Masses of Black Holes in Active Galactic Nuclei: Implications for NLS1s

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“NLS1s and Their Place in the Universe”

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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 Response of an Emission Line to a Variable Continuum

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

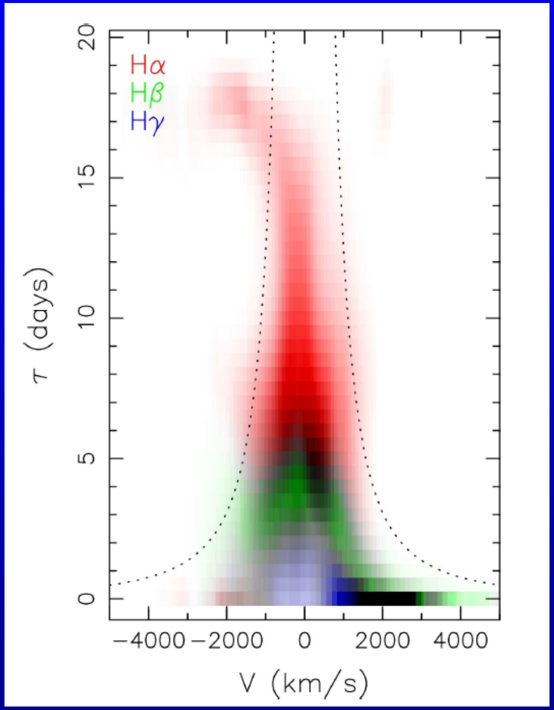
$$L(V,t) = \int \Psi(V,\tau)\; C(t-\tau)\; d\tau$$

Velocity-resolved emission-line light curve

"Velocity-delay map"

Continuum light curve

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



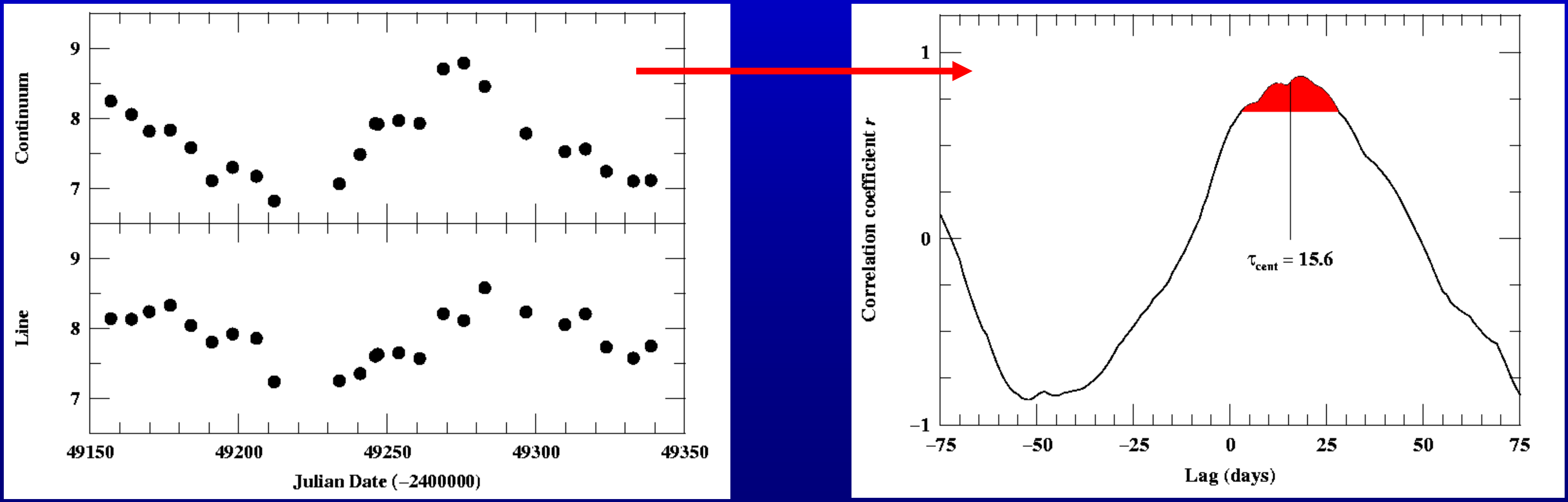
Arp 151

LAMP: Bentz et al. 2010

Emission-Line Lags

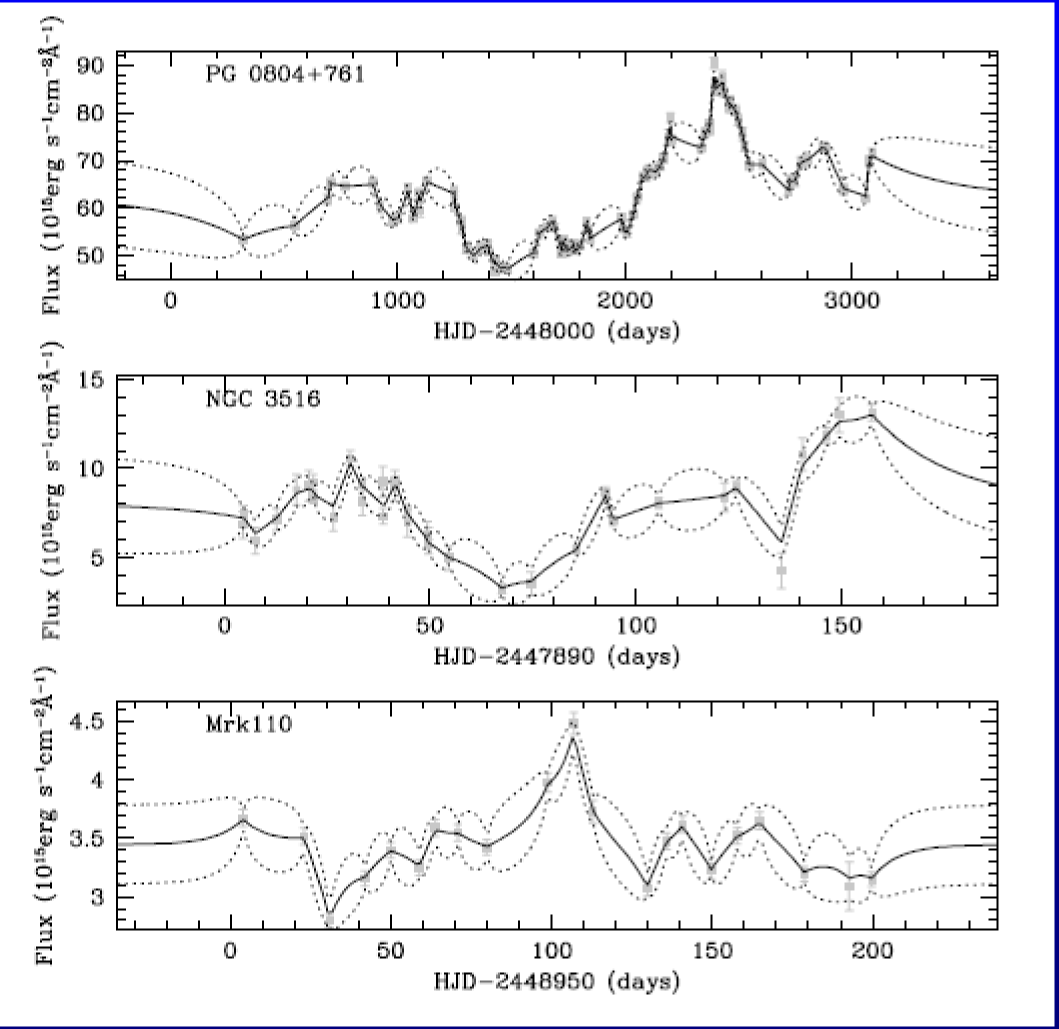
- Because the data requirements are *relatively* modest, it is most common to determine the cross-correlation function and obtain the "lag" (mean response time):

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



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
    - **Press, Rybicki, & Hewitt (1992)**
    - **Rybicki & Press (1992)**
    - **Rybicki & Kleyna (1994)**
  - "Stochastic Process Estimation for AGN Reverberation" (SPEAR)
- A likelihood estimator can be used to identify the most probable lags.

