Black hole – galaxy scaling relations and gas outflow

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Outline

1. Black hole – galaxy scaling relation and its evolution
2. Census of Ionized gas outflows in type 2 AGNs

Thanks to

Daeseong Park (UCI), Kenta Matsuoka, Jaejin Shin, Yosep Yoon (SNU), Hyun-Jin Bae (Yonsei)

&

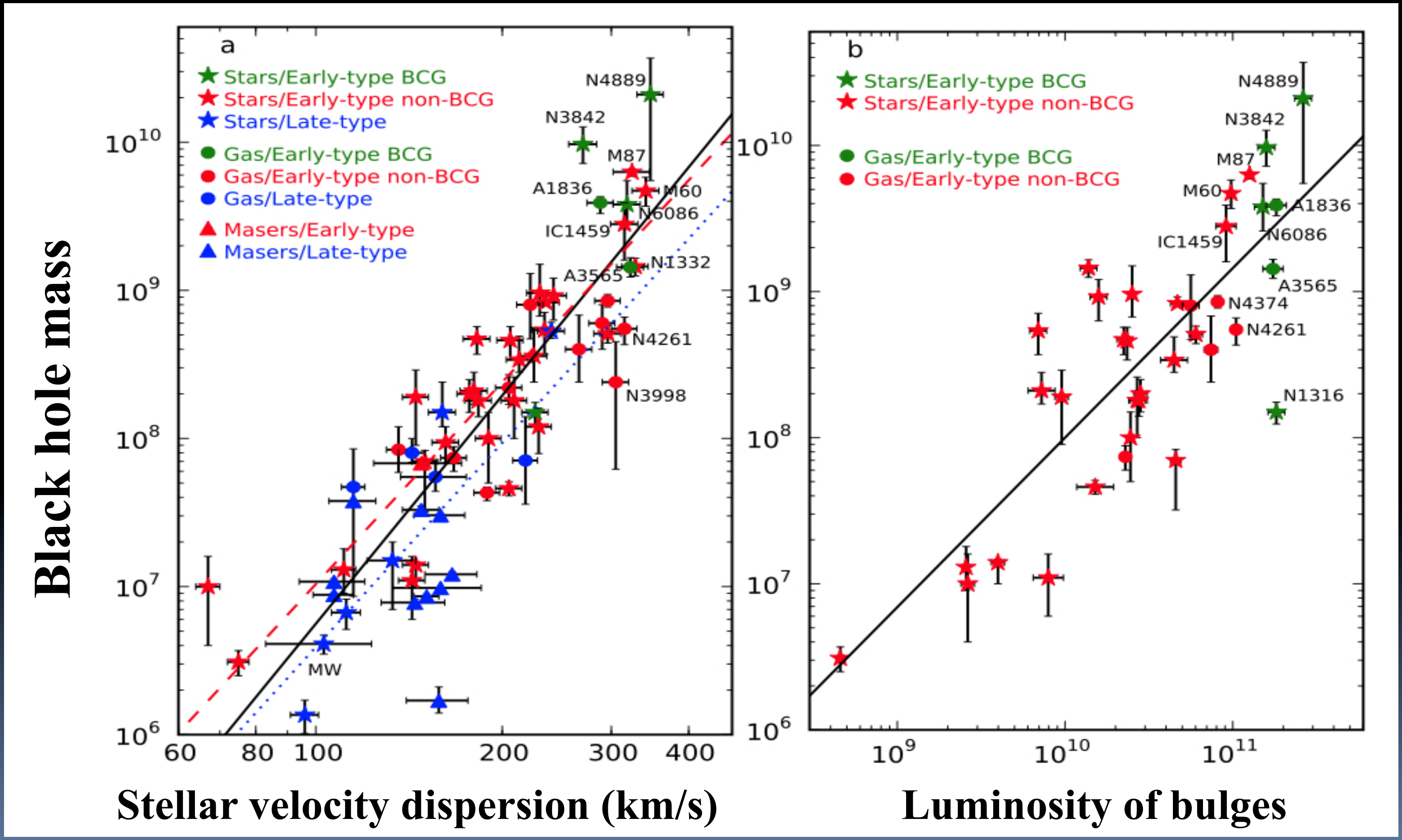
Tommaso Treu (UCSB), Aaron Barth (UCI), Vardha Bennert (Cal. Poly), Matt Malkan (UCLA), Roger Blandford (Stanford), Brandon Kelly (UCSB), Andreas Schulze (IPMU)…

Part 1.

Black hole-galaxy scaling relation and its evolution

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?

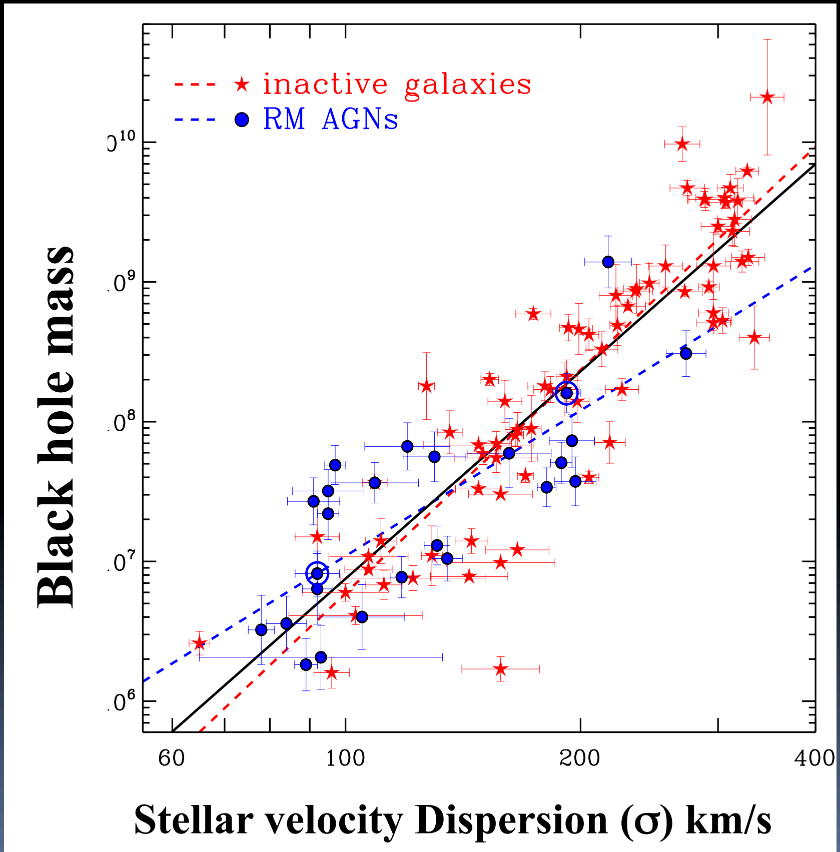
- Due to galaxy merging (Peng 07; Jahnke+11)

Dependence on galaxy type, mass, & evolution history

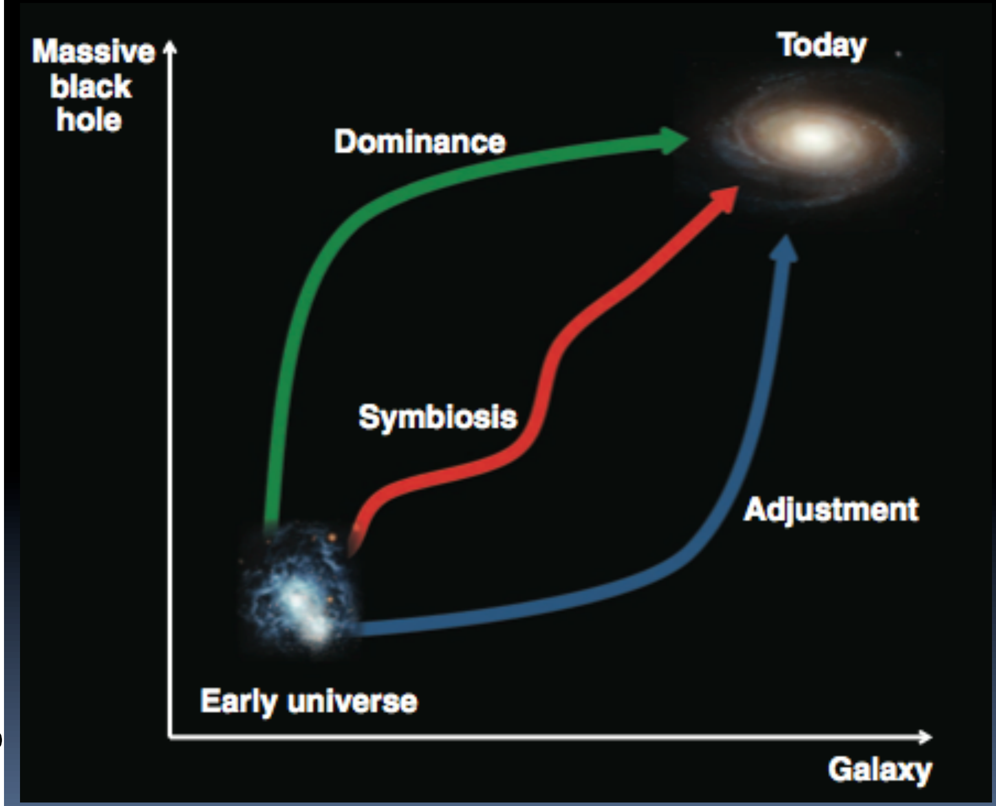
- Classical vs. pseudo bulges (Kormendy & Ho 2013)
- Early vs. late type galaxies (McConnell & Ma 2013)
- Merging vs. secular evolution (e.g., Croton 06, Shankar+13)

Evolution of the Scaling Relations

- Chicken or egg?
- Observational constraint is necessary.



Woo + 13

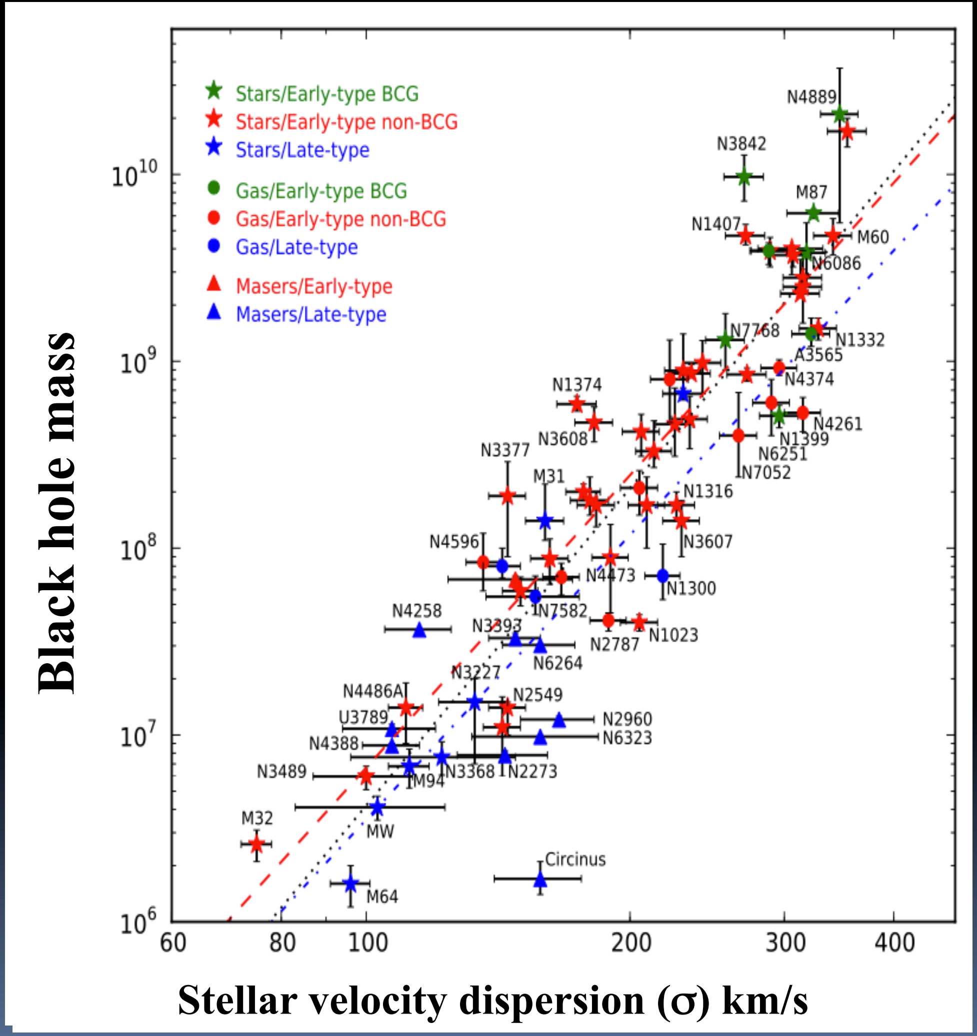


Volonteri 2012

Present-day M_{BH}-sigma relation

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

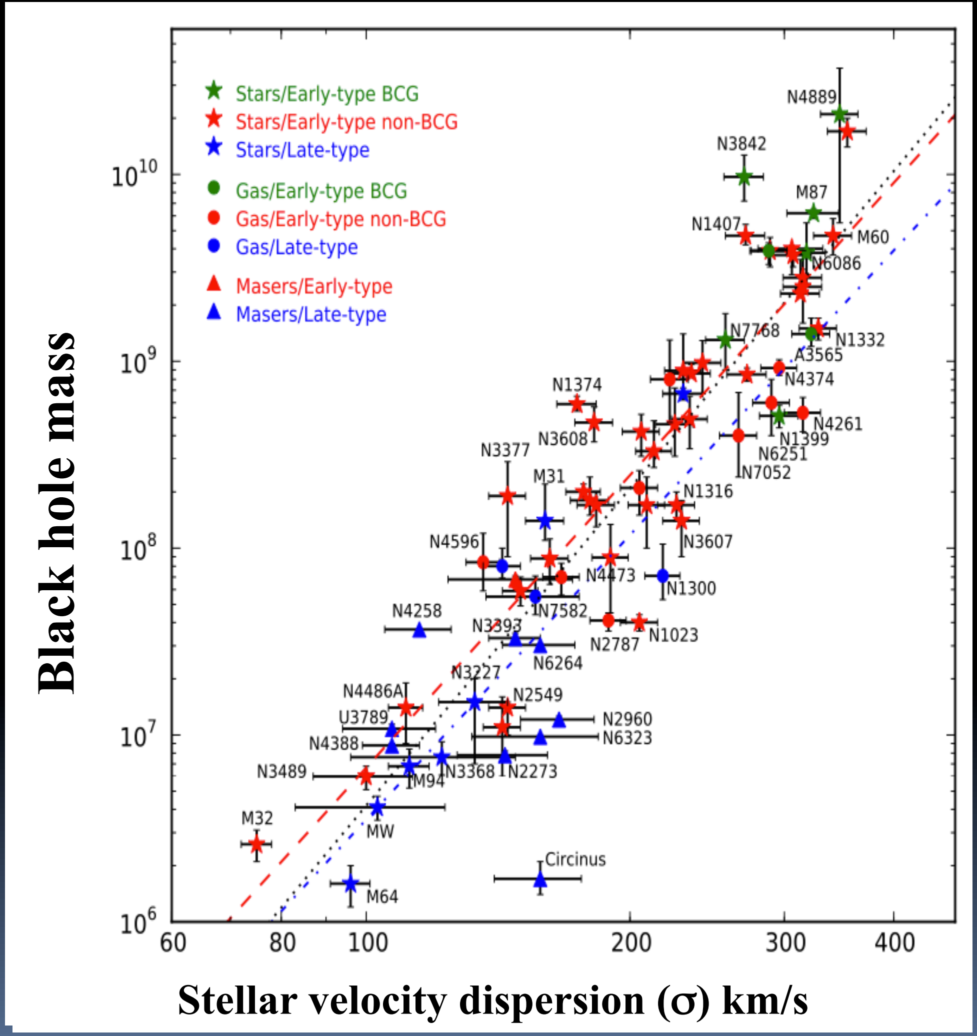
- Larger sample: 72 objects with new M_{BH} measurements (McConnell & Ma 13; Kuo+11)
- Improved dynamical modeling (e.g., Schulze +10)
- Steeper slop: $M_{BH} \sim \sigma^5$
- Larger scatter ~0.4-0.5 dex
- Dependence on galaxy types



McConnell & Ma 2013

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

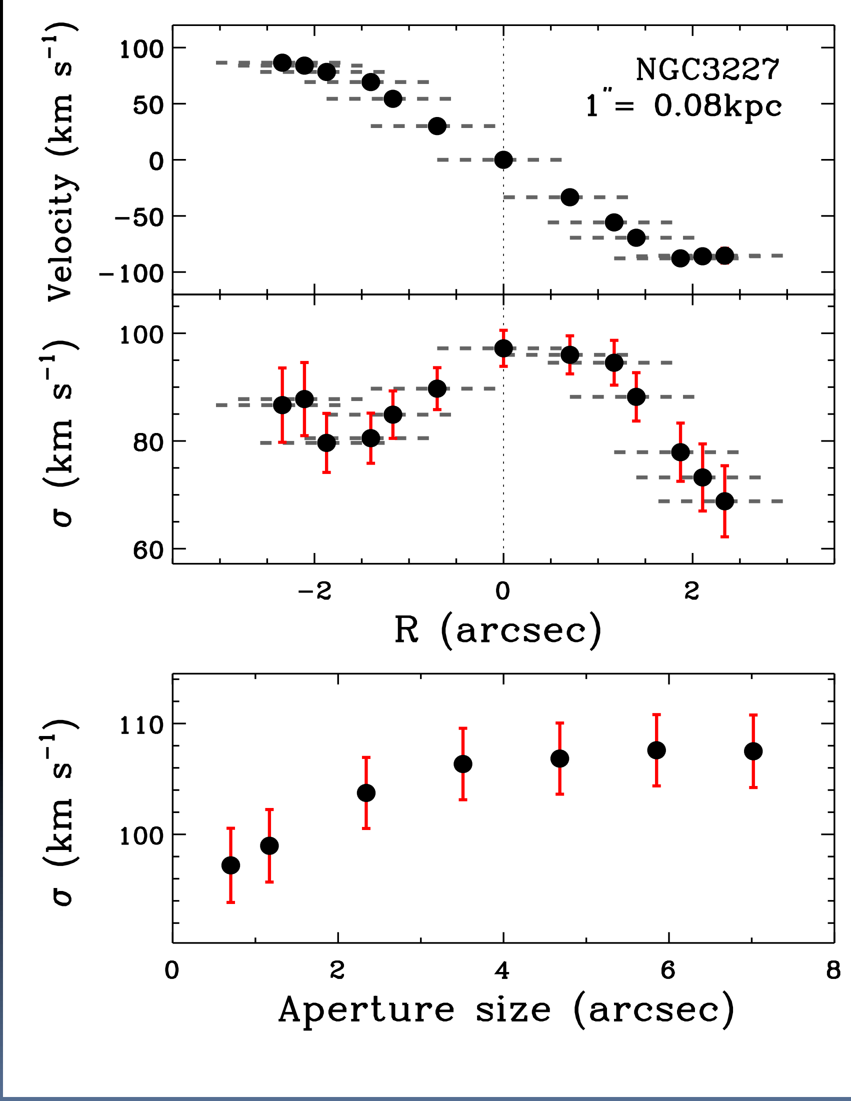
- Rotation effects should be corrected based on spatially resolved kinematics measurements

- 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)

