Revealing the Hidden Broad Line Region in AGN Using Reverberation Mapping

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Brendon Brewer (U. Auckland) and Tommaso Treu (UCLA)
+ LAMP 2008 collaboration

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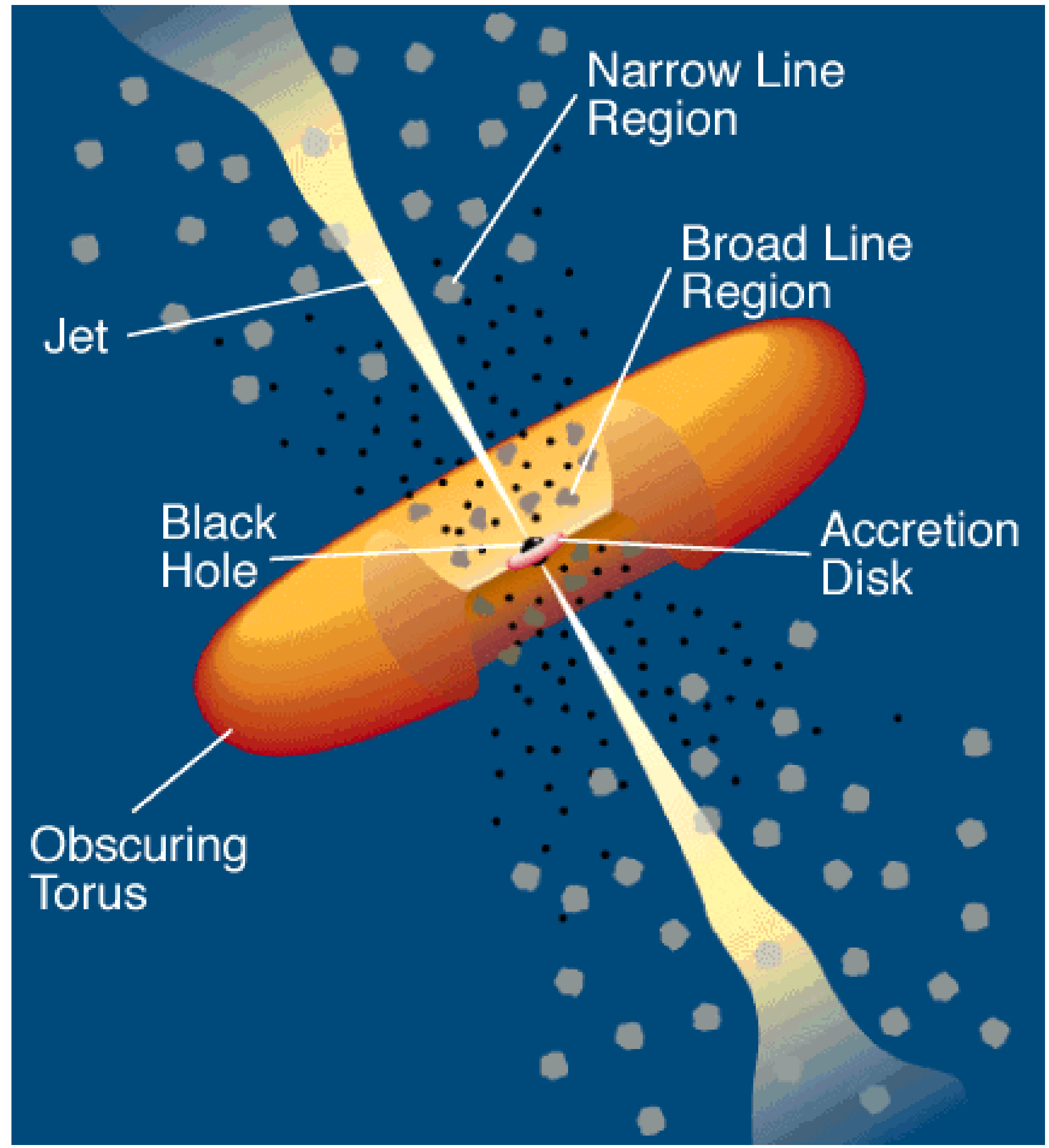
Black holes in active galaxies

- No hard distance limit on measuring M_{BH} in active galactic nuclei (AGN).
- Measure M_{BH} by constraining properties of the gas orbiting around the black hole in the broad line region (BLR).



Credit: C.M. Urry and P. Padovani

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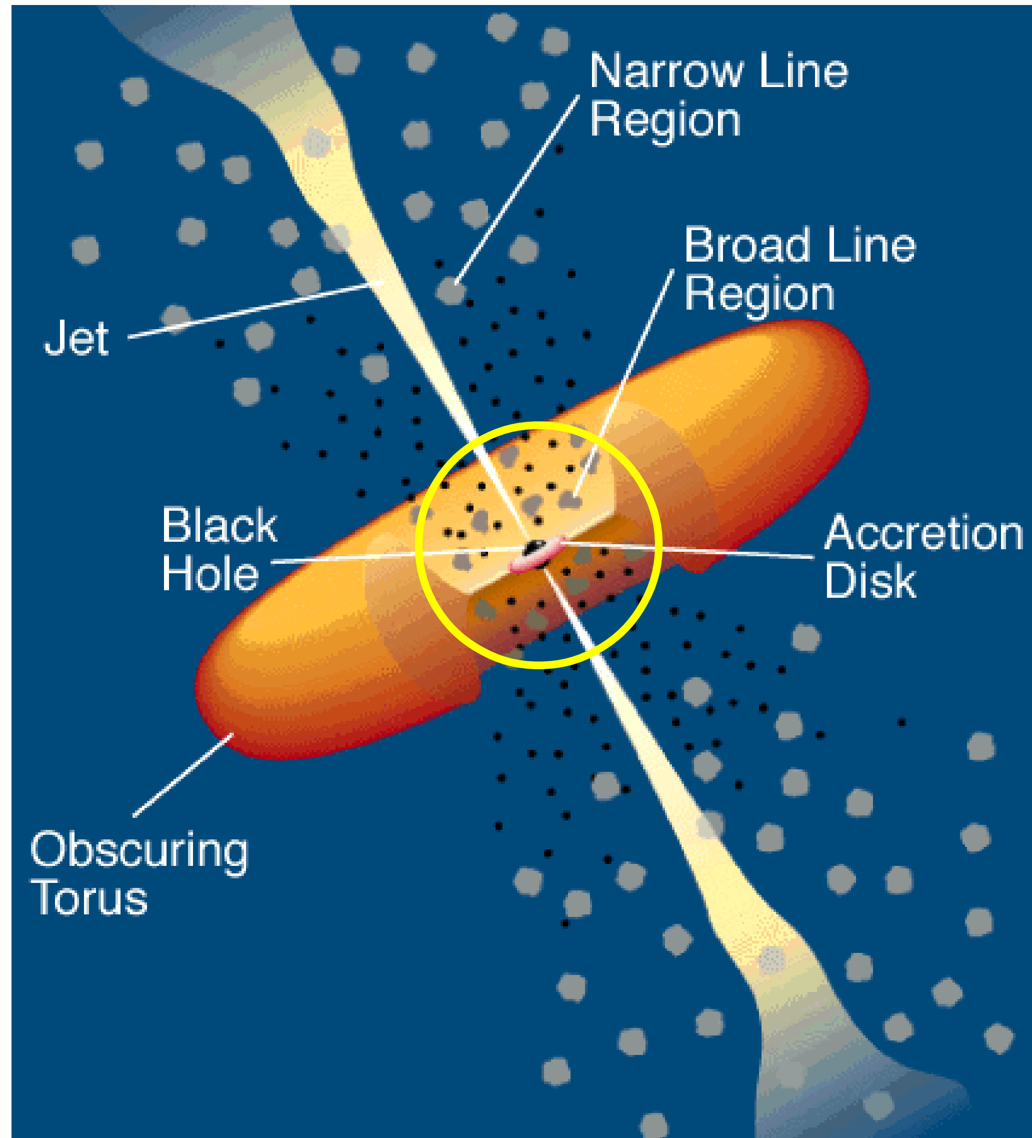

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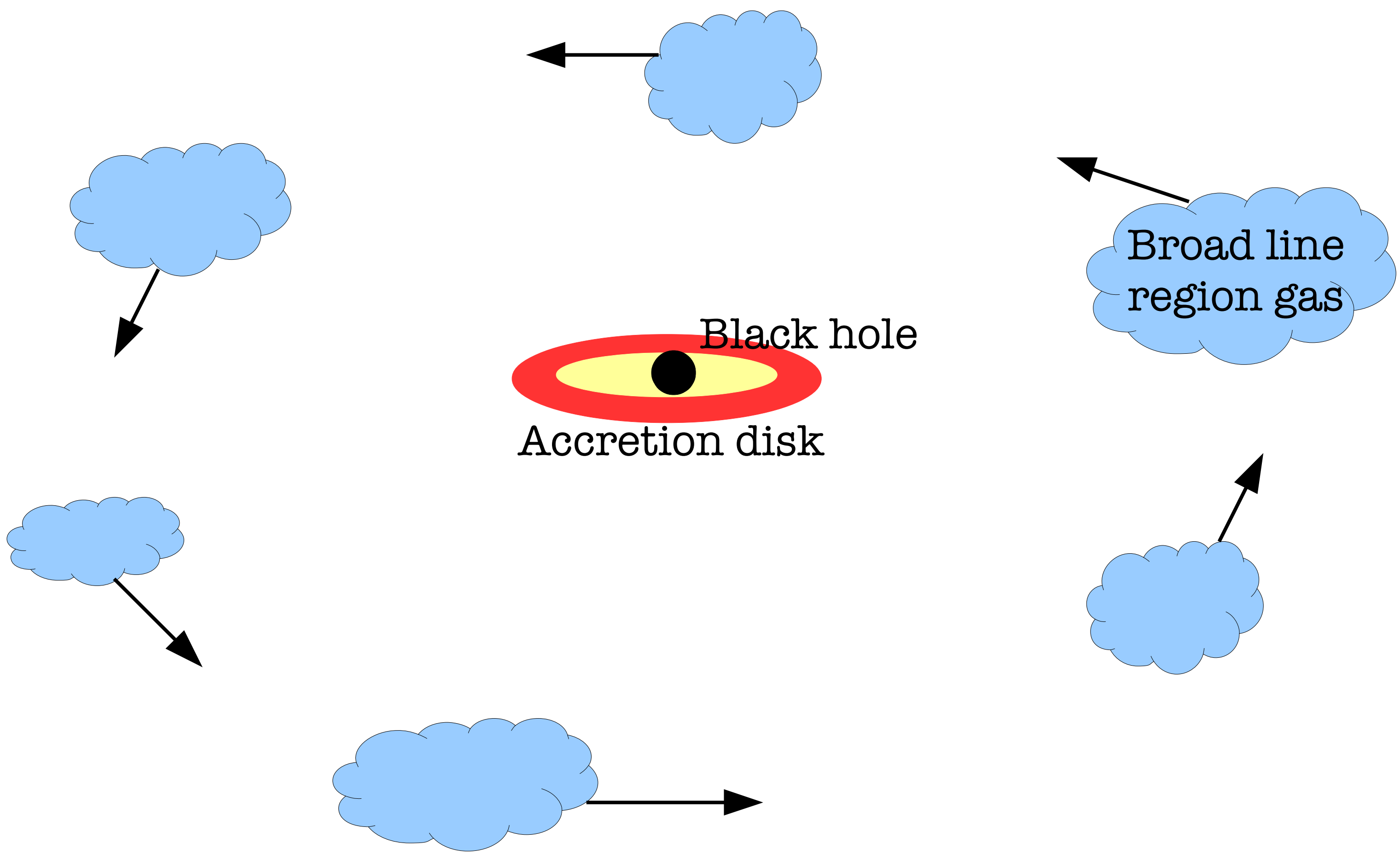
Reverberation mapping



