Reverberation in X-ray Binaries with STROBE-X

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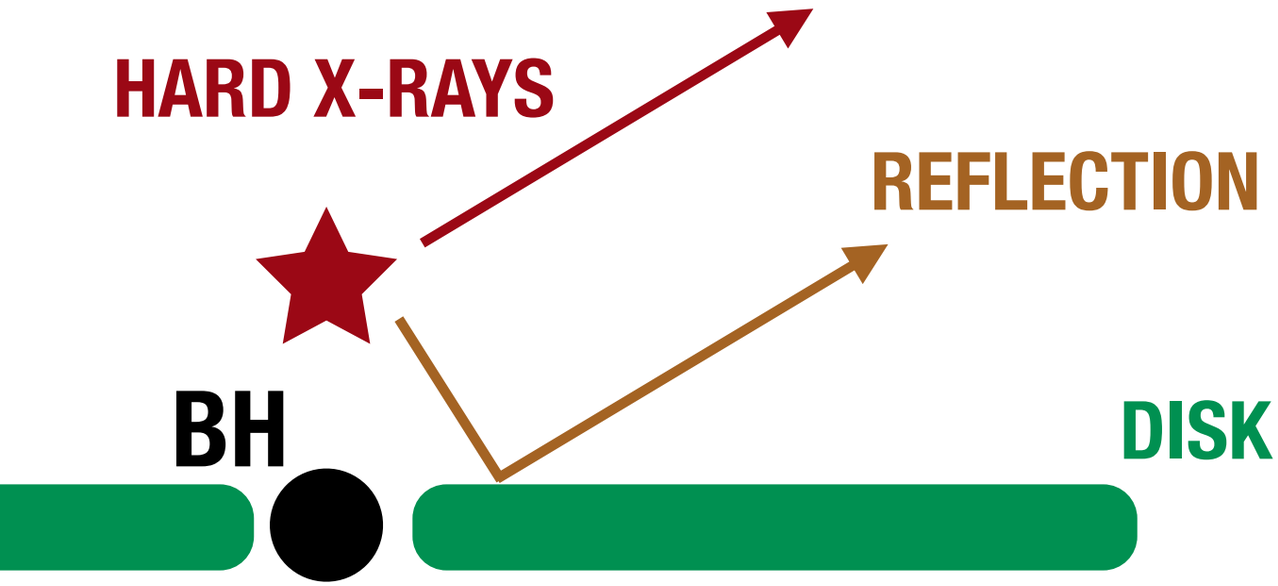
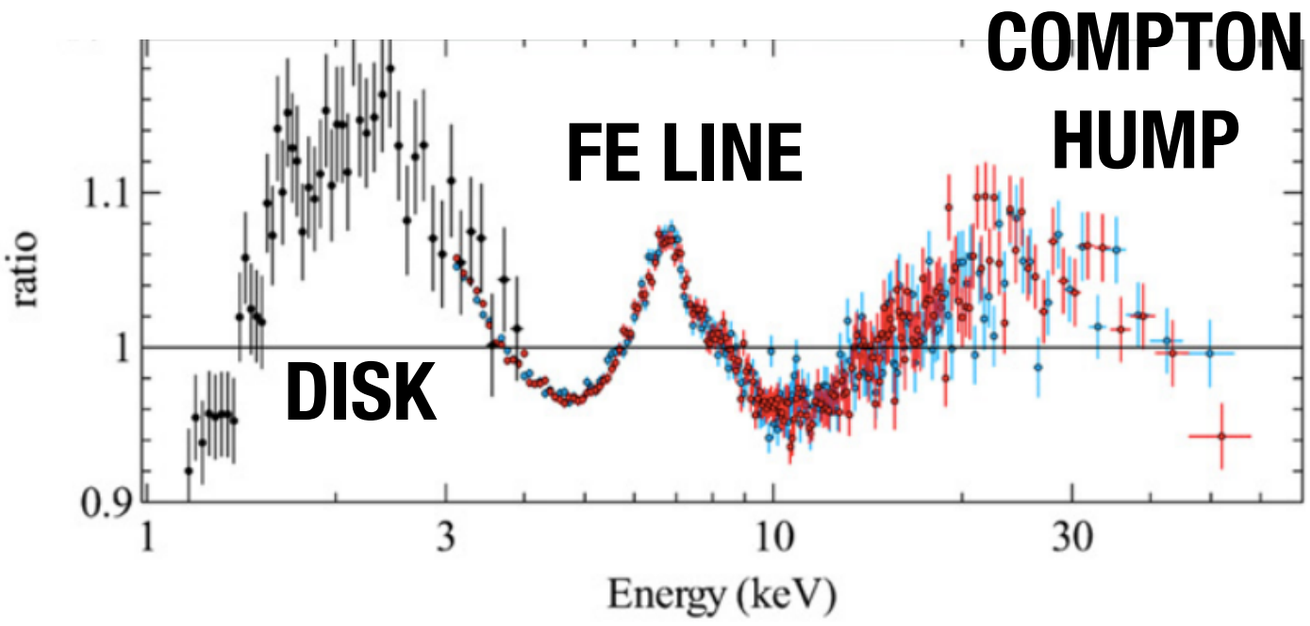
Reflection & Reverberation





Reflection spectrum in GX 339-4 with NuSTAR & Swift (Parker et al. 2016)

- Path-length difference between continuum and reflected photons will lead to a time lag
- Lag will depend on geometry and kinematics of region
- Determine lags between lightcurves in different energy bands using Fourier techniques
- Look at lags vs frequency (timescale) and energy

Comparison between AGN & X-ray Binaries

- All lags and frequencies scale linearly with mass, i.e. ~10^6 shorter lags and higher frequencies

