Supermassive Black Holes and Their Relationships with Their Host Galaxies

Bradley M. Peterson
The Ohio State University

Brera Lectures

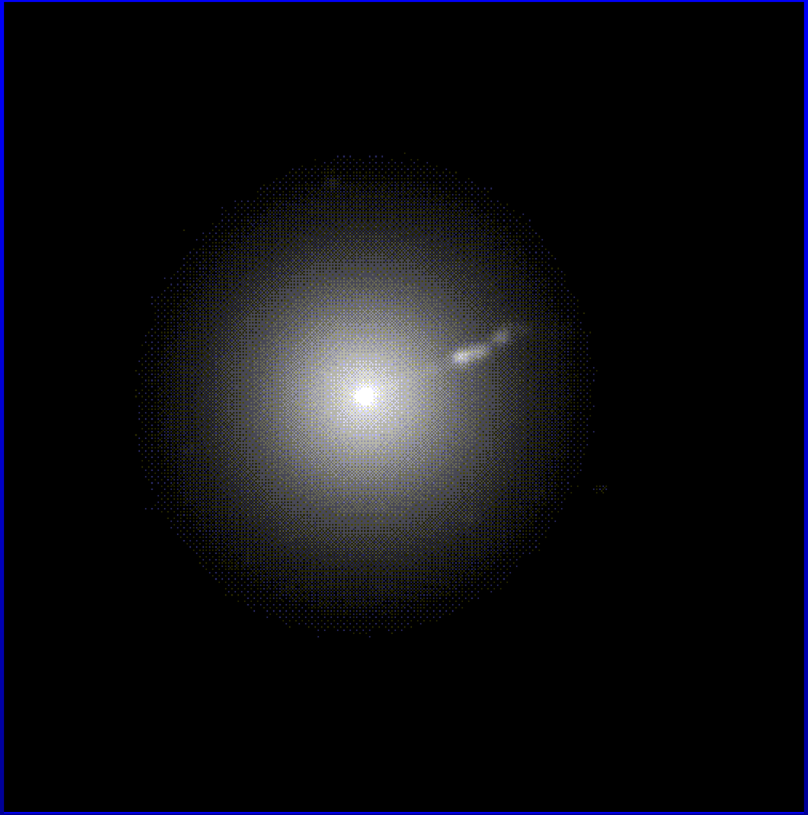
April 2011

Topics to be Covered

- *Lecture 1:* AGN properties and taxonomy, fundamental physics of AGNs, AGN structure, AGN luminosity function and its evolution
- *Lecture 2:* The broad-line region, emission-line variability, reverberation mapping principles, practice, and results, AGN outflows and disk-wind models, the radius–luminosity relationship
- *Lecture 3:* Role of black holes, direct/indirect measurement of AGN black hole masses, relationships between BH mass and AGN/host properties, limiting uncertainties and systematics

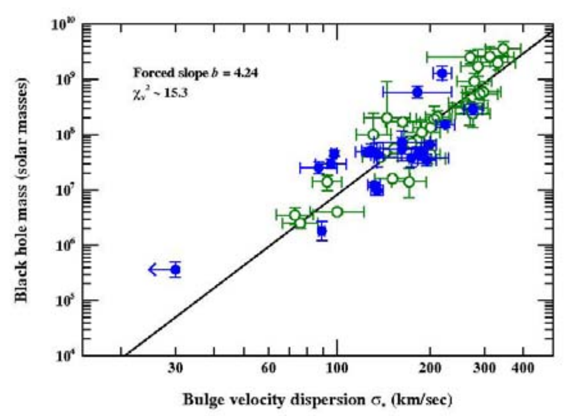
Supermassive Black Holes Are Common

- 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.

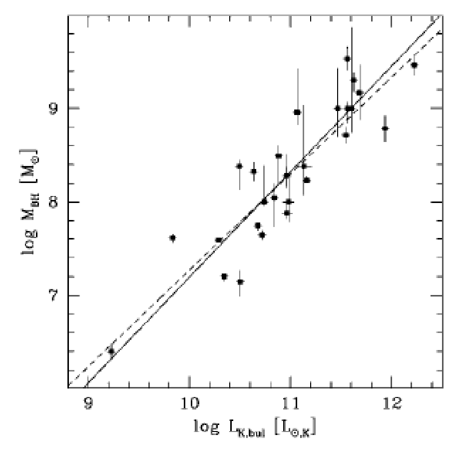


M 87, a giant elliptical
SMBH > $3\times10^9\ M_\odot$

Relationship Between Black Hole Mass and Host Galaxy Properties



$M_{\rm BH} - \sigma_*$ relationship



$M_{\rm BH} - L_{\rm bulge}$ relationship

Marconi & Hunt 2004

- Remarkable since BH constitutes 0.5% of the mass of the bulge.
- Indicates a close (evolutionary?) relationship between BH growth/bulge formation?
  - Do these evolve over time?
- Do supermassive black holes affect their host galaxies?

Emerging Paradigm: Feeding and Feedback

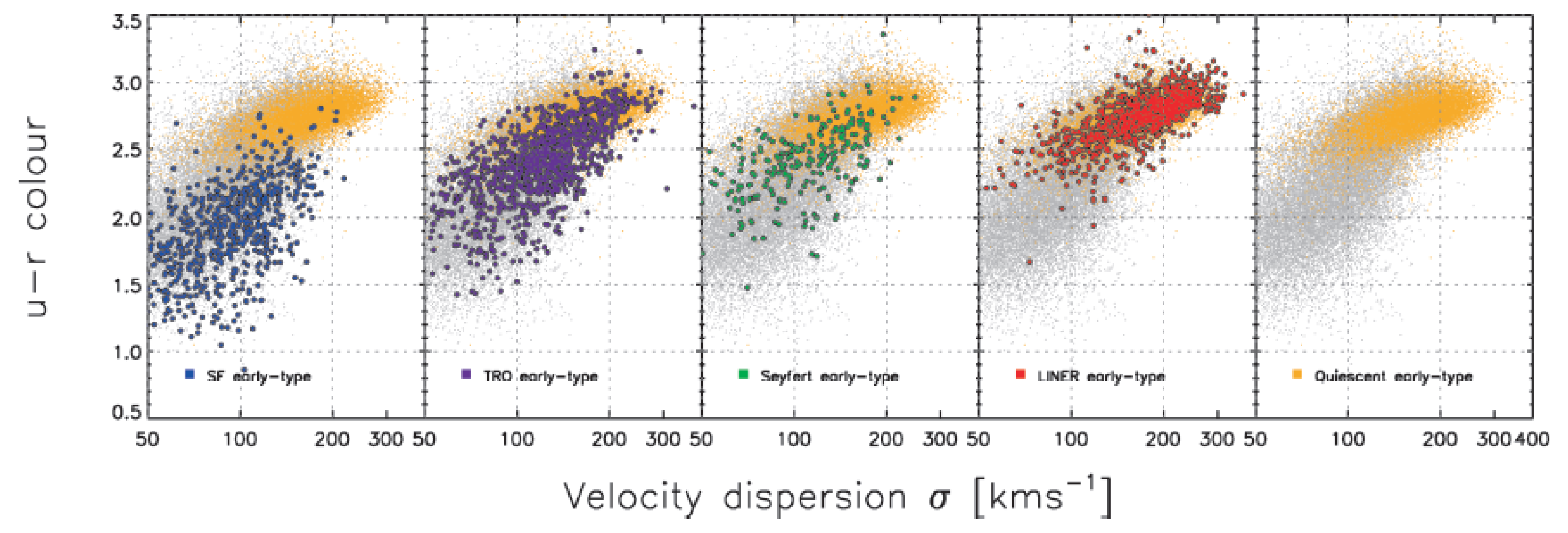
- Supermassive black holes are “active” if there is a large reservoir of gas to “feed” them.
  - Quasars were more common in the past because less gas was locked up in stars; galaxies were gas rich.
- Once a quasar reaches a high-enough luminosity, energetic “feedback” (radiation, winds, jets) from quasars (and massive stars?) heats or removes the ISM, shutting down star formation.
  - There is thus a close correlation between black hole mass and galaxy mass.

Role of Quasars in Galaxy Formation

(or why galaxy formation theorists suddenly like quasars…)

- Models of galaxy formation predict that massive galaxies should still have large reservoirs of gas and active star formation.
- Feedback from accretion onto supermassive black holes might provide the energy necessary to regulate cooling and subsequent star formation.

Does This Represent an Evolutionary Sequence?



Age →

Mass →

Schawinski et al. 2007

Orange dots: Quiescent early-type galaxies
Gray dots: Non-early type galaxies

Evolution of the M_{BH}–σ_* and M_{BH}–L_{bulge} Relationships

- Some claims for evolution of the M_{BH}–σ_* M_{BH}–L_{bulge} relationships, other claims for no evolution, or even no causal relation.
- To test this, we must use (indirect) scaling methods for strong UV emission lines for luminous and distant quasars.
  - One direct black hole mass measurement at $z = 2.17$ (Kaspi et al. 2007). No others at $z > 0.3$.

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 ⇒ 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)

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

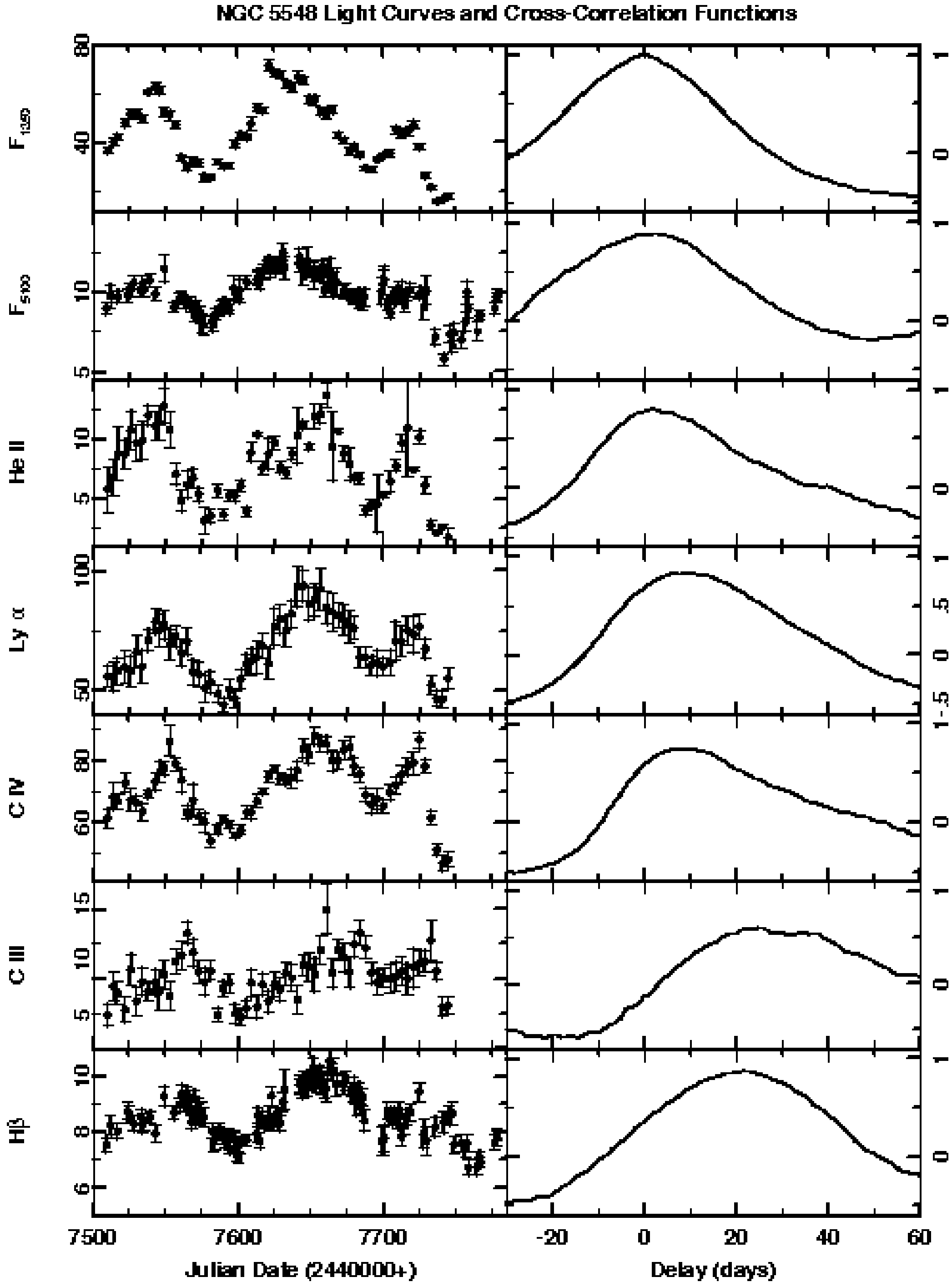
Direct vs. Indirect Methods

- *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.
  - $M_{\rm BH}$–σ_* and $M_{\rm BH}$–$L_{\rm bulge}$ relationships, fundamental plane, AGN scaling relationships ($R_{\rm BLR}$–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.”

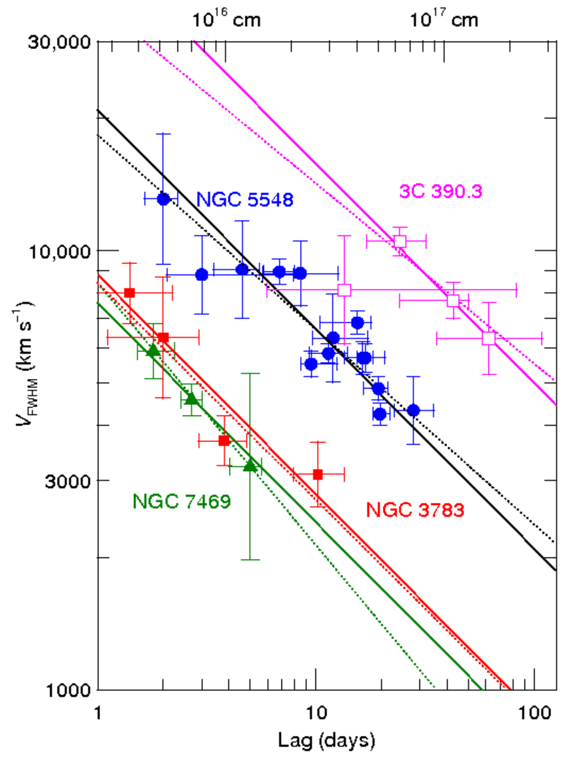
Reverberation Mapping Results


NGC 5548 Light Curves and Cross-Correlation Functions

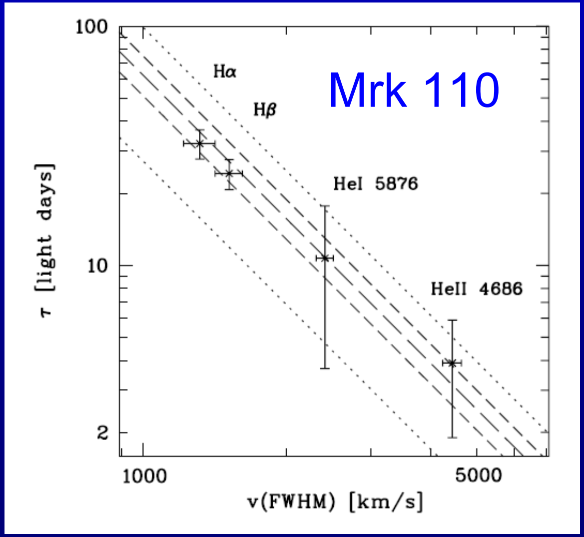
- Reverberation lags have been measured for ~45 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification
  - Highest ionization lines are also broadest!

