# Probing the M-sigma relation using active galaxies: from present to past

Jong-Hak Woo (Seoul National University)

# Outline

1. Present-day M-sigma relation
2. Cosmic evolution of the M-sigma relation

Thanks to

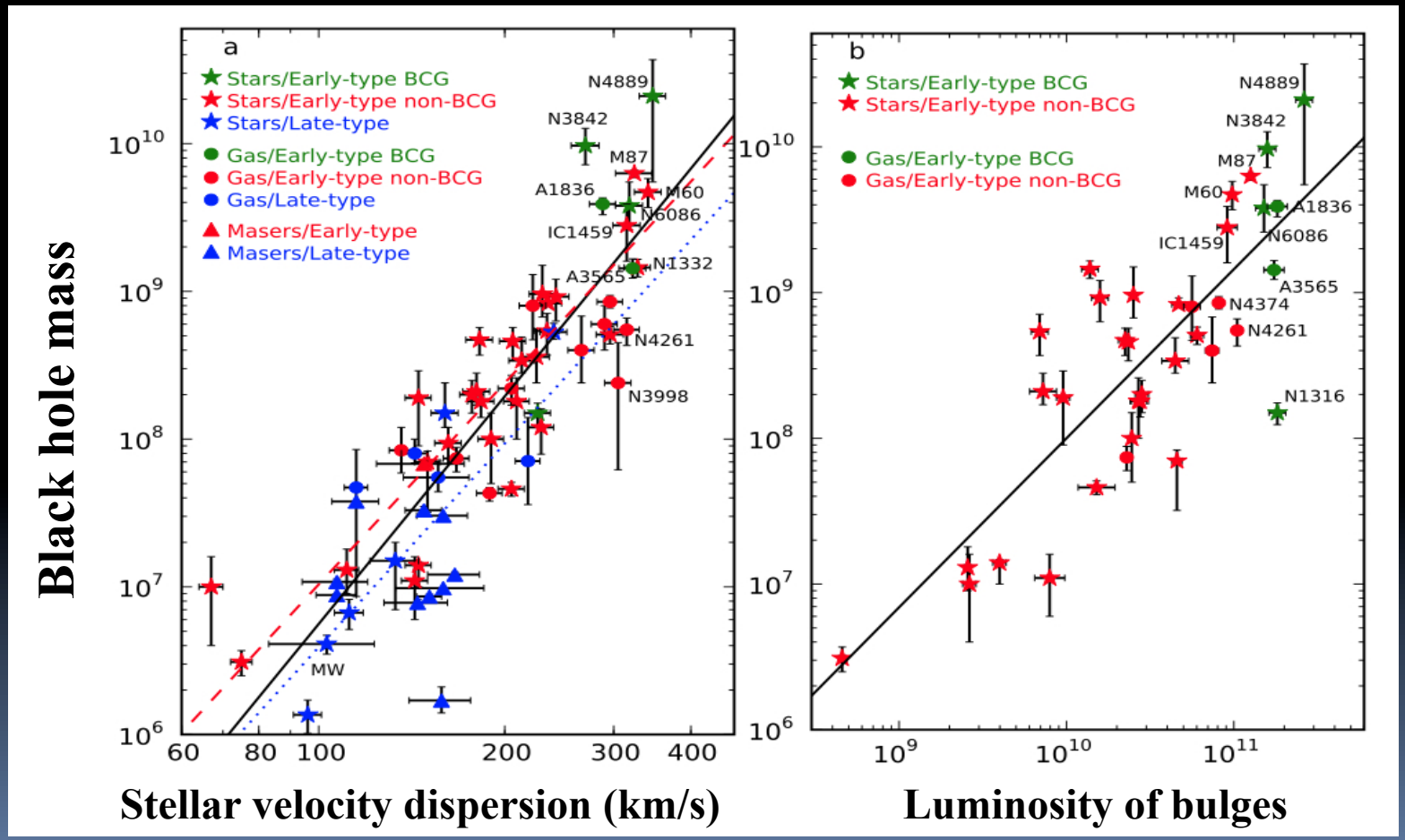
Daeseong Park, Wolrang Kang, Yoseph Yoon (SNU),

&

Tommaso Treu (UCSB), Aaron Barth (UCI), Vardha Bennert (Cal. Poly), Matt Malkan (UCLA), Roger Blandford (Stanford), Brandon Kelly (UCSB), Andreas Schulze (PU)…

# BH-Galaxy Scaling Relations

- BH mass scaling relations imply the connection between BH growth and galaxy evolution (Ferraresse+00; Gebhardt+00, Gultekin+09, Kormendy & Ho 13).




McConnell & Ma 2013

# BH-galaxy scaling relations

Coevolution?

- Self regulation between BH growth and galaxy evolution
- AGN feedback (e.g., Di Matteo+05, Hopkins+06, Croton+06; Bower+06; Somerville+08, Dubois+13…..)

Non-causality?

- Due to galaxy merging (Peng 07; Jahnke+11)

Dependence on galaxy type, mass, & evolution history

- Classical vs. pseudo bulges (Kormendy & Ho 2013)
- Early vs. late type galaxies (McConnell & Ma 2013)
- Merging vs. secular evolution (e.g., Croton 06, Shankar+13)

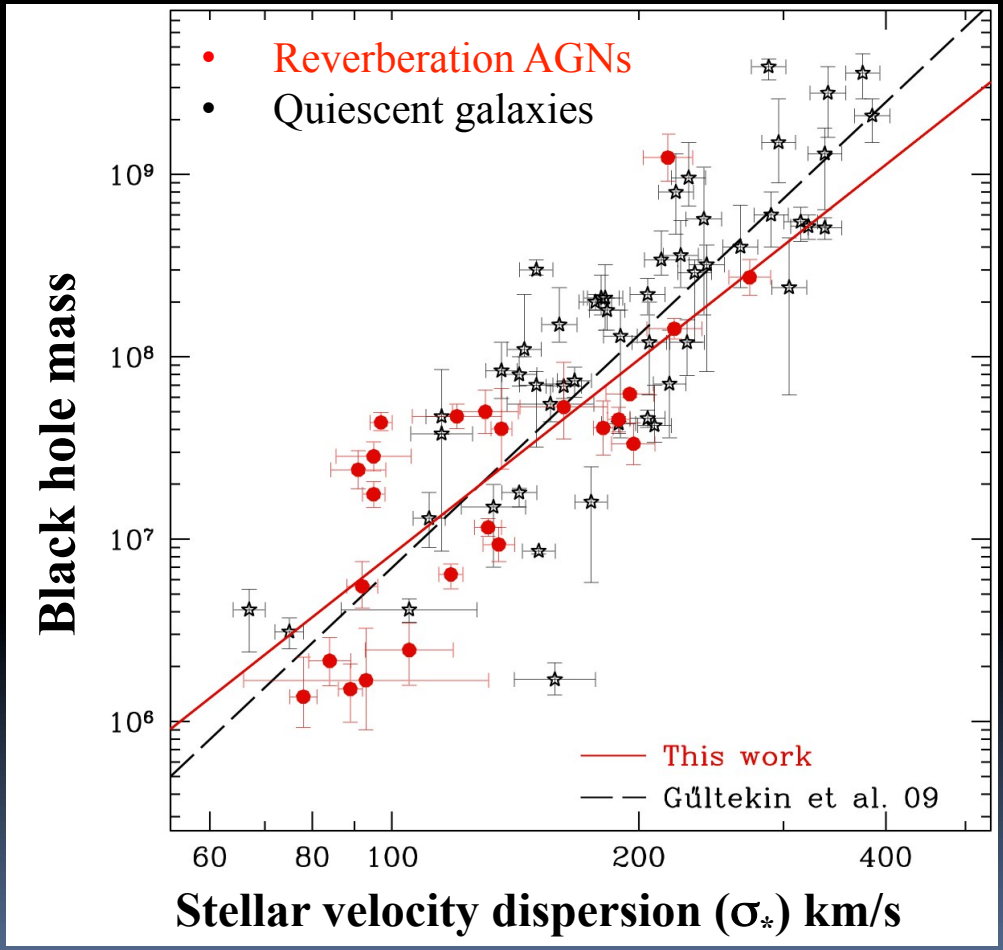
# 1. Present-day $M_{BH}$-sigma relation of active galaxies

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

# AGN $M_{BH}$ estimates partly depend on the M-sigma relation

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

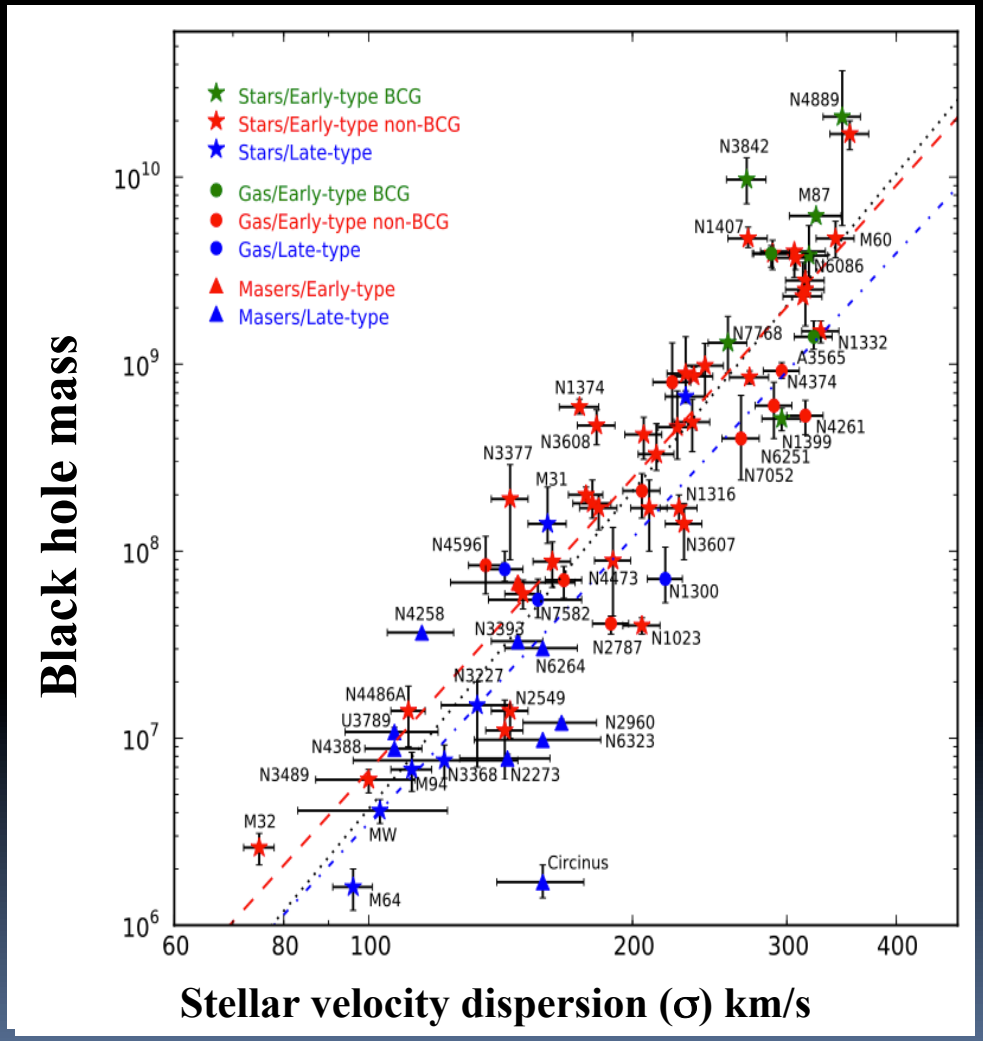
- By matching the M-sigma relations of RM AGNs and inactive galaxies, the virial factor (f) has been determined (Onken+04, Woo+10, 13, Park+12).
- Slopes are consistent within the errors.
- f = 5.2, implying non-spherical distribution of BLR




