Probing the co-evolution of black holes and galaxies

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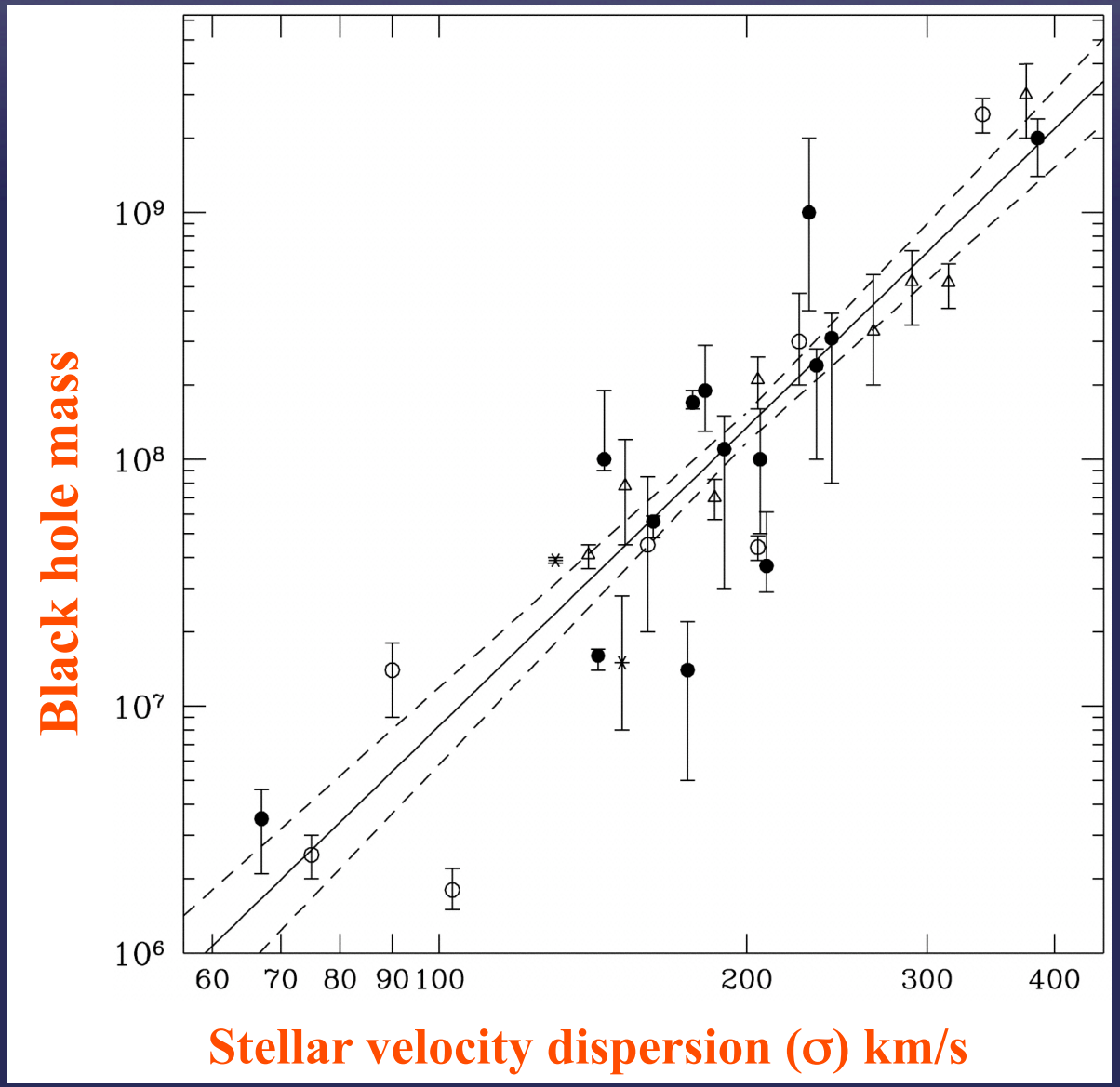
Roger Blandford (Stanford), Aaron Barth (UCI), + many more

M_{BH}- σ_* relation of quiescent galaxies

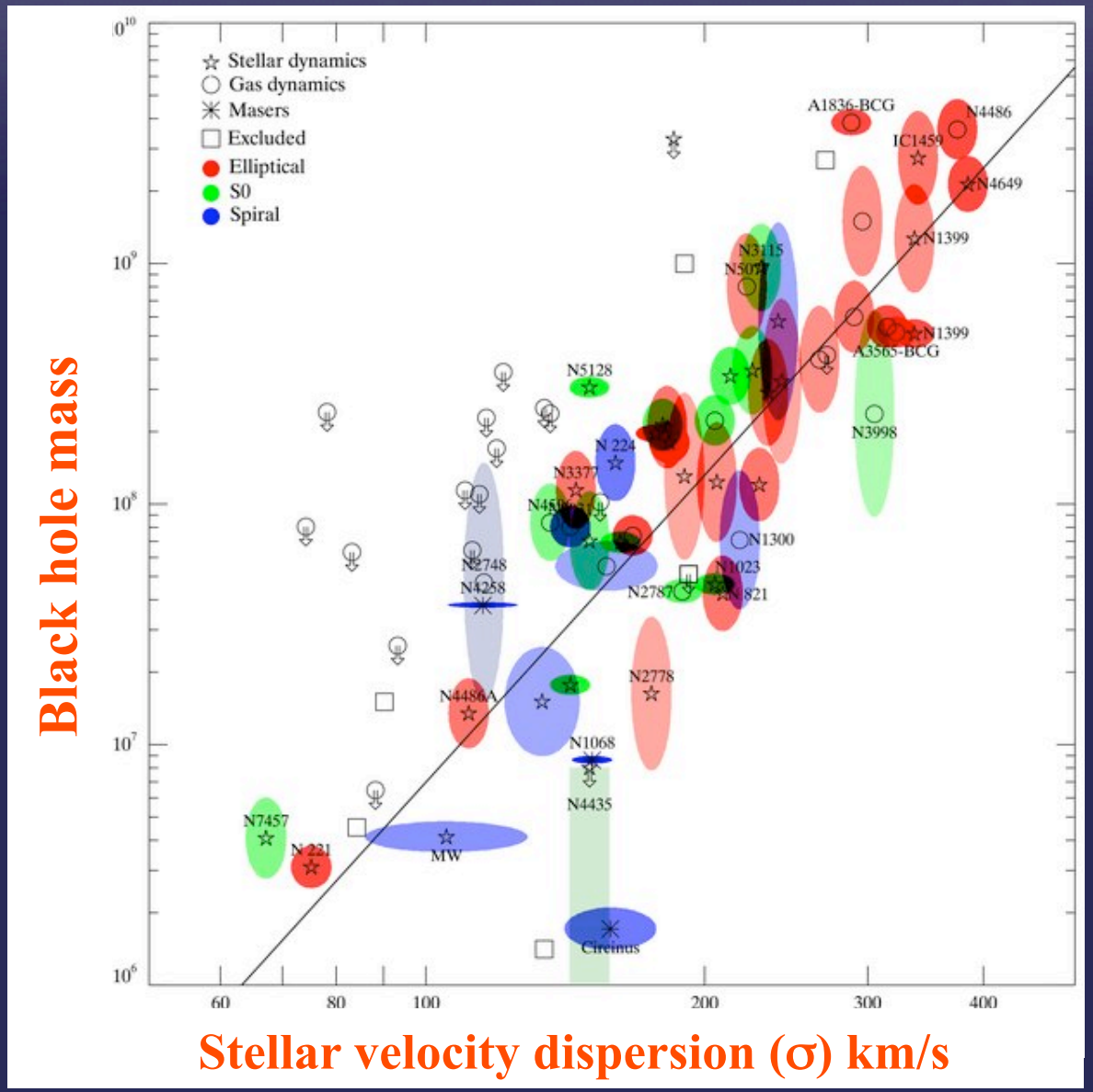
First reported by Ferraresse et al. (2000) & Gebhardt et al. (2000)



M_{BH}- σ_* relation of quiescent galaxies

Currently,
~45 nearby galaxies

(Gultekin et al. 2009)



An Open Question: Origin of the M_{BH}- σ_* Relations

- When did scaling relations form? Do they evolve?

Theoretical Predictions:

- No evolution? (Haehnelt & Kauffmann 2000)
- Galaxy grows first? (Robertson et al. 2005)
- BH grows first ? (Croton 2006; Bower et al. 2006; Somerville et al. 2008)

Core issues:

- BH growth faster than bulge growth? Or synchronized?
- transforming stellar disk to spheroid component

  (galaxy merging vs. secular evolution)

Evolution of the M-sigma relation

Observational studies are required!

