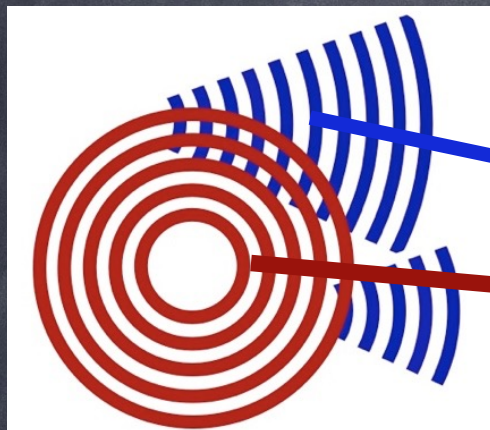




# Measuring Light Echos in NGC 4051

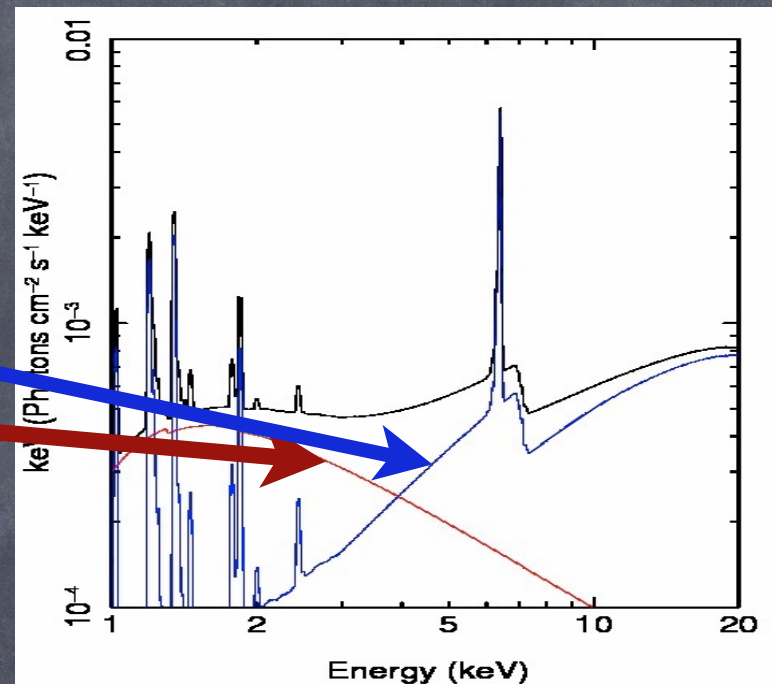
Jane Turner (UMBC), Lance Miller (Oxford), James  
Reeves (Keele), Valentina Braito (INAF-Brera)

# X-ray Reverberation



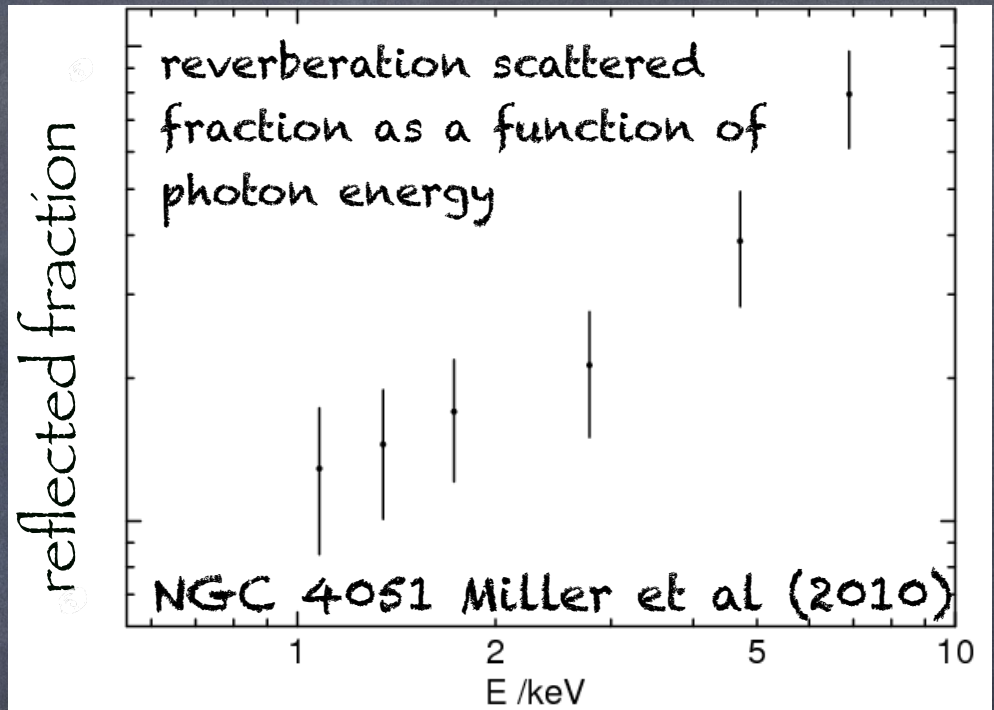
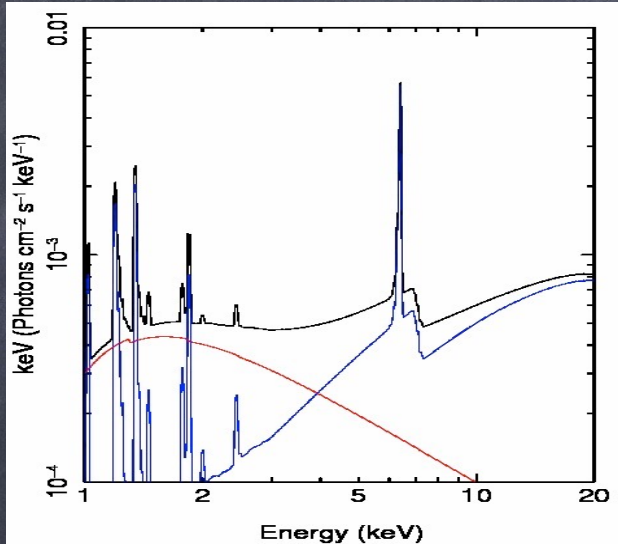
hard spectrum,  
scattered,  
delayed X-rays

