Investigating the cosmic evolution of the black hole mass - bulge luminosity relation

Daeseong Park (NAOC-based 2014 EACOA fellow)

with

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Matthew W. Auger, Matthew A. Malkan

2015/2/10 (Tue) 11:00-11:15am

EAYAM 2015 @ ASIAA, Taipei

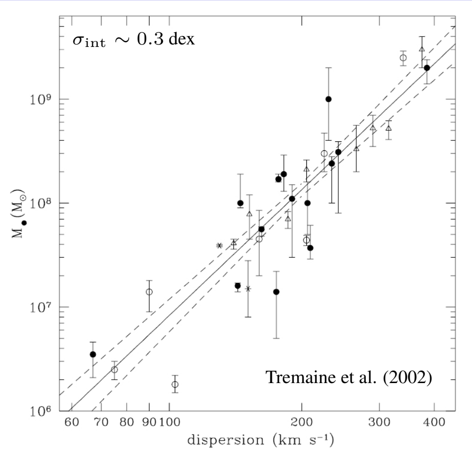
Contents

– The BH-galaxy correlations in local universe –

- $M_{\rm BH} - \sigma_*$ relation

Ferraresse & Merritt (2000) ApJL, 539, 9

Gebhardt et al. (2000) ApJL, 539, 13



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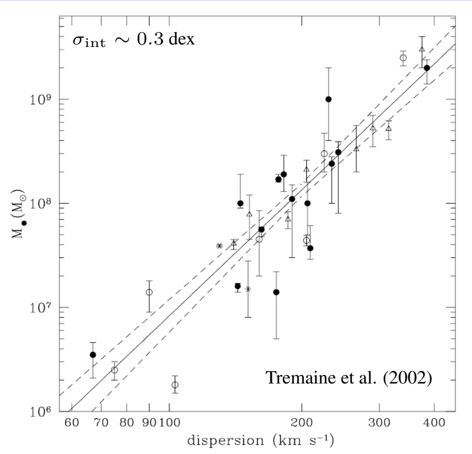
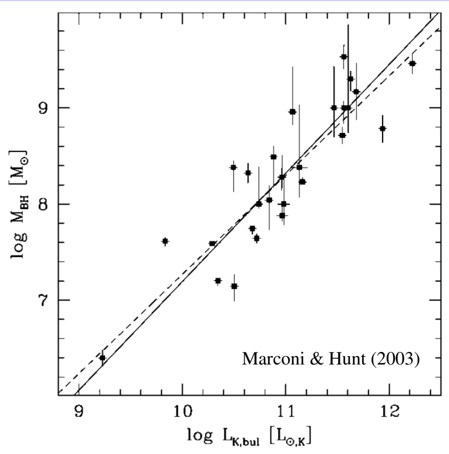


- $M_{\rm BH} - L_{\rm bulge}$ relation

Magorrian et al. (1998); McLure & Dunlop (2002)

Marconi & Hunt (2003)



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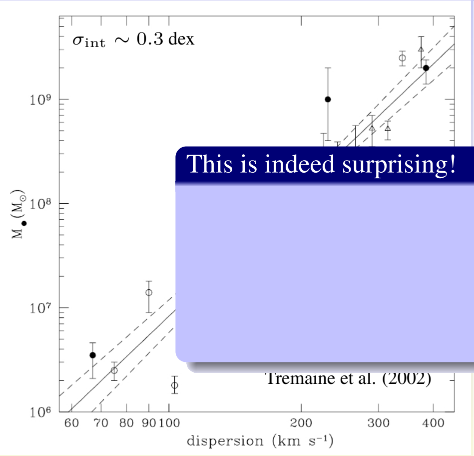

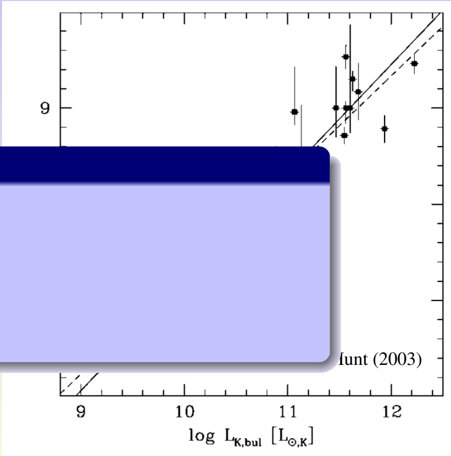

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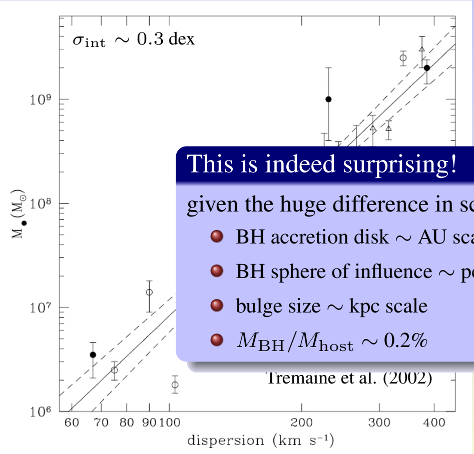

