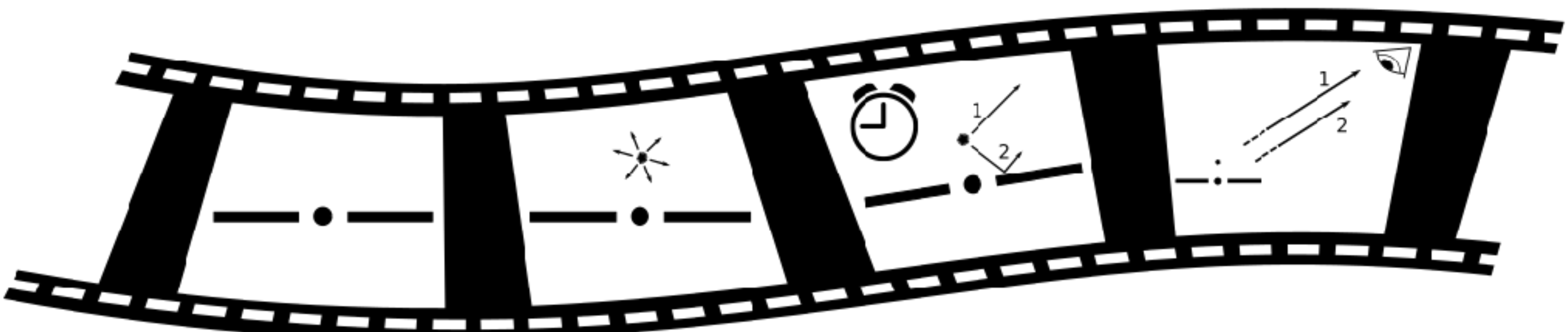
UNIVERSITY OF AMSTERDAM

ANTON PANNEKOEK INSTITUTE

X-ray Reverberation Mass Measurement of Cygnus X-1

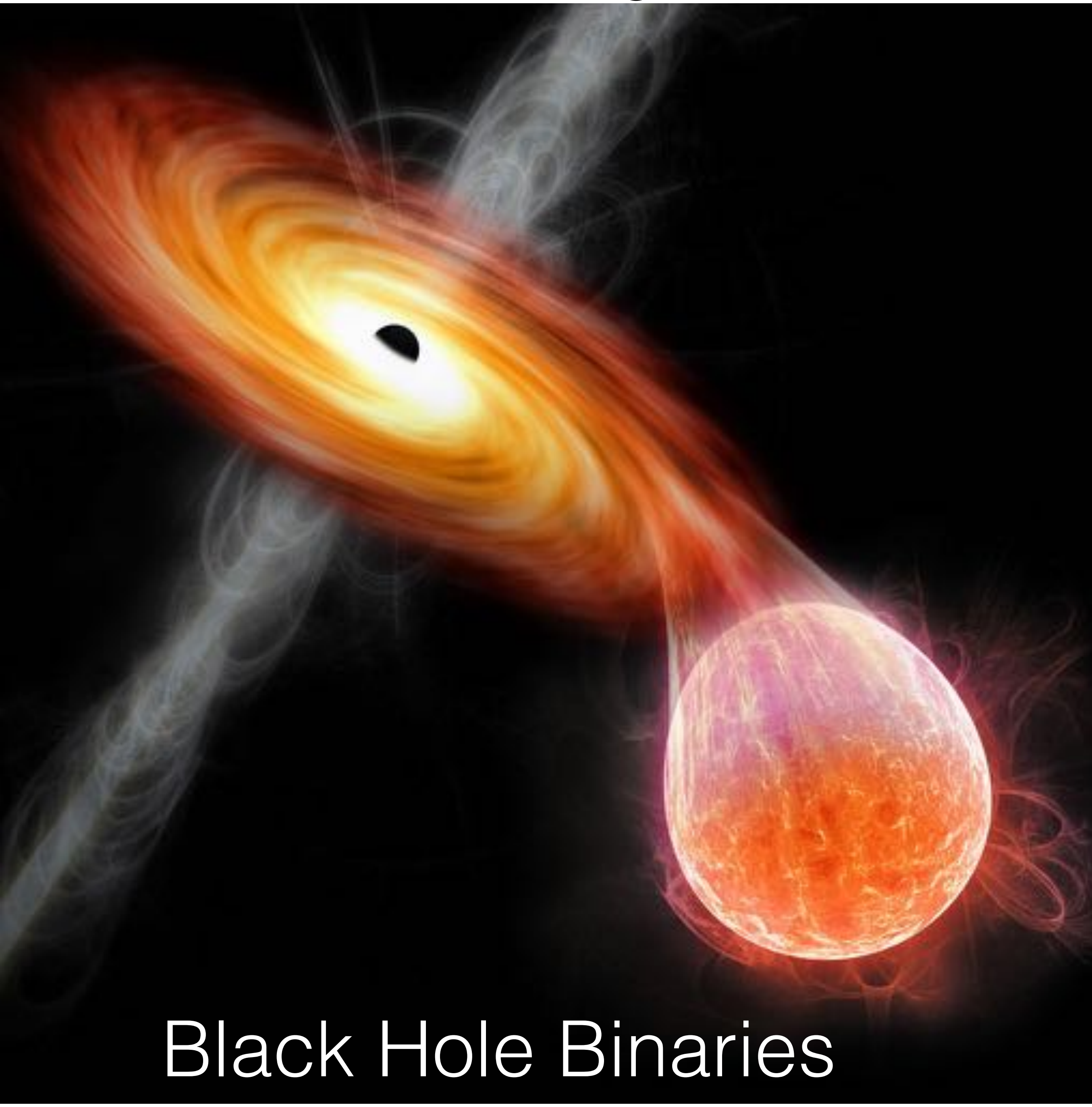
G. Mastroserio

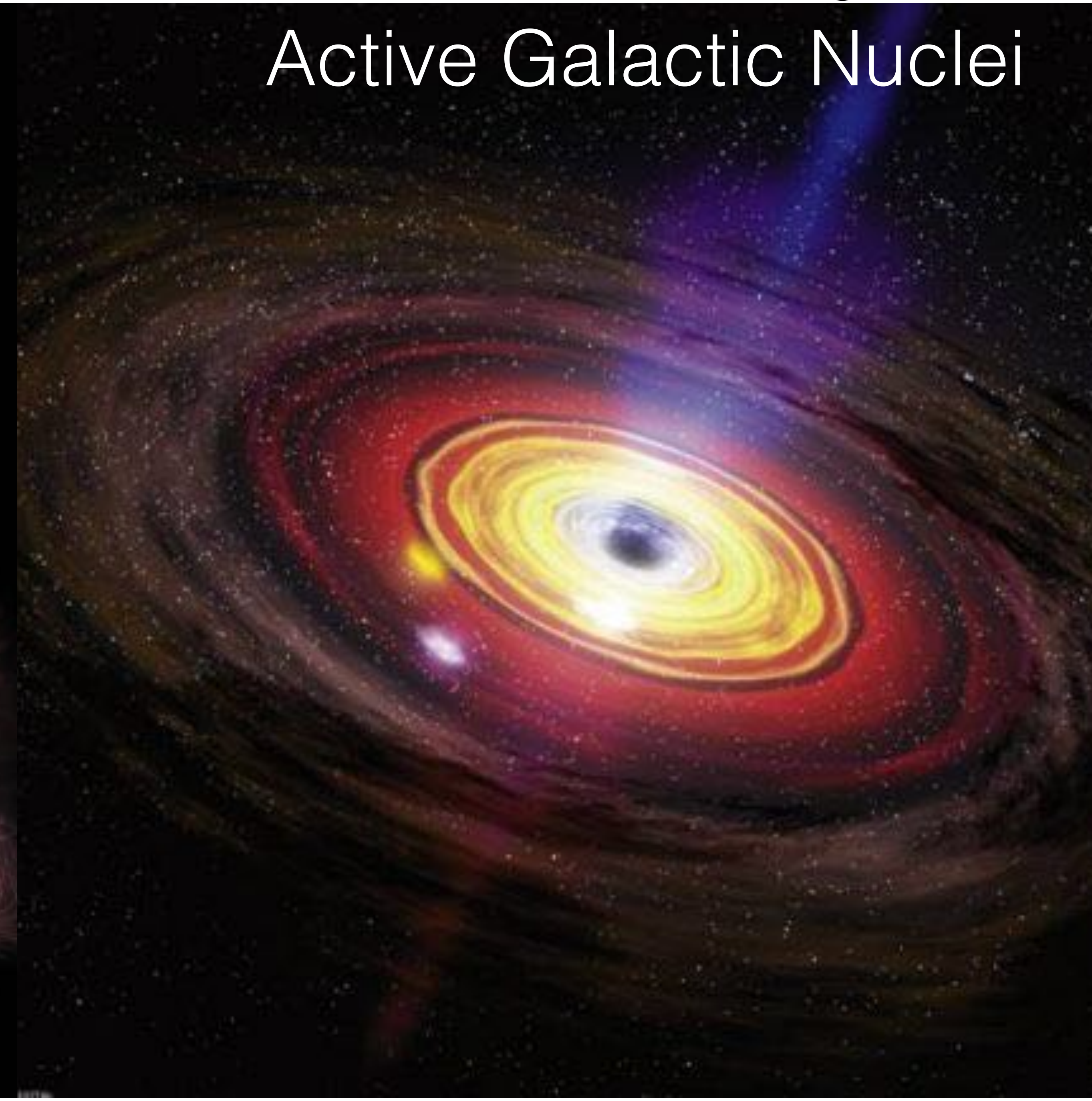
A. Ingram, M. van der Klis



BHBs and AGN

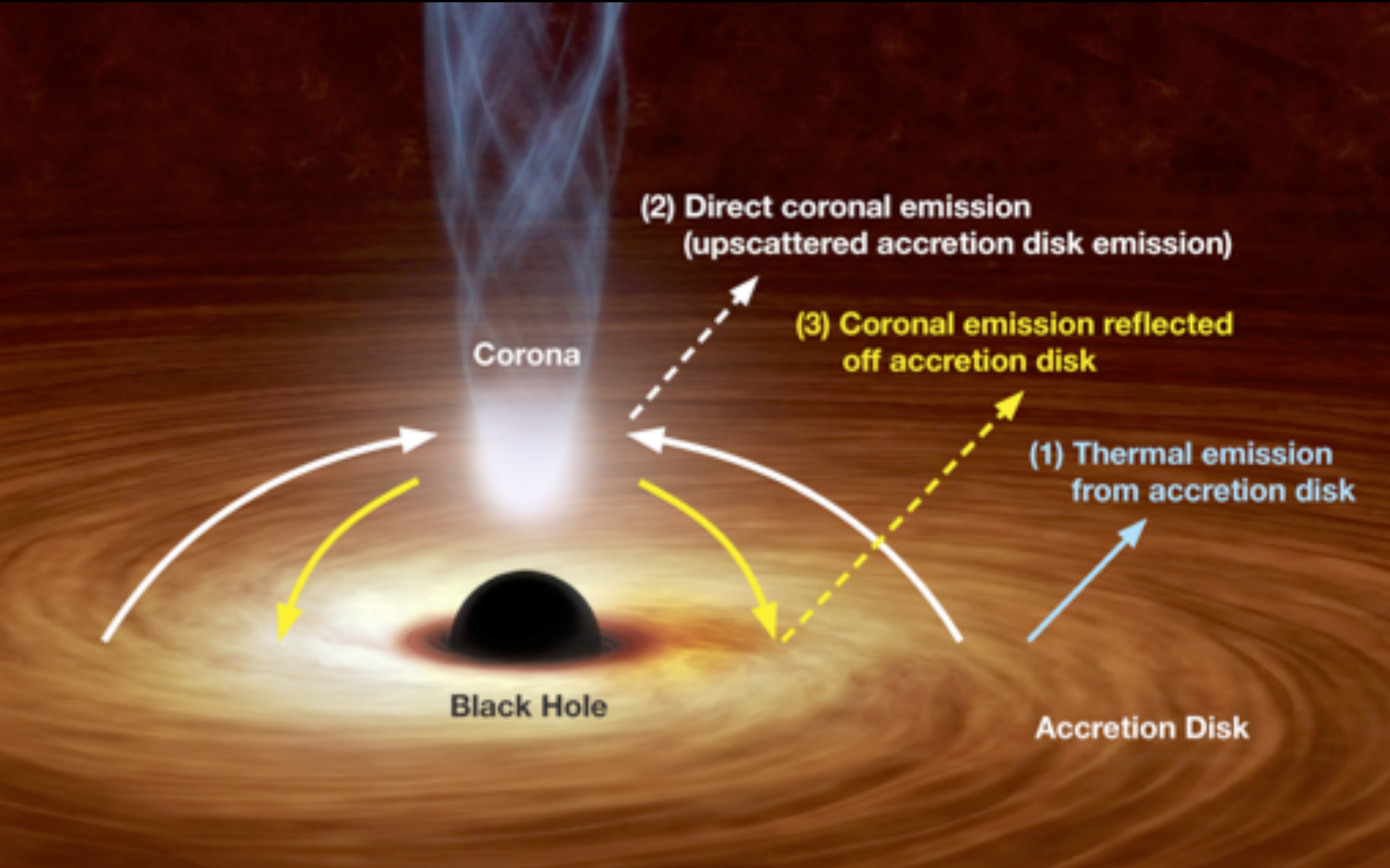
$\sim 10\,M_{\odot}$ Mass $\sim 10^6$ - $10^9\,M_{\odot}$

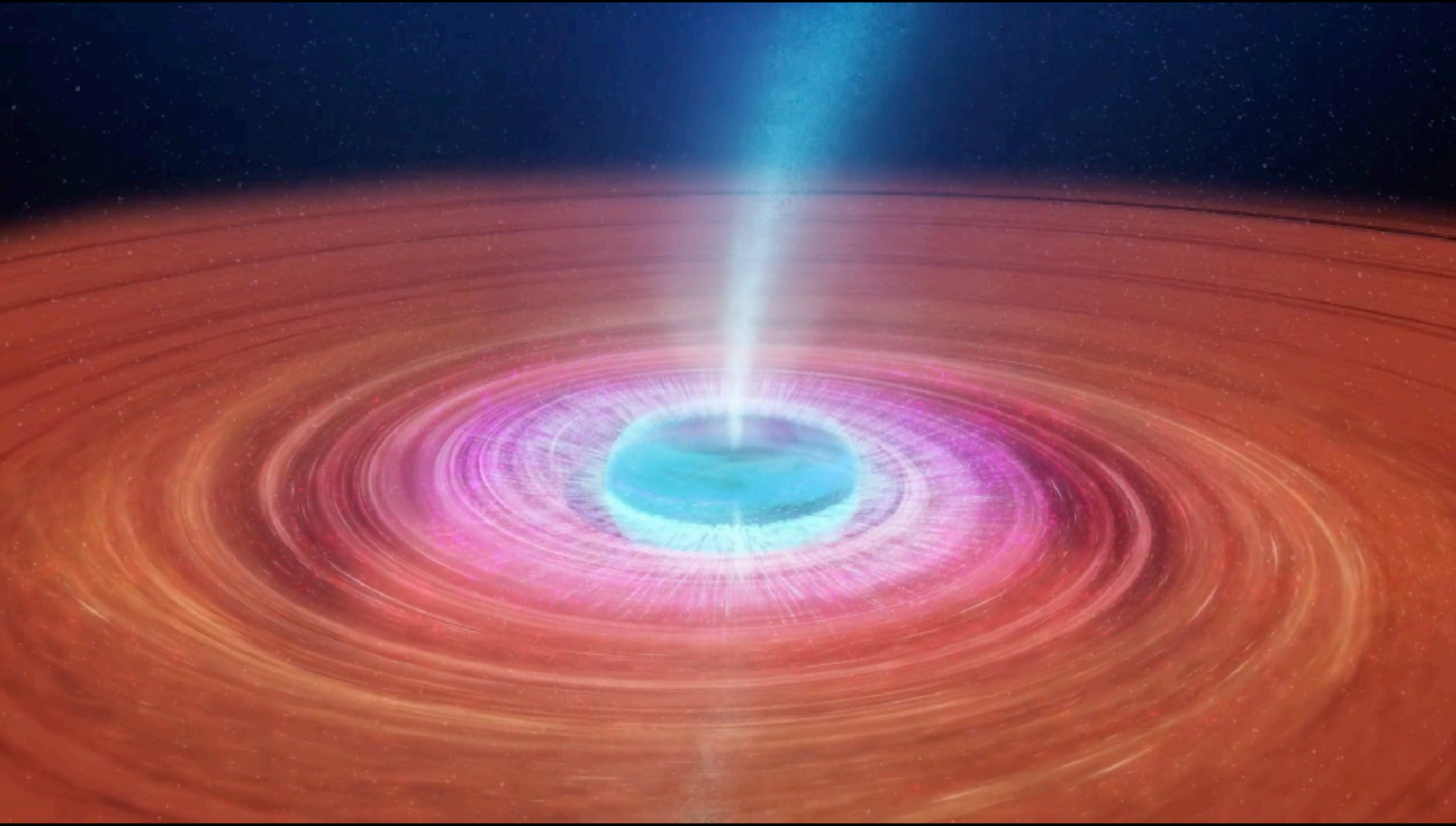




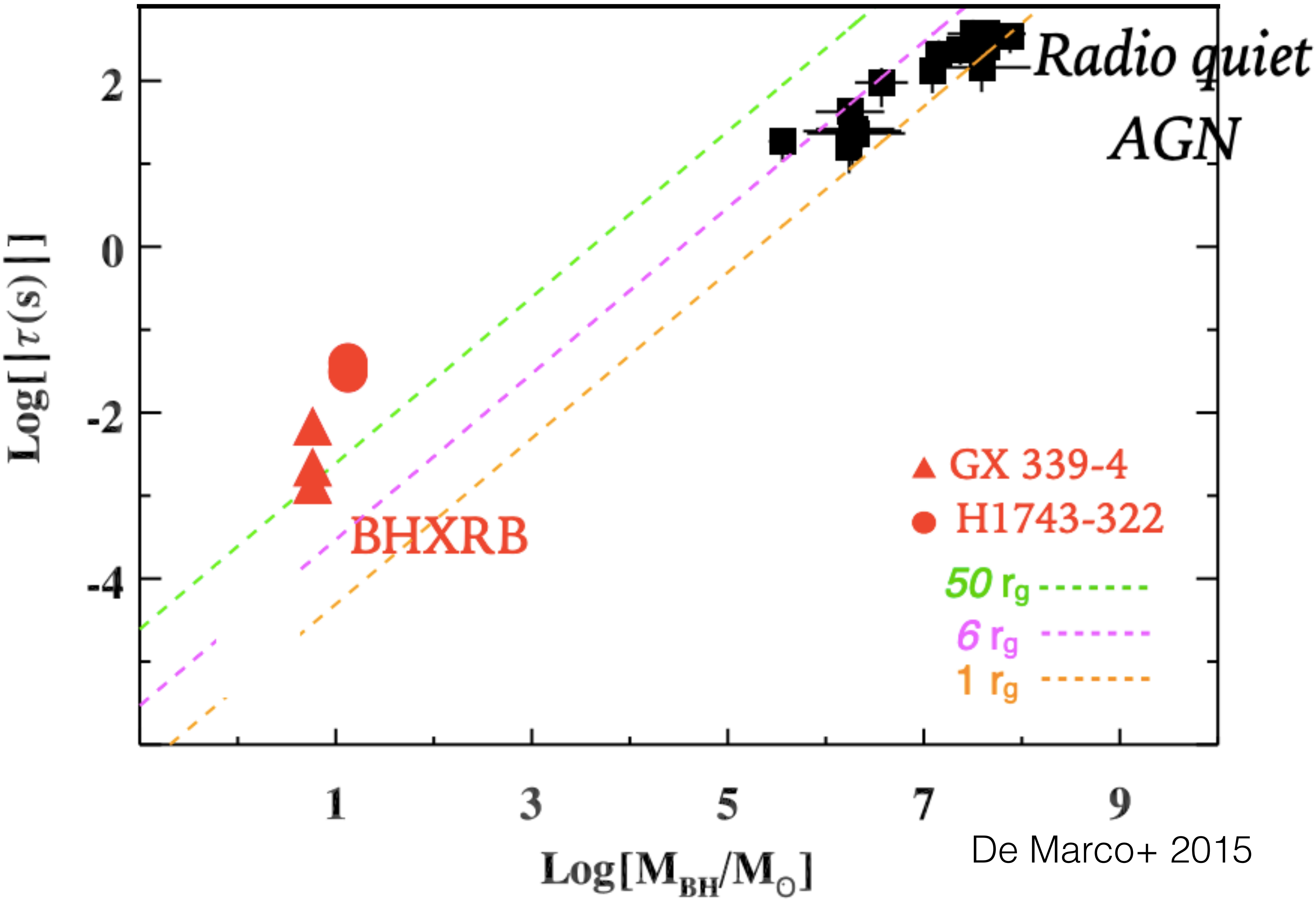
Different mass (!), same central geometry (?)

