Black Hole Masses from Reverberation and Scaling Relationships

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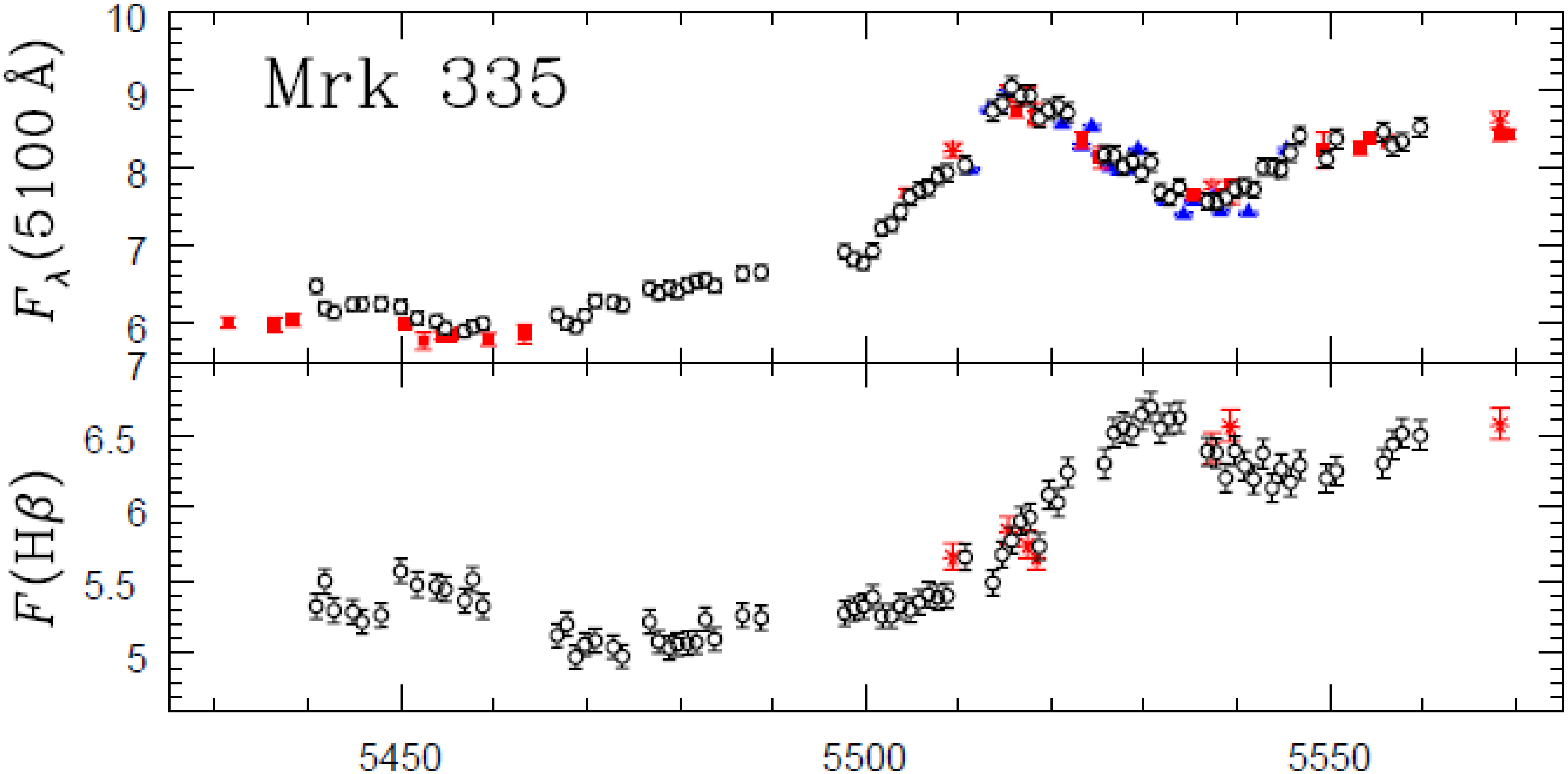
Using scaling relationships:

- AGNs are used as tracers of the black hole population up to high redshift
- Their masses can be inferred from their luminosity and emission-line widths using scaling relationships based on reverberation mapping of relatively local (hence bright) AGNs.
- I will discuss use of these scaling relationships which are often used incorrectly, thus biasing the black hole mass scale.

Reverberation Mapping

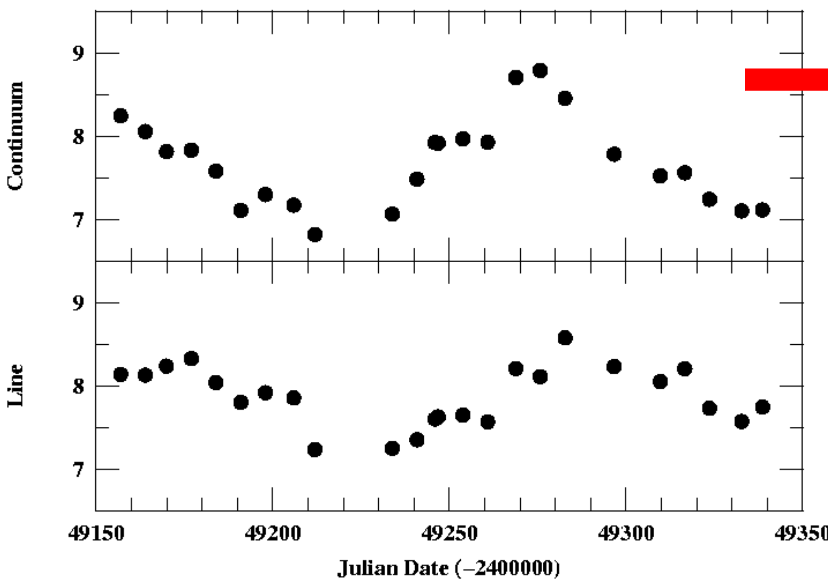


Emission-line variations follow those in continuum with a small time delay (14 days here) due to light-travel time across the line emitting region.

