Cosmic Evolution of Black Holes and Spheroids:

Testing Scaling Relations at z=0.4

Jong-Hak Woo (UCSB)

Collaborators: Tommaso Treu (UCSB),
Matt Malkan (UCLA), & Roger Blandford (Stanford)

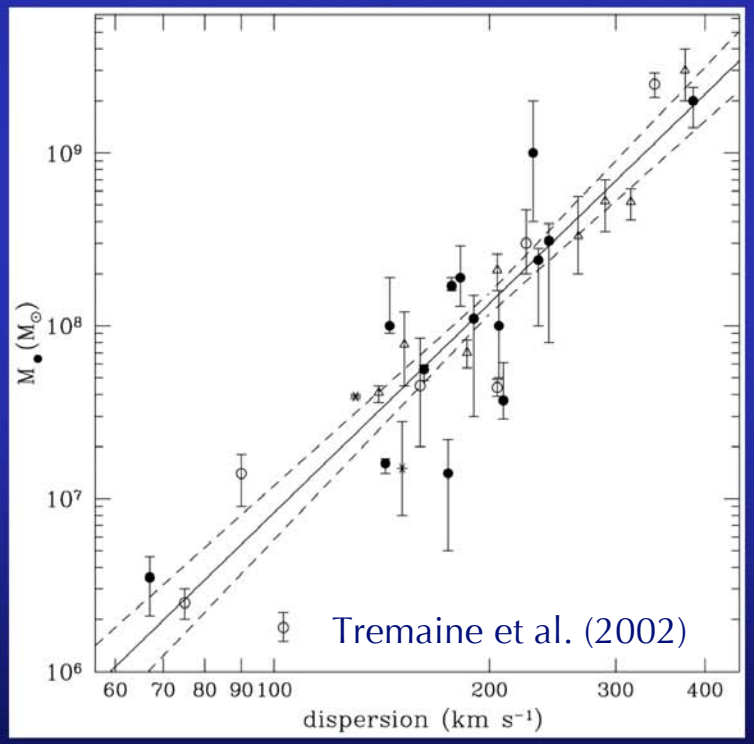
KITP 6/2006

Black Hole-Galaxy Connection

local universe

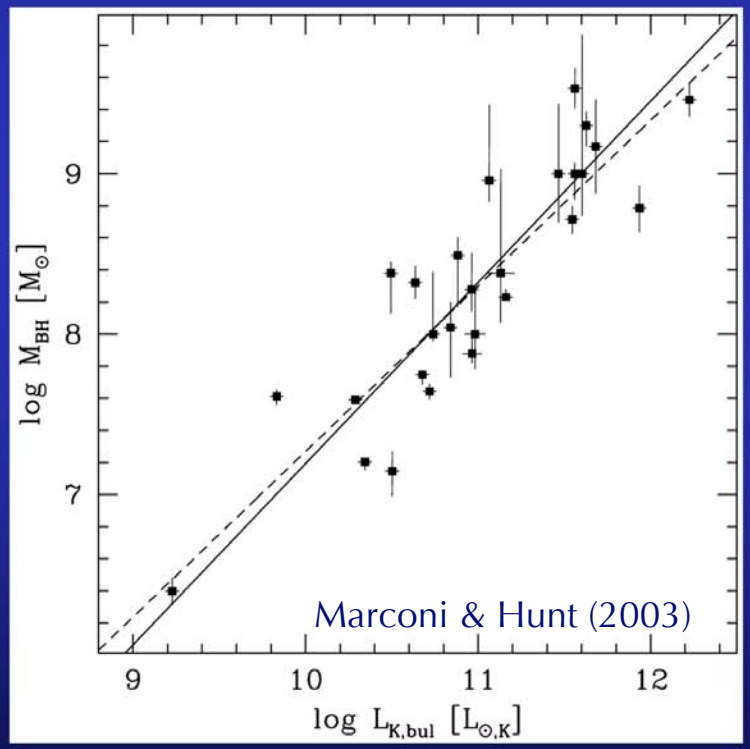
M_{BH}- σ relation

(Ferraresse et al. 2000; Gebhardt et al. 2000)



M_{BH} – L_{bulge} relation

(Magorrian et al. 1998; Marconi & Hunt 2003)



Open Questions

- Why M_{BH}-σ and M_{BH}-L_{bulge} relations so tight?
- When were they formed? Do they evolve?
- If spheroids evolve by mergers,
  what makes these scaling relations?

Theoretical studies show:

- No evolution (Granato et al. 2004)
- Sigma increases with redshift (Robertson et al. 2005)
- Stellar mass (sigma) decreases with redshift (Croton 2006)

→ Is the ratio of growth rates constant?

The distant universe: two problems

Black hole mass: CANNOT resolve the sphere of influence
(1″ at z=1 is ~8 kpc)

Solution: Active galaxies
1) Reverberation mapping (Blandford & McKee 1982)
2) Empirically calibrated photo-ionization method, based on reverberation masses (Wandel et al. 1999).

Velocity dispersion: distant objects are faint.
CANNOT avoid AGN contamination.

Solution: Seyfert 1 galaxies
integrated spectra have enough starlight to measure σ on the featureless AGN continuum.

Testing M_{BH}- σ Relation at z~0.36

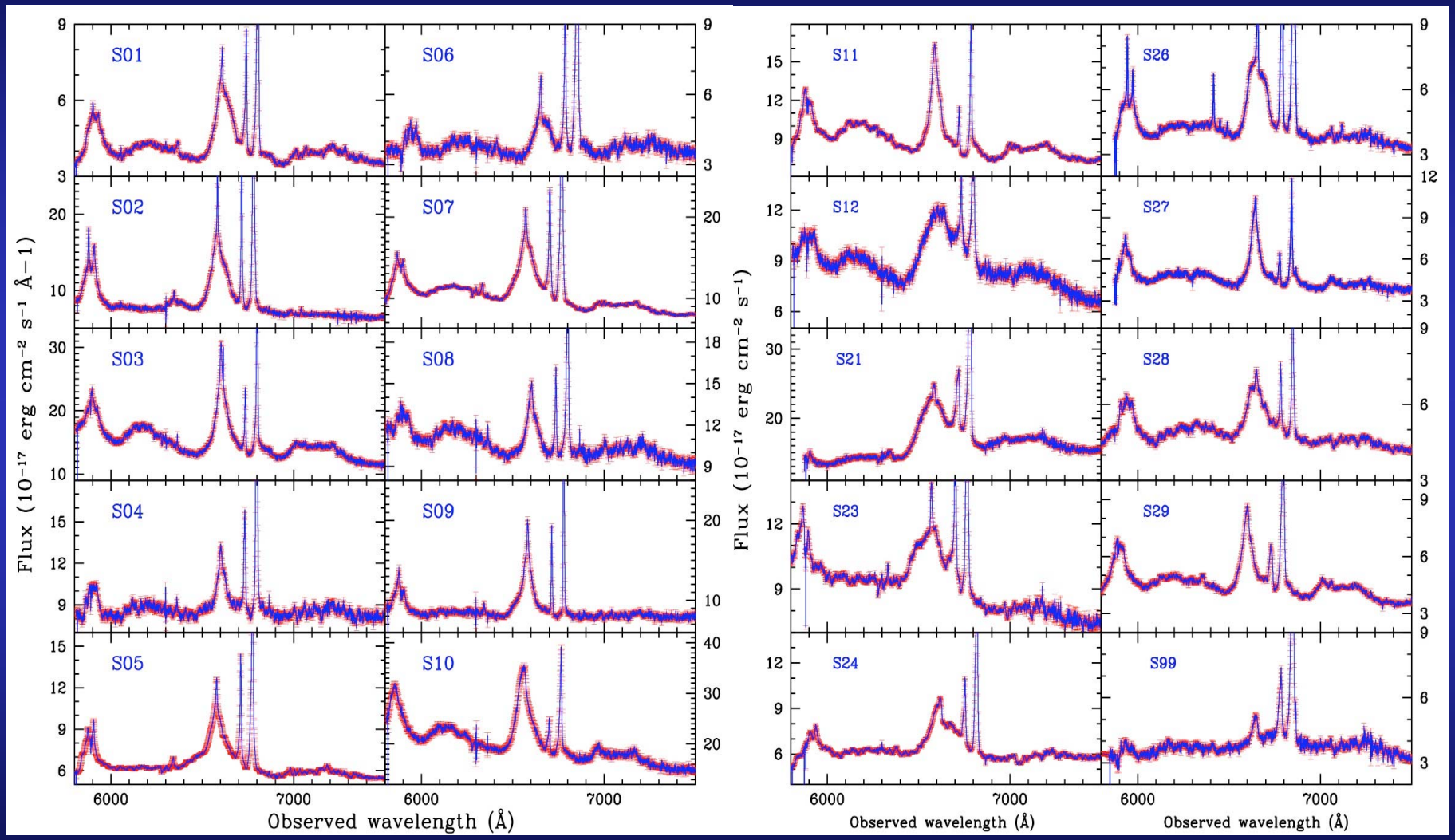
Sample selection

- redshift window: z=0.36±0.01 to avoid sky lines.
- 30 objects selected from SDSS, based on broad Hβ and z

