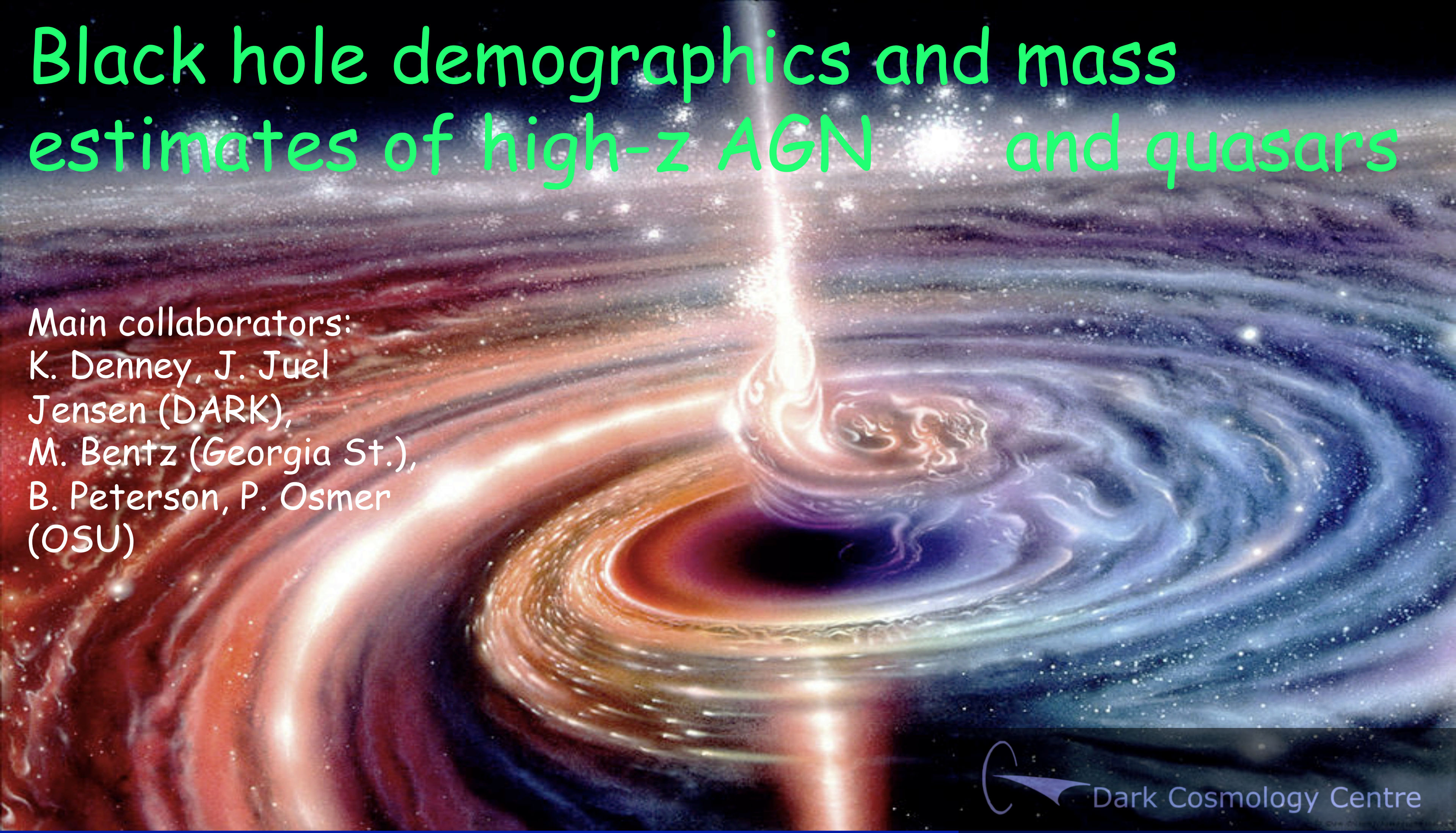
Black hole demographics and mass estimates of high-z AGN and quasars



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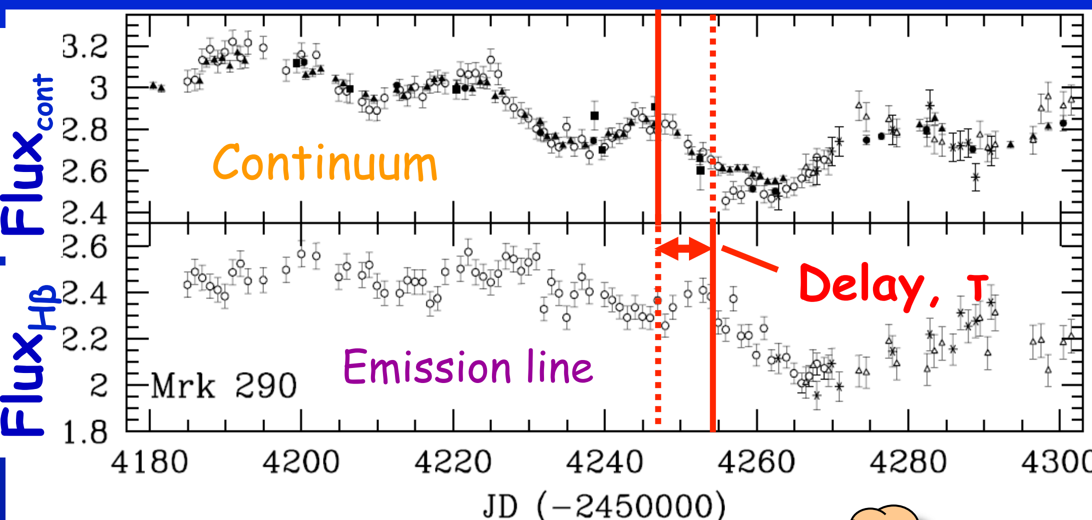
Dark Cosmology Centre, Copenhagen/Univ. of Arizona

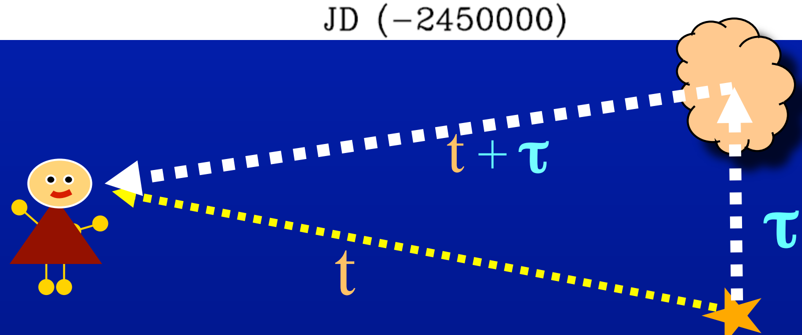
Massive Black Holes, KITP, August 8, 2013

AGN Virial Mass Estimates

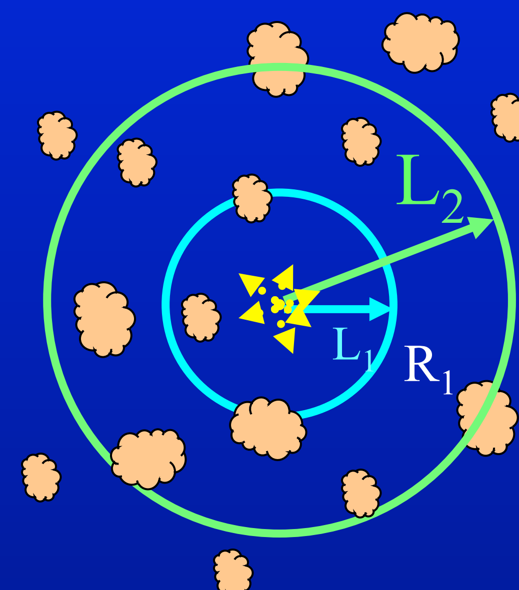
$$M_{BH} = v^2 R_{BLR}/G$$

- Variability Studies: $R_{BLR} = c\tau$





- Radius – Luminosity Relation:

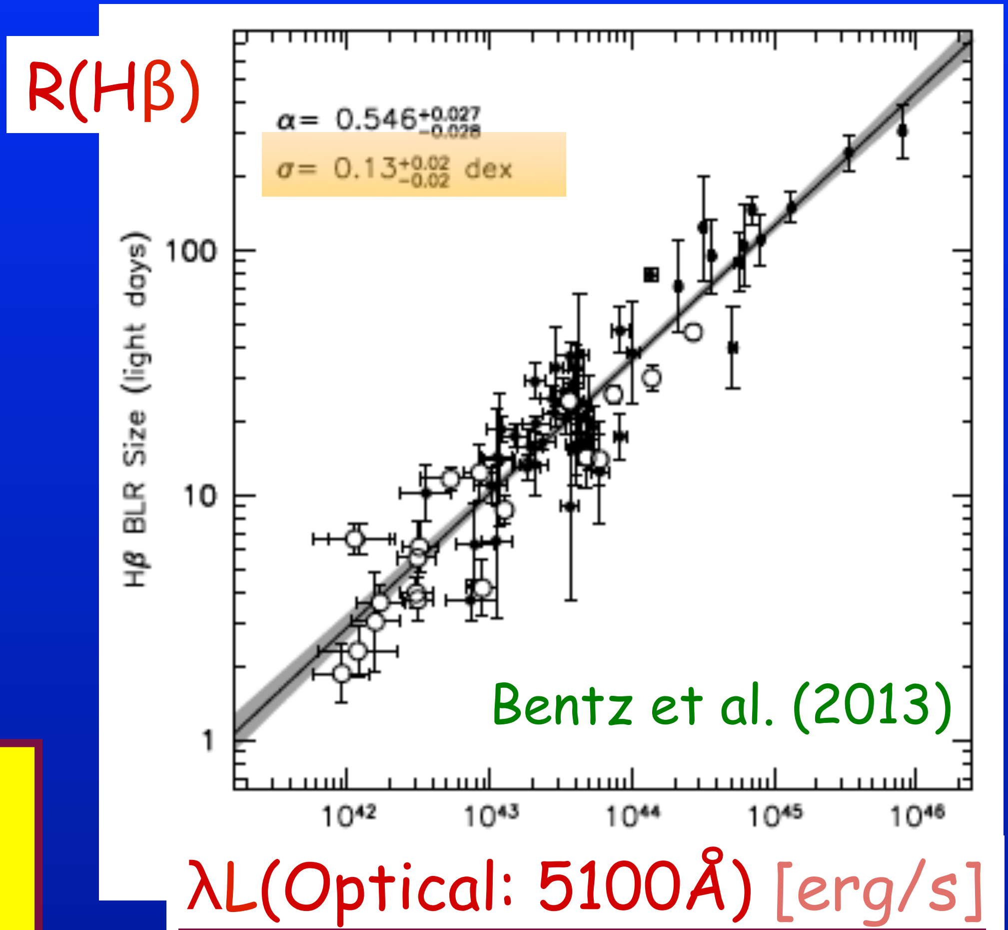


Radius – Luminosity Relation

Most recent update:

- Scatter low

- Velocity estimate is main limitation in mass uncertainty (los velocity only)



