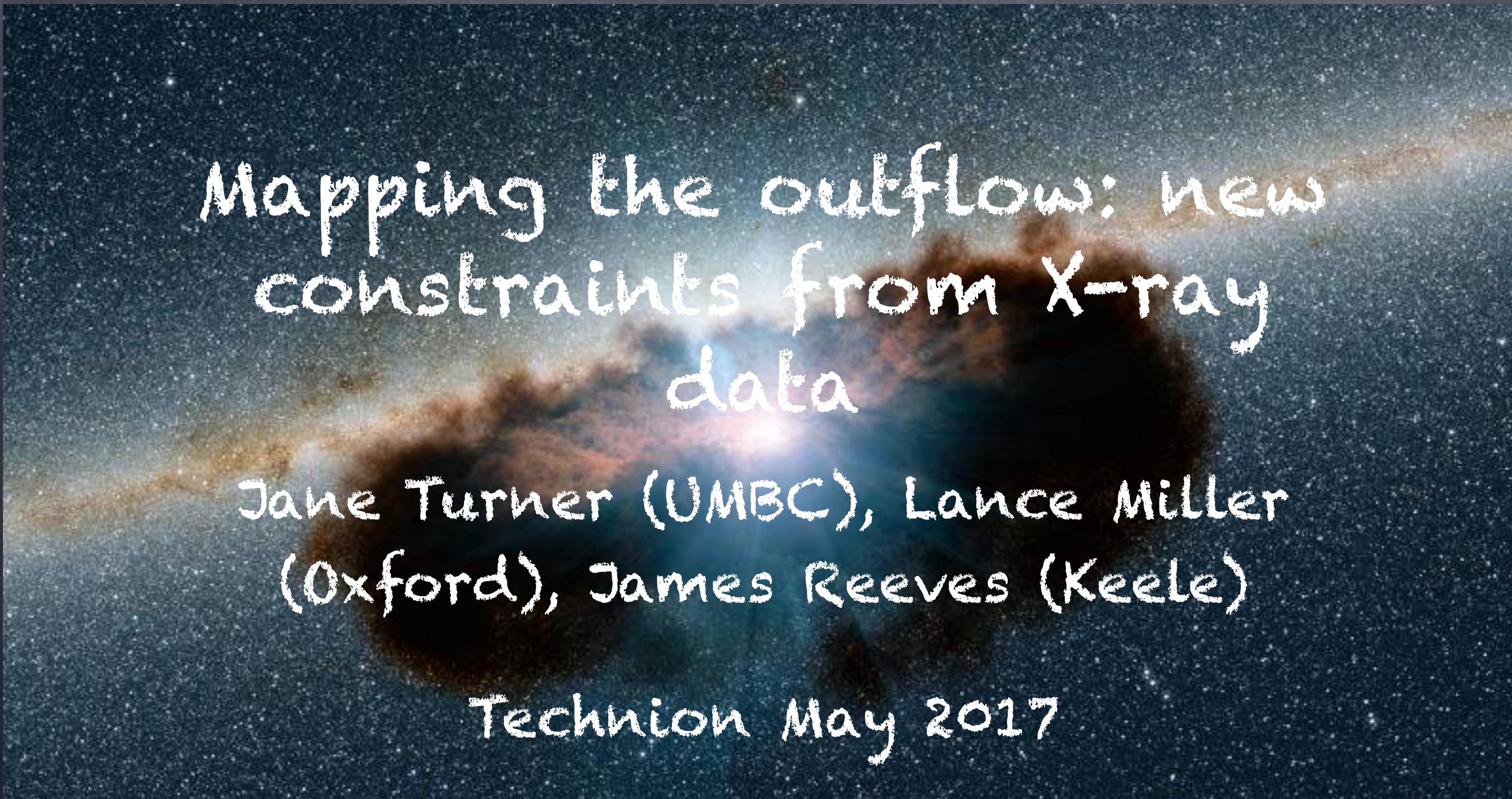
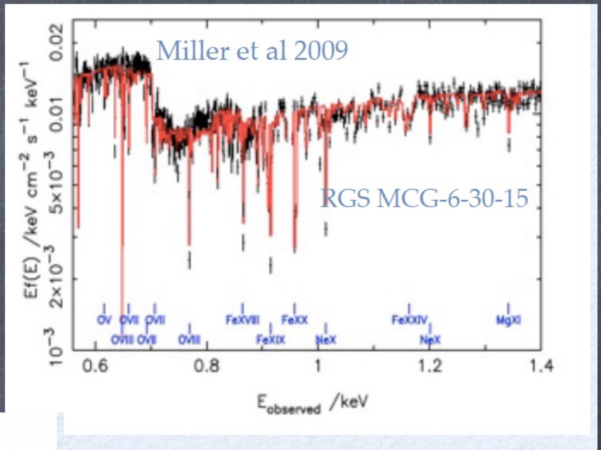


Mapping the outflow: new constraints from X-ray data

Jane Turner (UMBC), Lance Miller (Oxford), James Reeves (Keele)

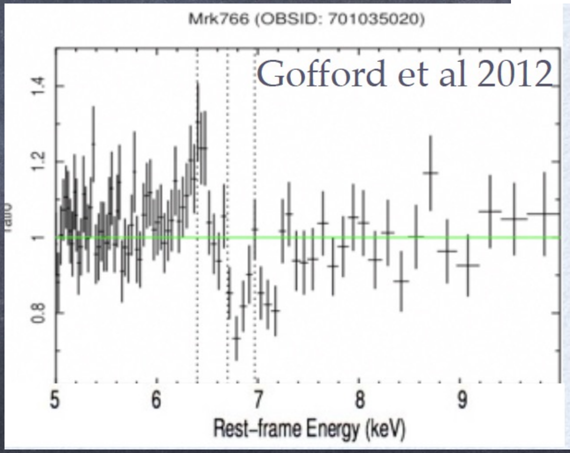
Technion May 2017

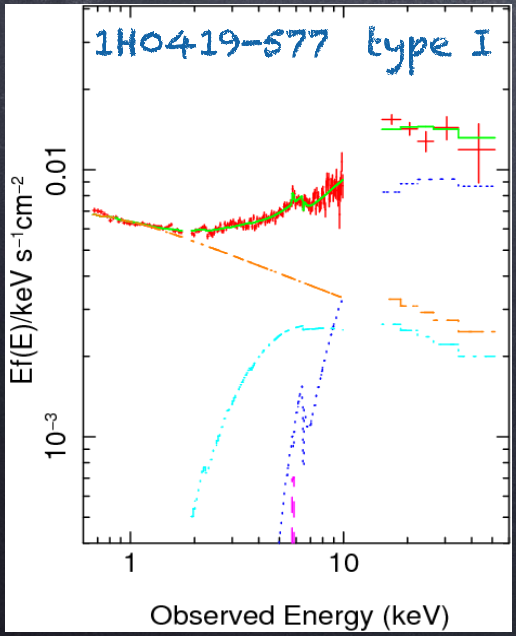
X-ray spectra – lots of evidence for outflowing reprocessor



Broad range N_H, ξ and velocity

Blue-shifted absorption lines, 100's km/s – fraction of c (talks by Reeves & Tombesi)



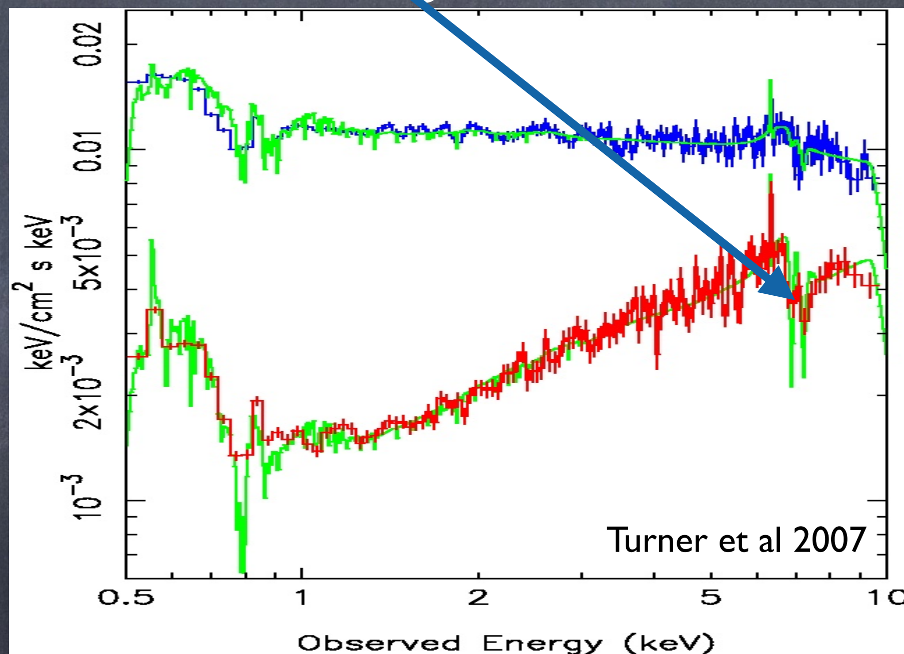


...extending to CT clumps, e.g. Turner et al 2009, Tatum et al 2013, 2016

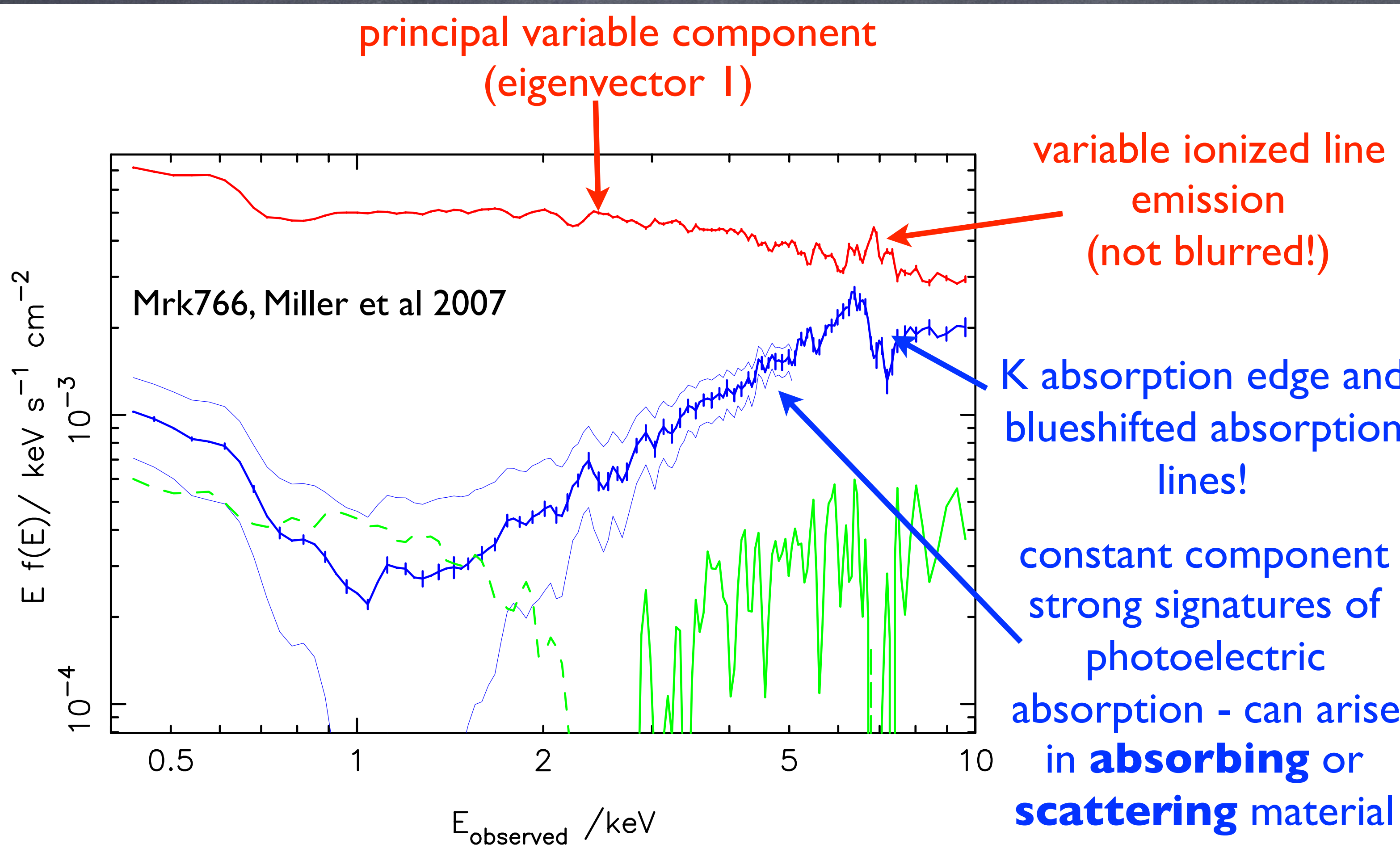
Variable covering absorption

- May explain general shapes of AGN spectra and big flux variations in AGN (e.g. Boller et al 1997, 2002) and Galactic BH (e.g. Dower, Bradt, Morgan 1982, Brandt et al 1996, Tanaka, Ueda and Boller 2003)
- A source of variability in some AGN on days (e.g. MCG-6-30-15 McKernan et al 1998; NGC 3516 Turner et al 2008)