Observations

- Keck spectra for 20 objects; sigma measured for 14
- HST images for 20 objects
- Monitoring ~10 objects with Lick for reverberation mapping

High S/N Keck Spectra

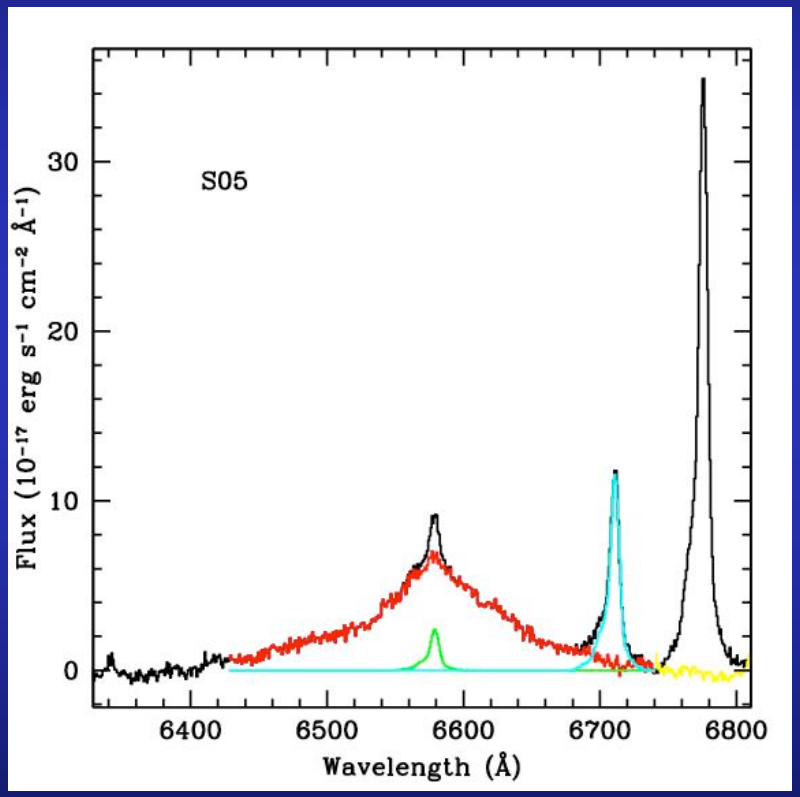


Estimating virial M_{BH} from BLR

$M_{BH} \sim R_{BLR} V^2 / G$ (Peterson et al. 1999, 2004)

1) Measuring Hβ line width

- The Hβ width should be measured on the rms spectrum (i.e. the variable component)
- Single epoch spectra provide a good approximation



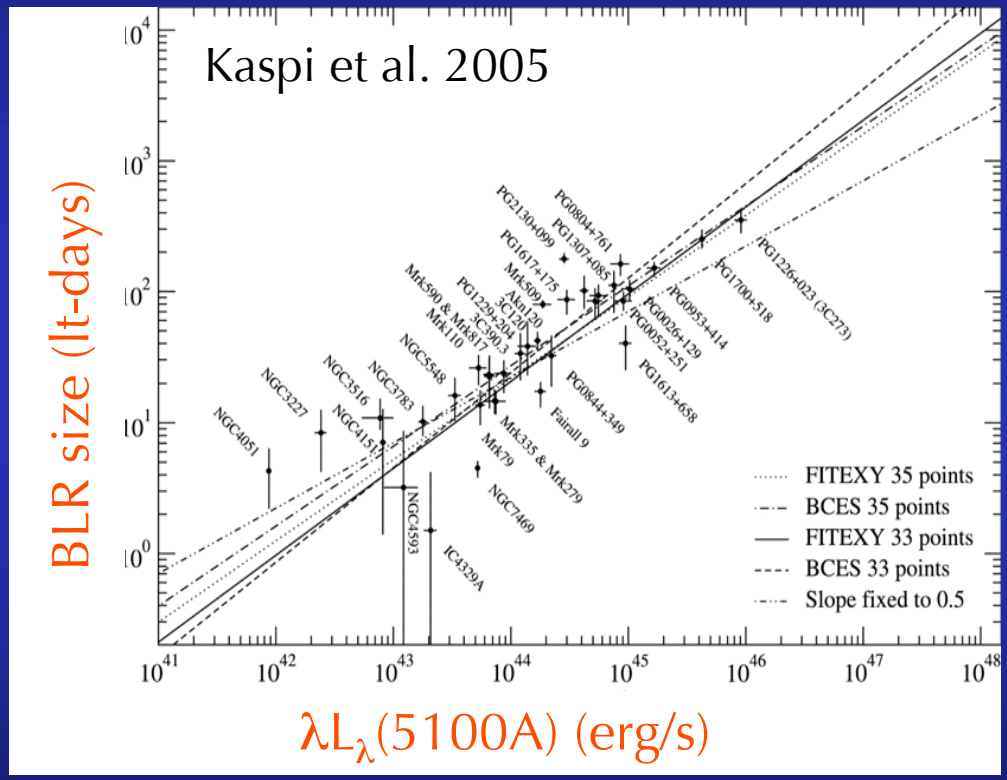
Treu, Malkan & Blandford 2004

Estimating virial M_{BH} from BLR

2) Estimating BLR size:

Empirically Calibrated Photo-Ionization Method

- The flux needed to ionize the broad line region scales as L(ion)/r^2.
- An empirical correlation is found, calibrated using reverberation mapping

