Quasar Black Hole Masses with GAIA

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GAGNES - Paris, July 8, 2015

Overview

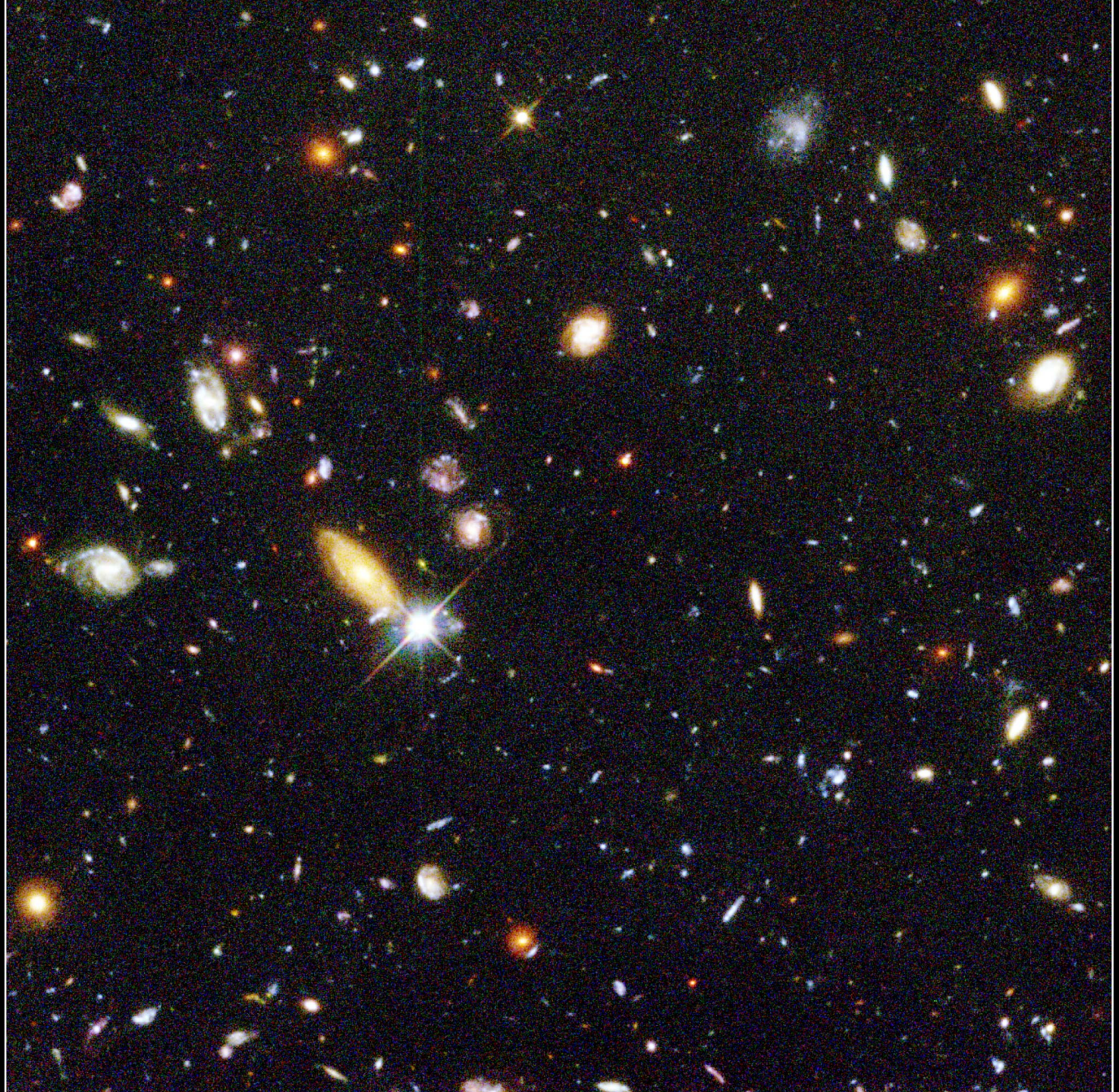
- Why do we need black hole mass determinations?
- Expected quasar counts with GAIA
- What can we *also* learn from black hole masses?

- Mass determination of super-massive black holes
  - Requirements and implications
- What can we learn from GAIA data?

Hubble Deep Field

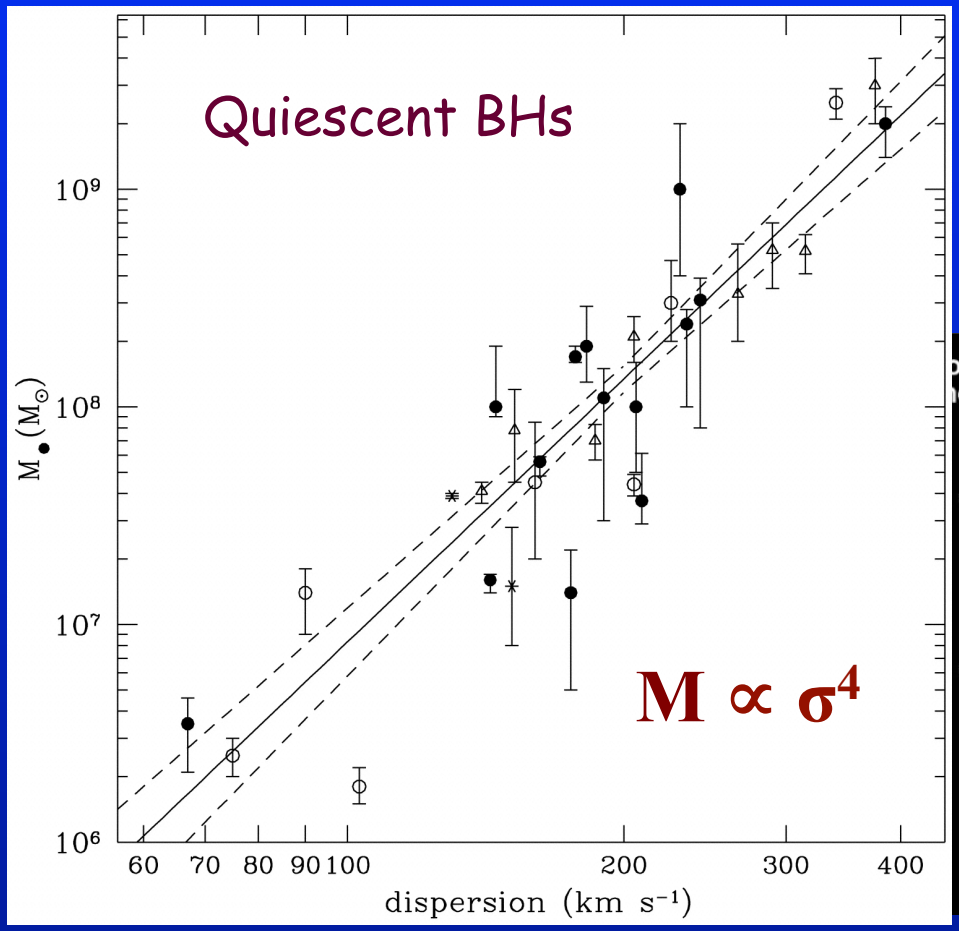
Most objects in this image are galaxies

WFPC2
1996

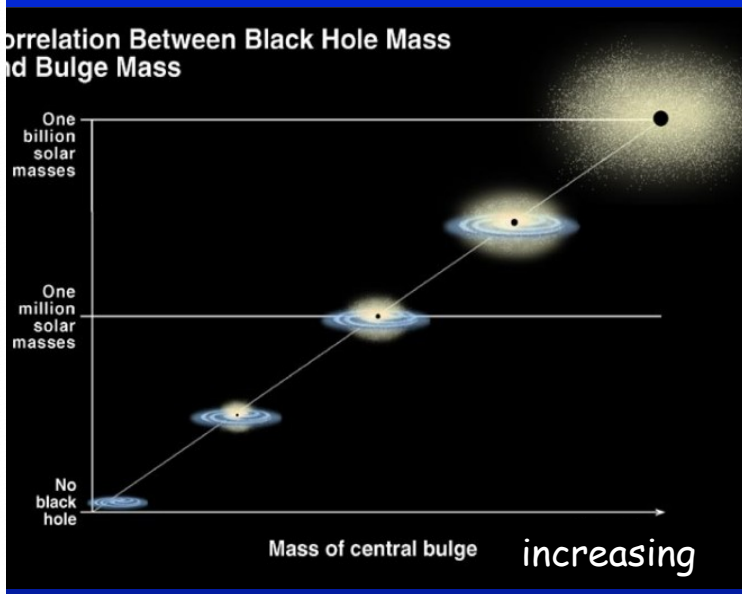


The M - M_{bulge} Relationship

Black Hole Mass



(Tremaine et al. 2002; See also Ferrarese & Merritt 2000; Gebhardt et al. 2000)

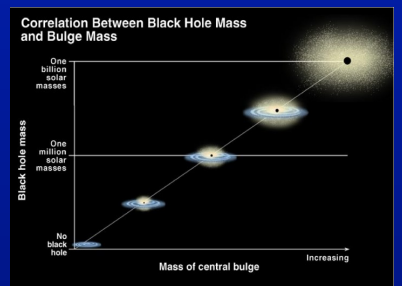


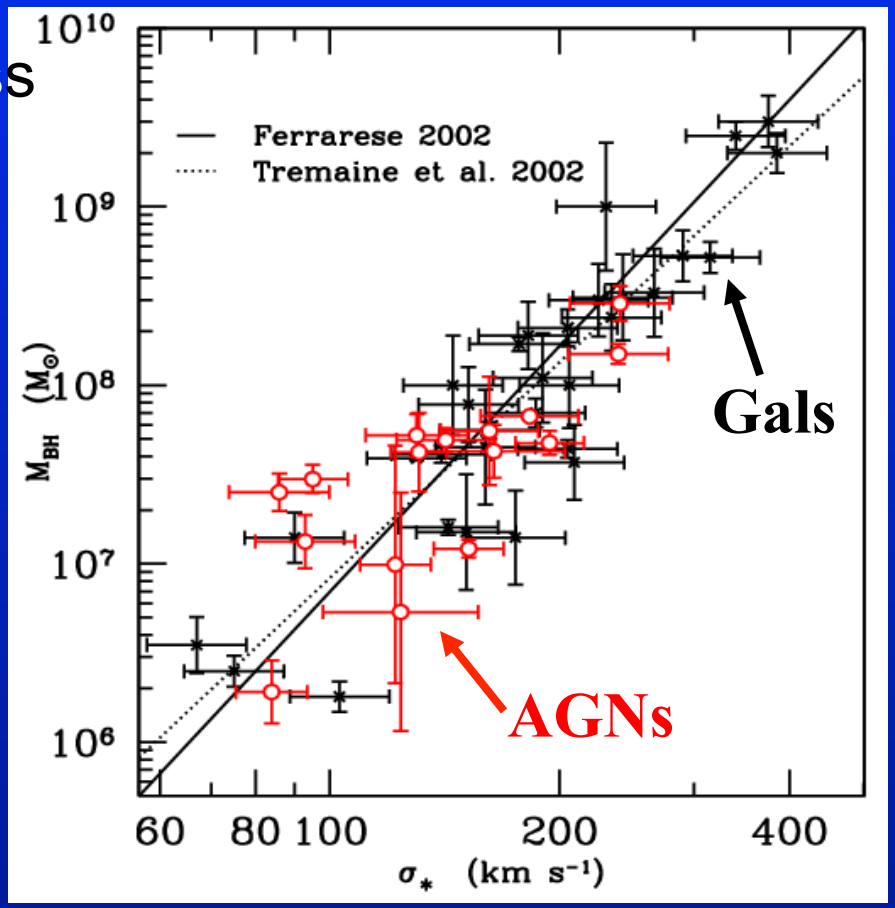
Mass of Galaxy Bulge

M(BH) ~ M(galaxy)/1000

M_{BH}-σ: Comparison of Active and Quiescent Galaxies

- Reverberation masses appear to fall along the M_{BH} - σ relation for quiescent galaxies
- The scatter is also similar: ≲ a factor of 3

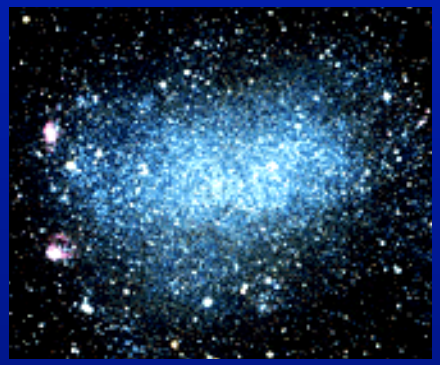


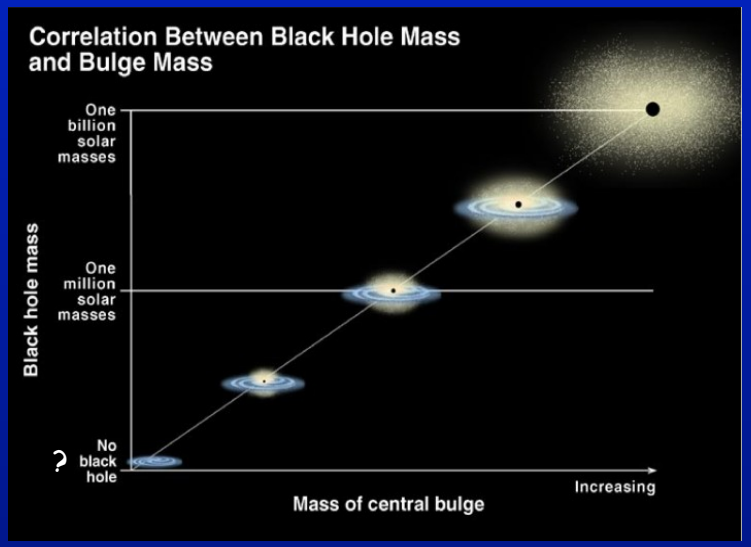


(Courtesy C. Onken)

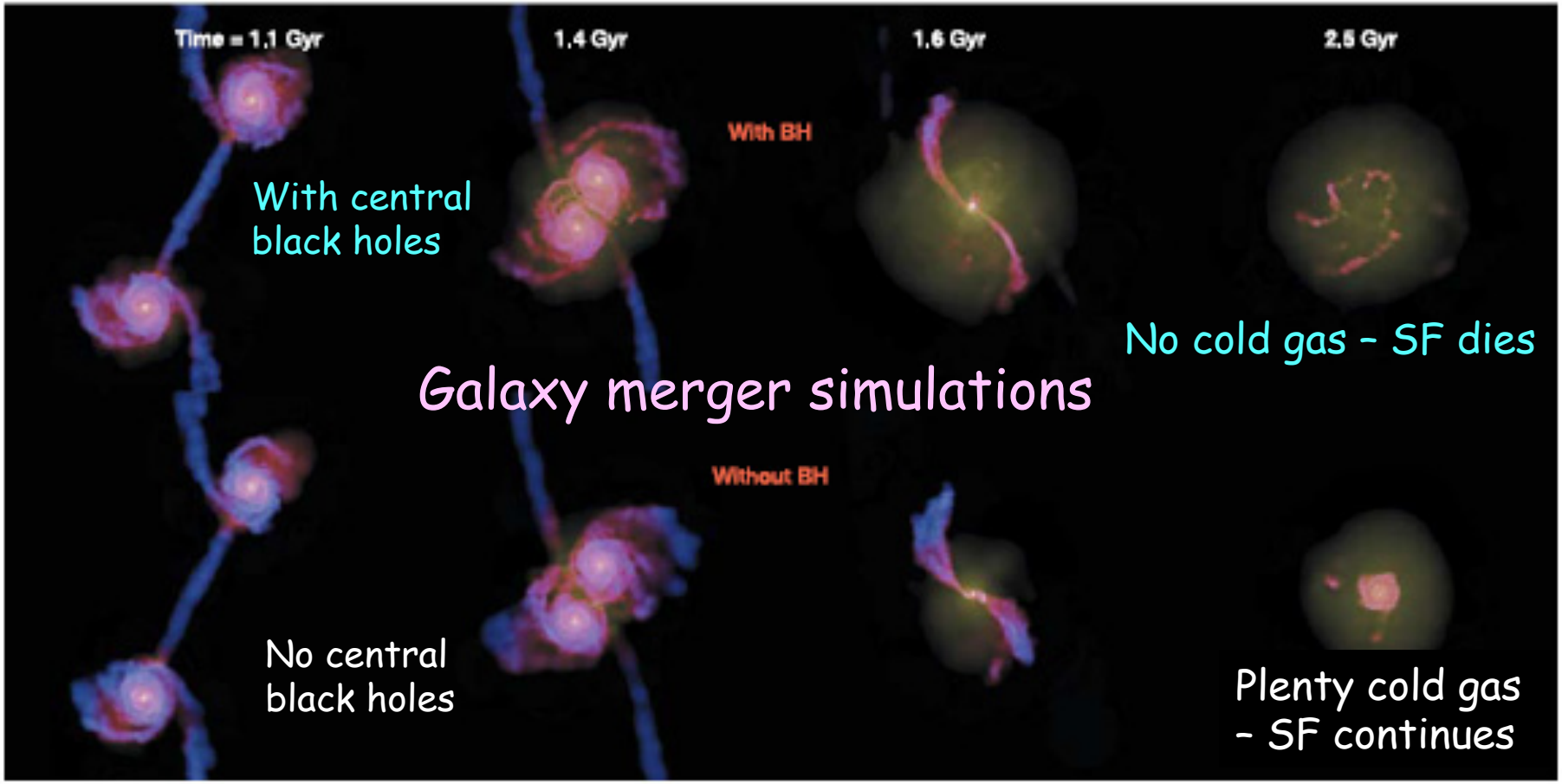
Role of supermassive black holes to galaxy evolution

What stopped star formation in the now red, "dead", elliptical galaxies?