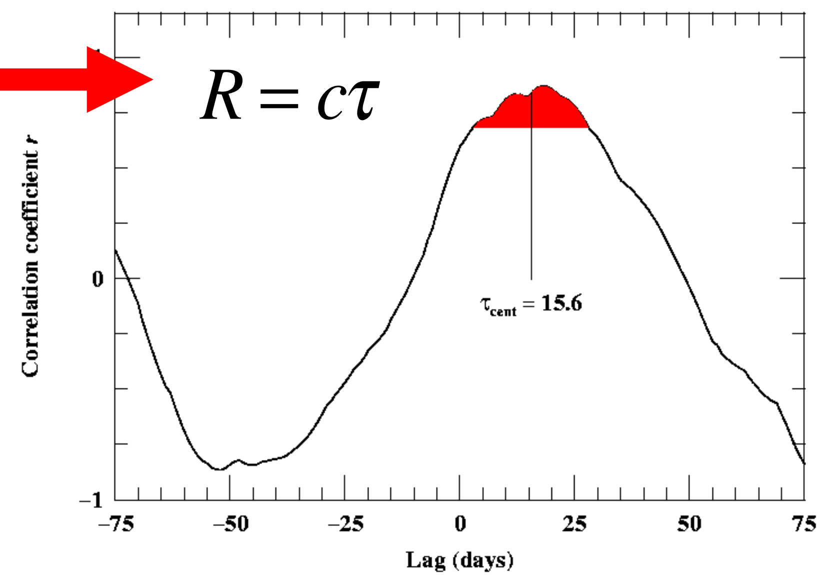
Grier+ 2012, ApJ, 744, L4

Emission-Line Lags

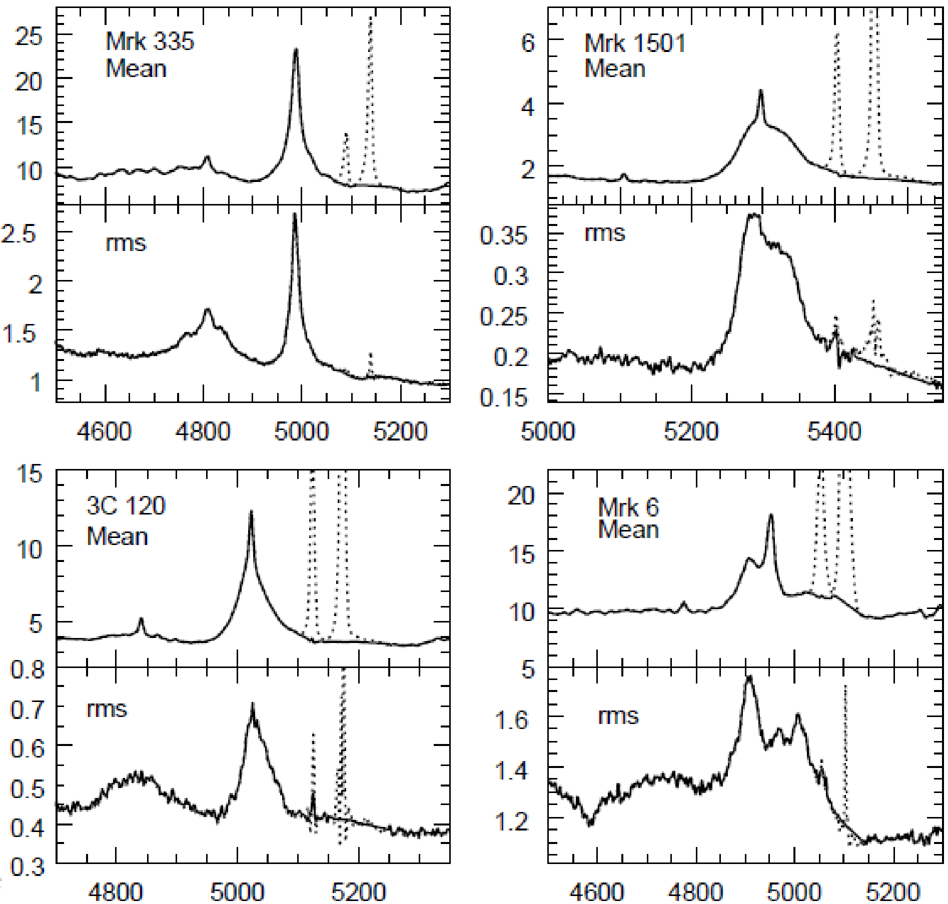
Because the data requirements are *relatively* modest, it is most common to determine the cross-correlation function and obtain the "lag" (mean response time). For an axisymmetric, isotropically emitting system, the lag is a measure of the size..



$$R = c\tau$$



Measuring the Emission-Line Widths



Grier+ 2012, ApJ, 755:60

We preferentially measure line widths in the rms residual spectrum.

- Constant features disappear, less blending.
- Captures the velocity dispersion of the gas that is responding to continuum variations.

Reverberation-Based Masses

"Virial Product" (units of mass)

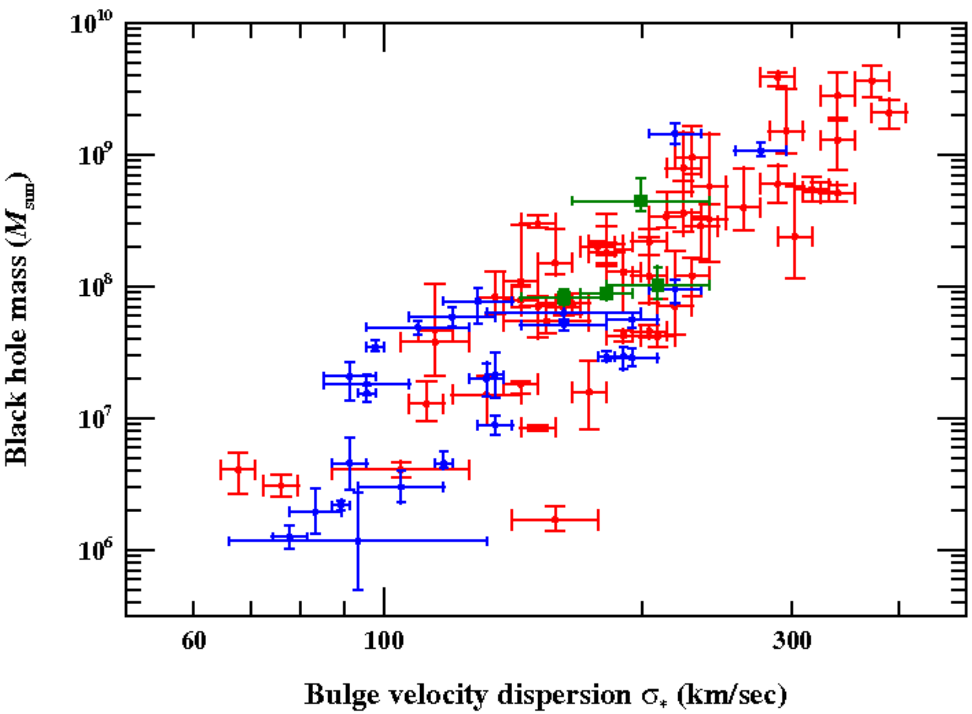
$$M_{\mathrm{BH}} = f \boxed{\left(\underline{R\Delta V}^{2} / G \right)}$$

Observables:
R = BLR radius (reverberation)
ΔV = Emission-line width

Set by geometry and inclination
(subsumes everything we don't know)

If we have independent measures of M_{BH}, we can compute an ensemble average $\langle f \rangle$

The AGN M_{BH}– σ_* Relationship



- AGN
- AGN *H*-band σ_*
- Quiescent galaxy

- Assume zero point of most recent quiescent galaxy calibration.

