X-ray time lags and reverberation from accreting black holes

Phil Uttley

University of Amsterdam

Thanks to: Ed Cackett, Erin Kara, Andy Fabian, Dan Wilkins

(Review paper: arXiv:1405.6575)

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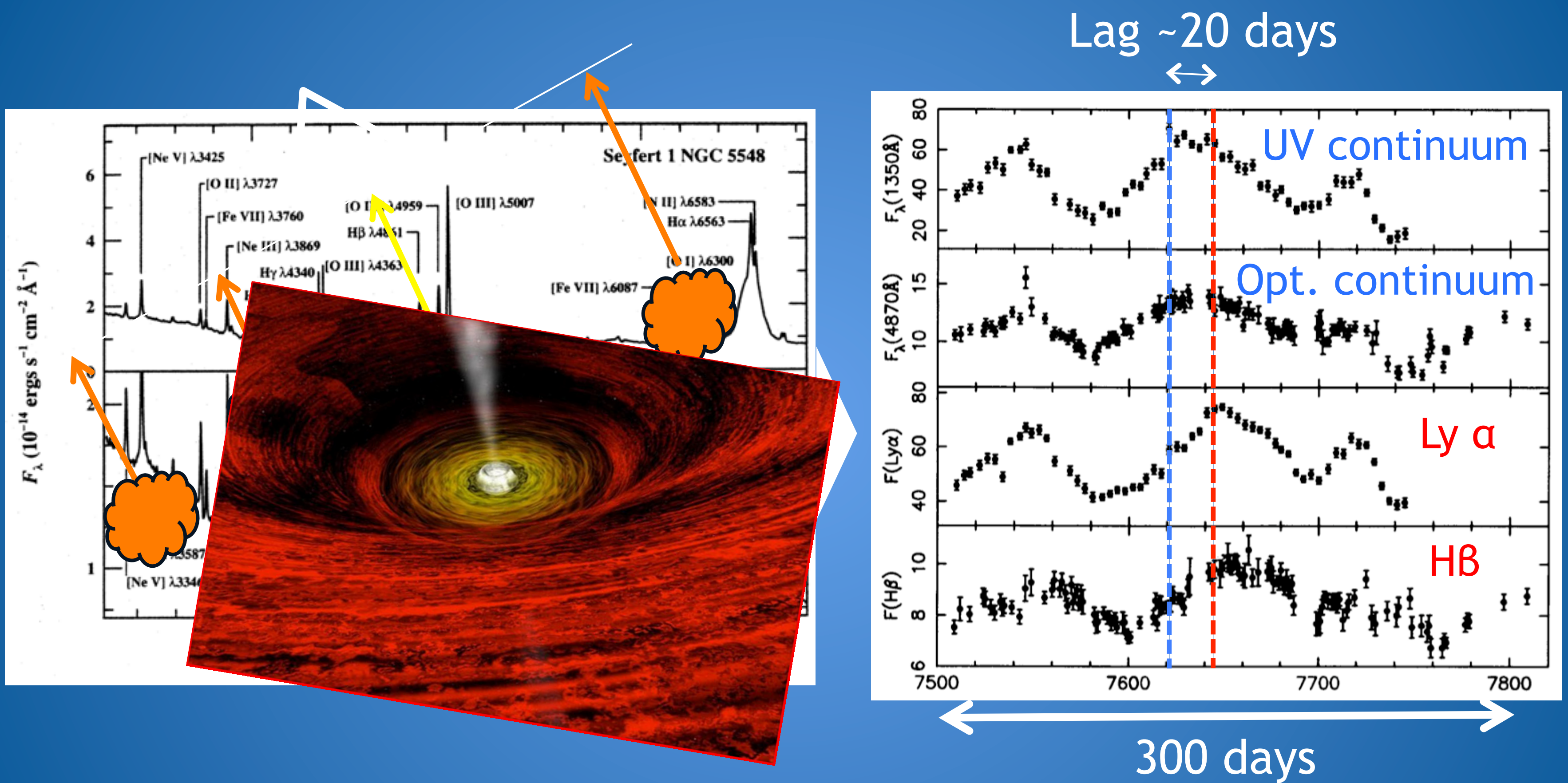
1. Background

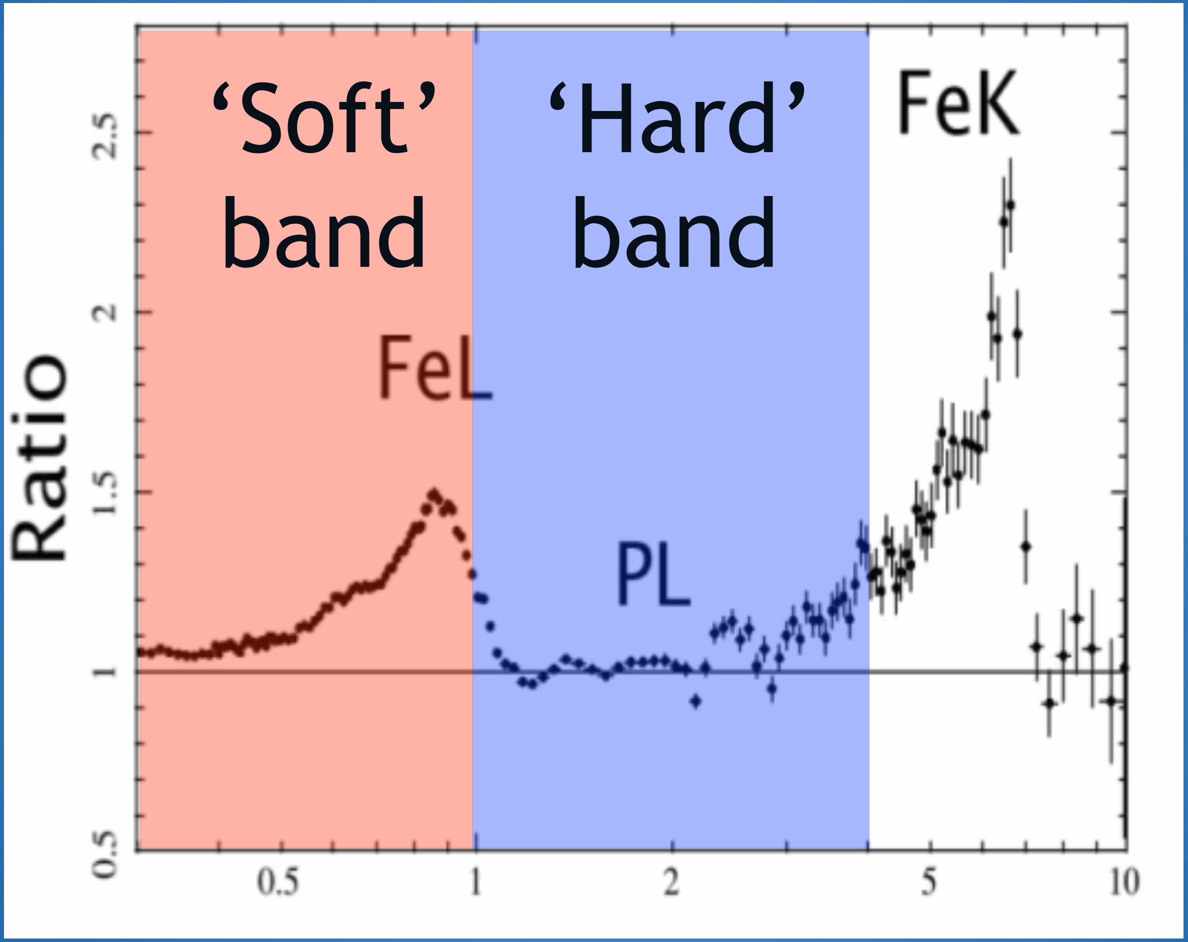
Reverberation mapping



Optical time lags in AGN can be used to map scales of light-days

X-rays can map <light-mins in AGN, and <light-ms in XRBs!

