X-ray reverberation in NLS1

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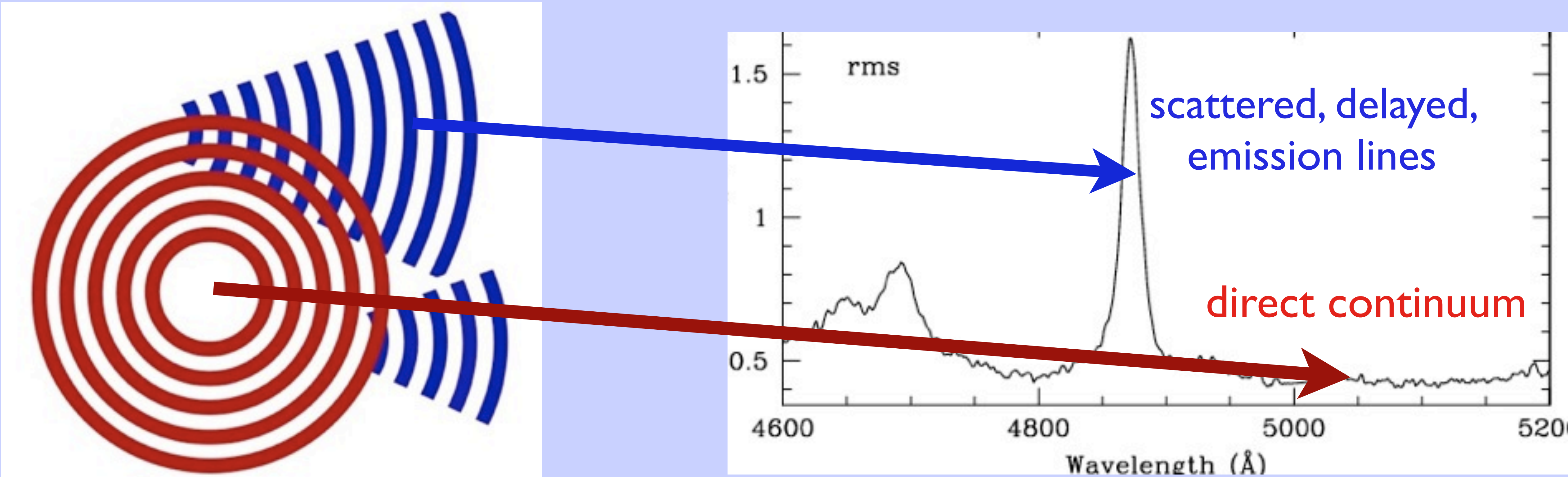
reverberation

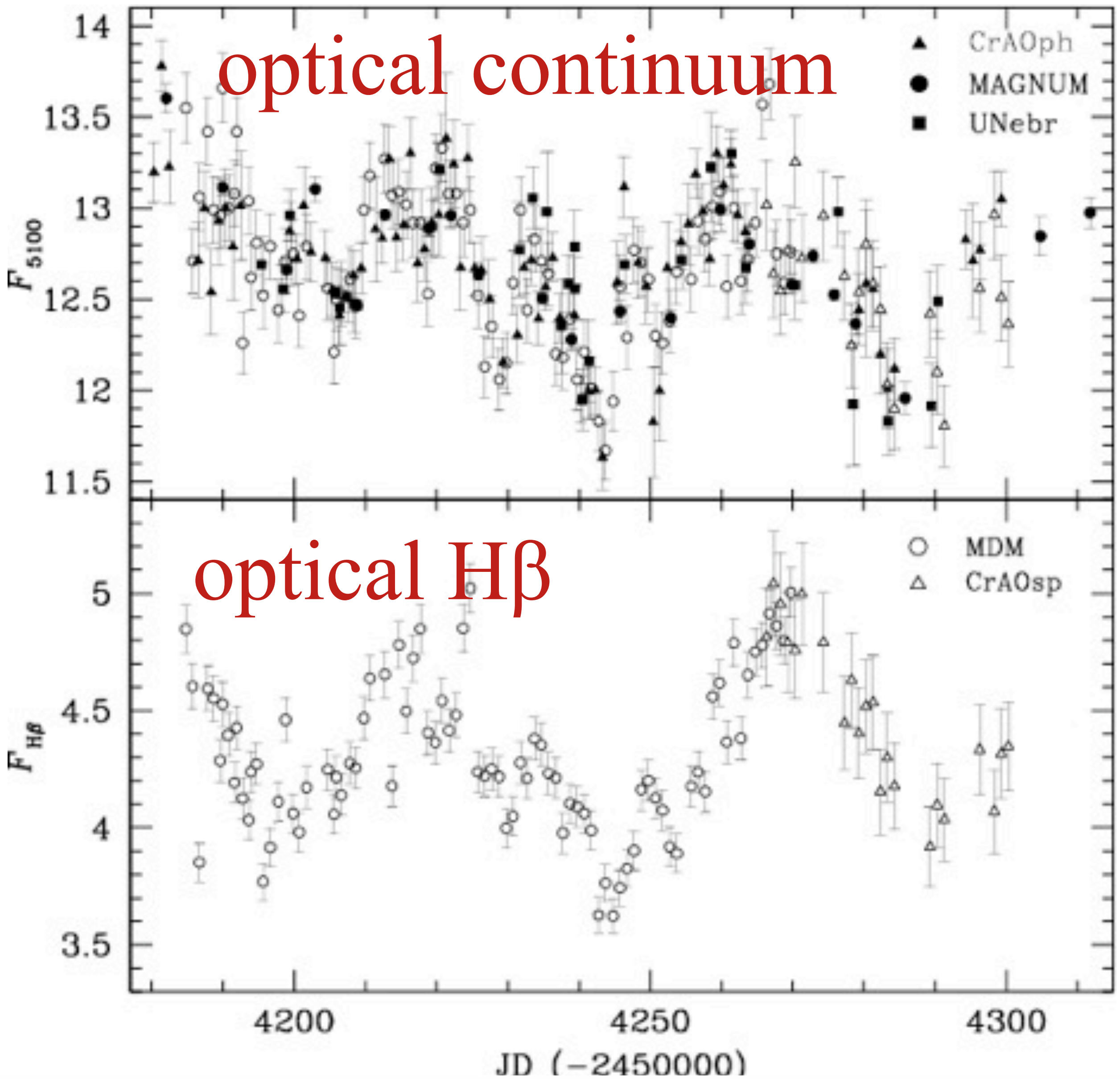


NGC 4051 optical: Denney et al 2009

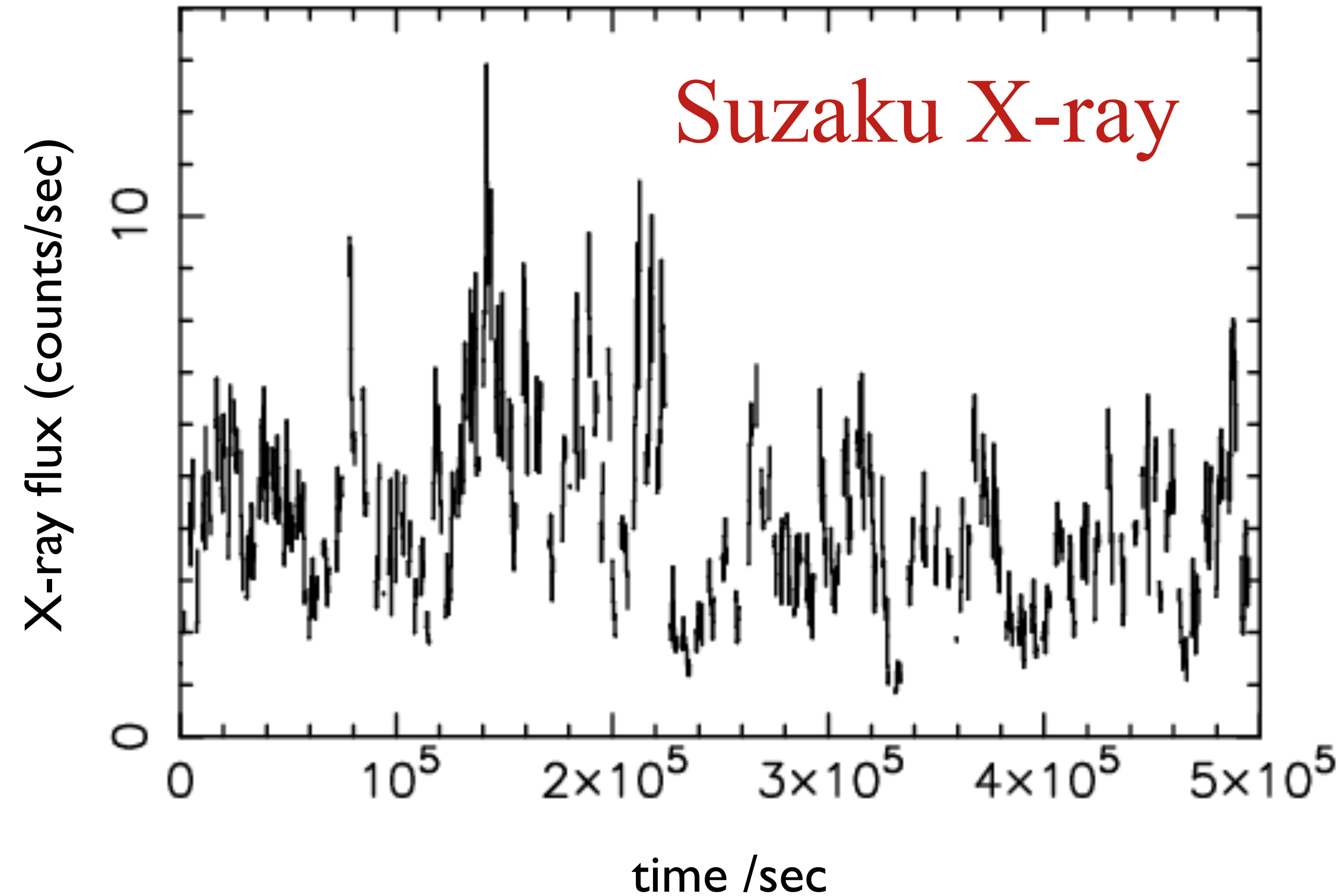
- reverberation between optical/UV continuum and optical emission lines is principal method of BH mass measurement in AGN (Peterson, Bentz, Denney tomorrow).
- in our analysis we consider how individual Fourier modes behave

