Masses of Black Holes in Active Galactic Nuclei

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INAF - OABO

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- T. Kawaguchi (NAOJ)
- M.A. Malkan (UCLA)
- D. Merritt (RIT)
- C.A. Onken (Australian National Univ.)
- S.G. Sergeev (Crimean Astrophys. Obs.)
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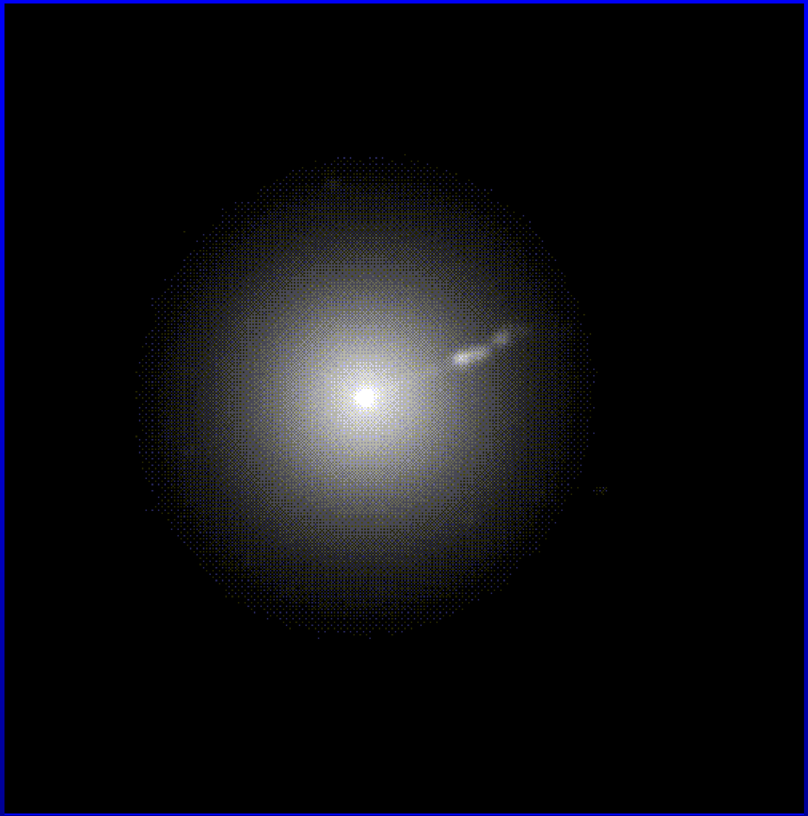
- A. Wandel (Hebrew Univ.)

Outline

1. Reverberation mapping: principles and practice
2. AGN masses from reverberation mapping and comparison with other direct methods
3. Scaling relationships and secondary methods
4. The “mass ladder”, unknowns and potential problems

Supermassive Black Holes Are Common

- Supermassive black holes are found in galaxies with large central bulge components.
- These are almost certainly remnant black holes from the quasar era.
- To understand accretion history, we need to determine black-hole demographics.



M 87, a giant elliptical
SMBH > $3\times10^9\ M_\odot$

Measuring Central Black-Hole Masses

- Virial mass measurements based on motions of stars and gas in nucleus.
  - Stars
    - Advantage: gravitational forces only
    - Disadvantage: requires high spatial resolution
      - larger distance from nucleus $\Rightarrow$ less critical test
  - Gas
    - Advantage: can be observed very close to nucleus, high spatial resolution not necessarily required
    - Disadvantage: possible role of non-gravitational forces (radiation pressure)

Direct vs. Indirect Methods

- *Direct methods* are based on dynamics of gas or stars accelerated by the central black hole.
  - Stellar dynamics, gas dynamics, reverberation mapping
- *Indirect methods* are based on observables correlated with the mass of the central black hole.
  - M_{BH}–σ_* and M_{BH}–L_{bulge} relationships, fundamental plane, AGN scaling relationships (R_{BLR}–L)

“Primary”, “Secondary”, and “Tertiary” Methods

- Depends on model-dependent assumptions required.
- Fewer assumptions, little model dependence:
  - Proper motions/radial velocities of stars and megamasers (Sgr A*, NGC 4258)
- More assumptions, more model dependence:
  - Stellar dynamics, gas dynamics, reverberation mapping
    - Since the reverberation mass scale currently depends on other “primary direct” methods for a zero point, it is technically a “secondary method” though it is a “direct method.”

Virial Estimators

Source	Distance from central source
X-Ray Fe Kα	3-10 R_S
Broad-Line Region	200–10^4 R_S
Megamasers	4×10^4 R_S
Gas Dynamics	8×10^5 R_S
Stellar Dynamics	10^6 R_S

In units of the Schwarzschild radius $R_S = 2GM/c^2 = 3 \times 10^{13}\ M_8$ cm .

Mass estimates from the virial theorem:

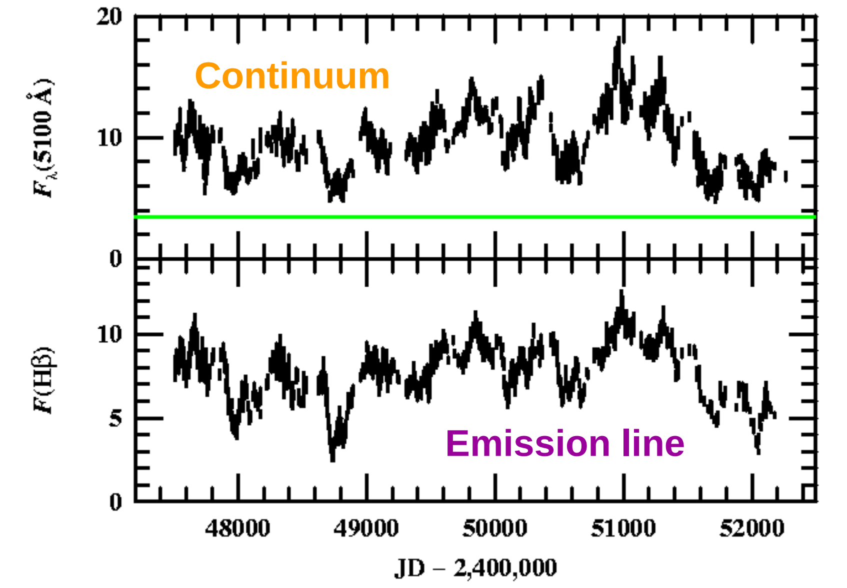
$$M = f\,(r\,\Delta V^{\,2}/G)$$

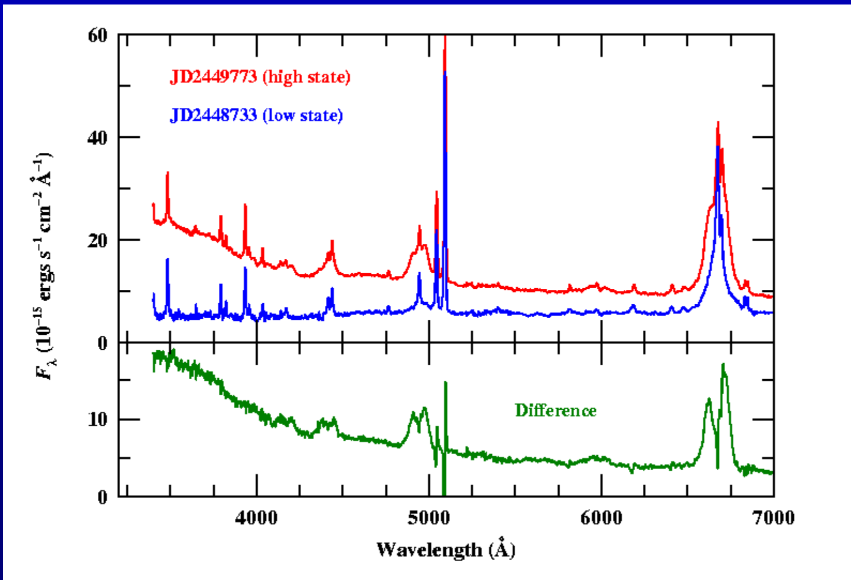
where

- r = scale length of region
- ΔV = velocity dispersion
- f = a factor of order unity, depends on details of geometry and kinematics

Reverberation Mapping

- Kinematics and geometry of the BLR can be tightly constrained by measuring the emission-line response to continuum variations.

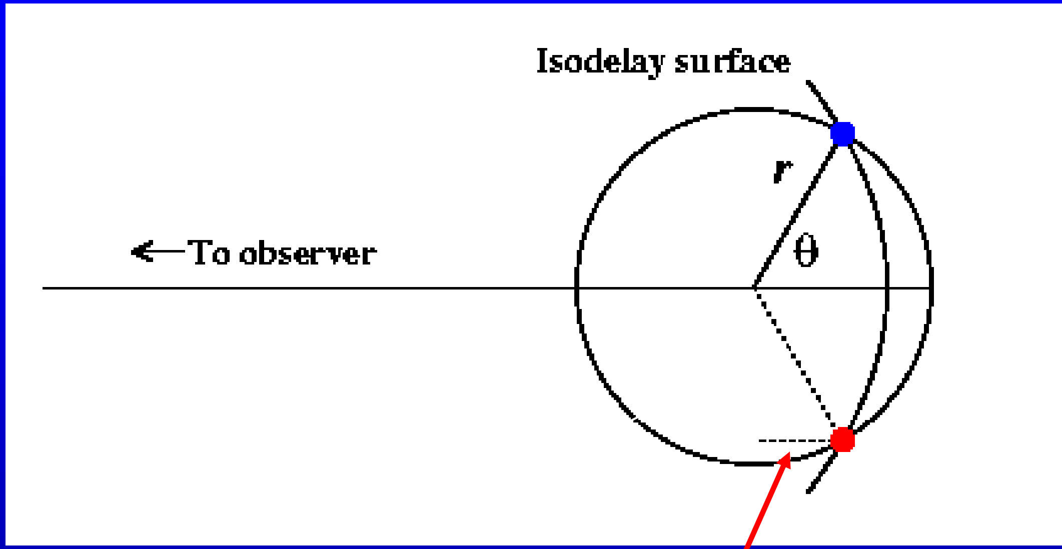




NGC 5548, the most closely monitored Seyfert 1 galaxy

Reverberation Mapping Concepts: Response of an Edge-On Ring

- Suppose line-emitting clouds are on a circular orbit around the central source.
- Compared to the signal from the central source, the signal from anywhere on the ring is delayed by light-travel time.
- Time delay at position (r,θ) is $\tau = (1 + \cos\theta)r / c$



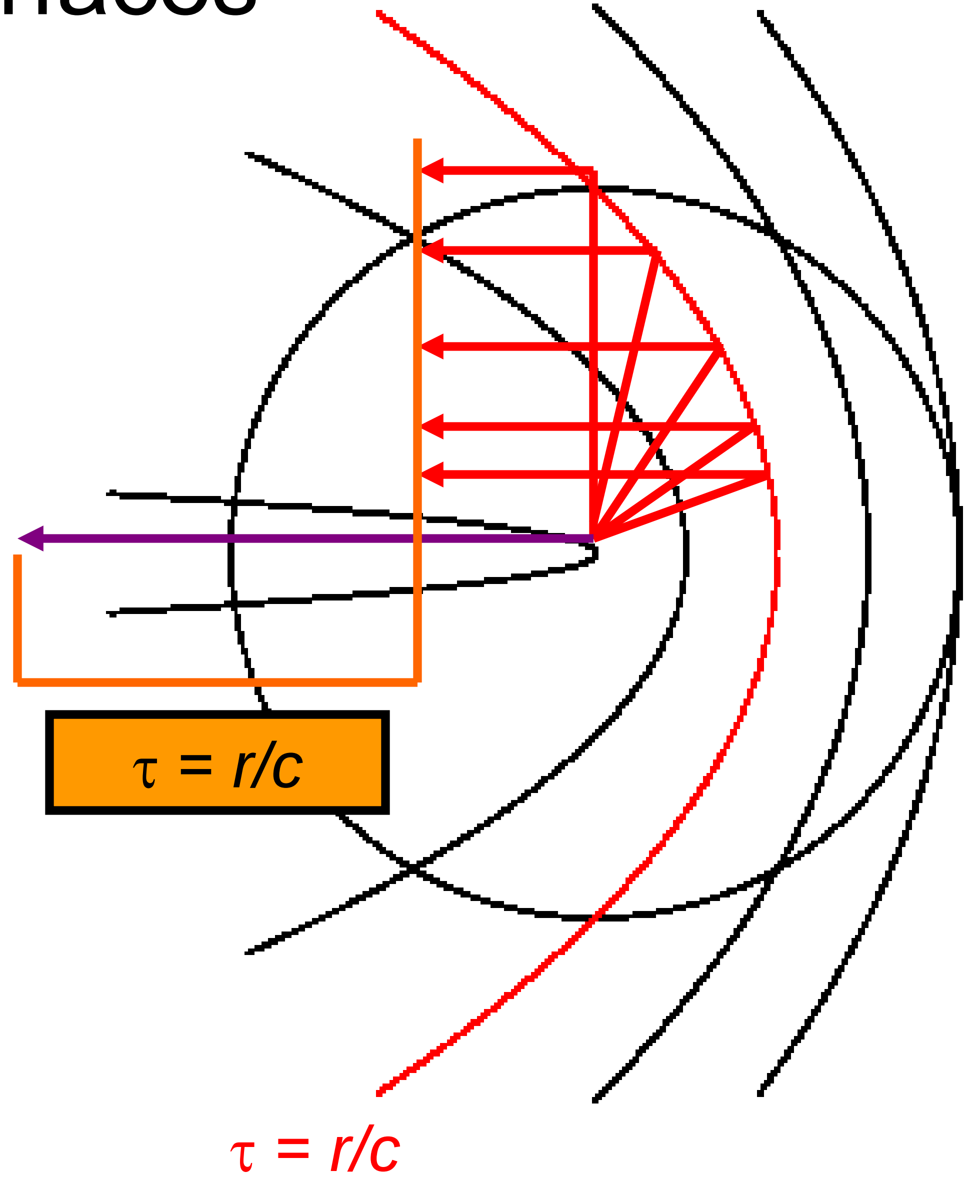
$\boxed{\tau = r \cos\theta / c}$

The isodelay surface is a parabola:

$$r = \frac{c\,\tau}{1+\cos\theta}$$

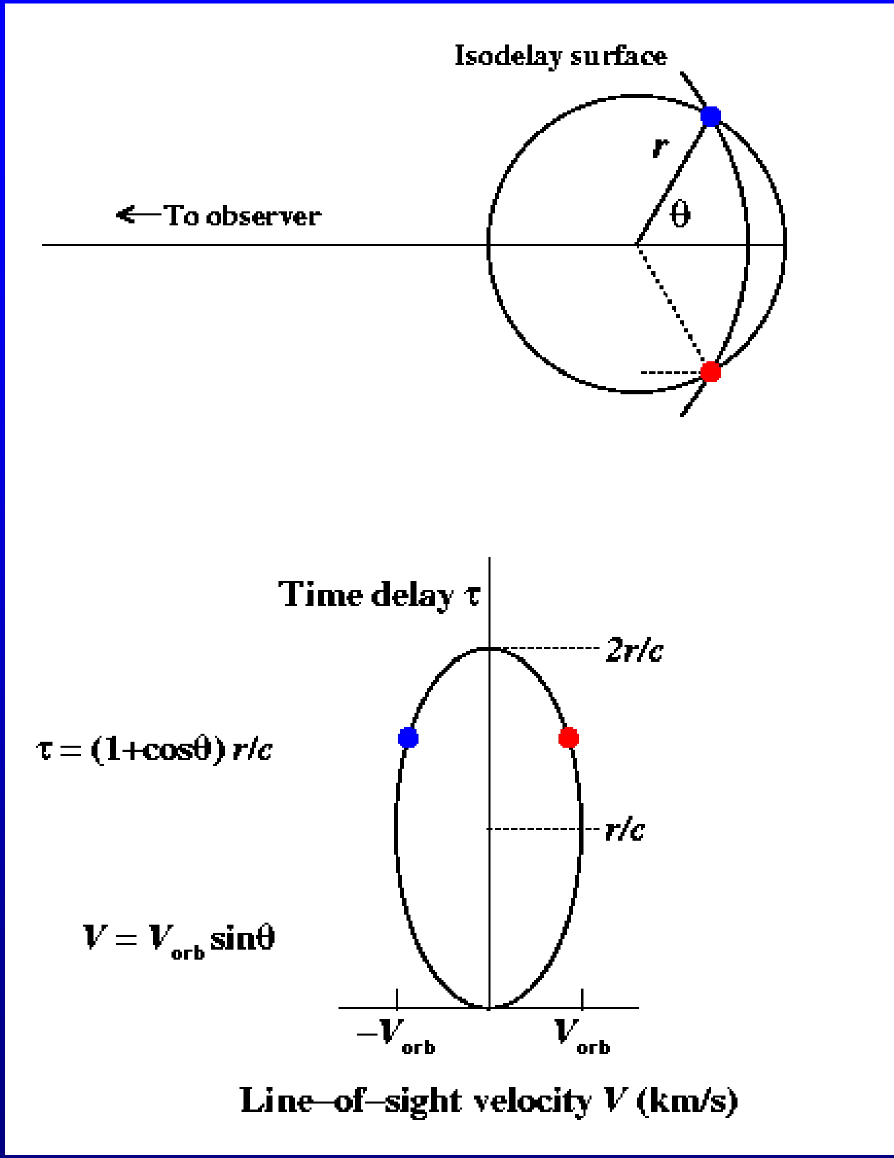
"Isodelay Surfaces"

All points on an "isodelay surface" have the same extra light-travel time to the observer, relative to photons from the continuum source.



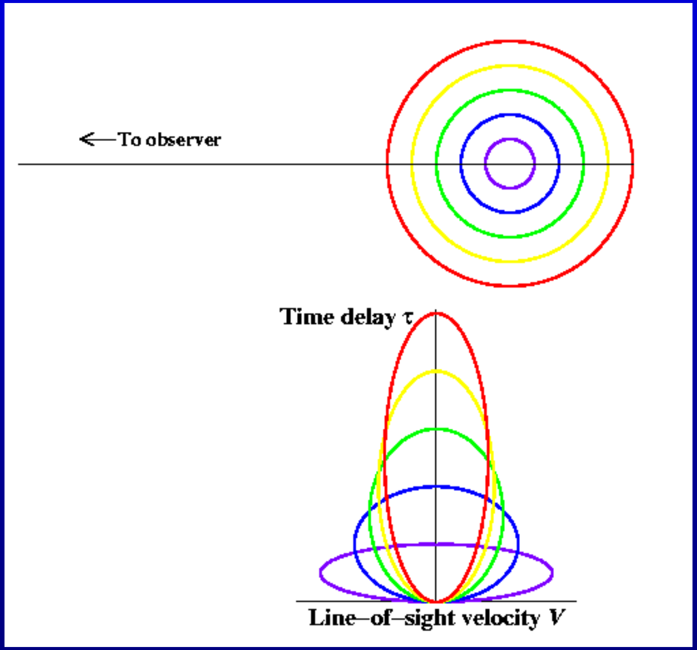
Velocity-Delay Map for an Edge-On Ring

- Clouds at intersection of isodelay surface and orbit have line-of-sight velocities $V = \pm V_{orb} \sin\theta$.
- Response time is $\tau = (1 + \cos\theta) r/c$
- Circular orbit projects to an ellipse in the (V, τ) plane.

