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Black hole masses and their relations with host galaxies

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ACTIVE GALACTIC NUCLEI 10
Dall'orizzonte degli eventi all'orizzonte cosmologico
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Outline

- Scaling Relations in Normal Galaxies
- BH Mass Estimates in Active Galaxies
- Scaling Relations in Active Galaxies & their redshift evolution

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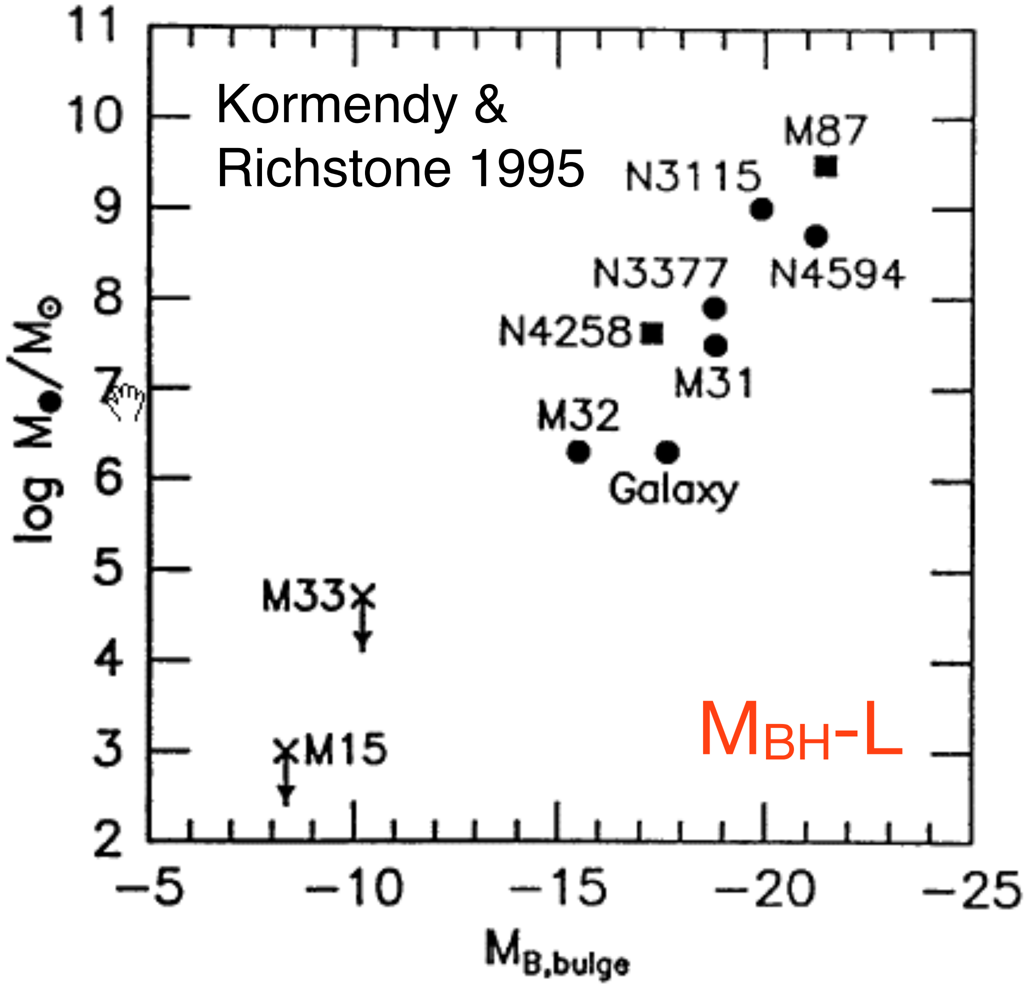
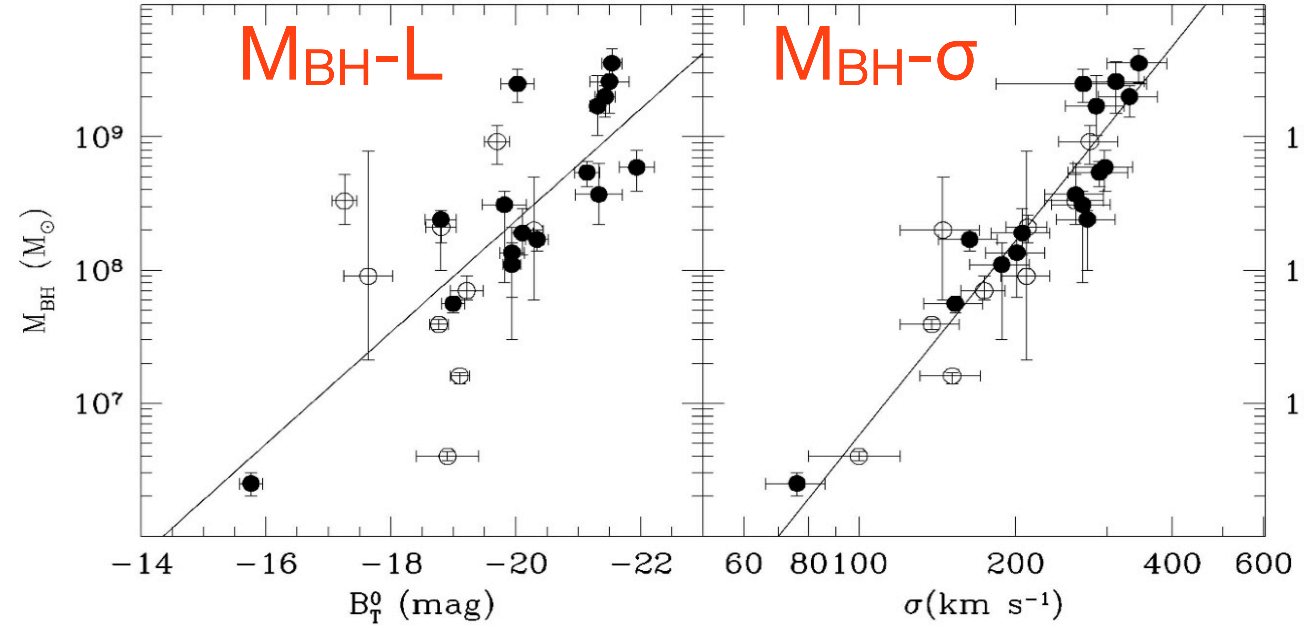
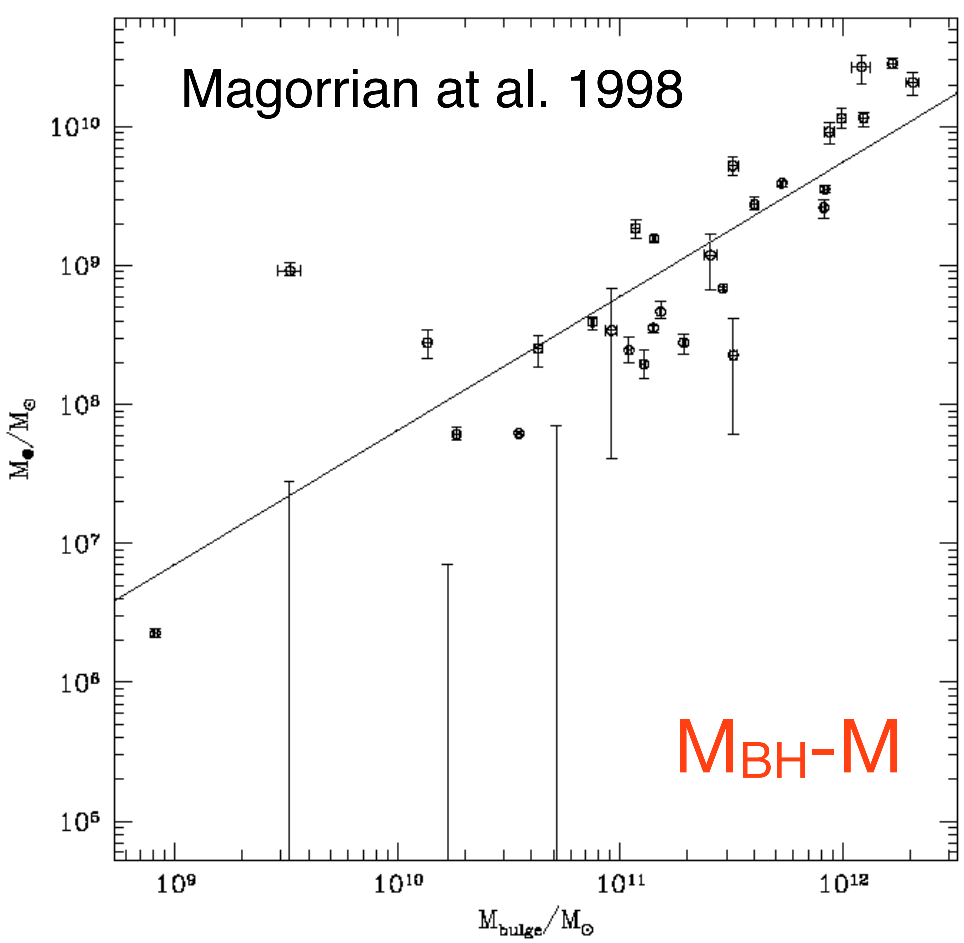
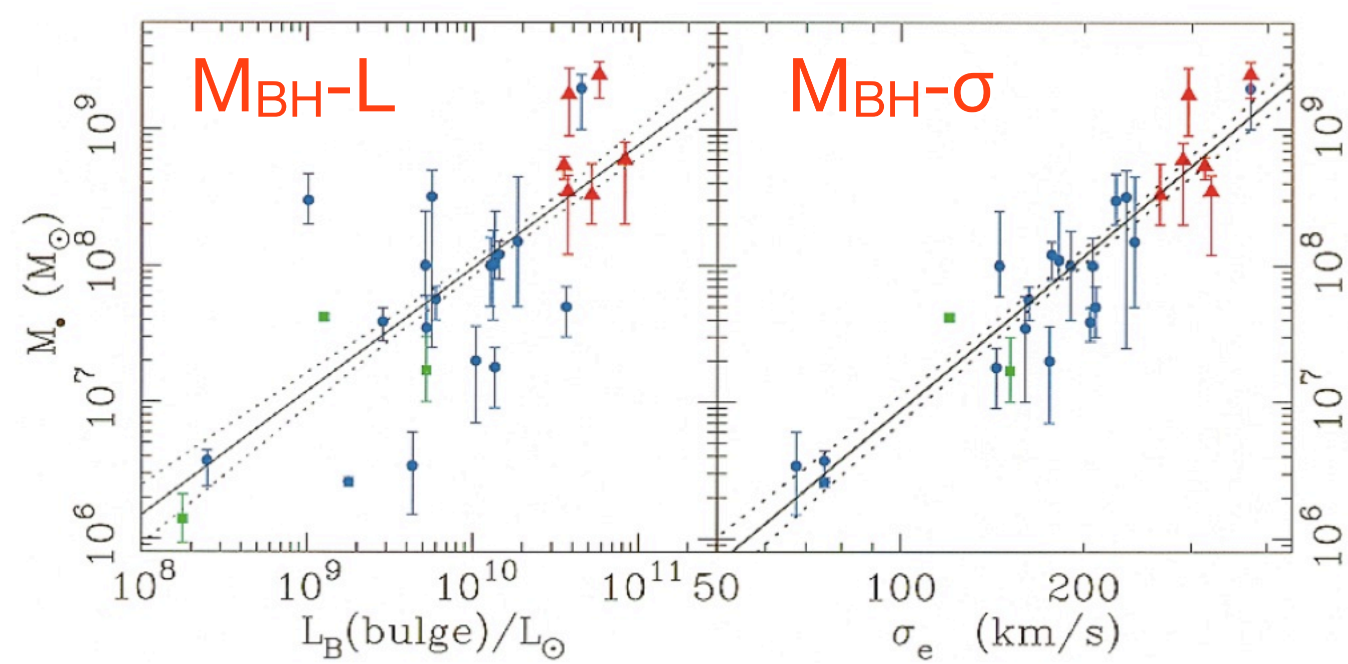


Ferrarese & Merritt 2000





Gebhardt et al. 2000



Importance of BH-galaxy relations

- Co-evolution of BHs and their host galaxies
- Physical link probably from BH (AGN) feedback on host galaxy (→Fabrizio's talk)
- Demography of supermassive BHs in nearby galaxy nuclei

$\rho_{BH} \simeq 3.5\text{-}5.5 \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}$

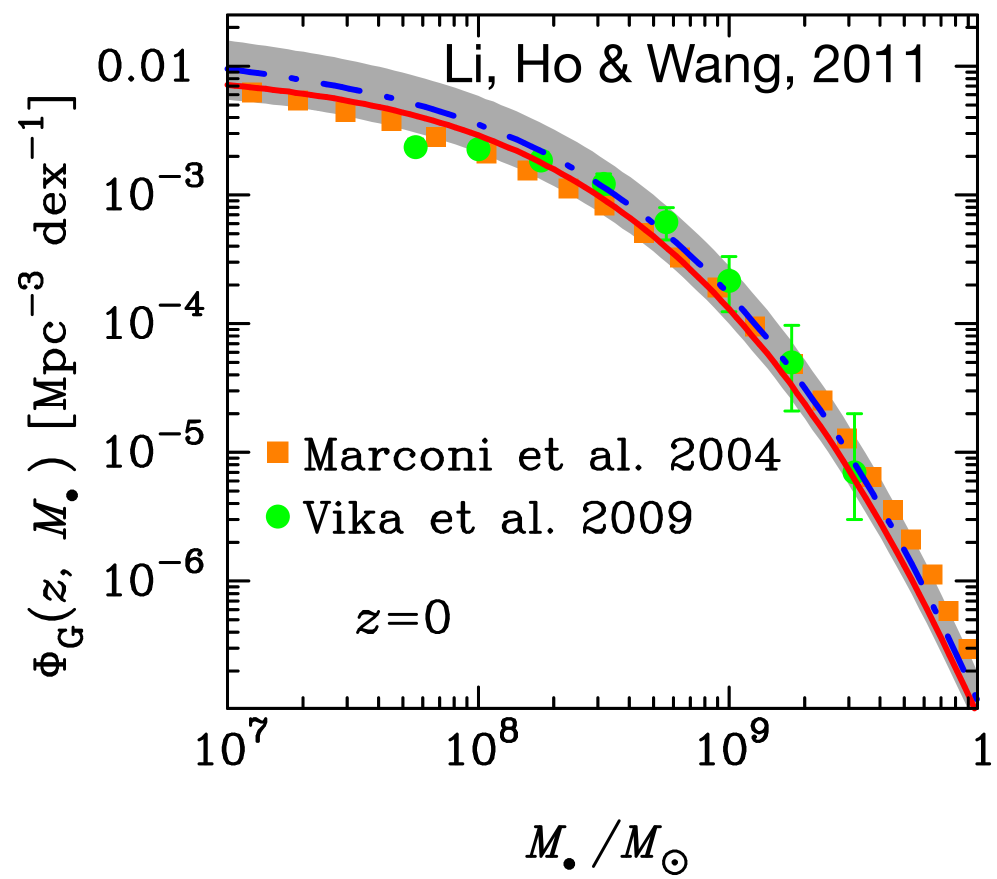
Salucci +99, Yu & Tremaine 02, Marconi +04, Shankar +04, Tamura+06, Tundo +07, Hopkins +07, Graham +07, Shankar +08, Vika+09 et many al.

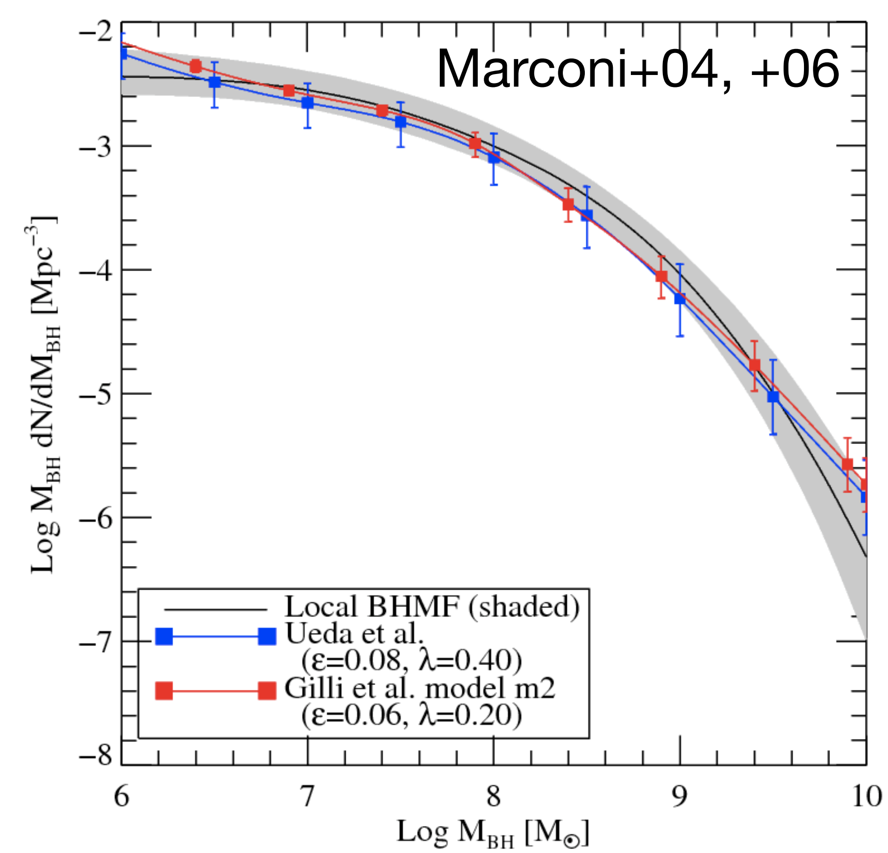
- Comparison with accreted mass function from AGN (Sołtan's argument and continuity equation)

$L/L_{Edd} \sim 1$ and $\varepsilon \sim 0.1$

Yu & Tremaine 02, Marconi +04, Shankar+04, Merloni 04, Shankar +08, Merloni & Heinz 2009, Cao 10, Shankar+12, et many al.

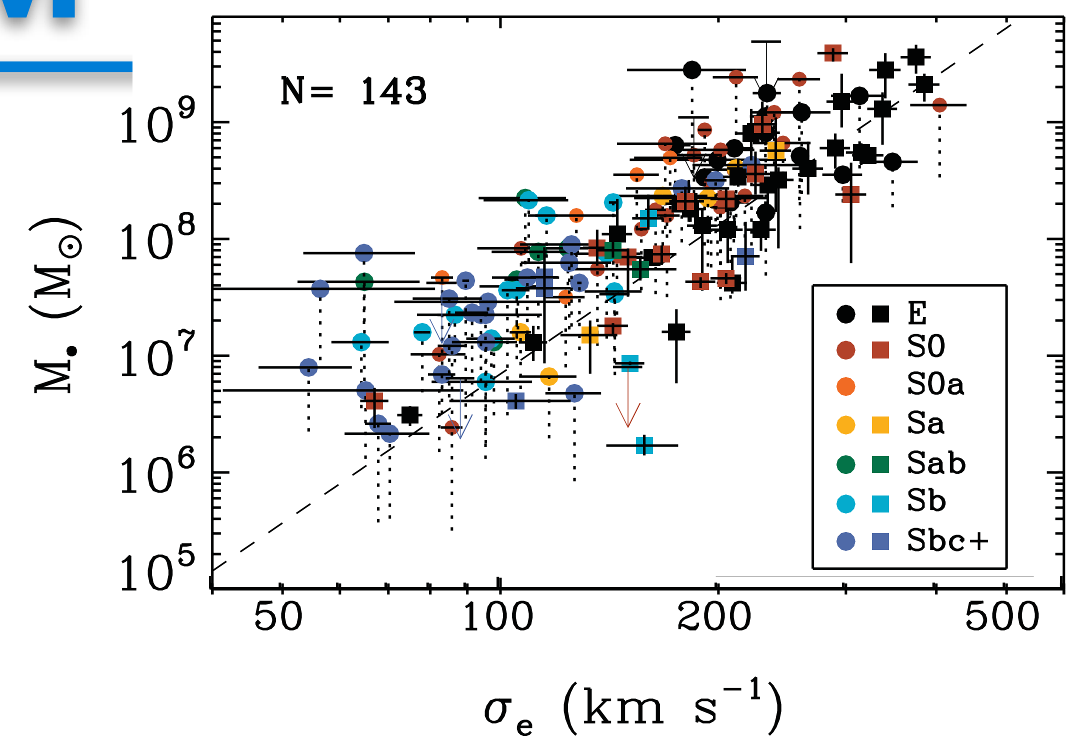
- Reliability and accuracy of BH masses critical!