direct X-rays



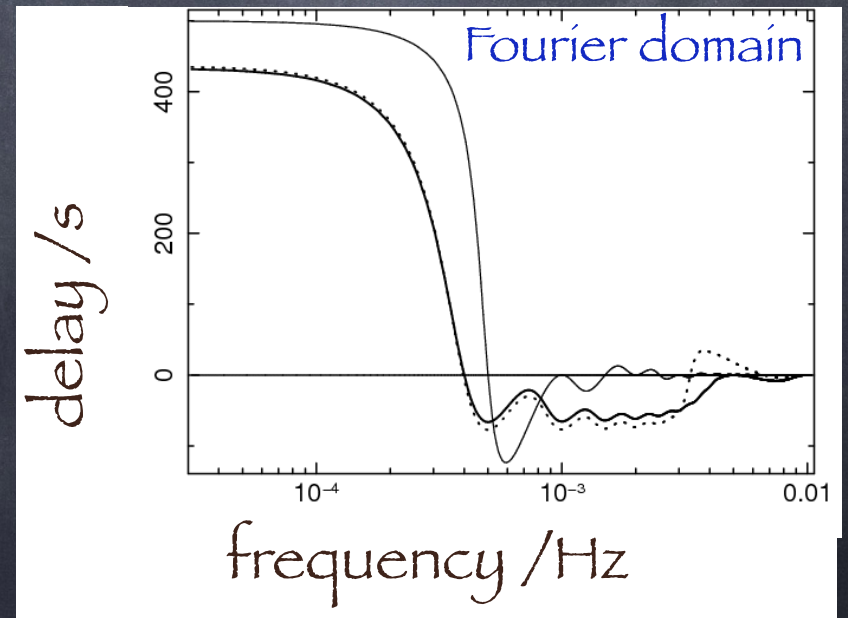
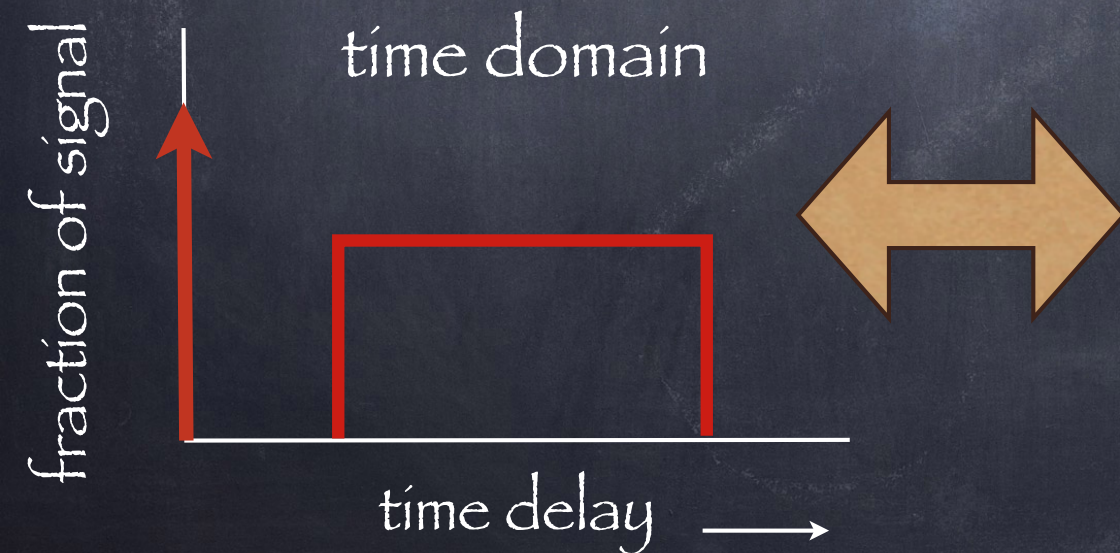
- ⊙ Insufficient counts to separate lines and continuum on short timescales
- ⊙ Measure reverberation between broad bands
- ⊙ Reflected & direct mixed in different fractions in the bands

