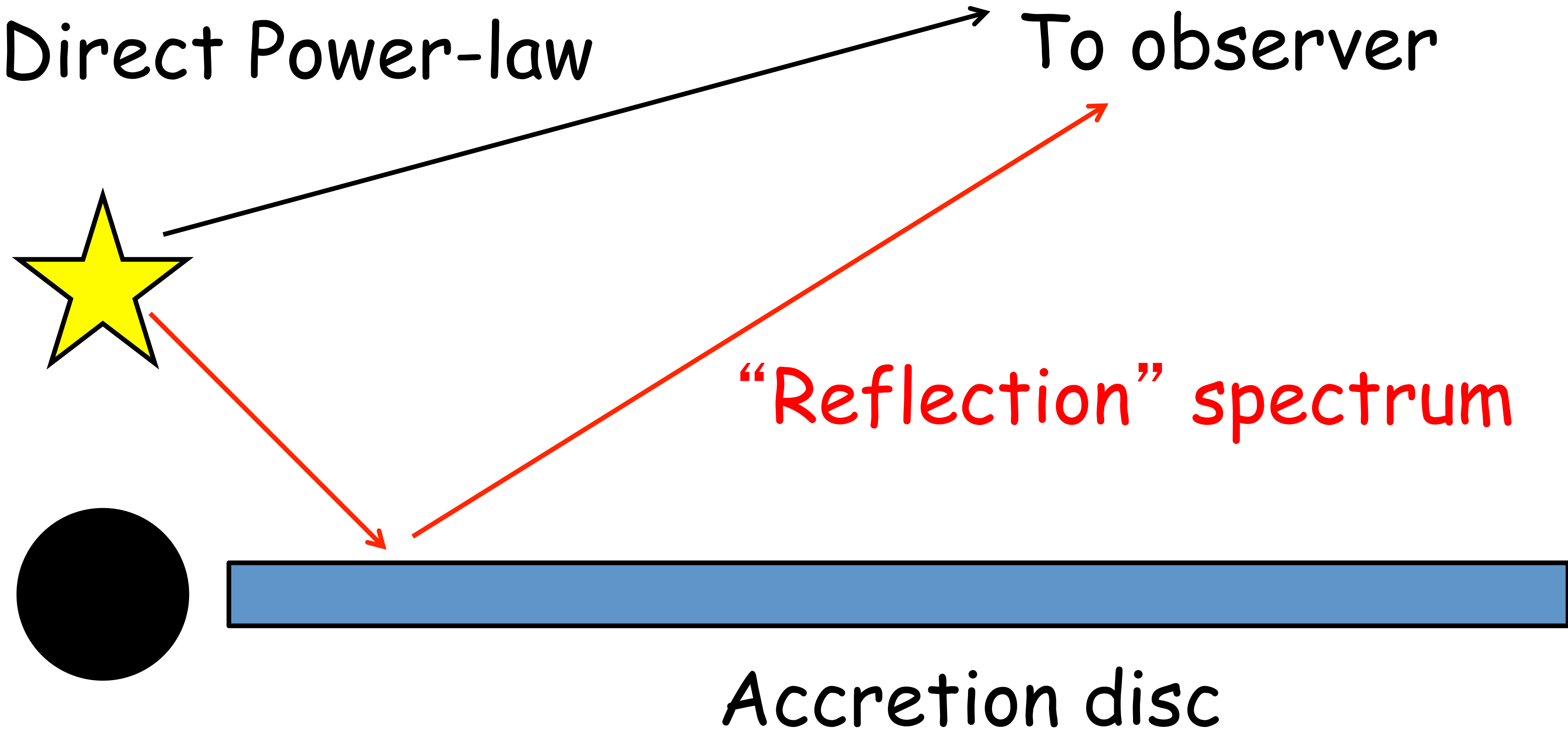
Established by the European Commission

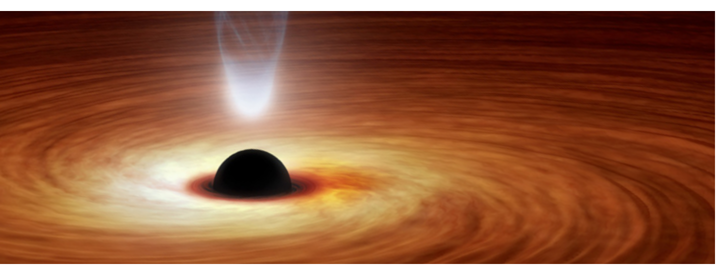


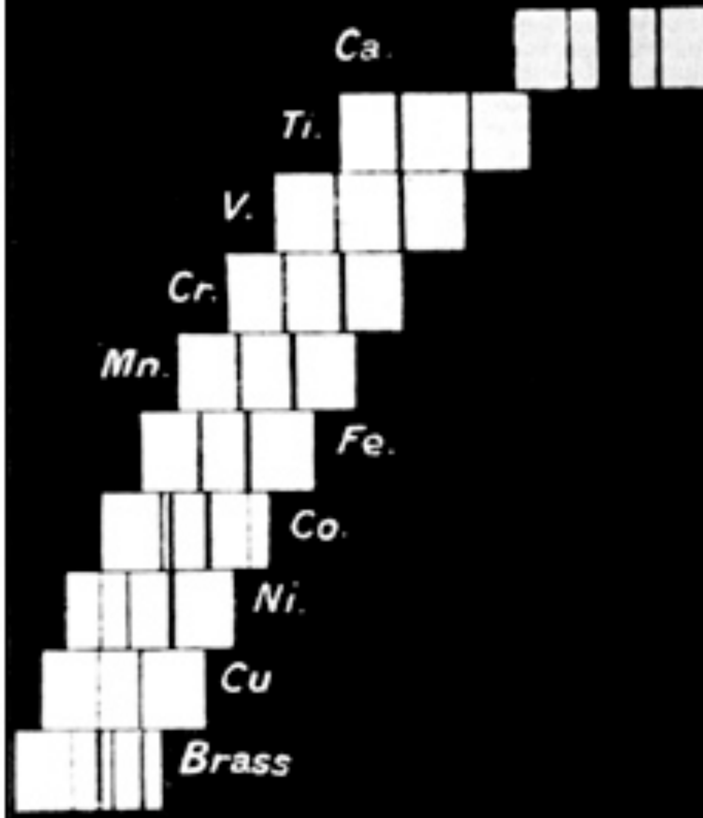
1H0707-495



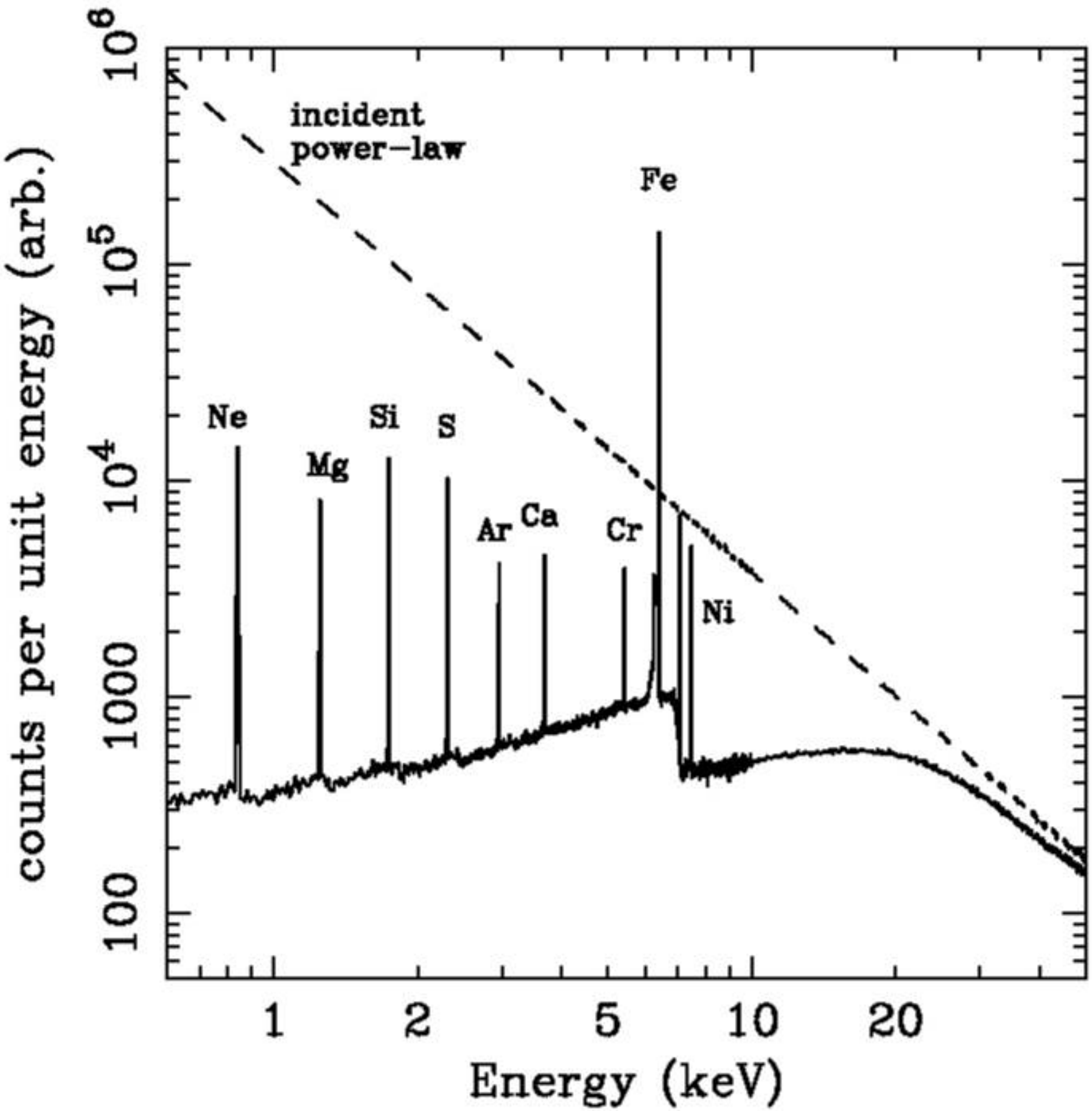
Gallo+04


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



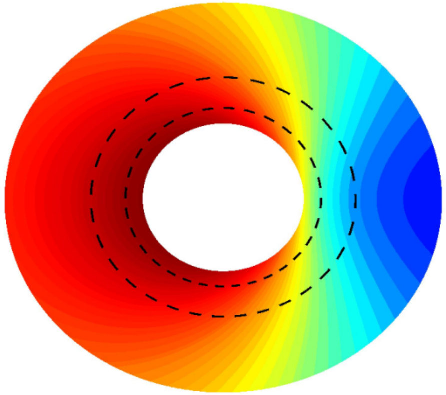


H Moseley

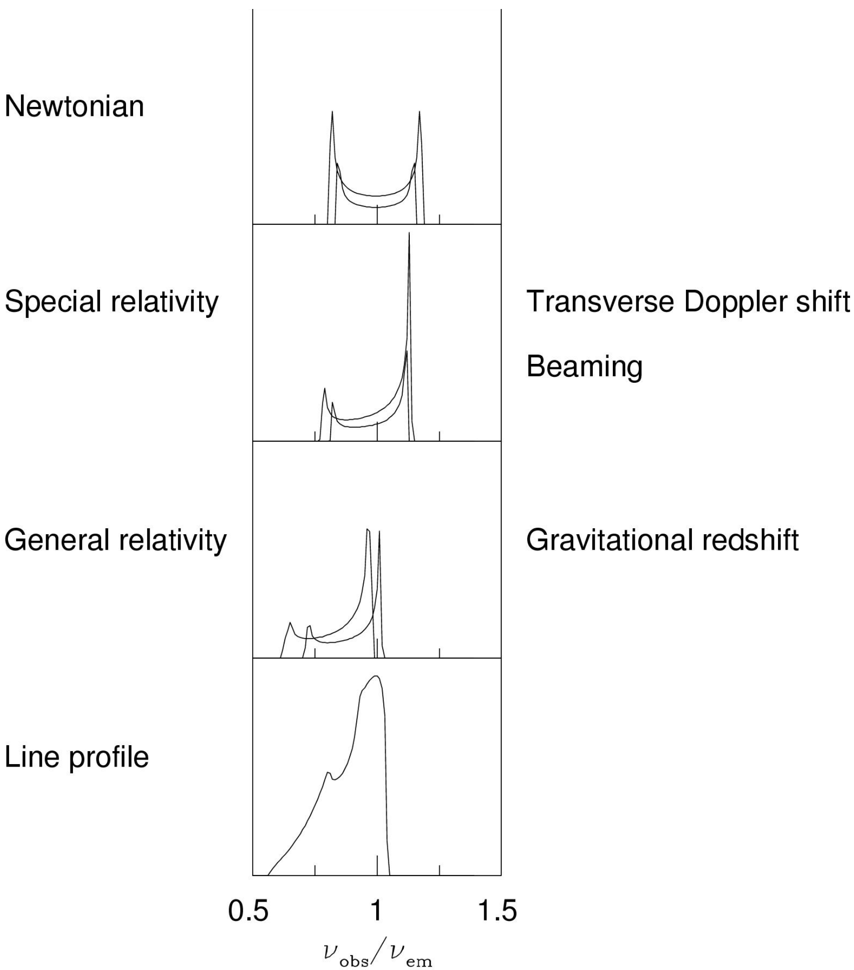


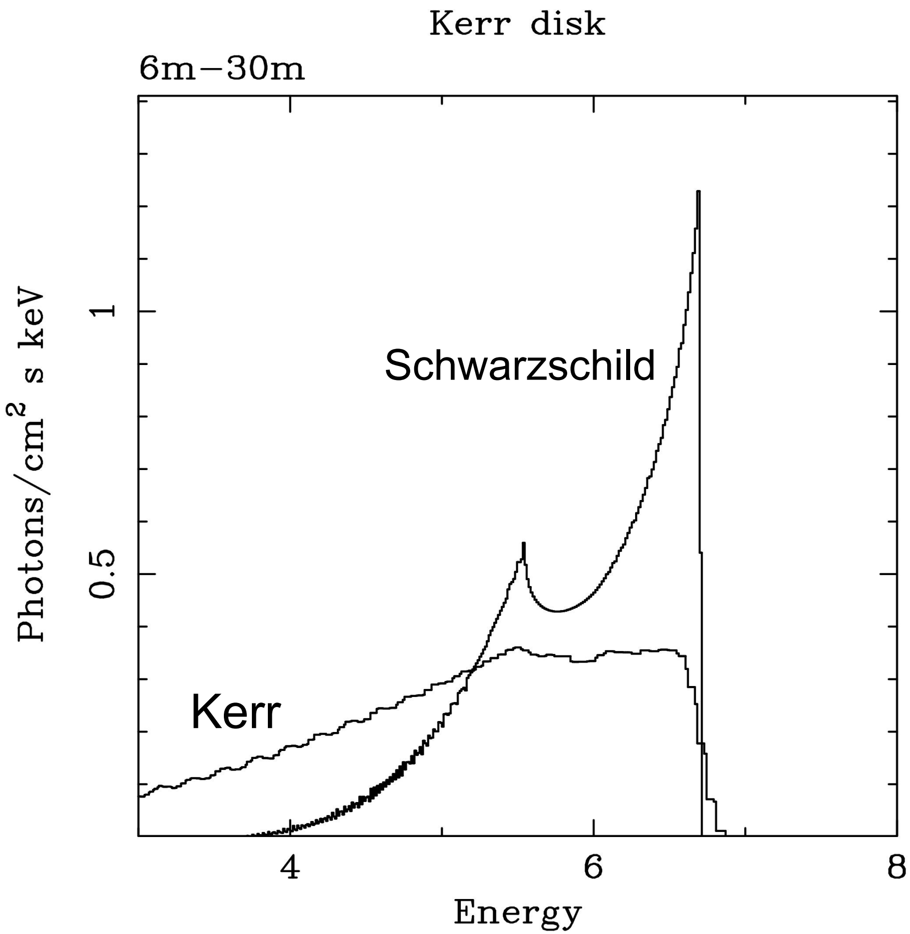
Reflection from cold matter of cosmic abundance