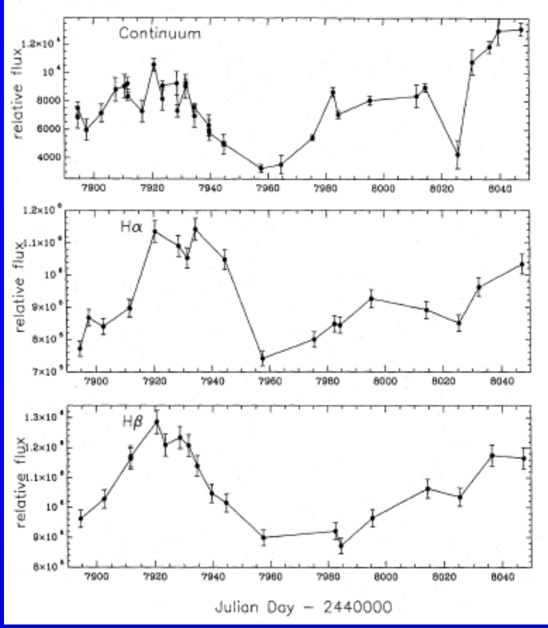


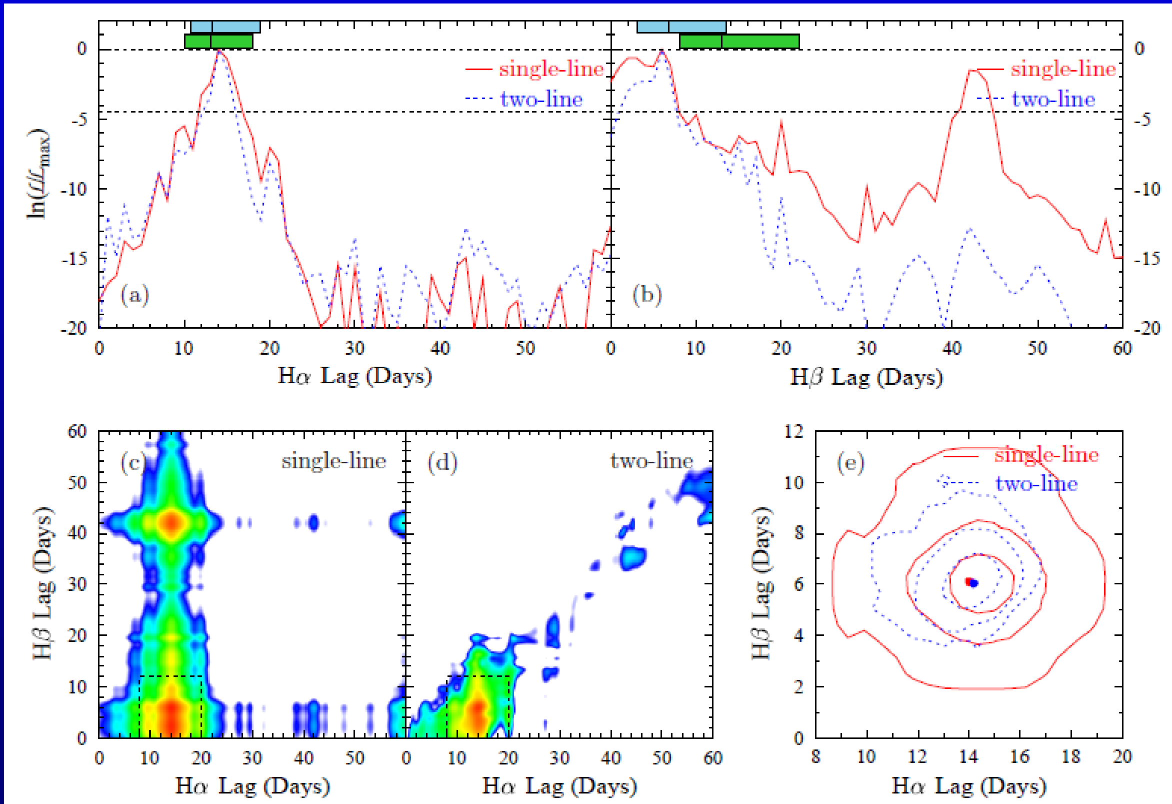
Zu, Kochanek, & Peterson 2011

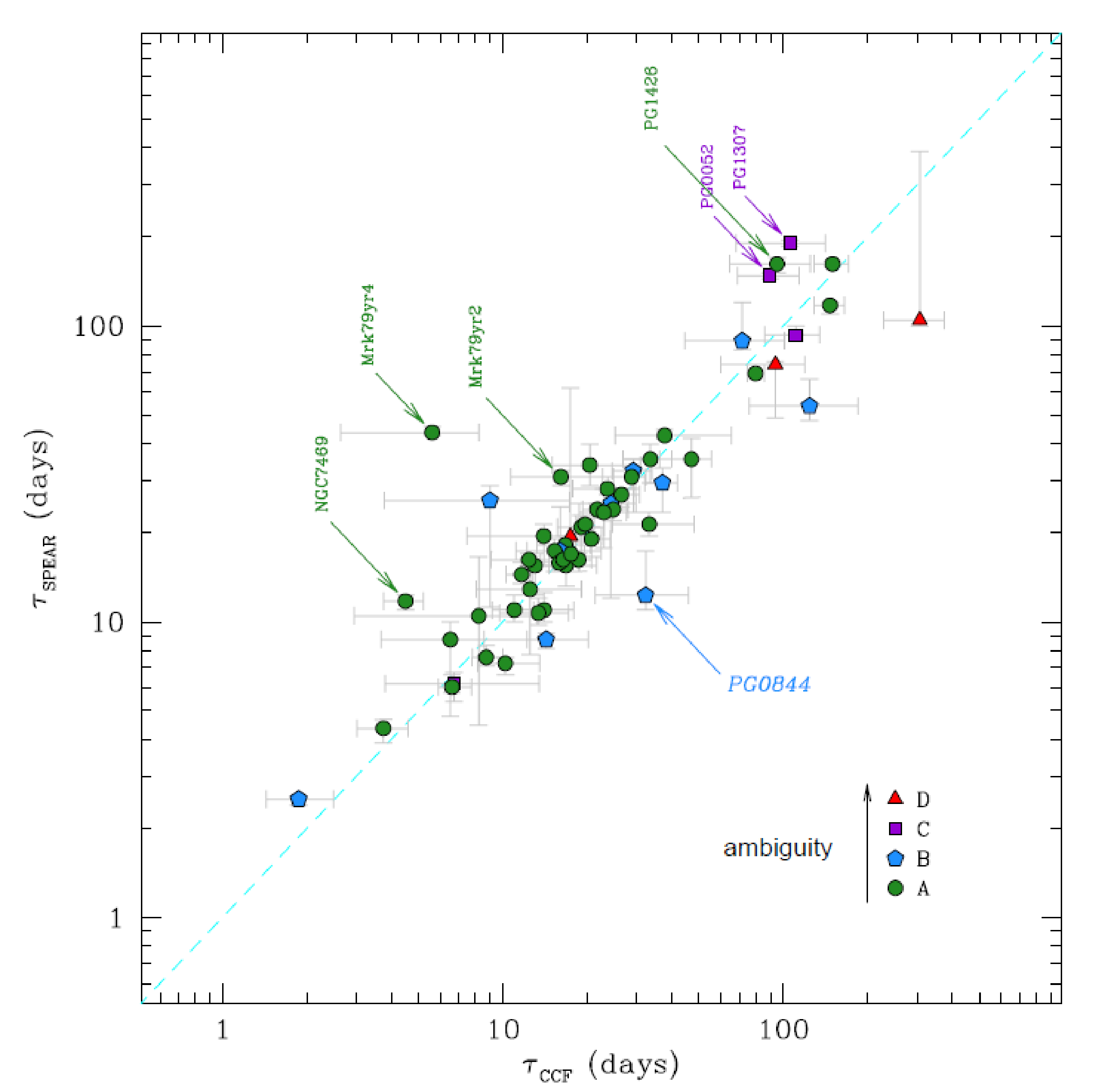
- Uncertainties are computed self-consistently and included in the model.
- Trends, correlated errors are dealt with naturally.
- Can simultaneously fit multiple lines (which effectively backfill gaps in the time series).

NGC 3516 in 1990

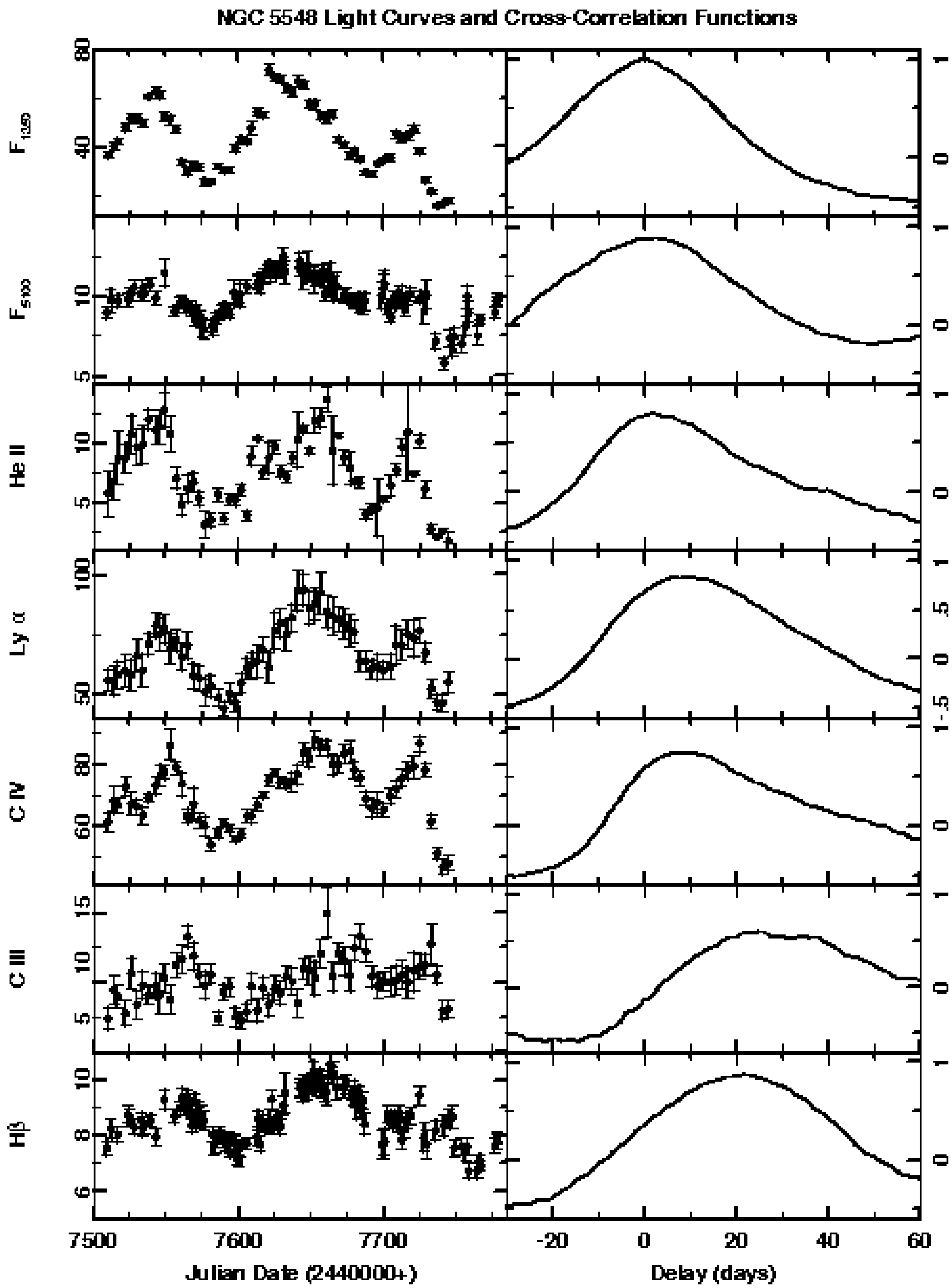
LAG: Wanders et al. 1993







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

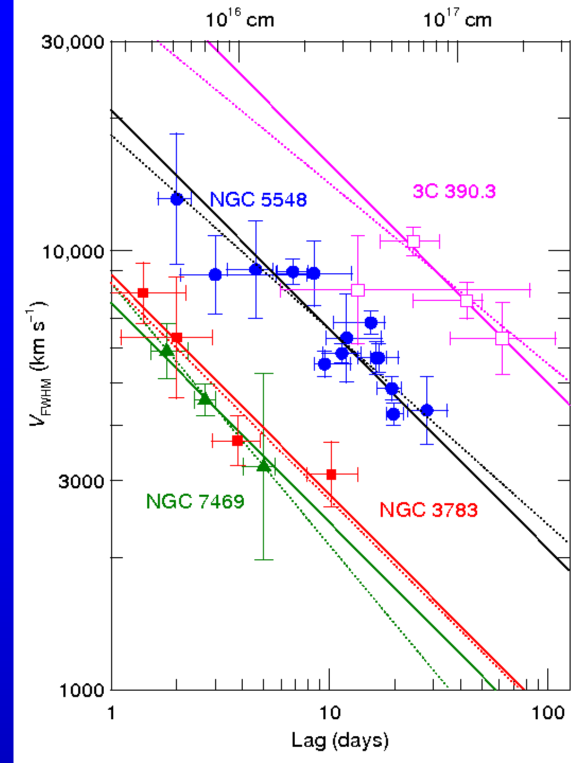


Reverberation Mapping Results

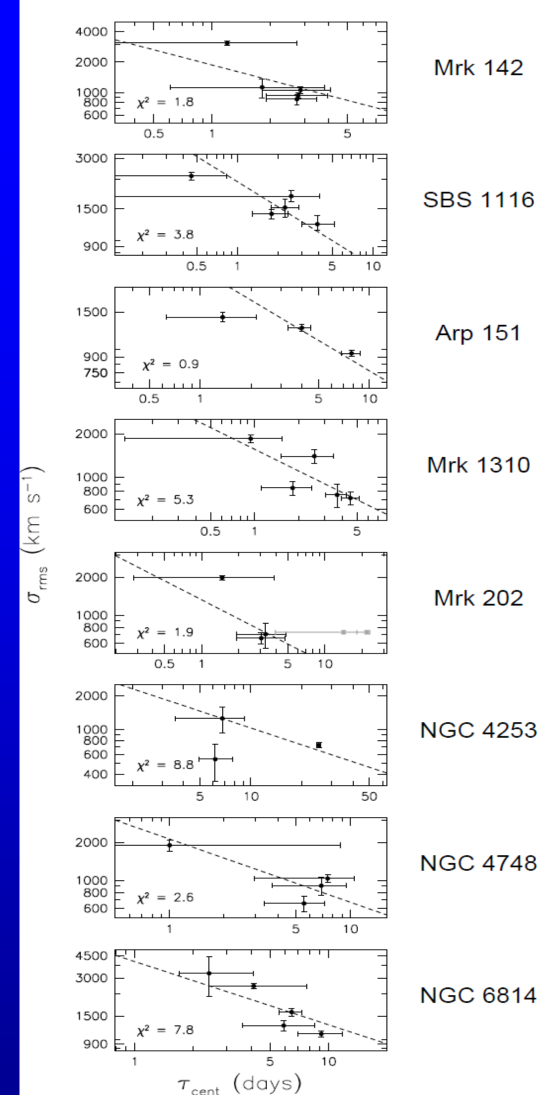
- Reverberation lags have been measured for nearly 50 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification

A Virialized BLR

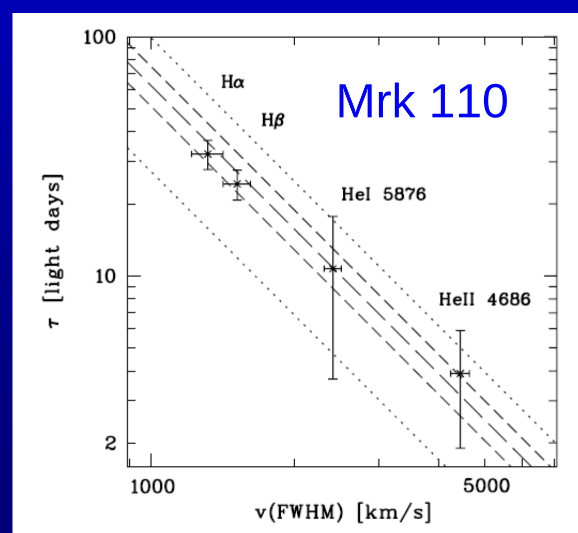
- $\Delta V \propto R^{-1/2}$ for every AGN in which it is testable.
- Suggests that gravity is the principal dynamical force in the BLR.
  - Caveat: radiation pressure! **(Marconi talk this afternoon)**