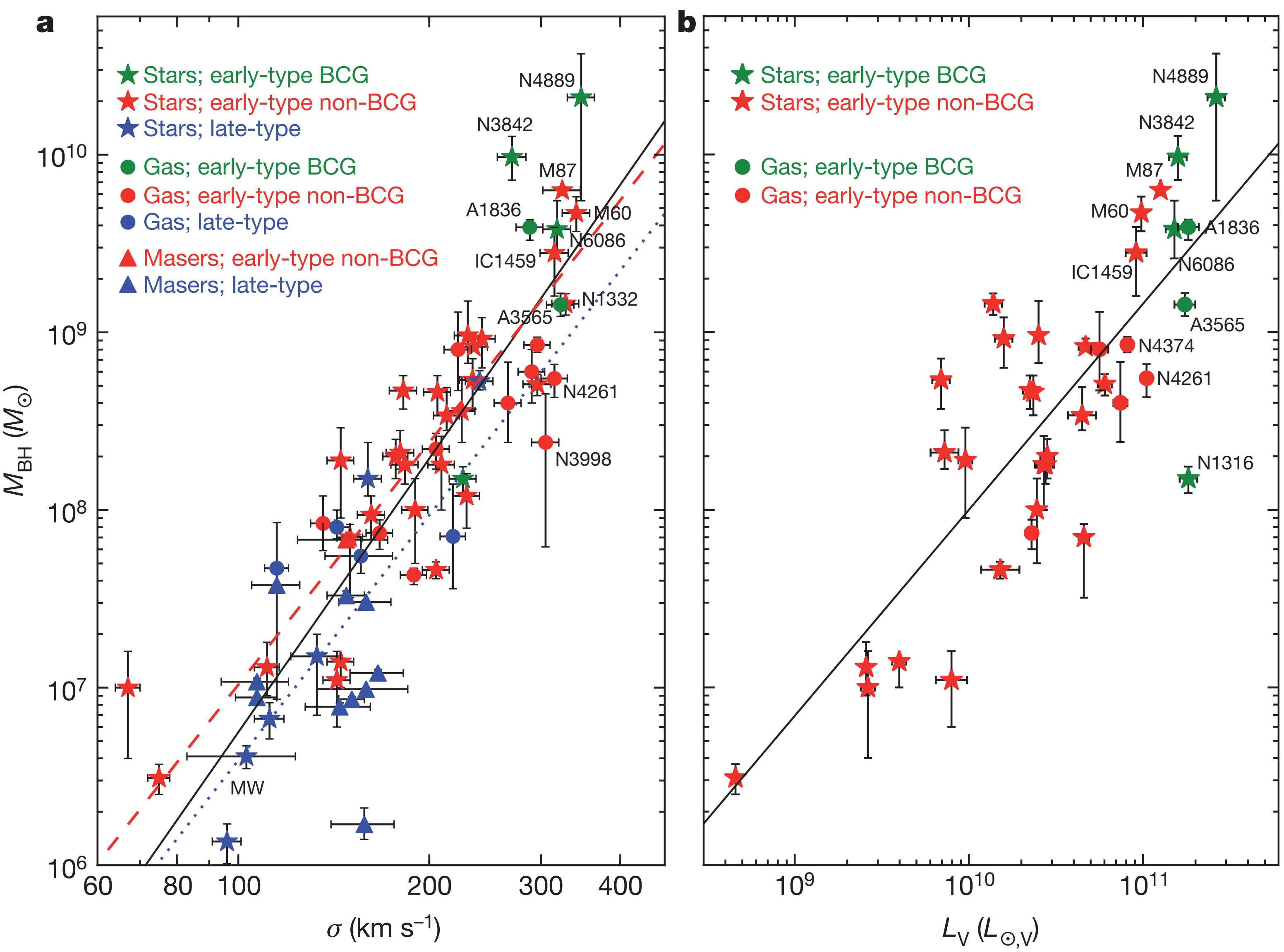




M_{BH}-σ M_{BH}-L & M_{BH}-M

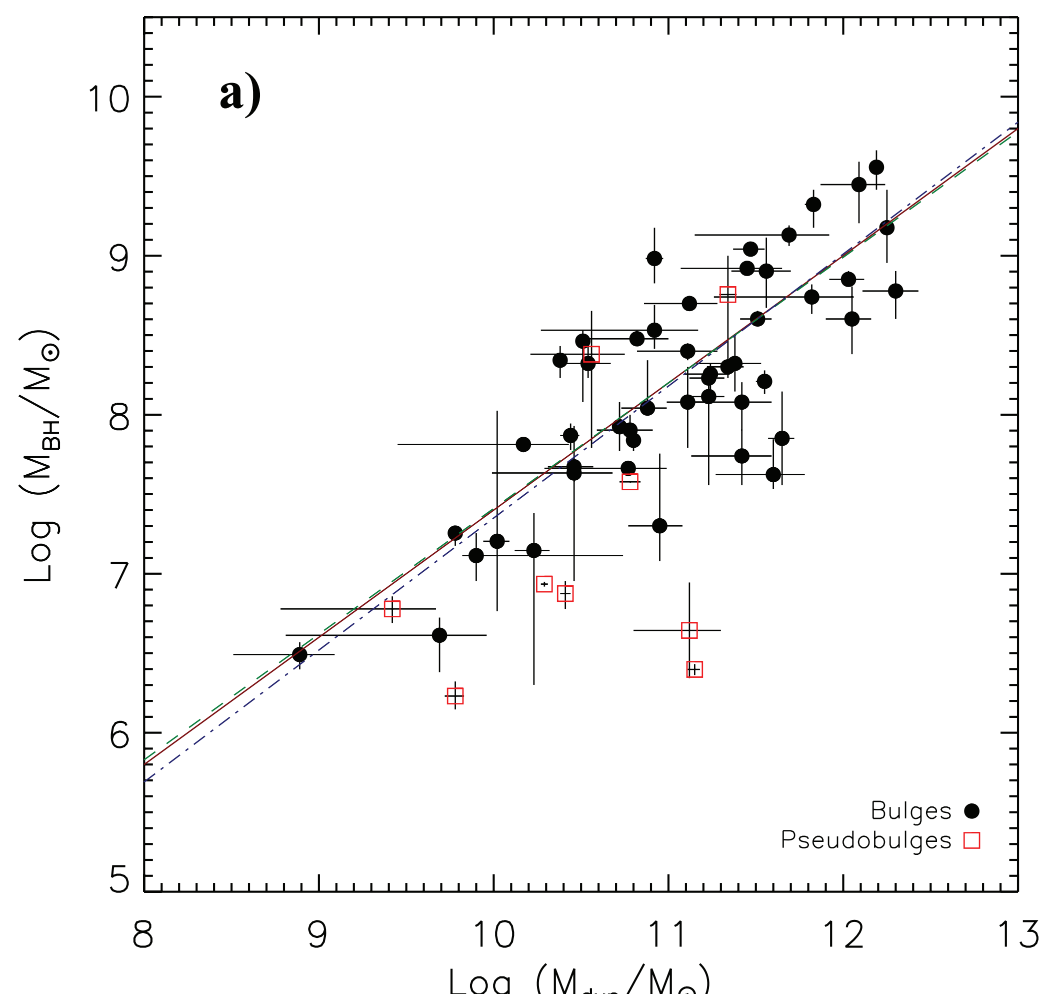
Beifiori+12





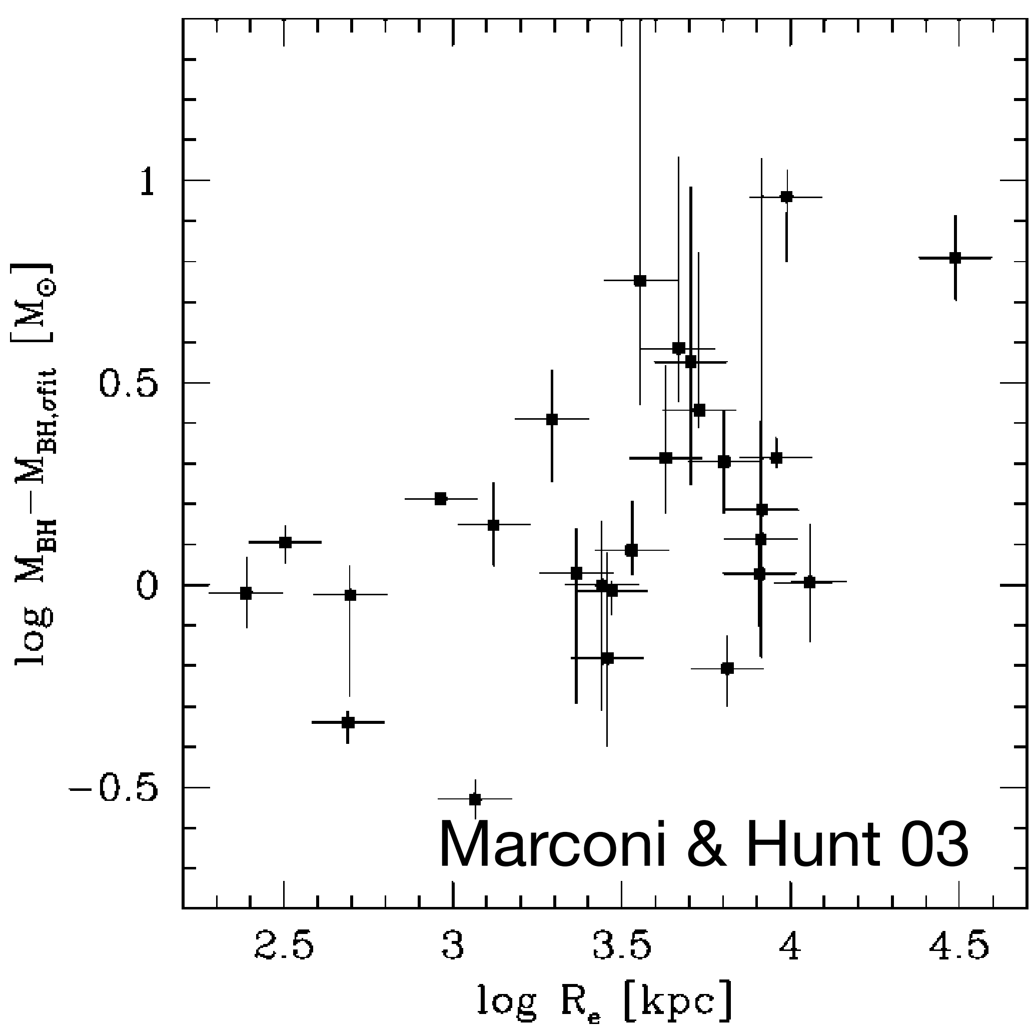
McConnell+2011

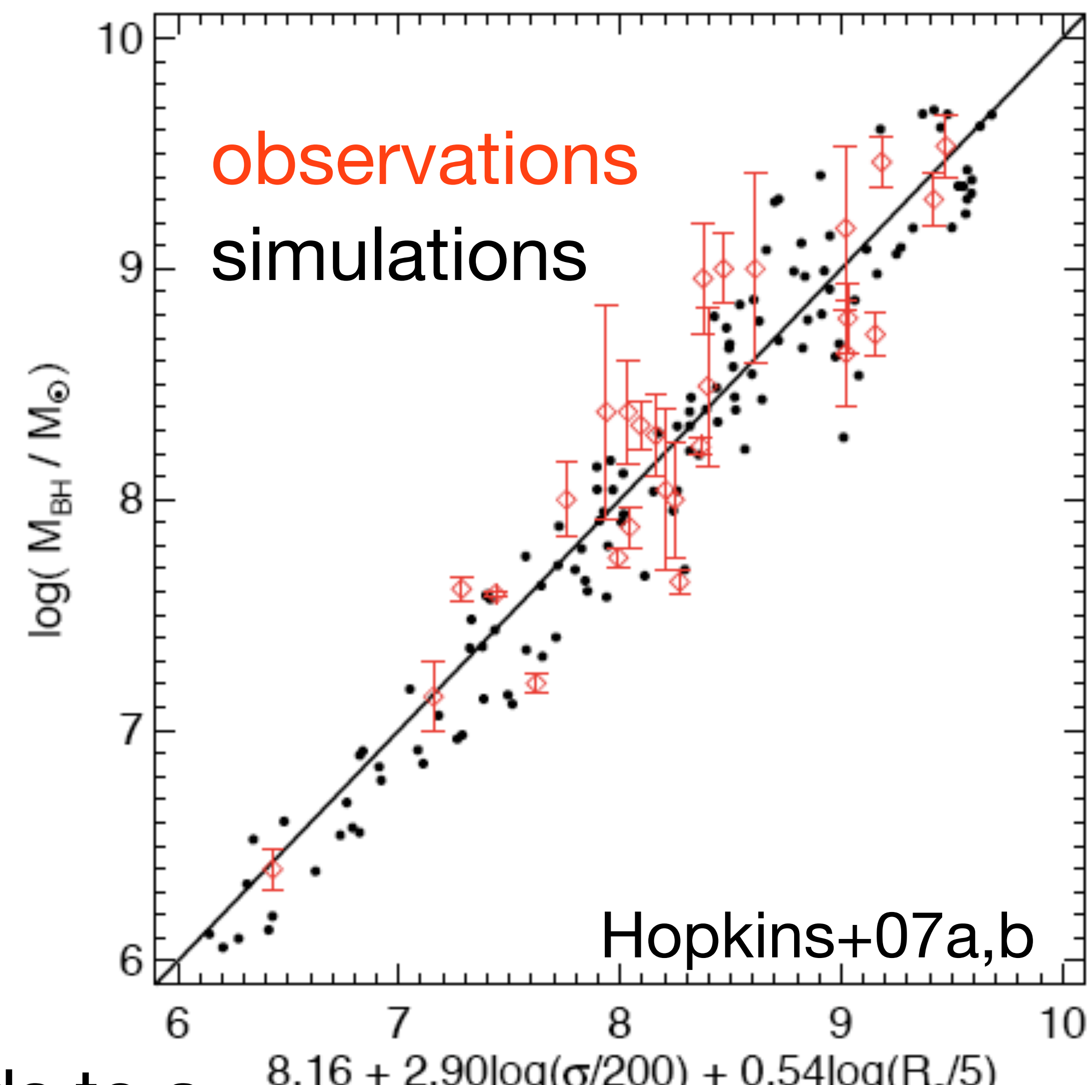
Sani+2010



BH fundamental plane

- Correlation of M_{BH} with virial bulge mass ($\sim R_e\sigma^2$) suggests that M_{BH} might correlate with combination of R_e, σ
- Indeed residuals of M_{BH}-σ (weakly) correlate with R_e (Marconi & Hunt 2003)
- Hopkins et al. (20007a,b) propose a "fundamental plane" for M_{BH} found *both in data and models* (Barway & Kembhavi 07, Aller & Richstone 07, Feoli & Mancini 09).

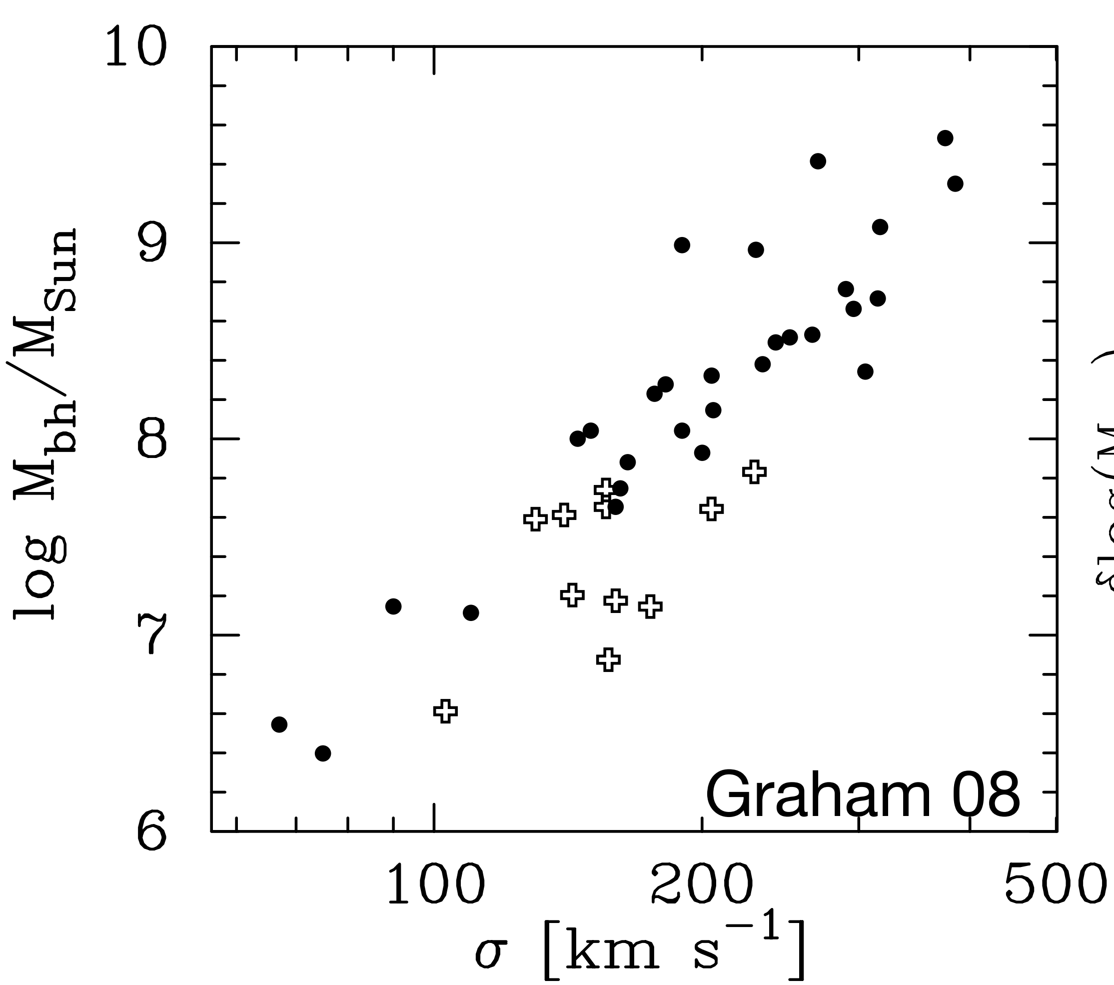


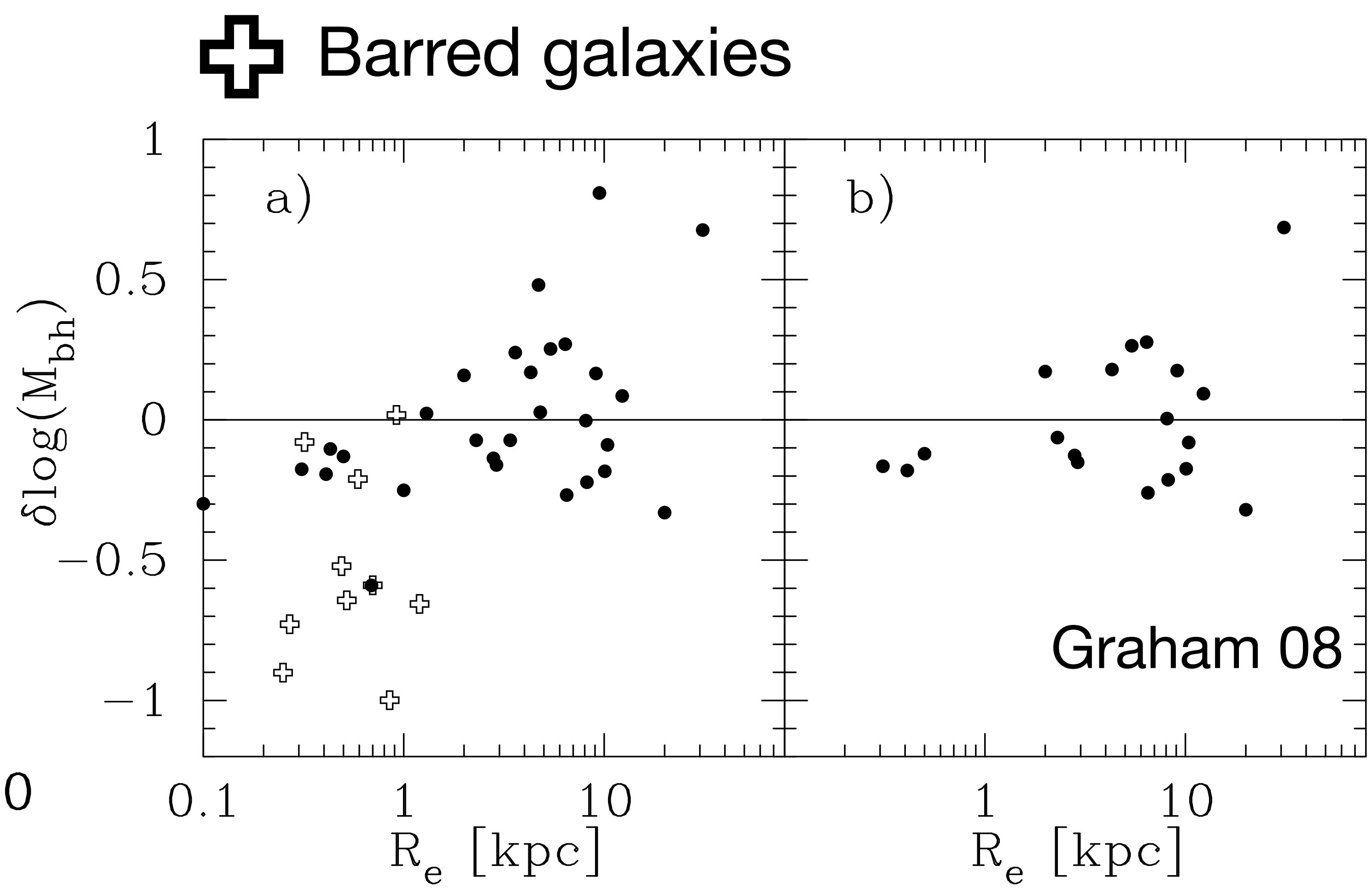


- The BH fundamental plane corresponds to a correlation of M_{BH} with gravitational binding energy
- Evidence for FP is still debated (e.g. Beifiori+12) and ...

BH fundamental plane?

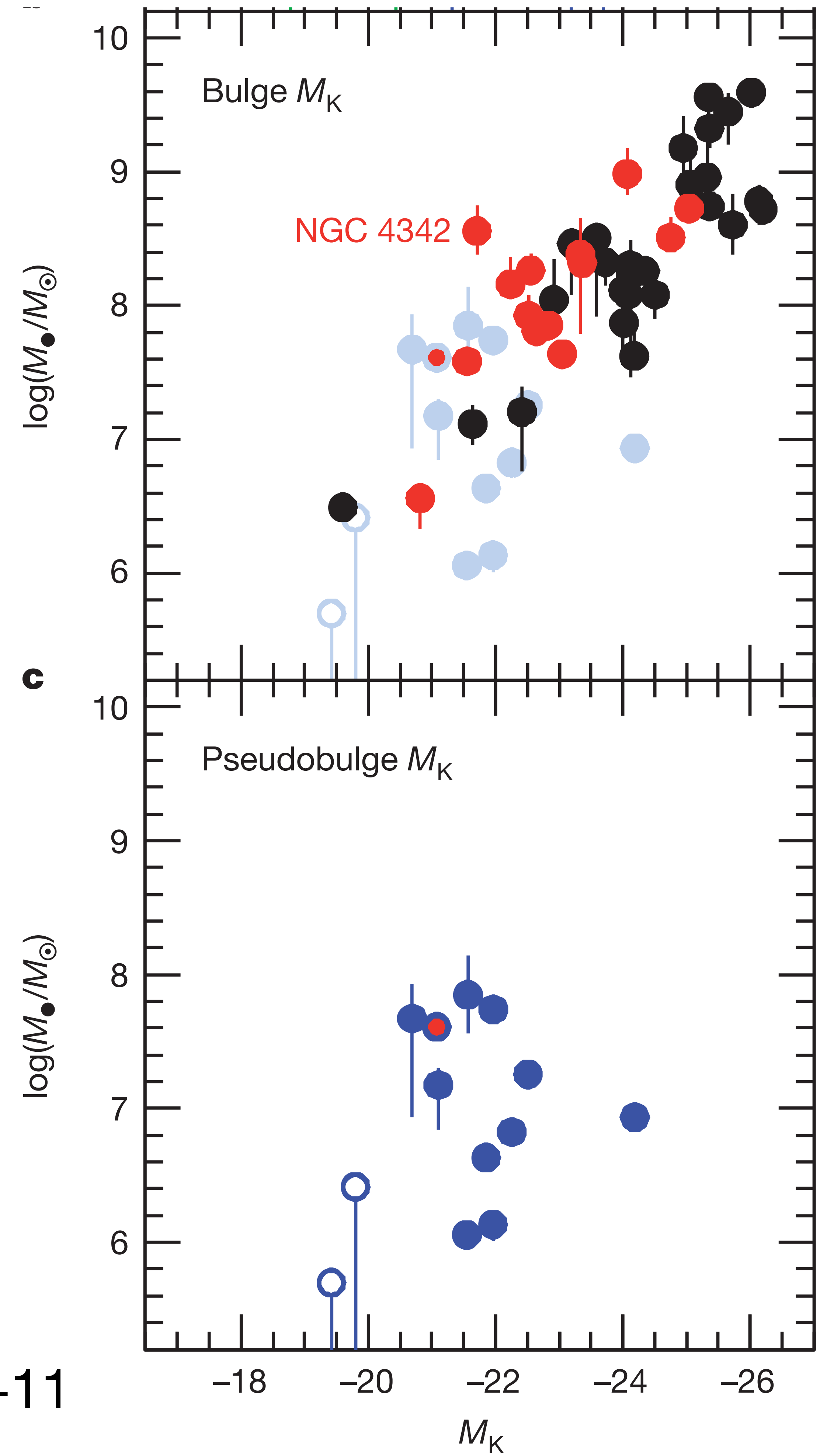
- Graham 08 shows
  - Barred galaxies are systematically offset from M_{BH}-σ relation
  - the need of FP is driven by “barred” galaxies. The bar affects σ and a combination of σ, R_e gives a tighter relation.
- Hu 08 notices the offset nature of “pseudobulges” (from mostly barred galaxies) in M_{BH}-σ relation





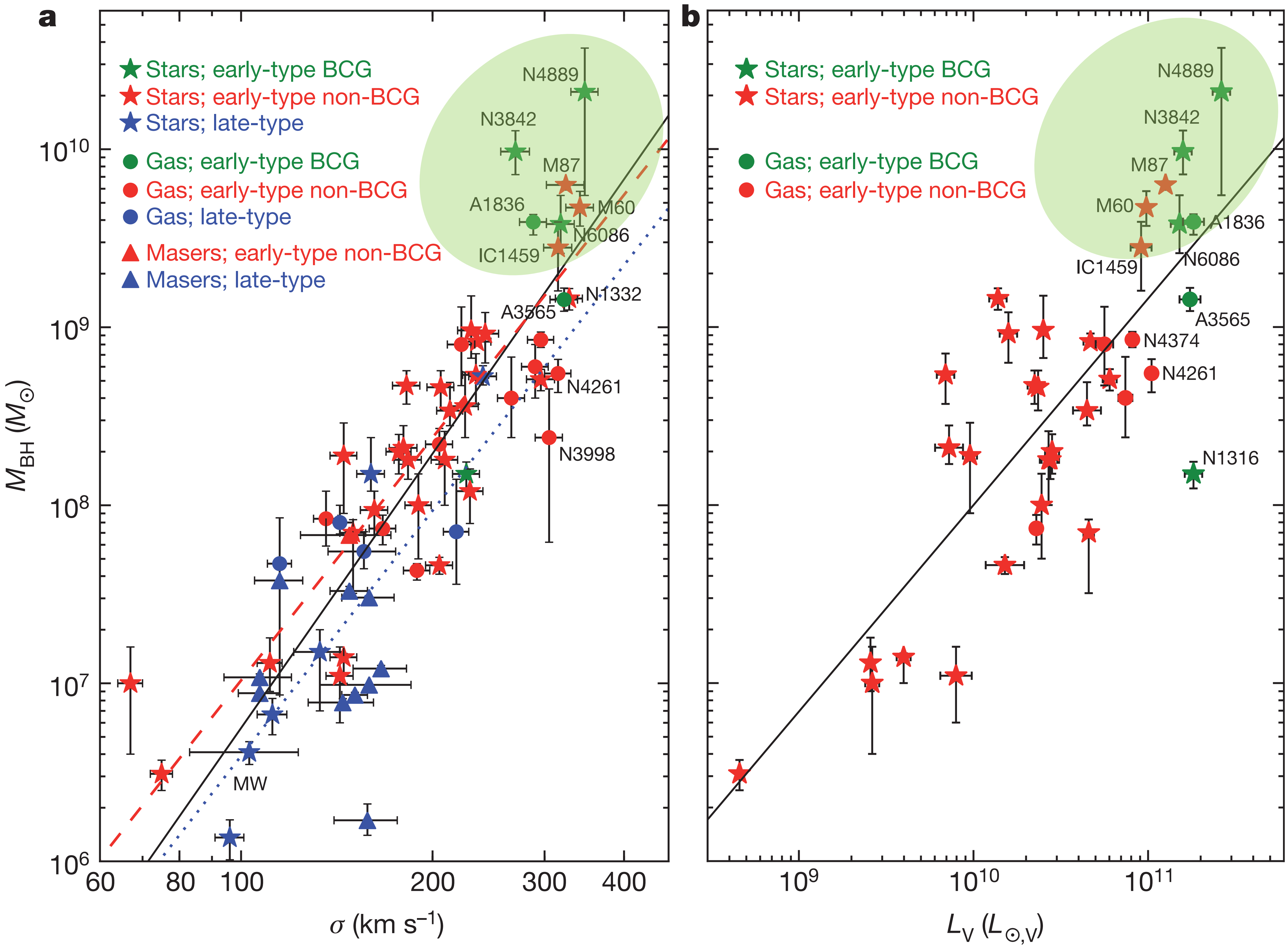
Pseudobulges

- Do pseudobulges or barred galaxies define a different correlation or no correlation at all?
- What is the origin of the offset nature? Different BH growth?



