Università degli Studi di Firenze

Coevolution of AGN, BHs and their host galaxies: the observational foundations

Beijing international summer school

"The physics and evolution of AGN"

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Outline of lectures

- Part 1: *Supermassive black holes in galactic nuclei: detections and mass measurements* (2 lectures)
- Part 2: *Scaling relations between black holes and their host galaxies* (2 lectures)
- Part 3: *The cosmological evolution of AGN and BHs* (2 lectures)
- **Part 4: *The observational signatures of coevolution* (2 lectures)**

Università degli Studi di Firenze

Dipartimento di Fisica e Astronomia
Sezione di Astronomia
Università di Firenze

Part 4: *the observational signatures of coevolution*

Black hole - galaxy coevolution

In previous lectures we have described in detail the following seminal results obtained in the last ~10 years:

- the detections of supermassive black holes in galactic nuclei
- the relations between M_{BH} and host spheroid properties
- the downsizing in the evolution of Active Galactic Nuclei
- the consistency between the mass function of local supermassive black holes and that of AGN remnants

We can infer that

- *supermassive black holes in nearby galaxies were grown during past AGN activity*
- *BH growth is tightly linked to galaxy growth and evolution, possibly due to AGN feedback on the host galaxy (co-evolution)*
- *BH/AGN are fundamental ingredients in galaxy evolution (→Cedric Lacey's lectures)*

BH-galaxy co-evolution

Here is one possible scenario for BH-galaxy coevolution.

1. Plenty of cold gas, frequent mergers and/or interactions: at the beginning SF and BH accretion proceed as fast as they can (Eddington limit).

   BH and stellar mass increase at high rate.

   BH and SF highly obscured by surrounding gas and dust.

2. When BH sizeable compared to host galaxy ($M_{BH} \sim 10^7$-$10^8\ M_\odot$), $L_{AGN} \sim L_{Edd}$ powerful enough to expel gas from galaxy (eg. Silk & Rees 98, King 03)

   BH growth and SF gradually reduces.

   At the end, most of the original gas is expelled and an unobscured type 1 AGN shines in a generally passive galaxy.

BH-galaxy co-evolution

3. Almost no gas left, BH growth and SF can occur only through gas and dust in stellar winds and/or accretion of pristine gas.

   Galaxy interactions or secular processes (eg. bars) can destabilize gas and make it available from BH growth or SF.

Local M_{BH}-galaxy relations are the result of the balance between AGN activity ($L_{Edd} \sim M_{BH}$), which tends to expel gas, and galaxy gravitational attraction ($E_{grav} \sim \sigma^4 R_e$), which tends to retain it.

The balance is found for $M_{BH} \sim 0.001\ M_{sph}$.

Open questions

- What process brings the gas into the bulge?
  - Is it mergers, secular processes (e.g. bars and the formation of pseudobulges), cold and/or hot accretion?
- What process brings the gas in the bulge from ~kpc scales to subpc scales for BH accretion?
- What process determines the fractions of gas transformed into stars and accreted onto the BH?
  - Why SFR/BHAR ~ 1000 ?
- What the process responsible for AGN feedback (if any) and what is the magnitude of its effects on the host galaxy?
- What comes first, the BH, the galaxy (stars) or are they co-eval?

The answers to these questions are still open, and we still do not have a complete and coherent observational and theoretical framework (see the review from Heckman 2009).

Black hole - galaxy coevolution ?

What are the observational evidences of this *standard* picture of BH-galaxy coevolution?

The first crucial step is how to measure BH masses at all redshifts:

- ⭐ *the "virial" BH masses*

We will then explore the relation between BH growth and galaxy evolution by studying

- ⭐ *the redshift evolution of M_{BH}-galaxy relations*
- ⭐ *the star formation activity in AGN hosts at high-z*
- ⭐ *the metallicity of AGN hosts ("integrated" star formation)*
- ⭐ *the observational evidences for AGN feedback*

Virial BH Masses

Single Epoch Virial BH Masses

M_{BH} from reverberation mapping ($\rightarrow R_{BLR}$, see Hagai Netzer's lectures) *does not depend on distance* ...

BUT is

- very demanding in terms of telescope time;
- difficult at high L and high z (small $\Delta F/F$, long ΔT, cosmological time dilation ...).

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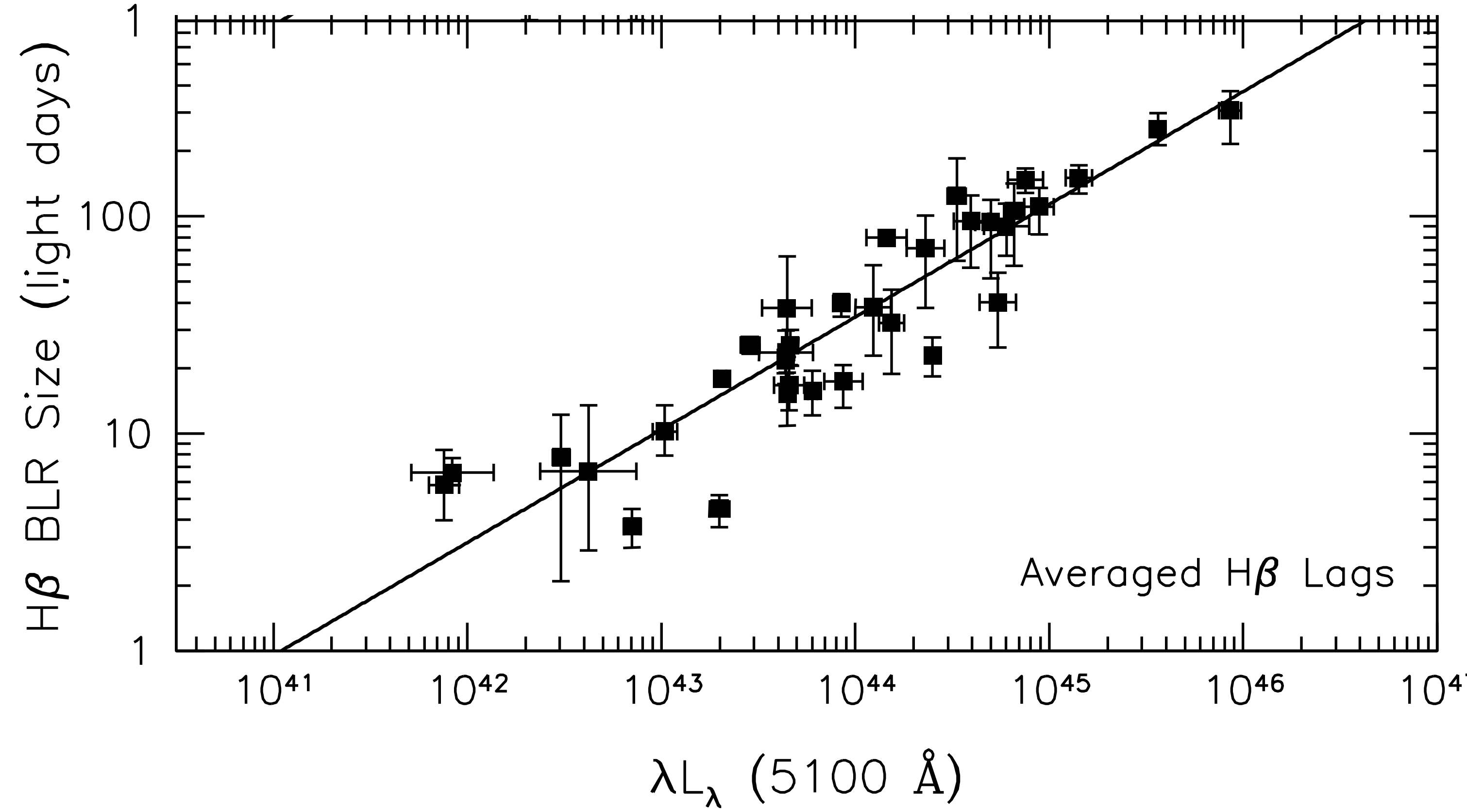
Bentz+09



Radius - Luminosity relation (Kaspi+2000,2005, Bentz+09): can estimate BLR size from continuum luminosity!

Single Epoch (SE) M_{BH}: combine line widths with continuum luminosity

Are consistent with Reverberation Mapping (RM) M_{BH} and with M_{BH}-σ/L correlation.

The BH mass ladder

(→Peterson 2002)

1

Spatially resolved
Gas & stellar Kinematics

Local universe (< 250 Mpc)

→ M_{BH}-σ,L,M correlations

calibration (Onken +04)

$\frac{M_{BH}(RM)}{M_{BH}}$ ~0.5 dex

2

Reverberation Mapping (RM)

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

Time expensive

→ R_{BLR}-L relation
(Kaspi +00, Bentz+09)

calibration (Vestergaard & Peterson 06)

$\frac{M_{BH}(SE)}{M_{BH}(RM)}$ ~0.4 dex

3

Virial BH masses
Type 1 AGNs only

Single Epoch (SE)

$$M_{BH} = \tilde{f}\,V^2 L^{\alpha}$$

The BH mass ladder (→Peterson 2002)

1 Spatially resolved Gas & stellar Kinematics → M_{BH}-σ,L,M correlations

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Virial BH masses

Type 1 AGNs only

3 Single Epoch (SE) $M_{BH} = \tilde{f}\, V^2 L^{\alpha}$

The effect of radiation pressure

Scattering of radiation from free electrons → classical Eddington limit

$$L \leq L_{Edd} = 4\pi G M_{BH} m_p c/\sigma_T \simeq 1.3 \times 10^{38} \left(\frac{M_{BH}}{\mathrm{M}_\odot}\right) \mathrm{erg\,s^{-1}}$$

Radiation pressure generally negligible (except for $L \sim L_{Edd}$).
However, BLR clouds are not completely ionized
→ consider radiation force for the absorption of ionizing photons.
Assume BLR clouds are optically thick to ionizing radiation:

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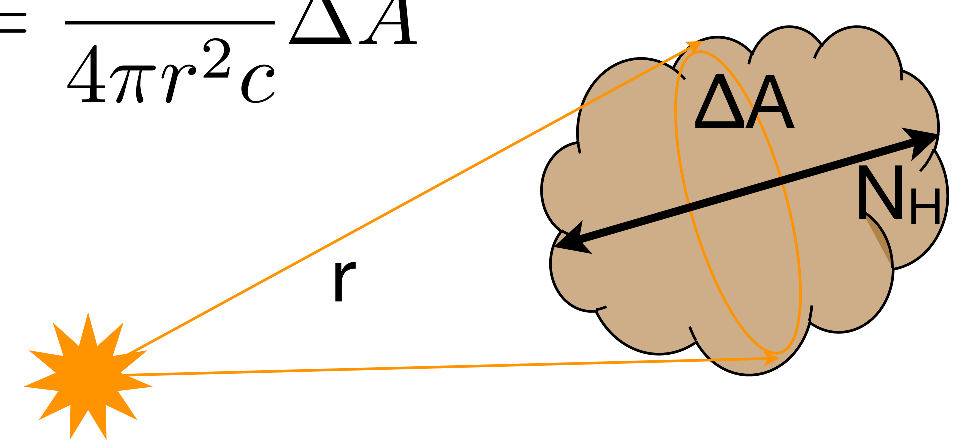
Assume BLR clouds are optically thick to ionizing radiation:

$$F = \int_{\nu_0}^{+\infty} \frac{L_\nu/h\nu}{4\pi r^2} \left(1 - e^{-\tau_\nu}\right) \Delta A \, \frac{h\nu}{c} d\nu = \frac{L_{ion}}{4\pi r^2 c} \Delta A$$



ΔA - cloud surface exposed to ionizing radiation
N_H - cloud column density

Circular orbits: $$\frac{V^2}{r} = \frac{G M_{BH}}{r^2} \left(1 - \frac{a}{4\pi\, G\, c\, m_p\, N_H\, M_{BH}} L\right) \qquad a = \frac{L_{ion}}{L}$$

The effect of radiation pressure

Adopted virial relation:

$$f\,V^2 = \frac{G\,M_{BH}}{r}$$

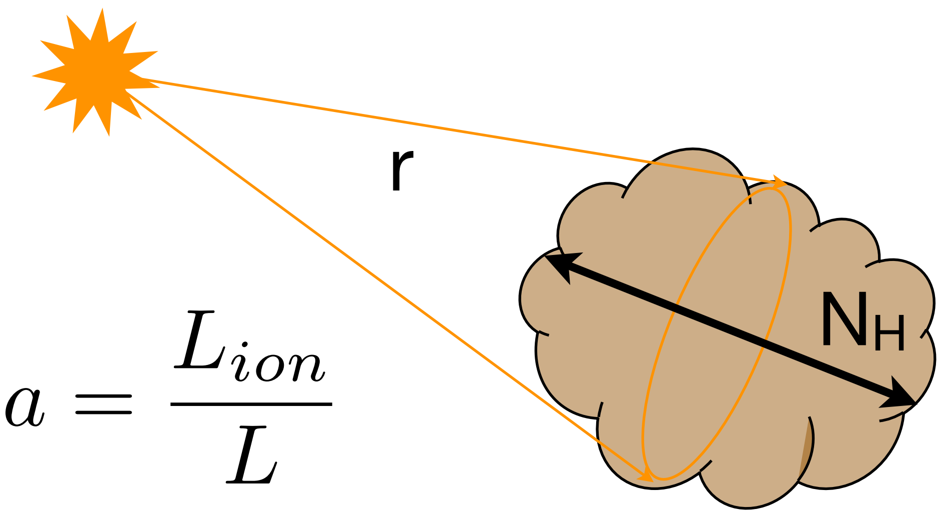
Marconi+08,09

The effect of radiation pressure

"Corrected" virial relation:

$$f\,V^2 = \frac{G}{r}\left(M_{BH} - \frac{a}{4\pi\,G\,c\,m_p\,N_H}\,L\right)$$

$$a = \frac{L_{ion}}{L}$$



BLR photoionized → radiation force due to absorption of ionizing photons

BLR clouds as "test" particles, optically thick to ionizing photons

Marconi+08,09

The effect of radiation pressure

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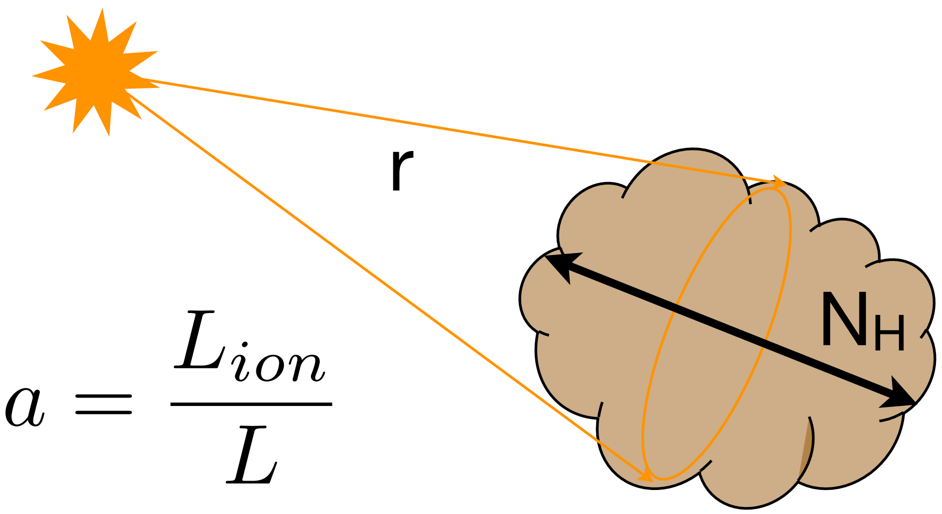

BLR photoionized → radiation force due to absorption of ionizing photons

BLR clouds as "test" particles, optically thick to ionizing photons

Corrected mass estimator:

$$M_{BH} = f\,\frac{V^2\,r}{G} + \frac{a}{4\pi\,G\,c\,m_p\,N_H}\,L$$

Calibrate virial BH masses using:

$$M_{BH} = f\,\frac{V^2 r}{G} + g\left(\frac{\lambda L_\lambda(5100)}{10^{44}\,\mathrm{erg\,s^{-1}}}\right)$$

Marconi+08,09

The effect of radiation pressure

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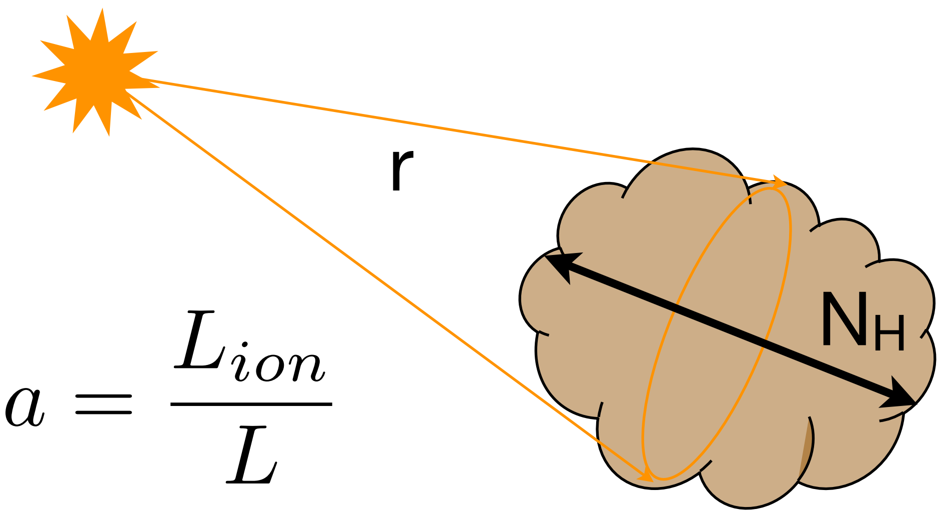

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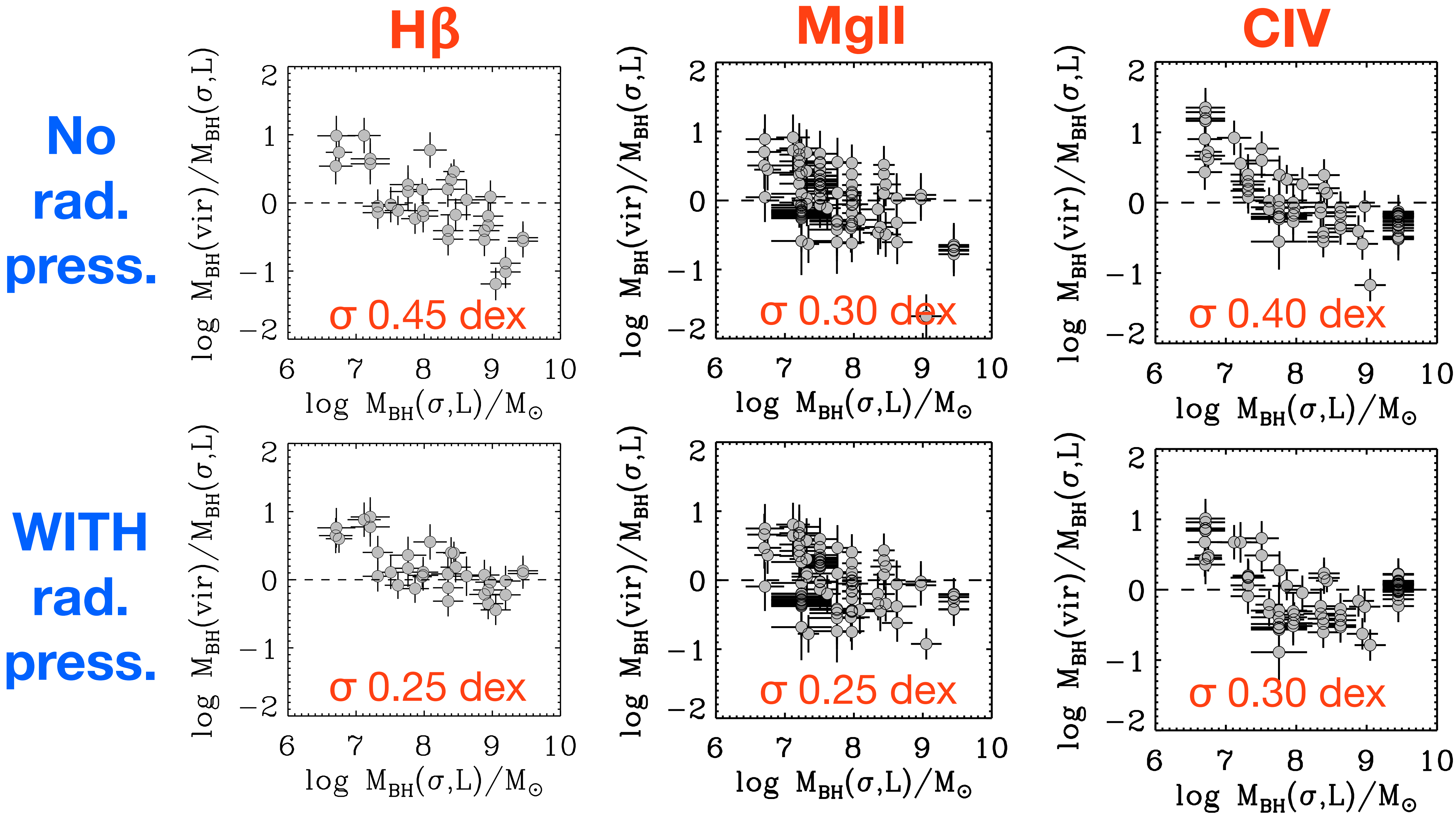
Marconi+08,09

Direct calibration of SE virial M_{BH}

calibrated directly using (true) M_{BH} estimated from M_{BH}-σ/L from Bentz+09



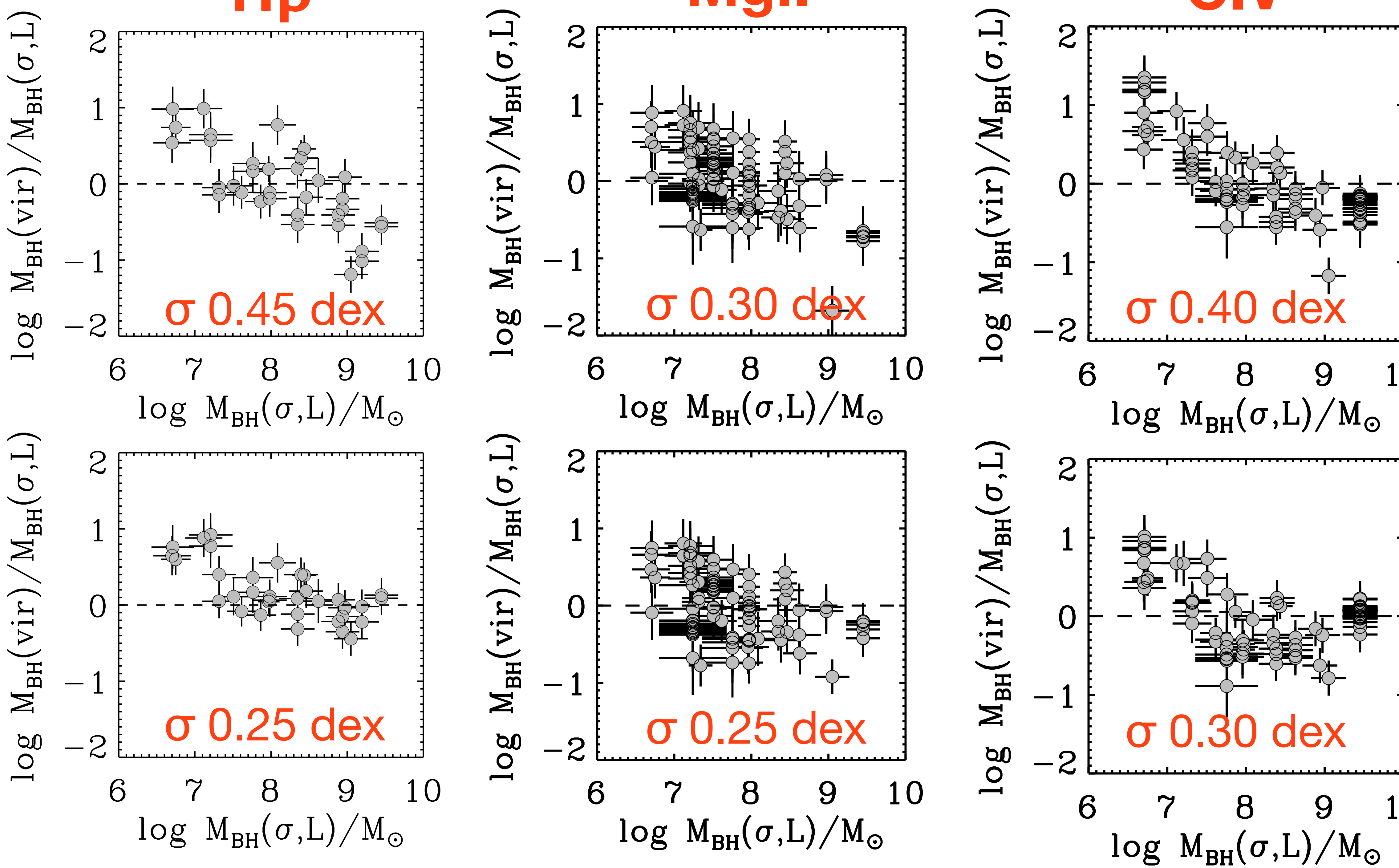
Direct calibration of SE virial M_{BH}

calibrated directly using (true) M_{BH} estimated from M_{BH}-σ/L from Bentz+09

Hβ **MgII** **CIV**

No rad. press.

WITH rad. press.



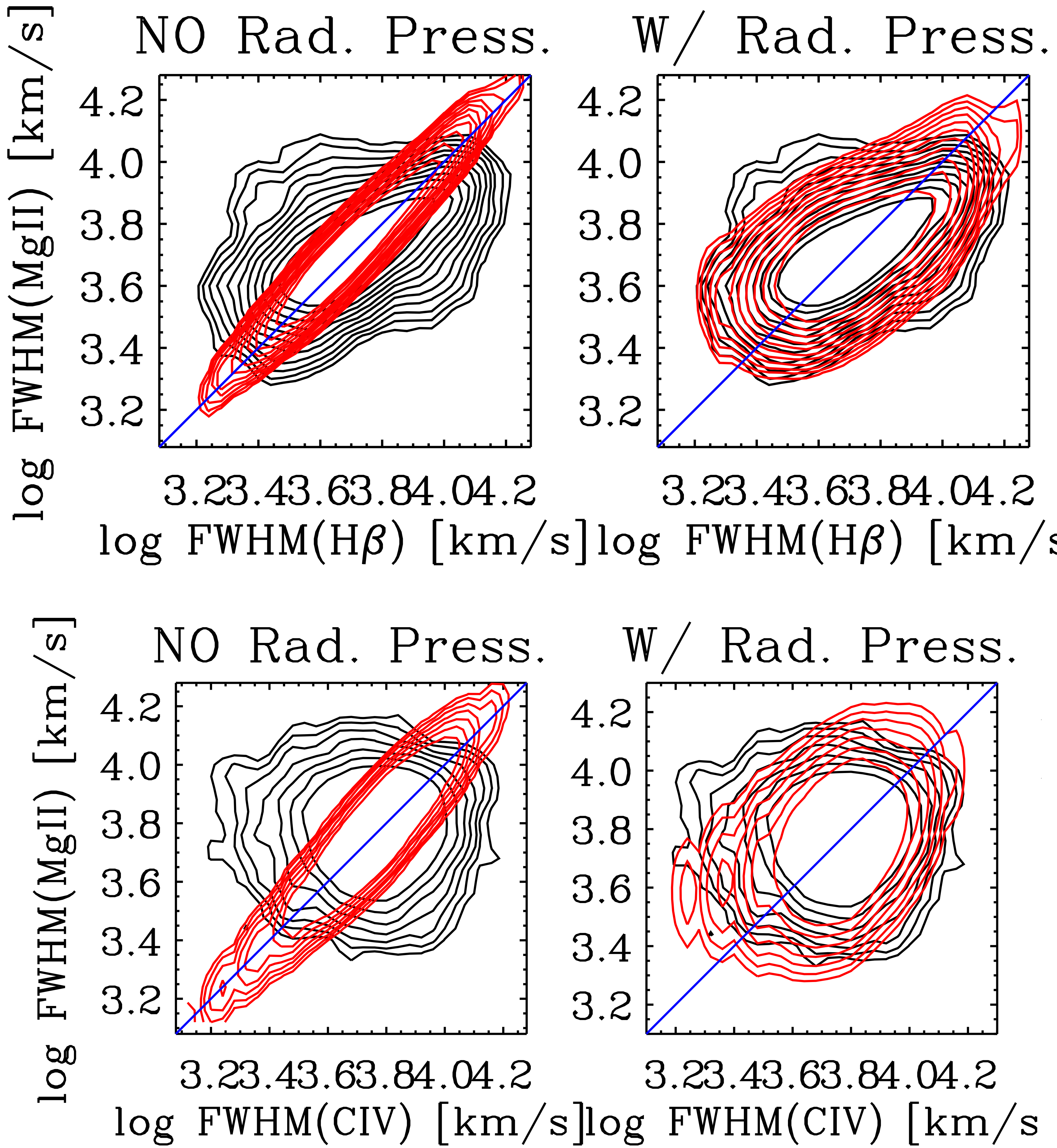
Toy model: g value → N_H

N_H~ 10^{23} cm^{-2} N_H~ $10^{23.6}$ cm^{-2} N_H~ 10^{23} cm^{-2}

Line widths

It is possible to compute the expected relations FWHM(Hbeta) vs FWHM(MgII) and FWHM(CIV) vs FWHM (MgII) and compare them with observed ones.

This is possible IF the virial M_{BH} estimates using these lines provide the same BH mass, with or without radiation pressure. The effect of radiation pressure can nicely explain the observed distributions.



