Soft X-ray lags in AGN: a (biased) review

Giovanni Miniutti

Centro de Astrobiología - Madrid

CAB Villafranca

STRONGGRAVITY
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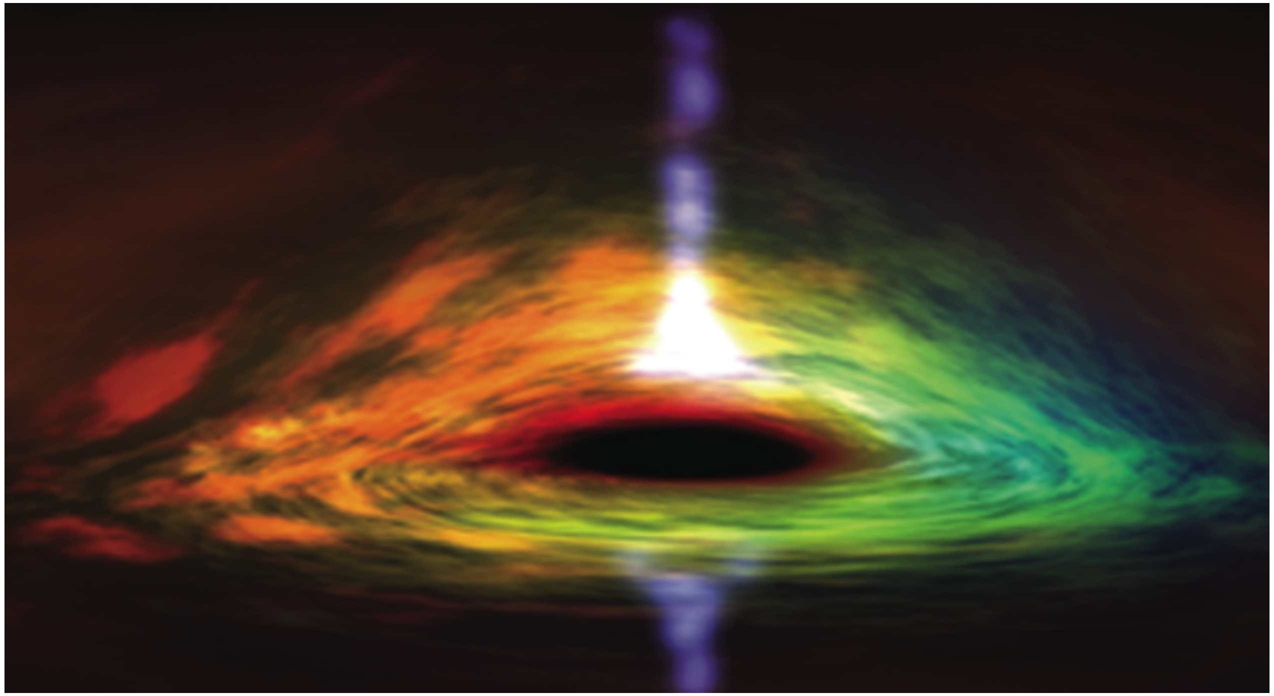
SEVENTH FRAMEWORK PROGRAMME

SXA 2013 – Barcelona

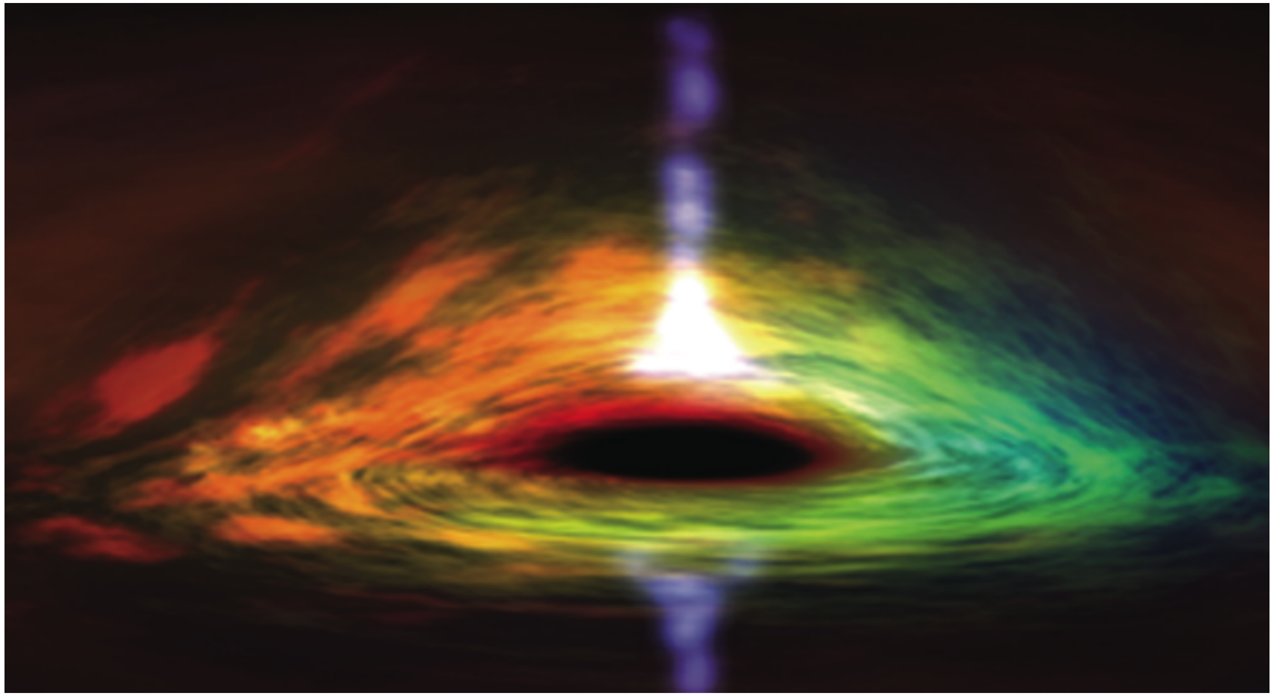
Acrreting BH



Some open questions (among many others):

- general spectral components and their variability mechanisms
- the innermost accretion flow, X-ray emitting region, jets and winds
- the central engine environment (winds/BLR/torus in AGN)
- the evolution across outbursts (binaries) and cosmic time (AGN)
- the impact of AGN on their surroundings

Acrreting BH



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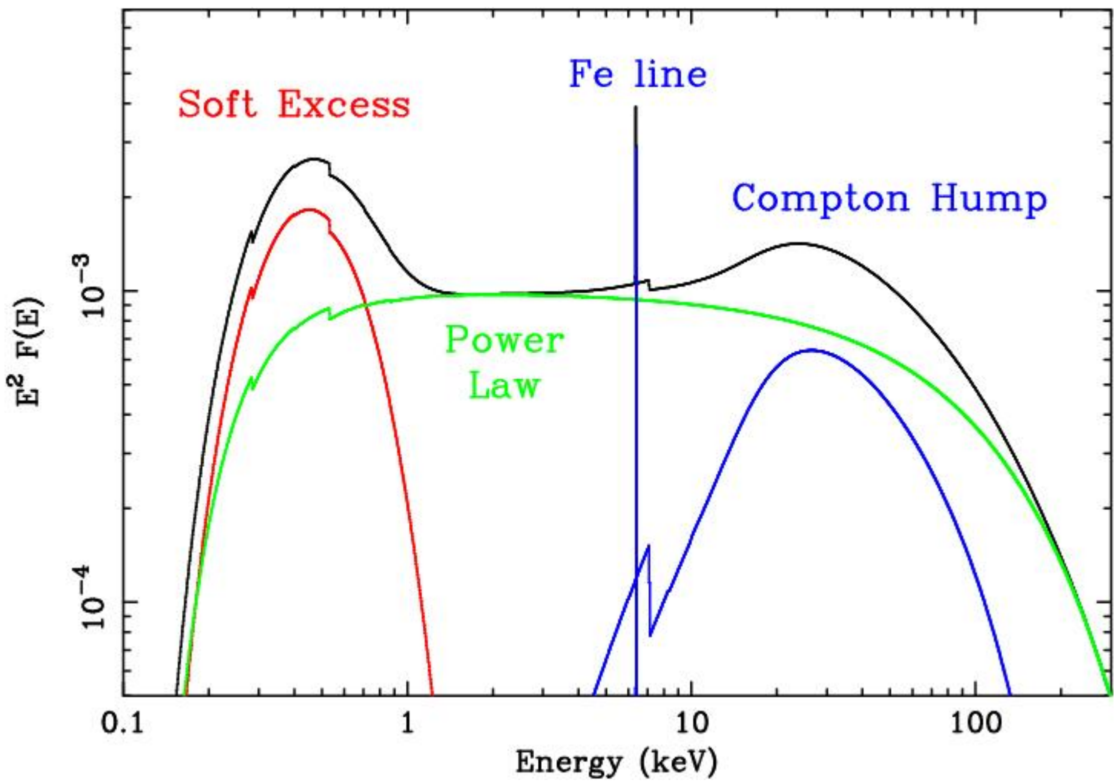
Acrreting BH: the X-ray view