A Virialized BLR

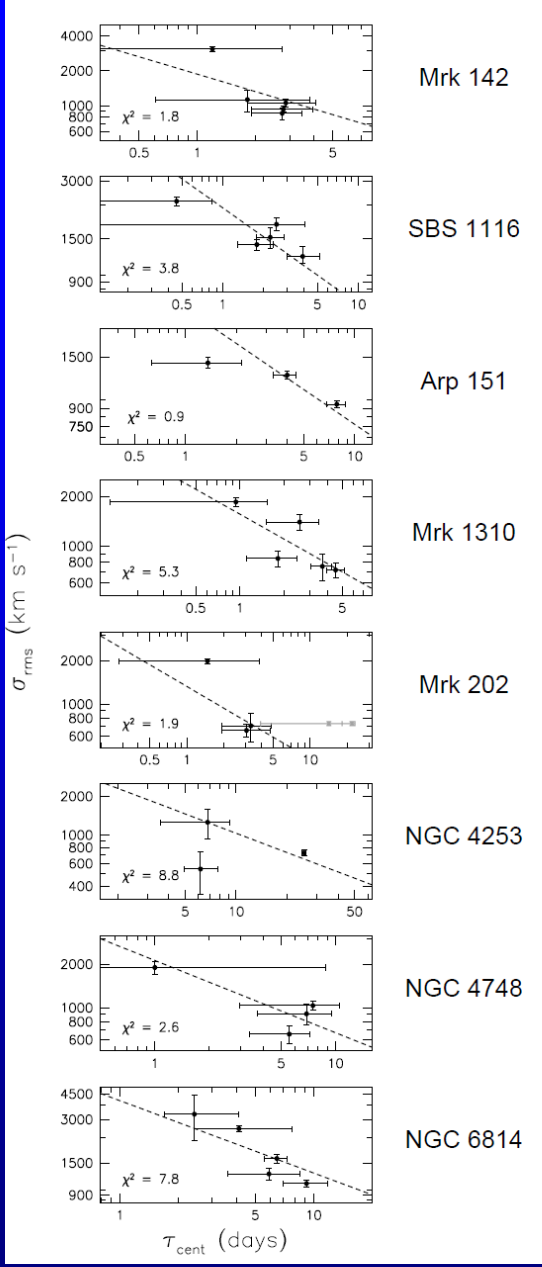
- $\Delta V \propto R^{-1/2}$ for every AGN in which it is testable.
- Suggests that gravity is the principal dynamical force in the BLR.



Onken & Peterson



Kollatschny 2003



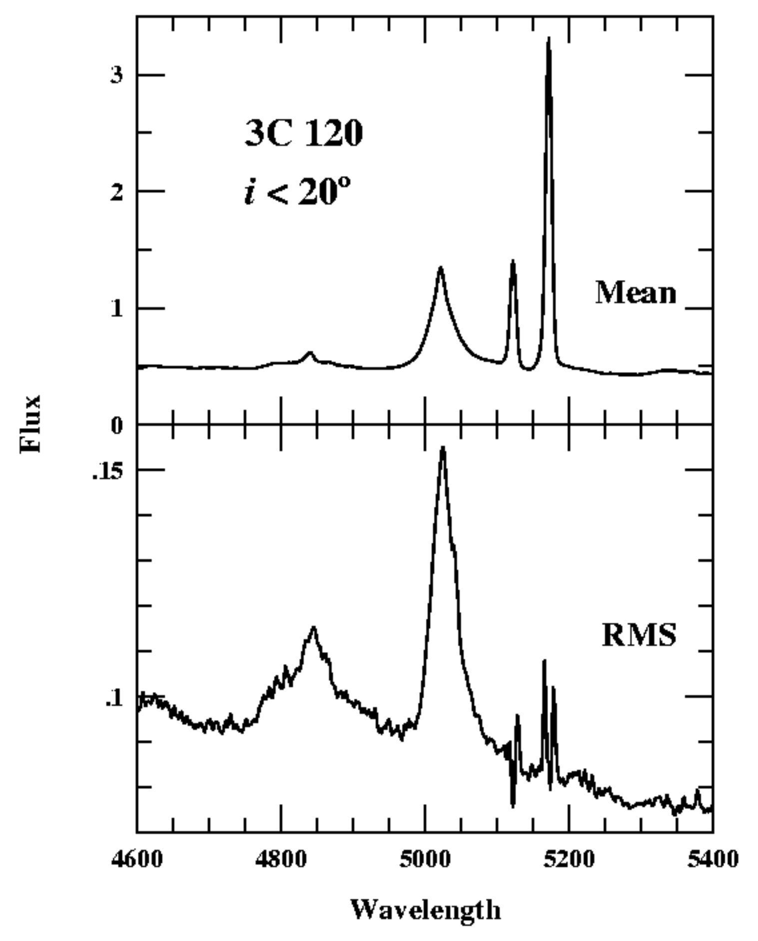
Bentz et al. 2009

Reverberation-Based Masses

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

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

- 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.

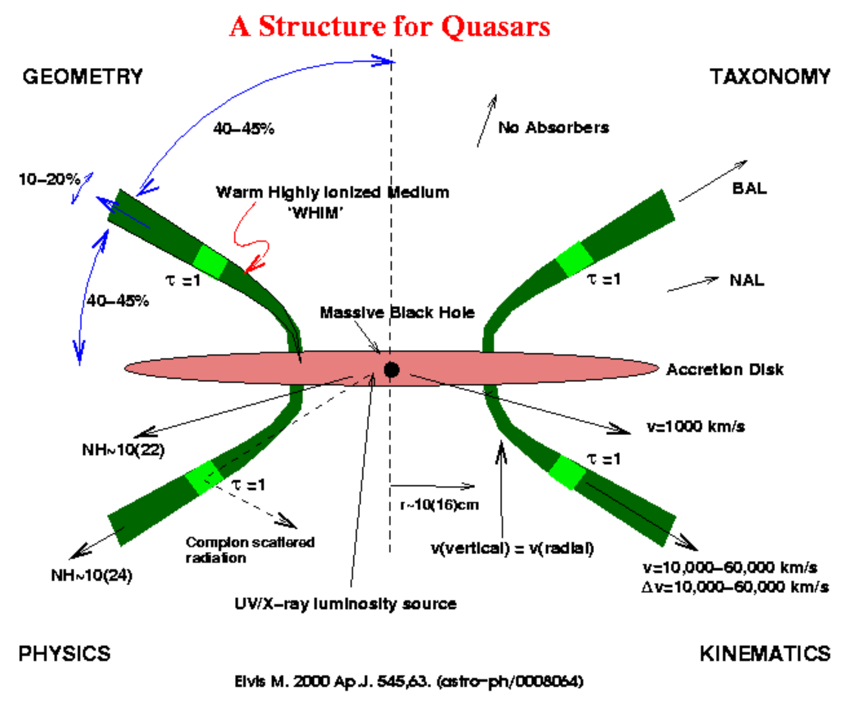


Plausible BLR Geometry

- 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)



Elvis M. 2000 Ap.J. 545,63. (astro-ph/0008064)

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

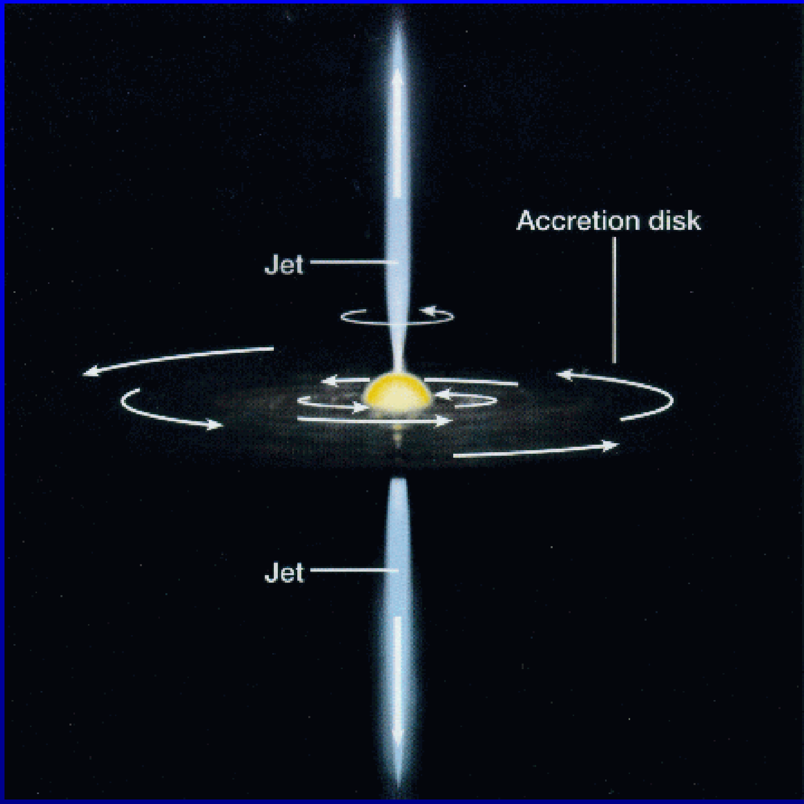
Evidence Inclination Matters

- 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
    - $\alpha_{radio} > 0.5$: Mean FWHM = 6464 km s^{-1}
    - $\alpha_{radio} < 0.5$: Mean FWHM = 4990 km s^{-1}
    - Width distribution for radio-quiets like flat spectrum sources (i.e., closer to face-on)

    Jarvis & McLure 2006

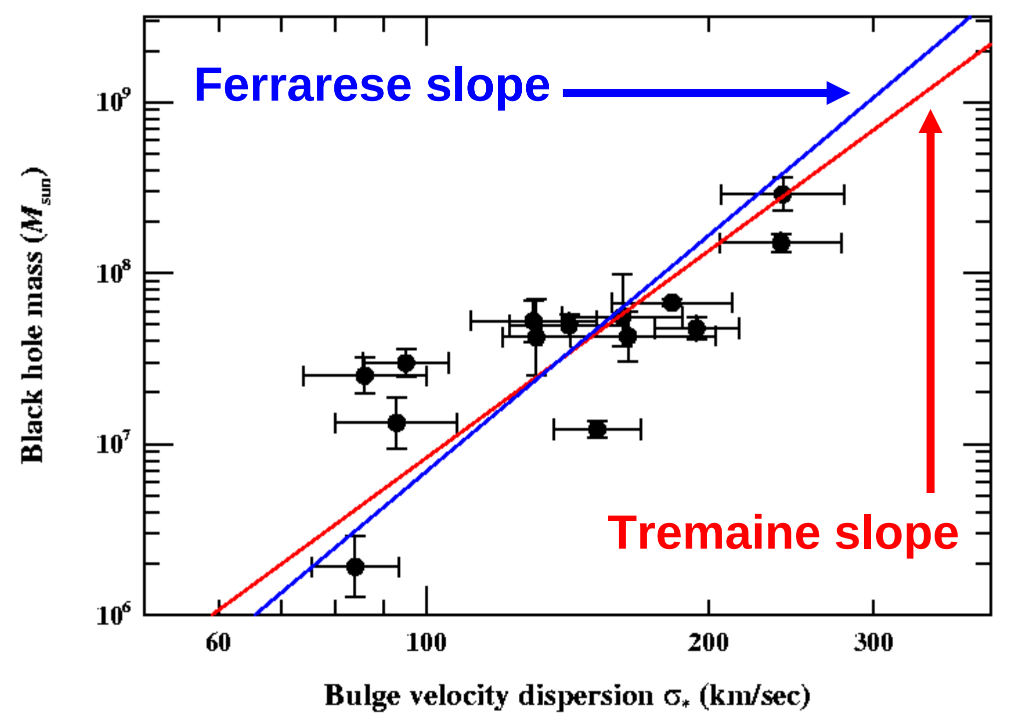


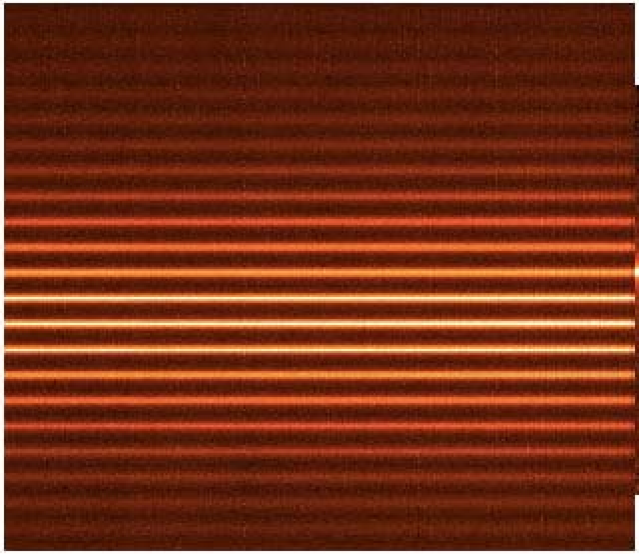
Calibration of the Reverberation Mass Scale Using $M_{\rm BH}$–σ_*

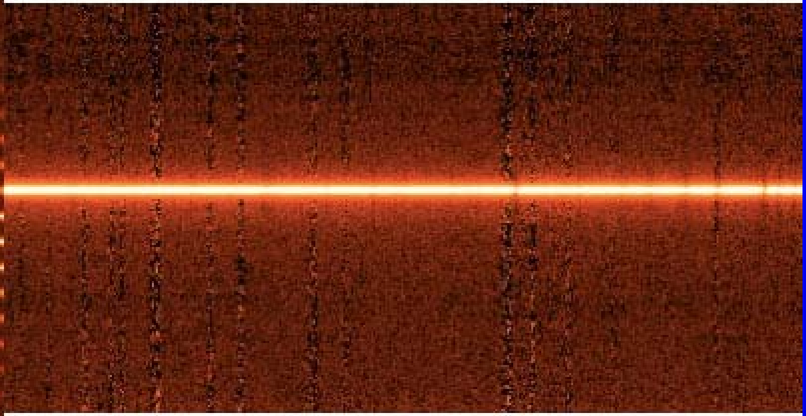
$$M = f\,(c\tau_{\rm cent}\sigma^2/G)$$

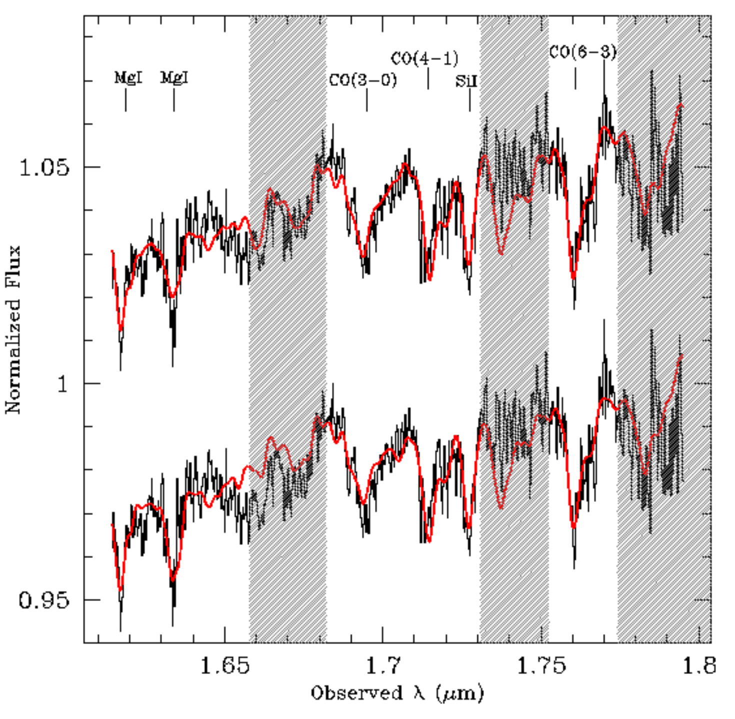
- Determine scale factor $\langle f\rangle$ that matches AGNs to the quiescent-galaxy $M_{\rm BH}$-σ_*. relationship
- First estimate: $\langle f\rangle = 5.5 \pm 1.8$