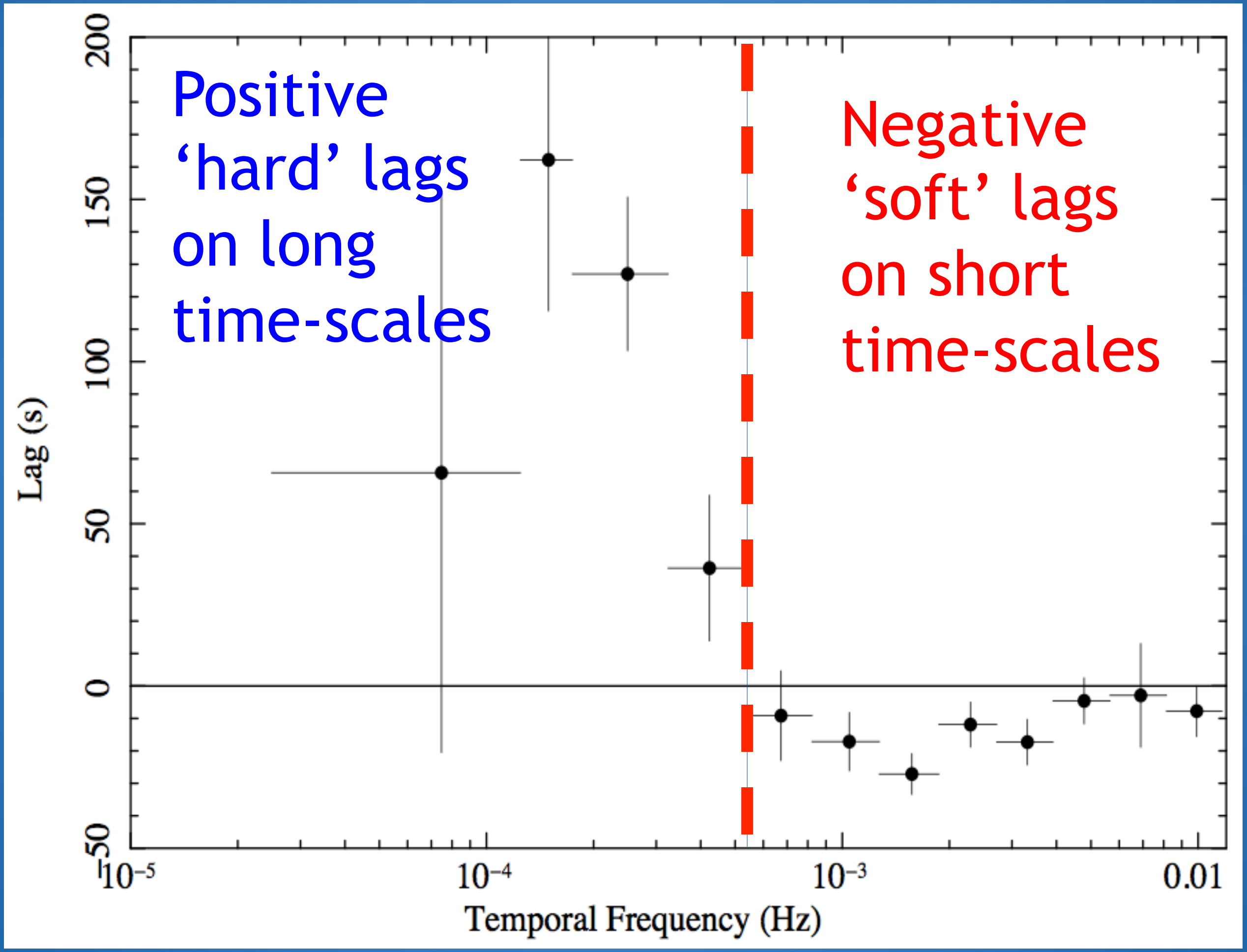
Discovery in 1H0707-495



Fabian et al. 2009

Discovery in 1H0707-495

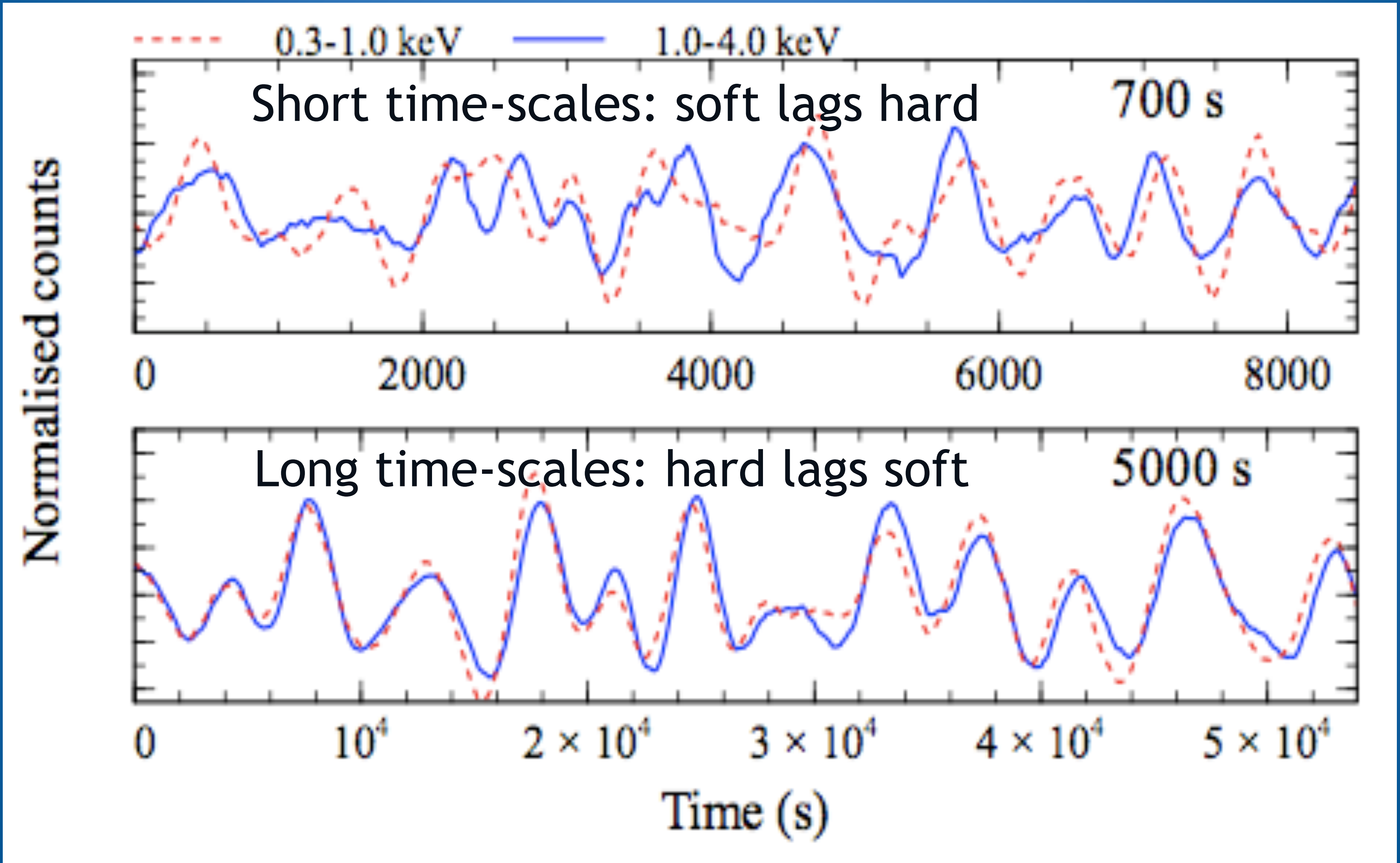
Fabian et al. 2009



Hard lags were already known in AGN & BHXRBs, soft lags new

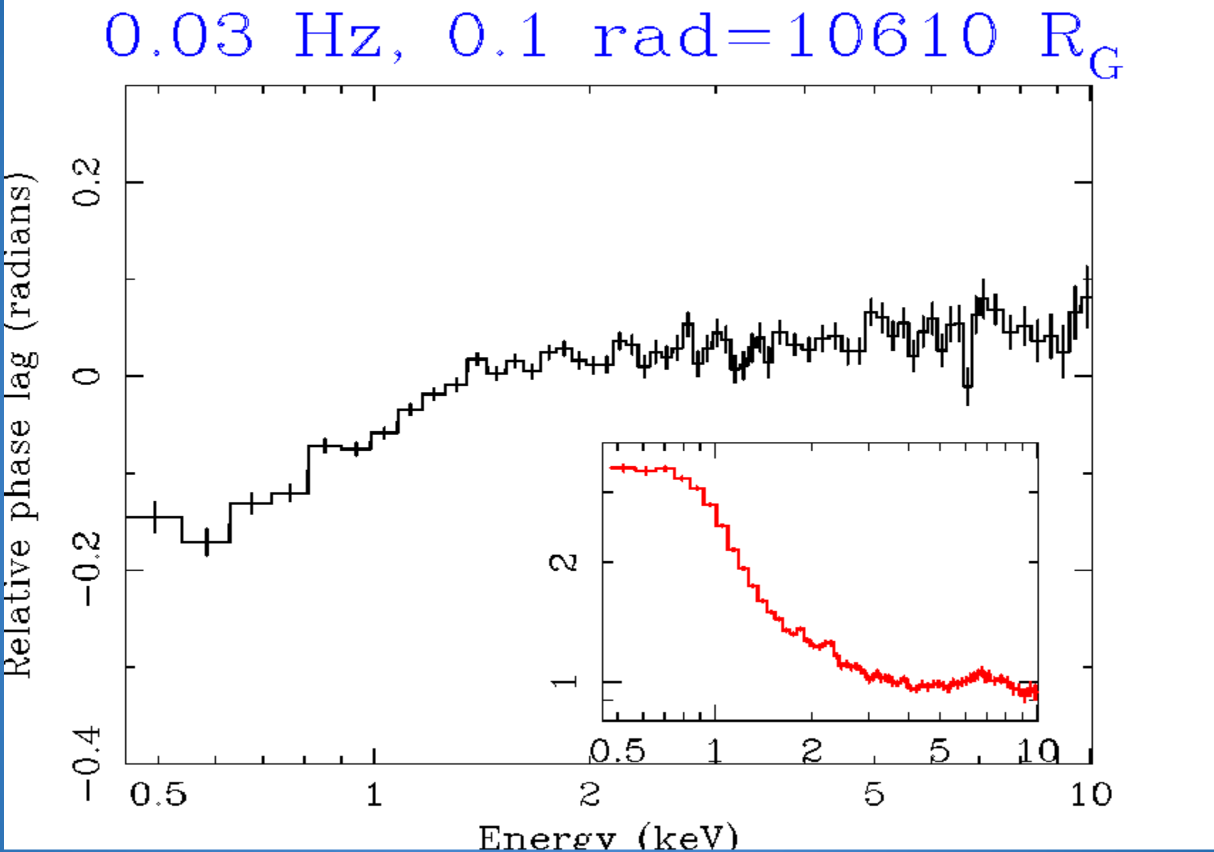
1H0707-495: Time-scale dependent lags

(Zoghbi et al. 2010)



