Reverberation in X-ray Binaries with STROBE-X

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Reflection & Reverberation

- 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.

Reflection spectrum in GX 339-4 with NuSTAR & Swift (Parker et al. 2016)
Comparison between AGN & X-ray Binaries

- All lags and frequencies scale linearly with mass, i.e. \( \sim 10^6 \) shorter lags and higher frequencies

- So, expect reverberation lags of \( \sim 10^{-3} \) s on frequencies of \( \sim 10 \) 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 \( \sim 50 \) 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% $L_{\text{Edd}}$

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

Cackett (2016)
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 \( \sqrt{\text{count rate}} \)
- **Much bigger gains for XRBs than AGN**
- 10x larger effective area (or brighter source), equivalent to 100 times longer exposure
Lag uncertainties for XRBs

- 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 jet connection

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

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