At high z, M_{BH} can be estimated only for active galaxies, using broad emission lines:

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

single-epoch mass $M_{BH} = f\ V^2 L^{1/2} / G$

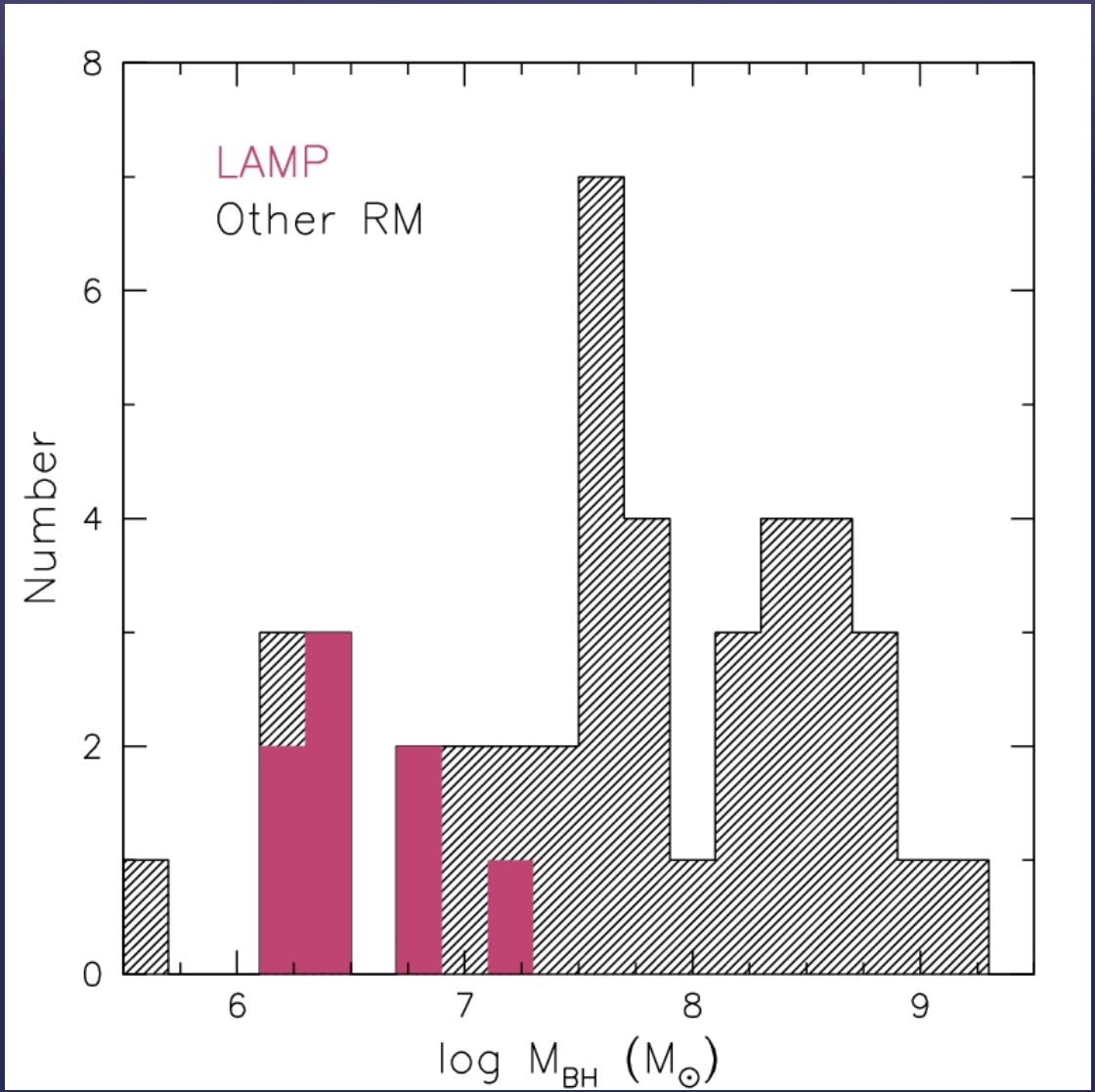
1) Velocity: from width of broad lines
2) Broad-line region size (R_{BLR}): from
   either Reverberation time scale (light echo)
   or Continuum luminosity based on the empirical size-luminosity relation
   (Kaspi et al. 2005; Bentz et al. 2006, 2008).

Do present-day active galaxies follow the same M-sigma relation as quiescent galaxies?

Best sample to use:
AGN with reverberation mass

Reverberation sample

Lick AGN Monitoring Project + Previous measurements



~40 AGN available with reverberation M_{BH}

(Bentz et al. 2009)

Present-day $M_{BH} - \sigma_*$ relation

- Non-AGN:

slope: 4.24±0.41

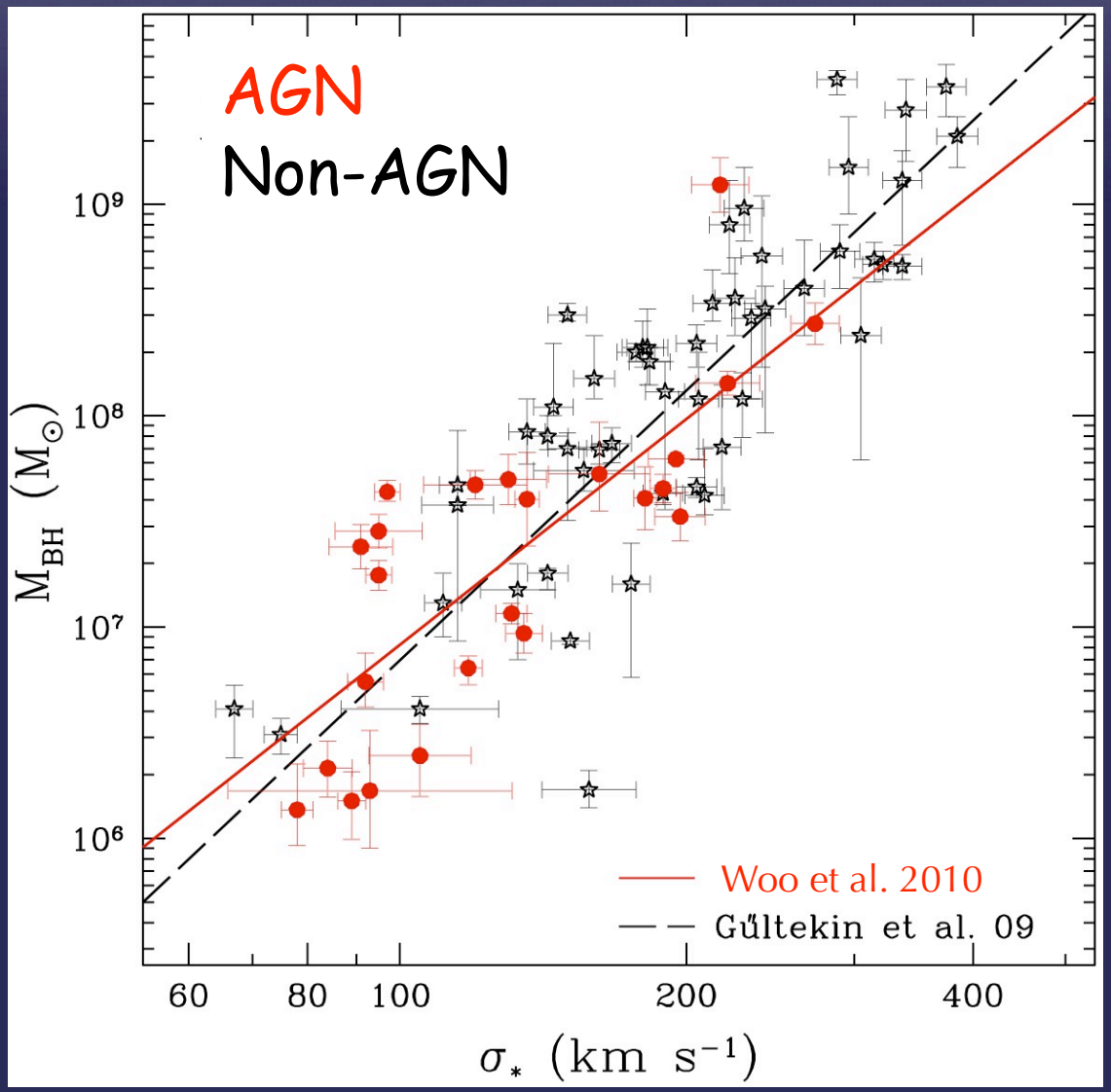
σ_{int}: 0.44±0.06 dex

- AGN:

slope: 3.55±0.60

σ_{int}: 0.43±0.08 dex

- M-sigma relation is similar regardless of AGN activity

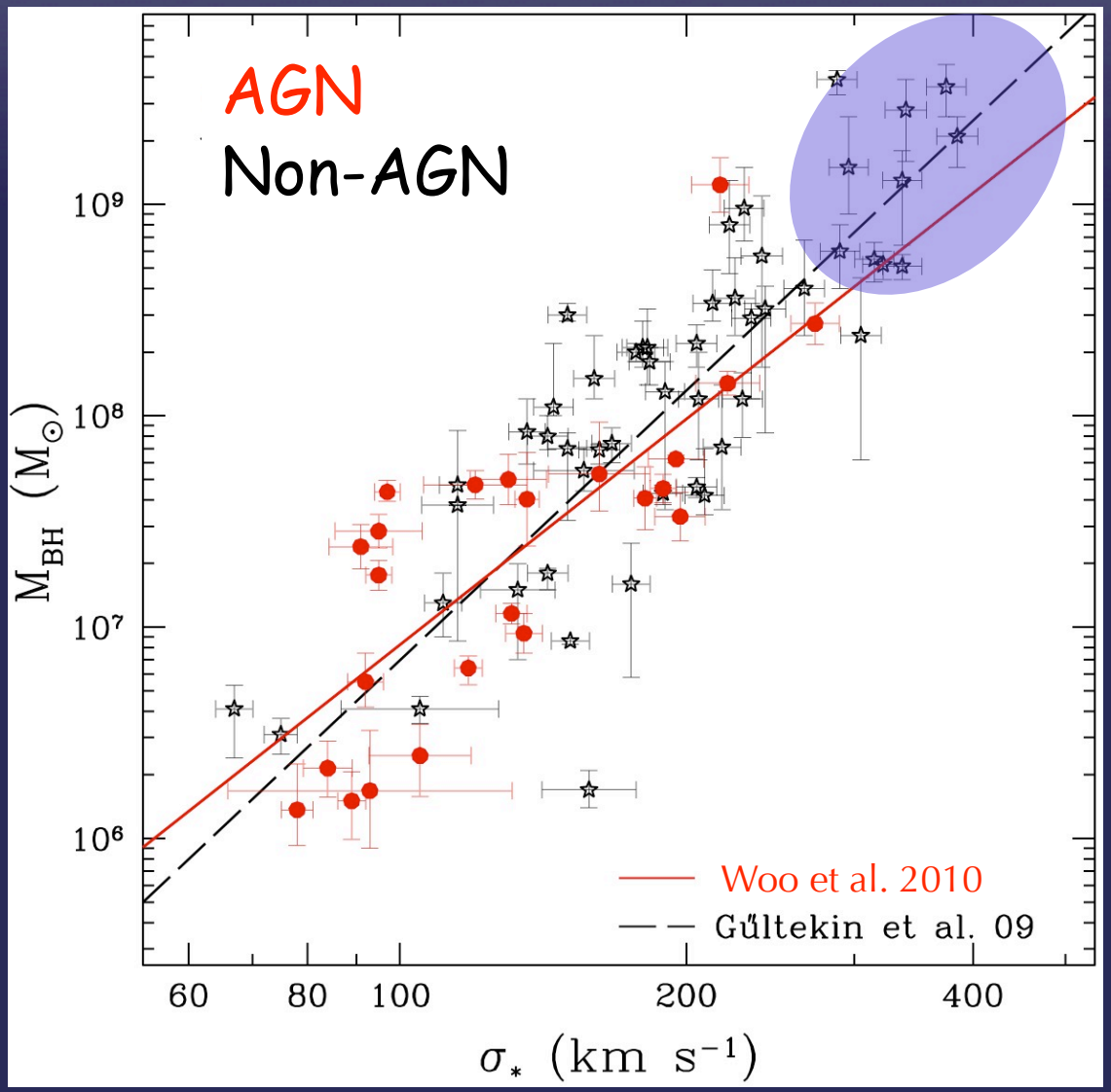


Woo et al. 2010

Present-day $M_{BH} - \sigma_*$ relation

Lack of high M_{BH} AGNs

due to the difficulty of velocity dispersion measurements



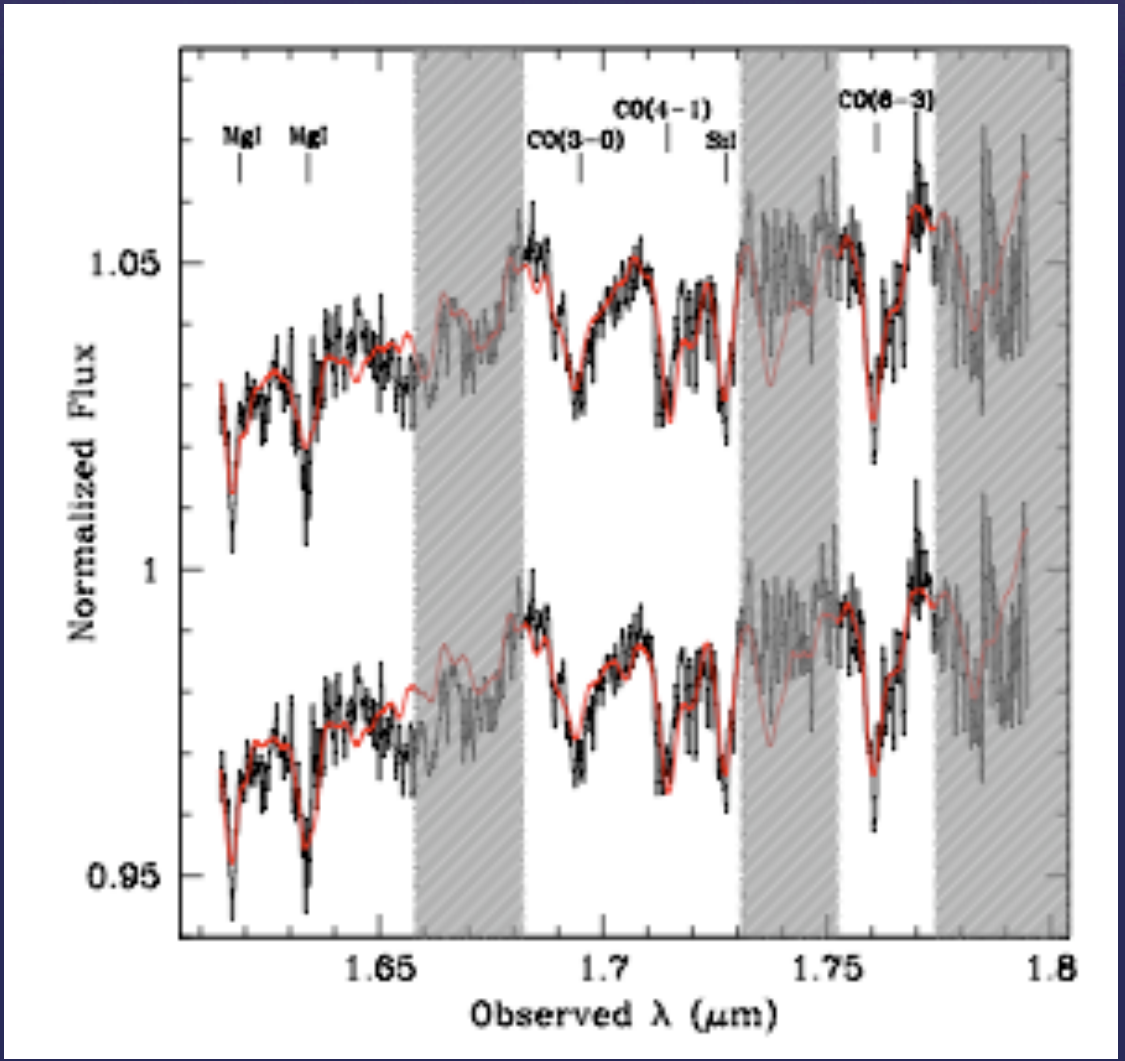
Woo et al. 2010

Measuring velocity dispersion of QSO host galaxies

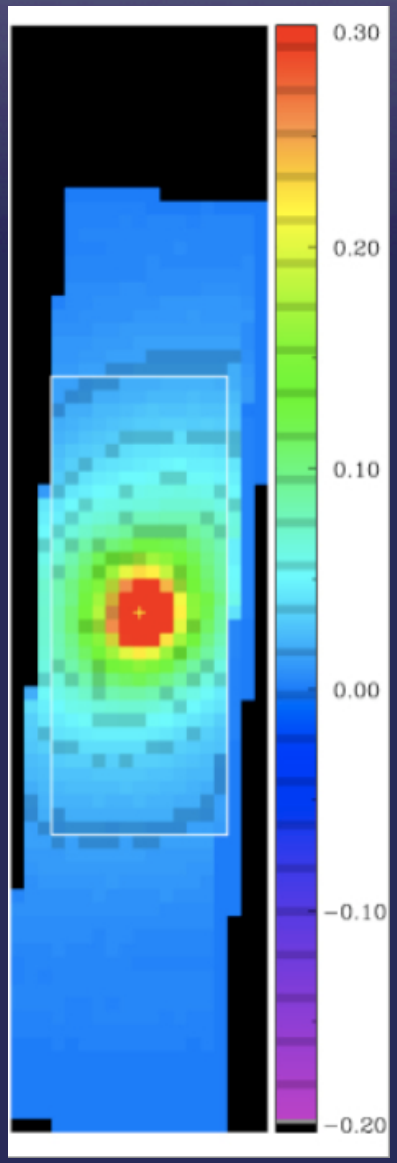
LGS-AO + NIR IFU

AGN light can be confined in central pixels.