BH X-ray binary GX 339-4 hard state

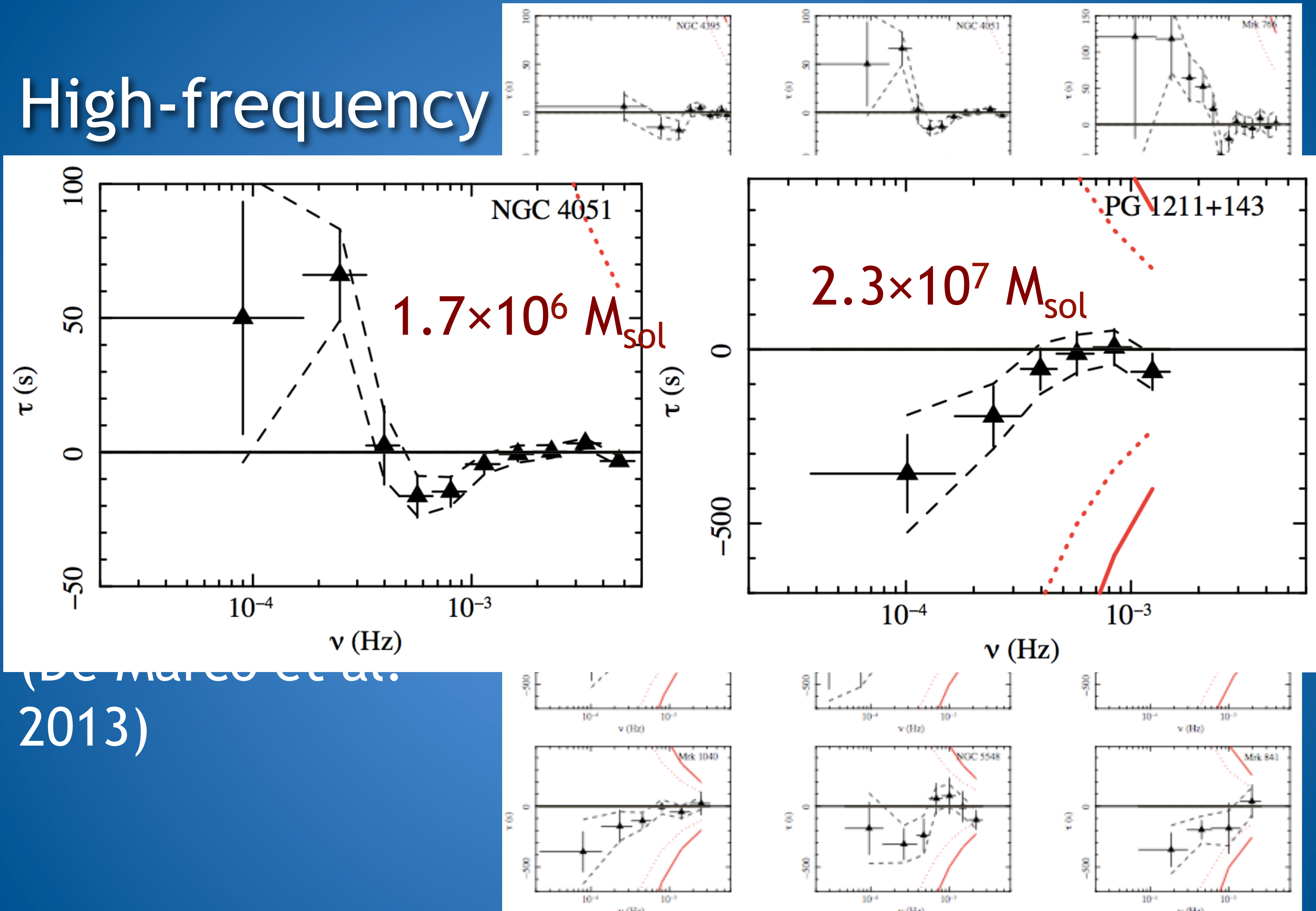
Uttley et al. 2011



Intrinsic accretion fluctuations drive the variability and lags on long time-scales (> 1 s), disc (thermal) reverberation explains switch in lags on shorter time-scales

2. Phenomenology

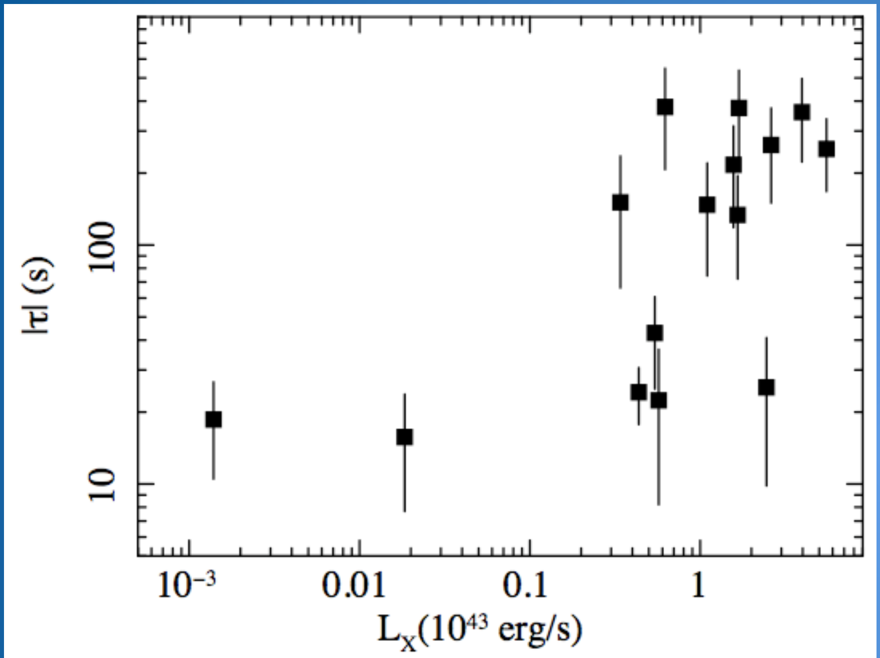
High-frequency

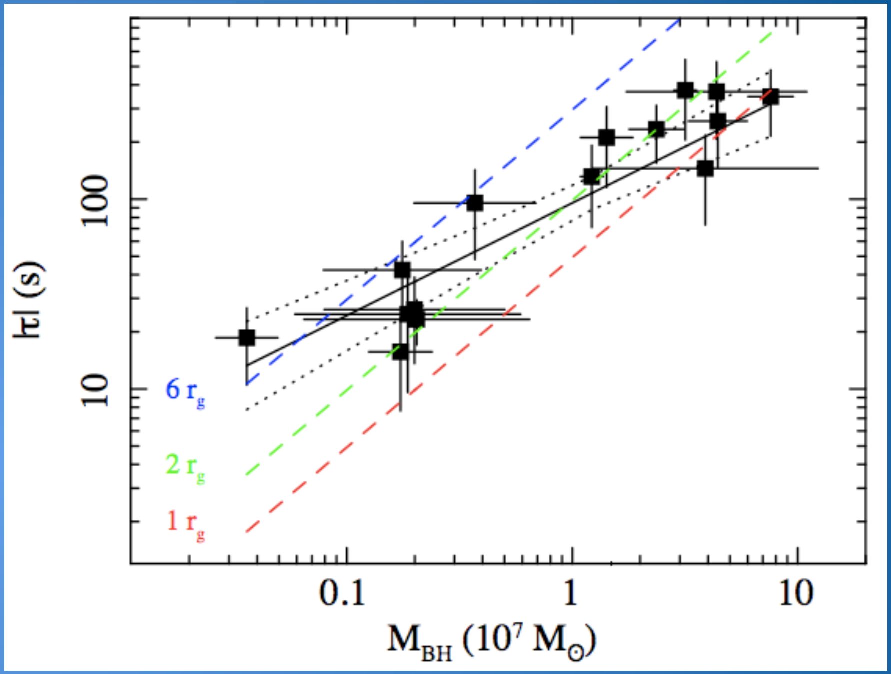


(De Marco et al. 2013)

Lag vs. luminosity and black hole mass

De Marco et al. 2013





Lag correlates with mass, not with luminosity

Contrasts with strong L vs. lag correlation found in optical reverberation (Kaspi et al. 2005)

