Accretion flow and corona coupling in accreting black hole systems

Phil Uttley

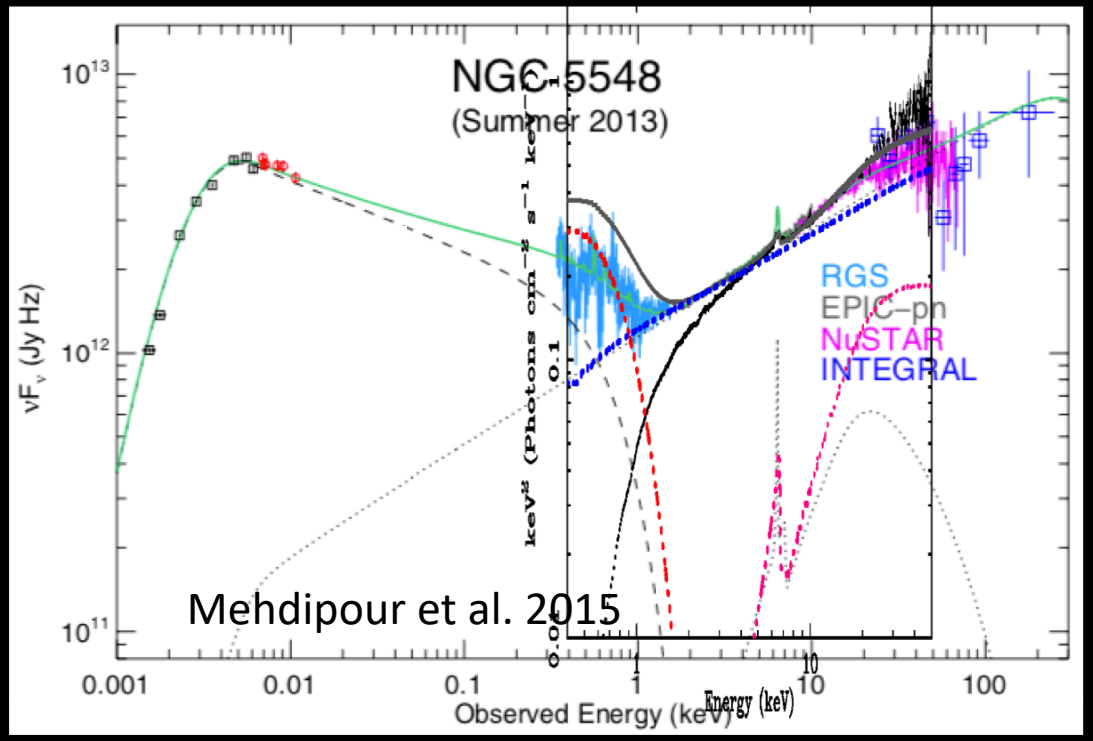
University of Amsterdam

100 YEARS

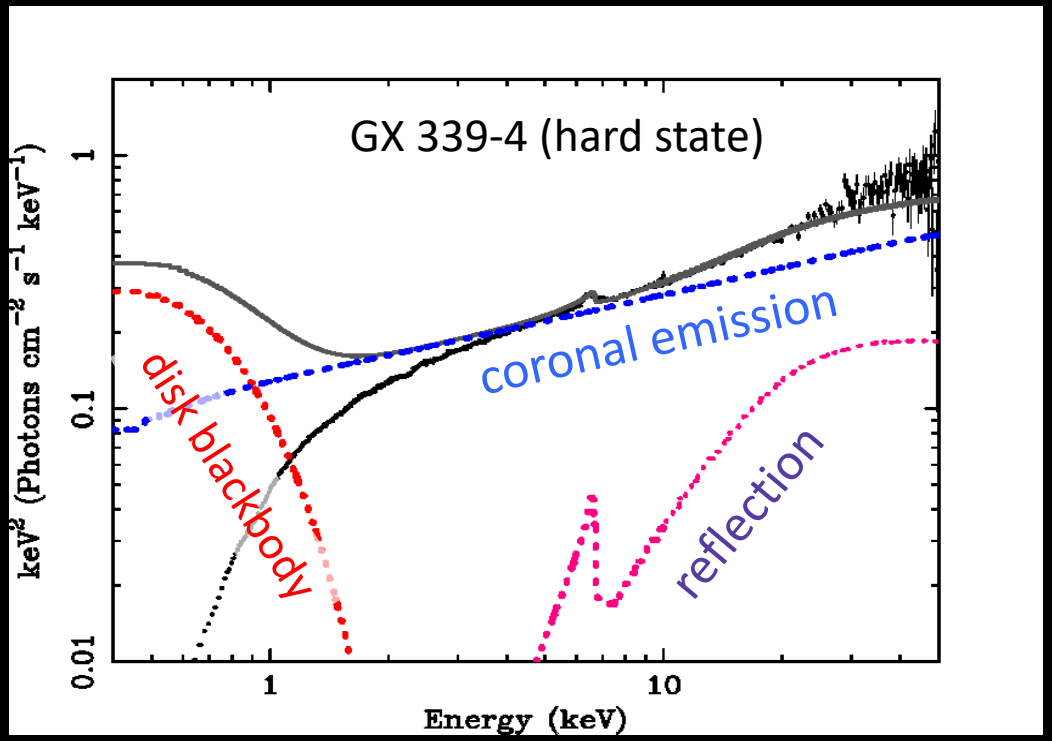
ANTON PANNEKOEK INSTITUTE

Accretion disk and corona in accreting black holes

SMBH



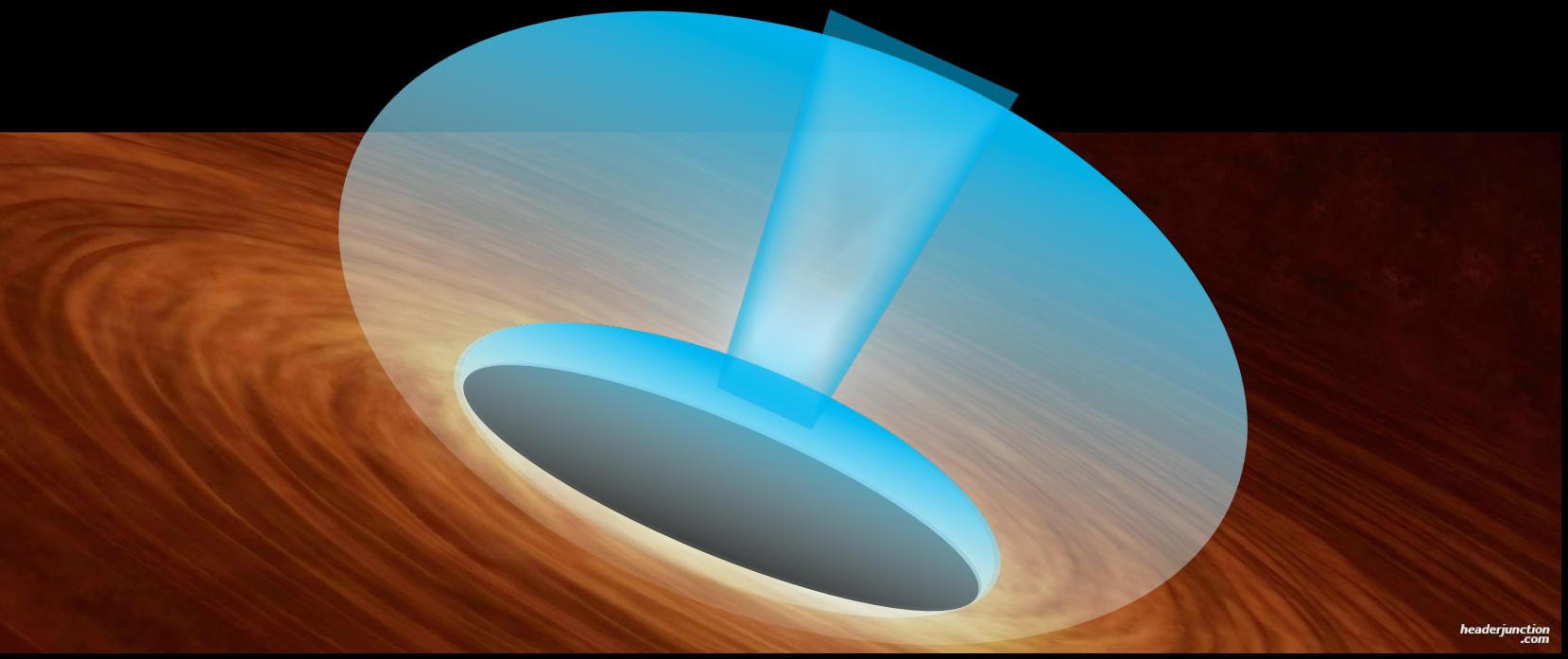
Stellar mass BH



I will focus on the stellar mass BH systems for two reasons:

- Clear view of the inner disk + corona in one spectrum, with no mysterious soft X-ray excess!
- We can study >10 decades of system time-scales, from outer viscous to inner disk light-travel times

What is the corona?