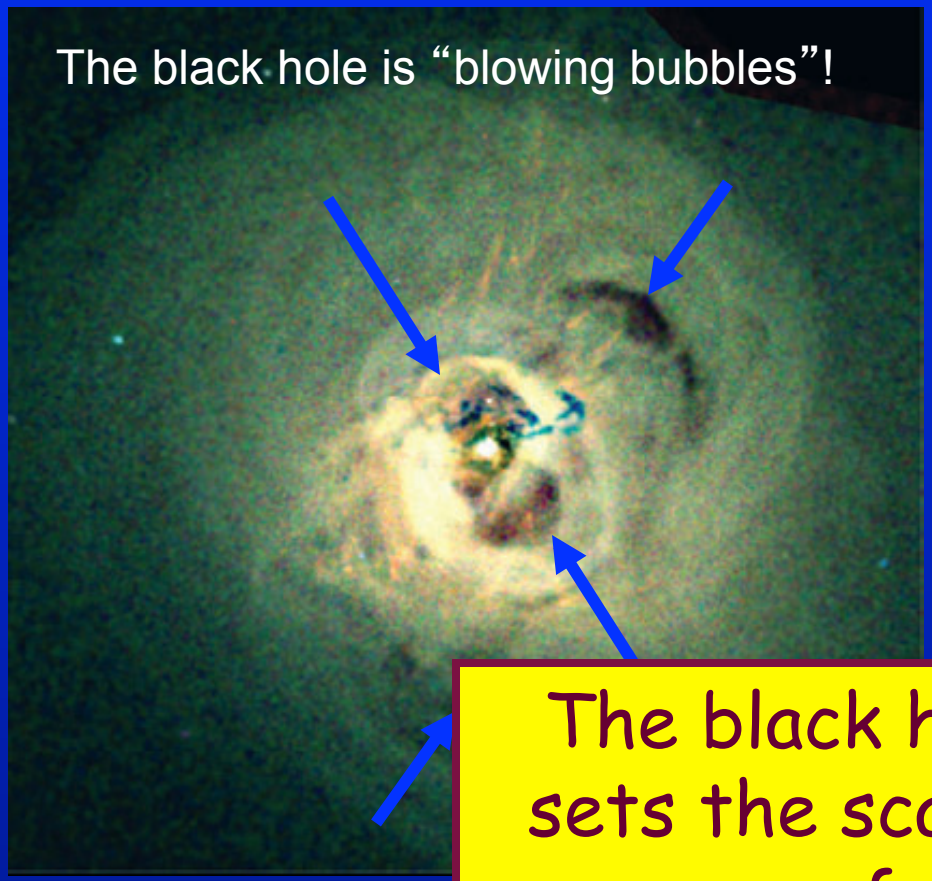
Energy feedback from black hole accretion heat and expel cold gas - the fuel for star formation

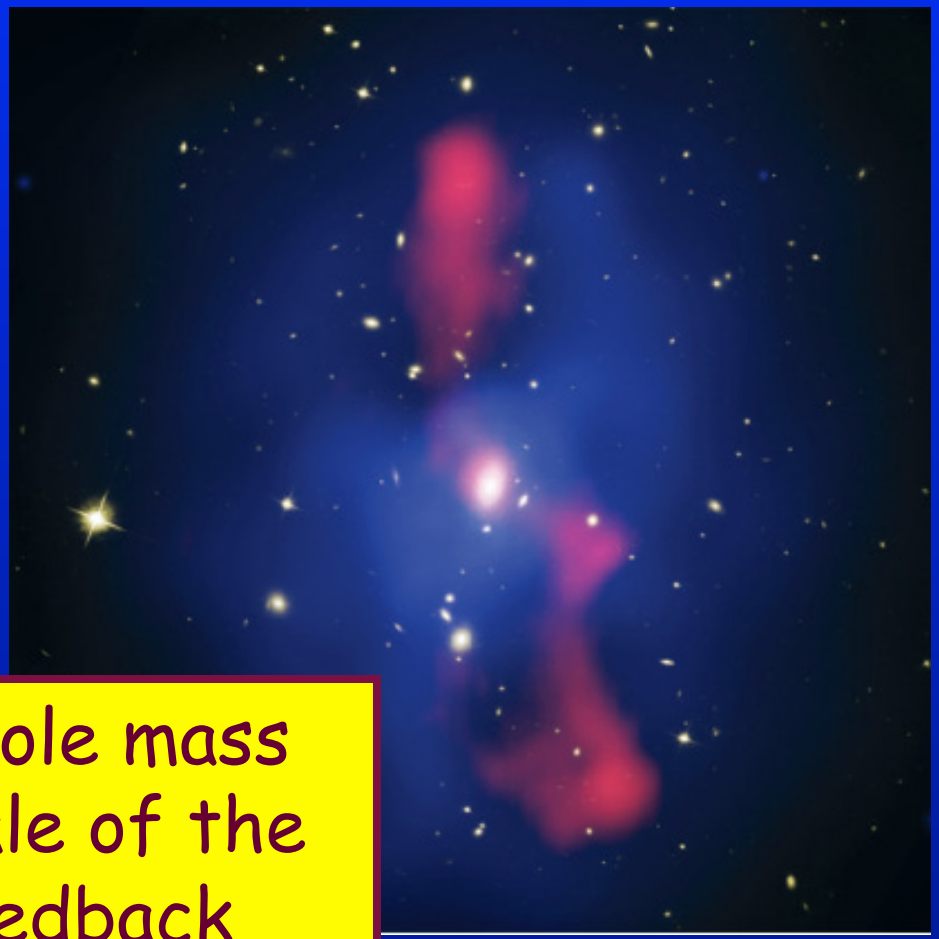


(eg Di Matteo et al 2005, Springel et al 2005, Hopkins et al. 2008)

Black Holes as Cosmological Probes: Cluster Properties and Evolution

Black Hole Activity Affects the X-ray Gas in Clusters: outflows + heating

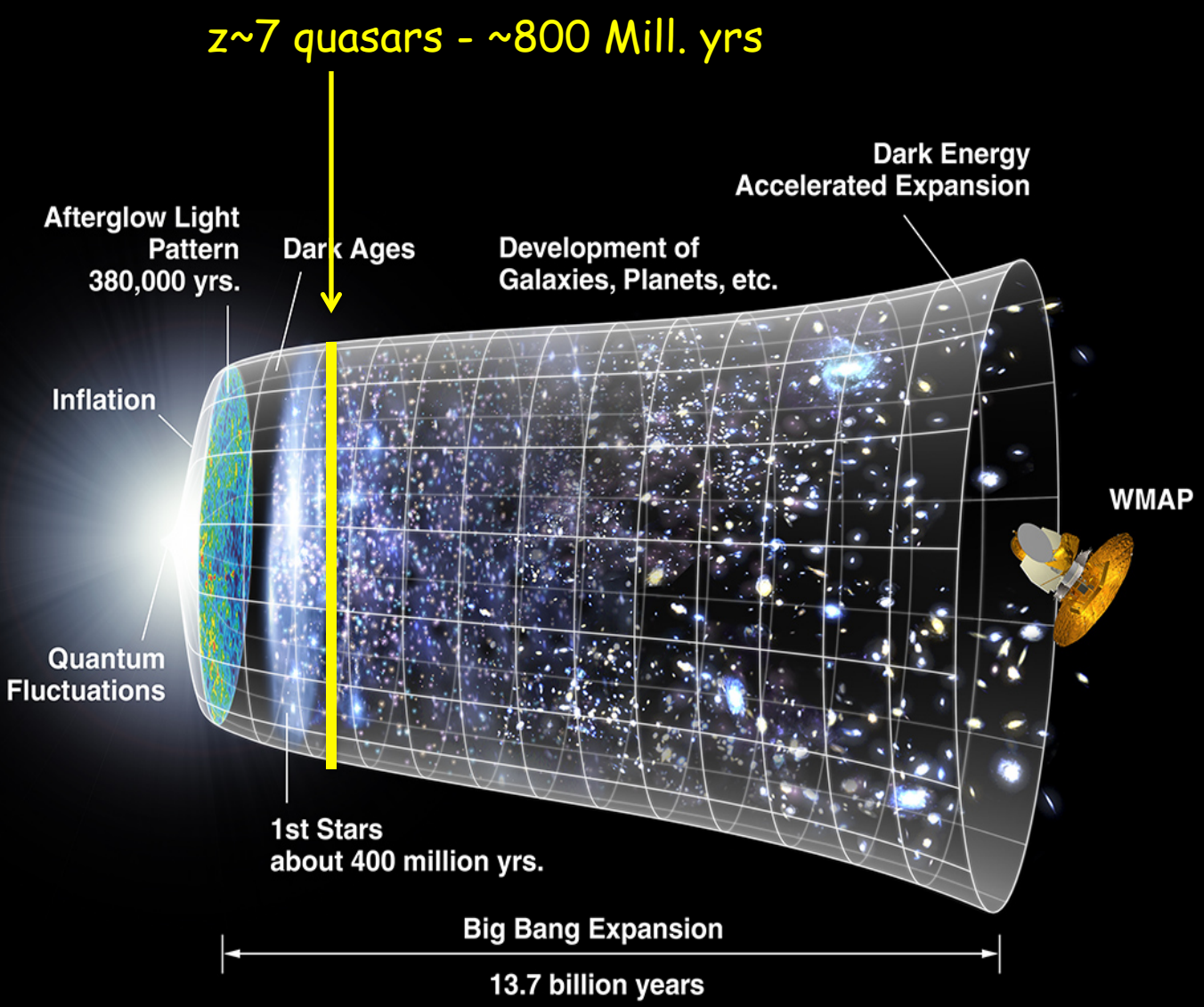




The black hole mass sets the scale of the energy feedback

Perseus A
(Fabian et al. 2006)

MS0735.6+7421 Cluster
(McNamara & Nulsen 2007)


z~7 quasars - ~800 Mill. yrs
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

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GAIA Quasar Counts

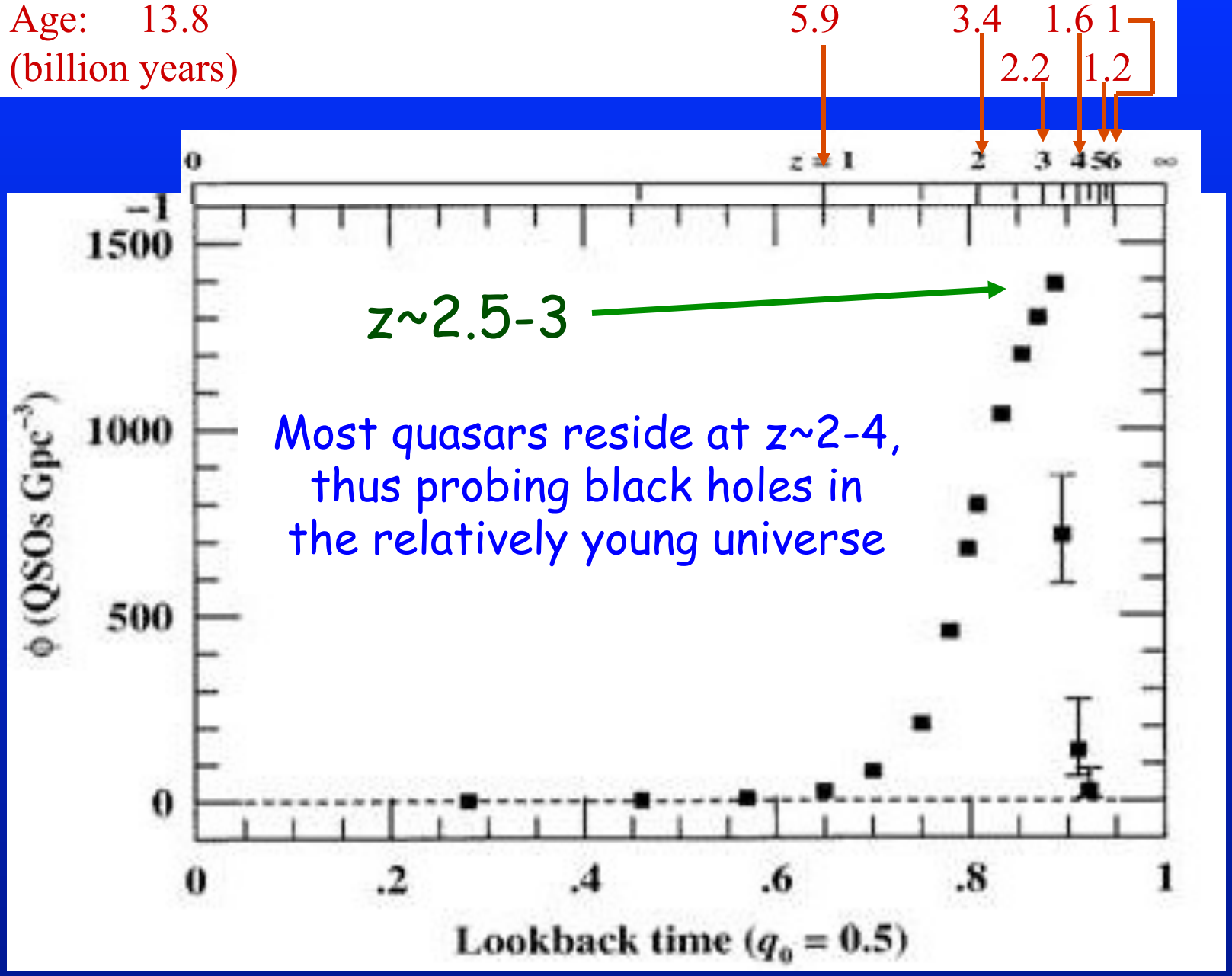
V	density deg^{-2}	Full sky #	60% sky #	known #	new #	Slezak et.al #
18.0	1.5	63 000	38 000	12 500	25 500	40 000
18.5	3	126 000	75 000	23 000	52 000	113 000
19.0	8	340 000	200 000	45 000	155 000	314 000
19.5	15	630 000	380 000	85 000	295 000	680 000
20.0	22	920 000	550 000	115 000	435 000	1 200 000
20.5	30	1 260 000	750 000	140 000	610 000	1 700 000

Mignard, 2012, Mem. Soc. Ast. It.,

- Quasar Population: Better statistics, broader representation
- Large potential for adding new knowledge

Courtesy F. Mignard

Age: 13.8
(billion years)



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Mass Functions of Active Supermassive Black Holes

- Combining the *luminosity function* and the *mass function* is a powerful tool for constraining black hole growth:

$$L_{BOL} = \eta \cdot \frac{dM}{dt} \cdot c^2$$

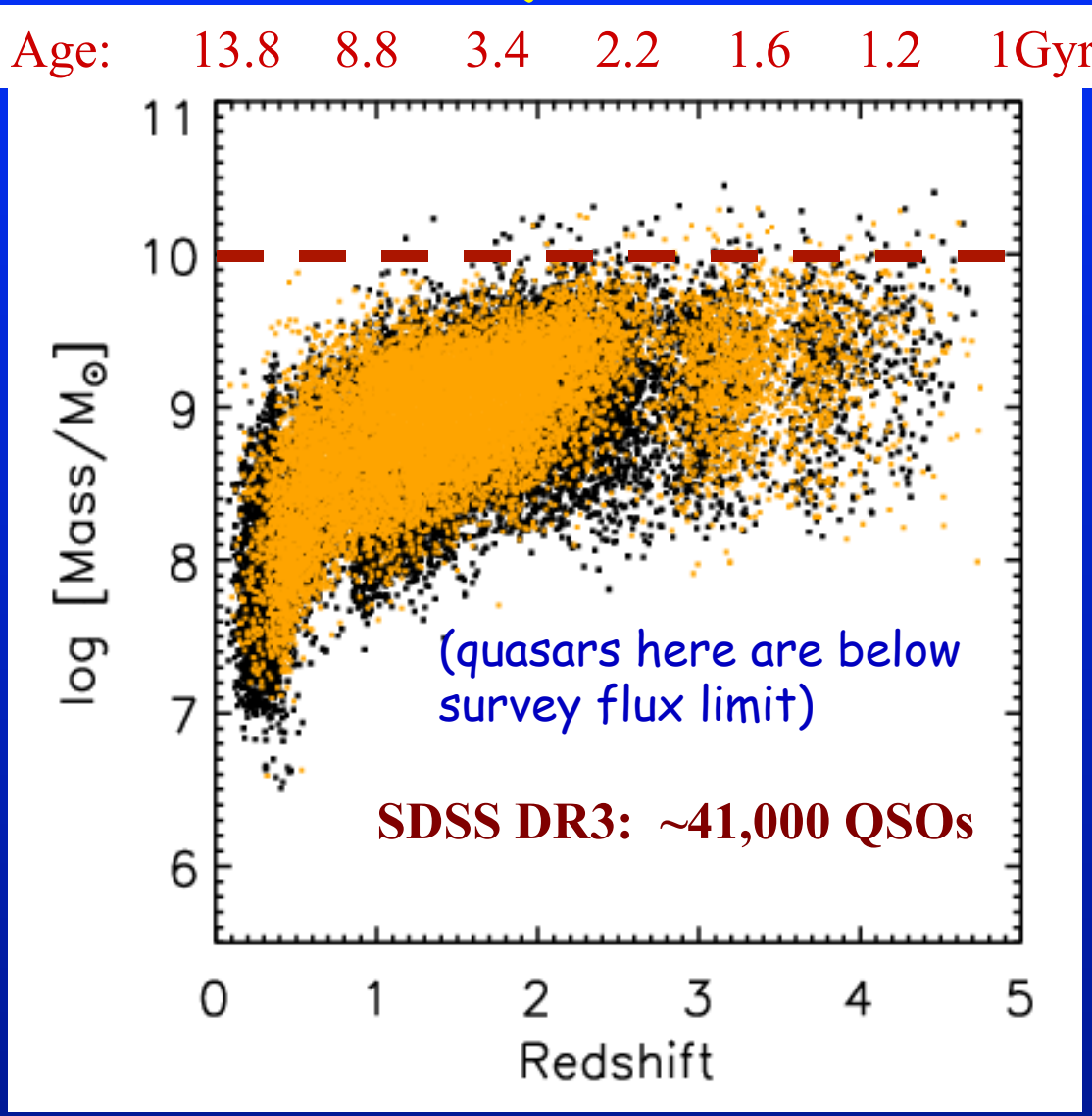
$$L = fct\left(M, \eta, \frac{dM/dt}{dM_{Edd}/dt}\right)$$

(eg, Wyithe & Radmanabhan 2006)

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 et al. in prep)

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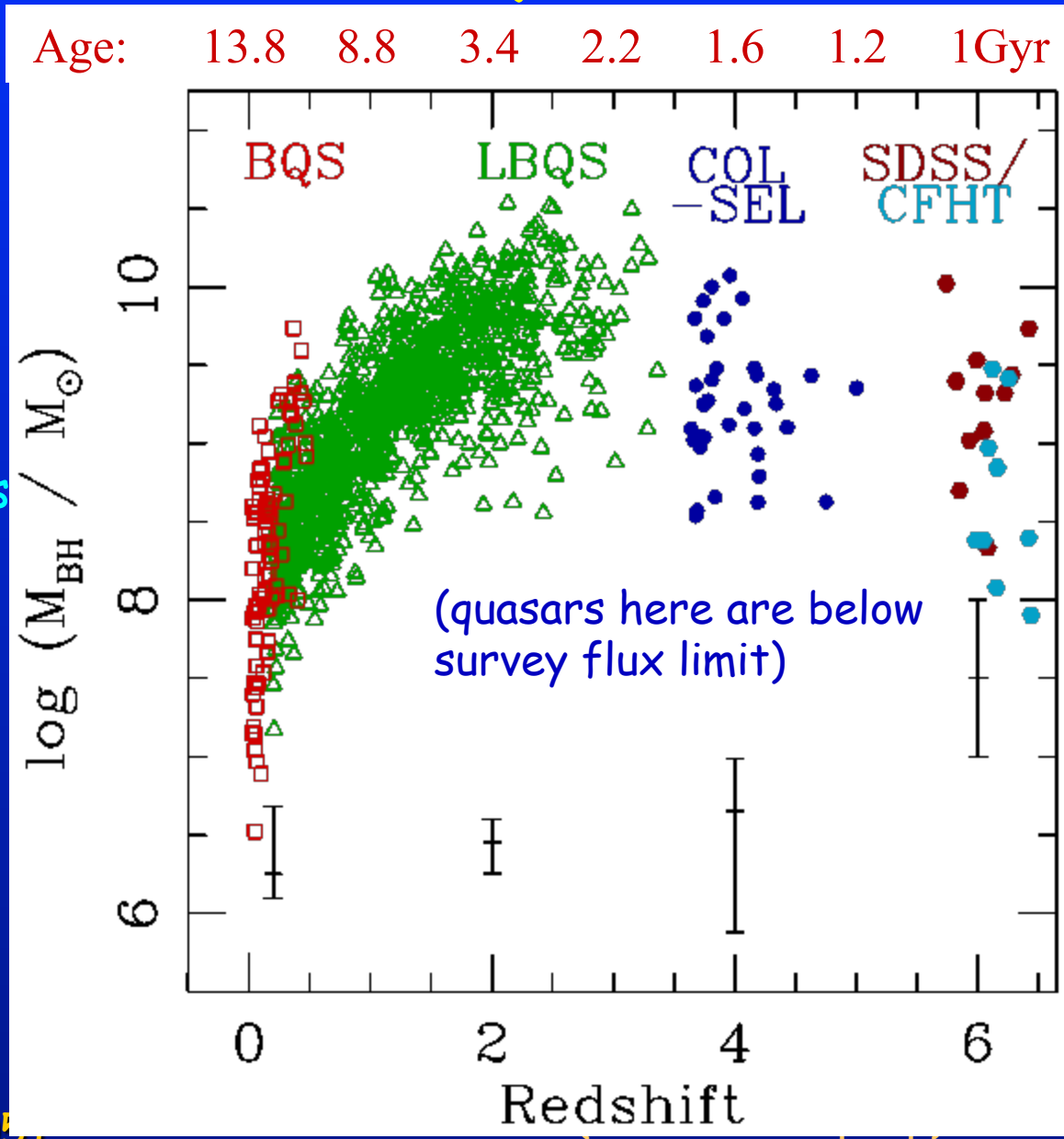
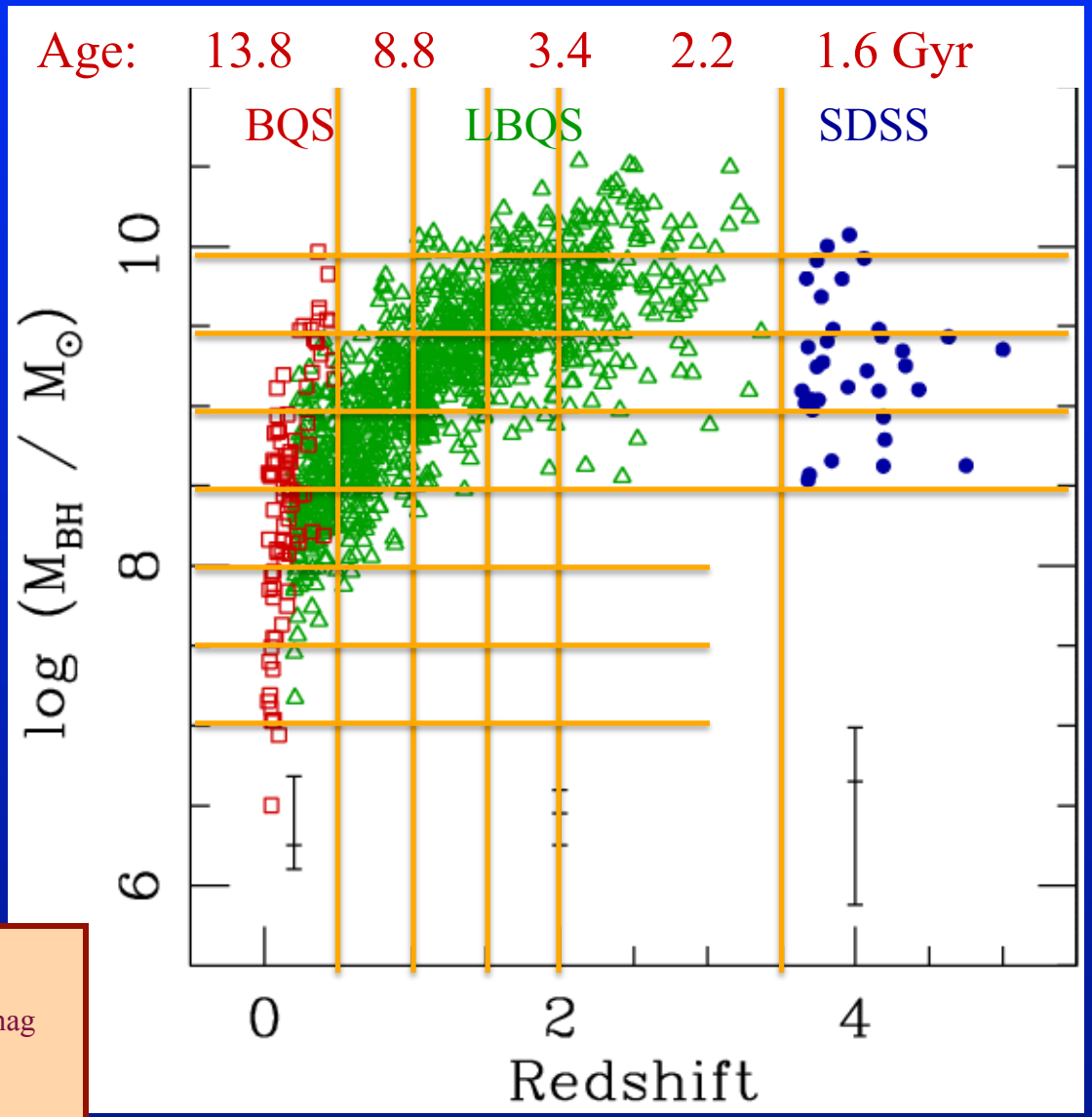