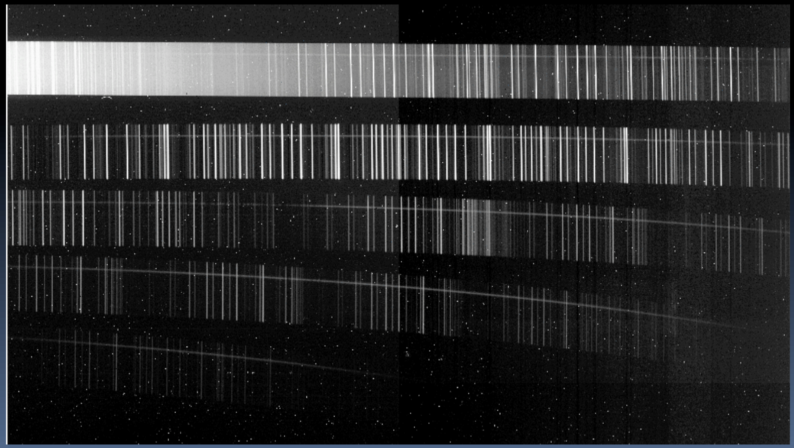
$$\sigma_* = \frac{\int_{-R_e}^{R_e} \sigma_*(r)\, I(r)\, \mathrm{d}r}{\int_{-R}^{R} I(r)\, \mathrm{d}r}$$



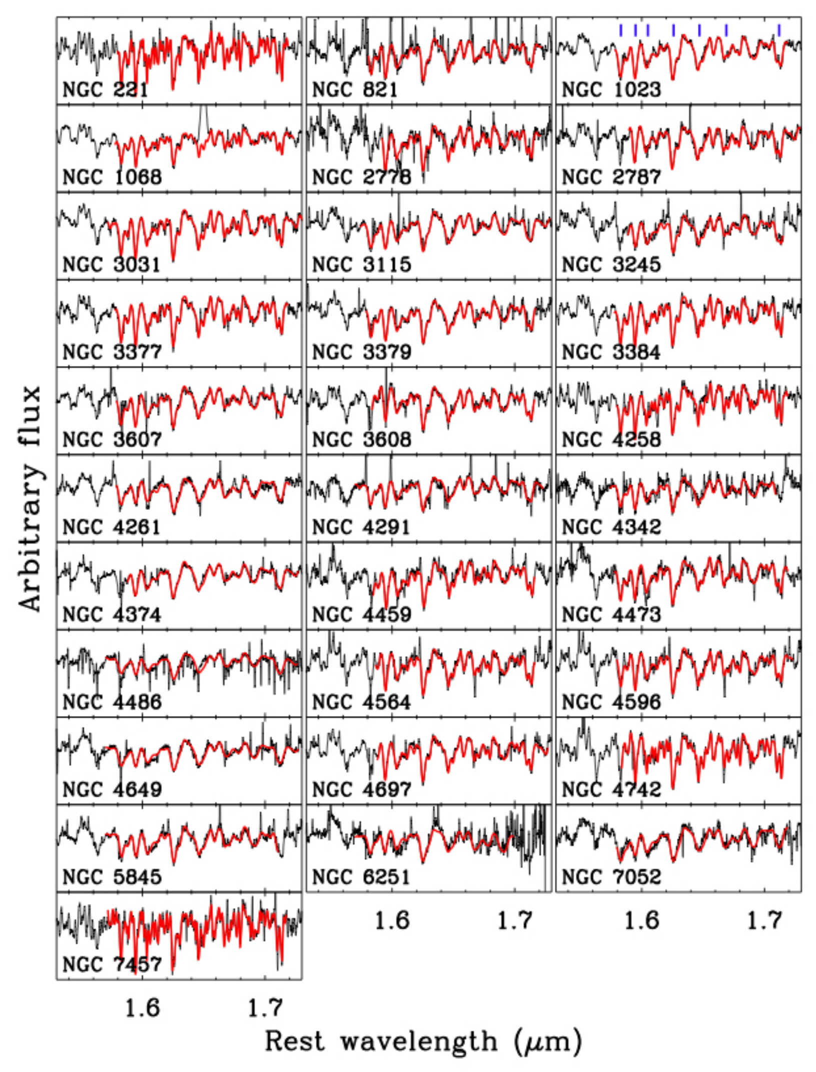
Woo et al. 2013

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



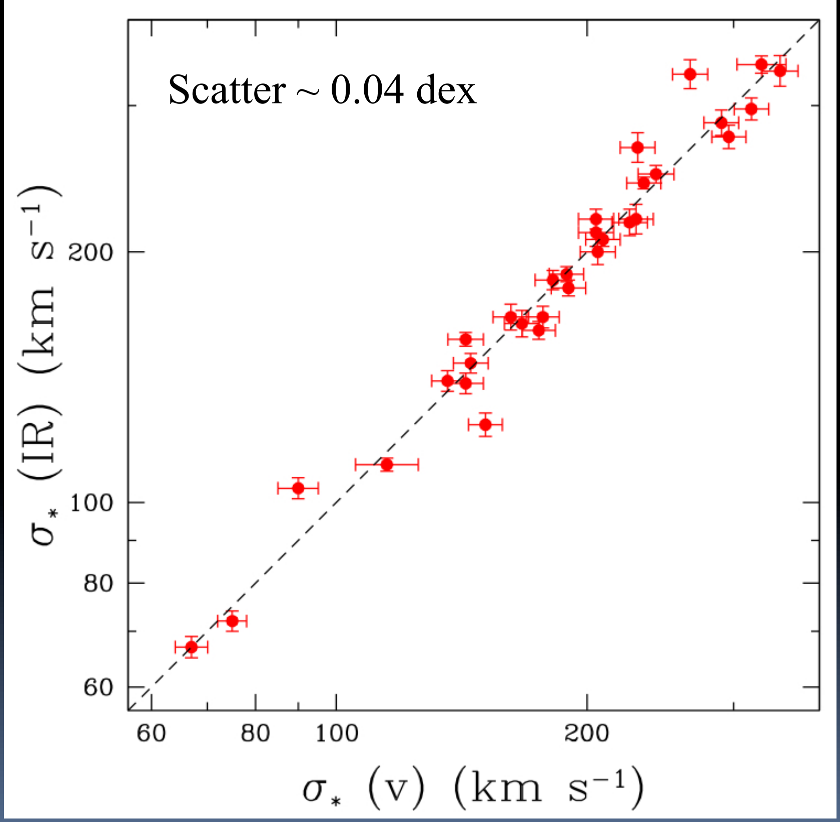
Palomar Triplespec data



Kang, Woo + 13

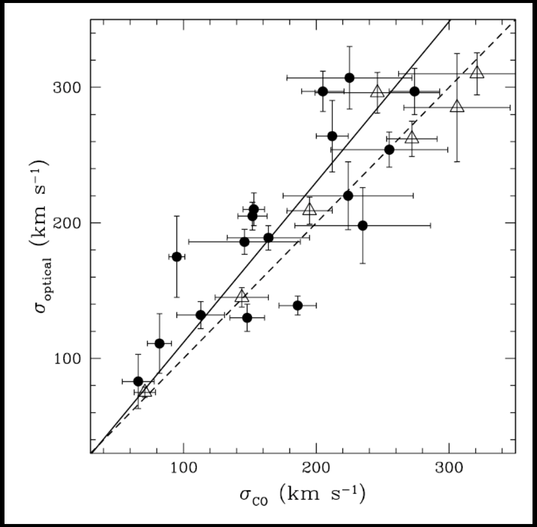
Comparison between optical and near-IR measurements

- Stellar velocity dispersions measured from optical and IR (H-band) spectra are consistent.

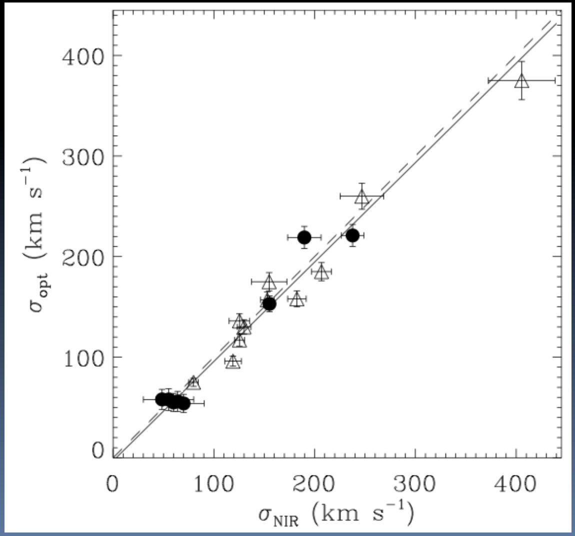


Kang, Woo et al. 2013

Cf. Based on K-band spectra



Silge & Gebhardt 2003

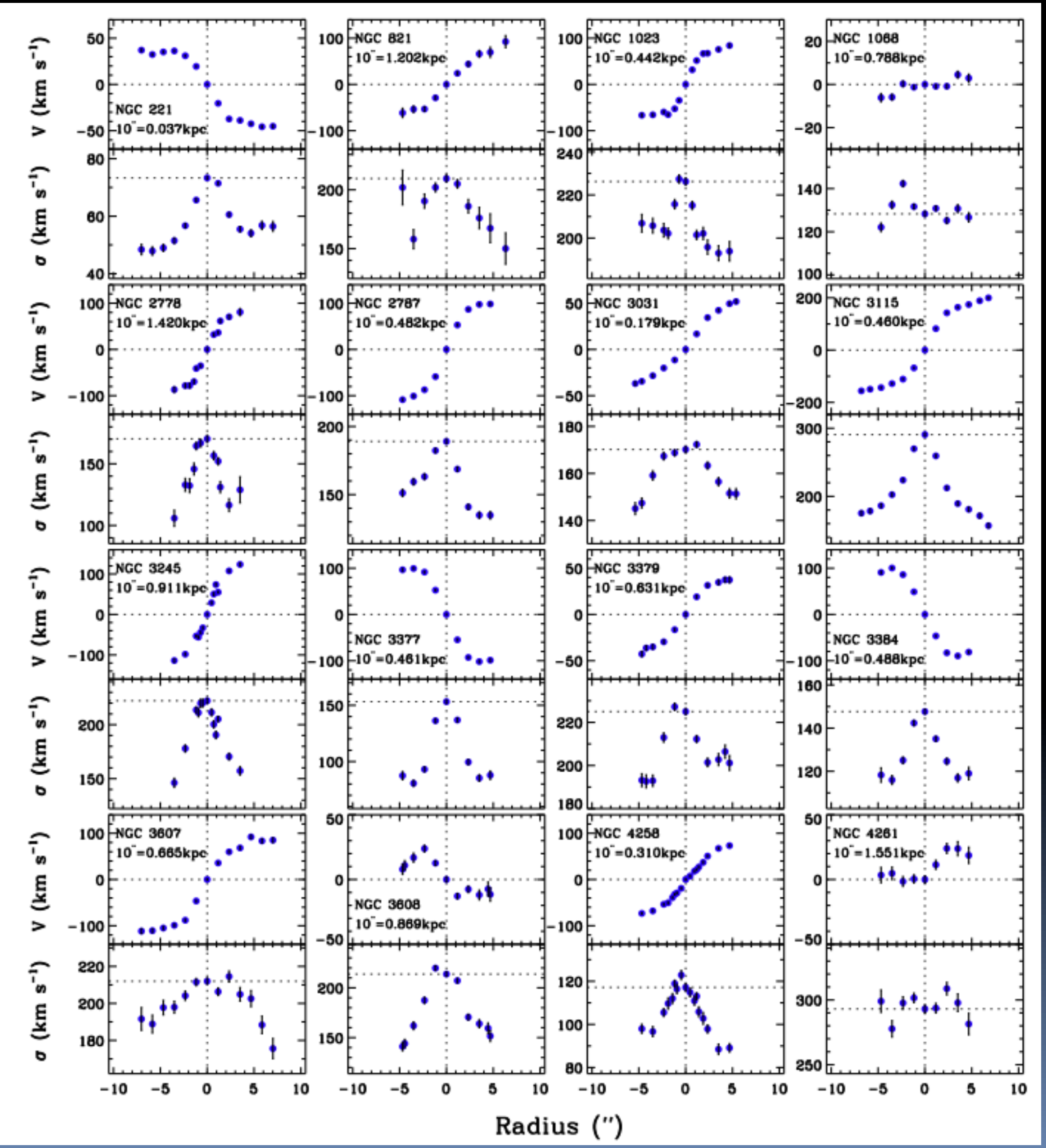


Vanderbeke et al. 2011

Radial distributions of velocity and velocity dispersion

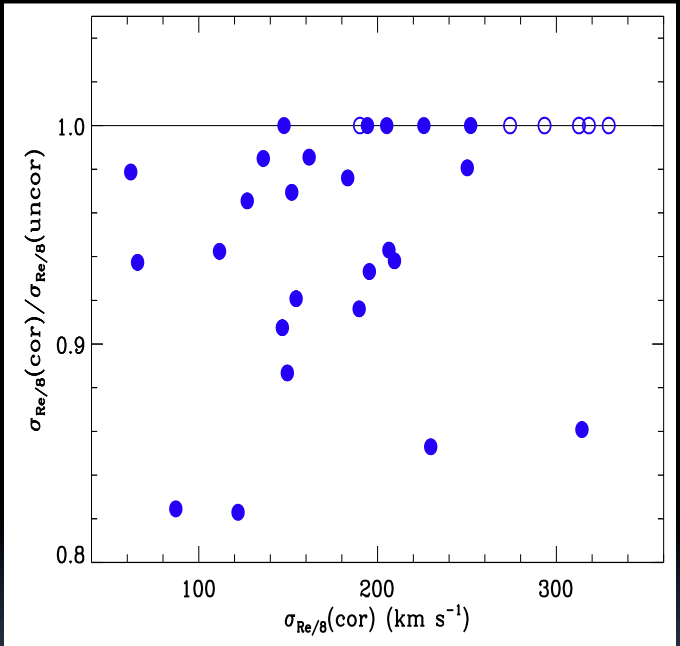
- Disk component is present in many early-type galaxies.
- Rotation & aperture effects should be corrected.
- Luminosity-weighted velocity dispersion should be used.

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

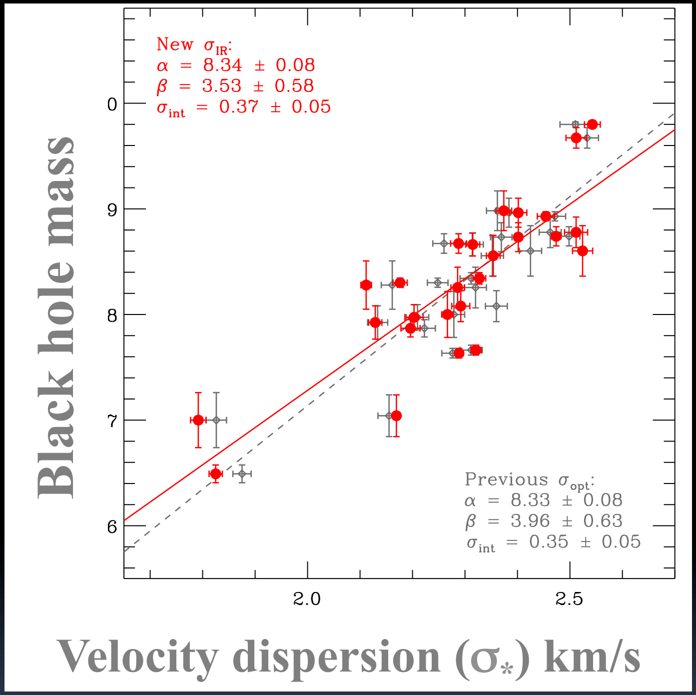


Rotation effect on the velocity dispersion

- 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 (σ < V), the rotation effect is expected to be much stronger.

Redefining the M_{BH}-sigma relation with rotation-free velocity dispersion

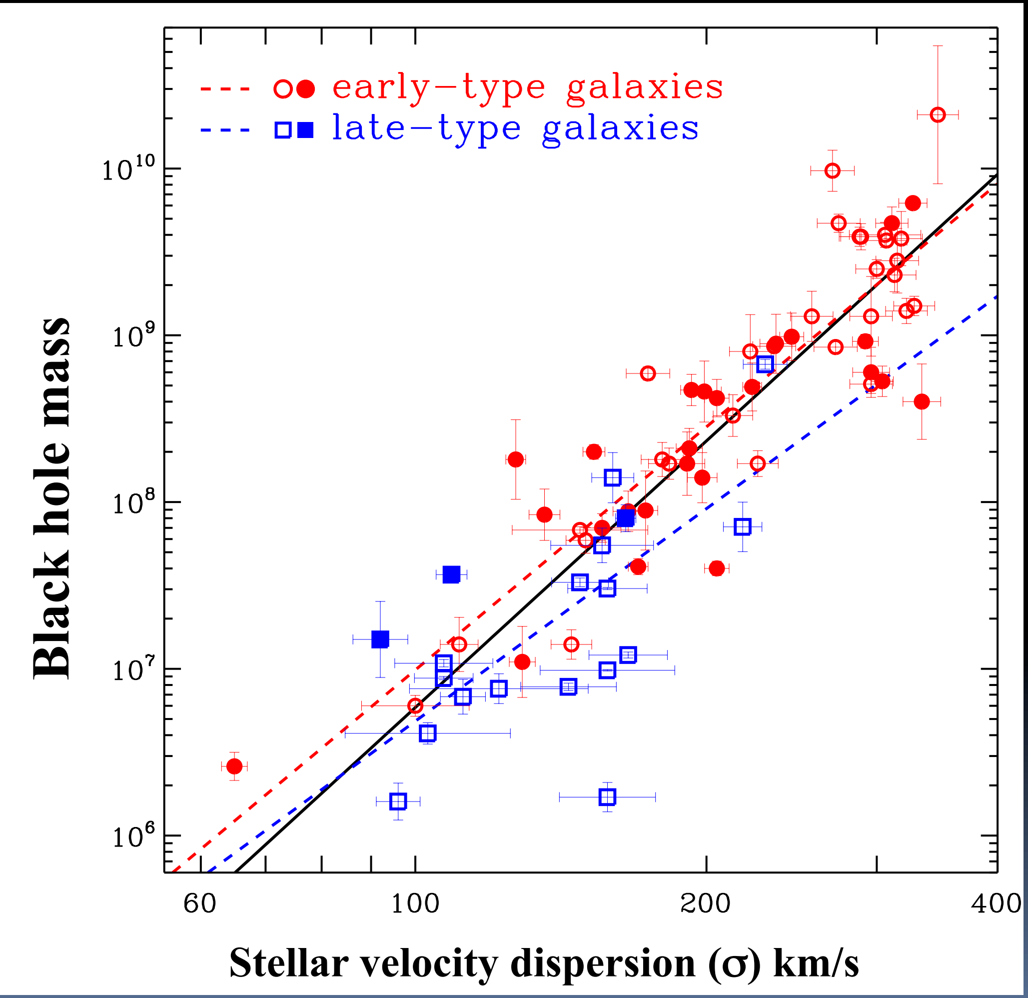
- Late-type galaxies, in particular edge-on galaxies, should be corrected for rotational broadening.

