ACTIVE GALACTIC NUCLEI: optical spectroscopy

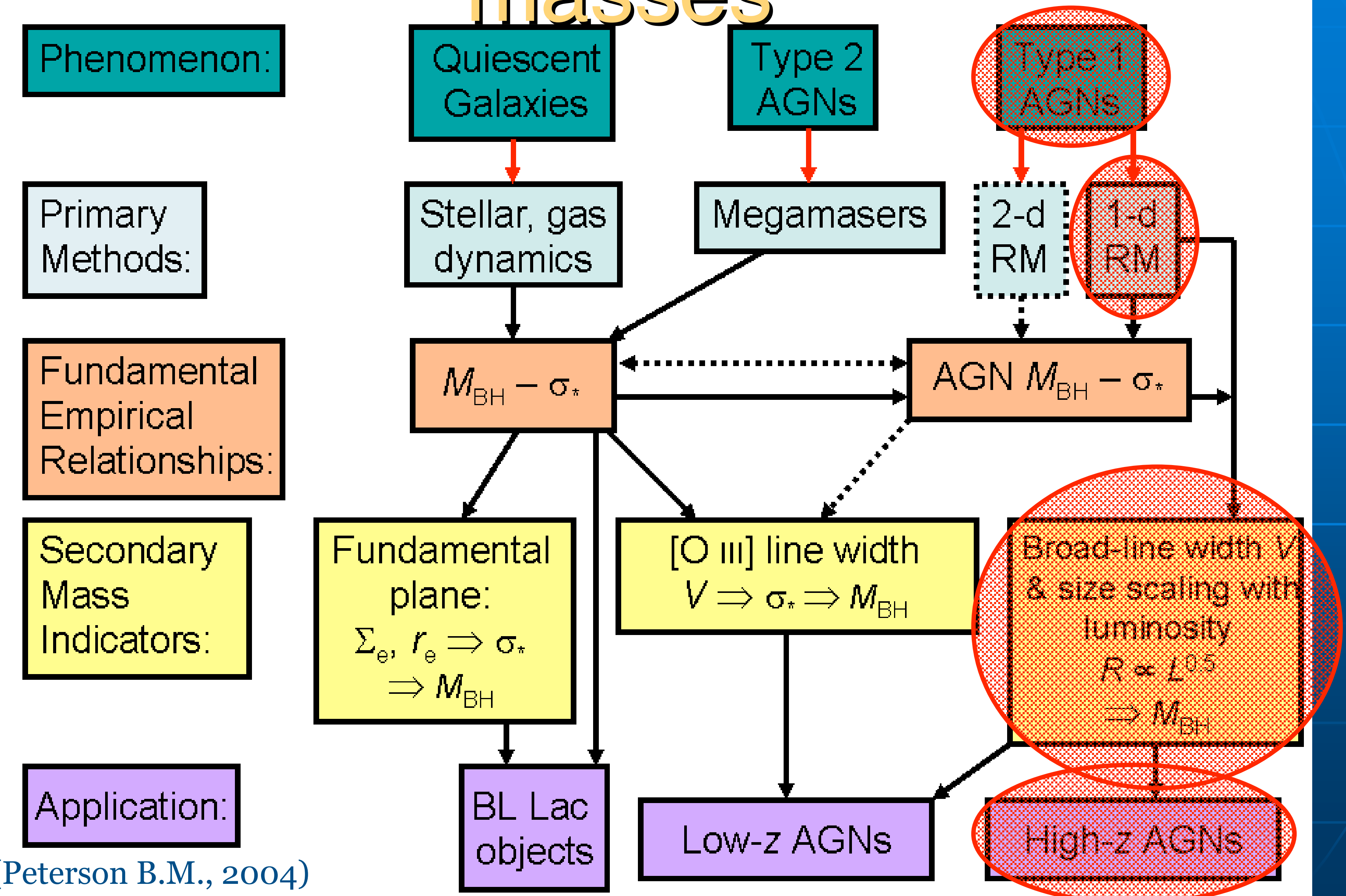
From AGN classification to Black Hole mass estimation

Second Lecture

Reverberation Mapping experiments

& virial BH masses estimations

Estimating AGN black hole masses



(Peterson B.M., 2004)

How can we measure BH masses?

- Virial mass measurements based on motions of stars and gas in nucleus.
  - Stars

    Advantage: gravitational forces only

    Disadvantage: requires high spatial resolution
  - Gas

    Advantage: can be found very close to nucleus

    Disadvantage: possible role of non-gravitational forces

Possible Virial Estimators

Source	Distance
X-Ray Fe K ?	3-10 R_S
Broad-Line Region	600 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
$R_S = 2GM/c^2 = 3$ _ 10^{13} M_8 cm .

Mass estimates from the virial theorem:

$$M = f\,(r\,\Delta v^2 / G)$$

where

r = scale length

Δv = velocity dispersion

f ≈ unity, depends on geometry & kinematics

BLR Virial Mass Estimates

$$M_{BH} = f\,v^2\,R_{BLR}/G$$

- Reverberation Mapping: **R_{BLR}=c_, v_{BLR}=FWHM**

Radius – Lu[...]n: (Kaspi et al. 2005; Bentz et al. 2006)

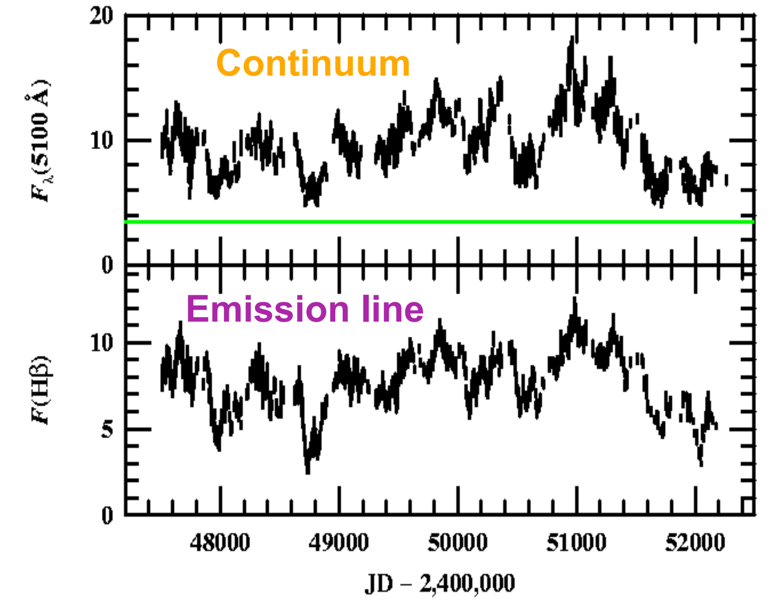
$$R_{BLR} \propto L\_(5100Å)^{0.52}$$
$$R_{BLR} \propto L(H\_)^{0.63}$$
$$R_{BLR} \propto L\_(1350Å)^{0.56}$$

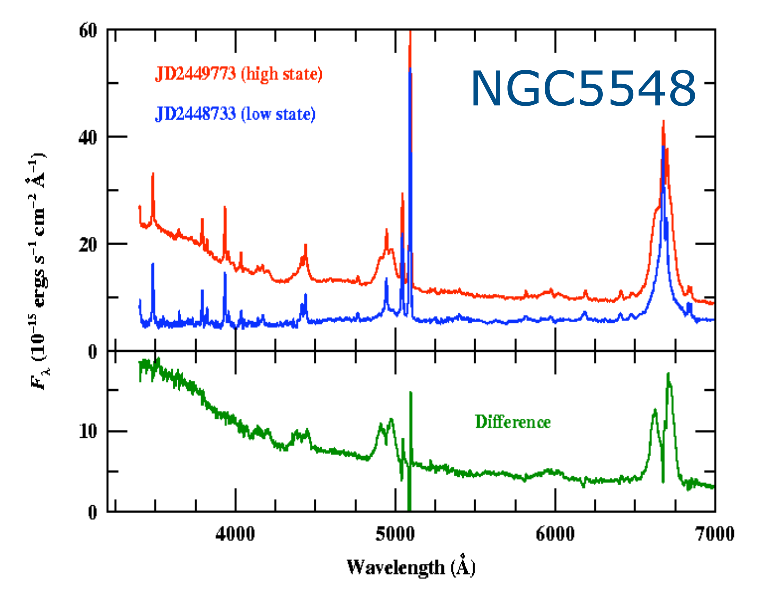
- Scaling Relationships:

$$M_{BH} \propto FWHM^2\,L\_$$

Reverberation Mapping: basics

- AGN variability both in emission lines and continuum, with a short time delay
- The delay of the emission lines response to a continuum variation is a measure of the BLR radius





- The kinematics and geometry of the BLR can be constrained by measuring the emission-line response to continuum variations.

Reverberation Mapping: assumptions

1. Continuum originates in a single central source.
   - Continuum source is much smaller than BLR
     Continuum source *not necessarily* isotropic
2. Light-travel time is most important time scale.
   - Cloud response instantaneous
     - $\tau_{rec} = (n_e \alpha_B)^{-1} \approx 0.1\, n_{10}^{-1}$ hr
   - BLR structure stable
     - $\tau_{dyn} = (R/V_{FWHM}) \approx 3 - 5$ yrs
3. There is a simple, though not necessarily linear, relationship between the observed continuum and the ionizing continuum.

The Transfer Equation

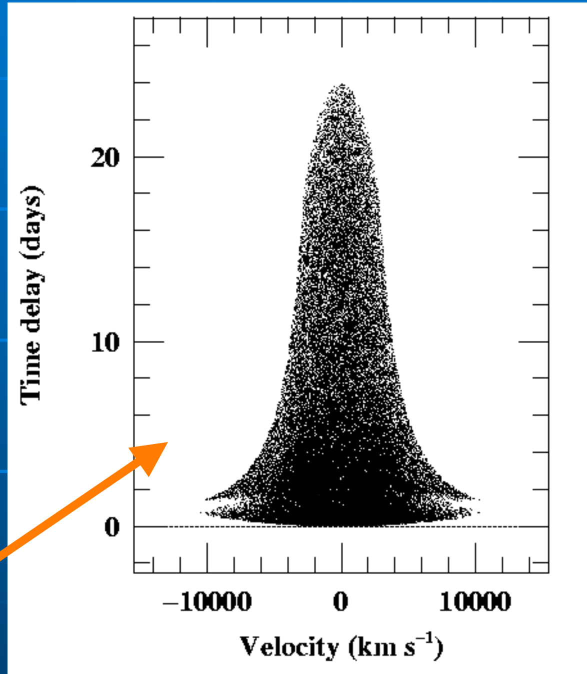
Under these assumptions, the relationship between the continuum and emission lines is:

$$L(V,t) = \int_{-\infty}^{\infty} \Psi(V,\tau)C(t-\tau)\,d\tau$$

Emission-line light curve — "Transfer Function" — Continuum Light Curve

Transfer function is line response to a δ-function outburst

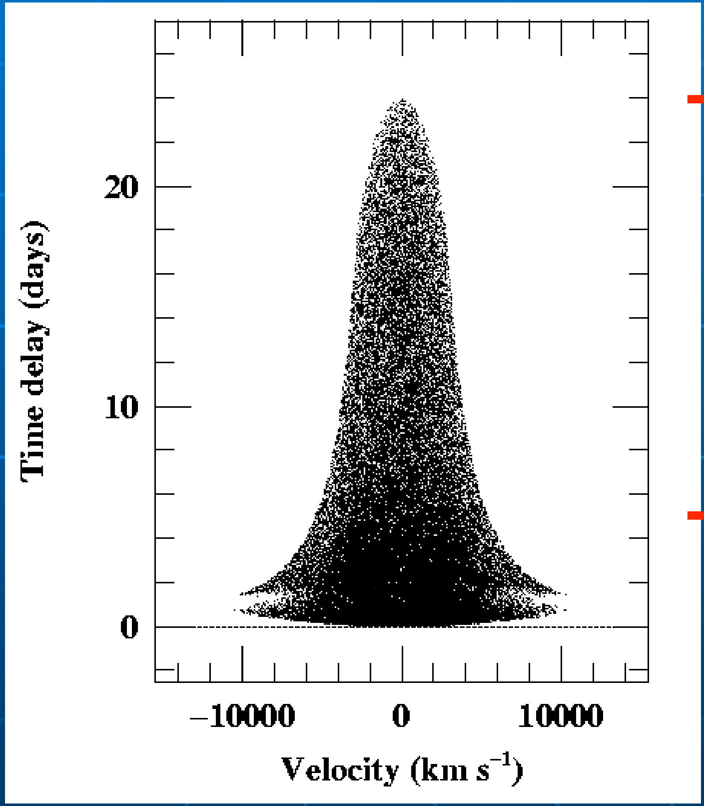
Transfer function is essentially a "velocity-delay map"



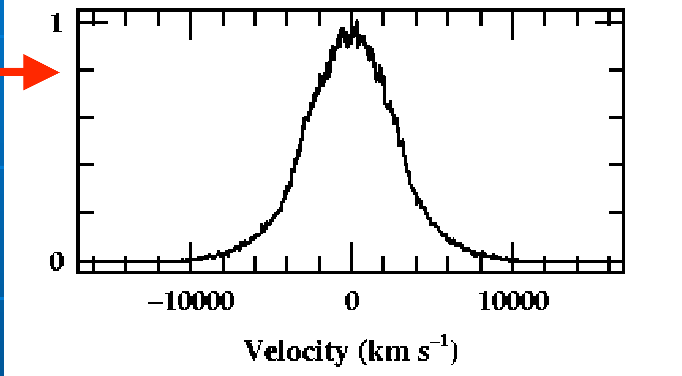
Simple velocity-delay map

The velocity-delay map

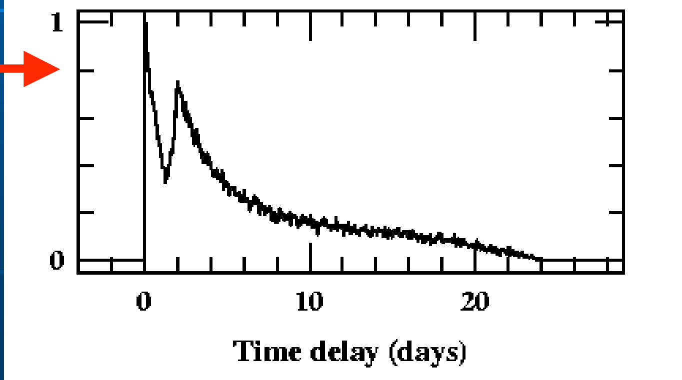
There has been limited success with efforts to obtain the one-dimensional transfer function, or "delay map".



Integrate over time delay to get the line profile

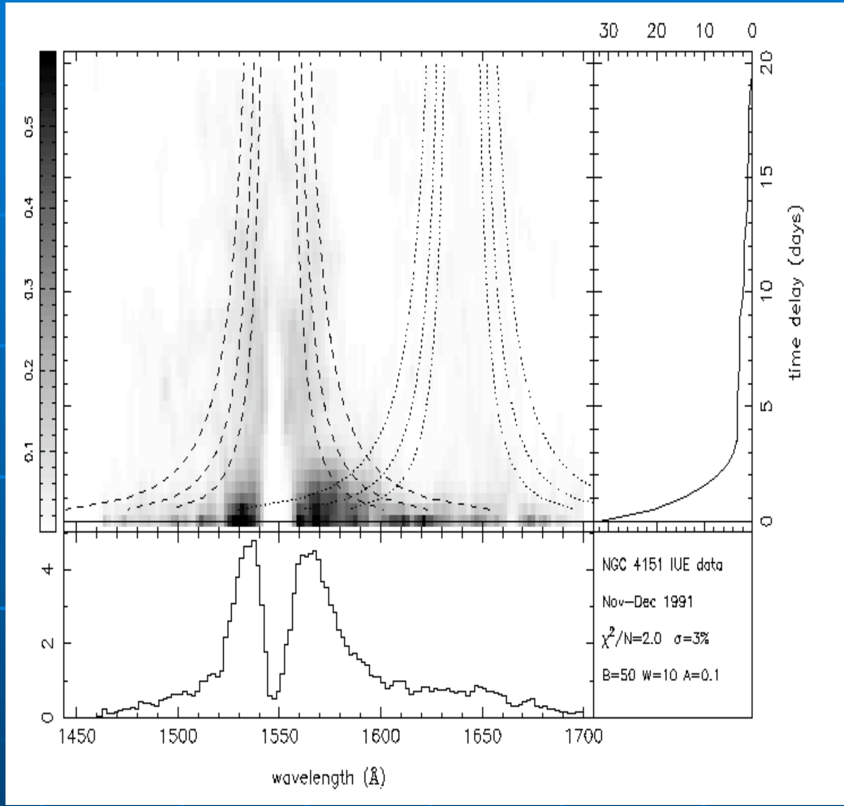


Integrate over velocity to get the delay map



Recovering velocity-delay maps

- Reconstruction of velocity-delay maps from real data requires:
  - High *S/N* in each spectrum
  - High *S/N* in phot. light curve
  - Moderately high spectral resolution
  - Long experiment duration
  - Dense sampling
- *To date, such specifications have never been fulfilled.*

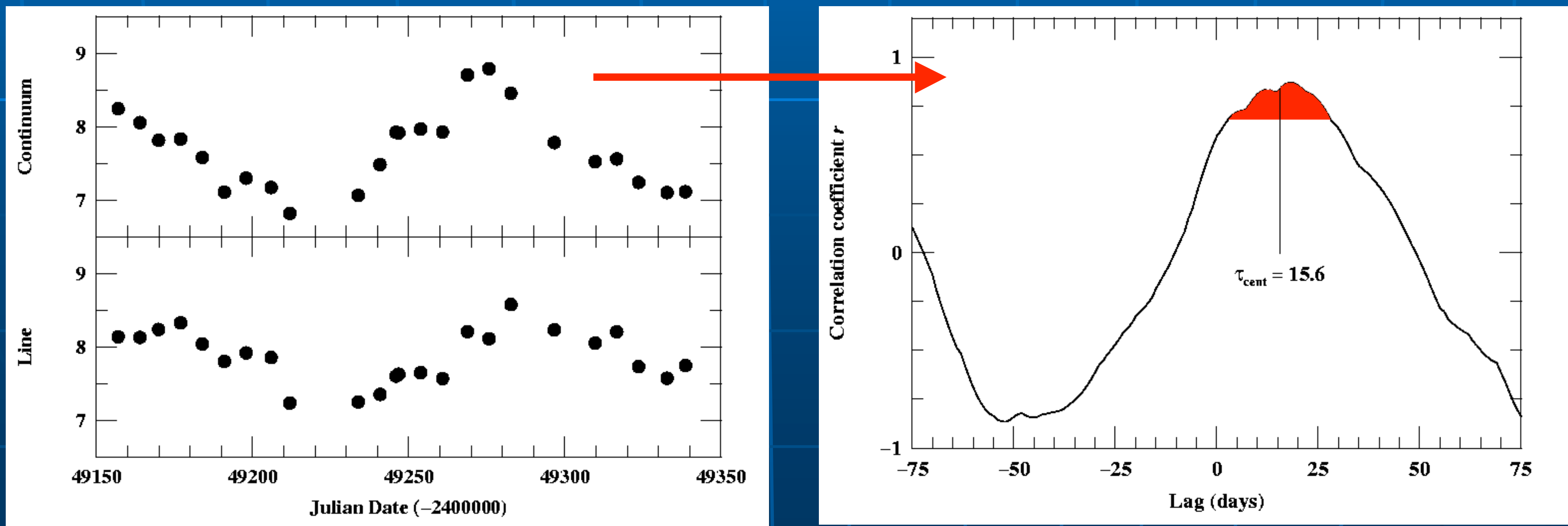


C IV and He II in NGC 4151
Ulrich & Horne (1996)