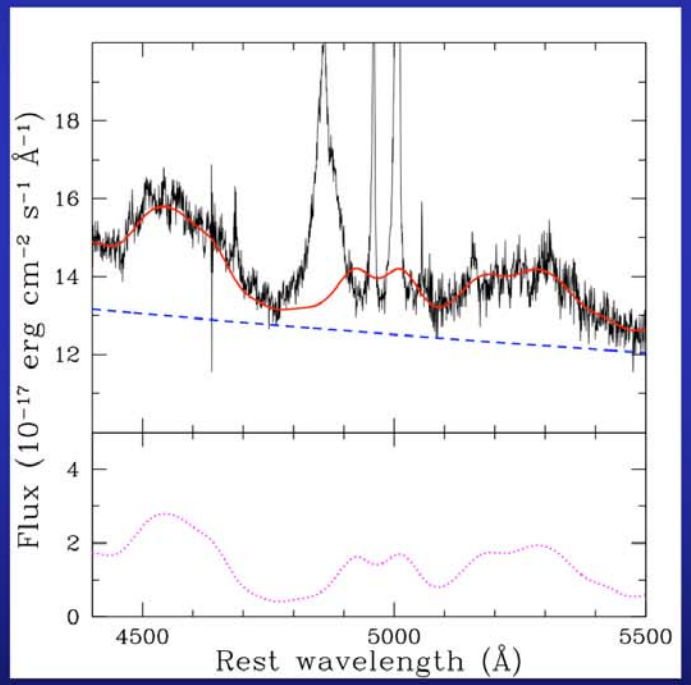


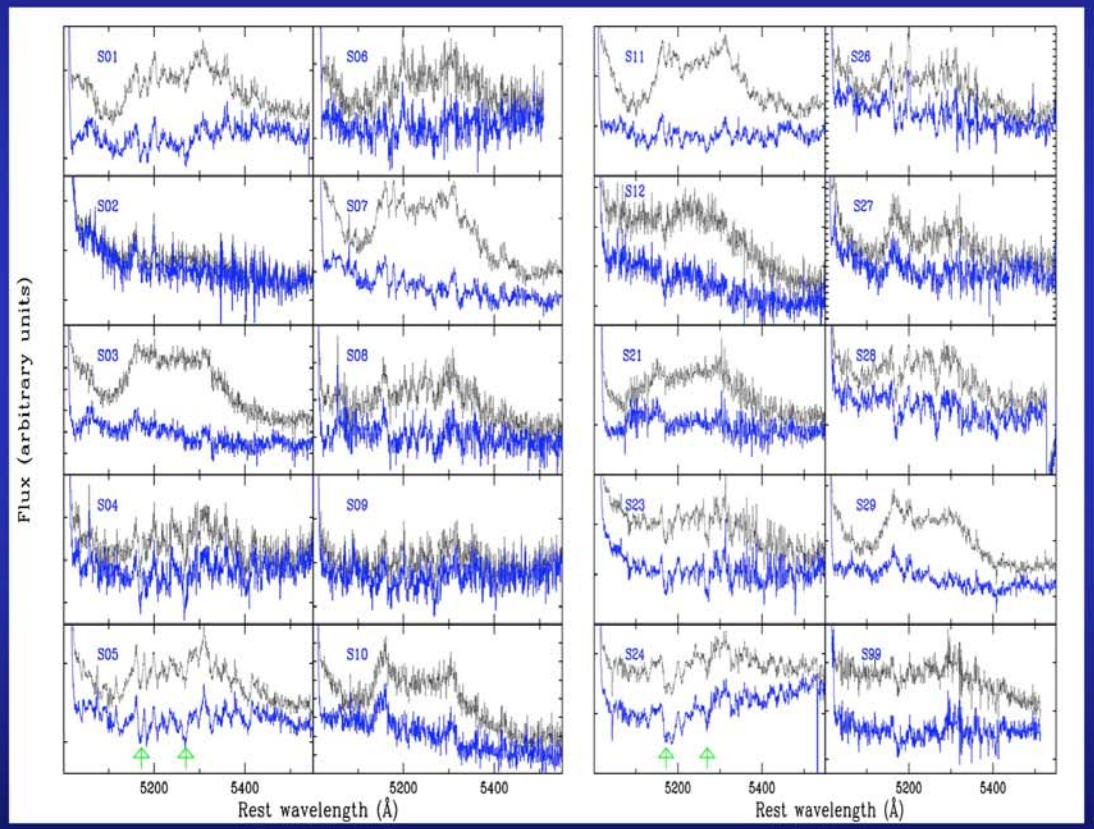
$$M_{BH} = 2.15 \times 10^8 M_\odot \times \left(\frac{\sigma_{H\beta}}{3000 \mathrm{kms}^{-1}}\right)^2 \left(\frac{\lambda L_{5100}}{10^{44} \mathrm{ergs}^{-1}}\right)^{0.69}$$

Measuring velocity dispersion (σ)

