X-ray signatures of circumnuclear gas in AGN

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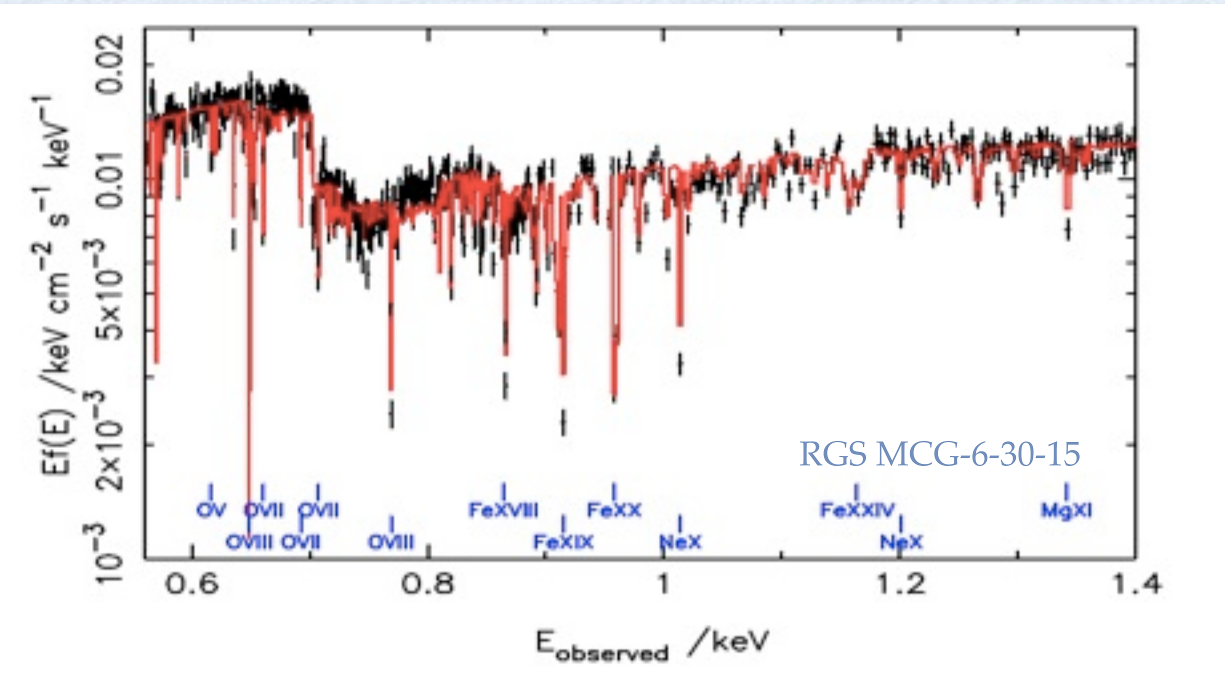
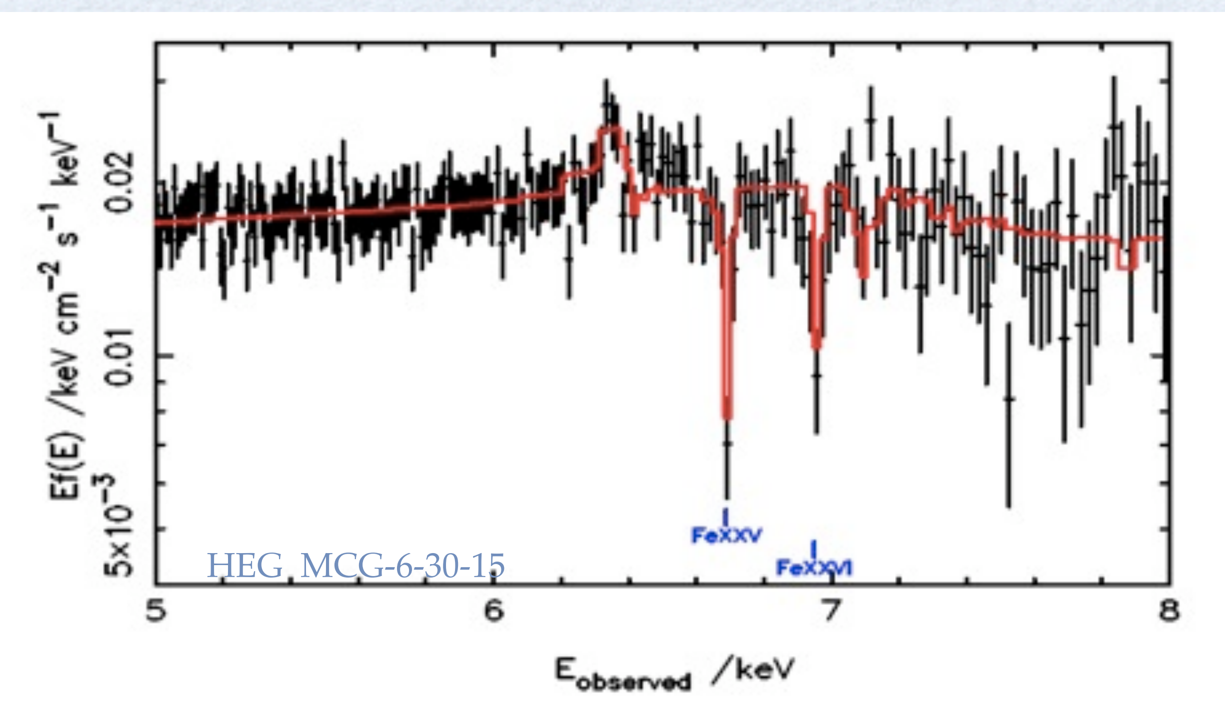
movie: radiatively-driven AGN wind by Daniel Proga

OVERVIEW

- X-ray observational results
- Absorption models for observed X-ray properties of AGN
- Predictions from a Compton-thick Wind

X-ray signatures of circumnuclear gas





Miller, Turner & Reeves 2008

Intrinsic X-ray absorbers in most nearby AGN (e.g. Blustin et al 2005, McKernan et al 2007)

Multiple X-ray zones

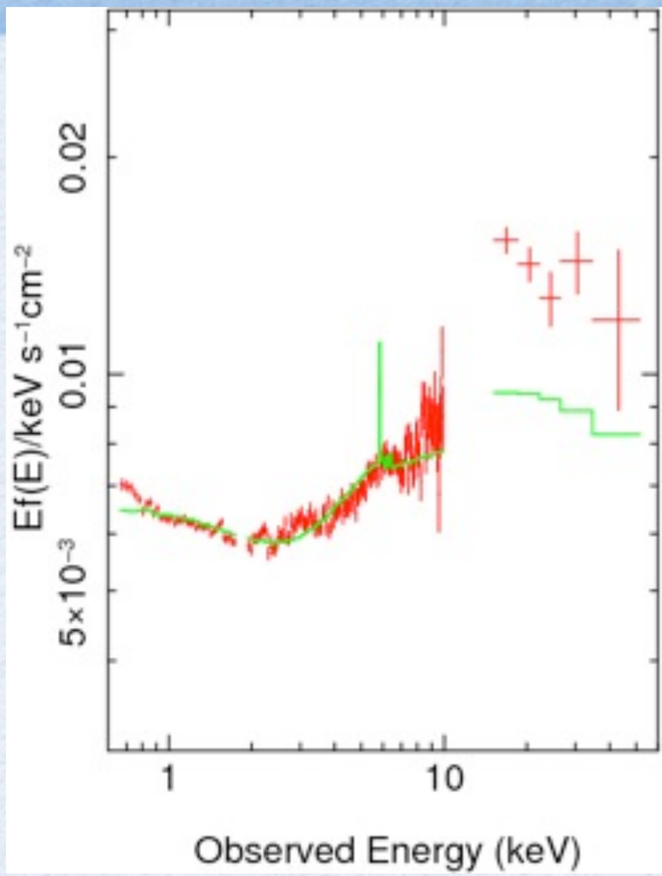
X-ray gas covers ~6 orders mag in ξ

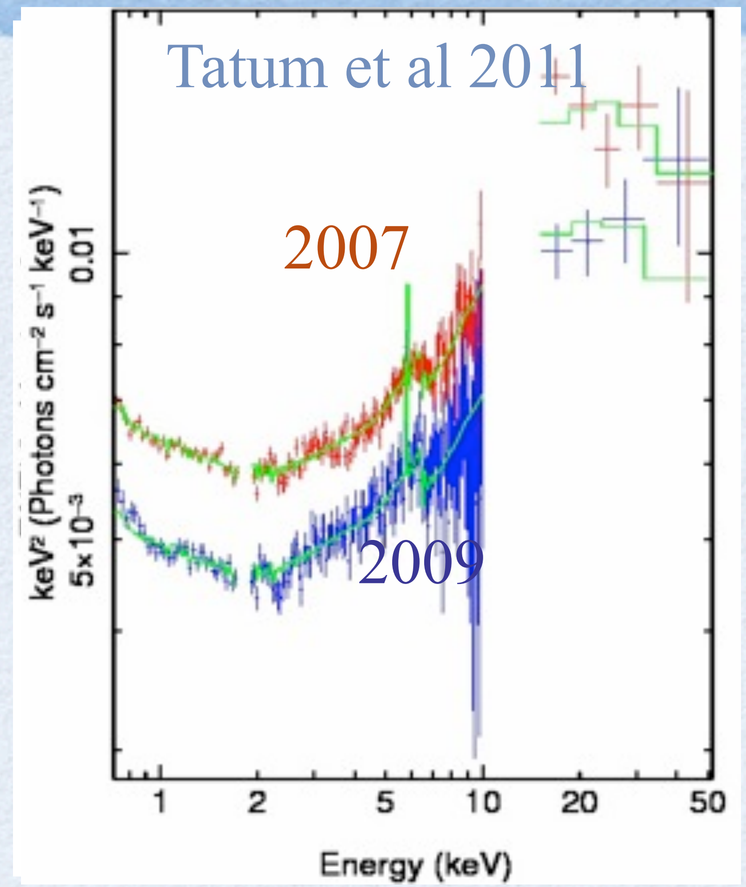
Columns 10^{20} - few x 10^{24} cm^{-2}

Few hundred - few thousand km/s outflow, low N_H/ξ zones

Few thousand - tens of thousands of km/s for highest N_H/ξ zones (e.g. L. Miller et al 07, Tombesi et al 2010)

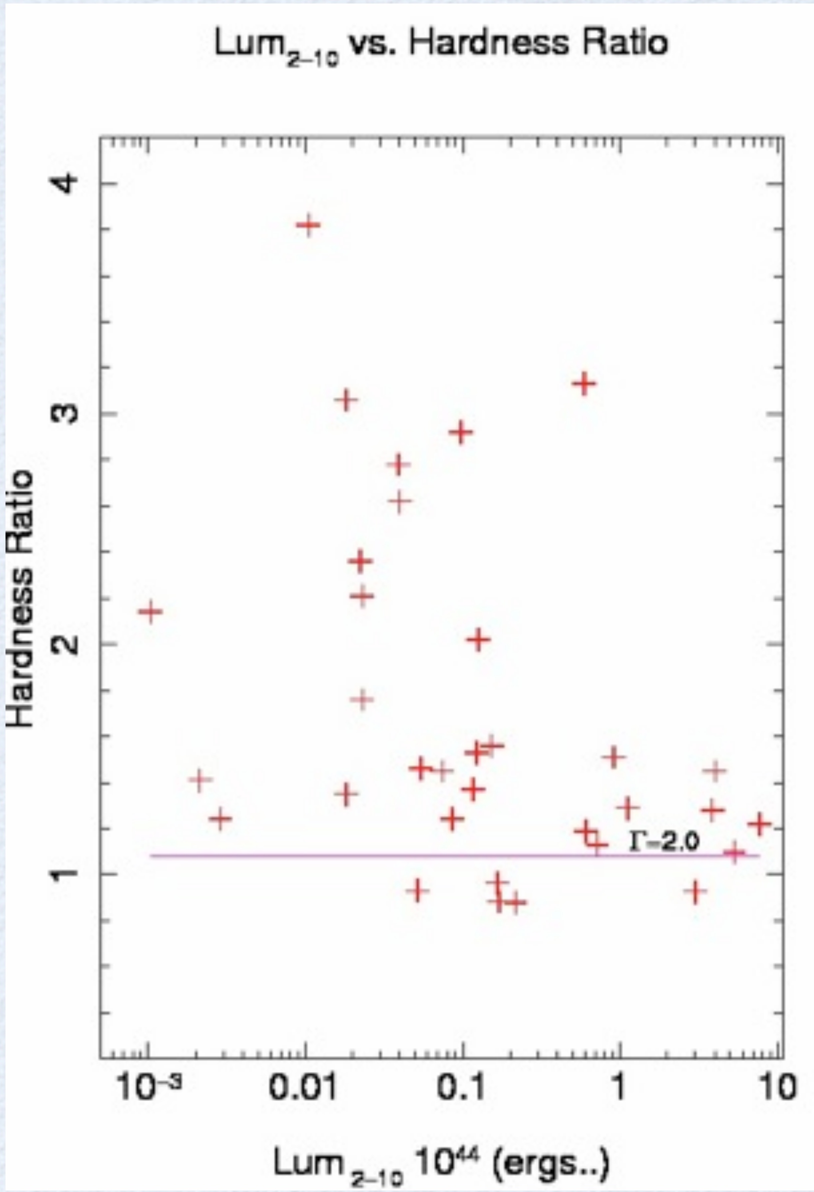
Evidence for Compton-thick gas in LOS





Tatum et al 2011

15-50 keV/2-10 keV



Compton-thick gas partially covering source

type 1 AGN, 1H0419-577 (Turner et al 2009)

Also: PDS 456 (Reeves et al 2009)

High flux above 10 keV:

NGC 4051 (Terashima et al 2009)

MCG-6-30-15 (Ballantyne et al ’03, Miniutti et al ’07)

Mrk 335 (Larsson et al ’08)

BAT-selected sample observed using Suzaku, PIN/XIS ratios only

Hardness ratio relative to slab subtending 2π steradians

Absorption Models

What do we have?

