Supermassive Black Holes in Active Galactic Nuclei

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UFRGS Lectures

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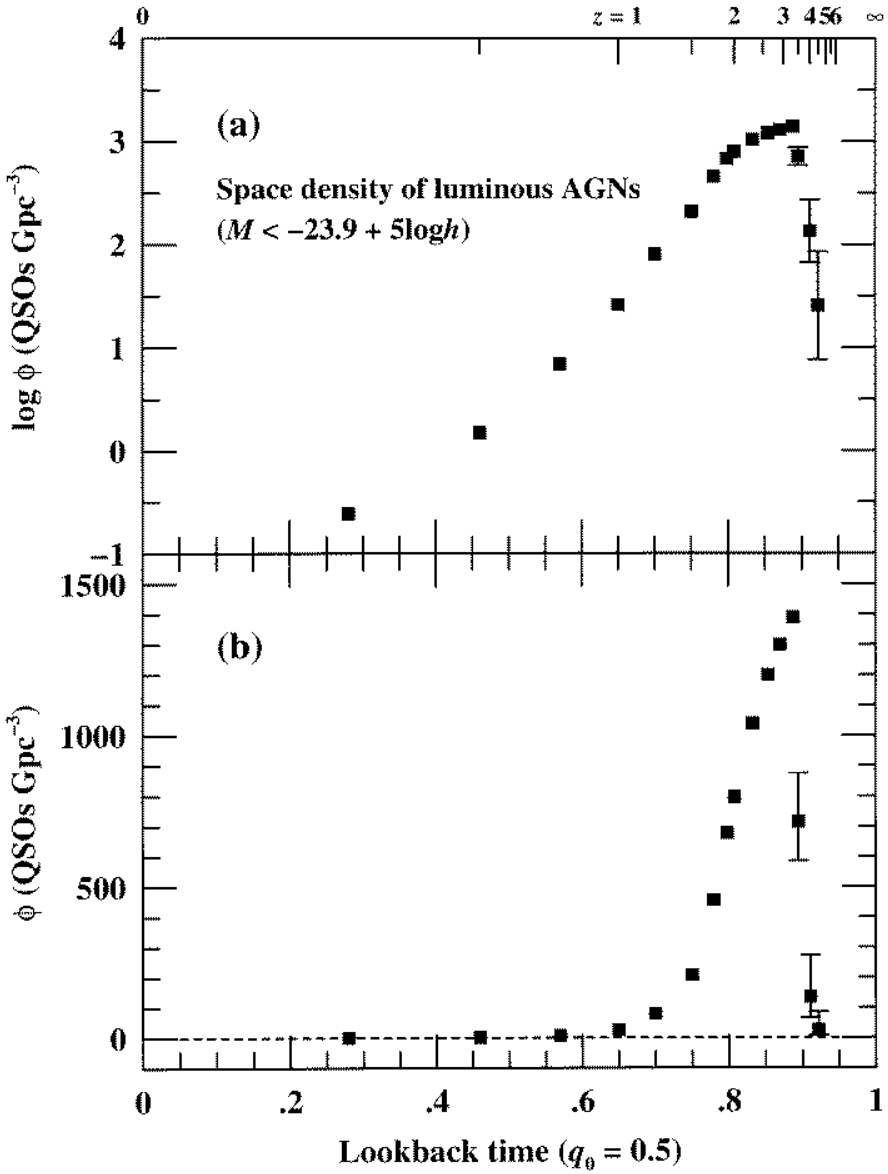
Topics to be Covered

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

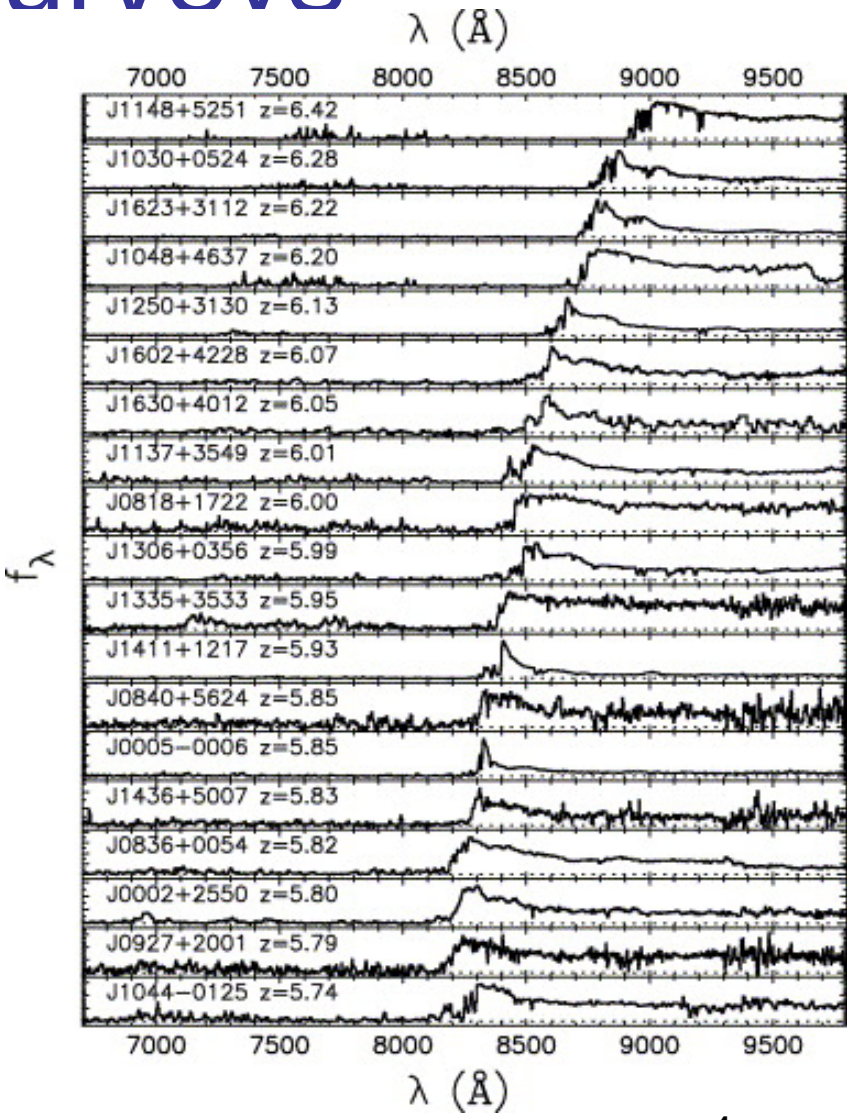
Cosmic Evolution of AGNs

- Very luminous AGNs were much more common in the past.
- The “quasar era” occurred when the Universe was 10-20% its current age.



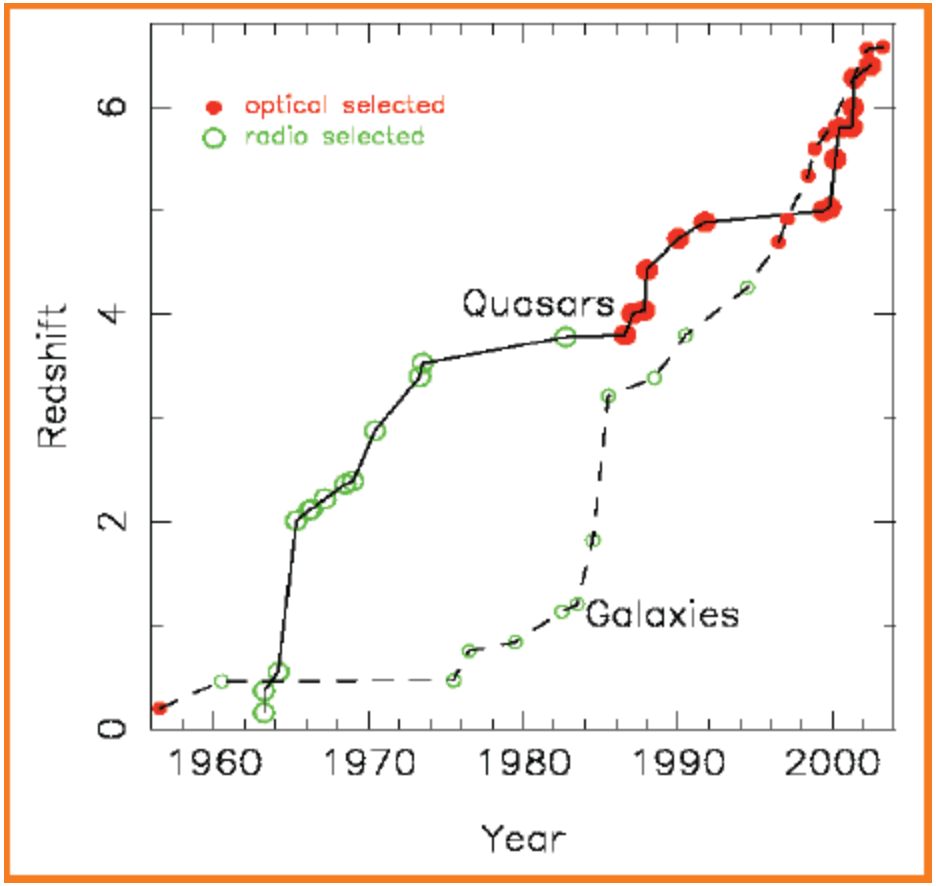
Modern Survevs

- Recent surveys are detecting luminous AGNs at very high redshift and large numbers of quasars at intermediate redshift.



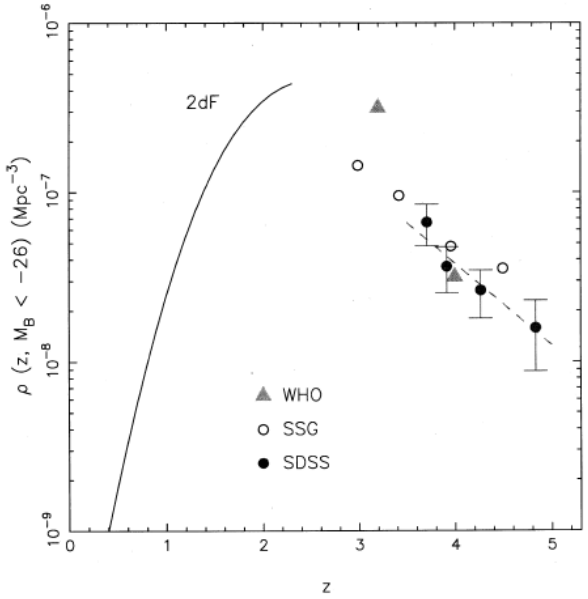
SDSS quasars with z > 5.7 Fan 2006

Largest Known Redshifts

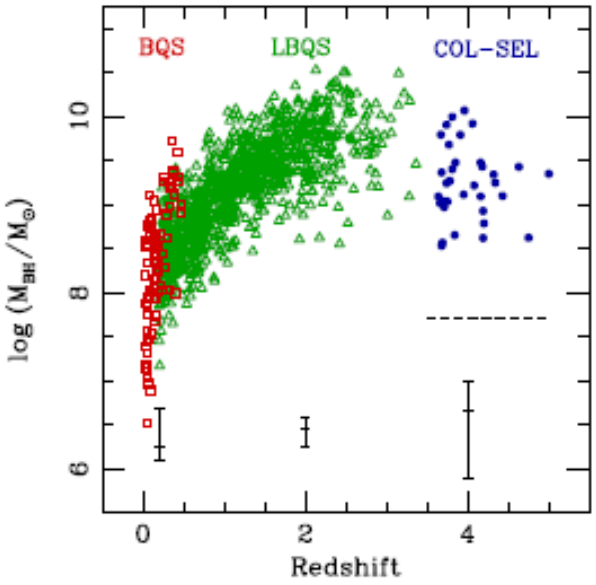


High-z Quasars

- Current highest quasar redshift $z \approx 7.1$
  - Supermassive black holes appeared within a few hundred million years of the Big Bang
  - Metals in their spectra indicate processing in stars already occurred.



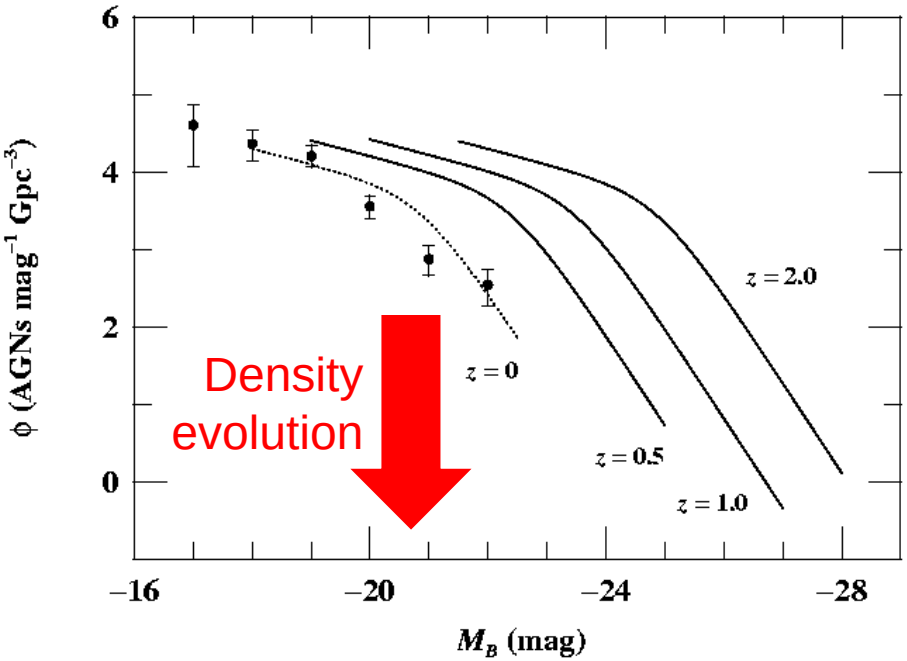
Fan et al. 2001



Vestergaard & Osmer 2009

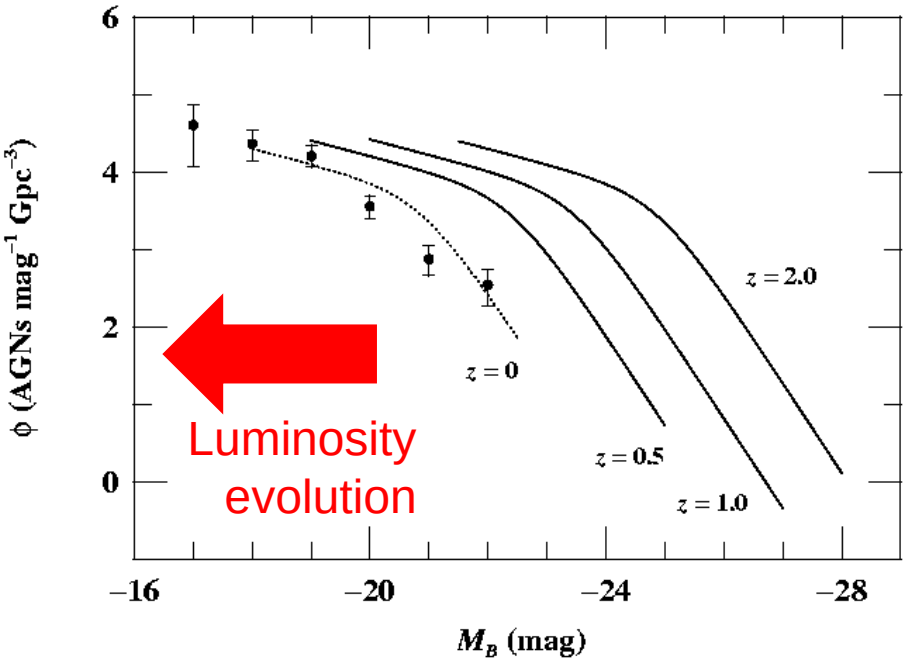
Evolution of the QSO Luminosity Function

- **Density evolution:** quasars "turn off" and luminosity function translates downward.
- Several problems, most importantly that local density of very luminous quasars is overpredicted.



