Winds and X-ray reverberation in AGN

Lance Miller (Oxford)

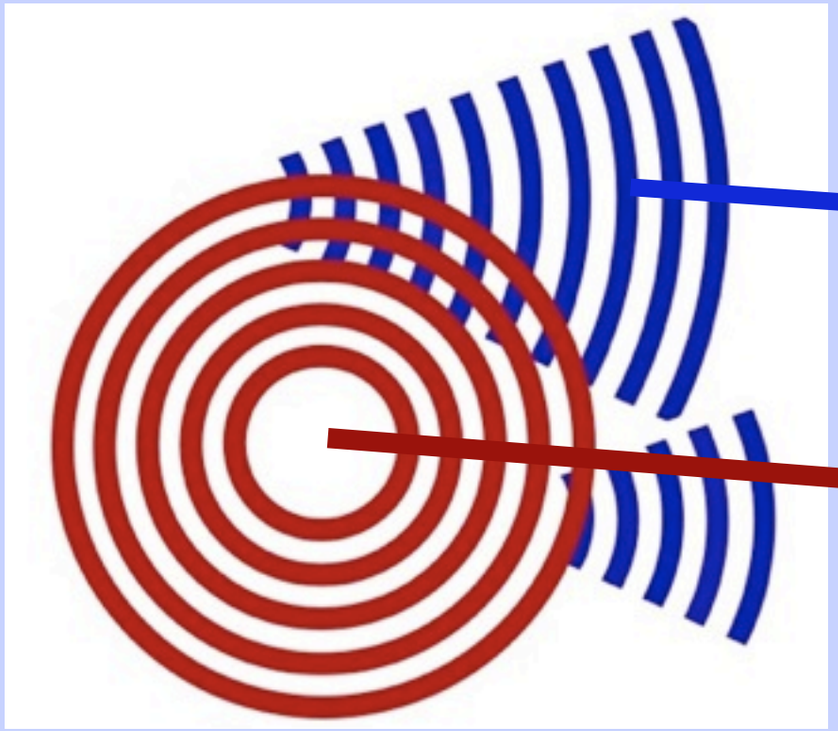
Jane Turner (UMBC)
James Reeves (Keele)
Valentina Braito (Leicester)
Andrew Lobban (Keele)
Stuart Sim (MPA)
Knox Long (STScI)
Daniel Proga (Nevada)
Steve Kraemer (Catholic)
Mike Crenshaw (Georgia)

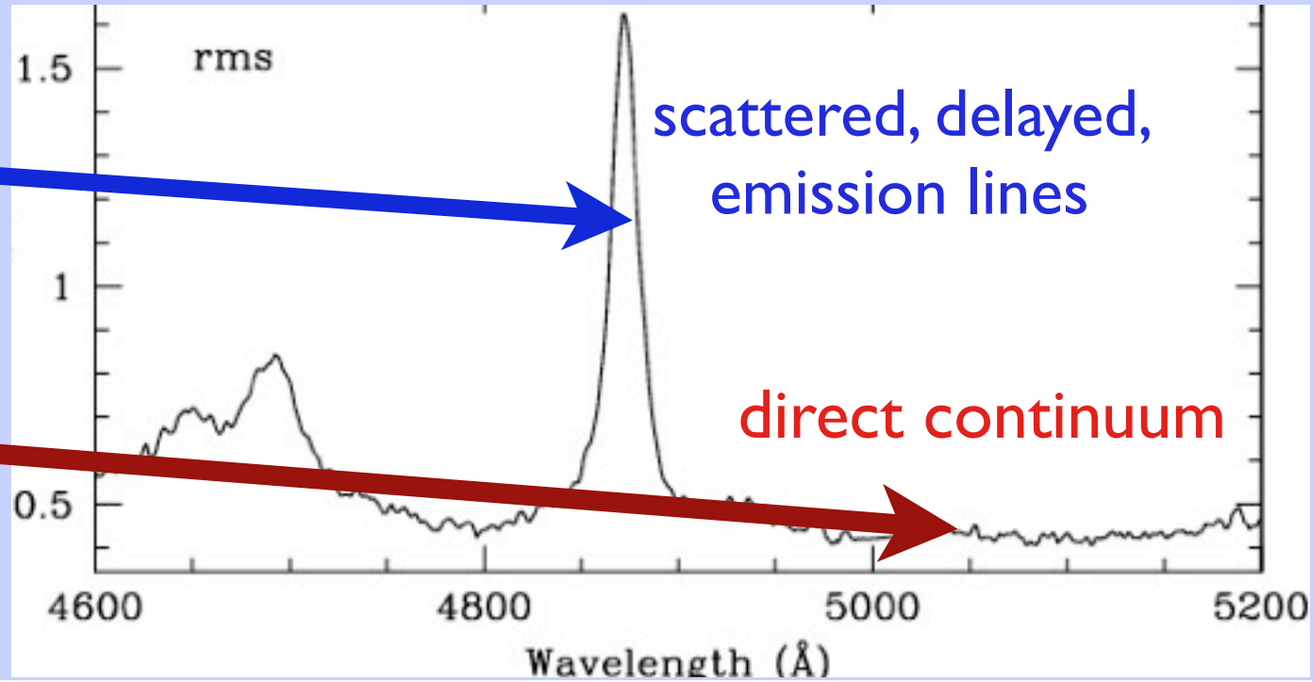
movie: radiatively-driven AGN wind by Daniel Proga

X-ray evidence for circumnuclear (wind) material from time lags

- Time lags between hard and soft X-ray photons known for 25 years (in galactic sources)
- Is this evidence for X-ray reverberation?
- What other explanations are there?
  - Componisation time lags (hard photons need more upscatters than soft photons)
  - accretion disk fluctuations + inner-disk reflection @ $1 r_g$

reverberation



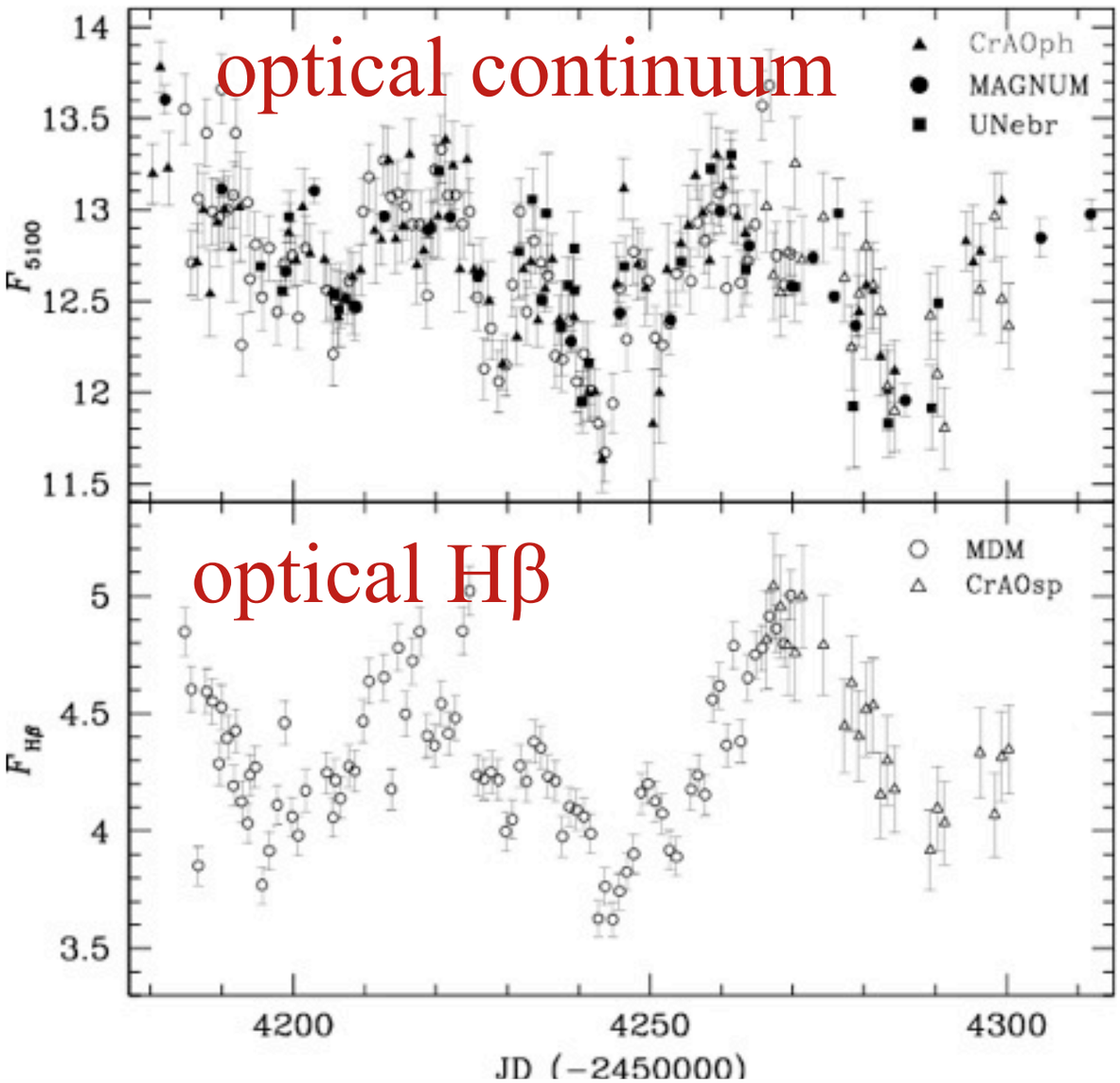


NGC 4051 optical: Denney et al 2009

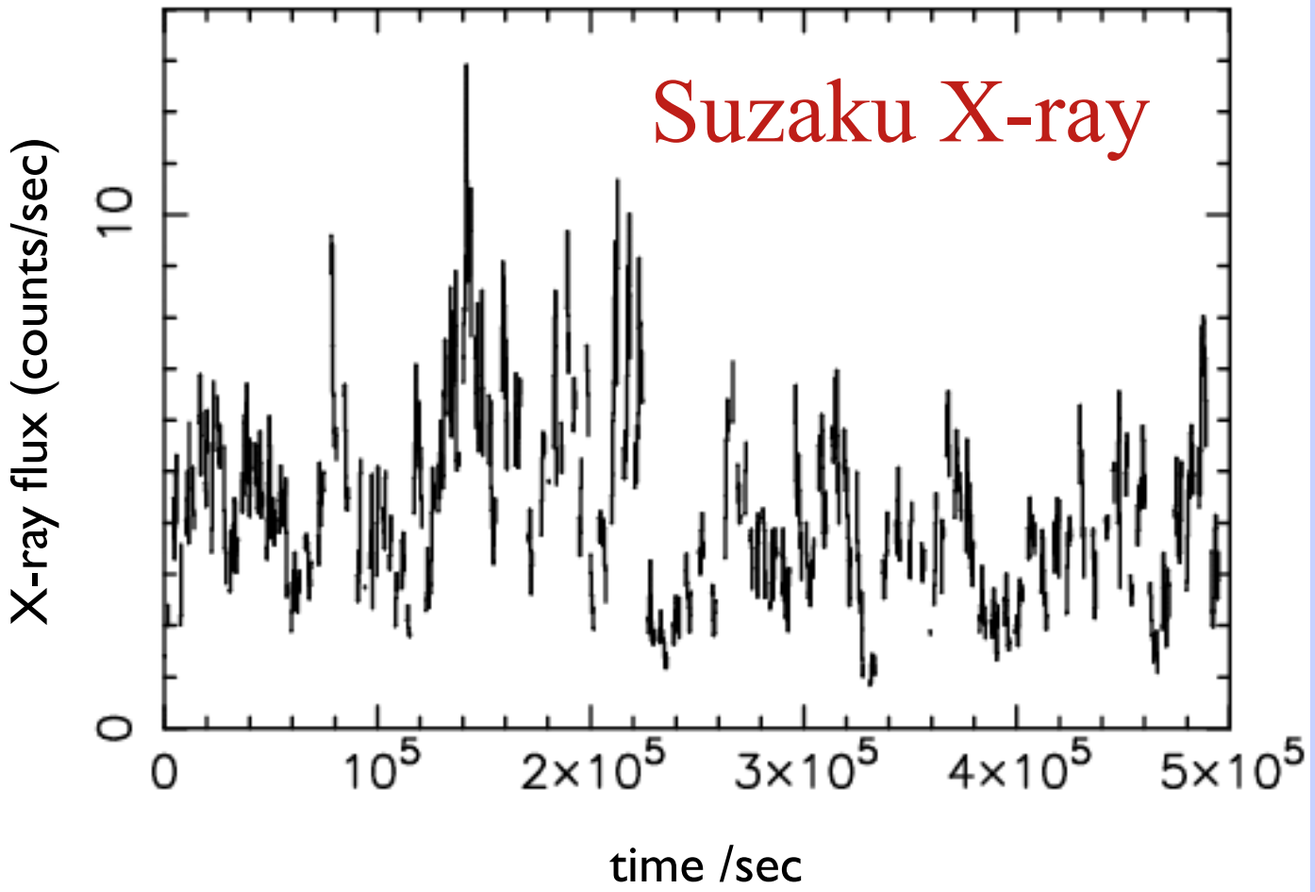
- reverberation between optical/UV continuum and optical emission lines is principal method of BH mass measurement in AGN
- in our analysis we consider how individual Fourier modes behave