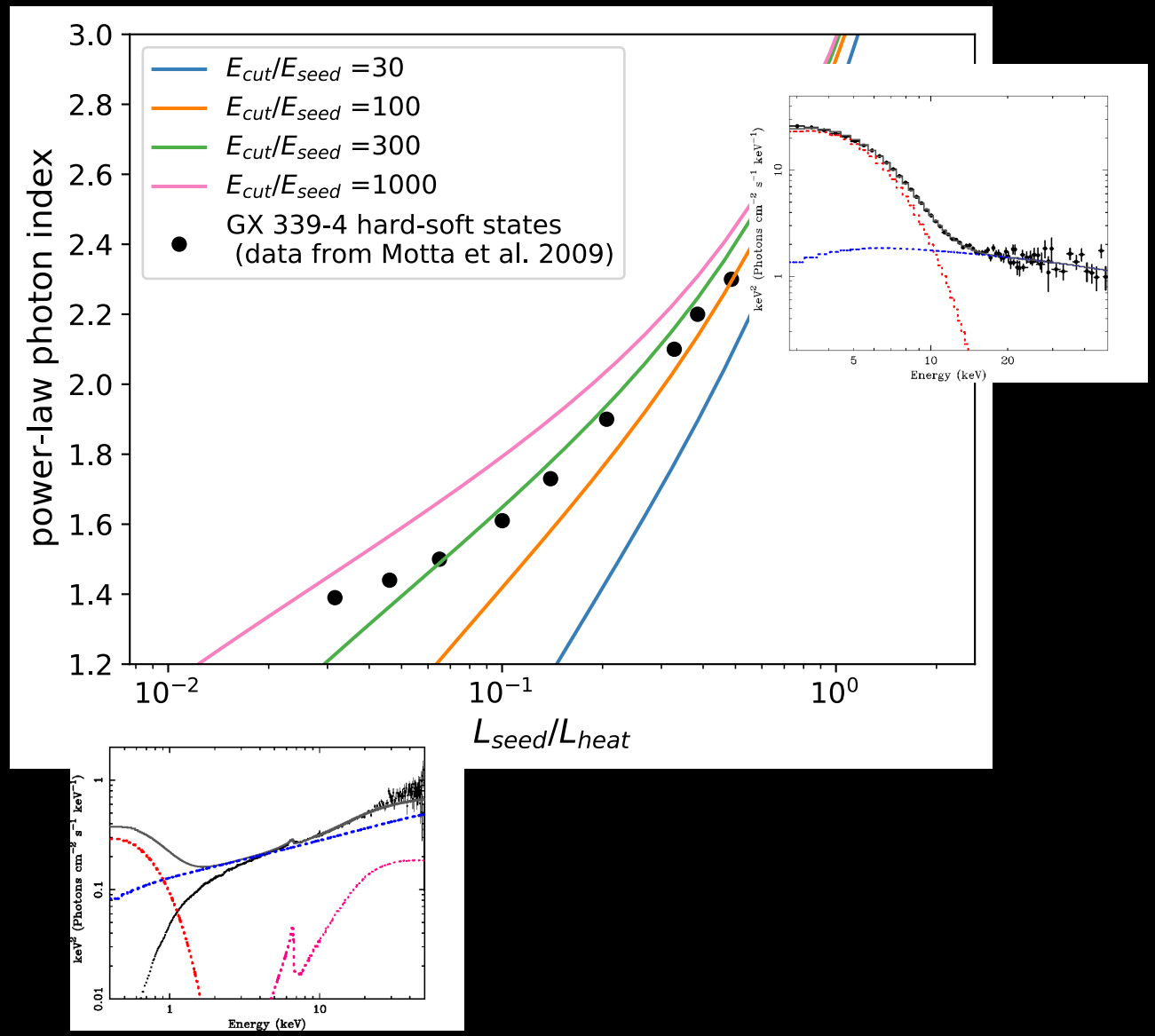
Physical properties - what we know:

- Predominantly thermal (in hard states)
- Weaker non-thermal-like component may appear > 100 keV
- Optically thick-ish ($\tau \sim 1$)
- Has some vertical extent above the disk

What we don't know:

- Geometry, geometry, geometry…
- Energy content (B-field? Protons?)

Seed photons and energy budget



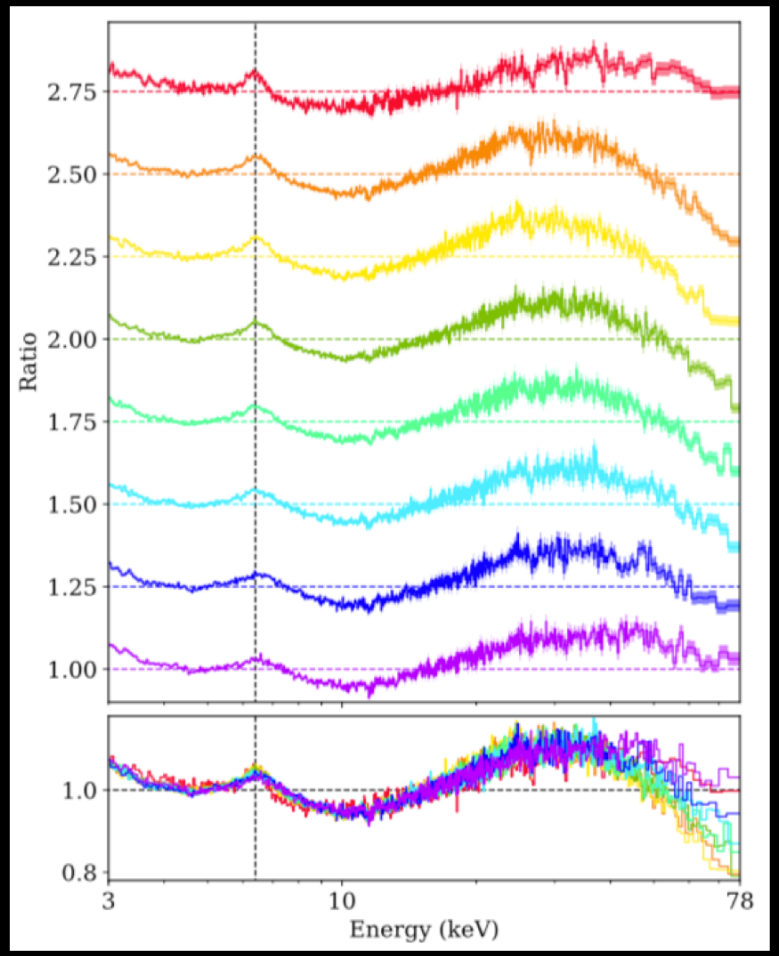
Assuming net coronal heating power $L_{\rm heat}$ and isotropic emission, the ratio of average photon energies:

$$\frac{\langle E_{\rm corona}\rangle}{\langle E_{\rm seed}\rangle} = 1 + \frac{L_{\rm heat}}{L_{\rm seed}}$$

Observed X-ray spectra imply strong evolution of seed-to-heating luminosity ratio during outburst:

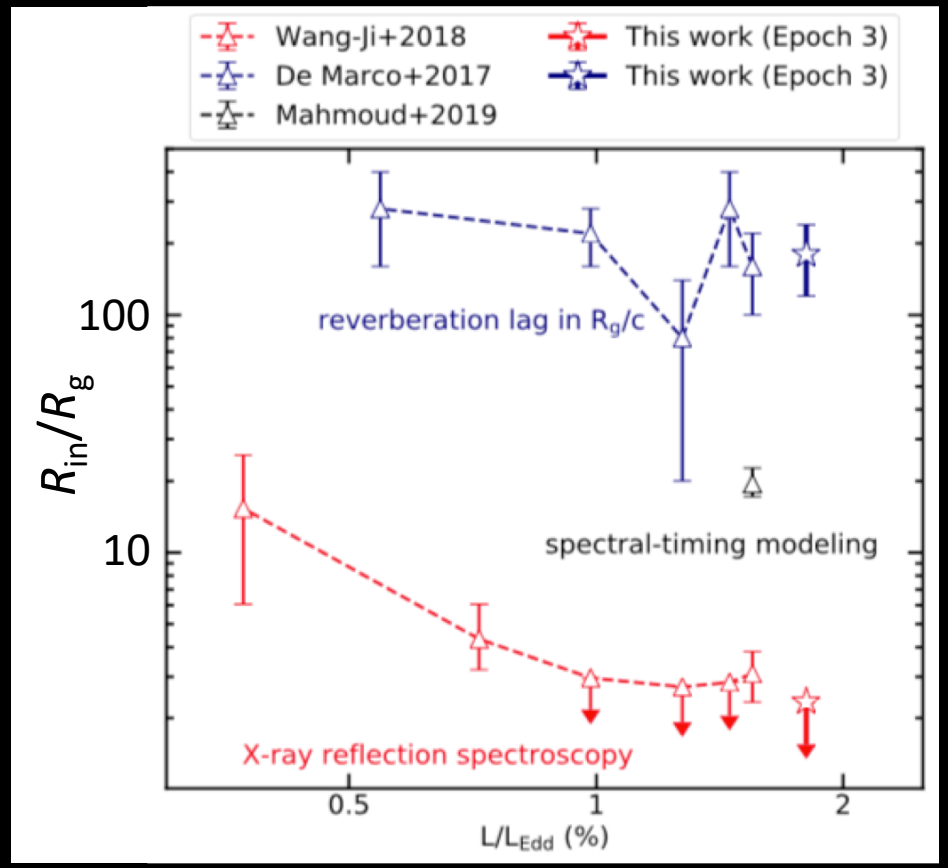
- Change in disk truncation radius?
- Local redistribution of accretion power disk/corona?
- Change in geometry (corona ‘sees’ more disk?)

