Observations of X-ray reverberation in AGN

Barbara De Marco

N. Copernicus Astronomical Center of the Polish Academy of Sciences

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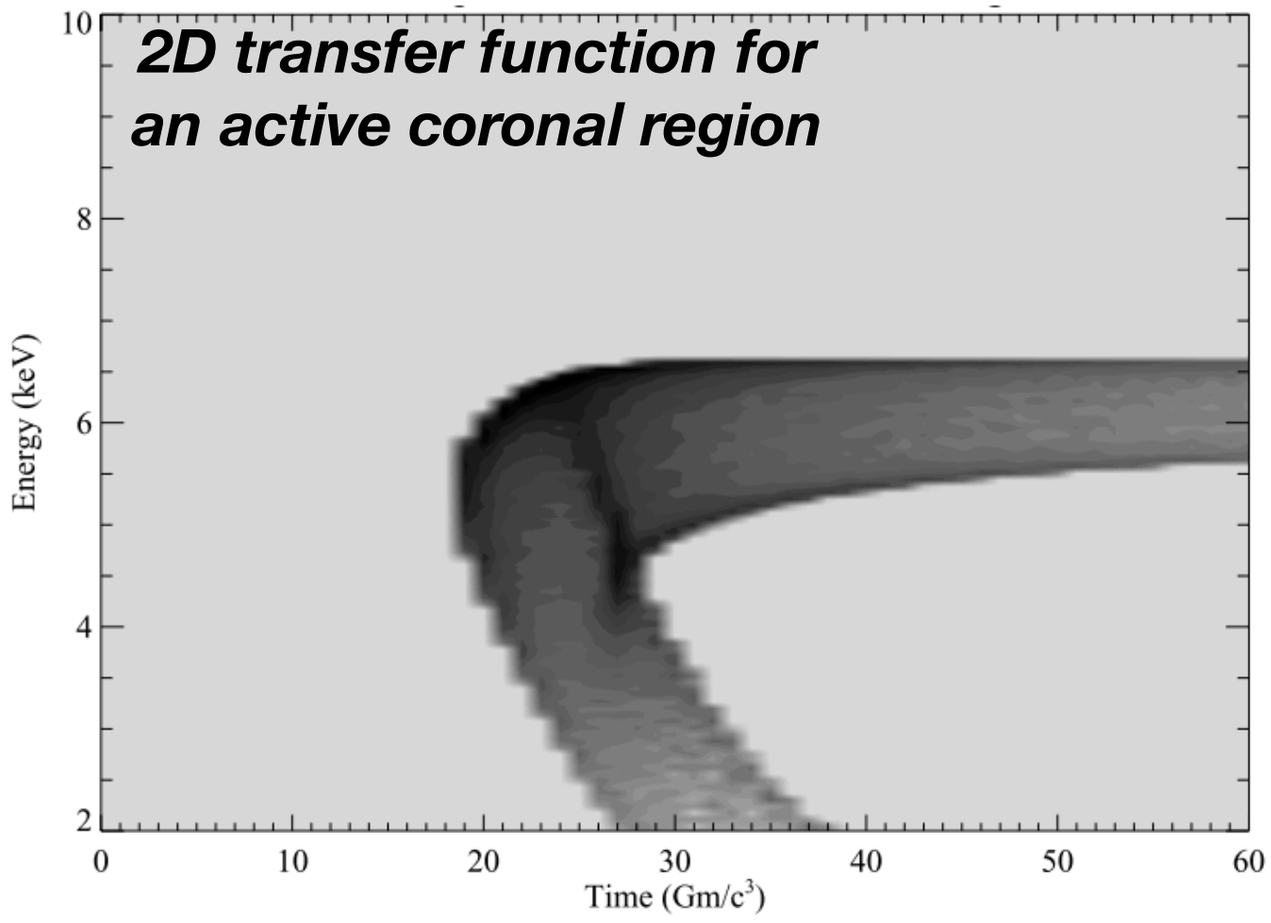
Predictions of X-ray reverberation

Relativistic Fe line responding to fast variability of primary continuum

[Reynolds+'99]



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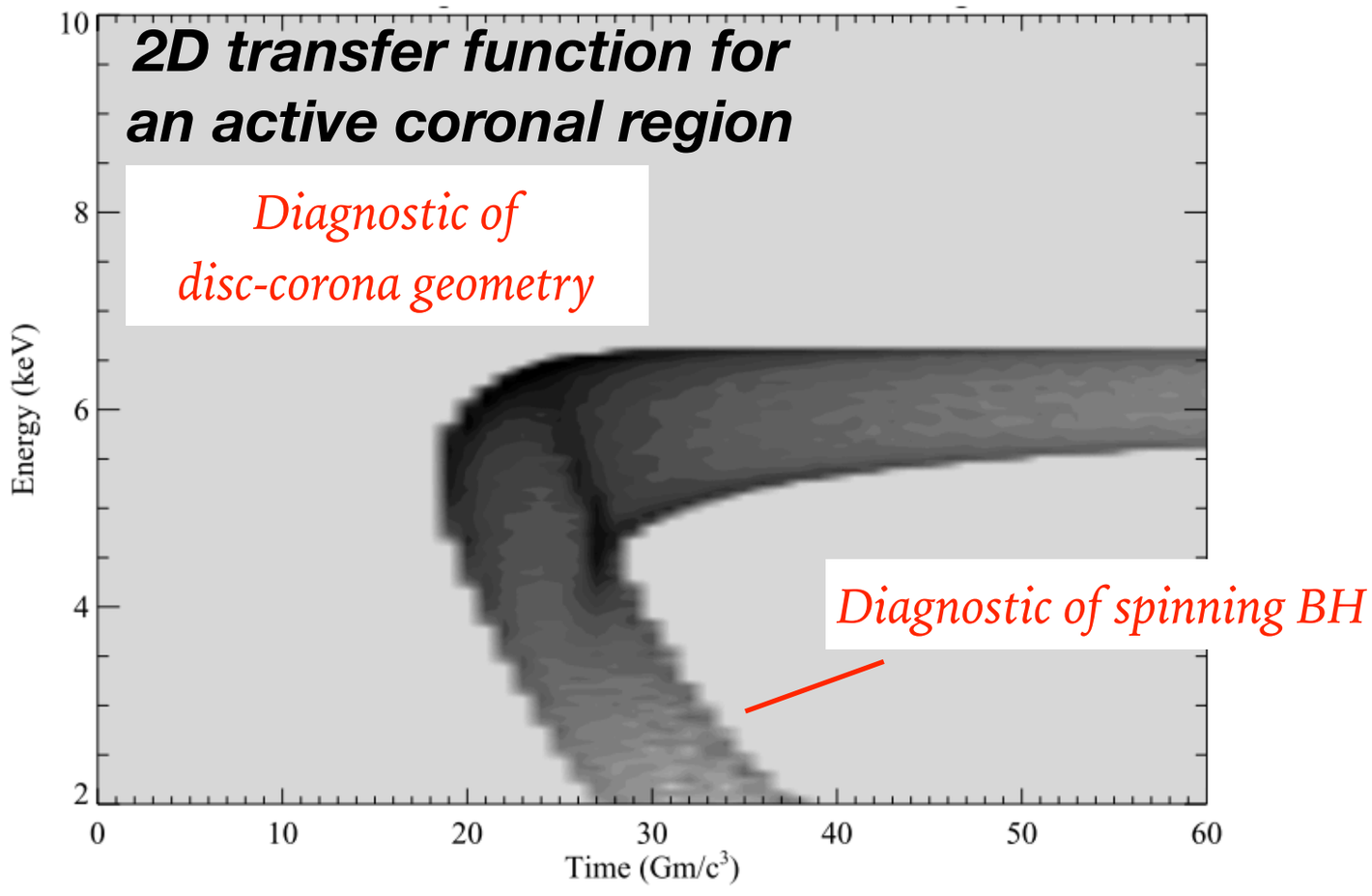


Reverberation + spectral modelling ➔ BH mass *[Stella '90]*

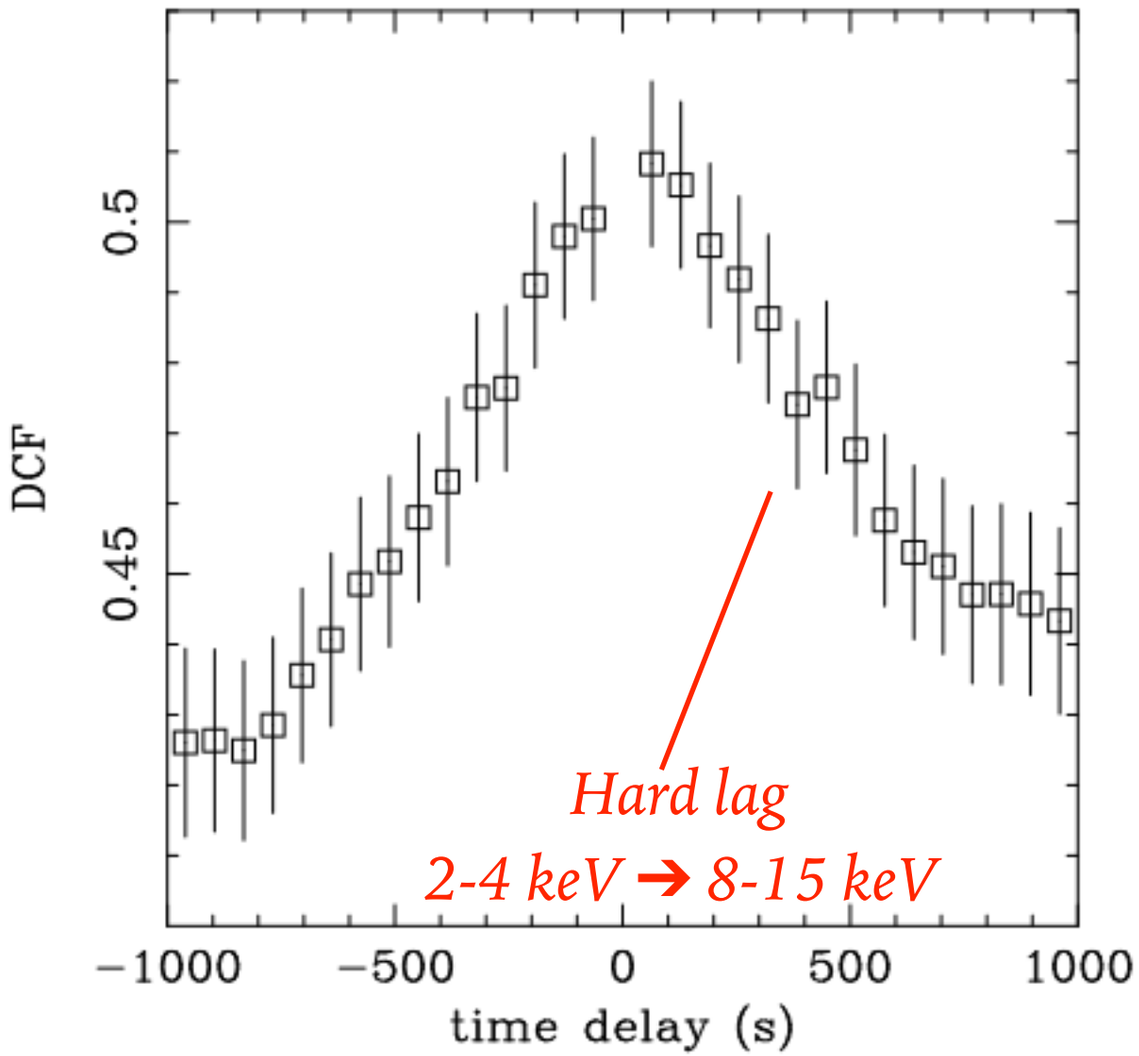
[see also Matt & Perola '92; Campana & Stella '93, '95]

Attempts to detect X-ray reverberation

FIRST RESULTS:

No signatures of FeK reverberation, hard lags commonly detected

[e.g. Reynolds'00; also Vaughan & Edelson '01; Papadakis+'01]



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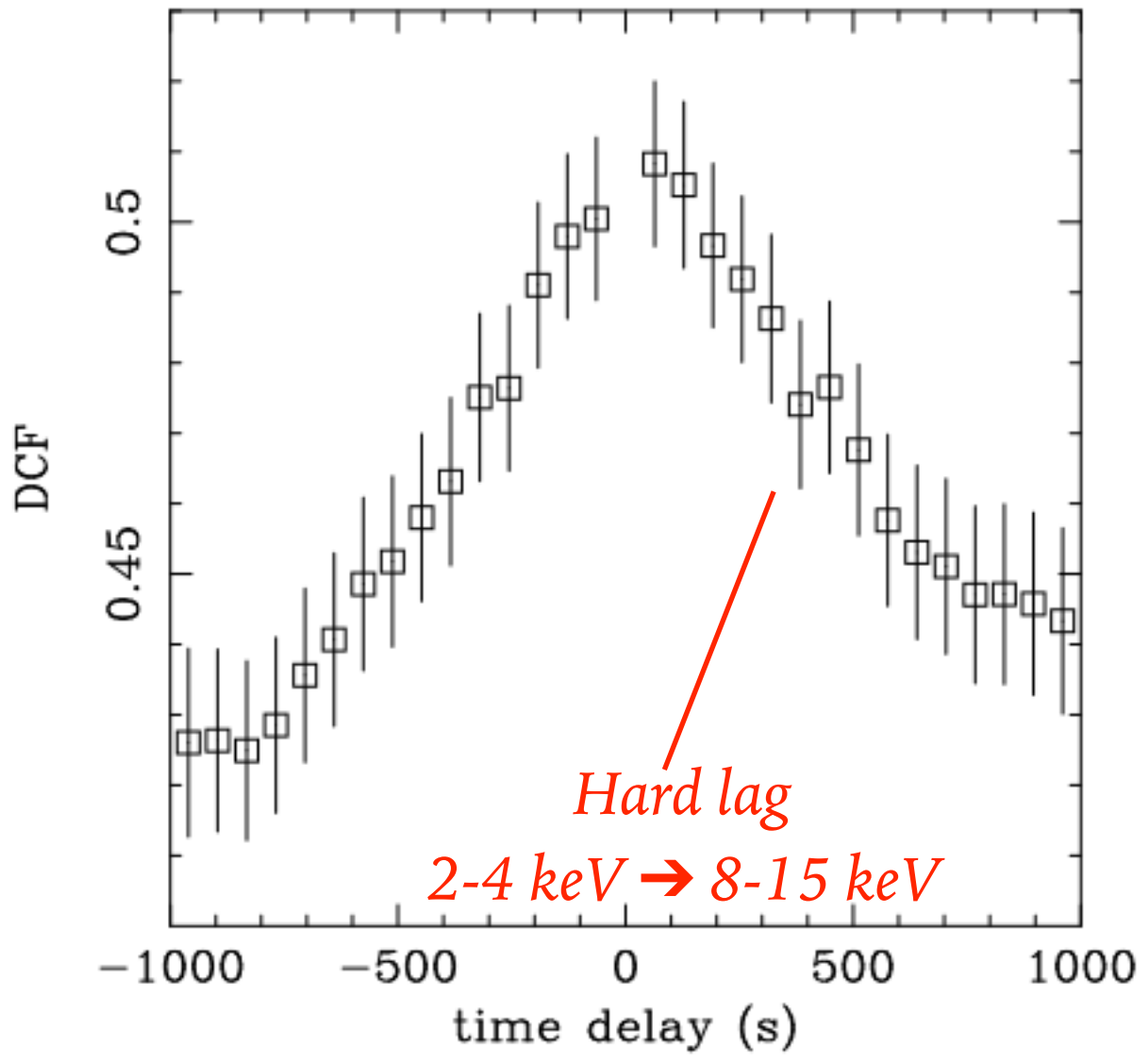

But first attempts based on time-domain spectral analysis!

First hints of reverberation

Fourier-domain techniques increase sensitivity by $\sim\sqrt{N_{var\_cyc}}$

+ allow separating different variability components

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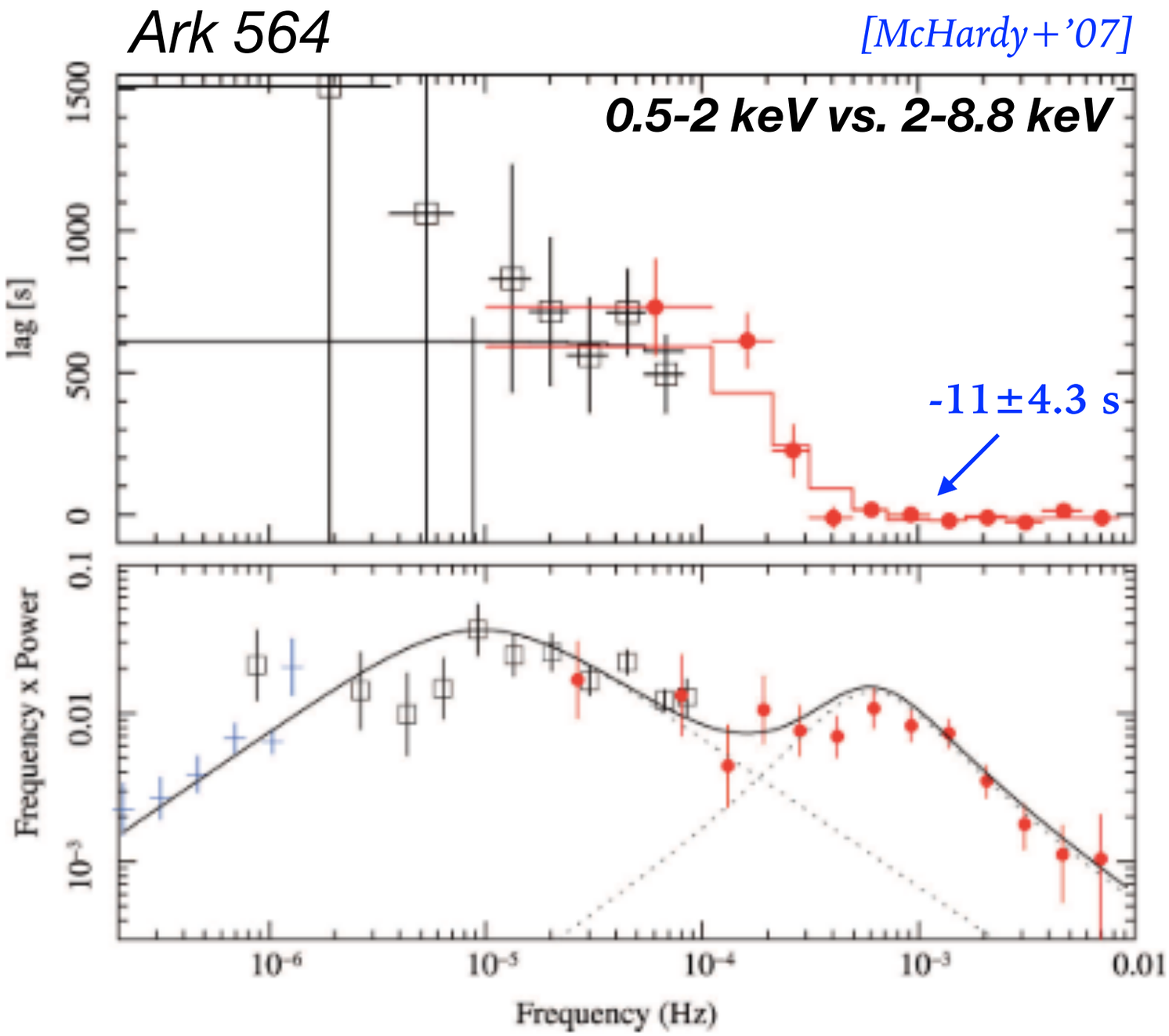
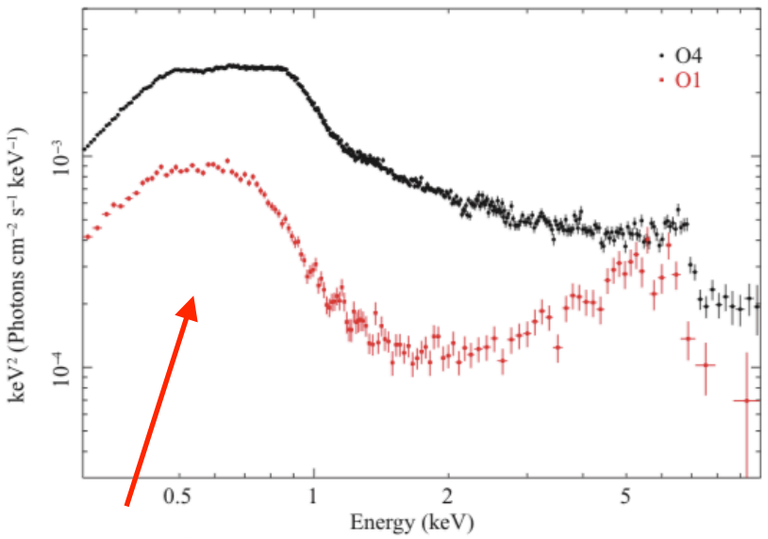


"This observation suggests that the high-frequency variability in the soft band might arise from reflection/ reprocessing within ~1Rg of the illuminating hard X-ray source, implying the existence of cold gas close to the central X-ray source."

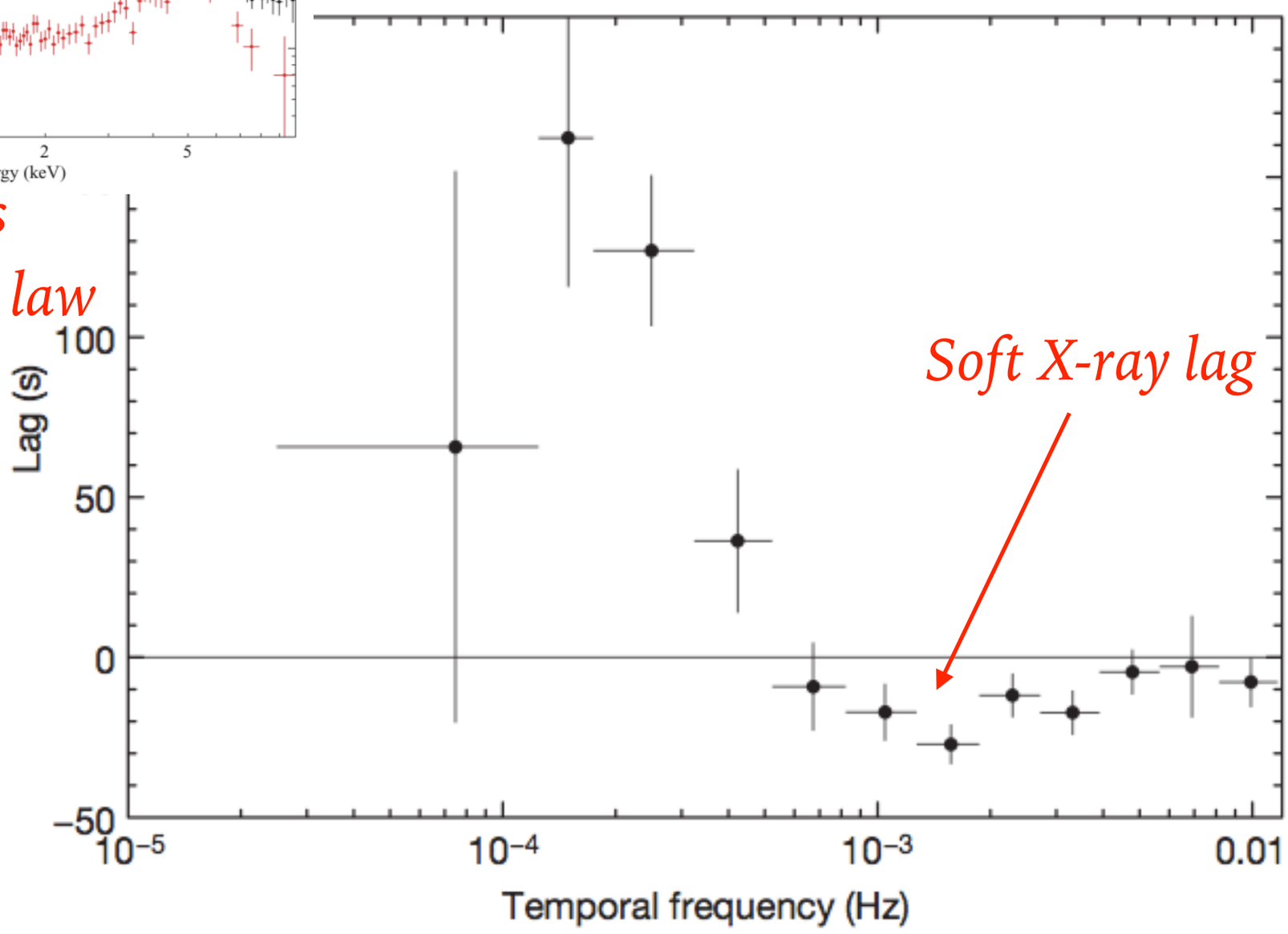
First significant detection: 1H0707-495



Soft excess

lagging power law

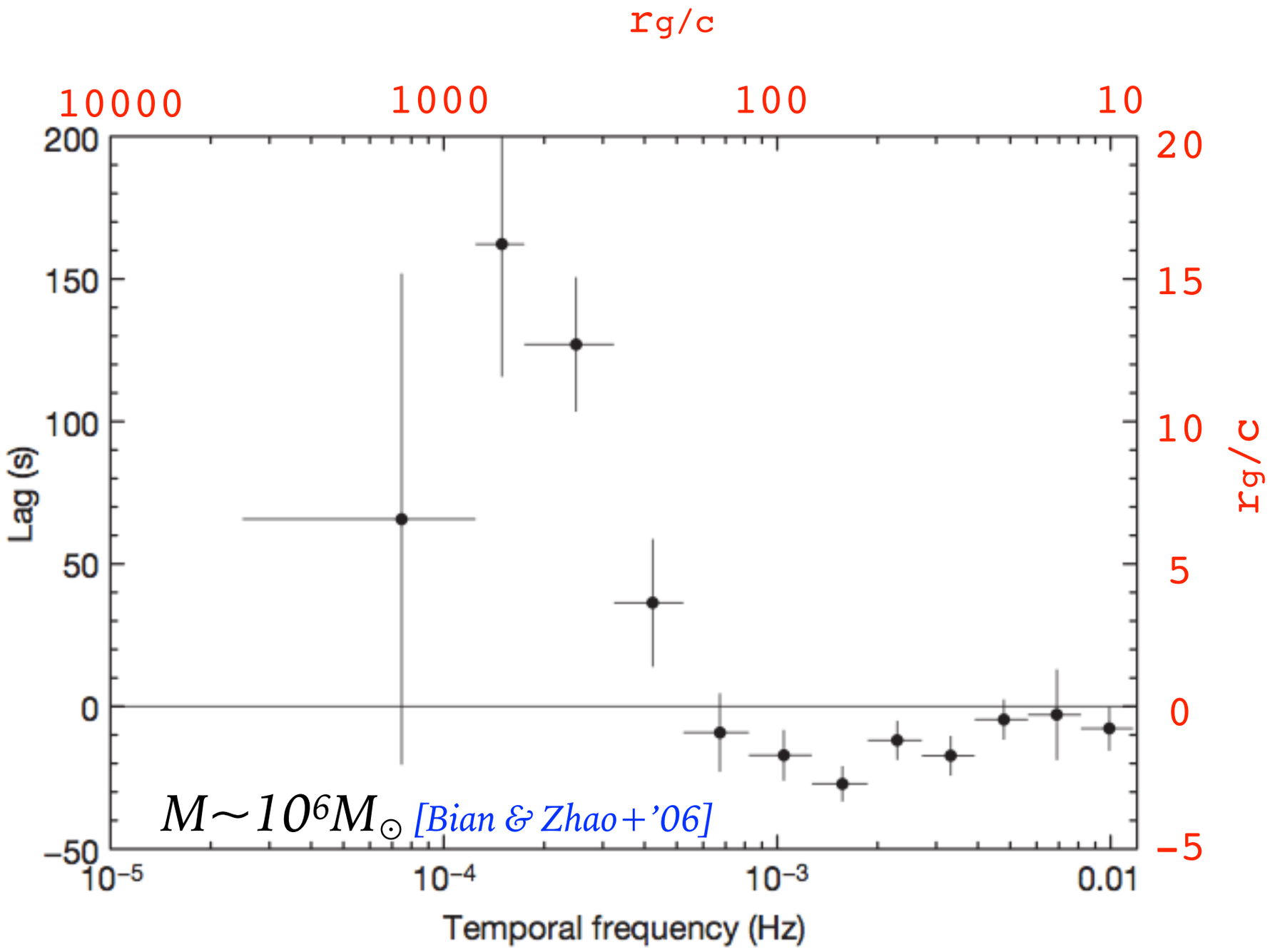
[Fabian+'09, Zoghbi+'10]