Relation allows an estimate of BH mass based on a single spectrum

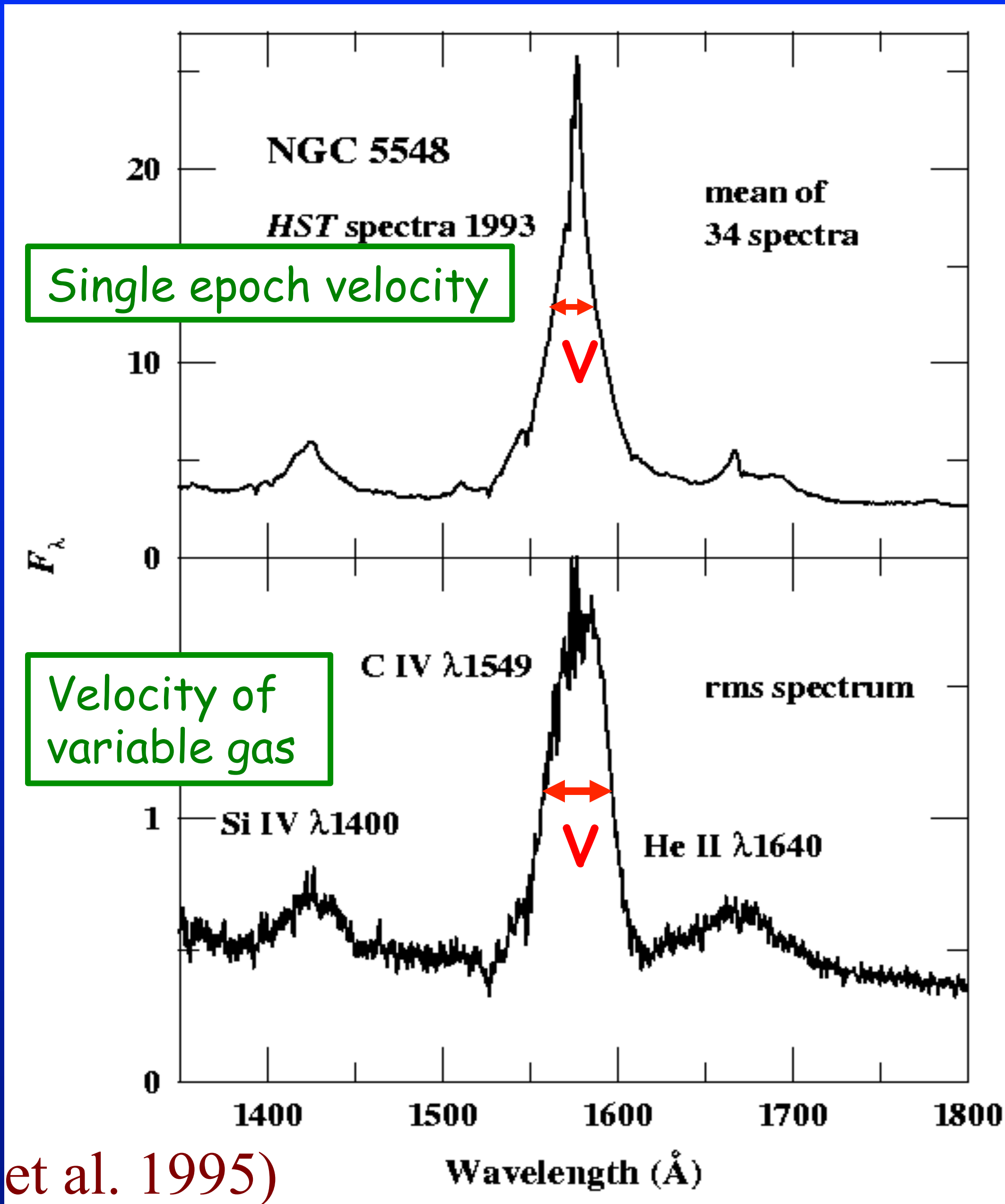
…provides a measure of R for Hβ

Velocity Dispersion of the Broad Line Region and the Virial Mass

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

f depends on structure, geometry, and inclination of broad line region

1σ absolute uncertainty relative to M-σ relation: factor ~3-4



(based on Korista et al. 1995)

Scaling Relationships on same mass scale:

and calibrated to 2004 reverberation masses

- Hβ:

$$M_{BH} = 8.3 \cdot 10^6 \left(\frac{\mathrm{FWHM(H\,\beta)}}{10^3\,\mathrm{km/s}} \right)^2 \left(\frac{\lambda L_\lambda(5100\mathrm{A})}{10^{44}\,\mathrm{ergs/s}} \right)^{0.50} M_\odot$$

- MgII:

$$M_{BH} = 6.2 \cdot 10^6 \left(\frac{\mathrm{FWHM(MgII)}}{10^3\,\mathrm{km/s}} \right)^2 \left(\frac{\lambda L_\lambda(2100\mathrm{A})}{10^{44}\,\mathrm{ergs/s}} \right)^{0.50} M_\odot$$

- CIV:

$$M_{BH} = 4.5 \cdot 10^6 \left(\frac{\mathrm{FWHM(CIV)}}{10^3\,\mathrm{km/s}} \right)^2 \left(\frac{\lambda L_\lambda(1350\mathrm{A})}{10^{44}\,\mathrm{ergs/s}} \right)^{0.53} M_\odot$$

(MV 02; MV & Peterson 06; MV & Osmer 09)

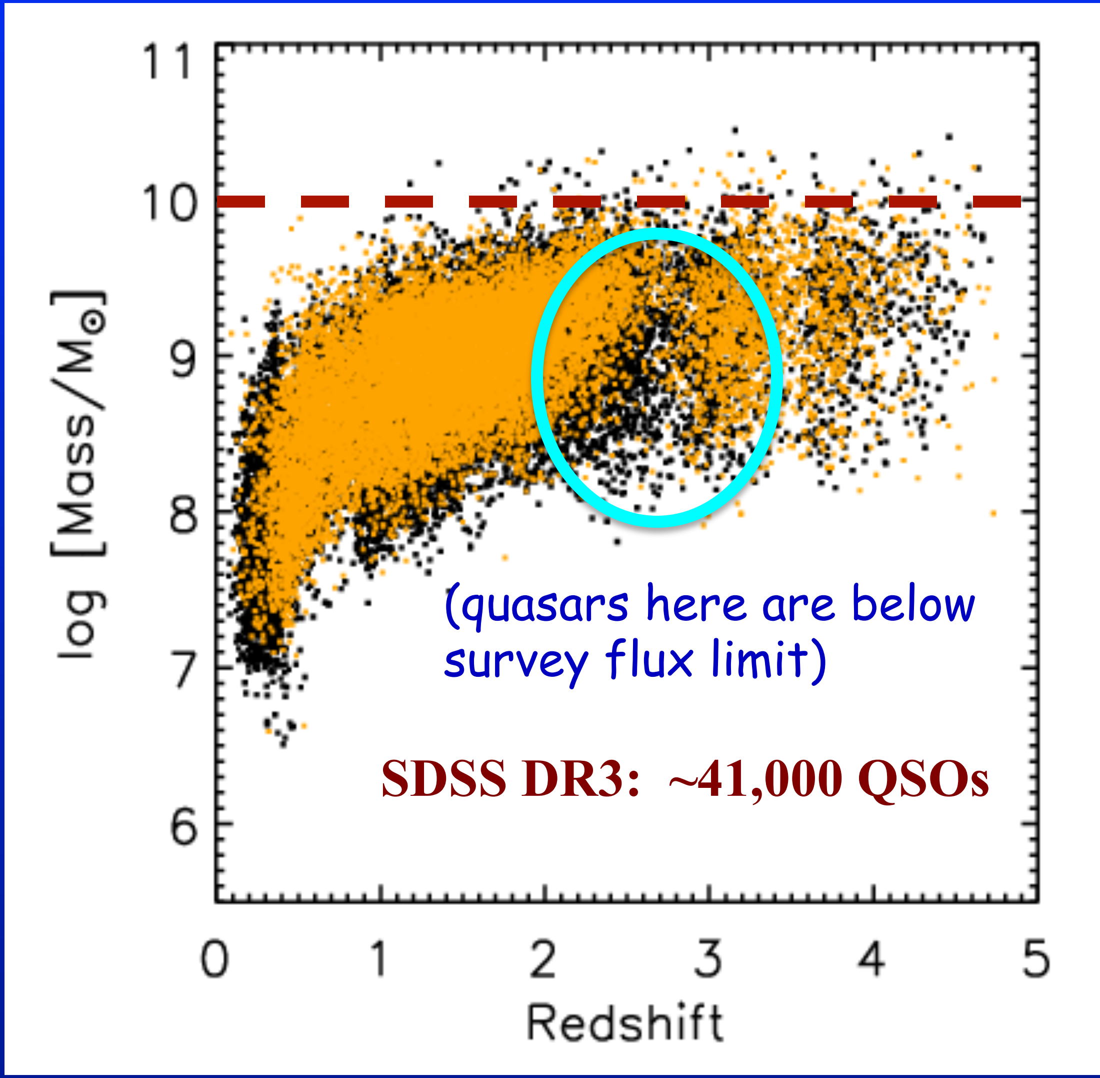
1σ absolute uncertainty: factor ~3.5 – 4

Note: Many relations exist - not all are on same mass scale
(e.g. Runnoe+2013; Park+ 2013; Tilton & Shull 2013; McGill+ 2008)

Masses of Distant Quasars

Distant active black holes are very massive:
M_{BH}: $10^8 - 10^{10}\ M_\odot$
and very luminous:
L_{BOL}: $10^{38} - 10^{41}$ W
$= 10^{45} - 10^{48}$ erg/s

- $M_{BH} \approx 10^9\ M_\odot$ - even beyond space density drop at $z \approx 3$



(DR3 Qcat: Schneider et al. 2005)

(MV + 2008; MV et al. in prep)

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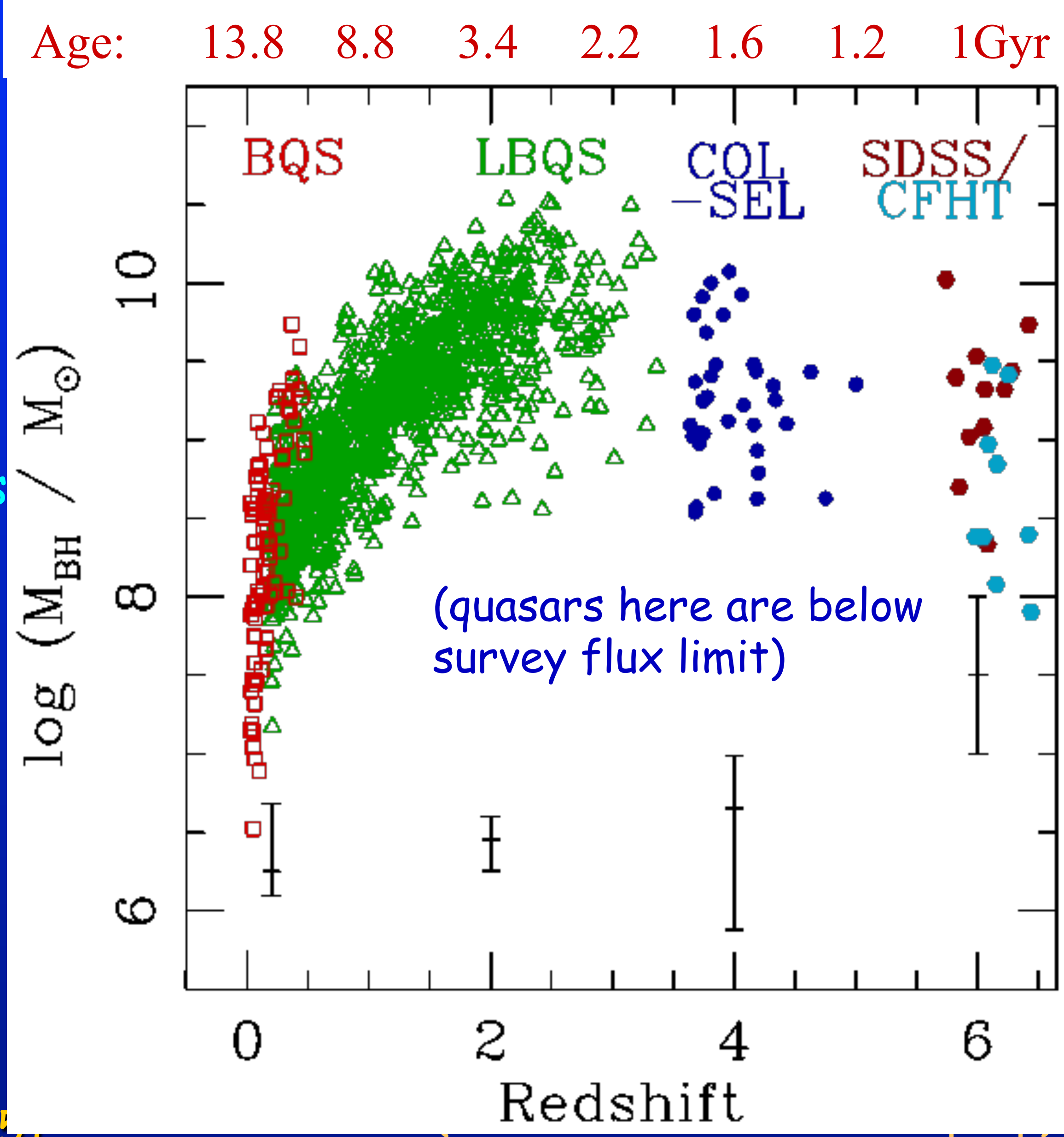
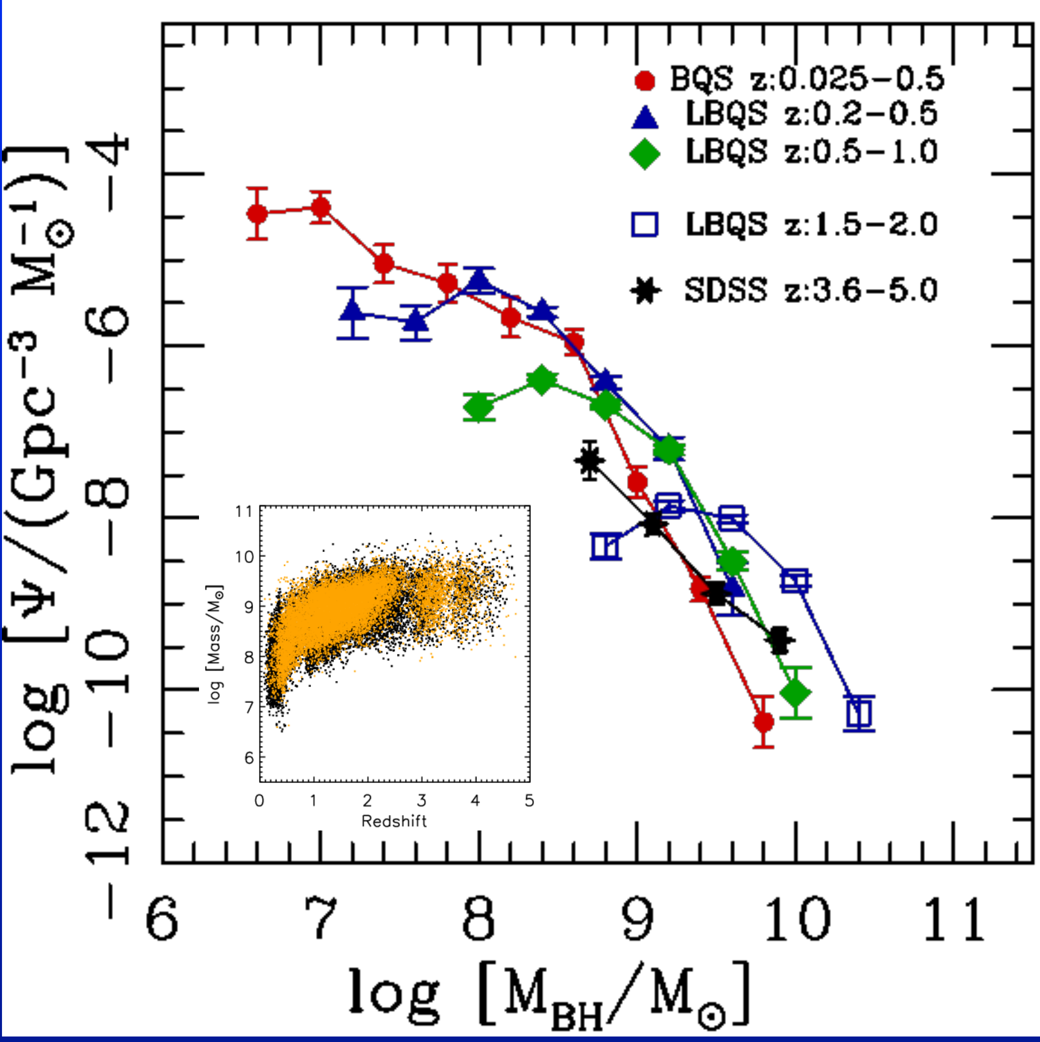