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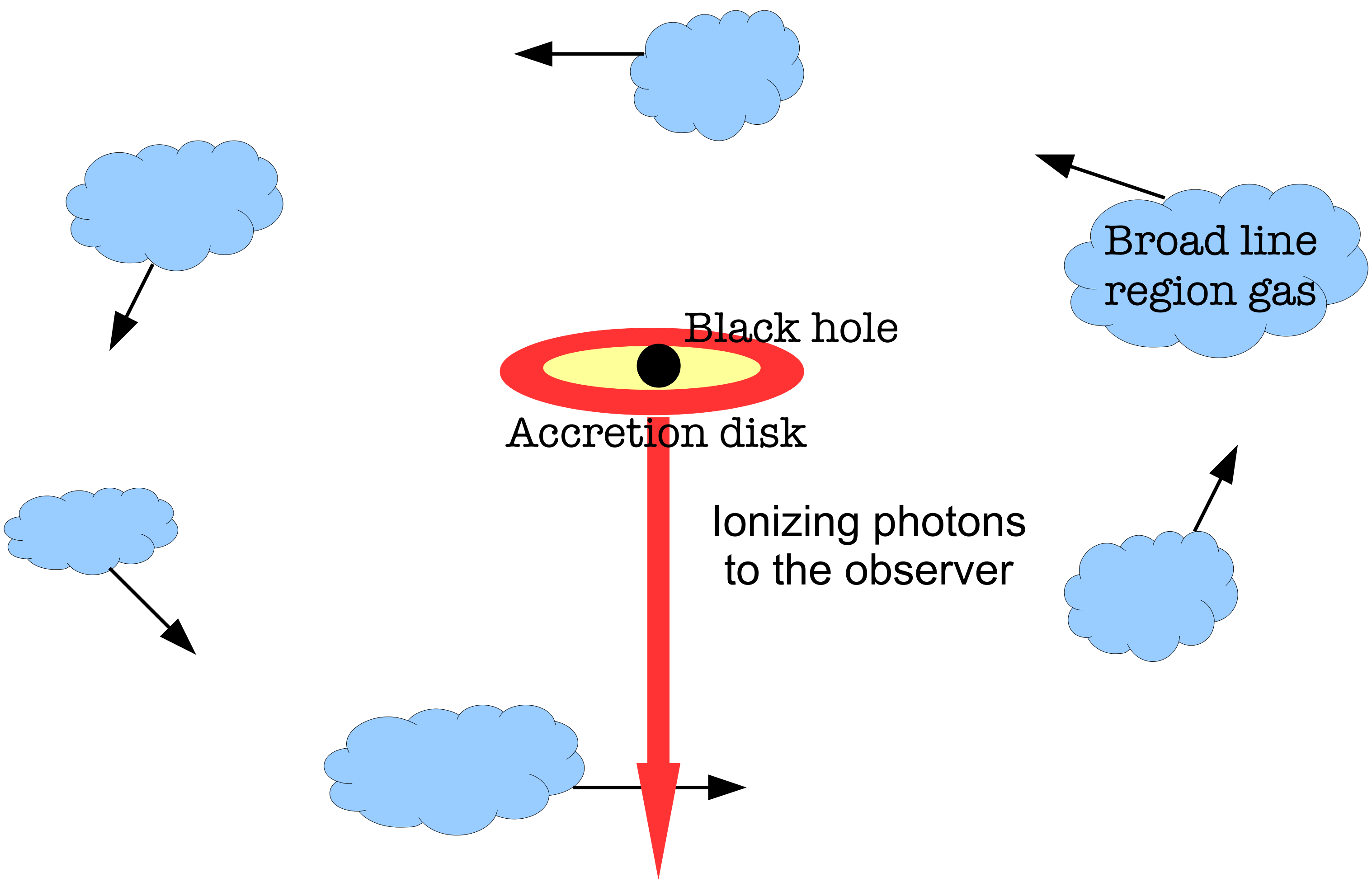

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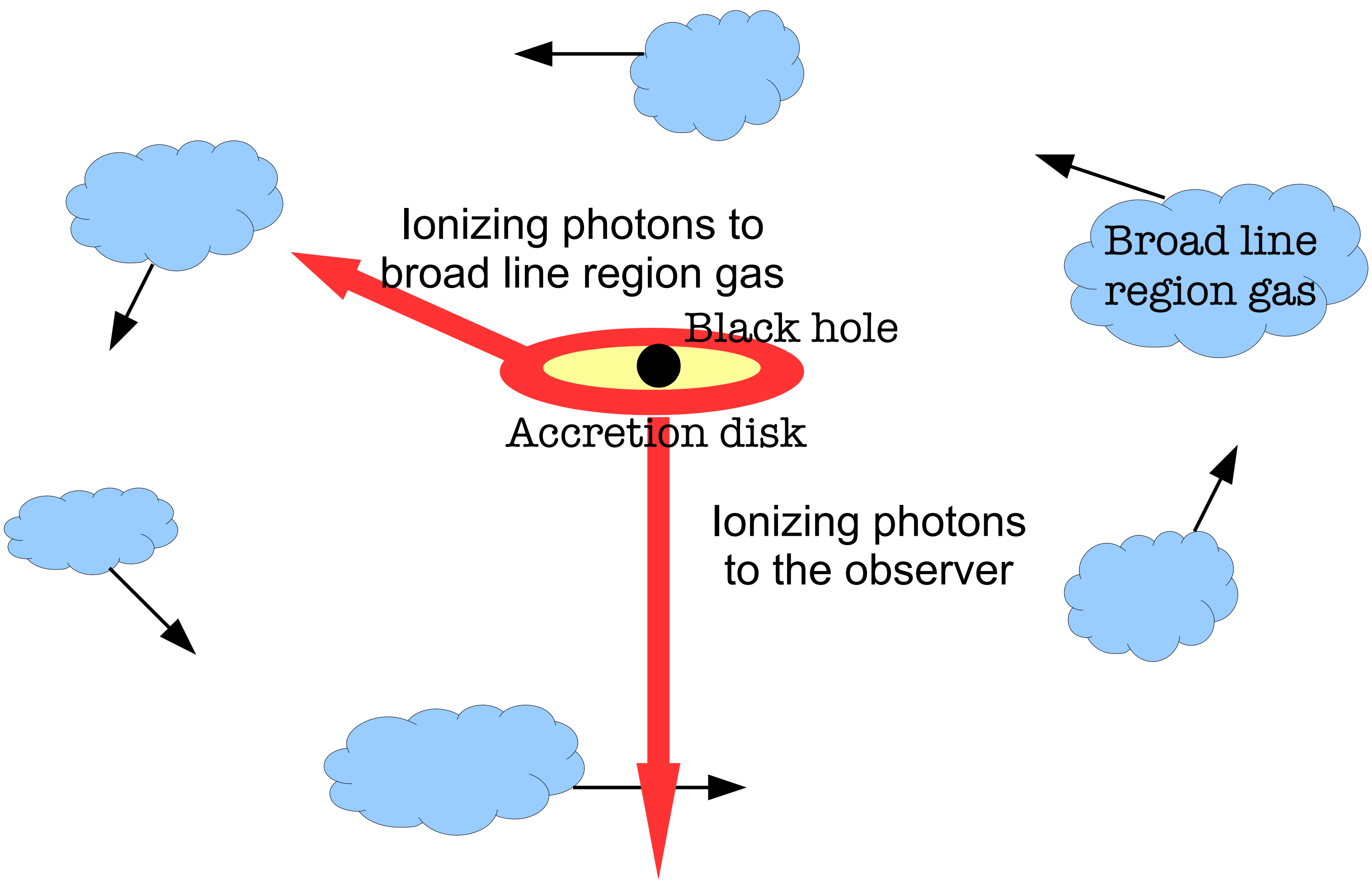

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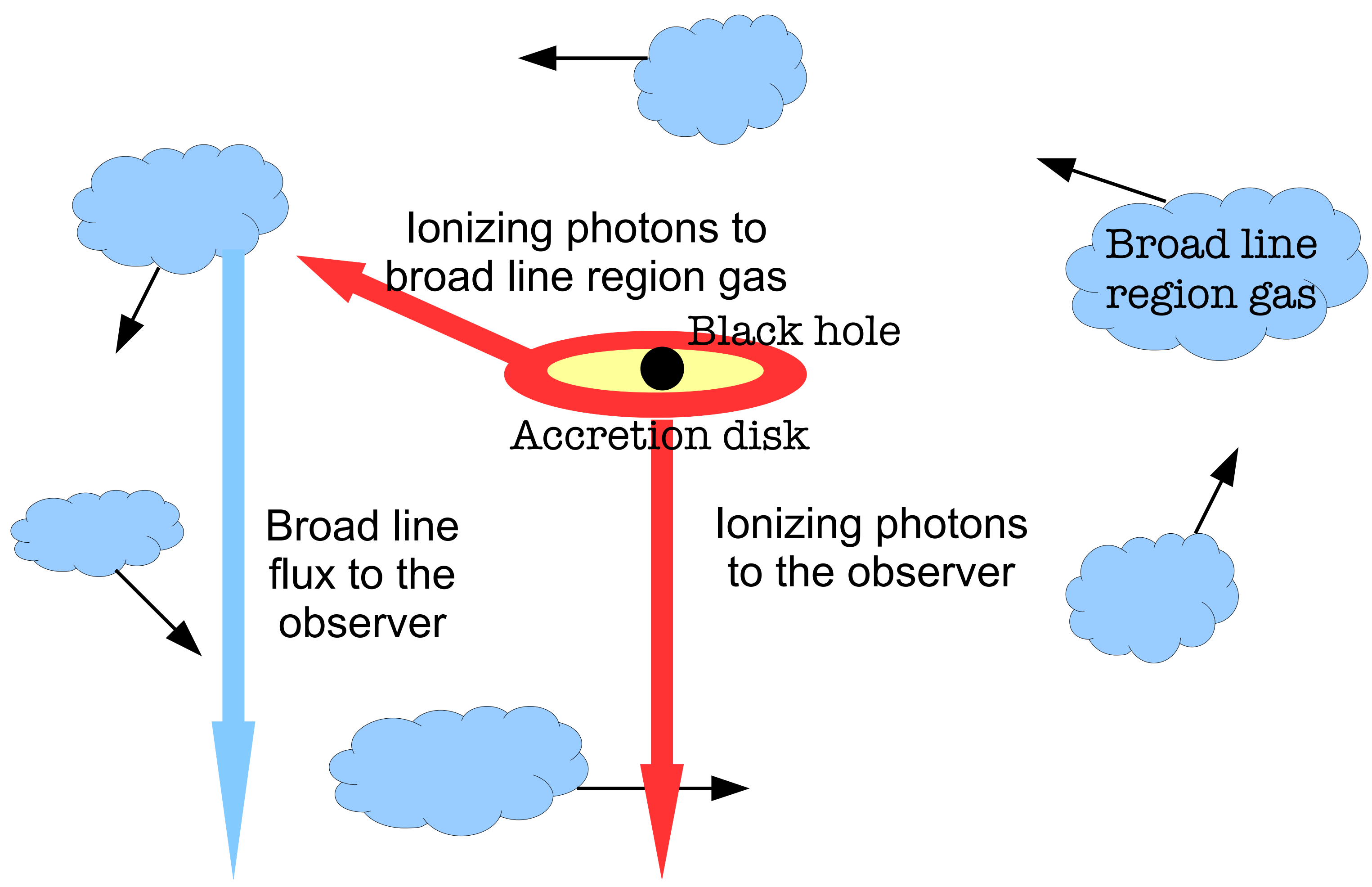