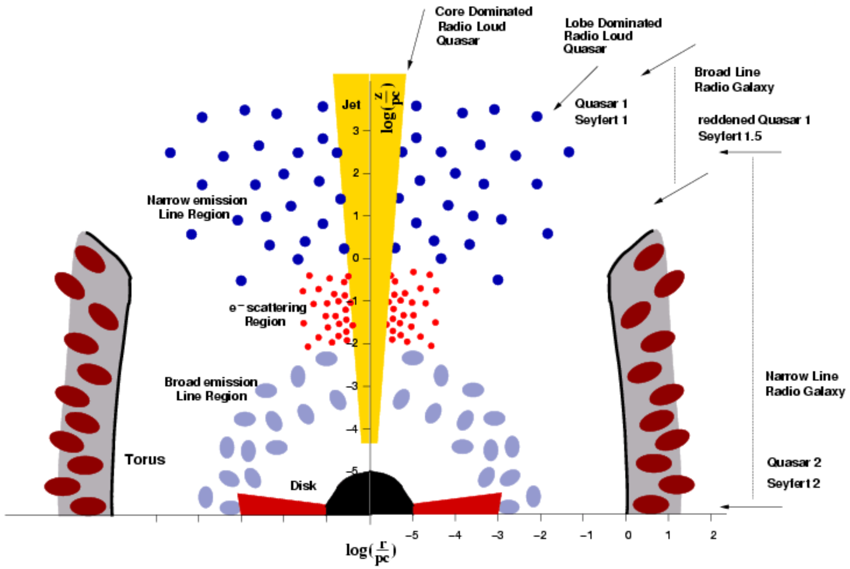
Soft excess

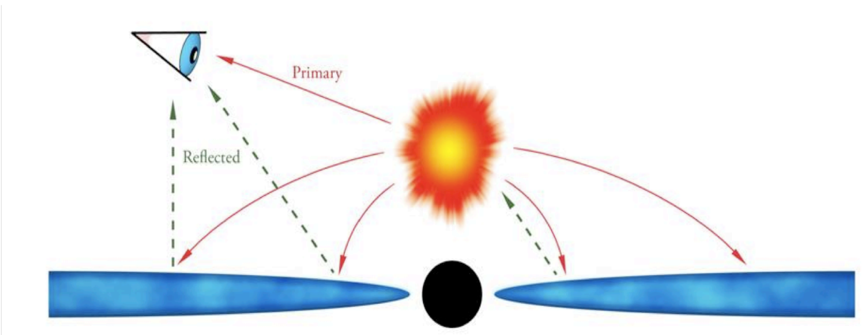
Power law

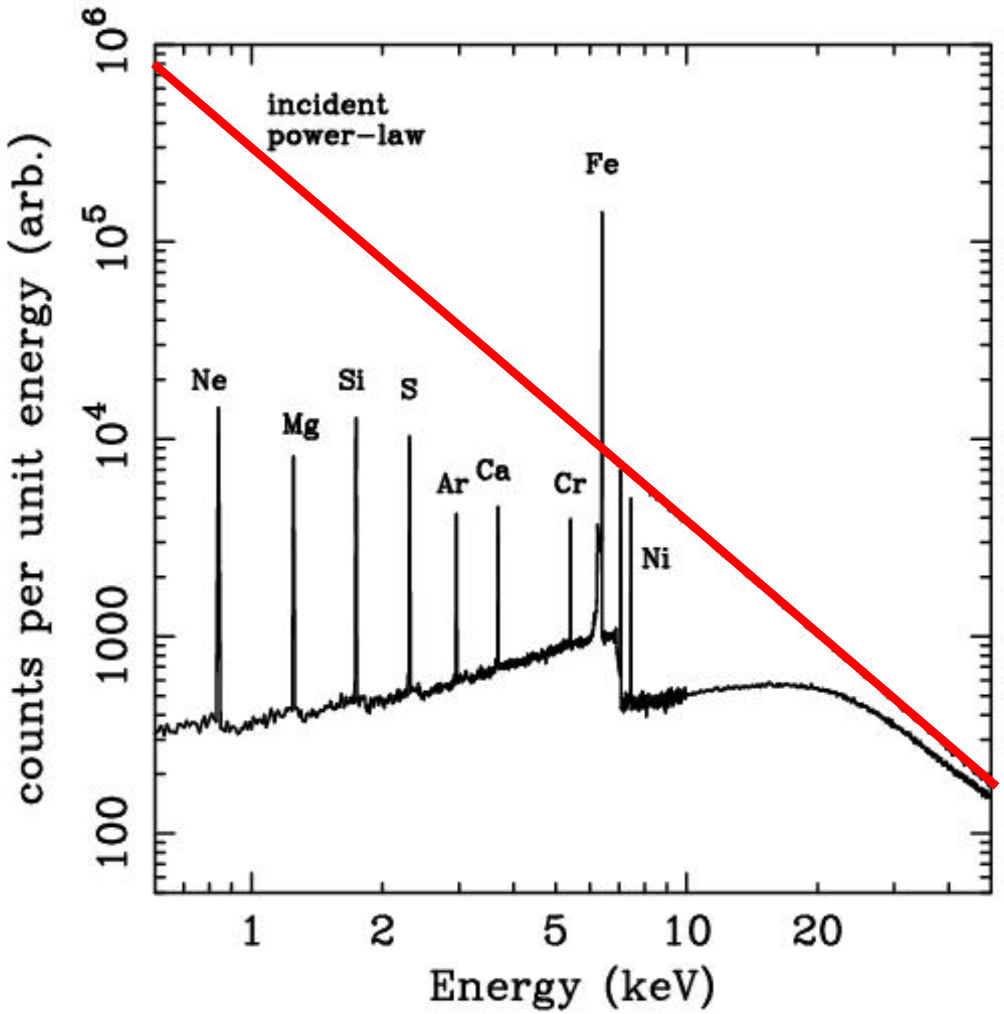
X-ray reflection

all modified by absorption, often in the form of outflowing ionized gas

X-ray reflection







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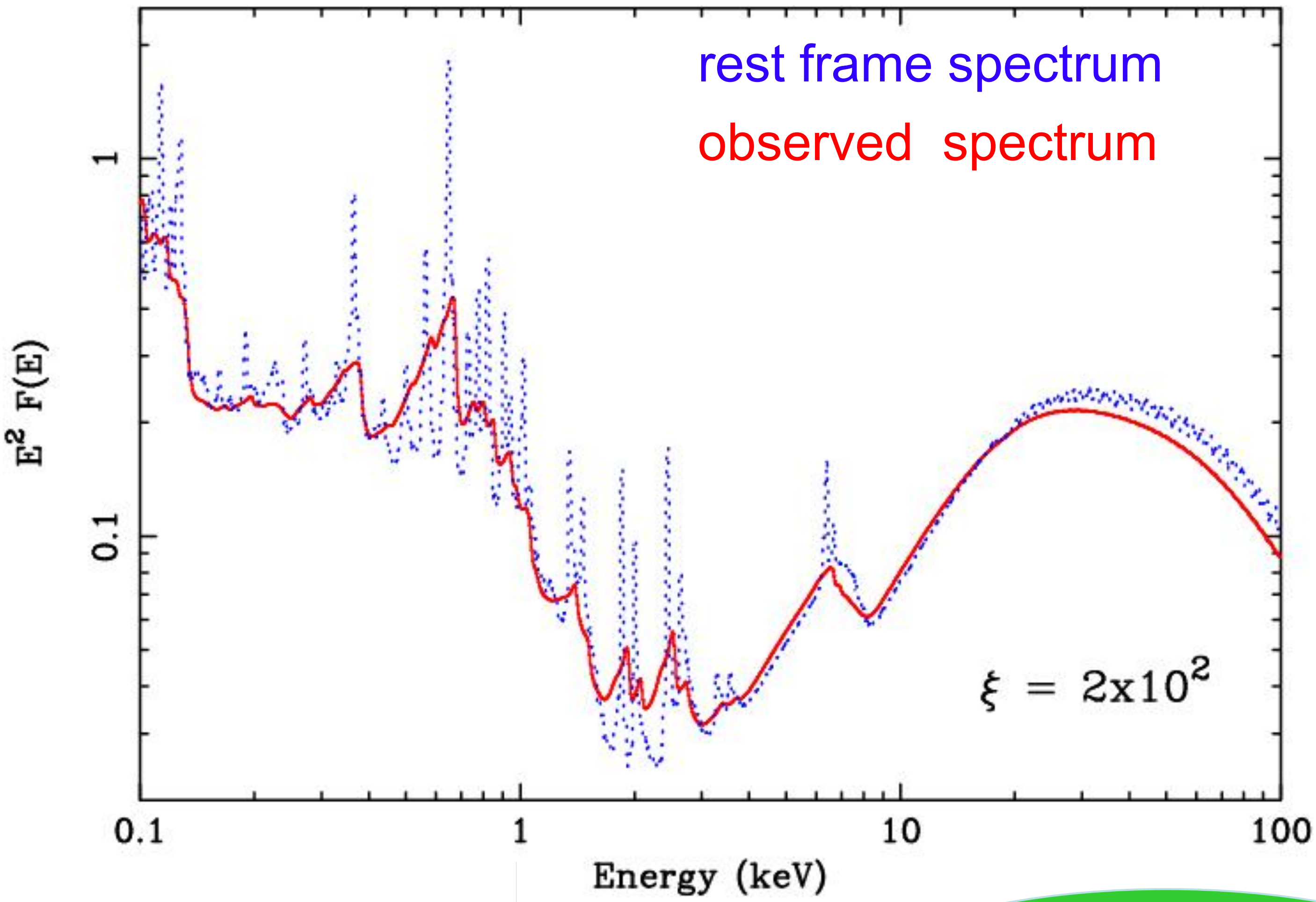
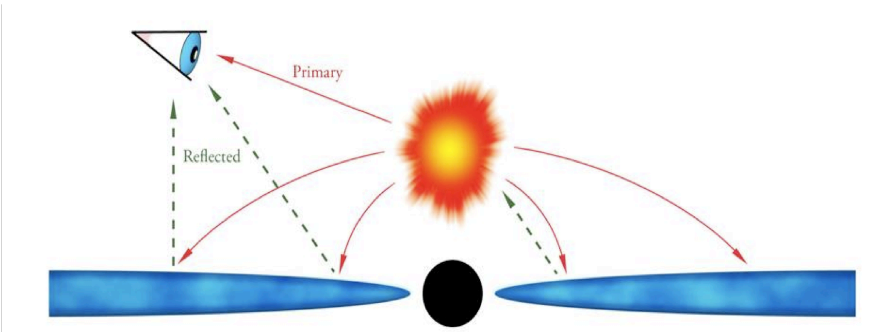
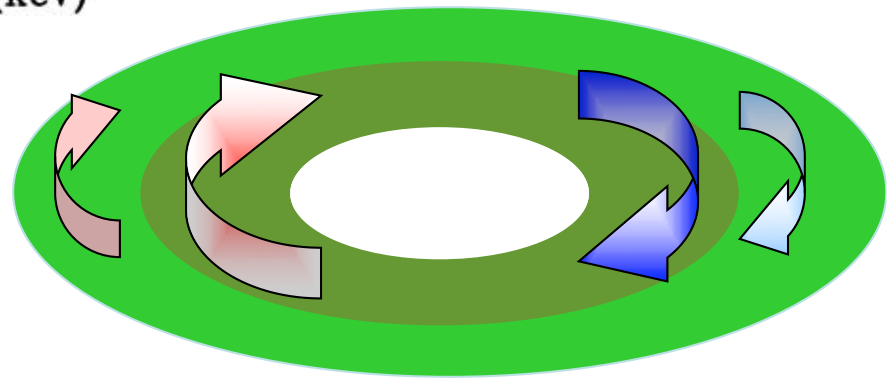
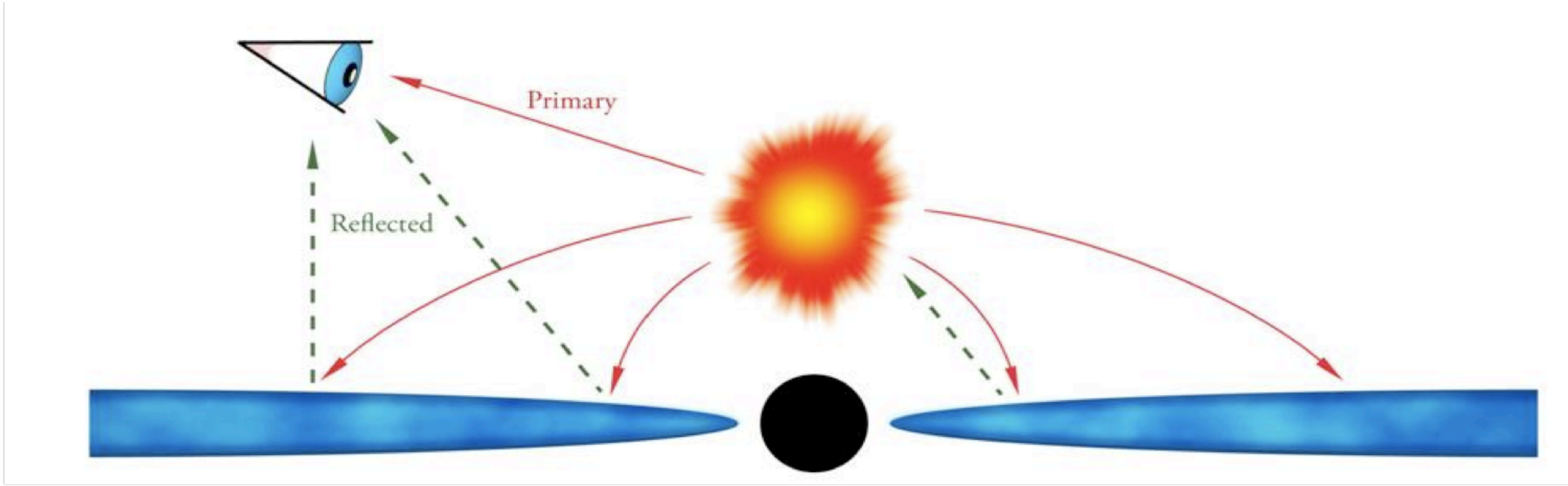




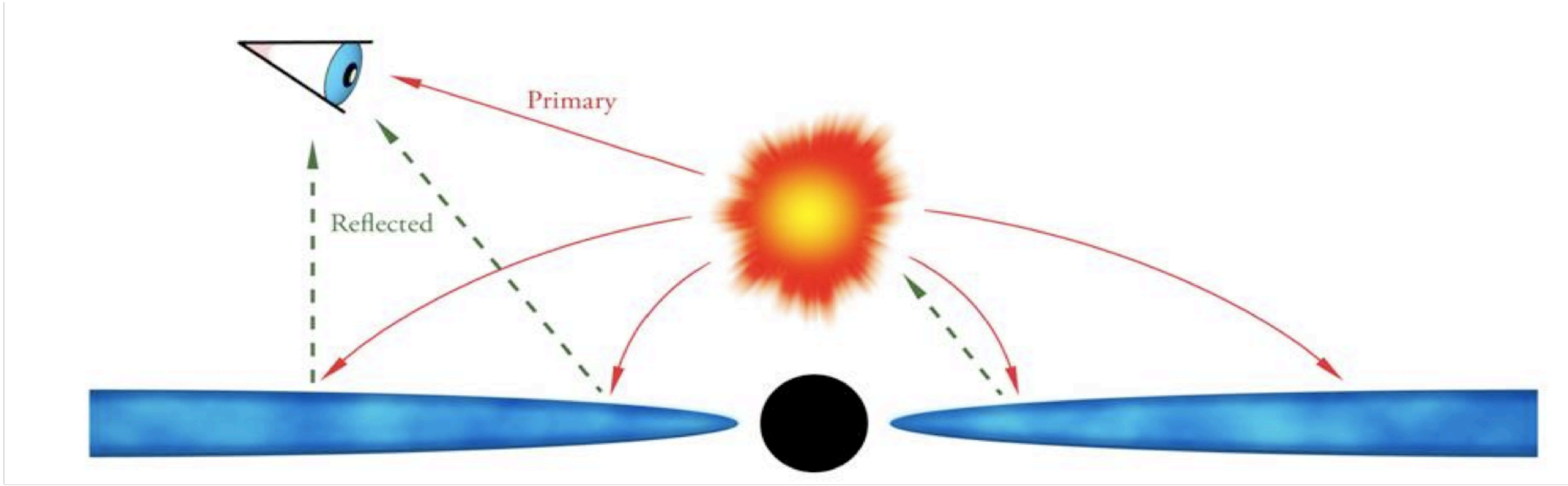


X-ray lags in AGN light curves



Spectral analysis alone often ambiguous (especially for broad features)

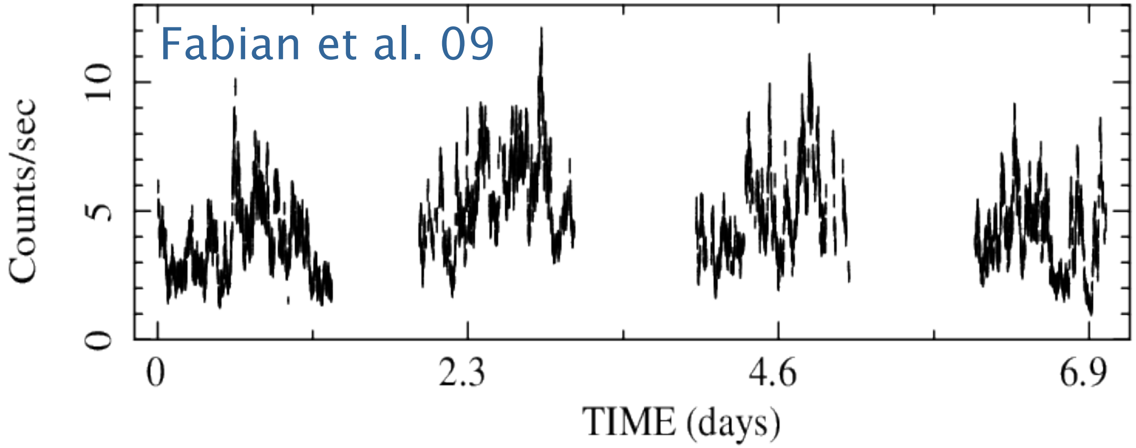
X-ray lags in AGN light curves

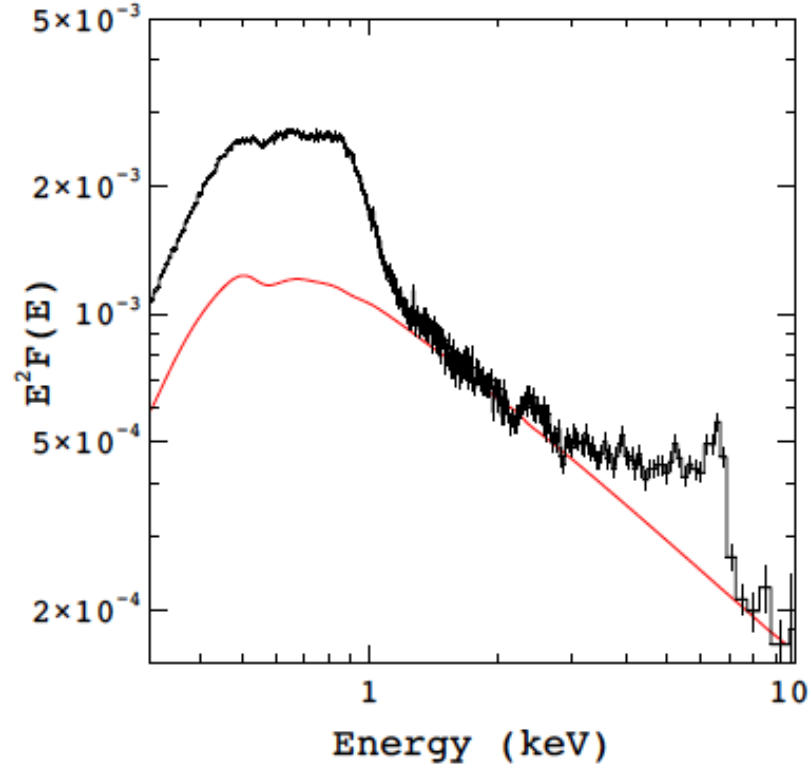


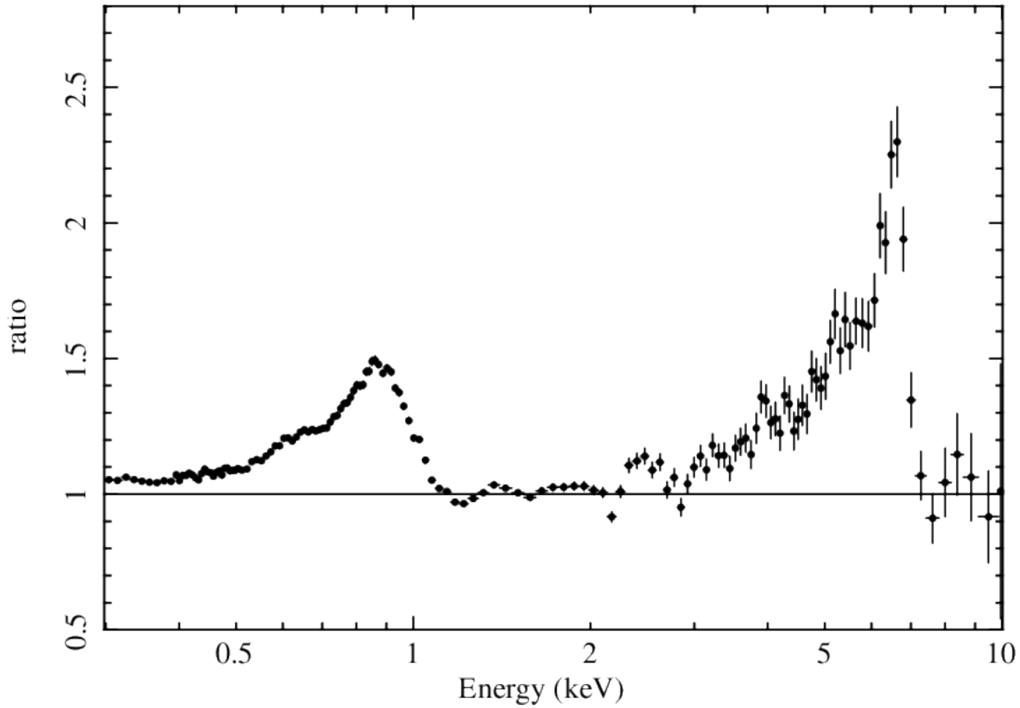
Spectral analysis alone often ambiguous (especially for broad features)

Let's turn to variability

A clear soft (negative) lag detection in 1H 0707-495







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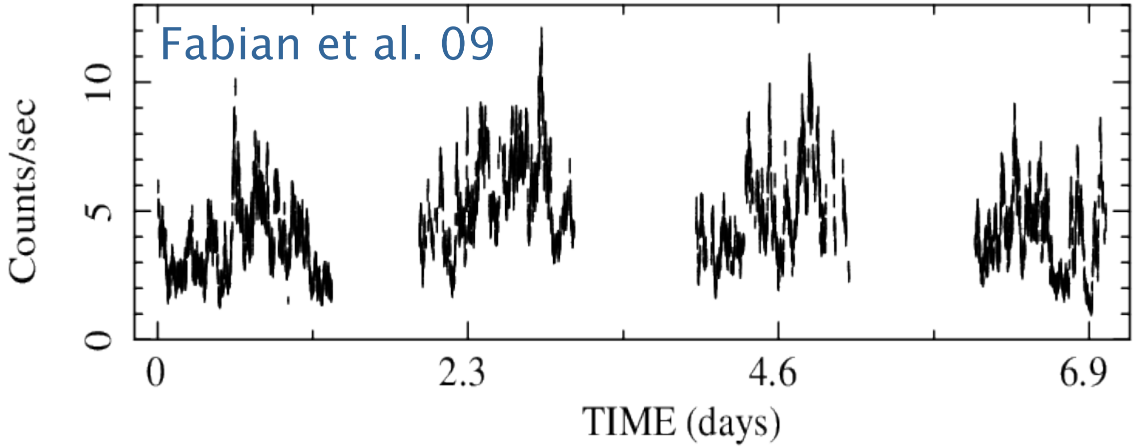

