Constraints on the Geometry and Dynamics of the BLR from Modeling of Reverberation Mapping Data

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"The Inner Regions of Quasars"
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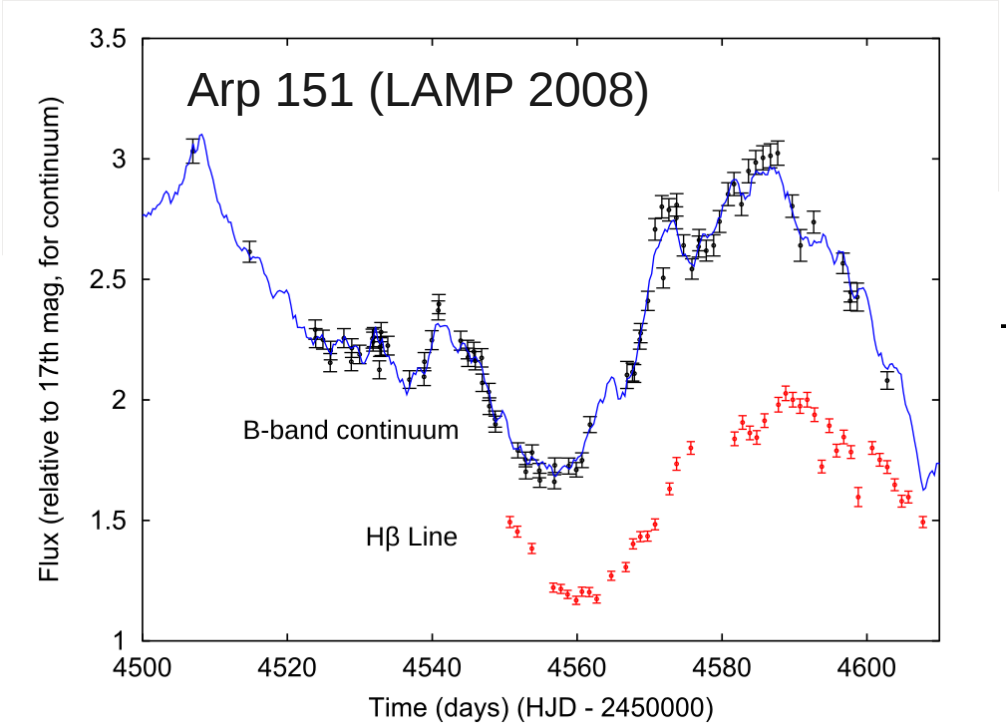
A brief overview

- Constraints on the BLR from high-quality reverberation mapping data
- See Keith Horne's talk for another method
- Results for the Lick AGN Monitoring Project (LAMP) 2008 dataset
- *Preliminary* results for the 2010 MDM Observatory dataset (AGN10) – led by C. Grier
- The next step: analyze even higher quality datasets (LAMP 2011, AGN12, AGN STORM)

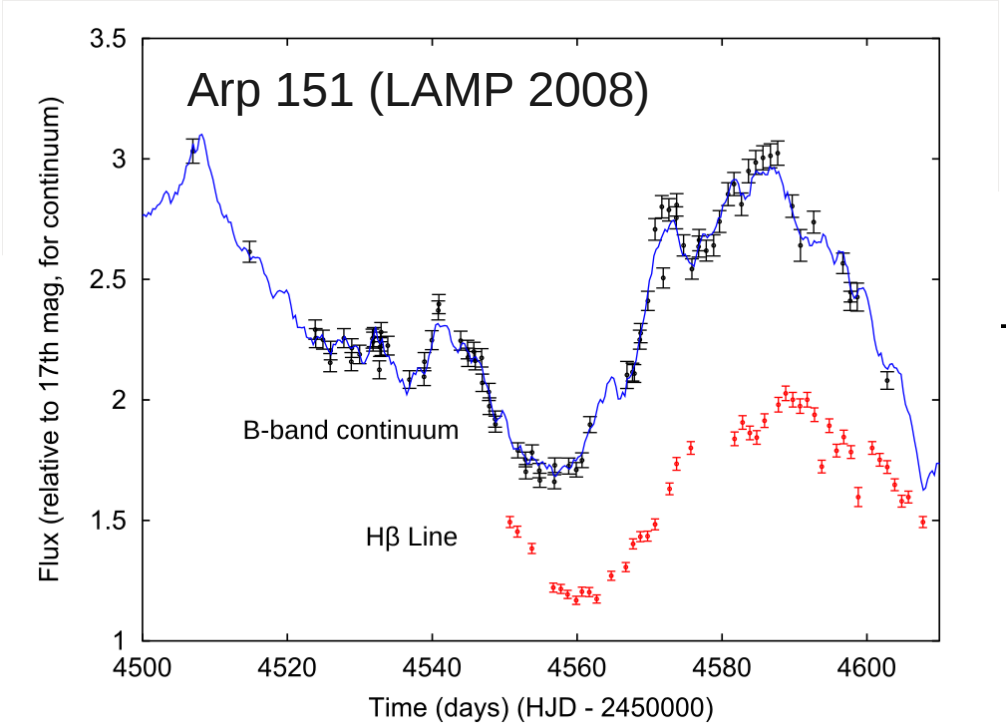
Motivation for direct modeling



τ

$$M_{\rm BH} = f \frac{(c\tau)(\Delta V)^2}{G}$$

Motivation for direct modeling



τ

Opening angle of disk

Inclination angle

Outflowing gas

Inflowing gas

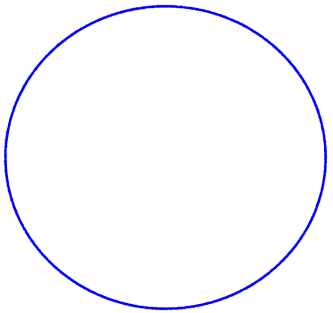
Disk or spherical geometry

Mean radius

$$M_{\rm BH} = f\frac{(c\tau)(\Delta V)^2}{G}$$

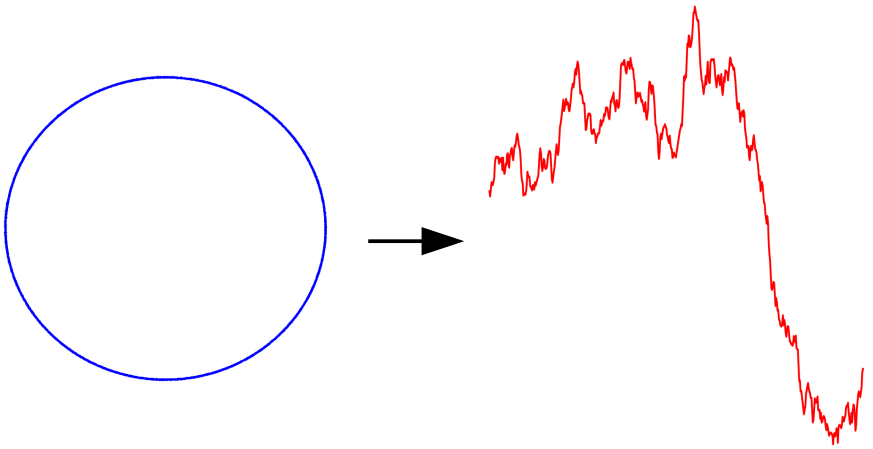
- Obtain an independent estimate of the BH mass, which also provides the *f* factor when combined with the traditional BH mass estimate
- Constrain the properties of the broad line region geometry and dynamics

