Uncertainties in AGN Black Hole Masses

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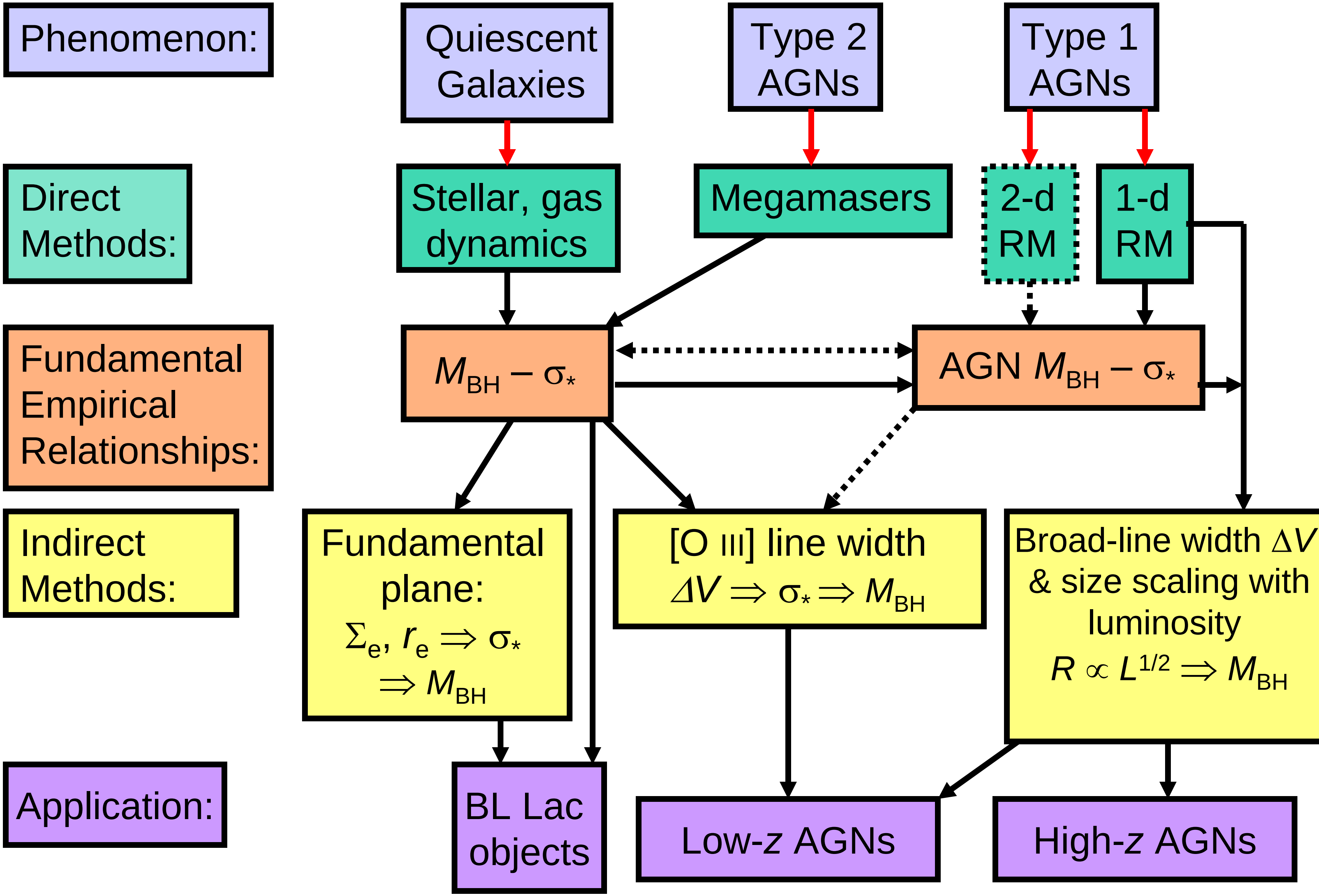
Measurement of Central Black Hole Masses



