The Central Black Hole and Relationships with the Host Galaxy

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“Active Galactic Nuclei at the Highest Angular Resolution”

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Topics to be Covered

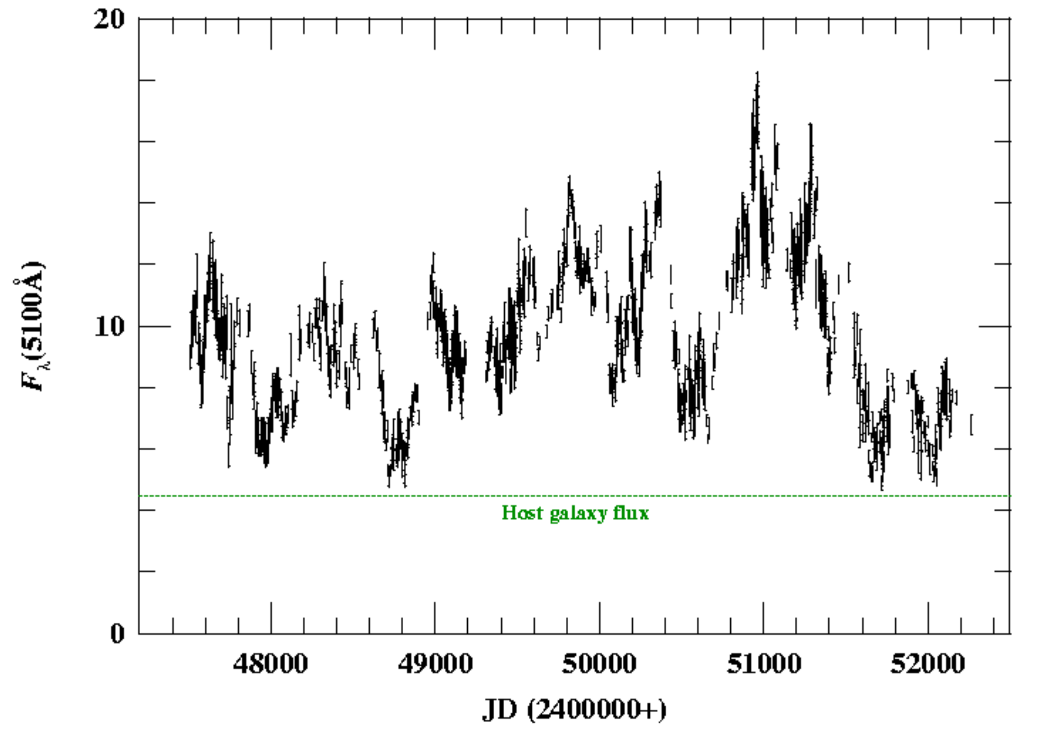
- *Lecture 1:* AGN fundamentals, evidence for supermassive black holes, AGN continuum variability
- *Lecture 2:* Emission-line variability, reverberation mapping, the radius–luminosity relationship
- *Lecture 3:* AGN black hole masses, comparisons between methods, relationships between BH mass and AGN/host properties, requirements for velocity–delay maps, the nature of NLS1s

Lecture 3

- Time-variable lags
  - How is the BLR fine-tuned?
- Reverberation-based black hole masses
  - Virial relationship and characterizing line widths
- Calibrating the mass scale via M_{BH}–σ_*
- The M_{BH} – L_{bulge} relationship
- The M_{BH} – L_{AGN} relationship
- Masses from scaling relationships
- Requirements for a velocity–delay map
- The nature of NLS1s (time permitting)

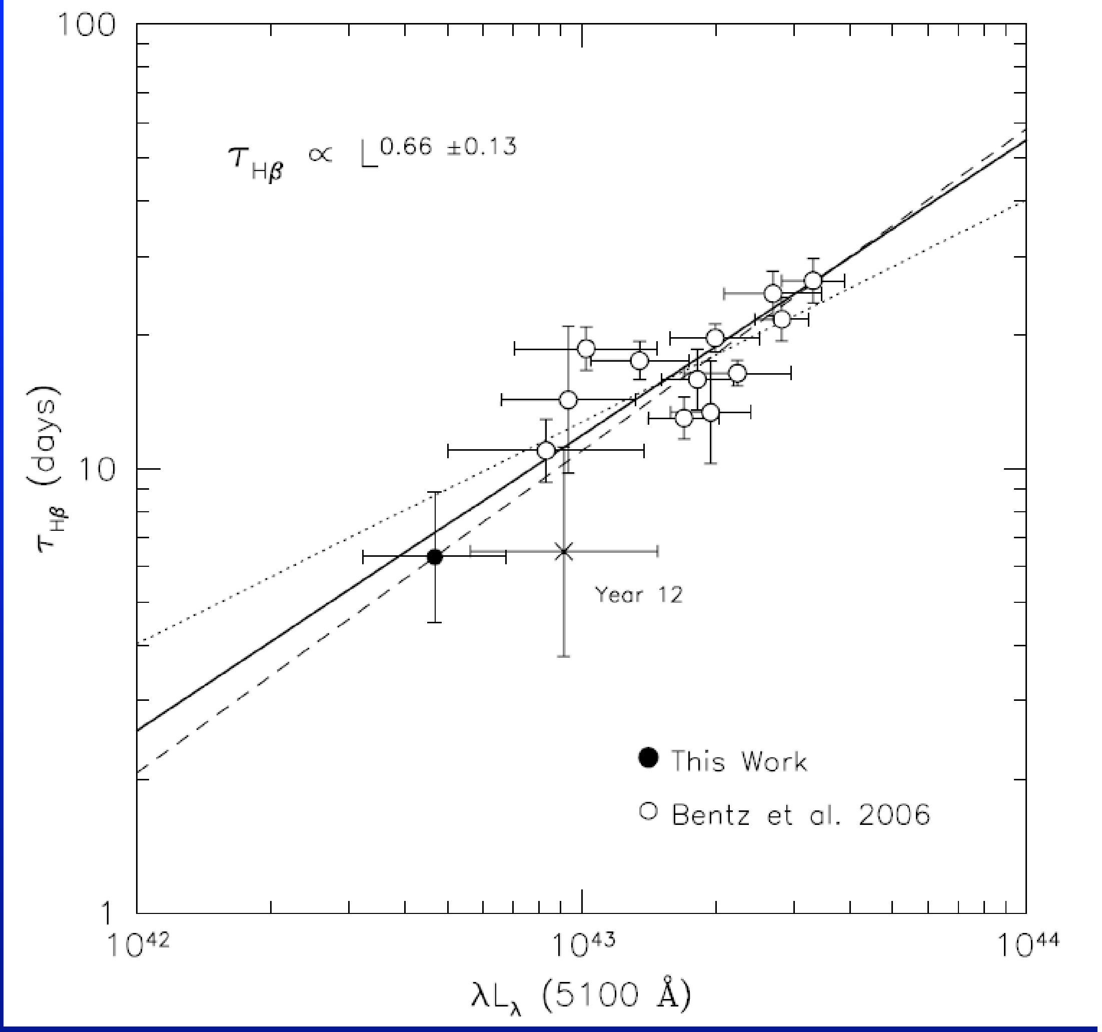
Time-Variable Lags

- 14 years of observing the Hβ response in NGC 5548 shows that lags increase with the mean continuum flux.



Time-Variable Lags

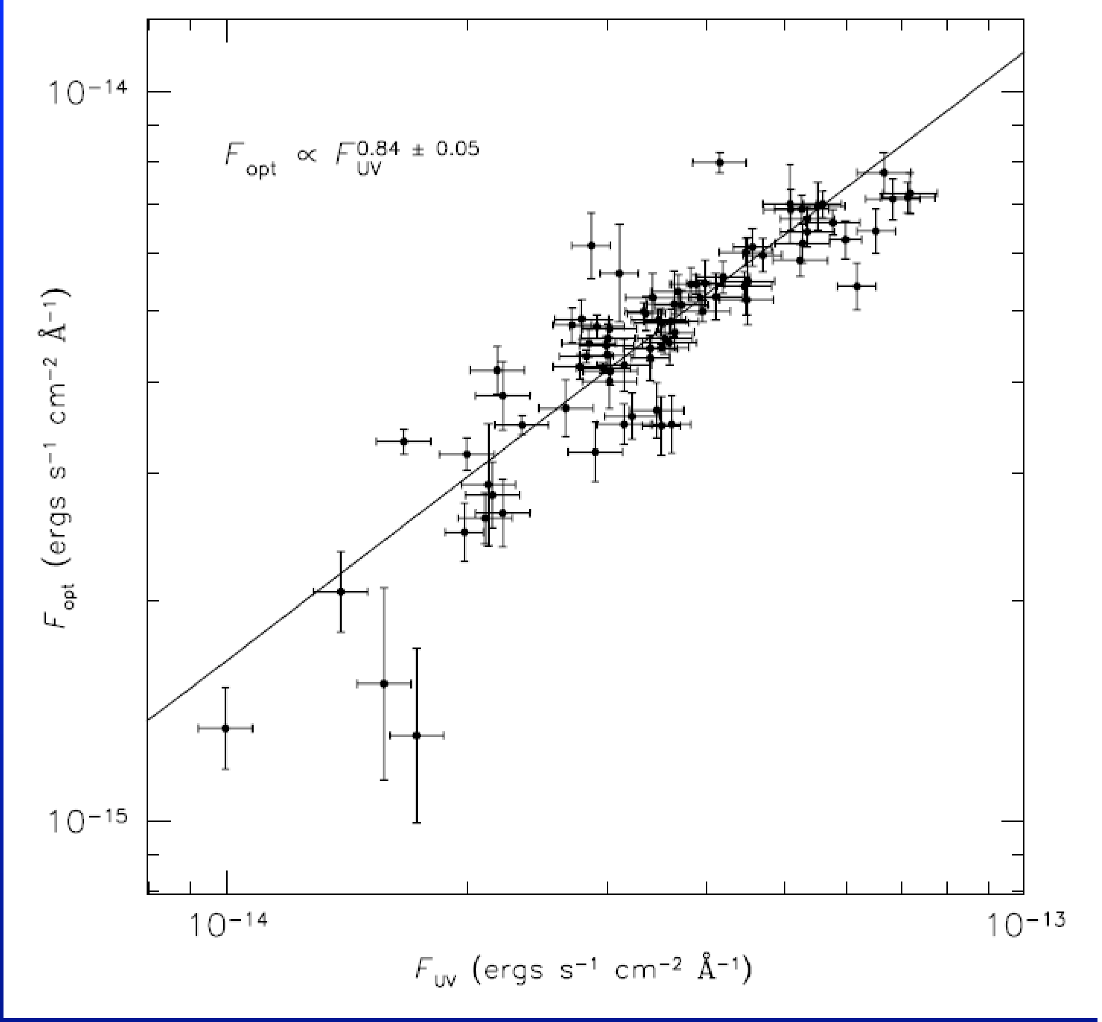
- Measured lags range from 6 to 26 days.
- Best fit is log $R \propto (0.66 \pm 0.13) \log L_{\rm opt}$



Bentz et al. 2007

Time-Variable Lags

- Measured lags range from 6 to 26 days.
- Best fit is $\log R \propto (0.66 \pm 0.13) \log L_{opt}$
- However, UV varies more than optical:
  - $\log L_{opt} \propto (0.84 \pm 0.05) \log L_{UV}$
- Thus, $\log R \propto (0.55 \pm 0.14) \log L_{UV}$



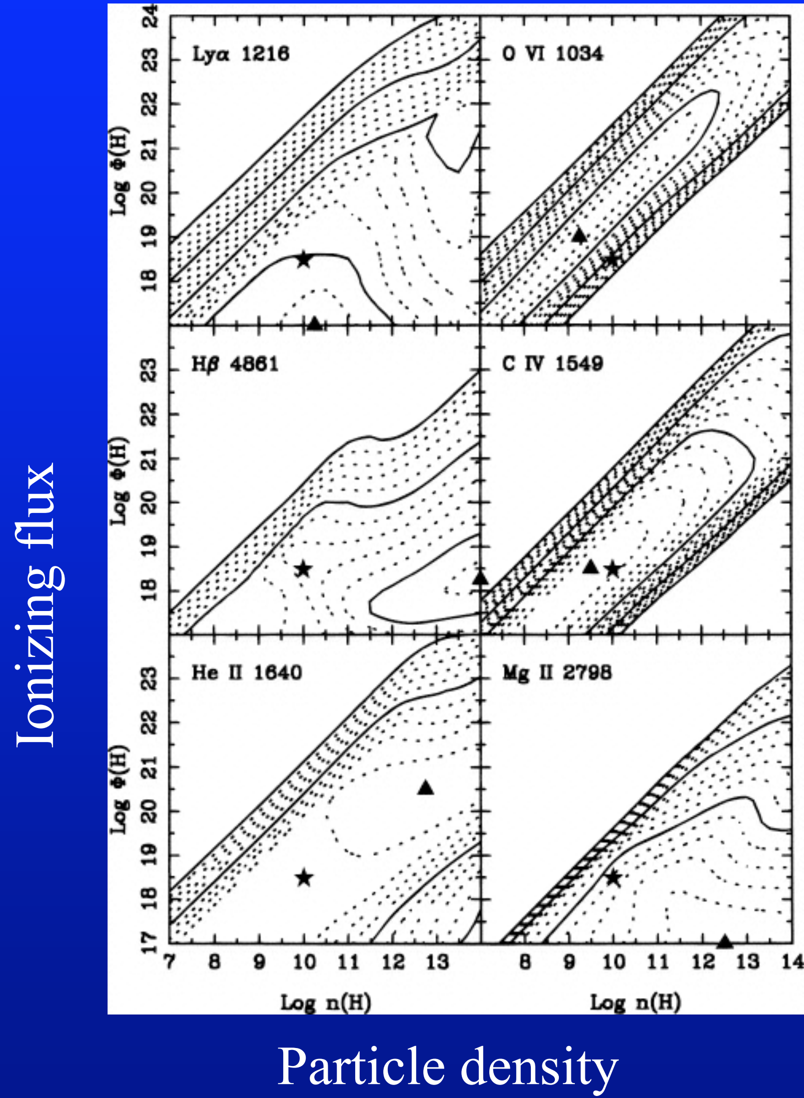
Bentz et al. 2007

What Fine–Tunes the BLR?

- Why are the ionization parameter and electron density the same for all AGNs?
- How does the BLR know precisely where to be?
- *Answer:* gas is everywhere in the nuclear regions. We see emission lines emitted under optimal conditions.

Locally optimally-emitting cloud (LOC) model

- The flux variations in each line are *responsivity-weighted.*
  - Determined by where physical conditions (mainly flux and particle density) give the largest response for given continuum increase.
- Emission response in a particular line comes predominantly from clouds with optimal conditions for that line.



Korista et al. 1997

Measuring Black Hole Masses by Reverberation Mapping

- 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 found very close to nucleus
    - Disadvantage: possible role of non-gravitational forces

Virial Estimators

Source	Distance from central source
X-Ray Fe Kα	3-10 R_S
Broad-Line Region	$200-10^4\ R_S$
Megamasers	$4\times10^4\ R_S$
Gas Dynamics	$8\times10^5\ R_S$
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

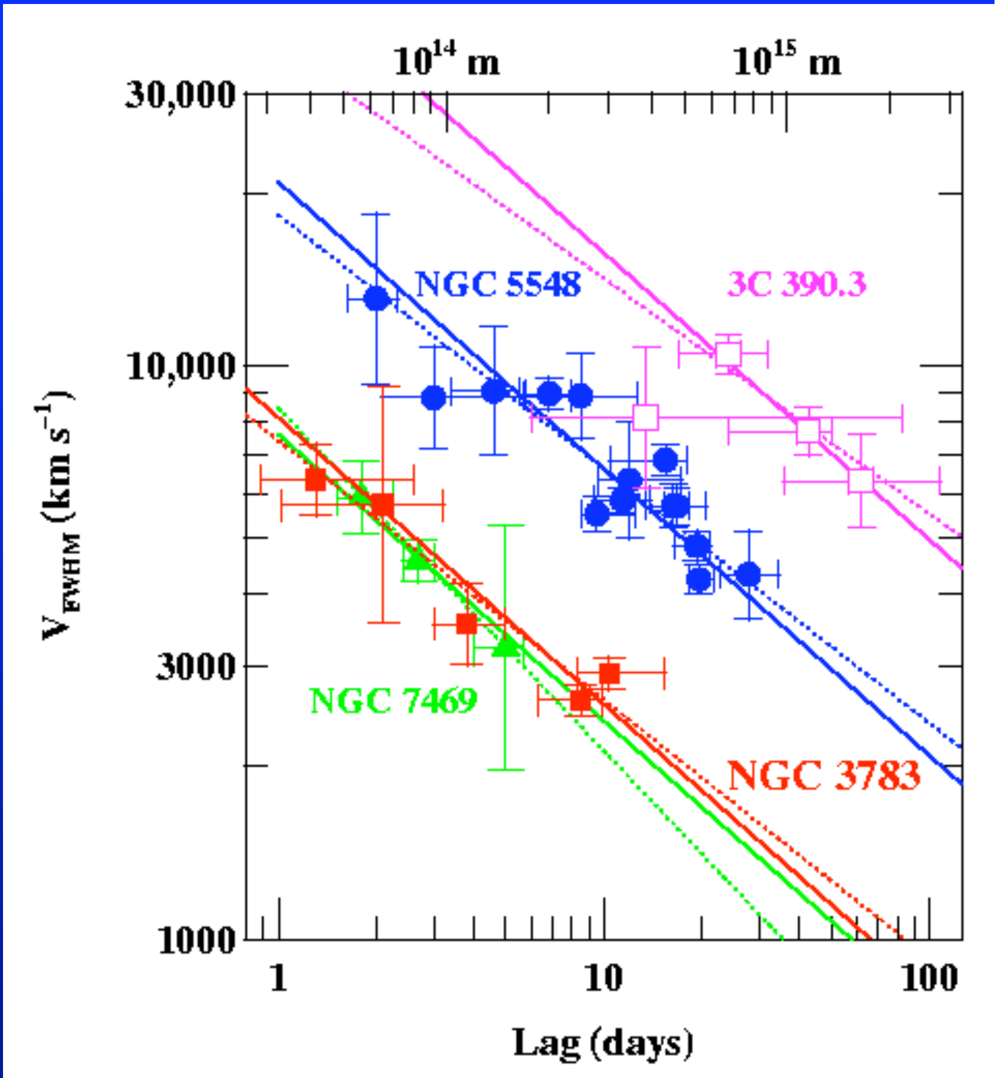
r = scale length of region

ΔV = velocity dispersion

f = a factor of order unity, depends on details of geometry and kinematics

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.