- So, expect reverberation lags of ~10^{-3} s on frequencies of ~10 Hz for BHs

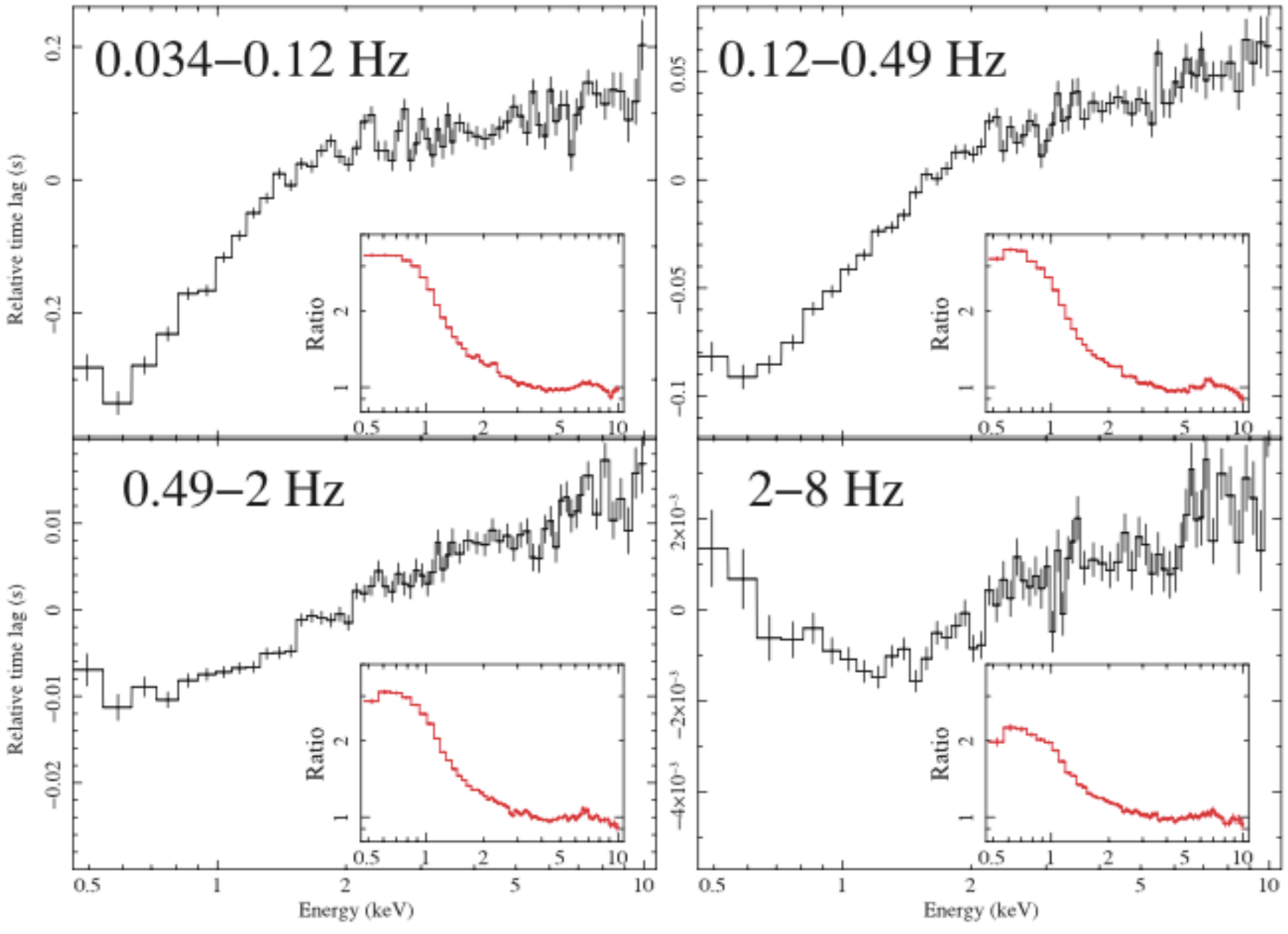
- Comparison of fluxes, e.g.
    - ➡ XRB: GX 339-4 (low/hard state): 0.1 Crab
    - ➡ AGN: NGC 5548, 2 mCrab (0.5 - 10 keV; Mathur et al. 2017)

- Fluxes are a factor of ~50 different, NOT a factor of 10^6

- **AGN have more counts per cycle compared to X-ray binaries**

X-ray Binary Reverberation with XMM

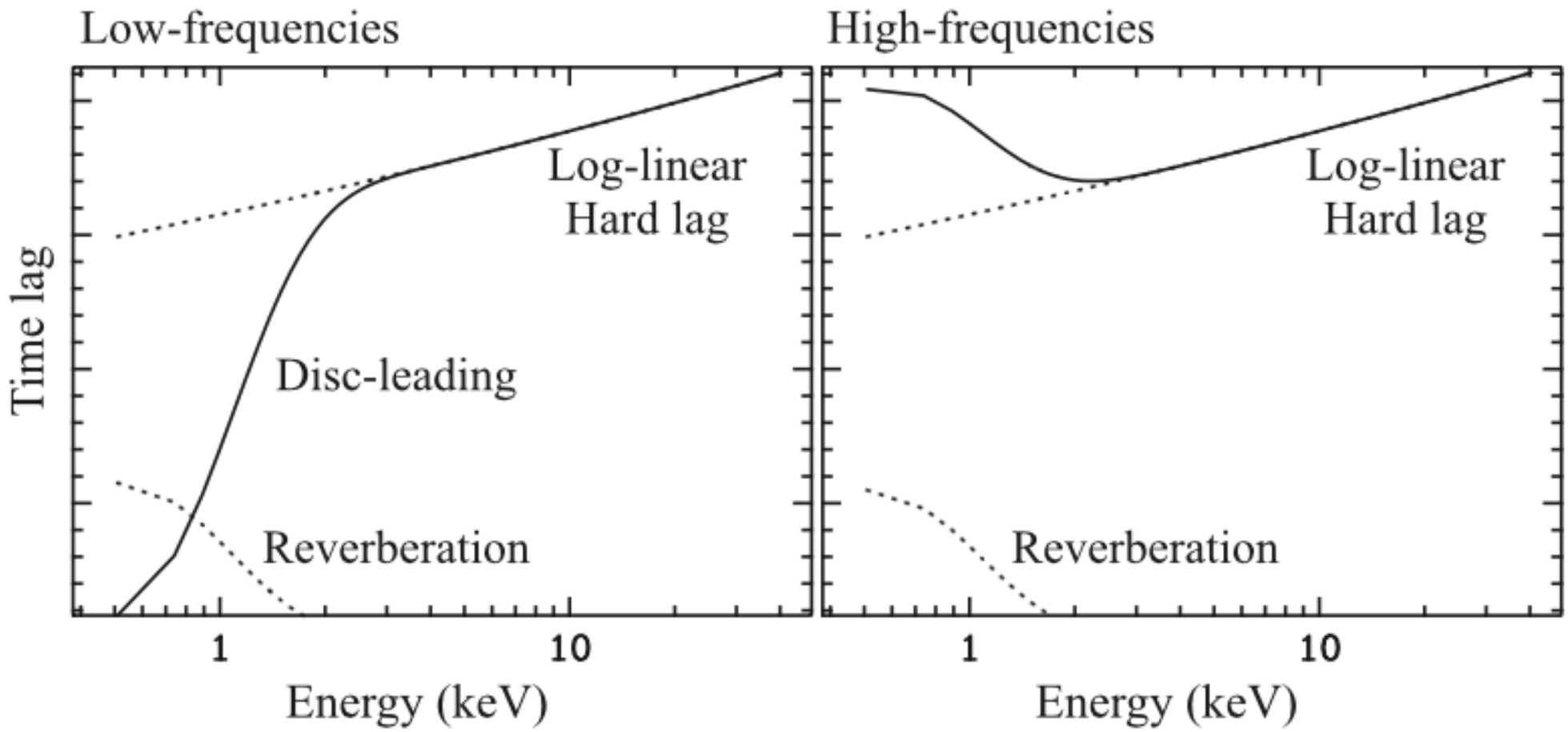
- First clear detection in GX 339-4, low-hard state (Uttley et al. 2011)
- See both accretion disk lagging (reverberation) and accretion disk leading (propagating fluctuations)
- Do not have S/N to detect Fe K lag