Woo et al. 2010

# Updates of the quiescent galaxy $M_{BH}$-sigma relation

- Larger sample: 72 objects with new $M_{BH}$ measurements (McConnell & Ma 13; Kuo+11)
- Improved dynamical modeling (e.g., Schulze +10)
- Steeper slop: $M_{BH} \sim \sigma^5$
- Larger scatter ~0.4-0.5 dex
- Dependence on galaxy types

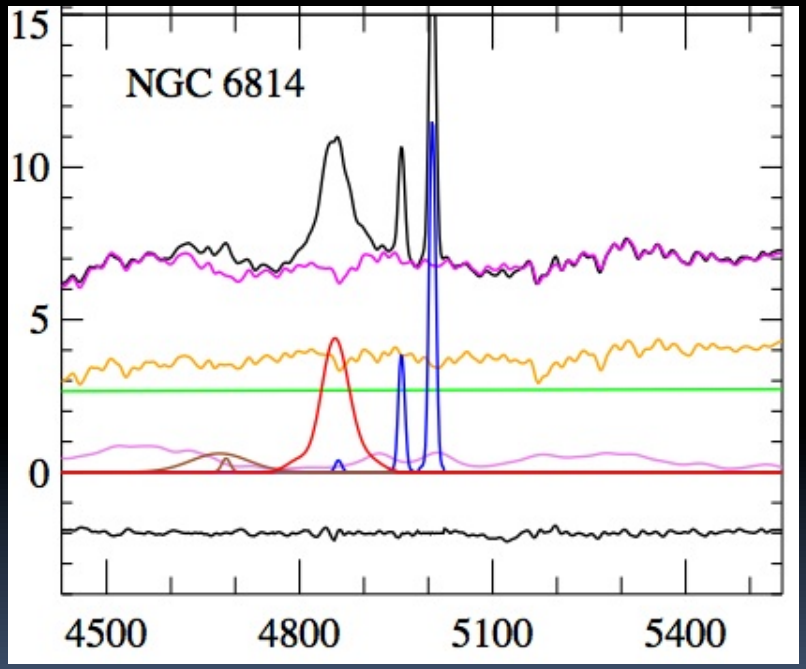



McConnell & Ma 2013

# Updates of the reverberation sample

- ~50 reverberation time lags (Lick AGN Monitoring Project, OSU group project)
- better Hb line width measurements based on multi-component spectral decomposition (Barth+11, Park+12)
- ~25 stellar velocity dispersion measurements based on AO, etc (Watson+08, Woo+10, 13, Grier+13)
- Independent virial factor determination for 2 objects based on velocity-resolved time-lags & modeling (Brewer+11, Pancost+13)

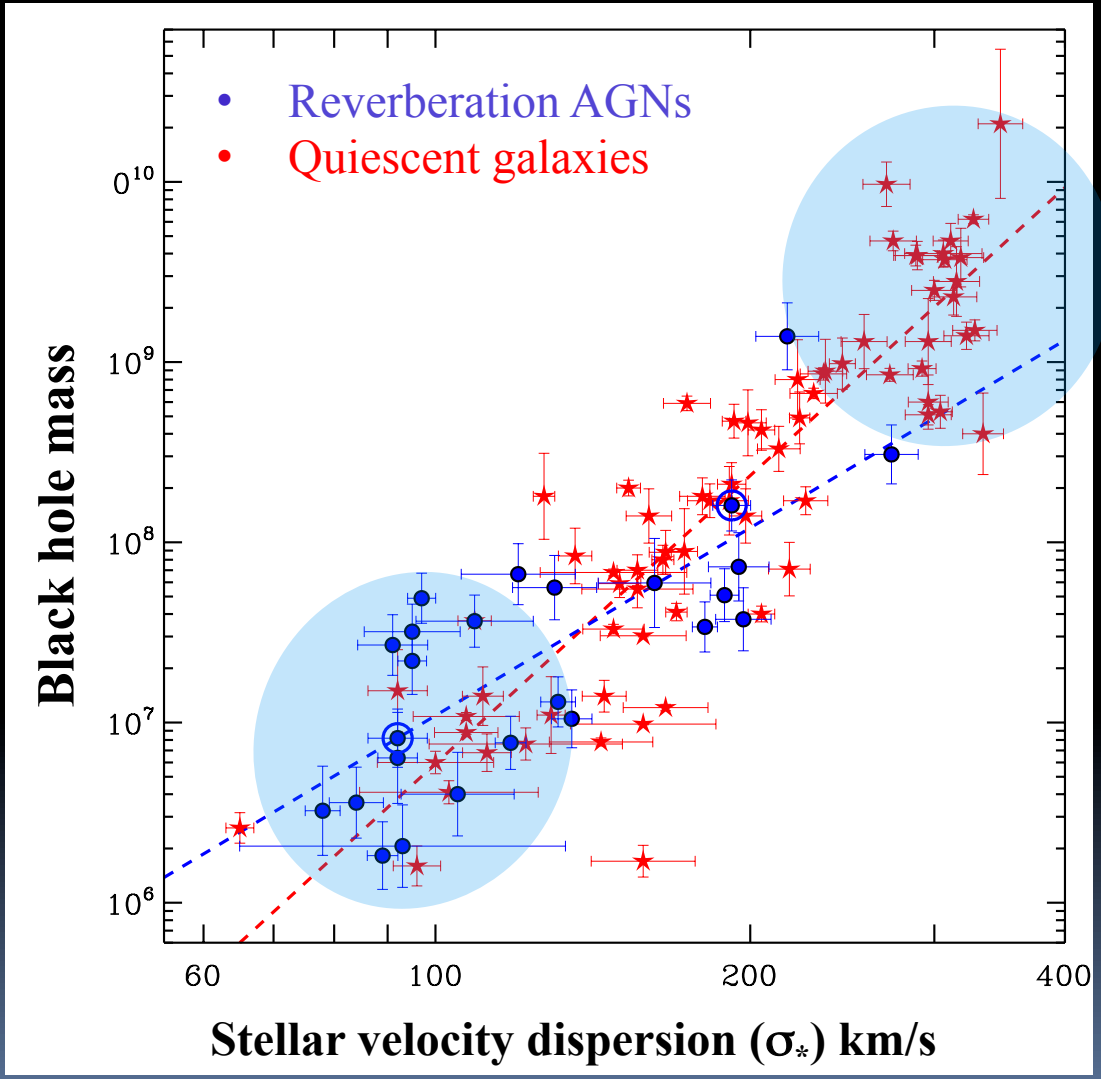
Example of multicomponent fitting with stellar, FeII emission, blended emission lines.




Park, Woo et al. 2012a

# Comparison between inactive and active galaxies

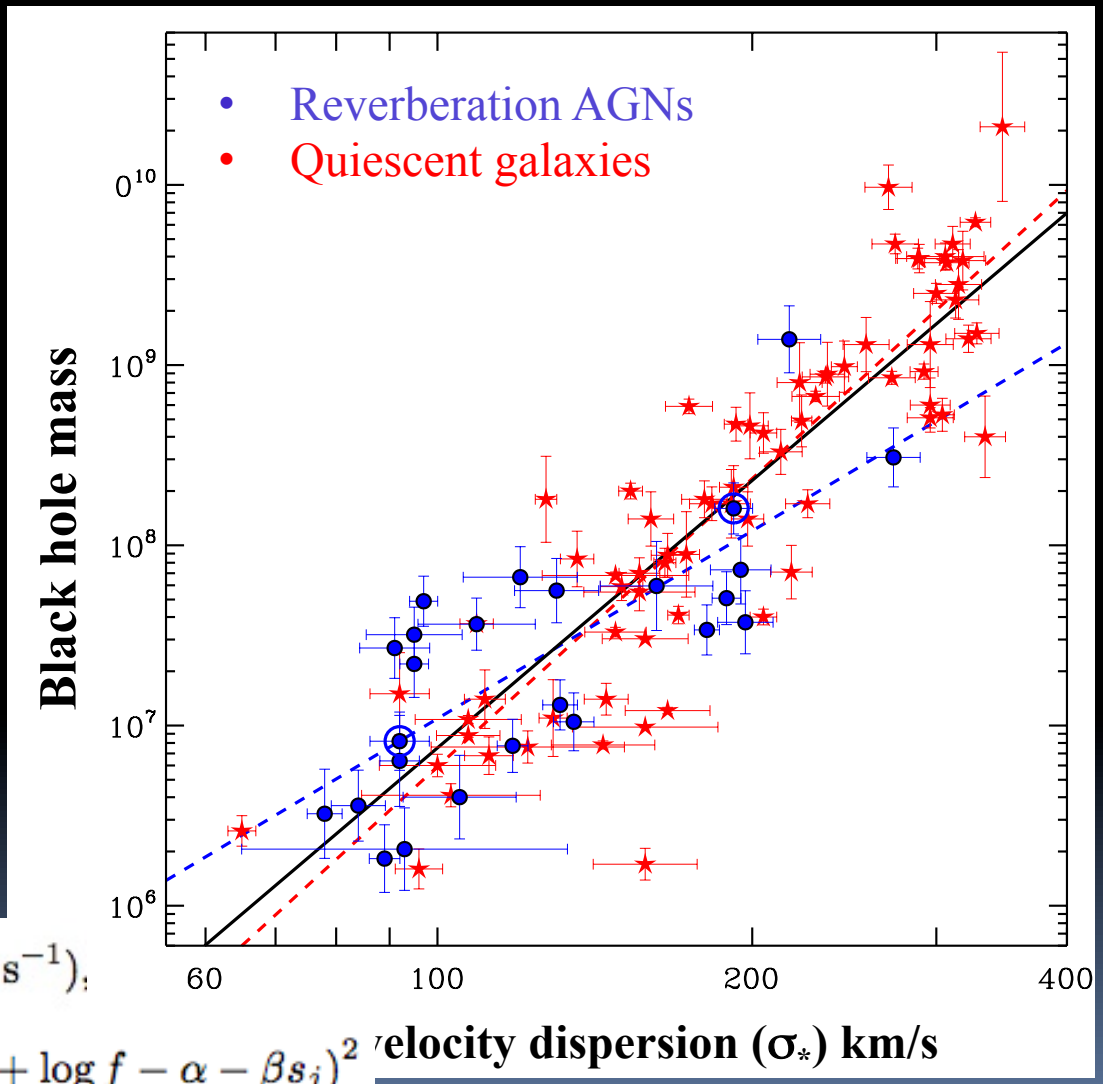
- quiescent galaxies:
  slope: 5.31±0.33
- AGN:
  new and updated $M_{BH}$ & σ
  slope: 3.46±0.61
- Is the relation same?
- Truncation in mass distribution




Woo et al. 2013

# Comparison between inactive and active galaxies

- quiescent galaxies:
  slope: 5.31±0.33
- AGN:
  new and updated $M_{BH}$ & σ
  slope: 3.46±0.61,  f=5.1
- Joint fit (Quiescent galaxies + AGNs):
  slope: 4.93±0.28,  f=5.9