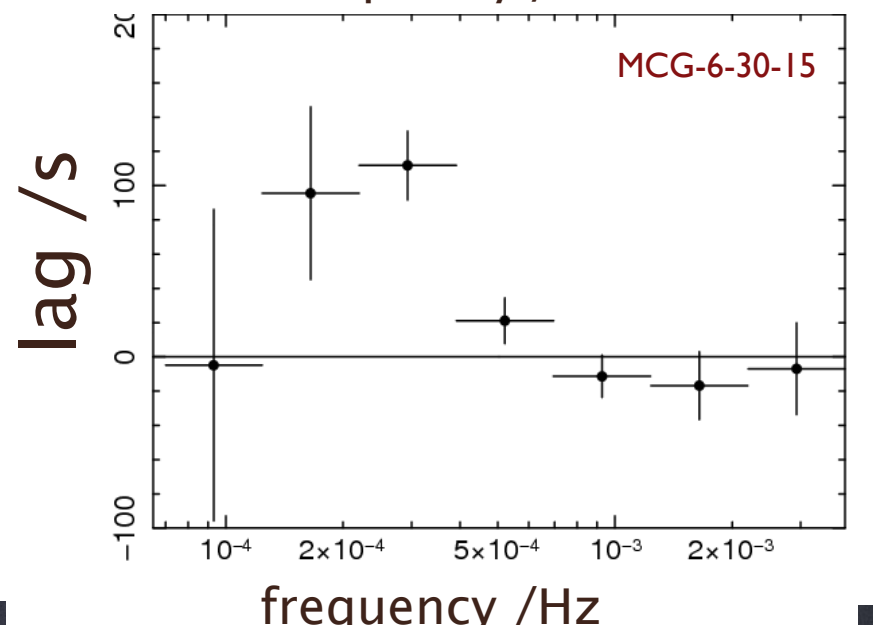
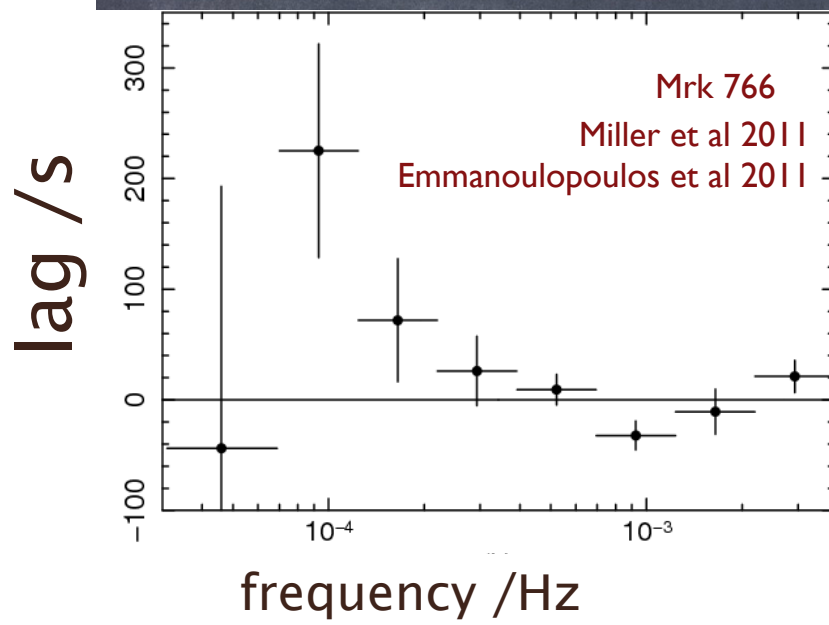
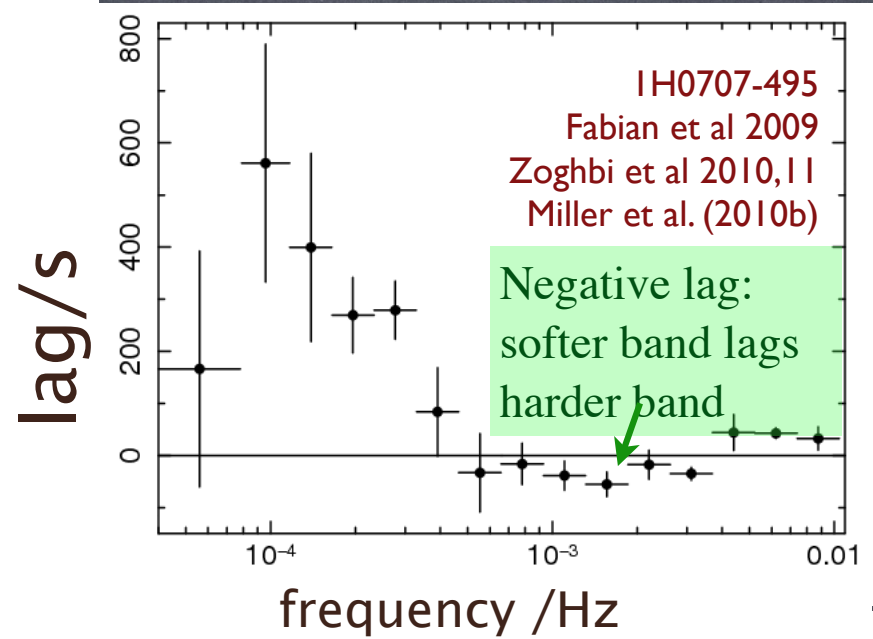
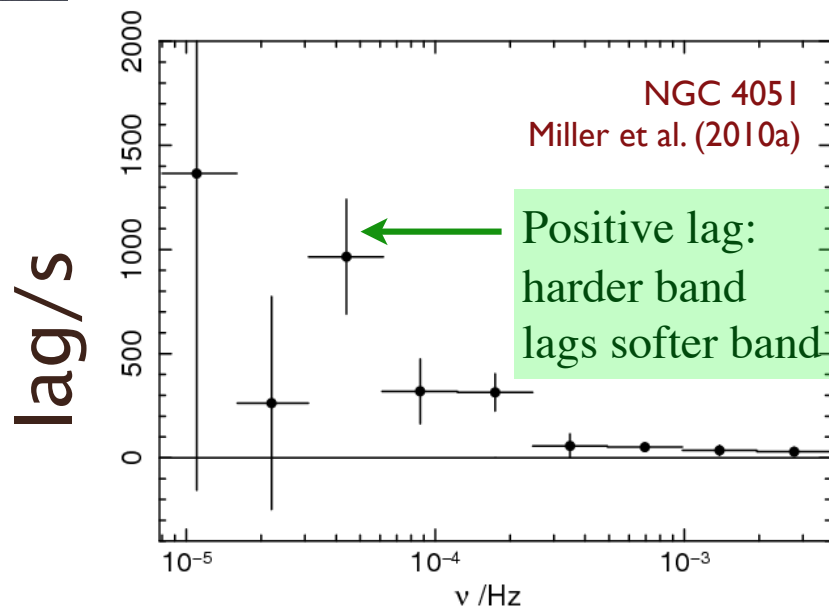
# Energy dependence