Onken et al. 2004

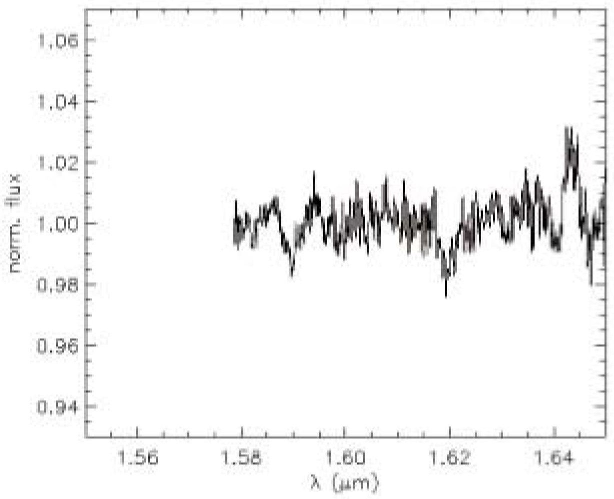








IFU+AO



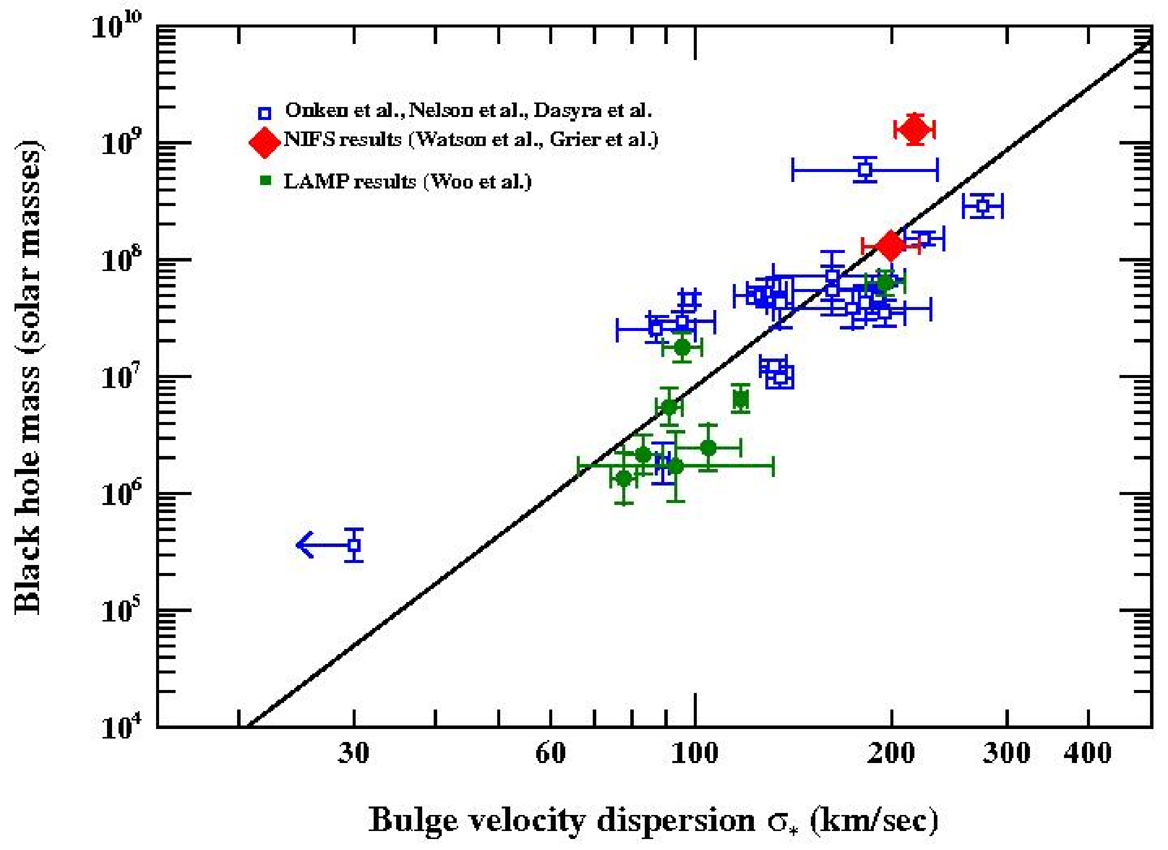
Long-slit spectrum

Calibration of the Reverberation Mass Scale Using $M_{\rm BH}$–σ_*

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

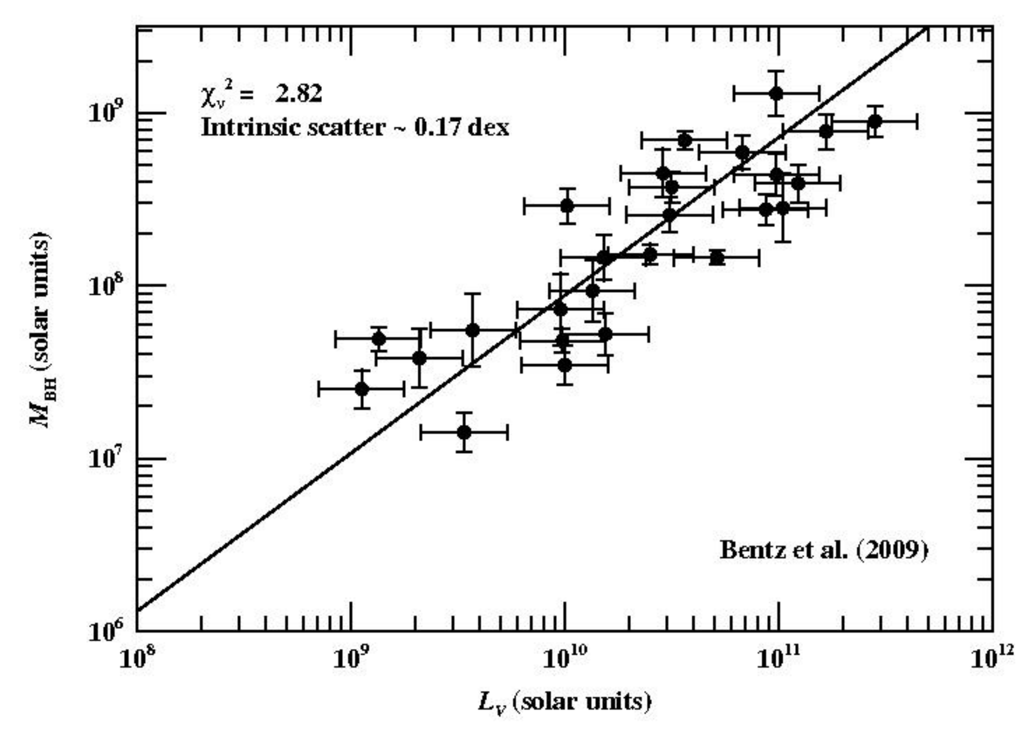
- Determine scale factor ⟨*f*⟩ that matches AGNs to the quiescent-galaxy $M_{\rm BH}$-σ_*. relationship
- Recent estimate: ⟨*f*⟩ = 5.25 ± 1.21

Woo et al. 2010



Intrinsic scatter: Δlog $M_{\rm BH}$ ~ 0.40 dex (Peterson 2010)
~ 0.44 dex (Woo+2010)
~ 0.38 dex (Gültekin+2009)

The AGN M_{BH}–L_{bulge} Relationship

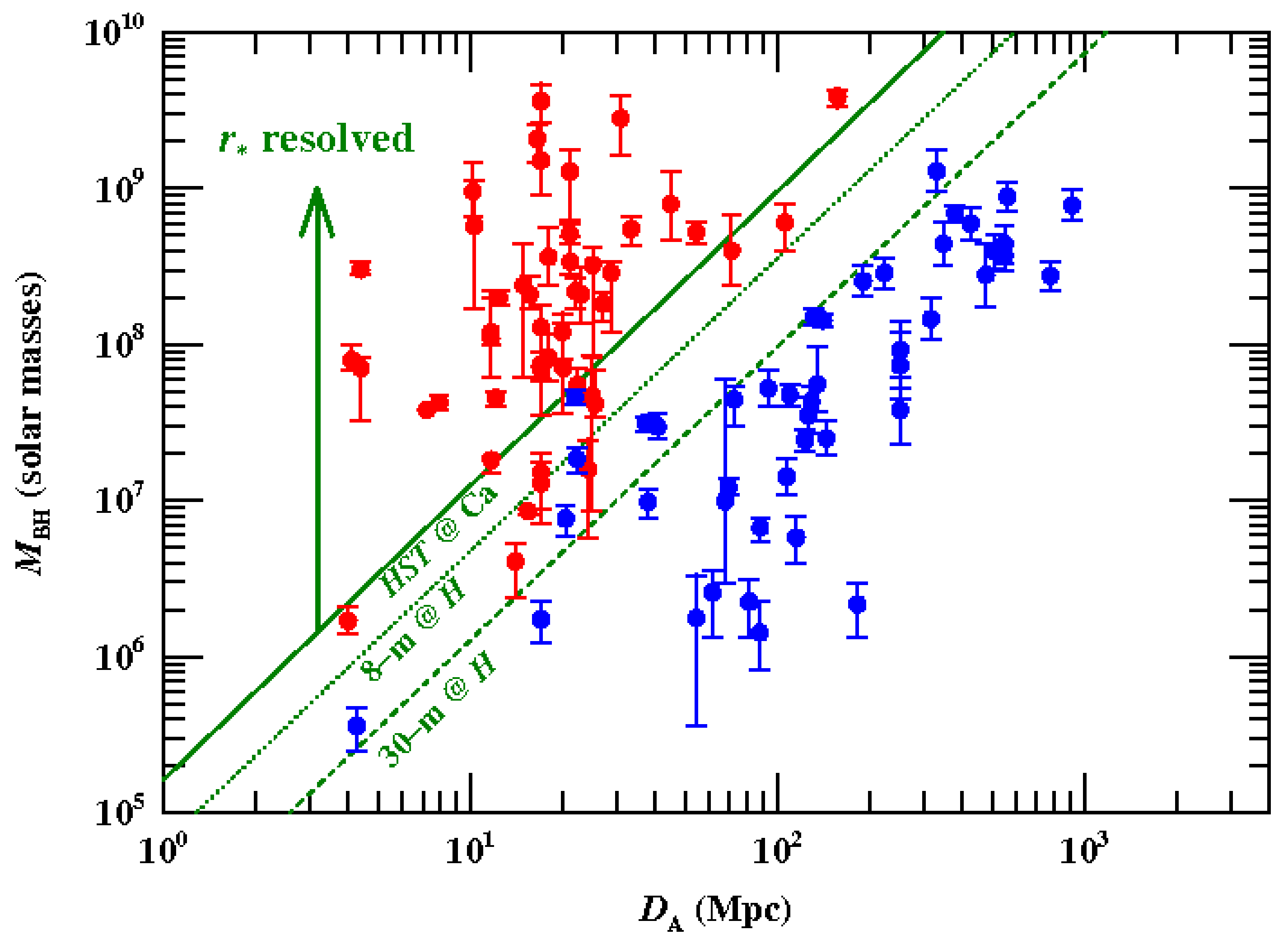


- Line shows best-fit to quiescent galaxies

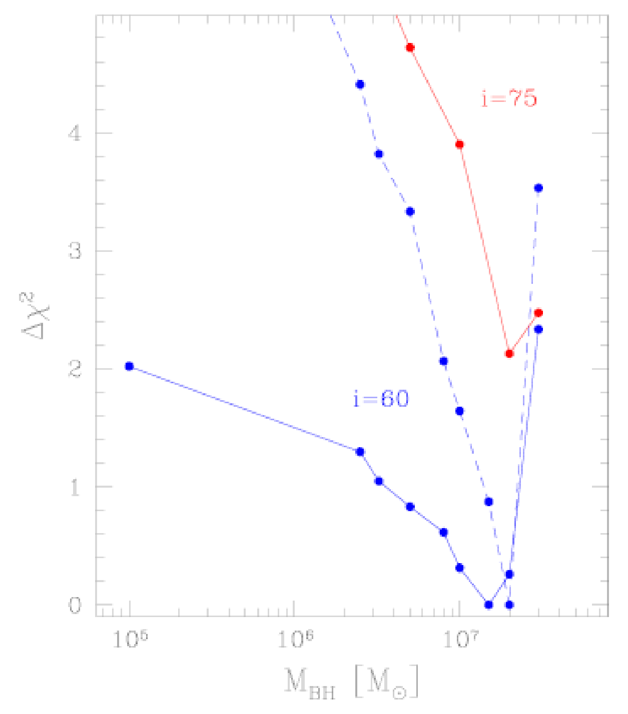
  Gültekin et al. 2009
- Maximum likelihood gives upper limit to intrinsic scatter $\Delta\log M_{\mathrm{BH}} \sim 0.17$ dex.
  - Smaller than quiescent galaxies ($\Delta\log M_{\mathrm{BH}} \sim 0.38$ dex).

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

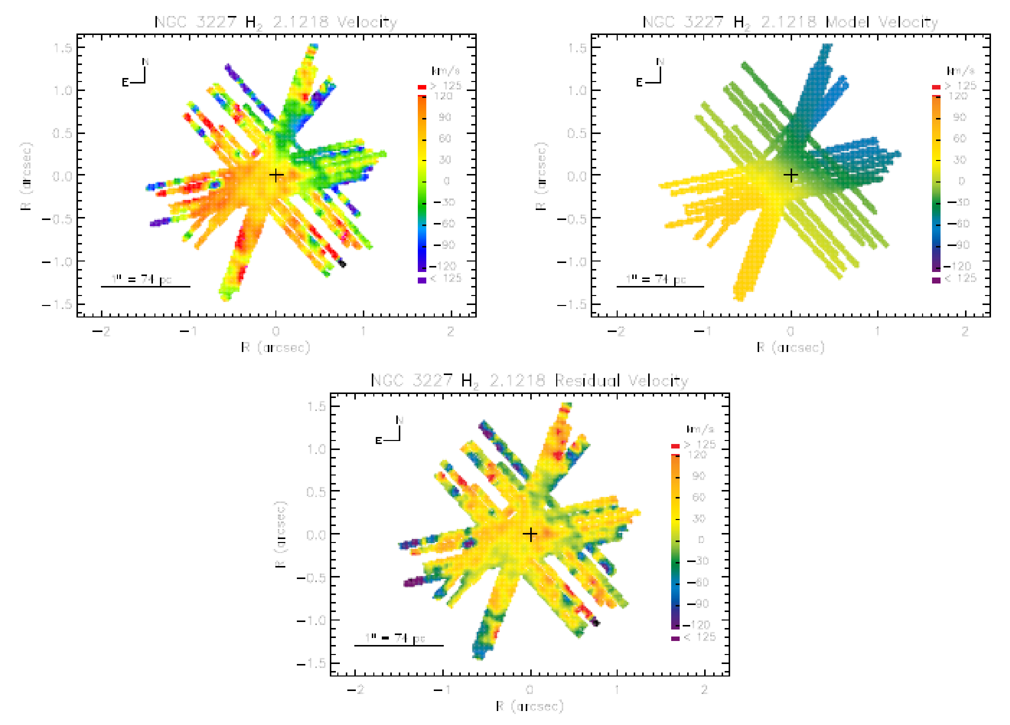
Quiescent galaxies RM AGNs



Direct Comparison: NGC 3227



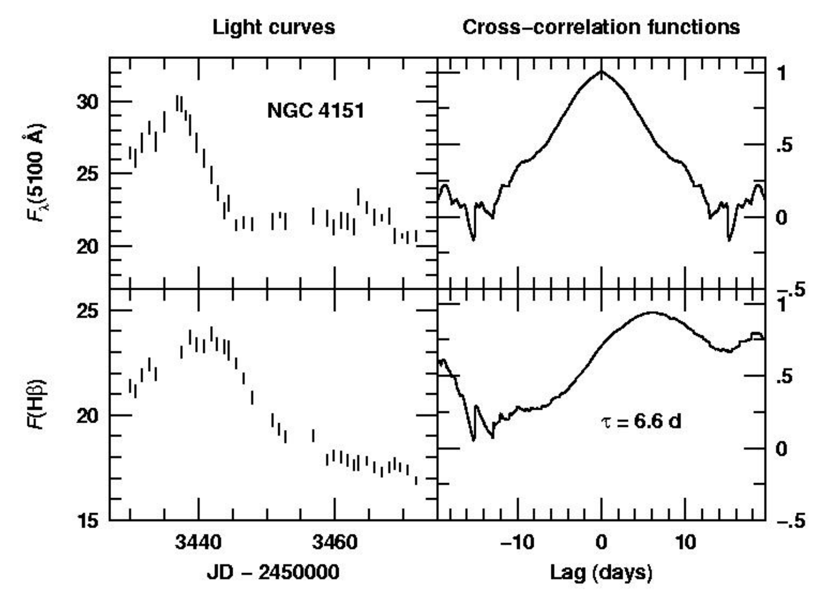
Davies et al. (2006)