(DR3 Qcat: Schneider et al. 2005)

Mass Functions of Active Supermassive Black Holes

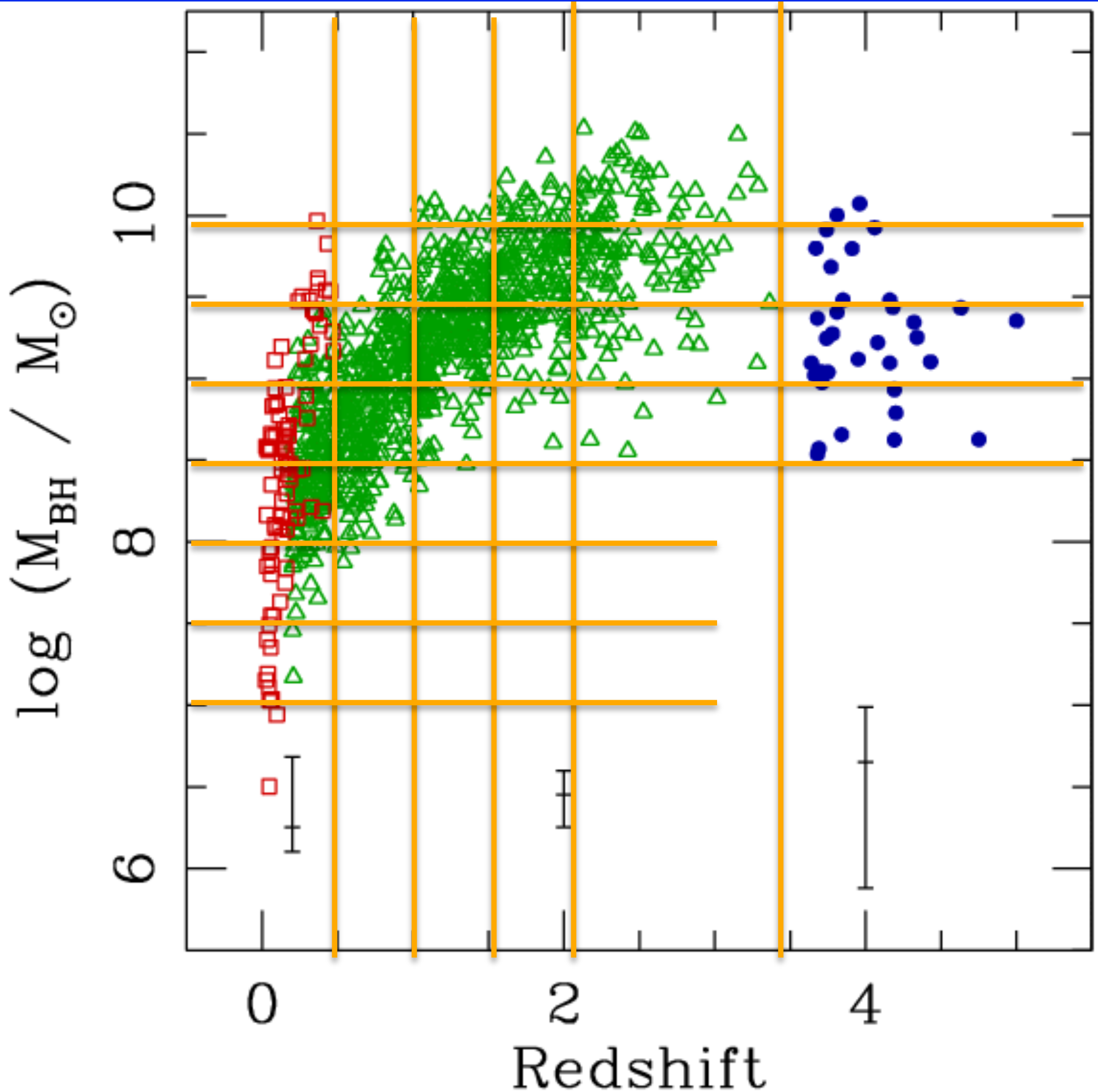
- MF = space density of BHs as function of both mass and redshift.
- What can each representation tell us?
- Rapid growth of black hole population between 1.6 Gyr and 3.3 Gyr

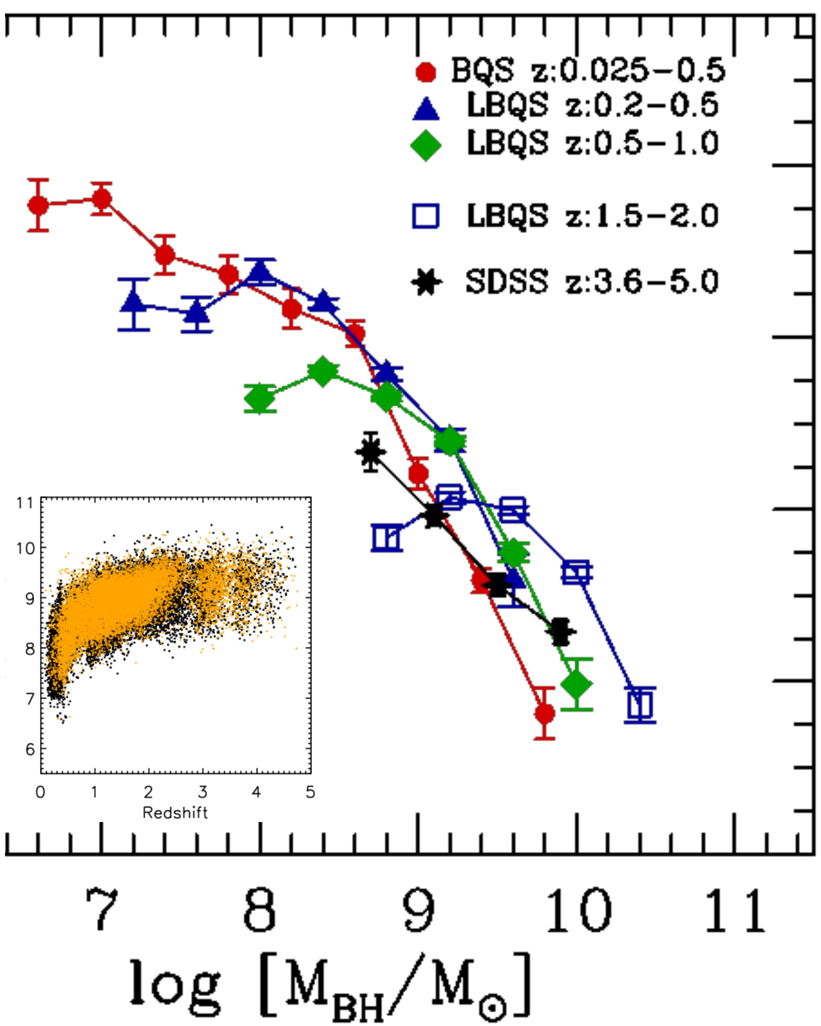


(Vestergaard & Osmer 2009)

- BQS: 10 700 sq. deg; B≤16.16^{mag}
- LBQS: 454 sq. deg; 16.0≤B_J≤18.85^{mag}
- SDSS: 182 sq. deg; i^* ≤20^{mag}

Mass Functions of Active Supermassive Black Holes

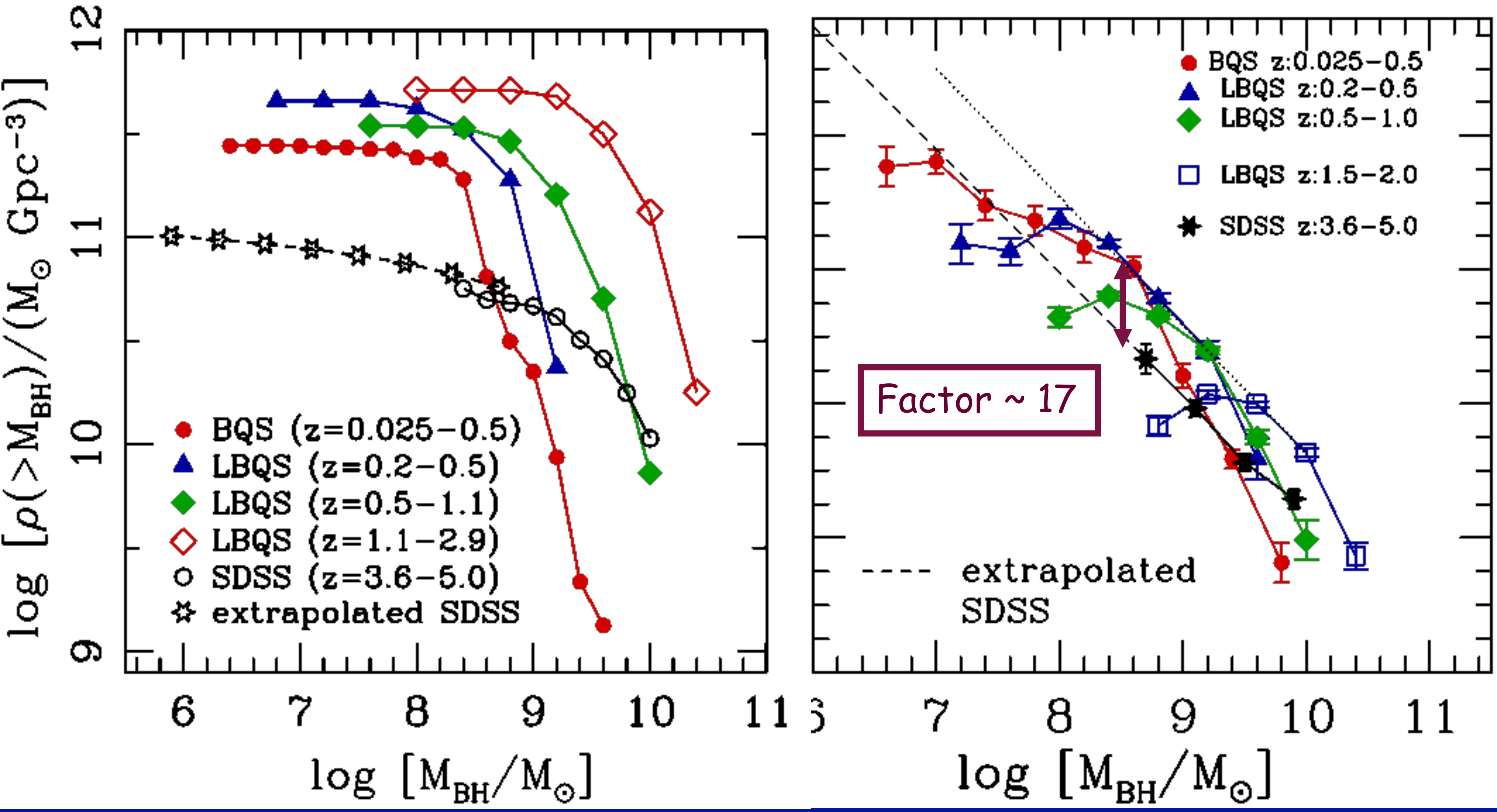




(Vestergaard & Osmer 2009)