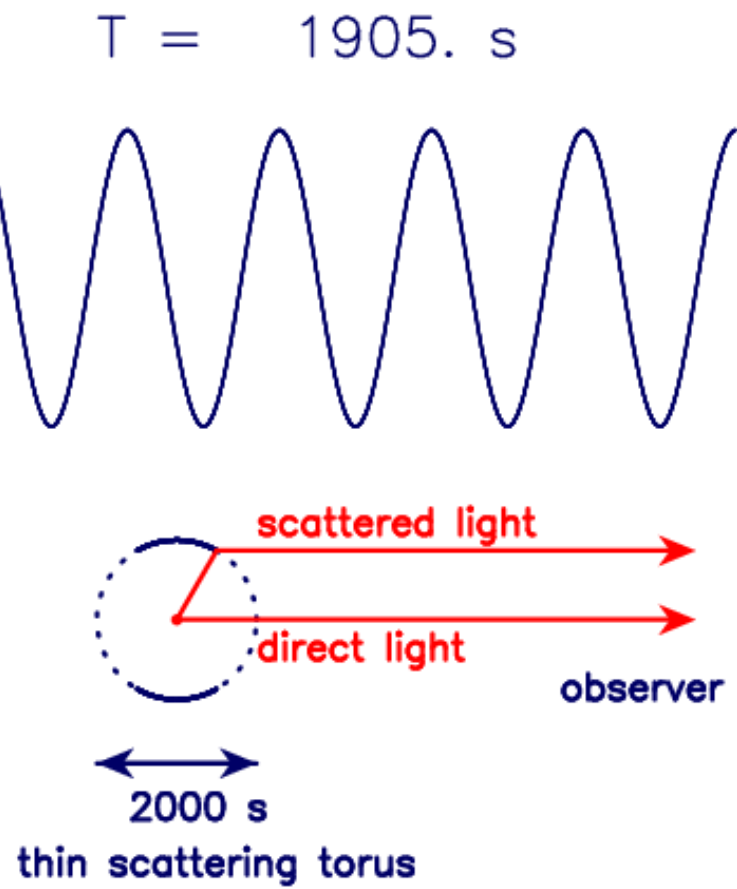
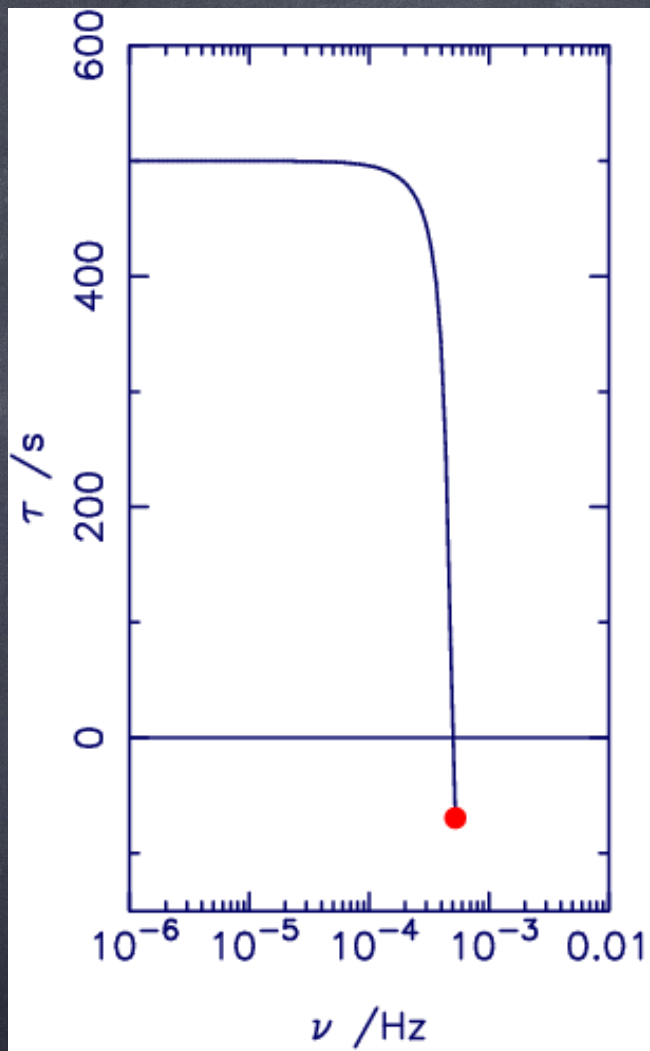
- Lag times increase with band separation

- Estimate cross-band power spectrum (max likelihood)  $\rightarrow$  time delay as function of source variations
- Lag spectrum given by phases of Fourier transform of the transfer function which describes spread of time delays in the signal

