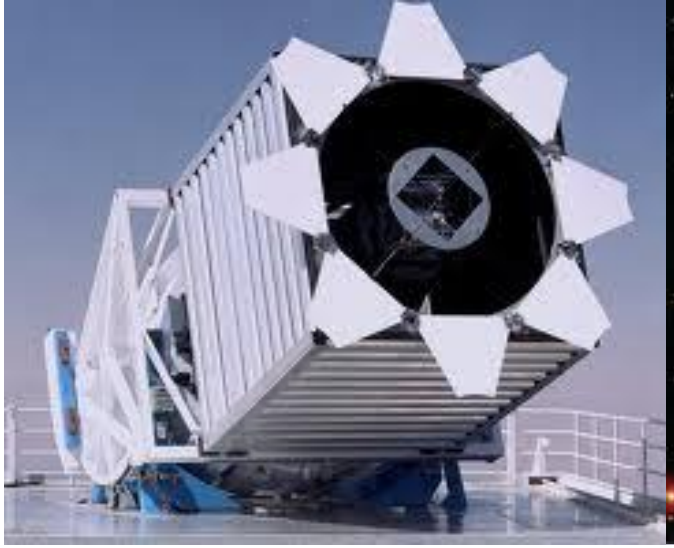
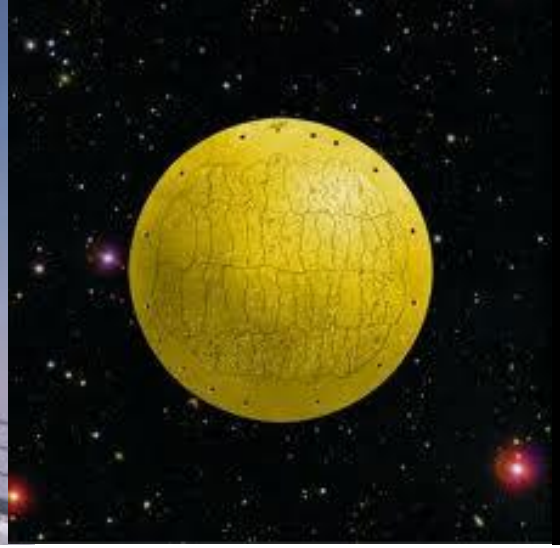
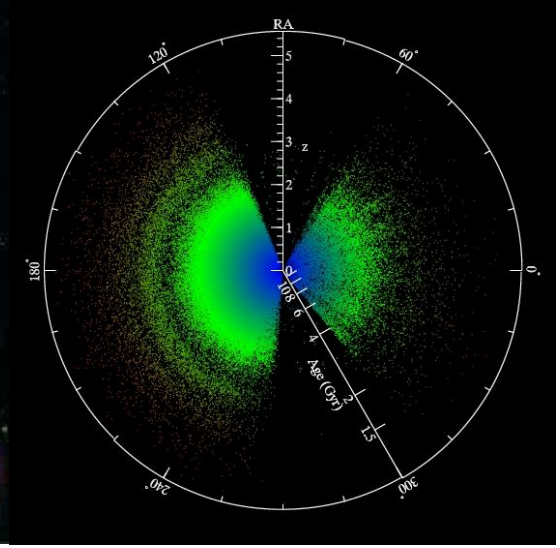




Search for Sub-parsec Binary Supermassive Black Holes (BBHs) with Multi-Epoch Spectroscopy

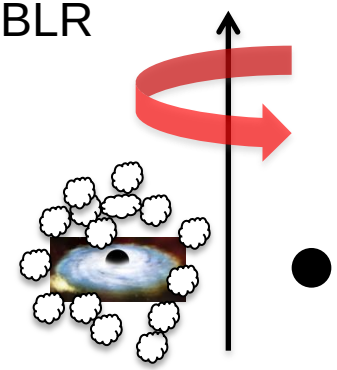
Yue Shen (Carnegie Observatories)

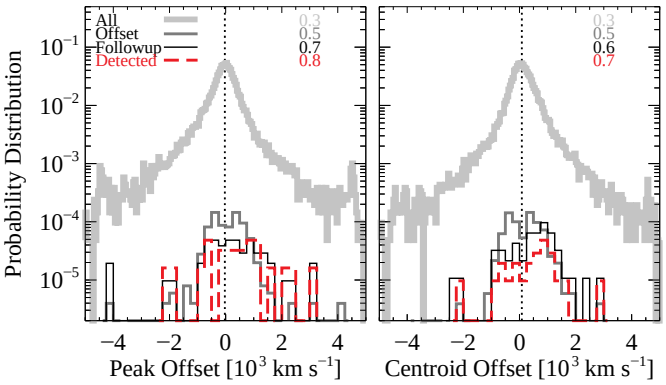
with Xin Liu (UCLA), Avi Loeb (CfA), Scott Tremaine (IAS)