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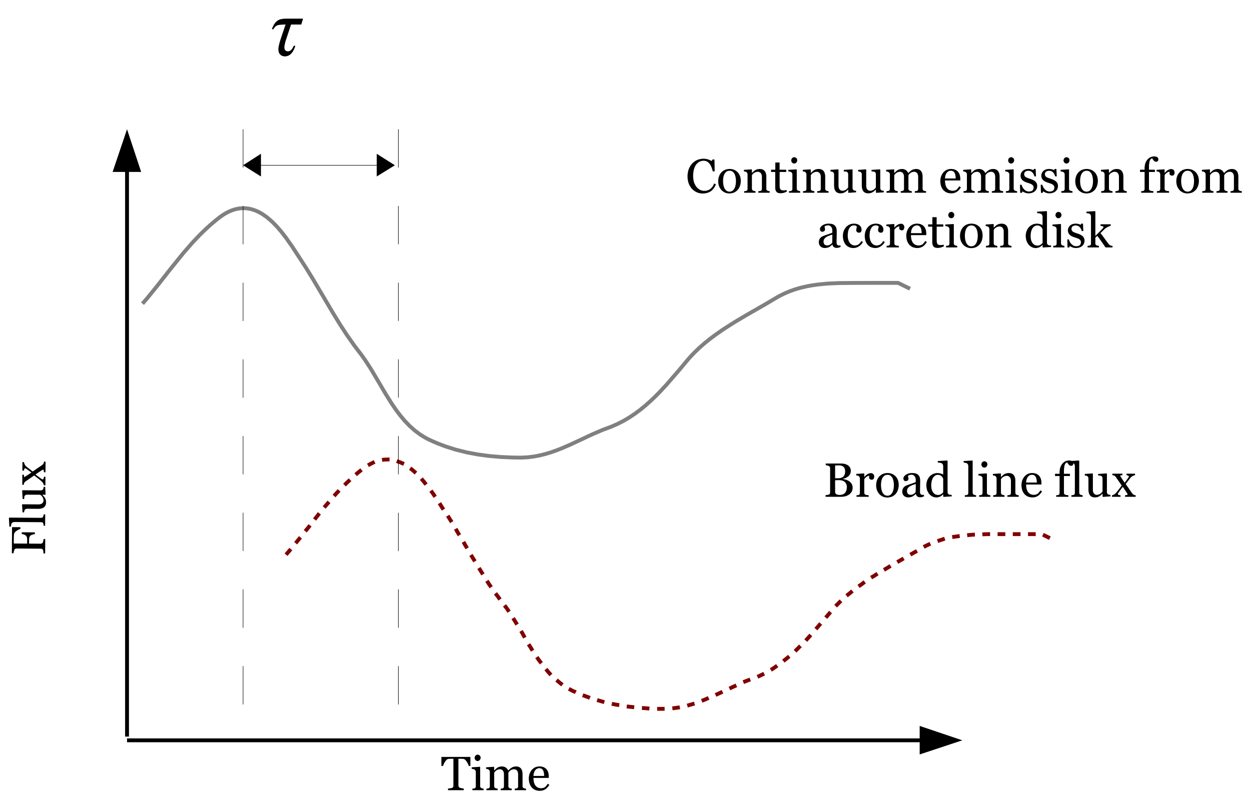

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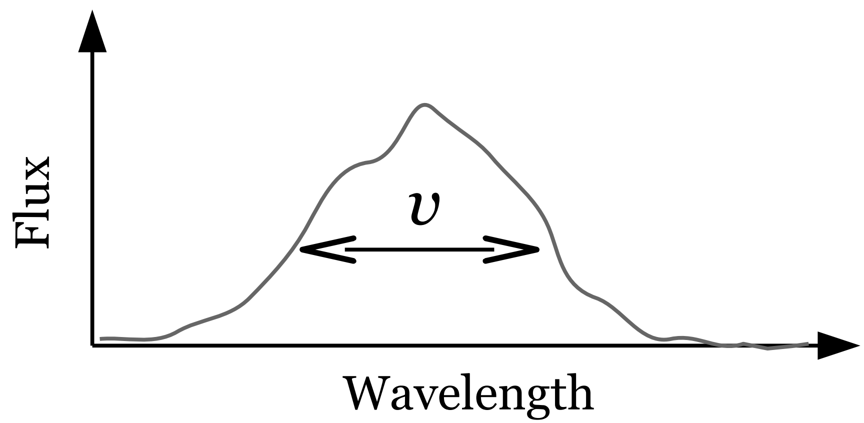

- Velocity of gas from the width of the broad emission line.

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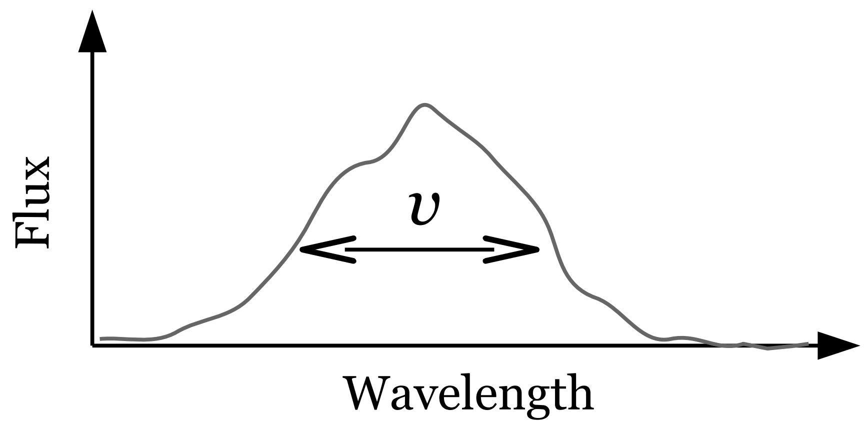

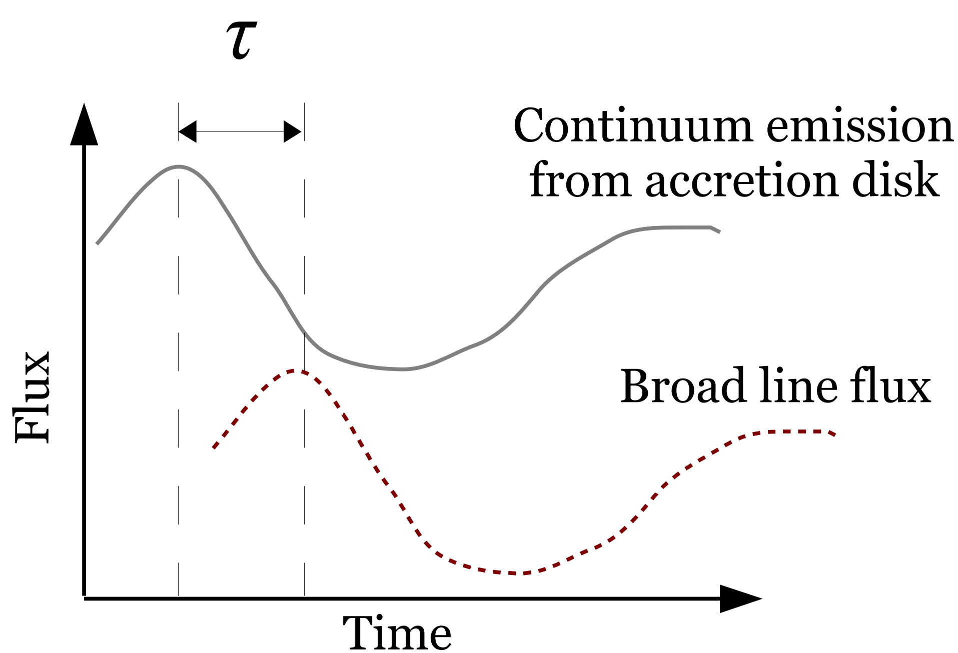

- Velocity of gas from the width of the broad emission line.
- Radius of the gas by measuring time lag between continuum and broad line flux changes.

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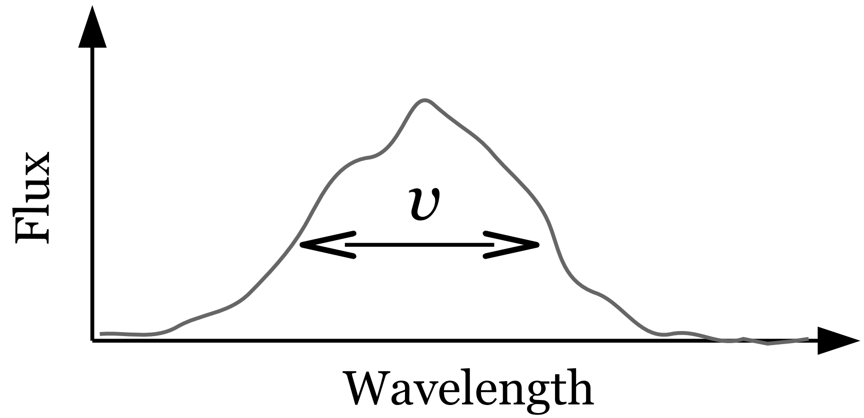
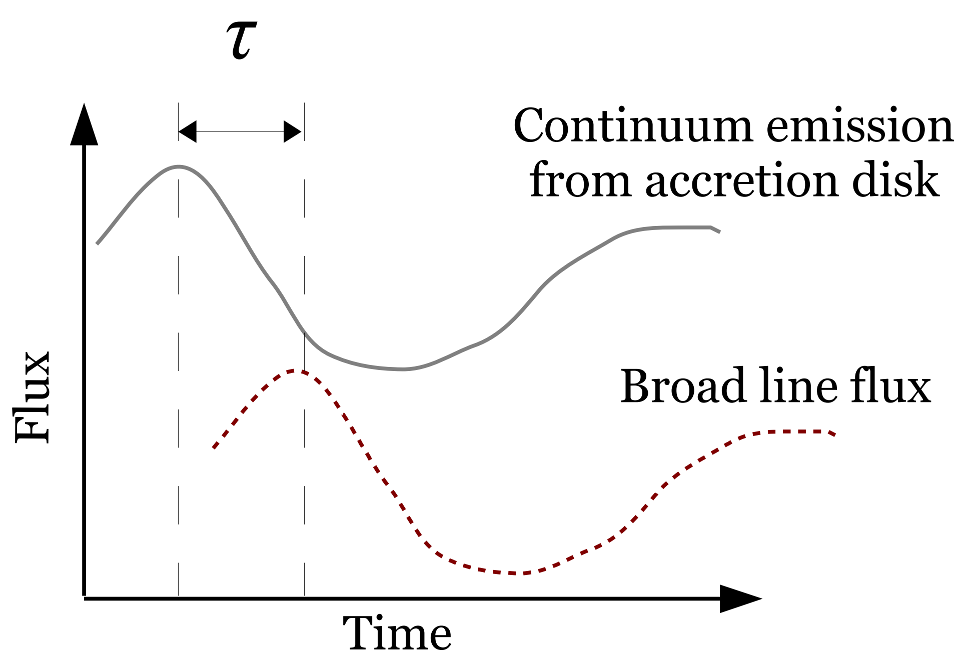
Reverberation mapping





- Velocity of gas from the width of the broad emission line.
- Radius of the gas by measuring time lag between continuum and broad line flux changes.
- Black hole mass:

$$M_{\mathrm{vir}} = f\, v^2\, c\, \tau / G$$

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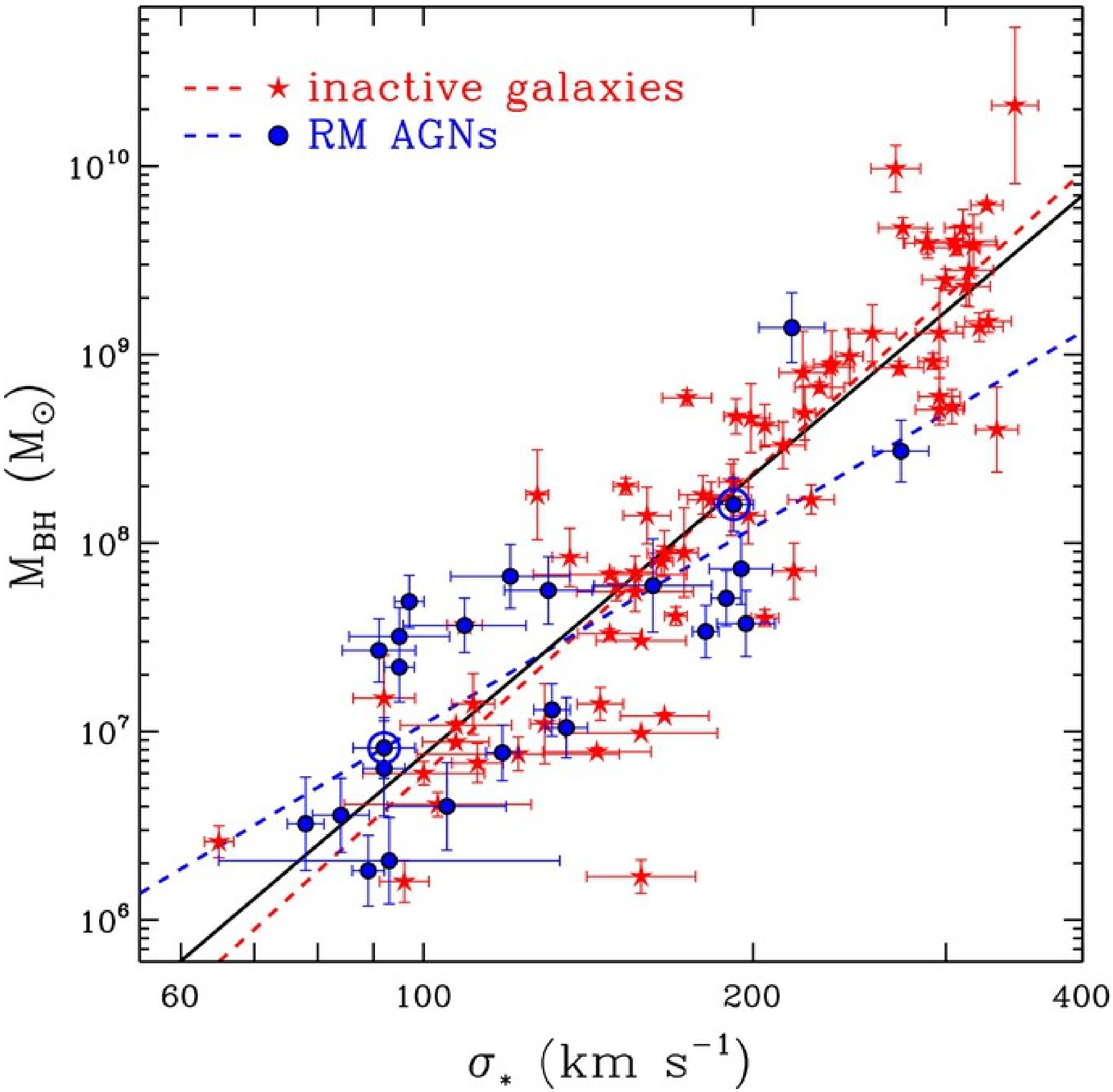
Measuring the mean f factor