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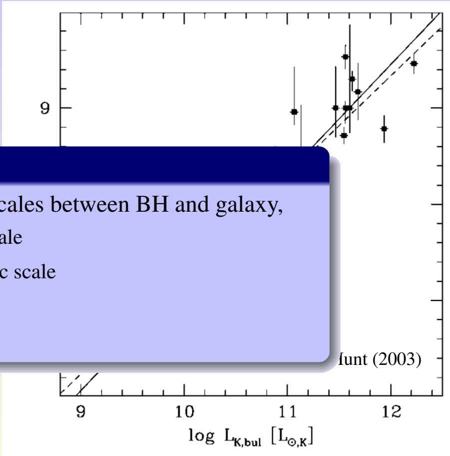

This is indeed surprising!

given the huge difference in scales between BH and galaxy,

- BH accretion disk $\sim$ AU scale
- BH sphere of influence $\sim$ pc scale
- bulge size $\sim$ kpc scale
- $M_{\rm BH}/M_{\rm host} \sim 0.2\%$

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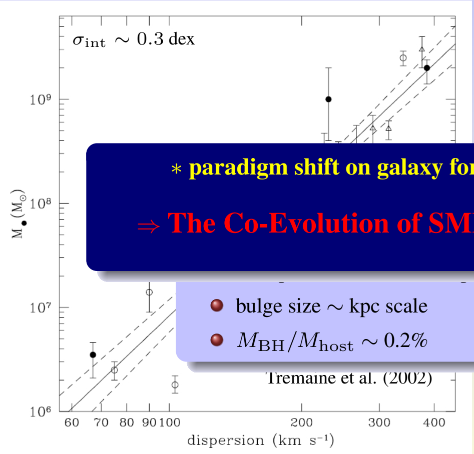

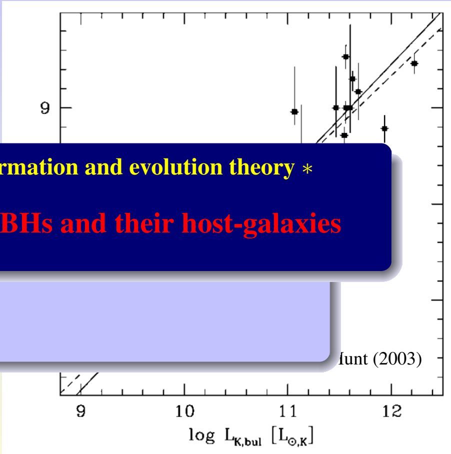

∗ paradigm shift on galaxy formation and evolution theory ∗

⇒ **The Co-Evolution of SMBHs and their host-galaxies**

- bulge size ∼ kpc scale
- $M_{\rm BH}/M_{\rm host} \sim 0.2\%$

The BH-galaxy co-evolution

- Fundamental Questions:

Q.1 What is the **physical origin** of the tight correlations?

Q.2 Do these correlations **evolve** with cosmic time?
(⇔ which comes first? BH? galaxy? or they evolve concurrently?)

Current understanding of the co-evolution from previous studies

In the standard cosmological scenario,

- bulges grow by galaxy mergers
- black holes grow by accreting surrounding matter

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1. investigating the origin from theoretical modelings

- AGN feedback mechanism

  (e.g., Silk & Rees 98; Fabian 99; Monaco+00; Kauffmann & Haehnelt 00; Wyithe & Loeb 03; Volonteri+03; Granato+04; Di Matteo+05; Springel+05; Croton+06; Bower+06; Robertson+06; Malbon+07; Colberg & Di Matteo 08; Somerville+08; Hopkins+06,08,09; Ciotti+09; Booth & Schaye 09; Johansson+09; Shankar+09)

- random merging events in hierarchical assembly without a physical coupling

  (e.g., Peng 07; Gaskell 10; Hirschmann+10; Jahnke & Maccio 11)

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⇒ But, it is still unclear because the models rely on many ad hoc assumptions and approximations

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? physically coupled process

? time offset and/or different timescales

2. investigating the evolution from observational approaches

- No evolution (synchronized growth)

  (e.g., Shields+03; Shen+08; Schulze+11; Schramm+13; Salviander+13; Schulze+14; Salviander+14)

- BH grows first

  (e.g., Treu+04,07; McLure+06; Shields+06; Peng+06; Woo+06,08; Salviander+07; Jahnke+09; Decarli+10; Merloni+10; Bennert+10,11; Cisternas+11; Hiner+12; Canalizo+12; Bongiorno+14)

- Galaxy grows first

  (e.g., Alexander+08; Shapiro+09; Urrutia+12; Busch+14)

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- Galaxy grows first

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$\Rightarrow$ But, these results are subject to sample selection biases and large measurement errors

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Given the uncertain and tentative understanding for the physical origin and cosmic evolution, **(more and accurate) direct observational constraints on how black holes and galaxies co-evolve over cosmic time** are thus necessary and will be essential inputs to better understand the physics of the black hole growth and galaxy evolution

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Purpose of this study

Investigating the evolution of the BH-galaxy scaling relation ($M_{\rm BH} - L_{\rm bul}$) over cosmic time to directly mapping the BH-galaxy co-evolution

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To probe the high-redshift scaling relation

One should rely on a sample of broad-line (Type 1) AGNs to obtain BH masses at high-z. However, this is subject to various measurement uncertainties and biases:

1. systematic uncertainties in SE virial BH mass estimates (Park et al. 2012a,b)
2. measurement systematics in host bulge luminosities (Kim et al. 2008a,b)
3. sample selection biases (Lauer et al. 2007; Schulze & Wisotzki 2011)

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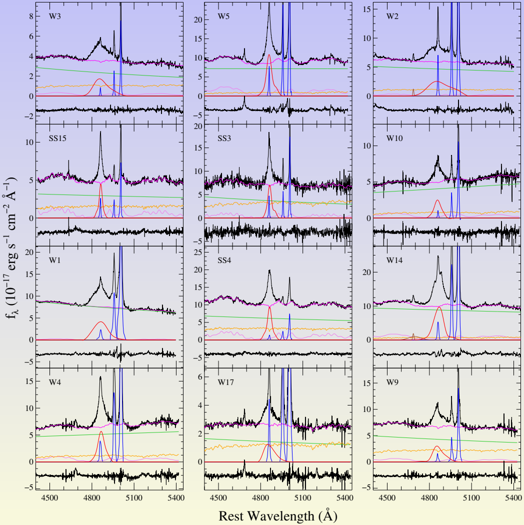
To mitigate these measurement uncertainties and selection biases

a total of 52 AGNs at moderate-redshifts (37 at $z \sim 0.36$; 15 at $z \sim 0.57$)
having moderate-luminosities ($\lambda L_{5100} \sim 10^{44}$ erg s^{-1})

1. high-quality Keck spectra & high-resolution HST images
2. uniform and consistent analysis to estimate $M_{\rm BH}$ and $L_{\rm bul}$
3. Monte Carlo simulation to take into account selection effects

the multi-component spectral decomposition of the Hβ region complex:



2. Measurements

2.1 Estimating black hole mass ($M_{\rm BH}$) by spectroscopic decomposition analysis on Keck sprectra

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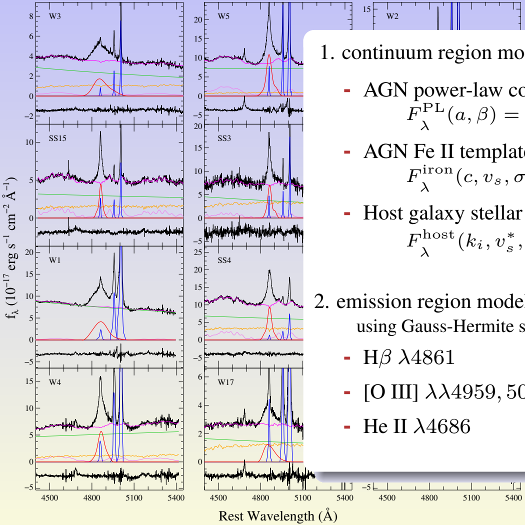

1. continuum region model:
   - AGN power-law continuum:
     $$F_\lambda^{\rm PL}(a, \beta) = a\,\lambda^\beta$$
   - AGN Fe II template:
     $$F_\lambda^{\rm iron}(c, v_s, \sigma_w) = c\,T_\lambda^{\rm IZw1} \otimes G_\lambda(v_s, \sigma_w)$$
   - Host galaxy stellar templates:
     $$F_\lambda^{\rm host}(k_i, v_s^*, \sigma_w^*) = \sum_{i=1}^{7} k_i\,T_{\lambda,i}^{\rm star} \otimes G_\lambda(v_s^*, \sigma_w^*)$$

2. emission region model:
   using Gauss-Hermite series and Gaussian functions for
   - Hβ λ4861
   - [O III] $\lambda\lambda$4959, 5007
   - He II λ4686

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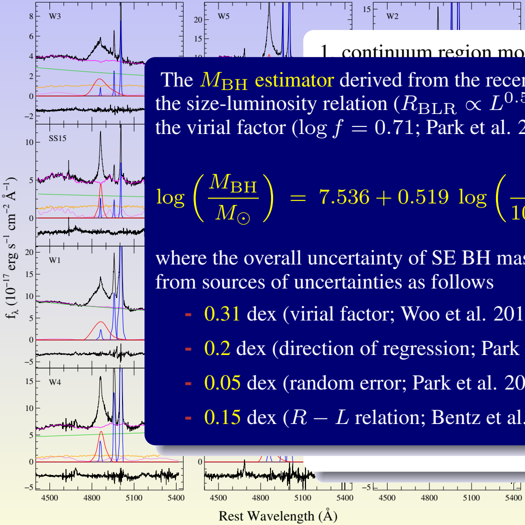


1. continuum region model:

The $M_{\rm BH}$ estimator derived from the recent calibrations of the size-luminosity relation ($R_{\rm BLR} \propto L^{0.519}$; Bentz et al. 2009a) and the virial factor (log $f = 0.71$; Park et al. 2012a)