gappy, noisy time-series

NGC 4051 optical: Denney et al 2009



NGC 4051 X-ray: Miller et al 2010

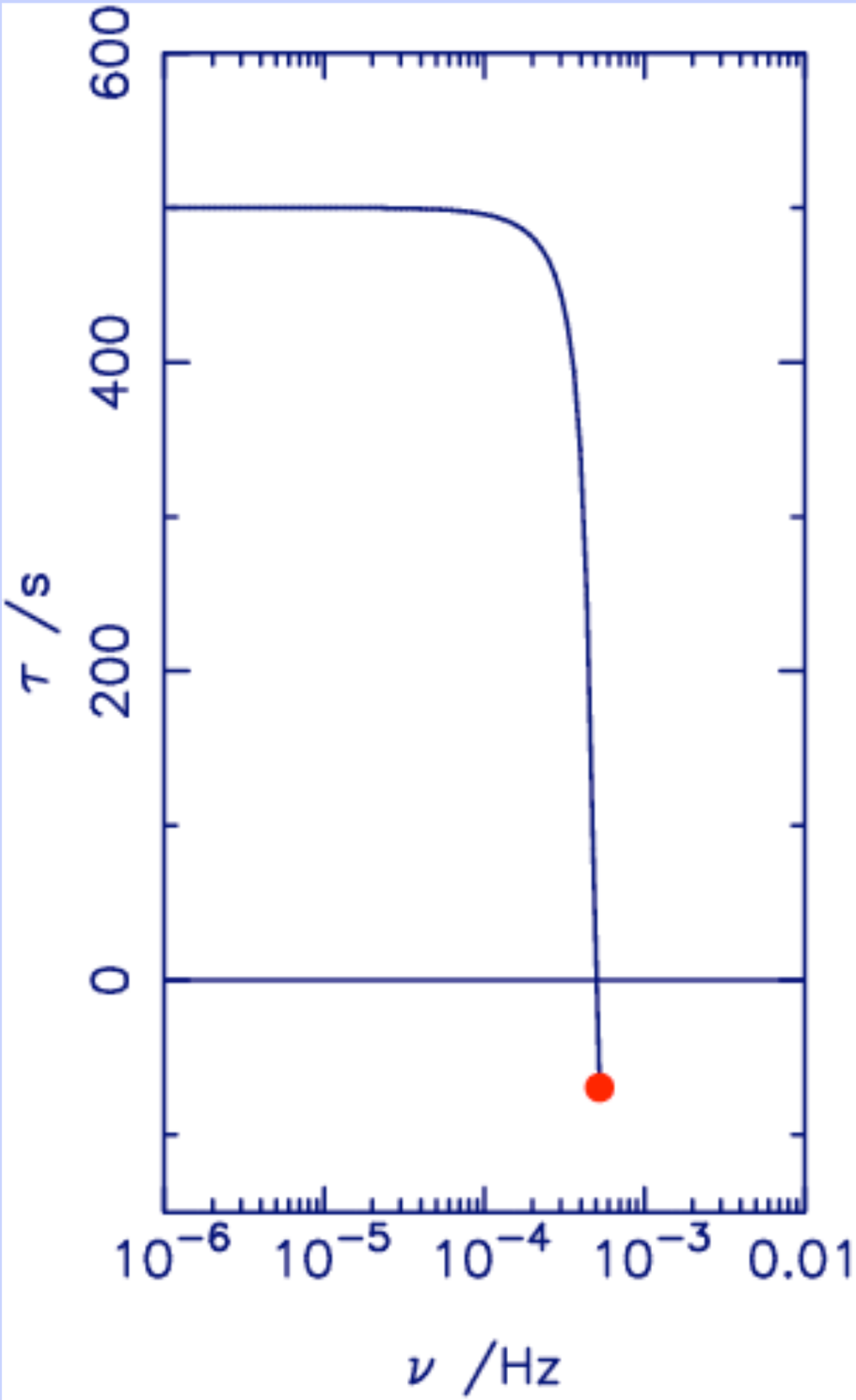


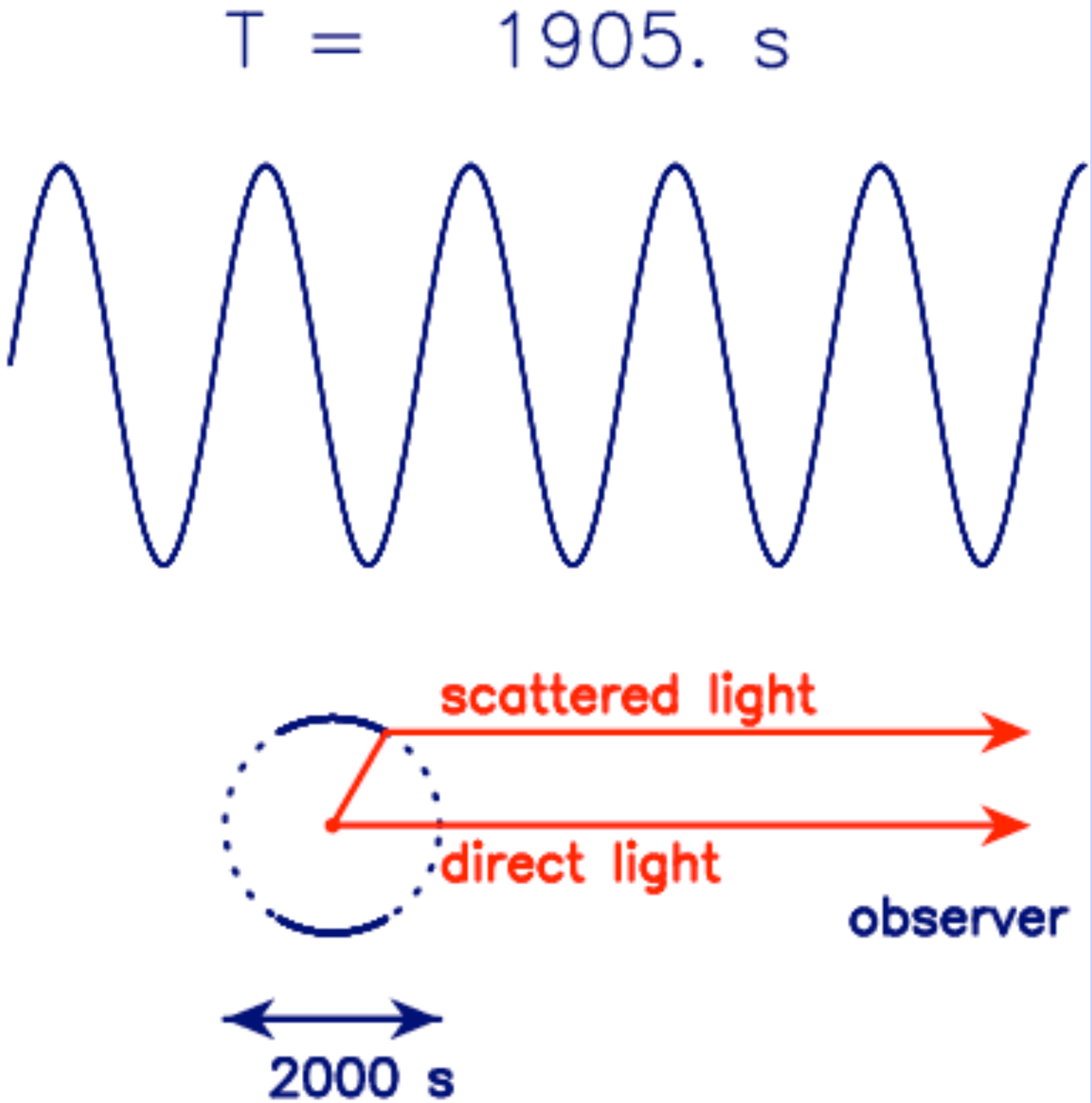
- time series are both "gappy" and noisy
- developed maximum-likelihood analysis based on CMB methods
- immune to gaps, accounts for shot noise, rigorous error estimation
- only method that accounts for covariance in Fourier domain