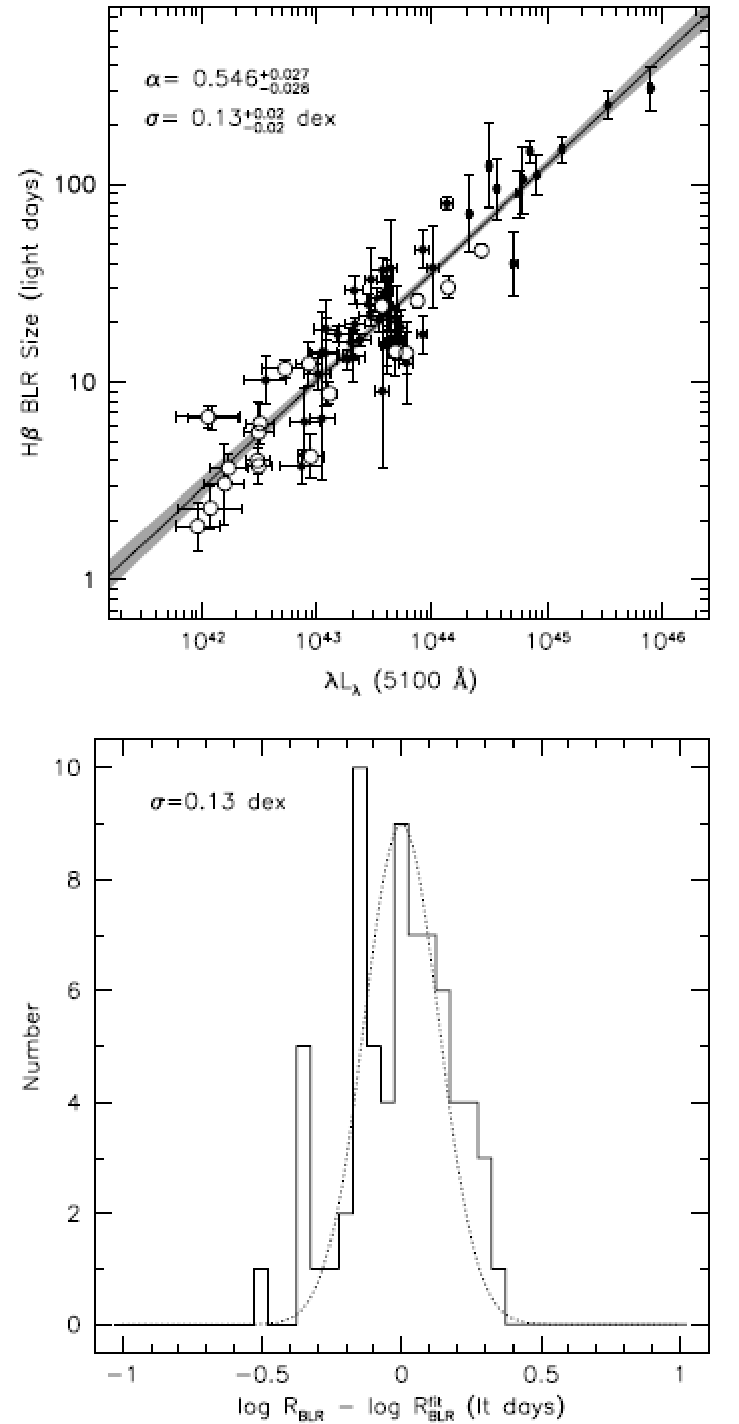
  $\langle f \rangle = 4.19 \pm 1.08$

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

Grier+ 2013, ApJ, 773:90

The *R*–*L* Relation

- Empirical slope ~0.55 ± 0.03
- Intrinsic scatter ~0.13 dex
- Typical error bars on best reverberation data ~0.09 dex
- Conclusion: for Hβ over the calibrated range ($42 \leq \log L_{5100}$ (ergs s^{-1}) ≤ 46 at $z \approx 0$), *R-L* is nearly as effective as reverberation.



Bentz+ 2013, ApJ, 767:149

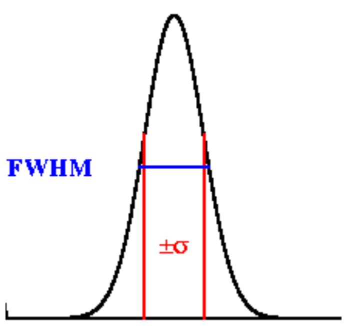
FWHM or Line Dispersion σ_{line}?

- Common misconception that they can be used interchangeably as long as you adjust the scale factor *f*

$$M_{\text{BH}} = f_{\sigma}\left(R\sigma_{\text{line}}^{2}/G\right) \neq f_{\text{FWHM}}\left(RV_{\text{FWHM}}^{2}/G\right)$$

- Argument is that since typical AGN line profiles are approximately Gaussian,

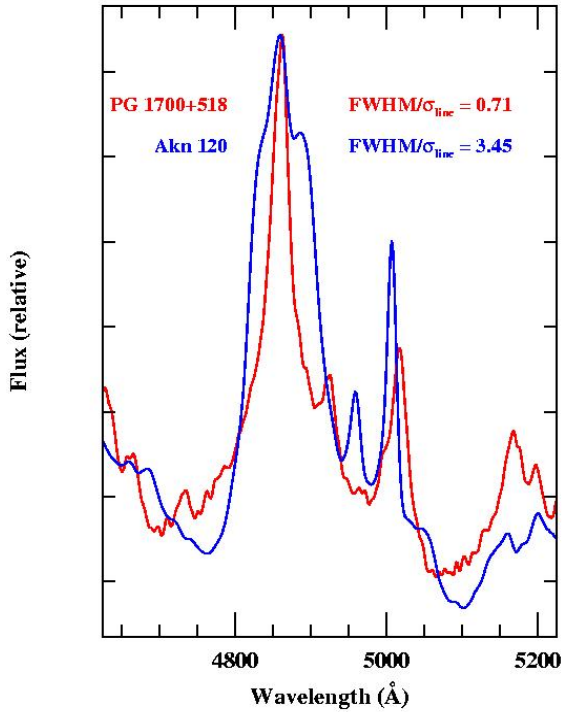
$$f_{\sigma}/f_{\text{FWHM}} \approx \left(V_{\text{FWHM}}/\sigma_{\text{line}}\right)^{2} \approx \left(2.35\right)^{2} \approx 5.5$$