Coronal geometry from reflection



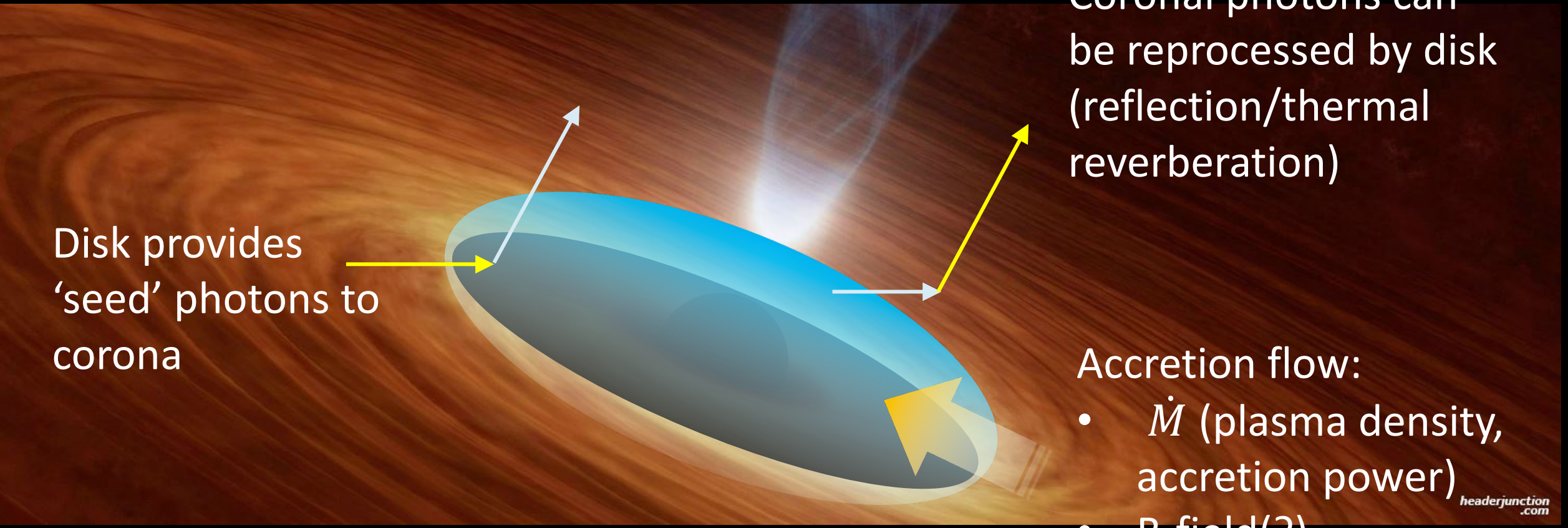
MAXI J1820+070 with NuSTAR
(Buisson et al. 2019,
see also Zdziarski et al. 2021)

- No strong consensus except that reflection spectra generally indicate hard state disk inner radii < 100 R_g
- ISCO-like radii are in tension with X-ray reverberation measurements

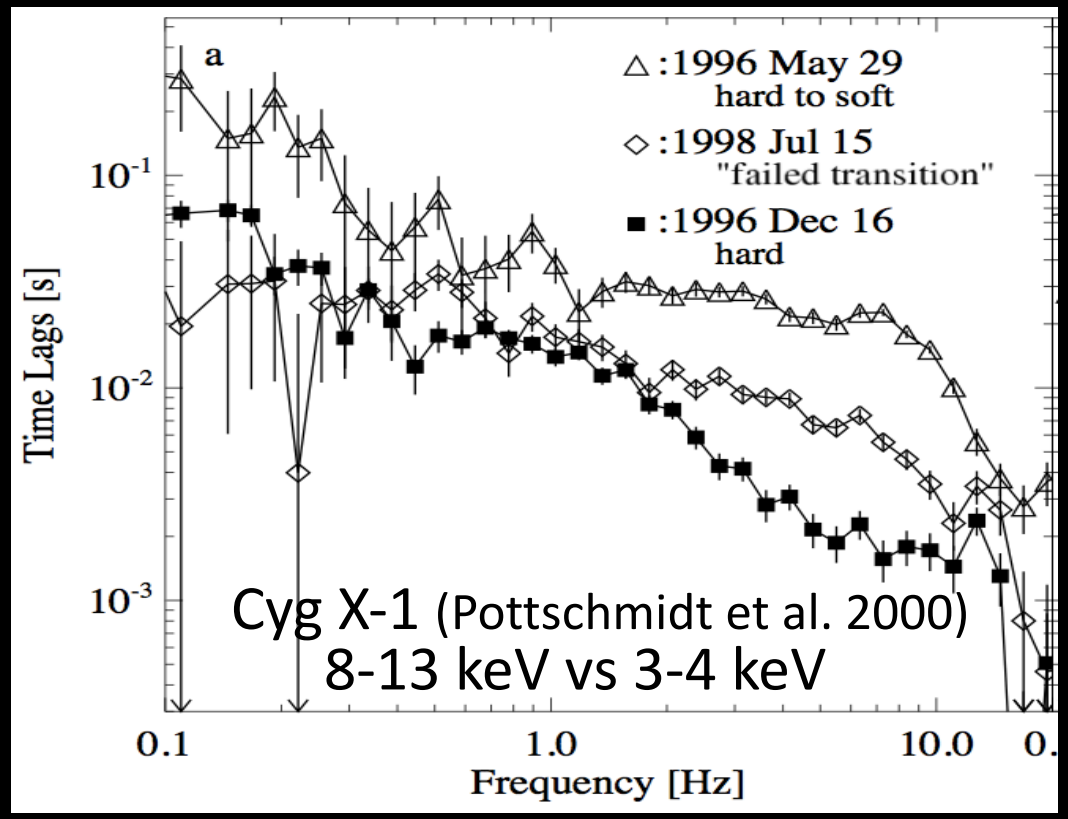


Wang, J. et al. 2020

Disk-corona interactions



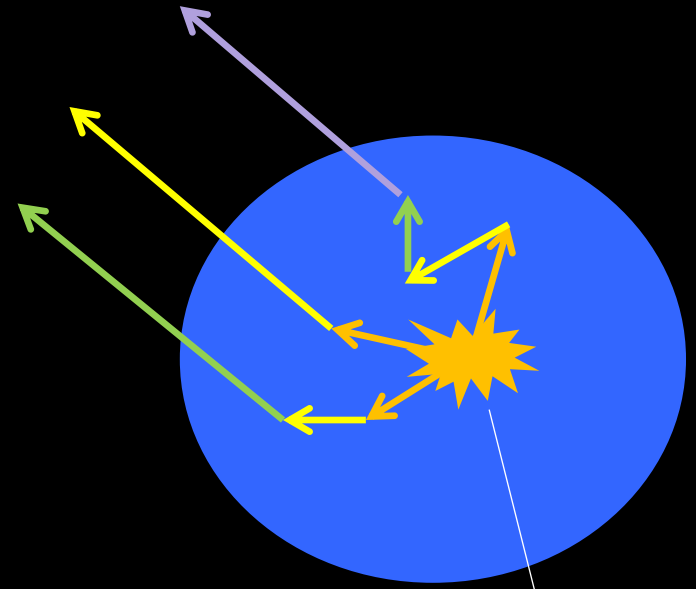
Hard lags & Comptonization delays



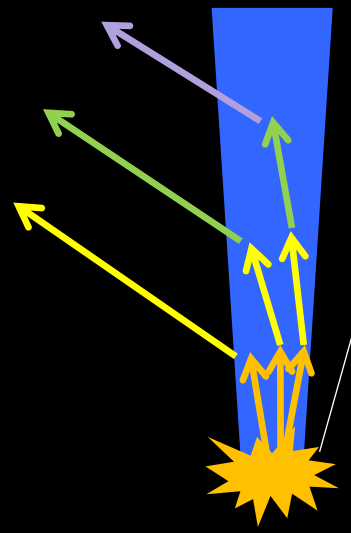
Cyg X-1 (Pottschmidt et al. 2000)
8-13 keV vs 3-4 keV

If hard lags due to Comptonisation, coronal scales > hundreds of R_g. Tension with reflection measurements?

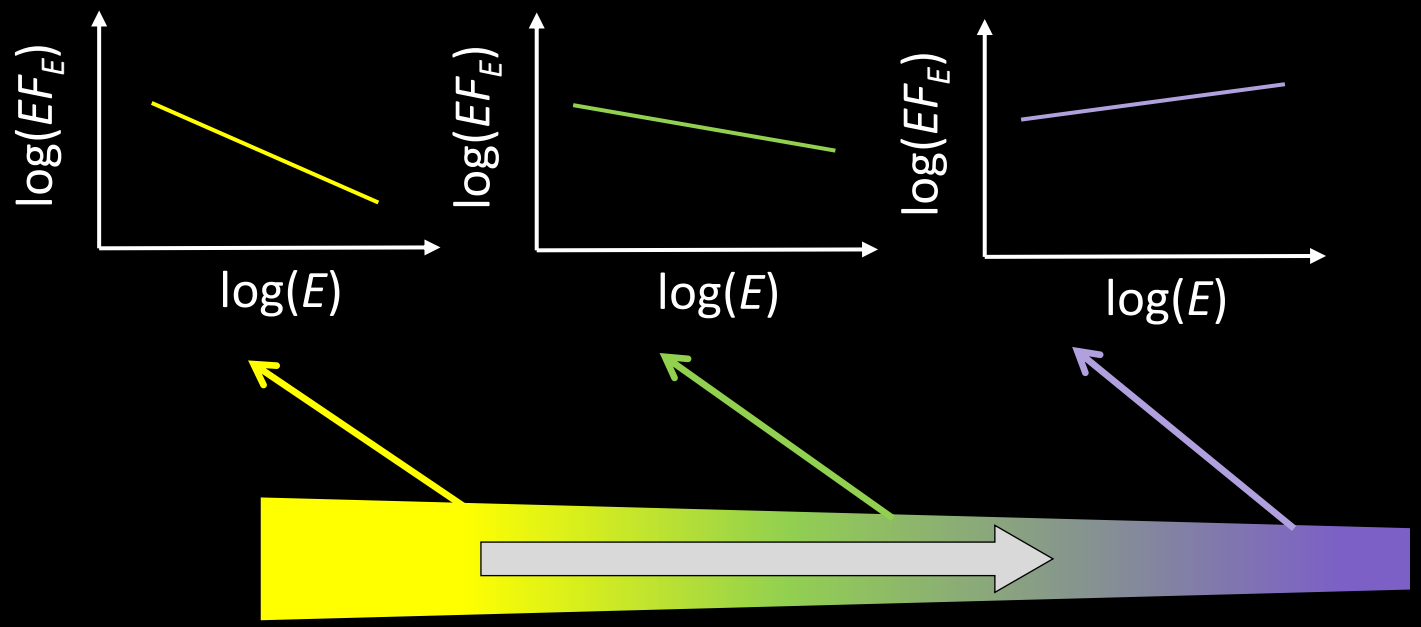
Comptonization delays produced in extended corona (largely inactive since late 90s)