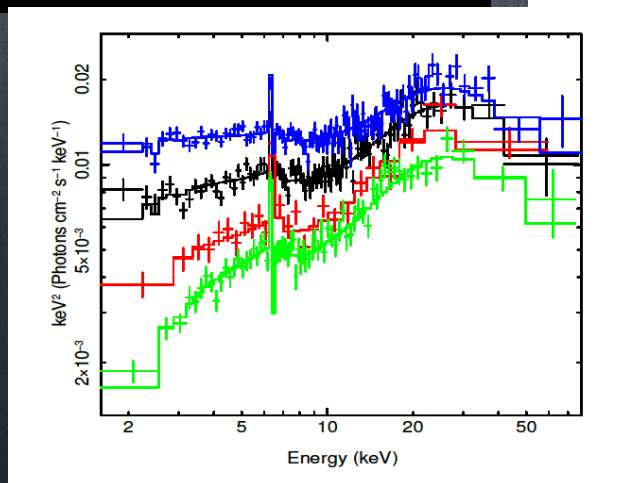
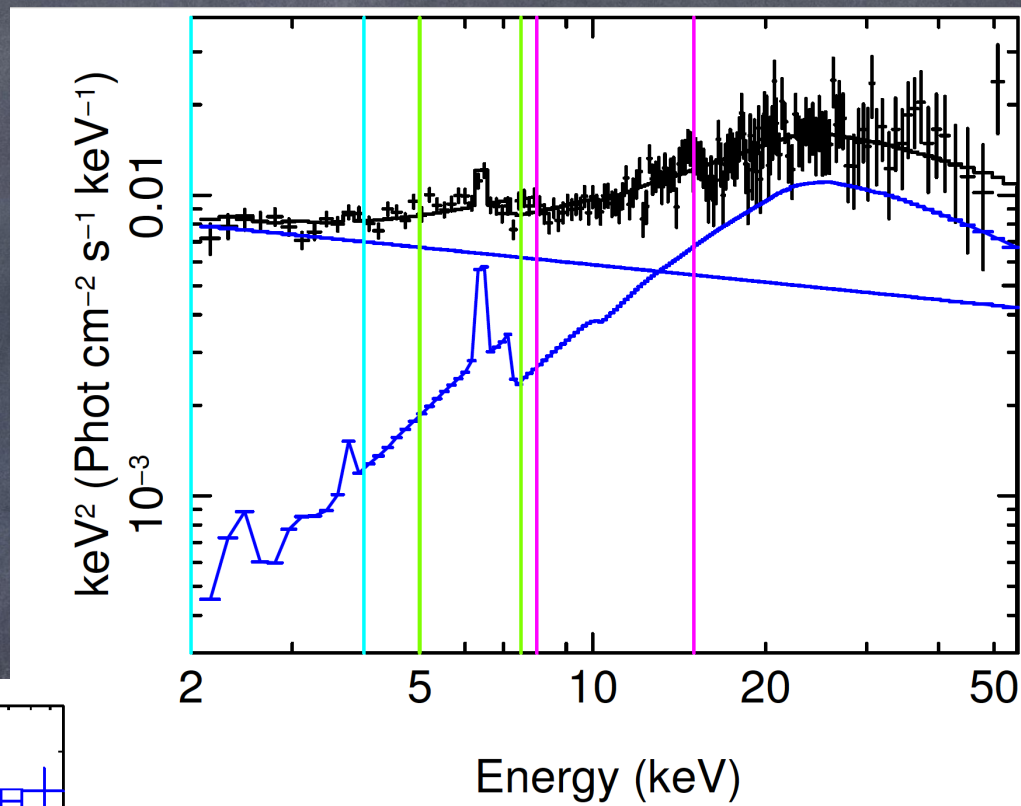
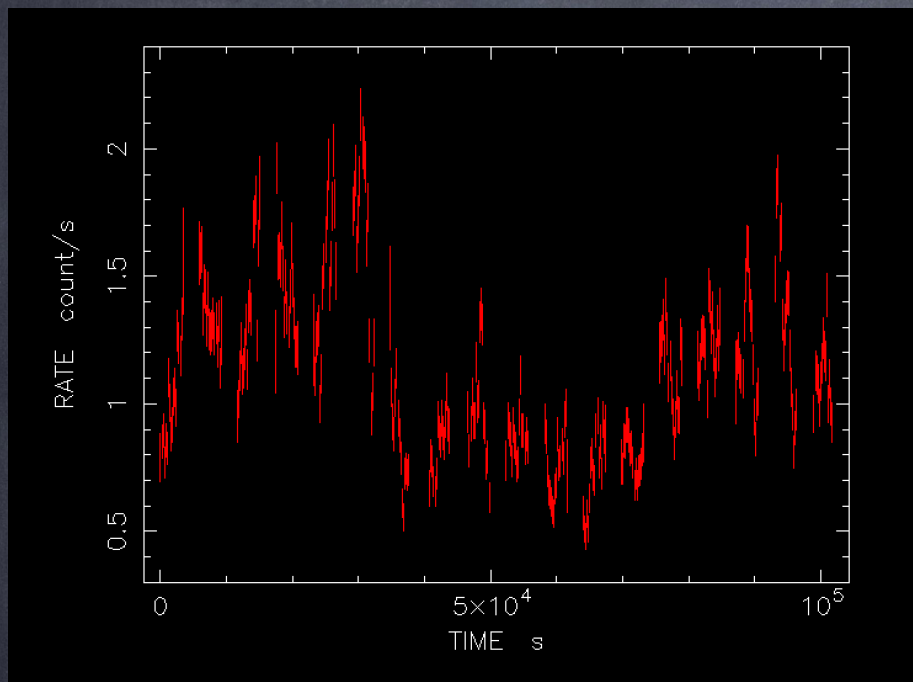