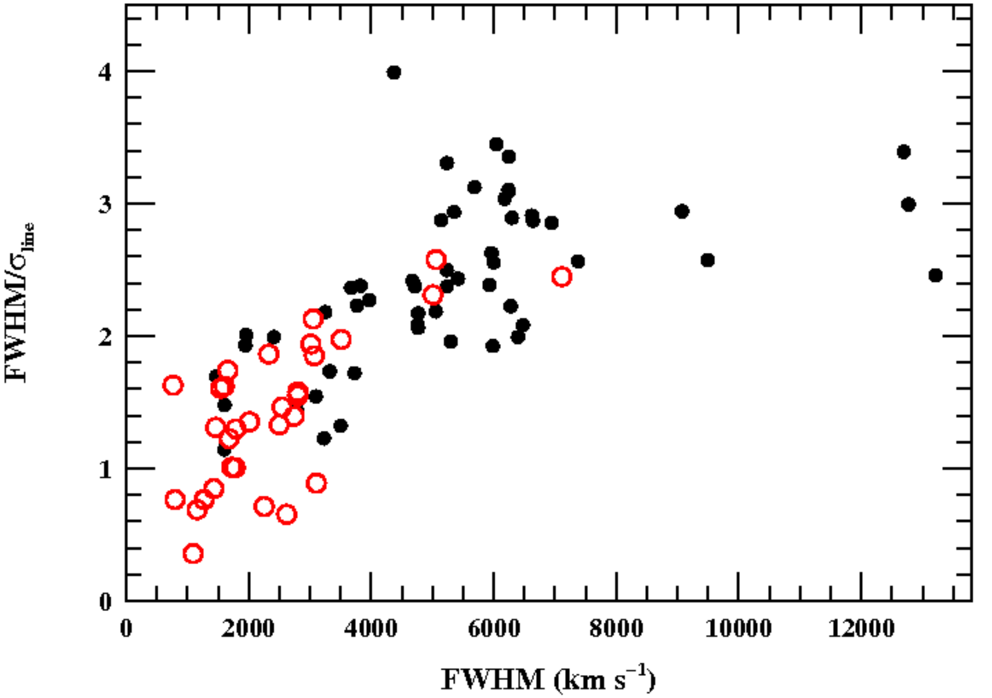


THIS IS INCORRECT

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

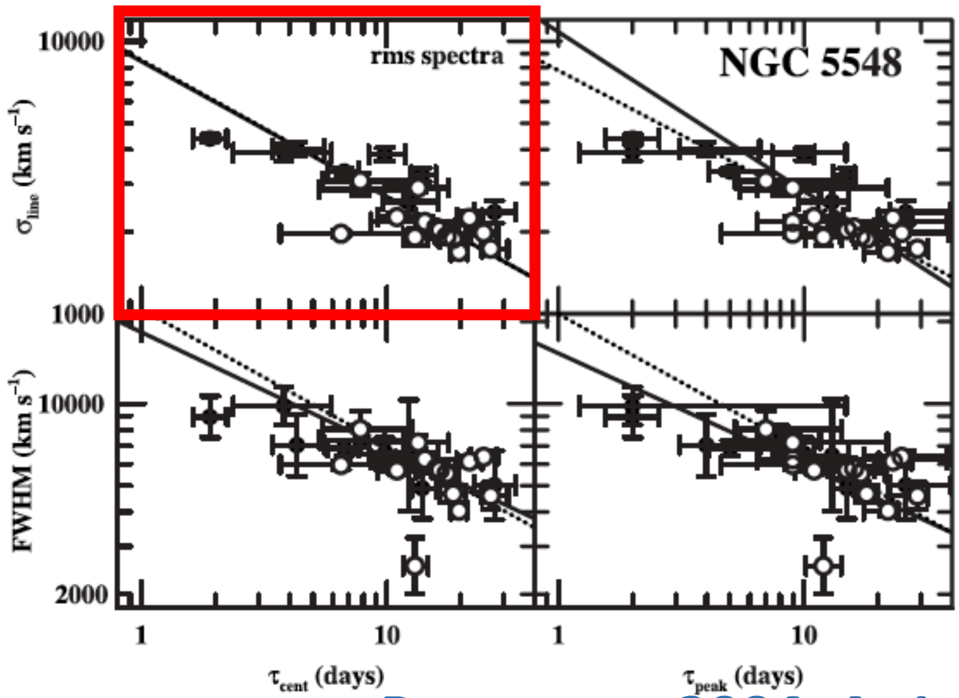
- This matters because their black hole masses depend on the line width measure (squared!).
- Systematically shifts high Eddington ratio objects (e.g., NLS1s) away from other AGN masses.



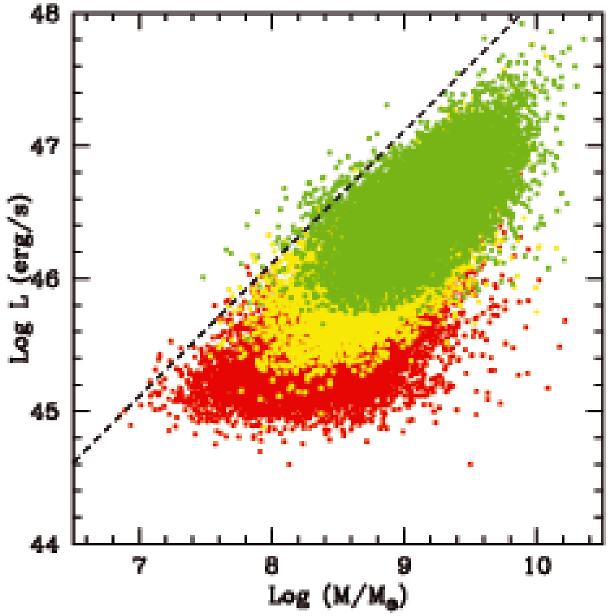


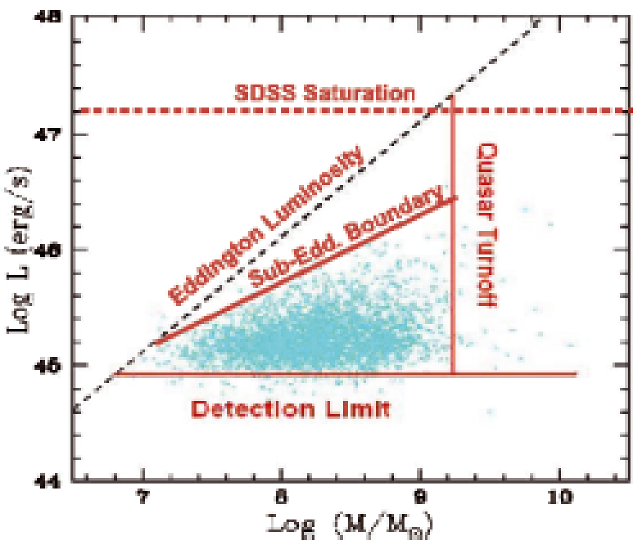
Which is the better line-width parameter?