reverberation Fourier analysis

thin scattering shell
partial covering

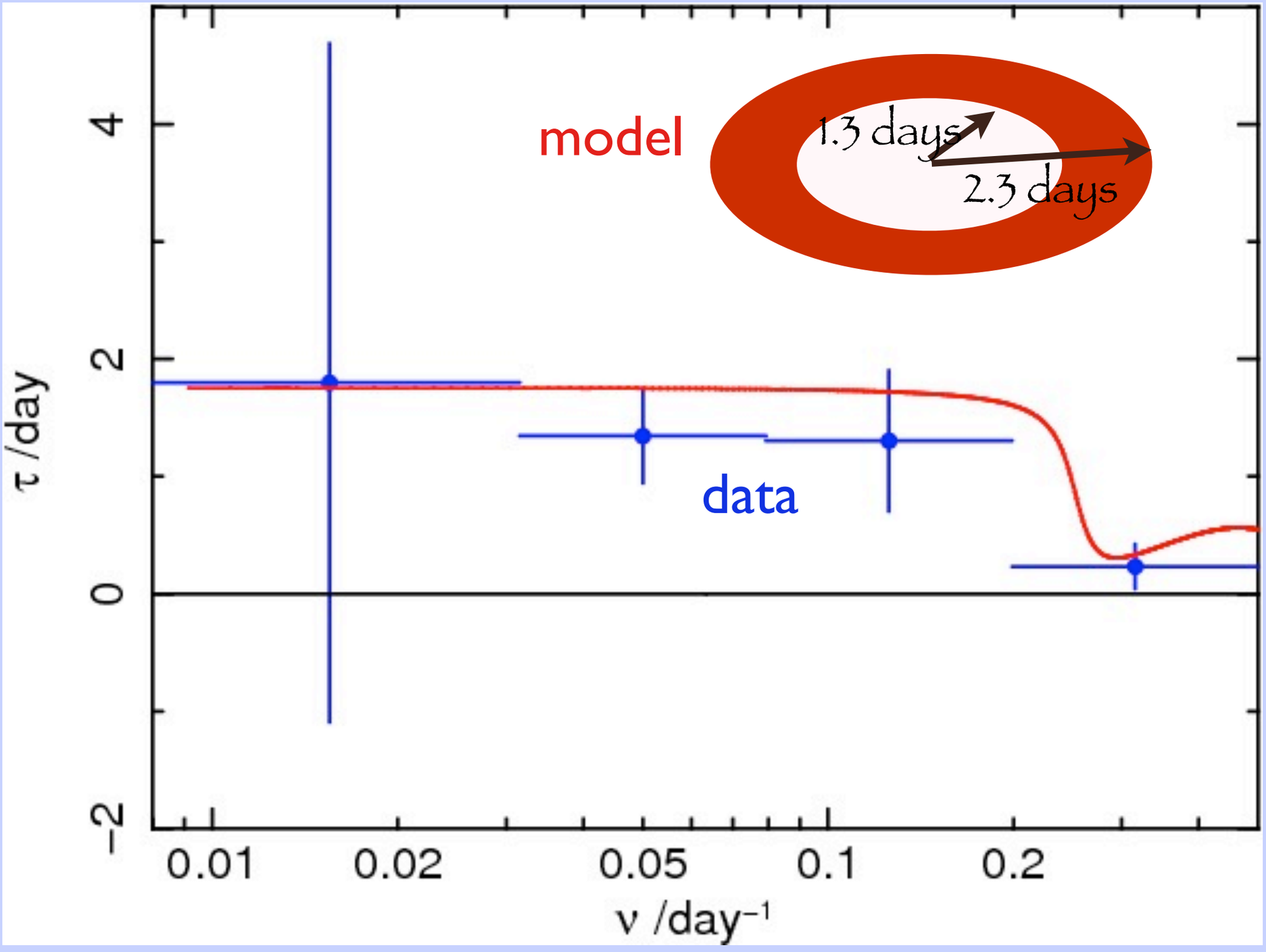
reverberation Fourier analysis



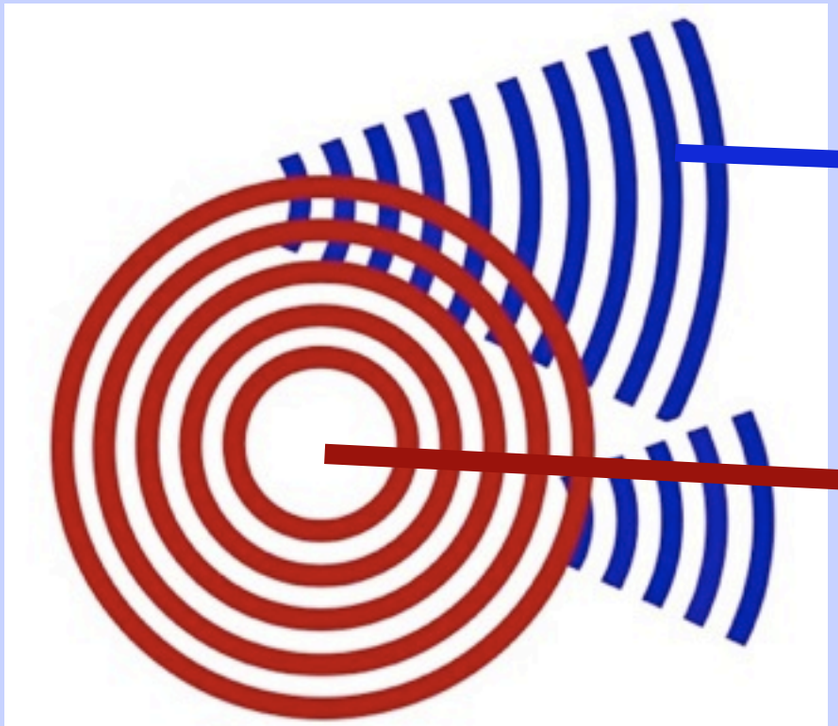


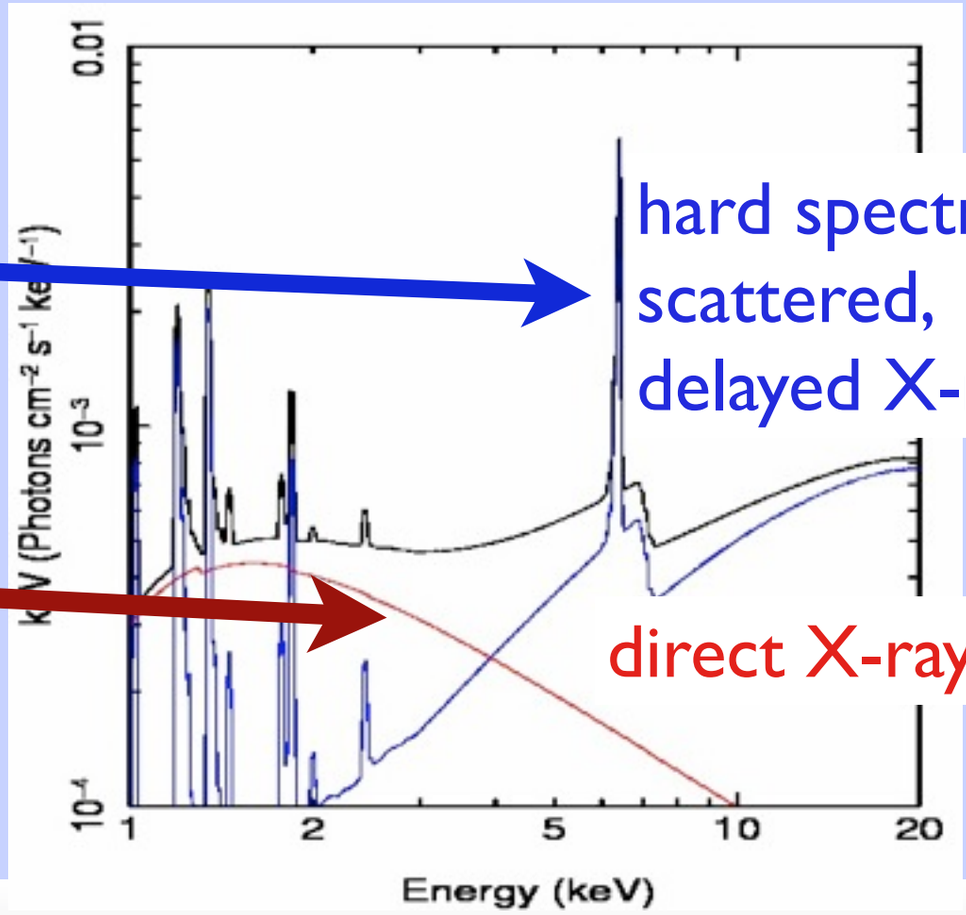
thin scattering shell
partial covering

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



X-ray reverberation





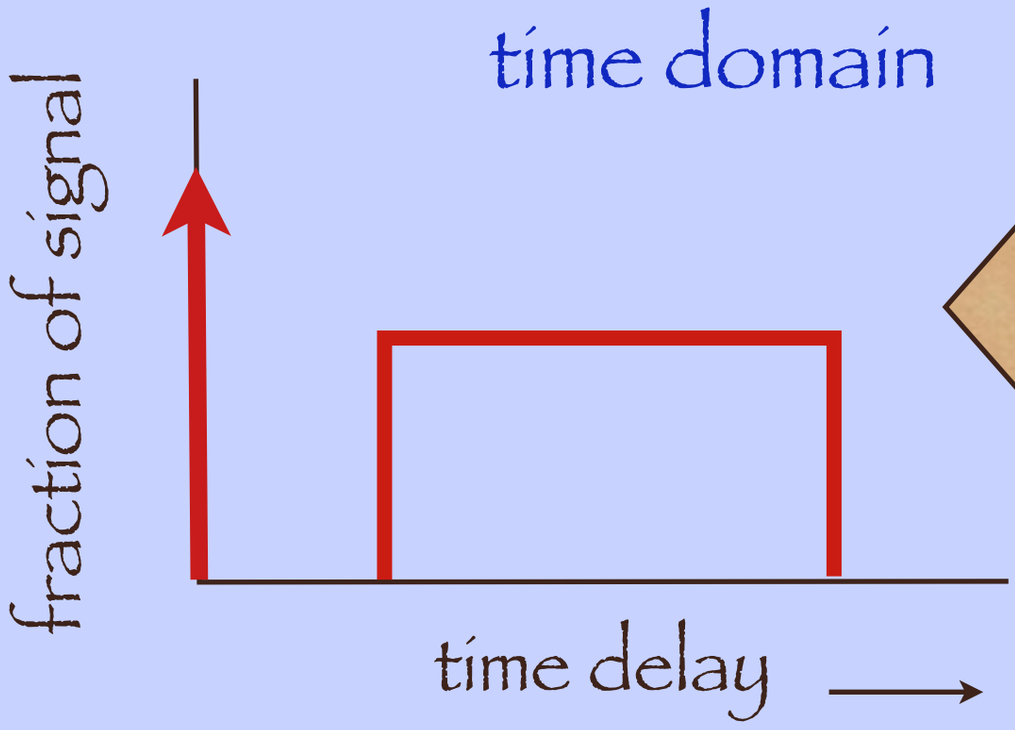
hard spectrum, scattered, delayed X-rays

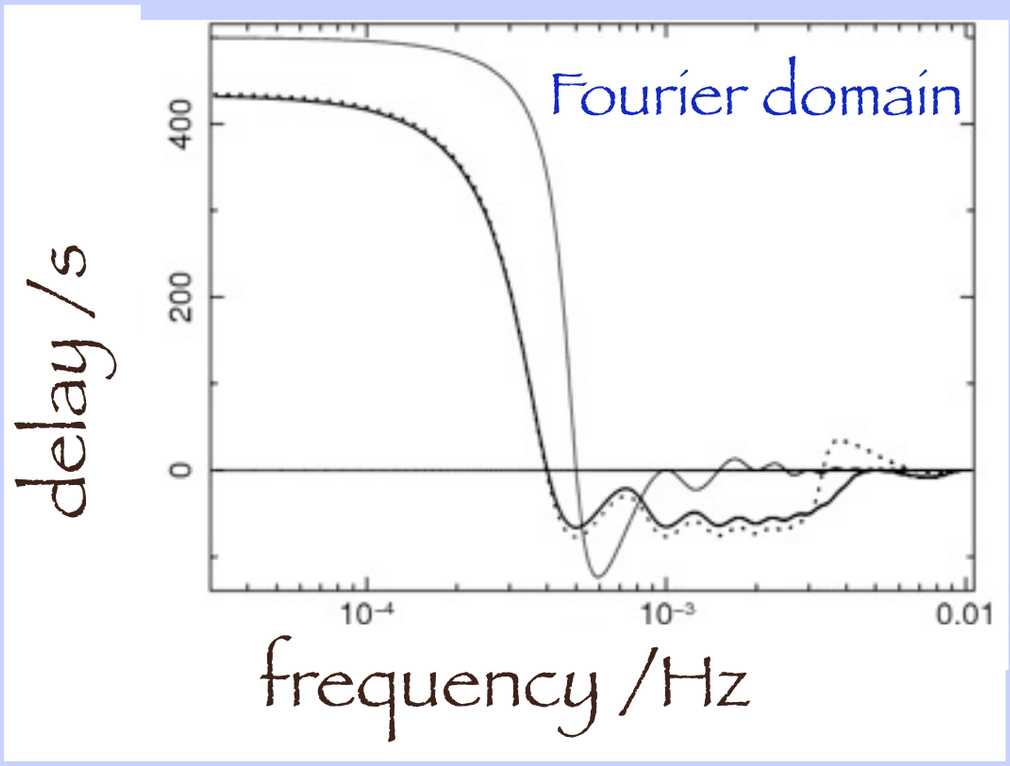
direct X-rays

- 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

- Cross-correlating hard X-rays with soft X-rays generally shows **hard X-rays are delayed**
- The lag spectrum is given by the phases of the Fourier transform of the transfer function, which describes the spread of time delays in the signal.
- Negative lags arise partly because of clumpy structure but also because soft band also has delays as well as hard band