A lot of evidence for absorption in and out of the line-of-sight

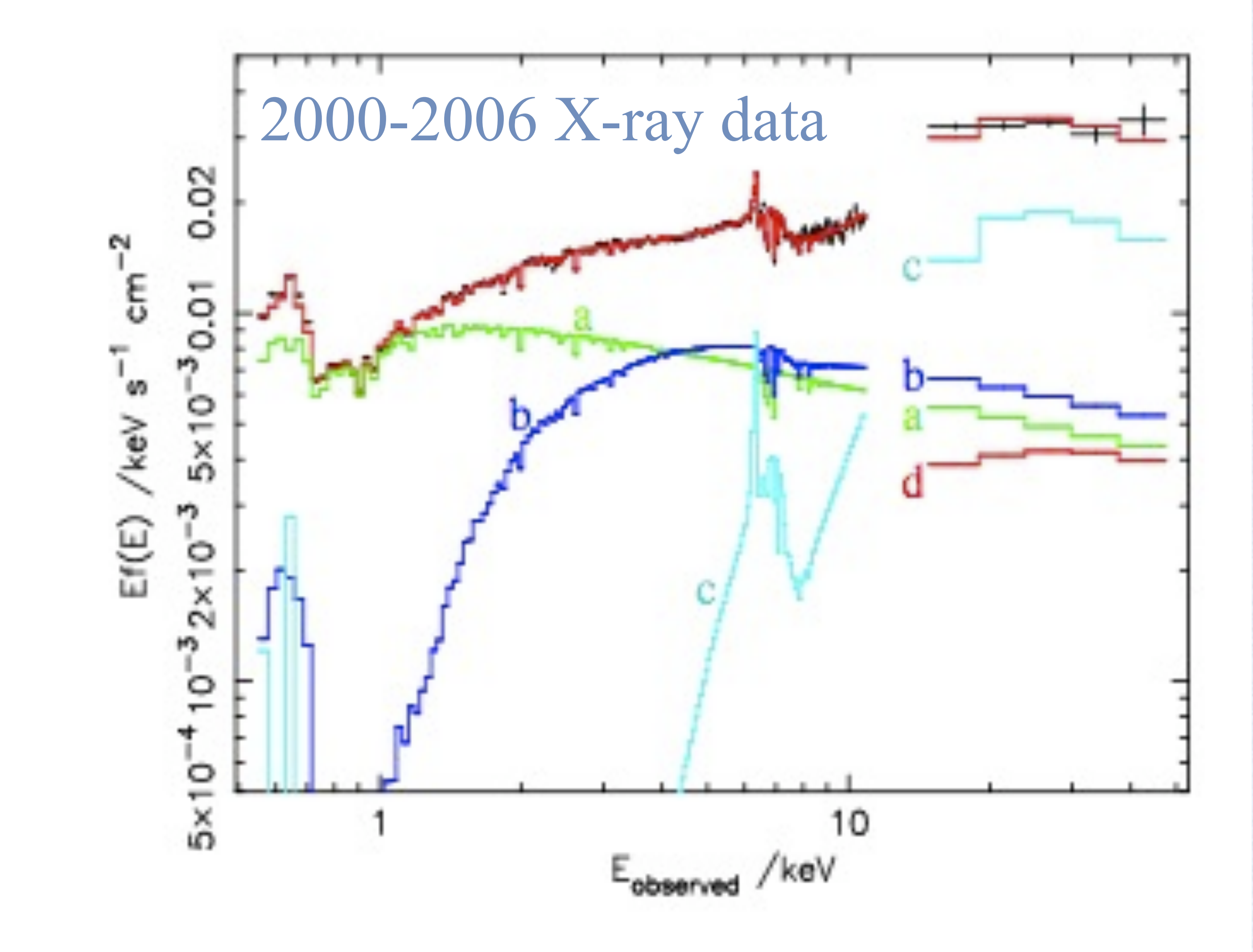
Natural extension of UV partial-covering absorber complex

Gas is outflowing

Wind? -inevitable for sources accreting at high fraction of Eddington (King 2010)

Build spectral/variability model

No Source Left Behind



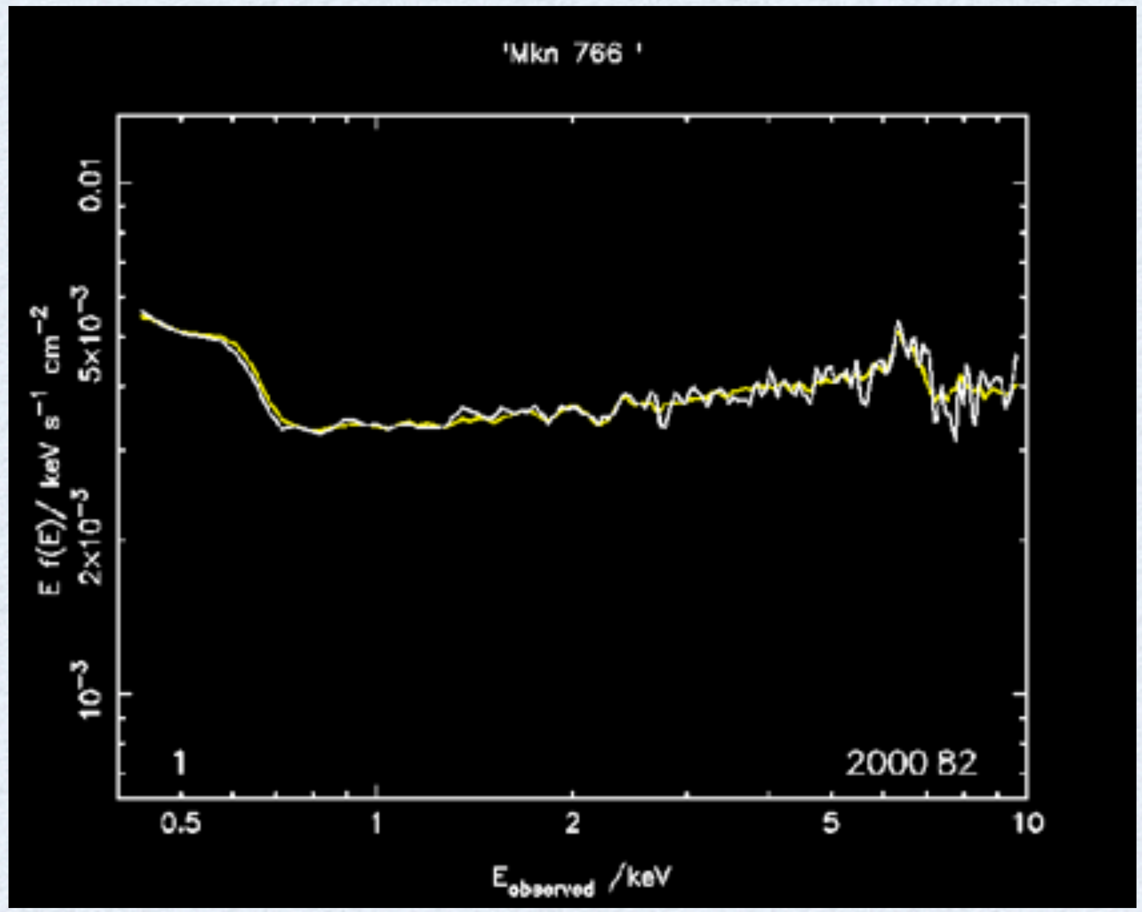
Absorption Models fit MCG -6-30-15 (Miller et al. 2008)

- **PL absorbed by low column complex**
- PC PL absorbed by 4E22
  - High state 50% covered
  - Low state, almost entirely covered
- **Reflection**

Fe K emission from absorber complex can be fairly weak

Miller et al 2009 & Yaqoob & Murphy - must consider all sources of opacity and cannot ignore line self-absorption with τ~3.5 at Fe Kα