gappy, noisy time-series

NGC 4051 optical: Denney et al 2009

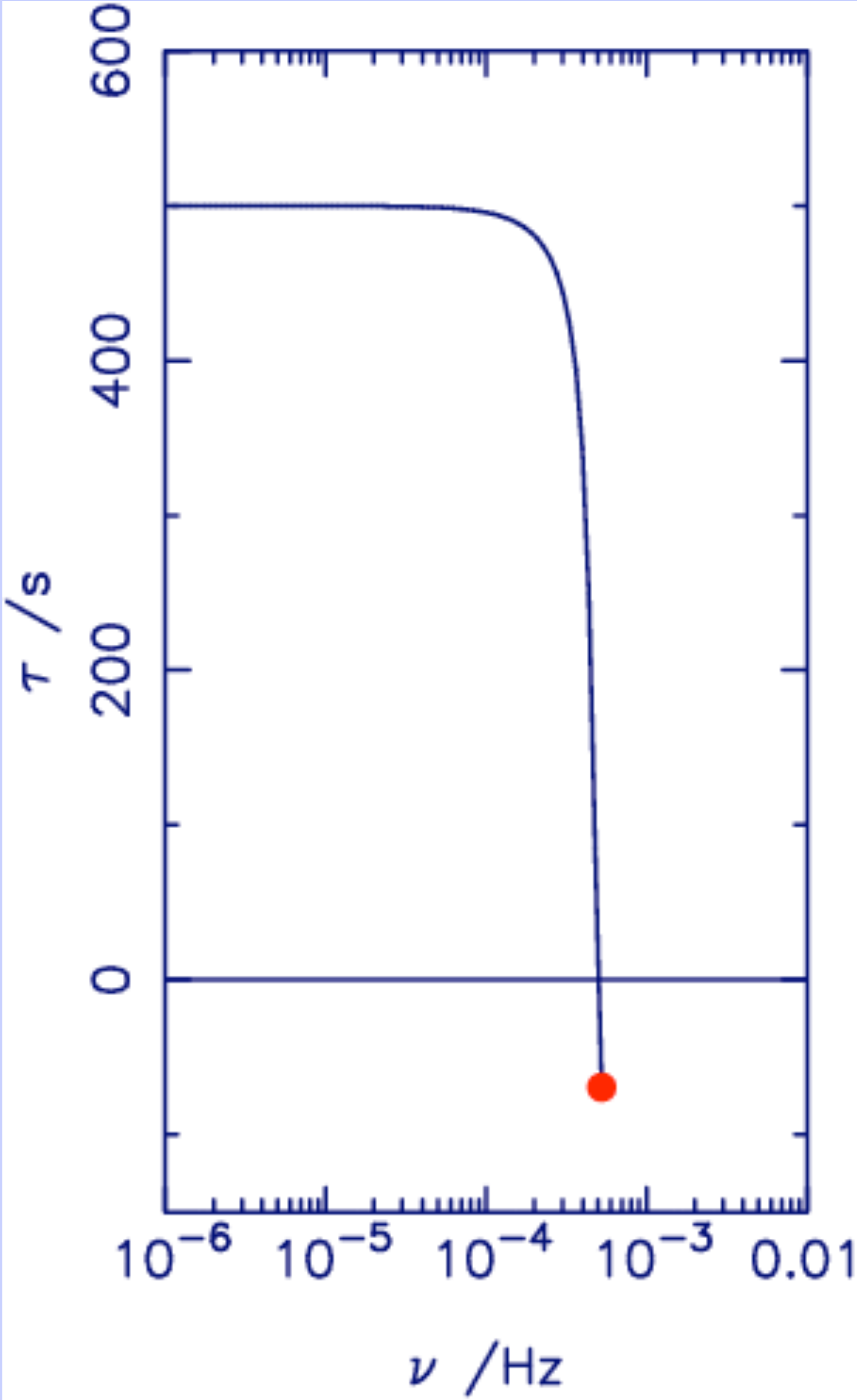


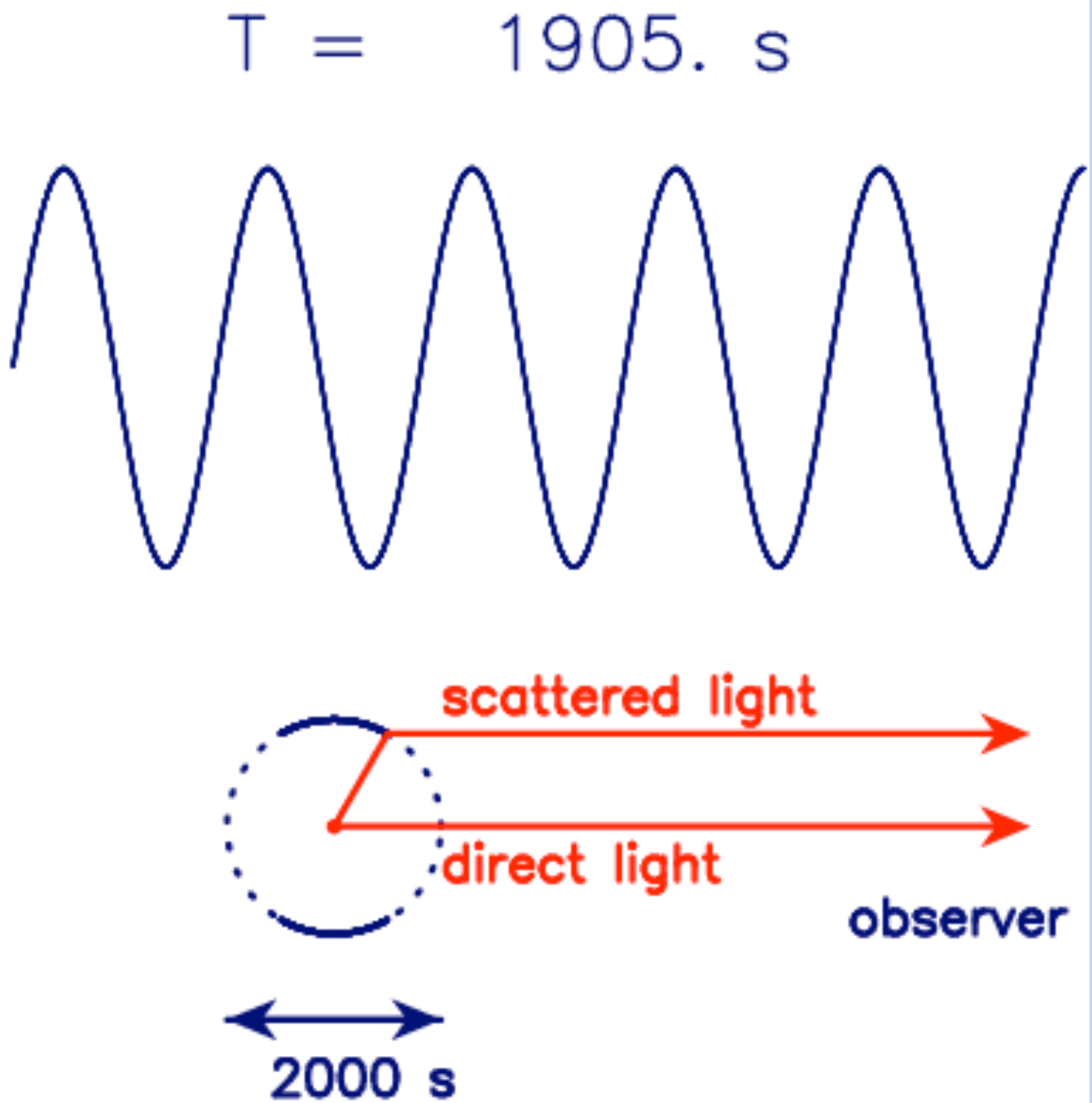
NGC 4051 X-ray: Miller et al 2010



- time series are both “gappy” and noisy
- developed maximum-likelihood analysis based on CMB methods
- immune to gaps, accounts for shot noise, rigorous error estimation
- only method that accounts for covariance in Fourier domain