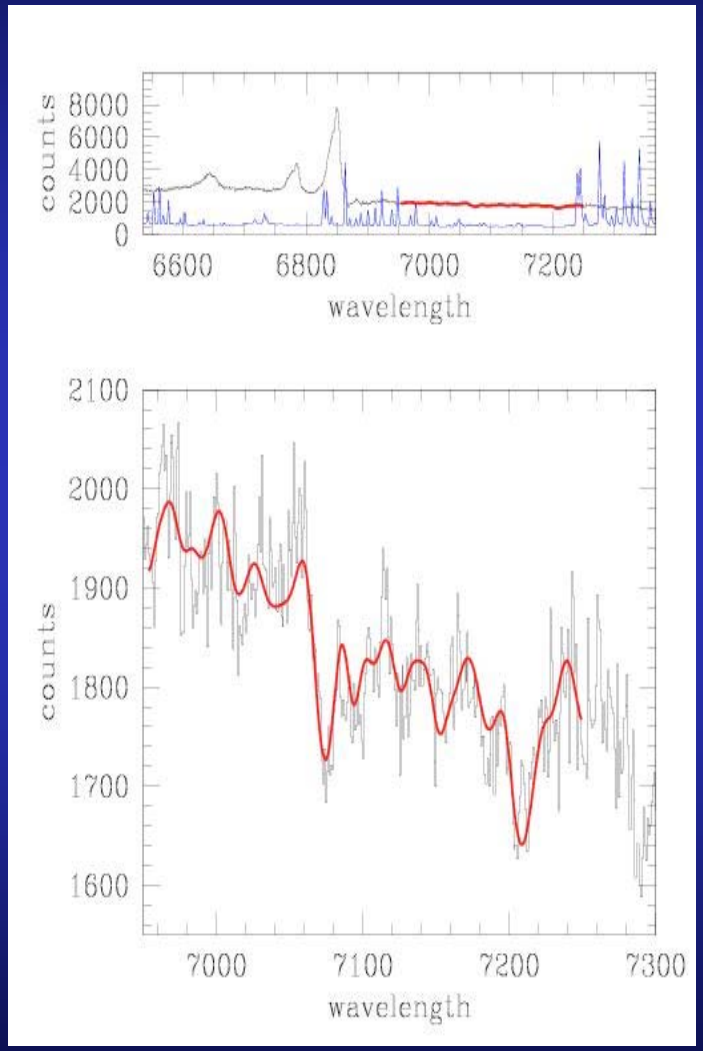
Fe II subtraction

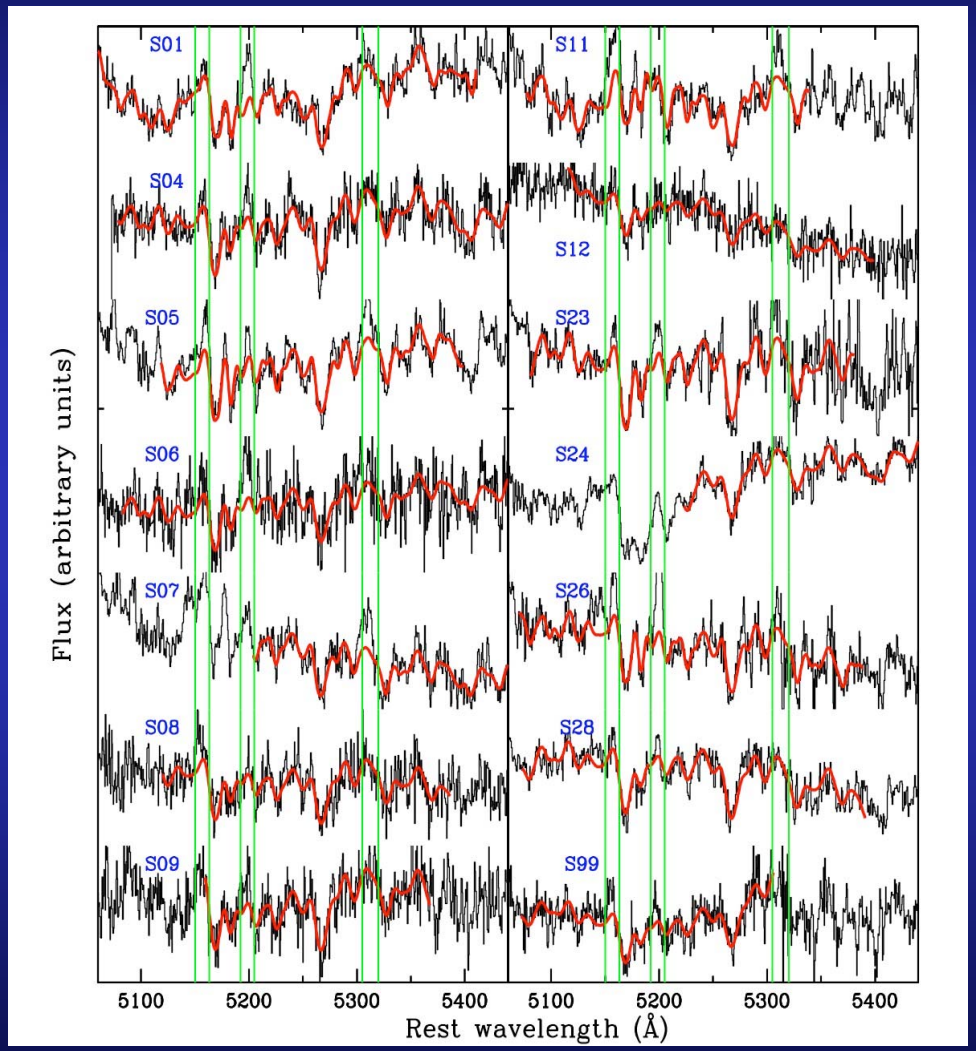
Fe II fit with I zw 1 template



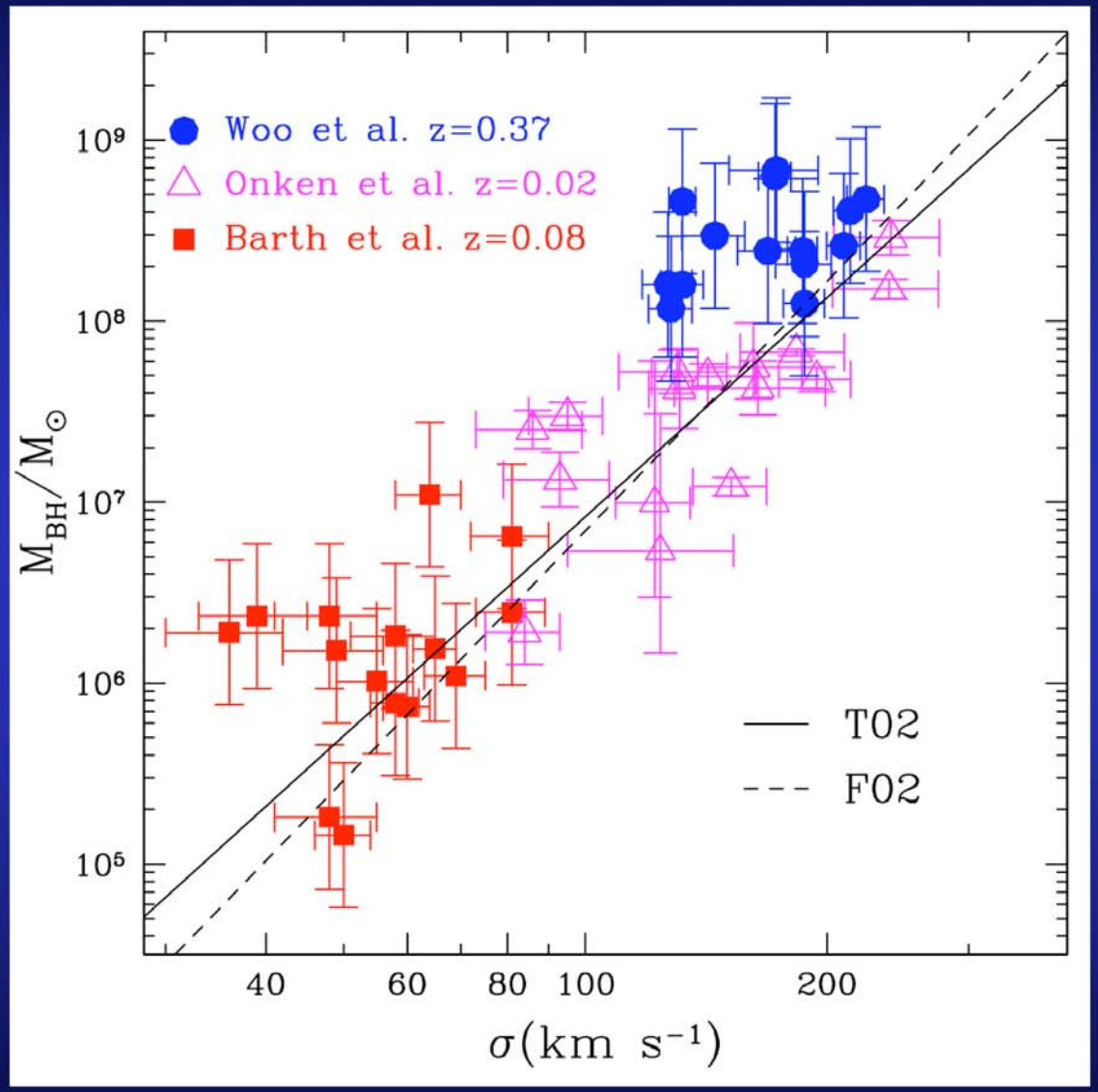


Measuring velocity dispersion (σ)



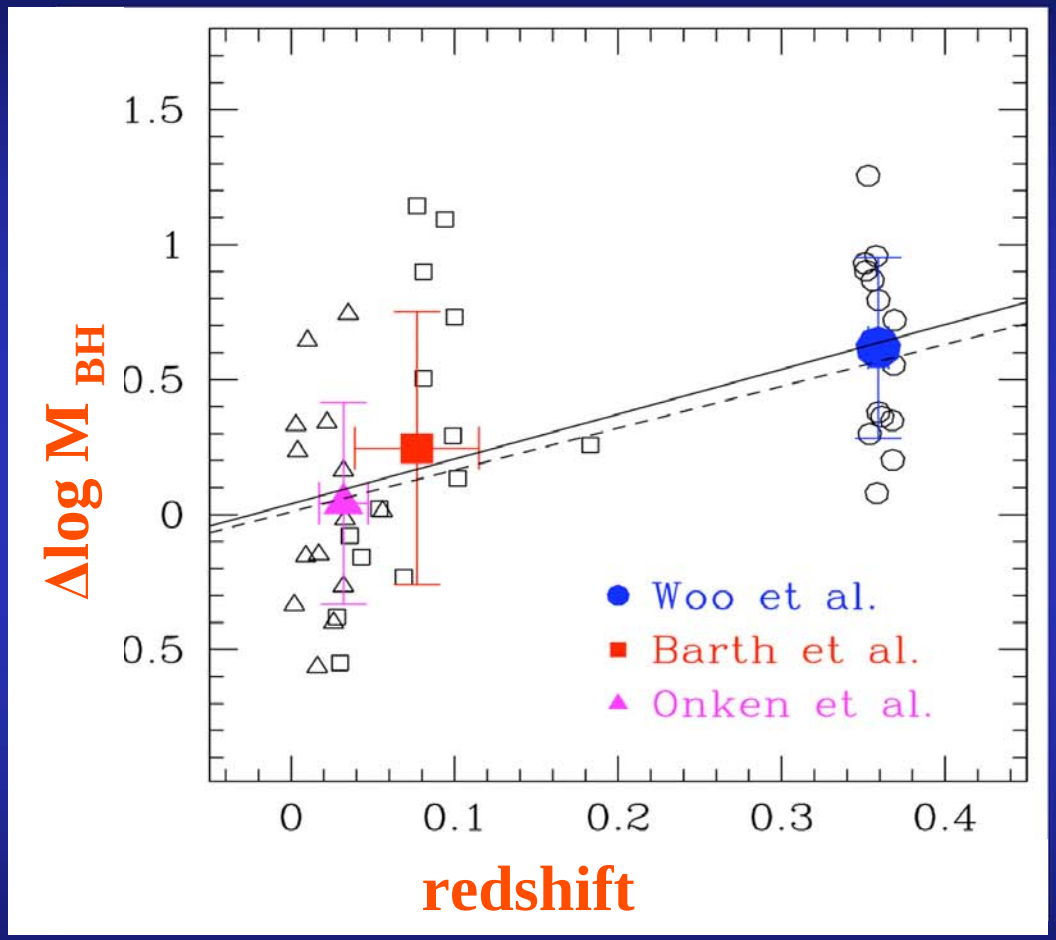


The M_{BH} - sigma Relation



Woo et al. 2006

Evolution of M-sigma Relation



$\Delta \log M_{BH} = 0.62 \pm 0.10 \pm 0.25$ dex for z~0.36 sample

