Black Hole Masses from the Time Domain

Mapping Broad Line Regions in AGNs by Photometry

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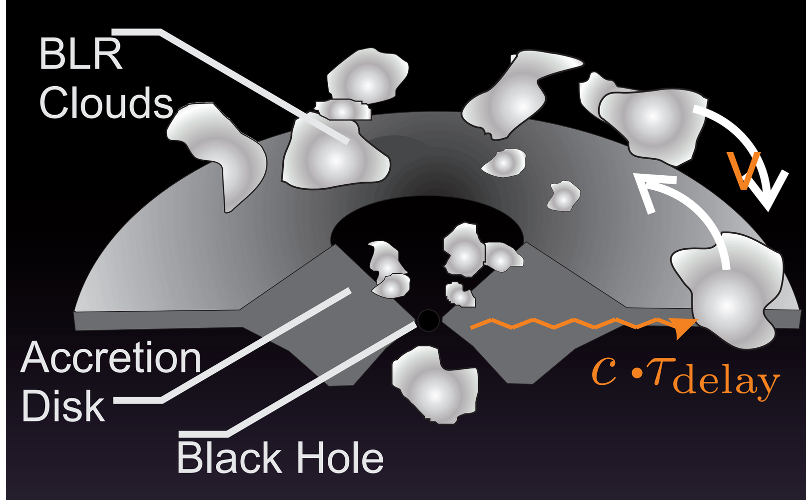
Abstract

We present the development and application of a rigorous approach for stochastic reverberation mapping of sparsely sampled AGN broad-band flux measurements. We show how - and that - the BLR size of (ensembles of) QSOs can be estimated from a single spectroscopic epoch and many epochs of precision broad-band photometry. The AGN continuum is modeled as a stochastic Gaussian process. A flux model describes variations of the observed flux with emission line contribution as a scaled version of the pure continuum band plus a scaled, smoothed and delayed version of the continuum. Through generating and evaluating problem-specific mock data, we verify that SDSS S82-like data can constrain $\tau_{\rm delay}$.
For well-sampled light curves in fortuitous redshifts bins with strongly differential line-flux contributions to different bands we get significant estimates of $R_{\rm BLR}$, which appear to be ~1.7 larger than found by [Kaspi2000].
The formalism developed here should also be useful for application to data sets from upcoming surveys.