Comptonization delays produced along the jet (ongoing studies, by Reig, Kylafis, Giannios)



Propagating $\dot{M}$ fluctuation delays

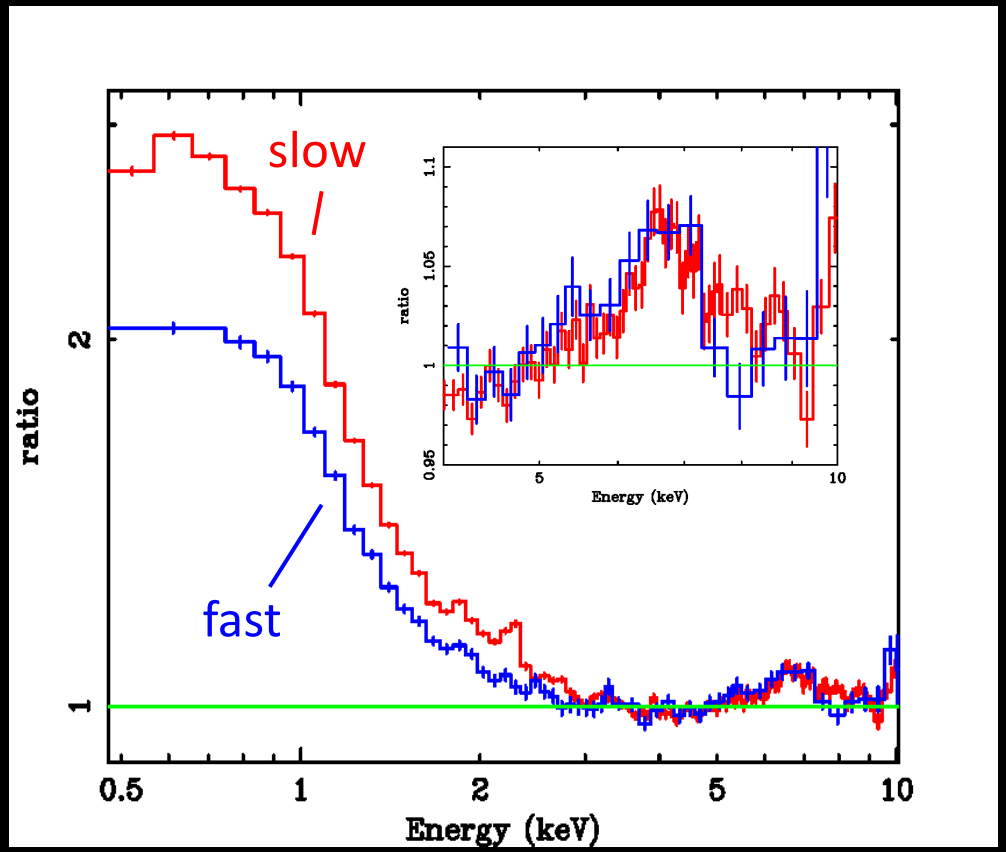


Large time lags can be produced by mass accretion fluctuations propagating through a coronal ‘hot flow’ with radially dependent Comptonised spectral shape

Various models:
Kotov et al. 2001, Arévalo & Uttley 2006, Ingram & Done 2012, Rapisarda et al. 2016, Mahmoud & Done 2018

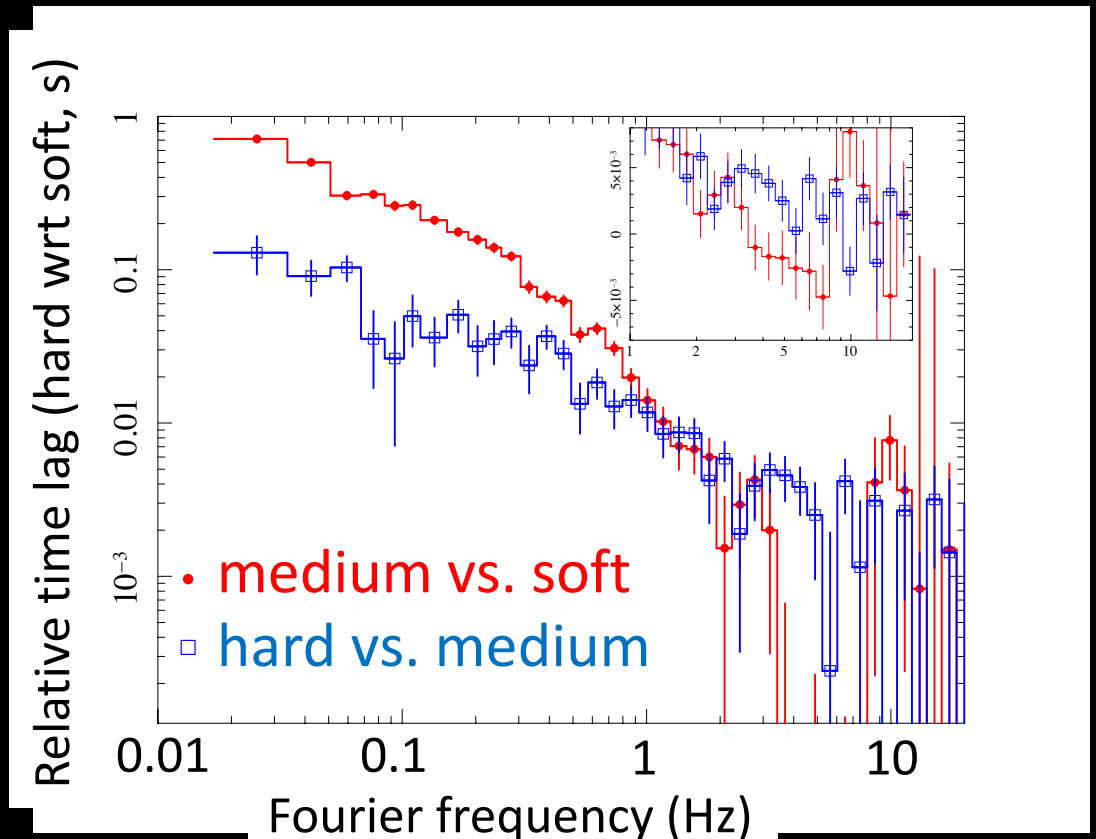
Extending lags to soft X-rays with XMM-Newton: the disk leads the corona

Variability spectra (covariance)



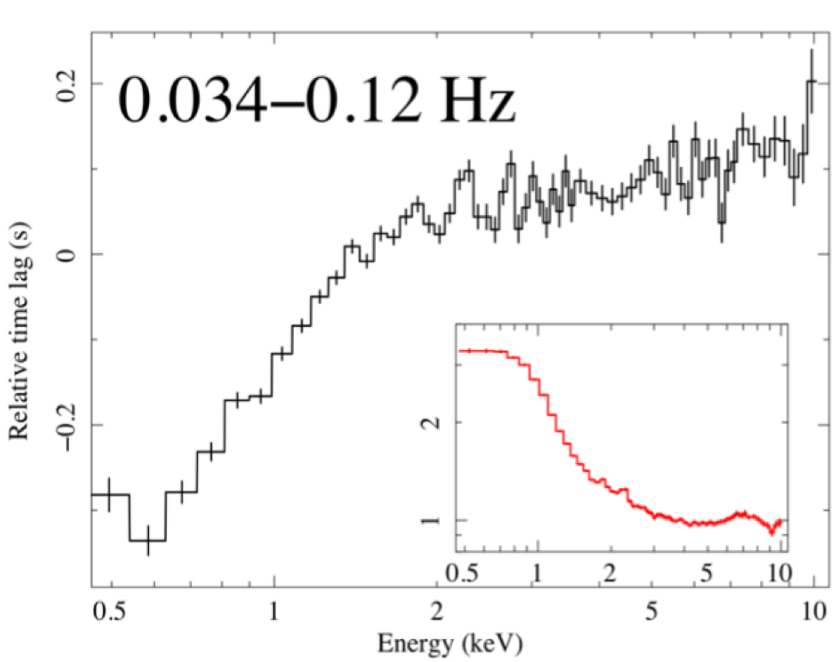
(Wilkinson & Uttley 2009)

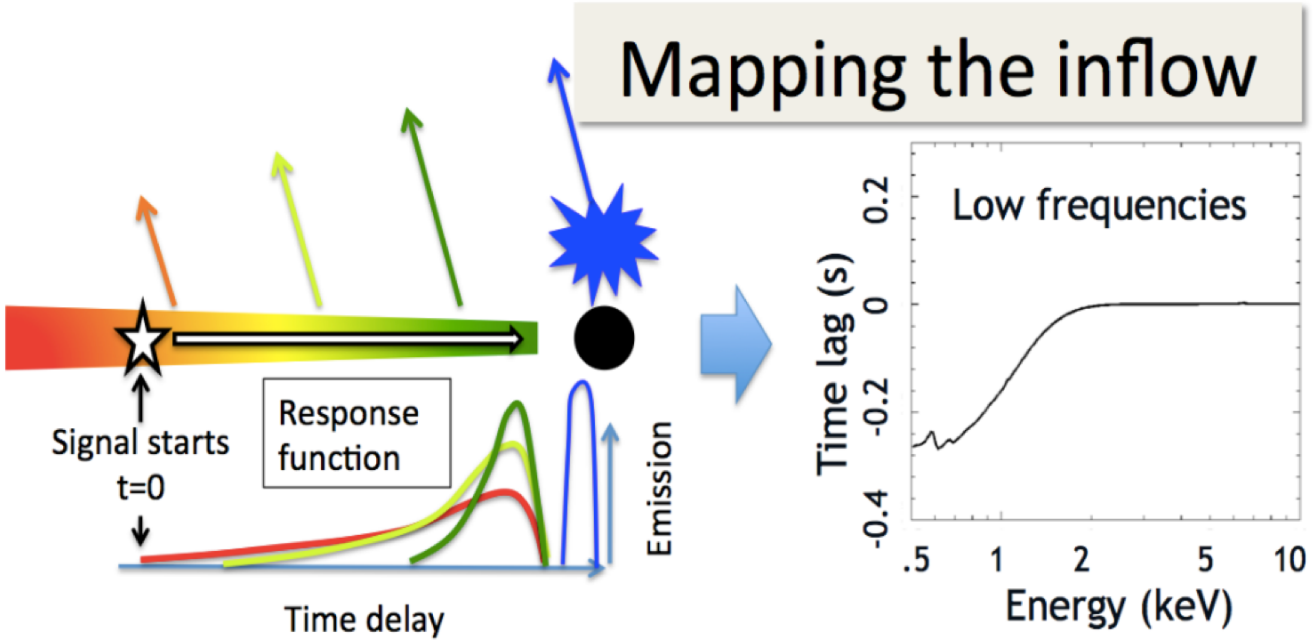
Time lags



(Uttley et al. 2011)