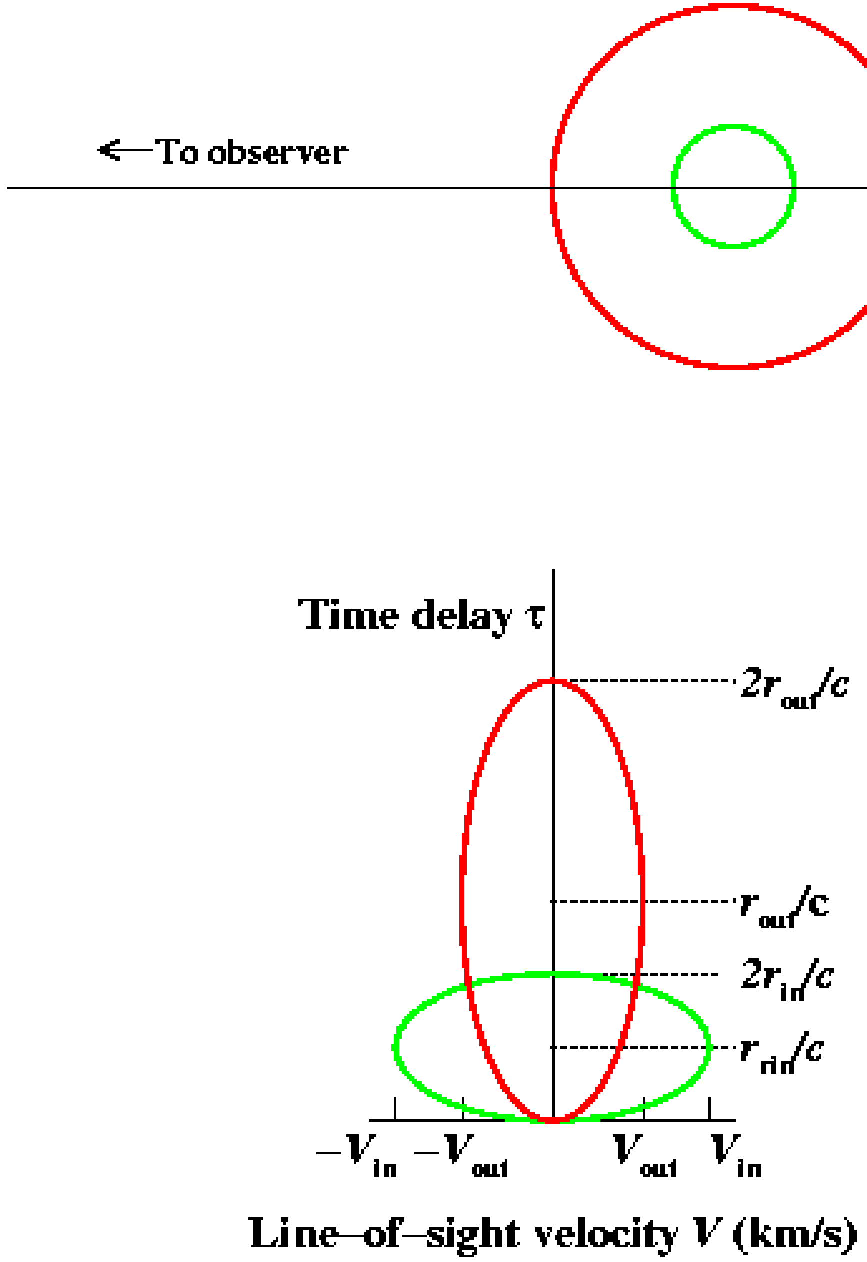


Thick Geometries

- Generalization to a disk or thick shell is trivial.
- General result is illustrated with simple two ring system.



A multiple-ring system



Observed Response of an Emission Line

The relationship between the continuum and emission can be taken to be:

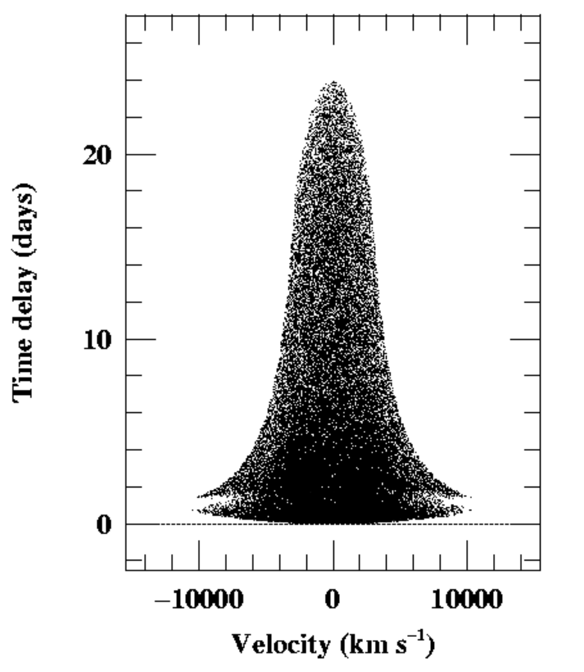
$$L(V,t) = \int \Psi(V,\tau)\ C(t-\tau)\ d\tau$$

Velocity-resolved emission-line light curve

"Velocity-delay map"

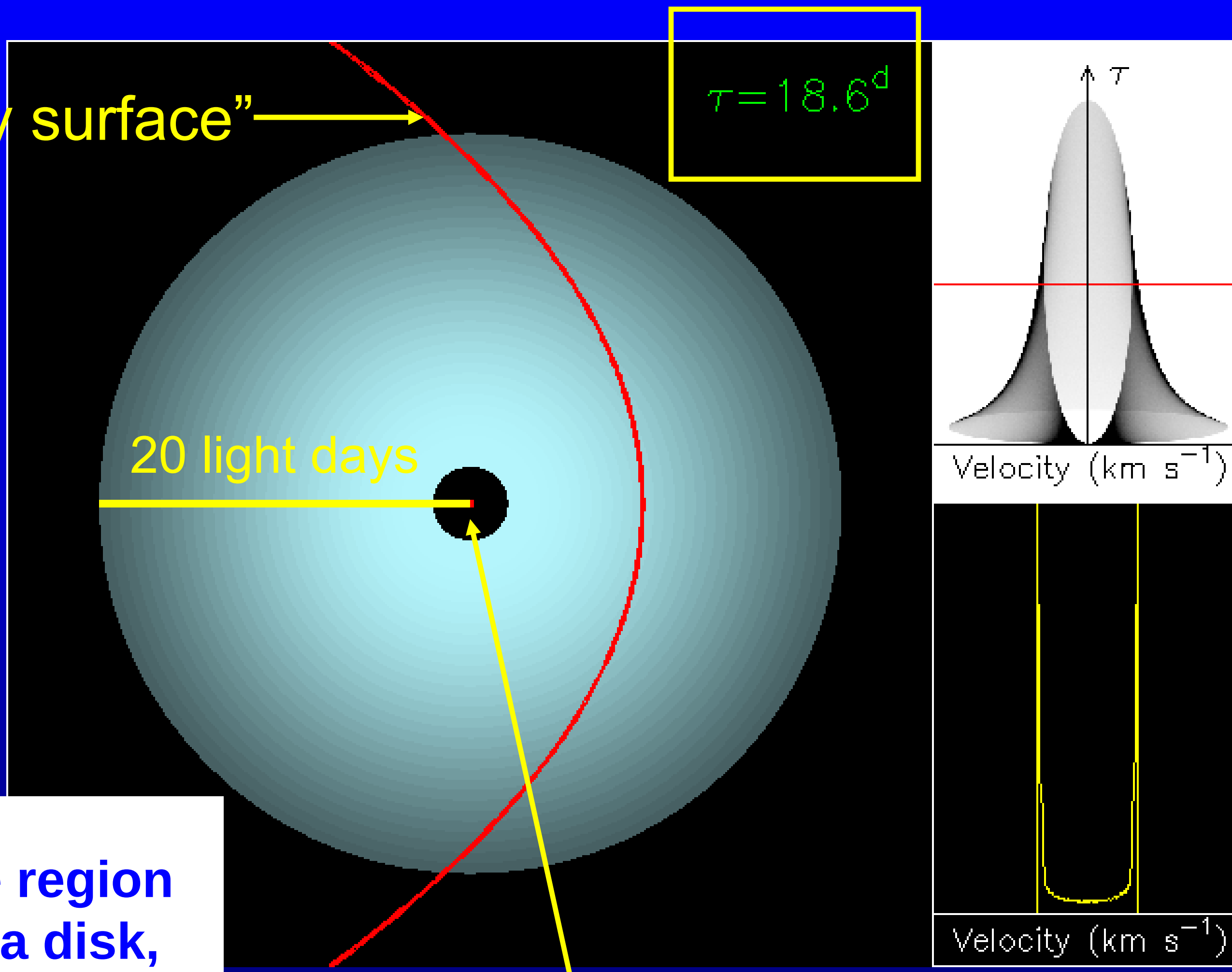
Continuum light curve

Velocity-delay map is observed line response to a δ-function outburst



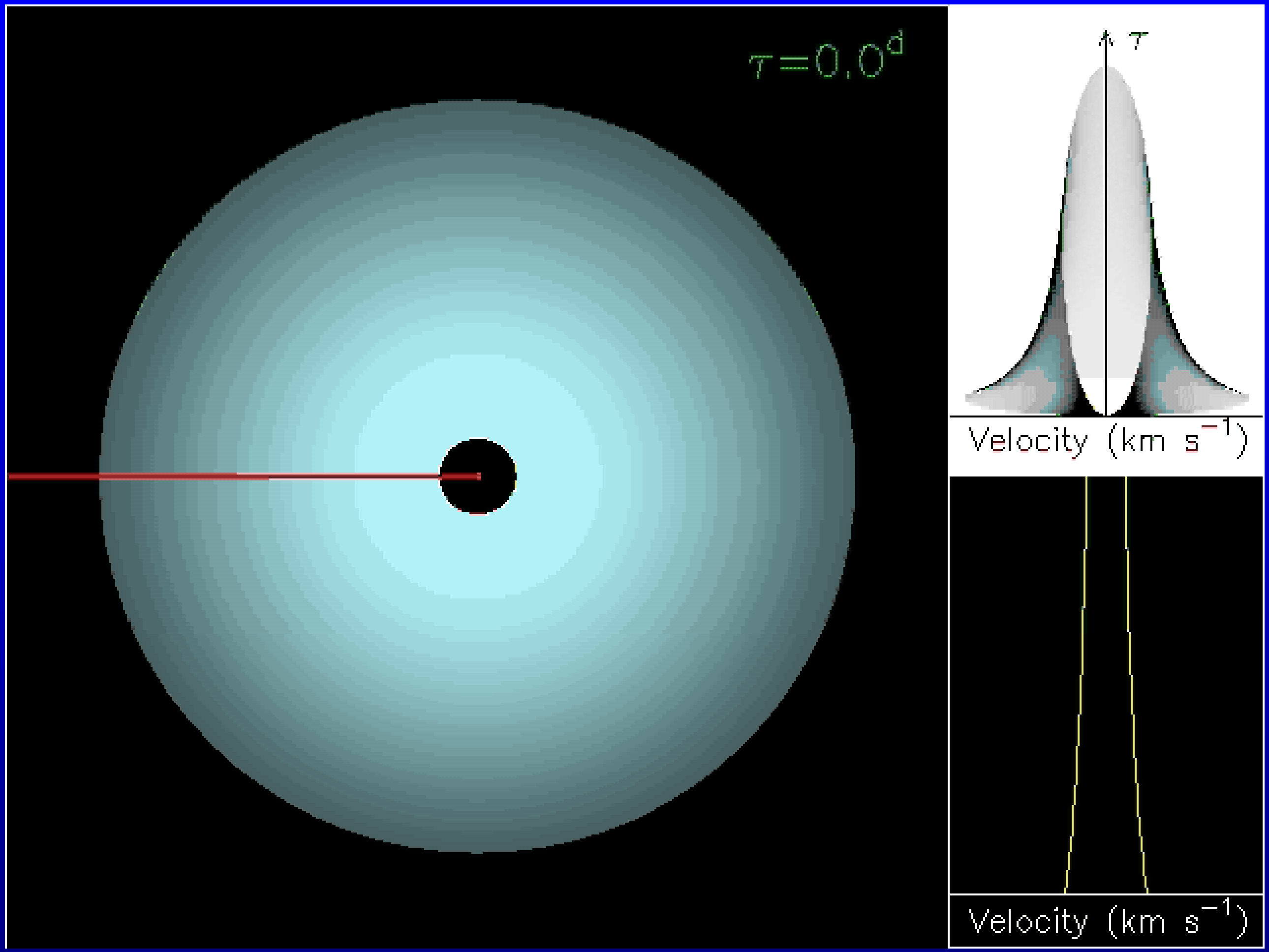
Simple velocity-delay map

Time after continuum outburst



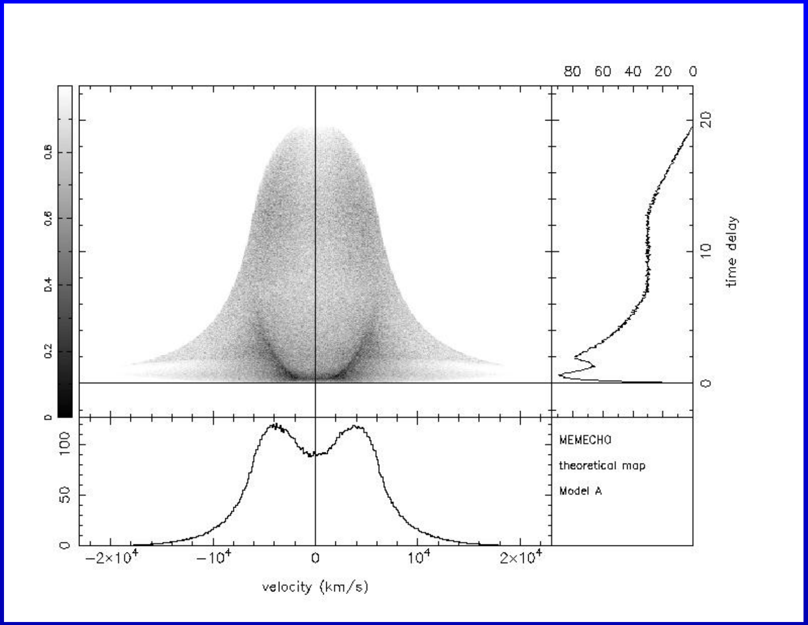
Broad-line region as a disk, 2–20 light days

Line profile at current time delay

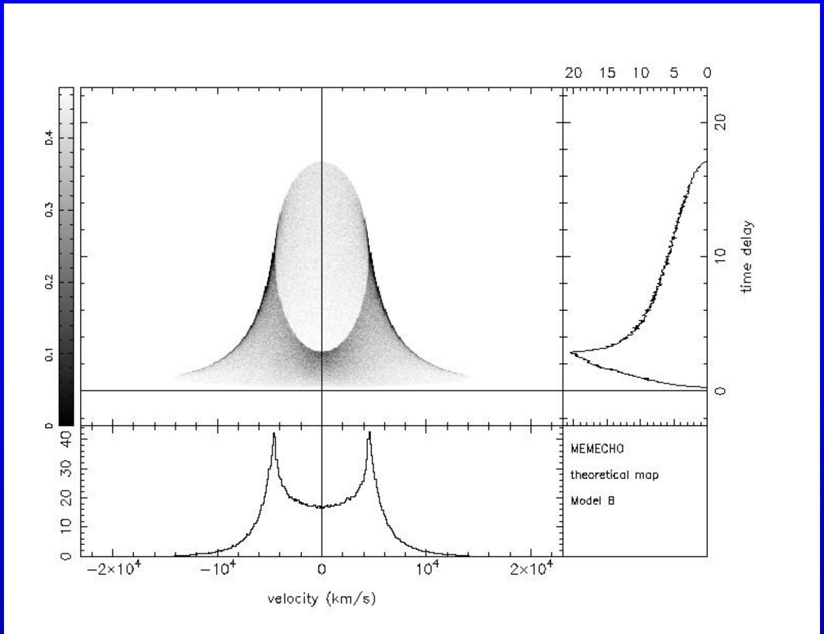


τ=0.0^d
τ
Velocity (km s^{-1})
Velocity (km s^{-1})