The M_{BH}-σ_* relation from Woo et al. 2013

$$\langle f \rangle = 5.9^{+2.1}_{-1.5}$$

$$\log_{10}\langle f \rangle = 0.77 \pm 0.13$$

Largest uncertainty in reverberation mapped masses is scatter in $\log_{10}(f) \sim 0.4$ dex

The dynamical modeling approach

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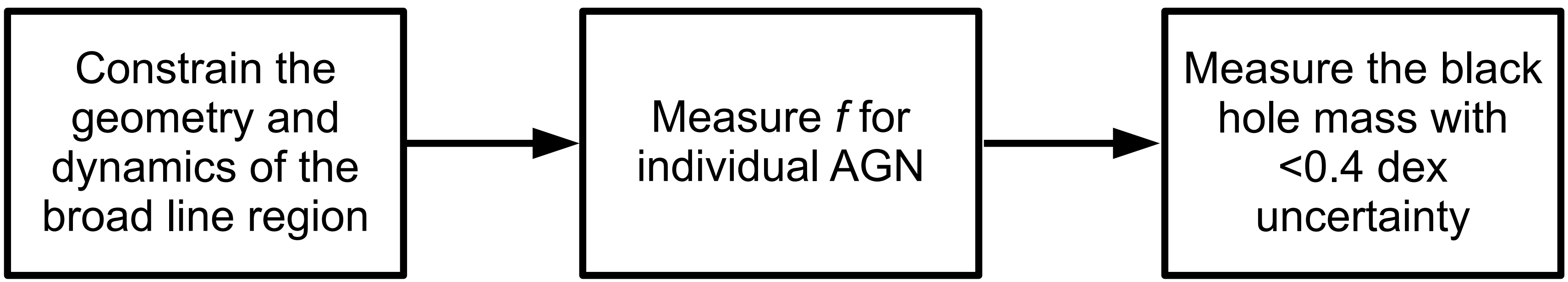

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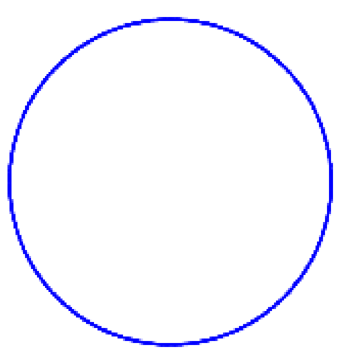
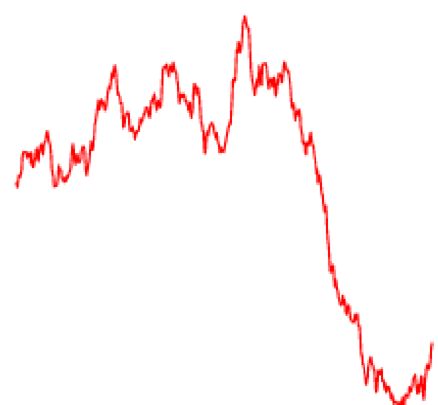
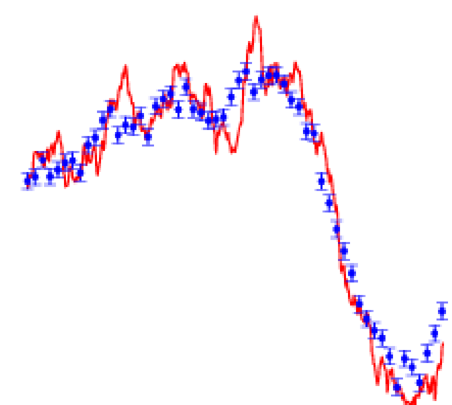
Constrain the geometry and dynamics of the broad line region → Measure *f* for individual AGN → Measure the black hole mass with <0.4 dex uncertainty



BLR geometry:
Face-on ring



Model broad line light curve



Model light curve + data (blue points)

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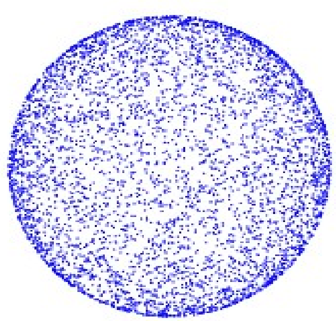
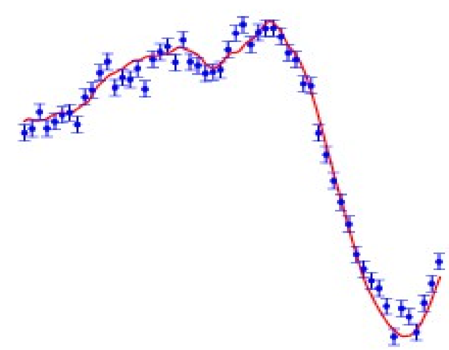


BLR geometry: Shell

Model broad line light curve



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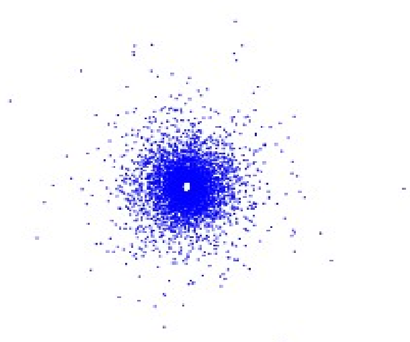
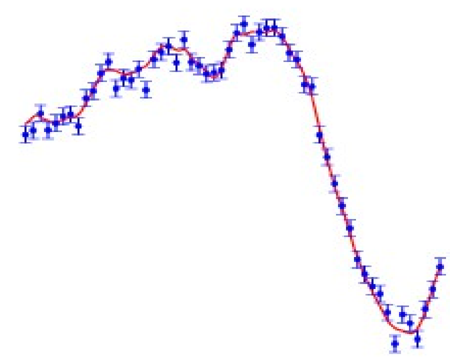


BLR geometry:
Face-on disk

Model broad line
light curve



Model light curve
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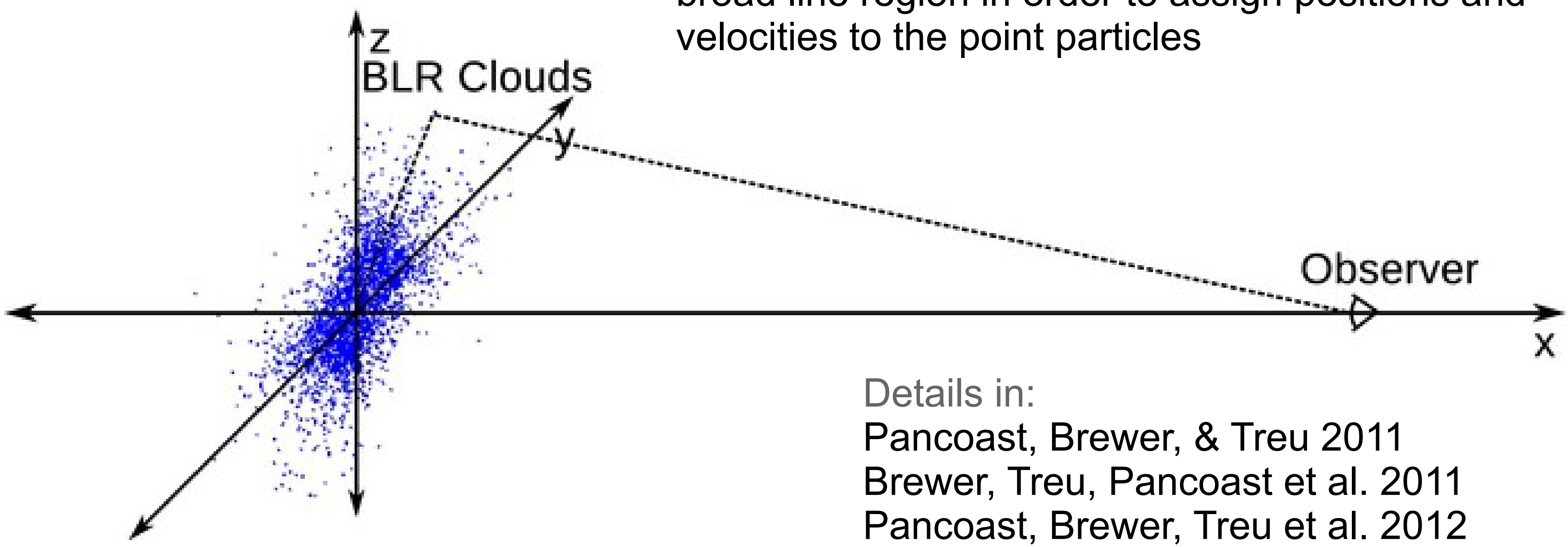
A simple phenomenological model of the broad line region



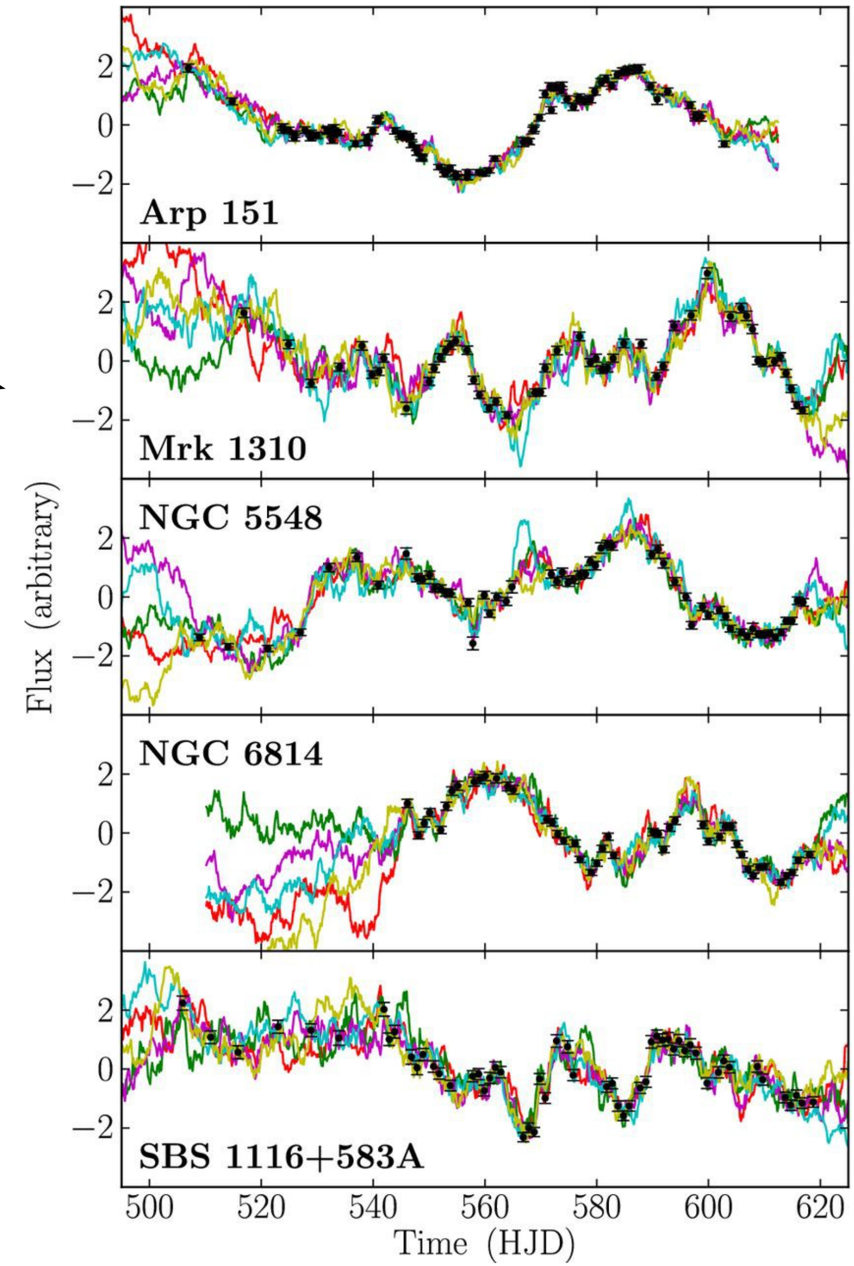
1. Model the AGN continuum light curve using Gaussian processes to evaluate the continuum flux at arbitrary times