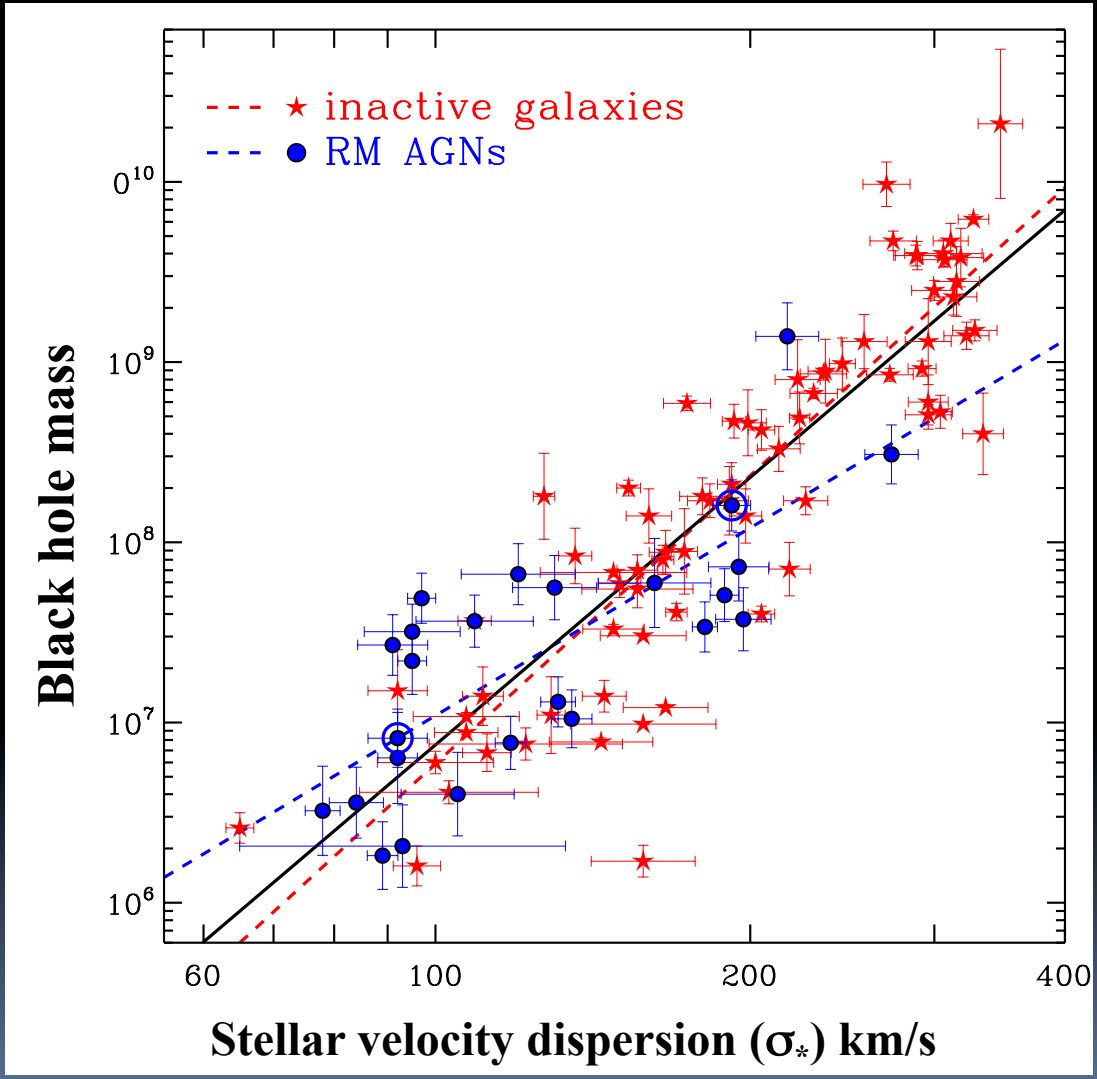

$$\log(M_{\rm BH}/M_\odot) = \alpha + \beta \log(\sigma_*/200 \text{ km s}^{-1}),$$

$$\chi^2 = \sum_{i=1}^{N} \frac{(\mu_i - \alpha - \beta s_i)^2}{\sigma_{\mu,i}^2 + \beta^2 \sigma_{s,i}^2 + \epsilon_0^2} + \sum_{j=1}^{M} \frac{(\mu_{{\rm VP},j} + \log f - \alpha - \beta s_j)^2}{\sigma_{\mu,j}^2 + \beta^2 \sigma_{s,j}^2 + \epsilon_0^2}$$

Woo et al. 2013

# Comparison between inactive and active galaxies

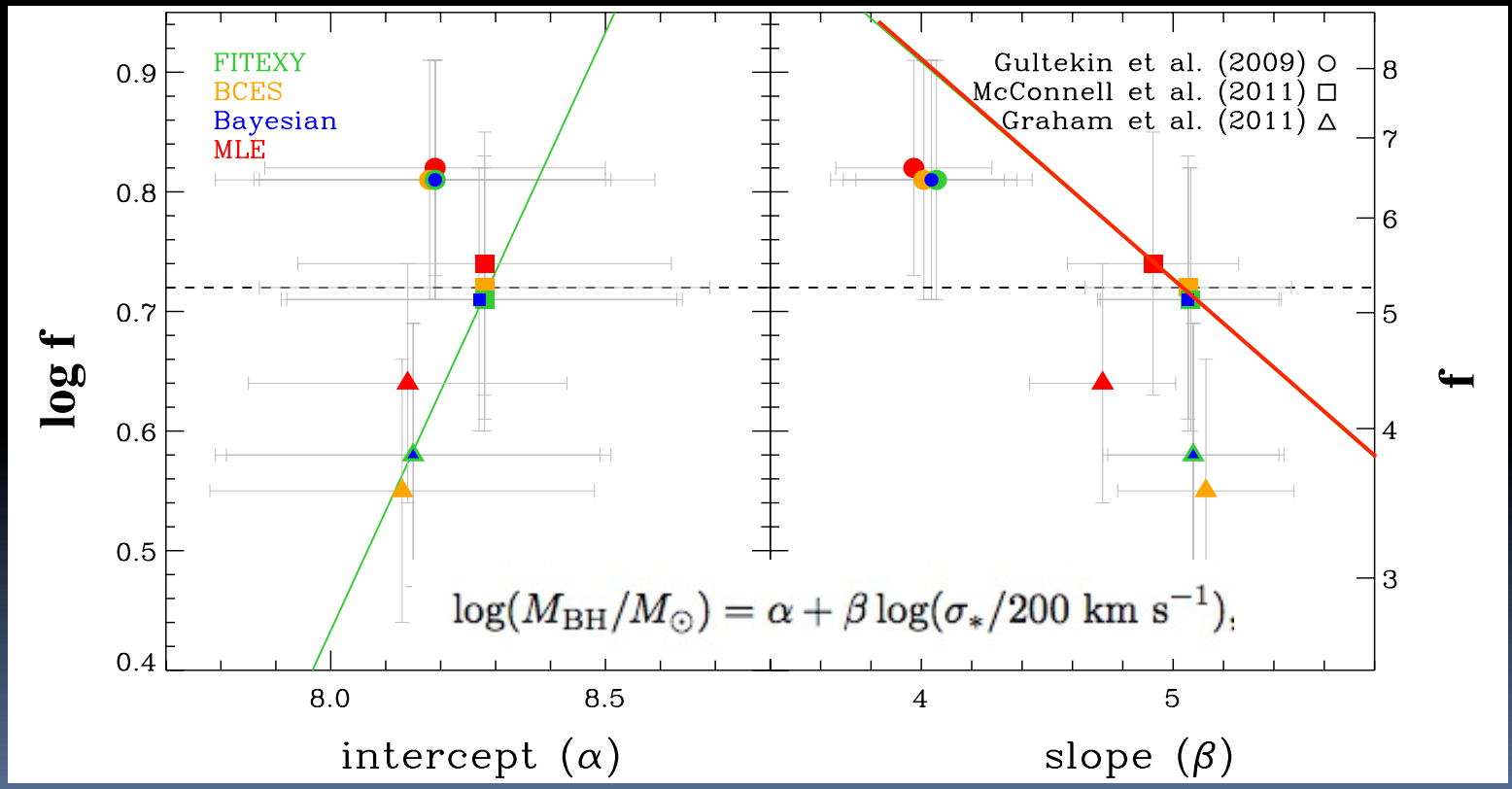
- Intrinsic scatter similar between inactive & active samples.
- Implies that <f> is close to the true value and the range f among type 1 AGNs is not large.
- For future we may obtain f for a number of individual objects based on velocity-resolved time-lags & modeling (Brewer+11, Pancost+13)




Woo et al. 2013

# Virial factor depends on the M-sigma slope

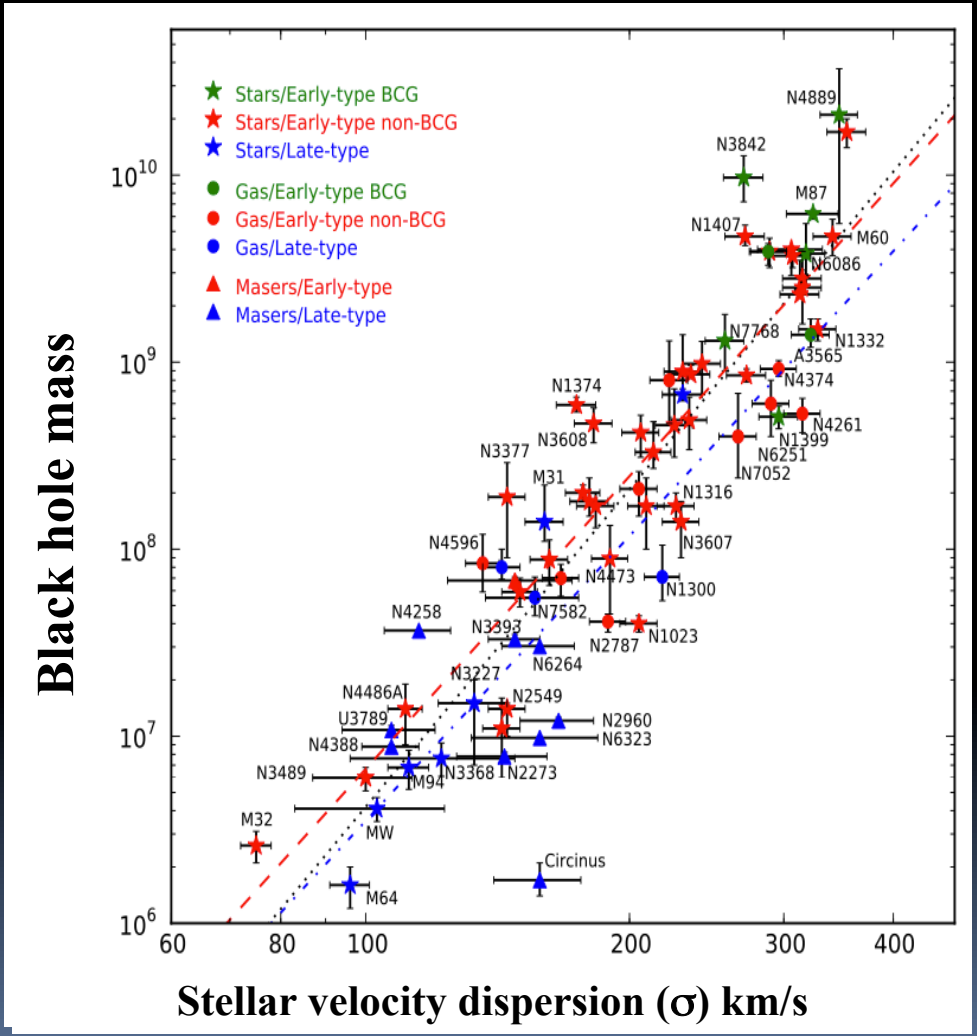
- f factor can change by 0.2-0.3 dex, depending on the slope.
- 3 compilations
  1) Gultekin et al. (2009)
  2) Graham et al. (2011)
  3) McConnell (2011)
- 4 fitting methods
  1) FITEXY
  2) BCES
  3) Bayesian
  4) Maximum likelihood




Park, Woo et al. 2012b, ApJS

# What about stellar velocity dispersions?

- Stellar velocity dispersions are not uniformly measured, hard to constrain intrinsic scatter.
- Rotation & aperture effects should be corrected.