Virial BH masses at high z

Virial M_{BH} from Hβ and CIV are affected by radiation pressure:

$$\frac{M_{BH}(H\beta)}{\mathrm{M}_\odot} = 10^{6.6}\left(\frac{FWHM(H\beta)}{1000\,\mathrm{km\,s}}\right)^2\left(\frac{\lambda L_\lambda(5100\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)^{0.5} + 10^{7.5}\left(\frac{\lambda L_\lambda(5100\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)$$

$$\frac{M_{BH}(CIV)}{\mathrm{M}_\odot} = 10^{6.4}\left(\frac{FWHM(CIV)}{1000\,\mathrm{km\,s}}\right)^2\left(\frac{\lambda L_\lambda(1350\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)^{0.5} + 10^{7.0}\left(\frac{\lambda L_\lambda(1350\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)$$

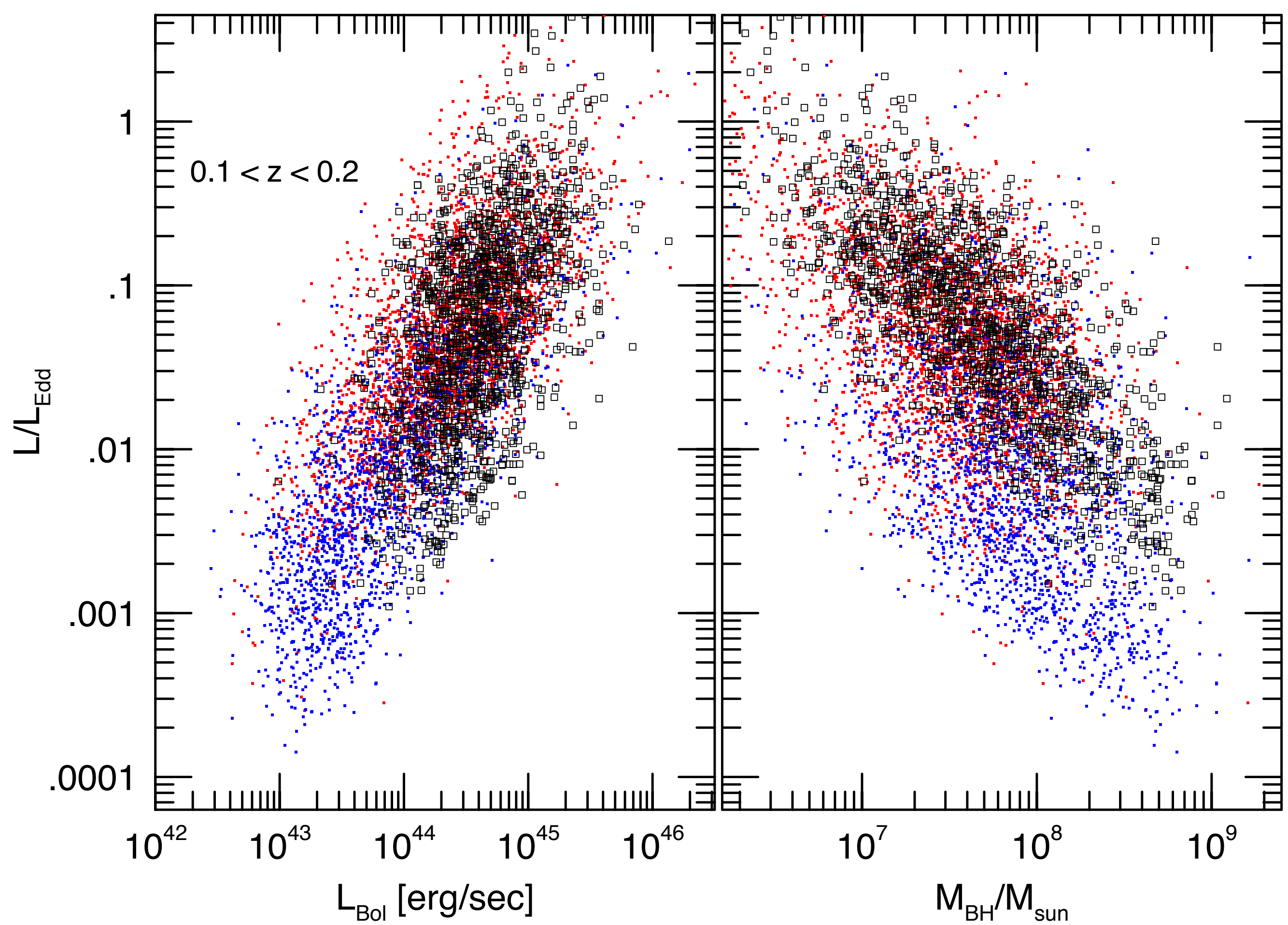
From the analysis of observed L, FWHM distributions MgII is less affected by radiation pressure ($N_H \sim 10^{23.5}$ cm^{-2}):

$$\frac{M_{BH}(MgII)}{\mathrm{M}_\odot} = 10^{6.7}\left(\frac{FWHM(MgII)}{1000\,\mathrm{km\,s}}\right)^2\left(\frac{\lambda L_\lambda(3000\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)^{0.5} + 10^{6.7}\left(\frac{\lambda L_\lambda(3000\text{Å})}{10^{44}\,\mathrm{erg\,s}}\right)$$

N_H distribution in BLR clouds, Hβ and CIV emission dominated by lower N_H (~10^{23} cm^{-2}) clouds, and MgII by larger N_H (~$10^{23.5}$ cm^{-2}) clouds (consistent with photoionization models).

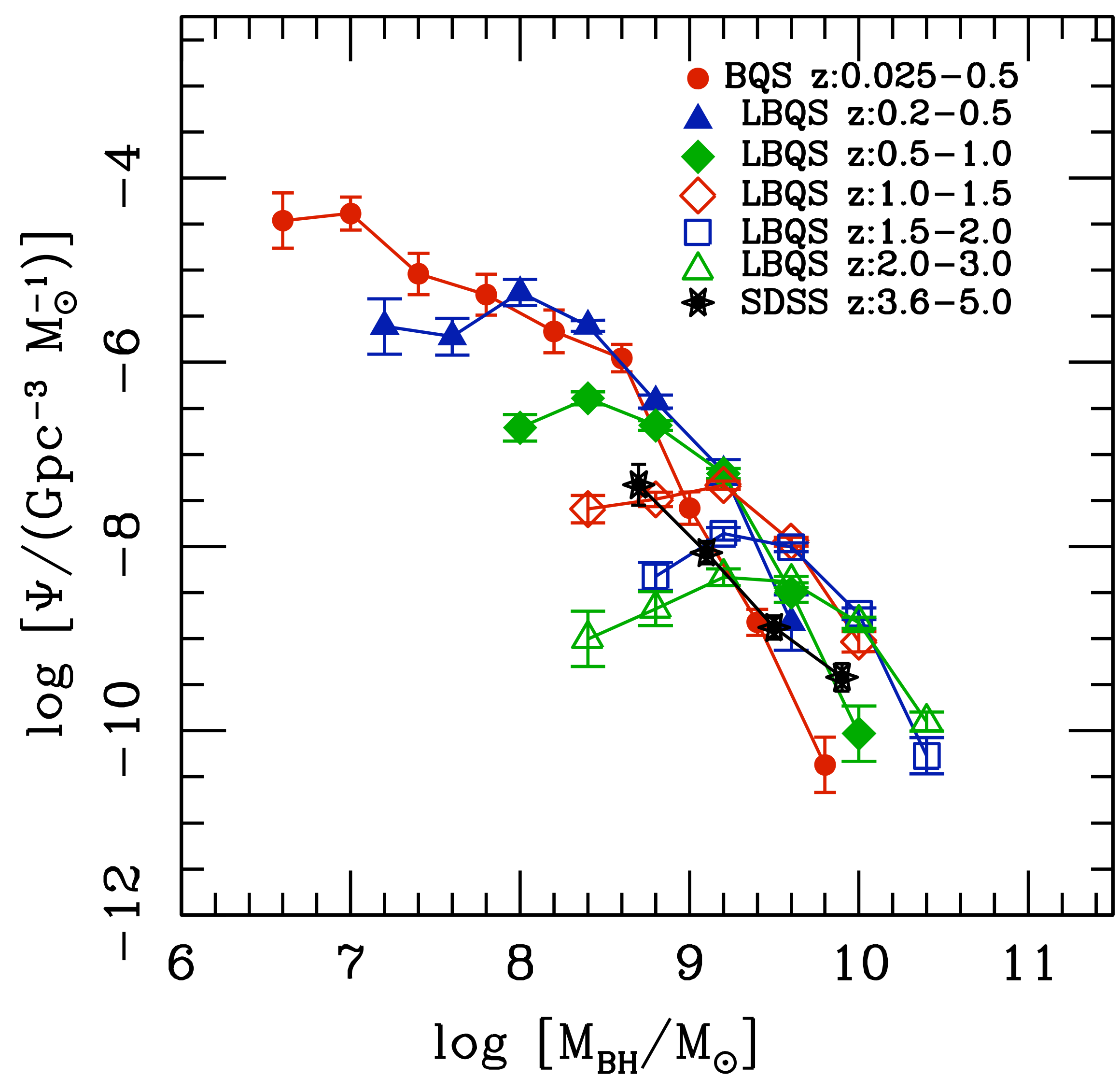
MgII seems to be the best line for virial M_{BH} estimates, can be used up to z<7.6 from the ground (Marconi +12)

With Masses of Active Black Holes ...

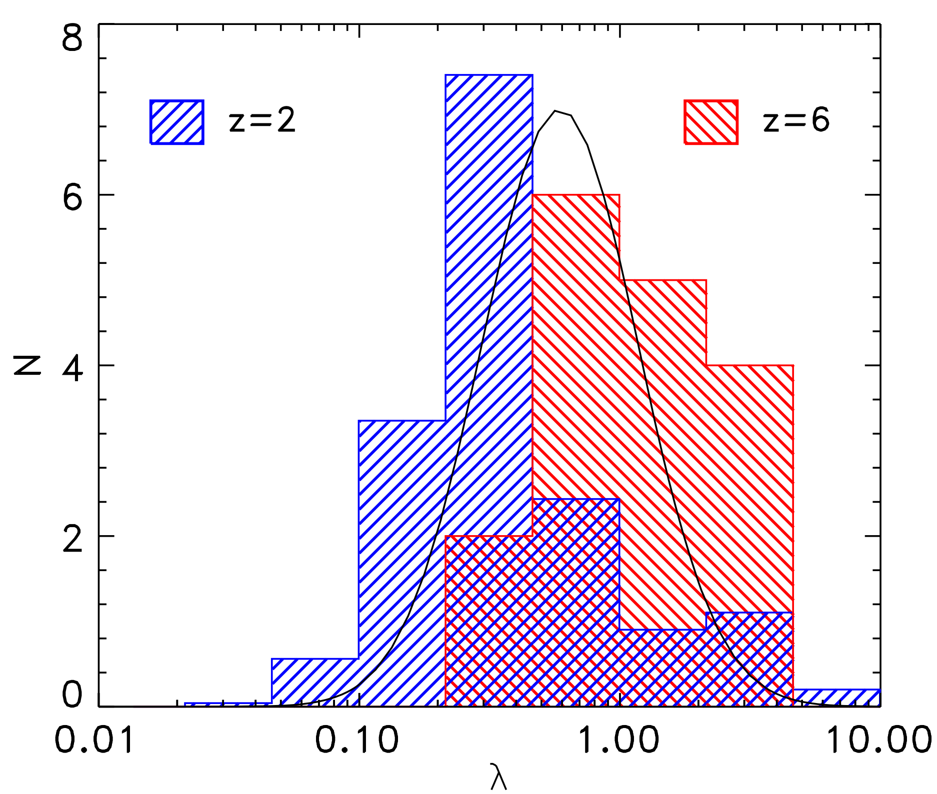


L/L$_{Edd}$ vs M$_{BH}$ (Netzer+09)

BH Mass Function of quasars
(Vestergaard & Osmer 2009)



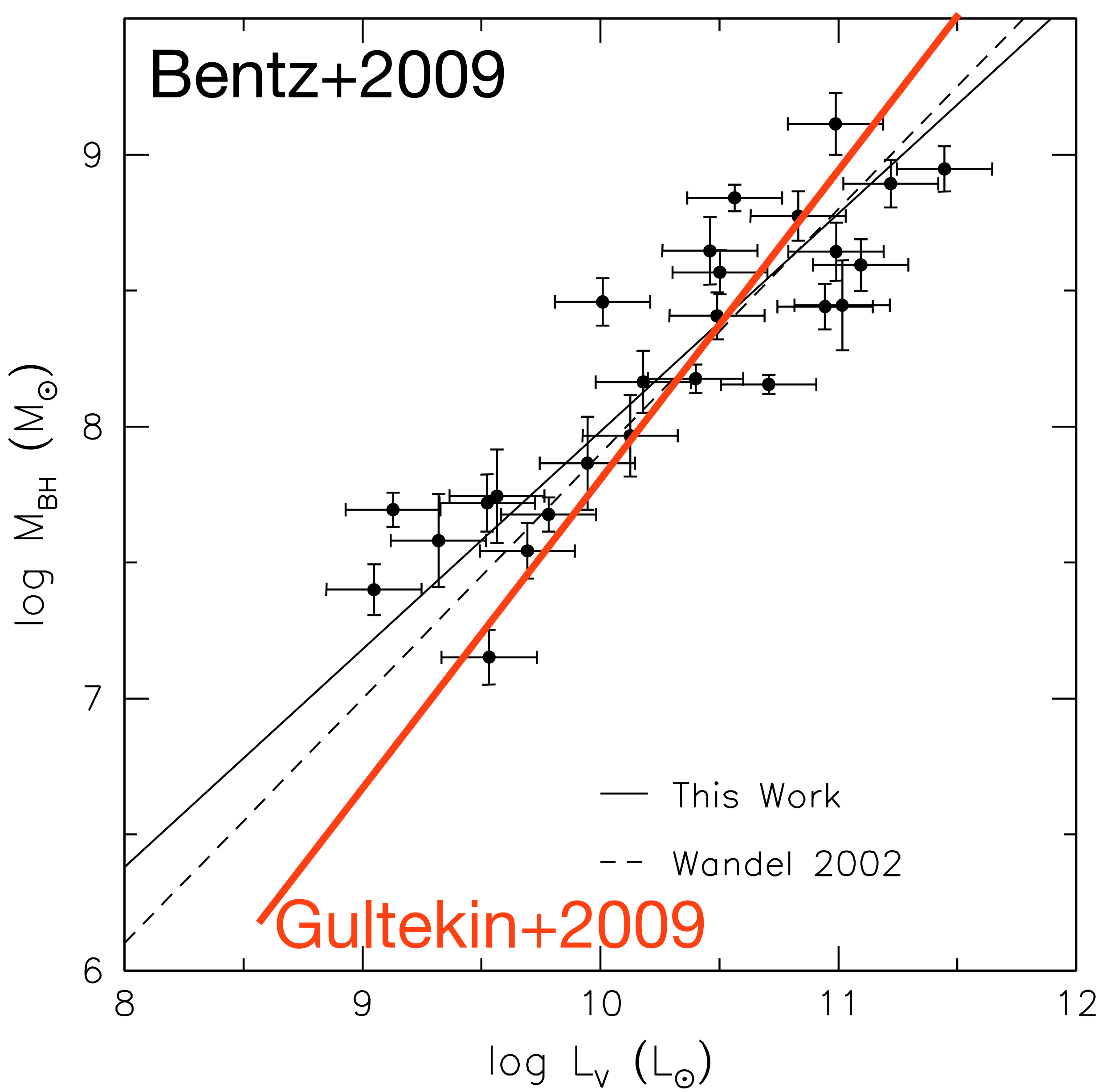
L/L$_{Edd}$ at
high z
(Willot+09)



Z-evolution of M_{BH}-galaxy relations

M_{BH}-galaxy relations for AGN at z=0

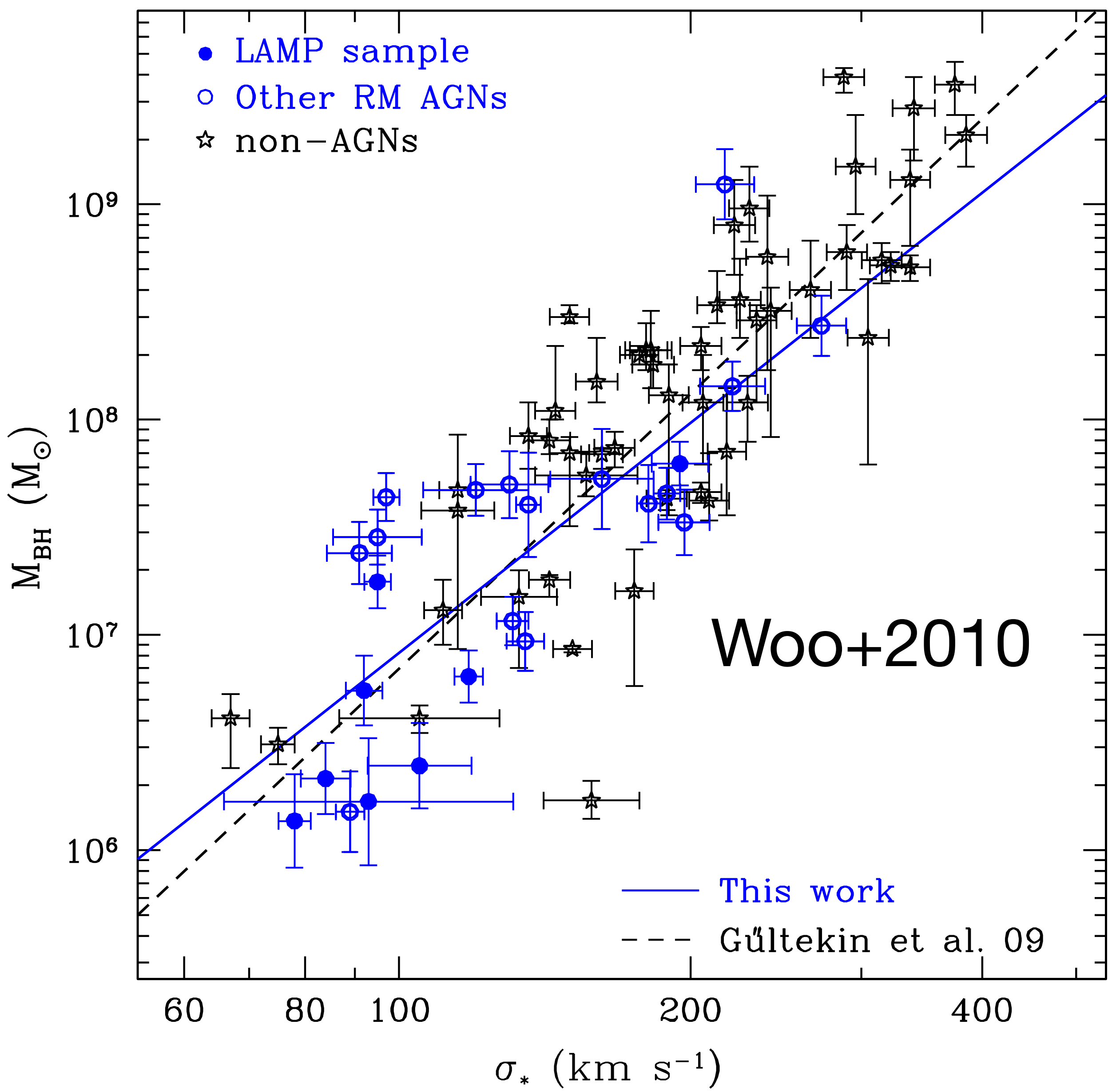
Bentz+2009 presents the results of HST imaging of the galaxies in the reverberation mapping database by Peterson+2004.
They deconvolve AGN and host galaxy emission at HST resolution to estimate $\lambda L_{\lambda,AGN}$ *(5100 Å)* and host bulge luminosity.



- Relation is surprisingly tight (intrinsic scatter ~0.4 dex, similar to quiescent galaxies);
- Slope is 0.75-0.85 compared to 0.9-1.3 of quiescent galaxies (Gultekin+09);
- is the different slope telling us about a different between locally active BHs and quiescent ones? Or is it due to observational biases?

M_{BH}-galaxy relations for AGN at z=0

Woo+11 combines data from reverberation mapping database (Peterson +2004) and new Rev. Map. observations at low L (Lick Monitoring project) and obtain the M_{BH}-σ relation for local AGN (also determine *f*, in agreement with earlier determinations (Onken+2004).



- Relation is also surprisingly tight (intrinsic scatter ~0.4 dex, similar to quiescent galaxies);
- Slope is 3.6 ± 0.6 compared to 4.2-0.4 of quiescent galaxies (Gultekin+09); consistent within the large errors
- Virial products are scaled by ~5.2 (similar to Onken+2004)
- *Quasars are missing (difficult to measure σ*

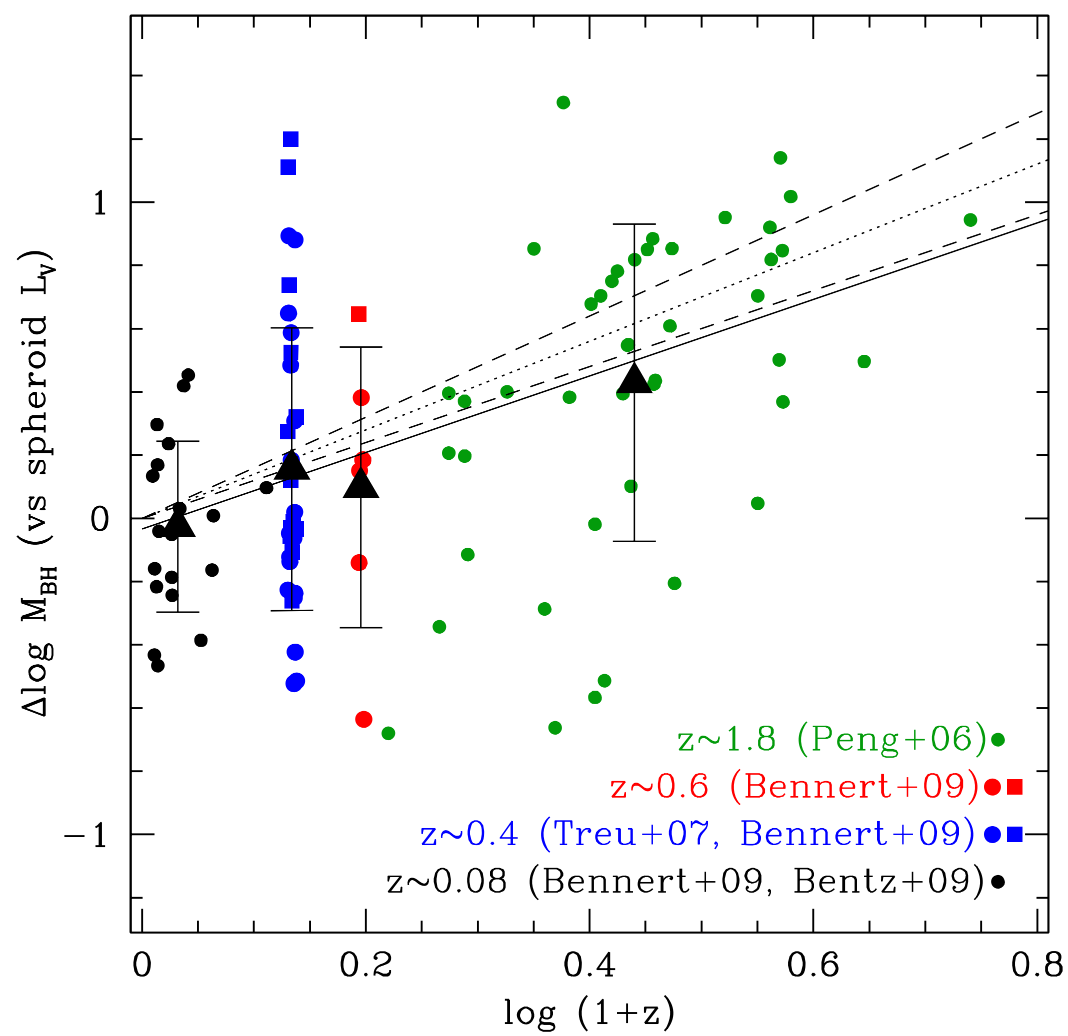
M_{BH}-galaxy relations at low z (<1)

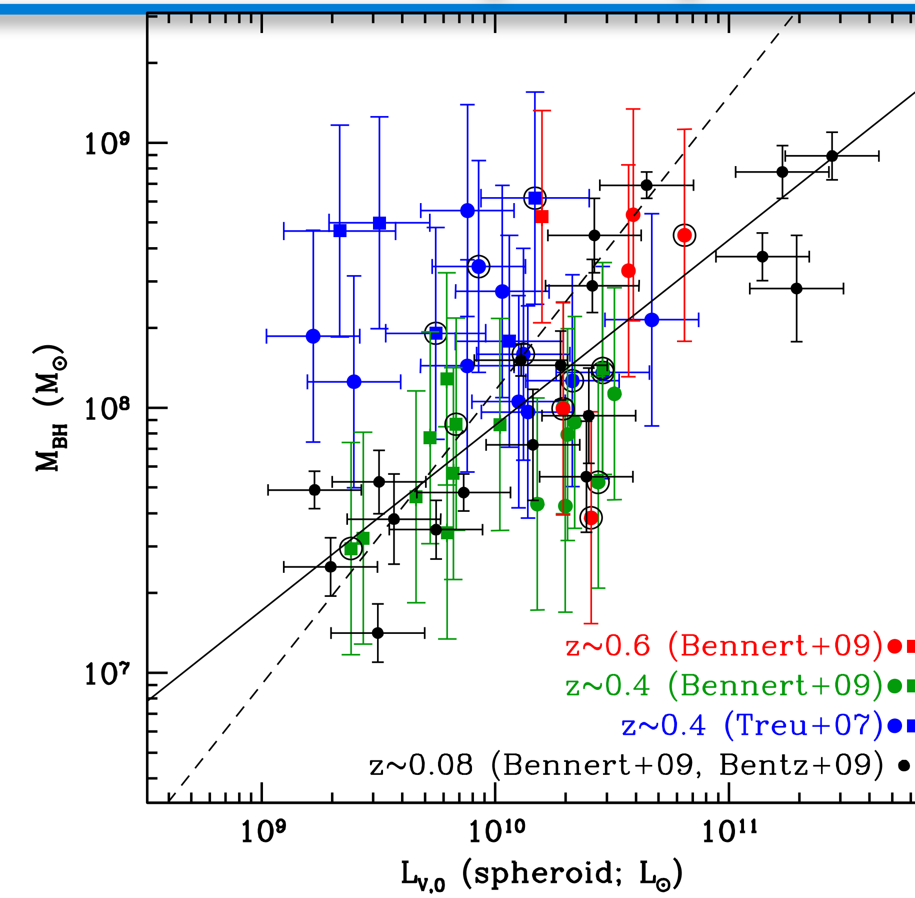
Treu et al. find evidence for evolution of M_{BH}-σ/L zero point since z~0.5 (e.g. Bennert+11). Intrinsic scatter (constant with z) is ~0.3 dex). With high z objects (see later) evolution is as

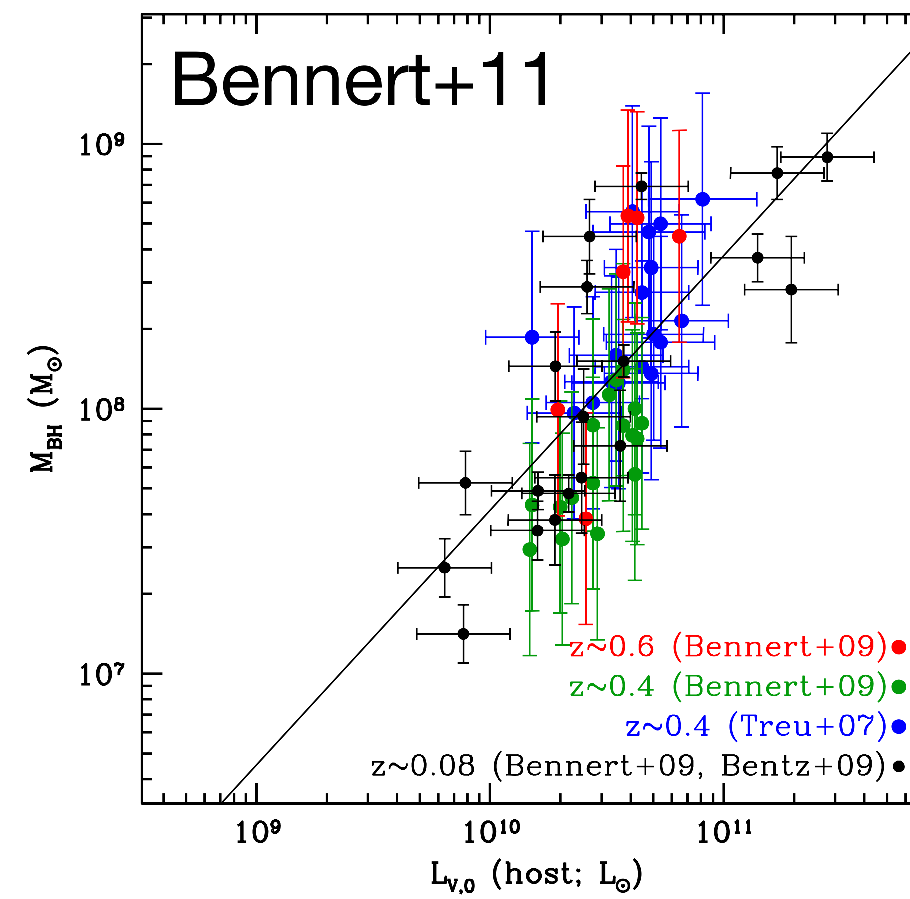
$$\frac{M_{\rm BH}}{L_{\rm sph}} \sim \frac{M_{\rm BH}}{M_{\rm sph}} \sim (1+z)^{1.4\pm0.2}$$

Intriguingly no evolution when considering Total host luminosity.

M_{BH}/M_{sph} is already ~1.6 times the local value at z~0.4 i.e. ~4 Gyr ago.







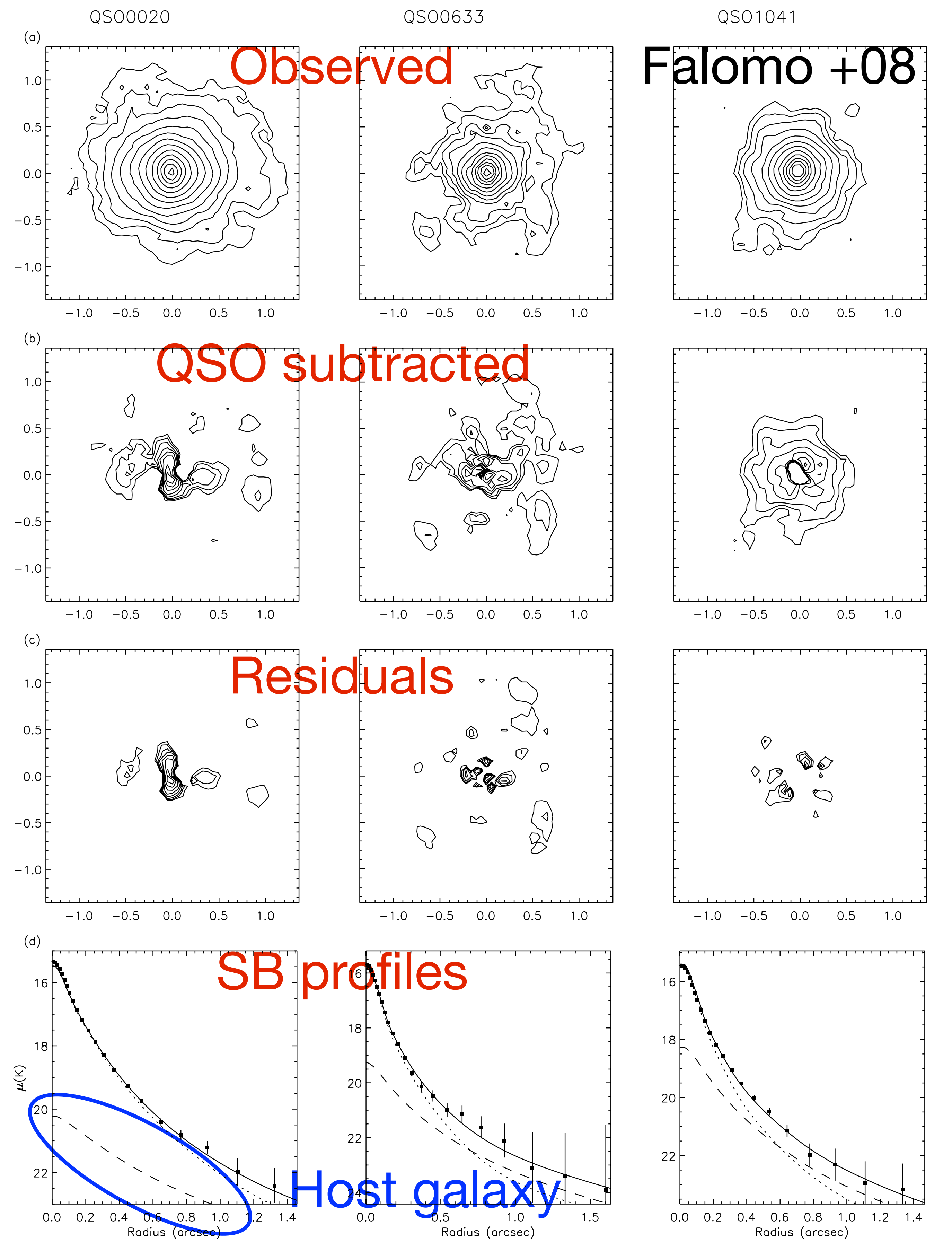
At high z ...

At high redshift the detection of the host galaxies is very difficult especially in luminous QSOs.