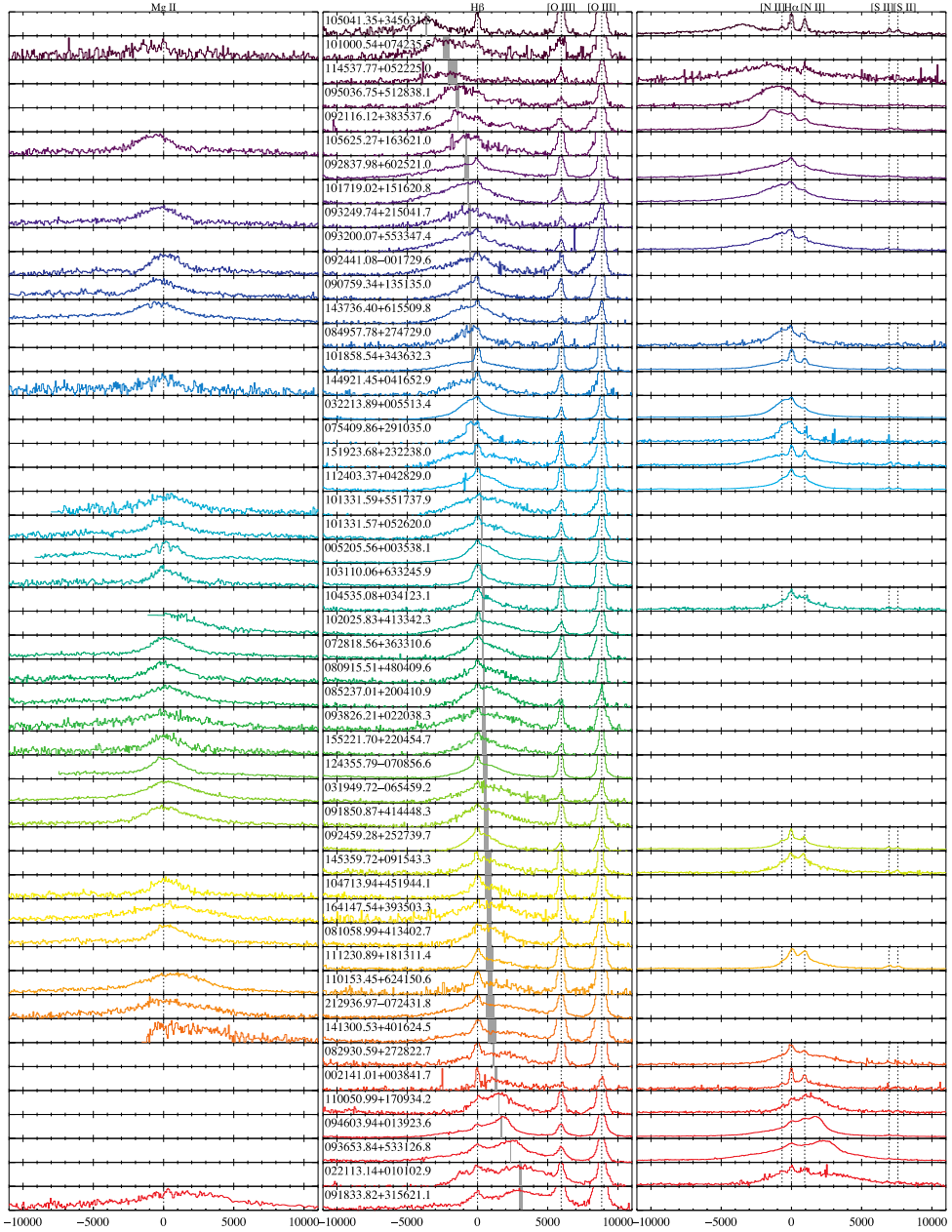
Single-peaked broad line sub-pc BBH candidates

The working scenario:

1. Only one BH is active, carrying its own BLR
2. The other (inactive) BH is orbiting outside the BLR







Liu, YS, et al. 2013, submitted

Need multi-epoch spectroscopy for confirmation

BBH period

$$P = 2\pi d^{3/2}(GM_{\rm tot})^{-1/2} = 300 d_{0.1}^{3/2} M_{8,\rm tot}^{-1/2}\ {\rm yr}$$

los velocity offset

$$V_1 = \frac{M_2}{M_{\rm tot}}\left(\frac{GM_{\rm tot}}{d}\right)^{1/2} \sin I \sin\phi = 2000\left(\frac{M_2}{M_{\rm tot}}\right) M_{8,\rm tot}^{1/2} d_{0.1}^{-1/2} \sin I \sin\phi\ {\rm kms}^{-1}$$

los acceleration

$$a_1 = \frac{GM_2}{d^2}\sin I\cos\phi = 44\left(\frac{M_2}{10^8\,M_\odot}\right) d_{0.1}^{-2} \sin I\cos\phi\ {\rm km\,s^{-1}yr^{-1}}$$

Broad lines with small offset may have large acceleration

Multi-epoch spectroscopy of broad lines

Two strategies:

1. **Targeting quasars with offset broad lines**: **Eracleous et al. (2012), Decarli et al. (2013), Liu et al. (2013, see poster by Xin Liu)**

1. **Targeting general quasars: Shen et al. (2013), Ju et al. (2013)**

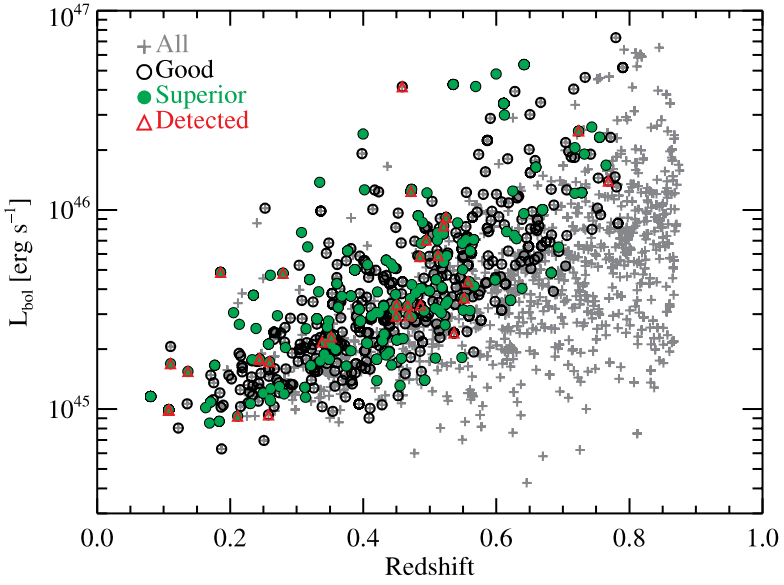
Multi-epoch spectroscopy of broad lines

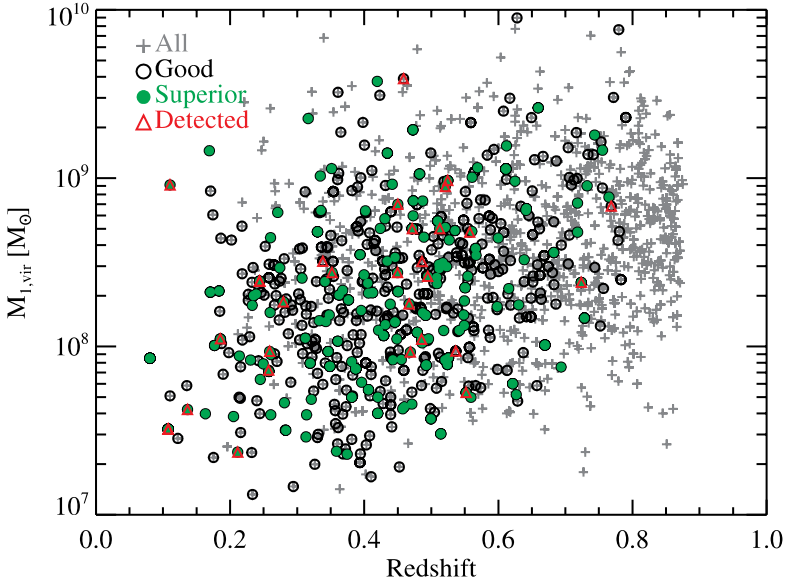
I. The general quasar population

Shen et al. 2013 (Hbeta); also see Ju et al. 2013 (MgII)

- Free 2-epoch spectroscopy of ~2000 quasars from SDSS DR7 with Hbeta coverage (most have small offsets)
- Restframe time separation: ~ 0.01-10 yr (peaks around 1 yr)