McConnell & Ma 2013

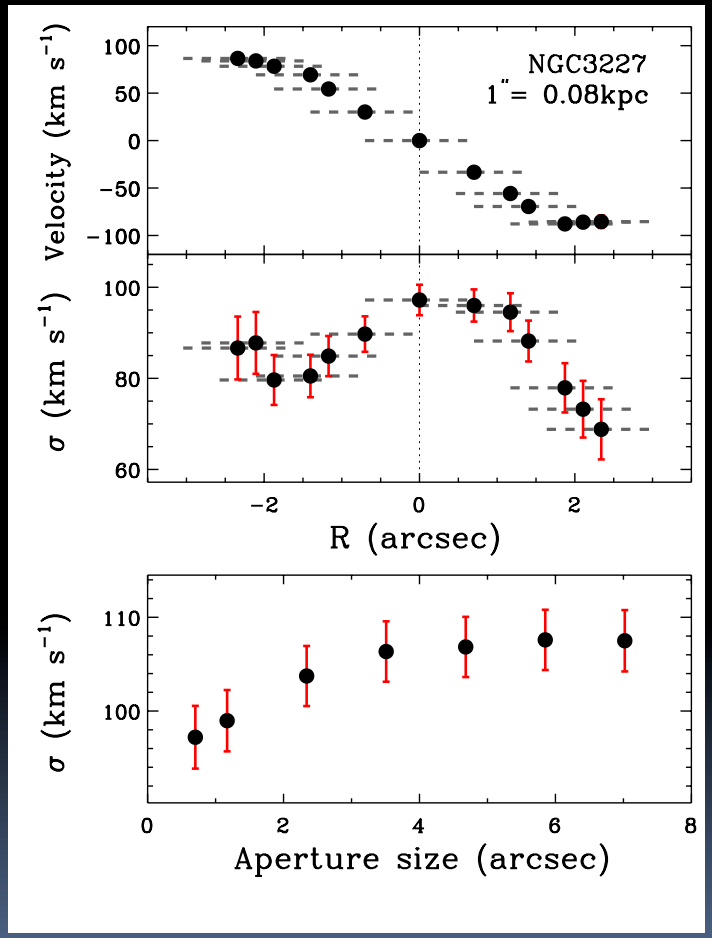
# Aperture and rotation effects

- Rotation effects should be corrected based on spatially resolved kinematics measurements
- Rotation added (McConnell+13, Gultekin+09)

$$\sigma_*^2 = \frac{\int_{-R_e}^{R_e} (\sigma_*(r)^2 + V(r)^2)\, I(r)\, \mathrm{d}r}{\int_{-R_e}^{R_e} I(r)\, \mathrm{d}r}$$

- Rotation-corrected (Woo+13, see also for AGN sample, Bennert+11, Harris+12)

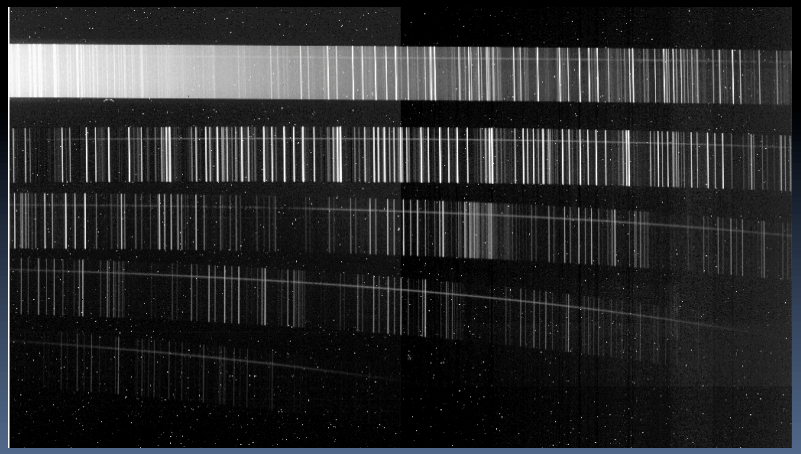
$$\sigma_* = \frac{\int_{-R_e}^{R_e} \sigma_*(r)\, I(r)\, \mathrm{d}r}{\int_{-R}^{R} I(r)\, \mathrm{d}r}$$



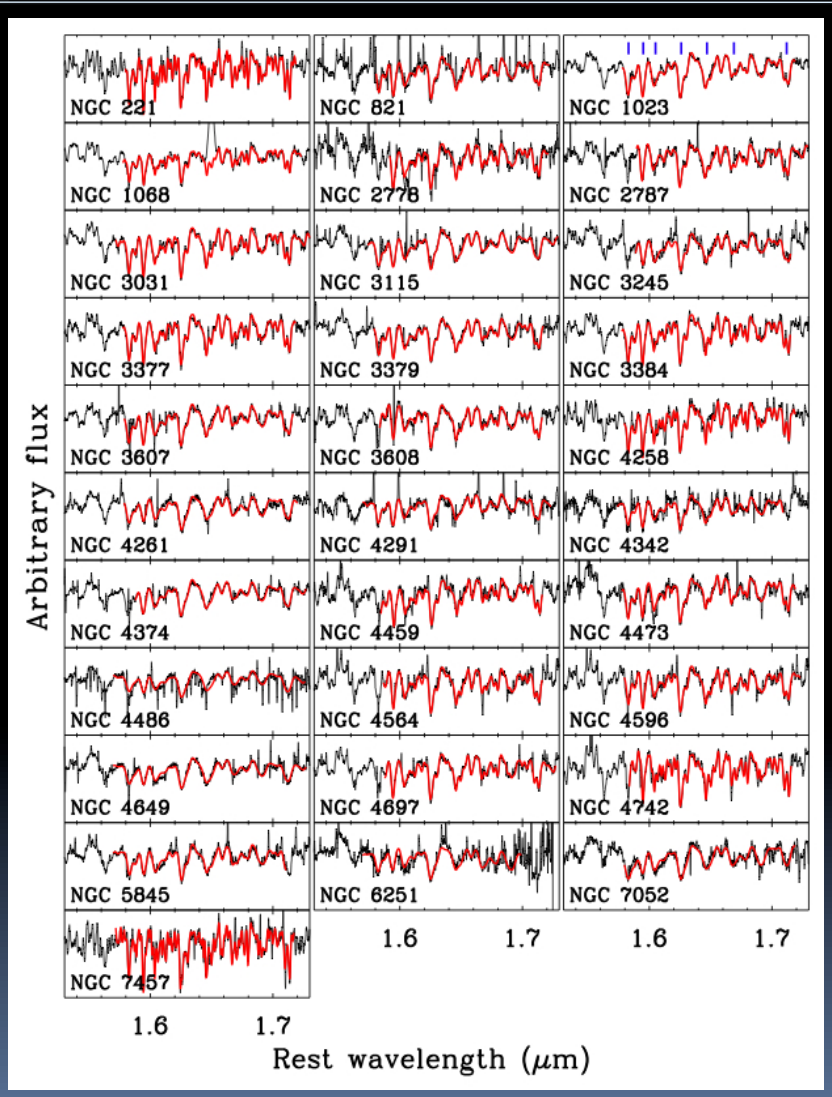

Woo et al. 2013

# Re-visiting the $M_{BH} - \sigma$ relation of quiescent galaxies

- New high S/N spectra from Palomar Triplespec (H-band)
- For 31 early-type galaxies
- Correcting for rotation and aperture effect