Fluctuations propagating through the disk

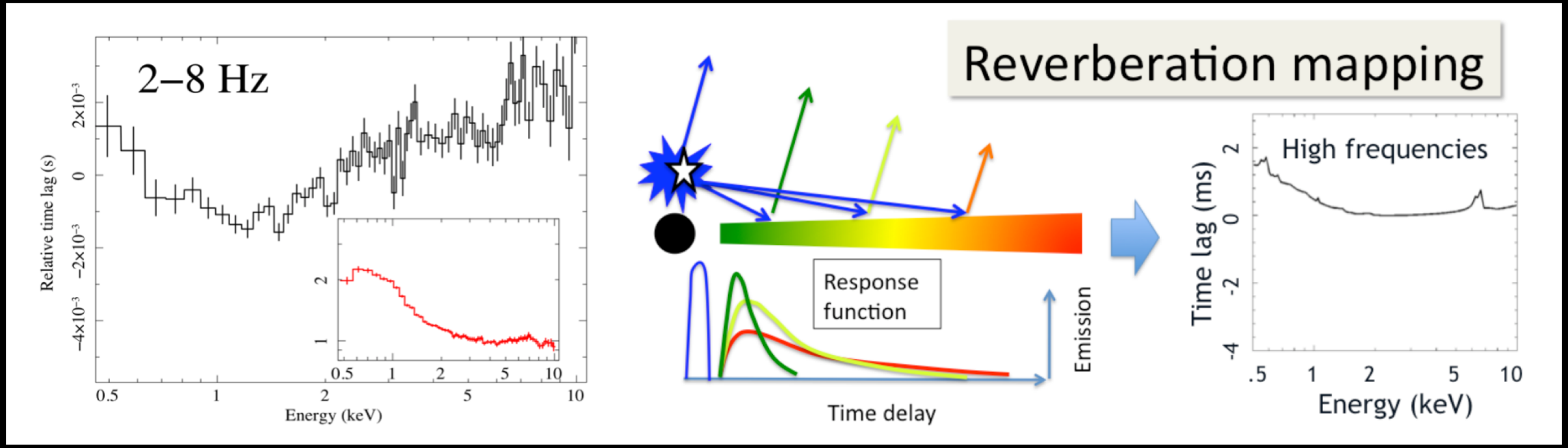




This simple picture can explain why disk variations lead those of the corona, but it cannot (on its own) explain the energy-dependent lags between power-law photons.

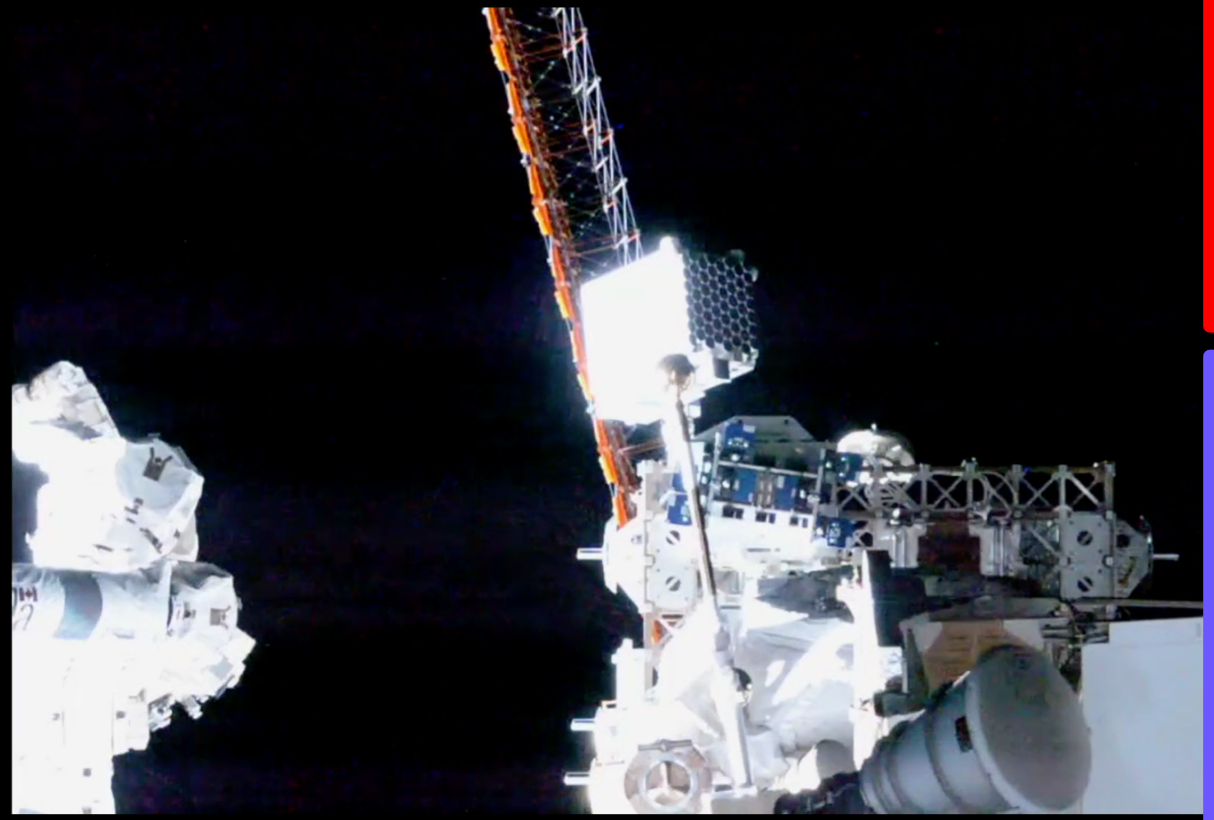
Short time-scales: disk lags the corona

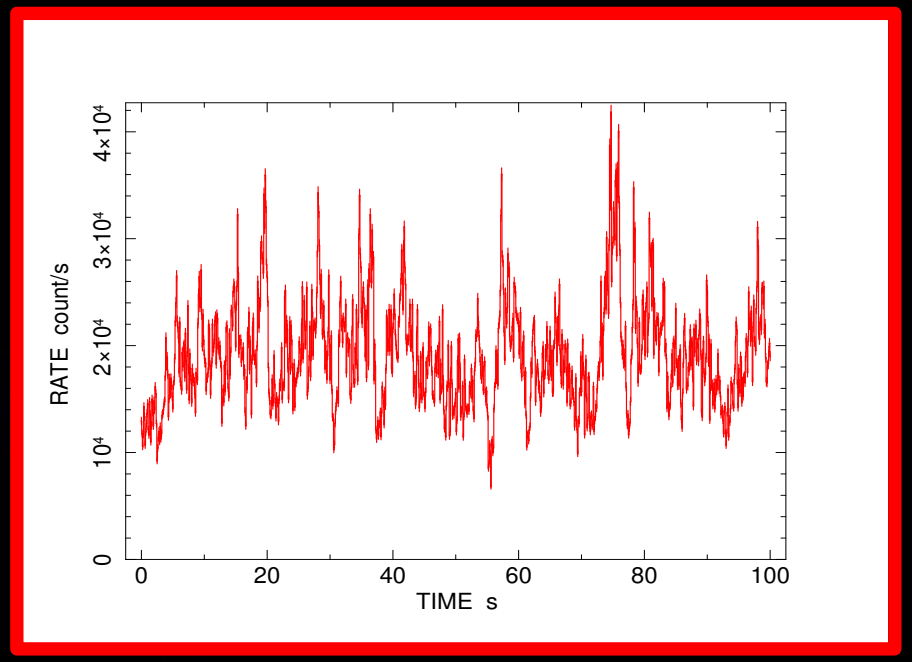
(Uttley et al. 2011)

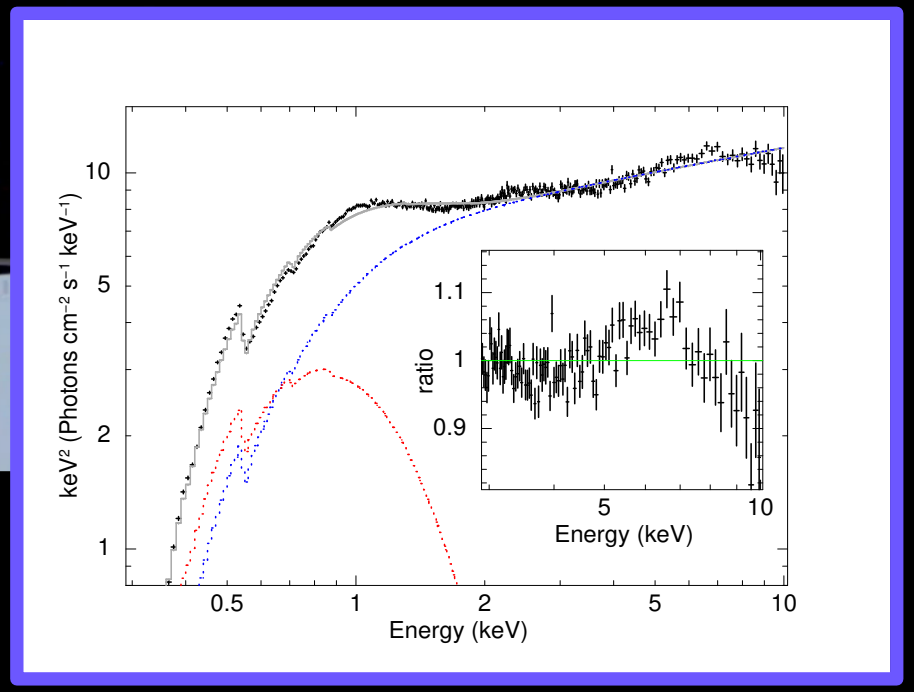


By analogy with AGN X-ray reverberation, we assumed that the disk lags correspond to light-travel delays from corona to disk