Emission from the system





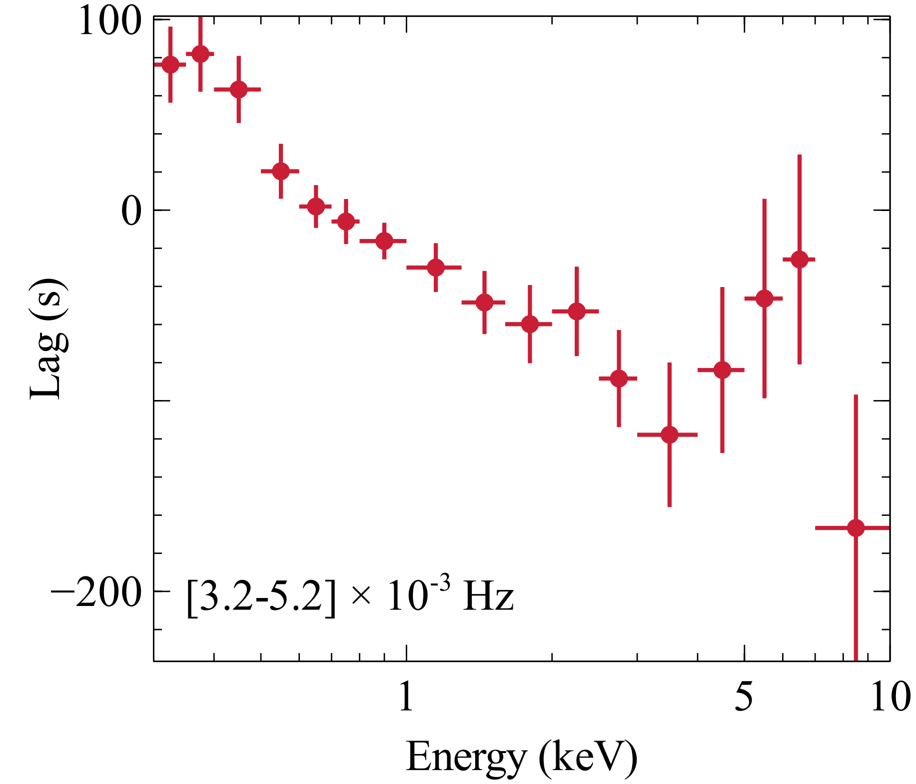
Lag vs BH mass

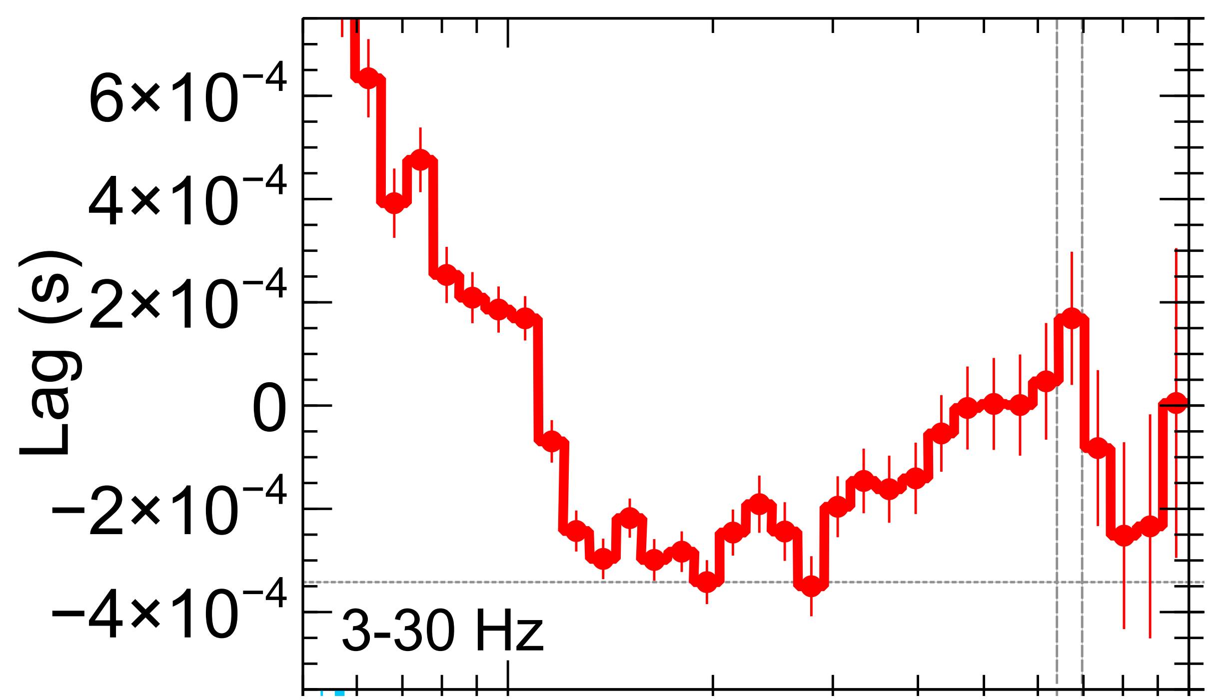


De Marco+ 2015

Lags vs Energy

AGN
Ark 564
$M \simeq 10^6 M_\odot$
Kara+ 2013





BHB
MAXI
J1820+070
$M \simeq 10 M_\odot$
Kara+ 2019

Lags vs Energy

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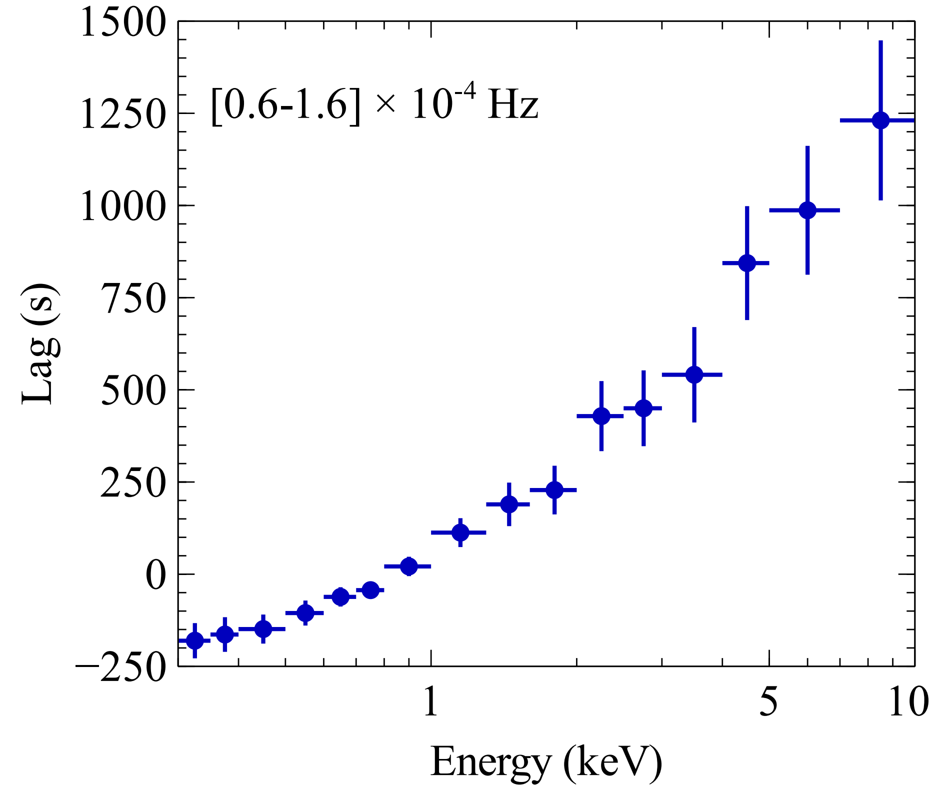
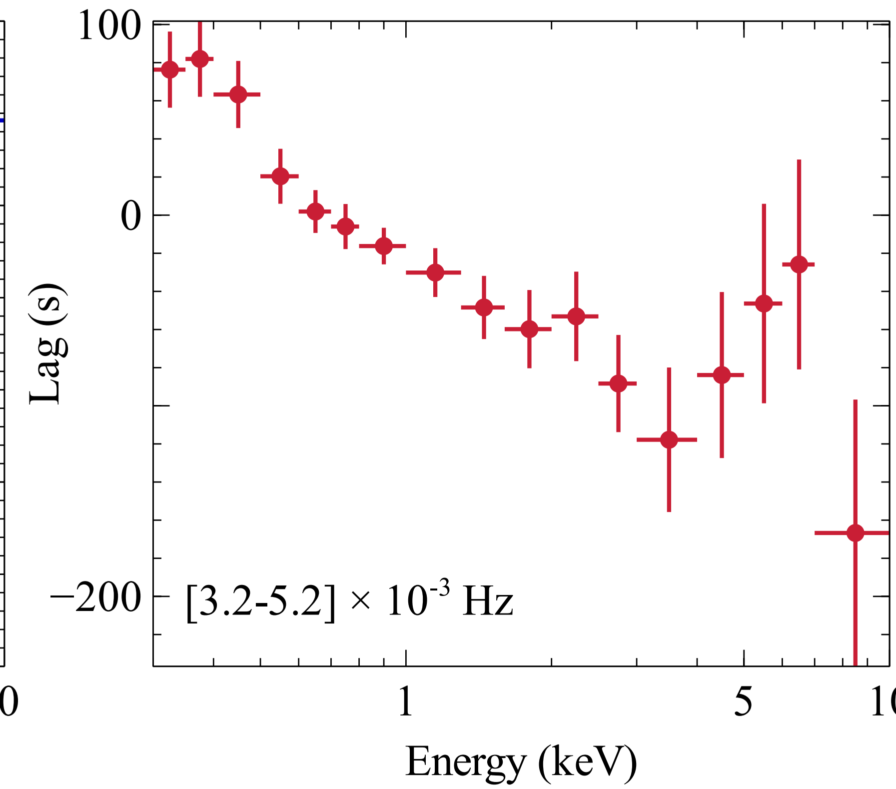
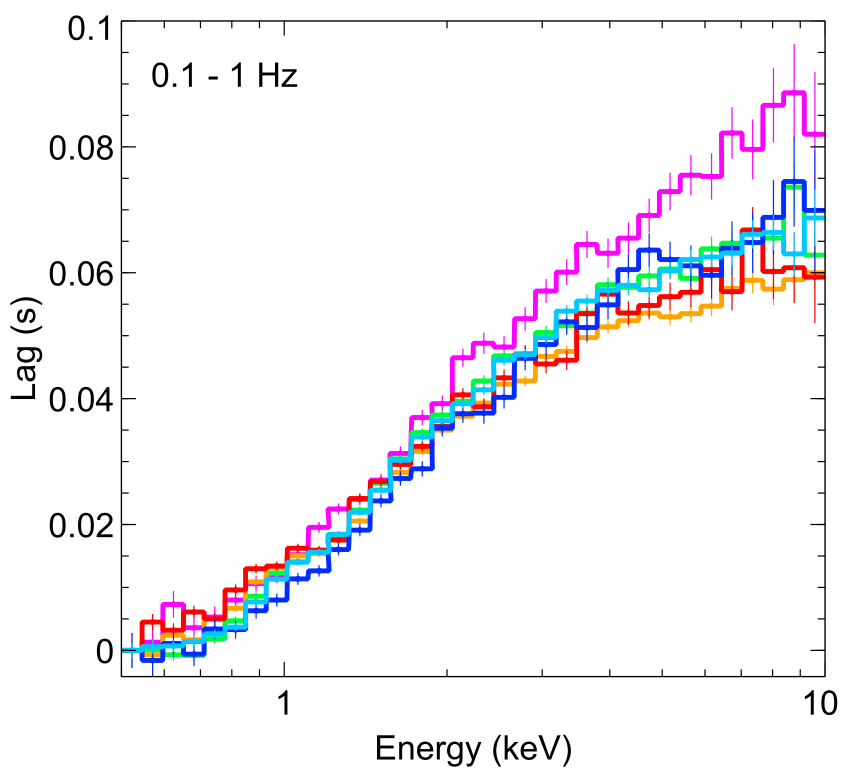
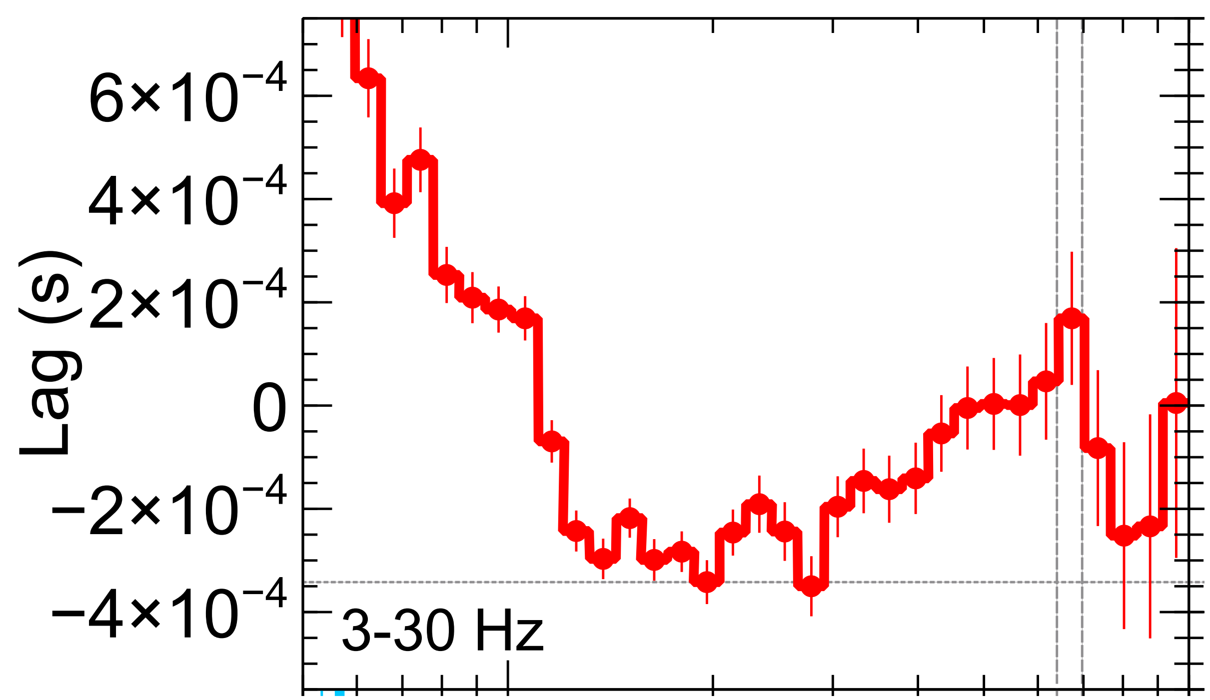
$M \simeq 10^6 M_\odot$