Palomar Triplespec data

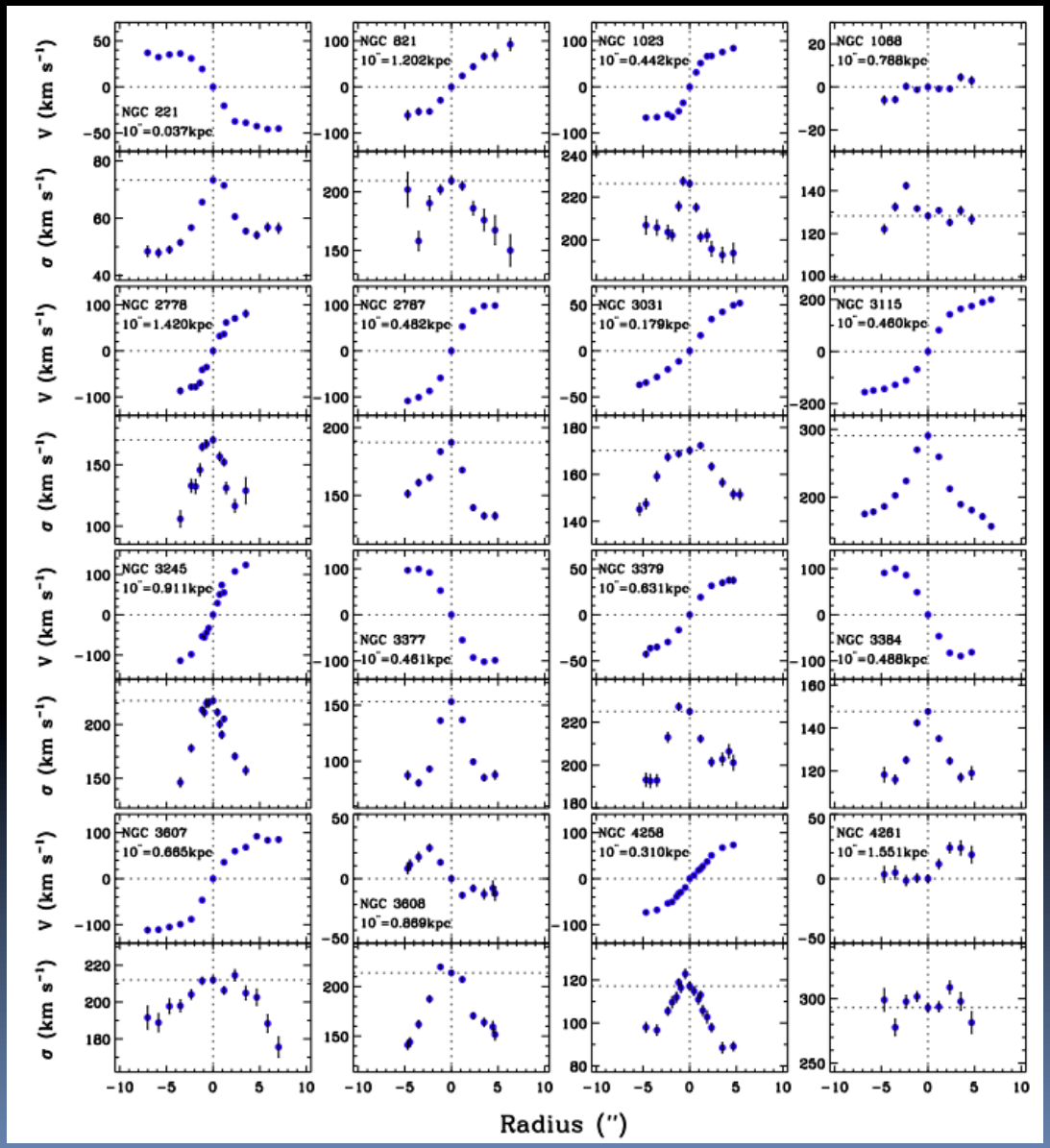



Kang, Woo + 13

# Radial distributions of velocity and velocity dispersion

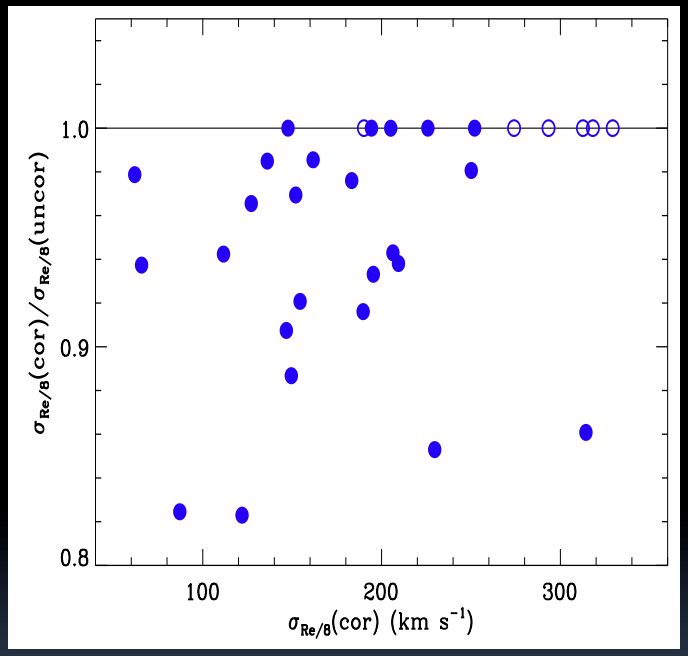
- Disk component is present in many early-type galaxies.
- Rotation & aperture effects should be corrected.
- Luminosity-weighted velocity dispersion should be used.

$$\sigma_* = \frac{\int_{-R_e}^{R_e} \sigma_*(r)\, I(r)\, \mathrm{d}r}{\int_{-R}^{R} I(r)\, \mathrm{d}r}$$

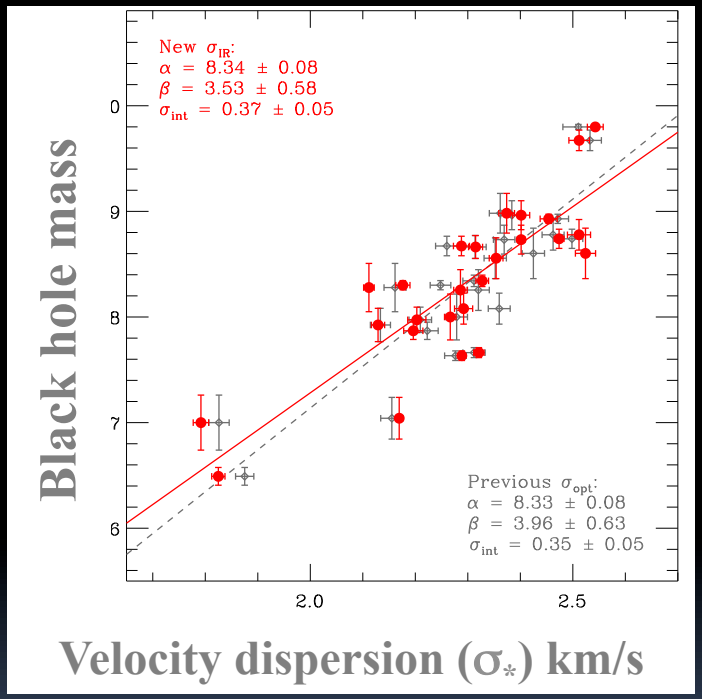


# Rotation effect on the velocity dispersion

- SVD changes by up to ~20%, if the rotation effect is corrected.




- Slope becomes slightly shallower due to smaller SVD.




Kang et al. 2013

- For late-type galaxies ( $\sigma < V$), the rotation effect is expected to be much stronger.

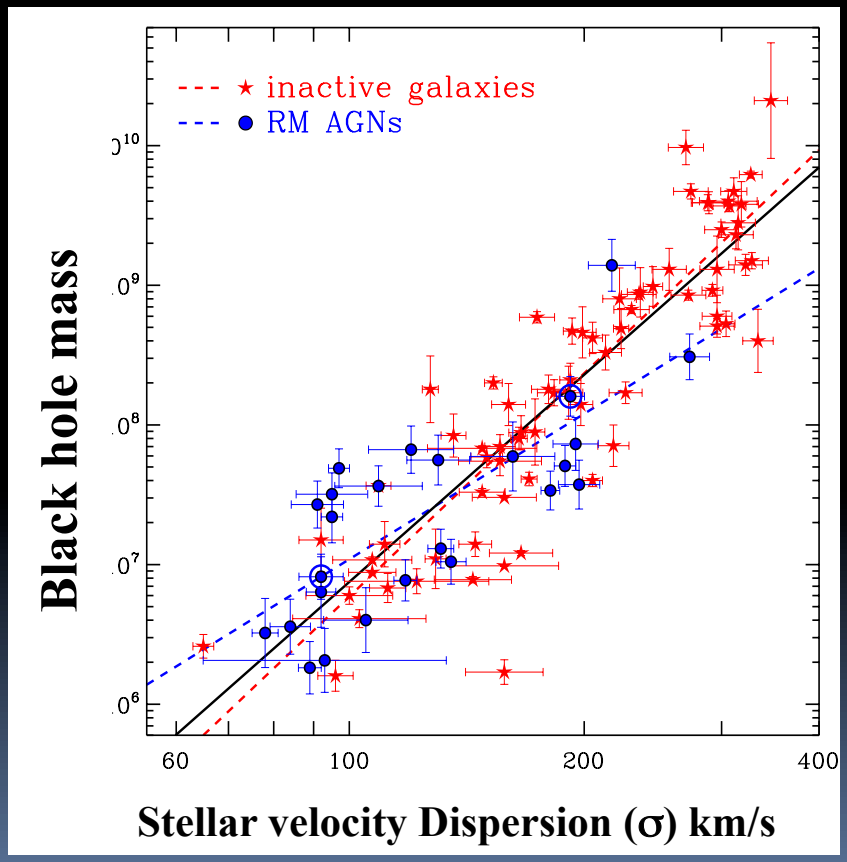
# Discussion / Summary

- AGN sample appears to have a shallower M-sigma slope than inactive galaxies. However, accounting for the difference in mass distribution, we find that active and inactive galaxies follow the same M-sigma relation.
- For proper comparison, more massive BHs in the AGN sample are needed (need to measure stellar velocity dispersion for quasars).
- The reverberation sample is not representative for AGNs. We need a large sample covering high L and high BH mass.
- Virial factor can vary by 0.2-0.3 dex if the M-sigma slope changes from 4 to 5.
- For low mass, disk-dominant galaxies, rotation effect should be corrected for measuring stellar velocity dispersion of bulges.

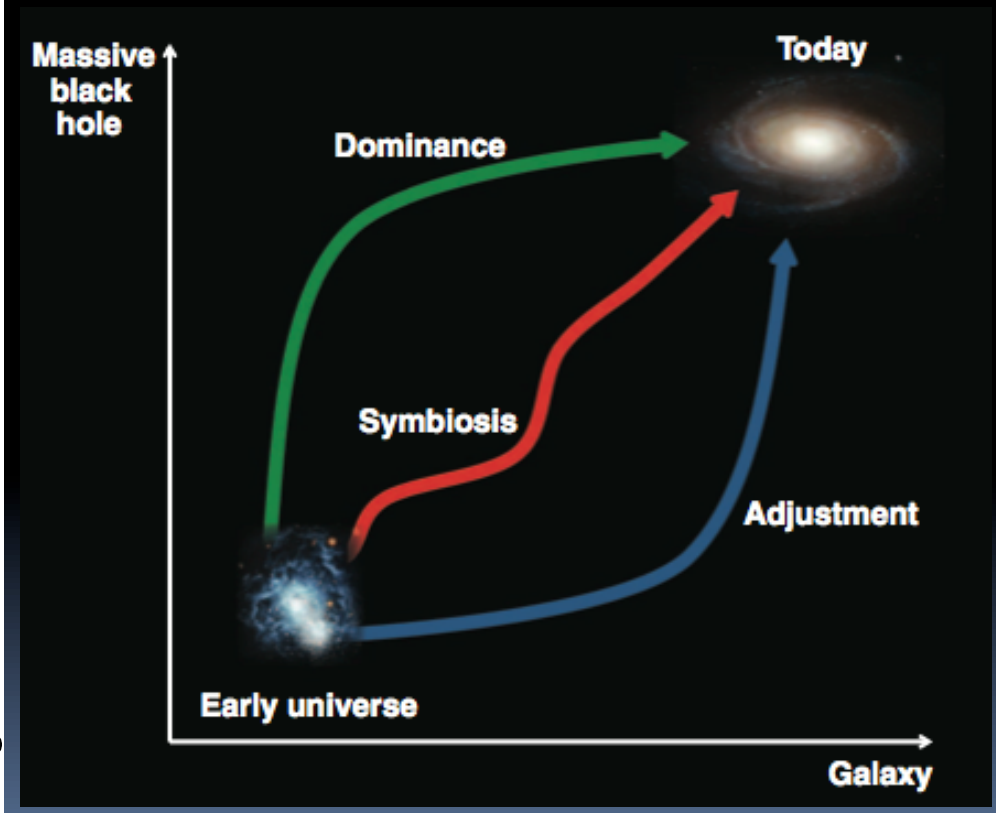
# 2. Cosmic evolution of $M_{BH}$-sigma relation

# Evolution of the Scaling Relations

- Chicken or egg?
- Observational constraint is necessary.