NICER: a window to Athena



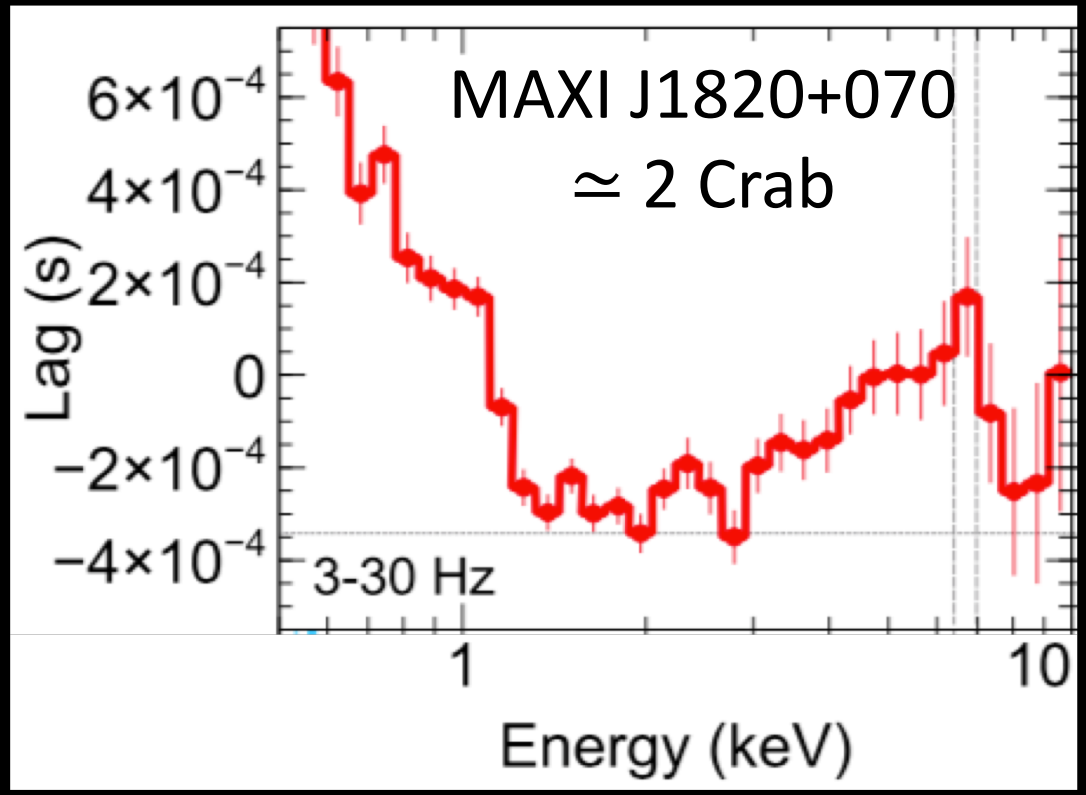




MAXI J1820+070: 100 s light curve and spectrum

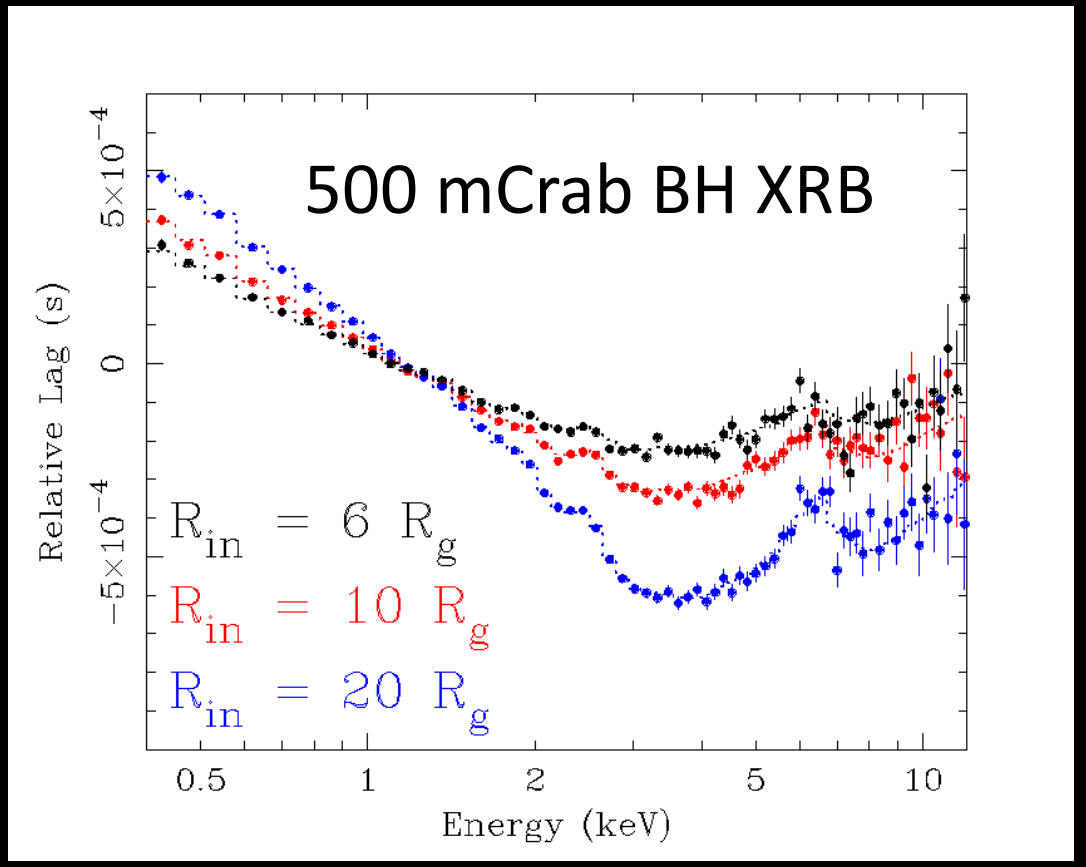
Fe K reverberation with NICER and Athena