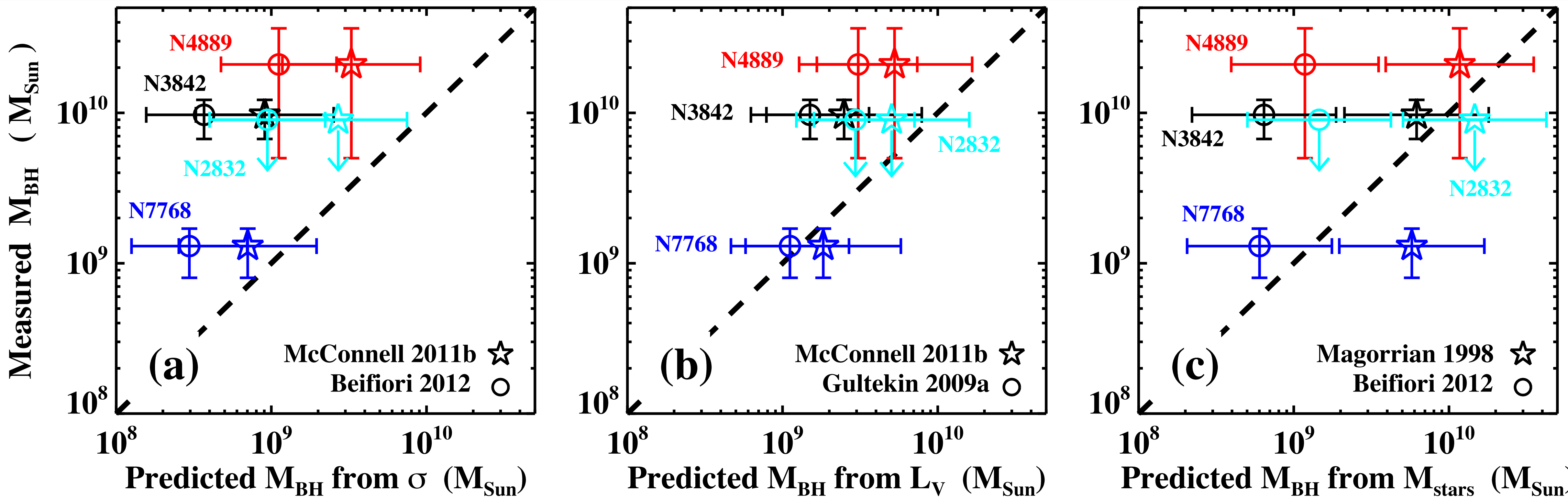
Kormendy+11

M_{BH}-σ & M_{BH}-L: high mass end?

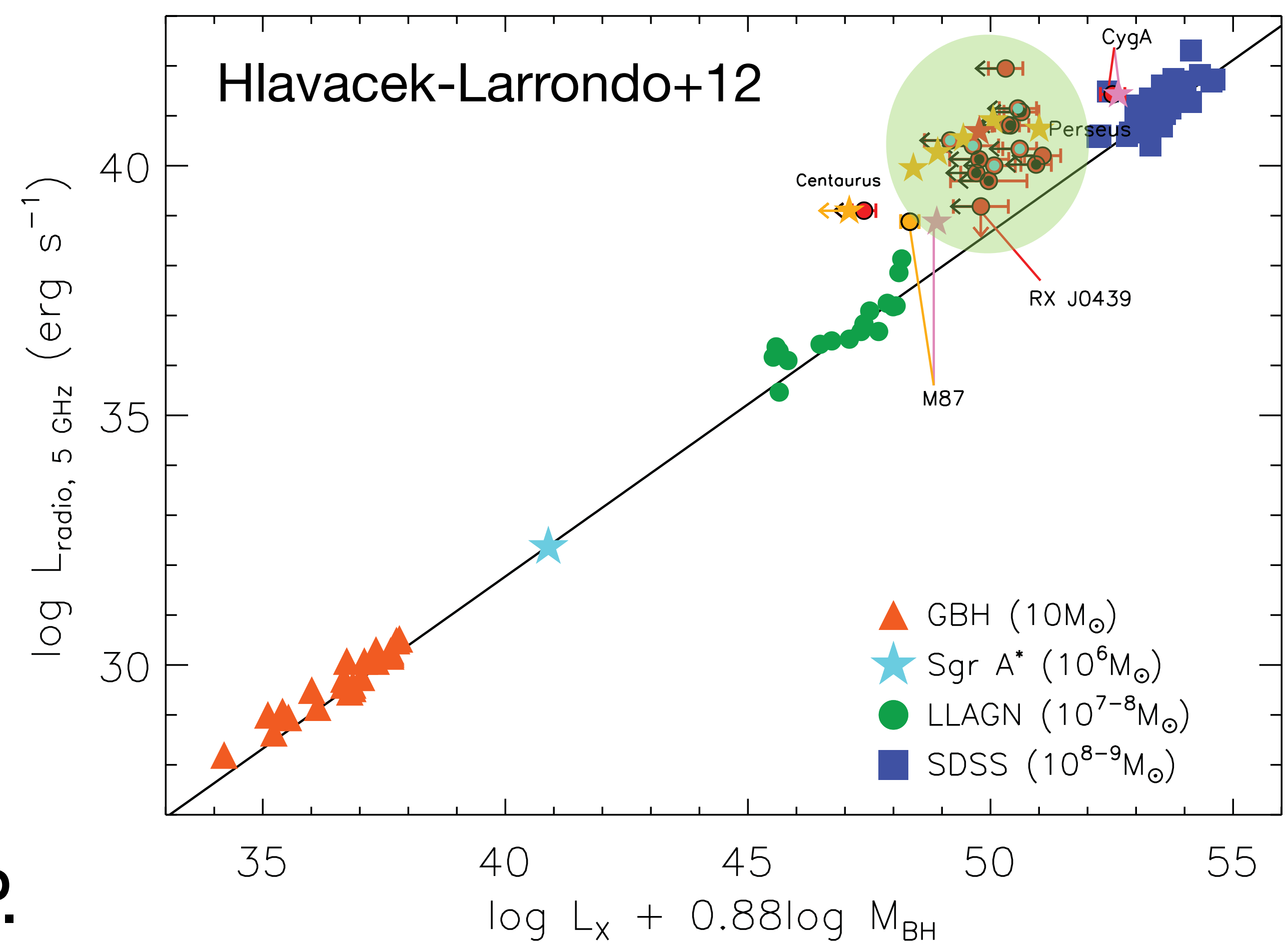


McConnell+2011

BHs in Brightest Cluster Galaxies



- Very massive black holes in BCGs ($M_{BH} \sim 10^9$ - $2\ 10^{10}\ M_\odot$)
- Most have BH masses larger than predicted by correlations (McConnell+2011, 2011a, 2012)
- BCGs are deviant from fundamental plane of BH activity (M_{BH}-L_X-L_R) unless M_{BH}-L_K underestimate M_{BH} by ~10 (Hlavacek-Larrondo+12)
- BCGs in cool core clusters should have $M_{BH} > 10^{10}\ M_\odot$ to follow the FP.



Outline

- Scaling Relations in Normal Galaxies
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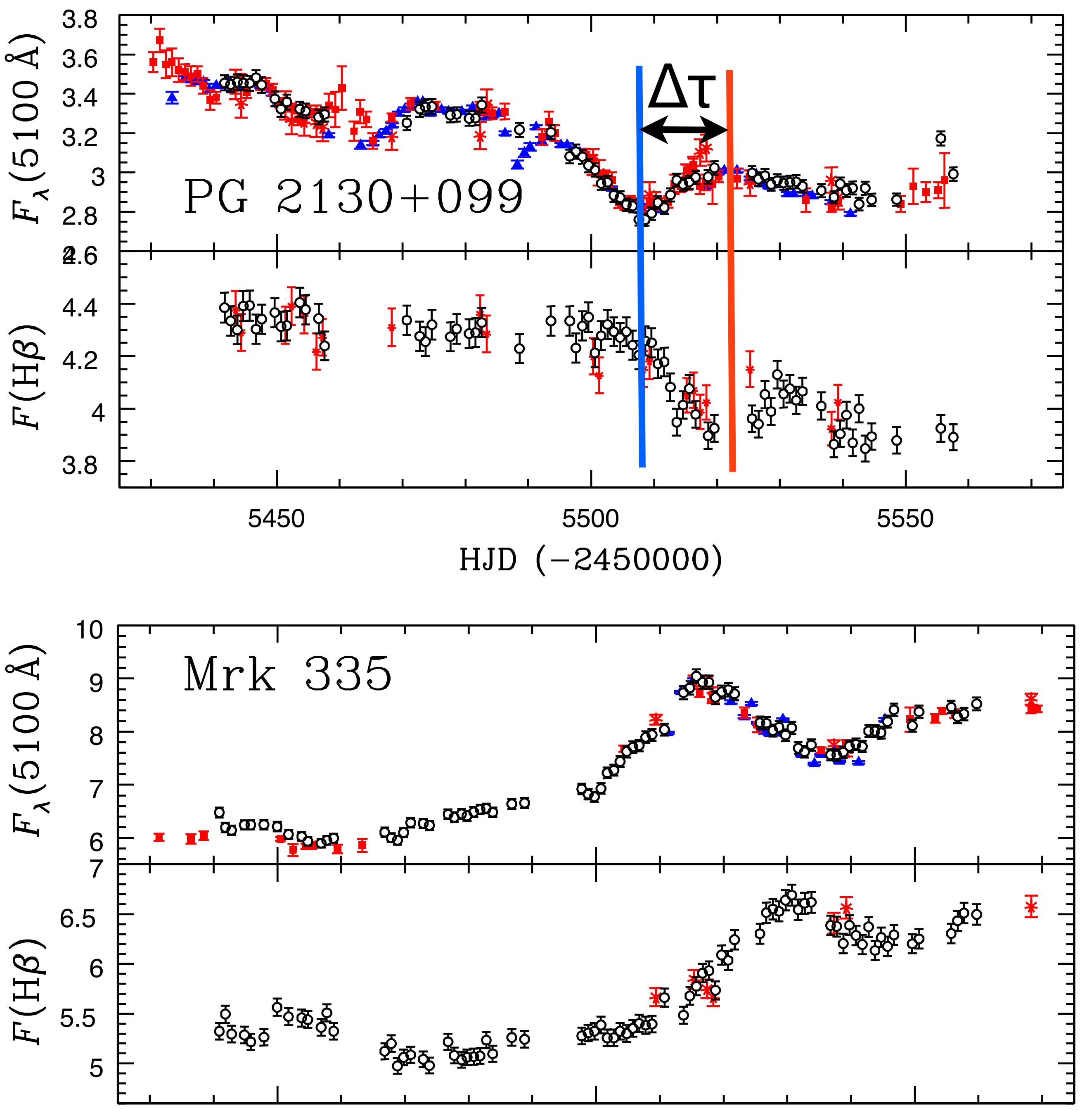
BH Mass measurements

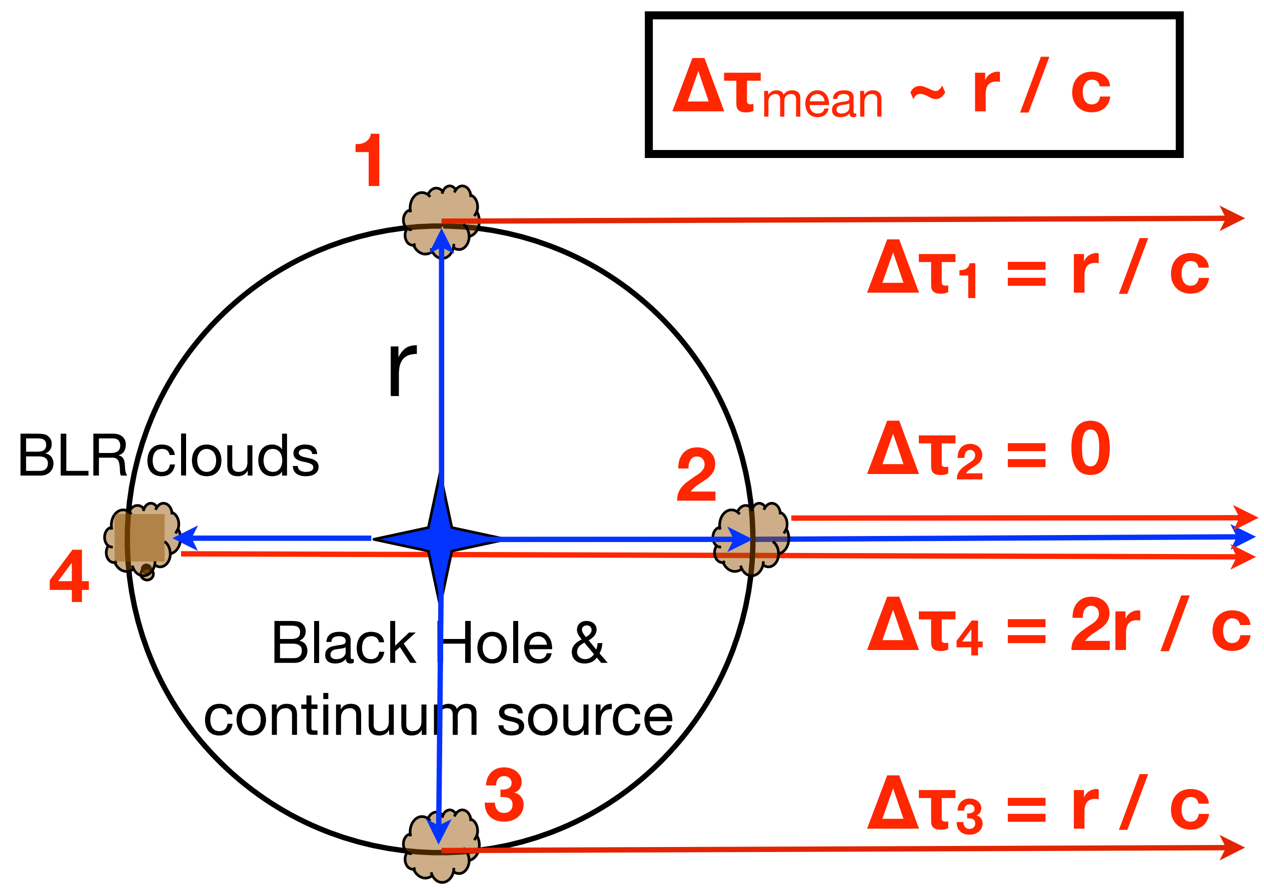
- motions or kinematics of test particles (stars, gas clouds)
  - Galactic Center, ~14 with $H_2$0 Megamasers in Galaxy Nuclei
- spatially resolved gas/stellar kinematics (average kinematics of large volumes)
  - in principle all galaxies within ~100 Mpc; in practice ~60 galaxies (mostly E/S0)
- reverberation mapping (in type 1 AGN: measure sizes from time delays)
  - in principle all type 1 AGN; in practice ~50 objects so far
- virial masses (in type 1 AGN: masses from spectral measurements of broad lines)
  - all type 1 AGN at all z; as many objects as many good spectra available
- Different methods are intercalibrated: BH mass ladder
  - gas/stellar kinematics → reverberation mapping → virial masses

Reverberation mapping

- time delay of broad line w.r.t. to continuum light curve is light travel time → R_{BLR}, BLR average distance from BH.



Grier+12



Virial Masses

Apply virial theorem to estimate M_{BH}:

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

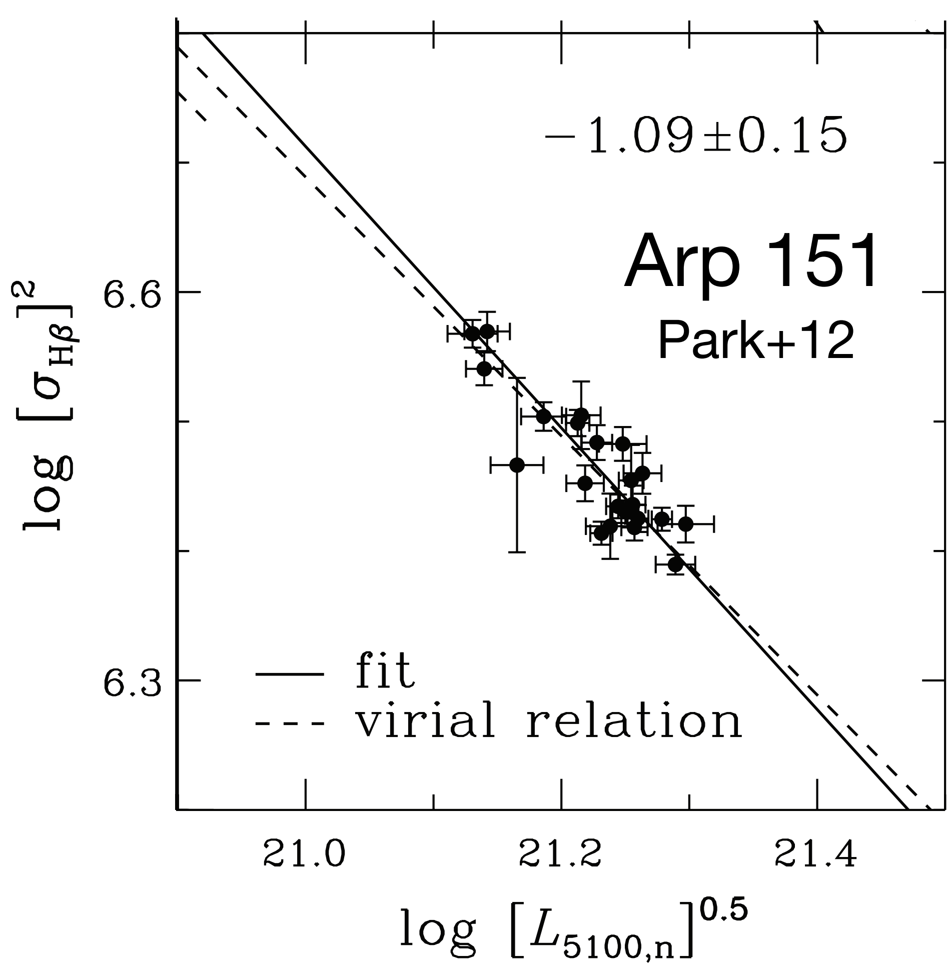
$$V = V_{\rm BLR} = \sigma(\text{rms spectrum})$$

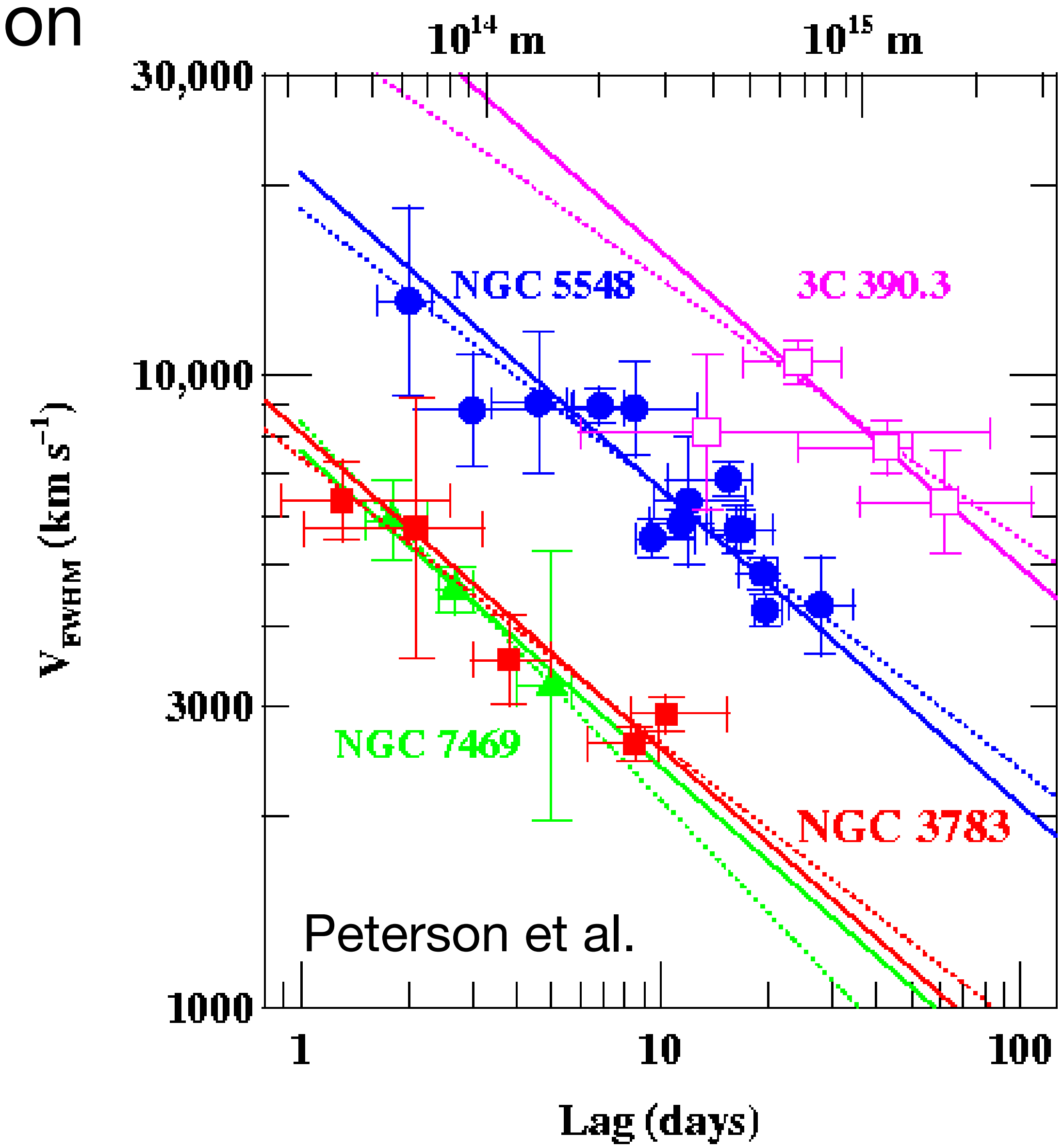
$$R = R_{\rm BLR} = c\Delta\tau$$

$$f = ?$$

f depends on BLR geometry and distribution of gas clouds → unknown

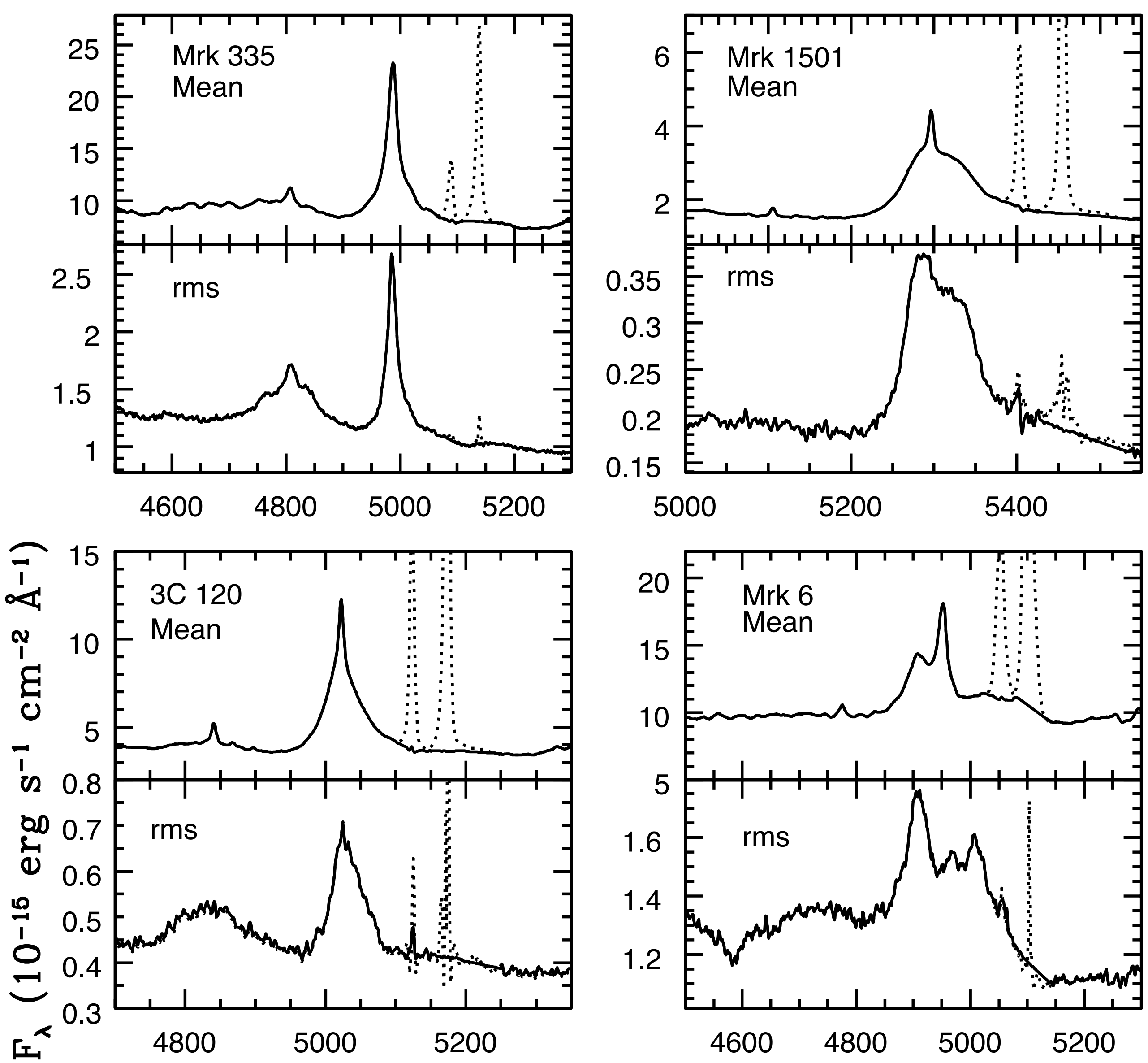
BLR virialized? Different lines: **$V \sim R^{-0.5}$**