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	29 –120

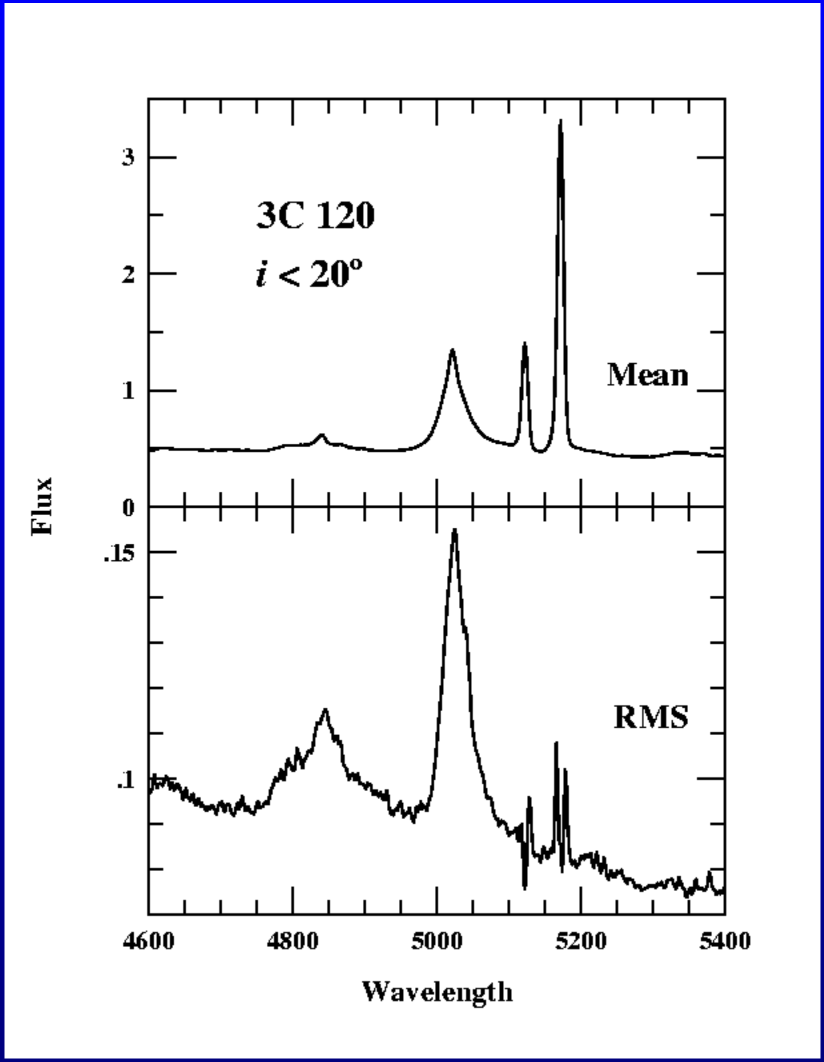
References: see Peterson (2010) [arXiv:1001.3675]

Reverberation-Based Masses

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

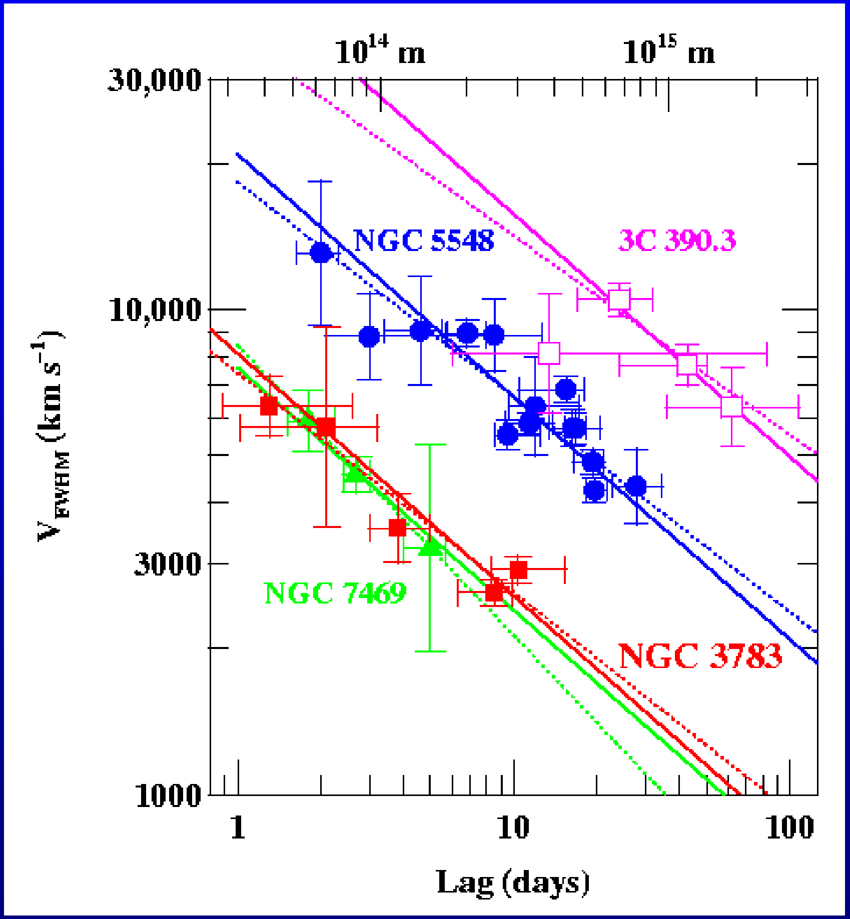
$$M = f\,(c\tau_{\rm cent}\sigma^2 / G)$$

- 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.



First Evidence that Lag + Line Width Measures Mass

- Virial relationship between lag and line width is constant for each source in which multiple measurements have been made.