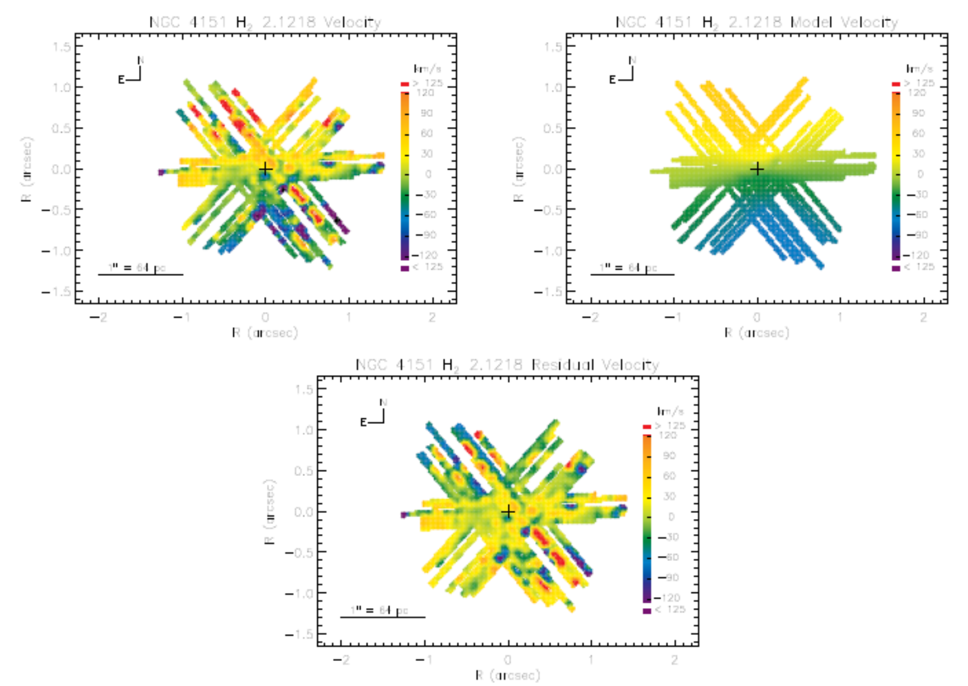


Hicks & Malkan (2008)

Stellar dynamics: $(7 - 20) \times 10^6\ M_\odot$ (Davies et al. 2006)
Reverberation: $7.63^{+1.62}_{-1.72} \times 10^6\ M_\odot$ (Denney et al. 2009)
Gas dynamics: $20^{+10}_{-4} \times 10^6\ M_\odot$ (Hicks & Malkan 2008)

Direct Comparison: NGC 4151





Bentz et al. (2006)

Hicks & Malkan (2008)

Stellar dynamics: $\leq 70 \times 10^6\,M_\odot$ (Onken et al. 2007)
Reverberation: $(46 \pm 5) \times 10^6\,M_\odot$ (Bentz et al. 2006)
Gas dynamics: $30^{+7.5}_{-22} \times 10^6\,M_\odot$ (Hicks & Malkan 2008)

Masses of Black Holes in AGNs

- Megamaser sources are rare.
  - NGC 4258 is (almost) unique.
- 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

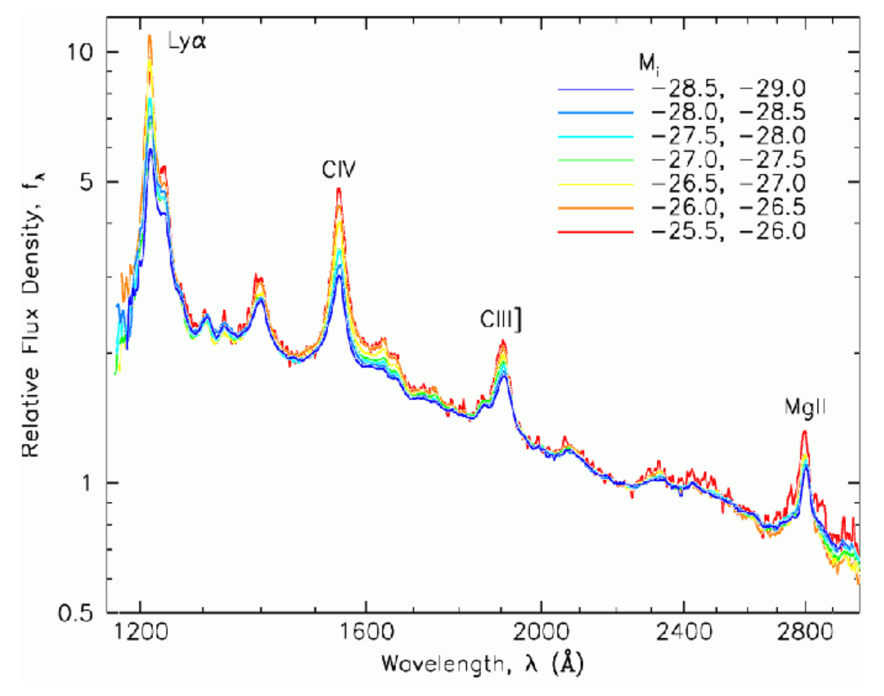
- To first order, AGN spectra look the same

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

$\Rightarrow$ Same ionization parameter U

$\Rightarrow$ Same density n_{H}

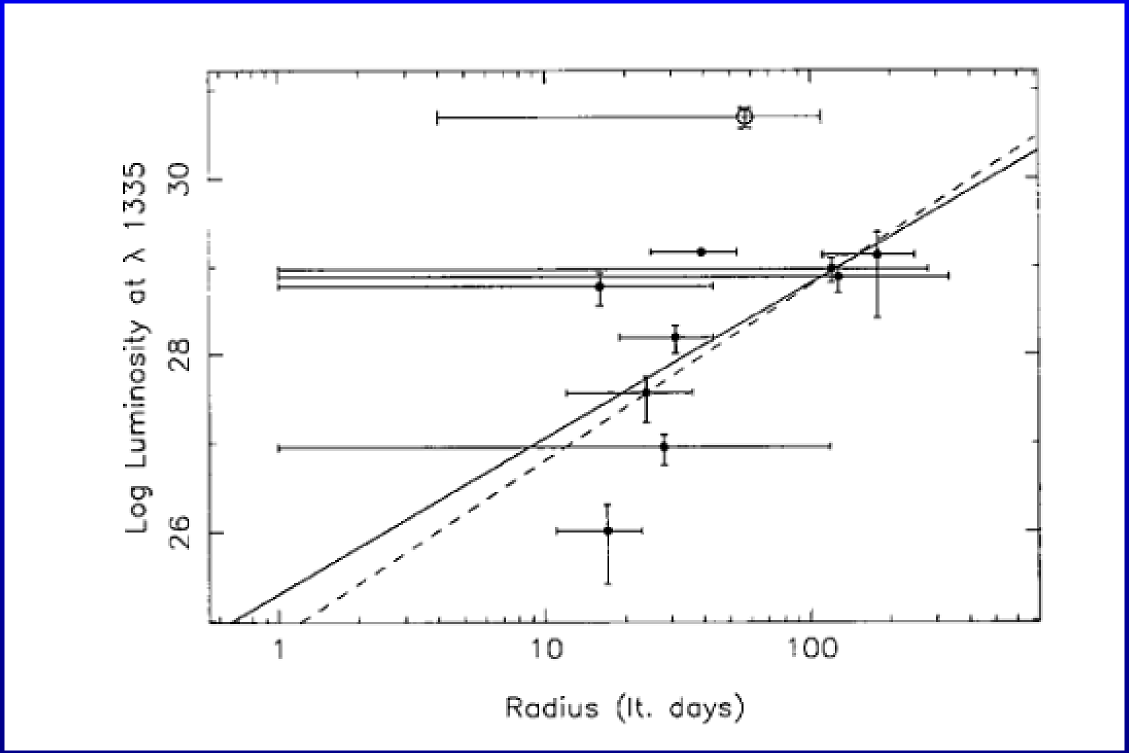
$$r \propto L^{1/2}$$



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

BLR Radius-Luminosity Relationship

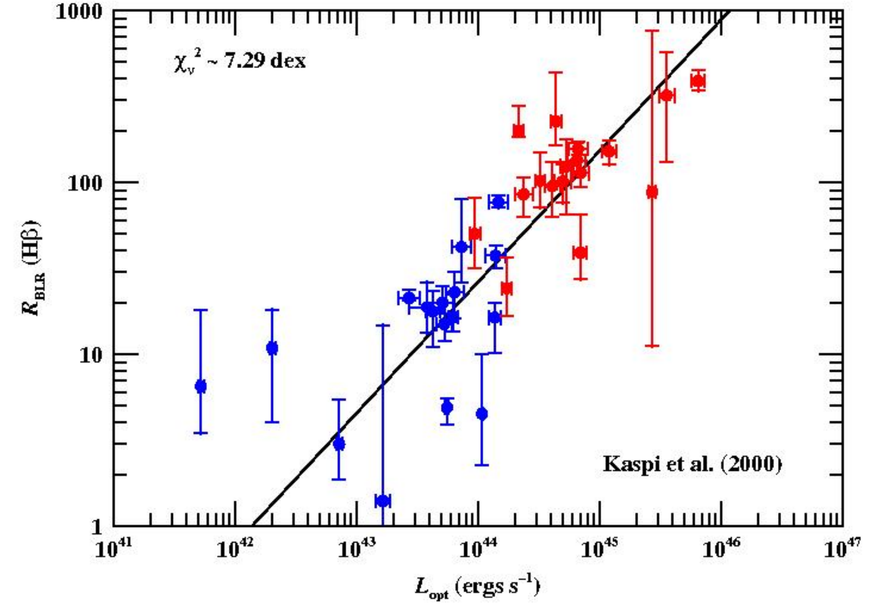
- $R \propto L^{1/2}$ relationship was anticipated long before it was well-measured.



Koratkar & Gaskell 1991

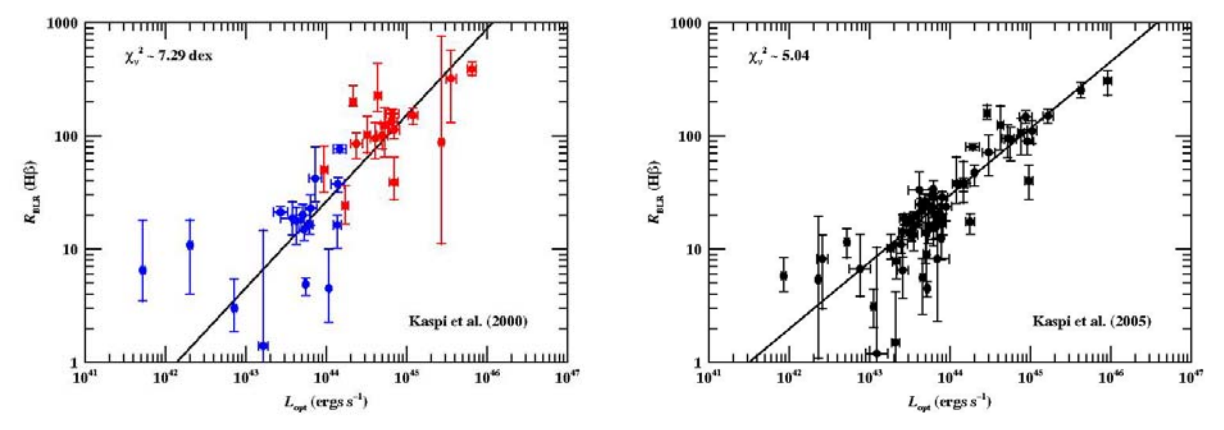
BLR Radius-Luminosity Relationship

- 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)
$\chi_\nu^2 \approx 5.04$
$R(\mathrm{H}\beta) \propto L^{0.59}$

Aperture Geometries for Reverberation-Mapped AGNs

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

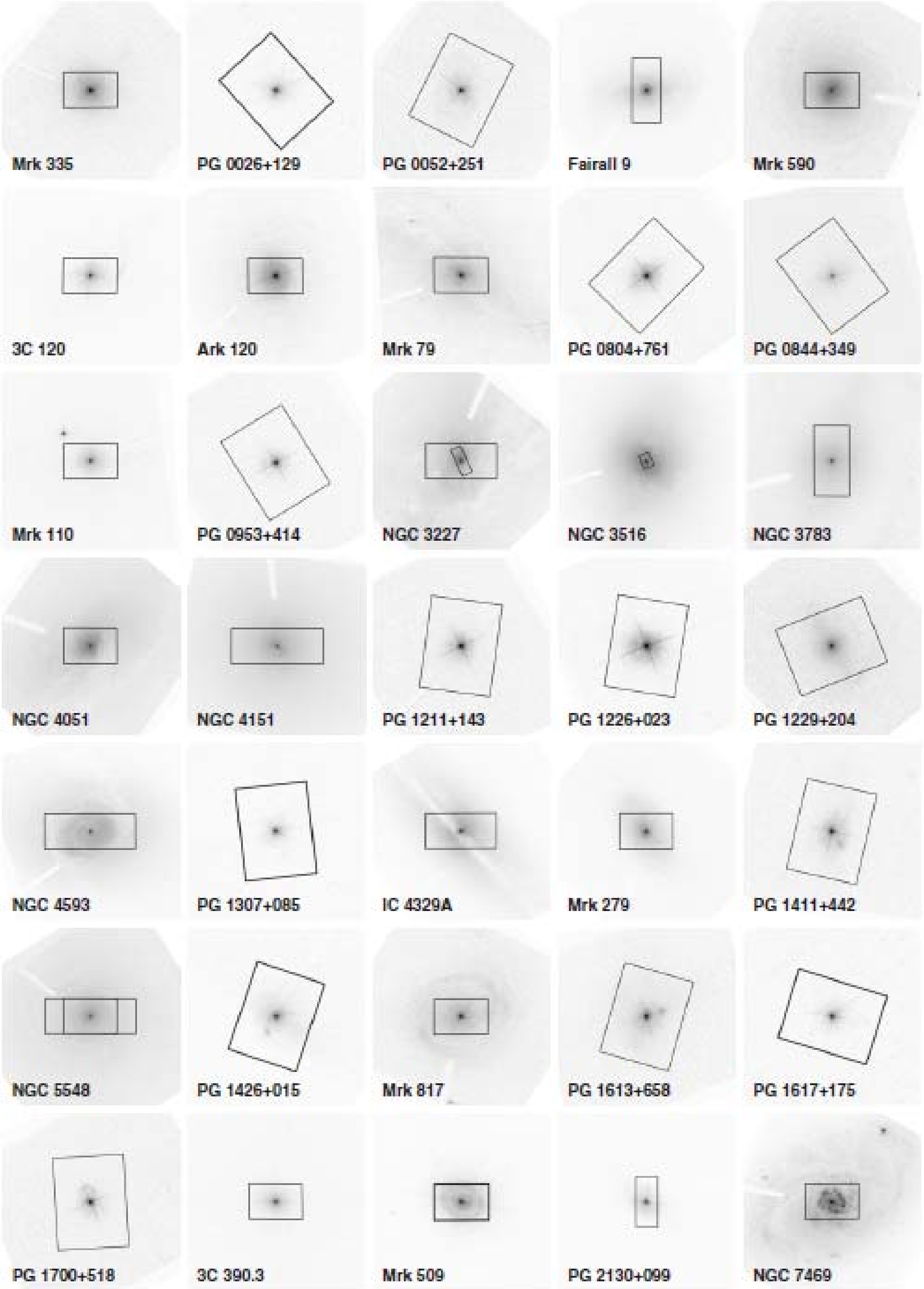
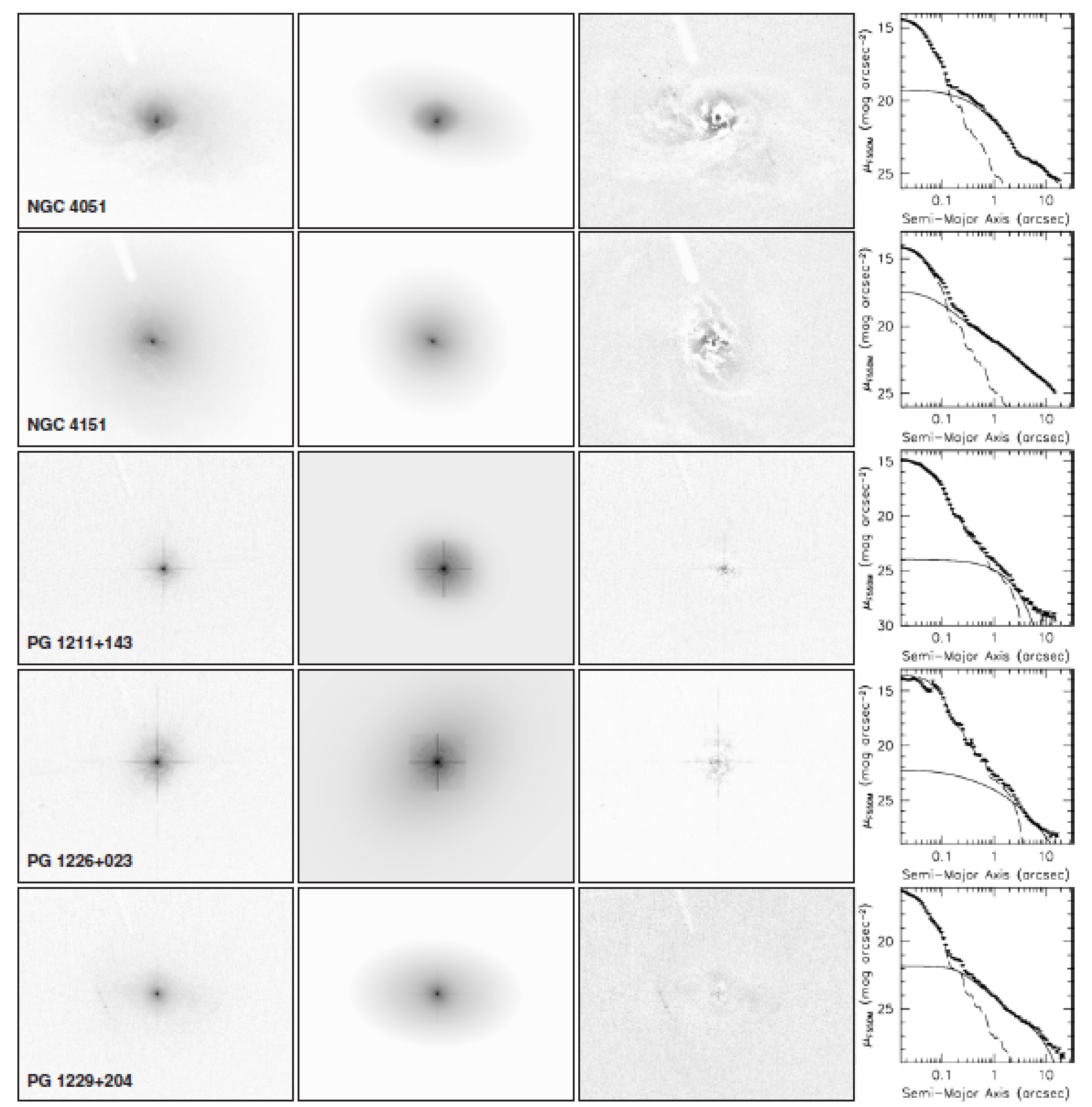
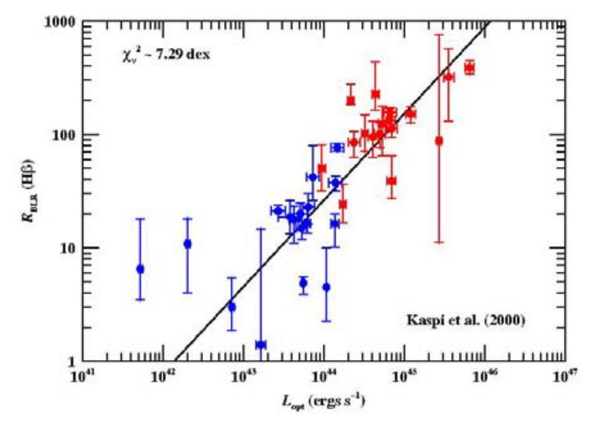


