Galaxies and Their Central Black Holes

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July 25, 2018

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Introduction: Black Holes are Everywhere!

✿ Supermassive BHs reside in essentially every massive galaxy.

✿ The strongest evidence we have for a BH comes from the Milky Way (e.g., Genzel et al. 2010, Boehle et al. 2016).

✿ Beyond the Milky Way, BHs have been dynamically detected in ~100 galaxies (e.g., Saglia et al. 2016).

(This image was created by Prof. Andrea Ghez and her research team at UCLA and are from data sets obtained with the W. M. Keck Telescopes.)
Precise $M_{\text{BH}}$ measurements require high angular resolution observations.

Observations need to probe region over which the BH potential dominates — the BH sphere of influence ($r_{\text{sphere}}$).

Typical values for $r_{\text{sphere}}$ are small, so we are limited to studying nearby (~100 Mpc) objects.

HST has played a fundamental role in detecting BHs over the past two decades.

Significant progress has recently been made using large ground-based telescopes + AO (e.g., Mazzalay et al. 2016, Erwin et al. 2018, Krajnović et al. 2018).

ALMA also provides superb sensitivity and angular resolution high enough to directly detect molecular gas within $r_{\text{sphere}}$ (e.g., Barth et al. 2016, Onishi et al. 2017, Davis et al. 2017).
The Current Black Hole Relations

- The correlations suggest that BHs and galaxies grow in tandem, but we still do not have a good understanding of the exact role that BHs play in galaxy evolution. We need more robust $M_{BH}$ measurements that:
  - better sample the extremes of the BH mass scale
  - probe a wider range of galaxy types with diverse evolutionary histories
HET Massive Galaxy Survey

- Observed 1022 galaxies over the course of 9 trimesters.
- Obtained optical spectra with HET/LRS.
- Measured stellar velocity dispersions of nearby, massive galaxies.
- The survey allows us to make best use of high-angular resolution facilities.

(citation: van den Bosch et al. 2015)

(credit: Marty Harris/McDonald Observatory)
The HET survey uncovered early-type galaxies that have small sizes and luminosities for their large stellar velocity dispersions:

- $r_e \sim 1-3$ kpc
- $L_K \sim 5 \times 10^{10} L_\odot - 2.5 \times 10^{11} L_\odot$
- $\sigma_c > 250$ km s$^{-1}$

Objects are interesting because they:

- could host some of the most massive BHs known
- are different from the massive elliptical galaxies expected to host the largest BHs (e.g., McConnell et al. 2011, 2012, Thomas et al. 2016)
- appear similar to $z \sim 2$ galaxies ("red nuggets") (e.g., Ferré-Mateu et al. 2015, 2017, Yildirim et al. 2017, Beasley et al. 2018)
Acquired HST near-infrared images and large-scale IFU data from PPAK at Calar Alto Observatory (Yildirim et al. 2017).

Obtained IFU data assisted by LGS AO from Gemini/NIFS (Walsh et al. 2015, 2016, 2017) and Keck/OSIRIS for 6 galaxies.

- probes the central ~1” (~330-530 pc) region with a PSF ~0.15”
- with the AO system, r_{sphere} is resolved if galaxies follow M-σ

From IFU data, we measured the velocity distribution of stars (V, σ, h3, h4) as a function of spatial location.
Construct orbit-based models using supercomputers.

Potential consists of contributions from the BH, stars, and dark matter.

Integrate orbits in the potential. Assign weights to each orbit such that the superposition matches the observed kinematics and surface brightness.

Repeat for different combination of parameters until lowest $\chi^2$ is found.

(van den Bosch et al. 2008)
Compact, High-dispersion Galaxies: Modeling Results

\[ \text{M}_\text{BH} = (4.9 \pm 1.7) \times 10^9 \text{M}_\odot \]

\[ \text{M}_\text{BH} = (3.0^{+1.0}_{-1.1}) \times 10^9 \text{M}_\odot \]

\[ \text{M}_\text{BH} = (4.9 \pm 1.6) \times 10^9 \text{M}_\odot \]

(Walsh et al. 2015, 2016, 2017)
NGC 1271, NGC 1277, and Mrk 1216 host some of the most massive BHs dynamically detected to date, with $M_{\text{BH}} \sim (3-5) \times 10^9 \, M_\odot$.