C Reynolds

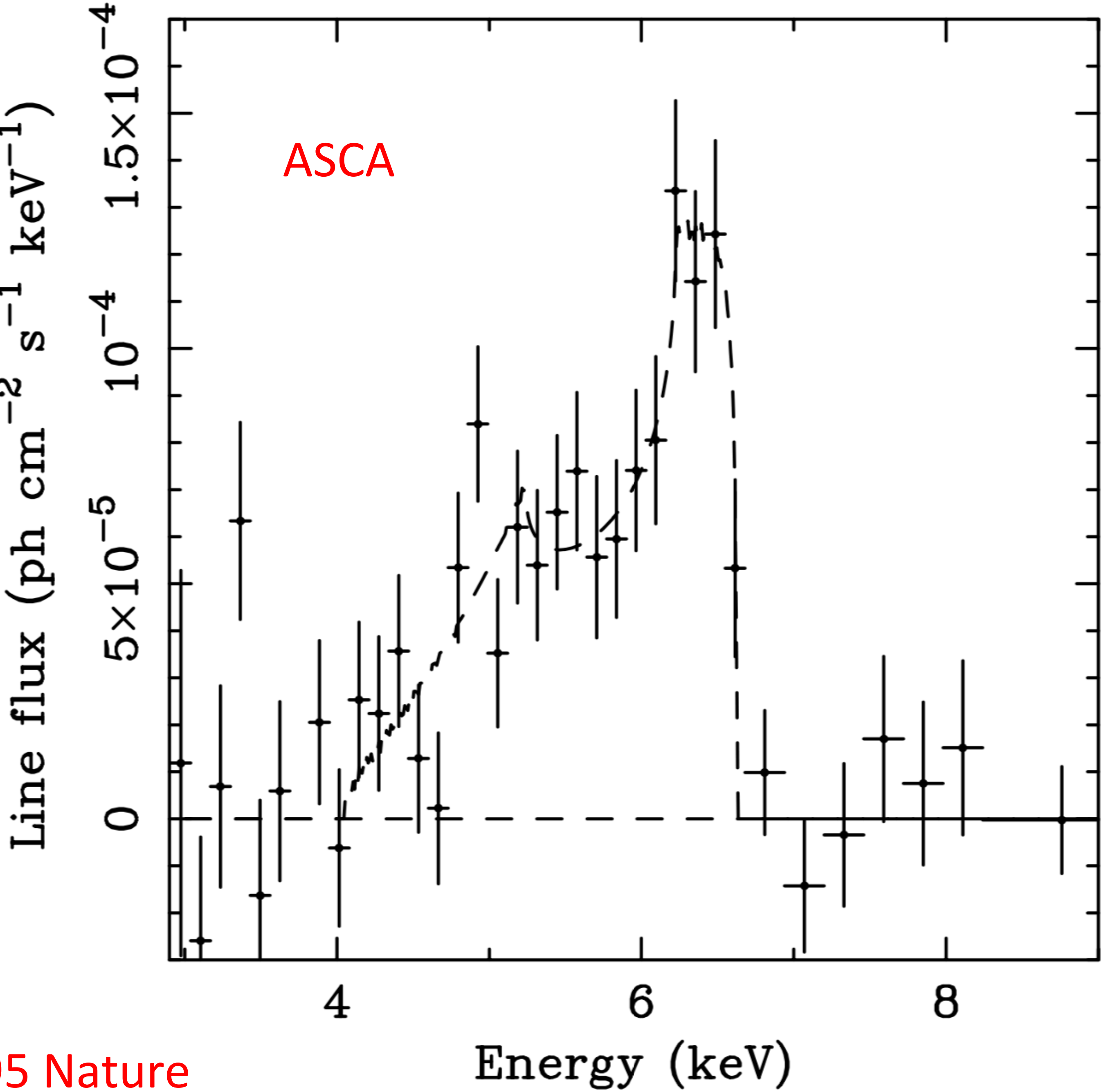


Relativistically Broadened Line



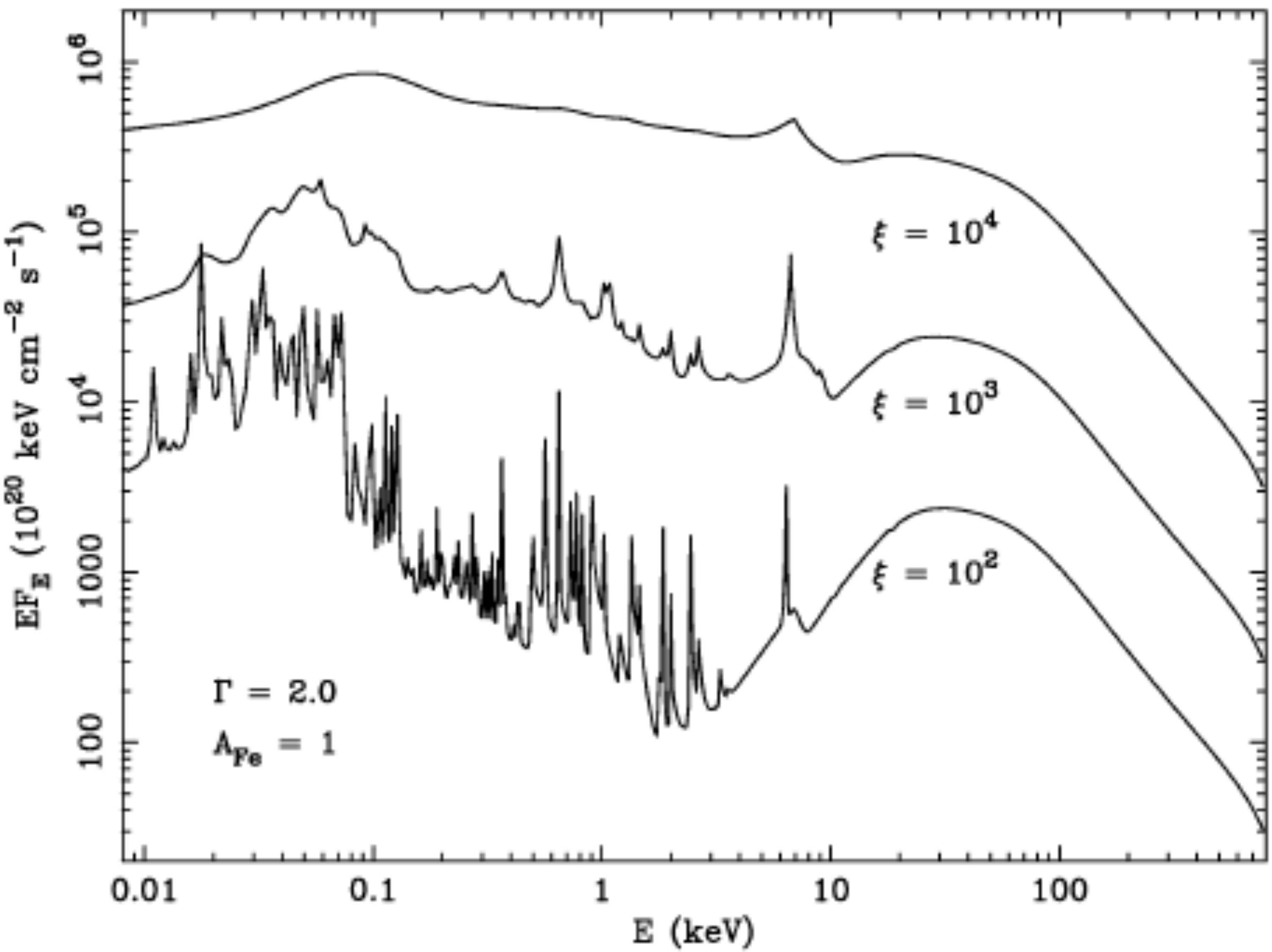


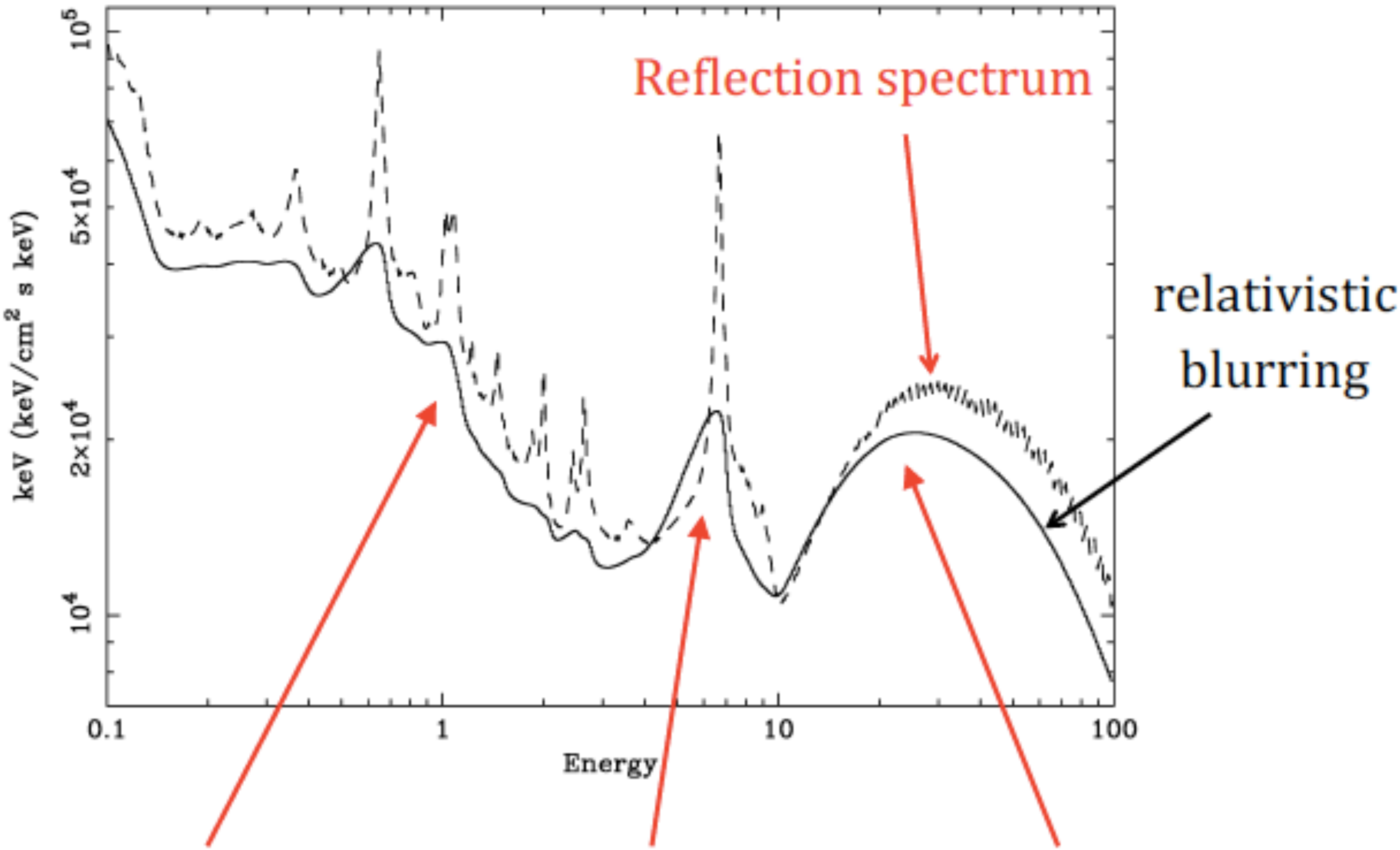
Fabian+89, Laor 91…



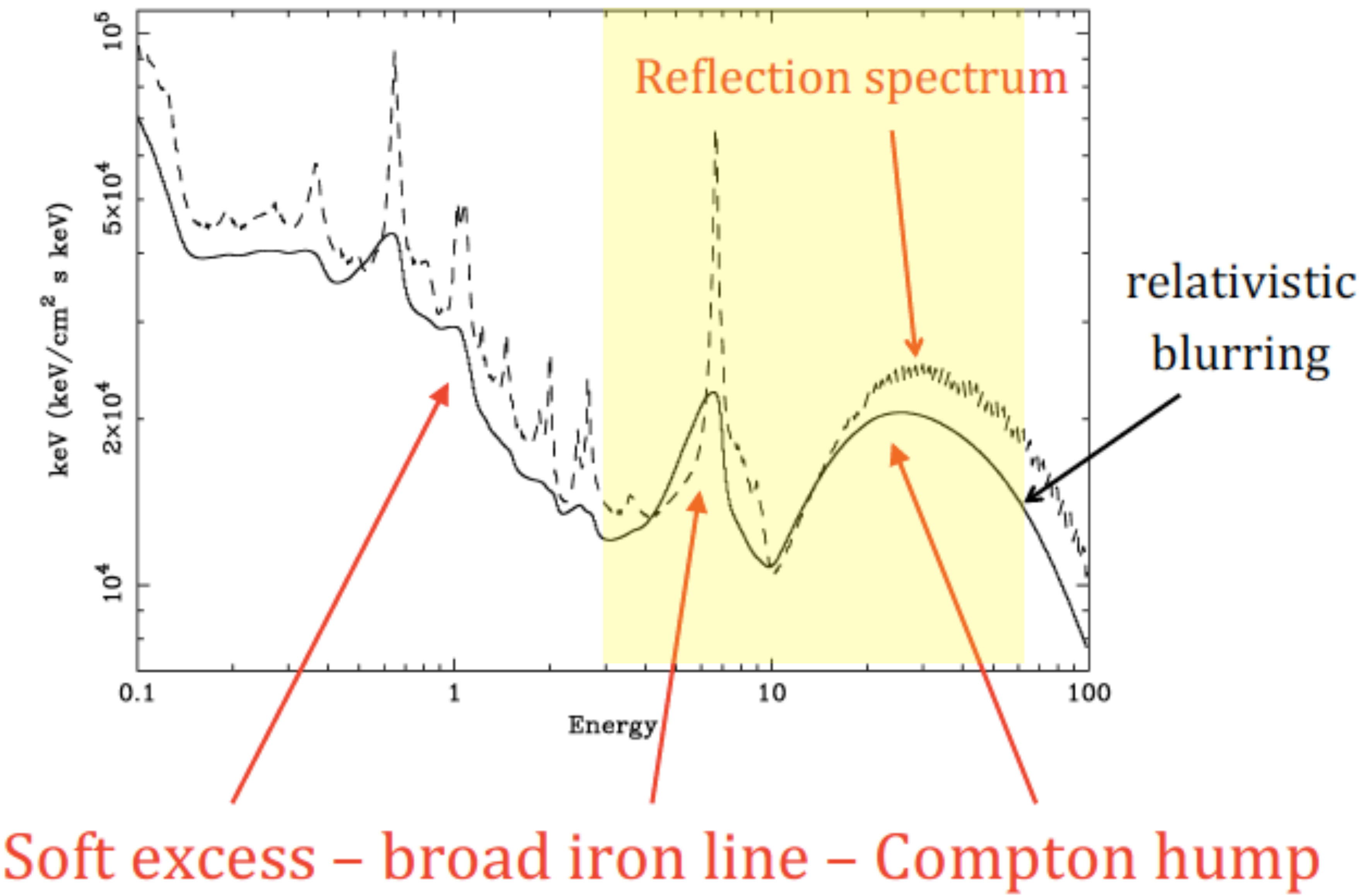
Tanaka+95 Nature

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



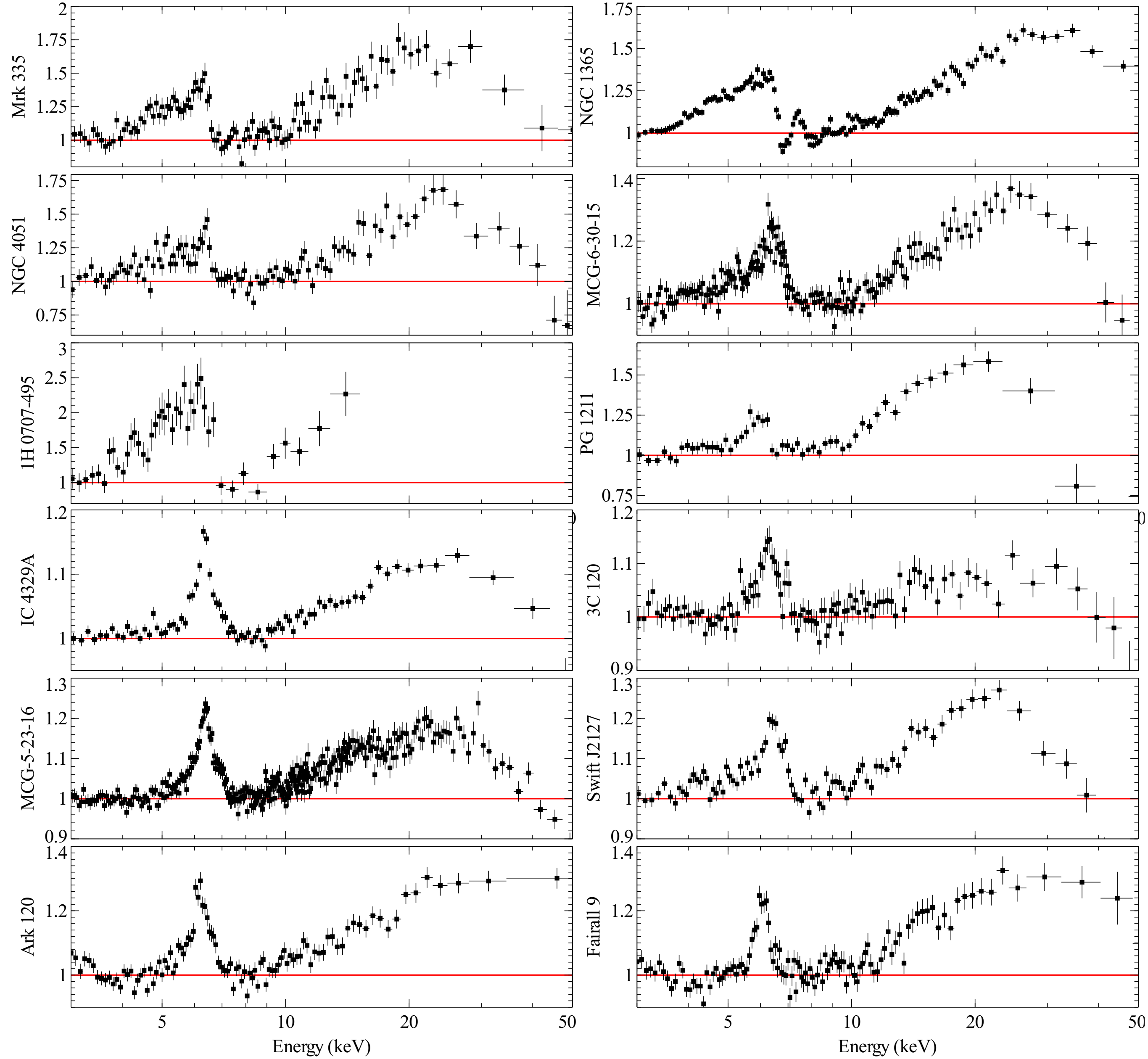


Soft excess – broad iron line – Compton hump



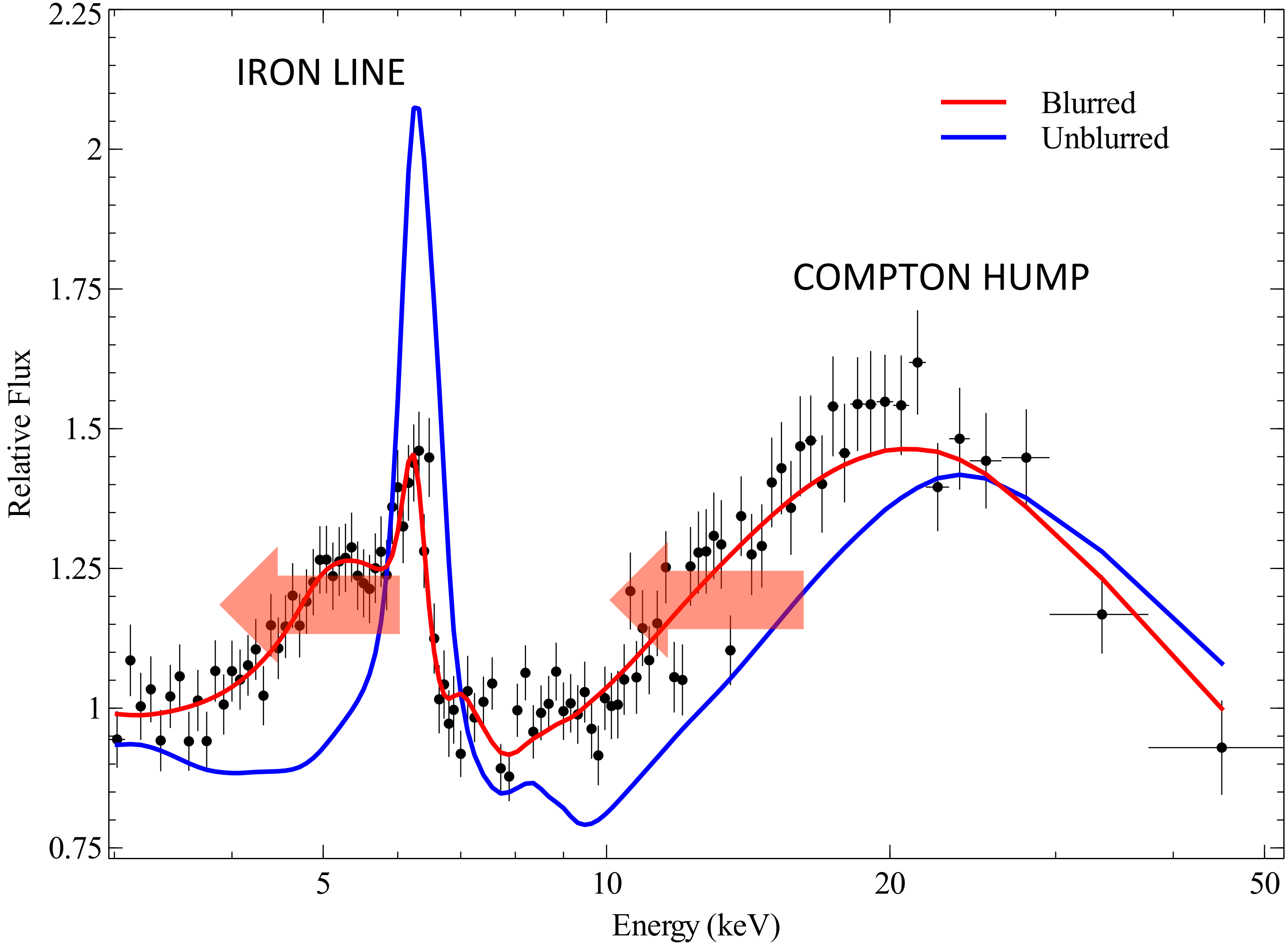
Reflection spectrum
relativistic
blurring
keV (keV/cm² s keV)
10^5
5×10^4
2×10^4
10^4
0.1
1
10
100
Energy
Soft excess – broad iron line – Compton hump