The direct modeling approach



BLR geometry:
Face-on ring

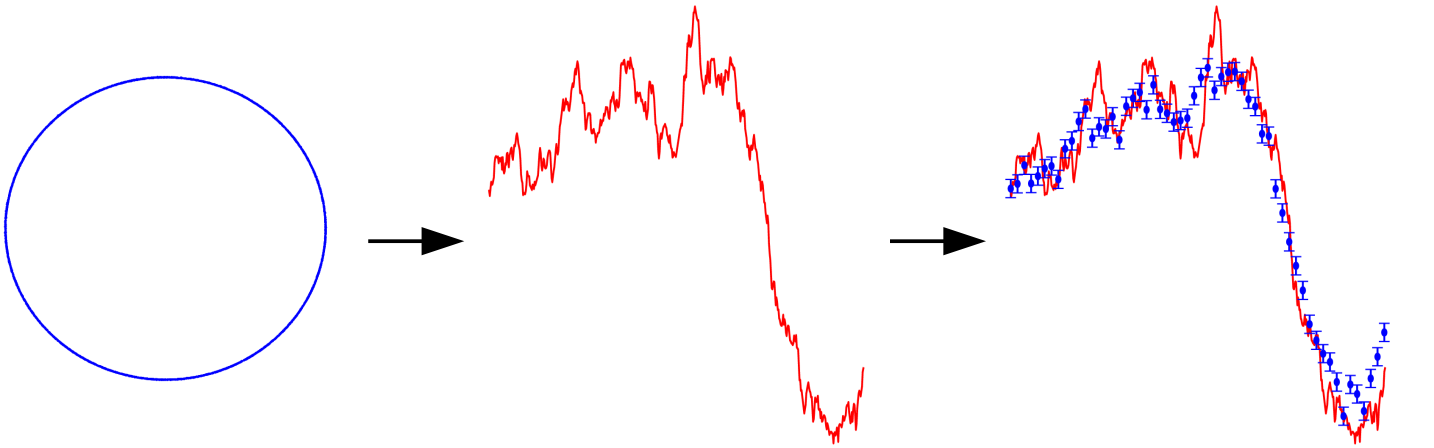
The direct modeling approach



BLR geometry:
Face-on ring

Model light curve

The direct modeling approach

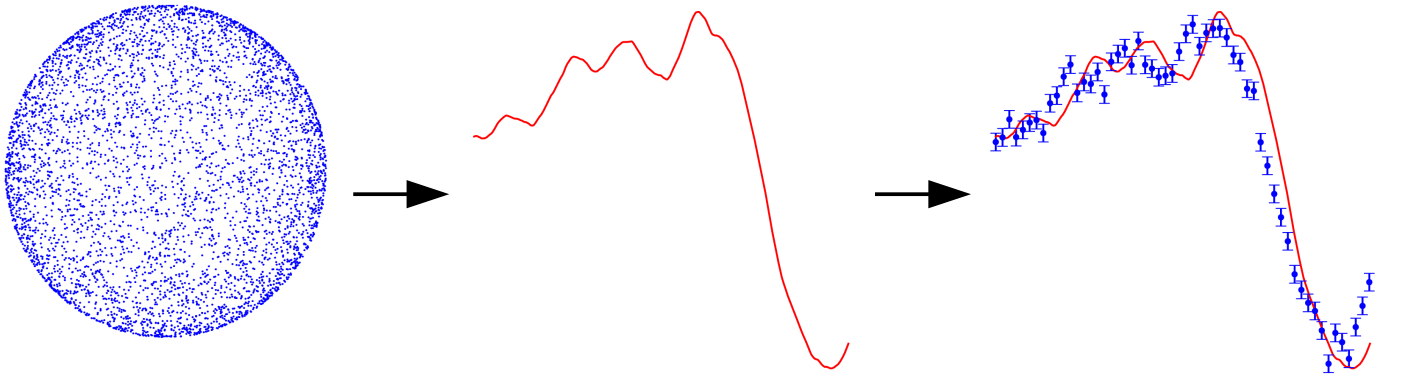


BLR geometry:
Face-on ring

Model light curve

Model light curve
+ Data (blue points)

The direct modeling approach

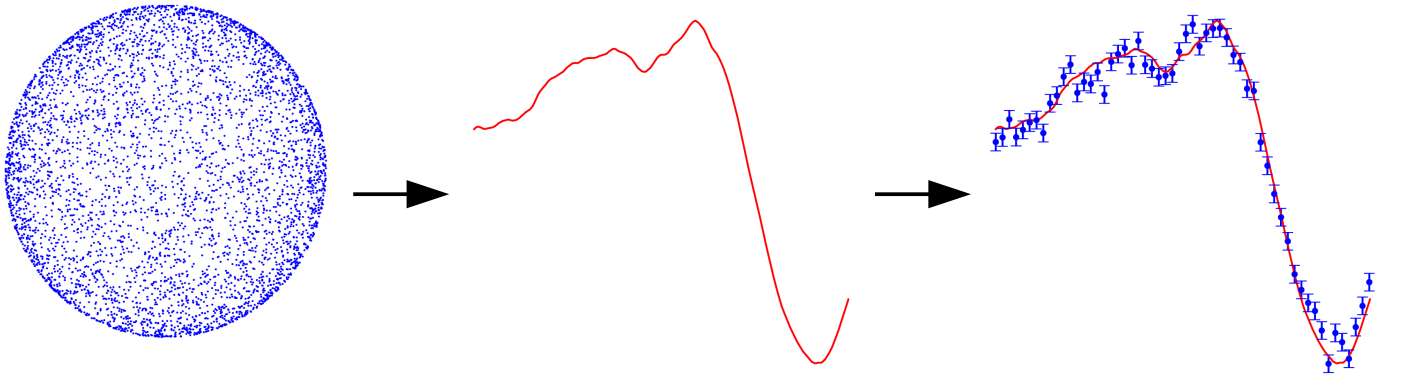


BLR geometry:
Back-illuminated
shell

Model light curve

Model light curve
+ Data (blue points)

The direct modeling approach

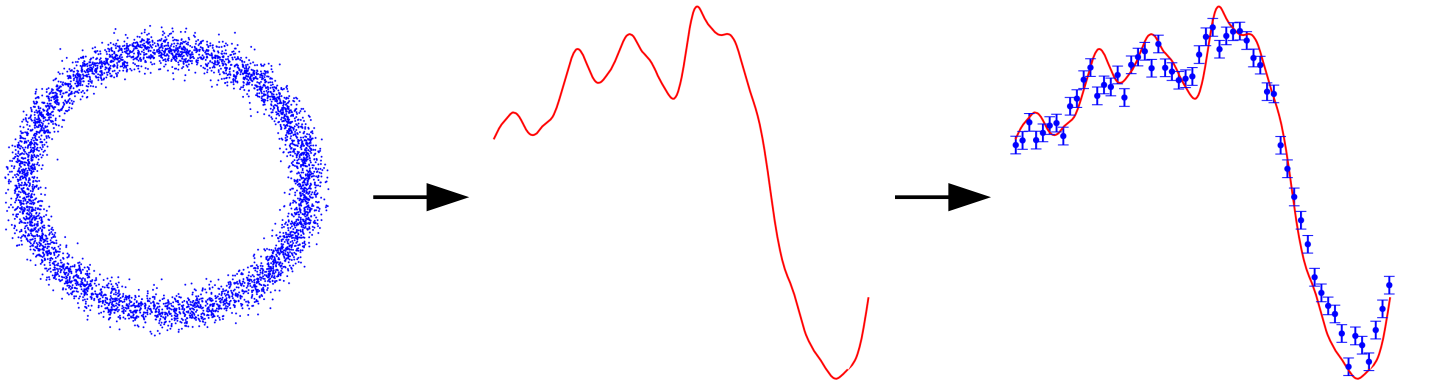


BLR geometry:
Shell

Model light curve

Model light curve
+ Data (blue points)

The direct modeling approach

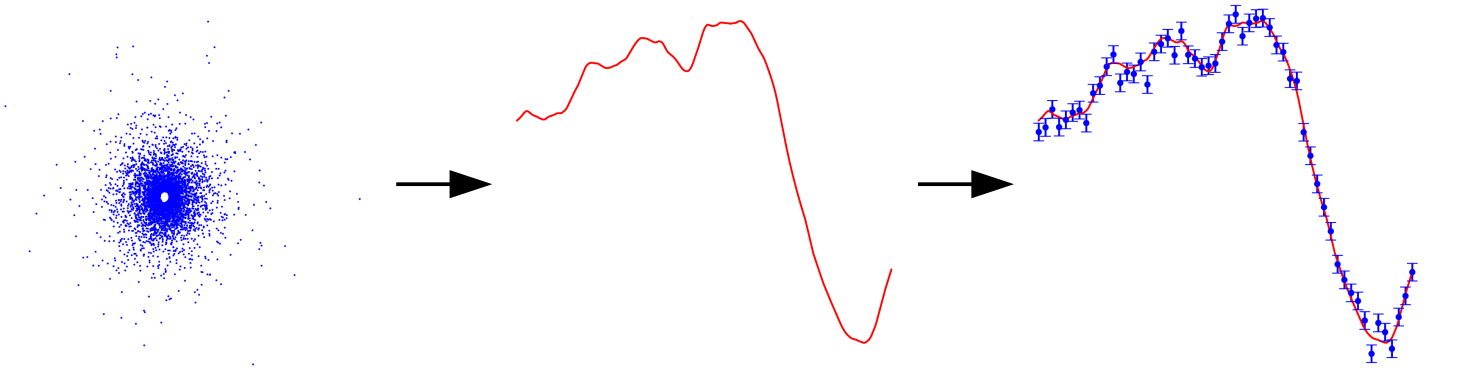


BLR geometry:
Face-on torus

Model light curve

Model light curve
+ Data (blue points)