Mrk 766: blue shifted absorption lines - wind signature

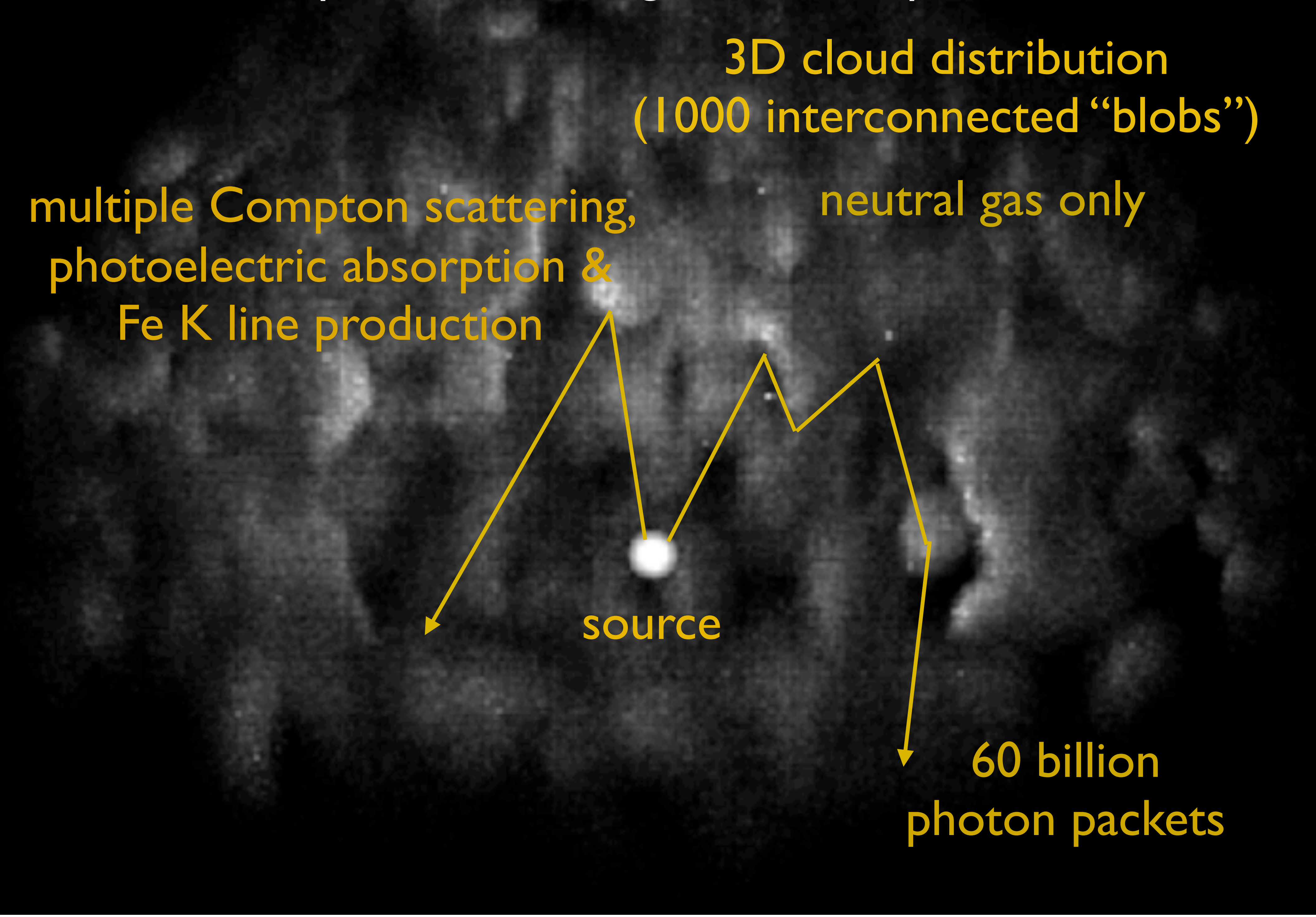


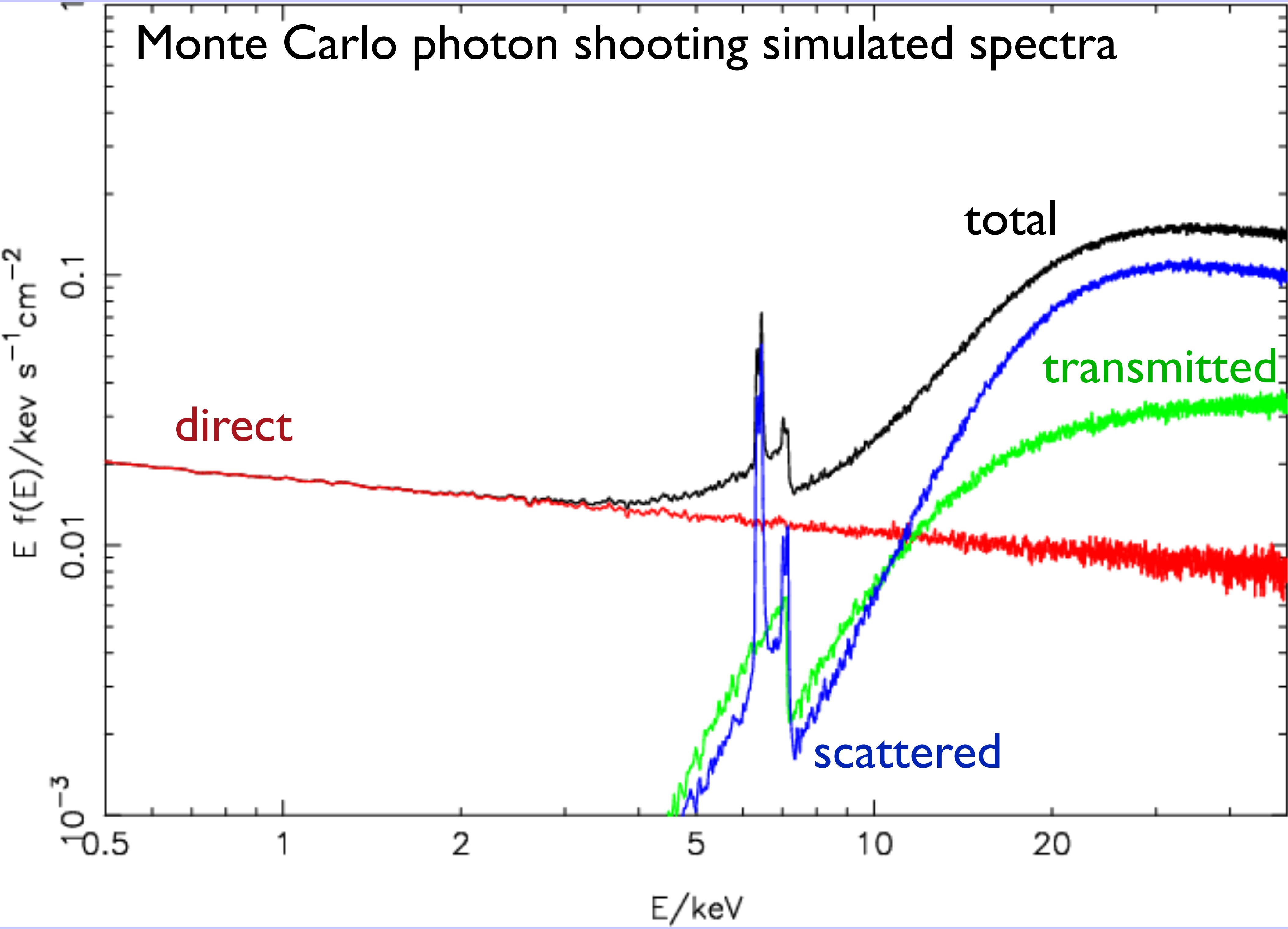
Spectral Variability



very common spectrum variability modes - see also MCG-6-30-15 (Miller et al 2008, 2009), NGC 4051 (Miller et al 2010) etc

Monte Carlo photon shooting simulated spectra



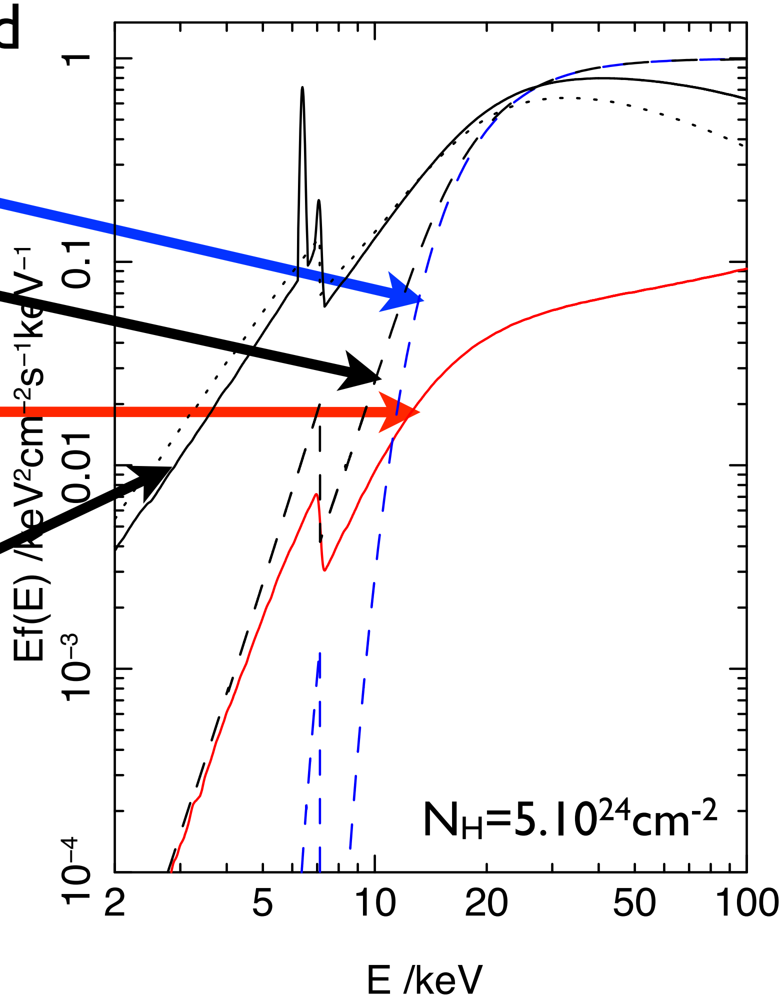


Monte Carlo photon shooting simulated spectra
total
transmitted
direct
scattered
E f(E)/kev s^-1cm^-2
1
0.1
0.01
10^-3
0.5
1
2
5
10
20
E/keV

Spectral Models - the importance of geometry and Compton Scattering

Comparison of sphere and slab absorbers

- standard slab calculation
- calculation for sphere
- sphere including Compton scattering
- scattered light from sphere (scaled to full global covering)



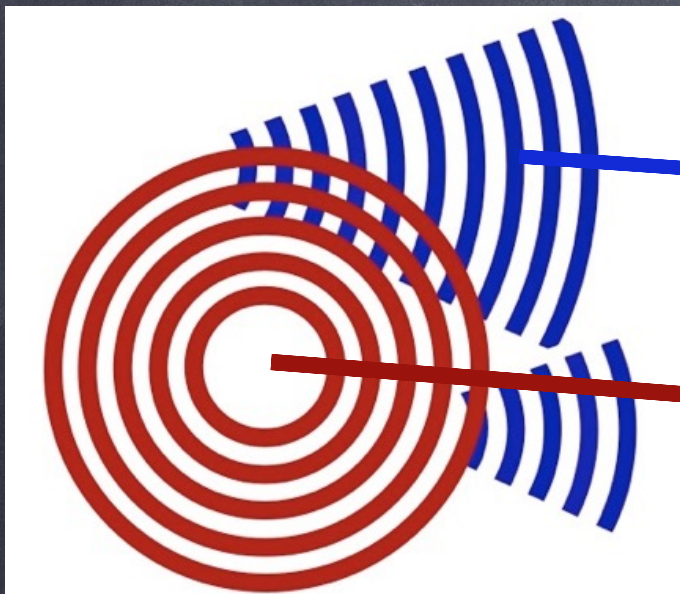
Do not use slab, non-scattering models for partial covering (e.g. Risaliti et al 2013) !!!