Uttley et al (2011)

XRB reverberation with XMM

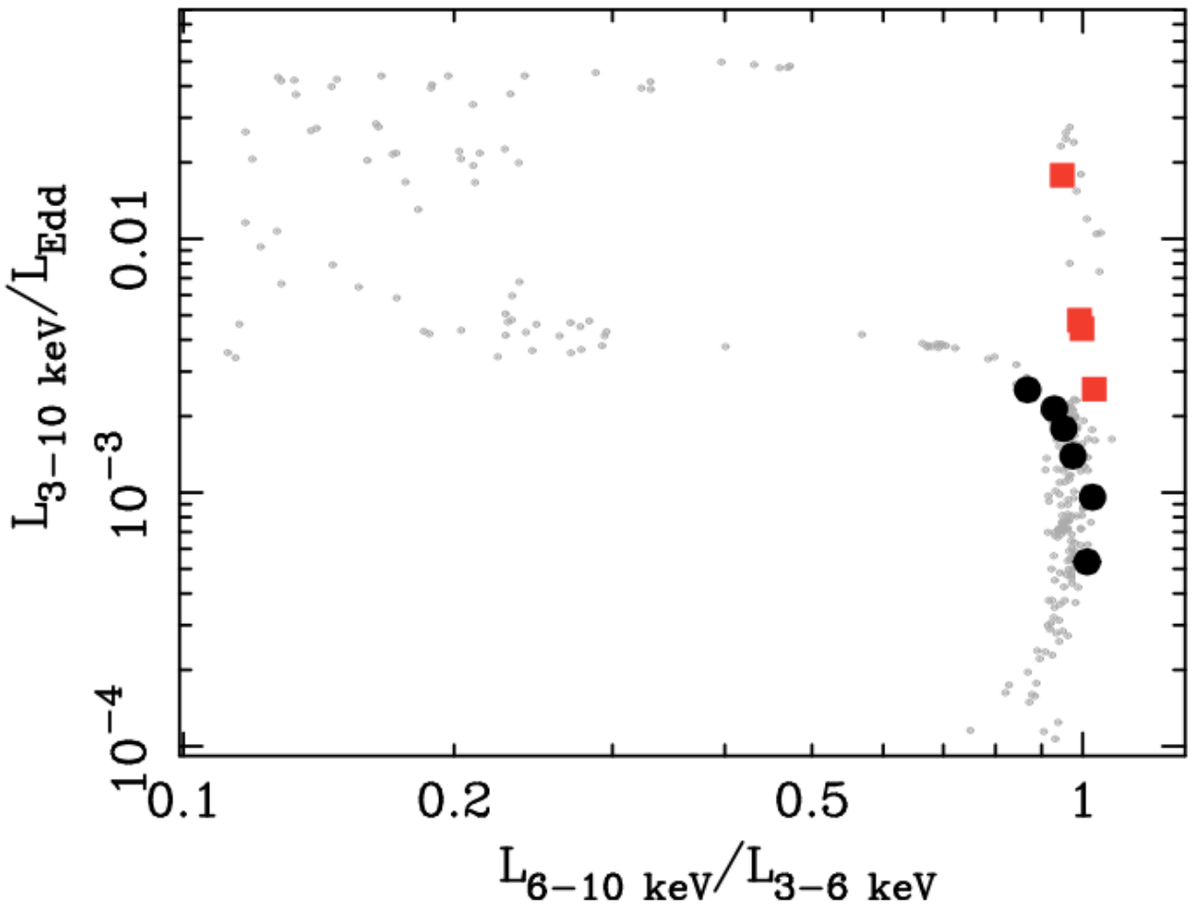
- Lags reveal different physical mechanisms on different timescales

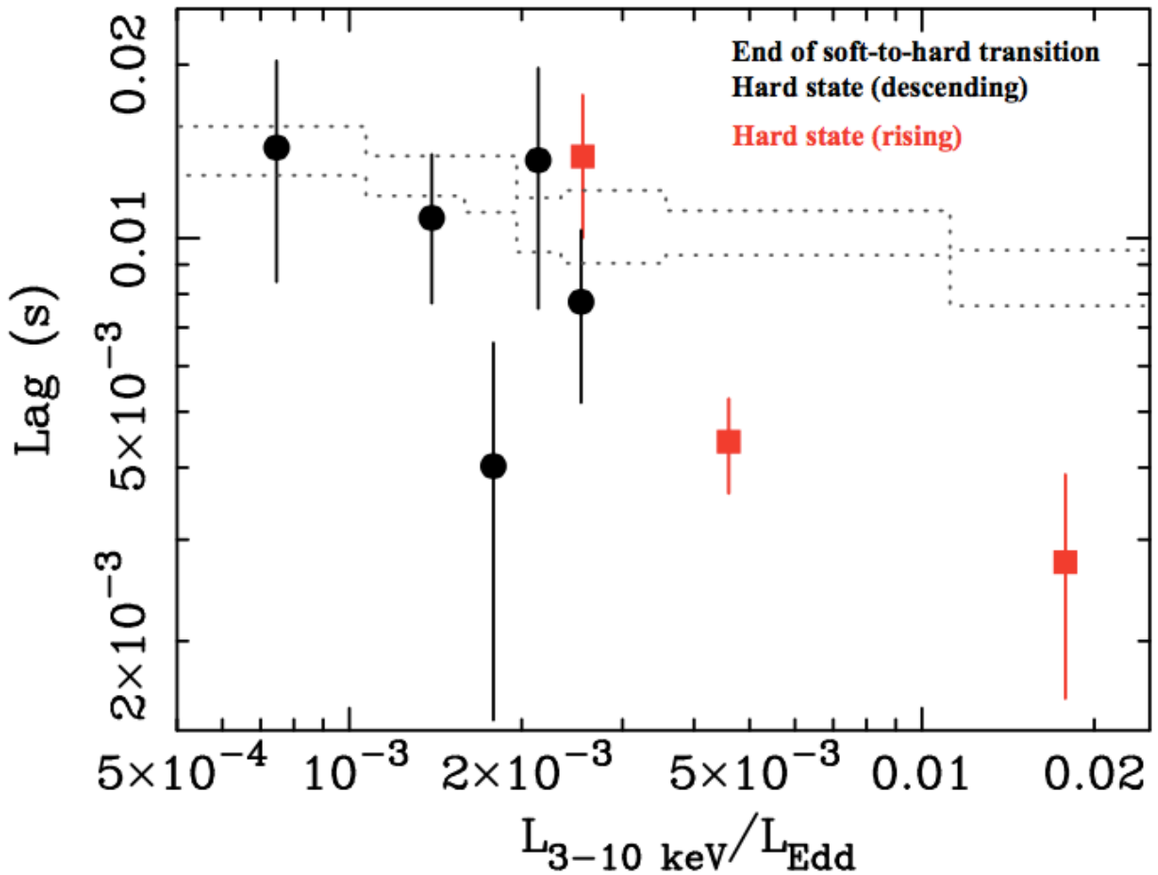


De Marco et al (2015)

How does the disk evolve?