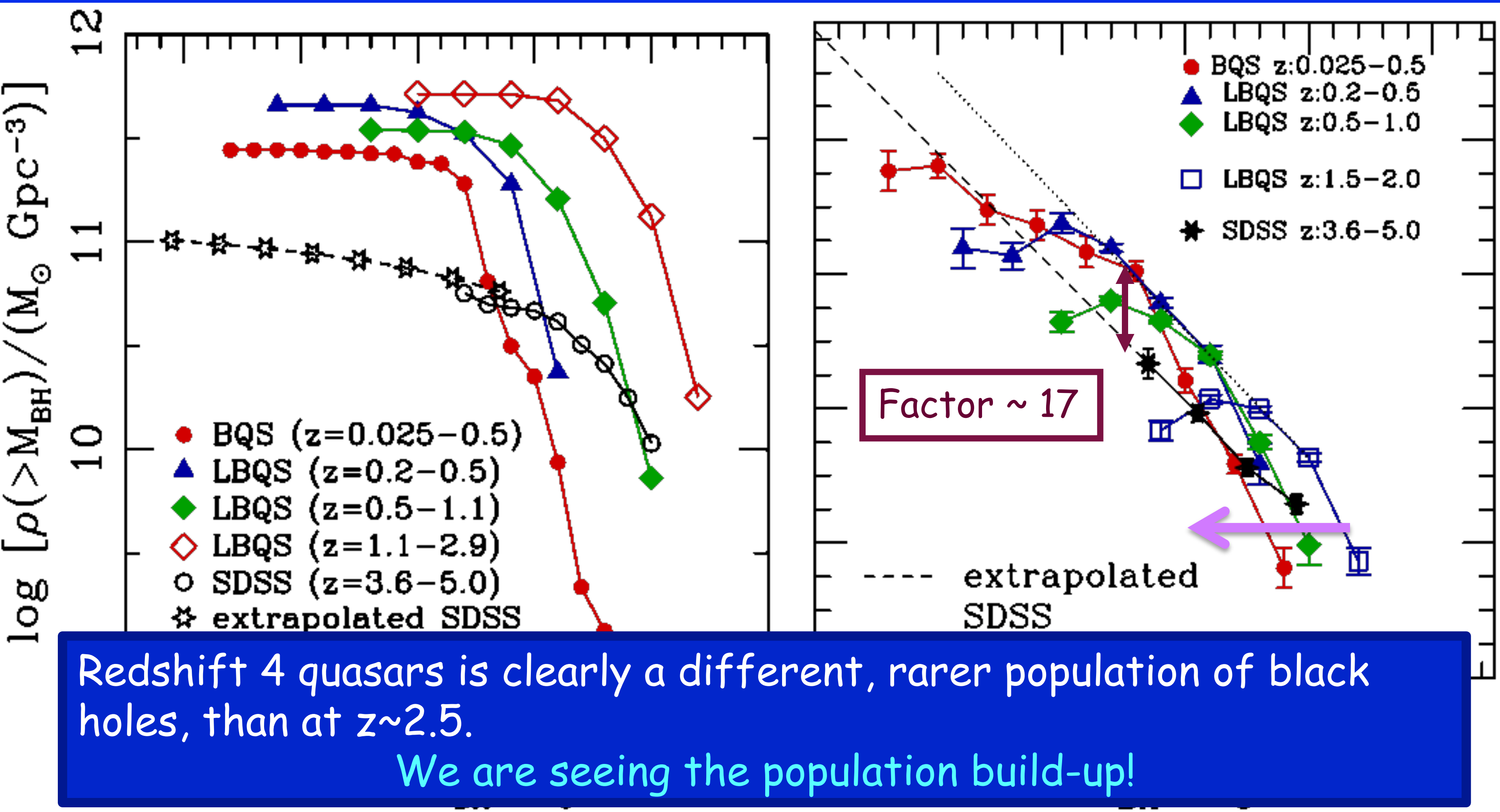
• SDSS: 182 sq. deg; $i^* \leq 20^{mag}$

Mass Functions of Active Supermassive Black Holes



(H_0=70 km/s/Mpc; $\Omega_\Lambda = 0.7$) (Vestergaard & Osmer 2009)

Mass Functions of Active Supermassive Black Holes



Redshift 4 quasars is clearly a different, rarer population of black holes, than at z~2.5.

We are seeing the population build-up!

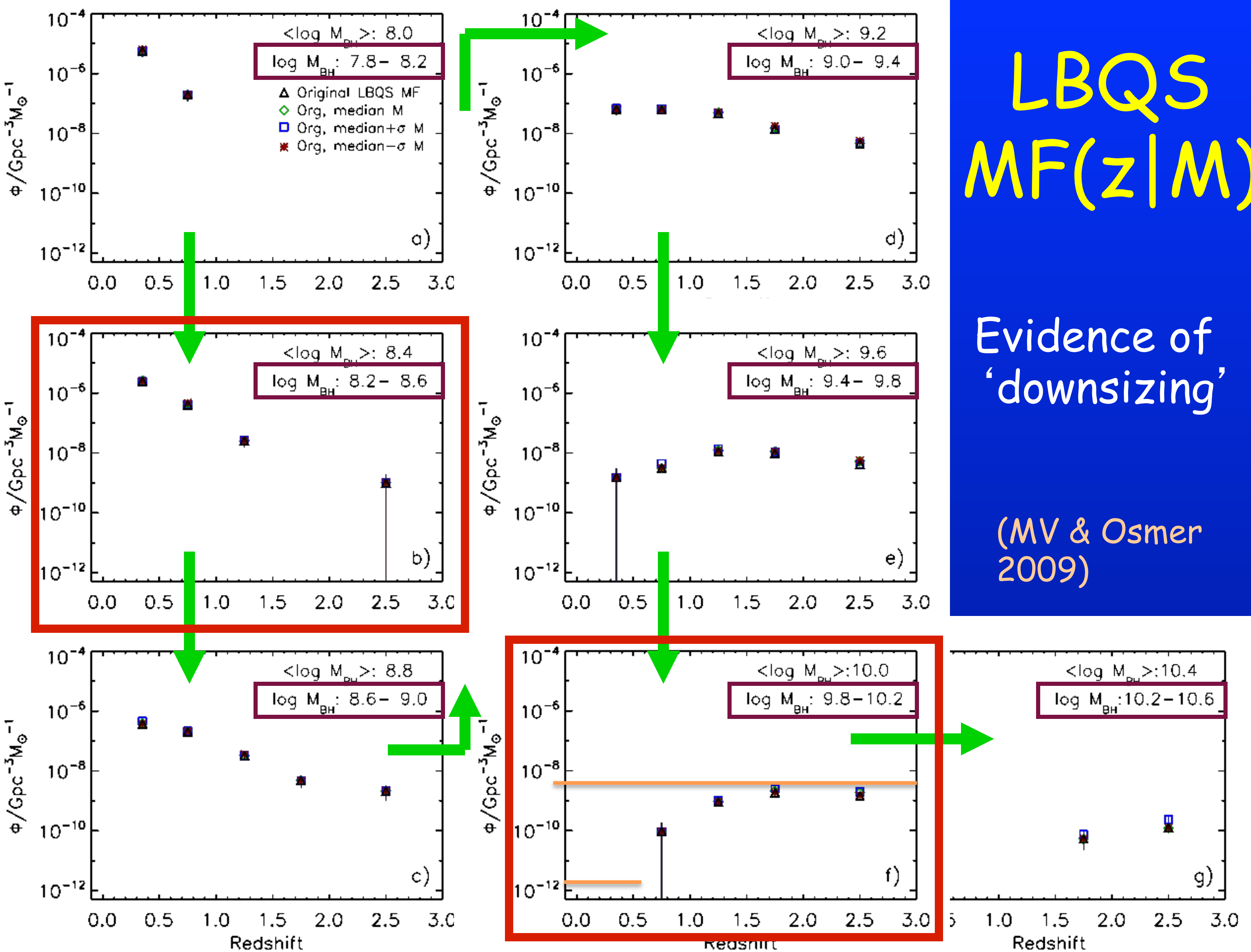
(H_0=70 km/s/Mpc; Ω_Λ = 0.7)

(Vestergaard & Osmer 2009)

LBQS MF(z|M)

Evidence of ‘downsizing’

(MV & Osmer 2009)



Masses of Distant Quasars

Distant active black holes are very massive:
M_{BH}: 10^9 – 10^{10} $M_\odot$

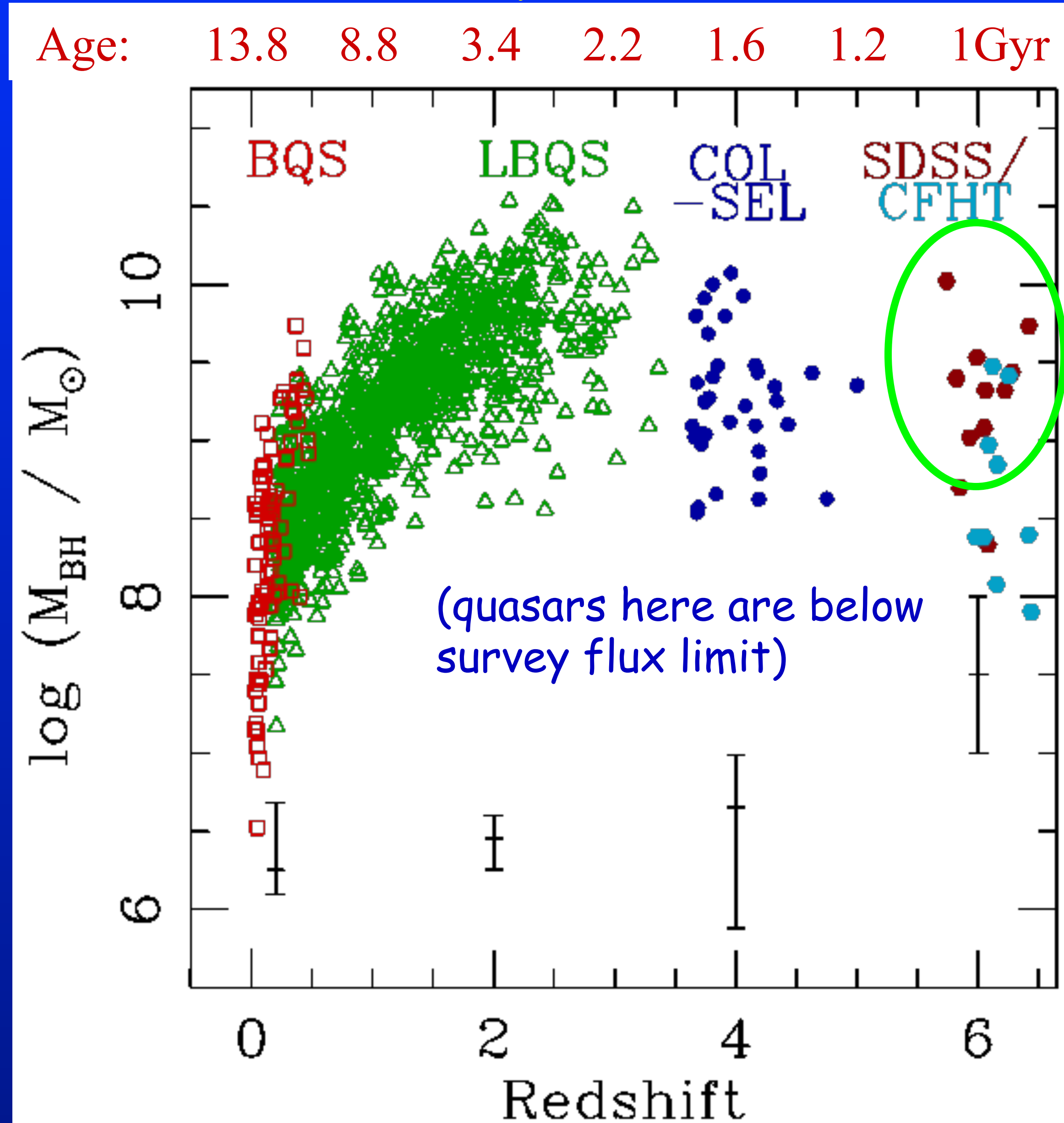
- Probably too massive!