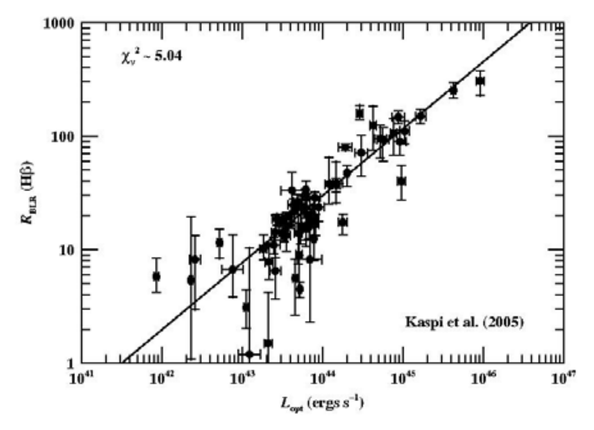
Image Model Residual Profile



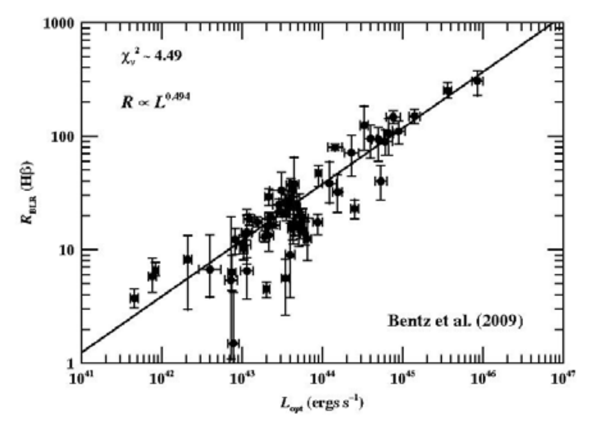
Progress in Determining the Radius-Luminosity Relationship



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



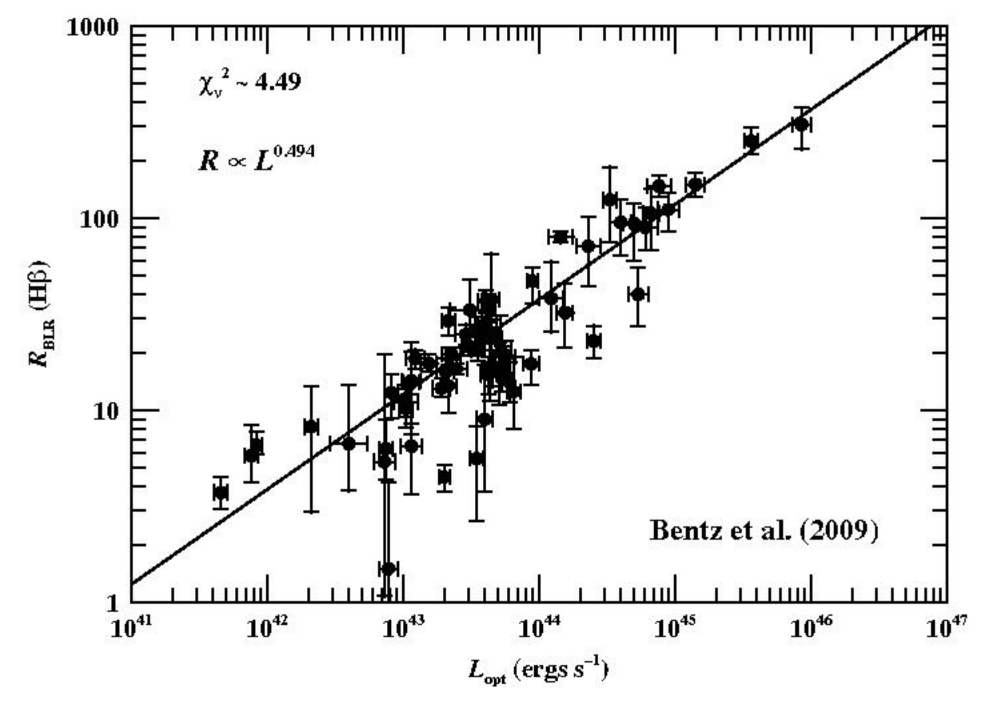
Expanded, reanalyzed
(Kaspi et al. 2005)
$\chi_\nu^2 \approx 5.04$
$R(\mathrm{H}\beta) \propto L^{0.59}$



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

BLR Radius-Luminosity Relationship

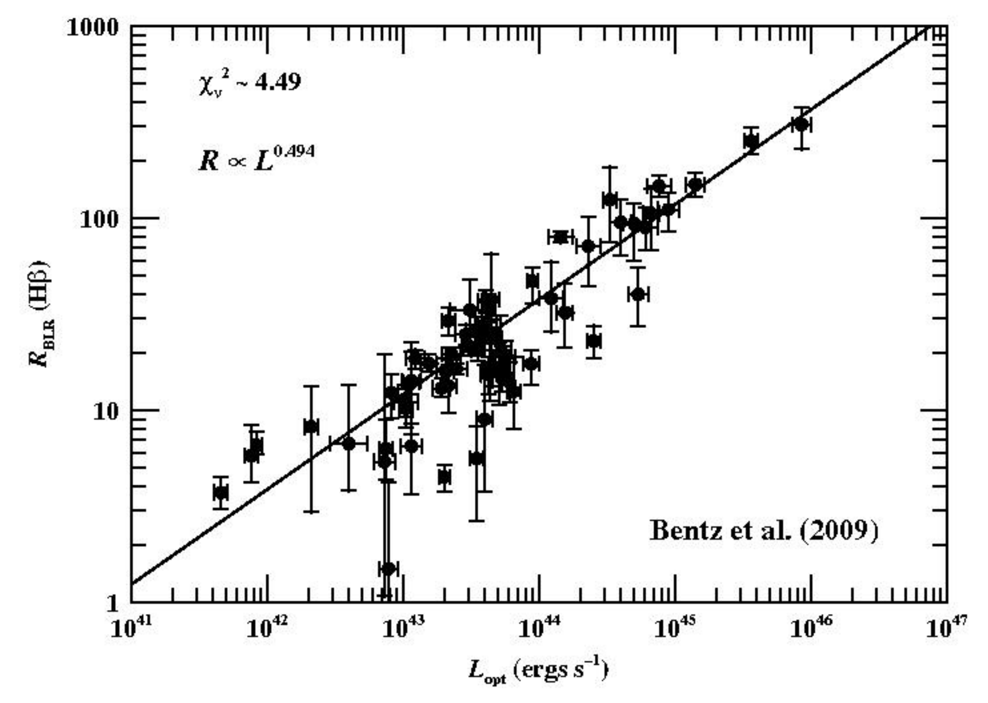
- Slope of the improved relationship is now consistent with $R \propto L^{1/2}$.
- We can use the *R-L* relationship to determine the BLR radius from luminosity, thus bypassing reverberation.



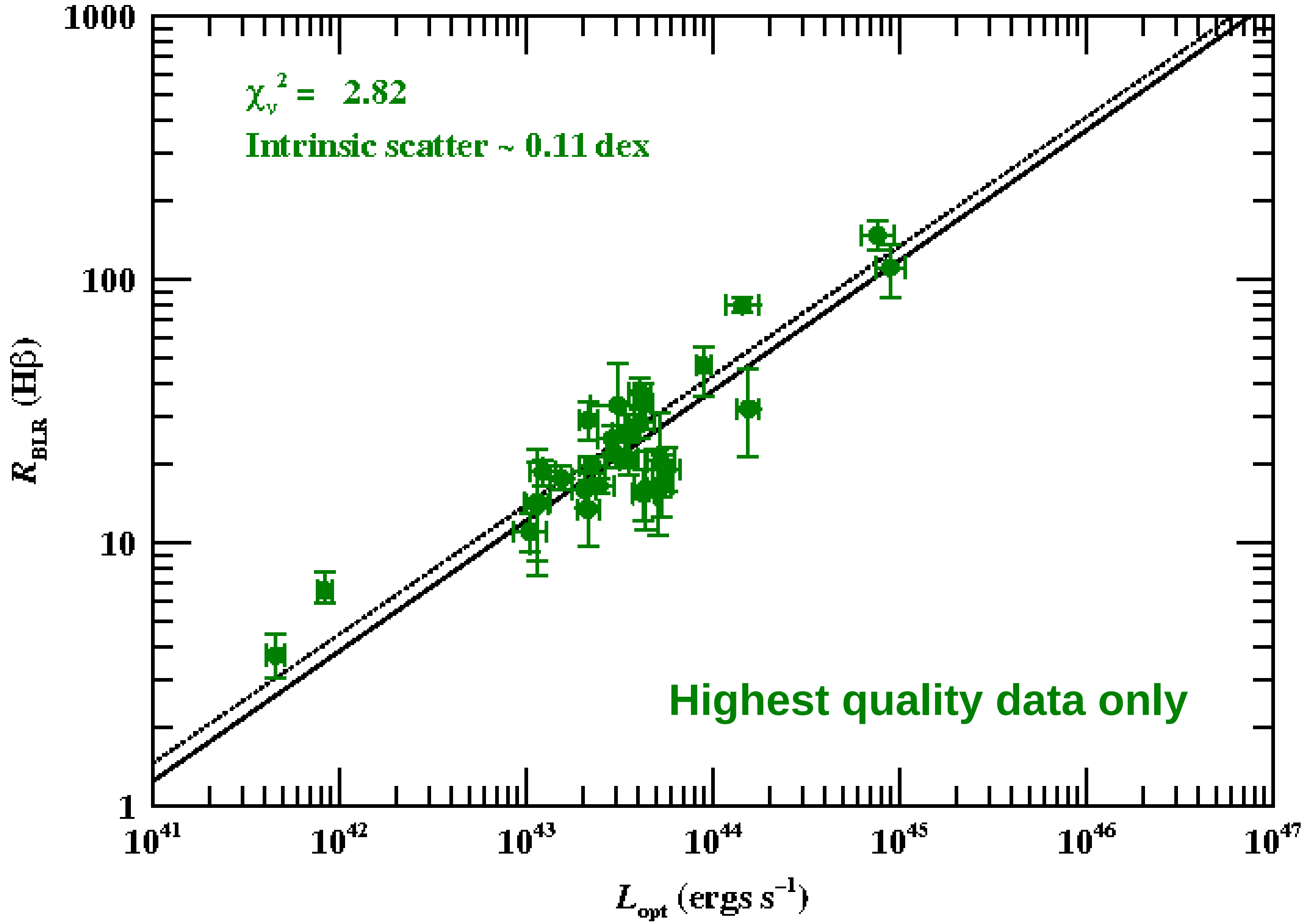
Bentz et al. 2009

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.



Bentz et al. 2009



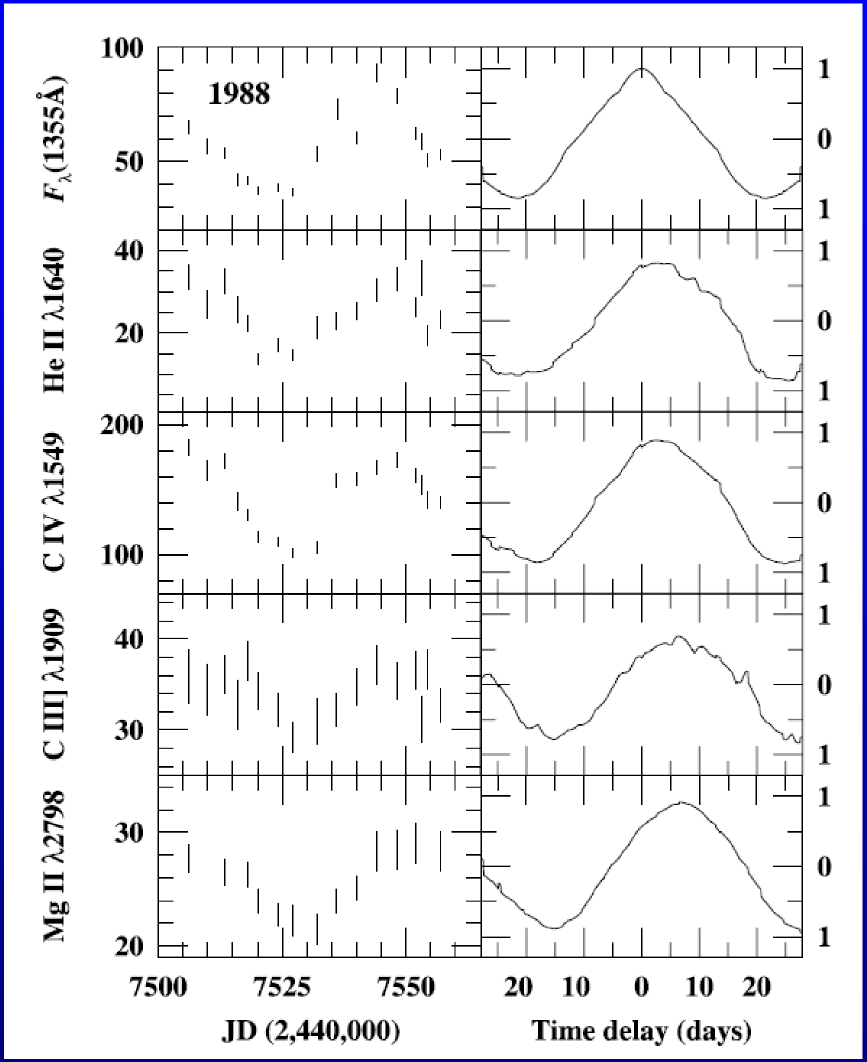
$\chi_\nu^2 = 2.82$
Intrinsic scatter ~ 0.11 dex
Highest quality data only
1000
100
10
1
10^{41}
10^{42}
10^{43}
10^{44}
10^{45}
10^{46}
10^{47}
R_{BLR} (Hβ)
L_{opt} (ergs s^{-1})

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.
- To go to higher redshift, we need to use rest-UV lines instead of Balmer lines.