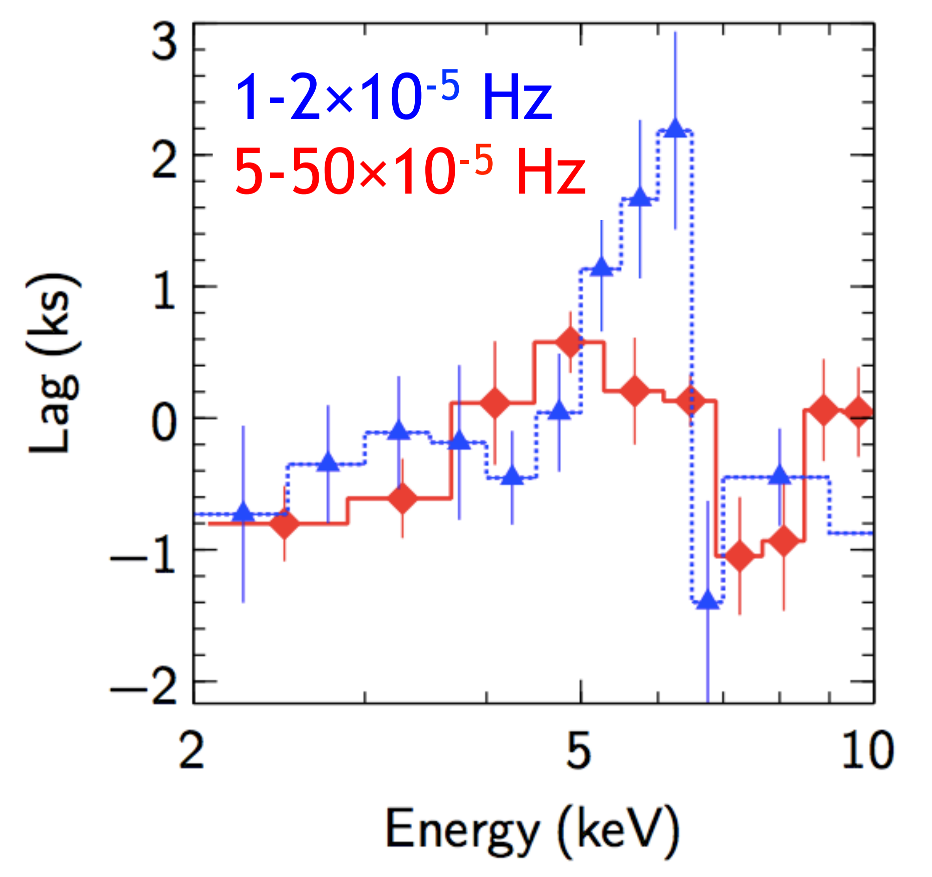
There is a common, *small* size-scale in AGN: set by inner edge of disc?

Discovery of Fe K reverberation in NGC 4151 (Zoghbi et al. 2012)

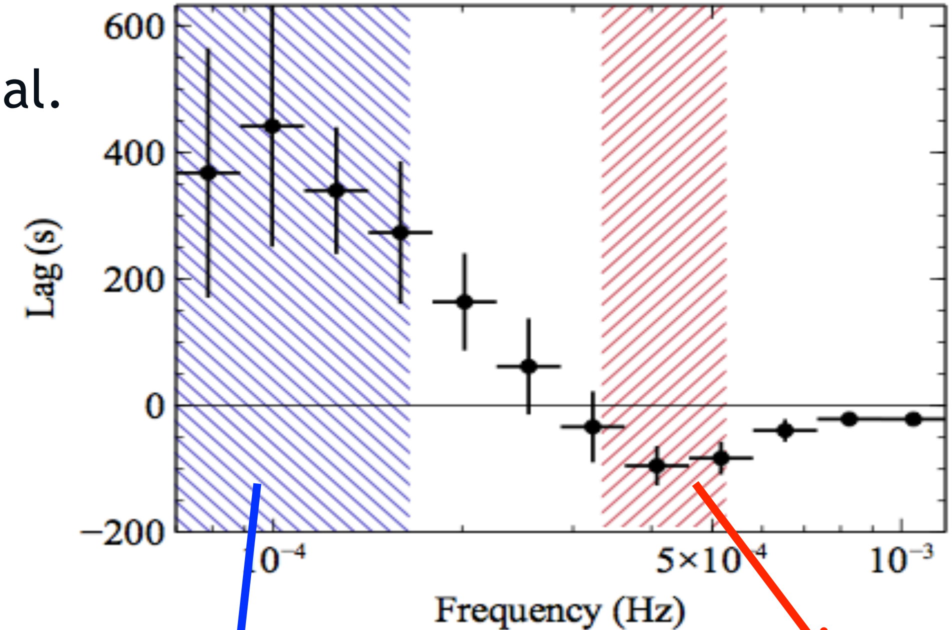
Longer time-scales: line core
shorter time-scales: red wing

Signature of disk reflection reverberation

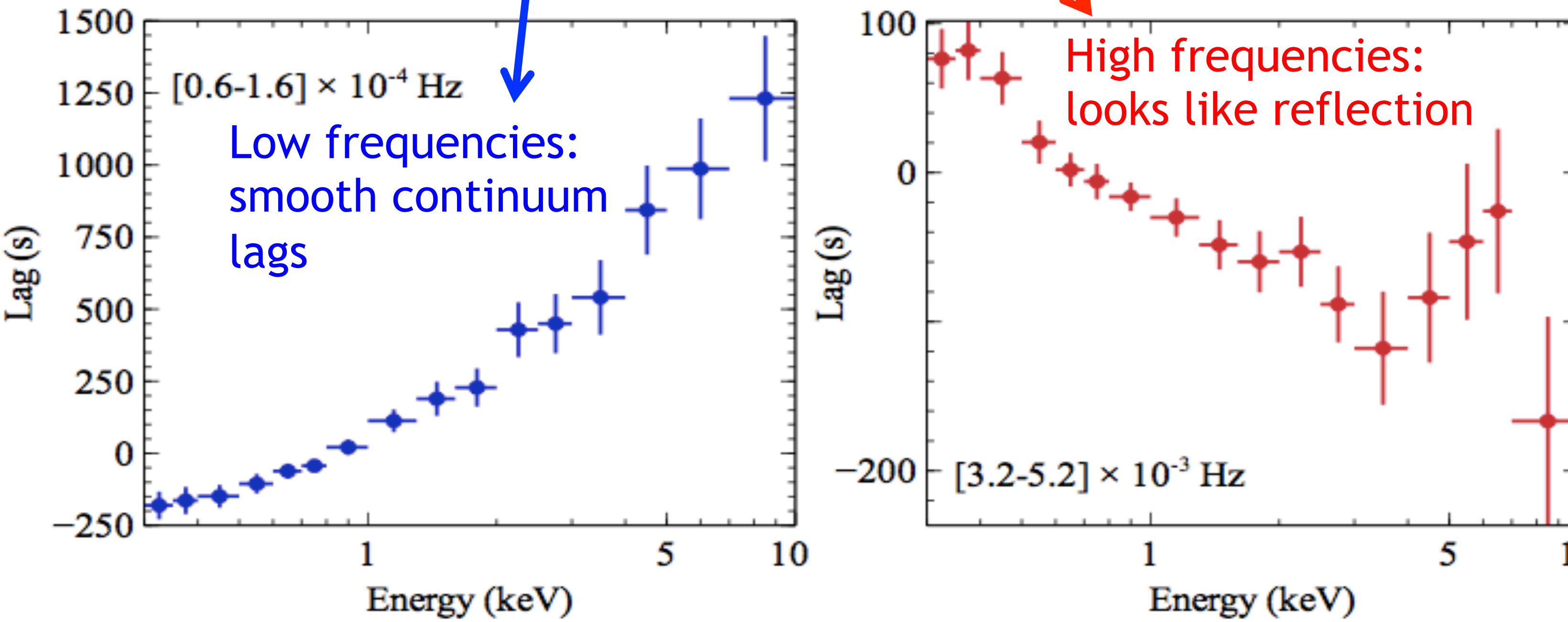
More importantly: first ***independent*** confirmation of inner-disk origin of broad Fe K feature seen in energy spectrum since its discovery!