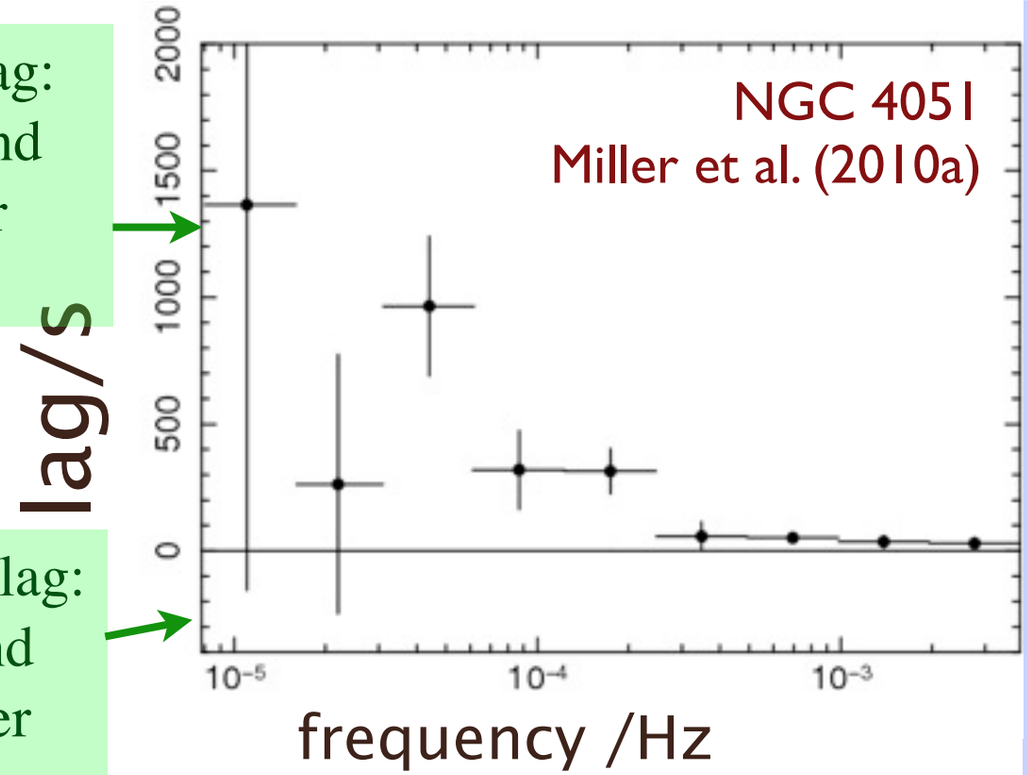


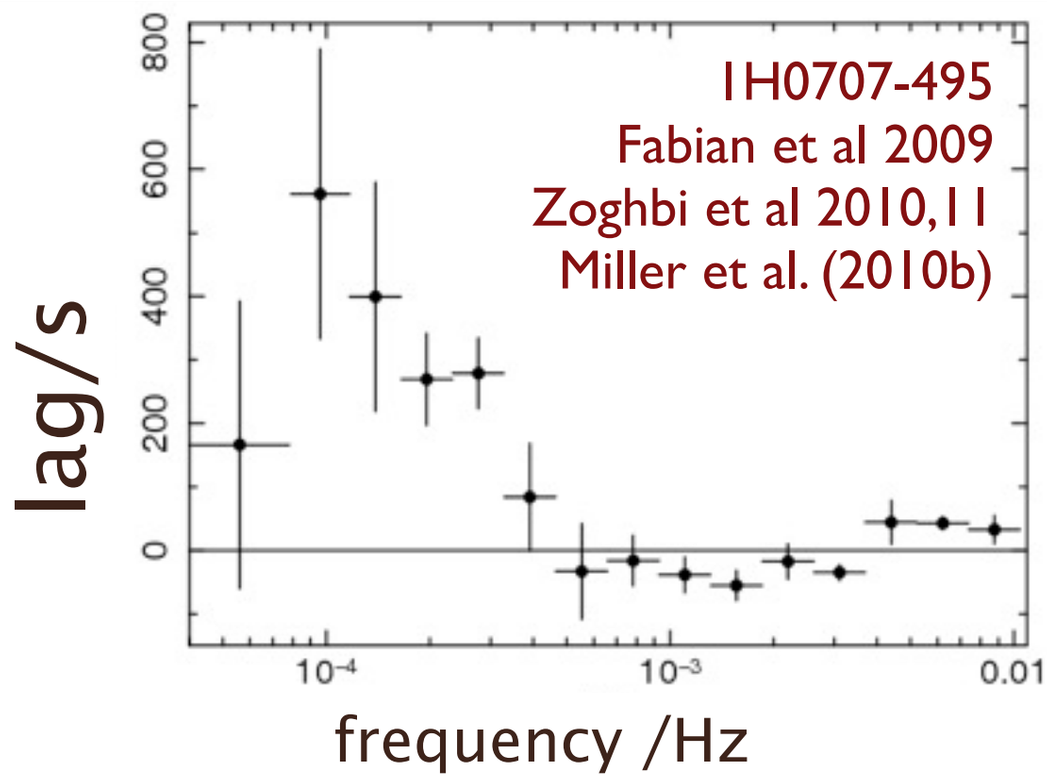


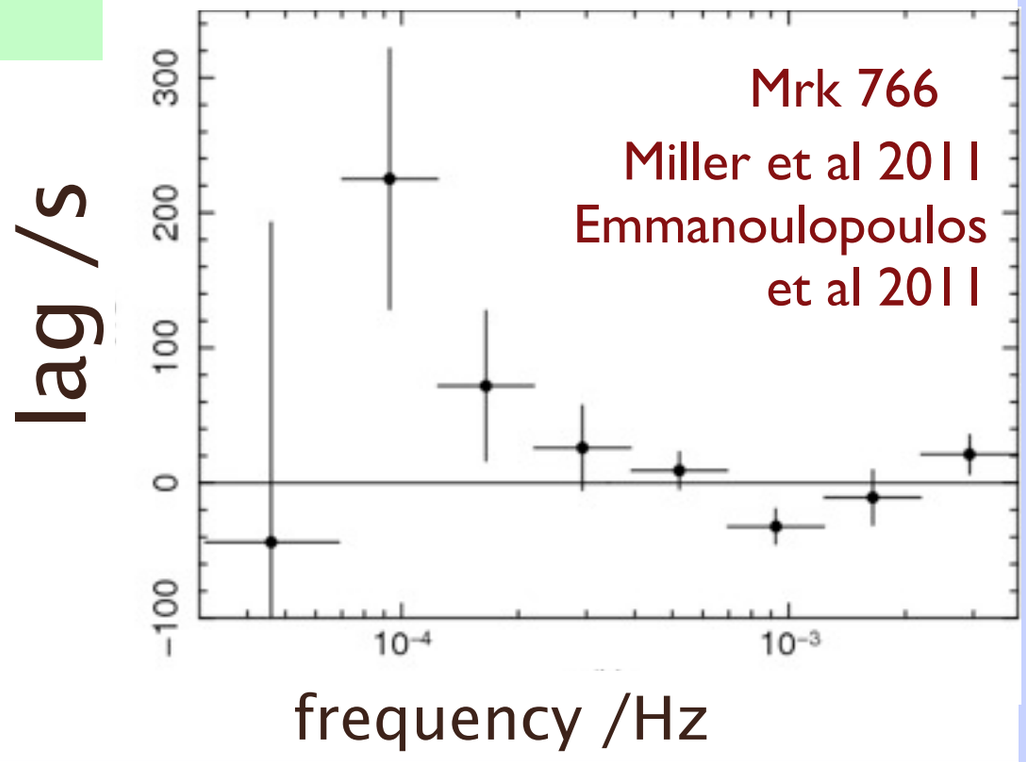
X-ray reverberation in AGN

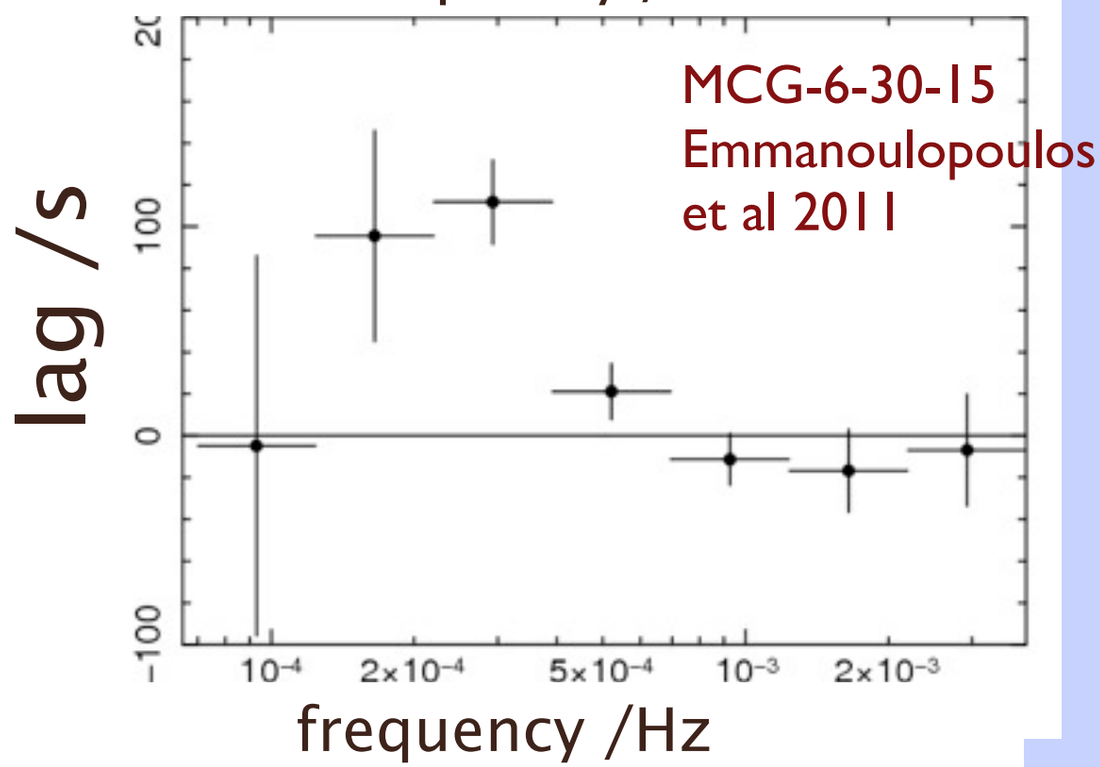
Positive lag: harder band lags softer band

Negative lag: softer band lags harder band





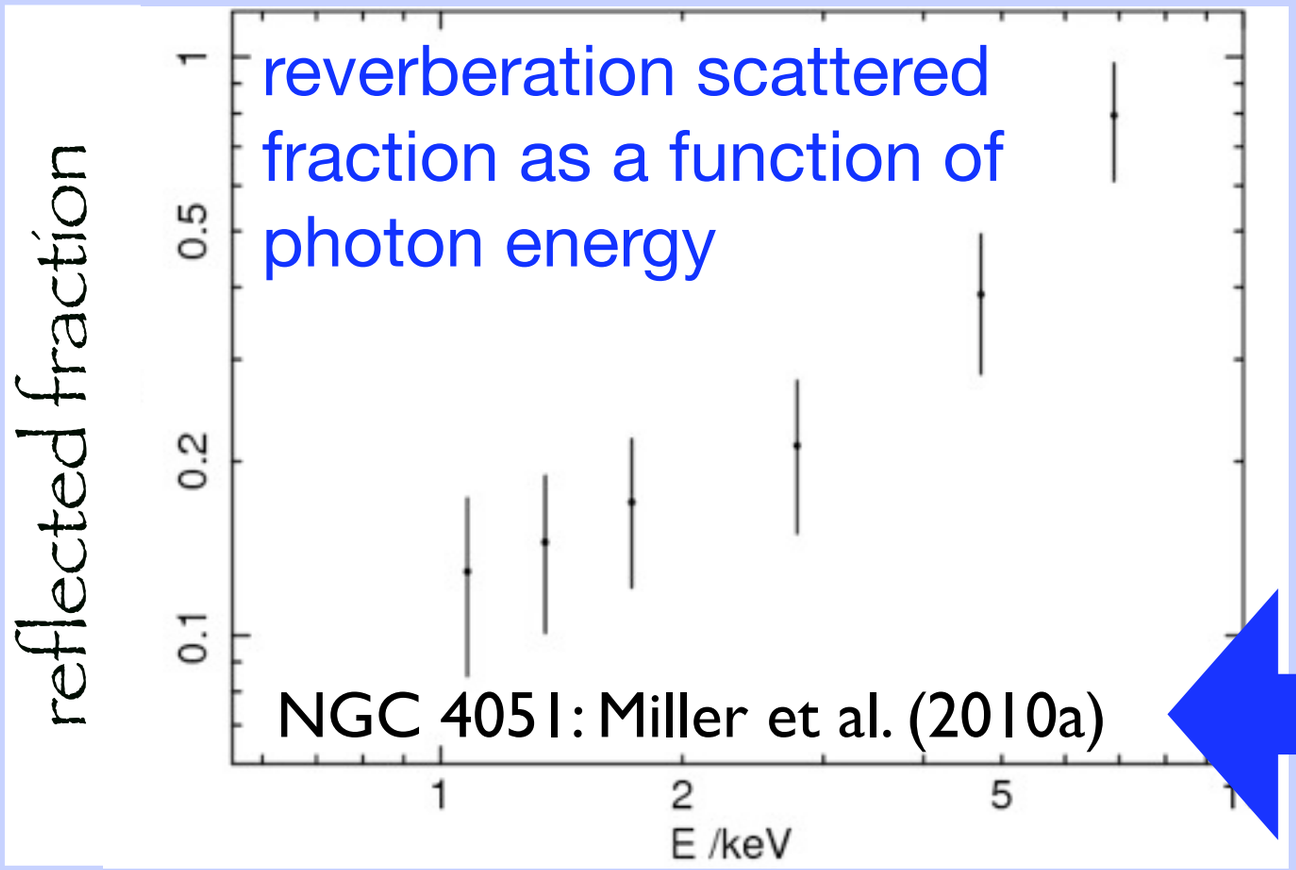


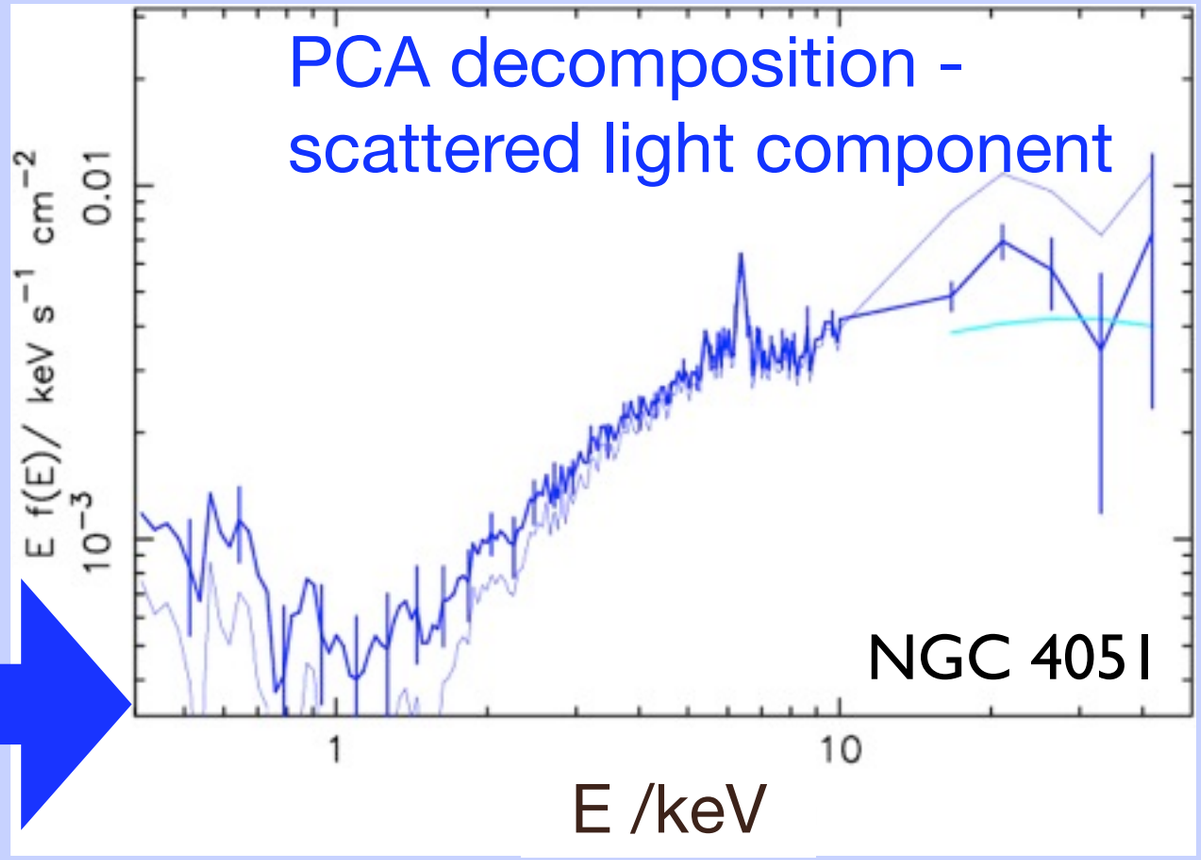


- Lags known for 25 years but not previously recognized as reverberation
- **Dependence on frequency as expected from reverberation**