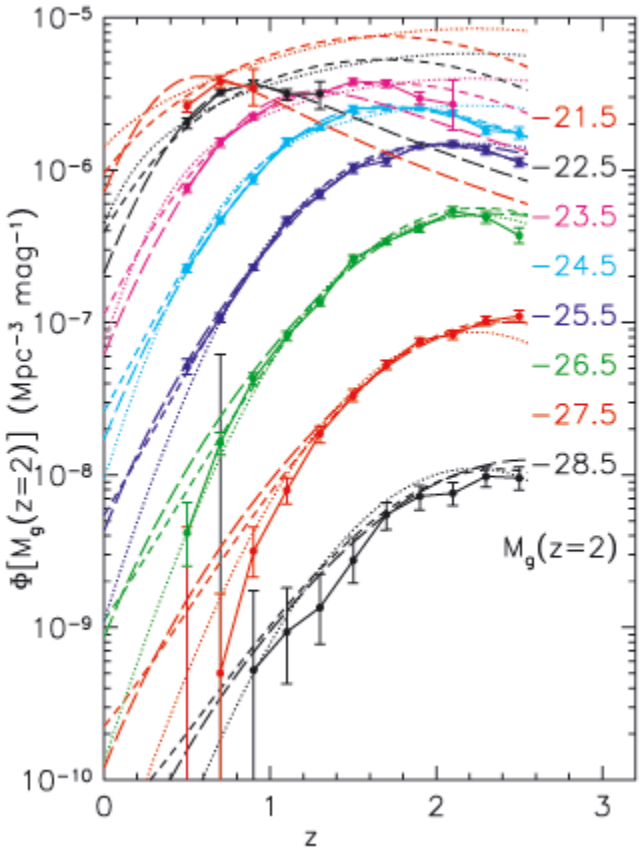
Evolution of the QSO Luminosity Function

- **Luminosity evolution:** quasars just become fainter with time.
- Does not agree with observation that most quasars are emitting near the Eddington limit: the typical nearby quasar is about 50 times fainter than it would have been at $z \approx 2$.



Evolution of the AGN Luminosity Function

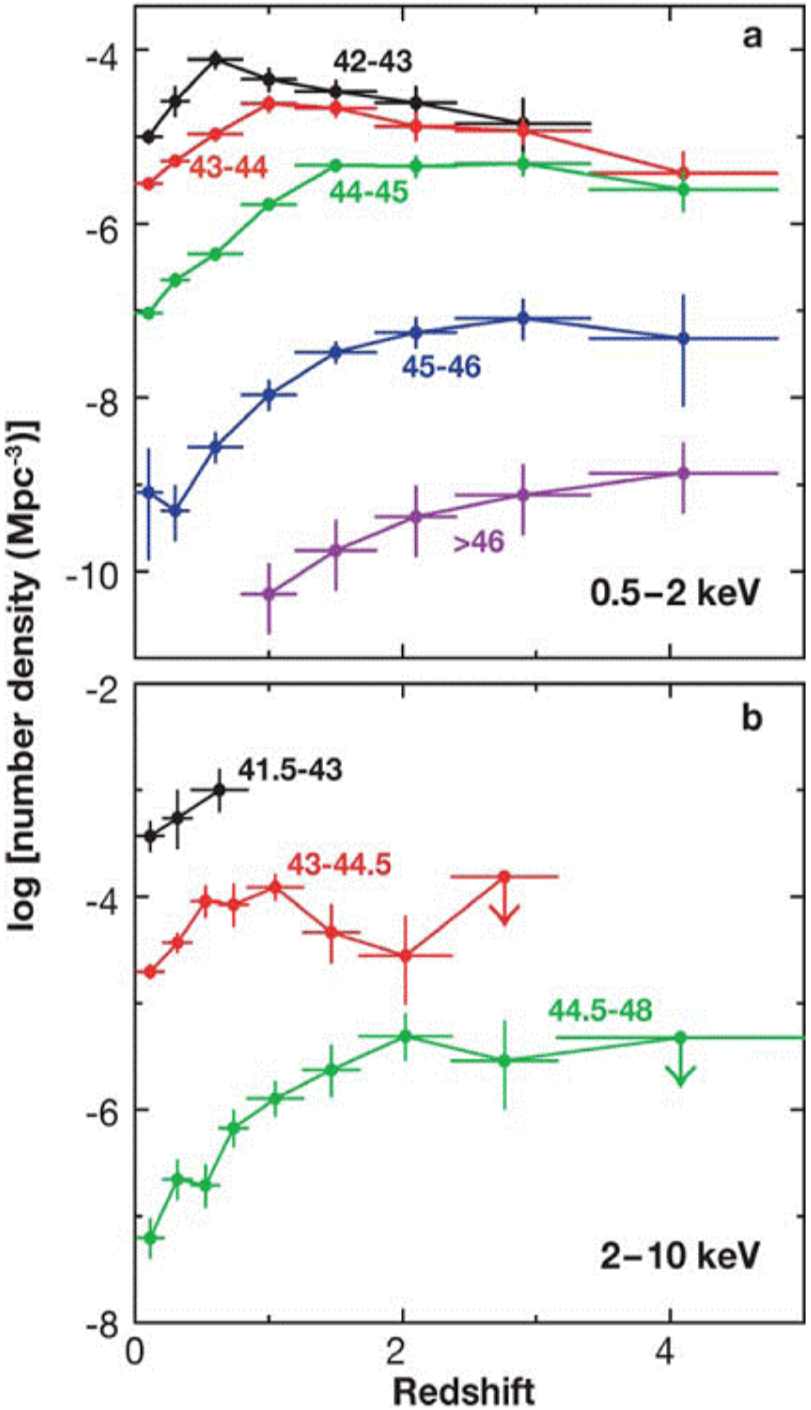
- Because we can now observe lower-luminosity AGNs at high-*z*, our view of evolution of the luminosity function has changed in the last decade.
- Preferred scenario is now “luminosity-dependent density evolution” (LDDE) or “cosmic downsizing.”



Comoving density of 2dF+SDSS quasars at different luminosities.
Croom et al. 2009

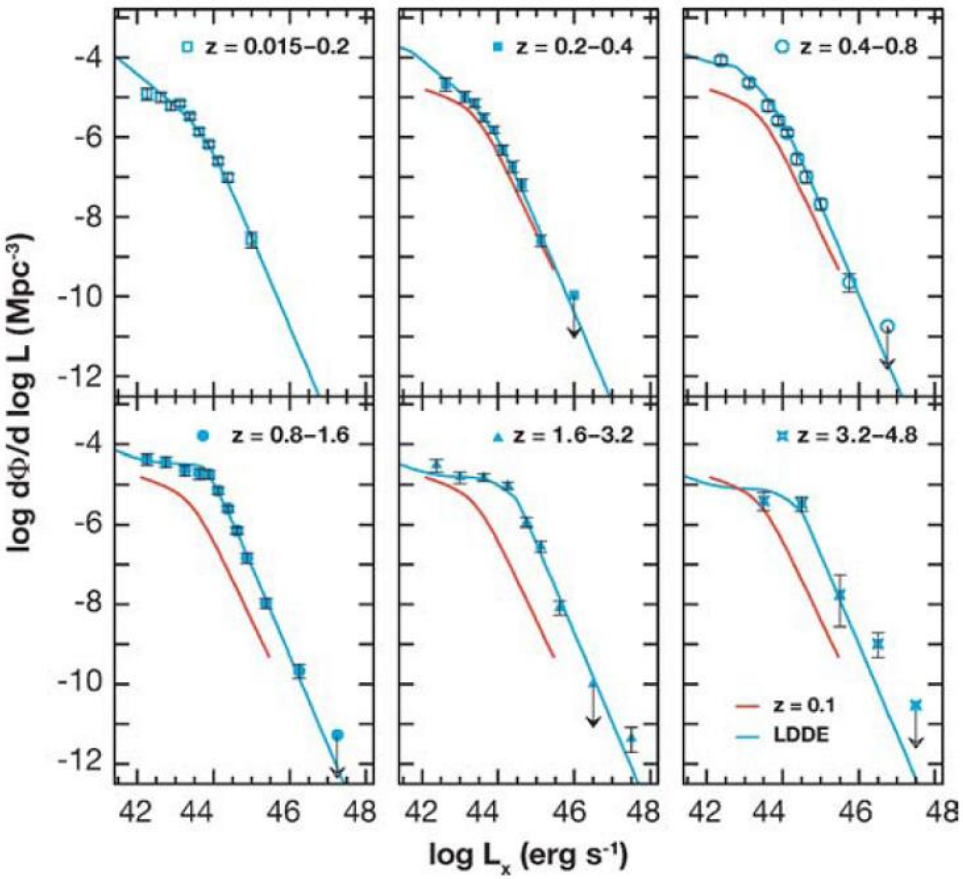
Cosmic Downsizing

- The space density of lower-luminosity AGNs peaks later in time than that of luminous AGNs.



Evolution of the AGN Luminosity Function

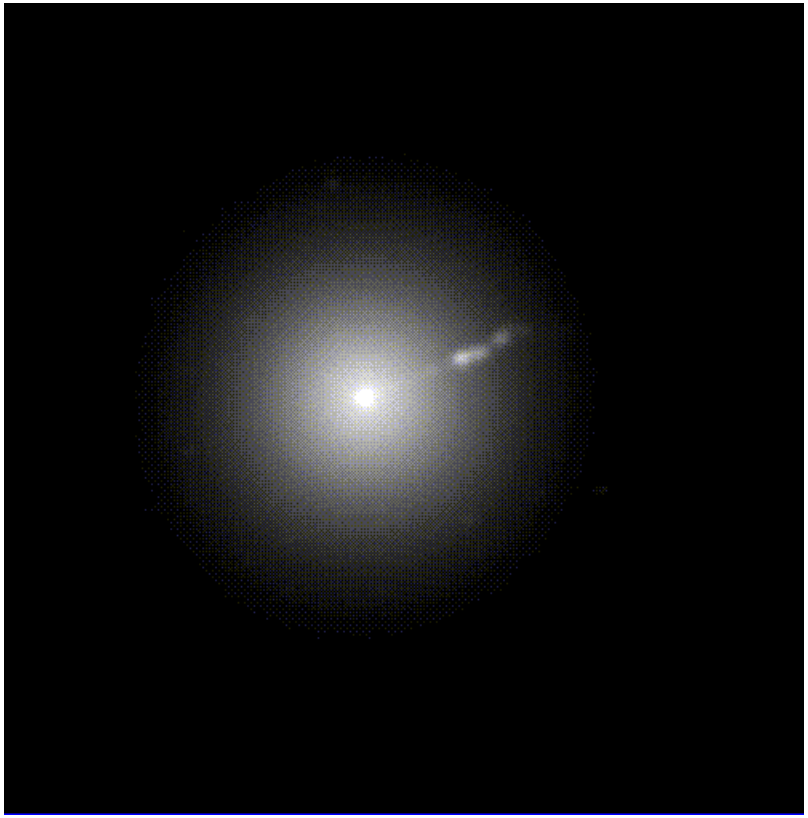
- Luminosity-dependent density evolution is most clearly seen in the X-rays
  - Low-luminosity systems are accessible at high *z* in X-rays



X-ray luminosity function
Brandt & Hasinger 2005

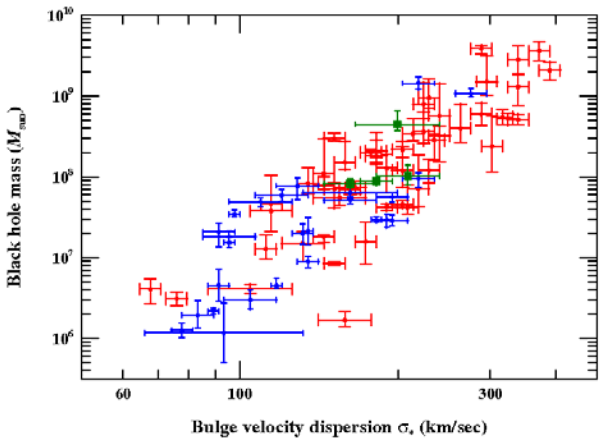
Supermassive Black Holes Are Common

- 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.

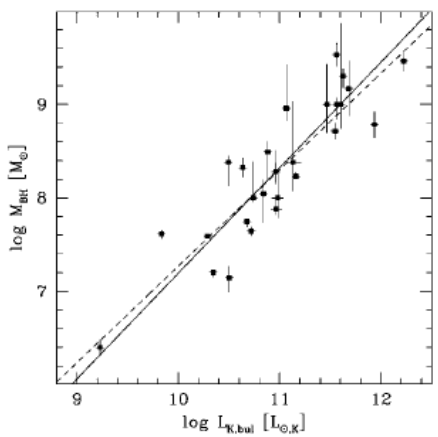


M 87, a giant elliptical SMBH > $3\times10^9\ M_\odot$

Relationship Between Black Hole Mass and Host Galaxy Properties



$M_{BH} - \sigma_*$ relationship



$M_{BH} - L_{bulge}$ 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?

A Current 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.