The direct modeling approach

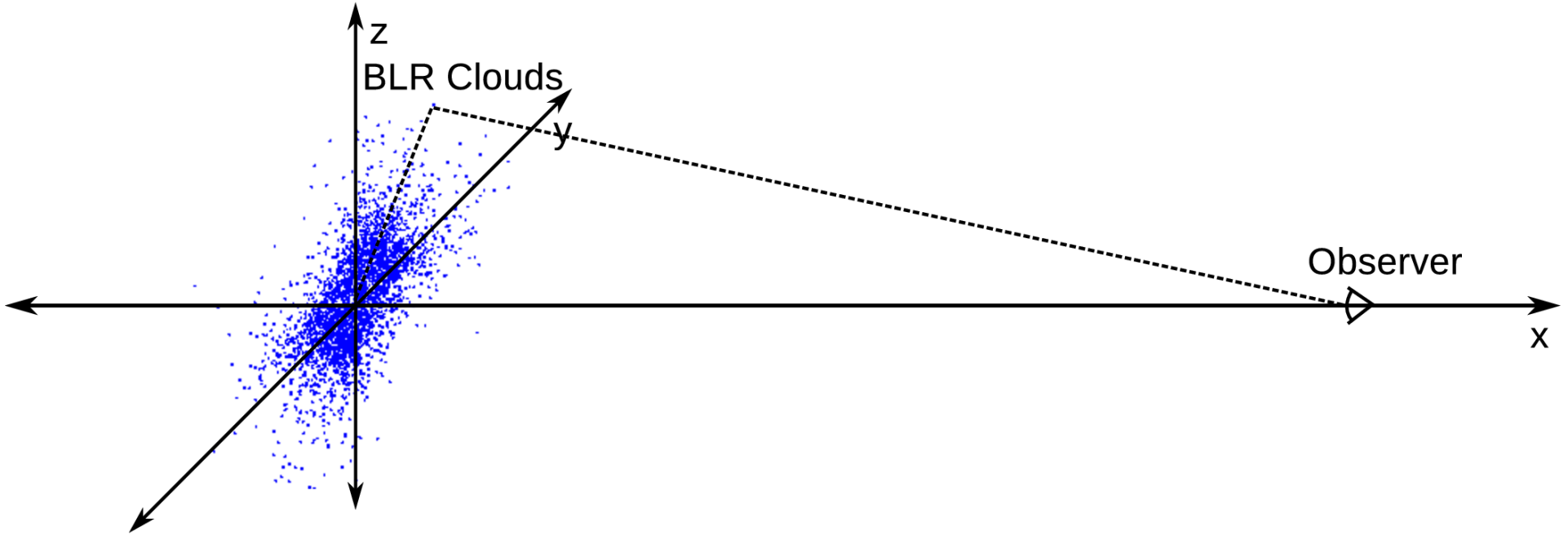


BLR geometry:
Face-on wide,
thick disk

Model light curve

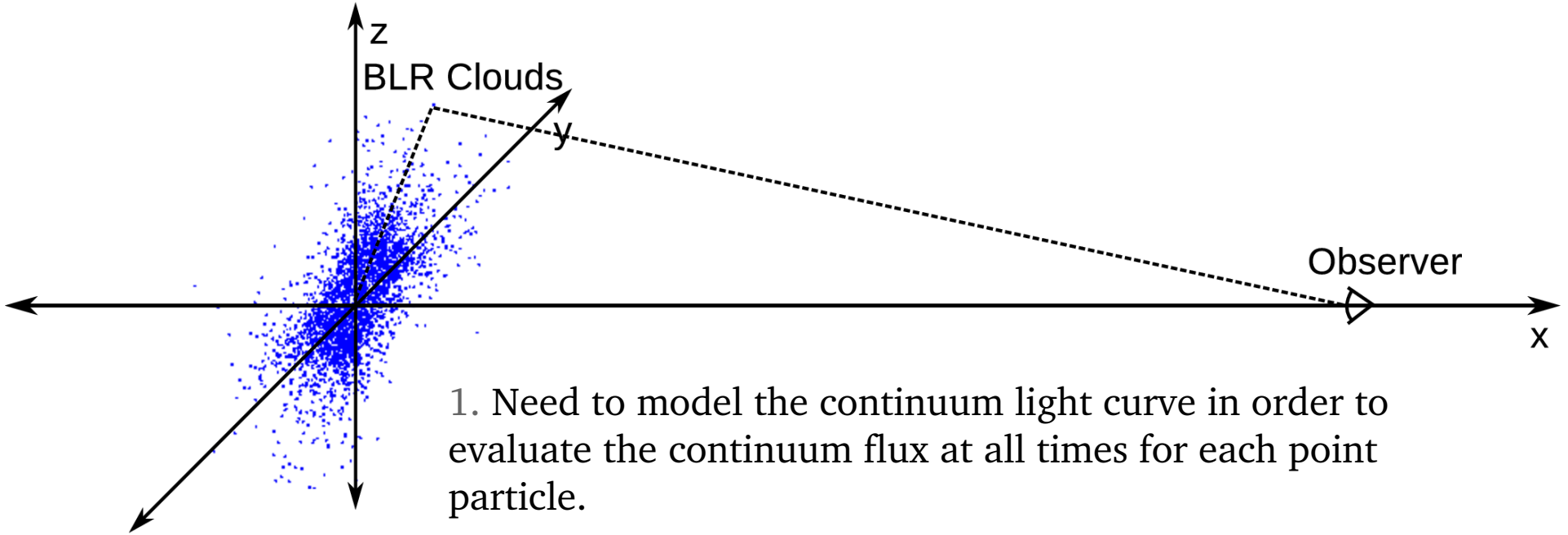
Model light curve
+ Data (blue points)

A simple model of the BLR



Brewer, Treu, Pancoast et al. 2011

A simple model of the BLR



1. Need to model the continuum light curve in order to evaluate the continuum flux at all times for each point particle.

2. Need to model the geometry and dynamics of the BLR in order to assign positions and velocities to the point particles.

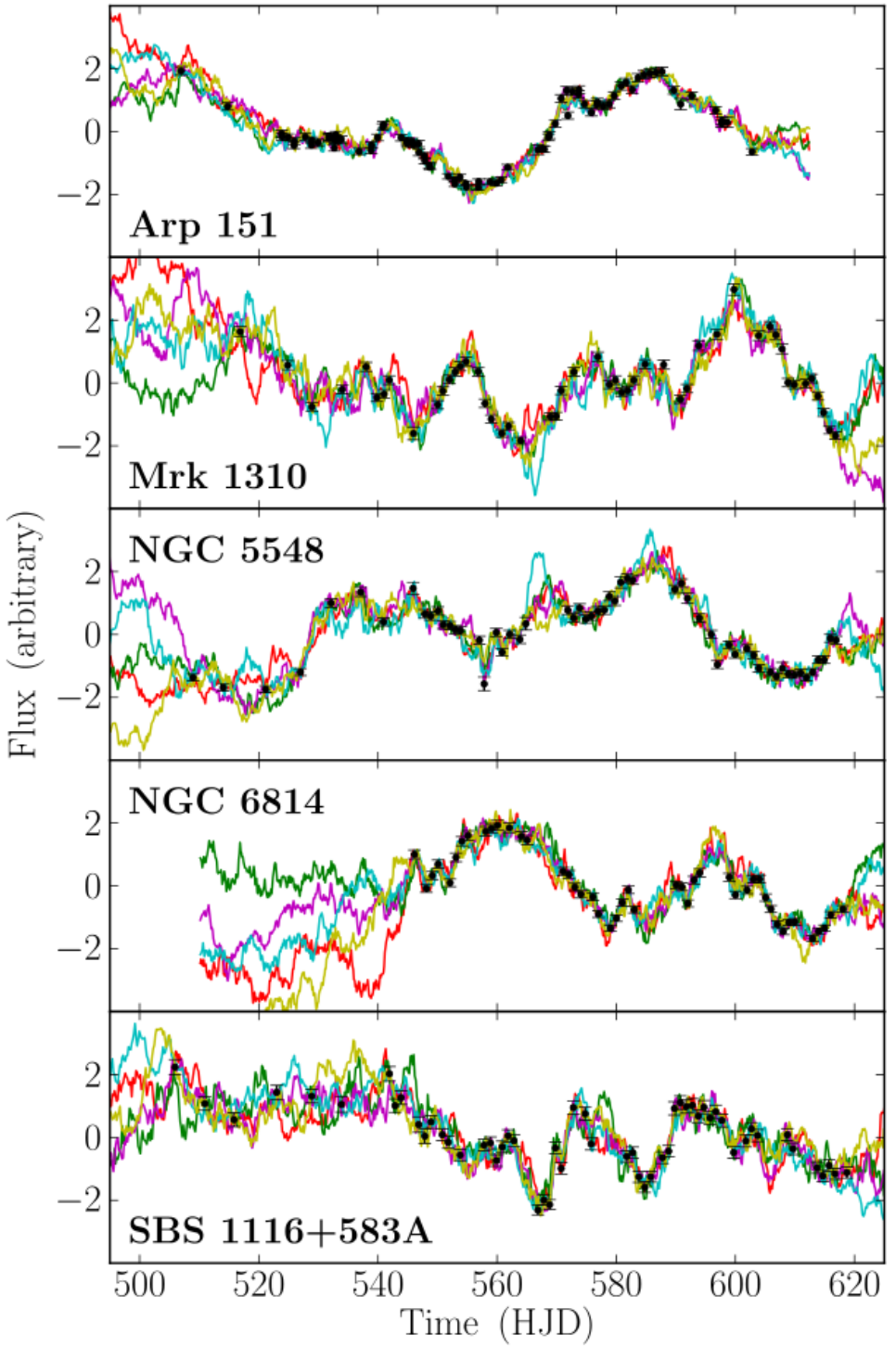
Brewer, Treu, Pancoast et al. 2011

AGN continuum light curve model

(examples for LAMP 2008)