- Rotation added

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

- Rotation-free

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



Kang, Woo + 13

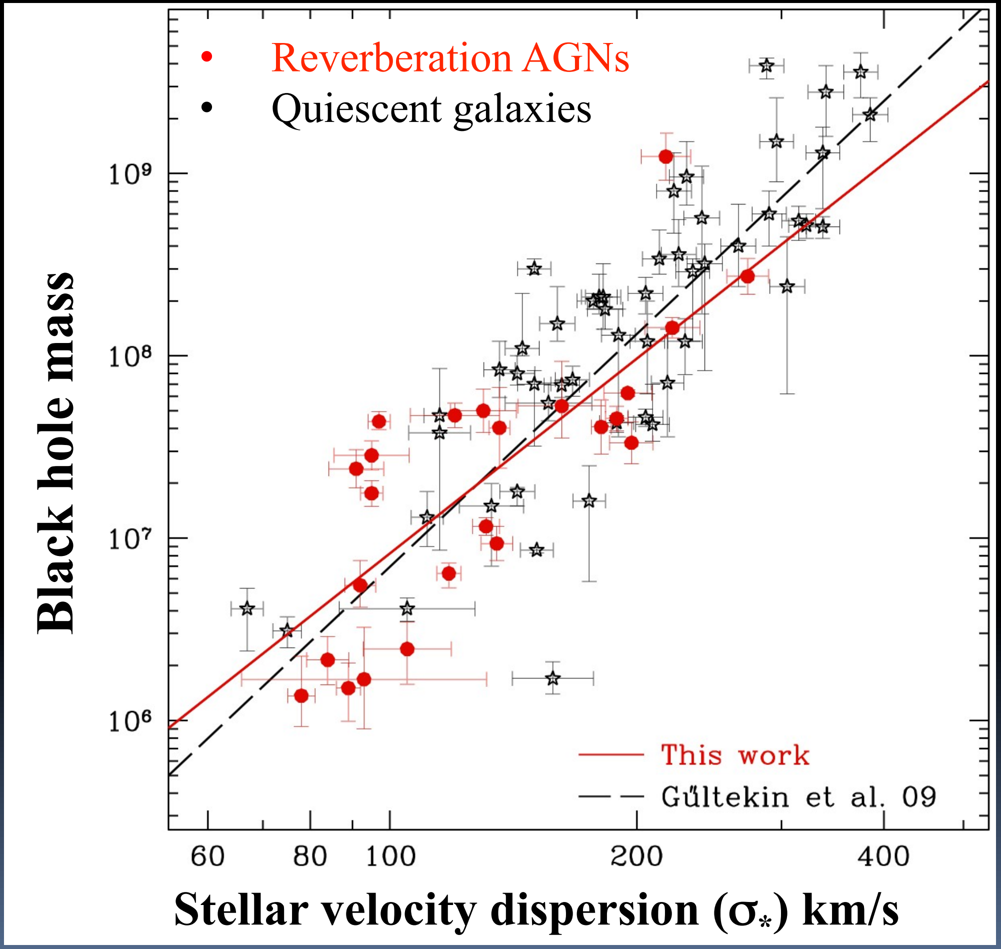
BH-galaxy scaling relation of active galaxies

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

AGN black hole mass:

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

- 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

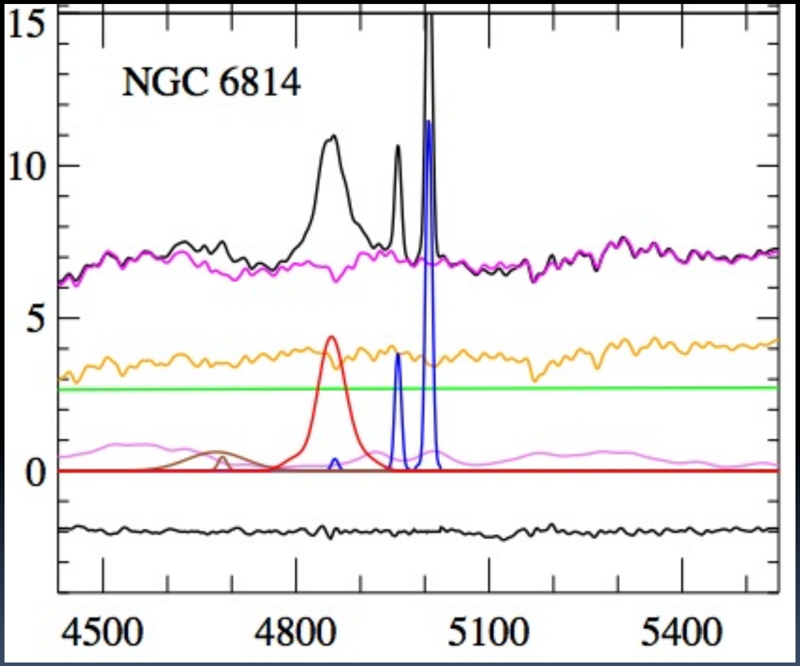


Woo et al. 2010

Updates of the 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)

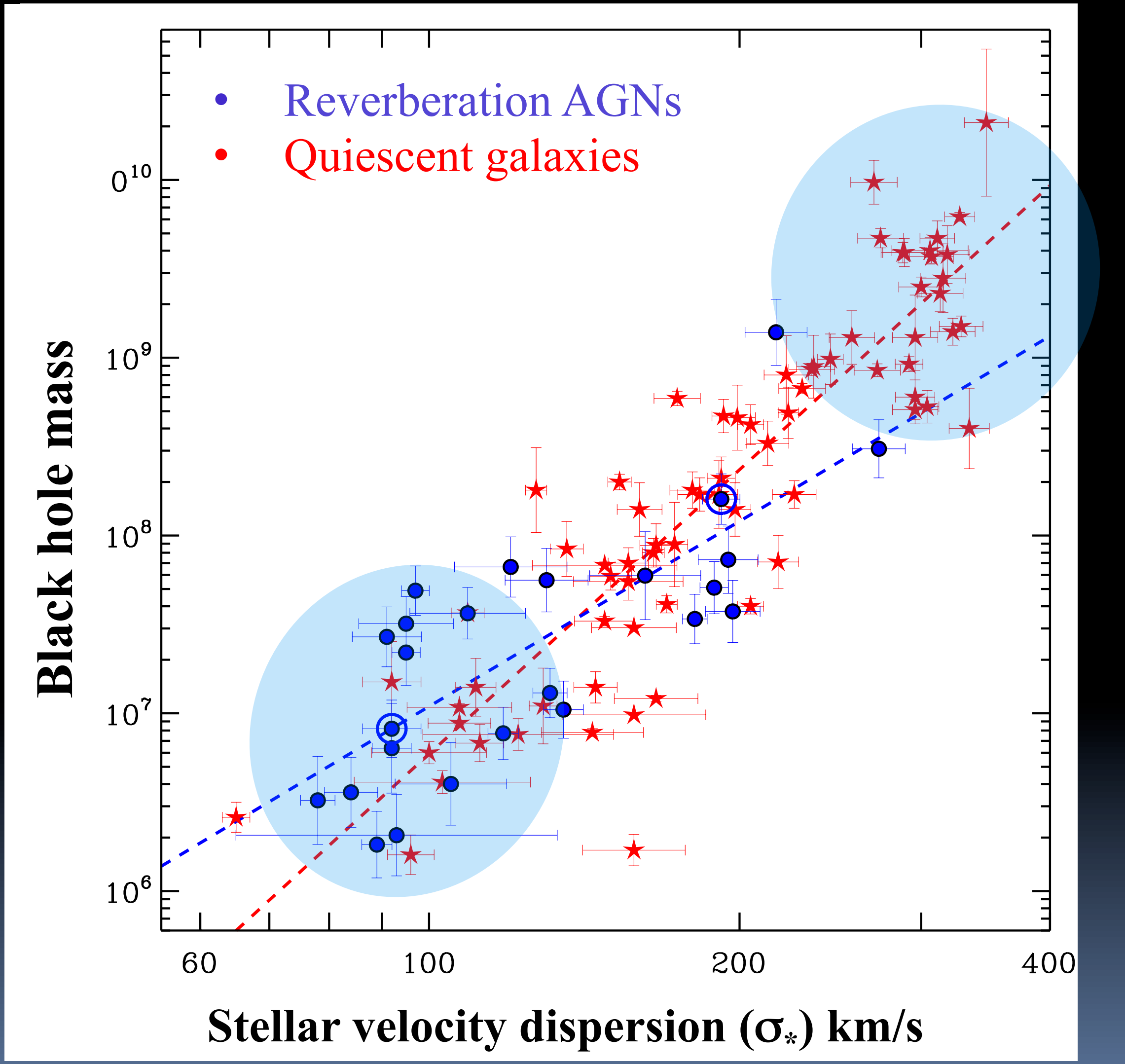
Example of multicomponent fitting with stellar, FeII emission, blended emission lines.



Park, Woo + 12

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



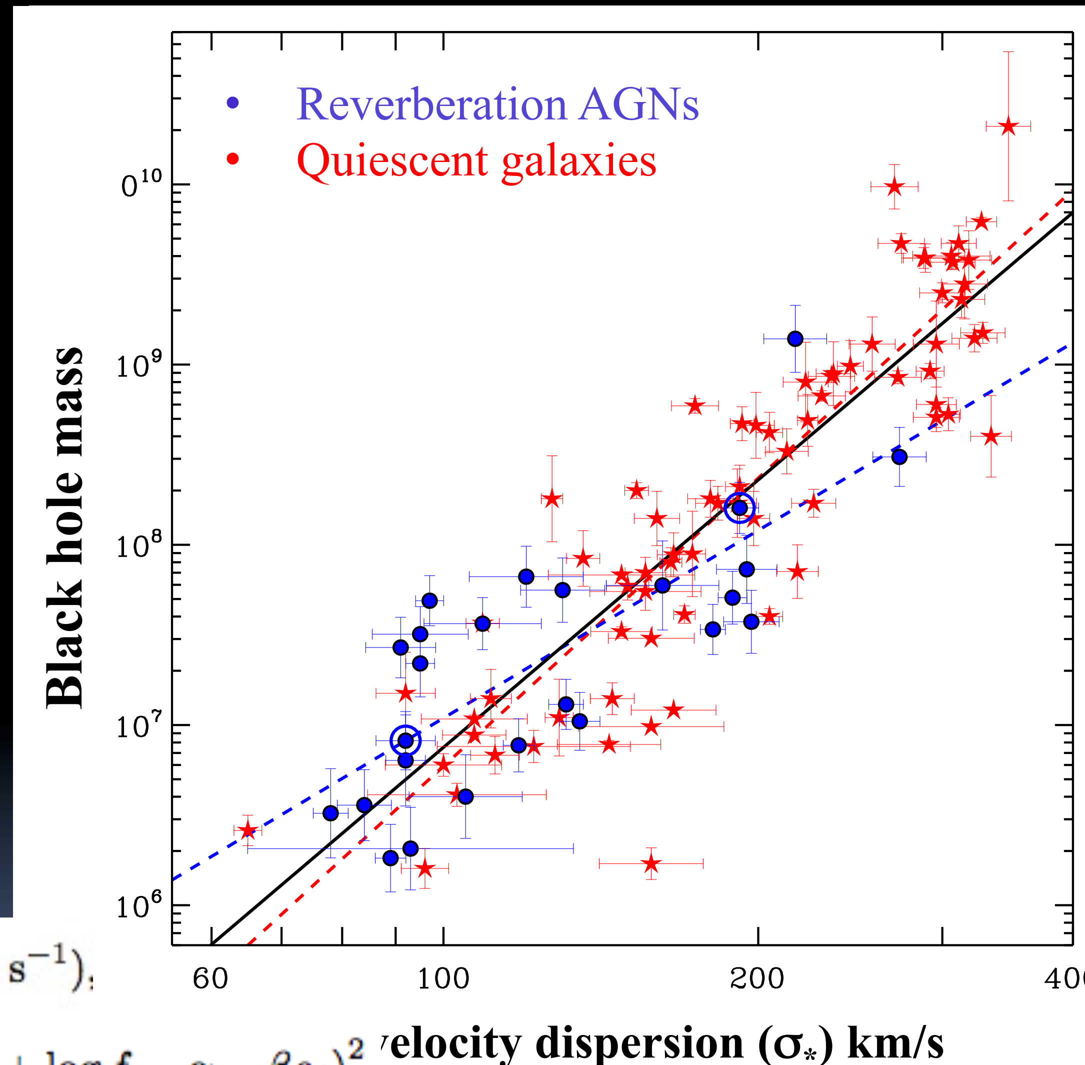
Woo et al. 2013

Active galaxies seem to follow the same M-sigma relation

- 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



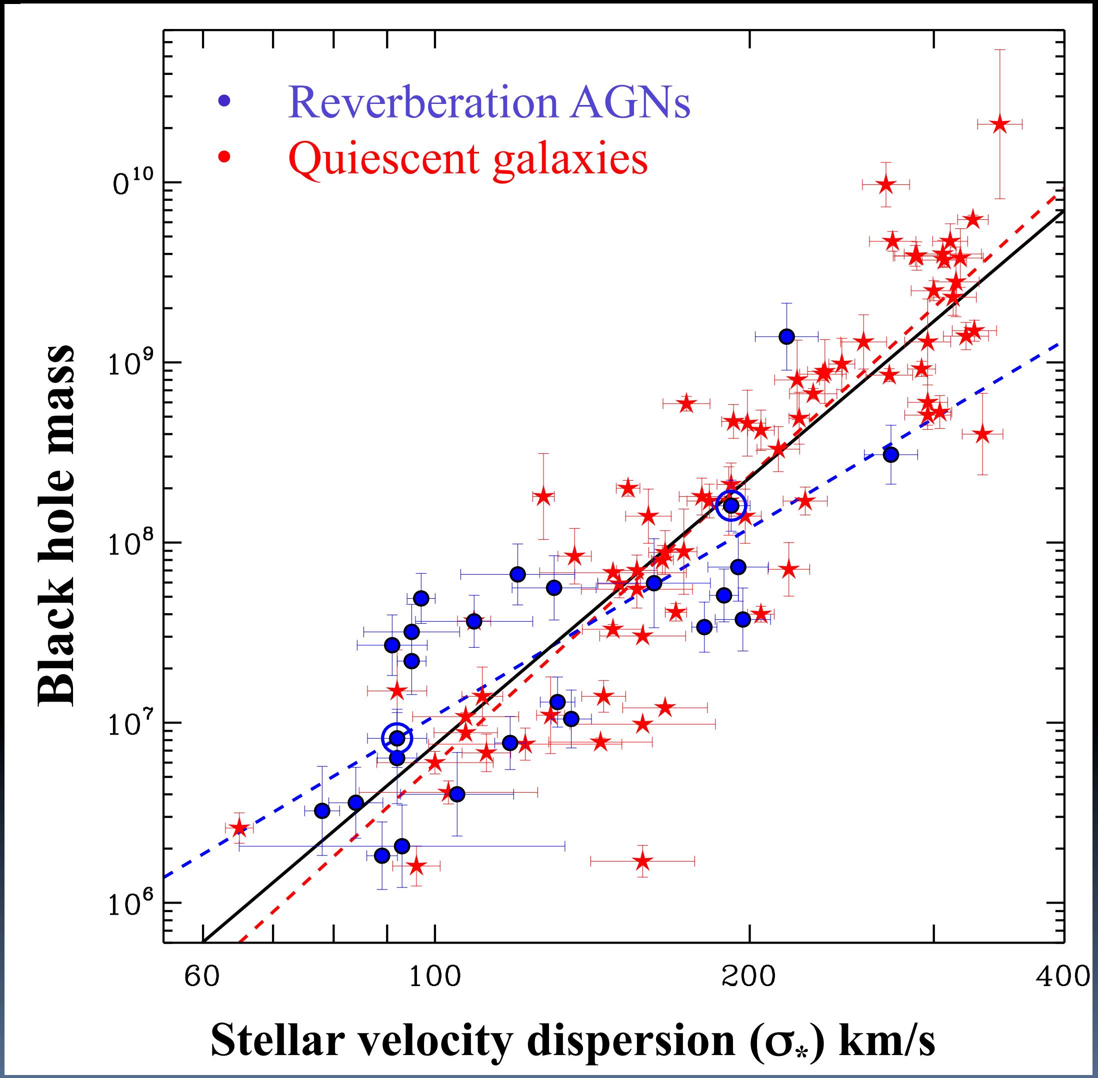
$$\log(M_{\rm BH}/M_\odot) = \alpha + \beta \log(\sigma_*/200 \text{ km s}^{-1}),$$

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

Woo et al. 2013

Comparison between inactive and active galaxies

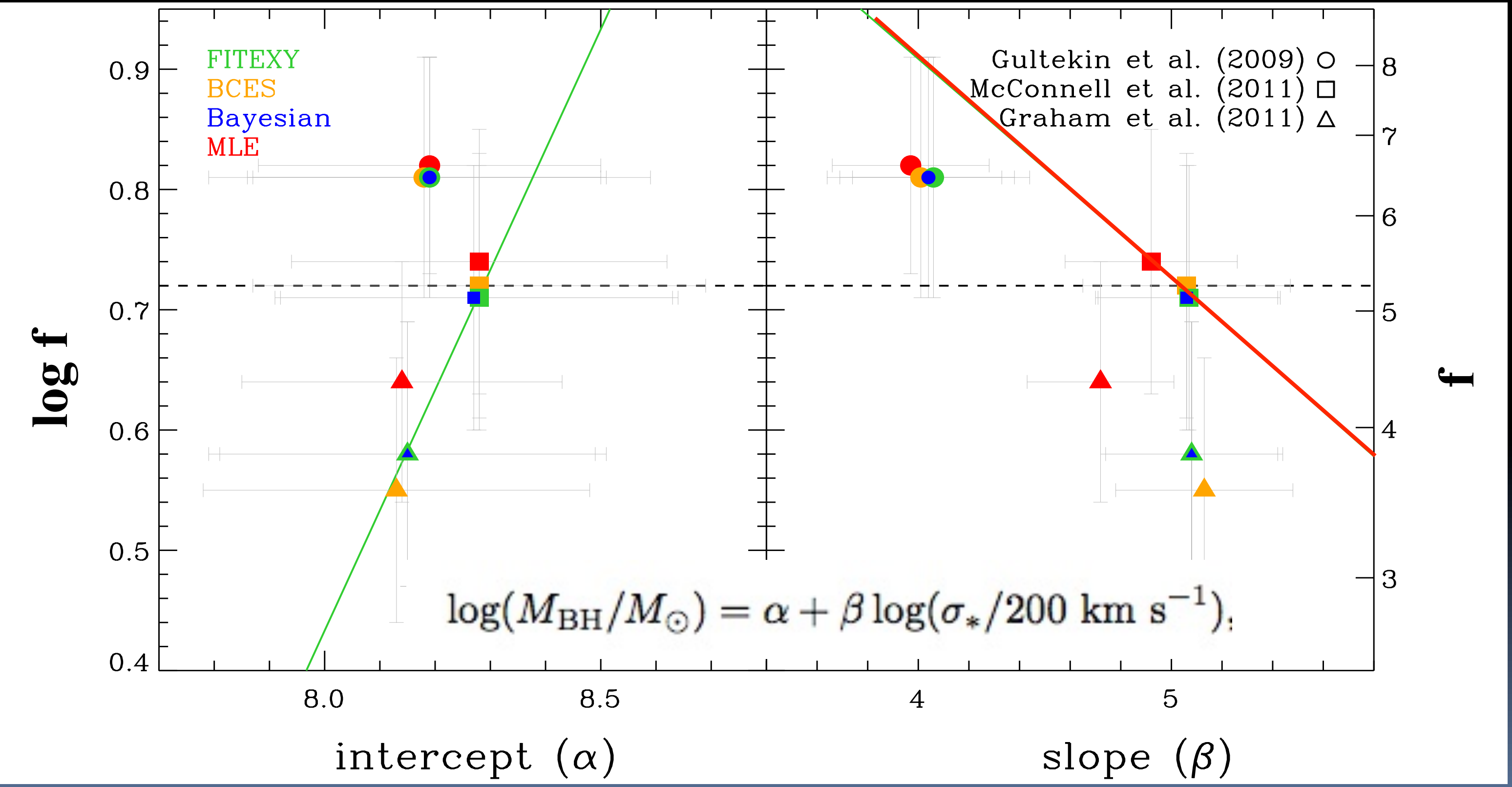
- Intrinsic scatter similar between inactive & active samples.
- Implies that <f> is close to the true value and the range of f among type 1 AGNs is not large.
- For future we may obtain f for a number of individual objects based on velocity-resolved time-lags & modeling (Brewer+11, Pancost+13)