Characterizing Line Widths

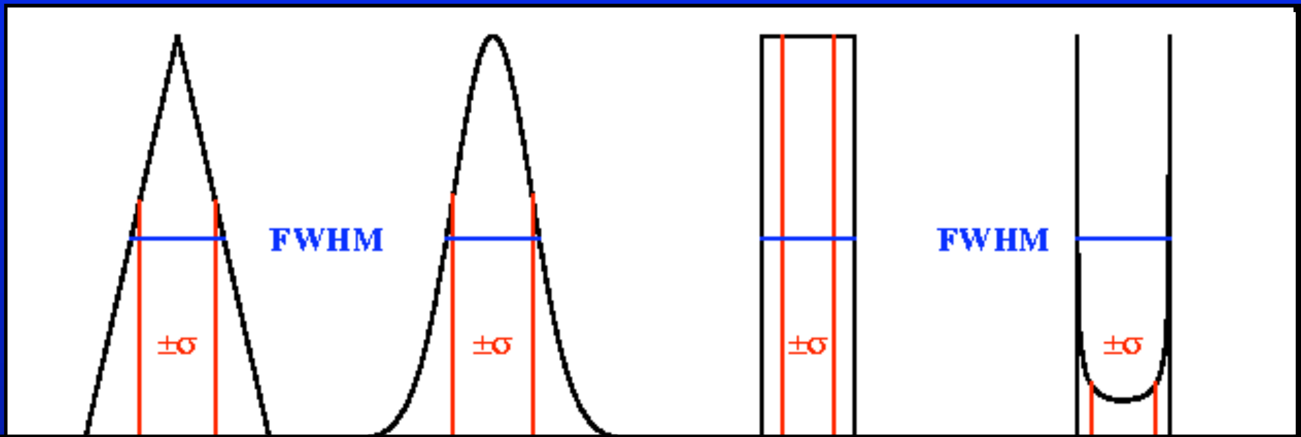
FWHM:

- 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

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

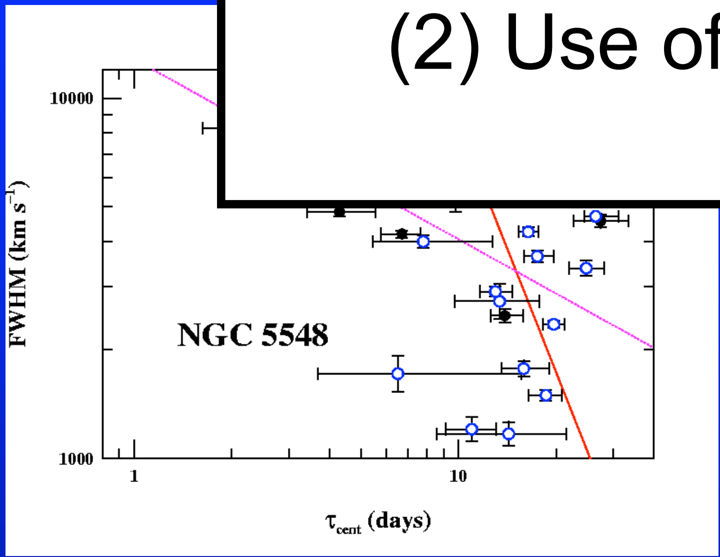
Virial

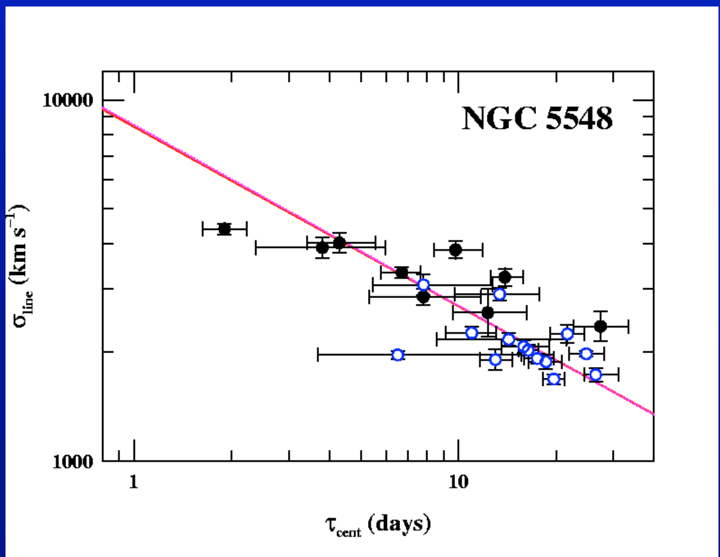
Three contributing factors account for additional scatter:

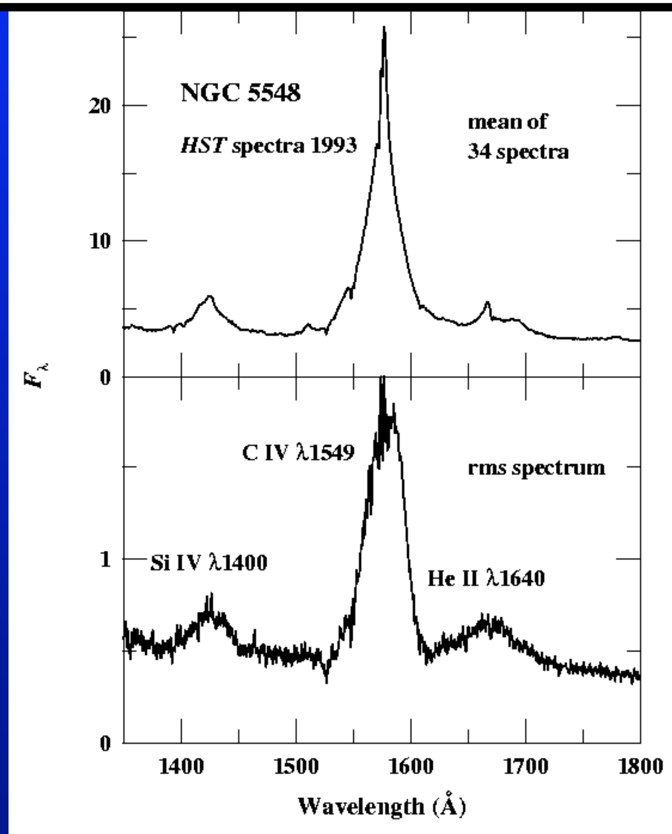
(1) Failure to account for narrow component

(2) Use of mean rather than rms spectrum

(3) Use of FWHM instead of σ_{line}



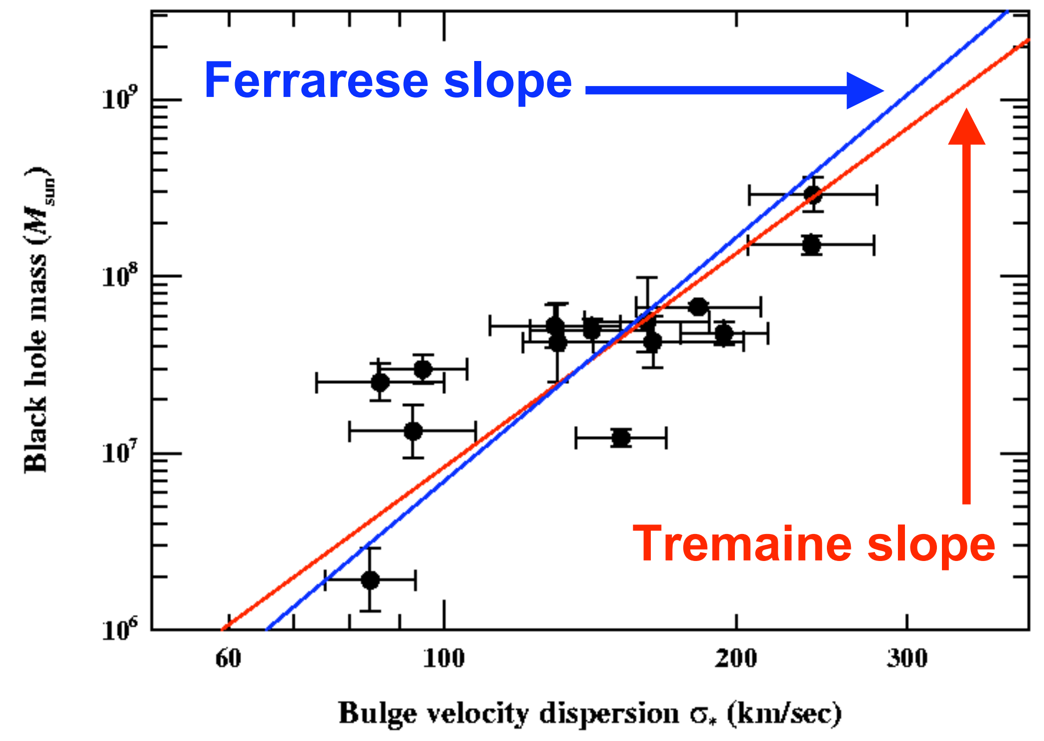




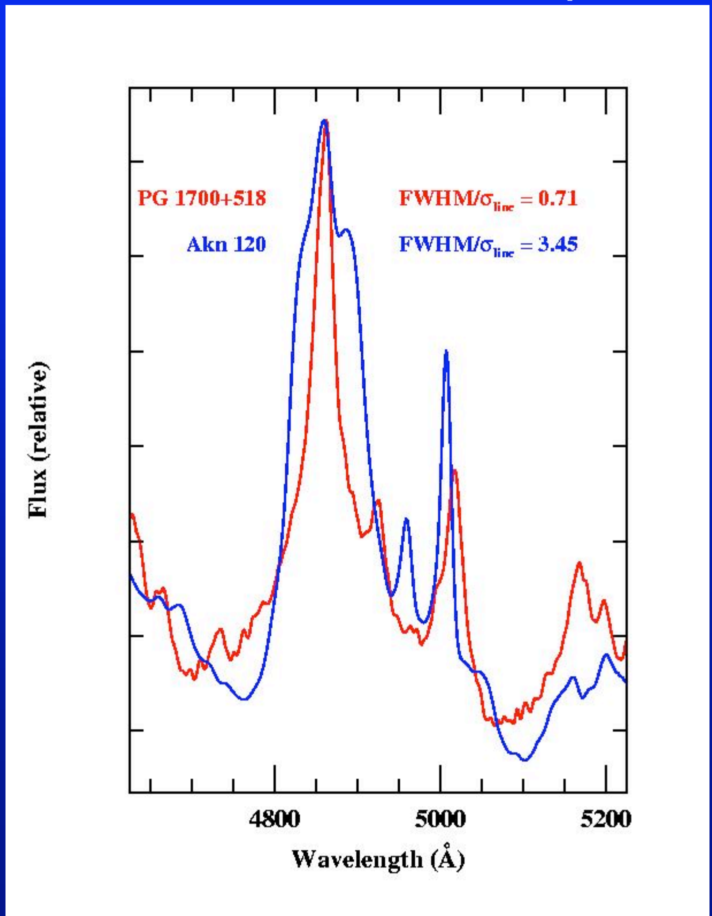
Calibration of the Reverberation Mass Scale

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

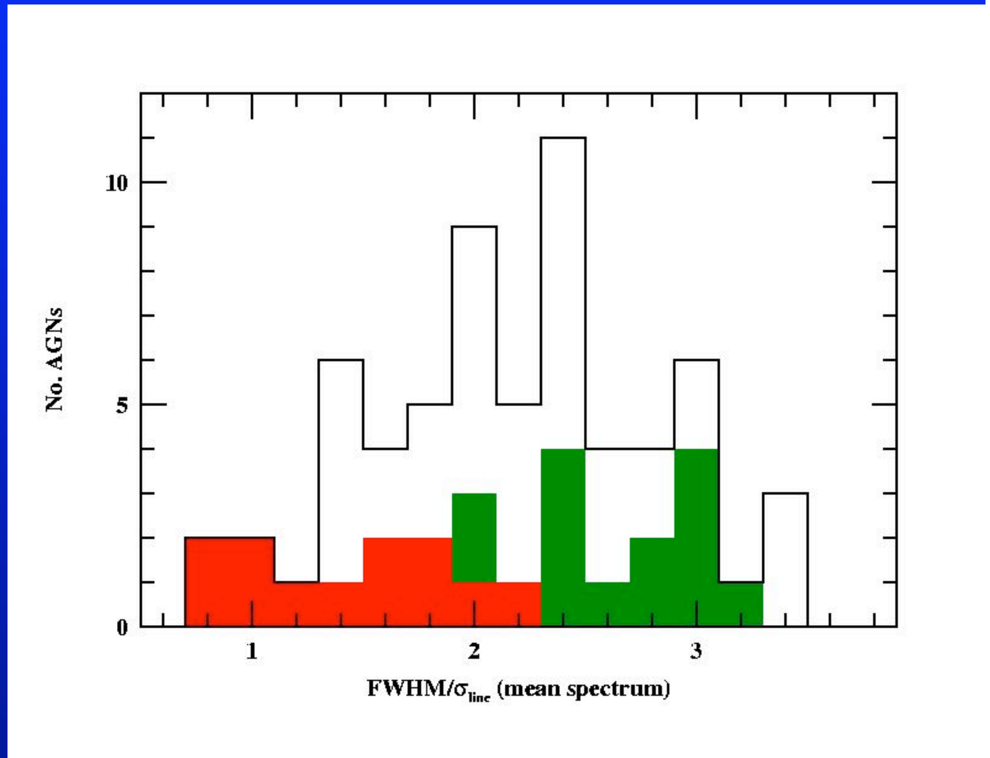
- Determine scale factor *f* that matches AGNs to the quiescent-galaxy M_{BH}-σ_*. relationship
- Current best estimate:
  f = 5.5 ± 1.8



- Reverberation-mapped AGNs show broad range of FWHM/σ_{line}.
- Mass calibration is sensitive to which line-width measure is used!
  - Even worse, there is a bias with respect to AGN type (as reflected in the profiles)

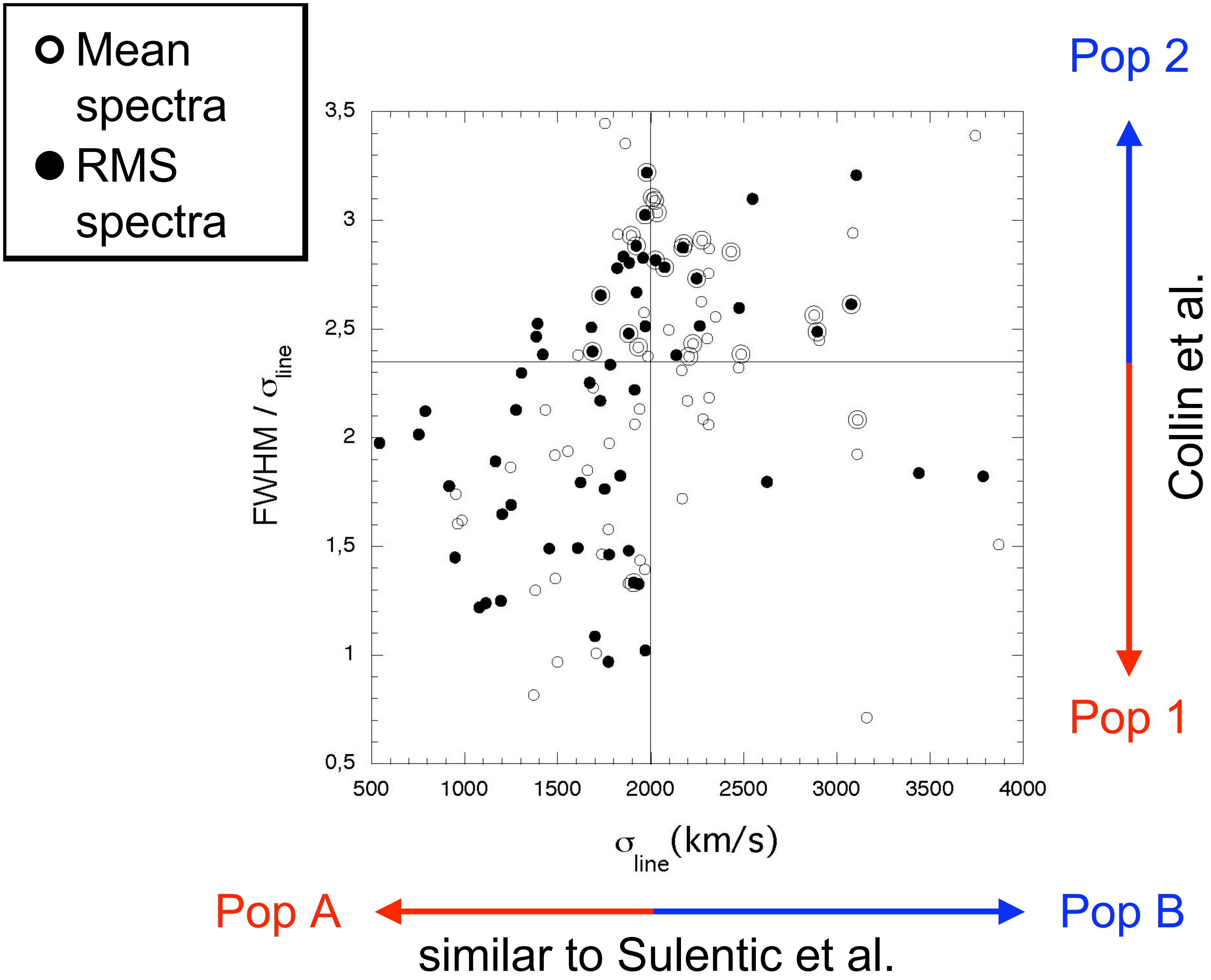


Extreme examples

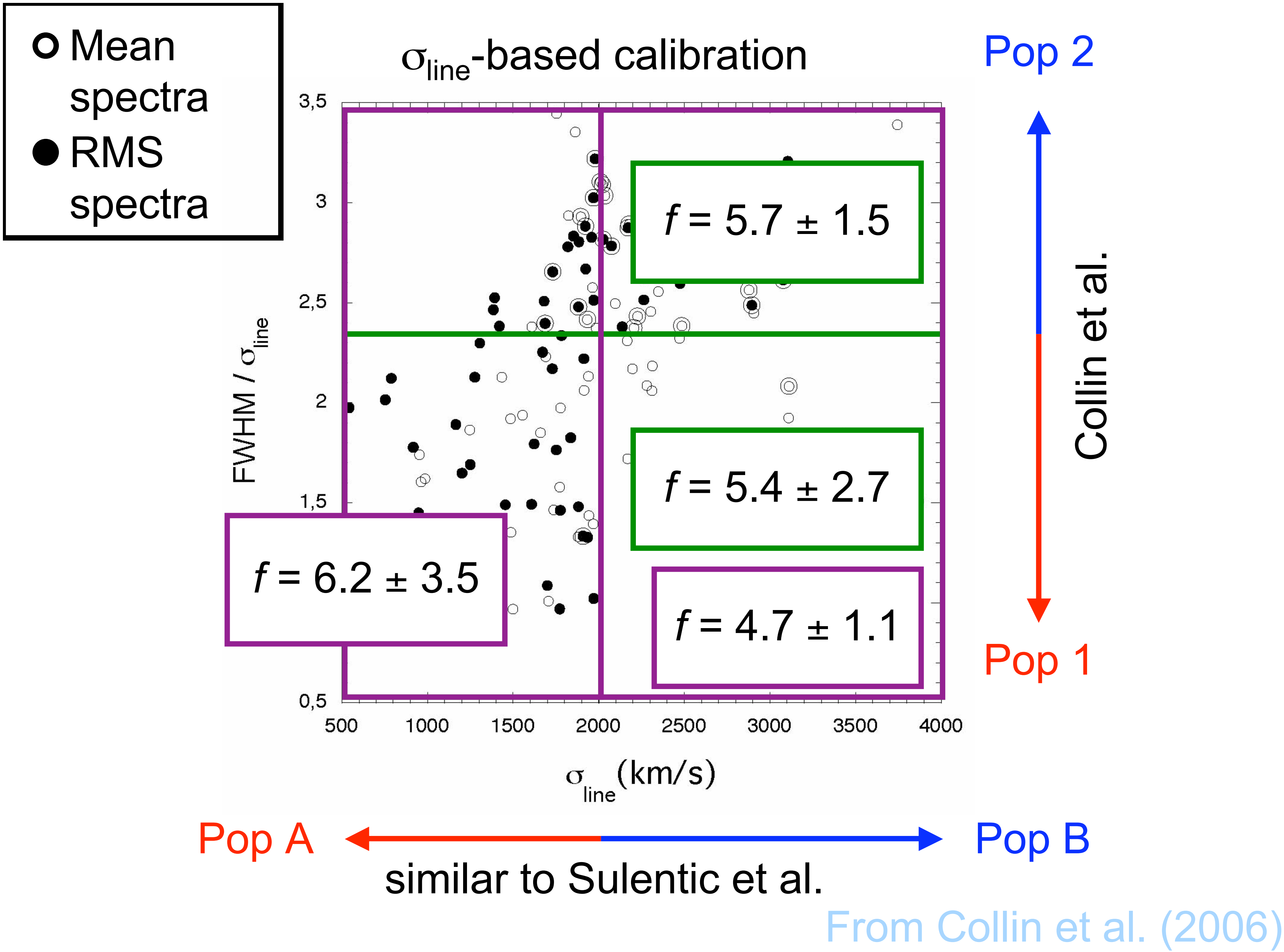


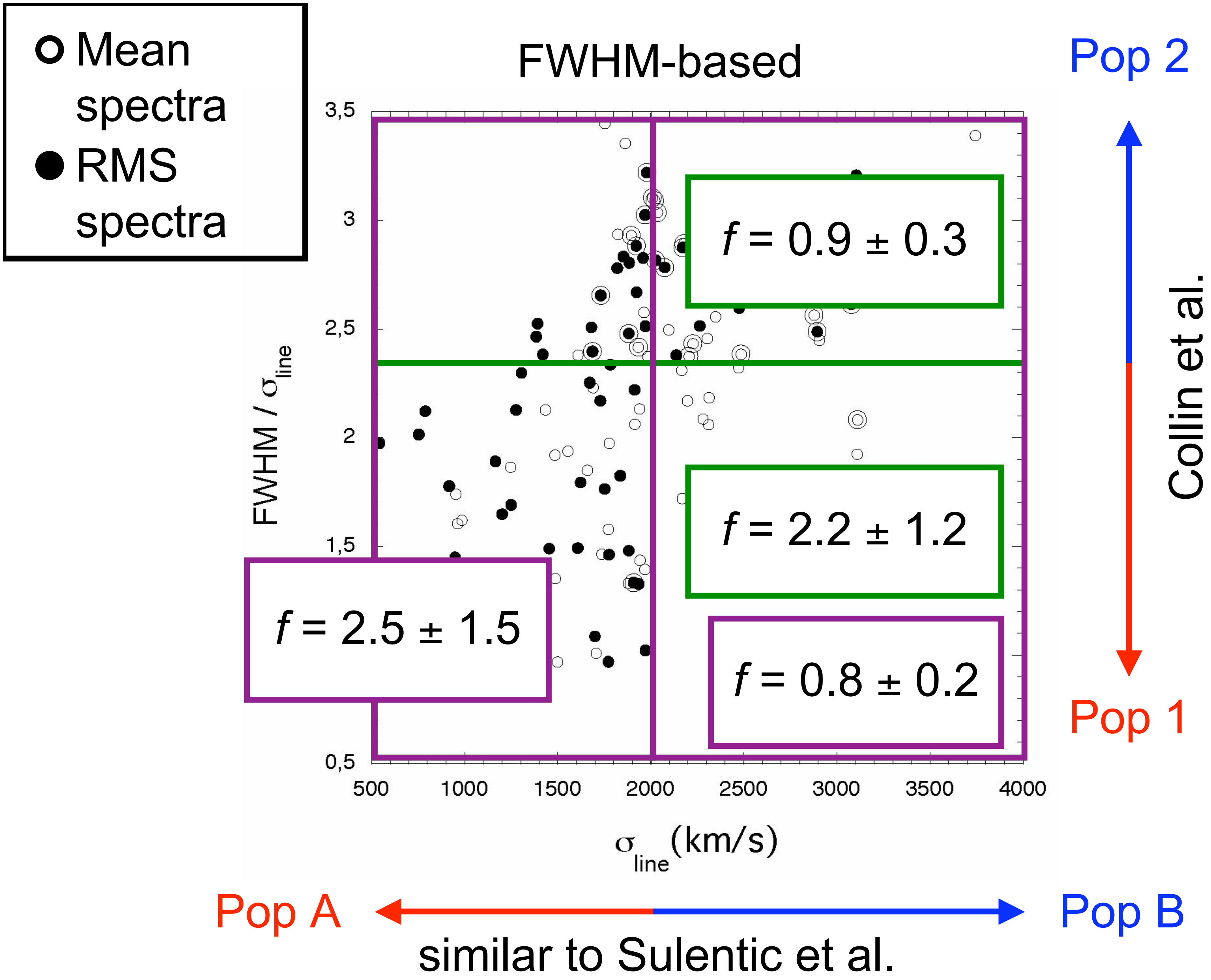
NLS1 + I Zw 1-type

NGC 5548 Hβ



From Collin et al. (2006)