Gaussian Processes:

- a good model for AGN variability
- includes errors from interpolation
- allows for extrapolation beyond ends of light curve

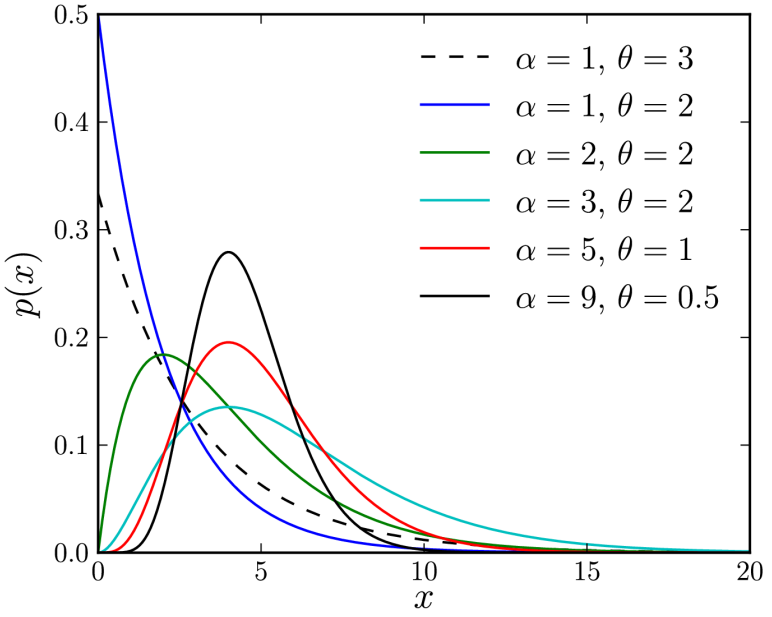


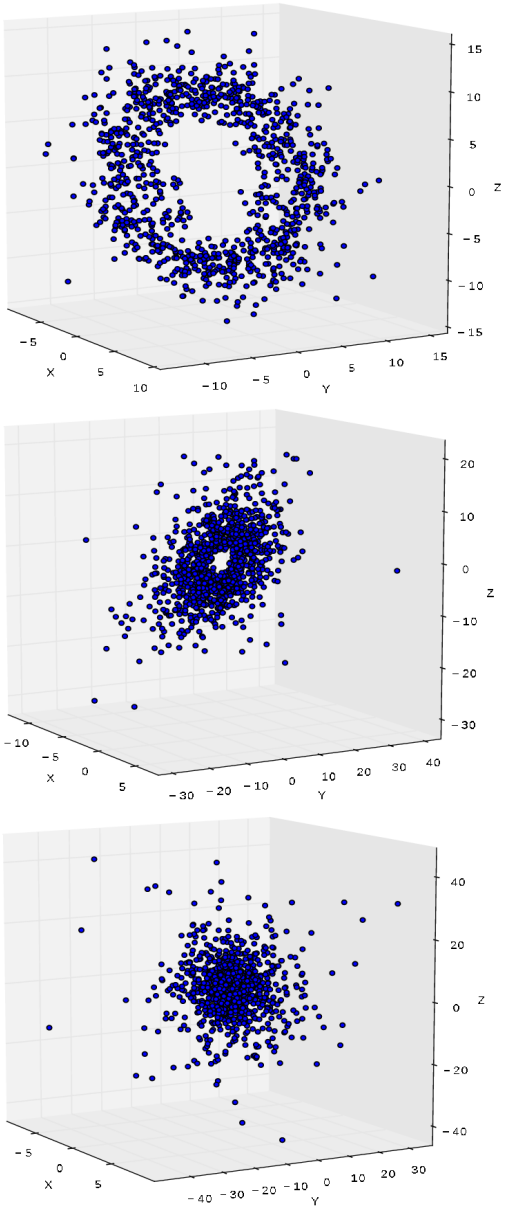
Pancoast, Brewer, & Treu et al. ArXiv:1311.6475

BLR Model: Geometry

- By modeling the geometry of the BLR, we can model *integrated broad line light curves*.

- Our geometry BLR model includes:
  - Radial distribution of emission: Gamma distribution
  - Inclination angle
  - Opening angle (disk or sphere)
  - Preferential emission by a cosine function
  - A transparent to opaque slab in the disk plane
  - Preferential emission at the edges of the disk (cone)



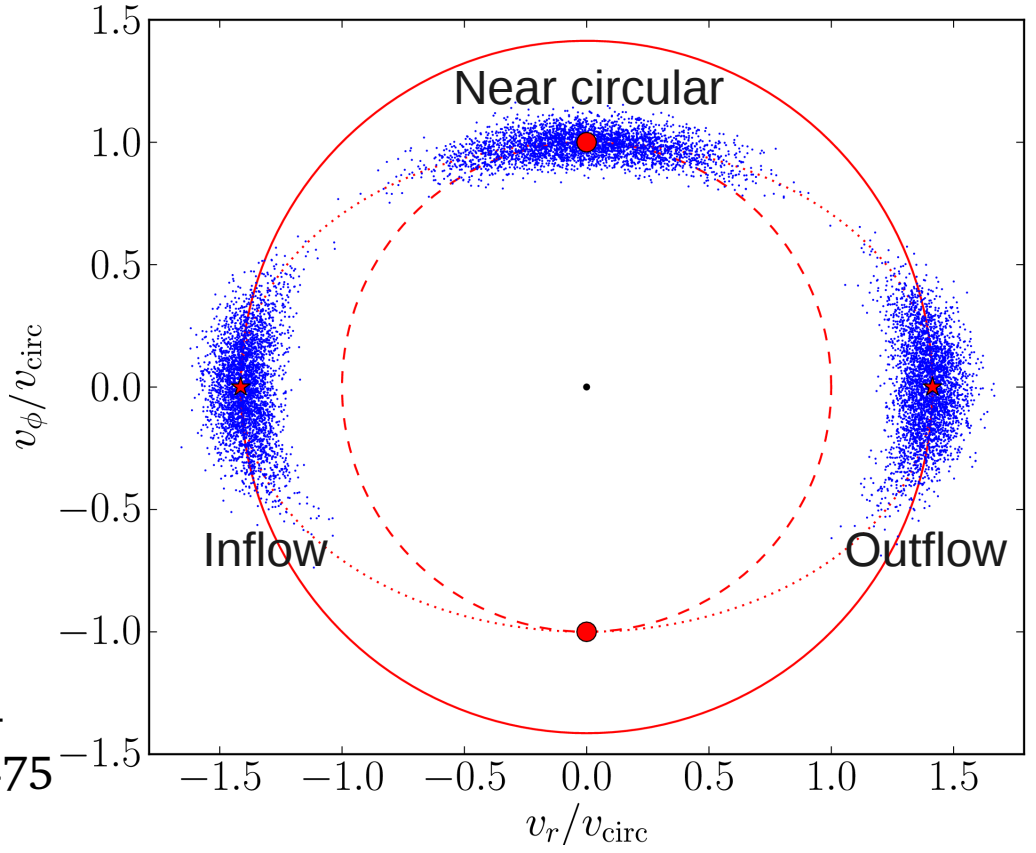


BLR Model: Dynamics

- By modeling both the geometry and dynamics of the BLR, we can model the full reverberation mapping dataset of a *spectral timeseries*.