Reverberation Mapping: the emission-line lags

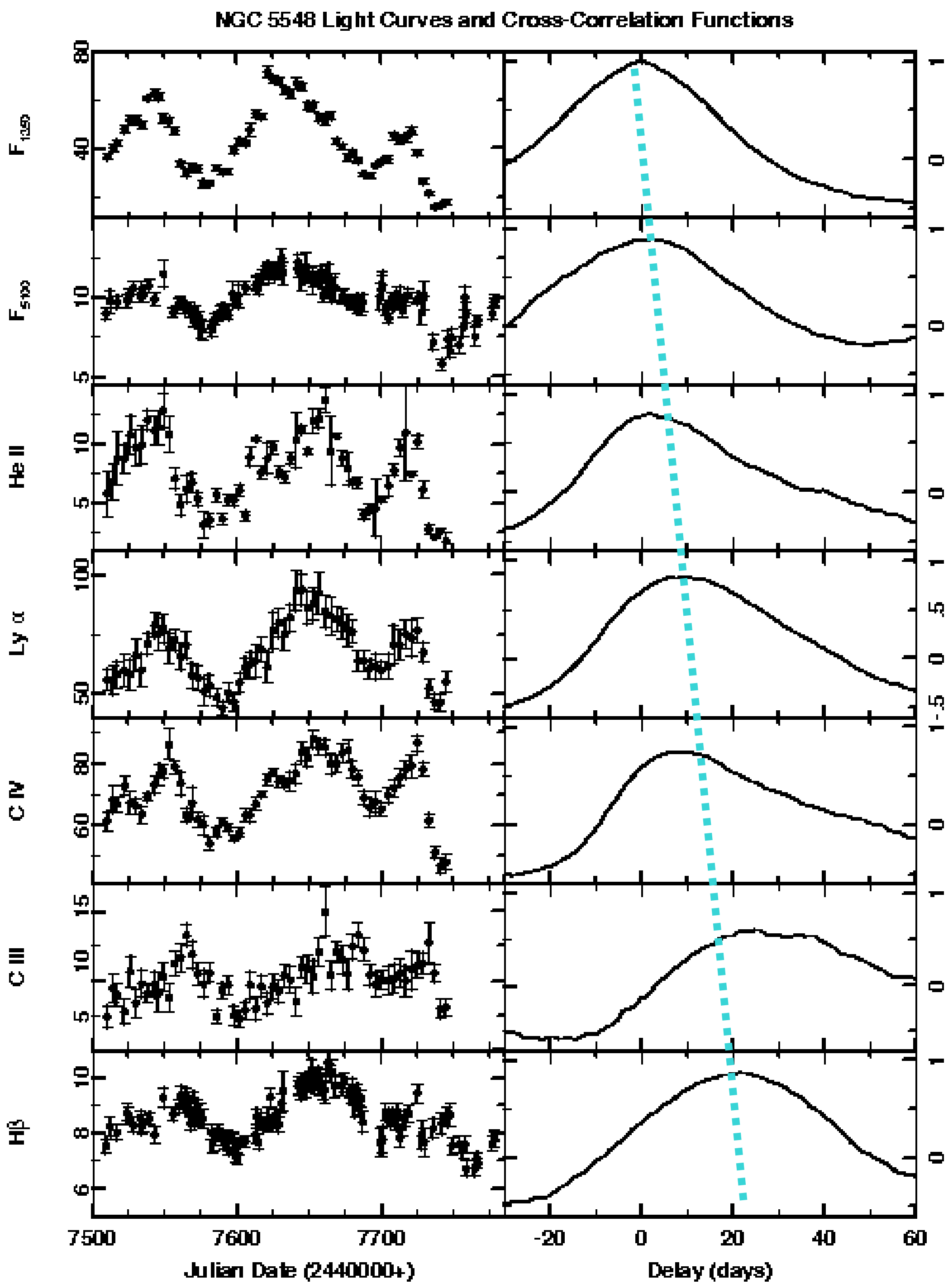
Rather than attempt to obtain the velocity-delay map, it is most common to determine the cross-correlation function, obtaining the "lag" (mean response time)

$$\mathrm{CCF}\,(t) = \int_{-\infty}^{\infty} \Psi(\tau)\,\mathrm{ACF}\,(t-\tau)\,d\tau$$



Reverberation Mapping Results (I)

- No experiment yet has recovered a reliable velocity-delay map.
- However, emission-line lags have been measured in 37 AGN, in some cases for multiple emission lines.



Reverberation Mapping Results

AGNs with multiple lag times show that highest ionization emission lines respond most rapidly

Ionization stratification

Reverberation Mapping table

MASSES DETERMINED FROM REVERBERATION MAPPING[a]

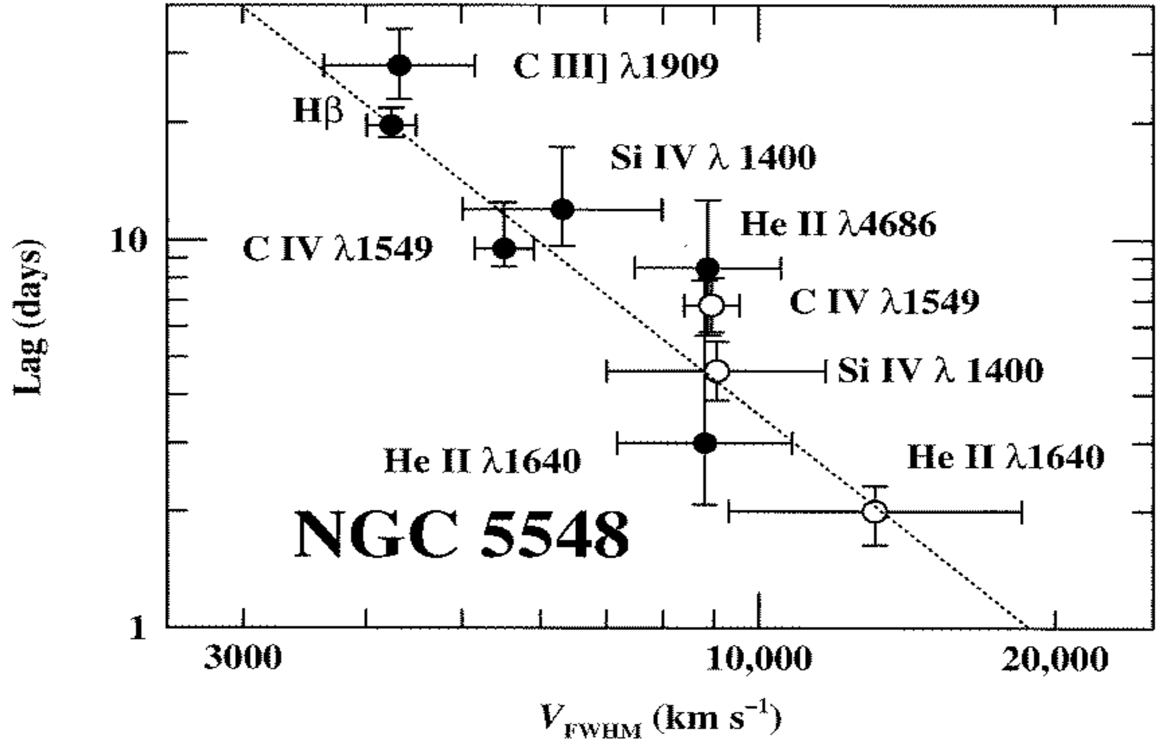
Galaxy (1)	Hubble Type (2)	D (Mpc) (3)	B_T^0 (mag) (4)	B/T (5)	M_B(bul) (mag) (6)	$r_{\rm BLR}$ (ltd) (7)	FWHM(Hβ) (km s^{-1}) (8)	$M_{\rm MDO}$ (M$_\odot$) (9)
3C 120	S0:	132	13.63	0.24	−20.42	44	2300	3.4×10^7
Ark 120	S0/a	121	13.64	0.86	−21.61	39	5450	1.7×10^8
Fairall 9	S?	188	13.50	0.08	−20.13	23	4200	5.9×10^7
Mrk 79	SBb	89	13.32	0.20	−20.12	18	6200	1.0×10^8
Mrk 110	Pair?	141	16.00	—	—	20	2500	1.8×10^7
Mrk 279	S0	118	14.43	0.06	−17.87	10	5360	4.2×10^7
Mrk 335	S0/a	103	13.85	0.64	−20.73	17	1800	8.0×10^6
Mrk 509	comp	138	13.00	0.12	−20.39	80	2800	9.0×10^7
Mrk 590	Sa:	105	13.66	0.47	−20.63	21	2300	1.6×10^7
Mrk 817	S?	126	14.50	0.50	−20.88	16	4100	3.8×10^7
NGC 3227	SABa	20.6	11.18	0.52	−19.68	17	3900	3.8×10^7
NGC 3516	SB0:	38.9	12.14	0.61	−20.27	7	4760	2.3×10^7
NGC 3783	SBa	38.5	12.04	0.33	−19.68	8	2980	1.0×10^7
NGC 4151	SABab	20.3	10.71	0.36	−19.72	5	4670	1.6×10^7
NGC 4593	SBb	39.5	11.43	0.48	−20.76	4	3720	8.1×10^6
NGC 5548	S0/a	67.0	12.81	0.47	−20.50	19	5610	8.8×10^7
NGC 7469	SABa	65.2	12.64	0.40	−20.44	5	3388	9.1×10^6

NOTE.— Cols.: (1) Galaxy name; (2) Hubble type from de Vaucouleurs et al. 1991; (3) distance from Tully 1988 or derived by assuming $H_0 = 75$ km s^{-1} Mpc^{-1}; (4) total apparent blue magnitude corrected for Galactic and internal extinction, from de Vaucouleurs et al. 1991; (5) ratio of bulge to total luminosity (host galaxy plus AGN); Mrk 110 is too disturbed to yield a reliable photometric decomposition; (6) absolute blue magnitude of the bulge component; (7) lag (in light days) between the continuum and the Hβ light curves; (8) FWHM of the broad Hβ emission line; (9) virial mass derived from $r_{\rm BLR}$ and FWHM(Hβ).

[a]All Seyfert 1 nuclei studied to date with reverberation mapping of the Hβ line. Optical monitoring data exist for 3C 390.3, but it was not included because the profiles of its Balmer lines are very complicated. References for the data entries have been omitted for brevity.

RM & AGN BH masses: a virialized BLR

NGC5548: Highest ionization lines have smallest lags and largest Doppler widths.



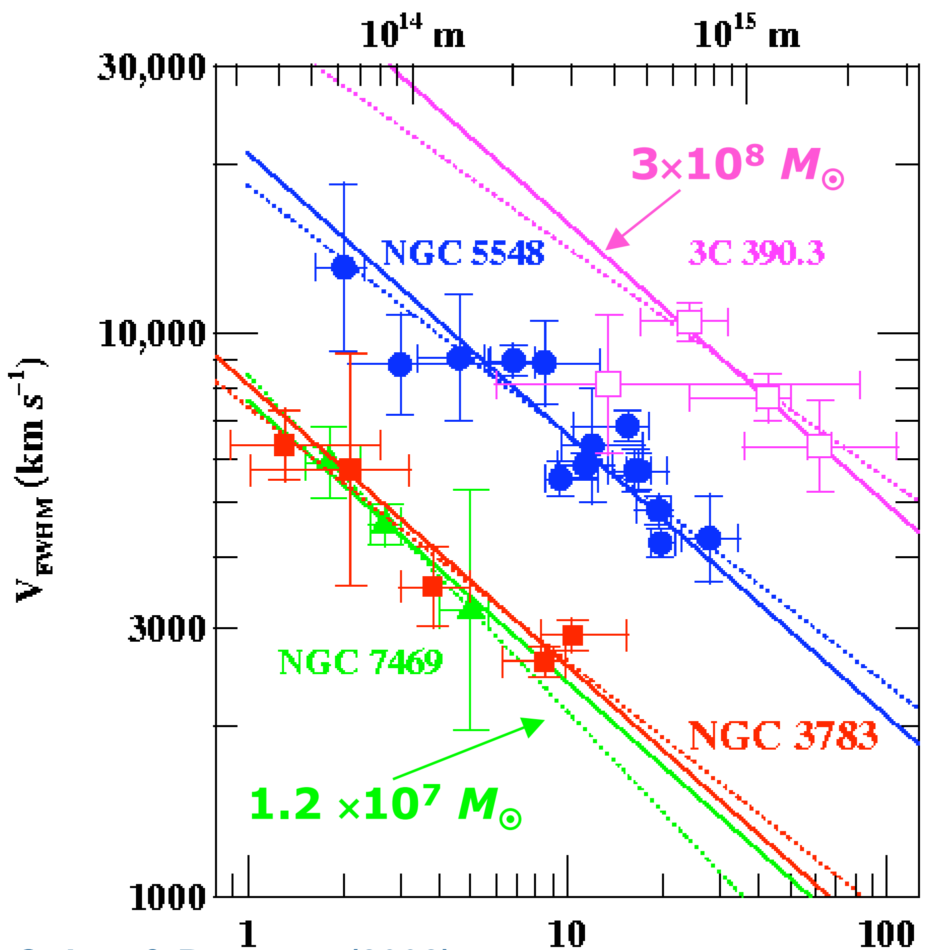
 Filled circles: 1989 data from *IUE* and ground-based telescopes

 Open circles: 1993 data from *HST* and *IUE*.