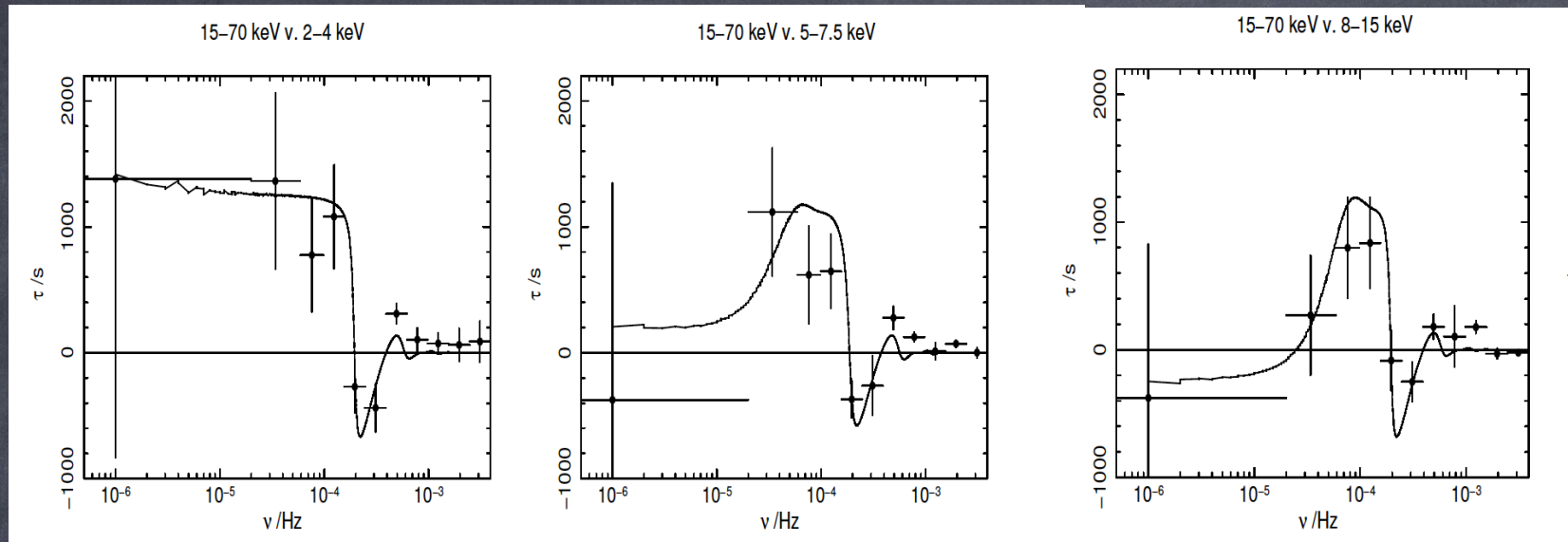
Hard lags known for 30 years but not recognized as reverberation