Soft X-ray lag

Minutes

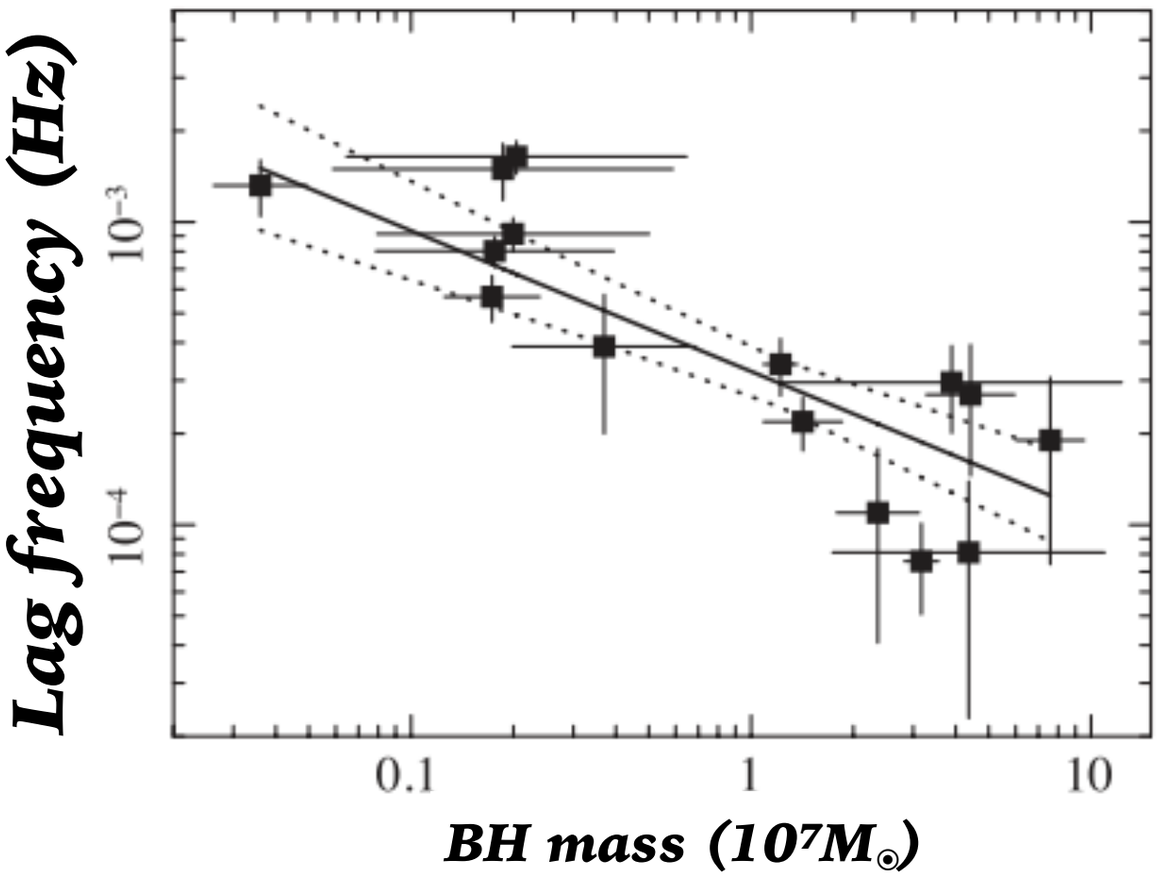
First significant detection: 1H0707-495

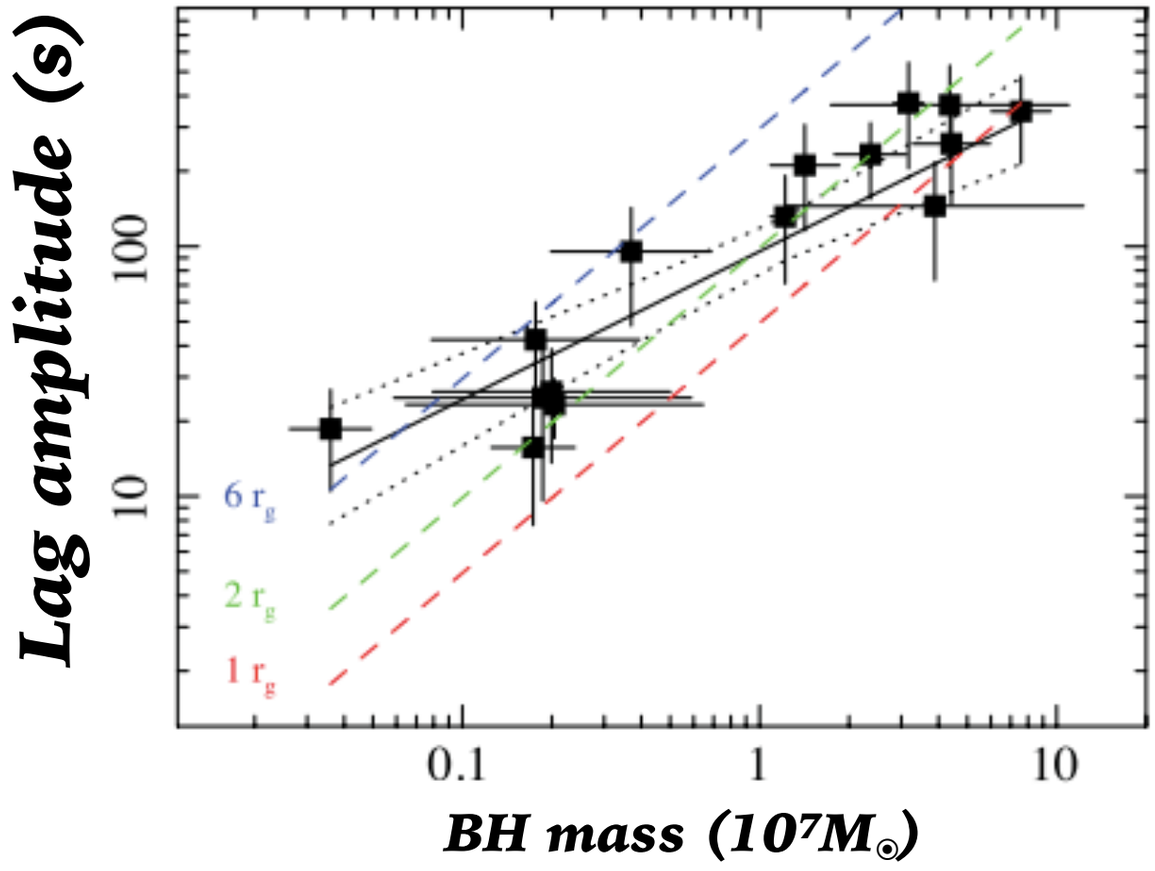


Is it reverberation from the inner disc?

Dependence of soft lags on BH mass

[De Marco+'13]





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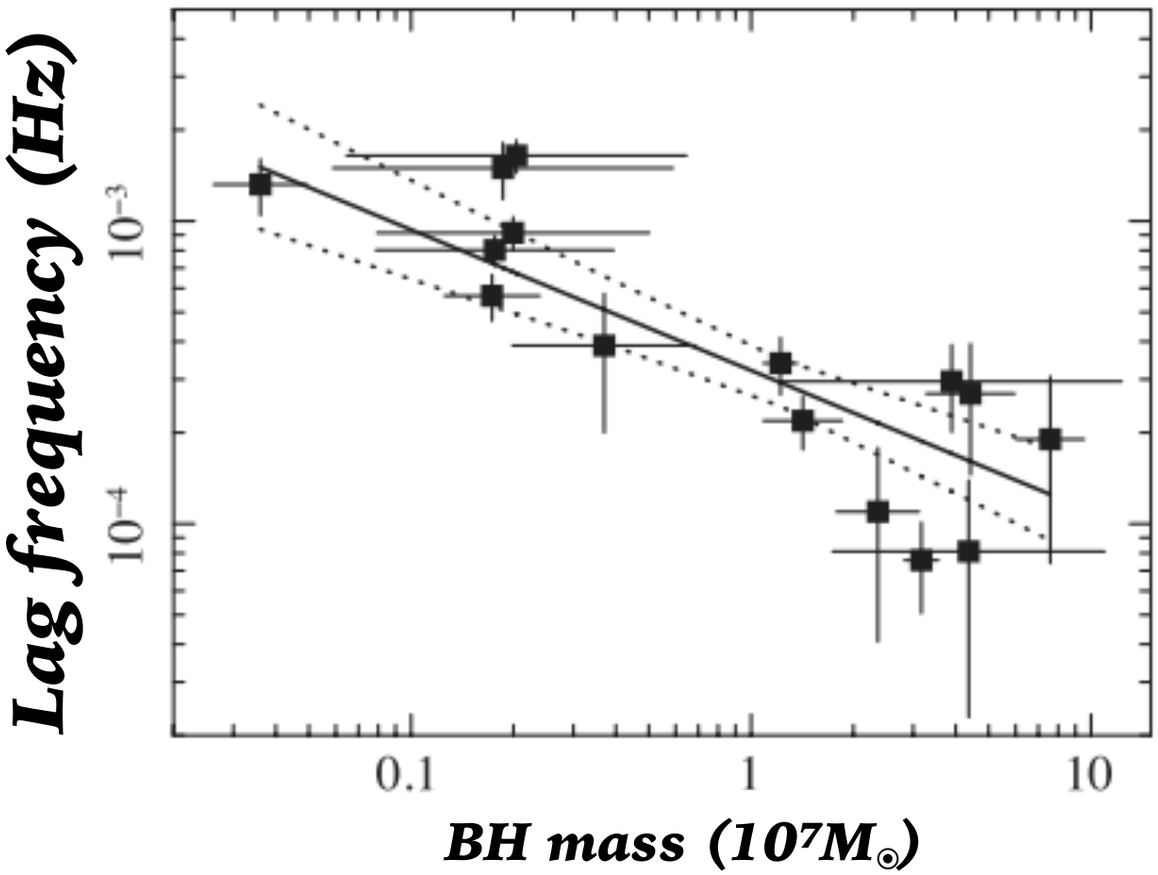

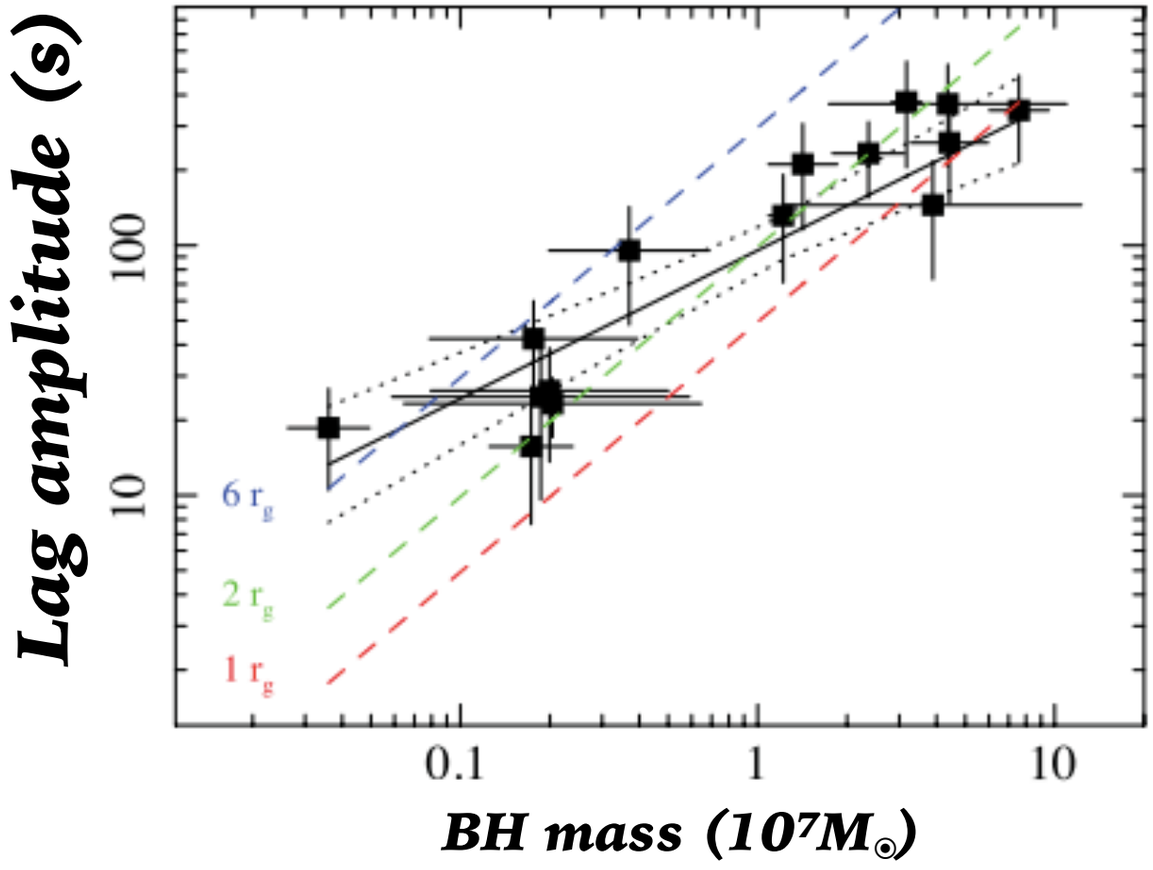

- *The soft excess contains a reprocessing component*

Dependence of soft lags on BH mass

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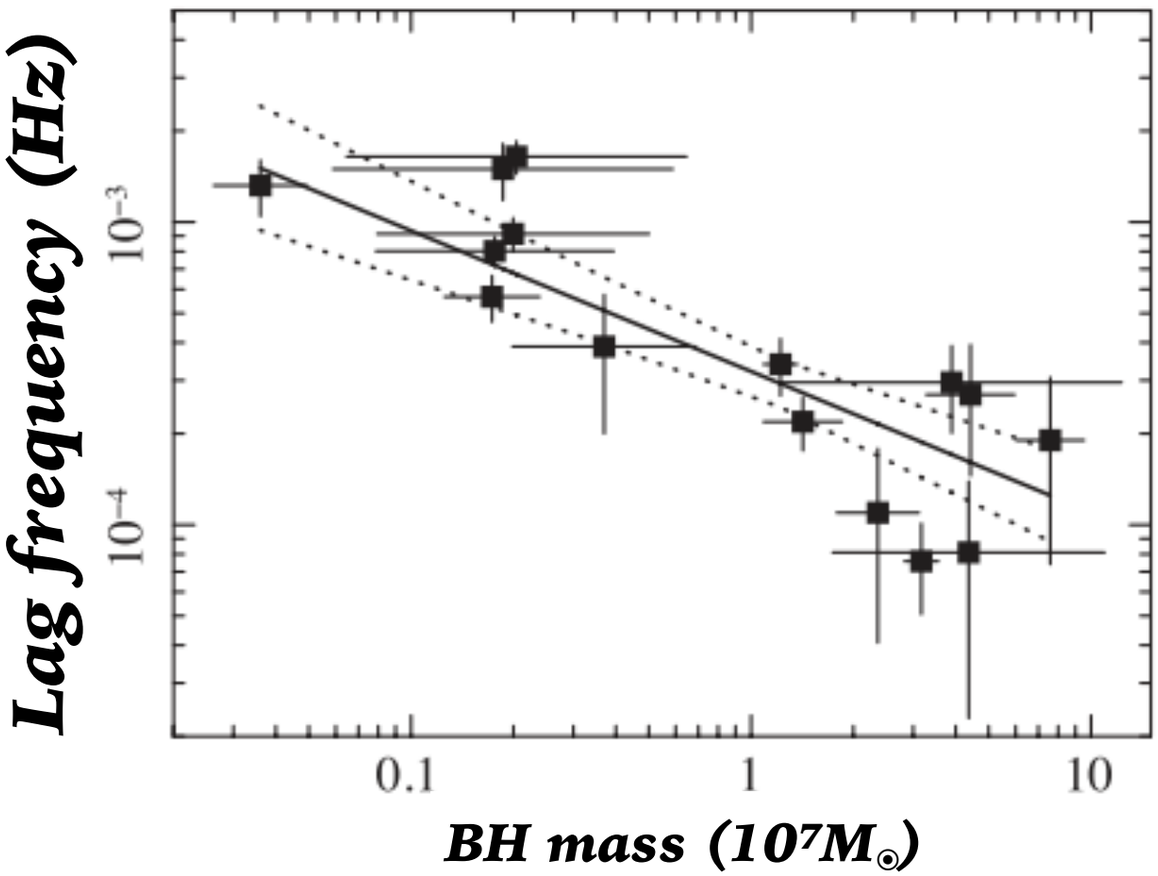

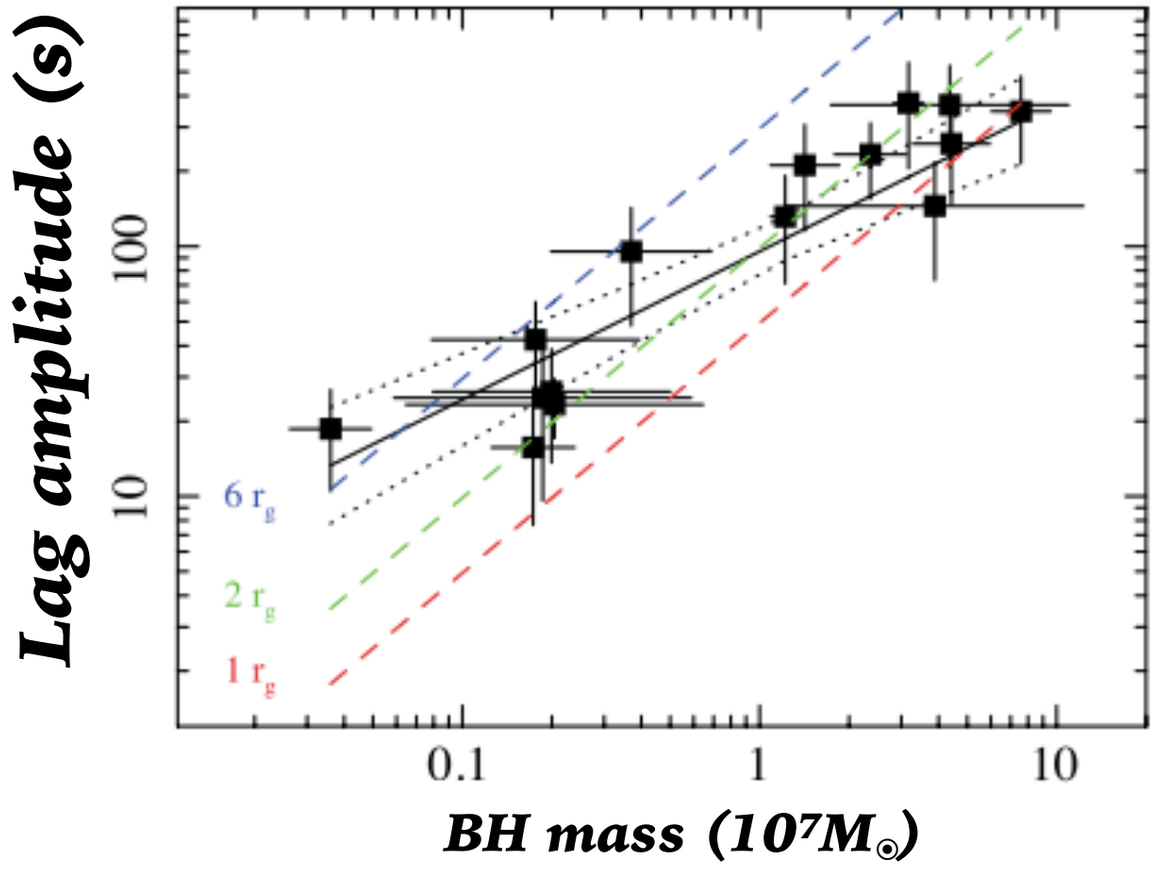

- *The soft excess contains a reprocessing component*
- *Same geometry, and lag scaling with the size of the system*

Dependence of soft lags on BH mass

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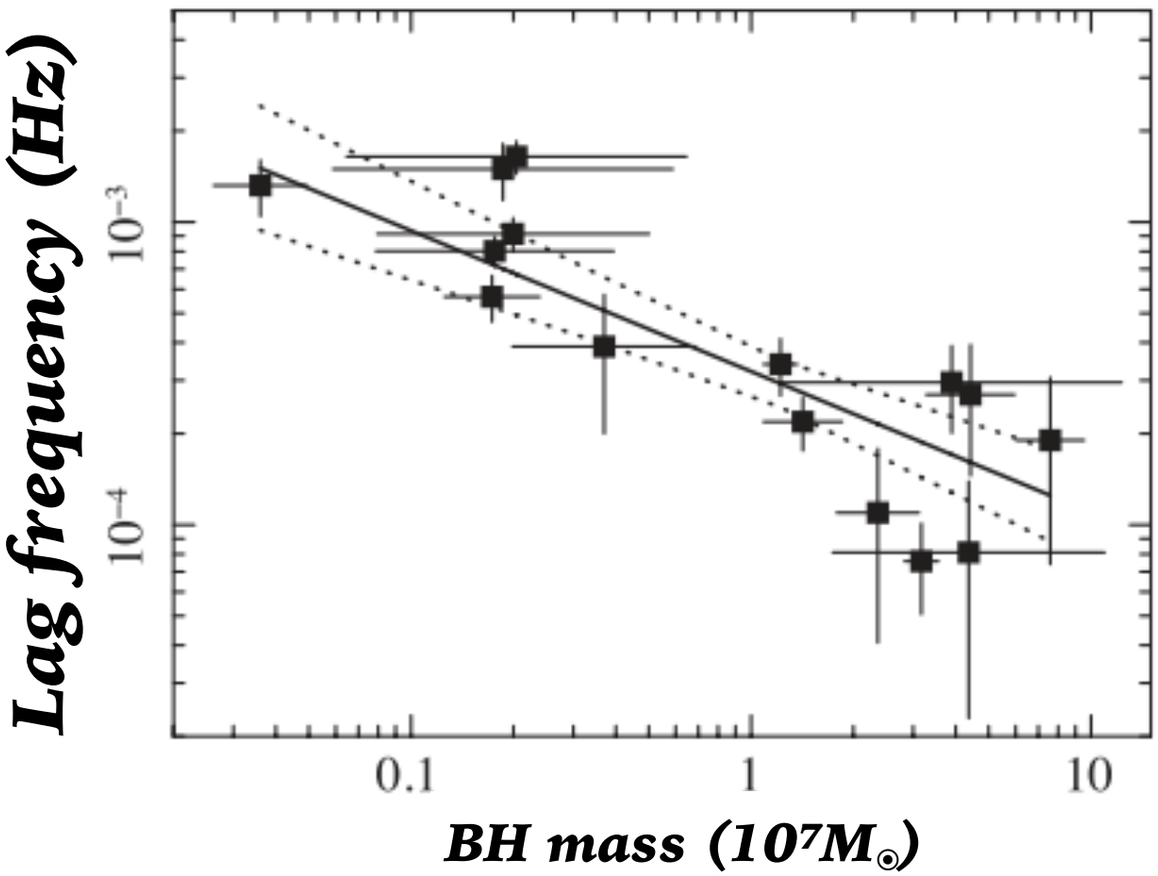

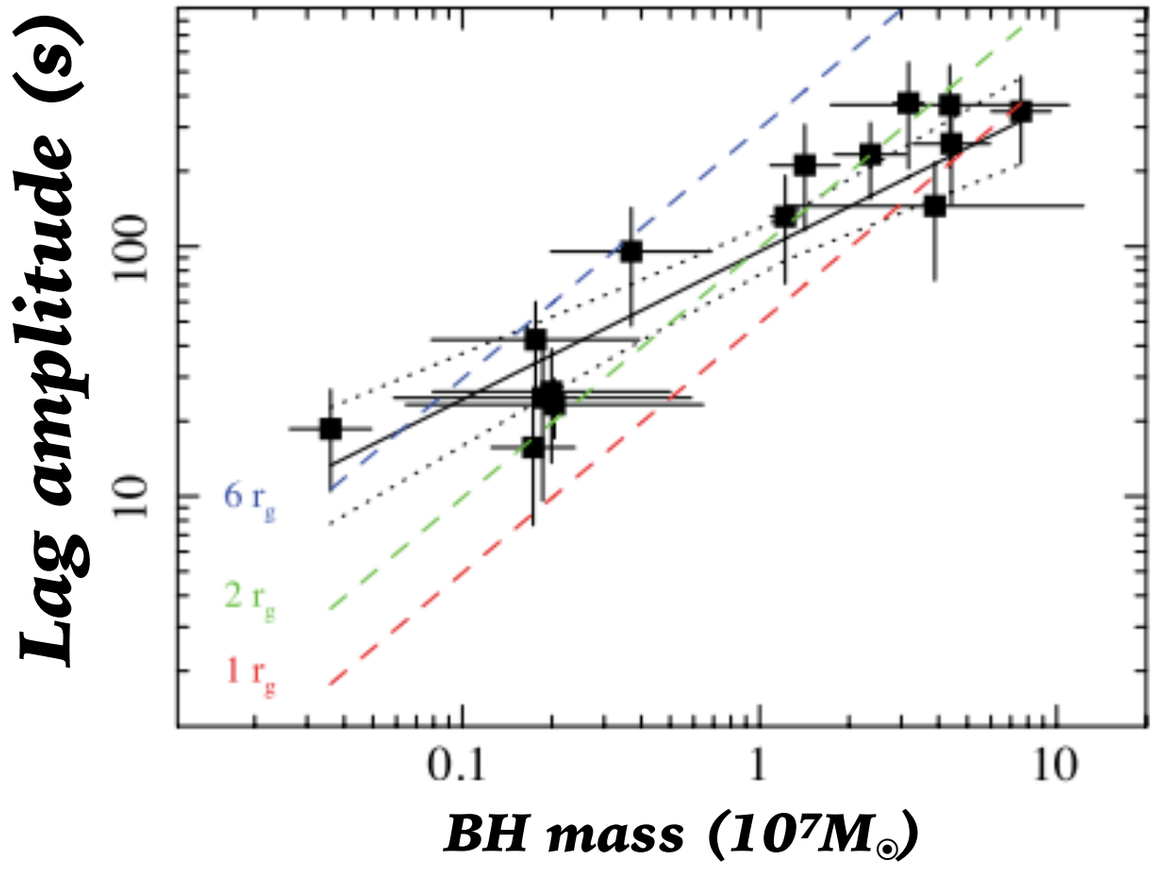

- *The soft excess contains a reprocessing component*
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- *Fast variability originates in a compact region*

