The 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.

NGC 4051 optical: Denney et al 2009
gappy, noisy time-series

NGC 4051 optical: Denney et al 2009

NGC 4051 X-ray: Miller et al 2010

optical continuum

optical Hβ

X-ray flux (counts/sec)

X-ray flux (counts/sec)

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

$T = 1905 \text{ s}$

thin scattering shell
partial covering
optical $(\text{H} \beta)$ reverberation in NGC 4051 (Denney et al 2009)
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

delayed X-rays

direct X-rays

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

- NGC 4051
  Miller et al. (2010a)

- 1H0707-495
  Miller et al. (2010b)

- Mrk 766
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).
Negative lags at high $\nu$ - 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 $\sim 0.9$ keV from reflector few 10s light-s away

“Relativistic blurring” spectral model fit requires strong GR blurring $r_{in}$=1.23 
$\epsilon_g$ emissivity $\sim r^{-7}$

Positive lags at low frequency attributed to different mechanism (see later)

lags: “medium”1-4 keV v. “soft” 0.3-1 keV
In this blurred reflection model, the hard (FeK) band has the most reflection, followed by the soft band, and then the medium band.

Reflection fractions: $f_{\text{soft}} = 1.60$, $f_{\text{med}} = 0.57$, $f_{\text{hard}} = 2.03$.

The model also requires Fe abundance $\times 9$.
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 $\nu$ lags should be positive if Zoghbi et al are correct. 

They are not!

Miller, Turner, Reeves & Braito, 2010
Confidence Regions for the Lags

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.

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

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

Miller, Turner, Reeves & Braito, 2010
problems with light bending

- Light-bending model was invented to fix the problems of the relativistic-blurred models ($R \gg 1, \epsilon \sim r^{-7}$, lack of response of line to continuum).
- Requires a small source close to the black hole ($\sim 1$ 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?
(over-)simple top-hat reverberation transfer functions easily fit lag spectra
Size of the reverberating region $\sim2000$ light-seconds
- $20-100r_g$ if $M_{BH} = 10^7M_\odot$ (Leighly 2004) or $2\times10^6M_\odot$ (Zoghbi et al 2010)
The soft band also needs time lag $\sim150s$ 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
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 rg 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).