Reflection in AGN with NuSTAR



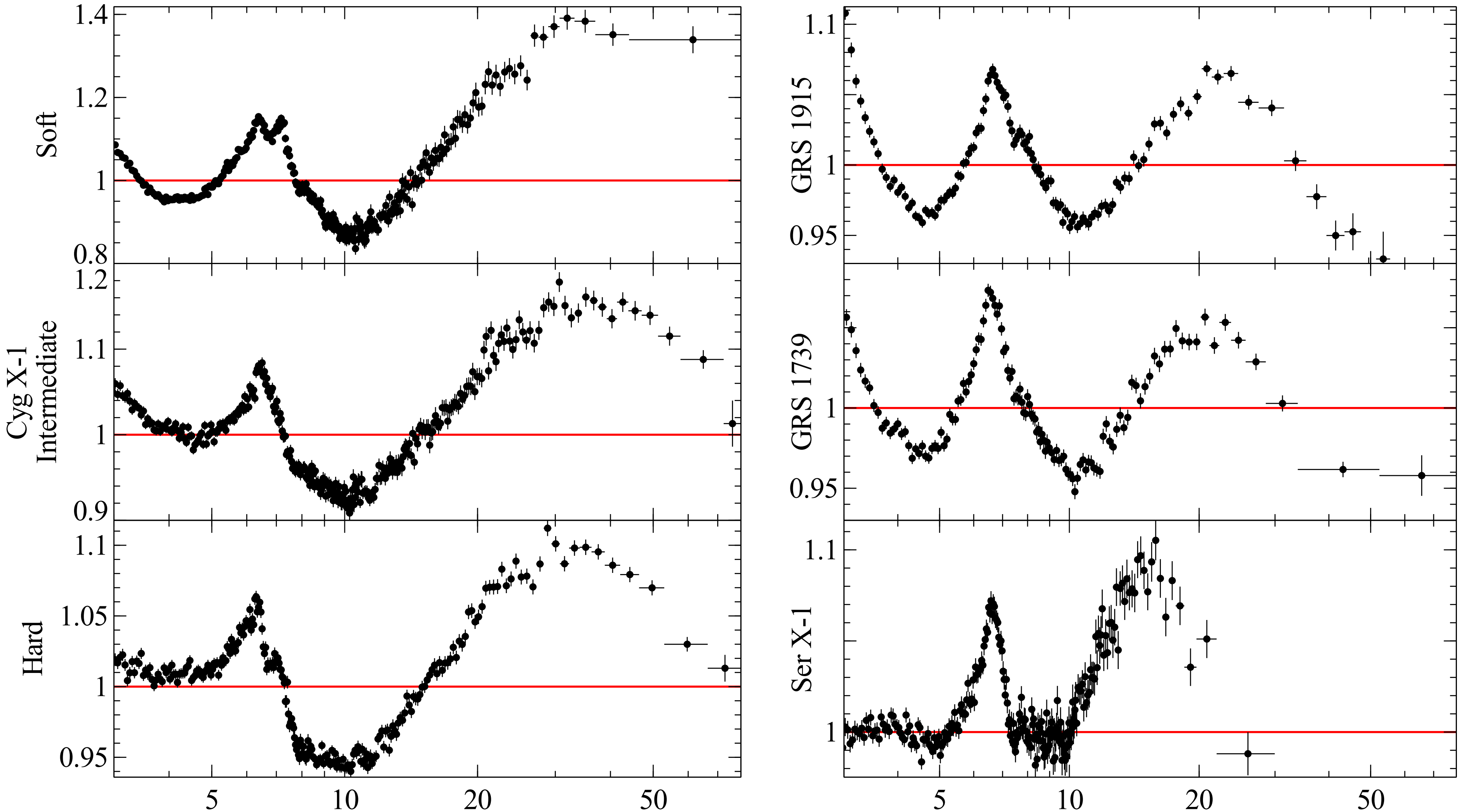
Parker, Matt+

Sometimes most emission from 1-2r_g

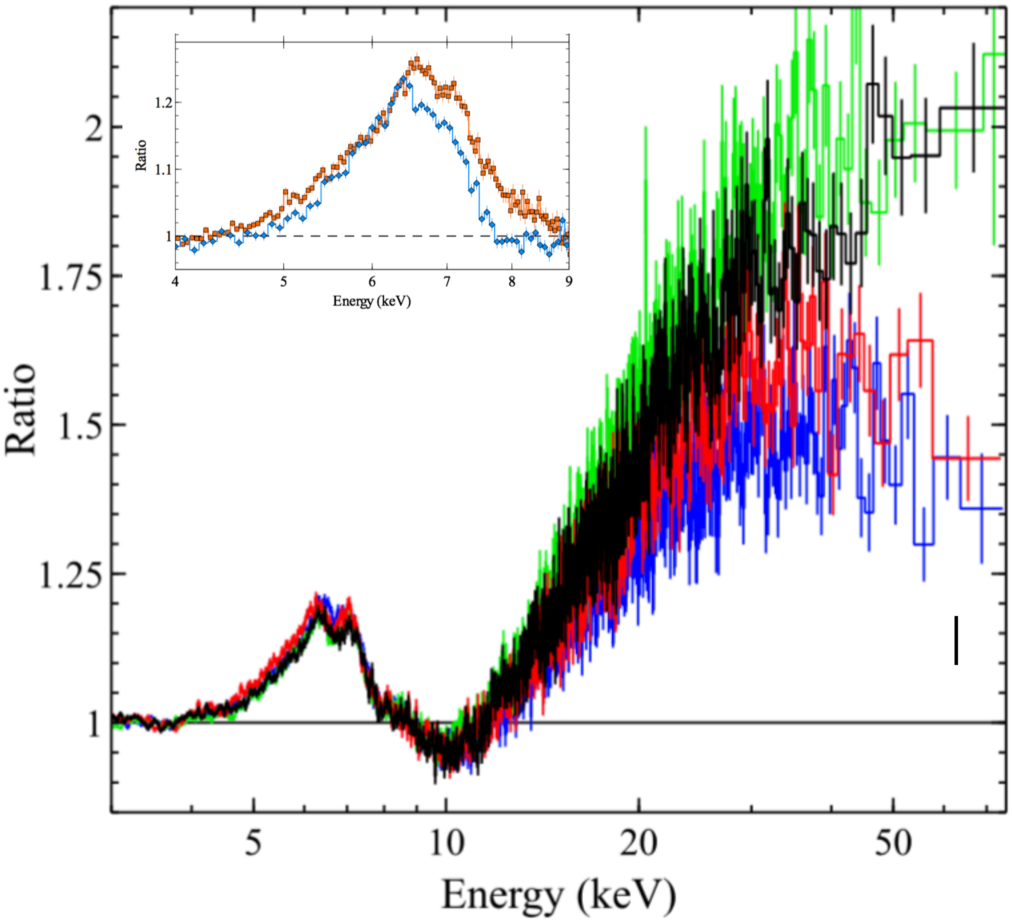


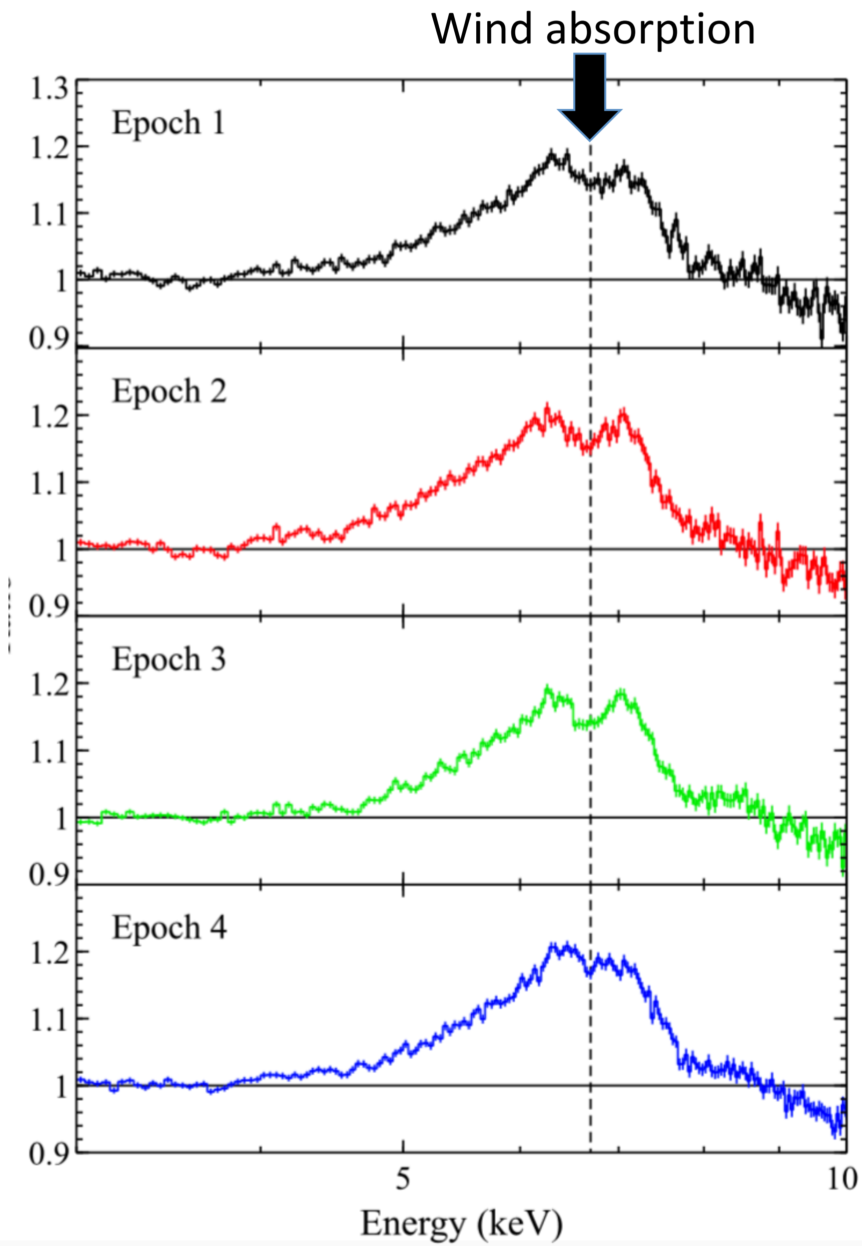
Mkn 335 Parker+14

and Galactic sources too



Parker, Tomsick+, JMiller+13,15

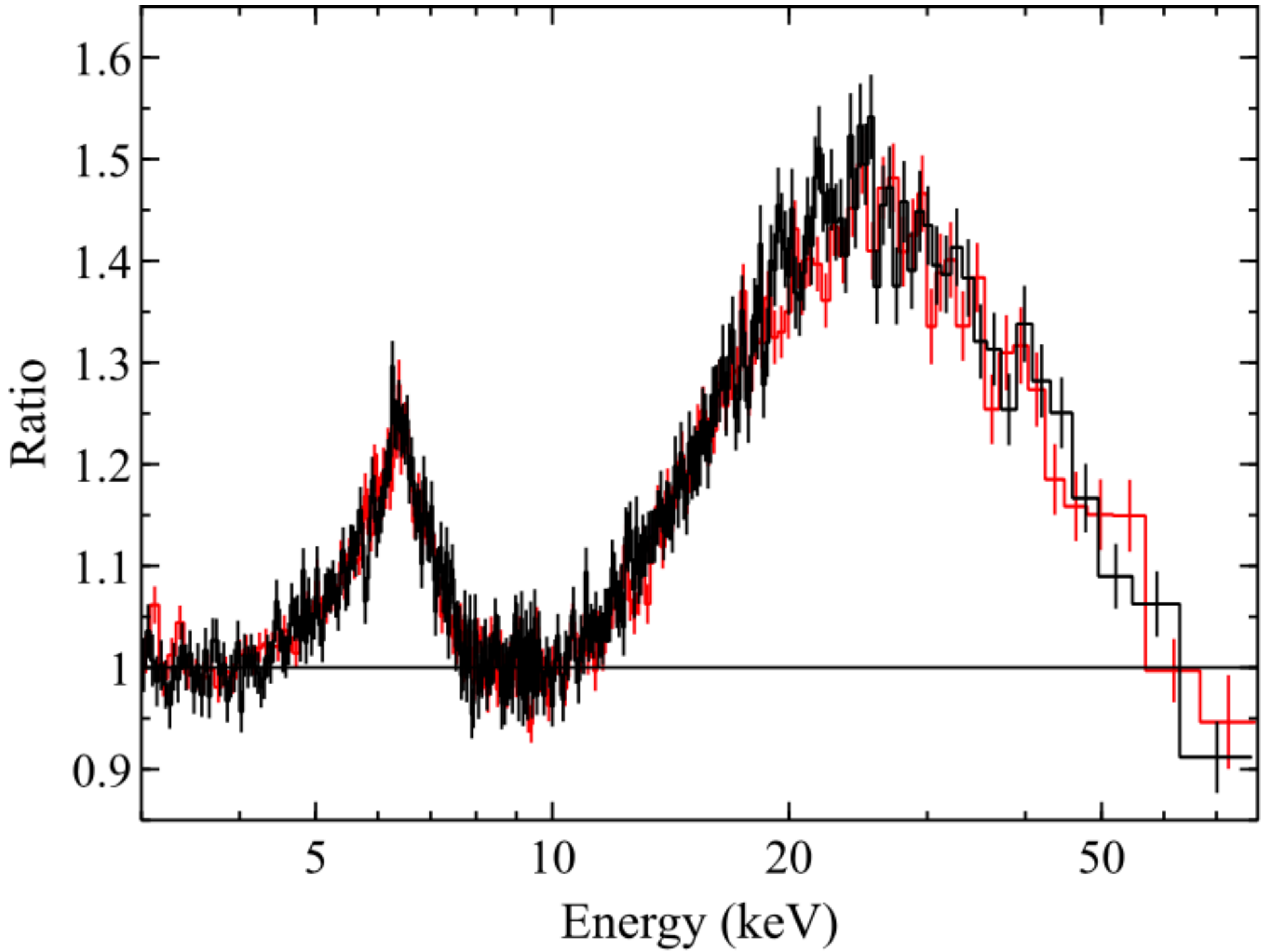




Cygnus X-1 a>0.93

Walton+16, Parker+15

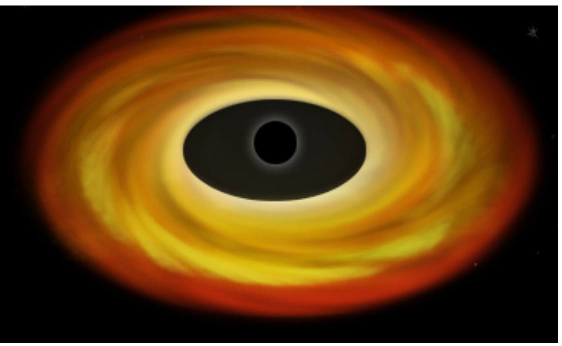
V404 Cyg Flare NuSTAR

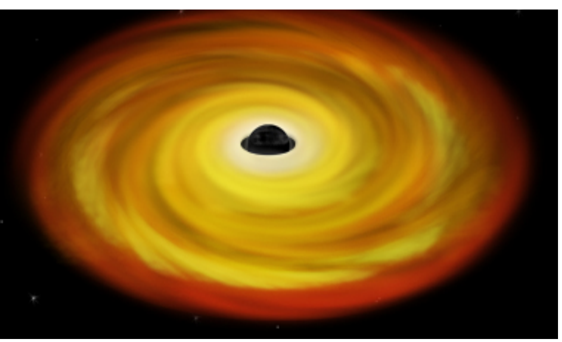


Walton+16

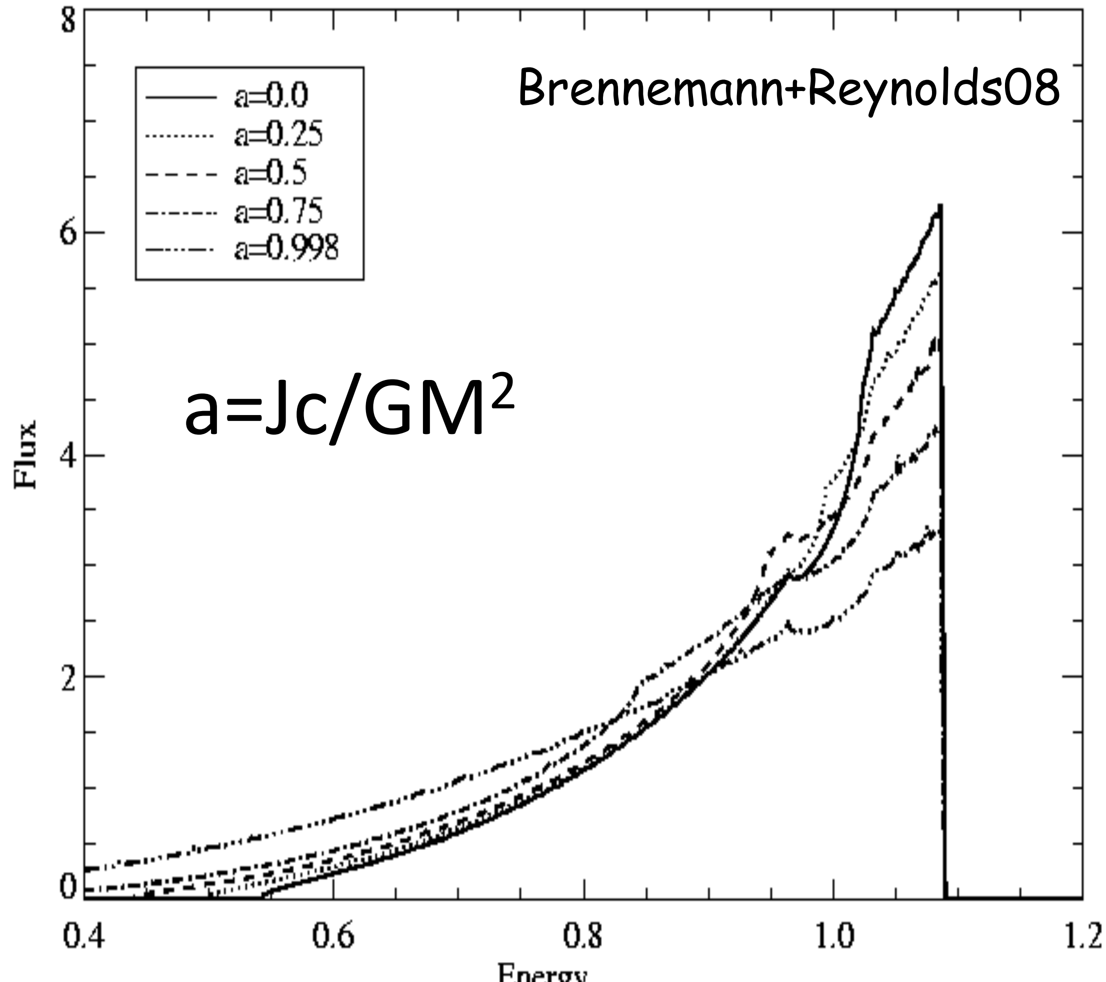
Probing Black Hole Spin

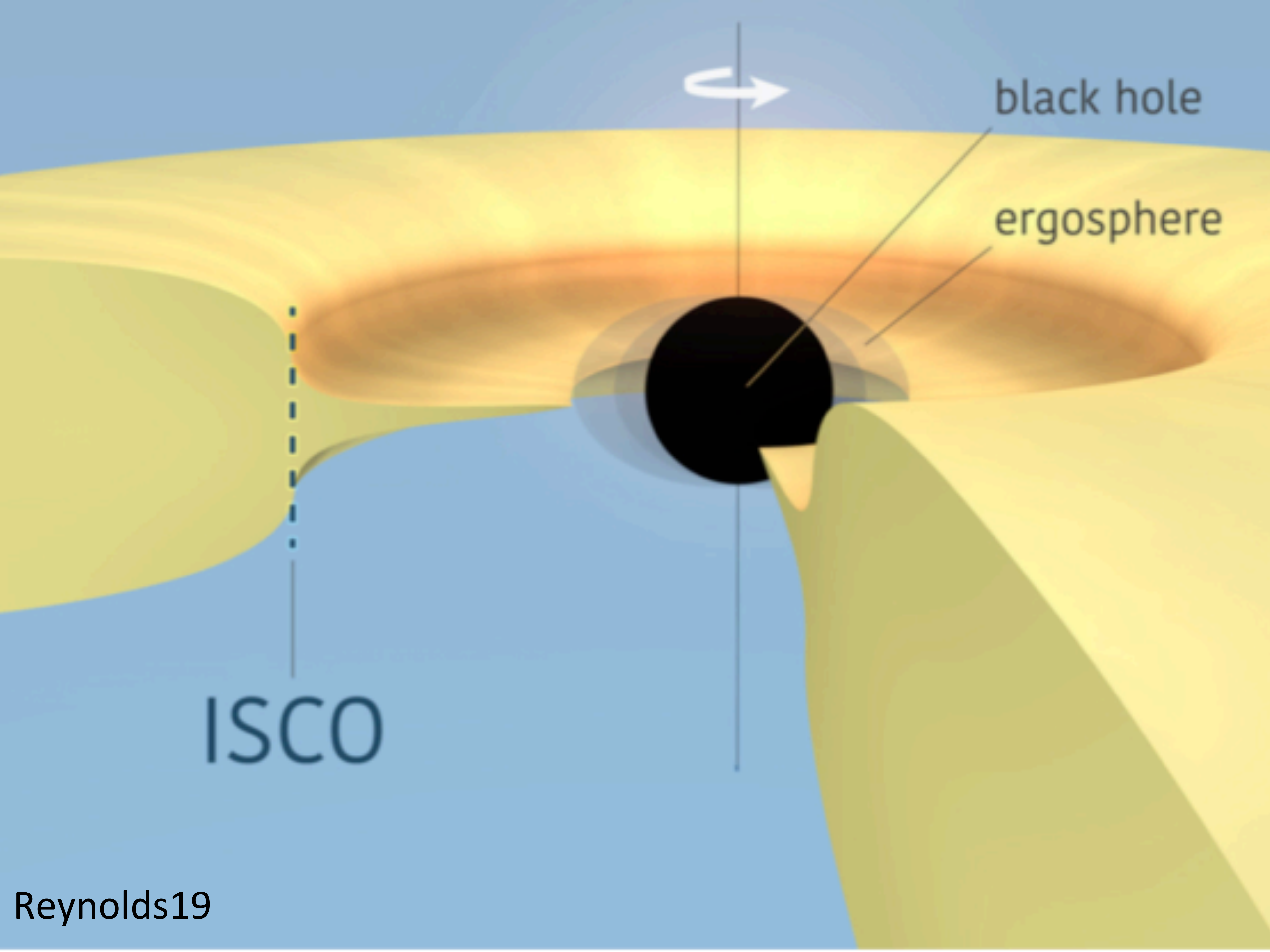
No spin





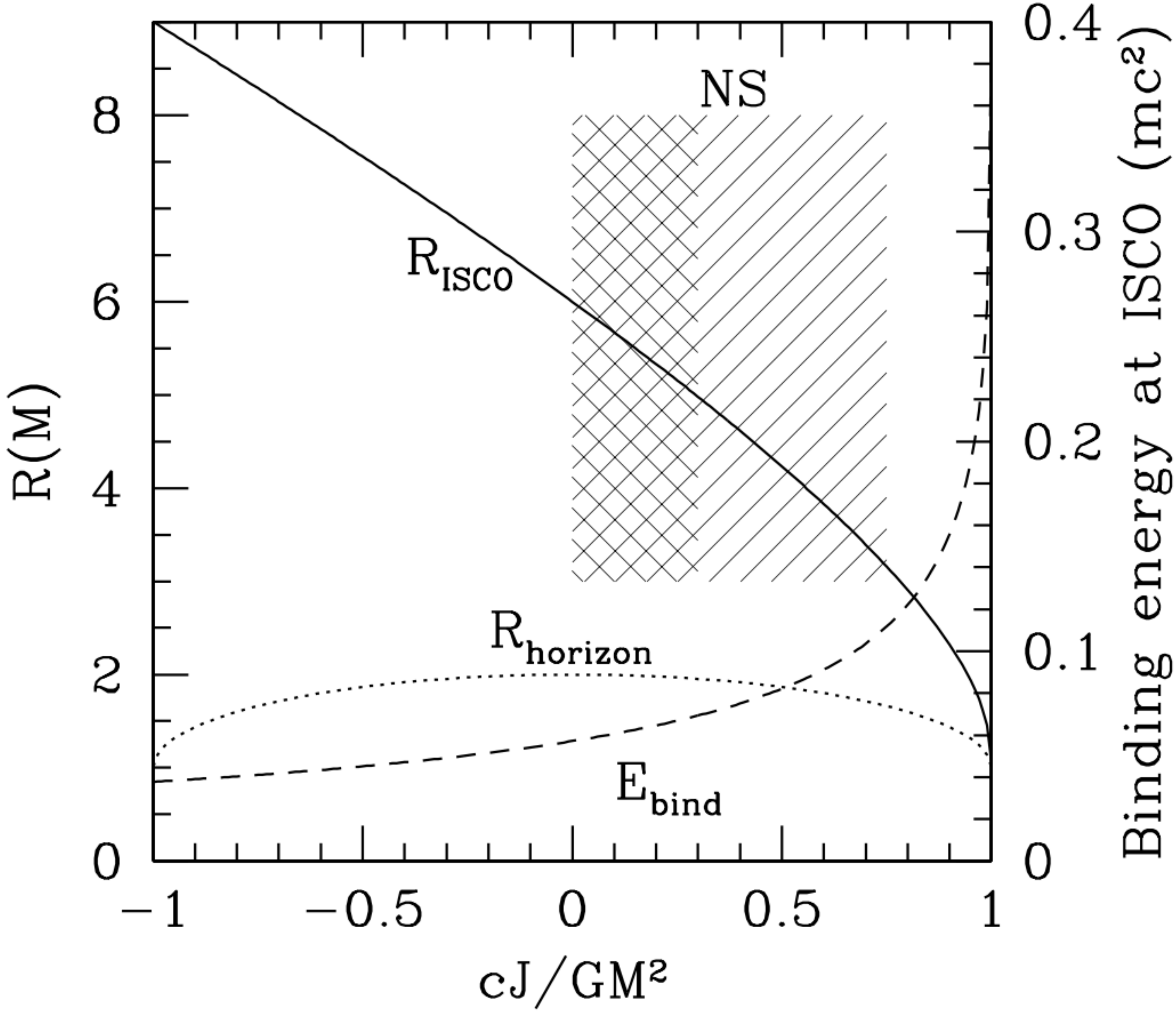
Max spin





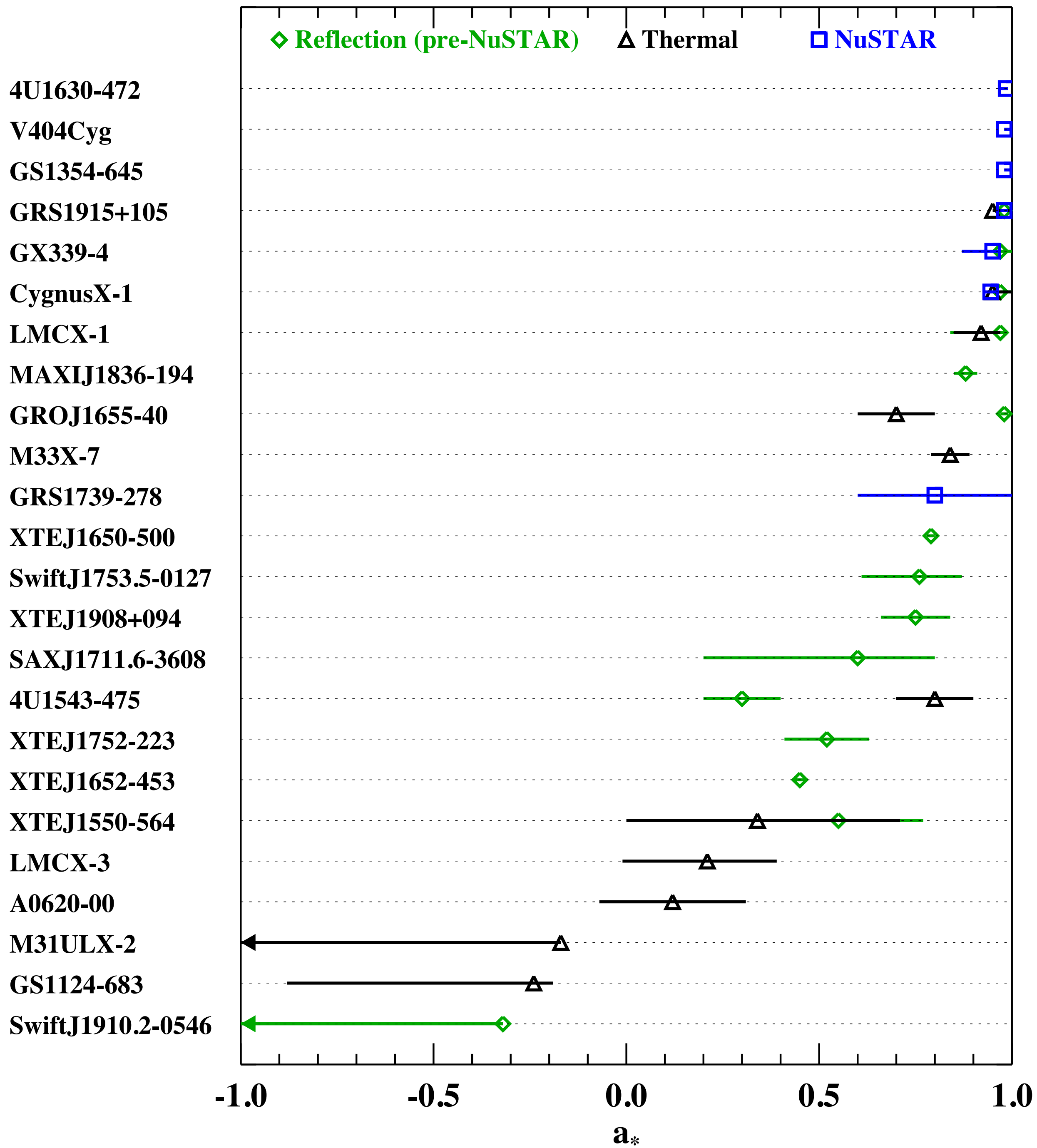