Reverberation Mapping



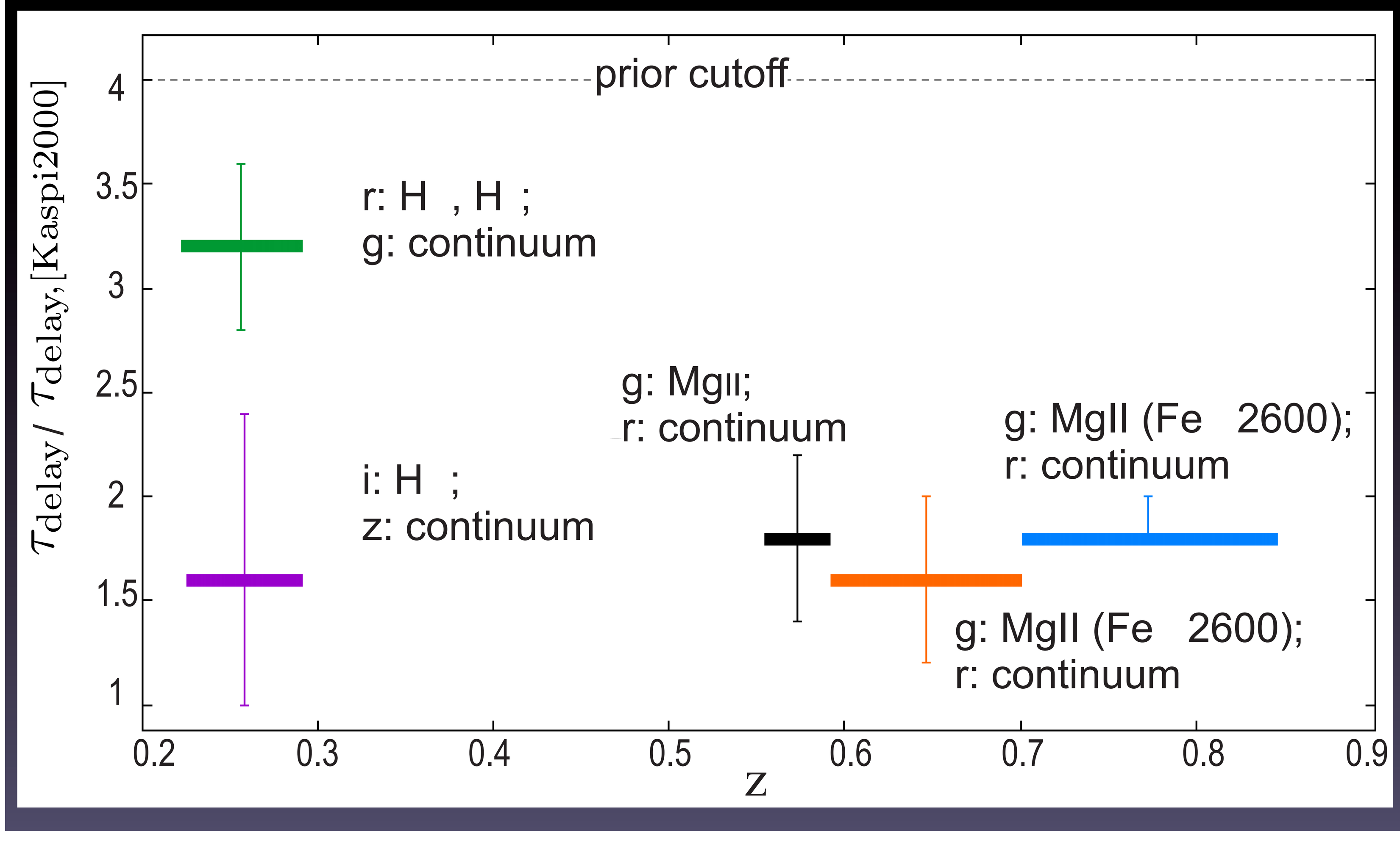
- continuum radiation from accretion disk excites BLR clouds
  $\Rightarrow$ broad emission lines
- changes in BLR excitation and luminosities
- finite light travel time
  $\Rightarrow$ delay $\tau_{\rm delay}$ of BLR luminosity variations w.r.t. accretion disk's

$$M_{\rm BH} = f\,\frac{\Delta V^2 c\tau_{\rm delay}}{G}$$

f: proportionality factor for BLR geometry and kinematics [Kaspi2000]

Application and Results

In application to SDSS S82 data, we estimated $\tau_{\rm delay}$ for a well-defined sample of 323 objects spanning redshifts from z = 0.225-0.846.



Despite the effectiveness of this approach in handling uneven time sampling, the S82 temporal sampling proves a serious limitation. Also, suitable redshift ranges must be identified. This makes pre-selection of sufficient light curves necessary.

1 spectrum and ~ 60 photometric epochs yield

- marginal $\tau_{\rm delay}$ estimates with mock & real data
- solid $\tau_{\rm delay}$ estimate in ensemble average
- application to 340 quasars in SDSS S82:

BLR 1.7 $\times$ larger than

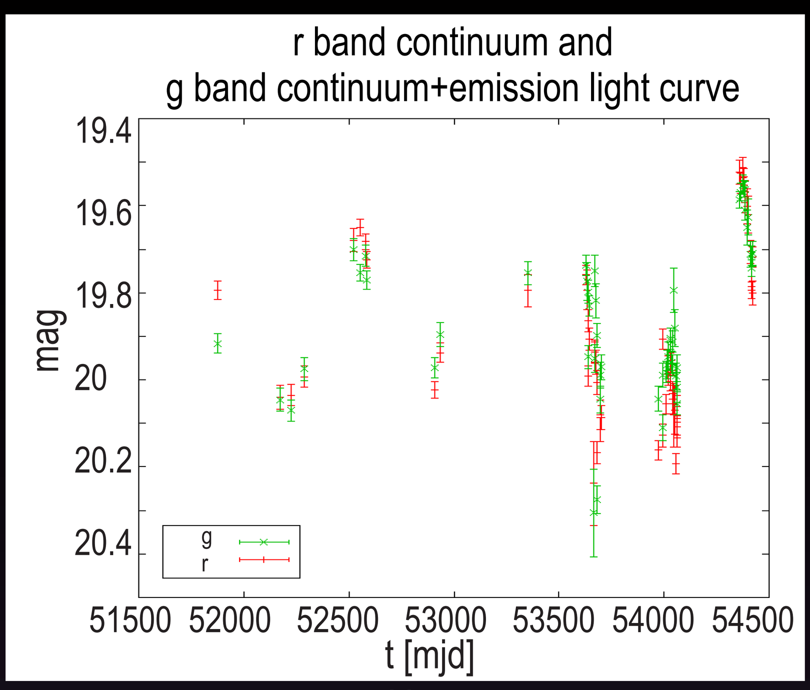
$$R_{\rm BLR,[Kaspi2000]} = \left(32.0^{+2.0}_{-1.9}\right)\left[\frac{\lambda L_\lambda(5100\text{Å})}{10^{44}\ {\rm erg\ s^{-1}}}\right]^{0.700\pm0.033} \text{light days}$$

Stochastical Reverberation Mapping - methodology

stochastic approach is capable to

i) not only interpolate between data points, but also make self-consistently estimates and include these uncertainties in the interpolation
ii) handle transfer functions $\Psi(\tau_{\rm delay})$ instead of simply a $\tau_{\rm delay}$
iii) separate light curve means and systematic errors in flux calibration from variability signals and measurement noise in a self-consistent way
iv) derive simultaneously the lags of multiple emission lines
v) provide statistical confidence limits on all estimated parameter

$\Rightarrow$ handle sparsely sampled data!