Peterson & Wandel 2002



Bentz et al. 2009



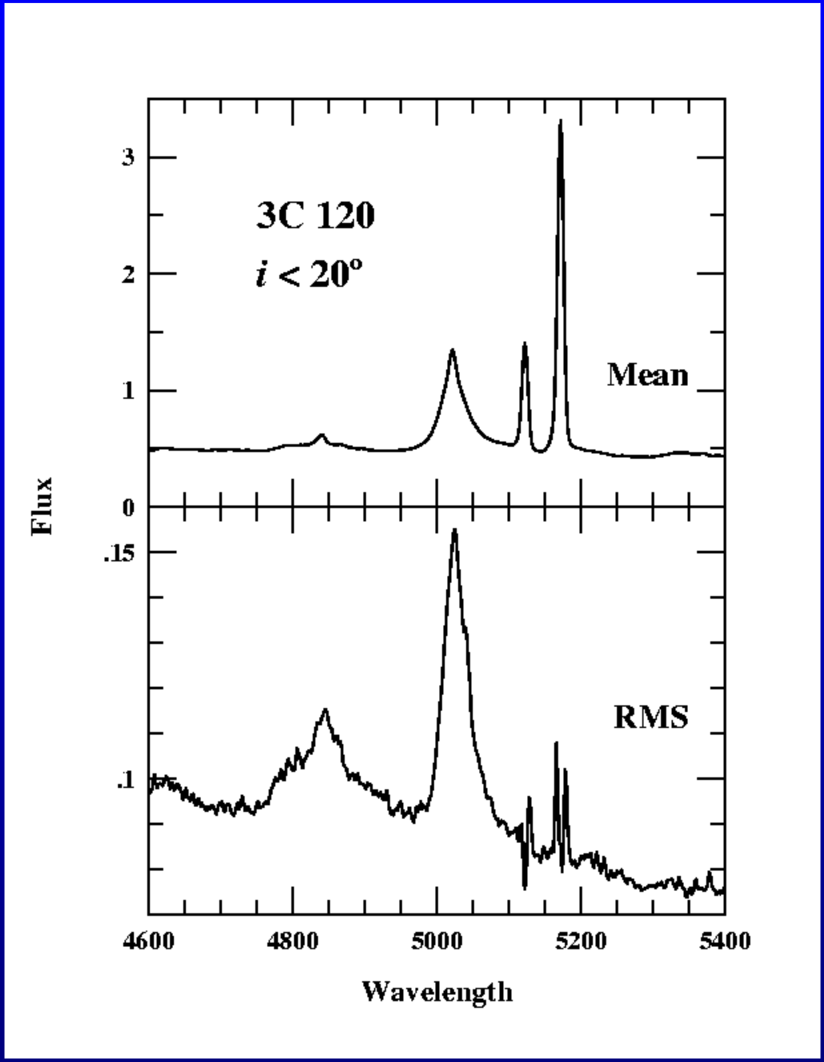
Kollatschny 2003

Reverberation-Based Masses

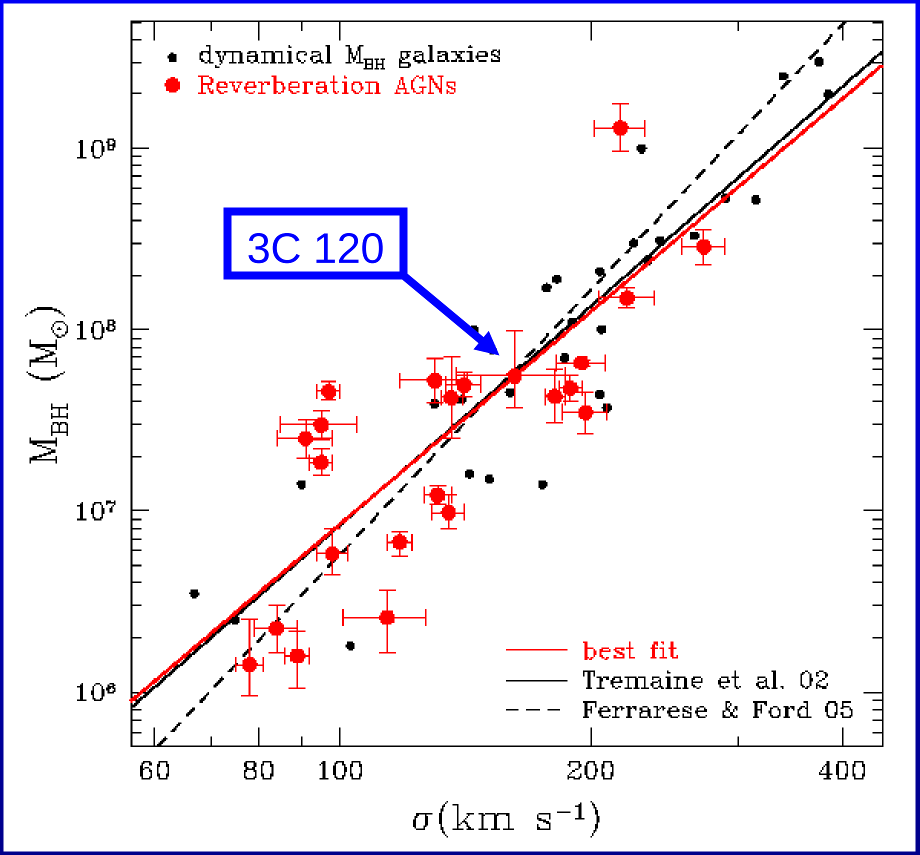
- Combine size of BLR with line width to get the enclosed mass:

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

- 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.



The AGN M_{BH}–σ_* Relationship



Woo et al. (2010)
(Woo talk this afternoon)

- Assume slope and zero point of most recent quiescent galaxy calibration.

  $\langle f \rangle = 5.25 \pm 1.21$

  Woo et al. 2010

- Maximum likelihood places an upper limit on intrinsic scatter $\Delta \log M_{BH} \sim 0.40$ dex.
  - Consistent with quiescent galaxies.

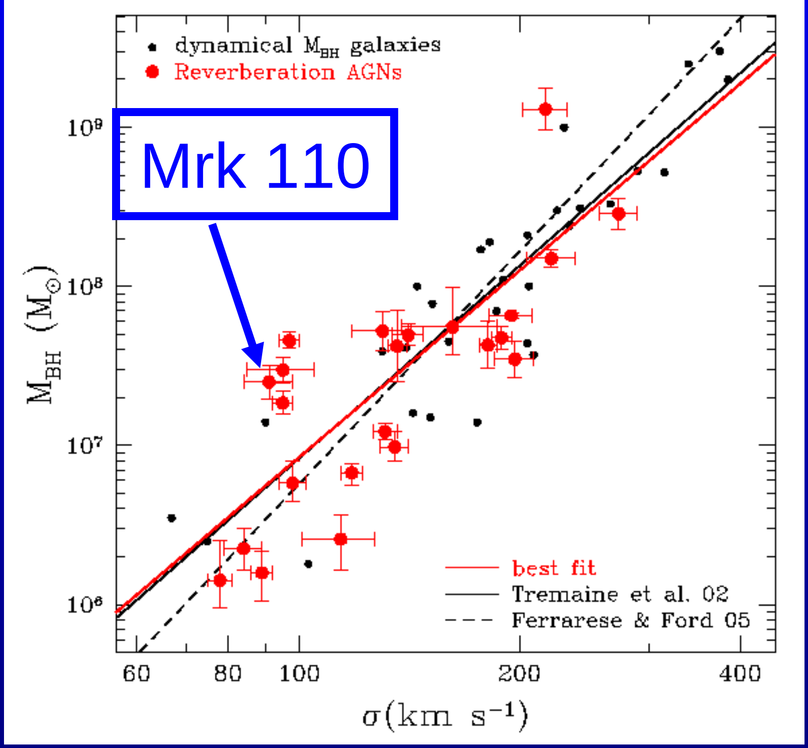
Is the NLS1 Phenomenon an Inclination Effect?

- Probably not exclusively.
- Test case: Mrk 110
  - An NLS1 with an independent mass estimate from gravitational redshift of emission lines (Kollatschny 2003):

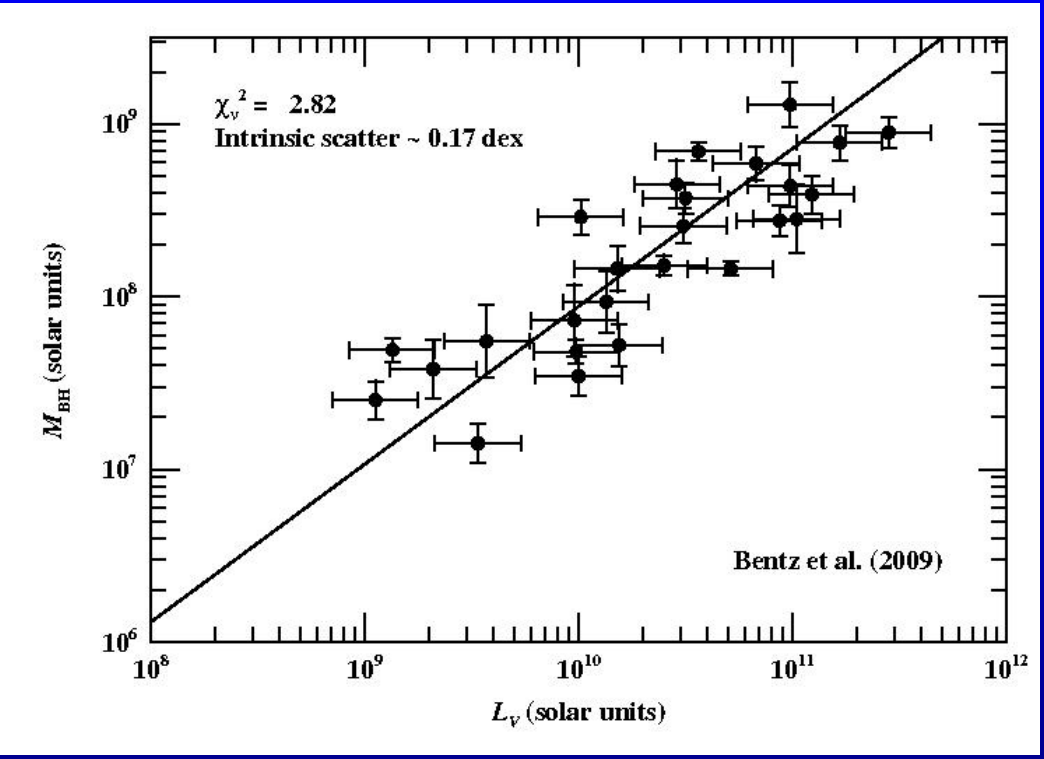
$M_{\sigma*} = 4.8 \times 10^6\ M_{\odot}$