All are surprising positive outliers from $M_{\text{BH}}$ - $L_{\text{bul}}$. Even when conservatively using the galaxy's total luminosity (instead of the bulge luminosity), the galaxies are $2\sigma$ outliers.
Over-massive Black Holes in Compact Galaxies

How did such large BHs end up in a relatively modest galaxies?

- Maybe the compact galaxies fall in the tails of a distribution between BH and galaxy properties that have yet to be fully established.
Over-massive Black Holes in Compact Galaxies

How did such large BHs end up in a relatively modest galaxies?

✦ Maybe the compact galaxies fall in the tails of a distribution between BH and galaxy properties that have yet to be fully established.

✦ Given the similarities to the z~2 galaxies, perhaps the local compact galaxies are relics, and reflect the relationship between BHs and galaxies at earlier times.

✦ perhaps BH growth precedes that of its host galaxy!
There are 8 compact, high-dispersion galaxies from the HET survey that have nuclear dust disks. This suggests the presence of cleanly rotating molecular gas.

Obtained Cycle 4 ALMA data to test for the presence of CO emission within $r_{\text{sphere}}$, measure the emission-line kinematics, and calculate gas-dynamical $M_{\text{BH}}$'s for 3 compact galaxies from the HET survey.
Initial kinematic measurements of the CO gas for all 3 compact galaxies observed with ALMA show regular rotation [courtesy of Benjamin Boizelle (UC Irvine)].

- **NGC 384**: CO (2–1) Surface Brightness (mJy km s$^{-1}$), $v_{\text{LOS}}$ (km s$^{-1}$), $\sigma$ (km s$^{-1}$).
- **PGC 11179**: CO (2–1) Surface Brightness (mJy km s$^{-1}$), $v_{\text{LOS}}$ (km s$^{-1}$), $\sigma$ (km s$^{-1}$).
- **UGC 2698**: CO (2–1) Surface Brightness (mJy km s$^{-1}$), $v_{\text{LOS}}$ (km s$^{-1}$), $\sigma$ (km s$^{-1}$).

**Resolution and On-source Time**
- 0.20” resolution, on-source time of 30 min.
- 0.22” resolution, on-source time of 25 min.
- 0.14” resolution, on-source time of 33 min.
A Gemini Large Program to Measure Black Holes

🔹 Awarded 253 hours with Gemini North to measure $M_{BH}$ using stellar-dynamical modeling methods in 31 galaxies using AO-assisted NIFS.
MBH measurements have been preferentially made in galaxies with small sizes at a given luminosity relative to the nearby galaxy population.

Proper sampling of the luminosity-size space is crucial for covering a wide variety of galaxies that have experienced diverse growth pathways (e.g., Cappellari 2016, Krajnovic et al. 2018).

Figure 2: Numerous galaxy properties such as velocity dispersions, mass-to-light ratios, bulge fractions, molecular gas content, stellar populations, and morphology vary from the top left to the bottom right of the galaxy size – mass plot. The prevailing growth process that moves galaxies in this direction are those associated with cold gas accretion, minor gas-rich mergers, and secular evolution. Conversely, dry merging increases galaxy size and mass, but not dispersion, and is the main growth channel for slow rotators found to the top right of the plot. Measuring MBH for objects that populate different regions of the galaxy size – mass (or similarly luminosity) plot is vital for properly characterizing the distribution of BH masses with galaxy properties and for gaining insight into the role BHs play in galaxy evolution. Figure adapted from Cappellari 2016.
Figure 2: We selected a sample that improves coverage of gala xy properties by examining a near face-on projection of the galaxy fundamental plane. Most BH measurements have been made for galaxies that fall within the oval. Our sample of 28 galaxies, suitable for AO observations and dynamical modeling methods, significantly improves coverage of parameter space without populating the region already well covered by previous work in this field. SDSS r-band images for 20 galaxies in the sample are shown along with their \( \langle \mu_e, R_e \rangle \) locations. Each box is 20 kpc on a side.