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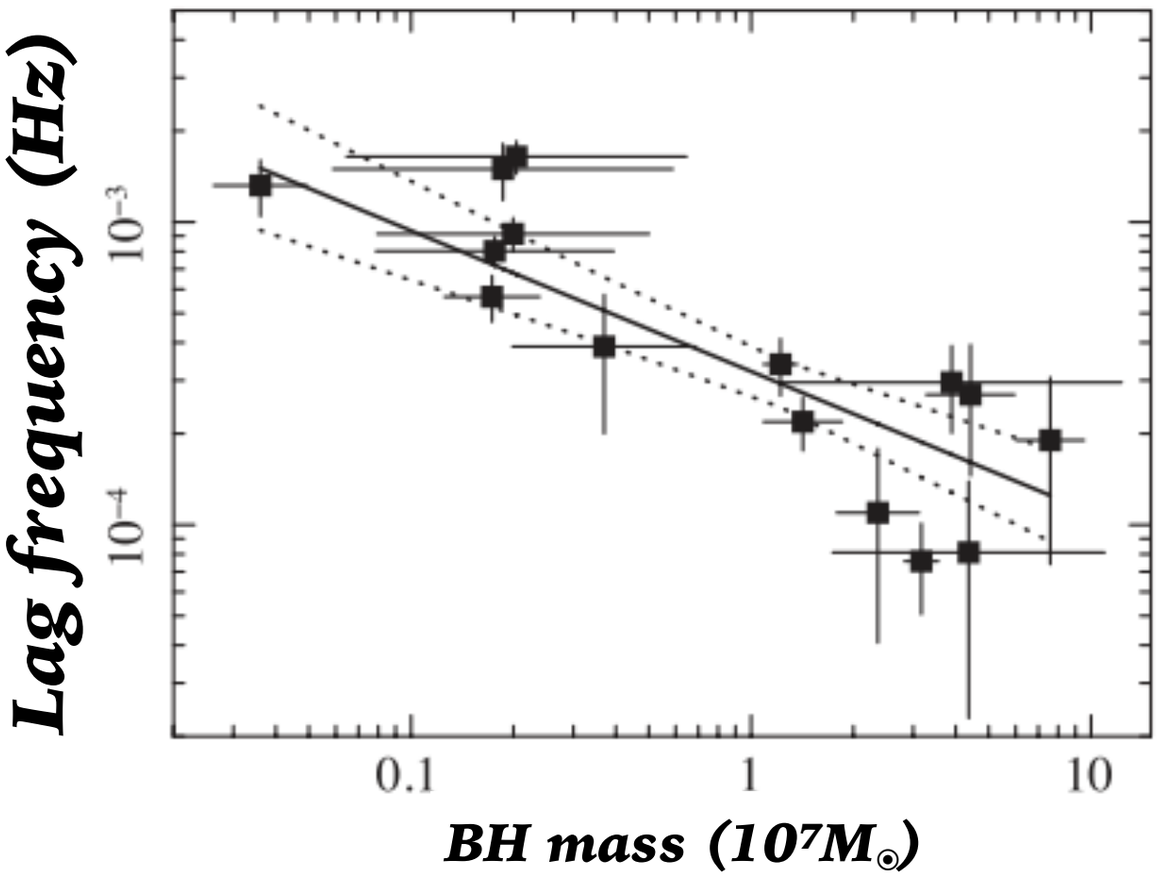

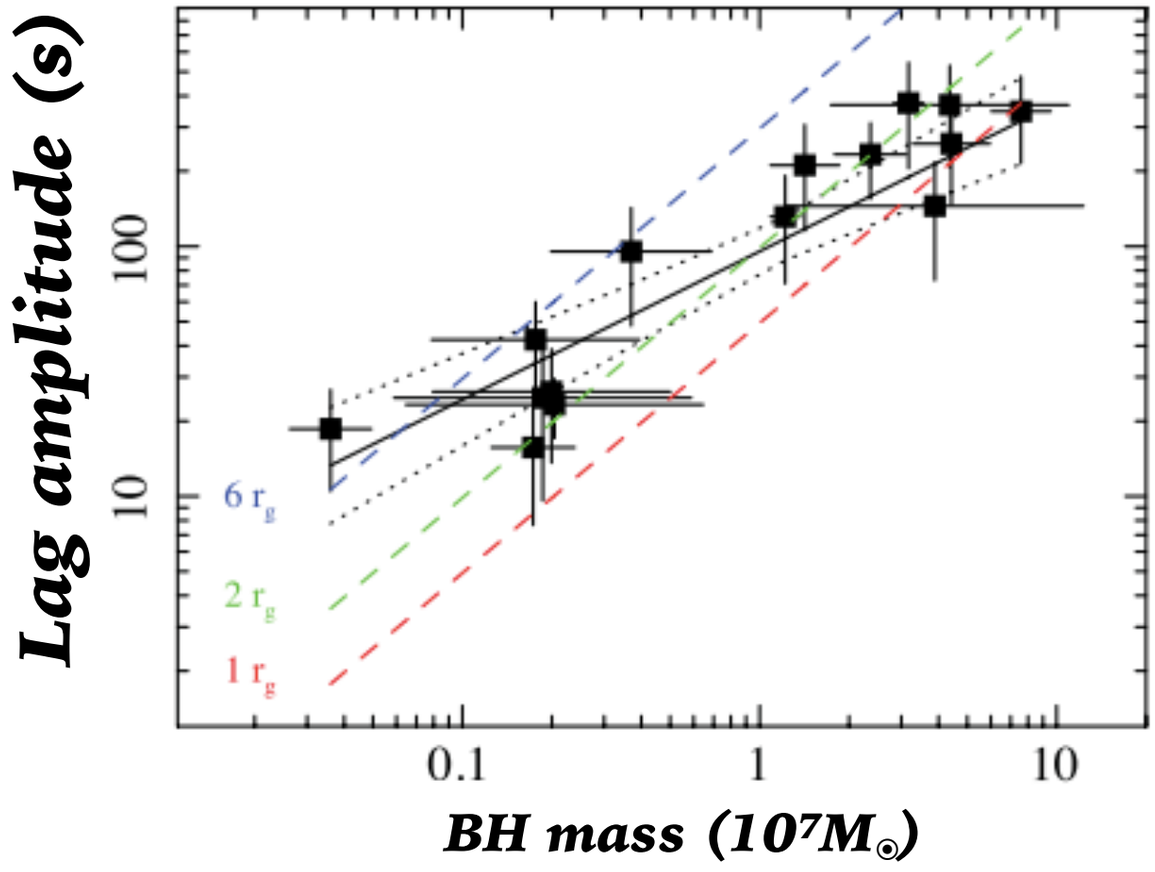

- *The soft excess contains a reprocessing component*
- *Same geometry, and lag scaling with the size of the system*
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- *The X-ray source and the reprocessing site are close*

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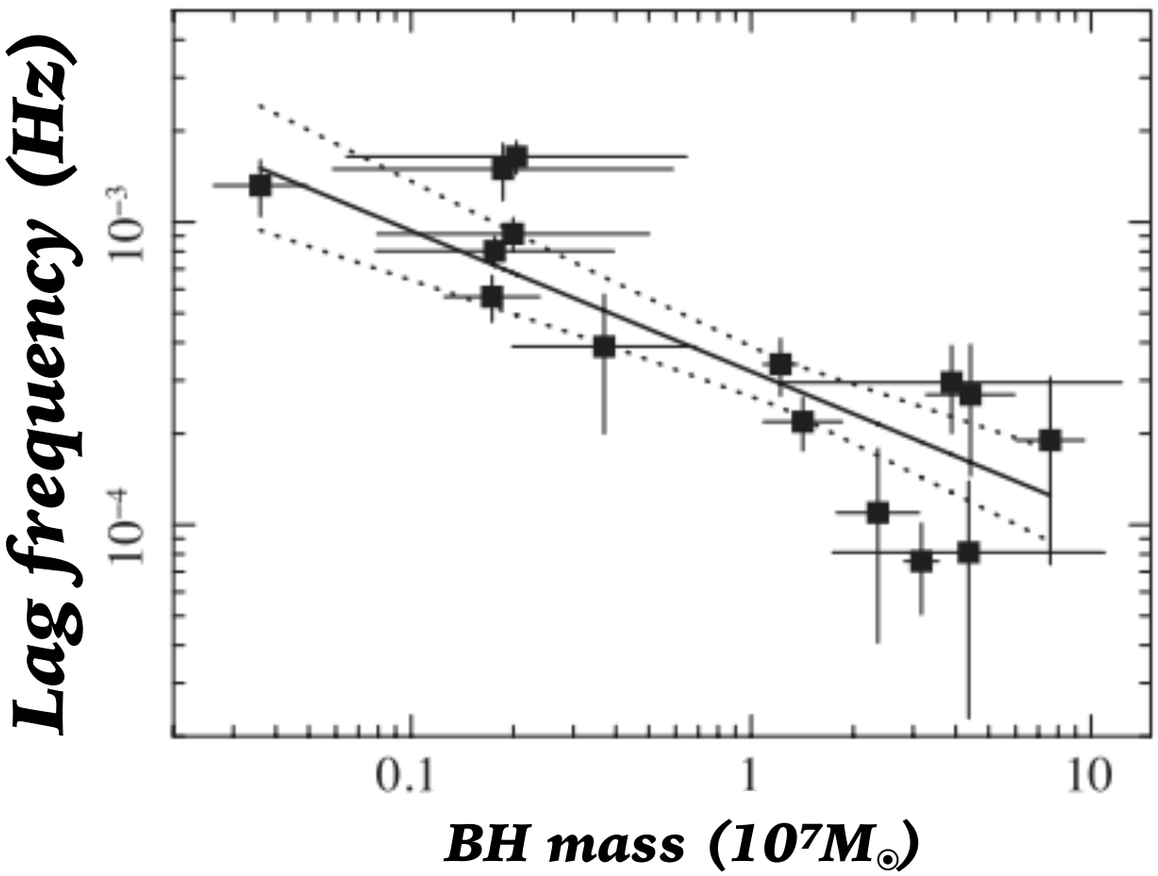
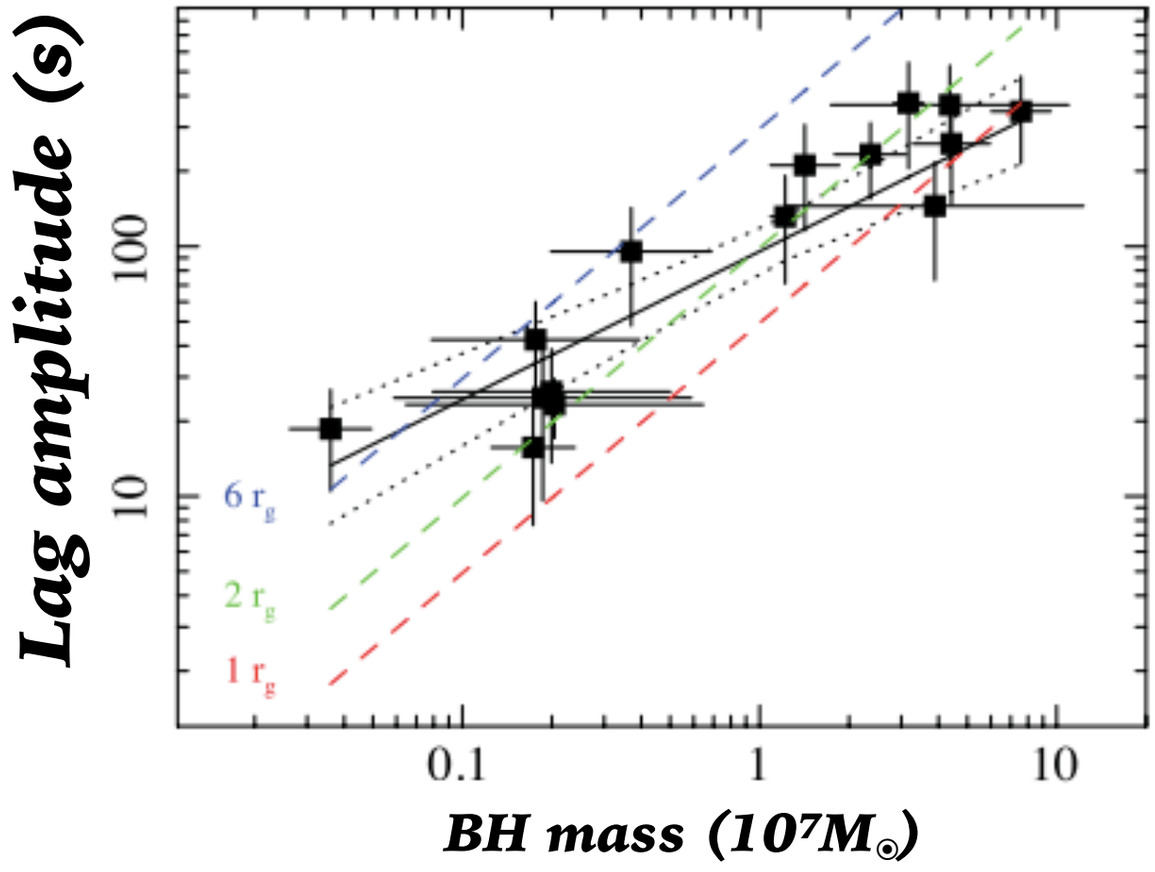
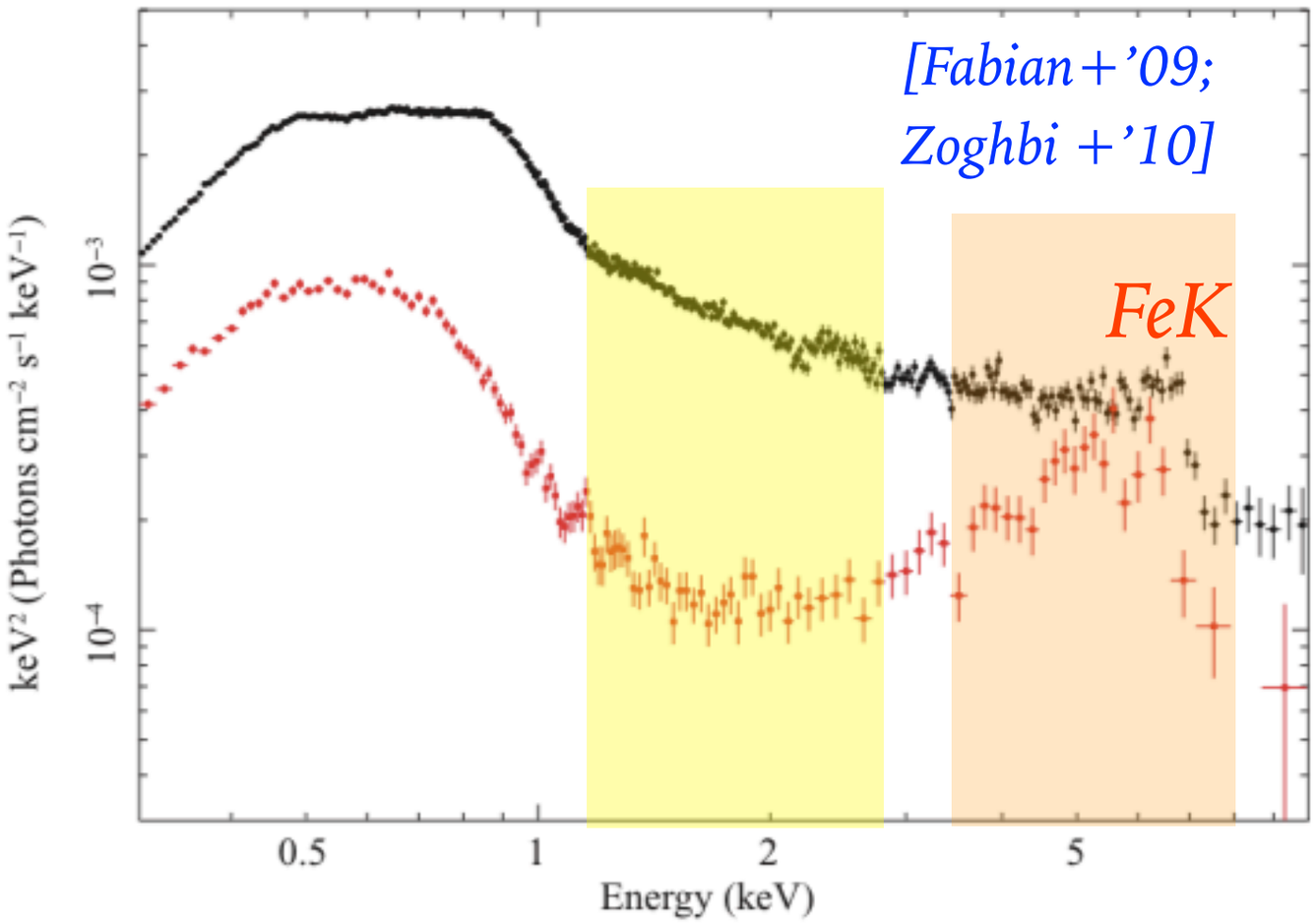
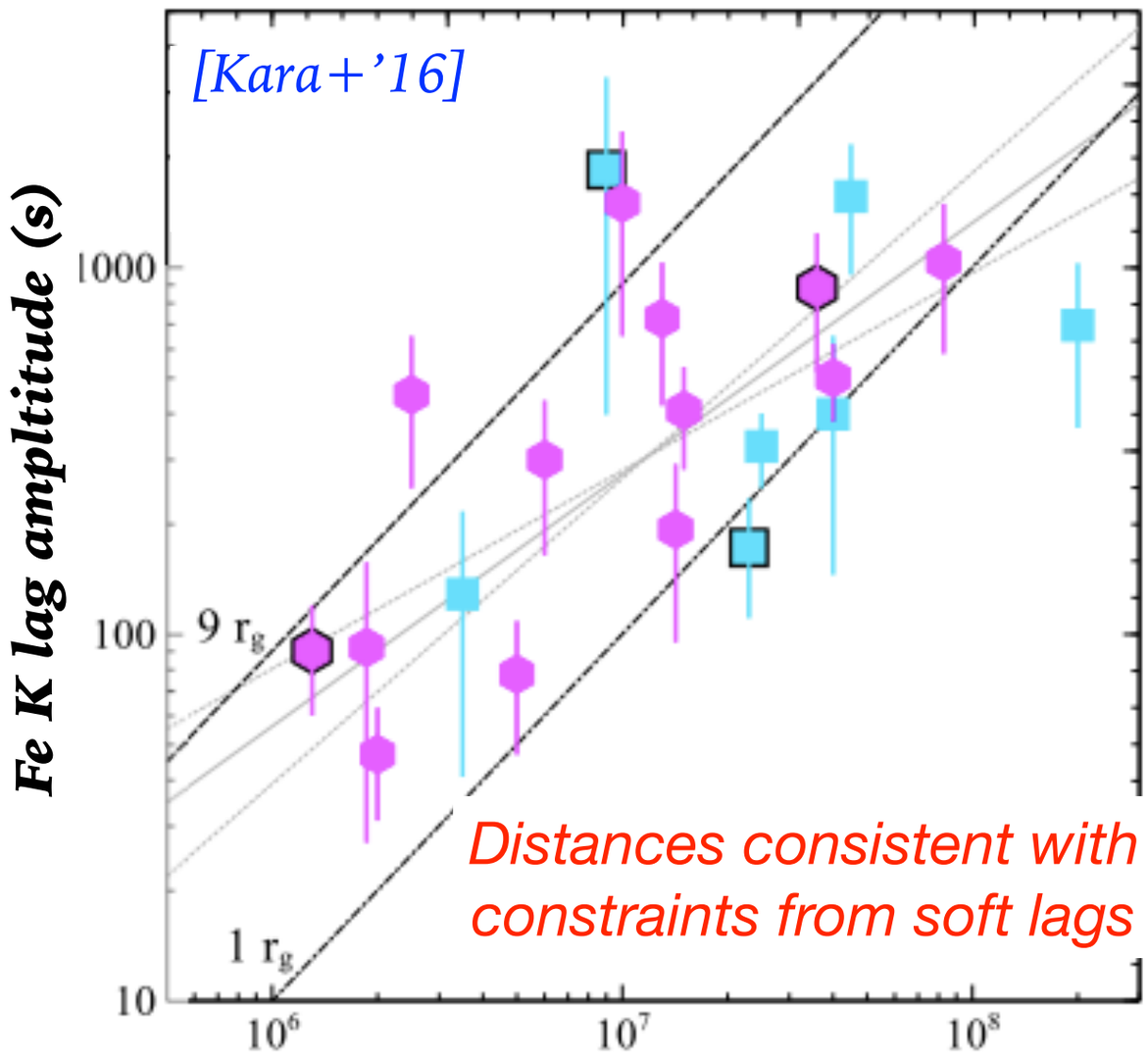




- *The soft excess contains a reprocessing component*
- *Same geometry, and lag scaling with the size of the system*
- *Fast variability originates in a compact region*
- *The X-ray source and the reprocessing site are close*
- *Tight correlation (scatter around best fit ~0.2~uncertainty in M_{BH})*

Fe K reverberation lags





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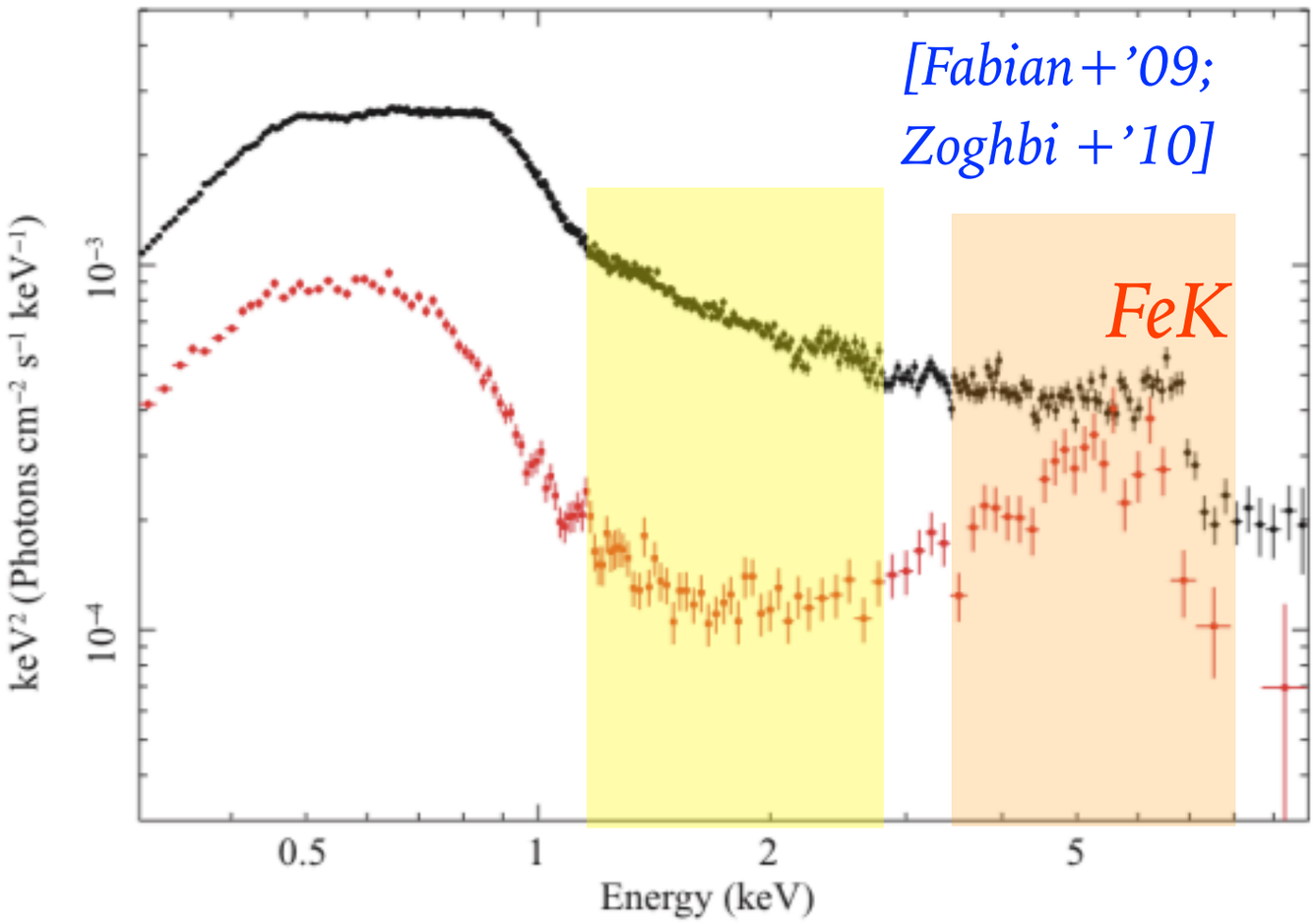
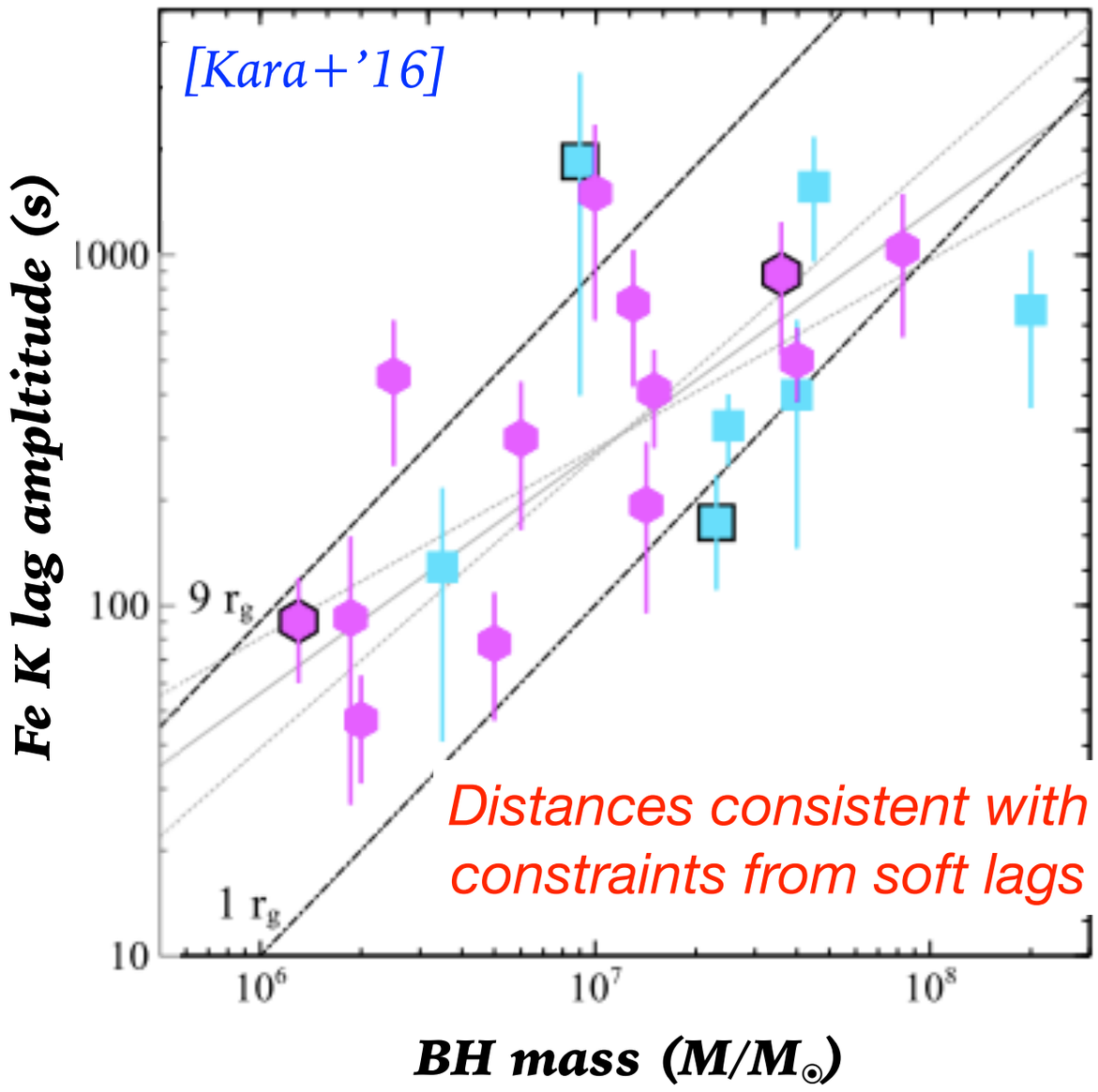