Spectral Variability



Mrk 766
Miller,et al ‘07,
Turner et al ’07

Deep Fe K edge

Fe XXV, XXVI outflow
13,000 km/s

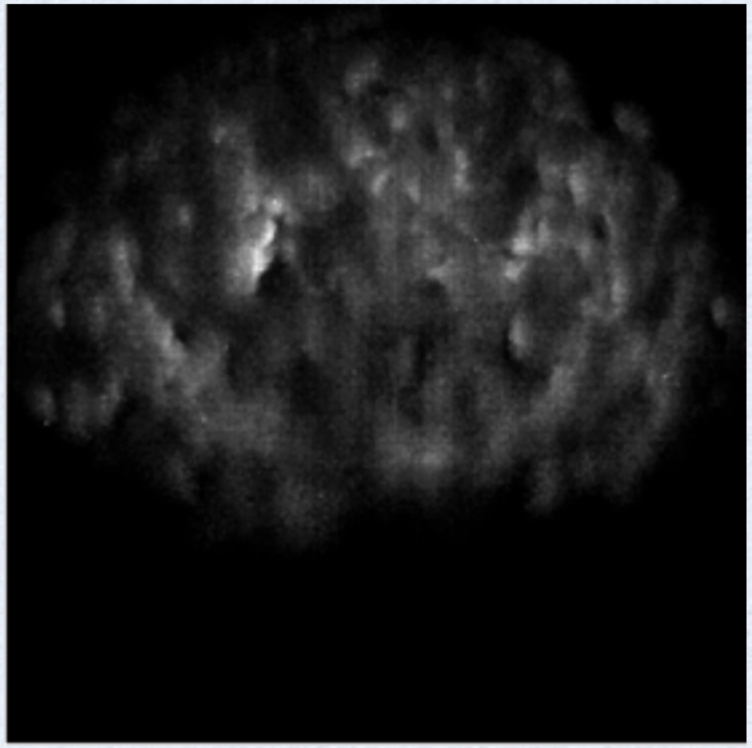
Can model as
variable covering

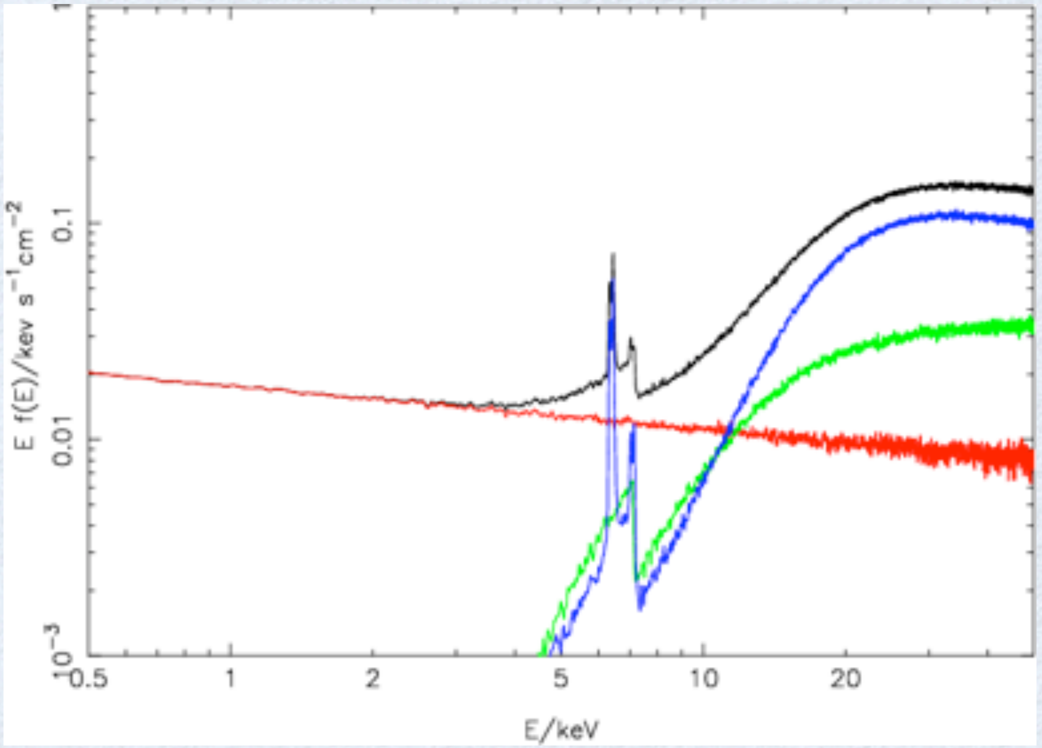
Variable covering by large columns in

Mrk 766	0-60% (Miller et al ’07, Turner et al ’07)
NGC 3516	30-70% (Turner PDS et al ’08)
MCG-6-30-15	50-100% (Miller et al ‘08)

Supported by Risaliti et al 2009a, 2009b - evidence for obscuration/de-obscuration in NGC 1365

Spectral Variability





Monte Carlo simulation (L. Miller) of constant continuum source surrounded by neutral absorbing clouds

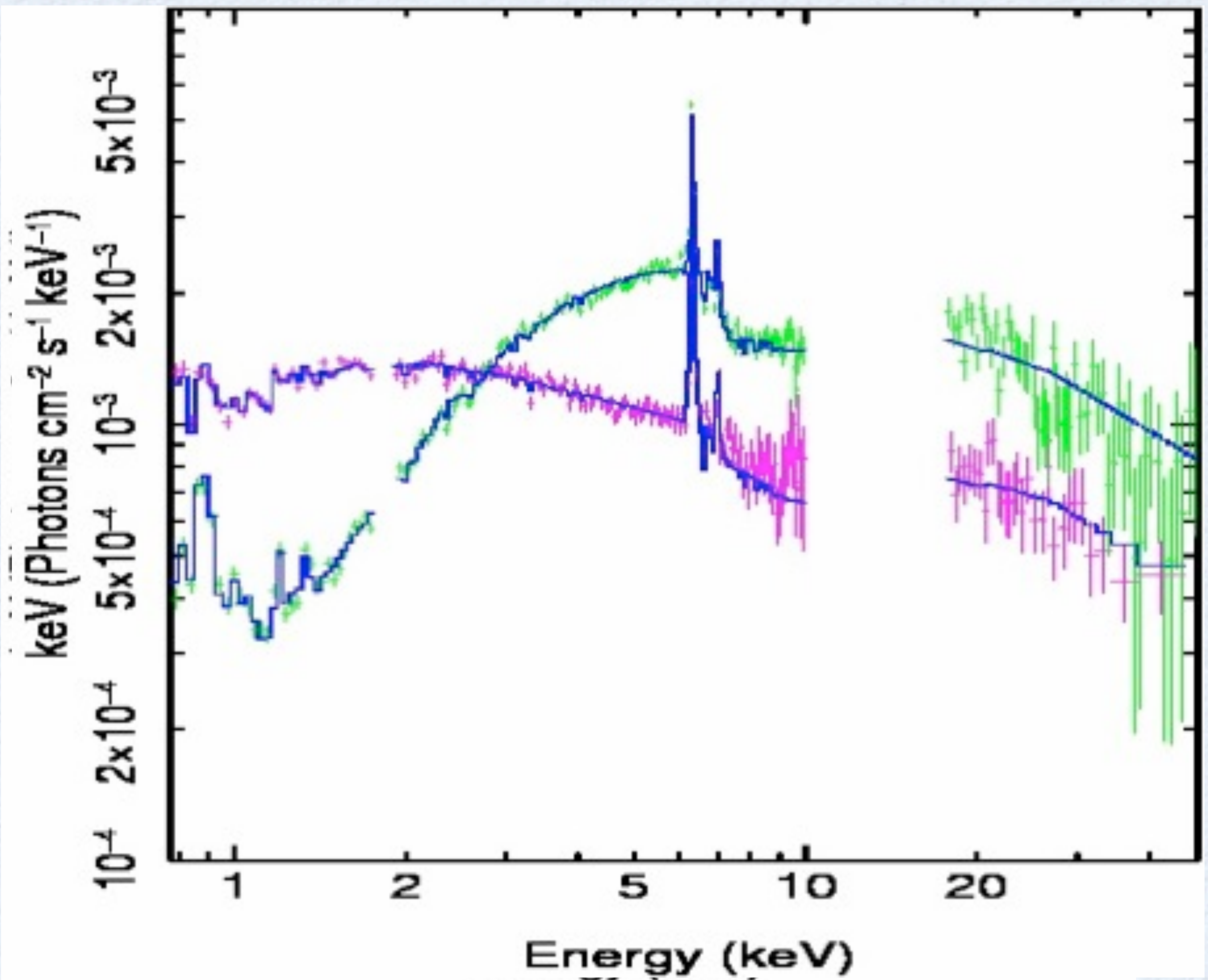
Expect flux and spectral variability from absorption changes

Timing behavior depends on whether low state dominated by absorbed fraction or by reflected component

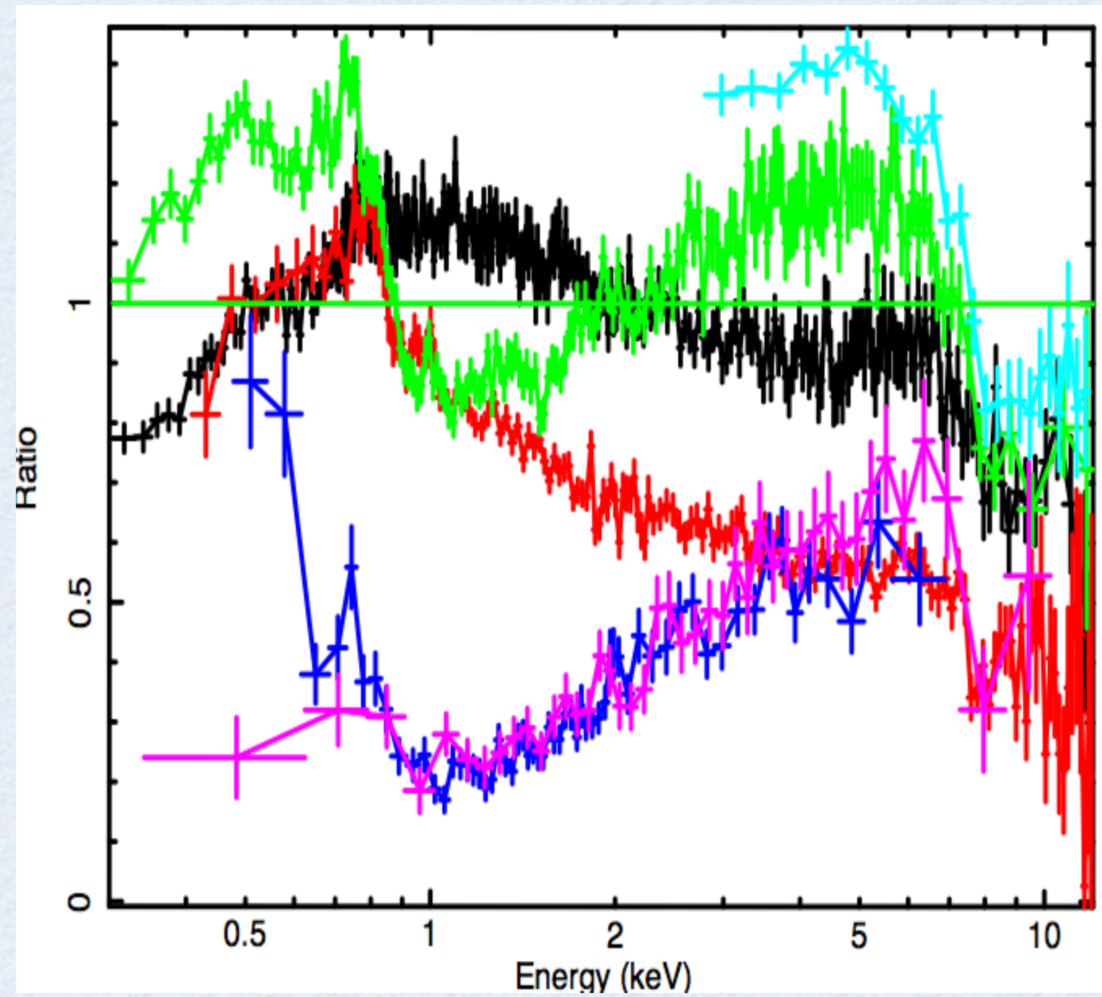
PCA offset component dominated by reflection in some AGN, absorbed state in others, timing results break degeneracy

Sources that can only be explained by absorption variations

Turner et al. (2008)



Reeves et al. (2009) & Behar et al. (2010)



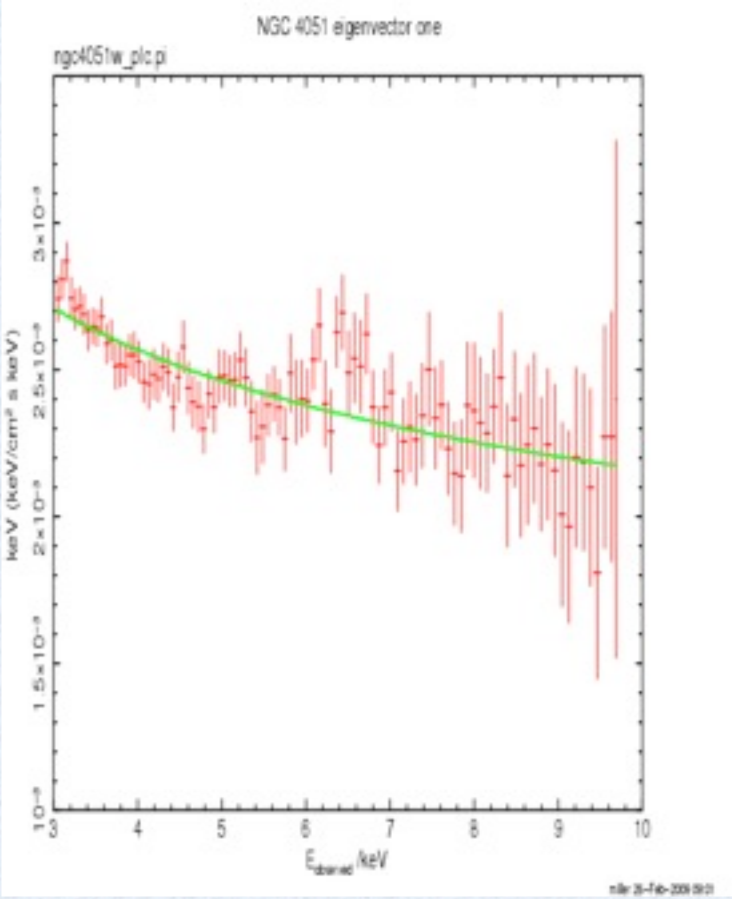
NGC 3516 and PDS 456 show some hard high states

Variations in los covering ($N_H > 10^{23}$ cm^{-2}, p_{cov}=40-70 % (3516) and 20-80%(456) req

Absorbing clouds must be compact (within BLR) and close to source (clumpy disk wind?)