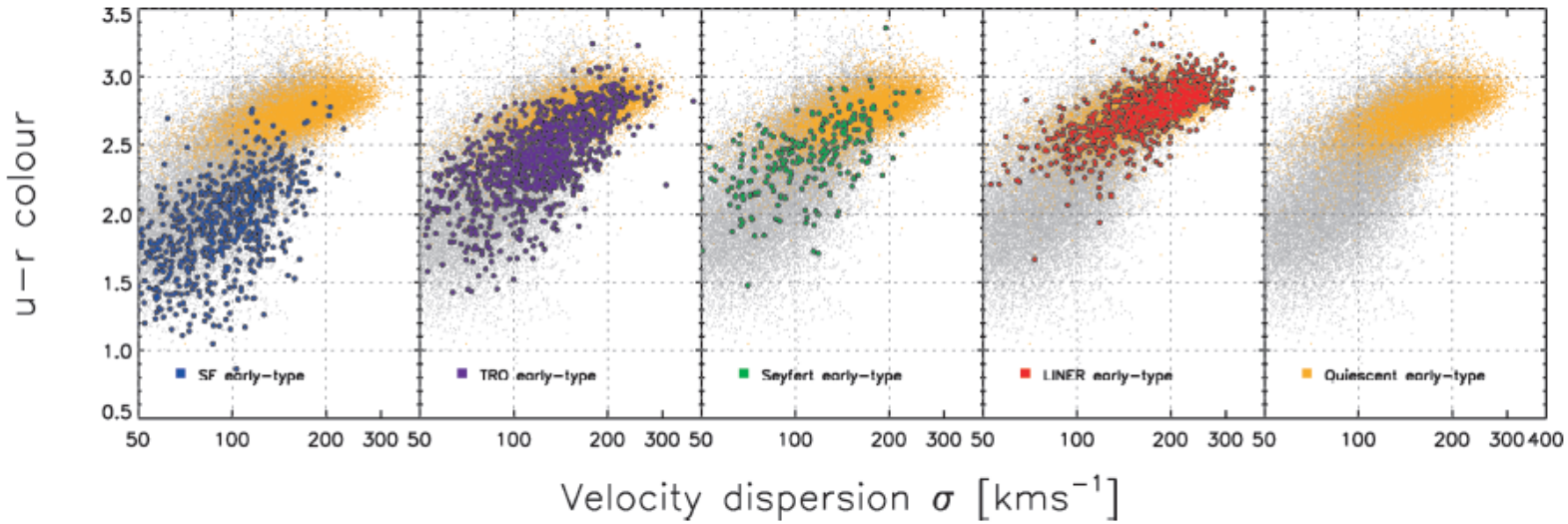
Role of Quasars in Galaxy Formation

(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 (dubious) 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 $\Rightarrow$ 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)

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

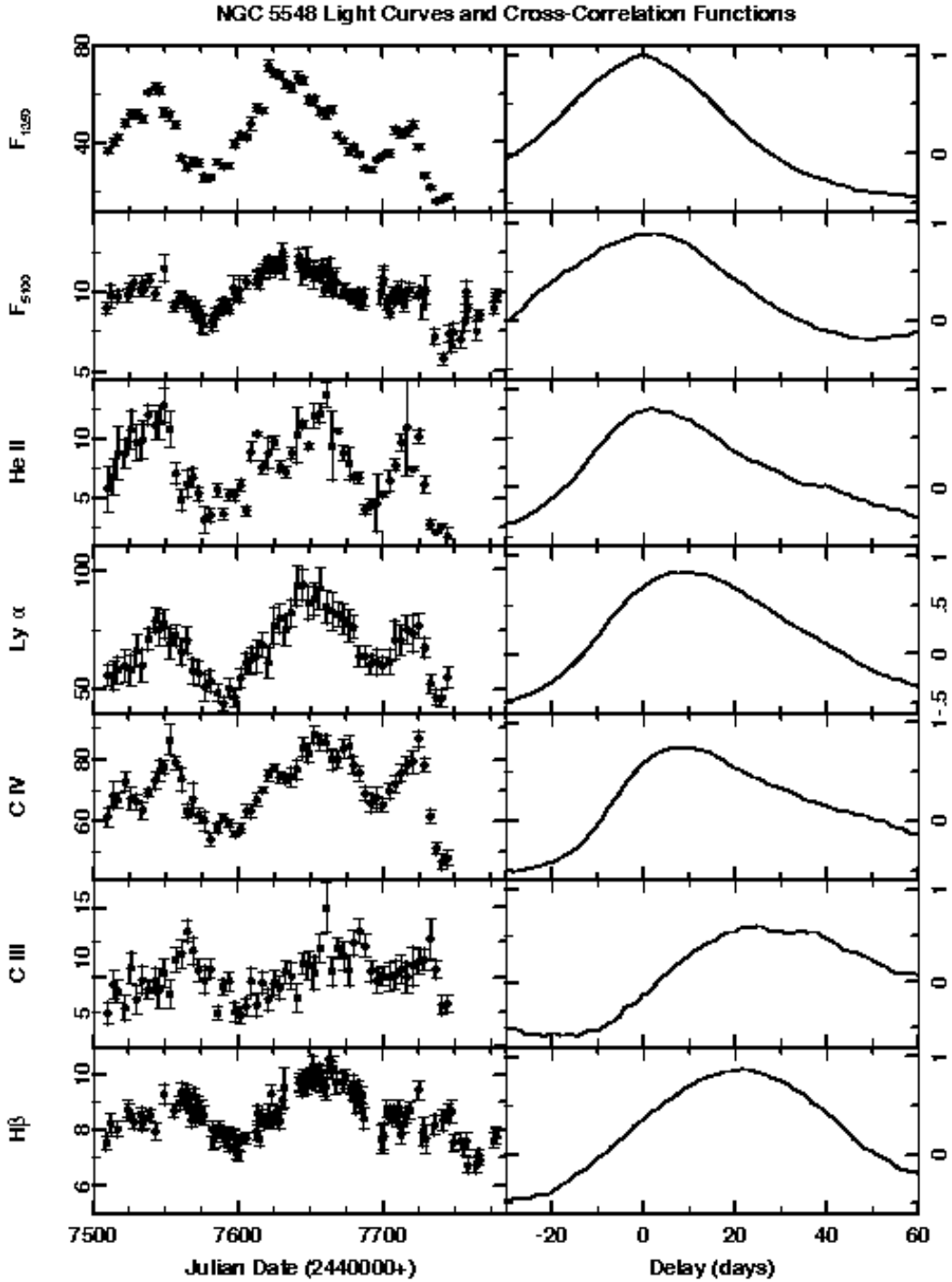
f = a factor of order unity, depends on details of geometry and kinematics

Direct vs. Indirect Methods

- ***Direct methods*** are based on dynamics of stars or gas 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.”

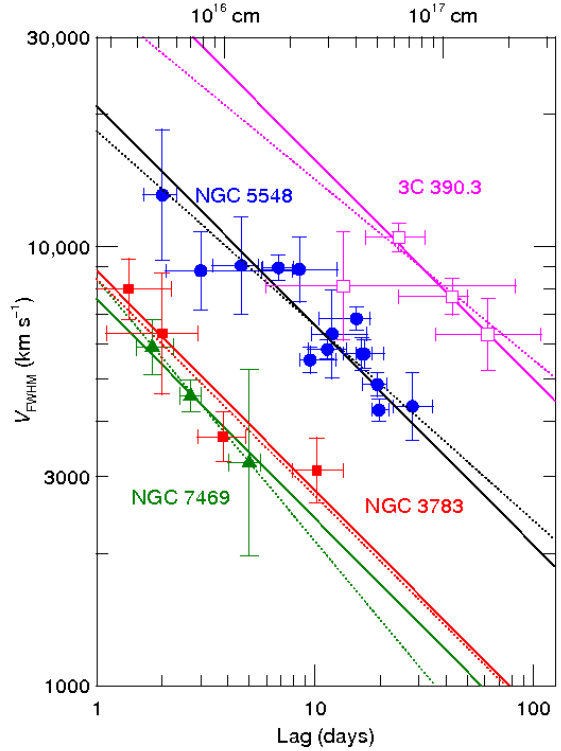


Reverberation Mapping Results

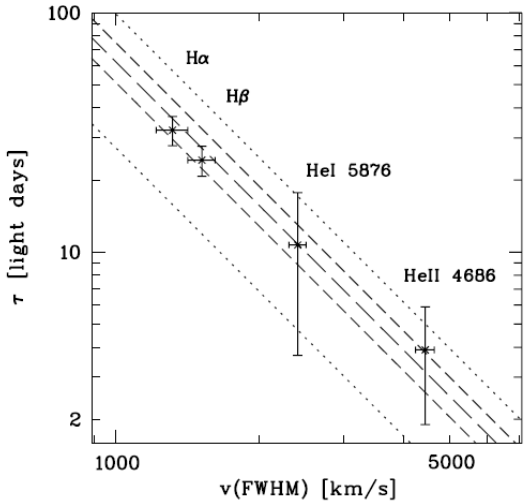
- Reverberation lags have been measured for ~50 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification
  - Highest ionization lines are also broadest!

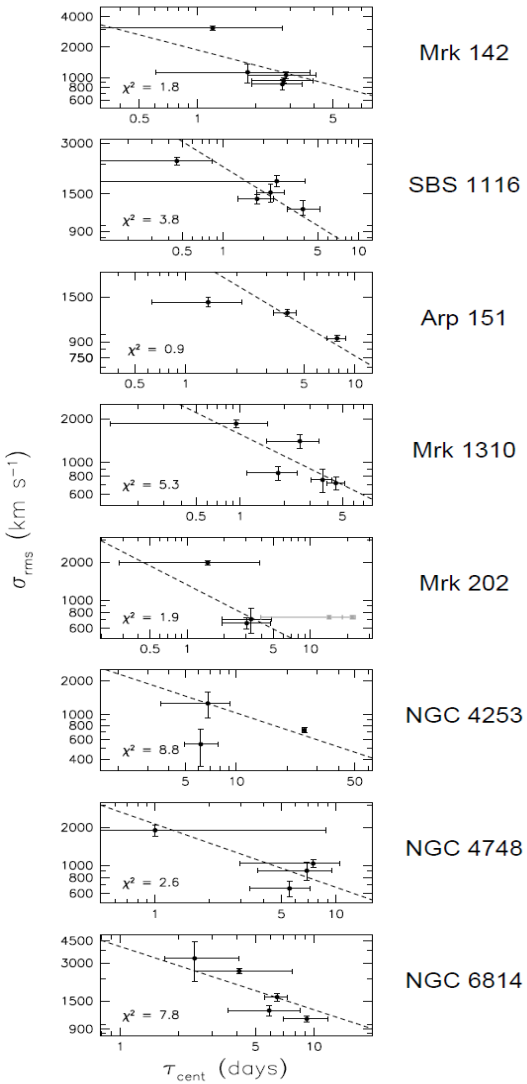
A Virialized BLR

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



Peterson & Wandel 2002





Bentz+ 2009

Kollatschny 2003

Reverberation-Based Masses

"Virial Product" (units of mass)

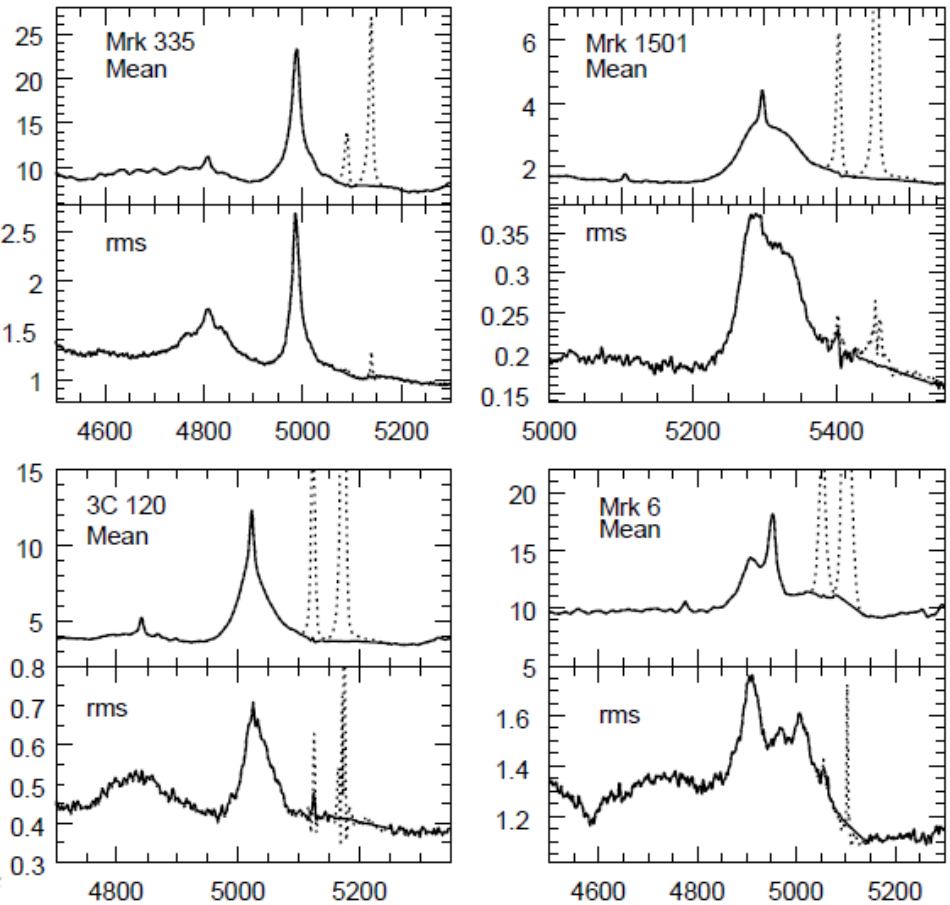
$$M_{\mathrm{BH}} = f \, \boxed{\underline{r\,\Delta V^2} / G}$$

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 $\langle f \rangle$

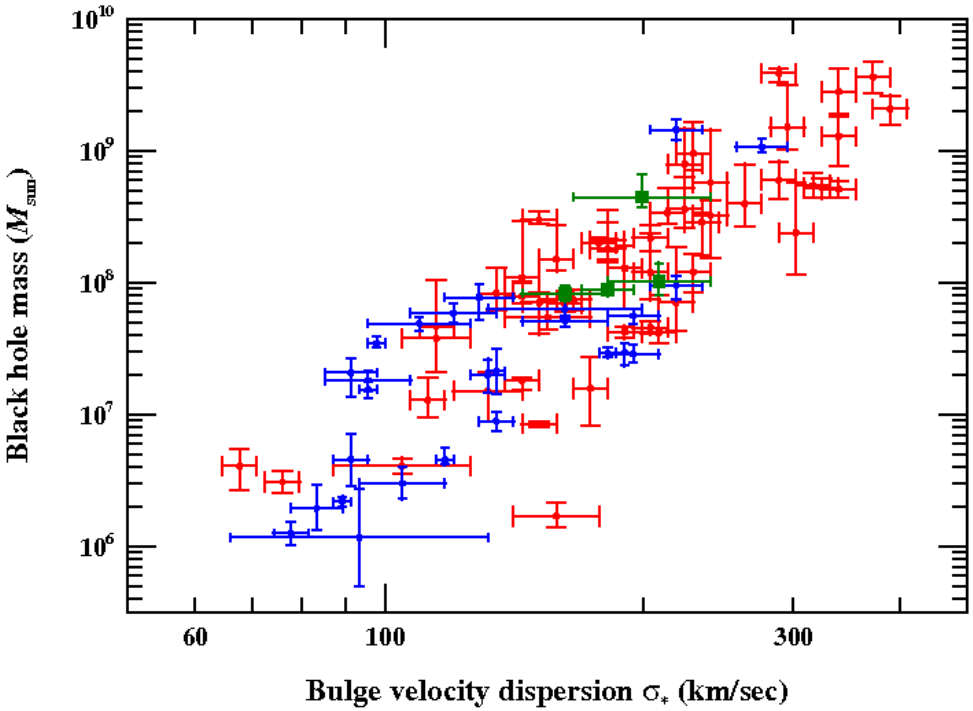
Measuring the Emission-Line Widths



- 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.