- Disk expected to truncate as accretion rate drops
- Lags consistent with this occurring below ~1% L_{Edd}





De Marco et al. (2017)

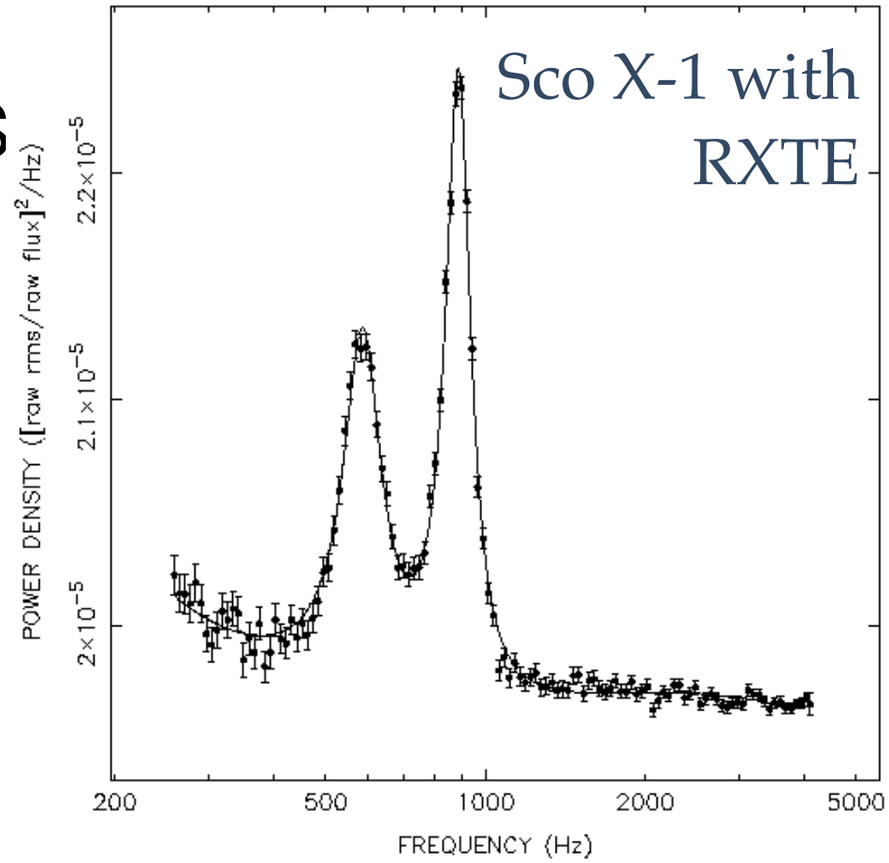
kHz QPOs in neutron star LMXBs

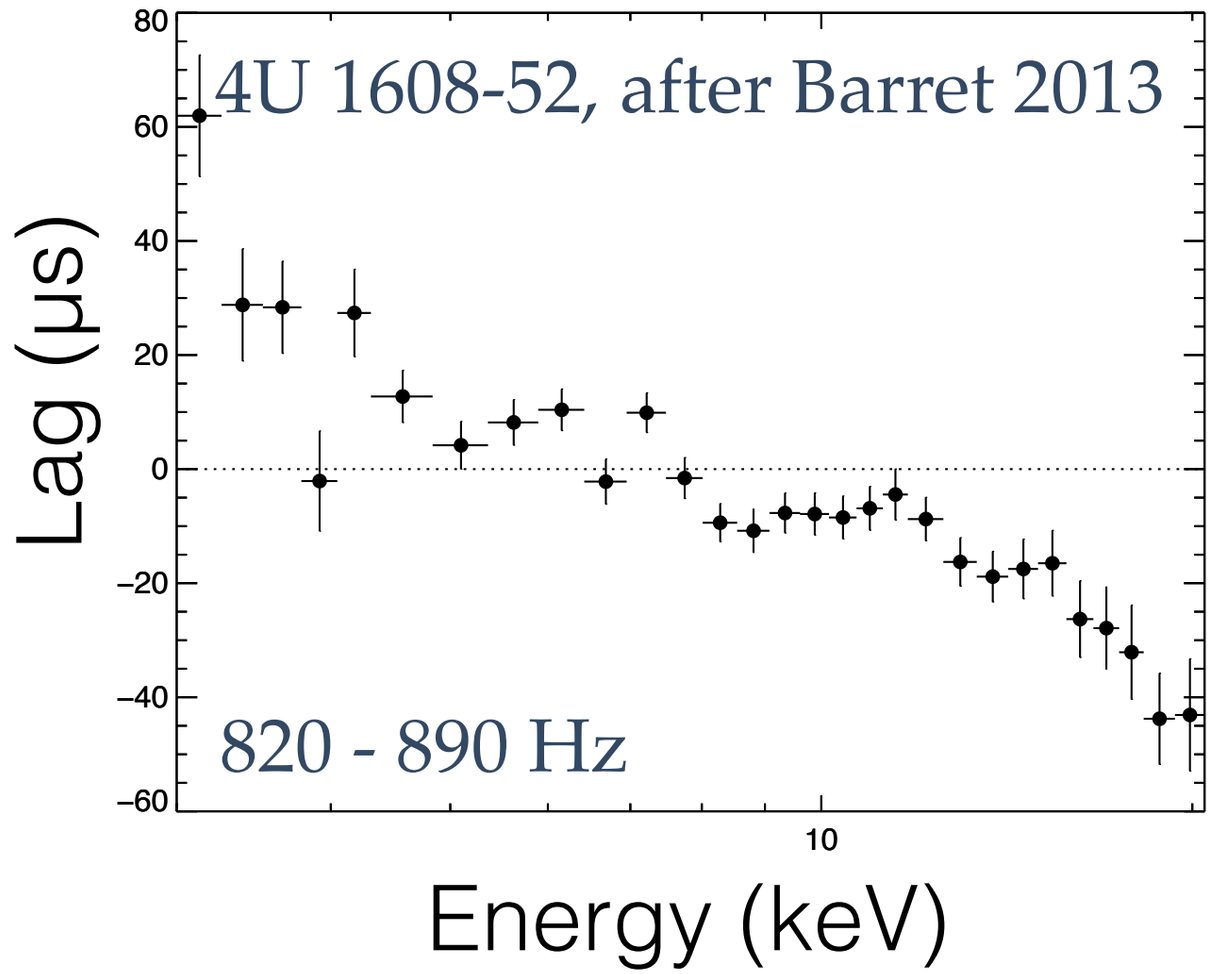
- kHz QPOs: highest frequency quasi-periodic oscillations in neutron star LMXBs