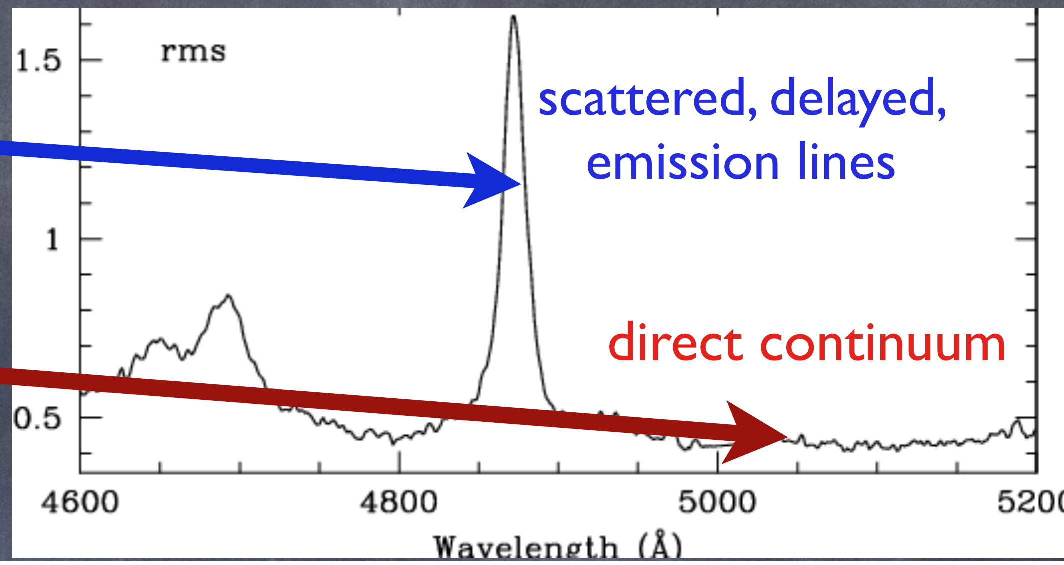
Miller & Turner 2013

X-ray evidence for wind from time lags

- Time lags between hard and soft X-ray photons known for ~25 years in Galactic sources and very common in AGN (e.g. DeMarco et al 2013, Kara et al 2016)
- Lags imply not all flux variations caused by absorption events… rapid (ks) events likely intrinsic… is this X-ray reverberation?
- What other explanations are there
  - Comptonization lags (hard photons undergo more scatterings than soft photons)
  - accretion disk fluctuations (only explains positive long timescale lag)
  - Inner disk - blurred reflection reveberation (only explains negative short timescale lag)

Reverberation

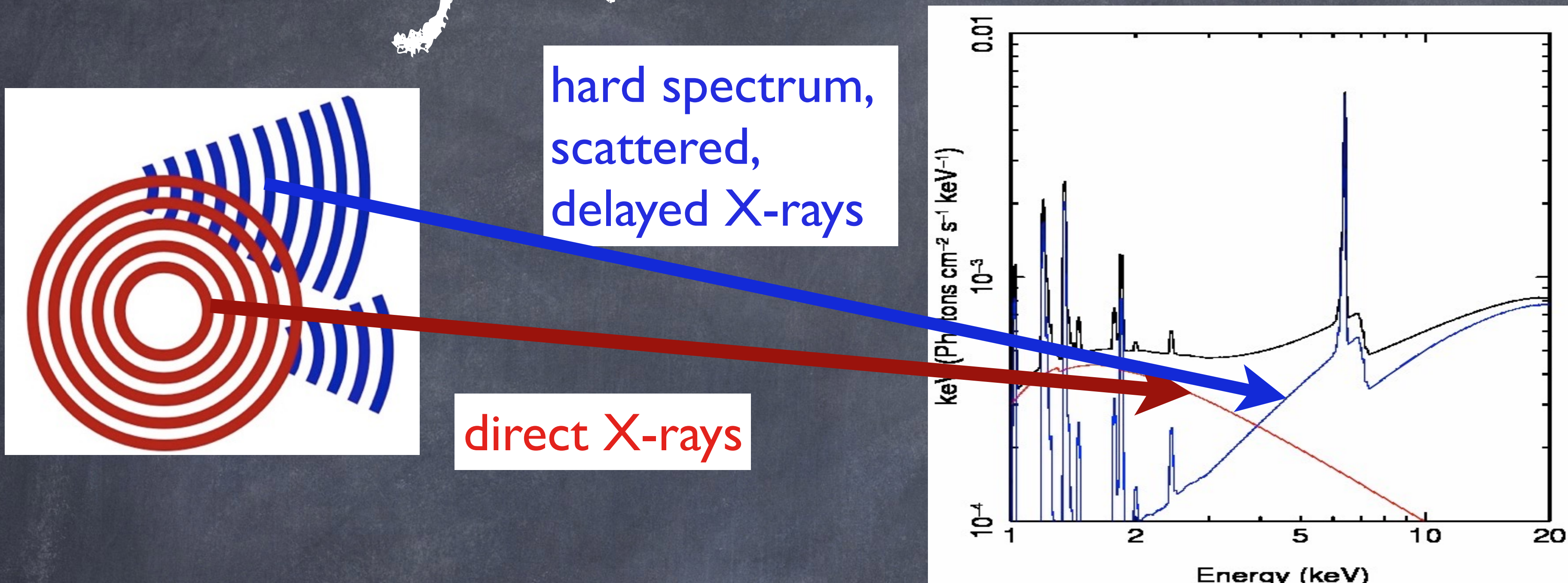




NGC 4051 optical: Denney et al 2009

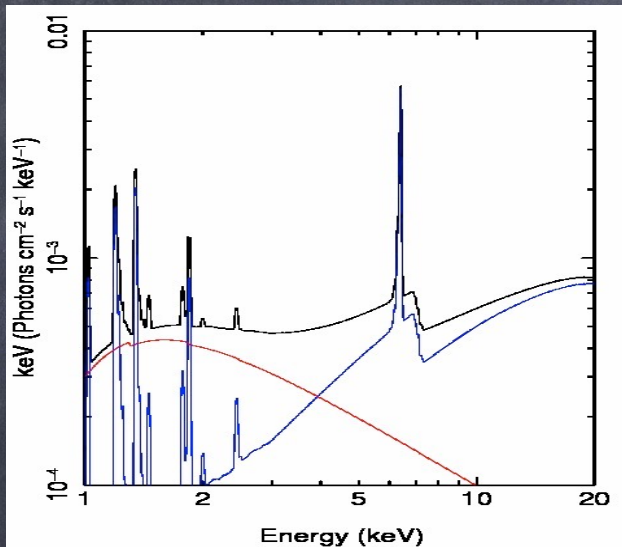
- Reverberation between optical/UV continuum and optical emission lines -principal method of BH mass measurement in AGN

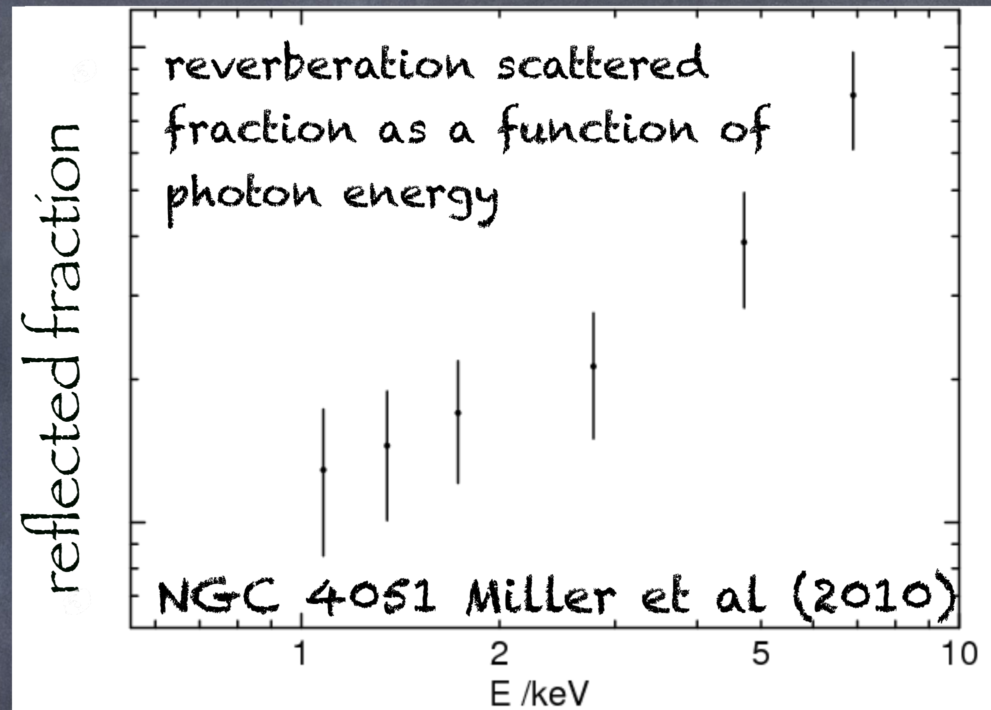
X-ray Reverberation



- 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





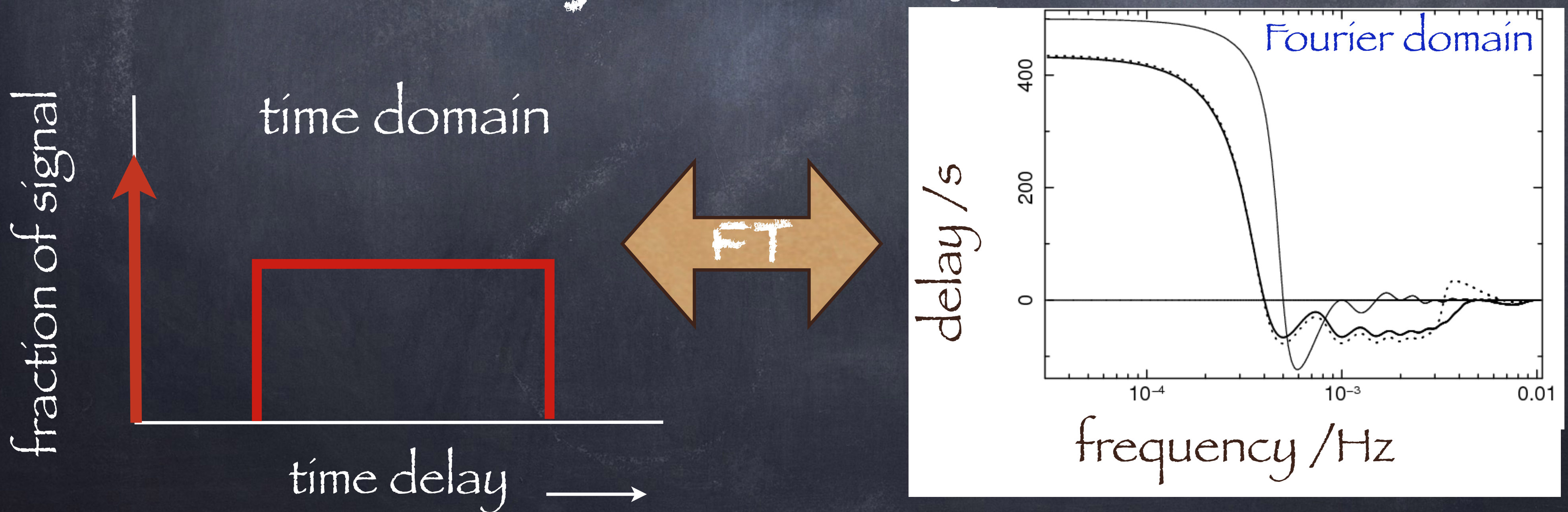
- Lag times increase with band separation
- dependence on photon energy as expected for scattering by X-ray opaque material

Gappy, noisy time series

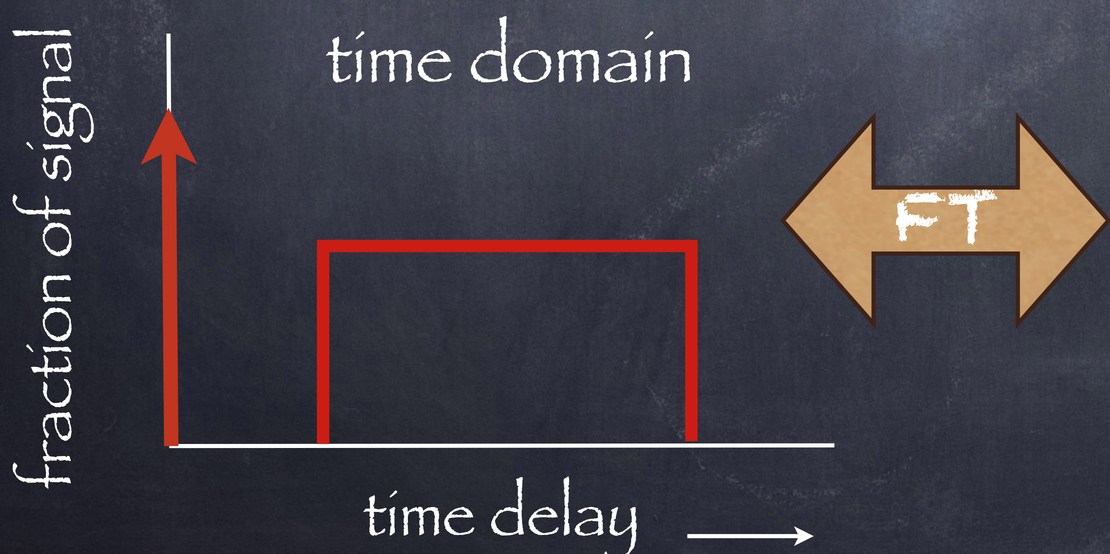
- Miller developed maximum likelihood analysis based on CMB methods
- No problem w/ gaps, accounts for shot noise, rigorous error estimation
- Only method that accounts for covariance in Fourier domain