Interpretation

1) Systematic errors?

Stellar contamination, aperture correction, inclination
overall systematic errors: $\Delta \log M_{BH} = 0.25$ dex,
much samller than offset $\Delta \log M_{BH} \sim 0.6$ dex

2) Selection effects?

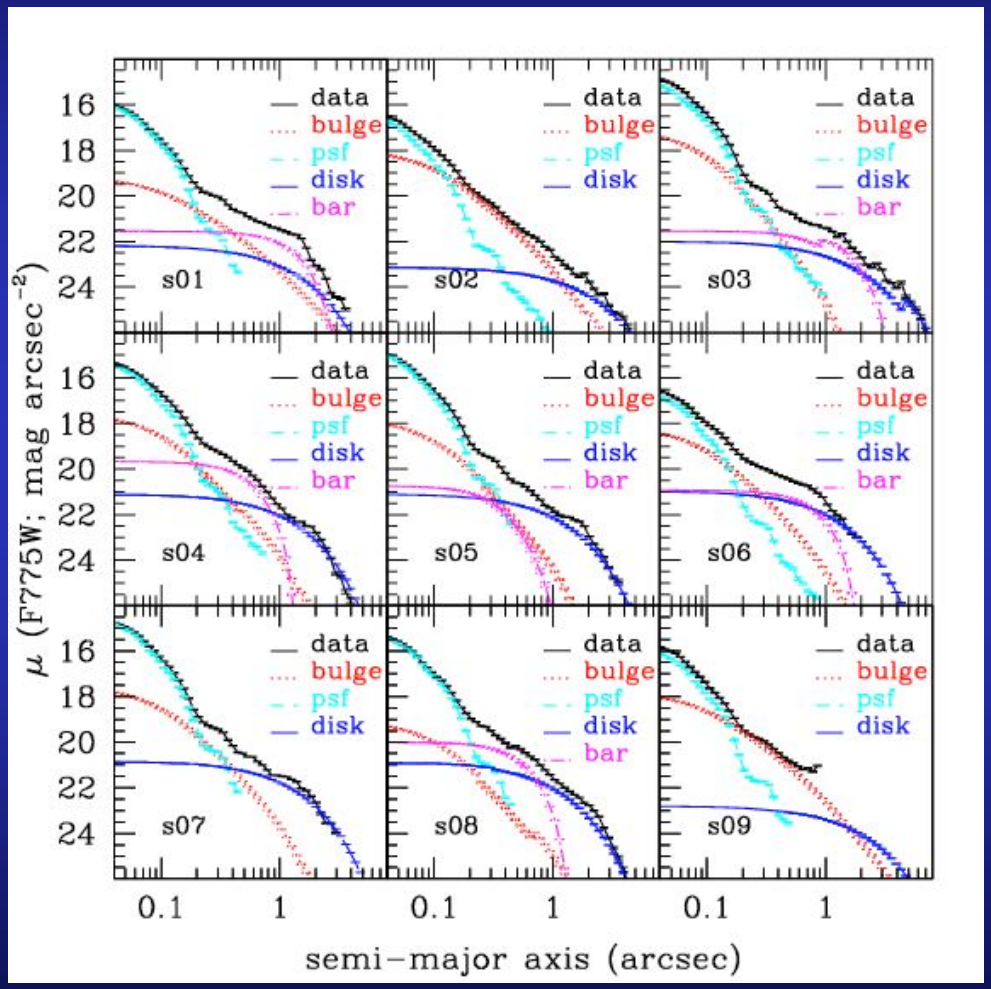
local sample: mostly early-type, large scatter? BH mass?
our sample: narrow range of parameters

3) Cosmic evolution?