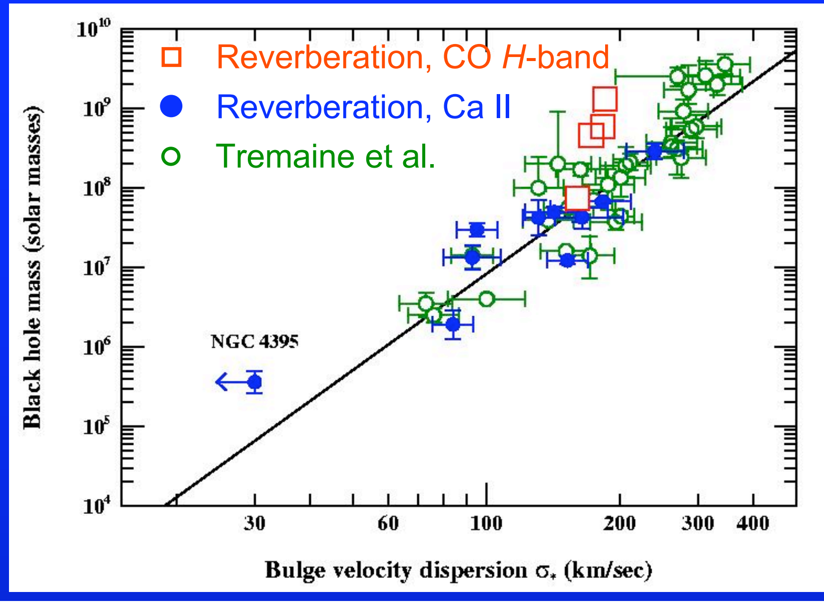

Mean spectra
RMS spectra
σline-based calibration
Pop 2
Pop 1
Collin et al.
FWHM / σline
σline (km/s)
3,5
3
2,5
2
1,5
0,5
500
1000
1500
2000
2500
3000
3500
4000
f = 5.7 ± 1.5
f = 5.4 ± 2.7
f = 6.2 ± 3.5
f = 4.7 ± 1.1
Pop A
Pop B
similar to Sulentic et al.
From Collin et al. (2006)

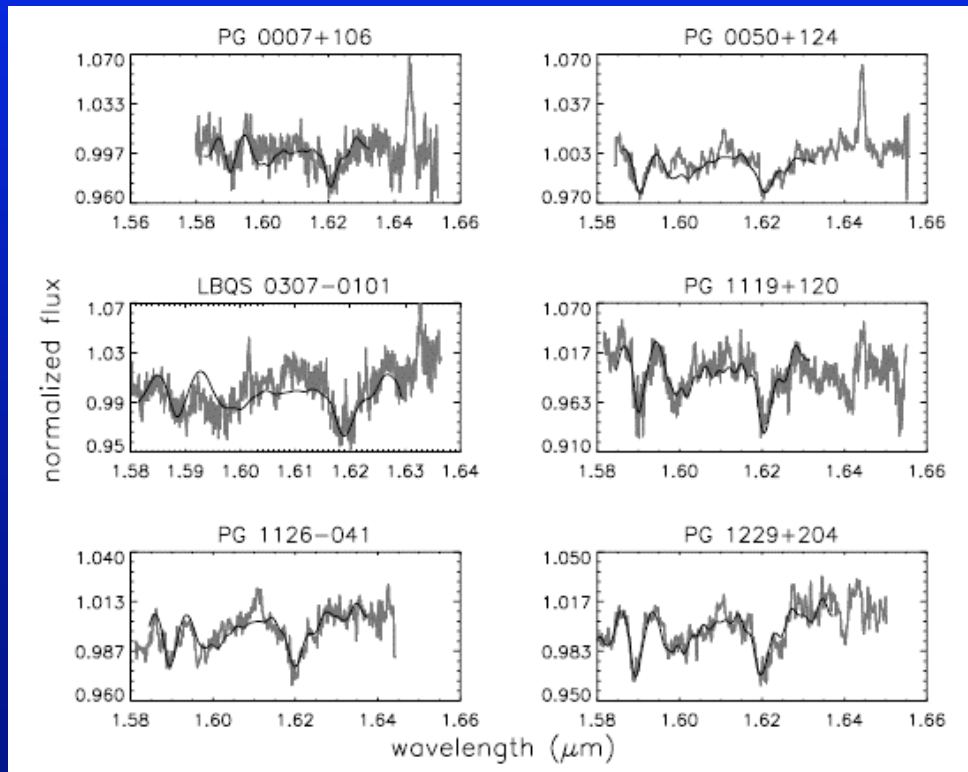


From Collin et al. (2006)

Measuring σ_*

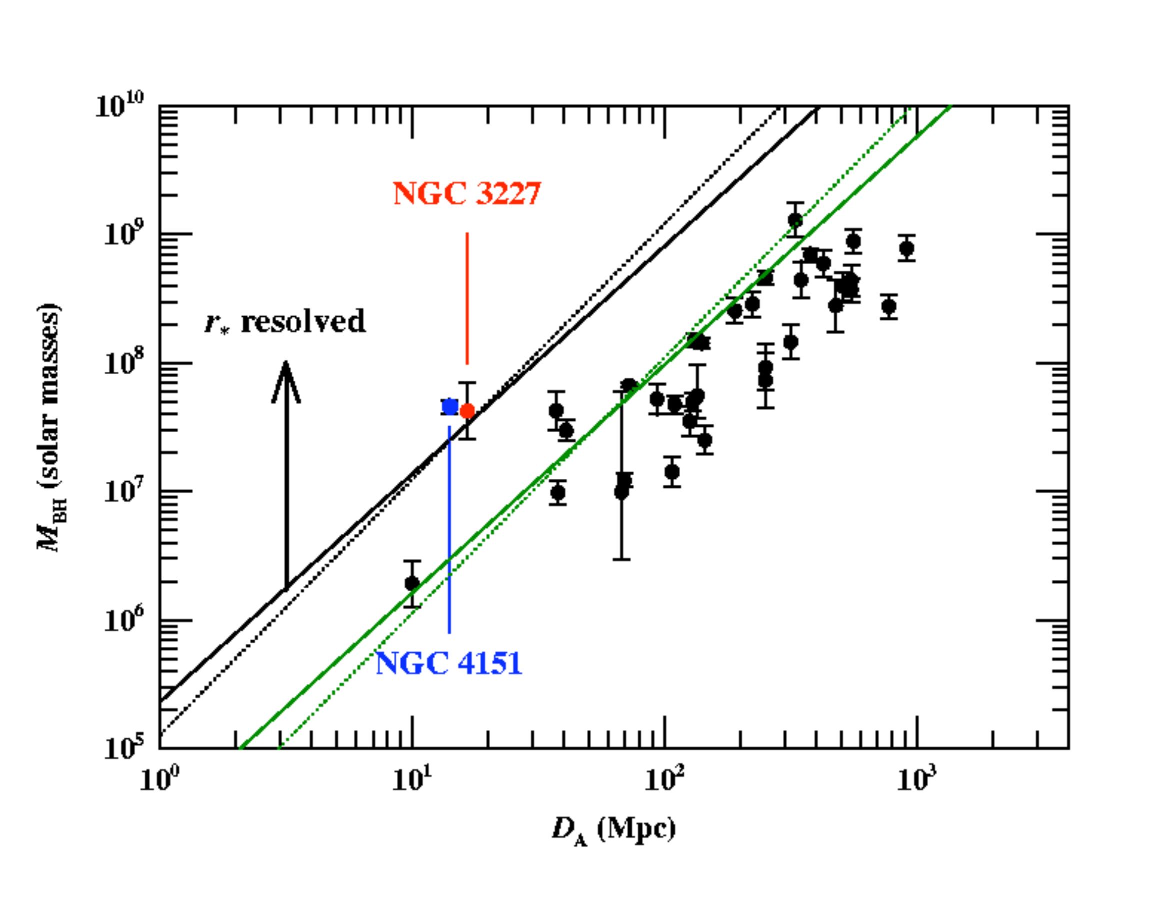
- For z > 0.06, requires observations of CO bandhead in *H*-band (1.6 μm).
- Preliminary results with VLT/ISAAC.
- Beginning to acquire Gemini North *H*-band spectra with NIFS/Altair/LGS system.





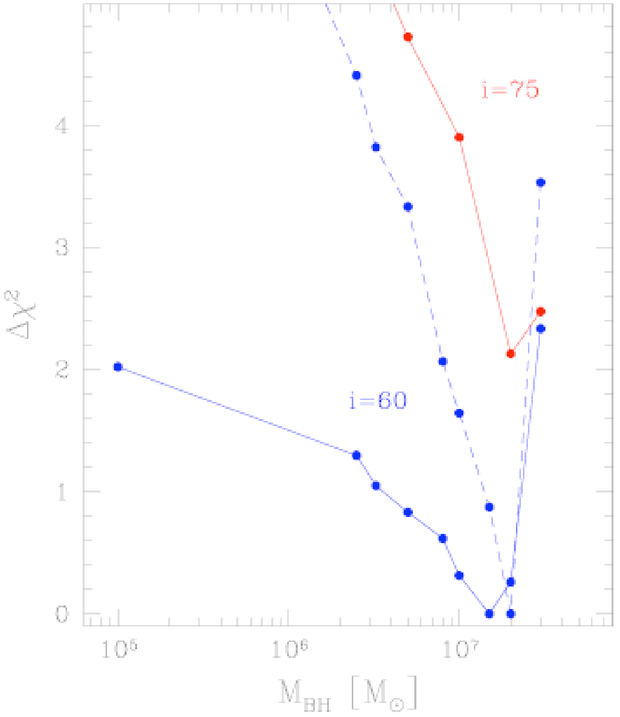
VLT spectra
Dasyra et al. (2007)

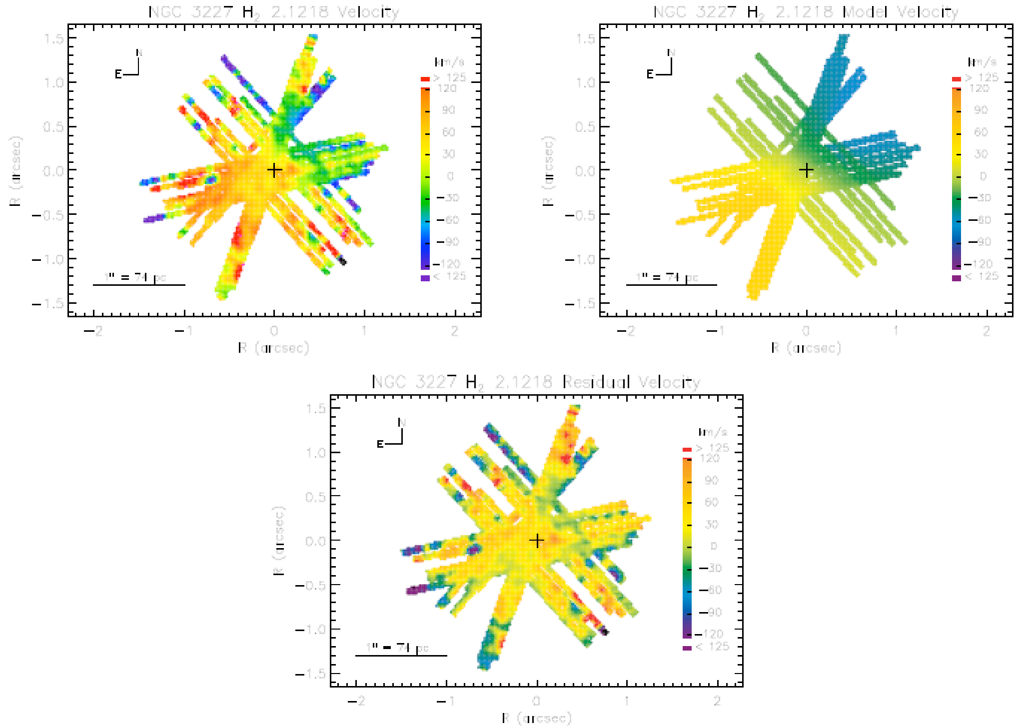
Measuring AGN Black Hole Masses from Stellar Dynamics



Only two reverberation-mapped AGNs are close enough to resolve their black hole radius of influence $r_* = GM_{BH}/\sigma_*^2$ with diffraction-limited telescopes.

Direct Comparison: NGC 3227



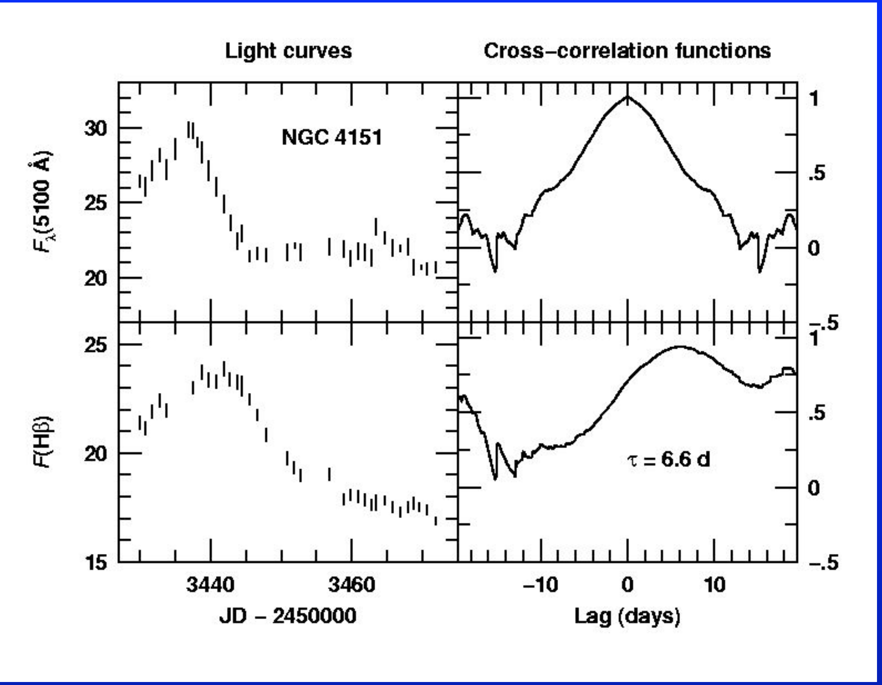


Davies et al. (2006)

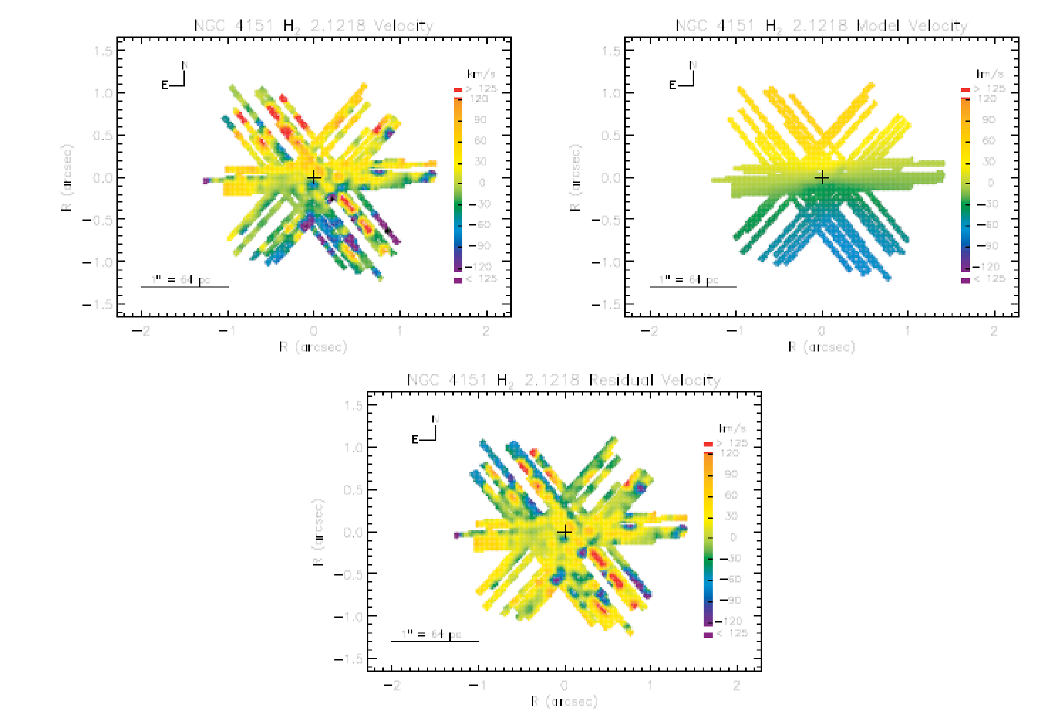
Hicks & Malkan (2007)

Stellar dynamics: (7 – 20) × 10^6 $M_\odot$ (Davies et al. 2006)
Reverberation: (42 ± 21) × 10^6 $M_\odot$ (Peterson et al. 2004)
Gas dynamics: 20^{+10}_{-4} × 10^6 $M_\odot$ (Hicks & Malkan 2007)

Direct Comparison: NGC 4151



Bentz et al. (2006)