X-ray reverberation: energy dependence

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



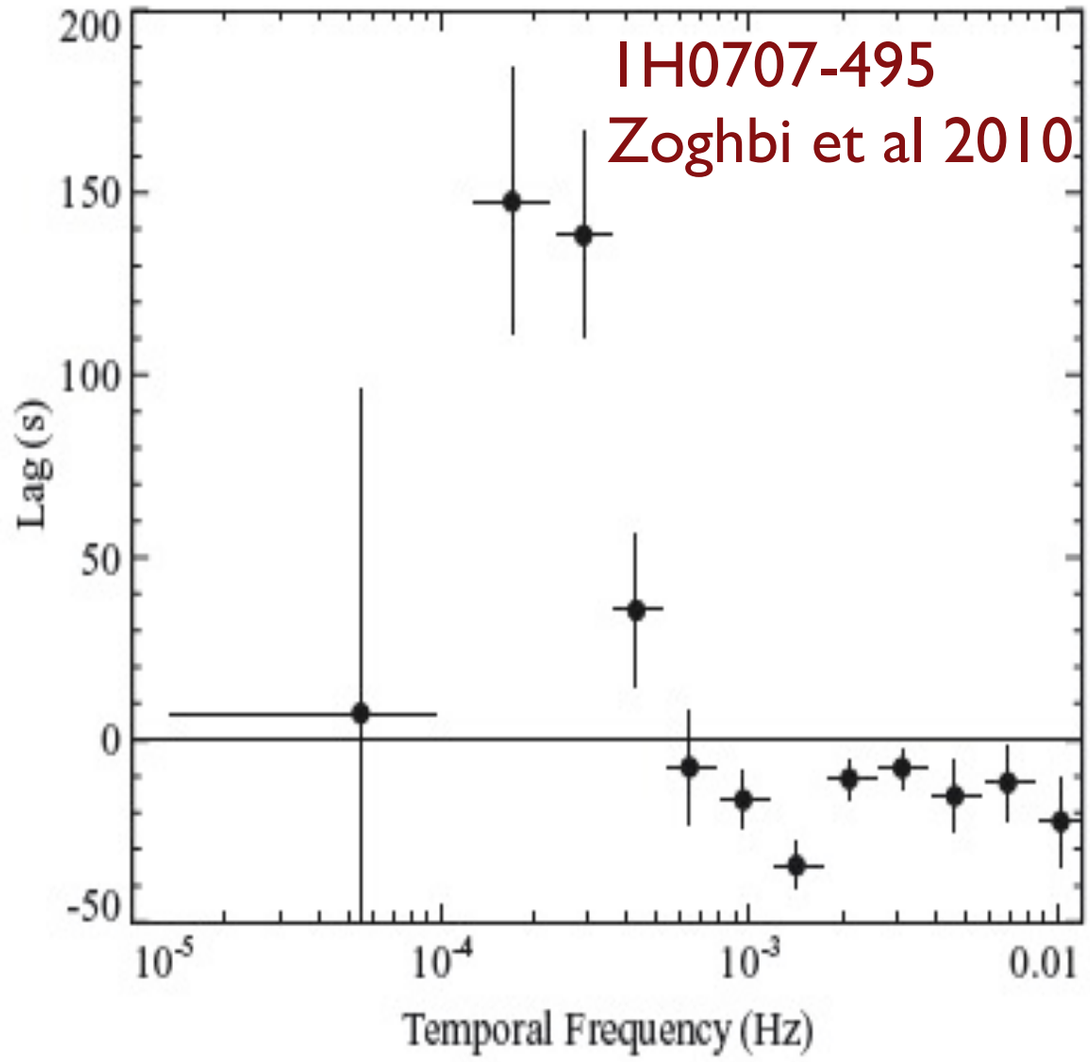


- lag times increase with the difference in photon energy of the bands being cross-correlated.

- compare the required reflection fractions with the "scattered-light" component seen in the spectral analysis.

other possible origins of lags

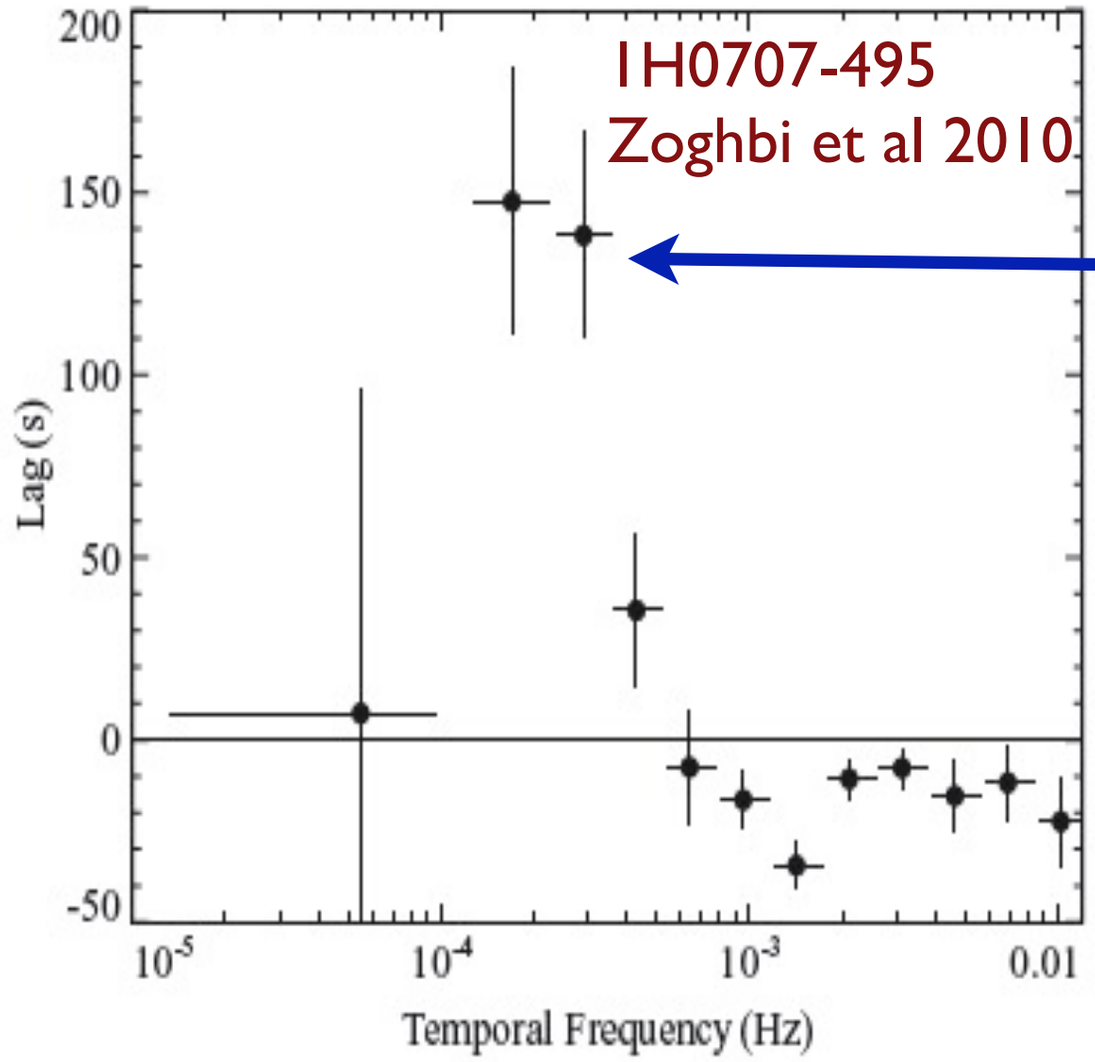
- fluctuations propagating over the accretion disk + reflection from the inner accretion disk (i.e. two mechanisms!) [Fabian et al 2009, Zoghbi et al 2010, 2011]



- Negative lags claimed to be enhanced FeL soft-band reflection from 1 r_g
- already strongly disfavoured by the wrong energy dependence of the negative lags (Miller et al 2010, 11)

other possible origins of lags

- 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]

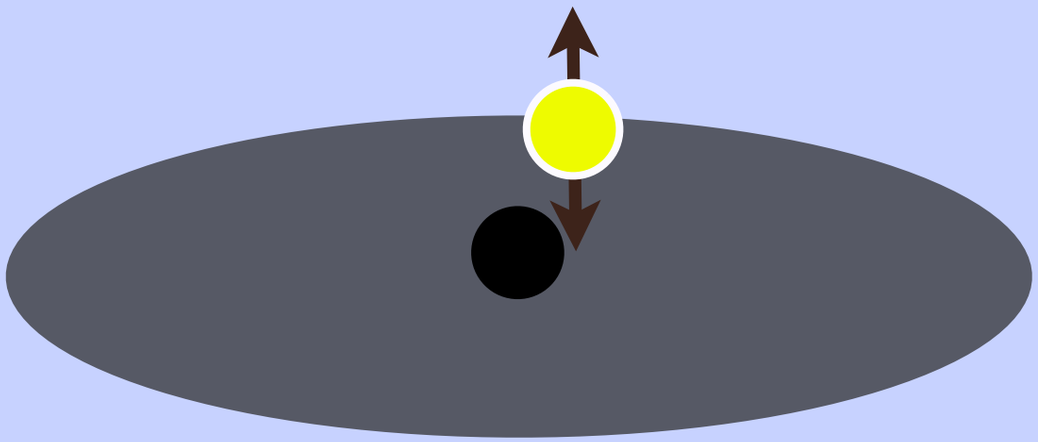


- Positive lags at low frequency attributed to lags propagating over accretion disk

- Negative lags claimed to be enhanced FeL soft-band reflection from 1 r_g
- already strongly disfavoured by the wrong energy dependence of the negative lags (Miller et al 2010, 11)

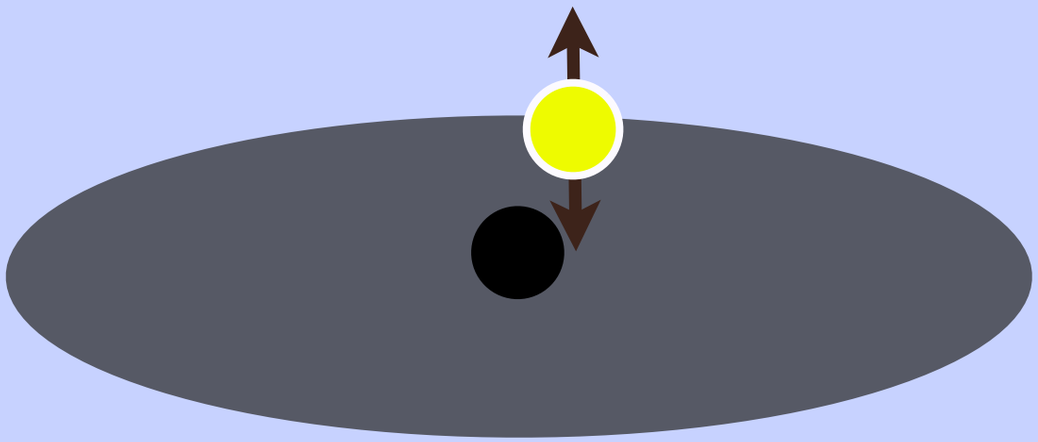
problems with light bending, lags and disk fluctuations

- 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.