Reynolds19

SPIN from ISCO



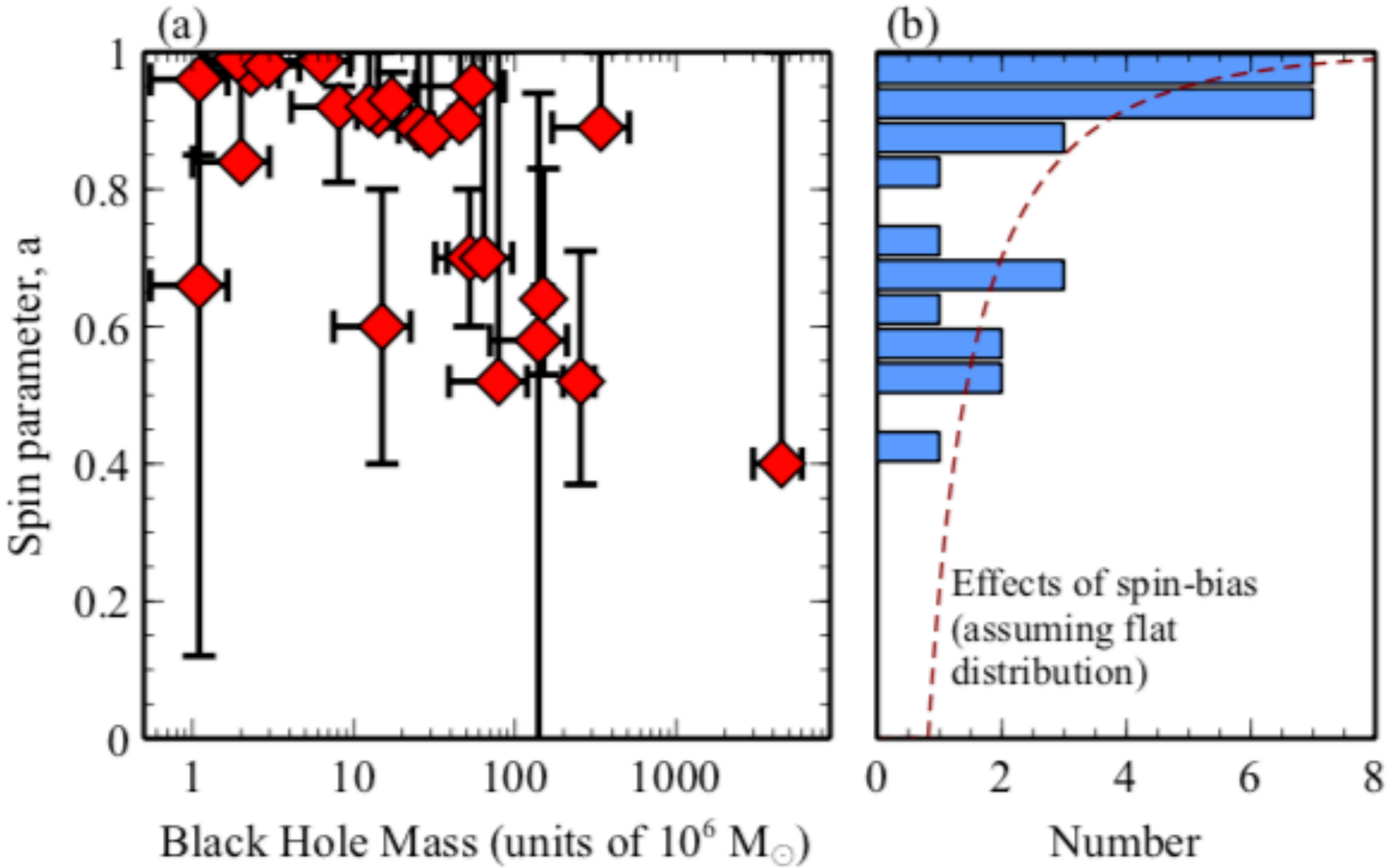
Spin a

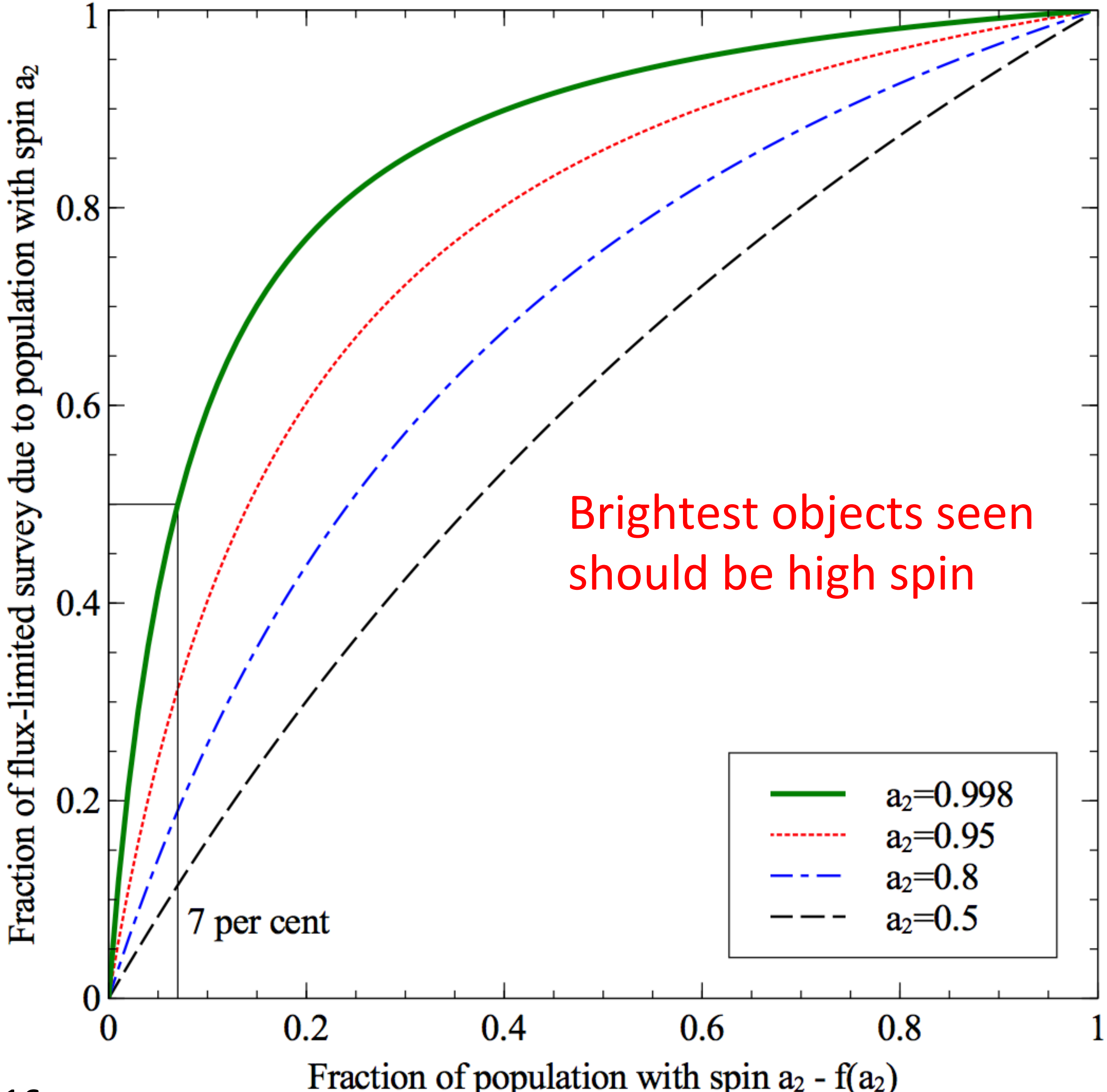
Miller+Miller15



Reflection (pre-NuSTAR)
Thermal
NuSTAR
4U1630-472
V404Cyg
GS1354-645
GRS1915+105
GX339-4
CygnusX-1
LMCX-1
MAXIJ1836-194
GROJ1655-40
M33X-7
GRS1739-278
XTEJ1650-500
SwiftJ1753.5-0127
XTEJ1908+094
SAXJ1711.6-3608
4U1543-475
XTEJ1752-223
XTEJ1652-453
XTEJ1550-564
LMCX-3
A0620-00
M31ULX-2
GS1124-683
SwiftJ1910.2-0546
-1.0
-0.5
0.0
0.5
1.0
a_*

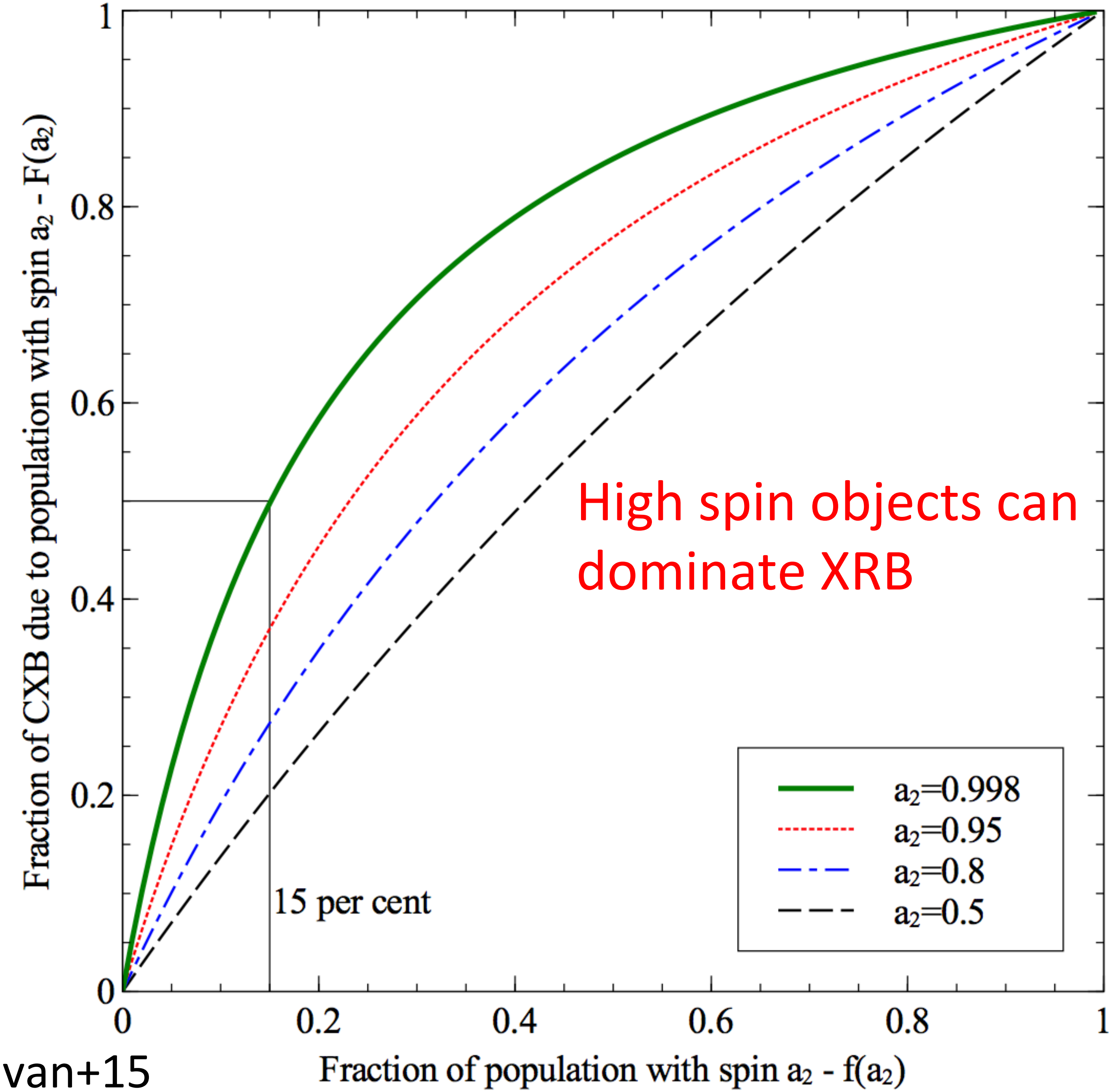
Tomsick16


(a)
(b)
Spin parameter, a
0
0.2
0.4
0.6
0.8
1
1
10
100
1000
Black Hole Mass (units of 10^6 $M_\odot$)
0
2
4
6
8
Number
Effects of spin-bias
(assuming flat
distribution)