(Kara et al. 2013)



Inconsistent with large-scale reflection (e.g. Miller et al. 2010)



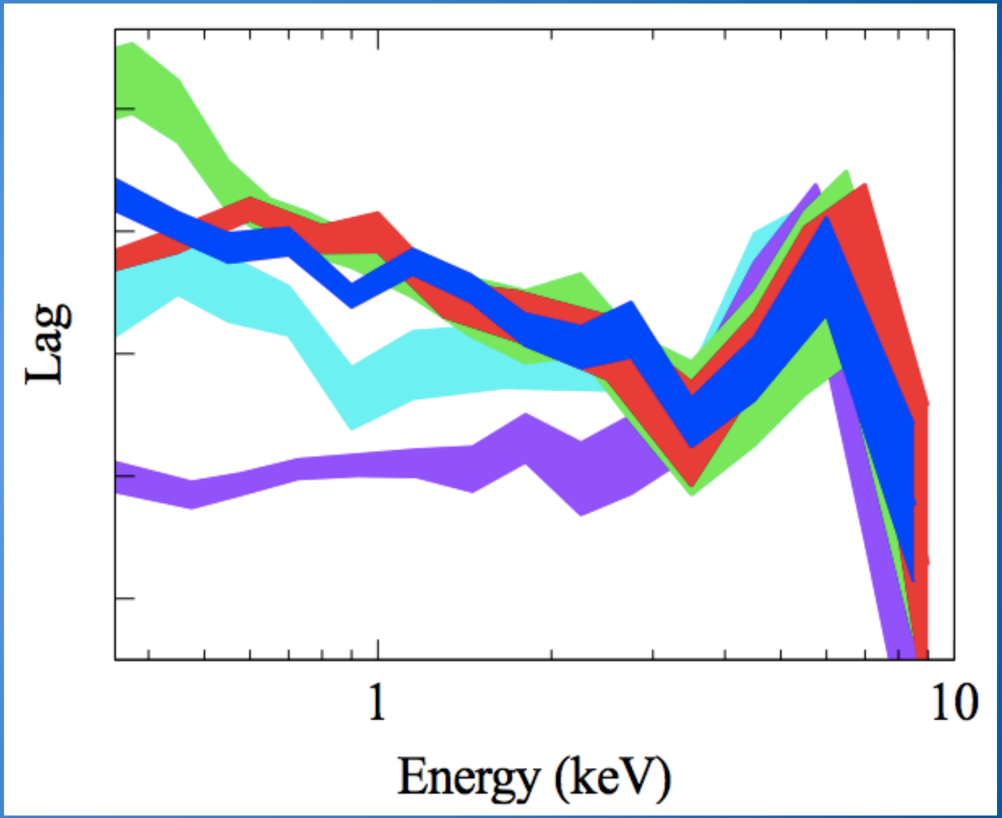
Complex soft lags, but 'clean' Fe K

Fe K 'bump' in lags is common (Kara et al. 2013)

Shape of soft lags changes from source to source!

Different origins for soft excess?

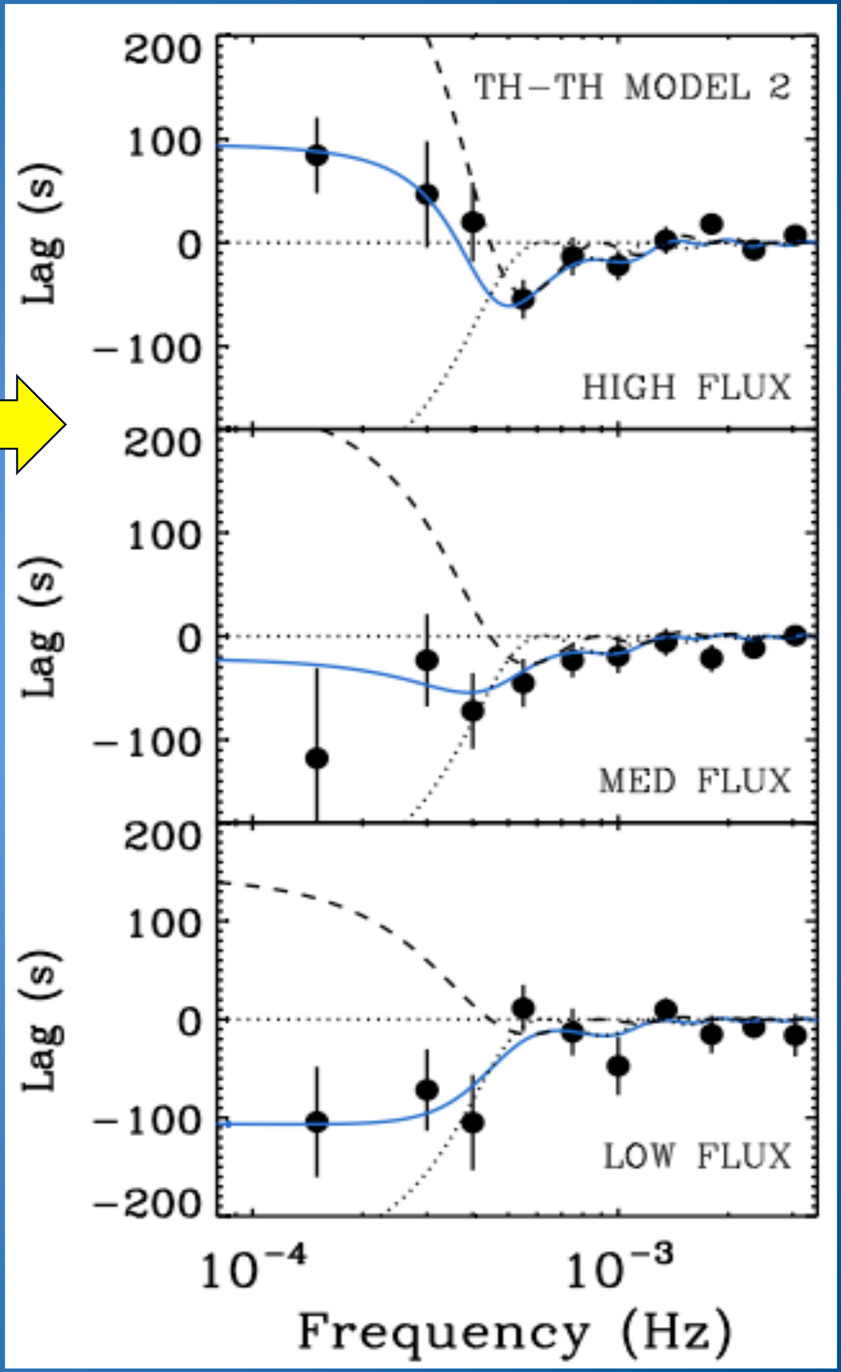
- Photoionised reflection
- Disc bb
- Comptonisation (e.g. see Gardner & Done 2014)

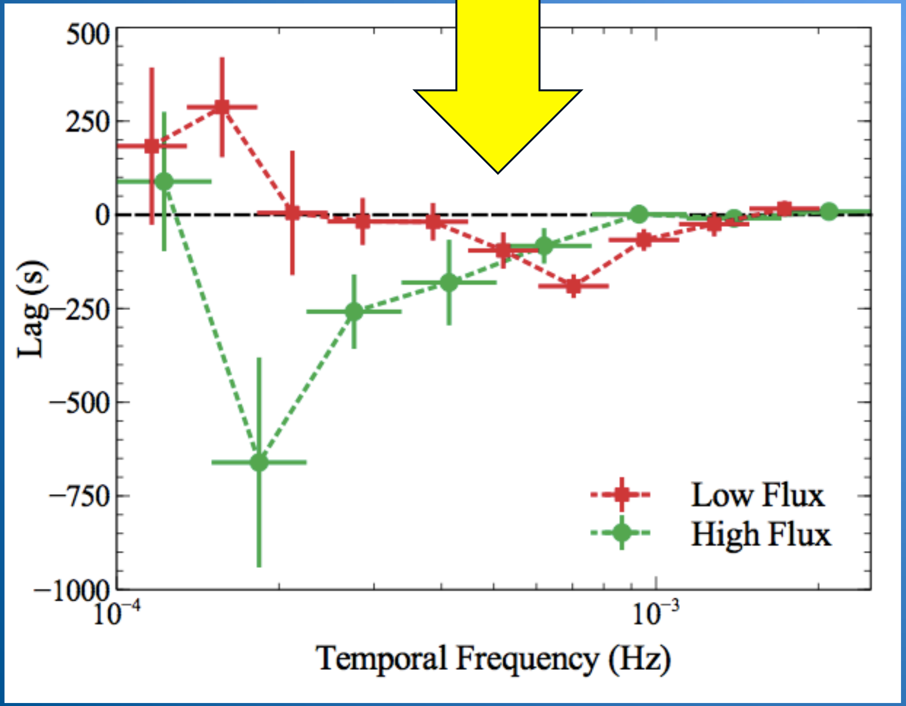


Flux-dependent lags: complex picture

NGC 4051: Alston et al. 2013

IRAS 13224-3809: Kara et al. 2013

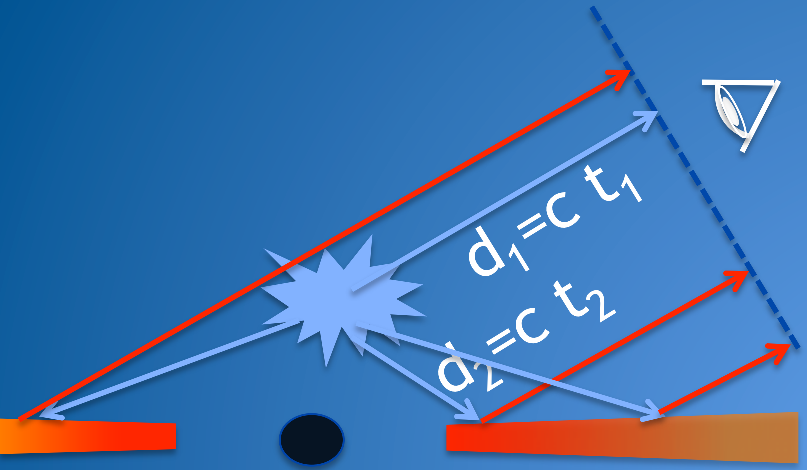


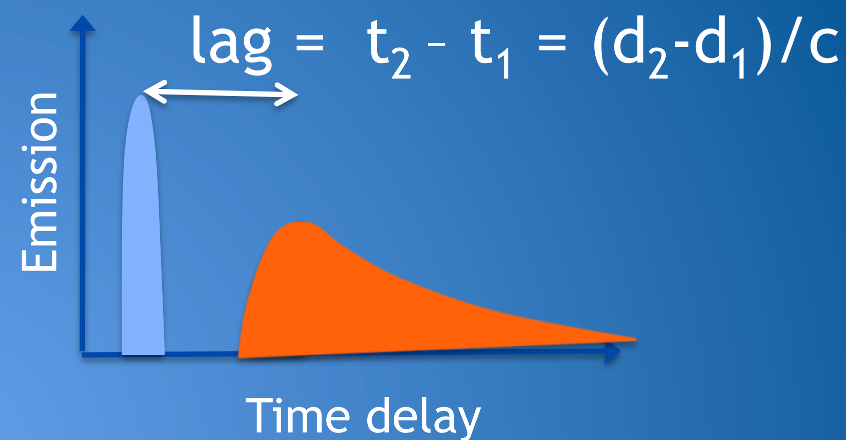


3. Basic interpretation

(see next talk for the full treatment!)