Grier+ 2012, ApJ, 755:60

AGN M_{BH}–σ_* Relationship



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

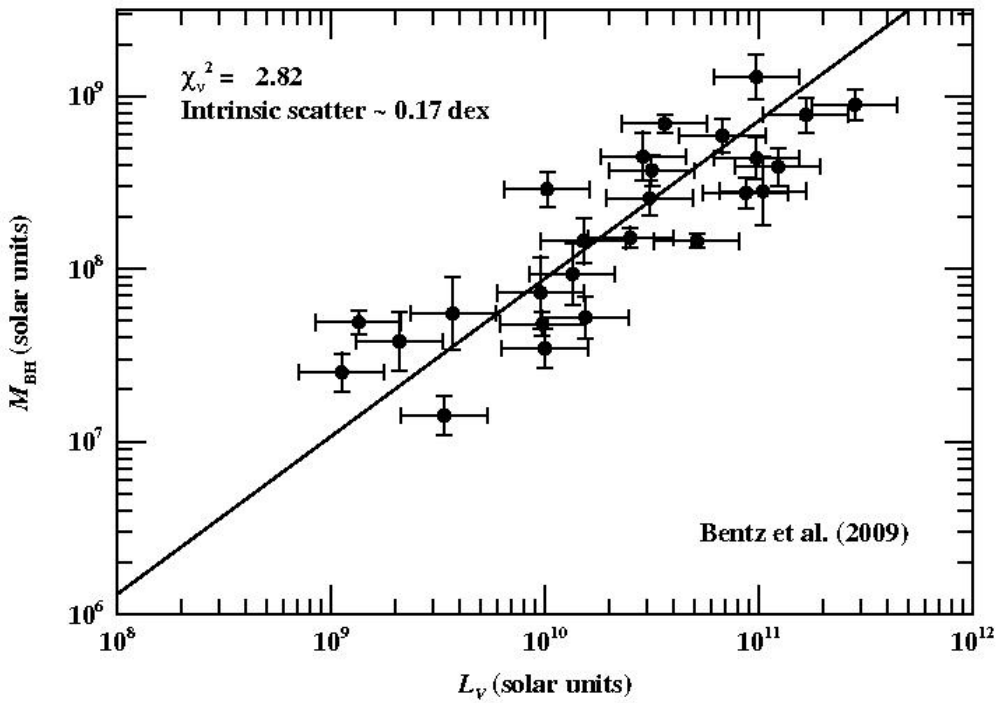
Grier+ 2013, ApJ, 773:90

- 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.

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).

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	47^{+11}_{-14} †
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]

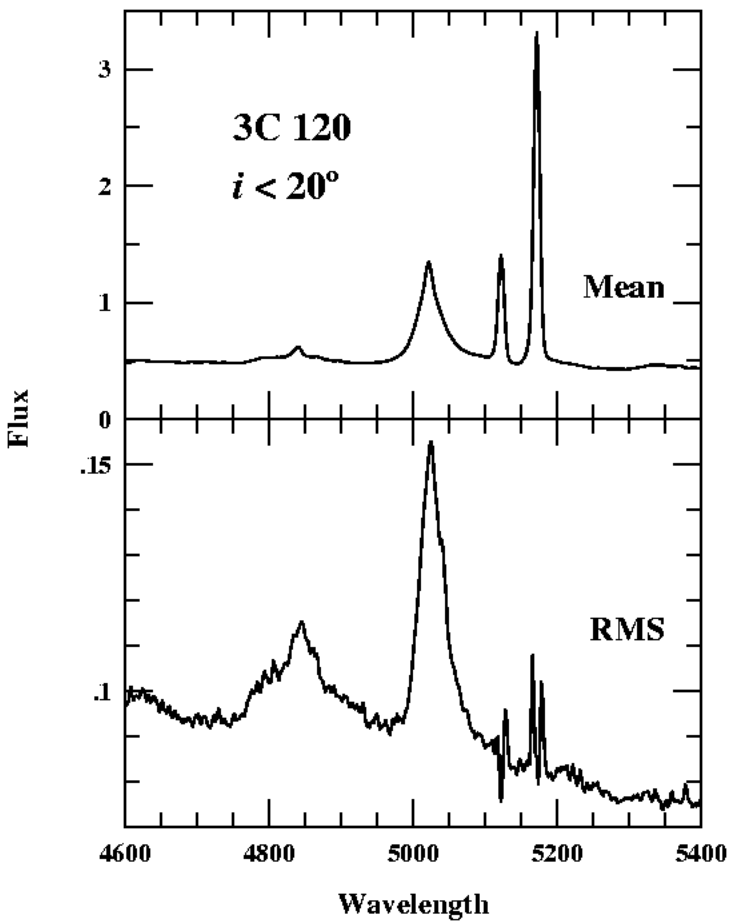
† Onken et al., in preparation

Reverberation-Based Masses

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

$$M_{BH} = f\,(r\,\Delta V^2 / G)$$

- 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.

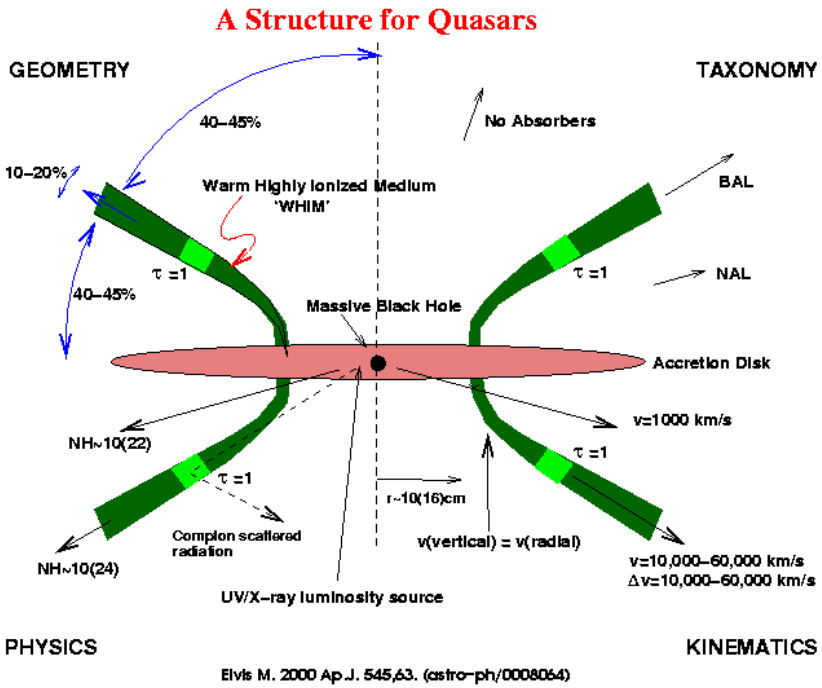


Plausible BLR Geometry

- Unified models suggest that Type 1 AGNs are observed at inclinations $0^o \leq i \leq \sim 45^o$.
  - Lags are unaffected if axial symmetry and isotropic line emission
  - Line widths can be severely affected by inclination.
    - A "generalized thick disk" parameterization:

$$f \propto 1 \big/ (a^2 + \sin^2 i)$$

Collin et al. (2006)



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

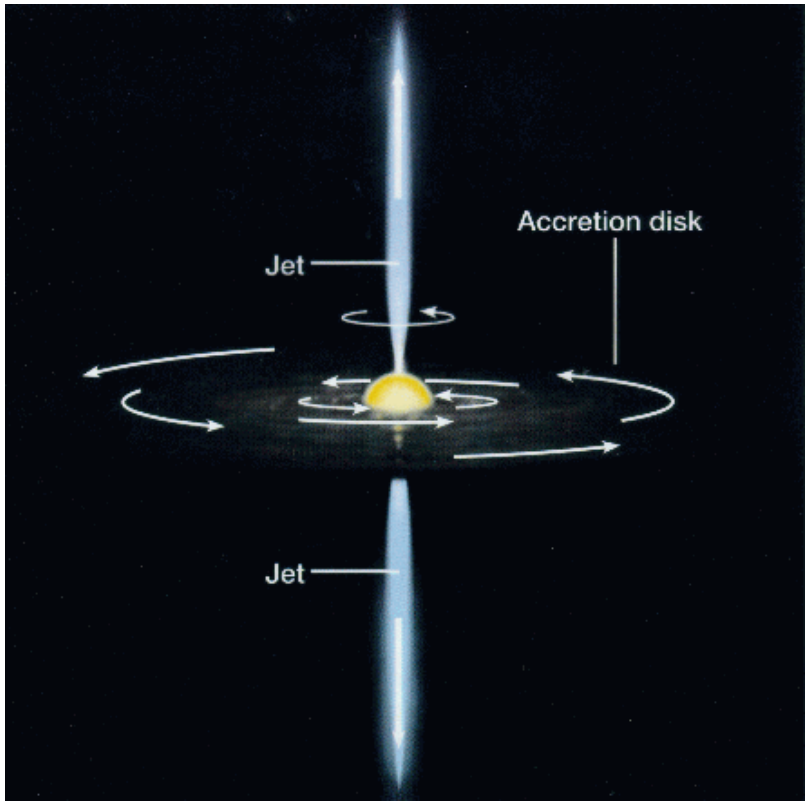
Evidence Inclination Matters

- Relationship between *R* (core/lobe) and FWHM.
  - Core-dominant are more face-on so lines are narrower.

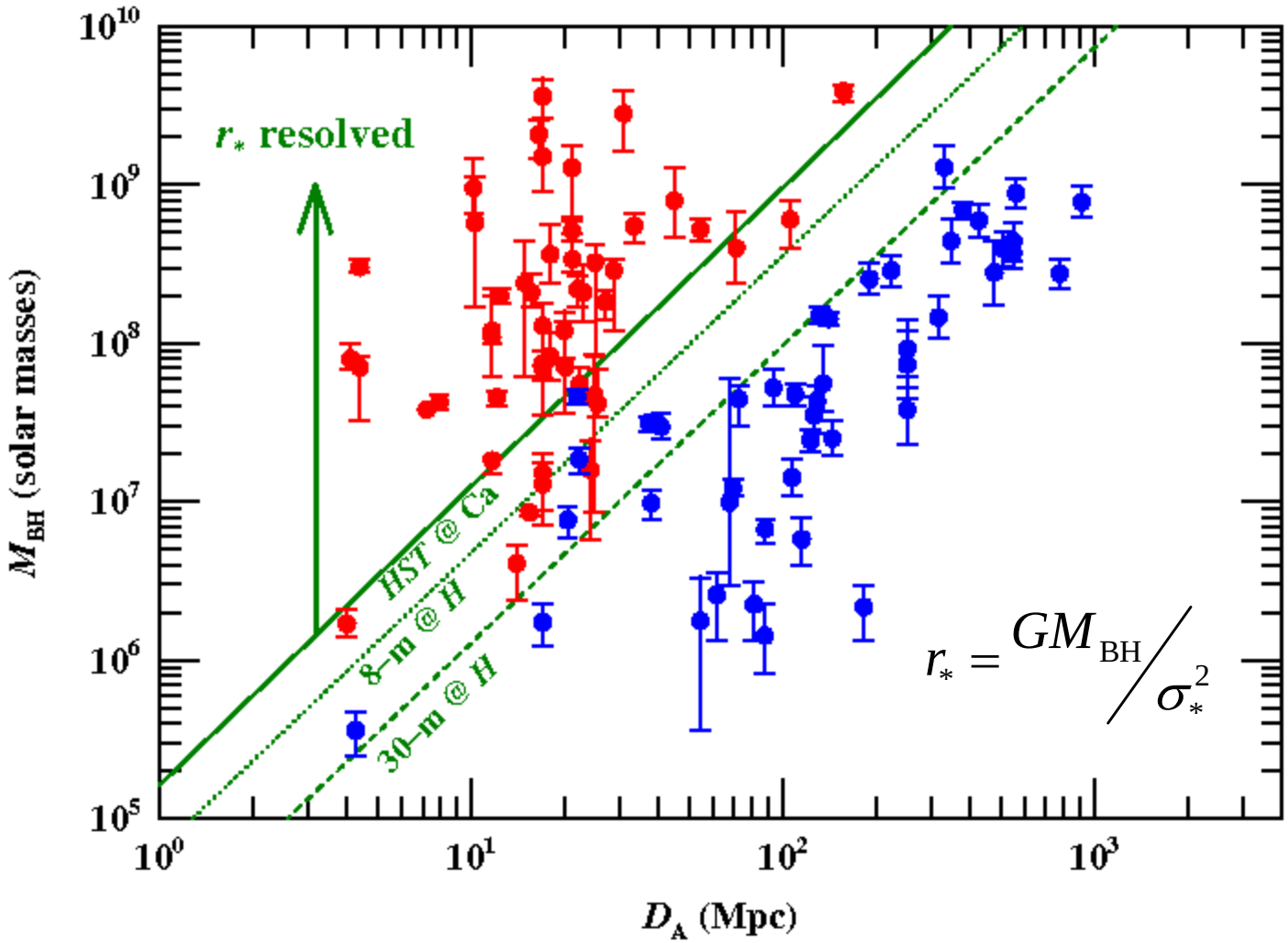
    Wills & Browne 1986

- 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



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

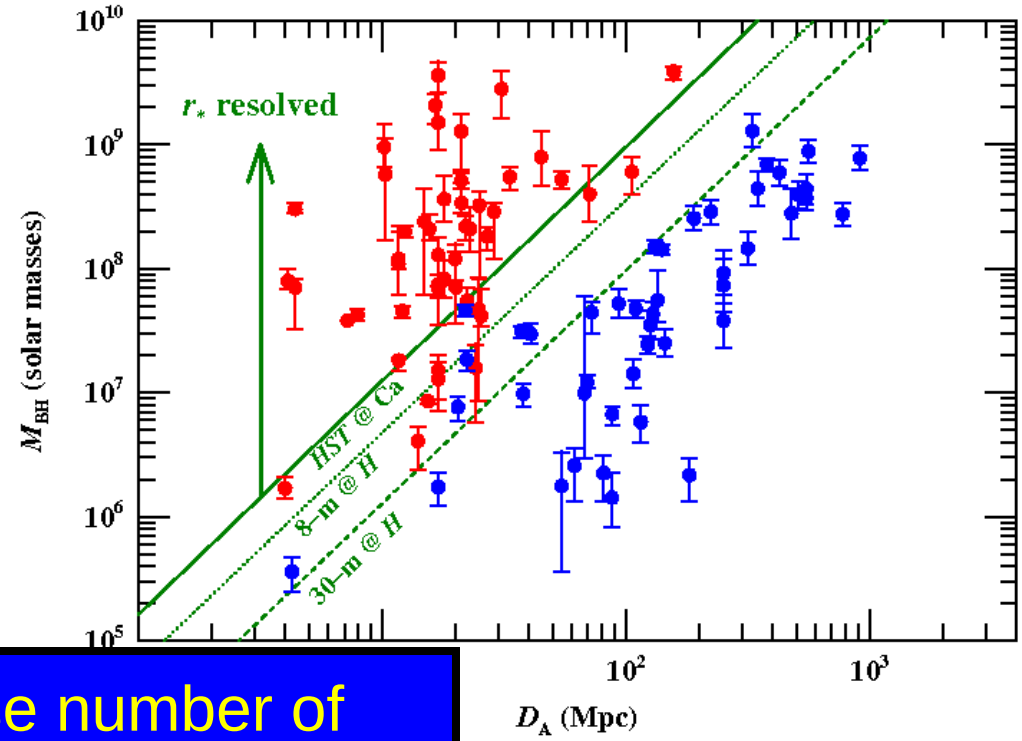


● Quiescent galaxies (stellar, gas dynamics, megamasers)