NICER data



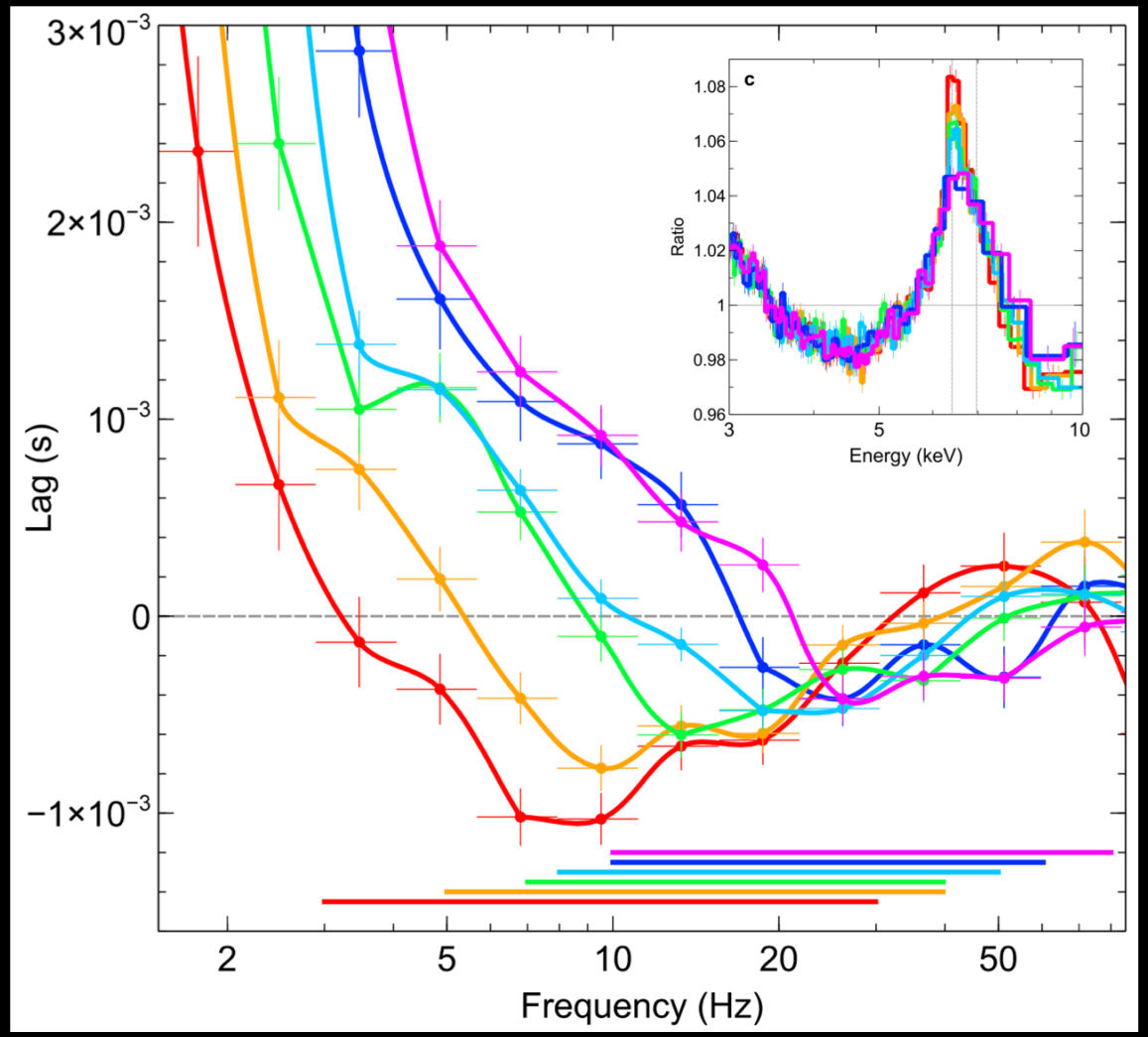
Kara et al. 2019

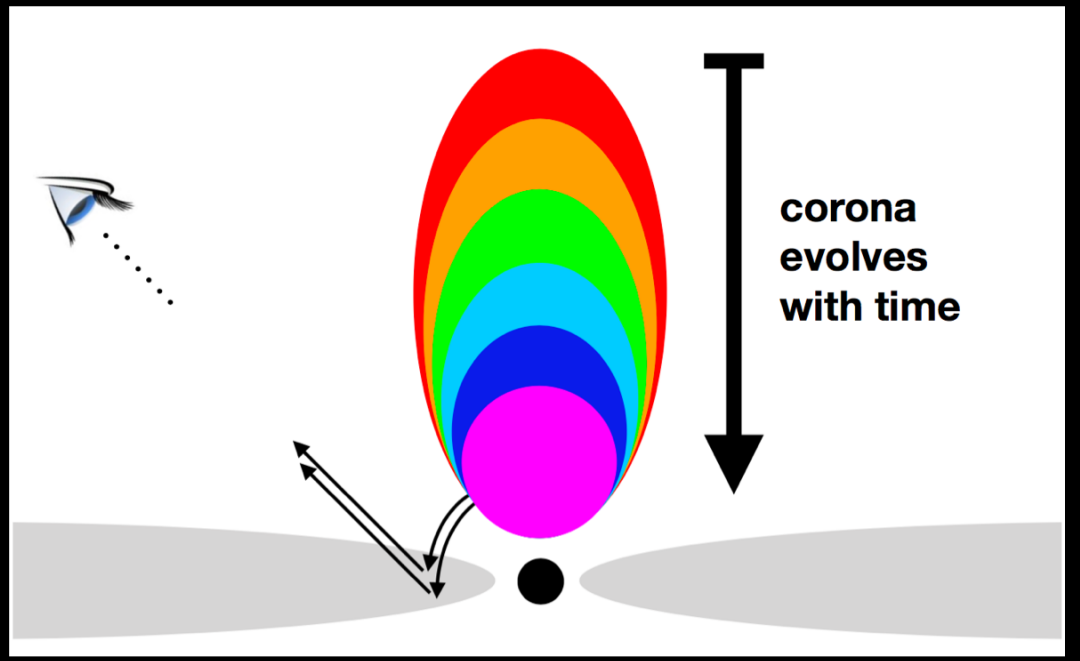
Athena (WFI) simulation



Evolution of disk lags in MAXI J1820+070

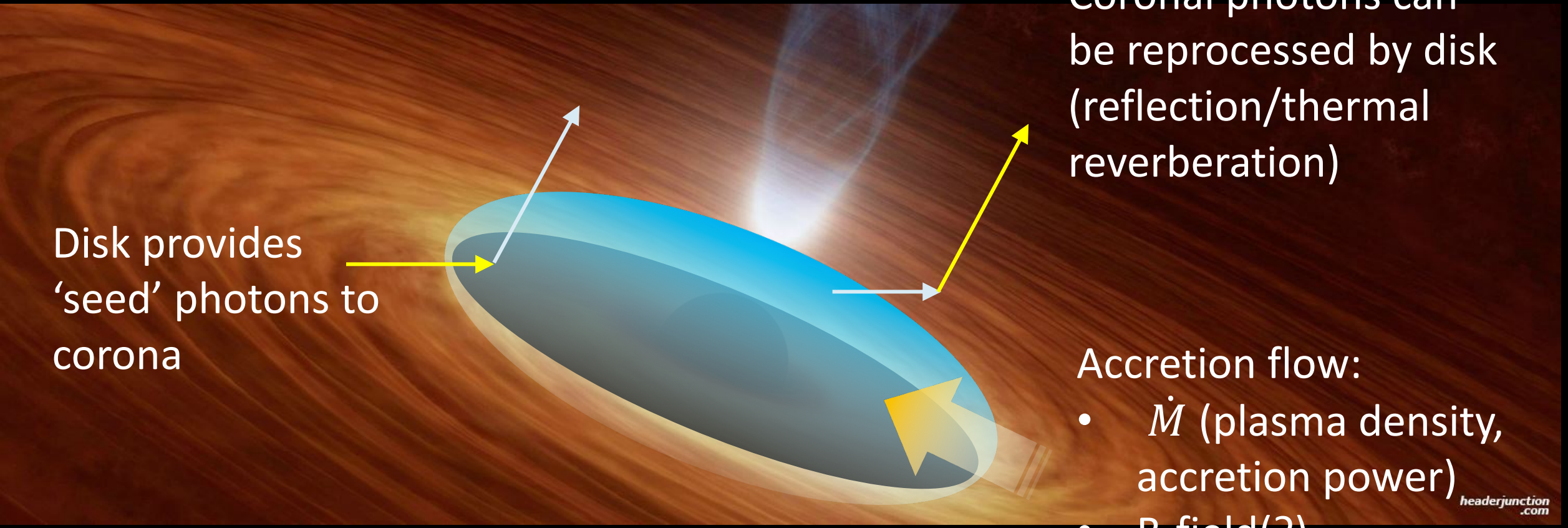
(Kara et al. 2019)





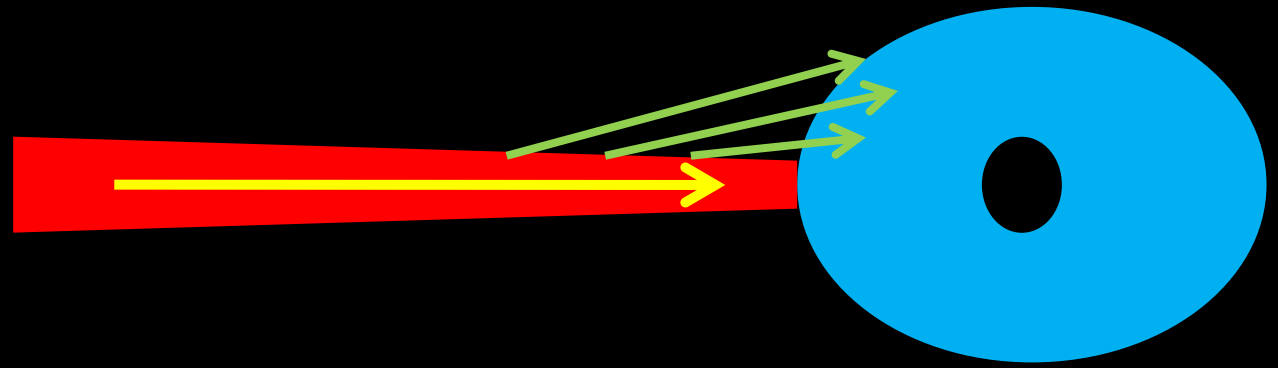
Disk lags increase (and move to longer time-scales) but ‘core’ reflection remains broadly similar: change in coronal height?