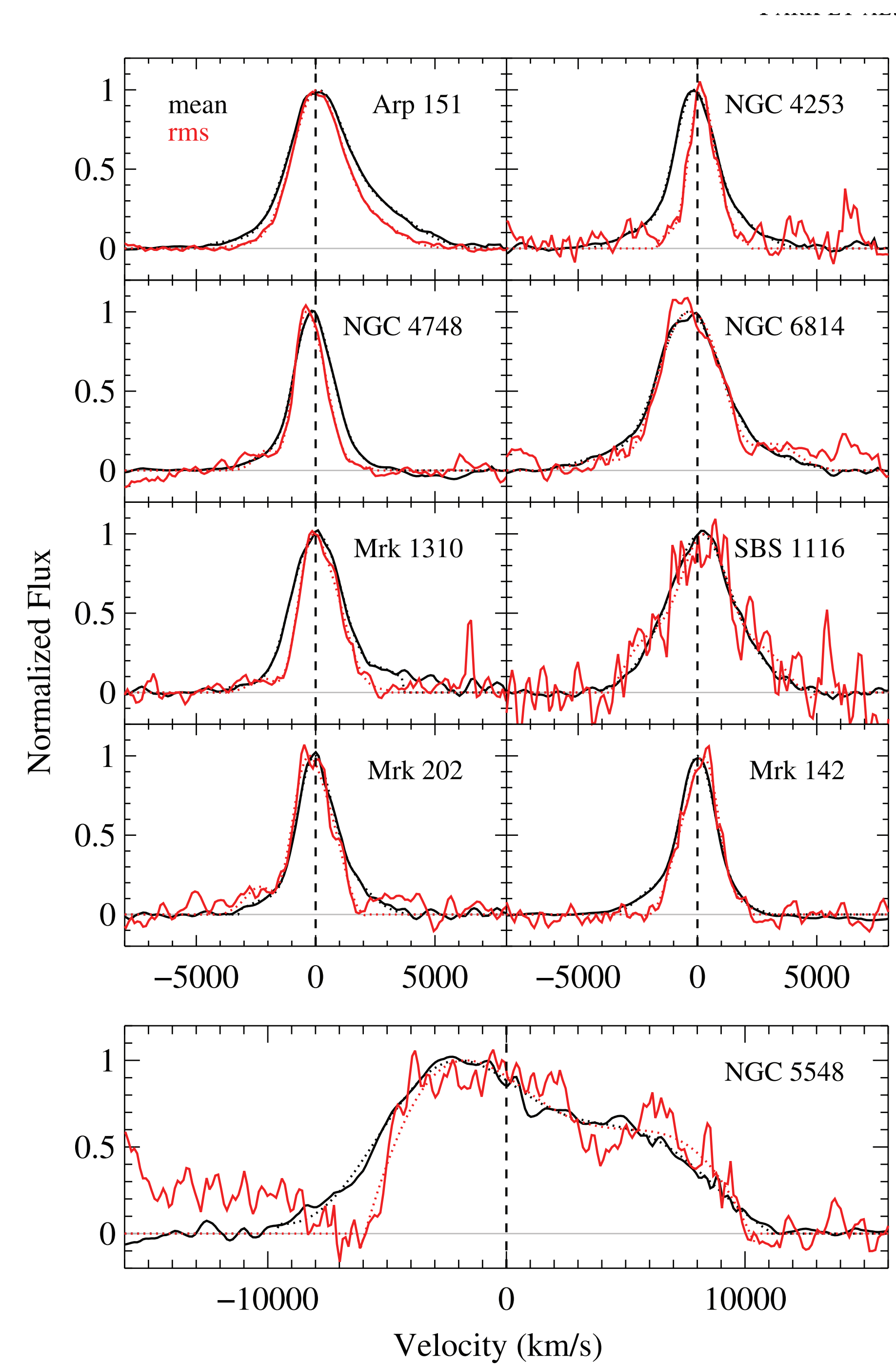


The use of *rms* spectra

- *rms* spectra isolate the variable (reverberating part) of the line
- *rms* line usually broader than *mean* line



Grier+12



Park+12

Calibration of virial M_{BH}: RM

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

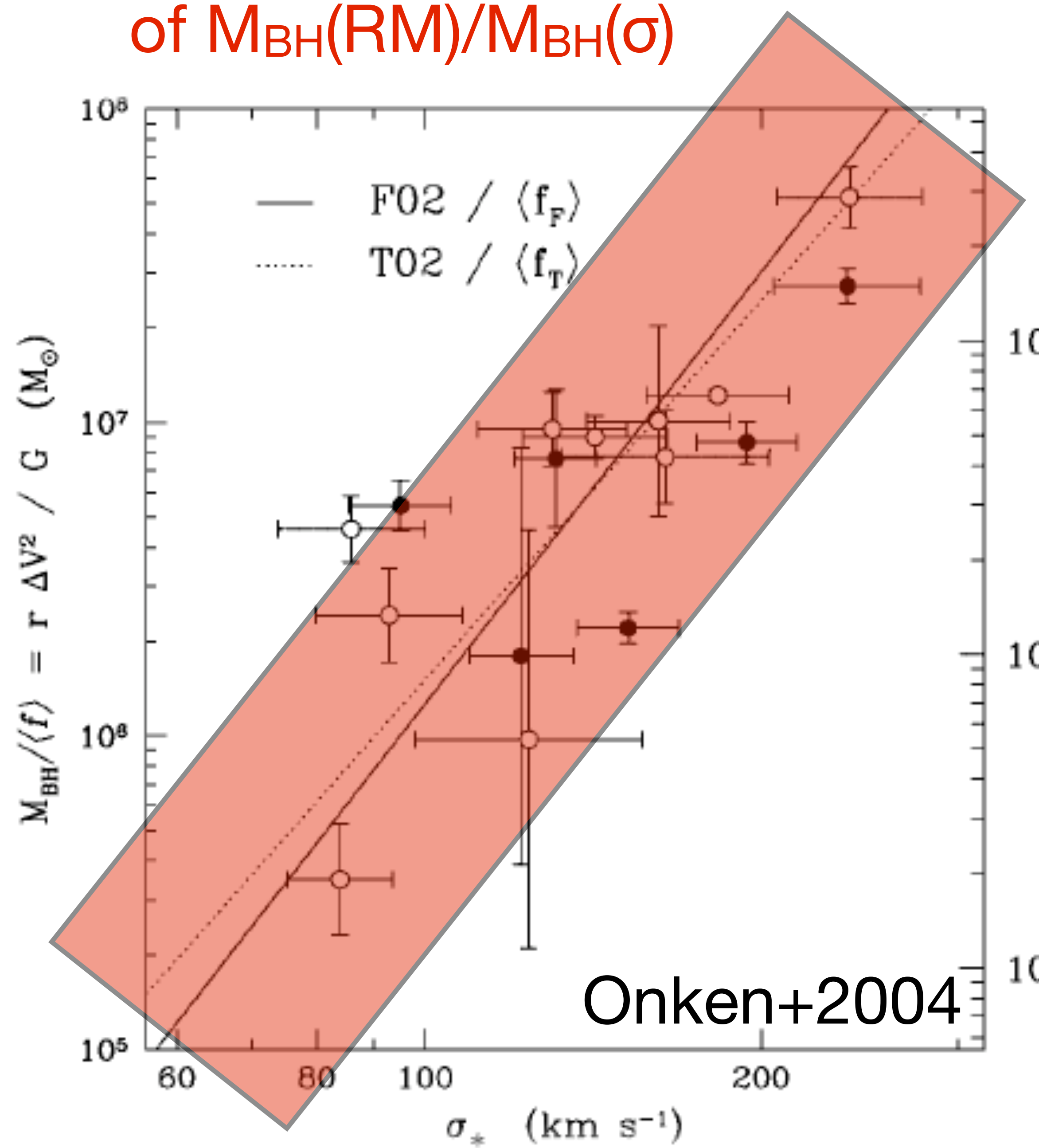
f factor is unknown.

Consider RM data and calibrate "average" f with M_{BH}-σ [Onken+2004]

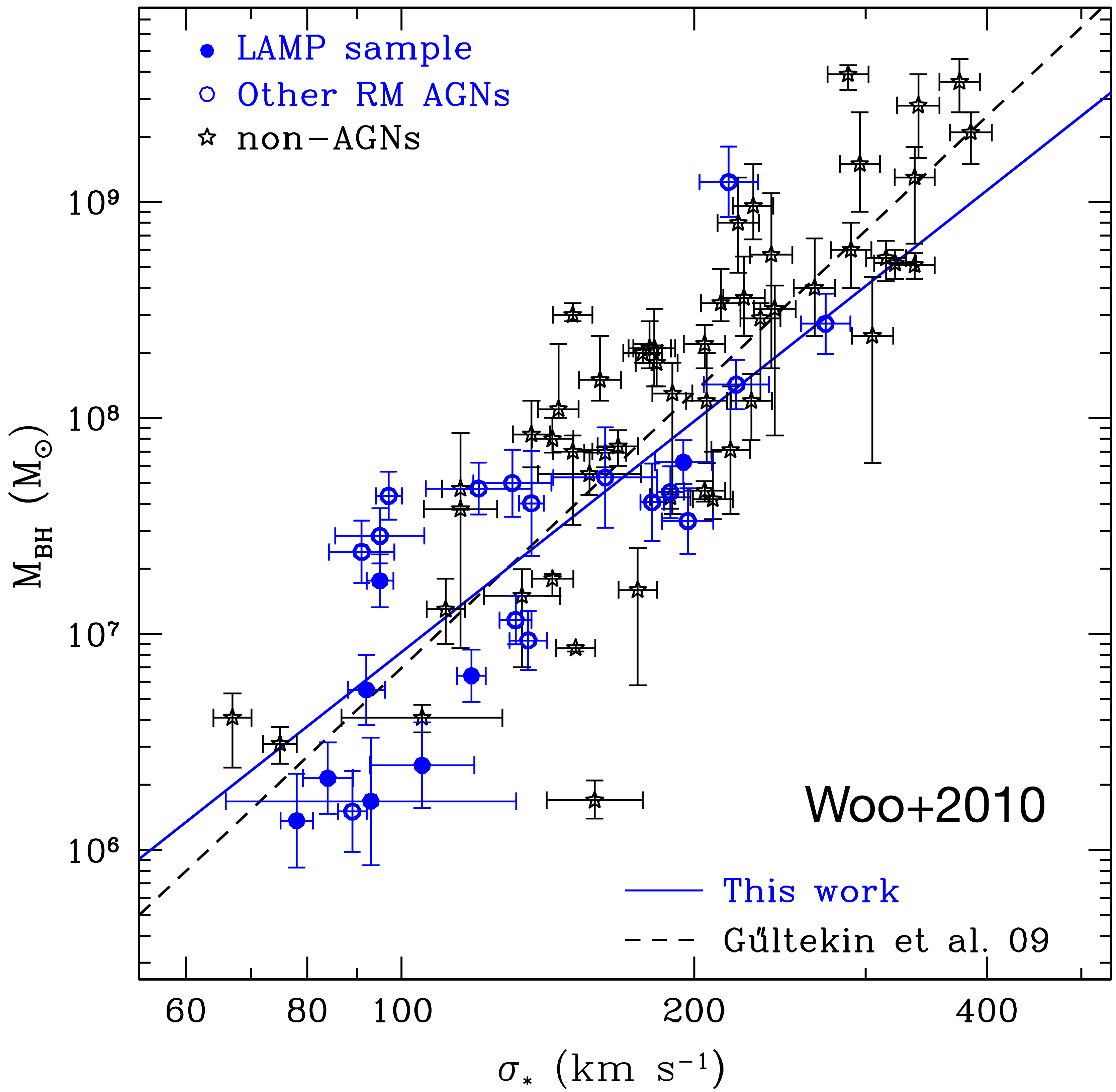
Find f which provides the best agreement between RM M_{BH} and M_{BH}-σ relation.

< f > = 5.5±1.8 if V is velocity dispersion of r.m.s. spectrum

Large scatter (~0.5 dex) of M_{BH}(RM)/M_{BH}(σ)



Calibration of virial M_{BH}: RM



Scatter of M_{BH}(RM)-σ similar to M_{BH}(σ)

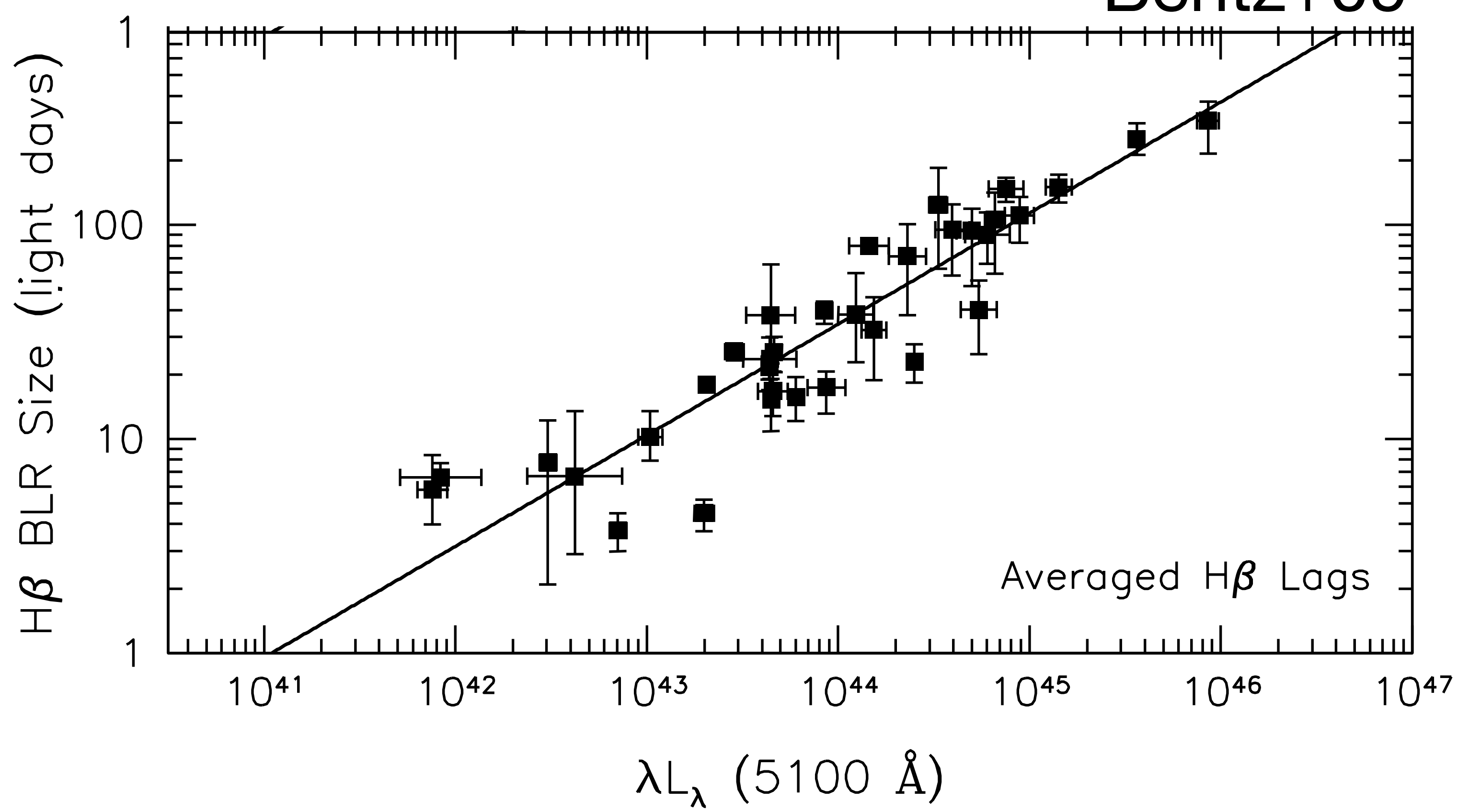
Single Epoch Virial BH Masses

M_{BH} from reverberation mapping ($\rightarrow R_{BLR}$) *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 ...).

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 (FWHM) with continuum luminosity

Calibration of virial M_{BH}: SE

M_{BH} for objects with RM (reverberation mapping) data are known from previous calibrations.

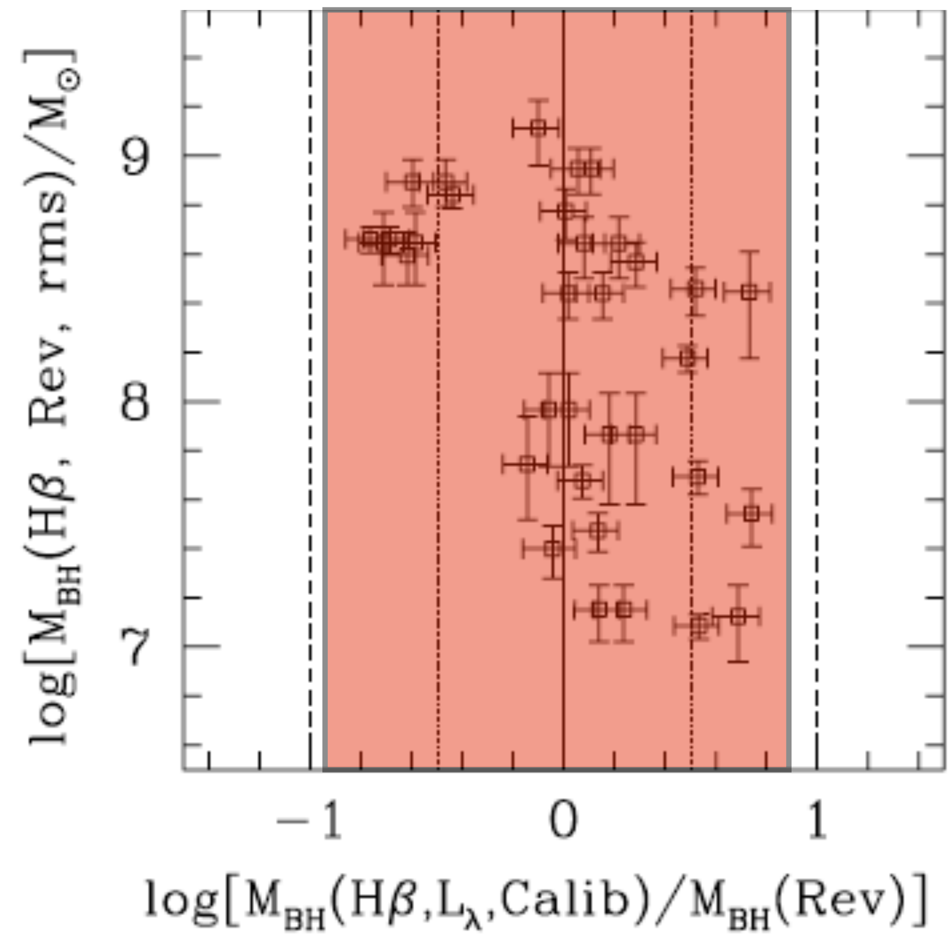
Consider many SE (single epoch) spectra of the same sources, measure FWHM and L_{cont} and find f' which calibrates SE MBH

- V from FWHM of line
- R from radius-luminosity relation $R \sim L^{\alpha}$

r.m.s. of log M_{BH}(SE)/M_{BH}(RM) is 0.4 dex

SE M_{BH} can be wrong even up to a factor 10, but are ok in a statistical sense.

Large scatter (~0.4 dex) of M_{BH}(SE)/M_{BH}(RM)



Vestergaard & Peterson 2006

$$M_{BH} = f' \left(\frac{FWHM(H\beta)}{1000\,\mathrm{km\,s^{-1}}} \right)^2 \left(\frac{\lambda L_\lambda(5100)}{10^{44}\,\mathrm{erg\,s^{-1}}} \right)^{0.5} \qquad \log f' = 6.91 \pm 0.02$$

The BH mass ladder (Peterson 2002)

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

Local universe (< 250 Mpc)

↓ calibration (e.g. Onken +04, Woo+10)

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

2 **Reverberation Mapping (RM)**

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

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

Time expensive

↓ calibration (Vestergaard & Peterson 06, Park+12)

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

3 *Virial BH masses*

Type 1 AGNs only

Single Epoch (SE)

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

Open issues

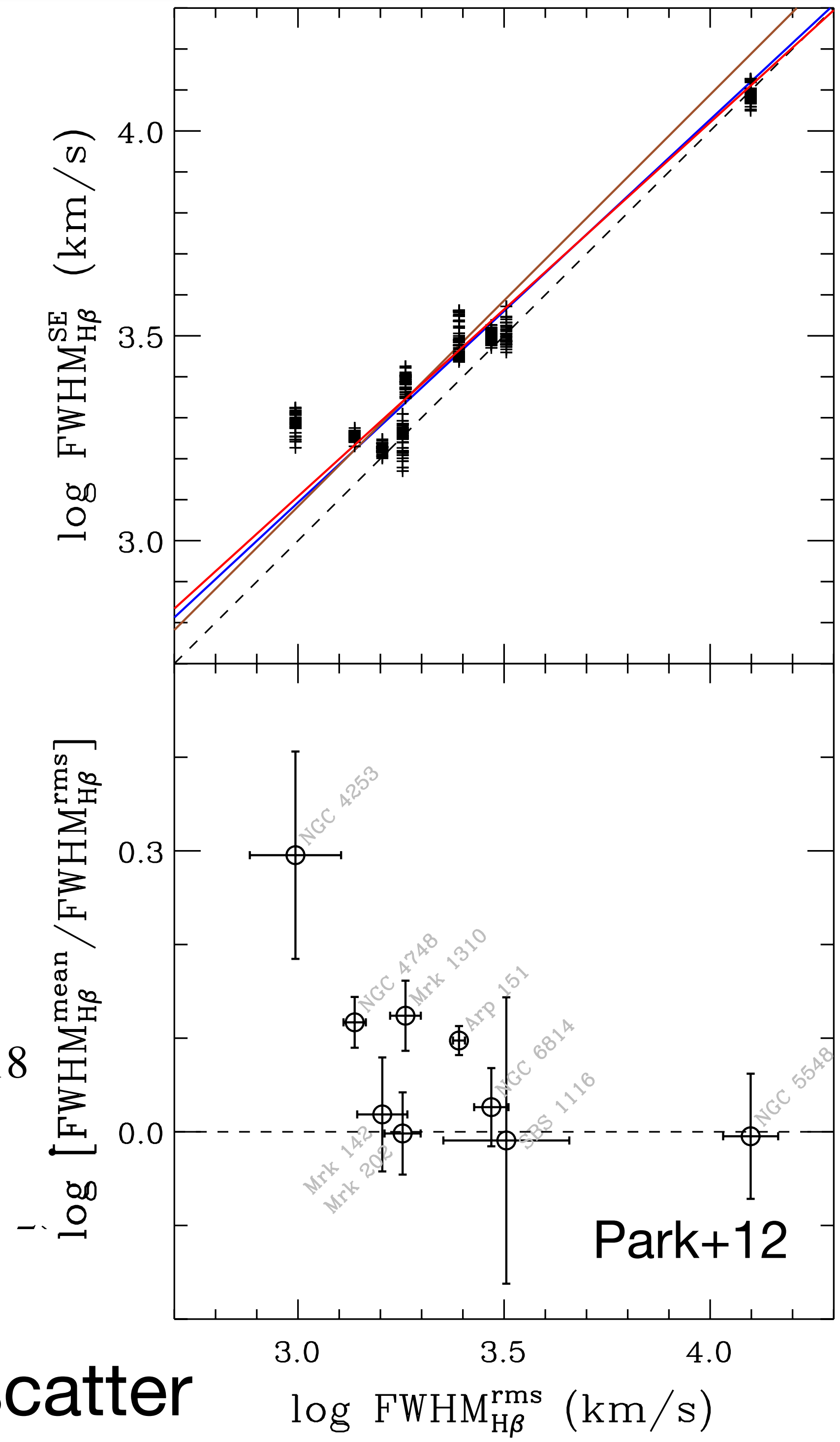
- We are missing a R_{BLR}-L for MgII and CIV (high z extension).
- The physical origin of the R_{BLR}-L relation
- Accuracies of M_{BH}(RM) and M_{BH}(SE)
- Reliability of CIV-based masses
- Effect of non-virial (e.g. outflow motions) in the BLR
- Effect of radiation pressure