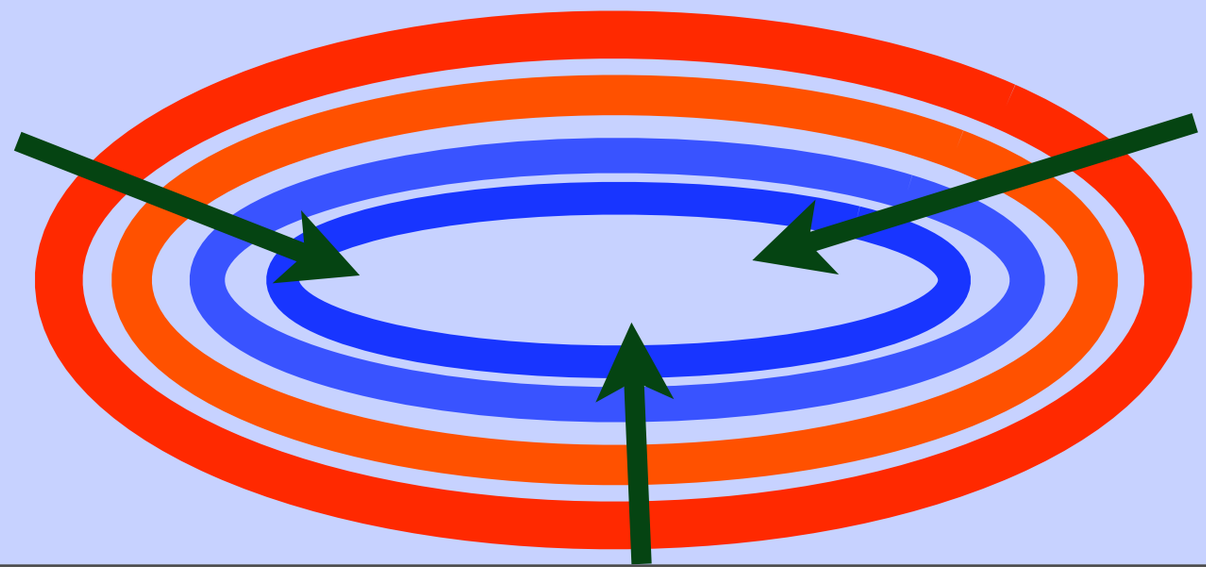


problems with light bending, lags and disk fluctuations

- 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.

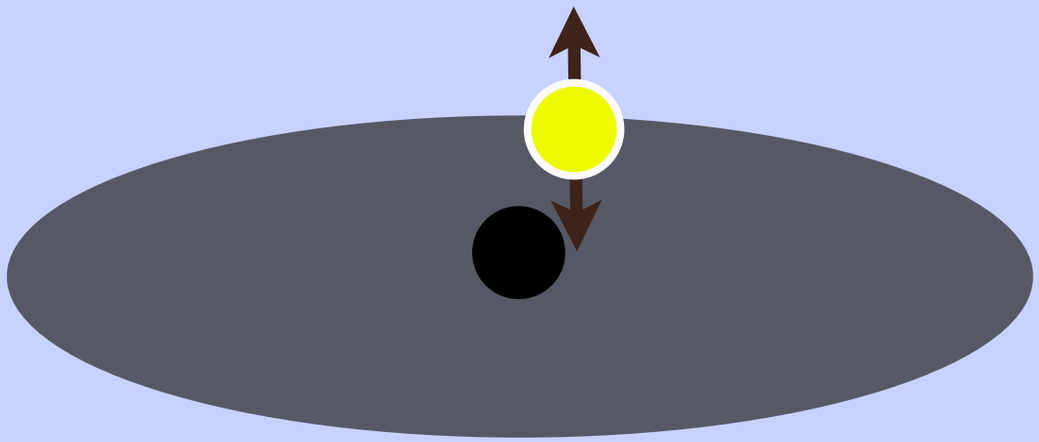


positive lags from fluctuations propagating inwards over the surface of the accretion disk from soft to hard regions?



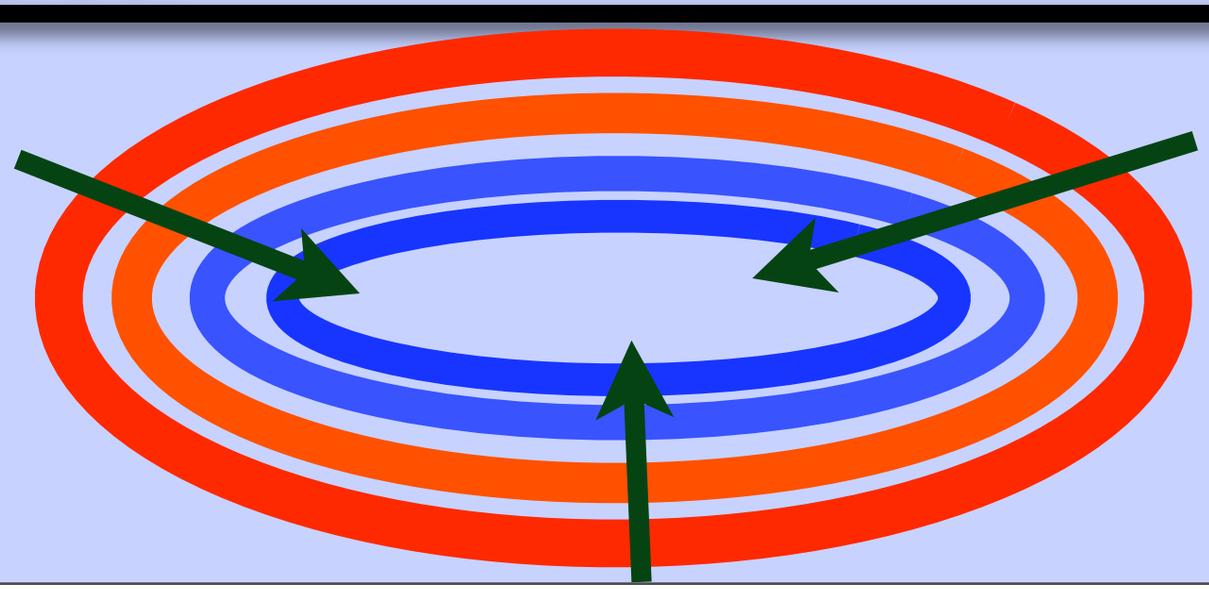
problems with light bending, lags and disk fluctuations

- 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.

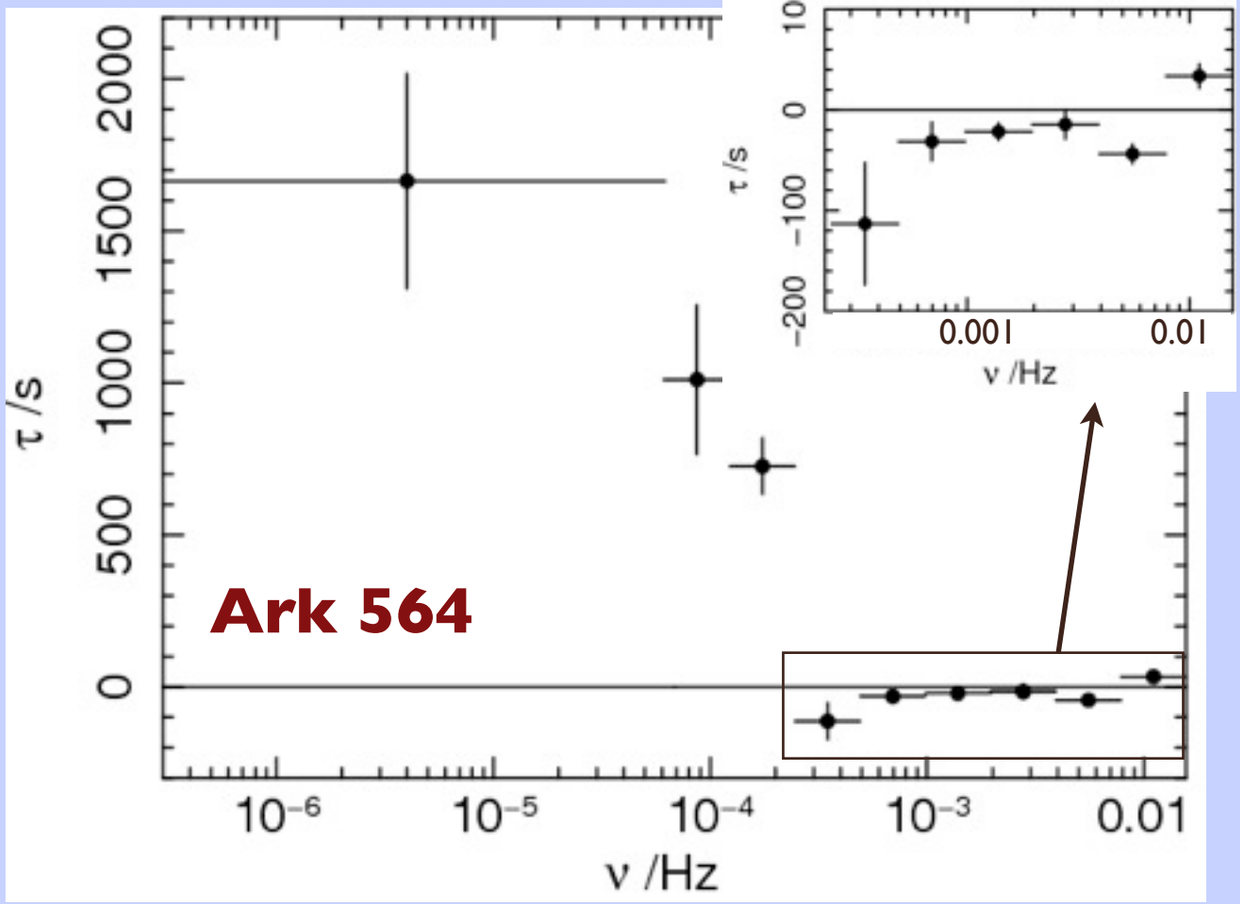


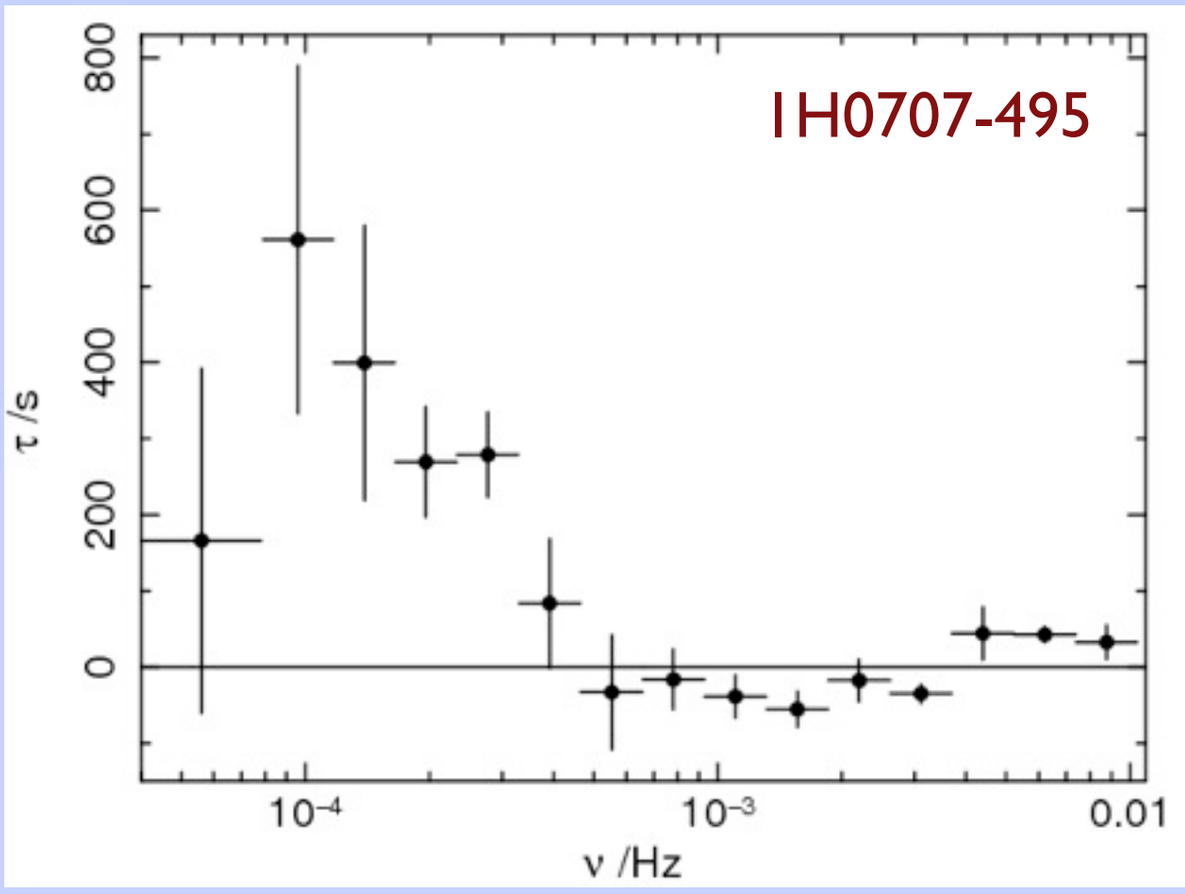
where is the continuum source and its variations produced? It can't be both in the accretion disk and in the "lamp-post" source.