Kara+ 2013









BHB

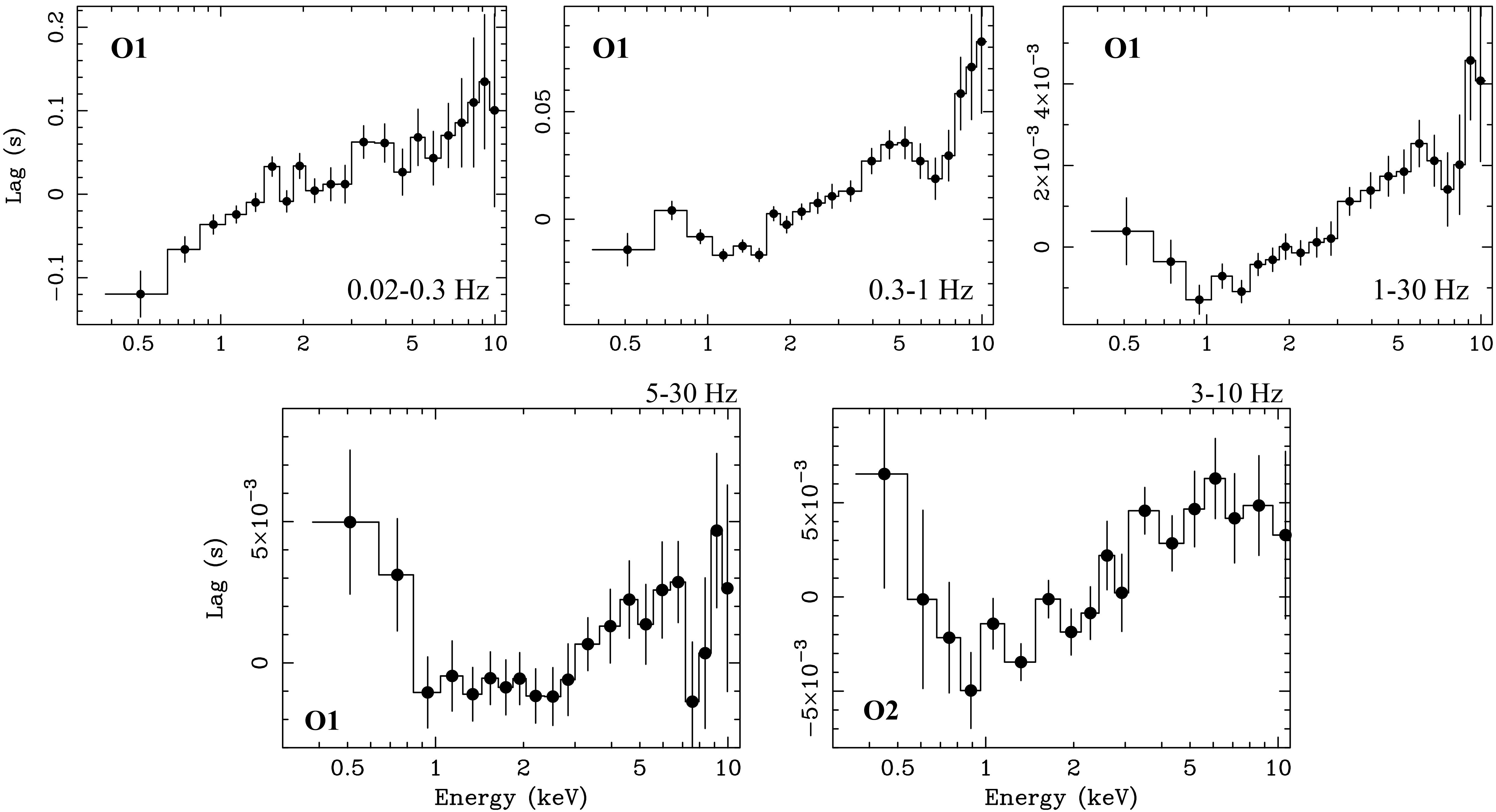
MAXI

J1820+070

$M \simeq 10 M_\odot$

Kara+ 2019

GX 339-4

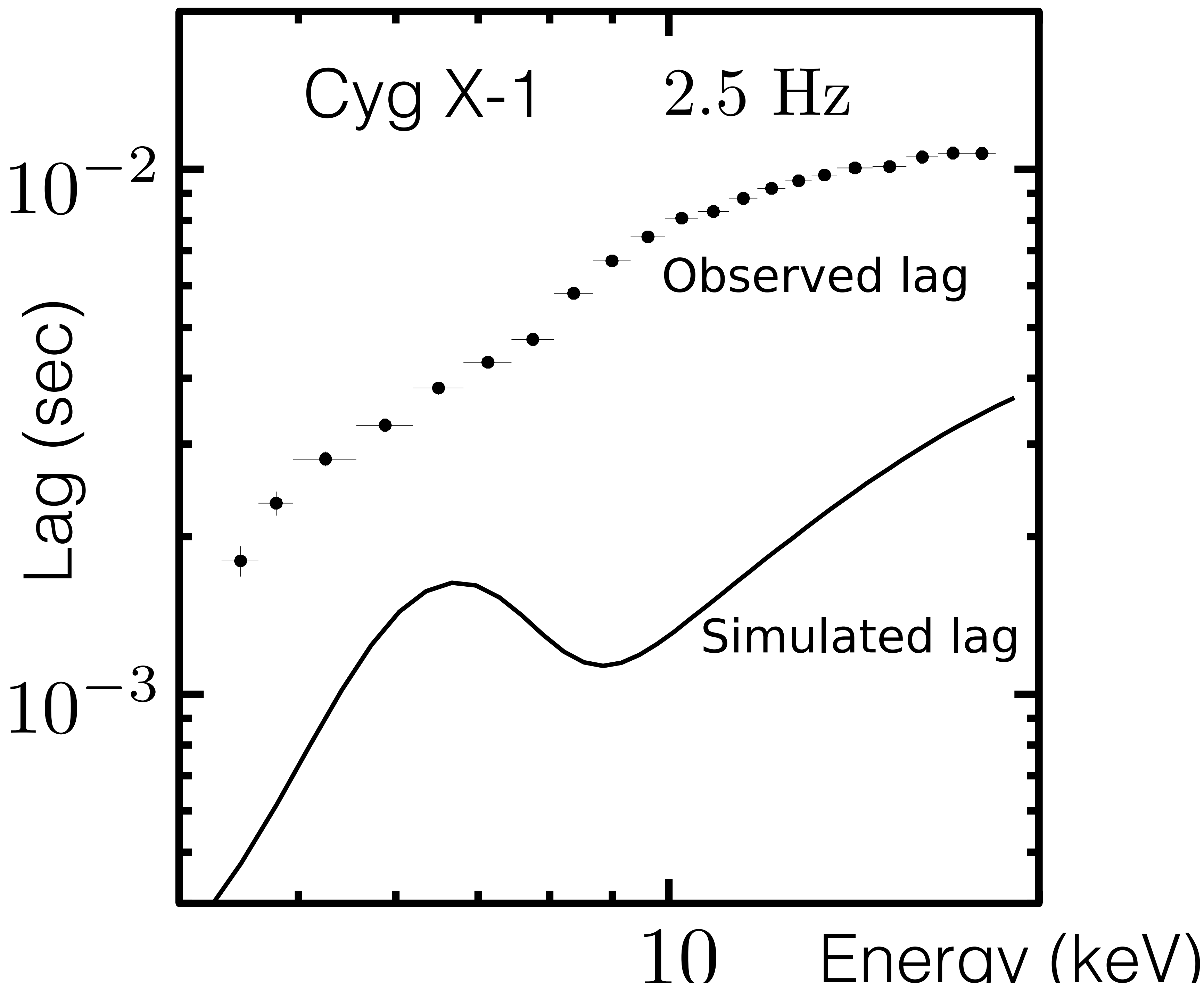


De Marco+ 2017

Cygnus X-1

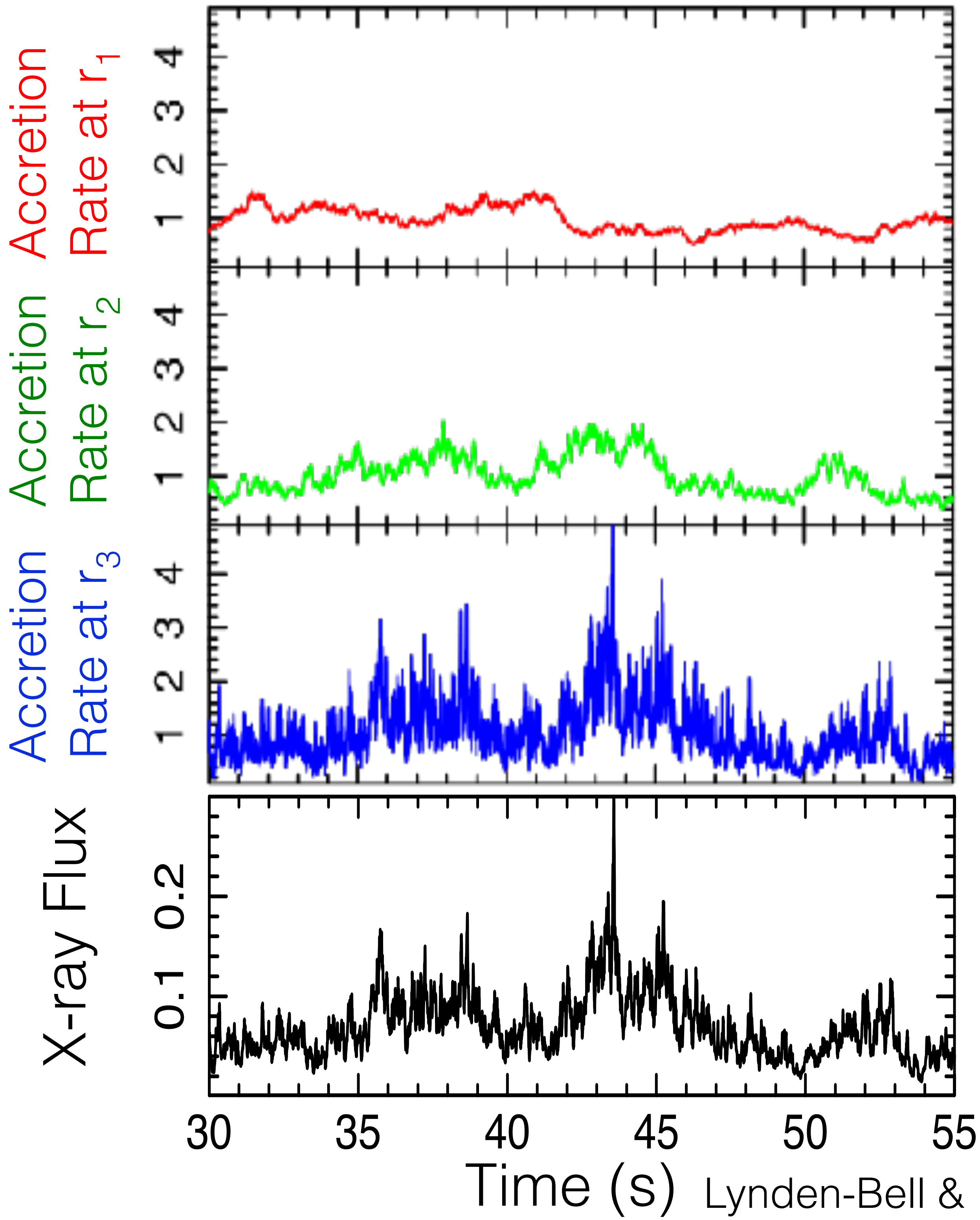
Hard state:
March 1996
(P10238)

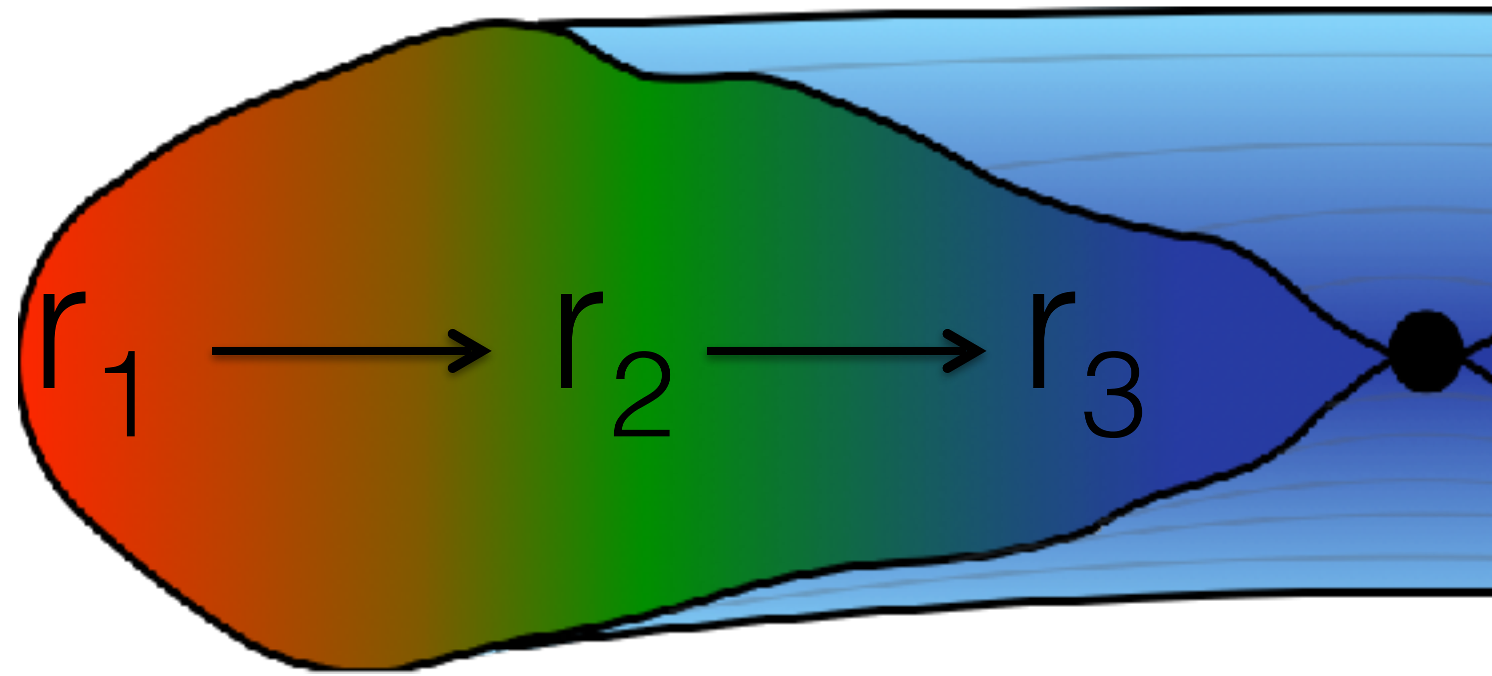
Attempt to reproduce Cygnus X-1 lags with X-ray reverberation



Kotov+ 2001

Propagating fluctuations model

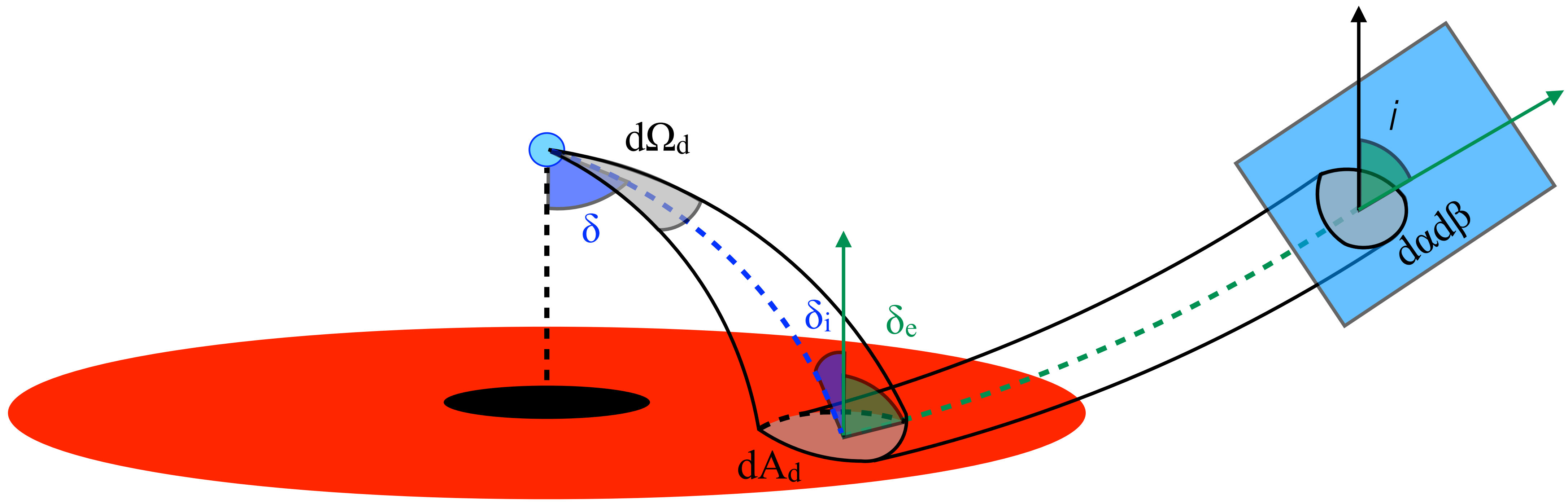




- The variability in the mass accretion rate is limited by the local viscous timescale
- Slow fluctuations originating far from the black hole propagate in to modulate the faster fluctuations

Lynden-Bell & Pringle (1974); Lyubarskii (1997); Arevalo & Uttley (2006)

Reltrans model



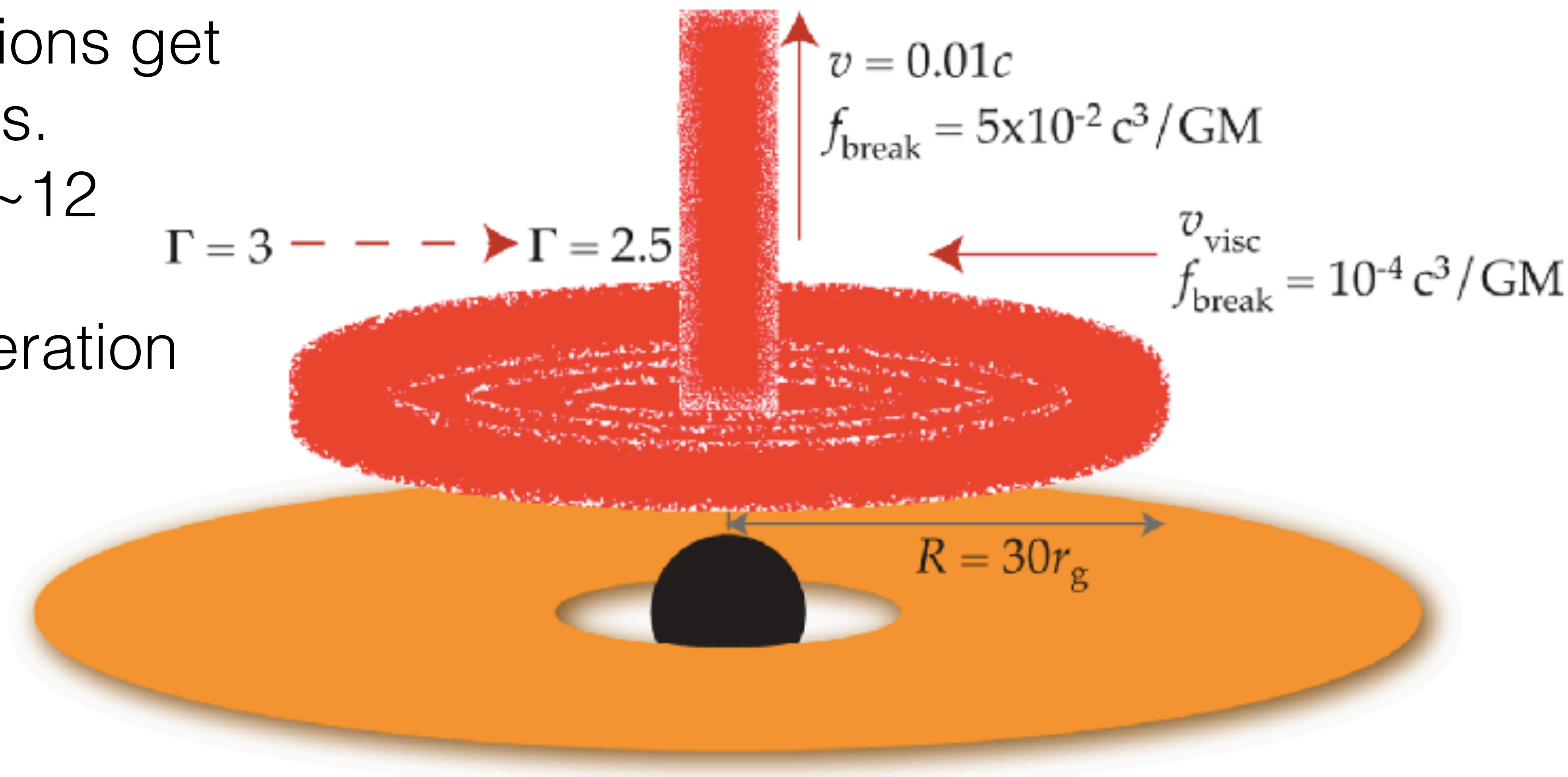
- Fully relativistic ray-tracing model
- Different emission angle of the reprocessed radiation
- Different high energy cut off seen by the disc
- Complex cross-spectrum fitting
- Accounting properly for the response matrix

Ingram, Mastroserio+ 2019

Extended Corona

It combines mass accretion rate propagating fluctuations and reverberation

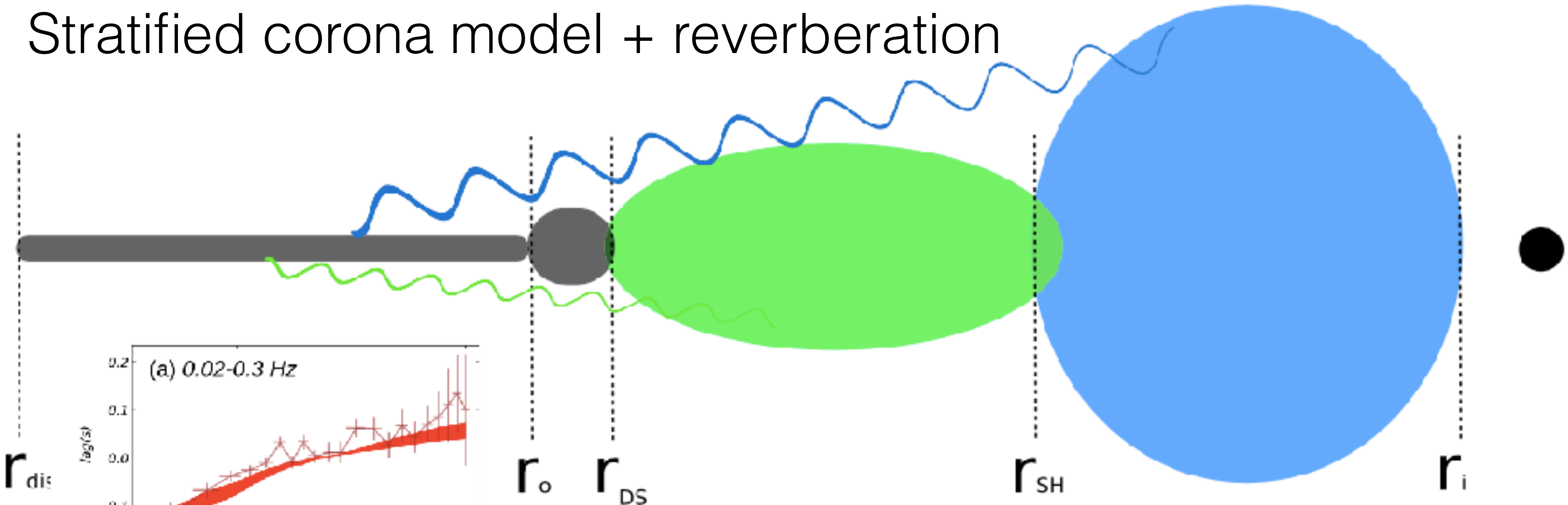
Propagating fluctuations get inwards and upwards. The model involves ~12 transfer functions to calculate the reverberation

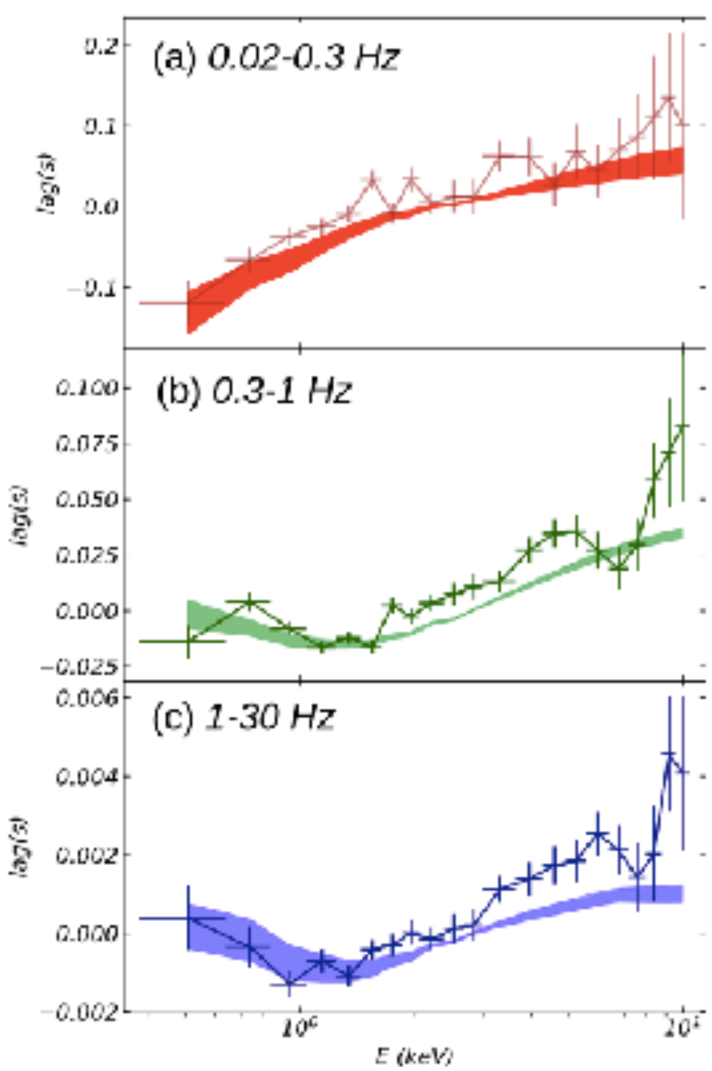


Wilkins+ 2016

Extended Corona

Stratified corona model + reverberation





Spectral timing analysis: time averaged spectrum, the power spectra in different energy bands, and the frequency-dependent lags between these bands