Accuracy of M_{BH} based on SE

- Use only spectra with S/N > 10-20 for accurate measurements of FWHM (Denney+09)
- Correct L for host galaxy contamination
- From M_{BH}(RM) to M_{BH}(SE) uncertainties from:
  - continuum and line variability ~0.05 dex
  - scatter of R-L and systematic on f ~0.45 dex
  - Much of the scatter is due to the non-linear relations FWHM(SE)-FWHM(rms) and σ(SE)-σ(rms)
  - Correct for this non linearity effectively changes the virial relation

$$M_{\rm BH} = 10^{6.966}\, M_{\odot} \left(\frac{\rm FWHM_{H\beta}(SE)}{1000\,{\rm km\,s^{-1}}}\right)^{1.734} \left(\frac{\lambda L_{5100,n}}{10^{44}\,{\rm erg\,s^{-1}}}\right)^{0.518}$$

[Park+12]

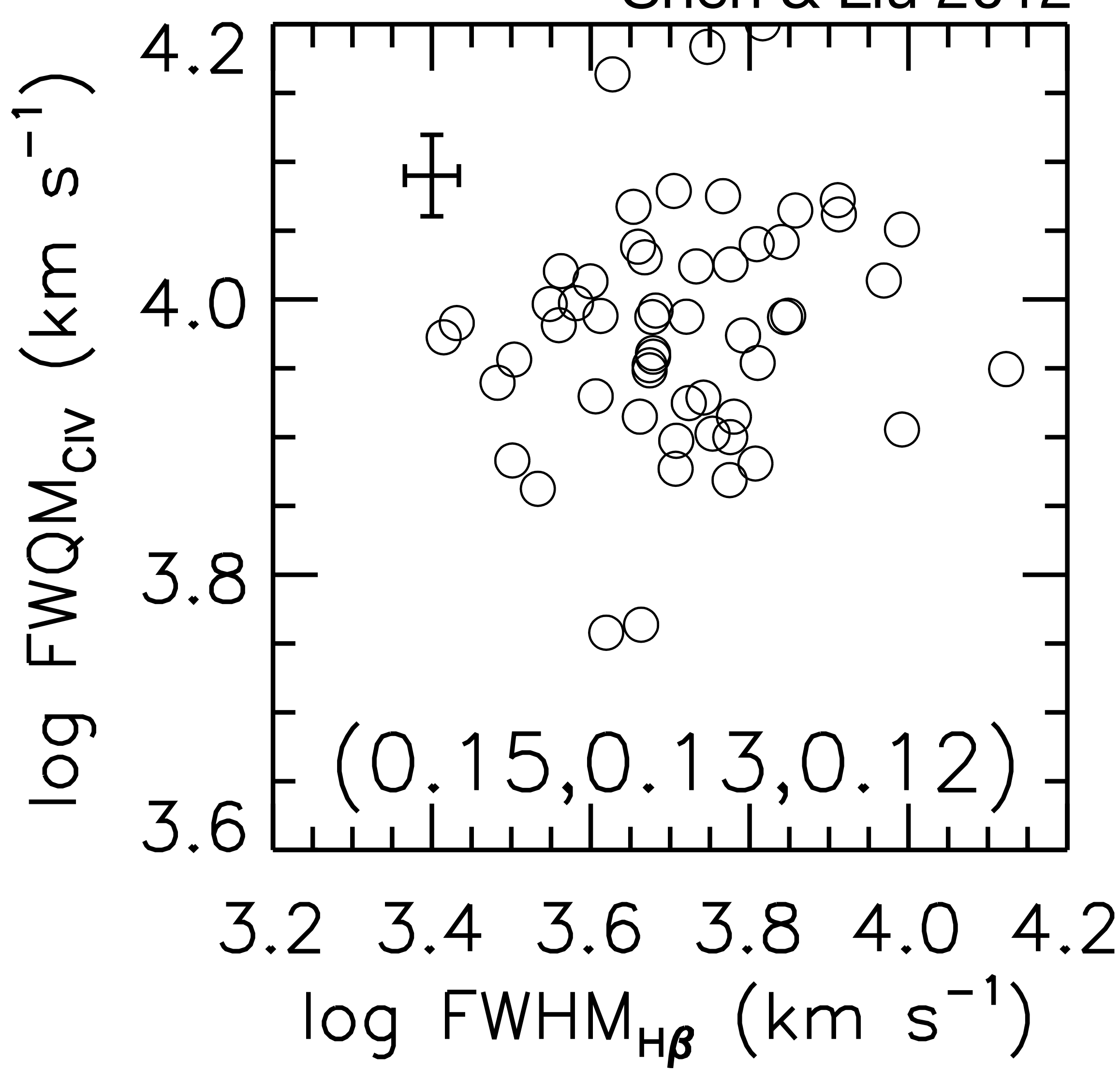


- A “corrected” virial relation also decreases the scatter between MgII and Hbeta based masses (Wang+09)
- *These are only empirical corrections, no physical reason behind.*

Accuracy of CIV-based M_{BH}

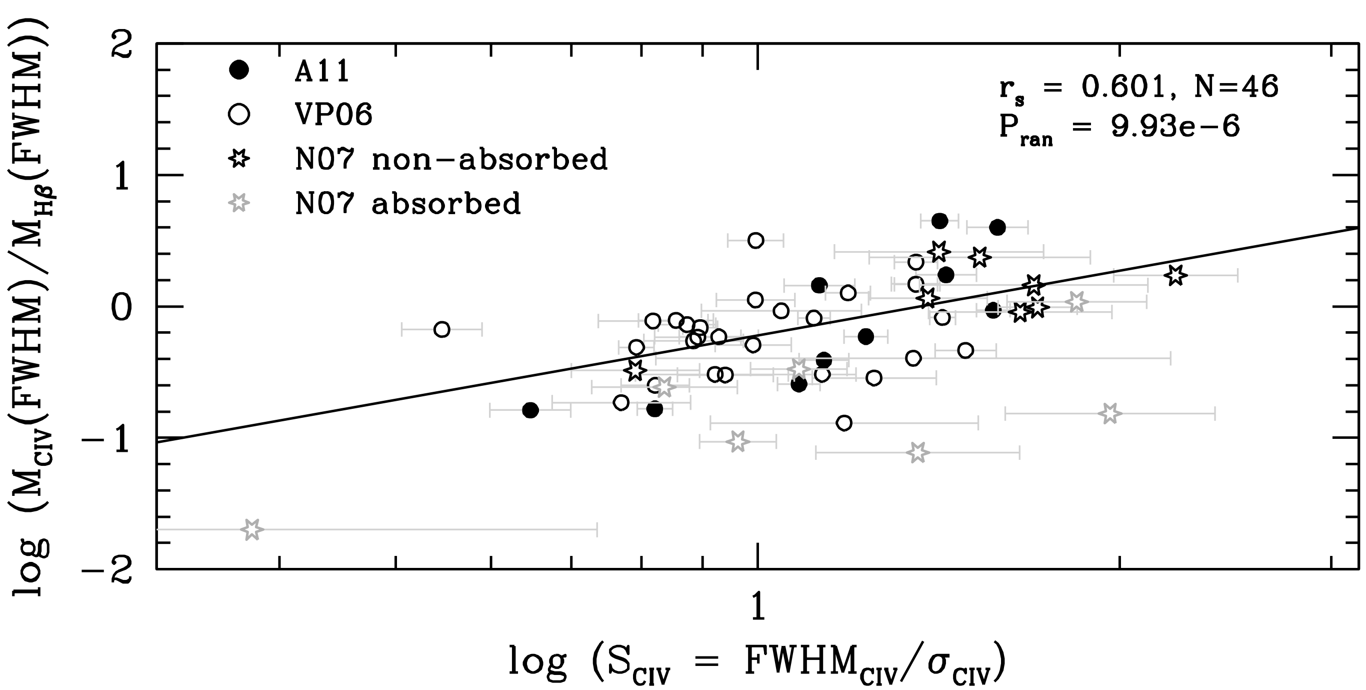
- CIV-based masses are deemed unreliable because
  - line is blueshifted compared to MgII (e.g. Shen+10)
  - line width is not well correlated with MgII and Hbeta (Baskin & Laor 2005; Netzer +2007; Sulentic +2007; Shen & Liu 2012)

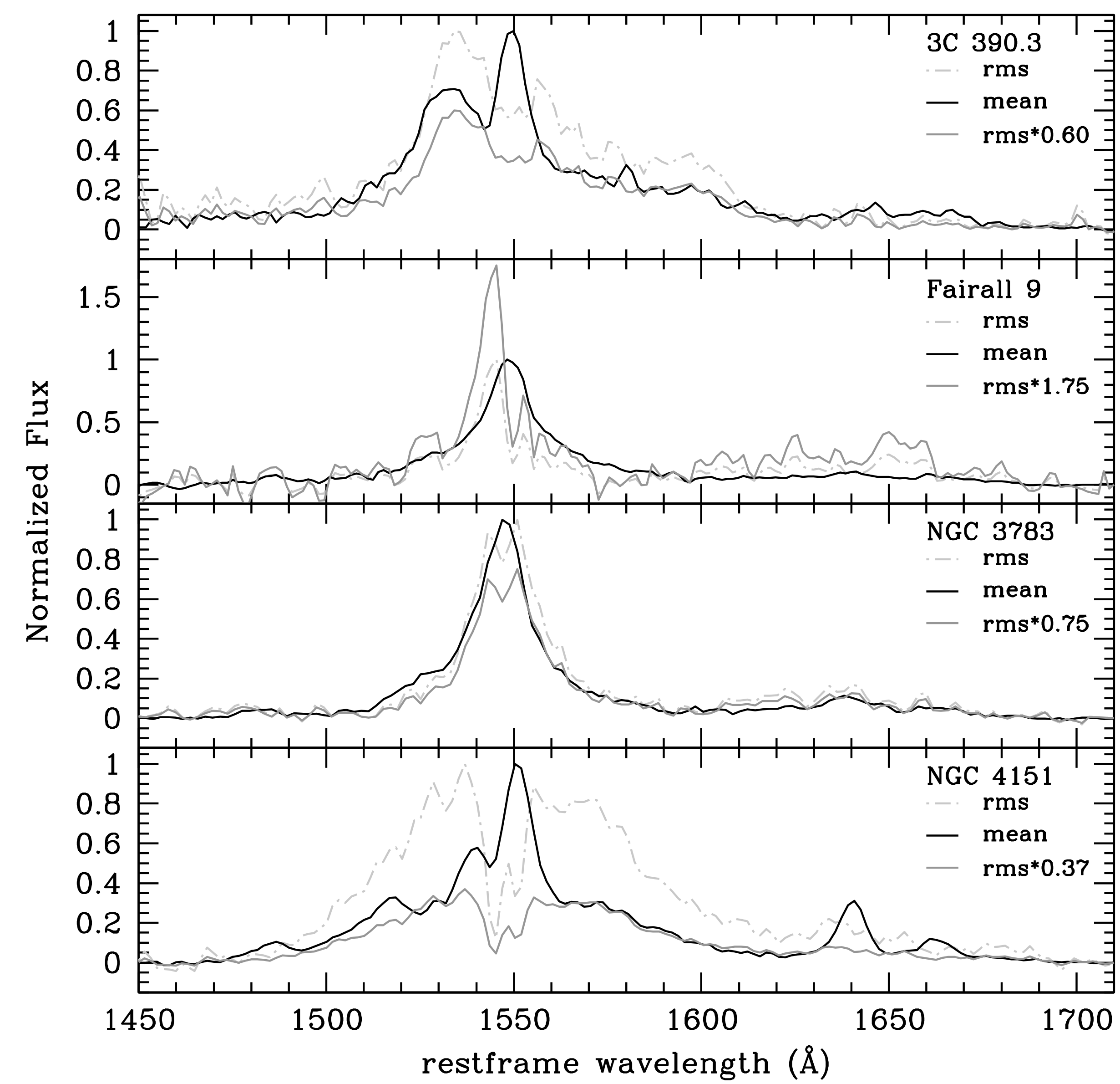
Shen & Liu 2012



Accuracy of CIV-based M_{BH}

- Comparison of *rms* and mean spectra:
  - non-variable component responsible for a large part of the discrepancies (not in Hβ!)
  - bias in CIV mass depends on profile shape (S=FWHM/sigma)
  - empirical correction ($M_{BH} \sim FWHM^{0.4}\,\sigma^{1.6}$) reduces M(CIV)/M(Hβ) scatter from 0.36 to 0.22 dex
  - Non variable component possibly originates in an orientation dependent outflow from BLR or ILR (inner extension of NLR)





Denney (2012)

The effect of radiation pressure

- BLR clouds are photoionized

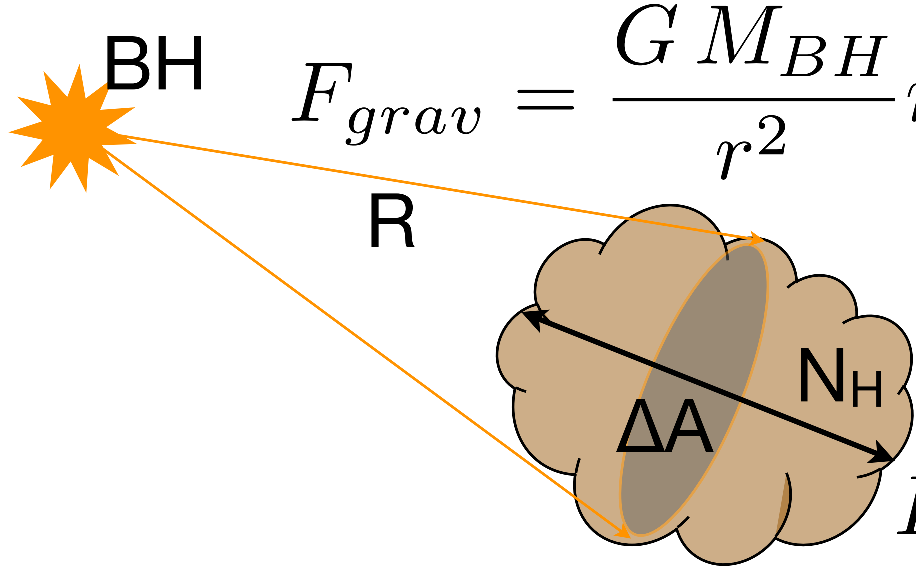
- Radiation pressure on BLR clouds is an unavoidable physical effect

- Corrected mass estimator:

$$M_{BH} = f \frac{V^2 R}{G} + g \lambda L_\lambda$$

f (Hβ) , *g* (Hβ) calibrated assuming AGN lie on M_{BH}-σ/L

A simple model for a physical interpretation of ***g***
→ BLR clouds optically thick to ionizing photons



$$F_{grav} = \frac{G\, M_{BH}}{r^2} m_p\, N_H \Delta A$$

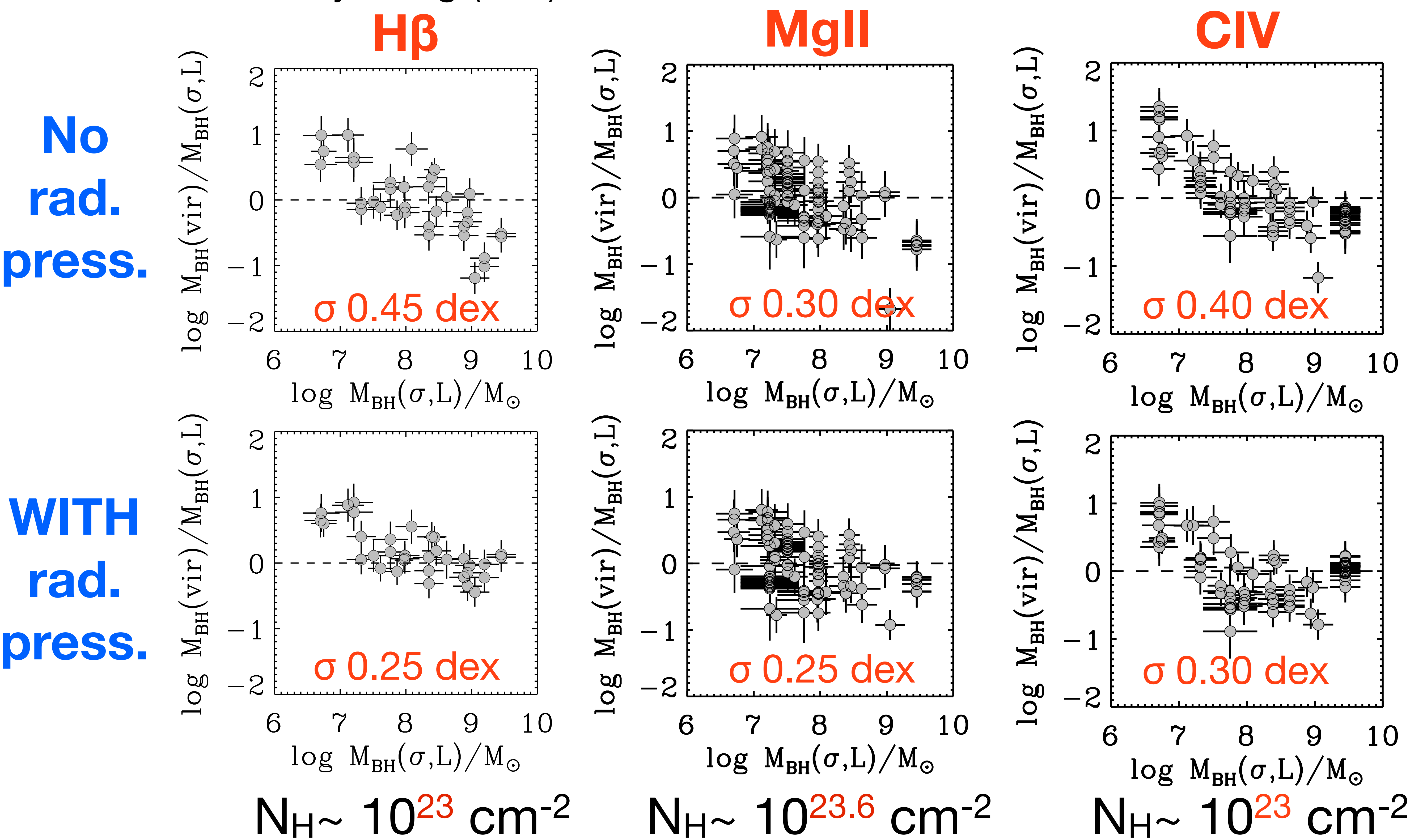
$$F_{rad} = \frac{L_{ion}}{4\pi\, r^2\, c} \Delta A$$

$$g = \frac{(L_{ion}/\lambda L_\lambda)}{4\pi\, G\, c\, m_p\, N_H}$$

[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



[Marconi+08,Marconi+09,Marconi+12]

Outline

- BH Masses & Scaling Relations in Normal Galaxies
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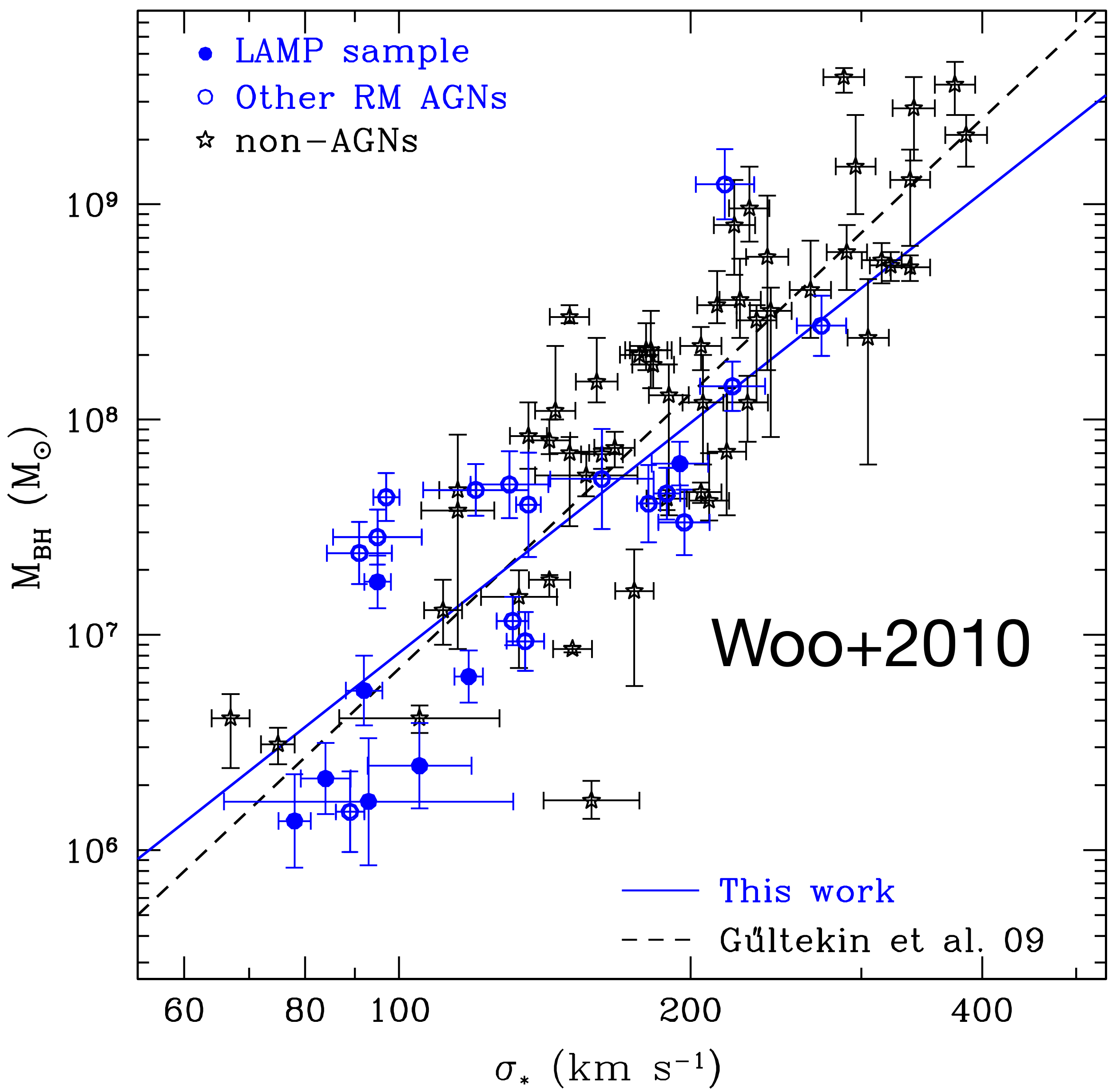
M_{BH}-galaxy relations for AGN at z=0

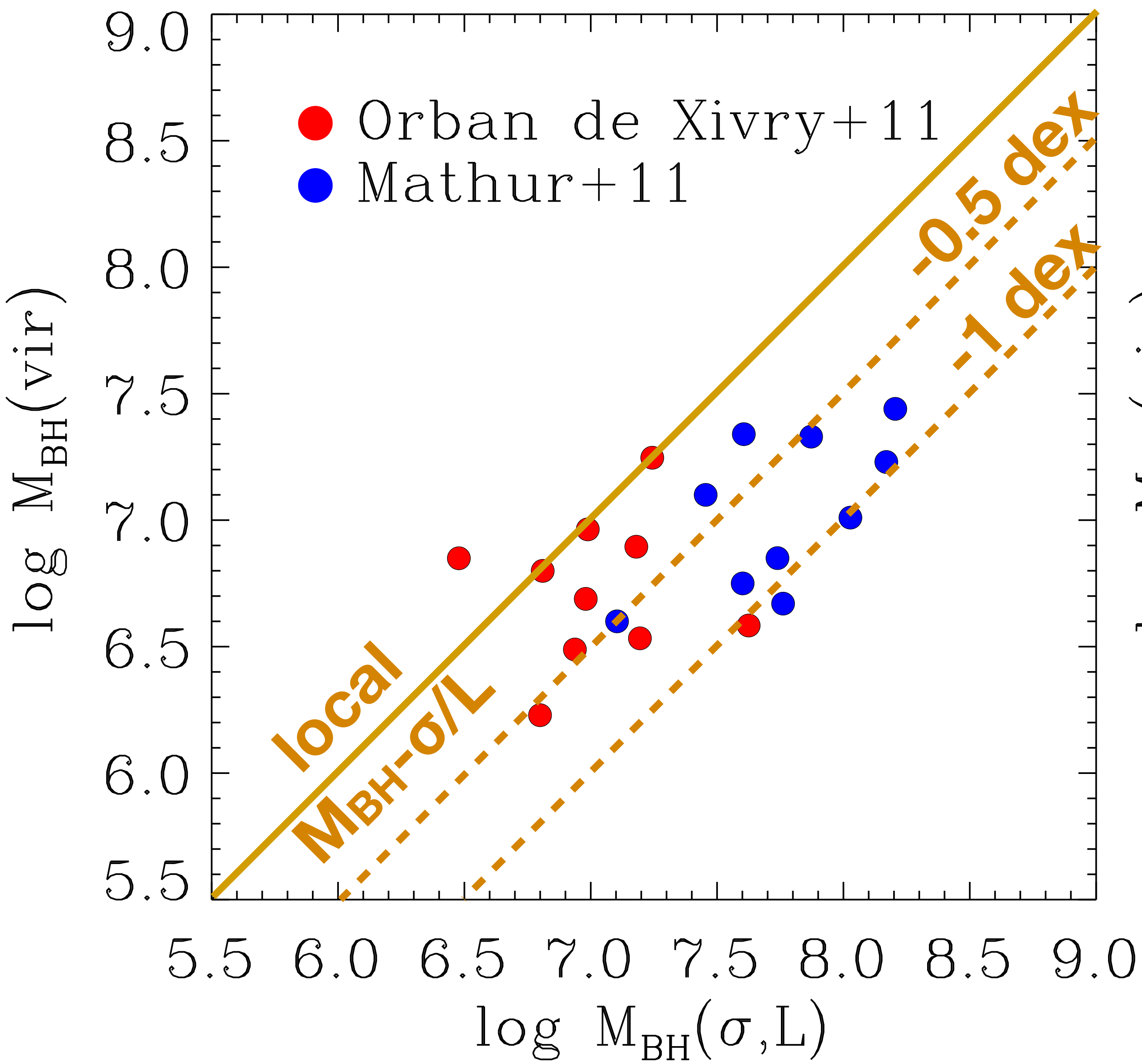
- M_{BH}-σ relation for local AGN from RM database (Peterson+2004) and new RM observations at low L (LAMP)
- determine *f*, in agreement with earlier determinations (Onken+2004).
- IMPORTANT: normalizations are imposed to be same but slope and scatter are not!