● Reverberation AGNs

Masses of Black Holes in Quasars

- 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

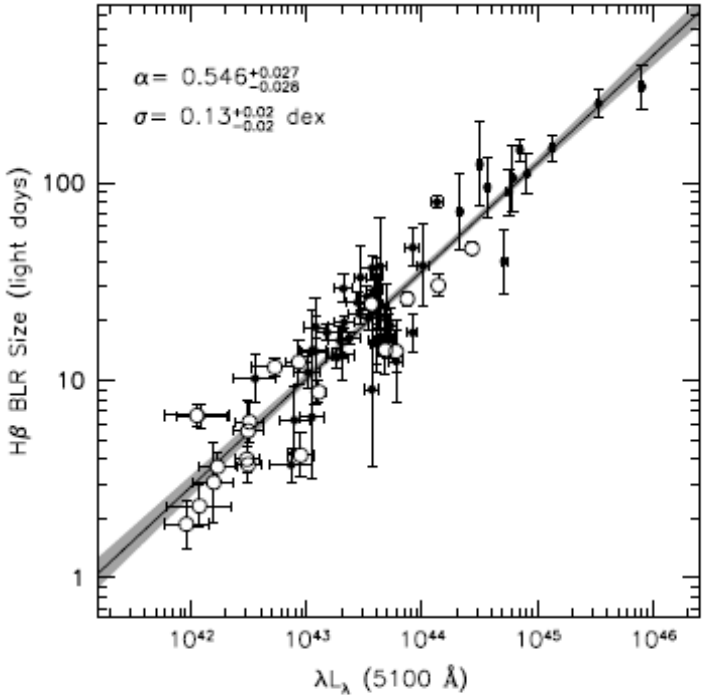


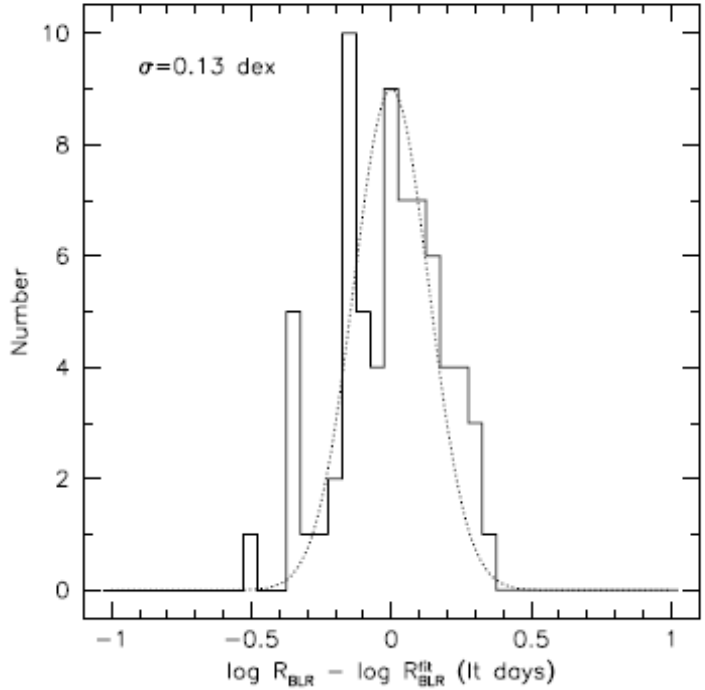
uiescent galaxies
M AGNs

To significantly increase number of measured masses, we need to go to secondary methods.

The *R*–*L* Relation

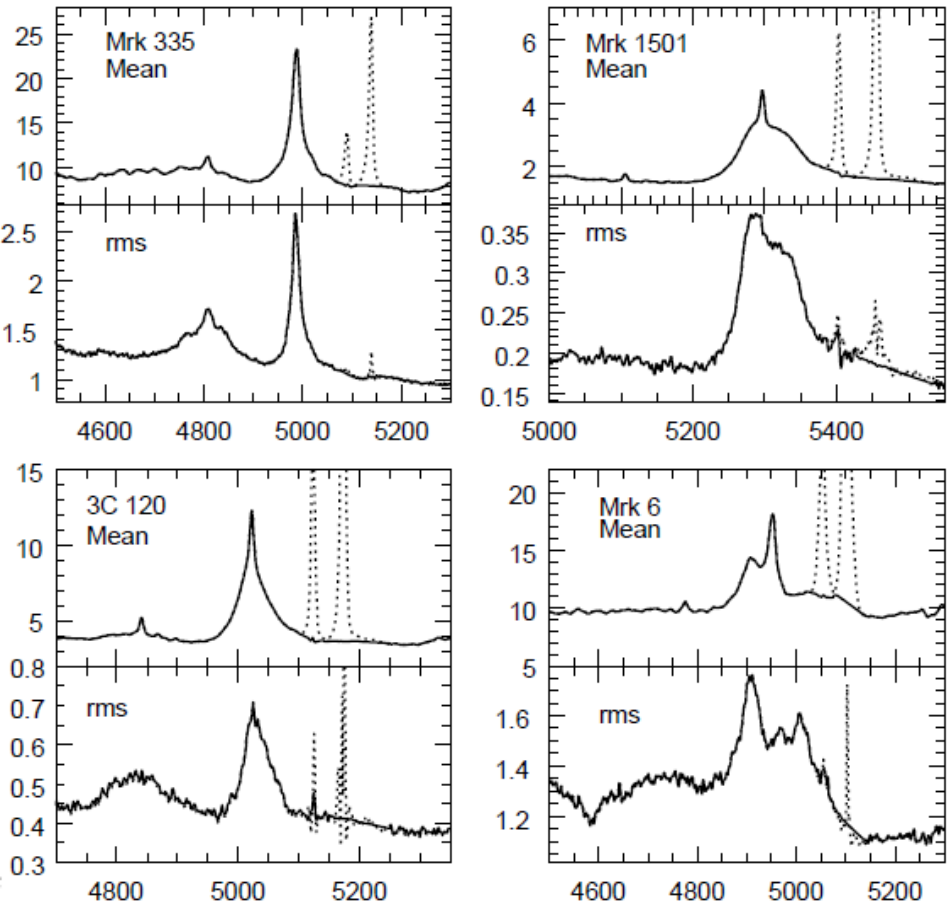
- Empirical slope ~0.55 ± 0.03
- For Hβ over the calibrated range ($42 \leq \log \lambda L_{5100}$ (ergs s^{-1}) ≤ 46 at $z \approx 0$), *R-L* is nearly as effective as reverberation.





Bentz+ 2013

Measuring the Emission-Line Widths



- Trickier in “mean” or “single-epoch” spectra because of blending.
- Another important issue is how to characterize the line width:
  - FWHM?
  - Line dispersion?

Grier+ 2012, ApJ, 755:60

Characterizing Line Widths

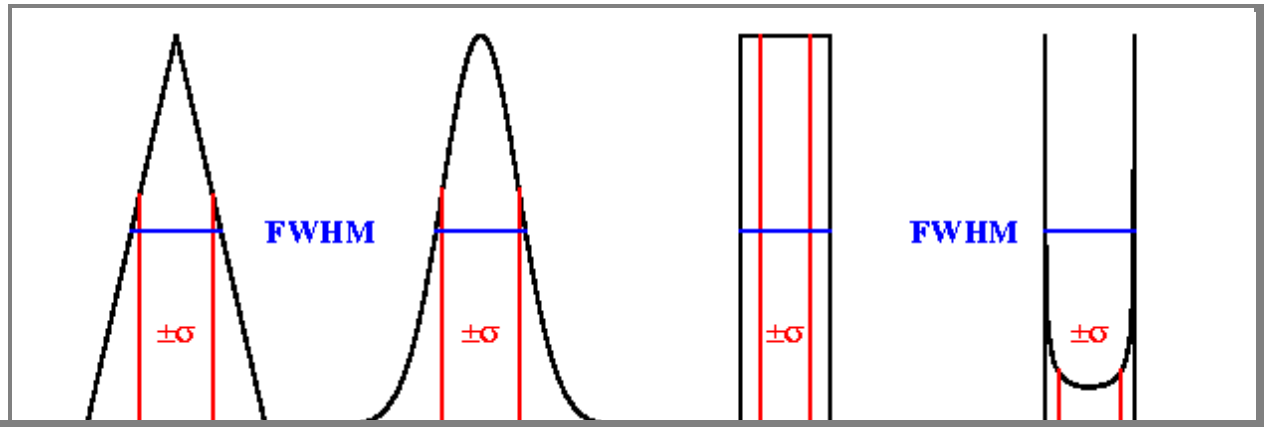
FWHM:

- 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:

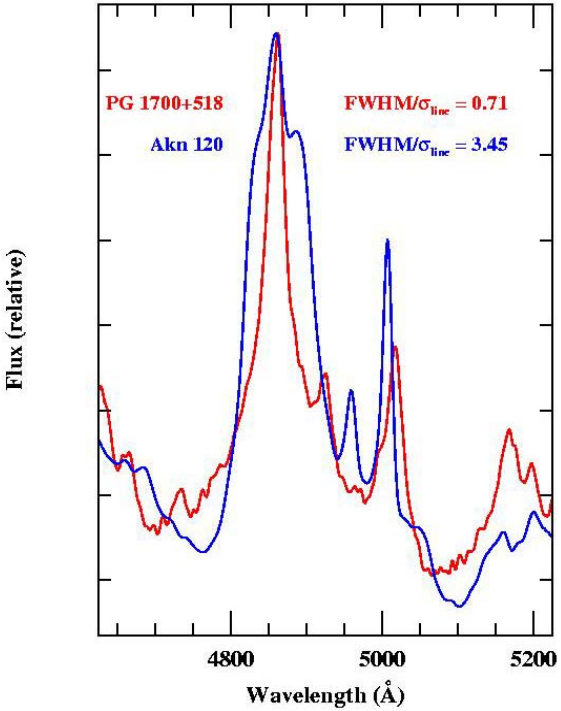


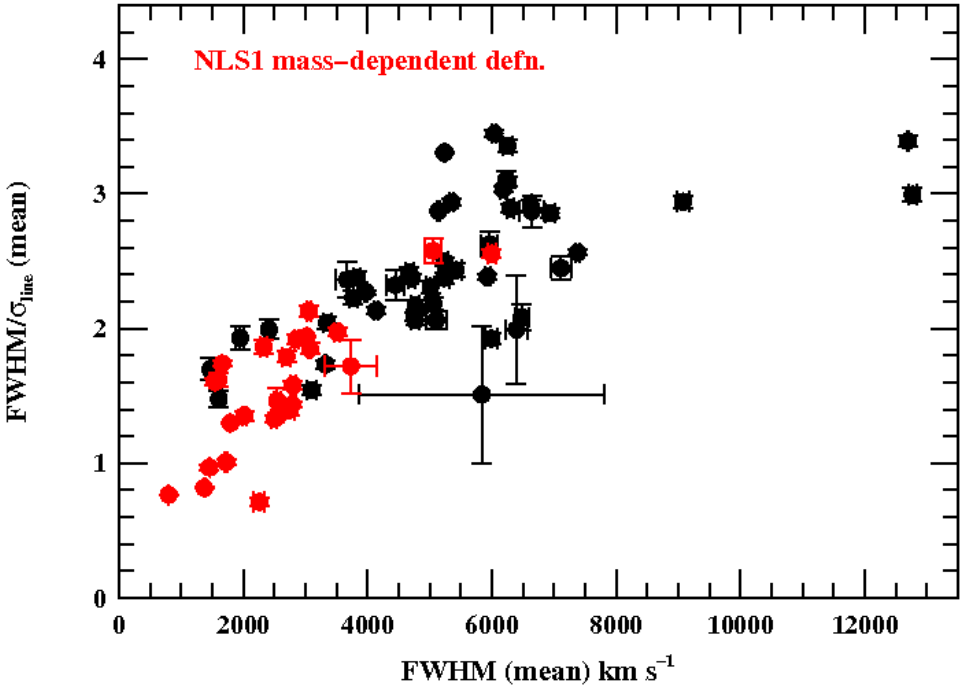
$\dfrac{\text{FWHM}}{\sigma_{\text{line}}} =$	$\sqrt{6}$	$2(2\ln 2)^{1/2}$	$2\sqrt{3}$	$2\sqrt{2}$
	2.45	2.35	3.46	2.83

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

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

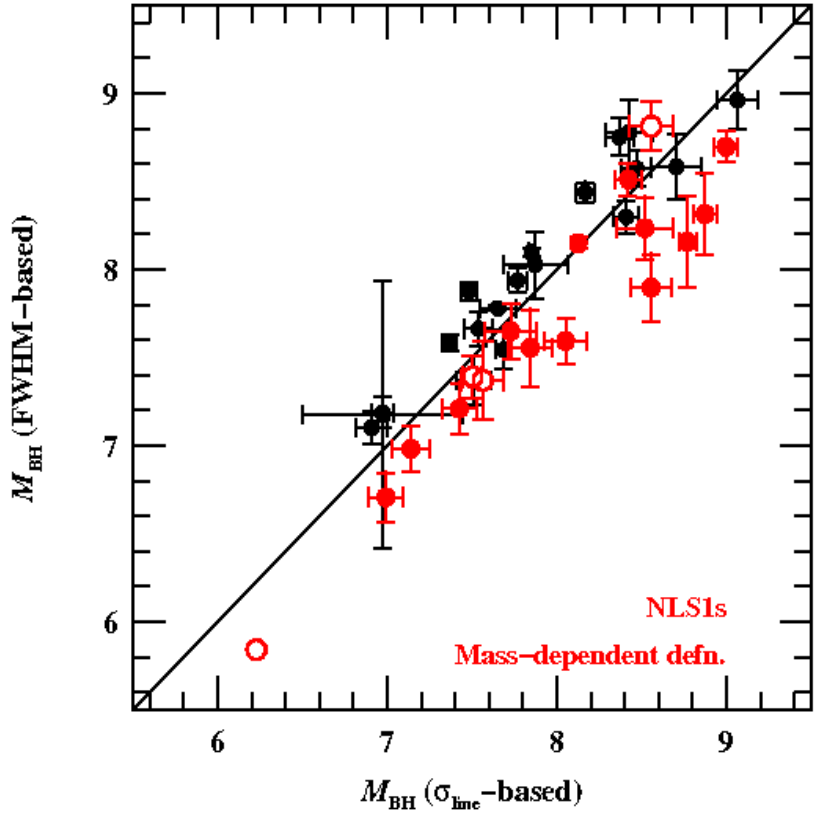
- This matters because their black hole masses depend on the line width measure (squared!).
- Systematically shifts NLS1s away from other AGN masses.