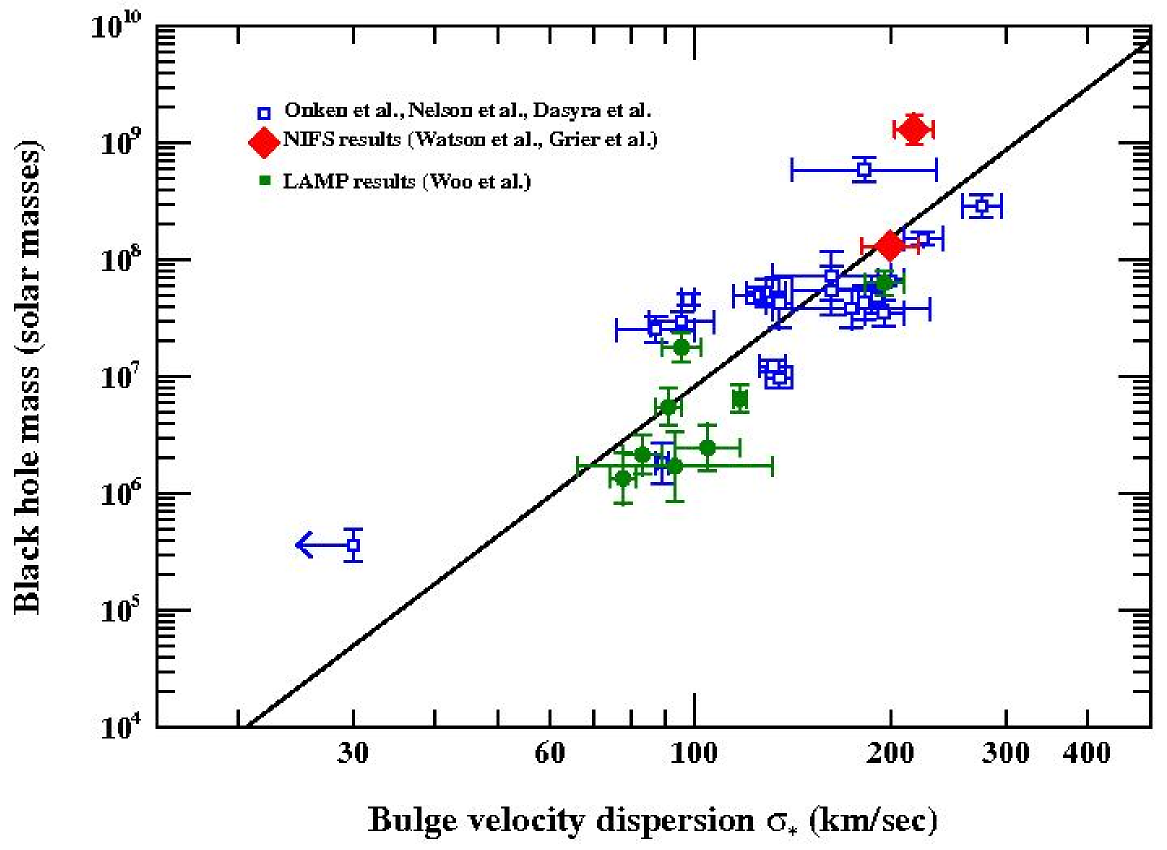


Calibration of the Reverberation Mass Scale Using M_{BH}–σ_*

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

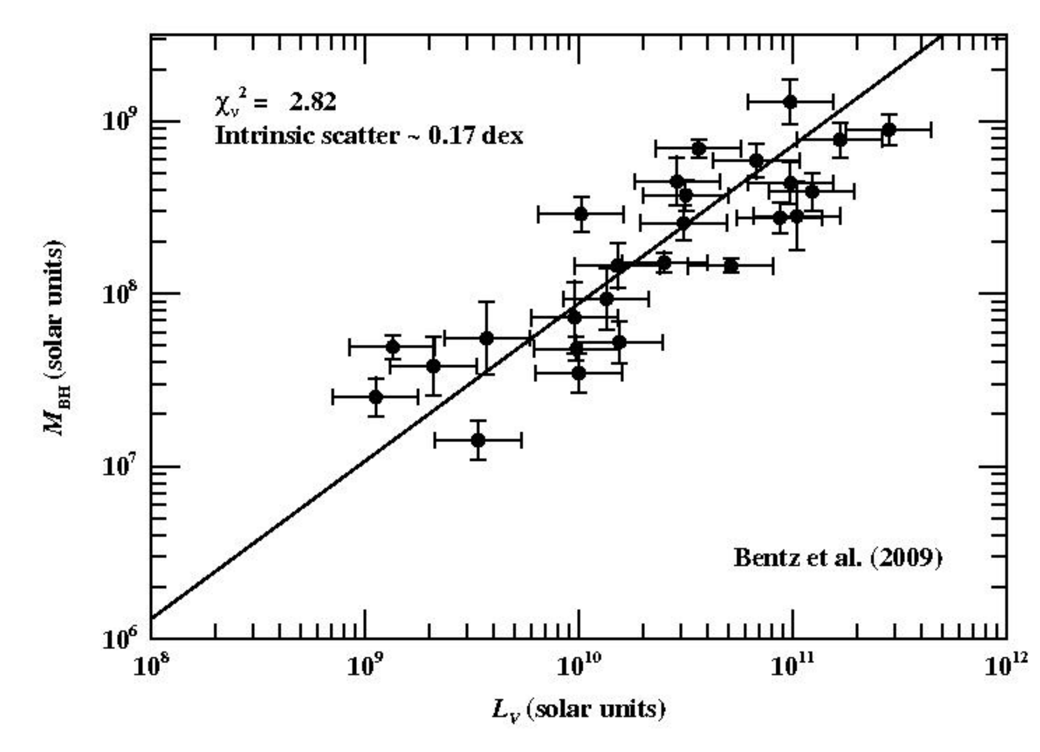
- Determine scale factor $\langle f \rangle$ that matches AGNs to the quiescent-galaxy M_{BH}-σ_*. relationship
- Recent estimate: $\langle f \rangle = 5.25 \pm 1.21$