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

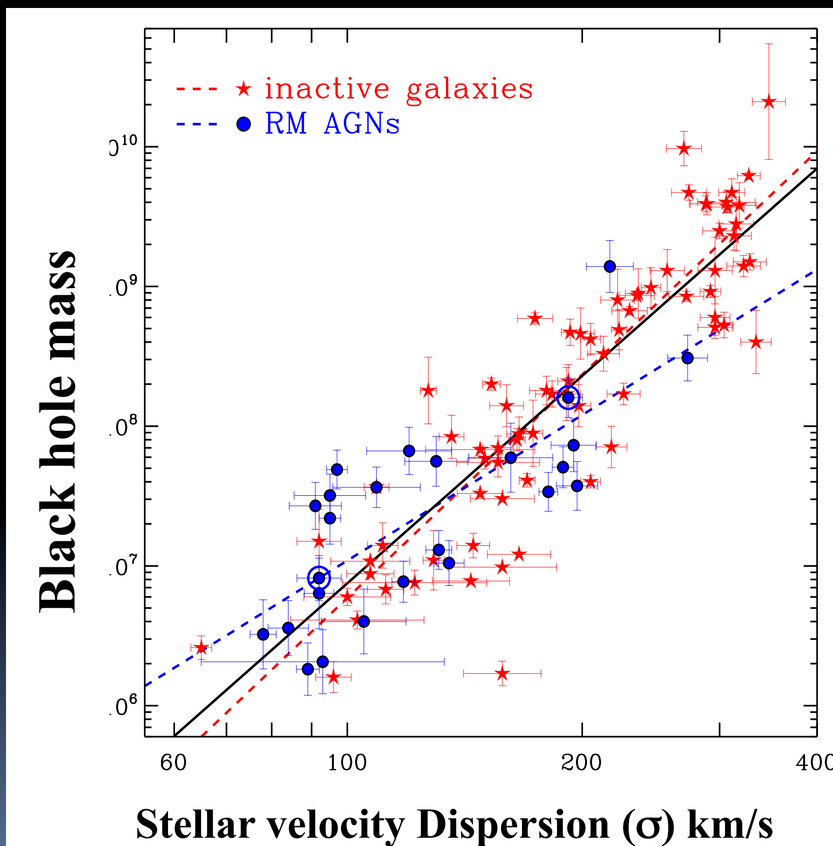


Park, Woo et al. 2012b, ApJS

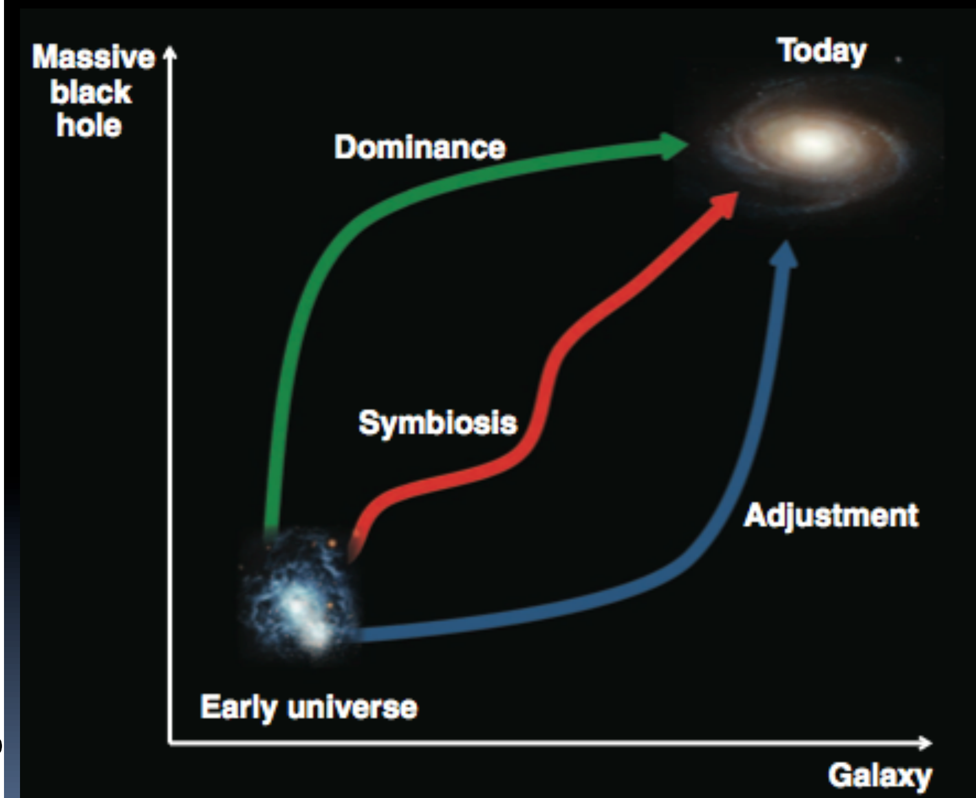
Cosmic evolution of M_{BH}-sigma relation

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

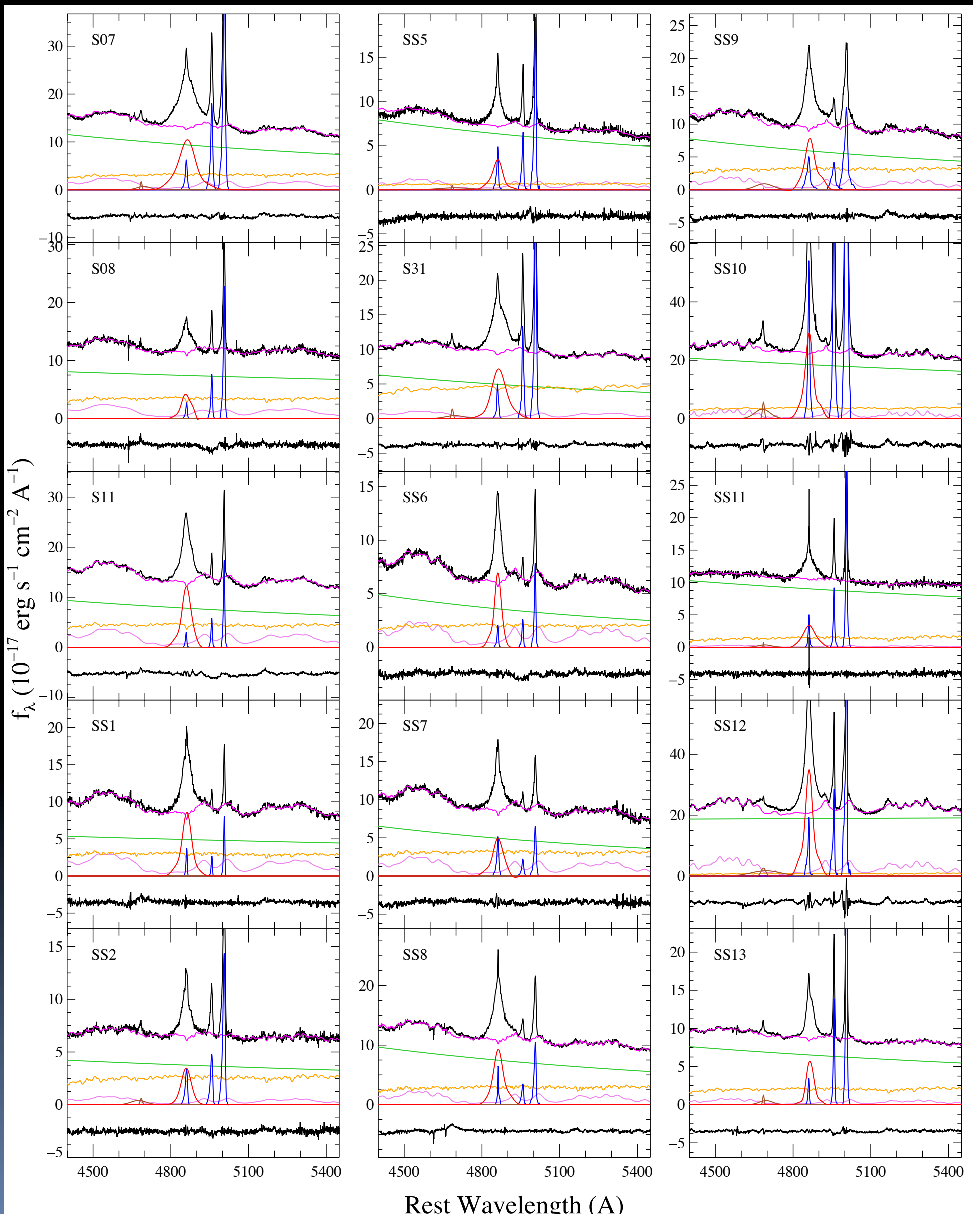
Sample

- 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

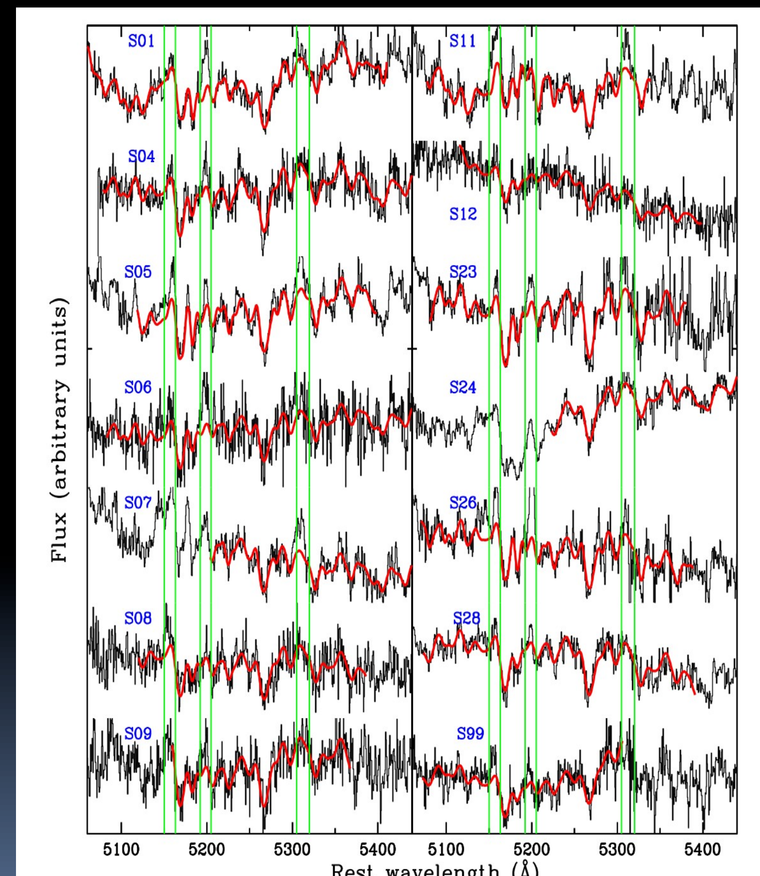
Observations

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

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



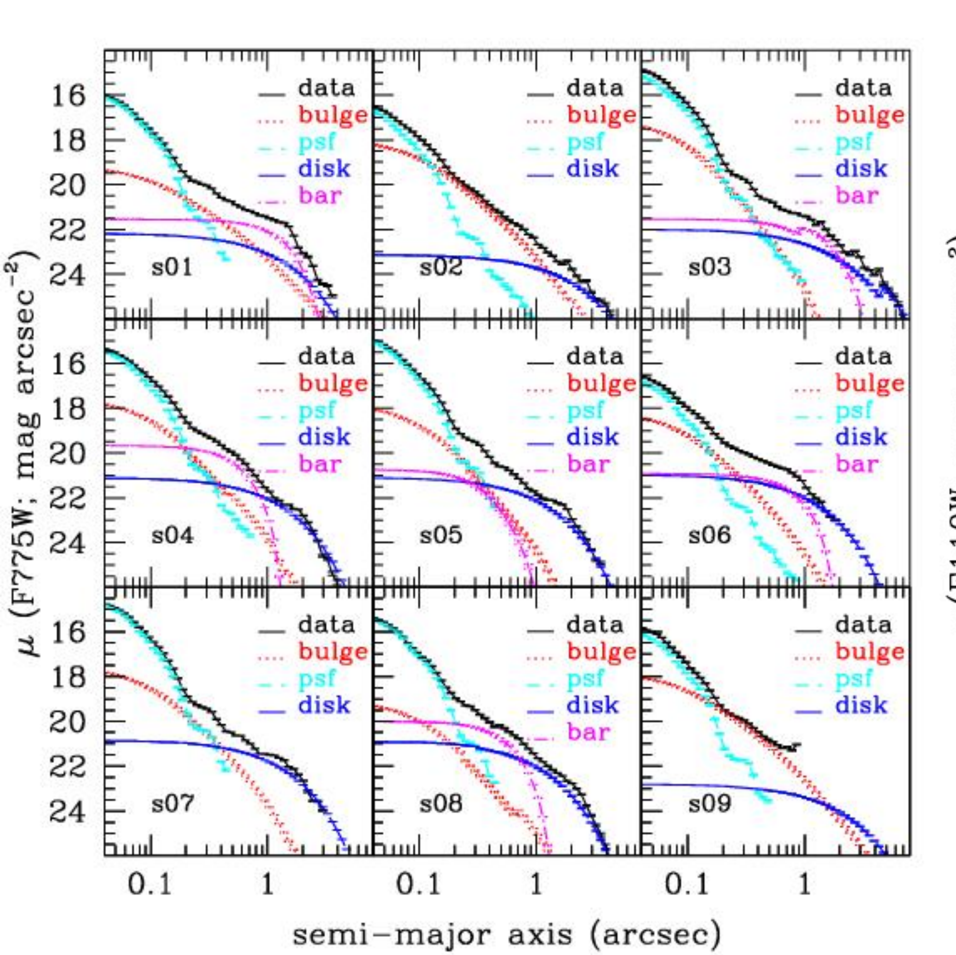
Measured for 34 objects,
no measurements for 18