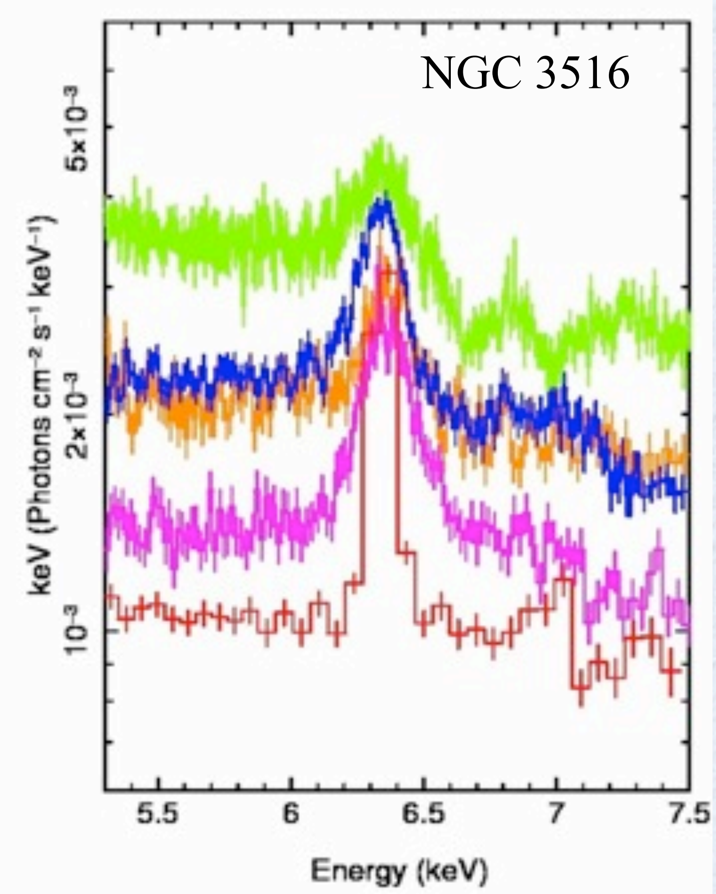
Not a simple ξ change (cf Mehdipour et al 2010) although ξ changes are expected and seen

Broad Fe lines in Seyferts

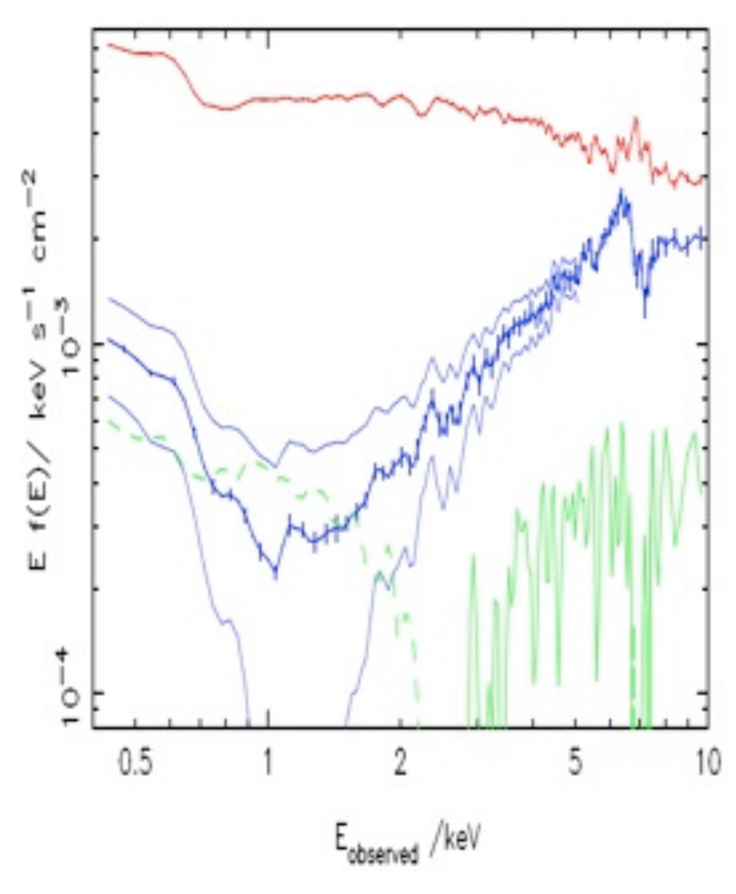


NGC 4051 variable component

Miller et al 2010



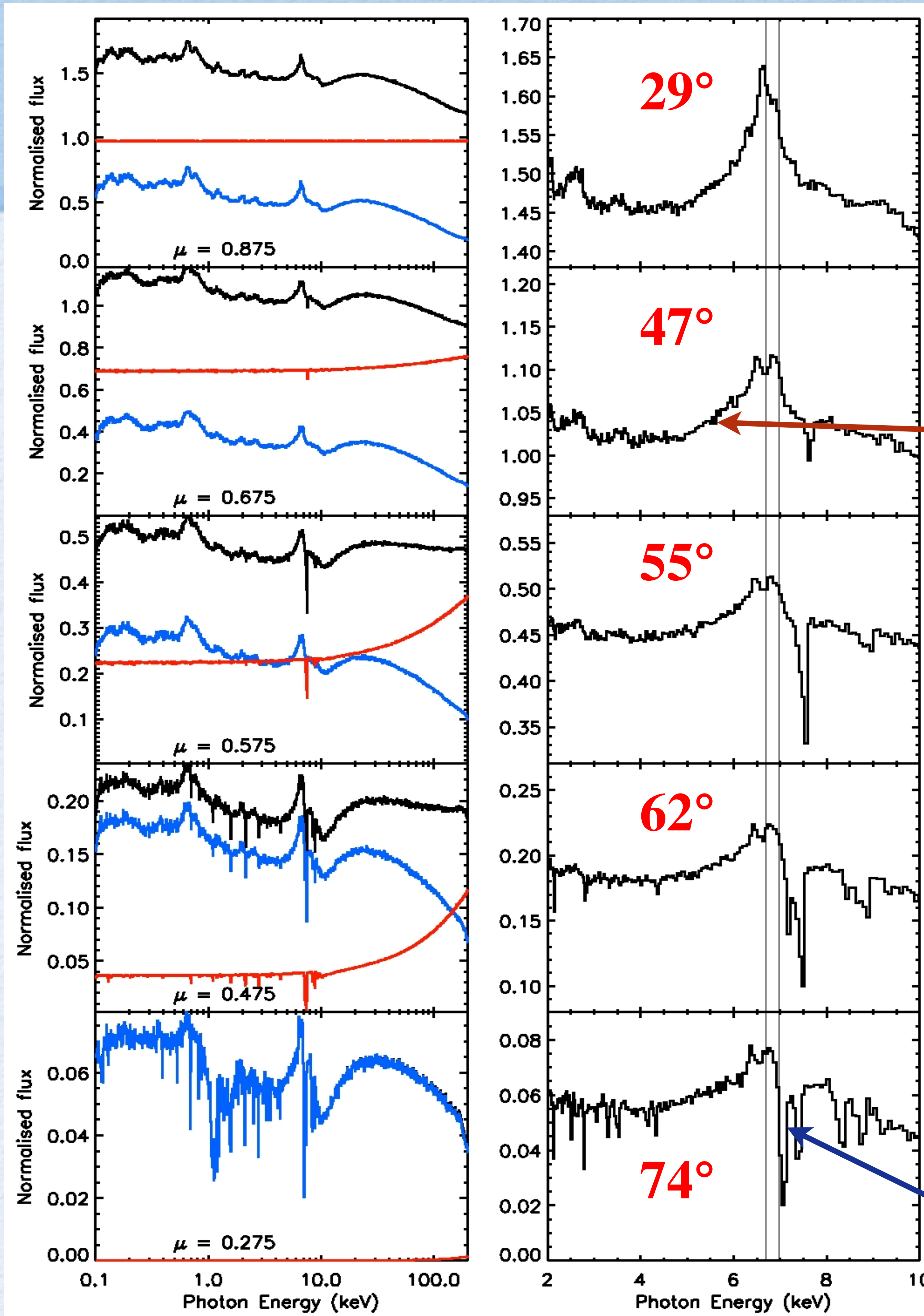
Turner et al 2010



Mrk 766 Miller et al 2006

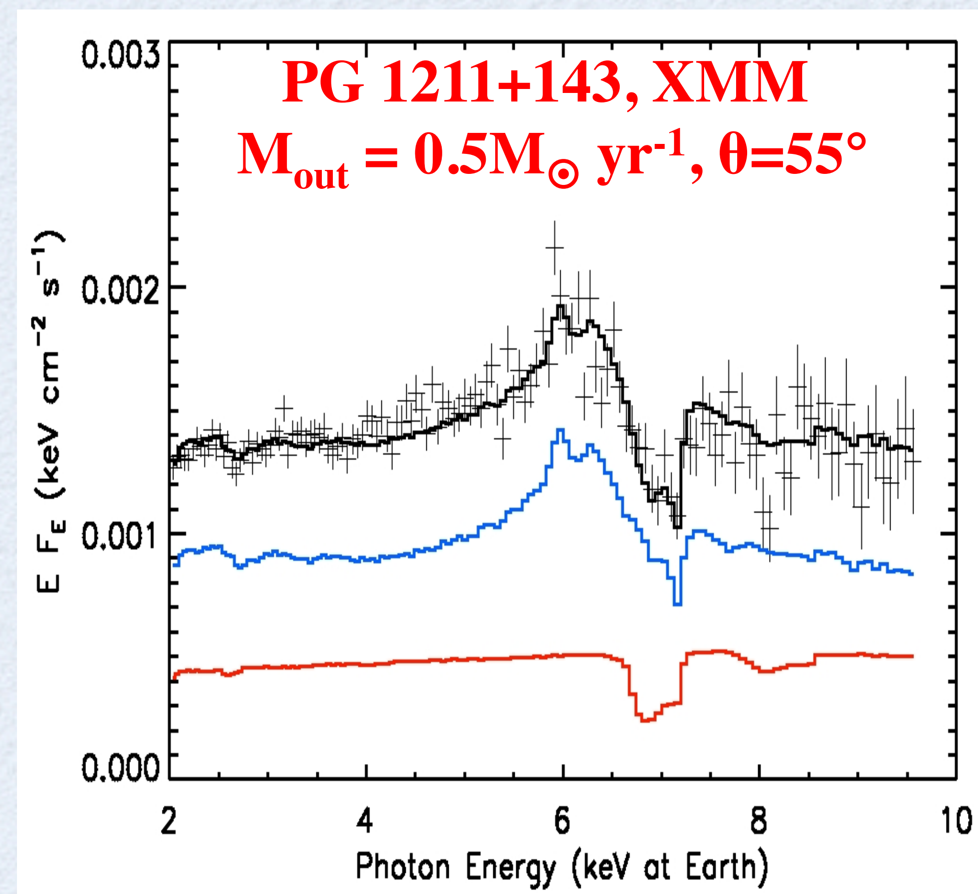
Modest broad components evident after absorption modeled (also see Guainazzi et al 2010, Patrick et al 2010)

Wind predictions for line emission
(Sim et al. 2010a,b)



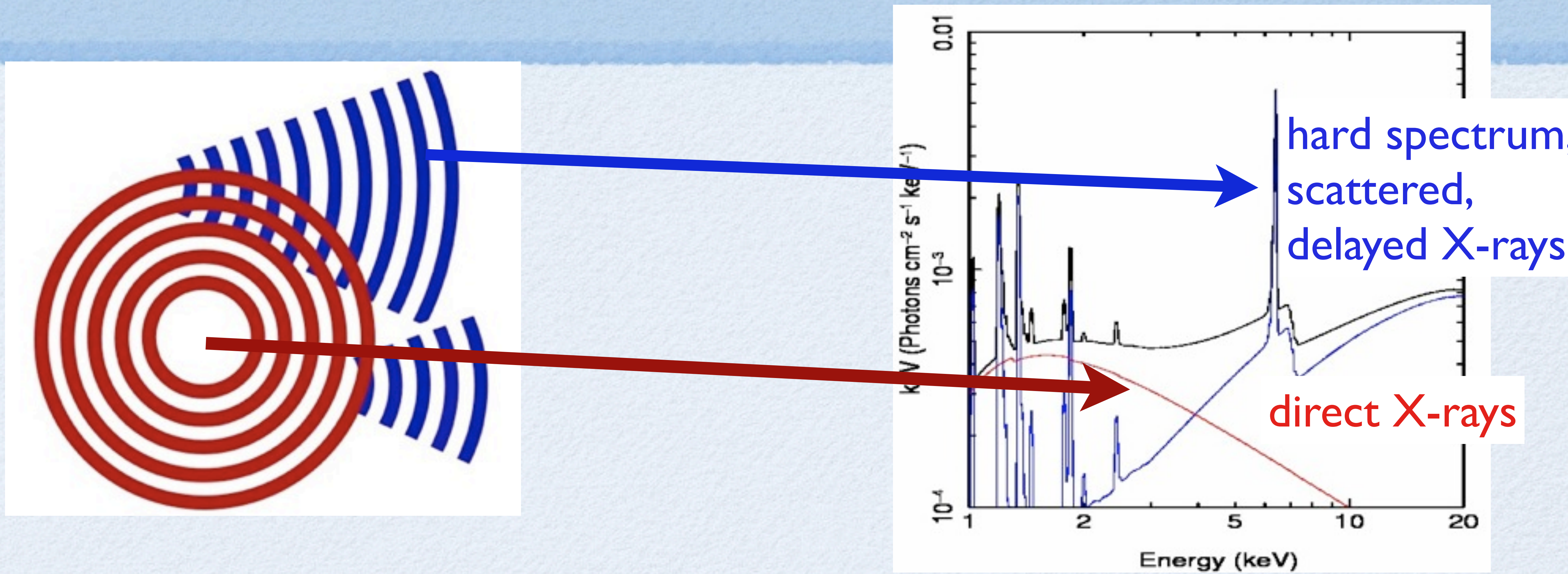
The outflow ***detected*** *in absorption lines predicts (modestly) broadened Fe K emission*

"red wing" produced by scattering and absorption - not by GR effects!