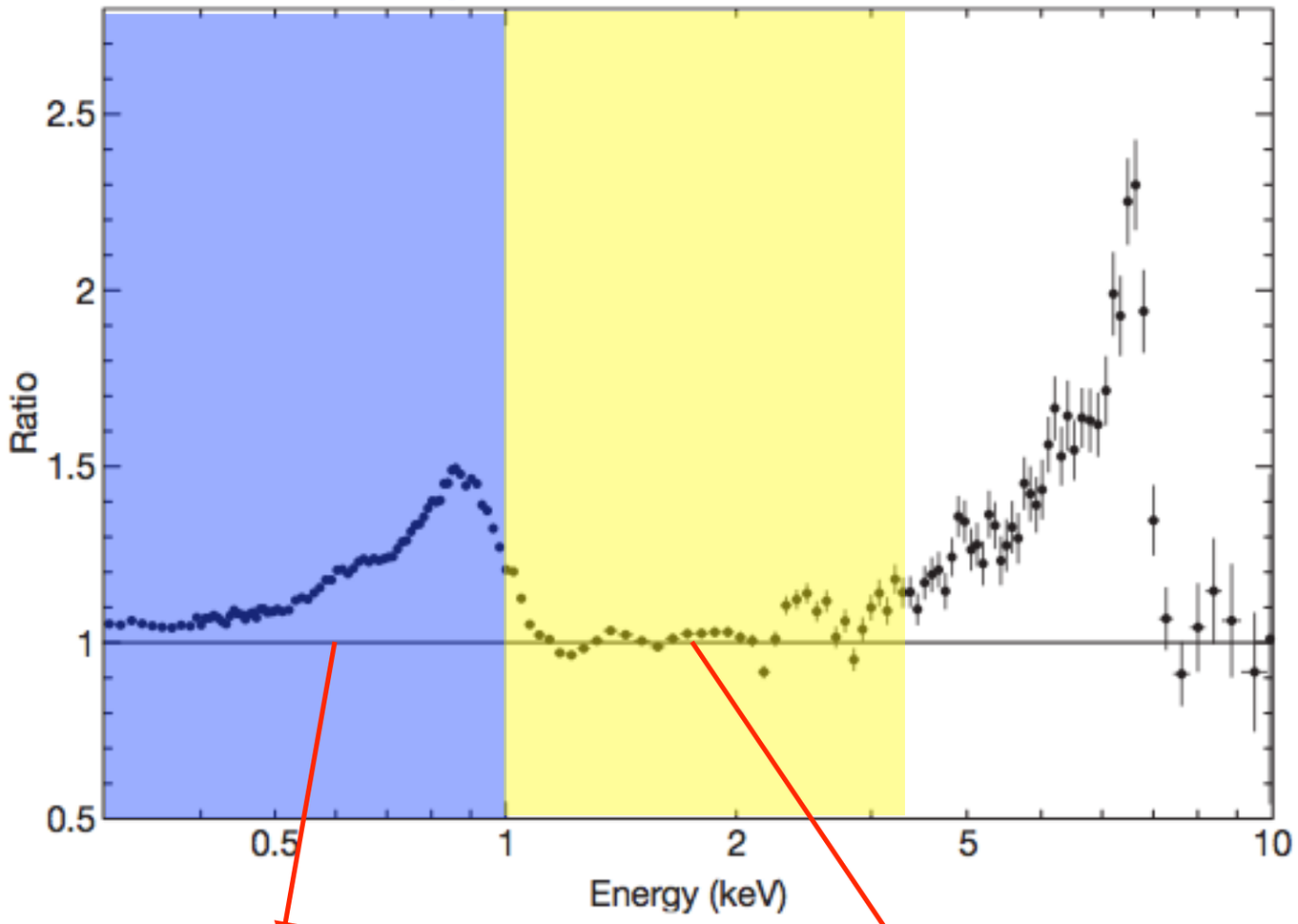


- *Both from reflection?* *[e.g. Zoghbi+'12; '13; '14; Kara +'13a; '13b; '14; '16; Vincentelli+'19]*
- *Or from different reprocessing but occurring in nearby regions? e.g. FeK lag from reflection, soft lags from thermal reprocessing in a warm corona* *[e.g. Gardner & Done '14]*

Factors that can affect lag measurements

Dilution

[Fabian+'09, Zoghbi+'10]



Soft excess (FeL) dominated (delayed) + power law (leading)

Power law dominated (leading) + reflection (delayed)

No possibility to separate the primary and reprocessed emission

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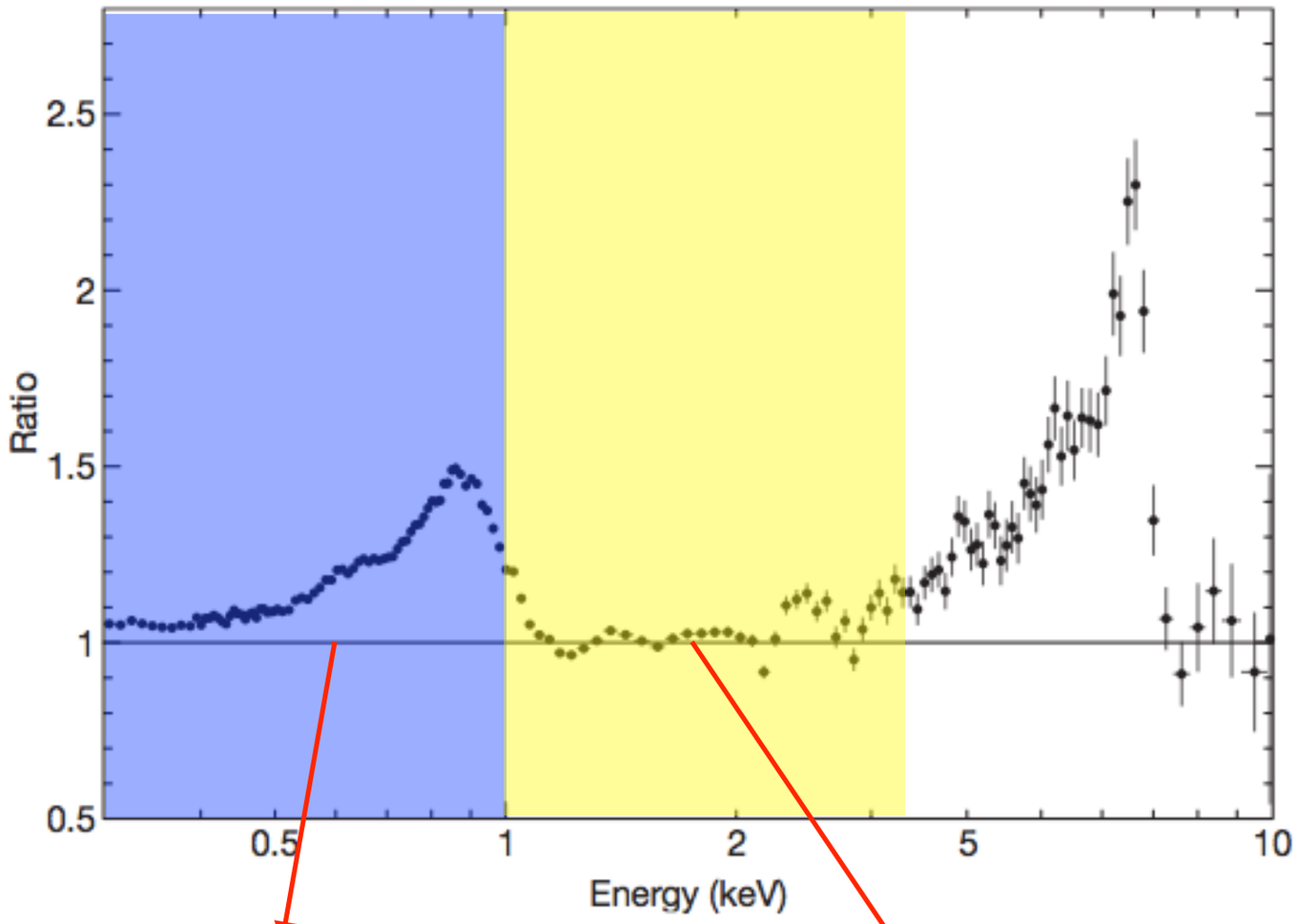

Soft excess (FeL) dominated (delayed) + power law (leading)

Power law dominated (leading) + reflection (delayed)

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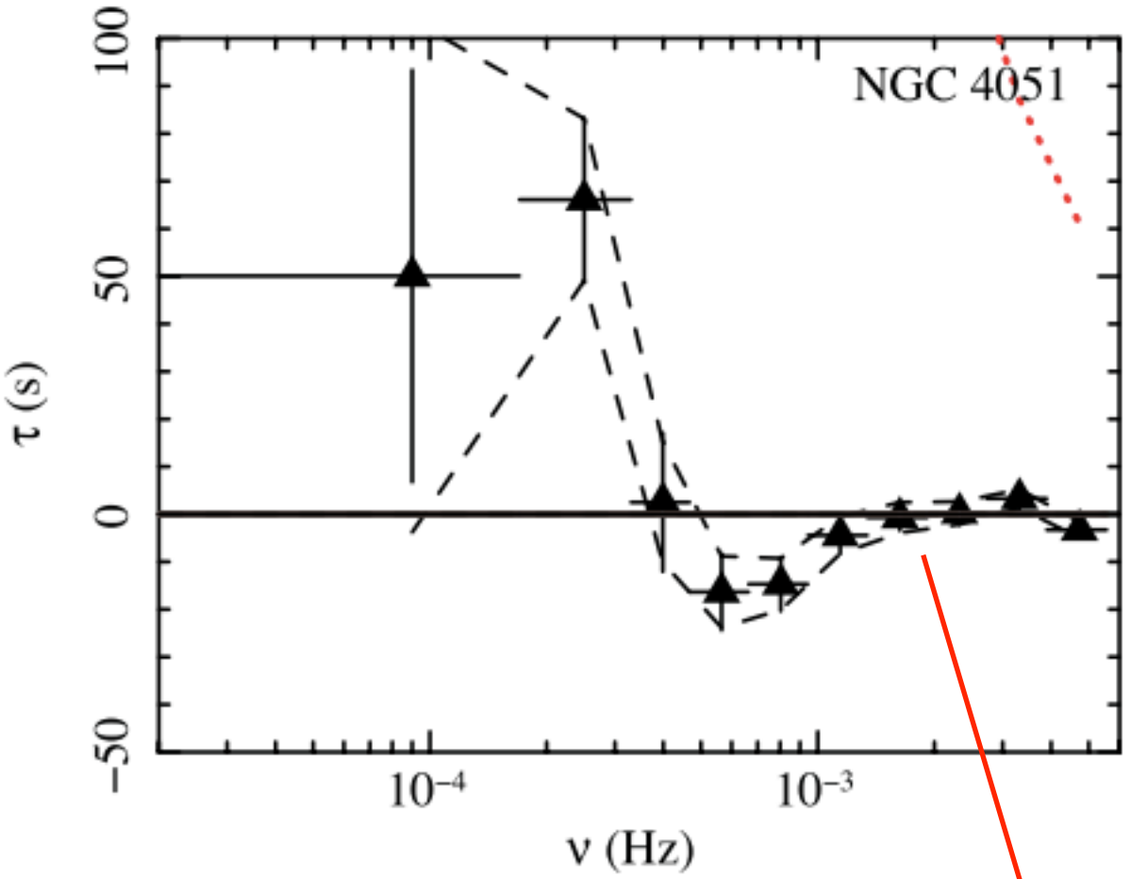
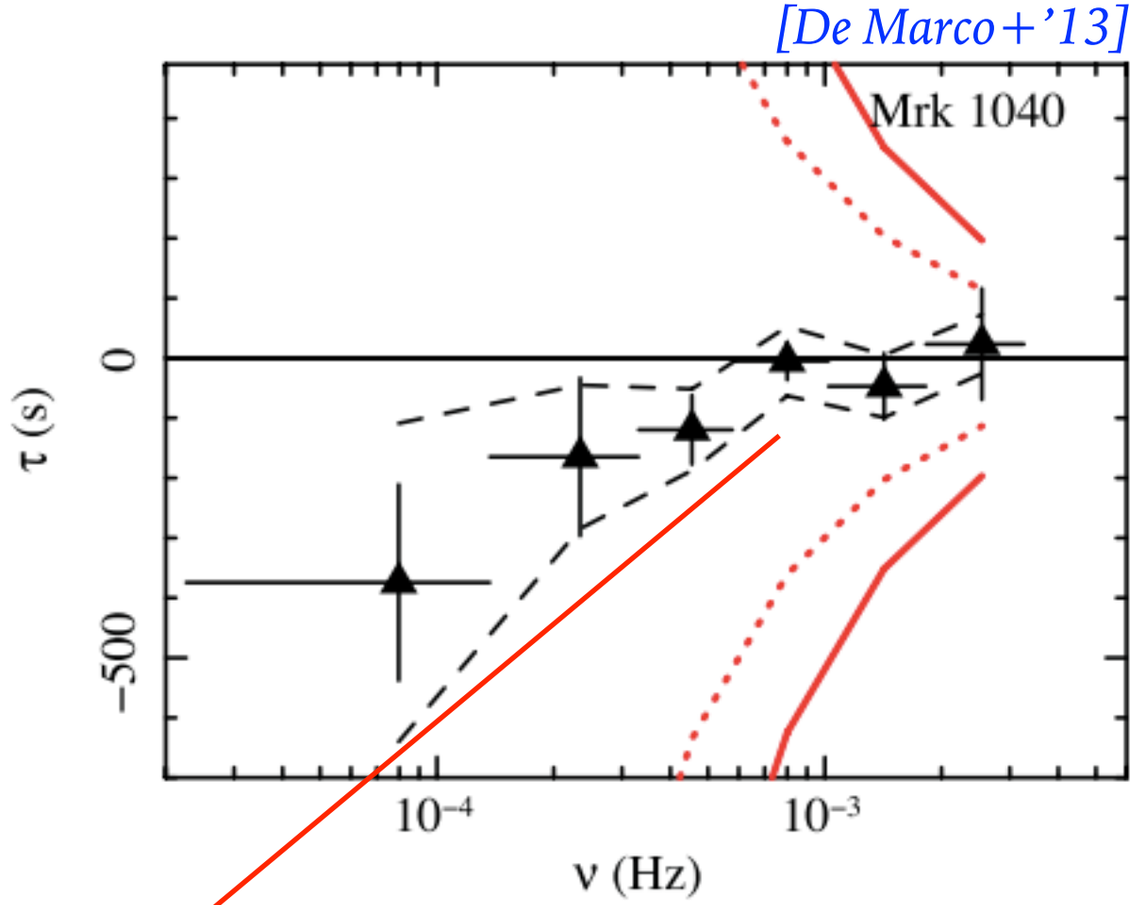
Correct the lag for the relative contribution of spectral components

[e.g. Uttley+'14; Mizumoto+'18]

Dilution

[De Marco+'13]



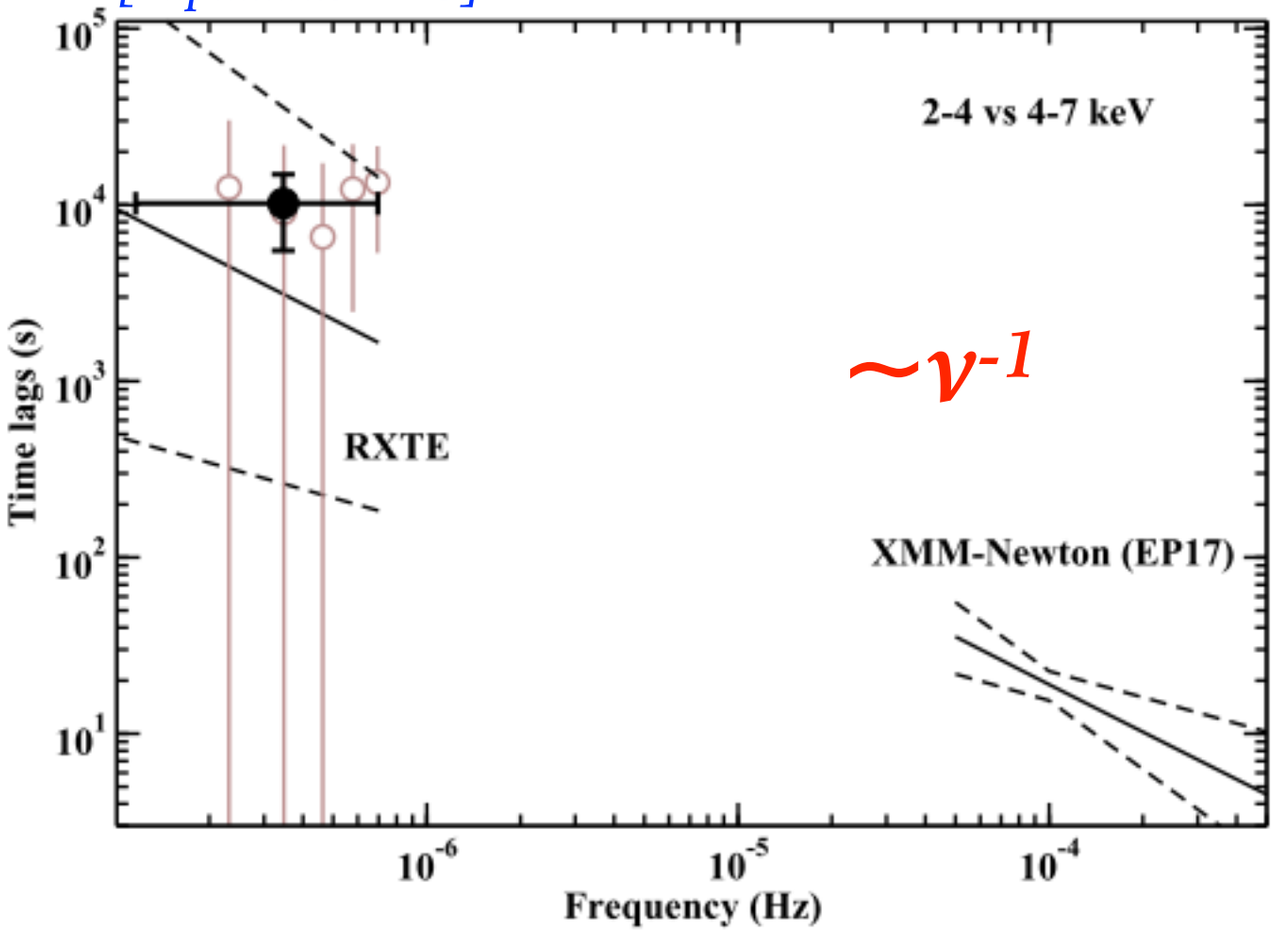


Frequency at which lag goes to zero not affected by dilution

[e.g. Miller+10; Mizumoto+'18]

Dilution: hard continuum lags

[Papadakis+'19]

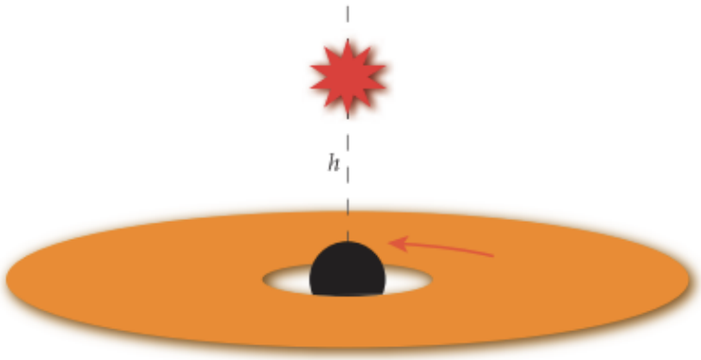


Modelling of hard lags needed..
but at very high frequencies
hard lags become negligible!

[see also Miyamoto & Kitamoto '89; Nowak & Vaughan '96; Nowak+'99; Pottschmidt+'00; Papadakis+'01; McHardy +'04, '07; Arévalo+'06; Markowitz+'07, Arévalo+'08; Epitropakis & Papadakis '17]

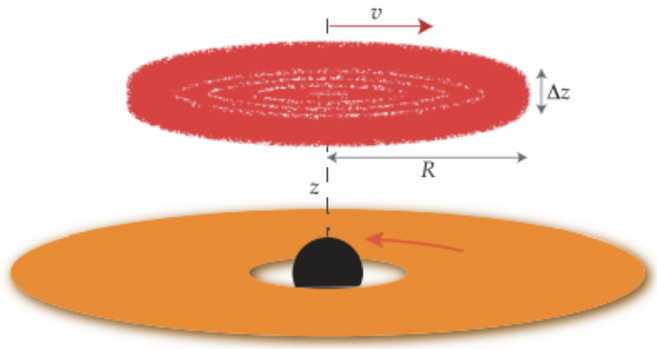
Modelling X-ray reverberation

lamp-post



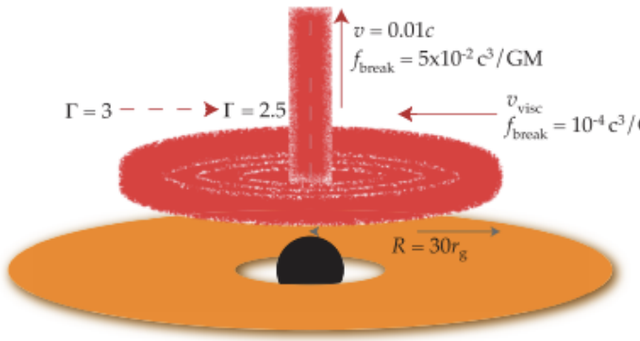
[Cackett+'14; Dovciak+'14; Emmanoulopoulus+'14; Epitropakis+'16; Chainakun+'16; Ingram+'19]

extended



[Wilkins & Fabian '13; Chainakun & Young '17]

composite



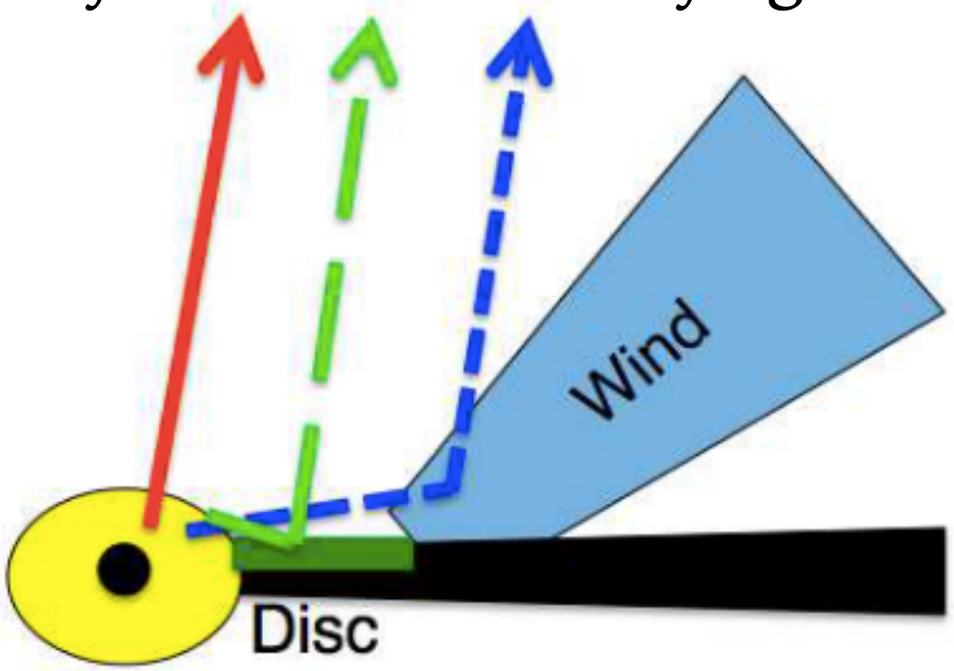
[Wilkins+'16]

Inferred disc-corona distances ≲10 r_g

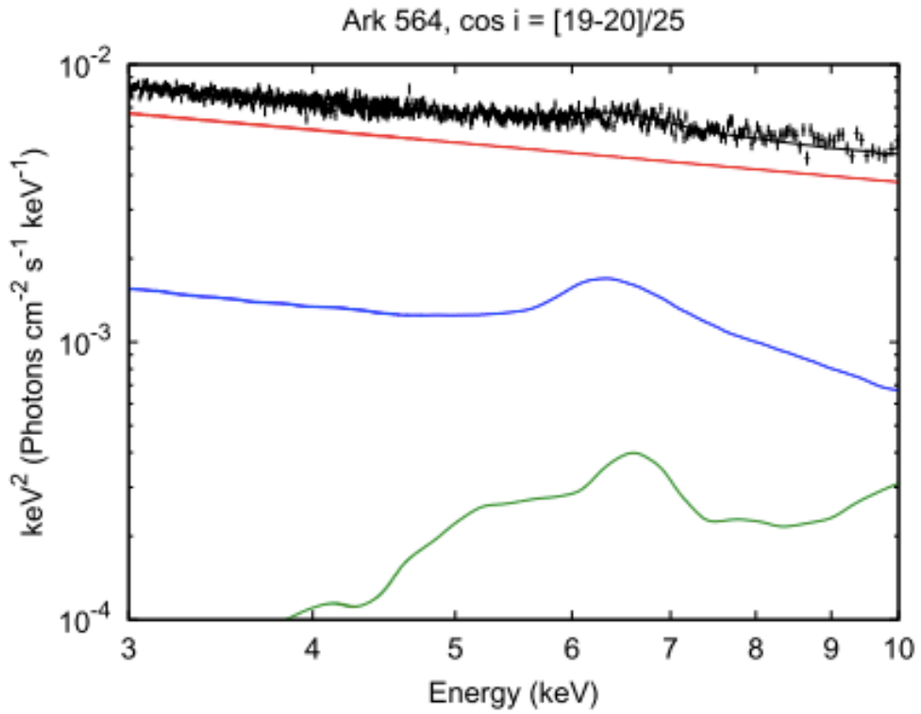
"Other-than-disc-reverberation" lags

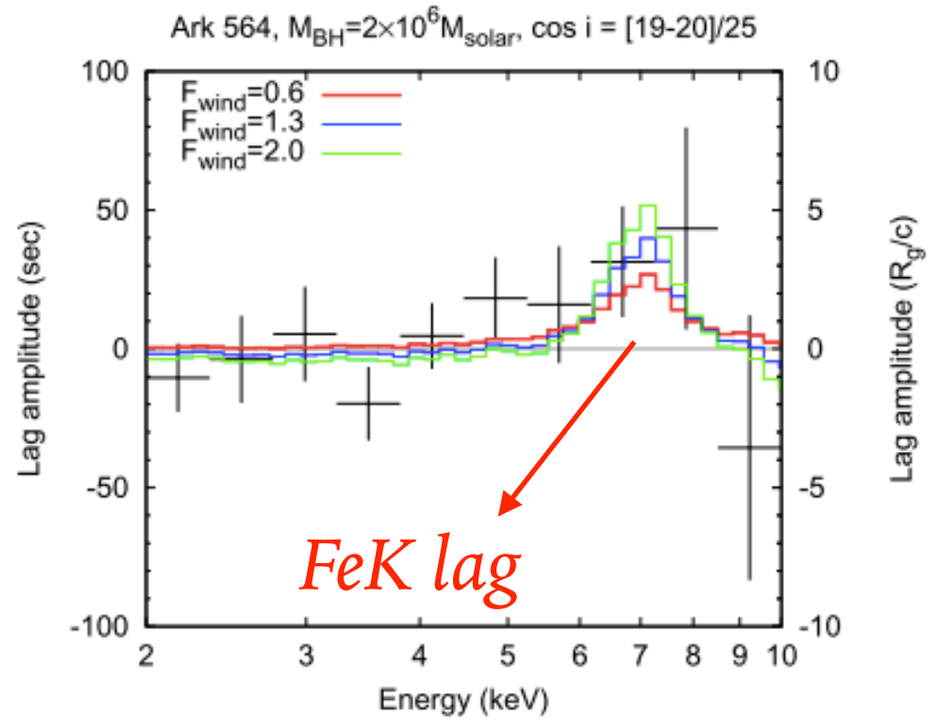
Large scale reflector

Reflector close to line of sight + dilution



[Miller+'10; Turner+'17; Mizumoto+'18,'19]