$M_{rev} = 25\ (\pm 6) \times 10^6\ M_{\odot}$

$M_{grav} = 14\ (\pm 3) \times 10^6\ M_{\odot}$

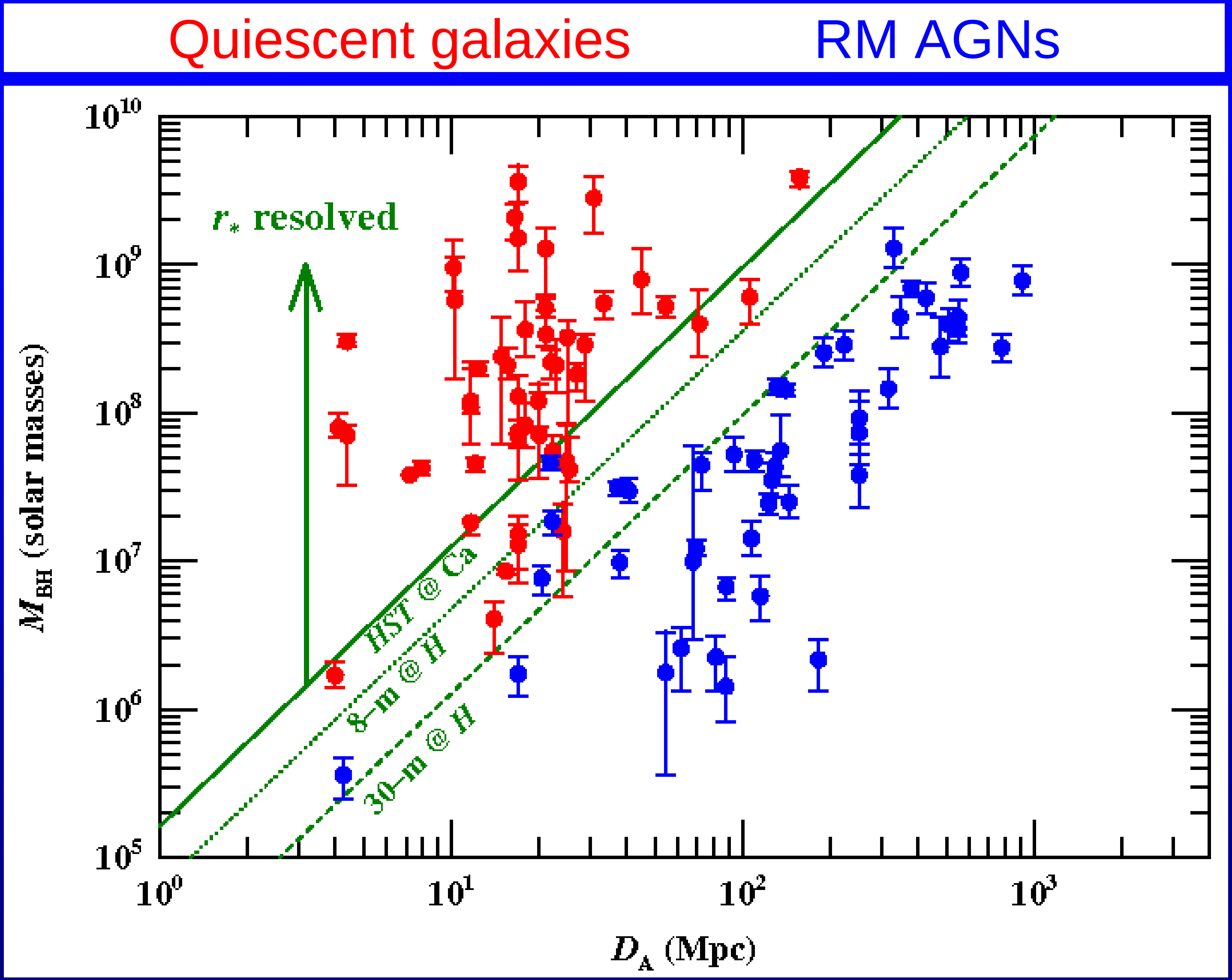


The AGN M_{BH}–L_{bulge} Relationship



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

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



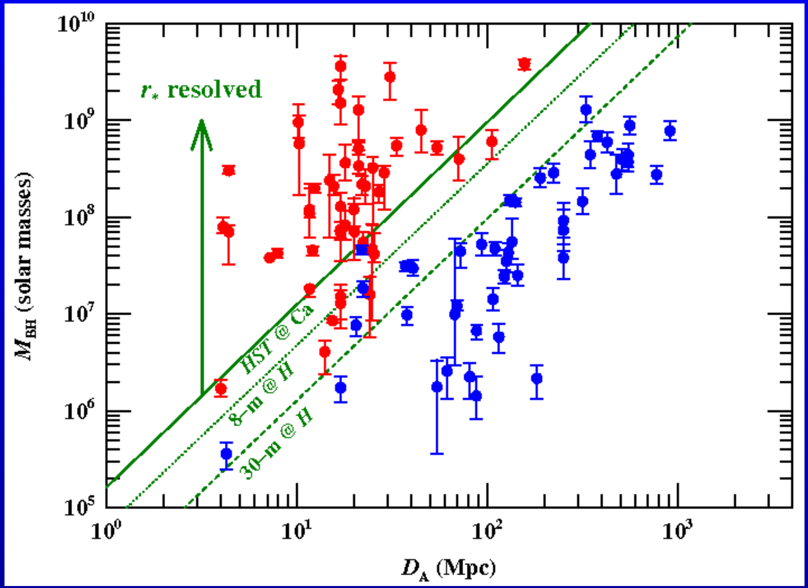
Black Hole Mass Measurements (units of $10^6\ M_\odot$)

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
Quoted uncertainties are statistical only, 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

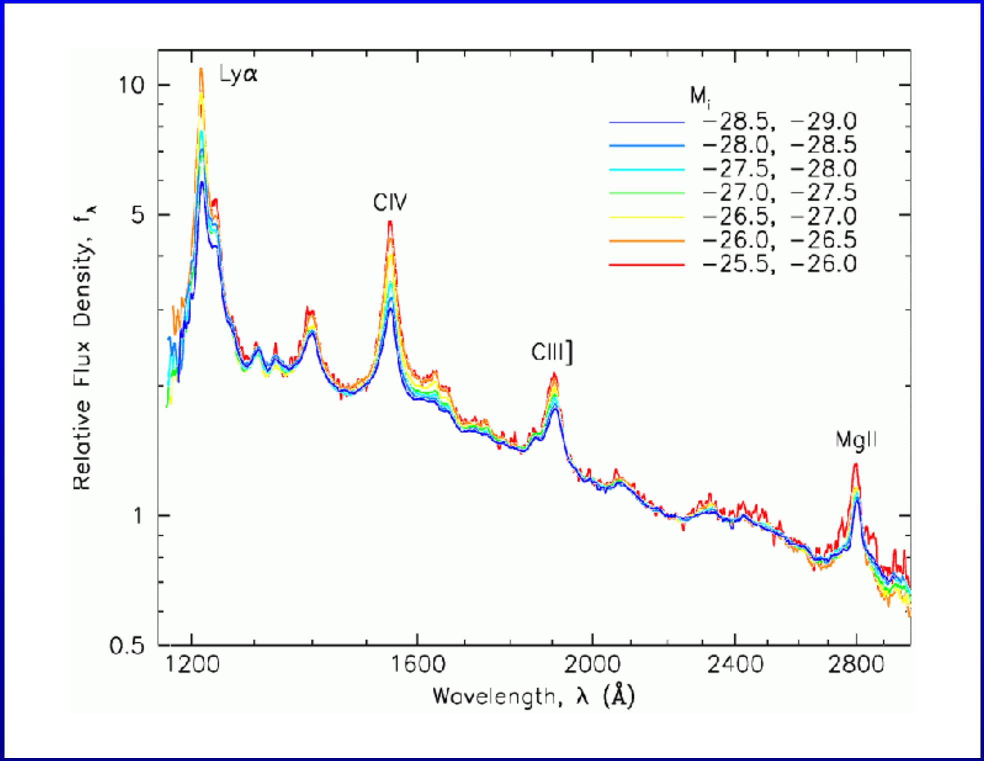
- To first order, AGN spectra look the same

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

$\Rightarrow$ Same ionization parameter U

$\Rightarrow$ Same density n_{H}

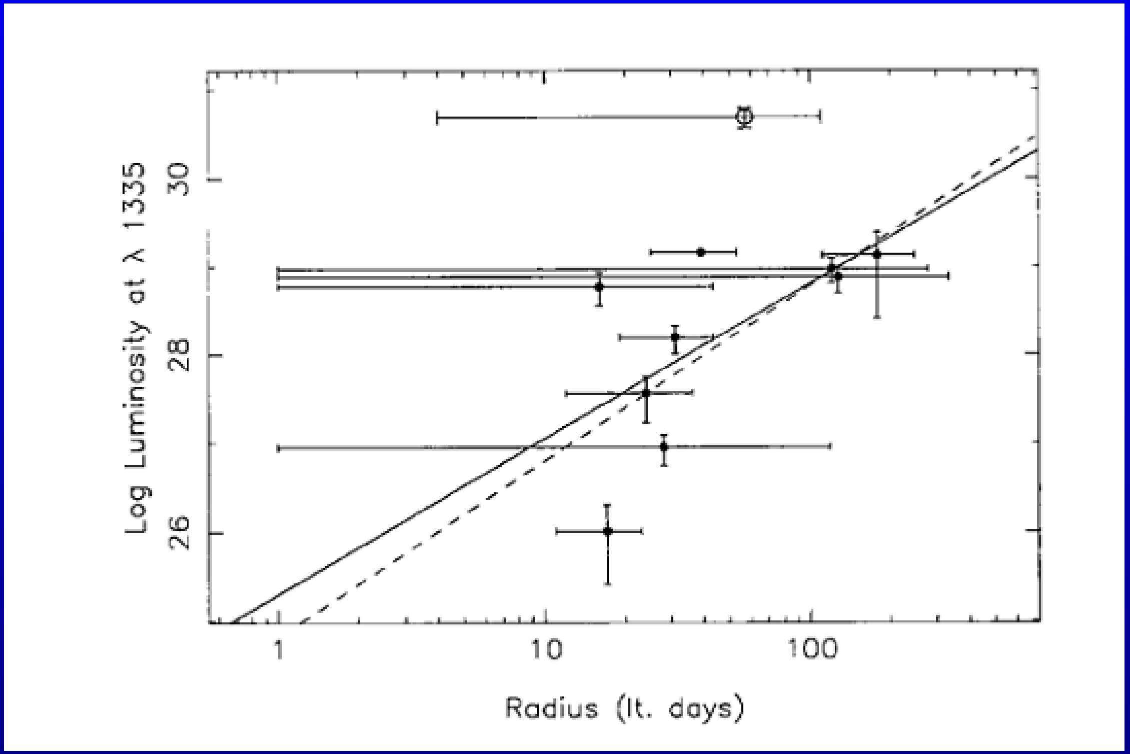
$$r \propto L^{1/2}$$



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



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

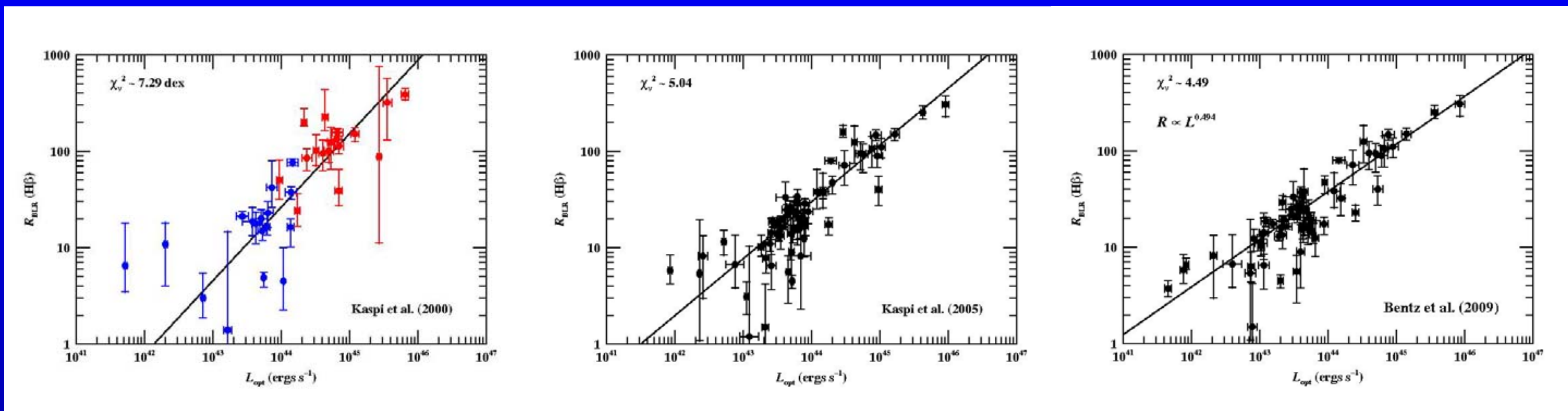
Mrk 79
$z = 0.0222$
$\log L_{opt} = 43.7$

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

Reverberation experiments use large spectrograph apertures for accurate spectrophotometry.
This results in significant starlight contribution to the measured optical luminosity.