Woo et al. (2010)



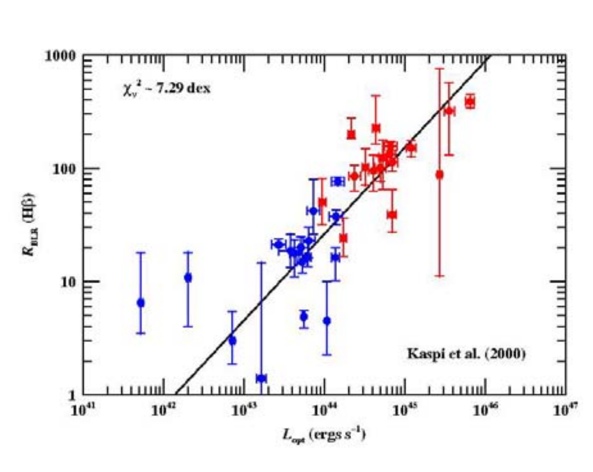
Intrinsic scatter: $\Delta\log M_{BH}$ ~ 0.40 dex (Peterson 2010)
~ 0.44 dex (Woo+2010)
~ 0.38 dex (Gültekin+2009)

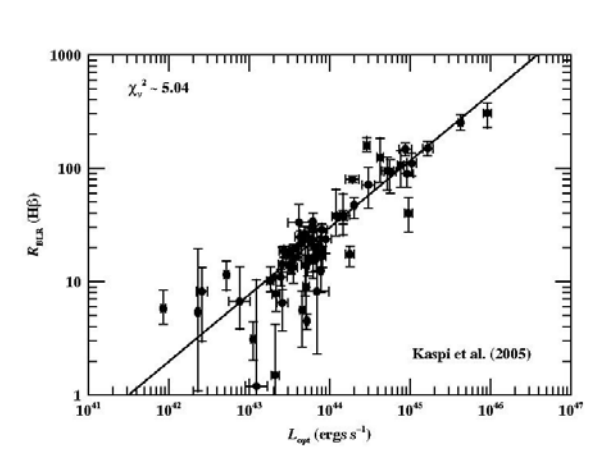
The AGN M_{BH}–L_{bulge} Relationship

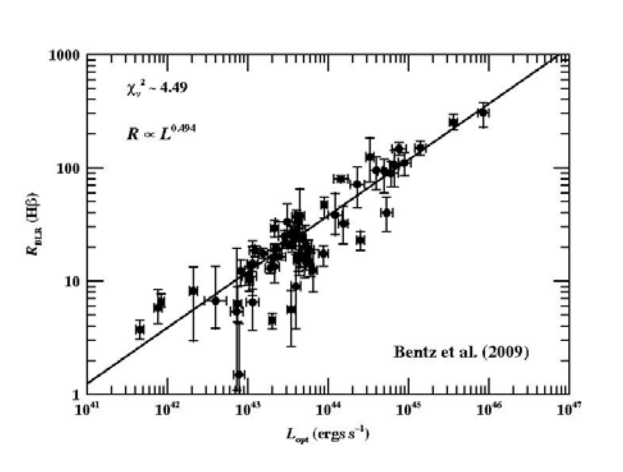


- Line shows best-fit to quiescent galaxies
- Maximum likelihood gives upper limit to intrinsic scatter $\Delta \log M_{BH}$ ~ 0.17 dex.
  - Smaller than quiescent galaxies ($\Delta \log M_{BH}$ ~ 0.38 dex).