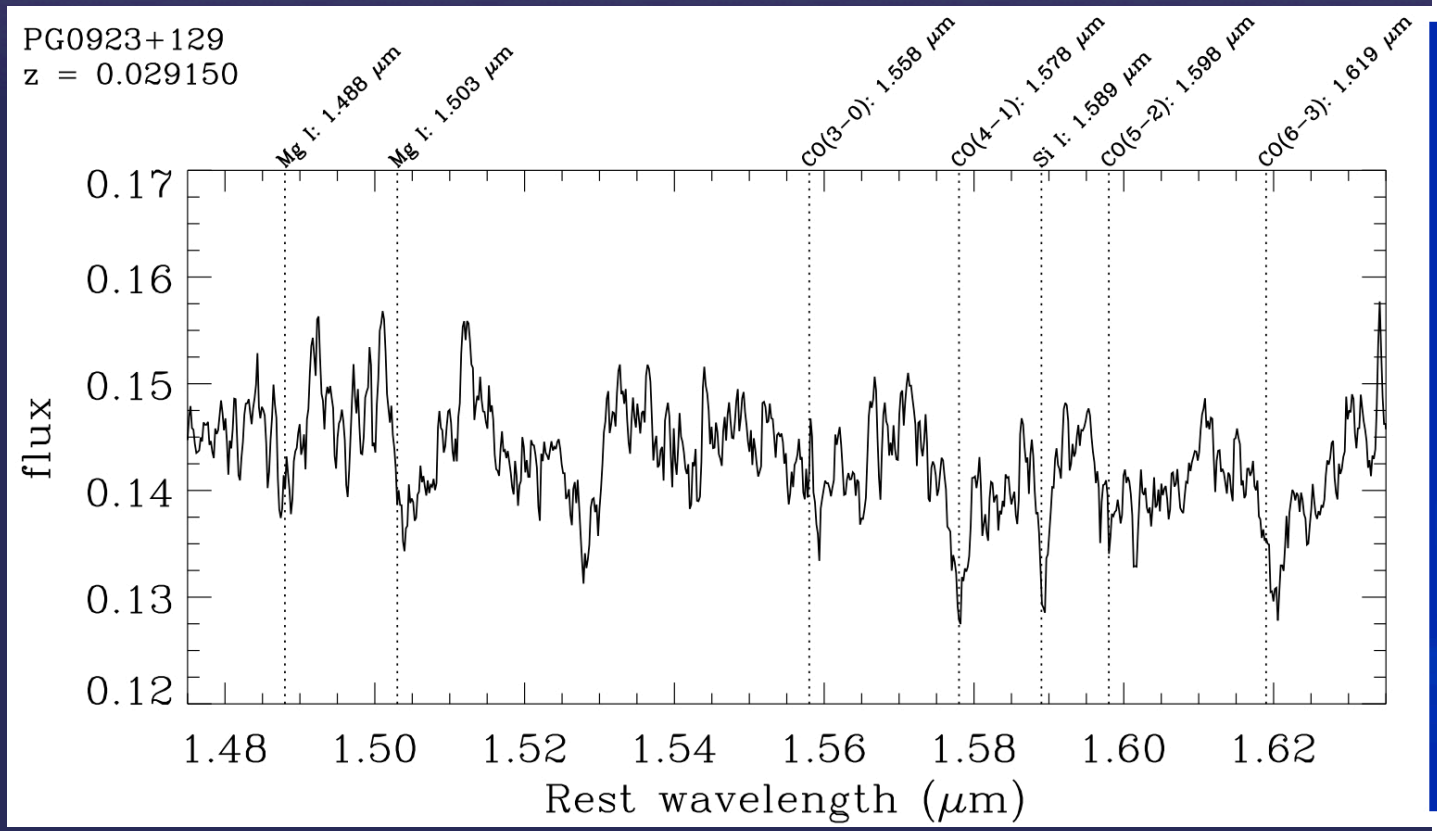
Gemini NIFS data (Watson et al. 2008)

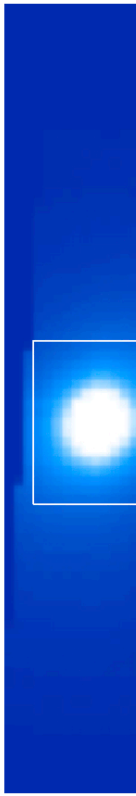


Measuring velocity dispersion of QSO host galaxies
with Keck (LGS-AO + OSIRIS)



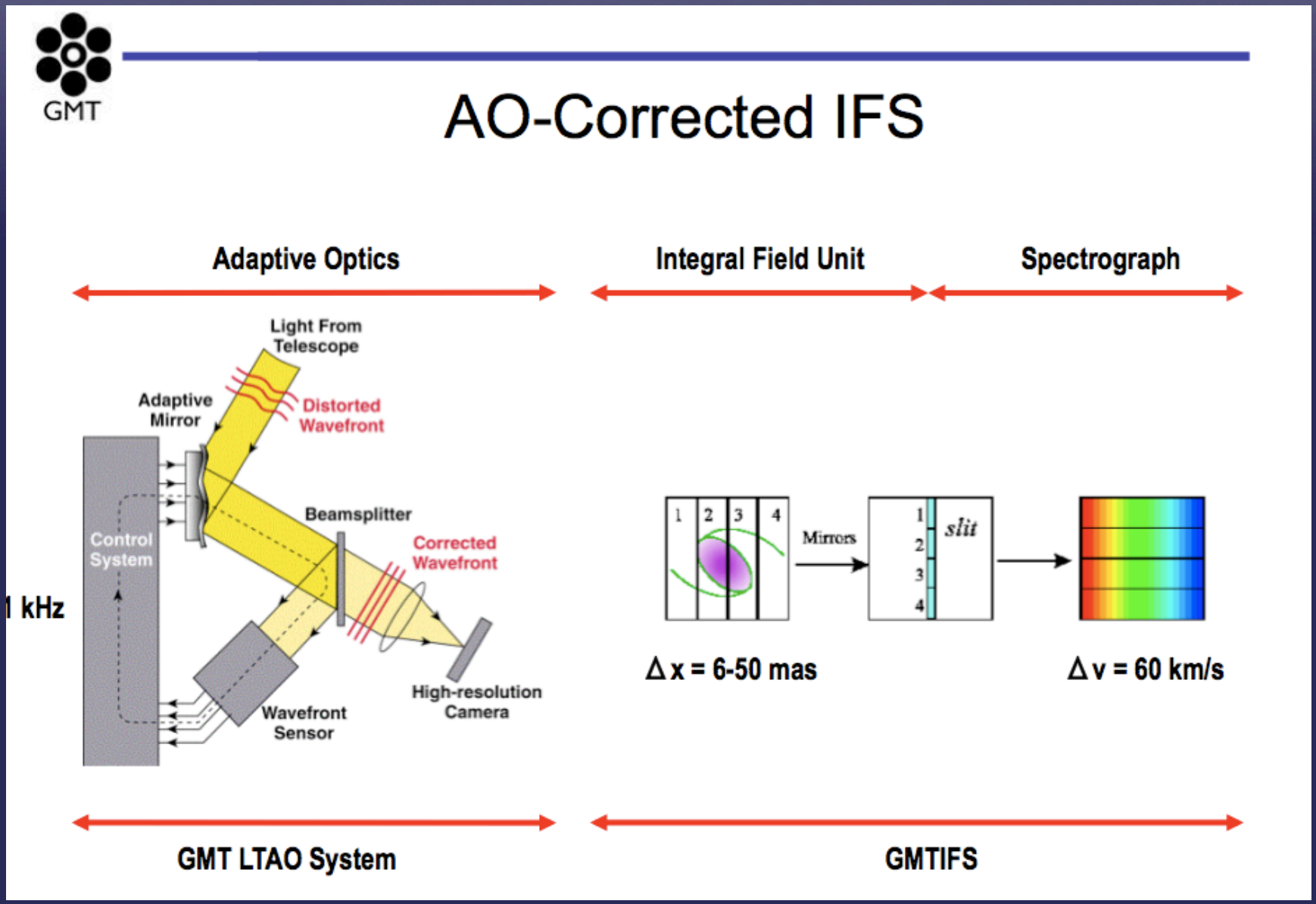
FOV: 6.4″ X 1.6“





Park, Woo, & Malkan 2010 in prep.

GMTIFS at GMT



From Peter McGregor's talk

What about the scale factor?