BH growth predates bulge assembly

Is evolution real? An independent check

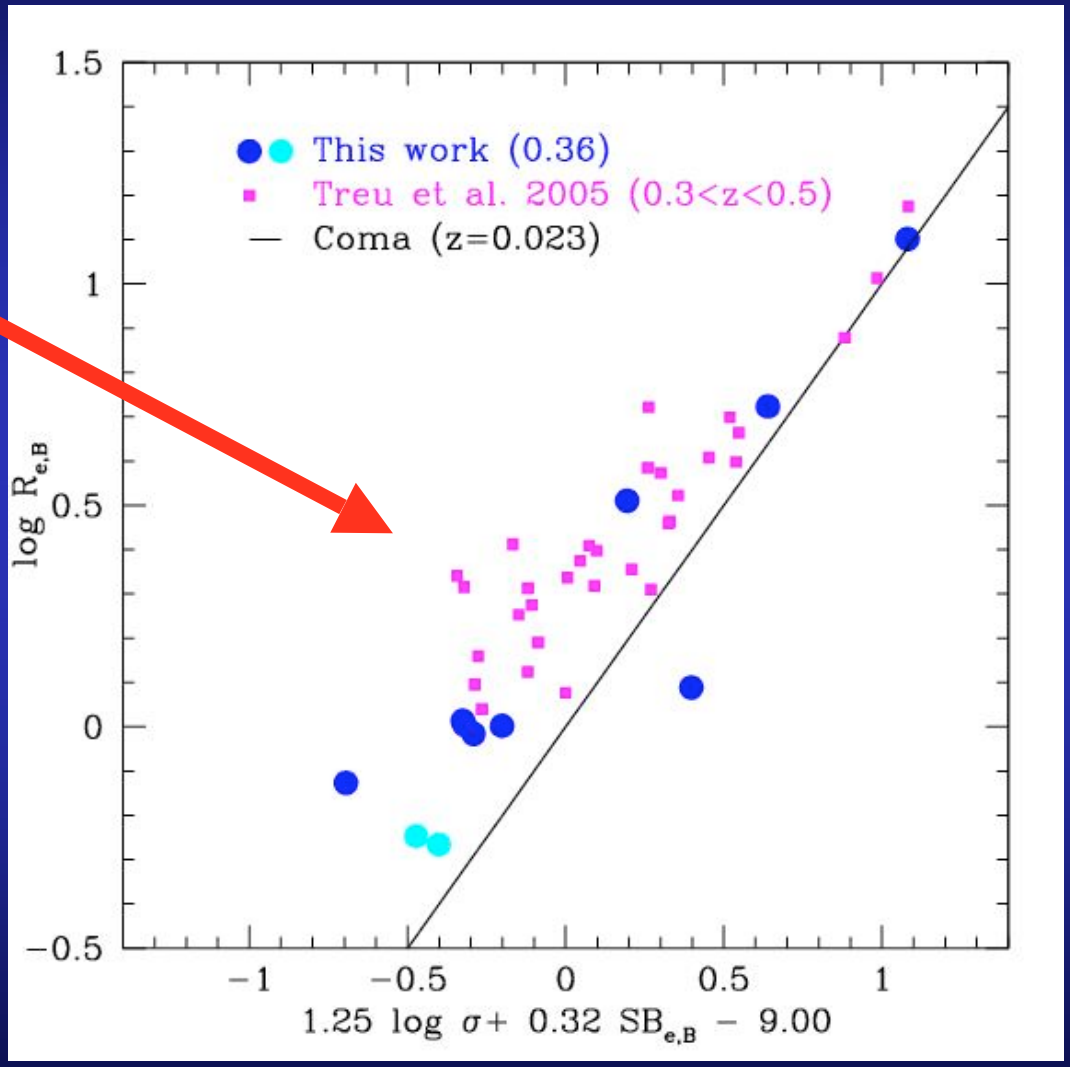
- Testing M_{BH}- L_{bulge}, M_{BH}- M_{dyn}, and fundamental plane relations.
- With available HST-ACS, host galaxy properties determined.



Treu et al. 2006 in prep.

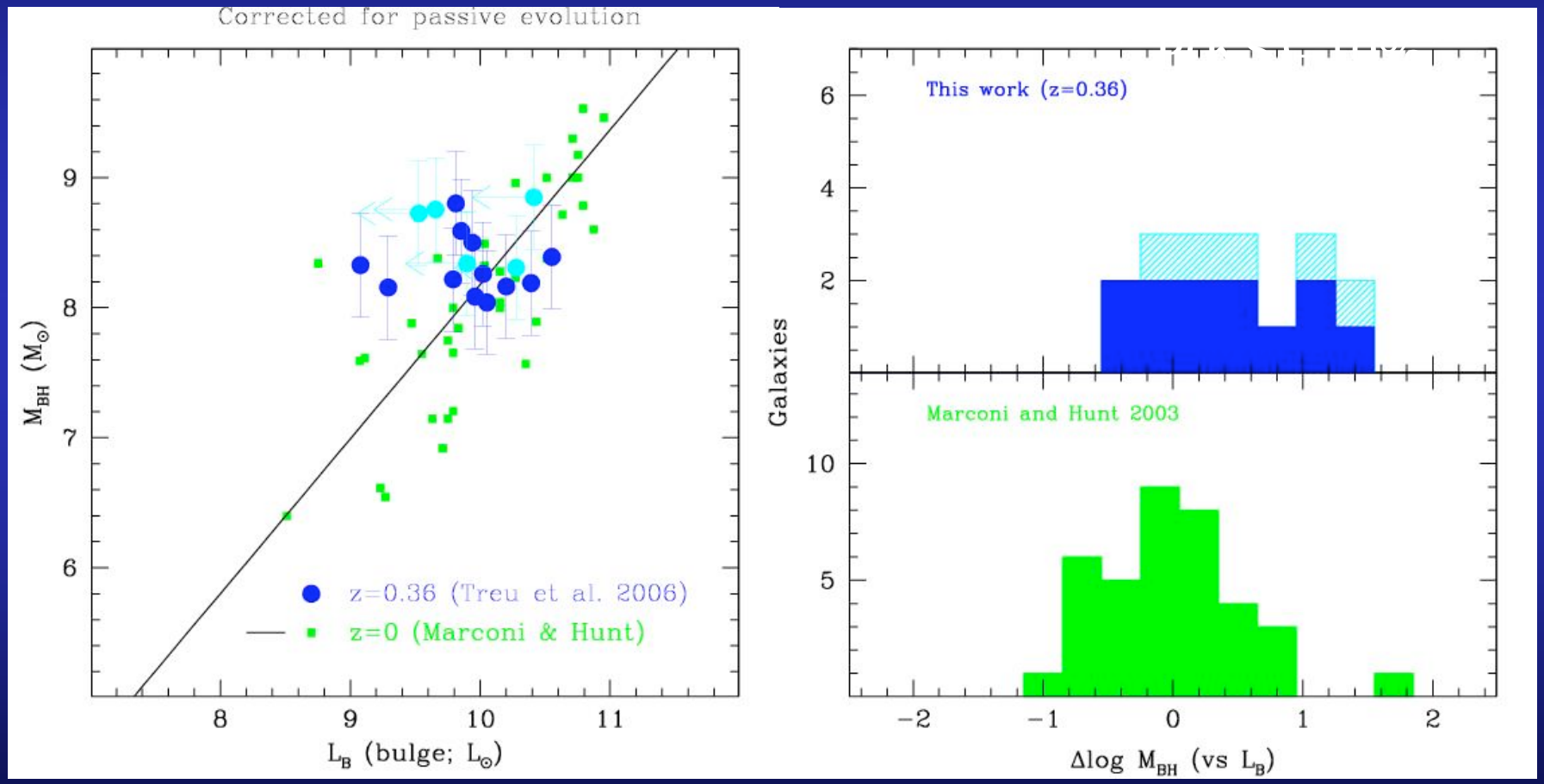
The FP of Spheroids at z~0.36

- Spheroids are overluminous for their mass.
- Generally interpreted as passive evolution.