Images courtesy of M. Bentz

Progress in Determining the Radius-Luminosity Relationship

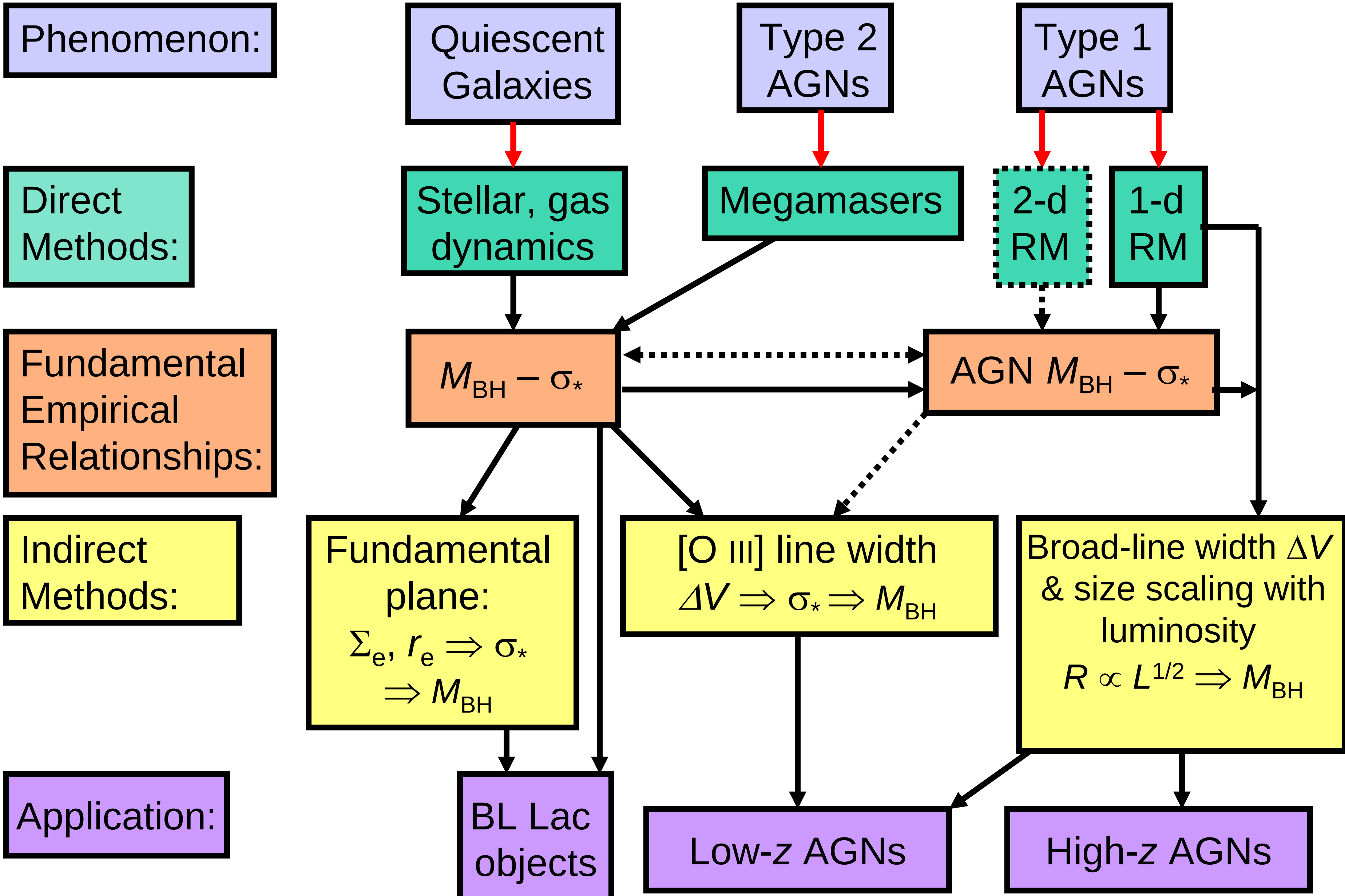


Original PG + Seyferts
(Kaspi et al. 2000)
$\chi_\nu^2 \approx 7.29$
$R(H\beta) \propto L^{0.76}$

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

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

Measurement of Central Black Hole Masses



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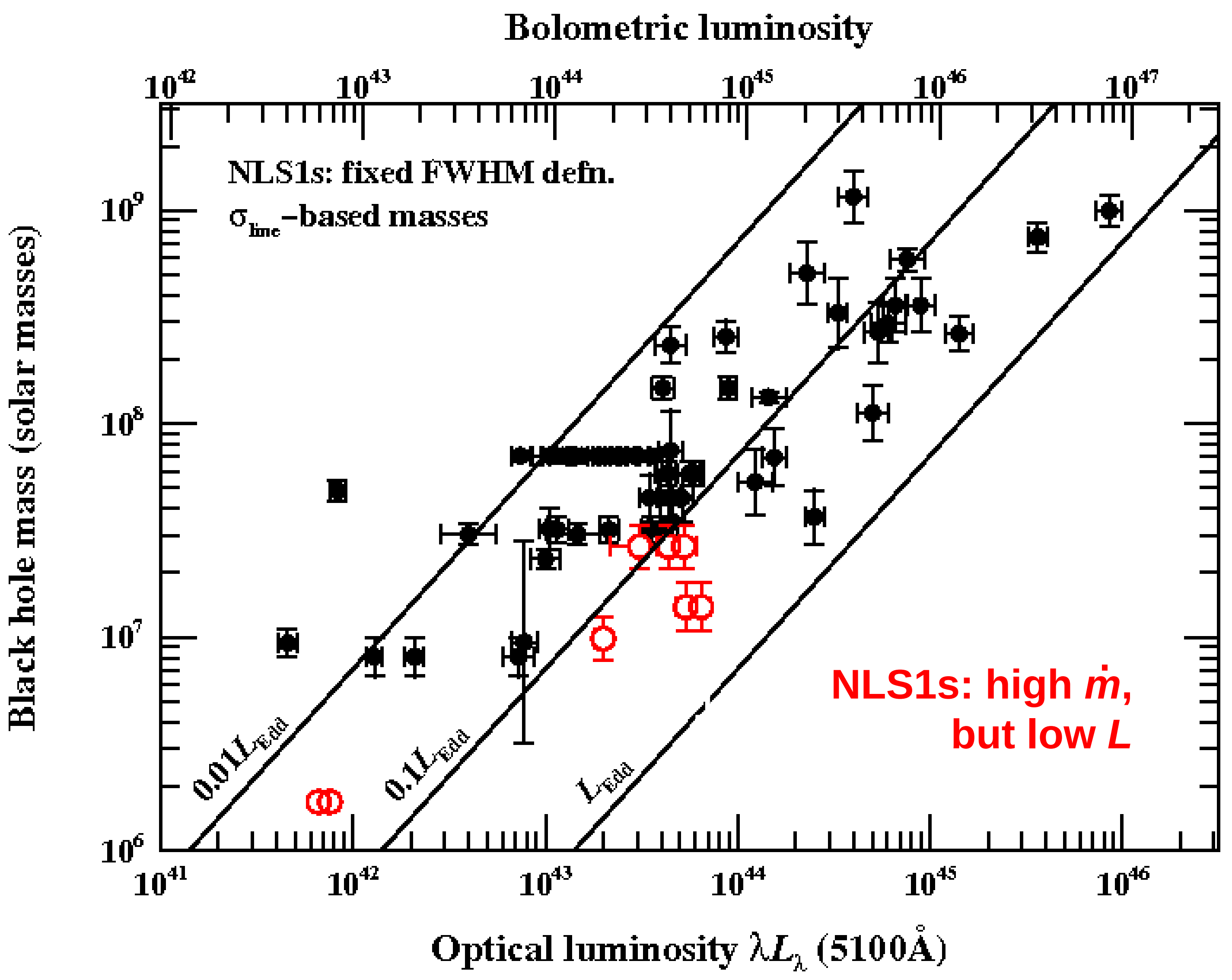
Reverberation	N/A	7.63 ± 1.7	46 ± 5
Indirect Methods:			
M_{BH}–σ_*	13	25	6.1
R–*L* scaling	N/A	15	29 –120

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

Black Hole Masses

- All direct methods have systematic uncertainties at the factor of 2 level (at least!).
  – NGC 4258 (megamasers) and Galactic Center are exceptions
- Ignoring zero-point uncertainties, the prescriptions for AGN masses are probably believable at the 0.5 dex level.
- If we desire higher accuracy, many difficulties appear.
  – e.g., should we characterize line widths by FWHM or line dispersion?

Implications for NLS1s



Implications for NLS1s

- Let's suppose that quasars are self-similar and the physics is captured by the Eddington rate:
  - Virial equation: $\Delta V \propto \left(M_{\rm BH}/r_{\rm BLR}\right)^{1/2}$
  - *R–L* relationship: $r_{\rm BLR} \propto L_{\rm AGN}^{1/2}$
  - Definition of Eddington ratio:

$$\dot{m} = \dot{M}/\dot{M}_{\rm Edd} \propto \dot{M}/M_{\rm BH}$$

$$\Delta V \propto \left(M_{\rm BH} \big/ L_{\rm AGN}^{1/2} \right)^{1/2} \propto \left(M_{\rm BH} \big/ \dot{M}^{1/2} \right)^{1/2} \propto \left(M_{\rm BH} \big/ \dot{m} \right)^{1/4}$$

Also see poster by Dultzin

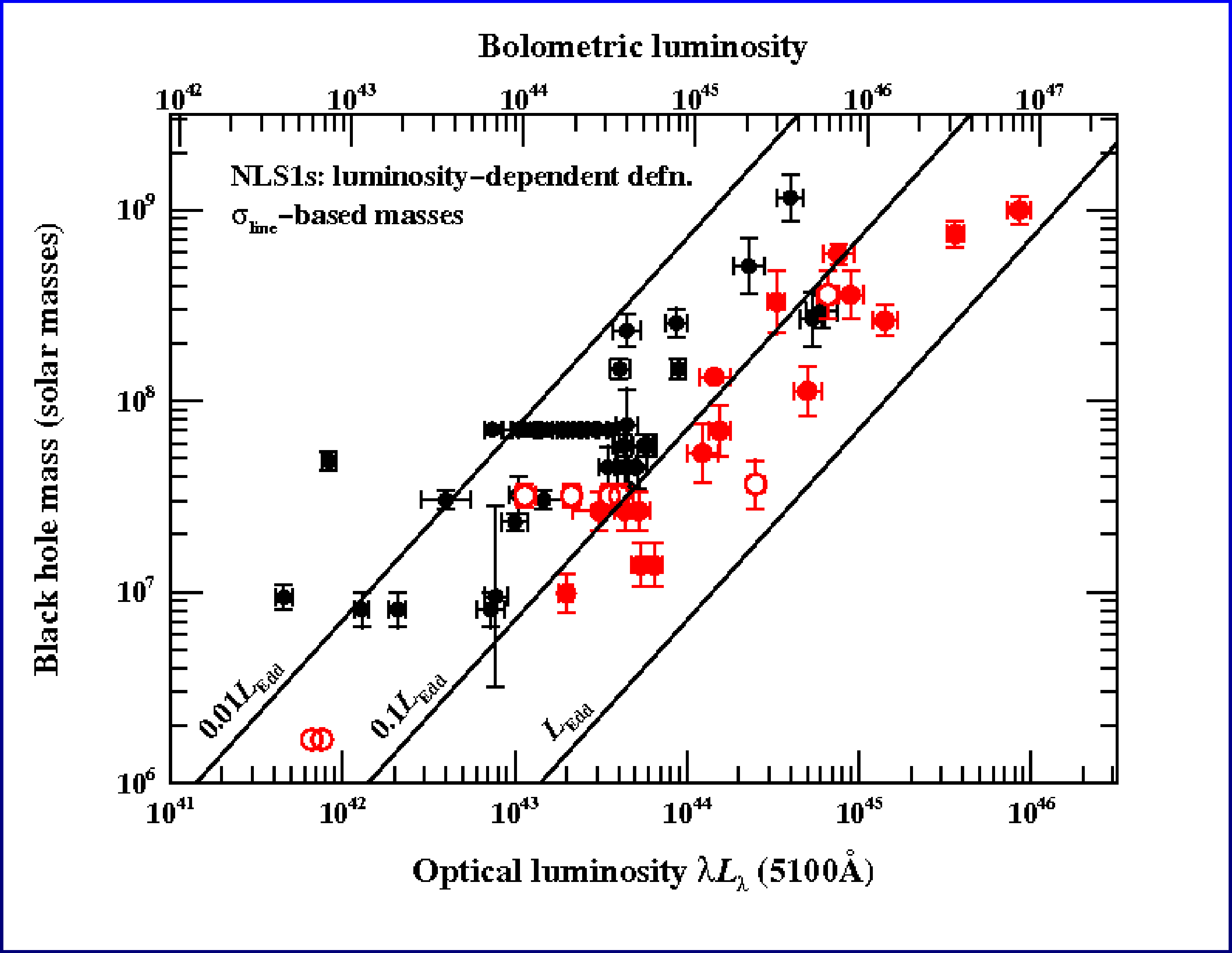
Implications for NLS1s

- Objects with the same physics have (slightly) broader lines with increasing black hole mass.
- Define (arbitrarily) a mass-dependent definition of high Eddington rate (HER) objects.