Dotted line corresponds to virial relationship with $M = 6 \_ 10^7 M_{}$.

Peterson and Wandel 1999

RM & AGN BH masses: a virialized BLR



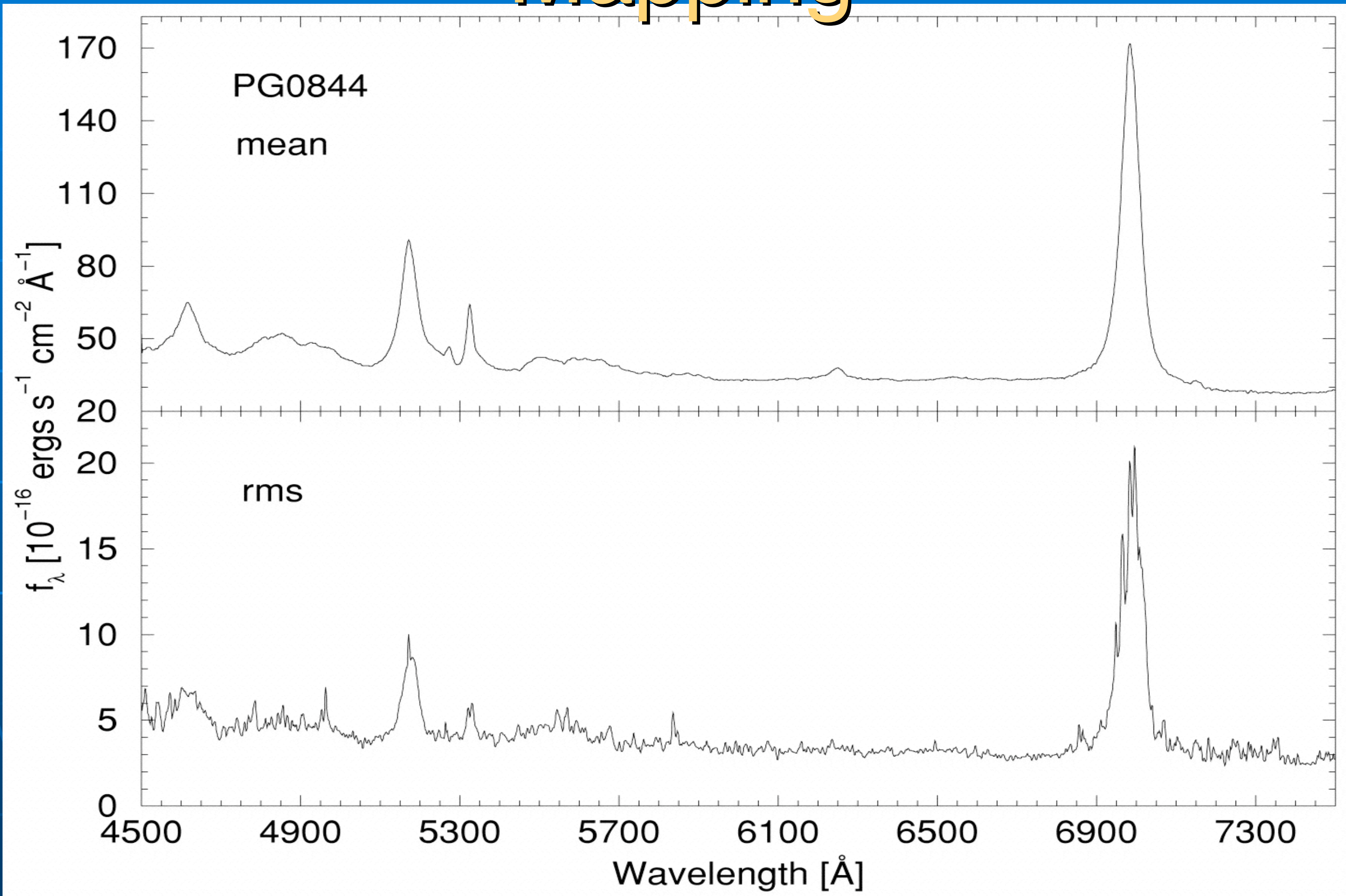
Onken & Peterson (2002)
Peterson & Wandel (2000)

For AGNs with reverberation measurements for multiple emission lines, there is virial relationship between line widths and time lags

$$M_{BH} = fc\tau\Delta v^2/G$$

Scaling between lines

BH masses from Reverberation Mapping



Calibration of the Reverberation Mass Scale

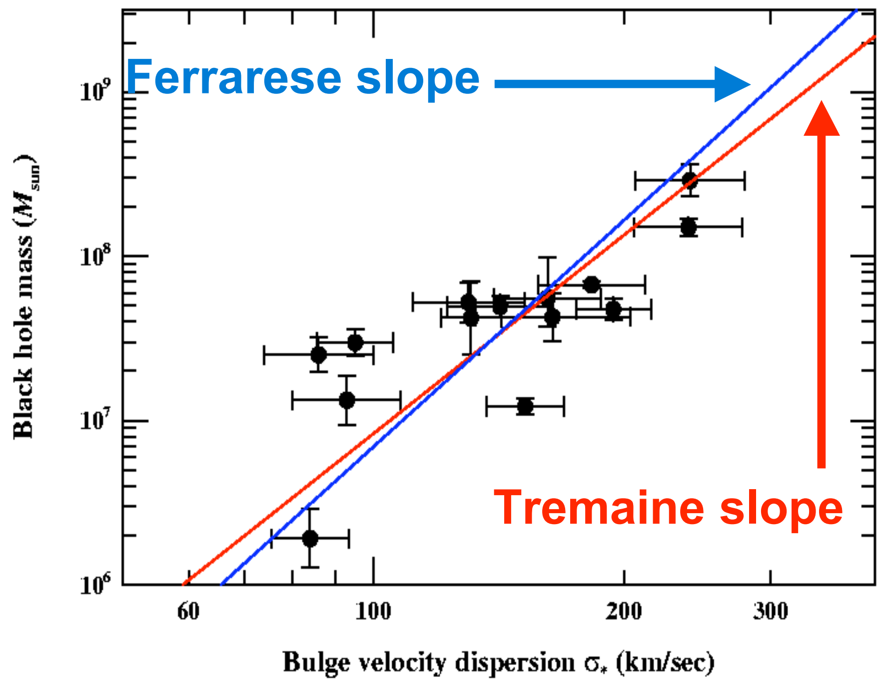
$$M_{BH} = 10^f \cdot \left[\frac{FWHM}{10^3\,Km \cdot s^{-1}}\right]^2 \left(\frac{\lambda L}{10^{44}\,erg \cdot s^{-1}}\right)$$

Determine scale factor *f* that matches AGN masses from RM to the (*quiescent-galaxy*) M_{BH}-σ_* relationship

Current best estimate:

$f \approx 5.5 \_ 6.6$

(Onken et al. 2004)



Reverberation Mapping table

MASSES DETERMINED FROM REVERBERATION MAPPING[a]

Galaxy (1)	Hubble Type (2)	D (Mpc) (3)	B_T^0 (mag) (4)	B/T (5)	M_B(bul) (mag) (6)	$r_{\rm BLR}$ (ltd) (7)	FWHM(Hβ) (km s^{-1}) (8)	$M_{\rm MDO}$ (M$_\odot$) (9)
3C 120	S0:	132	13.63	0.24	−20.42	44	2300	3.4×10^7
Ark 120	S0/a	121	13.64	0.86	−21.61	39	5450	1.7×10^8
Fairall 9	S?	188	13.50	0.08	−20.13	23	4200	5.9×10^7
Mrk 79	SBb	89	13.32	0.20	−20.12	18	6200	1.0×10^8
Mrk 110	Pair?	141	16.00	—	—	20	2500	1.8×10^7
Mrk 279	S0	118	14.43	0.06	−17.87	10	5360	4.2×10^7
Mrk 335	S0/a	103	13.85	0.64	−20.73	17	1800	8.0×10^6
Mrk 509	comp	138	13.00	0.12	−20.39	80	2800	9.0×10^7
Mrk 590	Sa:	105	13.66	0.47	−20.63	21	2300	1.6×10^7
Mrk 817	S?	126	14.50	0.50	−20.88	16	4100	3.8×10^7
NGC 3227	SABa	20.6	11.18	0.52	−19.68	17	3900	3.8×10^7
NGC 3516	SB0:	38.9	12.14	0.61	−20.27	7	4760	2.3×10^7
NGC 3783	SBa	38.5	12.04	0.33	−19.68	8	2980	1.0×10^7
NGC 4151	SABab	20.3	10.71	0.36	−19.72	5	4670	1.6×10^7
NGC 4593	SBb	39.5	11.43	0.48	−20.76	4	3720	8.1×10^6
NGC 5548	S0/a	67.0	12.81	0.47	−20.50	19	5610	8.8×10^7
NGC 7469	SABa	65.2	12.64	0.40	−20.44	5	3388	9.1×10^6