(DR3 Qcat: Schneider et al. 2005)

Mass Functions of Active Supermassive Black Holes

- MF = space density of BHs as function of both mass and redshift.

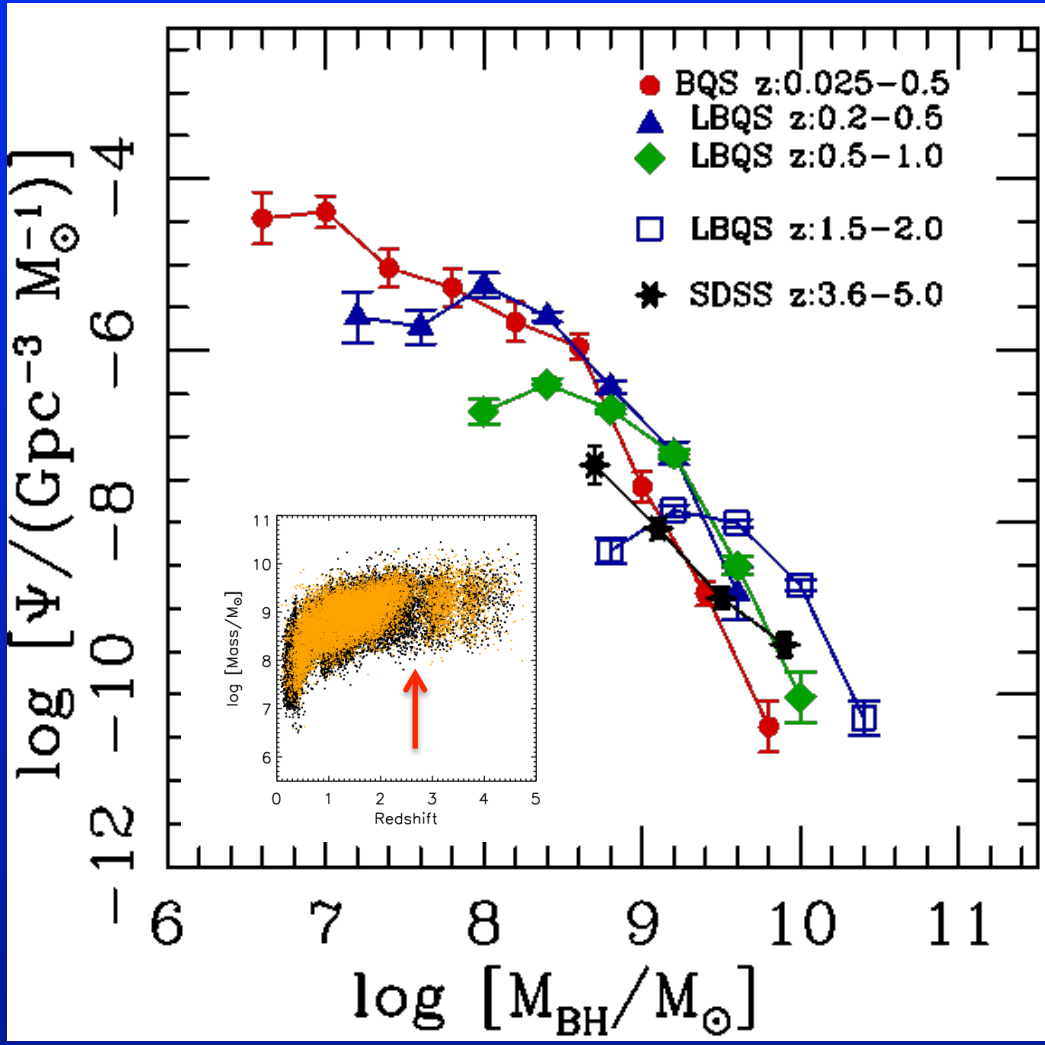


- BQS: 10 700 sq. deg; B≤16.16^{mag}
- LBQS: 454 sq. deg; 16.0≤B_J≤18.85^{mag}
- SDSS: 182 sq. deg; i^* ≤20^{mag}
- DR3: 1622 sq. deg.; i^* >15, ≤19.1, 20.2

(Vestergaard & Osmer 2009)

Mass Functions of Active Supermassive Black Holes

- Different samples show relatively consistent mass functions (shape, slope)
  (Vestergaard & Osmer 2009; Vestergaard et al., 2008)
- Goal: constrain BH growth



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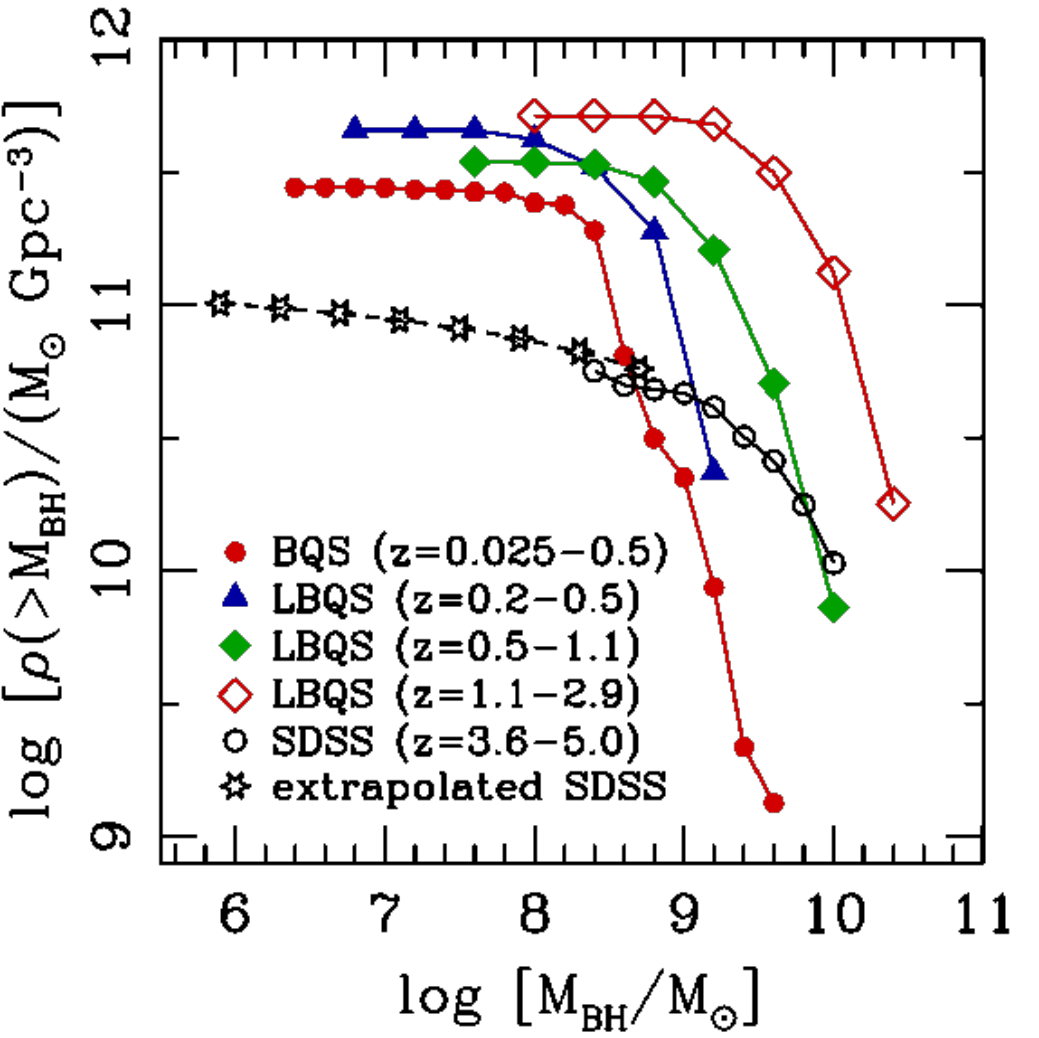
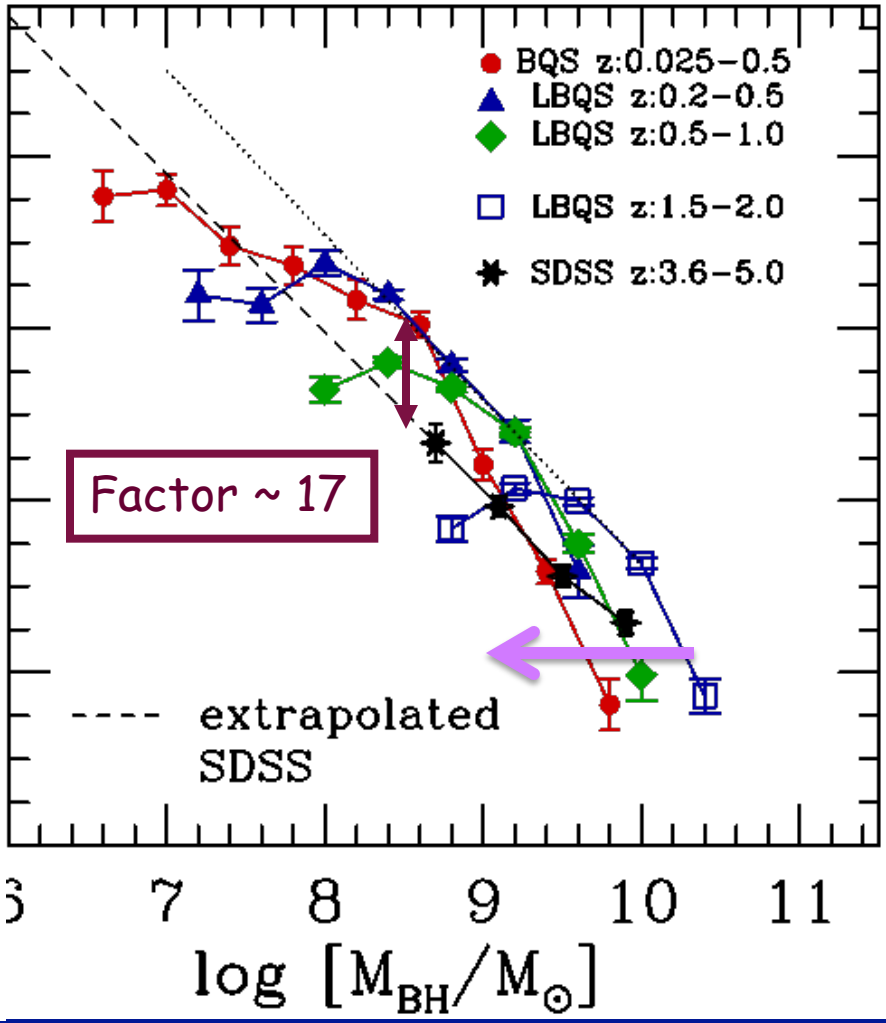
Mass Functions of Active Supermassive Black Holes

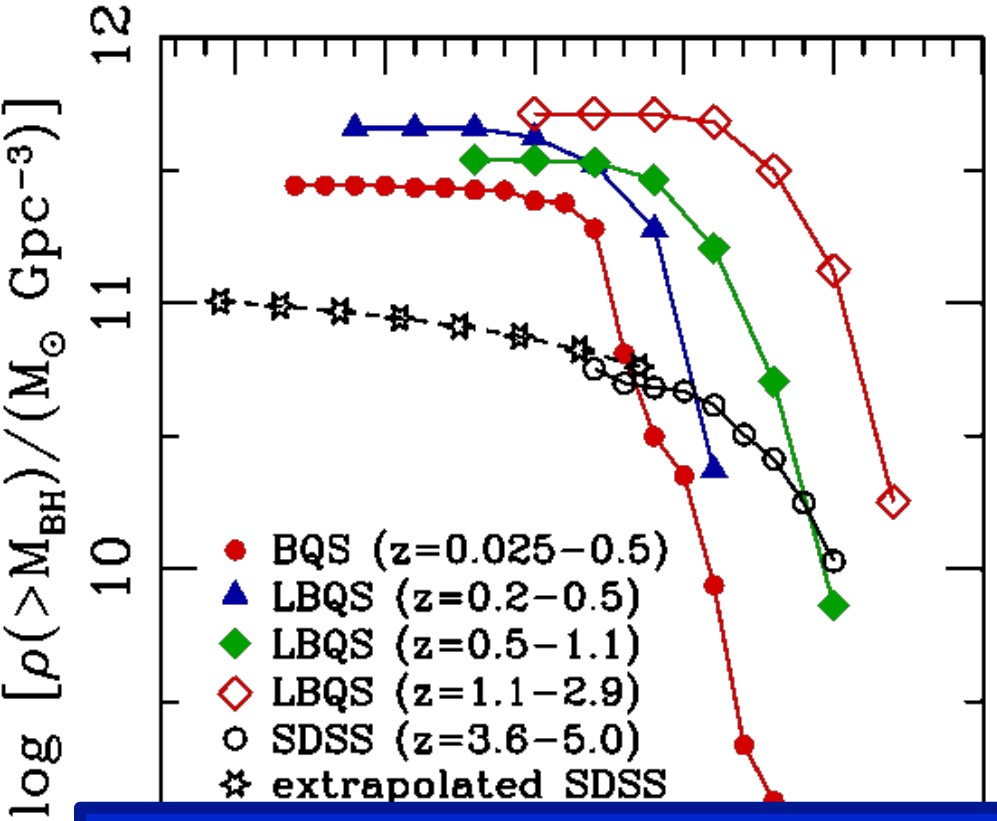


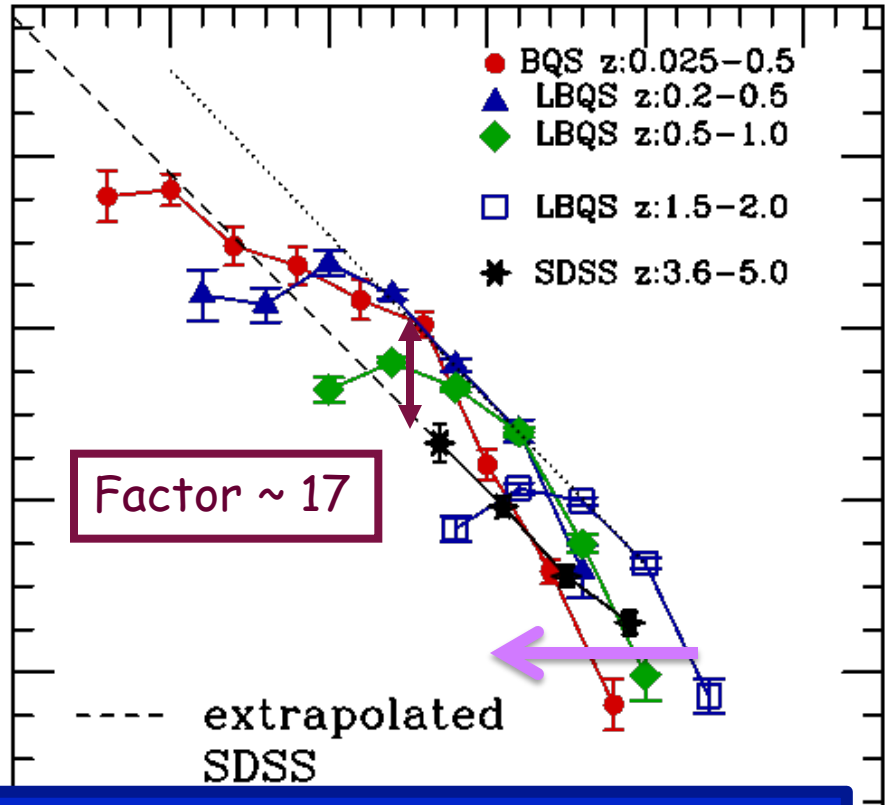


(H_0=70 km/s/Mpc; Ω_Λ = 0.7)

(Vestergaard & Osmer 2009)

Mass Functions of Active Supermassive Black Holes



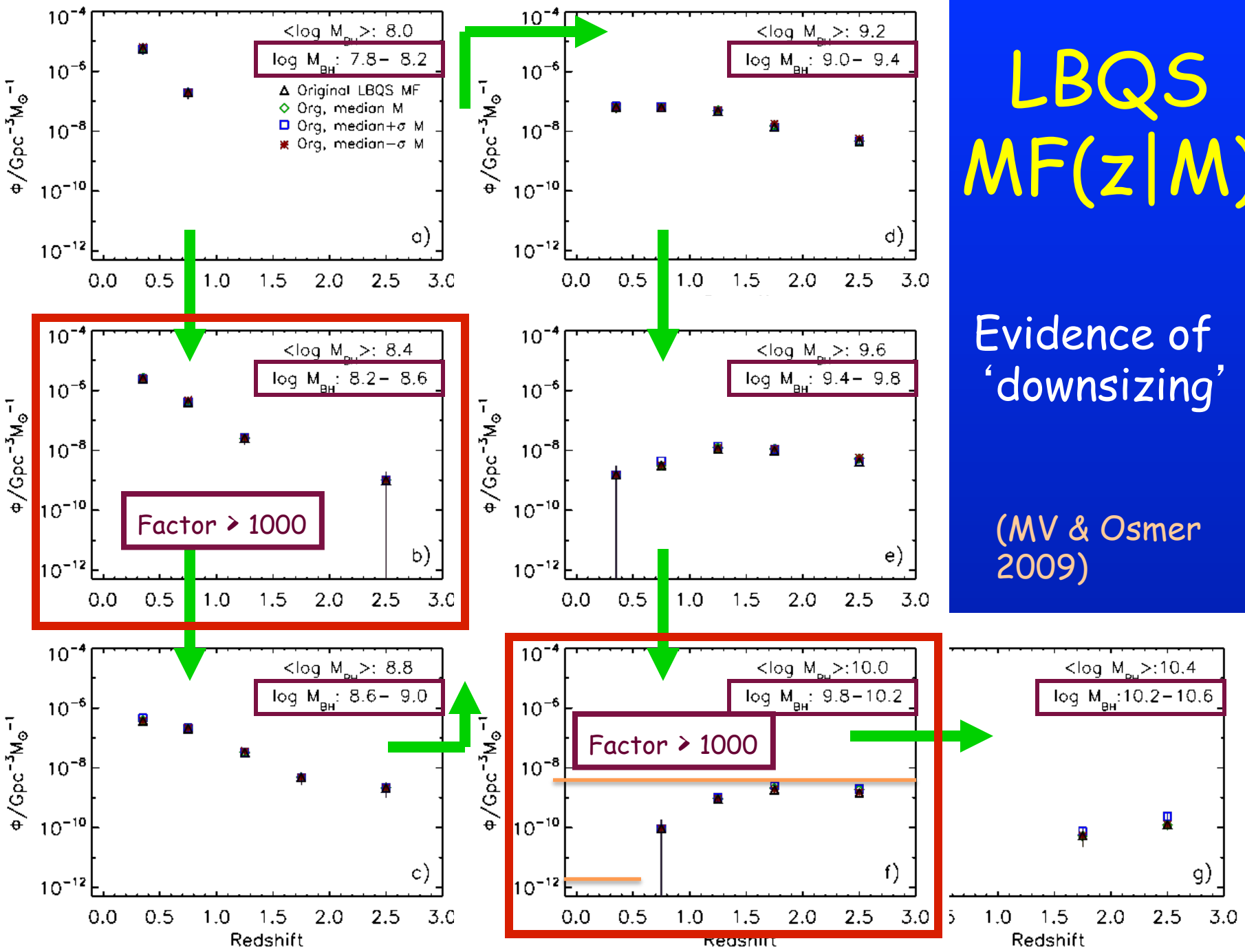


Redshift 4 quasars is clearly a different, rarer population of black holes, than at z~2.5.