Progress in Determining the Radius-Luminosity Relationship







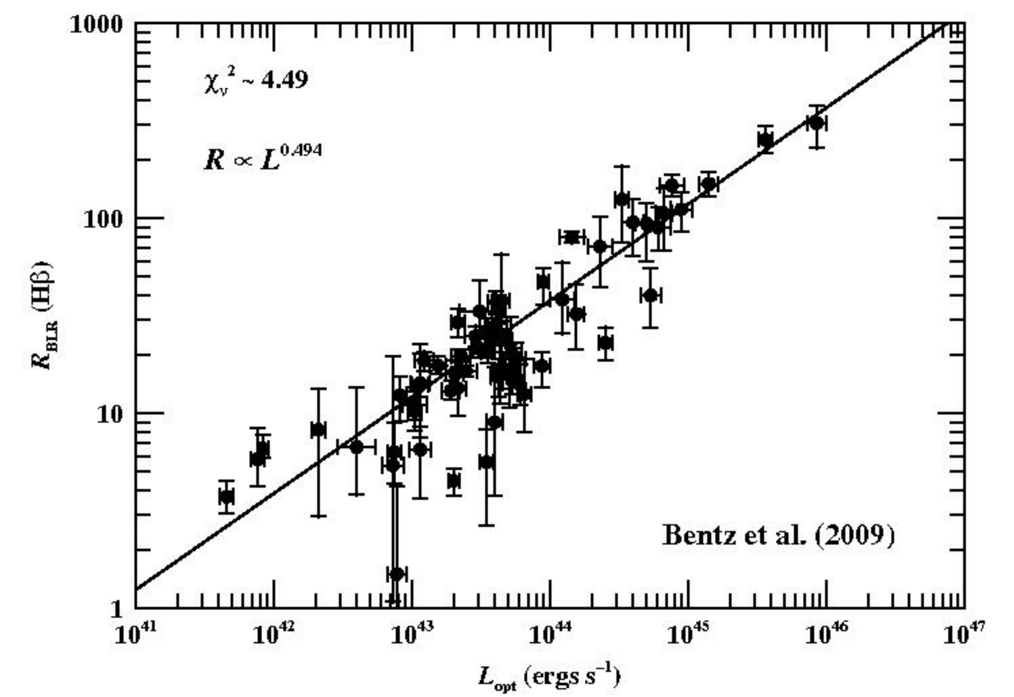
Original PG + Seyferts
(Kaspi et al. 2000)
$\chi_\nu^2 \approx 7.29$
$R(\mathrm{H}\beta) \propto L^{0.76}$

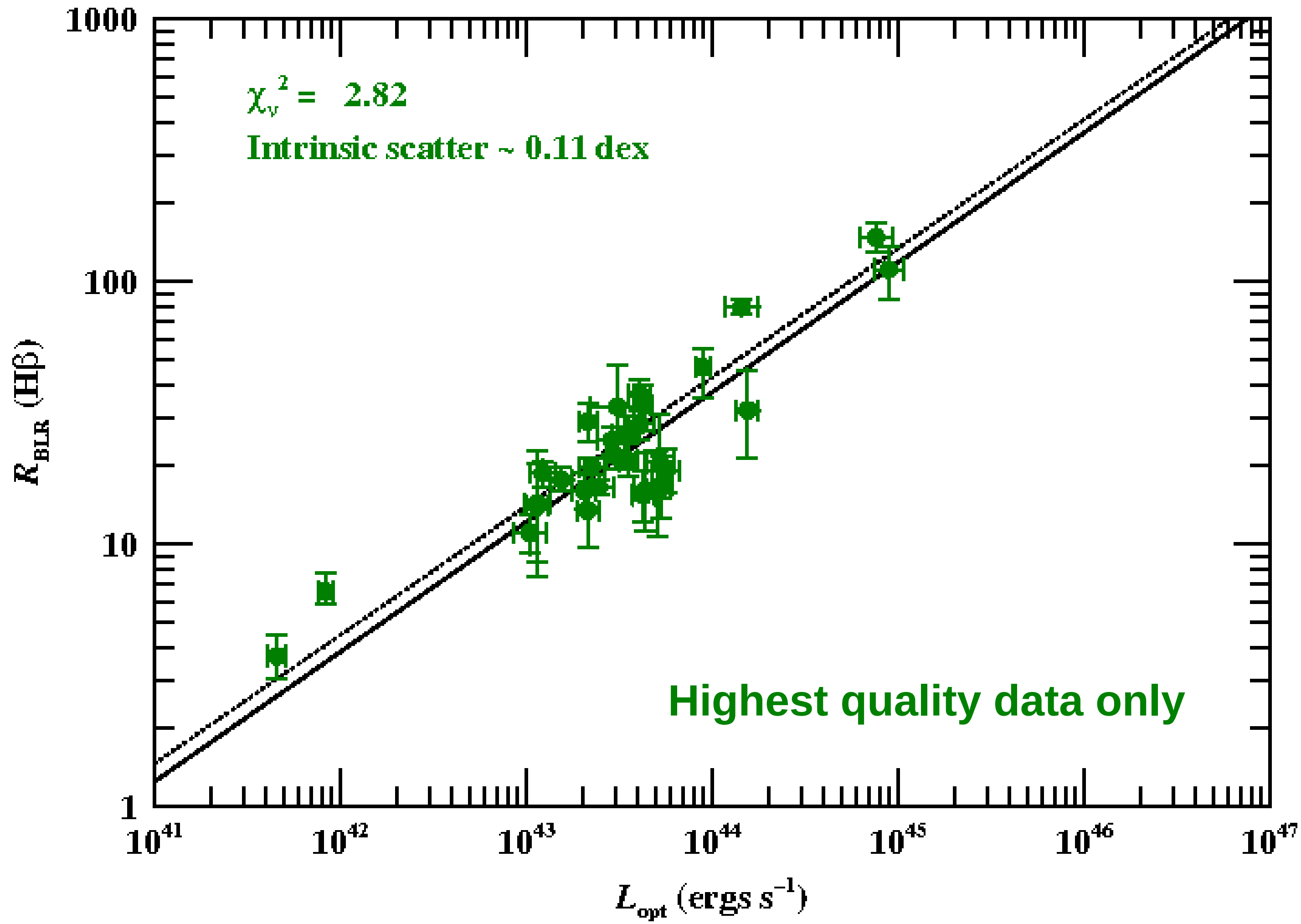
Expanded, reanalyzed
(Kaspi et al. 2005)
$\chi_\nu^2 \approx 5.04$
$R(\mathrm{H}\beta) \propto L^{0.59}$

Starlight removed
(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.