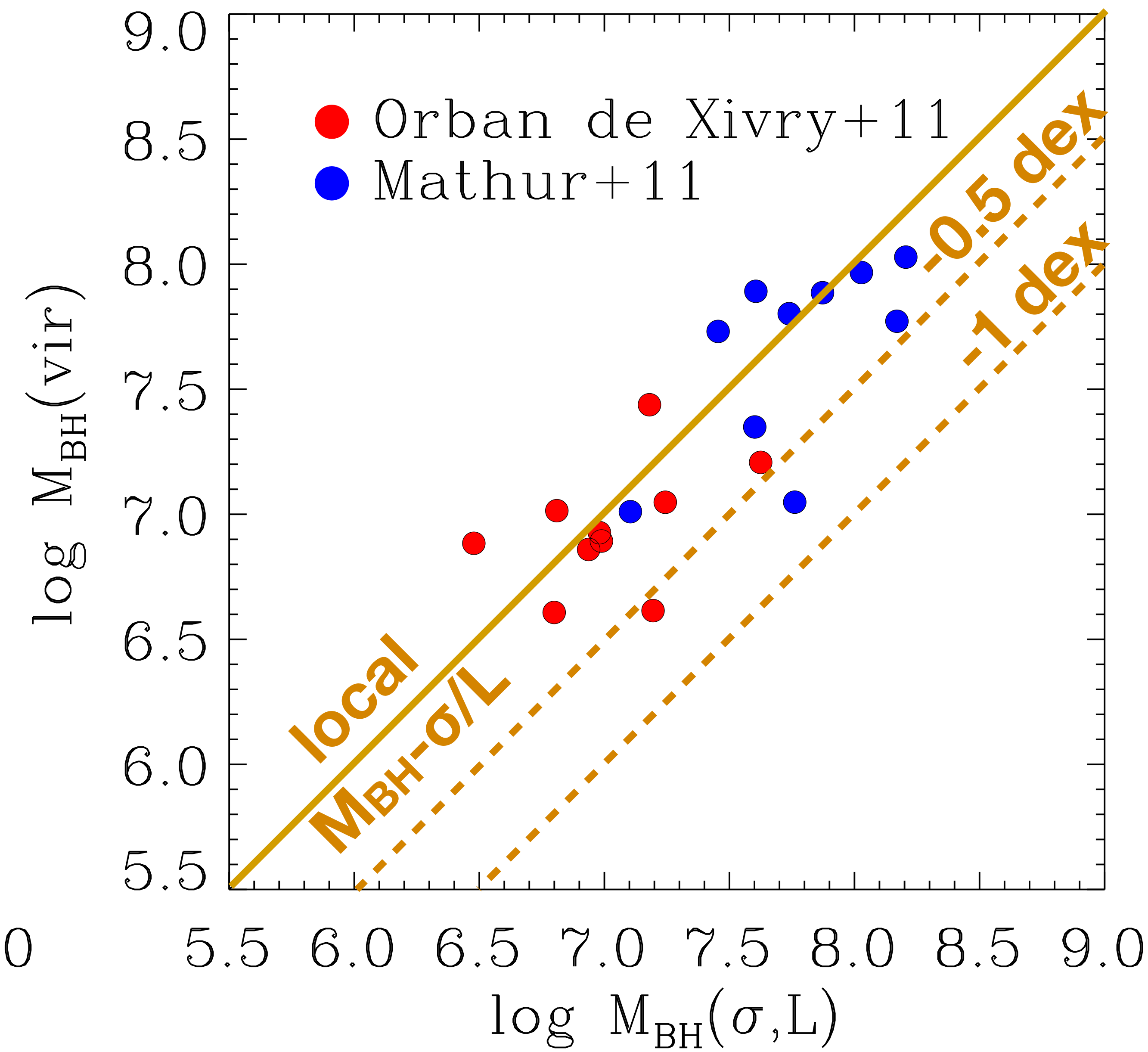


- Relation is also surprisingly tight (intrinsic scatter ~0.4 dex, similar to quiescent galaxies);
- Slope is 3.6 ± 0.6 compared to 4.2-0.4 of quiescent galaxies (Gultekin+09); consistent within the large errors
- Virial products are scaled by ~5.2 (similar to Onken+2004)
- *Quasars are missing (difficult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

NLSy1 galaxies *ON* M_{BH}-σ/L

- NLSy1 are believed to host small BHs (compared to their bulges), actively growing (large L/L_{Edd})





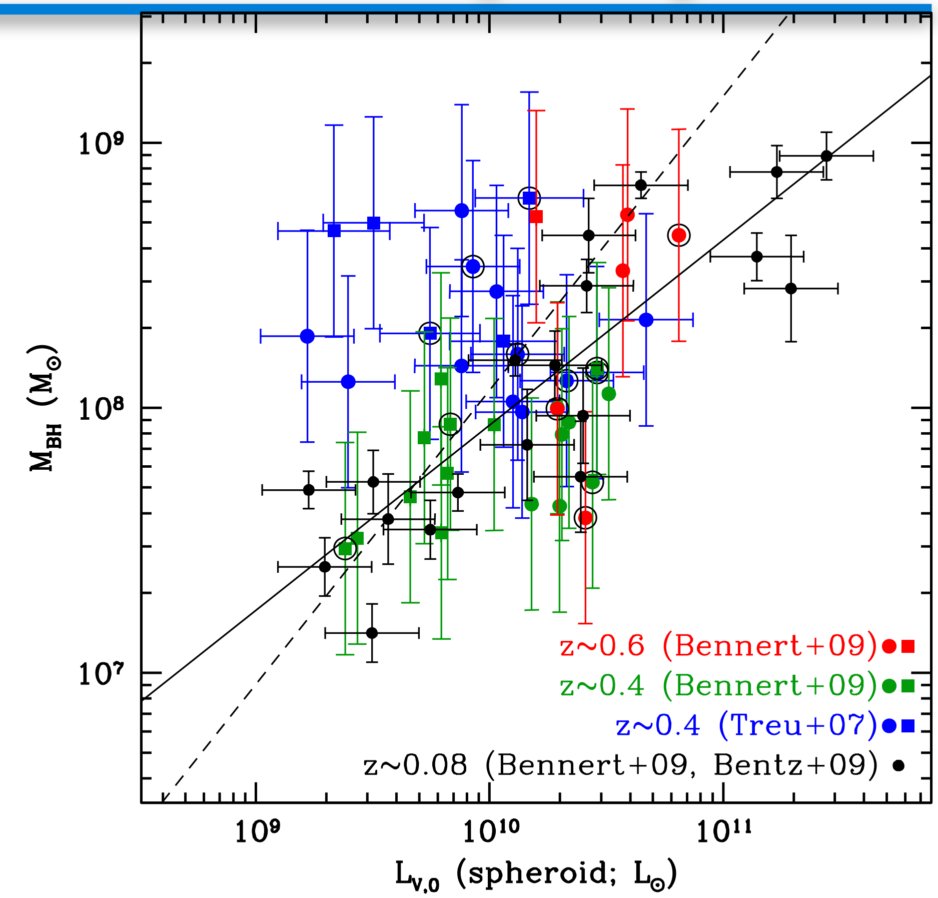
- NLSy1 bulges are mostly pseudo-bulges (Orban de Xivry+11, Mathur+11)
- When M_{BH} corrected for radiation pressure, consistent with relation and pseudo-bulge hosts.

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

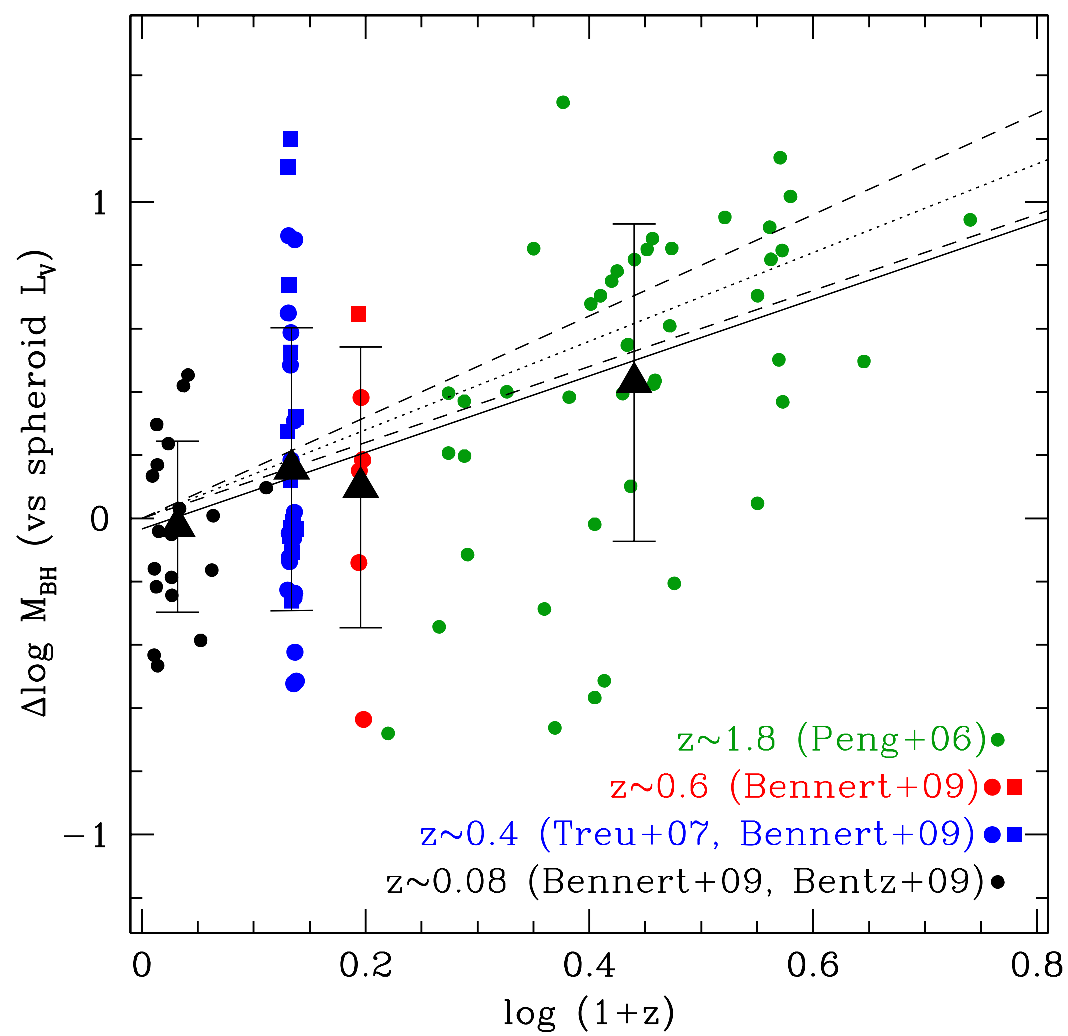
Treu et al. find evidence for evolution of M_{BH}-σ/L zero point since z~0.5 (e.g. Bennert+11). Intrinsic scatter (constant with z) is ~0.3 dex). With high z objects (see later) evolution is as

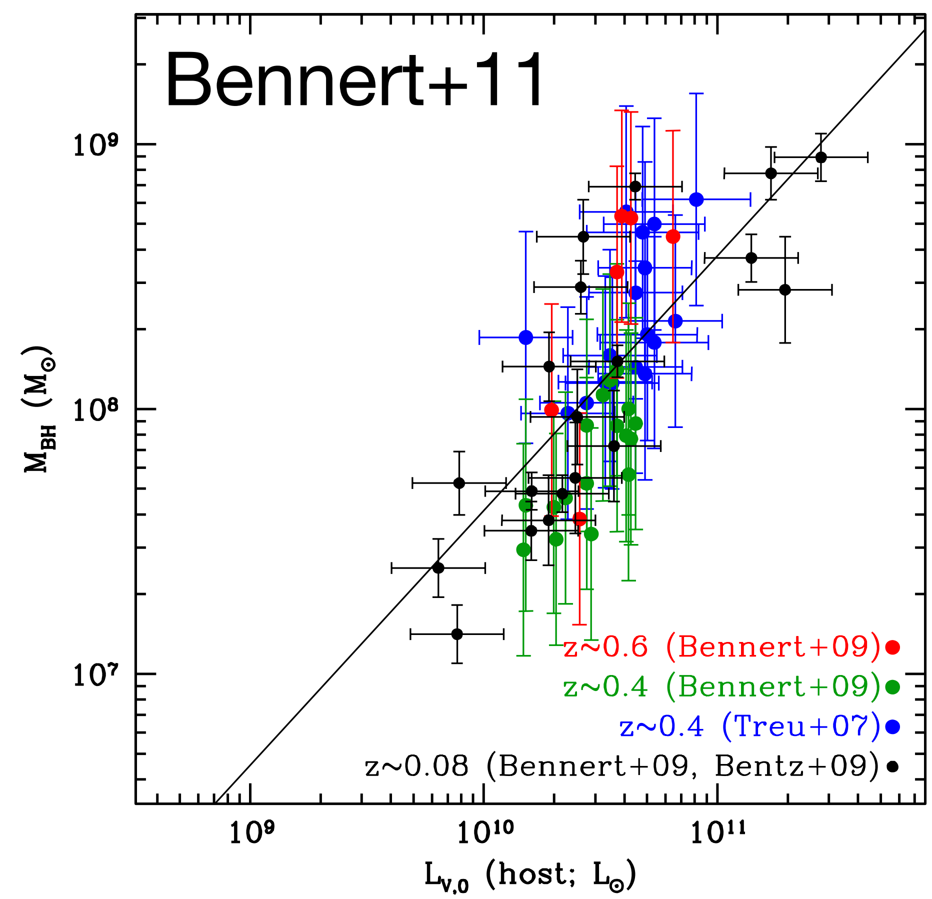
$$\frac{M_{\rm BH}}{L_{\rm sph}} \sim \frac{M_{\rm BH}}{M_{\rm sph}} \sim (1+z)^{1.4\pm0.2}$$

Intriguingly no evolution when considering Total host luminosity.



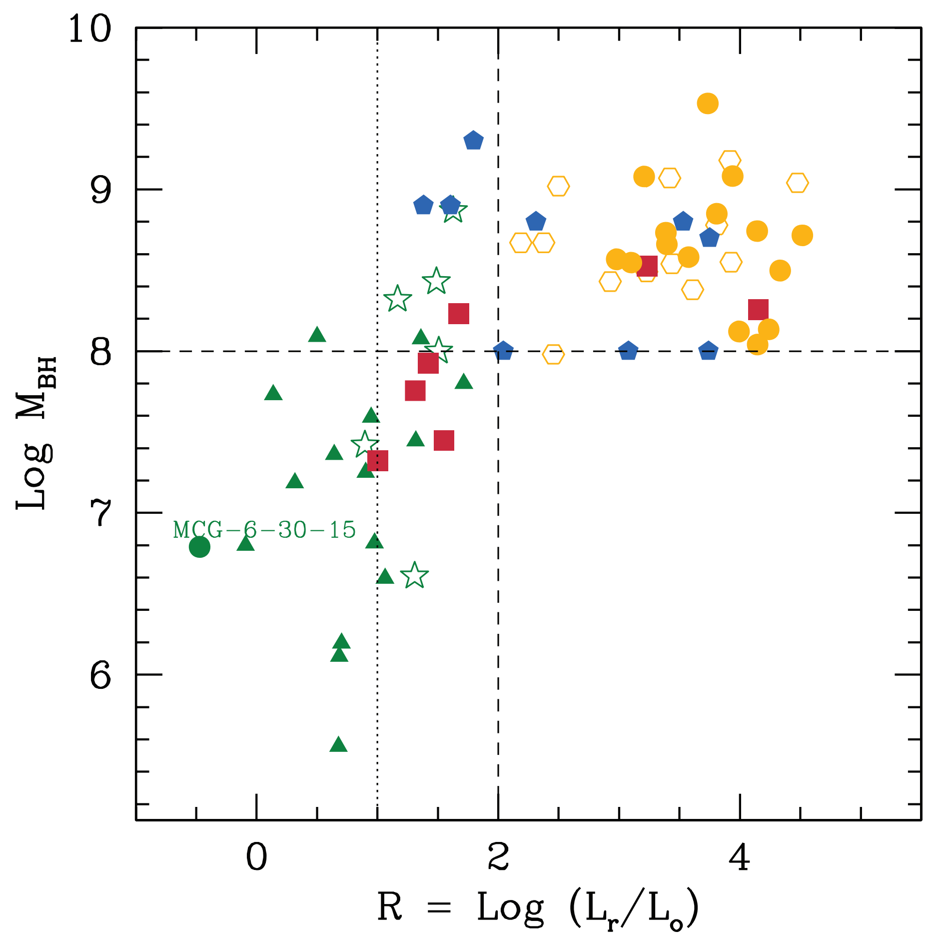
M_{BH}/M_{sph} is already ~1.6 times the local value at z~0.4 i.e. ~4 Gyr ago.



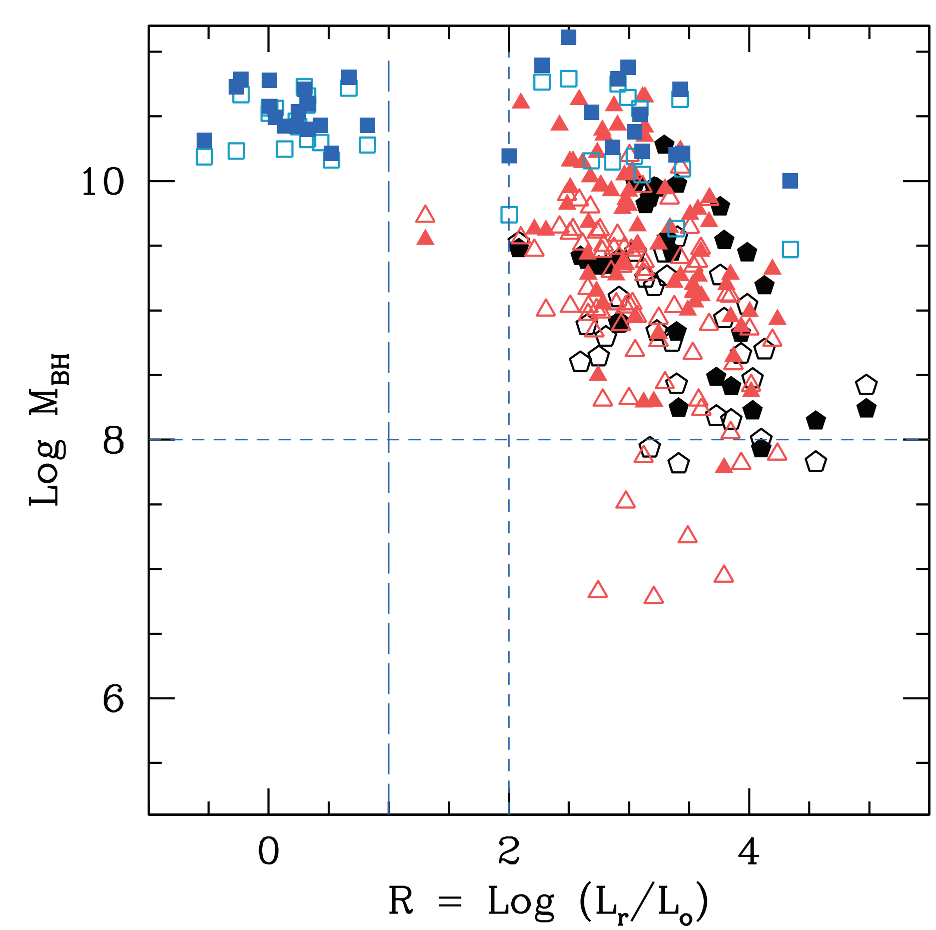


BH Mass & Radio Loudness

- When BH mass estimates for samples of radiogalaxies and quasars are carefully checked ...
- it turns out that there is no genuine radio-loud source with $M_{BH} < 10^8 M_\odot$
- large spin is not the only condition for radio loudness, there is also condition on BH mass ($M_{BH} > 10^8 M_\odot$)



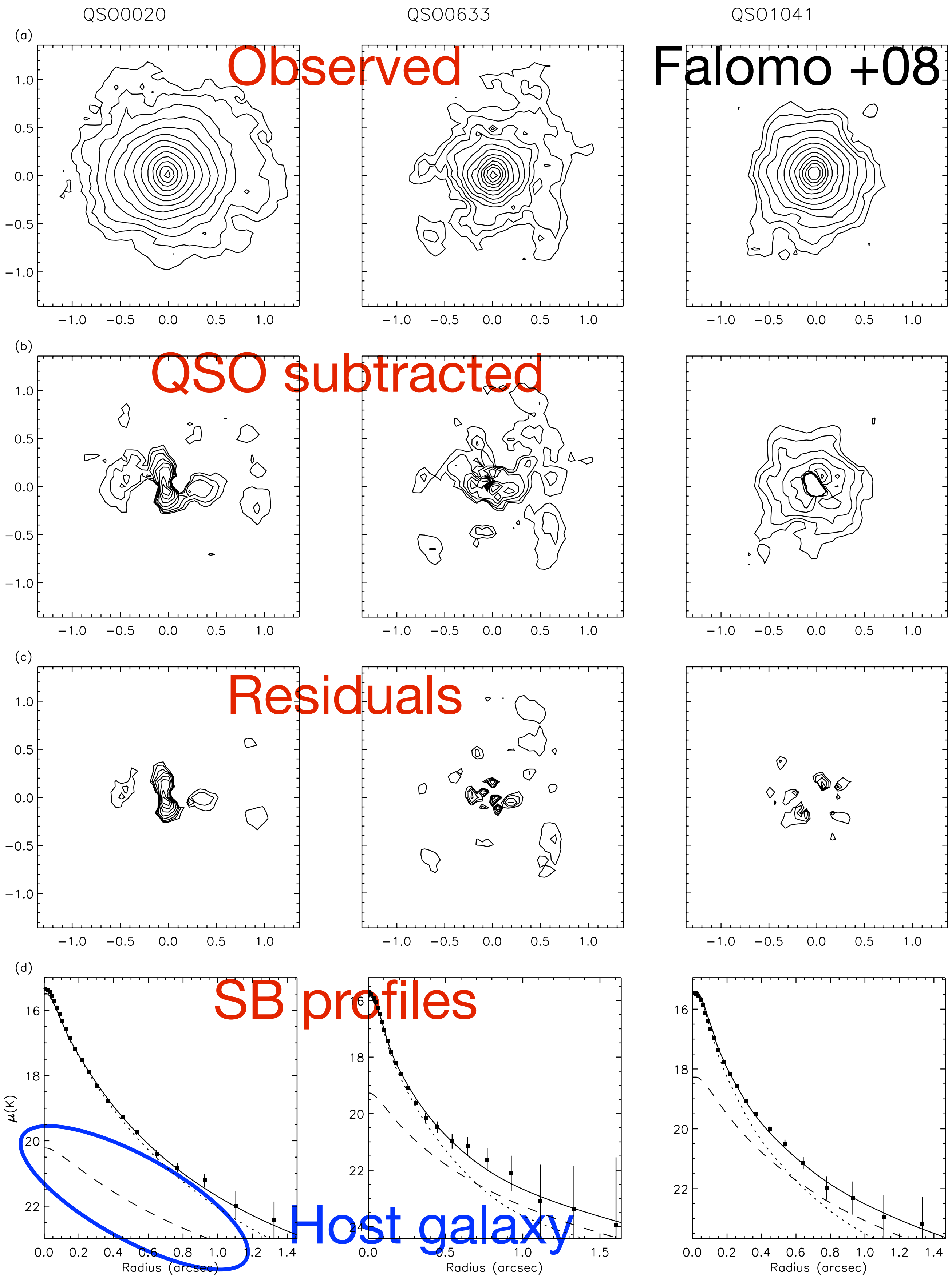
LLAGN

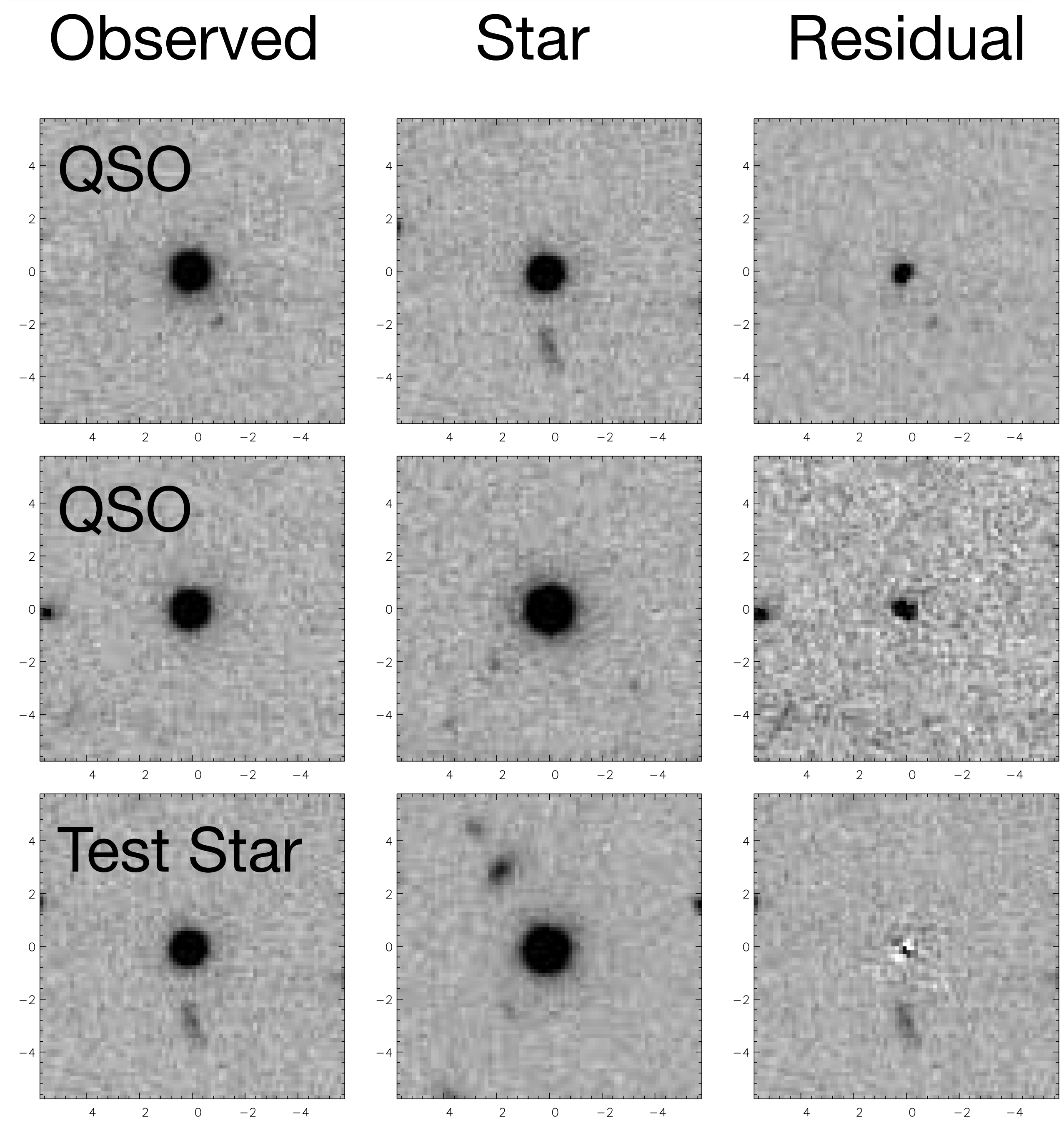


Quasars

Chiaberge & Marconi 11

At high z ...