Woo + 13



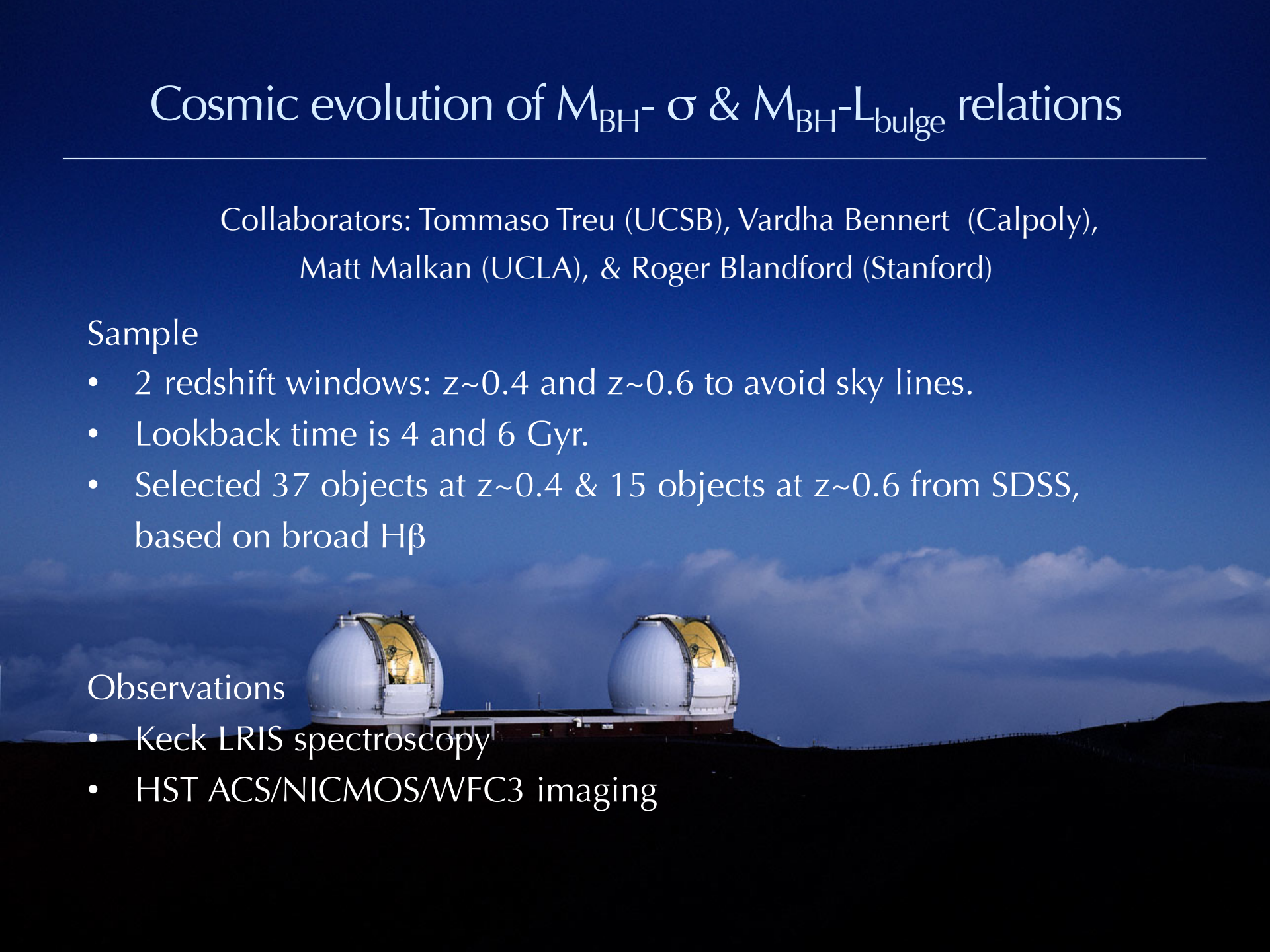

Volonteri 2012

# Cosmic evolution of $M_{BH}$- σ & $M_{BH}$-$L_{bulge}$ relations

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

Sample

- 2 redshift windows: z~0.4 and z~0.6 to avoid sky lines.
- Lookback time is 4 and 6 Gyr.
- Selected 37 objects at z~0.4 & 15 objects at z~0.6 from SDSS, based on broad Hβ

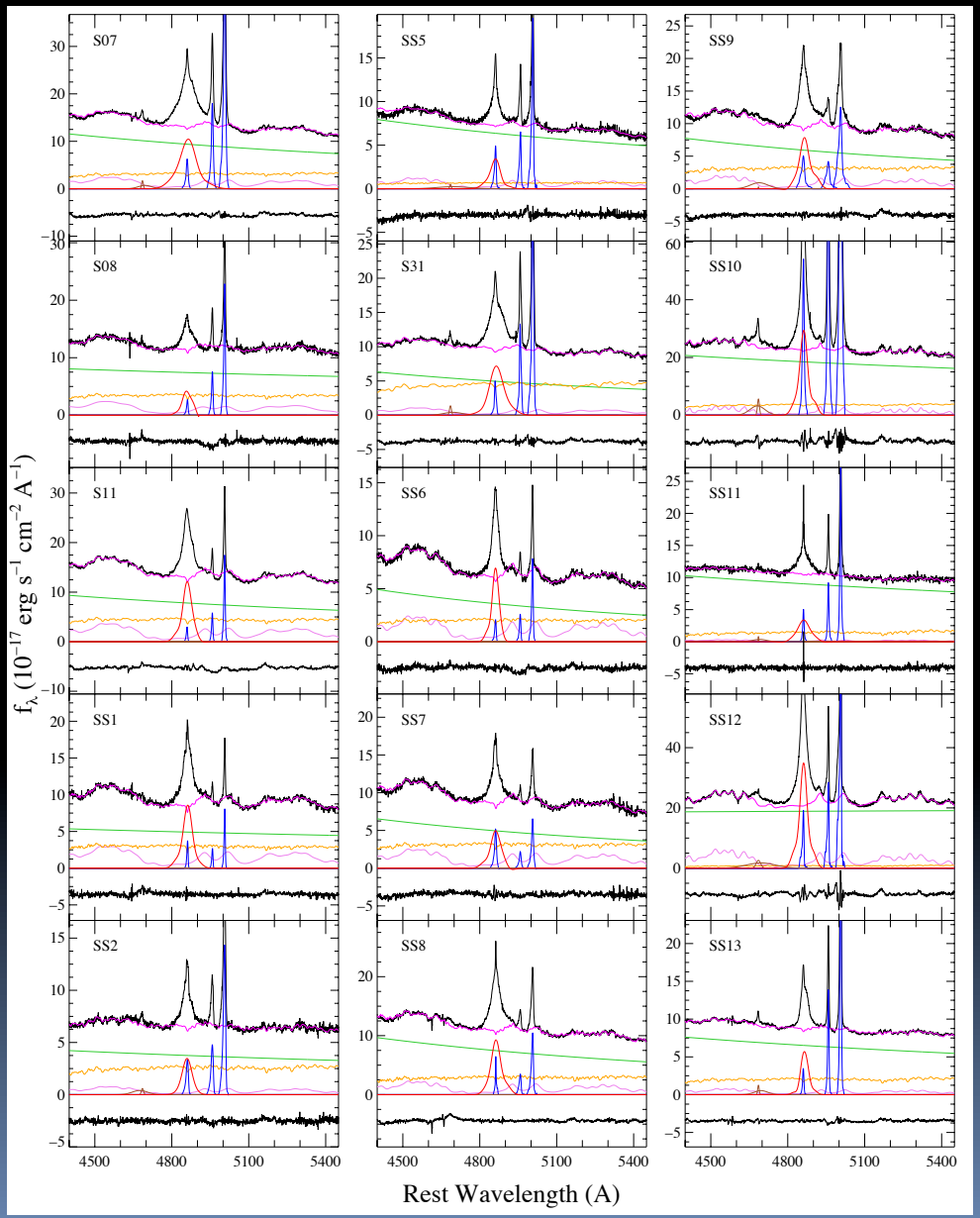


Observations

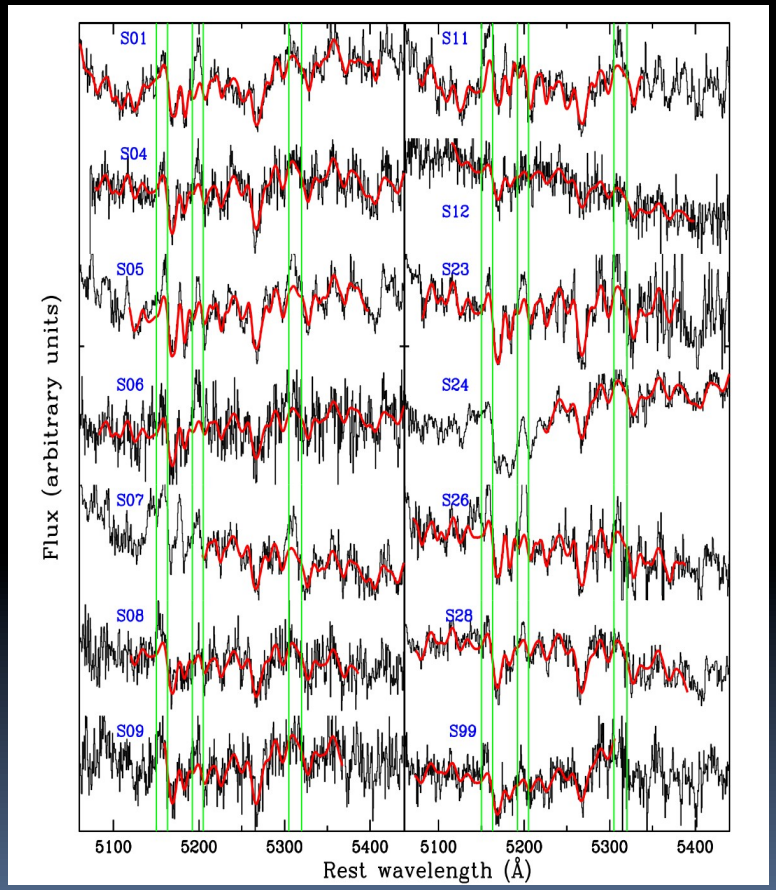
- Keck LRIS spectroscopy
- HST ACS/NICMOS/WFC3 imaging