R-L Relationship for Mg II λ2798

- Little reverberation data on Mg II λ2798
  - Existing lag data ambiguous, particularly those that are contemporaneous with Balmer lines.
  - Relies on assumption that Mg II arises co-spatially with Balmer lines.



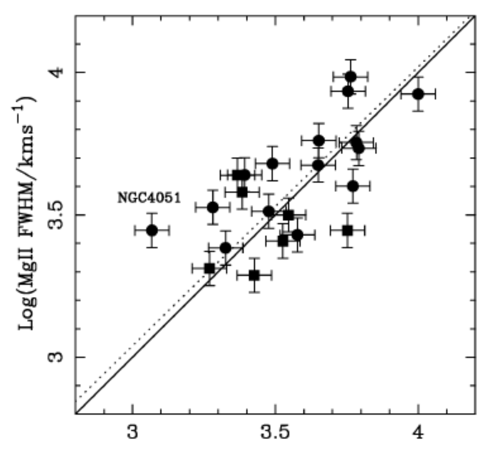
Metzroth, Onken, & Peterson (2006)

R-*L* Relationship for Mg II λ2798

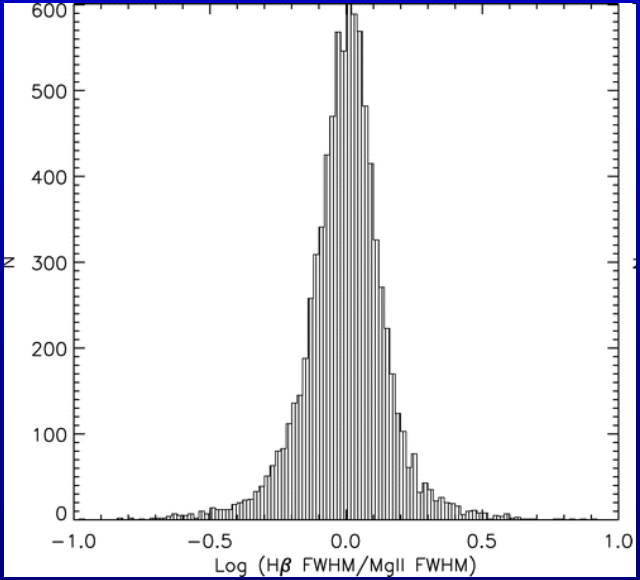
- From SDSS spectra, Shen et al. (2008) find

$$\log\left[\frac{\mathrm{FWHM}(\mathrm{H}\beta)}{\mathrm{FWHM}(\mathrm{Mg\ II})}\right] = 0.0062\ \mathrm{dex}$$

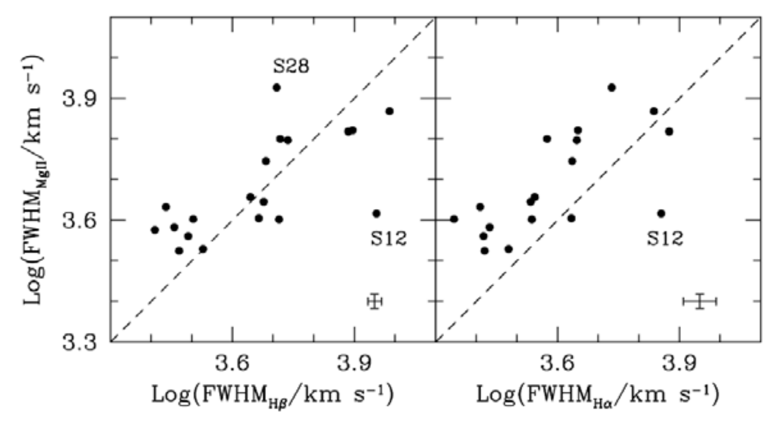
with scatter ~0.11 dex.



McLure & Jarvis (2002)



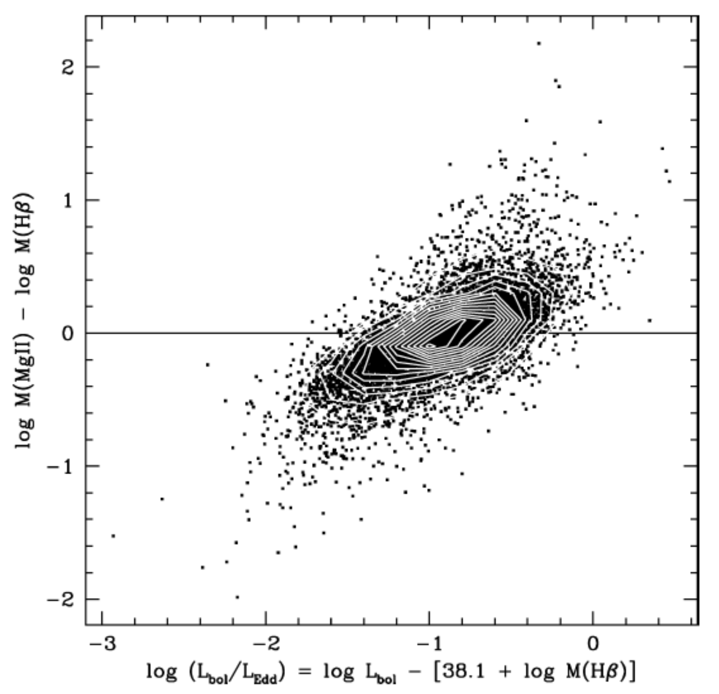
Shen et al. (2008)



McGill et al. (2008)

R-*L* Relationship for Mg II λ2798

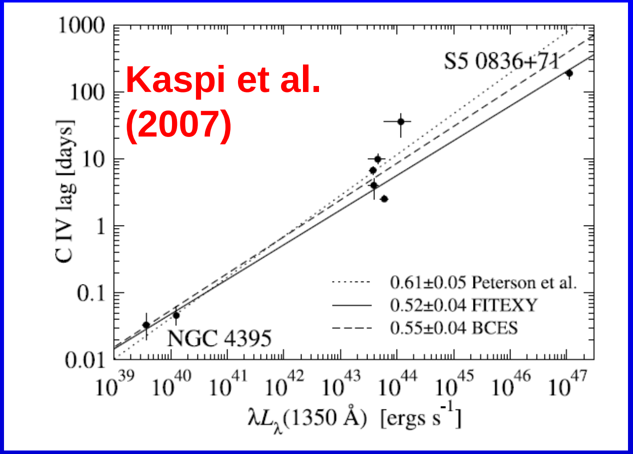
- Onken & Kollmeier find that the line width ratio has dependence on Eddington ratio and is correctable.

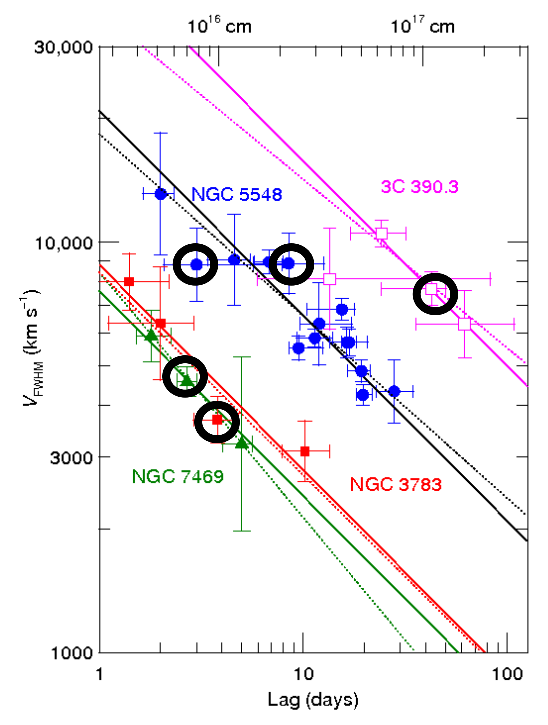


Onken & Kollmeier 2008

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.

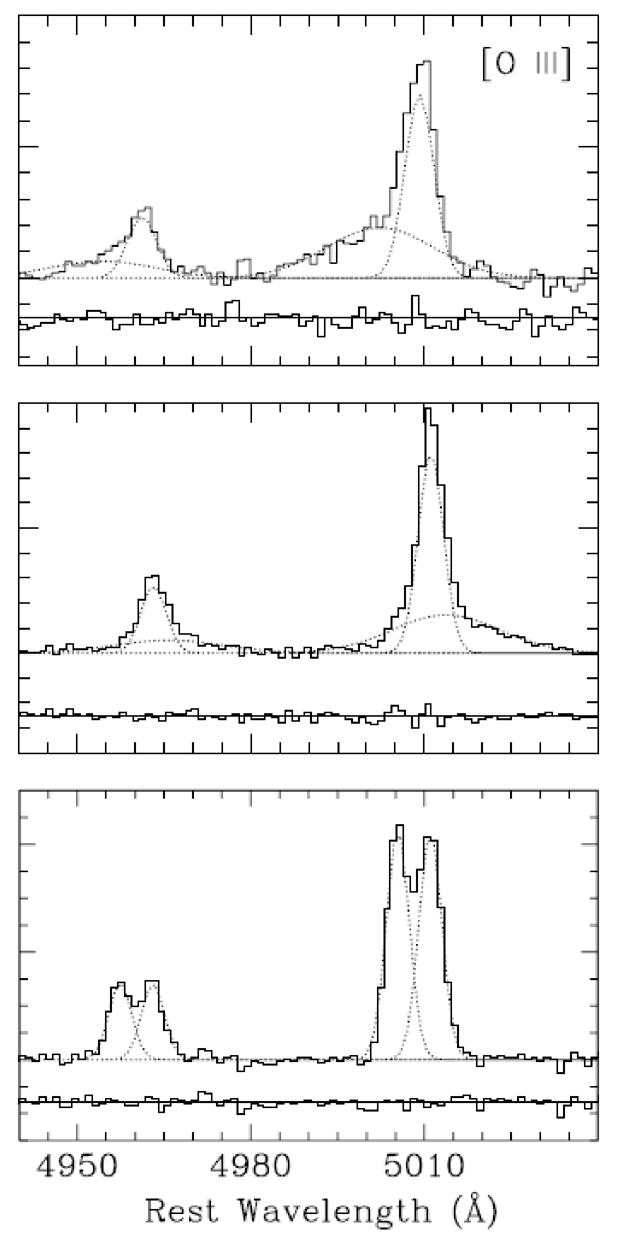

Kaspi et al. (2007)



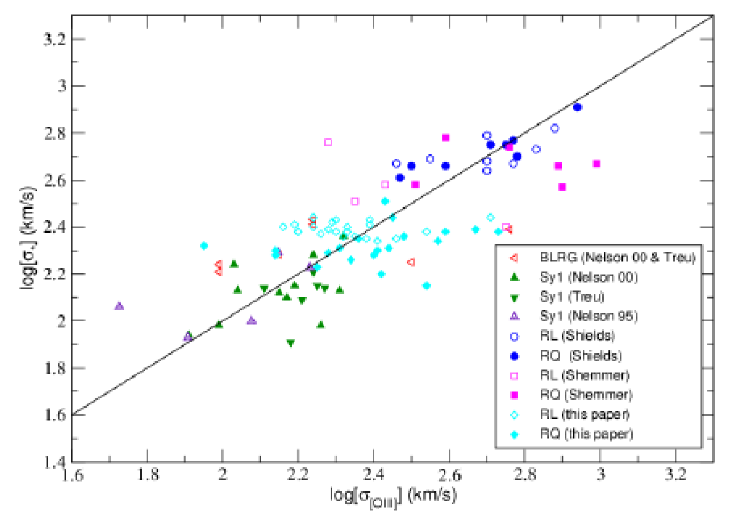
Other Scaling Relationships

- The width of the narrow [O III] λ5007 line can be used as a surrogate for the stellar velocity dispersion.
- Intrinsic scatter: 0.10 – 0.15 dex.