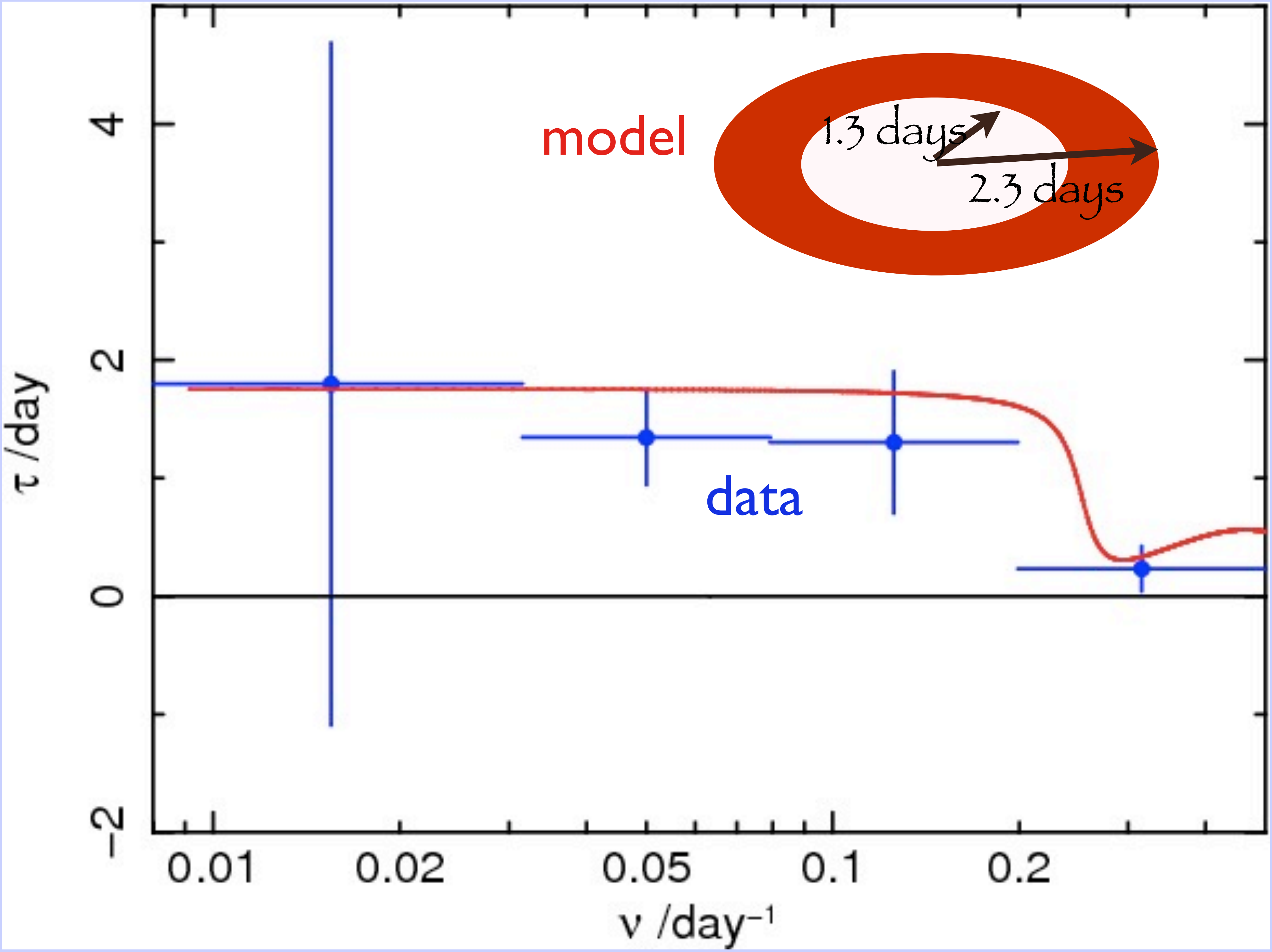
reverberation Fourier analysis



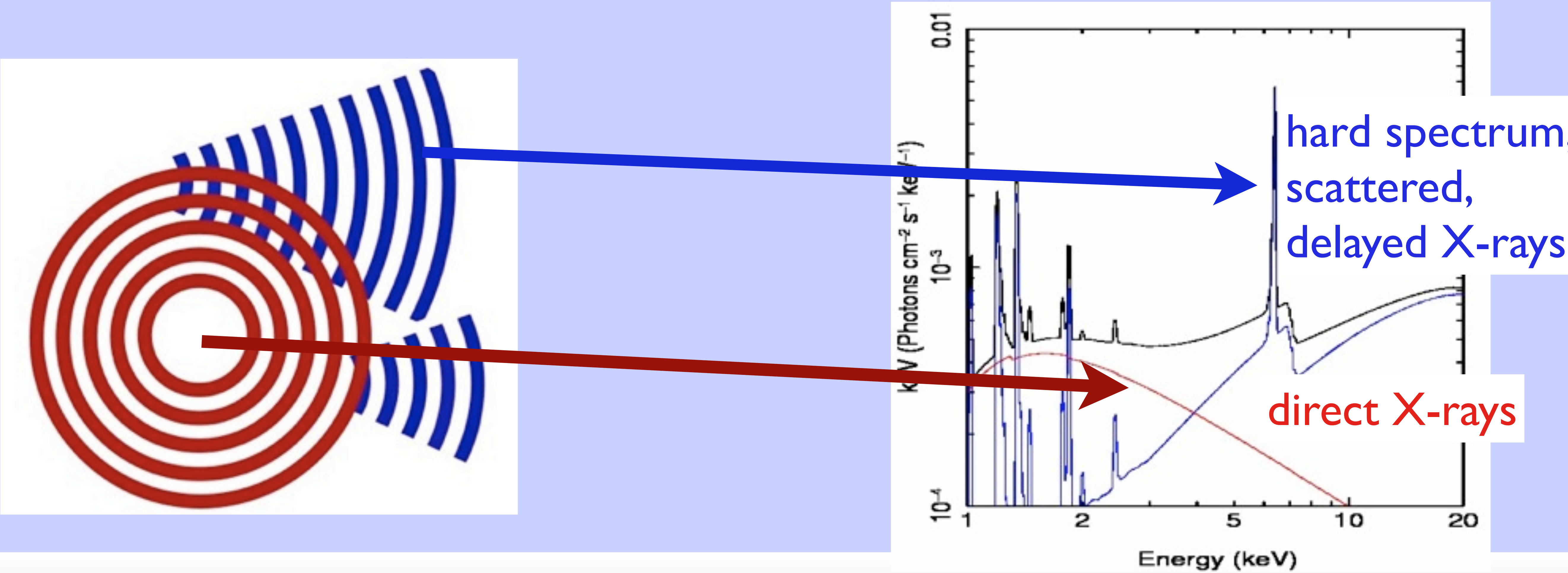


thin scattering shell
partial covering

optical (Hβ) reverberation in NGC 4051 (Denney et al 2009)