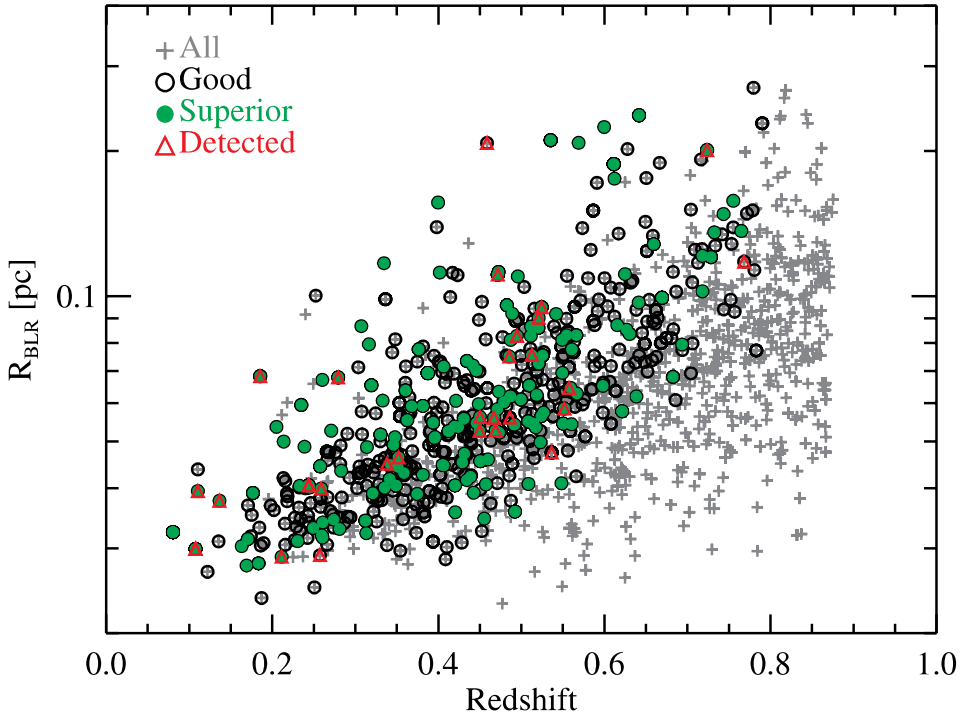
Luminosity and virial BH mass distributions of the active BH





Multi-epoch spectroscopy of broad lines

I. The general quasar population



BLR size estimated using the R-L relation found in reverberation mapping (e.g., Kaspi et al. 2000, Bentz et al. 2009, 2013)

$$R_{\rm BLR} \propto L^{0.5}$$

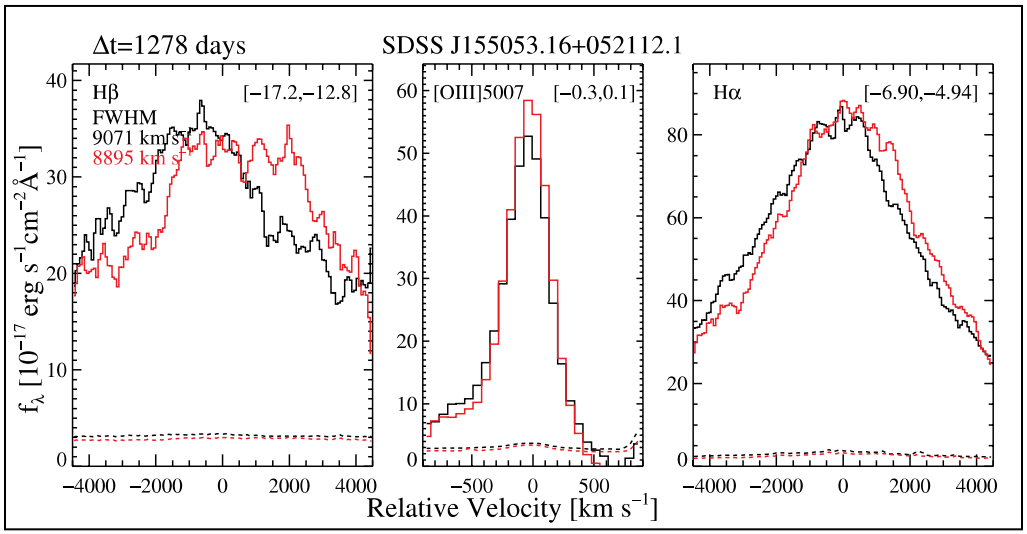
The binary separation must be larger than the BLR size