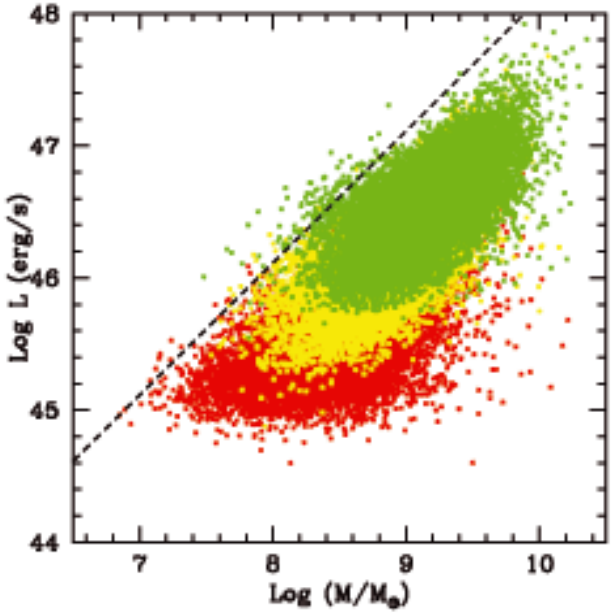


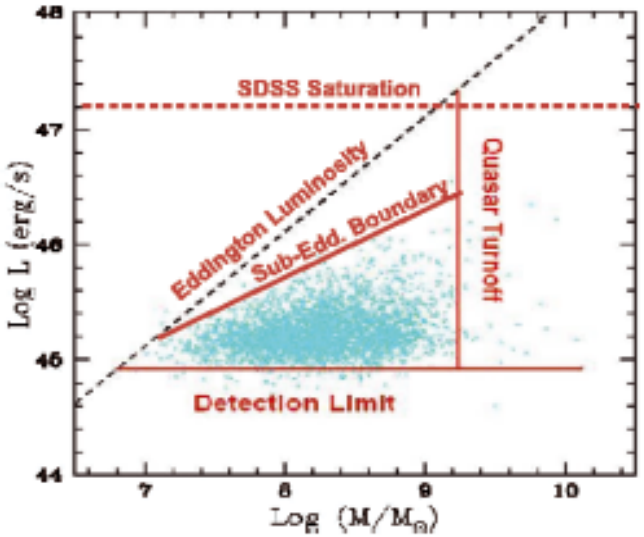
Incorrect Choice Introduces Bias Based on Line Width

- 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...



The Sub-Eddington Limit





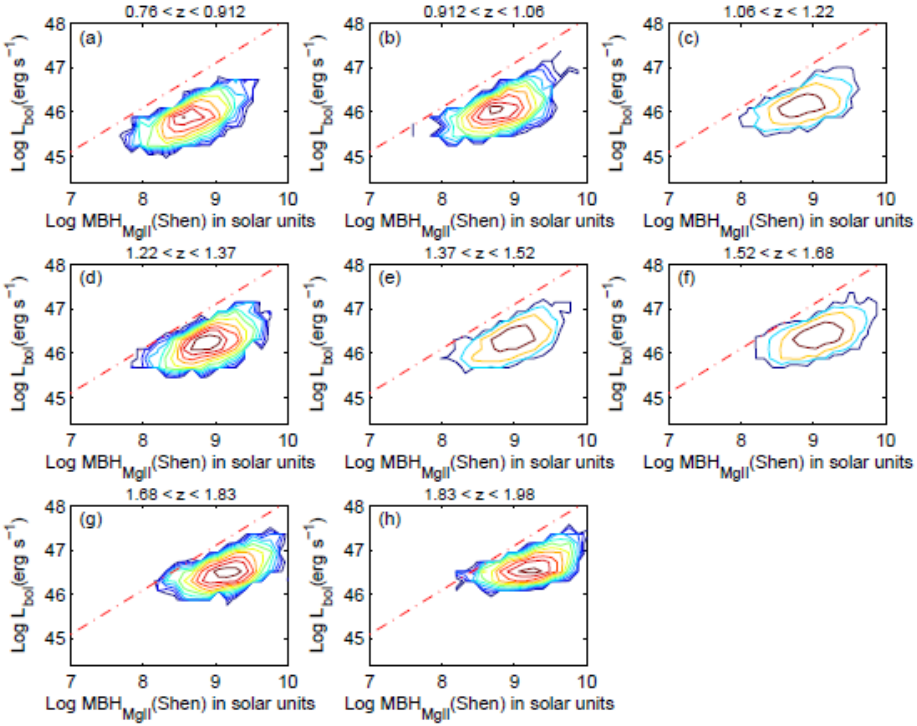
Steinhardt & Elvis 2010

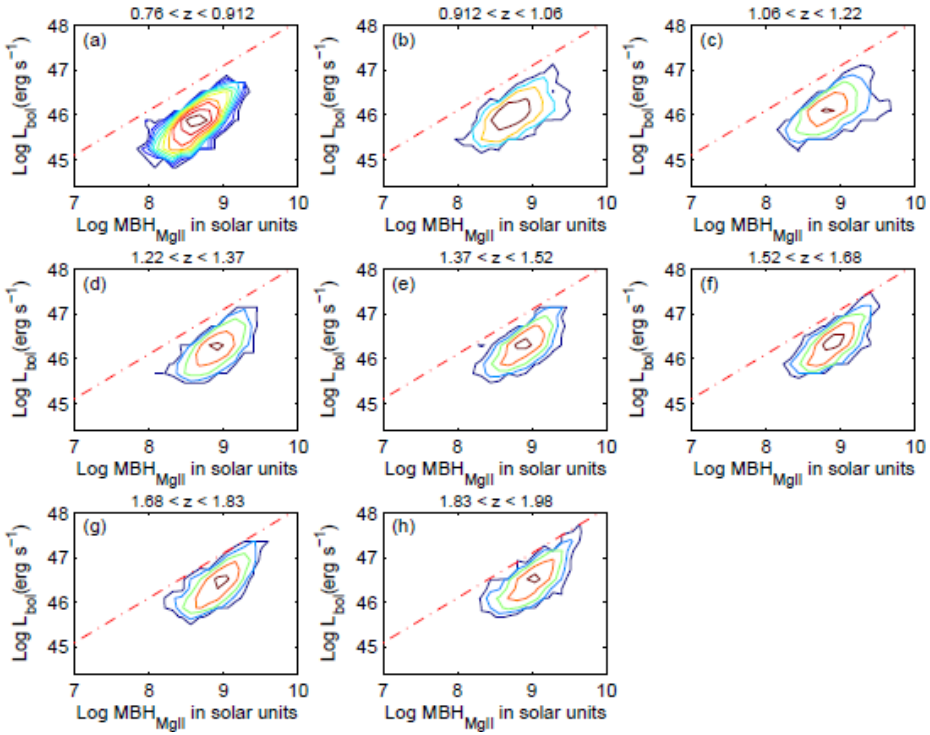
- The most massive black holes seem to be unable to approach the Eddington limit.

  Steinhardt & Elvis 2010

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

  Shen, Greene, et al. 2008





FWHM-based

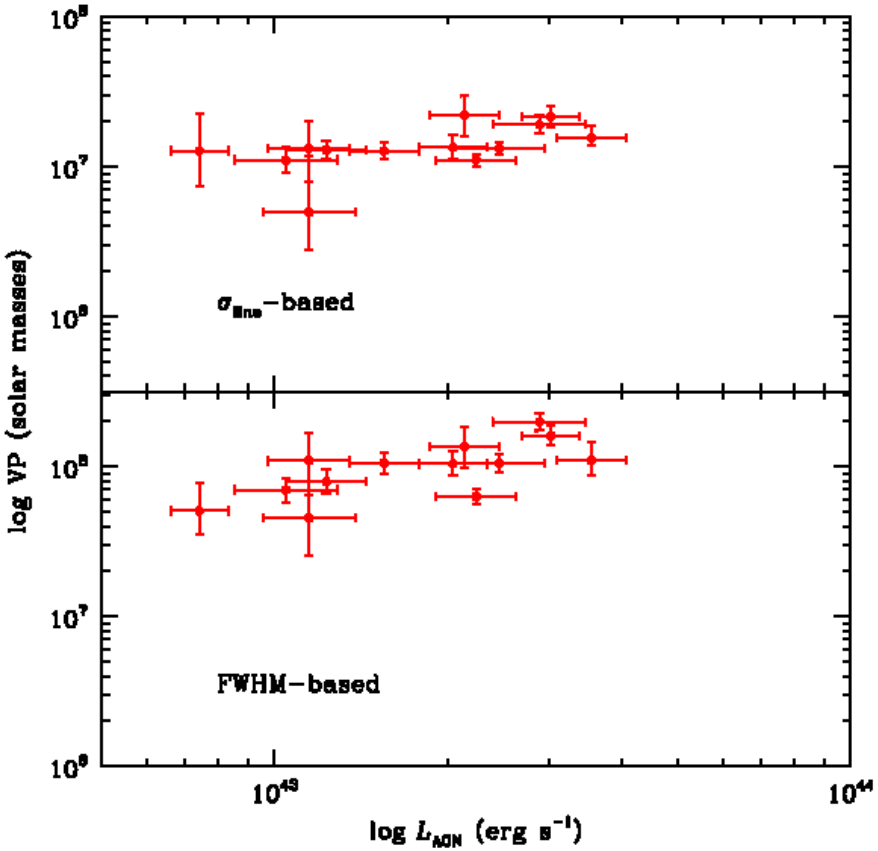
σ_{line}-based

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.

Direct Observational Test: Mass Must Be Constant

- Only NGC 5548 has much dynamic range
  - σ_{line} is slightly favored, but only slightly



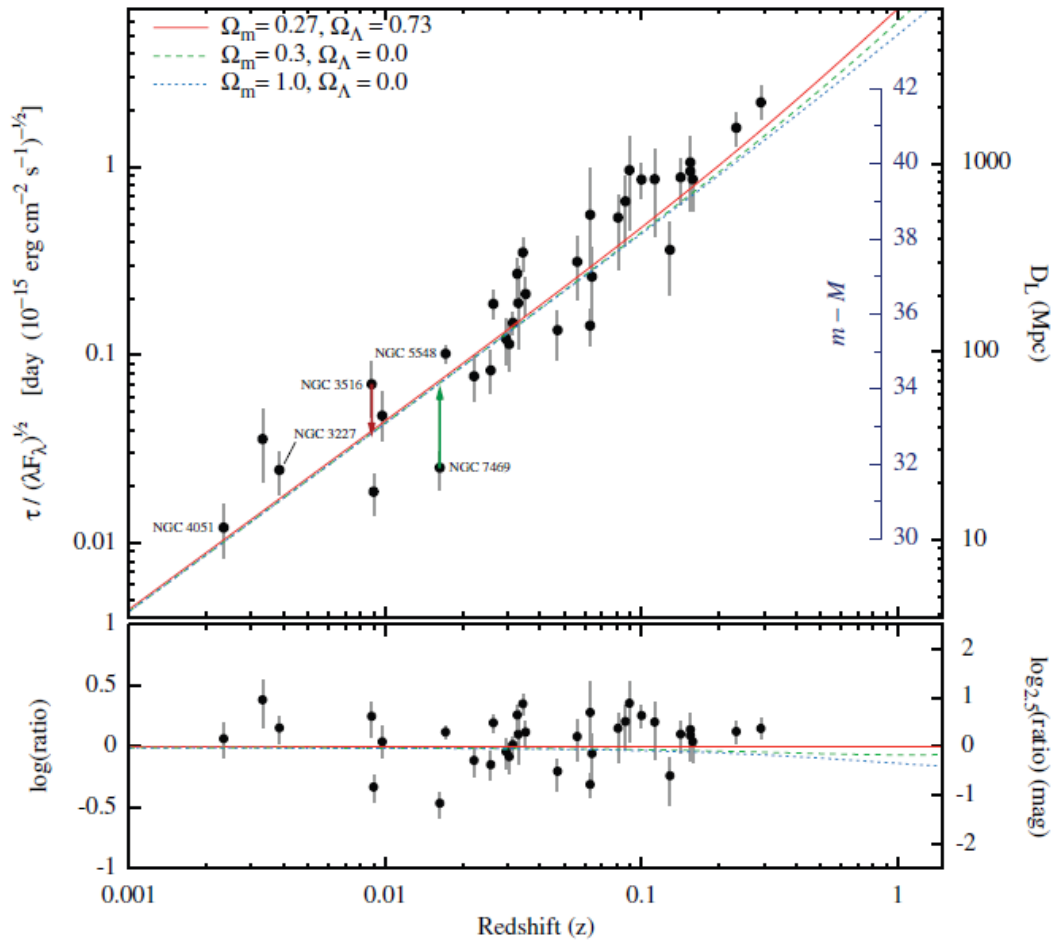
Black Hole Mass Measurements (units of $10^6\ M_\odot$)

Galaxy	NGC 4258	NGC 3227	NGC 4151
Direct methods:			
Megamasers	38.2 ± 0.1	N/A	N/A
Stellar dynamics	33 ± 2	7–20	47^{+11}_{-14}
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]

Cosmological Applications

- Because the *R–L* relationship has so little scatter, cosmological applications are possible.
- $R \Rightarrow L \Rightarrow D_L$



Watson, Denney, Vestergaard, & Davis 2011

Reverberation Mapping Goals

- Determine geometry and kinematics of BLR
- Determine black hole masses
- Calibrate scaling relationships for indirect black hole mass estimates
- Determine/confirm cosmological parameters