- Our simple dynamics BLR model includes:
  - Gravitational potential of the black hole (no radiation pressure)
  - Bound elliptical orbits centered around circular orbit values
  - Radial inflowing *or* outflowing gas
  - Additional turbulent velocities

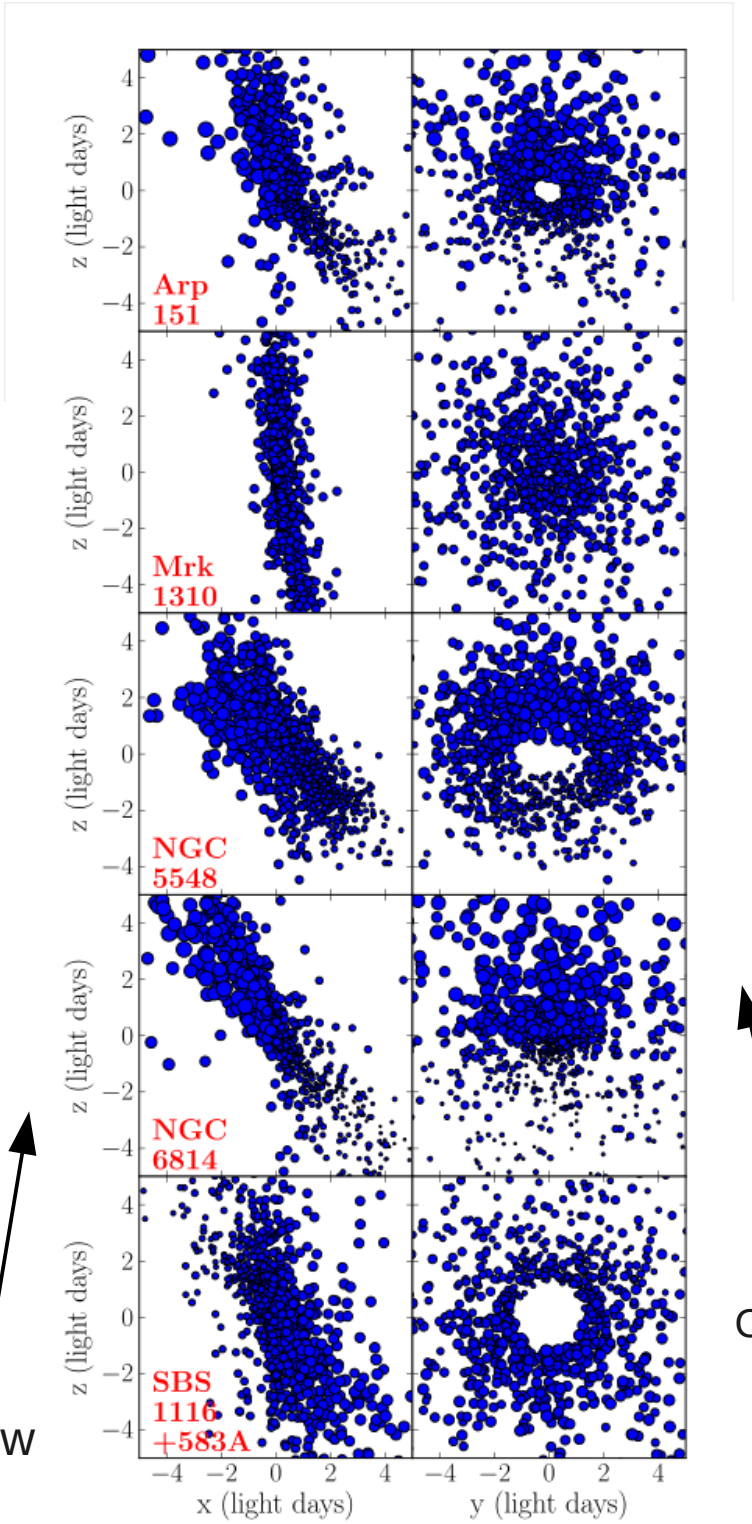
  - Gravitational redshift
  - Full expression for doppler shift



See the following for more information:
Pancoast, Brewer, & Treu, 2011, ApJ 730
Brewer, Treu, Pancoast et al. 2011, ApJ 733L
Pancoast, Brewer, & Treu et al. 2012, ApJ 754
Pancoast, Brewer, & Treu et al. ArXiv:1311.6475
Pancoast, Brewer, & Treu ArXiv:1407.2941

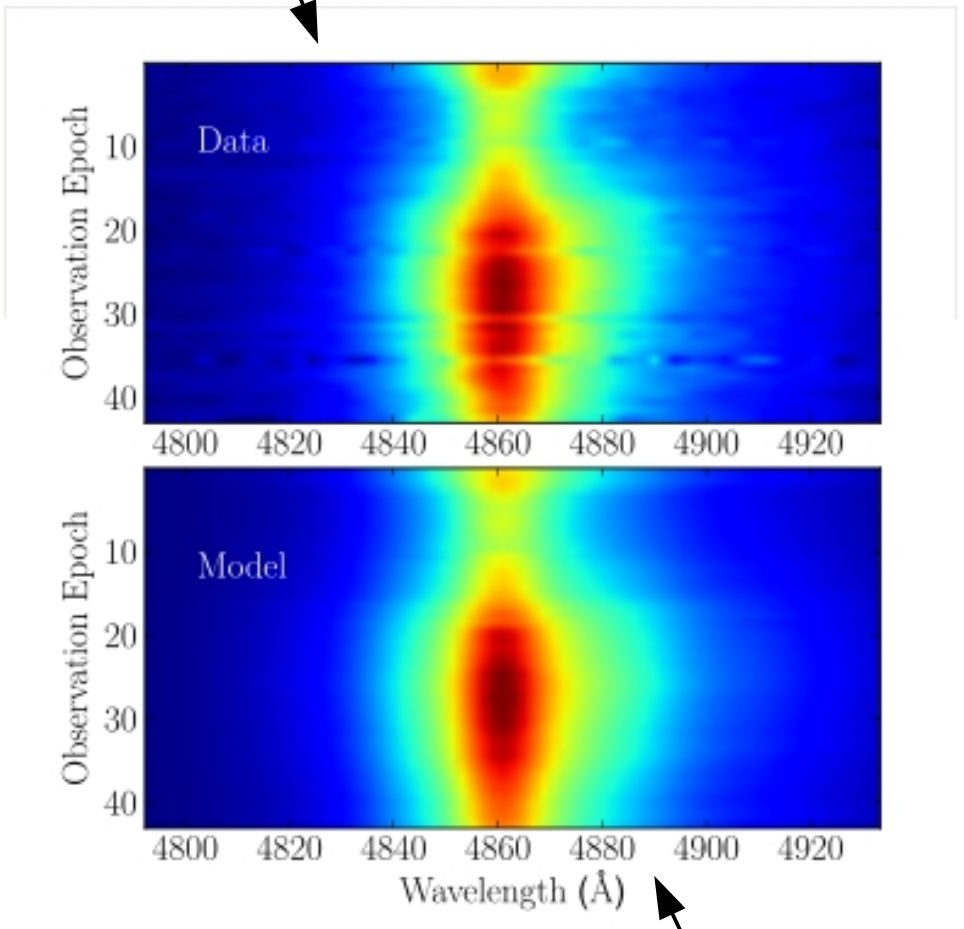
Direct modeling results for LAMP 2008

- Geometry: close to face-on thick disk.
- Generally we find preferential emission from the far side of the BLR.
- Dynamics: near circular or inflowing orbits.
- BH mass constrained to 0.15 – 0.3 dex uncertainty



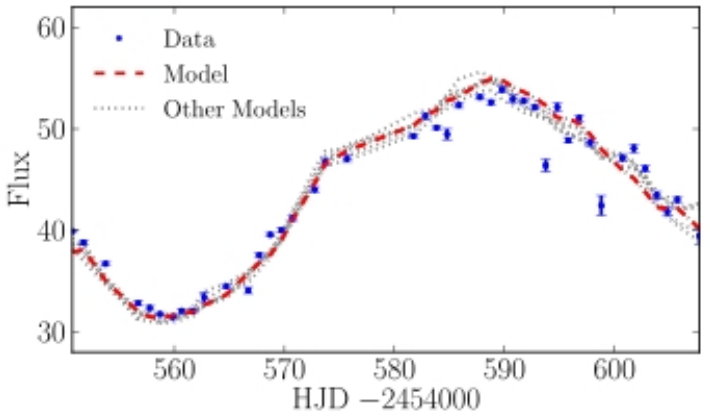
Example of detailed modeling results: Arp 151