2. Model the geometry and dynamics of the broad line region in order to assign positions and velocities to the point particles

Details in:
Pancoast, Brewer, & Treu 2011
Brewer, Treu, Pancoast et al. 2011
Pancoast, Brewer, Treu et al. 2012
Pancoast, Brewer, & Treu 2014
Pancoast, Brewer, Treu et al. 2014

AGN continuum light curve model

Examples of the continuum light curve model for LAMP 2008



Gaussian processes:

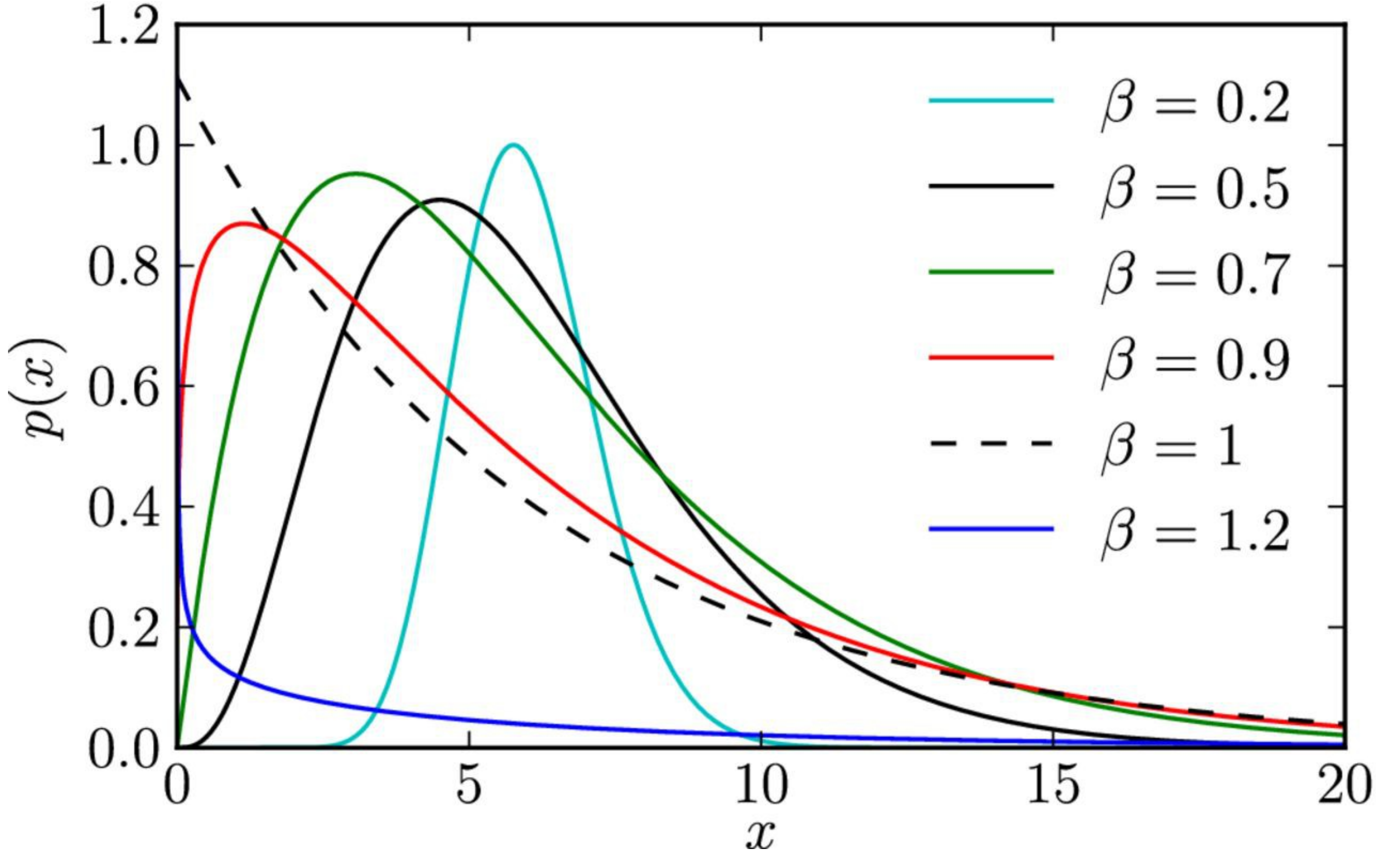
→ a good model for AGN variability on the timescales of reverberation mapping data

→ includes errors from interpolation

→ allows extrapolation beyond ends of light curve

Broad line region model: geometry and dynamics

- Geometry model of broad line emission:
  - Radial profile of emission: Gamma distribution



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Pancoast, Brewer, & Treu 2014

Broad line region model: geometry and dynamics

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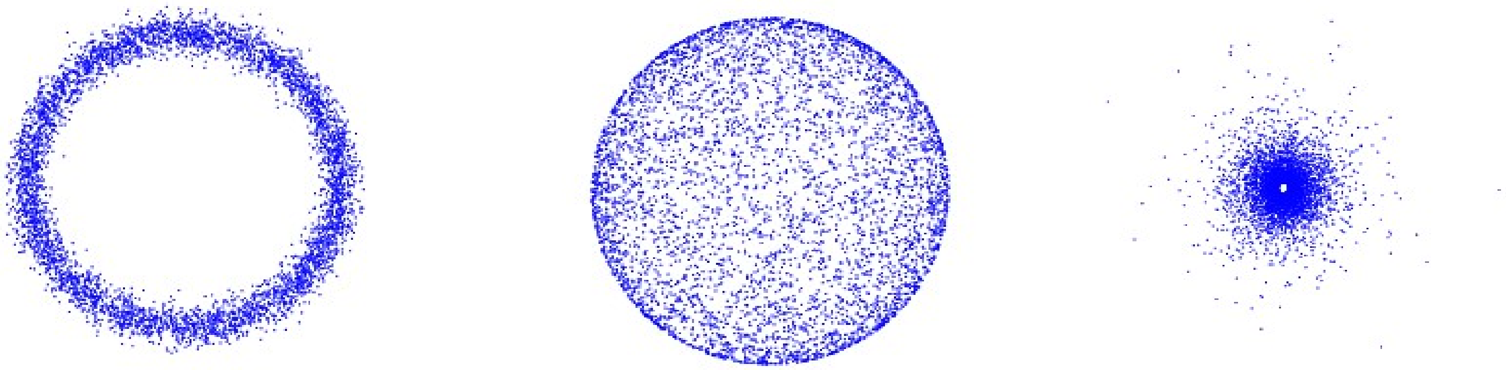

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  - Additional asymmetry:
    - More emission from near/far side
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The Lick AGN Monitoring Project (LAMP) 2008

64 nights of spectroscopy

Photometry from KAIT at Lick, Palomar 60", Tenagra II, & MAGNUM at Haleakala Obs.

Walsh et al. 2009
Bentz et al. 2009

Monitored 12 AGNs:

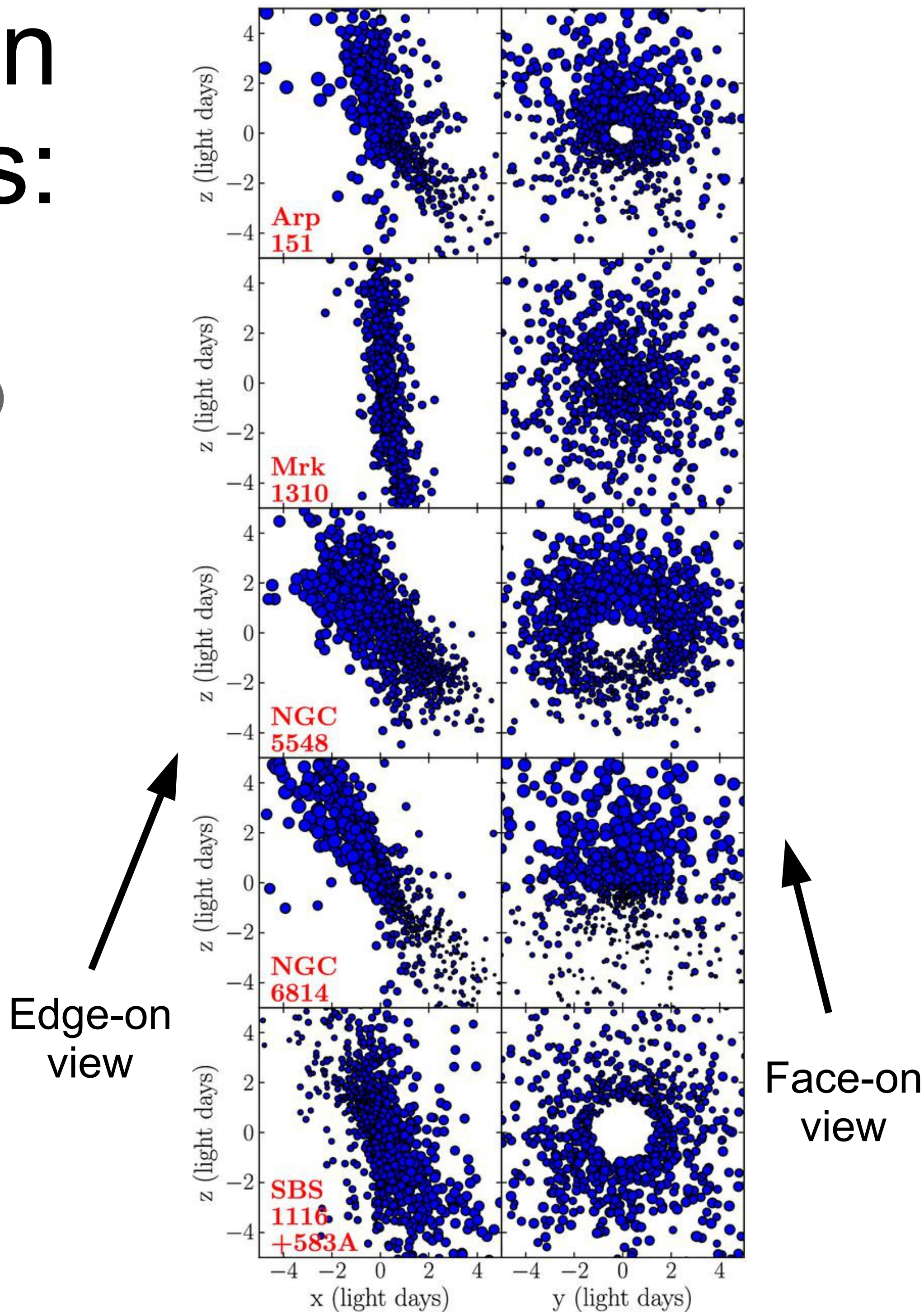
9 with measured time lags

5 with BLR modeling

Broad line region modeling results: LAMP 2008

(Pancoast, Brewer, Treu et al. 2014)