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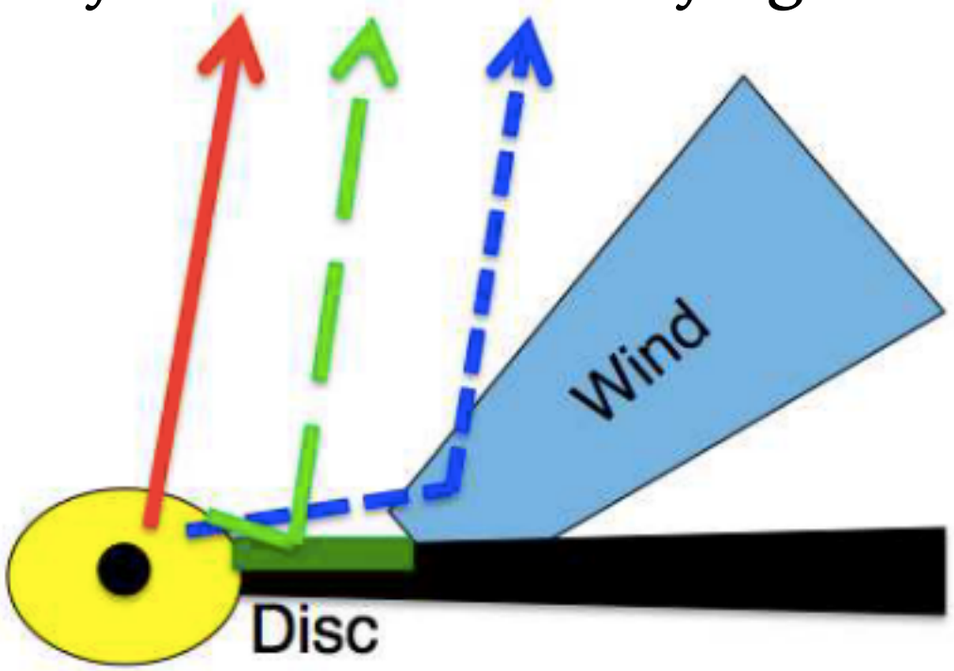

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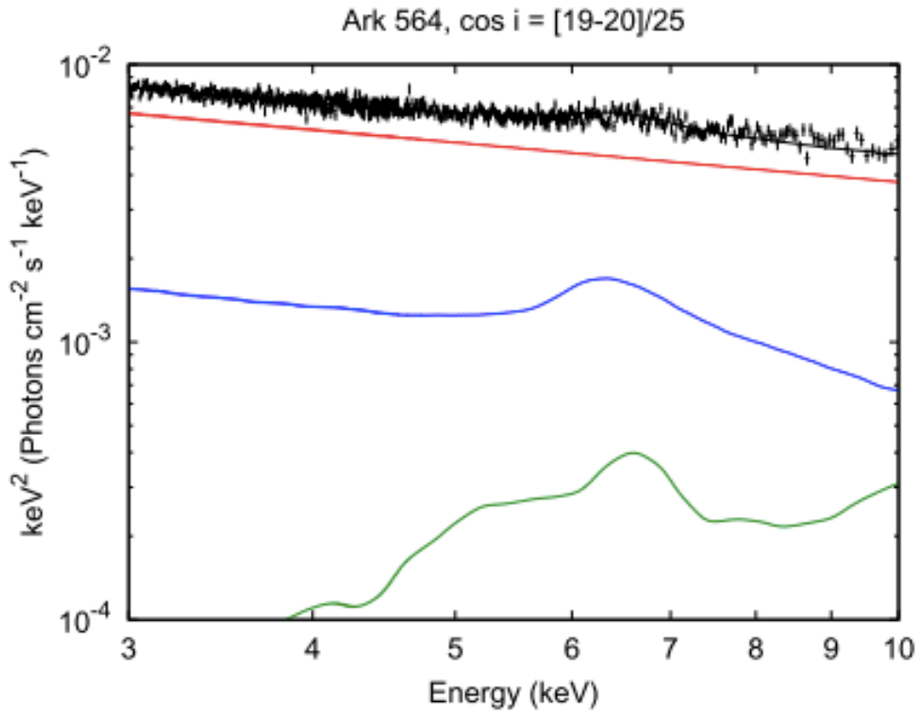
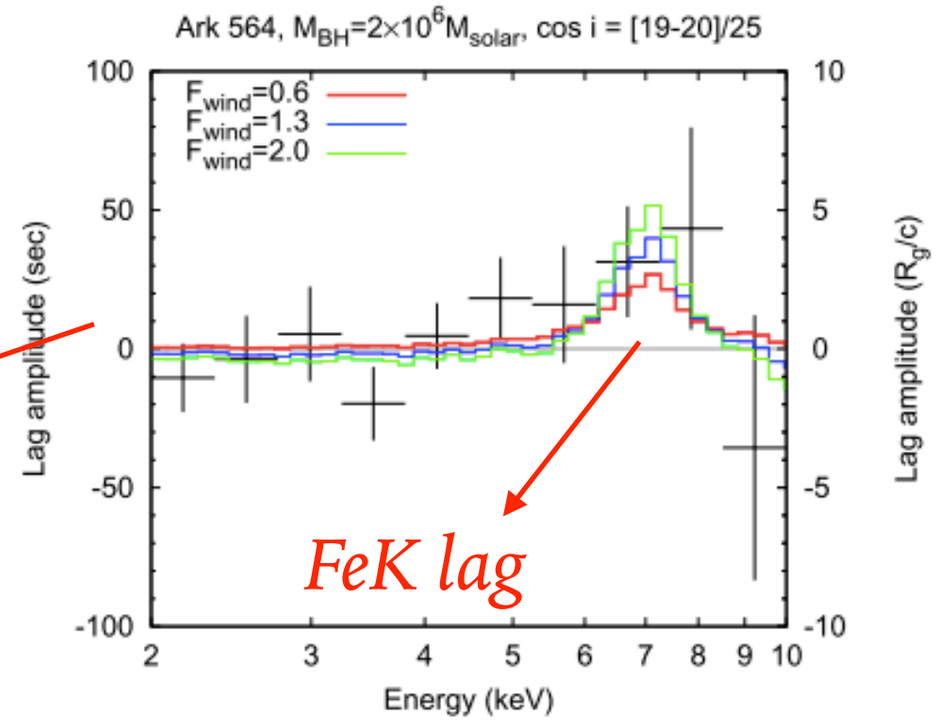




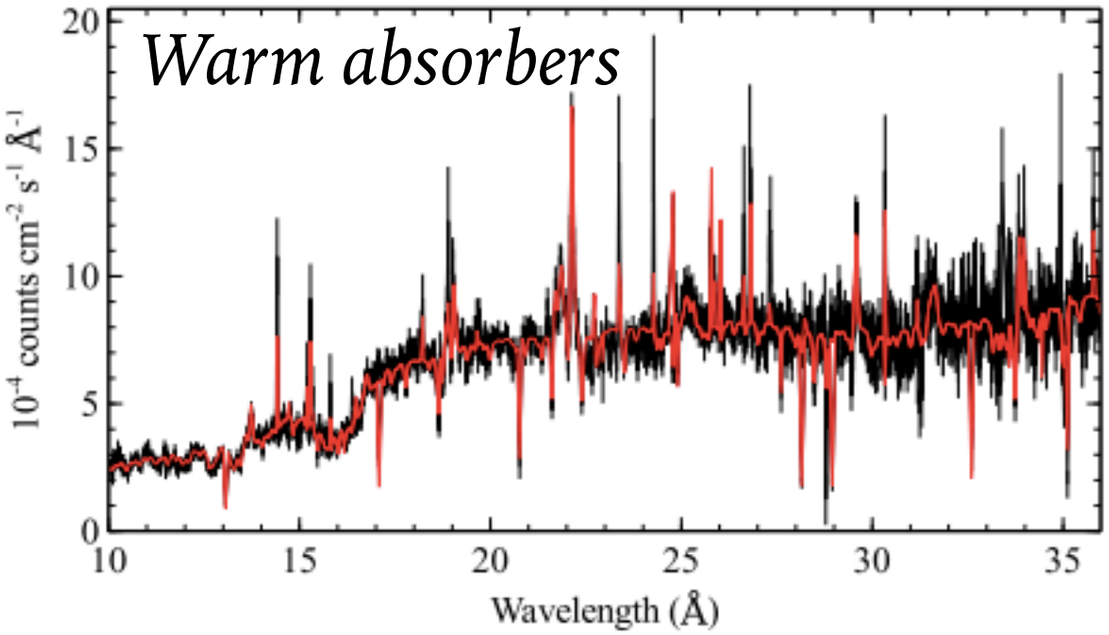
Soft lags?

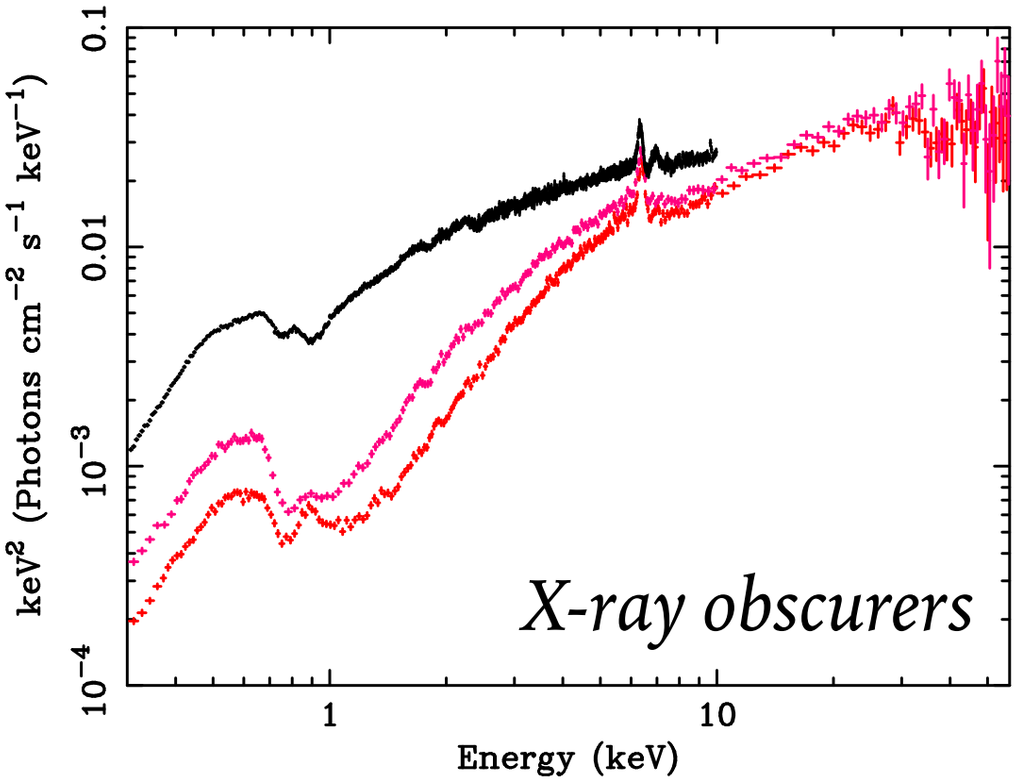
FeK lag

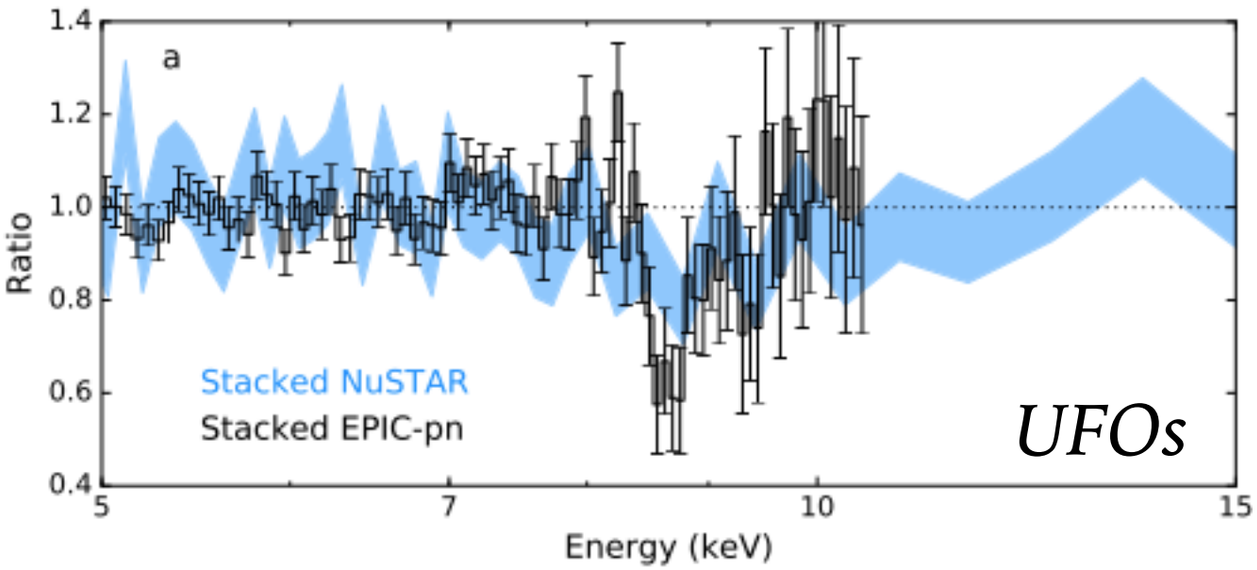
Scattering angle (wind opening angle+inclination) should scale with BH mass

"Other-than-disc-reverberation" lags

Absorbers







Absorbers may vary because of motions and/or changes in the ionizing continuum

"Other-than-disc-reverberation" lags

Warm Absorbers

$$\tau_{rec} \sim (\alpha_{rec} n_e)^{-1} (n_i / n_{i+1})$$

[e.g. Krolik & Kriss '95]

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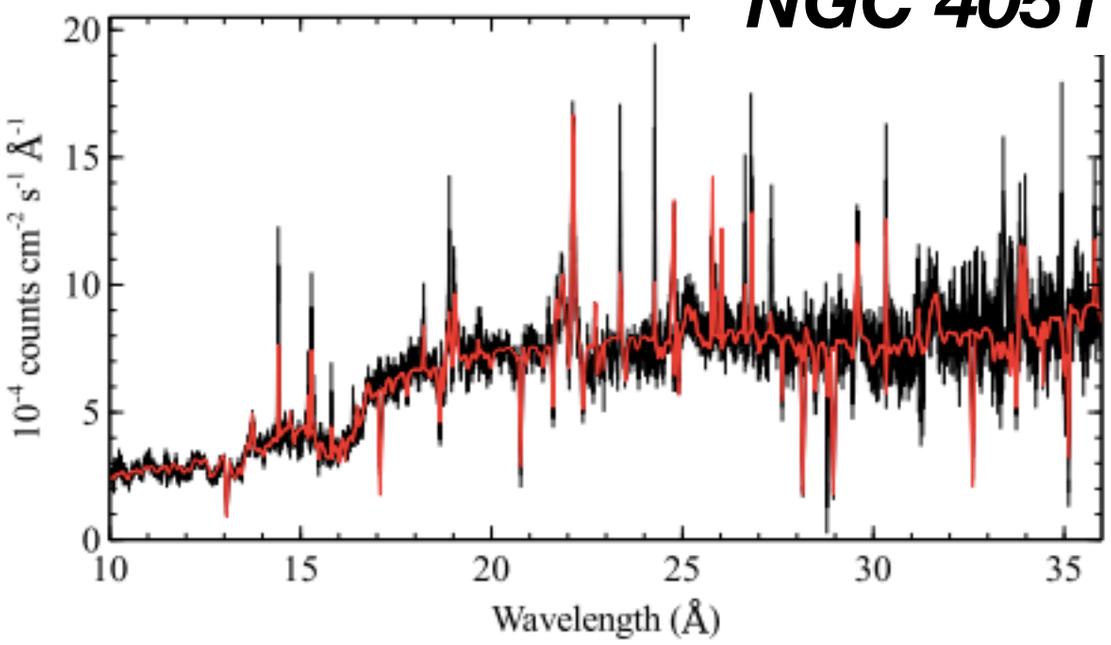
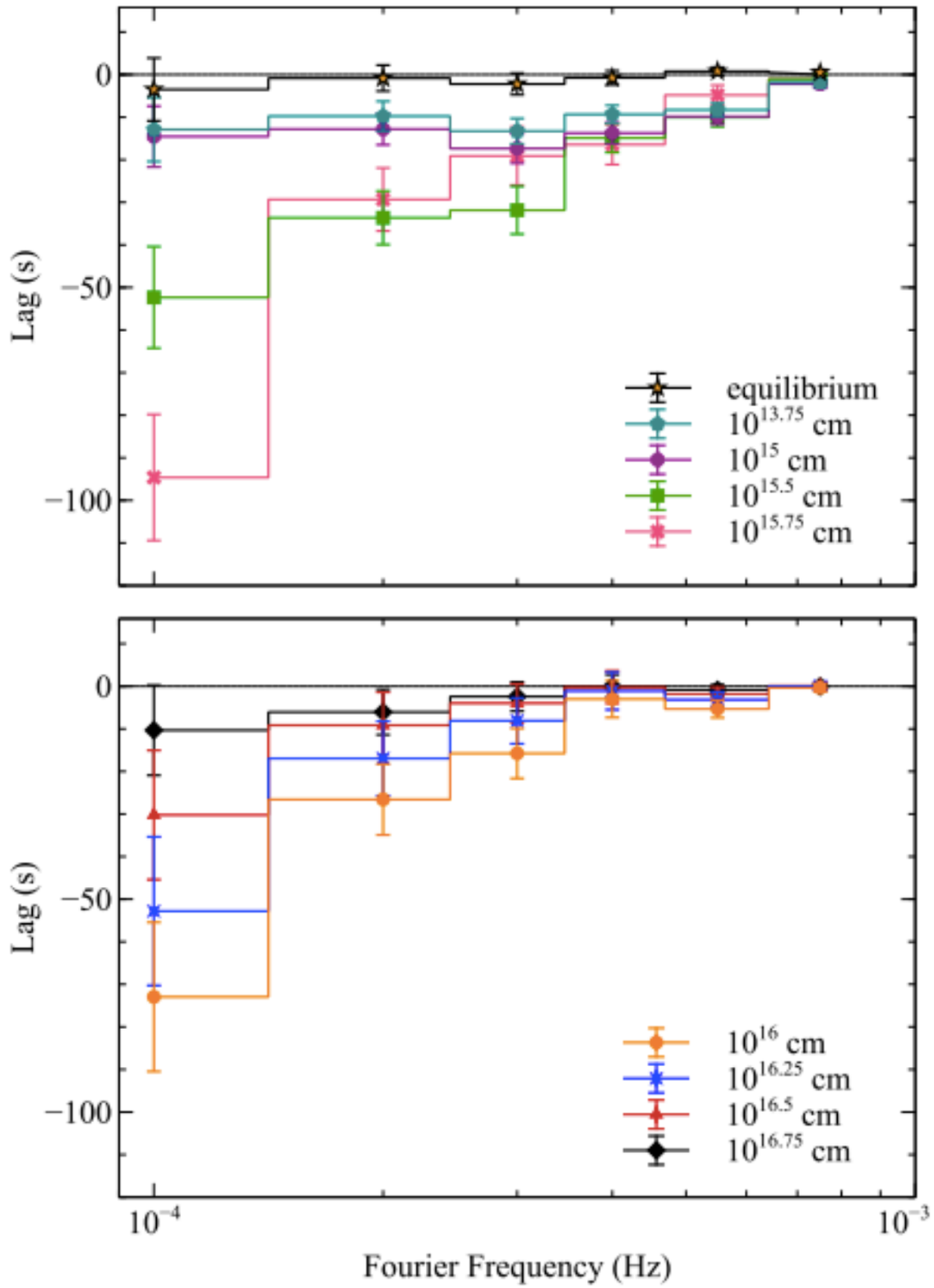


[Silva+'16]



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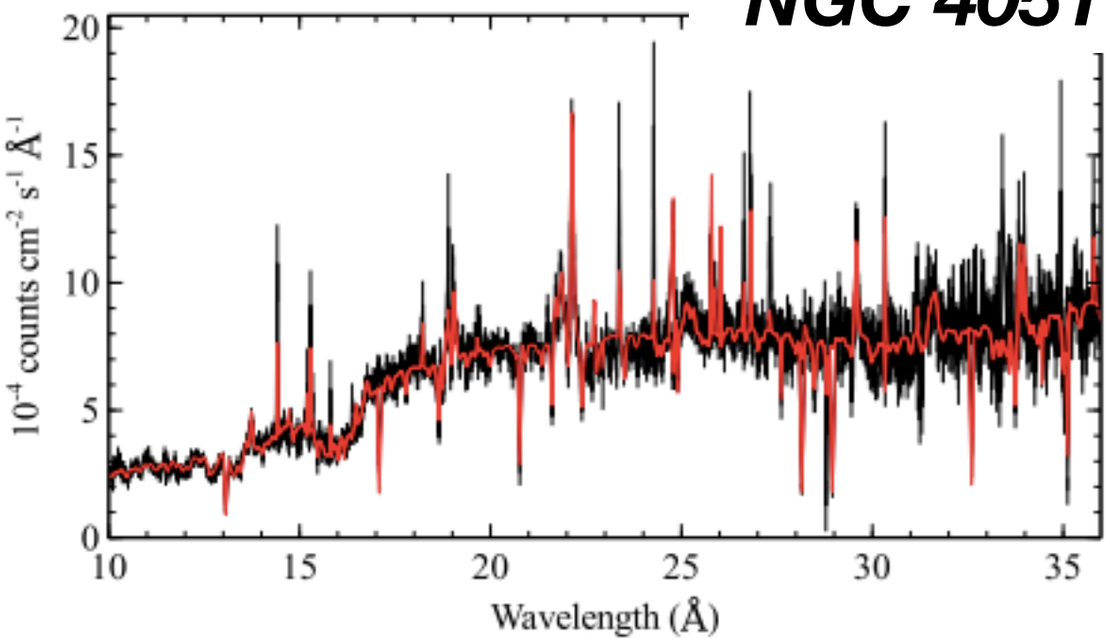