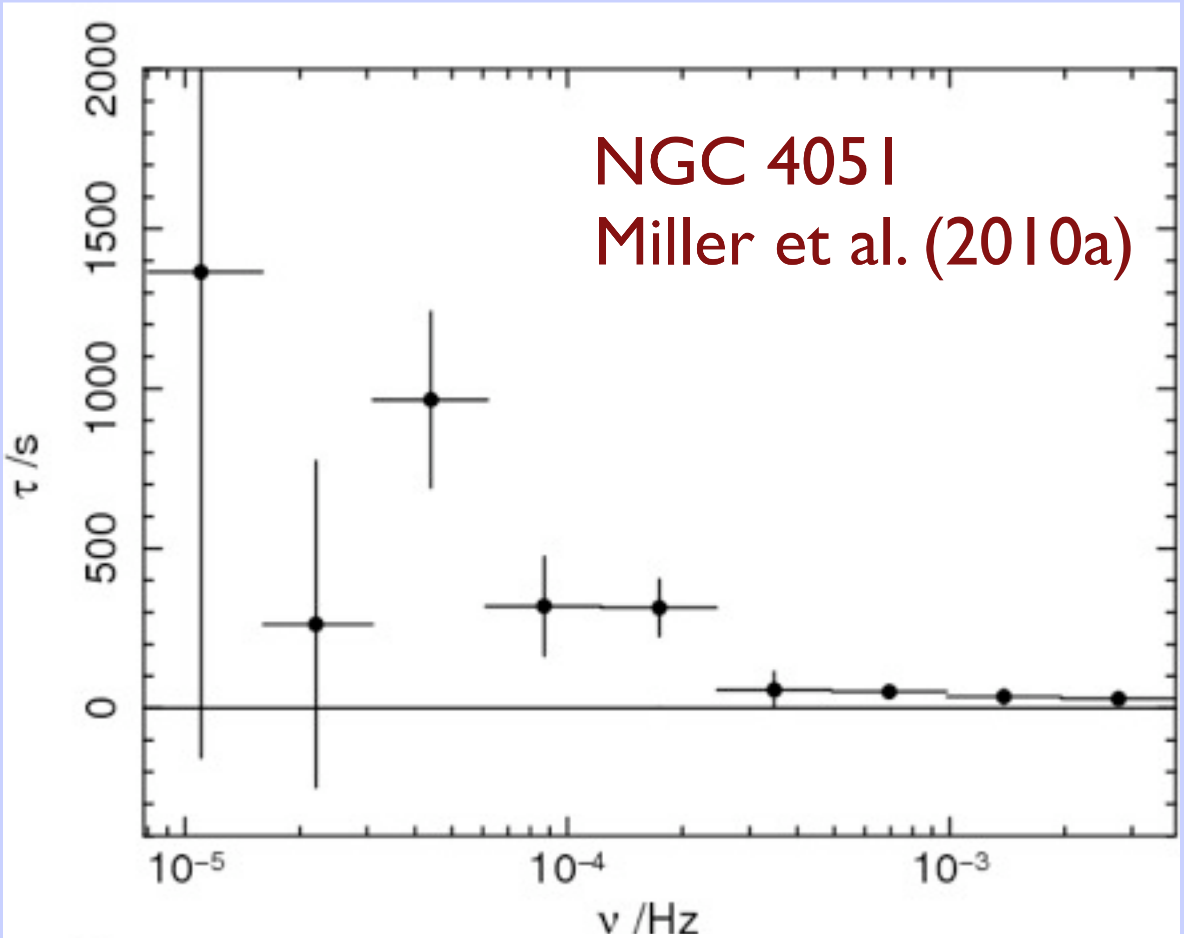


X-ray reverberation

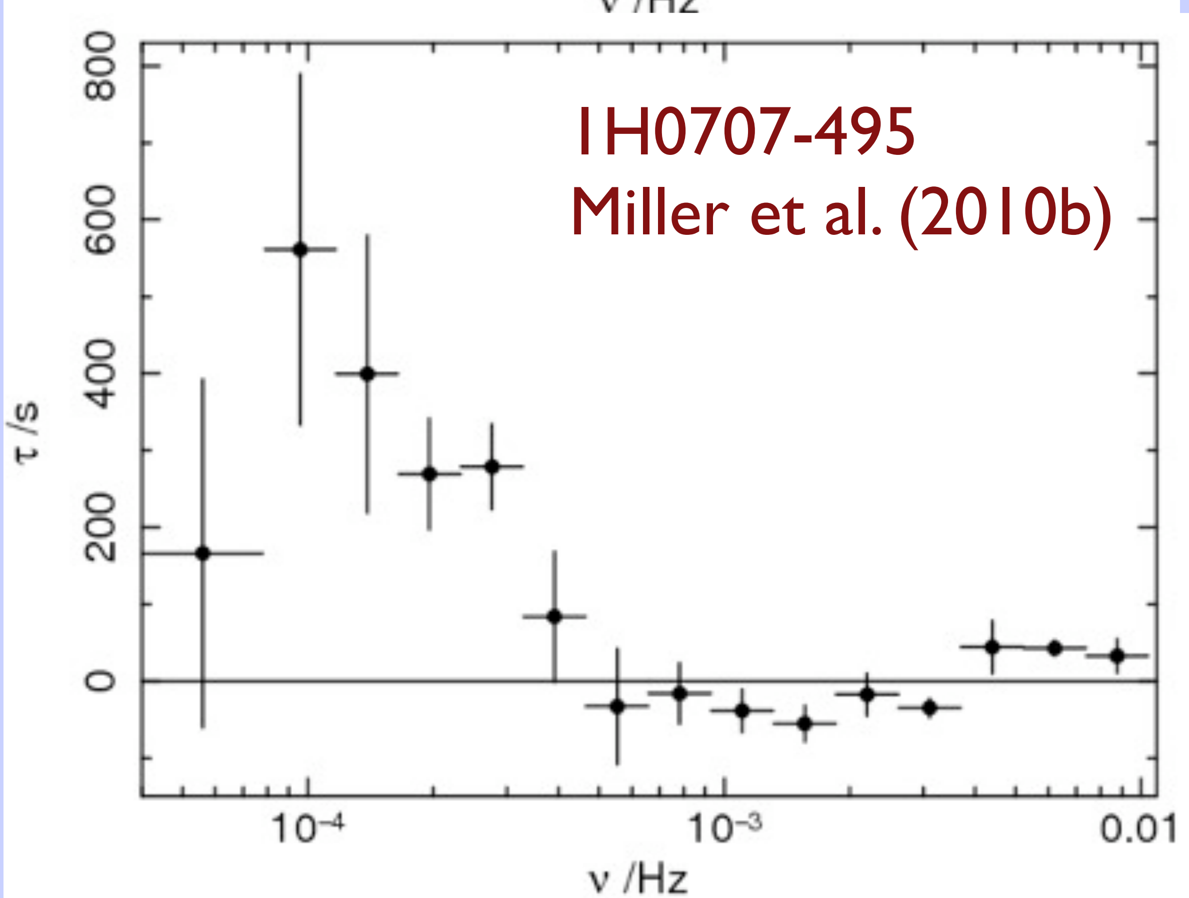


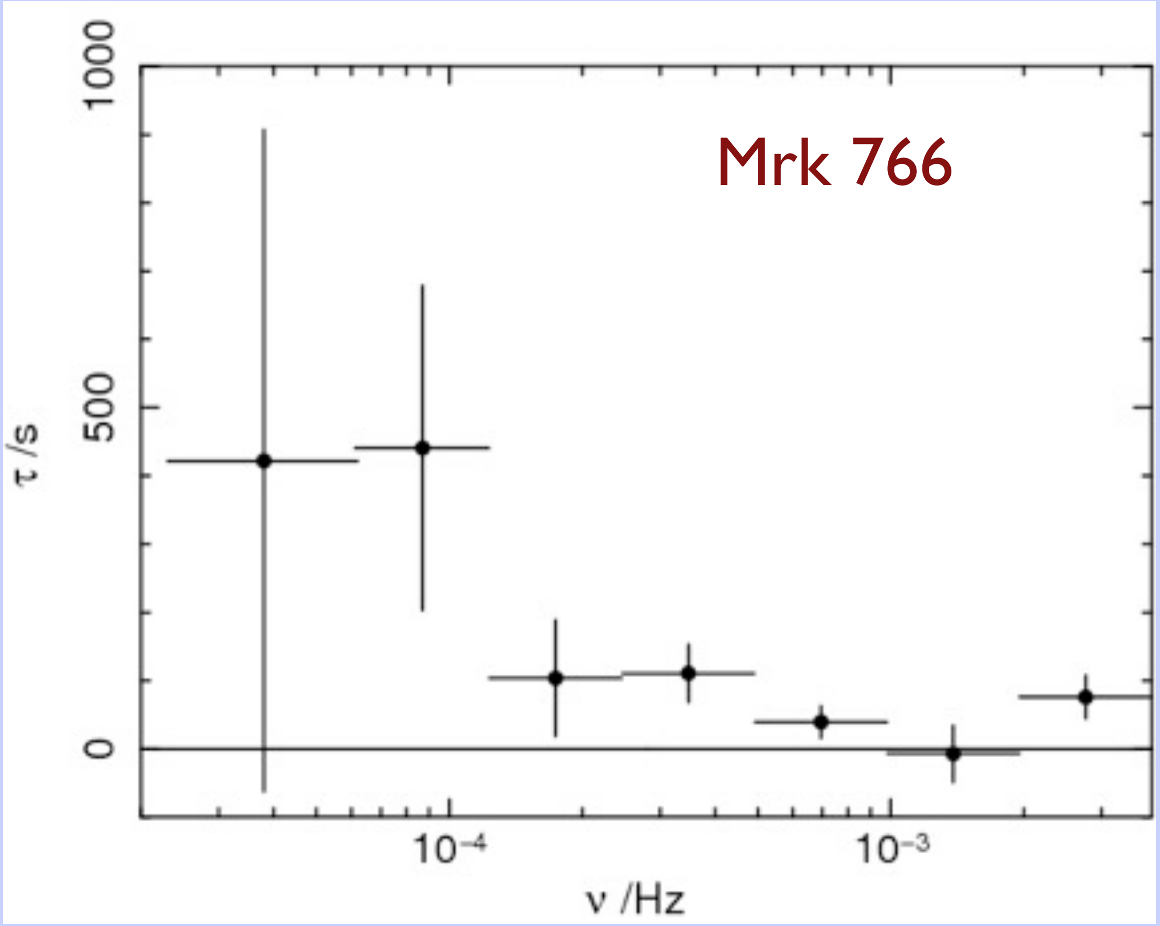
- at X-ray energies not enough counts to separate lines and continuum on short timescales.
- measure reverberation between continua in different broad X-ray bands: hard X-rays are Compton-scattered; soft X-rays are absorbed
- key difference with optical reverberation: we measure signals where the reflected and direct components are mixed together. Both bands can contain scattered light.