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



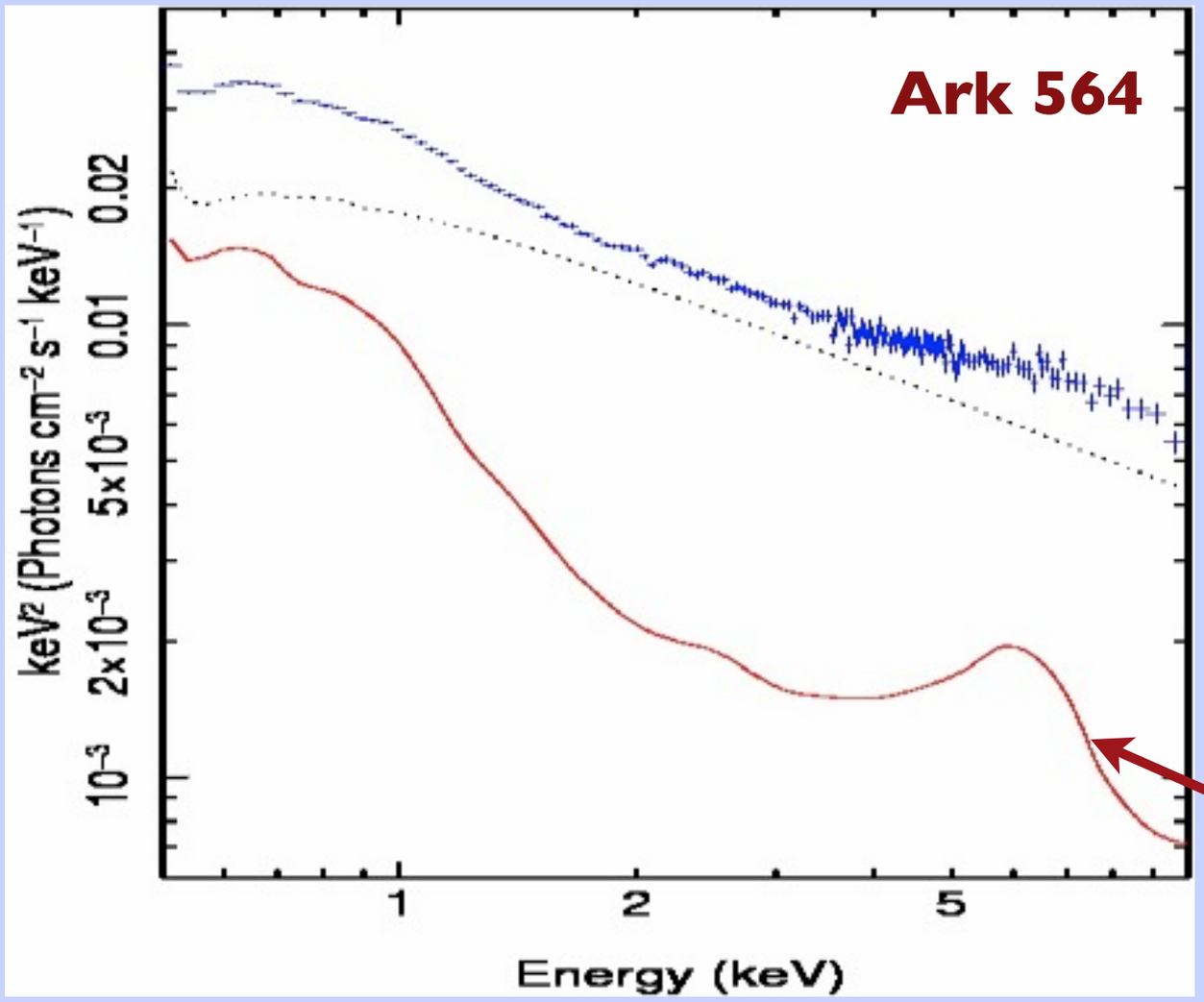
new! comparison of 1H0707-495 & Ark 564

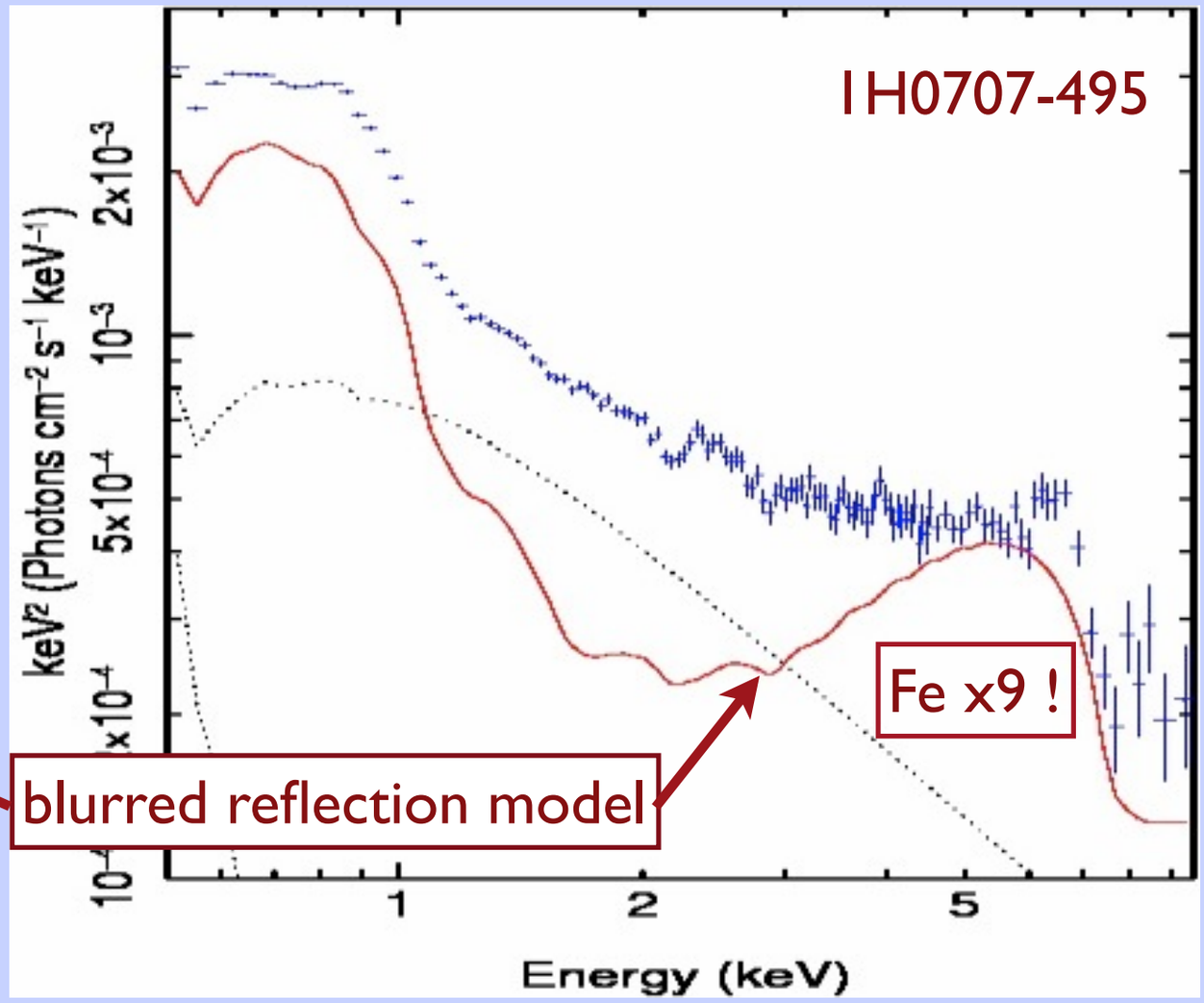




- New 450 ks XMM observation of Ark 564, July 2011.
- The lag spectra of Ark 564 & 1H0707-495 are remarkably similar (timescales in Ark564 are somewhat longer)