Two Simple Velocity-Delay Maps



Inclined Keplerian
disk

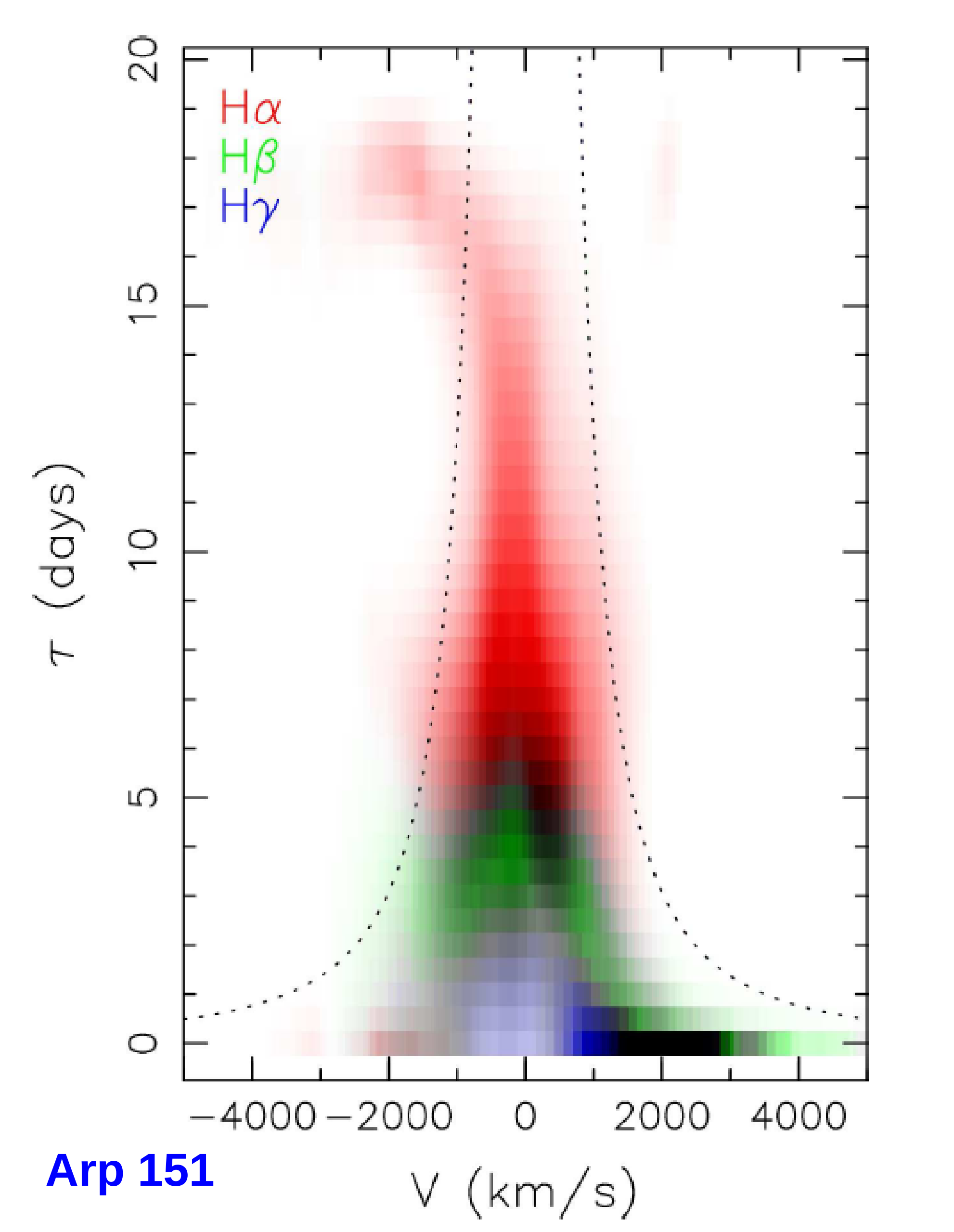


Randomly inclined
circular Keplerian orbits

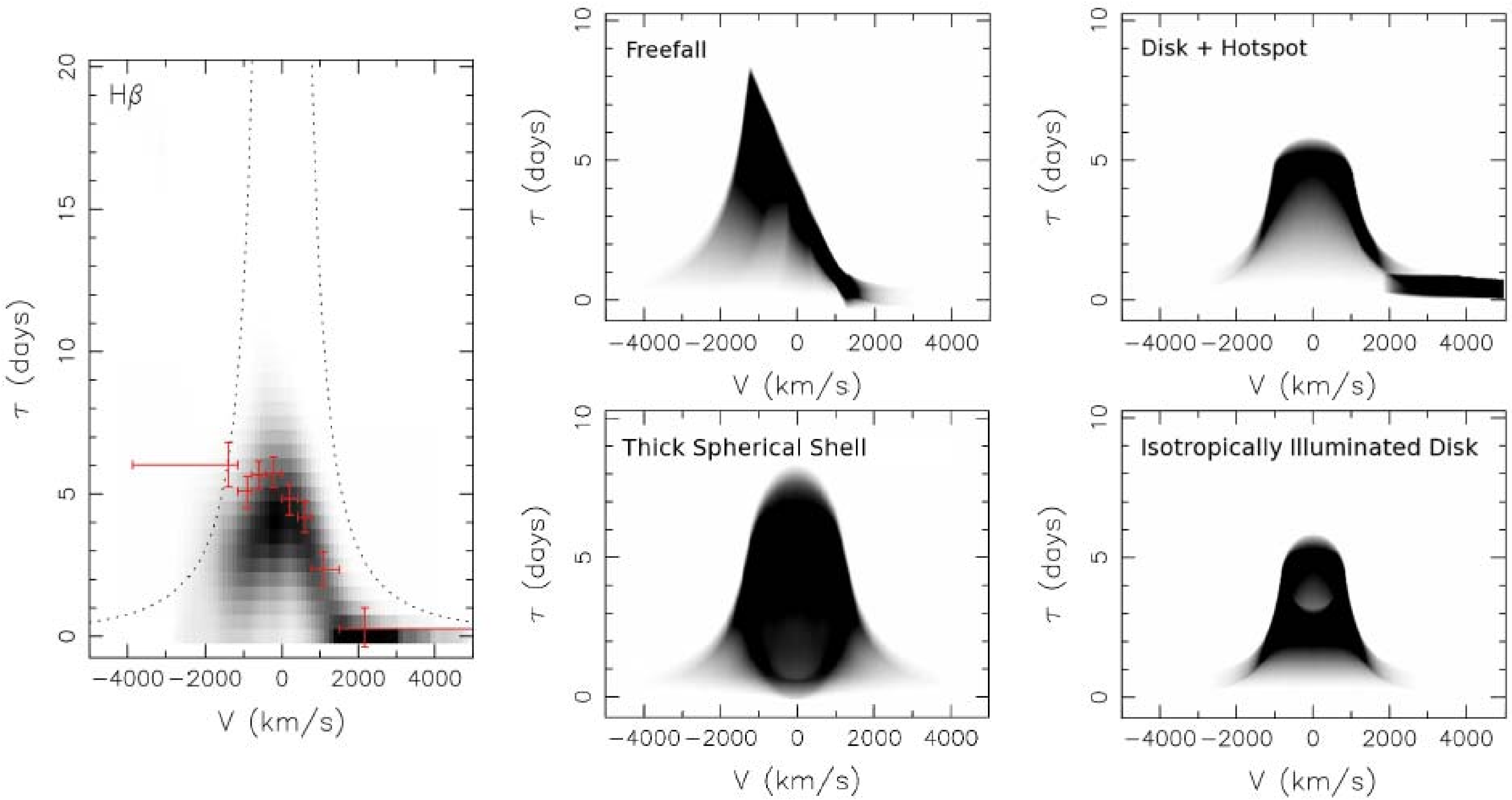
The profiles and velocity-delay maps are superficially similar, but can be distinguished from one other and from other forms.

Velocity-Delay Maps: Finally!

- Velocity-delay maps from LAMP and MDM campaigns are beginning to show believable structure.



LAMP: Bentz et al. 2010

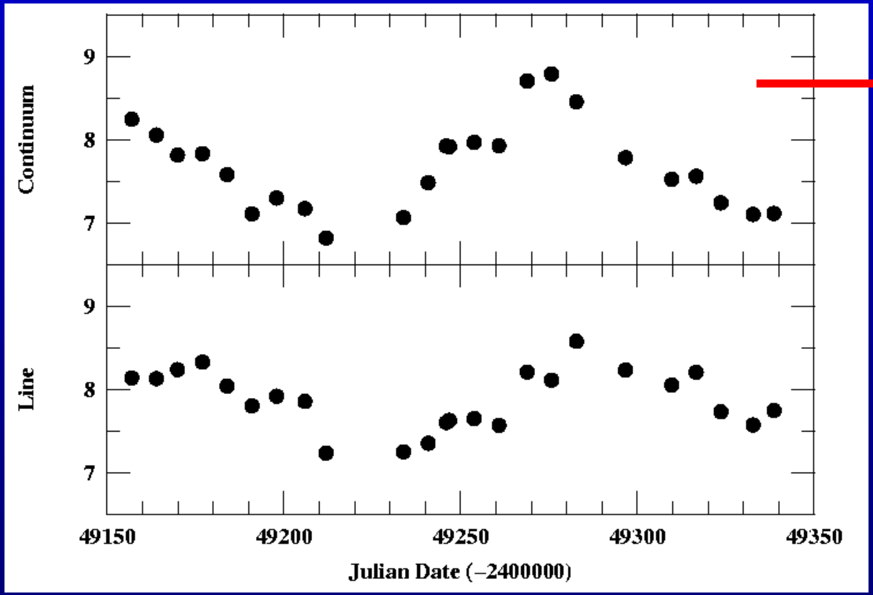


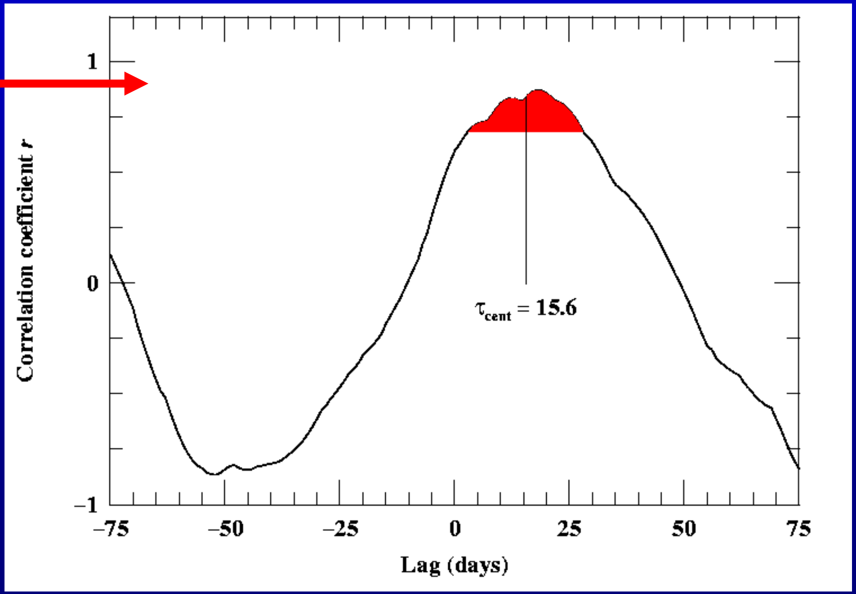
LAMP results from Bentz et al. 2010

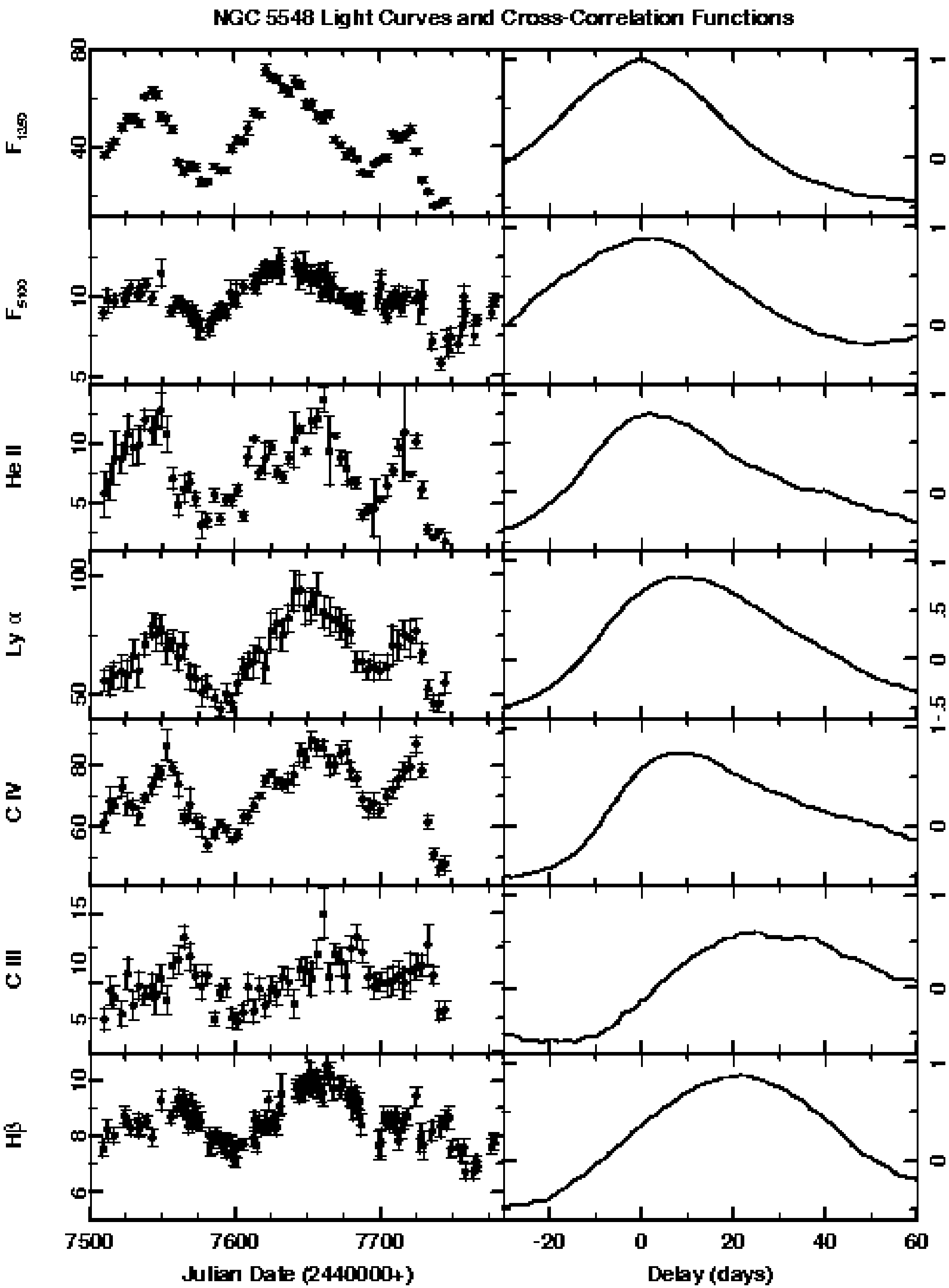
Emission-Line Lags

- Because the data requirements are *relatively* modest, it is most common to determine the cross-correlation function and obtain the "lag" (mean response time):

$$\mathrm{CCF}(\tau) = \int \Psi(\tau')\ \mathrm{ACF}(\tau - \tau')\, d\tau'$$





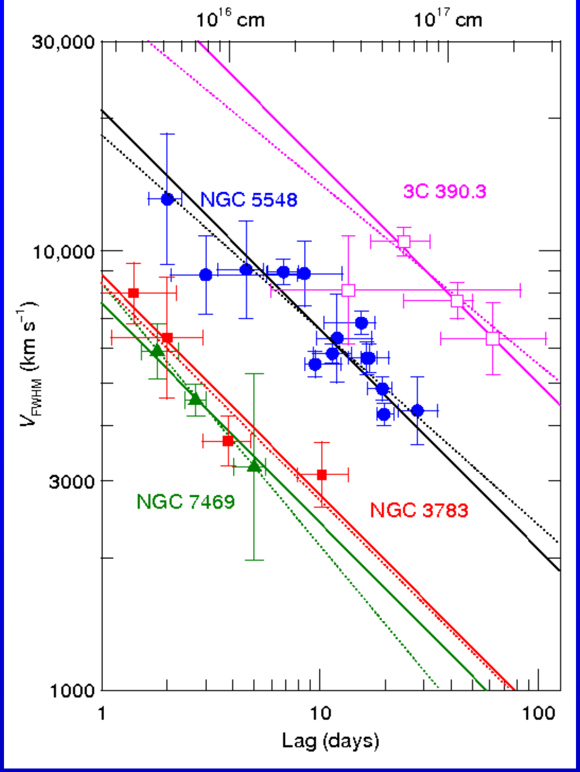


Reverberation Mapping Results

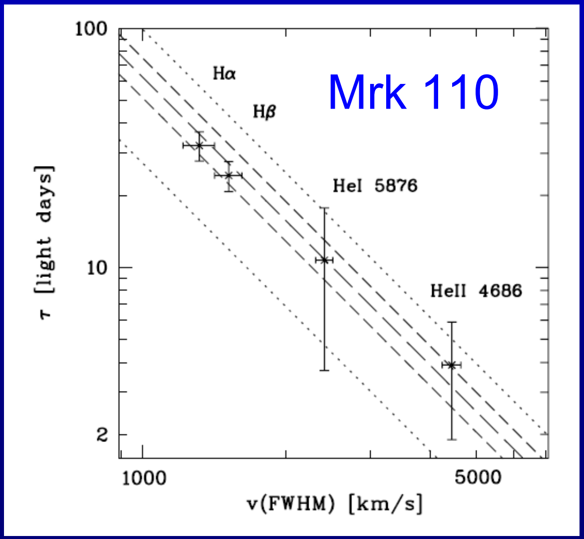
- Reverberation lags have been measured for nearly 50 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification

A Virialized BLR

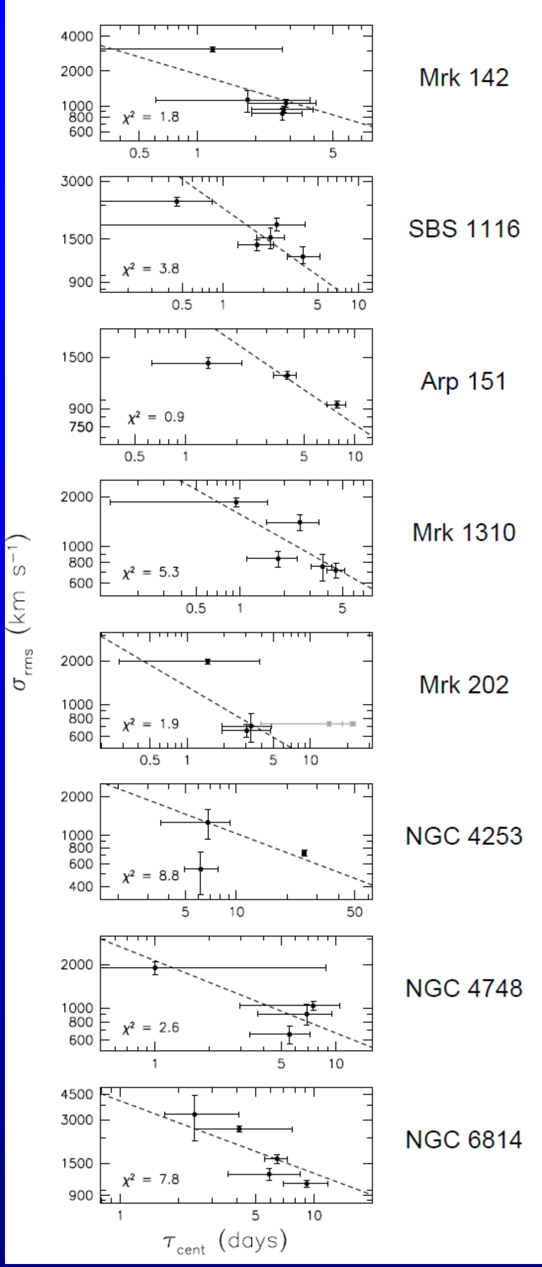
- $\Delta V \propto R^{-1/2}$ for every AGN in which it is testable.
- Suggests that gravity is the principal dynamical force in the BLR.