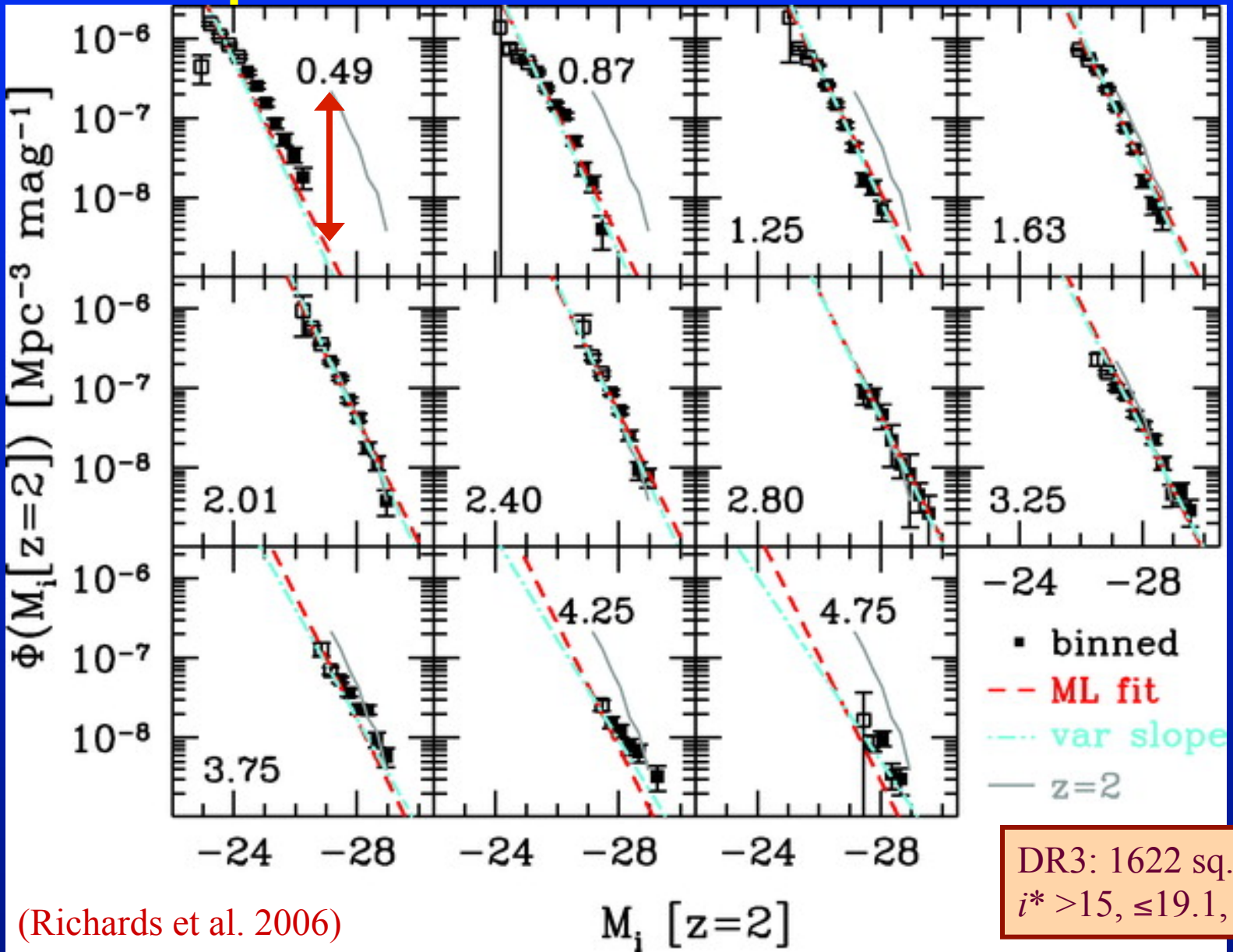
We are seeing the population build-up!

(H_0=70 km/s/Mpc; Ω_Λ = 0.7)

(Vestergaard & Osmer 2009)


LBQS MF(z|M)
Evidence of 'downsizing'
(MV & Osmer 2009)
<log M_BH>: 8.0
log M_BH: 7.8– 8.2
Original LBQS MF
Org, median M
Org, median+σ M
Org, median−σ M
a)
<log M_BH>: 9.2
log M_BH: 9.0– 9.4
d)
<log M_BH>: 8.4
log M_BH: 8.2– 8.6
b)
Factor > 1000
<log M_BH>: 9.6
log M_BH: 9.4– 9.8
e)
<log M_BH>: 8.8
log M_BH: 8.6– 9.0
c)
<log M_BH>:10.0
log M_BH: 9.8–10.2
Factor > 1000
f)
<log M_BH>:10.4
log M_BH:10.2–10.6
g)
Φ/Gpc^-3M_⊙^-1
Redshift

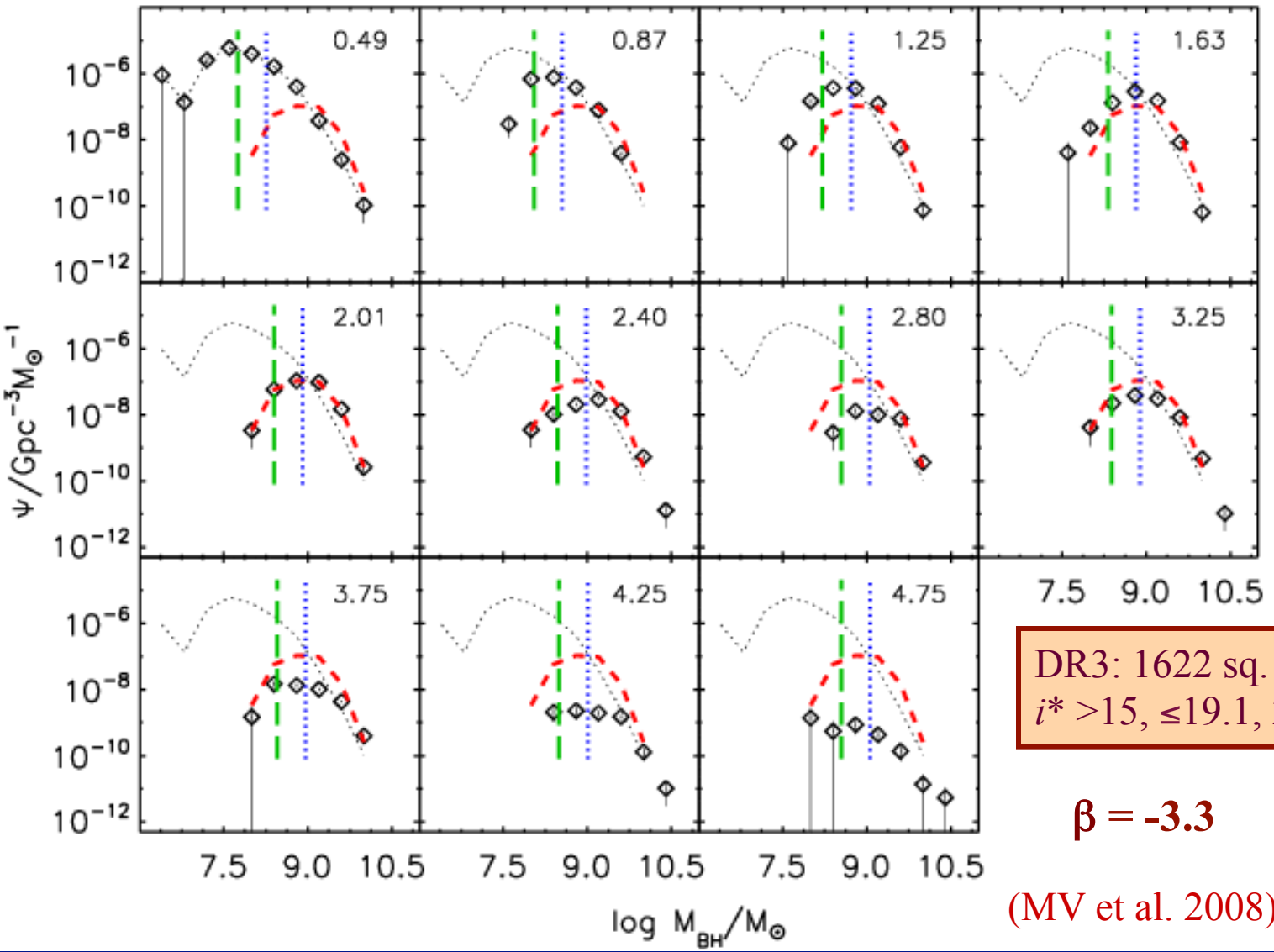
Luminosity Functions of Active Supermassive Black Holes



(Richards et al. 2006)

DR3: 1622 sq. deg.;
i^* >15, ≤19.1, 20.2

Mass Functions of Active Supermassive Black Holes

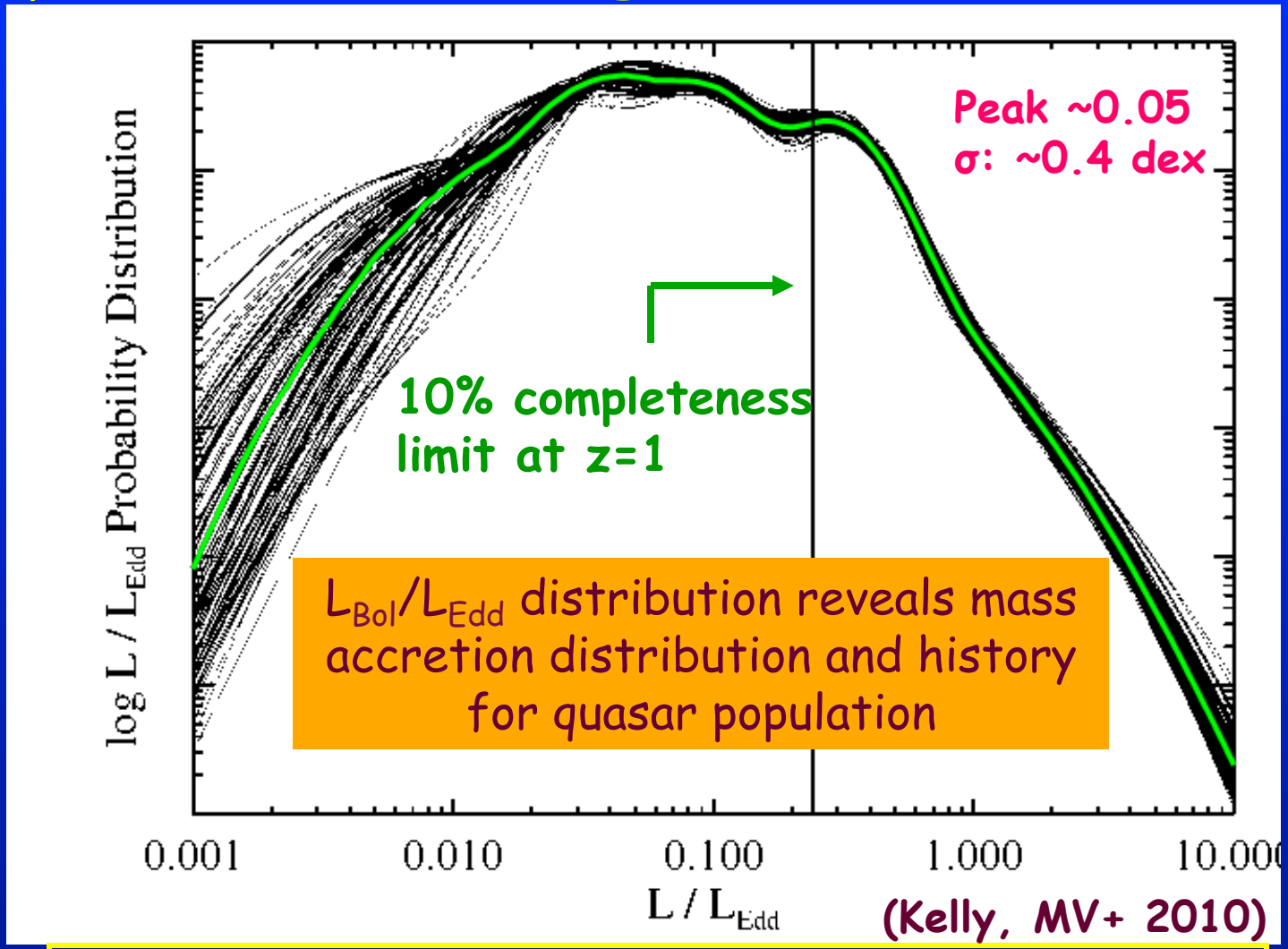


DR3: 1622 sq. deg.;
i^* >15, ≤19.1, 20.2

β = -3.3

(MV et al. 2008)

Bayes Stats: Eddington Ratio Distribution



Consistent with deeper quasar samples of [Gavignaud + 2008; Trump + 2009]

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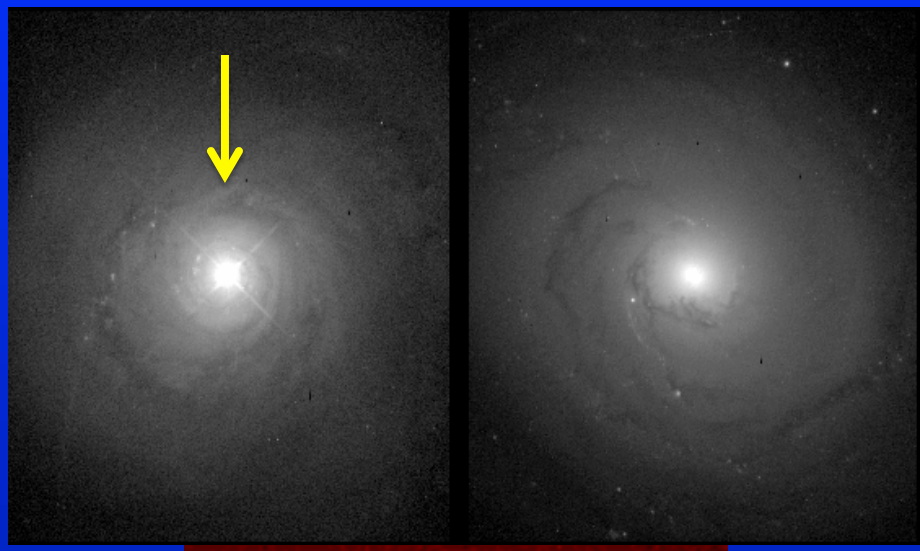
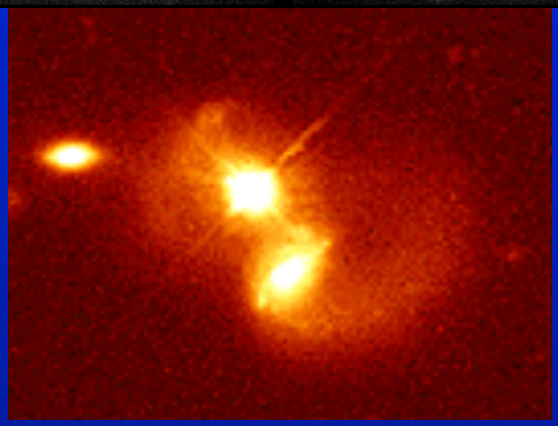
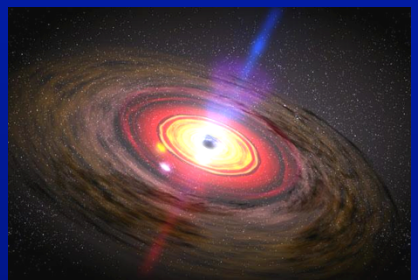
Active Galactic Nuclei

- Bright galaxies with a point-source of non-stellar activity in nuclei - powered by an accreting black hole
- They are rare – comprise only a few percent of ***bright*** galaxies
- Quasars are the most powerful subset. Observable from z~0.1 to z~7!
- While rare, these are the *only* massive black holes we can study beyond ~300Mpc

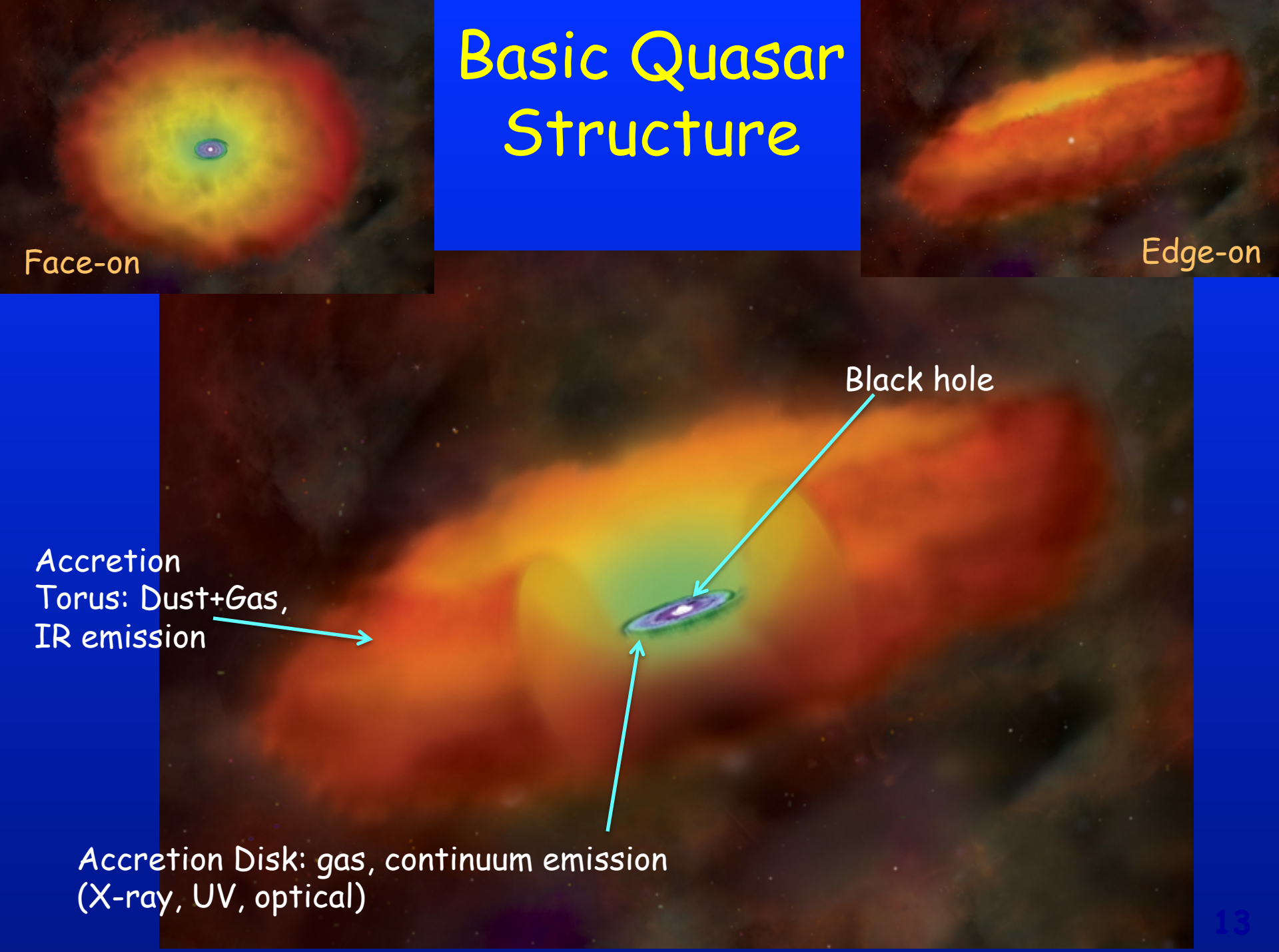




A quasar outshines its host galaxy



Basic Quasar Structure



Basic Quasar Structure

Broad Emission Line Gas

Black hole

Accretion Torus: Dust+Gas, IR emission

Accretion Disk: gas, continuum emission (X-ray, UV, optical)