- Hβ-emitting geometry: close to face-on thick disks
- Consistent with preferential emission from the far side of the broad line region
- Hβ-emitting dynamics: near-circular or inflowing orbits
- Black hole mass constrained to within 0.15 – 0.3 dex uncertainty



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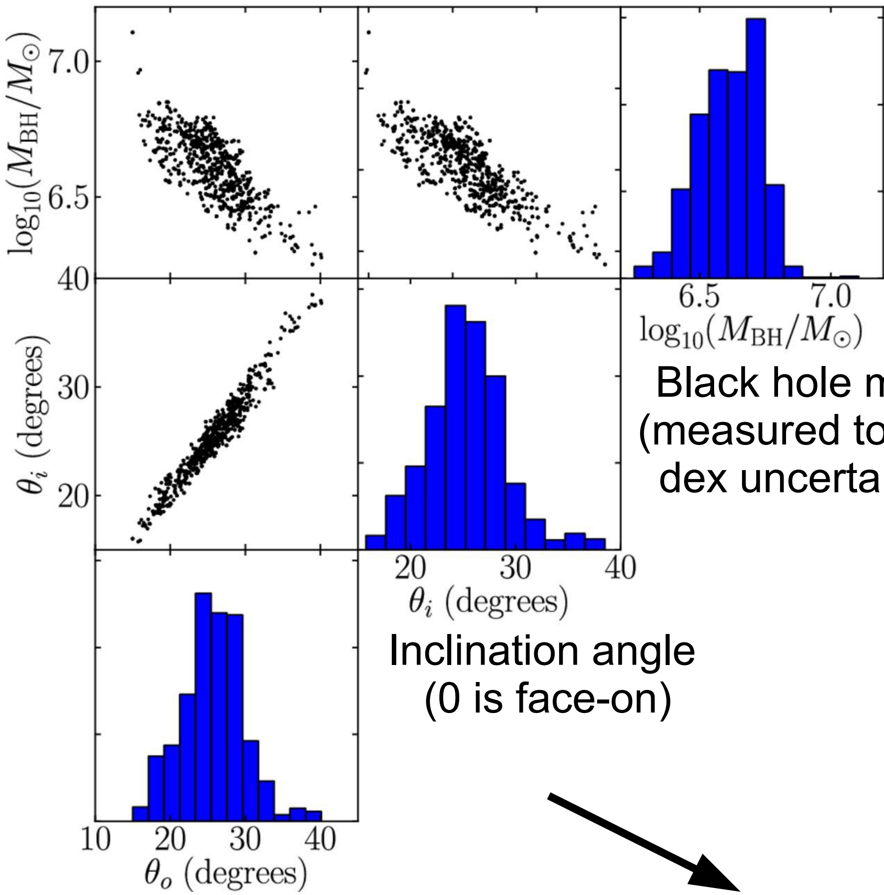
Detailed results: Arp 151

Posterior probability distributions
and parameter correlations

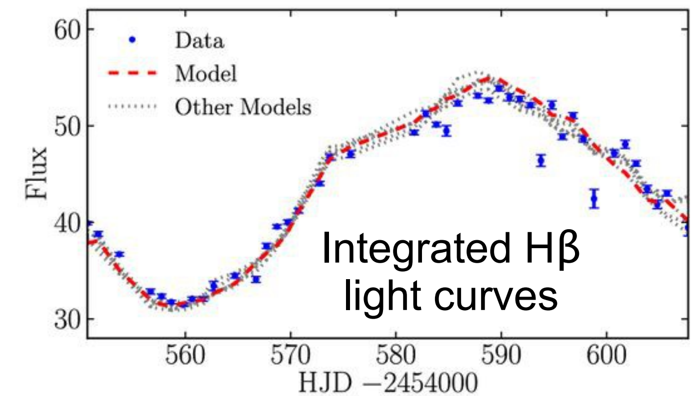


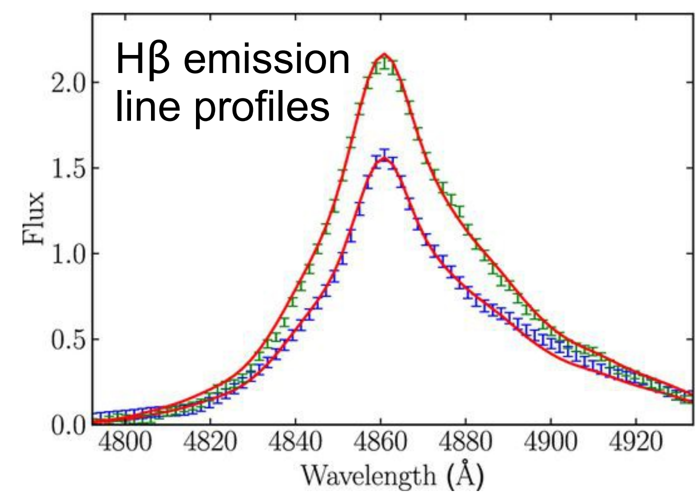
Black hole mass
(measured to 0.15
dex uncertainty)

Inclination angle
(0 is face-on)

Opening angle
(90 deg is a sphere)

Model fit to the data





Geometry: thick disk with opaque midplane and more emission from the far side and faces of the disk
Dynamics: mostly bound inflow

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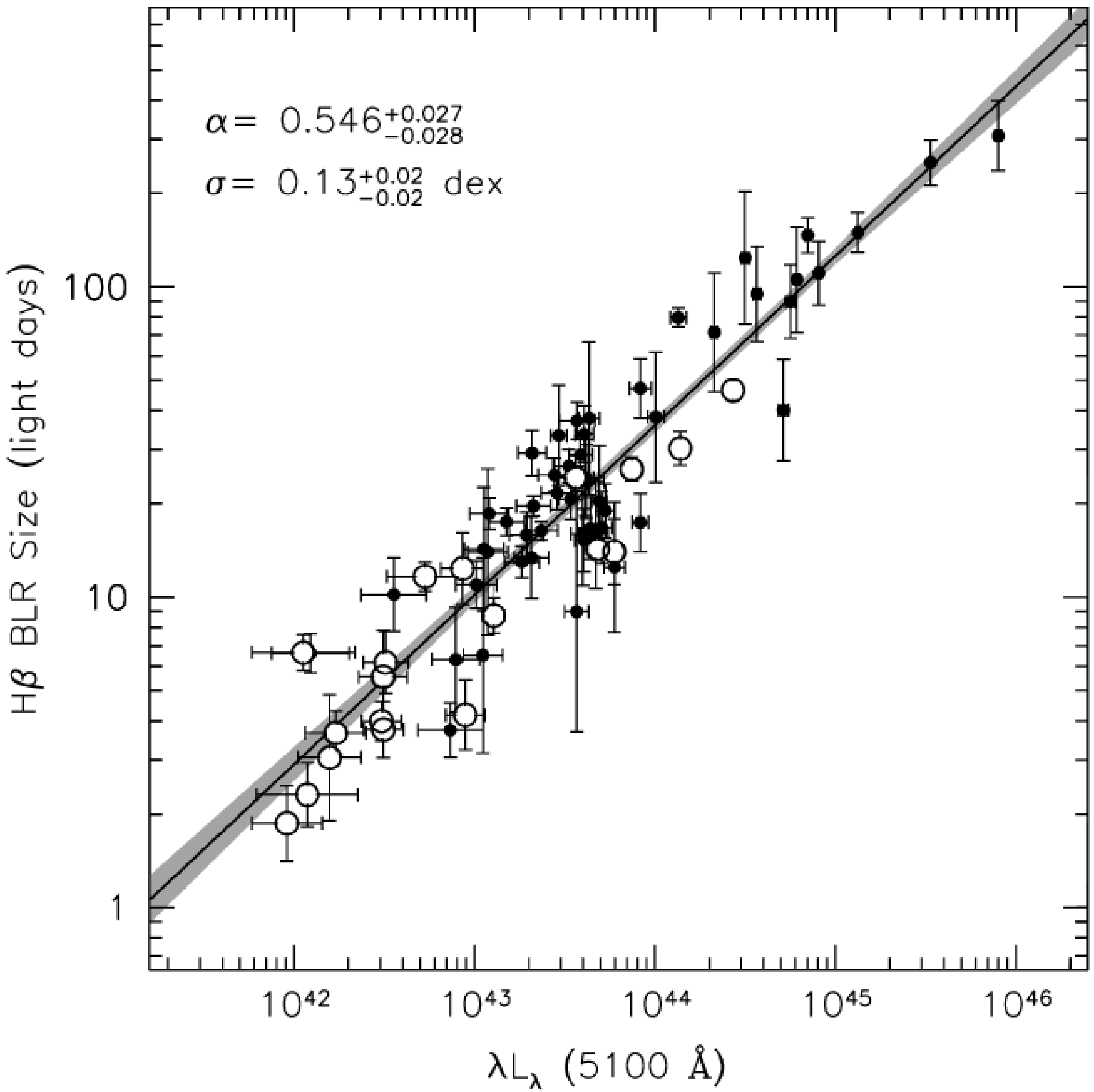
The r_{BLR} – L_{AGN} Relation



BLR radius – AGN luminosity relation from Bentz et al. 2013

Allows for single-epoch AGN black hole mass estimates:

- Use line width to get *v*
- Use L_{AGN} to get r_{BLR}

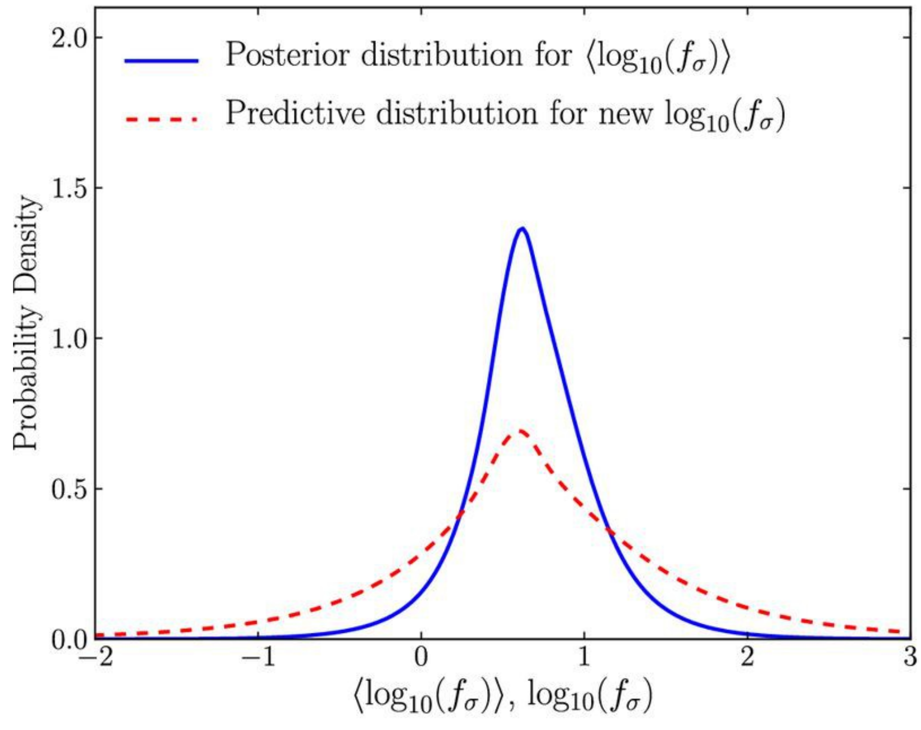
Apply to any AGN with a broad line spectrum

Recipes for single-epoch mass estimates vary by up to 0.4 dex

→ dominant source of uncertainty is unknown structure of the BLR

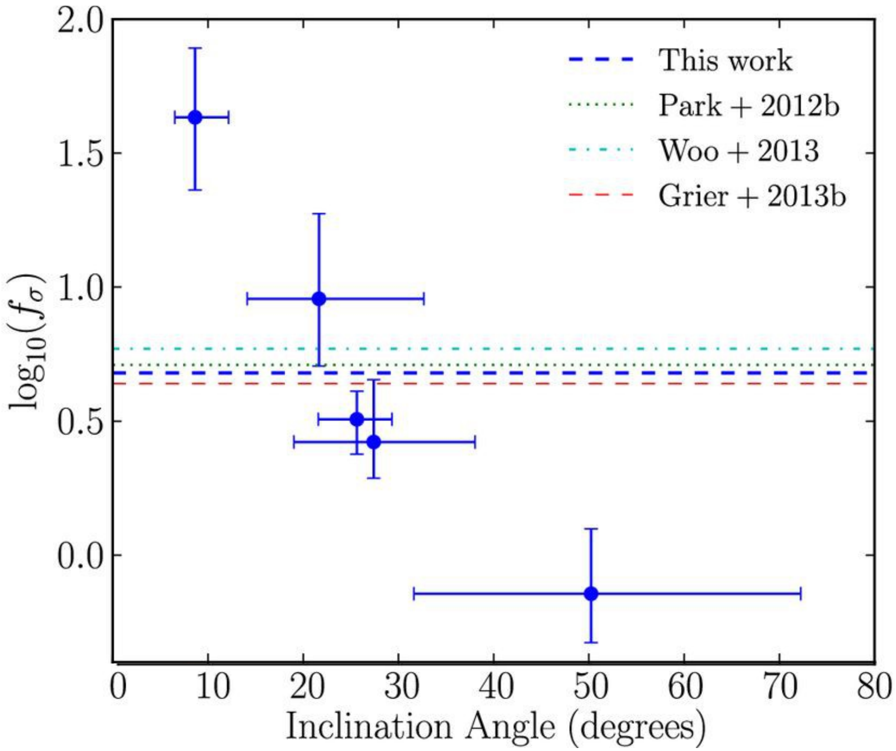
Decreasing AGN black hole mass uncertainties: the *f* factor

Measure a mean value of *f* without the $M_{BH} - \sigma_*$ relation



Mean value of *f* is 0.68 ± 0.4 with a dispersion of 0.75 ± 0.4

Is *f* correlated with any properties of the AGN or broad line region?