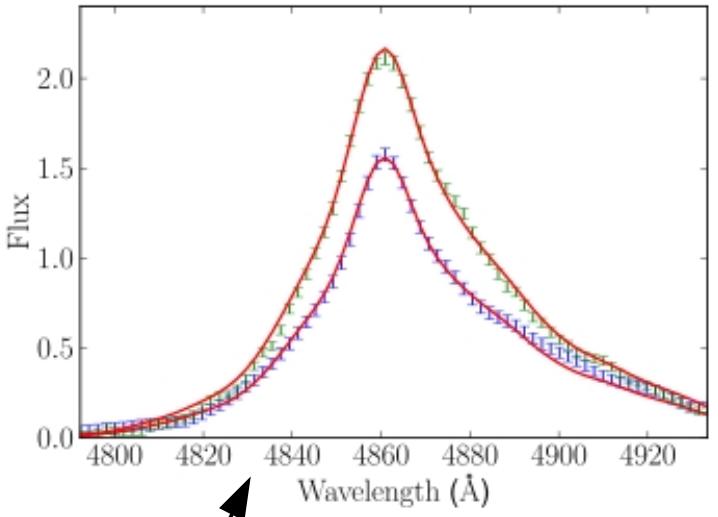
Time series of Hβ spectra



Example of model fit to time series of spectra

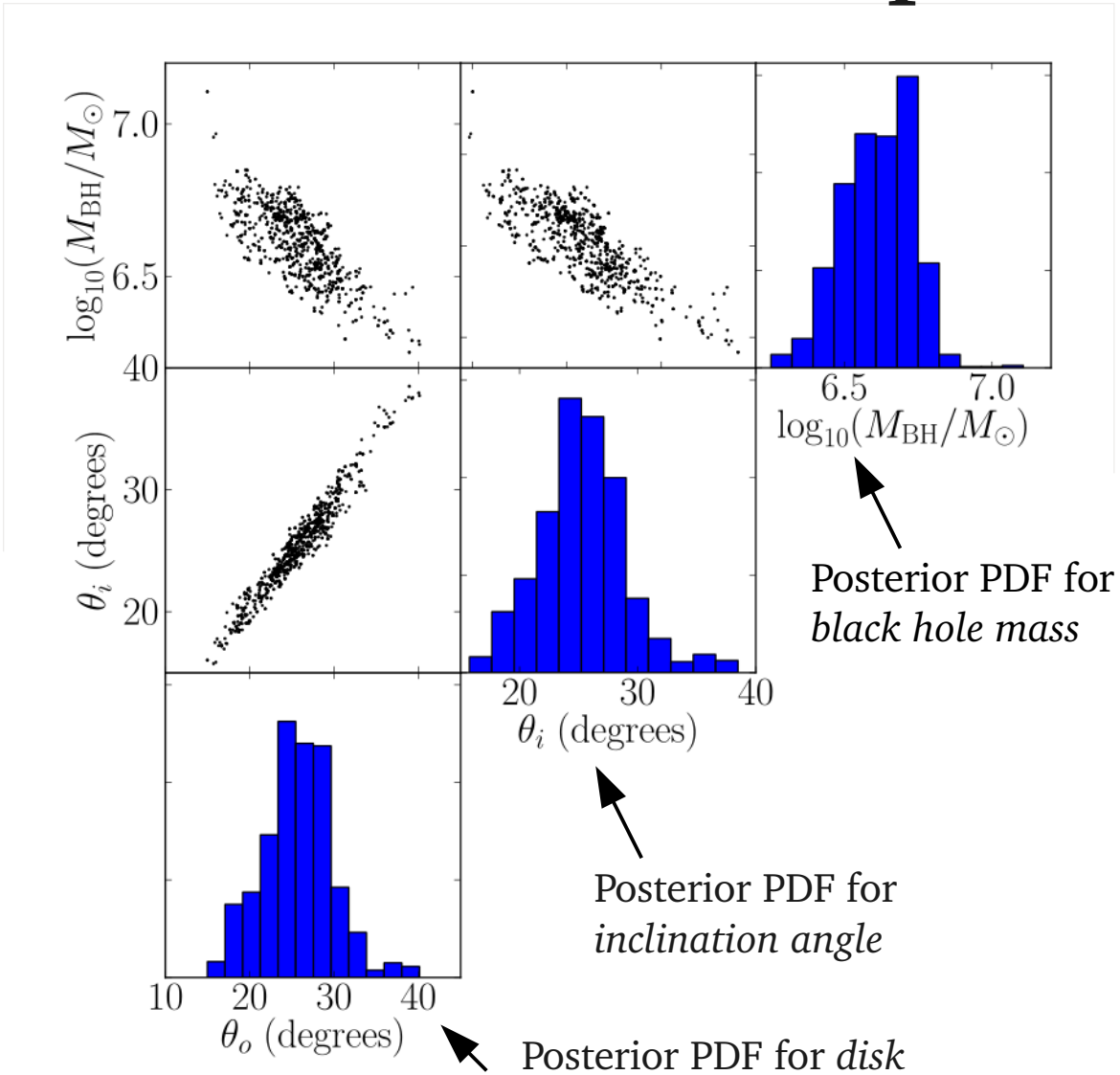
Integrated Hβ light curve and model fit





Model fits to individual Hβ spectra

Example of detailed modeling results: Arp 151

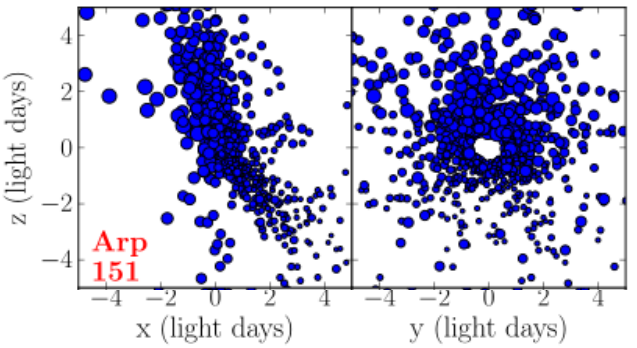


Posterior PDF for *black hole mass*

Posterior PDF for *inclination angle*

Posterior PDF for *disk opening angle*

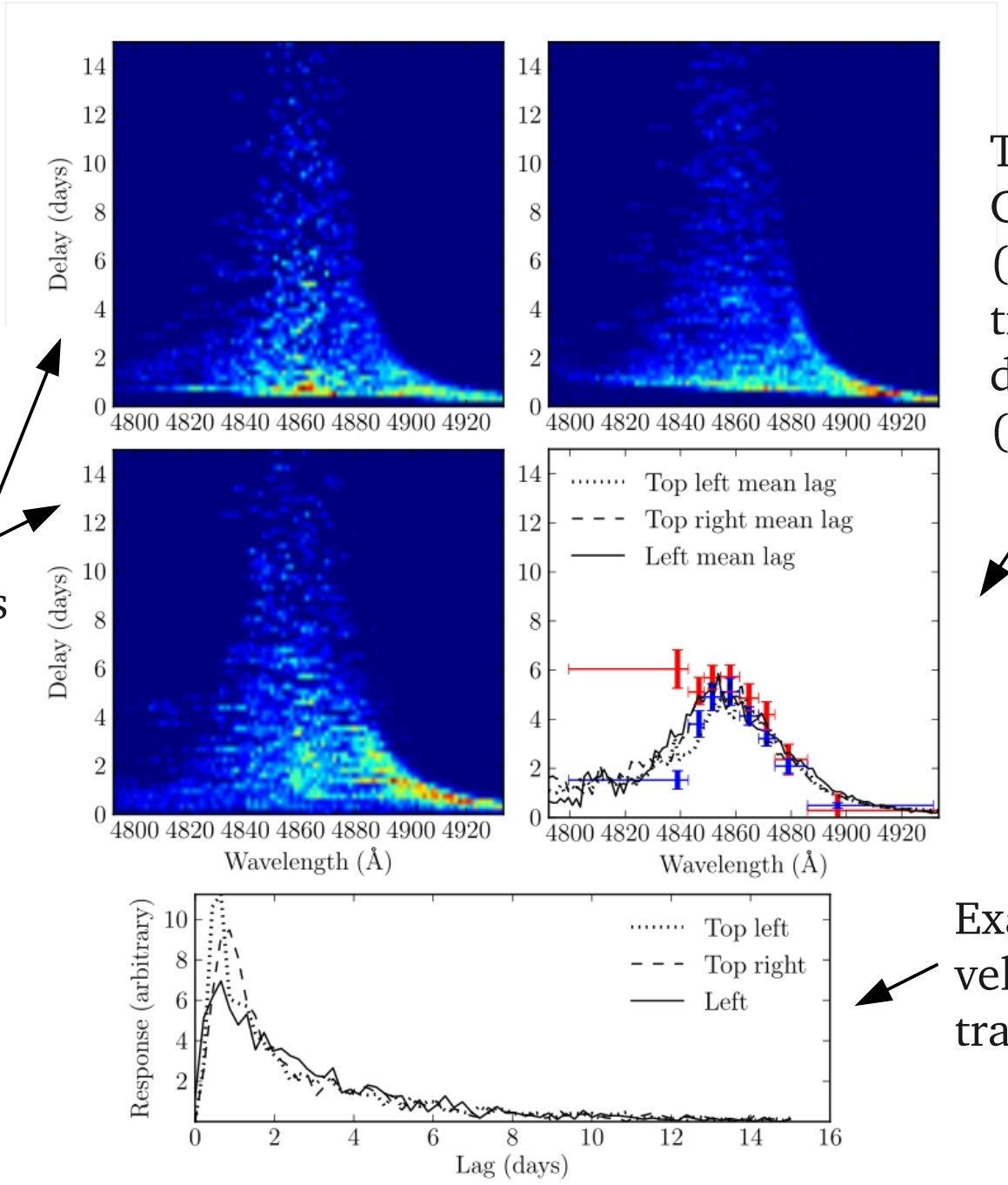
- Geometry: a wide thick disk with an opaque midplane and more emission from the faces and back of the disk.