$$M_{BH} = f\ V^2 R_{BLR} / G \sim f\ V^2 L^{1/2} / G$$

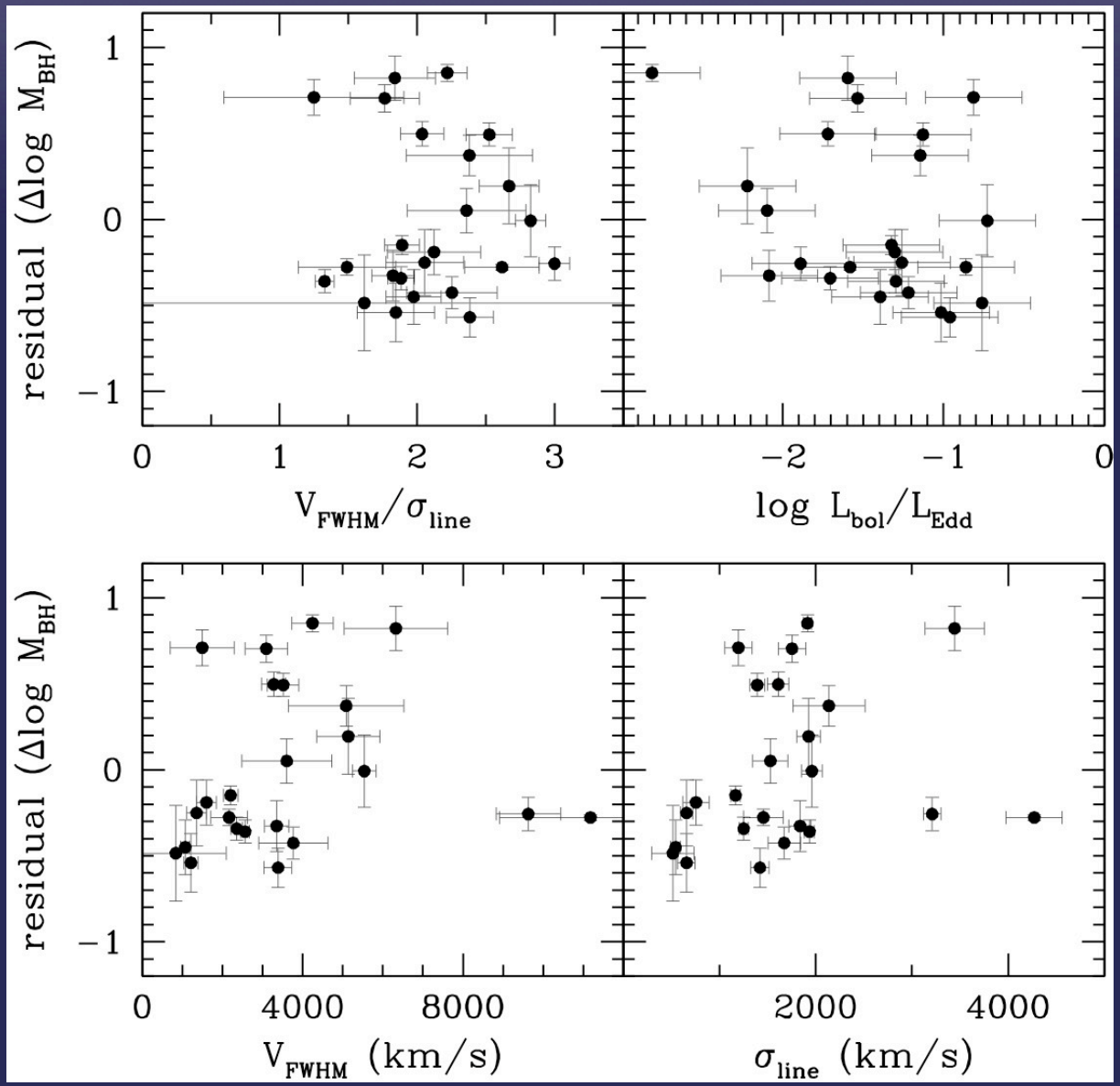
- <f > is determined by normalizing the M-sigma relation of AGN galaxies to that of non-AGN galaxies.

- f = 5.25 (larger than 3, implying non-isotropic distribution)

- What if f varies systematically?
- What if f varies as a function of z?

Dependence of the virial coefficient on AGN properties

No clear dependence on the Eddington ratio, velocity, or line profiles



Woo et al. 2010

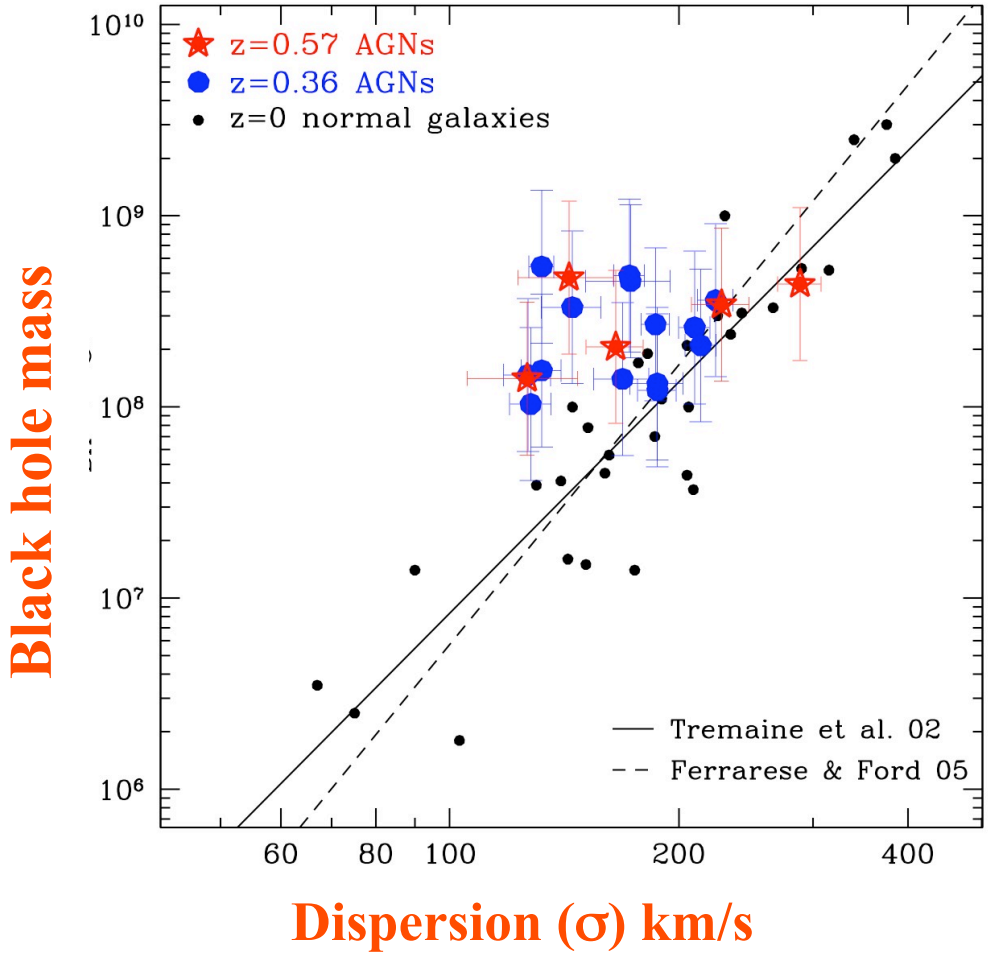
Does the M-sigma relation evolve?