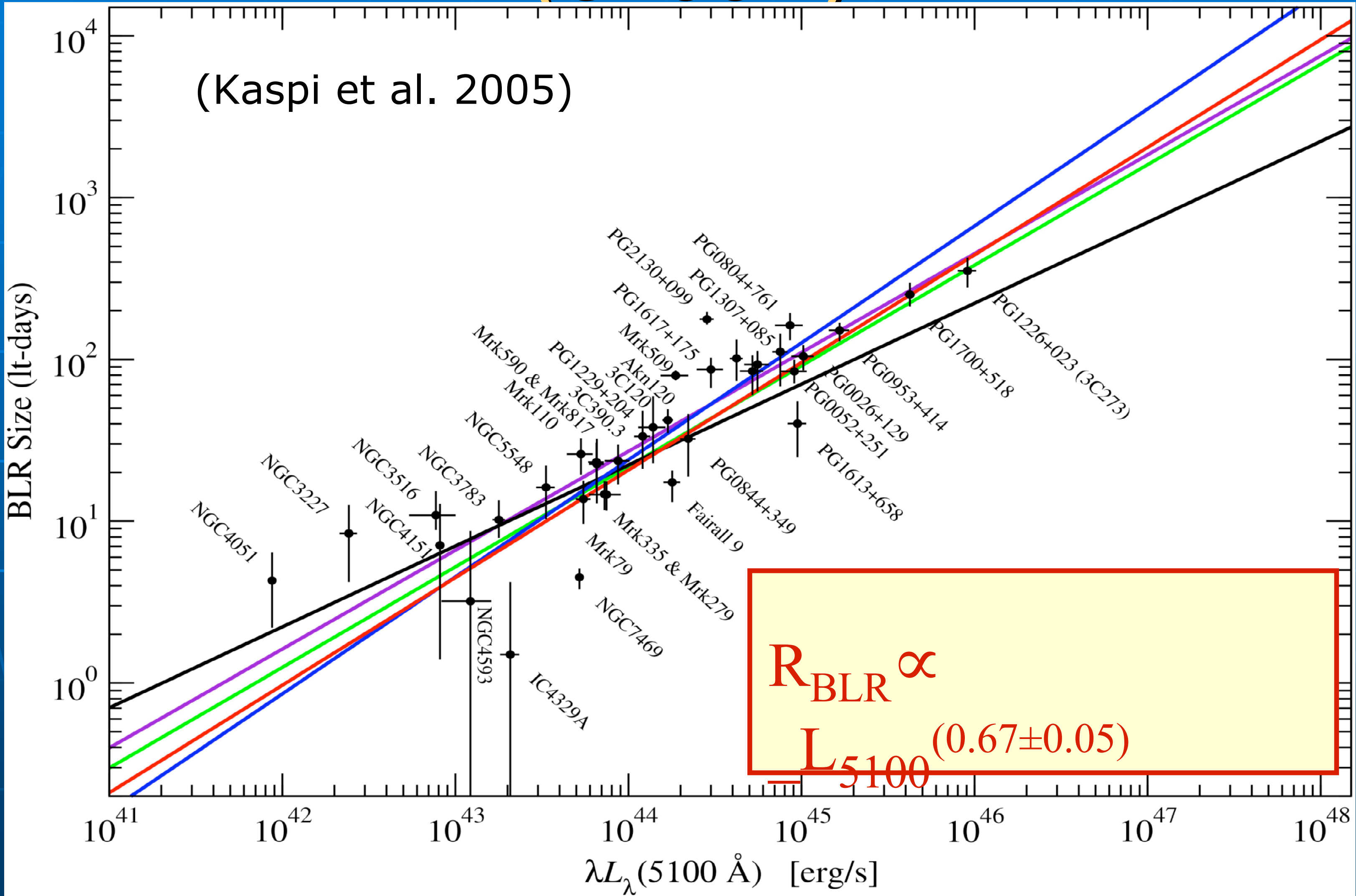
NOTE.— Cols.: (1) Galaxy name; (2) Hubble type from de Vaucouleurs et al. 1991; (3) distance from Tully 1988 or derived by assuming $H_0 = 75$ km s^{-1} Mpc^{-1}; (4) total apparent blue magnitude corrected for Galactic and internal extinction, from de Vaucouleurs et al. 1991; (5) ratio of bulge to total luminosity (host galaxy plus AGN); Mrk 110 is too disturbed to yield a reliable photometric decomposition; (6) absolute blue magnitude of the bulge component; (7) lag (in light days) between the continuum and the Hβ light curves; (8) FWHM of the broad Hβ emission line; (9) virial mass derived from $r_{\rm BLR}$ and FWHM(Hβ).

[a] All Seyfert 1 nuclei studied to date with reverberation mapping of the Hβ line. Optical monitoring data exist for 3C 390.3, but it was not included because the profiles of its Balmer lines are very complicated. References for the data entries have been omitted for brevity.

BH masses from RM: finale

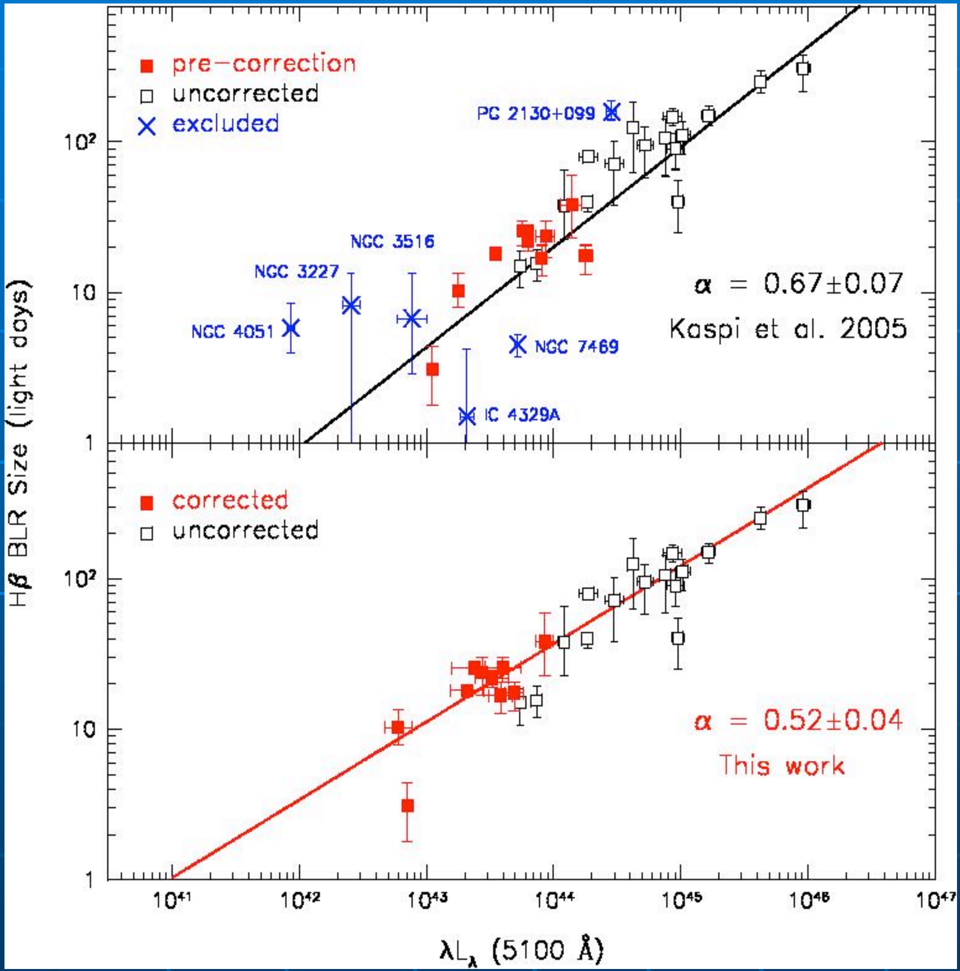
- Reverberation-based masses are *real* mass measurement.
- Reverberation-based masses are *not high-precision* measurements.
  - ~30% uncertainty in precision
    - Time lags and line widths measurement errors?
  - ~35% uncertainty in zero-point calibration
    - How well is scaling factor f determined?
  - ~0.5 dex uncertainty in accuracy for any given AGN
- Unfortunately, reverberation-mapping techniques are also very telescope- and time-consuming, especially for the more distant and fainter AGNs and for the (intrinsically) more luminous quasars, which vary on longer timescales.

R_{BLR} vs. Optical luminosity (5100Å)



$R_{BLR} \propto L_{5100}^{(0.67\pm0.05)}$

R_{BLR}-luminosity relationship: improvements (I)



Bentz et al. 2006 used HST *ACS* images to decompose light into nuclear and starlight components.

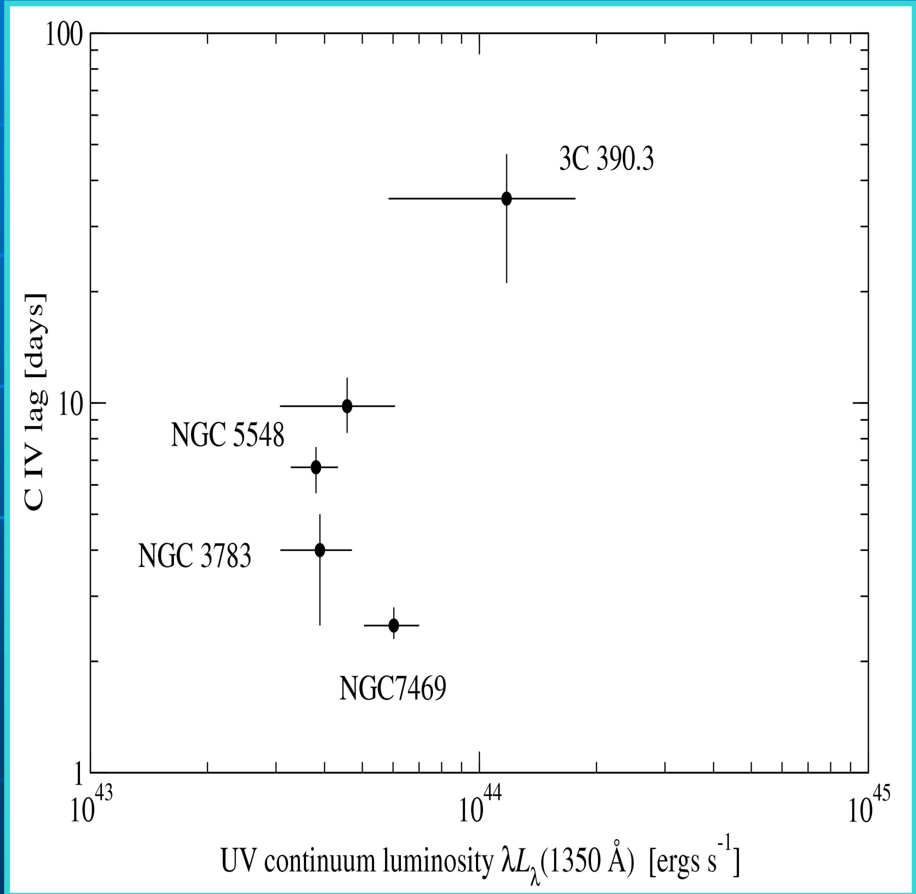
Starlight components are stronger than previously supposed and the effect is to flatten radius-luminosity relationship.