How to model the lags





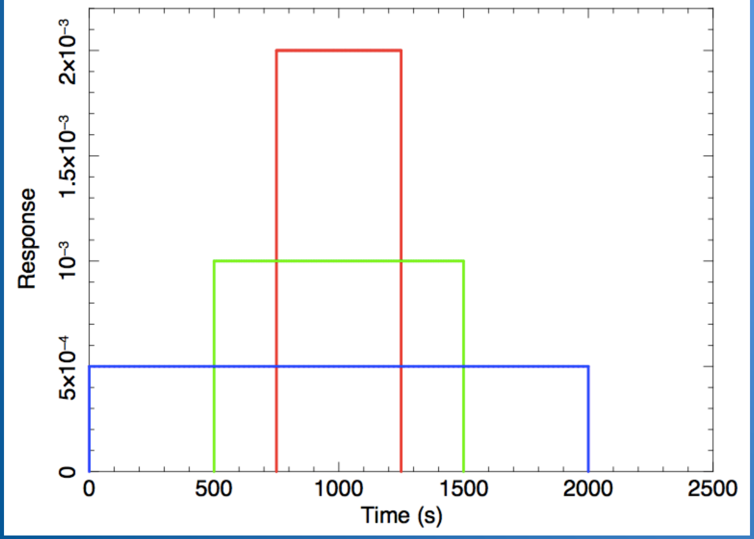
"Impulse response"

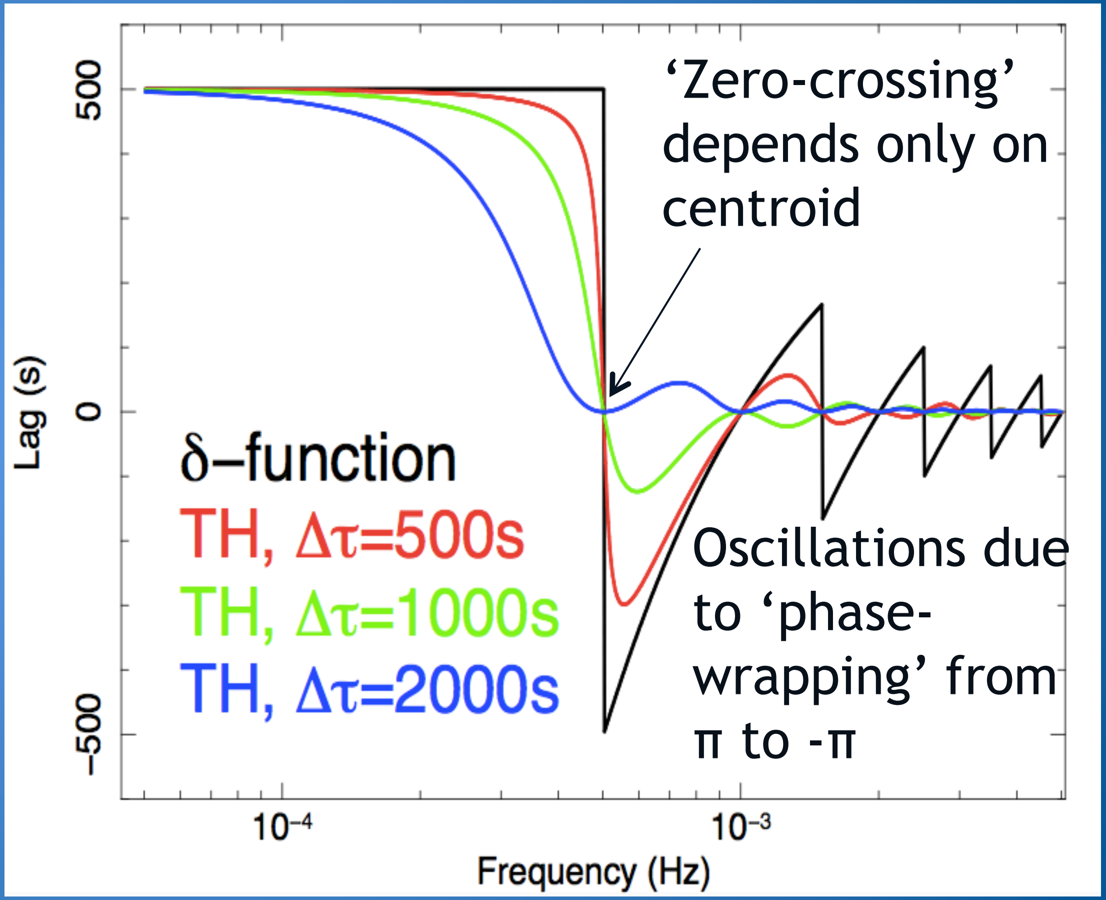
The light curve from the reflected/reprocessed component is a delayed and smeared out version of the continuum light curve.

The lags and amplitudes are given by the Fourier cross-spectra of the impulse response in each band

Effect of impulse response width

Top hats with same centroid but different widths

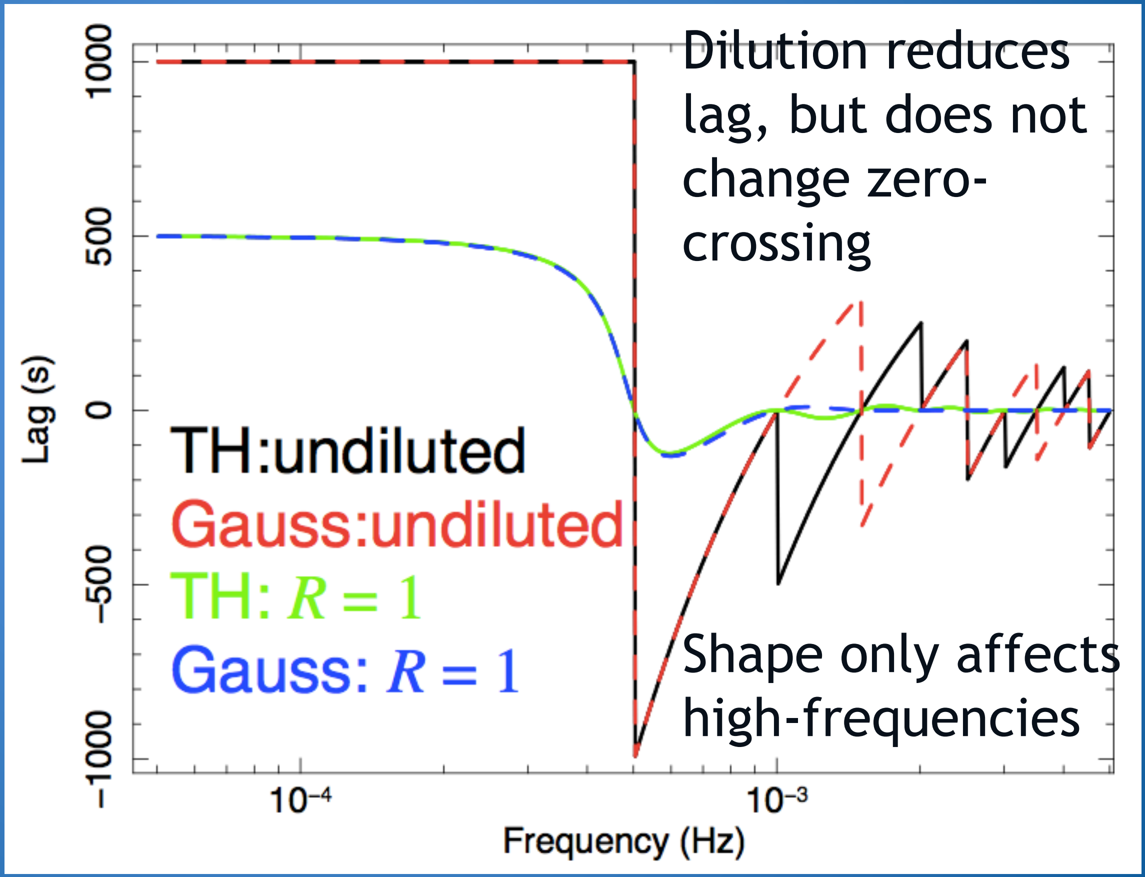




Effect of impulse response shape + ‘dilution’