Bonning et al. 2005, Gaskell 2009



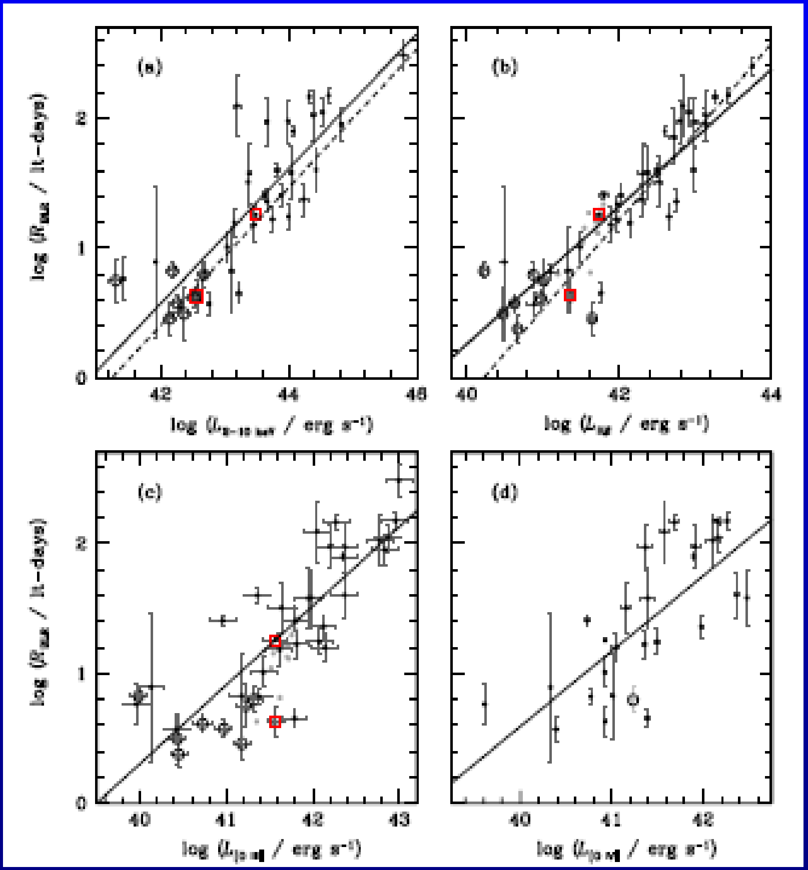
Greene & Ho 2005



Bonning et al. 2005

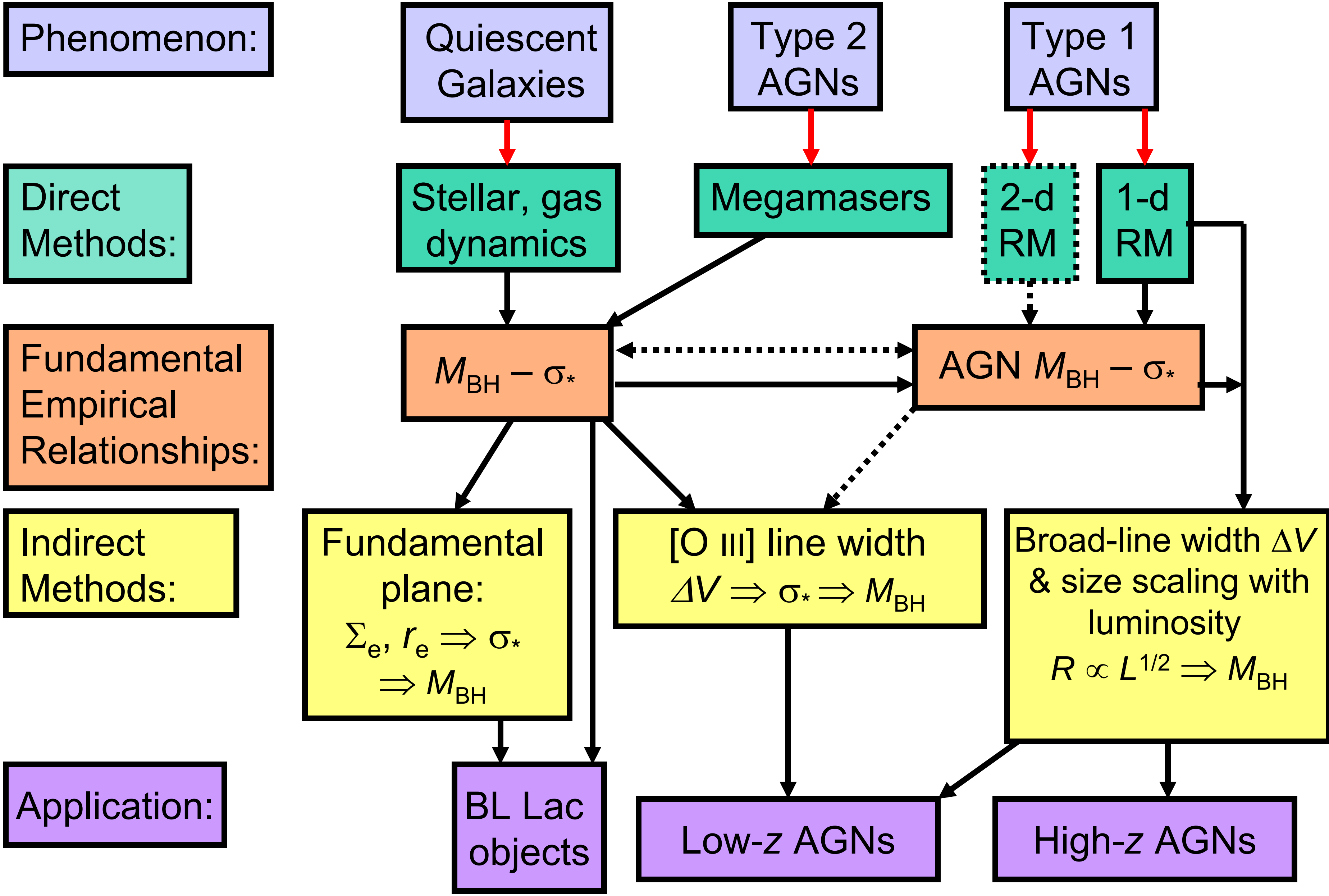
Other Scaling Relationships

- There are other luminosity indicators that can be used as proxies for R_{BLR}:
  - 2-10 keV flux. Scatter: 0.26 dex
  - Flux Hβ broad component. Scatter: 0.22 dex.
  - Flux [O III] λ5007. Scatter: 0.29 dex.
  - Flux [O IV] λ25.8μm. Scatter: 0.35 dex.
- These are useful when uncontaminated continuum is difficult or impossible to measure.



Greene et al. 2010

Measurement of Central Black Hole Masses: The Mass Ladder



Phenomenon:

Quiescent Galaxies

Type 2 AGNs

Type 1 AGNs

Direct Methods:

Stellar, gas dynamics

Megamasers

2-d RM

1-d RM

Fundamental Empirical Relationships:

$M_{\mathrm{BH}} - \sigma_*$

AGN $M_{\mathrm{BH}} - \sigma_*$

Indirect Methods:

Fundamental plane: $\Sigma_e, r_e \Rightarrow \sigma_* \Rightarrow M_{\mathrm{BH}}$

[O III] line width $\Delta V \Rightarrow \sigma_* \Rightarrow M_{\mathrm{BH}}$

Broad-line width ΔV & size scaling with luminosity $R \propto L^{1/2} \Rightarrow M_{\mathrm{BH}}$

Application:

BL Lac objects

Low-*z* AGNs

High-*z* AGNs

Scaling Relationships: Use with Caution

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

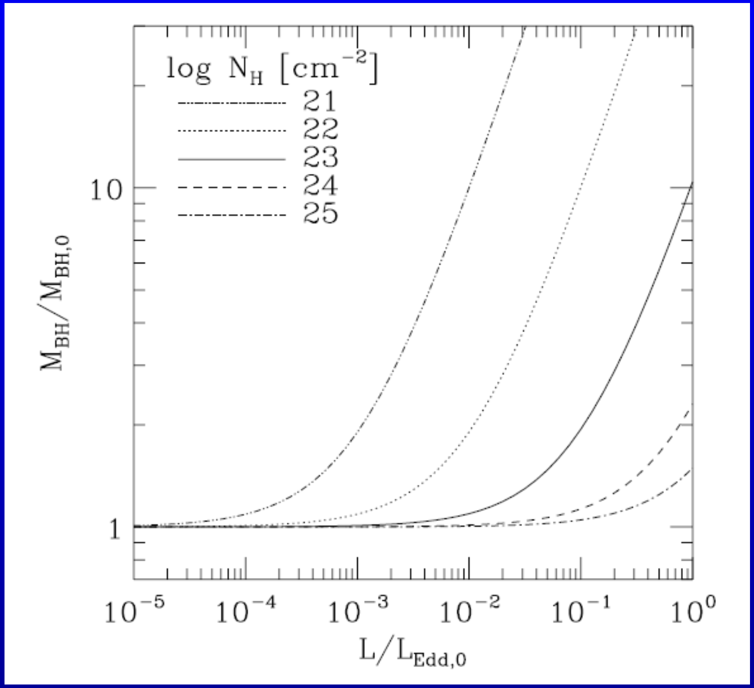
$$M_{\mathrm{BH}} \propto R(\Delta V^2) \propto L^{1/2}(\Delta V^2)$$

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

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

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}.

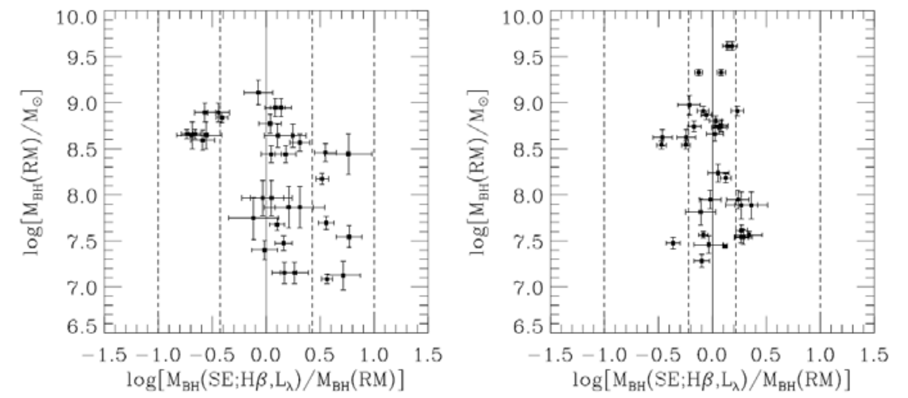


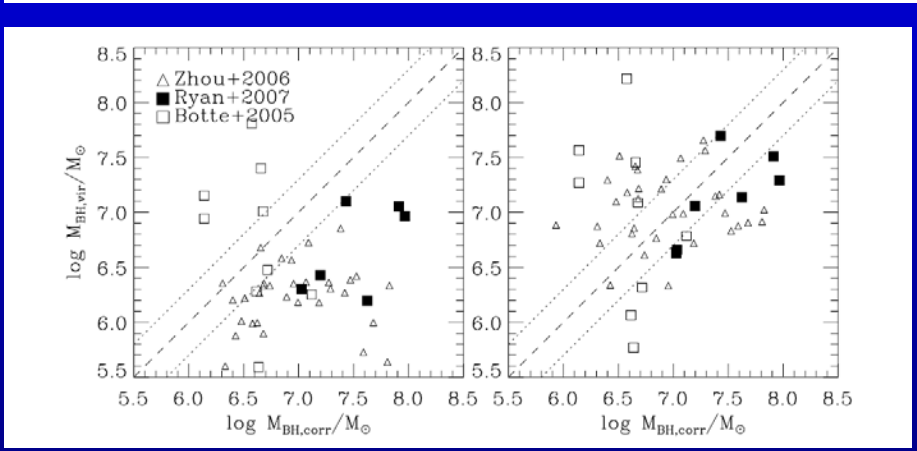
Marconi et al. (2008)

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



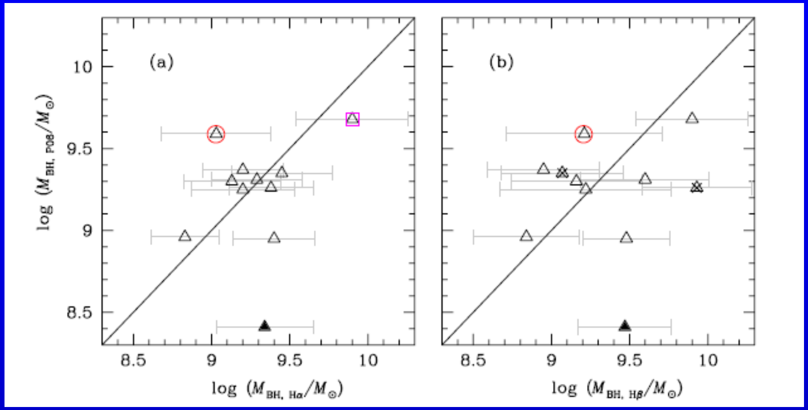


No correction With correction

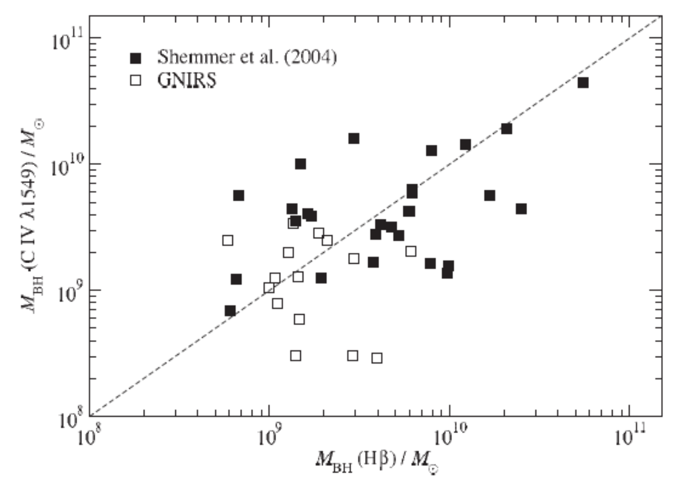
Marconi et al. (2008)

Can CIV-Based Masses Be Trusted?

- Some claims in the literature that, while masses based on C IV and Balmer lines seem to be correlated, there is much scatter.
- There are two issues:
  - – Signal-to-noise *S/N*
  - – Color dependence