- Frequency similar to that expected from orbital motion in the inner disk - *probe of strong gravity?*

- Can detect energy-dependent lags in the QPOs (e.g., de Avellar et al 2013, Barret et al. 2013, Peille et al. 2015, Troyer et al. 2017)

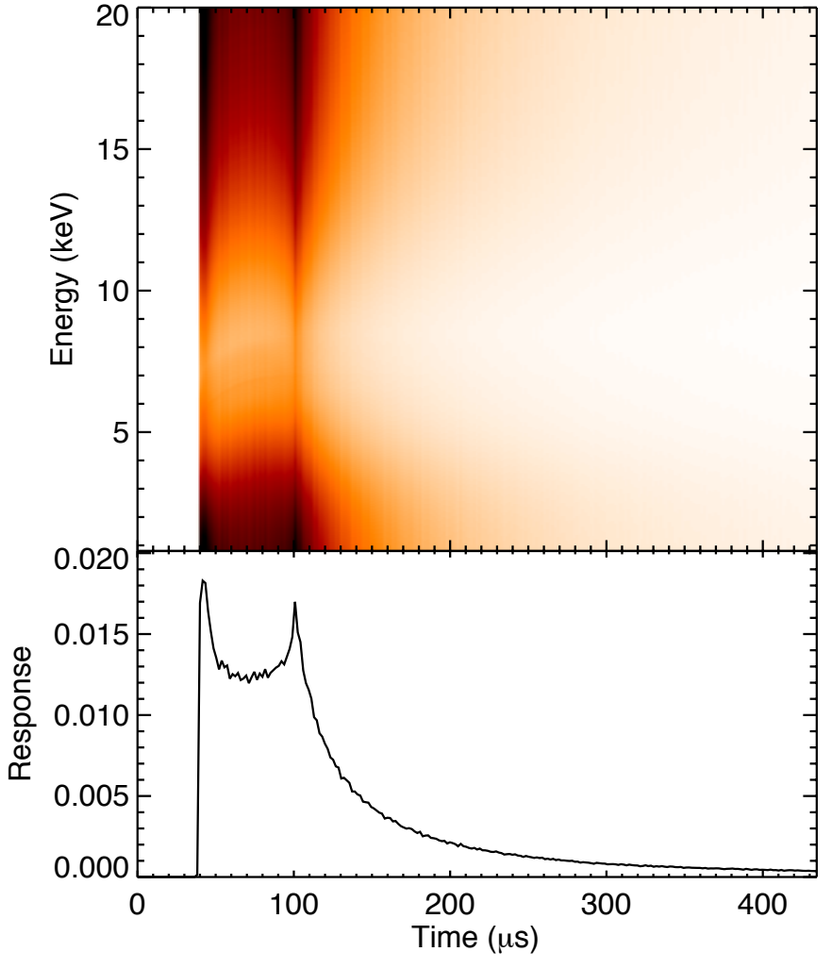
- **Are they consistent with reverberation?**