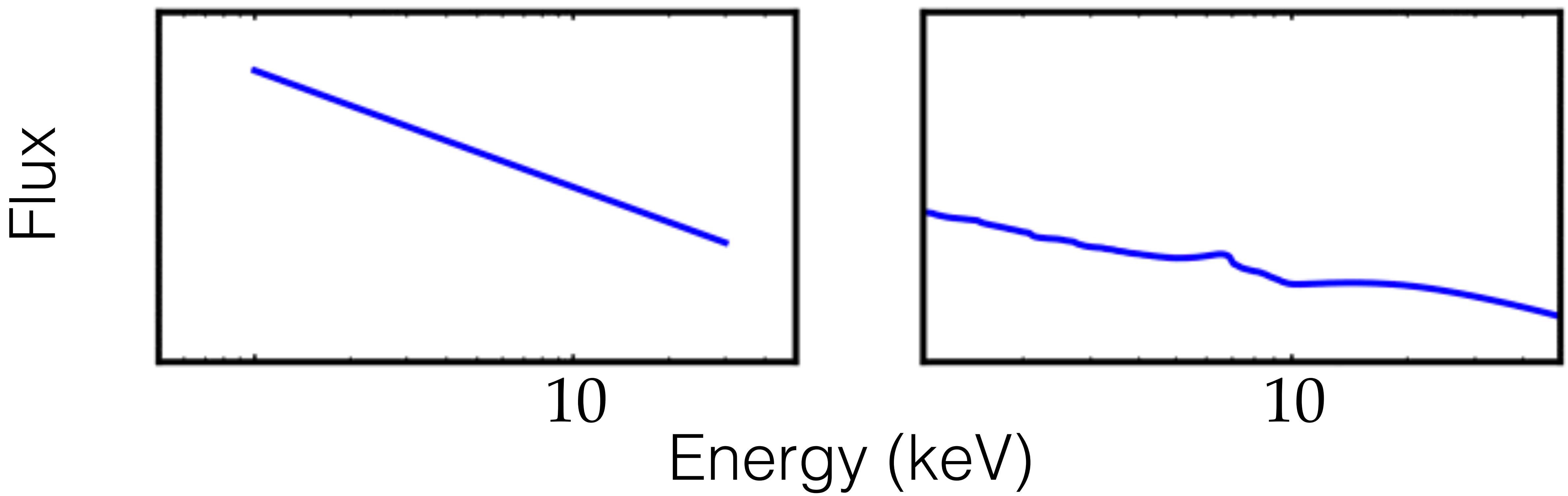
Mahmoud and Done 2019

Spectral Hardness Changes

Direct Emission

Reflection

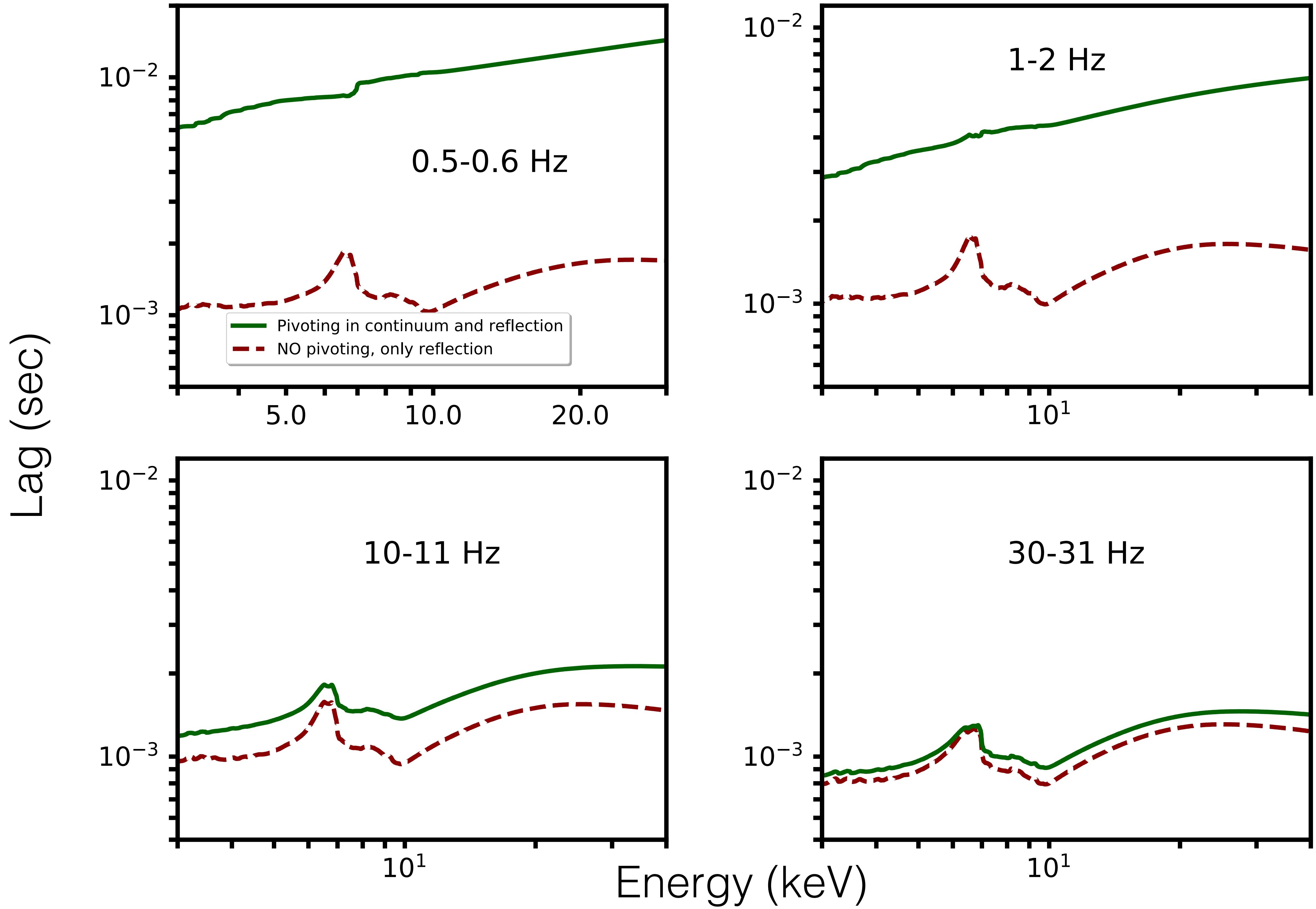
PIVOTING



The pivoting power-law produces the hard lags we observed in the data

The reflection is changing not only in the slope but also in the atomic physics

Pivoting Model



Mastroserio, Ingram+ 2018

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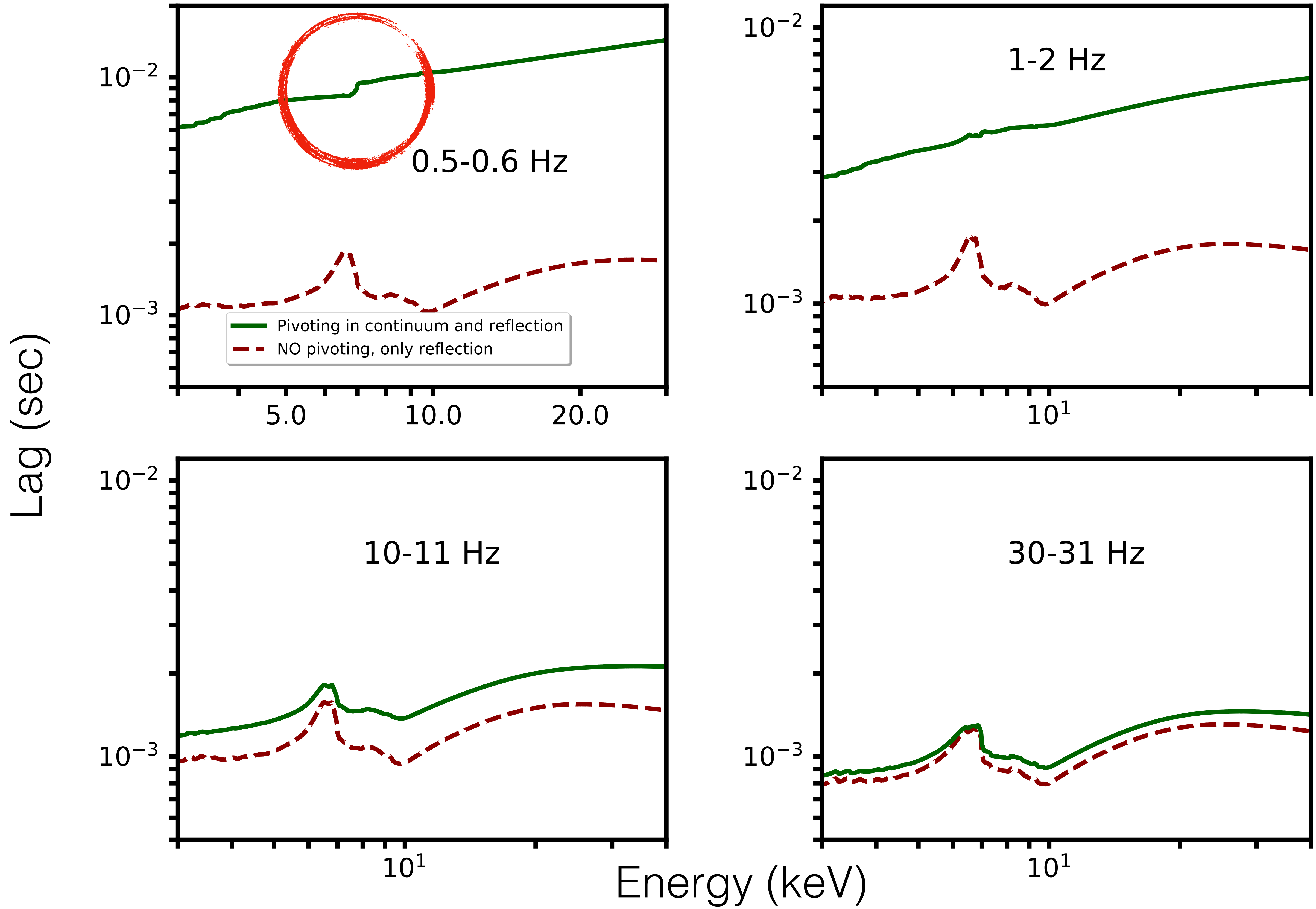
Pivoting Model



Mastroserio, Ingram+ 2018

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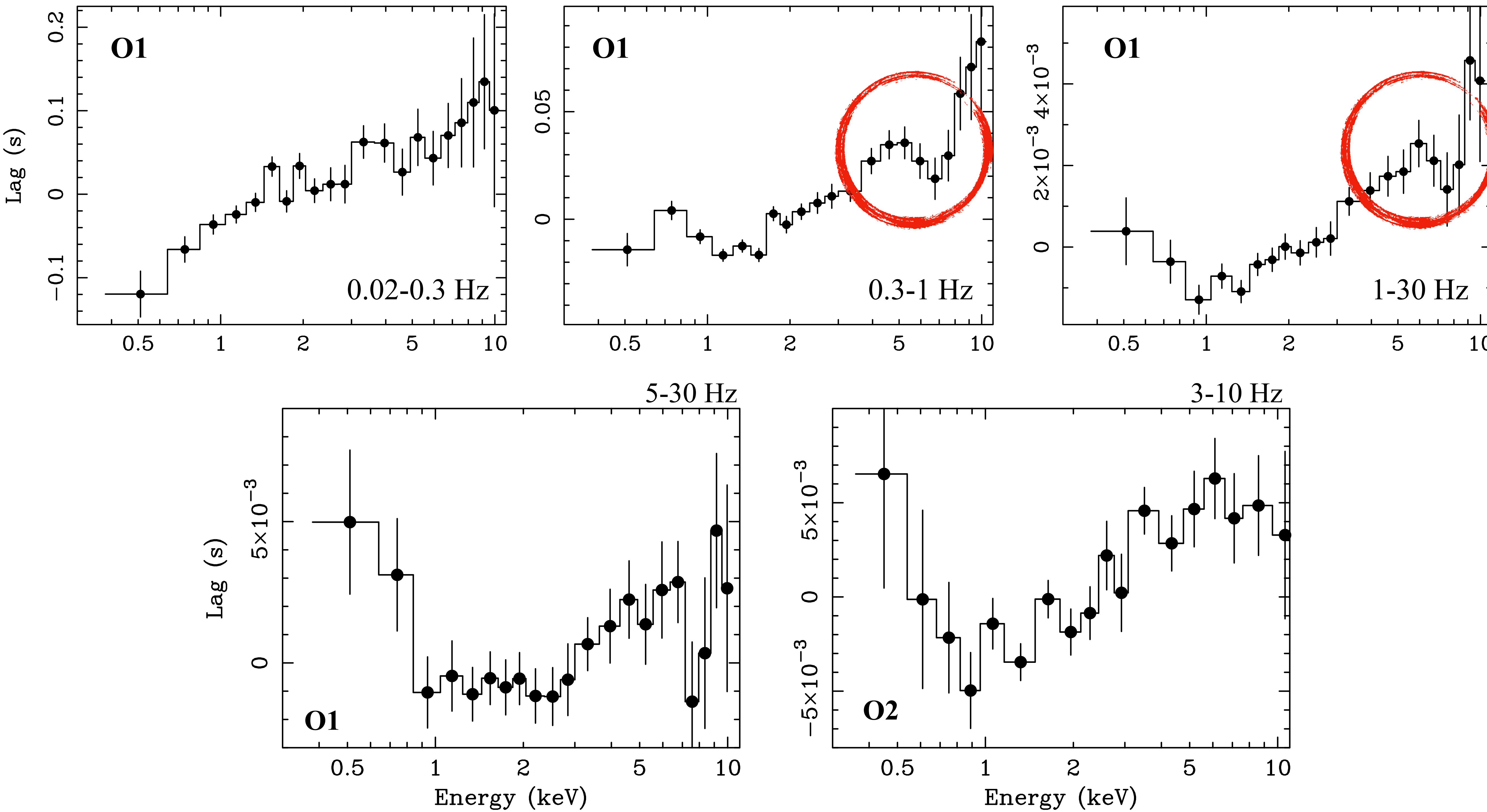
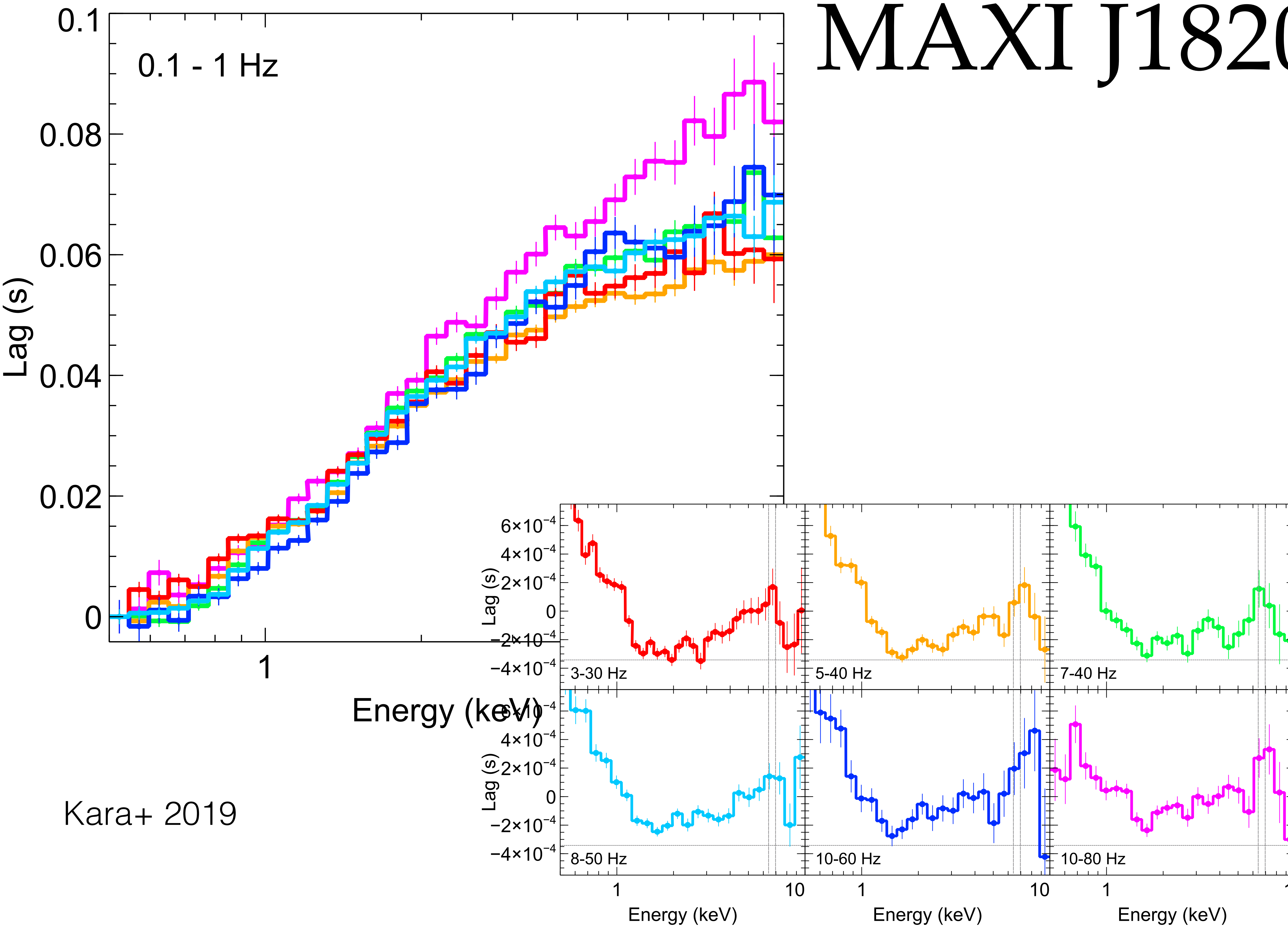
GX 339-4