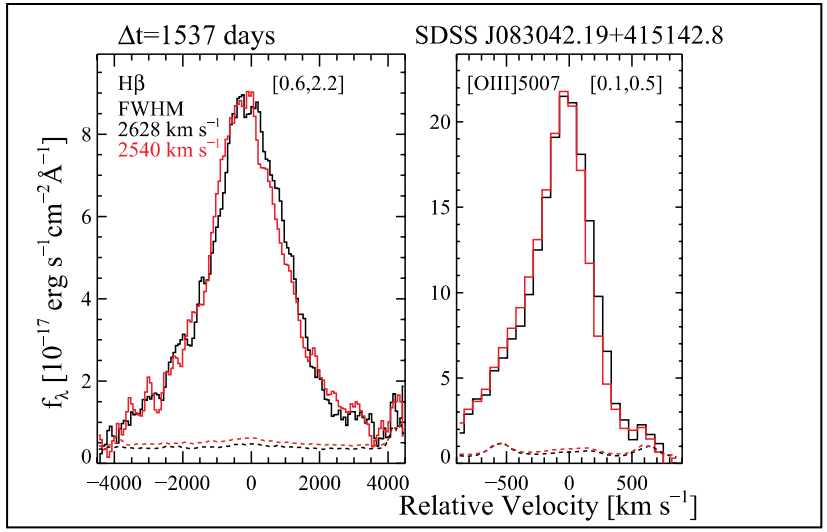
Multi-epoch spectroscopy of broad lines

I. The general quasar population

- ~ 700 pairs have good measurements of the broad line velocity change between 2 epochs; typical measurement errors in velocity shift: ~ 40 km/s (typical acceleration ~ 40 km/s/yr)