Onken & Peterson



Kollatschny 2003



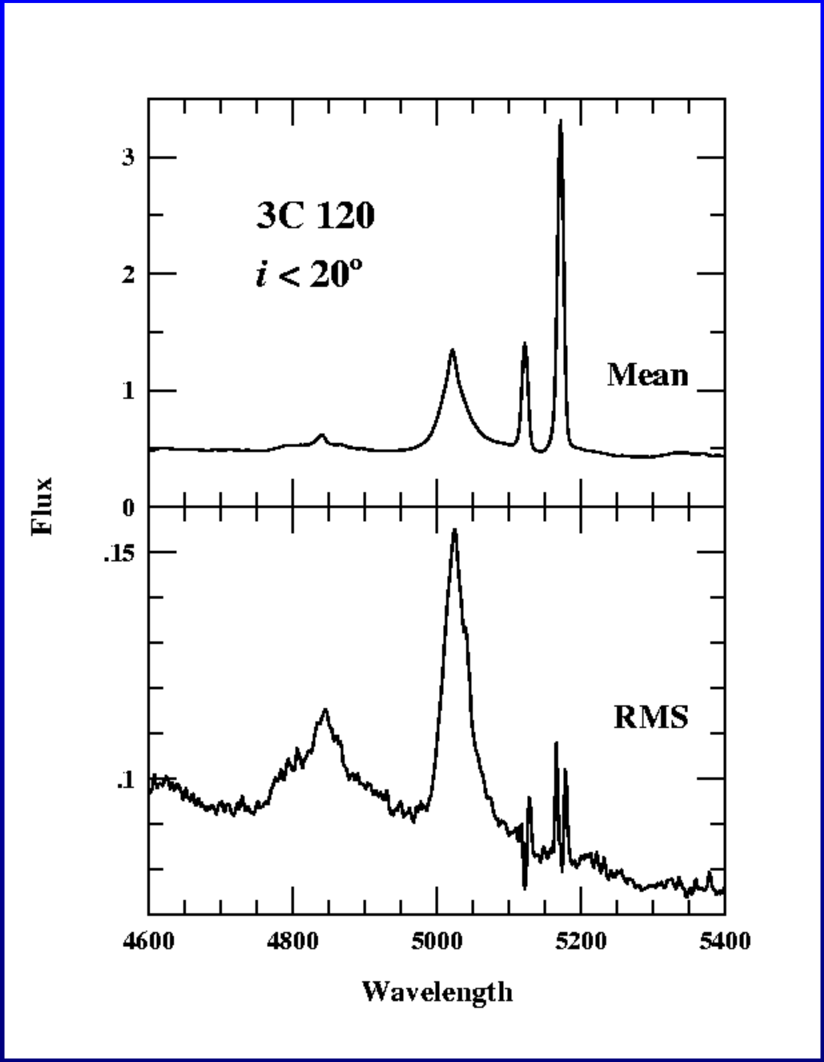
Bentz et al. 2009

Reverberation-Based Masses

- Combine size of BLR with line width to get the enclosed mass:

$$M = f\,(c\,\tau_{\rm cent}\,\sigma^2\,/G)$$

- Without knowledge of the BLR kinematics and geometry, it is not possible to compute the mass accurately or to assess how large the systematic errors might be.
  - Low-inclination thin disk ($f \propto 1/\sin^2 i$) could have a huge projection correction.

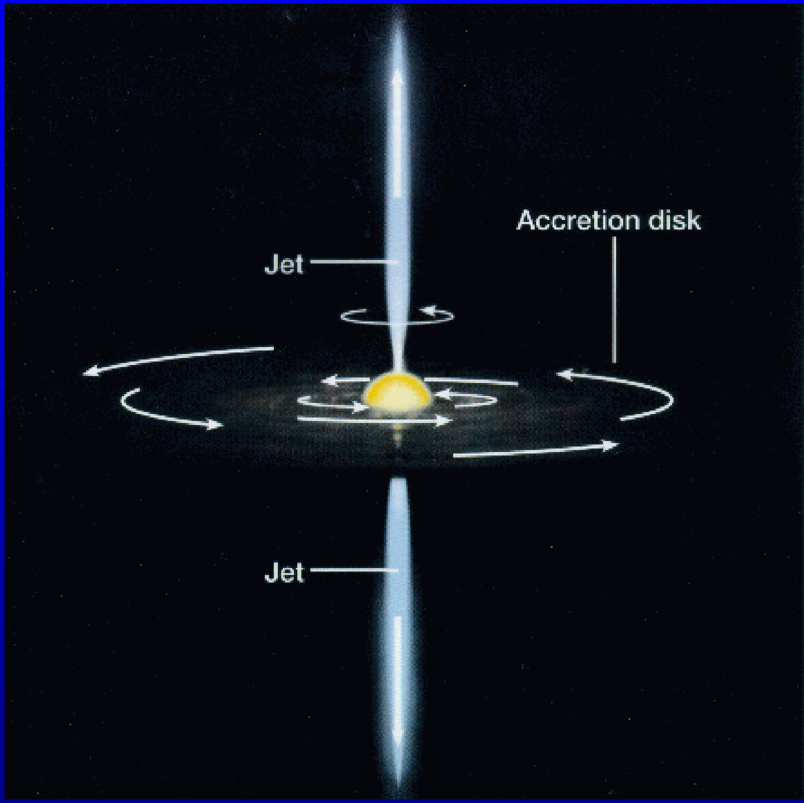


Evidence Inclination Matters

- Relationship between *R* (core/lobe) and FWHM.
  - Core-dominant are more face-on so lines are narrower.
    Wills & Browne (1986)

- Correlation between α_{radio} and FWHM
  - Flat spectrum sources are closer to face-on and have smaller line widths
    - α_{radio} > 0.5: Mean FWHM = 6464 km s^{-1}
    - α_{radio} < 0.5: Mean FWHM = 4990 km s^{-1}
    - Width distribution for radio-quiets like flat spectrum sources (i.e., closer to face-on)

  Jarvis & McLure (2006)

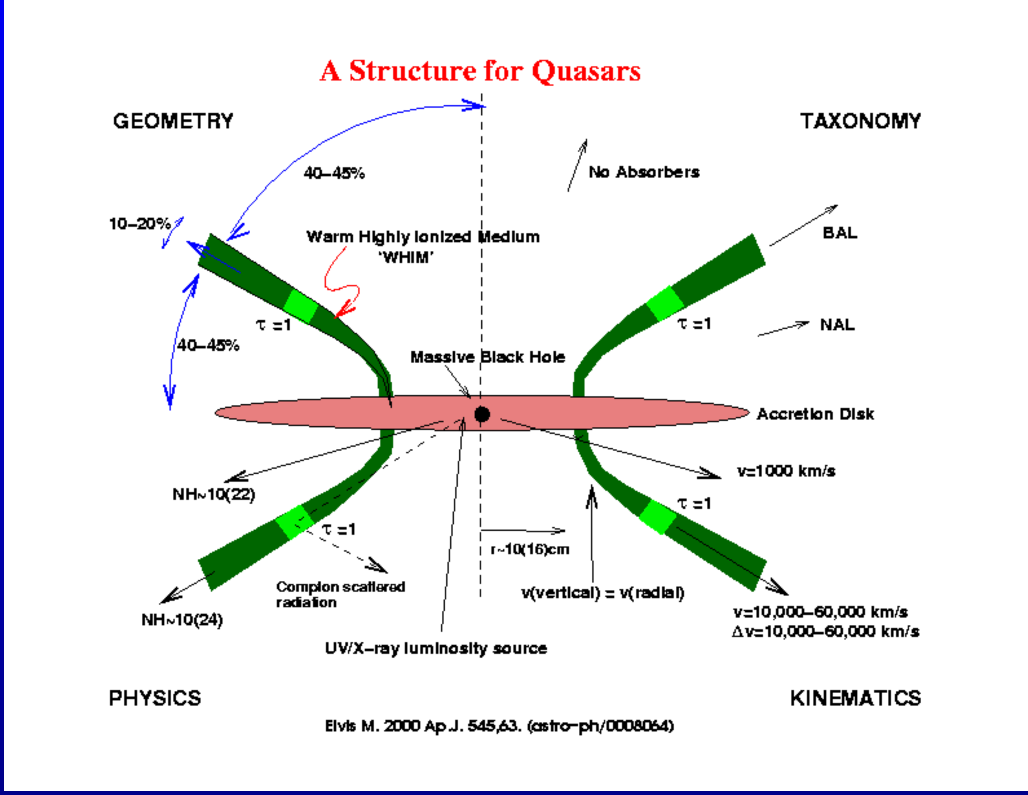


Plausible BLR Geometry

- Unified models suggest that Type 1 AGNs are observed at inclinations $0^\circ \leq i \leq \sim 45^\circ$.
  - Lags are unaffected if axial symmetry and isotropic line emission
  - Line widths can be severely affected by inclination.
    - A “generalized thick disk” parameterization:

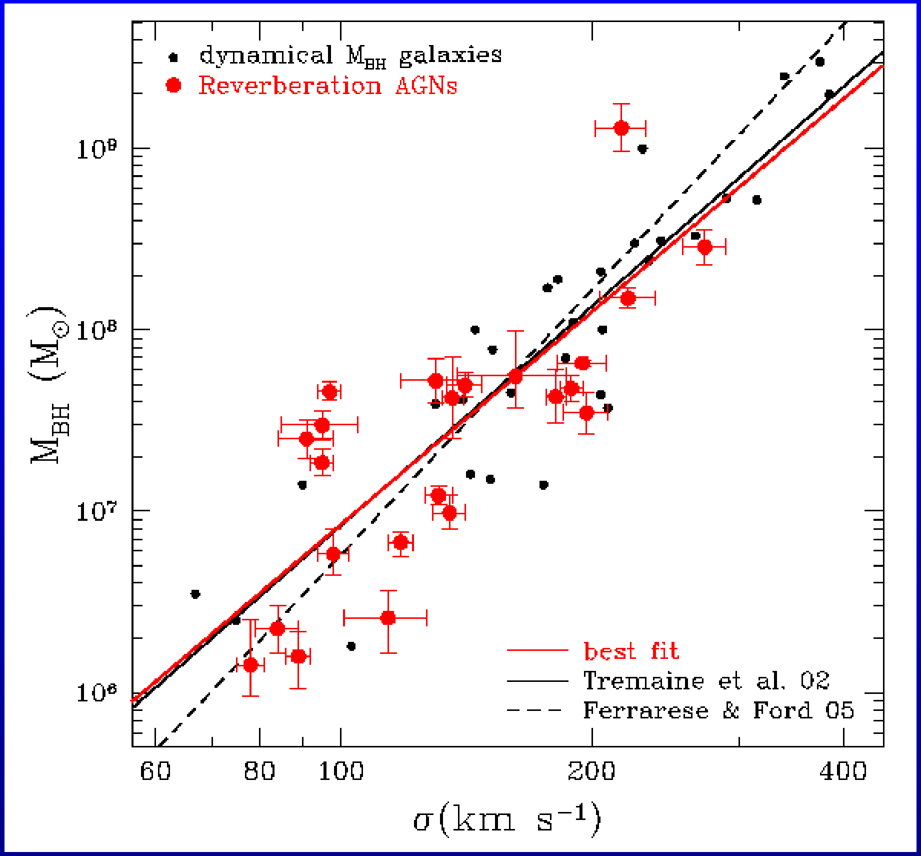
$$f \propto 1 \Big/ \left(a^2 + \sin^2 i\right)$$

Collin et al. (2006)



A plausible disk-wind concept based on Elvis (2000)

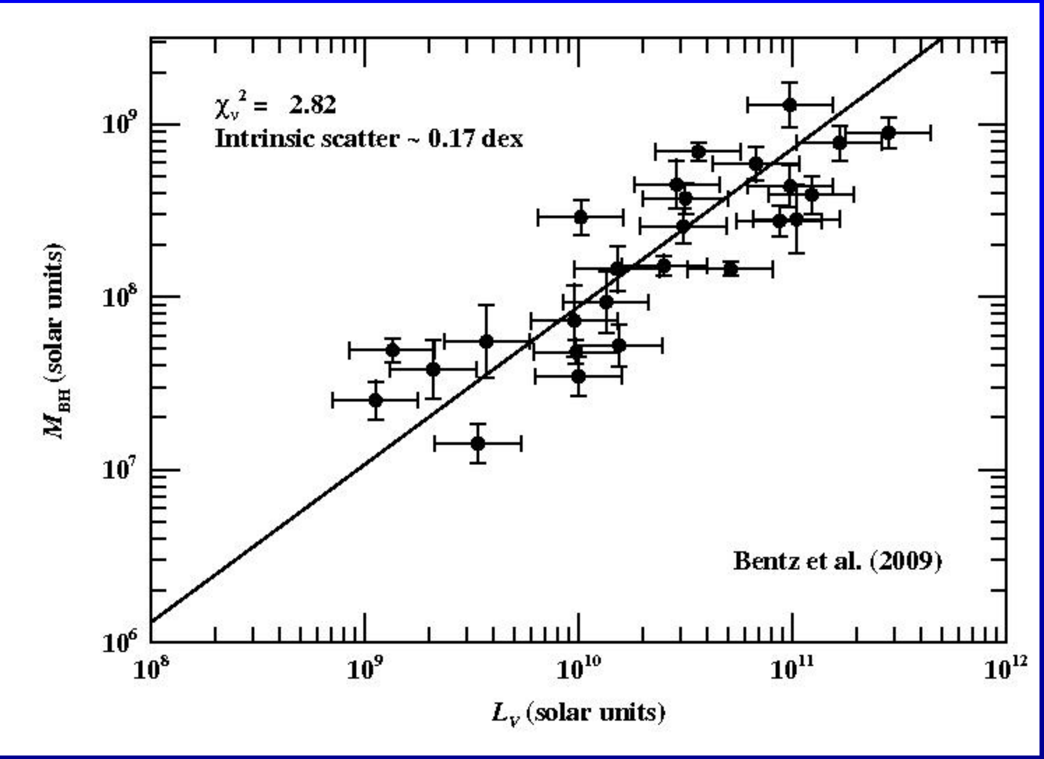
The AGN M_{BH}–σ_* Relationship



Woo et al. (2009)

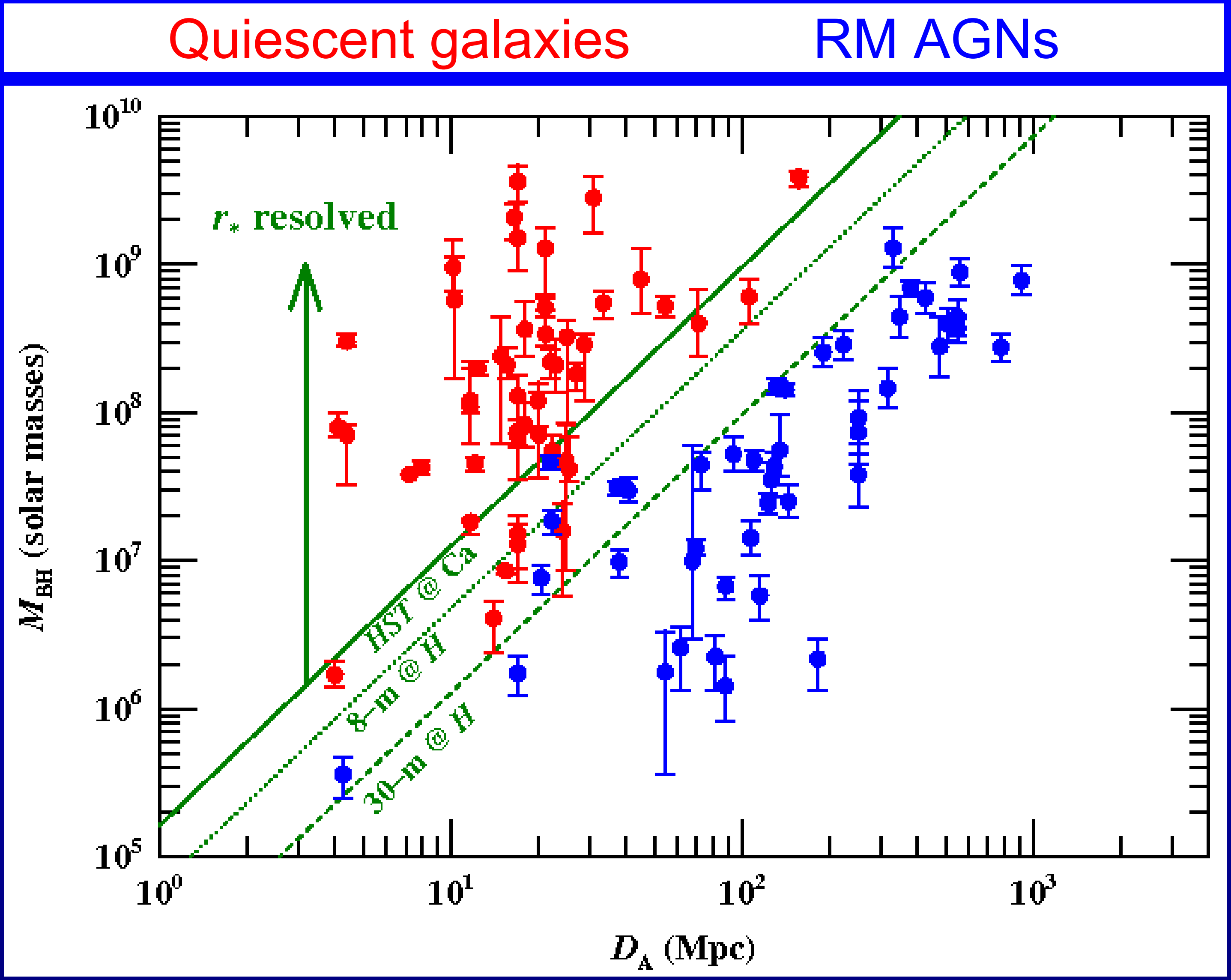
- Assume slope and zero point of most recent quiescent galaxy calibration.
- $\langle f \rangle = 5.25 \pm 1.21$
- Maximum likelihood places an upper limit on intrinsic scatter $\Delta\log M_{BH} \sim 0.40$ dex.
  - Consistent with quiescent galaxies.