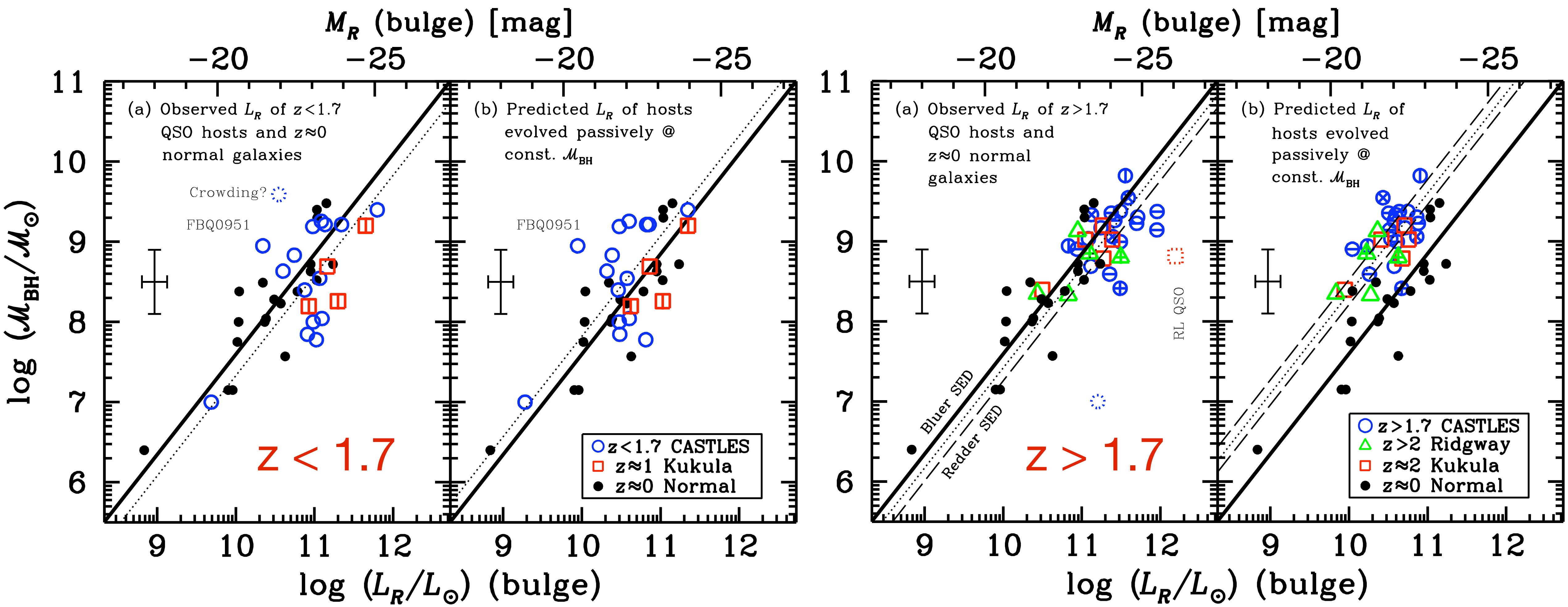
High spatial resolution mandatory (but not sufficient!) and we can "hope" to measure only total galaxy luminosity!

Host galaxies of QSOs appear already fully formed after ~2 Gyr and are passively evolving, ie fading in luminosity (eg Falomo +08).

To compare with local M_{BH}-L_{sph} relation need to correct for passive evolution (model dependent ...).



M_{BH}-galaxy relations at high z (>1)



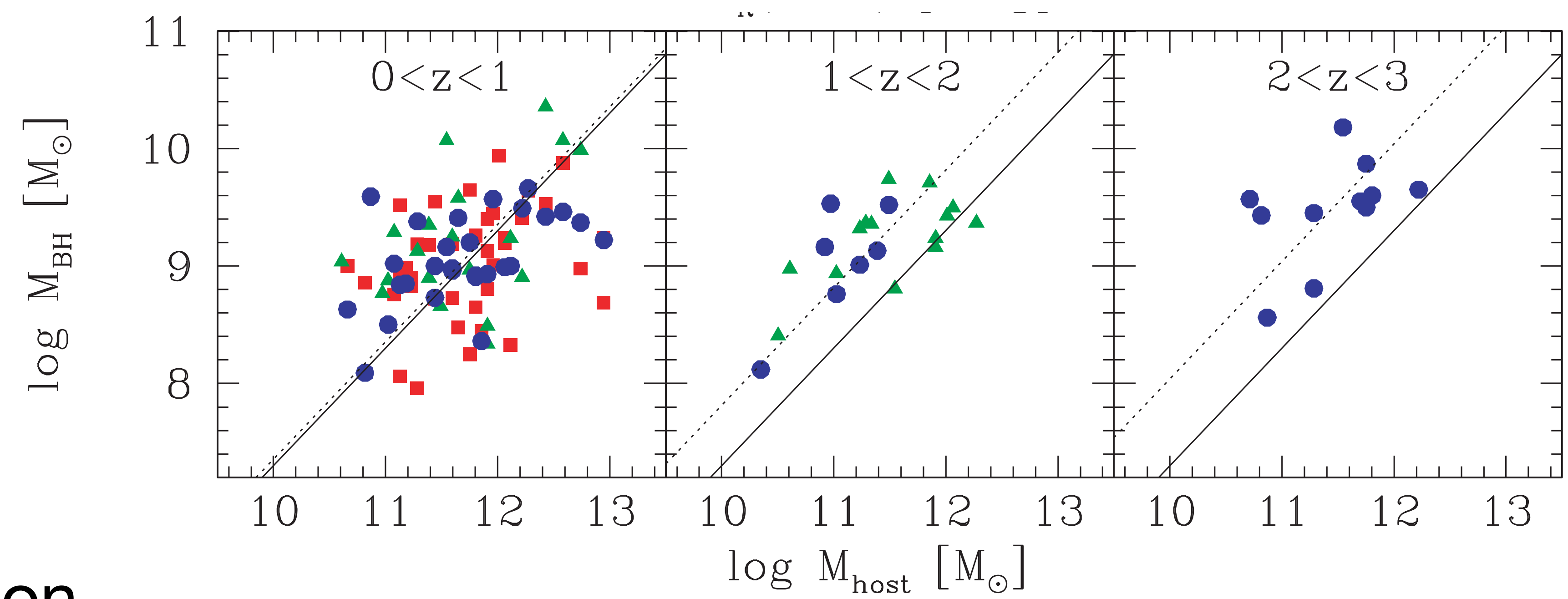
Peng +06 no evolution using observed L_R at z>1.7, evolution is found after correction for passive evolution of the host ... M_{BH}/M_{stars} ~3-6 times larger than today! Also McLure +03, Schramm +08, Salviander +07 ...

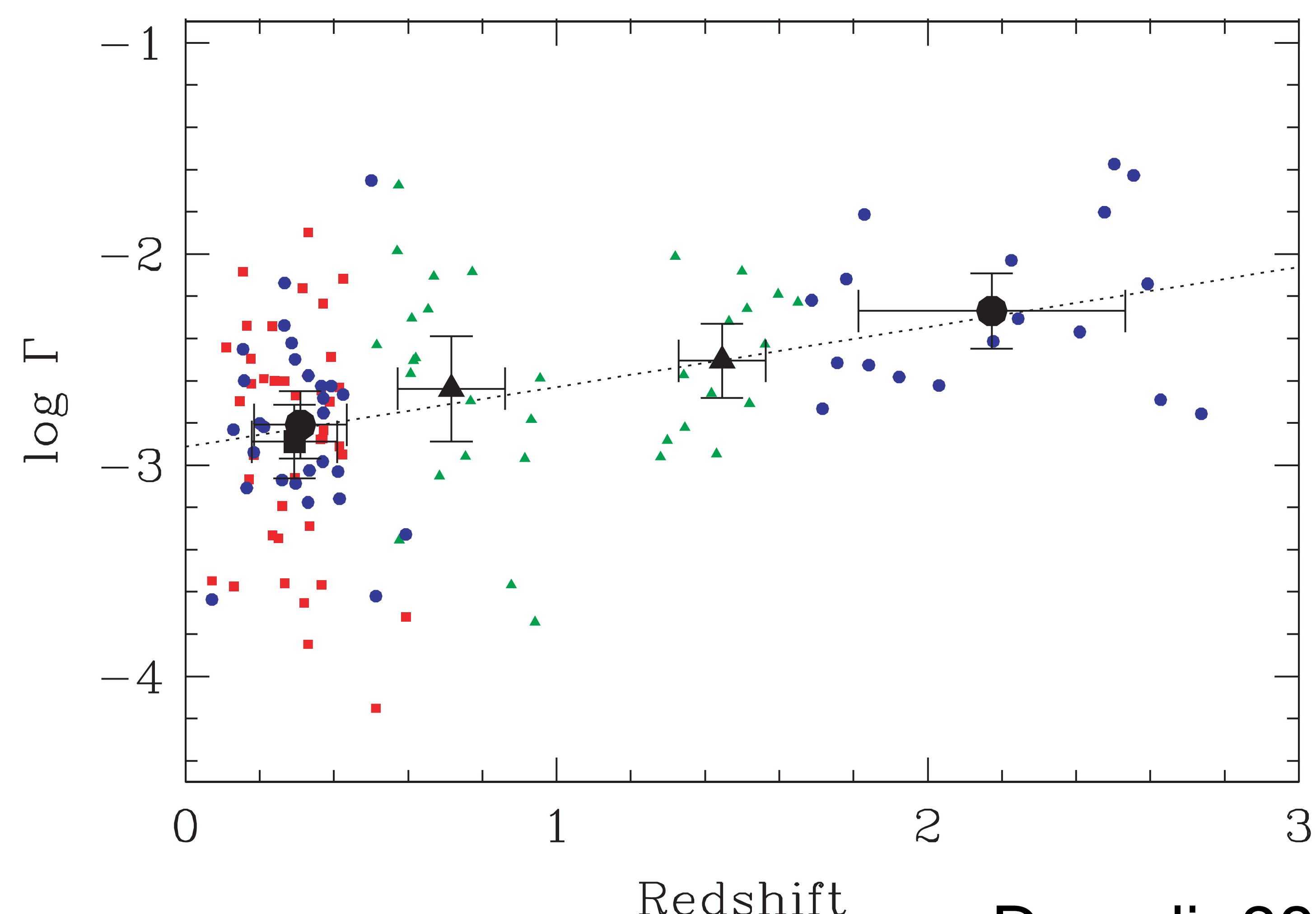
Lower evolution (less important passive evolution correction) at lower redshift (z<1.7), M_{BH}/M_{stars} ~1-2 as of today.

M_{BH}-galaxy relations at high z (>1)

Decarli+2009: ~100 quasars with HST imaging (~R band rest frame), and host galaxies classified as ellipticals.

- As for Peng+06,evolution is found *after* accounting for passive evolution.
- At z~3 M_{BH}/M_{sph} is ~7 times larger than at z=0



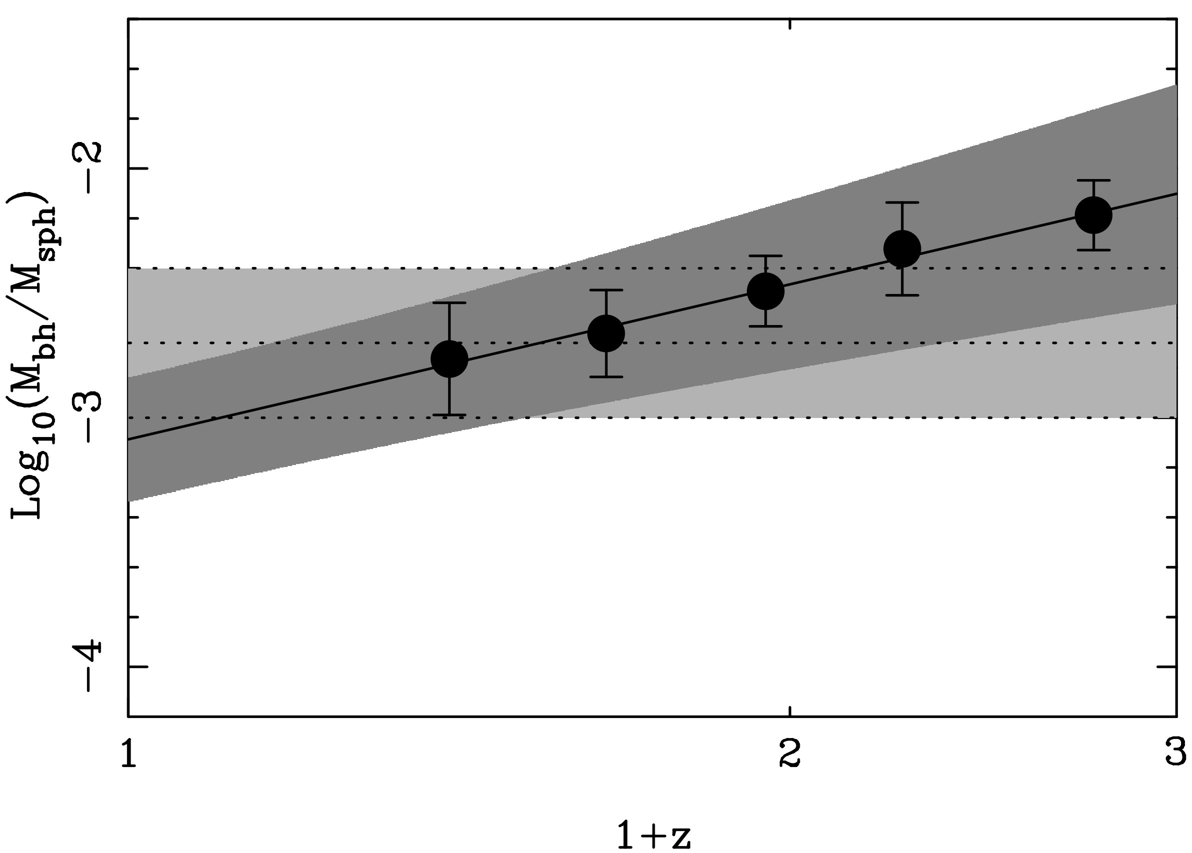


Decarli+2009

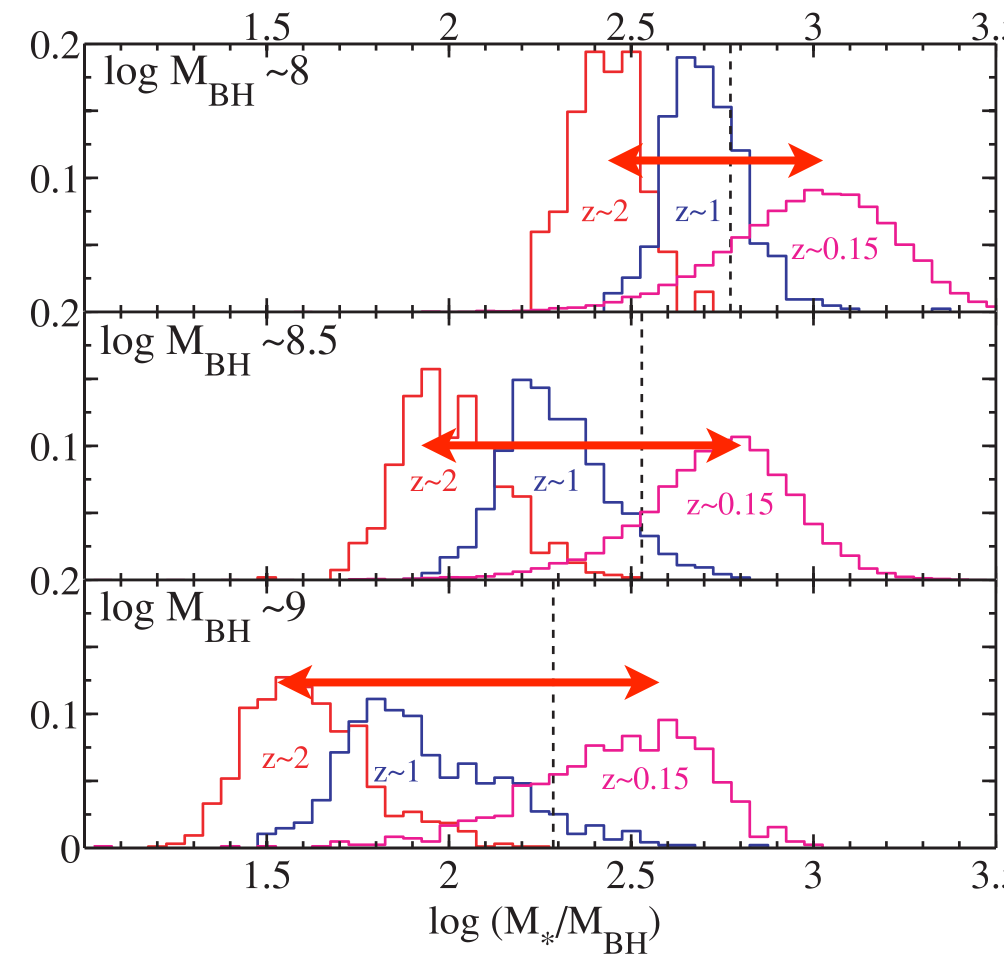
M_{BH}-galaxy relations at high z (>1)

McLure +06 selects a sample of 3C RR Radio Loud Quasars (broad lines → virial M_{BH}) and a sample of 3C RR Radio Loud galaxies (→ stellar masses). Assume they are extracted from the same parent population to estimate average M_{BH}/M_{star}

Find z evolution of M_{BH}/M_{sph} which is ~ 4 times larger at z~2 than today.



McLure+06

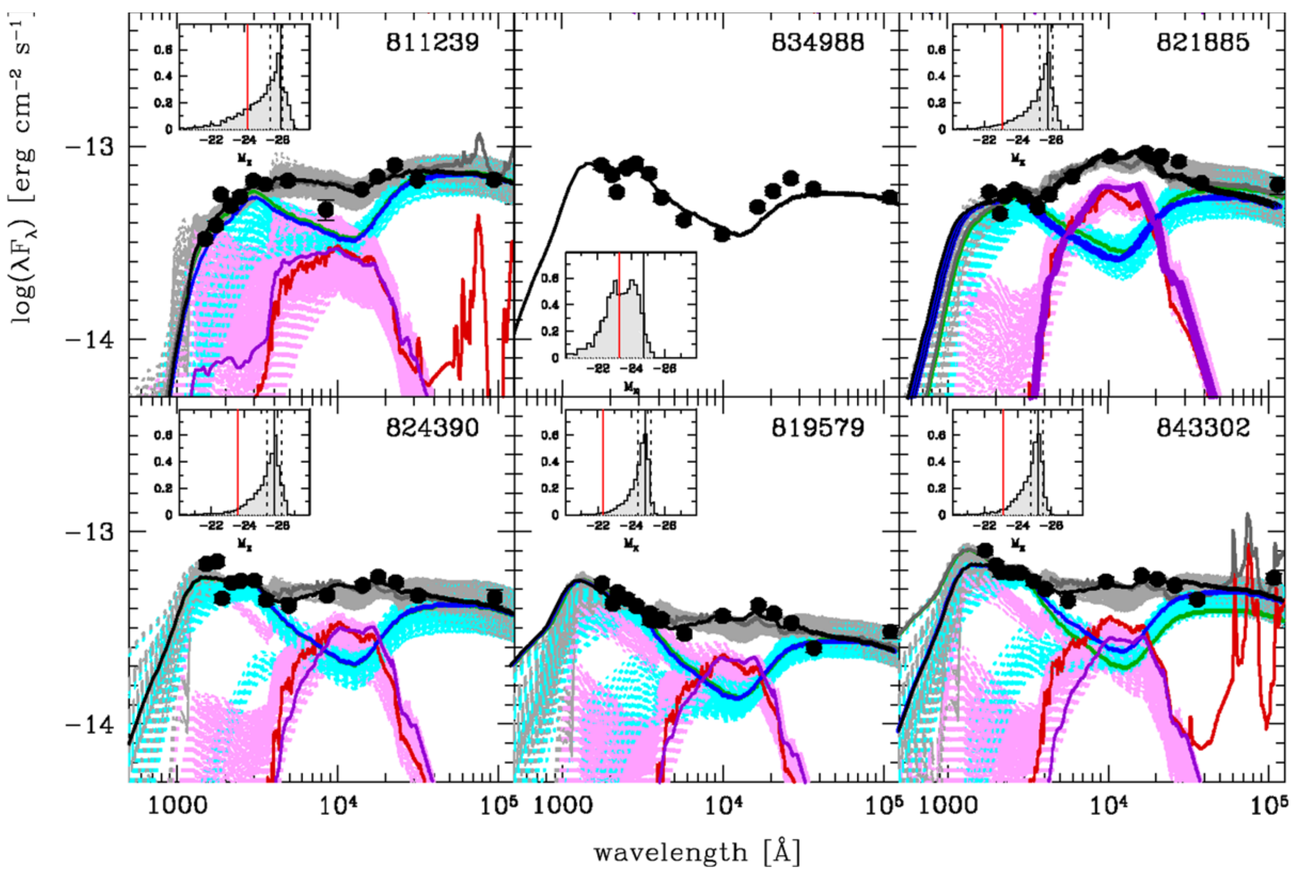


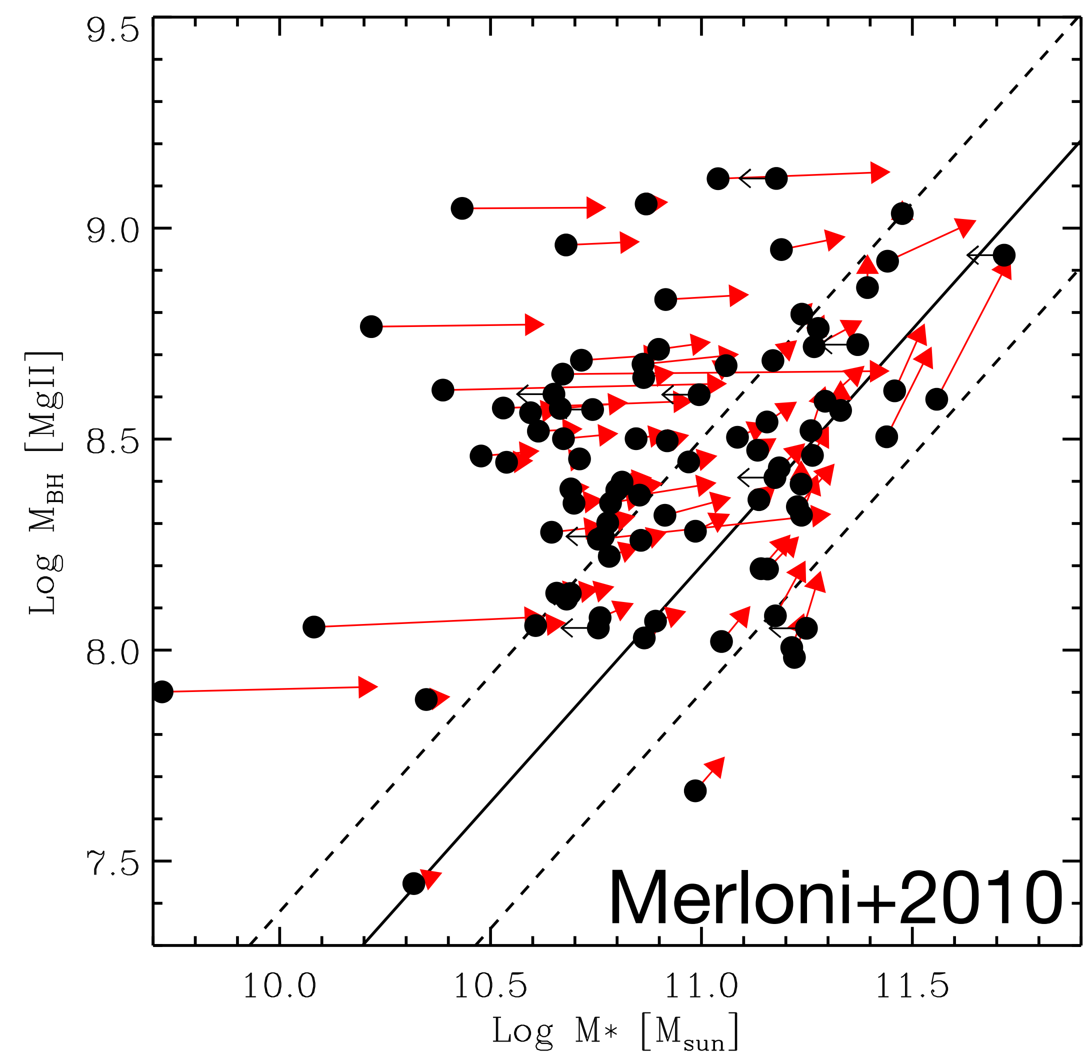
Trakhtenbrot & Netzer 2010

Statistical analysis similar to this (but with differences) have been conducted by eg, Merloni+2004, Trakhtenbrot & Netzer 2010, with similar results. Trakhtenbrot & Netzer 2010 find that M_{BH}/M_{star} depends on BH mass.

M_{BH}-galaxy relations at high z (>1)

Merloni+10 select type 1 AGN with L> $10^{44.5}$ erg/s at 1<z<2 from COSMOS.





Separate AGN and galaxy via SED fitting. Large uncertainties due to assumed galaxy and AGN templates, but more accurate than the use of single band L and direct estimate of *total* M_{star}.

They find evolution

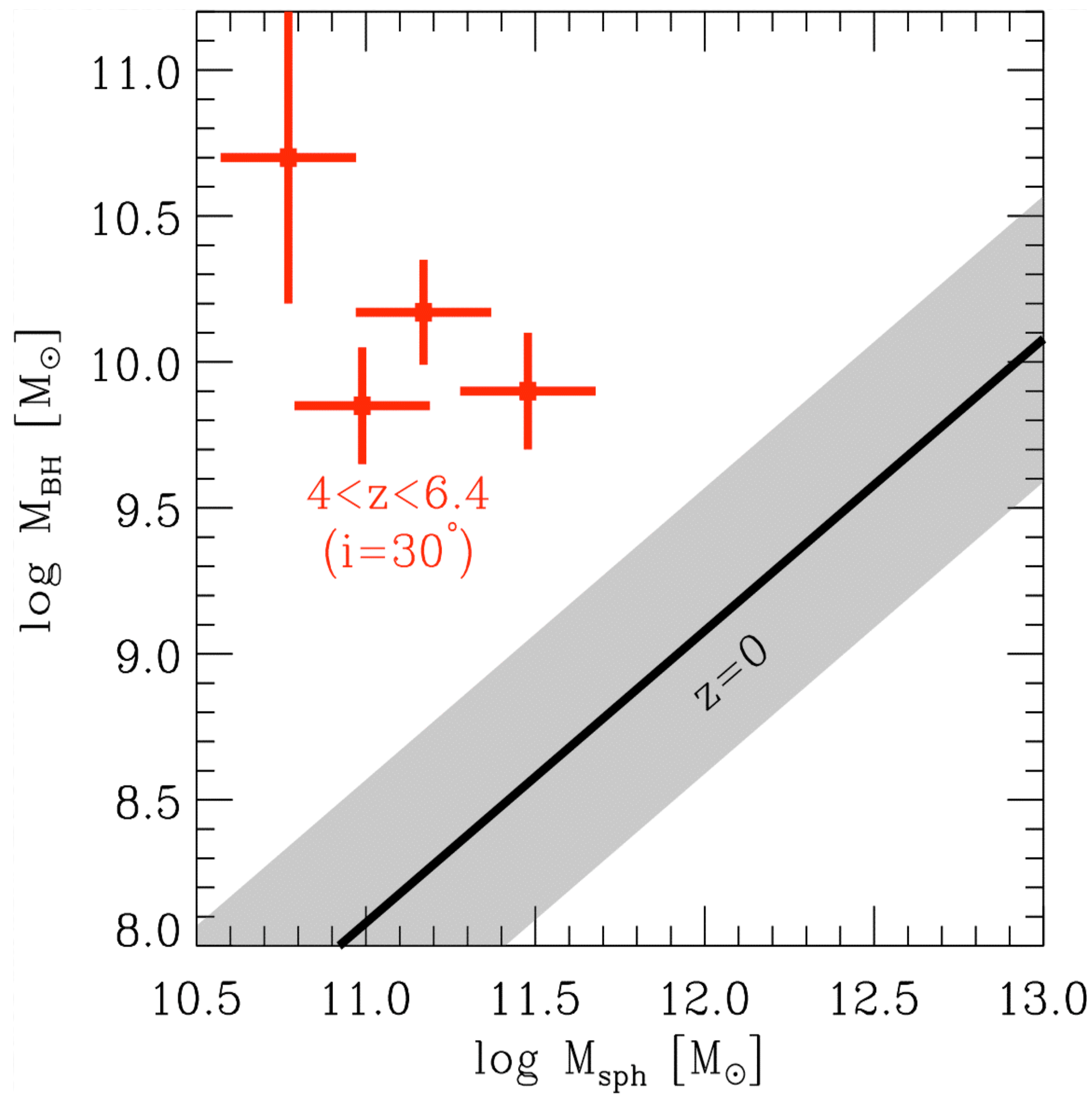
$$\frac{M_{BH}}{M_\star} \simeq \left(\frac{M_{BH}}{M_\star}\right)_{local} (1+z)^{0.68\pm0.12}$$

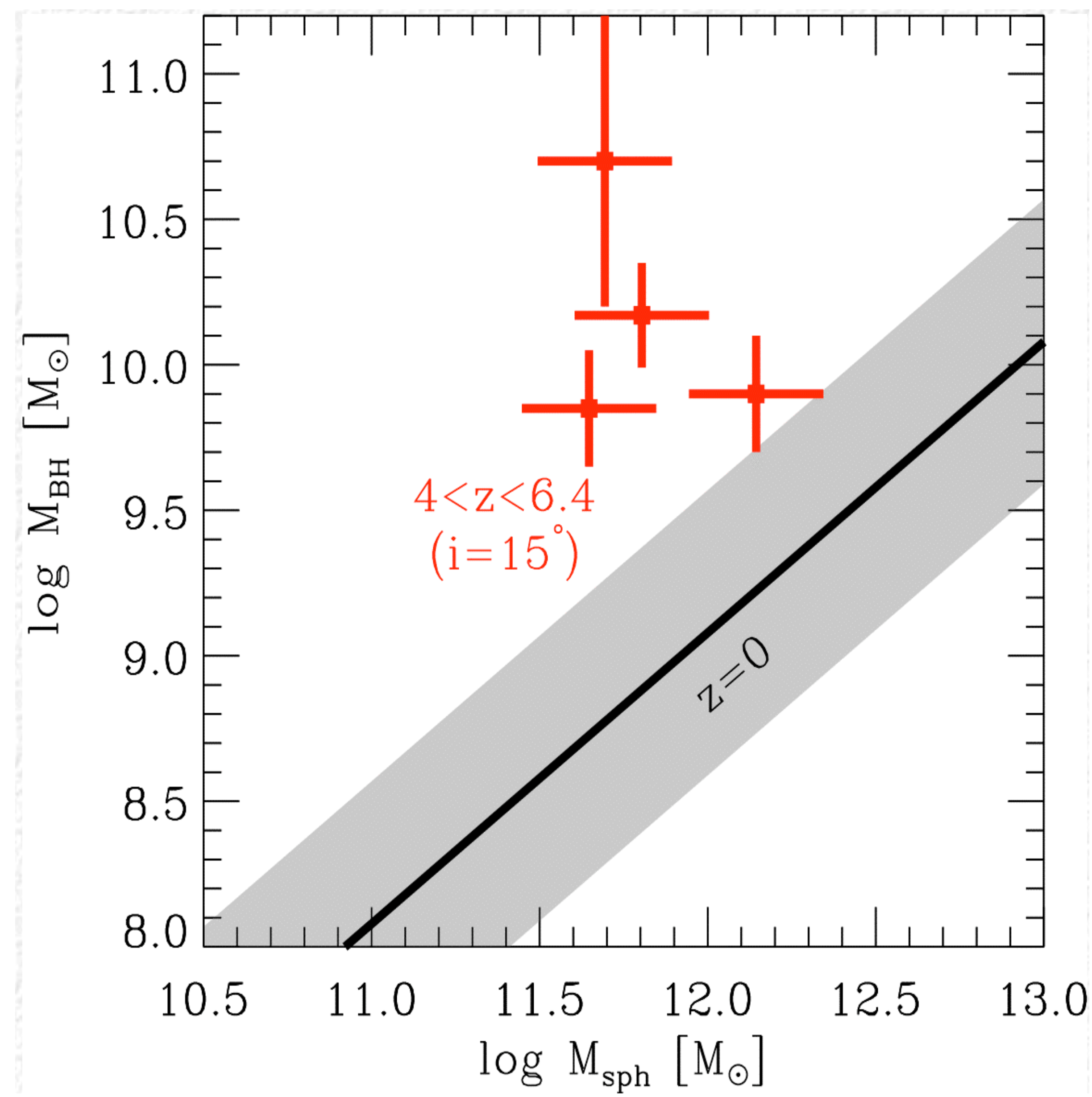
Red arrows: evolution in M_{BH}-M_{star} plane if L_{AGN} and SFR are maintained for 300 Myr considering AGN duty cycle δ(L,z) = $\phi_{AGN}(L,z)/\phi_{gal}(L,z)$;

convergence toward local relation!