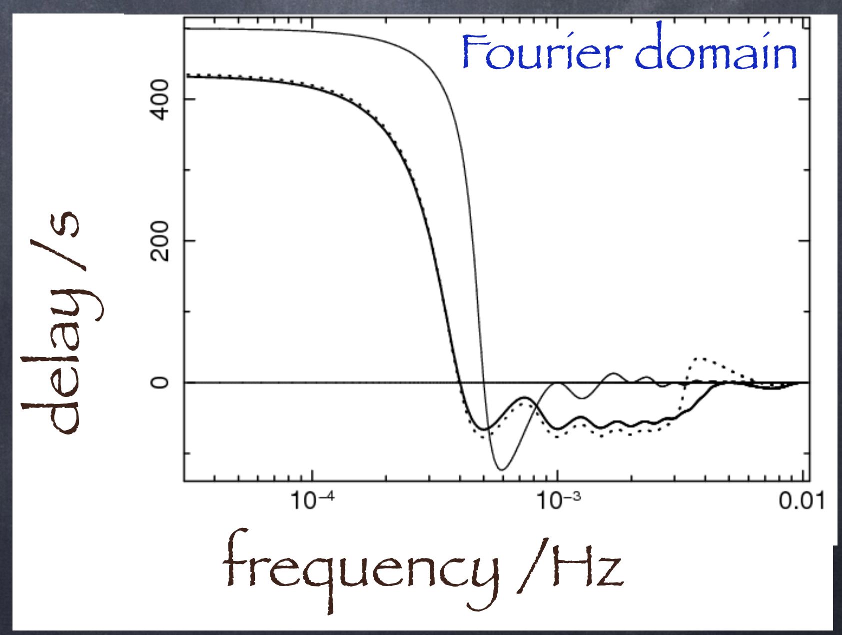
- Estimate cross-band power spectrum (max likelihood) -> time delay as function of source variations

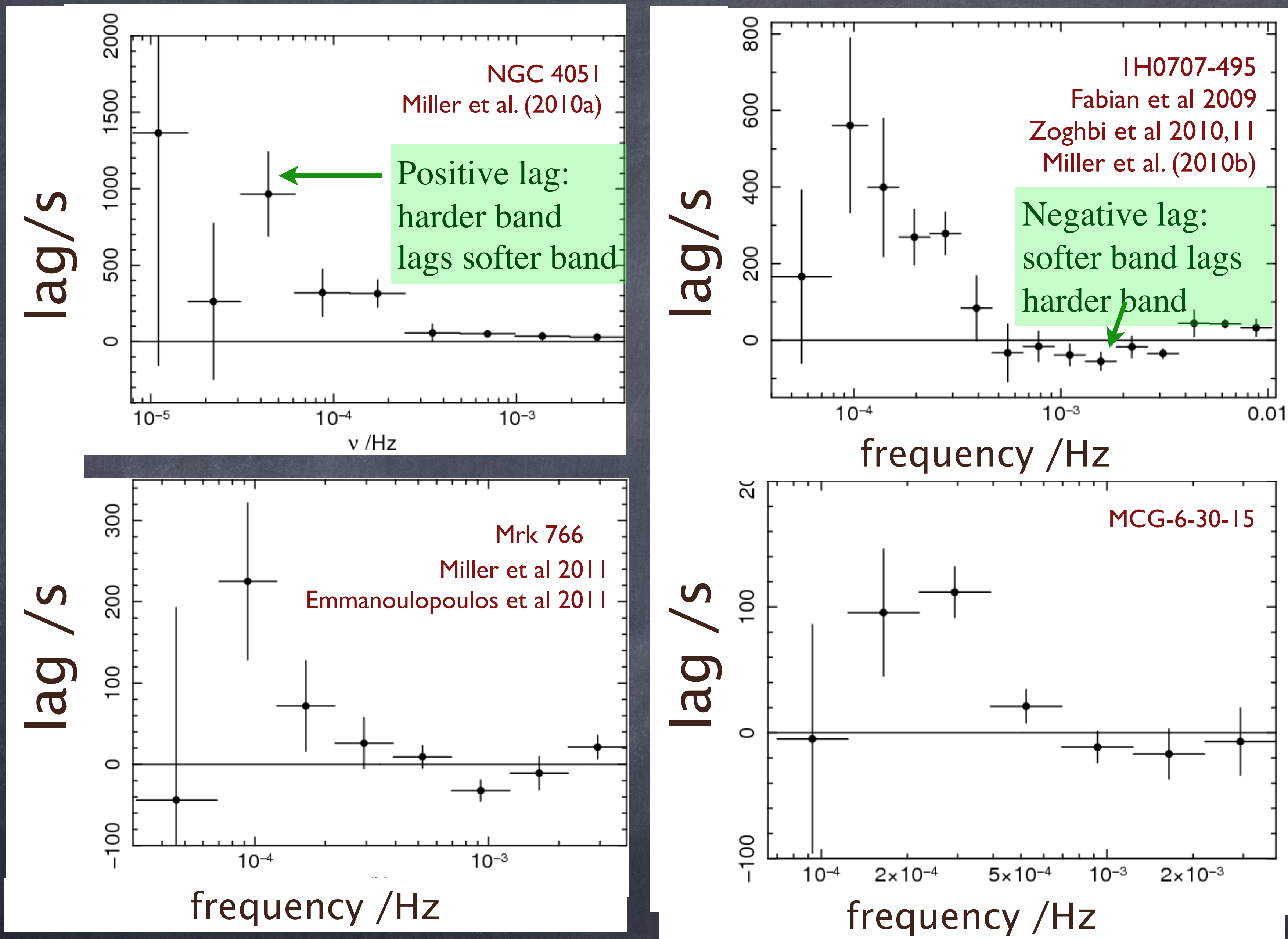
- Lag spectrum given by phases of Fourier transform of the transfer function which describes spread of time delays in the signal



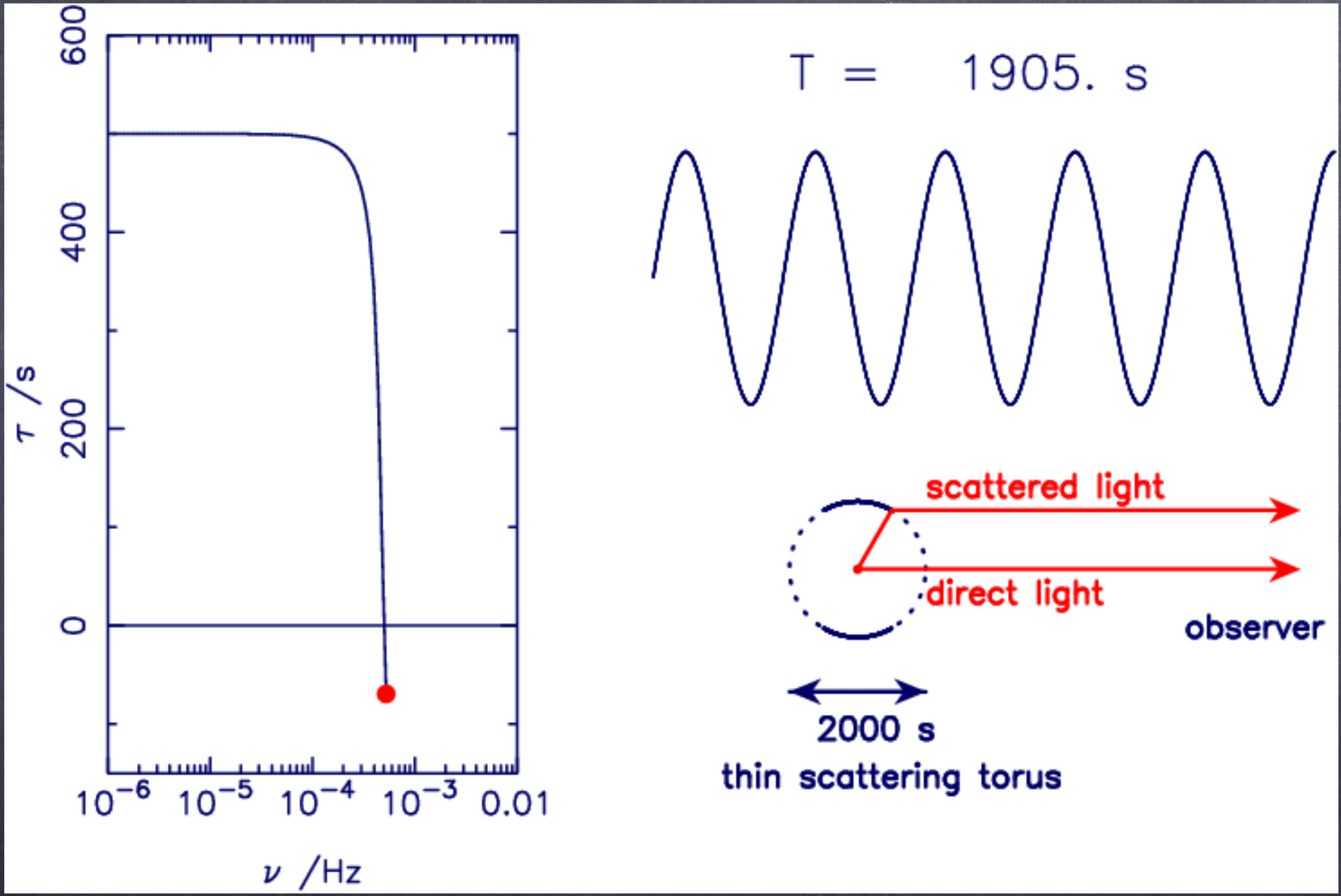
- Hard X-rays delayed wrt soft defined as positive lag
- Two ways to obtain negative lags (soft delayed wrt hard) from reverberation
  - either soft band also has delays OR
  - reprocessor is clumpy - negative lags arise from Fourier transform of transfer function



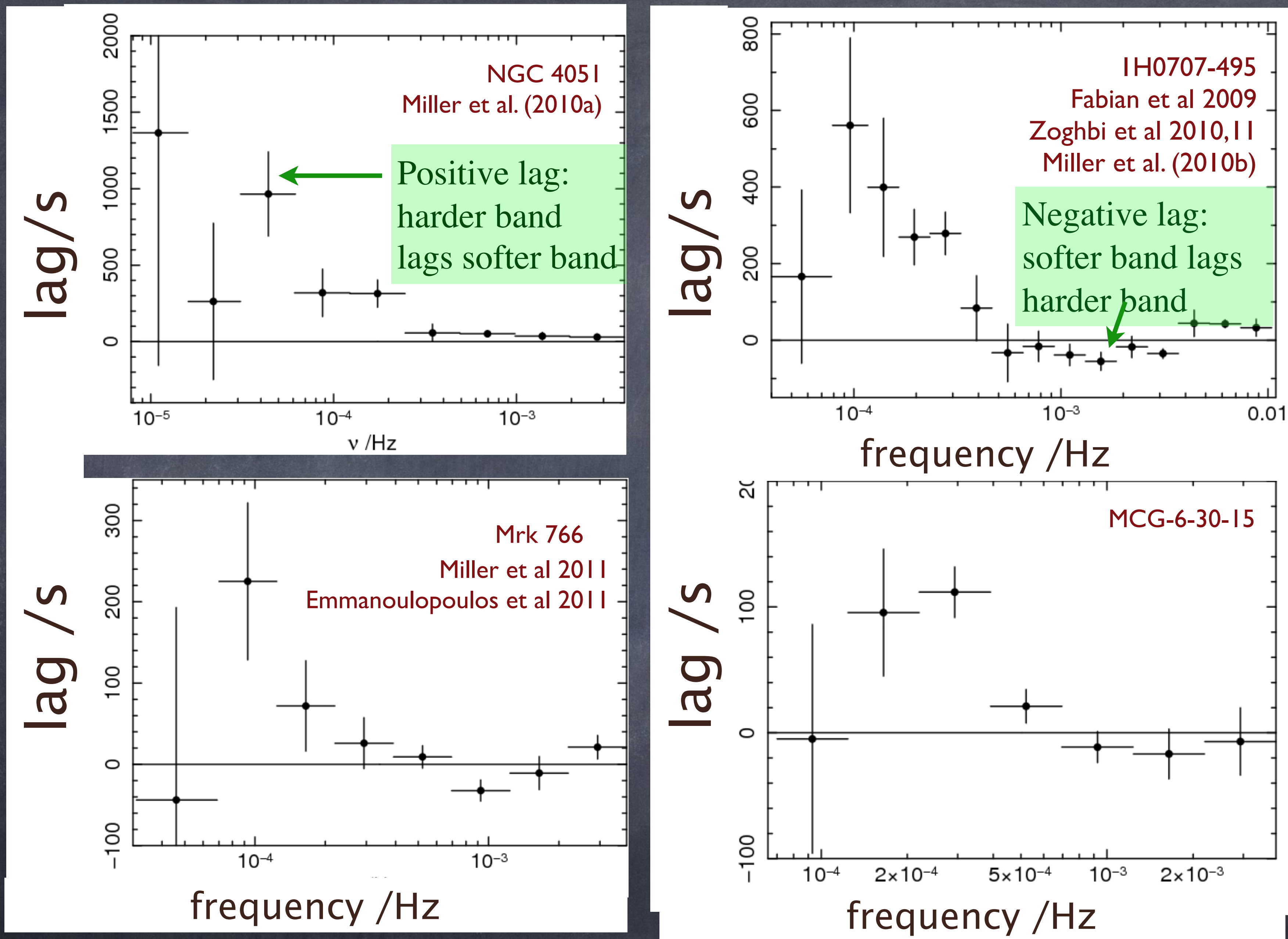




Hard lags known for 30 years but not recognized as reverberation



600
400
200
0
τ /s
10^−6 10^−5 10^−4 10^−3 0.01
ν /Hz
T = 1905. s
scattered light
direct light
observer
2000 s
thin scattering torus