- Dynamics: mostly bound inflowing orbits.

- Black hole mass is constrained to within 0.15 dex uncertainty.

The transfer function for Arp 151

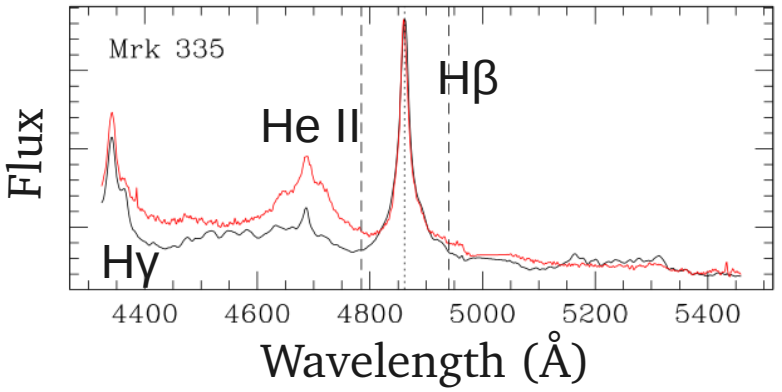


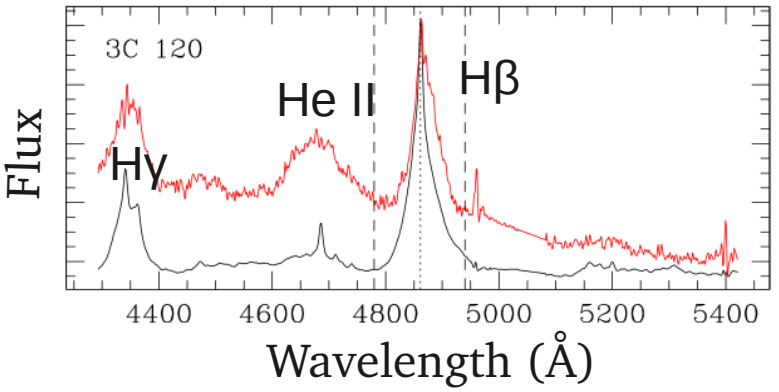
Examples of transfer functions drawn from the posterior PDF

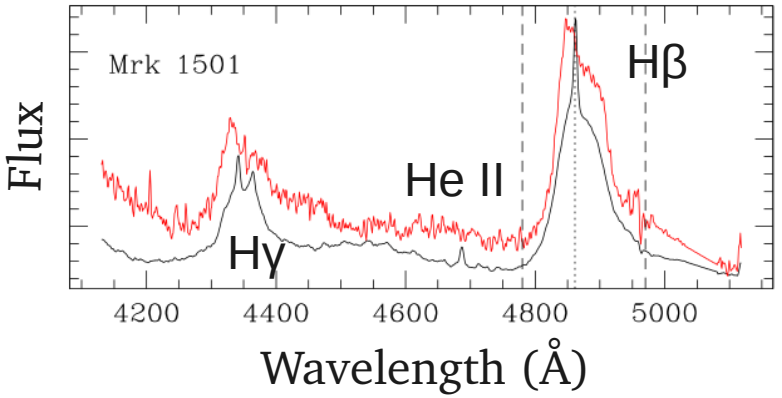
Time lags from CCF analysis (red) and mean time lags from direct modeling (blue)

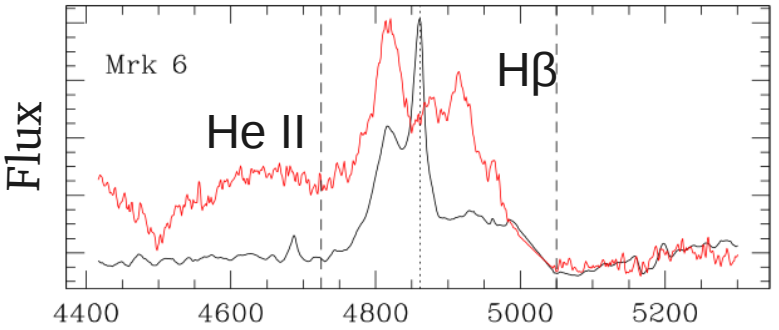
Examples of velocity-integrated transfer functions

The MDM 2010 dataset (AGN10)