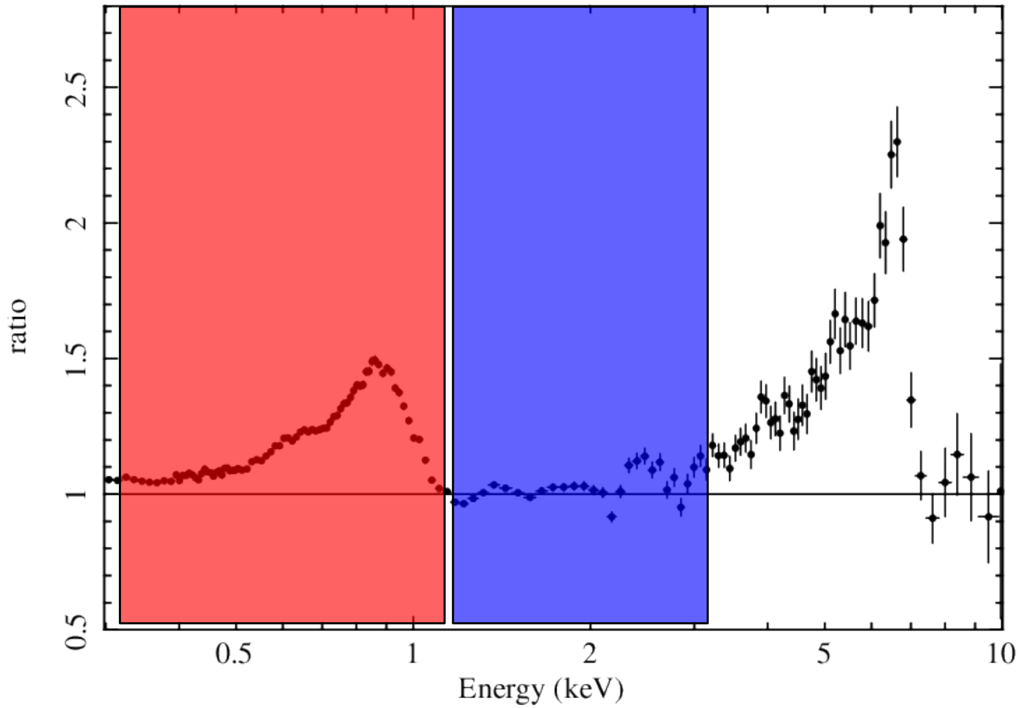

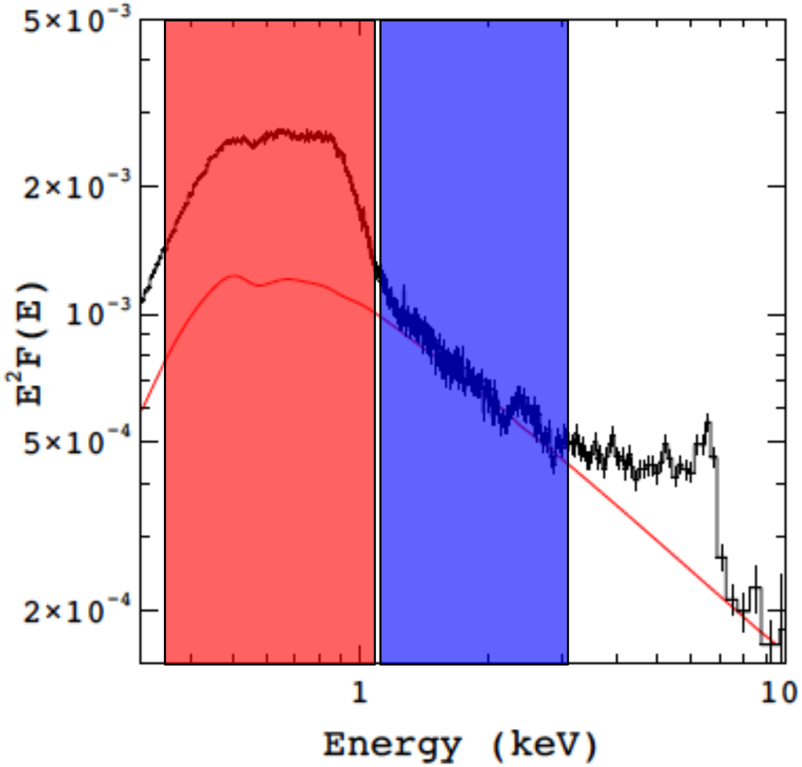

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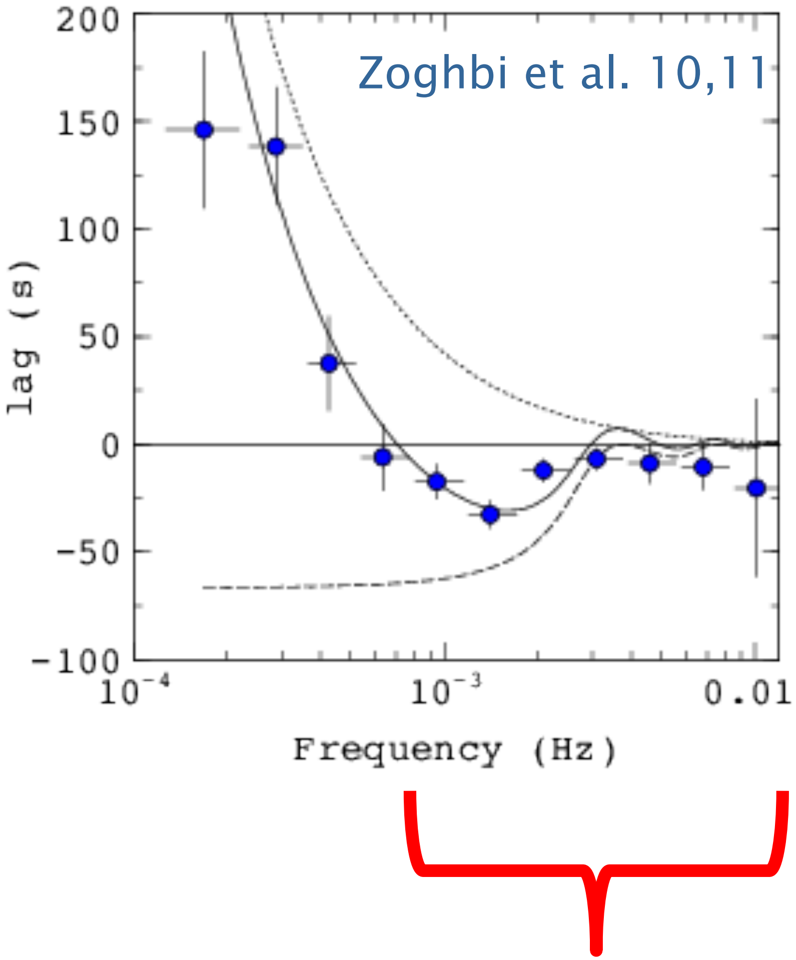
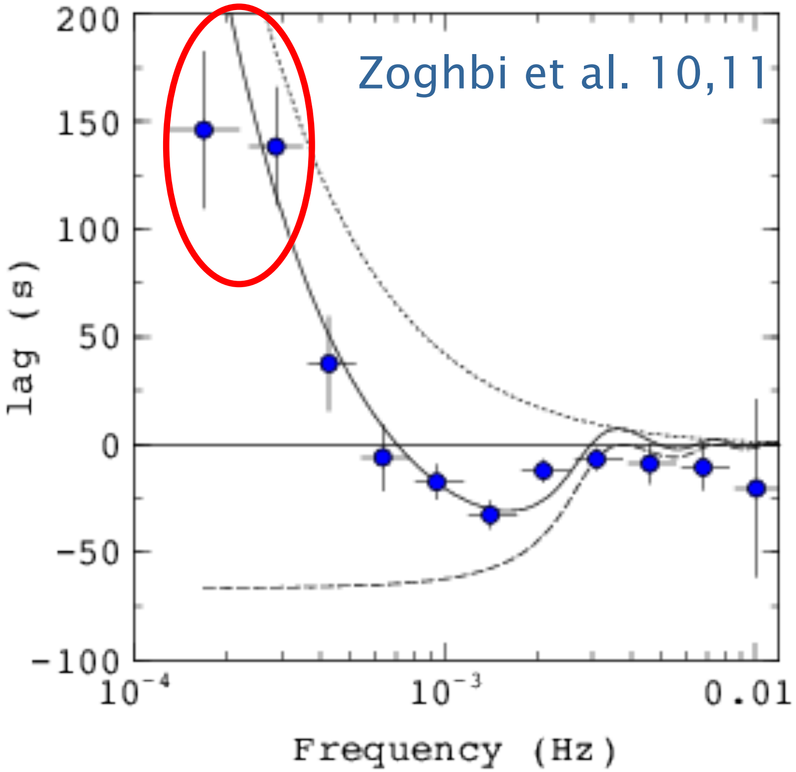
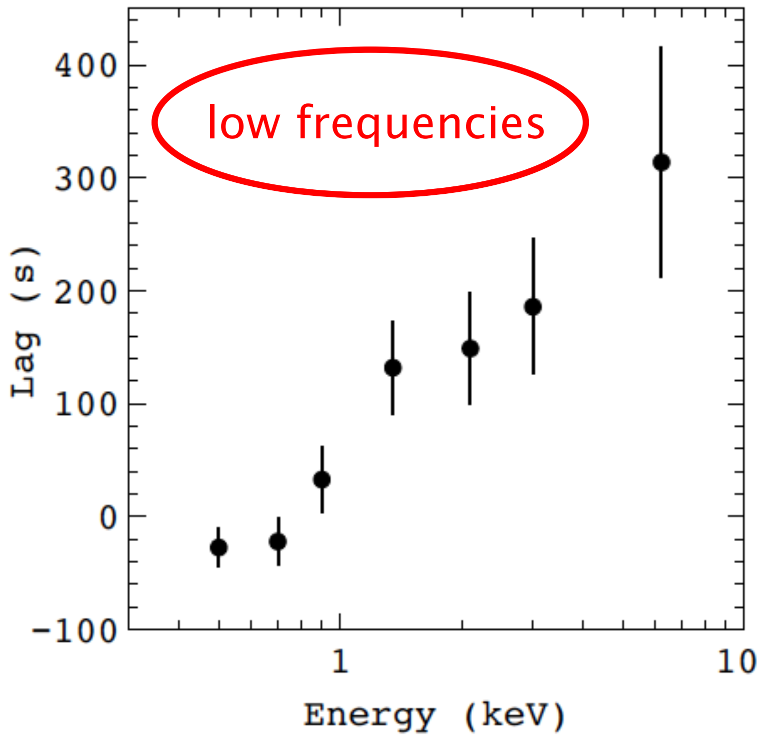


~ 10^2 – 10^3 Hz in a BH binary
(Poisson noise dominated)

this is then new territory for accreting BH

The case of 1H 0707-495





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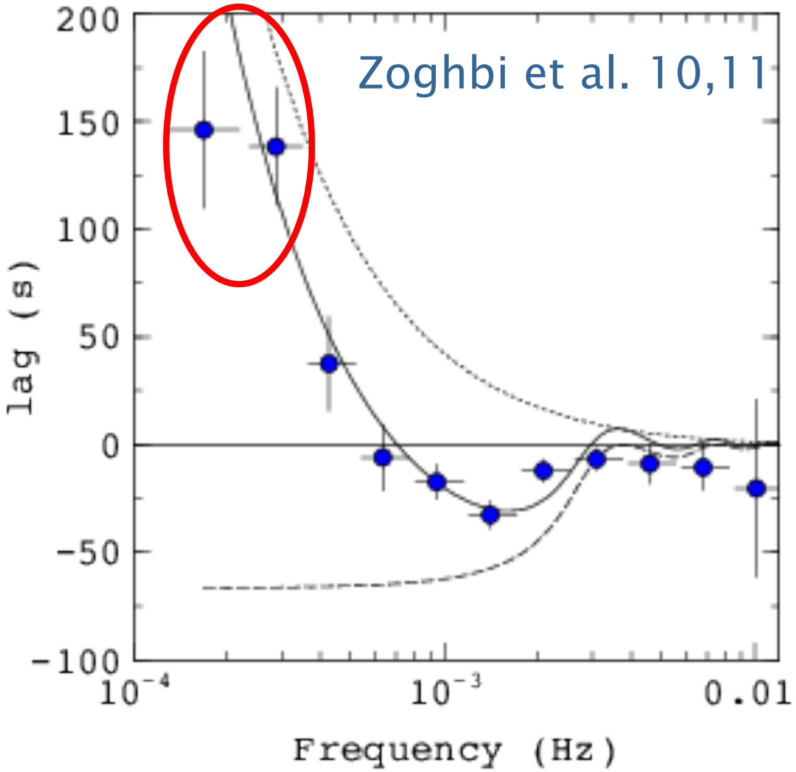
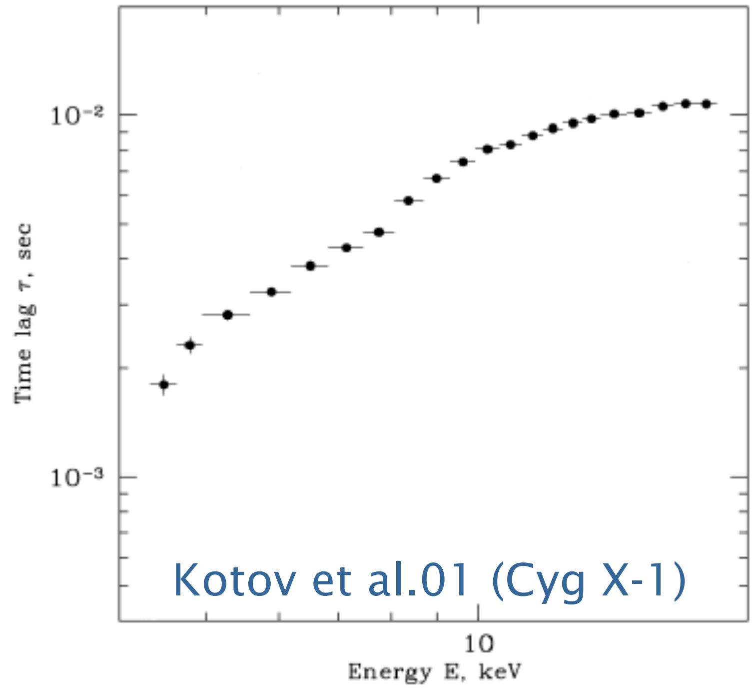
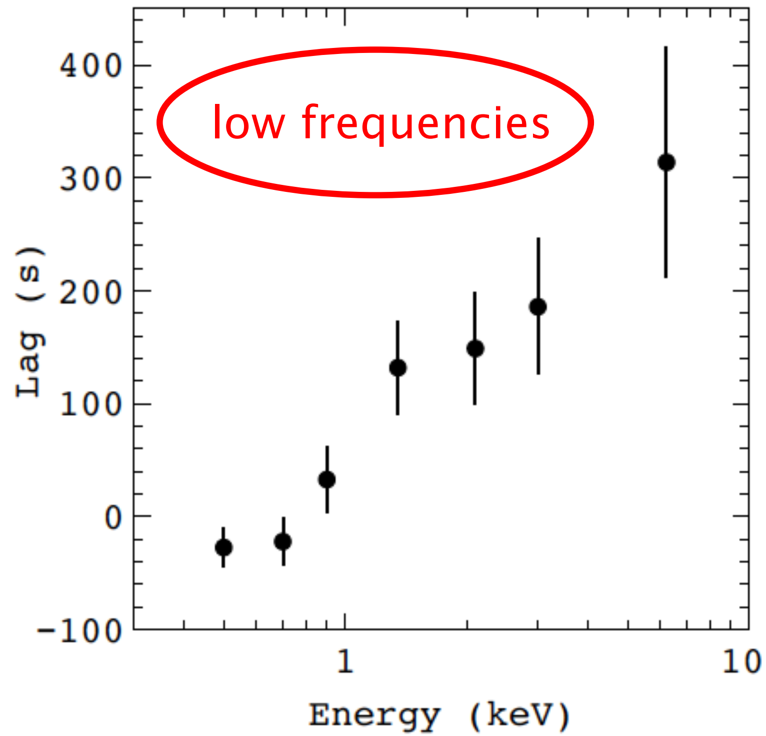


Low frequency lags are similar to what is seen in BH binaries
(lag increases with energy separation)
and in a similar range of (mass-scaled)
Frequencies

Leading interpretation: inwards propagating fluctuations (explains also other properties)





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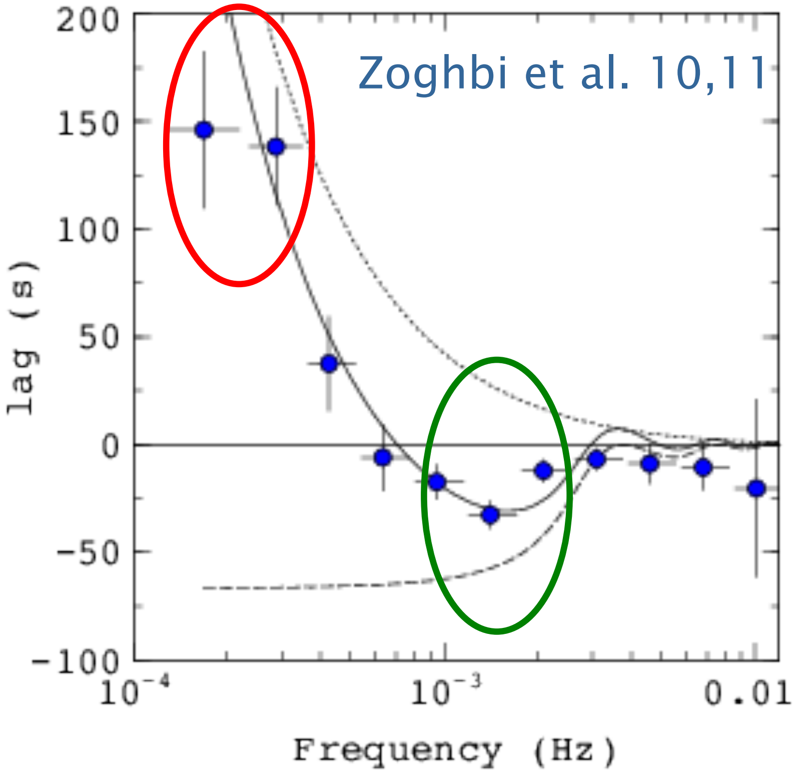
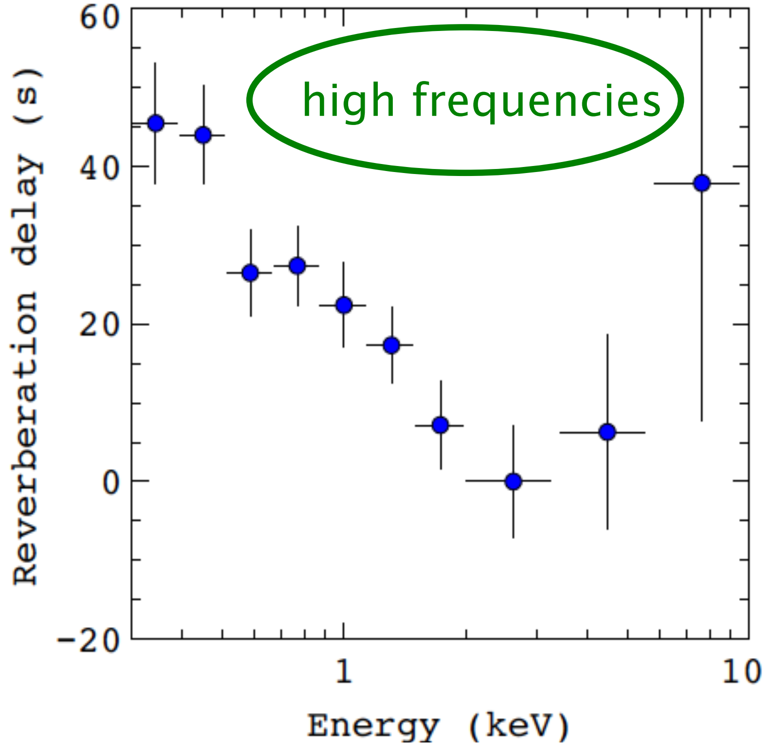
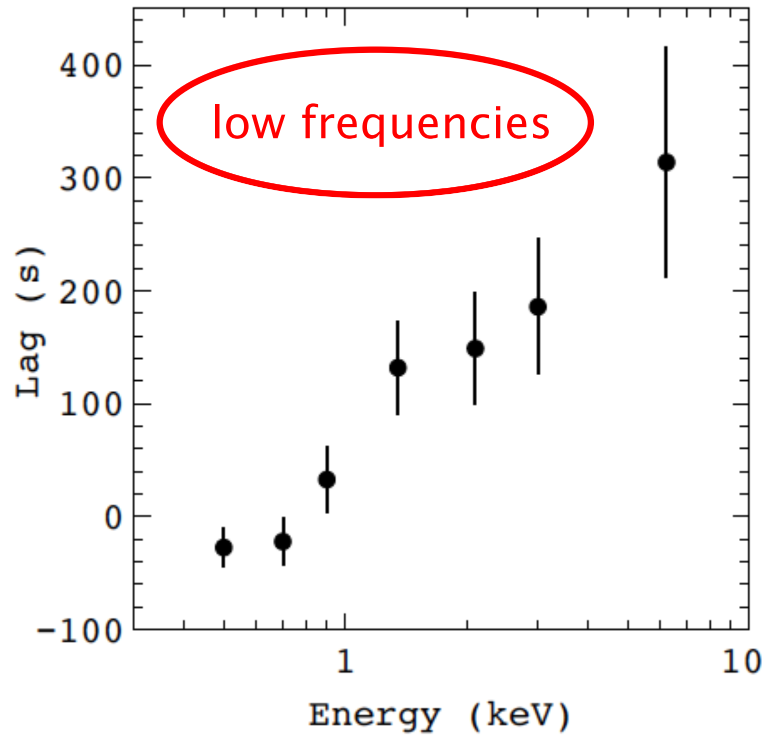