(Priya Natarayan talk Monday)

- Mass function likely too shallow @hi-end

(Brandon Kelly's Talk today)

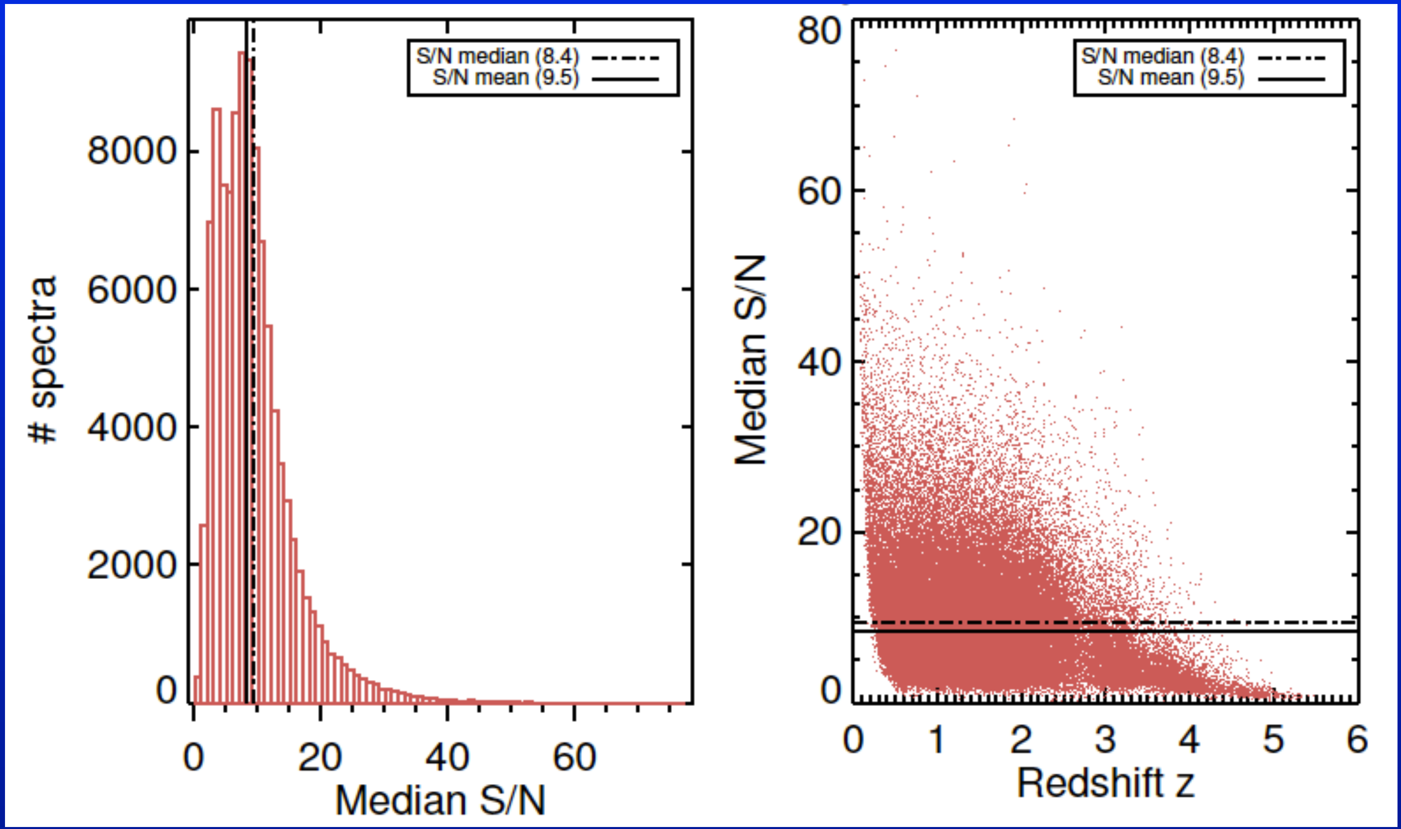
- M_{BH} error: factor ~5



Uncertainties in Mass Estimates

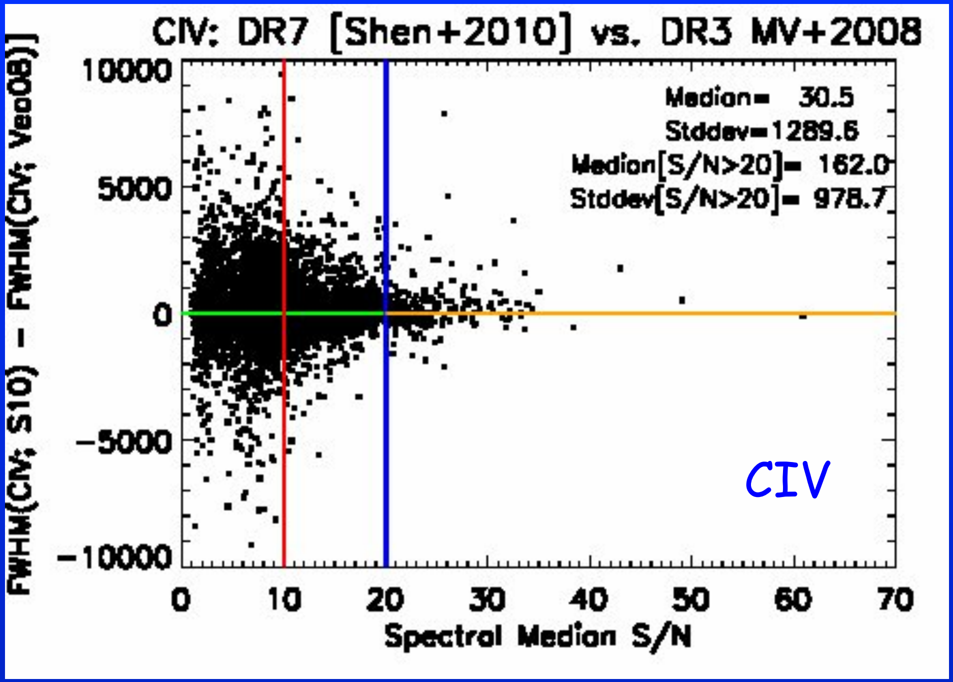
Be Aware:

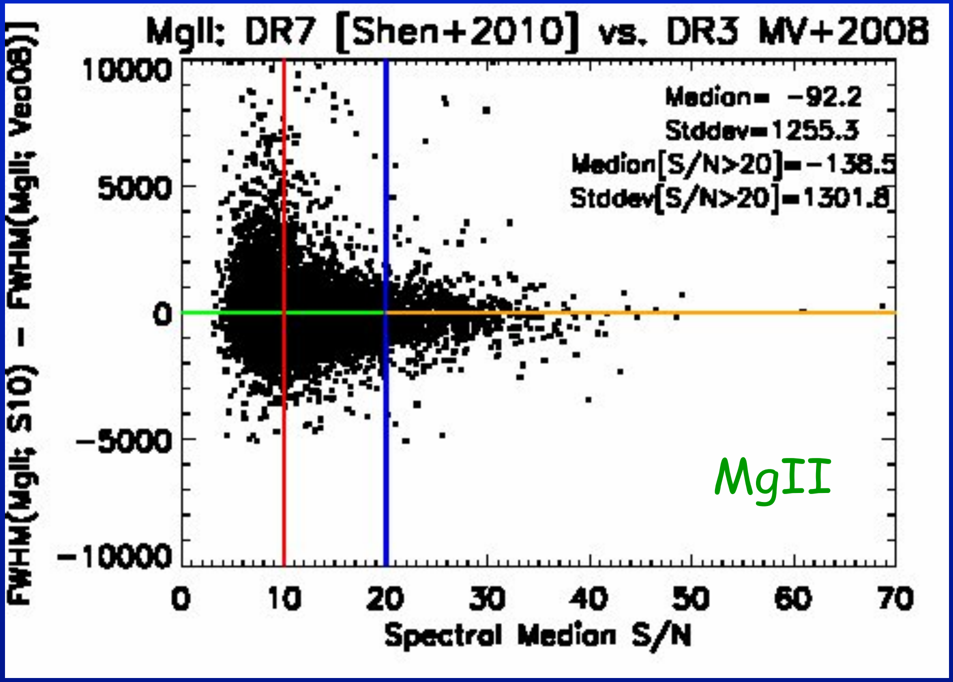
- Data Quality Matters (Denney+ 09; MV+ 11; Denney+ 13)
- Line Width Parameter Matters: FWHM vs line dispersion

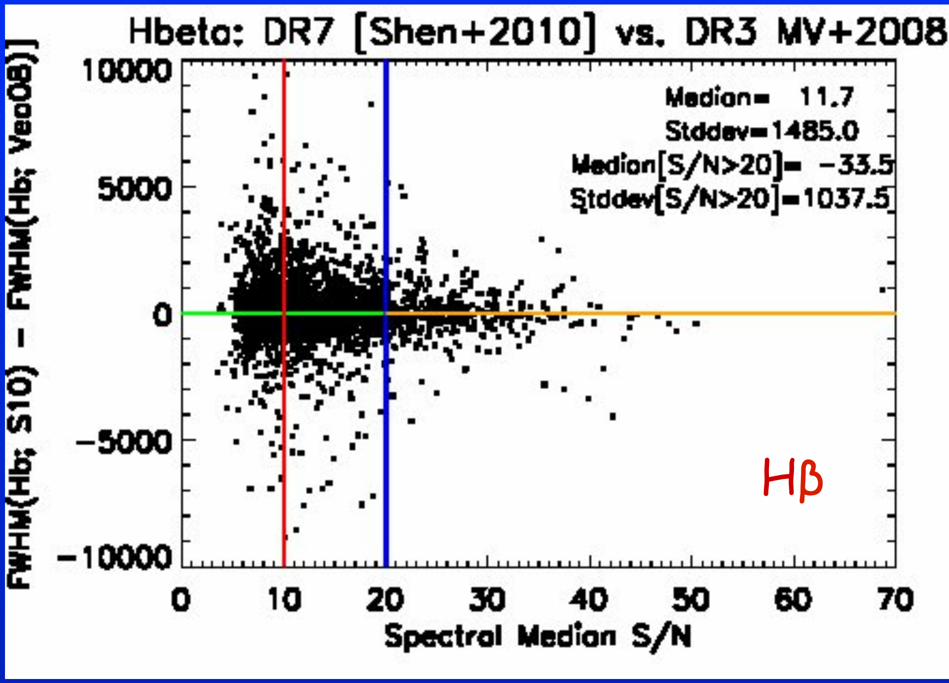


Median S/N of SDSS DR7 QSO Catalog = 8.4 !!!

S/N Matters!







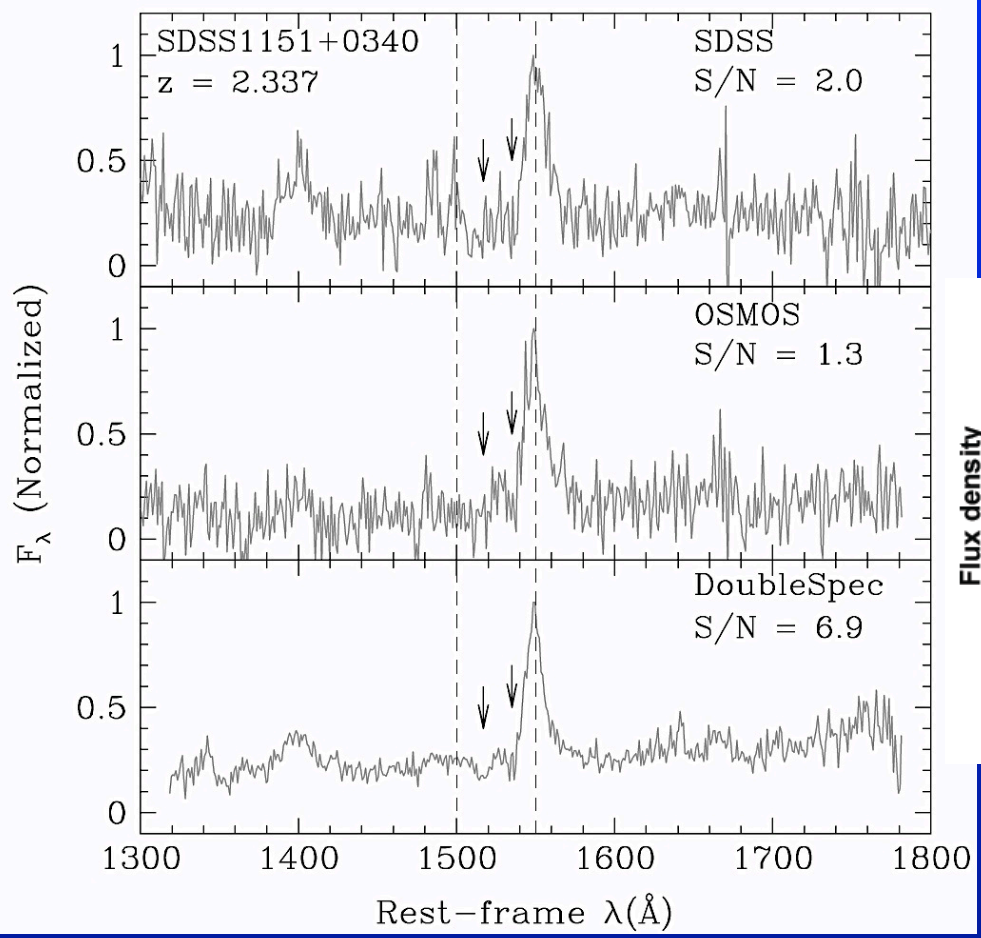
Comparing FWHM measured on same data by two groups/methods

So does the measurement approach!