X-ray reverberation in NLS1



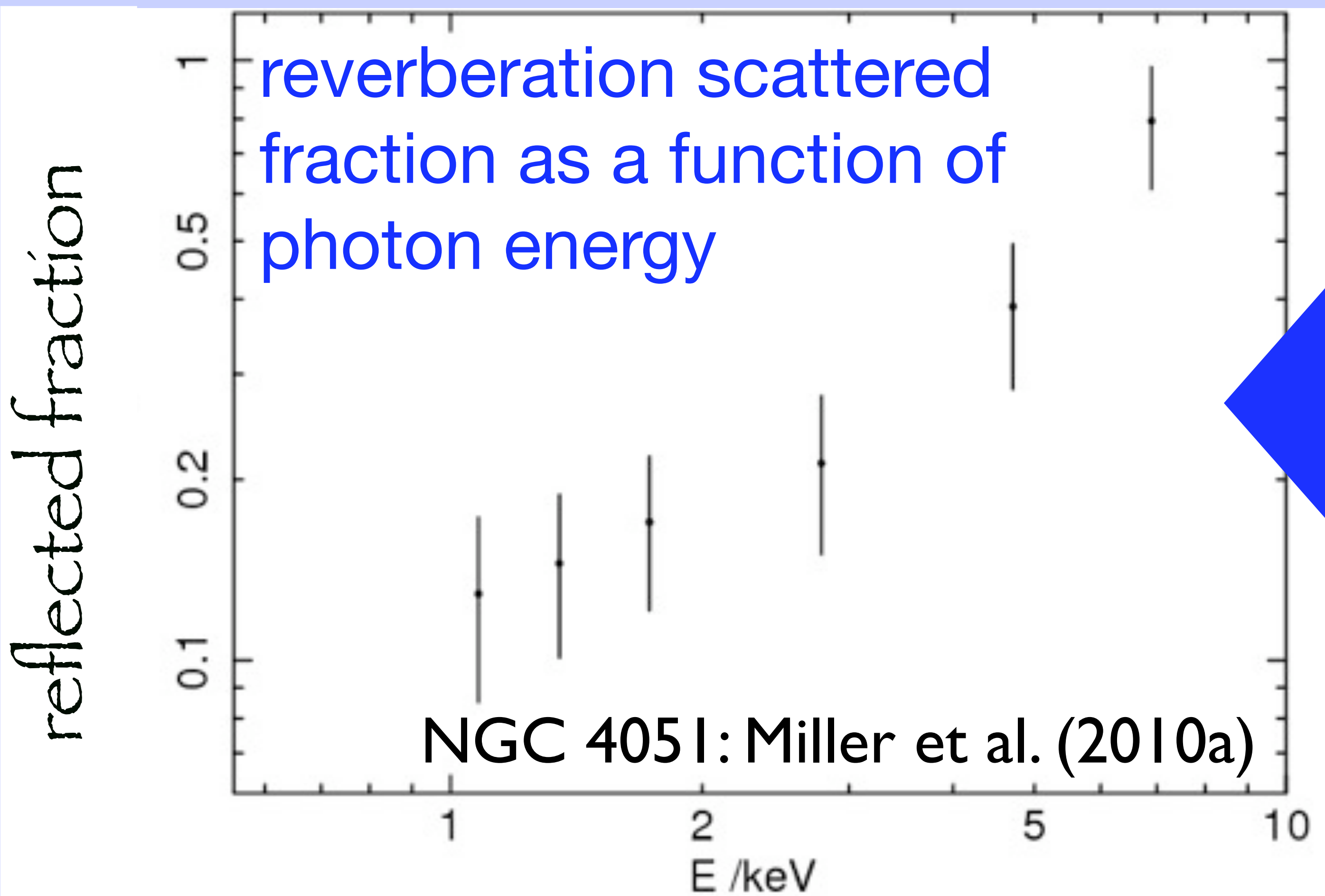
- Lags known for 10 years but not previously recognized as reverberation
- Primarily detected in highly-variable NLS1
- **Dependence on frequency as expected from reverberation**