$$R_{BLR} \propto [\_L_{5100}]^{(0.518\pm0.039)}$$

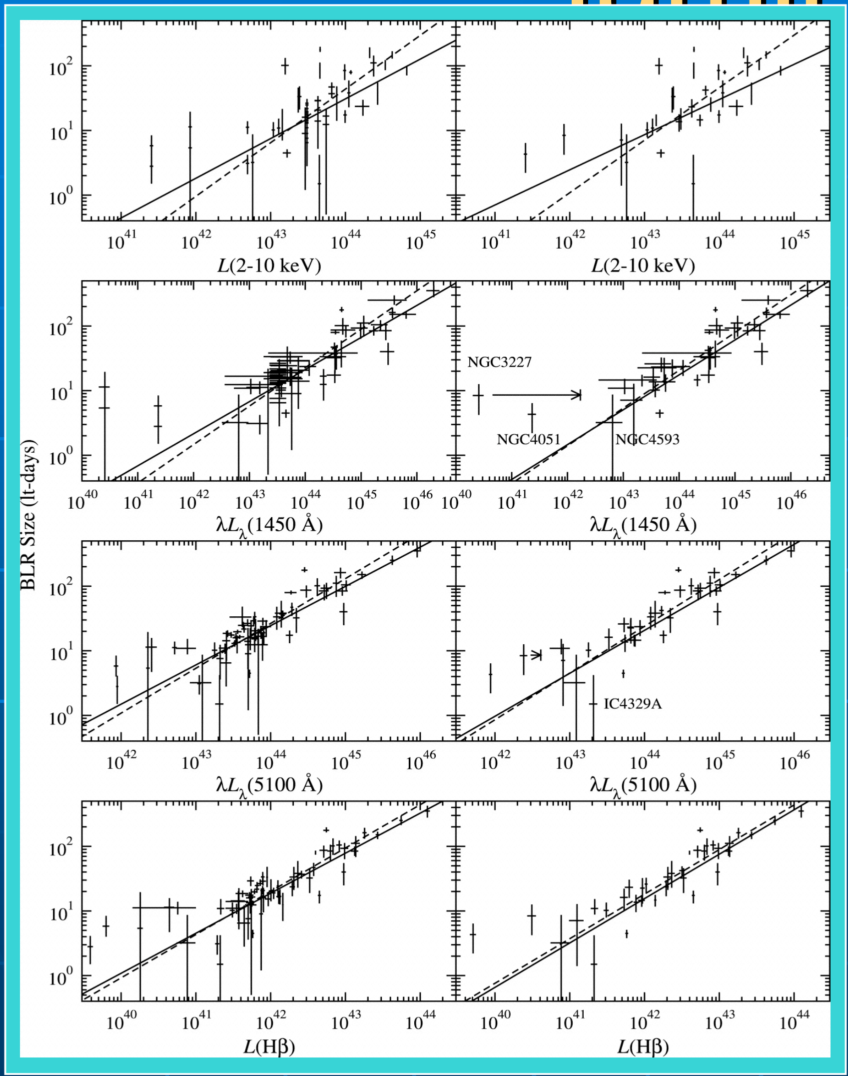
The new slope is consistent with the 0.5 value, expected from the naive theoretical assumption that all AGN have, on average, the same ionizing spectrum, ionization parameter and gas density in the line-emitting region.

R_{BLR}-luminosity relationship: improvements (II)

- Current studies span 4 orders of magnitude, but there is a wider luminosity range to be explored. Moreover, we need to extend the relationship to line in the UV range, to be exploited with high-z AGN.
- Up to now there are only a few AGNs with CIV measurements.
- Peterson et al. (2005) added up NGC4395, four orders of magnitude lower in luminosity.
- Kaspi et al. are monitoring (spec & phot) 11 quasar, with $2.1 < z < 3.2$ and up to $\lambda L\lambda(5100\ \text{Å}) = 10^{47}$ erg/s



BLR size vs. various luminosities



$R_{BLR} \propto L$–

the mean best-fitting slope indexes are:

- _ ≈ 0.52 ± 0.05 for the optical continuum and the broad H_ luminosity
- _ ≈ 0.56 ± 0.05 for the UV continuum luminosity
- _ ≈ 0.70 ± 0.14 for the X-ray luminosity.

There is an intrinsic scatter of 40% in these relations.

Why BLR size scales with luminosity ?

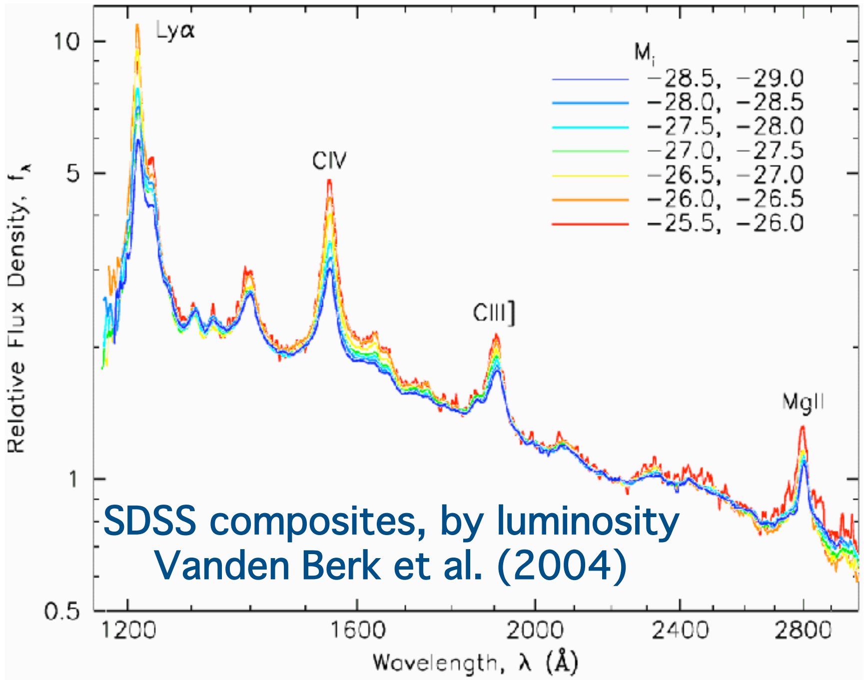
To first order, AGN spectra look the same:

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

⇒ Same ionization parameter U

⇒ Same density n_{H}

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



From reverberation-based masses to single epoch mass estimate

$M_{BH}= f\,(c\tau\ \ v^2 /G)$
virial mass recipe

\+

$R_{BLR} \propto$ _L_ –
radius–Luminosity Relation

$M_{BH} \propto (FWHM)^2$ _L_ –
A virial mass estimator

Assuming that such estimate is valid for all active galaxies, at each *L* & *z*, for different emission lines (especially UV ones) and that it is applicable also at single-epoch spectra, this is a powerful instrument for measuring (estimate) the black hole masses in large ensemble of AGN.

Single-epoch virial mass estimates

Updated (2004) Scaling Relationships:

- CIV:

$$M_{BH} = 4.5 \cdot 10^6 \left(\frac{\text{FWHM(CIV)}}{10^3\,\text{km/s}}\right)^2 \left(\frac{\text{ëL}_{\text{ë}}(1350\text{A})}{10^{44}\,\text{ergs/s}}\right)^{0.53} M\odot$$

- MgII:

$$M_{BH} = 4.7 \cdot 10^6 \left(\frac{\text{FWHM(MgII)}}{10^3\,\text{km/s}}\right)^2 \left(\frac{\text{ëL}_{\text{ë}}(3000\text{A})}{10^{44}\,\text{ergs/s}}\right)^{0.53} M\odot$$

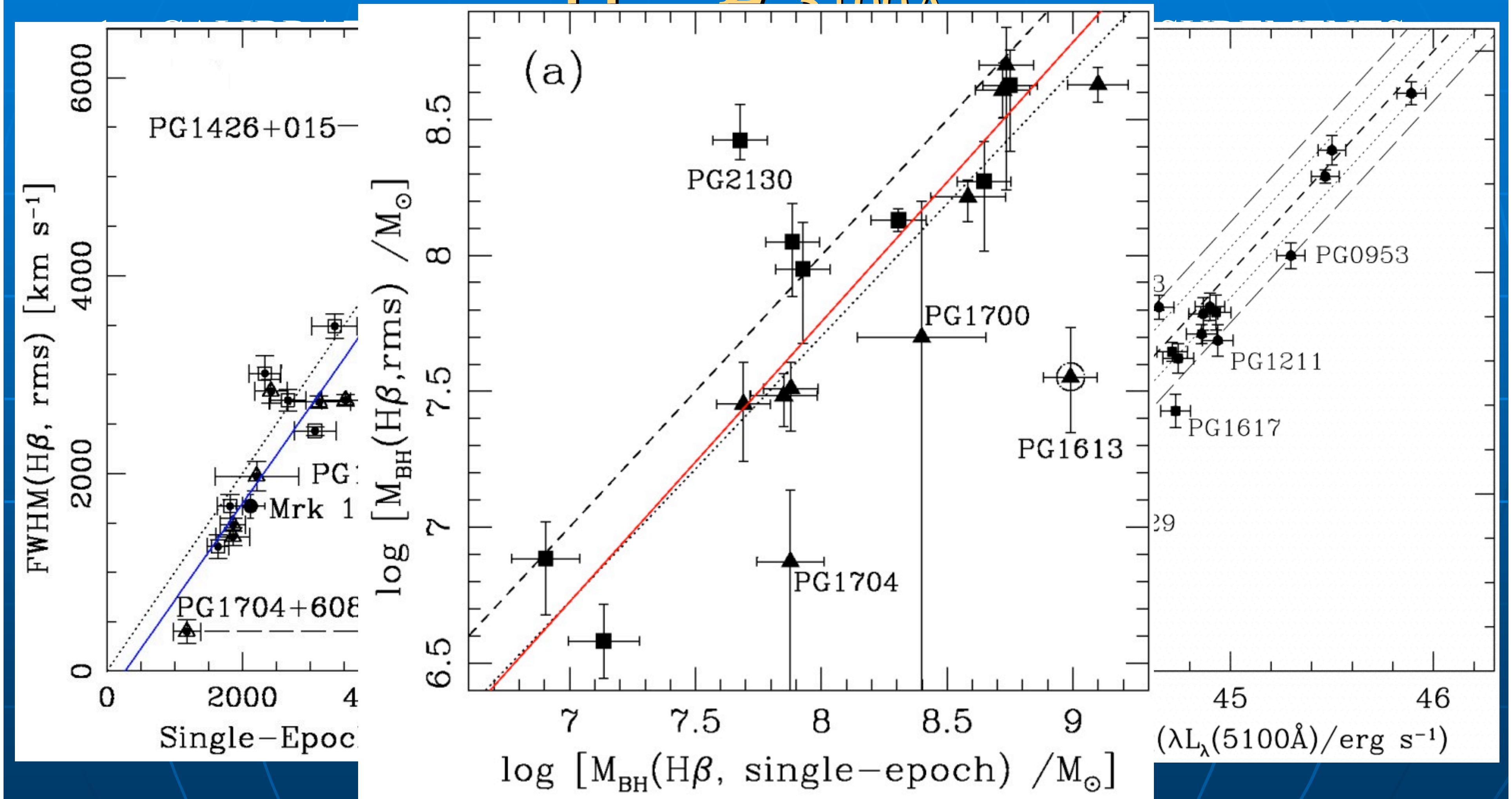
- H_:

$$M_{BH} = 8.3 \cdot 10^6 \left(\frac{\text{FWHM(H â)}}{10^3\,\text{km/s}}\right)^2 \left(\frac{\text{ëL}_{\text{ë}}(5100\text{A})}{10^{44}\,\text{ergs/s}}\right)^{0.50} M\odot$$

$$M_{BH} = 4.6 \cdot 10^6 \left(\frac{\text{FWHM(H â)}}{10^3\,\text{km/s}}\right)^2 \left(\frac{\text{L(Hâ)}}{10^{42}\,\text{ergs/s}}\right)^{0.63} M\odot$$