Hard lags known for 30 years but not recognized as reverberation

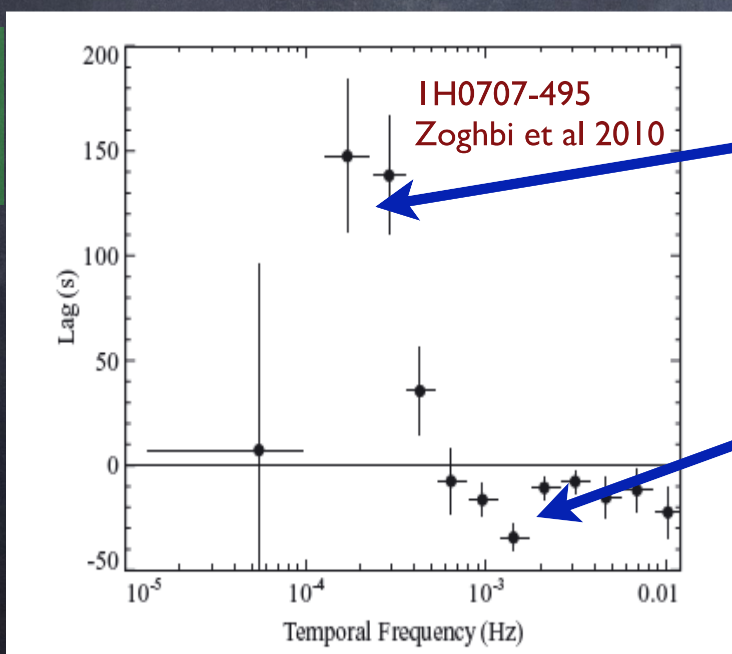
Other assertions put forward

- fluctuations propagating over the accretion disk + reflection from the inner accretion disk (i.e. two mechanisms!) (Fabian et al 2009, Zoghbi et al 2010, 2011)

lags: “medium”1-4 keV v. “soft” 0.3-1 keV

Positive lag: harder band lags softer band

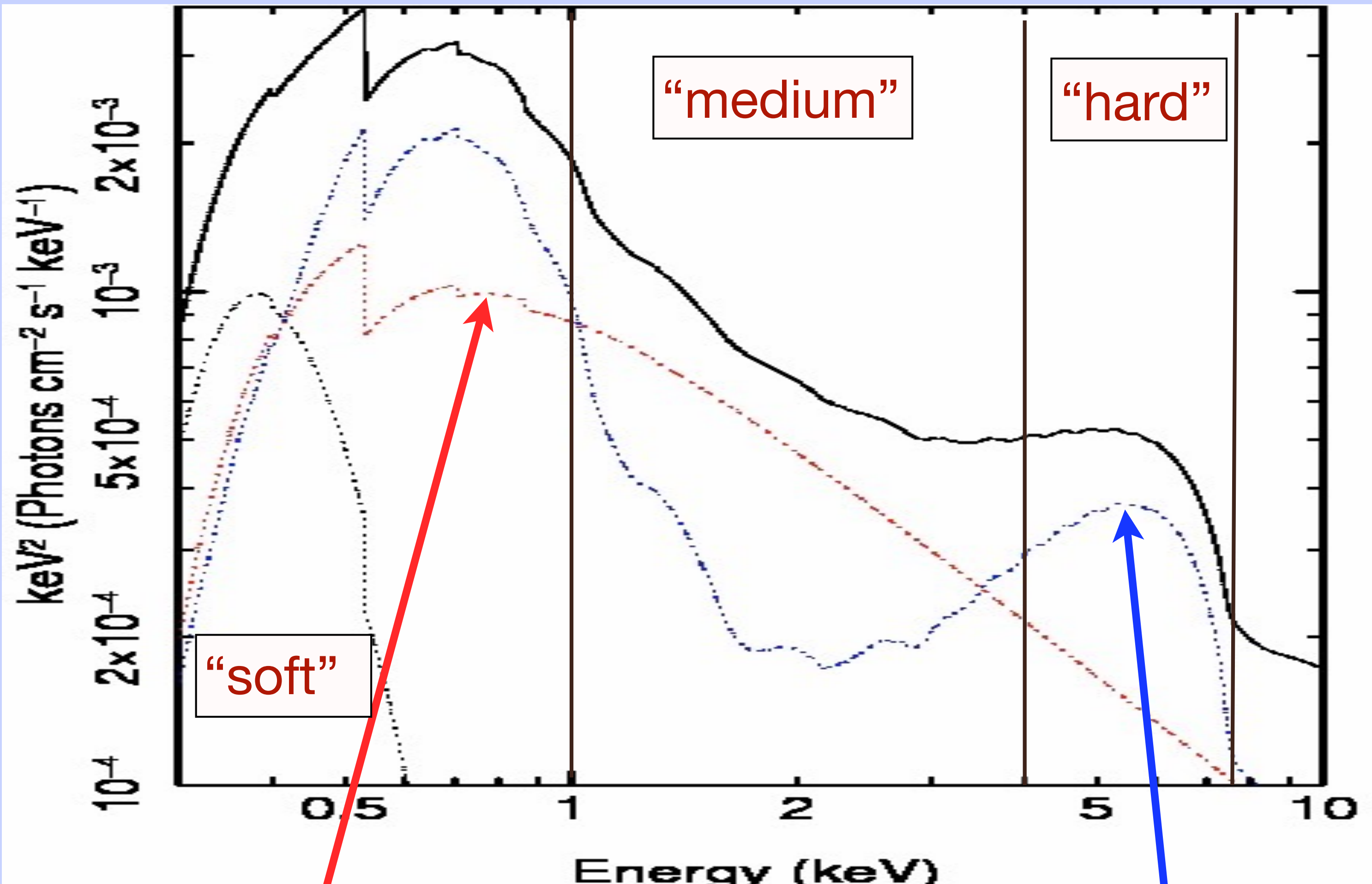
Negative lag: softer band lags harder band



- Positive lags at low frequency attributed to lags propagating over accretion disk
- Negative lags at high ν claimed to indicate soft band dominated by reflection because of strong Fe L emission from ~1 r_g, emissivity r^{-7}, 11x solar Fe, 5x Super Eddington

Zoghbi et al. 2010 model (Z10)

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

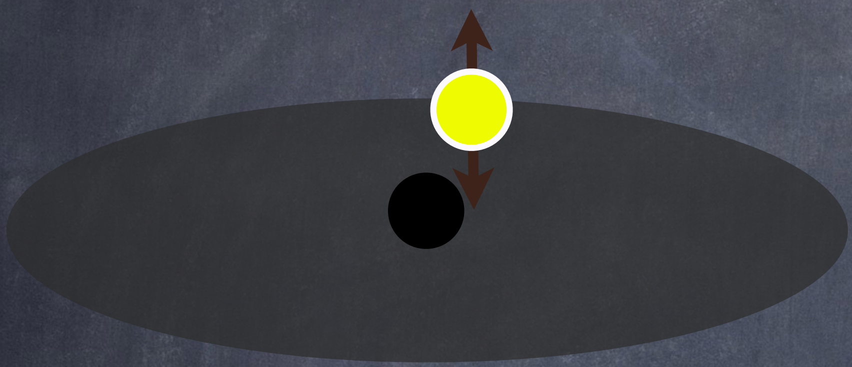


also requires Fe abundance x9

"direct" component "blurred reflection" component

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

Problems with light-bending models



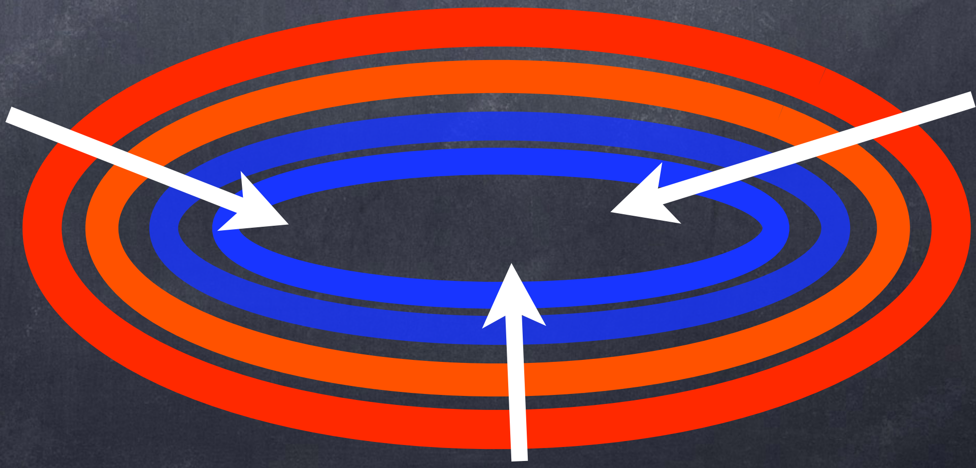
• light-bending model **invented to fix problems of the relativistic-blurred models** (R>>1, $\varepsilon \sim r^{-7}$, lack of response of line to continuum)

• requires small source close to black hole (~1 rg) moving vertically up and down (mechanism?)

• no a priori expectation of this

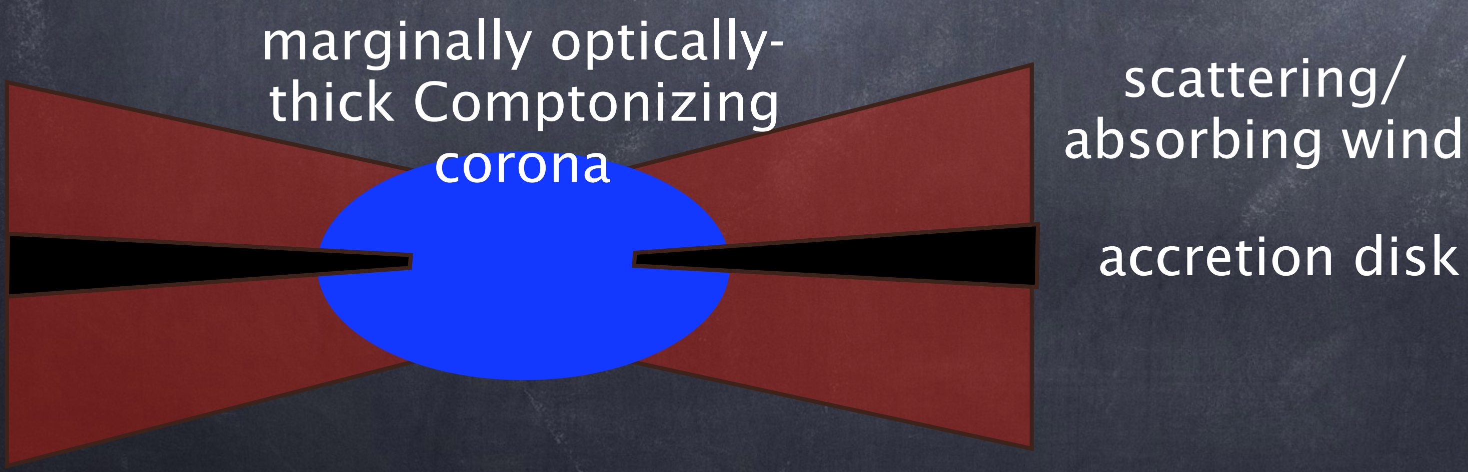
Where is the continuum source and its variations produced? It can't be both in the accretion disk and in the "lamp-post" source