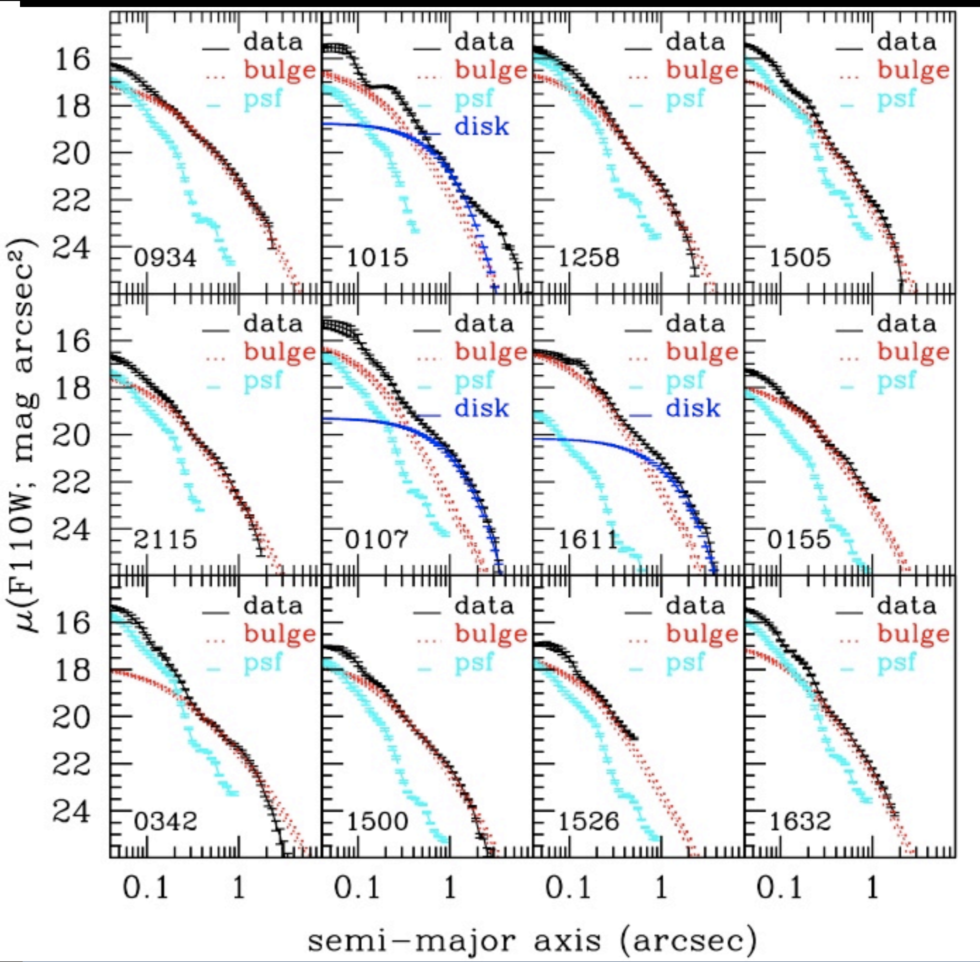


Woo + 06, 08, 14

Measuring host galaxy bulge luminosity

psf/bulge/disk decomposition with HST-ACS/NICMOS/WFC3 images



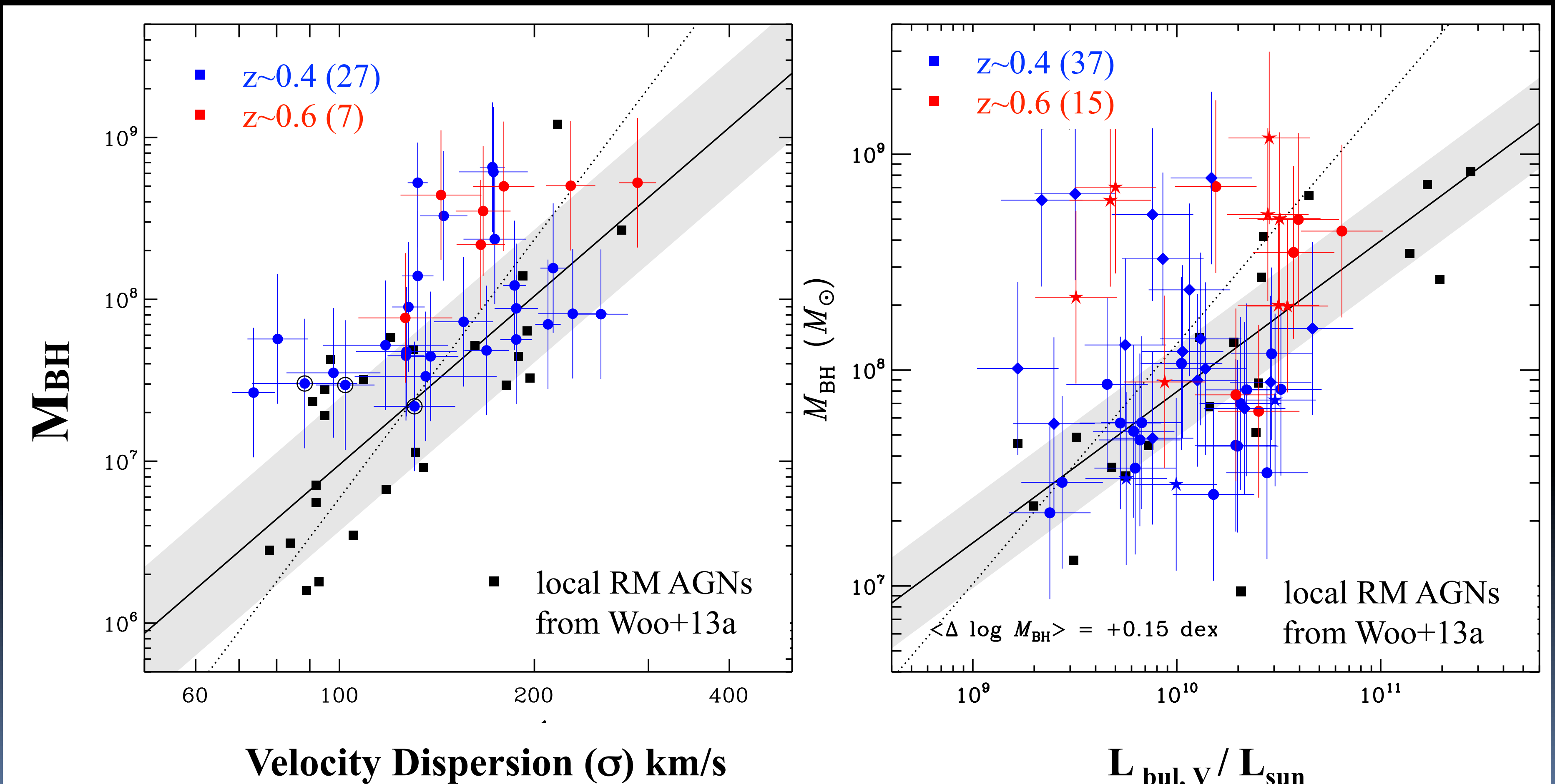


Treu+07, Bennert+10, Park+14

BH-galaxy scaling relations 4-6 Gyr ago

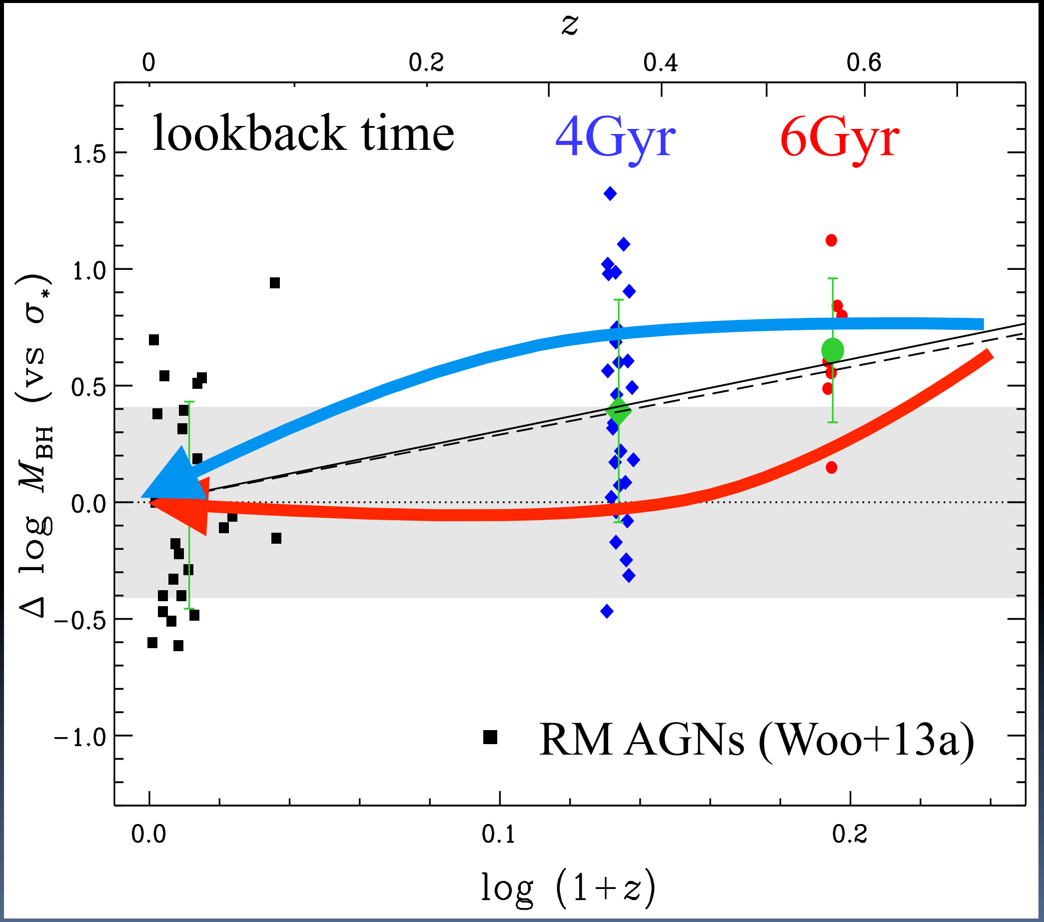
Distant bulges are smaller/less luminous than local bulges at fixed M_{BH}.

Woo+06, 08, 14 (in prep) | Treu+07, Bennert+10, Park+14 (in prep)



Evolution of the M_{BH} - sigma Relation

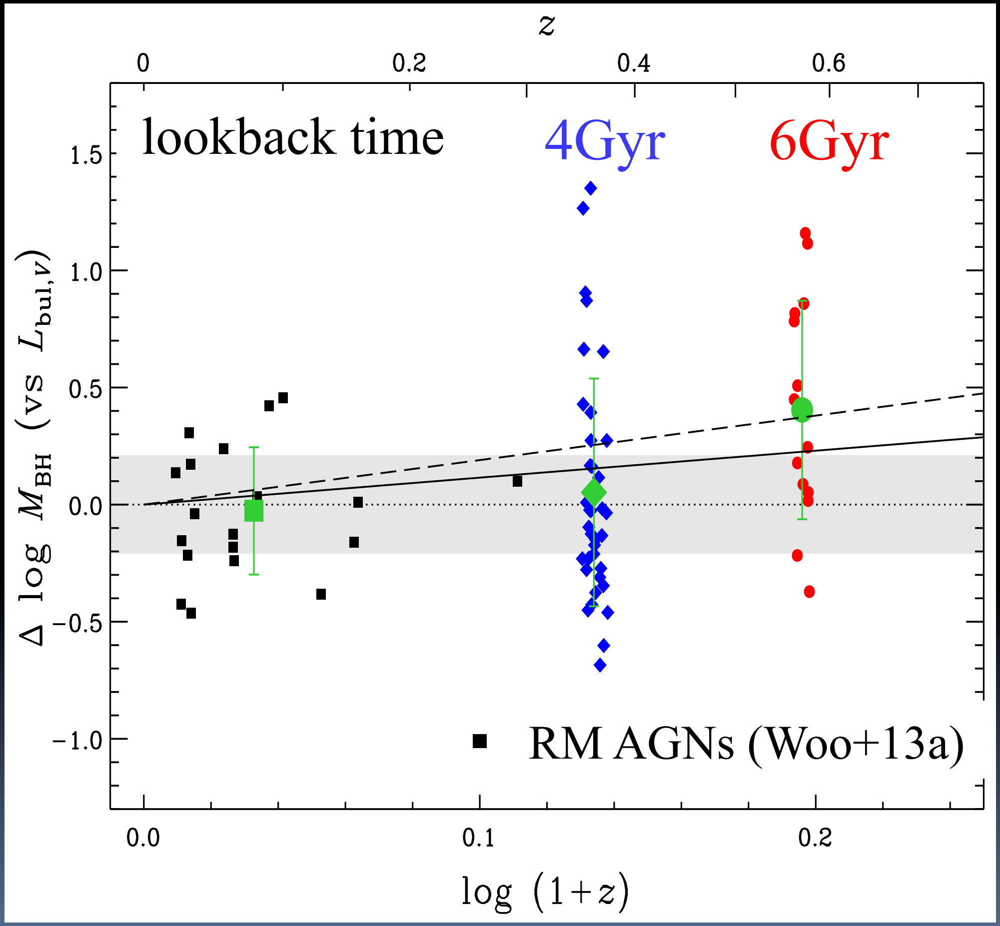
- Black holes seem to live in smaller galaxies in the past.
- Evolution is Independent of the virial factor
- Mass-dependent evolution



Woo + 14 (in prep).

Evolution of the M_{BH} - L_{bulge} Relation

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

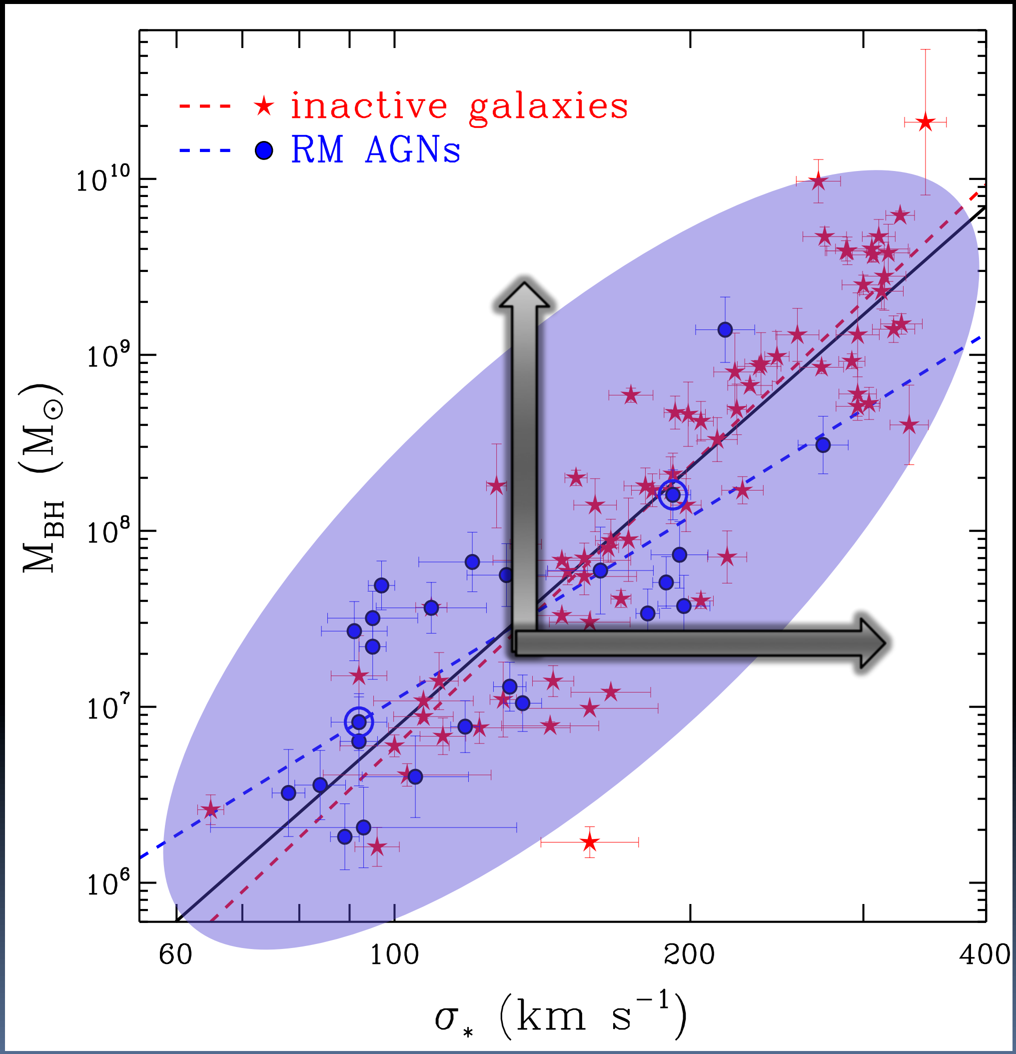


Woo + 14 (in prep).

Selection effect?

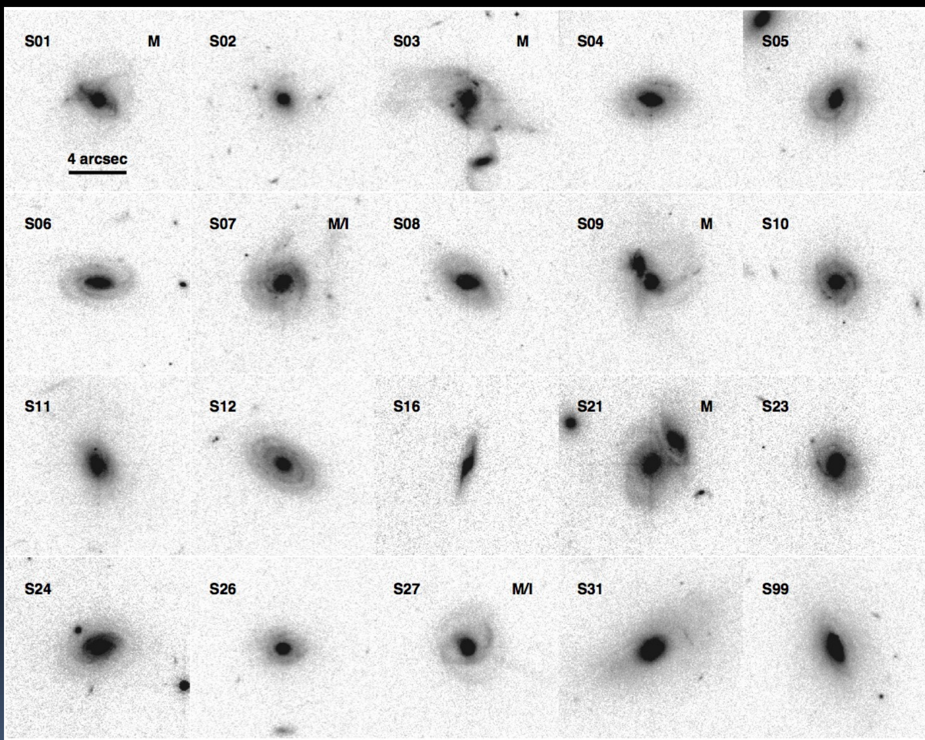
- **Luminosity bias:**
Since BHM determined from L, more massive BHs are selected. (strong effect at $M_{BH} > 10^9$)

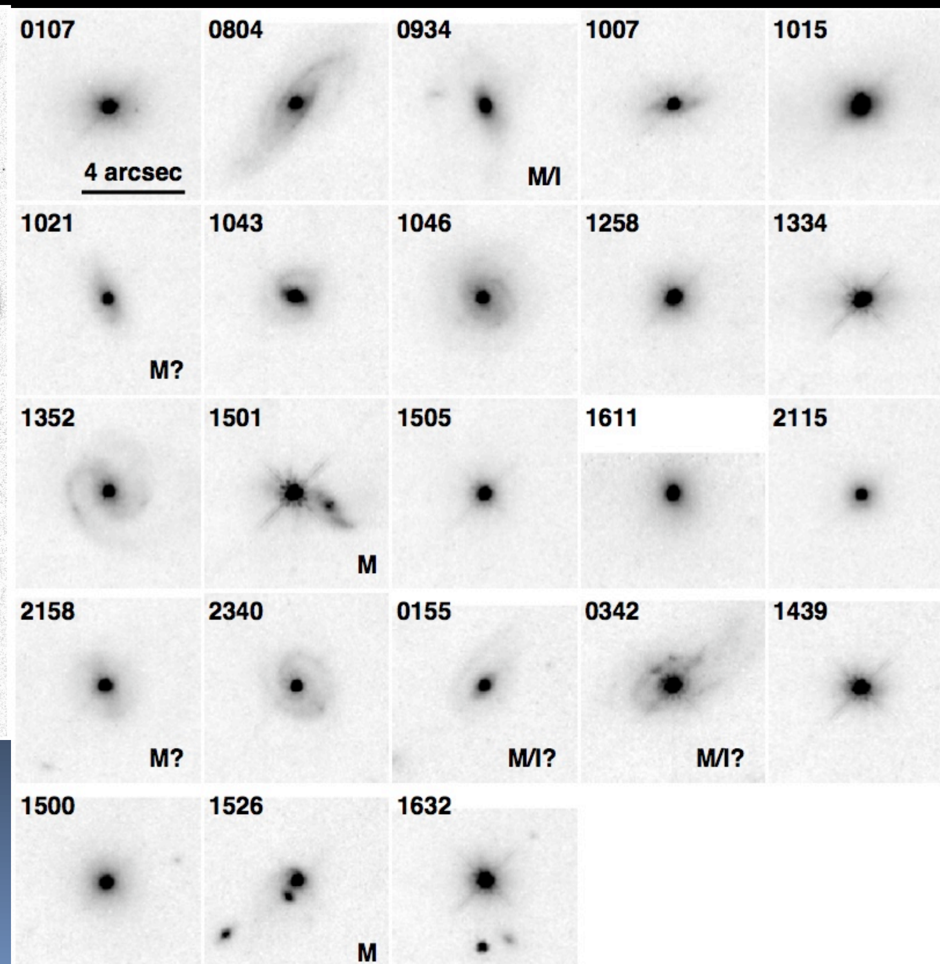
- **Host galaxy measurability:**
For given AGN sample, larger galaxies are easier to be measured



Recent evolution of (active) bulges?

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

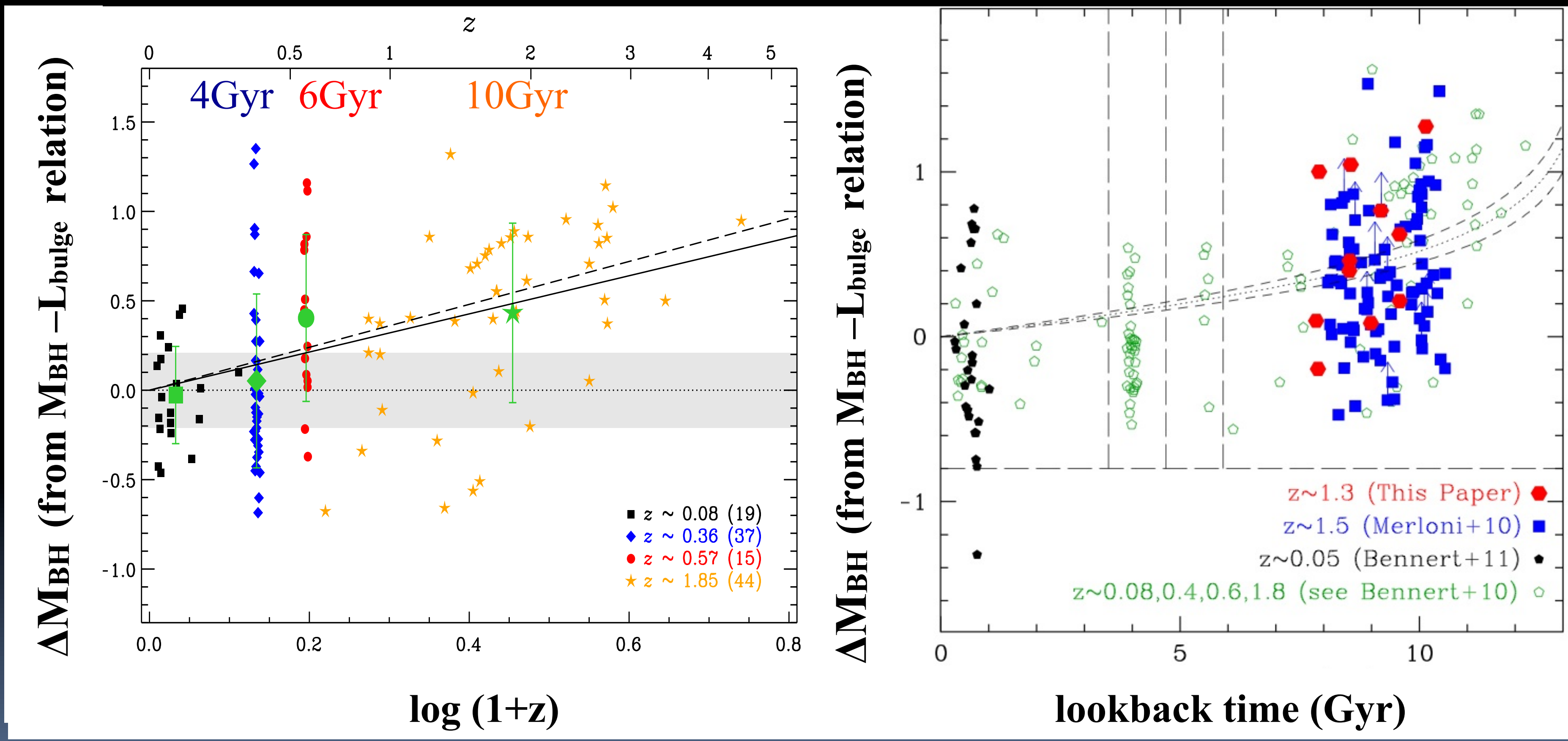




HST images (Treu+07, Bennert+10, Park+14)

Evolution of the scaling relation

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



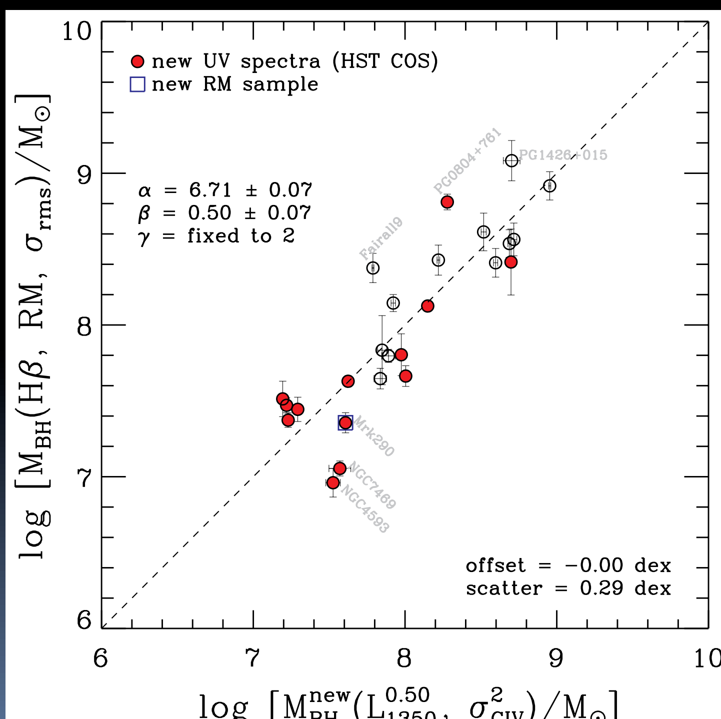
Park et al. 2014 in prep.