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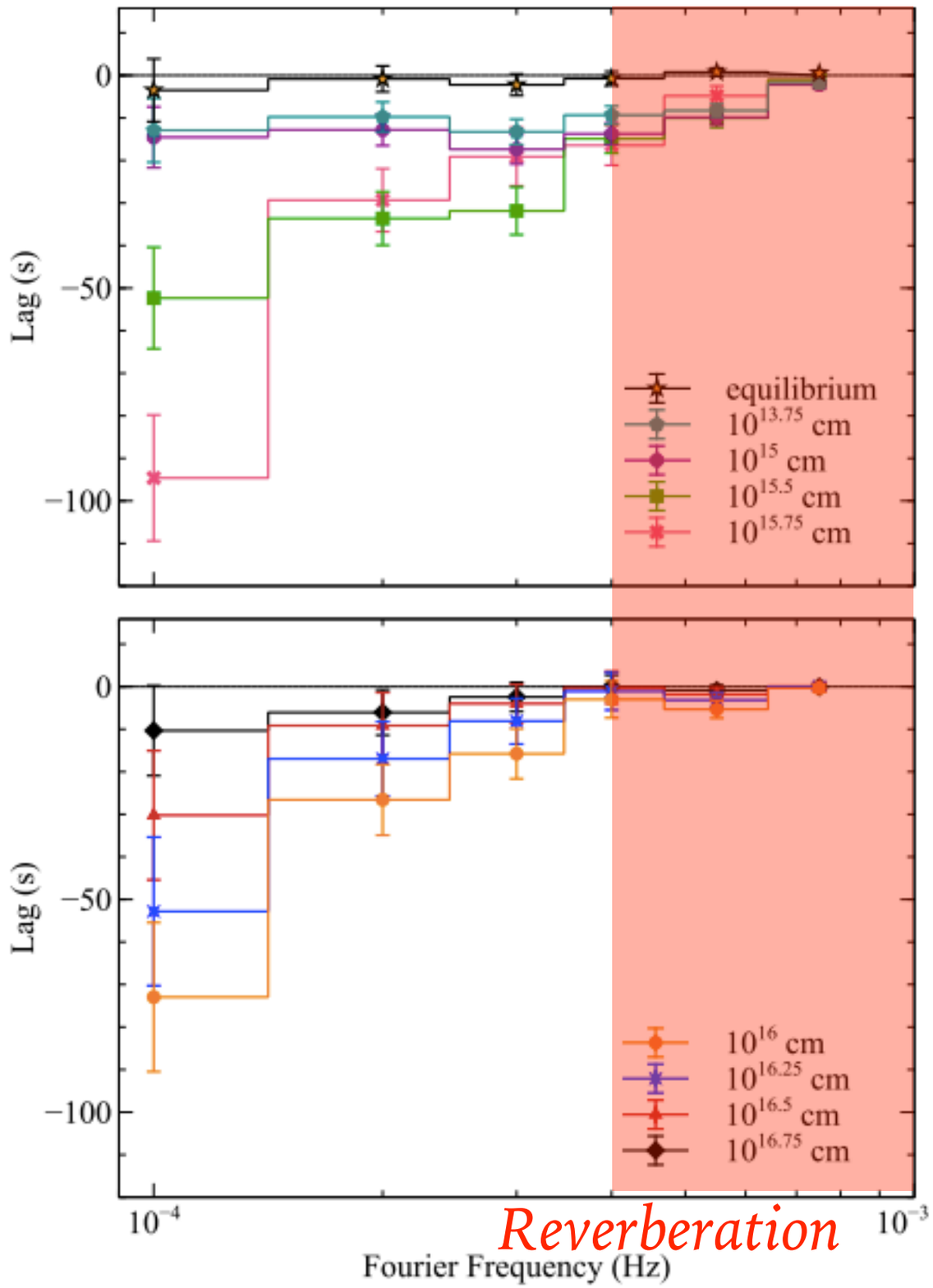
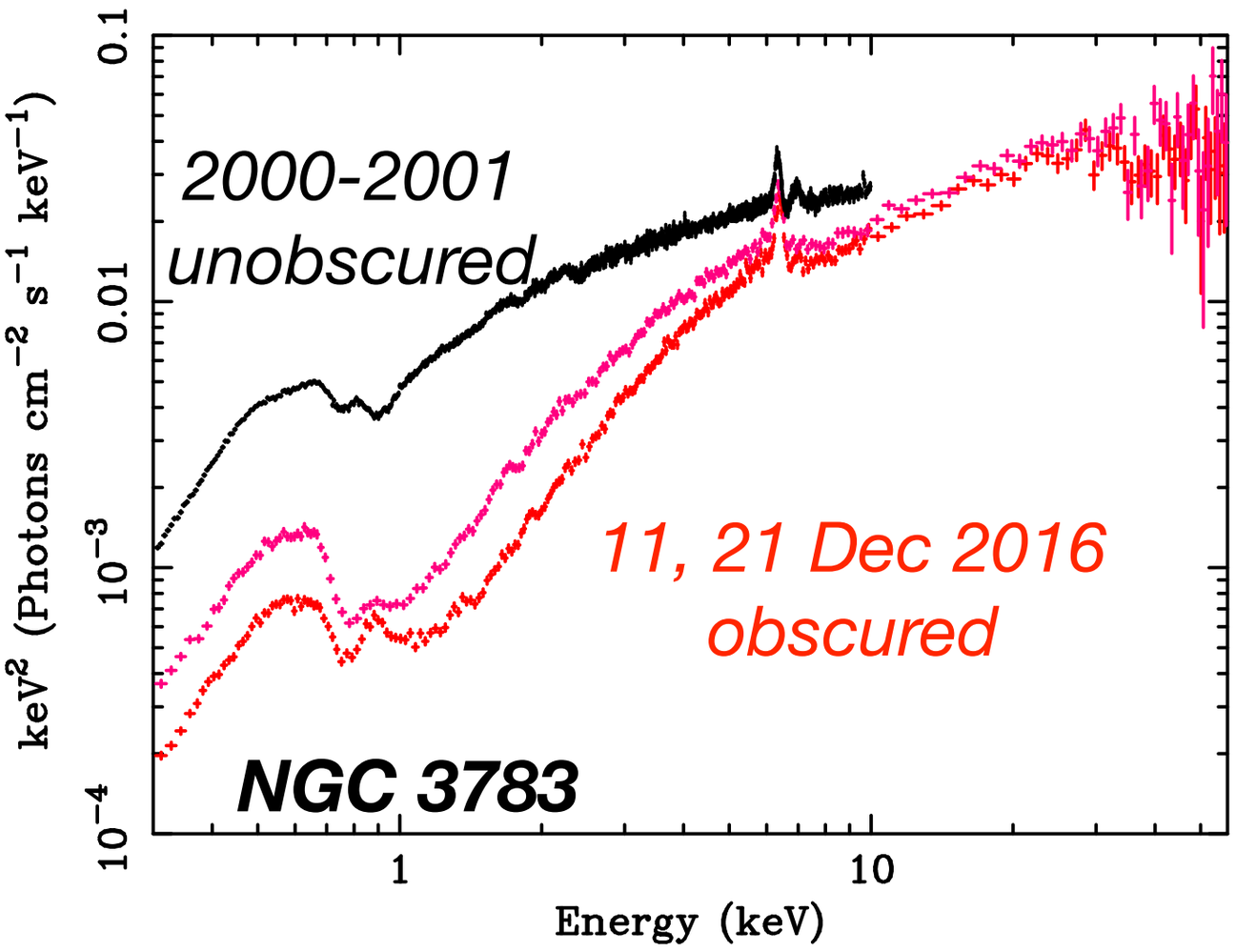


Reverberation

"Other-than-disc-reverberation" lags

X-ray obscurers

[Mehdipour +'17; Kaastra+'18; Kriss+'19; De Marco+'19]



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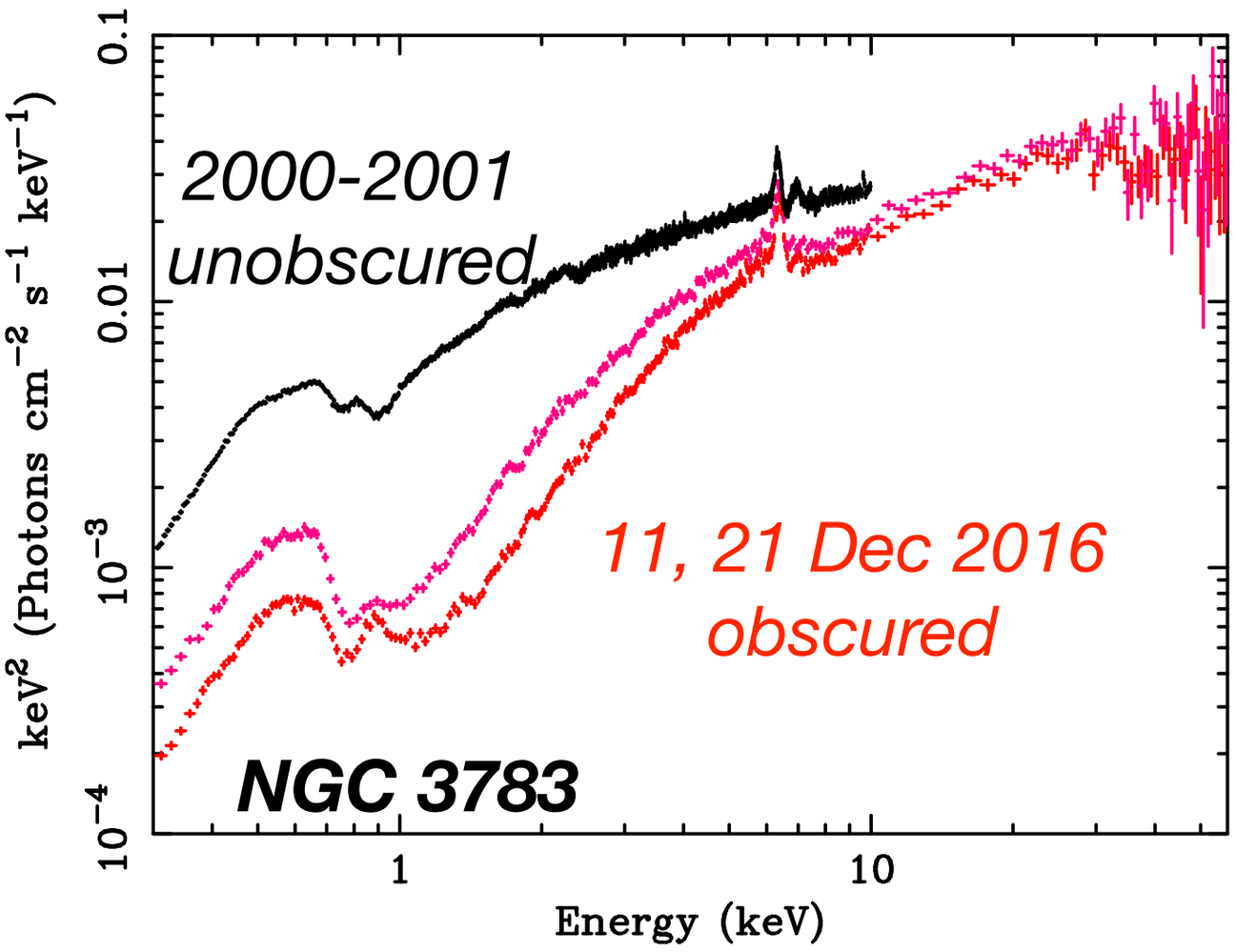
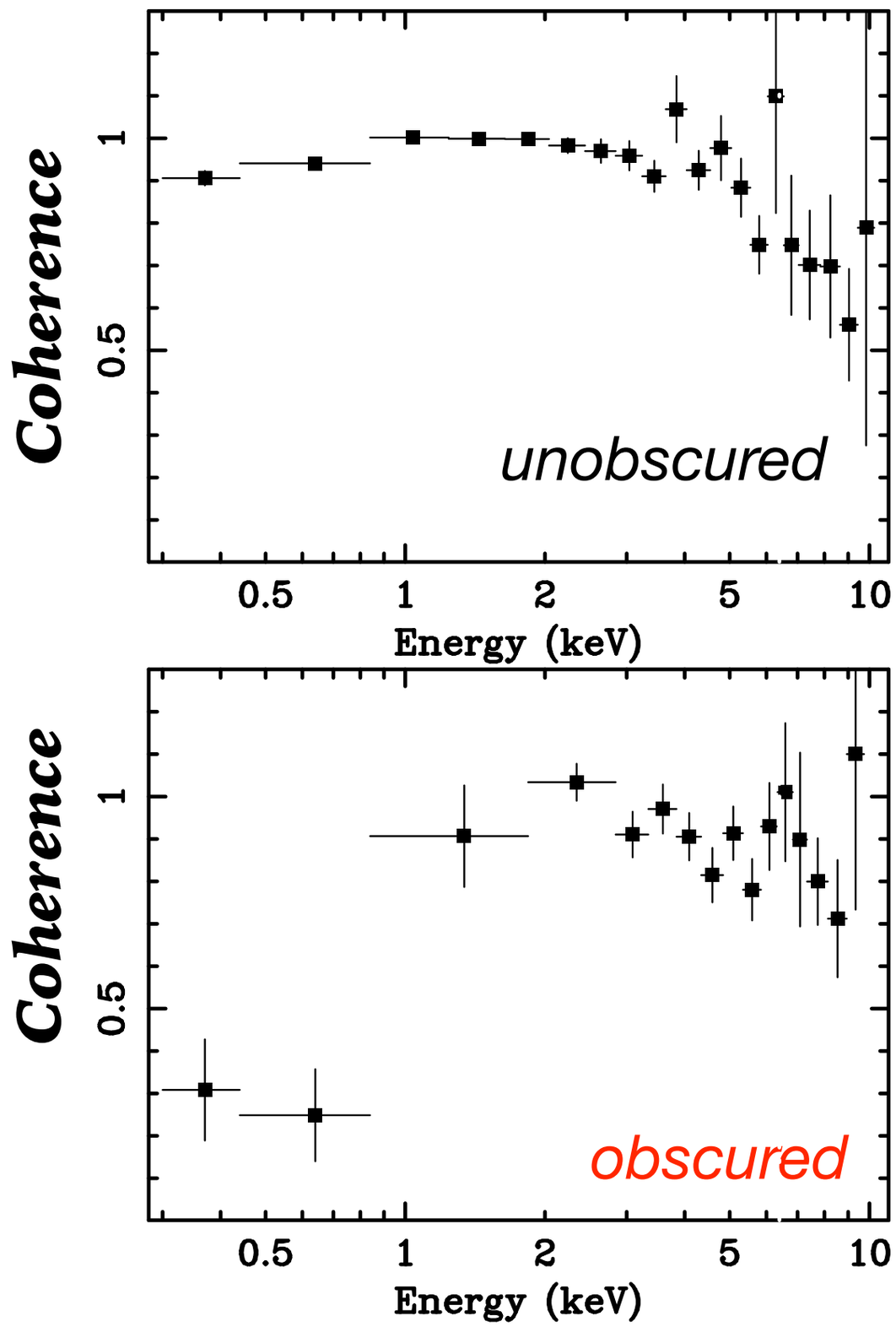


The X-ray obscurer is found to vary on short time scales (≲10 hours)

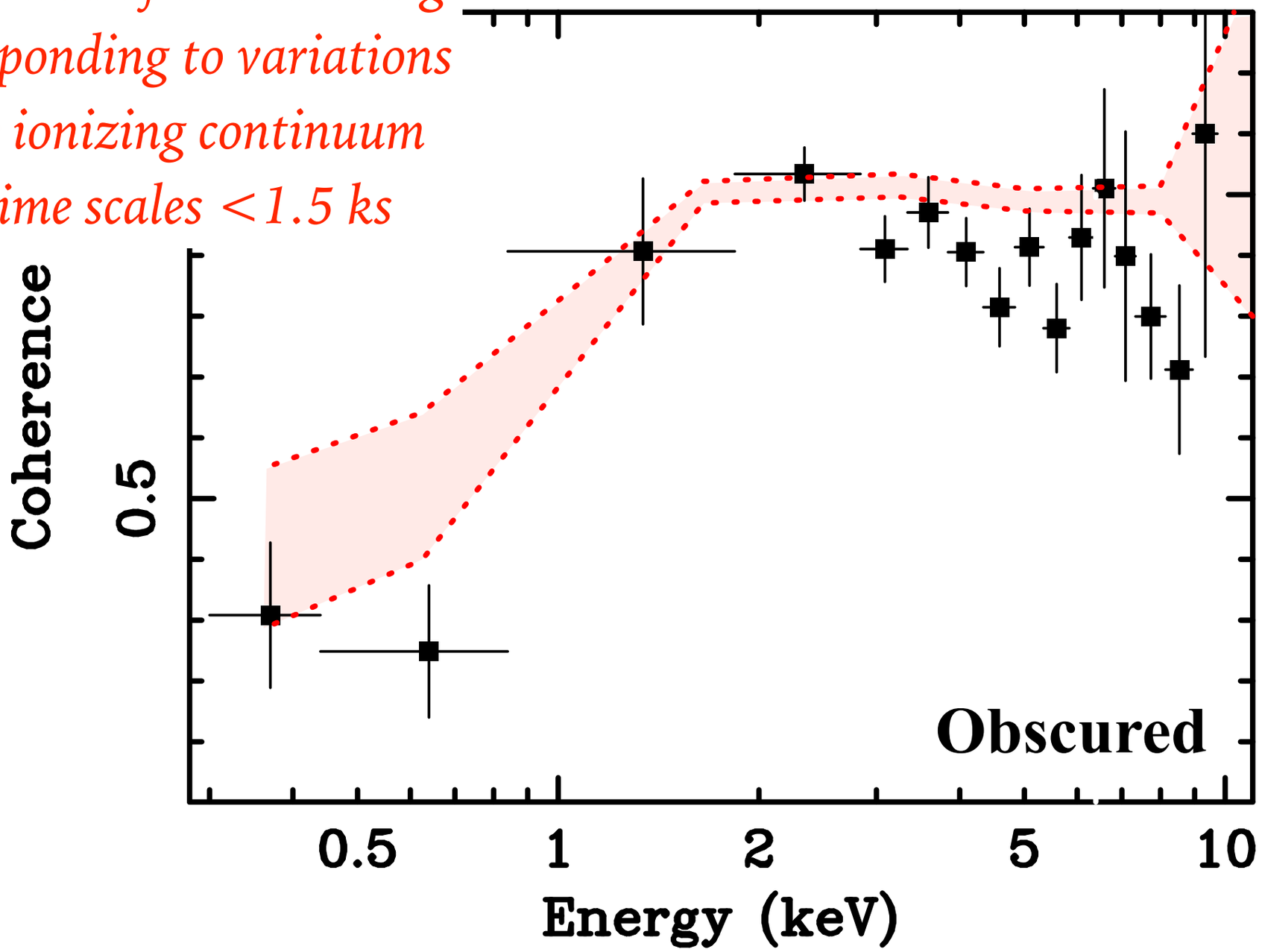
[De Marco+'19]



"Other-than-disc-reverberation" lags

X-ray obscurers

Time-dependent Cloudy simulations of an absorbing gas responding to variations of the ionizing continuum on time scales <1.5 ks

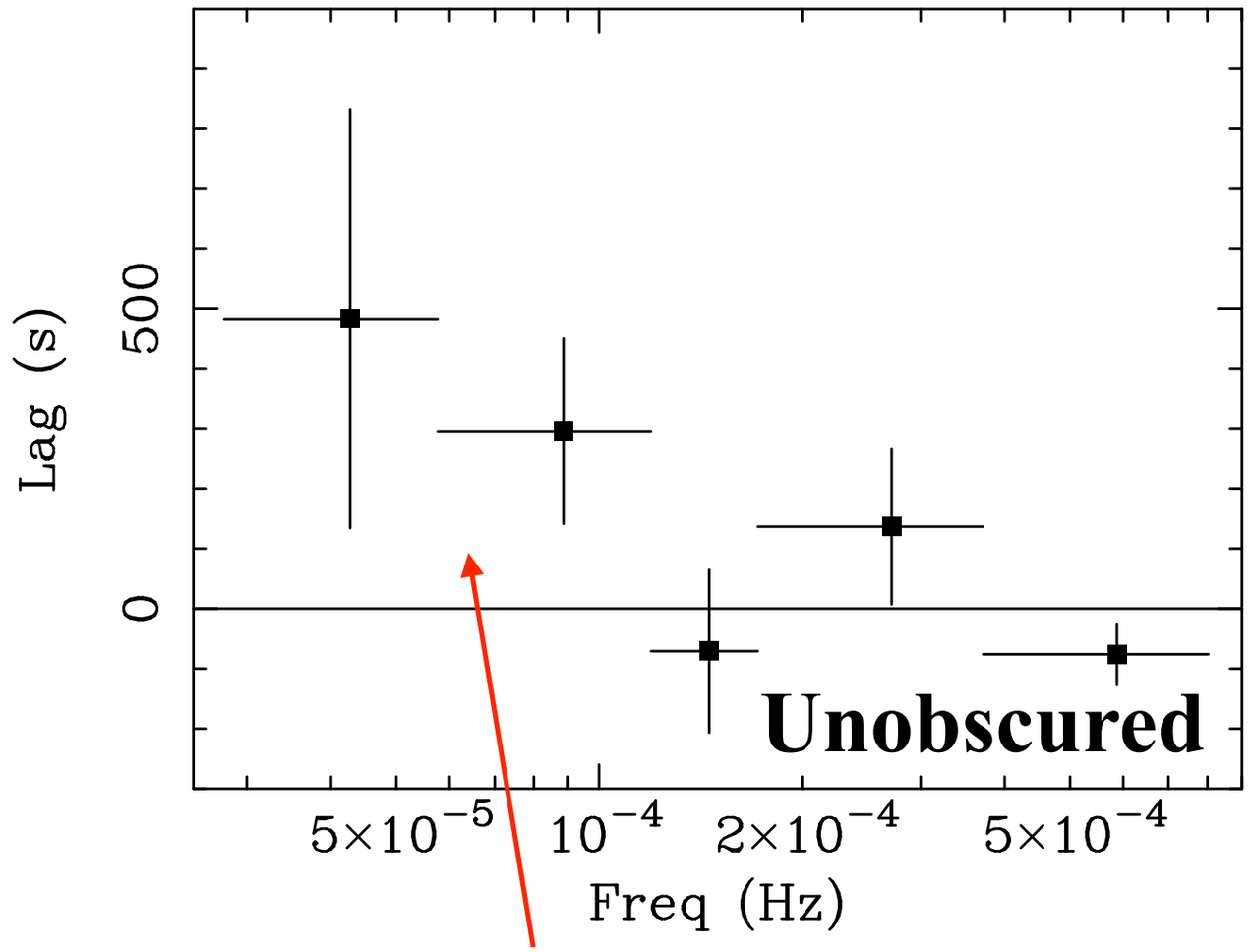


"Other-than-disc-reverberation" lags

X-ray obscurers

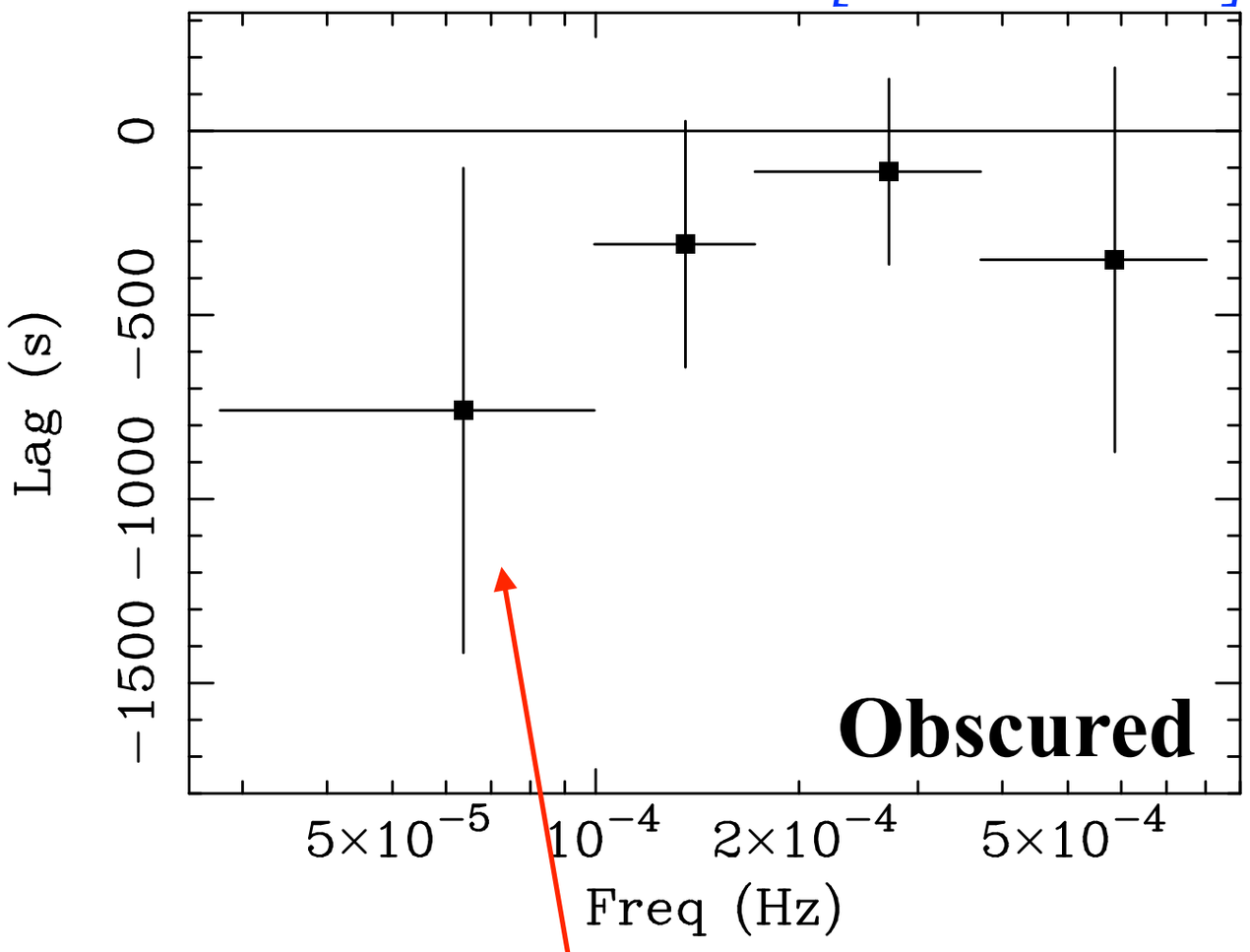
Time lags between 0.5-2 keV and 4-10 keV

[De Marco+'19]



Hard lags associated with the broad band X-ray continuum

[e.g. Kotov et al. 2001; Arévalo & Uttley 2006]



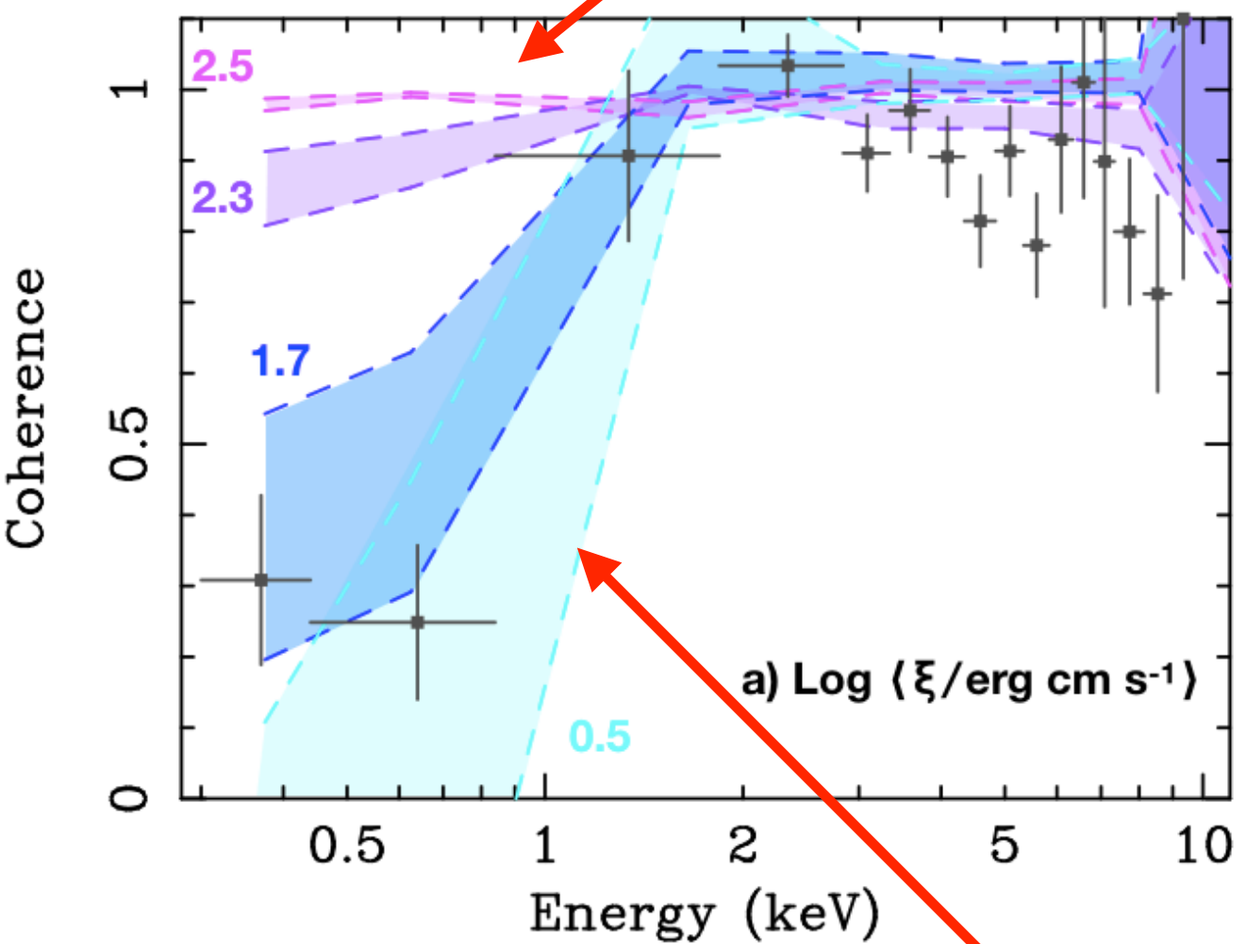
Tentative indication of a soft band delay of –760 ± 660 s