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

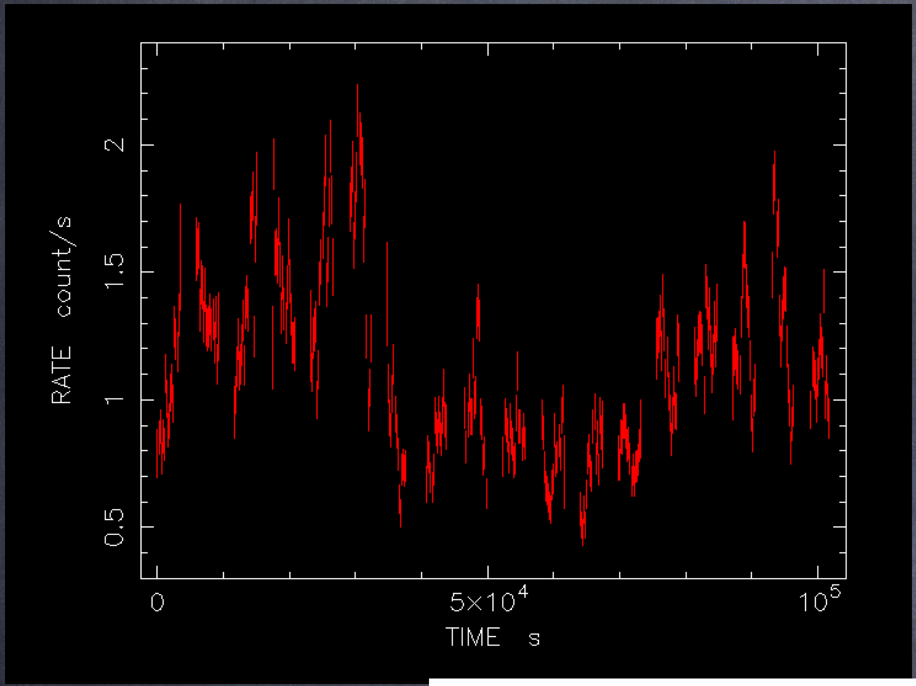


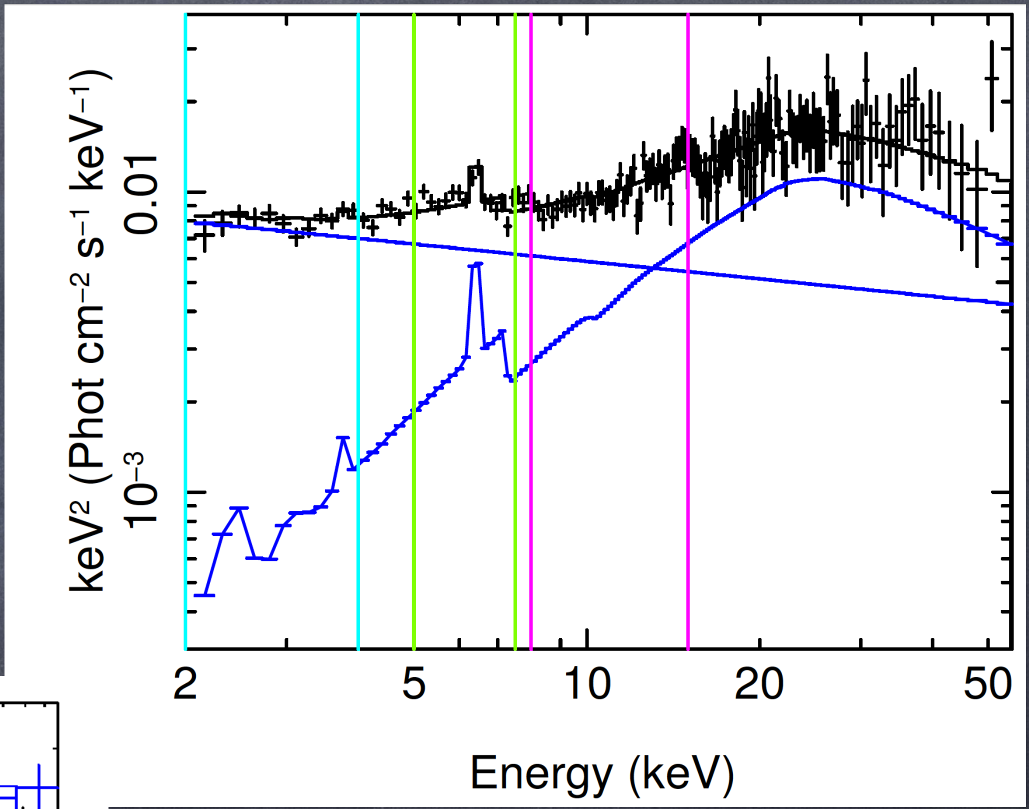
Comptonization models for lags

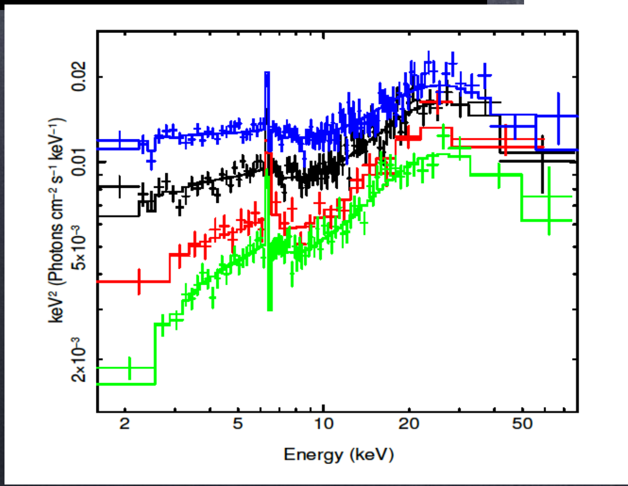
- Comptonization time delays - must be present at some level
  - >2ks timescale require would require very extended Comptonizing region
  - lack of dependence of cut-off frequency on photon energy implies time delays determined by geometry
  - Comptonizing corona could be viewed as a unified inner part of the wind



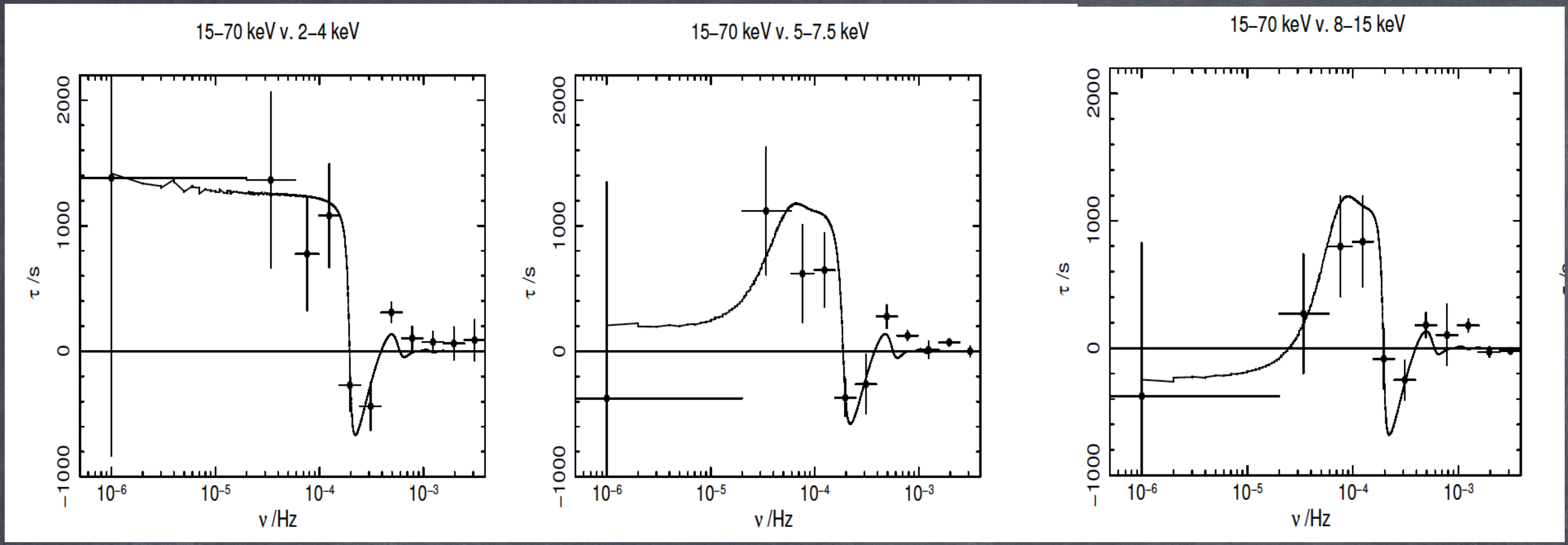
NuSTAR - NGC 4051



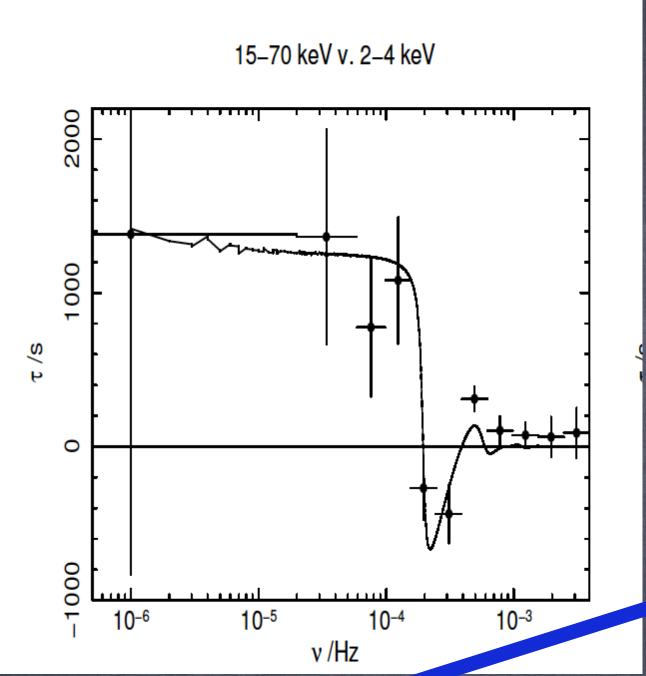


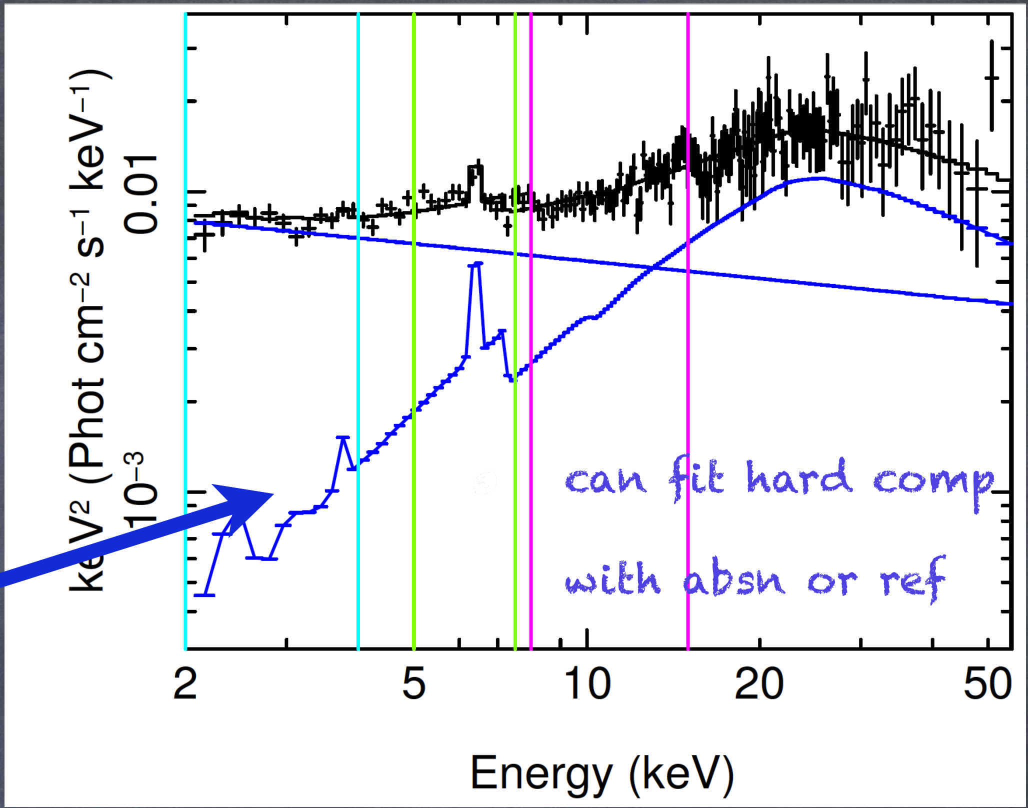


170 ks - 5 obs



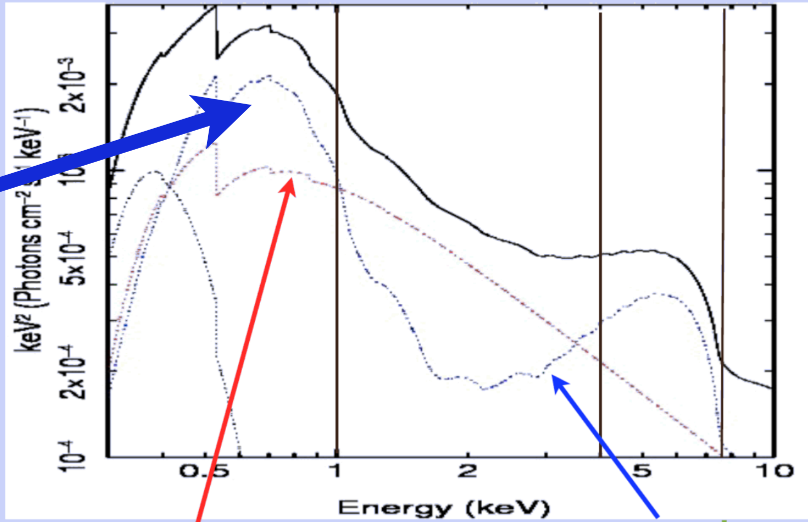
- large 15-70 keV lags at low ν
- negative lags ~400 s at 2×10^{-4} Hz
- negative lags cannot be due to anything specific to the soft band!