Bennert et al. 2011

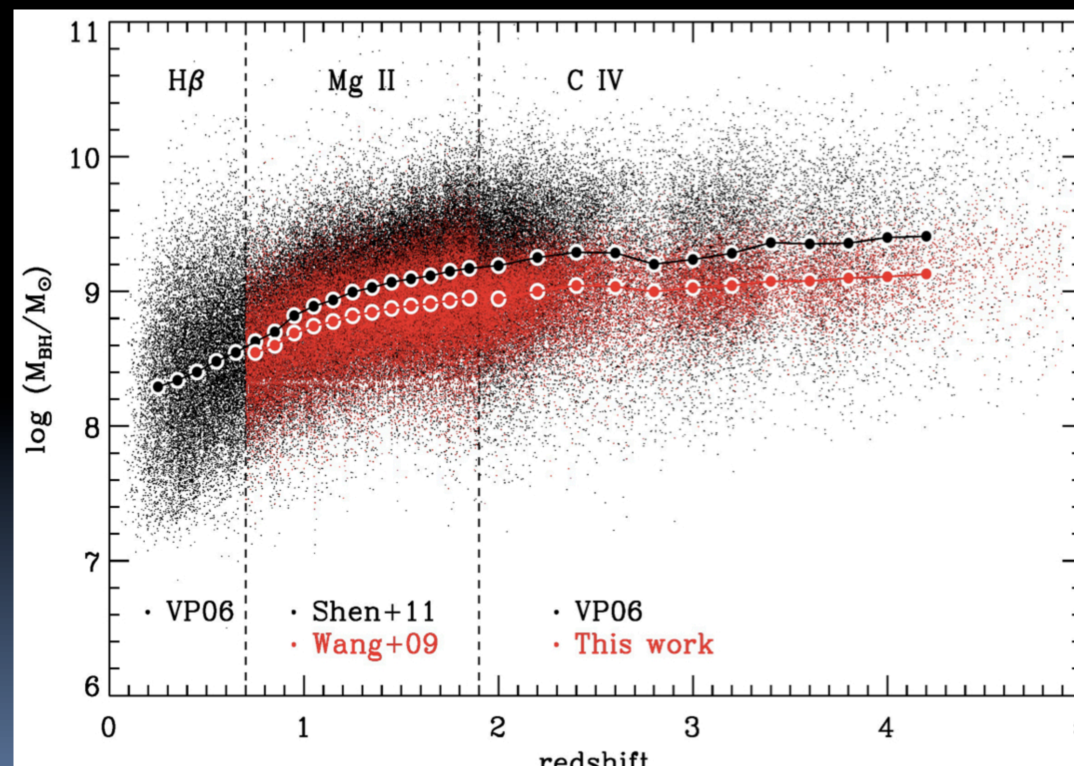
Issues on single-epoch M_{BH} estimates for high-z AGNs

- 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

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 I

- Accounting for the difference in mass distribution, active and inactive galaxies at z~0 seem to follow the same M-sigma relation.
- The reverberation sample is not representative for AGNs. We need a large sample covering high L and high BH mass.
- For low mass, disk-dominant galaxies, rotation effect should be corrected for measuring stellar velocity dispersion of bulges.
- At fixed M_{BH}, bulges in 4-6 Gyrs ago appear to be smaller/less luminous compared to the local sample, implying that BH growth predates final assembly of spheroid at intermediate mass scale.

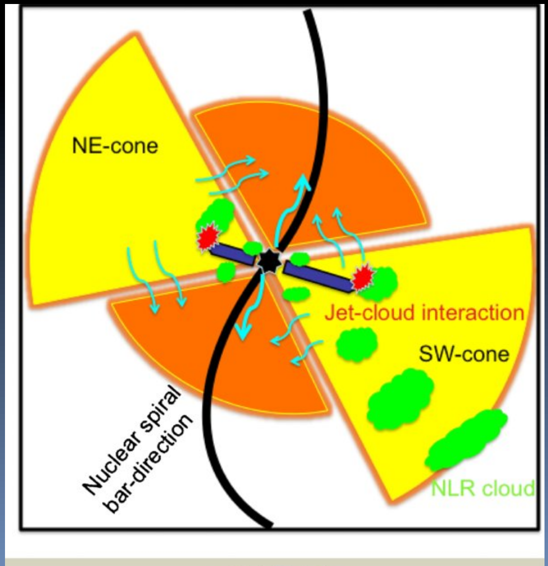
Part 2.

A census of ionized gas outflows in type 2 AGNs

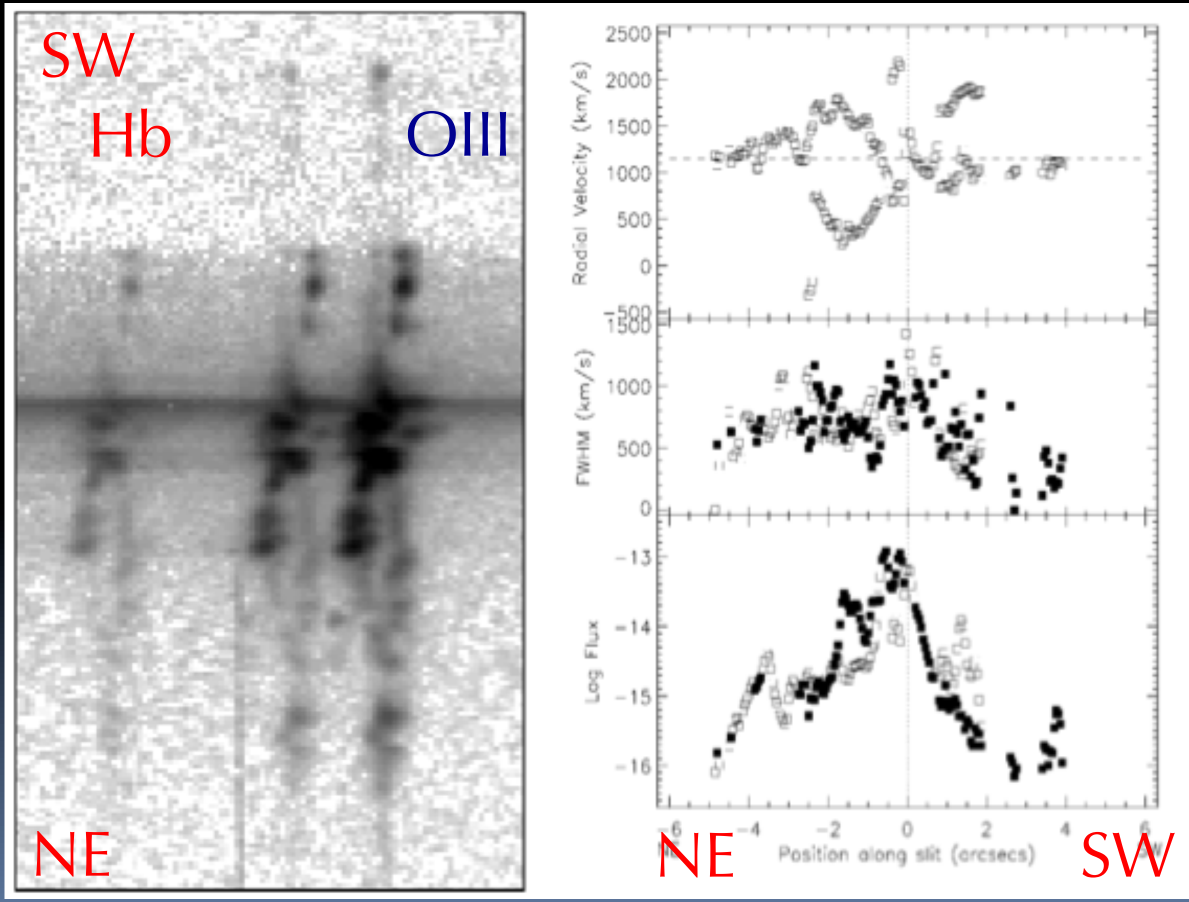
Example, a nearby Seyfert 2, NGC 1068

Outflows in NLR

- Bi-conical (not rotation)
- Acceleration & deceleration
- Relatively high velocity

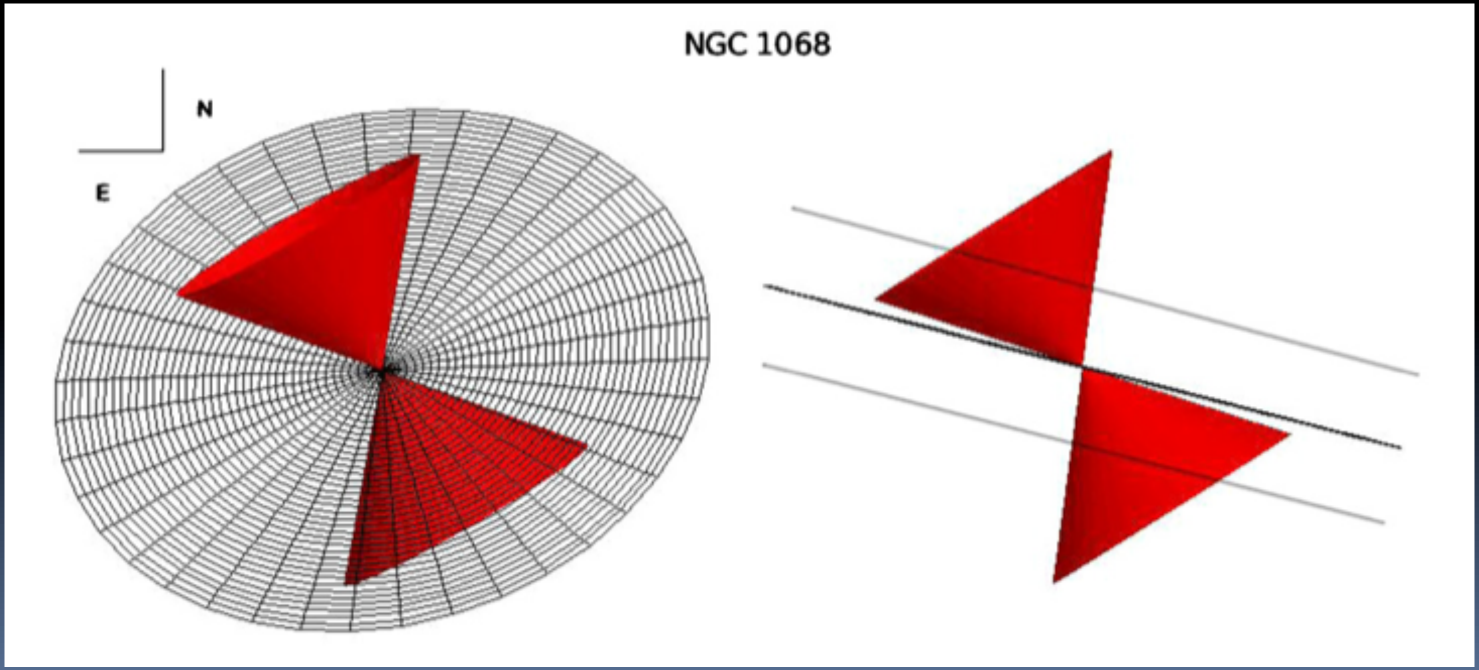


Central 720pc (Crenshaw+00)



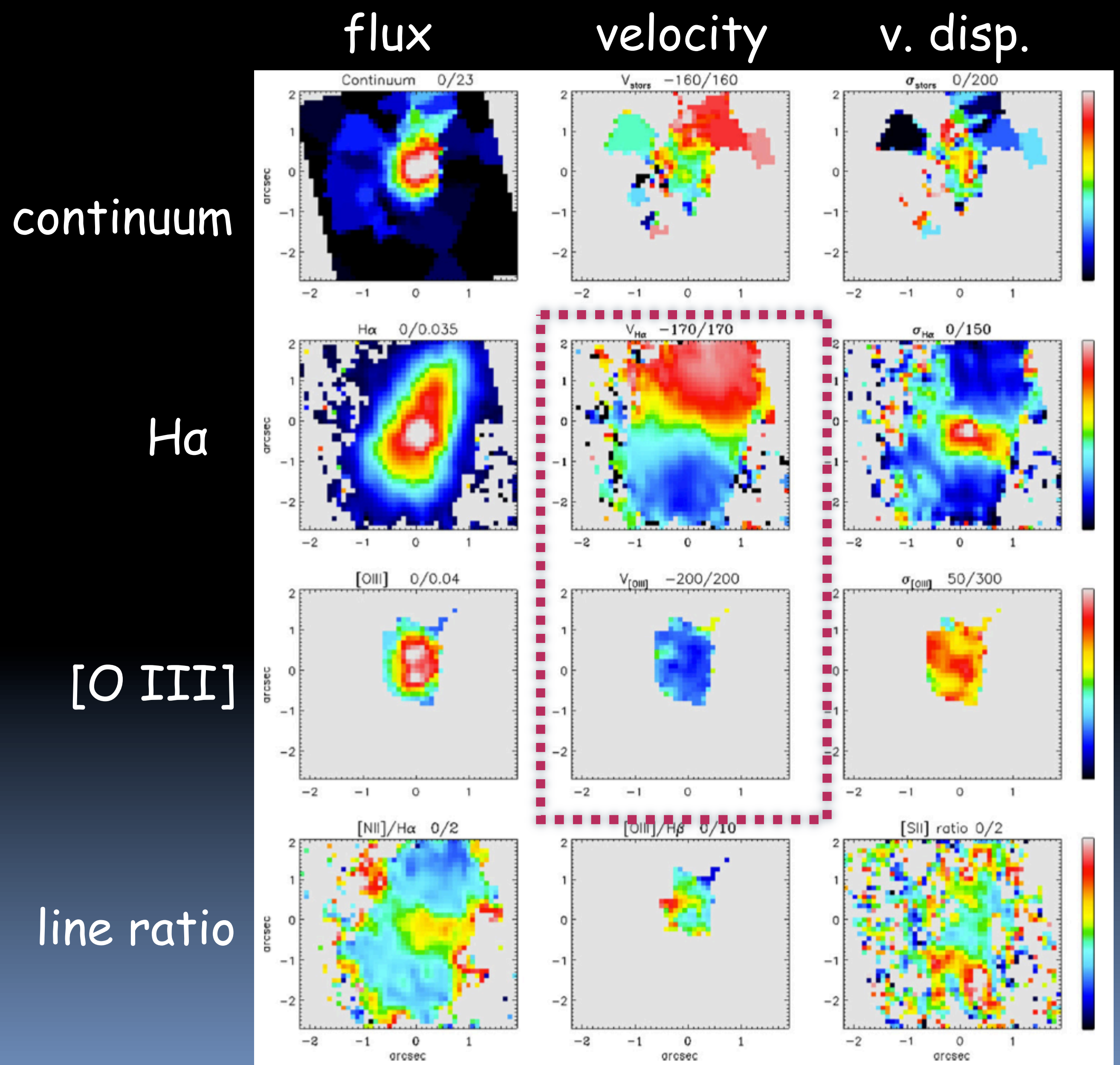
Case for a nearby Seyfert 2, NGC 1068

- Bi-conical outflows
- Wide opening angle
- Obscuration due to the dust in stellar disk



Crenshaw+10

An IFU example (Westoby+12)



Outflows fractions based on integrated spectra

Type 1 AGNs

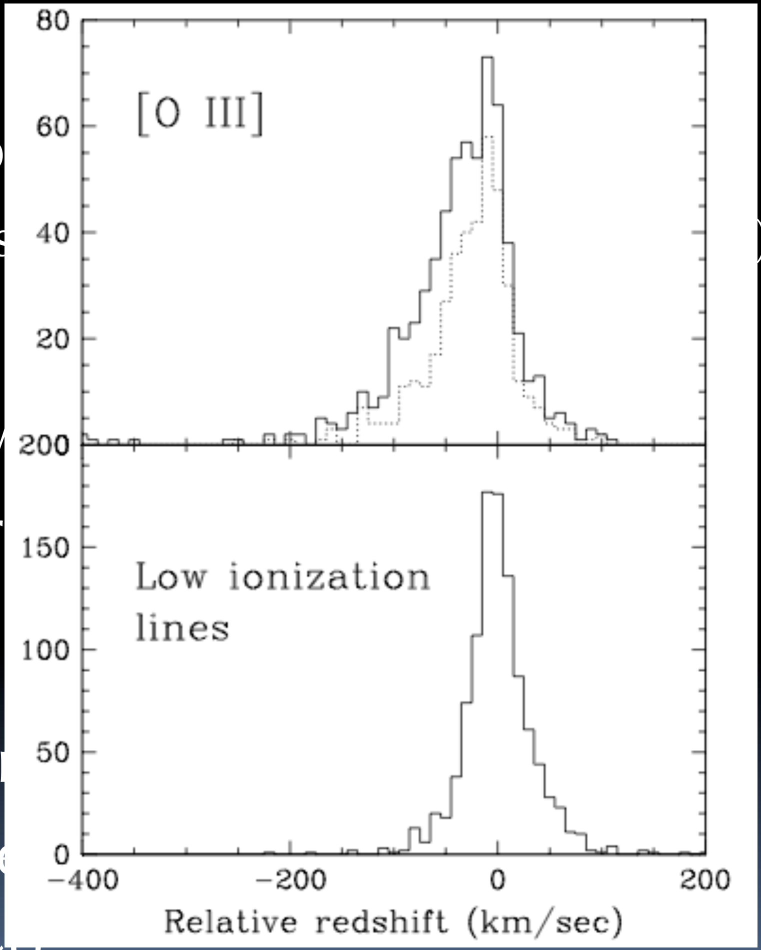
- Velocity offset of OIII with resp
- Outflow fraction is ~50% (Boros)

Type 2 AGNs

- V_{offset} of OIII with respect to lov
- Outflow fraction is 25-40% (Cr

Motivations

- Are low-ionization lines offsetti
- Reliable systematic velocity is r
- Constrain outflow fraction at z~0