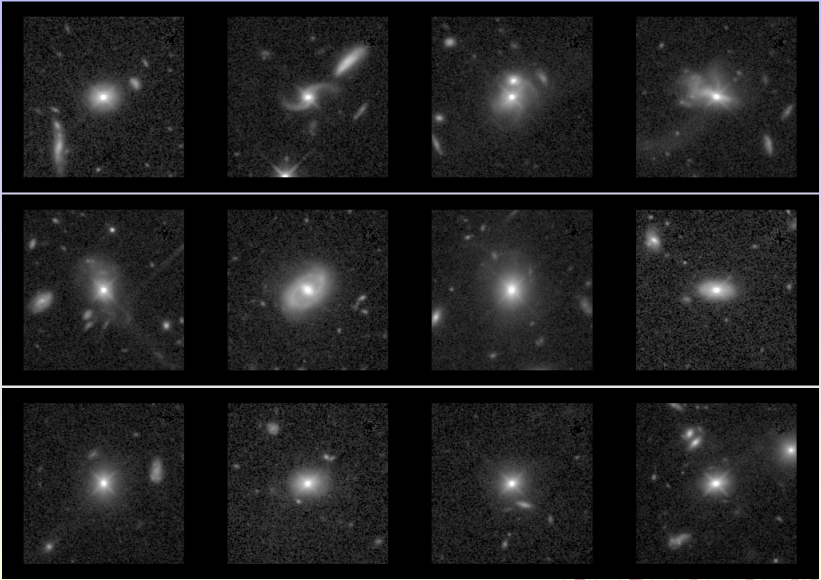
$$\log\left(\frac{M_{\rm BH}}{M_\odot}\right) = 7.536 + 0.519\ \log\left(\frac{\lambda L_{5100}}{10^{44}\ {\rm erg\ s^{-1}}}\right) + 2\ \log\left(\frac{\sigma_{\rm H\beta}}{1000\ {\rm km\ s^{-1}}}\right),$$

where the overall uncertainty of SE BH mass is estimated to be 0.4 dex from sources of uncertainties as follows

- 0.31 dex (virial factor; Woo et al. 2010)
- 0.2 dex (direction of regression; Park et al. 2012a)
- 0.05 dex (random error; Park et al. 2012b),
- 0.15 dex ($R - L$ relation; Bentz et al. 2009a).

2. Measurements

2.2 Estimating bulge luminosity ($L_{\rm bul}$) by photometric decomposition analysis on HST images



the multi-component structural decomposition of the AGN host galaxy:

Each image is decomposed into three main structural components:

1. Central point source (AGN; stellar PSFs)
2. Host galaxy bulge component (a de Vaucouleurs profile)
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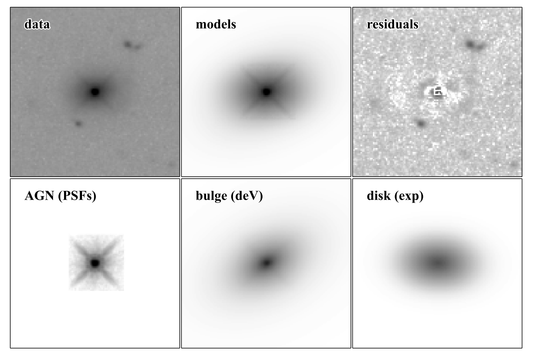

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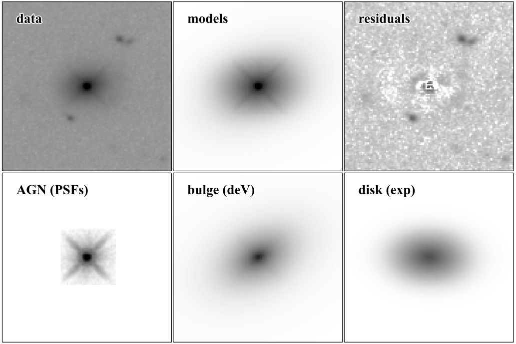

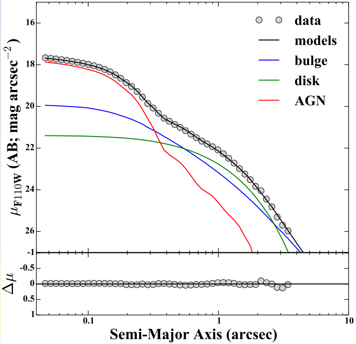

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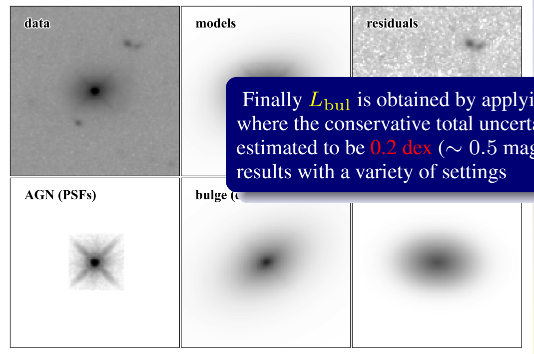
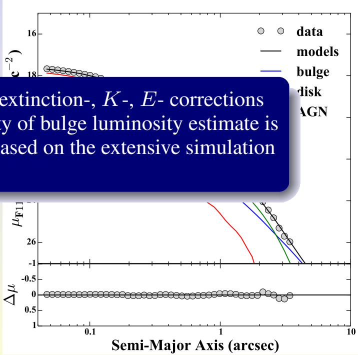
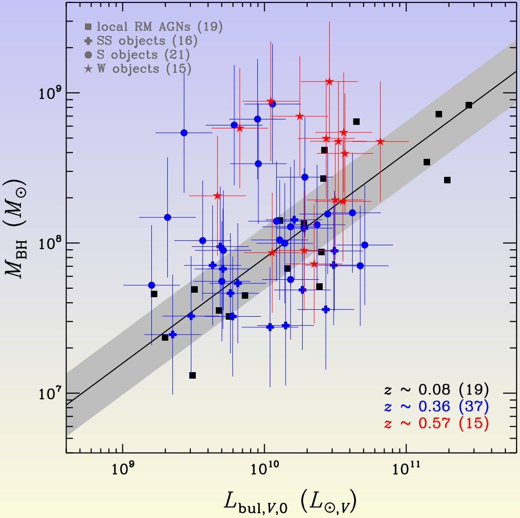