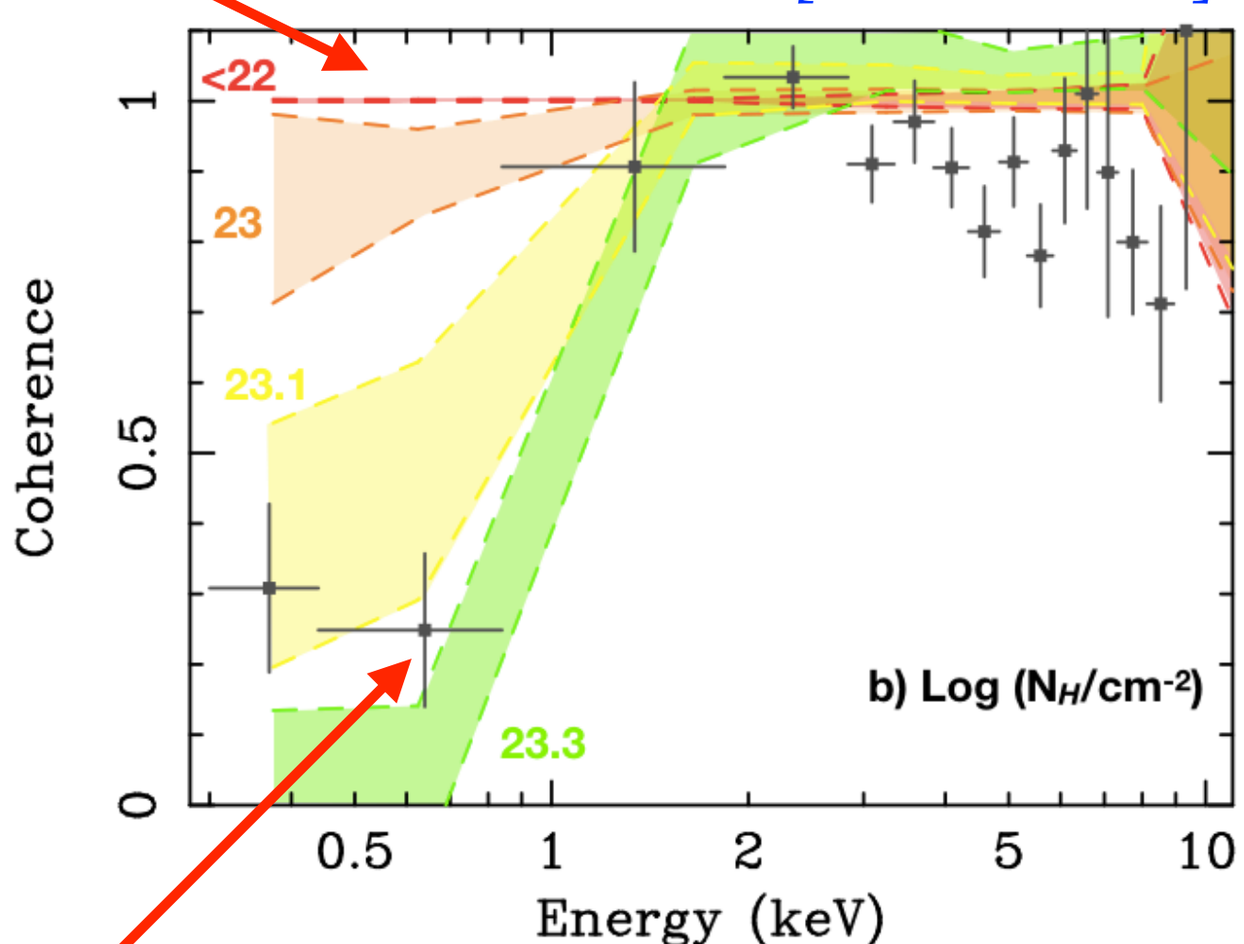
"Other-than-disc-reverberation" lags

X-ray obscurers

Warm absorbers

[De Marco+'19]





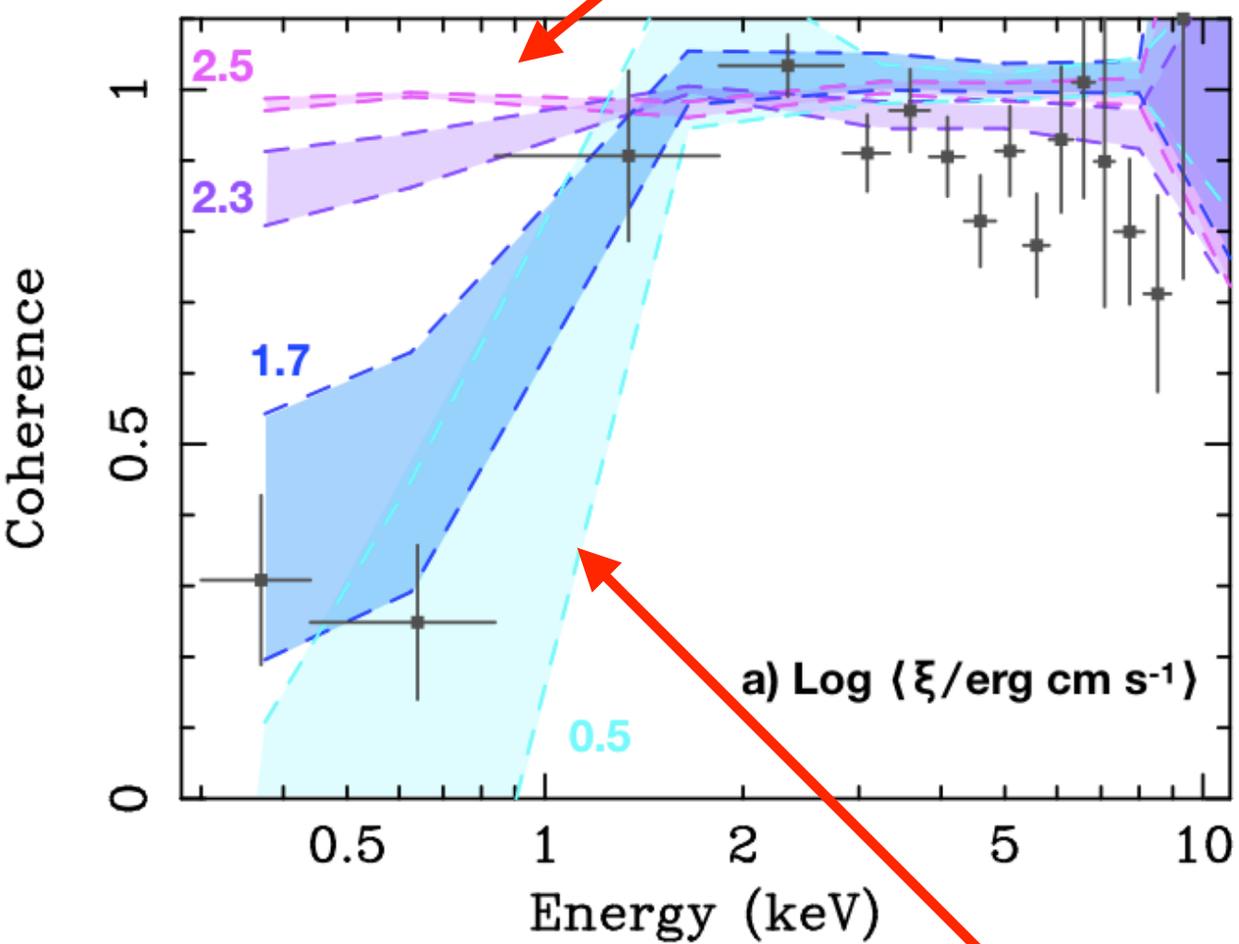
X-ray obscurers

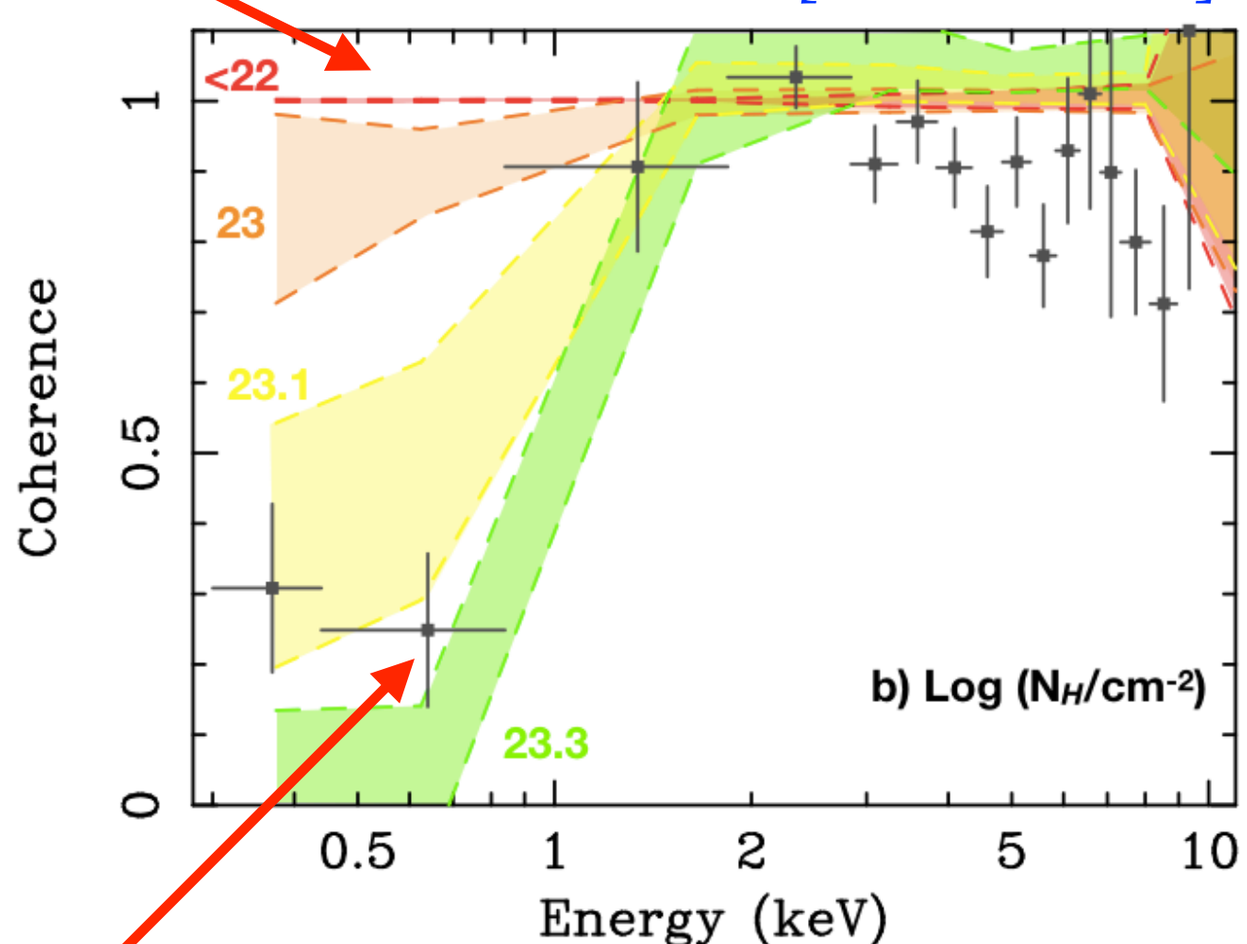
"Other-than-disc-reverberation" lags

X-ray obscurers

Warm absorbers

[De Marco+'19]





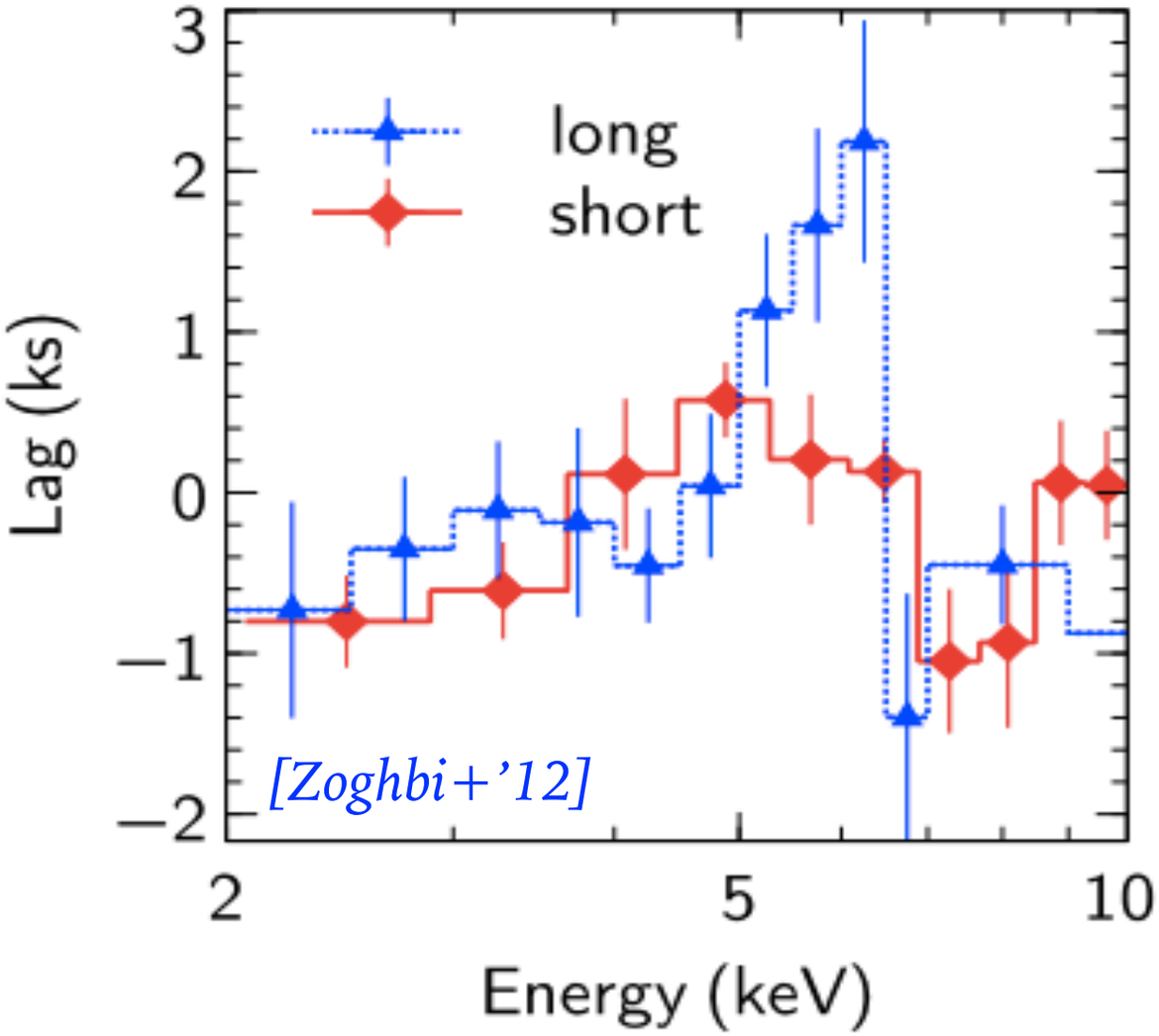
X-ray obscurers

Variable X-ray obscurers influence the intrinsic spectral-timing properties more than warm absorbers

"Other-than-disc-reverberation" lags

Absorbers

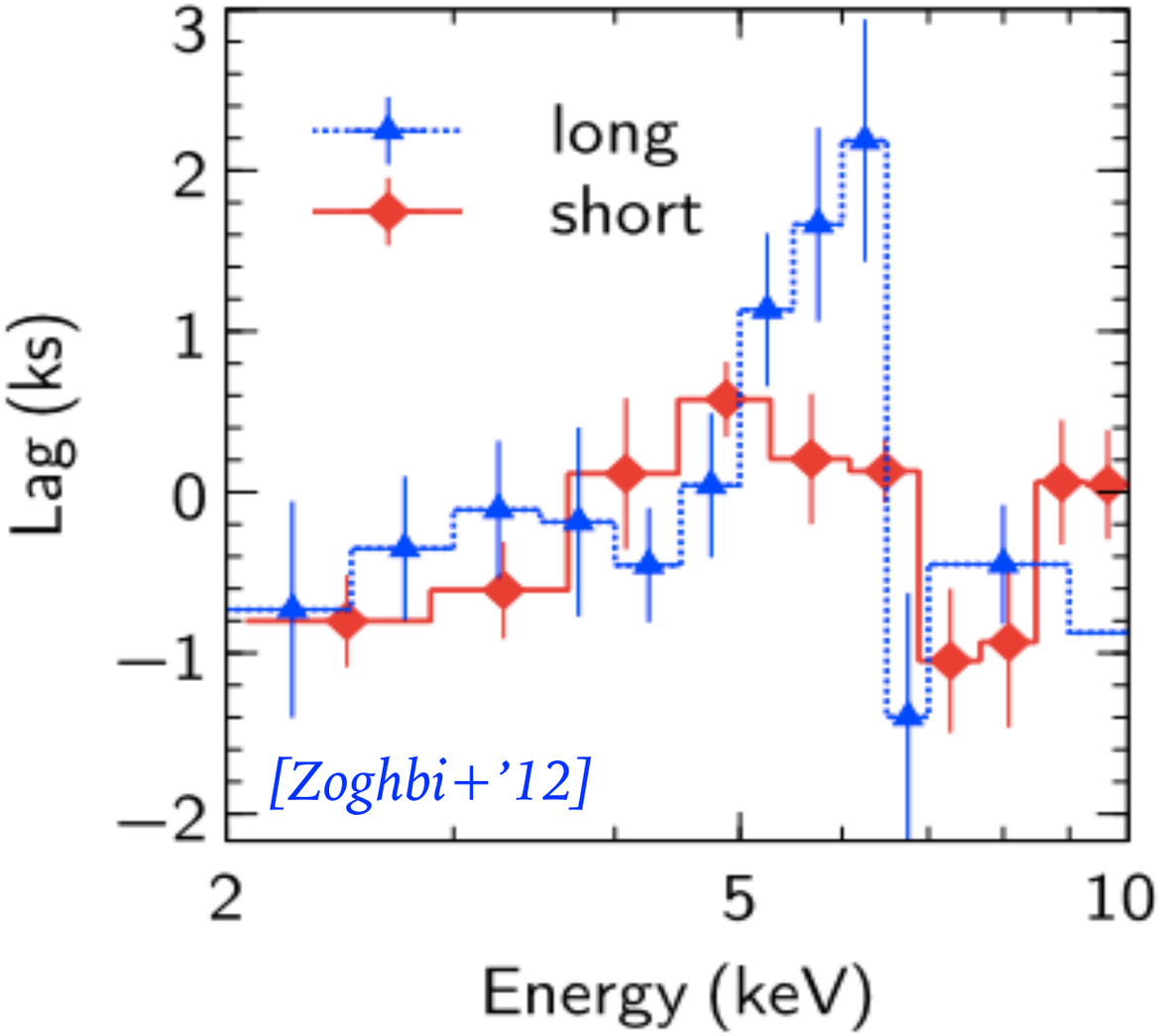
NGC 4151



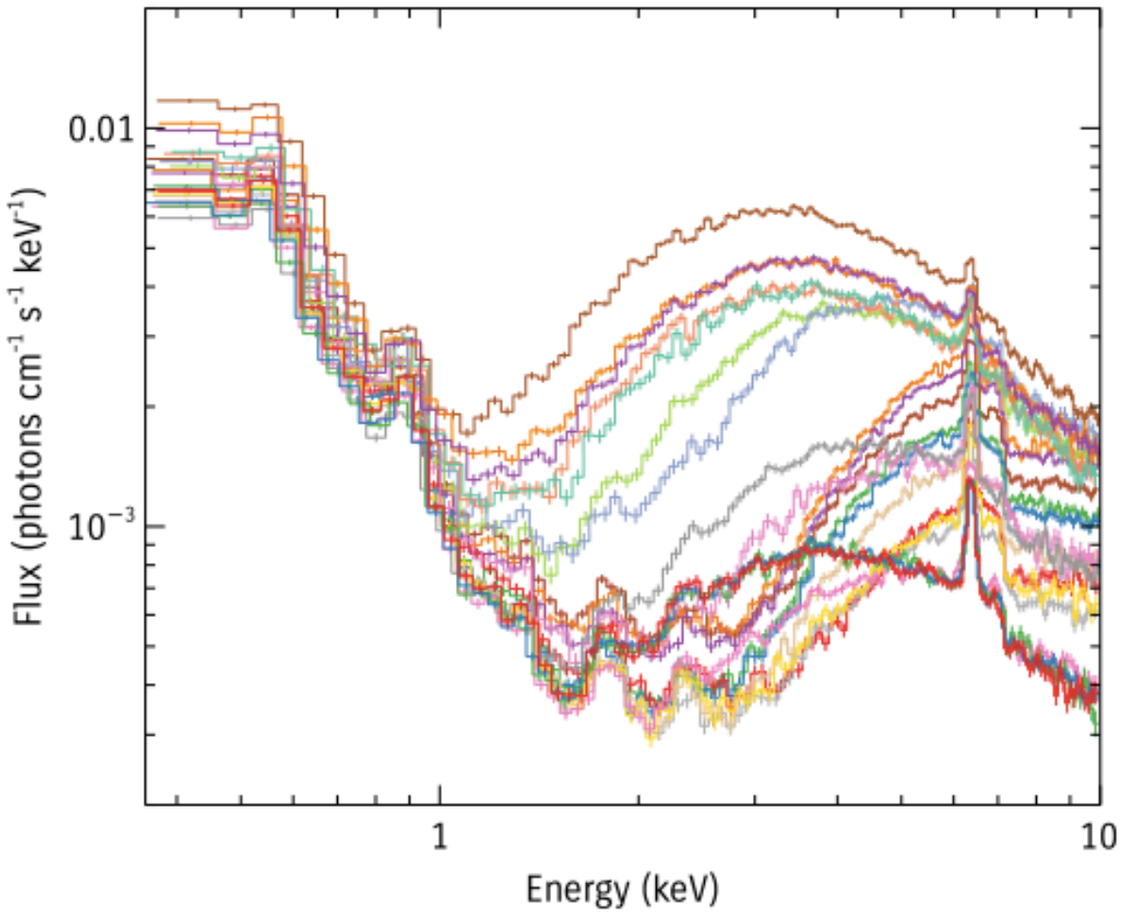
"Other-than-disc-reverberation" lags

Absorbers

NGC 4151



[Zoghbi+'19]

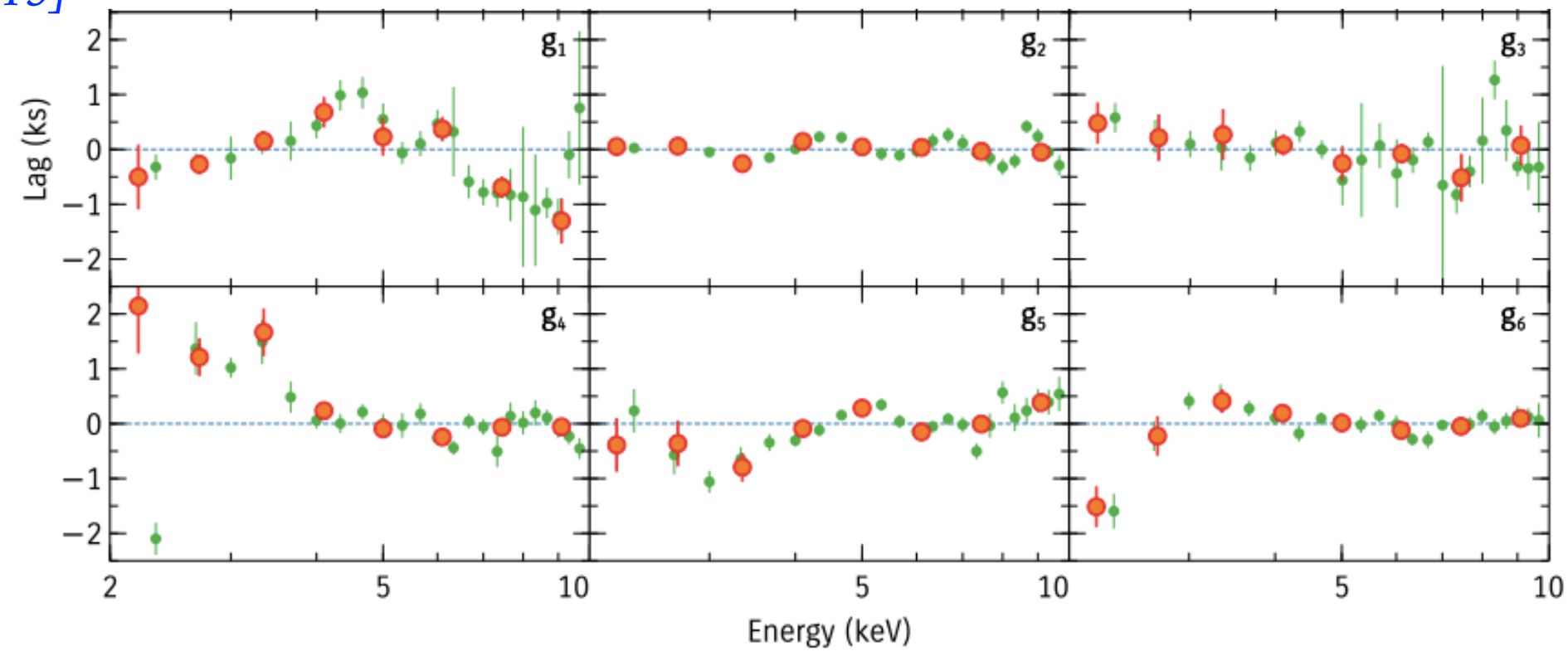


Energy and lag spectra in NGC 4151 can be explained by absorption

"Other-than-disc-reverberation" lags

Absorbers

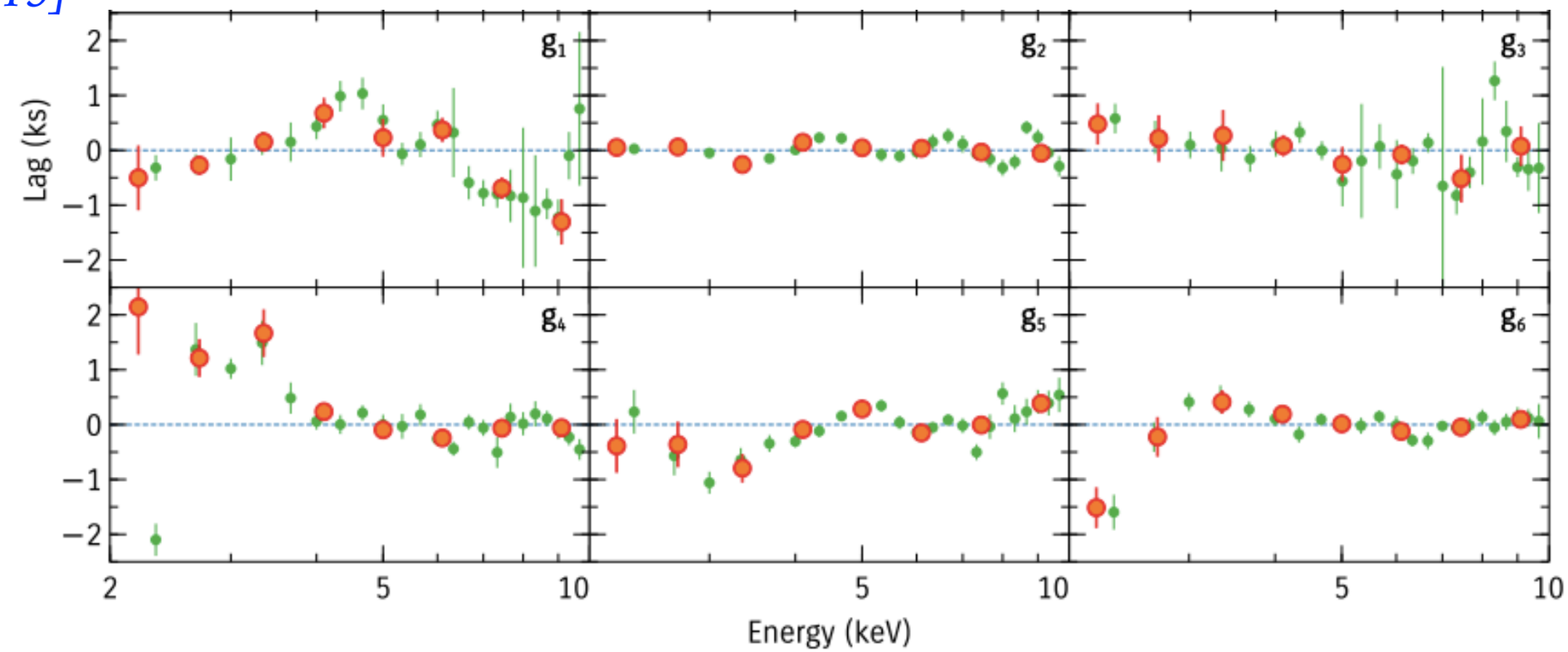
[Zoghbi+'19]