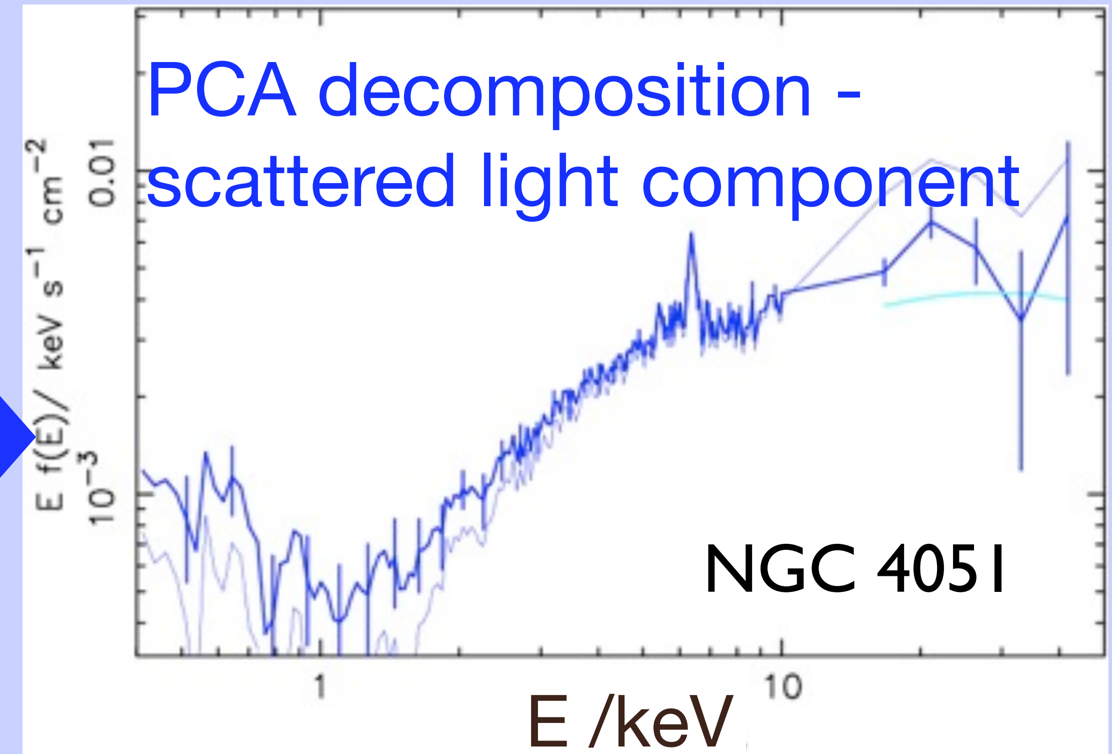


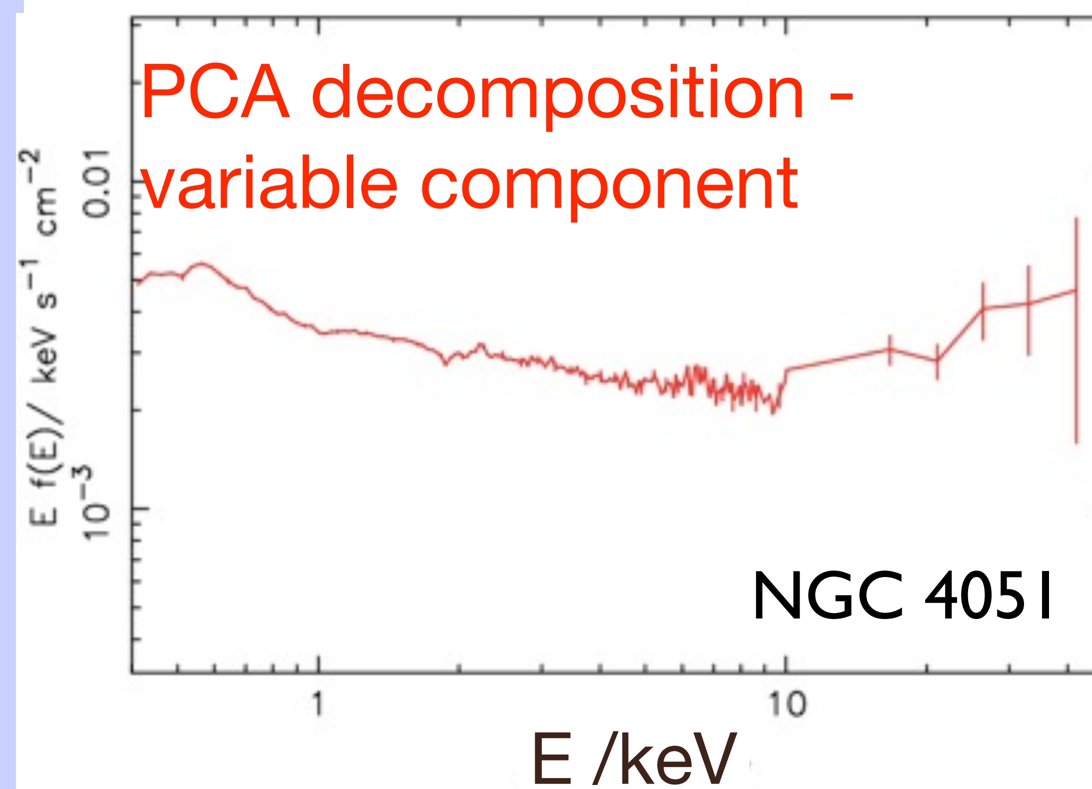


X-ray reverberation: energy dependence

Dependence on photon energy as expected from scattering by X-ray opaque material



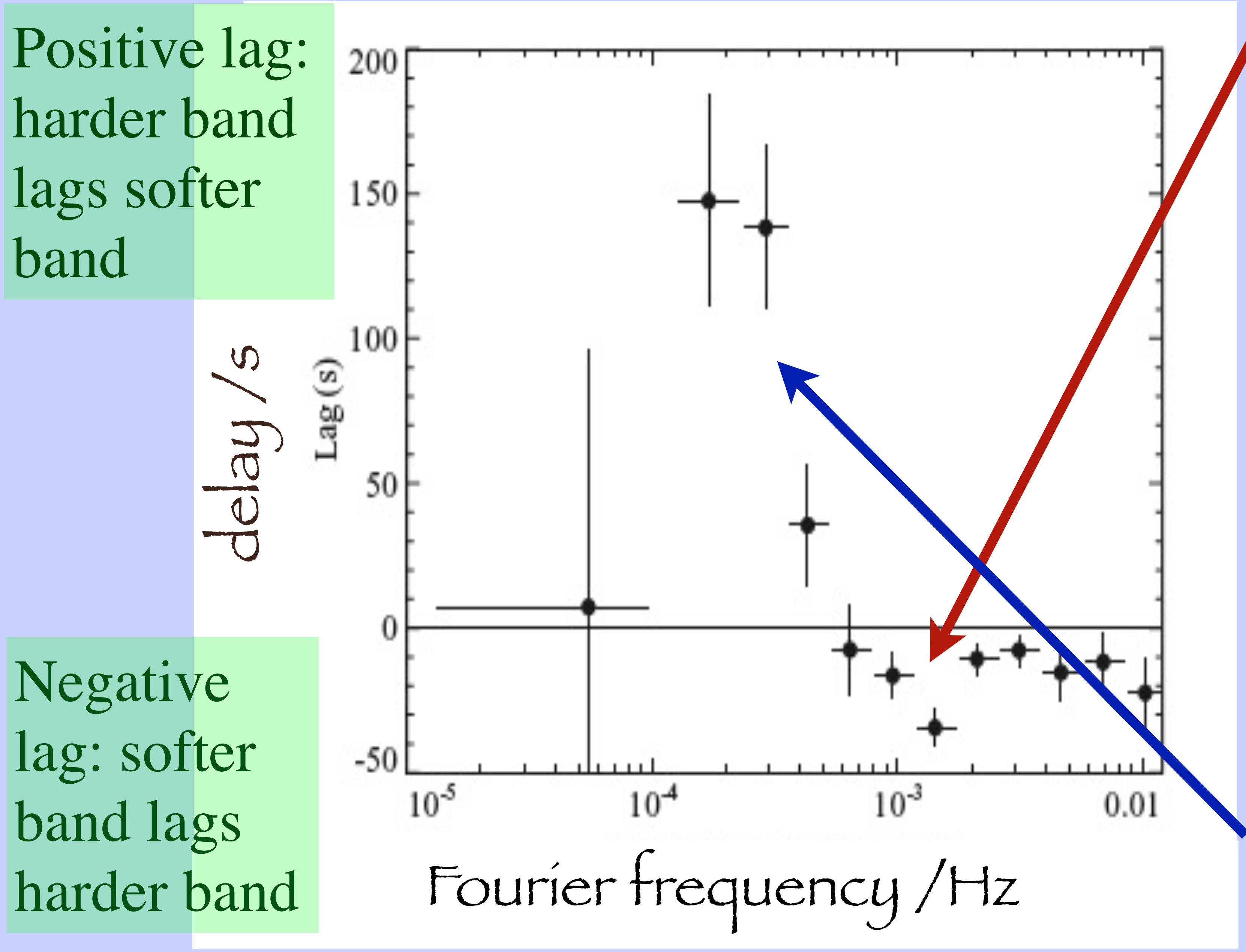




- lag times increase with the difference in photon energy of the bands being cross-correlated.
- compare the required reflection fractions with the "scattered-light" component seen in the spectral analysis (top right).

Time lags in 1H0707-495

Fabian et al. (2009); Zoghbi et al. (2010, 2011)

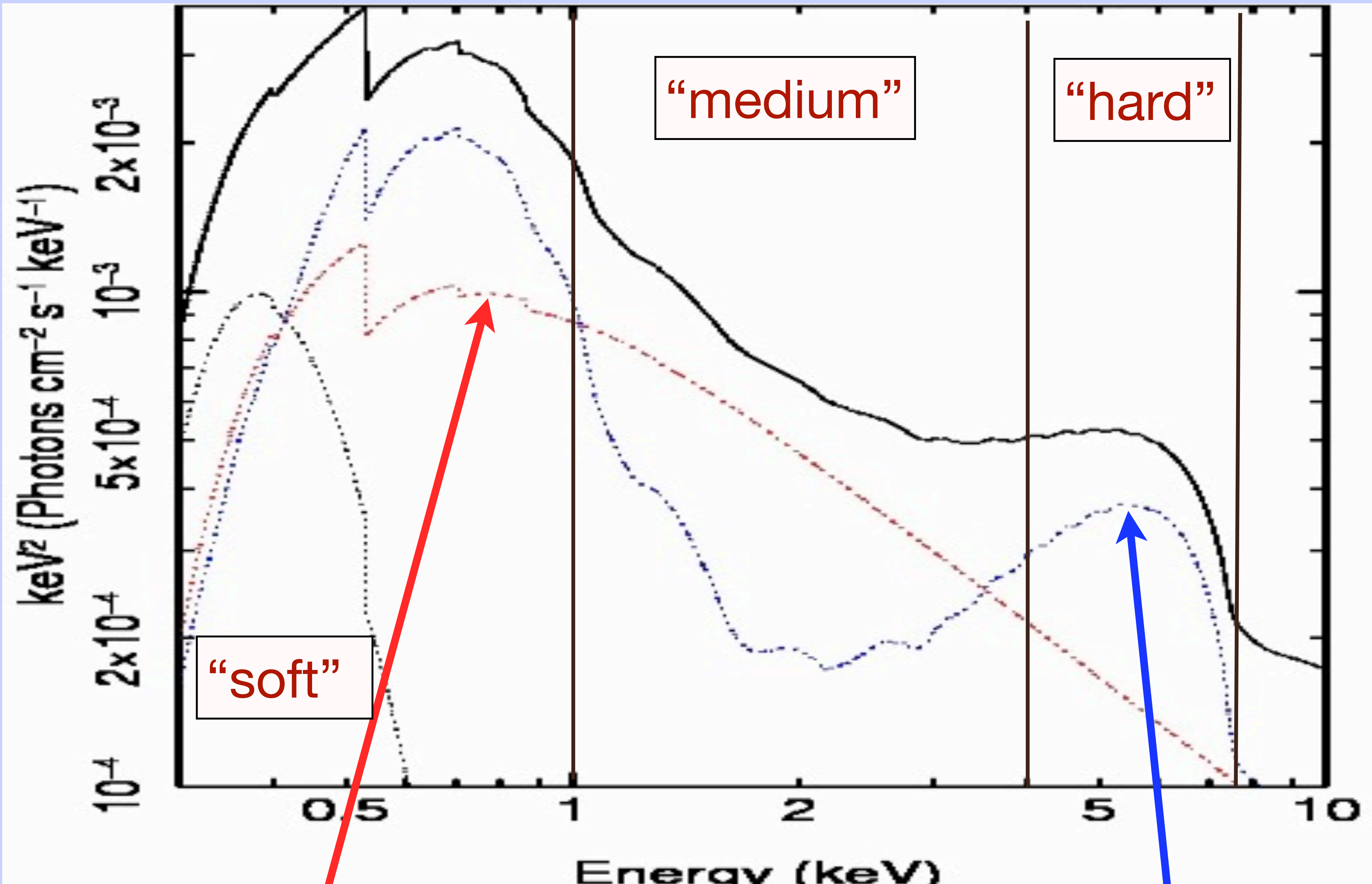


- Negative lags at high ν - ie SOFT band lags Medium band
- Claimed to indicate that soft band contains significant reflection, supposed to arise from strong Fe L-shell line emission at ~0.9 keV from reflector few 10s light-s away
- "Relativistic blurring" spectral model fit requires strong GR blurring r_{in}=1.23 r_g emissivity ~ r^{-7}
- Positive lags at low frequency attributed to different mechanism (see later)

lags: "medium"1-4 keV v. "soft" 0.3-1 keV

Zoghbi et al. 2010 model (Z10)