De Marco+ 2017

MAXI J1820

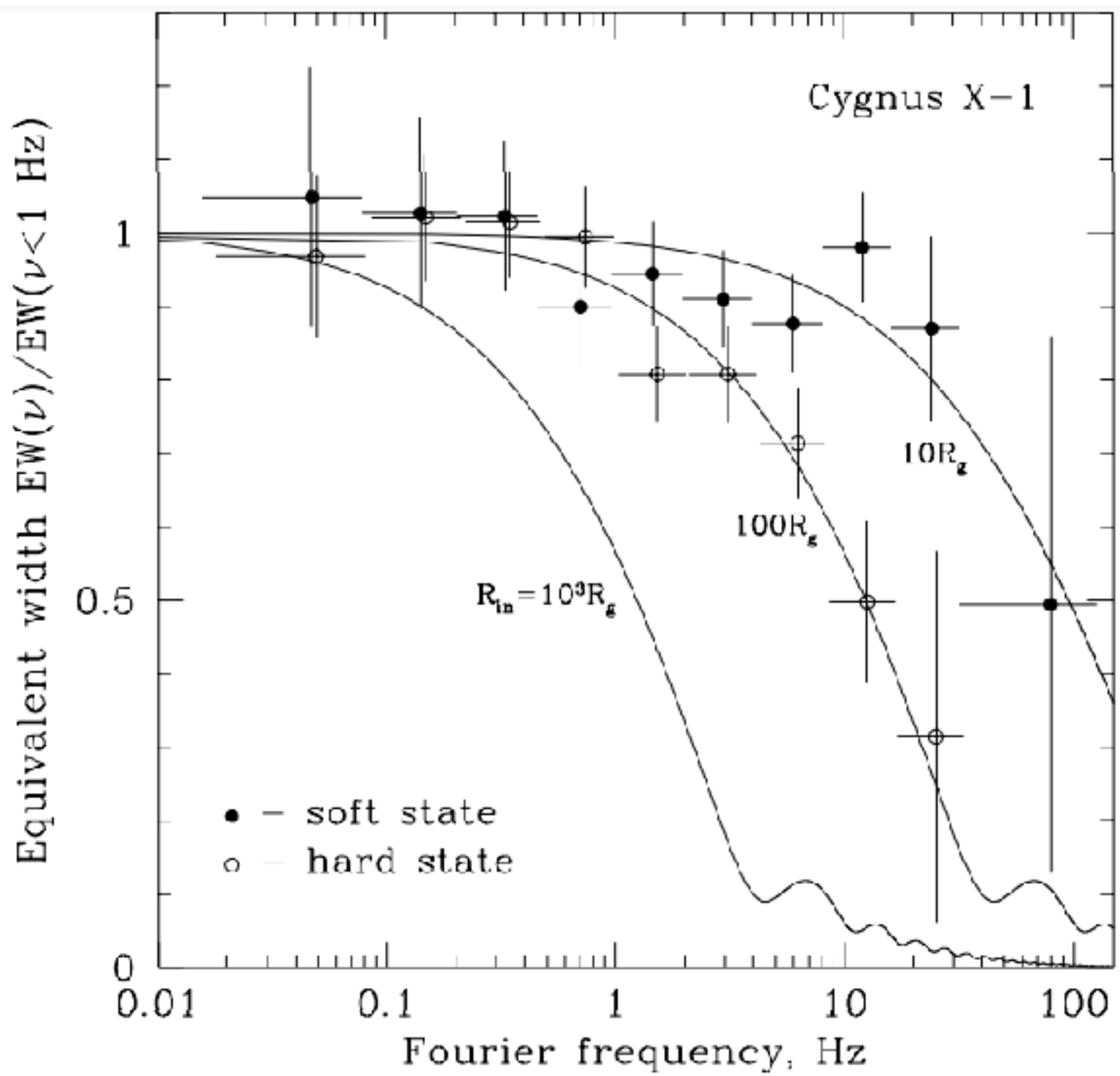


Kara+ 2019

Cygnus X-1

Hard state:
March 1996
(P10238)

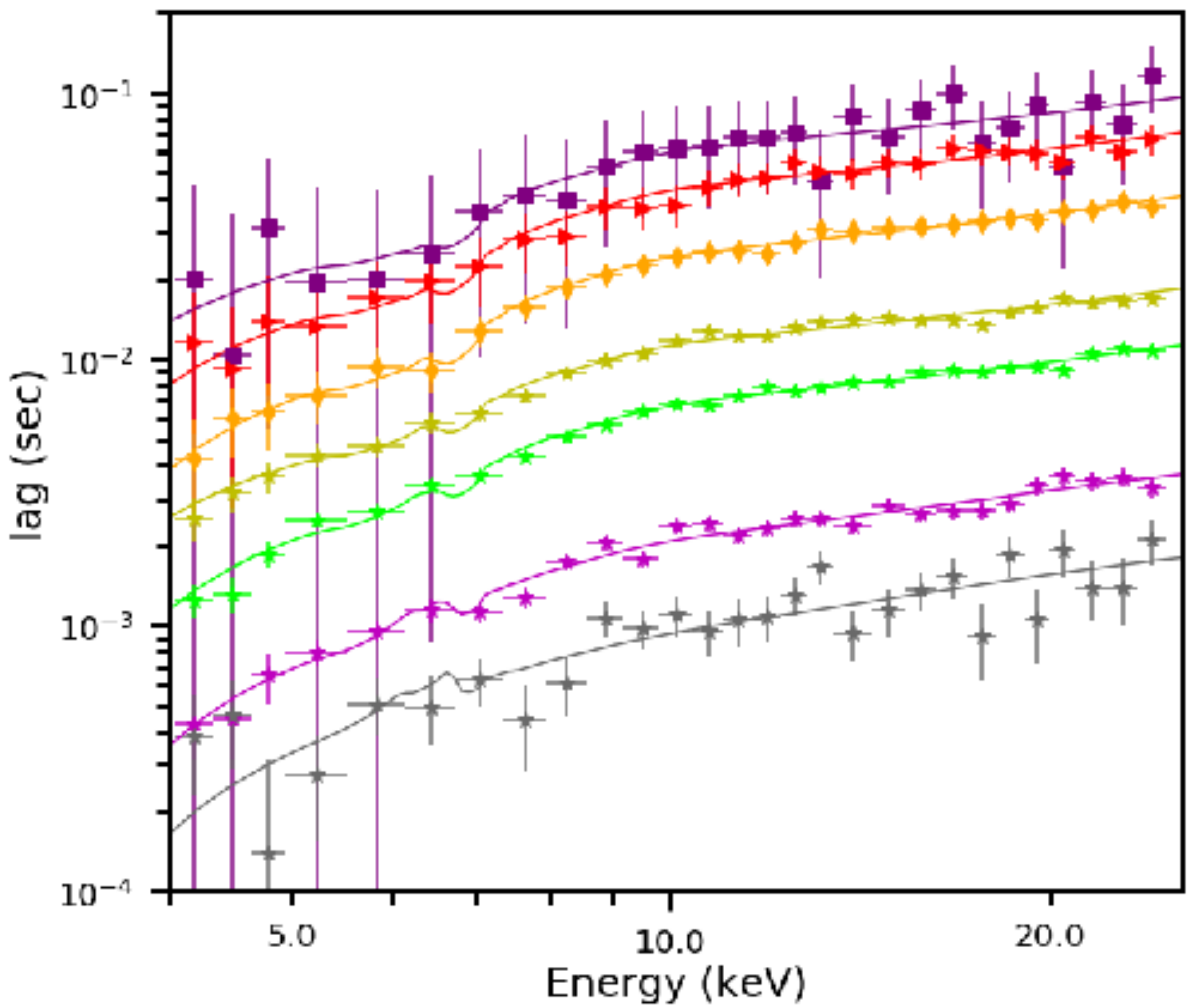
Soft state:
June 1996
(P10512)

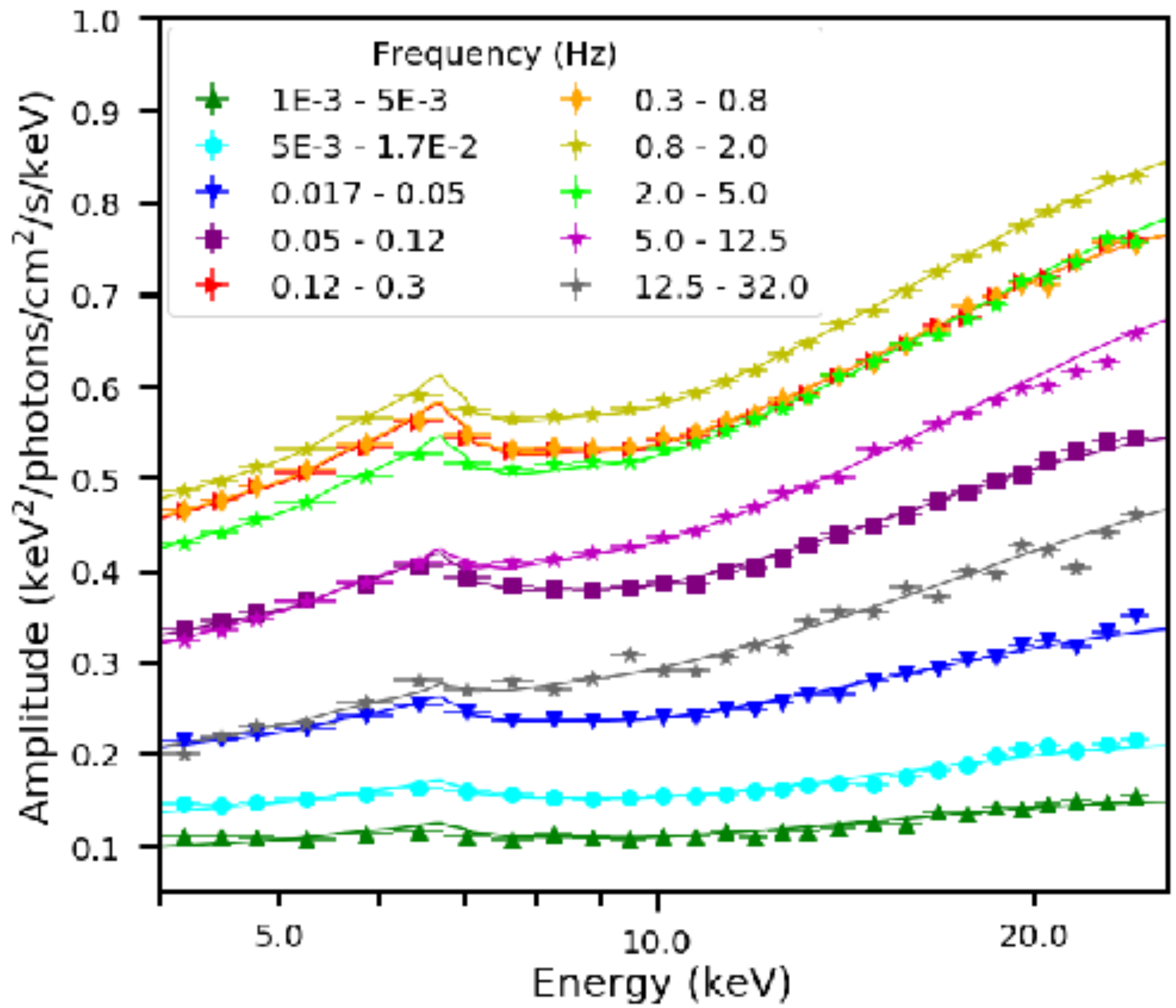


Gilfanov+ 2001

Cygnus X-1

RXTE data set from March 1996 (P10238)
Source in the hard state



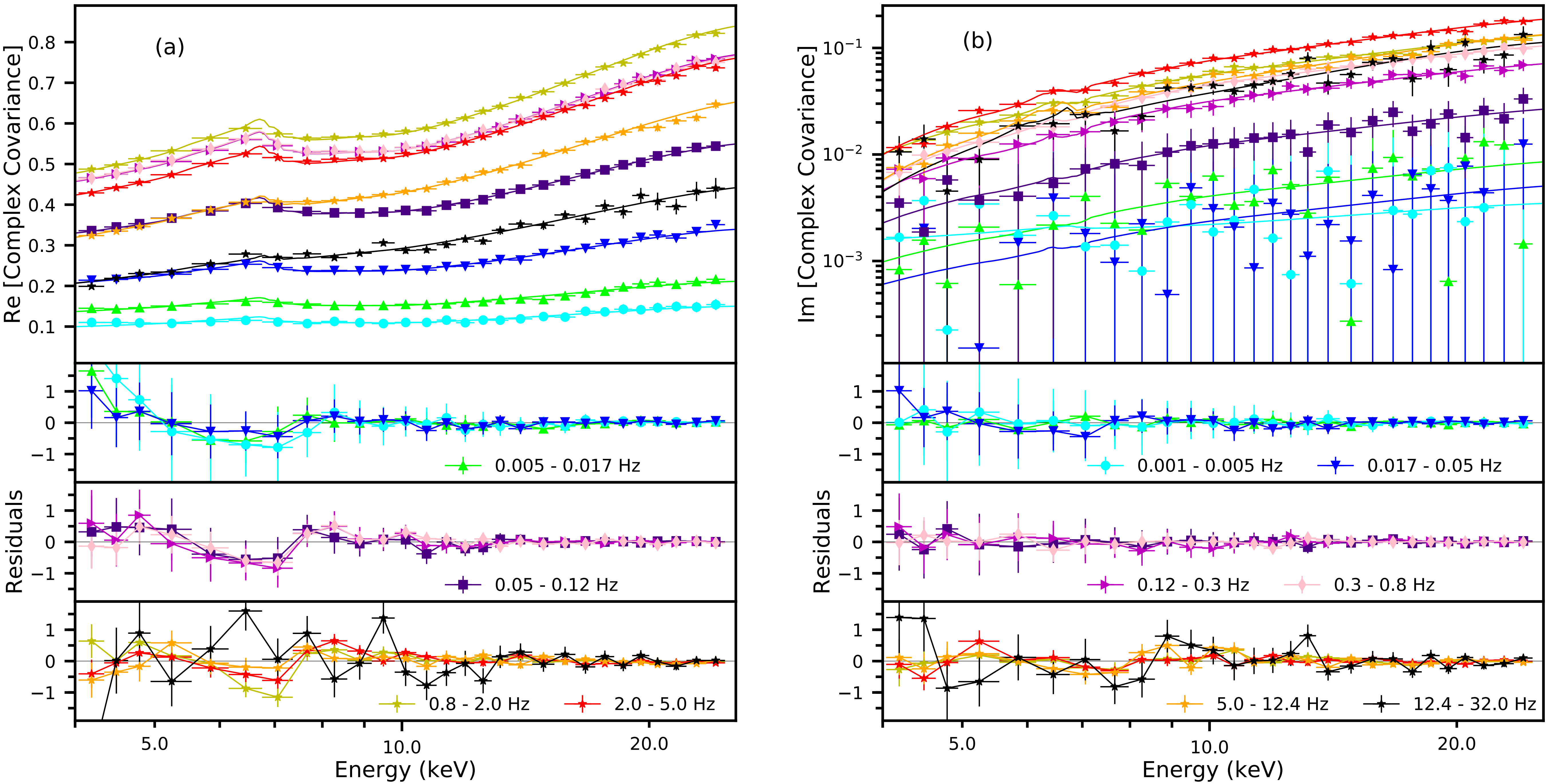


The model reproduce the argument and the amplitude of the cross-spectrum for the Fourier frequencies probed by RXTE

Cygnus X-1 FIT

Real Part

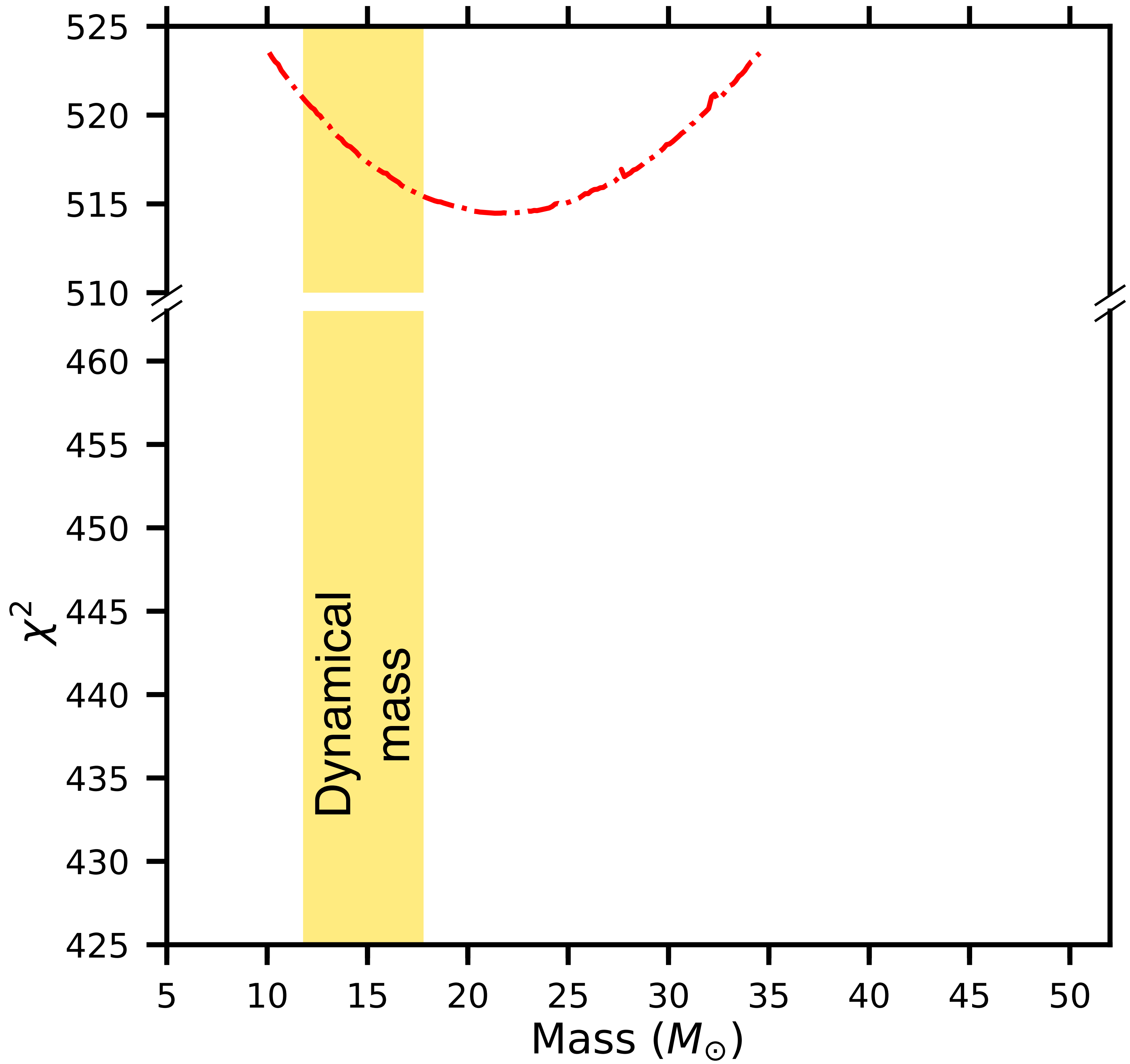
Imaginary Part



Fit to the data taking into account all the information of the cross-spectrum

Cygnus X-1

Chi-squared curve of the black hole mass



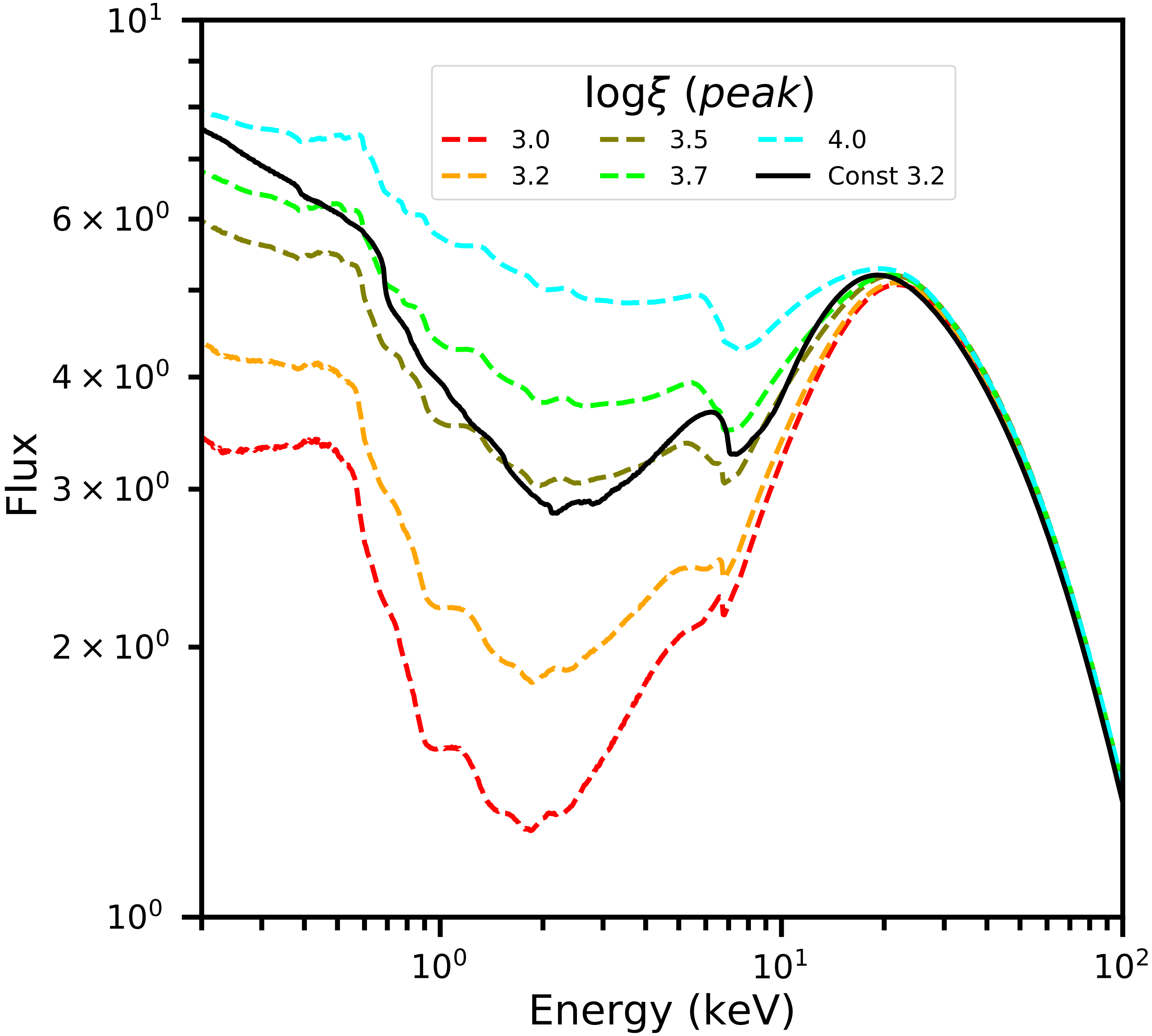
Data set from 1996 RXTE!