The AGN M_{BH}–L_{bulge} Relationship



- Line shows best-fit to quiescent galaxies
- Maximum likelihood gives upper limit to intrinsic scatter $\Delta \log M_{BH}$ ~ 0.17 dex.
  - Smaller than quiescent galaxies ($\Delta \log M_{BH}$ ~ 0.38 dex).

Stellar and gas dynamics requires resolving the black hole radius of influence r_*



Black Hole Mass Measurements (units of $10^6 M_\odot$)

Galaxy	NGC 4258	NGC 3227	NGC 4151
Direct methods:			
Megamasers	38.2 ± 0.1	N/A	N/A
Stellar dynamics	33 ± 2	7–20	< 70
Gas dynamics	25 – 260	20^{+10}_{-4}	$30^{+7.5}_{-22}$
Reverberation	N/A	7.63 ± 1.7	46 ± 5

Uncertainties are statistical, not systematic

References: see Peterson (2010) [arXiv:1001.3675]

Masses of Black Holes in AGNs

- Stellar and gas dynamics requires higher angular resolution to proceed further.
  - Even a 30-m telescope will not vastly expand the number of AGNs with a resolvable r_*
- Reverberation is the future path for direct AGN black hole masses.
  - Trade time resolution for angular resolution.
  - Downside: resource intensive.
- To significantly increase number of measured masses, we need to go to secondary methods.

BLR Scaling with Luminosity

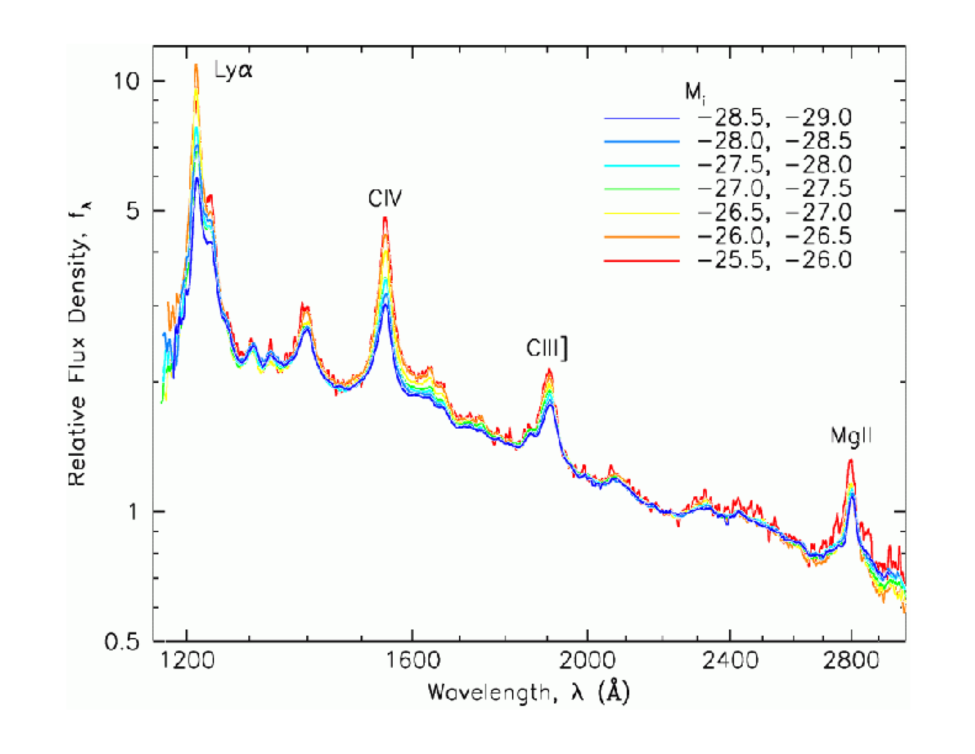
- To first order, AGN spectra look the same

$$U = \frac{Q(\mathrm{H})}{4\pi r^2 n_{\mathrm{H}} c} \propto \frac{L}{n_{\mathrm{H}} r^2}$$

$\Rightarrow$ Same ionization parameter *U*

$\Rightarrow$ Same density n_{H}

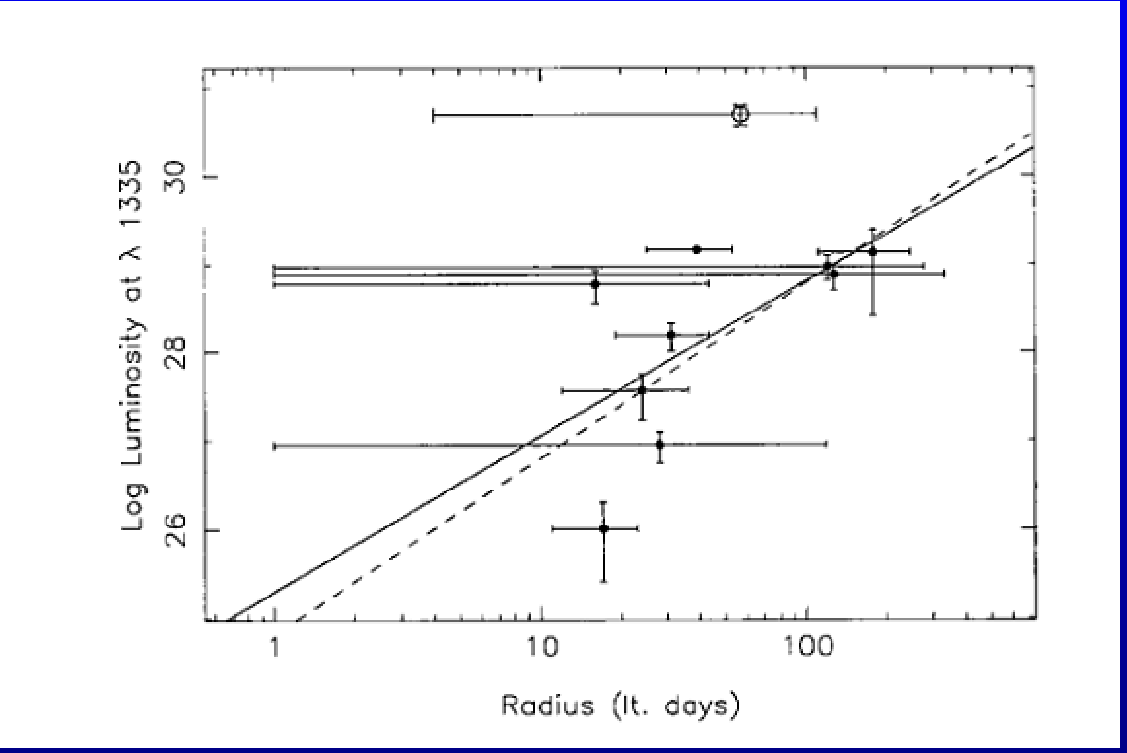
$$\boxed{r \propto L^{1/2}}$$



SDSS composites, by luminosity
Vanden Berk et al. (2004)

BLR Radius-Luminosity Relationship

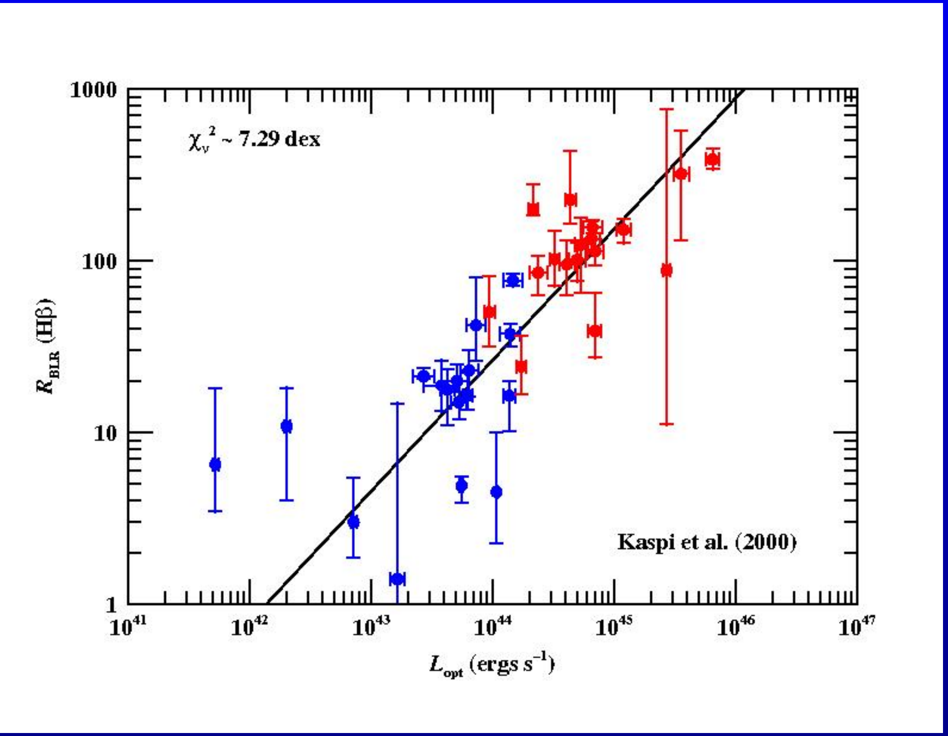
- $R \propto L^{1/2}$ relationship was anticipated long before it was well-measured.



Koratkar & Gaskell 1991

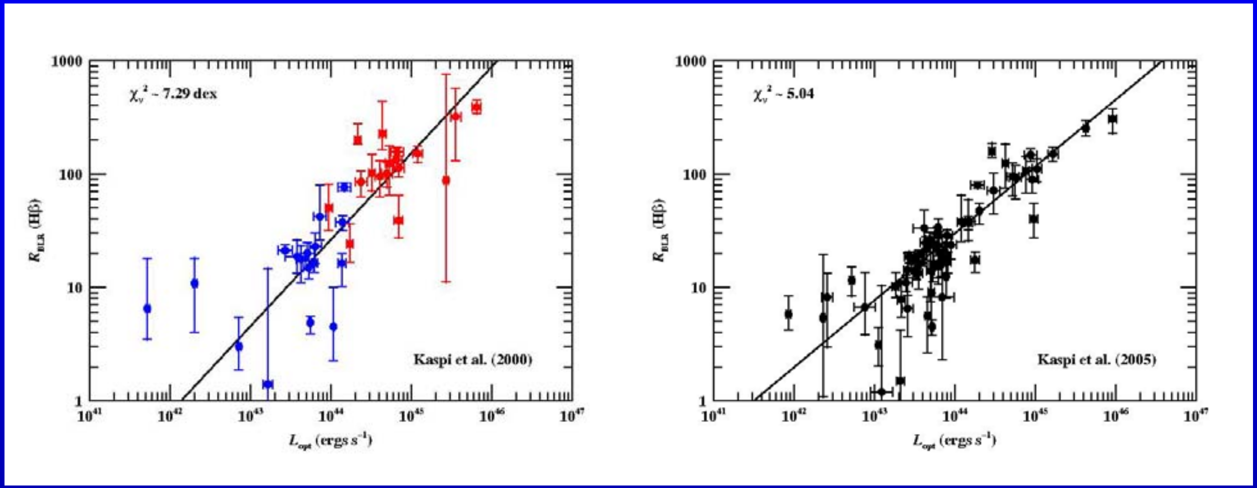
BLR Radius-Luminosity Relationship

- Kaspi et al. (2000) succeeded in observationally defining the *R-L* relationship
  - Increased luminosity range using PG quasars
  - PG quasars are bright compared to their hosts



Kaspi et al. 2000

Progress in Determining the Radius-Luminosity Relationship



Original PG + Seyferts
(Kaspi et al. 2000)
$\chi_\nu^2 \approx 7.29$
$R(\mathrm{H}\beta) \propto L^{0.76}$

Expanded, reanalyzed
(Kaspi et al. 2005)
$\chi_\nu^2 \approx 5.04$
$R(\mathrm{H}\beta) \propto L^{0.59}$

NGC 4051
$z = 0.00234$
$\log L_{opt} = 41.8$

Mrk 79
$z = 0.0222$
$\log L_{opt} = 43.7$

PG 0953+414
$z = 0.234$
$\log L_{opt} = 45.1$

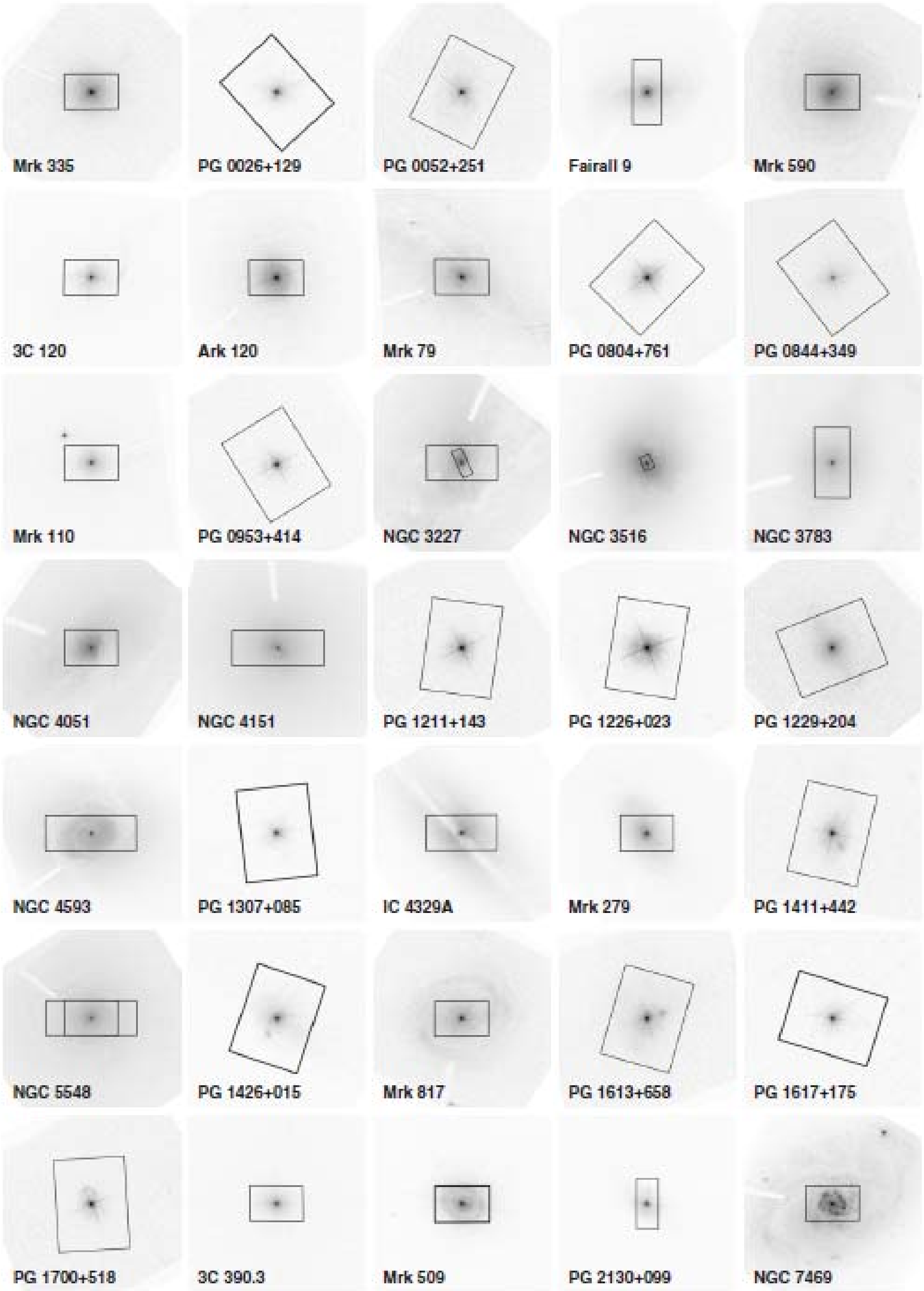
Measurement of host-galaxy properties is difficult even for low-*z* AGNs

- Bulge velocity dispersion σ*
- Starlight contribution to optical luminosity

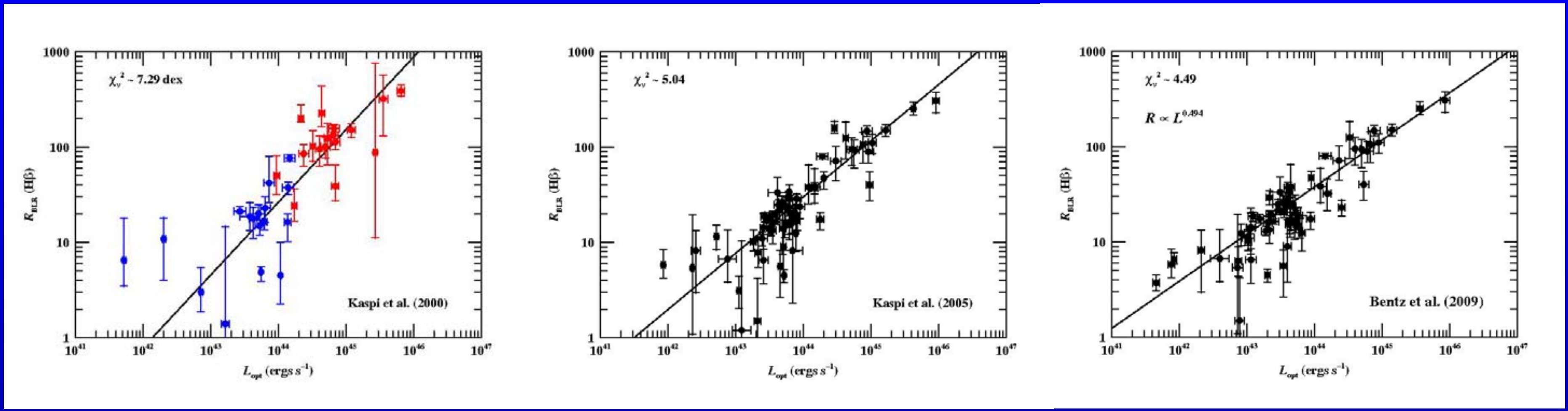
Images courtesy of M. Bentz

Aperture Geometries for Reverberation-Mapped AGNs

- Large apertures mitigate seeing effects.
- They also admit a lot of host galaxy starlight!