reflection fractions: fsoft = 1.60 fmed = 0.57 fhard = 2.03

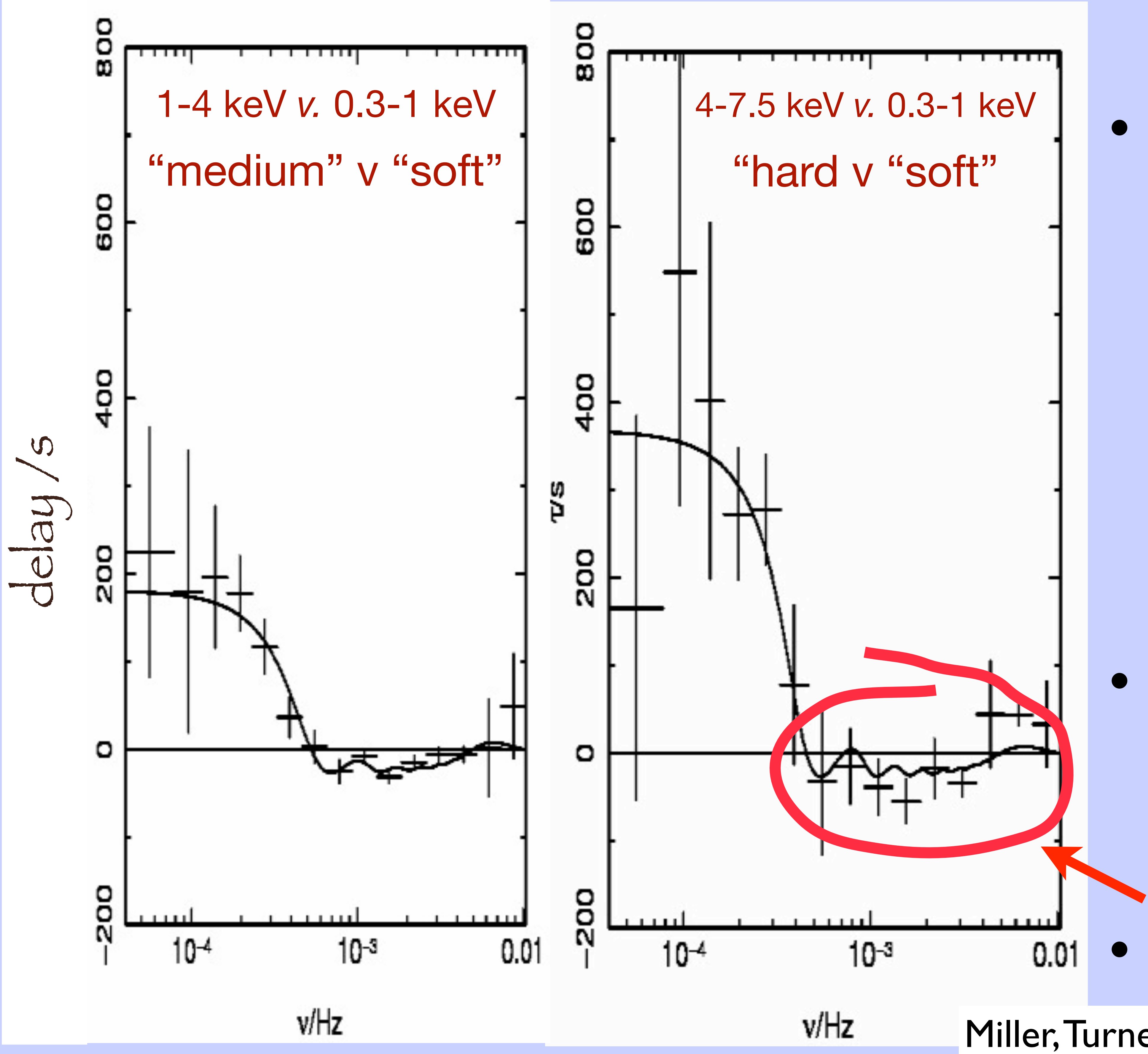


also requires Fe abundance x9

"direct" component "blurred reflection" component

- In this blurred reflection model, **hard (FeK) band has most reflection**, then soft band, then medium band

New measurements of 1H0707-495



- From the Z10 spectral model, the hard 4-7.5 keV band should contain larger fraction of reflection than the softer bands and hence should be the most lagged.
- High ν lags should be positive if Zoghbi et al are correct.
- They are not!

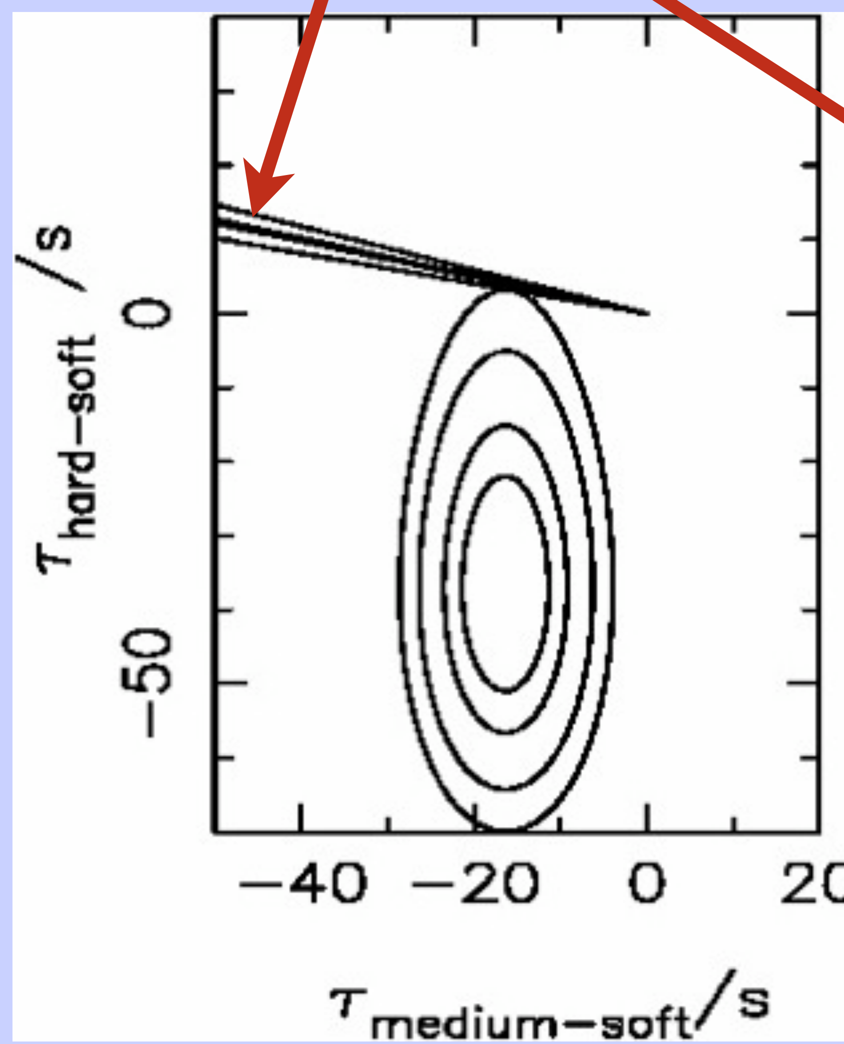
Miller, Turner, Reeves & Braito, 2010

Confidence Regions for the Lags

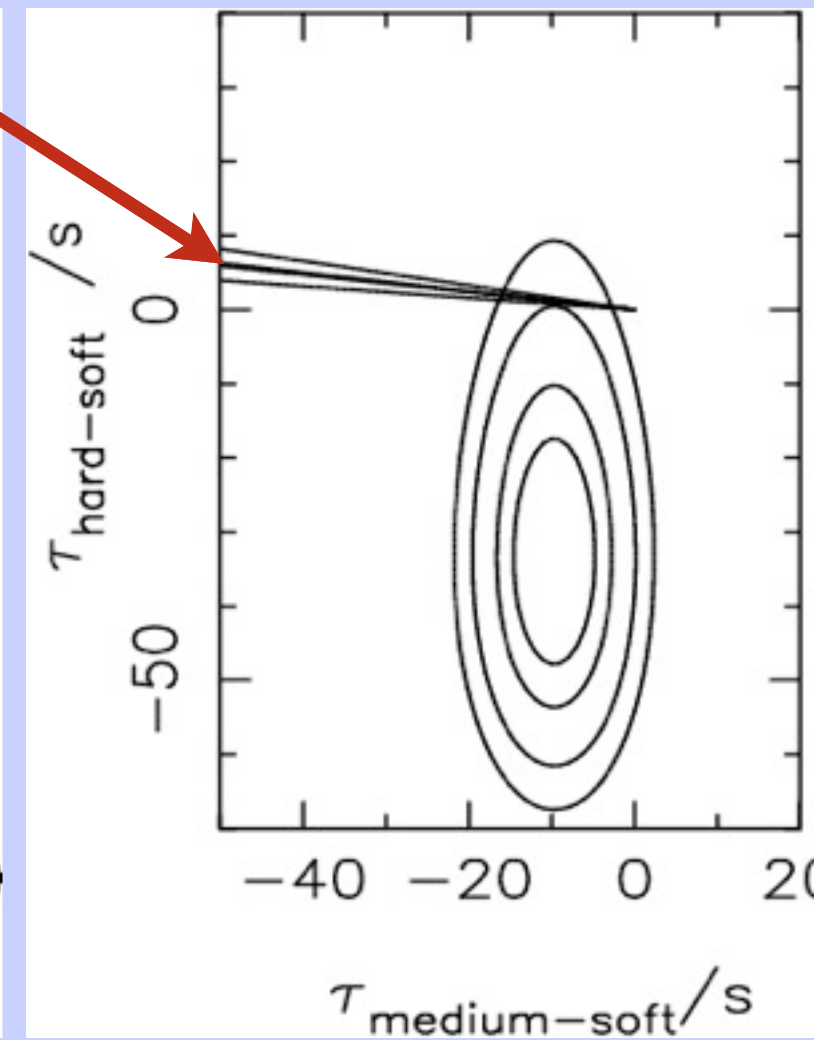
Z10, Z11 model predictions (lines show estimate of spectral model uncertainty)

68%, 90%, 99%, 99.9% confidence contours

- Lag constraints from the full high-state data set
- Z10 spectral model lies outside the 99.9% confidence region.
- Revised Z11 spectral model outside 99% confidence region.



