Theoretical Re-evaluations of Scaling Relations between SMBHs and Their Host Galaxies
— 1. Effect of seed BH mass

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Abstract
We explore the effect of varying the mass of a seed black hole (BH) on the resulting black hole mass – bulge mass relation at z = 0, using a semi-analytic model of galaxy formation combined with large cosmological N-body simulations. When the mass of the seed is set at 10^6 M_sun, we find that the model results become inconsistent with recent observational results of the black hole mass – bulge mass relation for dwarf galaxies. On the other hand, when we employ seed black holes of 10^5 M_sun or select their mass randomly within a 10^4–5 M_sun range, the resulting relation is consistent with observational results including the dispersion. We also find that black hole mass — bulge mass relations for less massive bulges at z = 0 put stronger constraints on the seed BH mass than the relations at higher redshifts.

Introduction
Candidates of seed BHs:

- via a star/star cluster 
- direct collapse

Question: How massive are seed BHs?

To answer these questions:
- Show M_BH — M_bulge relations obtained from semi-analytic model
- Compare them with observations

Strategy: Get constraints on seed BH mass from this relation!

Semi-Analytic Model of Galaxy Formation
We employ a revised version of semi-analytic model of galaxy formation, "New Numerical Galaxy Catalogue" (vNGC: Makita et al. 2016). The merging histories of dark matter haloes are obtained from cosmological N-body simulations (Ishiyama et al. 2015).

Spheroid formation
- starbursts
- migration of disk stars triggered by
- galaxy mergers (major/minor)
- disk instability

SMBH growth
- gas accretion accompanying with spheroid growth

\[ \frac{\dot{M}_{\text{BH}}}{\dot{M}_{\text{acc}}} = \left( \frac{f_{\text{BH}}}{0.01} \right) \]
\[ \text{accreted mass} \]
\[ \text{stellar mass formed by a starburst} \]

- SMBH - SMBH mergers (neglecting energy loss by gravitational waves)
- radio mode AGN feedback (same as Bower et al. 2006)

Setting of seed BH mass (3 models)
1. massive seed model: \(10^6\) M_sun for all galaxies
2. random seed model: \(3 \leq \log(\text{seed mass/M}_\odot) \leq 5\)
3. light seed model: \(10^3\) M_sun for all galaxies

Compare these three models

Is there some differences on the M_BH — M_bulge relation?

Results
Answer: Light (10^3 M_sun) seed BHs are dominant!

Cannot reproduce them with massive seed model...

It is possible to get constraints on seed mass from M_BH — M_bulge relation @ z = 0.
However, it is difficult to estimate masses of low mass BHs/bulges.

Can we get the constraints from the same relation in higher z, with more massive galaxies?

NO!!

Next Stage
1. Need pseudo-bulge model
Spheroids formed by disk instability should be treated as pseudo-bulges, which is not included in SA models.

2. M_BH — \(\sigma\) relation is better?

- Large scatter exists in the M_BH — M_bulge relation
- Depends on selection criteria (e.g., Sivonman et al. 2016)
- Need larger sample of less massive bulges

Is this “bend” a real feature?

Reference
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Theoretical Re-evaluations of Scaling Relations between SMBHs and Their Host Galaxies

— 2. Importance of AGN Feedback Suggested by Stellar Age — Velocity Dispersion Relation

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Abstract
We present the galactic stellar age -velocity dispersion relation obtained from a semi-analytic model of galaxy formation. We divide galaxies into two populations: galaxies which have an over-massive/under-massive BH against the best-fitting BH mass - velocity dispersion relation. We find that galaxies with an over-massive BH have older stellar age. This result is consistent with observational results obtained from Martin-Navarro et al. (2016) and Merrifield et al. (2000). We also find that to obtain this result, AGN feedback is one of the key processes; without the AGN feedback, galaxies with larger velocity dispersion have younger stellar age. In this poster, we also present some statistical properties of galaxies and AGNs obtained from the semi-analytic model to confirm that the model results are consistent with recent observational results.

Introduction
Do AGNs quench star formation?
— Actively discussed matter.

They argue that this trend appears by AGN feedback effect: massive BH → strong AGN feedback → quench star formation earlier less massive BH → weak AGN feedback → quench star formation later

Investigate whether their scenario is correct by using a semi-analytic model of galaxy formation!

Semi - Analytic Model of Galaxy Formation
We employ a revised version of semi-analytic model of galaxy formation, “New Numerical Galaxy Catalogue” (vGC: Makiya et al. 2016). The merging histories of dark matter haloes are obtained from cosmological N-body simulations (Ishiyama et al. 2015).

- Spheroid formation
  - starbursts
  - migration of disk stars triggered by
  - galaxy mergers (major/minor)
  - disk instability
(spheroids are treated as “classical bulges”)

- SMBH growth
  - gas accretion accompanying with spheroid growth
  \[ M_{\text{acc}} = f_{\text{BH}} \Delta M_{\text{star burst}} \] (\( f_{\text{BH}} = 0.01 \))

  - SMBH - SMBH mergers (neglecting energy loss by gravitational waves)
  - radio mode AGN feedback (same as Bower et al. 2006)

AGN feedback is efficient if:
\[ t_{\text{dyn}}(r_{\text{cool}}) < \alpha_{\text{cool}} t_{\text{cool}} \]
and \( \epsilon_{\text{SMBH}} L_{\text{BH}} > L_{\text{cool}} \)

Possible to satisfy
with more massive haloes

Possible to satisfy
with more massive BHs

Then, no gas cooling occurs. Accretion rate onto a BH is:
\[ M_{\text{BH}} = \frac{L_{\text{cool}}}{\eta} \]
(\( \alpha_{\text{cool}} = 1.0, \epsilon_{\text{SMBH}} = 0.012, \eta = 0.1 \))

Results of the fiducial model
We can explain many statistical properties of galaxies/SMBHs obtained from observations.

Results
We show \( M_{\text{BH}} - \sigma \) relation obtained from vGC (I[A]).

The best fit of the Min - \( \sigma \) relation (red line):
That of van den Bosch (2016) (blue line) is:

When we set \( \alpha_{\text{cool}} = 0.1 \) (AGN feedback becomes weak), under-massive BH galaxies become older (IC).

Now we employ the cooling cutoff determined by circular velocity of DM haloes instead of the radio mode AGN feedback (ID). Under-massive BH galaxies become little older.

(Gas doesn't cool in a DM halo whose circular velocity is larger than 210 km/s)

We conclude that the radio mode AGN feedback will play a part to explain the observational relation between stellar age, \( M_{\text{BH}} \), and \( \sigma \) (II).

We, however, have smaller difference between over-/under- massive BH galaxies than the observational suggestion.

- Selection biases?
- Need quasar mode feedback?

Appendix
Results of GALFORM public data (Bower + 06)

Reference
Bower R. G. et al. (2006), MNRAS, 370, 645
Ishiyama T. et al. (2013), PASJ, 65, 41
Martin-Navarro, I. et al. (2016), ApJ, 832, L11
Makiya R. et al. (2016), PASJ, 68, 25
van den Bosch, K. C. E. (2010), ApJ, 831, 334

If you are interested in vGC and need more information, please contact me! (mail: shirakata(at)astro1.sci.hokudai.ac.jp)