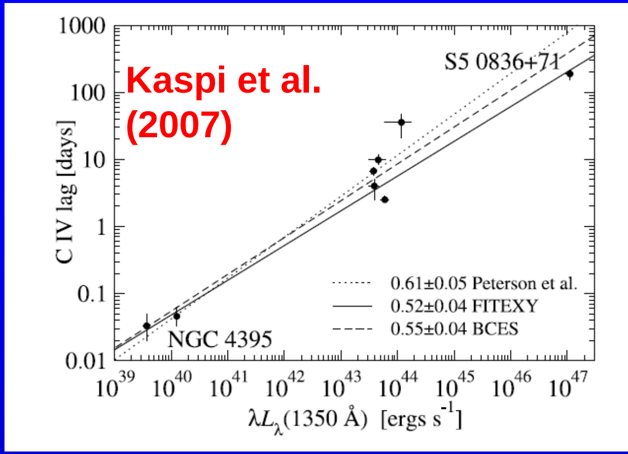
χ_ν^2 = 2.82
Intrinsic scatter ~ 0.11 dex
Highest quality data only
1000
100
10
1
R_{BLR} (Hβ)
10^{41}
10^{42}
10^{43}
10^{44}
10^{45}
10^{46}
10^{47}
L_{opt} (ergs s^{-1})

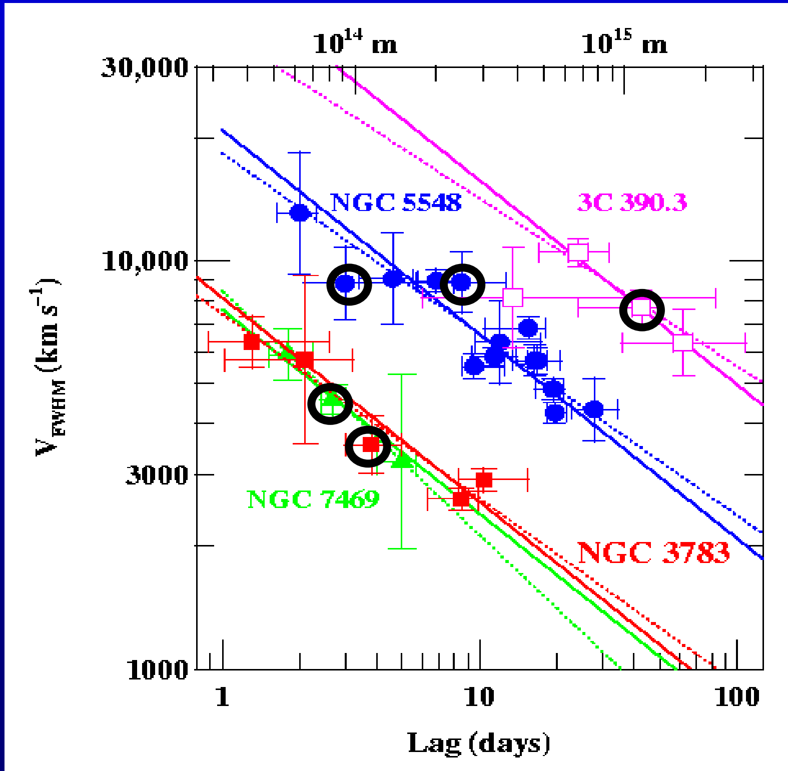
R-*L* Relationship

- 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.