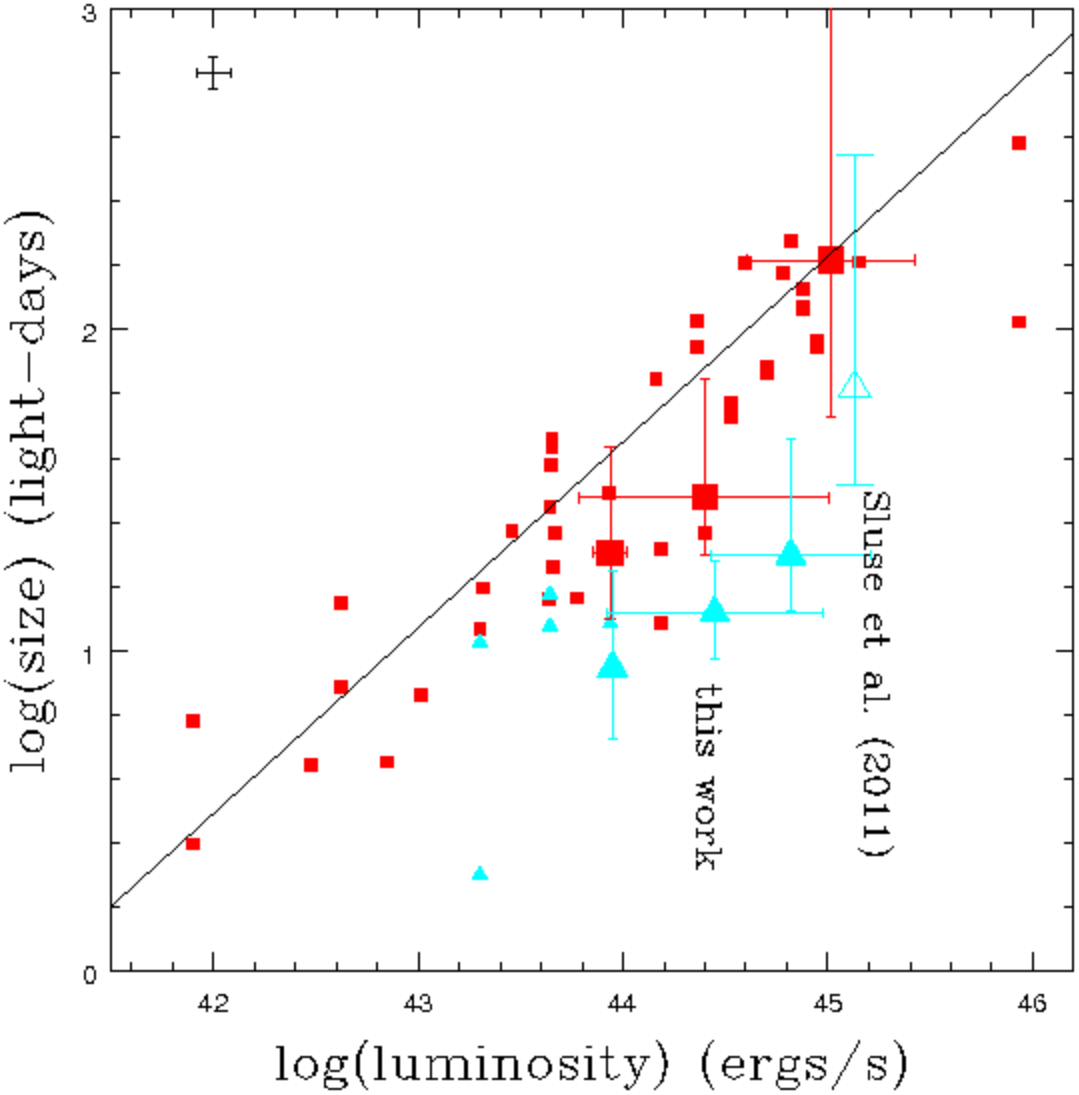
Reverberation Mapping Goals

- Geometry and kinematics of BLR
  - Velocity-resolved RM (expensive!)
- Black hole masses
  - High accuracy (~50% or better)
    - Velocity-resolved RM (expensive!)
  - Moderate accuracy (factor of ~3–5)
    - Mean lag measurement (moderately expensive)
    - High *S/N* single spectra + scaling relationships (somewhat expensive)
  - Low accuracy (order of magnitude)
    - Survey-quality single spectra + scaling relationships (inexpensive. But you get what you pay for)

Reverberation Mapping Goals

- Calibrate scaling relationships for indirect black hole mass estimates
  - Hβ R–L well-characterized with intrinsic scatter ~0.13 dex
  - Still somewhat of an open issue for other lines
    - Or is it?

Independent confirmation of *R*–*L* from microlensing, including high-ionization lines.



RM measurements, low ionization lines

Microlensing, Low-ionization lines

RM measurements, high-ionization lines

Microlensing, high-ionization lines

Guerras, Kochanek + 2012

Reverberation Mapping Goals

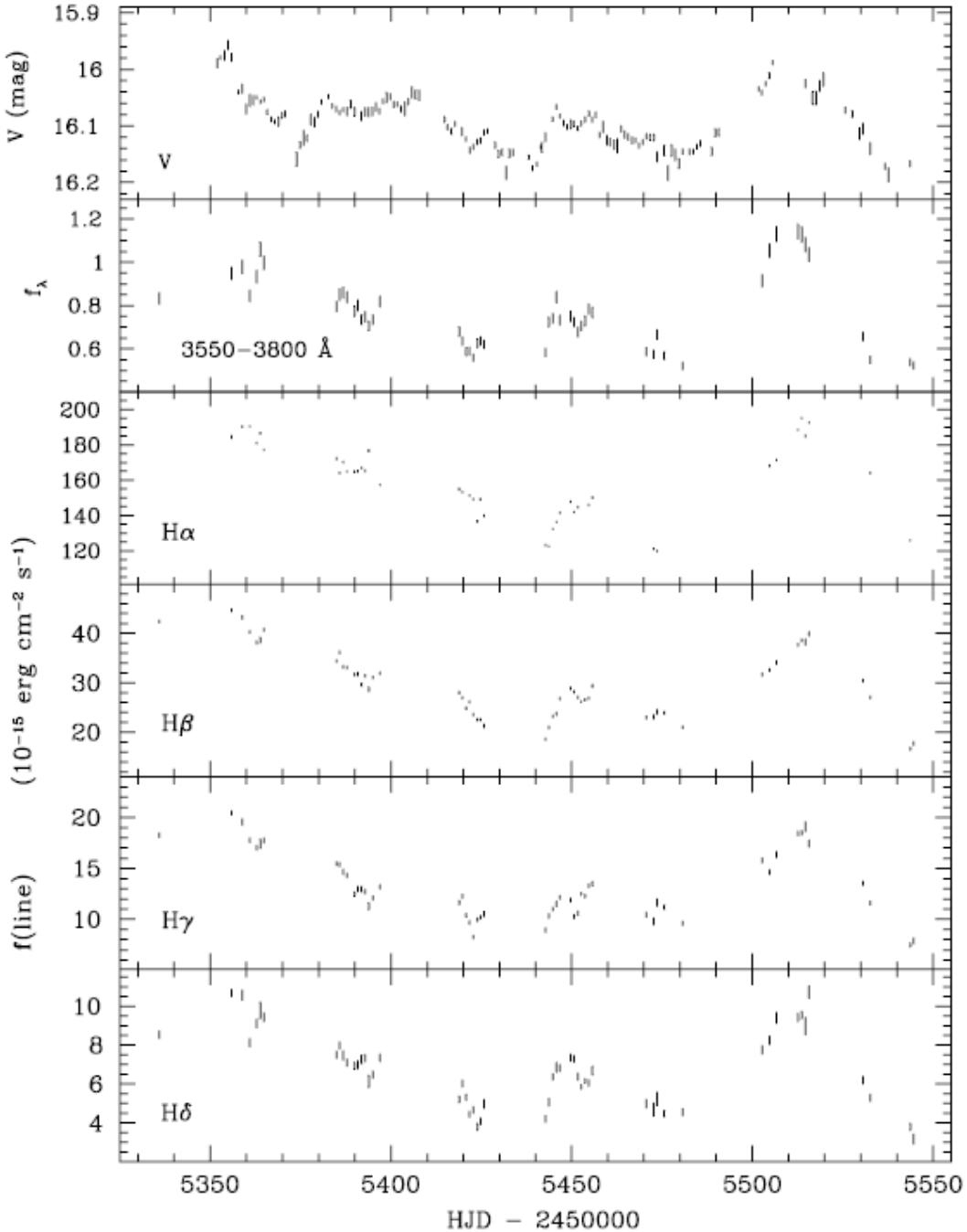
- Calibrate scaling relationships for indirect black hole mass estimates
- Cosmological applications

These require measurement of BLR size, preferably in a large number of sources. Are there less expensive ways to do this?

Sparse Sampling

- If you have a good continuum light curve, you can get by with more sparsely sampled line light curves
  - Especially if you use multiple lines with different lags

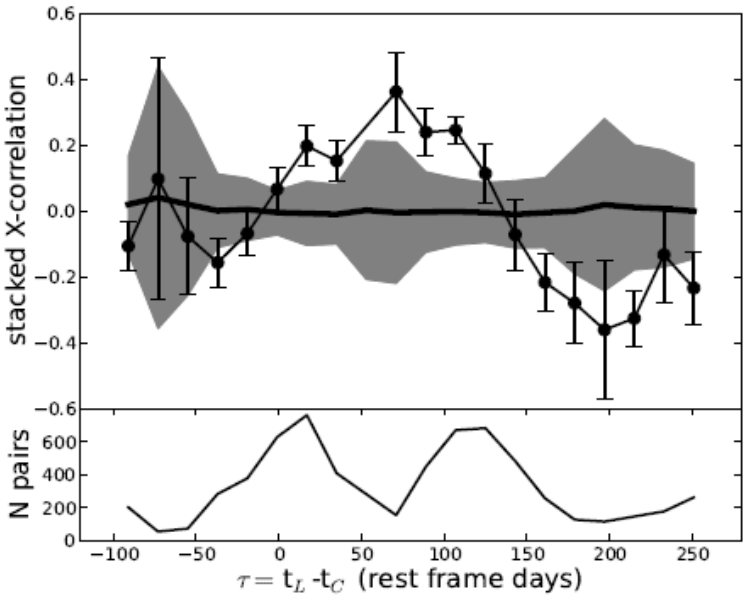
Zw 229-015 (*Kepler* field)



Barth+ 2011

“Stacked Spectra” or Extremely Sparse Sampling

- A minimal number of line measurements can be probabilistically matched to a particular lag with good continuum sampling.
  - Can be done with as few as two spectra, though fidelity low.



Fine+ 2013

Photometric Reverberation

- The Great Hope:
  - If we can get emission-line lags from ground-based broad-band data, we can get thousands of BLR radii and black hole masses efficiently.
  - With surveys like Pan-STARRS and LSST, we can get the monitoring data essentially for free.
    - *R-L* for cosmology for free!
    - Add one (high-quality) spectrum per target to get masses.

Photometric Reverberation

- The Great Challenge:
  - The line flux is typically a small part of the total waveband flux.
  - Line flux variations are relatively small.

$$\Delta F / F = \frac{EW_{\text{line}}}{FWHM_{\text{filter}}} \times F_{\text{var}}$$

Estimating these quantities for Hβ in Johnson *B*-band:

$$\Delta F / F \approx \left(\frac{60\,\text{Å}}{940\,\text{Å}} \right) \times (0.10 \pm 0.06) = 0.006 \pm 0.004$$

Typical photometric errors are $\sigma/F \sim 0.01$

Photometric Reverberation

- Approaches:

Stronger line, e.g., Hα

$$\Delta F / F = \frac{EW_{\text{line}}}{FWHM_{\text{filter}}} \times F_{\text{var}} \gg \sigma / F$$

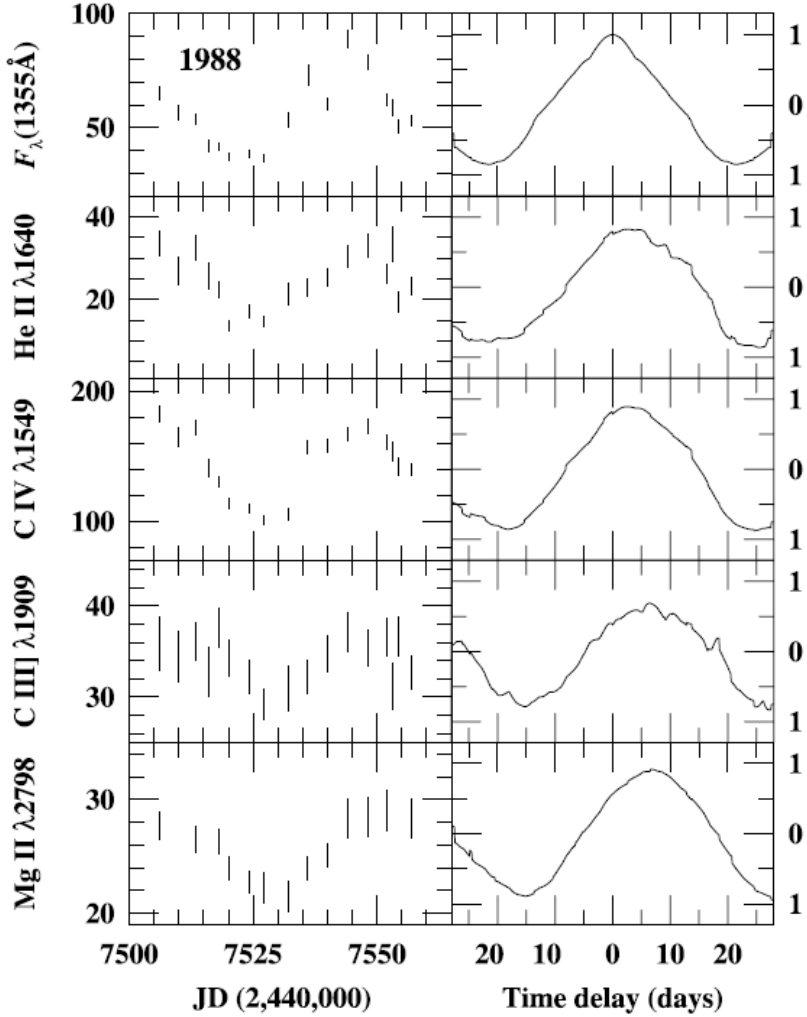
Narrower filter

Reduce photometric errors

Caution: As with spectroscopic reverberation, time sampling and duration remain important issues.

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.



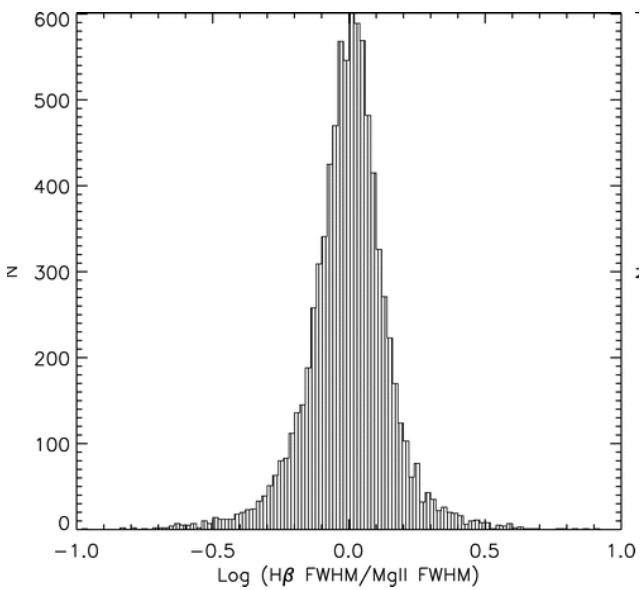
Metzroth, Onken, & Peterson (2006)

R-L Relationship for Mg II λ2798

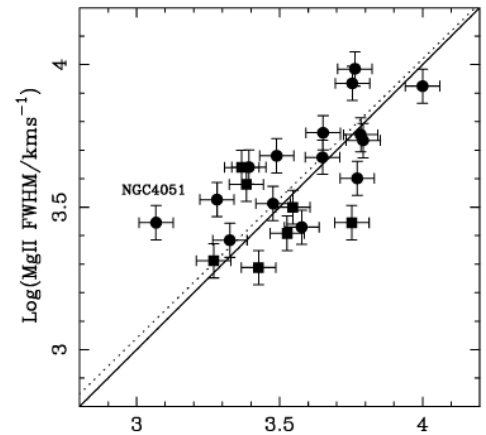
- From SDSS spectra, Shen et al. (2008) find

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

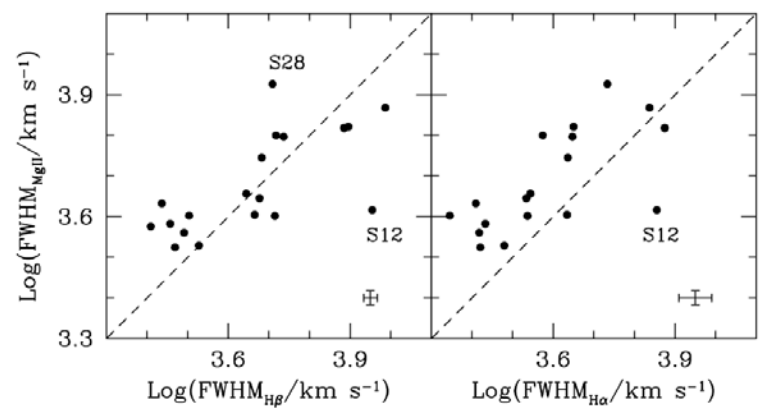
with scatter ~0.11 dex.