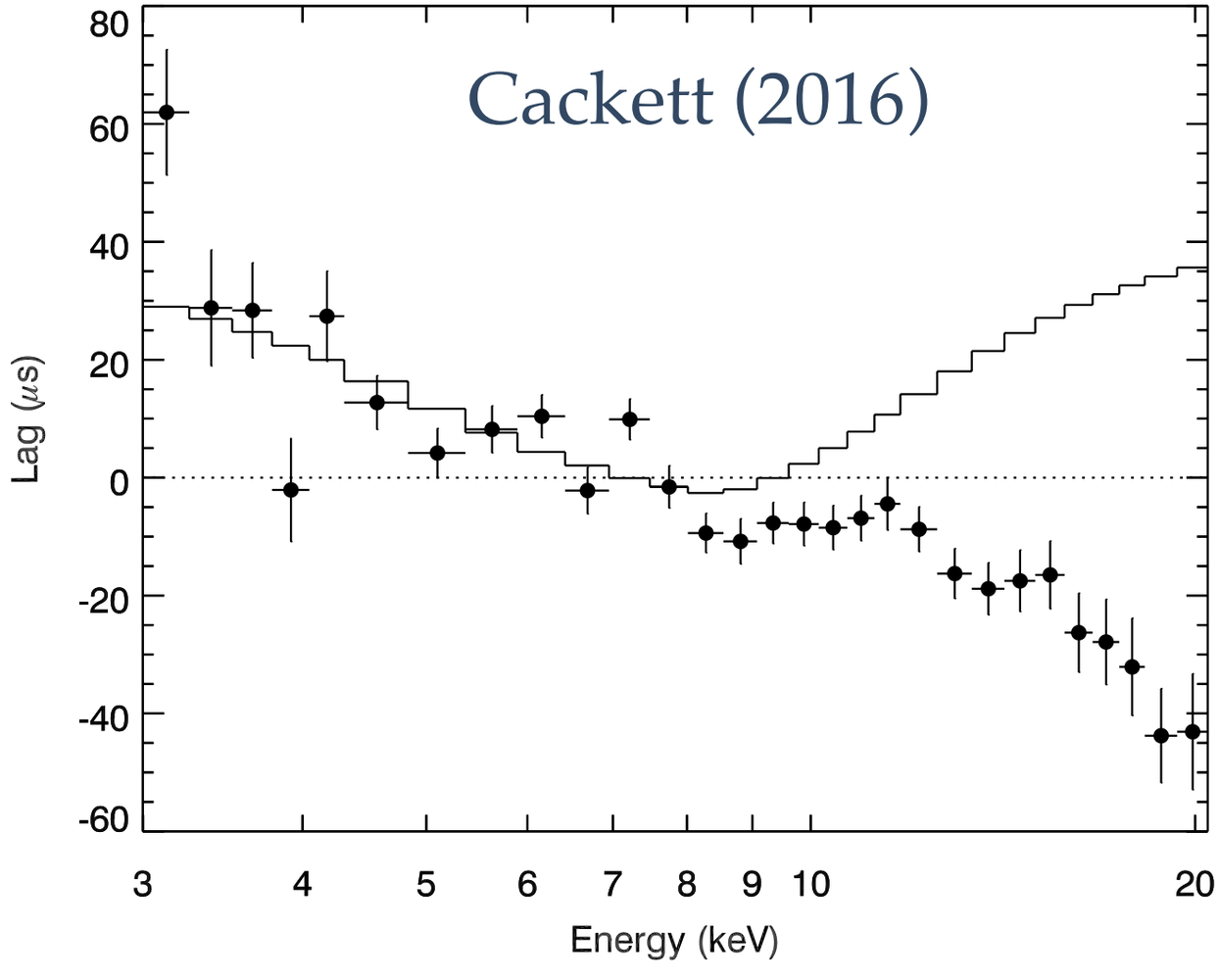




Lower kHz QPO lags not reverberation

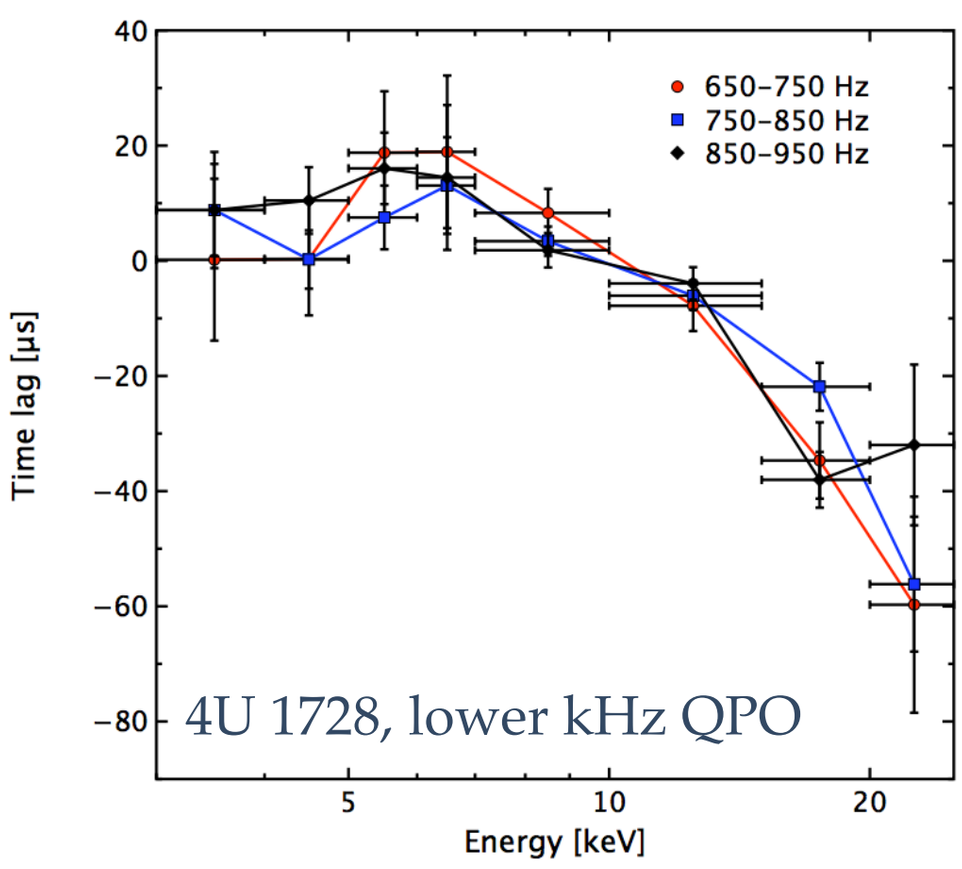
- Reverberation provides a poor fit
- Lower kHz QPO lags not solely due to reverberation