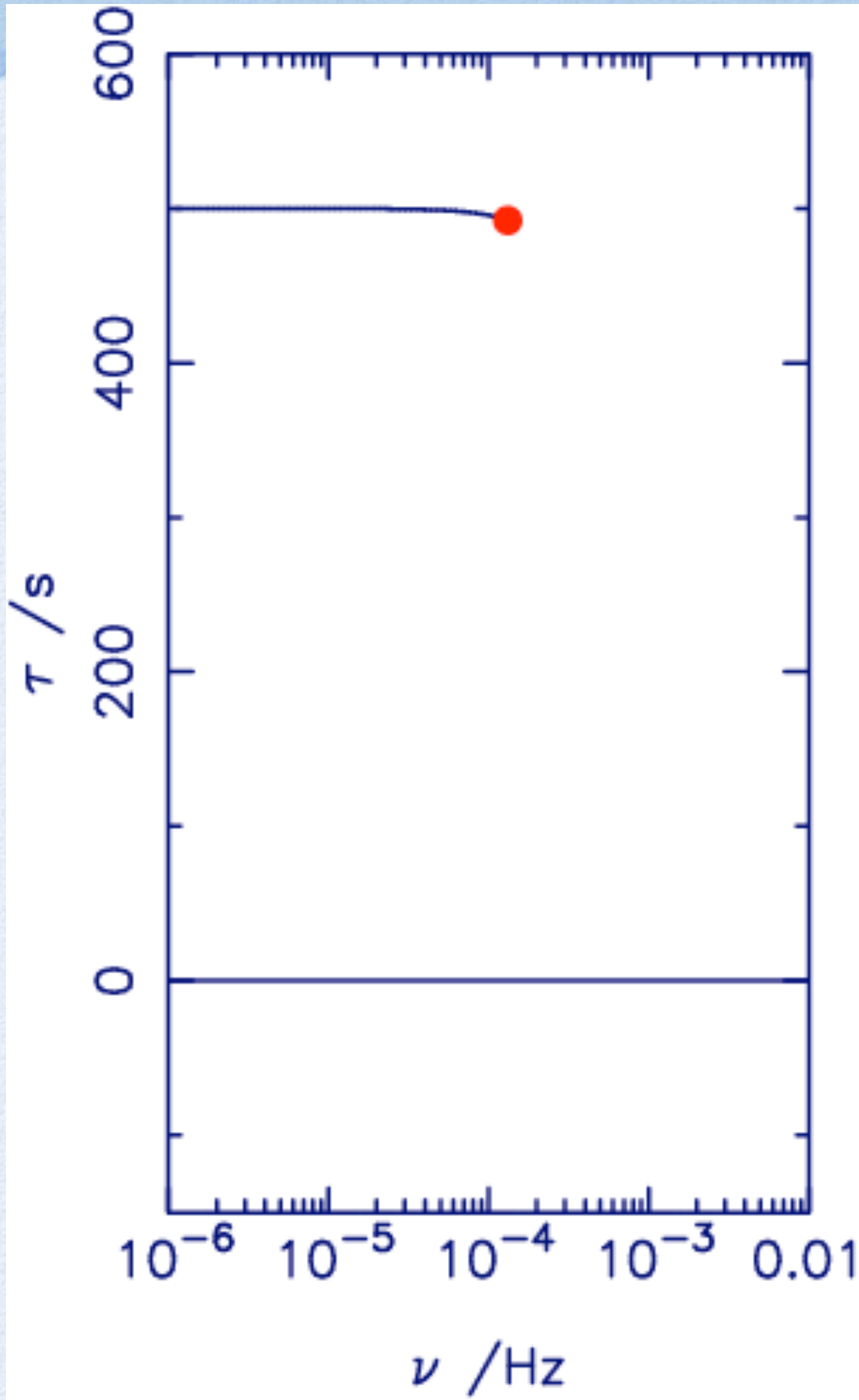
edge and blue-shifted Fe Kα absorption

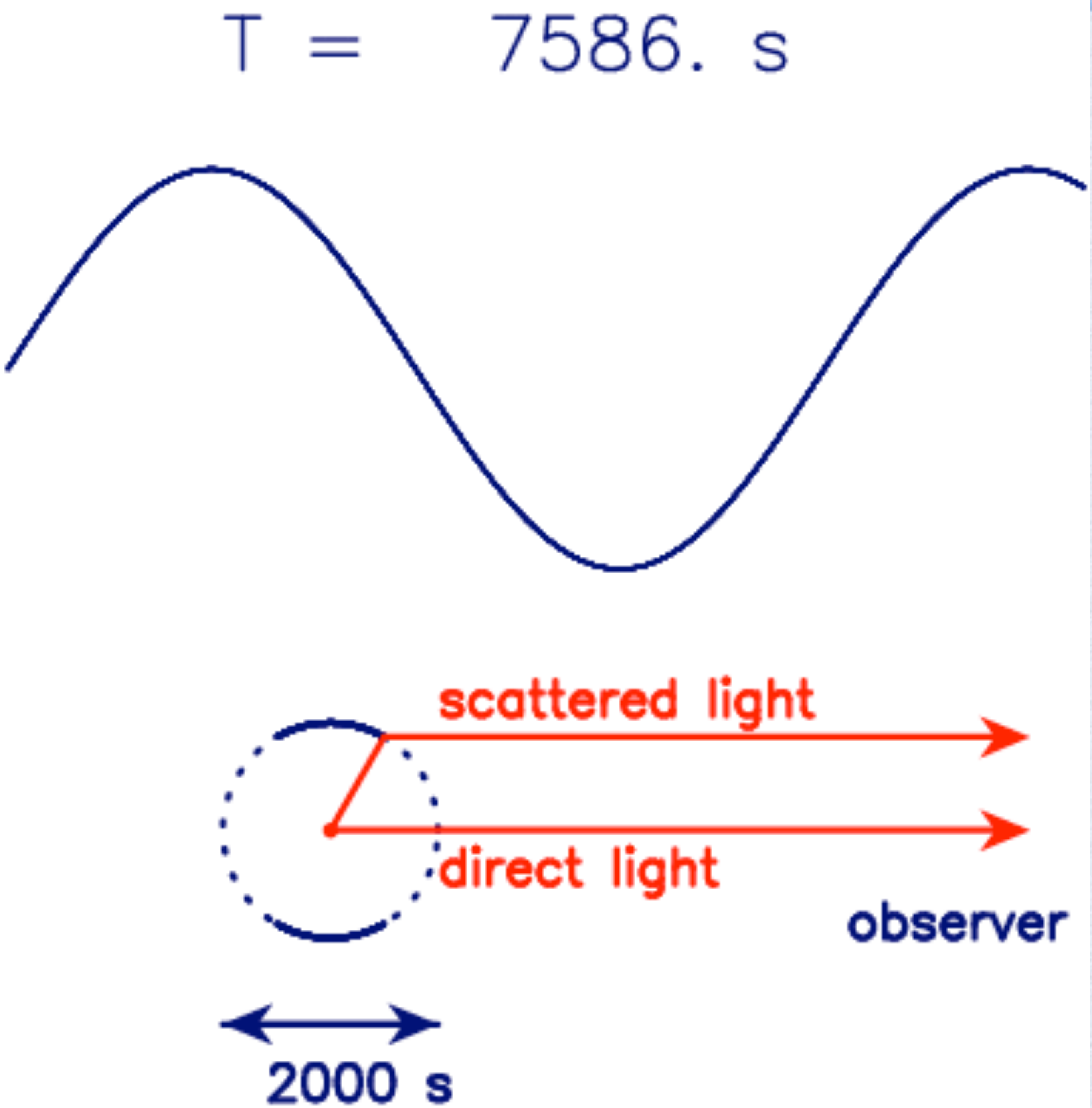
X-ray Reverberation



- reverberation between optical continuum and emission lines principal method of BH mass measurement in AGN
- can measure reverberation between continuum in different X-ray energy bands, because reflection is energy-dependent
- key difference compared to optical reverberation is that we have to deal with signals where the reflected and direct components are mixed together, we cannot separate them spectrally
- We measure the signal by estimating the cross-band power spectrum (using max-likelihood analysis based on CMB methods), enabling us to plot the “lag spectrum” the time delay as a function of frequency of the source variations