R-L Relationship for C IV λ1549

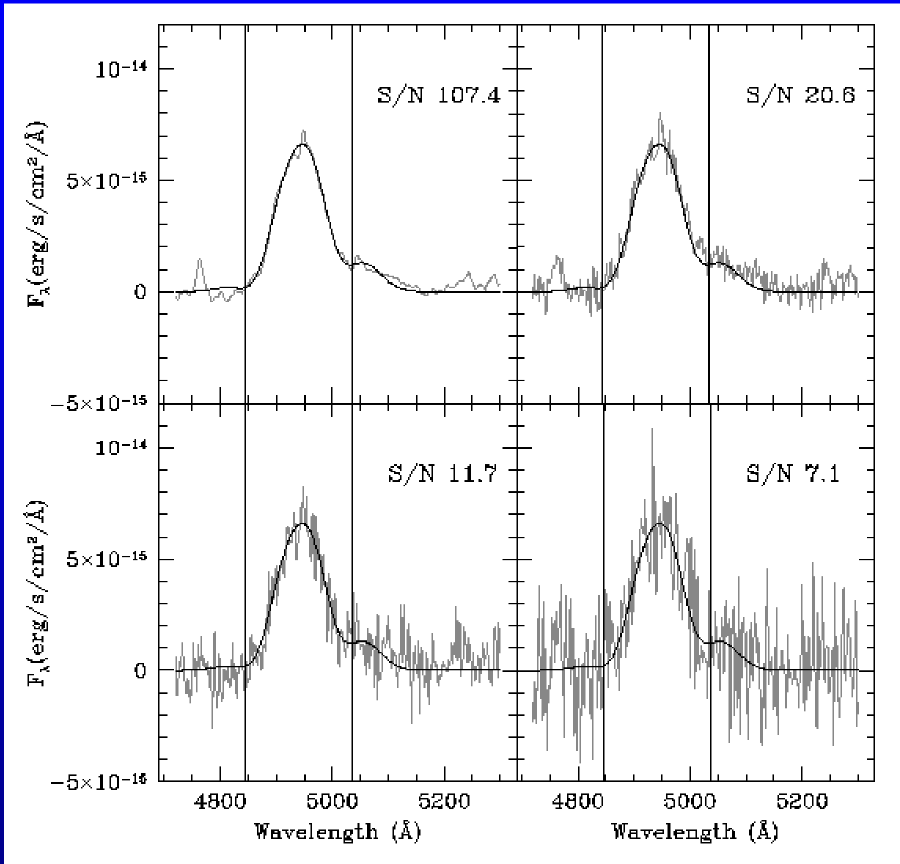
- First used by Vestergaard (2002) to estimate BH masses at high-*z*.
- Pros:
  - Limited data suggest same *R-L* slope as Hβ (despite Baldwin Effect).
  - Consistent with virial relationship, at least in low-luminosity AGNs.
- Cons:
  - Often strong absorption, usually in blue wing.
  - Extended bases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



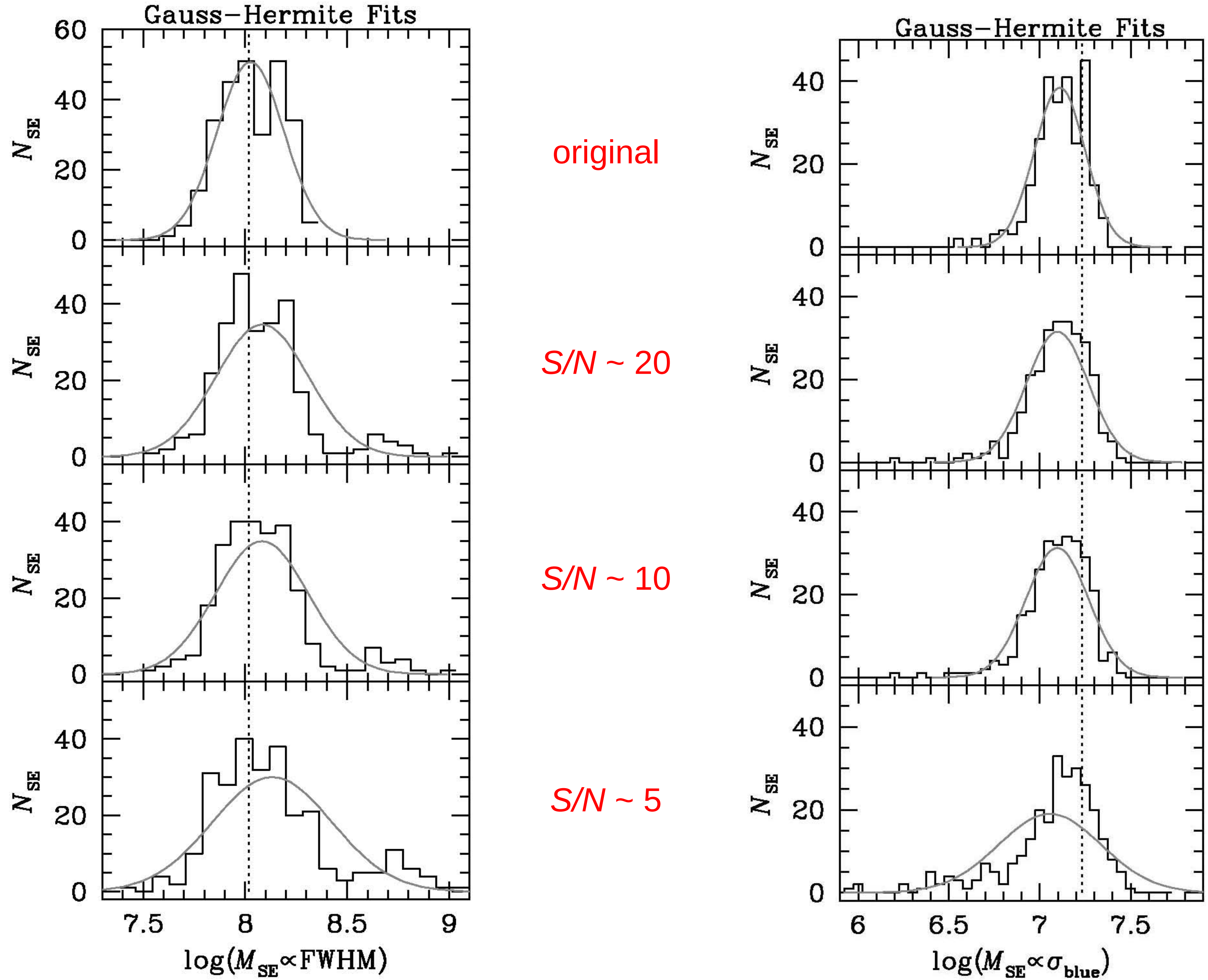


An Overlooked Issue

- 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.