$$\Delta V \propto \left(M_{\mathrm{BH}} / \dot{m} \right)^{1/4}$$

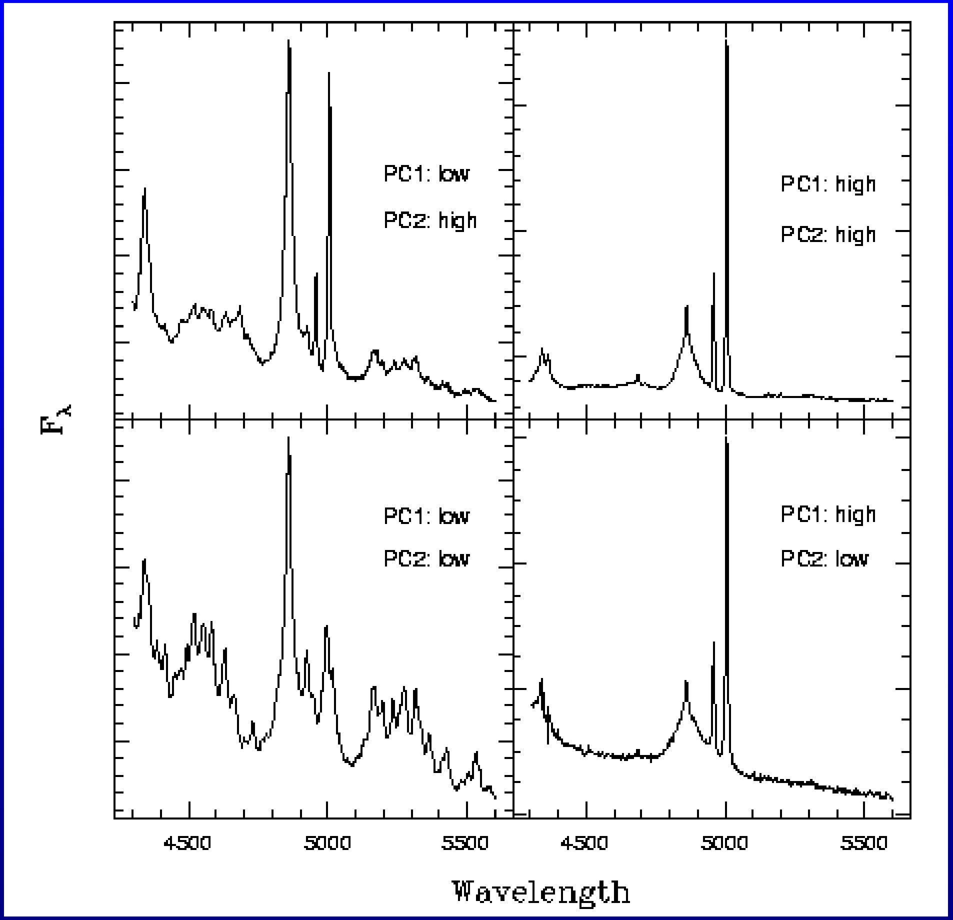
$$\Delta V_{\mathrm{HER}} \leq \left(\frac{M_{\mathrm{BH}}}{10^7 M_{\odot}} \right)^{1/4} 2000 \ \mathrm{km\ s^{-1}}$$

Implications for NLS1s



Implications for NLS1s

- Many spectral properties of AGNs are correlated as shown by PCA.
  Boroson & Green (1992)
- One of these properties is Hβ profile.
- NLS1s constitute an extreme of PC1.



Boroson 2001

Characterizing Line Widths

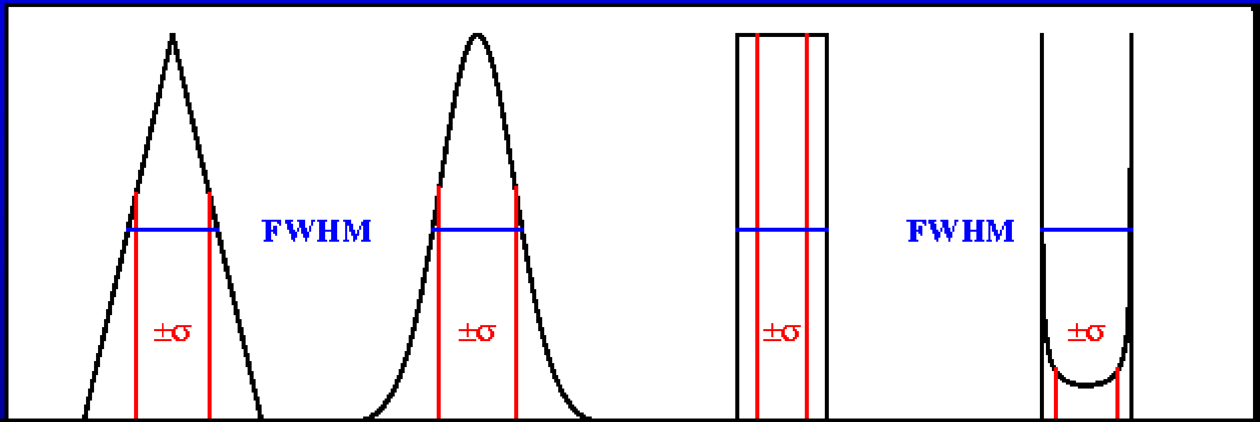
FWHM:

- Trivial to measure
- Less sensitive to blending and extended wings

Line dispersion σ_{line}:

- Well defined
- Less sensitive to narrow-line components
- More accurate for low-contrast lines

Some trivial profiles:

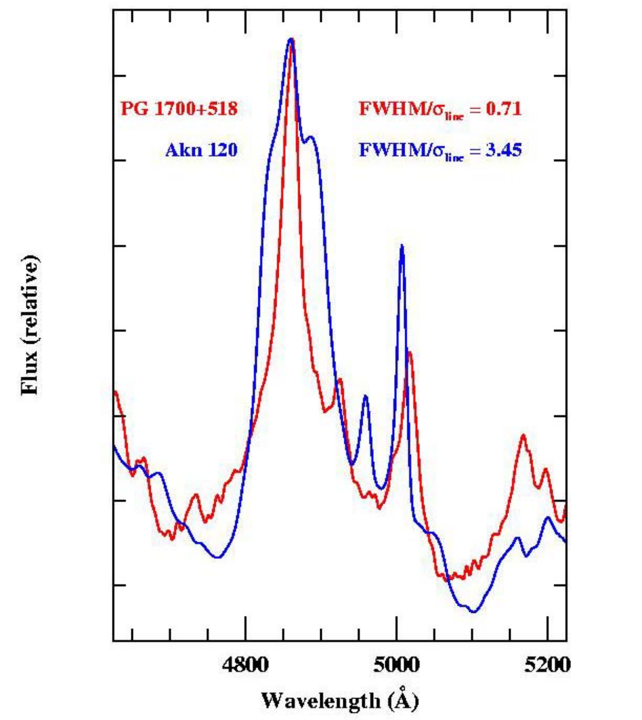


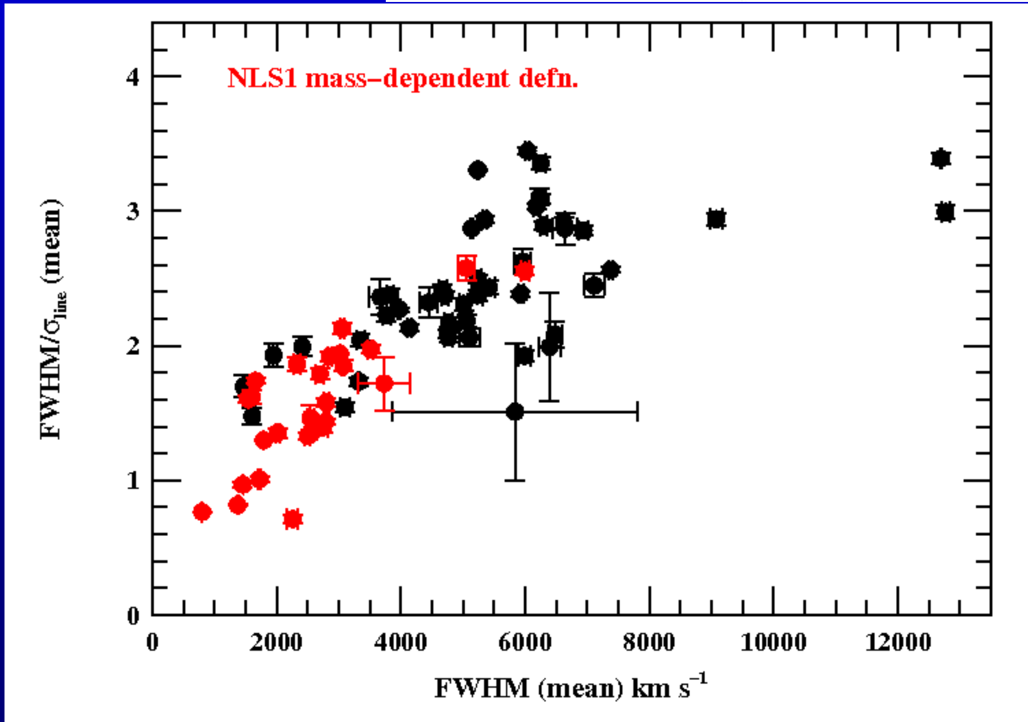
$\dfrac{\text{FWHM}}{\sigma_{\text{line}}} =$	$\sqrt{6}$	$2(2\ln 2)^{1/2}$	$2\sqrt{3}$	$2\sqrt{2}$
	2.45	2.35	3.46	2.83

$$\sigma_{\text{line}} = \left\langle \lambda^2 \right\rangle - \lambda_0^2 = \left(\int \lambda^2 P_\lambda \, d\lambda \, / \int P_\lambda \, d\lambda \right) - \lambda_0^2$$

Hβ Profiles in NLS1s Have Low Values of FWHM/σ_{line}

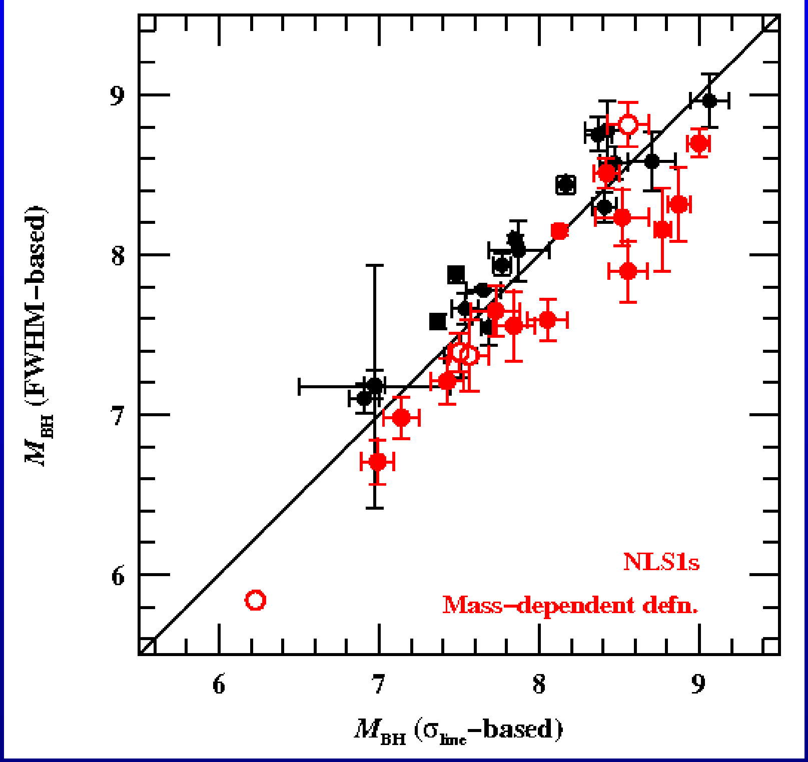
- This matters because their black hole masses depend on the line width measure (squared!).
- Systematically shifts NLS1s away from other AGN masses.