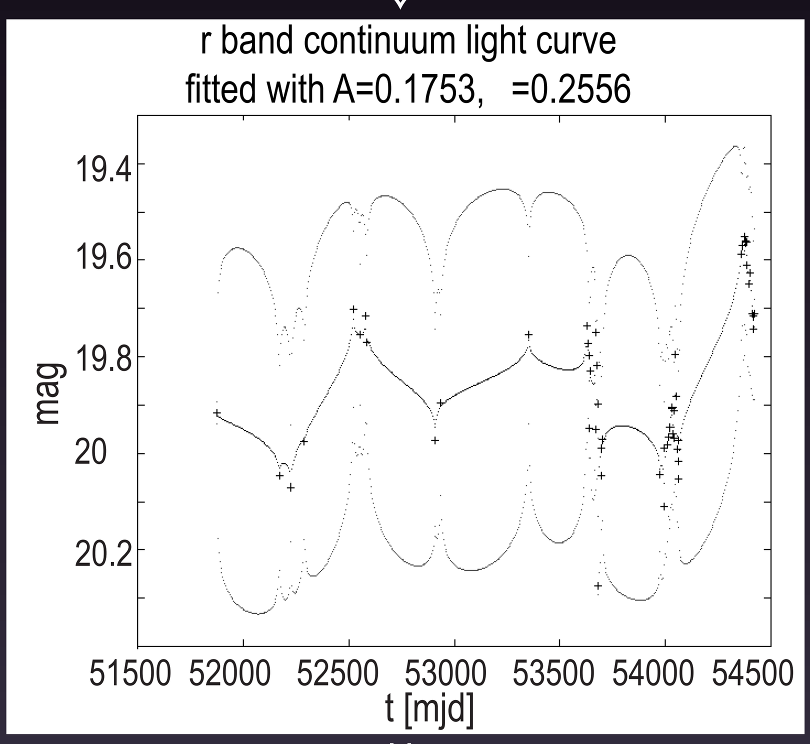


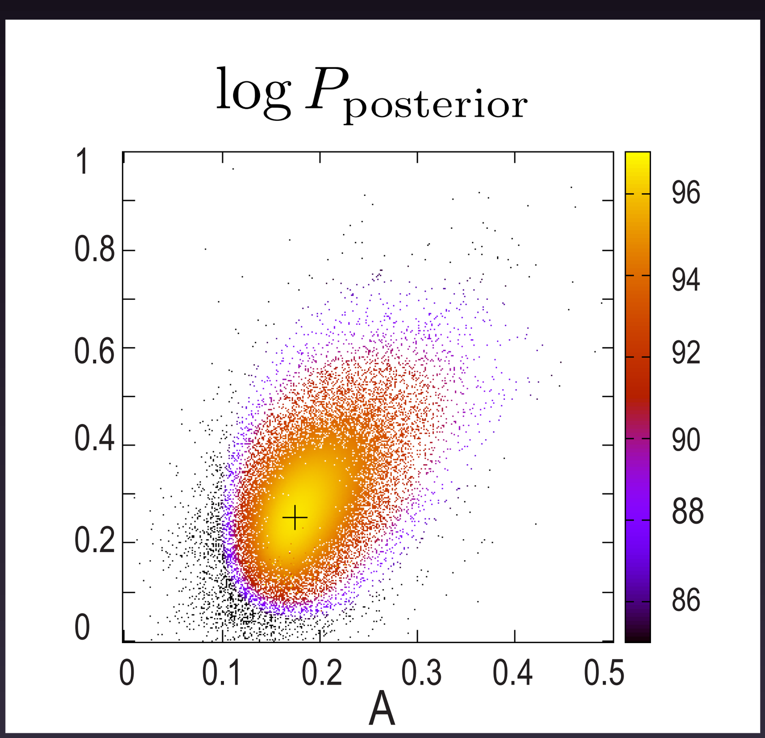
model continuum-only band x

$$\log P_{\rm posterior} = \log P(\mathbf{p}) + \log \mathcal{L}(\mathbf{m}|\mathbf{p})$$

where $\mathbf{p}$ are the structure function parameters and $\mathbf{m}$ the measured light curve points

$\Downarrow$





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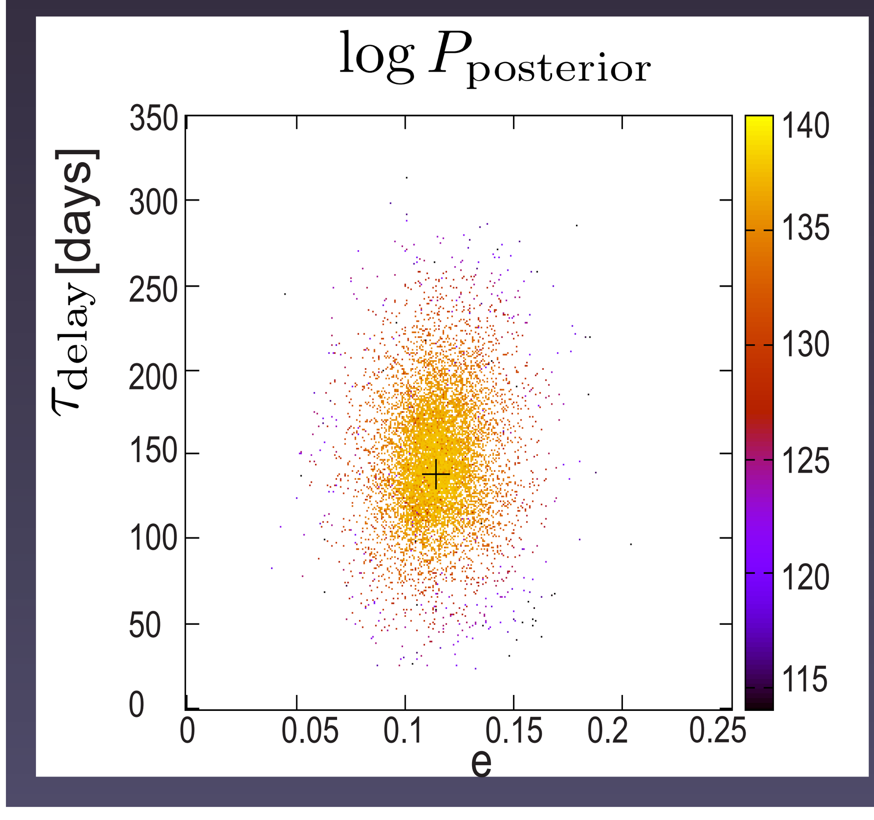