# NUSTAR - NGC 4051

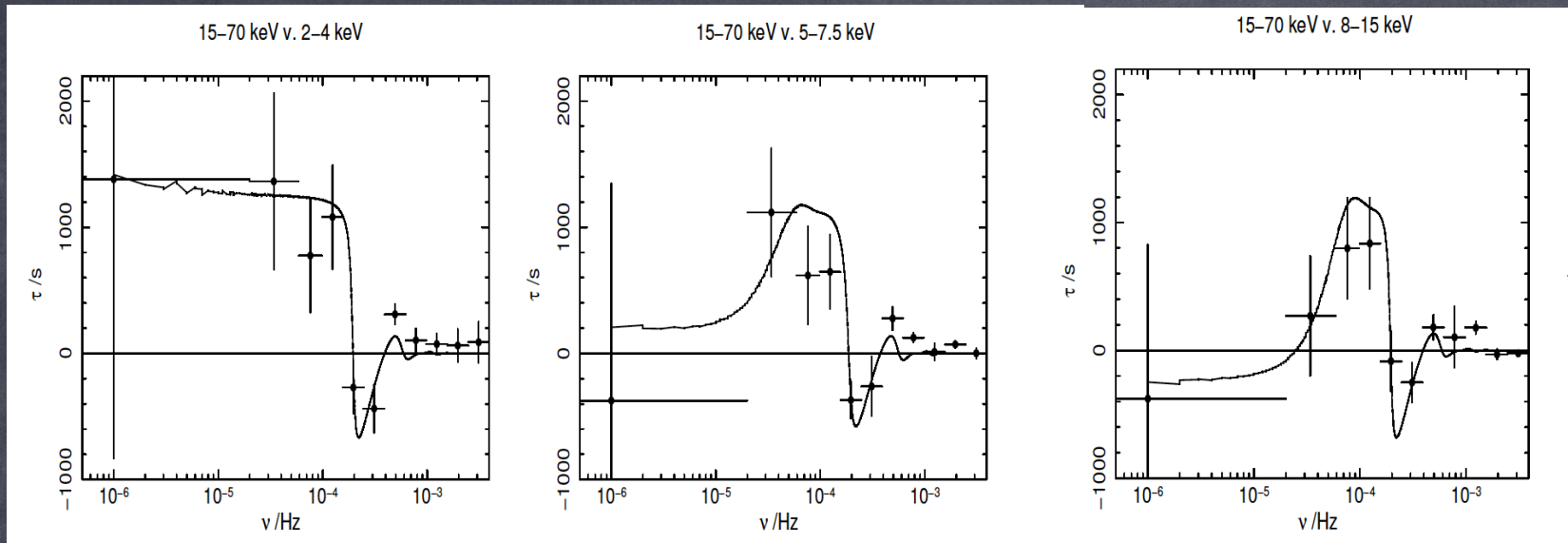


170 ks - 5 obs

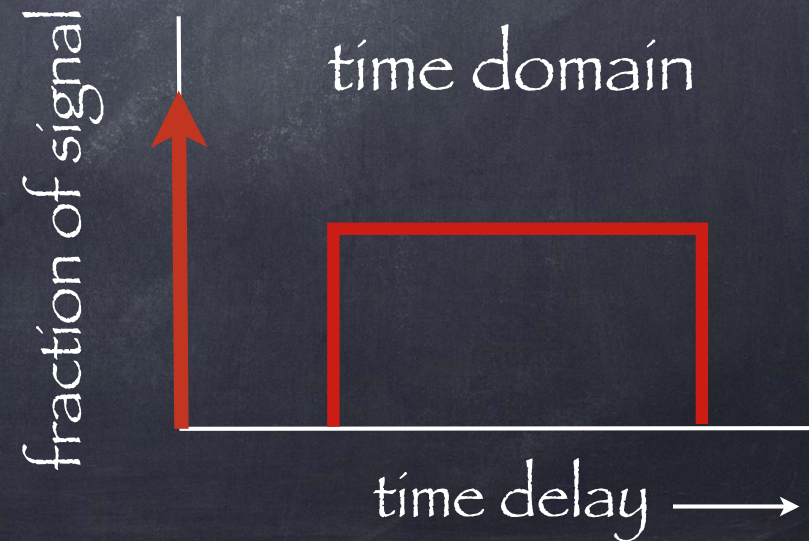


- Hard lags soft by  $> \sim 1000$  s at  $5 \times 10^{-5}$  Hz for all band pairs
- Negative lags  $\sim 400$  s at  $2 \times 10^{-4}$  Hz
- top hat model fits - simplistic but data do not warrant more complex model



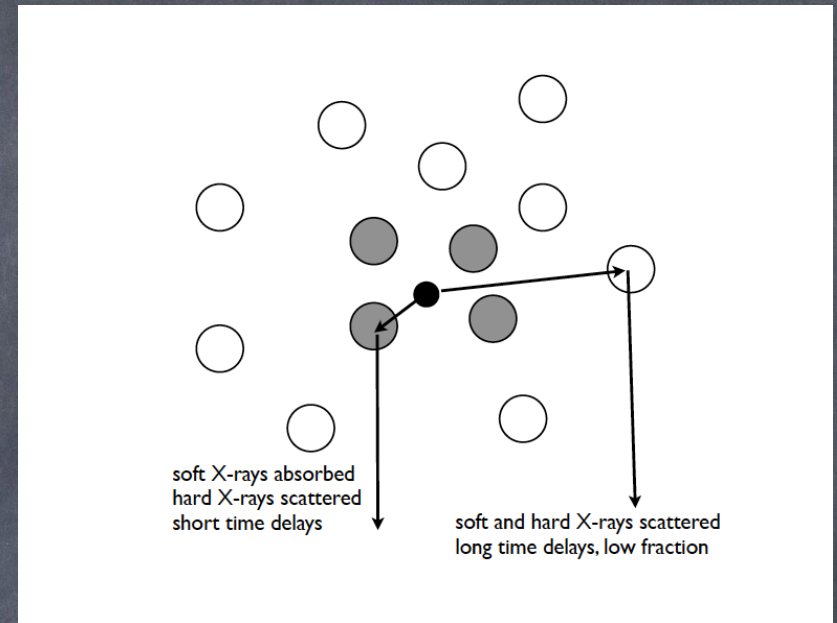


- Light echos from shell,  $t_{\min} 2,200s \rightarrow$  scatt light close to los is absent  $\rightarrow$  shell with holes/clumps
- $t_{\max} 14,000s$  (Fe K band)
  - Light travel time across shell diameter
- not a unique model