Progress in Determining the Radius-Luminosity Relationship



Original PG + Seyferts
(Kaspi et al. 2000)
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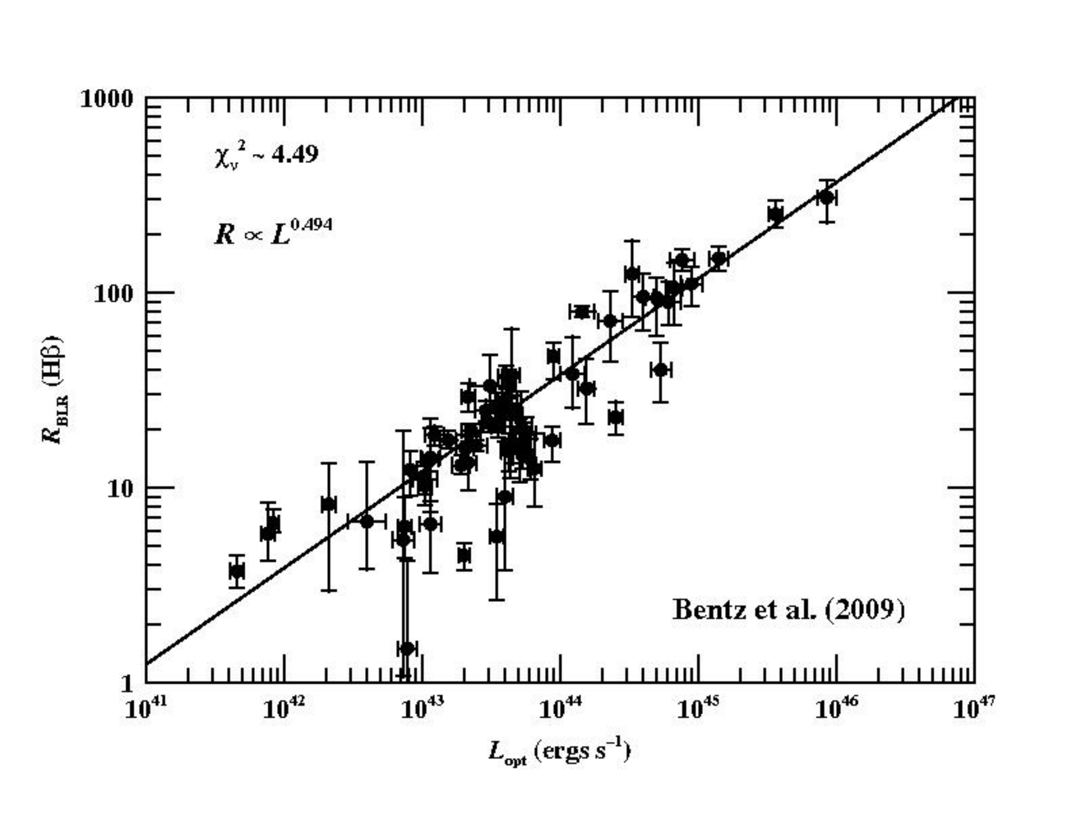
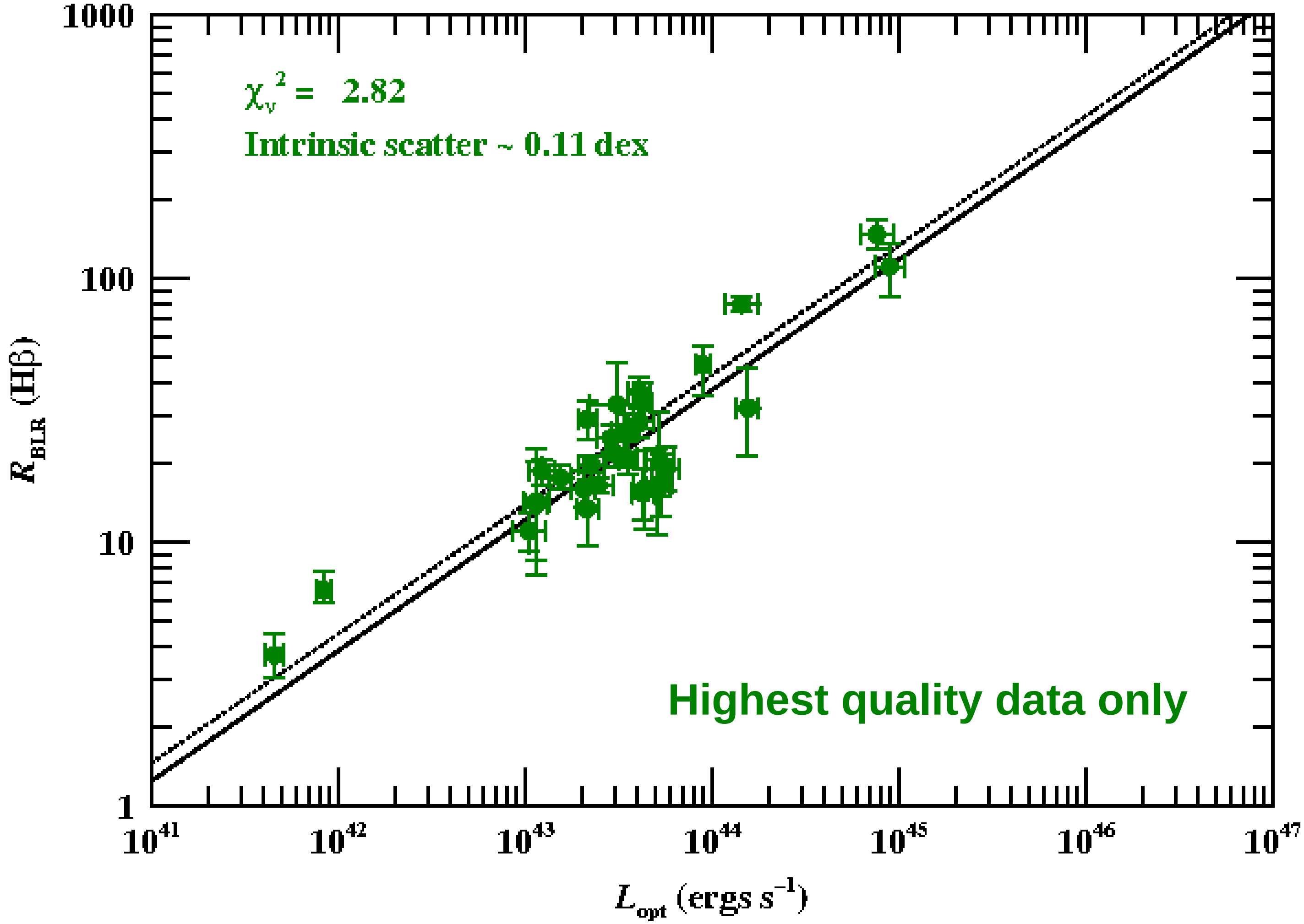
Expanded, reanalyzed
(Kaspi et al. 2005)
$\chi_\nu^2 \approx 5.04$
$R(\mathrm{H}\beta) \propto L^{0.59}$

Starlight removed
(Bentz et al. 2009)
$\chi_\nu^2 \approx 4.49$
$R(\mathrm{H}\beta) \propto L^{0.49}$

How Much Intrinsic Scatter?

- Fundamental limit on accuracy of masses based on *R-L*.
- Dictates future observing strategy:
  - If intrinsic scatter is large, need reverberation programs on many more targets to overcome statistics.
  - If scatter is small, win with better reverberation data on fewer objects.



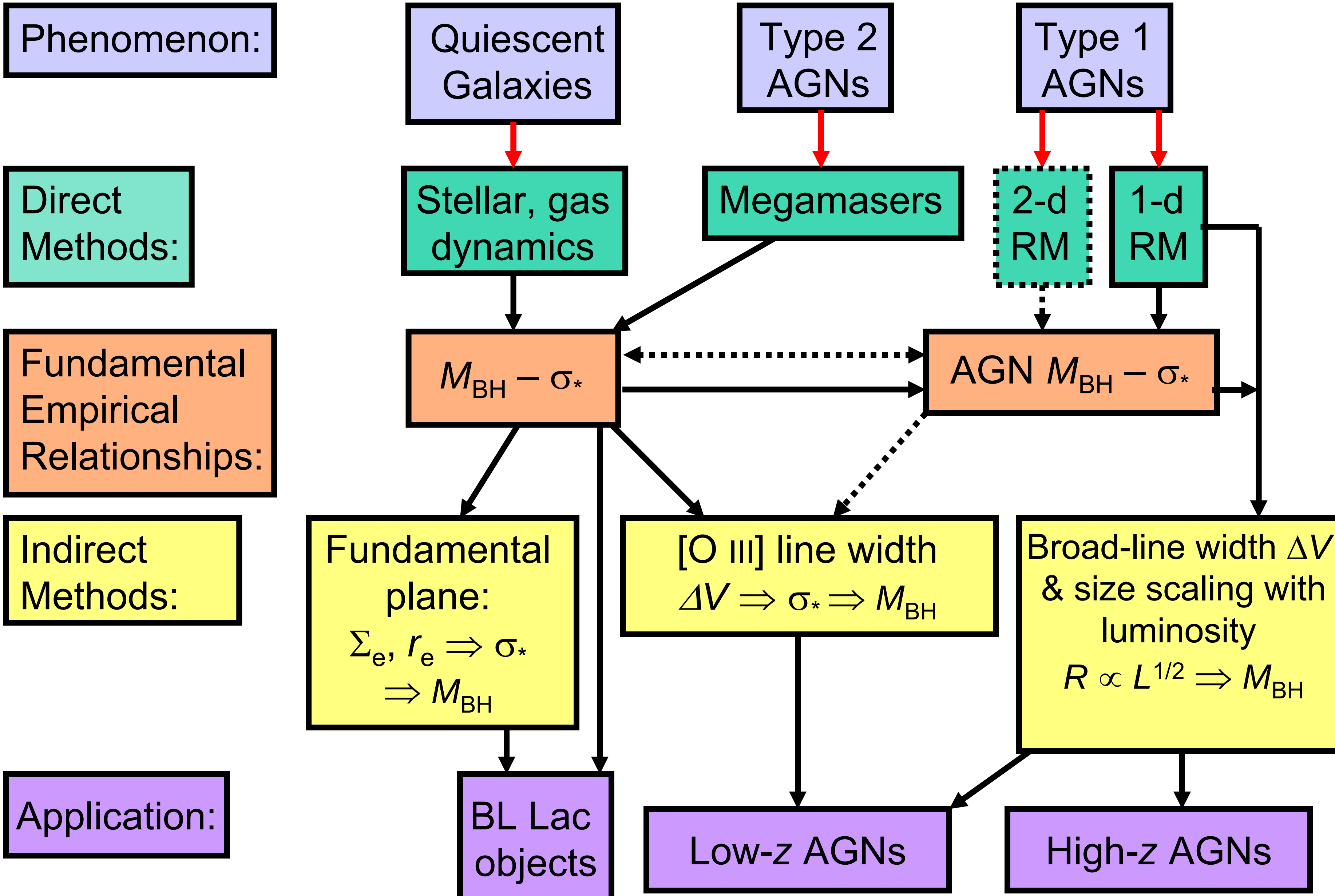


χ_ν^2 = 2.82
Intrinsic scatter ~ 0.11 dex
Highest quality data only
R_{BLR} (Hβ)
L_{opt} (ergs s^{-1})
1
10
100
1000
10^{41}
10^{42}
10^{43}
10^{44}
10^{45}
10^{46}
10^{47}

R-L Relationship

- Intrinsic scatter ~0.11 dex
- Typical error bars on best reverberation data ~0.09 dex
- Conclusion: for Hβ over the calibrated range ($41.5 \leq \log L_{5100}$ (ergs s^{-1}) ≤ 45 at $z \approx 0$), *R-L* is as effective as reverberation.

Measurement of Central Black Hole Masses



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Stellar dynamics	33 ± 2	7–20	< 70
Gas dynamics	25 – 260	20^{+10}_{-4}	$30^{+7.5}_{-22}$
Reverberation	N/A	7.63 ± 1.7	46 ± 5
Indirect Methods:			
M_{BH}–σ_*	13	25	6.1
R–L scaling	N/A	15	65

References: see Peterson (2010) [arXiv:1001.3675]

Scaling Relationships: Use with Caution

- When you think you're measuring mass, you're really measuring

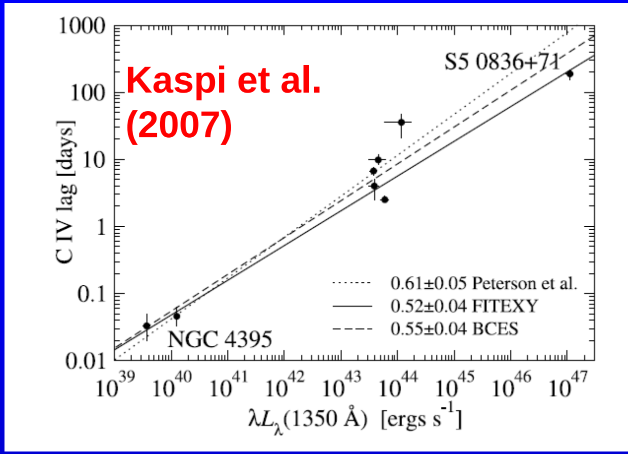
$$M_{BH} \propto R(\Delta V^2) \propto L^{1/2}(\Delta V^2)$$

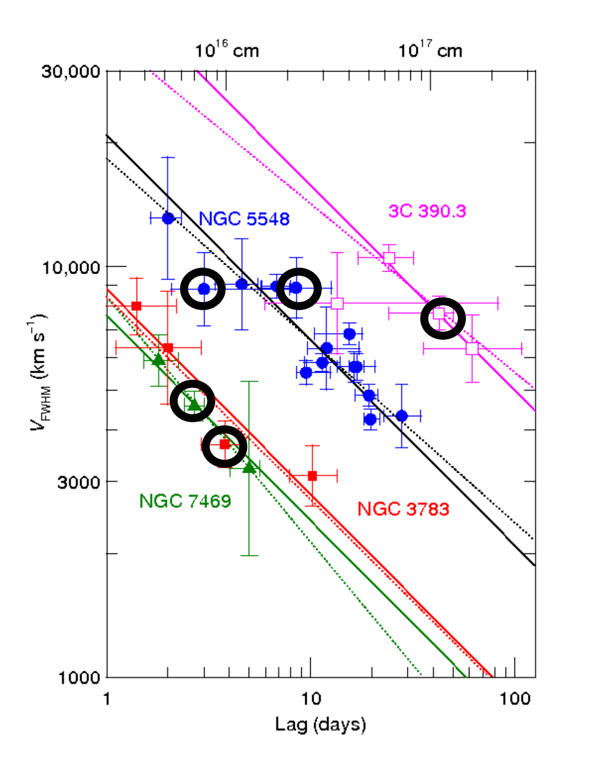
- When you think you're measuring Eddington ratio, you're really measuring

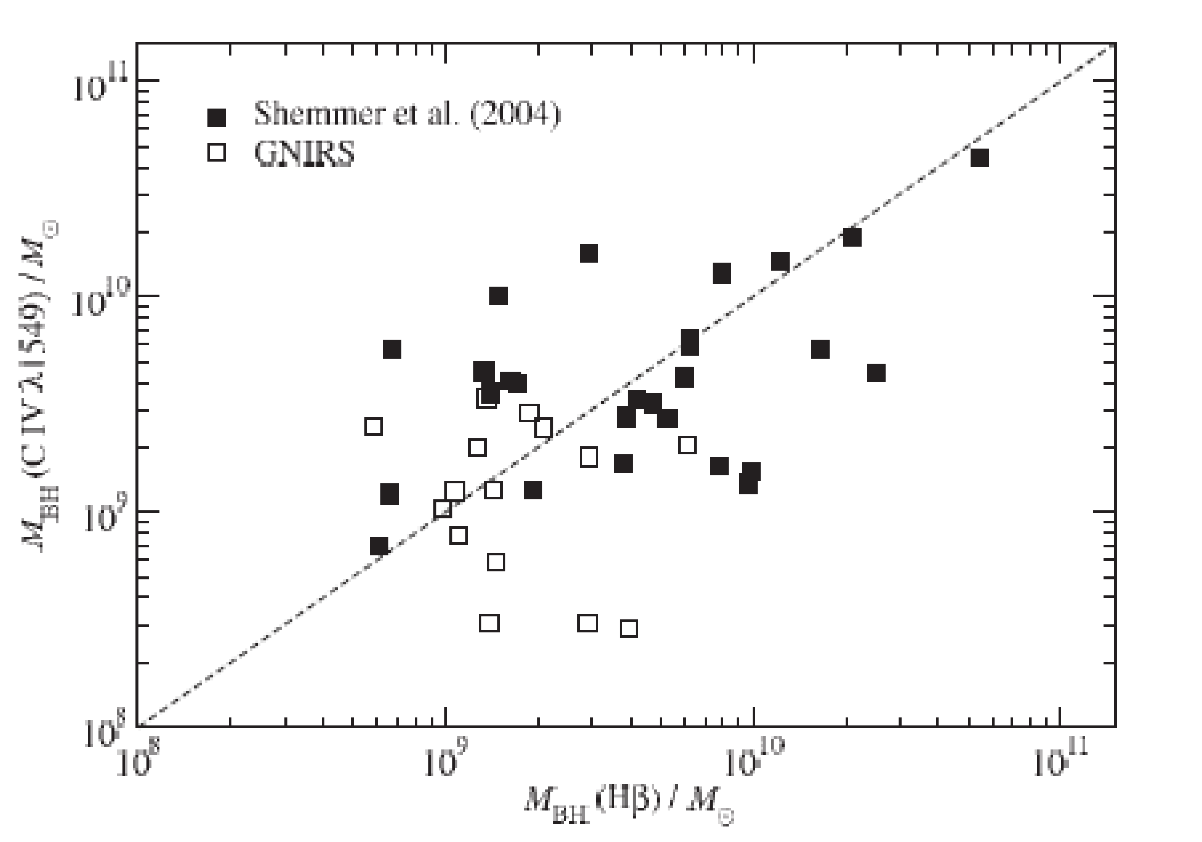
$$L/L_{Edd} \propto L/M_{BH} \propto L/L^{1/2}(\Delta V^2) \propto L^{1/2}/\Delta V^2$$

R-L Relationship for C IV λ1549

- First used by Vestergaard (2002) to estimate BH masses at high-z.
- Pros:
  - Limited data suggest same R-L slope as Hβ (despite Baldwin Effect).
  - Consistent with virial relationship, at least in low-luminosity AGNs.
- Cons:
  - Often strong absorption, usually in blue wing.
  - Extended bases (outflows), especially in NLS1s.