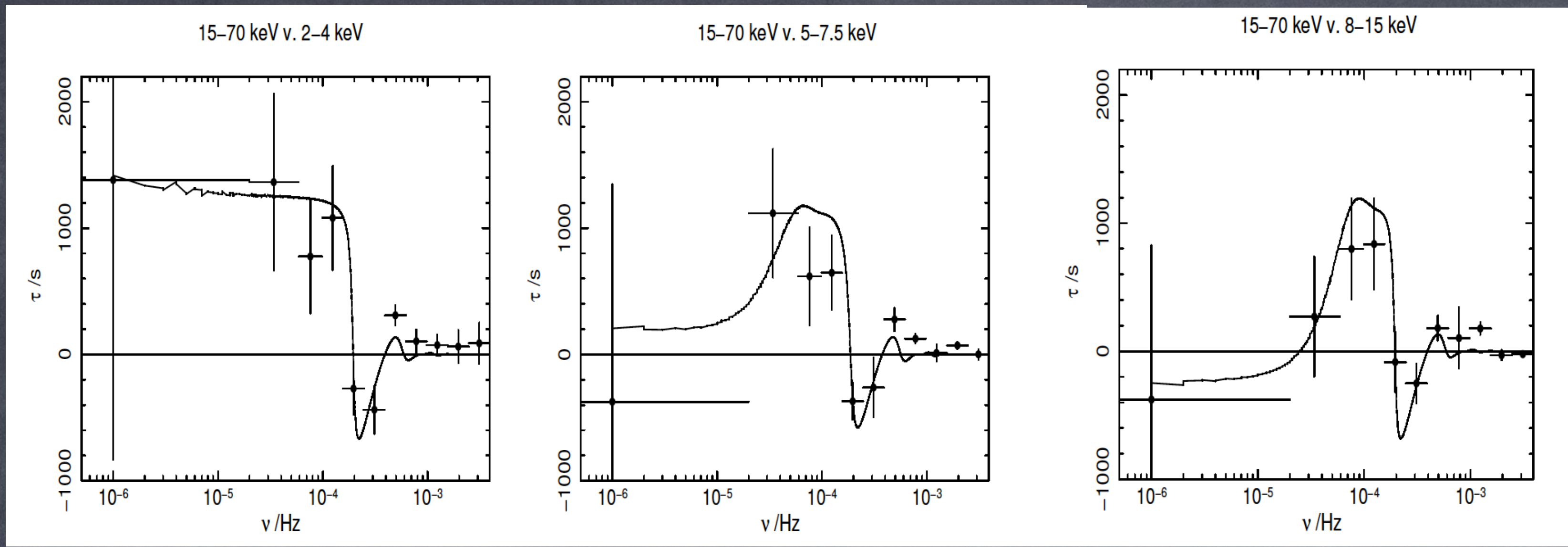


- Negative lag - but soft band has no reflected contribution

- (cf blurred ref model for 1H0707)

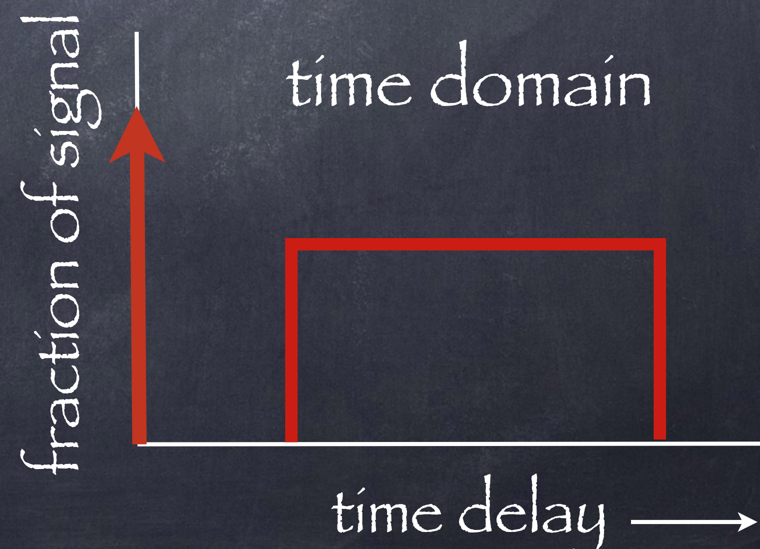


- In this blurred reflection model, **hard (FeK) band has most reflection**, then soft band, then medium band



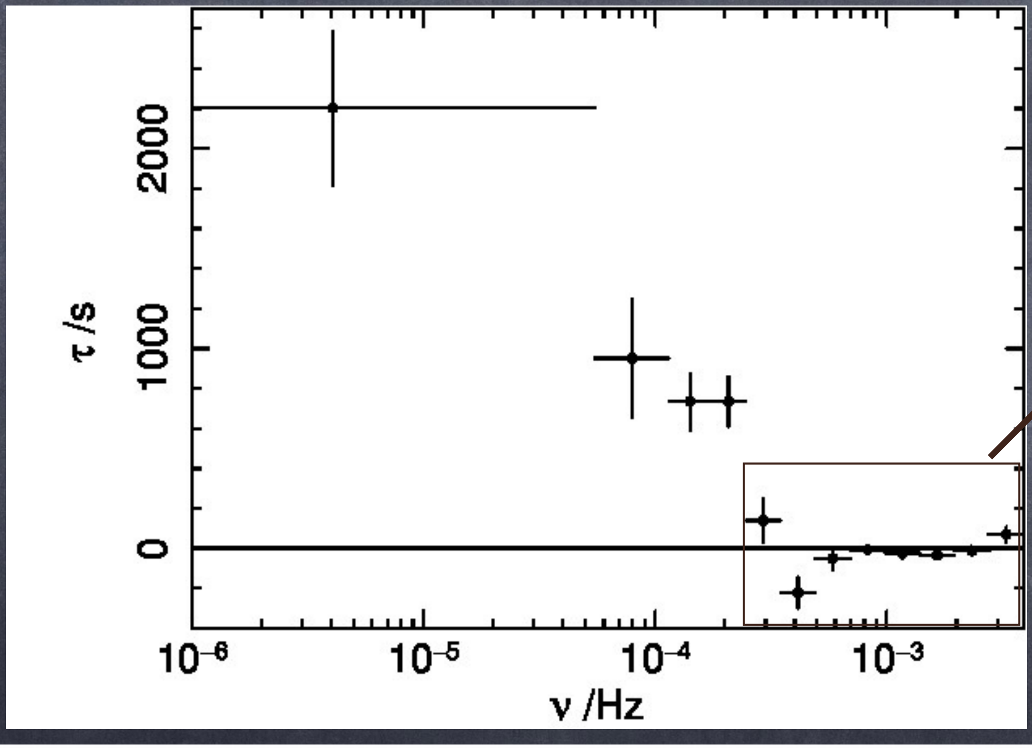
- light echos from shell with holes/clumps

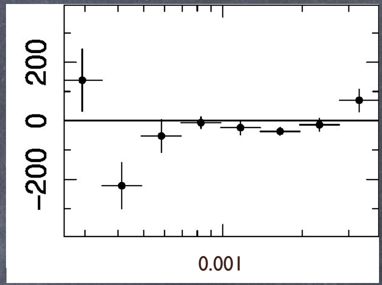
- light travel time across shell diameter places reprocessor at few hundred r_g



Ark 564

ν dependent lags between 4-7.5 and 0.4-1 keV

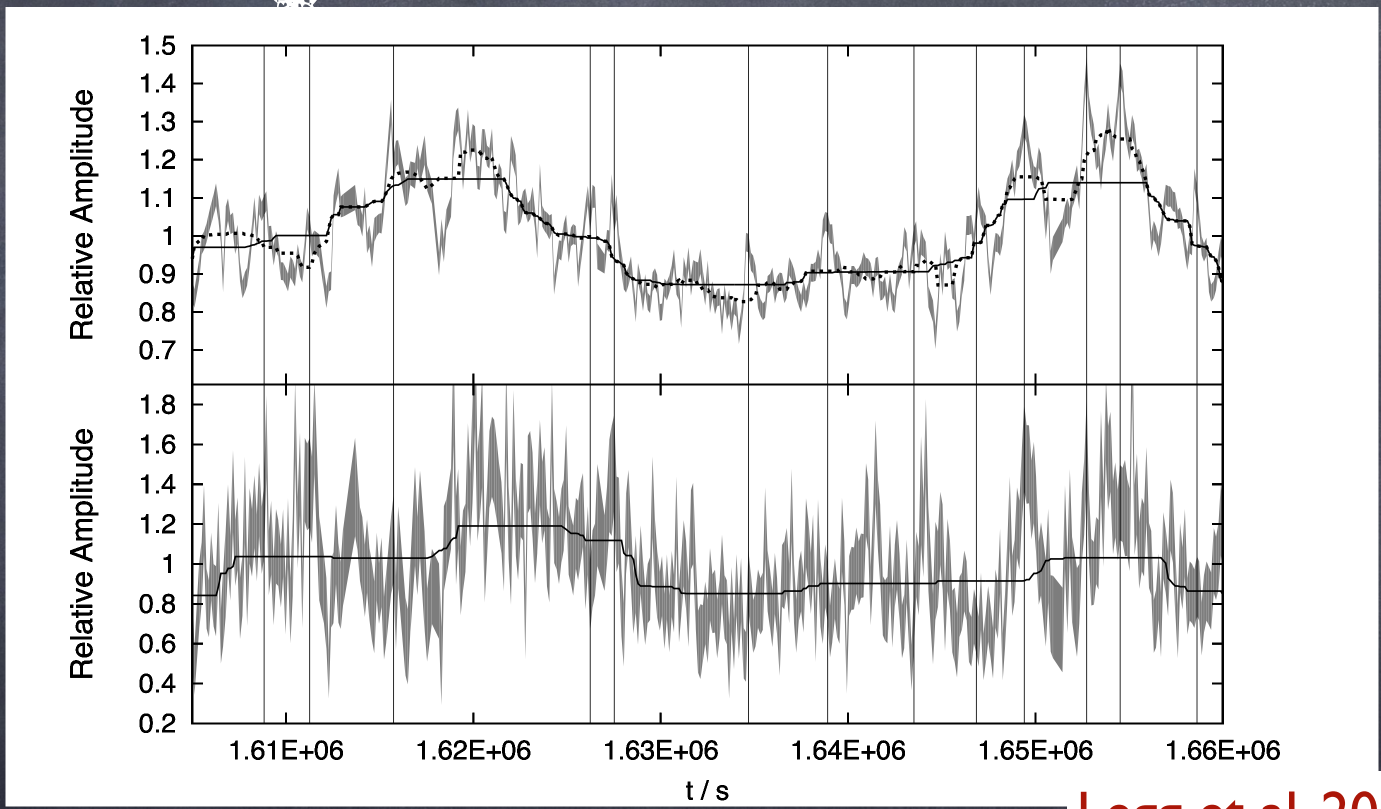




Ark 564
Legg et al 2012

- 450 ks XMM observation of Ark 564, July 2011.
- Note again the sharp negative feature (soft band lags hard)