# Estimating $M_{BH} \sim f\ V^2\ L^{0.5} / G$

# Measuring velocity dispersion




\Measured for 34 objects
No measurements for 18

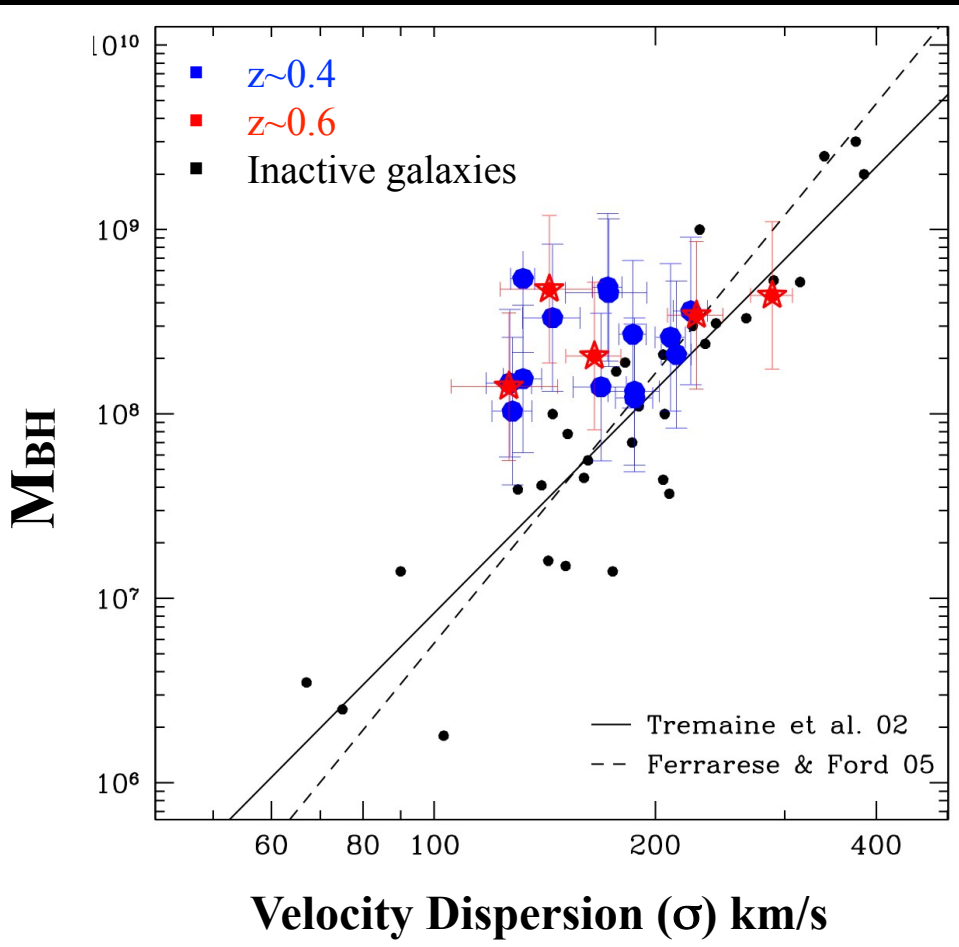



Woo + 06, 08

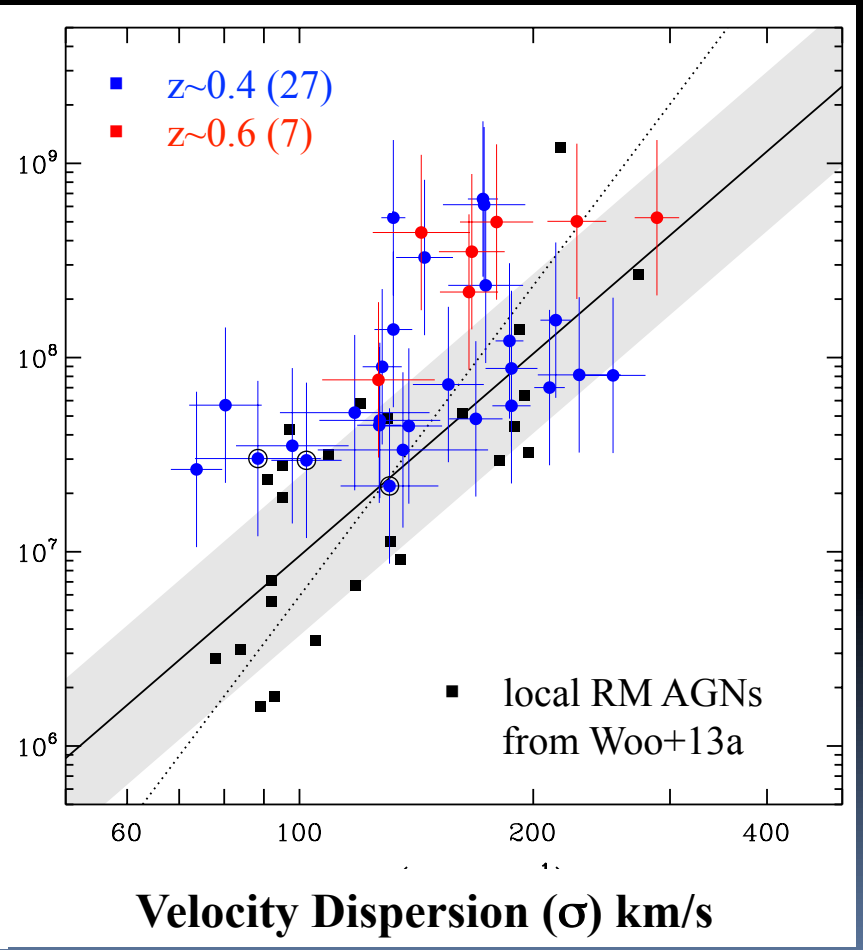
# The $M_{BH}$ – sigma relation 4-6 Gyr ago

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

Woo et al. 2006, 2008



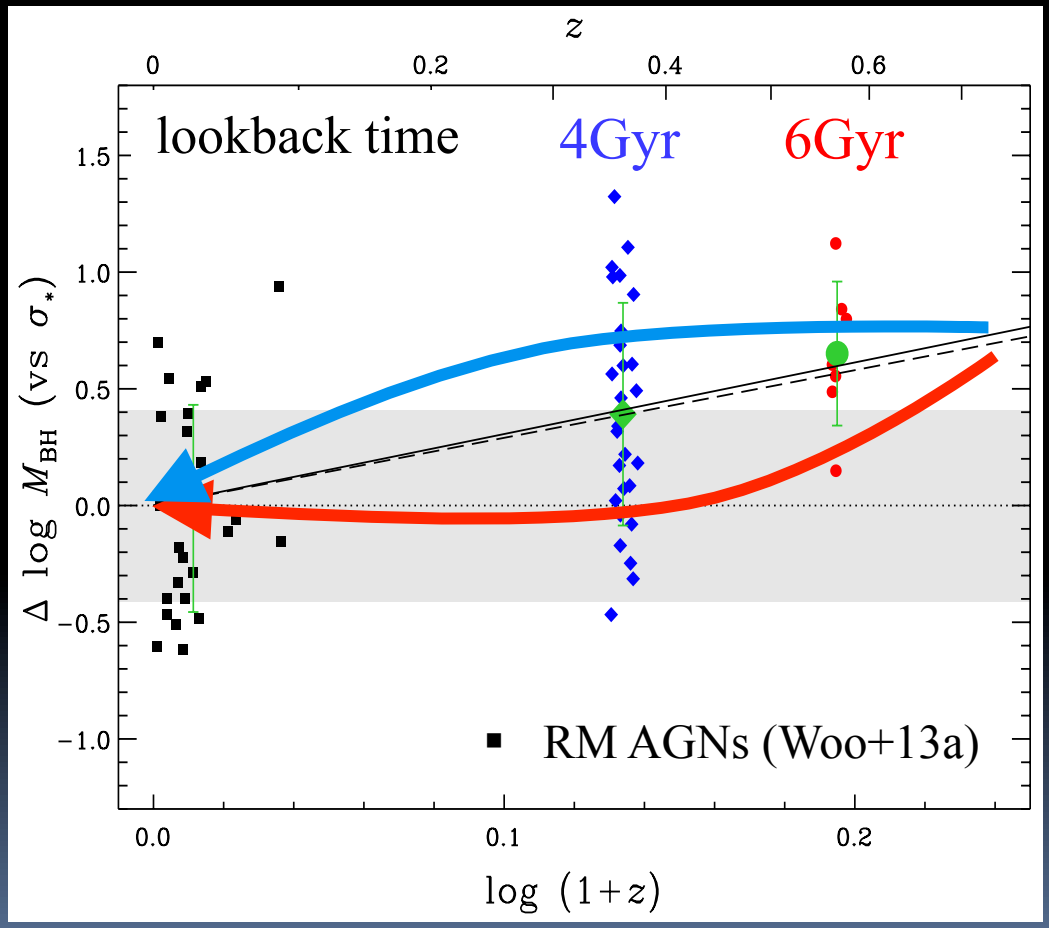

Woo et al. 2013b in preparation



# Evolution of the $M_{BH}$ - sigma Relation

- Black holes lived in smaller galaxies in the past.
- Evolution is Independent of the virial factor
- Mass-dependent evolution

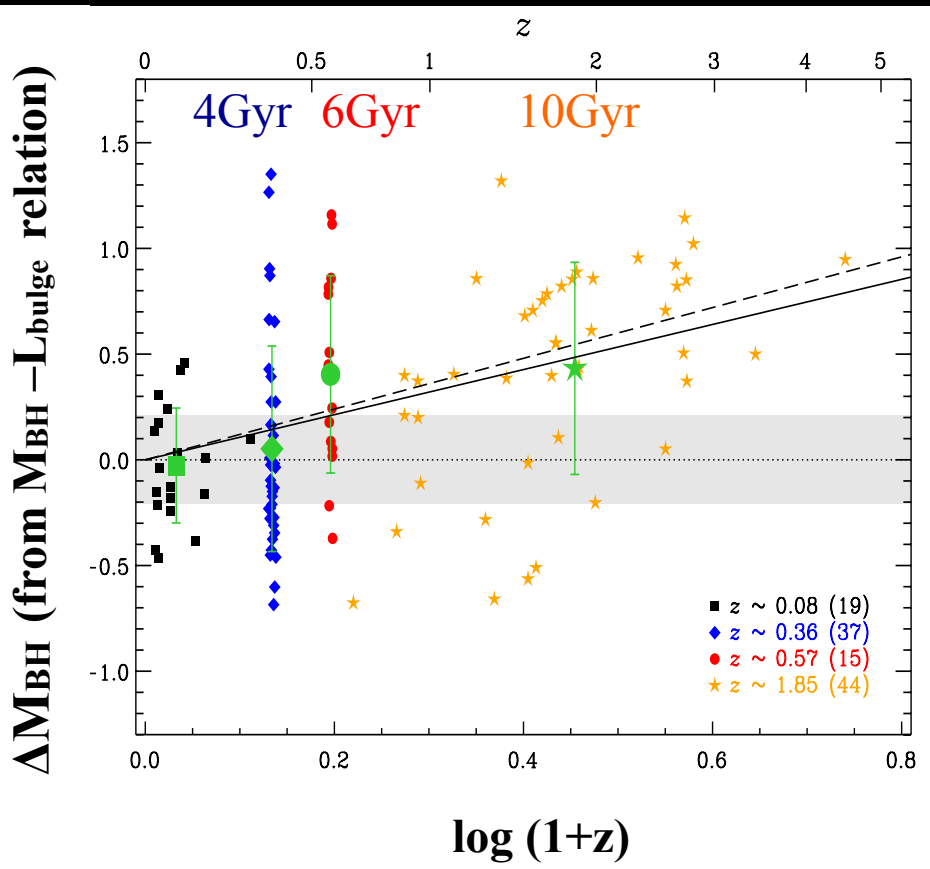
$$\Delta M_{BH} = (1 + z)^{2.9 \pm 0.7}$$

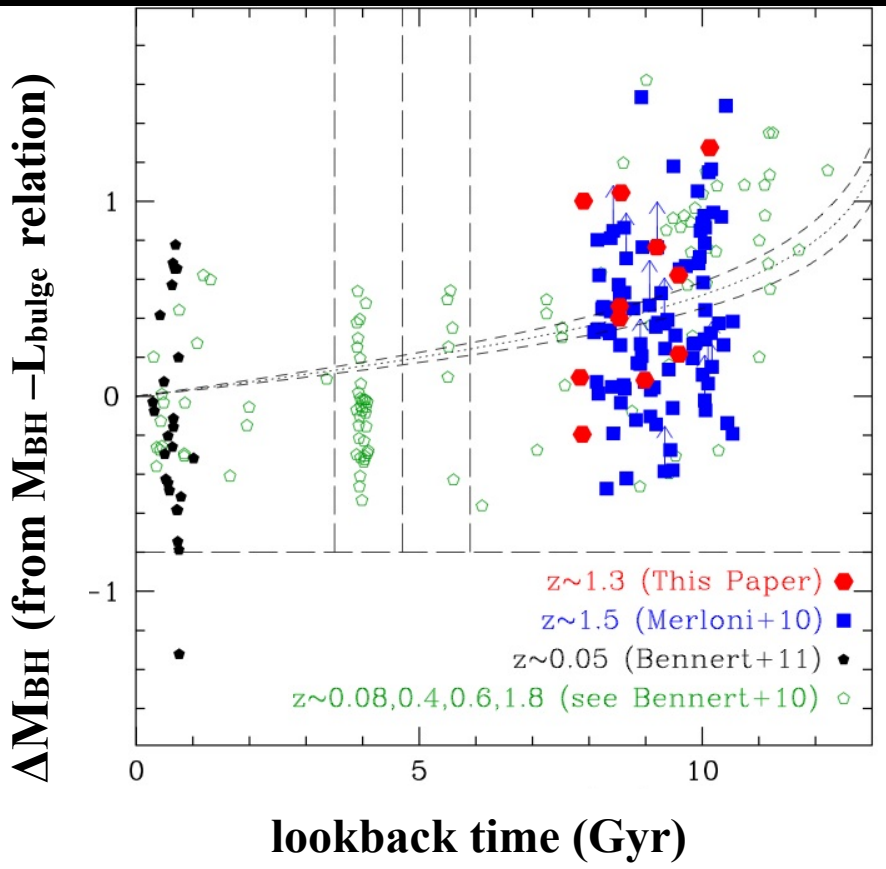



Woo et al. 2013b in prep.