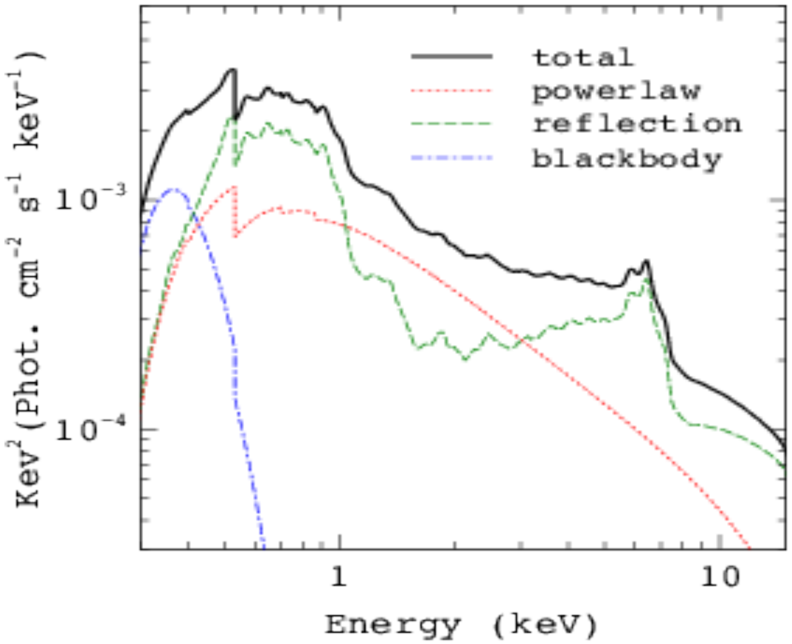


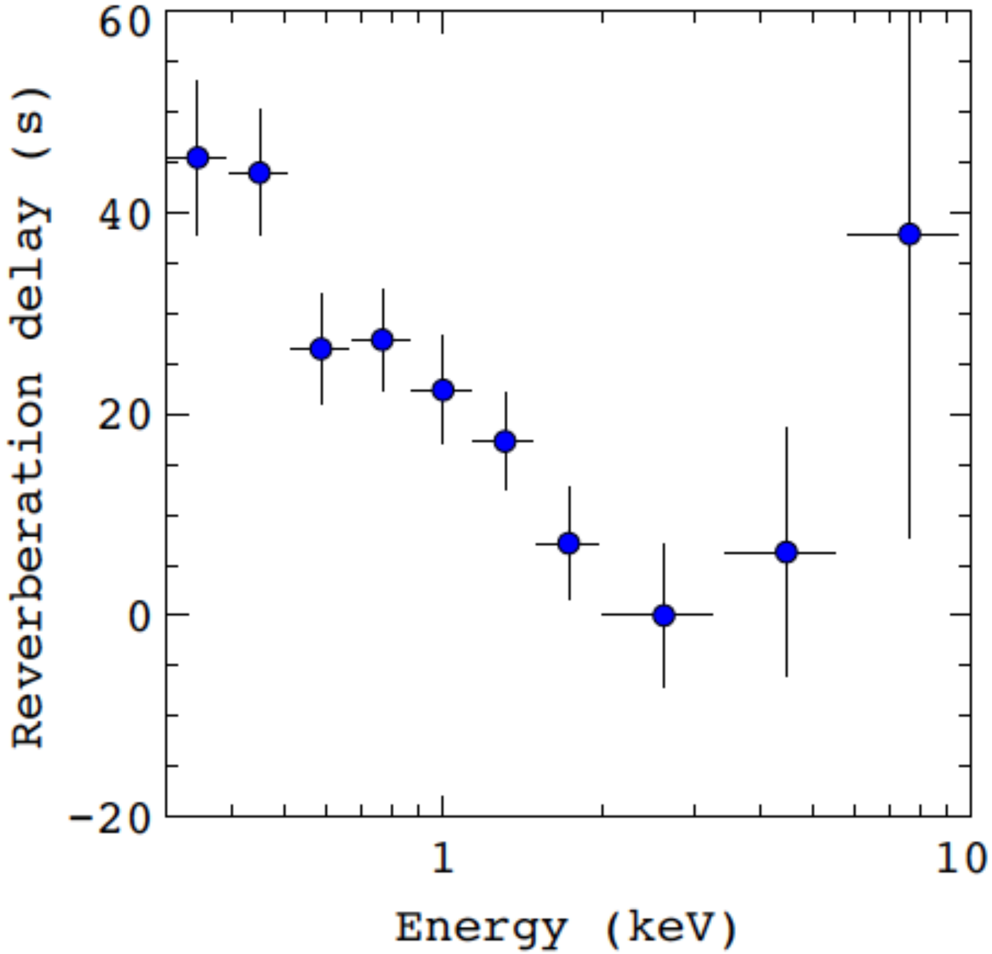


High frequency lags are different to what is seen in BH binaries and show a much more complex pattern

To understand the lag-energy spectrum at high frequencies, the photon spectrum can be useful

The case of 1H 0707-495





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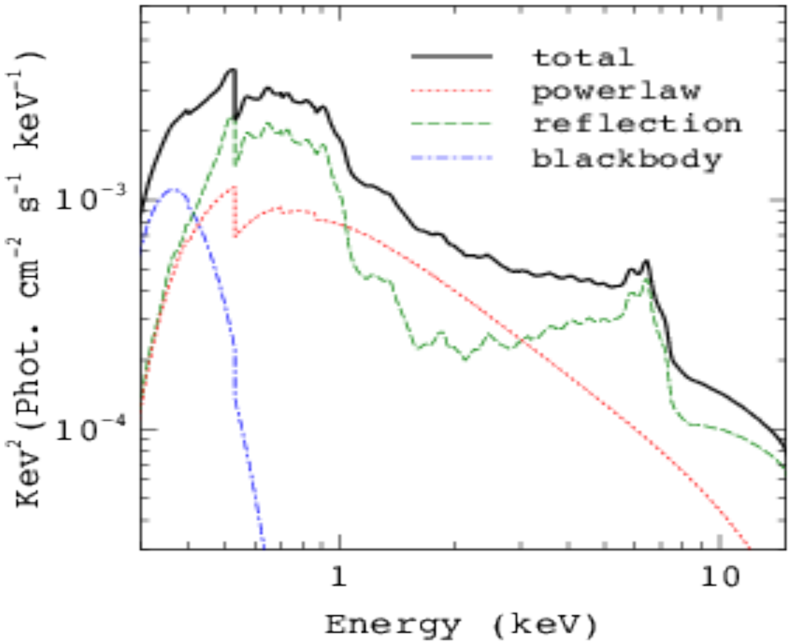
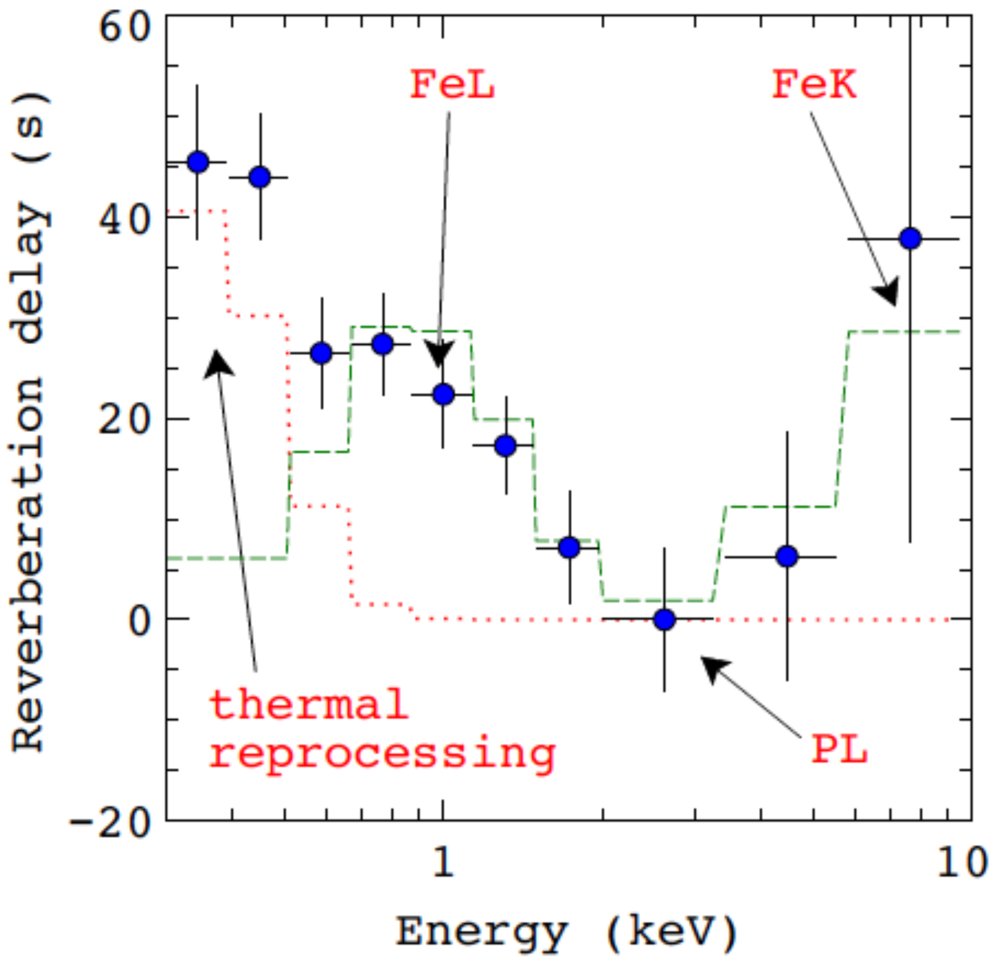
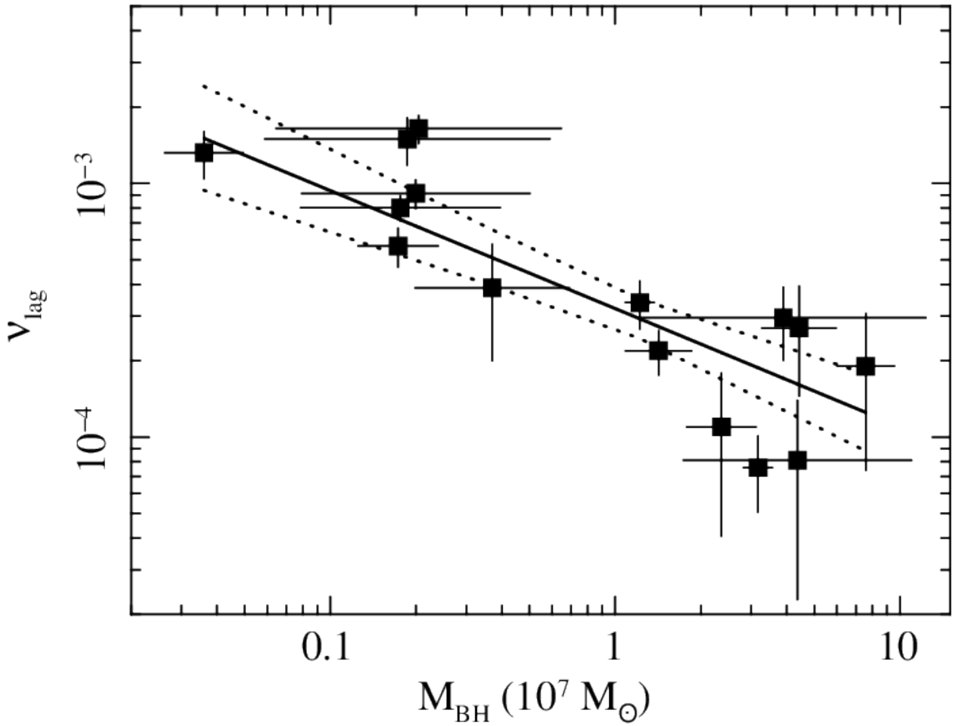
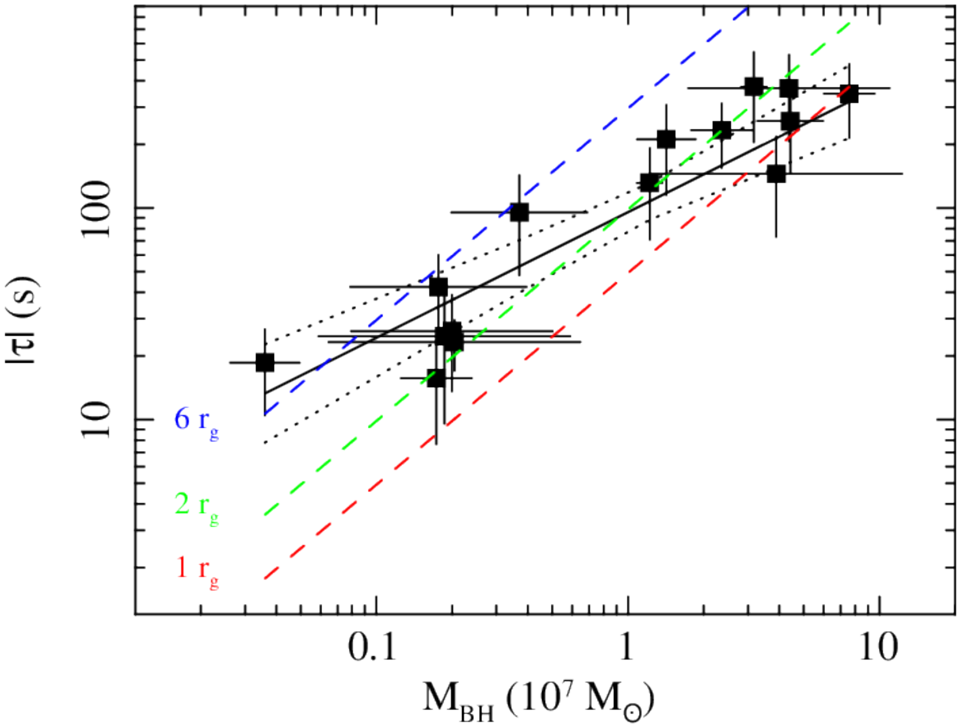




Soft X-ray lags in a sample of variable AGN

De Marco et al. 13



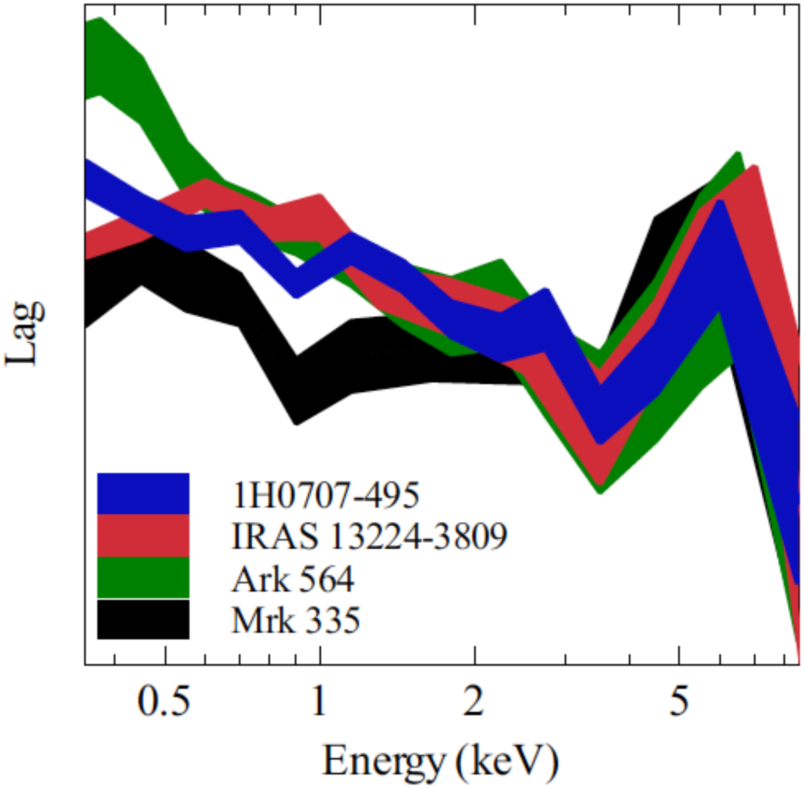


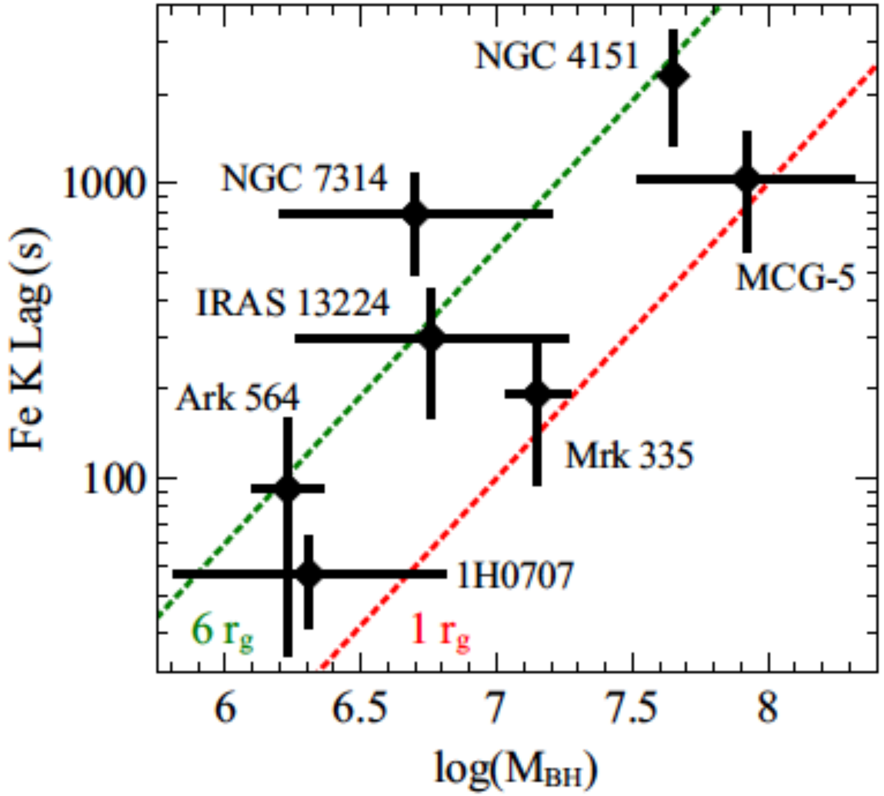
At high frequency (depending on BH mass) the soft X-ray excess emission lags the X-ray continuum

The amplitude of the lag is proportional to BH mass and corresponds to a few r_g if interpreted as light-crossing-time