Z10 model

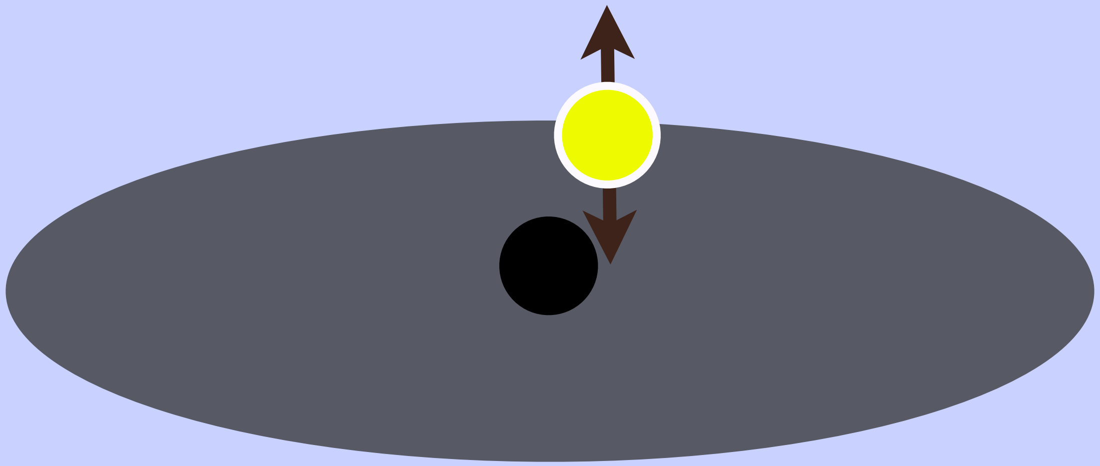


Z11 model (with black body also reverberating)

Miller, Turner, Reeves & Braito, 2010

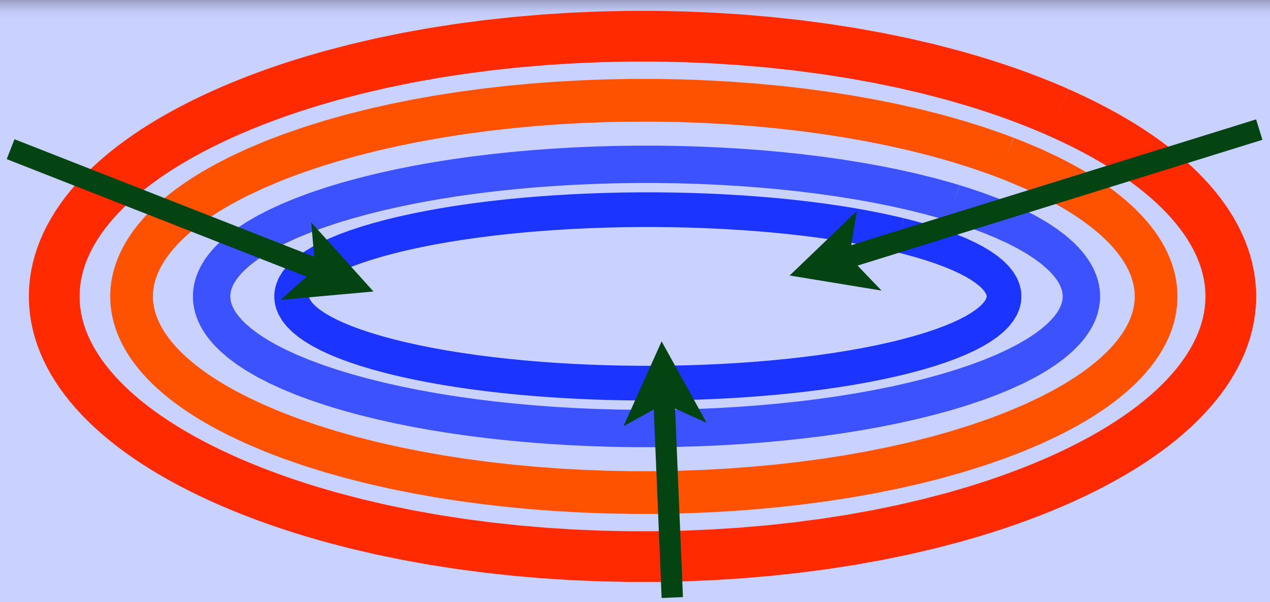
problems with light bending

- light-bending model was **invented to fix the problems of the relativistic-blurred models** (R>>1, $\varepsilon \sim r^{-7}$, lack of response of line to continuum).
- requires a small source close to the black hole (~1 rg) moving vertically up and down (mechanism?).
- no a priori expectation of this.



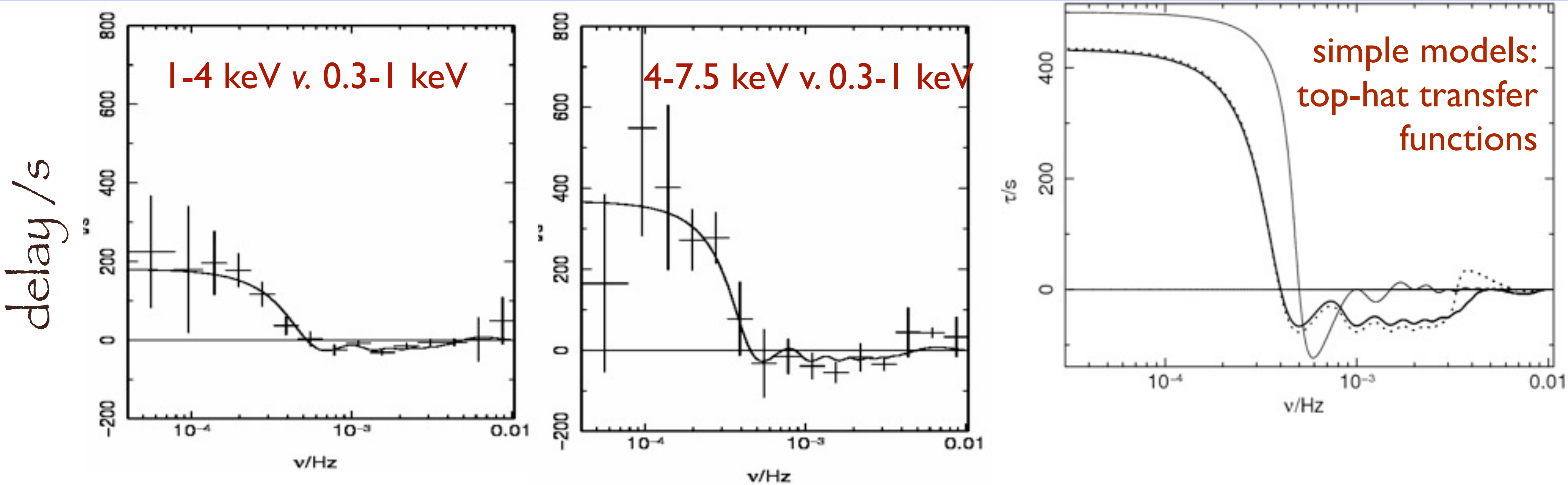
where is the continuum source and its variations produced? It can't be both in the accretion disk and in the "lamp-post" source.

positive lags from fluctuations propagating inwards over the surface of the accretion disk from soft to hard regions?



X-ray reverberation: 1H0707-495

Miller, Turner, Reeves & Braito 2010



- (over-)simple top-hat reverberation transfer functions easily fit lag spectra
- Size of the reverberating region ~2000 light-seconds
  - 20-100r_g if $M_{BH} = 10^7 M_\odot$ (Leighly 2004) or 2×10^6 $M_\odot$(Zoghbi et al 2010)
- The soft band also needs time lag ~150s coupled with 2000s hard-band lags
  - no requirement for reflection physically close to the BH
  - difference between hard & soft caused by energy-dependent opacity
  - the hard-band FeK region cannot be dominated by short timescale lags
  - short lags may also arise in transfer function of primary source

Summary

- **Reverberation predicts clear signatures in Fourier lag spectra which are observed in both optical and X-ray AGN/NLS1 time series.**
- We see both the expected **frequency behaviour** and **energy behaviour** in X-ray data.
- **X-ray reverberation places gas 10s - 100s r_g from central source.**
- Simple X-ray reverberation explains BOTH small negative lags and large positive lags with a **single, simple physical model.**
- Next aim to measure time lags in Sim et al radiative transfer code.
- We are not seeing a naked accretion disk. Both **timing** and **spectroscopic** results independently show that X-rays are reprocessed by large amounts of circumnuclear gas with high global covering, >40 percent, often seen in absorption, likely outflowing (see *Jane Turner*'s talk).