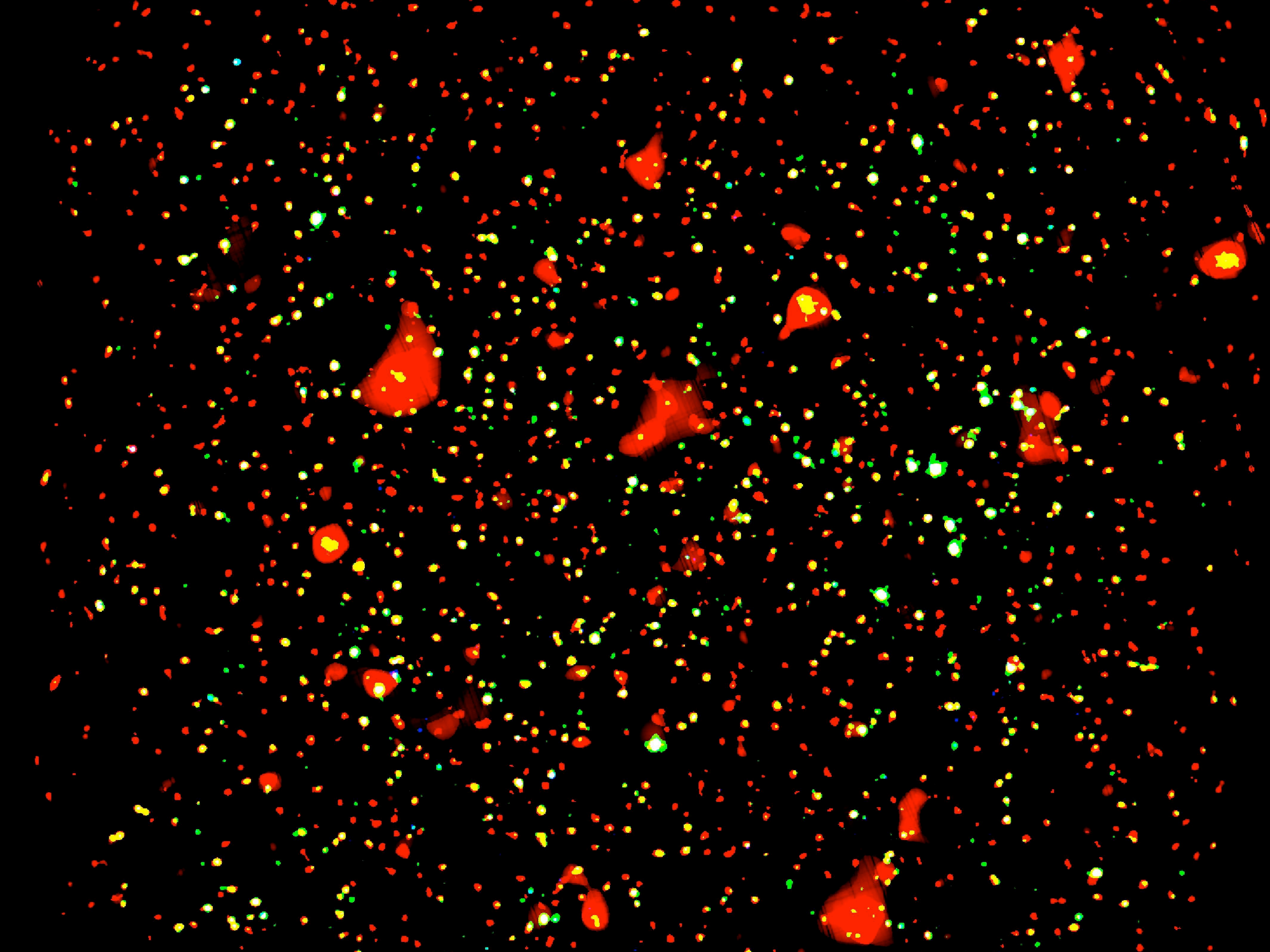


Brightest objects seen should be high spin

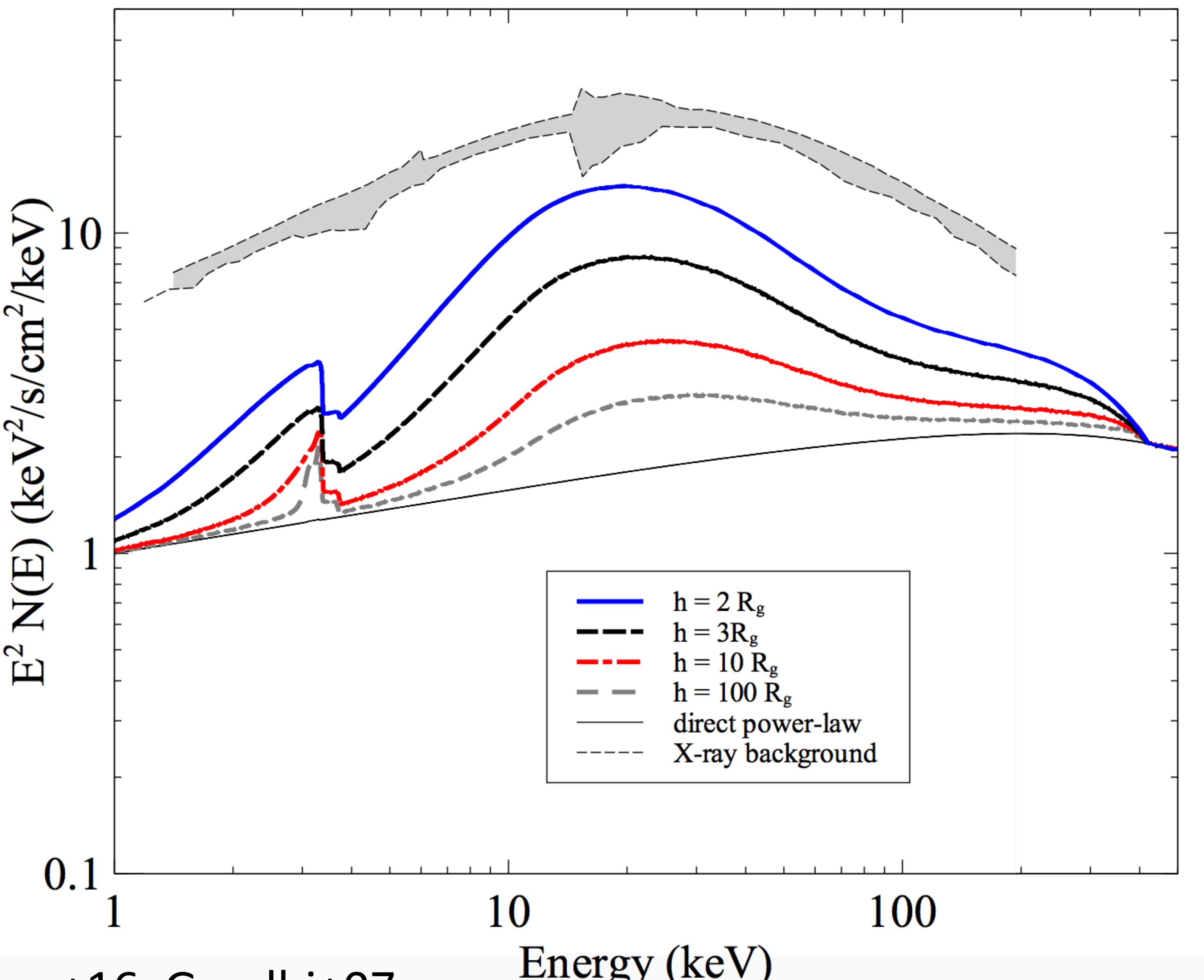
Vasudevan+16



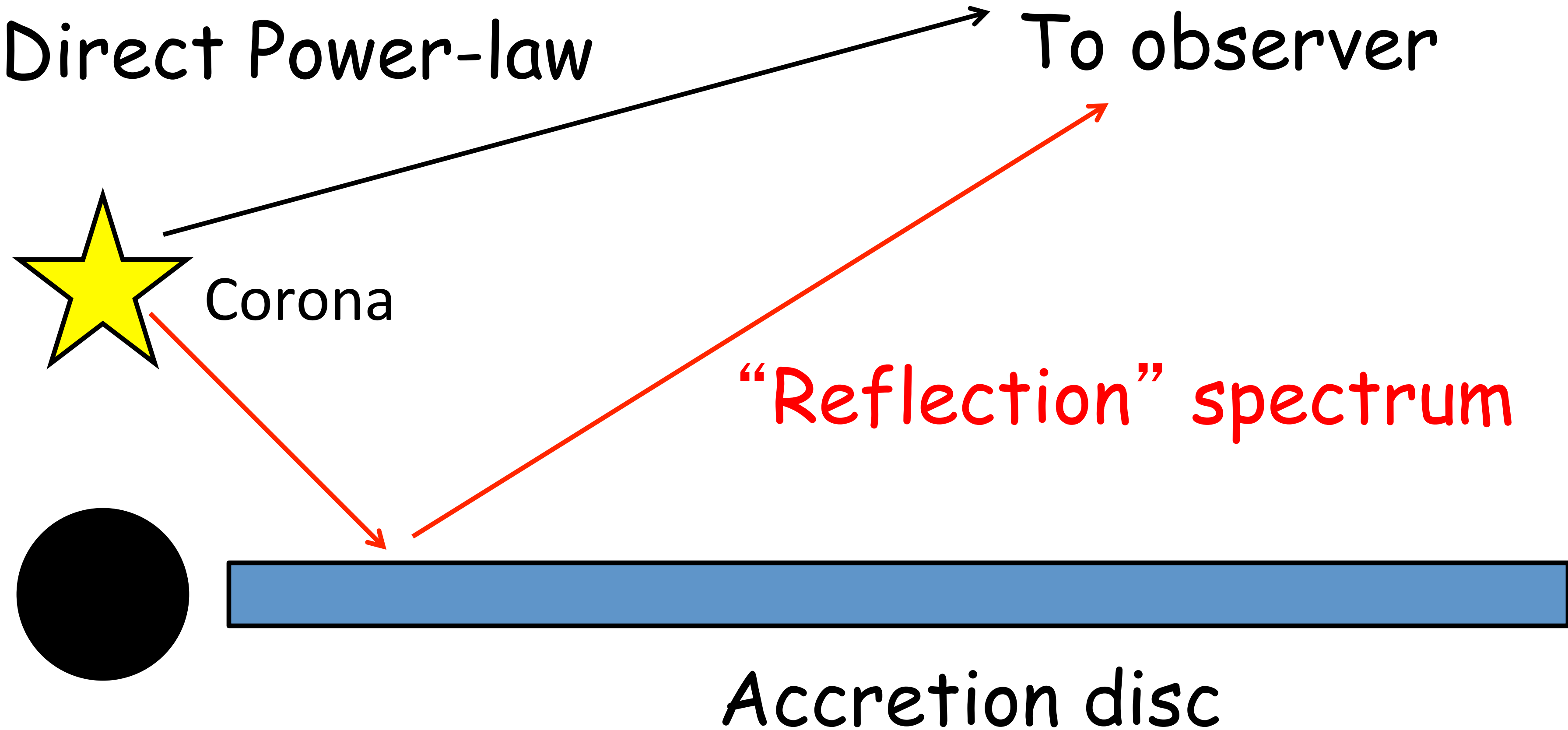
Vasudevan+15

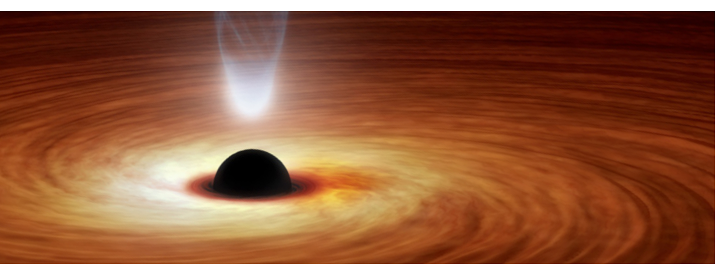


X-ray Background Spectrum



Vasudevan+16, Gandhi+07





Path difference leads to

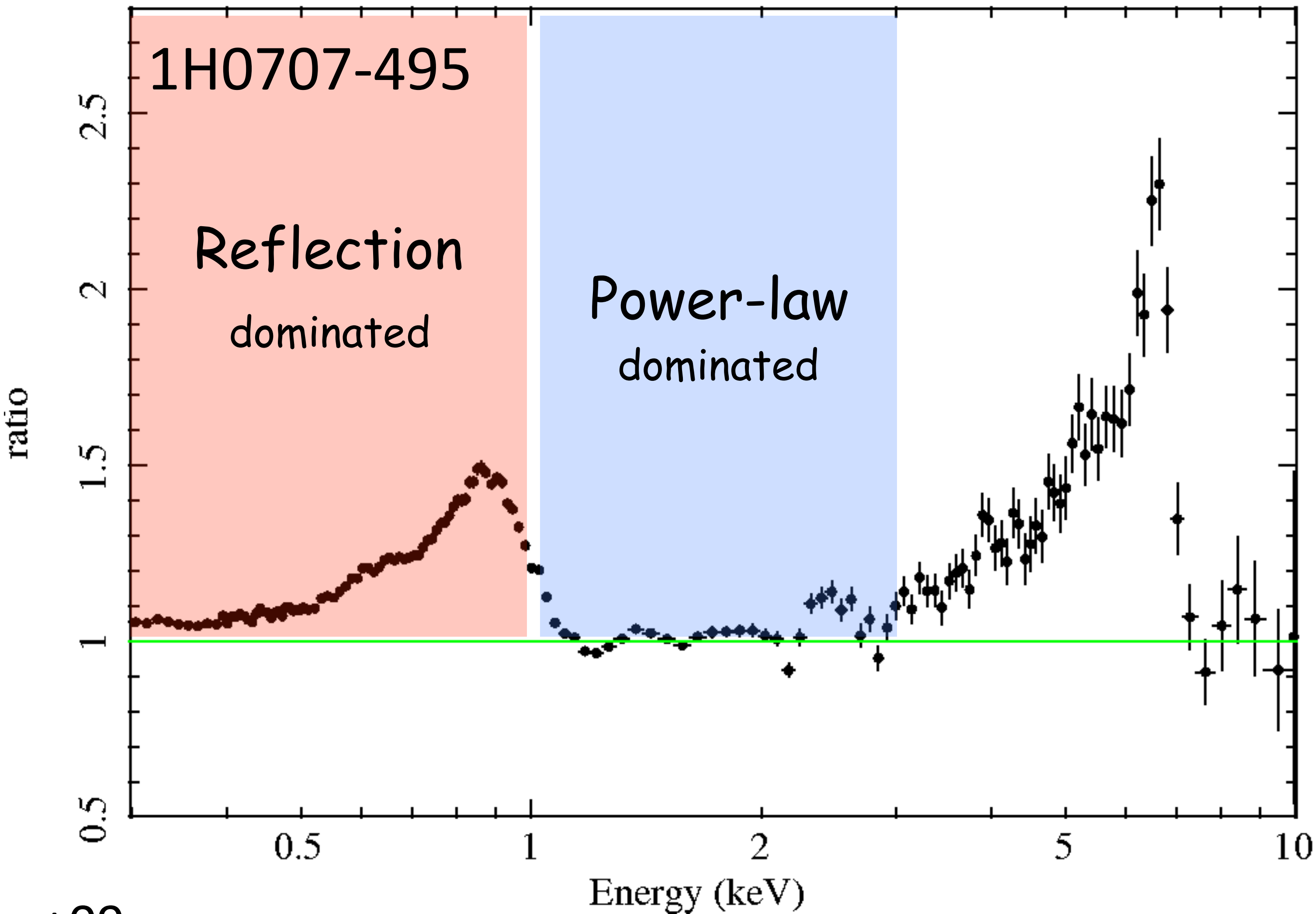
Reverberation

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

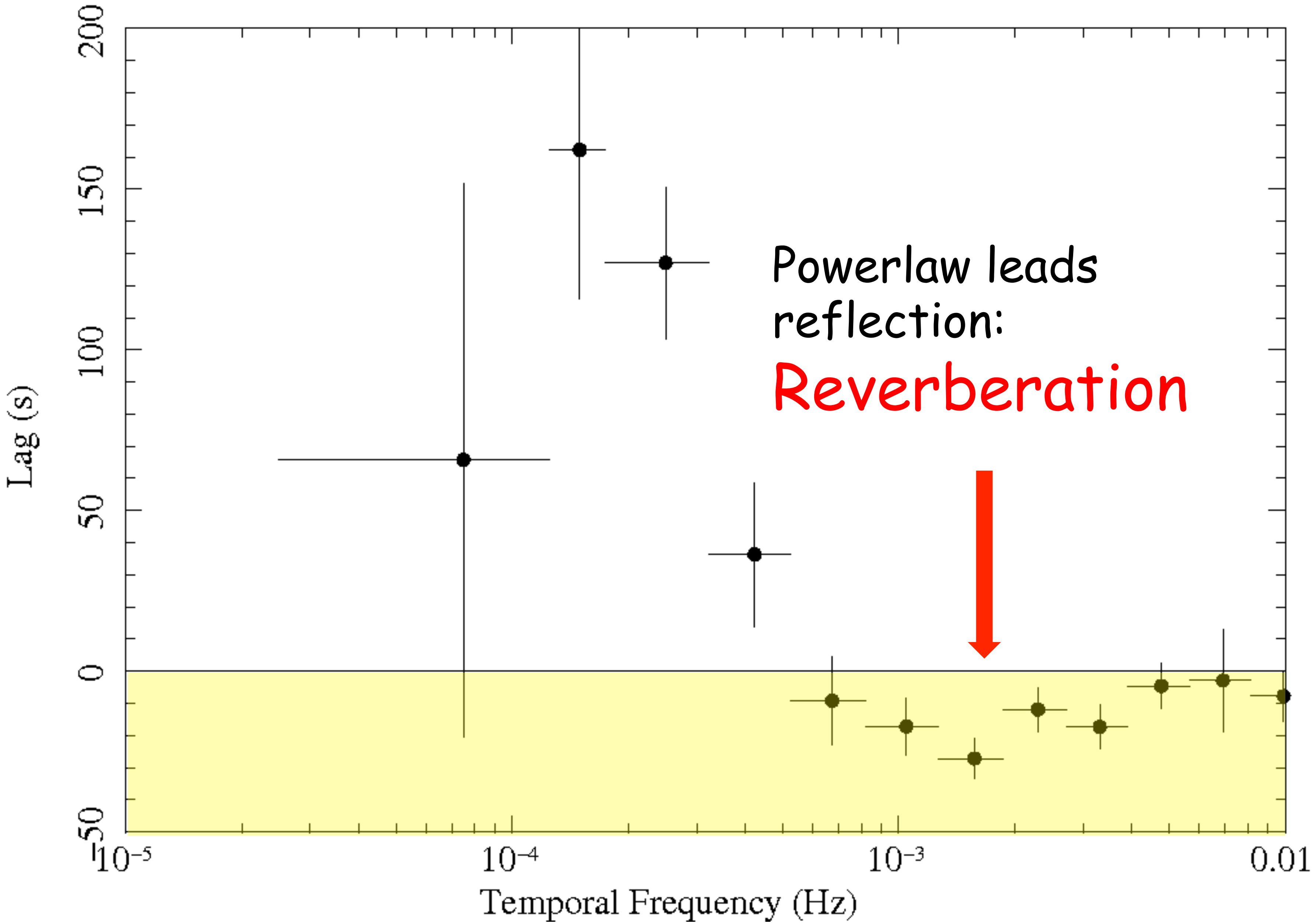
Separate spectrally
(contributions vary with energy)

Need Spectral Timing

X-ray Reverberation

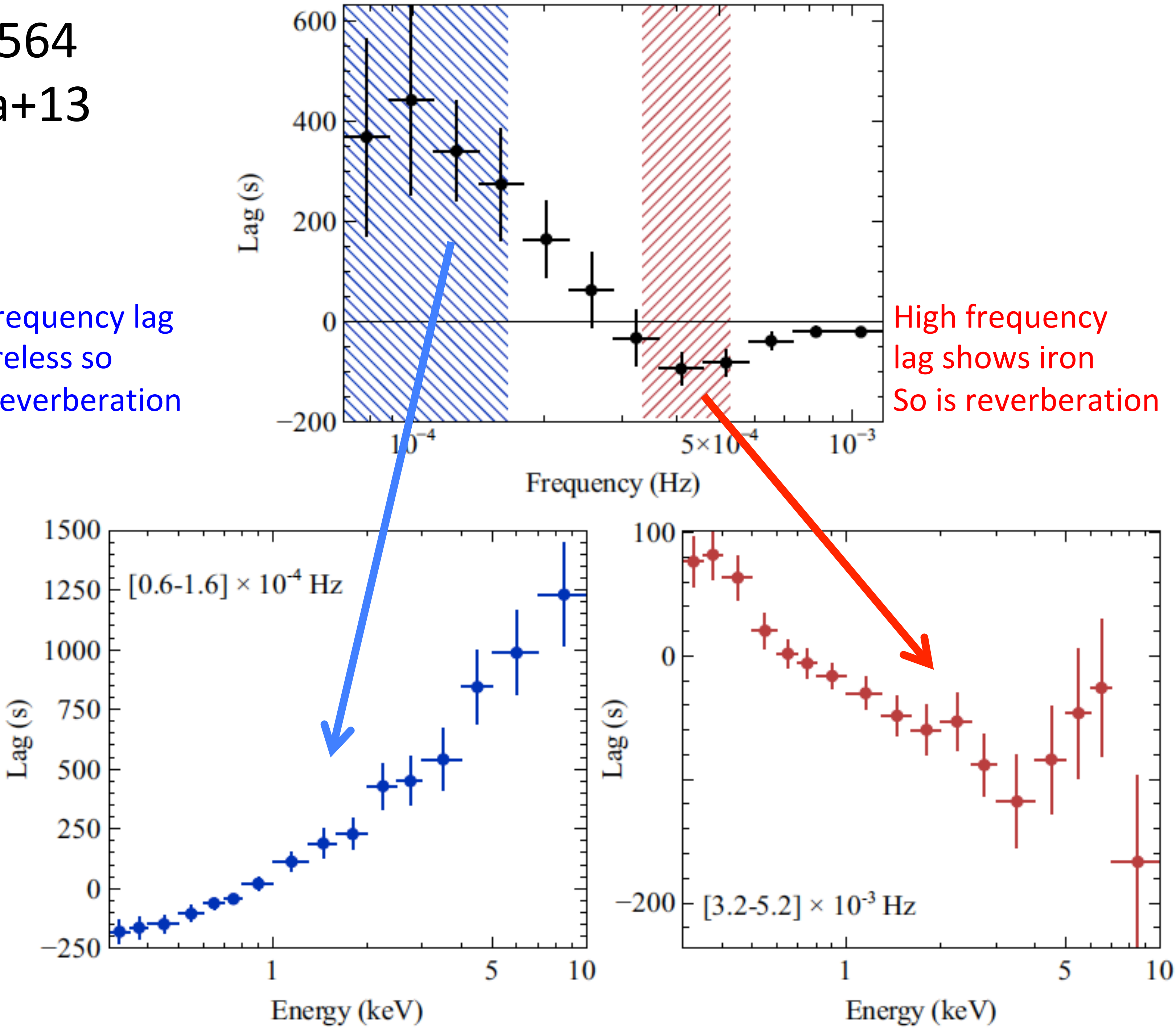


Fabian+09



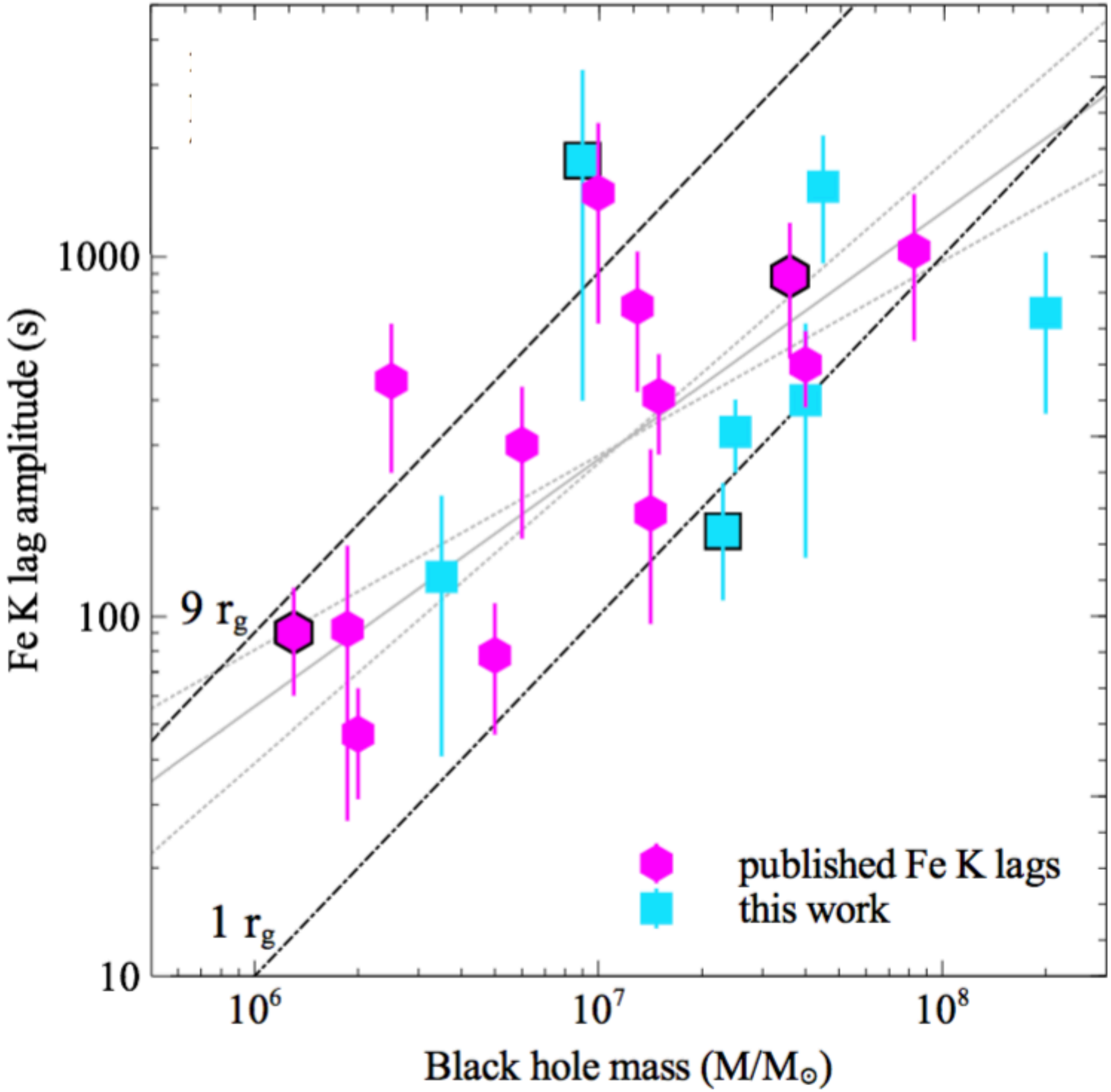
Powerlaw leads reflection:
Reverberation
Lag (s)
200
150
100
50
0
−50
10^{-5}
10^{-4}
10^{-3}
0.01
Temporal Frequency (Hz)

Akn564
Kara+13



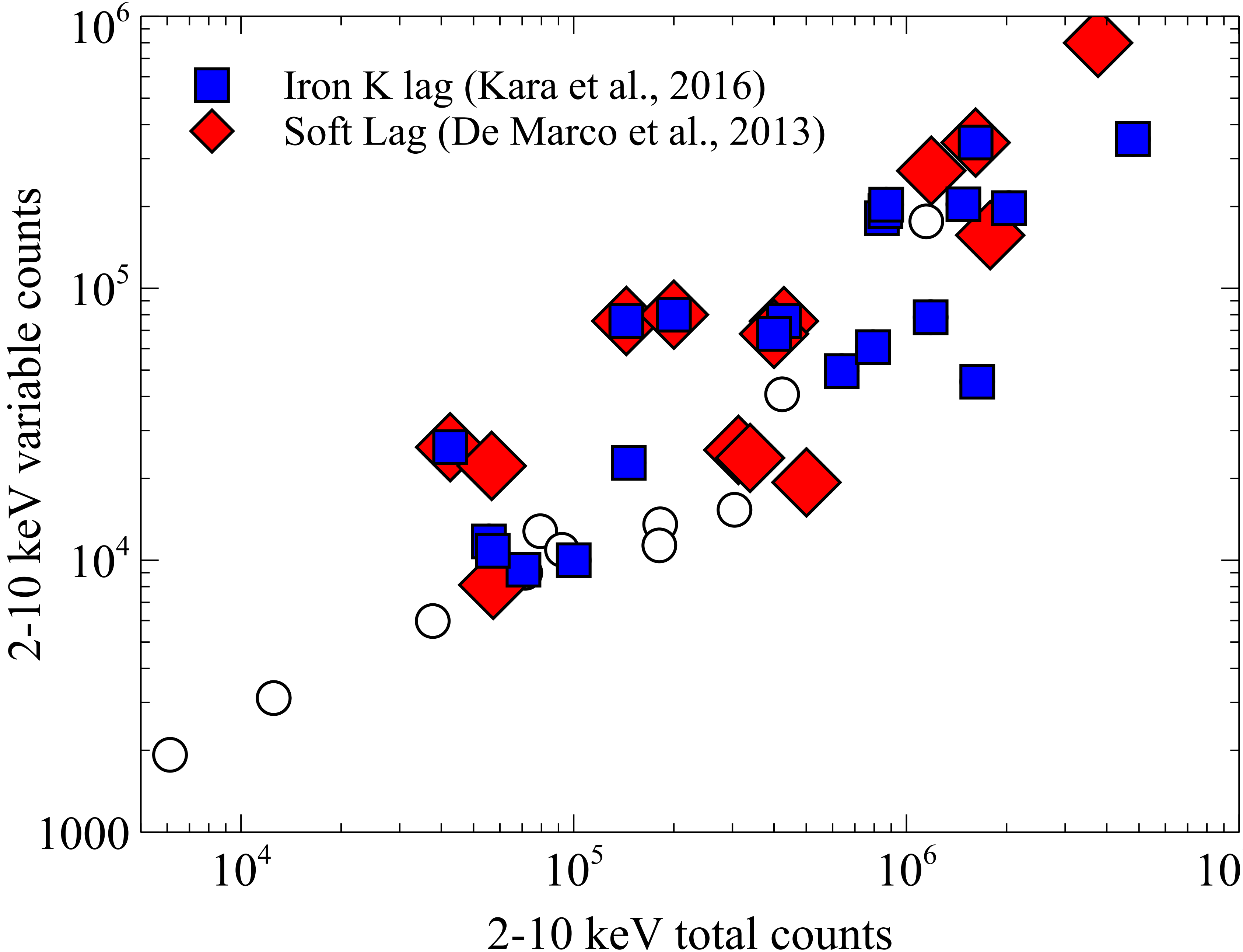
Low frequency lag
featureless so
NOT reverberation

High frequency
lag shows iron
So is reverberation



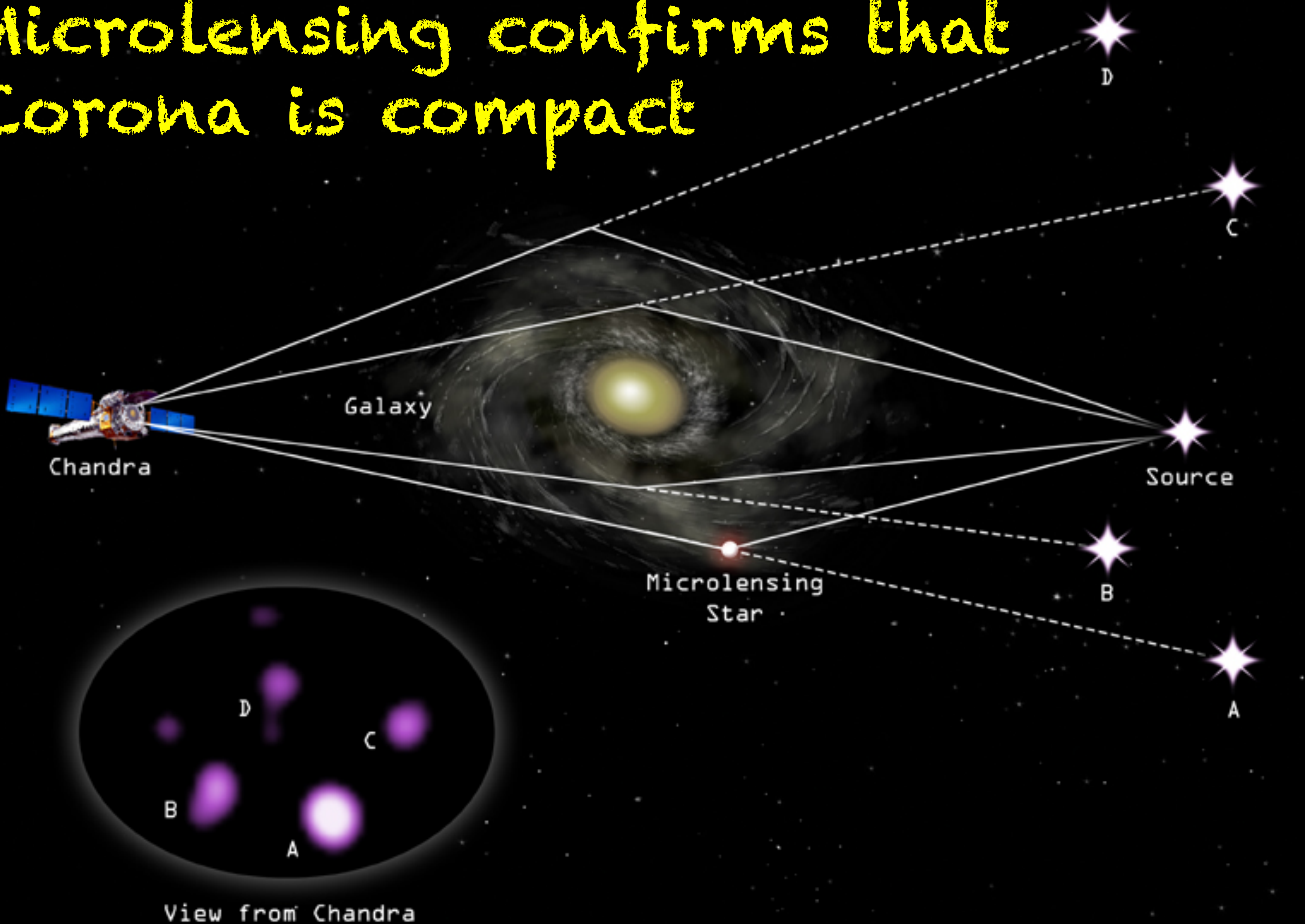
Fe K lag amplitude (s)
Black hole mass (M/M⊙)
9 r_g
1 r_g
published Fe K lags
this work
1000
100
10
10^6
10^7
10^8