The model is sensitive to the mass and can constrain it

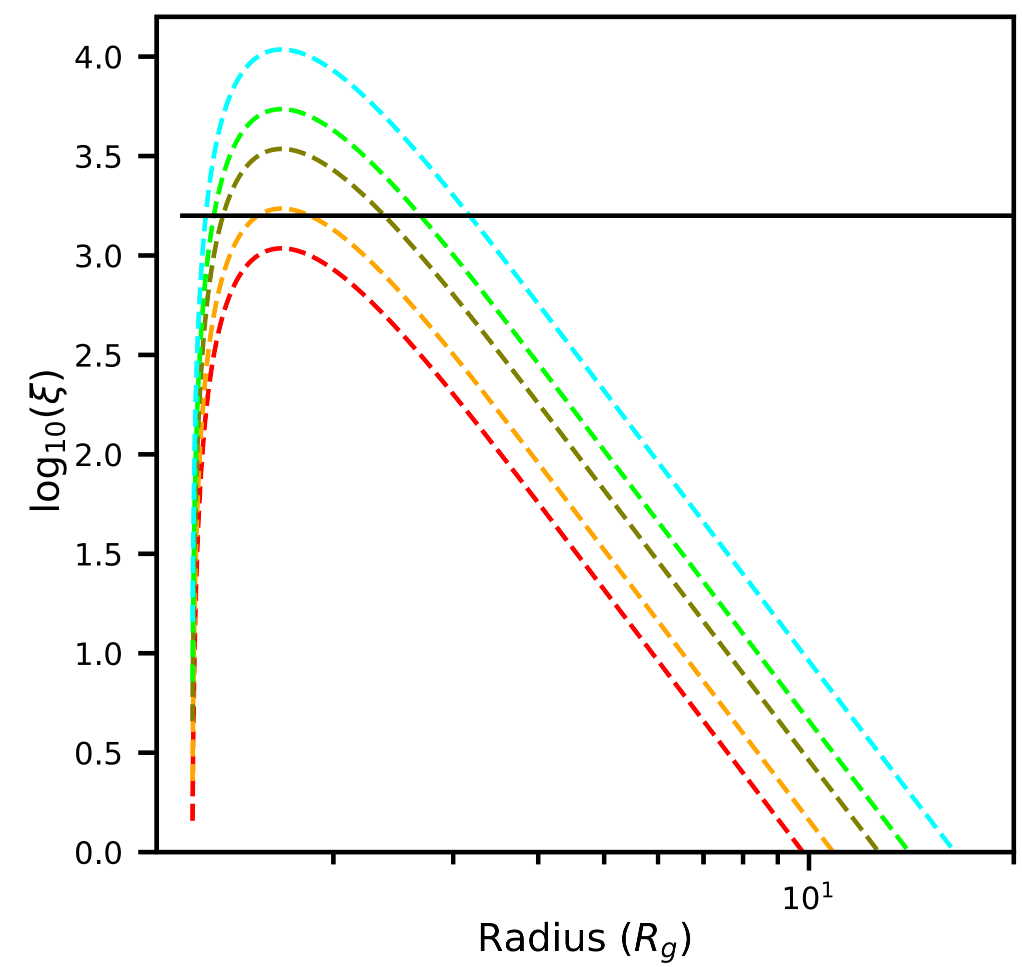
Mastroserio, Ingram+ 2019

Ionisation profile

Introducing a radial ionisation profile changes the shape of the time-averaged spectrum

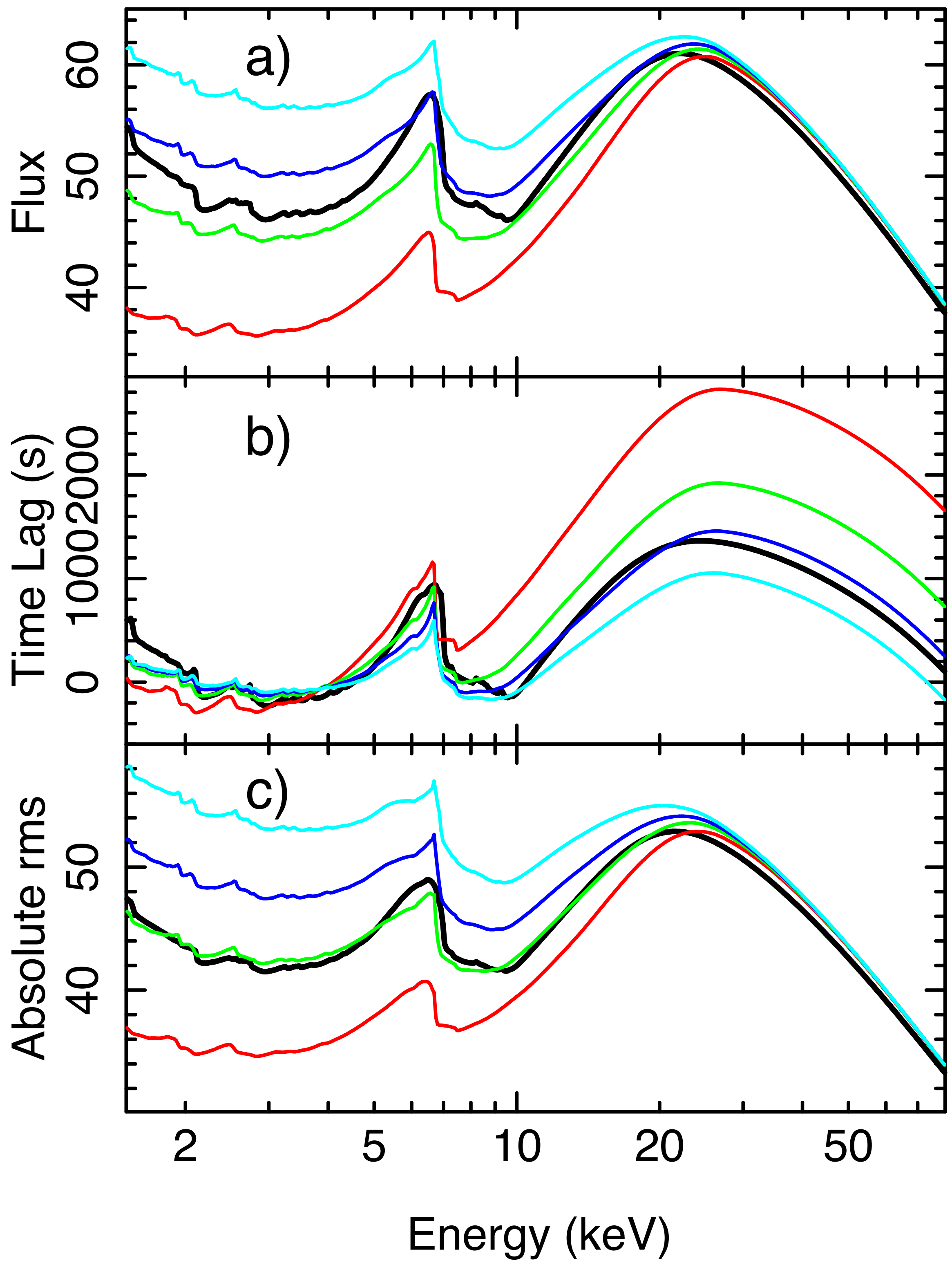


Different radial ionisation profile in the disc



Ingram, Mastroserio+ 2019

Ionisation profile

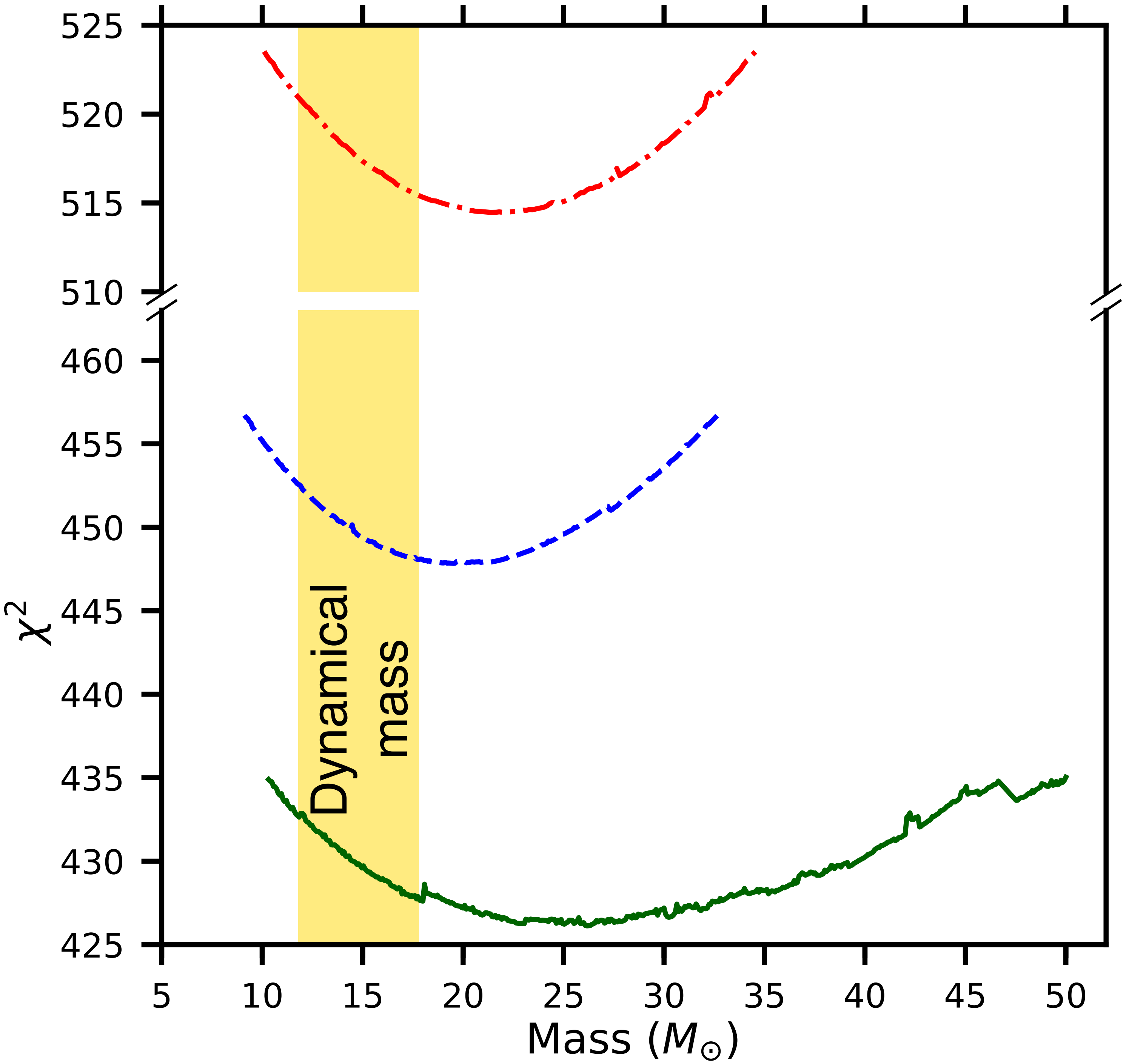


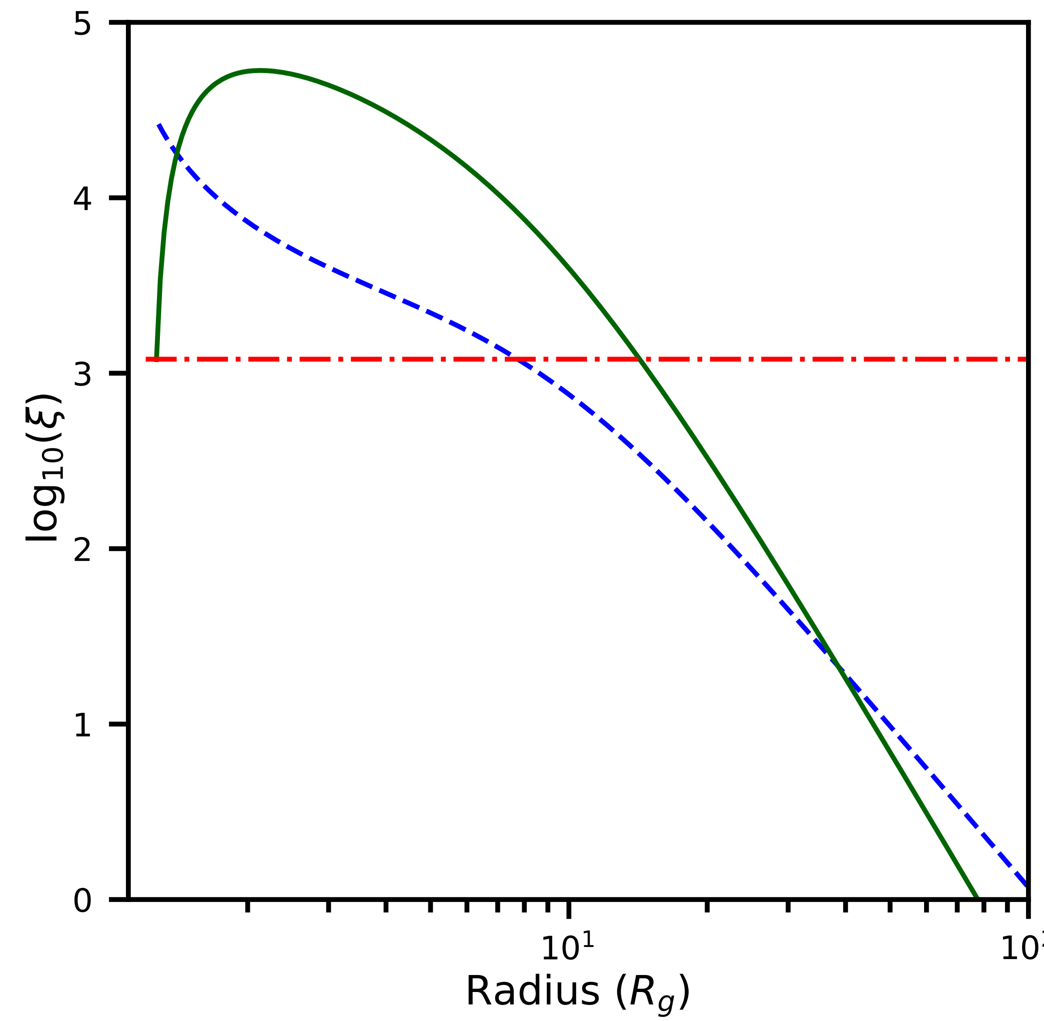
Not constant ionisation changes not only the shape of the time average spectrum but also of both the time lag and the amplitude spectrum

Ingram, Mastroserio+ 2019

Cygnus X-1

Not-constant radial ionisation profiles in the disc improves the fit

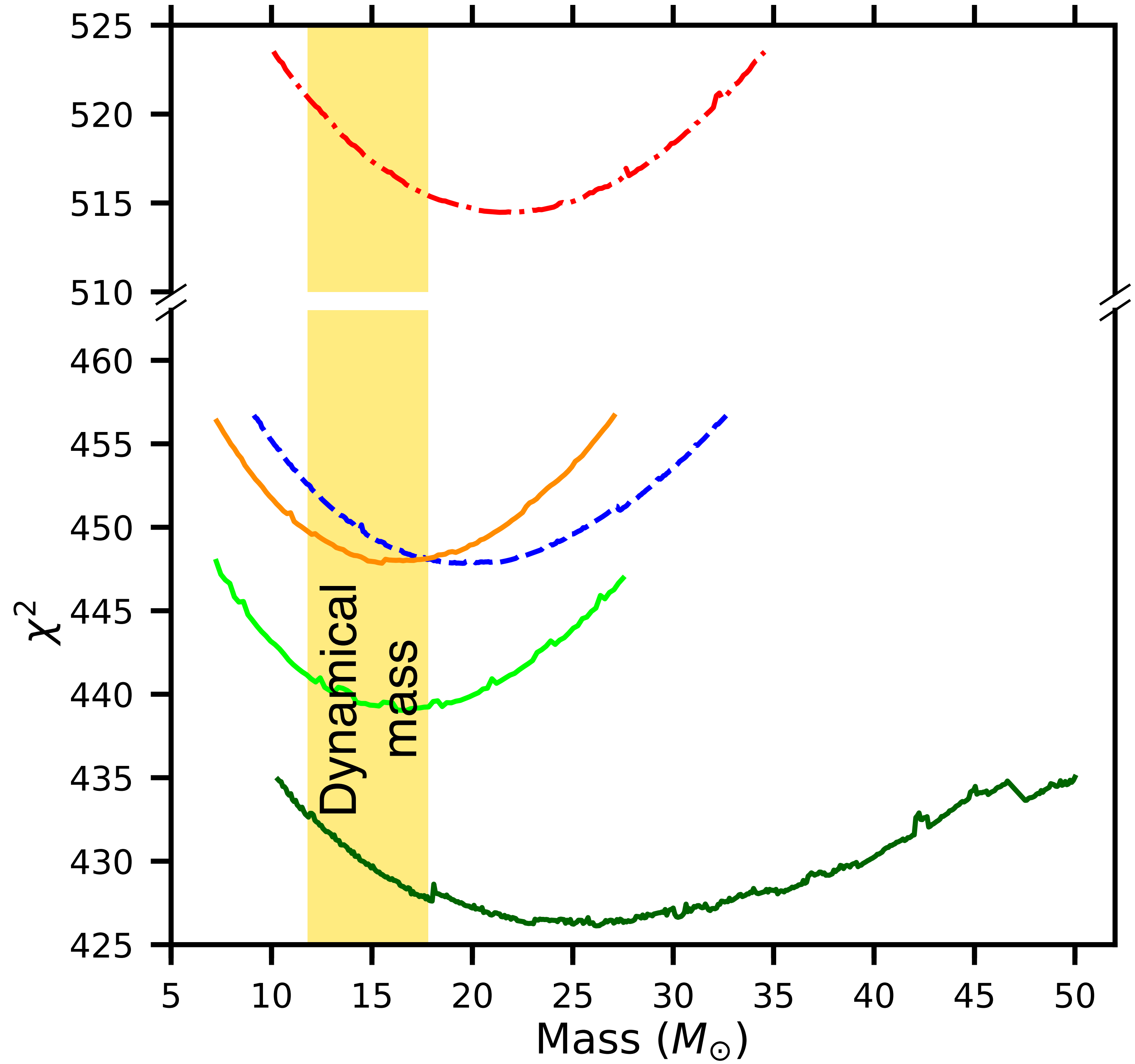


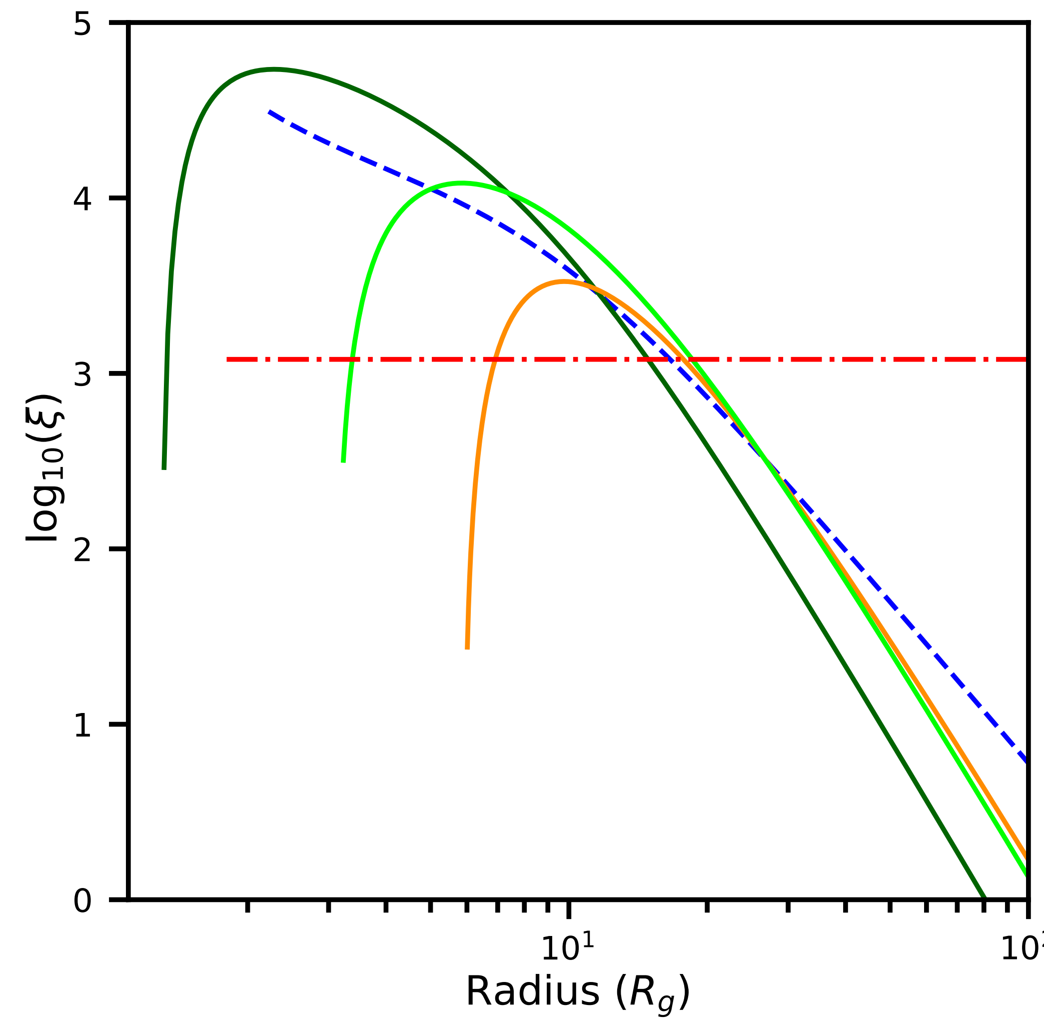


$$\xi = \frac{4\pi F_x}{n_e}$$

Cygnus X-1

We put an upper limit on the peak of the ionisation derived from the lower lower limit on the electron density of the disc