Finally $L_{\rm bul}$ is obtained by applying extinction-, K-, E- corrections where the conservative total uncertainty of bulge luminosity estimate is estimated to be 0.2 dex ($\sim$ 0.5 mag) based on the extensive simulation results with a variety of settings

$M_{\rm BH} - L_{\rm bul}$ distributions for local and distant active galaxies:



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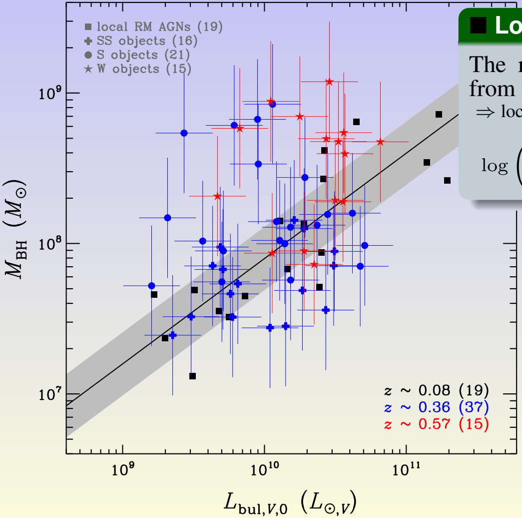

■ Local comparison sample

The reverberation-mapped local AGNs taken from Bennert et al. (2010)

⇒ local baseline relation:

$$\log\left(\frac{M_{\rm BH}}{M_\odot}\right) = 7.89 + 0.70 \log\left(\frac{L_{{\rm bul},V}}{10^{10}\ L_{\odot,V}}\right)$$

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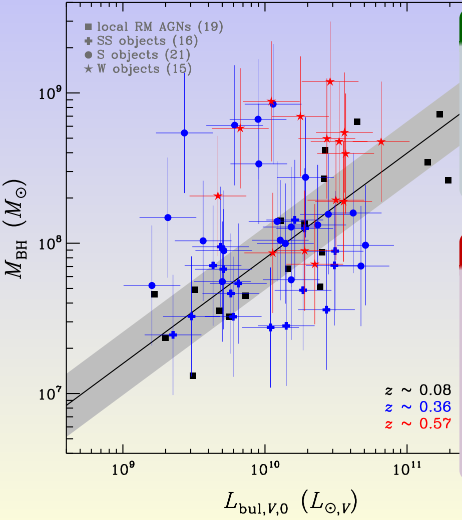

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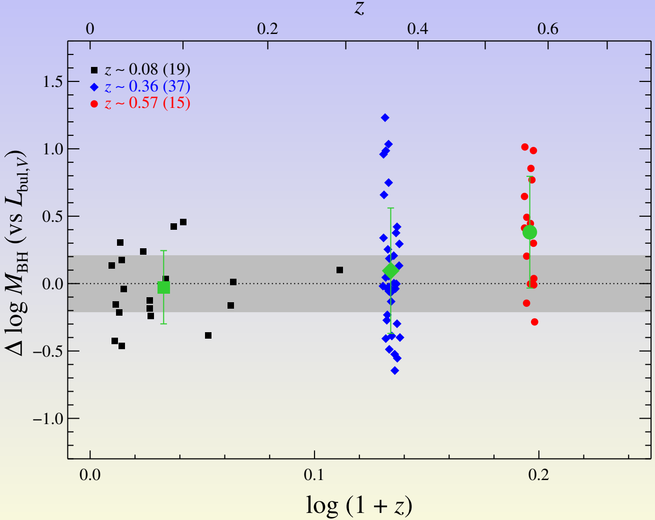
Sample selection

52 moderate-luminosity AGNs at moderate-redshifts, selected based on nuclear luminosity and Hβ broad emission line width (i.e., $M_{\rm BH}$)

- S objects at $z \sim 0.36$
- W objects at $z \sim 0.57$
- SS objects supplementary at $z \sim 0.36$ with additional selection criterion $M_{\rm BH} \lesssim 10^8 M_\odot$

Redshift distribution of the offset in $\log M_{\rm BH}$ for a given $L_{\rm bul}$ wrt the local baseline:



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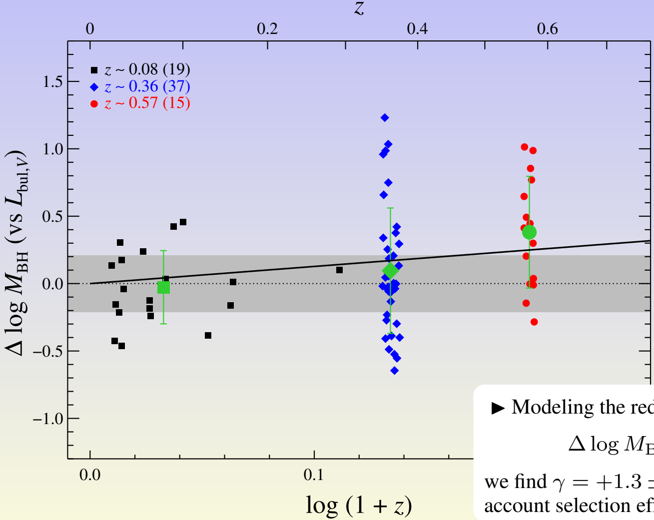
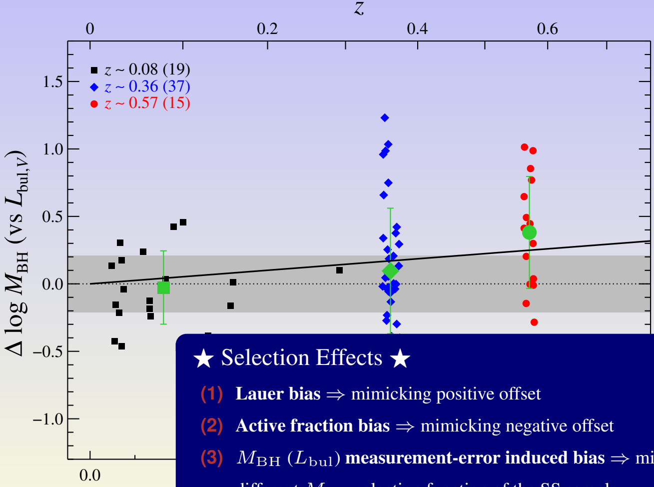


▶ Modeling the redshift evolution with a form of

$$\Delta \log M_{\rm BH} = \gamma \log(1+z),$$

we find $\gamma = +1.3 \pm 0.4$, without taking into account selection effects

Redshift distribution of the offset in $\log M_{\rm BH}$ for a given $L_{\rm bul}$ wrt the local baseline:



★ Selection Effects ★

(1) **Lauer bias** ⇒ mimicking positive offset

(2) **Active fraction bias** ⇒ mimicking negative offset

(3) $M_{\rm BH}$ ($L_{\rm bul}$) **measurement-error induced bias** ⇒ mimicking positive (negative) offset

— different $M_{\rm BH}$ selection function of the SS sample

▶ Monte Carlo simulation to incorporate the effects of observational selection processes:

1. generate simulated sample:
   - combining the local active BH mass function (Schulze & Wisotzki 2010) and the local baseline $M_{\rm BH} - L_{\rm bul}$ relation (Bennert et al. 2010)
   $\Rightarrow$ full joint distribution of $M_{\rm BH}$ and $L_{\rm bul}$
   - add Gaussian random errors on both axes

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   - applying simple hard threshold (upper and lower limits) from the observed $\log M_{\rm BH}$ distribution to the simulated sample

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3. compute likelihood on gird of input γ and $\sigma_{\rm int}$:
   $\ln \mathcal{L}(\gamma, \sigma_{\rm int}) = \sum_{i=1}^{N_{\rm obs.}} \ln P_i(\gamma, \sigma_{\rm int})$
   - making the probability distribution of black hole masses from the simulated sample which have the corresponding bulge luminosity within the measurement uncertainty

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4. evaluate posterior distribution with uniform and log-normal priors for $\sigma_{\rm int}$:
   - find best-fit values $(\gamma, \sigma_{\rm int})$ at maximum of marginalized posterior with 68% confidence interval

3. Analysis & Results

3.2 constraining the evolution of the $M_{\rm BH} - L_{\rm bul}$ relation

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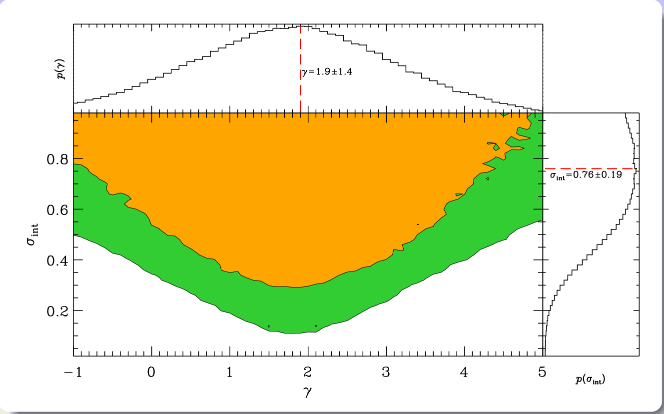