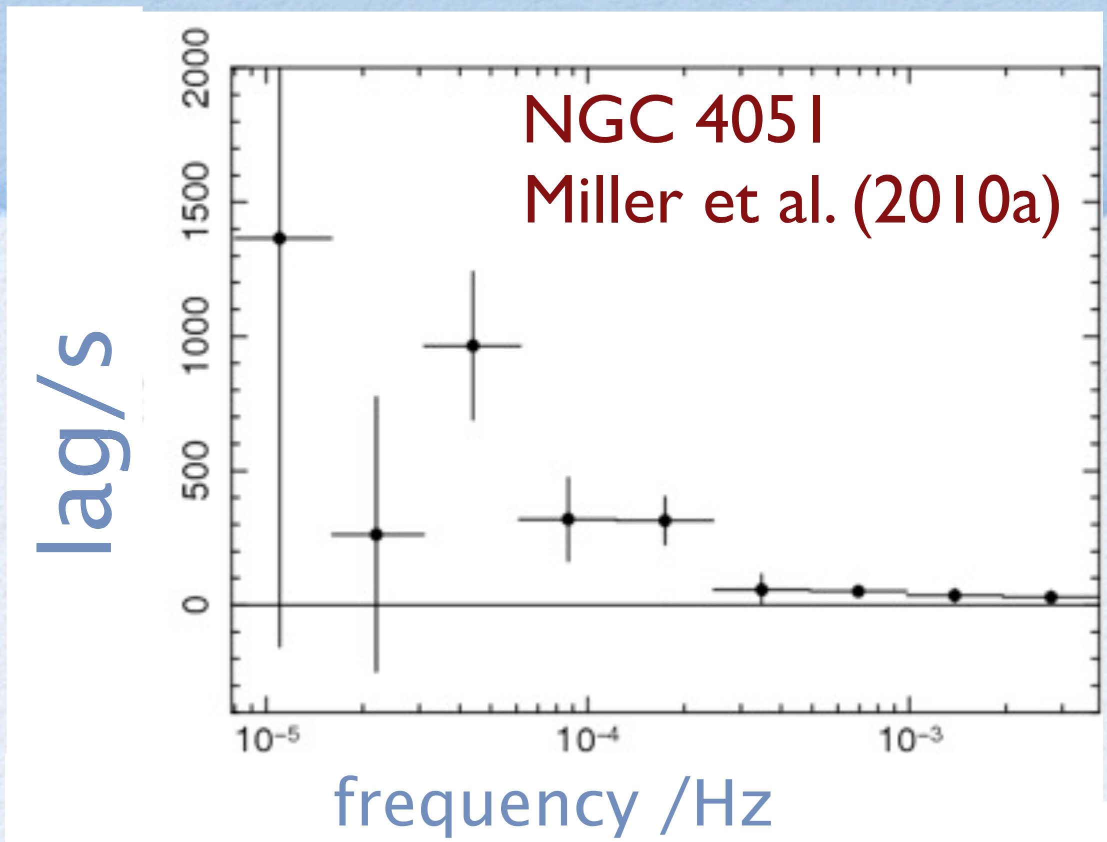
Reverberation Fourier Analysis

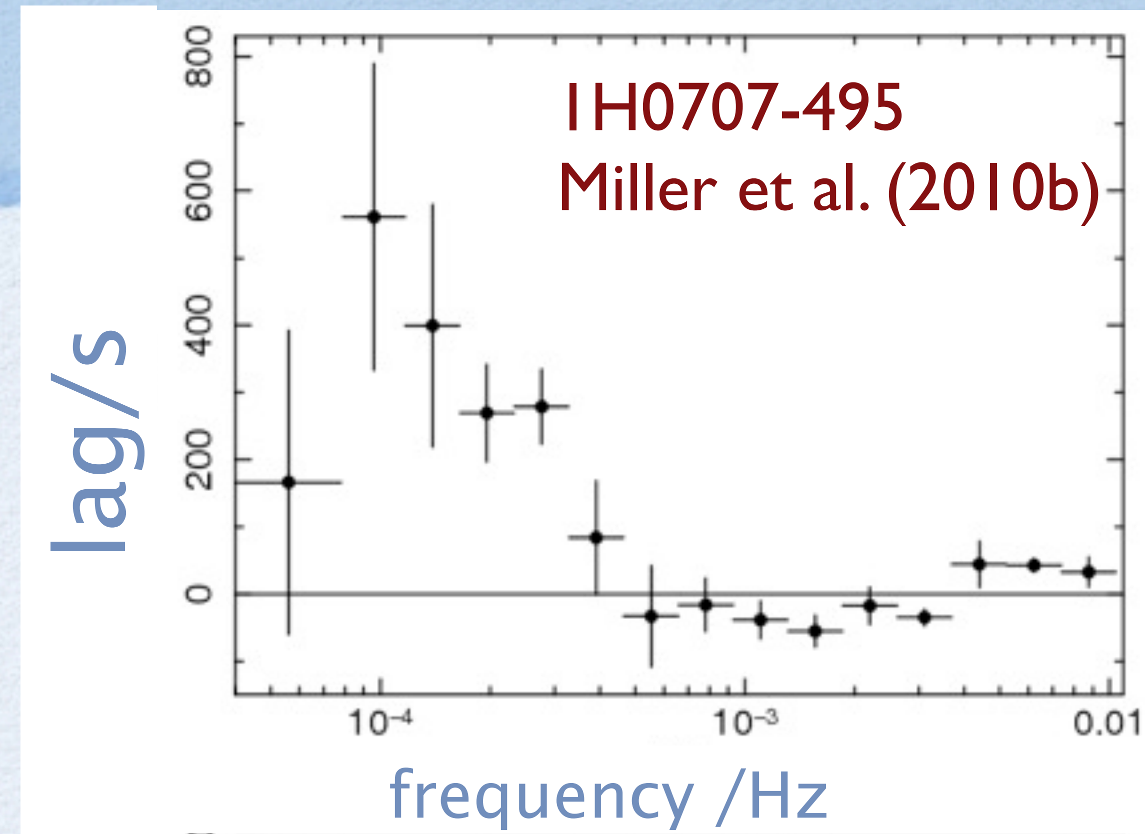


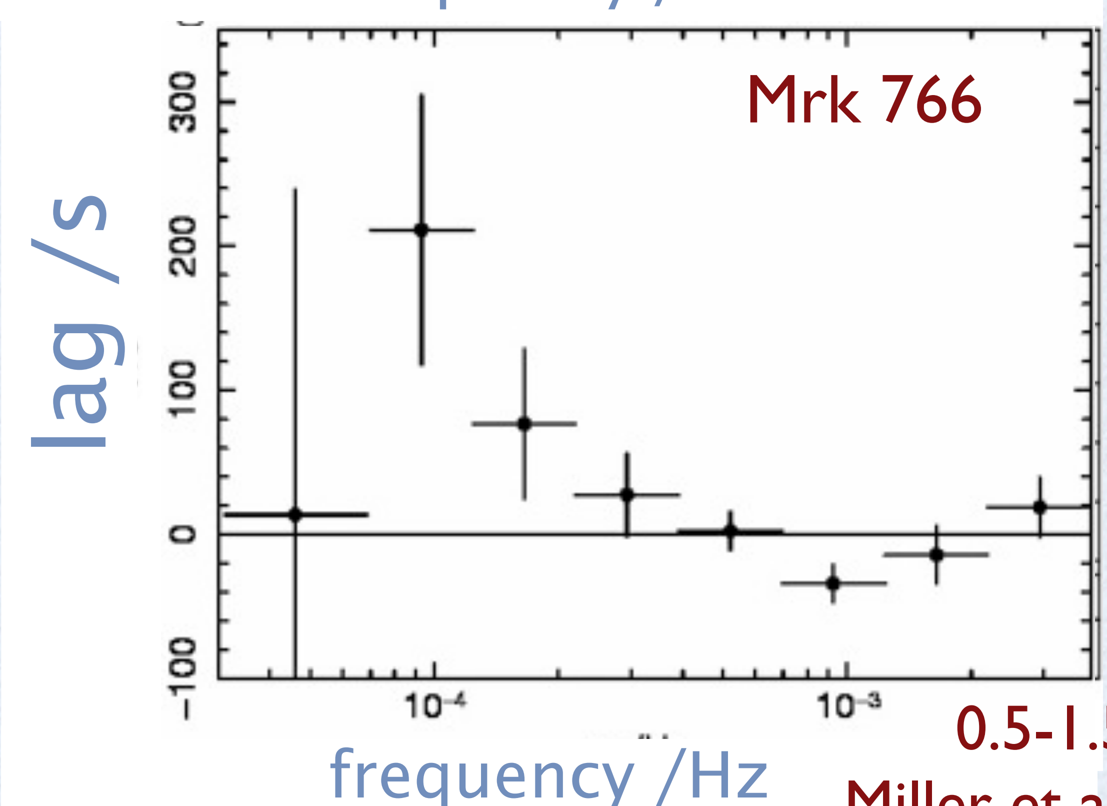


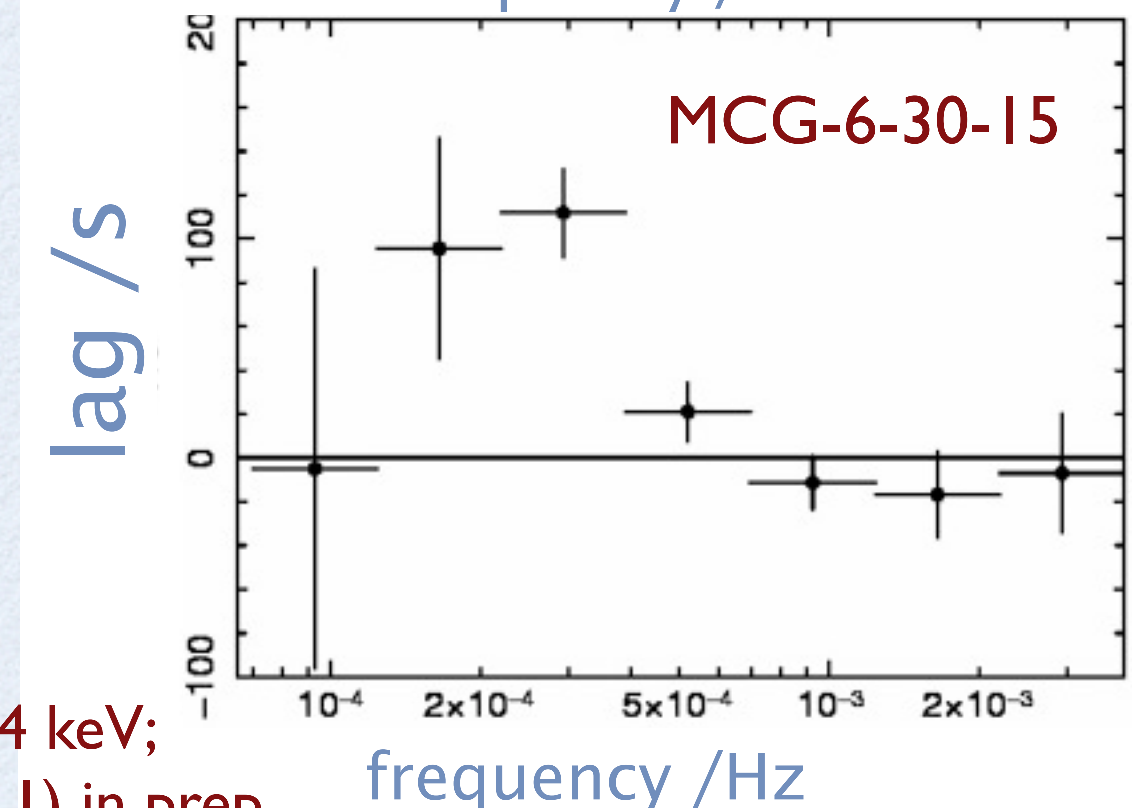
thin scattering shell
partial covering

X-ray reverberation in AGN







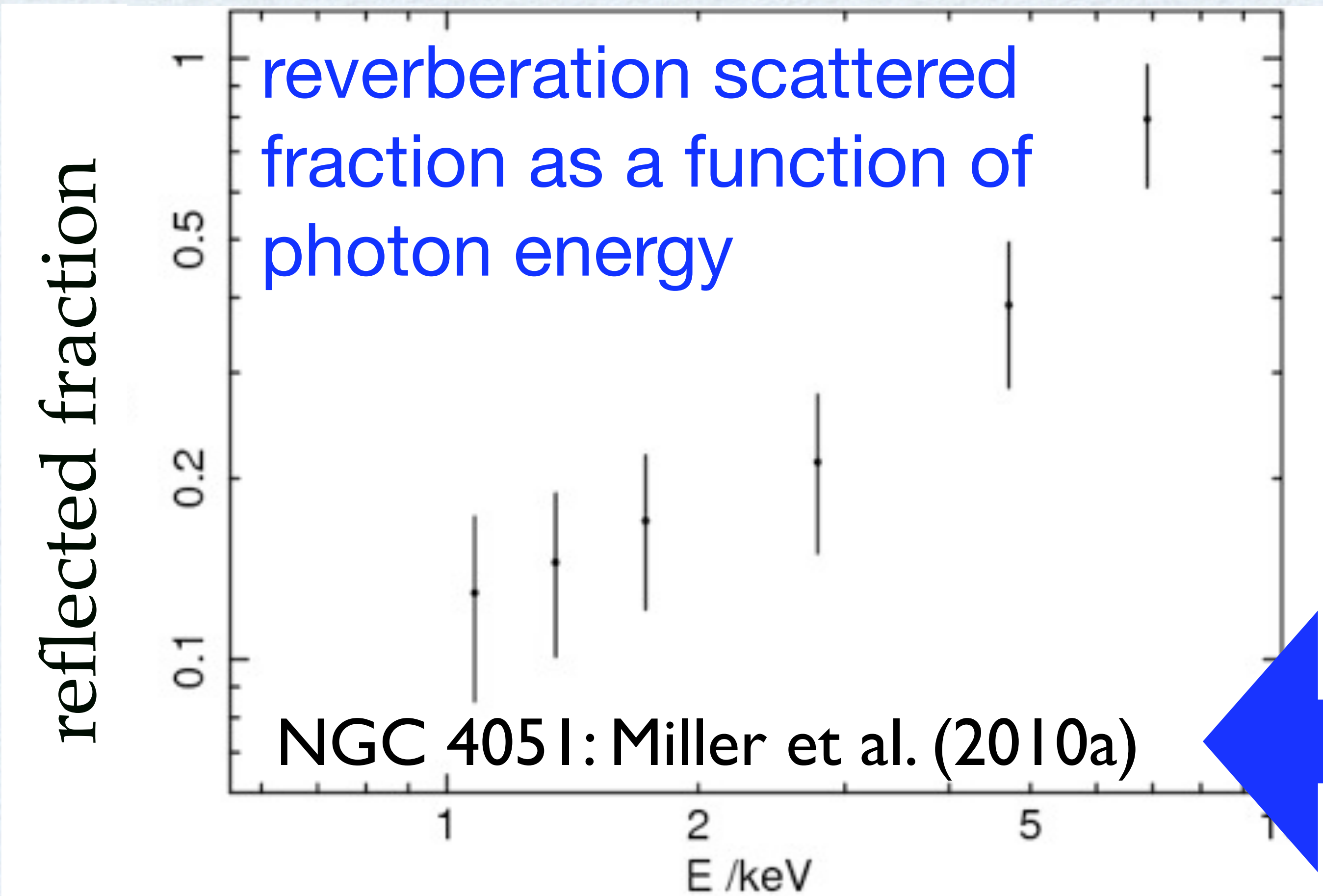


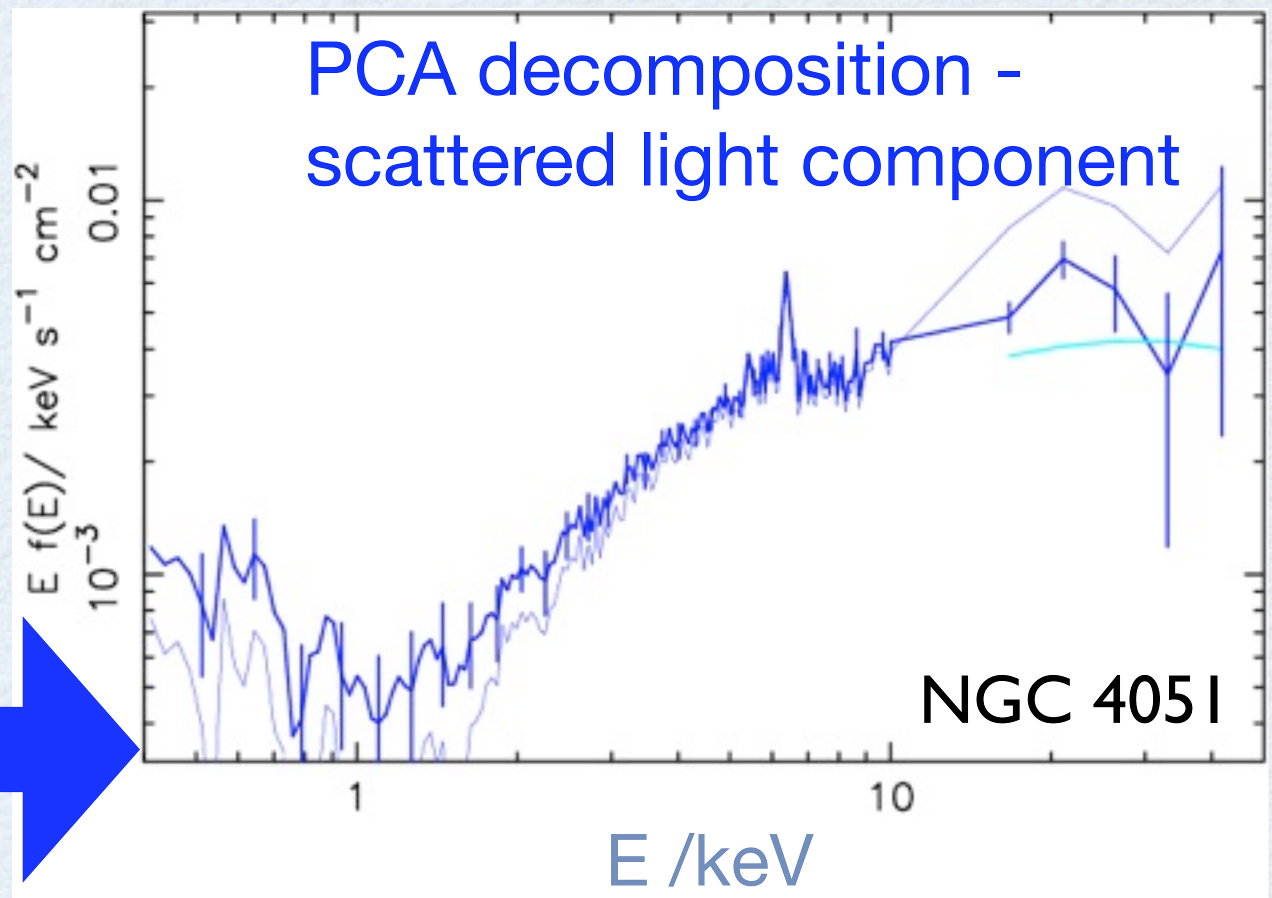
0.5-1.5 v 2-4 keV;
Miller et al. (2011) in prep

- Hard lags known for 10 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