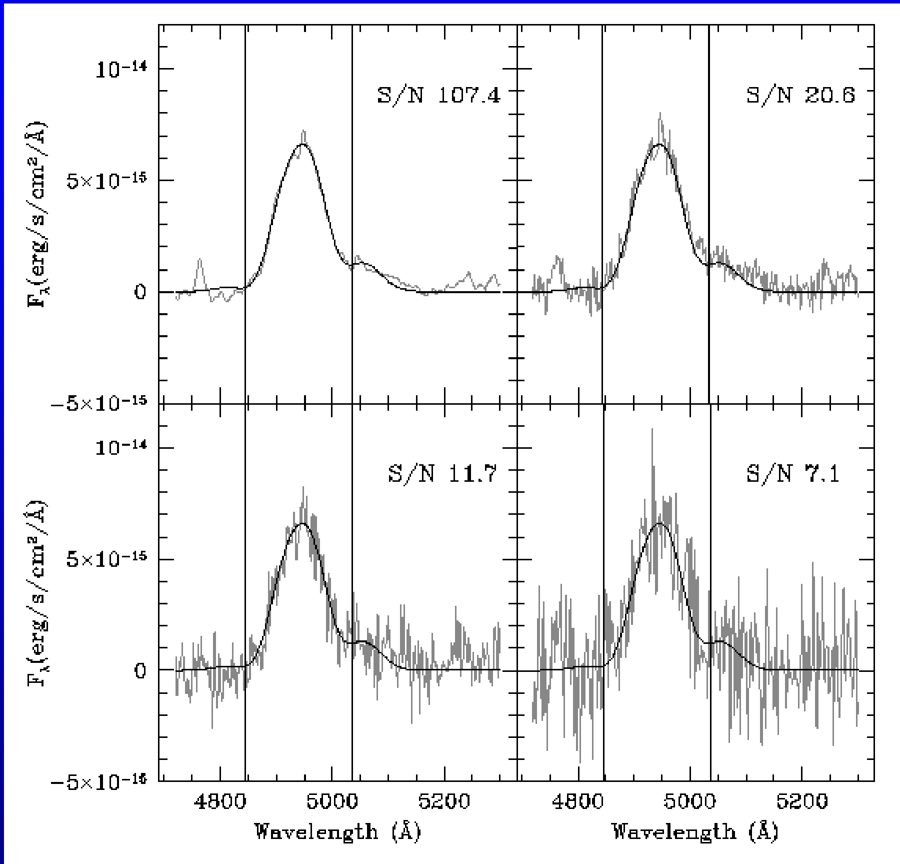




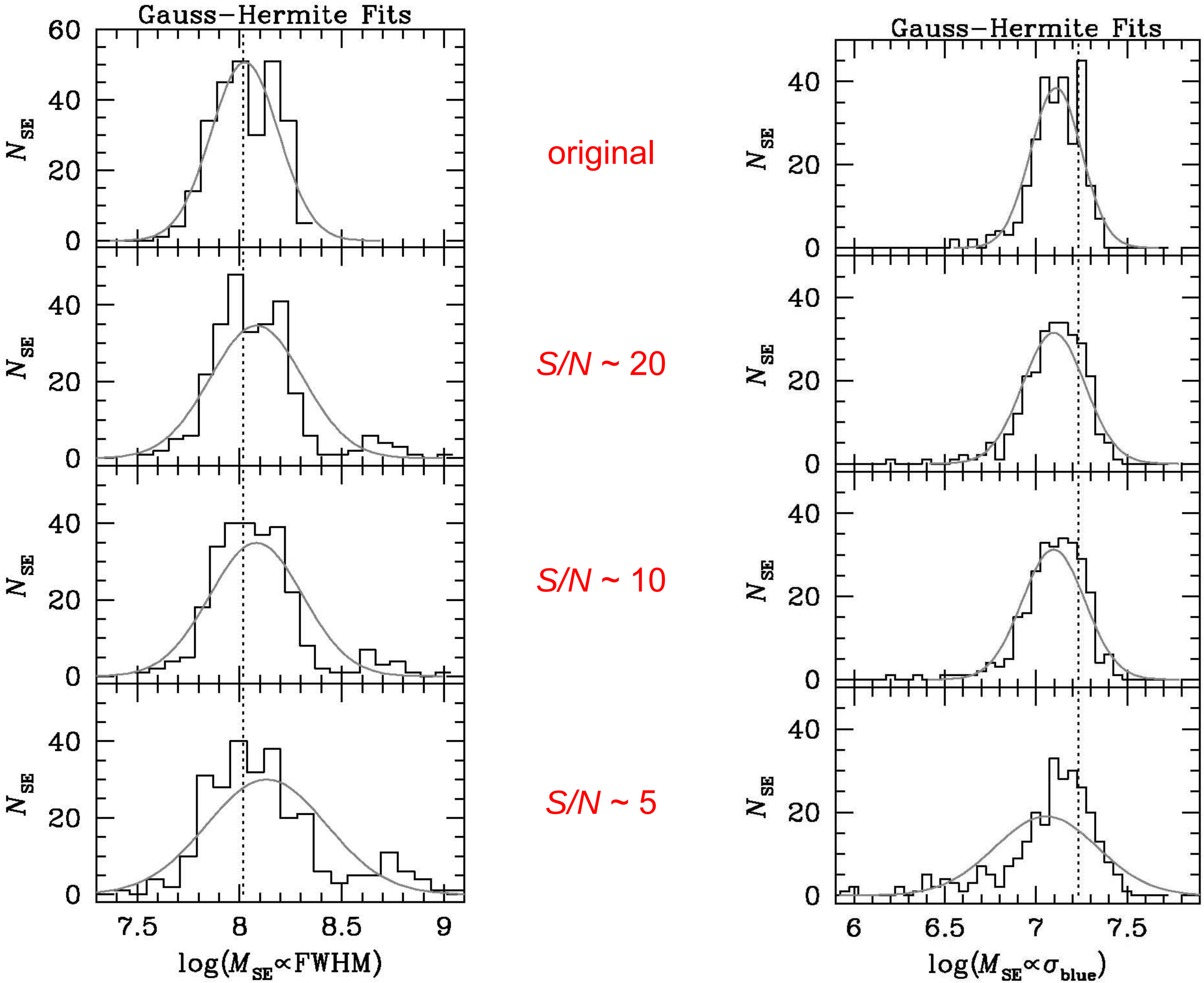
Netzer et al. (2007)

An Overlooked Issue

- Accurate measurement of line widths becomes problematic at *S/N* < 10.
  - Error distribution becomes skewed and non-normal.
  - At very low *S/N*, the number of outliers (masses off by an order or magnitude or more) increases significantly.
- Claims that C IV cannot be used for BH masses are based on low-*S/N* spectra.



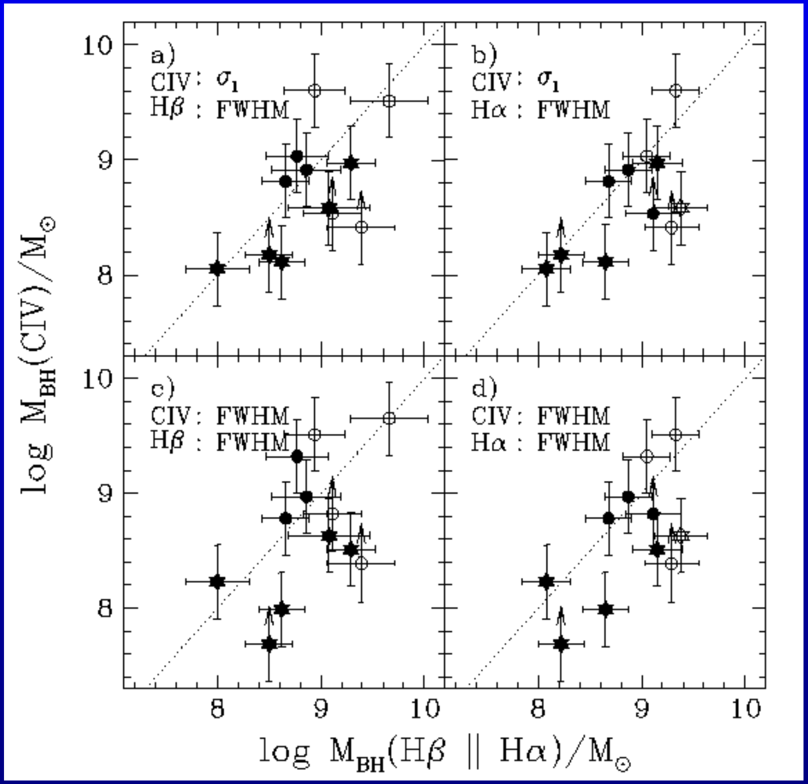
Denney et al. 2009, ApJ, 692, 246



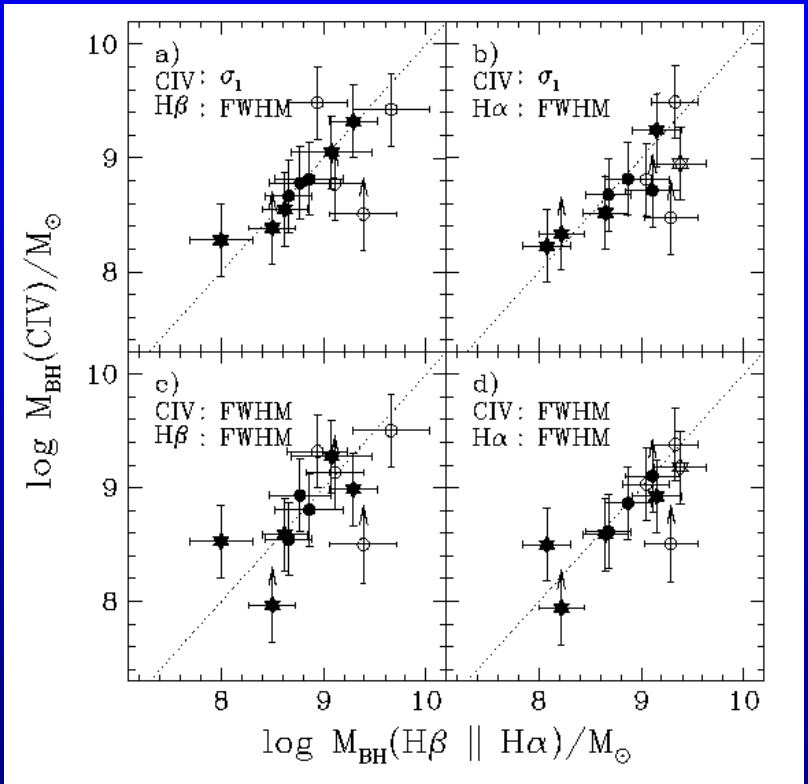
Gauss-Hermite Fits
Gauss-Hermite Fits
original
S/N ~ 20
S/N ~ 10
S/N ~ 5
N_{SE}
$\log(M_{SE} \propto \mathrm{FWHM})$
$\log(M_{SE} \propto \sigma_{blue})$

Another Overlooked Issue

C IV and Hβ/Hα mass estimates are based on UV and optical luminosities, respectively. A color correction needs to be included.
In sample below, color term decreases scatter by factor of 2!



No 1350 Å /5100 Å color correction.



1350 Å /5100 Å color correction included.

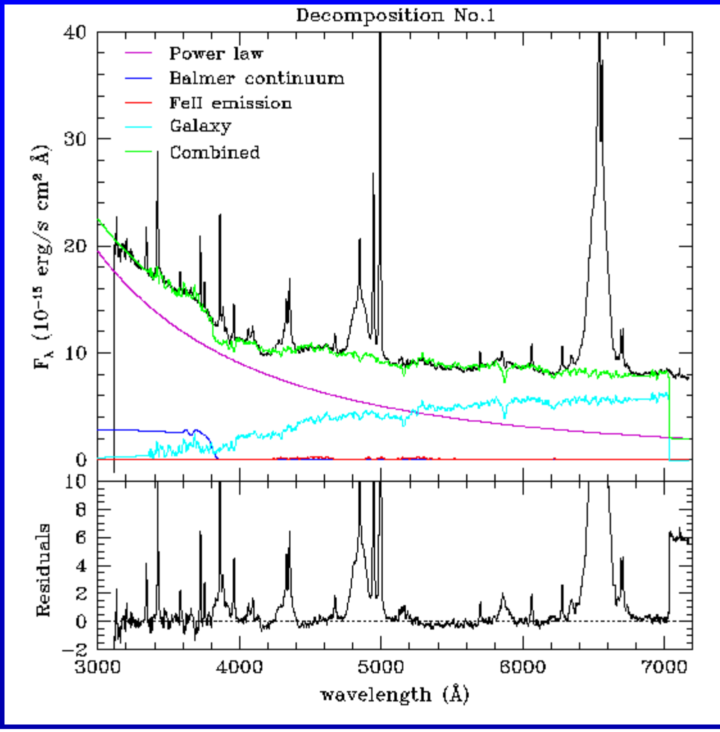
Assef, Denney et al. (2011) arXiv:1009.1145

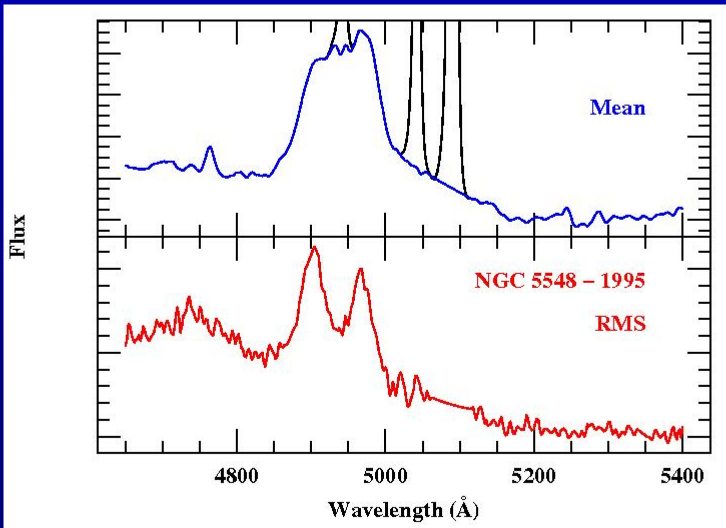
Mass-Ladder Issues

- Direct methods
  - Reverberation mass-scale zero point
    - Importance of radiation pressure
    - Independence from quiescent-galaxy scale
      - BLR geometry, kinematics
  - Dynamical Methods
    - Uncertainties in distances
    - Dark matter halos, orbit libraries, other resolution-dependent systematics

Mass-Ladder Issues

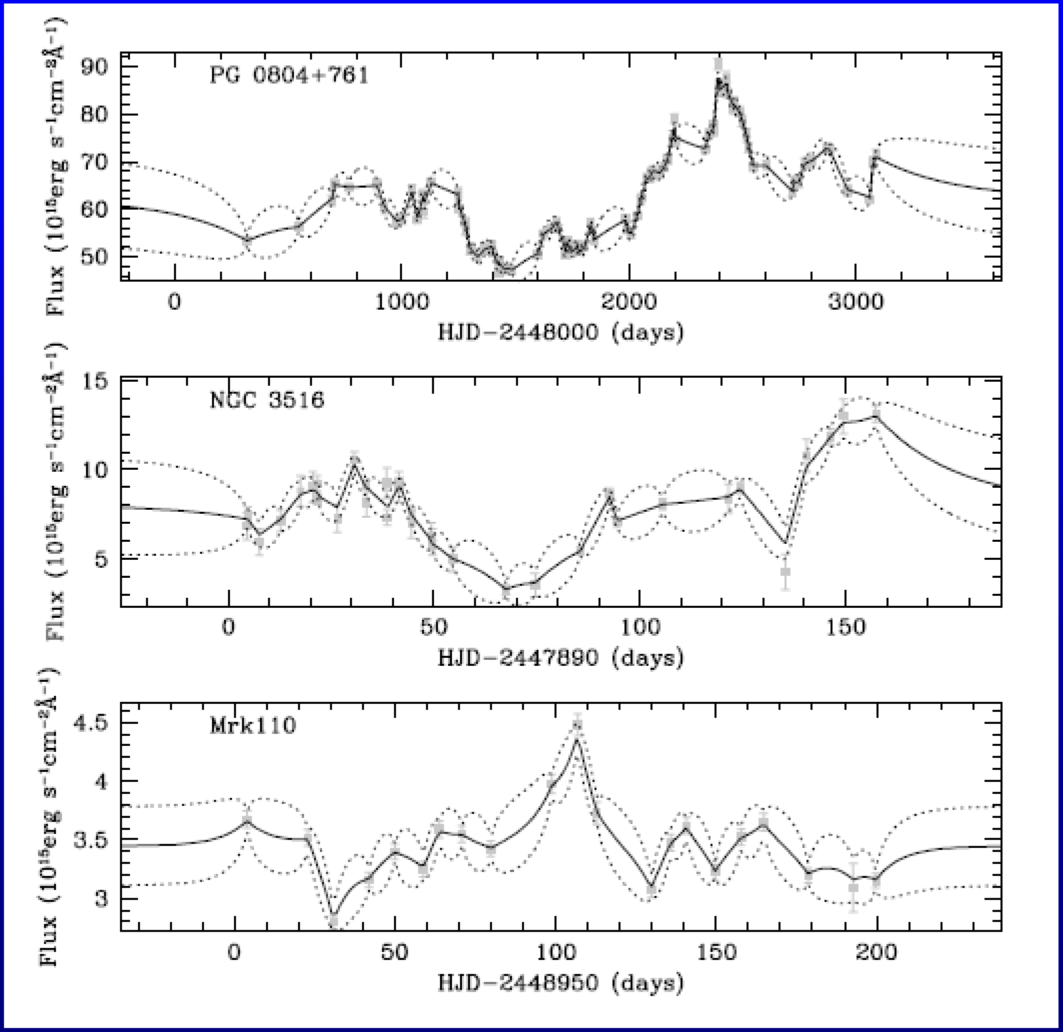
- Scaling relationships
  - Line-width characterization
    - Simple prescription that is unbiased wrt to *L*, L/L_{Edd}, profile, variability, etc.
  - Use of C IV emission line
    - Identification and mitigation of systematics
    - *R*–*L* validation