- 28 systems show detected (2.5sigma) velocity shifts between two-epochs

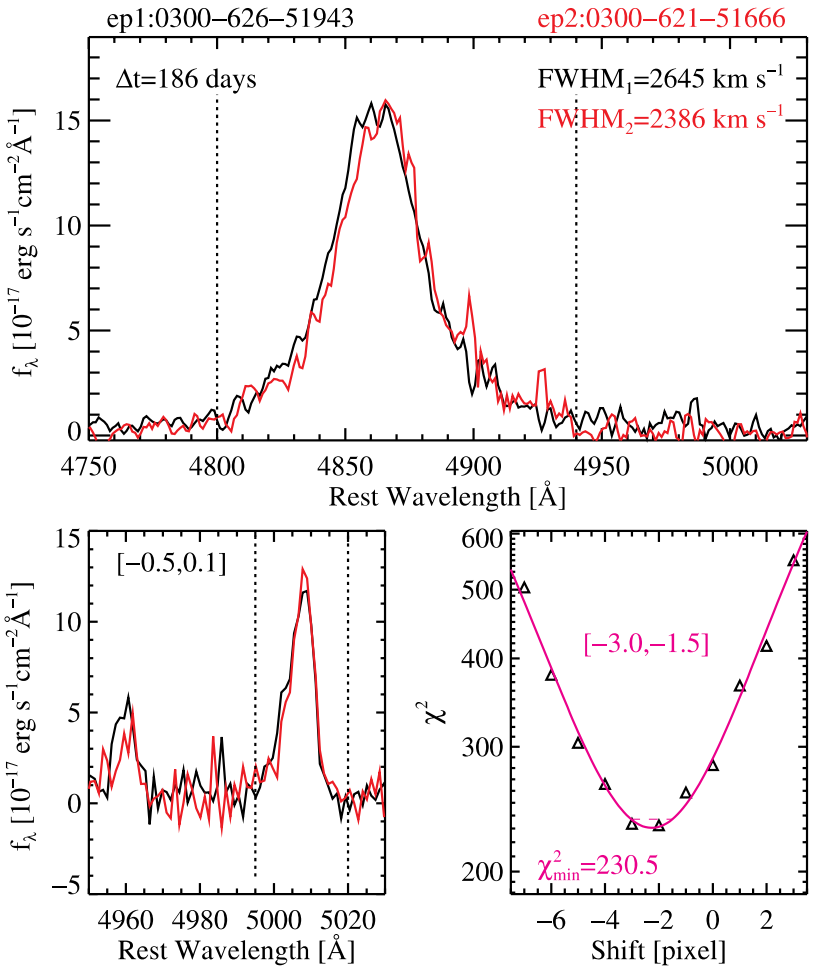




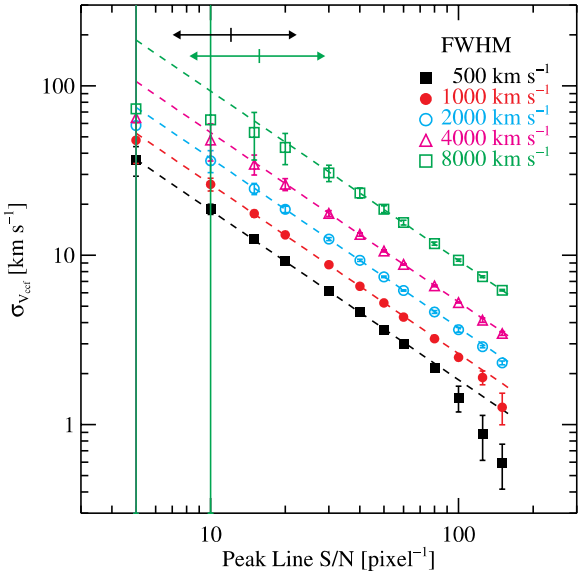
Multi-epoch spectroscopy of broad lines

I. The general quasar population

Cross-correlation method following Eracleous et al. (2012)



proper error analysis is key

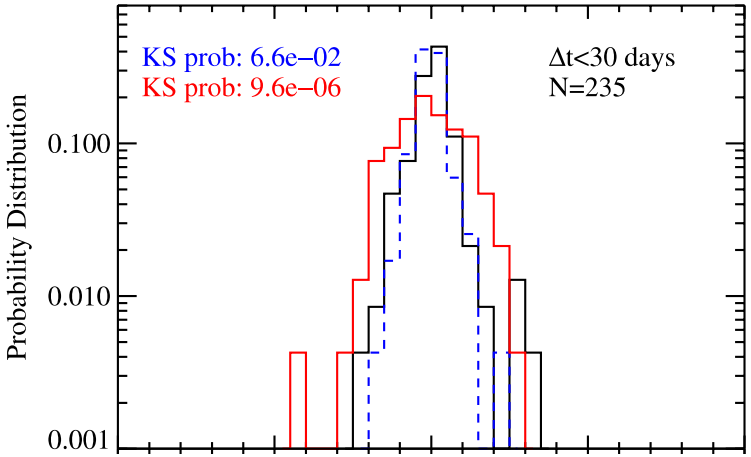


Typical measurement errors in velocity shift: ~ 40 km/s

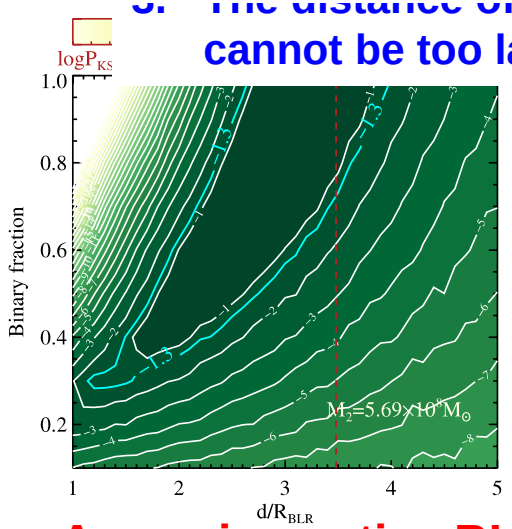
Multi-epoch spectroscopy of broad lines

I. The general quasar population

Constraints from non-detections



3. The distance of
cannot be too la



Assuming active BH M1=1.8d8 Msun
R_{BLR}<Roche radius

Excess variance in velocity shift for large time separations

Multi-epoch spectroscopy of broad lines

I. The general quasar population

Caveat

BBHs versus broad-line-region variability

Typical dynamical time of the BLR is $\tau_{\rm dyn} = \frac{R_{\rm BLR}}{V_{\rm FWHM}} \approx {\rm a\ few\ yrs}$

BLR variability should mostly produce stochastic velocity shifts. Additional spectroscopic epochs needed.

What's next?

- Additional spectra can easily strengthen or rule out the binary scenario
  - More spectroscopic epochs coming in SDSS-III and SDSS-IV (TDSS, 2014-2020) for thousands of quasars
  - Need to understand the BLR better (i.e., through reverberation mapping)
- Continued monitoring could eventually lead to orbit constraints for many candidates