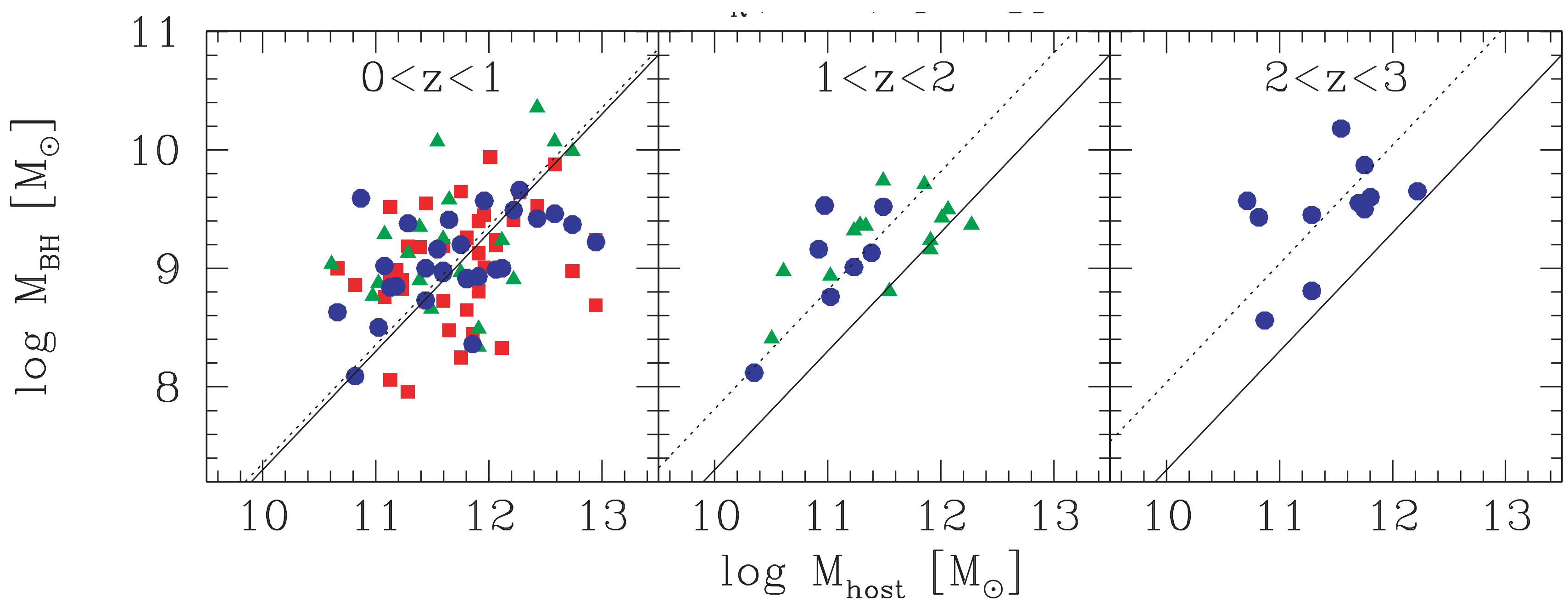
z=4 QSOs
K, 0.4” seeing with AO,
~5h / target on VLT

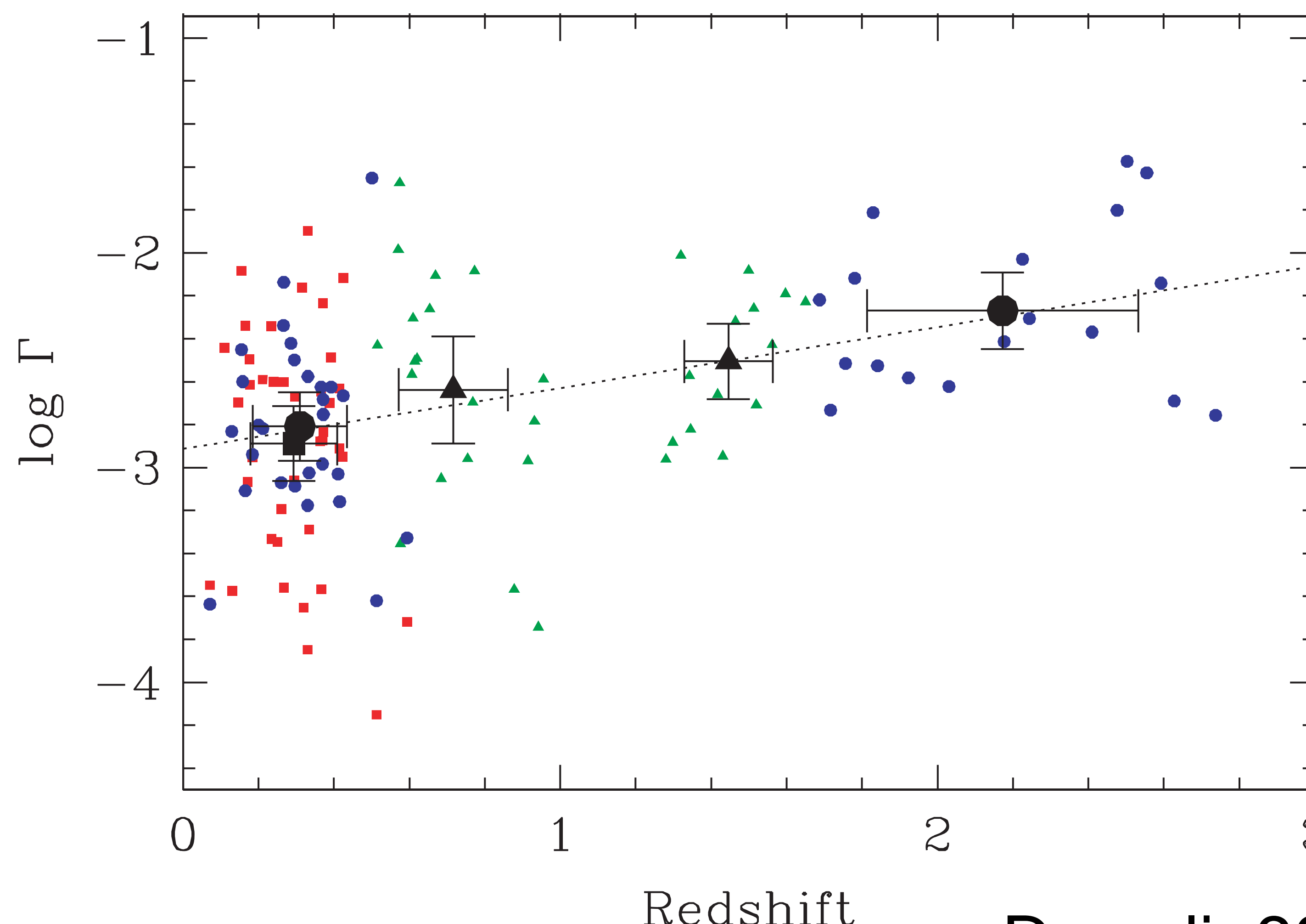
Targett+12

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 in previous studies,evolution is found *after* accounting for passive evolution.
- At z~3 M_{BH}/M_{sph} is ~7 times larger than at z=0
- Also McLure +03, Peng +06, Schramm +08, Salviander +07, Targett +12 ...

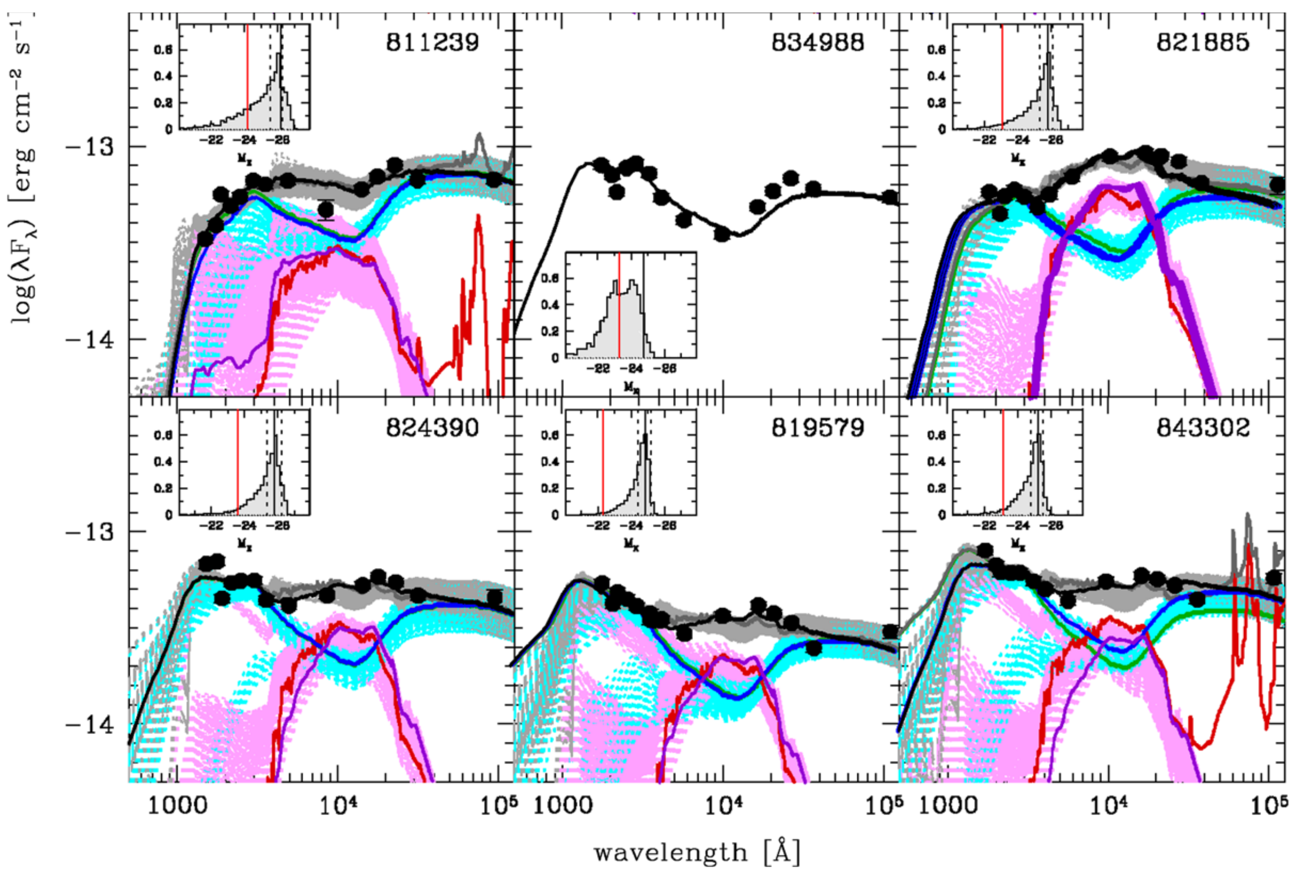


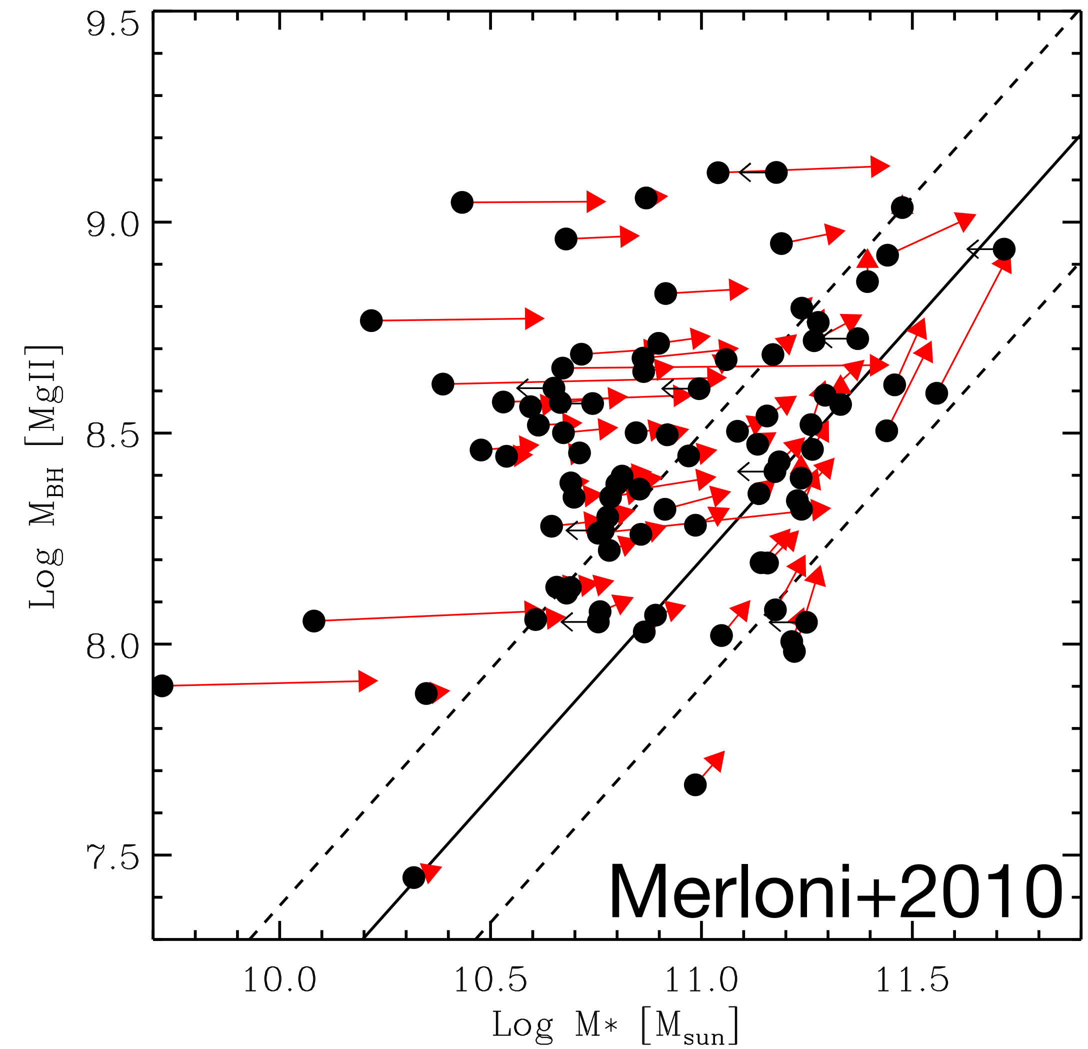


Decarli+2009

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

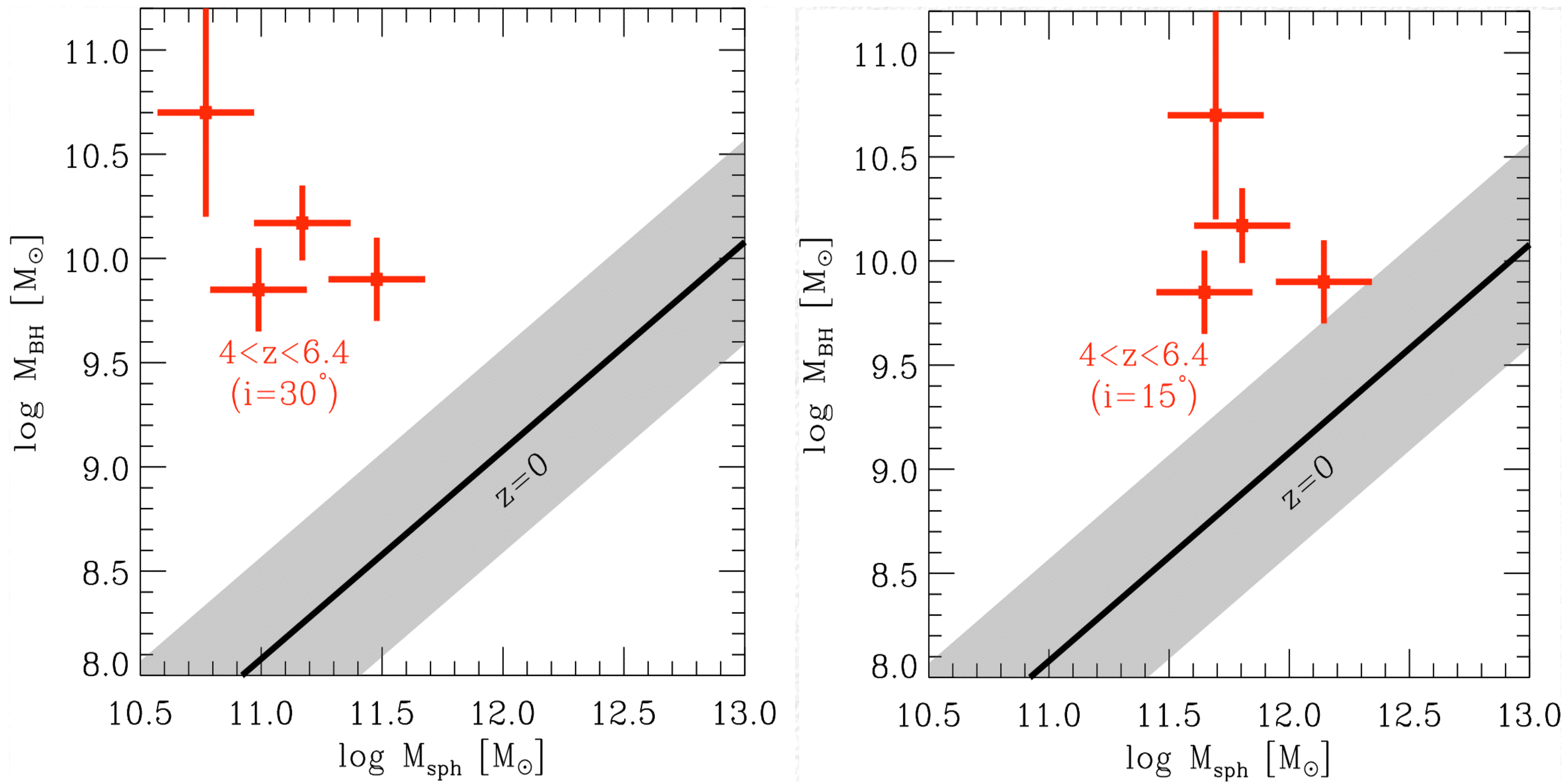
$$\frac{M_{BH}}{M_\star} \simeq \left(\frac{M_{BH}}{M_\star}\right)_{local} (1+z)^{0.68\pm0.12}$$

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!

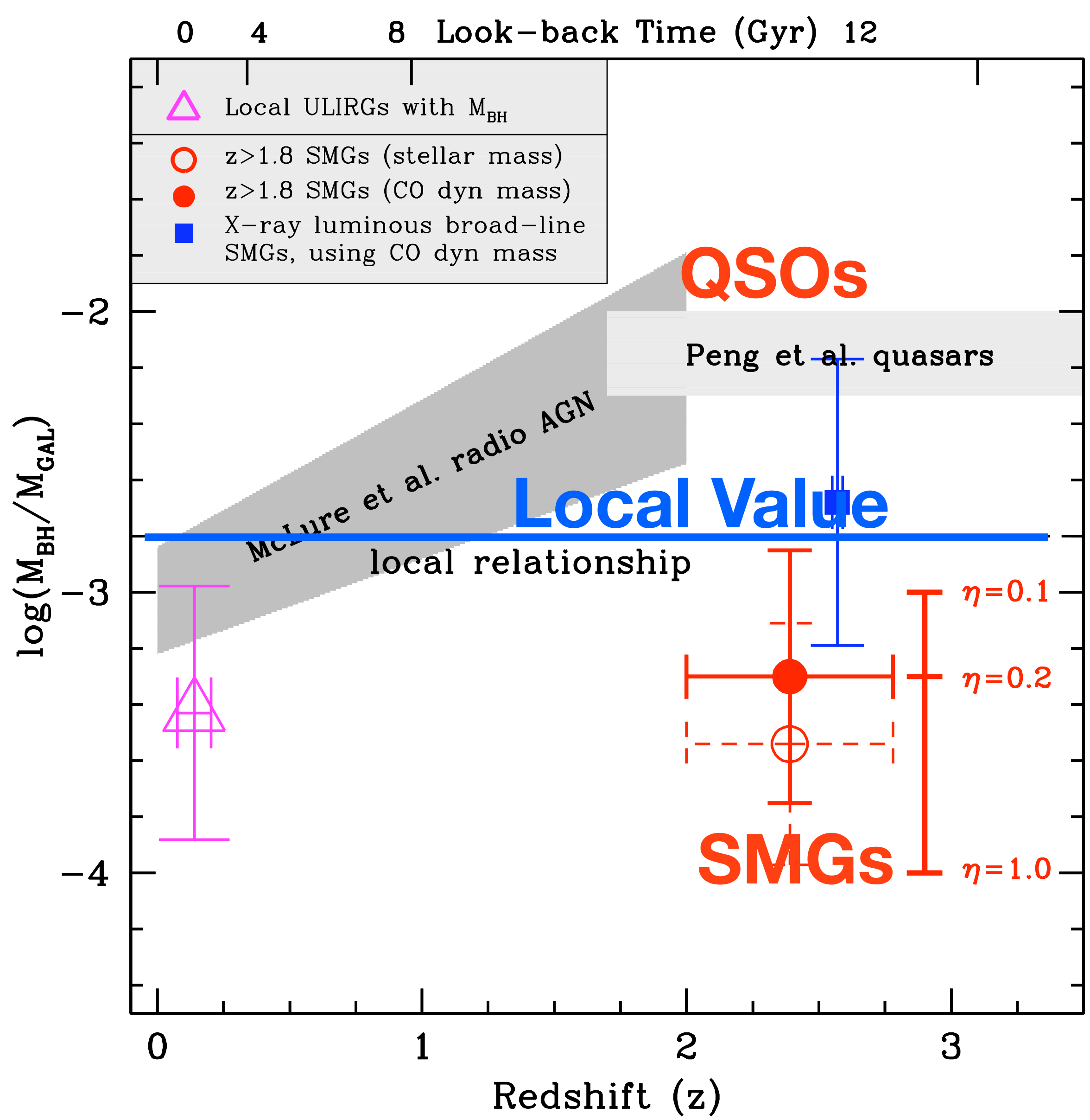


Maiolino 2009, Walter+10, Wang+10 ...