- Compelling circumstantial evidence points to σ_{line} having advantages over FWHM
  - Better virial relationship (closer to predicted slope, less scatter)
  - Better agreement between masses inferred from Hβ and C IV
  - Eliminates the physically implausible "sub-Eddington boundary"



Peterson + 2004, ApJ, 613:682





Steinhardt & Elvis 2010

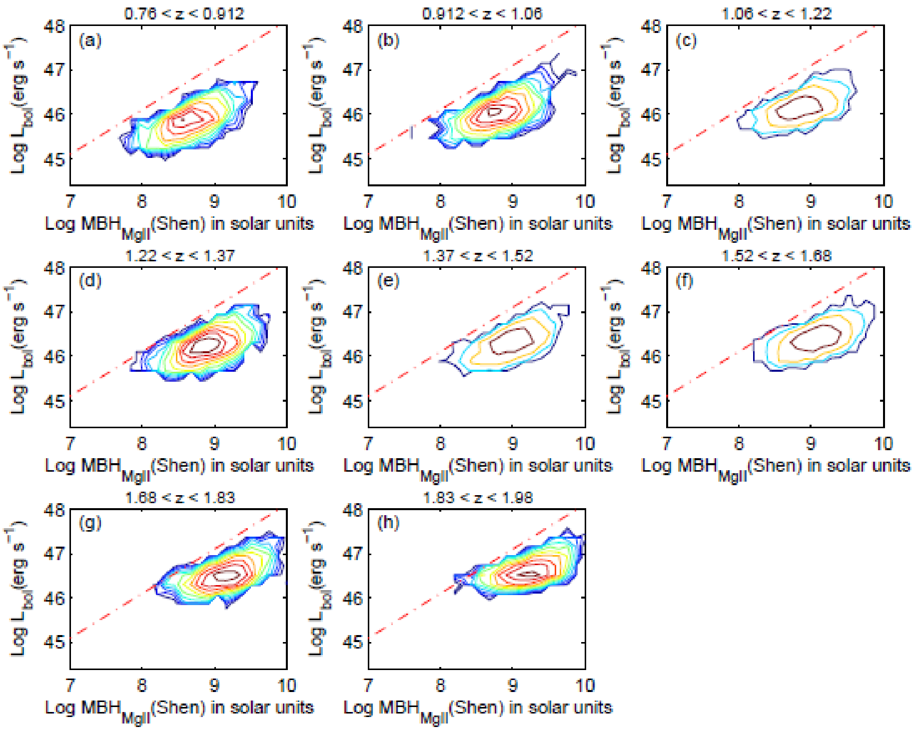
The Sub-Eddington Limit

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

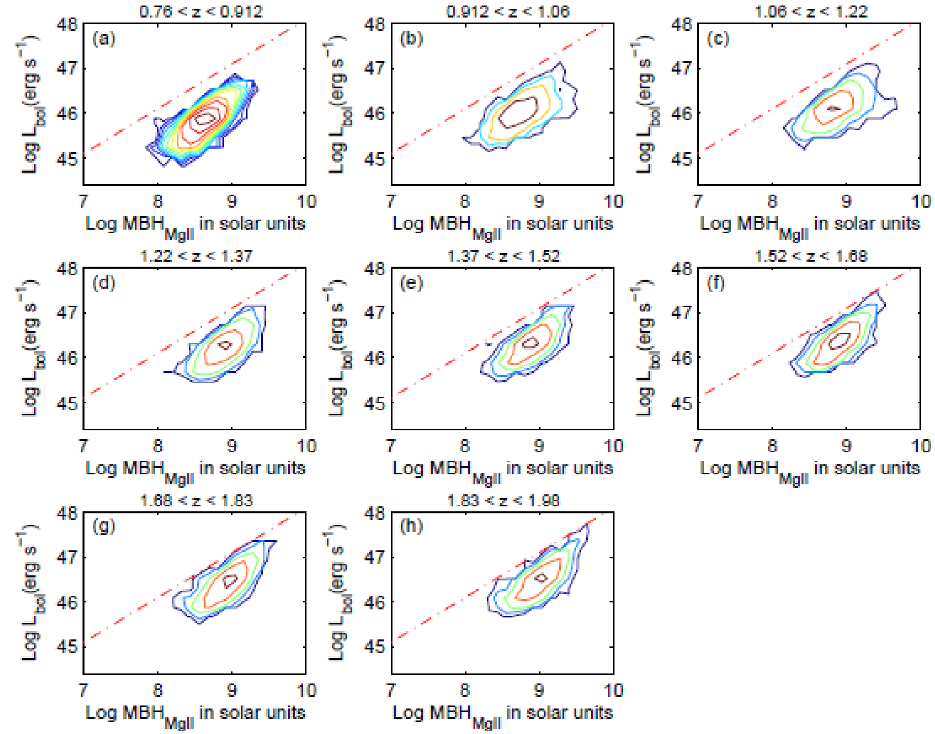
  Steinhardt & Elvis 2010

- Line widths used were from multiple Gaussian fits to broad emission lines. Model profiles added together and FWHM measured.

  Shen, Greene, et al. 2008



FWHM-based



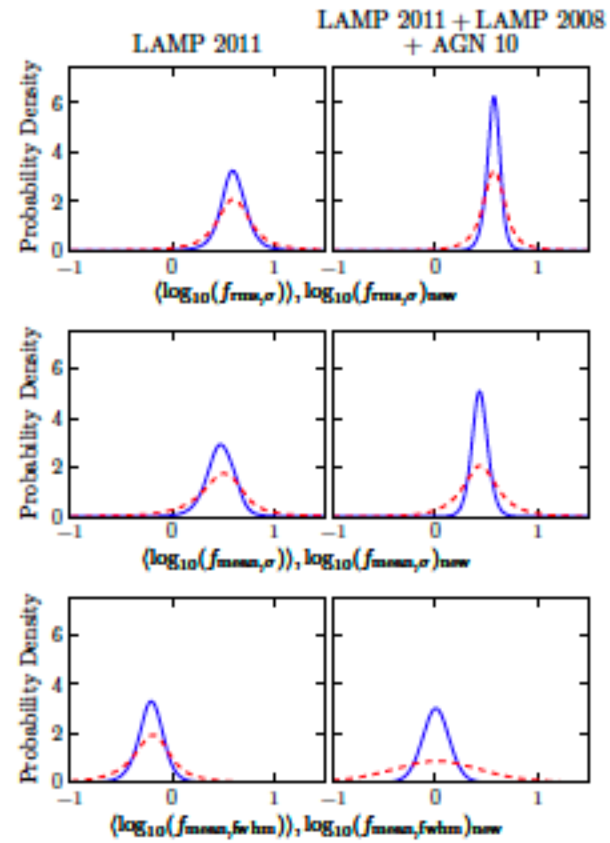
σ_{line}-based

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.