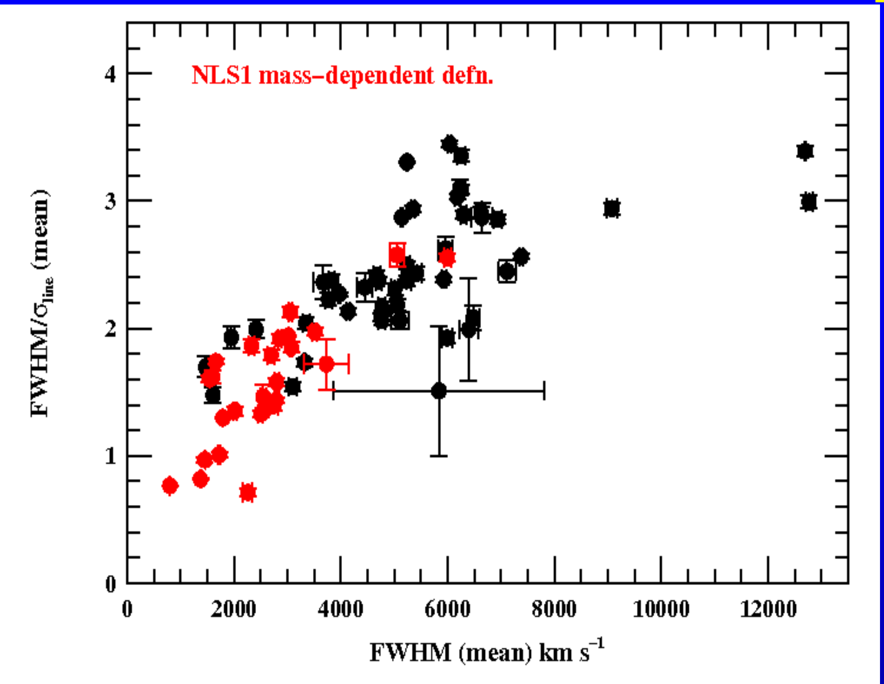


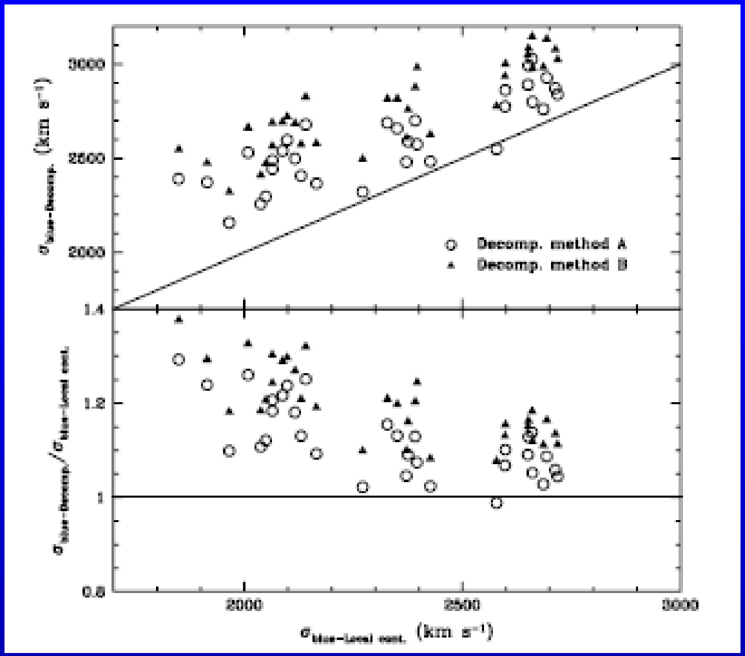
Incorrect Choice Introduces Bias Based on Line Width

- The importance of this is that the masses are shifted *systematically*
  - In this case, the high-Eddington rate objects have smaller masses for FWHM than for σ_{line}
- Leads to incorrect BH mass function and other troubles...

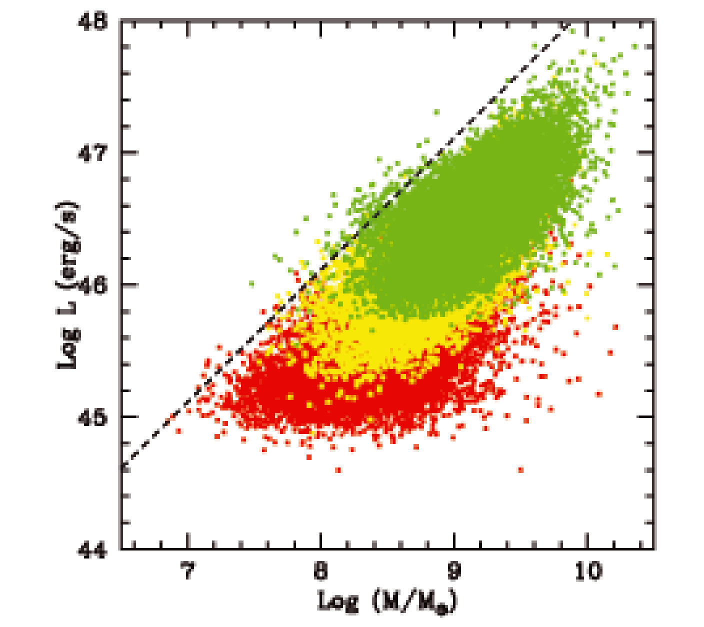


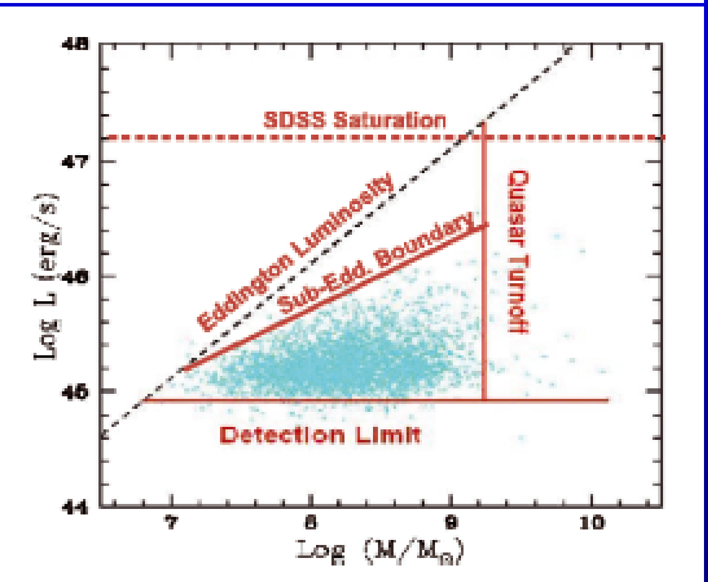
Line Dispersion σ_{line}





- So why hesitate in declaring σ_{line} the winner?
- For Hβ, σ_{line} is underestimated due to contamination by He II 4686.
- This effect is small compared to real change with line width.





Steinhardt & Elvis 2010

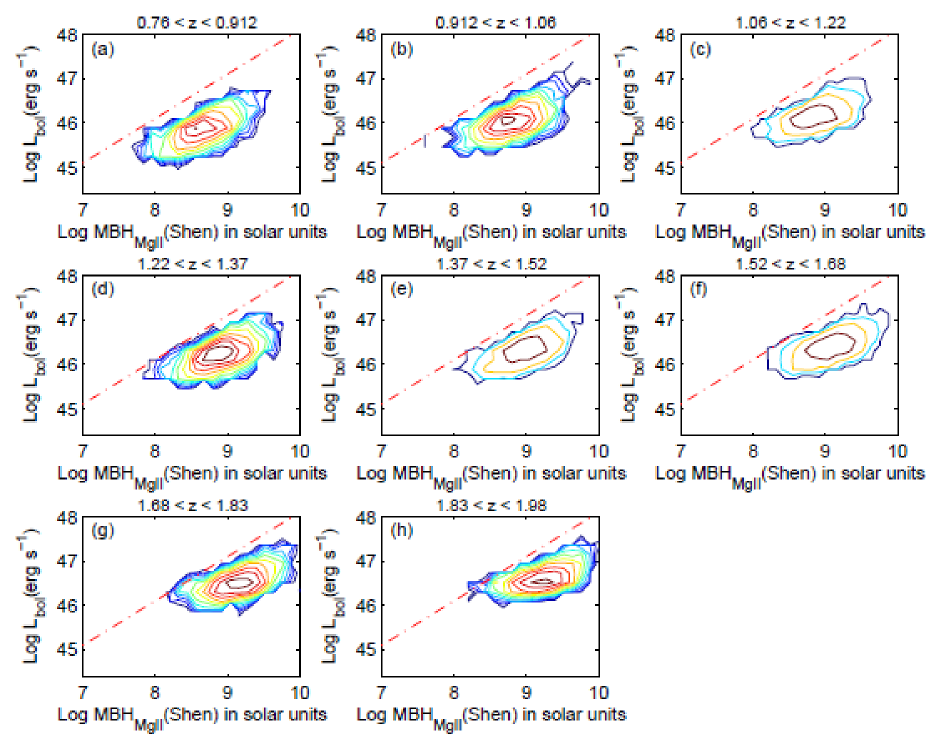
The Sub-Eddington Limit

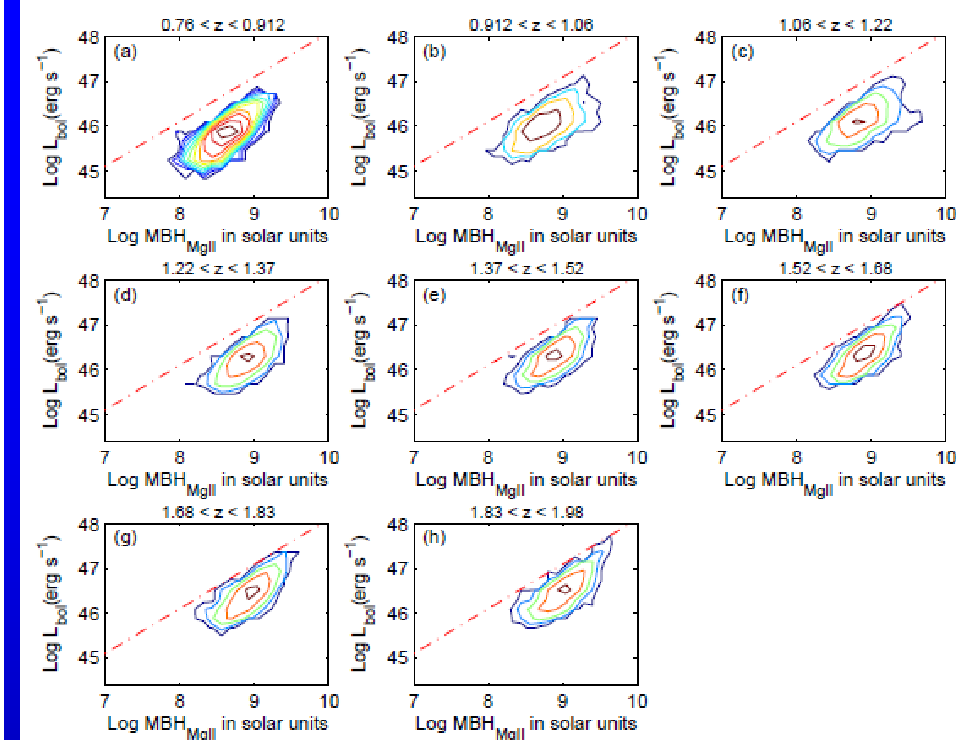
- The most massive black holes seem to be unable to approach the Eddington limit.

  Steinhardt & Elvis 2010

- Line widths used were from Gaussian fits to broad emission lines.