Lags at Fe K energies

Kara et al. 13



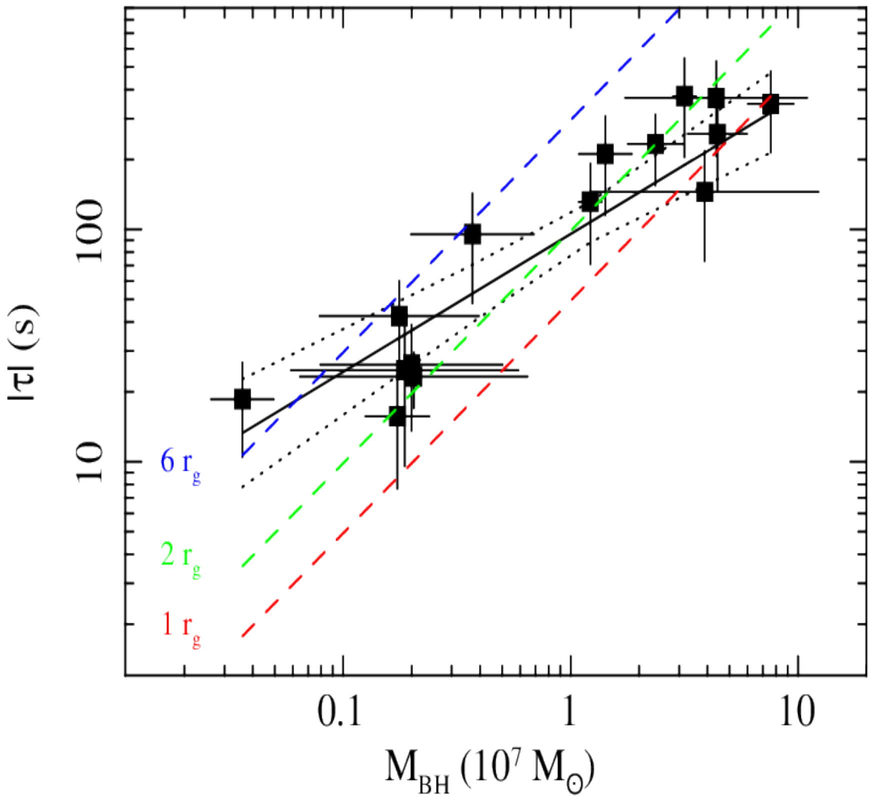


X-ray lags detected at Fe K energies are know detected in 7 sources

The lags amplitude appears to scale with BH mass, as the soft lags do

Lags at Fe K energies

De Marco et al. 13



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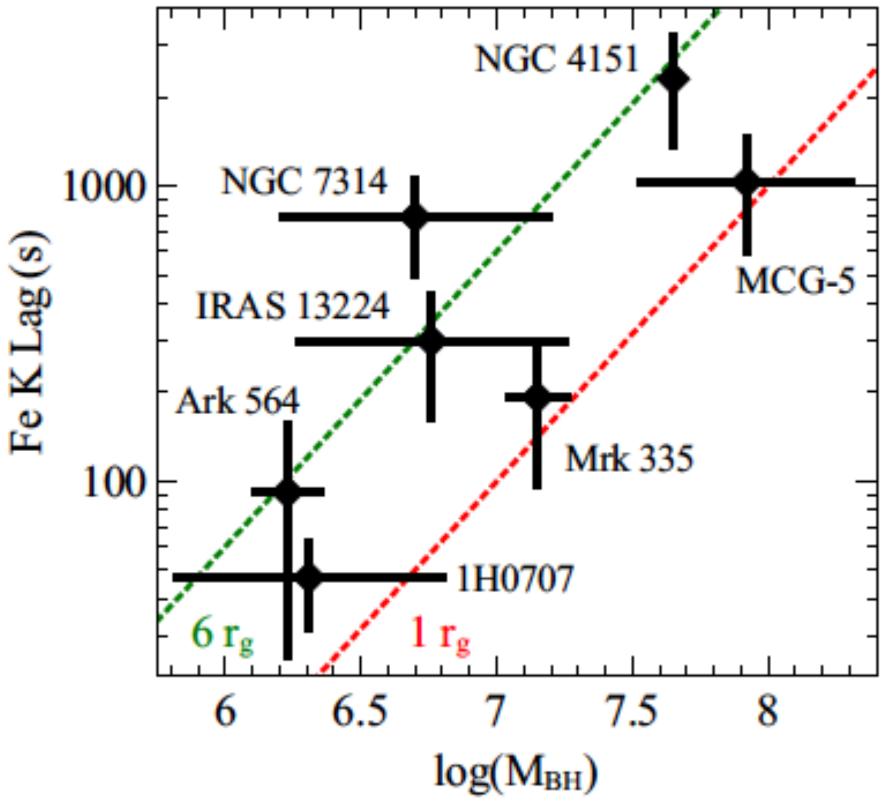

X-ray lags of both the soft excess and Fe K line correspond to distances of few r_g pointing towards a common origin in the innermost accretion flow

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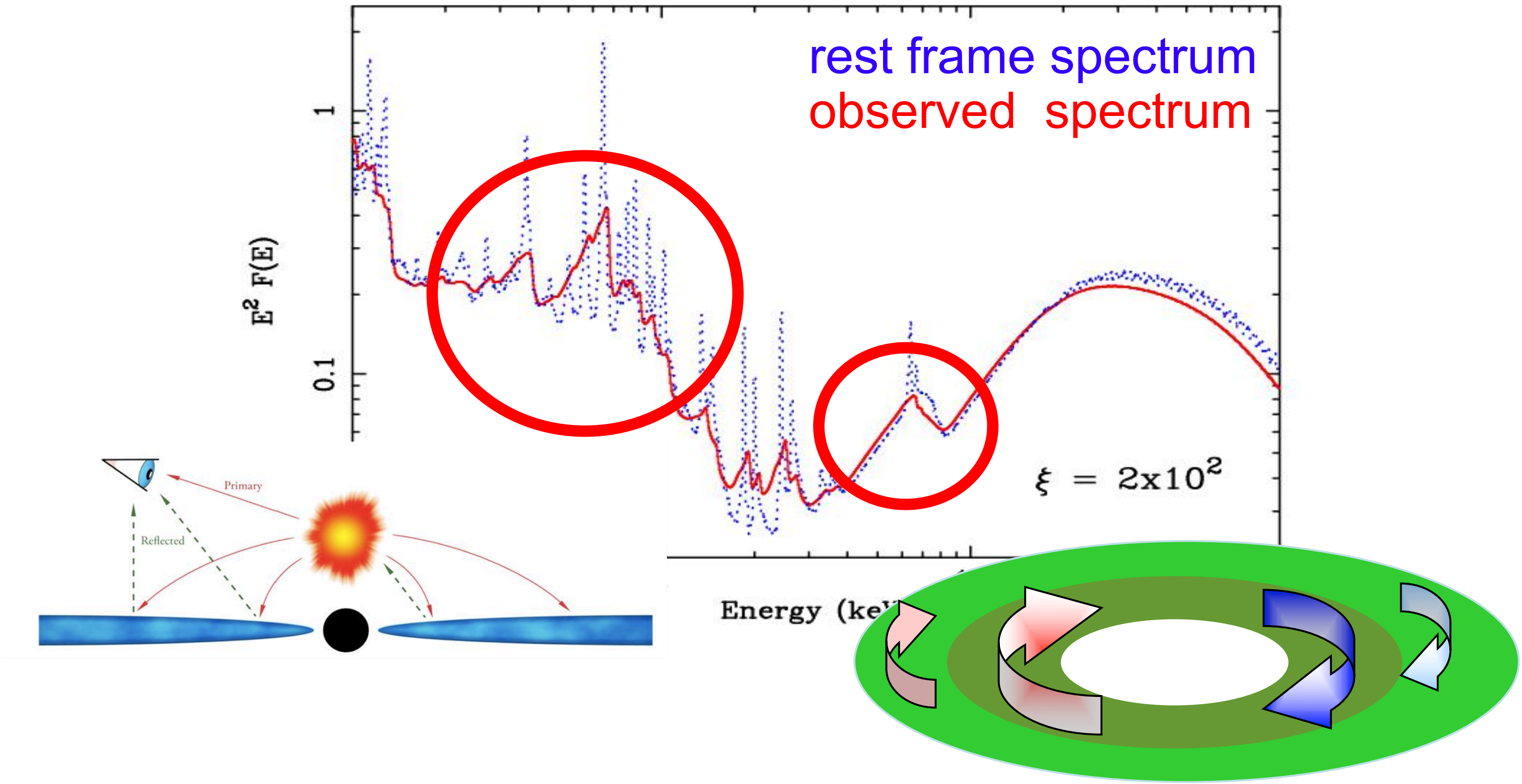

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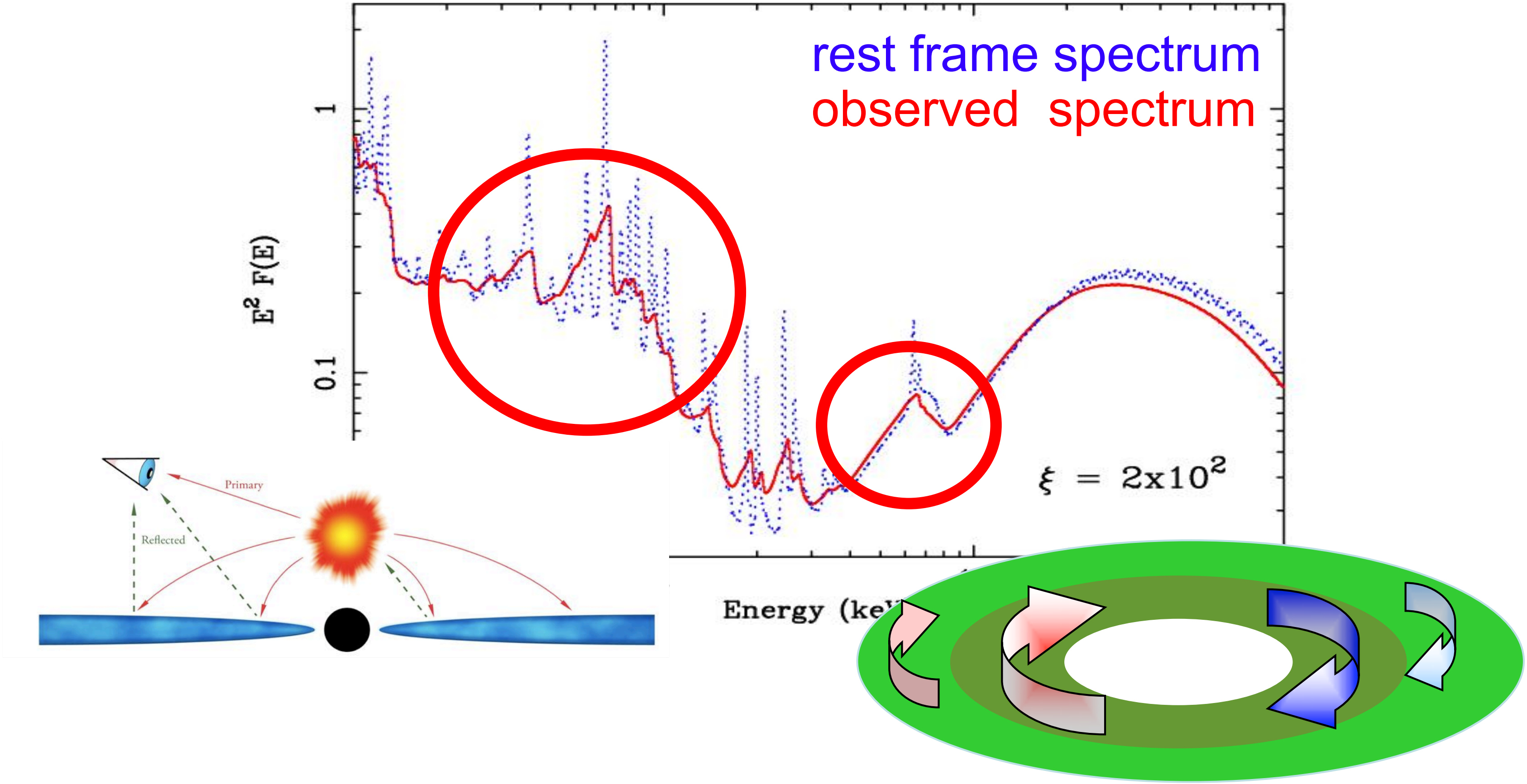
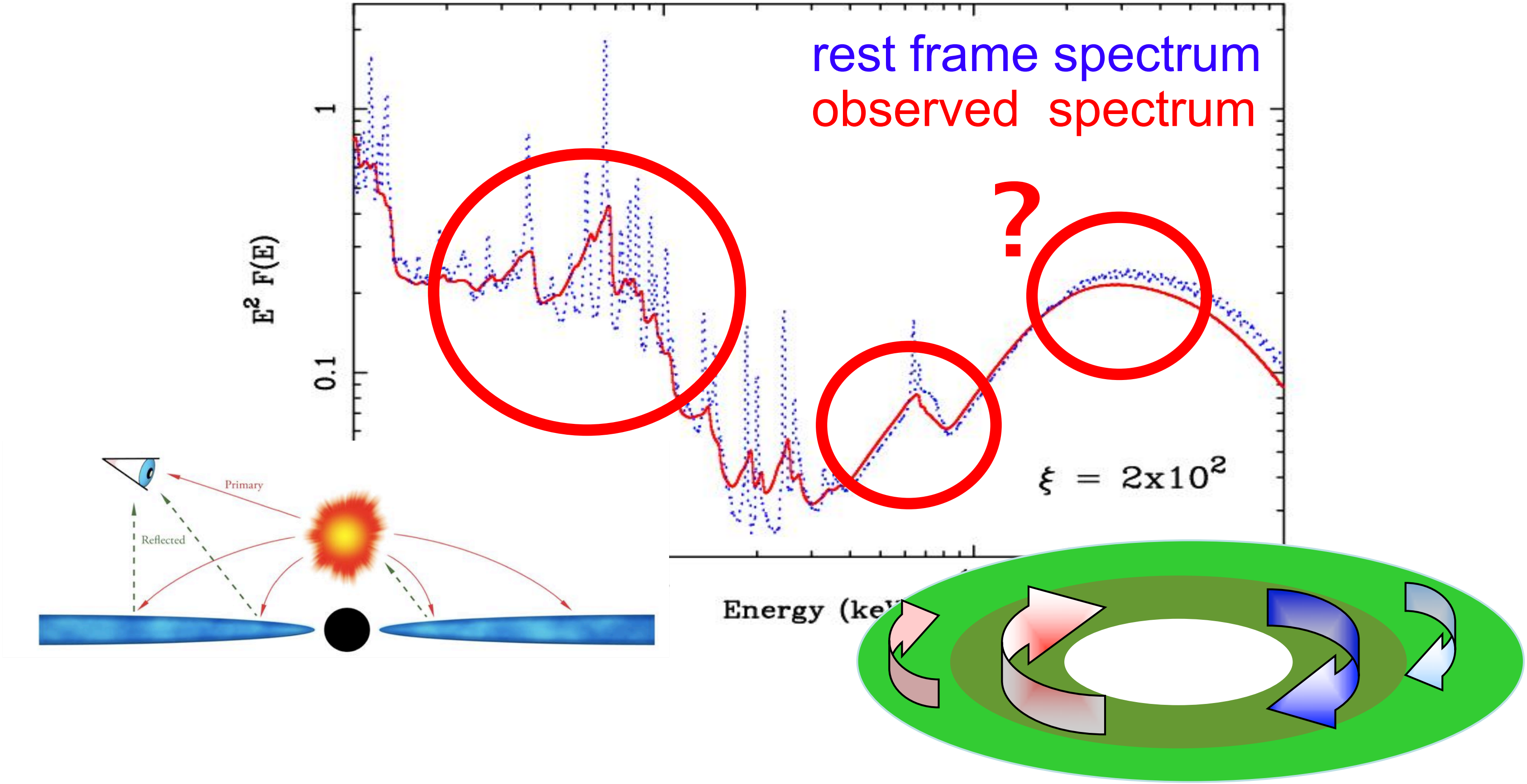


Only one of the signatures of reflection is left out: the Compton hump @ 20-30 keV

Lags at Fe K energies



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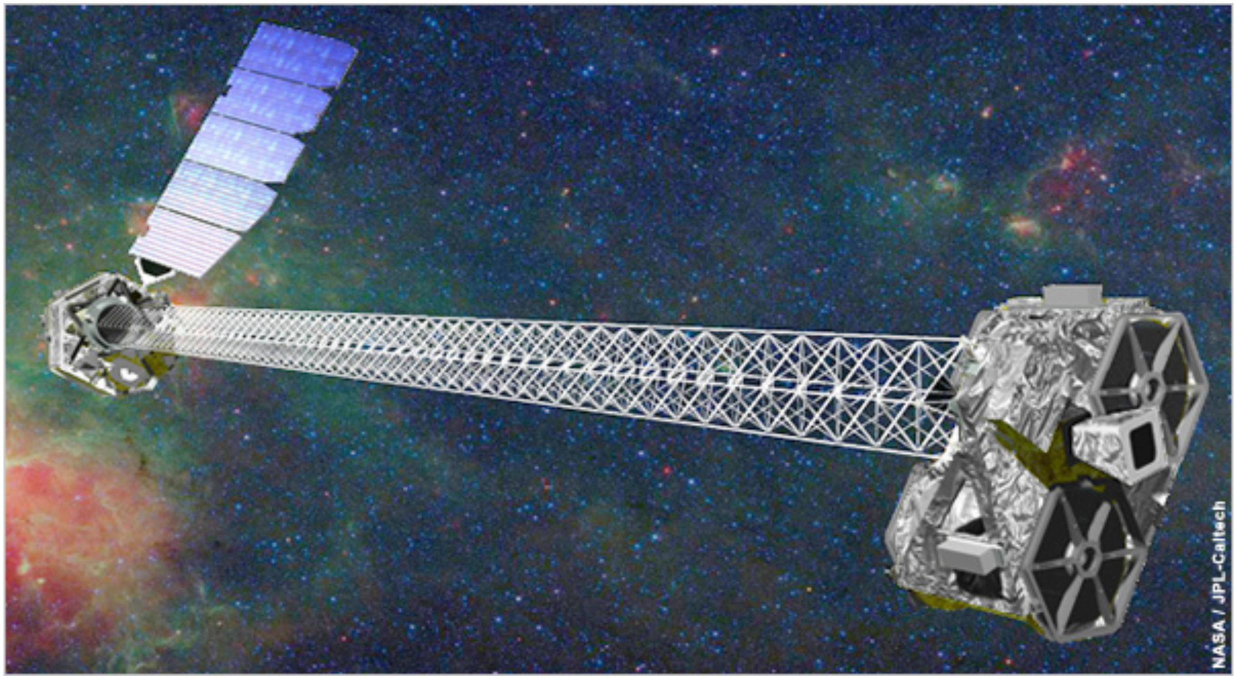
The NuSTAR contribution