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.

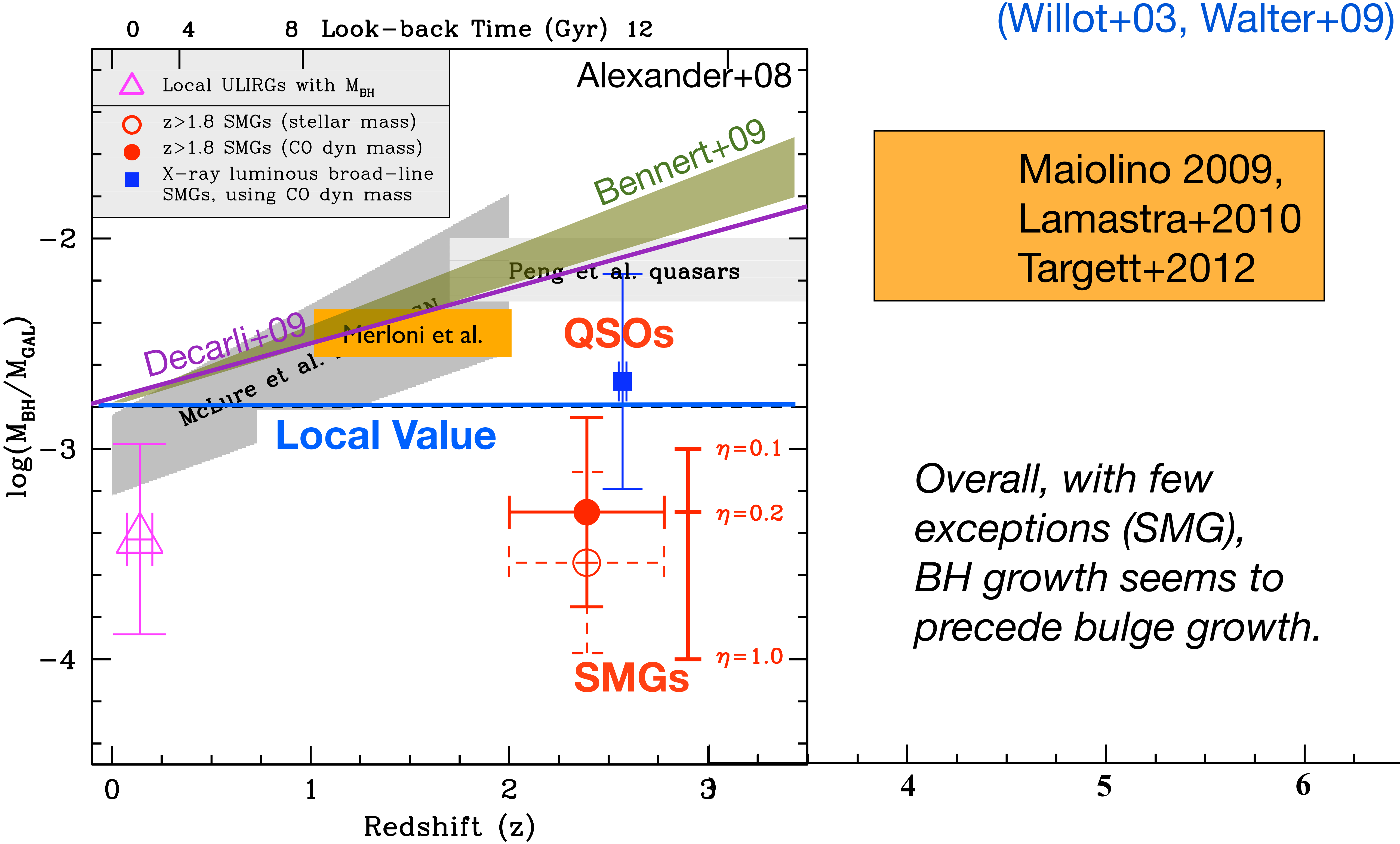
With typical virial BH masses, ≈ 6 ×10^7 $M_\odot$, SMGs appear to be in a phase of rapid BH growth.



Alexander+08,+09

MBH-galaxy relations vs z

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



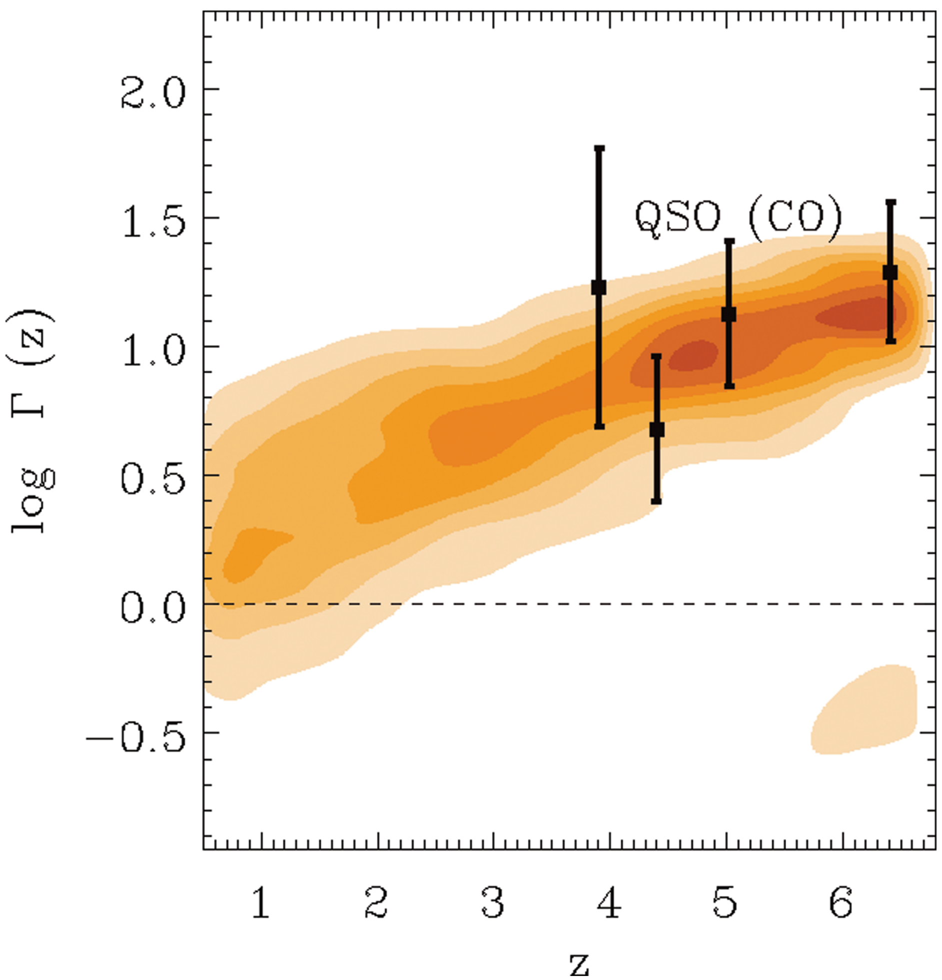
Maiolino 2009,
Lamastra+2010
Targett+2012

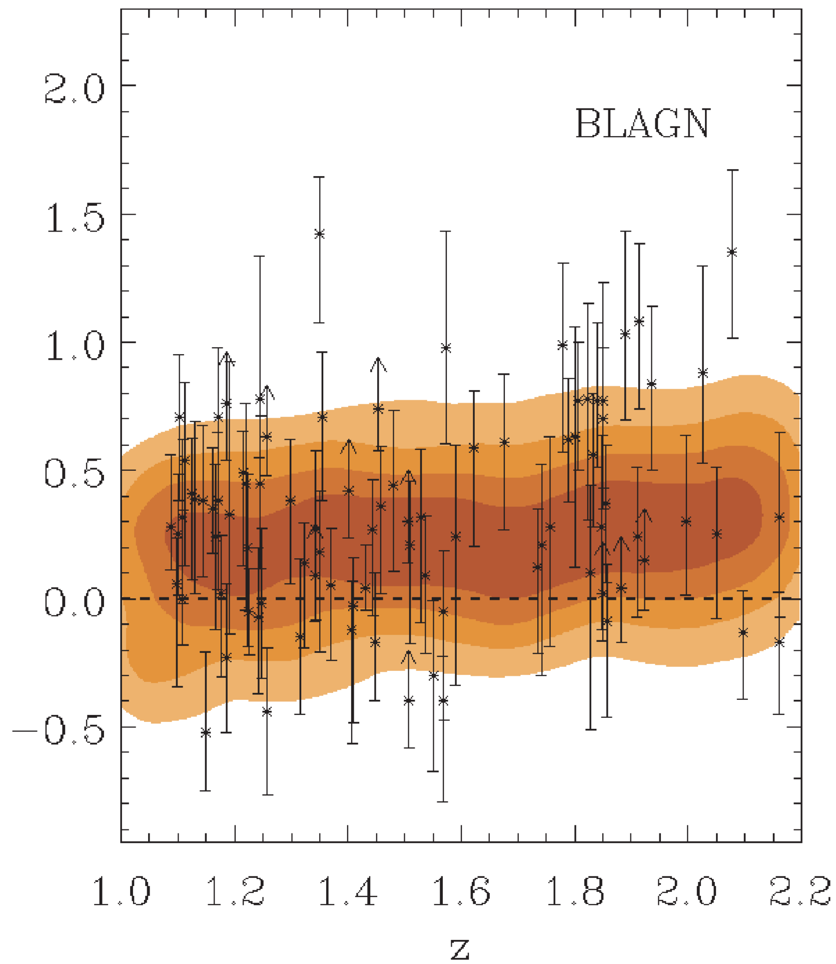
Overall, with few exceptions (SMG), BH growth seems to precede bulge growth.

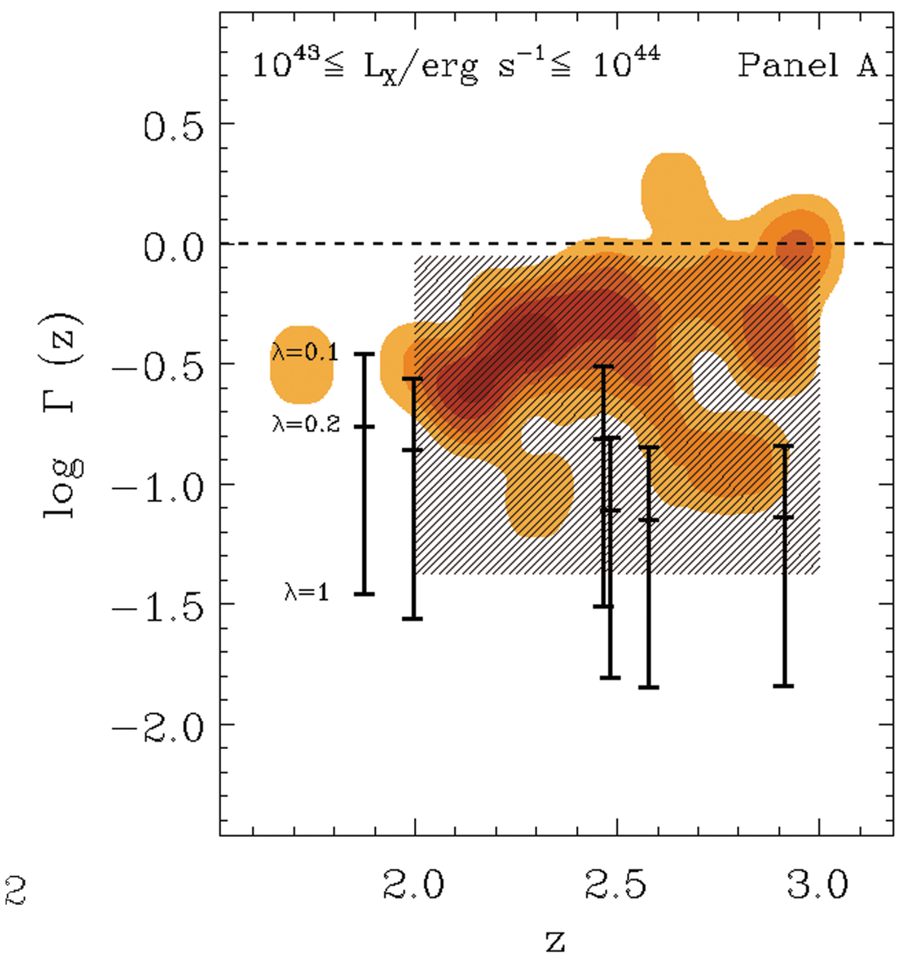
Errors or selection effects?

- Position on M_{BH}-galaxy relations depends on the evolutionary stage (Lamastra+10)

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







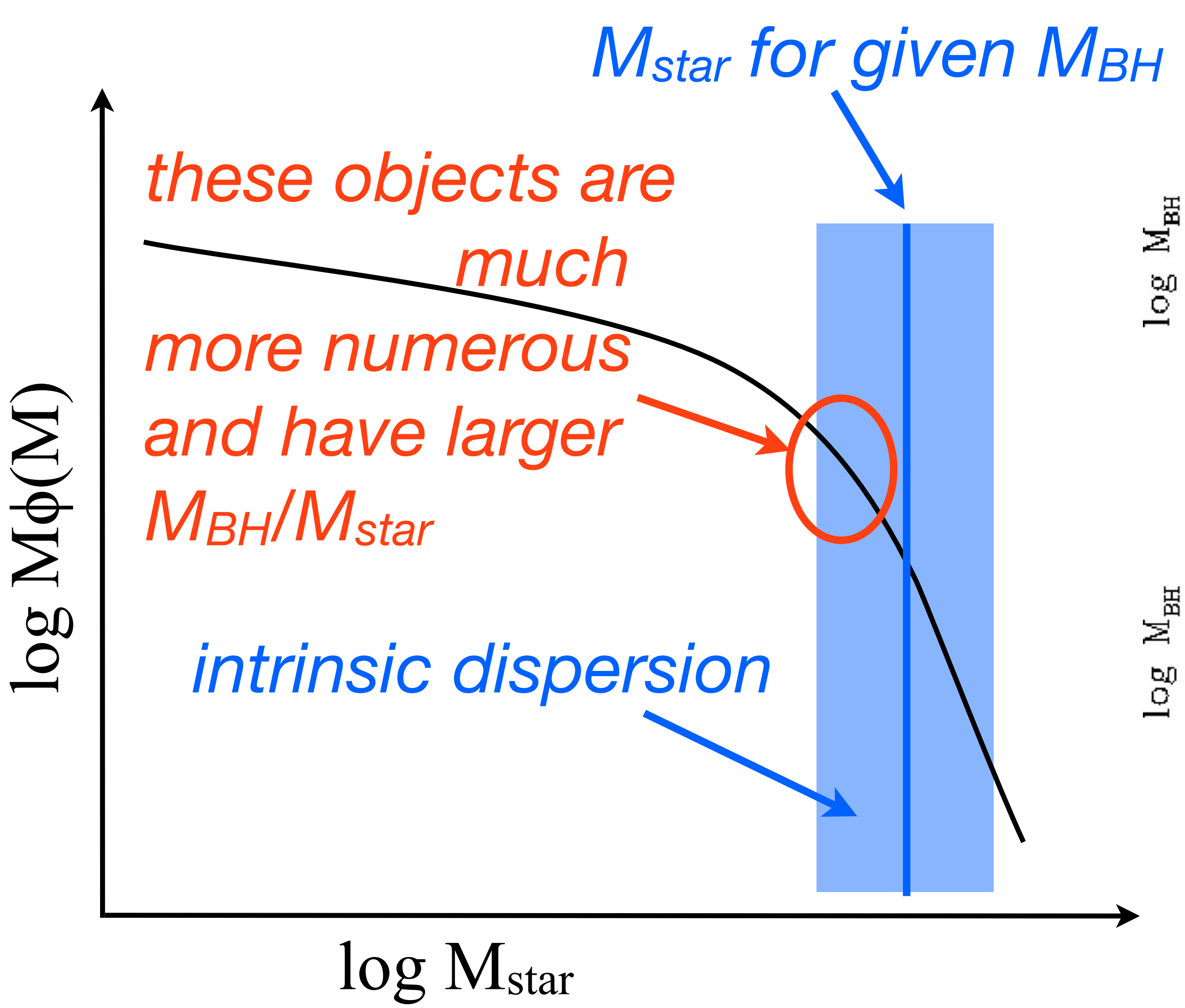
Objects with $M_{BH} > 10^9\ M_\odot$ @z=4: BH growth precedes growth of stellar mass.

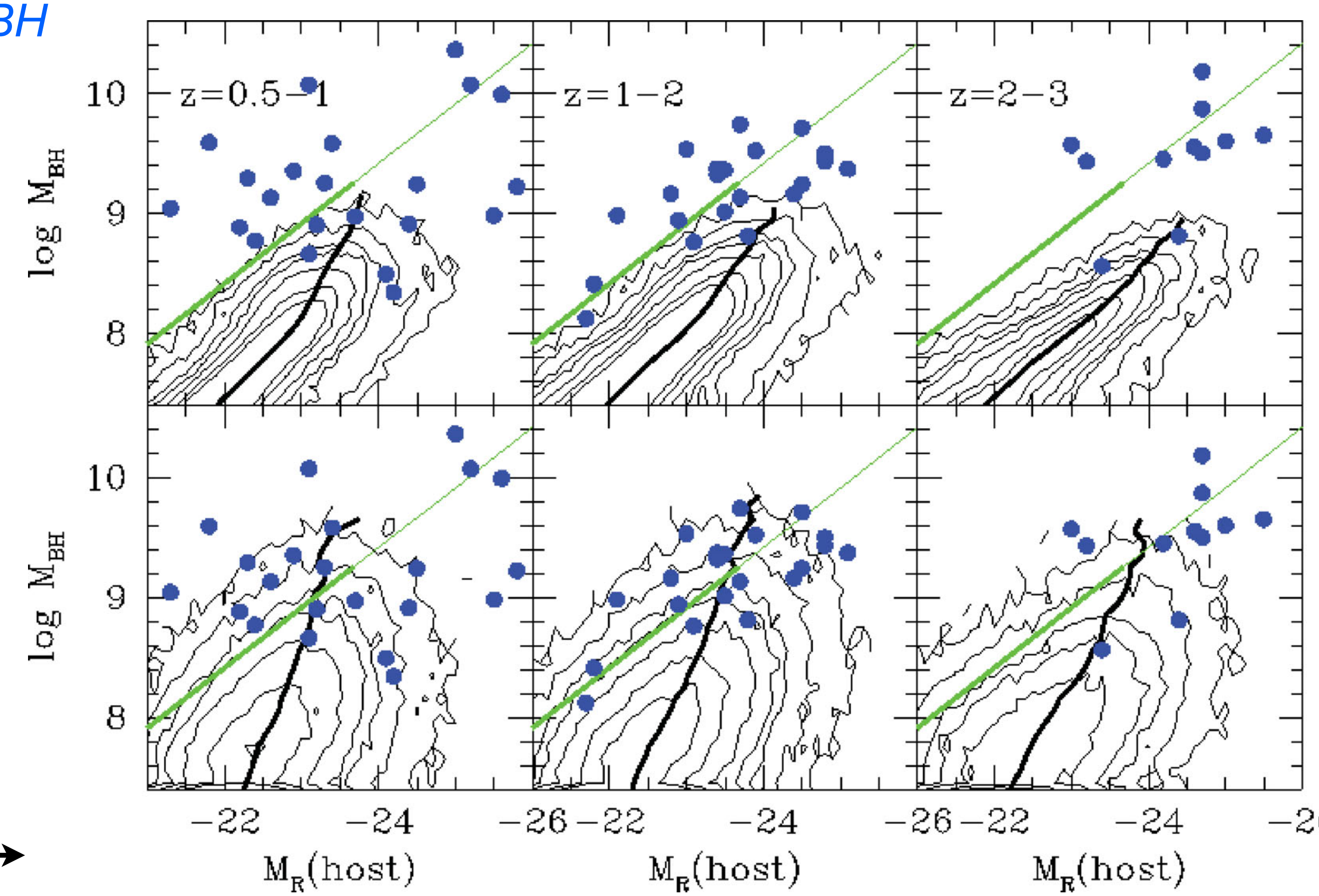
Objects selected as in Merloni et al. 2010 @1<z<2: BH growth is "stalling".

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

Errors or selection effects?

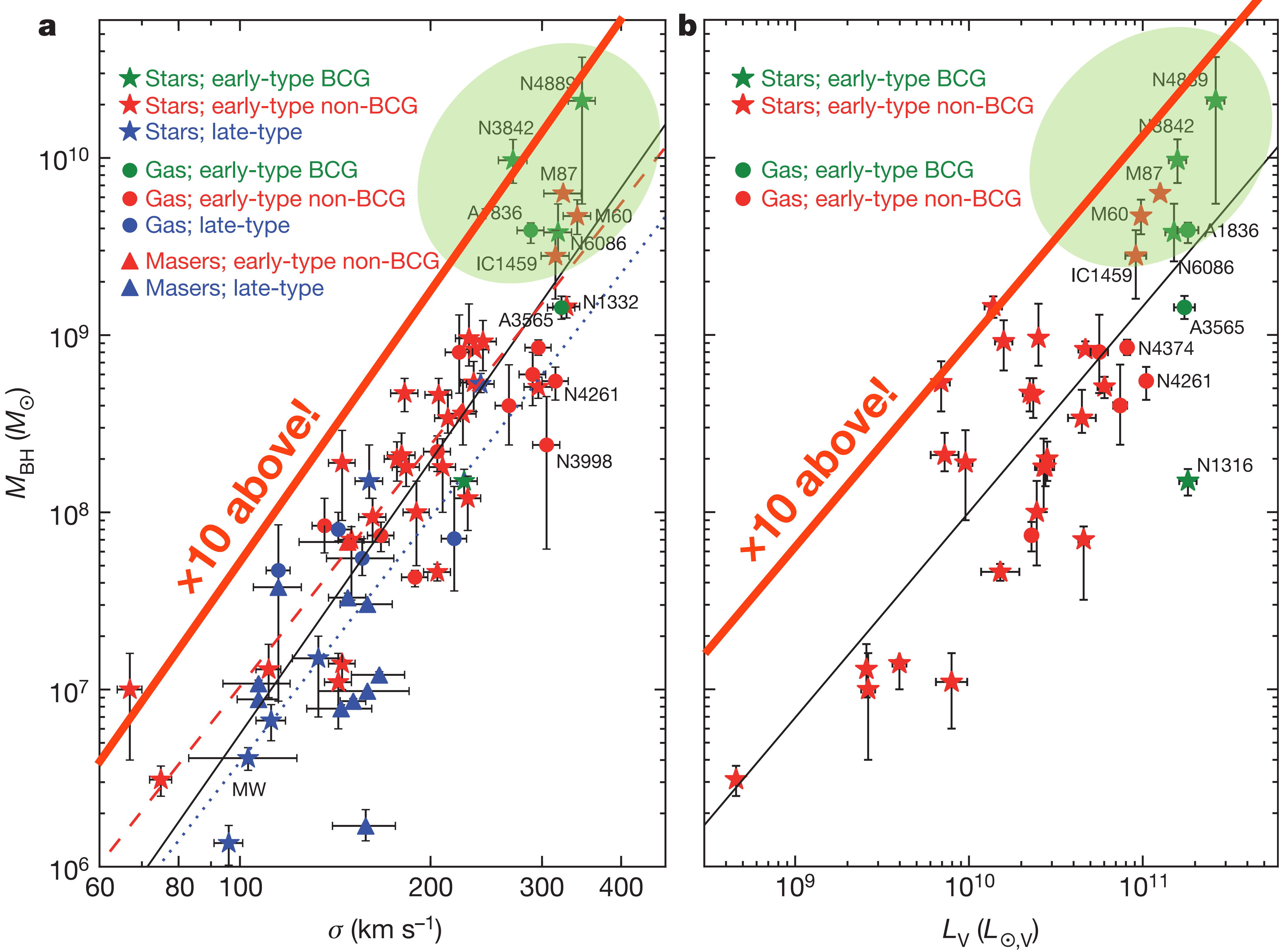
- Difference with observations possibly due to biases (Portinari+12):
  - Quasar host galaxies in peculiar phase of evolution
  - Difficult decomposition in bulge/disk, use all galaxy light
  - Luminous quasars trace overmassive BH for M_{BH}-L relation (Lauer+07)
  - Observational errors on BH masses introduce bias (Shen & Kelly 10)
    → sample is skewed towards apparently larger masses
- *M_{BH}-L /M_{star} relation might show little evolution after all*





Portinari+12

M_{BH}-σ & M_{BH}-L: high mass end?



McConnell+2011

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}
  - NB: possible problems in M_{BH} and measurement of host galaxy
  - M_{sph} is stellar mass: 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 $z\sim1.3$ 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?