M_{BH}-galaxy in very high-z quasars

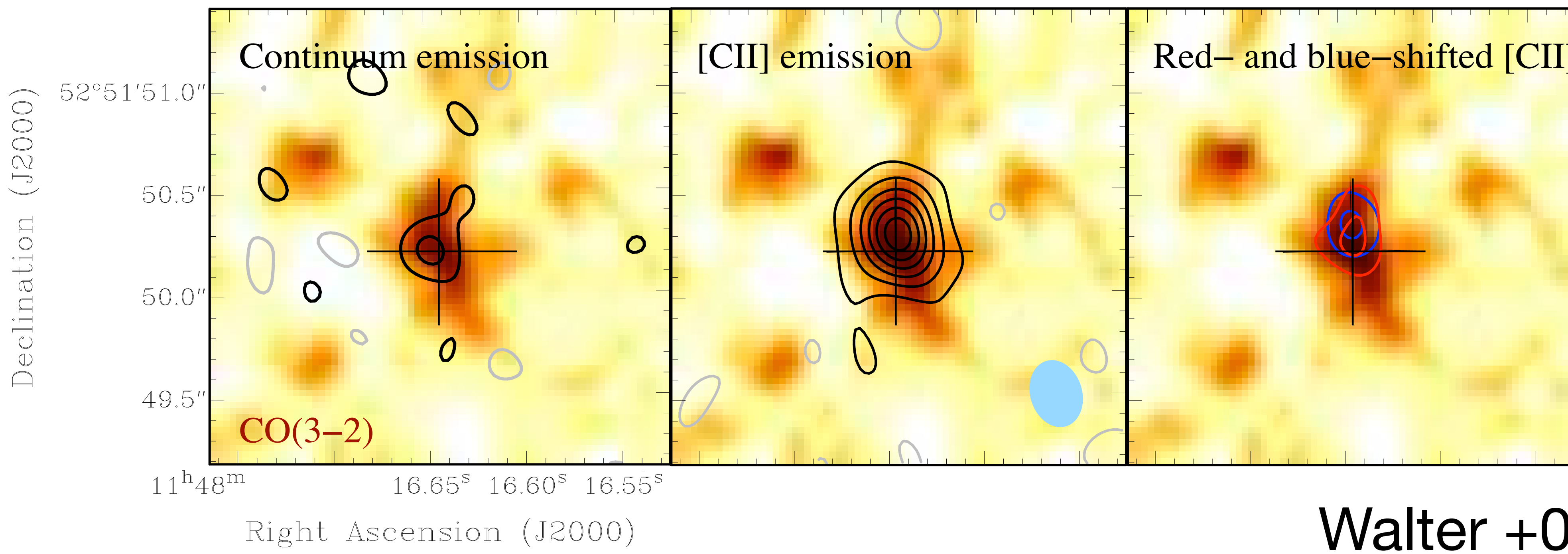
4<z<6.4 quasars with M_{sph} estimate from CO and virial M_{BH}.
Even reducing to low inclination, very high M_{BH}/M_{sph} compared to local value!



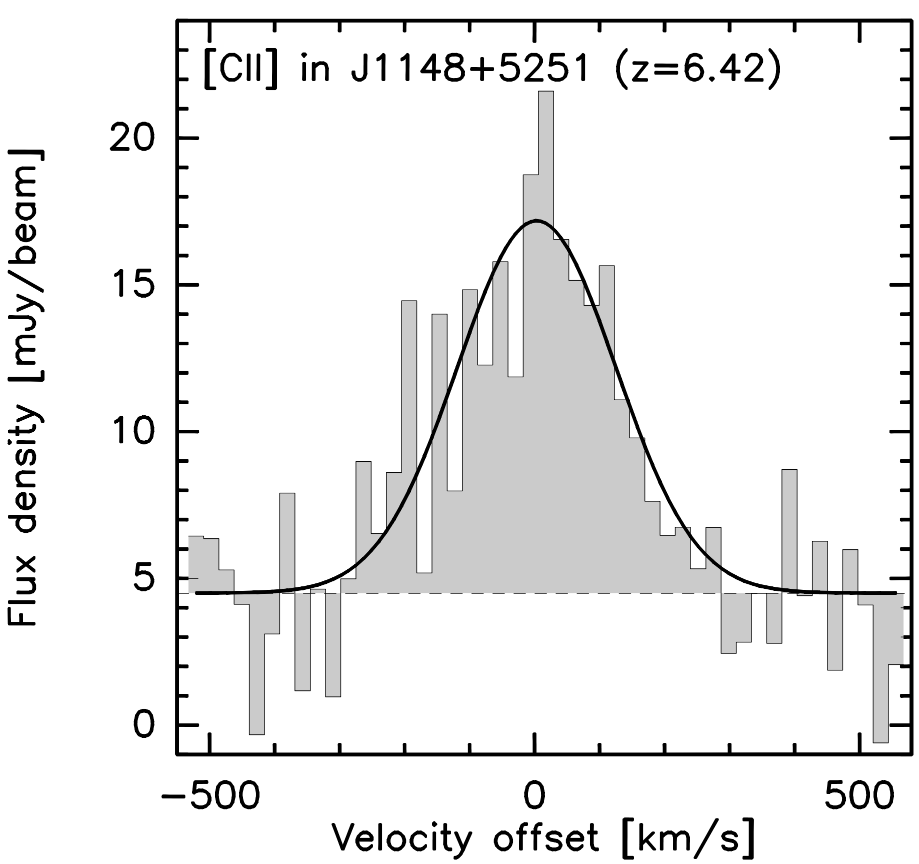


Maiolino 2009

Very high z (~6)



Walter +09



Impossible to image the host galaxy ...

Highest redshift QSO has z=6.42;

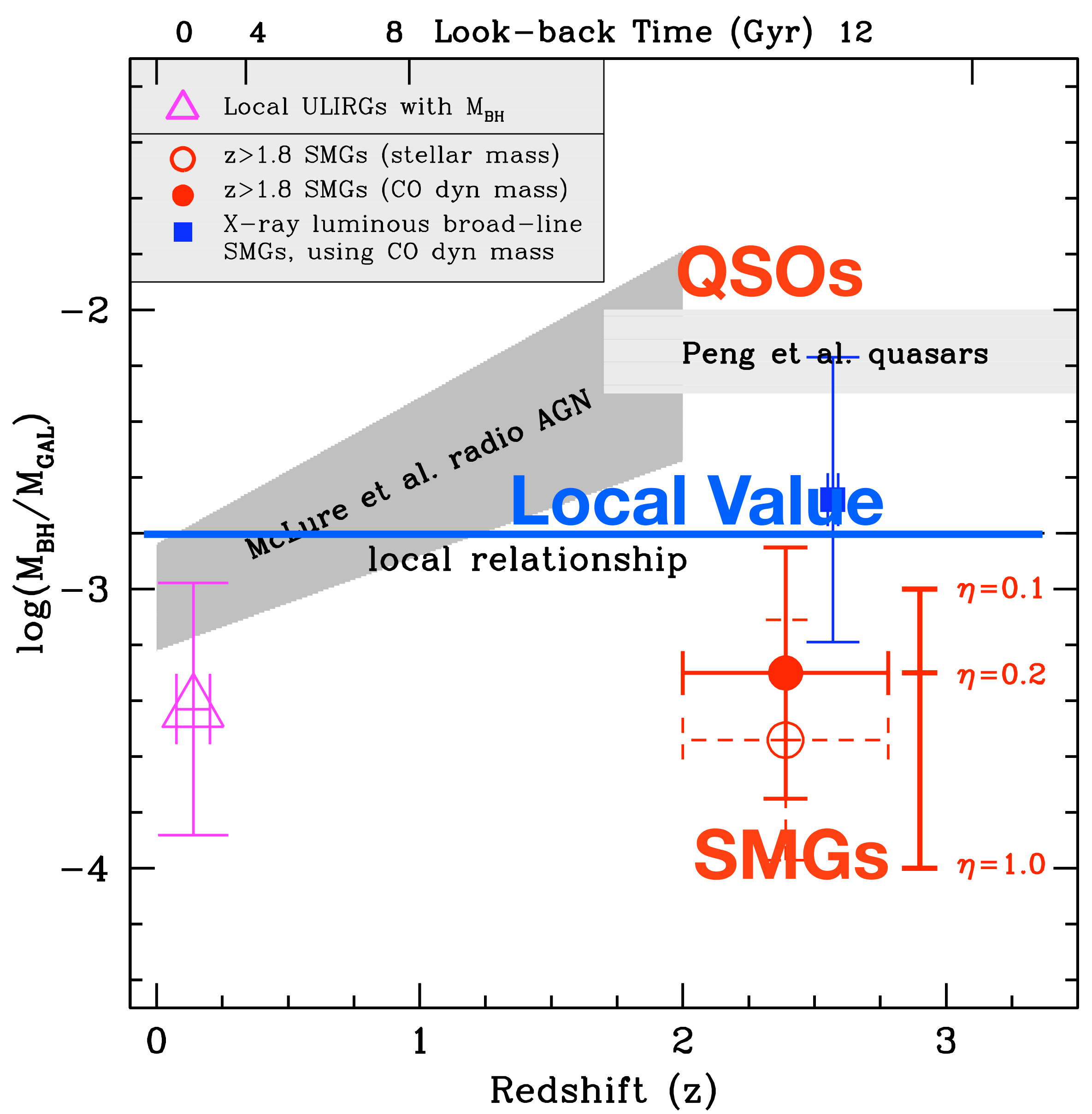
$M_{BH} \sim 3 \times 10^9 M_\odot$ (Willot +03)

From resolved CO emission, virial dynamical mass $M_{dyn} \sim 10^{10} M_\odot$ within the central 1.5 kpc.

M_{BH} might be up to 10-30% of total dynamical mass (Walter +03, +09).

SMG galaxies

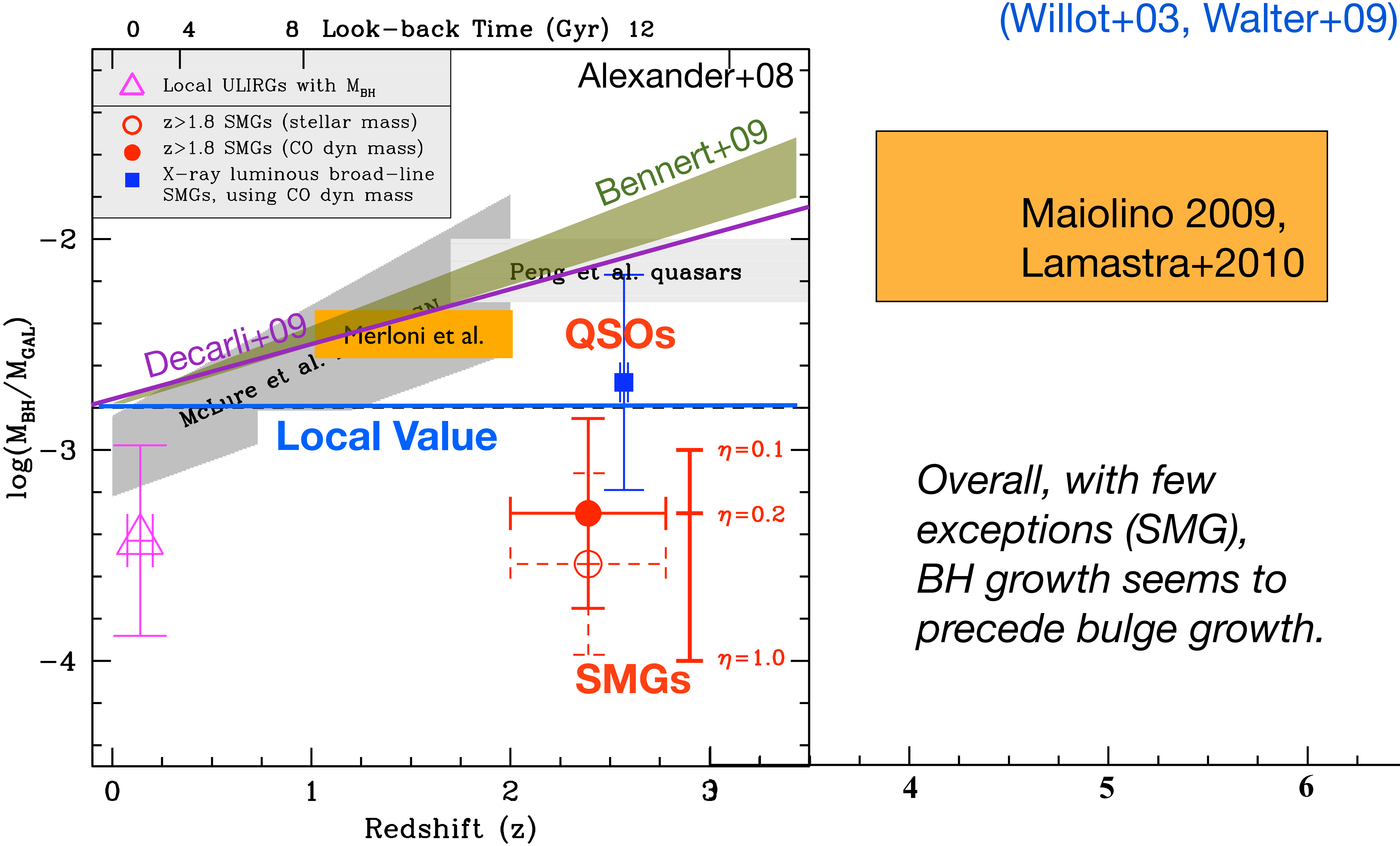
SMG (SubMm Galaxies, high z analogs of ULIRGs with typical SFR ~ 1000 $M_\odot$/yr) seem to have smaller BHs compared to host spheroid w.r.t. quasars at similar redshifts.
With typical virial BH masses, ≈ 6 ×10^7 $M_\odot$, SMGs appear to be in a phase of rapid BH growth.



Alexander+08,+09

M_{BH}-galaxy relations vs z

Quasar at z~6.4
(Willot+03, Walter+09)

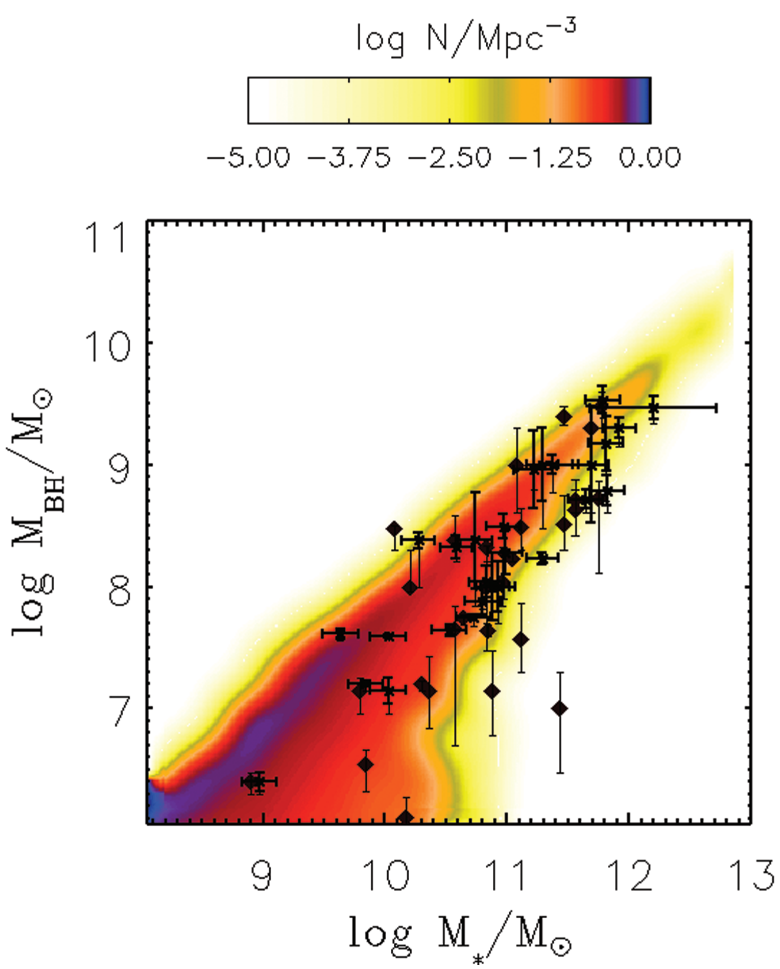


Maiolino 2009,
Lamastra+2010

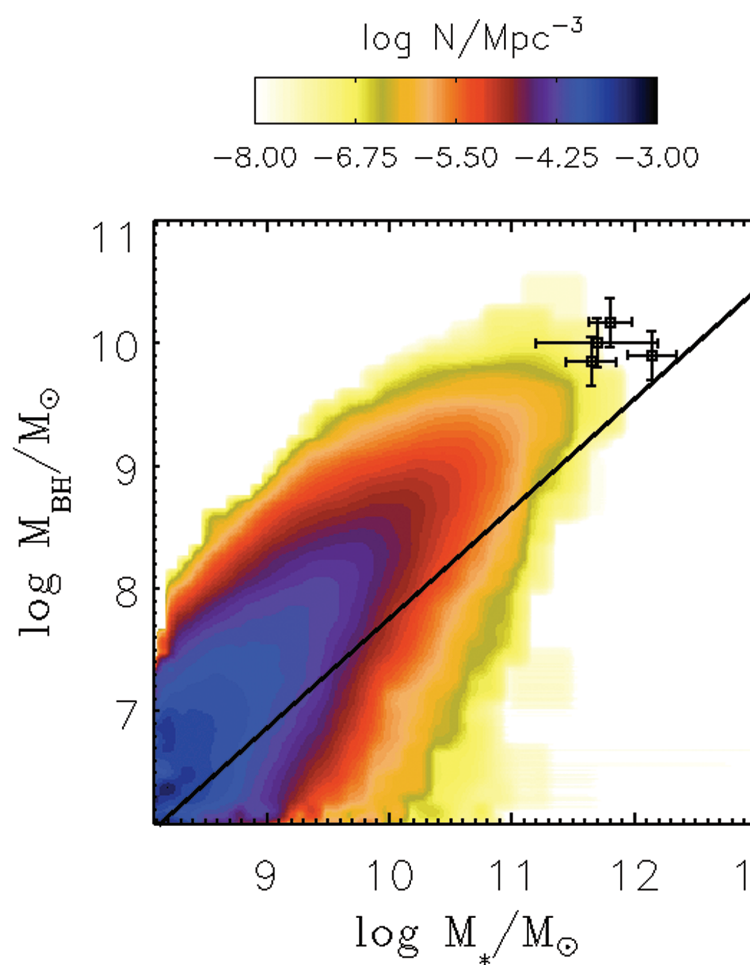
Overall, with few exceptions (SMG), BH growth seems to precede bulge growth.

Errors or selection effects?

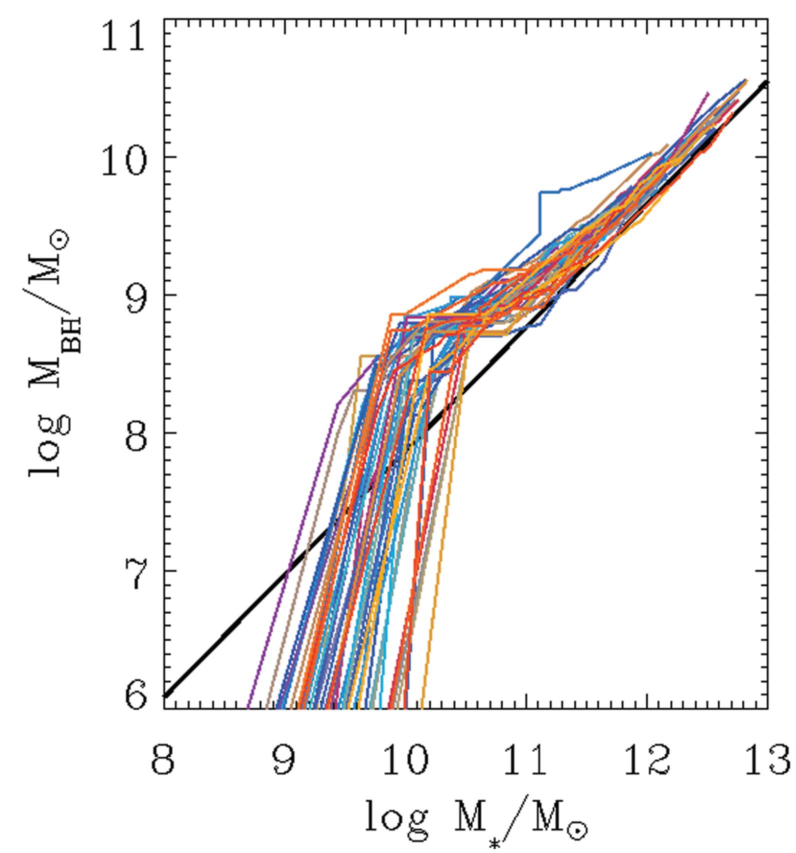
Lamastra et al. (2010) considered Semi-Analytical models of galaxy evolution by Menci et al. which takes into account hierarchical buildup of structures (galaxies and BHs) and feedback effects. BH accretion (AGN) is triggered by galaxy encounters/merging in haloes.
They looked at predicted M_{BH}/M_{star} for different objects.



M_{BH}-M_{star} relation @z=0



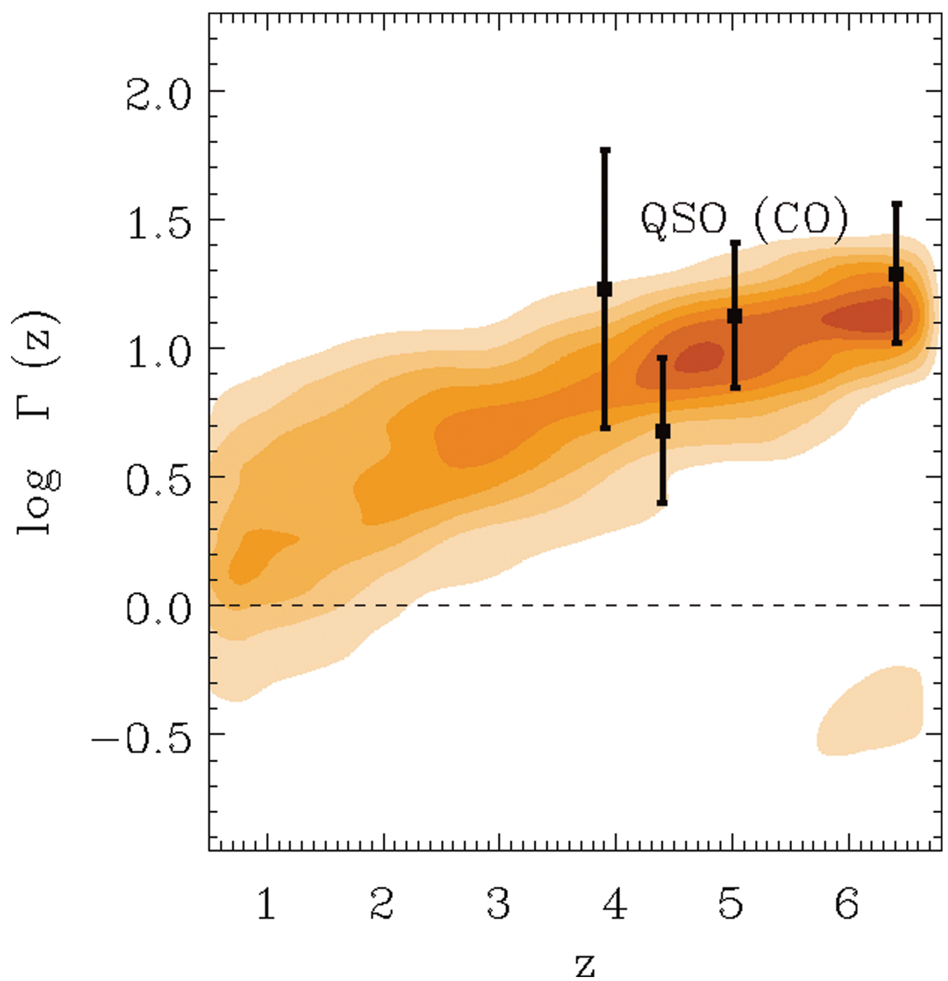
M_{BH}-M_{star} relation, for objects @ 4<z<6

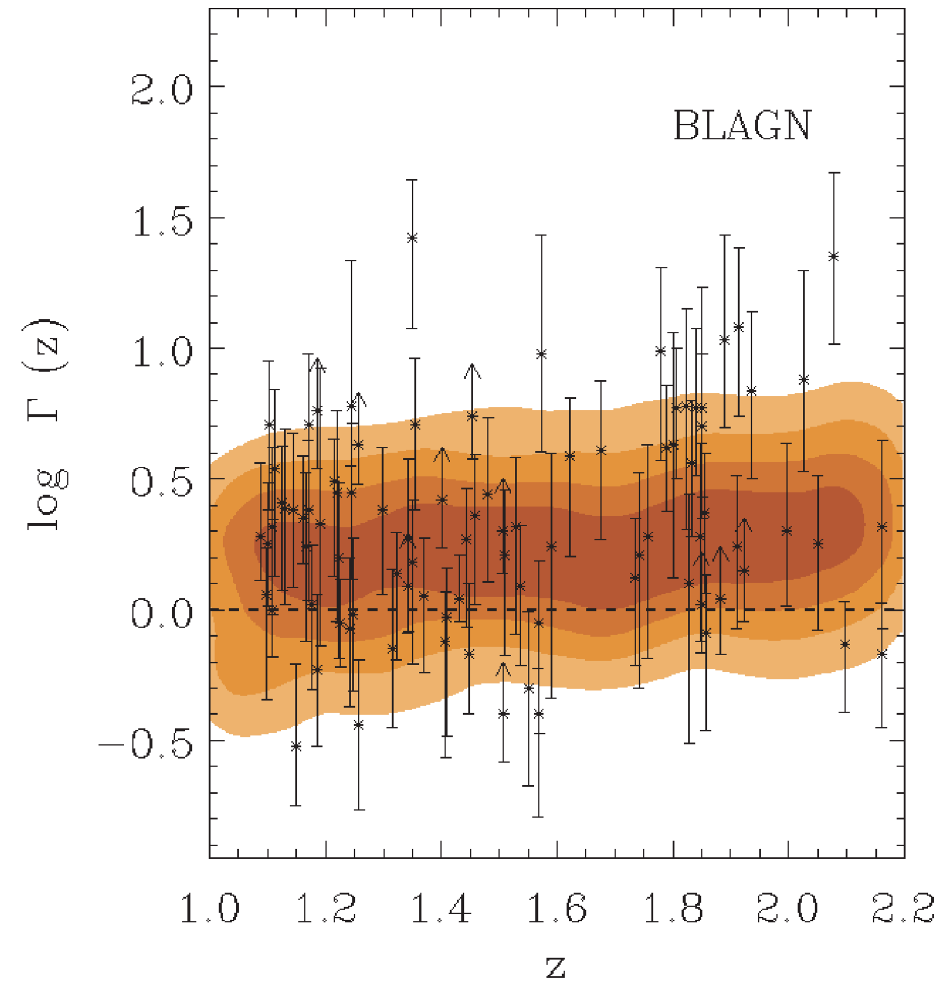


Growth tracks for M_{BH}(final)>10^{10} $M_\odot$

Errors or selection effects?

$$\Gamma = \frac{(M_{\rm BH}/M_\star)(z)}{(M_{\rm BH}/M_\star)(0)}$$

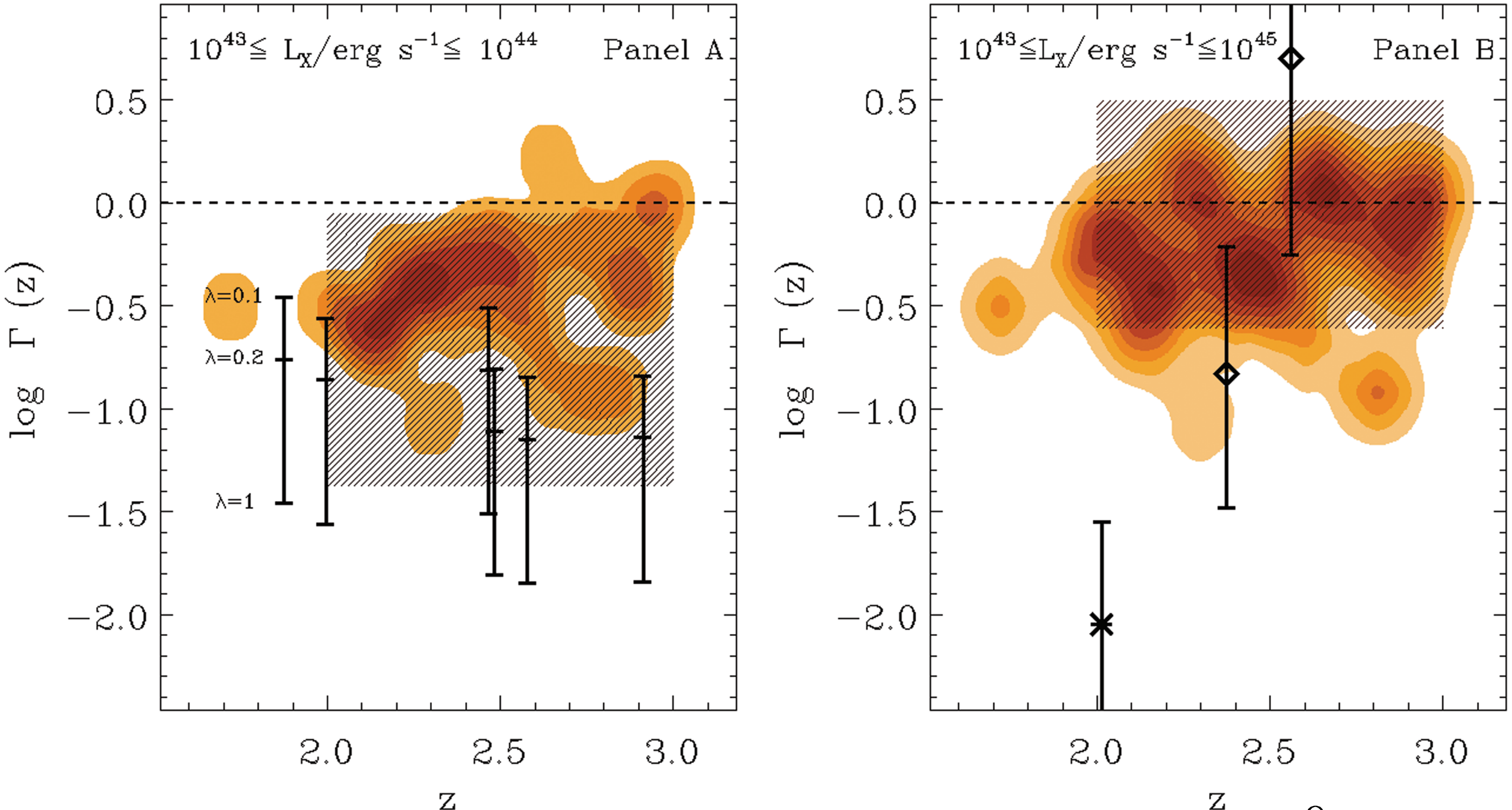




Objects with $M_{BH}>10^9\ M_\odot$ @z=4. BH growth precedes growth of stellar mass because of many galaxy encounters in deep potential wells.