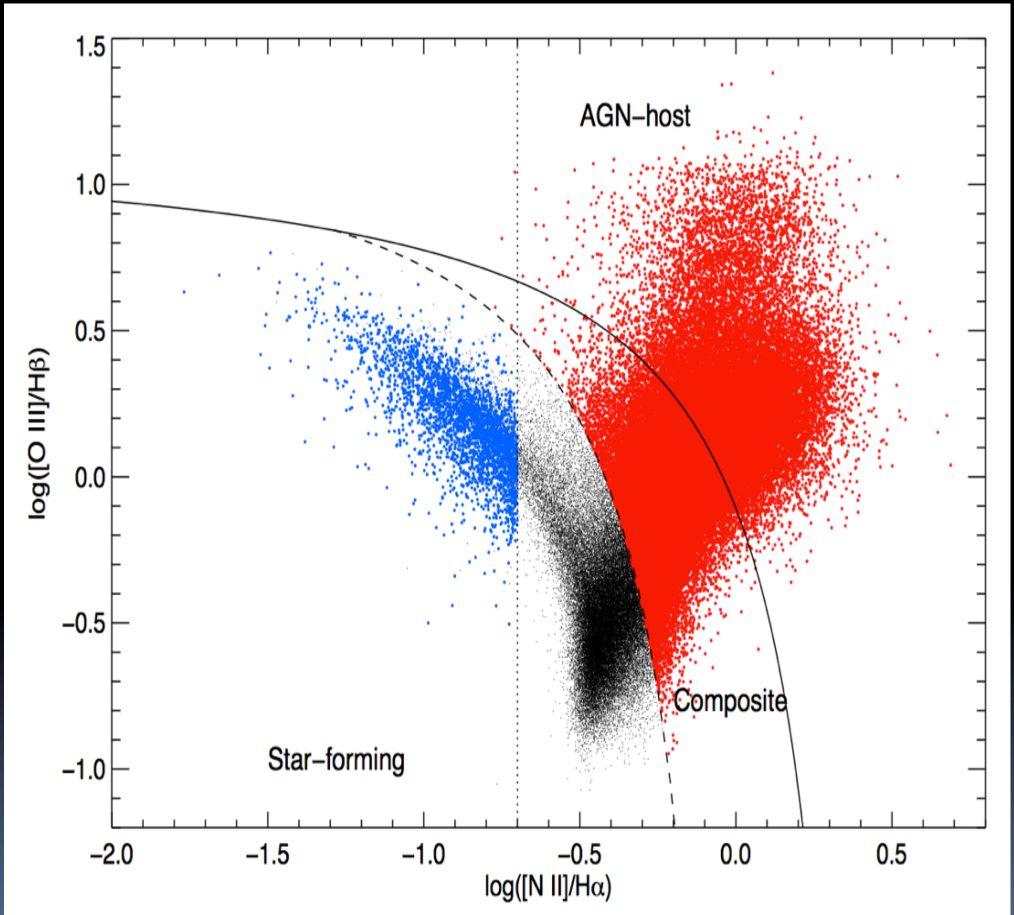


Boroson 05

Sample: SDSS Type 2 AGNs

- Redshift: 0.02 < z < 0.1
- Total ~60,000 galaxies with S/N >3 for emission lines
- 22,000 type 2 AGNs
- 2,000 Star-forming galaxies for comparison

(Bae & Woo 2014 submitted)



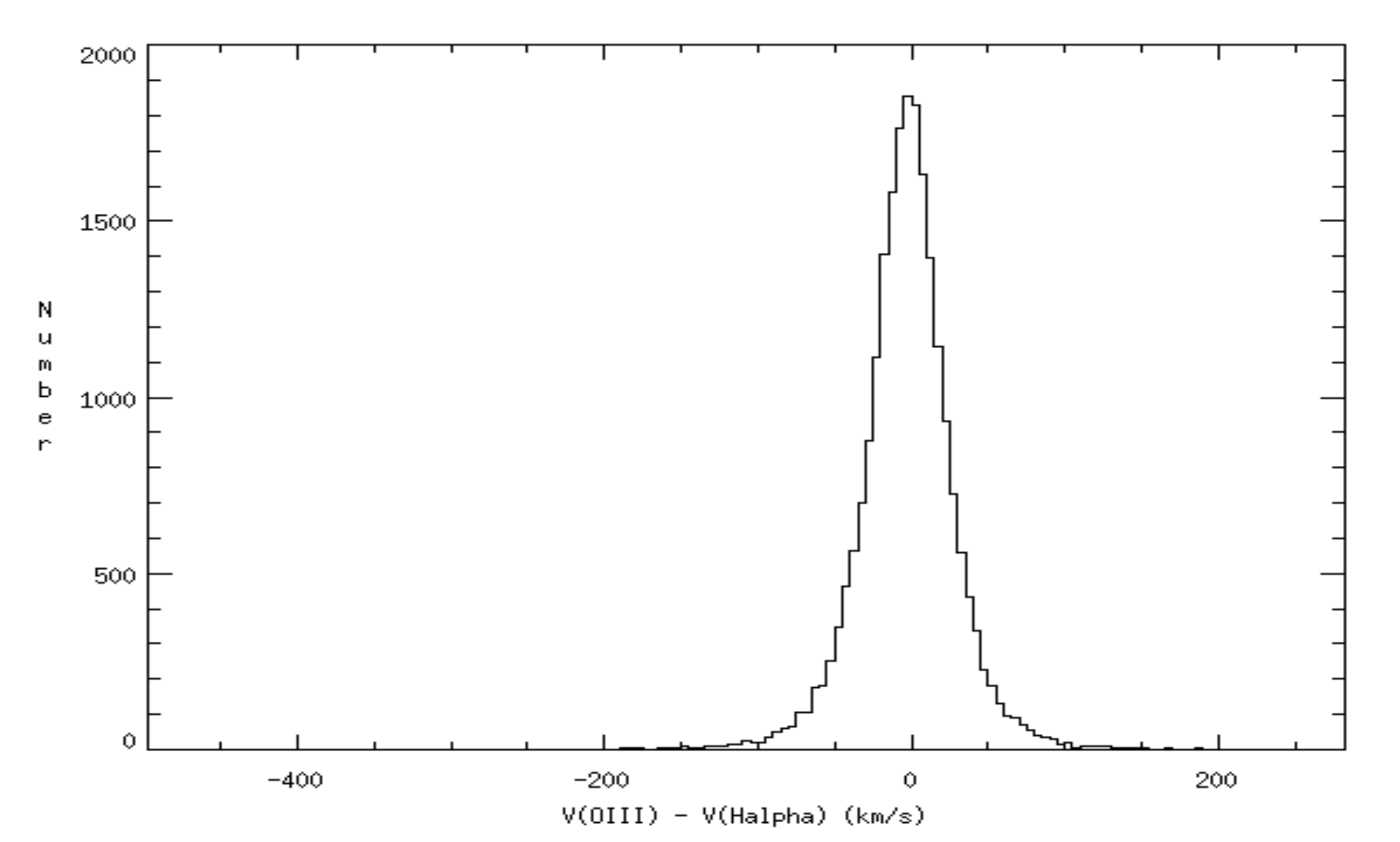
Emission line flux ratio diagram

Outflow AGNs

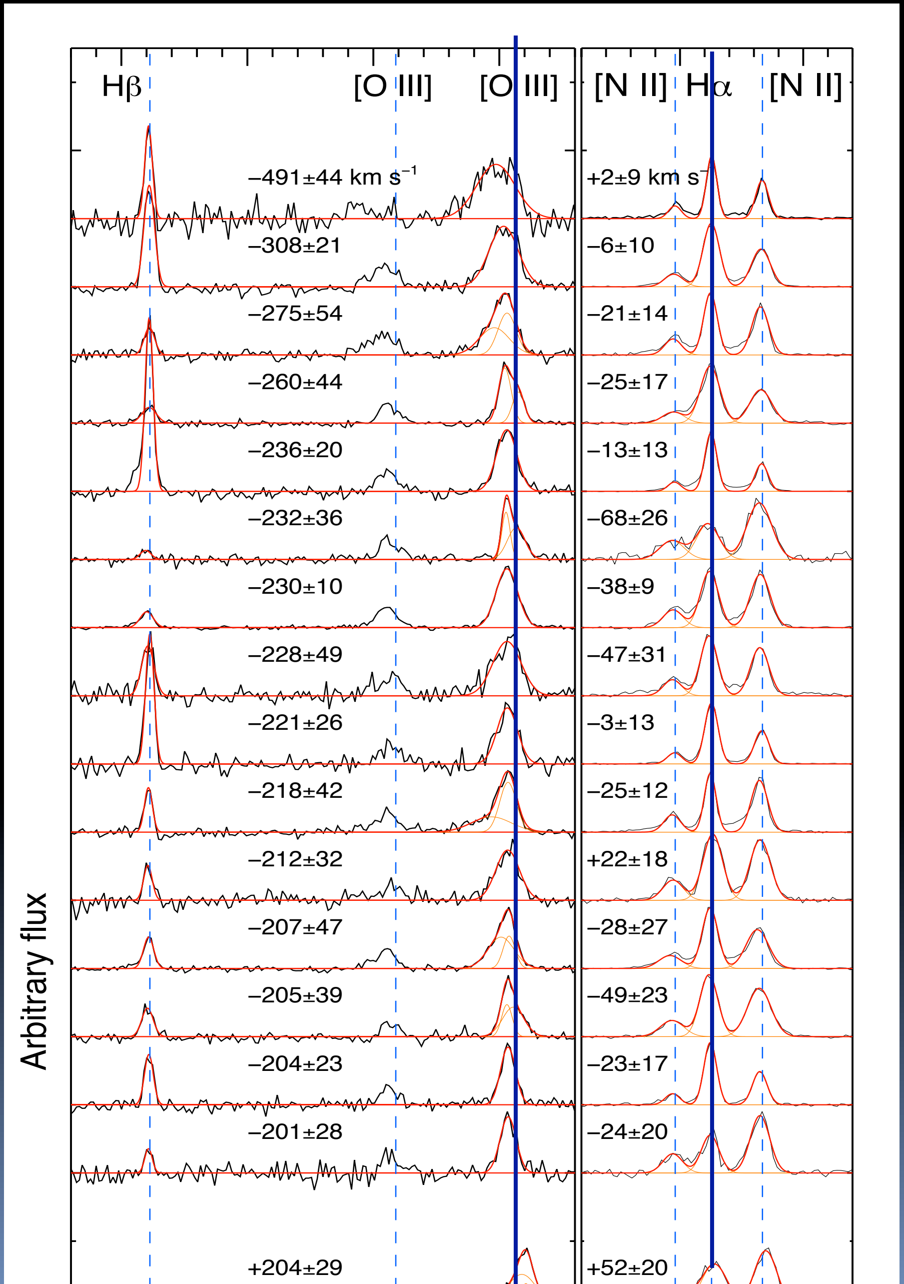
- Determine V_{offset} = V(OIII) – V(Ha) as done for type 1 AGNs

V_{offset} > 50 km/s : ~9%

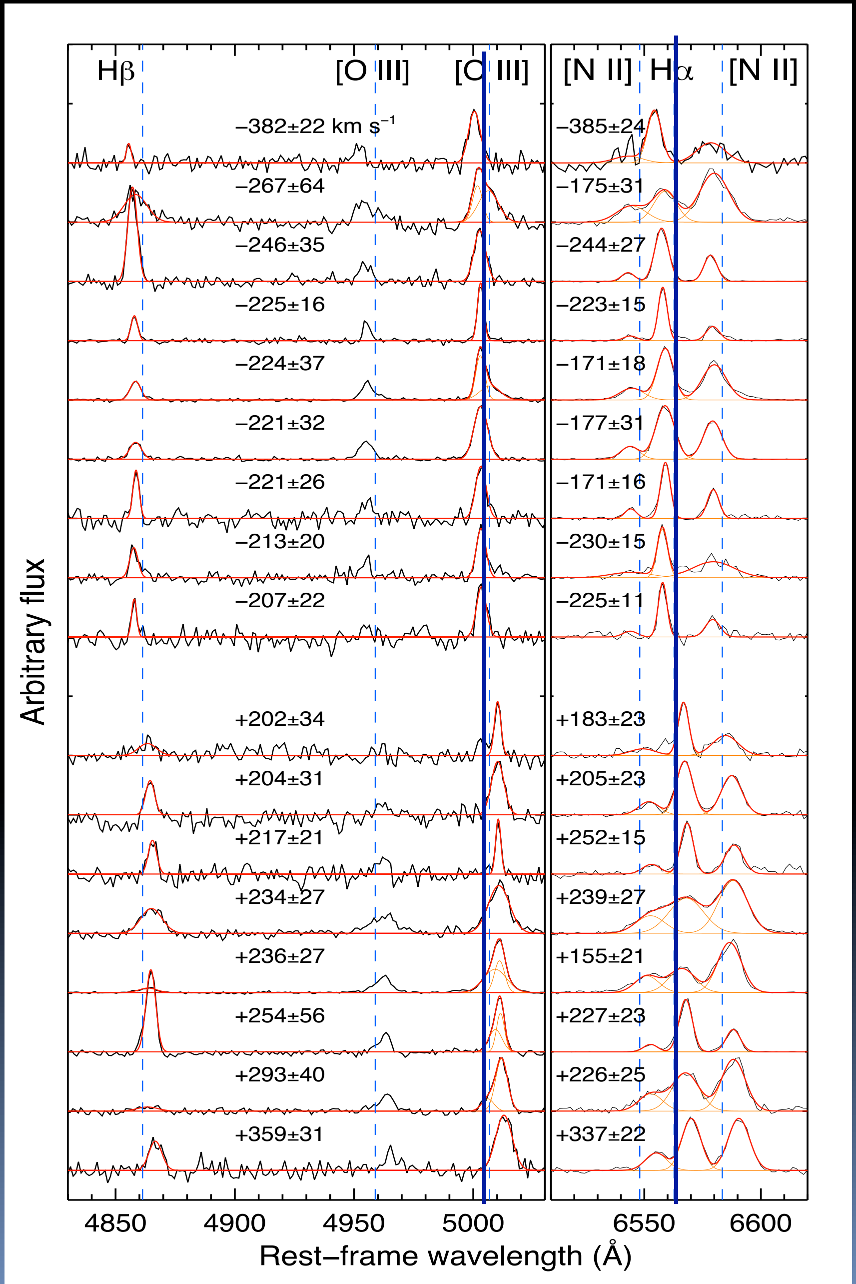
V_{offset} > 30 km/s : ~24%



Group A

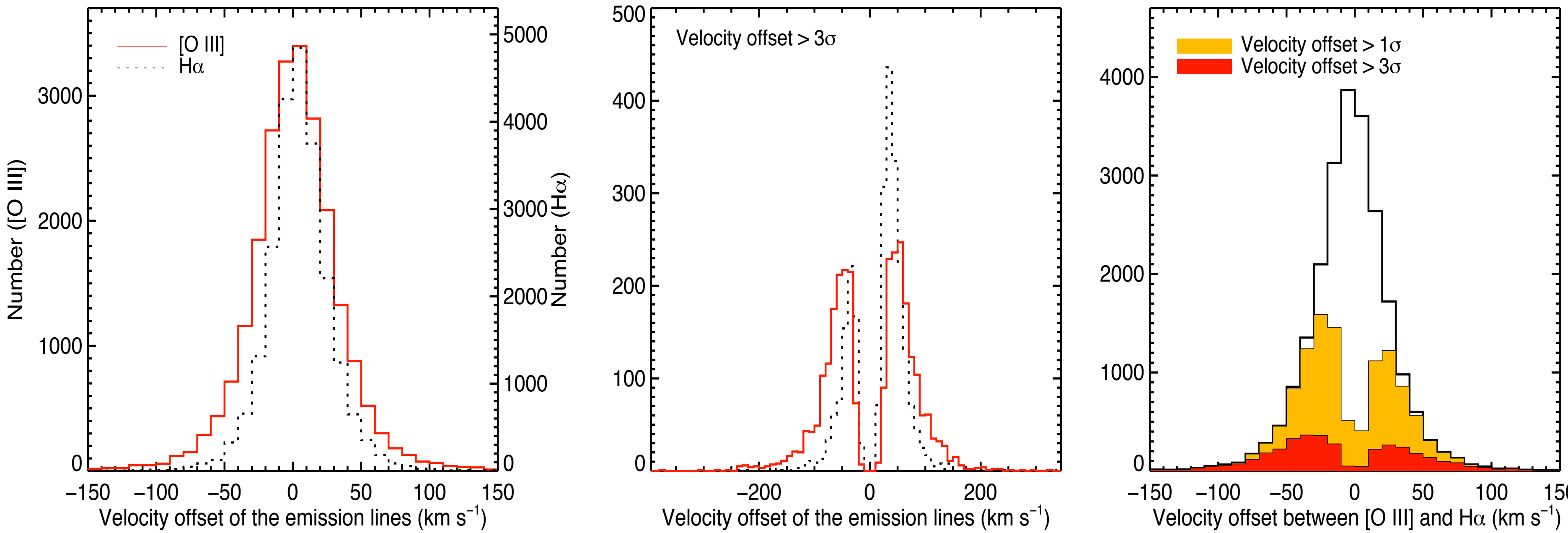


Group B



Vel. offsets of OIII vs. Ha w.r.t stellar lines

1. Voff (OIII) > 50 km/s (~13%).
2. Voff (OIII) > 30 km/s (~26%).



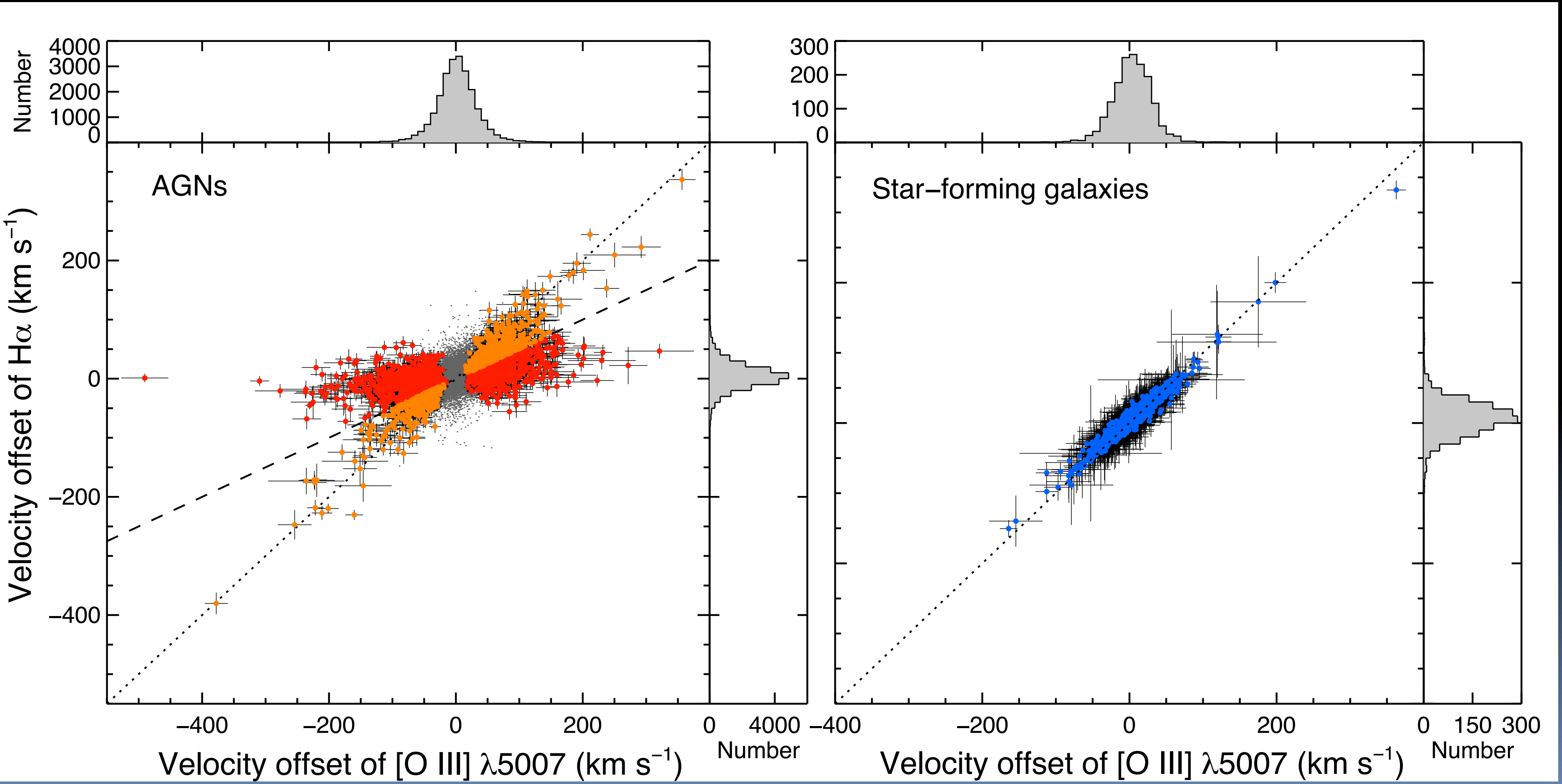
Bae, Woo +14 (submitted)