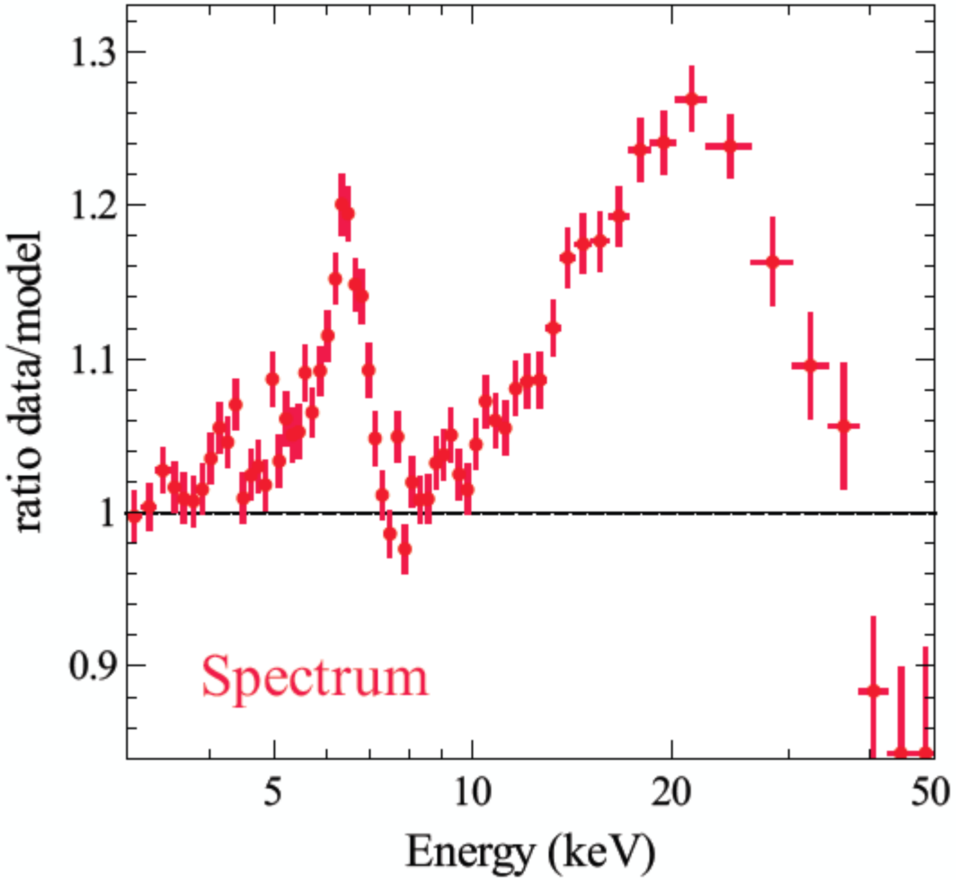


NuSTAR is the first X-ray observatory capable of imaging in the hard X-rays (3-80 keV) enabling to accurately account for contamination and background and with good sensitivity

The good sensitivity means that X-ray variability analysis can be carried out almost at the same level as with XMM-Newton in the hard X-rays, at least in X-ray bright AGN

The NuSTAR contribution

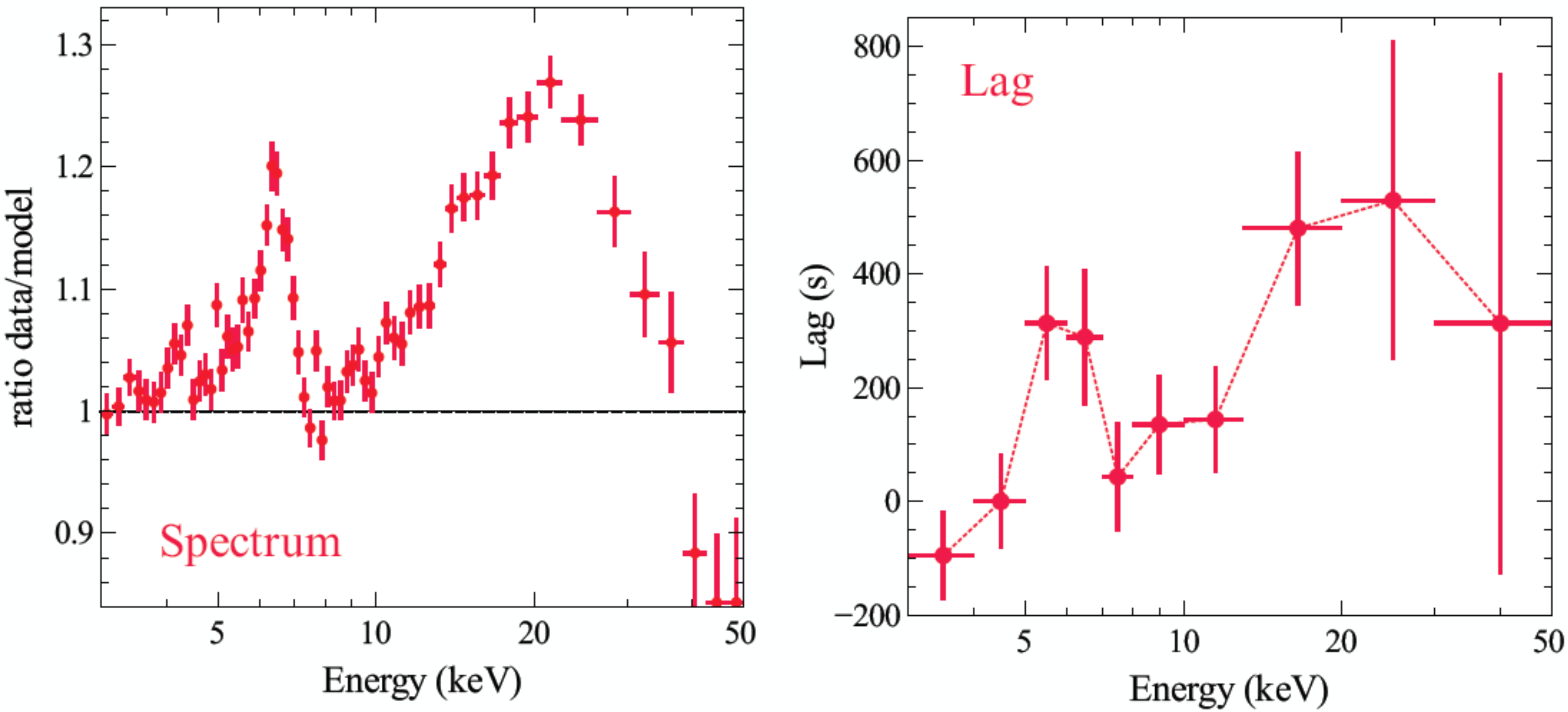
Kara et al. 14



SWIFT J2127.4 is a NLS1 galaxy for which a BH spin of ~0.6 was measured (GM et al. 09 + Sanfrutos et al. 13 + others) and NuSTAR confirms the presence of a strong relativistic reflection component

The NuSTAR contribution

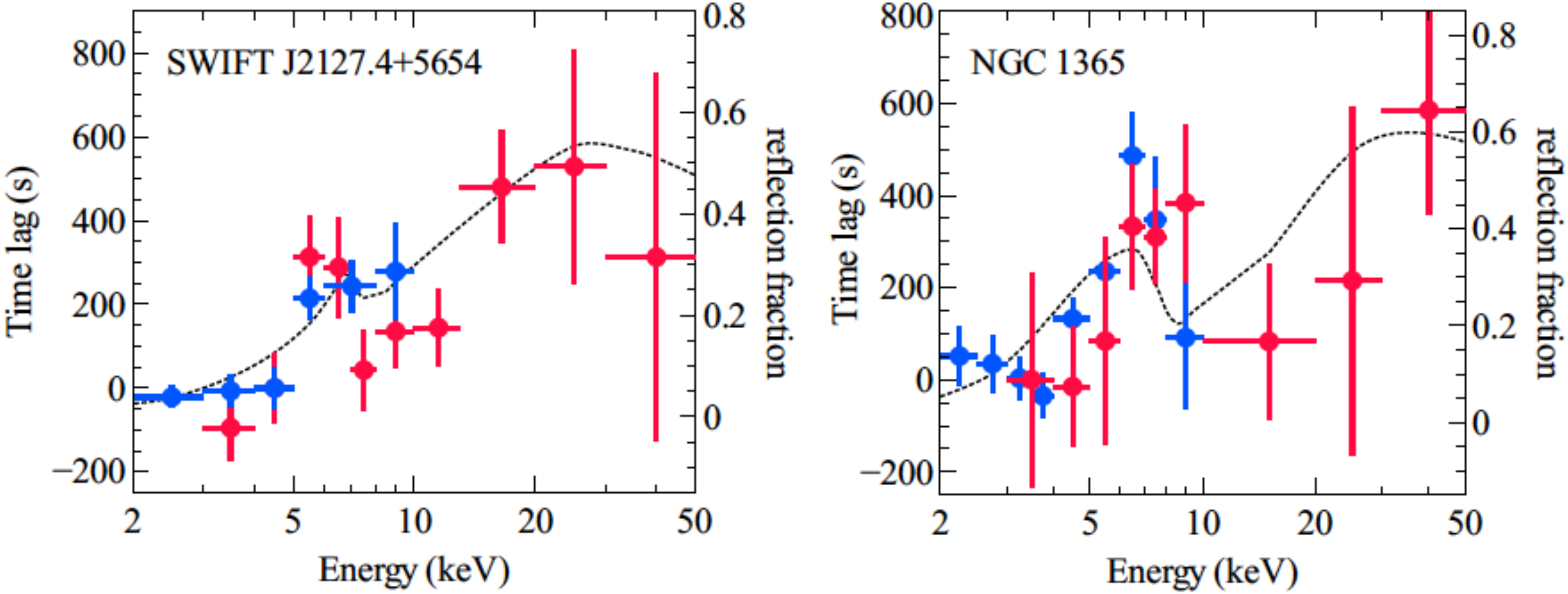
Kara et al. 14



NuSTAR lags detection: Fe K and Compton hump !

The NuSTAR contribution

Kara et al. 14



NuSTAR confirms the Compton hump lag in other sources as well: the lag spectrum is fully consistent with the reflection component as derived from the photon spectrum

Conclusions

X-ray lags strongly suggest that the X-ray variability in accreting BH comprise contributions from reprocessing

At high frequencies (fast variability) both the soft excess and Fe K line energy band lag the intermediate energies, likely dominated by the continuum emission

One single reprocessed component peaking in the soft X-ray band and at Fe K is the simplest explanation

NuSTAR observations reveal lags at 20-30 keV that are fully consistent with the Compton hump contribution, meaning that all reflection signatures are now detected confirming our initial interpretation

This is an almost model-independent description of what X-ray reflection from partially ionized gas looks like

The amplitudes of the lags in the soft excess, Fe K, and Compton hump are consistent with each other, and they correspond to only few r_g in terms of light-crossing-time

Thank you !

(backup slides on some theory / modeling available)

Some theory

Simple lamp-post geometry: a primary source of X-rays with power-law energy spectrum is located on the symmetry axis at height h

Photons are followed in full GR

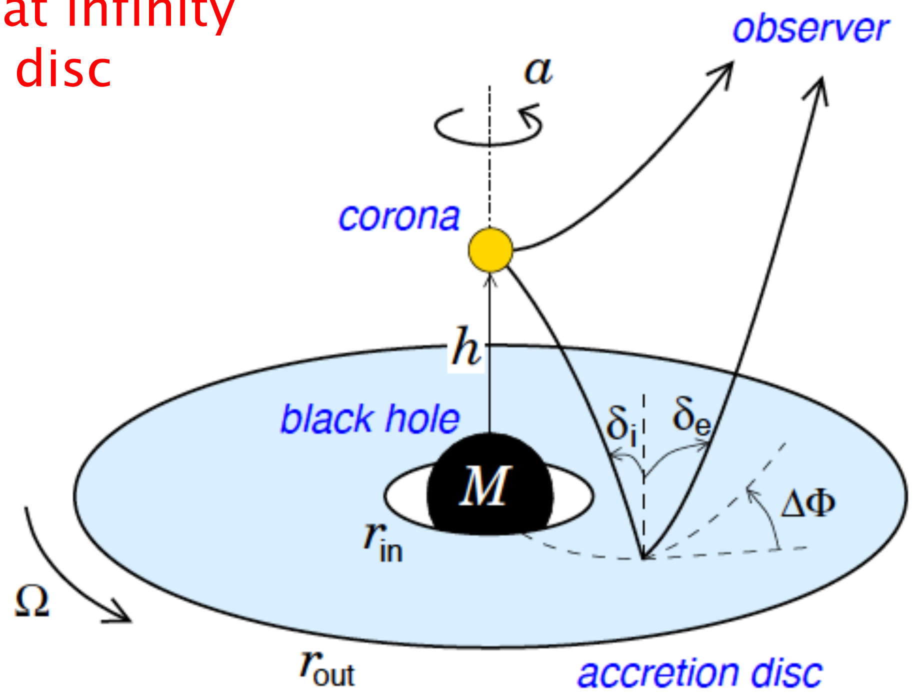
a) from the source to the observer at infinity
b) from the source to the accretion disc

and

c) from the disc to infinity

to calculate

the observed primary flux and
the disc irradiation
the observed reflected flux



Some theory

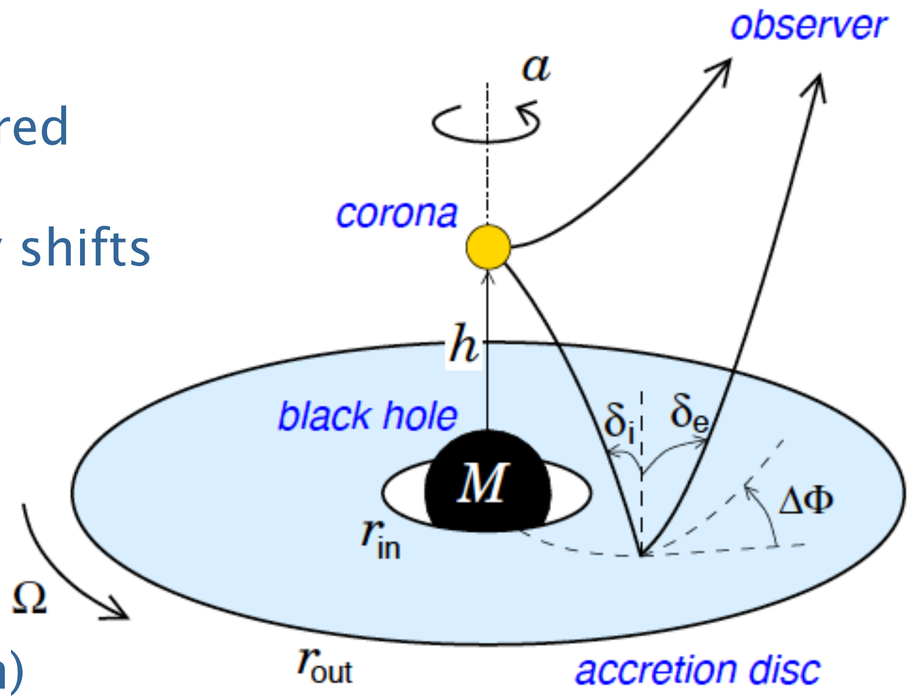
To compute the local reprocessed component, the code is coupled with the reflionx reflection model where we can vary

- the reflection directionality (isotropic or not)
- the ionization profile on the disc (as a function of self-consistent irradiation and local disc density

Relativistic effects are fully considered

- Doppler and gravitational energy shifts
- Light bending
- Beaming
- Light travel time

We consider the response to a flash of primary emission (approximated with a delta function)



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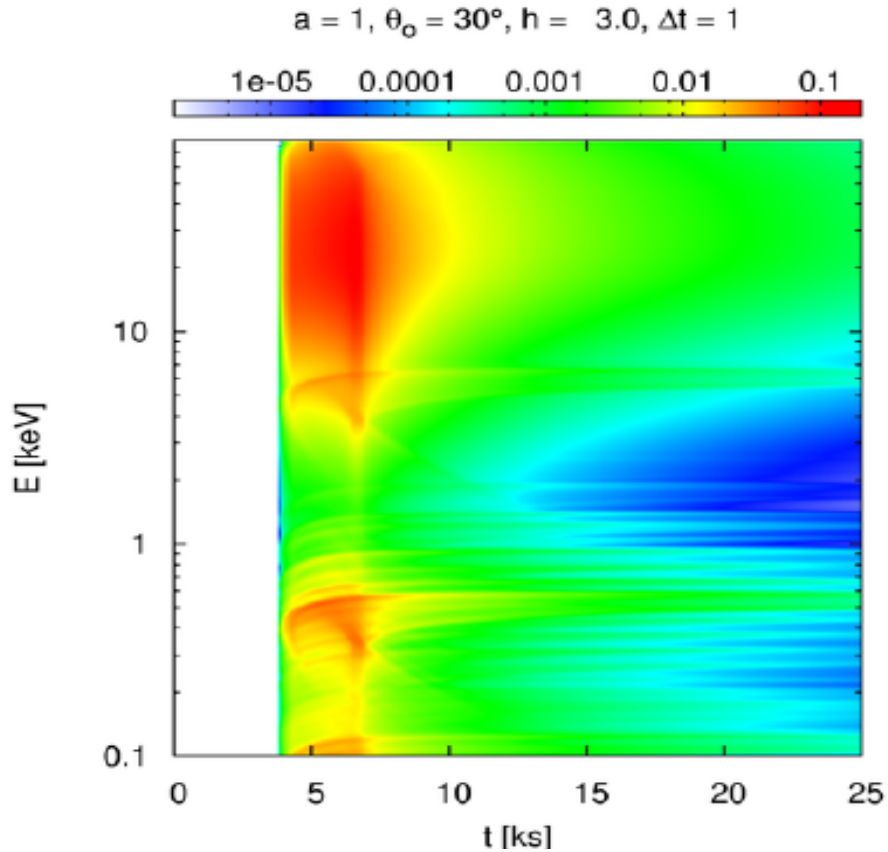
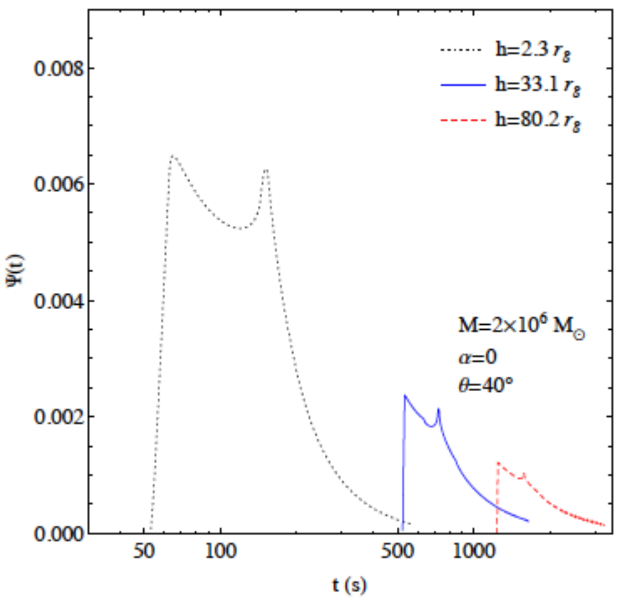
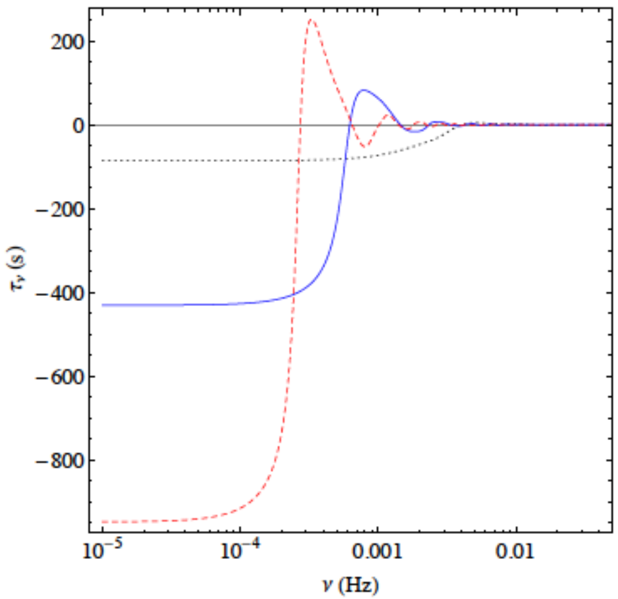


a = 1, θ$_o$ = 30°, h = 3.0, Δt = 1
1e-05
0.0001
0.001
0.01
0.1
E [keV]
10
1
0.1
0
5
10
15
20
25
t [ks]