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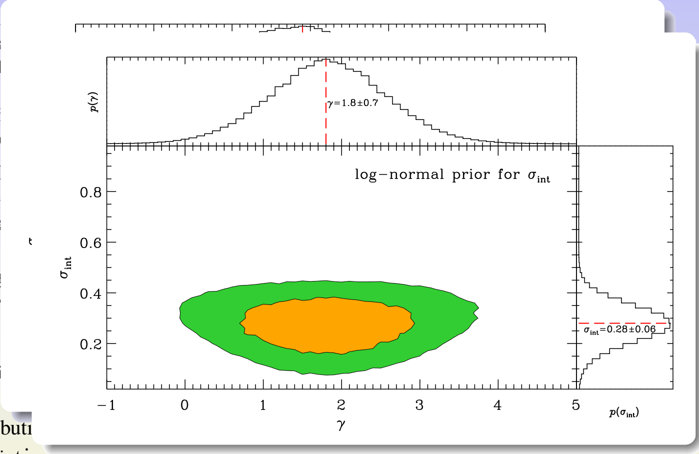

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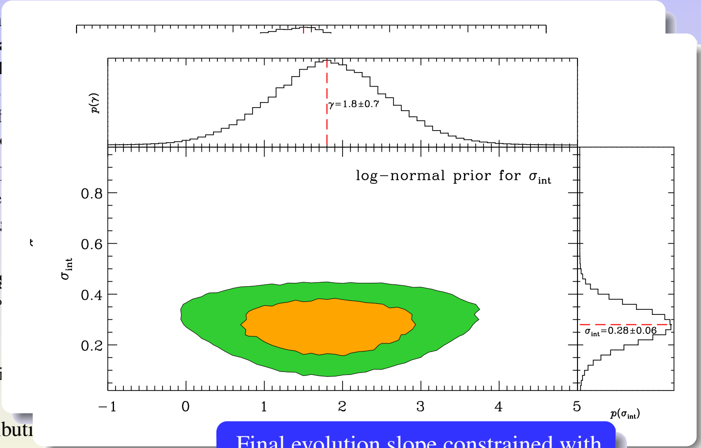
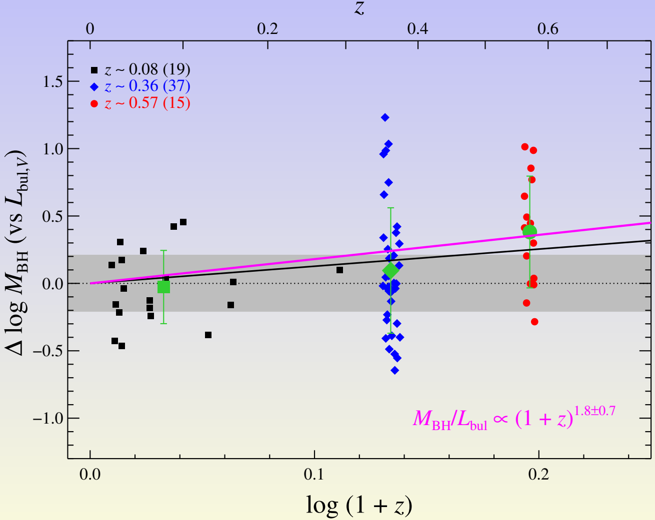
   (Schulze & Wisotzki 201
   $M_{\rm BH} - L_{\rm bul}$ relation (B
   $\Rightarrow$ full joint distribution of
   - add Gaussian random err
2. model the observational
   - applying simple hard thre
   its) from the observed lo
   simulated sample
3. compute likelihood on
   $\ln \mathcal{L}(\gamma, \sigma_{\rm int}) = \sum_{i=1}^{N_{\rm ob}}$
   - making the probability
   masses from the simulated
   responding bulge luminosi
   uncertainty
4. evaluate posterior distributi
   log-normal priors for $\sigma_{\rm int}$:
   - find best-fit values $(\gamma, \sigma_{\rm int})$ at maximum of
   marginalized posterior with 68% confidence interval



Final evolution slope constrained with proper accounting for selection effects:
$\gamma = +1.8 \pm 0.7$

★ **selection-bias corrected evolution:**



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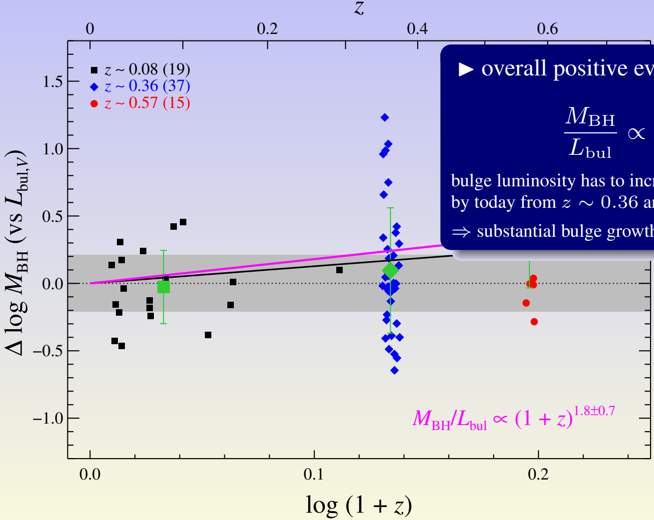

▶ overall positive evolutionary trend:

$$\frac{M_{\rm BH}}{L_{\rm bul}} \propto (1+z)^{1.8\pm0.7}$$

bulge luminosity has to increase by 0.24 dex and 0.35 dex by today from $z \sim 0.36$ and $z \sim 0.57$