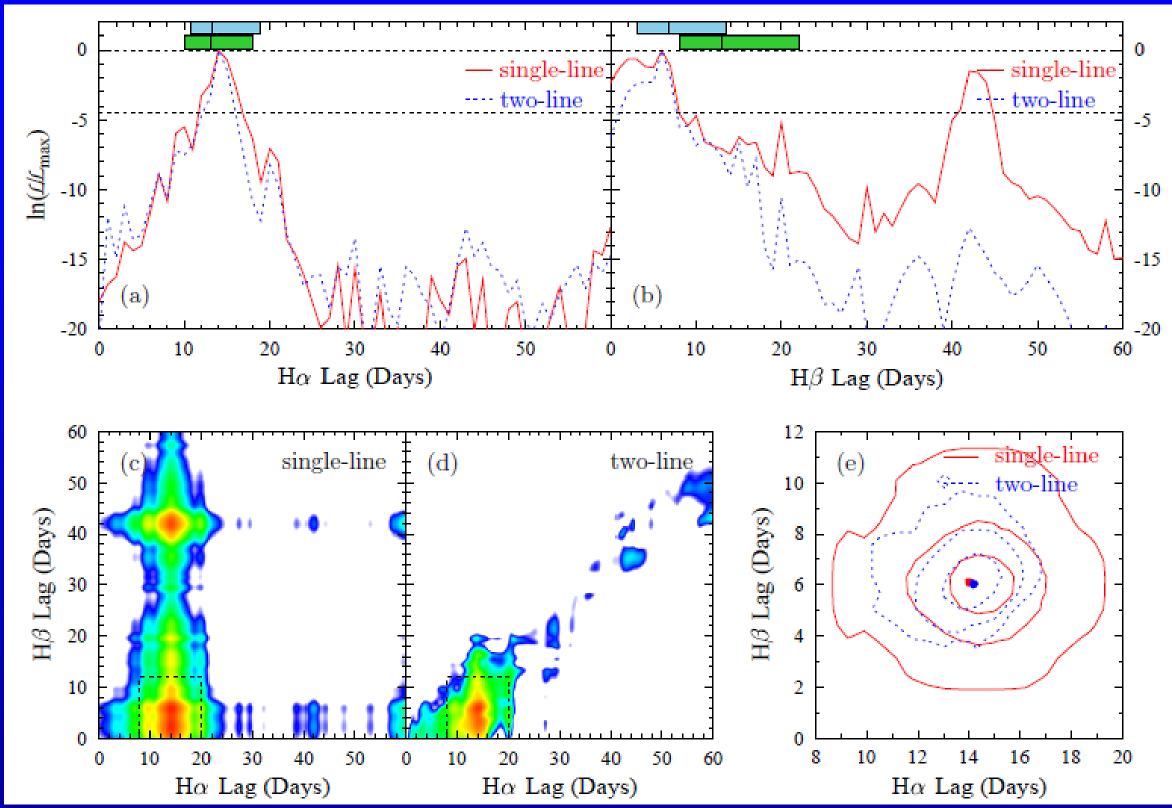
A New Reverberation Methodology

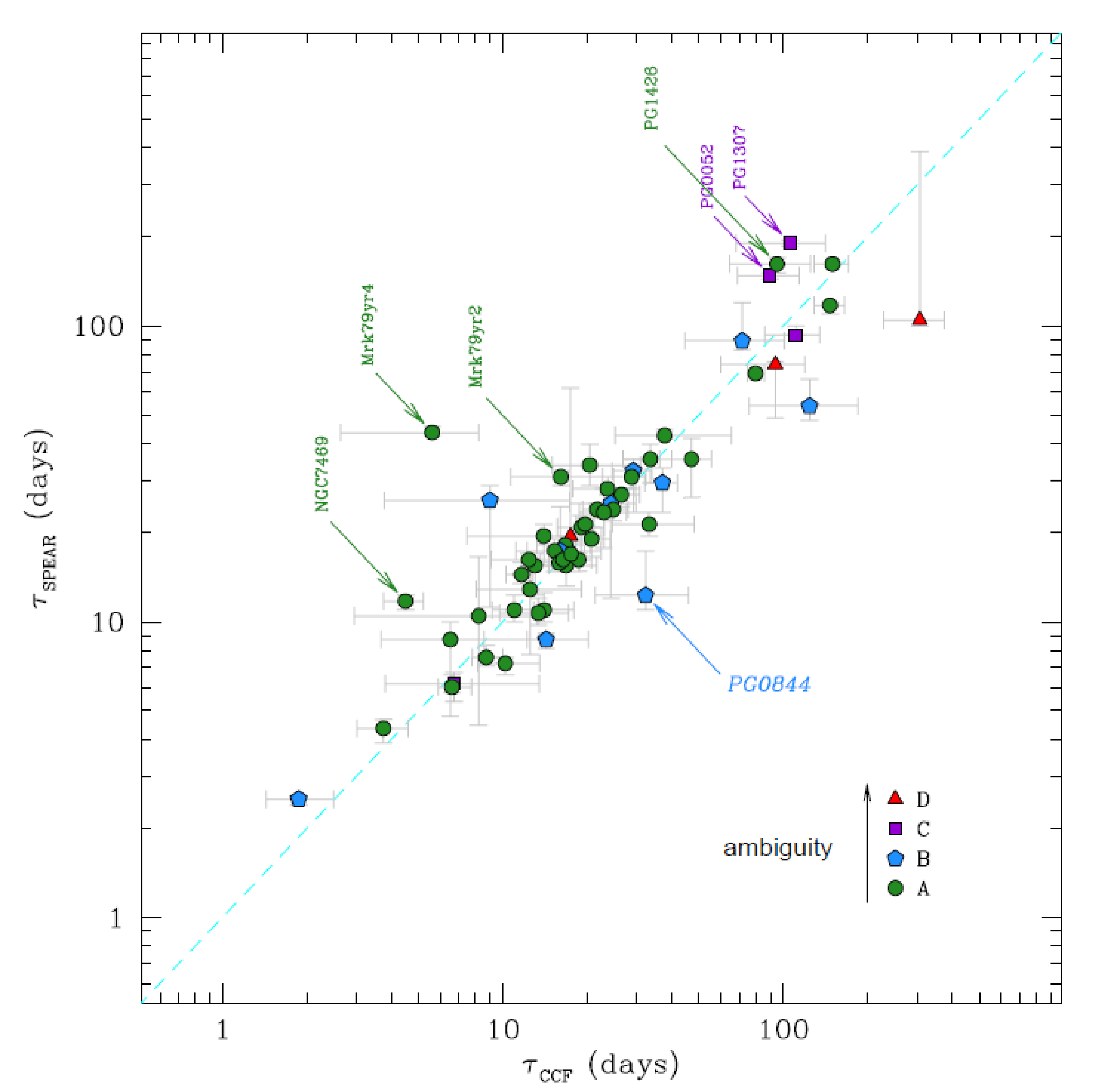
- Statistical modeling of light curves can be used to fill in gaps with all plausible flux values.
  - Based on statistical process modeling by Press, Rybicki, & Hewitt (1992), Rybicki & Press (1992), and Rybicki & Kleyna (1994).
  - “Stochastic Process Estimation for AGN Reverberation” (SPEAR)
- A likelihood estimator can be used to identify the most probable lags.



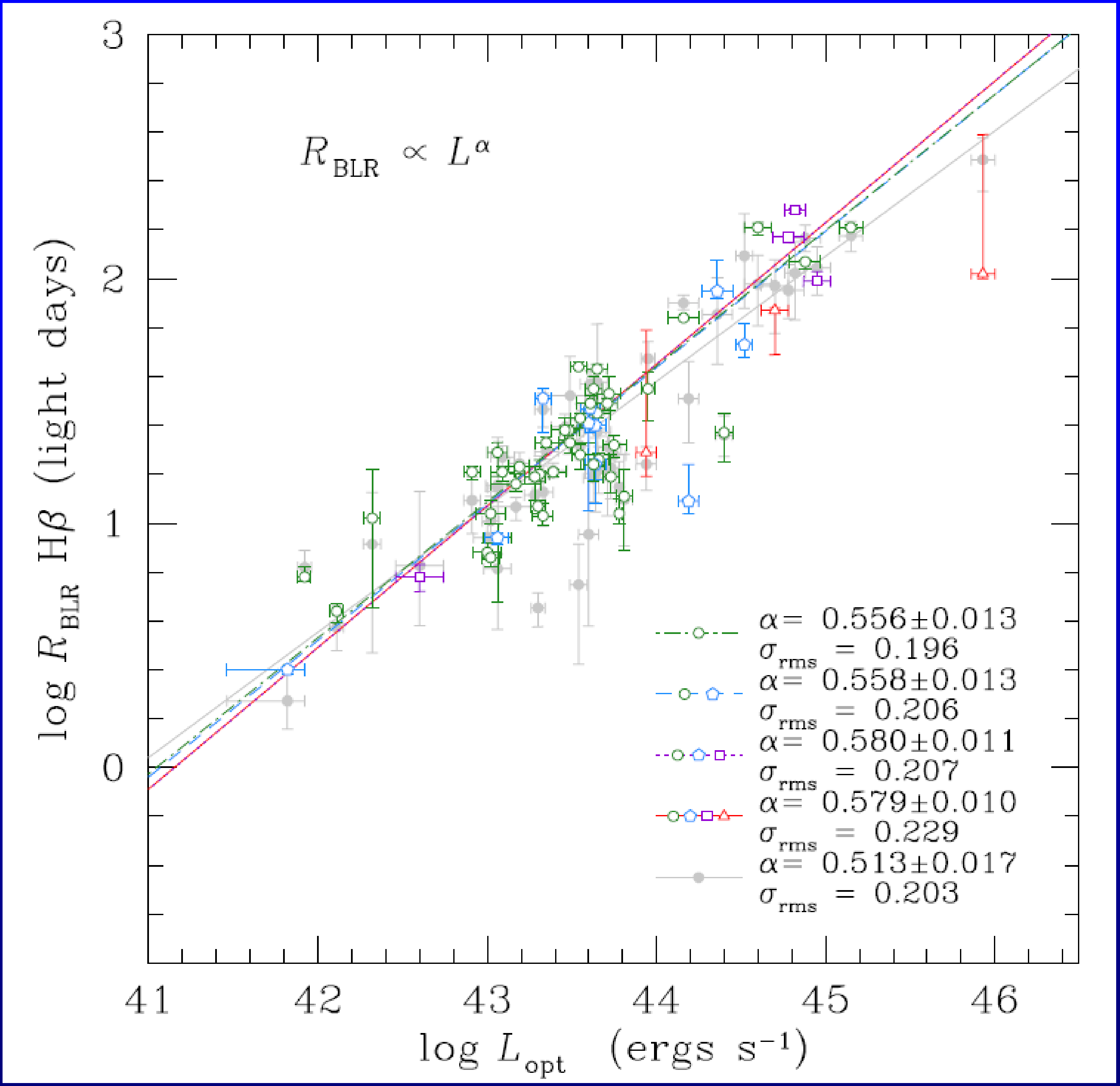
Zu, Kochanek, & Peterson 2010

- Uncertainties are computed self-consistently and included in the model.
- Trends, correlated errors are dealt with naturally.
- Can simultaneously fit multiple lines (which effectively backfill gaps in the time series).





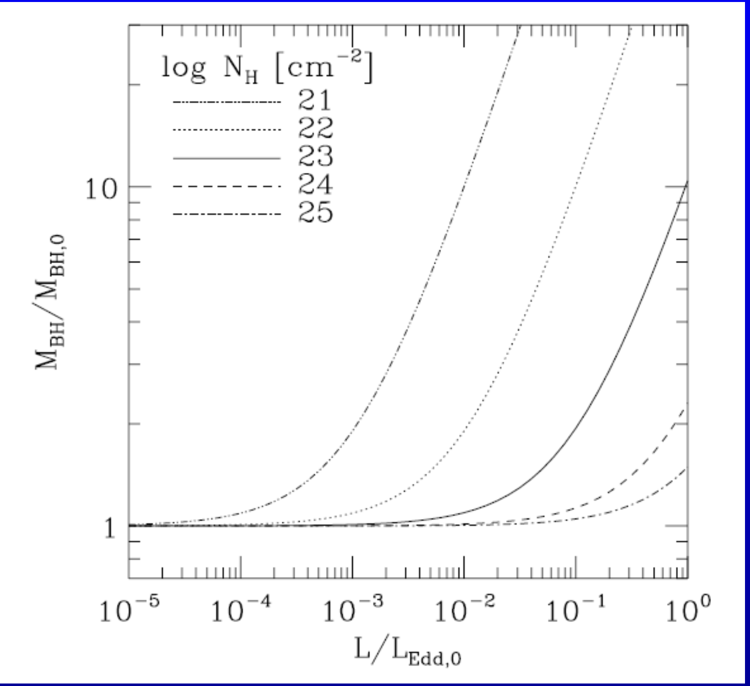
Results are in good agreement with results from CCF and formal errors are somewhat smaller.



$R_{\mathrm{BLR}} \propto L^{\alpha}$
log R_{BLR} Hβ (light days)
log L_{opt} (ergs s^{-1})
3
2
1
0
41
42
43
44
45
46
$\alpha = 0.556 \pm 0.013$
$\sigma_{\mathrm{rms}} = 0.196$
$\alpha = 0.558 \pm 0.013$
$\sigma_{\mathrm{rms}} = 0.206$
$\alpha = 0.580 \pm 0.011$
$\sigma_{\mathrm{rms}} = 0.207$
$\alpha = 0.579 \pm 0.010$
$\sigma_{\mathrm{rms}} = 0.229$
$\alpha = 0.513 \pm 0.017$
$\sigma_{\mathrm{rms}} = 0.203$

Possible Importance of Radiation Pressure

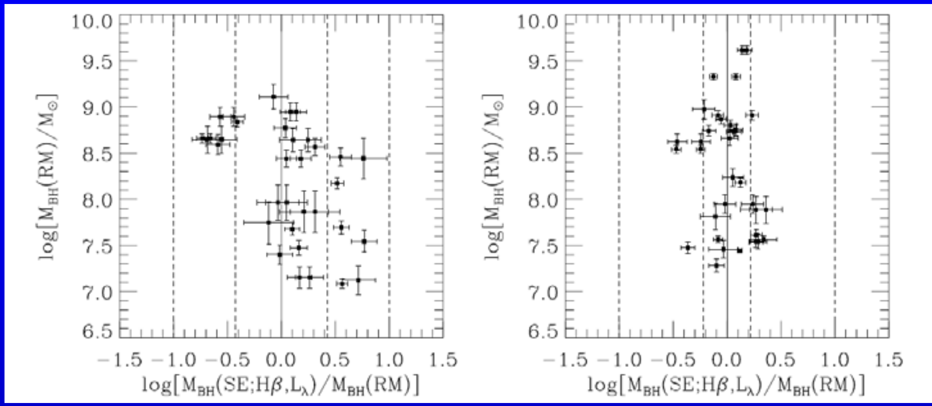
- Marconi et al. suggest that BH masses are underestimated because of failure to account for radiation pressure.
  - Important if BLR clouds have column densities $\leq 10^{23}$ cm^{-2}.



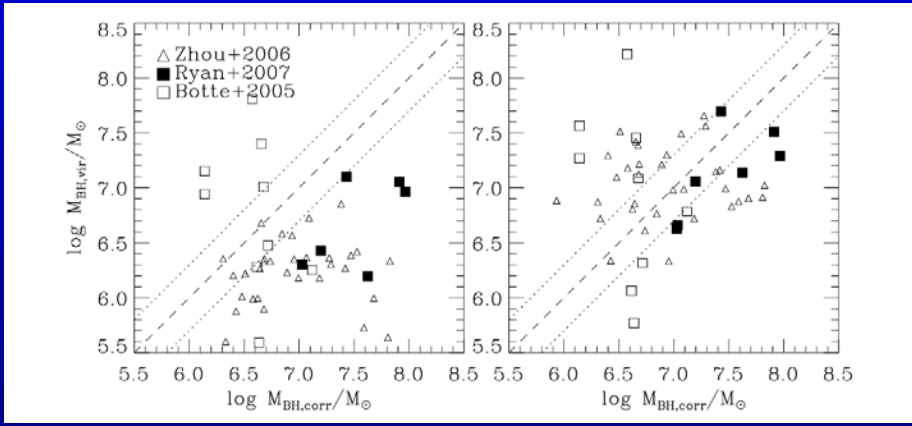
Marconi et al. (2008)

Possible Importance of Radiation Pressure

- Differences between RM and R-L masses decreases with radiation correction.



- NLS1s lie closer to the M_{BH}–σ_* relationship



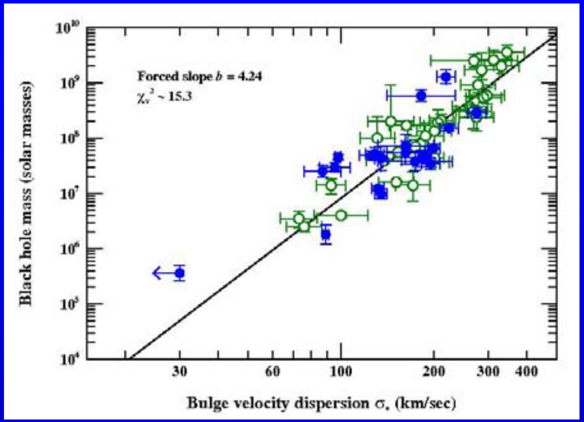
No correction With correction

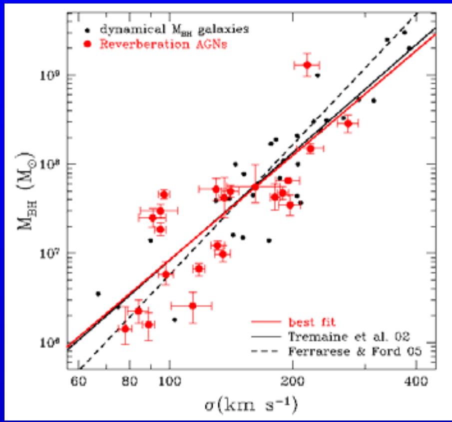
Marconi et al. (2008)

Reiteration: Evidence That Reverberation-Based Masses Are Reliable

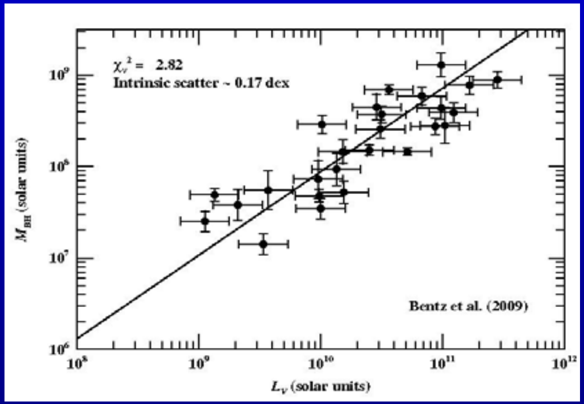
1. Direct comparisons

2. $M_{BH} - \sigma_*$ relationship





3. $M_{BH} - L_{bulge}$ relationship



30 Years of NGC 5548

Hβ & Continuum Variability

1972–2002

Sergei Sergeev (CrAO)

Richard Pogge (OSU)

Bradley Peterson (OSU)

T · H · E OHIO STATE UNIVERSITY