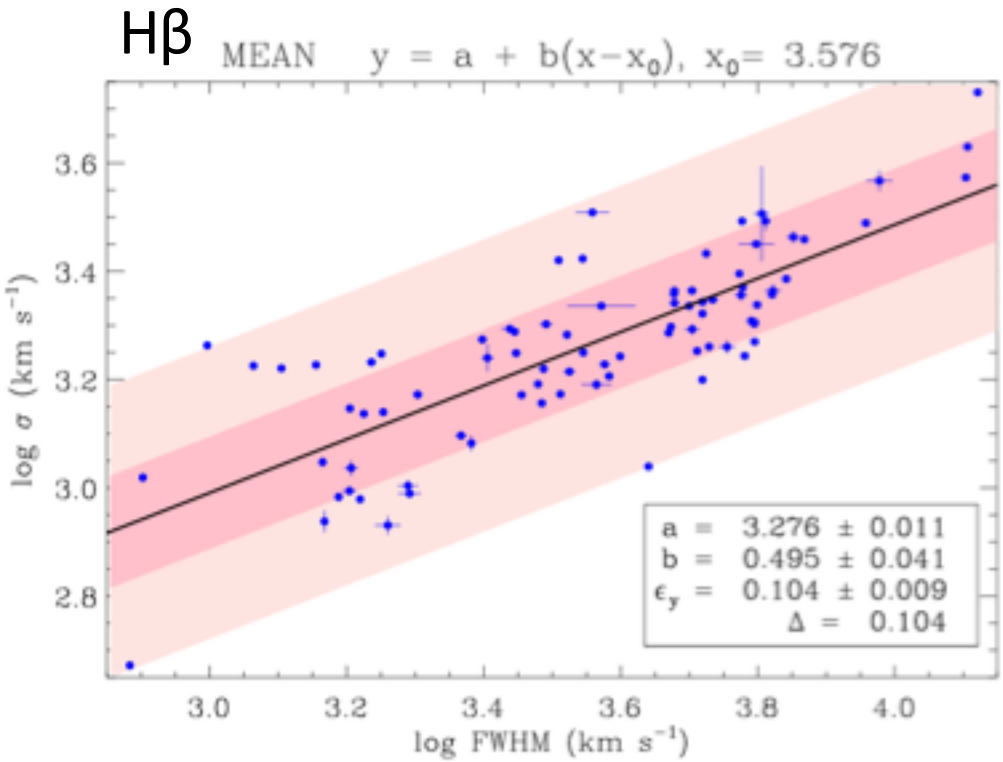
Additional evidence supporting σ_{line} over FWHM

Recent dynamical modeling results for 16 reverberation-mapped AGNs favor σ_{line} over FWHM



Williams+ submitted

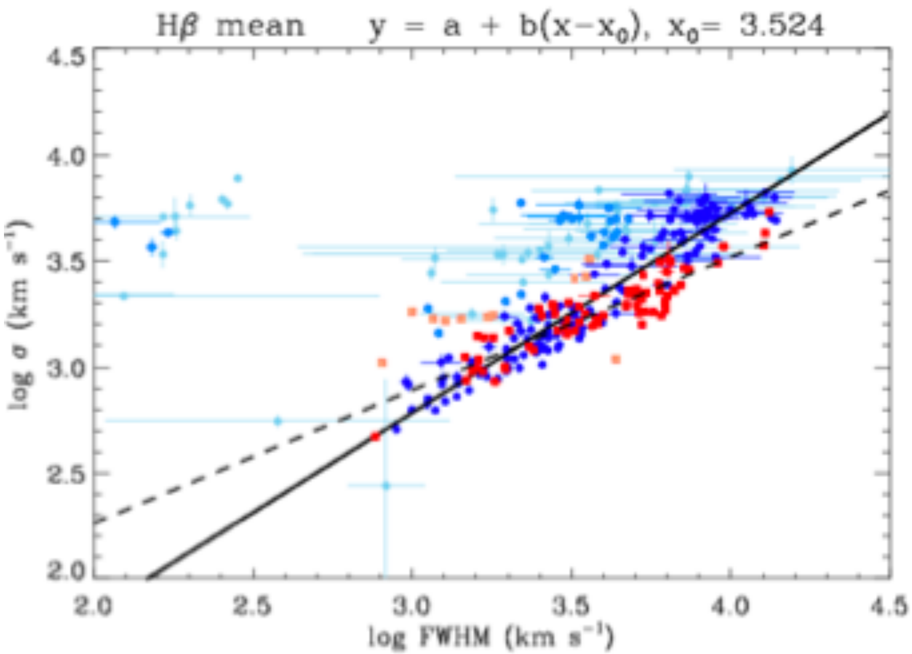
I hate line dispersion! I don't want to (or can't) deblend! FWHM is so much easier to measure!

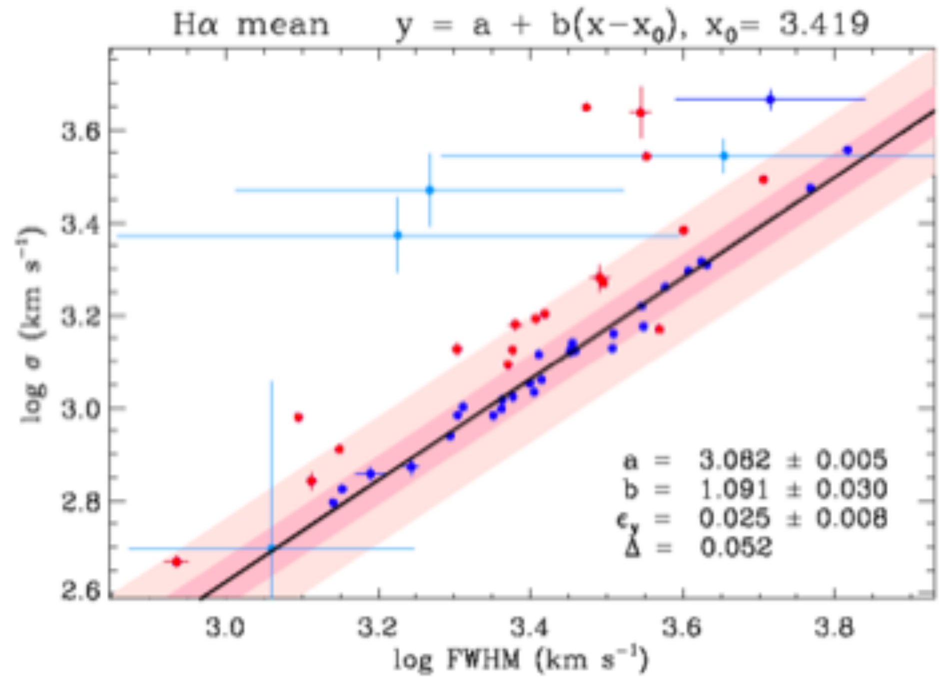


Use an empirical fit to log σ_{line} = a + b log FWHM.
Penalty: increase intrinsic scatter by ~0.1 dex