Using single-epoch M_{BH} estimates

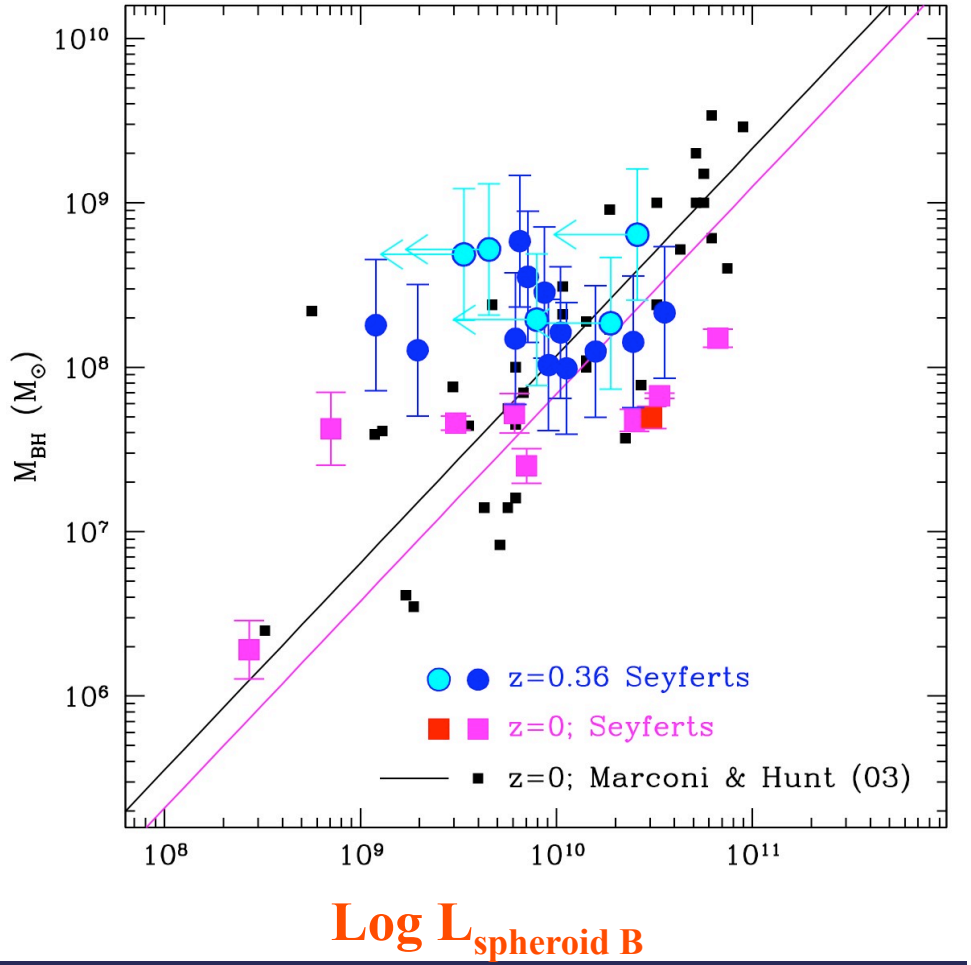
Scaling Relation at z~0.4 & 0.6

- Distant bulges are smaller/less luminous than local bulges at fixed M_{BH}

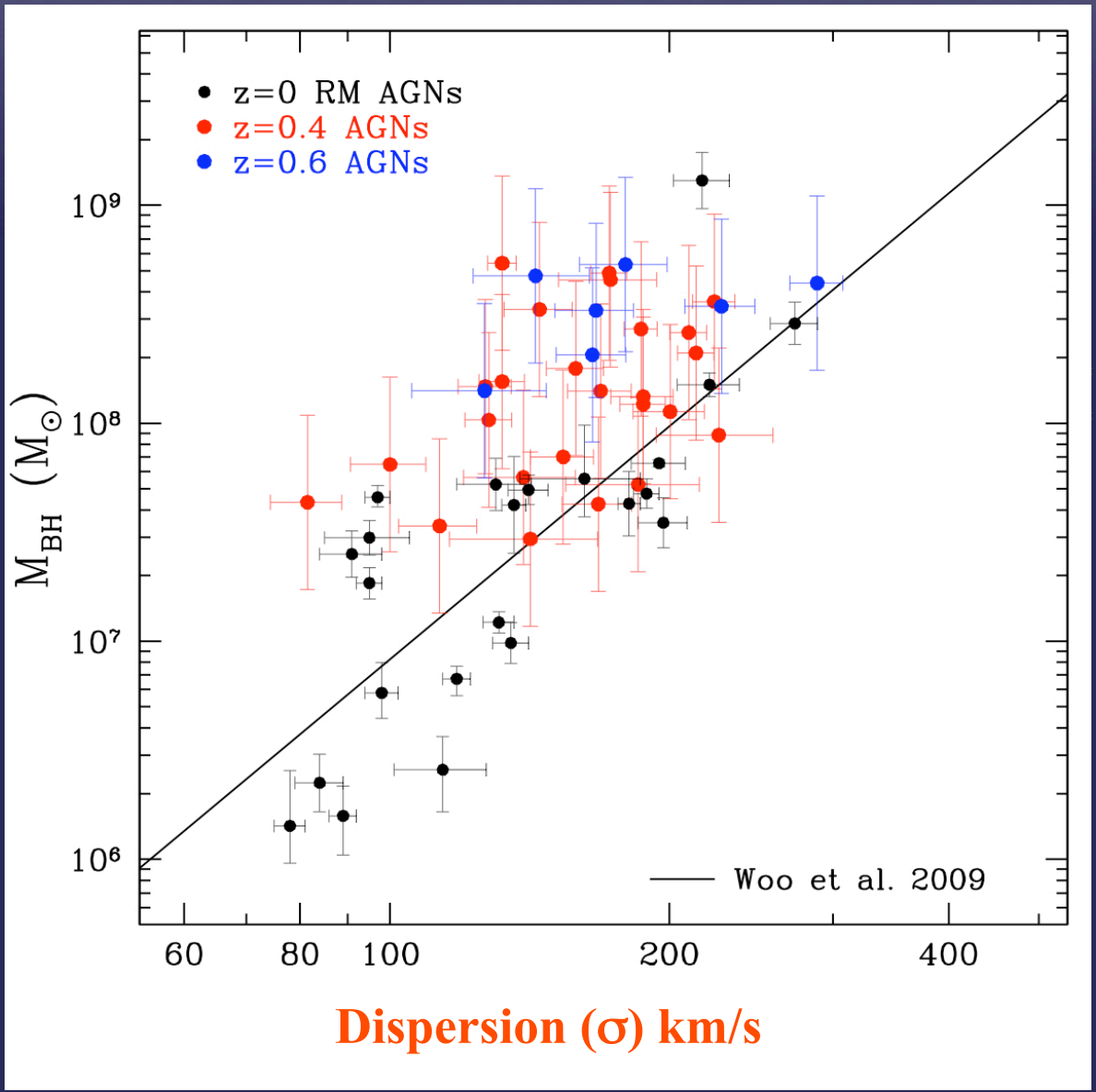
Woo et al. 2006, 2008



Treu et al. 2007



Update of M_{BH}-sigma Relation at z~0.4 & 0.6



Distant bulges have lower sigma than local bulges

(Woo et al. 2006 & 2008, in prep.)