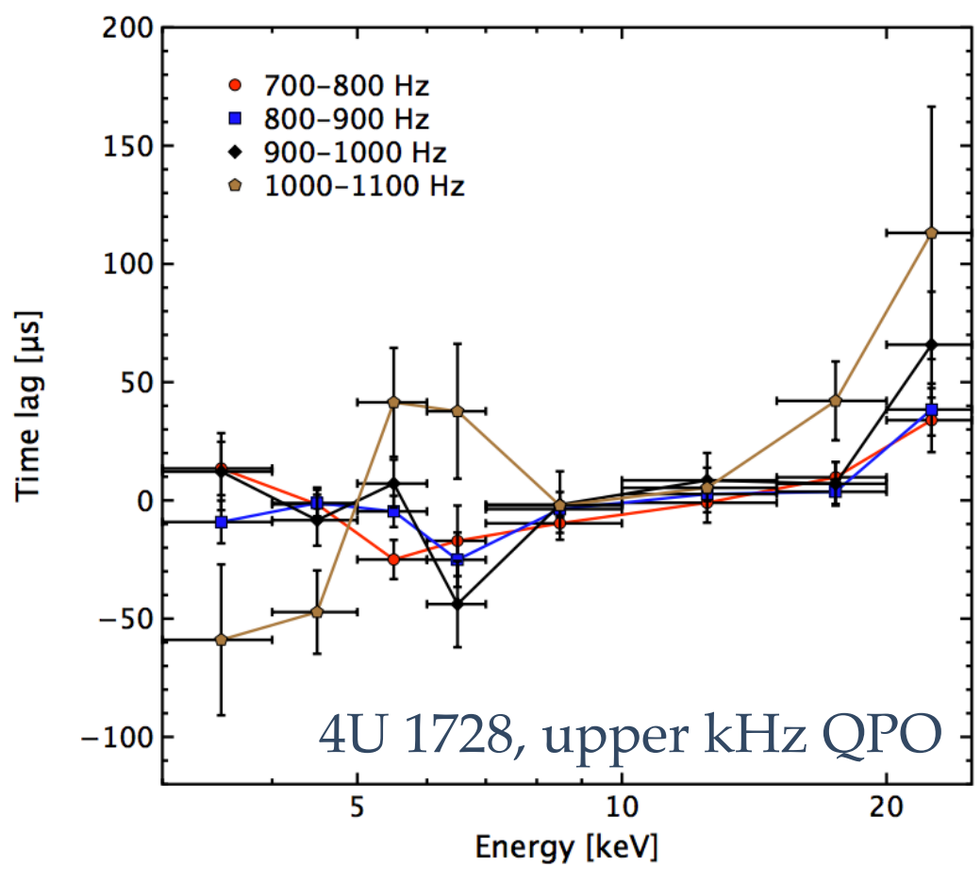




Reverberation may be in upper kHz QPO

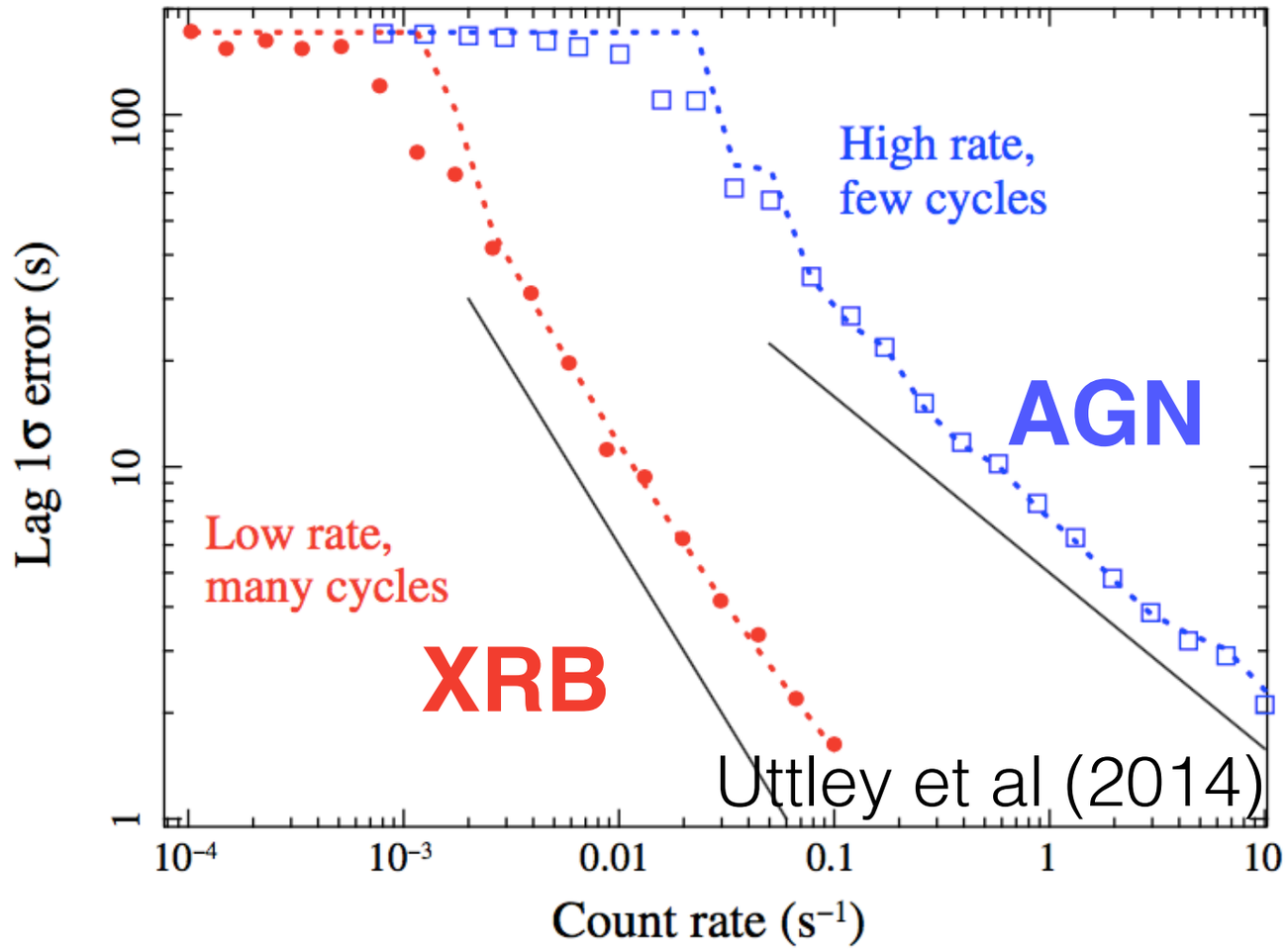
- Reflection models predict increase in lags with energy at > 8 keV
- This is more consistent with results from the upper kHz QPO lags in 4U 1728-34 (Peille et al. 2015)
- Limited by S/N…..but, this will be trivial for STROBE-X