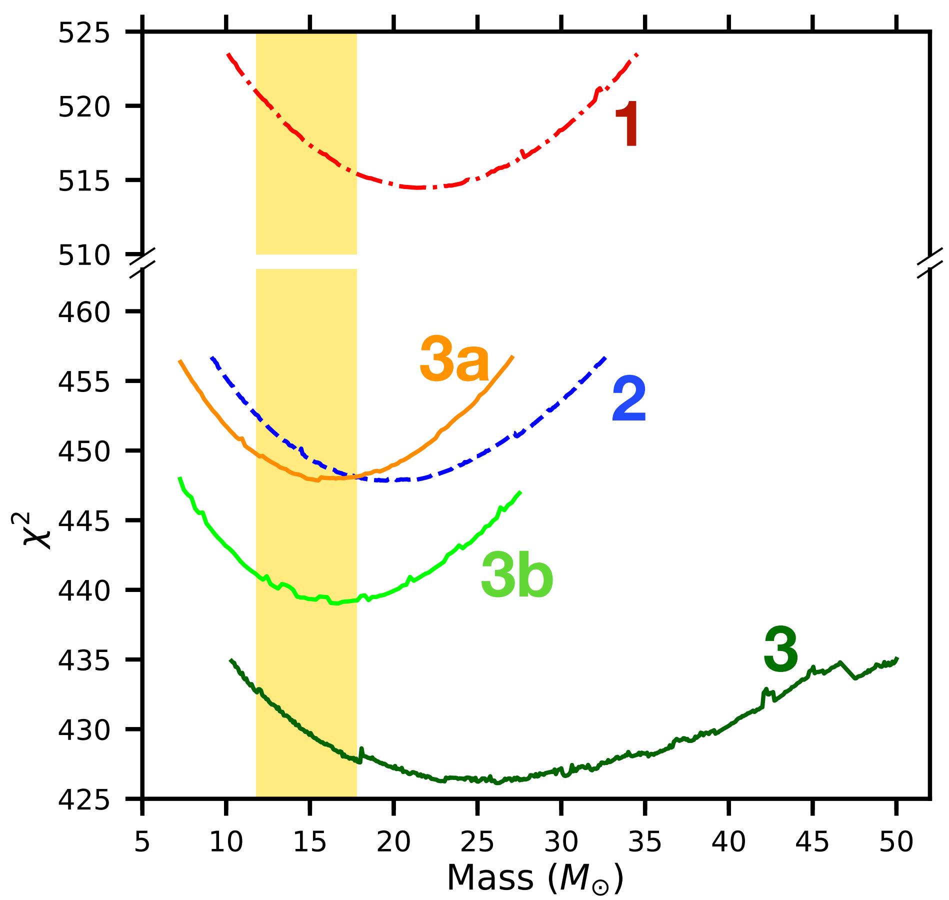
$$\xi = \frac{4\pi F_x}{n_e}$$

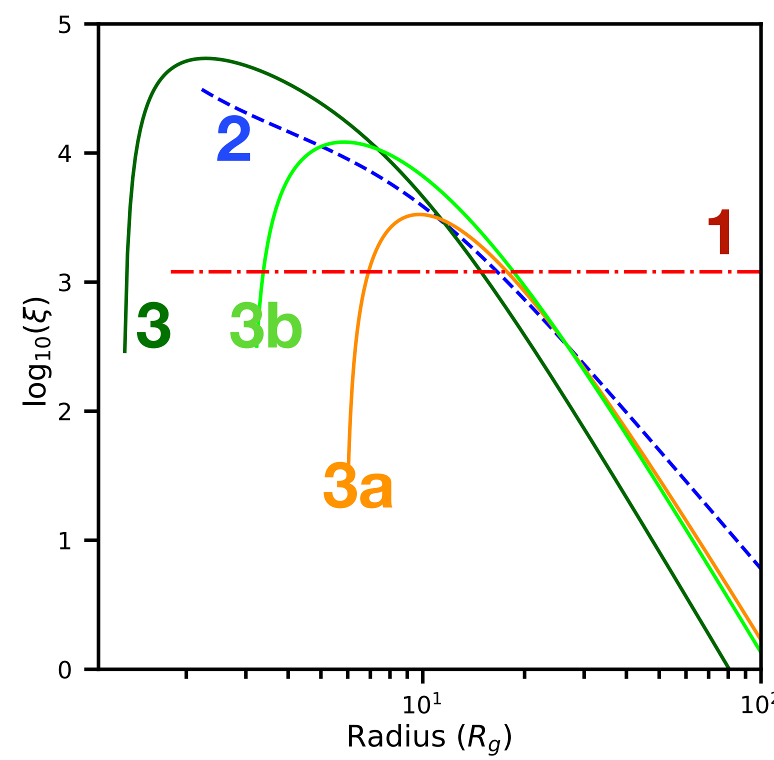
Mastroserio, Ingram+ 2019

Cygnus X-1

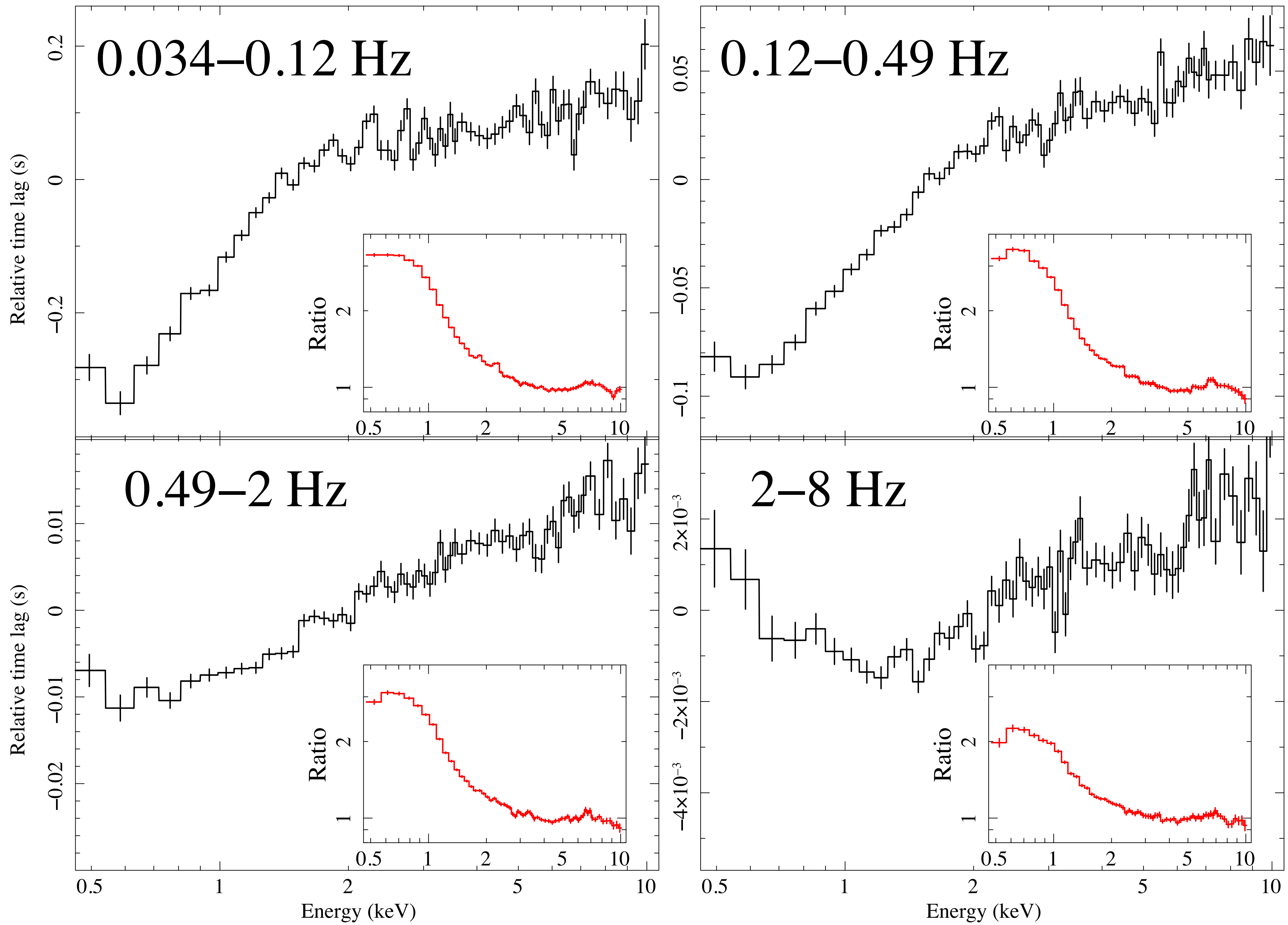
Other results from the fit

	$N_h\ \left(10^{22}\mathrm{cm}^{-2}\right)$	h (R_g)	Incl (deg)	$r_{in}\,(R_g)$	Γ	$\log\xi^{(a)}$	A_{Fe}	$E_{cut,o}$ (keV)	Boost	Mass	red χ^2
1)	$0.13^{+0.08}_{-?^{(b)}}$	$6.2^{+0.6}_{-0.8}$	$32.4^{+0.6}_{-1.0}$	$1.8^{+0.4}_{-(c)}$	$1.60^{+0.01}_{-0.01}$	$3.08^{-0.02}_{-0.01}$	$3.7^{+0.1}_{-0.1}$	218^{+13}_{-9}	$0.28^{+0.01}_{-0.01}$	$21.6^{+6.8}_{-6.6}$	515/563
2)	$0.7^{+0.2}_{-0.1}$	$9.7^{+1.9}_{-1.4}$	$33.8^{+1.4}_{-1.5}$	$2.2^{+0.9}_{-1.0}$	$1.65^{+0.02}_{-0.02}$	$4.5^{+0.6}_{-0.7}$	$2.0^{+0.4}_{-0.2}$	371^{+55}_{-63}	$0.50^{+0.05}_{-0.04}$	$19.7^{+5.3}_{-5.4}$	448/563
3)	$0.6^{+0.1}_{-0.1}$	$9.0^{+1.4}_{-1.7}$	$35.0^{+1.2}_{-1.2}$	$1.3^{+0.7}_{-(c)}$	$1.67^{+0.01}_{-0.01}$	$4.7^{+0.7}_{-0.6}$	$1.7^{+0.2}_{-0.3}$	712^{+82}_{-97}	$1.1^{+0.2}_{-0.1}$	$26.0^{+9.6}_{-8.6}$	426/563
3a)	$0.79^{+0.04}_{-0.10}$	$9.5^{+2.7}_{-3.9}$	$35.1^{+1.4}_{-1.0}$	$5.9^{+0.7}_{-0.7}$	$1.67^{+0.01}_{-0.02}$	$3.5^{(d)}$	$1.8^{+0.2}_{-0.1}$	377^{+36}_{-36}	$0.46^{+0.02}_{-0.03}$	$16.5^{+5.0}_{-5.0}$	447/563
3b)	$0.75^{+0.09}_{-0.24}$	$10.8^{+1.9}_{-1.2}$	$35.0^{+0.8}_{-1.8}$	$3.1^{+0.4}_{-0.4}$	$1.66^{+0.02}_{-0.02}$	$4.0^{(d)}$	$1.7^{+0.5}_{-0.3}$	355^{+54}_{-96}	$0.60^{+0.04}_{-0.03}$	$16.5^{+6.1}_{-5.2}$	439/563





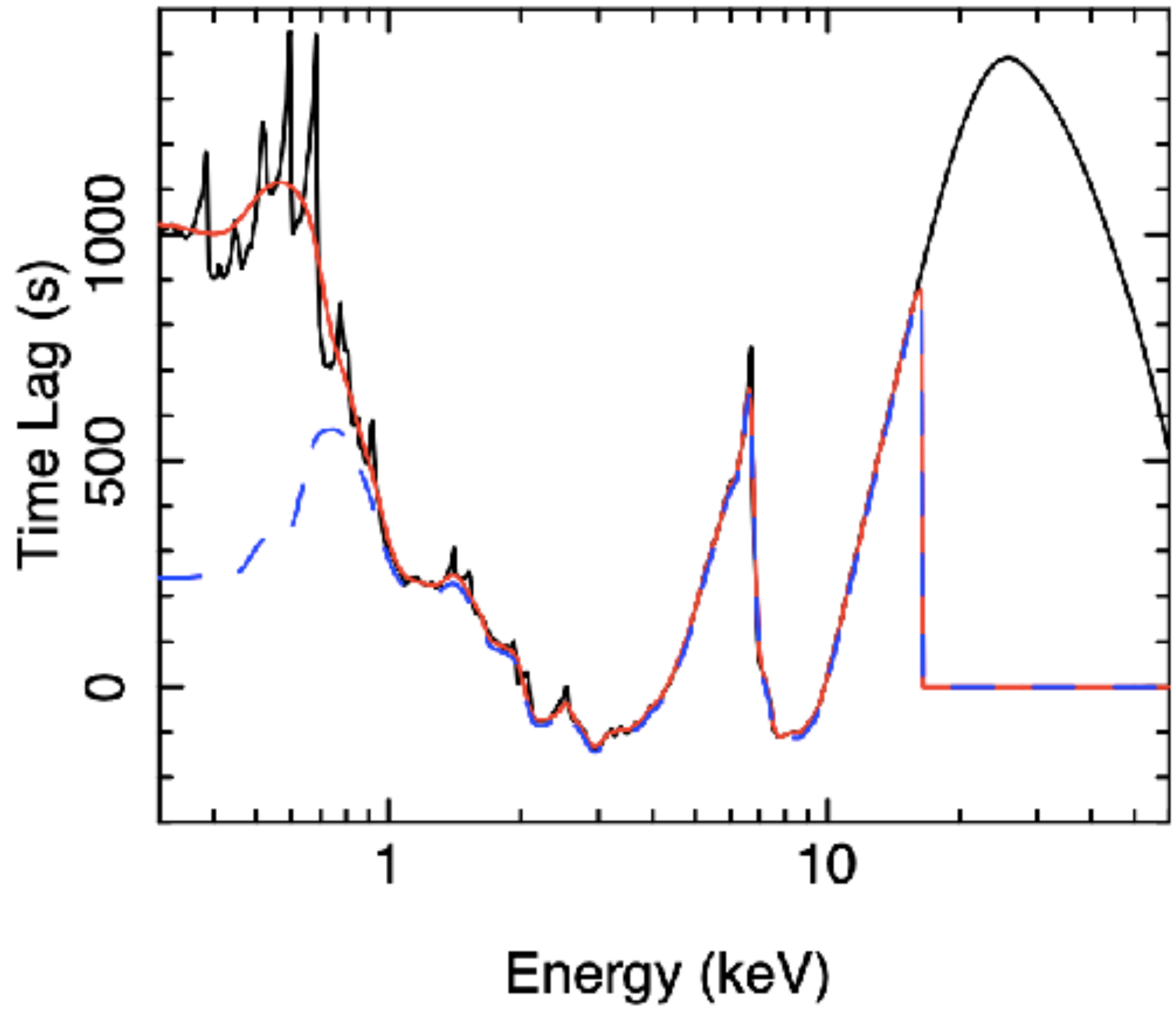
Thermal reverberation



Uttley+ 2014

Telescope response

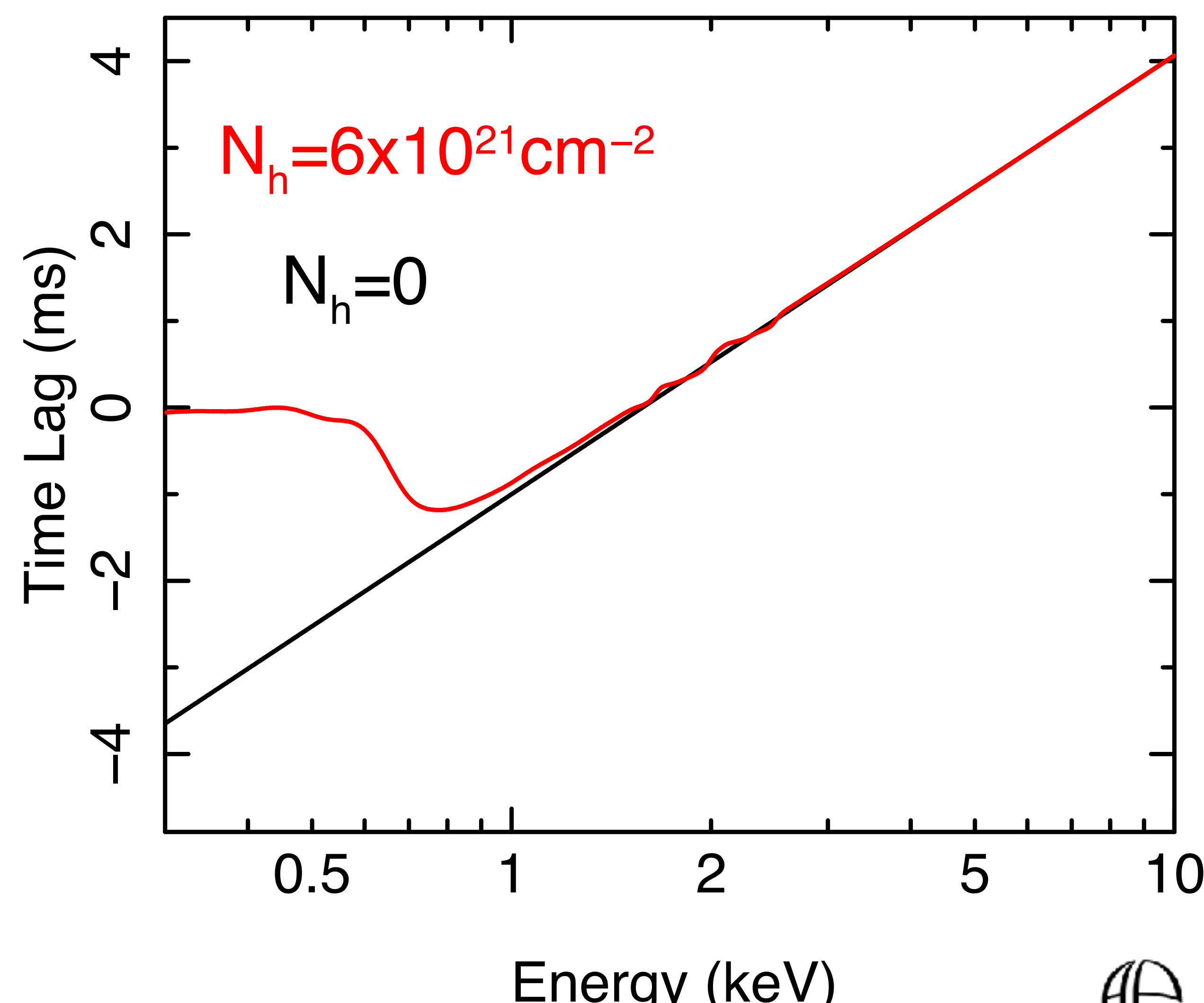
Ignoring the telescope response introduces a bias in the lag spectrum