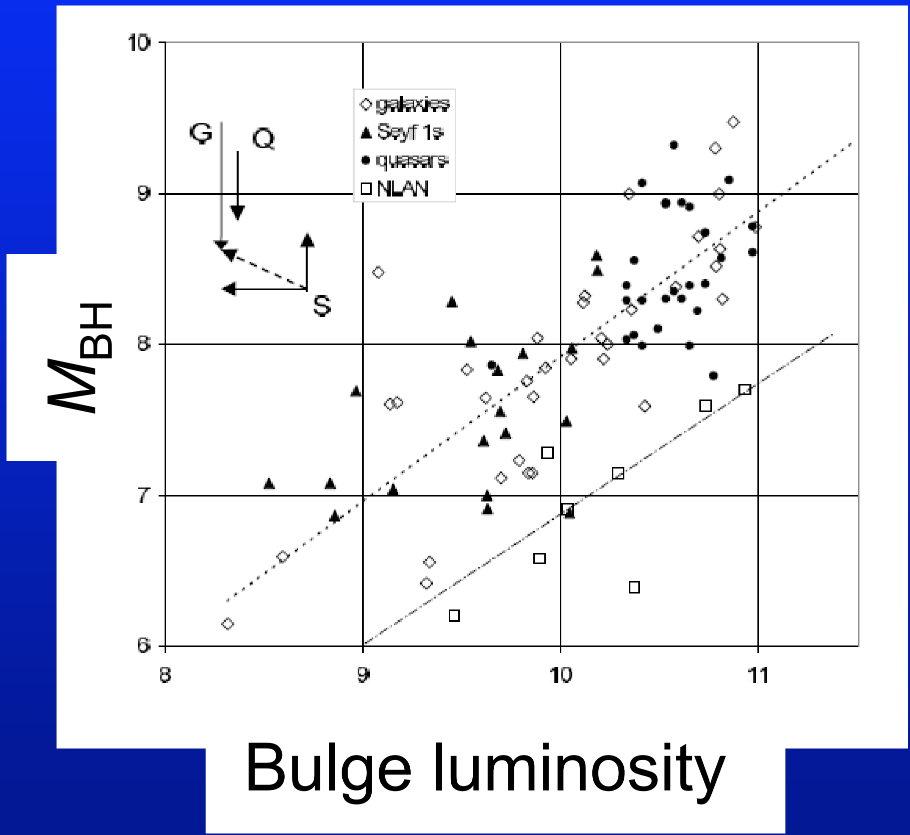
Hicks & Malkan (2007)

Stellar dynamics: ≤ 70 × 10^6 $M_\odot$ (Onken et al. 2007)
Reverberation: (46 ± 5) × 10^6 $M_\odot$ (Bentz et al. 2006)
Gas dynamics: $30^{+7.5}_{-2.2}$ × 10^6 $M_\odot$ (Hicks & Malkan 2007)

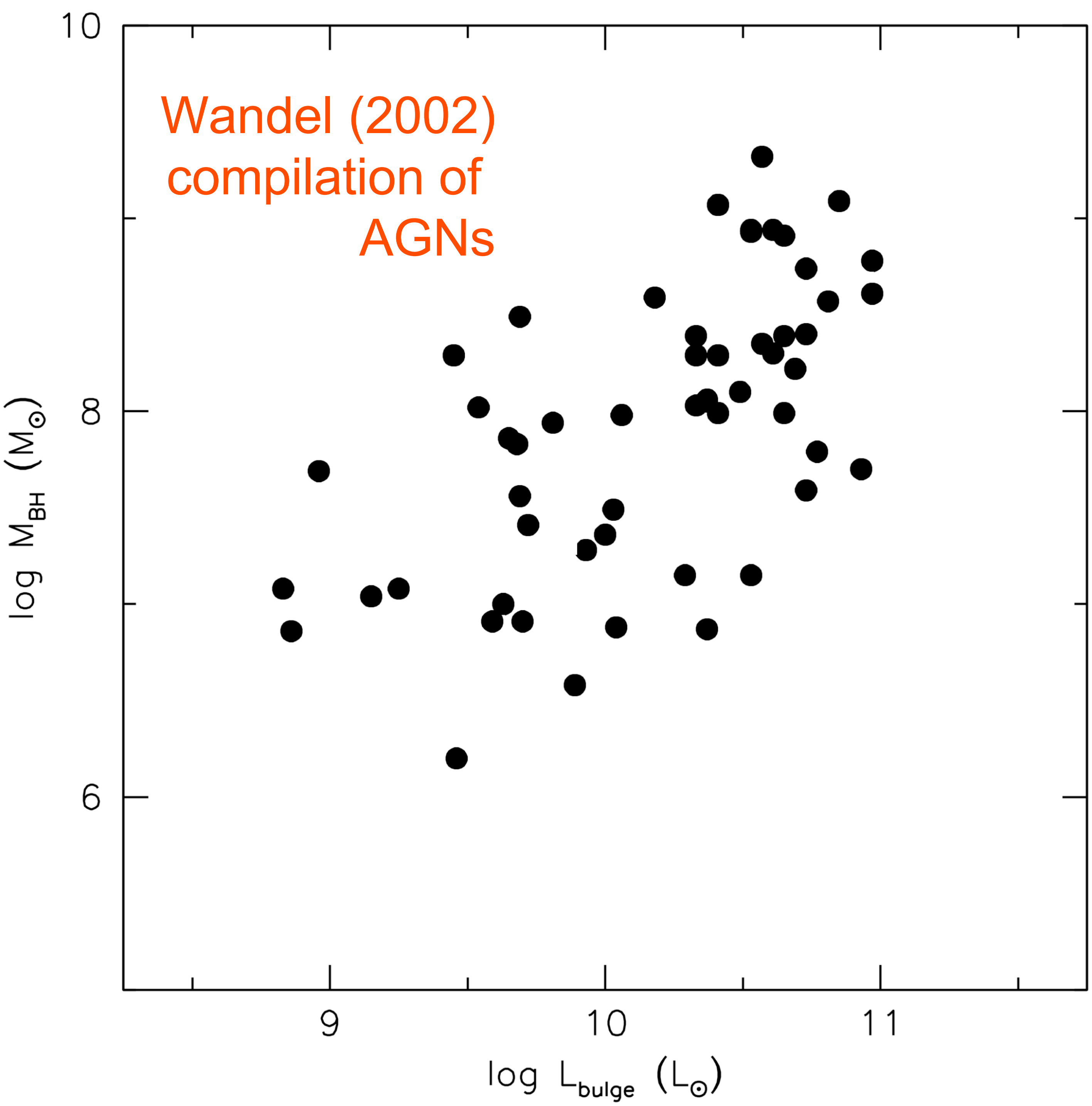
Additional Check on Masses: M_{BH} vs. L_{bulge}

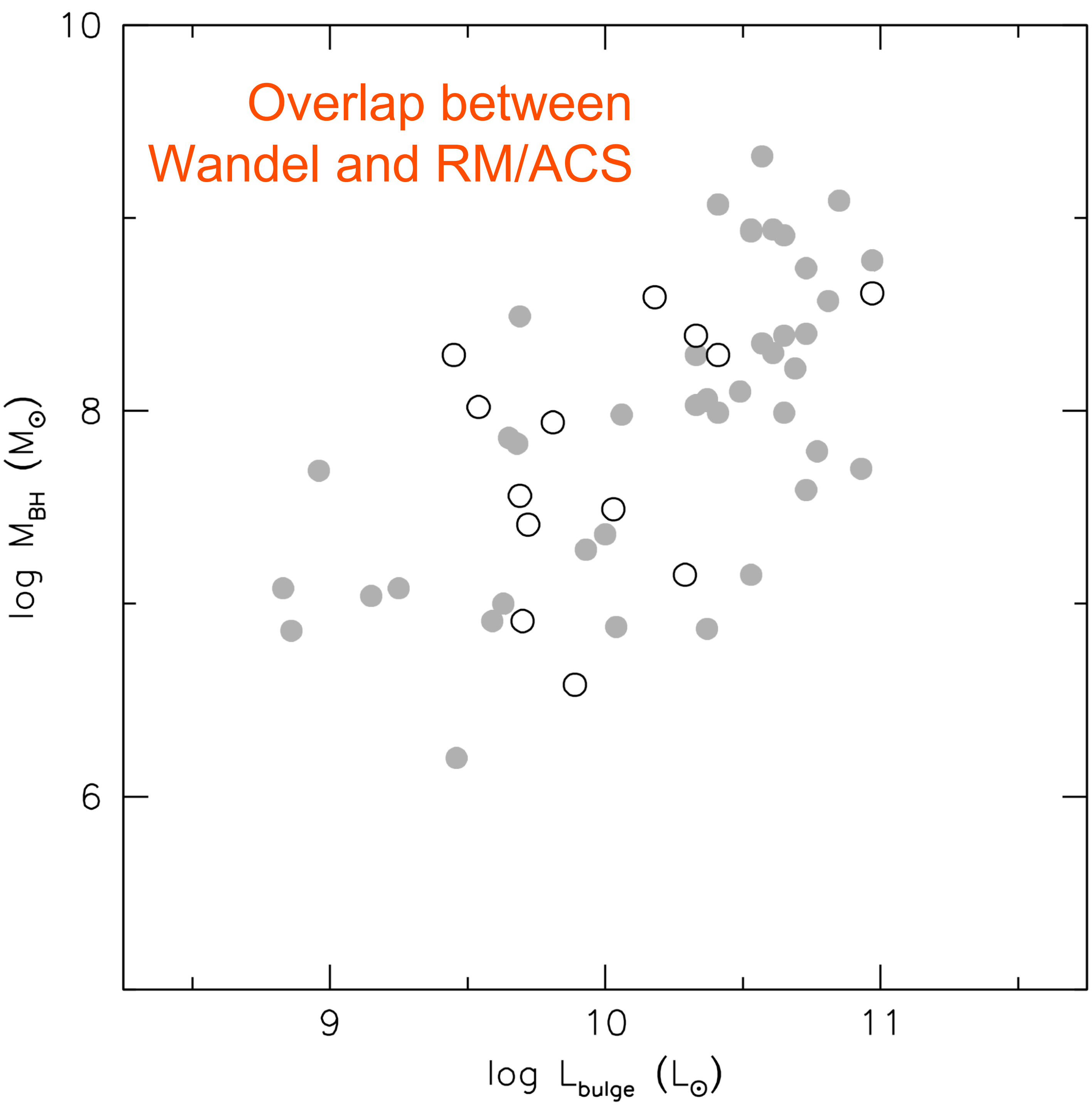
- Modeling the surface brightness distributions of AGNs in our ACS sample give L_{bulge}.
- Is there a correlation between black hole mass and bulge luminosity (or mass)?
- If so, is it the same as that for quiescent galaxies?

Magorrian et al. (1998)

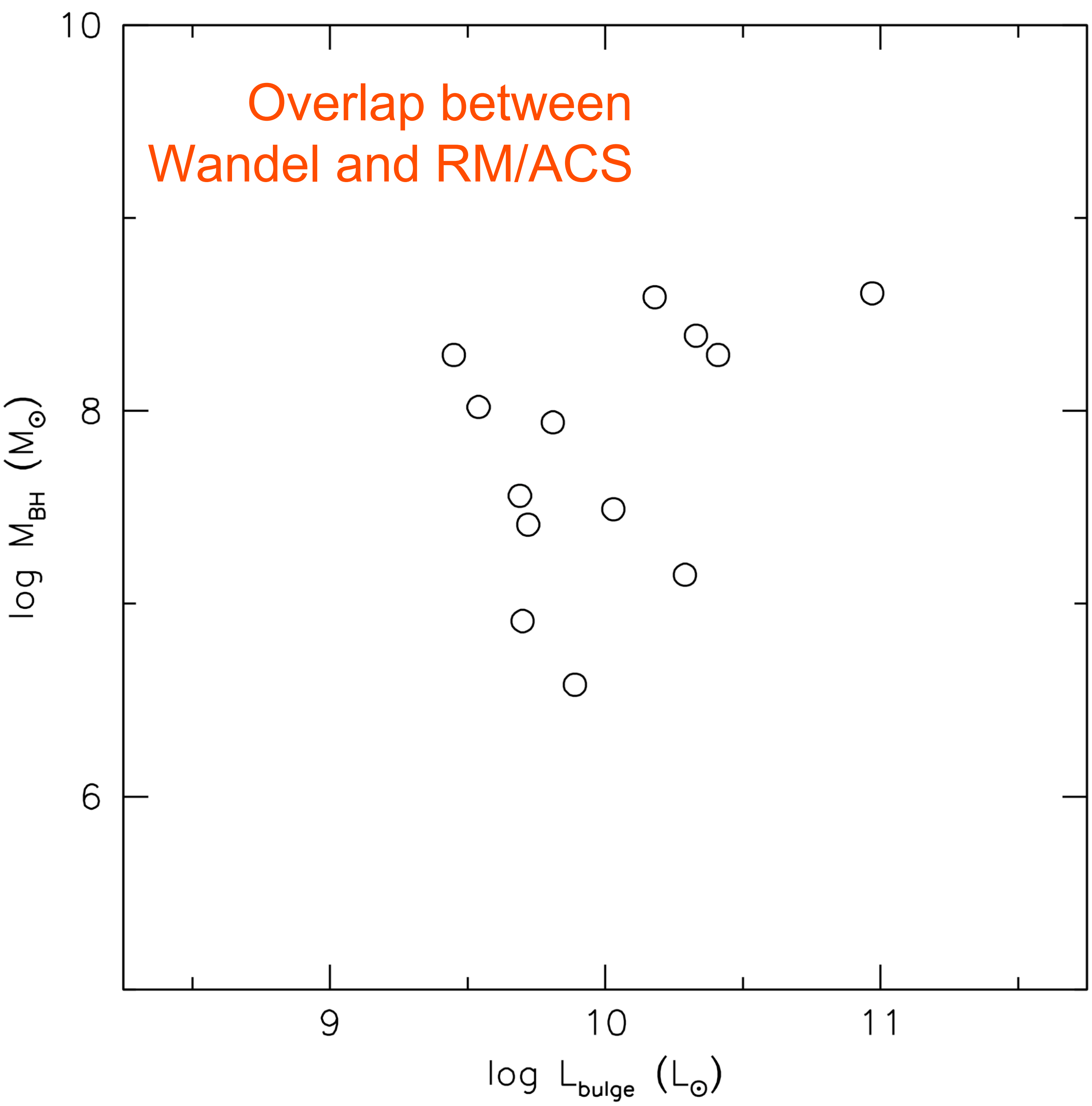


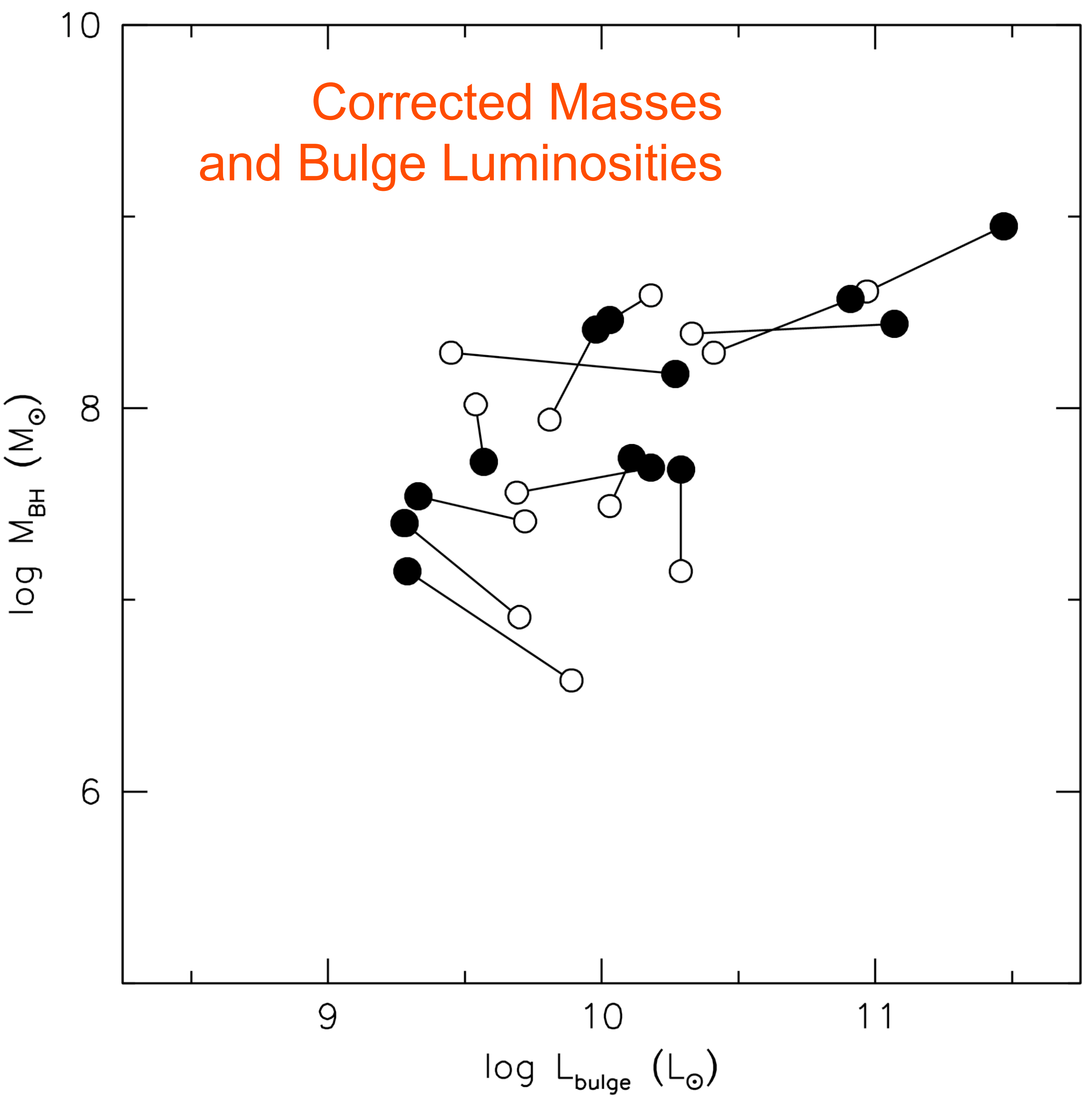
Wandel (2002)

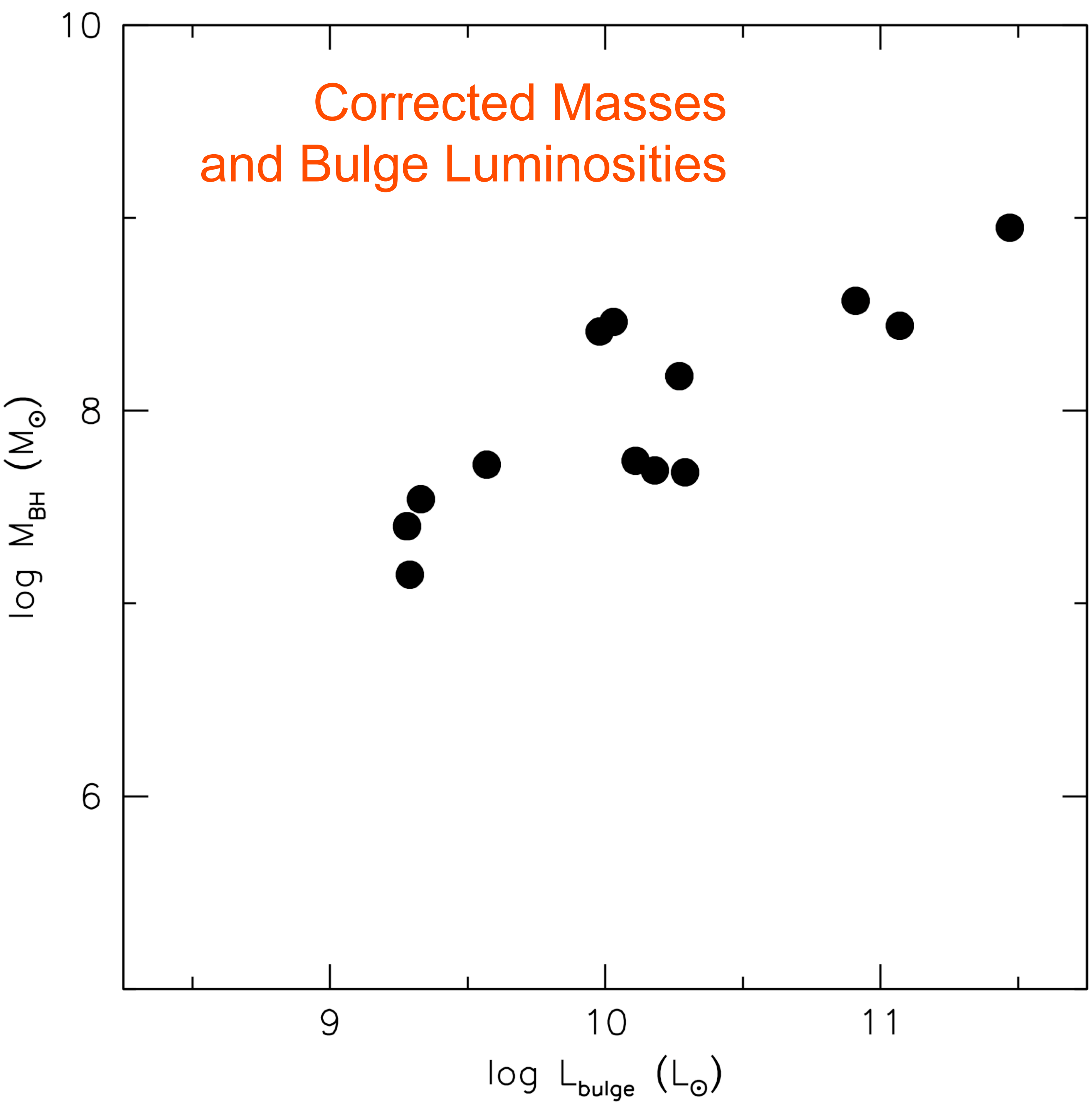

Wandel (2002) compilation of AGNs
log M_{BH} ($M_\odot$)
log L_{bulge} ($L_\odot$)
10
8
6
9
10
11