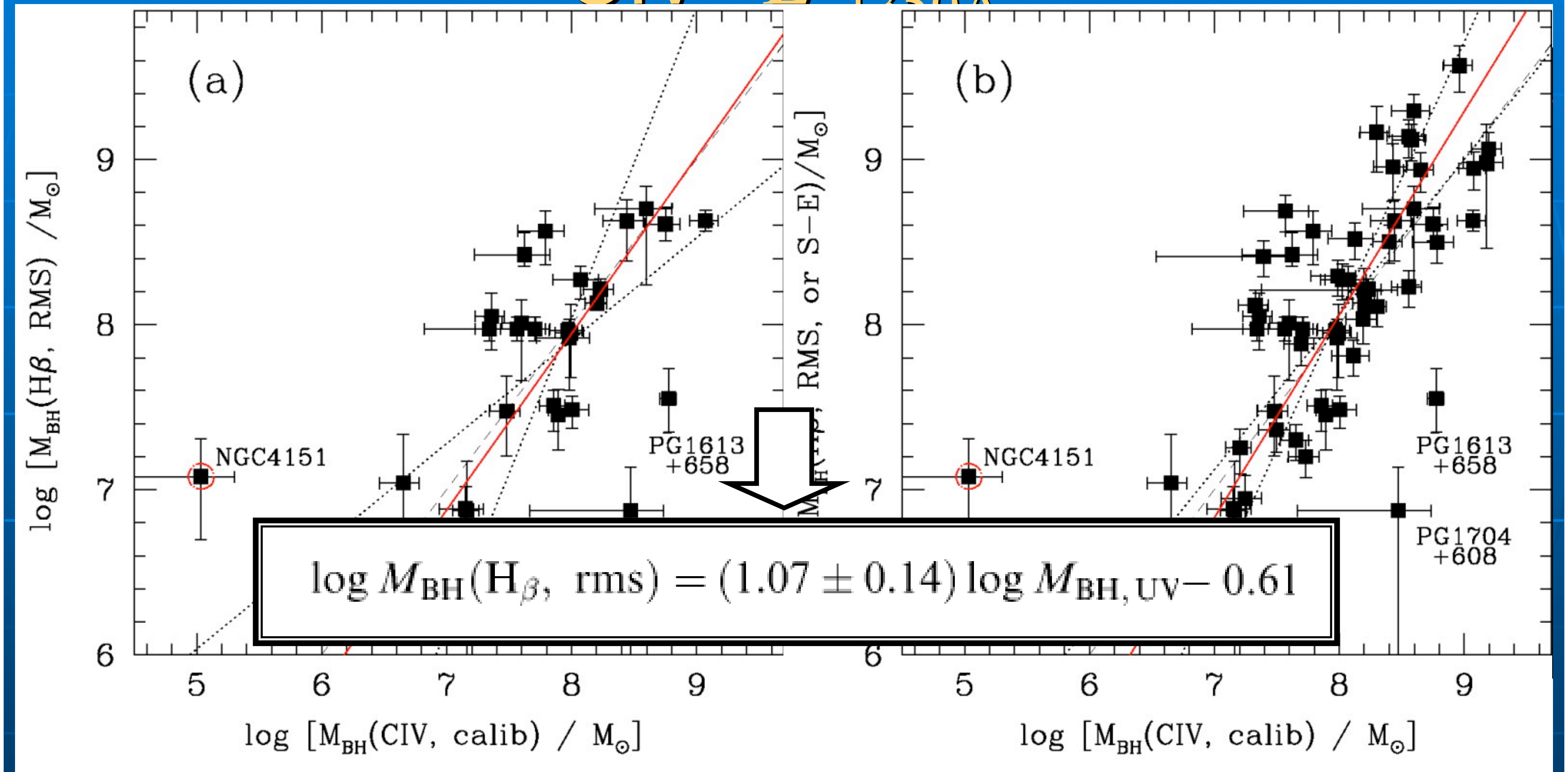
(H_0=70 km/s/Mpc; _ _ = 0.7)

How these relationships have been shaped?
H - $L_{5100Å}$



Vestergaard 2002, *ApJ* **571**:733

How these relationships have been shaped? CIV- $L_{1350Å}$

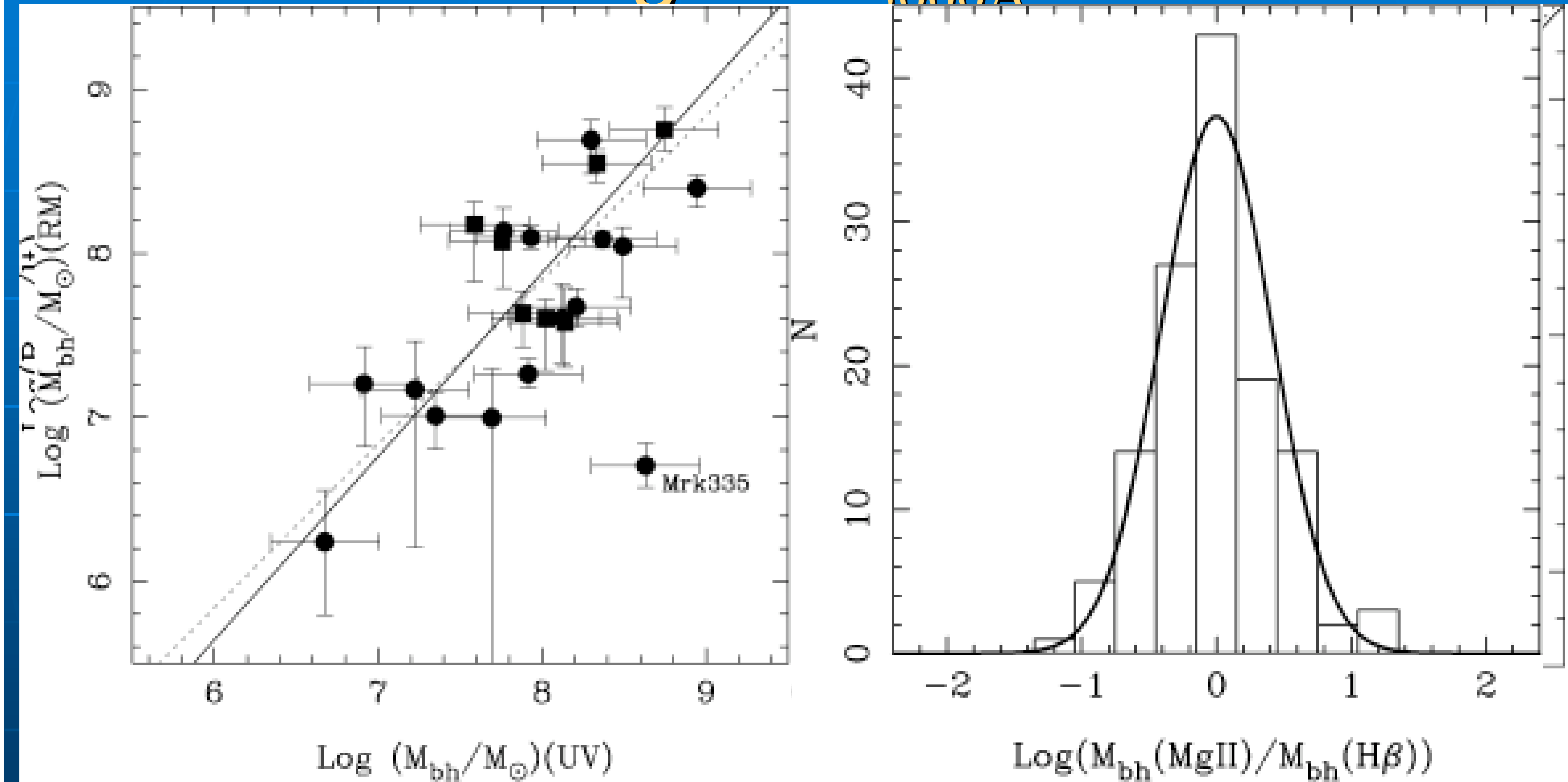


$$\log M_{\rm BH}(\mathrm{H}_\beta,\ \mathrm{rms}) = (1.07 \pm 0.14) \log M_{\rm BH,\,UV} - 0.61$$

indicating that the UV calibration is robust.

Vestergaard 2002, *ApJ* **571**:733

How these relationships have been shaped?
MgII- $L_{3000Å}$



McLure, & Jarvis *MNRAS* **337**,109

Black Hole Virial Masses: blind spots

- Many underlying assumptions:
  - Virial hypothesis
  - R_{BLR}-$L_{\_}$ relationship holds true for all L,z

Black Hole Virial Masses: blind spots

- Many underlying assumptions:
- They are secondary mass indicators:
  - SE measurements ≈ multi-epoch (RM) data
  - MgII & CIV FWHMs as proxies of H_ FWHM
  - Simple correlation between different *L*_

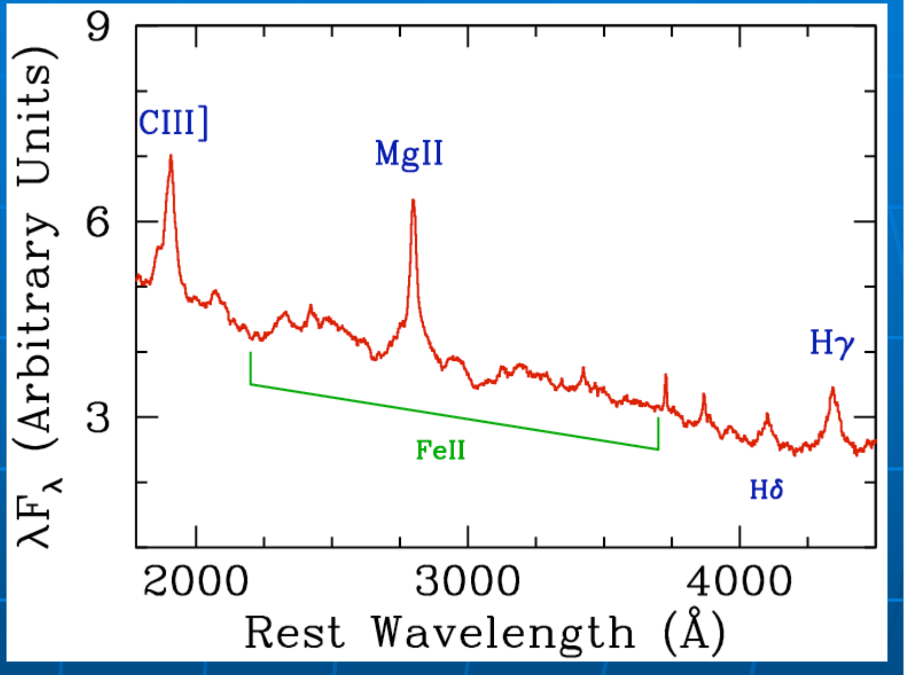
Black Hole Virial Masses: blind spots

- Many underlying assumptions:
- They are secondary mass indicators:
- Measurements errors and biases:
  - FWHM measurement difficulties:
    - Blending, NL subtraction
    - Noisy spectra
  - Continuum definition
    - Non-variable components (host galaxy, radio)