Reverberation lag

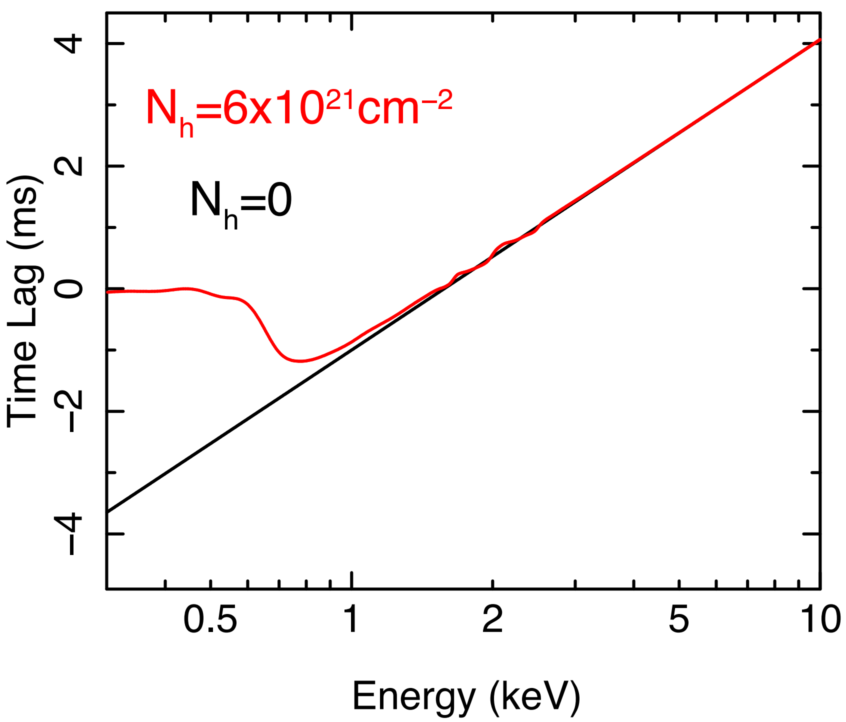
Continuum lag

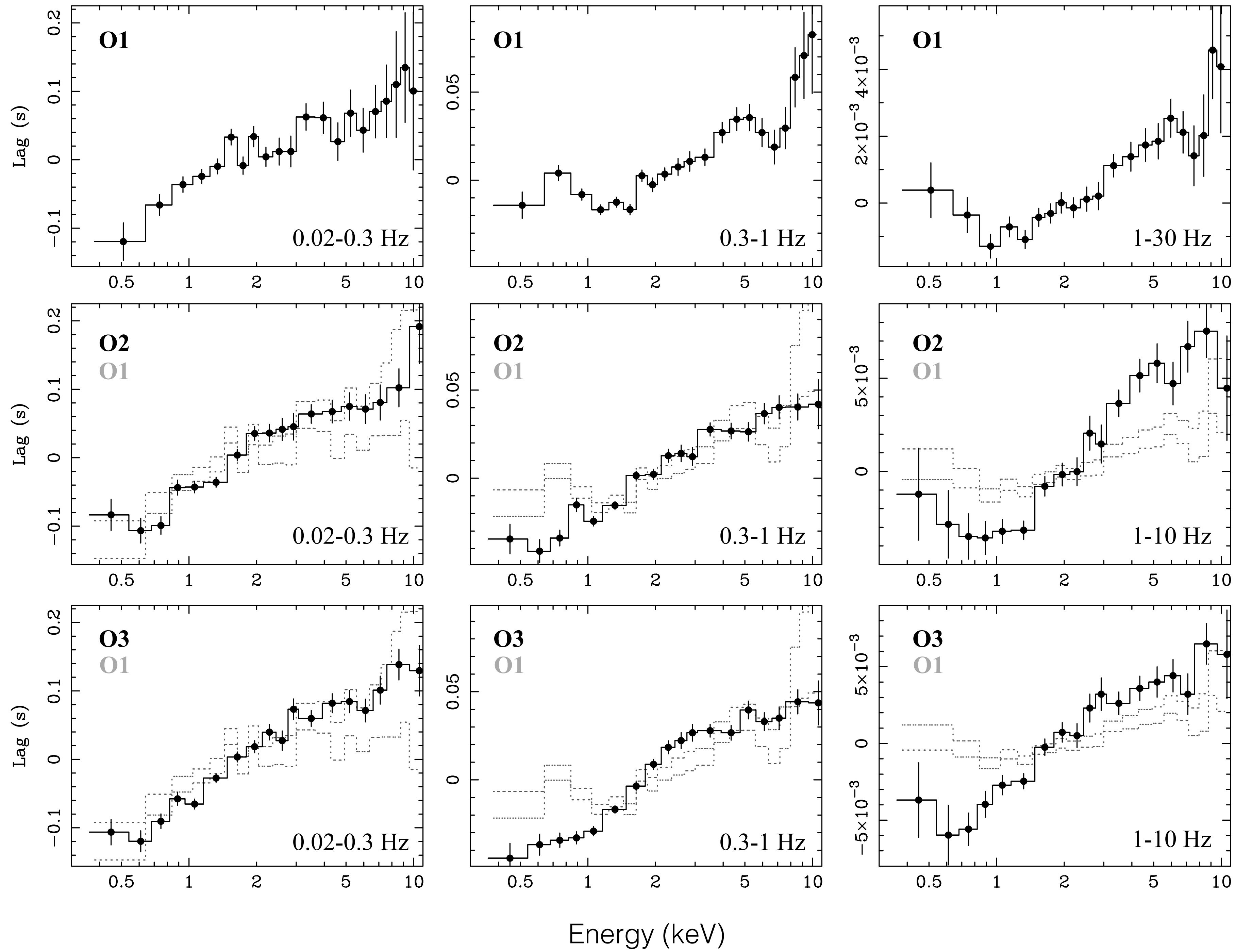
assuming: TBABS∗NTHCOMP
and rms increases linearly with energy



Ingram, Mastroserio et al. 2019

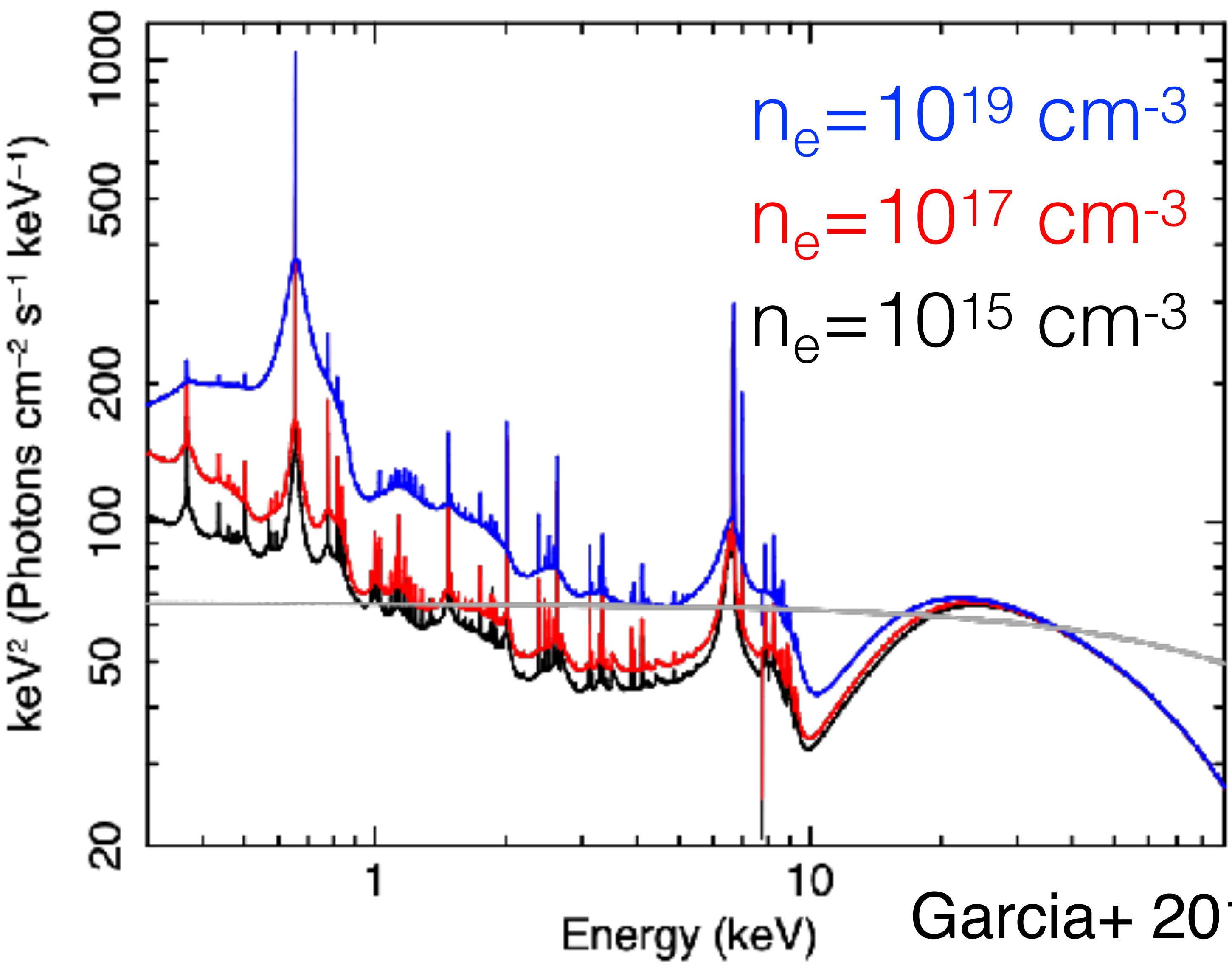
Thermal reverberation





Disc density

Currently using restframe reflation model (xillver) that assumes $n_e=10^{15}$ cm^{-3}

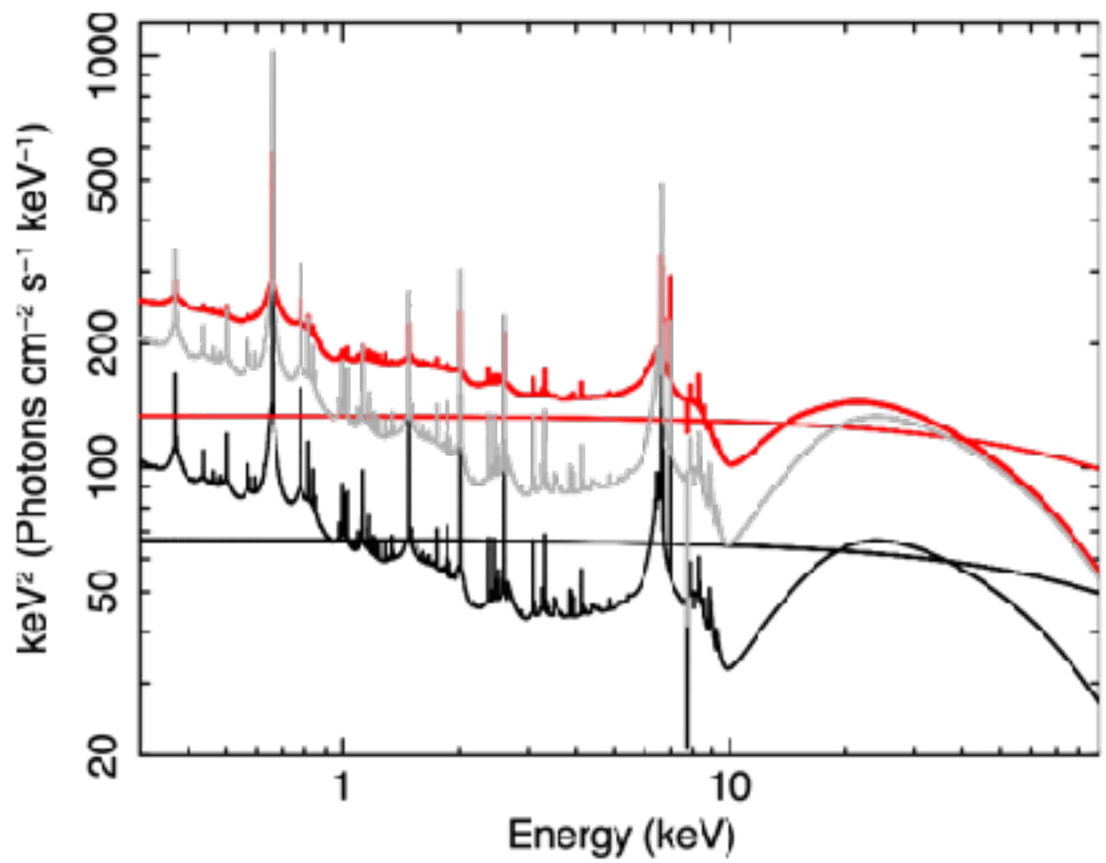


DISC DENSITY

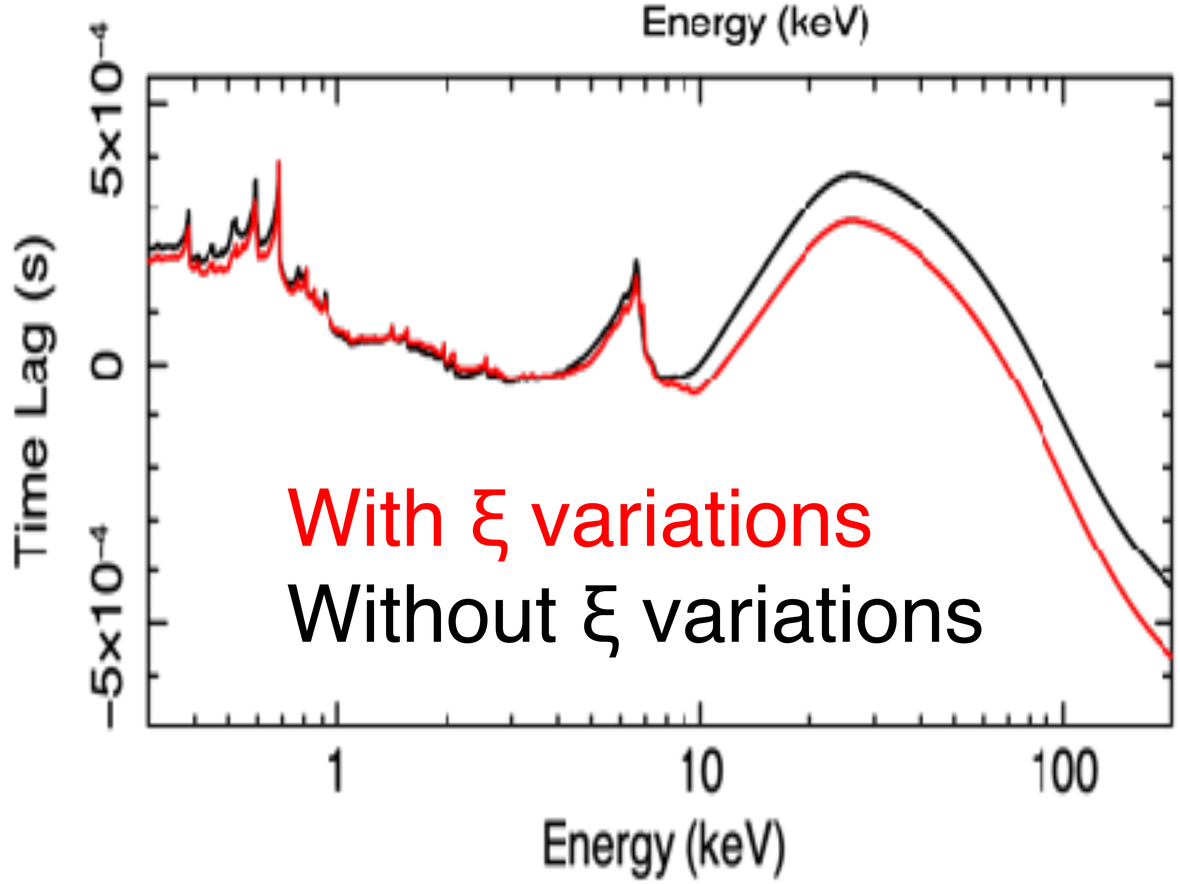
higher density => hotter disc for same ionisation state => different reflection spectrum for same ionisation state

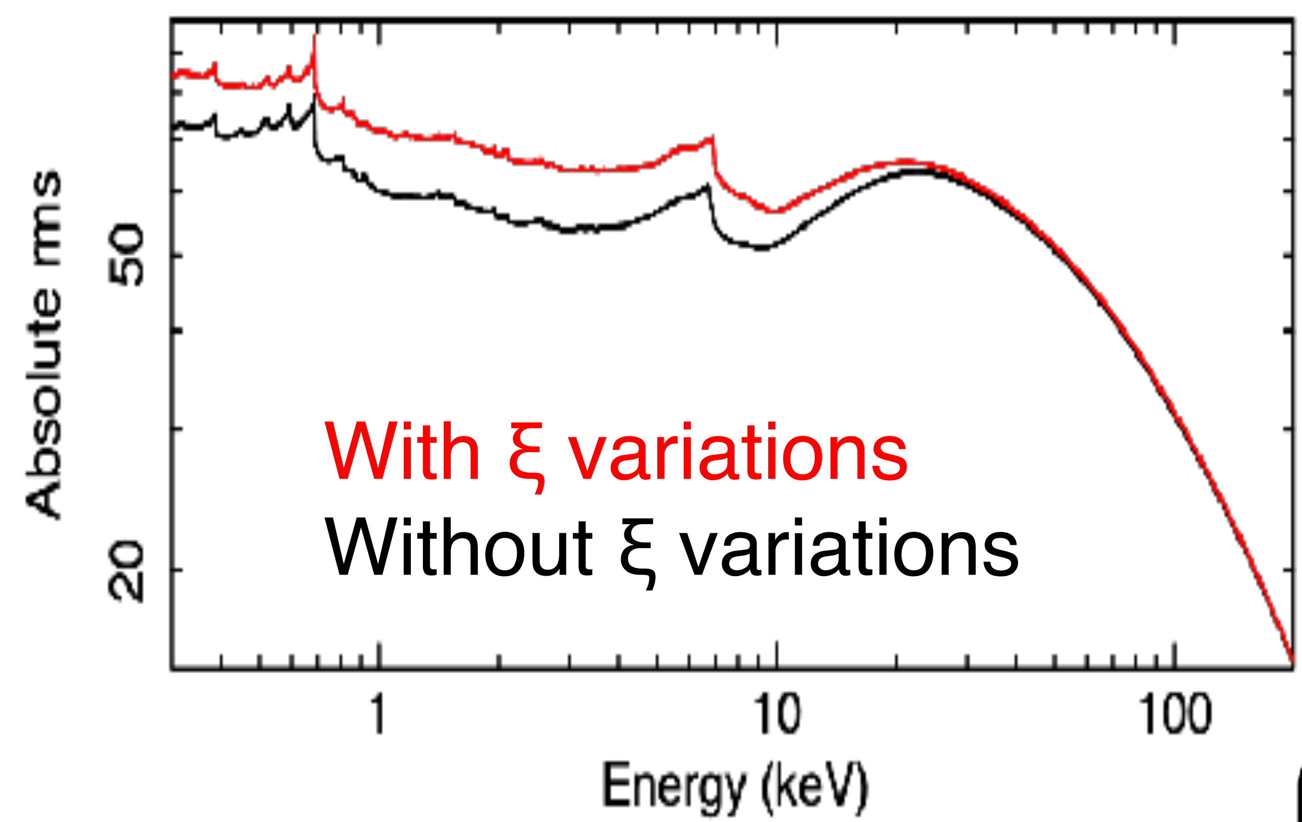
Garcia+ 2016; Tomsick+ 2017; Jiang+ 2019a,b

Thermal reverberation



- Increase continuum flux => increase $\xi = 4\pi Fx / n_e$
- This is never taken into account
- New model will account for this (subtle changes)





Ingram, Mastroserio in prep