Dalla Bontà, Peterson+ in preparation

SDSS-RM data





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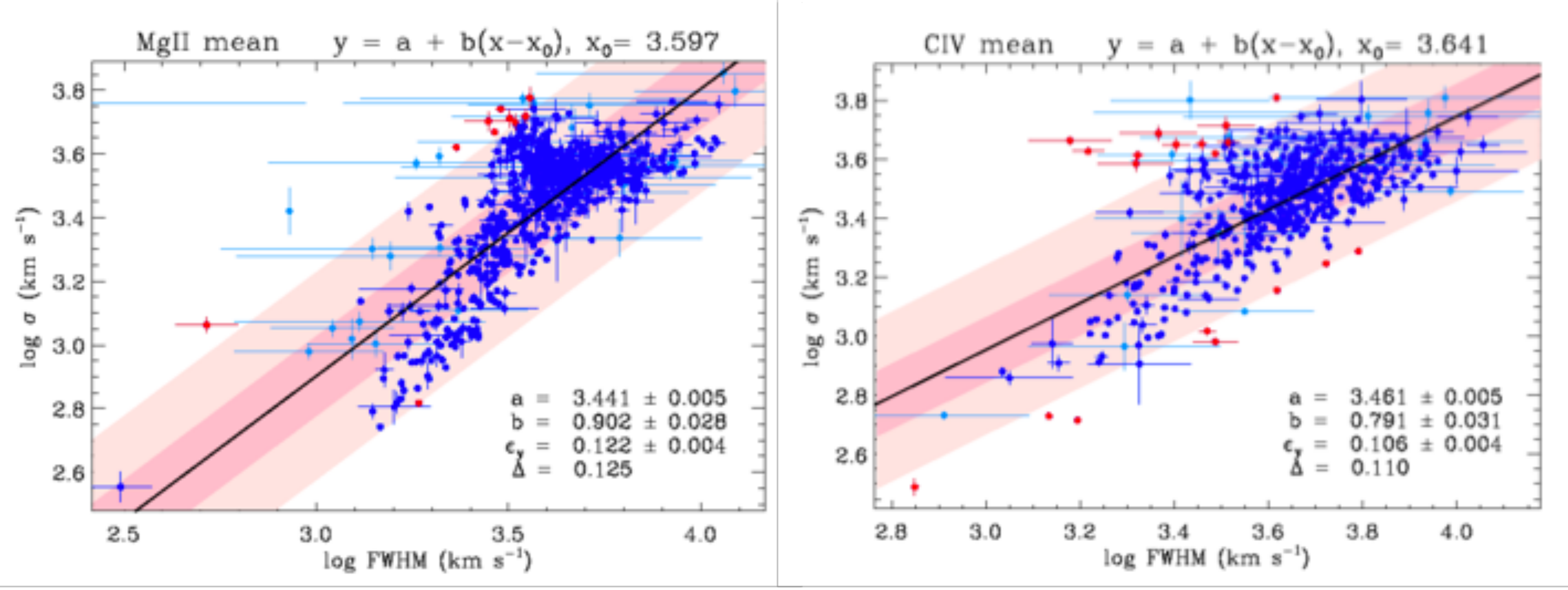

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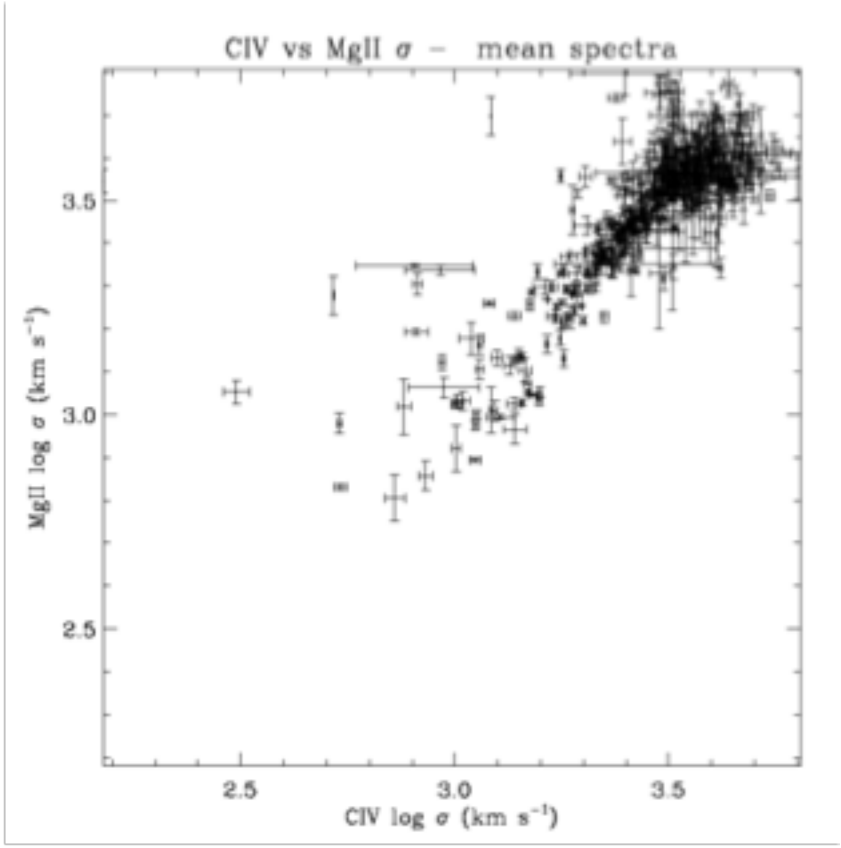
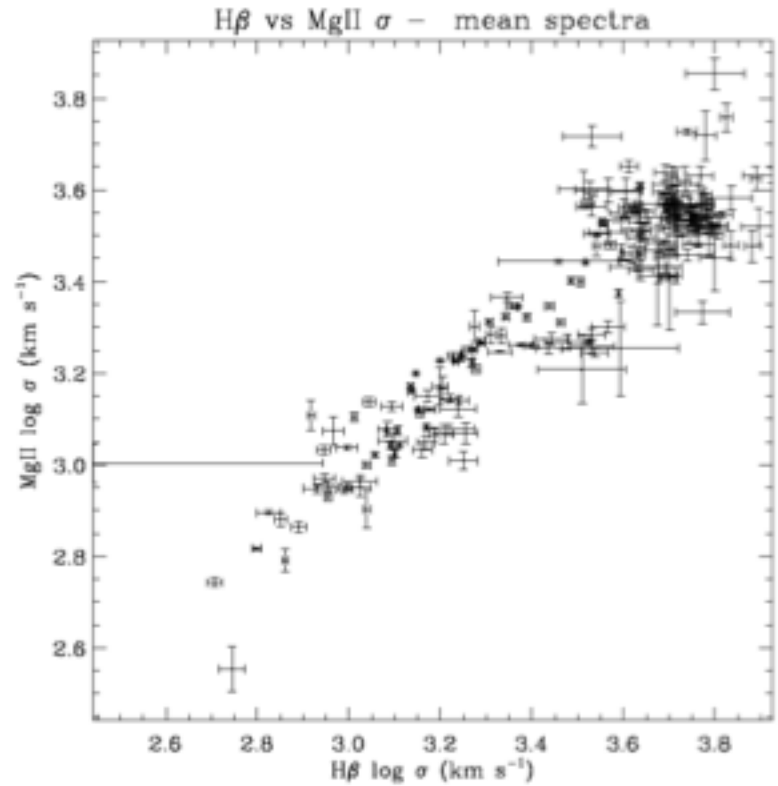
SDSS-RM data