# Evolution of the scaling relation

- Black holes lived in smaller bulges (galaxies) in the past
  (e.g., Peng+06, Merloni+10, Schramm & Silverman 13…)



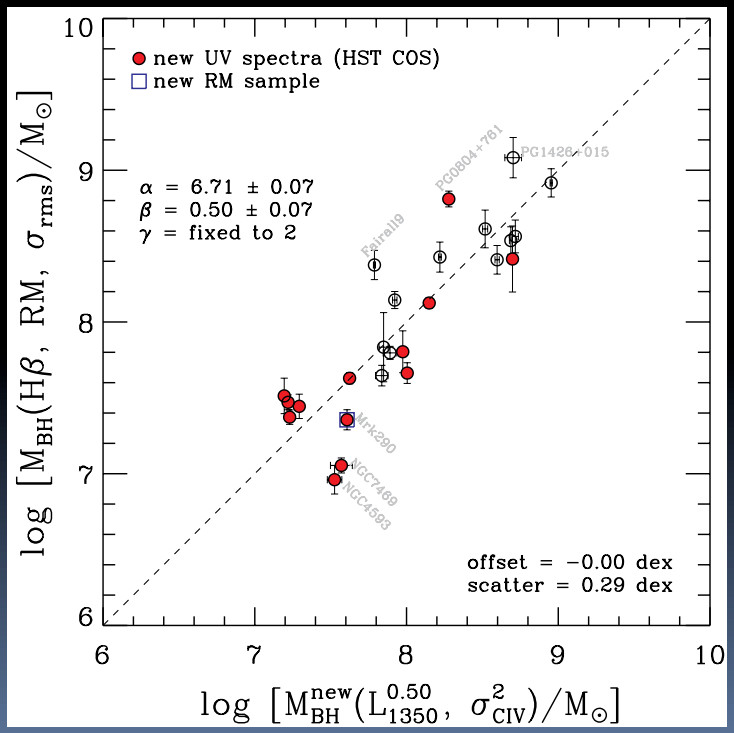

Park et al. 2013 in prep.

Bennert et al. 2011

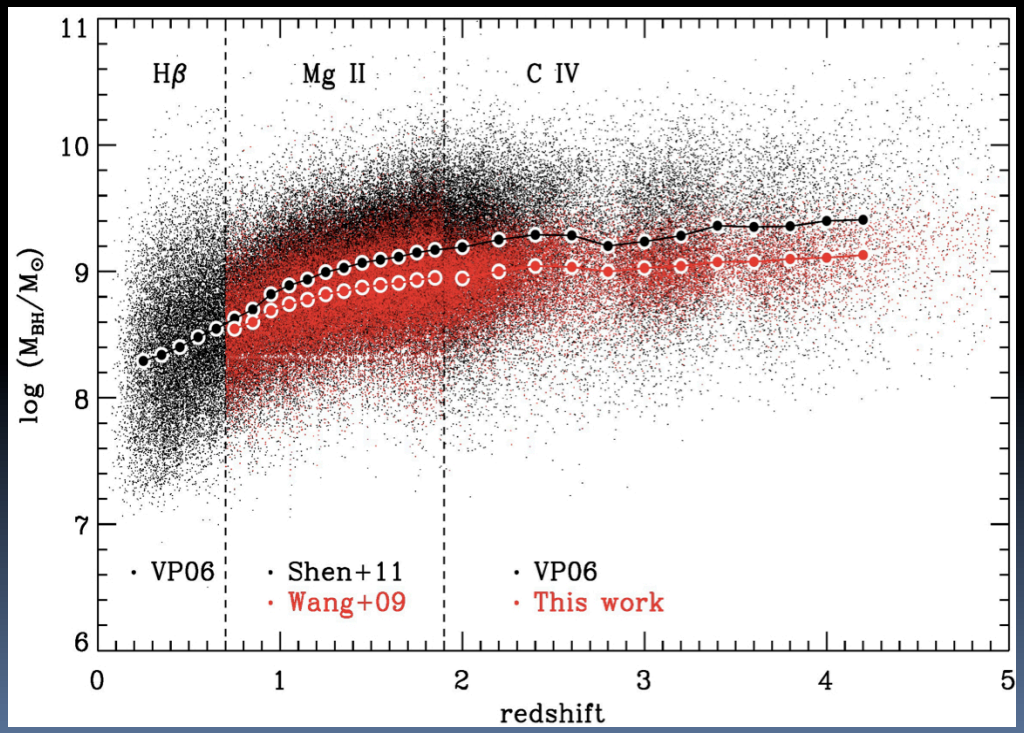
# Issues on single-epoch $M_{BH}$ estimates for high-z AGNs

- more uncertain due to additional calibration for MgII or CIV.
- could be systematically lower or higher depending on calibration.

New calibration of the CIV-based $M_{BH}$ estimator



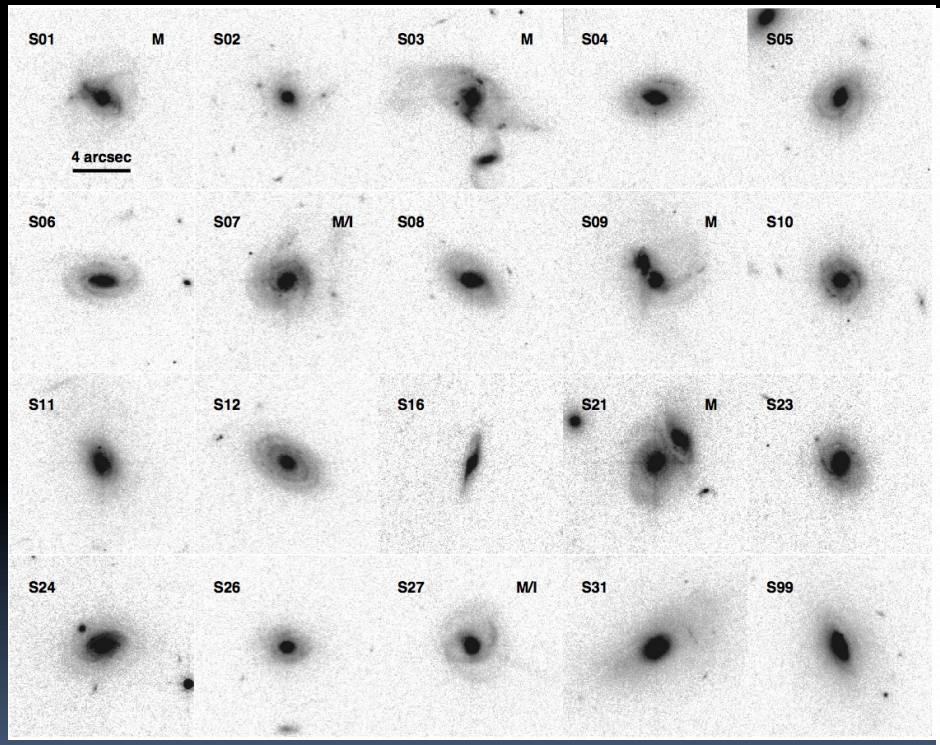

$M_{BH}$ estimates based on Hb/MgII/CIV lines

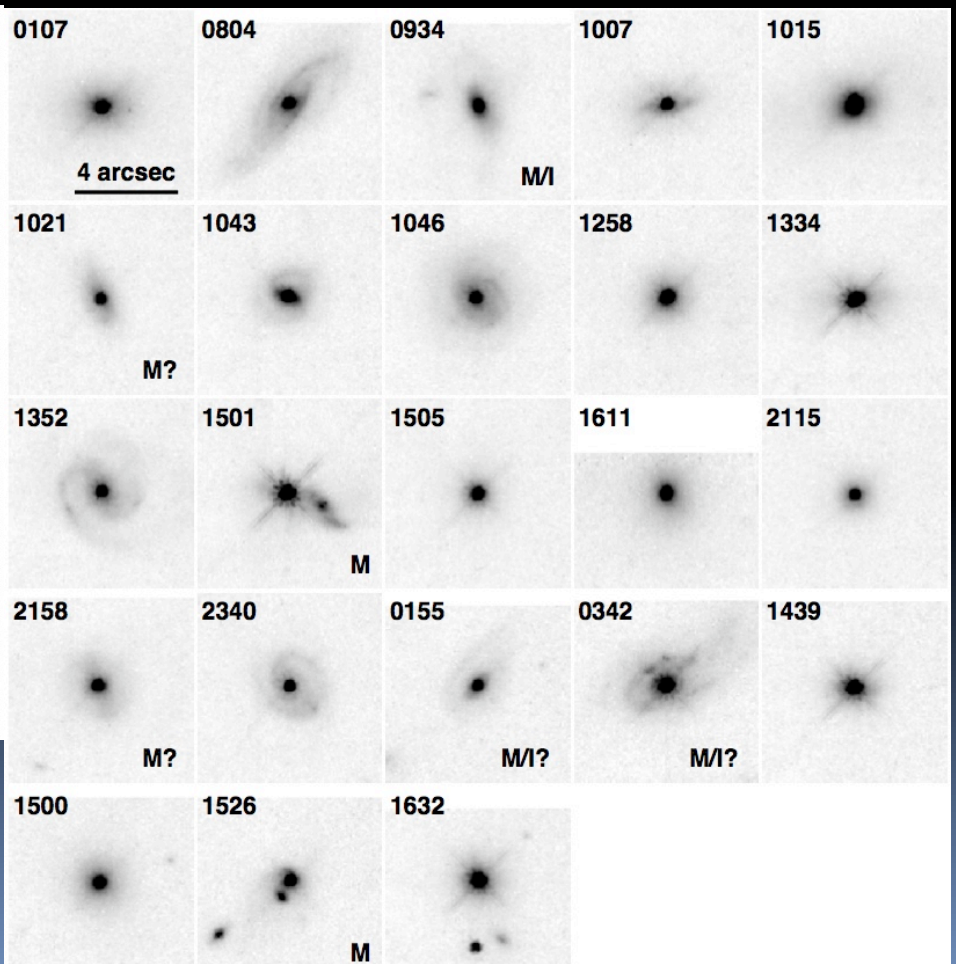



Park, Woo +13

# Recent evolution of (active) bulges?

- 1/3 shows disturbed morphology (cf. local Swift-BAT sample by Kross+10,11)
- Galaxy merging is still playing at this mass scale
- Transformation of rotation-supported to pressure-supported




HST images (Treu+07, Bennert+10, Park+13)

# Current limitations/challenges

- The uncertainty of BH mass estimates is a limiting factor.
- More representative local AGN sample is needed (reverberation sample may be biased).
- Stellar velocity dispersion of AGN host galaxies: Challenging at z~0.5. Possible at z~1?
- Bulge/disk decomposition with HST resolution: Challenging for small bulges at z~0.5. Total luminosity?

# Summary II

- At fixed $M_{BH}$, bulges at z~0.4 & 0.6 appear to be smaller/ less luminous compared to the local sample.
- Selection effects alone cannot explain the observation.
- BH growth predates final assembly of spheroid at intermediate mass scale.
- We need to study mass-dependent evolution.