Shen et al. (2008)



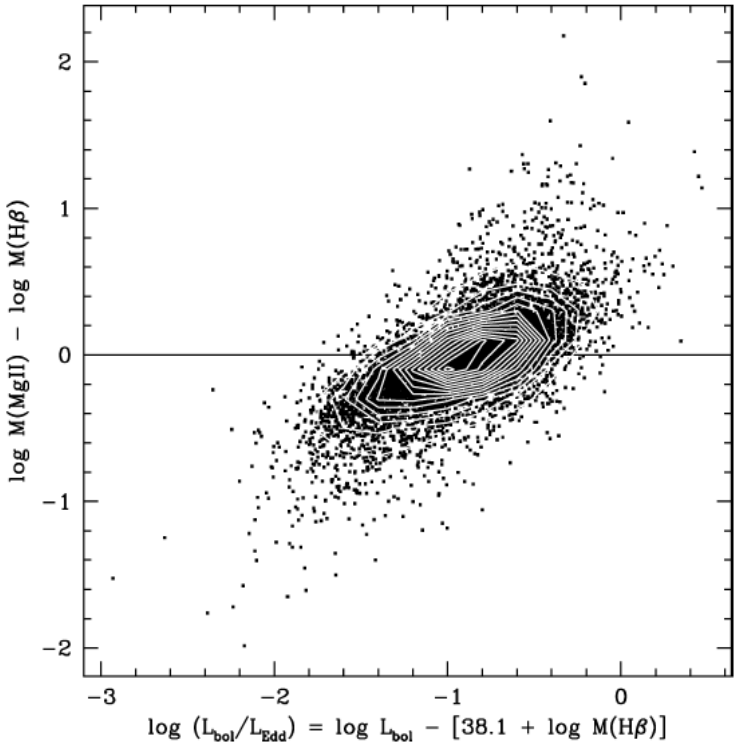
McLure & Jarvis (2002)



McGill et al. (2008)

R-L Relationship for Mg II λ2798

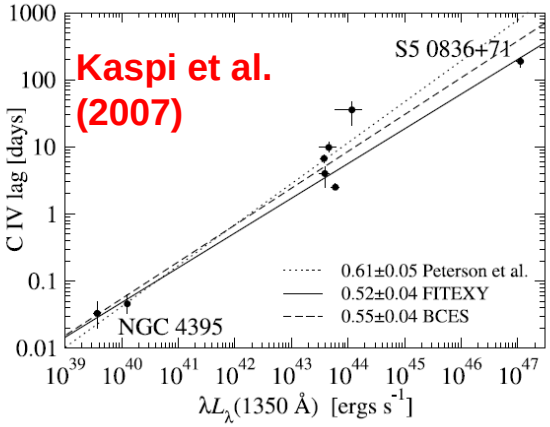
- Onken & Kollmeier find that the line width ratio has dependence on Eddington ratio and is correctable.

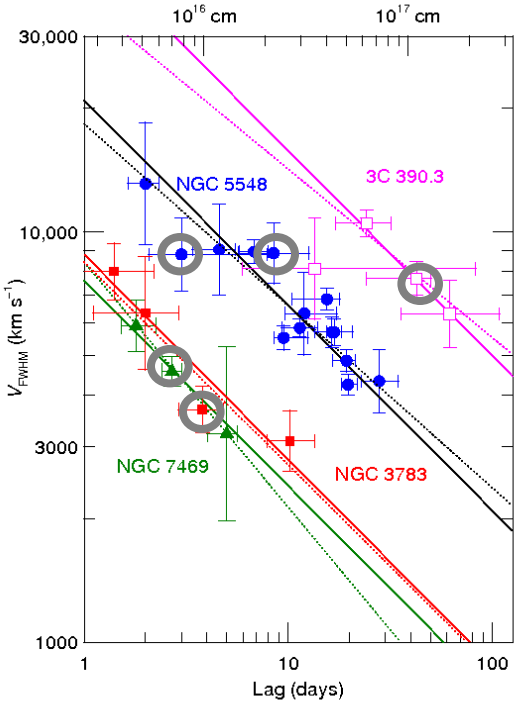


Onken & Kollmeier 2008

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.

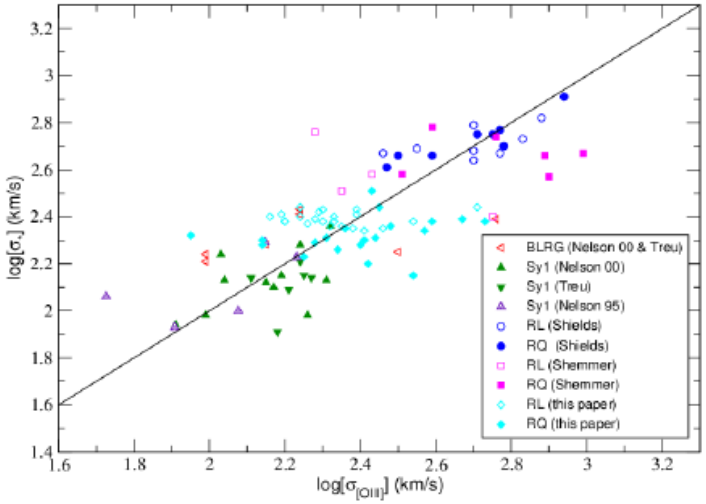




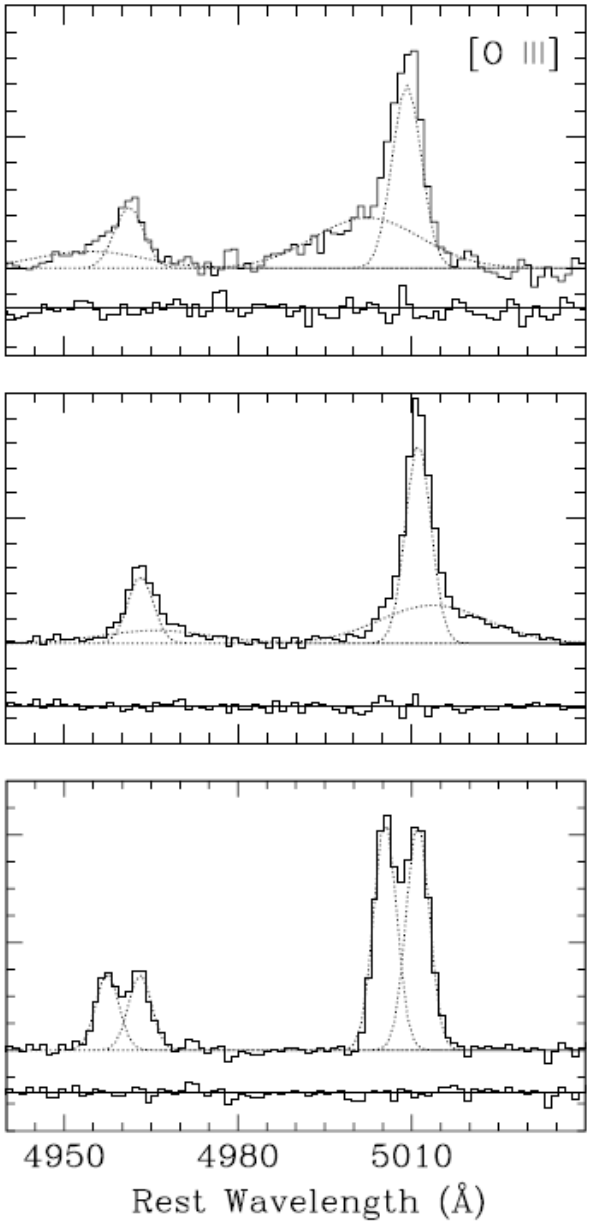
Other Scaling Relationships

- 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



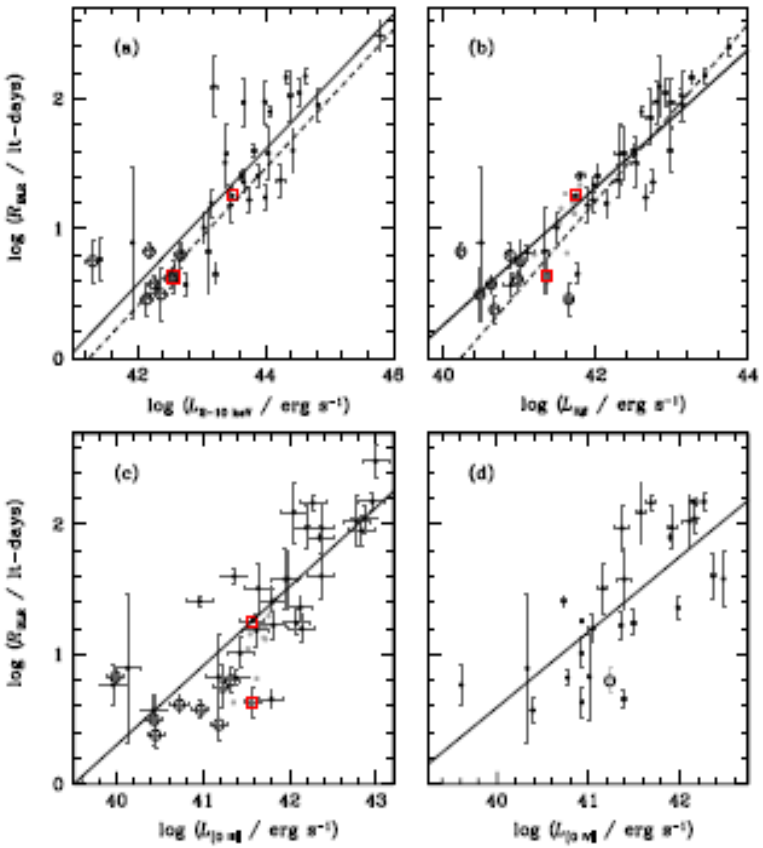
Bonning et al. 2005



Greene & Ho 2005

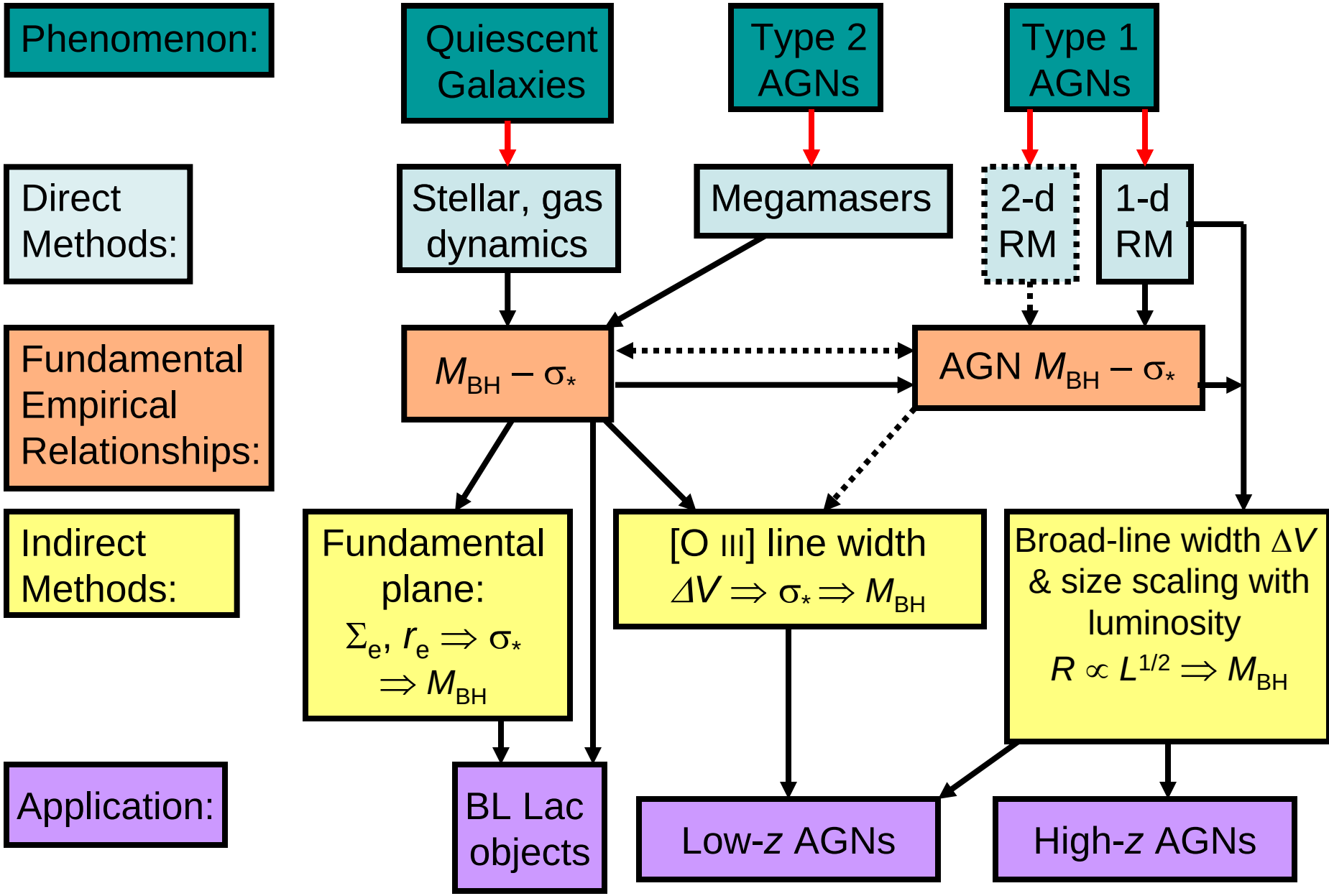
Other Scaling Relationships

- 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



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

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

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.