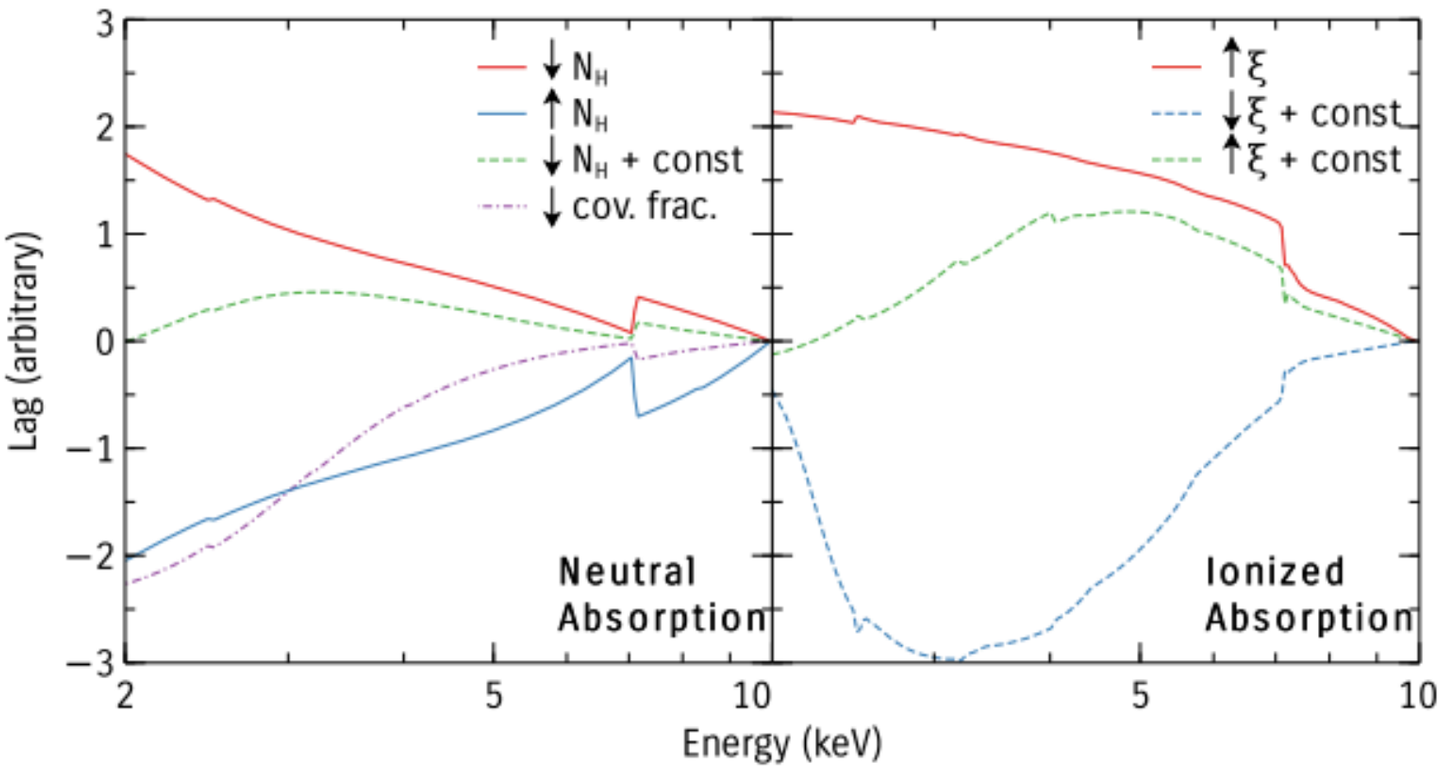


"Other-than-disc-reverberation" lags

Absorbers

[Zoghbi+'19]

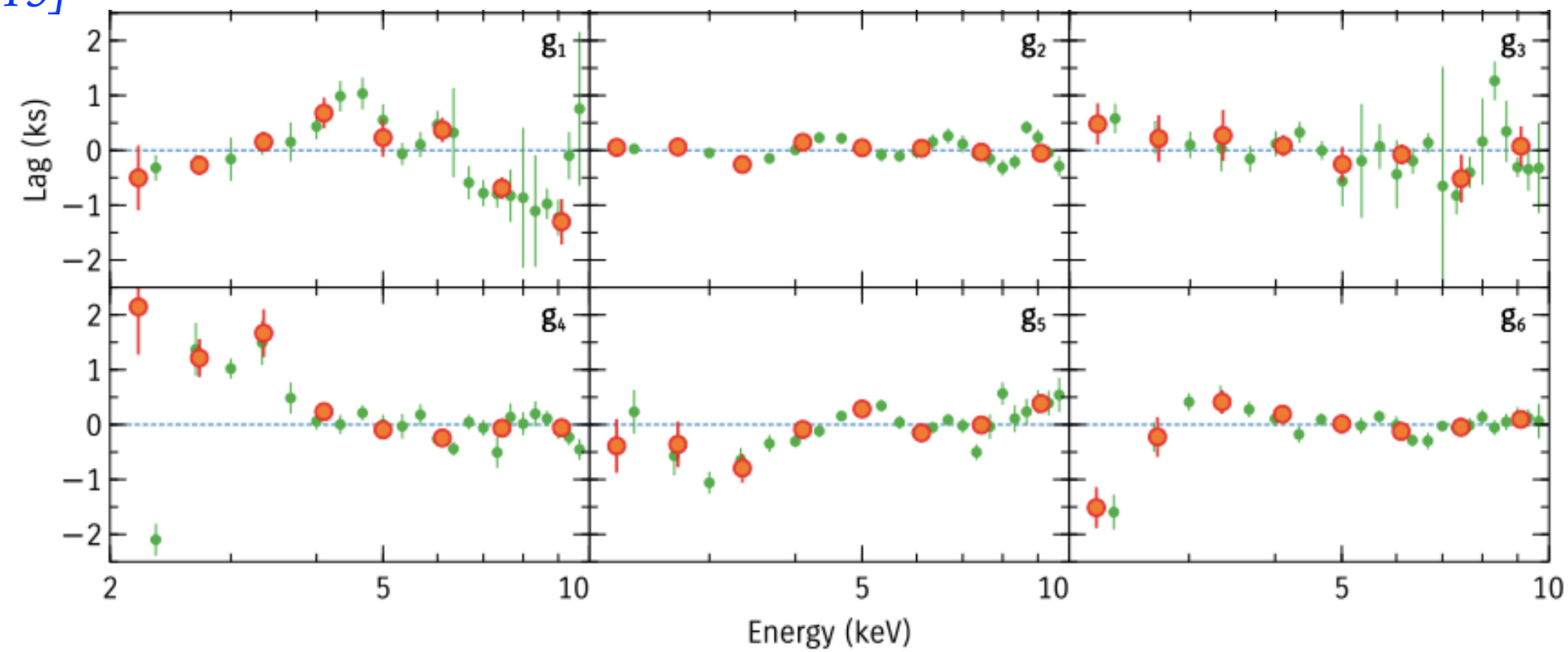


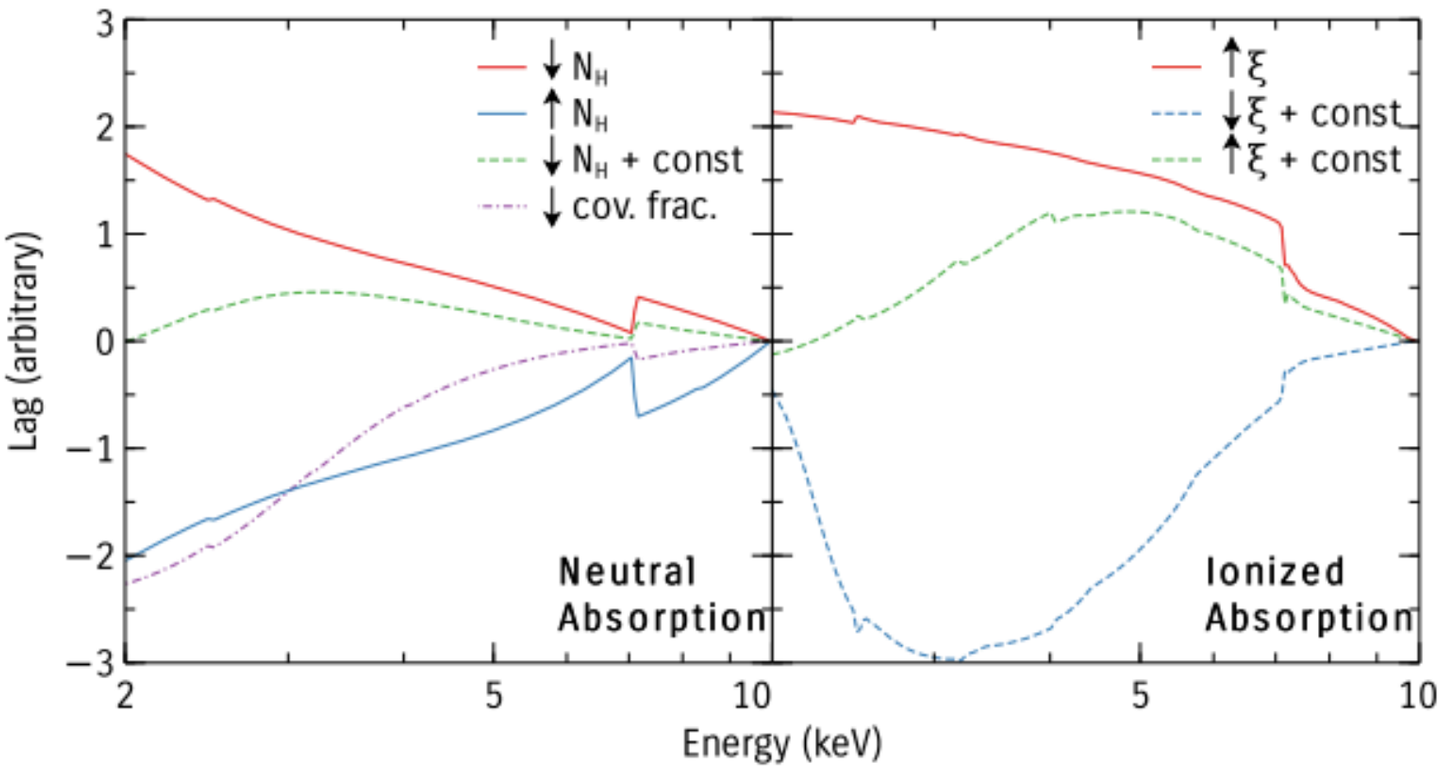


"Other-than-disc-reverberation" lags

Absorbers

[Zoghbi+'19]





If lags only due to absorption, much larger scatter in the measured lags, especially in soft lags

"Other-than-disc-reverberation" lags

Absorbers

$\tau \propto 1/n_e \propto 1/L_{ion}$

Anti-correlation with ionizing luminosity/Eddington ratio expected if lags due to variable absorbers

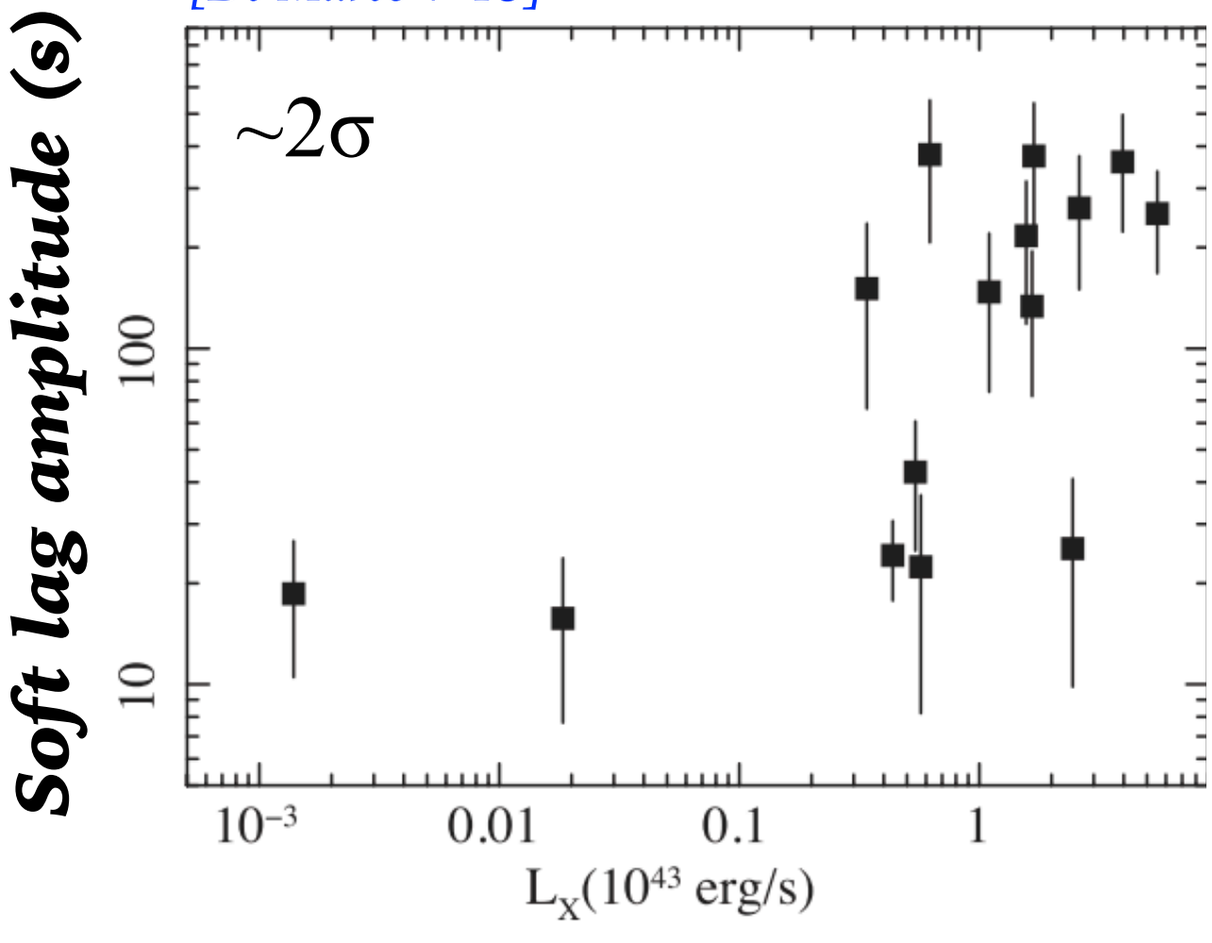
"Other-than-disc-reverberation" lags

Absorbers

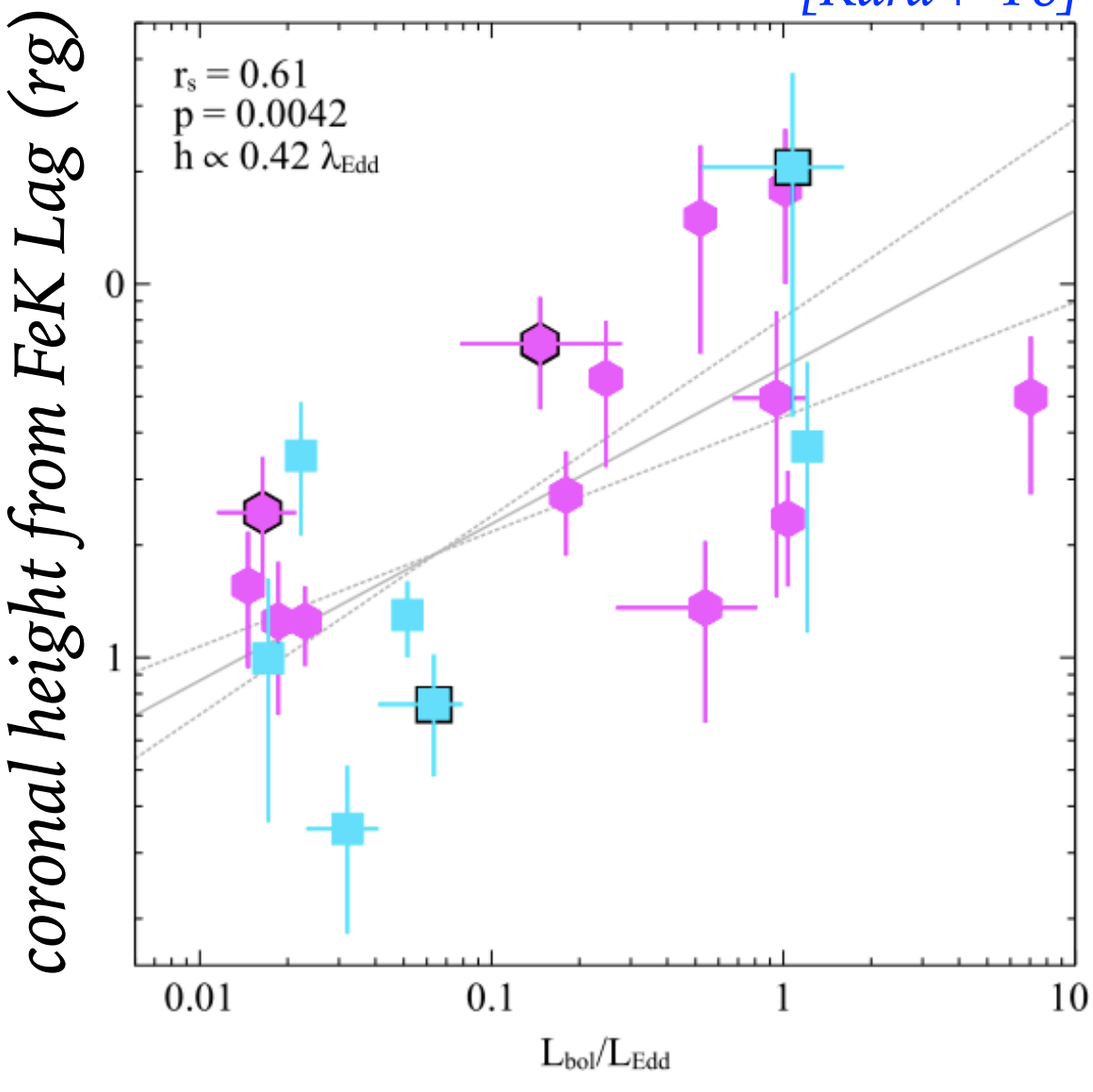
$\tau \propto 1/n_e \propto 1/L_{ion}$

Anti-correlation with ionizing luminosity/Eddington ratio expected if lags due to variable absorbers

[De Marco+'13]



[Kara+'16]

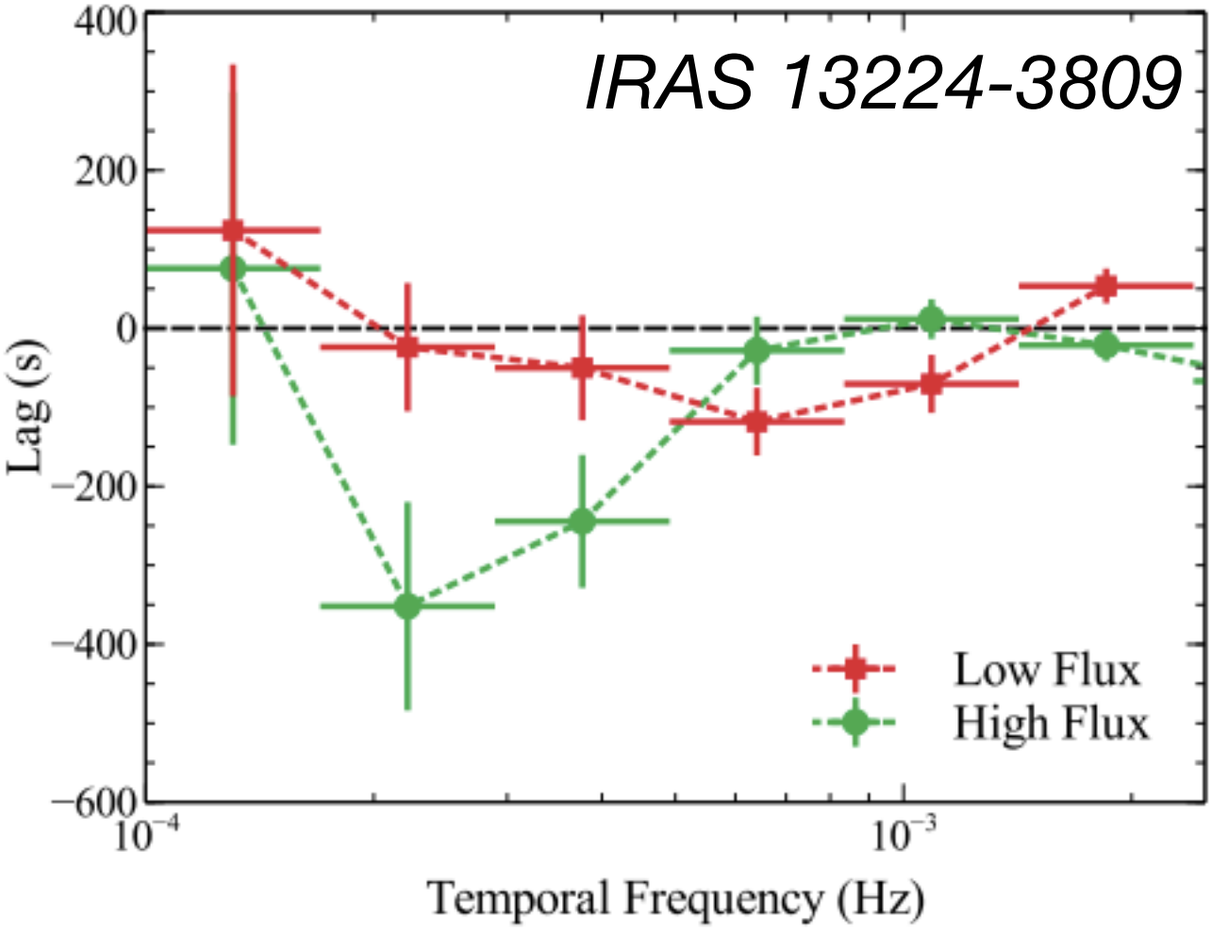


but this is not observed

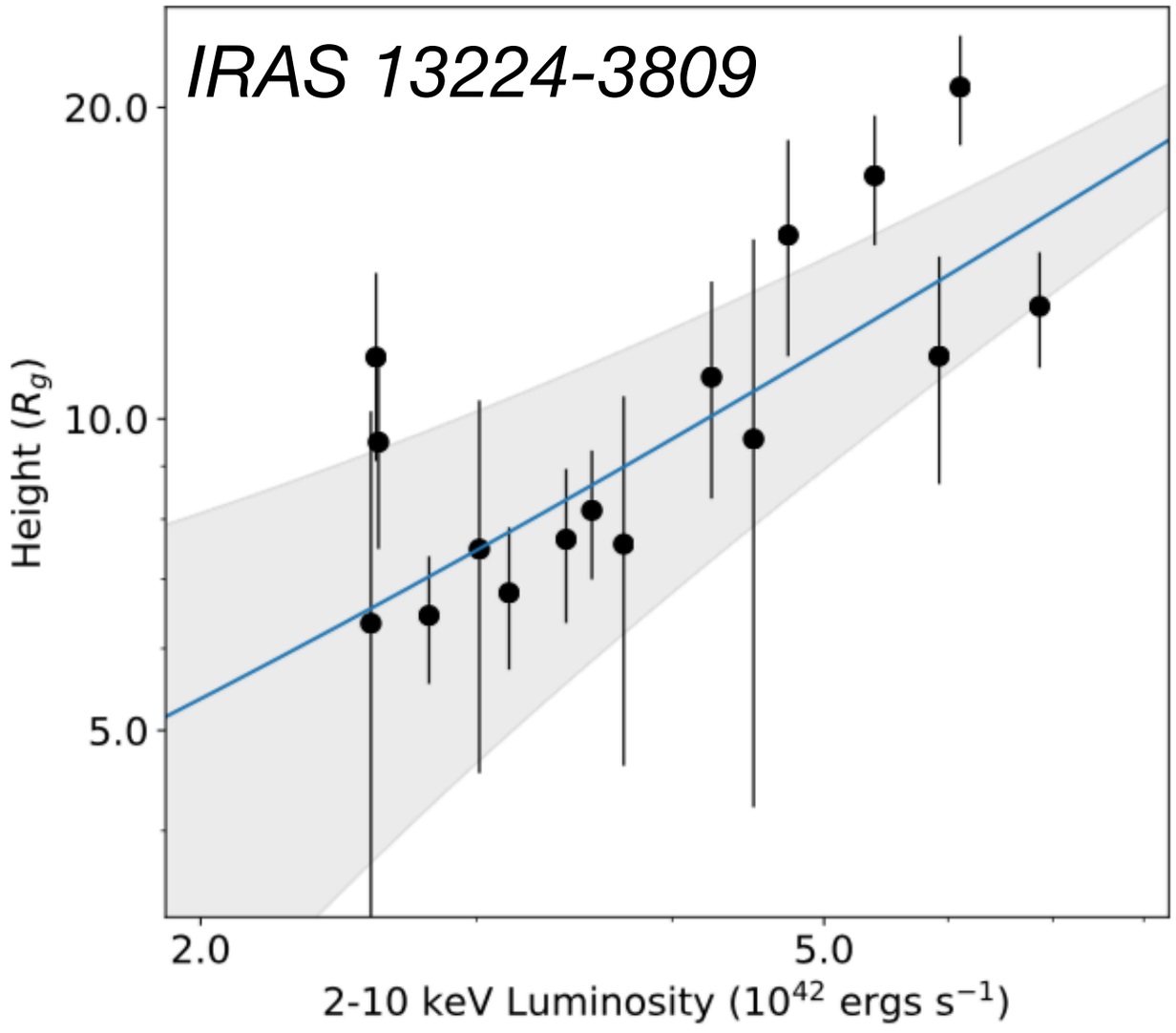
Evolving reverberation lags

Lags depend on flux

[Kara+'13; see also Alston+'13; Frederick+'18]



[Alston+'20]



Summary

Reverberation in the inner disc offers a simple and self consistent explanation for the overall detections of soft and Fe K lags in AGN and their correlation with BH mass

Several other effects (dilution, distant reflectors, absorbers) can affect our measurements

Nonetheless, it is difficult to envisage how these effects could reproduce the strong and tight correlation with BH mass