With 5 AGN from LAMP 2008, no correlation between *f* and black hole mass or AGN luminosity

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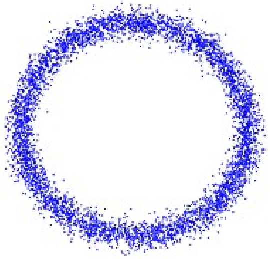
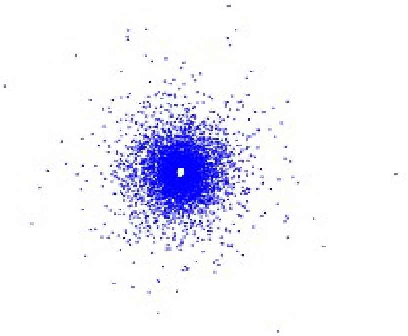
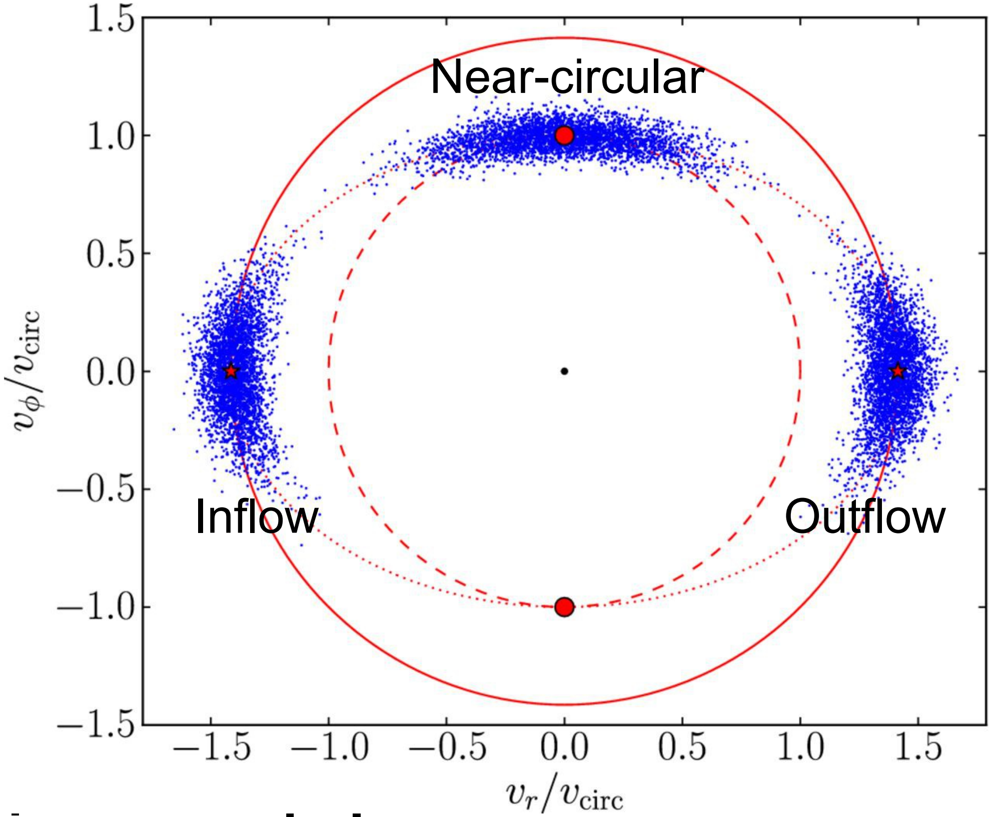
Conclusions





- Broad line region modeling of reverberation mapping allows us to:
  - Measure AGN black hole masses more precisely (0.15 – 0.3 dex uncertainty vs. ~0.4 dex)
  - First measurements of *f* for individual AGN
  - Constraints on the detailed geometry and dynamics of the broad line region
  - Published results for 6 AGN (LAMP 2008/2011) with more in progress
  - Flexible framework to test broad line region models

Broad line region model: geometry and dynamics



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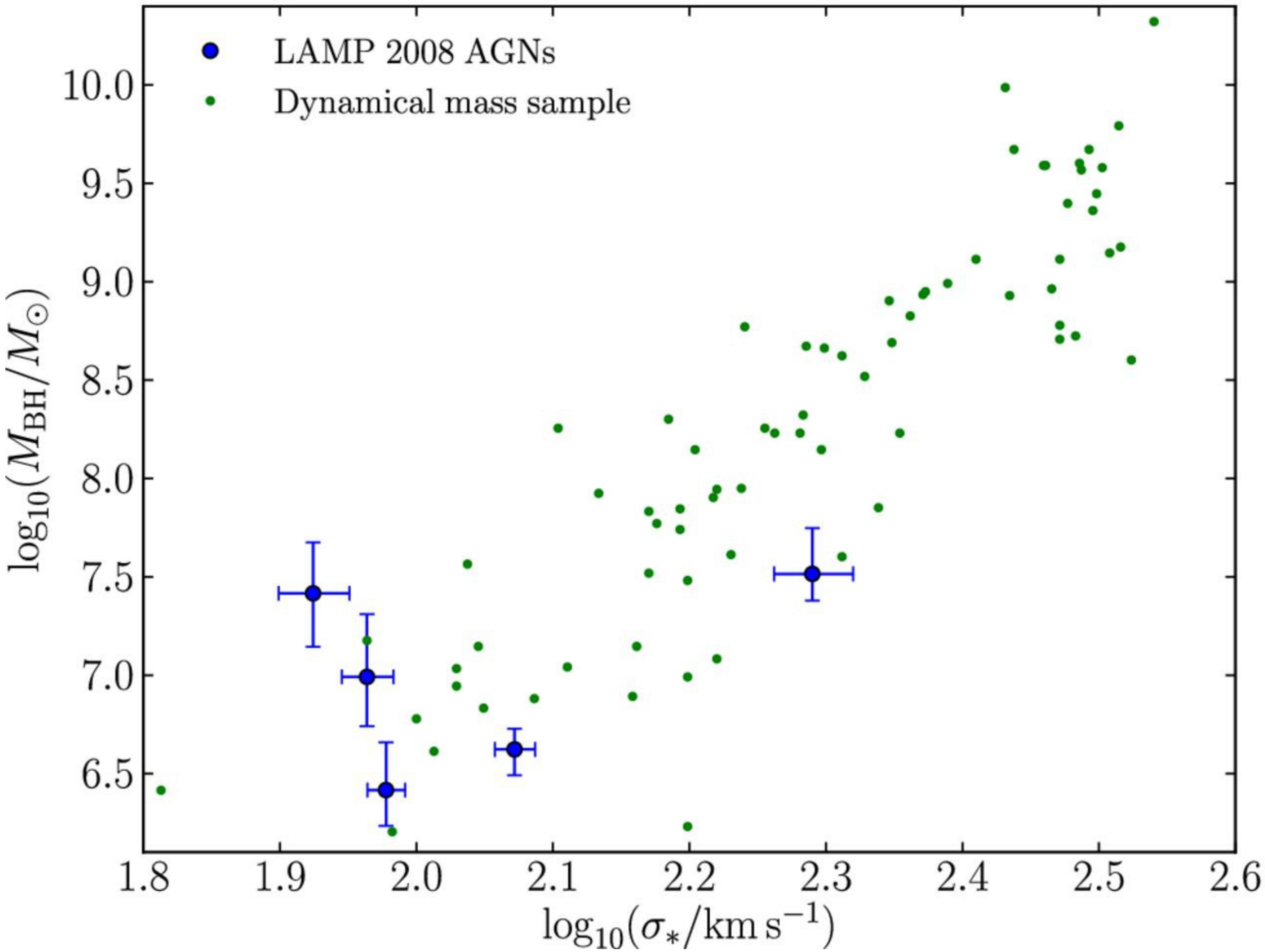
$M_{BH} - \sigma_*$ Relation



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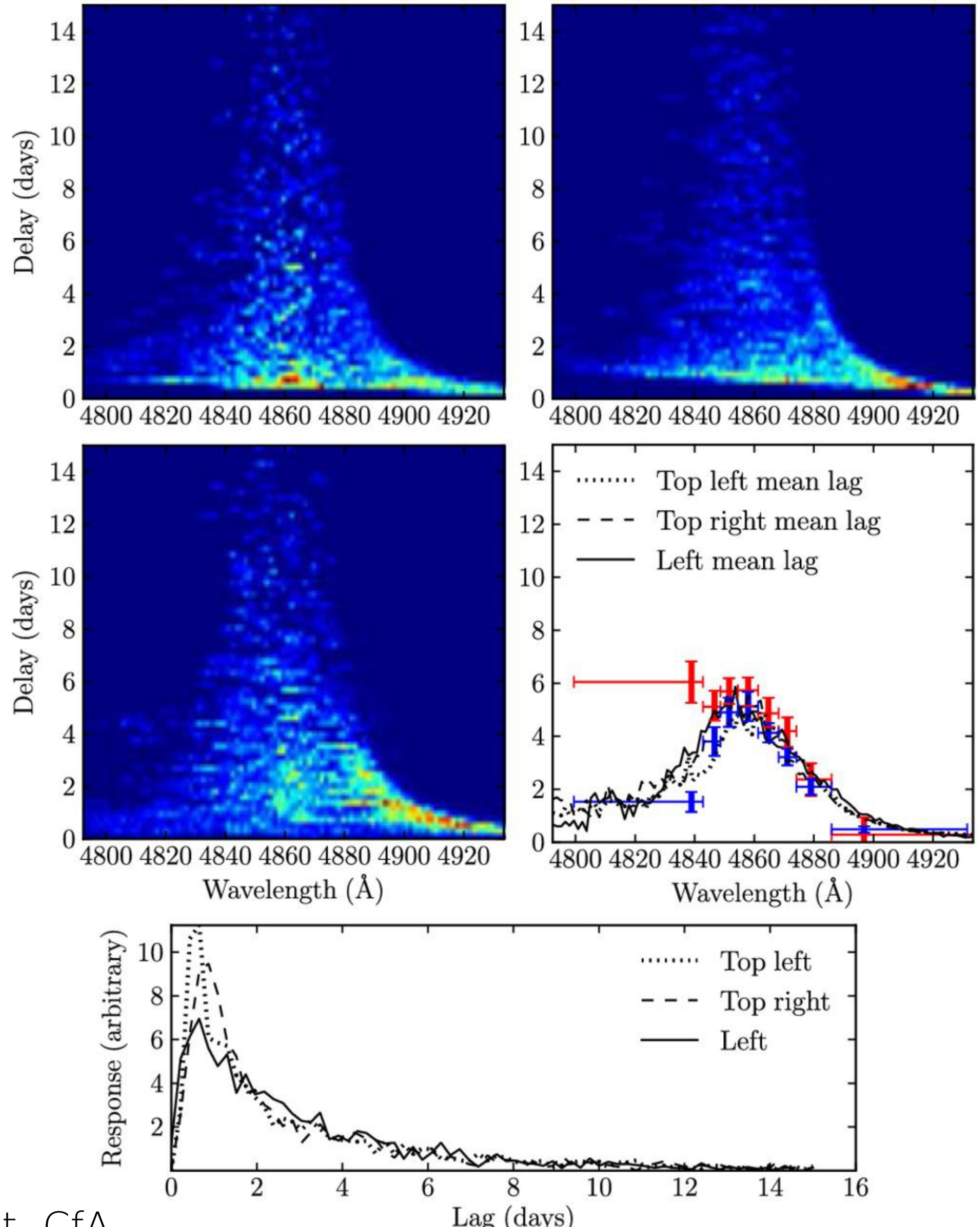
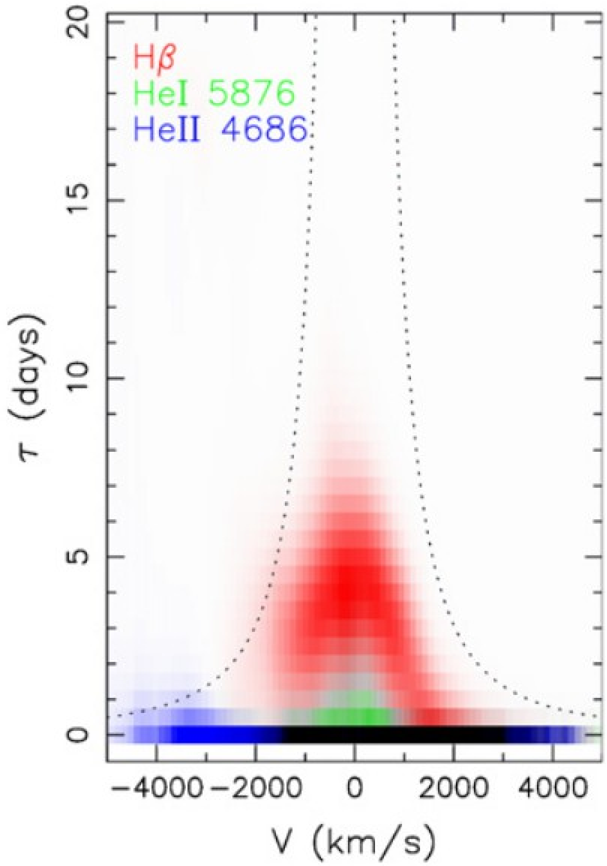
Transfer functions: Arp 151