Kara+16

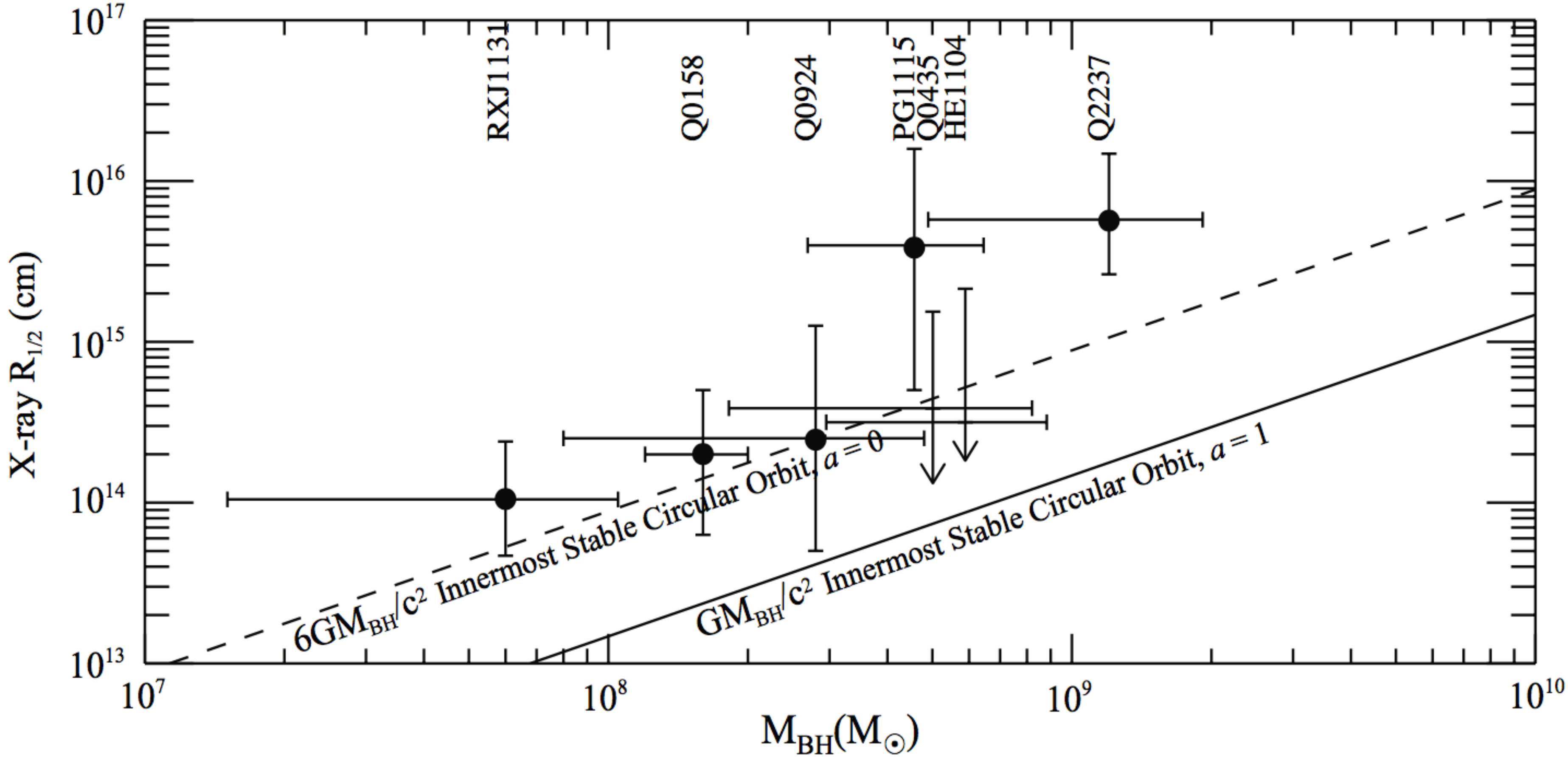


Iron K lag (Kara et al., 2016)
Soft Lag (De Marco et al., 2013)
2-10 keV variable counts
2-10 keV total counts
10^6
10^5
10^4
1000
10^4
10^5
10^6
10^7