(fitting to the data doesn't help)

Dark Cosmology Centre

Undetected Absorption skews the width measurements



Absorption can easily go unrecognized – biasing the line widths measured !

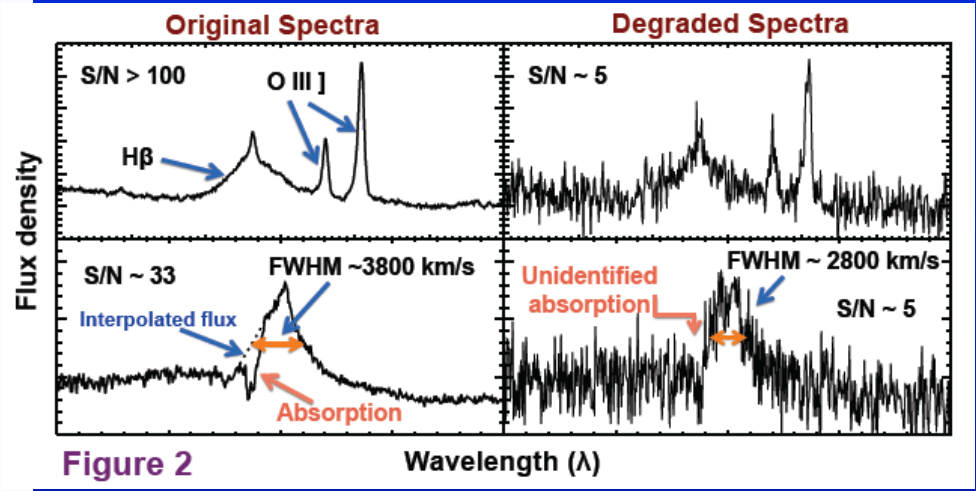
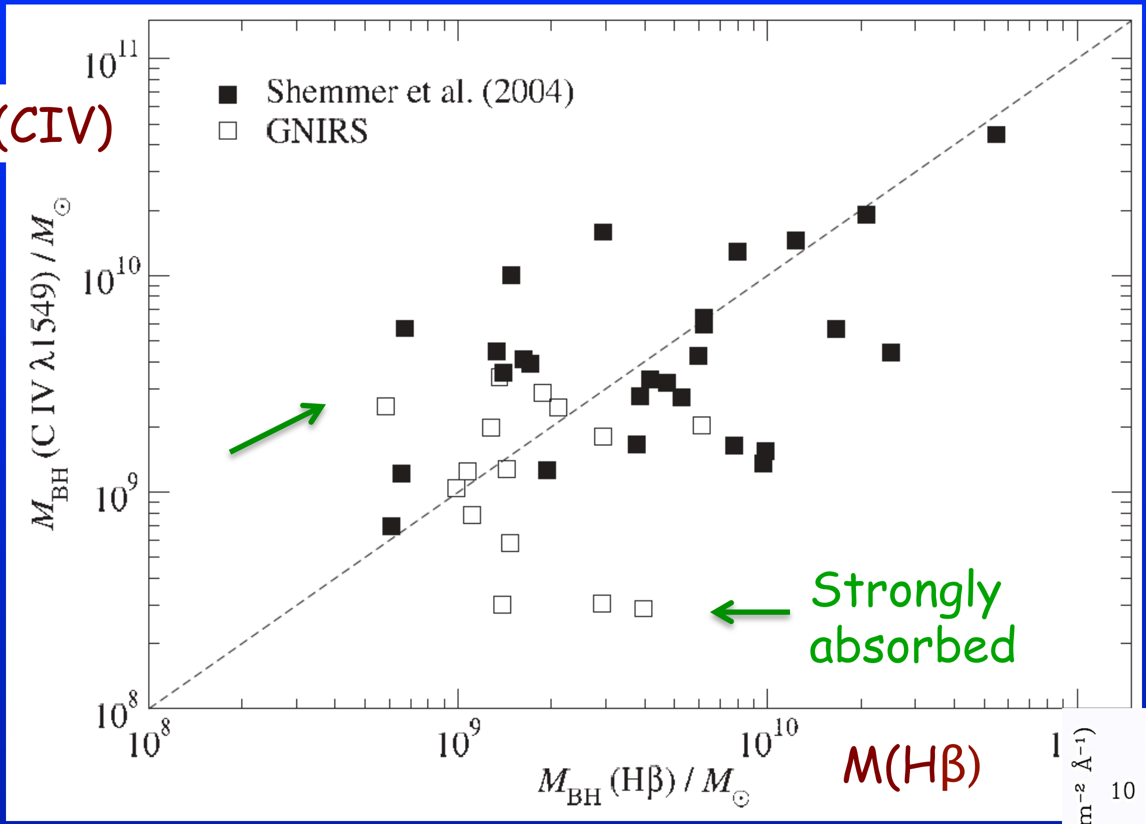


Figure 2

(MV test)

Assef + 2011

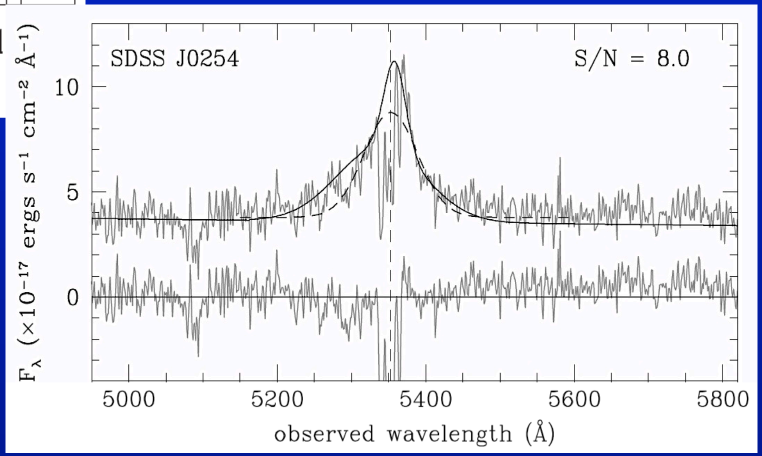
Low data quality yields inconsistent masses



- SDSS UV (CIV)
- Gemini IR (Hβ)
- NON-simult. data

Survey data prone to low S/N and undetected absorption

(Netzer + 2007)



Absorption can yield both a too high and too low FWHM value depending on location on profile

Denney et al. (2013)

Summary

M_{BH} determinations:

- Reverberation mapping (z~0) and scaling relations (z>0)

M_{BH} estimates – issues to be aware of:

- Use multiple broad emission lines for better M_{BH} estimates
  - No broad line is ideal, each have issues: e.g., blending, absorption, blueshift
  - Use scaling relations on same mass scale
- Statistical uncertainty in single-epoch M_{BH} estimates: factor 4-5
- Poor data quality and intervening absorption worsen accuracy
- Line width measures: FWHM more sensitive to spectral noise; line dispersion sensitive to line blending
- We are working on improving mass estimates through spectral measurements and Velocity-Delay Maps for RM. Stay tuned.

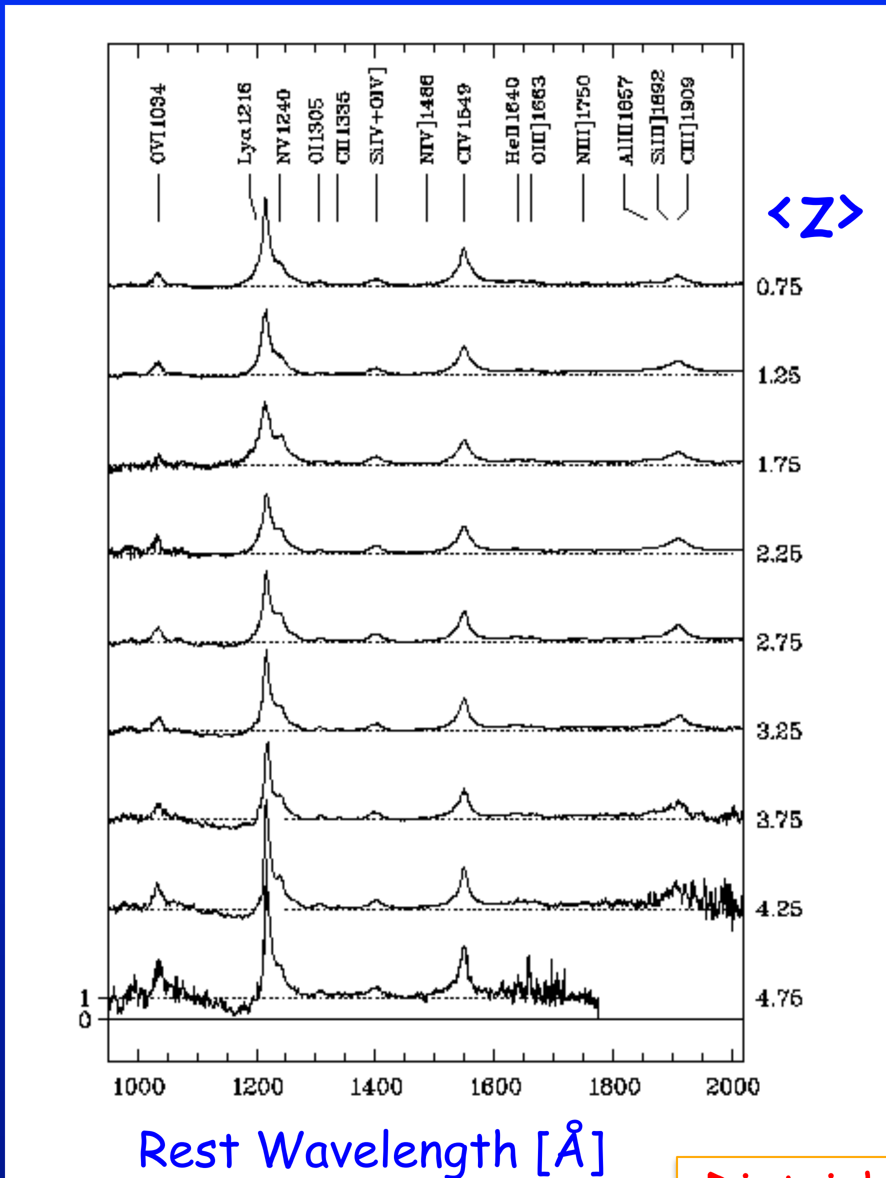
BH Demographics:

- Rapid growth from z~4 to z~2.5: factor 17 in space density
- Observe 'down-sizing' of BHs in MFs
- High-mass end known to be too shallow - high masses overestimated

Dark Cosmology Centre

Can mass estimates be off by a factor ~10 or more?