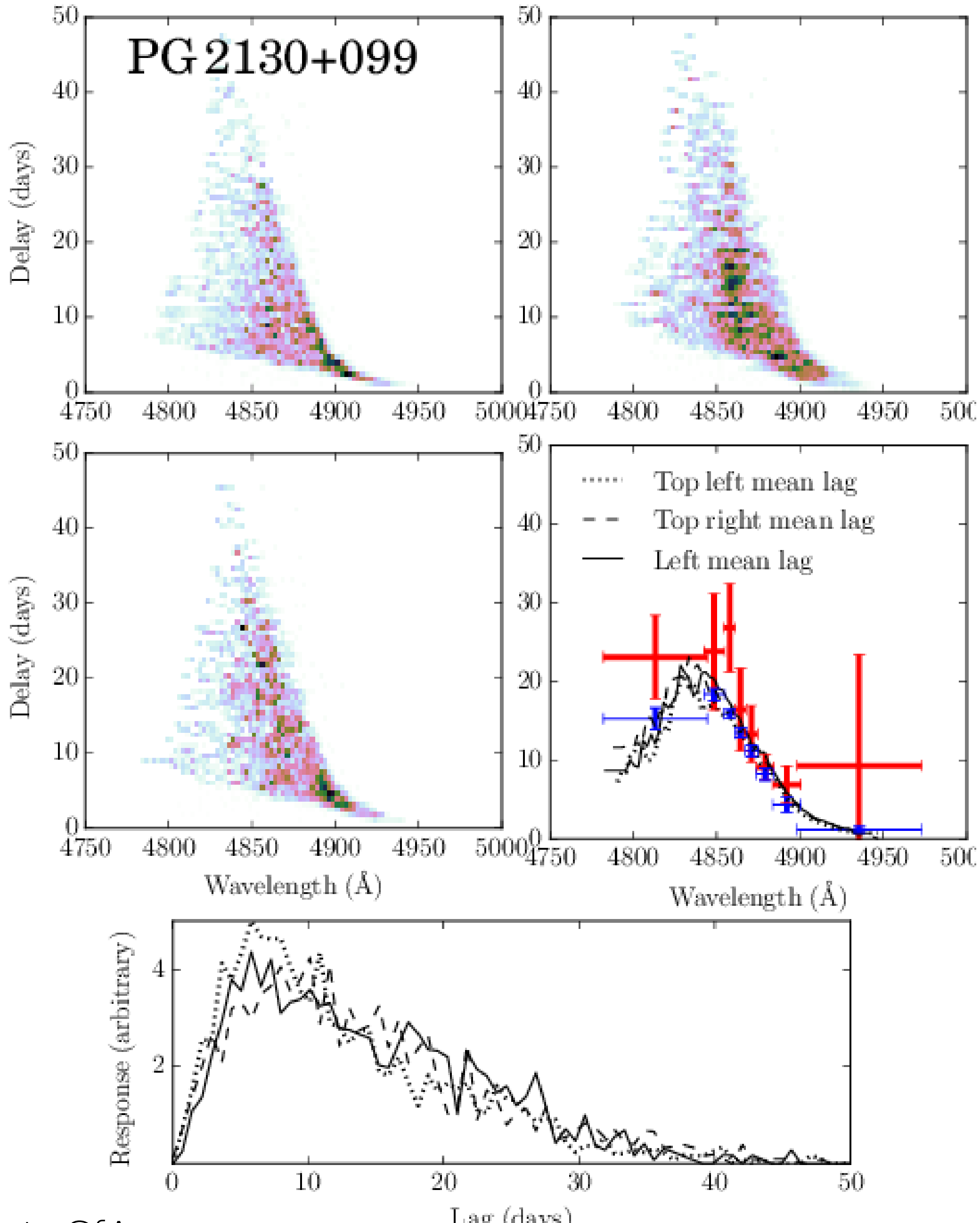


MEMEcho results from Bentz et al. 2010

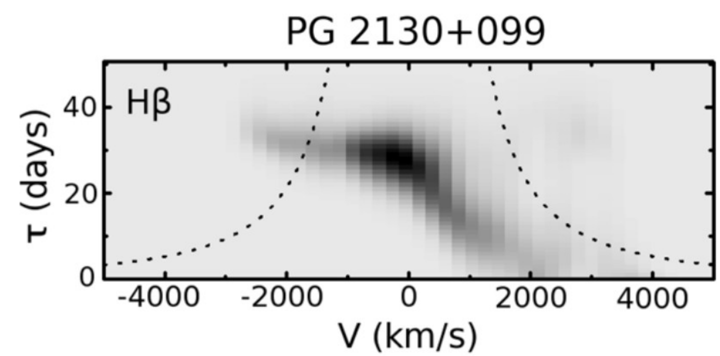


(20 Å ~ 1100 km/s)

Transfer functions: PG 2130+099

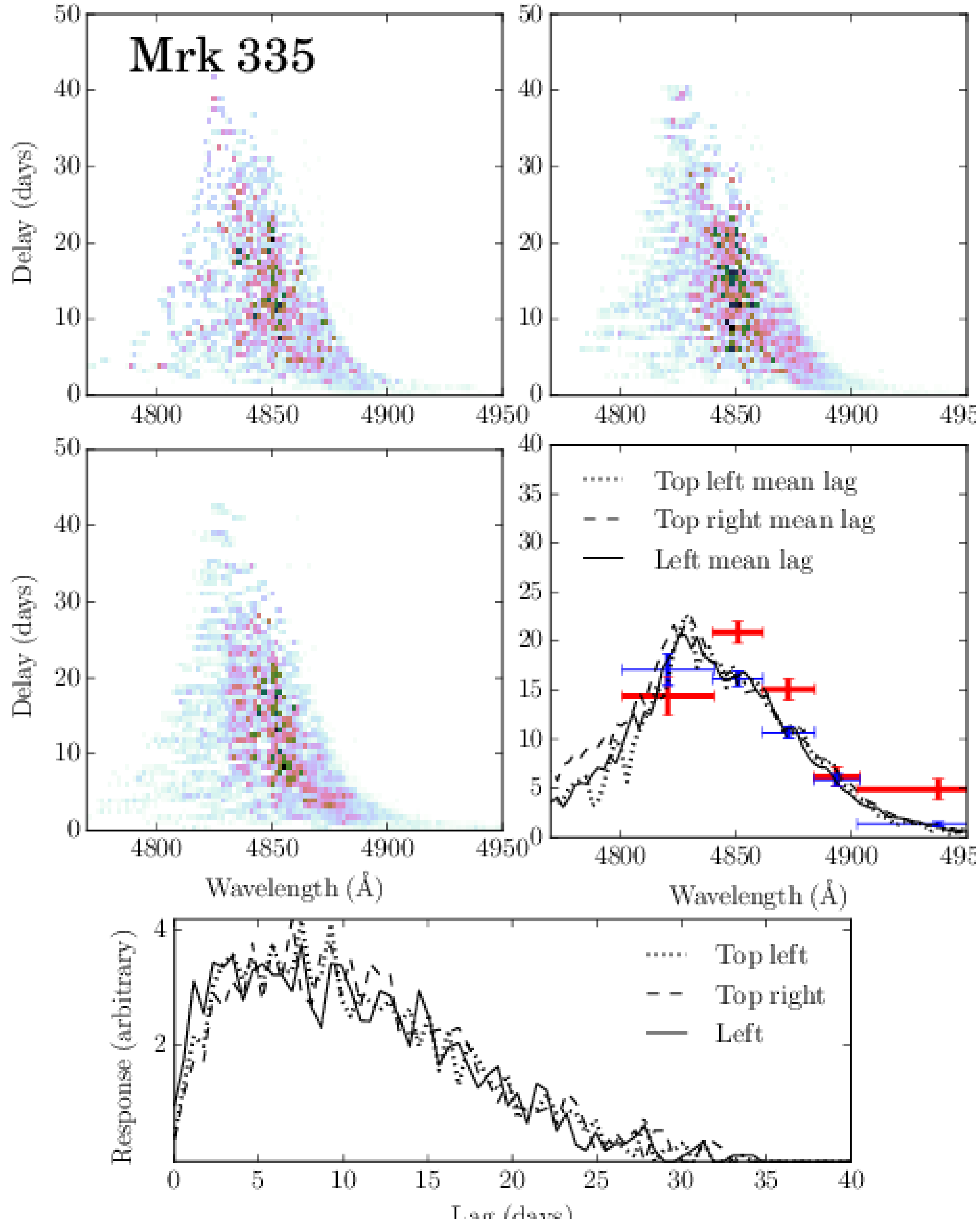


MEMEcho results from
Grier et al. 2013



(20 Å ~ 1100 km/s)

Transfer functions: Mrk 335



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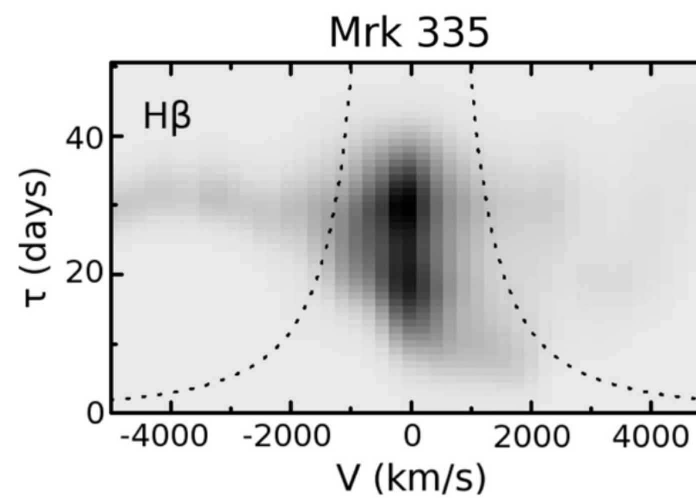

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