Dalla Bontà, Peterson+ in preparation

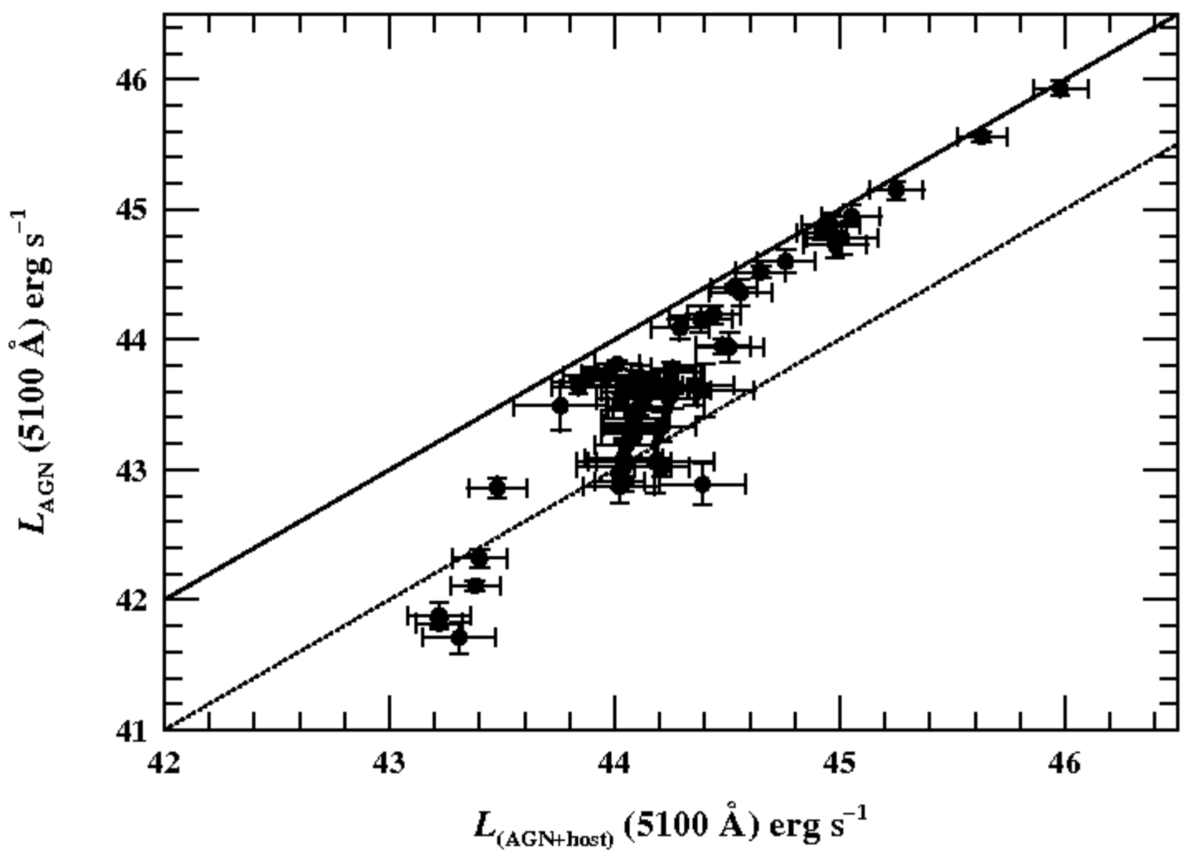
  

NGC 4051	Mrk 79	PG 0953+414
z = 0.00234	z =0.0222	z = 0.234
log $L_{\rm opt}$ = 41.8	log $L_{\rm opt}$ = 43.7	log $L_{\rm opt}$ = 45.1

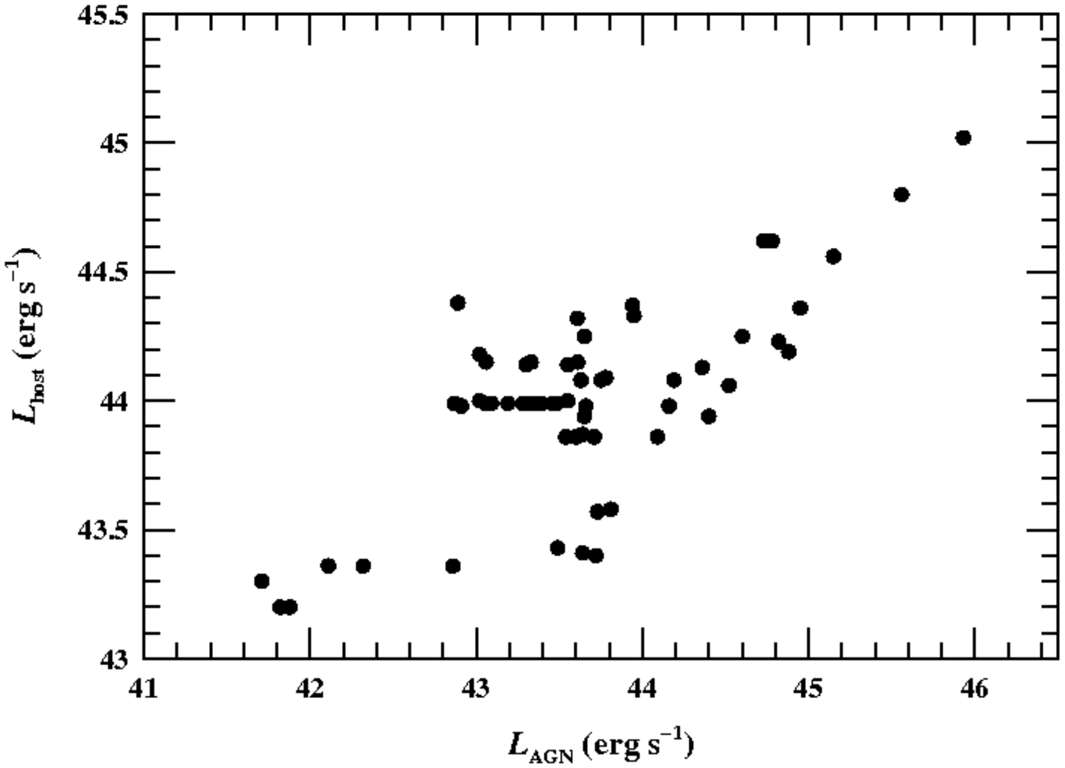
Reverberation experiments use large spectrograph apertures for accurate spectrophotometry.
This results in significant starlight contribution to the measured optical luminosity.

Images courtesy of M. Bentz

Host-galaxy starlight needs to be corrected for, particularly at the low-luminosity end.



There is a correlation between AGN and host luminosity, but there's a lot of scatter.



Dalla Bontà, Peterson+ in preparation

Conclusions

- Careful attention on the adopted values entering the virial product and scaling relations
- σ_{line} better than FWHM but correction is possible if FWHM is used → corrections will be provided
- R-L for MgII and CIV

Stay tuned!