Compared to Local quiescent galaxies

RMS scatter is ~0.45 dex

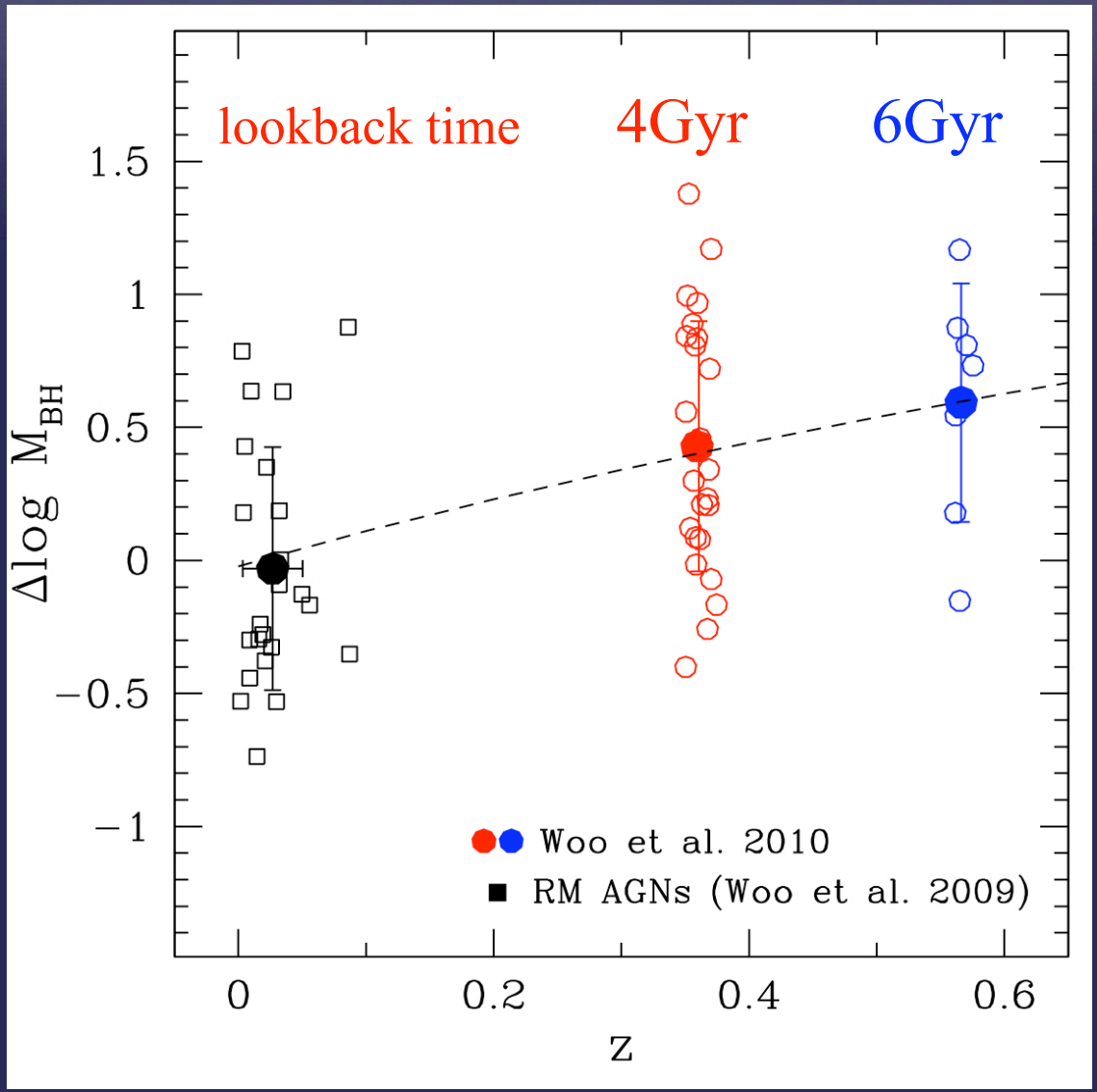
scatter does not increase

Evolution of the M_{BH} - sigma Relation

z~0.4 sample
$\Delta \log M_{BH} = 0.41 \pm 0.09$

z~0.6 sample
$\Delta \log M_{BH} = 0.57 \pm 0.17$

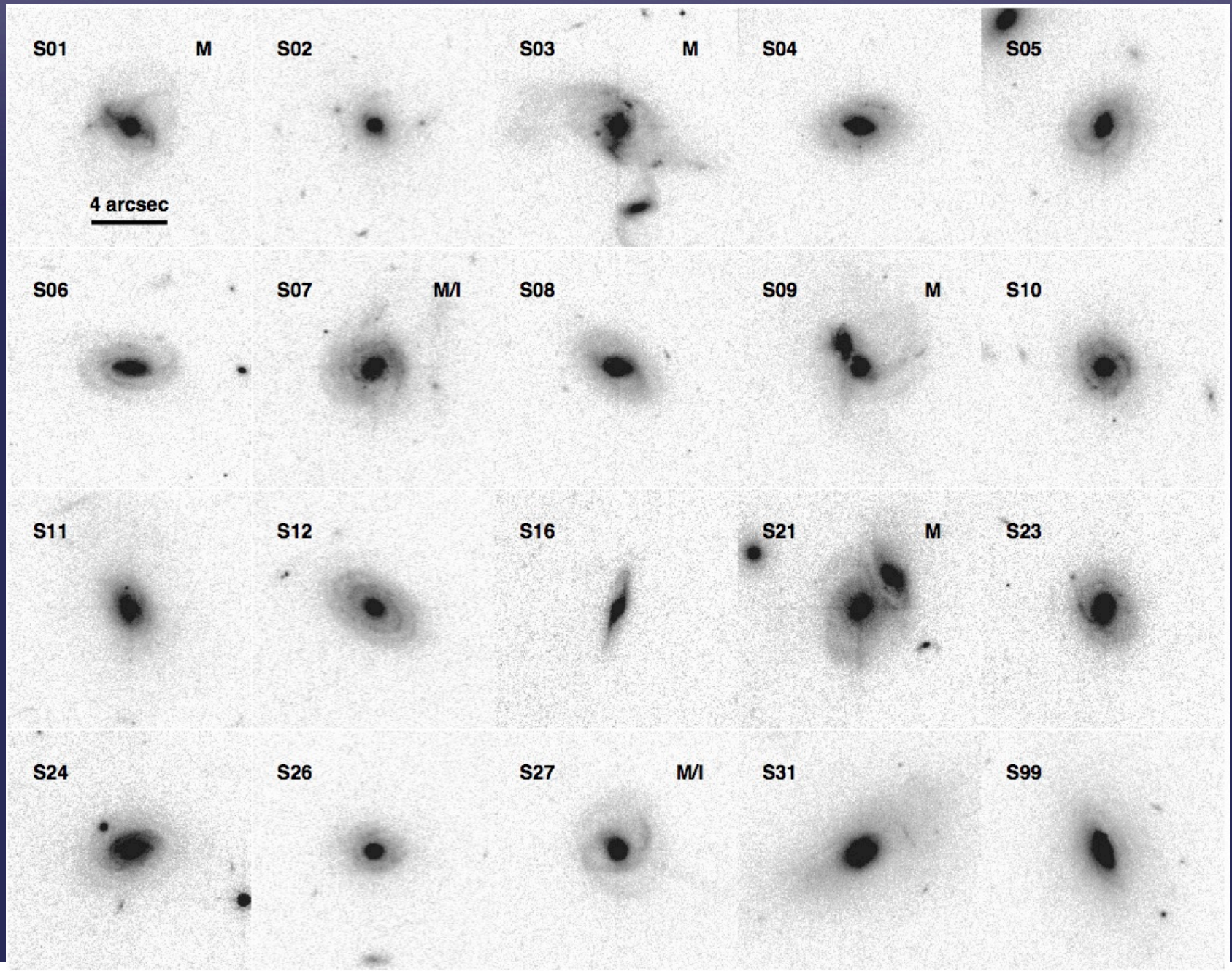
Offset is independent of the scale factor, f.

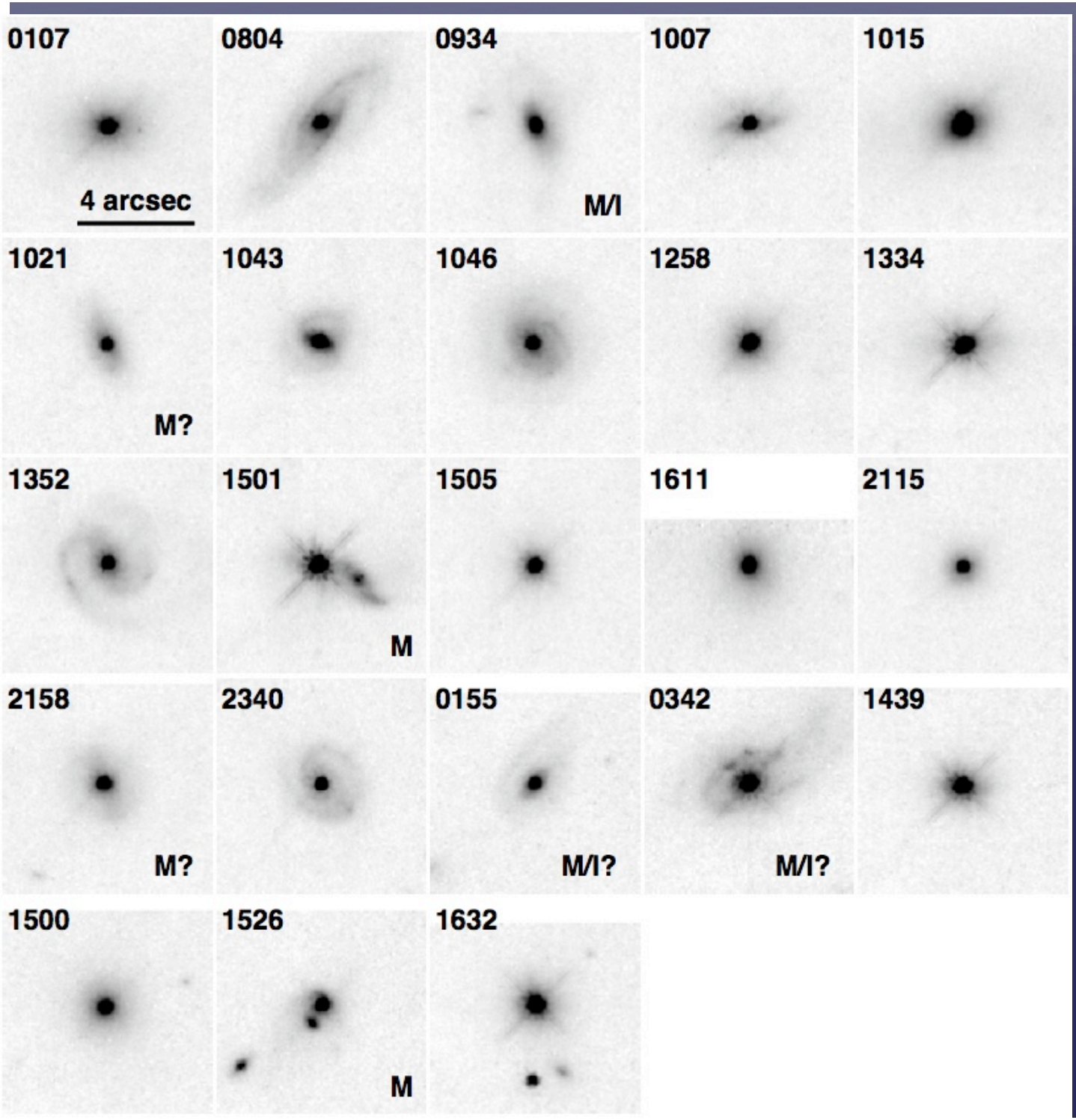


Woo et al. 2010 in prep.

Recent evolution of (active) bulges?

HST ACS images
(Treu et al. 2007)

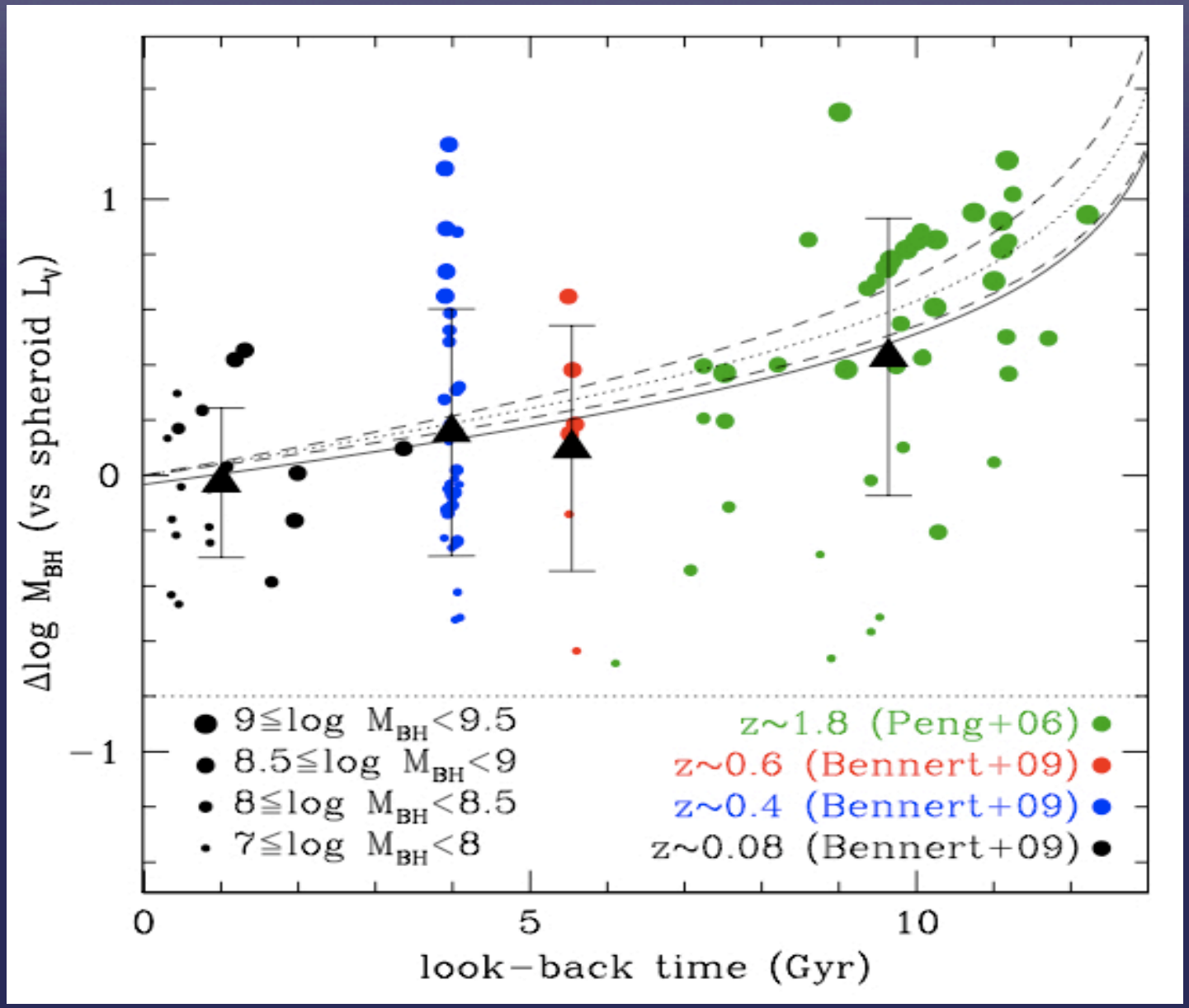




Recent evolution of (active) bulges?

