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

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Outline

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

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&
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
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.
Comparison between inactive and active galaxies

- **quiescent galaxies:**
  slope: $5.31 \pm 0.33$

- **AGN:**
  new and updated $M_{BH}$ & $\sigma$
  slope: $3.46 \pm 0.61$

- Is the relation same?

- Truncation in mass distribution
Comparison between inactive and active galaxies

- quiescent galaxies:
  slope: $5.31 \pm 0.33$

- AGN:
  new and updated $M_{\text{BH}}$ & $\sigma$
  slope: $3.46 \pm 0.61$, $f=5.1$

- Joint fit (Quiescent galaxies + AGNs):
  slope: $4.93 \pm 0.28$, $f=5.9$

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

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

\[ \log(M_{BH}/M_\odot) = \alpha + \beta \log(\sigma_*/200 \text{ km s}^{-1}) \]
What about stellar velocity dispersions?

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

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

- Rotation added (McConnell+13, Gultekin+09)

\[
\sigma^2 = \frac{\int_{-R_e}^{R_e} \left( \sigma_*(r)^2 + V(r)^2 \right) I(r) \, dr}{\int_{-R_e}^{R_e} I(r) \, dr}
\]

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

\[
\sigma_* = \frac{\int_{-R_e}^{R_e} \sigma_*(r) I(r) \, dr}{\int_{-R}^{R} I(r) \, dr}
\]
Re-visiting the $M_{\text{BH}} - \sigma$ 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.

\[ \sigma_\ast = \frac{\int_{-R_e}^{R_e} \sigma_\ast(r) I(r) \, dr}{\int_{R_e}^{R_e} I(r) \, dr} \]
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.
- For late-type galaxies (σ < V), the rotation effect is expected to be much stronger.

Kang et al. 2013
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 $M_{\text{BH}}$-sigma relation
Evolution of the Scaling Relations

- Chicken or egg?
- Observational constraint is necessary.
Cosmic evolution of $M_{\text{ BH}} - \sigma$ & $M_{\text{ BH}} - L_{\text{ bulge}}$ relations

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

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

Observations
- Keck LRIS spectroscopy
- HST ACS/NICMOS/WFC3 imaging
Estimating $M_{BH} \sim f \cdot V^2 L^{0.5} / G$

Measuring velocity dispersion

Measured for 34 objects
No measurements for 18

Woo + 06, 08
The $M_{\text{BH}}$– sigma relation 4-6 Gyr ago

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

Woo et al. 2006, 2008

Woo et al. 2013b in preparation

![Graph showing the relation between black hole mass ($M_{\text{BH}}$) and velocity dispersion ($\sigma$) at different redshifts (z~0.4 and z~0.6) with local RM AGNs from Woo+13a.](image)

- z~0.4
- z~0.6
- Inactive galaxies

- z~0.4 (27)
- z~0.6 (7)
- local RM AGNs from Woo+13a
Evolution of the $M_{\text{BH}}$ - sigma Relation

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

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

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 $z \sim 0.5$. Possible at $z \sim 1$?
- Bulge/disk decomposition with HST resolution: Challenging for small bulges at $z \sim 0.5$. Total luminosity?
Summary II

- At fixed $M_{\text{BH}}$, bulges at $z \sim 0.4$ & 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.