Vel. offsets of OIII vs. Ha

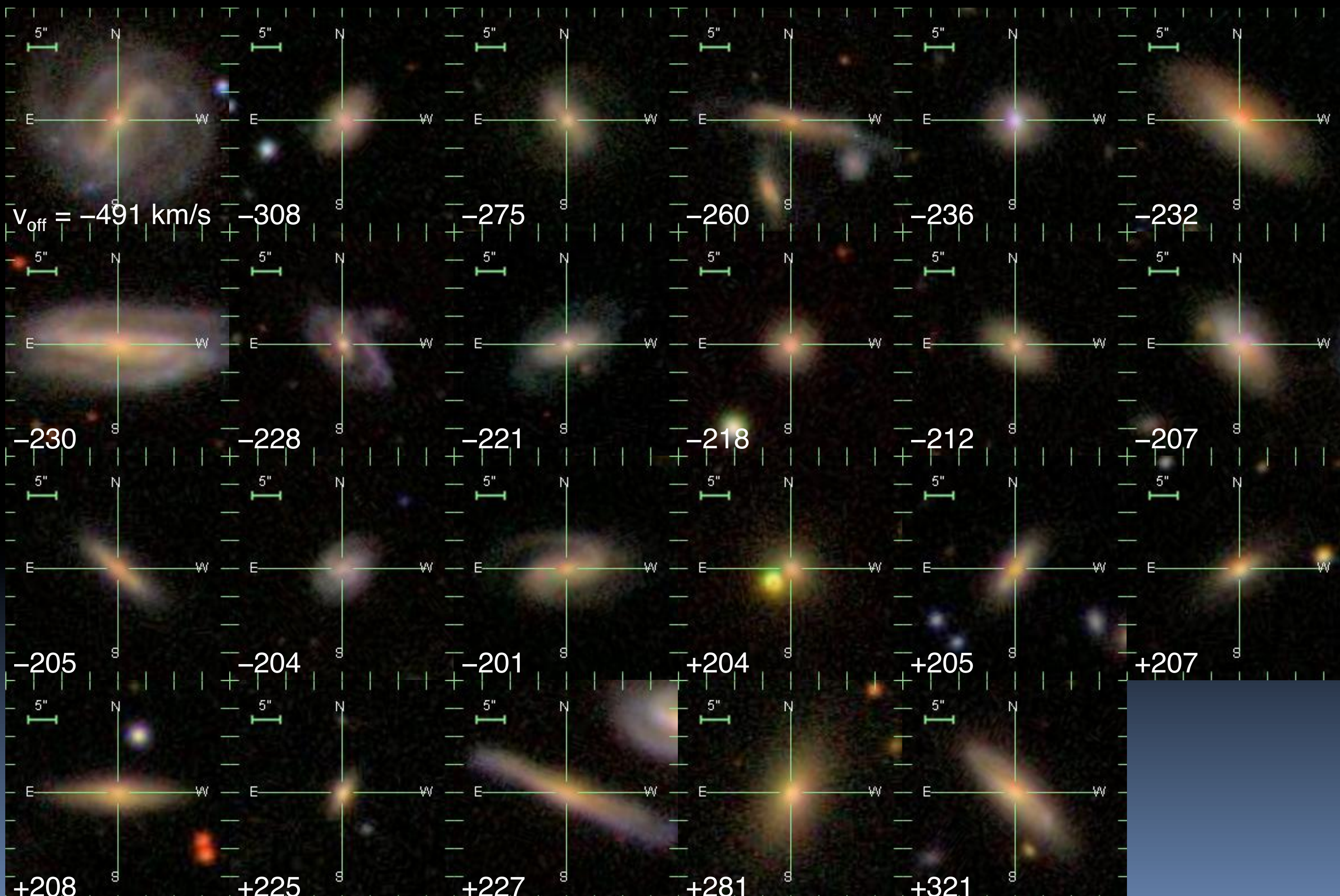
- We find two classes:

Group A: Voff (OIII) > Voff (Ha) - decelerating? (~8%).

Group B: Voff (OIII) ~ Voff (Ha) - ambiguous?(~5%).

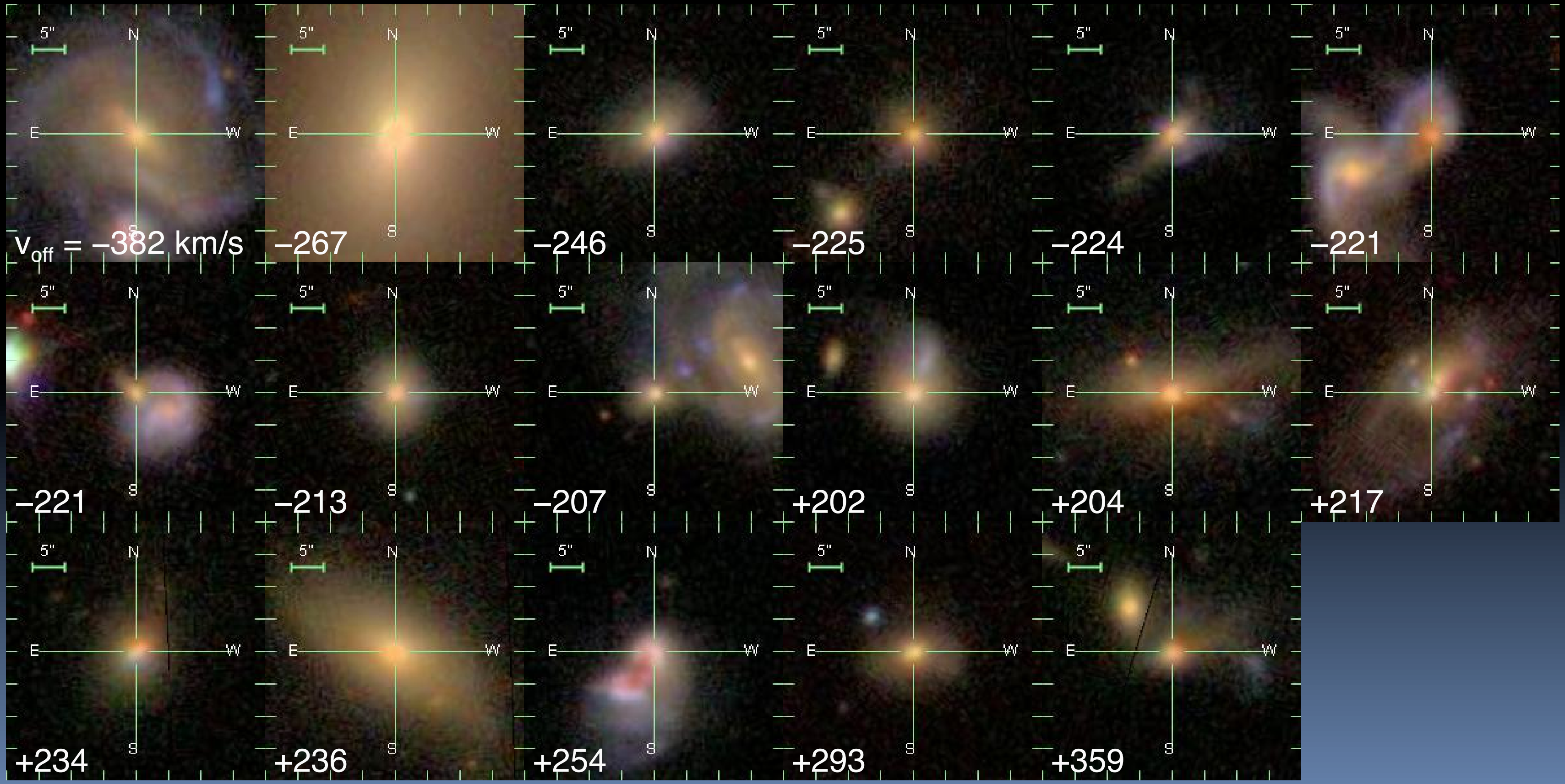


Group A (V > 200 km/s)



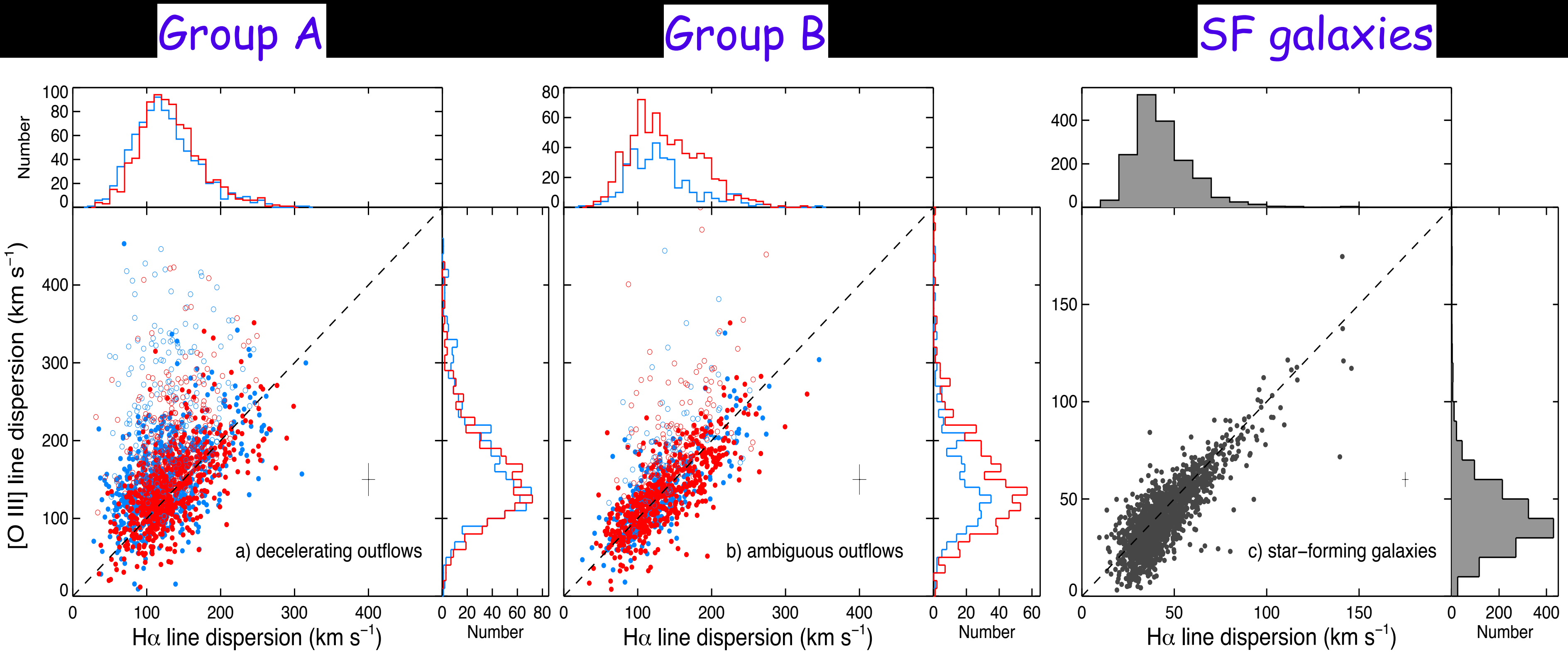
Group B (V > 200 km/s)

- Merging/interacting galaxies
- Offset (insprialling /recoiling) BHs?
- Gas & stellar decoupled?



Velocity dispersions of OIII and Ha

- AGNs have much broader lines than SF galaxies.
- Outflows show long tail toward high velocity dispersion.
- OIII is broader than Ha in Group A.



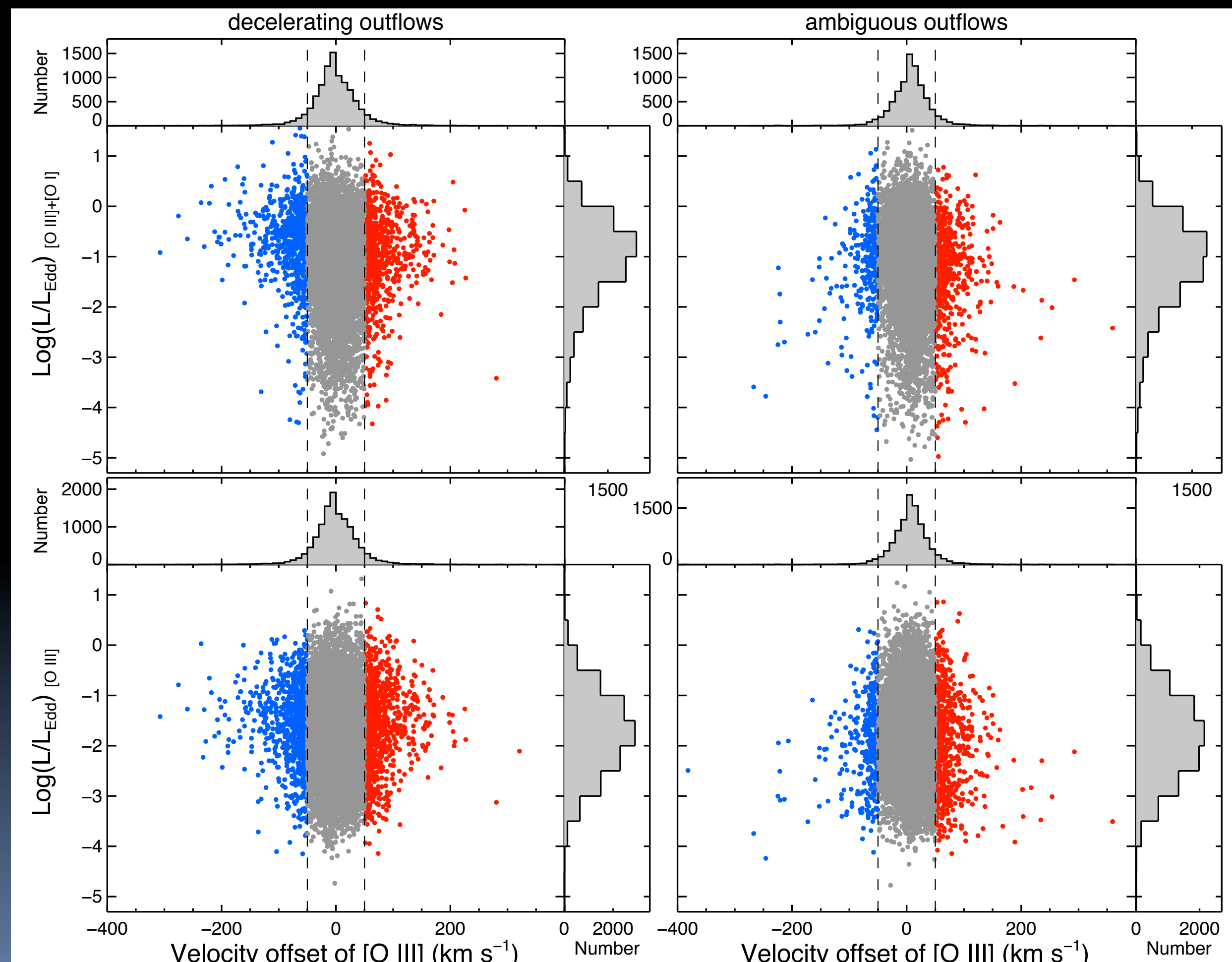
Velocity offset vs. Eddington ratio

Group A

Group B

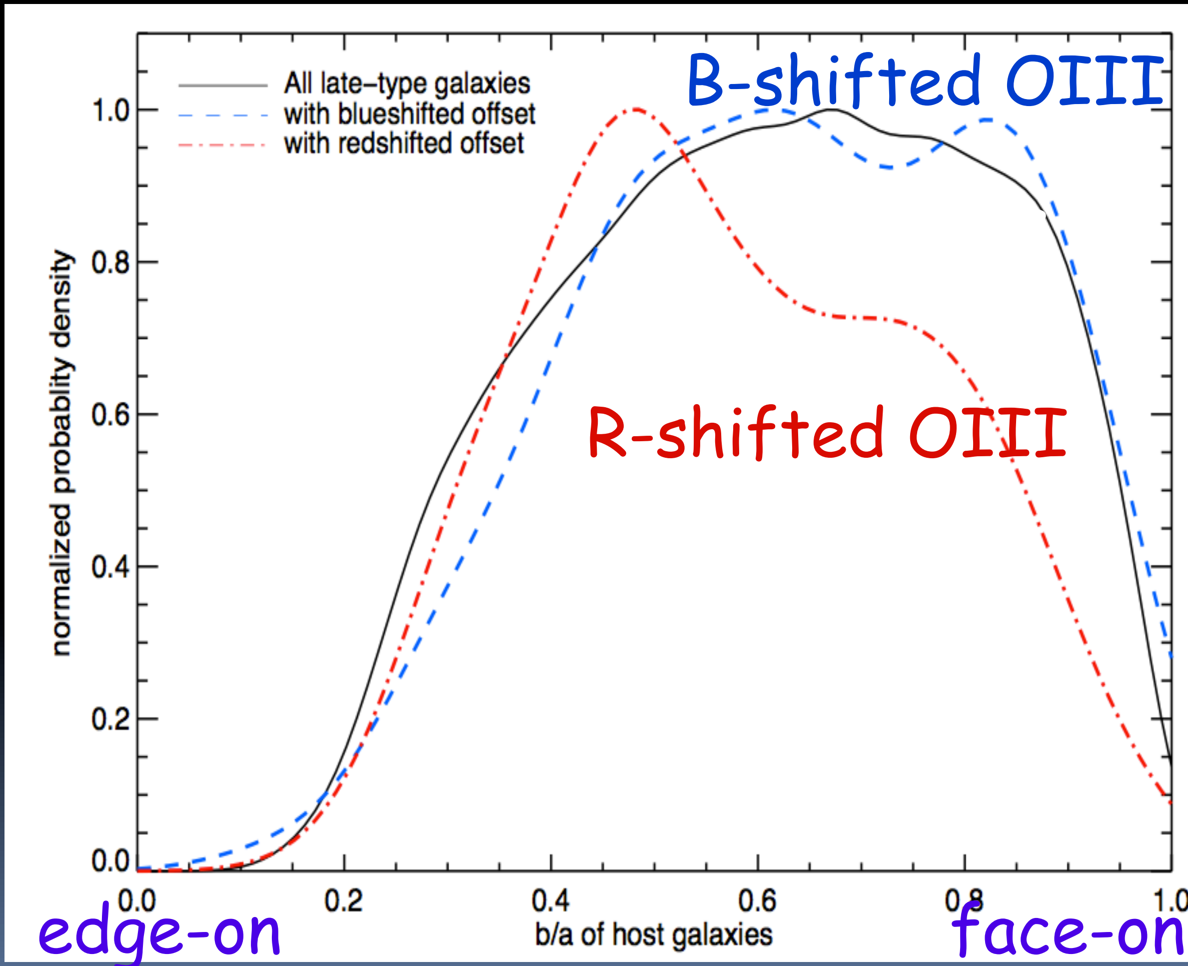
- High vel. outflows are preferentially hosted by high ER AGNs

- Some high ER AGNs have low outflow vel., presumably due to projection



Integrated OIII velocity offset is related to galaxy inclination

- ~260 AGN Outflows with V > 100 km/s
- Lack of face-on galaxies among R-shifted OIII
- Consistent with a bi-conical outflows and dust obscuration (Crenshaw+10)



Outflow fraction

- Type 1 AGNs: ~50 % with [O III] velocity > 50 km/s, (e.g., Boroson 2005; Komossa et al. 2008; Crenshaw et al. 2010; Zhang et al. 2011).
- Type 2 AGNs: ~13% with [O III] velocity > 50 km/s,

  ~26% with [O III] velocity > 30 km/s.
- The lower fraction of type 2 AGNs is presumably due to the projection effect.

Summary

- Using 22,000 type 2 AGNs, we find ~13% of AGNs showing outflows with LOS velocity > 50 km/s. The lower outflow fraction compared to type 1s is presumably due to projection effect.
- AGNs with larger outflow velocity preferentially have higher Eddington ratio, implying that outflow is radiation-driven.
- The distribution of the velocity offset measured from integrated spectra is consistent with a bi-conical outflow + dust obscuration scenario.
- For ~5% of AGNs, OIII and Ha show comparable velocity, indicating a complex origin, e.g., non-decelerating outflows or inspiralling/recoiling black holes.
- Following IFU observations can constrain how AGNs affect ISM and star formation in the host galaxies.