NICMOS images
(Bennert et al. 2010)

Evolution of M_{BH}-L_{host} Relation



(Bennert et al. 2010)

Systematic errors

1) Systematic errors

overall systematic error: $\Delta \log M_{BH} \sim 0.2$ dex,
smaller than offset 0.4-0.6 dex

2) Selection bias (Lauer et al. 2007)

Not significant

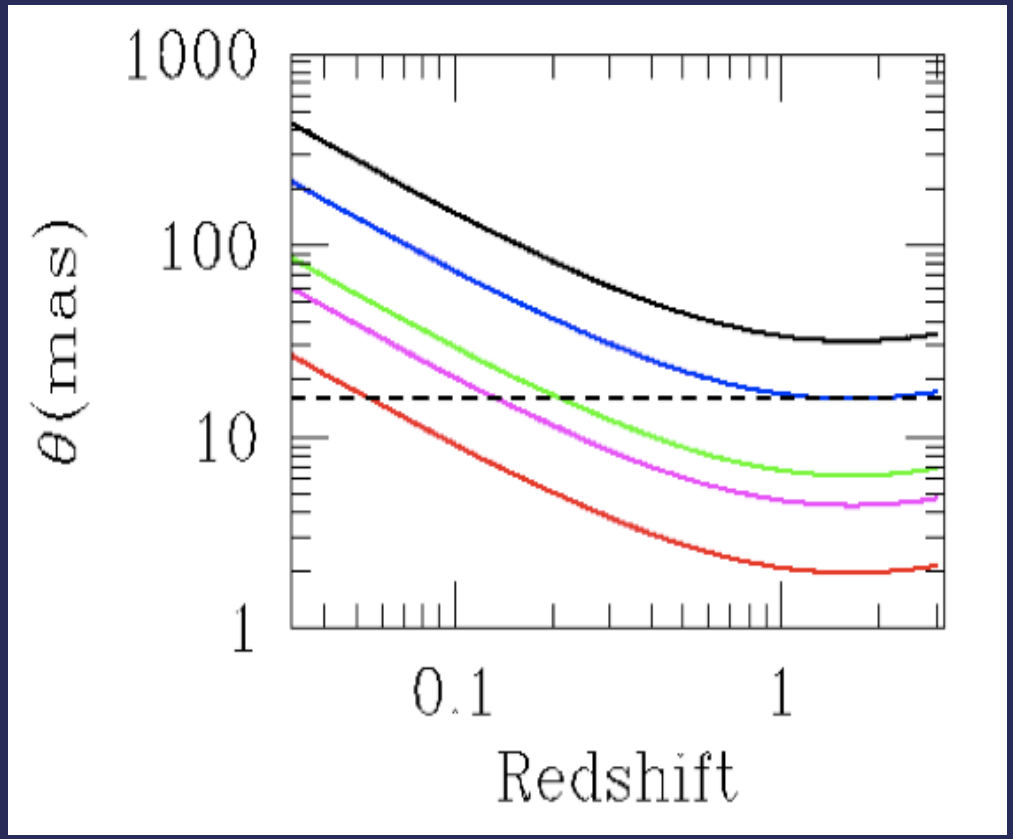
3) BH mass uncertainty

- Scatter in the size-luminosity relation (Shen & Kelly 2010)
  Not significant ~0.1 dex in M_{BH}
- Uncertainty of the scale factor
  doesn't affect the relative offset
- Systematic difference between rms and single-epoch spectra
  Currently investigated

Measuring M_{BH} out to z~0.1-1 with the GMT resolution!

The angular size of sphere of influence ($r_{sphere} = GM_{BH}/\sigma^2$) for

$M_{BH} \sim 10^{10}$, $5x10^9$, $2x10^9$, 10^9, $2x10^8$



With 16 mas resolution,

r_{sphere} of M_{BH} ~10^9 M_{sun} can be resolved out to z~0.1.

If r_{sphere} of $M_{BH} > 5 \times 10^9$ M_{sun}, it can be done to z~1.

With the GMT,

- Using a large sample of quiescent galaxies, we can probe the M-sigma relation out to z~0.1.
- Dynamical M_{BH} based on spatially resolved kinematics and AGN BH mass based reverberation can be directly compared and calibrated.
- Using AGN samples, the M-sigma relation can be probed out to z~1.

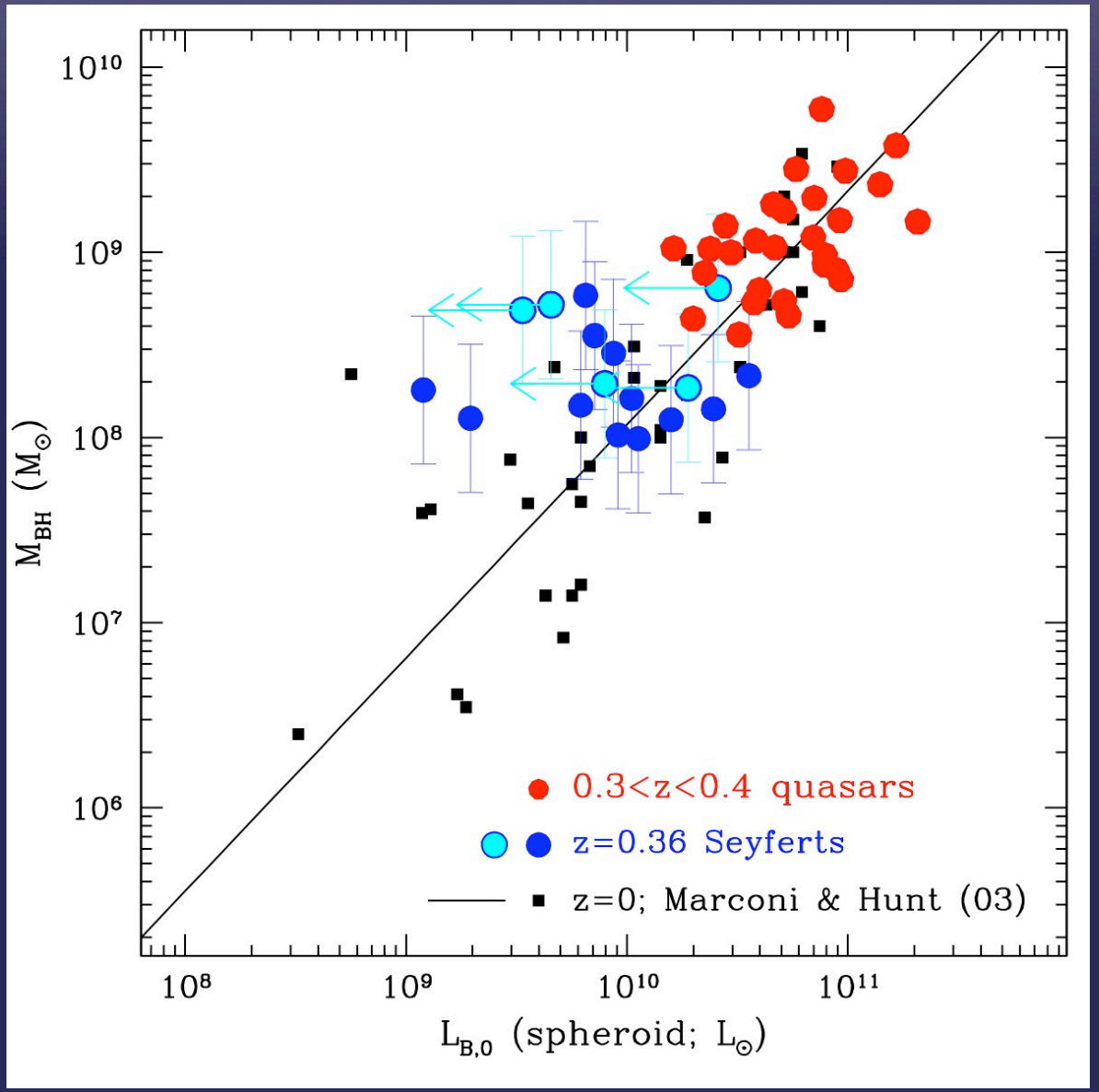
Conclusions

- Present-day AGN and non-AGN galaxies have a similar M-sigma relation.
- For given M_{BH}, bulges in the past appear to be smaller compared to the local bulges.
- BH growth predates final assembly of spheroid (with mass-dependency).
- Bulges will grow by gas-rich merging and/or secular evolution to arrive on the present-day scaling relations.
- M_{BH} estimates still have large uncertainty.
- GMT can provide a detailed picture of the coevolution.

Mass-dependent Evolution?

More massive galaxies show smaller offset

Downsizing of scaling relation?



Woo et al. 2010 in prep.