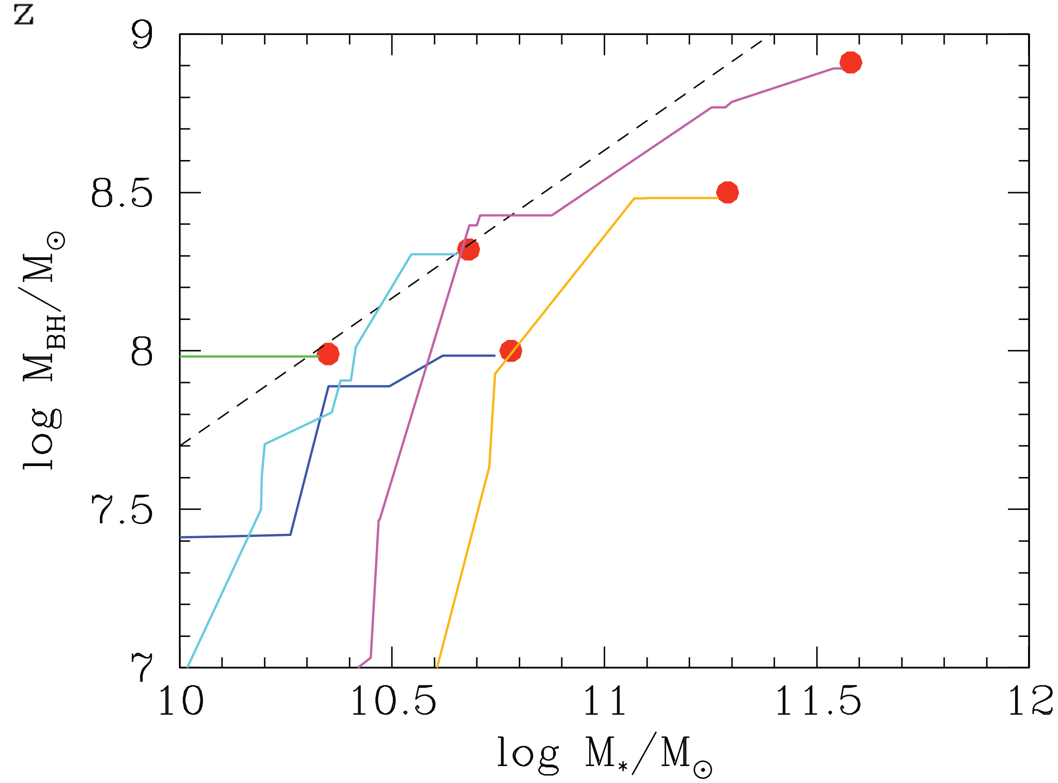
Objects selected as in Merloni et al. 2010 @1<z<2. BH growth is “stalling” and star are catching up.

Errors or selection effects?



Objects selected like SMG galaxies, i.e. extremely gas rich galaxies with large SFR @z=2-3

SMG-like galaxies represent rare evolutionary paths. They end up in M_{BH}(final)<10^9 $M_\odot$ and approach local M_{BH}-M_{star} relation from below.



A few caveats

- M_{BH} are virial masses and are plagued by several possible problems (different calibration of *f*, radiation pressure and in general winds and non gravitational motions)
- L and M_{star} are not directly measured: are obtained after applying K-corrections, correction for passive evolution (L) and depend on assumed SF histories and IMF (M_{star})
- L (hence M_{star}) are difficult to measure when the AGN is very bright compared to the host galaxy (eg for quasars) and could be significantly contaminated by scattered light from the AGN itself (Young+2009)
- There are many observational biases (after all we are mostly observing bright type 1 AGN) and they are difficult to account for.
- An obvious bias is the observation of sources in different evolutionary stages (eg Lamastra+2010)

Summary on M_{BH}-galaxy z evolution

- There seems to be a consensus on the evolution of the M_{BH}/M_{sph} ratio from 0 to high z: at high z M_{BH} is larger than local value for a given M_{sph}
  - M_{sph} alway refers to the stellar mass, thus it seems that the bulge growth in stars is lagging behind BH growth
  - M_{BH}/M_{dyn} has not been studied yet for obvious difficulties in determining the host galaxy dynamical mass (wait for ALMA?); for 1 (one) object at z~1.3 M_{BH}/M_{dyn} is roughly equal to the local value (Inskip+2011)
  - Obviously is M_{dyn} which determines the capability of the galaxy to retain its gas under the effect of AGN feedback.
- There are hints that M_{BH}/M_{total} might not vary (Bennert+2009, Jahnke +2009) or vary less (Peng+2006, Merloni+2010) at z<1-1.5 compared to M_{BH}/M_{bulge}; this is not true at higher redshift (quasars of Peng+2006).
  - Are most stars in AGN hosts formed at z>1.5 during, eg merging processes, and then redistributed to form the bulges through secular processes?

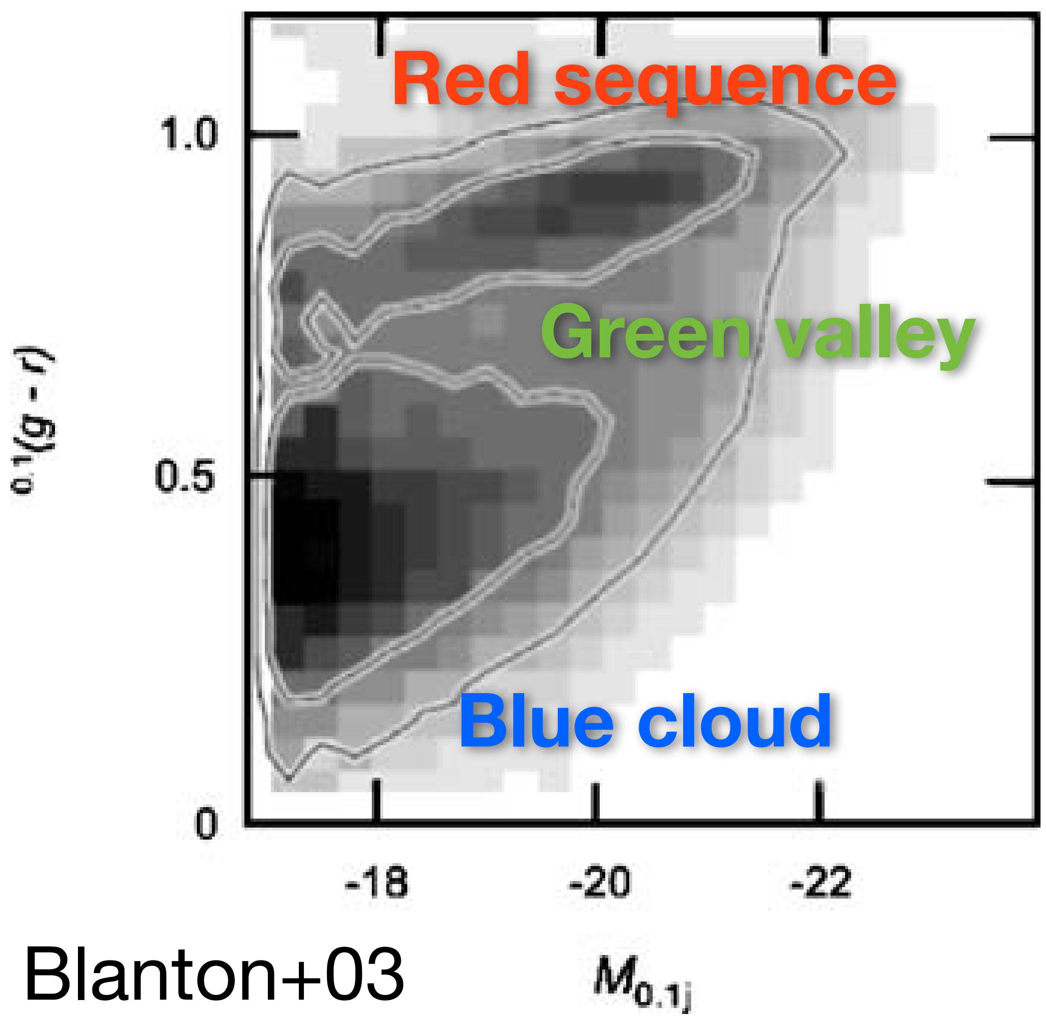
Star formation in high z AGN hosts

New galaxy classification

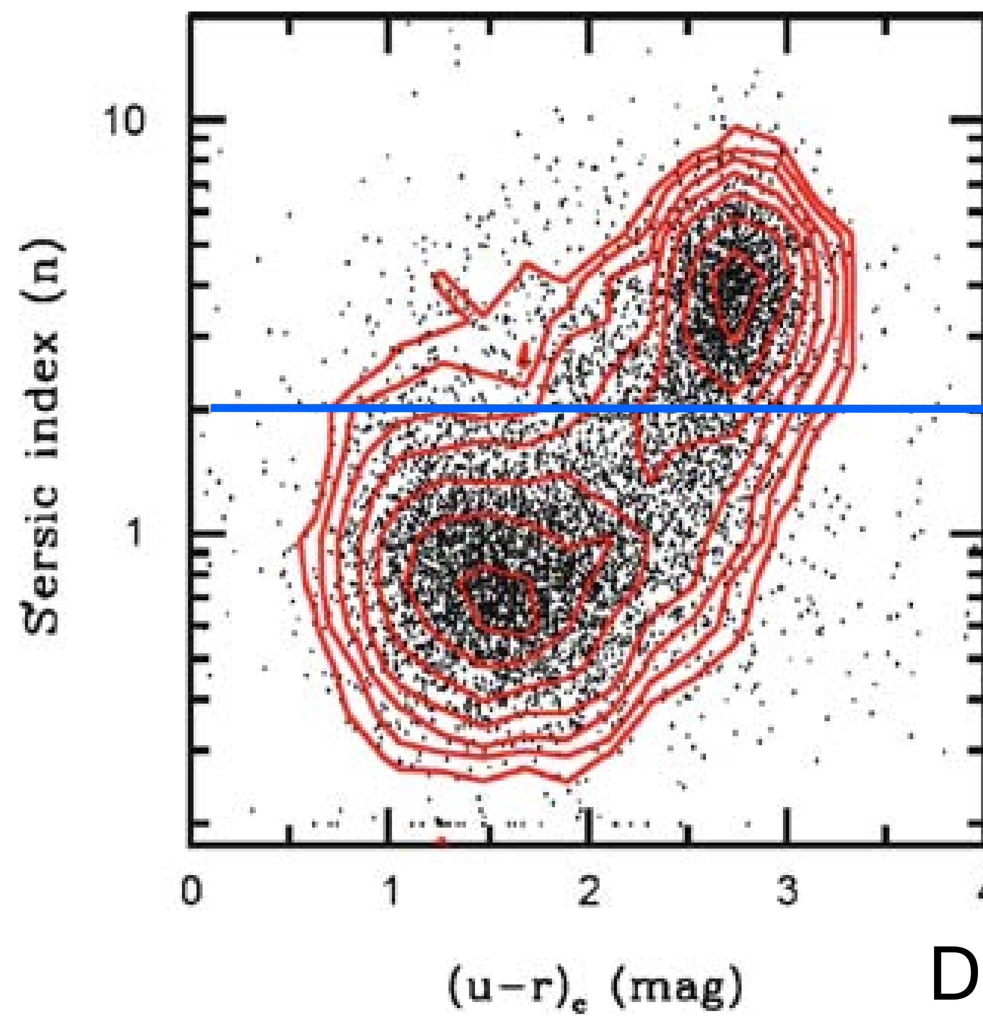
With the huge number of galaxies observed by SDSS a new classification scheme for galaxies has emerged beyond the Hubble one.

Early and late type galaxies form two sequences (seen in many properties):

- the **red sequence** made of non-star-forming, high mass spheroidal galaxies, (old, red and dead galaxies)
- the **blue sequence** (blue cloud) consists of star-forming, low mass galaxies which are disc-dominated.



Blanton+03



n>2 spheroid dominated (red galaxies)

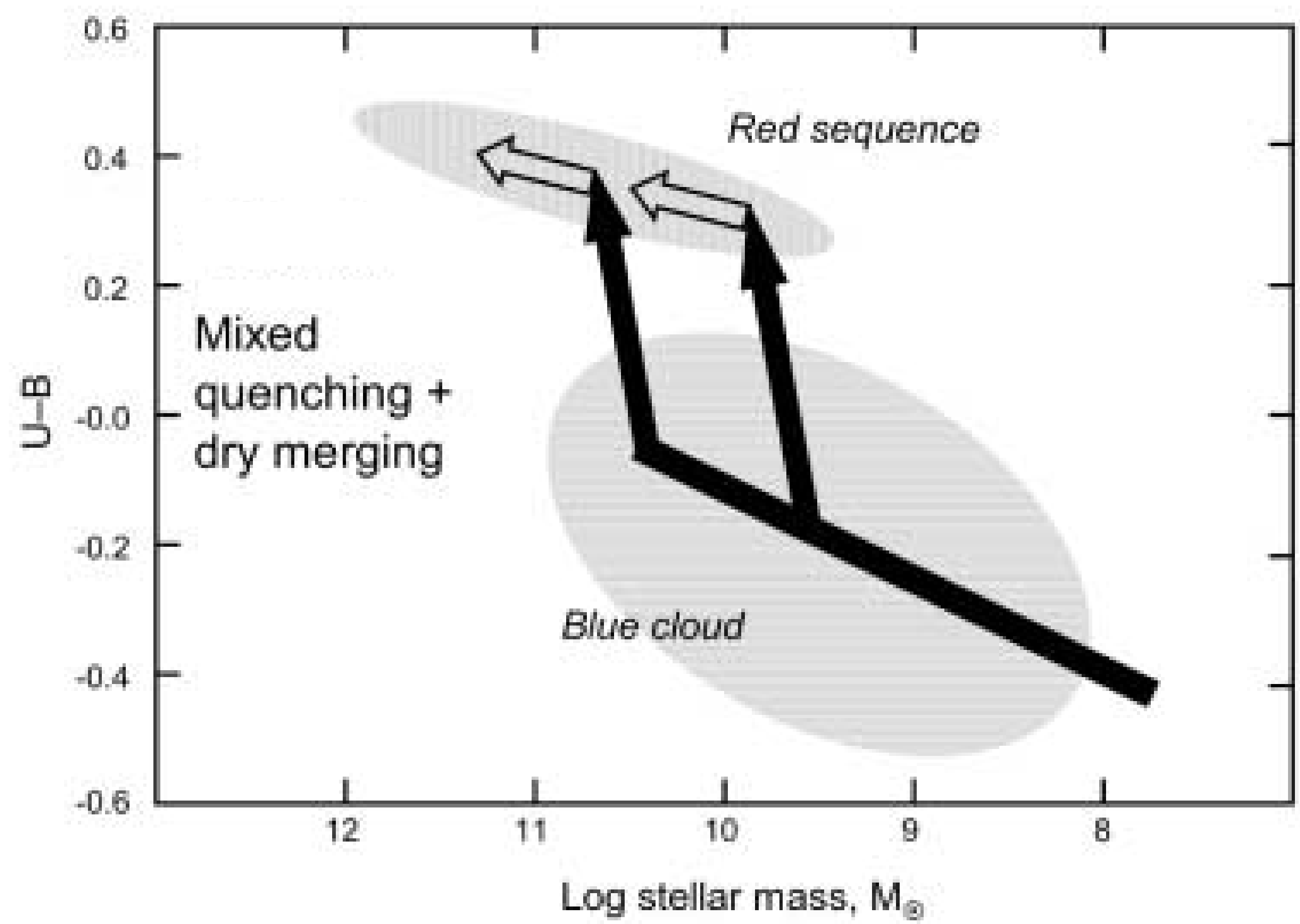
n<2 disk, pseudobulge dominated (blue galaxies)

Driver+06

New galaxy classification

One possibility (Faber+07) is the following:

- galaxies form most of their stars in the blue cloud;
- star formation is then quenched after a major merging (e.g. AGN feedback?) which doubles its mass and moves the galaxy to the red sequence;
- the galaxy stays there evolving passively or moves along the red sequence following many dry mergers.



The final position on the red sequence will mostly depend on the time when the major merging takes places.

Faber+07

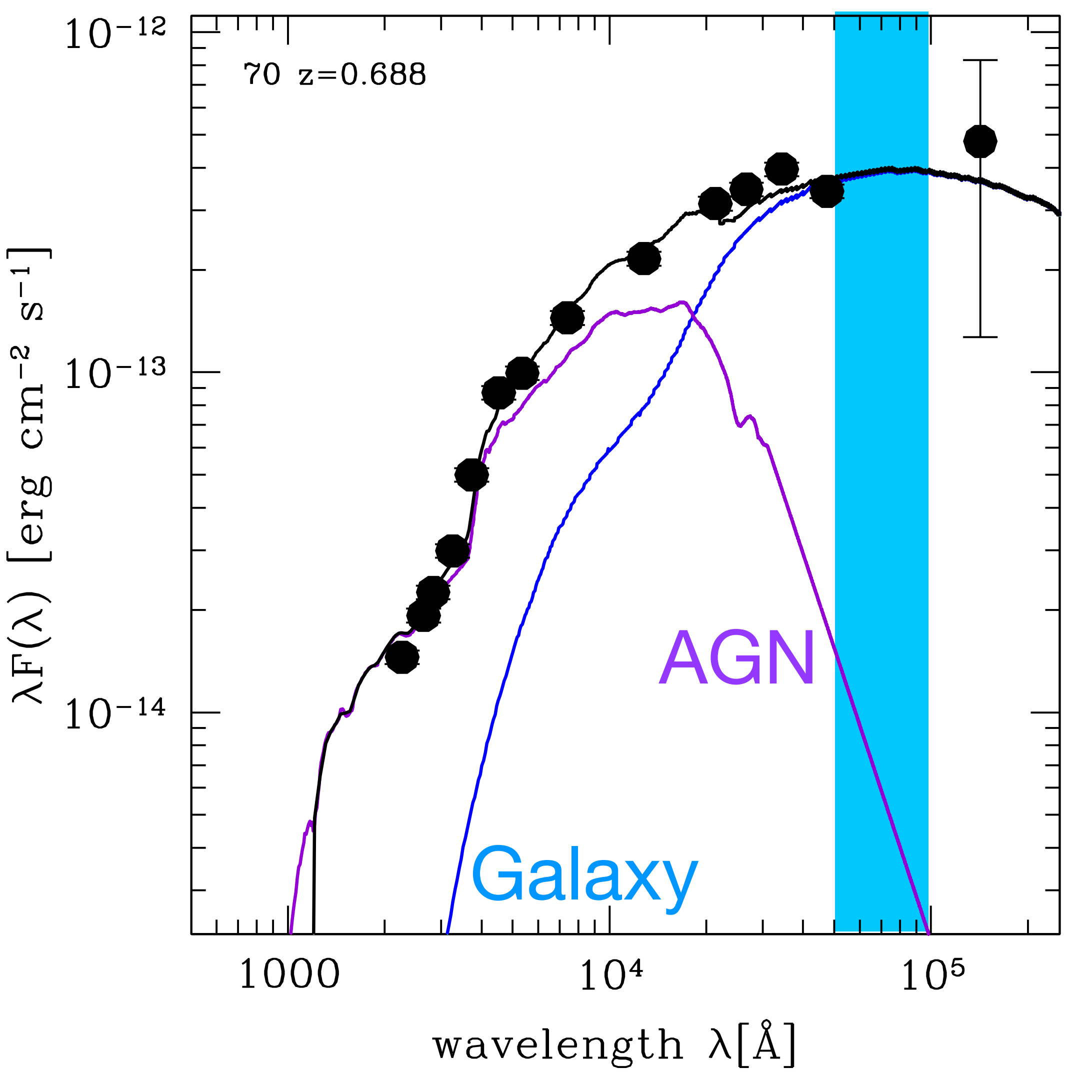
Star Formation in AGN

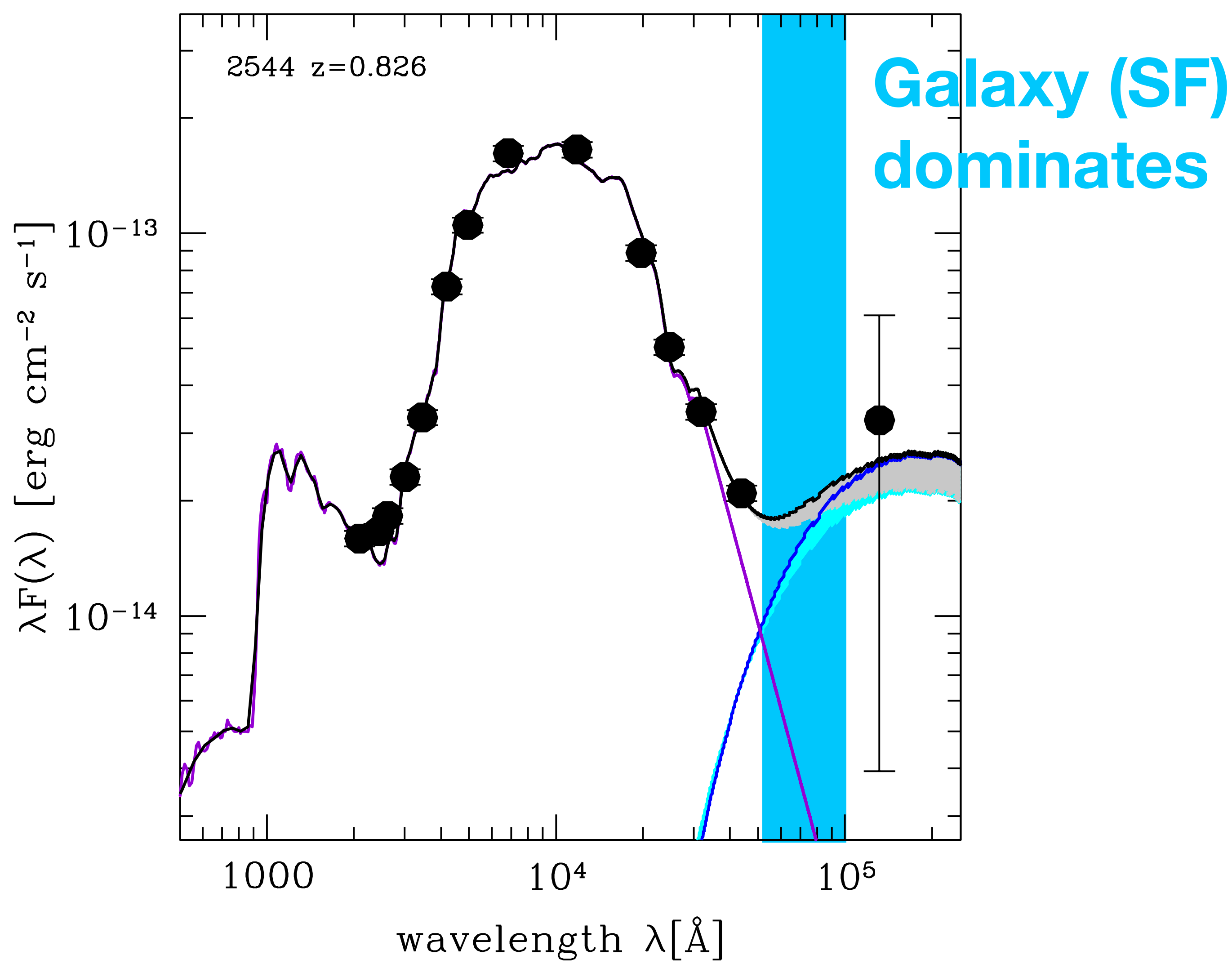
In AGN UV and H emission are severely contaminated by emission from the accretion disk.

A reliable estimator is usually FIR emission at 60-100 μm because this is mostly due to emission from cold dust in SF regions.

Important AGN contribution due to torus emission is for ~< 50 μm

Beware of radio loud objects (e.g. synchrotron emission).





example of sed fitting (Mainieri+11)

Summary for local AGN (Heckman 09)

Two modes of accretion:

- One associated with Seyfert, Quasars: radiatively efficient accretion with L/L_{EDD}~0.01-0.1.
  - This is the mode primary responsible for BH growth;
  - locally only low mass ($<10^8$ $M_\odot$) BH are growing (eg. Heckman+04)
- One associated with (massive) Radio galaxies: radiatively inefficient accretion with very low L/L_{EDD}
  - Most of the energy is injected into highly collimated relativistic jets

Most studies made in type-2 (obscured) AGN using the torus as a coronograph for the central source

- Most local AGN hosts lie in the "green valley", actually most galaxies in the green valley host AGN (eg. Kauffmann+07)
- most present day accretion in galaxies with young stellar populations, intermediate M_{star}, high surface mass densities (eg. Heckman+04)
- Kauffman+07 showed that the necessary condition to have a strong AGN or young bulge, is to have blue (young) disk: does the gas that builds the bulge and BH come from the disk?
- But there are no evidences for association of AGN activity with merger events!

(→Mike Crenshaw's lectures)

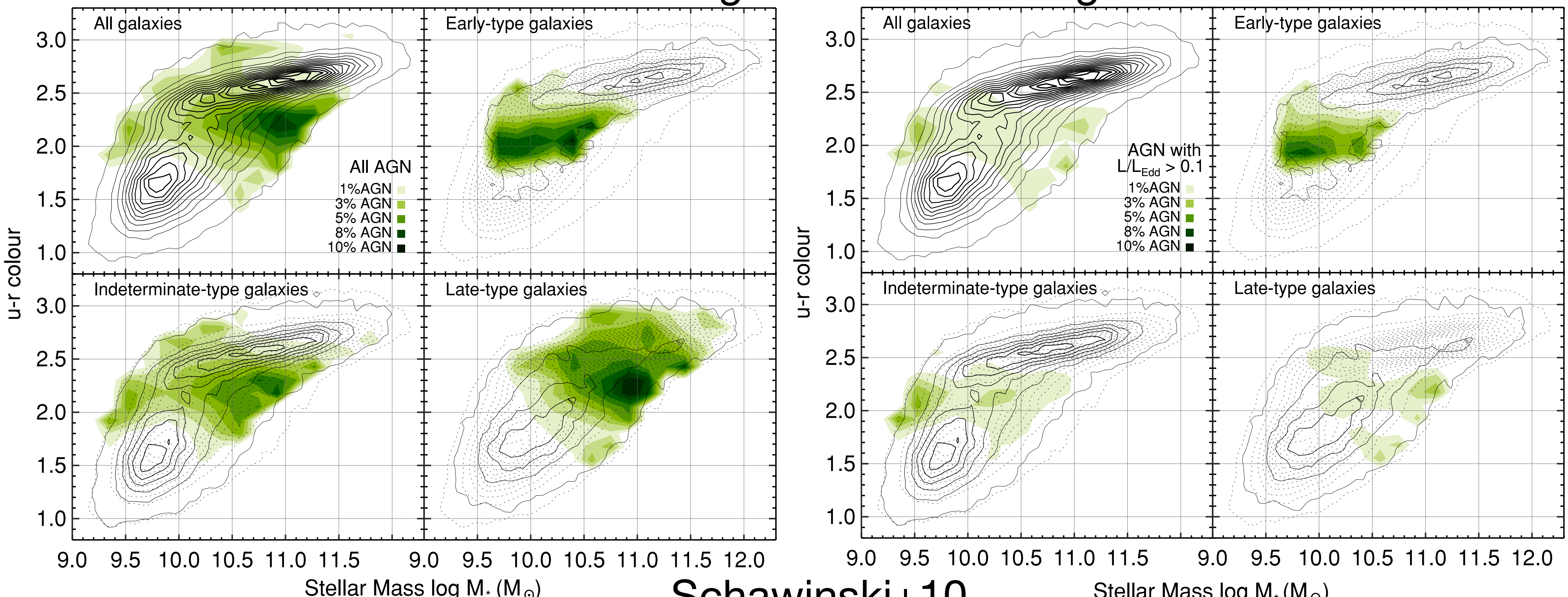
Summary for local AGN

Recent work by Schawinski+10 taking advantage of morphological classification by galaxy zoo (made by ~250.000 volunteers) allowed to separate galaxies in green valley:

- early type galaxies: least massive BHs are growing
- late type galaxies: most massive BHs are growing
- only low mass early types are growing at high L/L_{Edd}

All galaxies **L/L_{Edd}>0.1**

Fraction of galaxies that are Agn



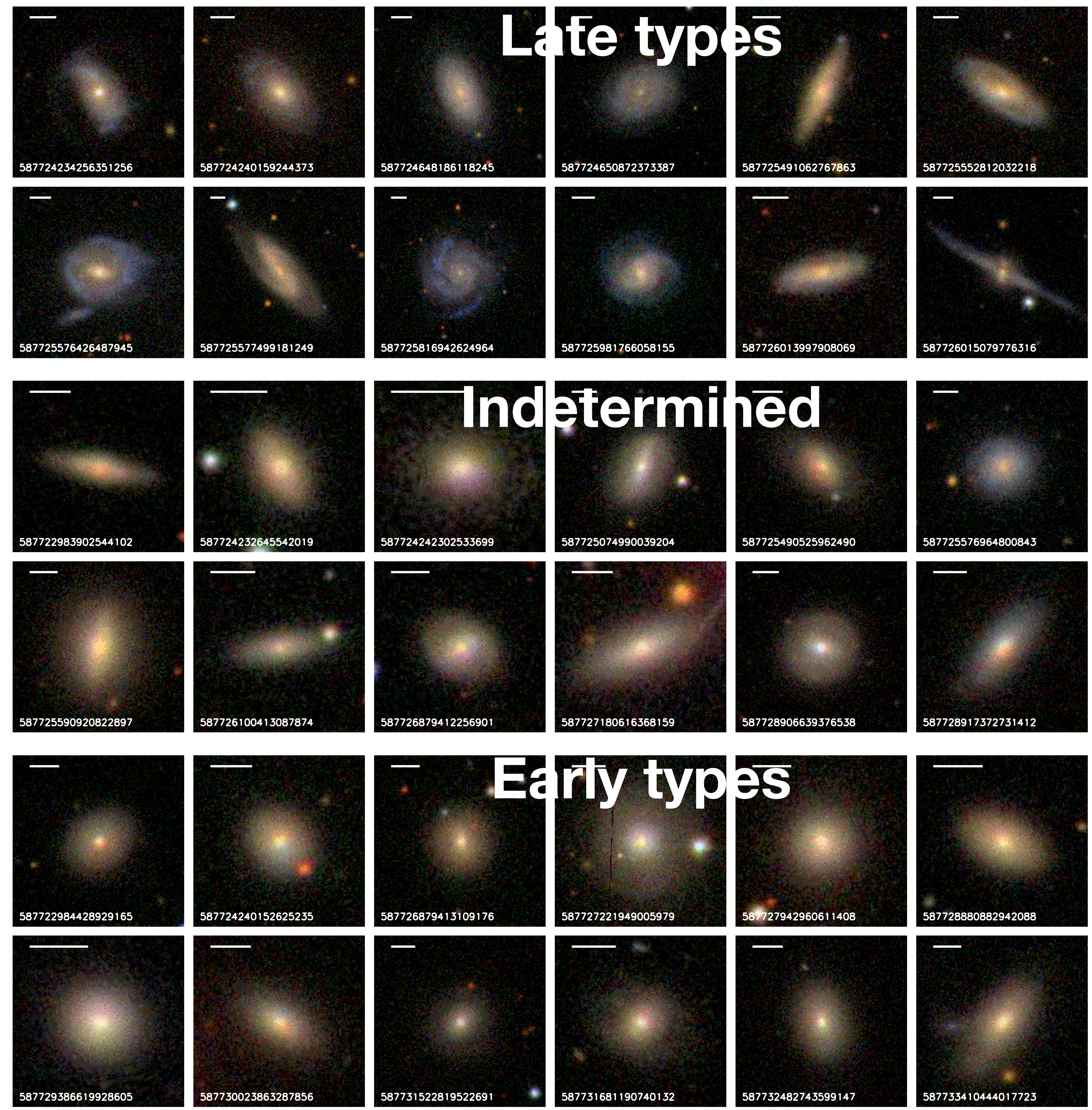
Schawinski+10

Summary for local AGN

Possible explanation: 2 modes of BH growth in early and late type galaxies

- low mass, early type AGN are post starburst galaxies moving toward low mass end of red sequence (following a major merger?) and can be the low mass, low luminosity (downsized) version of evolution mode involved in formation of massive galaxies (and the production of quasars)

- role of agn in late types less clear: high host stellar masses, grand design stellar disks indicates they are not the product of major mergers. Are they the result of secular processes like those that lead to the formation of pseudobulges?