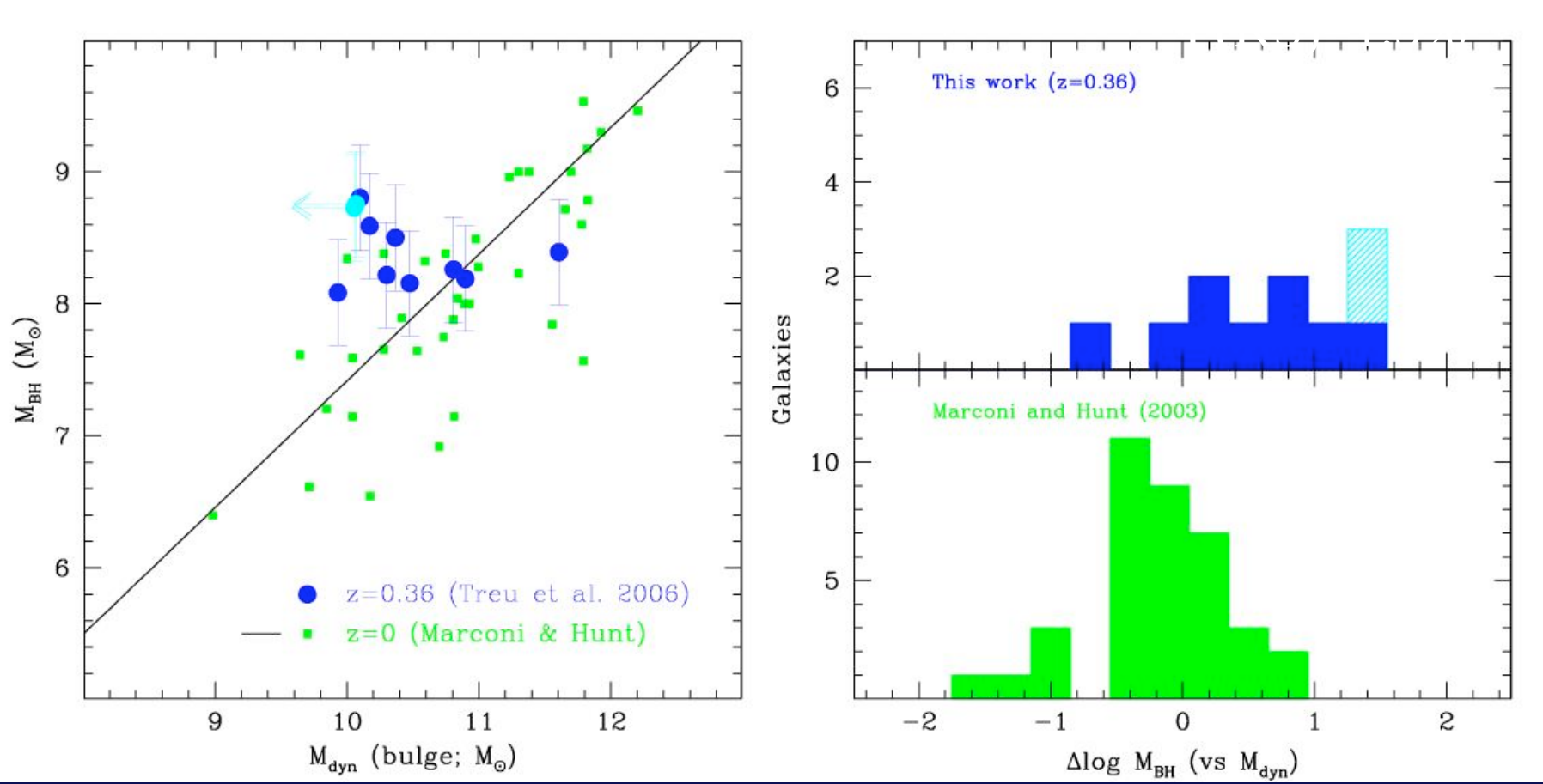
The M_{BH}- L_{bulge} relation

$\Delta \log M_{BH} > 0.42 \pm 0.14$ dex

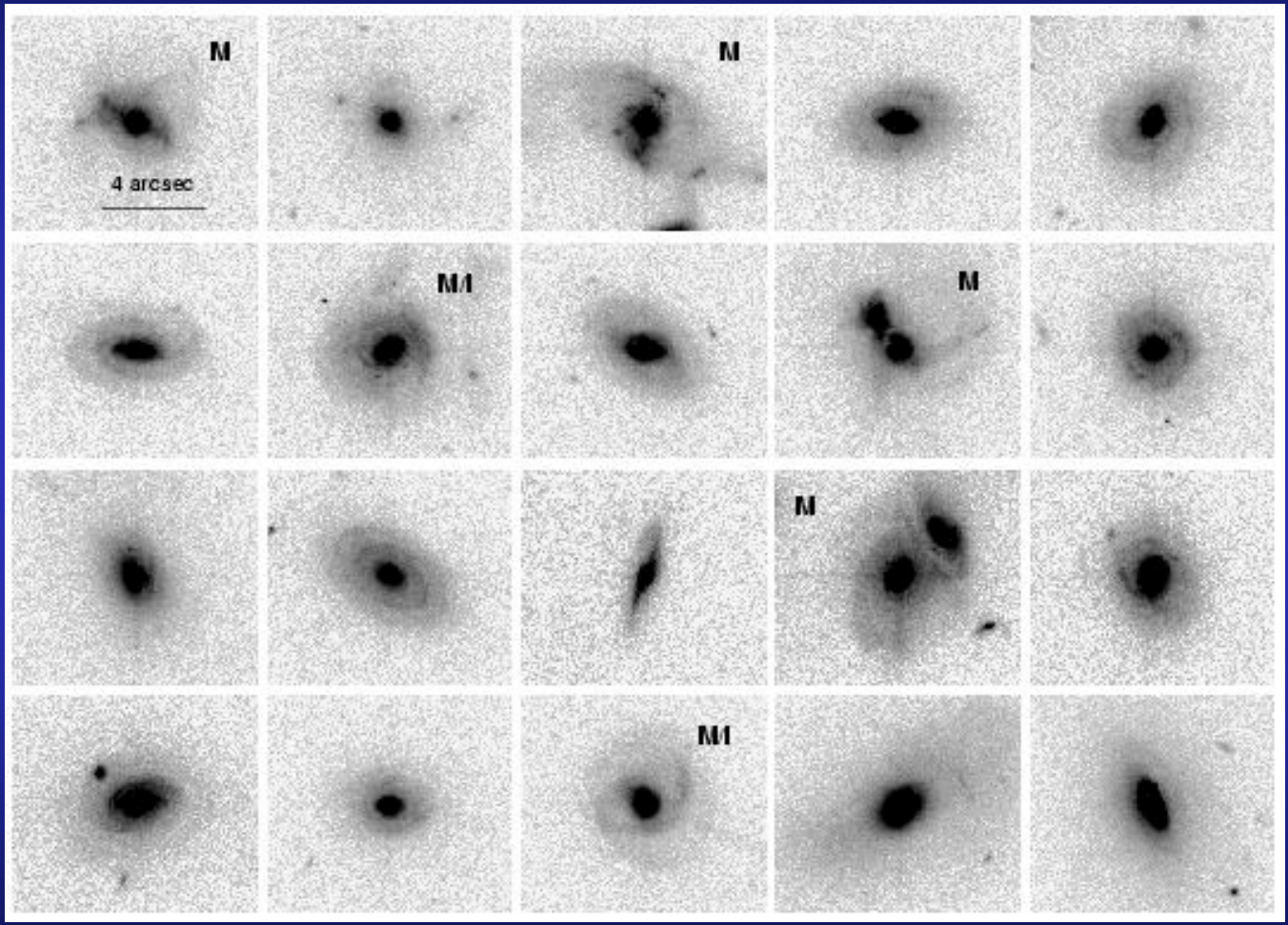


The M_{BH}- M_{bulge} relation

$\Delta \log M_{BH} > 0.59 \pm 0.19$ dex



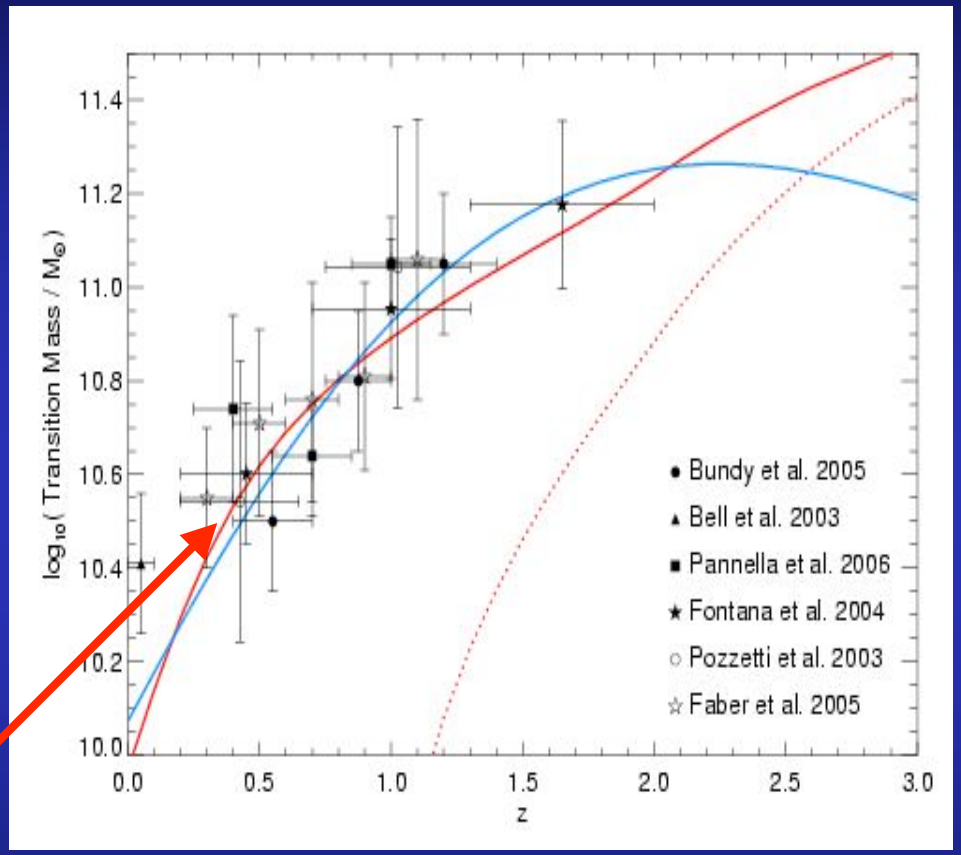
Recent evolution of (active) bulges?



A Scenario

- Major mergers
  1) trigger AGN & SF,
  2) quench SF by feedback,
  3) increase bulge size

- The characteristic mass scale decreases with time (downsizing), consistent with that of our galaxies at z=0.36



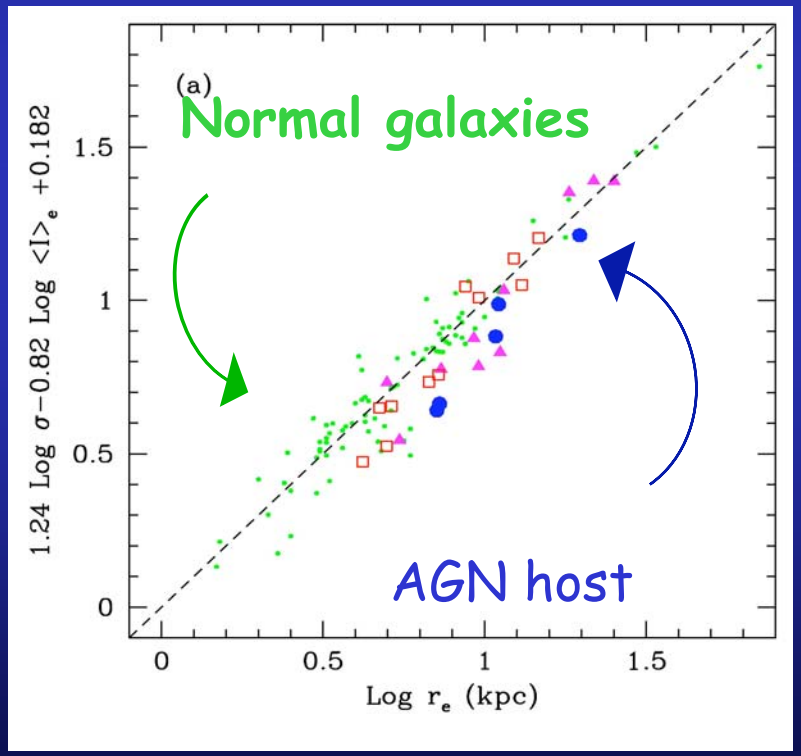
Hopkins et al. 2006

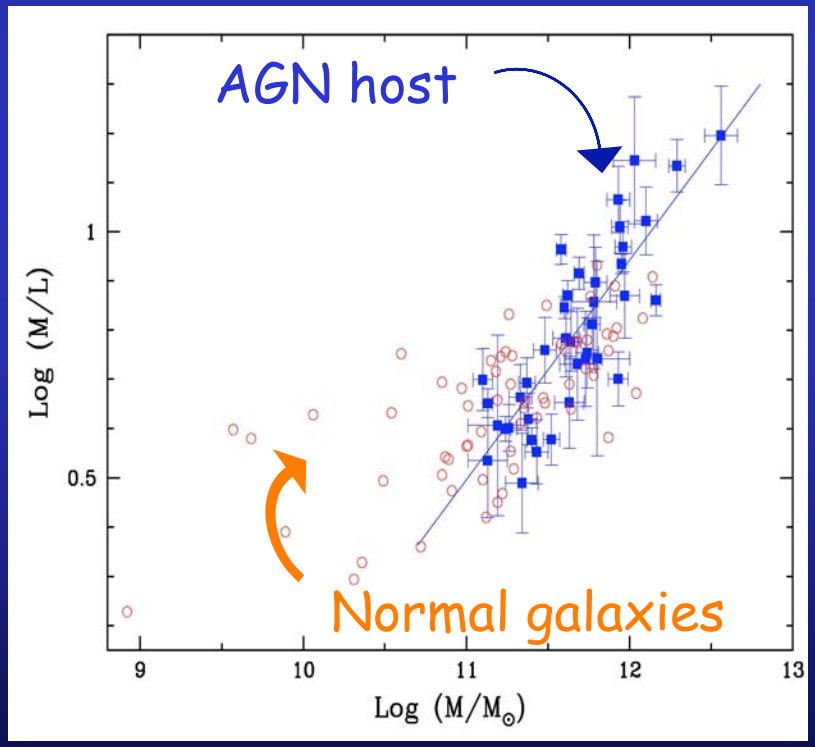
The M-sigma relation should be already in place for larger masses!

Future works

- Probe more massive host galaxies at z~0.4 with FP
- Test of M_{BH}-sigma at higher z (~0.6)
- Test of M_{BH}-L_{bulge} at high z (z<~1)