Basic Quasar Structure

Face-on

Edge-on

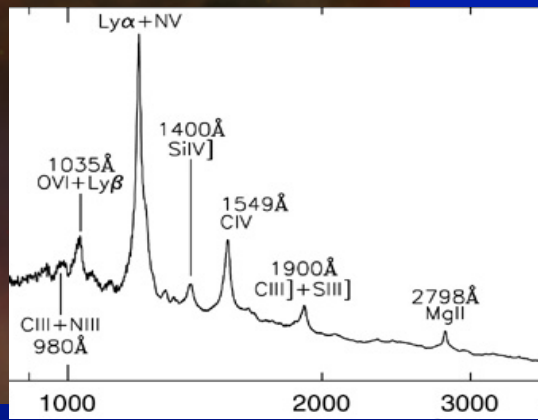
Broad Emission Line Gas

Fast-moving gas

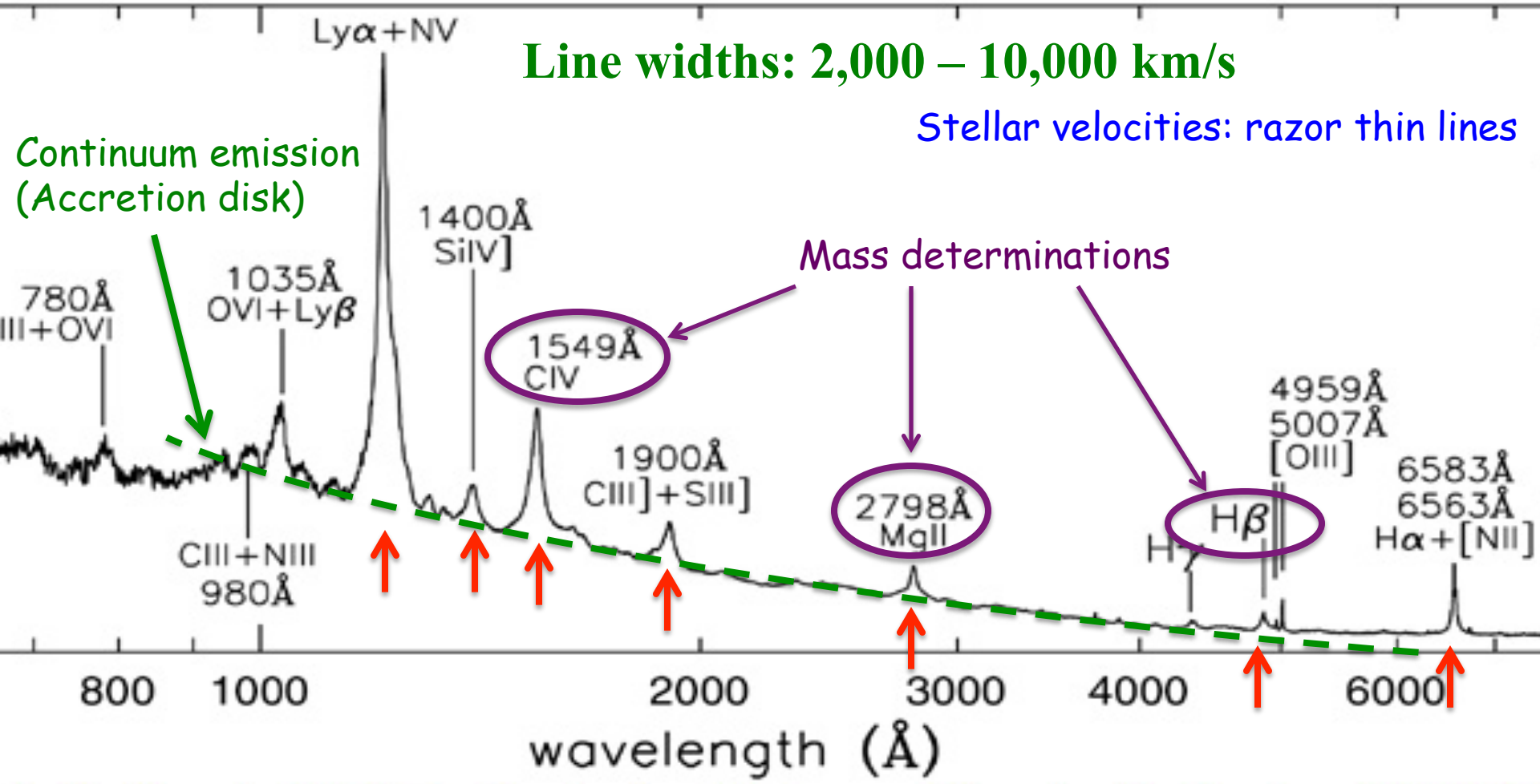
Black hole

Accretion Torus: Dust+Gas, IR emission

Accretion Disk: gas, continuum emission (X-ray, UV, optical)



AGN broad emission lines from gas in motion around the black hole

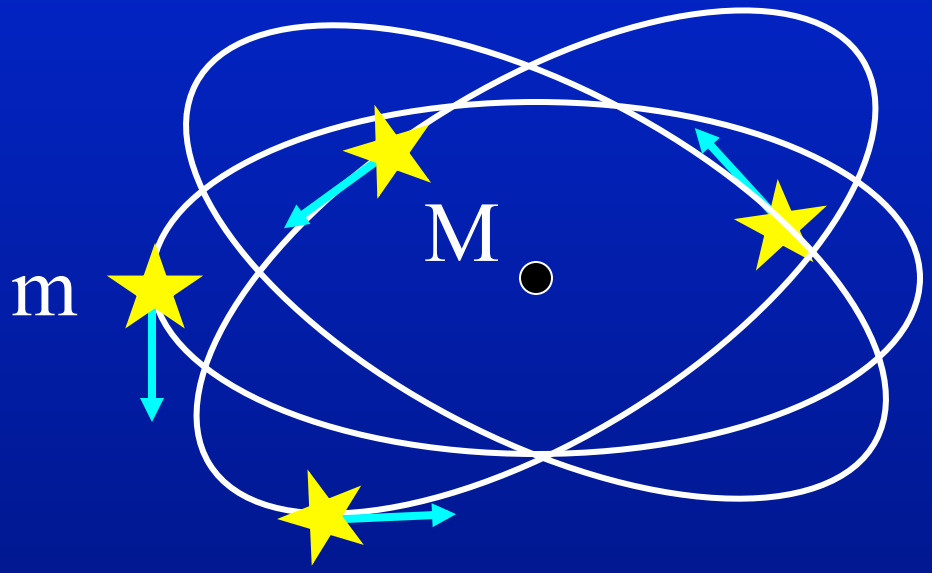


Black Hole Mass

2 x Kinetic Energy + Potential Energy = 0

$$mv^2 - GmM_{BH}/R = 0$$

$$M_{BH} = v^2 R/G$$



Virial Theorem
- for systems in equilibrium

Black Hole Virial Mass

$$M_{BH} = v^2 R / G$$

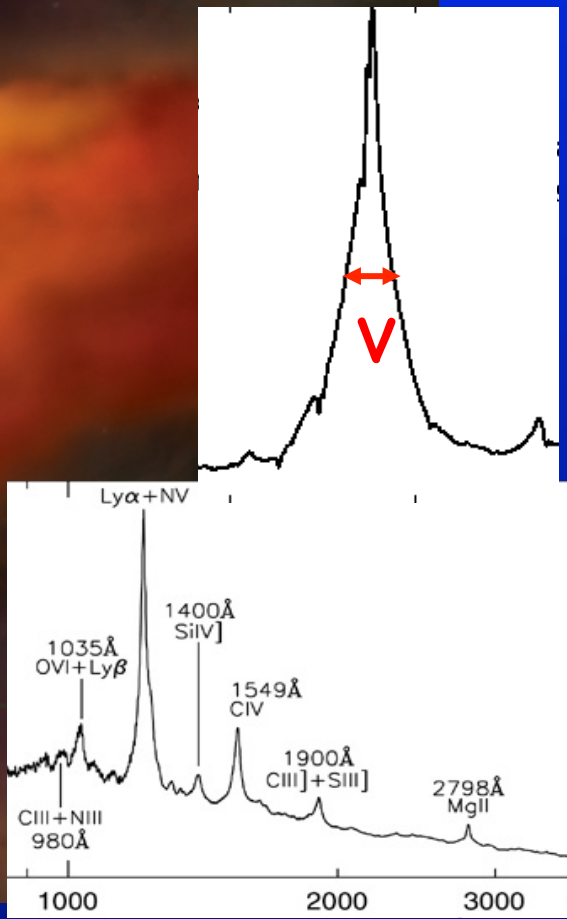
Face-on

Edge-on

Broad Emission Line Gas ("clouds")

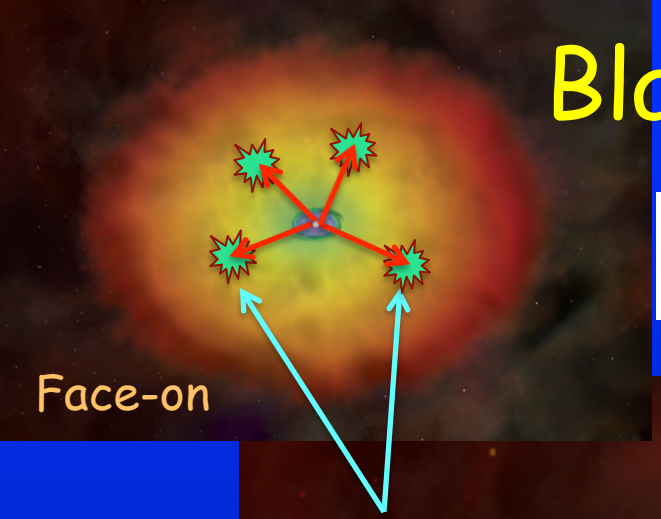
Fast moving gas

BH



Black Hole Virial Mass

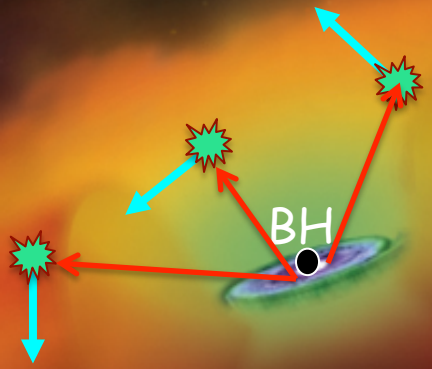
$$M_{BH} = v^2 R / G$$



Broad Emission Line Gas ("clouds")

- ionized by photons from accretion disk

It takes time for light to travel to the BEL gas from the accretion disk



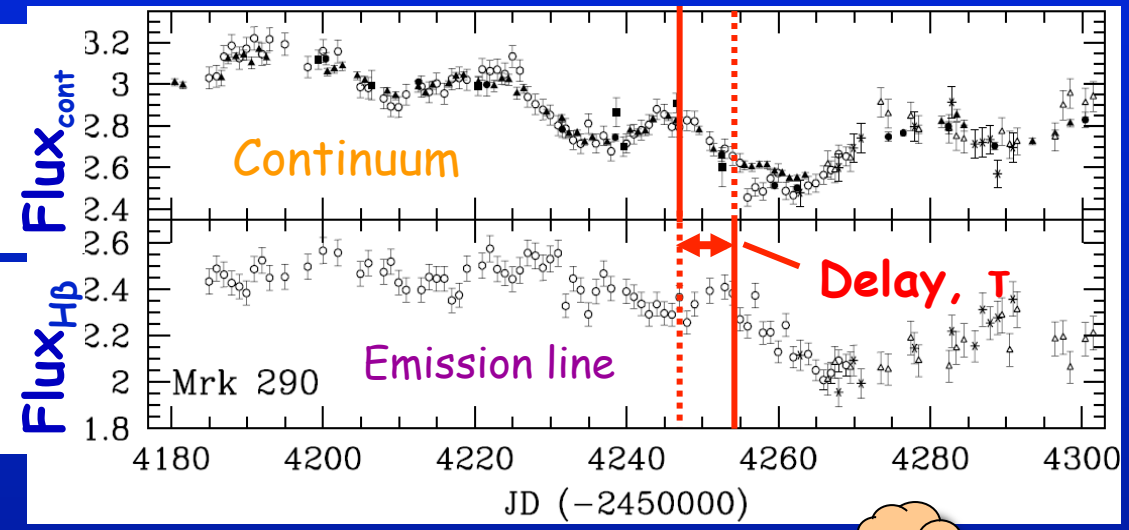
We can measure this time delay (or distance) with variability studies

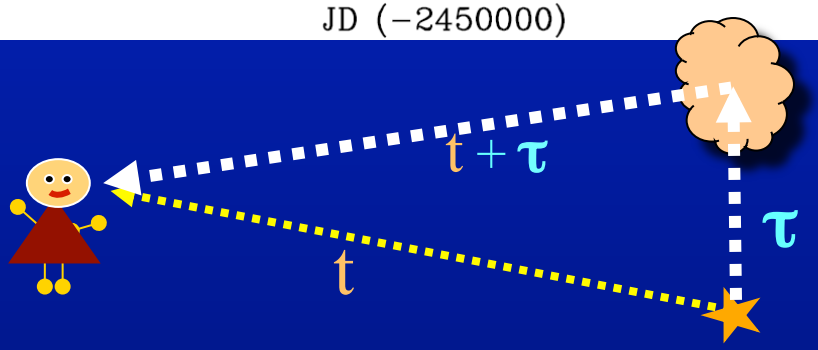
$R_{BLR} = c\,\tau$

AGN Virial Mass Estimates

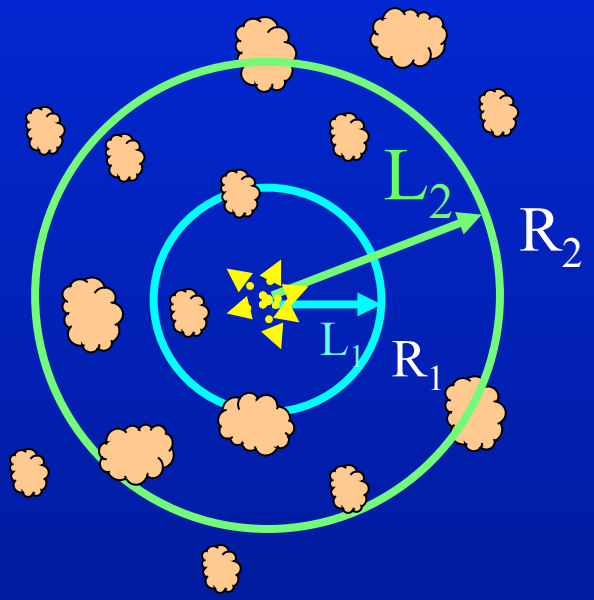
$$M_{BH} = v^2 R_{BLR}/G$$

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



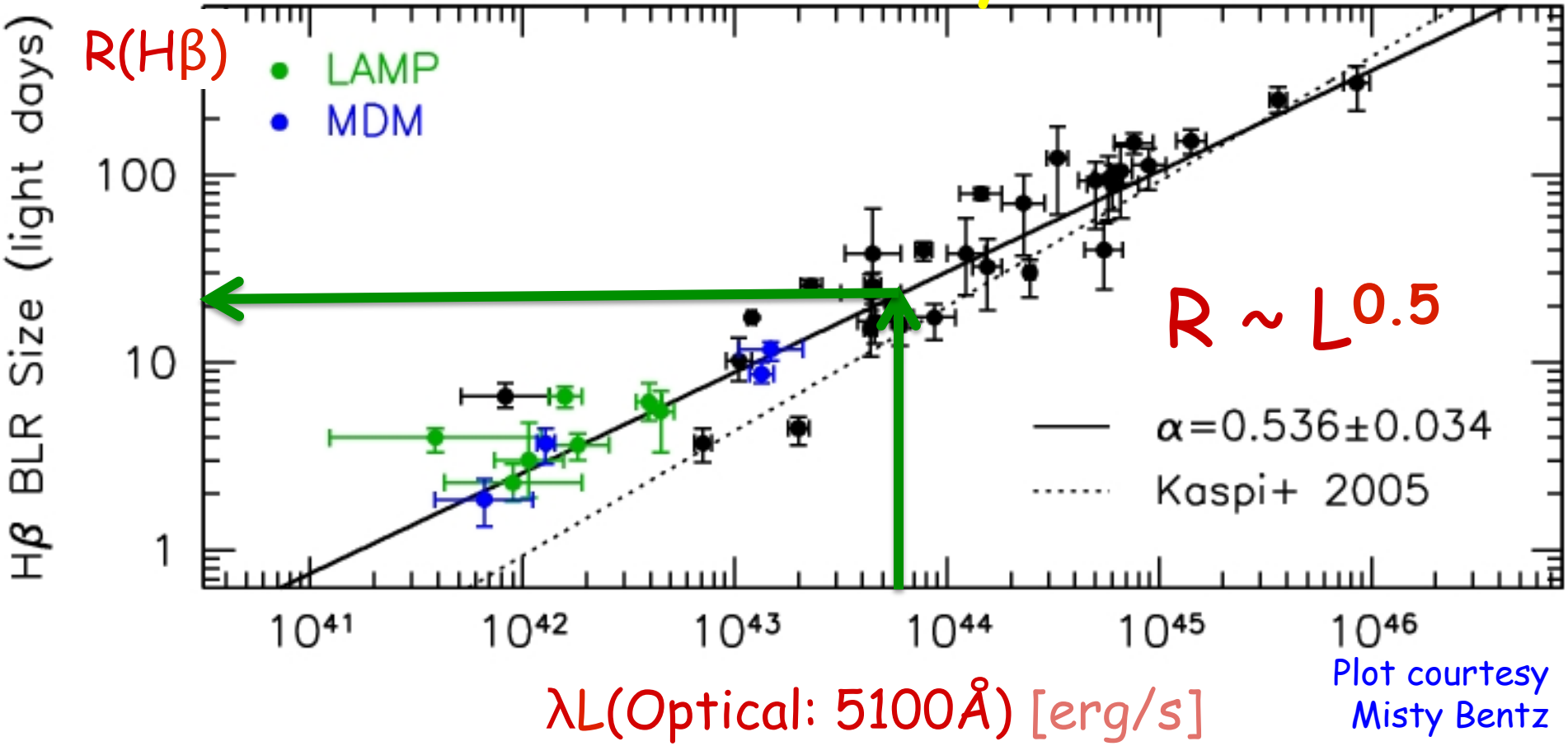


- Radius – Luminosity Relation:



Dark Cosmology Centre

Radius – Luminosity Relation



We thus have a measure of R for Hβ

Scatter: 0.13dex (Bentz+ 2013)

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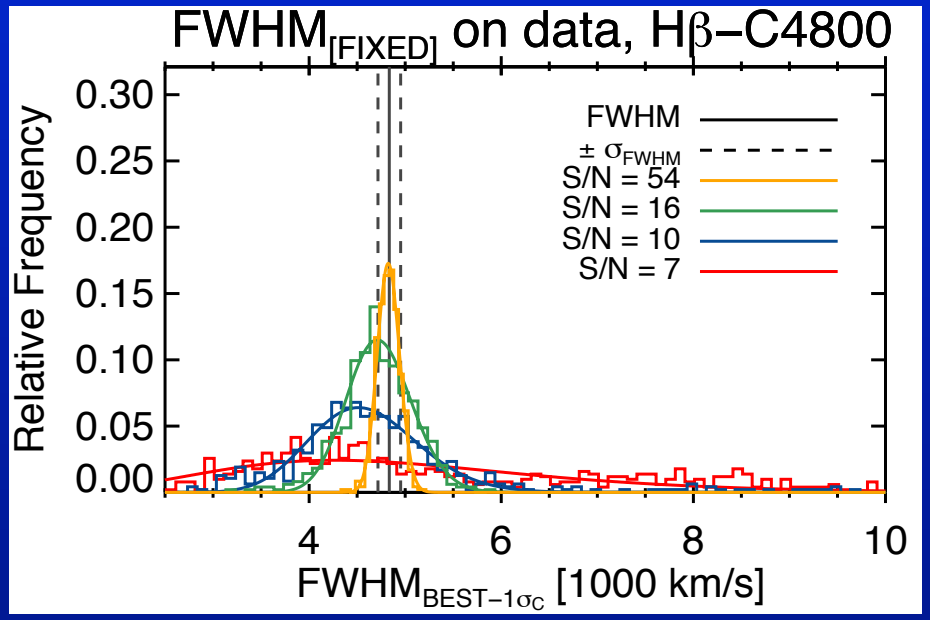
Using Broad Emission Lines to Estimate the Black Hole Mass: what we know

- Three lines: CIV 1549Å, MgII 2800Å, Hβ
- Multiple lines preferable – no line is perfect
- Line shape and measurement method matters!