$\Rightarrow$ substantial bulge growth without significant BH growth

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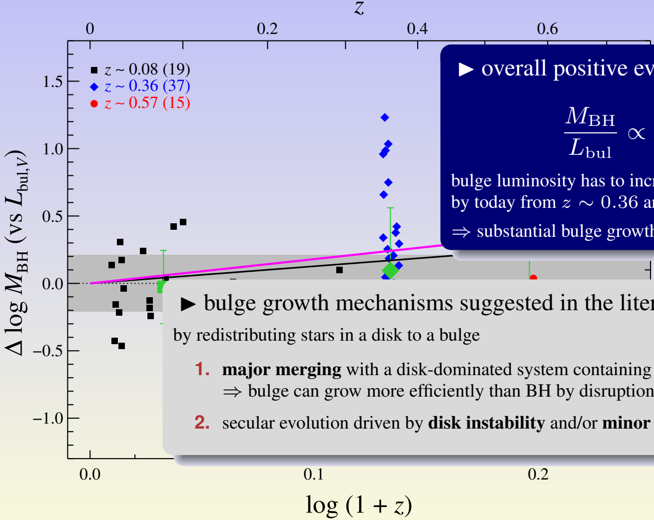

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▶ bulge growth mechanisms suggested in the literature:

by redistributing stars in a disk to a bulge

1. **major merging** with a disk-dominated system containing no or negligible BH (Croton 2006)
   ⇒ bulge can grow more efficiently than BH by disruption of stellar disk
2. secular evolution driven by **disk instability** and/or **minor merging** (Parry et al. 2009)

Summary & Conclusion

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- **Method**: multi-component spectral and structural decomposition techniques
- **Results**:
  1) Black hole masses and bulge luminosities are measured uniformly and consistently
  2) Comparing our sample to the local $M_{\rm BH} - L_{\rm bul}$ relation as evolutionary end-point, we find that **black holes at distant universe reside in smaller bulges than today**.
  3) Performing the Monte Carlo simulation designed to account for selection effects, we constrain the **positive evolutionary trend** in the form of $M_{\rm BH}/L_{\rm bul} \propto (1+z)^{1.8\pm0.7}$

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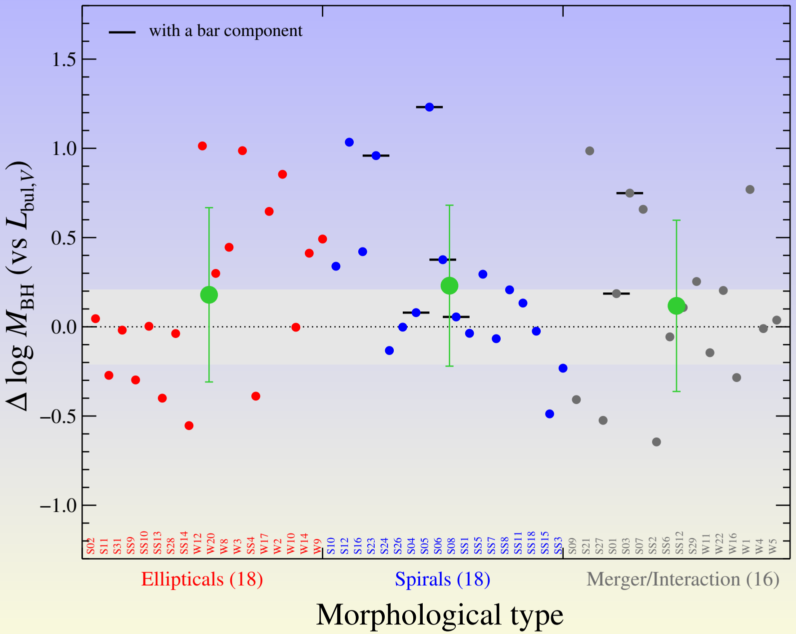
But, there is still large scatter with limited dynamic ranges. And, for now, we cannot exclude an another possibility that the observed evolution is originated from increased intrinsic scatter at higher-z.

$\Longrightarrow$ **need much more and uniformly (better) selected samples with wider dynamic ranges**

Thank you∼ ☺

▶ Please see **Park et al. 2015**, ApJ, 799, 164 for details with the series of our previous papers:

- **Treu et al. 2004**, ApJL, 615, 97
- **Woo et al. 2006**, ApJ, 645, 900
- **Treu et al. 2007**, ApJ, 667, 117
- **Woo et al. 2008**, ApJ, 681, 925
- **Bennert et al. 2010**, ApJ, 708, 1507



with a bar component
Δ log M_{BH} (vs $L_{bul,V}$)
1.5
1.0
0.5
0.0
−0.5
−1.0
S02 S11 S31 SS9 SS10 SS13 S28 SS14 W12 W20 W8 W3 SS4 W17 W2 W10 W14 W9
S10 S12 S16 S23 S24 S26 S04 S05 S06 S08 SS1 SS5 SS7 SS8 SS11 SS18 SS15 SS3
S09 S21 S27 S01 S03 S07 SS2 SS6 SS12 S29 W11 W22 W16 W1 W4 W5
Ellipticals (18)
Spirals (18)
Merger/Interaction (16)
Morphological type