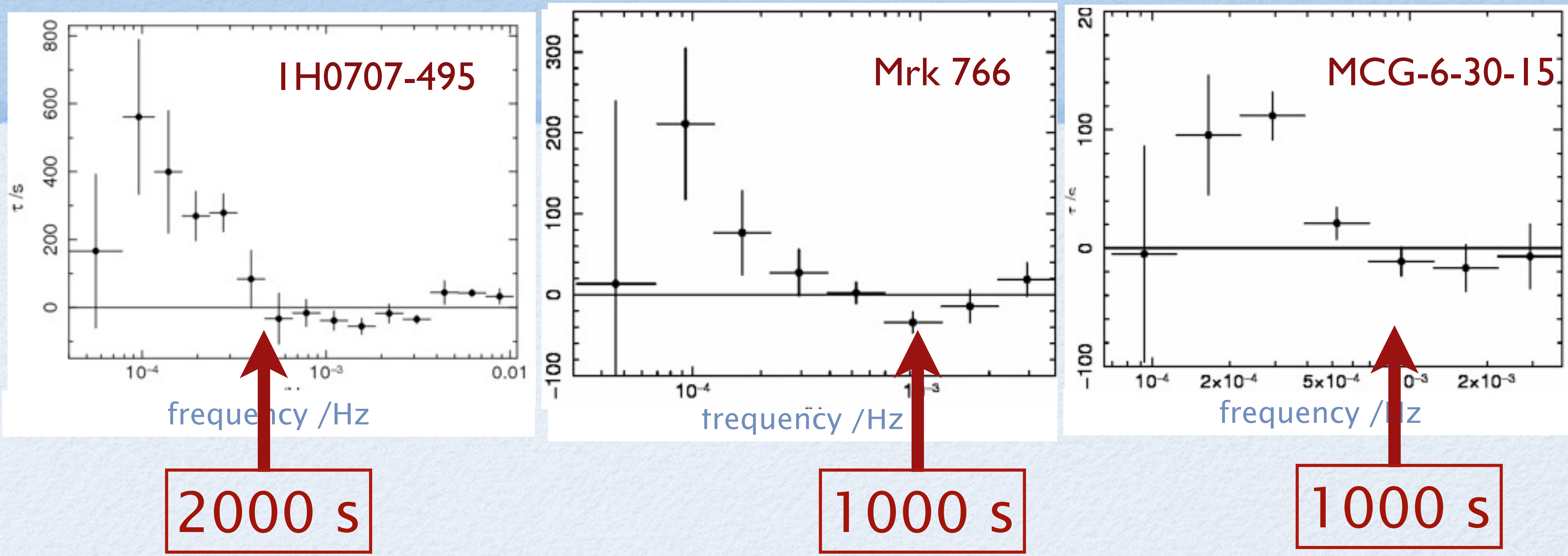




- lag times increase with the difference in photon energy of the bands being cross-correlated.

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

The Characteristic Timescale

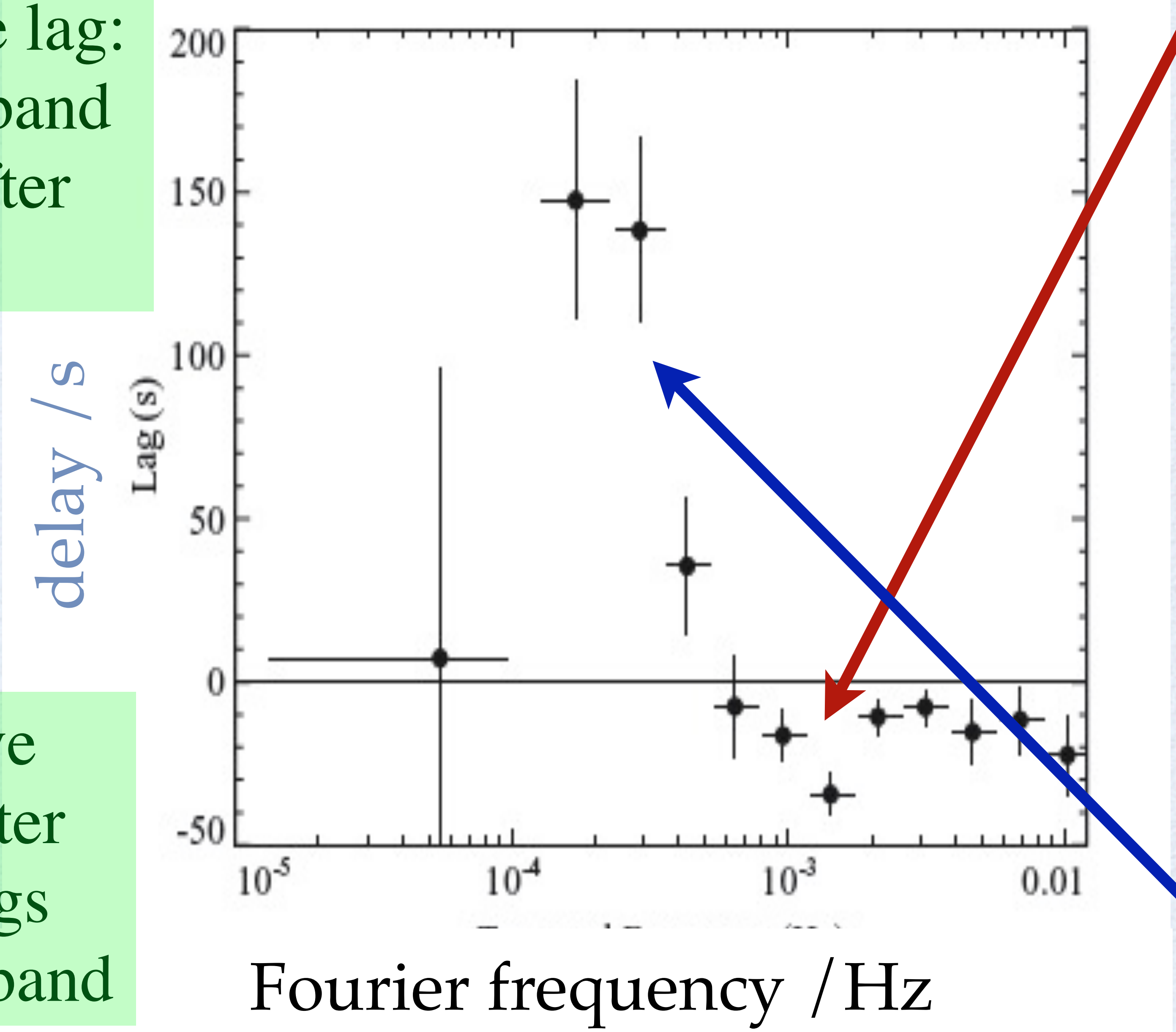


- There seems to be a characteristic timescale > 1 ks
- Implies light-travel length-scale 200 r_g ($M_{BH}=10^6 M_\odot$), 20 r_g ($M_{BH}=10^7 M_\odot$) whatever the origin of the lags
  - reprocessor too far out to experience significant light-bending