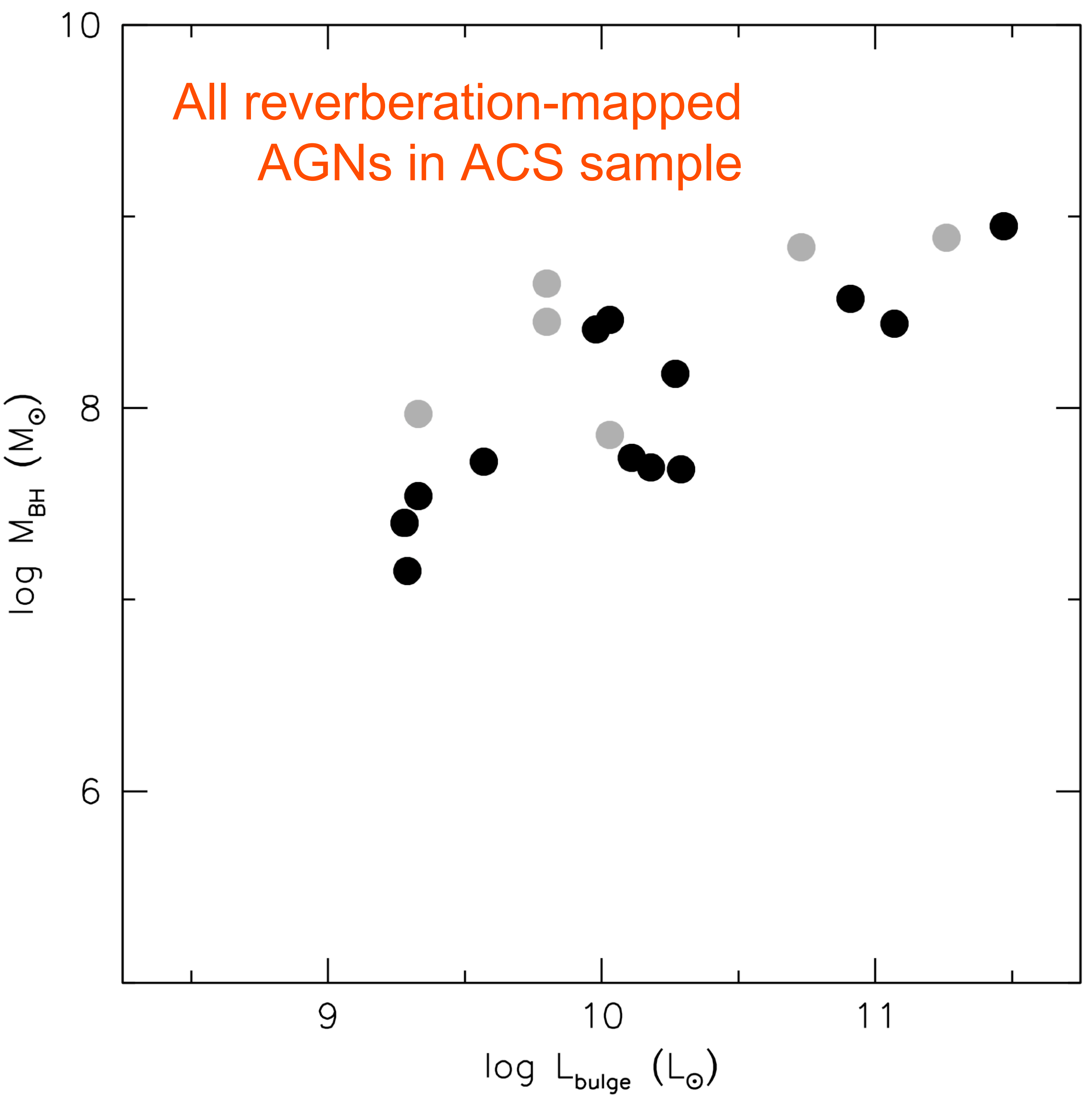
Overlap between
Wandel and RM/ACS
10
8
6
9
10
11
log M_BH (M_⊙)
log L_bulge (L_⊙)


Overlap between
Wandel and RM/ACS
10
8
6
9
10
11
log M_{BH} ($M_\odot$)
log L_{bulge} ($L_\odot$)

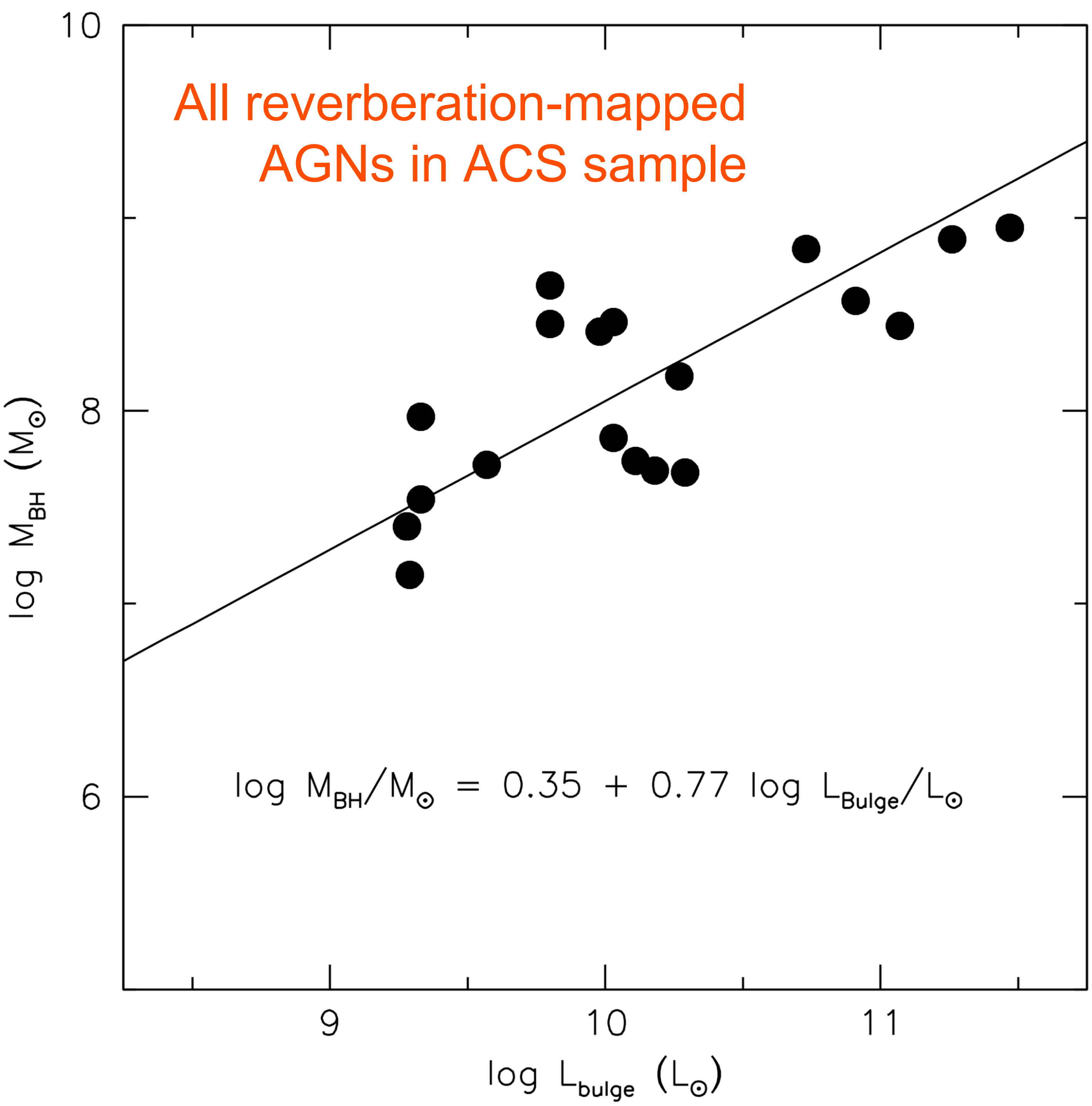

Corrected Masses
and Bulge Luminosities
10
8
6
9
10
11
log M_BH (M_⊙)
log L_bulge (L_⊙)



Corrected Masses
and Bulge Luminosities
10
8
6
9
10
11
log M_{BH} ($M_\odot$)
log L_{bulge} ($L_\odot$)



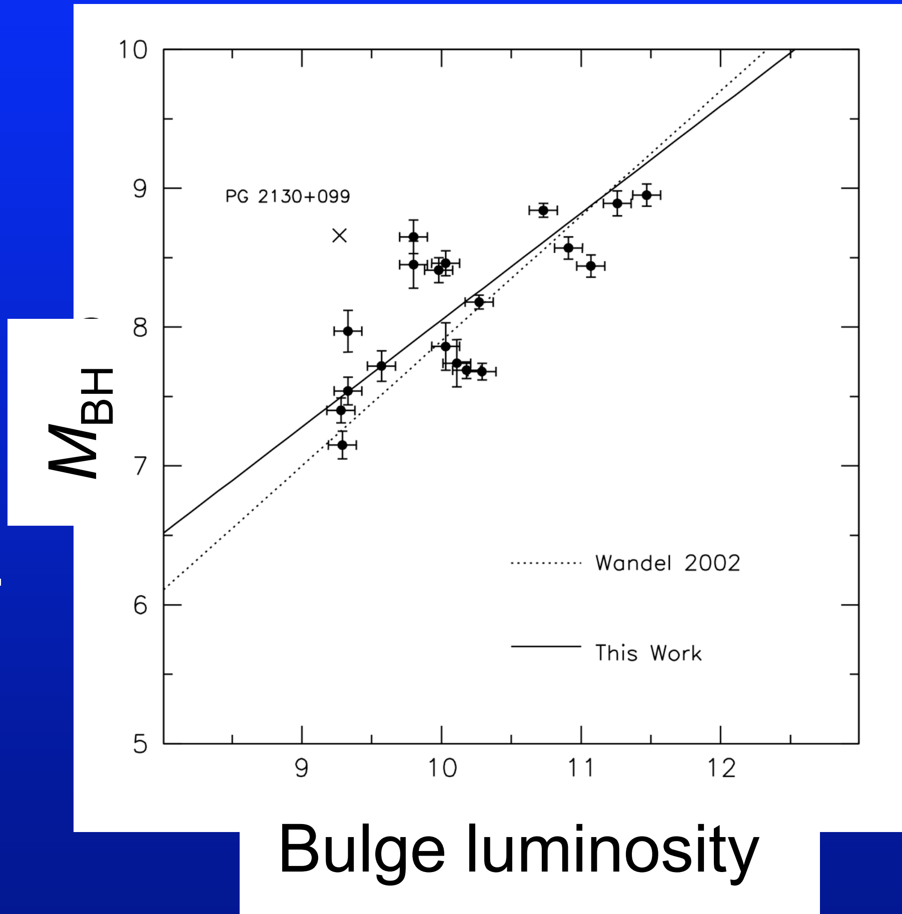
All reverberation-mapped
AGNs in ACS sample
10
8
6
9
10
11
log M_BH (M_⊙)
log L_bulge (L_⊙)



All reverberation-mapped
AGNs in ACS sample
log $M_{BH}/M_\odot$ = 0.35 + 0.77 log $L_{Bulge}/L_\odot$
10
8
6
9
10
11
log M_{BH} ($M_\odot$)
log L_{bulge} ($L_\odot$)

M_{BH} vs. L_{bulge}

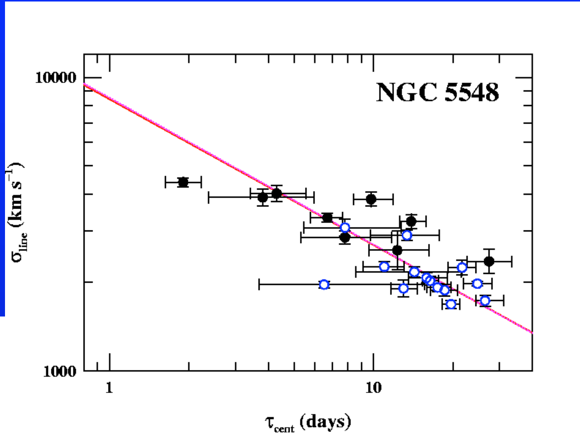
- There is a clear correlation, but more work is necessary to improve slope determination and to compare zero-points with quiescent galaxies.
- At this point, no inconsistency with quiescent galaxies.



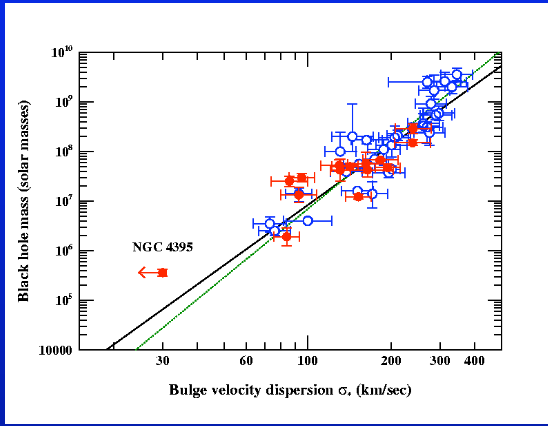
Bentz et al., in preparation

Evidence That Reverberation-Based Masses Are Reliable

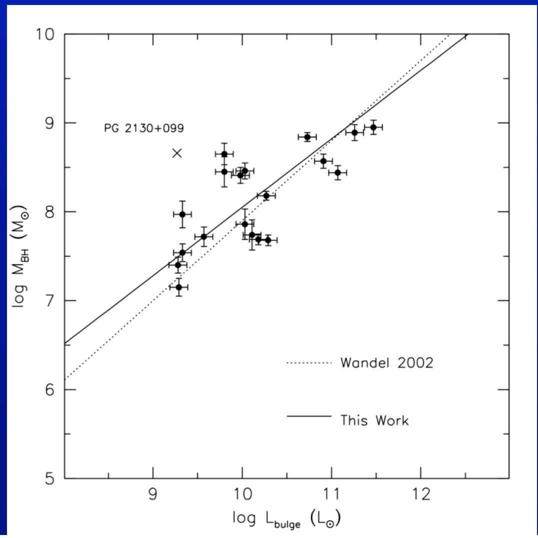
1. Virial relationship for emission-line lags (BLR radius) and line widths



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



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

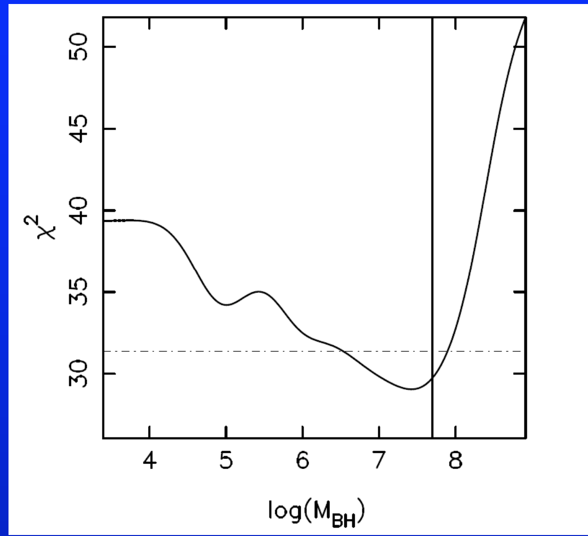


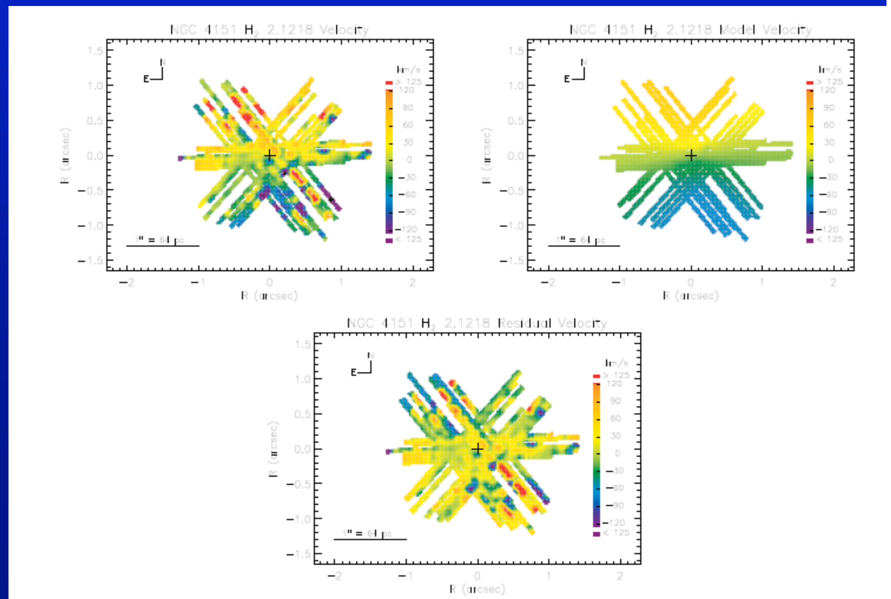
Evidence That Reverberation-Based Masses Are Reliable

4. Direct comparisons with other methods:

- Stellar dynamical masses for NGC 3227 and NGC 4151

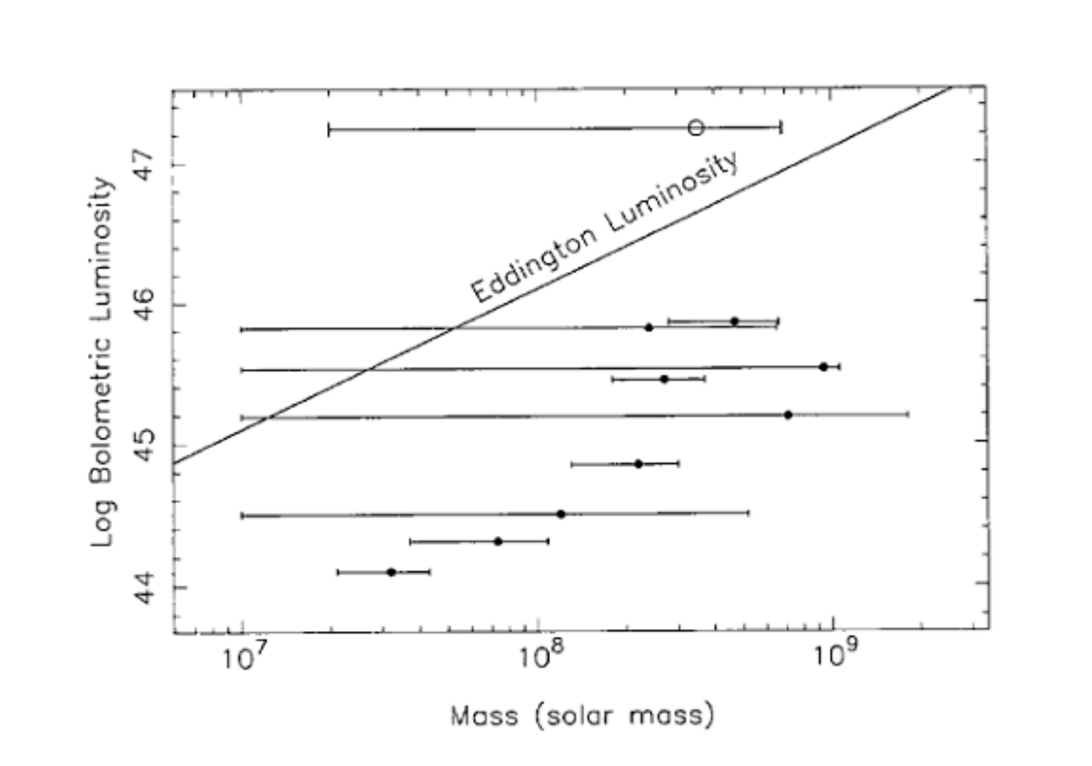
- Gas dynamical masses for NGC 3227, NGC 4151, and NGC 7469