  Shen, Greene, et al. 2008





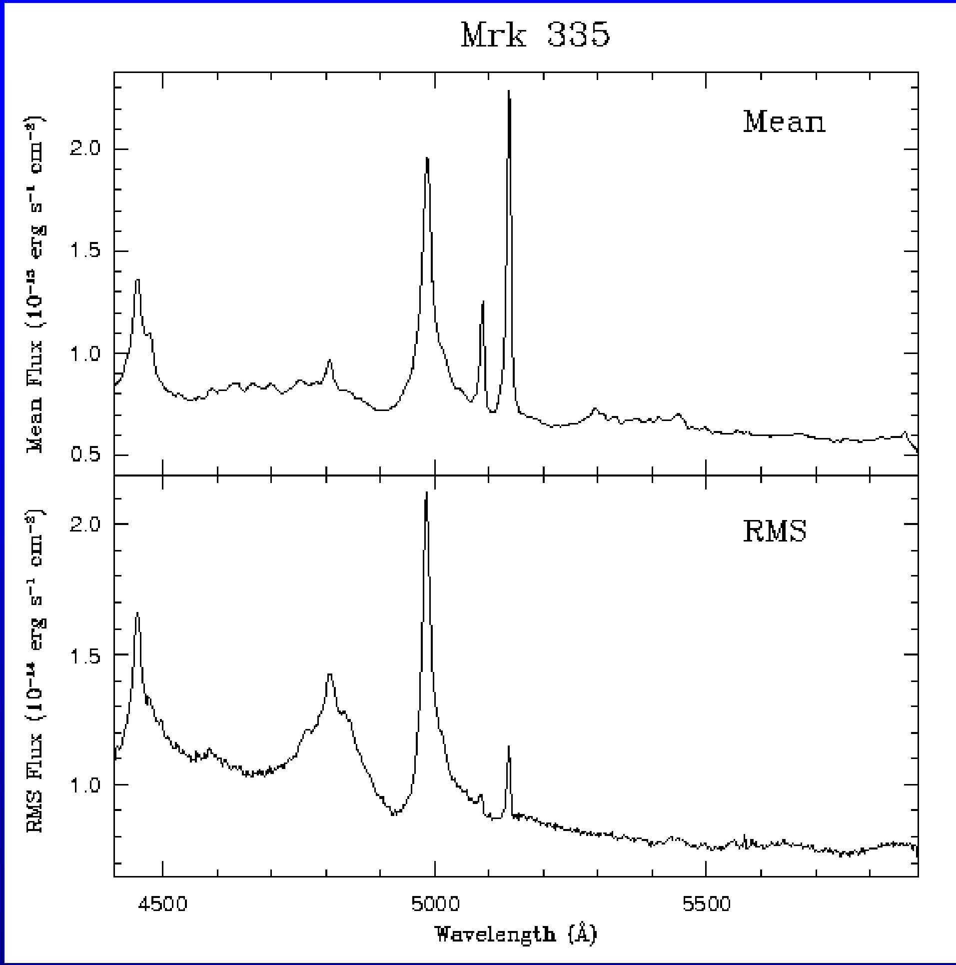
FWHM-based

σ_{line}-based

Rafiee & Hall 2011

The sub-Eddington limit vanishes when the masses are based on σ_{line} measured directly from the spectra instead of FWHM from a Gaussian fit.

Speaking of σ_{line}…

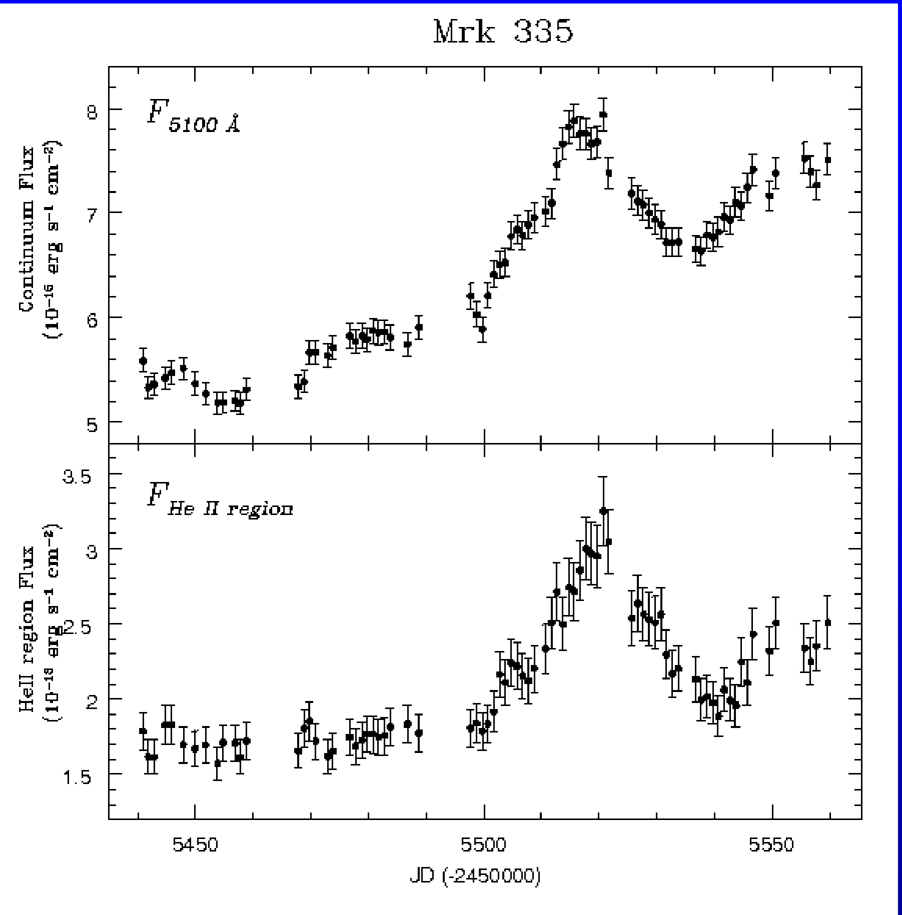


Grier et al. in prep
See poster by Grier

New Reverberation Results on Mrk 335

- Exceptionally broad (FWHM ~ 5000 km s^{-1} He II in RMS spectra) is characteristic of NLS1s
  - Easy to see in RMS spectrum because while Fe II *varies*, it doesn't *reverberate*.
  - Line dispersion σ_{line} can be measured pretty cleanly in the rms spectrum because of less blending than in mean spectrum.

New Reverberation Results on Mrk 335



- For the first time, time resolution good enough to measure response of a high-ionization line (He II 4686) in an NLS1. Preliminary values:
  - $\tau = 2.6 \pm 0.8$ days
  - $\sigma = 2716 \pm 50$ km s^{-1}

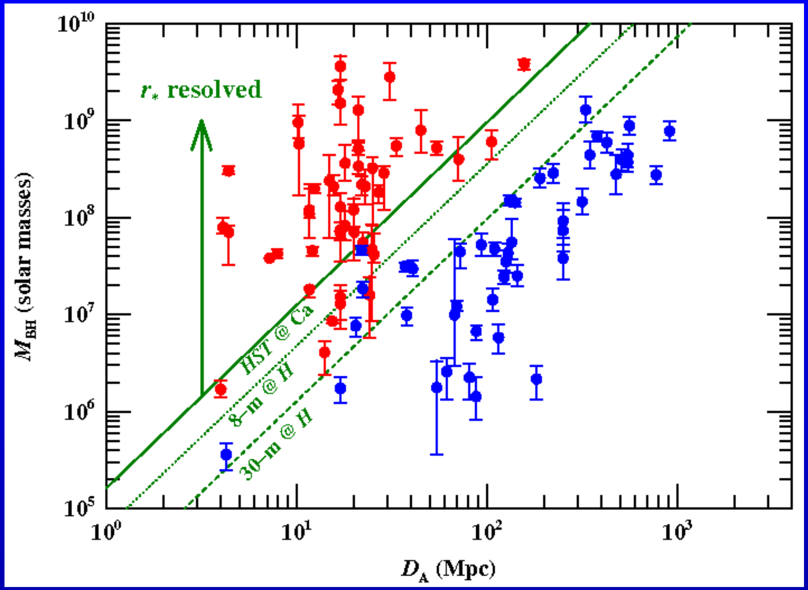
Grier+ in prep
See Grier poster

$$M_{BH}(\text{He II}) = (1.99 \pm 0.62)\times 10^7 M_\odot$$
$$M_{BH}(\text{H}\beta) = (1.44 \pm 0.37)\times 10^7 M_\odot$$

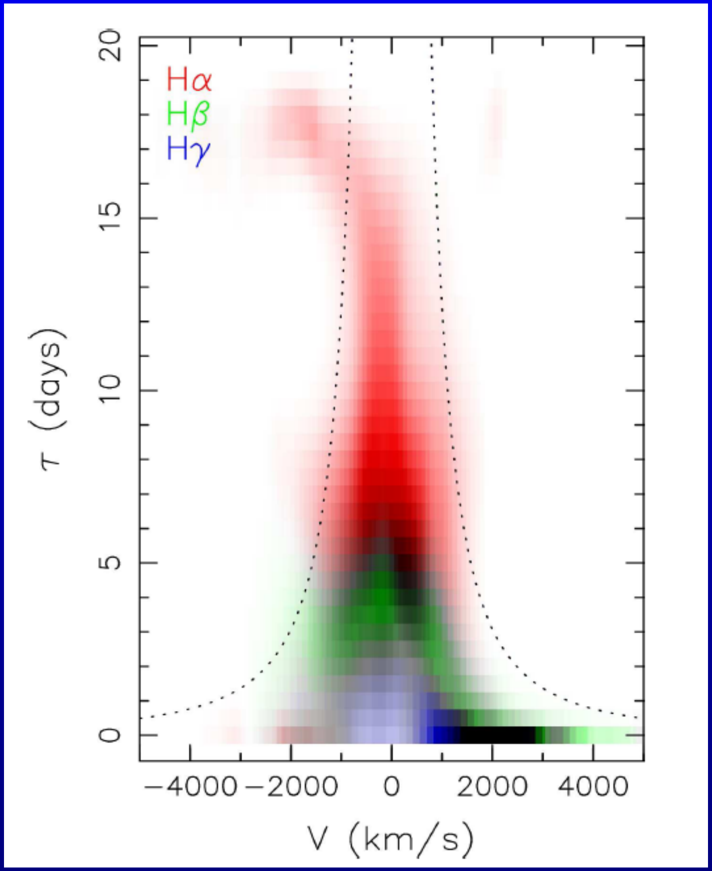
Higher Precision Masses

- AGN mass scale currently relies heavily on correlations between M_{BH} and host-galaxy properties.
- Larger sample sizes, higher-quality data lead to new questions, many of which will be addressed by today's speakers.
  - Are M_{BH}-host correlations the same in AGNs and quiescent galaxies? How reliable are scaling relations over L and z ?
  - Are M_{BH}-host correlations the same in NLS1s and other AGNs?
  - Does failure to account for radiation pressure lead us to underestimate M_{BH}?
    - NLS1s are the testing ground for this!
  - What problems do we encounter using different emission lines to determine M_{BH}?
  - How can we resolve the inclination/Eddington rate ambiguity in NLS1s? Is there a line-width parameter that is unbiased with respect to these?
  - Are there other systematic effects that are important?

…which leads us back to reverberation mapping.



Reverberation mapping remains our best hope for obtaining reliable black hole masses locally and over cosmic time.



Brad's gripe du jour:

- Estimating masses from the *R*–*L* relationship and line widths is sometimes erroneously called the "Dibai method."
- Dibai (1977 Soviet Astronomy, 3, 1) argument:
  - AGN emission lines have equivalent widths independent of luminosity $L_{\rm line} \propto L_{\rm cont}$
  - Assume constant line emissivity per unit volume ε $L_{\rm line} = \varepsilon\left(\frac{4\pi}{3}R_{\rm BLR}^3\right)$
  - Implied relationship between BLR size and AGN luminosity $R_{\rm BLR} \propto L_{\rm cont}^{1/3}$
  - Apply virial theorem for mass $M_{\rm BH} \propto \Delta V_{\rm line}^2 L_{\rm cont}^{1/3}$
- Physics wrong, dependence on *L* incorrect, and incorrectly ascribes credit
  - Kris Davidson seems to have been the first to have understood the implications of the ionization parameter as a predictor of the BLR size.