S/N dependence tested on data with resolution ~2000 or higher (SDSS or better)

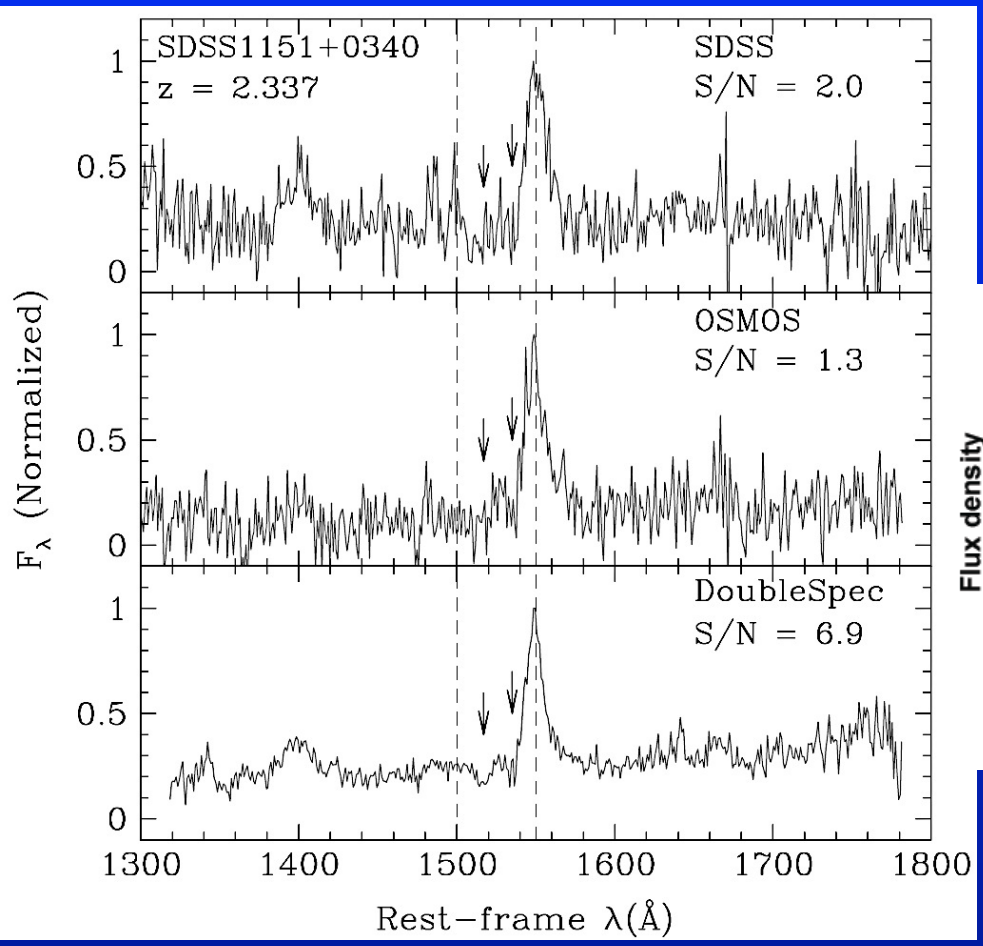
Need :

- high S/N spectra (~20 per pix) [Denney+ 2009, Juel Jensen+ in prep.]
- Medium-to-high resolution to ID absorption lines



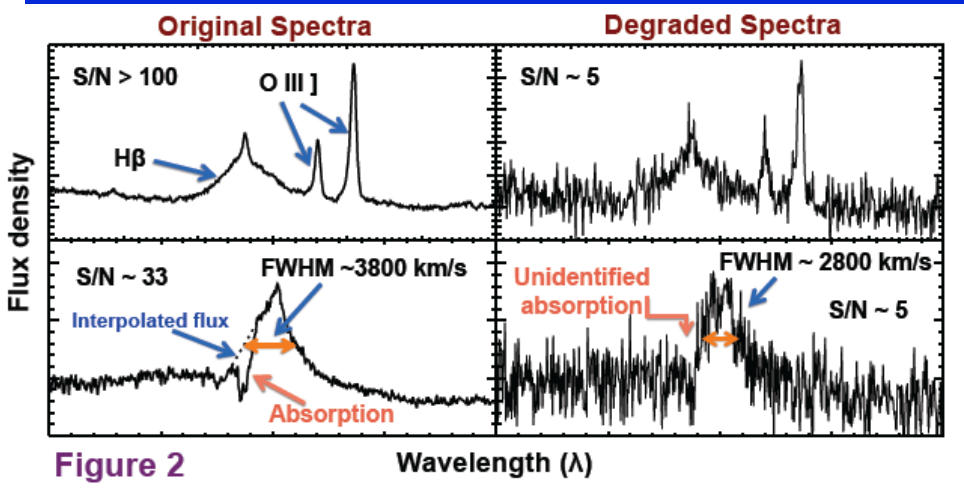
(Juel Jensen +MV, in prep.)

Undetected Absorption skews the width measurements



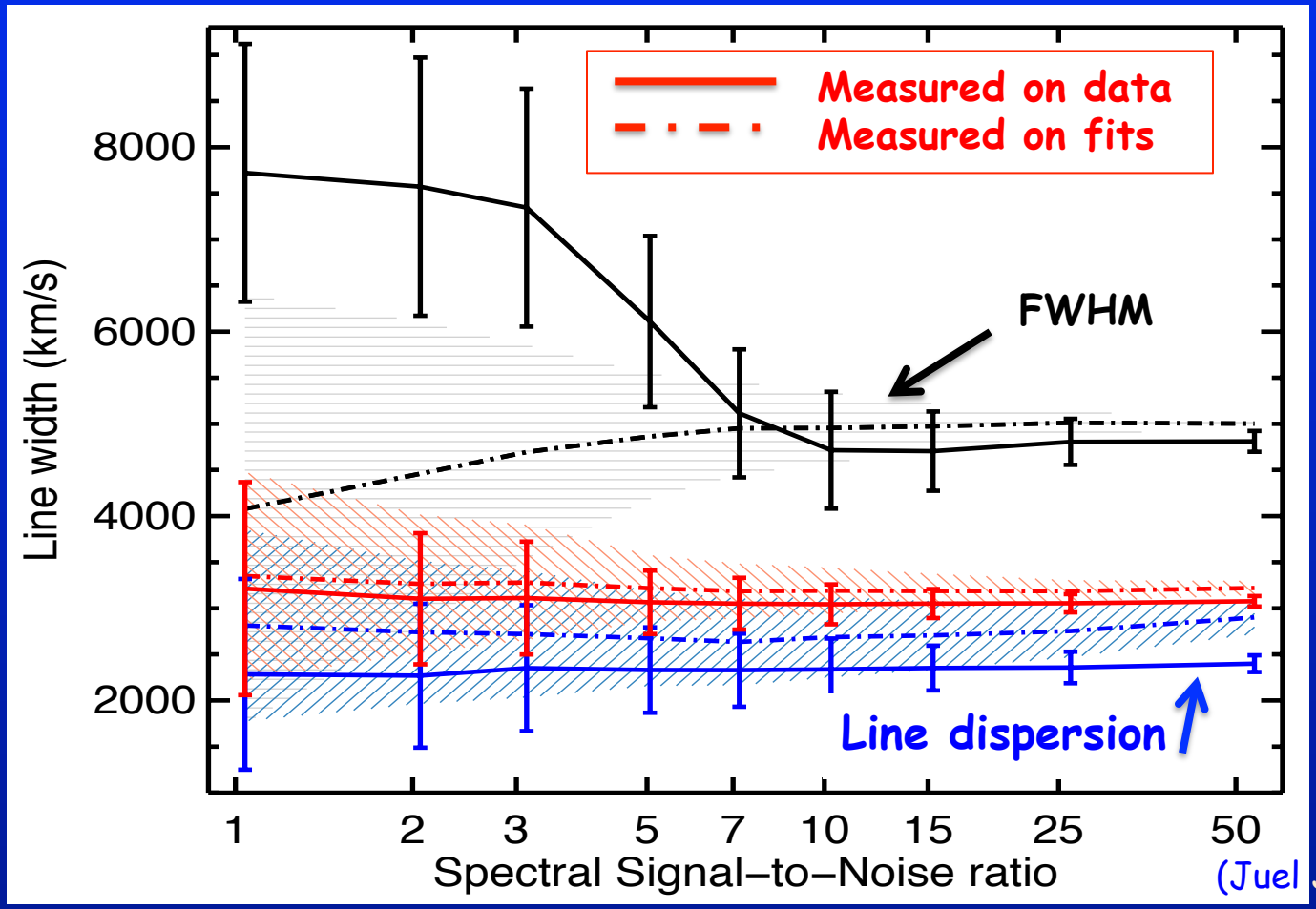
(Assef + 2011)

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



(Juel Jensen +MV 2012)

Measurement method and Quality matters



Mean & std-dev of 500 Monte Carlo realizations per S/N level

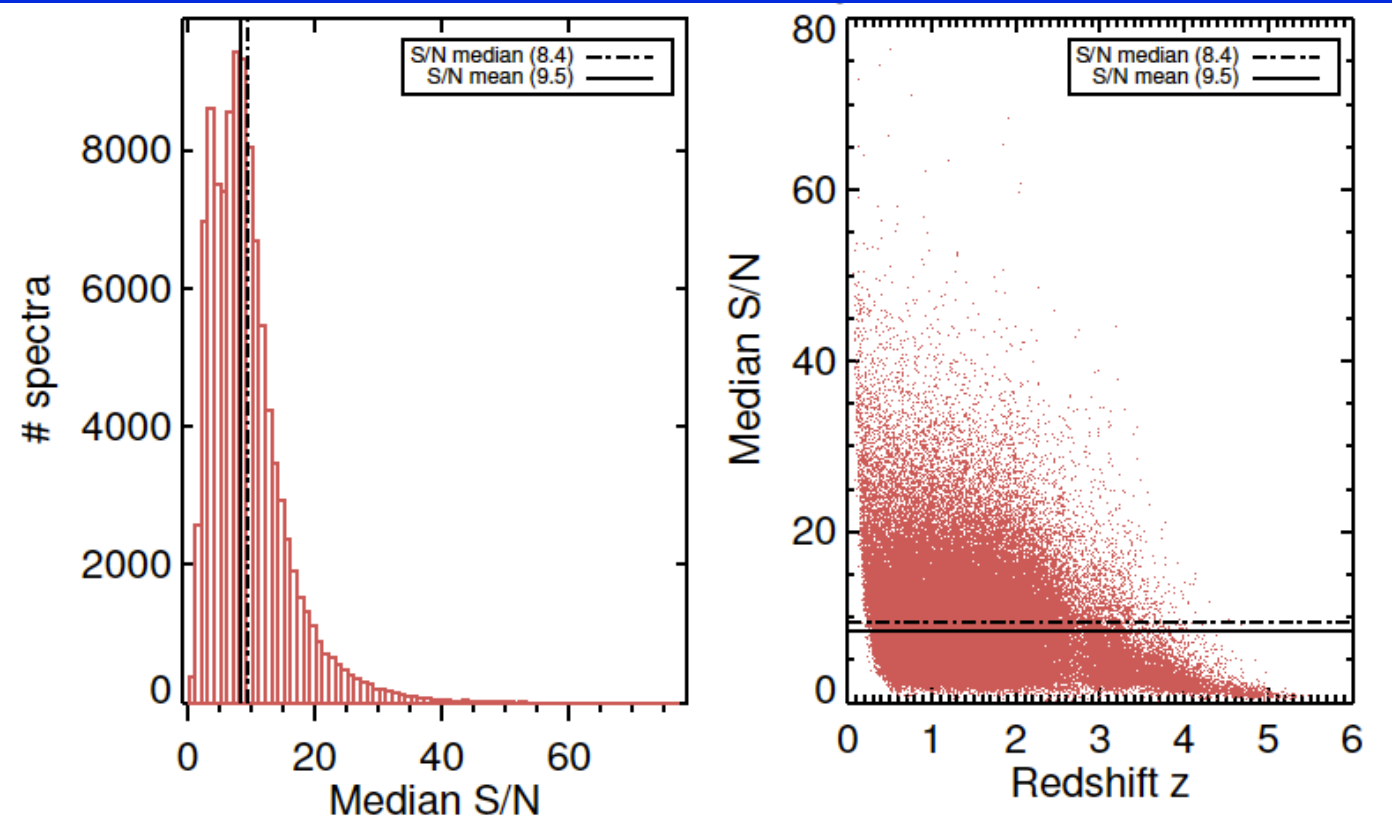
(Juel Jensen +MV, in prep)

Line Width Parameter Matters: FWHM vs line dispersion

Uncertainties in Mass Estimates

Be Aware:

- Data Quality Matters (Denney+ '09, '13; MV+ '11)
- Many surveys have mediocre S/N, even SDSS.....



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

Overview

- Why do we need black hole mass determinations?
- Expected quasar counts with GAIA
- What can we *also* learn from black hole masses?

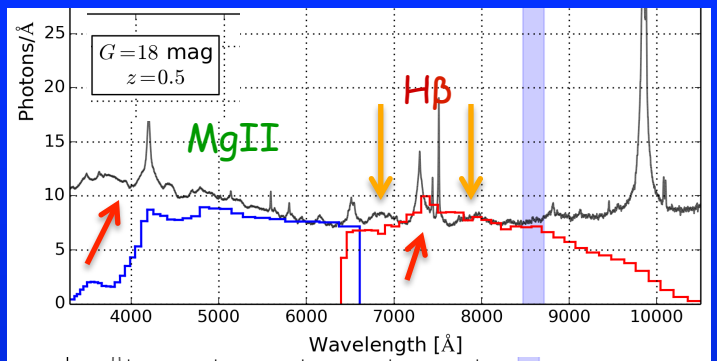
- Mass determination of super-massive black holes
  - Requirements and implications
- What can we learn from GAIA data?

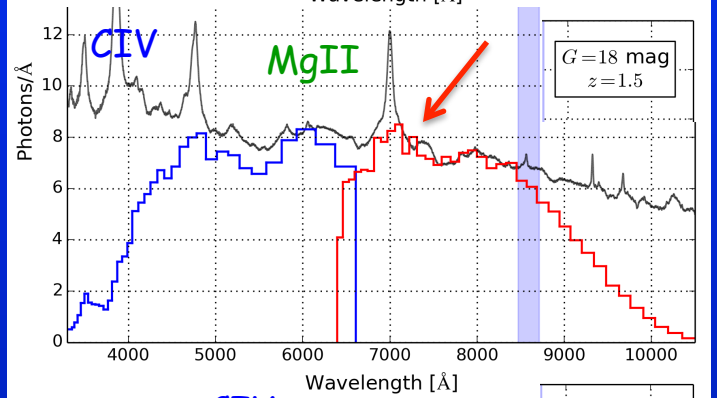
Simulated GAIA data

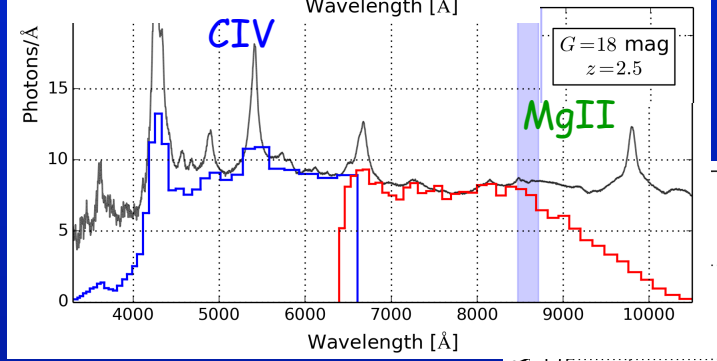
(Proft & Wamsganss 2015)

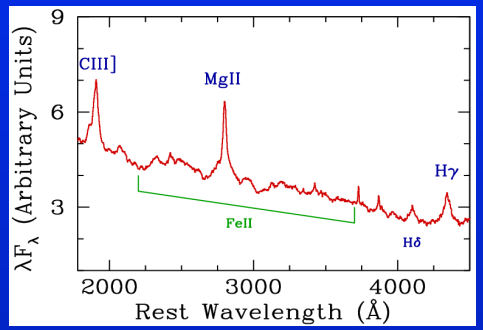
Complications:

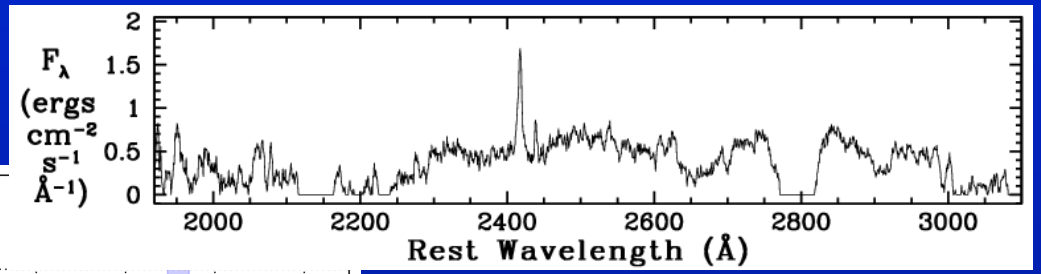
- The low resolution smears the line shapes
- Hβ blends with [OIII] lines
- MgII blends with FeII
- Requires template fitting



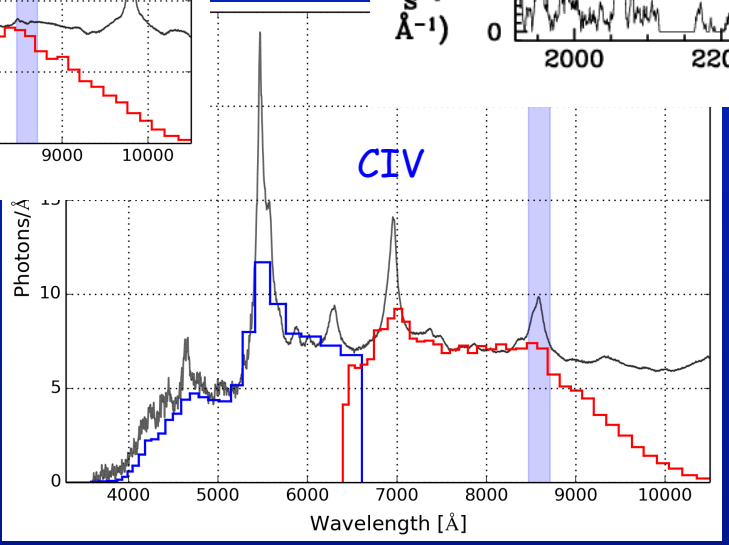








(MV+Wilkes 2001)