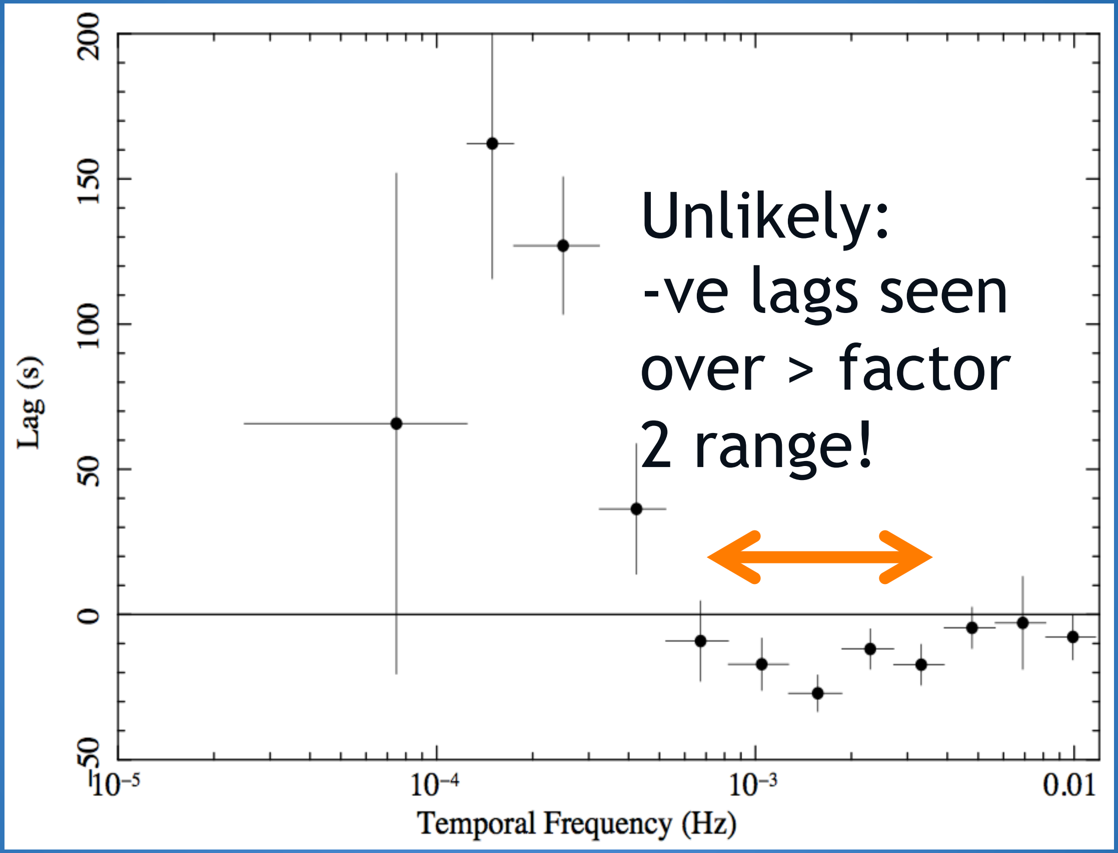
Dilution is the inclusion of some primary continuum in the same band as the reflector

R=1 means equal contributions



Are we seeing phase-wrapping?

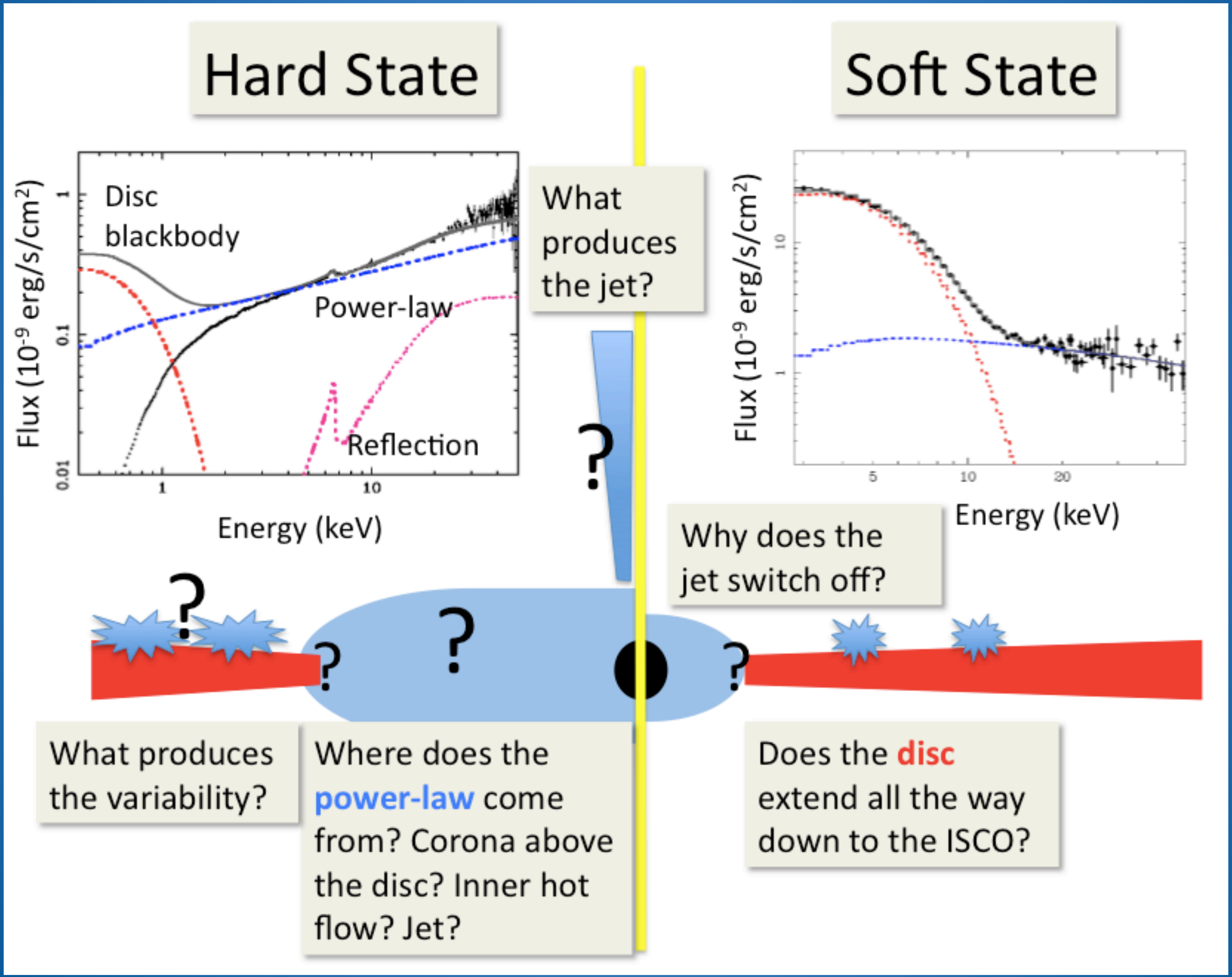
(e.g. Miller et al. 2010, Legg et al. 2013)



Suggests hard-soft lag switch is due to change in lag mechanism: continuum -> reverberation (consistent with lag-energy spectra)

4. Future of lag observations

XRBs – the next breakthroughs?

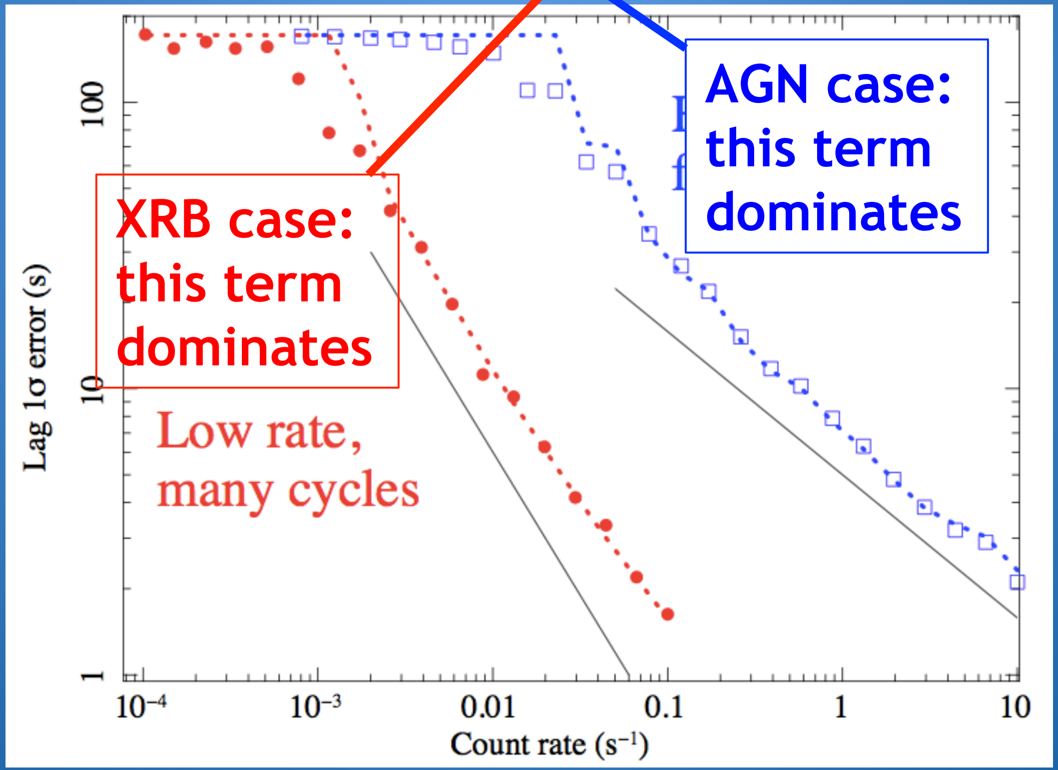


Sensitivity of lag measurements

$$\Delta\phi(\nu_j) = \sqrt{\left(\frac{P_{X,\mathrm{noise}}}{P_{X,\mathrm{signal}}} + \frac{P_{Y,\mathrm{noise}}}{P_{Y,\mathrm{signal}}} + \frac{P_{X,\mathrm{noise}}P_{Y,\mathrm{noise}}}{P_{X,\mathrm{signal}}P_{Y,\mathrm{signal}}}\right)/2M}$$