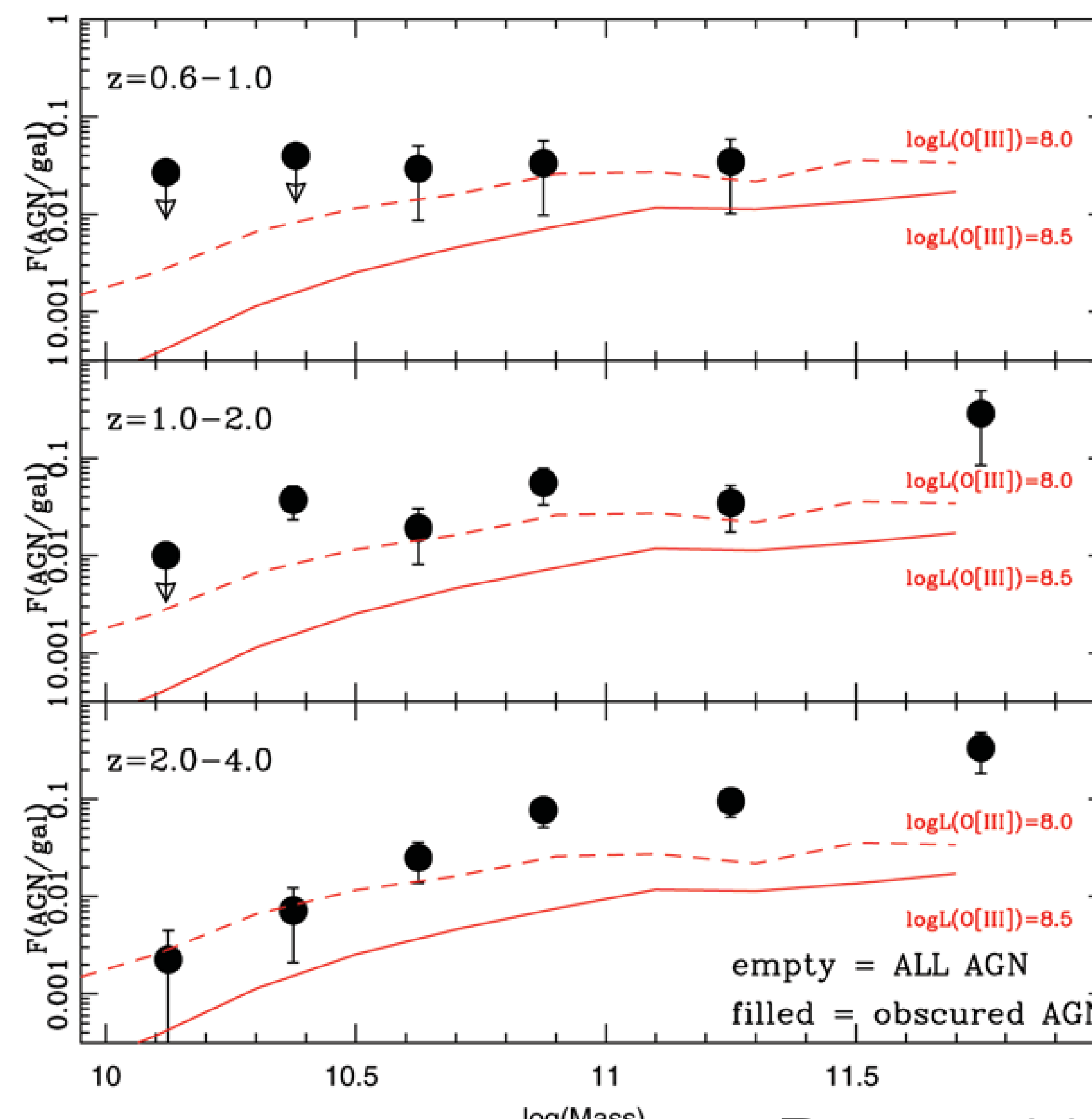
AGN at z>1

At higher redshifts it is almost impossible to study the host galaxies of quasars for them we can only get information on their overall star formation.

Obscured AGNs from X-ray or IR surveys (I will use mostly COSMOS).

- Obscured AGN populate the red sequence and green valley like at z~0.
- AGN are found in the most massive galaxies
- ~2/3 of the hosts show substantial SF (>10 $M_\odot$/y)
- in general, ~half of them live in galaxies which are still actively forming stars (1/SSFR< t_{Hubble})
- for these, red colors means blue colors with extinction

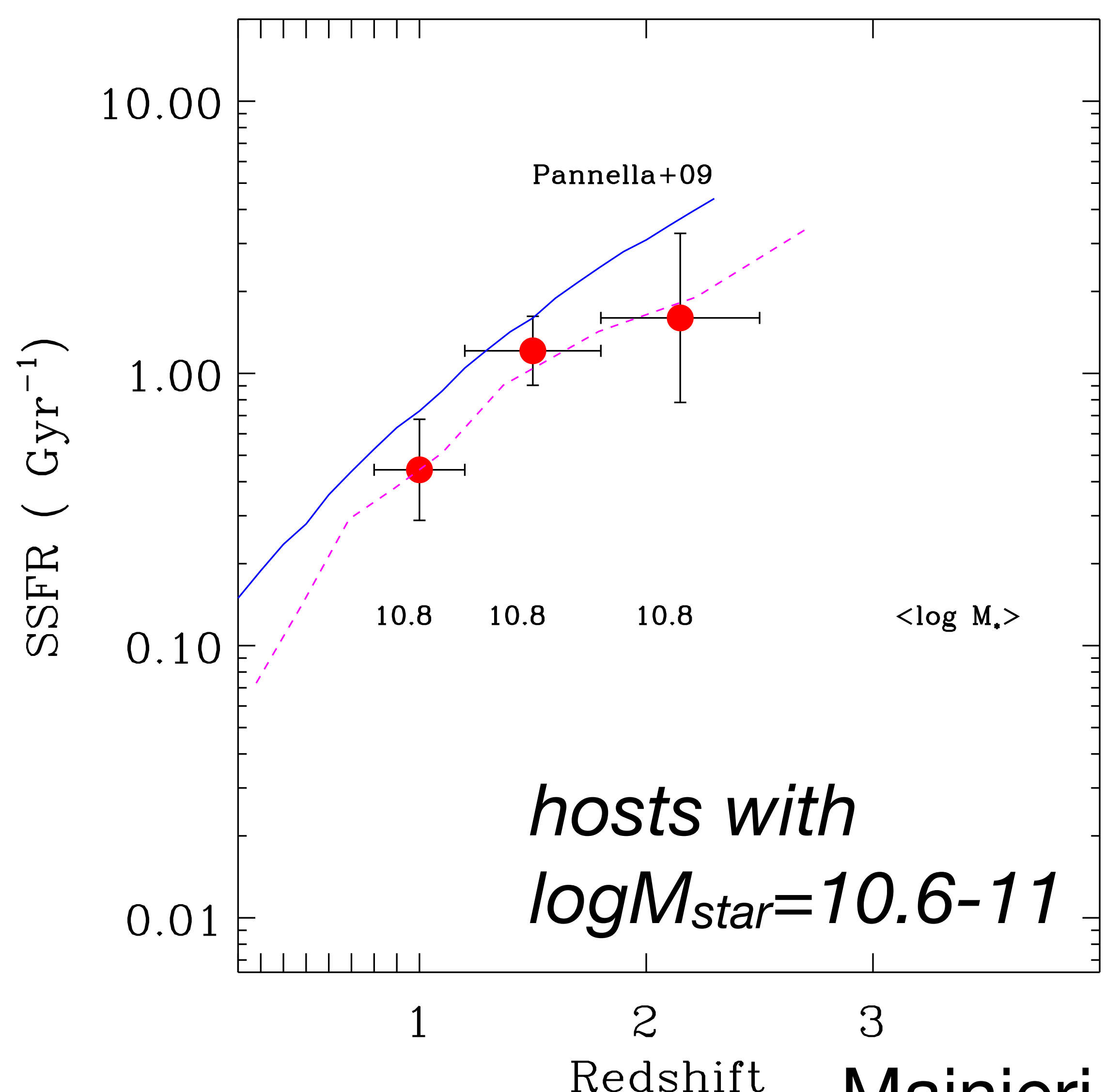
- AGN fraction increases with host galaxy stellar mass (as observed locally) but AGN fraction (eg. duty cycle) is overall larger than local universe



Brusa+09

AGN at z>1

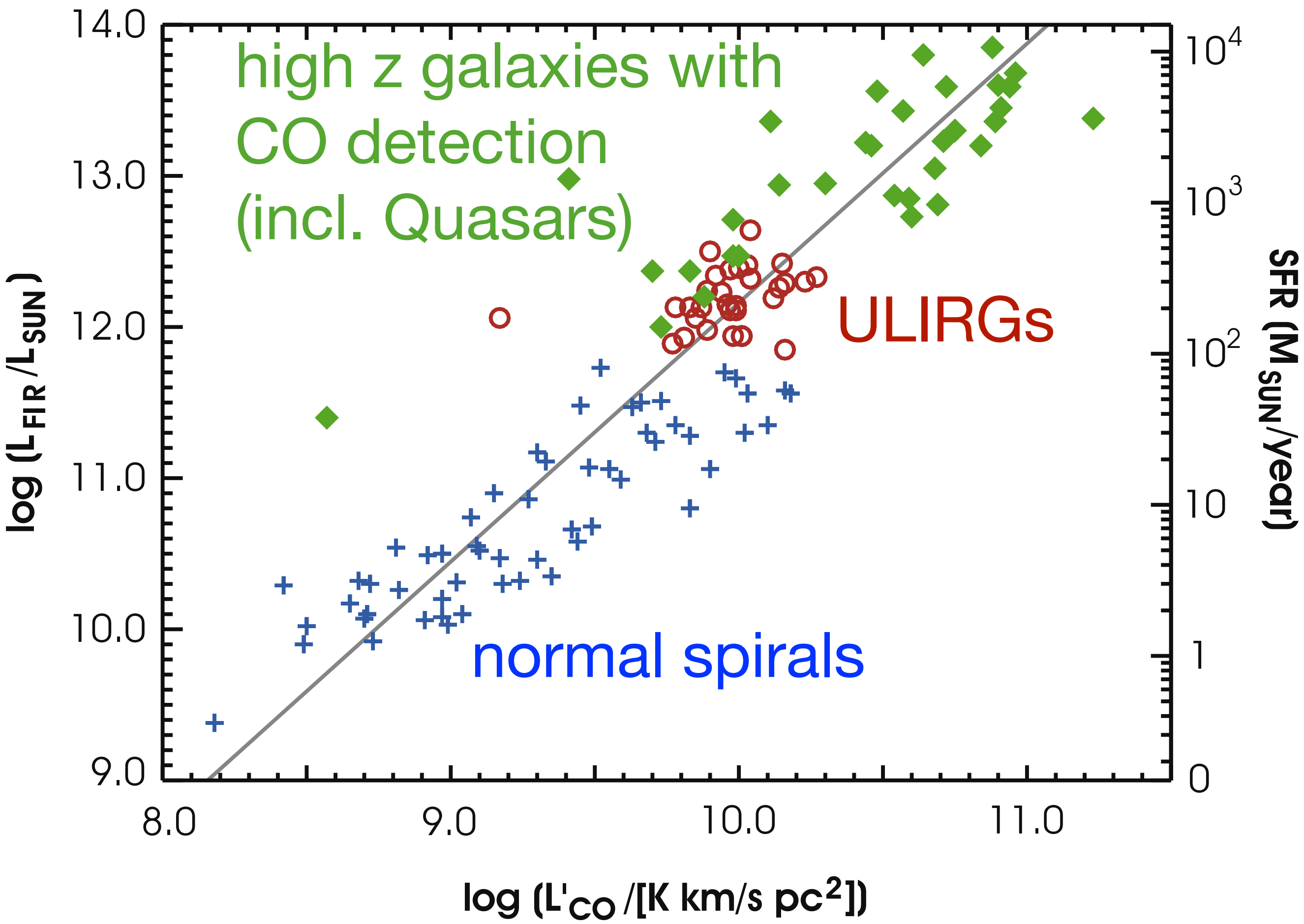
- Obscured quasars (rare) mainly reside in massive galaxies
- At z~1 >50% of all type 2 QSO are actively forming stars at a rate comparable to that of normal SF galaxies
- fraction of hosts increases with redshift (~70% at z~2, 10% at z~3)
- morphologically, most hosts seem to be bulge dominated, *there are few signs of mergers and interaction*
- as seen locally, it seems that
  - bulge dominated have $L/L_{Edd} < 0.1$
  - disk dominated $L/L_{Edd} > 0.1$ (high L/L_{Edd} is not due to (major mergers) which would disrupt the disk.



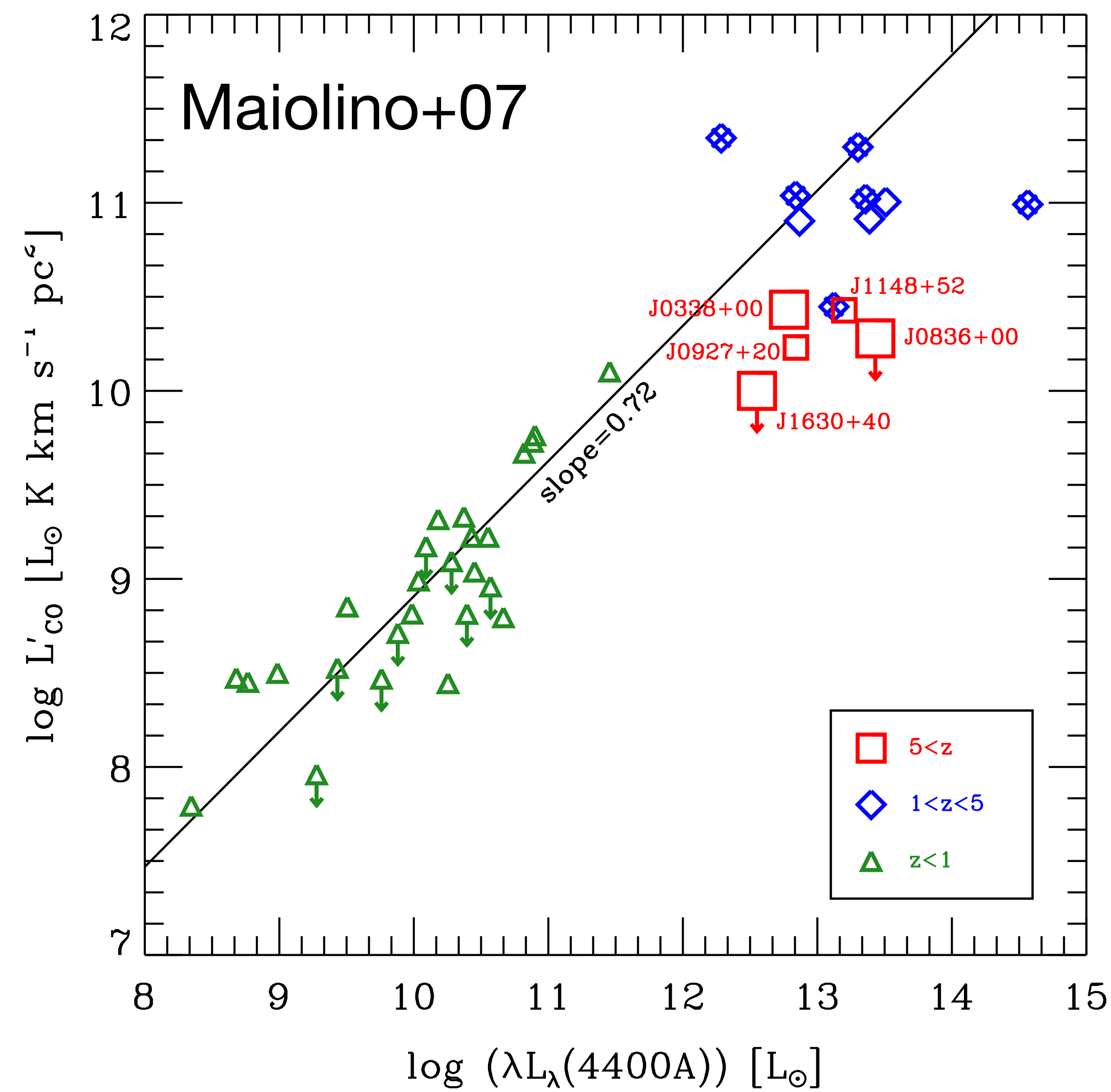
Mainieri+11

SF in quasars

CO(1-0) is the strongest molecular line from ISM and star forming regions, and is correlated with FIR emission, i.e. it is strongly correlated with SF Quasar host galaxies are also rich in molecular gas, and the properties of. CO emission in high-z quasars and radio galaxies are not strongly different from local and lower redshift powerful starburst.



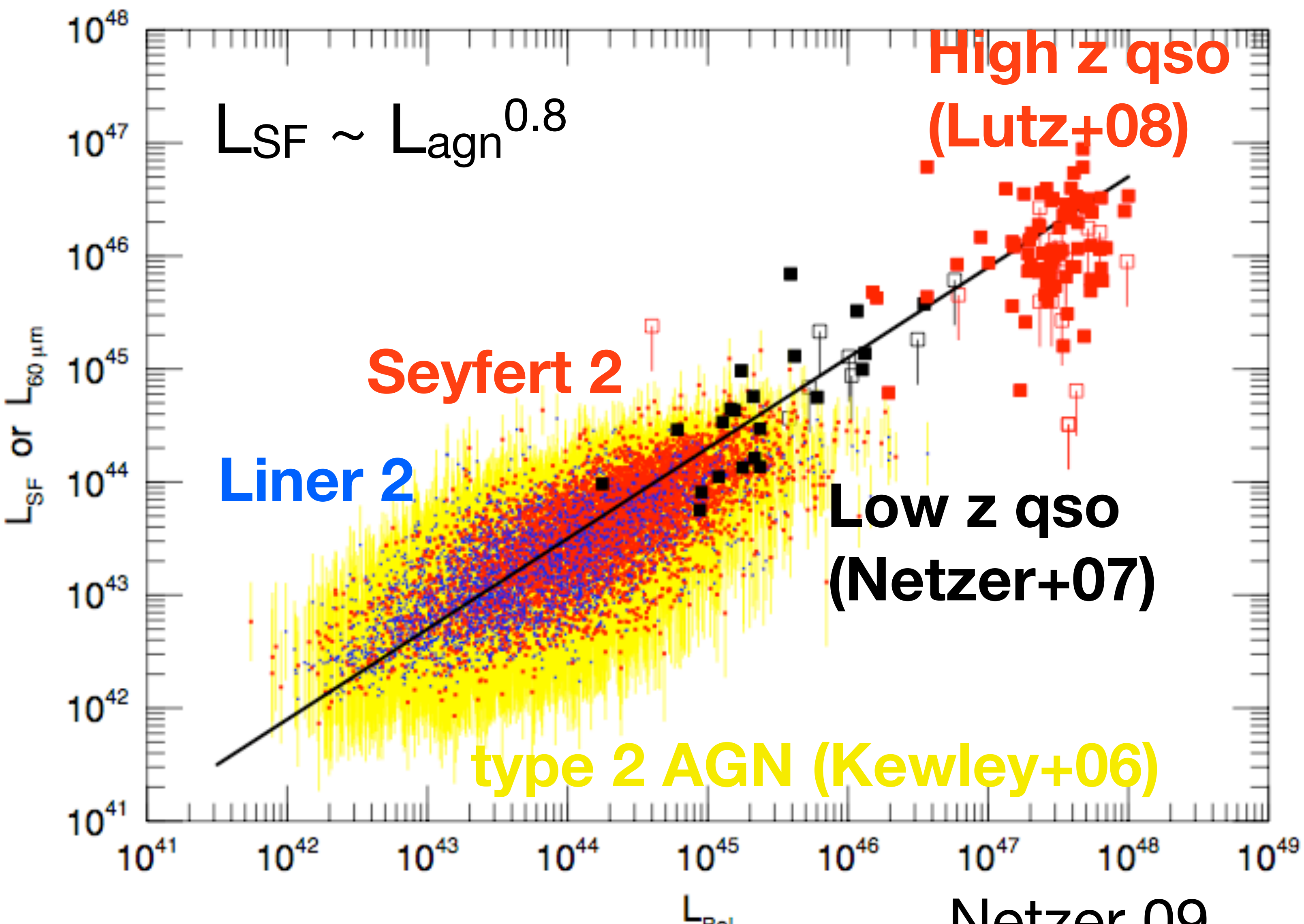
Solomon & Vanden Bout (2005)



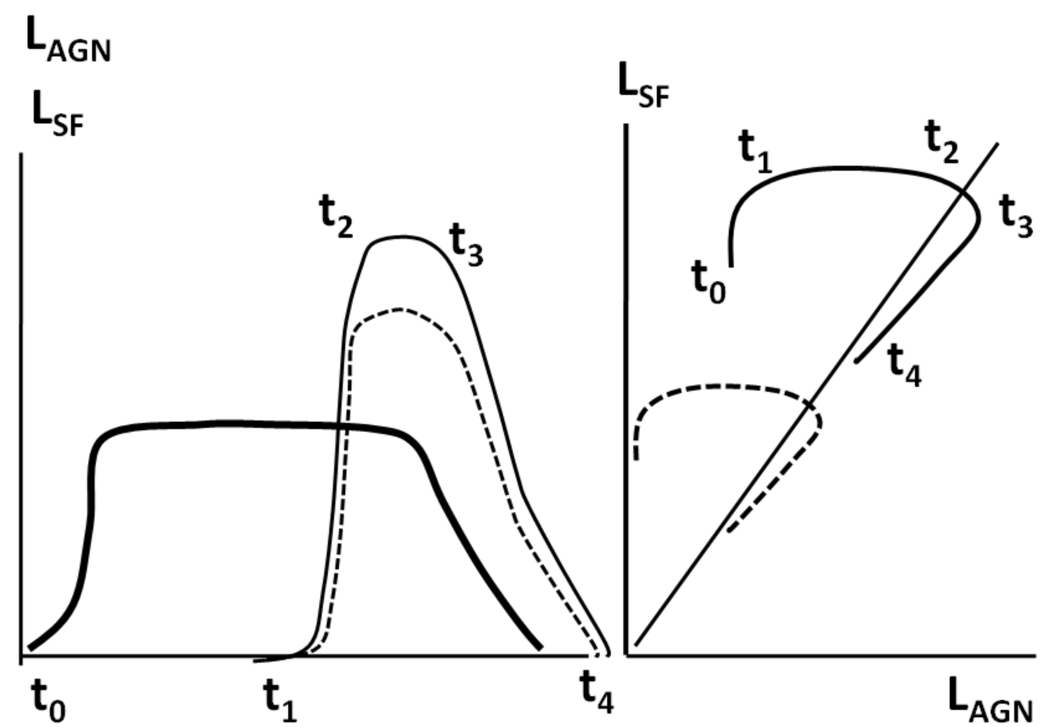
SF in quasars

Type 1 quasars: host galaxies difficult to study but can compare global properties that can be obtained from the analysis of spectra, eg. total SF in the host (see eg the use of FIR emission)

L_{AGN} - L_{SF} correlation: even if there maybe selection effects it means that AGN activity is tightly linked with SF activity and this extend from low to high Luminosity AGN



Netzer 09



- This correlation has been explained by Netzer+09 with offset BH growth
- no distinction between quasars and lower luminosity AGN

SF in quasars

Since $L_{SF} = \varepsilon_{SF} \dot{M}_{SF} c^2$

$$L_{AGN} = \varepsilon_{AGN} \dot{M}_{AGN} c^2$$

$L_{SF} \sim L_{agn}^{0.8}$ is translated to

$$\frac{\dot{M}_{bulge}}{\dot{M}_{BH}} \simeq 115 \left(\frac{\varepsilon_{BH}/0.1}{\varepsilon_{SF}/7 \times 10^{-4}} \right) \left(\frac{L_{AGN}}{10^{42}\,\mathrm{erg\,s^{-1}}} \right)^{-0.2}$$

If that ratio were constant with time, then its time integral should give M_{bulge}/M_{BH} i.e. ~1000

Slow accreting BHs ($L \sim 10^{42}$ erg sec^{-1}) are growing at a rate which is ~6 times faster than global average over cosmic time

Very luminous BHs ($L \sim 10^{48}$ erg sec^{-1}), are accreting at even faster rate, ~100 times faster than average

it also tells that the time of AGN activity must be shorter than the time of star formation / bulge growth

This is consistent with the fact that we find M_{star}/M_{BH} < local value in quasars and other high z AGN.

Netzer 09

Metallicity of AGN

Metal abundances

$$Z_\odot \simeq 0.02$$

$$\left[12 + \log\left(\frac{O}{H}\right)\right]_\odot \simeq 8.7$$

Metal abundance is defined as

$$Z = \frac{\text{Mass of heavy elements } (> \text{He})}{\text{Mass of H}}$$

Element abundance is usually based on number of atoms and characterized by (e.g. for O):

$$12 + \log\left(\frac{O}{H}\right) = 12 + \log_{10}\left[\frac{\text{number of O atoms}}{\text{number of H atoms}}\right]$$

The metal abundances of galaxies (metallicities) and the relative abundances of elements are determined by the star formation history.

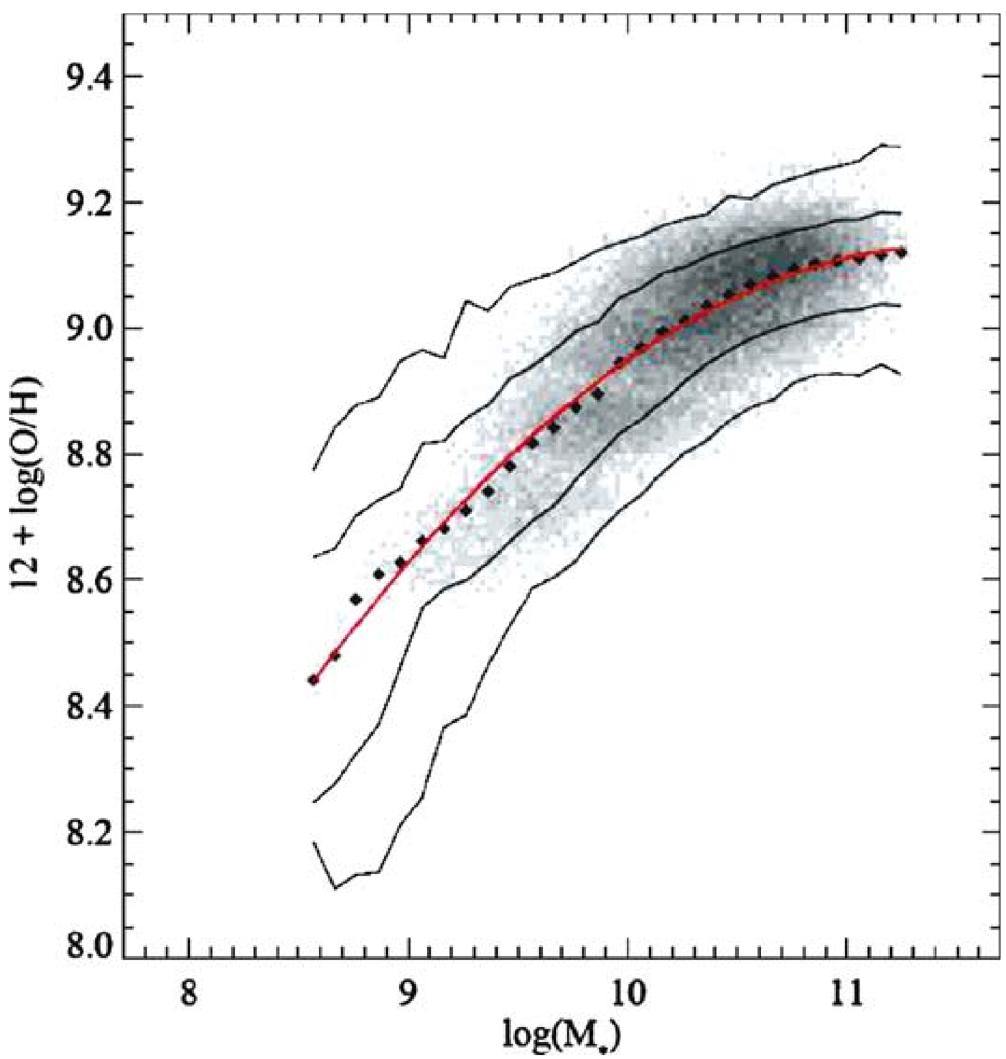
- The tracers of star formation like L_{UV}, L(H), L_{FIR}, L_{PAH} trace the current star formation rate (SFR).
- In contrast metallicity traces time integrated star formation, i.e. the build up of the galaxy stellar population.

Metallicity provides a much more global picture of galaxy evolution, less subject to episodic or sporadic phenomena.

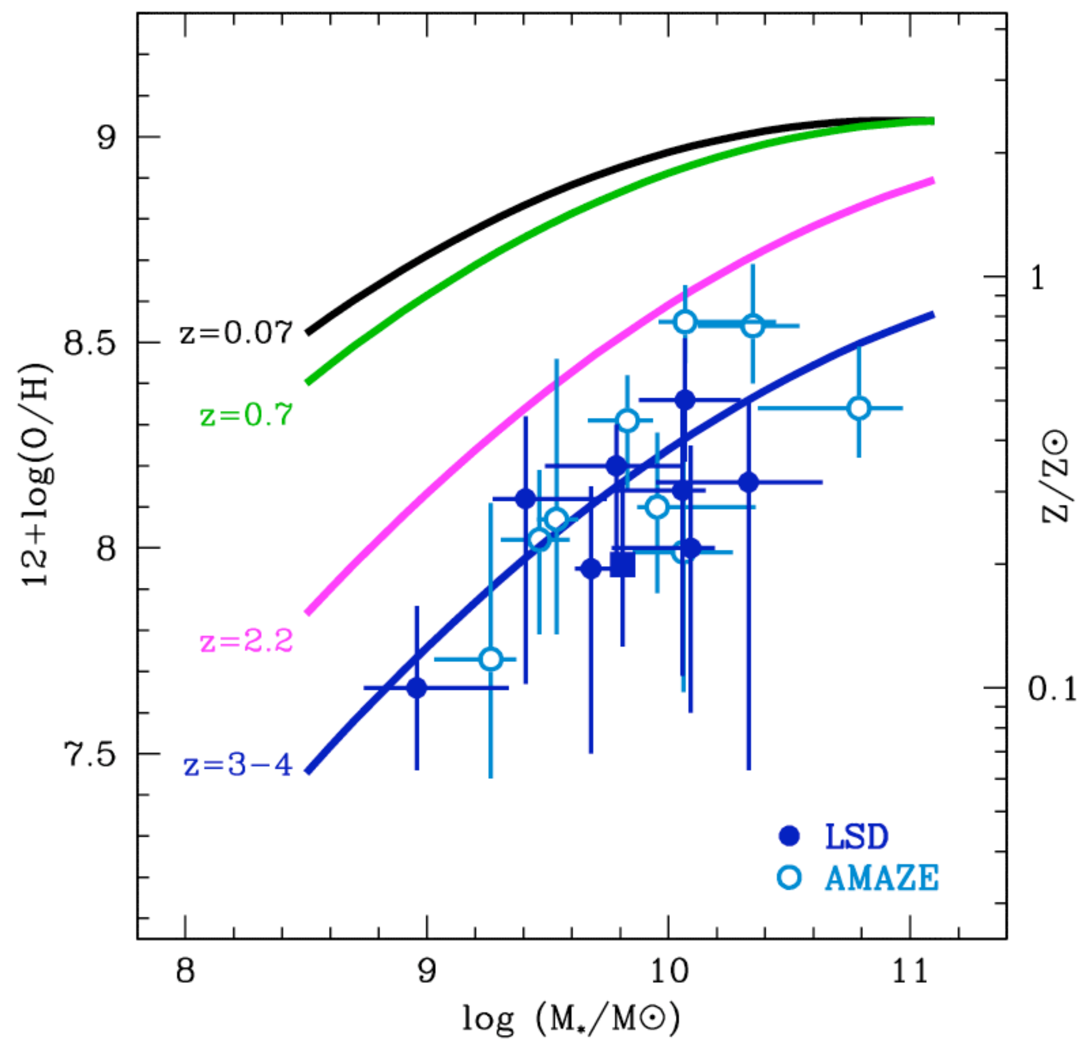
Metallicities in normal galaxies

One well known result is that the metallicity of galaxies (measured through the O abundance) correlates with stellar mass: most massive galaxies are also the most metal rich (e.g. Tremonti+04)

This Mass-Metallicity relation evolves showing evidence for "chemical" downsizing: most massive galaxies reach their final metallicities at z~2, while less massive galaxies do that at z<1.