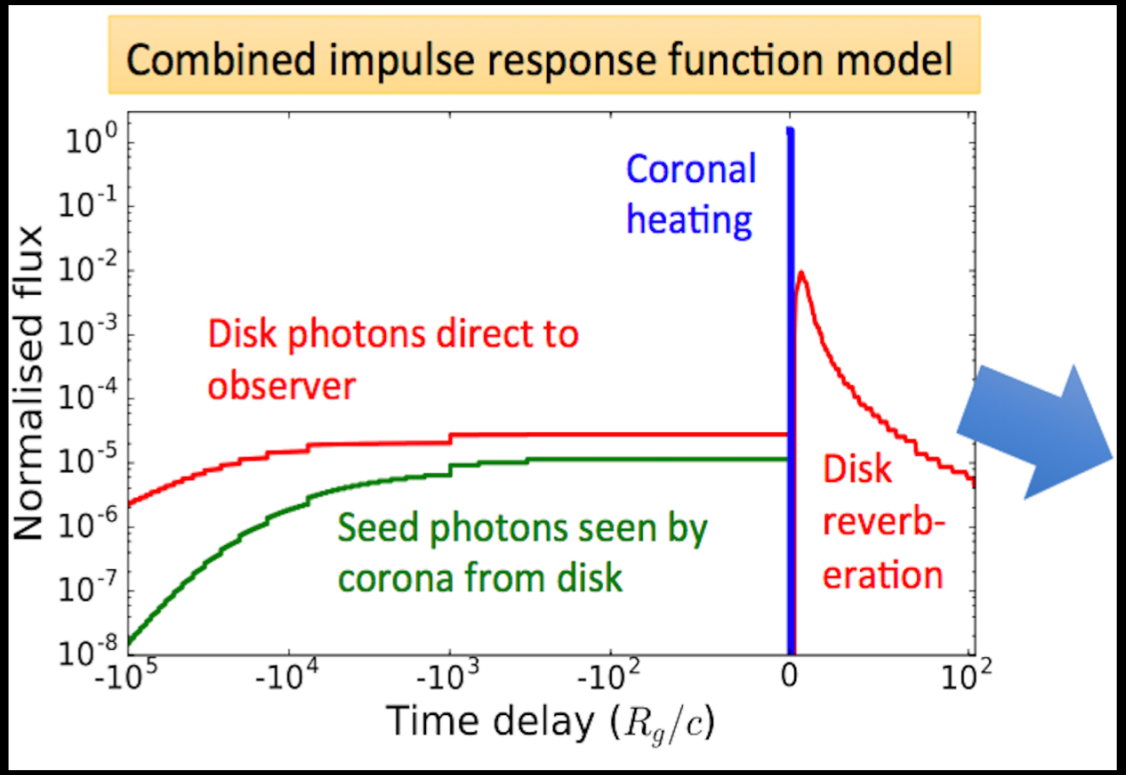
Disk-corona interactions



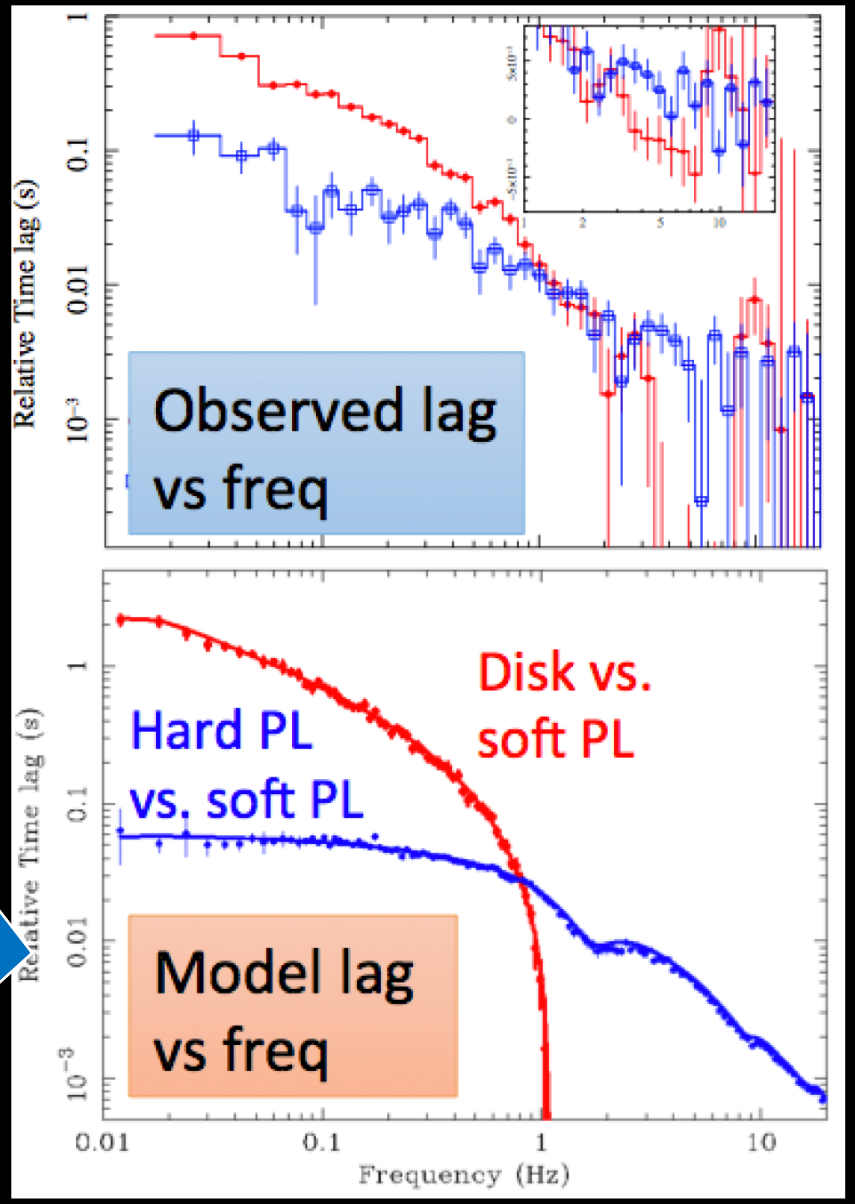
We should also account for the seed photon variations!

Accounting for seed photon variability (Uttley & Malzac, in prep.)



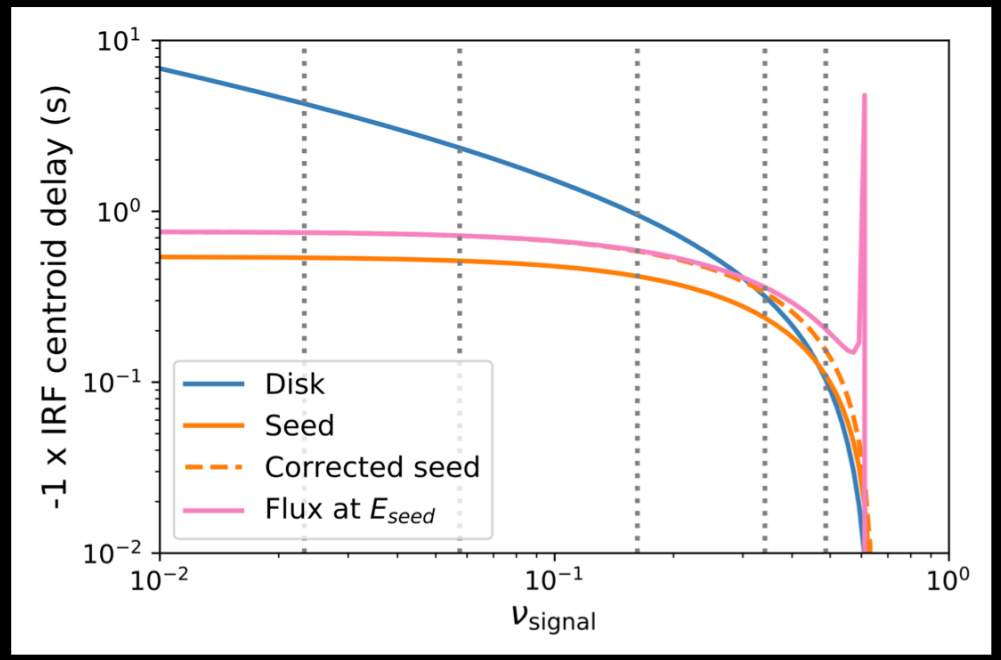


$$\Gamma \propto \left(\frac{L_{\rm seed}}{L_{\rm heat}}\right)^{1/6}$$

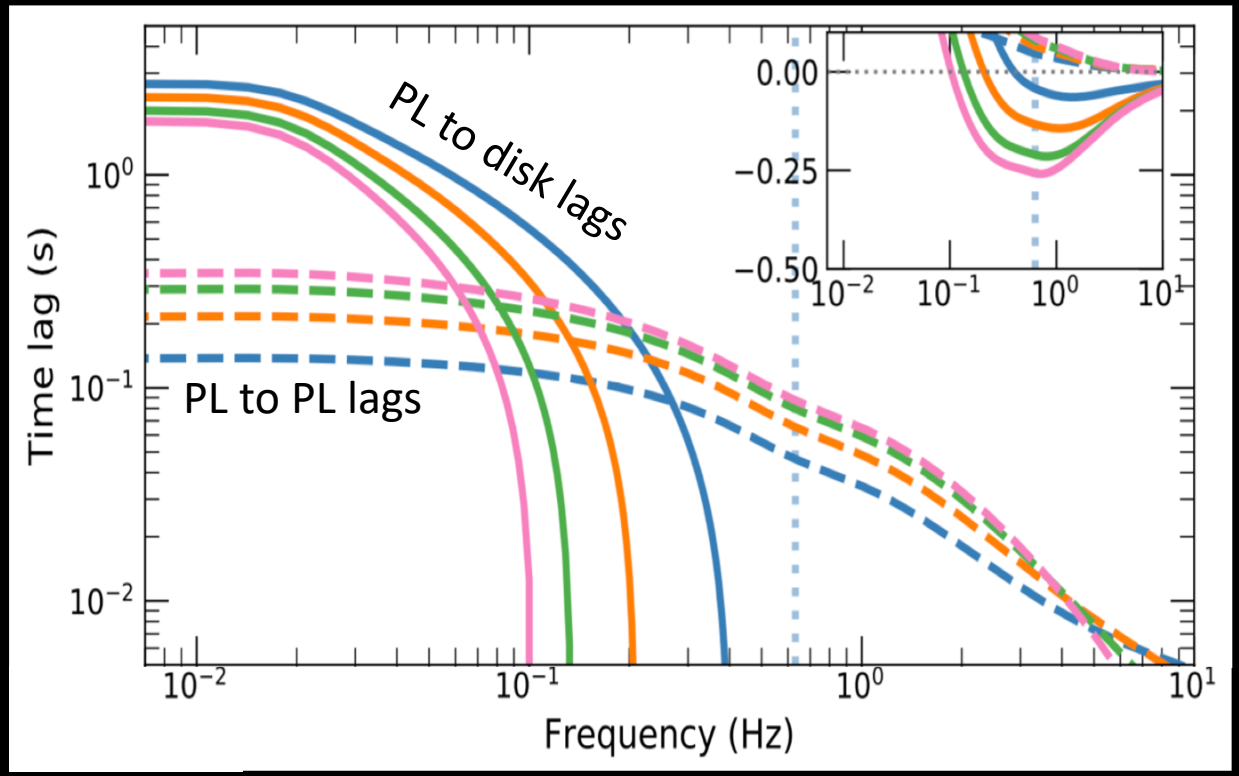


Interpreting the ‘soft’ (disk) lags

The blackbody lags are relative to seed variations rather than coronal heating – depend on propagation delays ***and coronal geometry***, not just light-travel time.



Assuming ***zero intrinsic reverberation lag*** relative to coronal heating:



Note: lags produced (assuming radial propagation time-scales are 1000 x Keplerian time) are really large! Propagating fluctuations must be even faster than this.

Summary

- Coronae couple to the accretion flow in complex ways: soft X-ray spectral-timing coverage is crucial to understanding how! Athena will dramatically improve S/N for these studies and push to fainter sources.
- Accounting for the known disk variability (direct blackbody, seed photons and accretion power heating the corona) can explain a large number of observed spectral-timing properties
- Heating vs seed photon delays are hard to avoid and imply compact coronae unless the coronae have substantial internal seed photons
- It is still unclear whether coronal ‘hot flows’ exist or have large extent