Radius - Luminosity Relations



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
- Same density

i.e., $R \sim L^{1/2}$

Dietrich et al. 2002

Radius-UV Luminosity Relationship for High-z Quasars

Full argument in MV (2004)

$$M = V_{FWHM}^2 \, R_{BLR}/G$$

↑ ↑ ↓

$0.1 \cdot 10^9 \, M_\odot$ 4500km/s 33 lt-days

1. Assume M is really 1/10th of measured value

2. Adopt the *average* CIV line width of <L> ~10^{47} erg/s quasars

3. We get an R, short for QSOs, but OK for Seyferts… and R => Φ

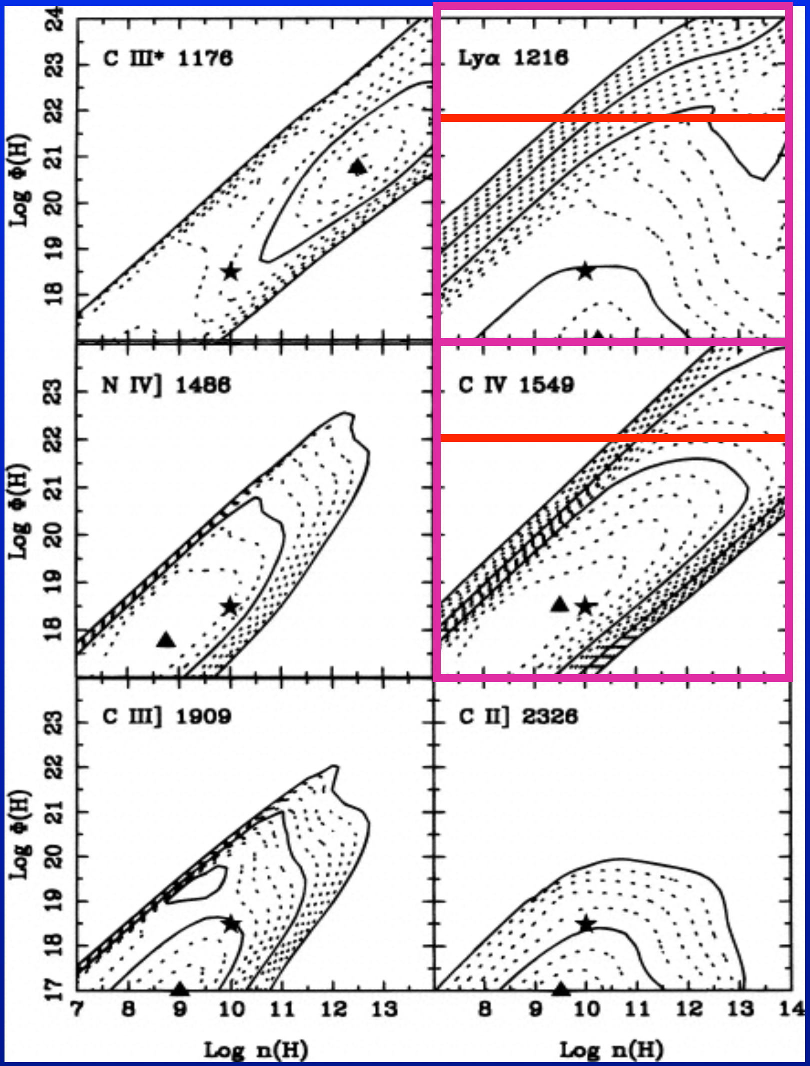
$$\Phi \propto R_{BLR}^{-2} \, L$$

$$\langle L \rangle \approx 10^{47} \text{ ergs/s}$$

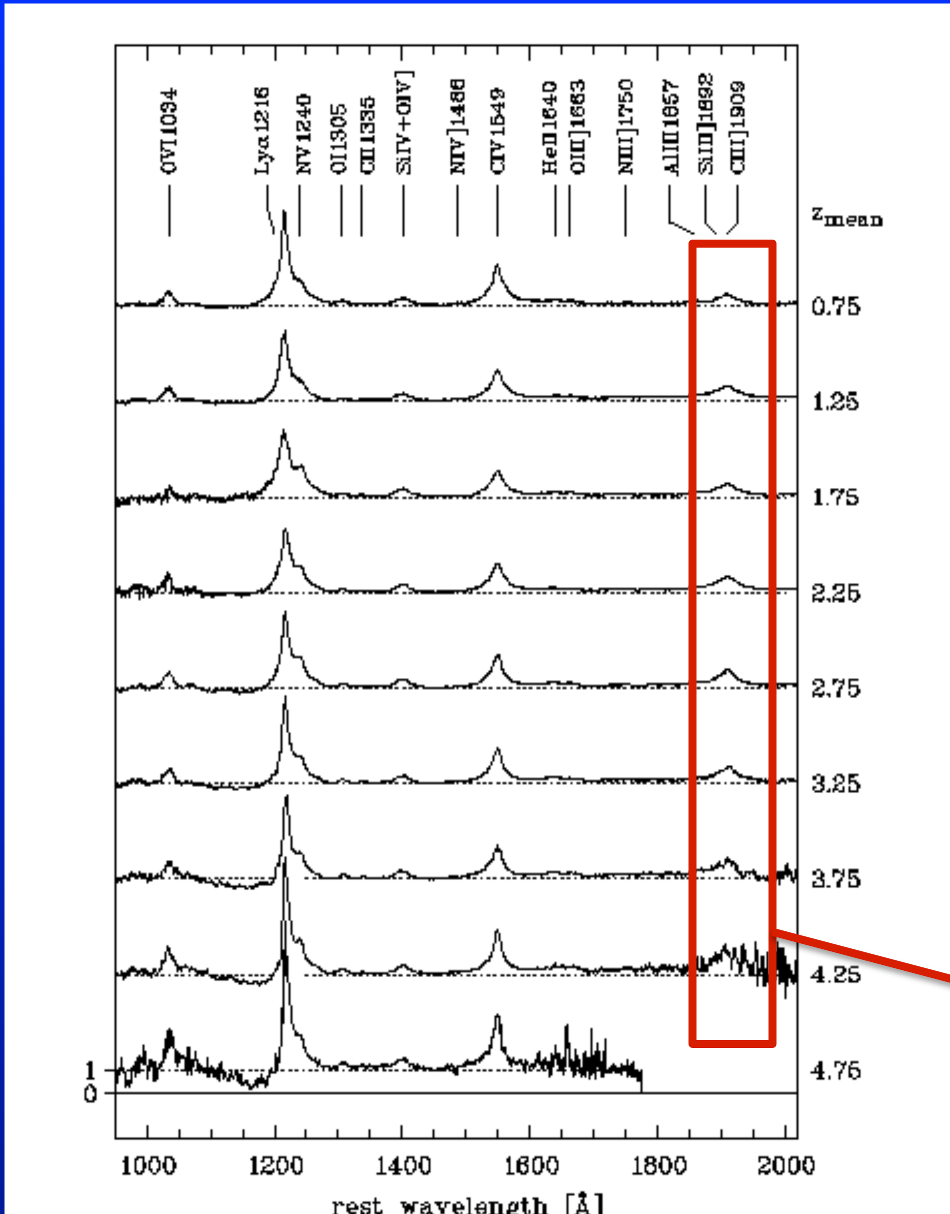
Log Φ ↑

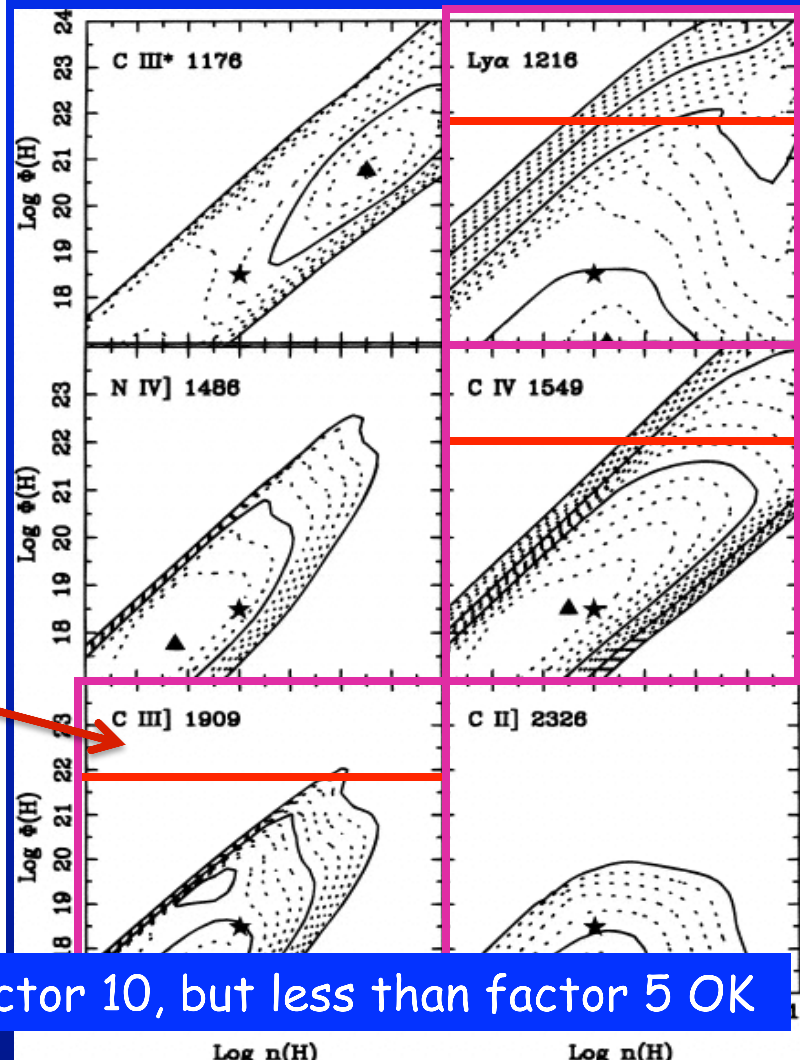
Log n(H) →

(Korista et al. 1997)