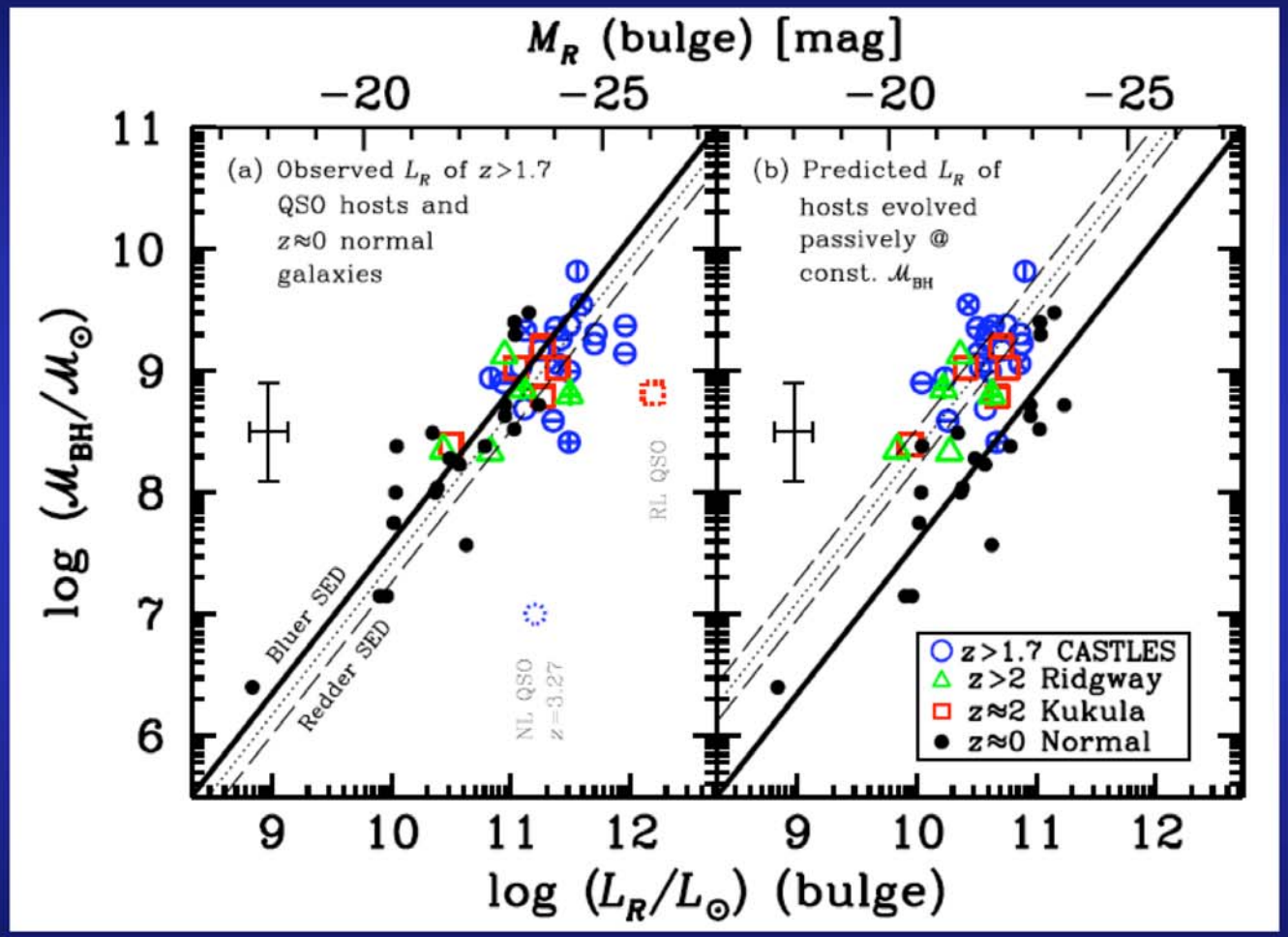
Massive AGN host galaxies at 0.1<z<0.5





Woo, Urry, van der Marel et al. 2004, 2005

M_{BH}-L_{bulge} relation at high z

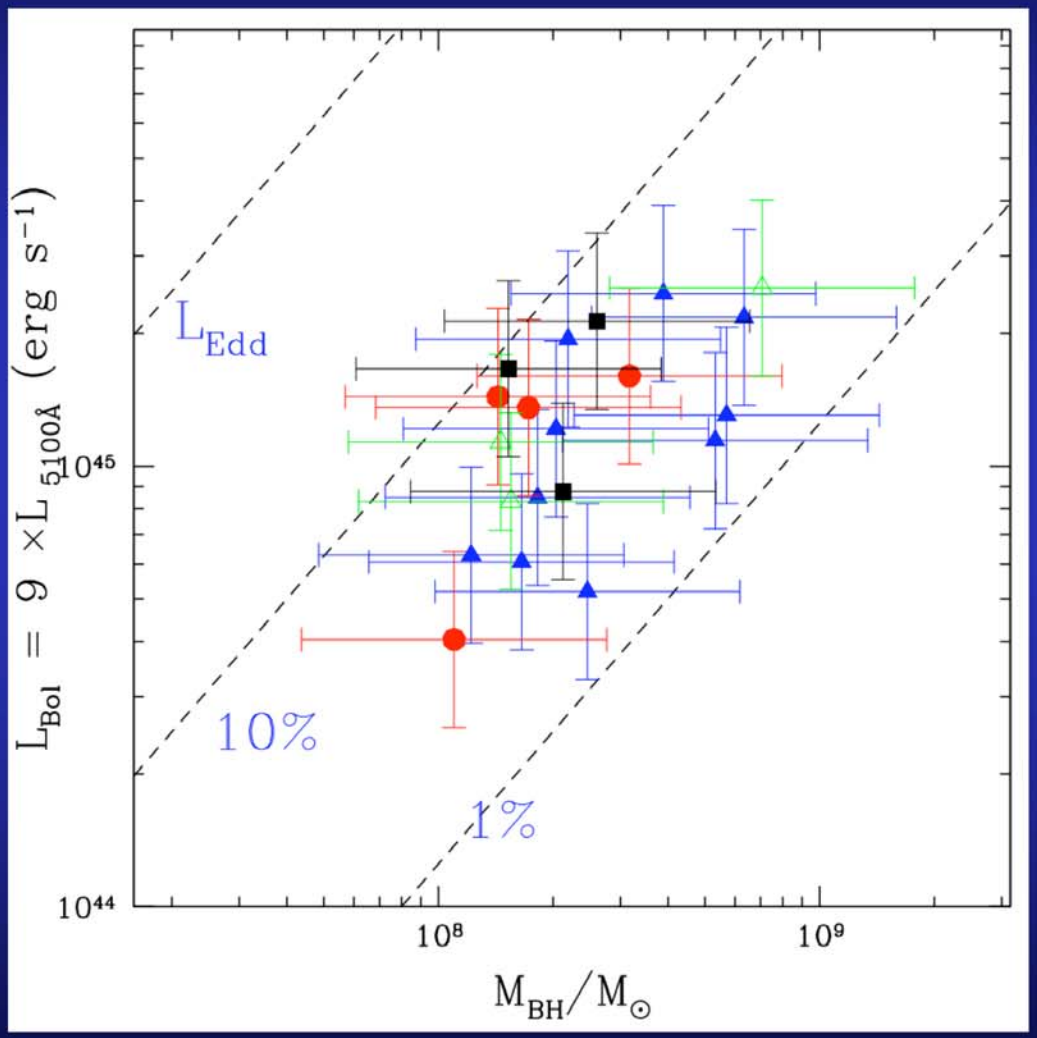


Peng et al. 2006

Conclusions

- Bulges at z~0.36 appear to be smaller/less luminous than suggested by the local M_{BH}-sigma relation.
- Systematic error? (< 0.25 dex in log M_{BH})
- Selection effects (possibly in the local relationship; spirals vs bulge dominated systems)?
- Significant recent evolution of bulges if M-sigma relation is the final destiny of BH-galaxy co-evolution.

Are these BHs rapidly growing?

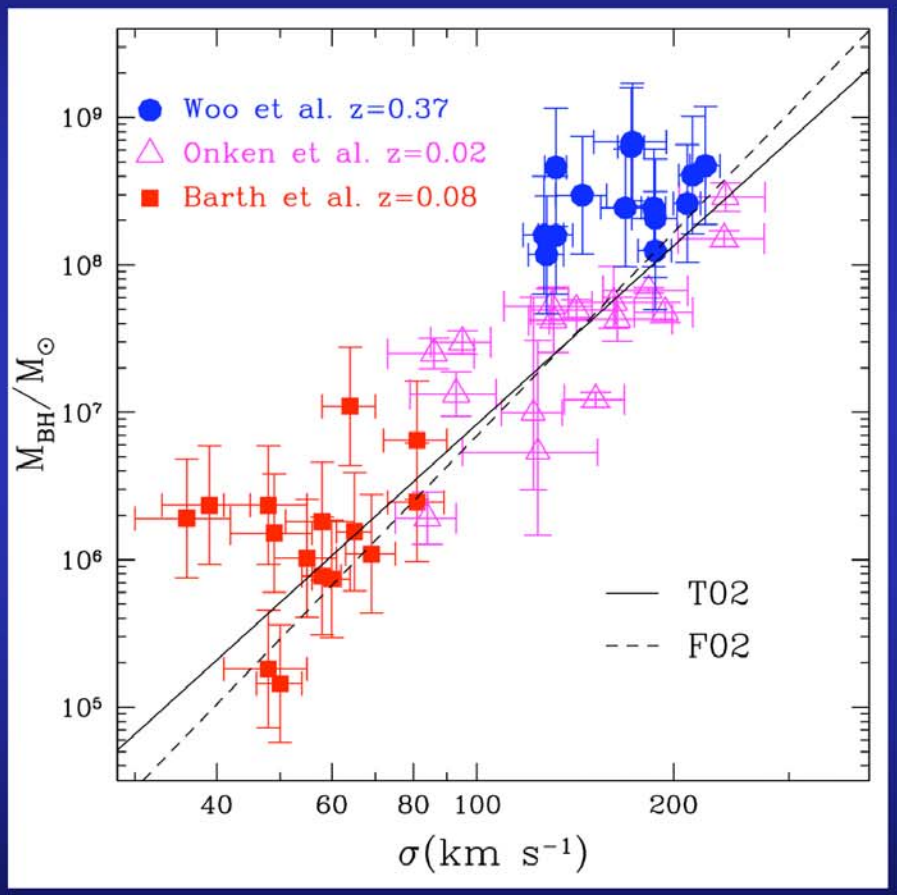


< 10% of Eddington

mass accretion rate
= ~ 0.1-0.5 (solarmass/yr)

Updated with L_{5100A} correction

Old



New