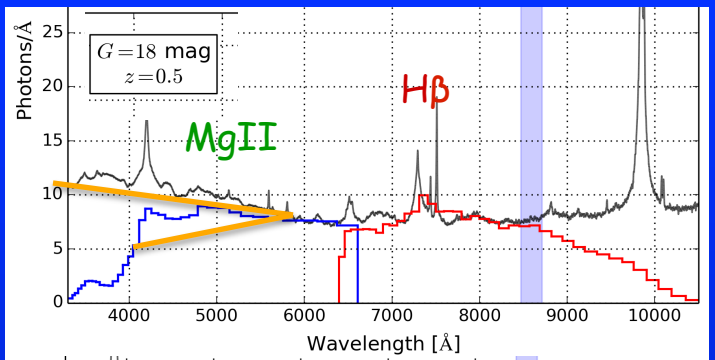


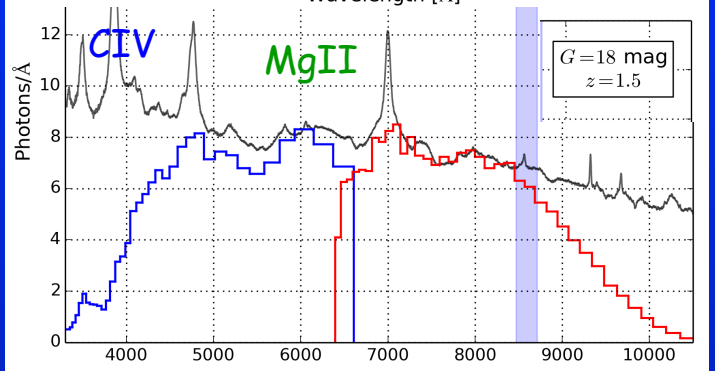
Blue & Red Photometers

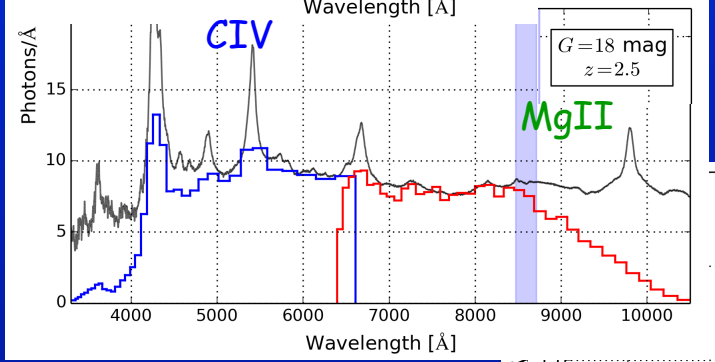
- Rebinned quasar template (Vanden Berk+ 2004)
- 5 exposures stacked

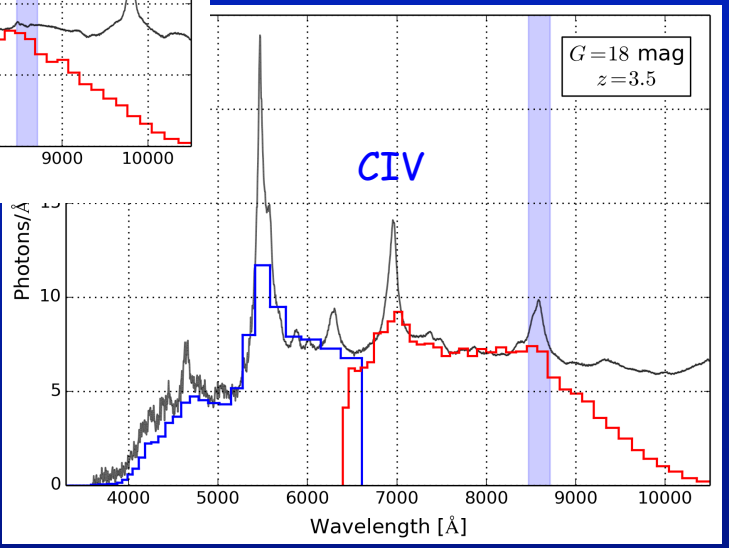
Simulated GAIA data

(Proft & Wamsganss 2015)









Issues to consider:

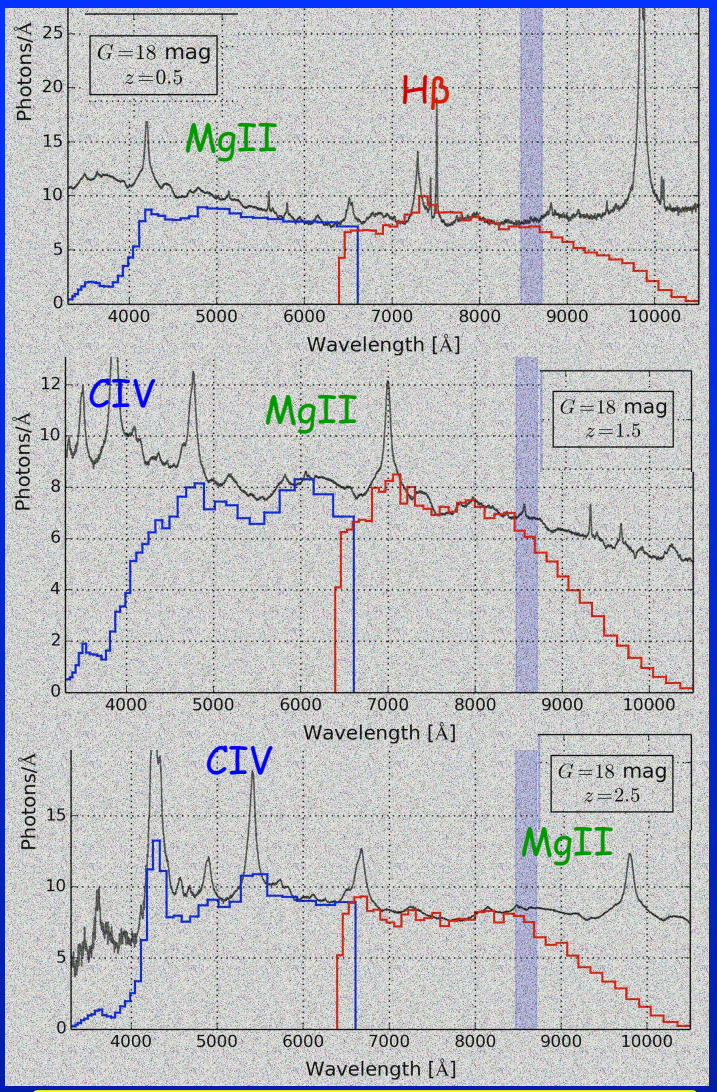
- The low resolution smears the line shapes
- Hβ blends with [OIII] lines
- MgII blends with FeII
- How to identify and isolate the Hβ and MgII lines?
- Direct measurements not useful
  - Can correct for sensitivity accurately?

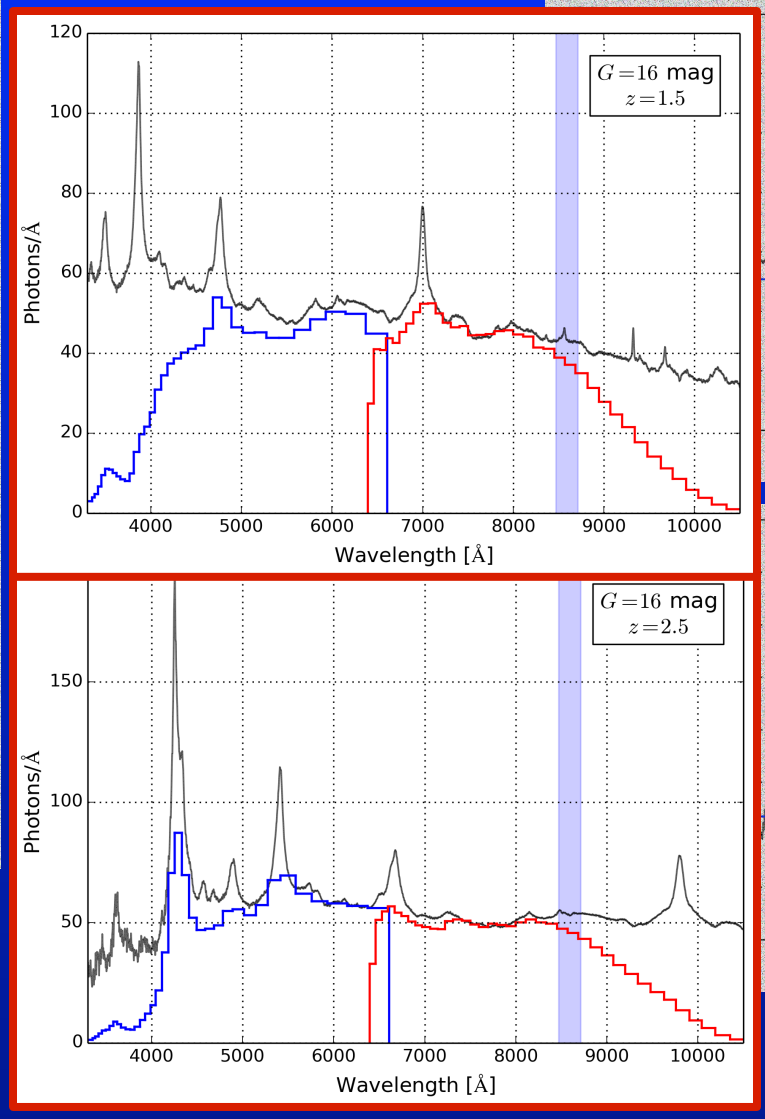
Blue & Red Photometers

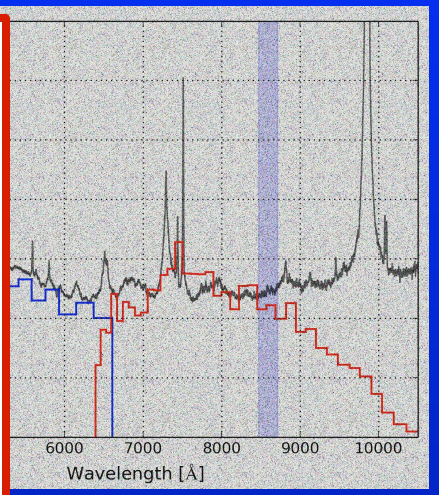
- Rebinned quasar template (Vanden Berk+ 2004)
- 5 exposures stacked

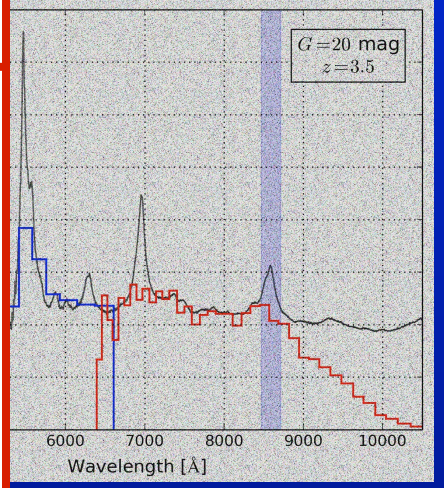
Simulated GAIA data

(Proft & Wamsganss 2015)







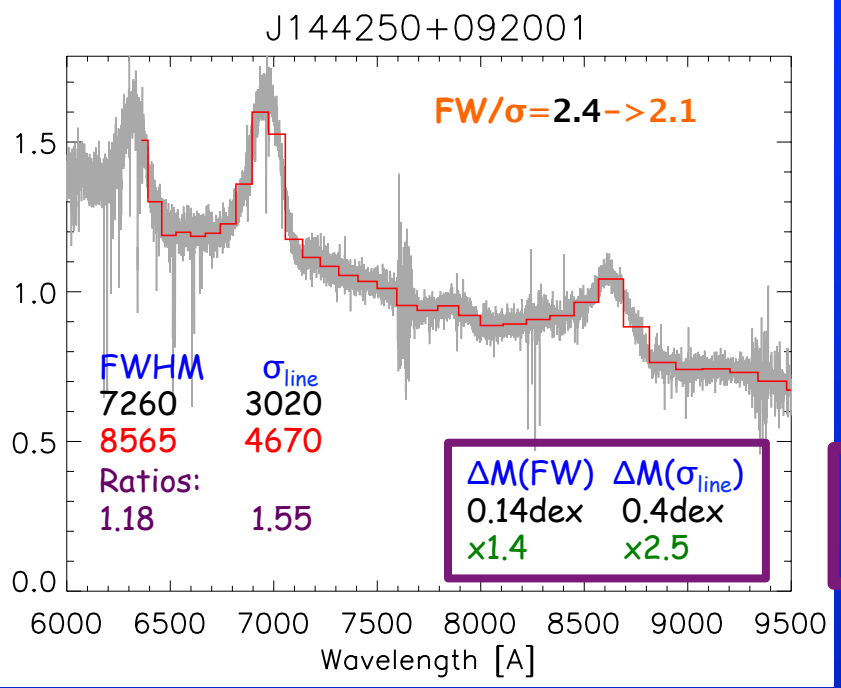


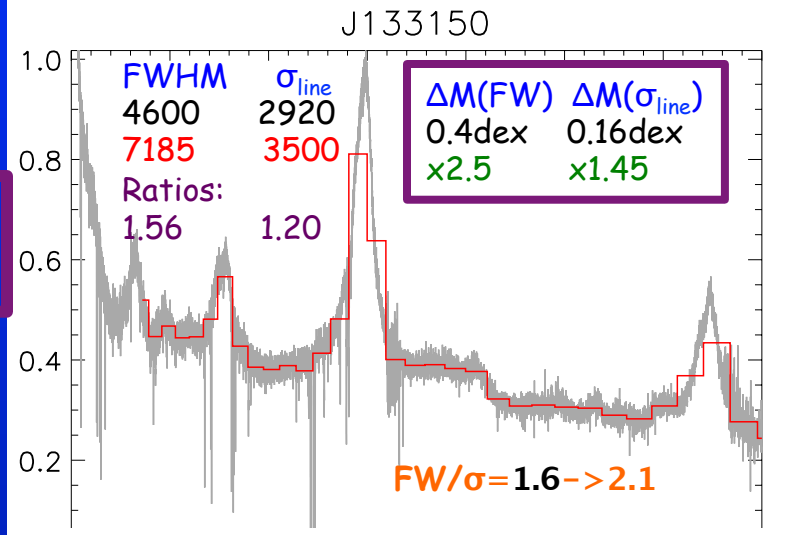
The low resolution is an issue, also for bright quasars

Resolution Effects

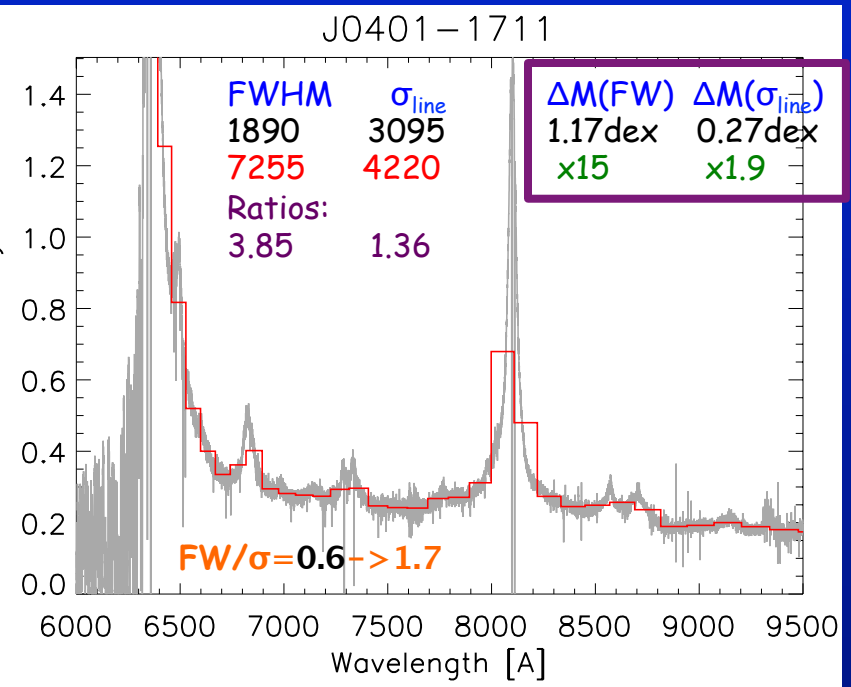
M_{BH} increases by factors ~1.5-15 (FWHM) and by factors ~1.5-3 (Line dispersion)

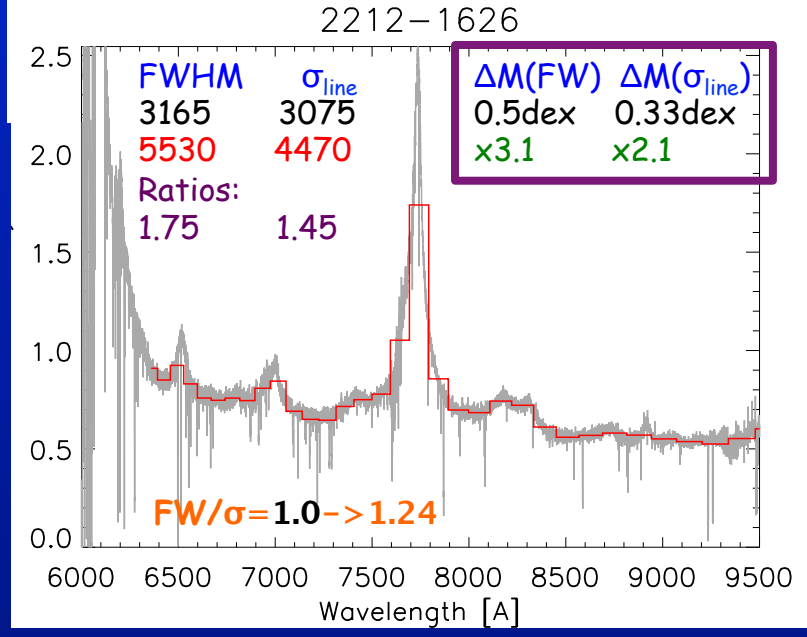
CIV 1549Å Line





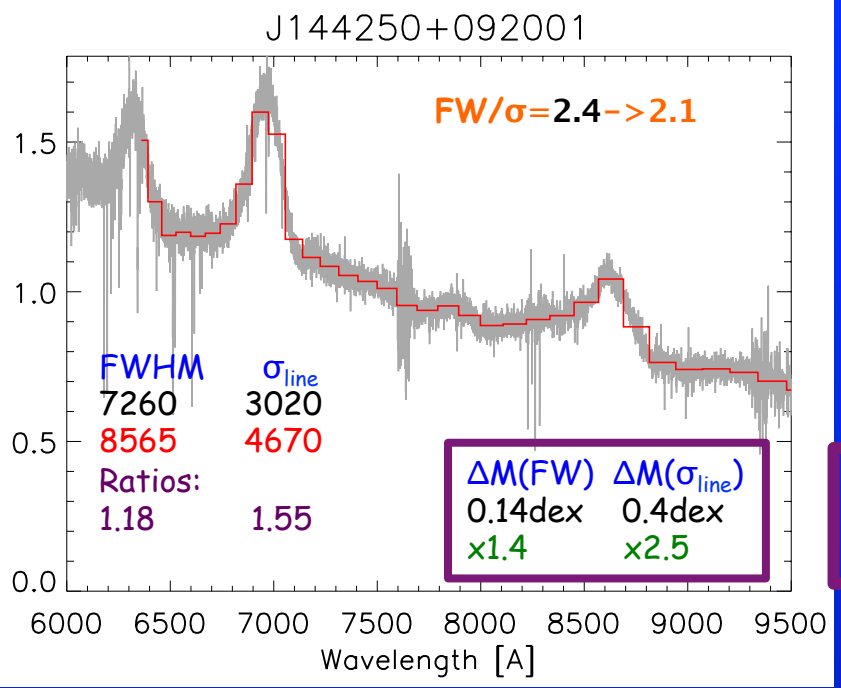
Xshooter spectra-> Red Photometer `spectra'