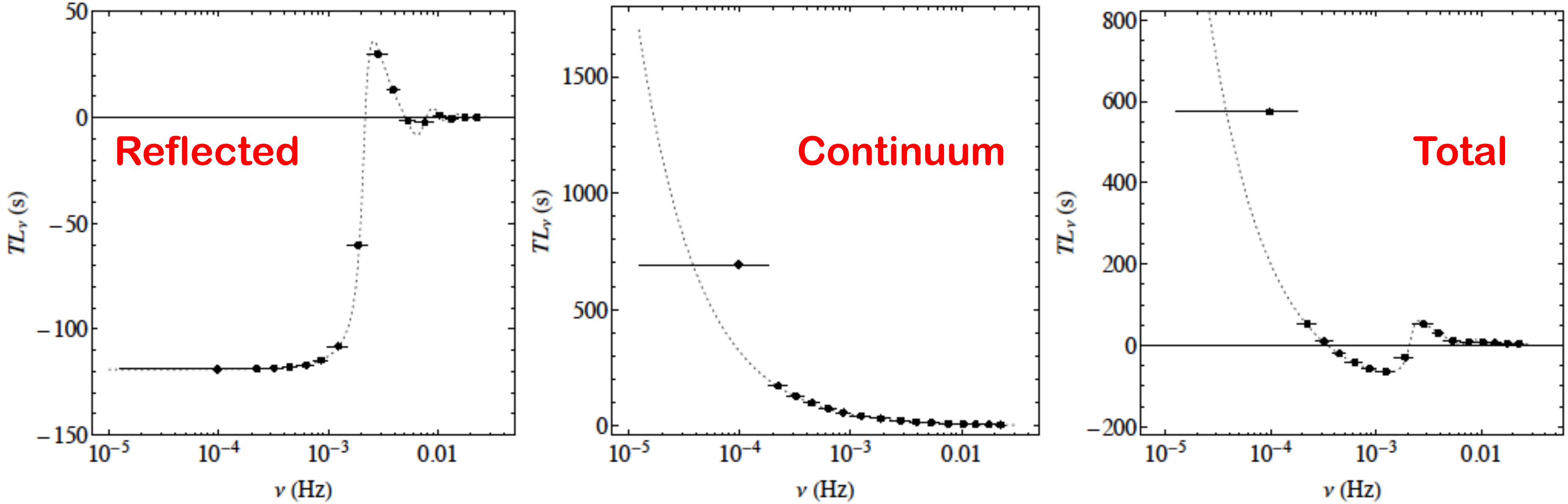


h=2.3 r_g
h=33.1 r_g
h=80.2 r_g
M=2×10^6 M$_\odot$
α=0
θ=40°
Ψ(t)
0.008
0.006
0.004
0.002
0.000
50
100
500
1000
t (s)



τ_ν (s)
200
0
−200
−400
−600
−800
10^{-5}
10^{-4}
0.001
0.01
ν (Hz)

Emmanoulopoulos et al. 14



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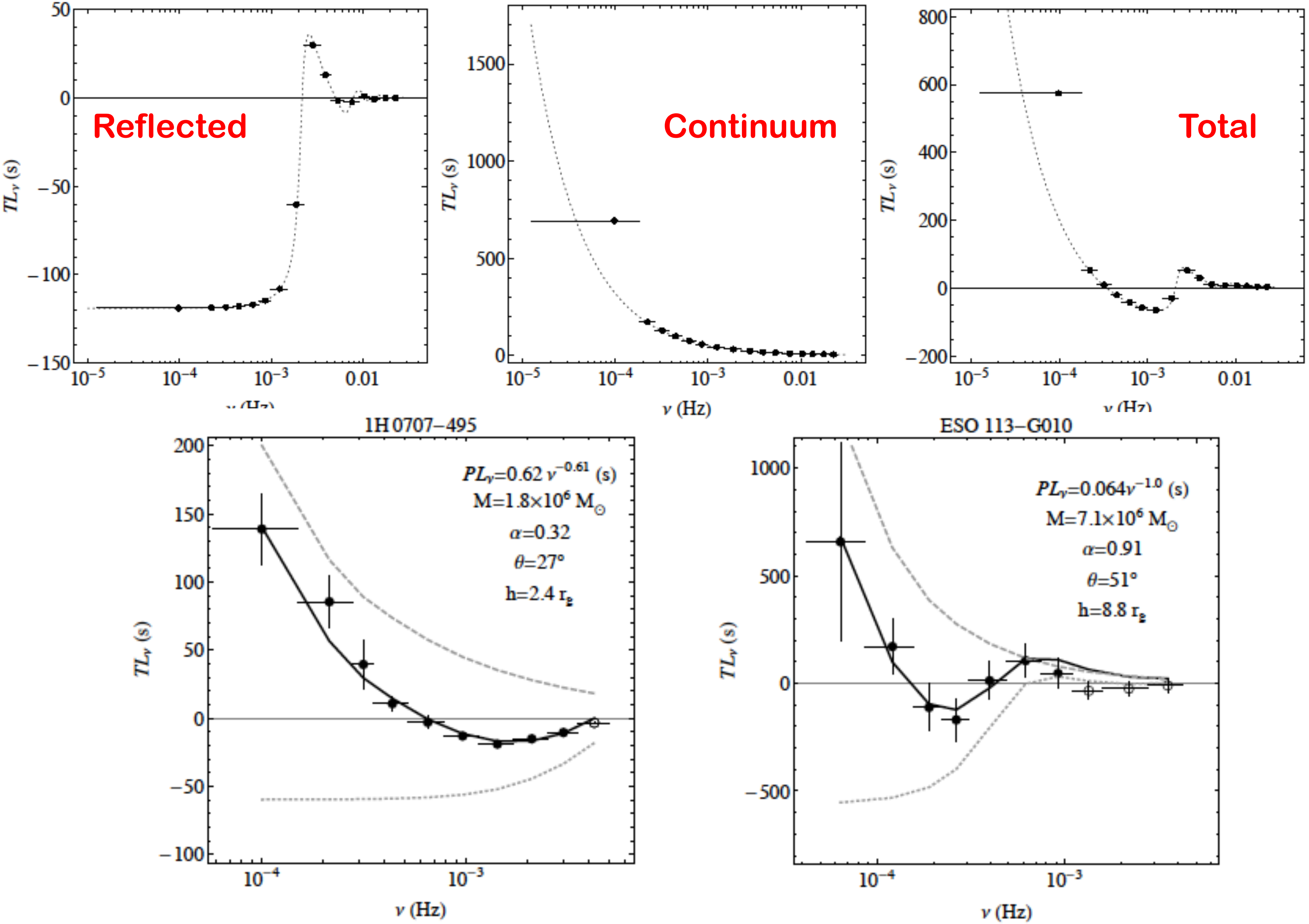
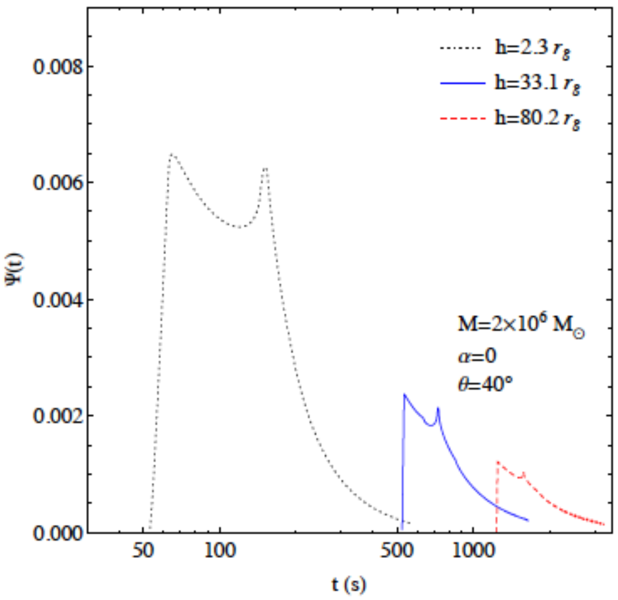
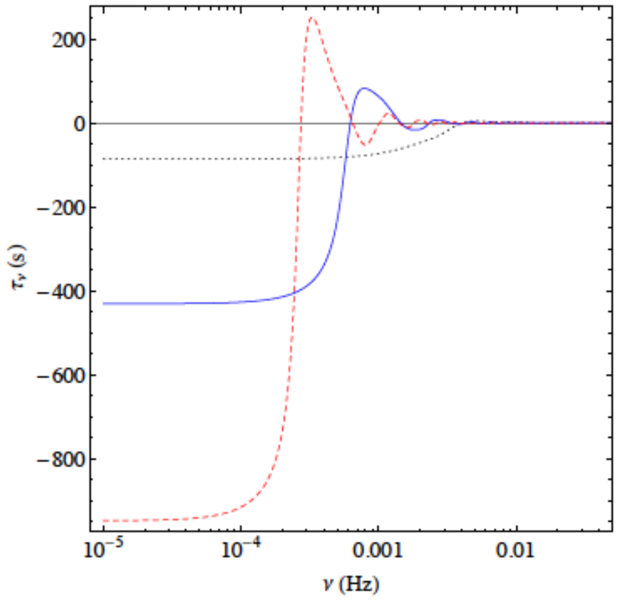




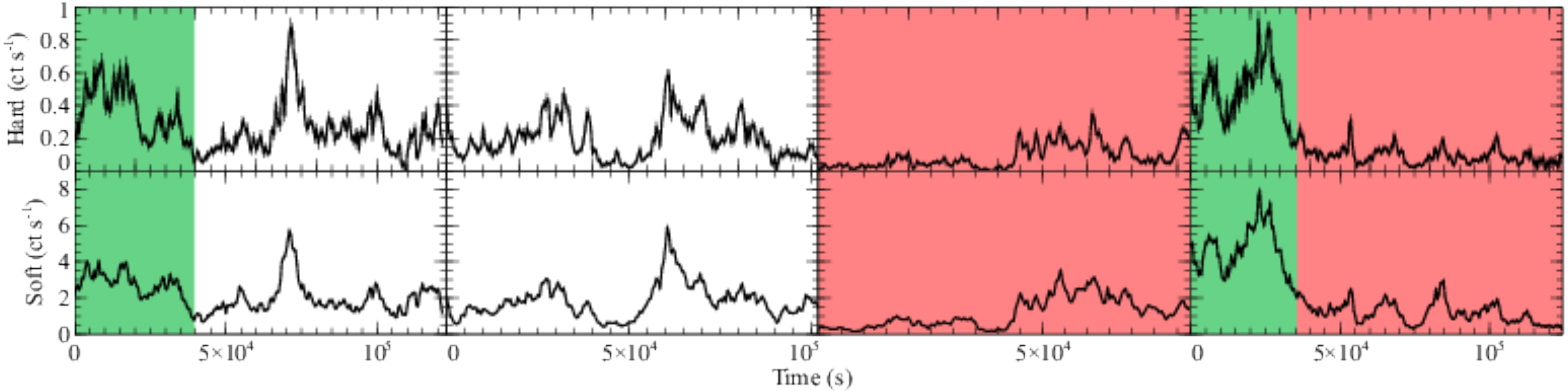


Effects of source h

lags get longer with h,
lags have lower frequencies,

and (e.g. light bending models)
X-ray flux increases with h

→ longer and lower frequency lags
at higher flux levels expected



Kara et al. 13

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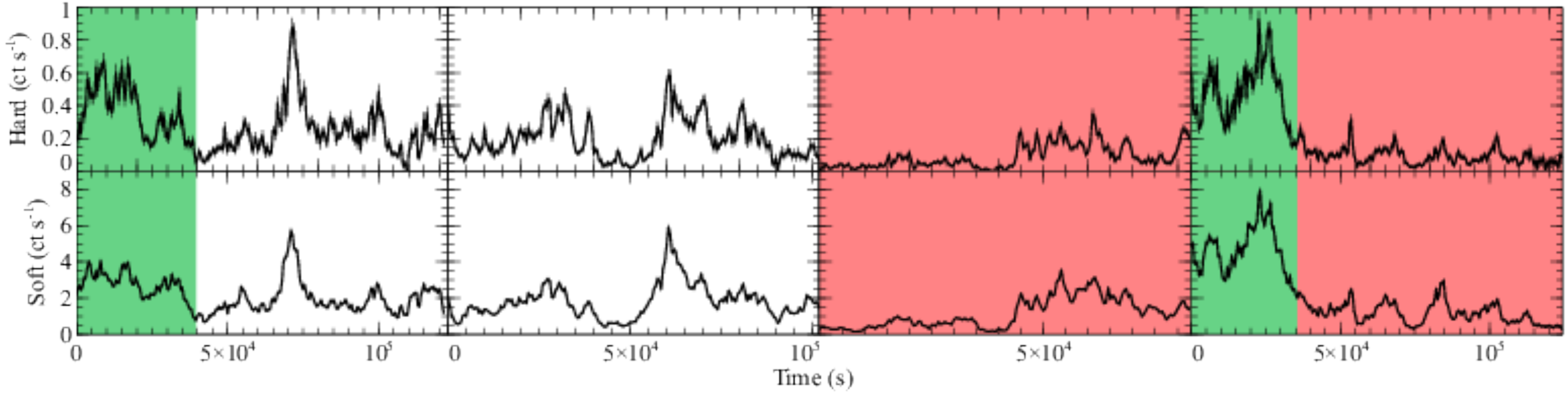