model continuum + emission line band y

$$\log P_{\rm posterior} = \log P(\tau_{\rm delay}, e, s) + \log \mathcal{L}(\mathbf{m}_x, \mathbf{m}_y|\tau_{\rm delay}, e, s)$$

- operationally, we fit a light curve by maximizing the likelihood of the flux model given the photometric data points
- approach by [Rybicki1994] and [Zu2011] applied to broad band photometry with many modifications
- carried out by Parallel Affine Invariant MCMC Ensemble Sampler

model continuum-only band x

describe AGN continuum light curve as Gaussian stochastic process (e.g. [Kozlowski2009] [McLeod2012])

- damped random walk [Kelly2009]
- power-law structure function model [Schmidt2010]

$\Rightarrow$ continuum model is characterized by a variance matrix C_{xx}^{cc}

model continuum + emission line band y

model band y as a scaled version of band x plus scaled, smoothed and displaced version of band x

flux model:

$$f_x(t) = f_x^c(t) \quad \text{continuum only band}$$

$$f_y(t) = f_y^c(t) + f_y^e(t) \quad \text{continuum + emission line band}$$

$$= s \cdot f_x^c(t) + e\int {\rm d}\tau_{\rm delay}\,\Psi(\tau_{\rm delay})\,f_x^c(t-\tau_{\rm delay})$$

emission-line covariance matrix

$$C_{yy}^{ee}(\Delta t) = \langle f_y^e(t), f_y^e(t+\Delta t)\rangle$$

$$= e^2\int {\rm d}\tau_{\rm delay,1}\int {\rm d}\tau_{\rm delay,2}\,\Psi(\tau_{\rm delay,1})\,\langle f_y^c(t-\tau_{\rm delay,1})\,f_y^c(t+\Delta t-\tau_{\rm delay,2})\rangle$$

continuum-emission cross terms

$$C_{yy}^{ec/ce}(\Delta t) = s\cdot e\int {\rm d}\tau_{\rm delay}\,\Psi(\tau_{\rm delay})\,C_{xx}^{cc}(\Delta t \pm \tau_{\rm delay})$$

$\Longrightarrow$ **covariance matrix for x and y band fluxes**

$$C = \begin{pmatrix} C_{xx}^{cc} & C_{xy}^{c,(e+c)} \\ C_{yx}^{(e+c),c} & C_{yy}^{(e+c),(e+c)} \end{pmatrix}$$

likelihood $\mathcal{L}$ from covariance matrix C and data $\mathbf{m}$ [Zu2011]

$$\mathcal{L} \equiv |S+N|^{-1/2}\,|L^T C^{-1} L|^{-1/2}\,\exp\left(-\frac{\mathbf{m}^T C_\perp^{-1}\mathbf{m}}{2}\right)$$