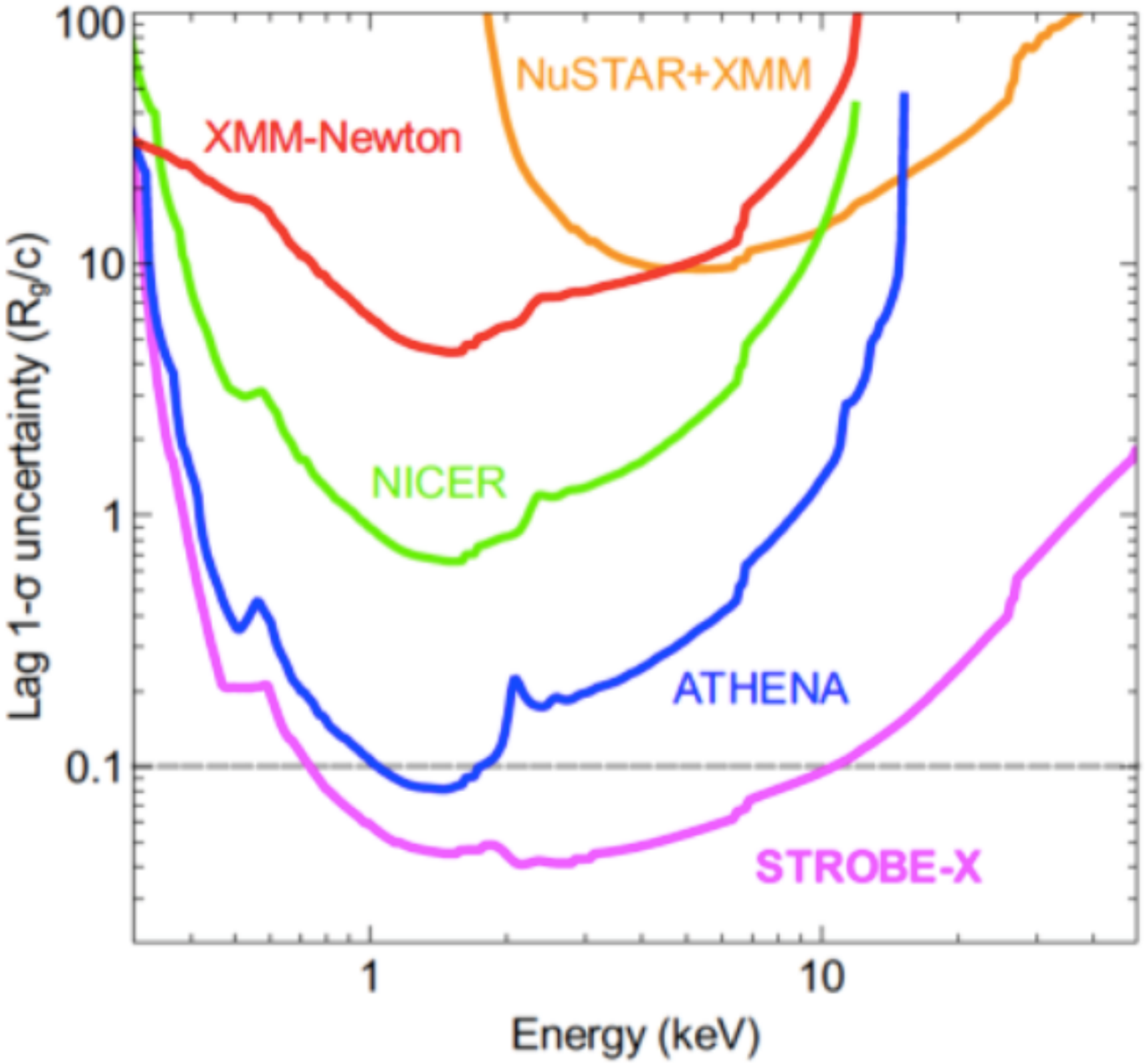
Gains with STROBE-X

- AGN and X-ray Binaries are in different regimes:
  - ➡ AGN - high counts per cycle, low number of cycles
  - ➡ XRBs - have low count per cycle, high number of cycles



- For XRBs, S/N of lag scales **linearly** with count rate
- In AGN, S/N of lag scales as sqrt(count rate)
- **Much bigger gains for XRBs than AGN**
- 10x larger effective area (or brighter source), equivalent to 100 times longer exposure

Lag uncertainties for XRBs



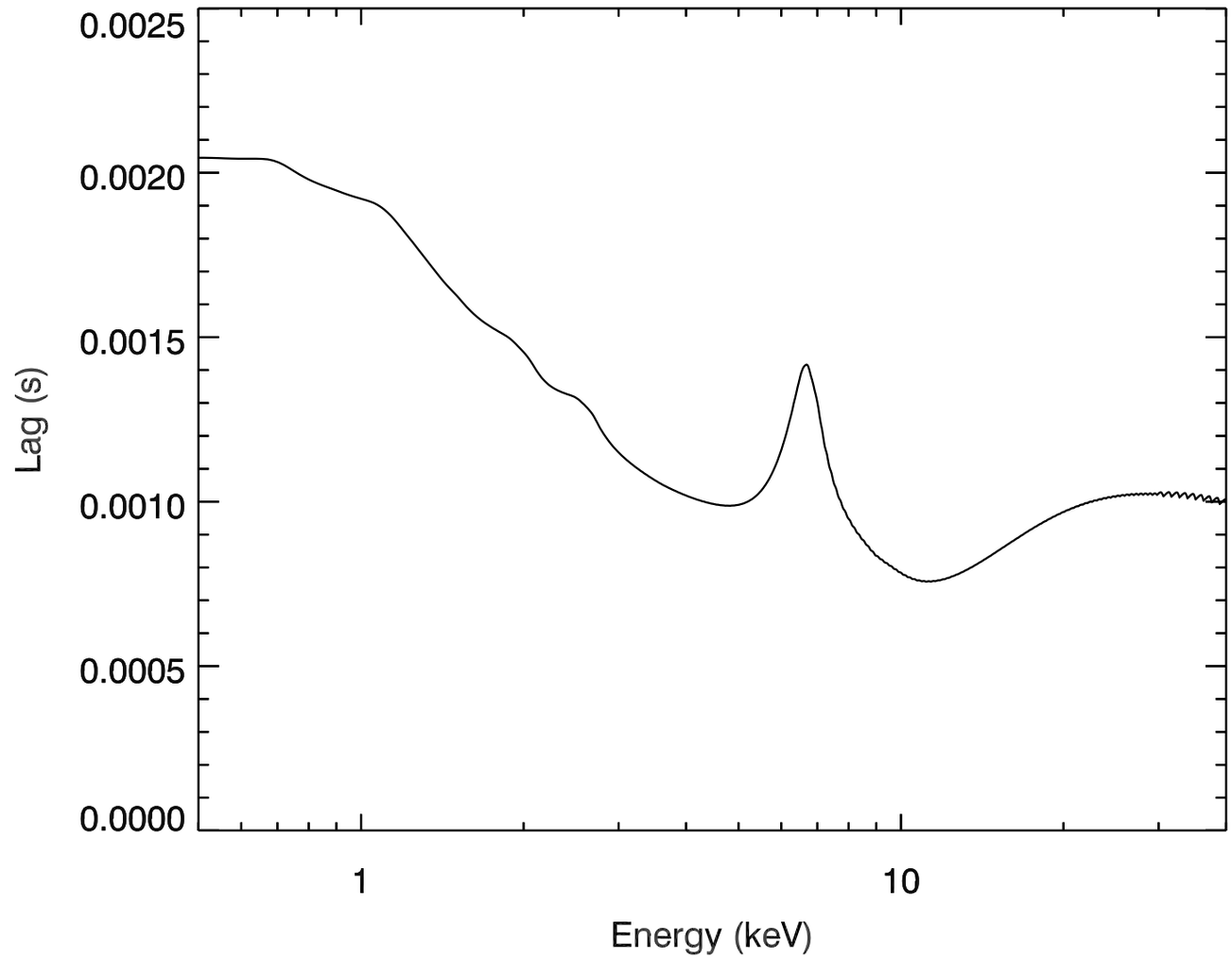
Two orders of magnitude better than XMM!

Ability to handle high count rates is key

- STROBE-X *better than Athena everywhere*, especially Fe K, will uniquely cover Compton hump
- ***Descope warning:*** lag uncertainty scales linearly with count rate, so a decrease in effective area has a big impact!

Simulations

- **A work in progress**…..not quite there yet
- Use the best-fitting model to the time-averaged XMM spectrum used in Uttley et al (2011)



- Combining with GR ray-tracing transfer function (Cackett et al. 2014) predict lag spectrum in 1 - 10 Hz
- Get correct lag amplitude without tuning!
- Need to still include log-linear hard lags, and do full lightcurve simulations with STROBE-X count rates…..

Summary

- For XRBs, lag uncertainty scales linearly with count rate (effective area), so STROBE-X is 2 orders of magnitude improvement over XMM!

- Broad energy range perfect for full reflection spectrum: disk, Fe line and Compton hump

- Can study state transitions in BH XRBs easily - combine with radio to explore disk-jet connection

- Can begin to study upper kHz QPO lags in detail (frequency and energy dependence)

- **STROBE-X will revolutionize reverberation studies in XRBs**