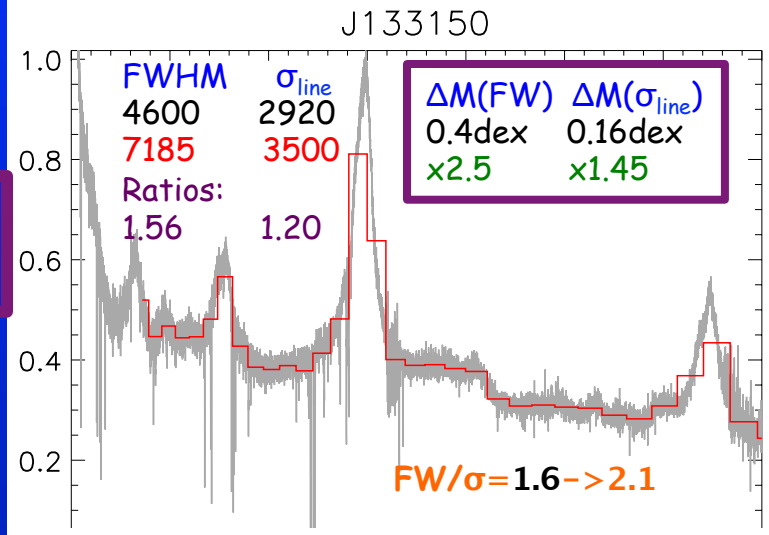


Resolution Effects

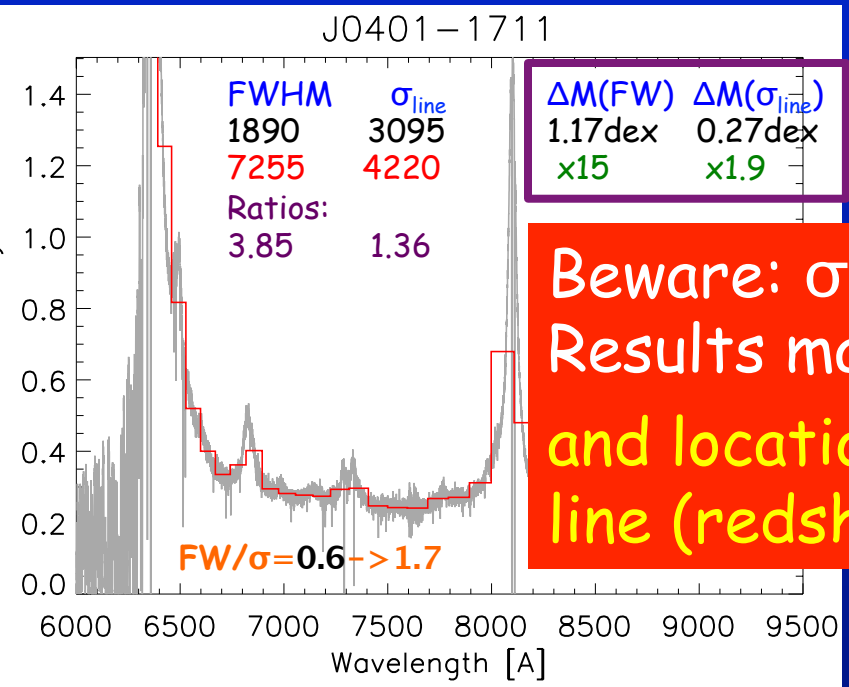
M_{BH} increases by factors ~1.5-15 (FWHM) and by factors ~1.5-3 (Line dispersion)

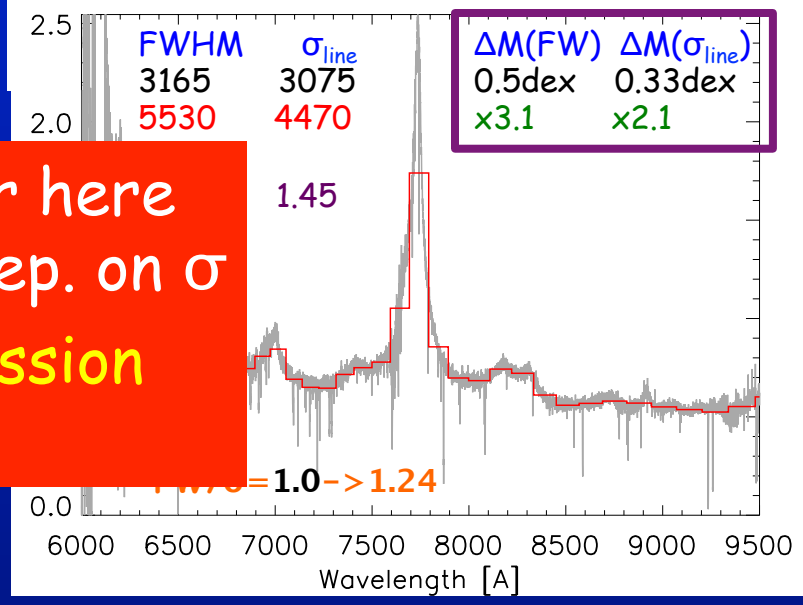


CIV 1549Å Line



Xshooter spectra-> Red Photometer `spectra'

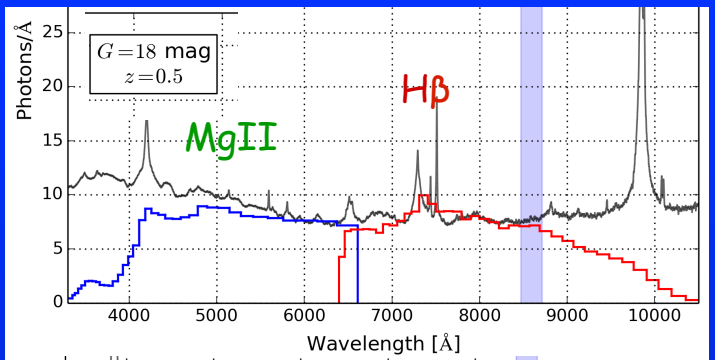


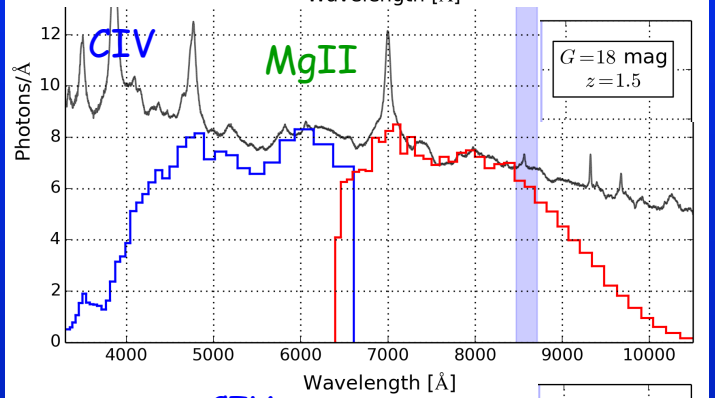


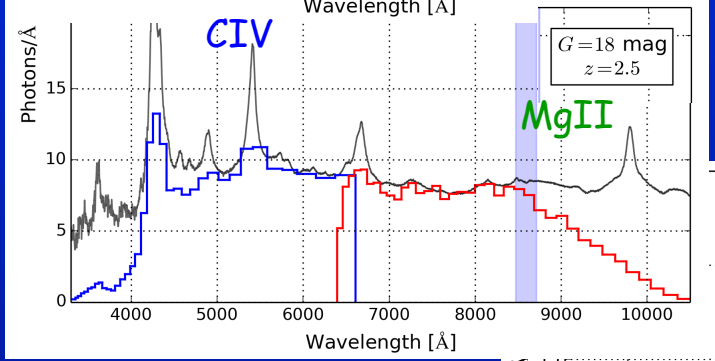
Beware: σ is similar here
Results may vary dep. on σ
and location of emission line (redshift)

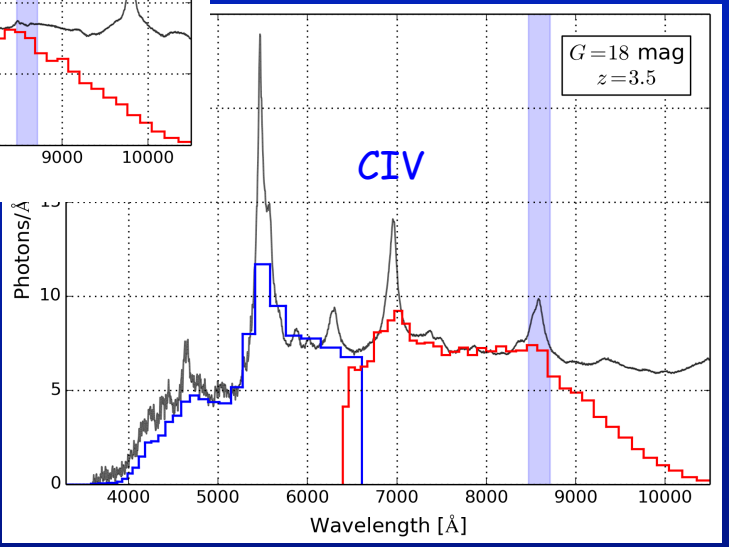
Simulated GAIA data

(Proft & Wamsganss 2015)









Issues to consider:

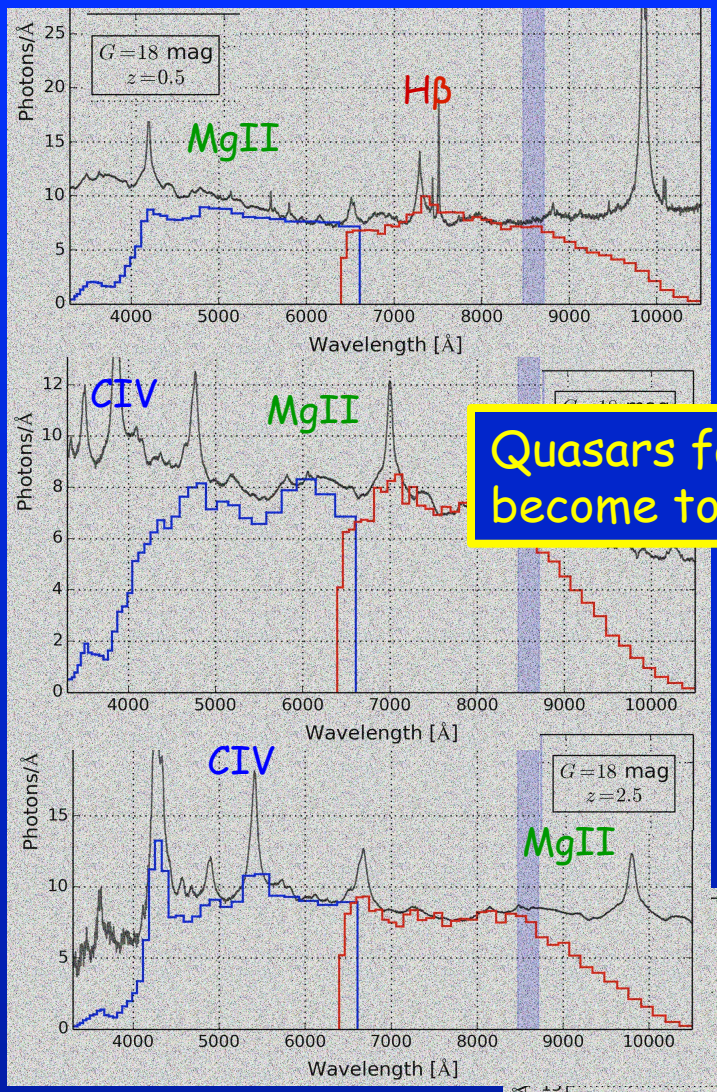
- Certain redshift ranges problematic
- Template modeling is needed
  (incl. range of line shapes and widths)
- Recovering with template modeling is non-unique so mass estimates will be uncertain
- Simulations needed to quantify uncertainties (incl. S/N, blending, sensitivity to line shape, etc)
- Higher redshifts: more isolated CIV line

Blue & Red Photometers

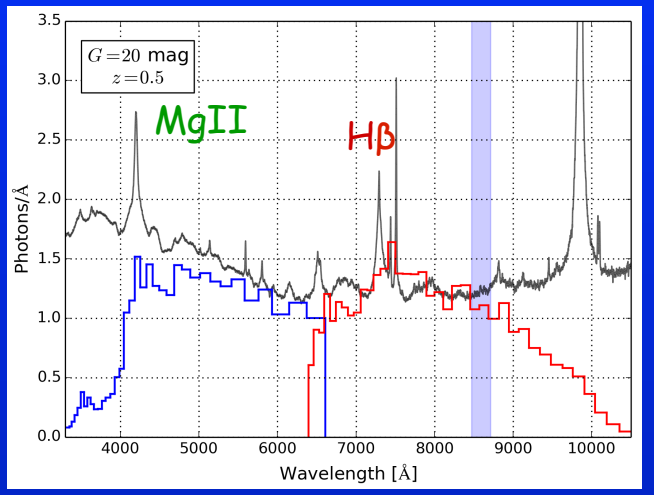
- Rebinned quasar template (Vanden Berk+ 2004)
- 5 exposures stacked

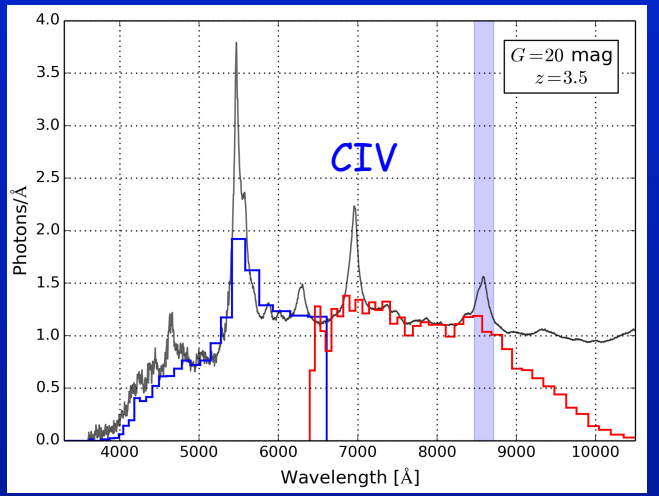
Simulated GAIA data

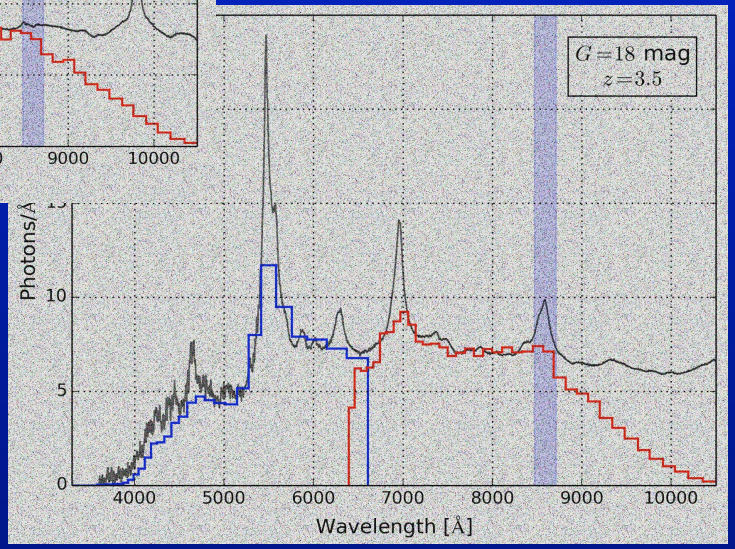
(Proft & Wamsganss 2015)



Quasars fainter than ~18.5mag become too noisy







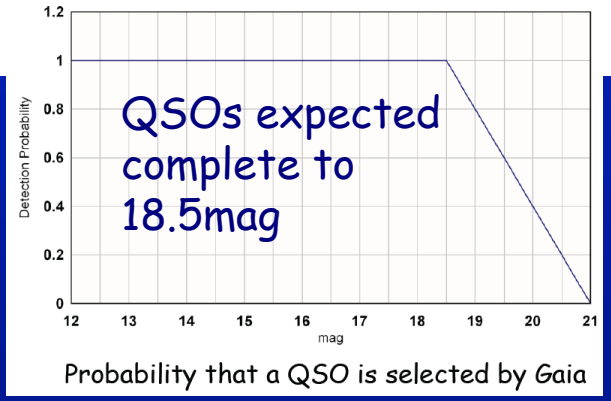
Blue & Red Photometers

GAIA Quasar Counts

V	density deg^{-2}	Full sky #	60% sky #	known #	new #	Slezak et.al #
18.0	1.5	63 000	38 000	12 500	25 500	40 000
18.5	3	126 000	75 000	23 000	52 000	113 000
19.0	8	340 000	200 000	45 000	155 000	314 000
19.5	15	630 000	380 000	85 000	295 000	680 000
20.0	22	920 000	550 000	115 000	435 000	1 200 000
20.5	30	1 260 000	750 000	140 000	610 000	1 700 000

Mignard, 2012, Mem. Soc. Ast. It.,

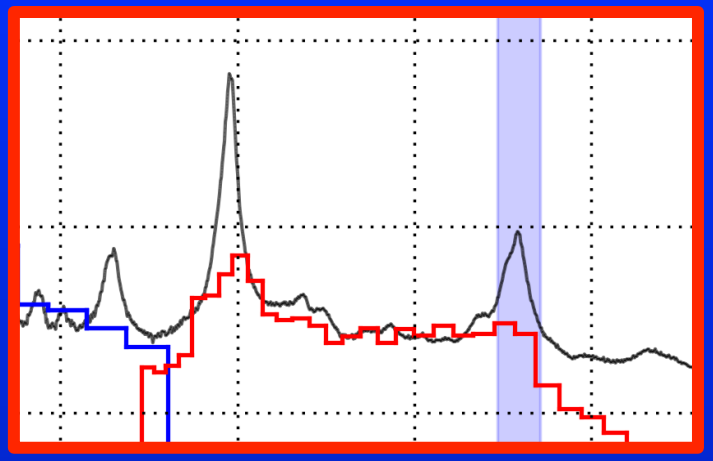
- The useful quasar sample is somewhat smaller
- Potential for gaining new knowledge still exists!

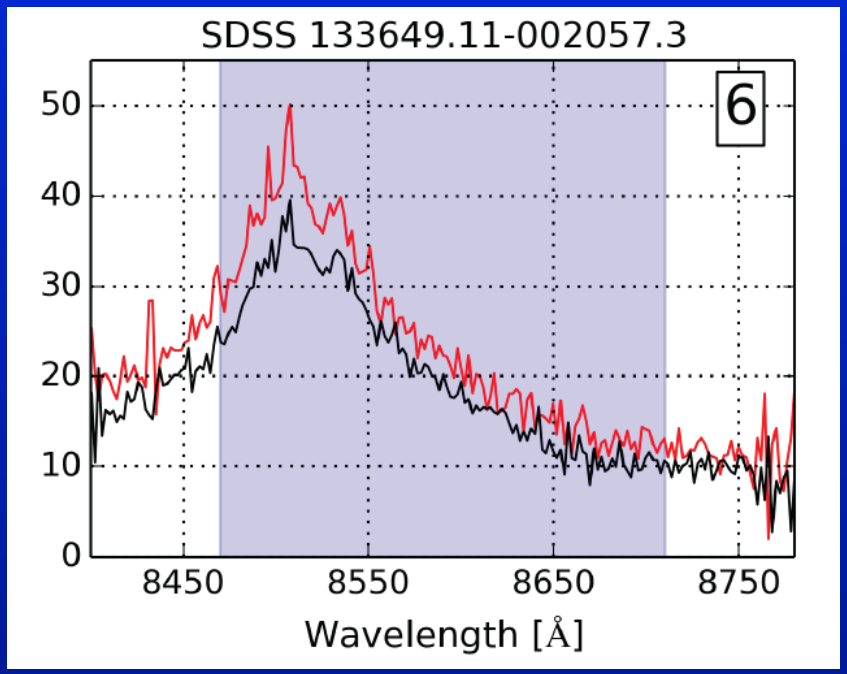


Probability that a QSO is selected by Gaia

Courtesy F. Mignard

Can we use RVS spectra?





(Proft & Wamsganss 2015)

- $\Delta\lambda = 230$Å

- Quasar broad lines typically span several hundred Å at zero intensity
- The full profile will not be accessible for accurate width measurement for any broad line.
- Black hole mass measurements with RSV is not possible

Bottom Line

- Mass estimates of supermassive black holes may be possible with photometers, but need
  - template modeling
  - extensive simulations to quantify uncertainties: line dispersion is potentially the better width measure
- Accuracy expected: factor ~6 or more
- Implications: limited use for studies of BH growth and quasar physics
- Best approach for quasar physics:
  - identify the quasars and their redshifts with GAIA
  - follow-up with other telescopes