Luminosity High-z Quasars

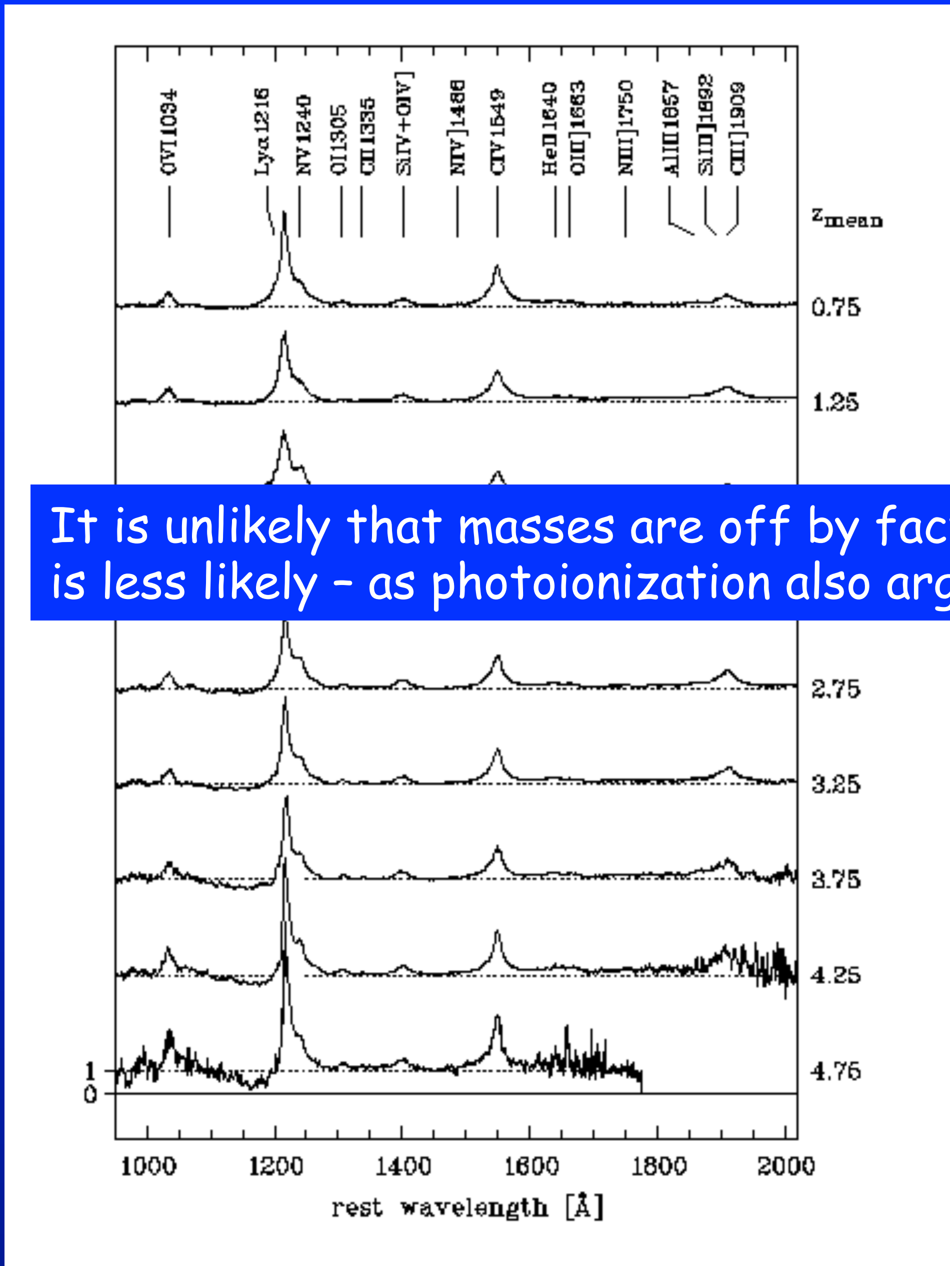




So it is unlikely that masses are off by factor 10, but less than factor 5 OK

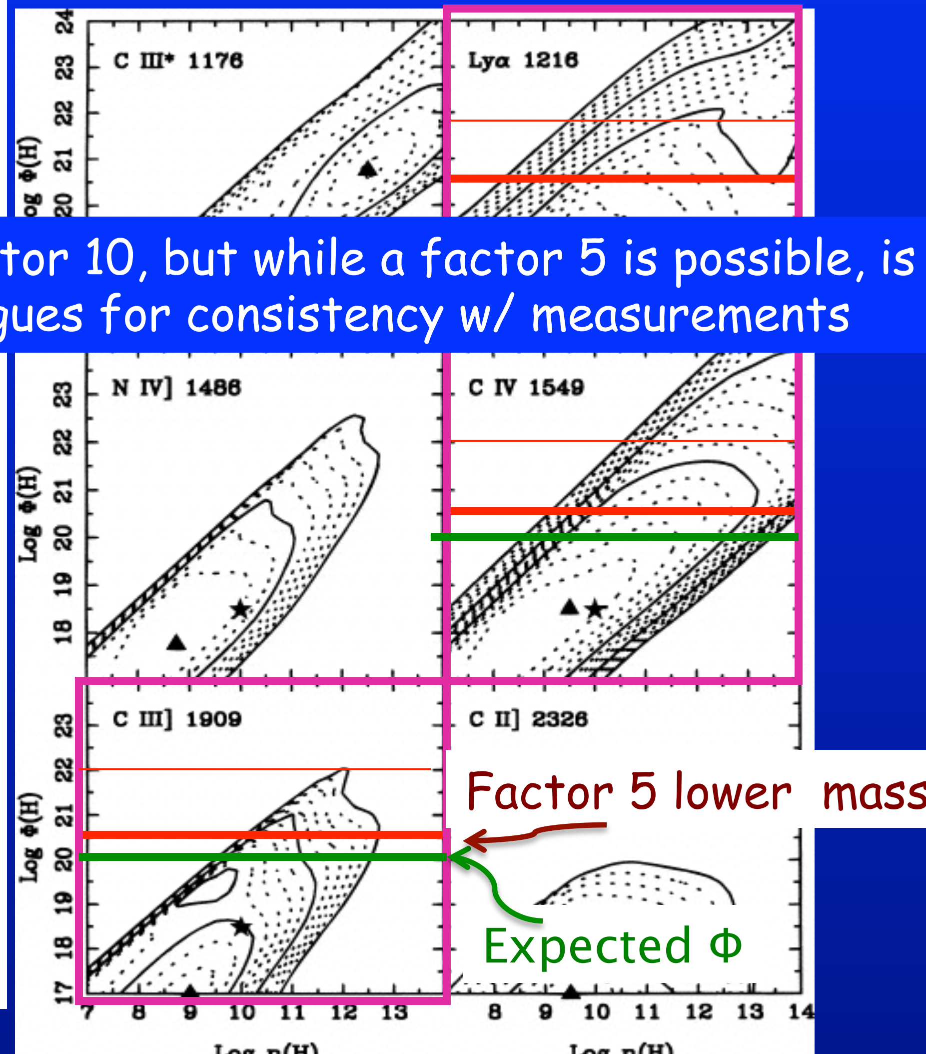
(Dietrich et al. 2002)

Luminosity High-z Quasars



(Dietrich et al. 2002)

It is unlikely that masses are off by factor 10, but while a factor 5 is possible, is is less likely – as photoionization also argues for consistency w/ measurements



But isn't the velocity also uncertain?

The previous argument focuses mostly on the R-L relation…

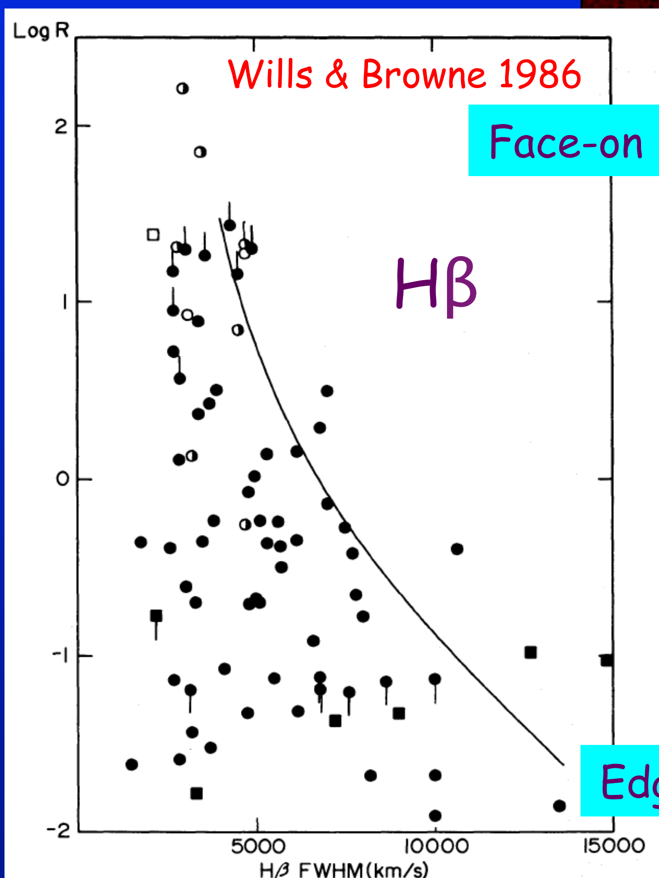
Yes, but a combined factor ~5 is probably still realistic because:

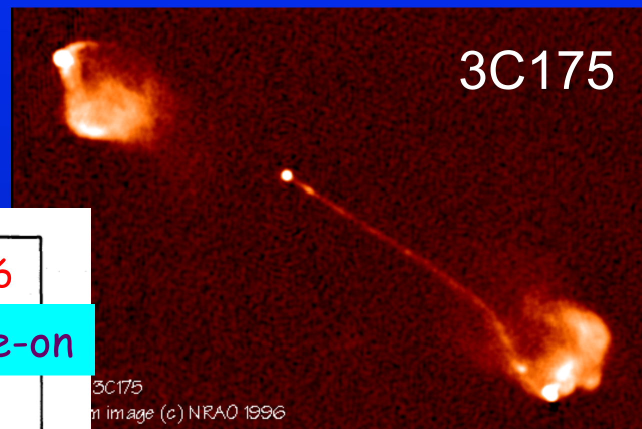
- An *average* velocity for the population is good in terms of
  - measurement uncertainty
  - the average population inclination (see below)
- Type 1 AGN are mostly inclined toward us, so inclinations range between 0 – 45 degrees – i.e. only ± ~20degrees from an average inclination, and statistically more objects will be more inclined
- Scatter in M-σ relation for AGN is similar to that for quiescent galaxies (factor of ~3) so inclination probably does not introduce a large uncertainty
- The next slides argue that when we know the inclination to within ~25 degrees (realistic cf. above) then the uncertainty in the mass estimates is only a factor of 3 or less.

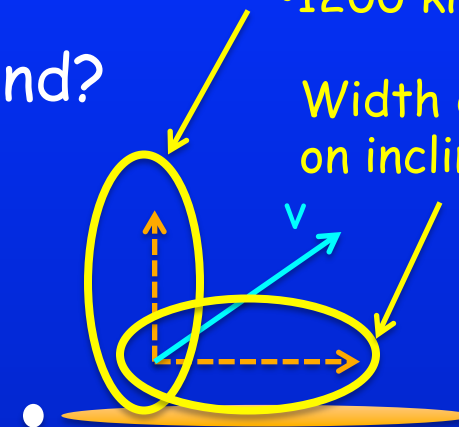
BLR velocity field

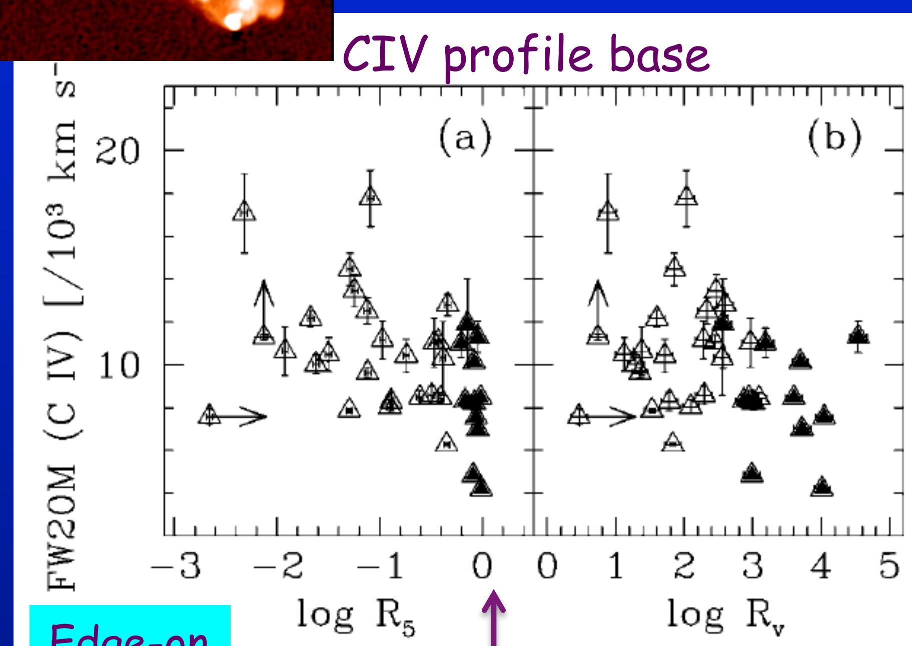
- Two component velocity field: disk + wind?

R = ratio of radio core flux to total flux





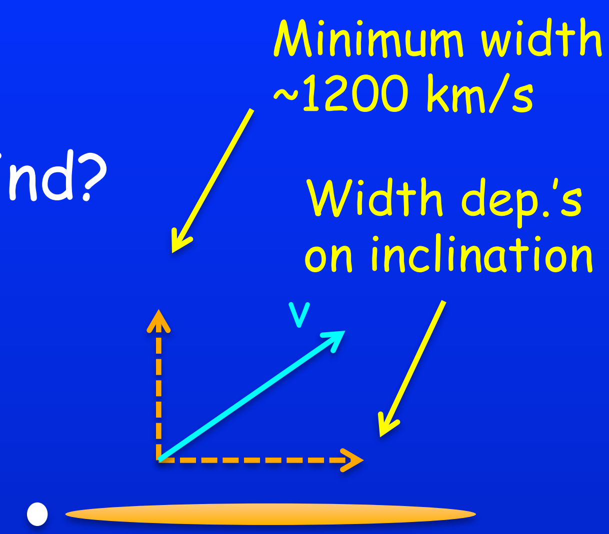




Vestergaard + 2000

BLR velocity field

- Two component velocity field: disk + wind?
- BLR as flared disk ?
- BLR as warped disk ?
- Similar velocity field description:



$$\Delta V_{\rm obs} \approx \left(a^2 + \sin^2 i\right)^{1/2} V_{\rm Kep},$$

a = H/R of disk or
V(turbulent) /V(Kepler): 0.1 – 0.3
i = inclination of disk normal to LOS

$$V_{Kepler} = \frac{V_{Obs}}{\sqrt{(a^2 + \sin^2 i)}};$$

$$M_{BH} = f \times R V_{Kepl}^2 / G$$

- *Only Factor 3 Scatter in M-σ* relation: *a* not small – so *a* is probably closer to 0.3 than 0.1 ?

Collin + 2006, *A&A*, 456,75

Uncertainty due to inclination

$$\Delta V_{\rm obs} \approx \left(a^2 + \sin^2 i\right)^{1/2} V_{\rm Kep},$$

$$V_{Kepler} = \frac{V_{Obs}}{\sqrt{(a^2 + \sin^2 i)}};$$

$$M_{BH} = f \times RV_{Kepl}^2 / G$$

- a can be H/R of disk or $V_{TURBULENT}$ / V_{KEPLER}
- i is inclination of disk. Face-on: i=0°

a	inclination	V_{KEP}/V_{OBS}	$(V_{KEP}/V_{OBS})^2$
0.1	10	5	25
0.1	80	1	1
0.3	80	1	1
0.3	60	1.1	1.2
0.3	50	1.2	1.4
0.3	45	1.3	1.7
0.3	40	1.4	2
0.3	30	1.7	2.9
0.3	20	2.2	4.8
0.3	10	2.9	8.4

Assume a = 0.3:

$\Delta i \sim 70°$ -> $\Delta M_{BH} < 8.4$

$\Delta i \sim 30°$ -> $\Delta M_{BH} < 4.2$

$\Delta i \sim 20°$ -> $\Delta M_{BH} < 2.4$

Collin et al. 2006