Mass-Luminosity Relationship

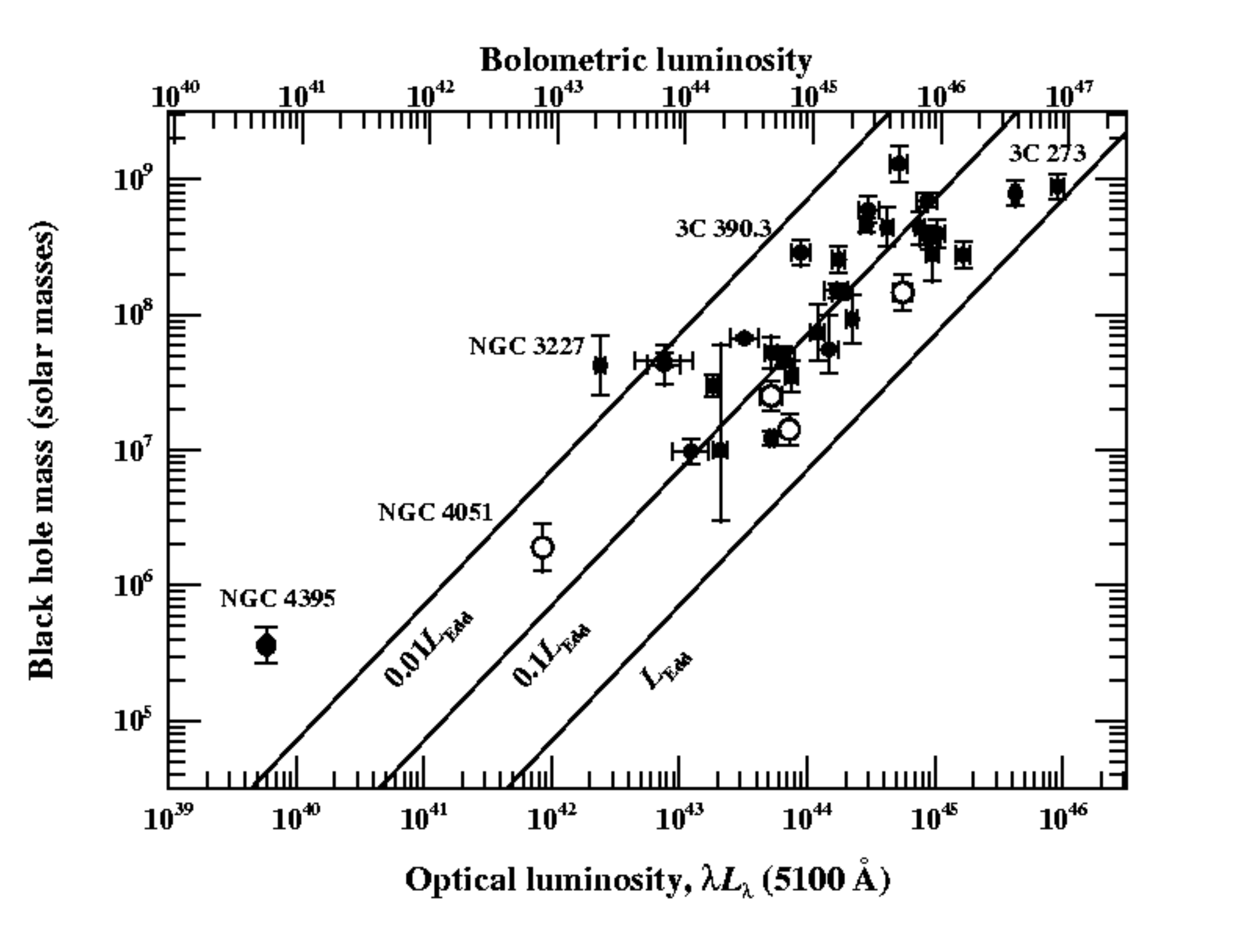
- Like radius-luminosity, the mass-luminosity relationship was anticipated early.



Koratkar & Gaskell 1991

Mass-Luminosity Relationship

- All are sub-Eddington
- NLS1s have high Eddington rates
- At least some outliers are heavily reddened
- These 36 AGNs anchor the black hole mass scale



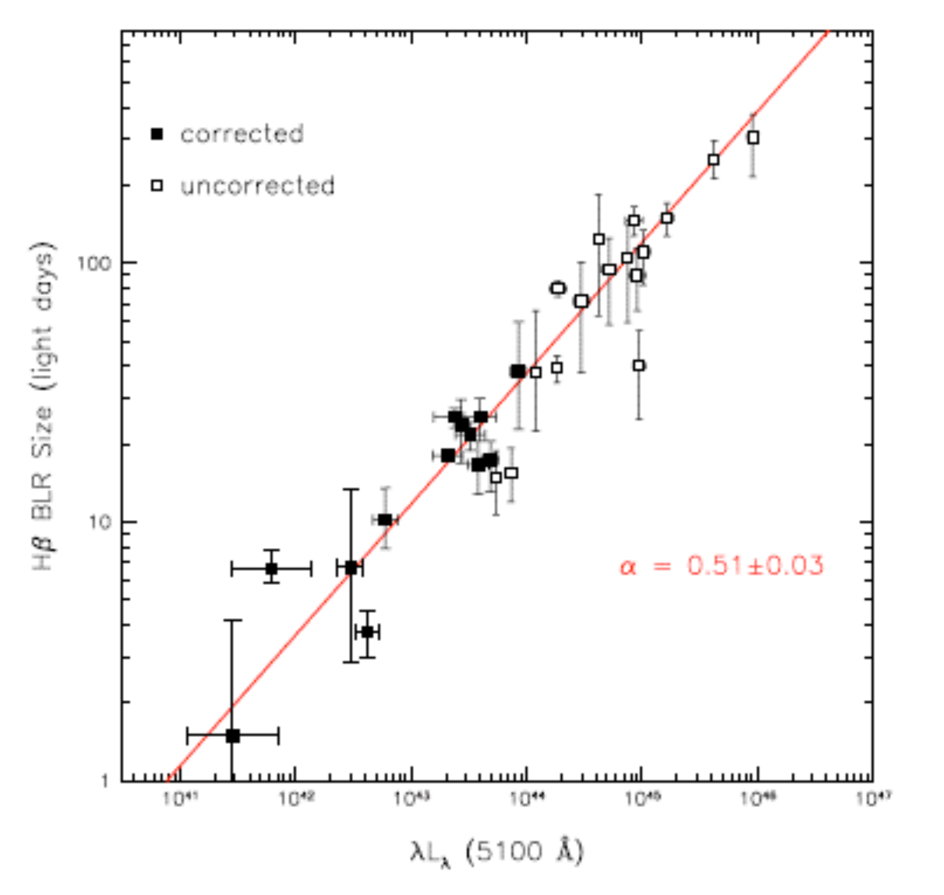
Estimating Black Hole Masses from Individual Spectra

Correlation between BLR radius R (= $c\tau_{cent}$) and luminosity L allows estimate of black hole mass by measuring line width and luminosity only:

$$M = f\,(c\tau_{cent}\,\sigma_{line}^2\,/G) \propto f\,L^{1/2}\,\sigma_{line}^2$$

Dangers:

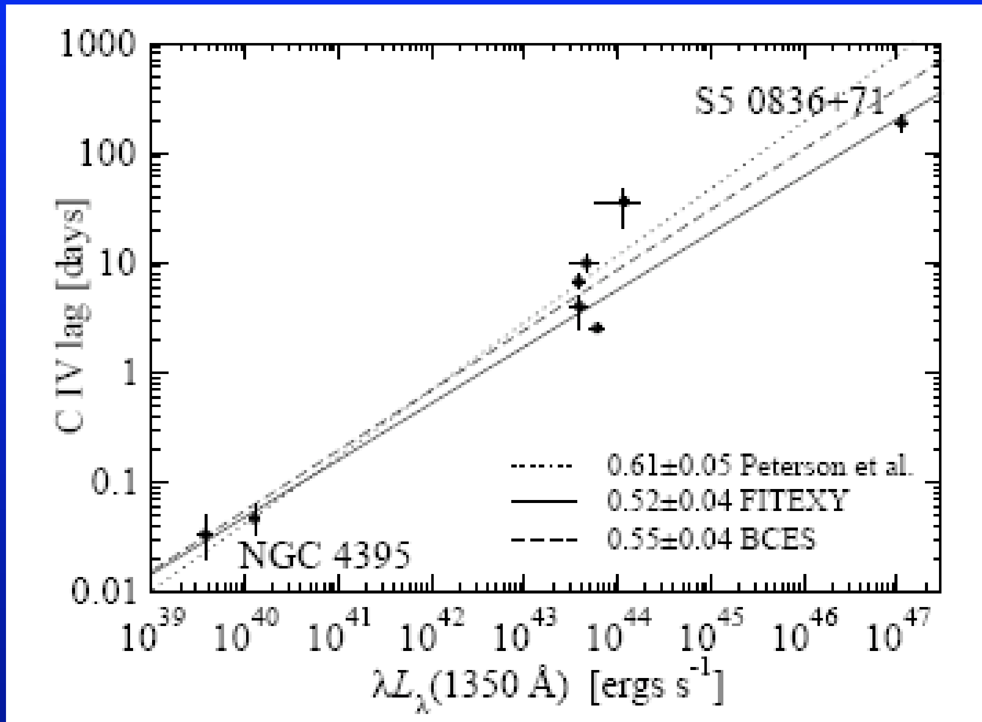
- blending (incl. narrow lines)
- using inappropriate f
  - *Typically, the variable part of Hβ is 20% narrower than the whole line*



Bentz et al. 2006

Radius-Luminosity for Lines Other than Hβ

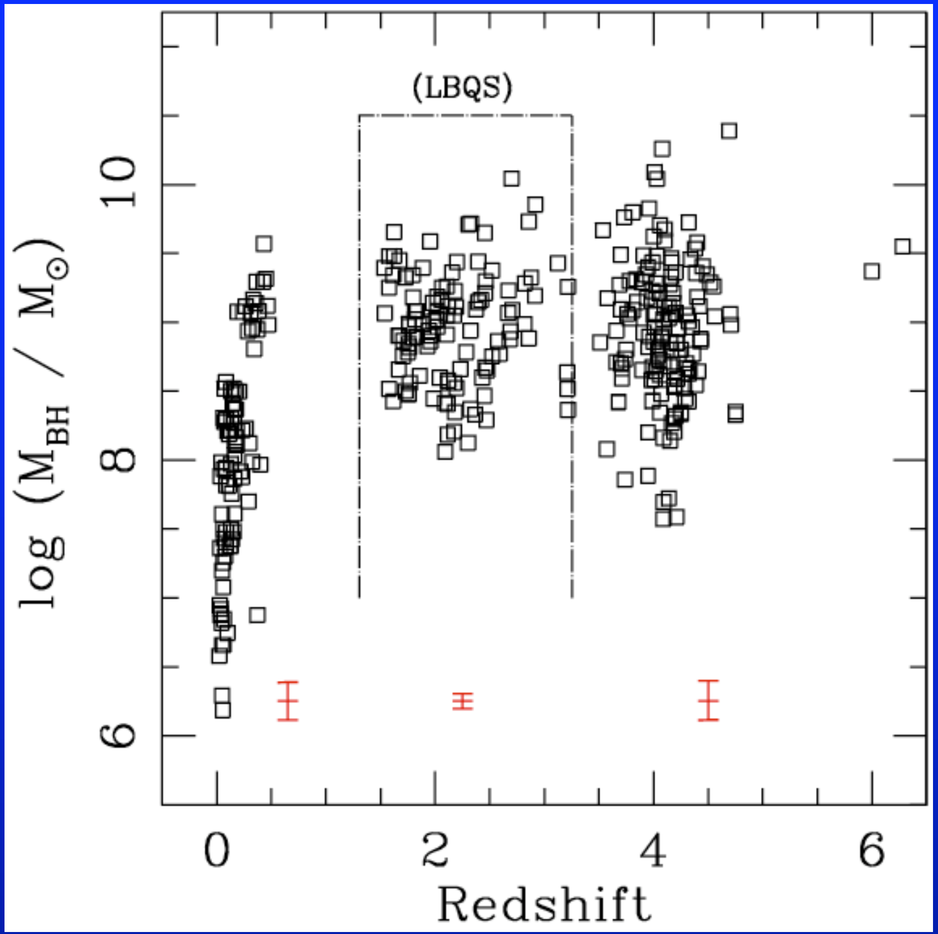
- *R*–*L* relationship is well-established only for Hβ
- For C IV, there are relatively new results from high-*z*, high-*L* studies and dwarf Seyferts.



Kaspi et al. (2006)

Secondary Mass Indicators

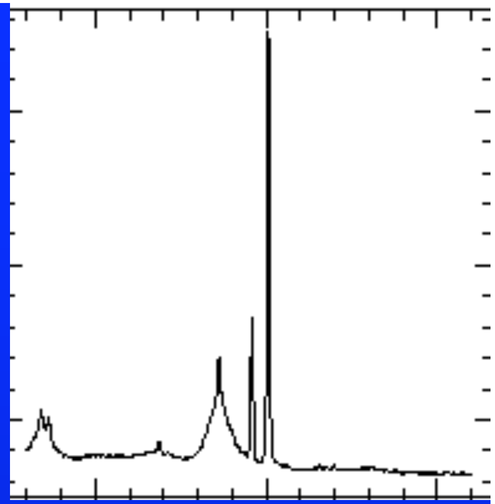
- Reverberation masses serve as an anchor for related AGN mass determinations (e.g., based on photoionization modeling)
  - Will allow exploration of AGN black hole demographics over the history of the Universe.



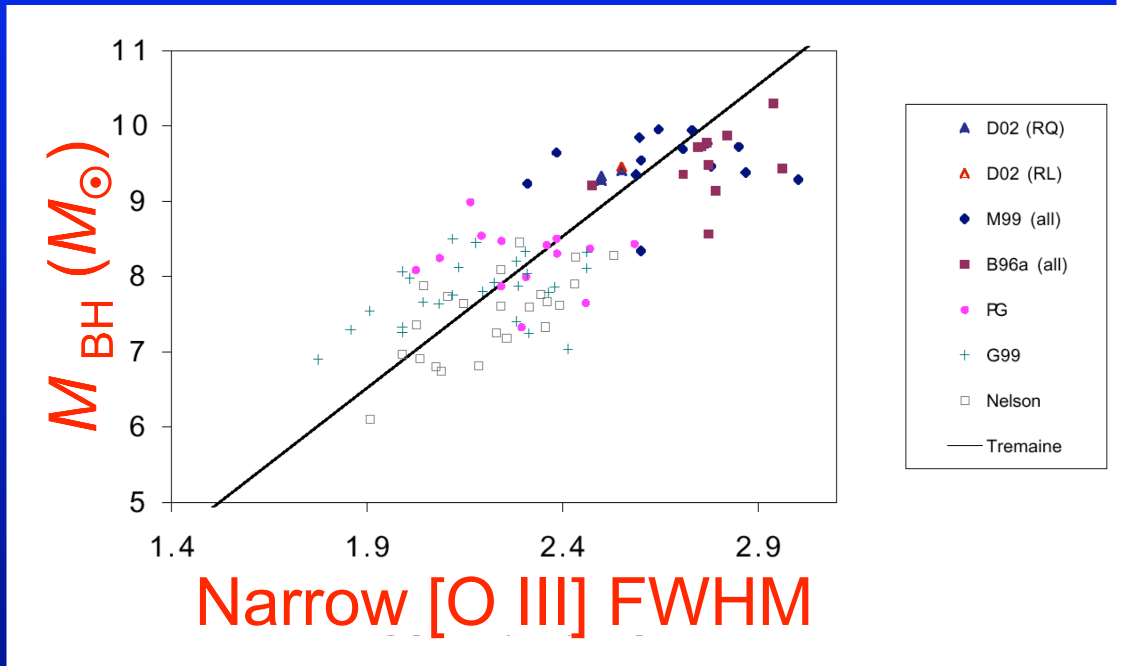
Vestergaard (2002)

$$M = f\,(c\tau_{cent}\sigma^2/G) \propto L^{1/2}\sigma^2$$

Narrow-Line Widths as a Surrogate for σ_*

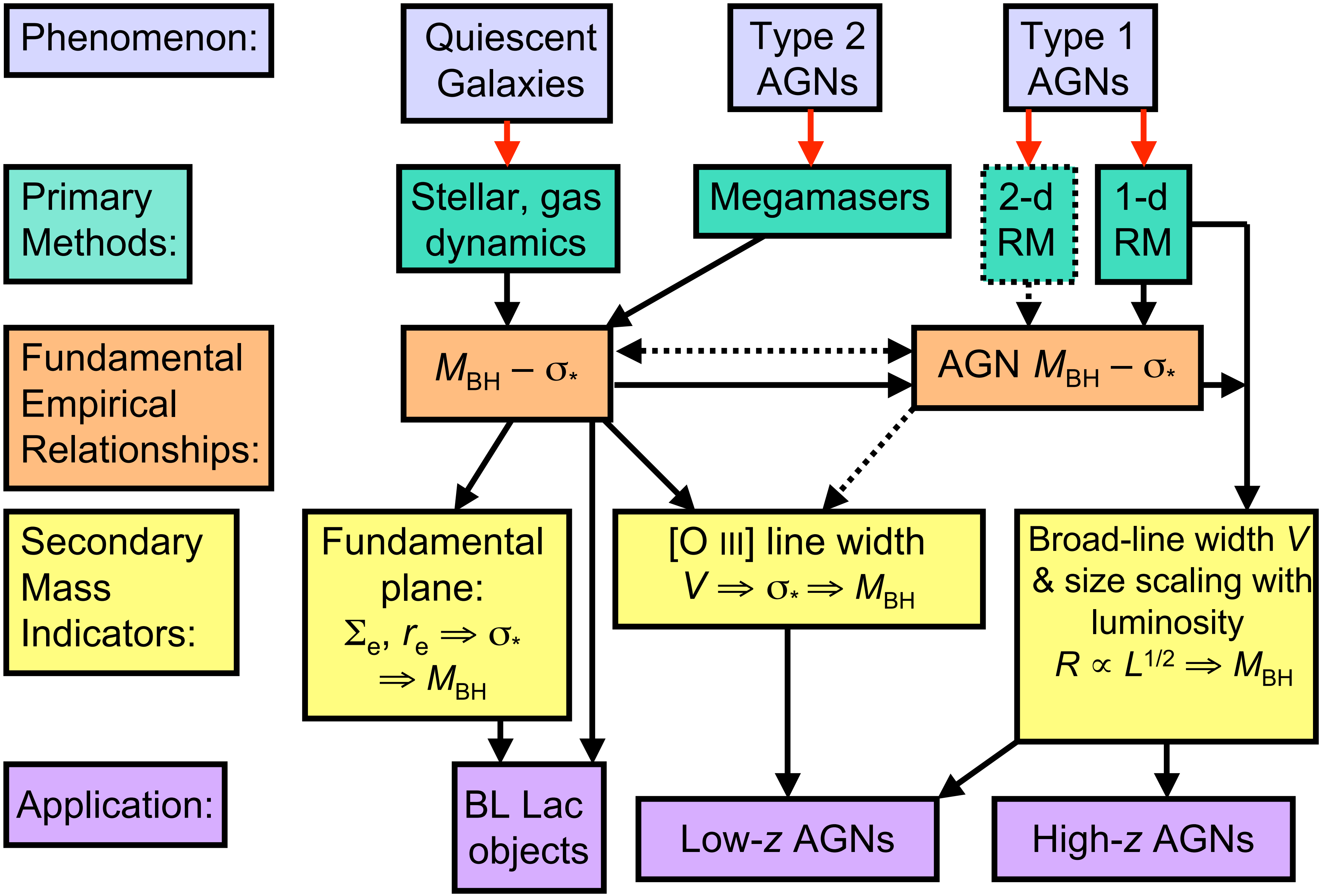


- Narrow-line widths and σ_* are correlated
  - The narrow-line widths have been used to estimate black-hole mass, based on the M_{BH}- σ_* correlation
  - Limitations imposed by angular resolution, non-virial component (jets)