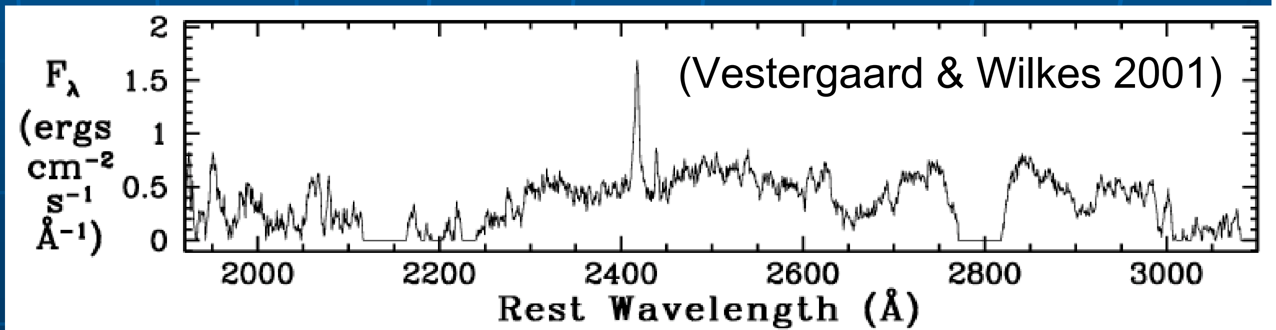
Using MgII for BLR velocity dispersion

- 0.8 _ z _ 1.3 range
- MgII and H_ have similar FWHMs
- Complications:

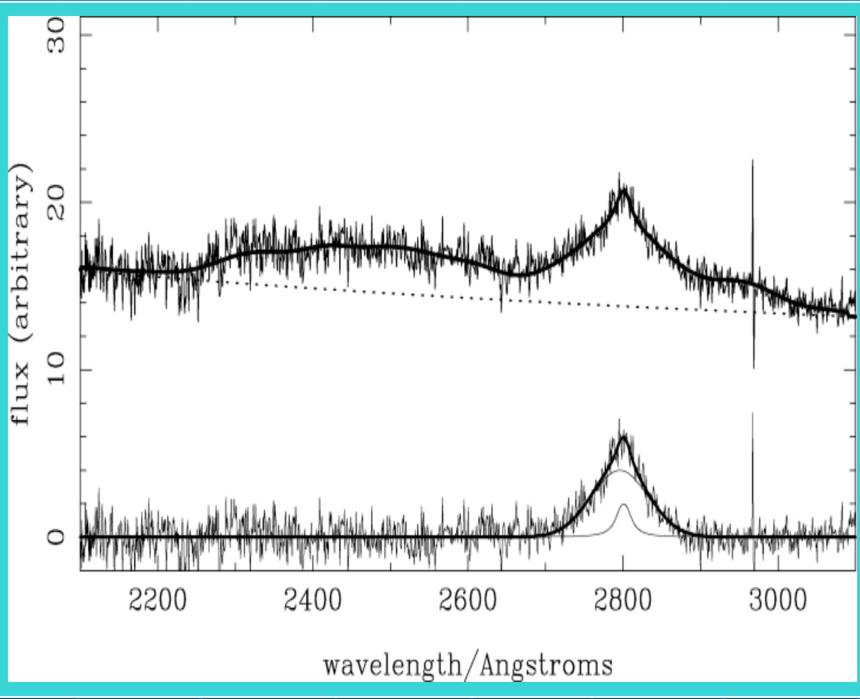
  FeII contamination of line and continuum

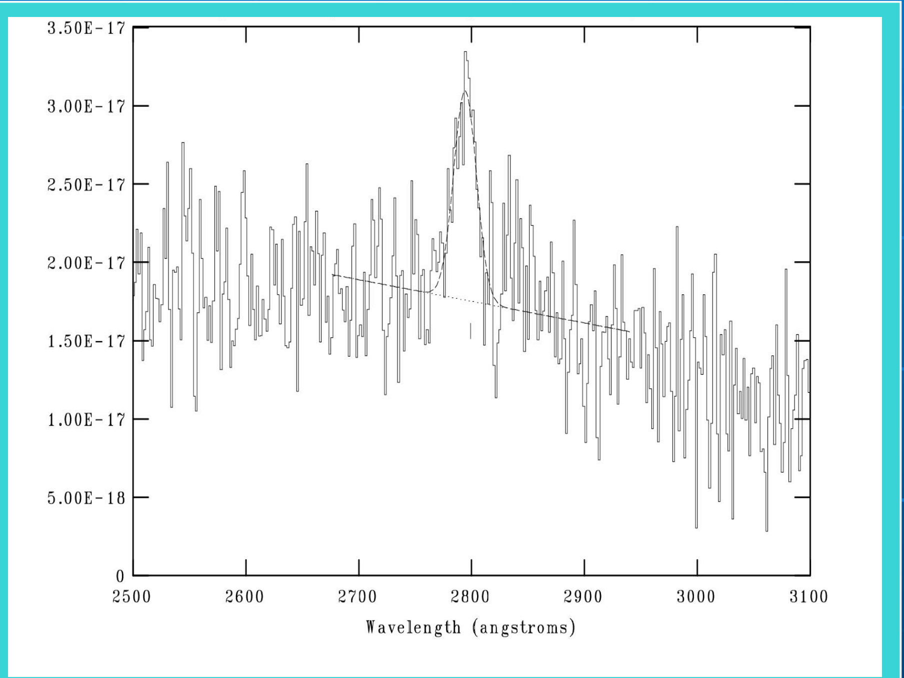


Requires template fitting



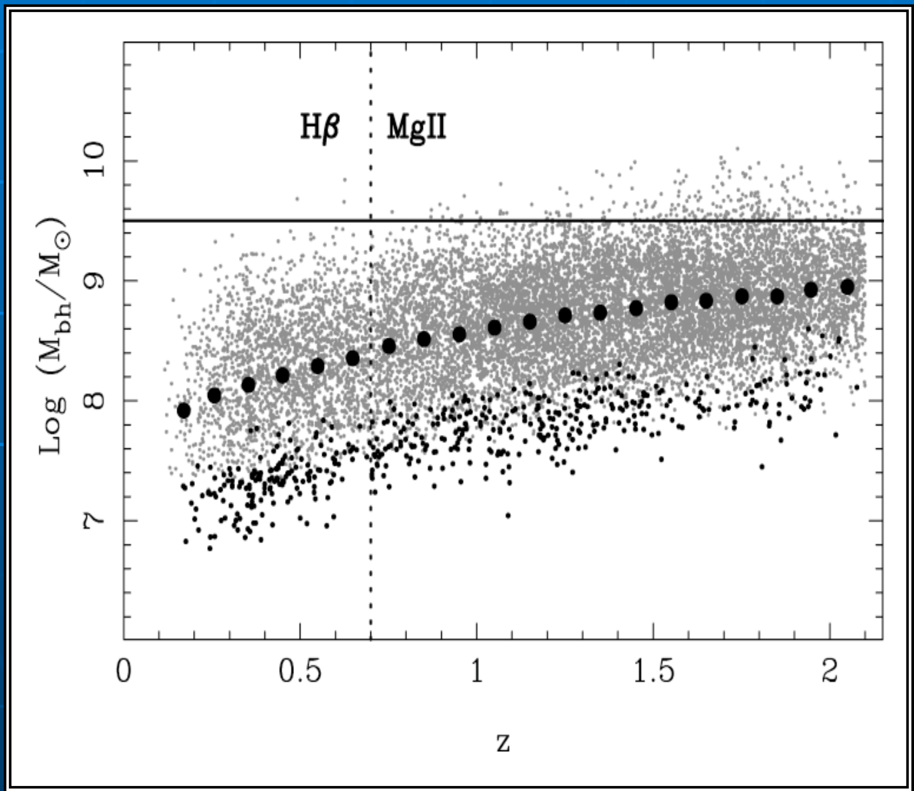
Measuring the broad MgII FWHM in real spectra

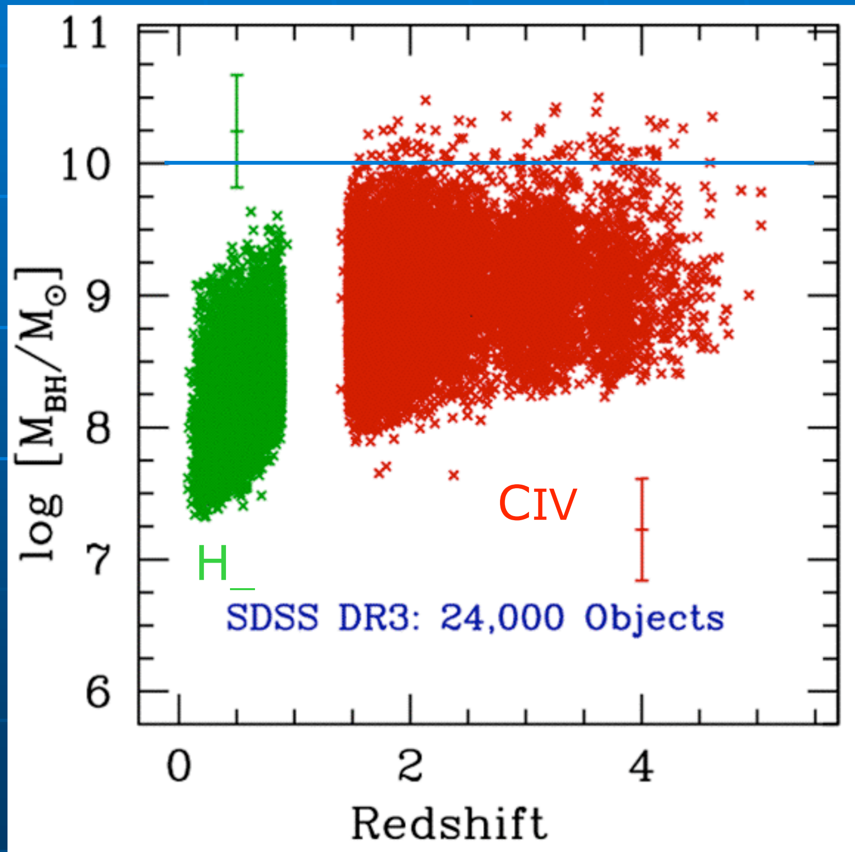




The prize: masses of distant QSOs

Easy measurements in huge quasar samples (LBQS, SDSS, 2dF…)
from the local Universe up to the highest redshifts (z=6.4)





BH Virial Masses: applications

- BH masses evolution
  - no evolution
  - limiting black hole mass
  - BH mass decrease at high z (?)
- Eddington ratio
  - No Super Edd. Accretion
- FINAL GOAL: Cosmological evolution of the BH mass function