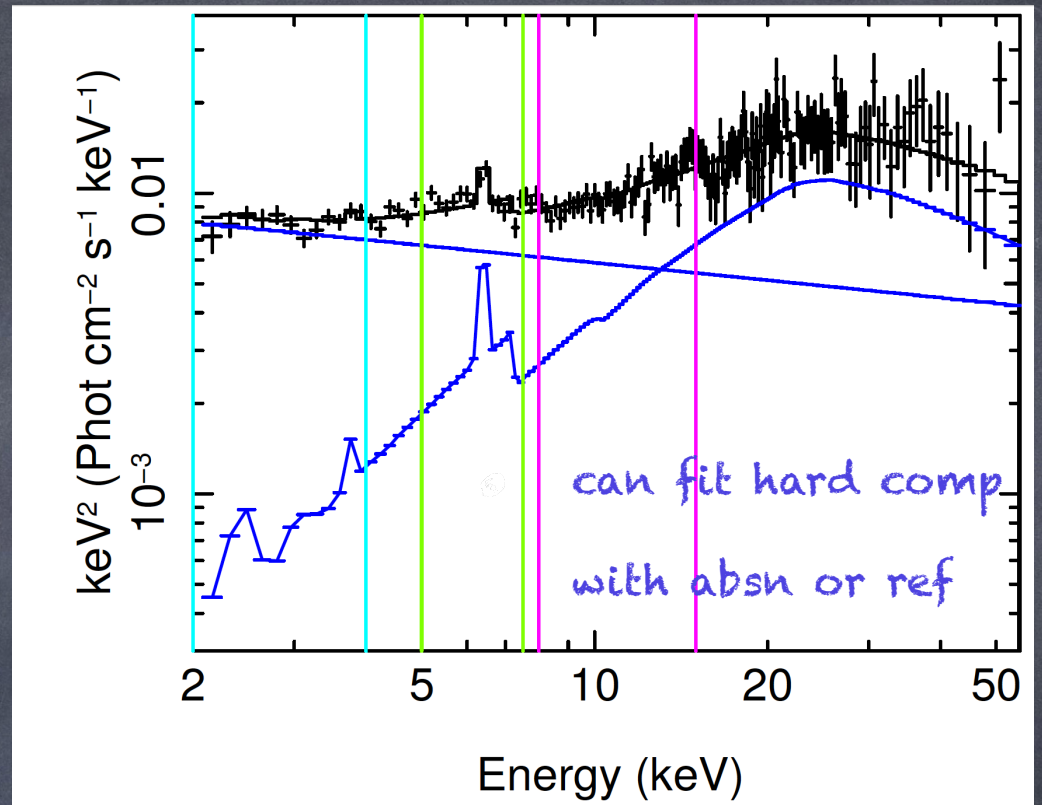
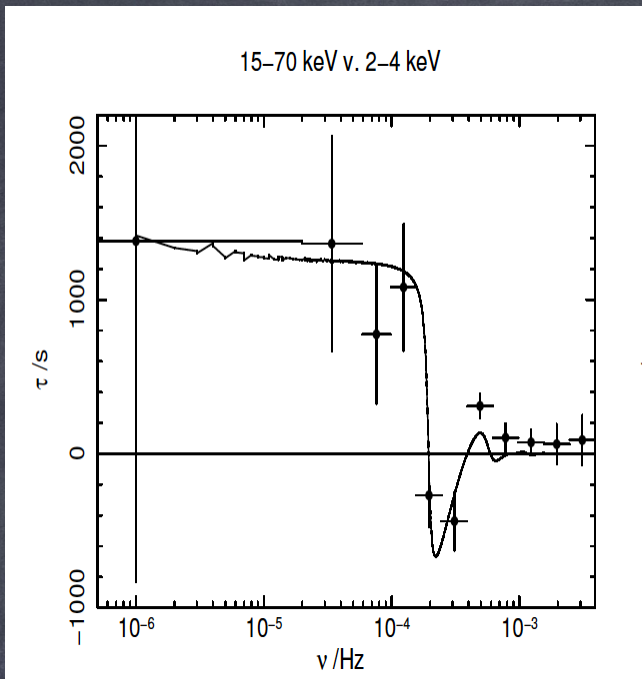


Scattered fraction increases with photon energy while max time delay decreases

Higher fraction of soft photons scattered from larger radii?

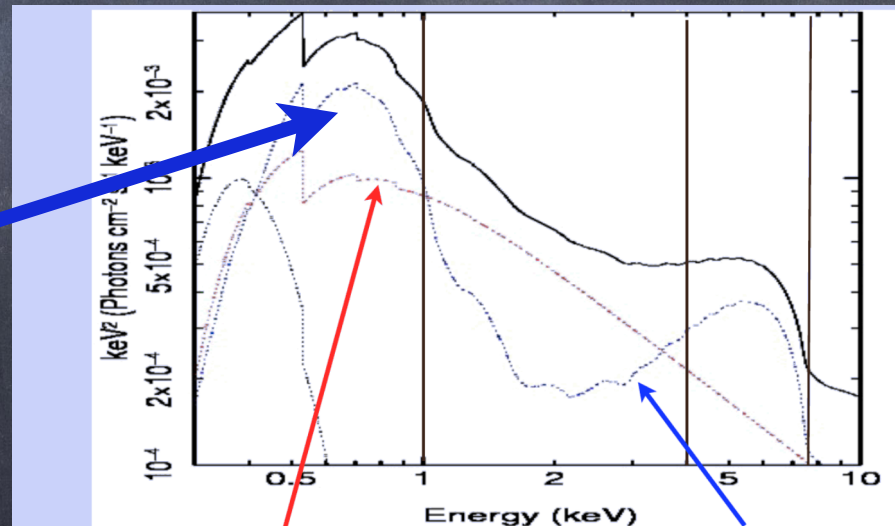


band	$t_{\min}/s$	$t_{\max}/s$	$R$
2-4 keV	-	-	0
5-7.5 keV	2200	14400	0.14
8-15 keV	2200	10600	0.22
15-70 keV	2200	2900	0.47



• Negative lag - but soft band has no reflected contribution

• (cf blurred ref model for 1H0707)



“direct” component “blurred reflection” component  
 • In this blurred reflection model, **hard (FeK) band has most reflection**, then soft band, then medium band

# Conclusions

- Hard band flux variations consistently lag softer band in NuSTAR data from NGC 4051
- Negative lag seen but cannot be from inner disk reflection as soft band has no reflection
- Top hat model fits lags - consistent with reverberation from cloud ensemble but not a unique solution
- Reverberation likely mapping stratified clumpy wind
- Zones out to 7000  $L_s$  radii, global covering  $\sim 50\%$