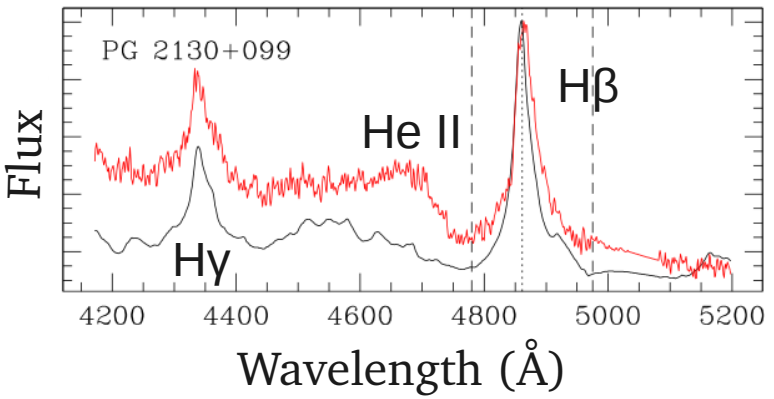








Black = mean
Red = RMS

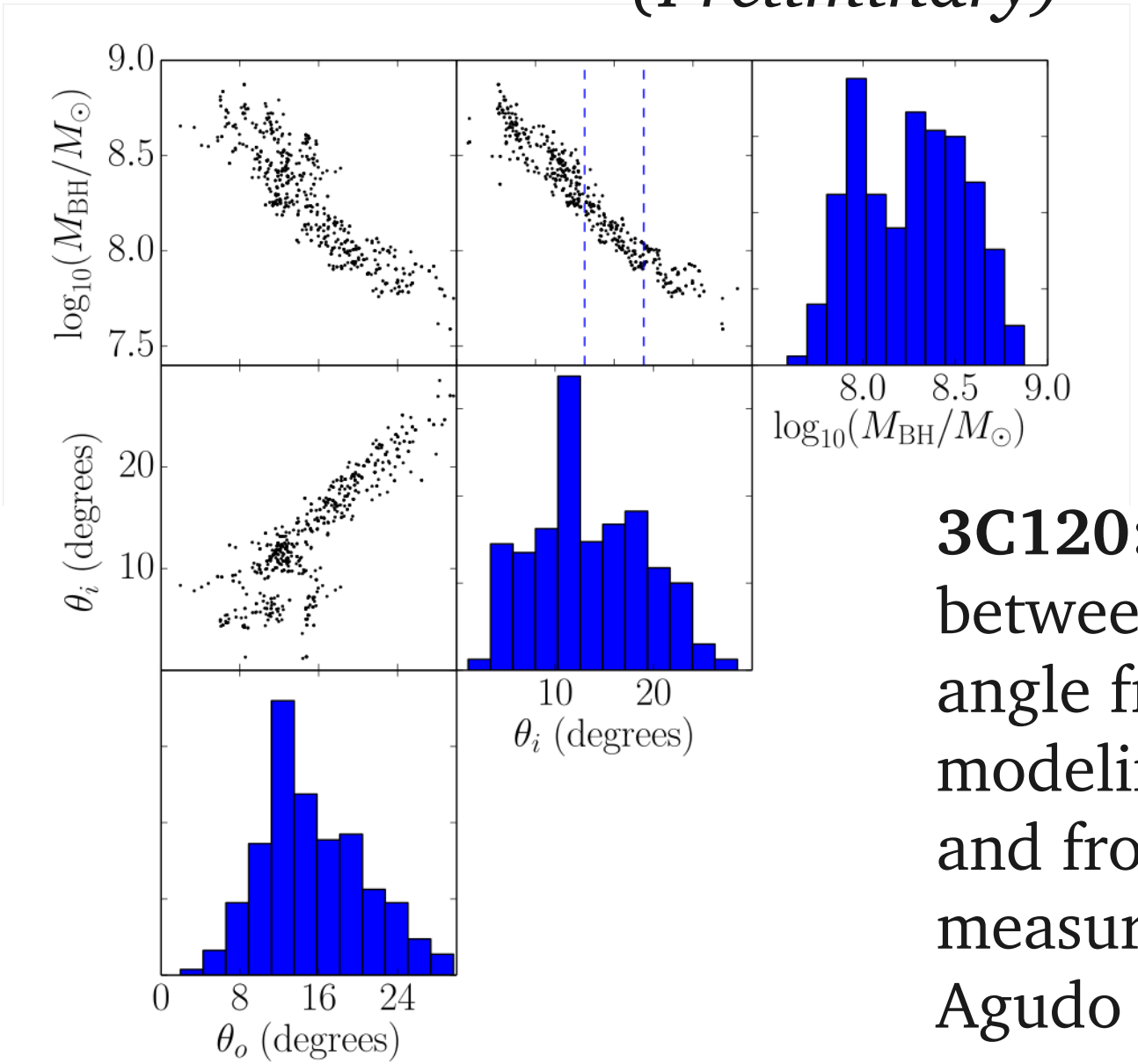


- 5 AGNs with **preliminary** constraints on the BLR
- Higher luminosity, black hole mass, and redshift than LAMP 2008 sample

Grier, Pancoast et al. (in preparation)

AGN10 Modeling Highlights

(Preliminary)



3C120: agreement between the inclination angle from direct modeling ($12.5^{+7.0}_{-5.4}$ deg) and from radio jet measurements (16 deg, Agudo et al. 2012)

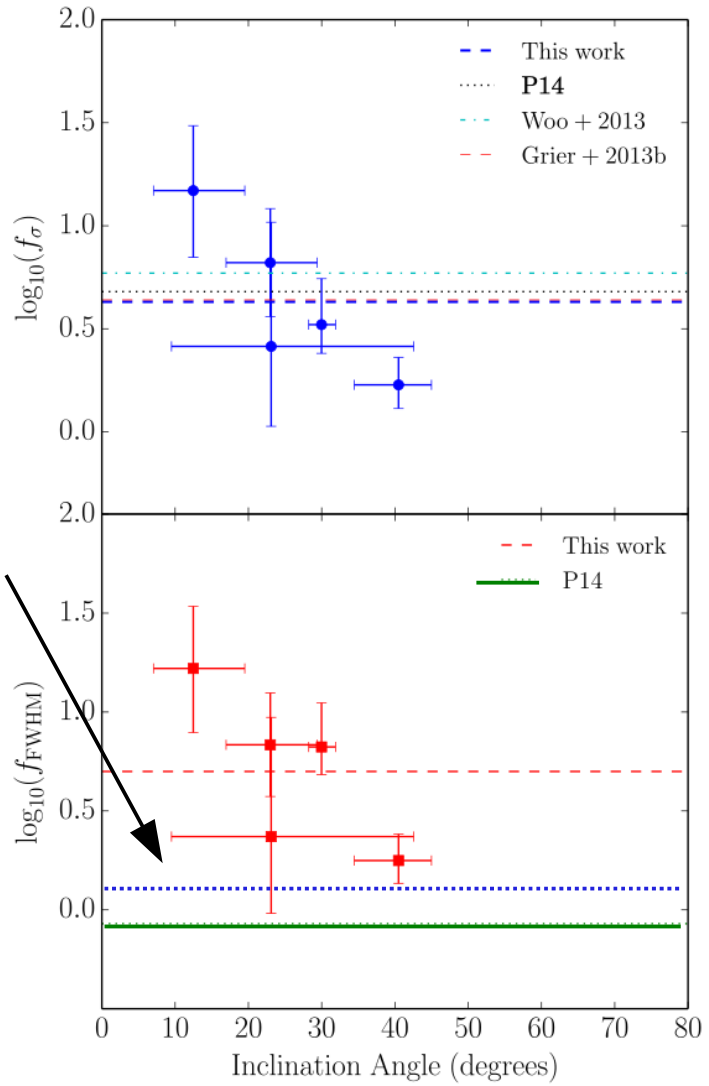
Grier, Pancoast et al. (in preparation)

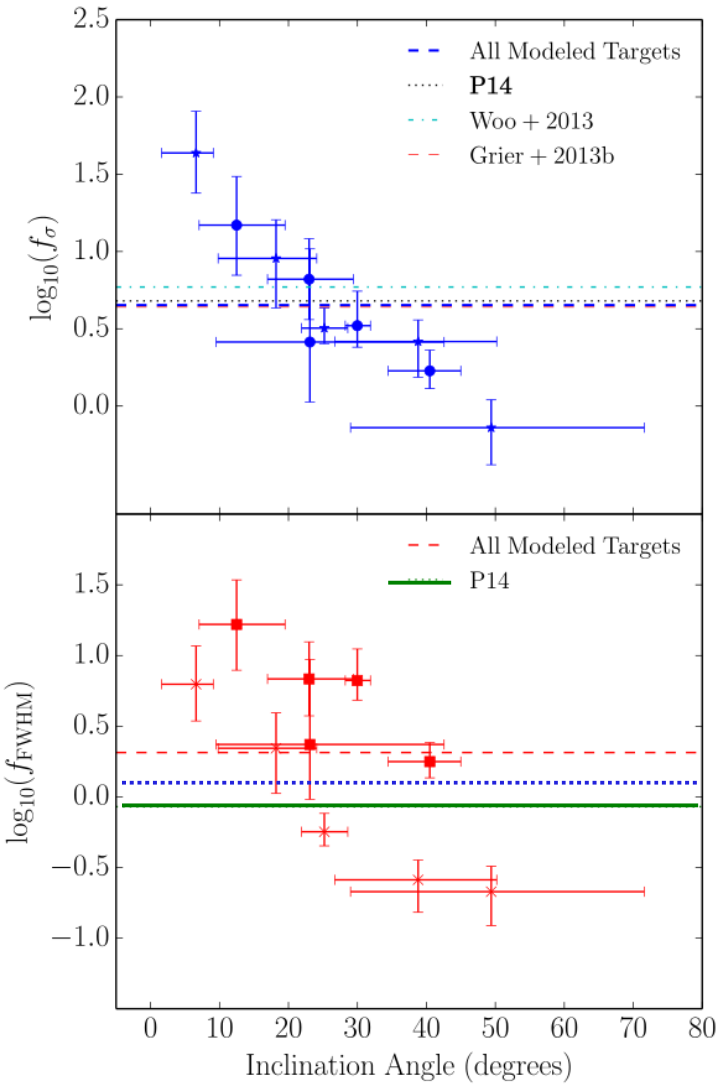
AGN10 Modeling Highlights

(Preliminary)

For AGN10 sample, $f_\sigma \sim f_{FWHM}$

Collin et al. 2006 value (blue line)





Grier, Pancoast et al. (in preparation)

AGN10 Modeling Highlights
(Preliminary)

- Geometry: Generally close to face-on thick disks
- Dynamics: Mostly elliptical orbits and/or inflow
- Black hole mass: Mostly constrained to <0.3 dex uncertainty

- 4/5 AGNs have MEMECHO transfer functions for comparison
- Still working on how spectral decomposition affects the modeling results (complicated by different Fe templates)

Grier, Pancoast et al. (in preparation)

The next step: combining UV + optical data for NGC 5548

- Multiple strong emission lines for BLR modeling
- Future expansions for the BLR model:
  - Possible non-linear response of BLR gas
  - Changing size of the BLR: breathing effects
  - More realistic treatment of outflows
  - Simultaneous modeling of multiple emission lines
  - Connection to the physics of the BLR gas through photoionization constraints (using CLOUDY)

Conclusions

- For the 5 AGNs in the LAMP 2008 sample:
  - Hβ BLR geometry is consistent with a thick disk where the far side contributes more emission.
  - Hβ BLR dynamics is consistent with a combination of elliptical orbits and inflow.
  - BH mass can be constrained to <0.3 dex.
- Work on increasing the modeling sample using 5 AGNs from AGN10 sample
  - Only correlation with f (so far) is inclination angle
- *Next project:* model optical + UV spectra for NGC 5548 from AGN STORM