Direct detection of X-ray reverberation

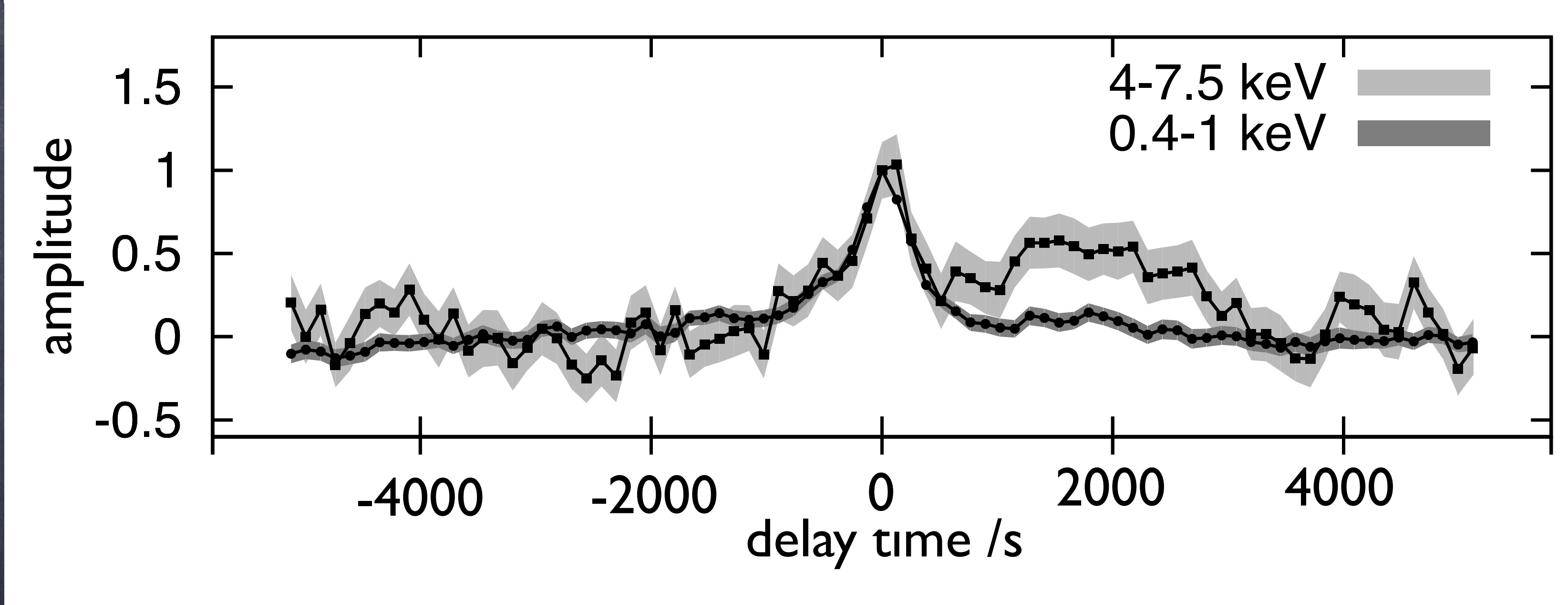


Legg et al. 2012

- stack flares of emission to see the relative shapes in hard and soft X-rays

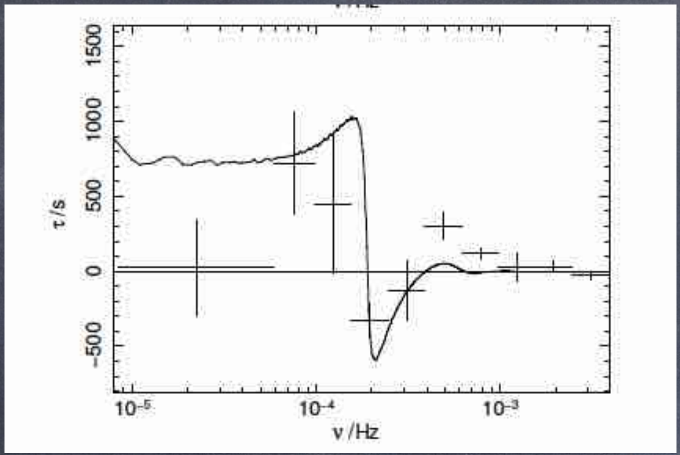
Direct detection of X-ray reverberation

Ark 564: Legg et al. 2012

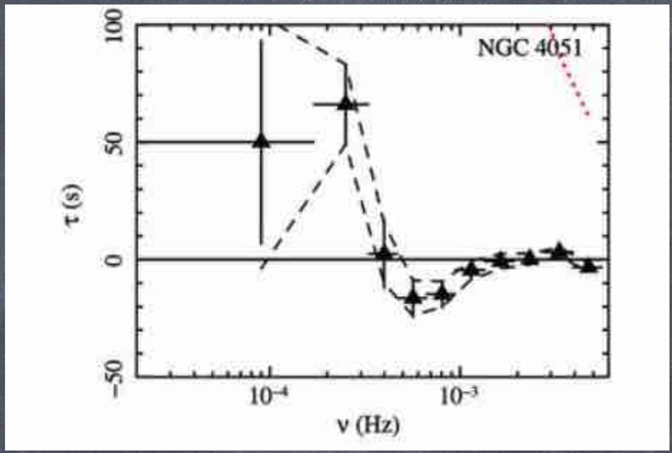


- hard X-rays have a significant secondary peak 1-3 ks after the main flare!
- main flare peaks are coincident in time (within errors)
  - delay not caused by comptonization upscattering (peaks occur at same time)
  - delay not easily caused by propagating disk fluctuations
- direct evidence for reverberation region ~200 r_g radius

Time Variability of lags



Turner et al 2017



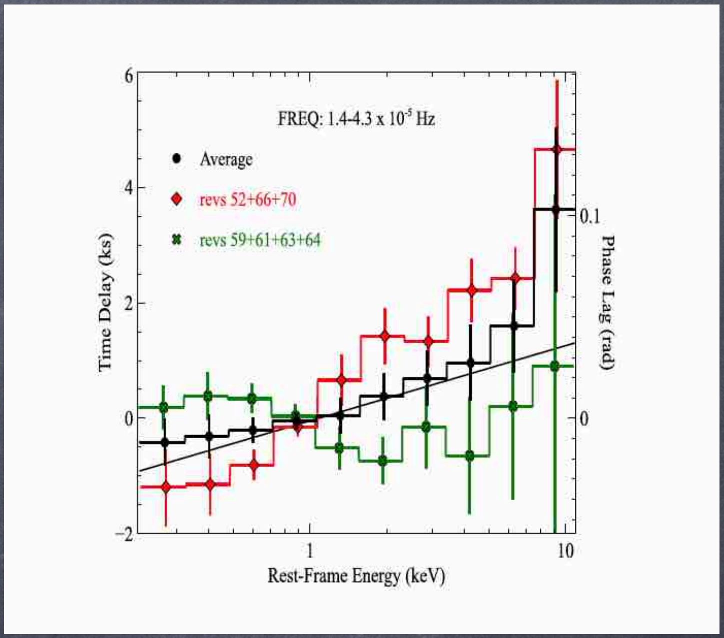
De Marco et al 2013

cutoff timescale is geometrical in origin

Transition frequency changes with time- dynamic nature of the reprocessor?

PG 1211+143

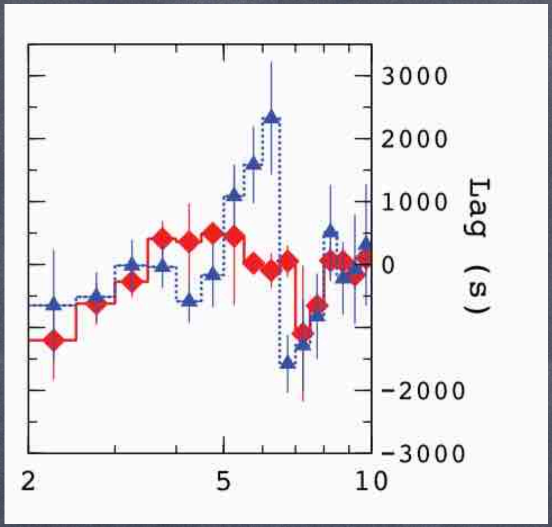
- Energy dependence of lags against broad reference band minus the band of interest
    - Green points - lag behavior in low/ absorbed state
    - Red - lags in high state
    - Black is the mean



- Change in lag behavior during heavy X-ray absorption
- N_H increase -scattered photons from smaller physical depth in clouds -> smaller time delay
- X-ray reprocessor dynamic in nature!

Lobban et al 2017 - see talk Weds by James Reeves

"Fe K lags"



NGC 4151 Zoghbi et al 2012

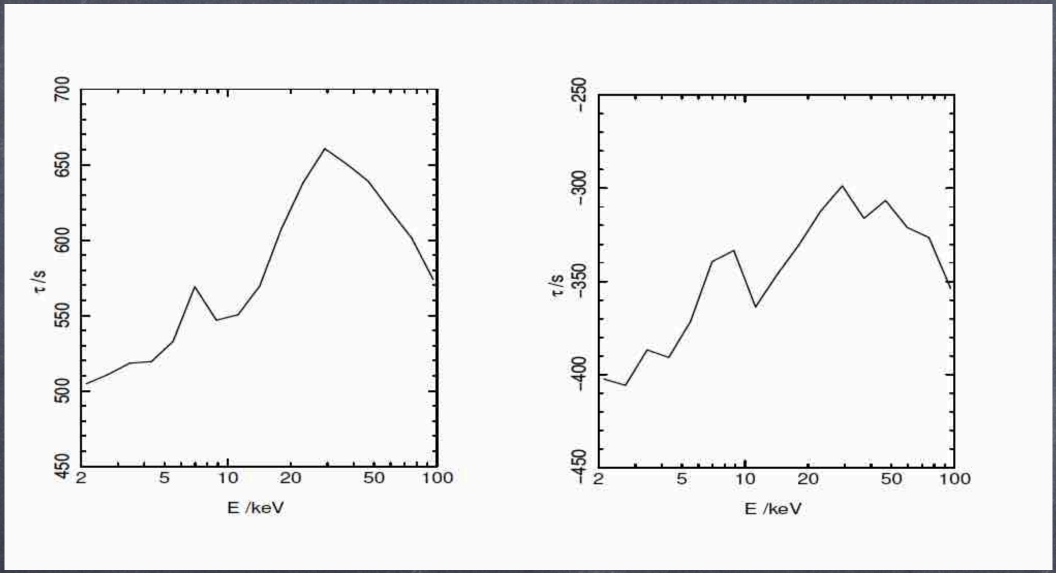
Blue > 50 ks

Red 2-20 ks

- claim to show mid-ν lags associated w/ relativistically blurred Fe K

Lag energy plots

sampled at 0.0006 Hz (1.7 ks)   sampled at 0.0011 Hz (0.9 ks)



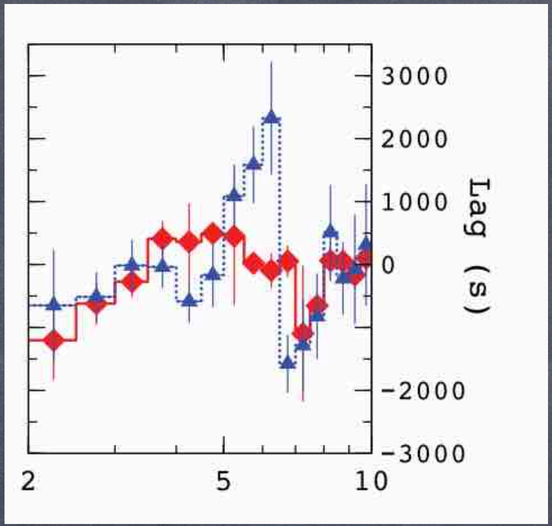
Simulation lag spectrum from reprocessor very different when sampled on different timescales

-qualitatively similar to that reported by Kara et al 2016

Optical depth is a function of energy

Different energies scatter at differing depths in the material

"Fe K lags"



NGC 4151 Zoghbi et al 2012

Blue > 50 ks

Red 2-20 ks

- claim to show mid-ν lags associated w/ relativistically blurred Fe K
- Cannot separate out narrow ν ranges in this way if signatures arise in time domain. Energy dependence arises from energy-dependence of the time domain transfer function
- In any scattering/reverberation model the spectrum below Fe K edge has a high scattered fraction, so no diagnostic power

Conclusions

- Complex X-ray absorption from outflowing wind with variable covering fraction
- Time lag spectra consistent with reverberation on ks timescales - 10-100 GM/c^2, not 1-2 GM/c^2 !
- Imprints variability on day+ timescales
- "Negative" time lags arise from ringing in Fourier transform of hard band transfer function, not from excess soft band reflection
- Lag-energy features (e.g. "FeK" lags) have little power to distinguish origin of scattering material (disk or circumnuclear)
- In combination, X-ray spectroscopy and timing analysis powerful tools to study complex outflows from accretion disks - but need long quasi-continuous observations

Discussion topics

- What is the origin of the time lags between X-ray bands?
- What are the distance, global covering, physical state, velocity of the X-ray outflow?
- Do other waveband data constrain the X-ray reprocessor?
- What new observations would be the most effective test/step forward?