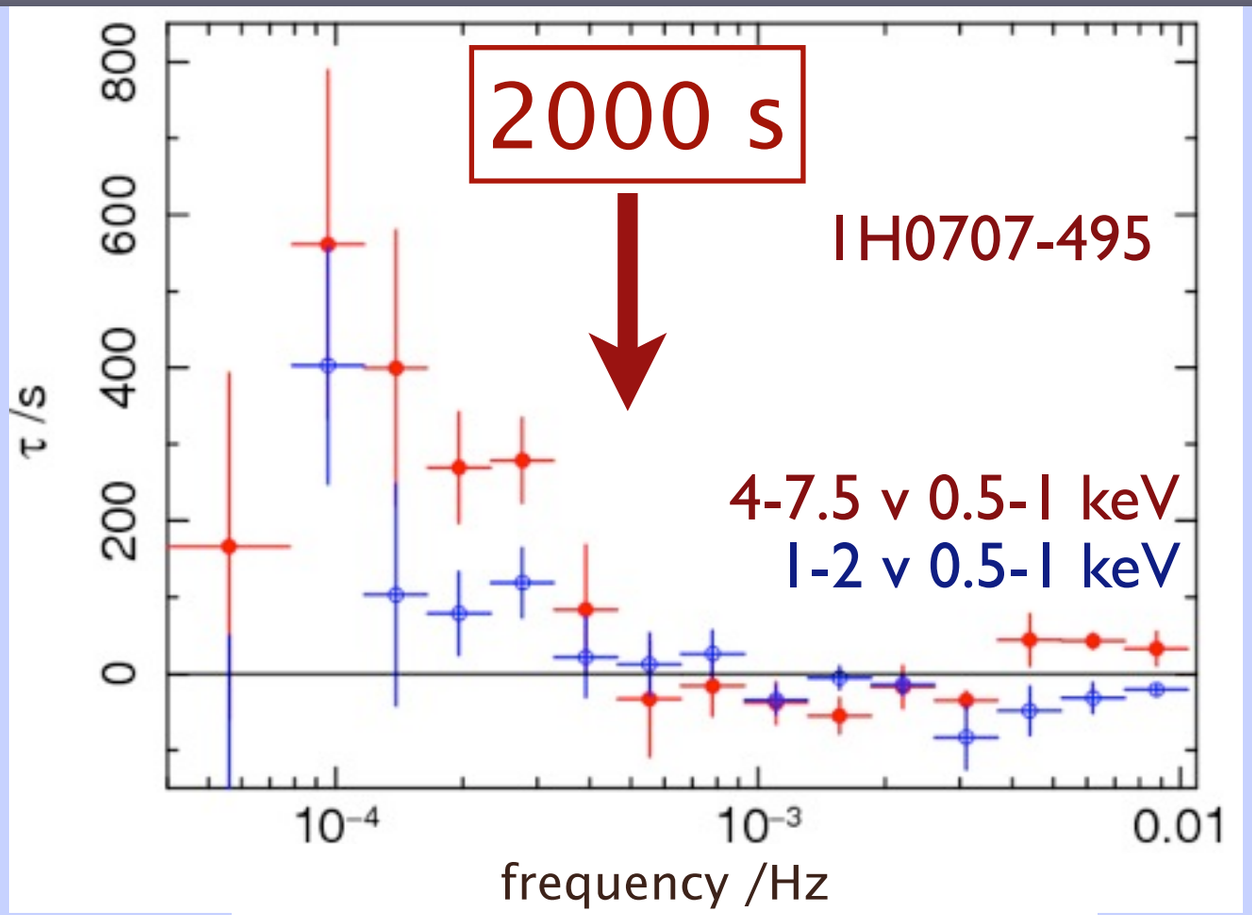
comparison of 1H0707-495 & Ark 564

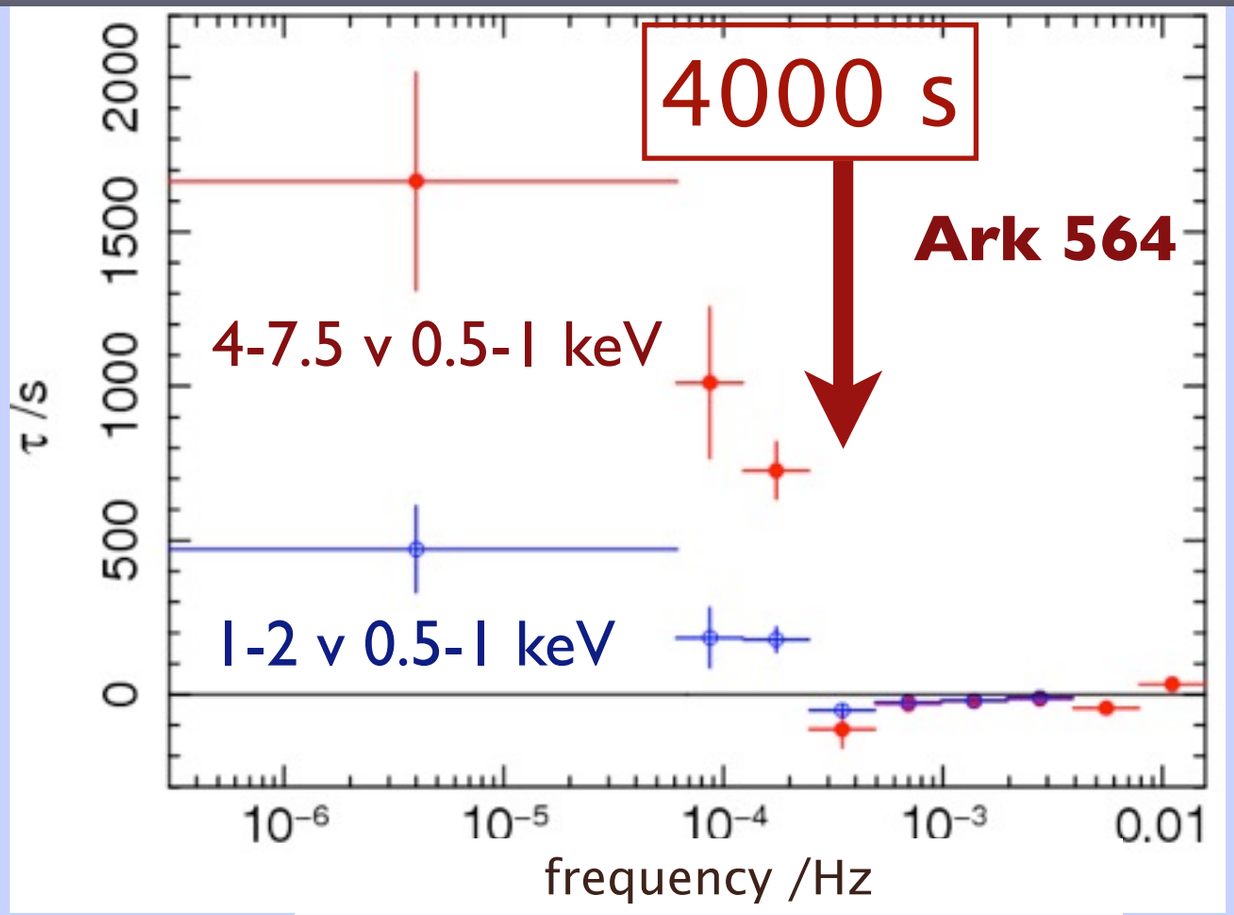




- The blurred model fits to 1H0707-495 require x9 Fe abundance
- Extreme, blurred FeL at 0.9keV claimed to produce negative lags
- But Ark 564 has no room for such extreme blurred line emission
- **Rules out the blurred line explanation for the lag spectrum**

The characteristic timescale



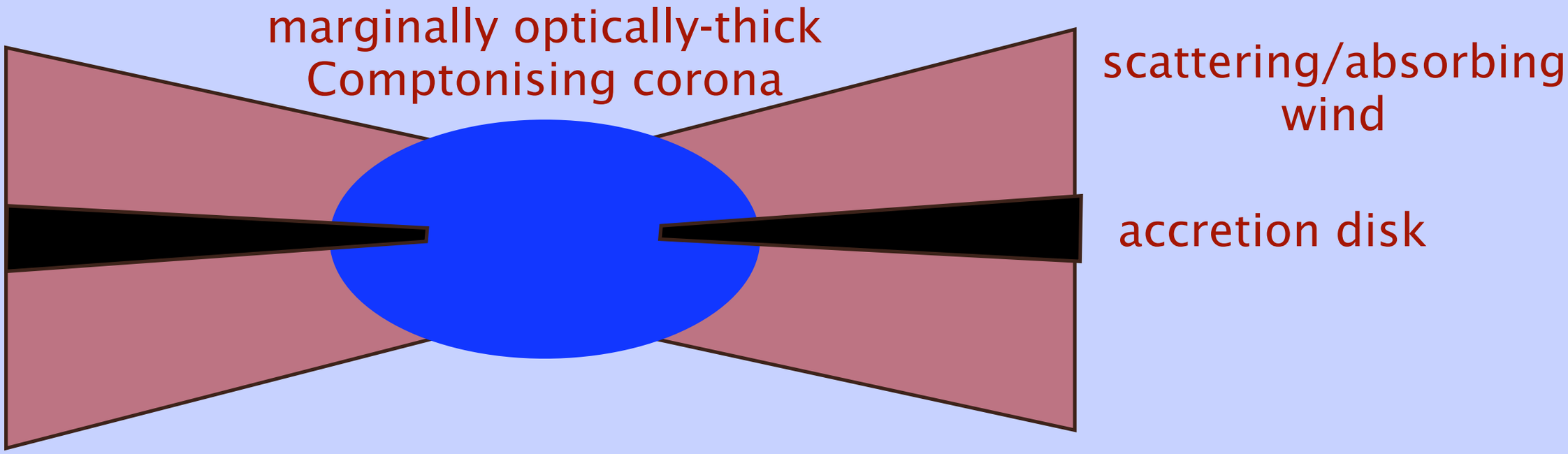


- Characteristic timescale > 2 ks
- Lag amplitude depends on energy but cutoff timescale does not!
  ⇒ **cutoff timescale is geometrical in origin**

  ⇒ light-travel length-scale >400 r_g ($M_{BH}=10^6 M_\odot$), >40 r_g ($M_{BH}=10^7 M_\odot$)
- Primary positive lags are probably not due to Comptonisation (cutoff timescale and lag value should be linked)

Comptonisation

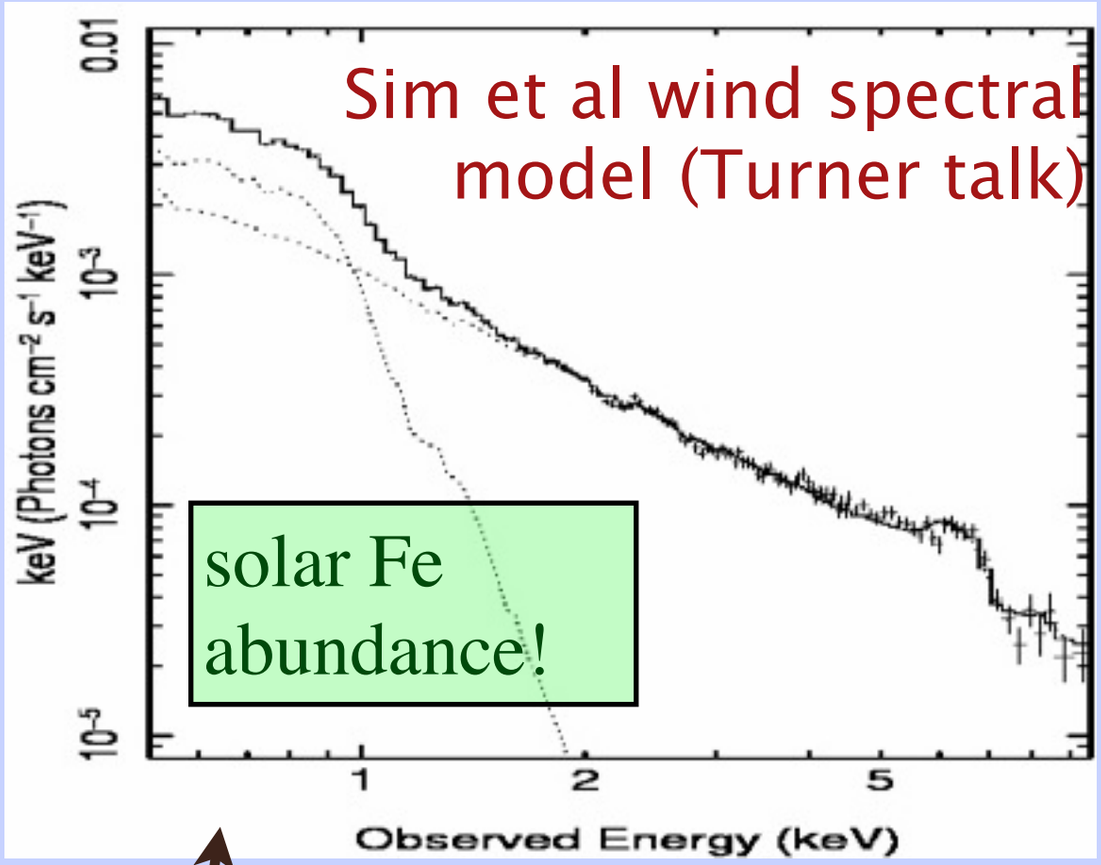
- Comptonisation time delays - must be present at some level
  - >2ks timescale require would require very extended Comptonising region
  - difficult to explain negative lags
  - lack of dependence of cutoff frequency on photon energy implies time delays determined by geometry
- But Comptonisation lags may modulate the lag spectrum at high freq
- Comptonising corona could be viewed as a unified inner part of the wind



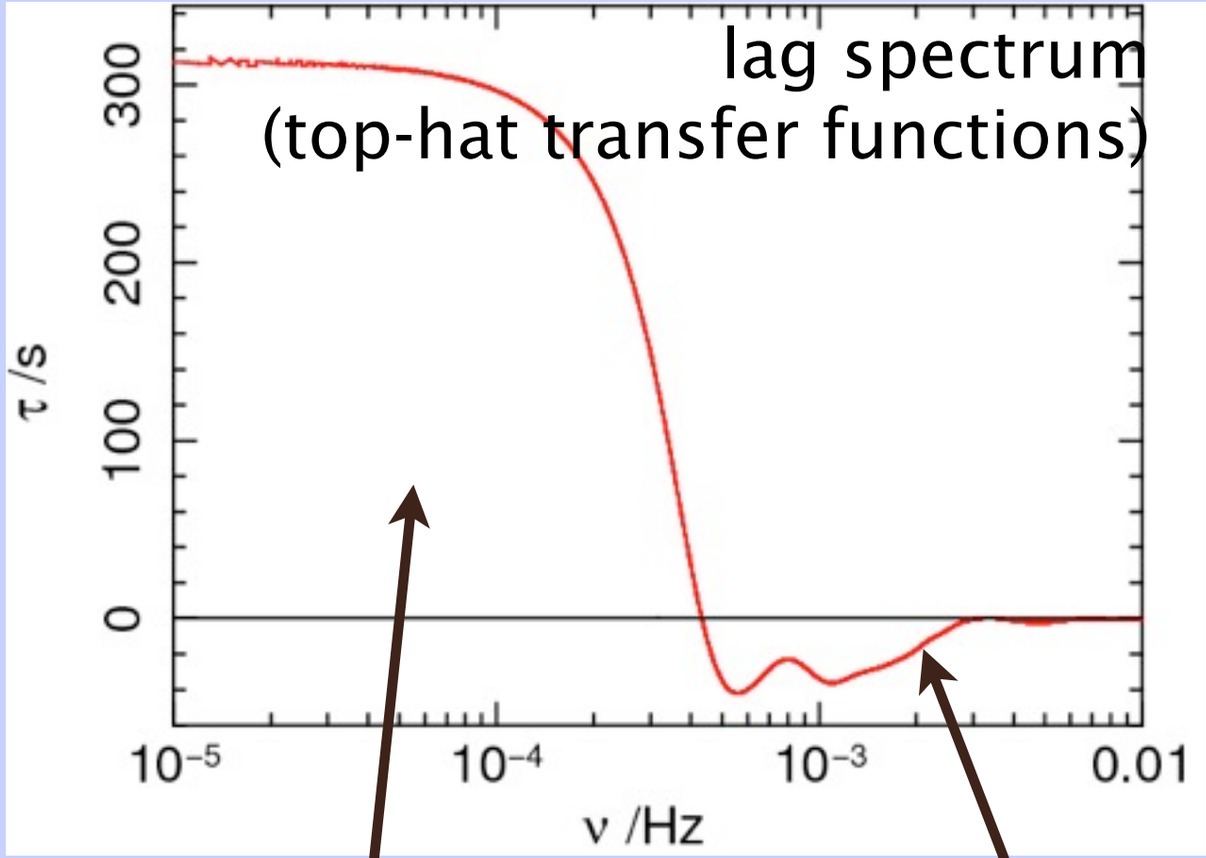
Summary

- **Reverberation signatures in Fourier lag spectra observed in both optical and X-ray AGN time series.**
- We see both the expected **frequency behaviour** and **energy behaviour** in X-ray data.
- Characteristic timescale > 2ks requires non-compact scattering length
- Timescale independent of energy ⇒ geometrical origin
- Ark 564 & 1H0707-495 have very similar lags but very different X-ray spectra - strong argument against blurred inner-disk reflection
- **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 directly 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,

reverberation models: 1H0707-495



- Sim et al wind radiative transfer model fits 0.5-10 keV
- Clumpy wind models to fit >10keV (Jane Turner talk)



- Primary positive lags and frequency cutoff caused by hard-band reverberation from material > 2ks distant
- Extended negative lags require ~300s lags in soft band