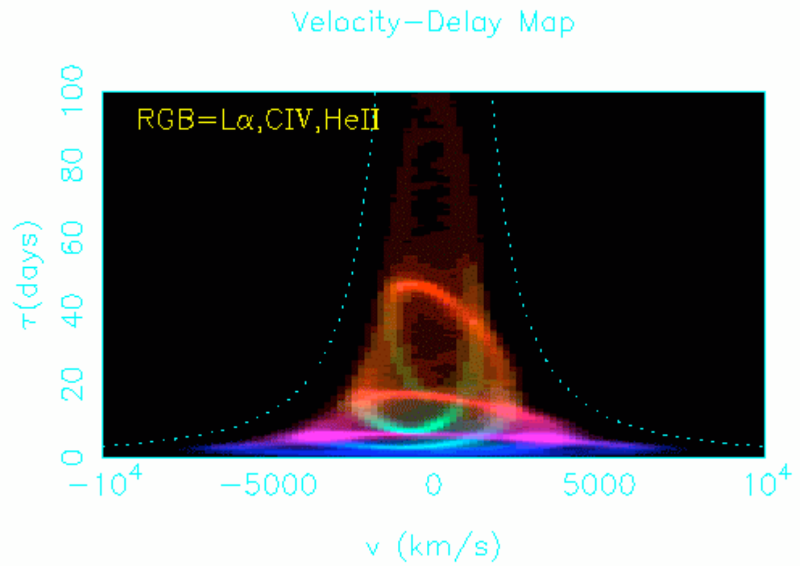
Shields et al. 2003

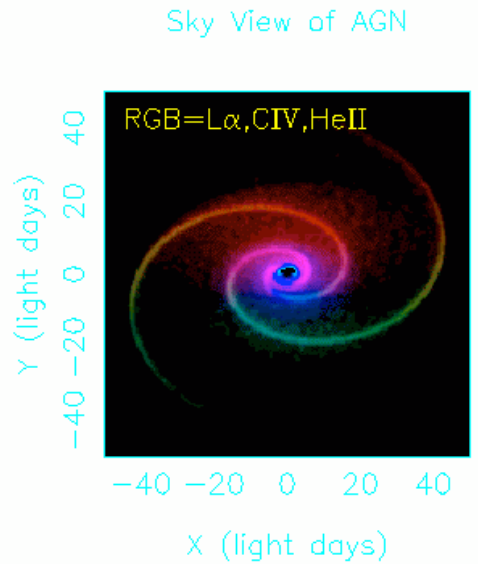
Estimating AGN Black Hole Masses



Next Crucial Step

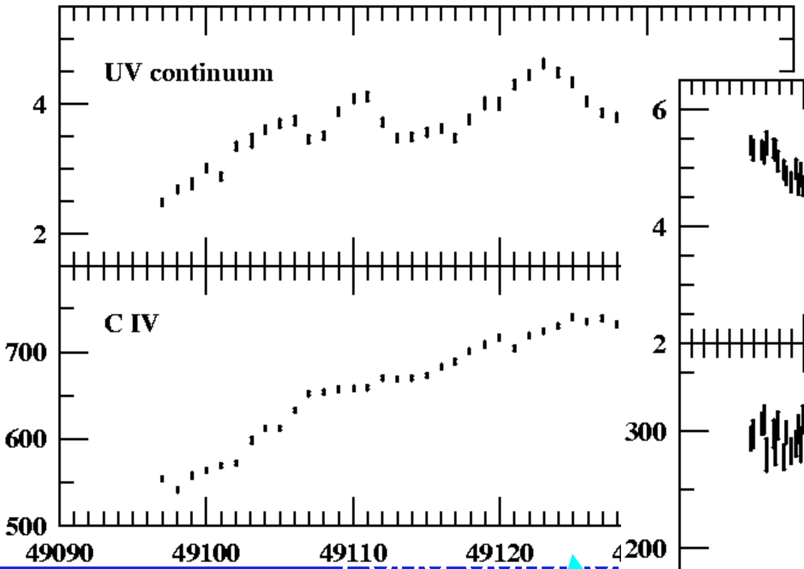
- Obtain a high-fidelity velocity-delay map for at least *one line* in *one AGN.*
  - Cannot assess systematic uncertainties without knowing geometry/kinematics of BLR.
  - Even one success would constitute “proof of concept”.

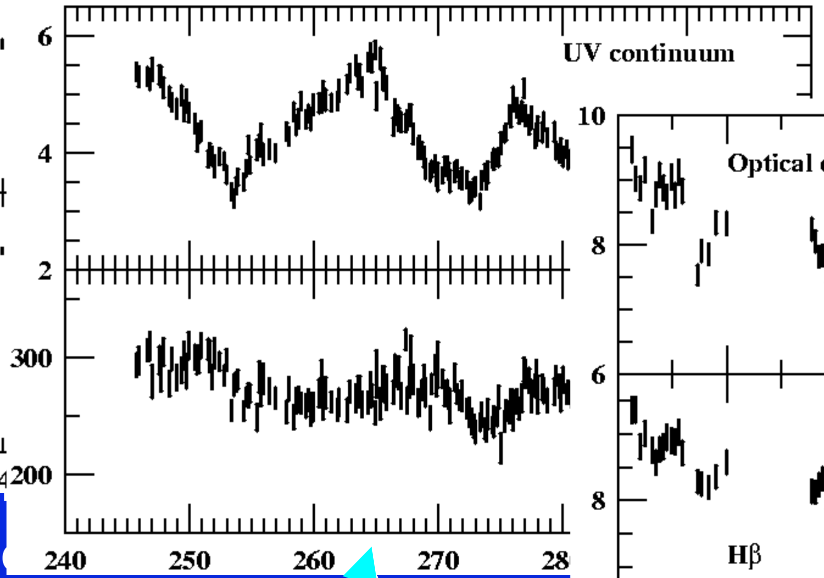


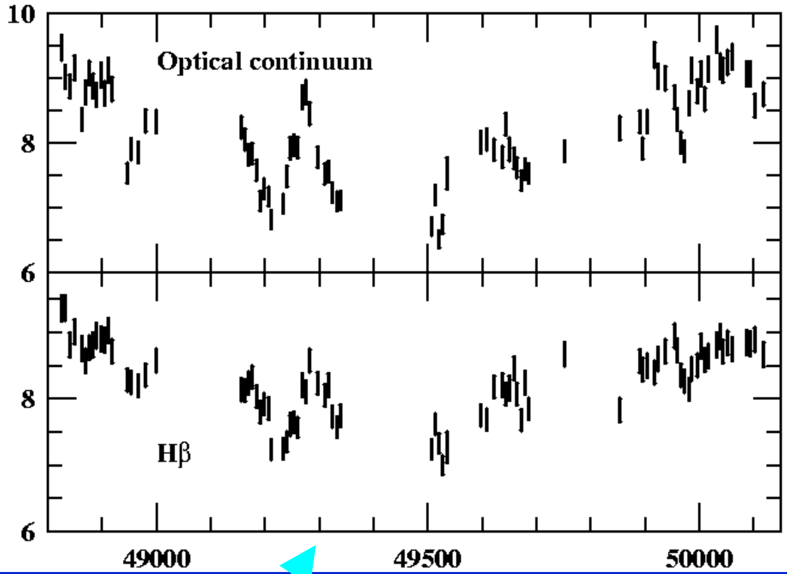


BLR with a spiral wave and its velocity-delay map in three emission lines

BLR





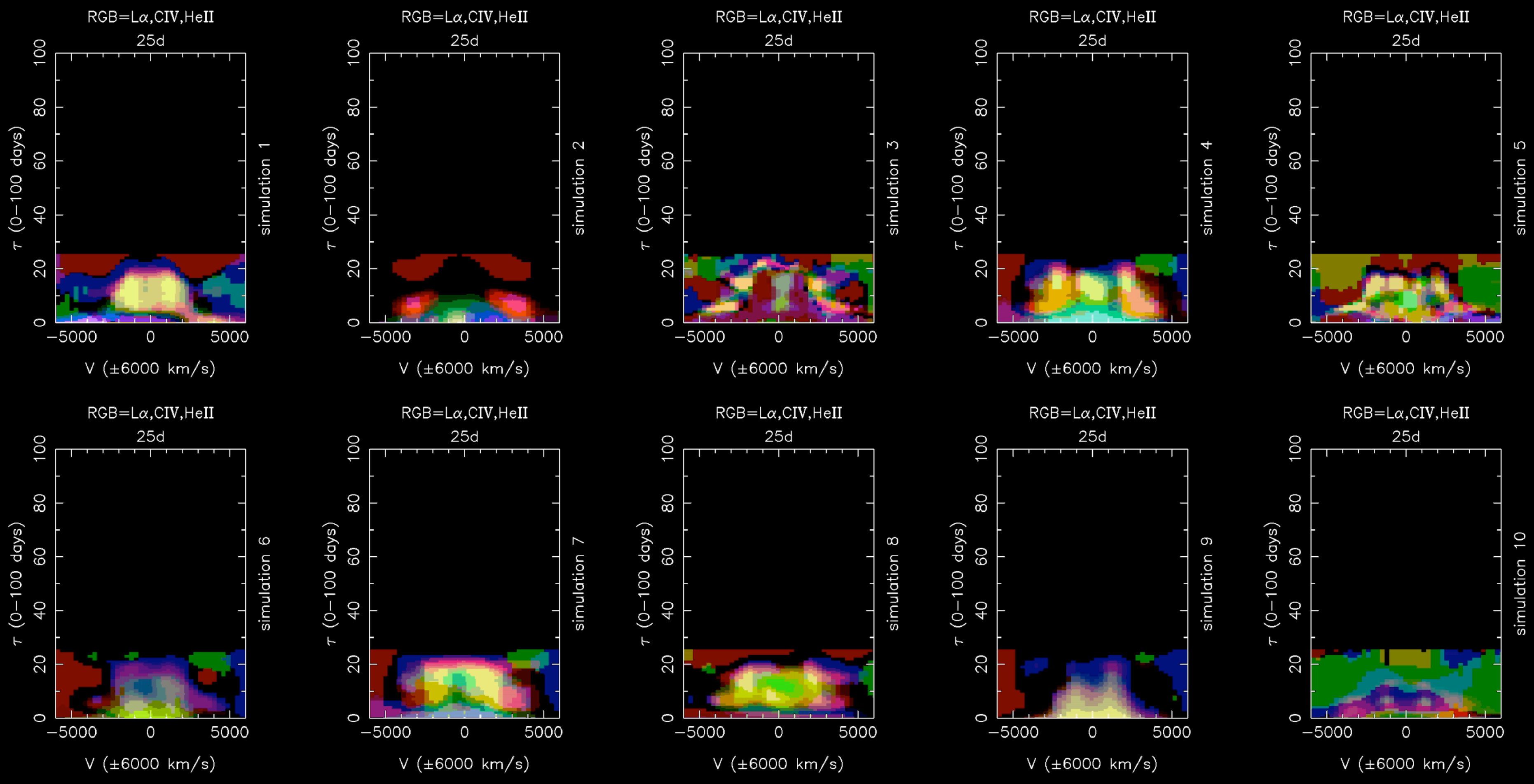


– Long dura...
– Moderate sp...
– High homogeneity and signal-to-noise

Program	AGN Watch NGC 5548			AGN Watch NGC 4151		AGN Watch NGC 7469		AGN Watch (other)		OSU	CTIO/ OSU	LAG	Wise 1988	Wise/ SO PG
	IUE 89	HST 93	Opt	IUE	Opt	IUE	Opt	IUE	Opt	Opt	Opt	Opt	Opt	Opt
No. Sources	1	1	1	1	1	1	1	3	5	8	2	5	3	15
Time Resolution														
Duration														
Spectral Resolution														
Homogeneity														
Signal/Noise Ratio														

A program to obtain a velocity-delay map is not much more difficult than what has been done already!

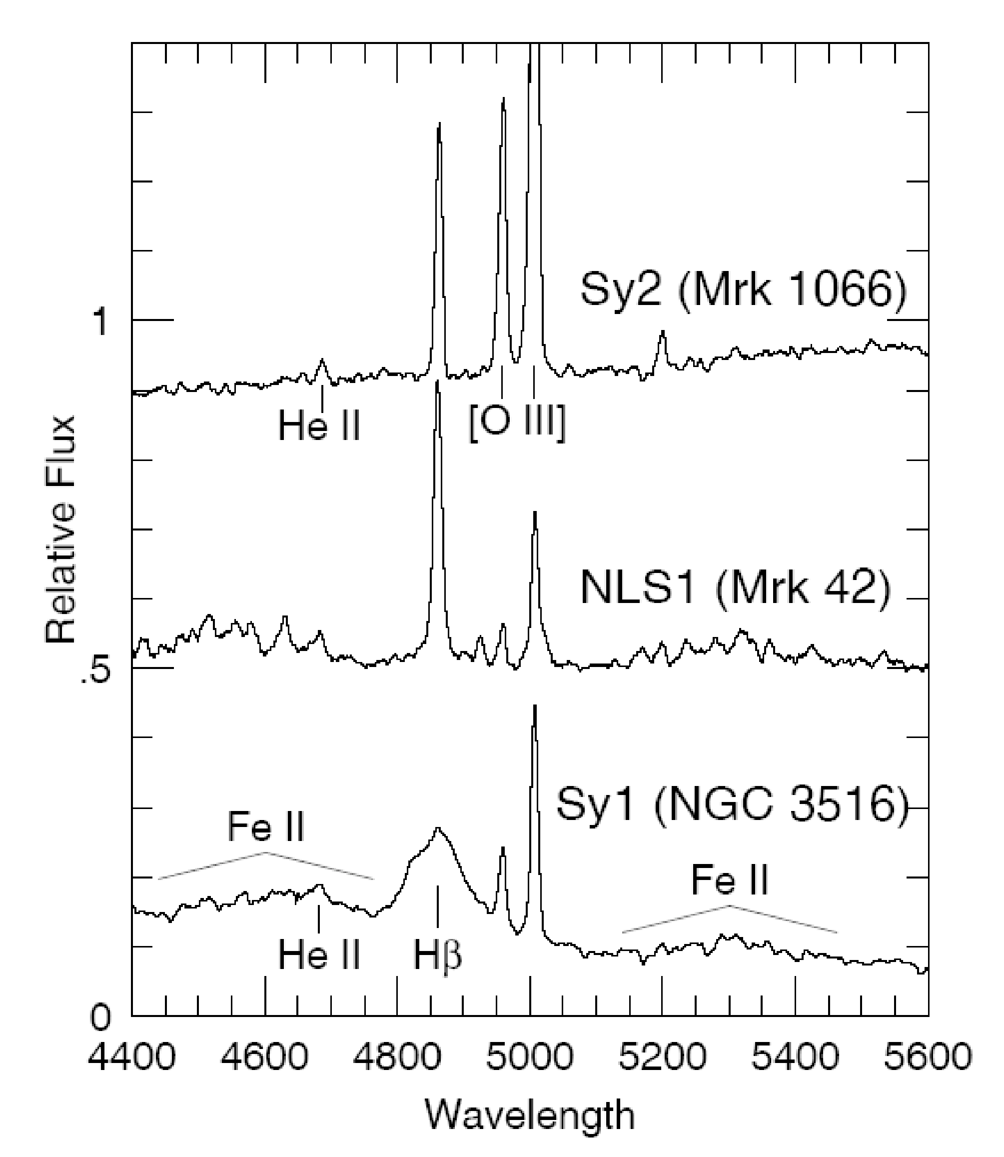
10 Simulations Based on *HST*/STIS Performance



Each step increases the
experiment duration by 25 days

The Nature of NLS1s

- Narrow-line Seyfert 1 (***NLS1***) galaxies are true broad-line objects, but with an especially narrow broad component, FWHM < 2000 km s^{-1}



Definition of NLS1s

- FWHM(Hβ) ≤ 2000 km s^{-1}
- Flux ratio [O III] λ5007/Hβ ≤ 3
  - Ensures they are true Sy1s
- Consider the following:

$$R_{\mathrm{BLR}} \propto L_{\mathrm{AGN}}^{1/2}$$

$$\Delta V \propto \left(GM_{\mathrm{BH}} / R_{\mathrm{BLR}} \right)^{1/2}$$

$$\Delta V \propto \left(M_{\mathrm{BH}} / L^{1/2} \right)^{1/2} \propto \left(M_{\mathrm{BH}} / \dot{M}^{1/2} \right)^{1/2} \propto \left(M_{\mathrm{BH}} / \dot{m} \right)^{1/4}$$

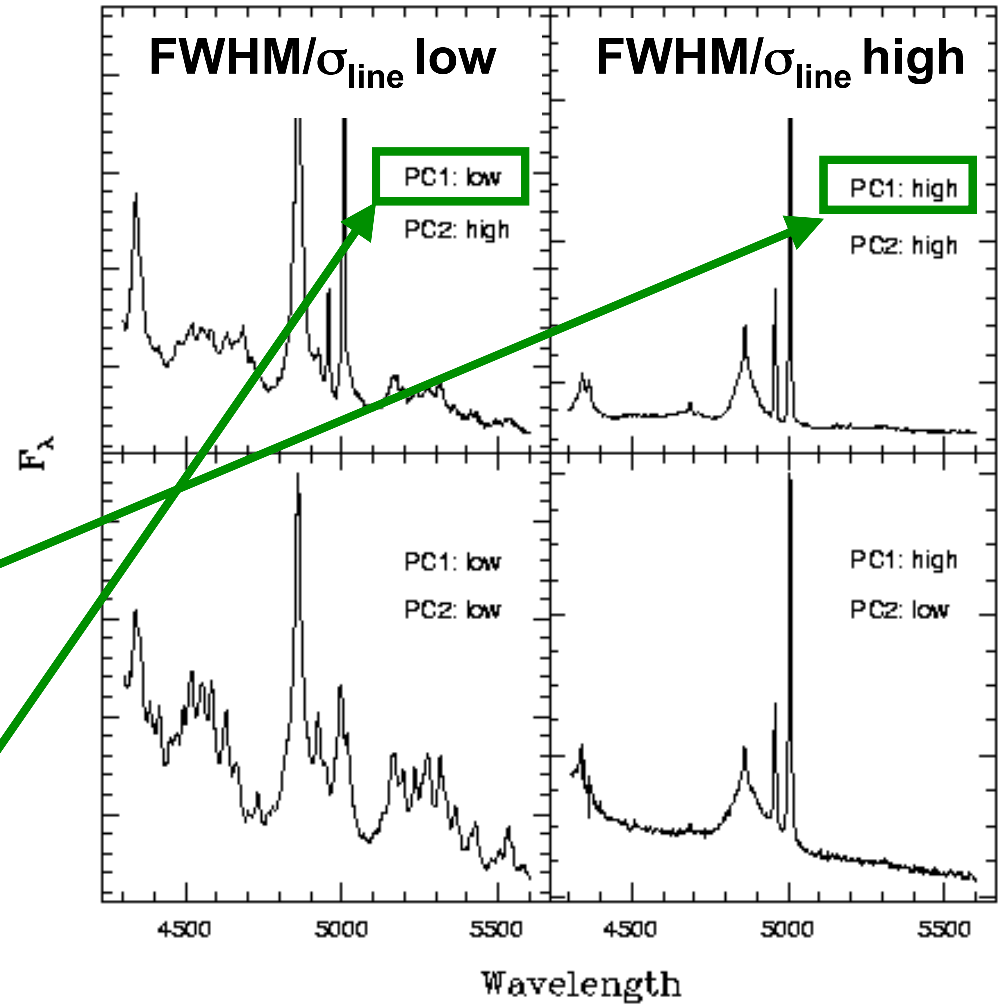
Definition of NLS1s

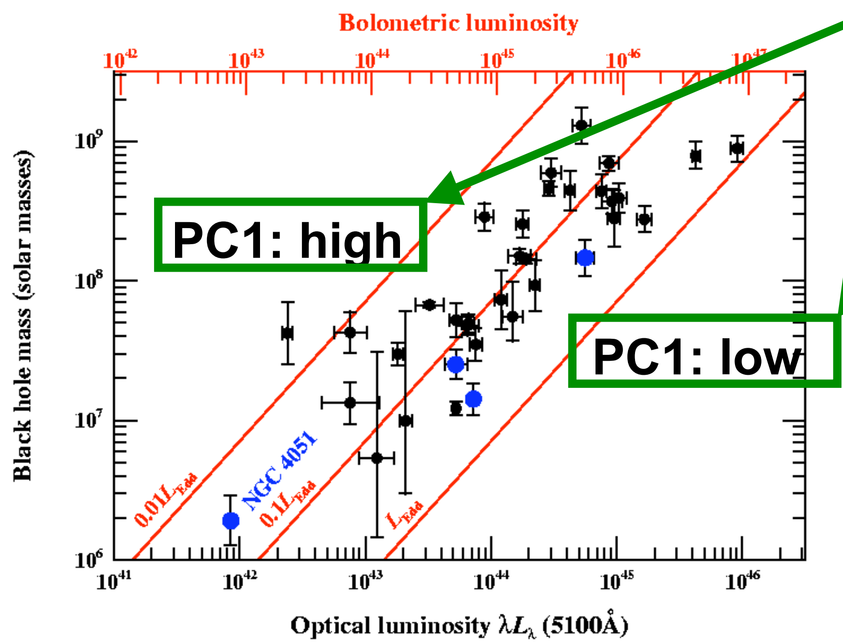
$$\Delta V \propto \left(M_{\mathrm{BH}} / \dot{m} \right)^{1/4}$$

- If NLS1s are physically defined by high Eddington rate, then high-mass black holes are missed.
  - Includes 3C 273 and PG 1700+518, which have NLS1-type spectra.