Time Lags in 1H0707-495

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

Positive lag: harder band lags softer band



Negative lag: softer band lags harder band

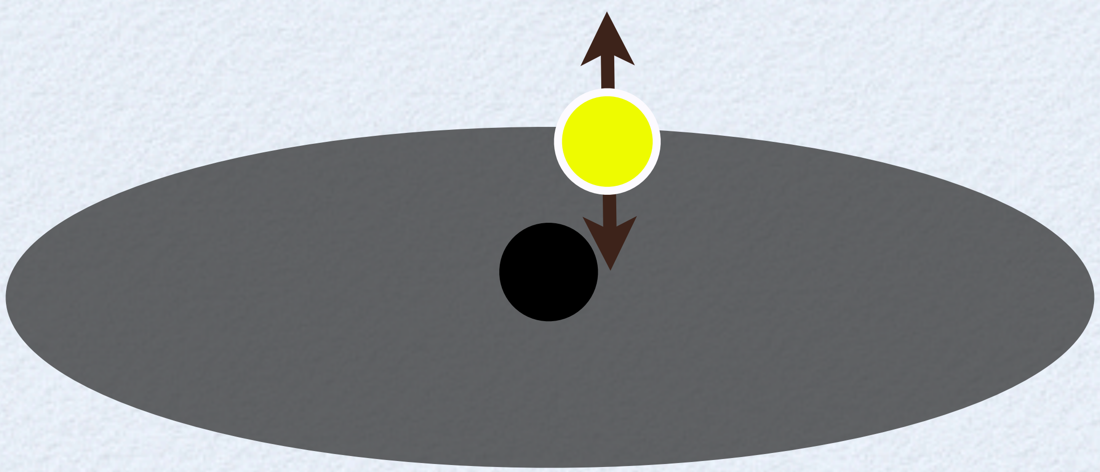
lags: “medium”1-4 keV v. “soft” 0.3-1 keV

- 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*
- *Fe abund > 9*
- *Hard band should have greatest lags*

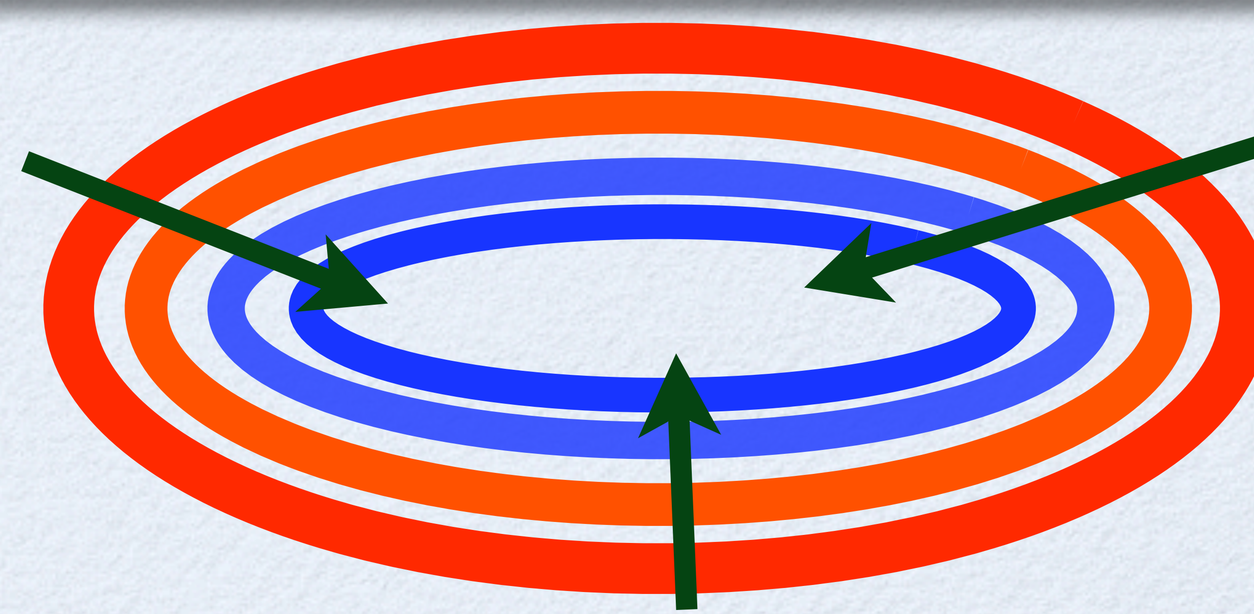
Problems with light bending

- 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.

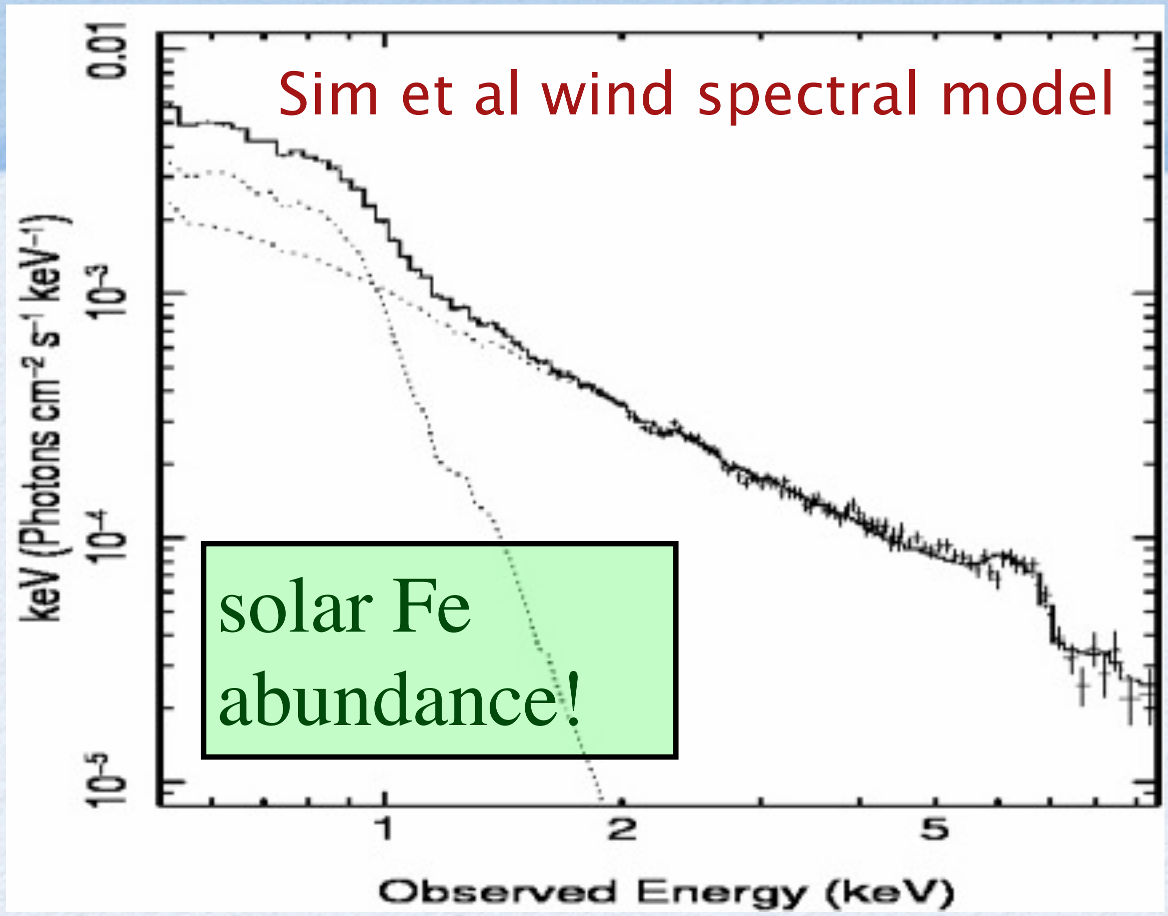
where is the continuum source and its variations produced? It can't be both in the accretion disk and in the "lamp-post" source.

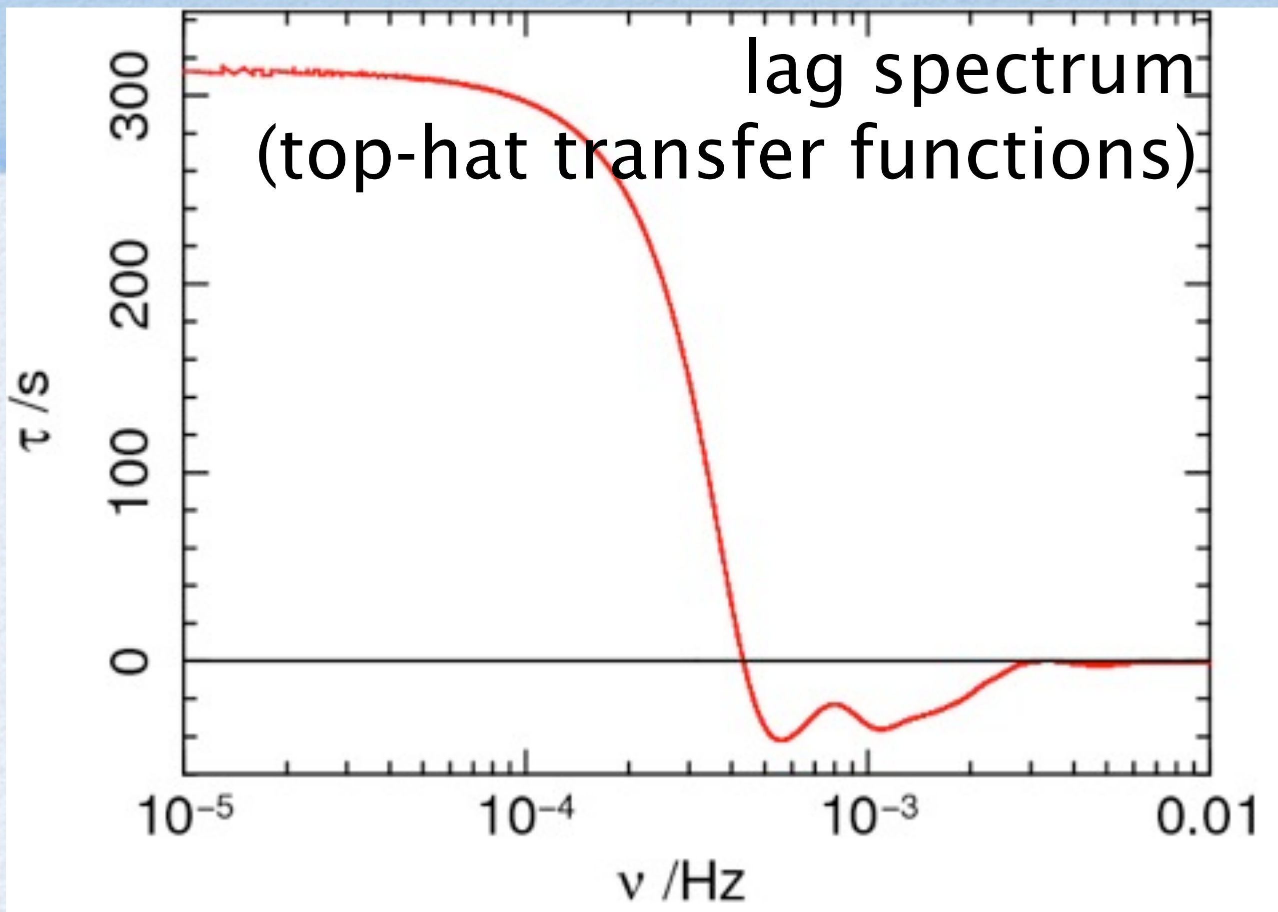


positive lags from fluctuations propagating inwards over the surface of the accretion disk from soft to hard regions?



X-ray Reverberation: 1H0707-495





- simple top-hat reverberation transfer functions easily fit lag spectra
- 3D radiative-transfer Sim et al. model fits spectrum
- Size of the reverberating region ~2000 light-seconds
  - $20r_g$ if $M_{BH} = 10^7 M_\odot$ (Leighly 2004) or $100r_g$ if $2\times10^6\ M_\odot$ (Zoghbi et al '10)
  - no requirement for reflection physically close to the BH
  - difference between hard & soft caused by energy-dependent opacity

Summary

- Outflowing X-ray absorber up to Compton-thick column densities, in and out of the line-of-sight
- Not seeing naked accretion disk- X-rays are reprocessed by large amounts of circumnuclear gas with high global covering
- Absorption models explain spectral variability properties with covering changes and reverberation
- Reverberation predicts clear signatures in Fourier lag spectra which are observed in X-ray time series of AGN
    - We see both the expected frequency behavior and energy behavior in X-ray data
    - Simple X-ray reverberation explains BOTH small negative lags and large positive lags with a single, simple physical model
    - X-ray reverberation places gas 10s - 100s r_g from central source
- Compton-thick wind/reverberation models look promising to explain even the most complex sources