Tremonti+04



Mannucci+09, Maiolino+09

Metallicities in AGN (from BLR)

The metallicities of most distant galaxies provide key insight into their star formation histories.

However, what we can currently do with great efforts (eg. ~6h observation time with VLT per galaxy) is to measure Z for galaxies up to z~3.

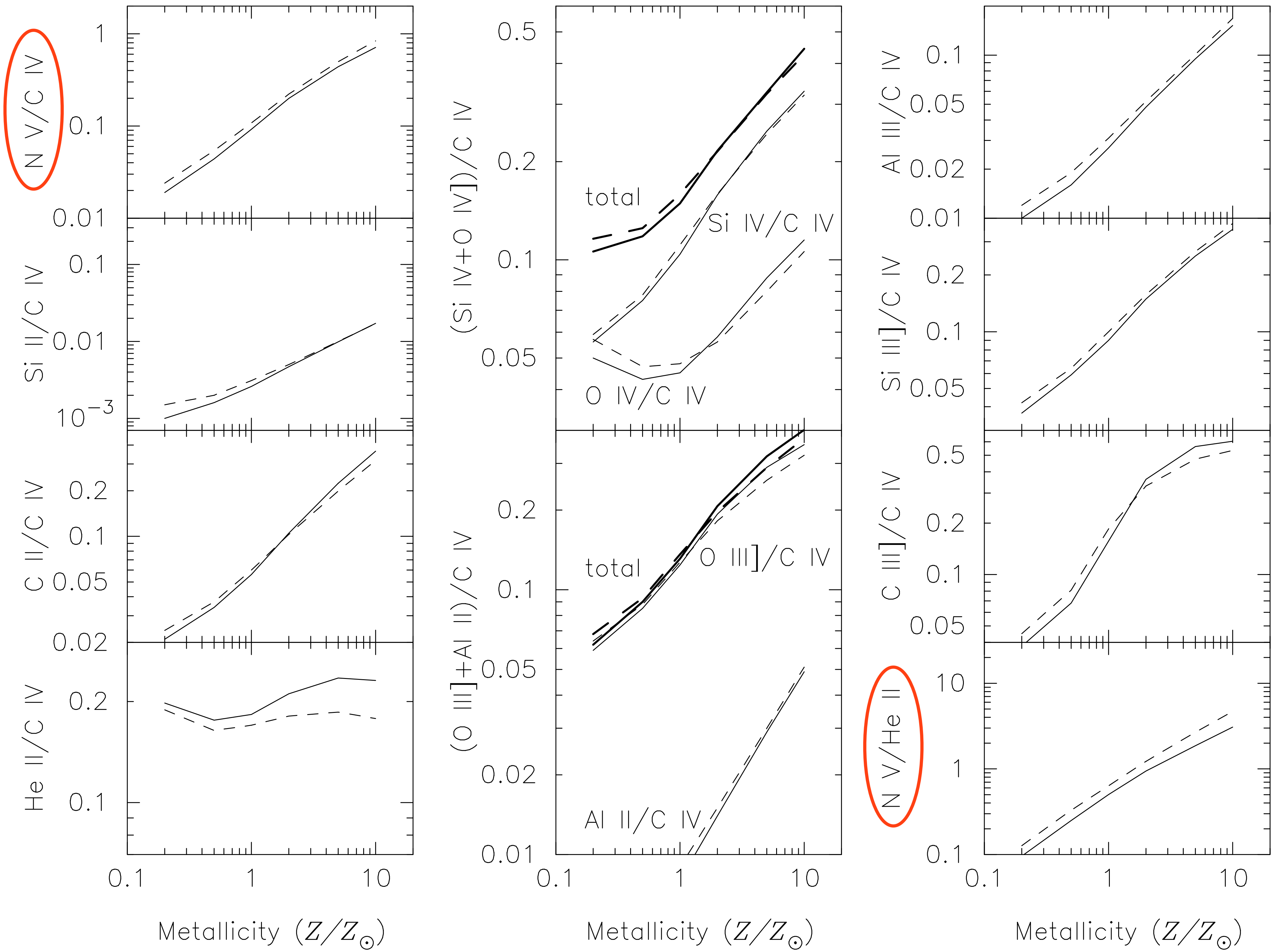
Much easier is the use of BLR spectra which can have high S/N up to the highest redshifts.

To measure metallicities one can use ratios of lines which have similar excitations and therefore are mostly sensitive on metal abundances (e.g. NV/CIV, NV/HeII, FeII/MgII, Hamann & Ferland 89,93).

In practice one should compute BLR photoionization models for several values of abundances and then find the best match with observations to determine the value of Z_{BLR}.

Of course, the results depends also on the relative abundances among the elements: since it is not possible to determine all the relative abundances, assumptions are made (e.g.relative abundances based on chemical evolution models of starburst galaxies, Hamann & Ferland 1999).

Metallicities in AGN (from BLR)

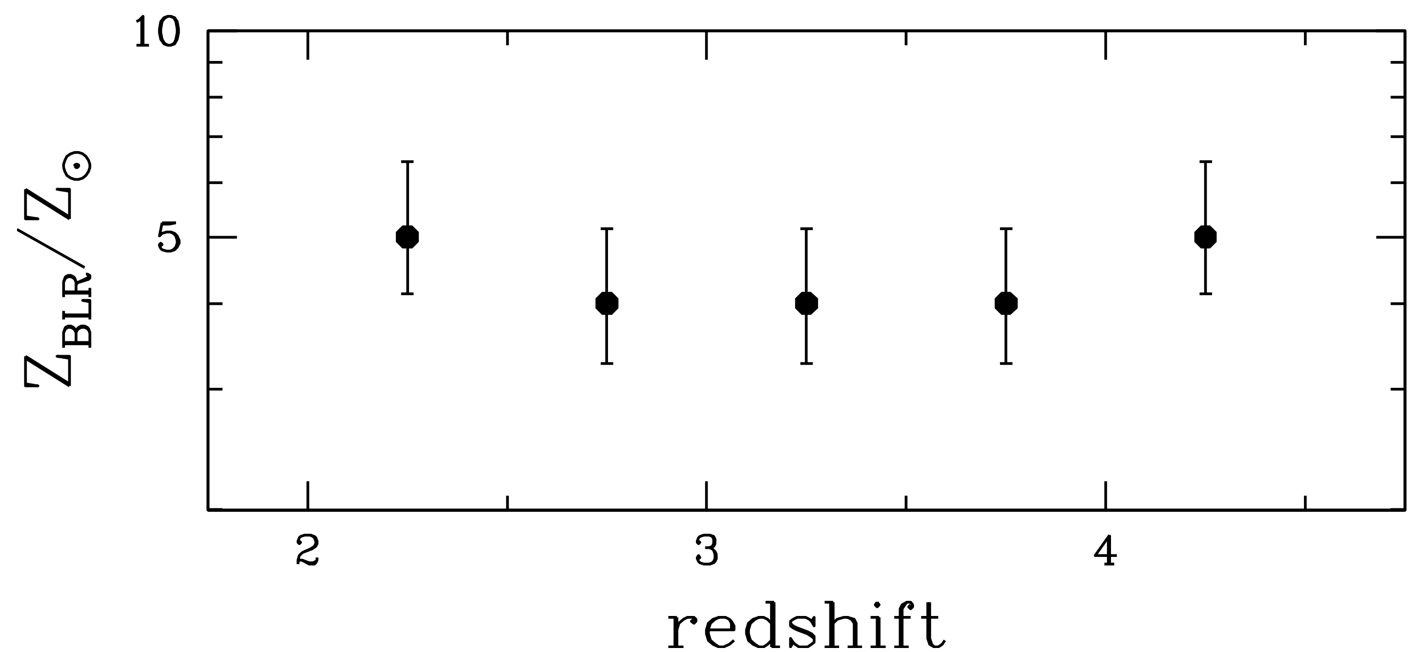


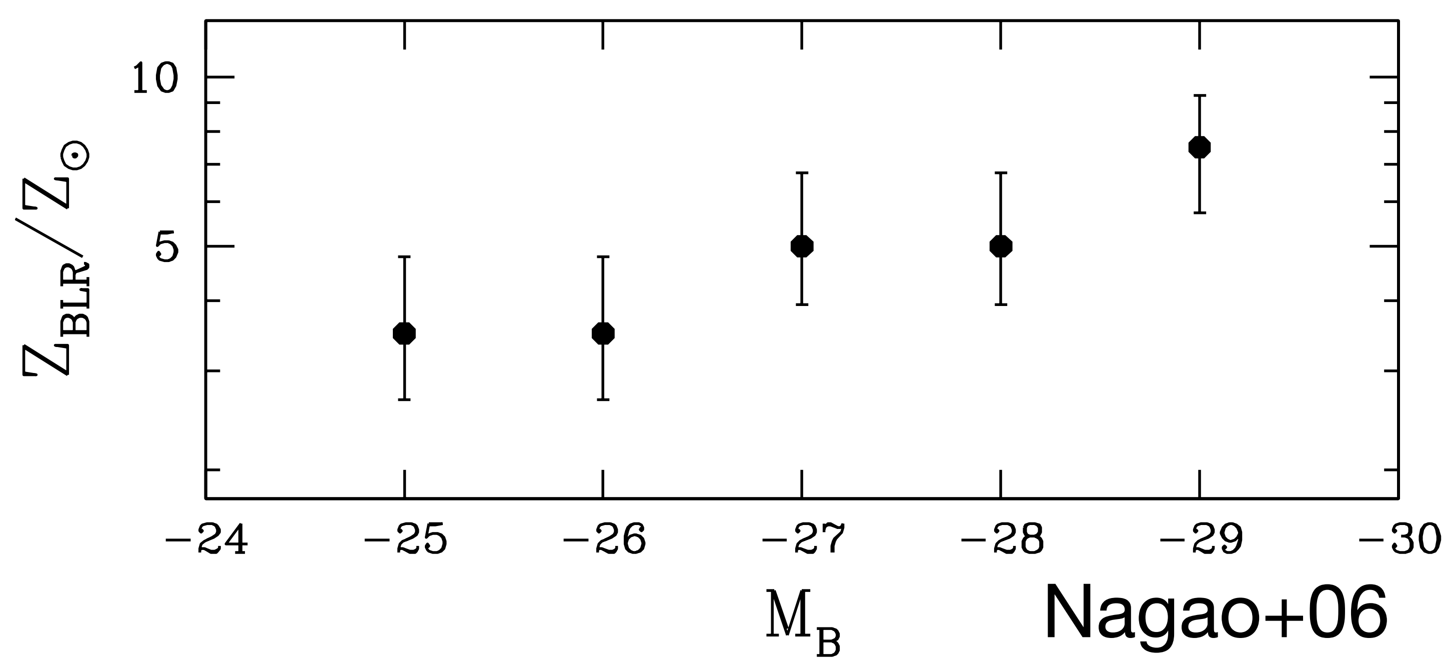
BLR line ratios from Nagao+06

BLR Metallicity

There are many studies in the literature on BLR abundances and among the most important results there are

- BLR metallicities are usually much larger than solar (Baldwin & Netzer 78, Hamann & Ferland 89,92, Nagao+06).
- In some extreme cases they can reach even ~15 $Z_\odot$ (Baldwin+03)
- BLR metallicities do not appear to vary with redshift (Dietrich+03, Maiolino+03, Nagao+06, Juarez+09).
  - To understand implications, Z_{BLR}~5 $Z_\odot$ at z~4 means that active SF occurred at z>7.
- there is a correlation between Z_{BLR} and L_{AGN}: more luminous AGN have more metal reach BLR (Hamann & Ferland 93,99)





Nagao+06

BLR metallicity

Matsuoka+11 find that Z_{BLR}-L might be the consequence of Z-M_{BH} relation

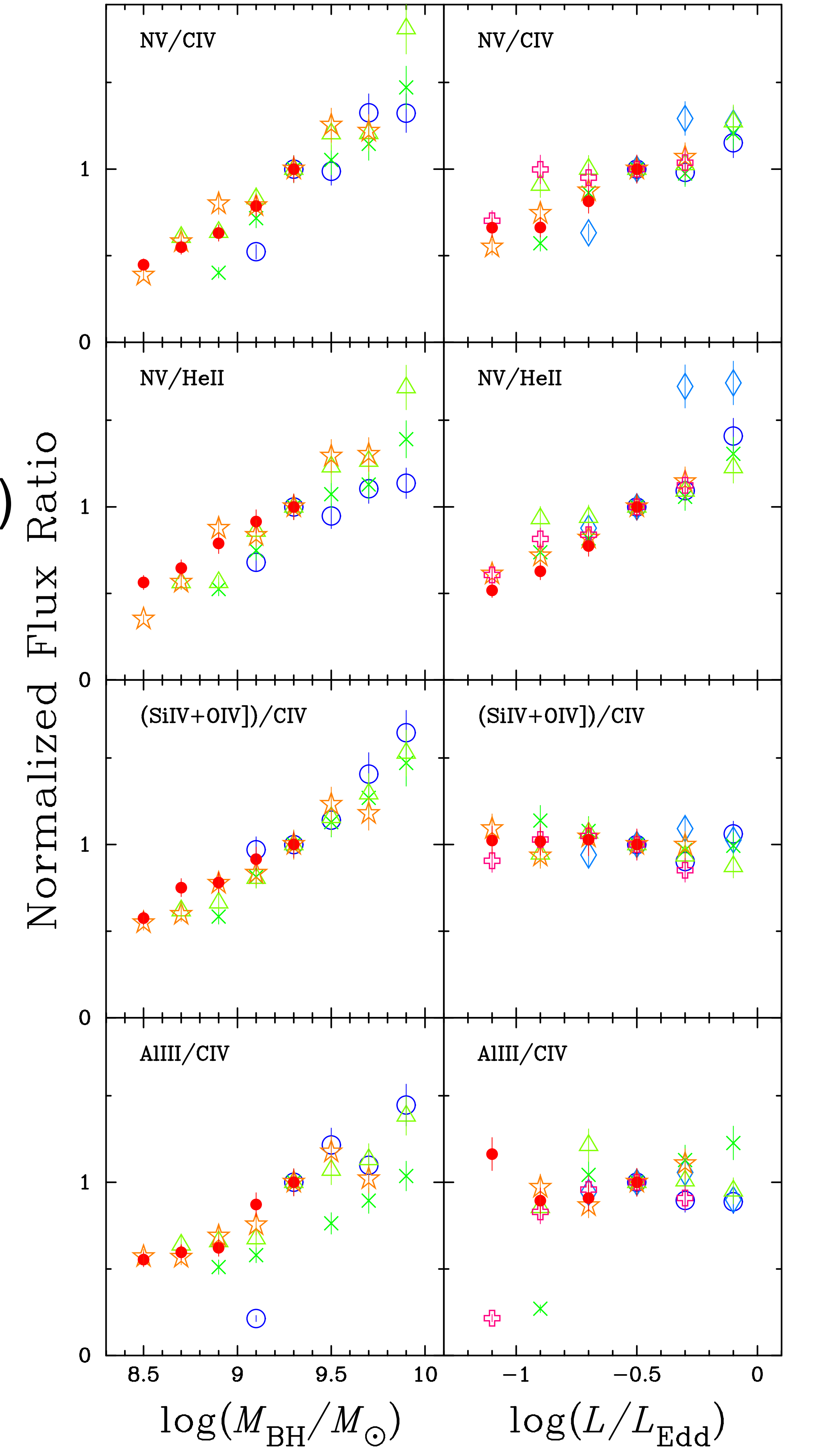
- all Z sensitive line ratios correlate with M_{BH}
  - Z_{BLR}-M_{BH} might derive from M_{BH}-M_{star} and Z_{BLR}-M_{star} relations(physical quantities integrated over cosmic history)
- only N line ratios (i.e. Z(N))correlate with L/L_{Edd} (see also Shemmer+04)

Taking into account that

- elements like O, Si, Al are produced on short timescale and go into the ISM with SNII explosions (~10^6-10^7 yr)
- N is mostly produced by AGB stars on ~10^8 yr timescales

- Z(N)-vs L/L_{Edd} can be understood if AGN activity takes place in a post-starburst galaxy ~10^8 yr after the burst of star formation and AGN activity is fueled by the winds of AGB stars (e.g. Cen 2011)

Matsuoka+11



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Taking into account

- elements like C
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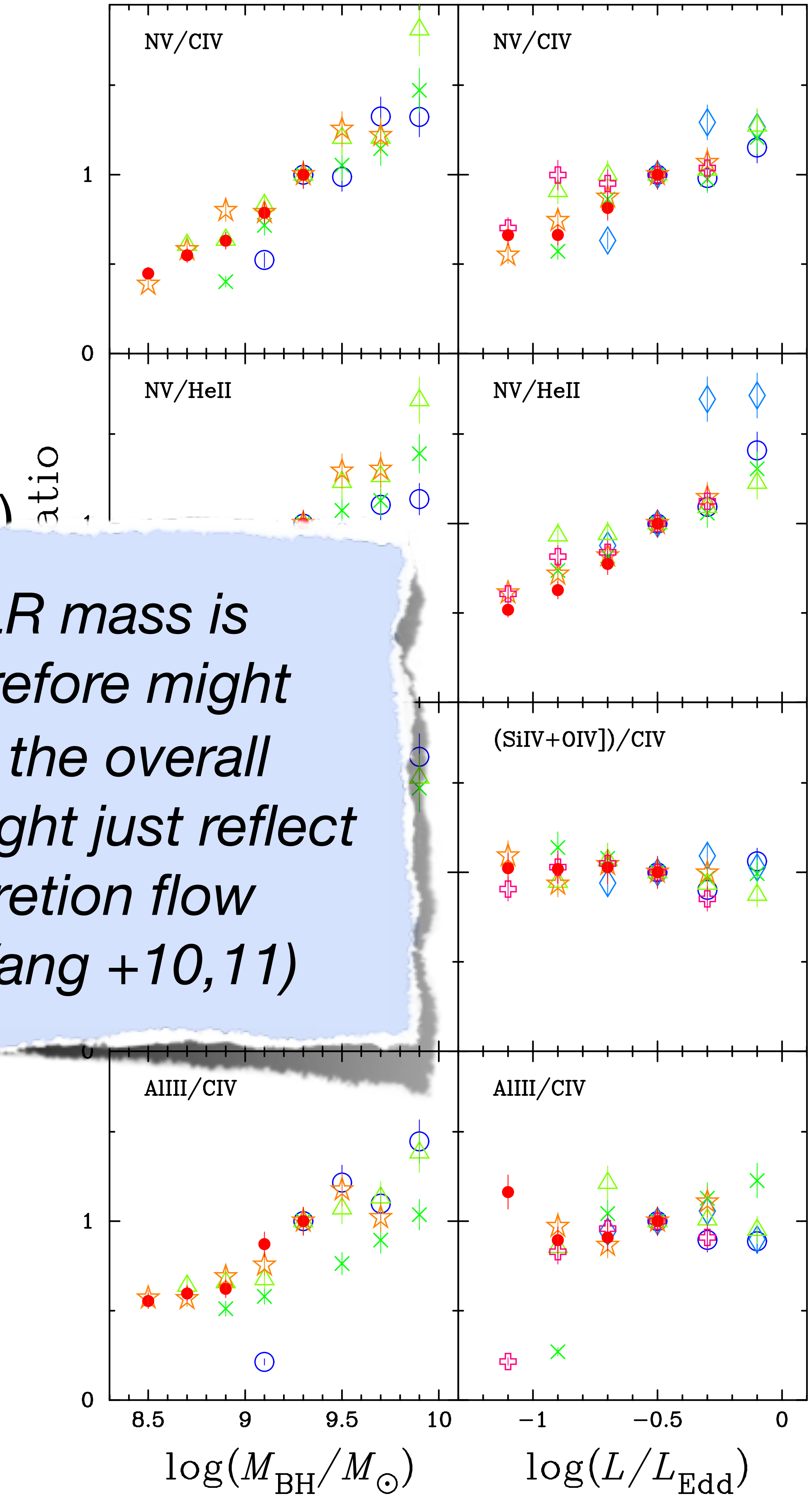
An important caveat: BLR mass is small (~10^2-10^4 $M_\odot$) therefore might not be representative of the overall formation history but might just reflect enhanced SF in the accretion flow (e.g. models by J.-M. Wang +10,11)

Matsuoka+11



NLR Metallicity

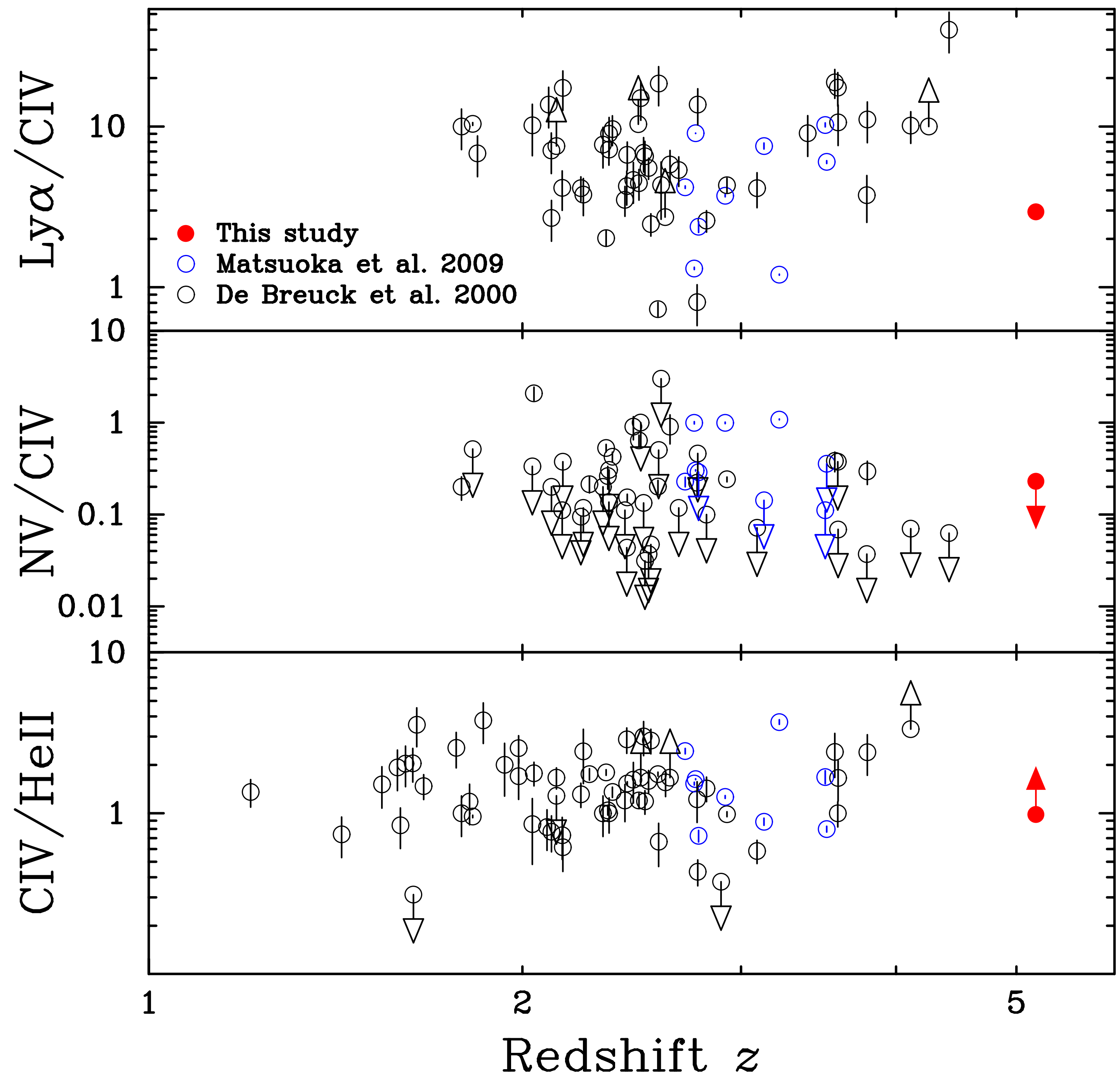
Metallicities of the NLR would be a better tracer of the metallicity of the host galaxies, because of the much larger size compared to the BLR.

Also for high-L quasars, the NLR can be so large to encompass the whole galaxy.

However NLR emission lines are very weak or totally undetected in high redshift quasars.

One possibility is to study the NLR of high redshift radio galaxies.

- Observations seem to indicate that Z_{NLR} does not evolve with redshift up to z~4 (e.g. Nagao +06, Matsuoka+11)
- There might be a Z_{NLR}-L_{AGN} correlation as for the BLR (Nagao+06)



Matsuoka+11

Observational evidences of AGN feedback

Feedback from AGN

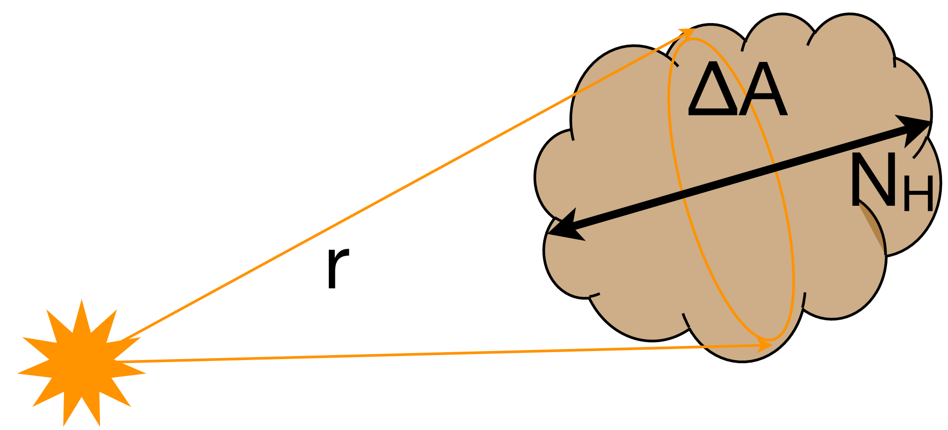
Feedback from an accreting BH is *probably* needed to link BH and host galaxy growth (see, eg, Fabian 09 for a review).

Feedback is now believed to come in two flavors:

- **Radiative mode**
  - operates in bulges with BH accreting close to L/L_{Edd}
  - due to radiation pressure *in situ* or to winds driven by radiation pressure
  - duration set by short timescales of AGN activity
- **Radio mode (→Cedric's Lacey Lectures)**
  - operates in galaxies with BHs accreting at low L/L_{Edd} (galaxies with hot haloes and at the centers of clusters)
  - due to jets and outflows
  - much longer timescales than those of high L/L_{Edd} AGN activity

More on the Eddington limit ...

Gravitational force is



$$F_{grav} = \frac{GM(r)[\mu m_p \, N_H \, \Delta A]}{r^2}$$

Radiative force on a cloud is

$$F_{rad} = \Delta A \int_{\nu_0}^{+\infty} \frac{L_\nu / h\nu}{4\pi r^2} \frac{h\nu}{c} (1 - e^{-\tau_\nu}) d\nu$$

Generalized Eddington limit is for $F_{grav} = F_{rad}$

$$\tau_\nu \ll 1 \qquad F_{rad} = \Delta A \frac{L}{4\pi r^2 \, c} \langle \tau_\nu \rangle$$

$$\mathcal{L}_{Edd} = 4\pi G \, c\mu \, m_p M(r) \frac{N_H}{\langle \tau_\nu \rangle} \simeq \frac{4\pi G \, c\mu \, m_p M(r)}{\sigma_{abs}}$$

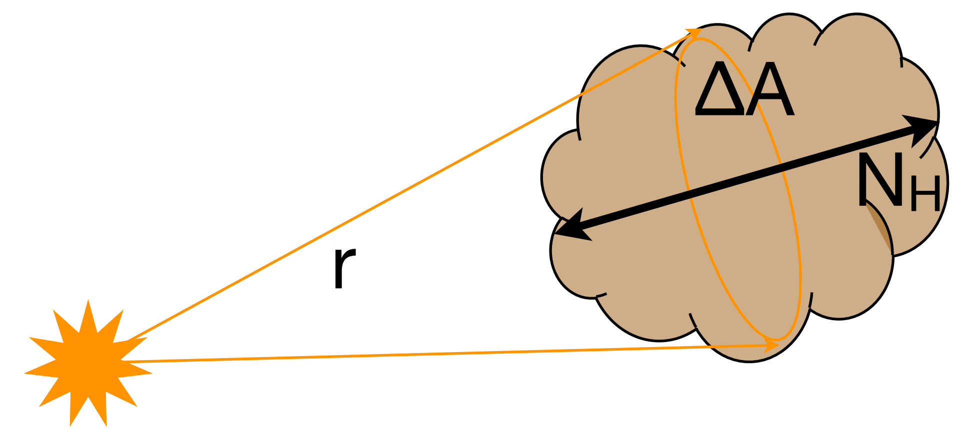
with $M(r) = M_{\rm BH}$ $\quad \langle \tau_\nu \rangle = N_H \sigma_T$ $\qquad L_{Edd} = 4\pi G \, c\mu \, m_p M_{\rm BH} \frac{1}{\sigma_T}$

"classical" Eddington limit

More on the Eddington limit ...

$$\tau_\nu \gg 1 \qquad F_{rad} = \Delta A \frac{L}{4\pi r^2\, c}$$

$$\mathcal{L}_{Edd} = 4\pi G\, c\mu\, m_p M(r)\, N_H$$



Let's now consider a cloud in the galaxy with mass M(r) where there is a BH accreting at a fraction λ of the Eddington limit

$$L_{AGN} = \lambda\, L_{Edd} = \lambda\, 4\pi G\, c\mu\, m_p M_{\rm BH} \frac{1}{\sigma_T}$$

To unbind the gas cloud (and have feedback) the ratio between the AGN luminosity and the generalized Eddington luminosity must be > 1

$$\frac{L_{AGN}}{\mathcal{L}_{Edd}[\tau_\nu \ll 1]} = \lambda\, \frac{M_{\rm BH}}{M(r)}\, \frac{\sigma_{abs}}{\sigma_T} > 1$$

More on the Eddington limit ...

$$\frac{\sigma_{abs}}{\sigma_T} > \frac{1}{\lambda}\frac{M_{gal}}{M_{\rm BH}} \simeq \frac{1}{\lambda}10^3$$

If optical depth is dominated by the absorption of ionizing photons then

$$\sigma_{abs} \simeq \sigma_{ion,\nu}(H) \sim 6\times 10^{-18}\,{\rm cm}^{-2}\left(\frac{\nu}{13.6\,{\rm eV}}\right)^{-3}$$

with $\langle h\nu\rangle \simeq 25\,{\rm eV}$

$$\frac{\sigma_{abs}}{\sigma_T} \simeq 1.5\times 10^6$$

OK, optically thin clouds opaque to ionizing photons can be accelerated.
Ionized gas column density, i.e. optical depth depends on ionization parameter

If optical depth is dominated by the absorption by dust then (Fabian 09)

$$\sigma_{dust} \sim 10^3\sigma_T$$

~OK, it seems almost a cosmic conspiracy!

Optically thin clouds can be accelerated and expelled by the galaxy from radiation pressure in situ!

More on the Eddington limit ...