Microlensing confirms that Corona is compact

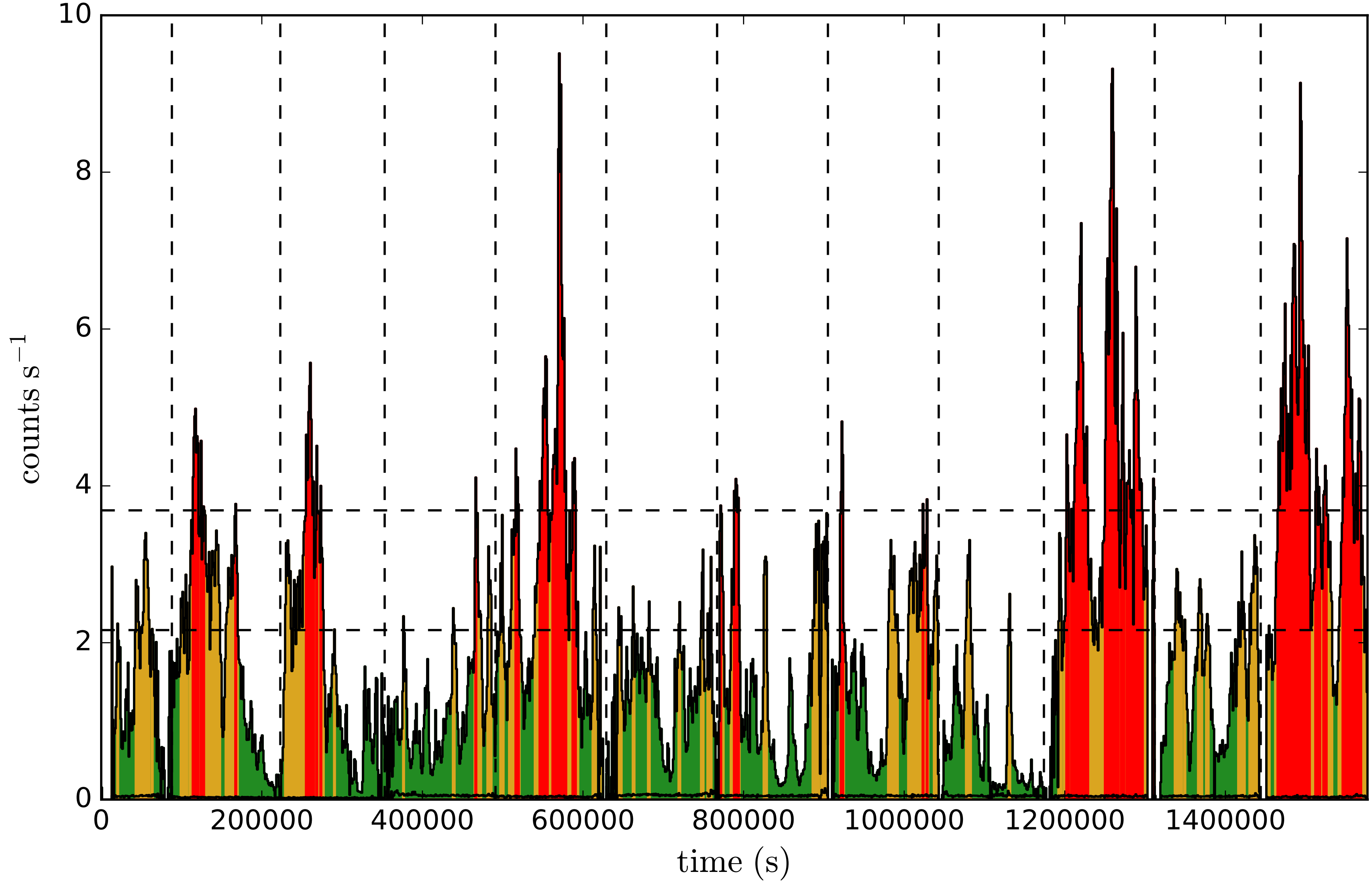


Coronal Size from Microlensing: Coronae are Compact



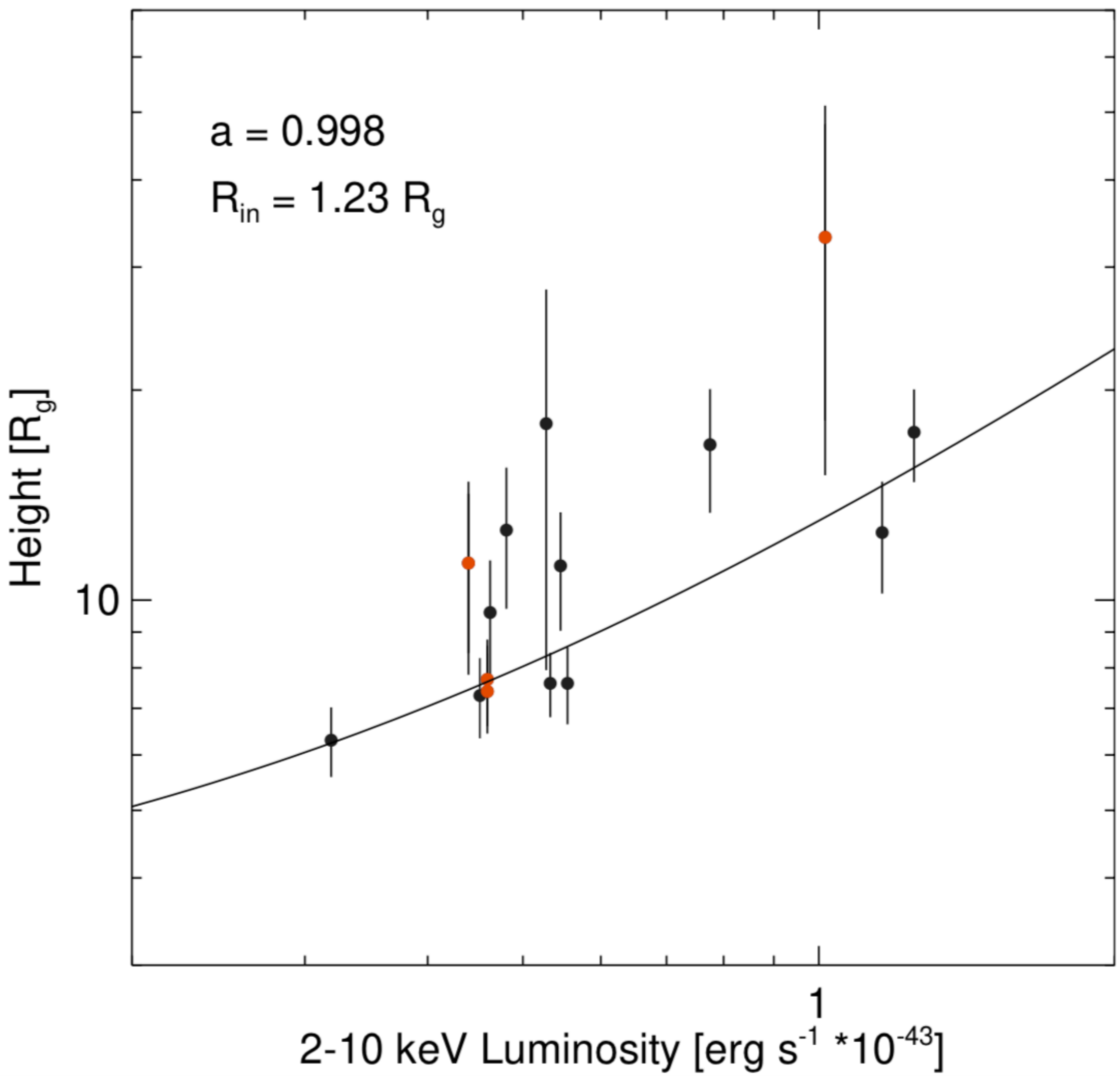
Chartas15

IRAS13224-3809 – MOST VARIABLE AGN IN X-RAYS
XMM + NuSTAR PROGRAMME 1.5Ms

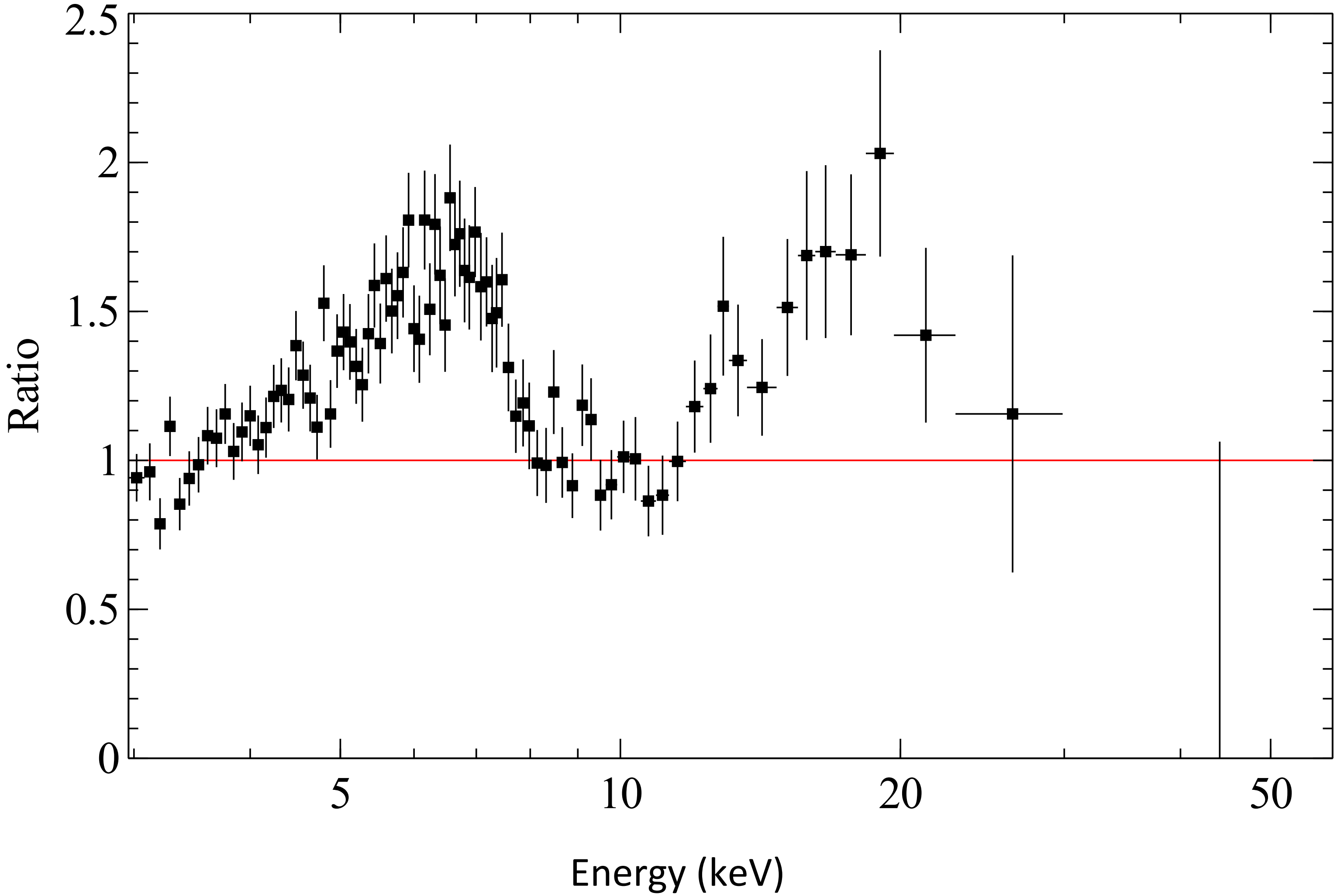


W. N. Alston et al.

Reverberation using KYNREFREV



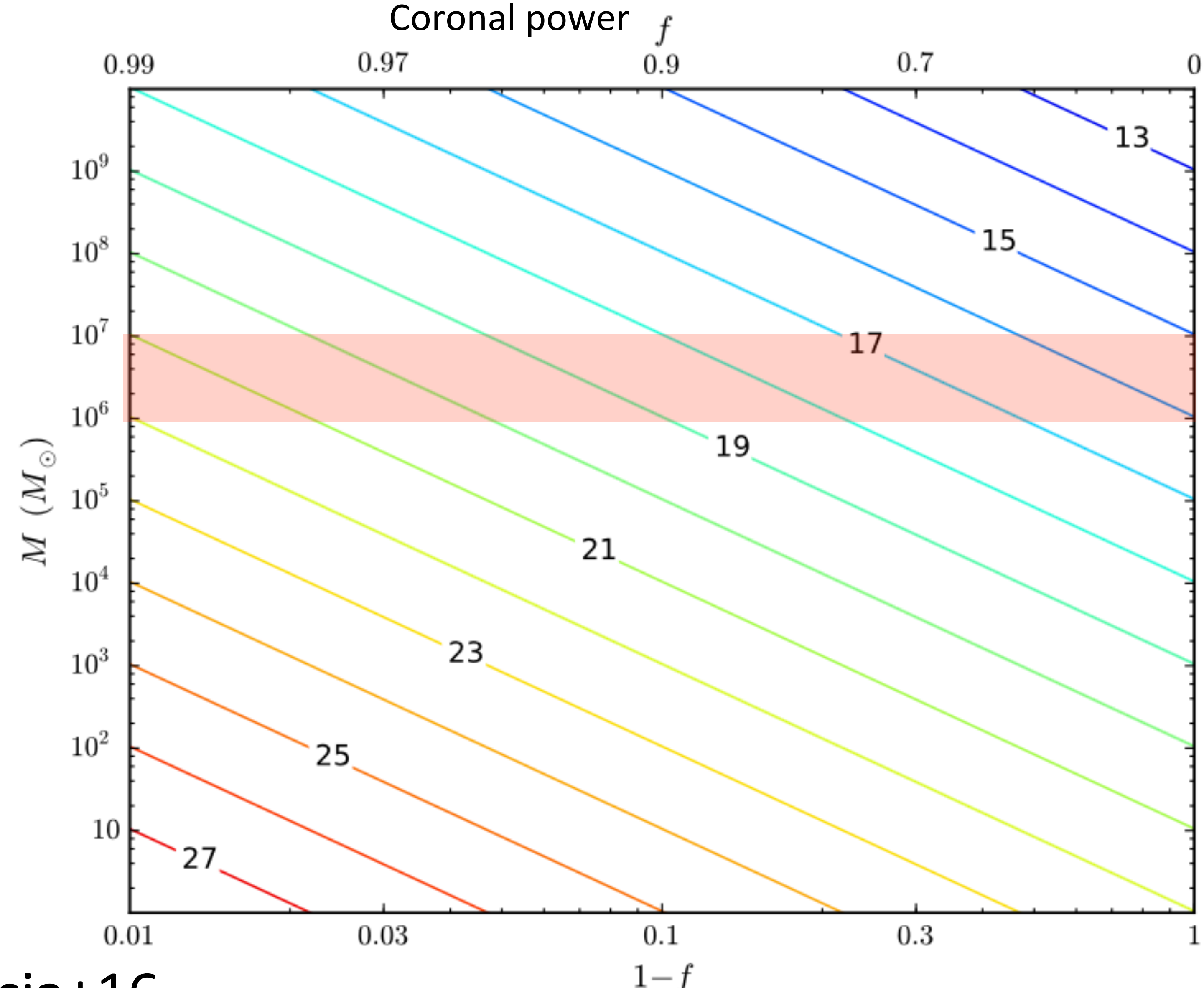
NuSTAR spectrum from 2016



Jiang+18

HIGH Density Reflection Models appropriate

Coronal power



10^8

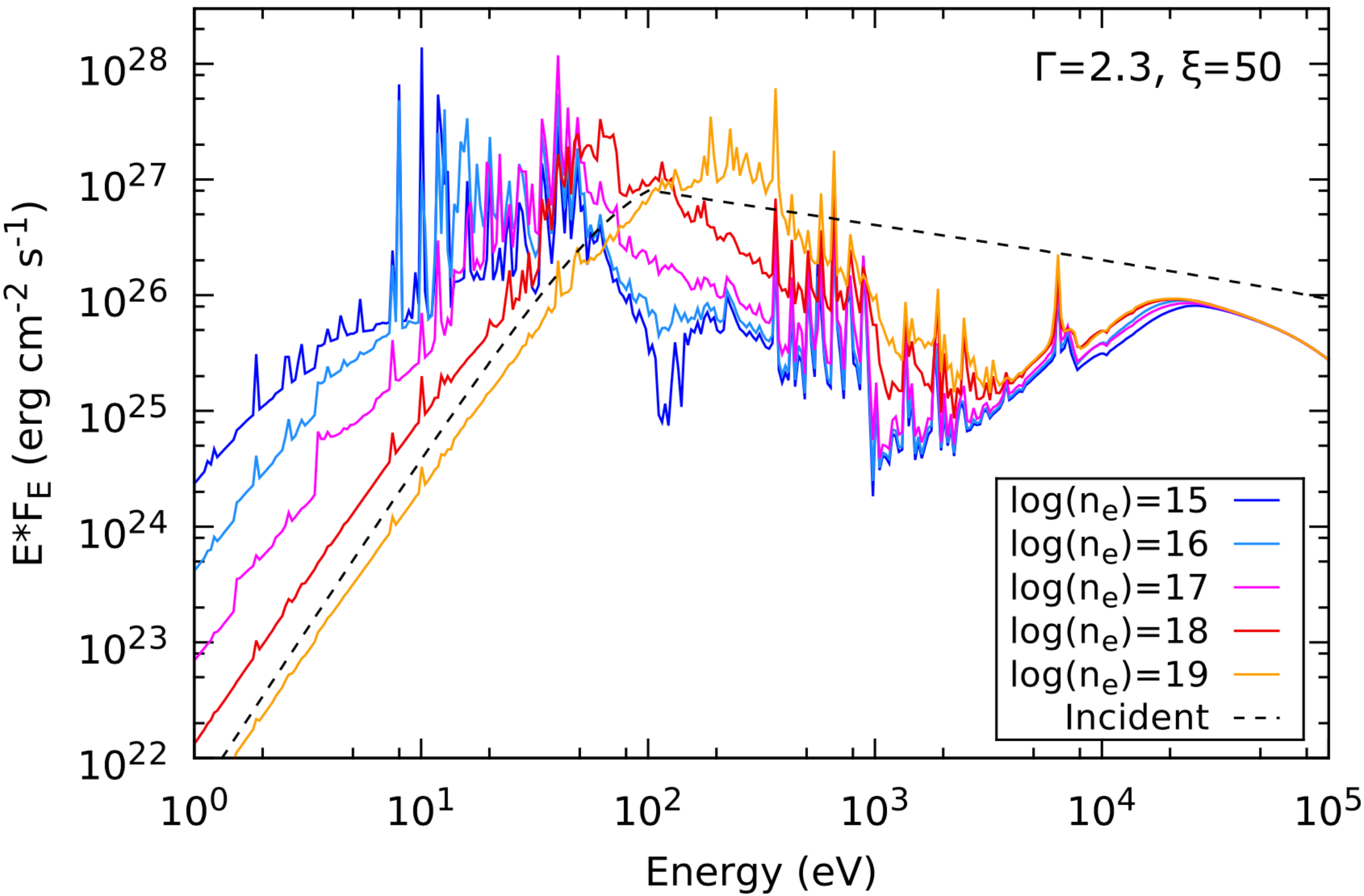
10^7

10^6

10 M_{sun}

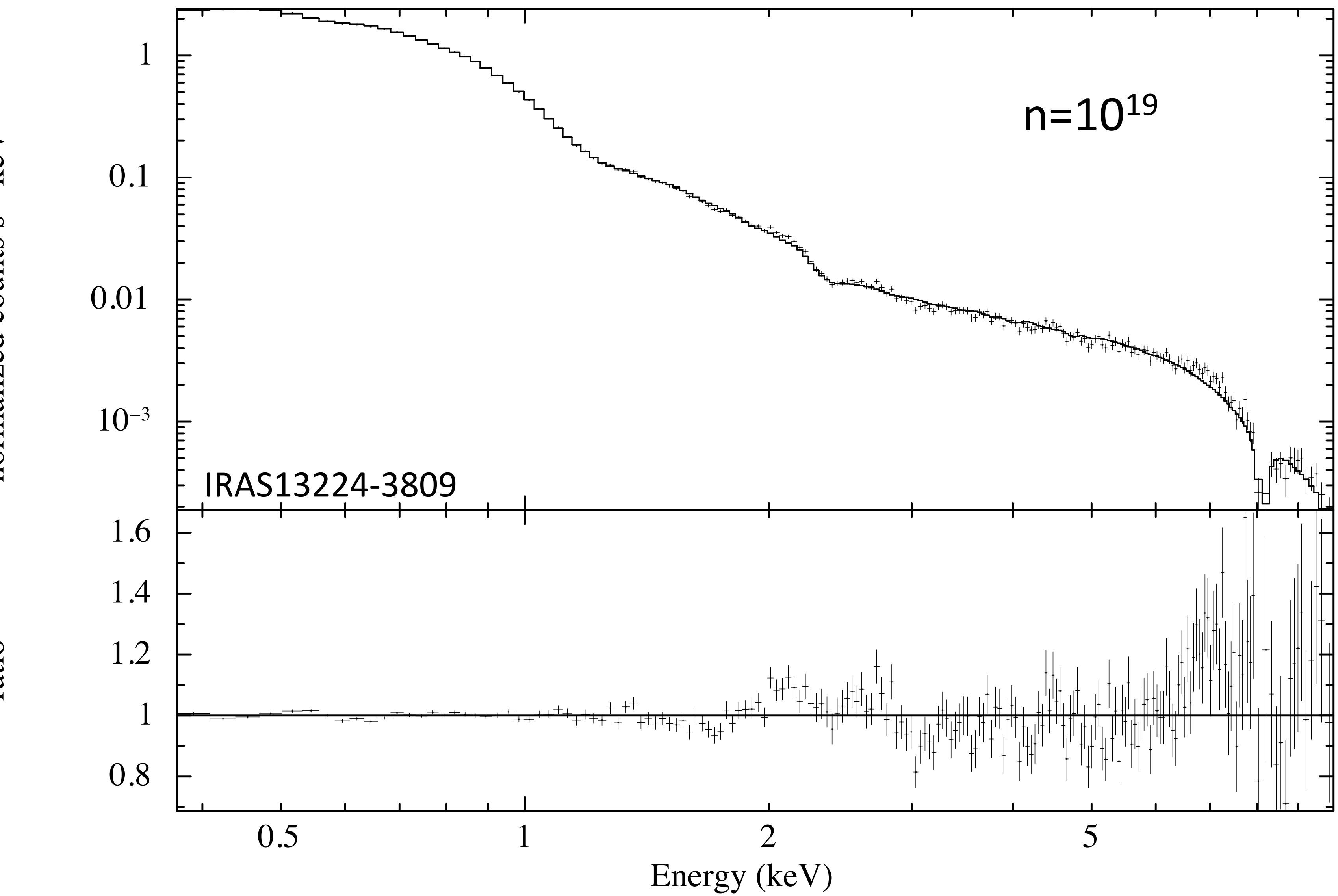
Garcia+16

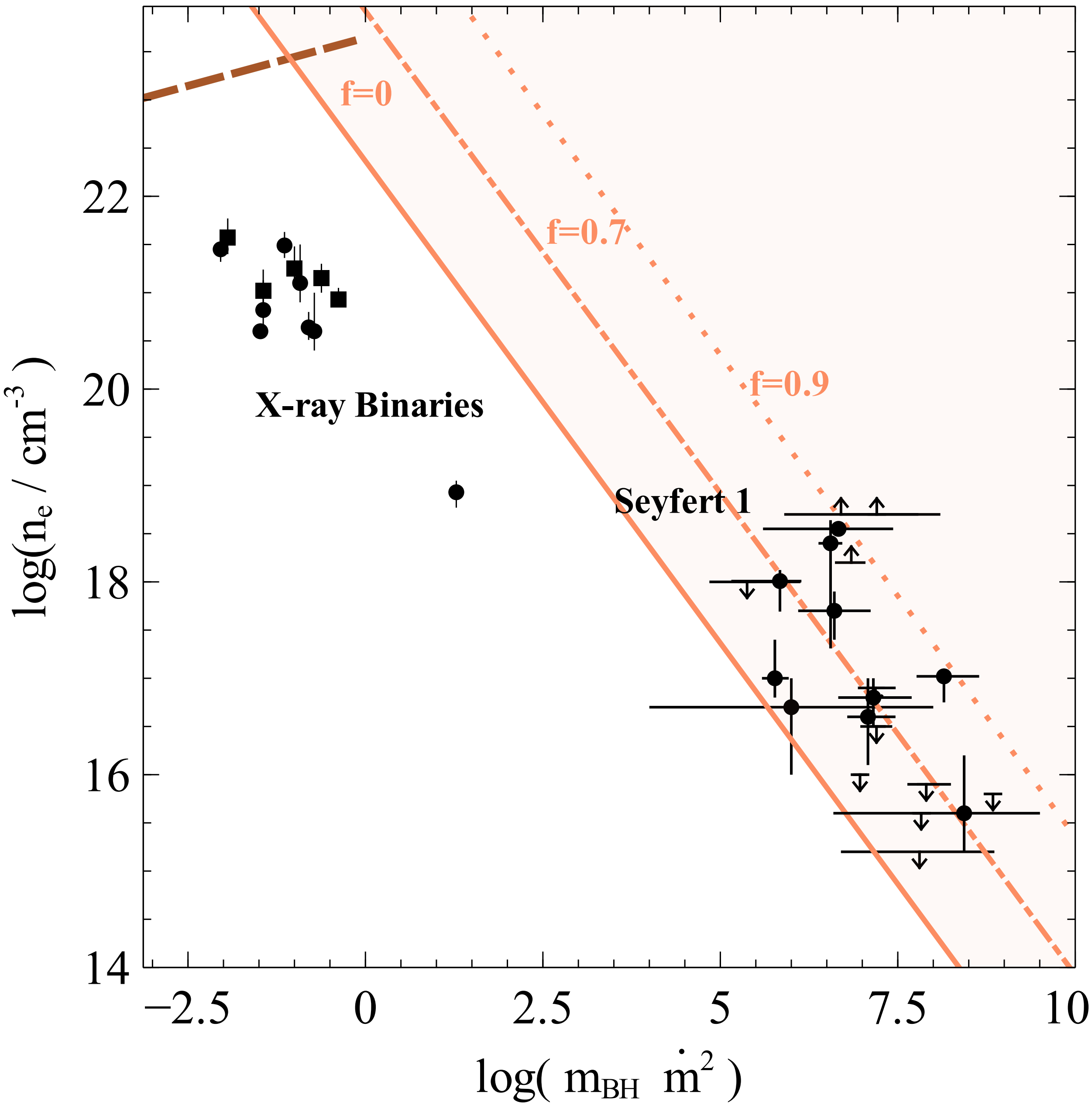
from Svensson & Zdziarski94


Γ=2.3, ξ=50
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
10^{23}
10^{22}
$E*F_E$ (erg cm^{-2} s^{-1})
10^0
10^1
10^2
10^3
10^4
10^5
Energy (eV)
log(n_e)=15
log(n_e)=16
log(n_e)=17
log(n_e)=18
log(n_e)=19
Incident

Garcia+16

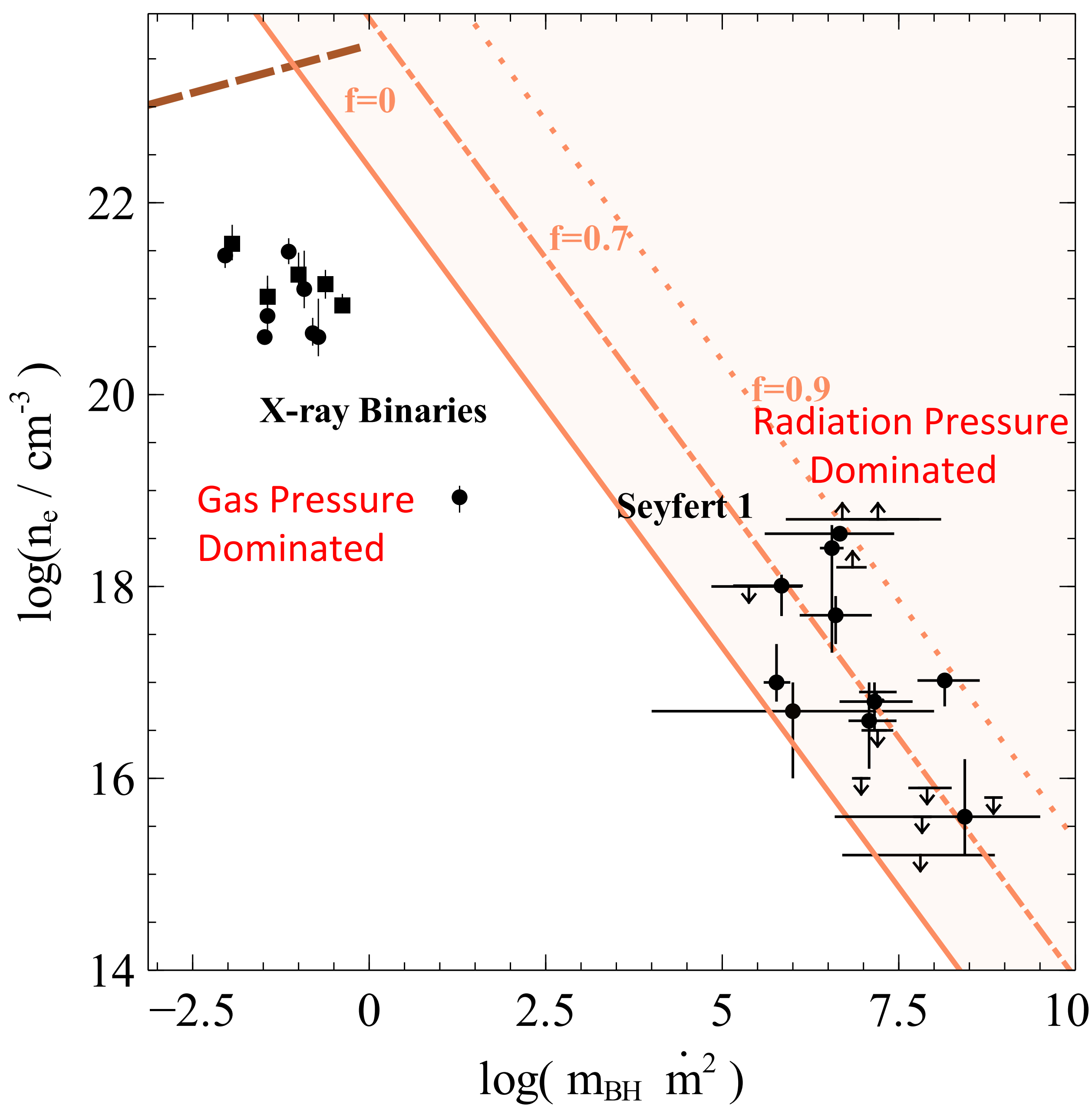
High Density Fit to low state





f=0
f=0.7
f=0.9
X-ray Binaries
Seyfert 1
22
20
18
16
14
−2.5
0
2.5
5
7.5
10
log(n_e / cm^-3)
log(m_BH ṁ^2)

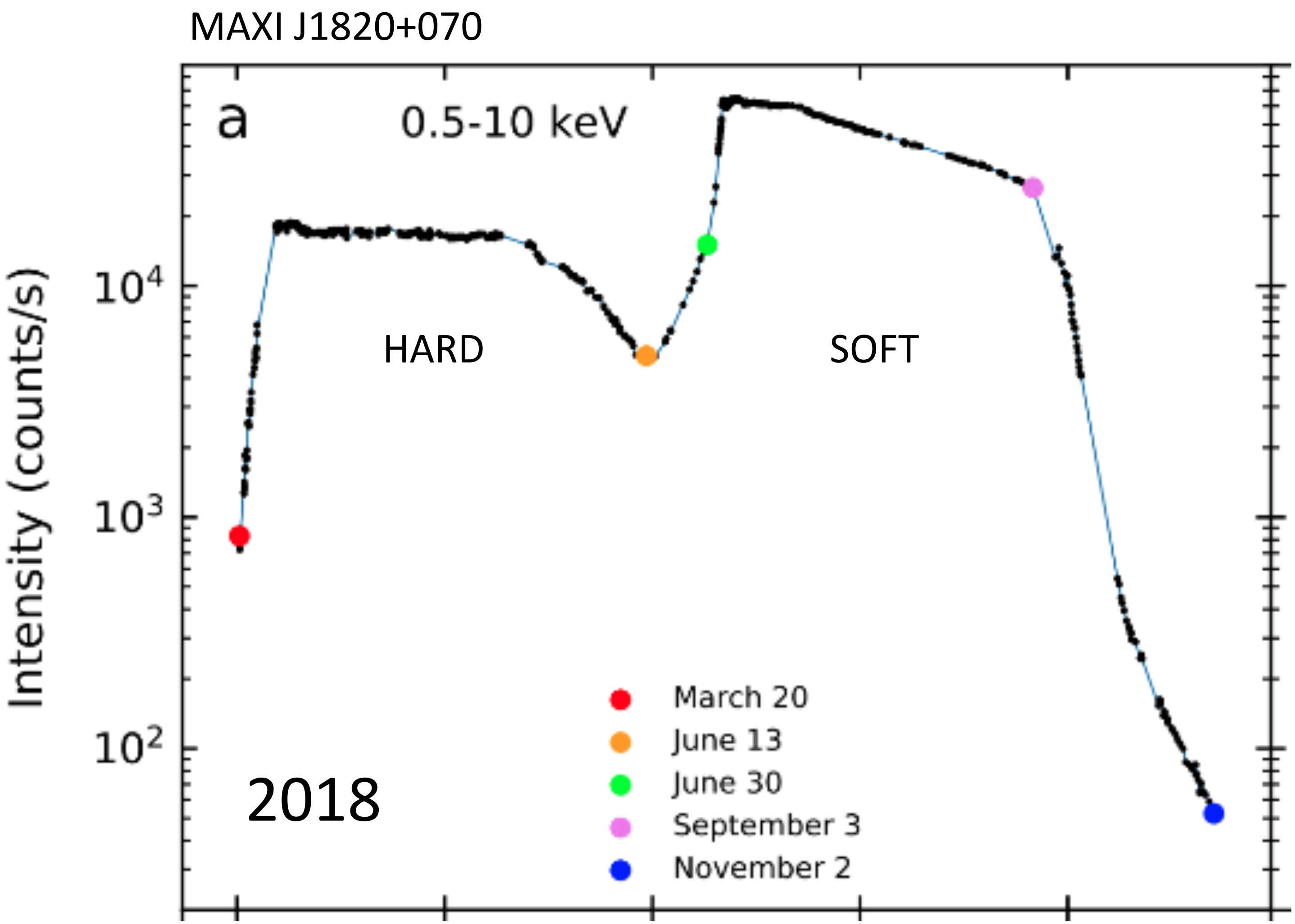
Jiang+19

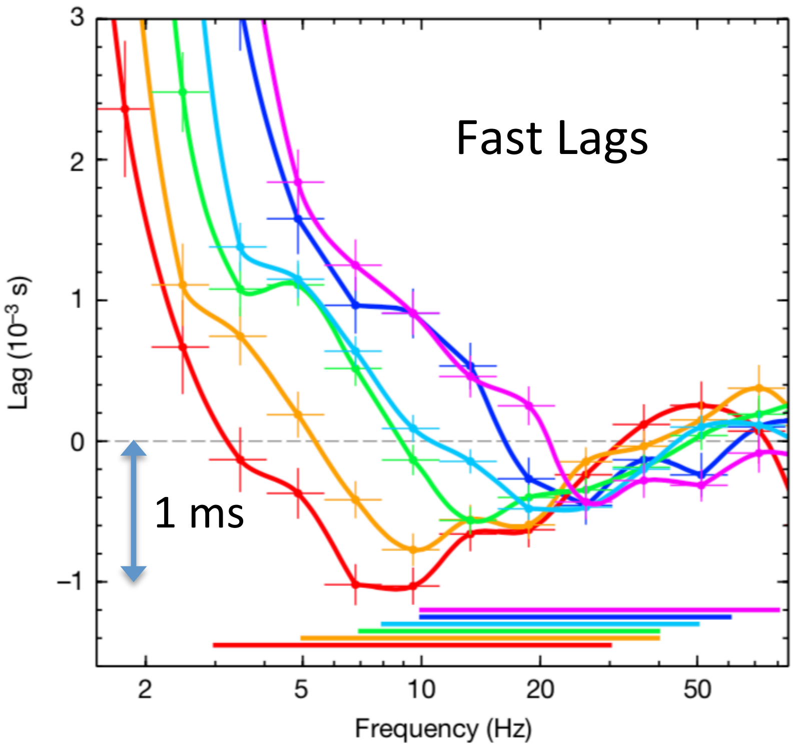


f=0
f=0.7
f=0.9
22
20
18
16
14
−2.5
0
2.5
5
7.5
10
$\log(n_e\ /\ cm^{-3})$
$\log(m_{BH}\ \dot{m}^2)$
X-ray Binaries
Gas Pressure
Dominated
Seyfert 1
Radiation Pressure
Dominated