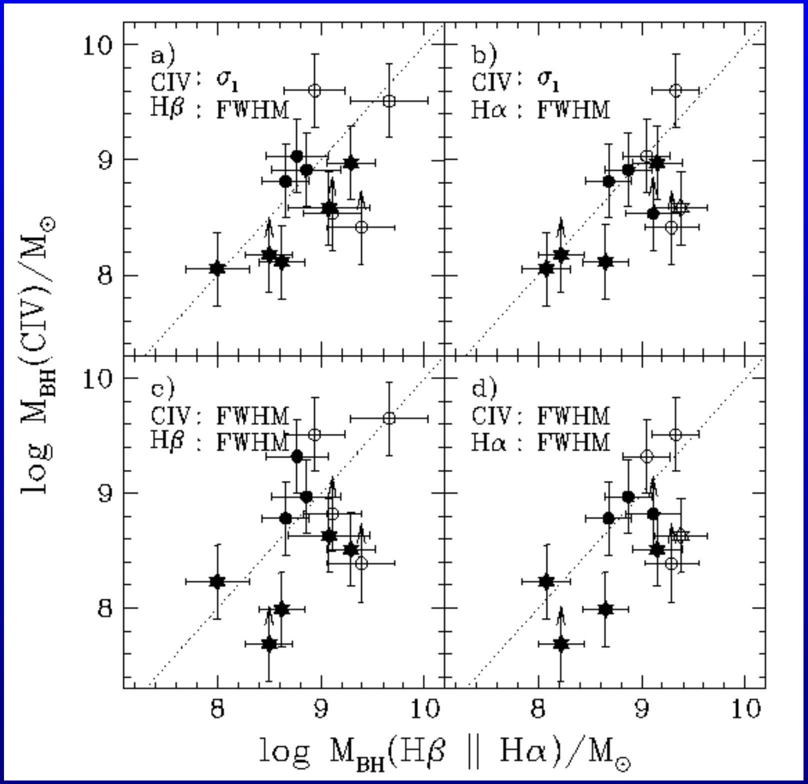
Denney et al. 2009, ApJ, 692, 246

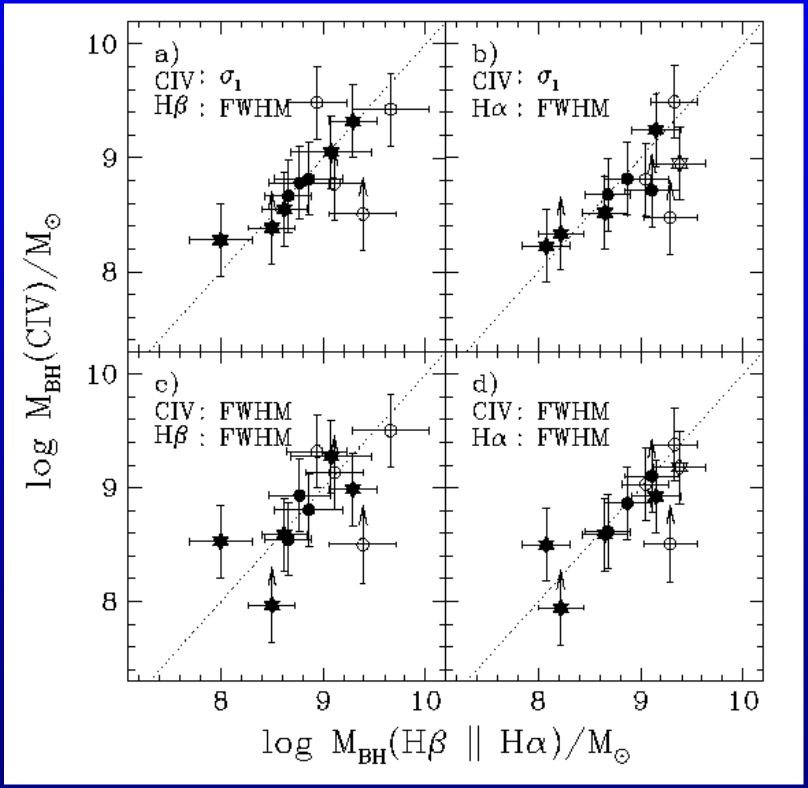


Gauss−Hermite Fits
Gauss−Hermite Fits
original
S/N ~ 20
S/N ~ 10
S/N ~ 5
N_SE
log(M_SE∝FWHM)
log(M_SE∝σ_blue)

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.

From Assef, Denney+, 2010 (astro-ph very soon)

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