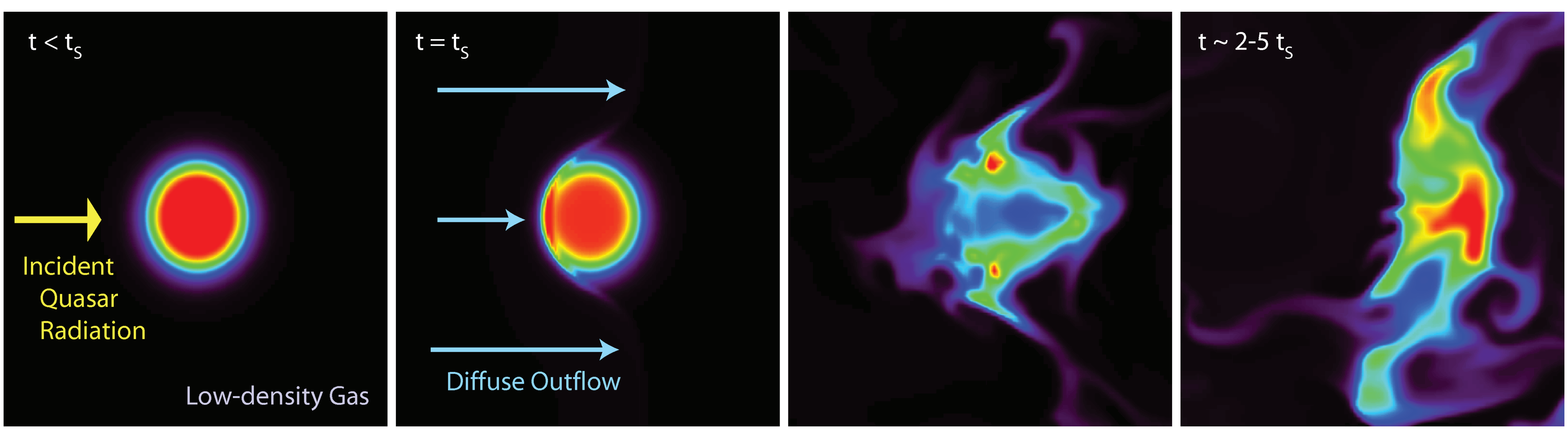
In the case of completely thick clouds (both for gas and dust absorption)

$$\frac{L_{AGN}}{\mathcal{L}_{Edd}[\tau_\nu \gg 1]} = \lambda \frac{M_{\rm BH}}{M(r)} \frac{1}{\sigma_T N_H} > 1$$

$$N_H < \frac{1}{\lambda} \frac{M_{gal}}{M_{\rm BH}} \frac{1}{\sigma_T} \simeq 1.5 \times 10^{21}\,{\rm cm}^{-2}\,\lambda$$

High column density (massive and compact) clouds cannot escape when accelerated *in situ*. Must start close to the BH where M(r) << M_{gal}

These clouds can only be expelled by fast flowing winds (v~1000 km/s) Alternatively a slow moving wind from AGN (easier to create) could “inflate” cloud due to Kelvin-Helmholtz instabilities reducing N_H toward AGN and then slowly ablate it with radiation pressure (e.g. Hopkins & Elvis 2009)



What outflows do feedback?

What we need to find are outflows with the following properties

- ☆ $V_{outflow} > V_{escape}$
- ☆ $(\dot{M}\Delta t)_{outflow} \simeq (M_{gas})_{galaxy}$

Suppose the galaxy is an isothermal sphere

$$\rho(r) = \frac{\rho(r_0)}{(r/r_0)^2} = \frac{M_{gal}}{4/3\,\pi\,R_{gal}^3}\left(\frac{r}{R_{gal}}\right)^{-2}$$

$$V_{esc}^2 = 2V_{circ}^2 = 6\frac{G\,M_{gal}}{R_{gal}} \quad const.!$$

Then we should observe velocities of at least

$$V_{esc} \simeq 300\,\mathrm{km\,s^{-1}}\left(\frac{M_{gal}}{10^{10}\,\mathrm{M_\odot}}\right)^{1/2}\left(\frac{R_{gal}}{3\,\mathrm{kpc}}\right)^{-1/2}$$

If the gas must travel $f\,R_{gal}$ to escape then the time required is roughly

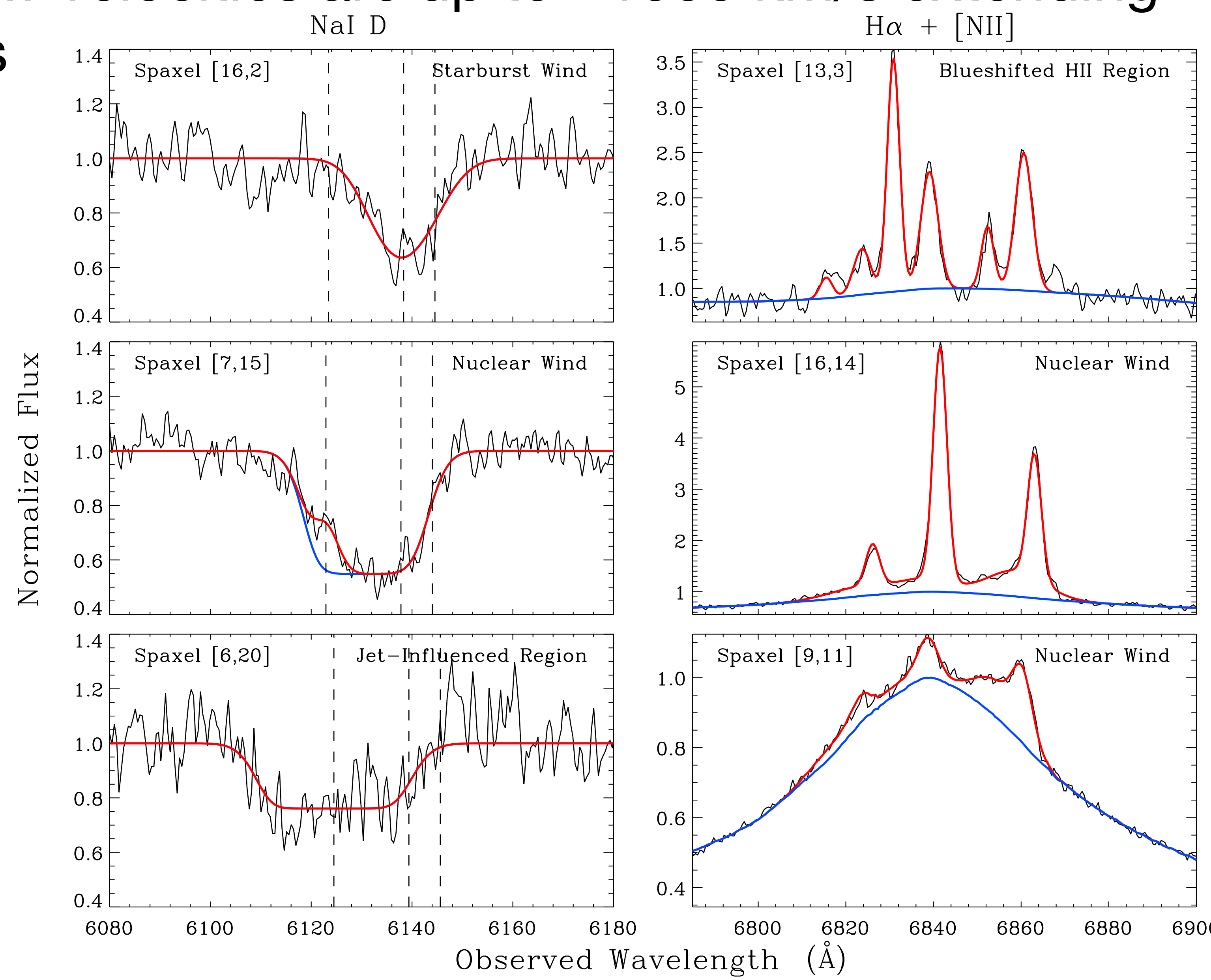
$$\Delta t = f\frac{R_{gal}}{V_{esc}} \simeq 10^7\,\mathrm{yr}\,f\left(\frac{M_{gal}}{10^{10}\,\mathrm{M_\odot}}\right)^{-1/2}\left(\frac{R_{gal}}{3\,\mathrm{kpc}}\right)^{3/2}$$

A nearby example: Mrk 231

Mrk 231 is the nearest ULIRG; combines powerful SF and AGN activity.

Outflows have been detected in:

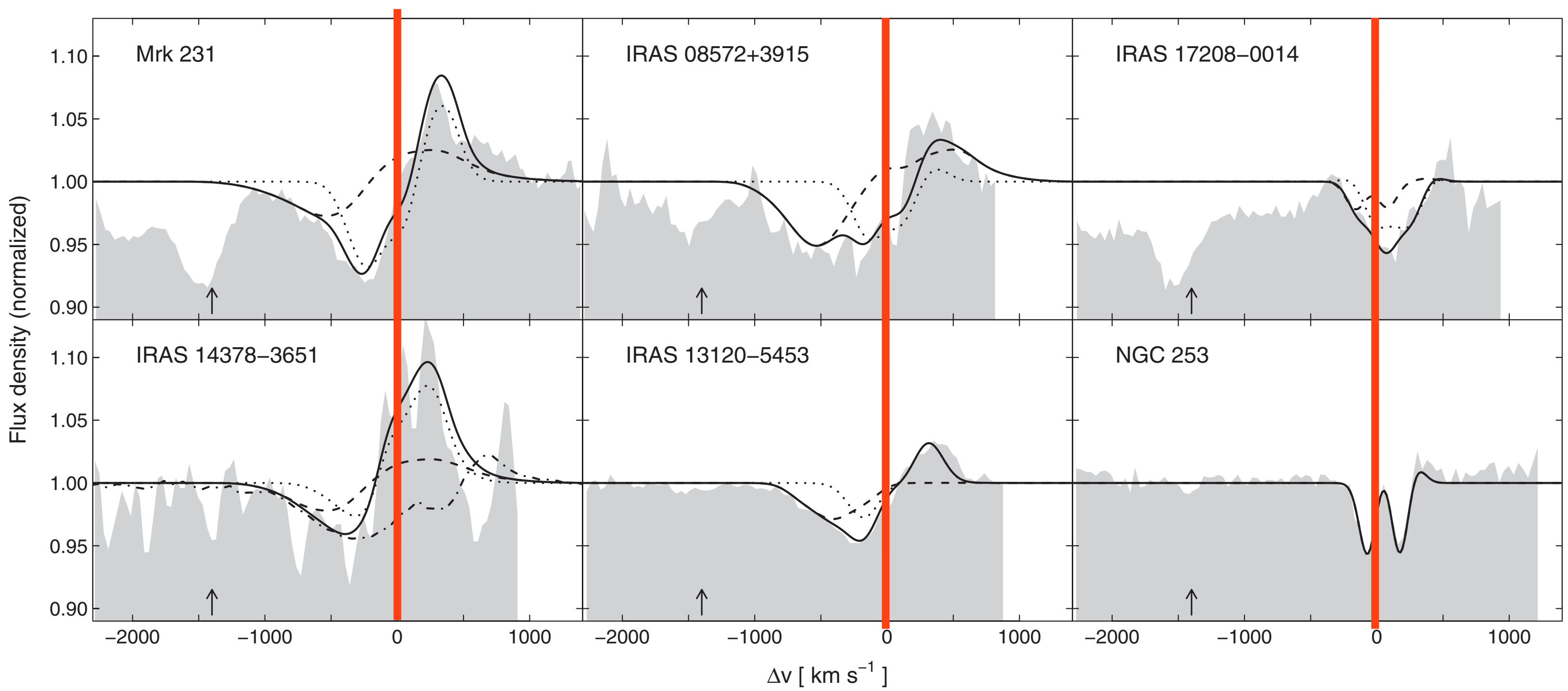
- ionized gas and absorption lines (Rupke & Veilleux 10)
  - in the nuclear region outflow velocities are up to ~1000 km/s extending up to 2-3 kpc from nucleus in all directions
  - there is interaction with a radio jet with v~1400 km/s
  - there is also a slower (~600 km/s) outflow powered by star formation
  - mass and energy flux from outflow are > 2.5 ×SFR and > 0.7% ×L_{AGN} consistent with feedback model from AGN



Rupke & Veilleux 10

A nearby example: Mrk 231

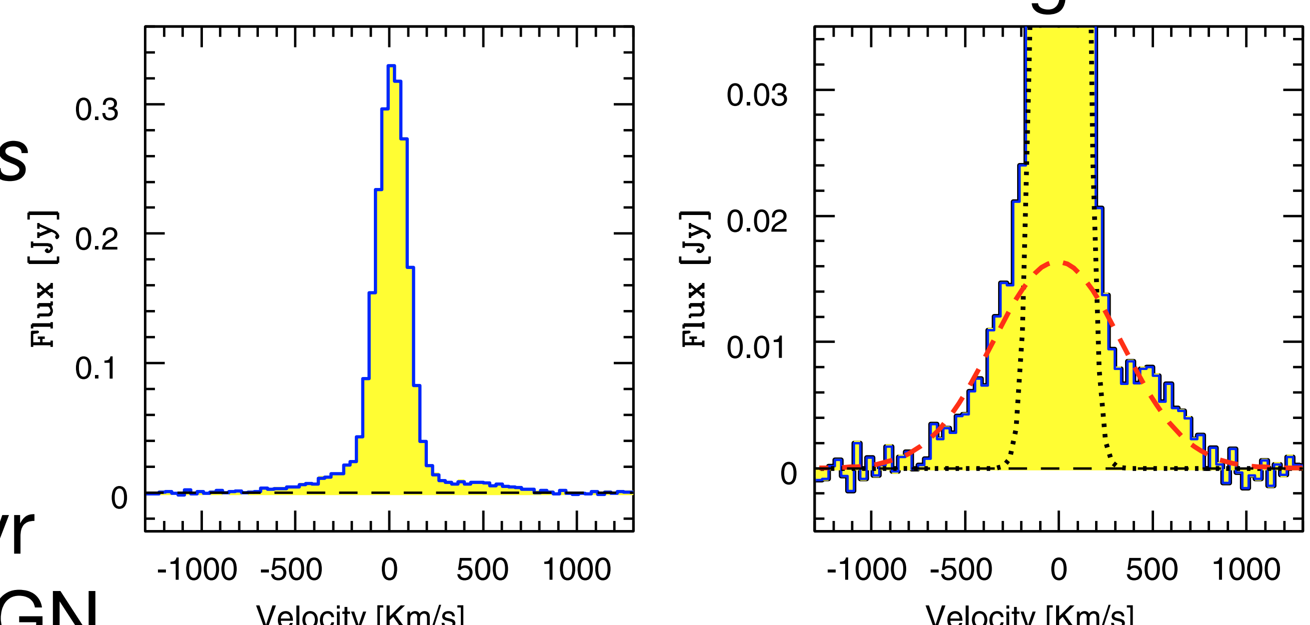
- molecular OH line with Herschel (Sturm+11)
  - terminal velocities of *molecular gas* up to ~1000 km/s
  - outflow rates up to ~1200 $M_{\odot}$/yr, several time the SFR (~200 $M_{\odot}$/yr)
  - cold reservoir of gas in ULIRGs can be expelled in ~10^6-10^8 yr



Sturm+11

Feruglio+11

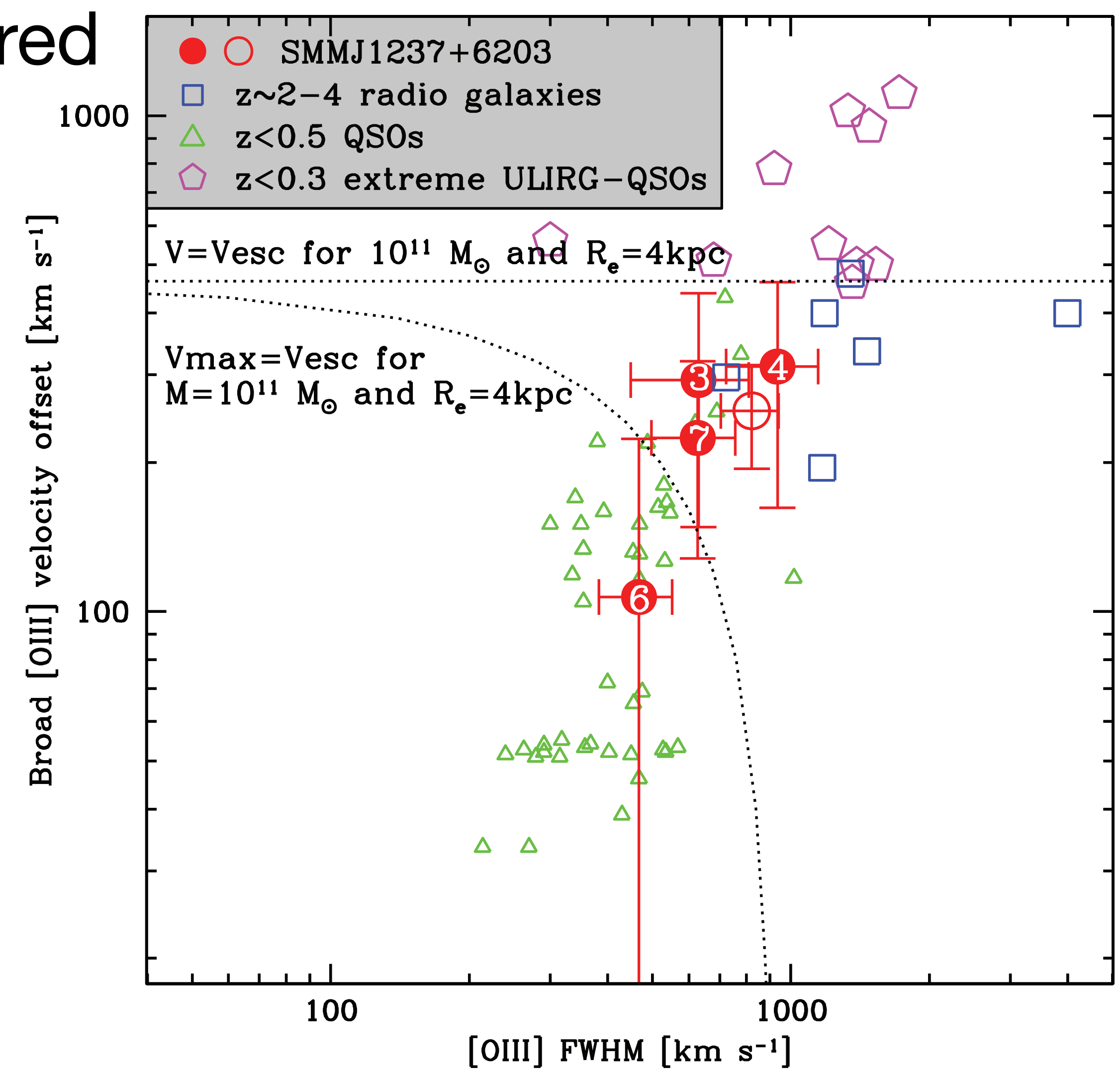
- molecular CO(1-0) line (Feruglio+11)
  - terminal velocities of *molecular gas* up to ~1000 km/s
  - outflow rates up to ~700 $M_{\odot}$/yr, several time the SFR (~200 $M_{\odot}$/yr)
  - cold gas can be expelled in ~10^7 yr
  - energy of outflow is ~few % of LAGN



Examples at high z

Outflow detected in a submm galaxy (high z analogs of ULIRG) at z~2 where the obscured AGN has L_{AGN}~0.1 L_{SF} (first phases of obscured BH growth?).

- broad [OIII] emission over ~4-8 kpc with velocities of ~100-1000 km/s
- the estimated energy input required to produce large-scale outflow (~10^{59} erg over ~30 Myr) could be delivered by a wind radiatively driven by the AGN and/or supernovae winds from intense star formation.



Alexander+09

Large scales outflows are also detected in

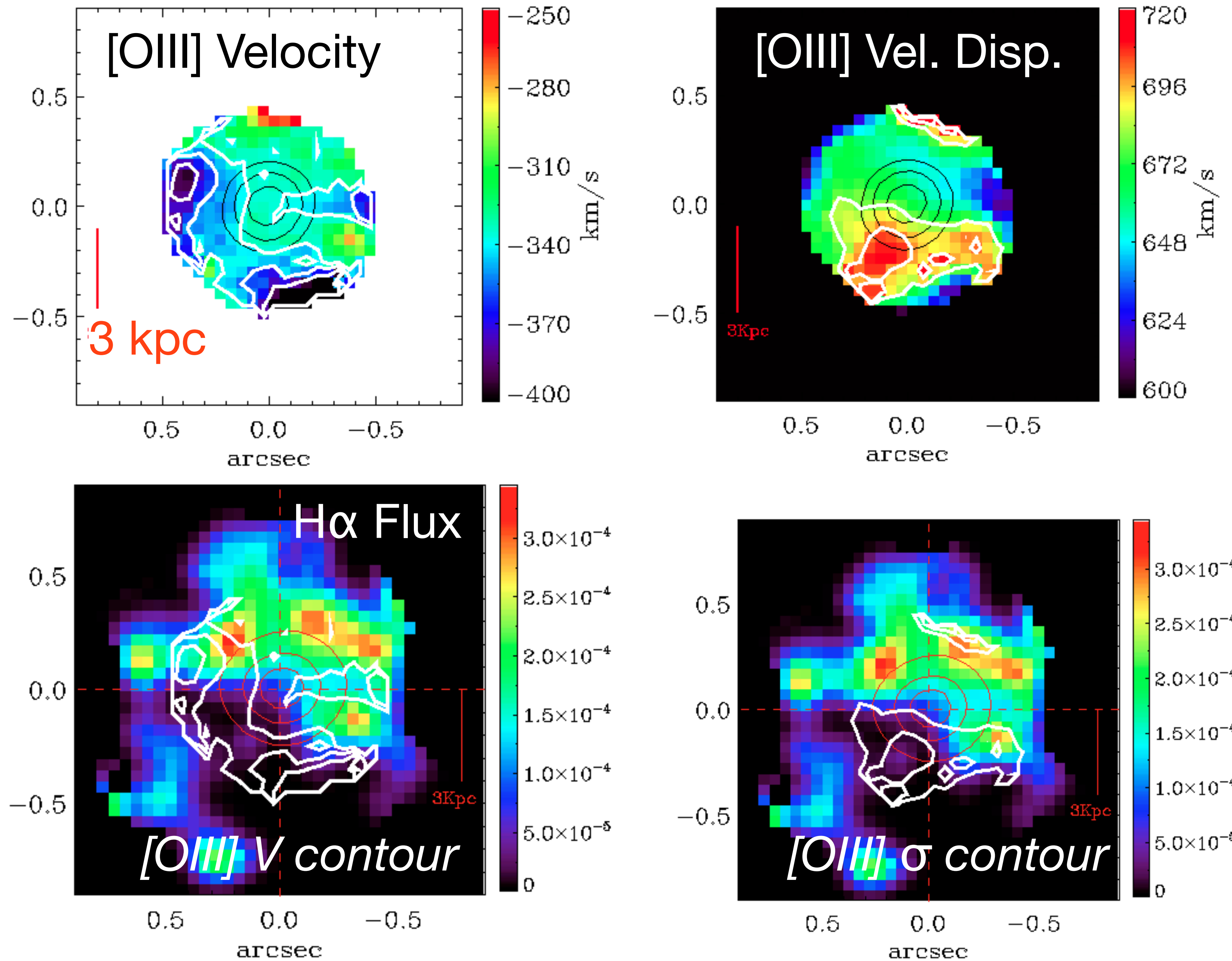
- quasars at z<0.5 (eg Komossa+08)
- obscured quasars at z<0.5 (Greene+11)
- radio galaxies at z~2-4 but fast velocity outflows over ~1kpc are from interaction with the radio jet (eg Nesvadba+11)

Feedback in a quasar at z~2.4 ?

First (?) example of a z~2.4 quasar which shows an outflow of ~300 km/s, associated with a velocity dispersion of ~700 km/s (FWHM ~ 1500 km/s!).

In the region with high [OIII] blueshift Hα emission is suppressed.

Hα emission is due to SF in the galaxy, and is quenched by the outflow seen in ionized gas.



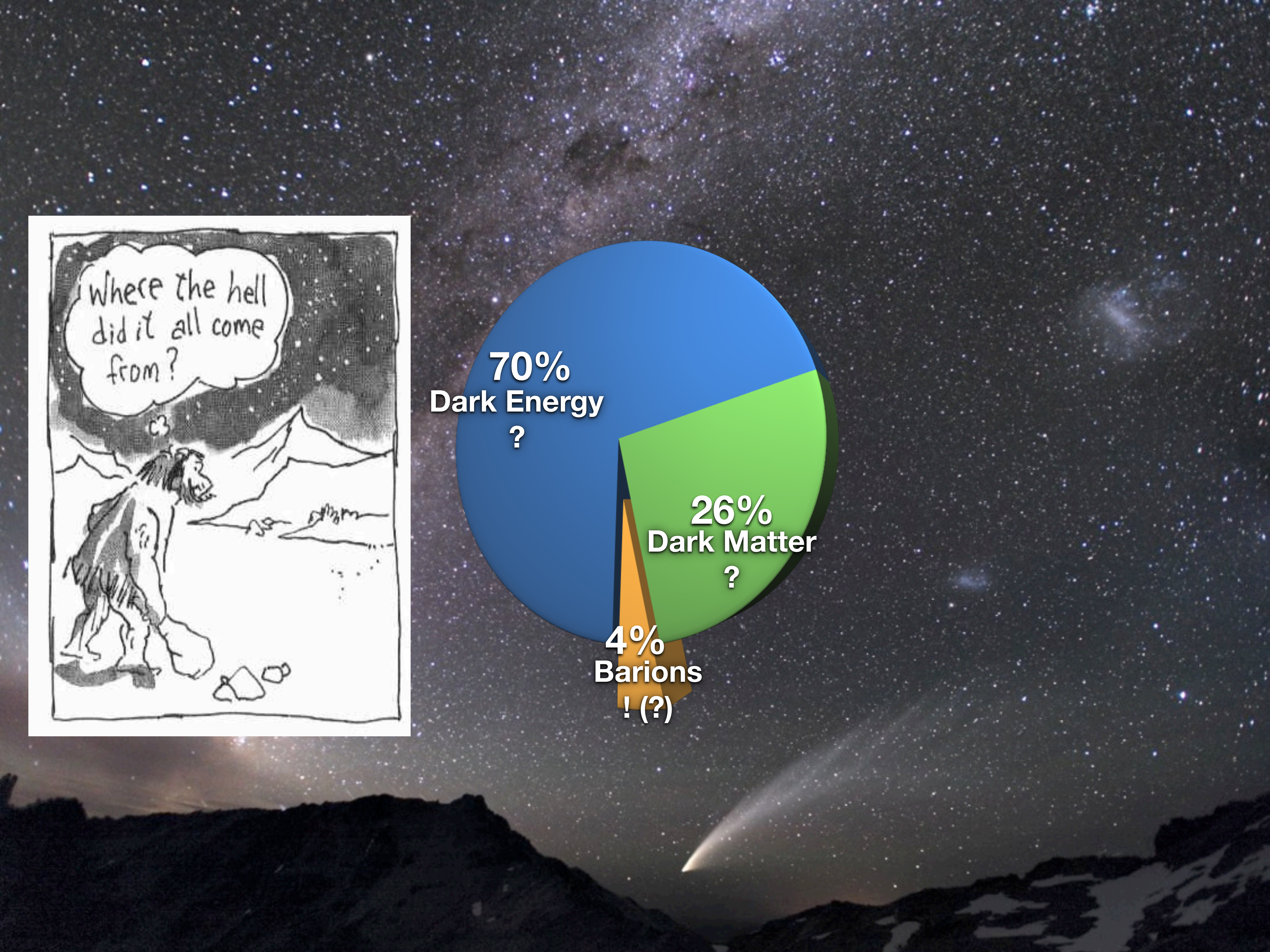
Cano-Diaz+11, in preparation

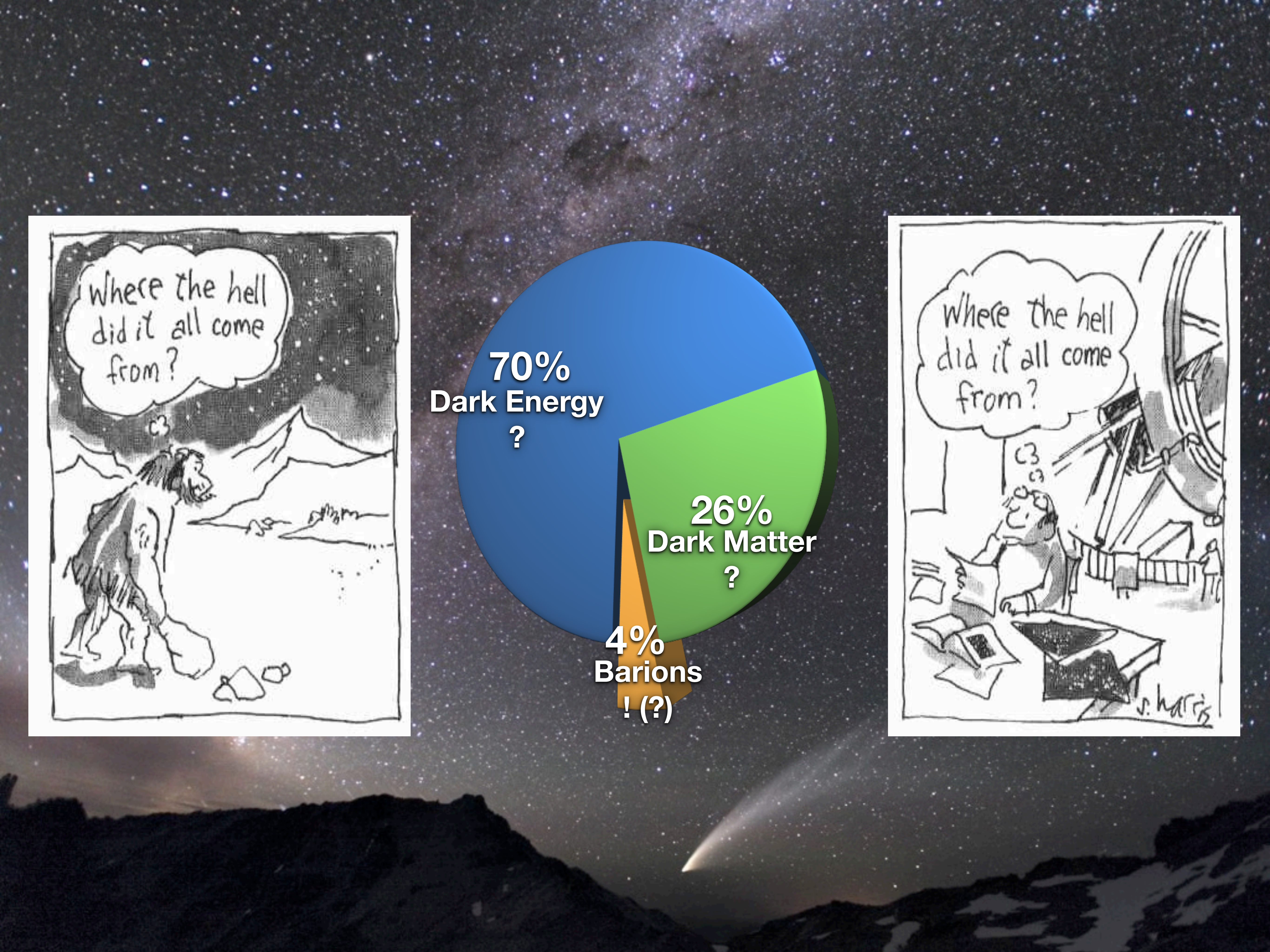
Outflows in AGN

- Outflows seems quite ubiquitous in AGN, but they are mostly located close to the BH (up to ~1-10 pc scales).
- There are outflows of ionized gas in Seyferts on NLR scales, e.g. ~few 100 pc (→ see Mike Crenshaw's lectures).
- Outflows of ionized gas are starting to be studied and detected even at high z in luminous star forming and active galaxies.
- Outflows are also being detected in molecular gas with mass outflow rates larger than the SF rate.
- Except when dealing with molecular gas, most of these outflows are detected in [OIII] and masses of ionized gas are usually small (~10^7-10^8 $M_\odot$); therefore it is difficult to prove they are significantly affecting the host galaxies.

However, when feedback is in action this is just what we should see.


Where the hell did it all come from?


Where the hell did it all come from?
70%
Dark Energy
?
26%
Dark Matter
?
4%
Barions
! (?)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