Jiang+19

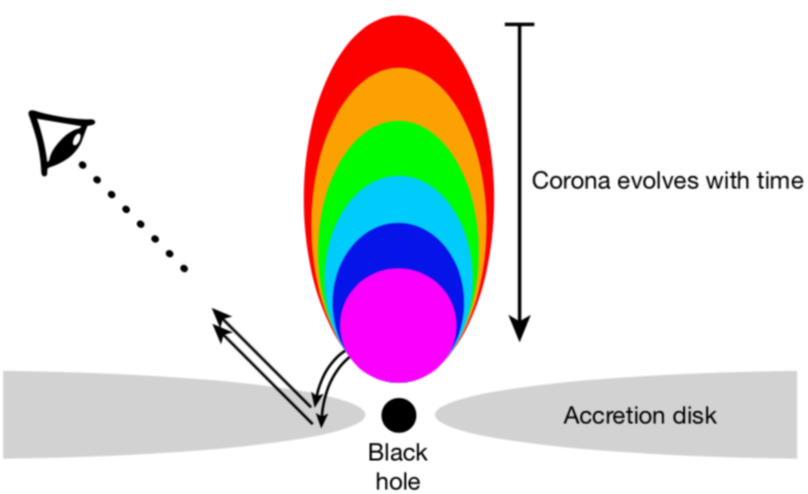
NICER lightcurve J Homan



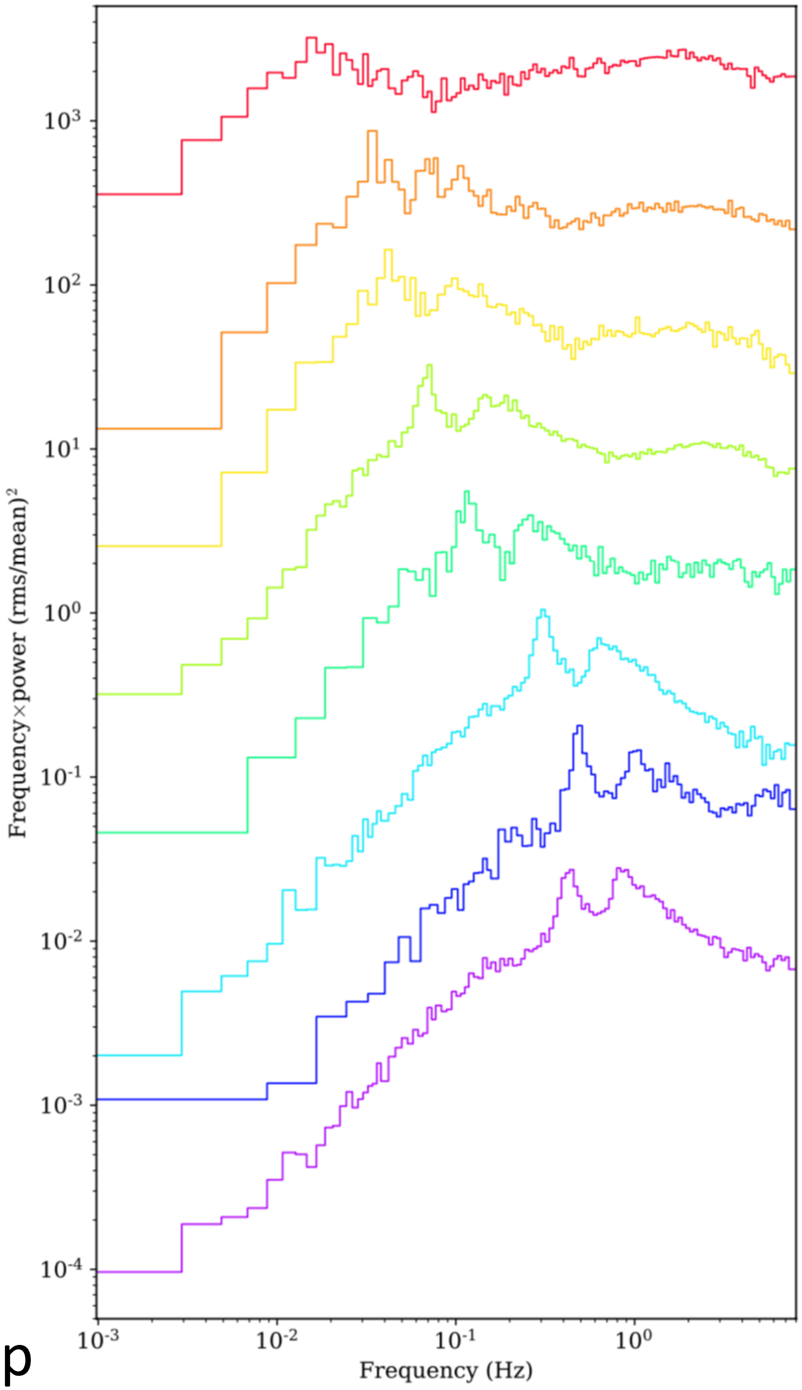


Kara+19

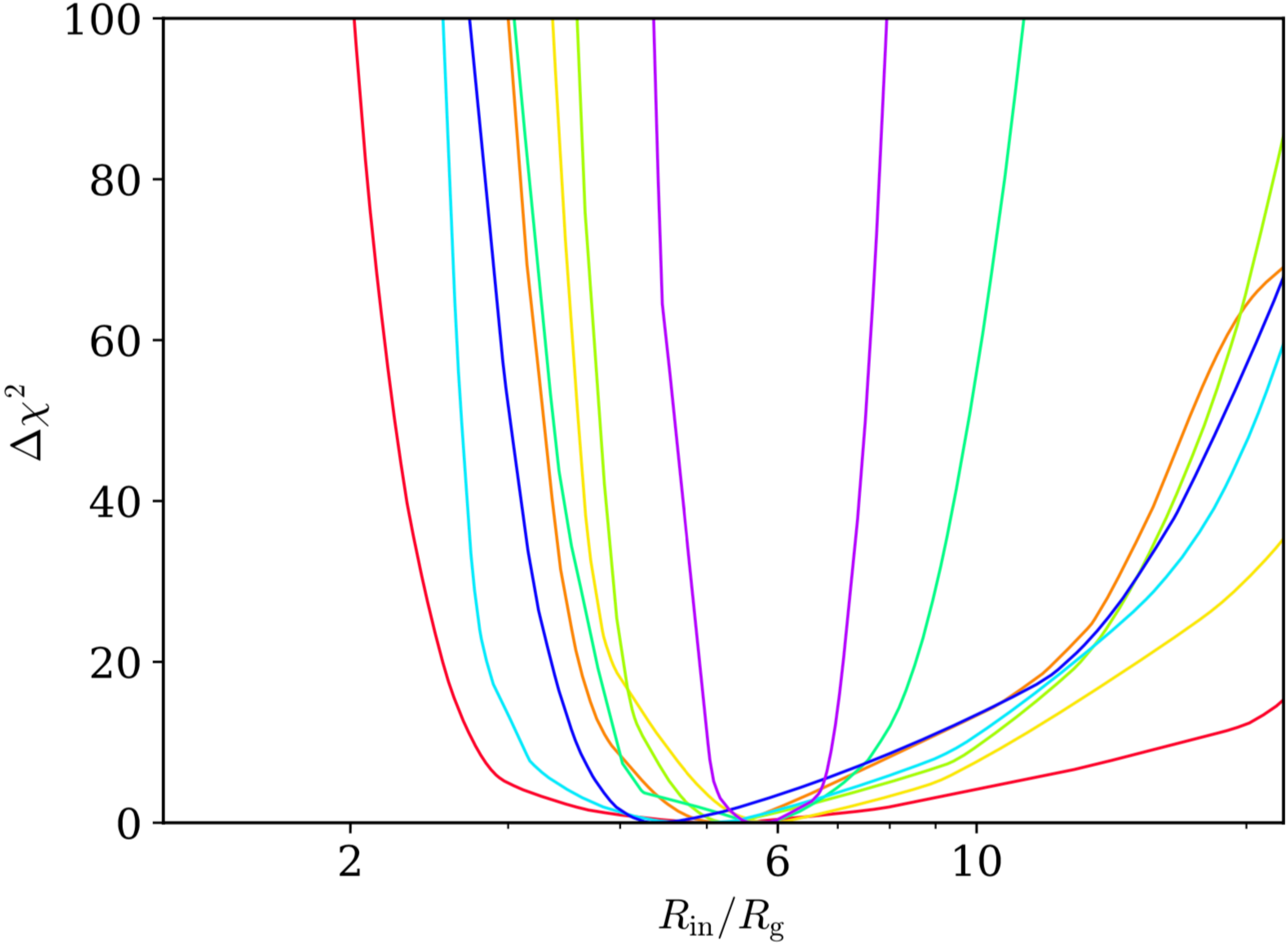
NICER data



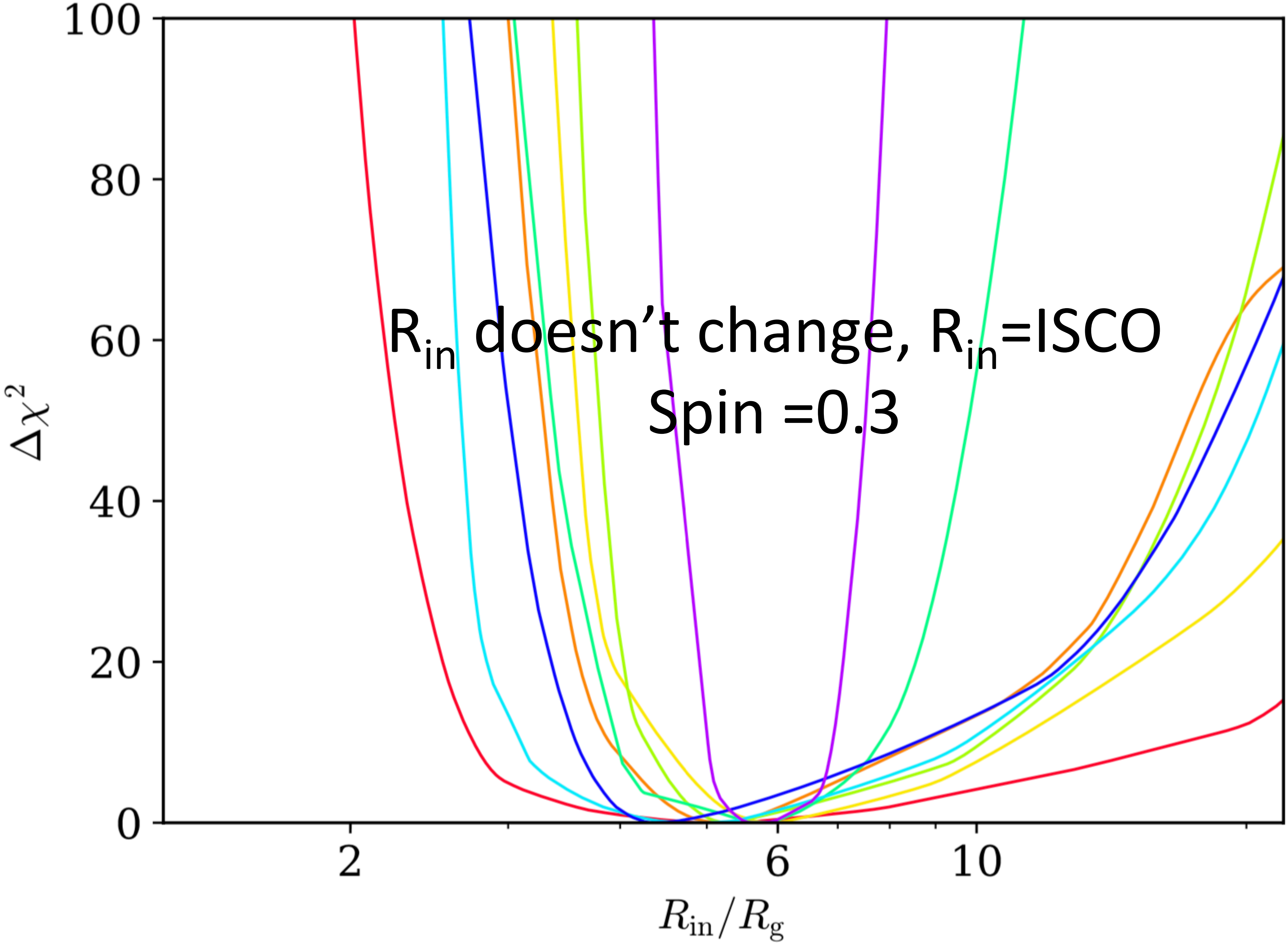
QPO



Buisson+19 in prep

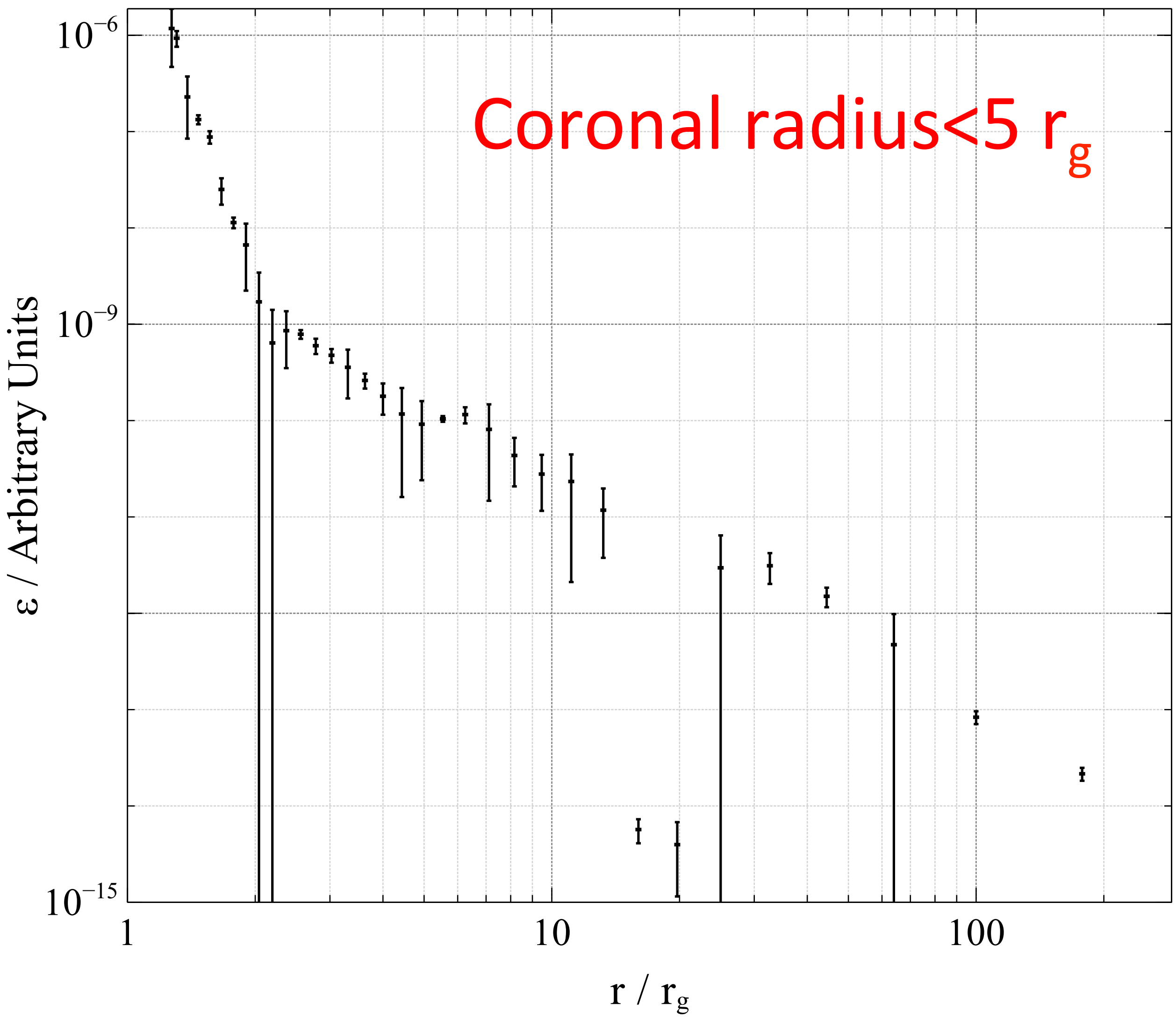


Buisson+19


R_{in} doesn't change, R_{in}=ISCO
Spin =0.3
100
80
60
40
20
0
$\Delta\chi^2$
2
6
10
R_{in}/R_g

Buisson+19

Emissivity Profile (D. Wilkins)



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?

CORONA IS RADIATIVELY COMPACT

Dimensionless compactness parameter, GuilbertFabianRees83

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

$$l = \left(\frac{m_{\rm p}}{m_{\rm e}}\right)\left(\frac{R}{R_{\rm S}}\right)^{-1}\left(\frac{L}{L_{\rm Edd}}\right)$$

For AGN, ℓ typically 10-1000

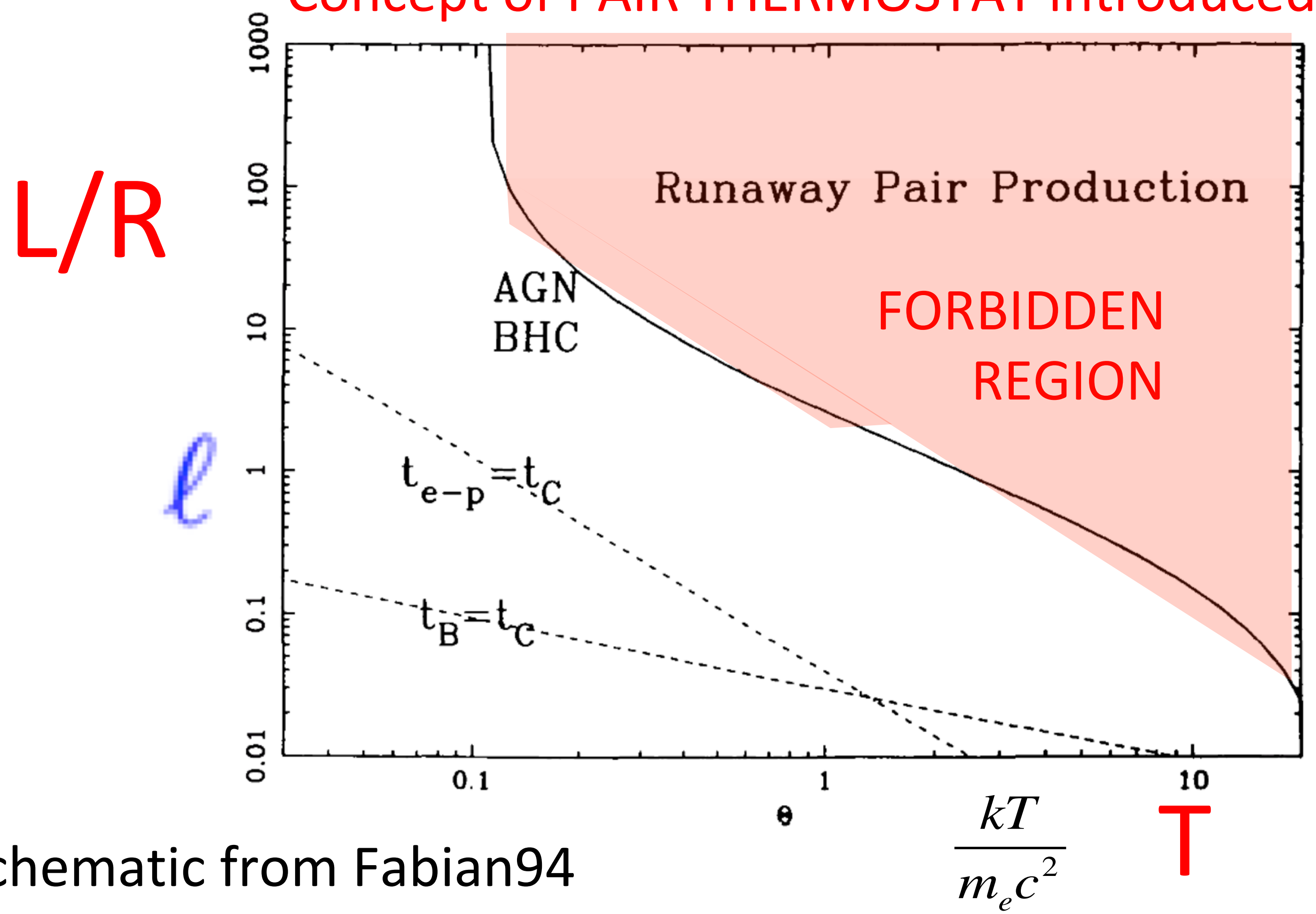
Compton cooling time < light crossing time

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

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

Svensson, 82,84, Zdziarski 85, many other papers and workers 80s + 90s

Concept of PAIR THERMOSTAT introduced



Schematic from Fabian94

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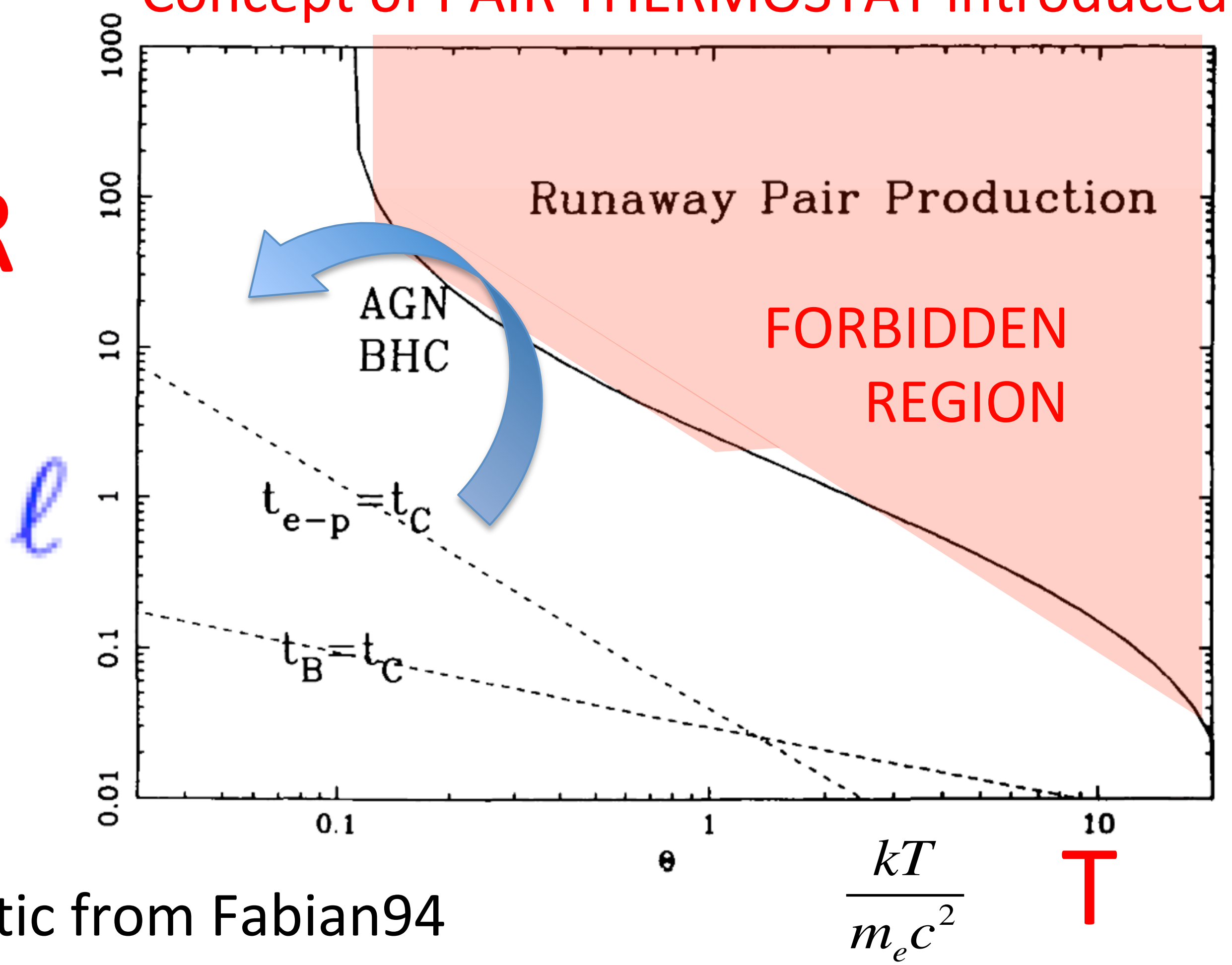
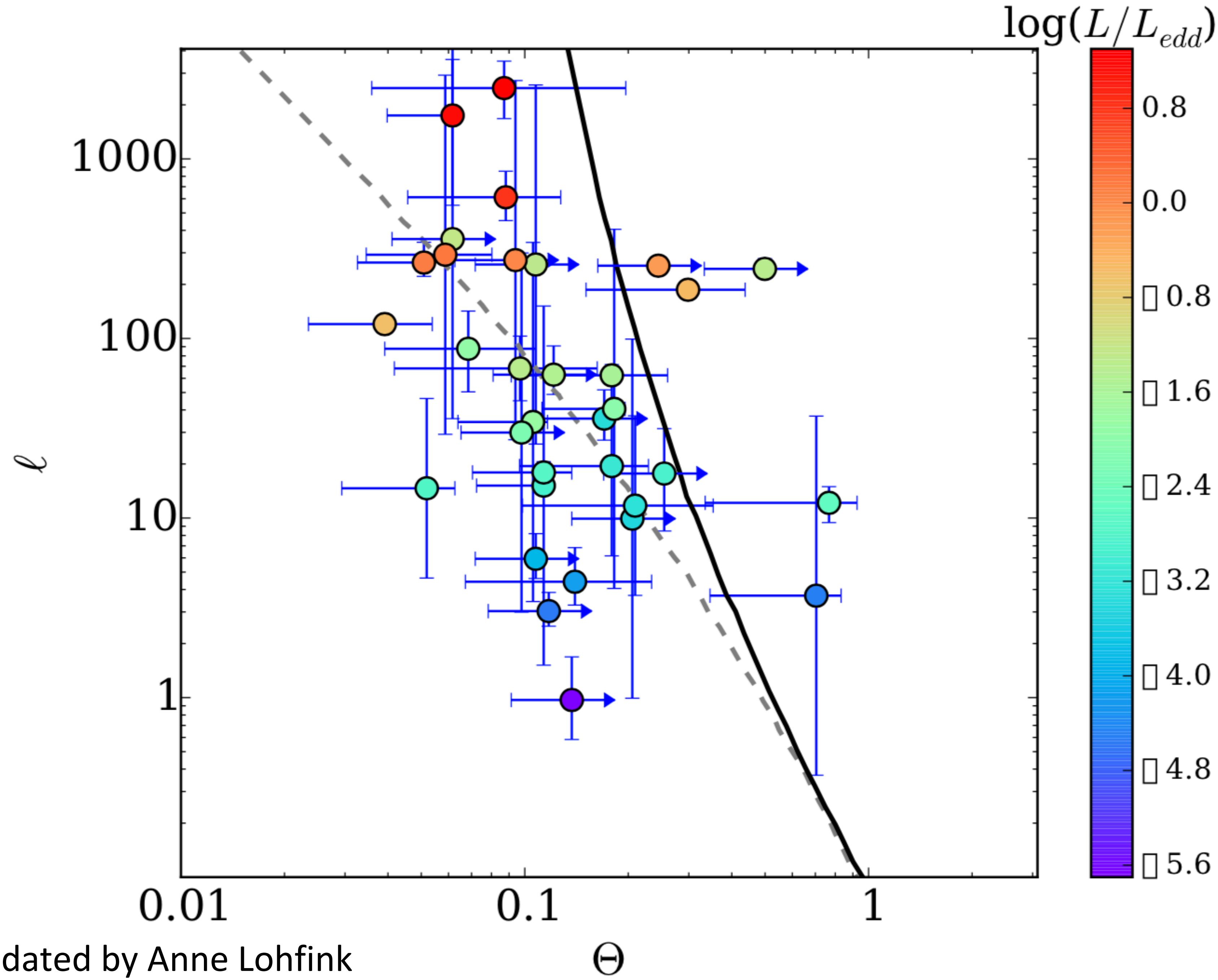


Schematic from Fabian94



Updated by Anne Lohfink

JAXA/NASA/ESA XRISM launch 2022

Summary

- We're now doing Relativistic Astrophysics of the immediate region around rapidly spinning accreting Kerr black holes – the central engine of quasars – using X-ray spectral timing, including relativistic reflection and reverberation.