Eigenvector 1

- FWHM/σ_{line} also correlates with PC1 (Eigenvector 1)
- Both show some correlation with Eddington rate
  - Some indications inclination matters

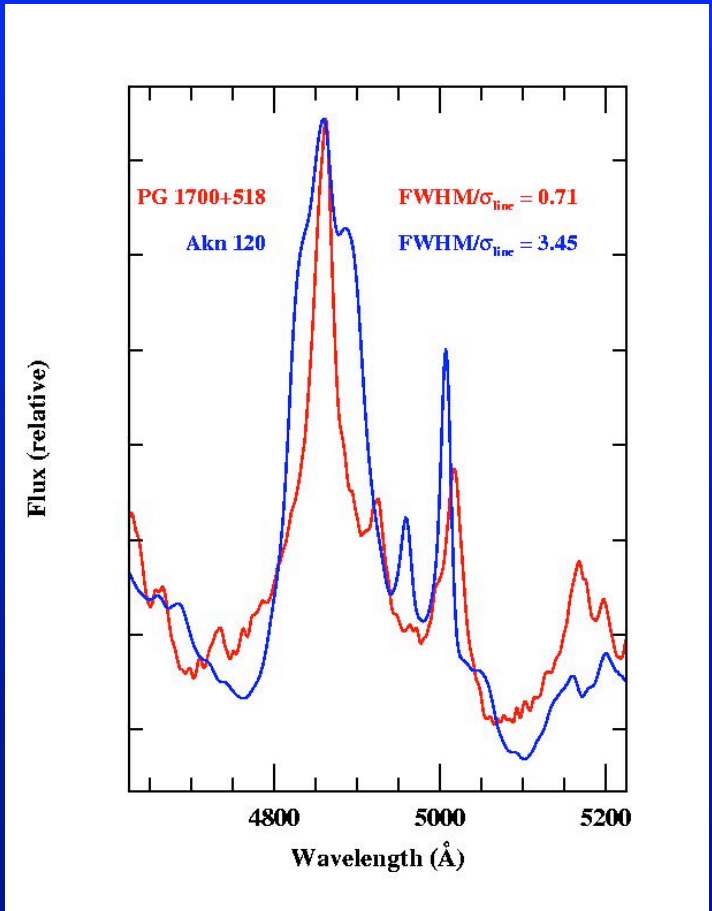




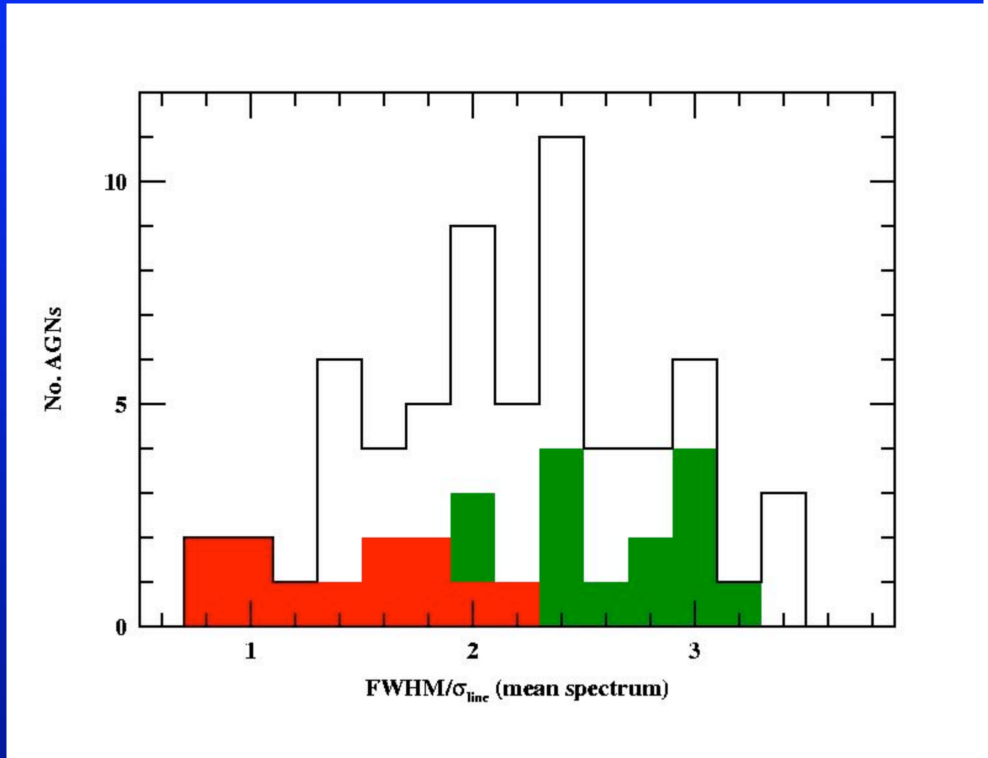
Boroson 2002

What does FWHM/σ_{line} actually measure?

Not just inclination (NGC 5548).



Extreme examples



NLS1 + I Zw 1-type

NGC 5548 Hβ

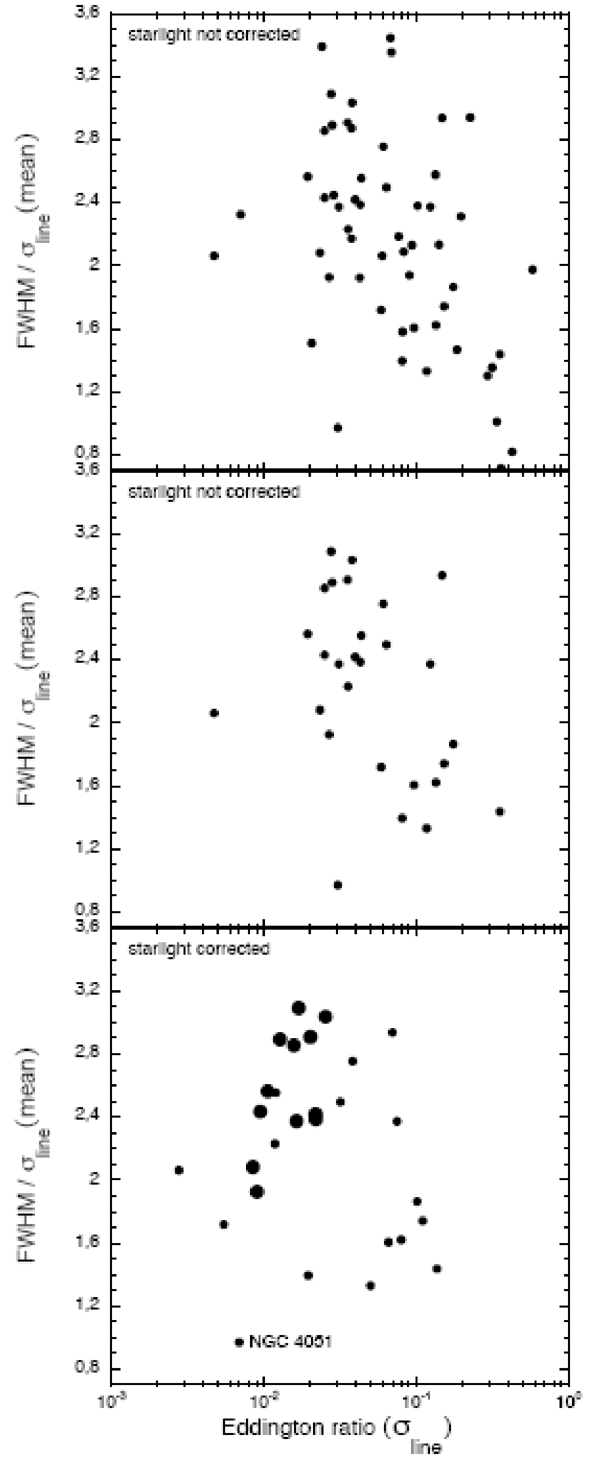
What does FWHM/σ_{line} actually measure?

- Not just Eddington rate.

All data

Subset correctable for starlight

Corrected for starlight: big symbols are NGC 5548



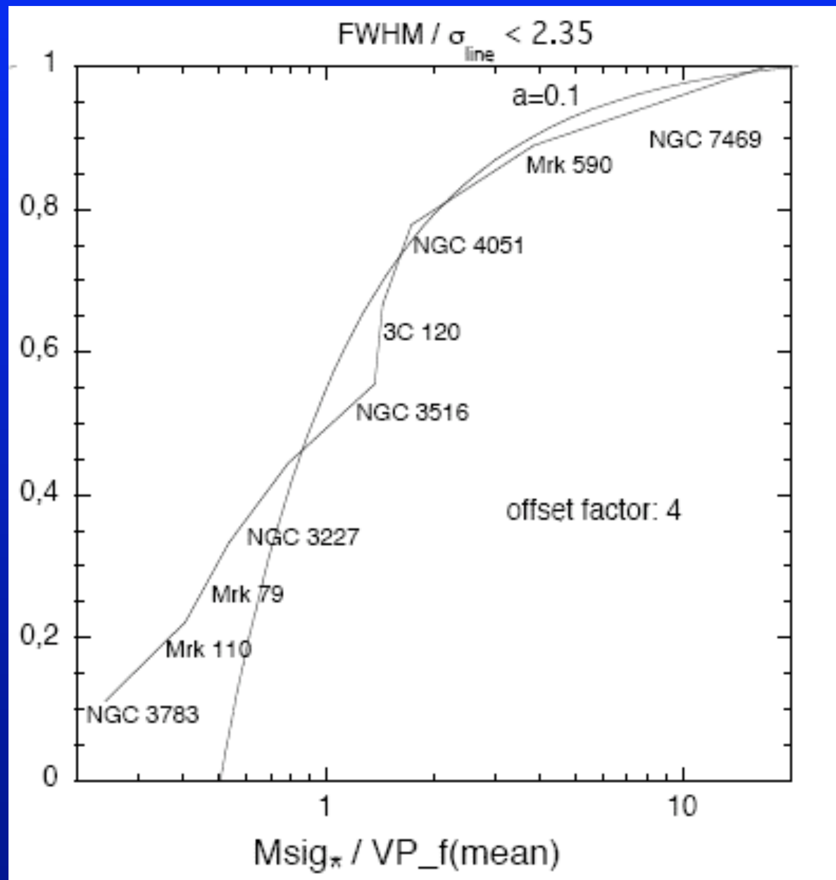
Collin et al. (2006)

Can We Determine Inclination?

- Suggestion (Wu & Han 2001; Zhang & Wu 2002; McLure & Dunlop 2001): Use prediction of $M_{BH} - \sigma_* \Rightarrow M_{\sigma*}$ (assumed isotropic)
  - Compare to reverberation measurement M_{rev}
  - Expect that small $M_{rev} / M_{\sigma*} \Rightarrow$ low (face-on) inclination
  - Similarly, expect that some NLS1s or other likely low inclination to have small $M_{rev} / M_{\sigma*}$

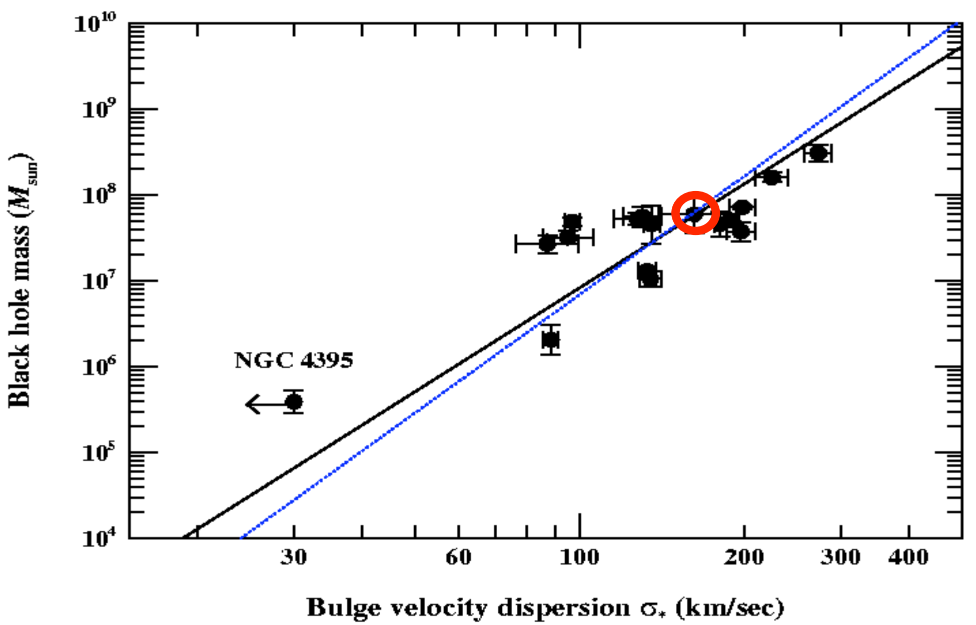
Can We Determine Inclination?

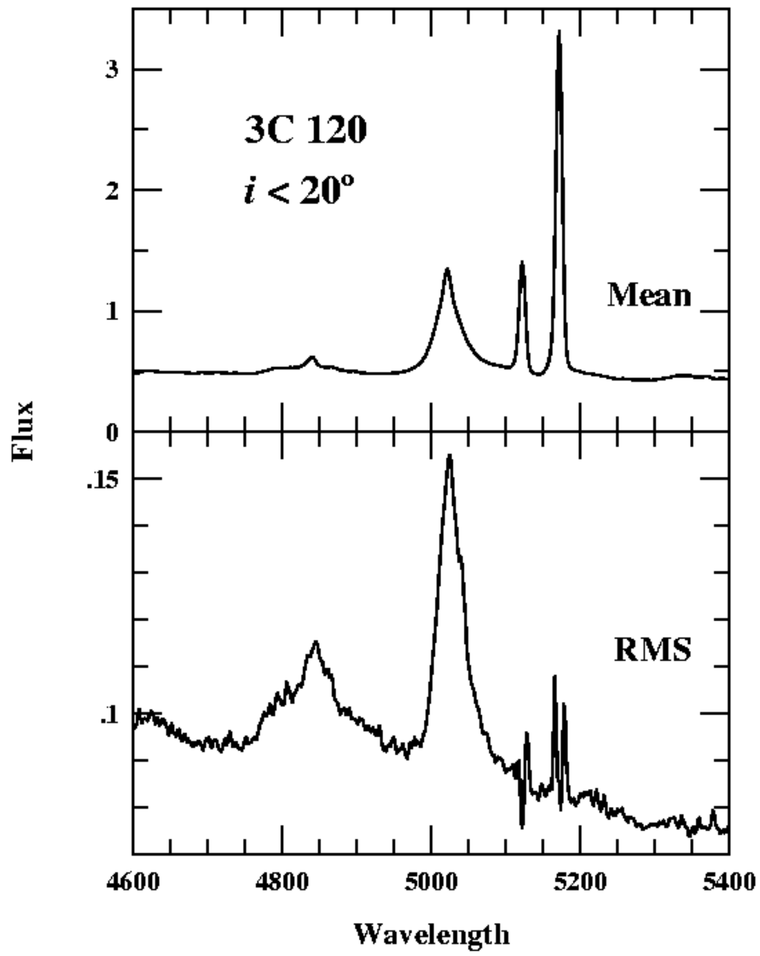
- Even if M_{rev} / $M_{\sigma *}$ is a poor inclination predictor for specific sources, Collin et al. (2006) make a statistical argument that some objects with low FWHM/σ_{line} values are low inclination.



Test Case 1: 3C 120

- Superluminal jet implies that 3C 120 is nearly face-on (i < 20 º)
- Does not stand out in $M_{BH} - \sigma_*$





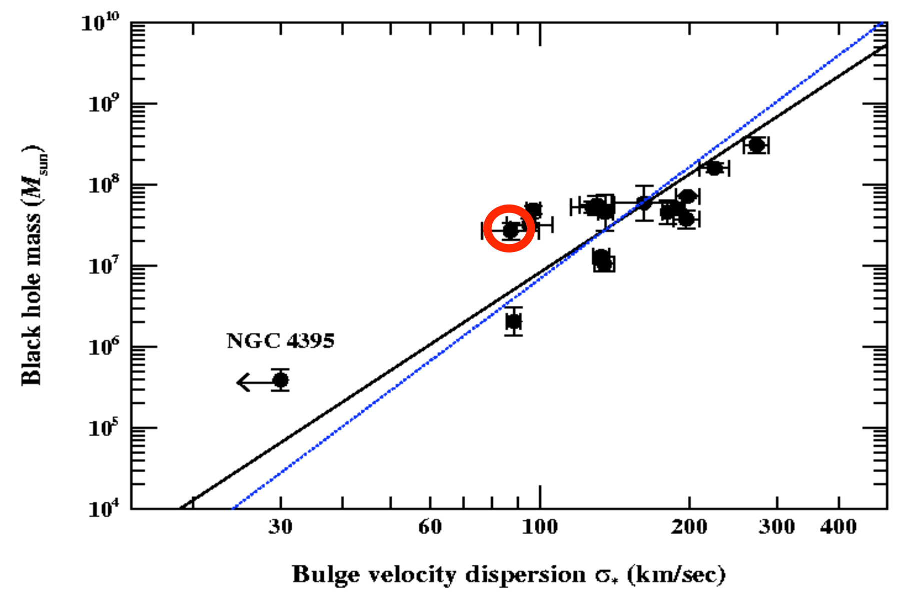
Test Case 2: Mrk 110

An NLS1 with an independent mass estimate from gravitational redshift of emission lines (Kollatschny 2003):

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

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

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



Other Ways to Determine Inclination

- Radio jets
- Spectropolarimetry
- Reverberation mapping (full velocity-delay map)

Evidence Inclination Matters

- Inverse correlation between *R* (core/lobe) and FWHM (Wills & Browne 1986)
  - Core-dominant are more face-on so lines are narrower
- Correlation between α_{radio} and FWHM (Jarvis & McLure 2006)
  - Flat spectrum sources are closer to face-on and have smaller 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)
- Width of C IV base is larger for smaller *R* (Vestergaard, Wilkes, & Barthel 2000)
  - Line base is broader for edge-on sources

Concluding Points

- Masses of the supermassive black holes in AGNs have been measured by reverberation mapping, stellar and gas dynamics, and scaling relationships.
  - Typical Eddington ratios are ~0.1
  - Reverberation-based masses appear to be accurate to a factor of about 3. Direct tests and additional statistical tests are in progress.
  - Scaling relationships allow masses of many quasars to be estimated easily. Uncertainties typically ~4 at this time
- AGN $M_{BH} - \sigma_*$ slope consistent with quiescent galaxy $M_{BH} - \sigma_*$ slope. Zero point currently calibrates reverberation mass scale
- AGN $M_{BH} - L_{bulge}$ currently consistent with that for normal galaxies.
- Full potential of reverberation mapping has not yet been realized.
  - Significant improvements in quality of results are within reach.

Backup Slides

A Plausible Disk-Wind Concept