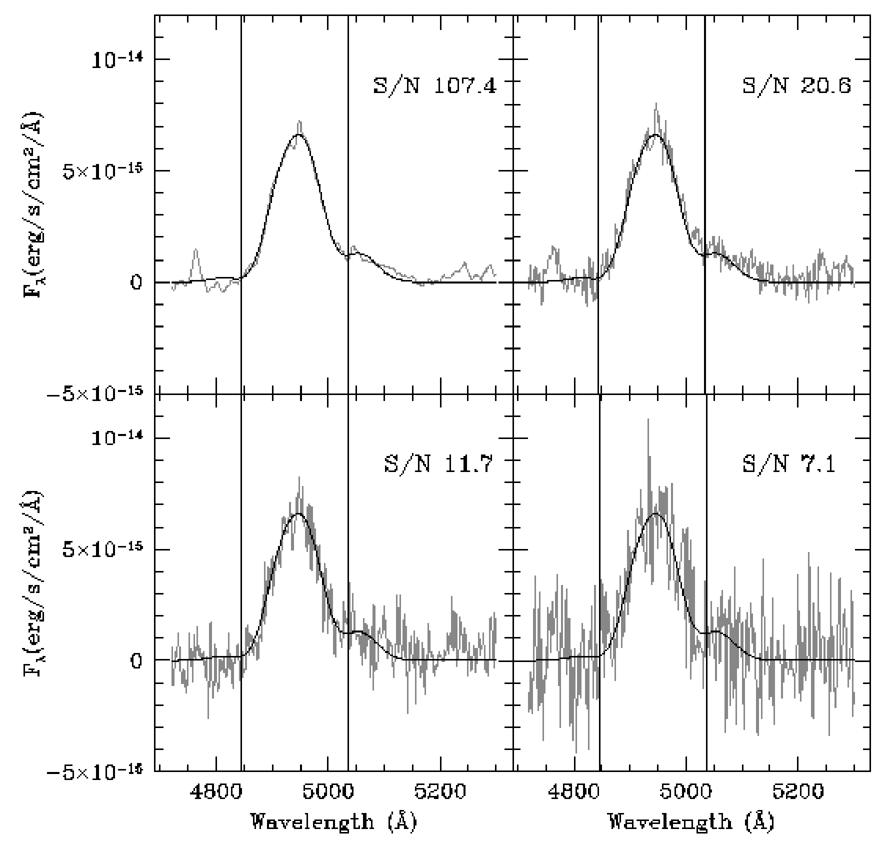
Green, Peng, & Ludwig 2010



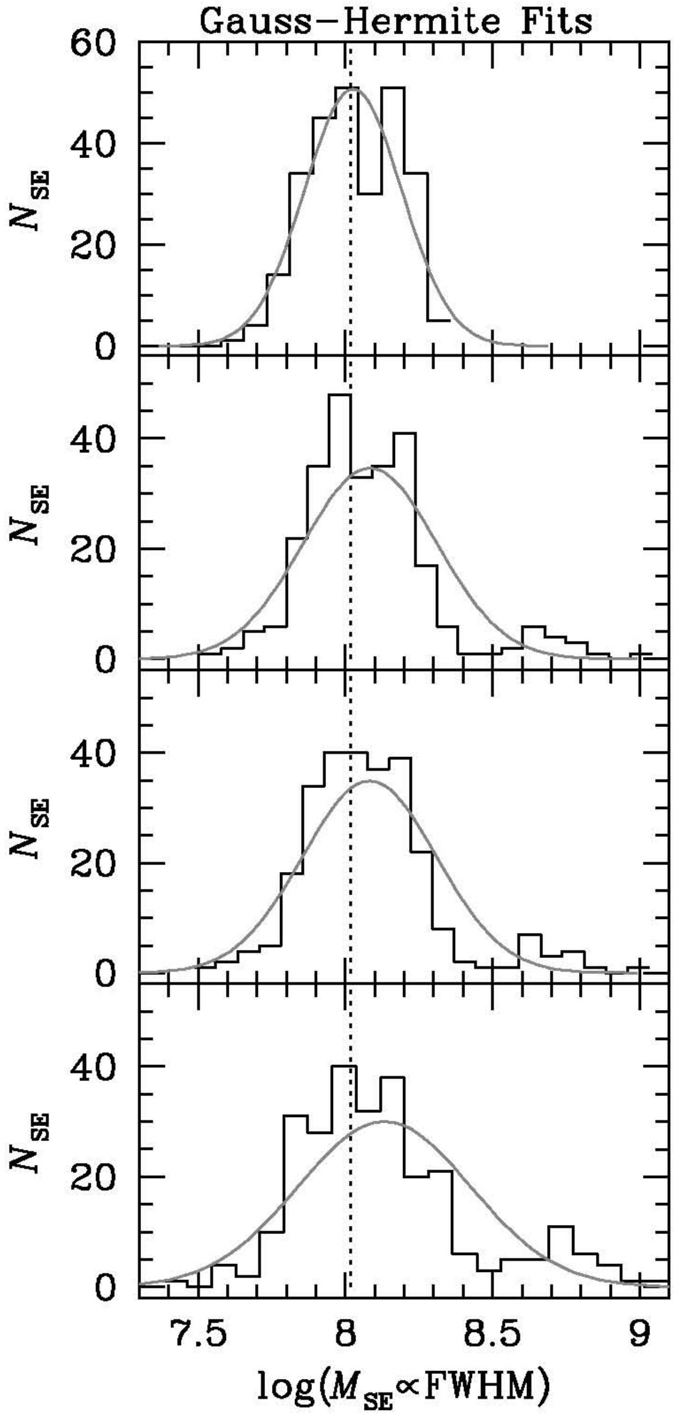
Netzer et al. 2007

S/N 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

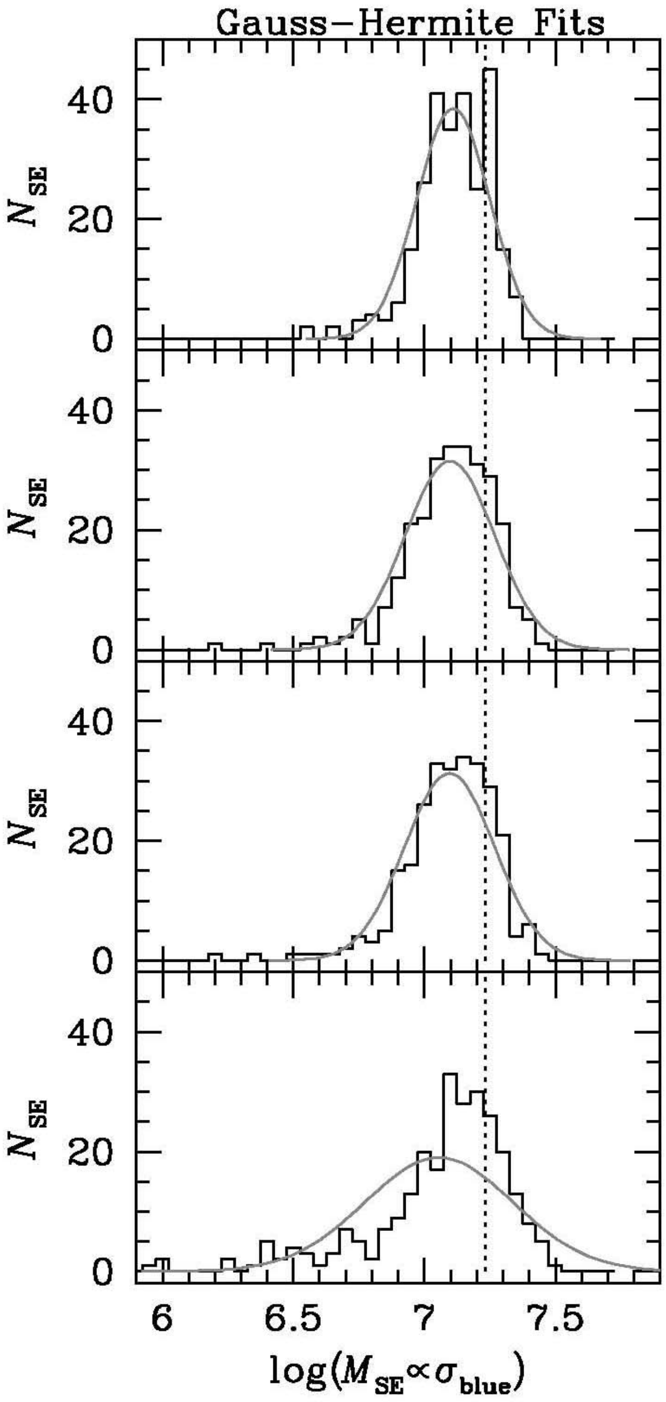


original

S/N ~ 20

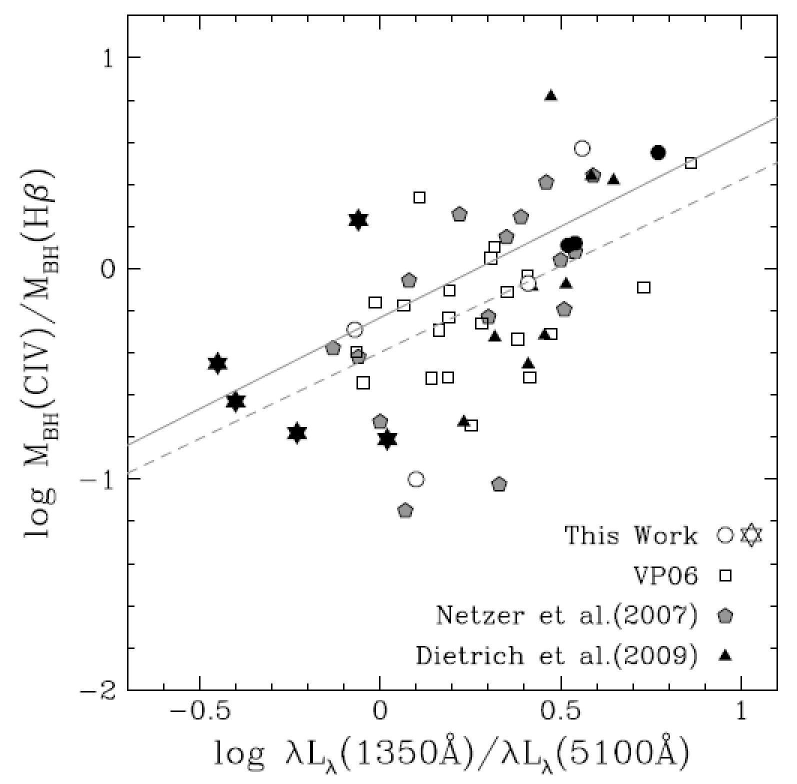
S/N ~ 10

S/N ~ 5



Color Dependence Issue

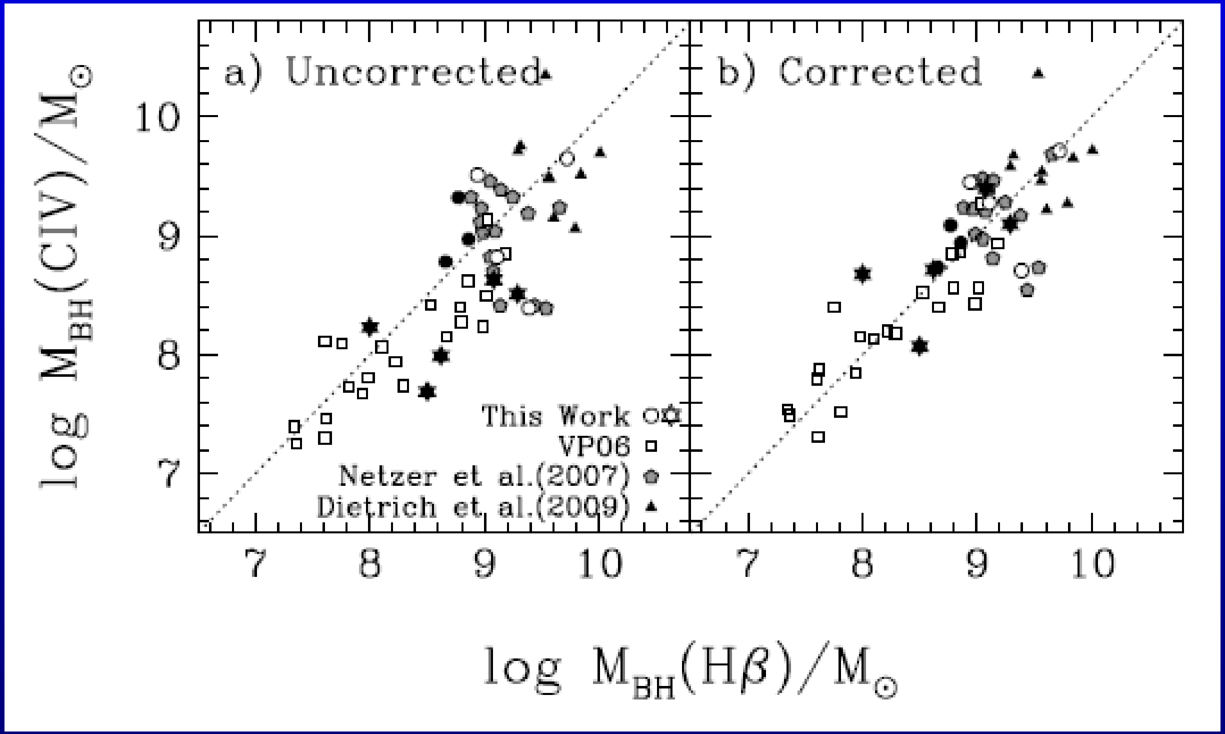
- C IV and Hβ/Hα mass estimates are based on UV and optical luminosities, respectively.
  - A color correction needs to be included, as empirically demonstrated.
  - In sample shown, color term decreases scatter by factor of 2!



Assef et al. 2010 (arXiv:1009.1145)

Color Dependence Issue

- Scatter decreases from 0.35 dex to 0.18 dex by applying a color correction.
  - Could be host galaxy, internal reddening, or differences in SEDs



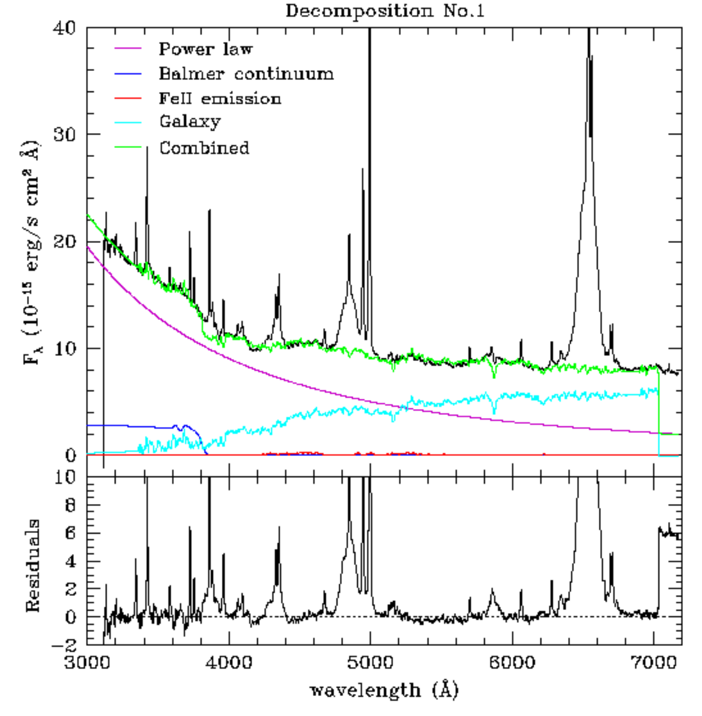
Assef et al. 2010

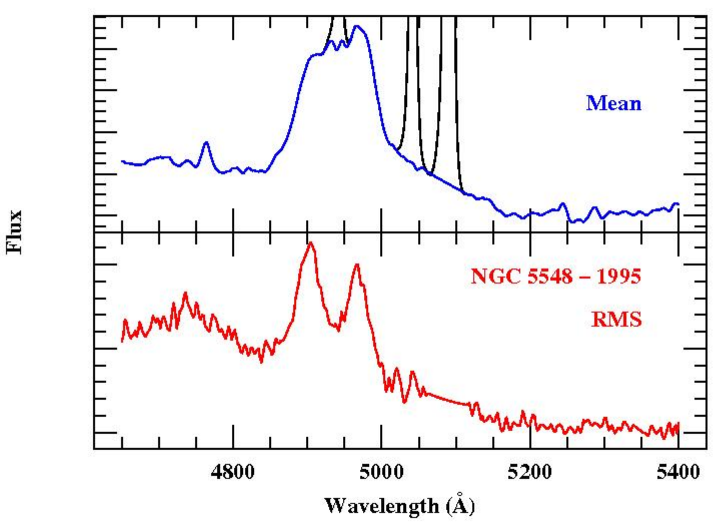
Mass-Ladder Issues

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

Mass-Ladder Issues

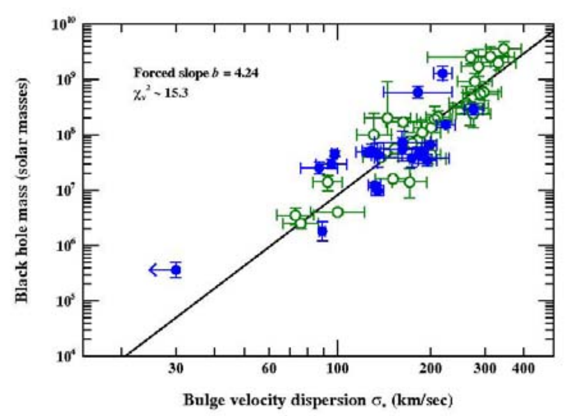
- Scaling relationships
  - Line-width characterization
    - Goal: a simple prescription that is unbiased wrt to L, L/L_{Edd}, profile, variability, etc.
  - Use of C IV emission line
    - Identification and mitigation of systematics
    - *R*–*L* validation

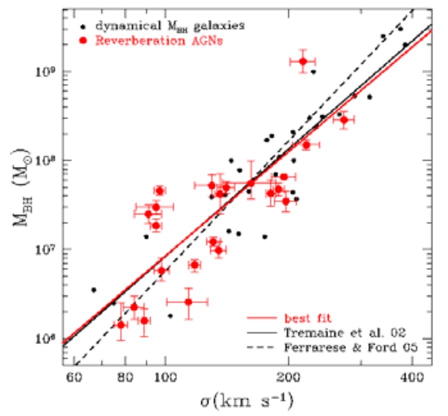




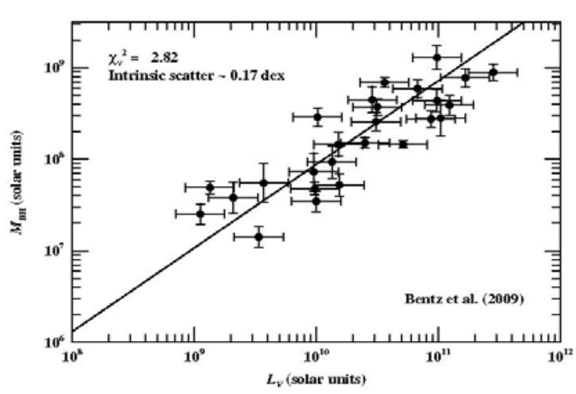
Evidence That Reverberation-Based Masses Are Reliable

1. $M_{\mathrm{BH}} - \sigma_*$ relationship



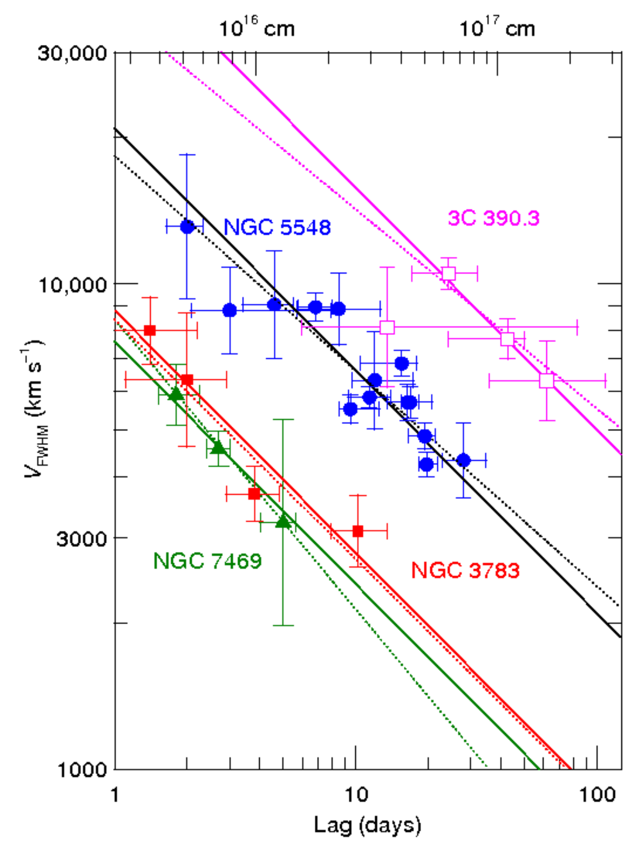


2. $M_{\mathrm{BH}} - L_{\mathrm{bulge}}$ relationship



Evidence That Reverberation-Based Masses Are Reliable

3. Virial relationship for emission-line lags (BLR radius) and line widths.



4. Direct comparisons with other direct methods:
   - Stellar dynamical masses
   - Gas dynamical masses

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
Indirect Methods:			
M_{BH}–σ_*	13	25	6.1
R–L scaling	N/A	15	65

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

Summary of Key Points

- Direct methods of mass measurement:
  - Most dynamical methods are limited by angular resolution to nearest tens of Mpc.
  - Reverberation mapping is effective even at large distances, but currently limited by systematics and dependence on other methods for calibration.
- Indirect methods:
  - Can be used for large samples, but less reliable for individual sources.