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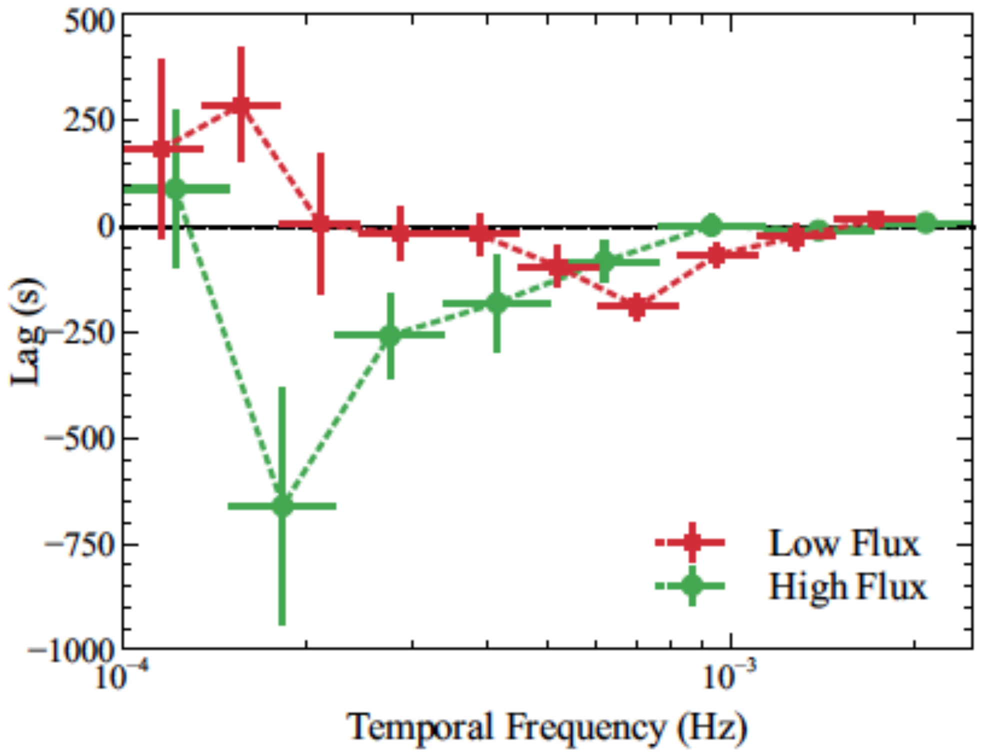
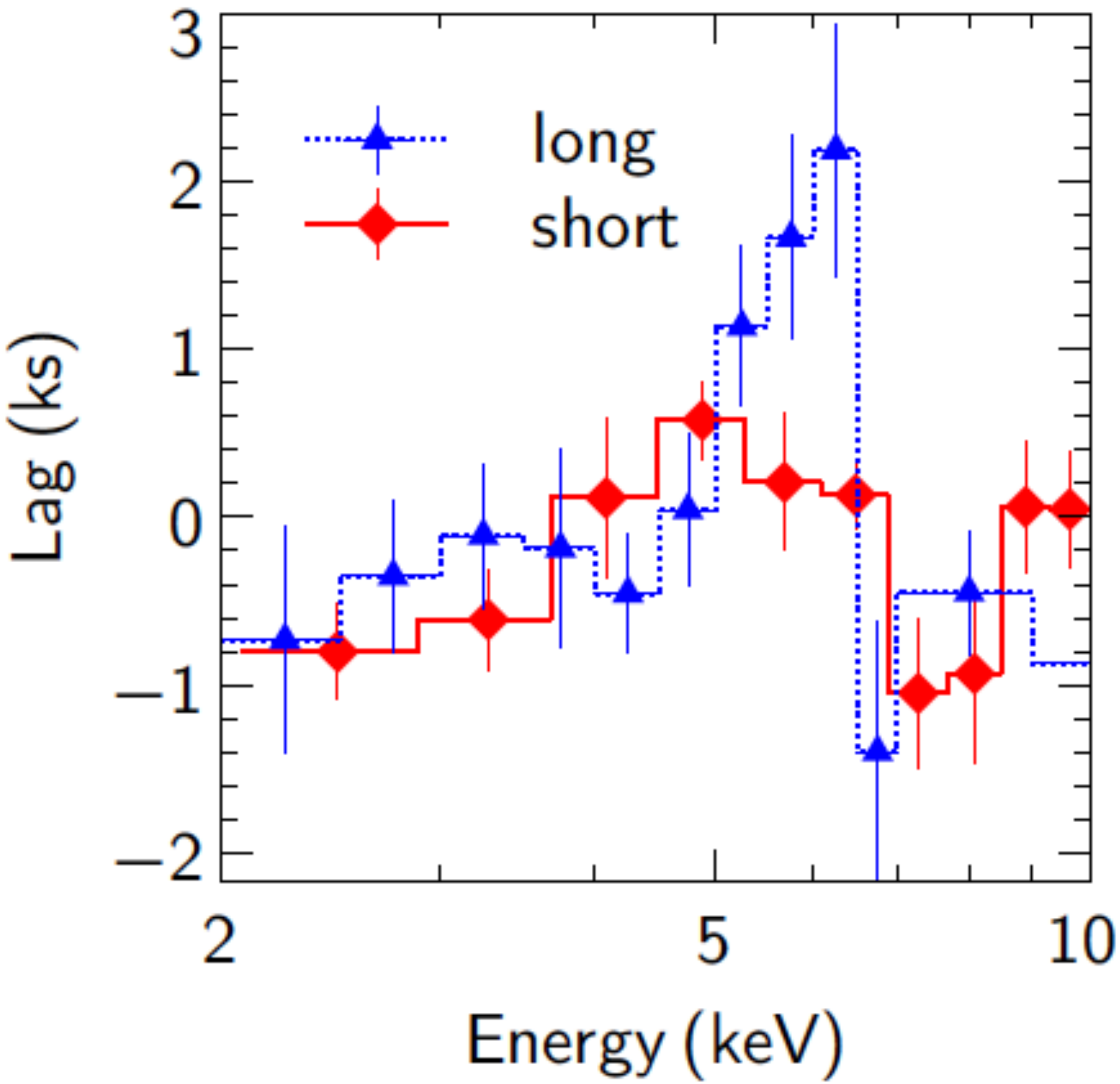
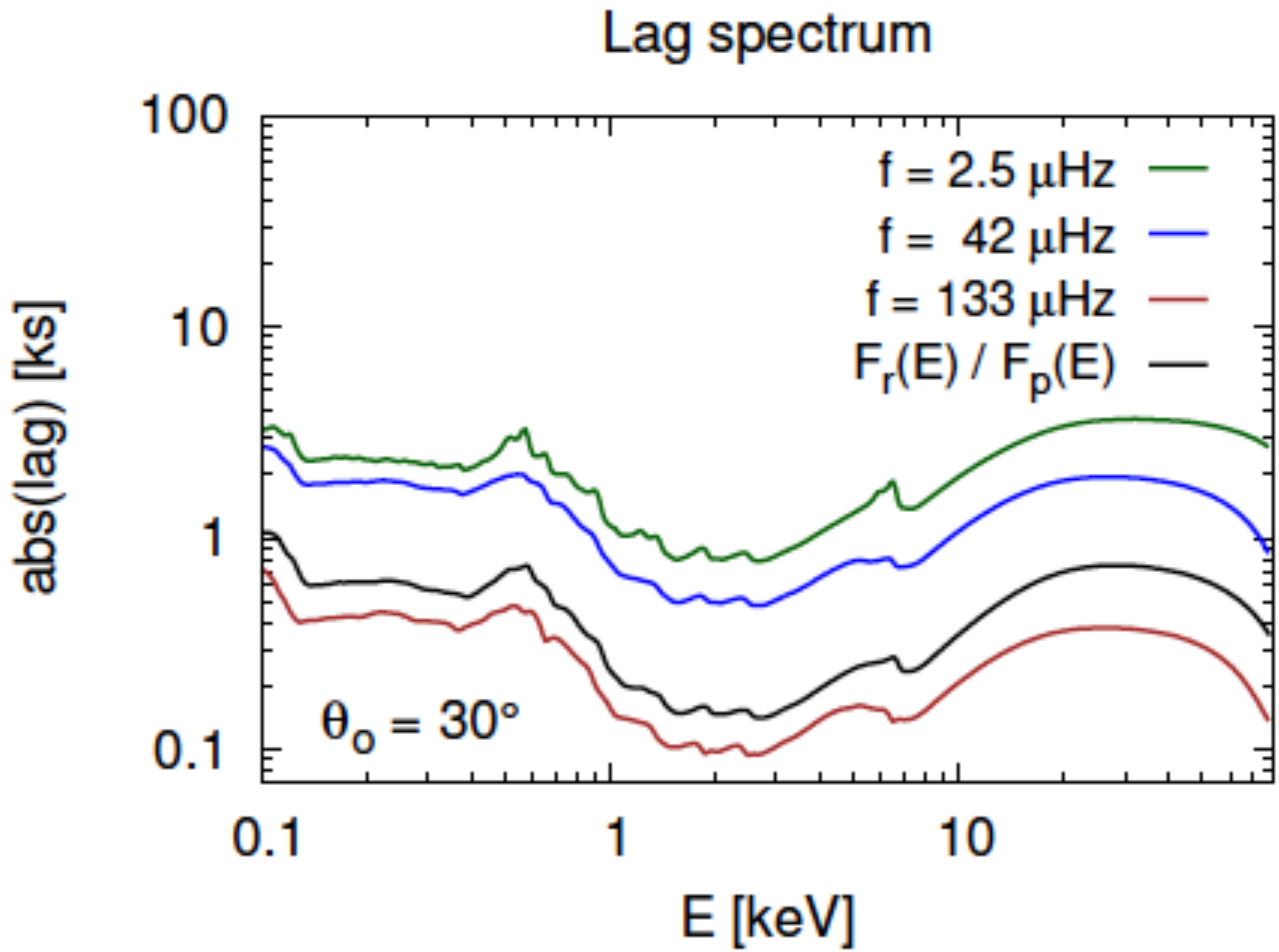
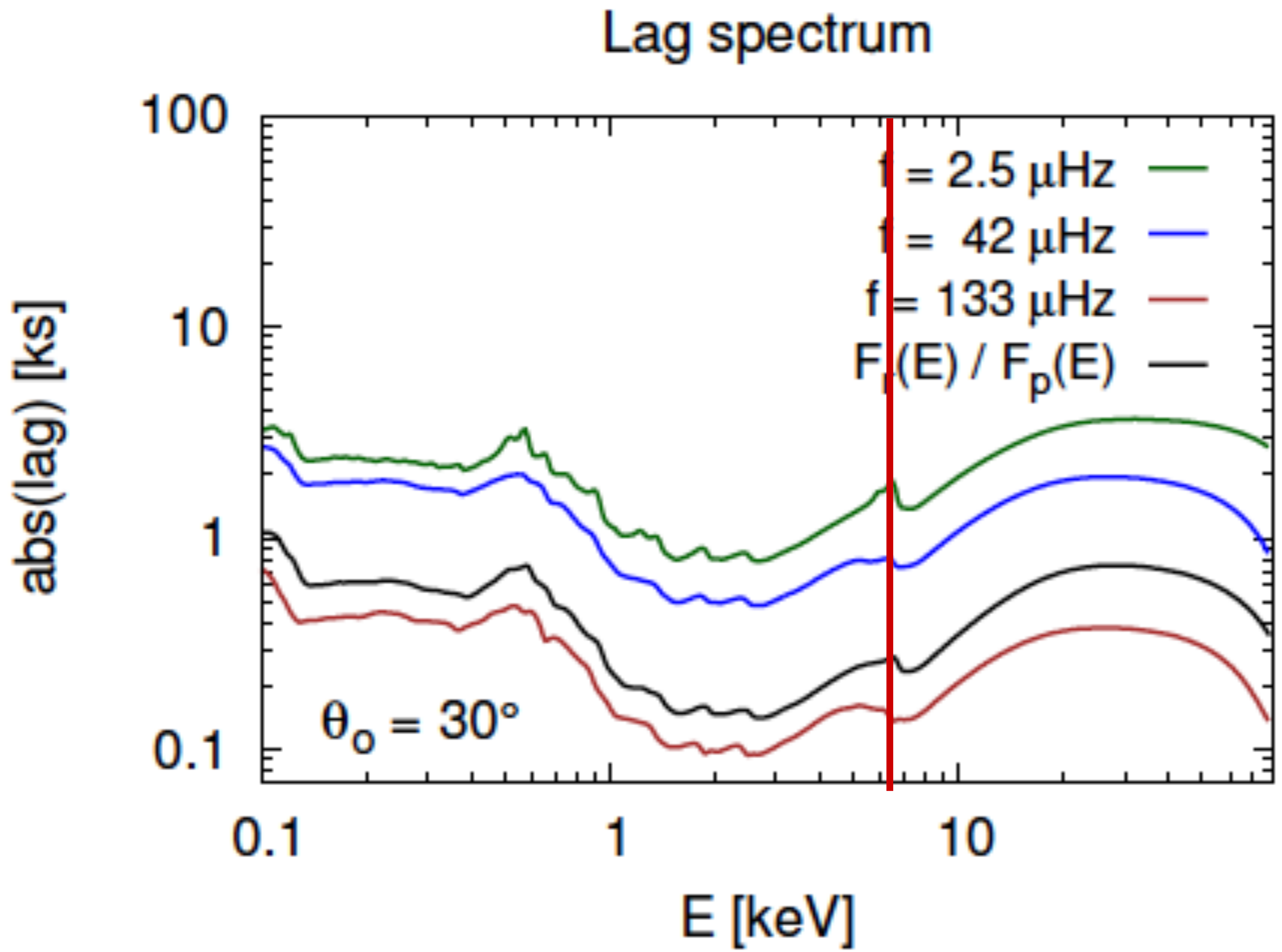




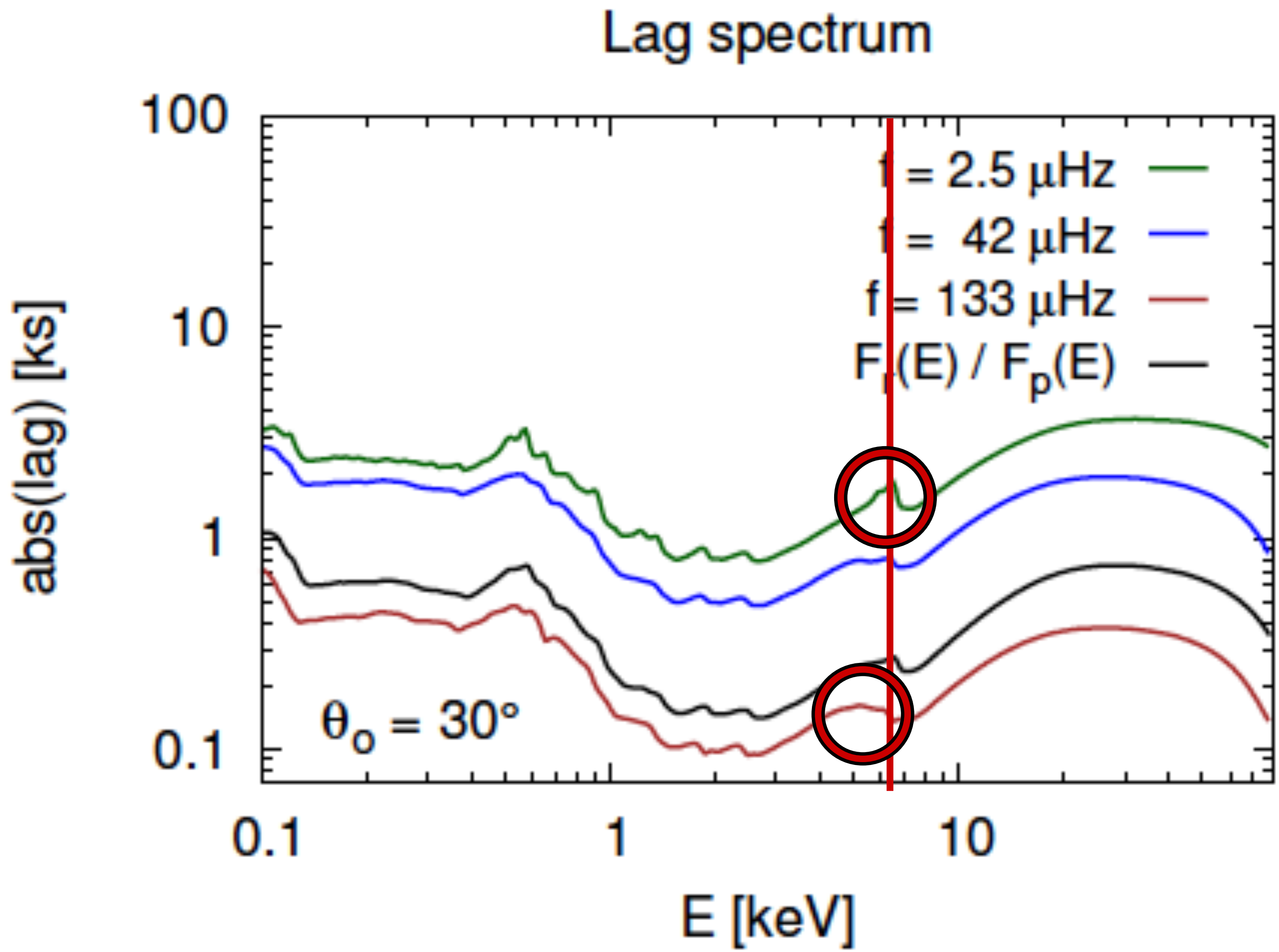
Zoghbi et al. 12



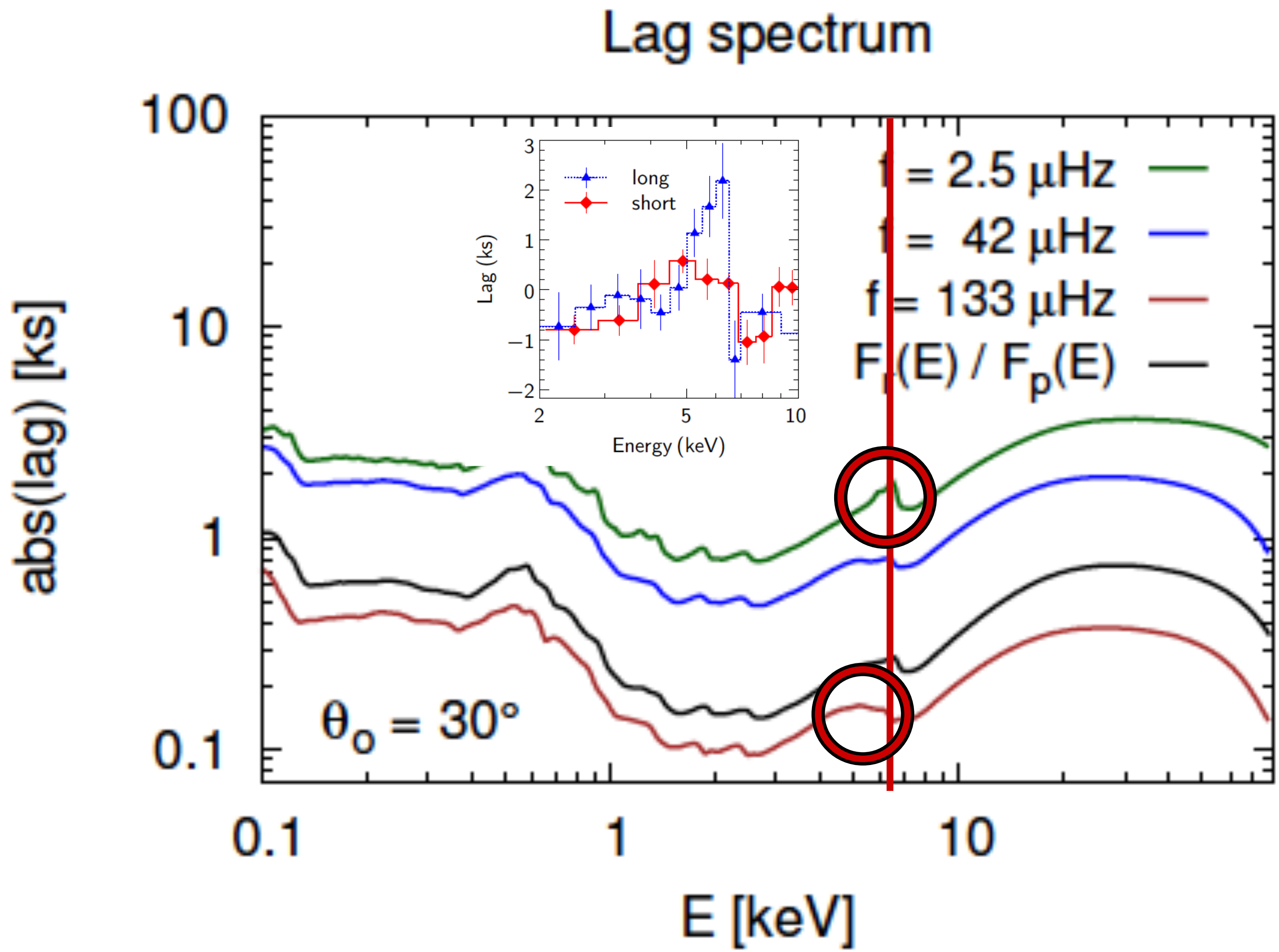
Lag spectrum
100
10
1
0.1
abs(lag) [ks]
f = 2.5 μHz
f = 42 μHz
f = 133 μHz
F_r(E) / F_p(E)
θ_o = 30°
0.1
1
10
E [keV]



Lag spectrum
100
10
1
0.1
abs(lag) [ks]
f = 2.5 μHz
f = 42 μHz
f = 133 μHz
F_l(E) / F_p(E)
θ_o = 30°
0.1
1
10
E [keV]



Lag spectrum
100
10
1
0.1
abs(lag) [ks]
f = 2.5 μHz
f = 42 μHz
f = 133 μHz
F(E) / F(E)
θo = 30°
0.1
1
10
E [keV]


Lag spectrum
abs(lag) [ks]
100
10
1
0.1
0.1
1
10
E [keV]
f = 2.5 μHz
f = 42 μHz
f = 133 μHz
F_l(E) / F_p(E)
θ_o = 30°
Lag (ks)
Energy (keV)
long
short