1-σ error on phase lag (time-lag = Φ/2πν)

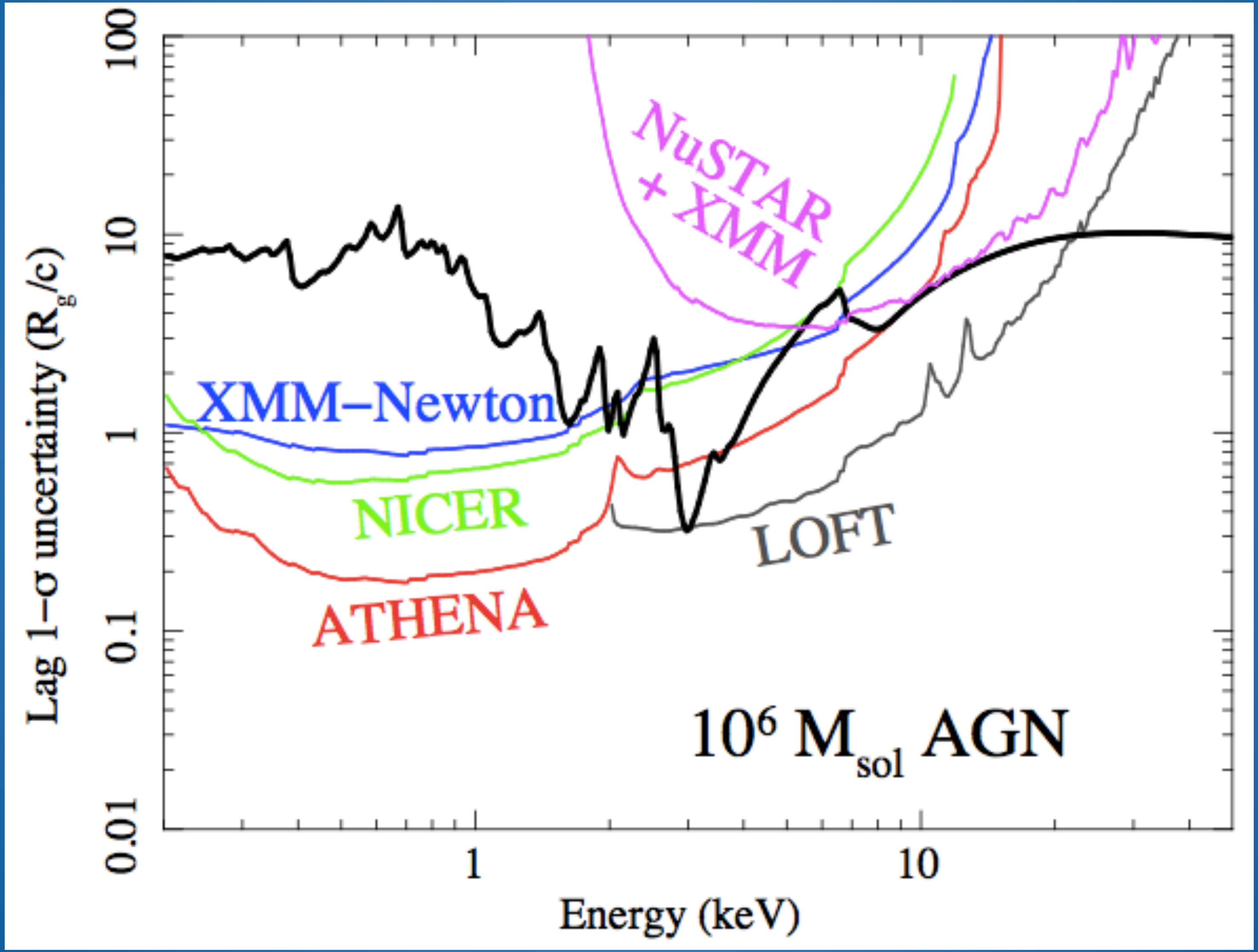
Number of cycles



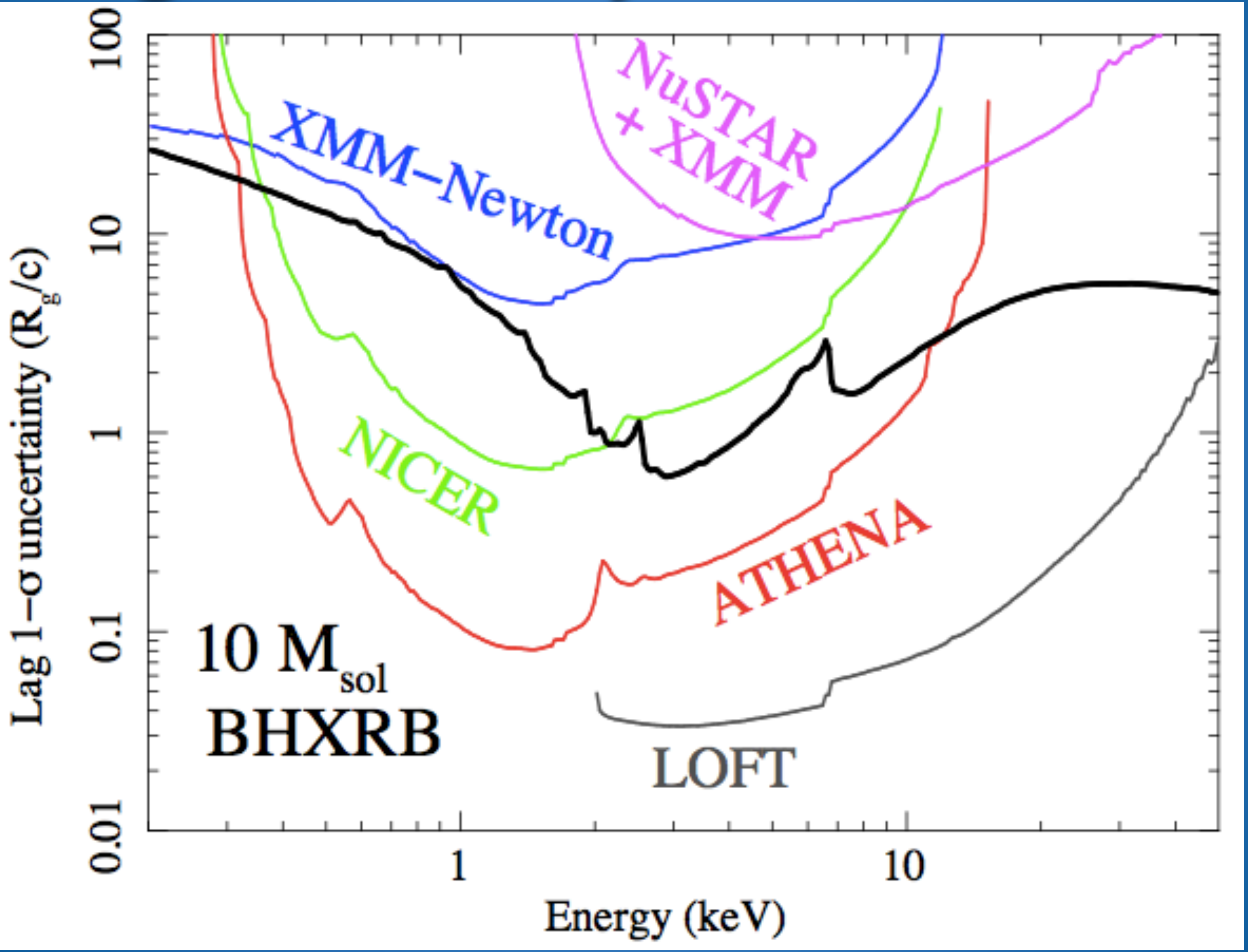
XRB case: this term dominates

AGN case: this term dominates

Lag sensitivity curves: AGN



Lag sensitivity curves: XRBs



Conclusions

- Wealth of evidence that the high-frequency lags are associated with **light-travel delays on small scales** : soft lags due to reverberation + possibly continuum lags

- Fe K reverberation has been found – confirmation of basic diskline interpretation and that reflection plays a role in generating lags

- Reverberation measurements of XRBs will overtake quality of AGN measurements: should finally resolve controversies about disc inner radius changes, coronal geometry etc.