We will significantly increase the number of BH measurements for small galaxies, large galaxies, high-luminosity galaxies, low-luminosity galaxies, low-dispersion galaxies, and spiral galaxies.

Figure 3: The Kormendy & Ho (2013) relations (black dot-dash ed line) are shown along with the galaxies used to derive the relations (gray circles). Objects with BH masses that occupy sparsely sampled galaxy property regimes (i.e., the green triangles outside of the oval in Figure 2) are shown by the green triangles here as well. A number of these measurements are offset from the \( M_{BH} \)−\( \sigma_\star \) and \( M_{BH} \)−\( L_{bul} \) relations. We show where our proposed sample could fall on the relations (red crosses). The sample is placed on \( M_{BH} \)−\( \sigma_\star \) using \( M_{BH} \) from the \( M_{BH} \)−\( L_{bul} \) prediction and on \( M_{BH} \)−\( L_{bul} \) using \( M_{BH} \) from the \( M_{BH} \)−\( \sigma_\star \) expectation. We have adopted the HET \( \sigma_c \) measurements and bulge luminosities measured from decompositions of 2MASS images. Our sample is ideal for gaining a better understanding of the distribution of BH with galaxy properties, thereby honing the only practical tool for exploring the role of BHs in galaxy evolution throughout the Universe.
We obtained AO Gemini/NIFS observations of 6 galaxies using 36 hrs.
A Gemini Large Program to Measure Black Holes

- We obtained AO Gemini/NIFS observations of 6 galaxies using 36 hrs.

- We have approved HST cycle 25 and mid-cycle 24 observations for all 31 galaxies. Thus far, 16 galaxies have been observed with WFC3 in the F475W, F814W, and F160W filters.

- We have observed most of the 31 galaxies with HET/LRS2 and have completed VIRUS-P/VIRUS-W observations of 16 galaxies from the 2.7m telescope at McDonald Observatory.
A Gemini Large Program to Measure Black Holes

Using the NIFS stellar kinematics and HST F160W image, we constructed orbit-based models (van den Bosch et al. 2008), assuming an oblate axisymmetric shape and $i=75^\circ$.

The AO PSF was described by the sum of two circular Gaussians, with dispersions of 0.07” and 0.27” and weights of 0.51 and 0.49, respectively.

Sampled 31 values of $M_{BH}$ between $10^8$-$10^{10}$ M$_\odot$, 28 M/L$_H$ values between 0.3-3.0 M/L$_\odot$, and 3 NFW halos with c=10 and dark matter fractions of 10, 100, 1000.

$M_{BH} = (1.0^{+1.2}_{-0.1}) \times 10^9$ M$_\odot$
We tested running an independent axisymmetric stellar-dynamical modeling code (Valluri et al. 2004) and found consistent results for PGC 12257, with $M_{\text{BH}} = 2.0 \times 10^9 \, M_\odot$ and $M/L_H = 1.5 \, M/L_\odot$.

This study will address a bias in the galaxies for which $M_{\text{BH}}$’s have been measured, could re-invent the BH scaling relations, and will provide a deeper understanding of the interplay between BHs and galaxies.
Summary

✦ We need more $M_{BH}$ measurements, particularly at the extremes of the BH mass scale and in a wider range of galaxy types with varied evolutionary pasts.

✦ From stellar-dynamical modeling of AO observations, we find $M_{BH} \sim (3-5) \times 10^9 M_\odot$ for 3 HET compact, high-dispersion galaxies. The objects are outliers from $M_{BH}$-$L_{bul}$ and, given the similarities to the $z\sim2$ galaxies, could hint that BH growth precedes host galaxy growth.

✦ ALMA provides an exciting opportunity to measure $M_{BH}$ through gas-dynamical methods. We will derive $M_{BH}$ for 3 compact, high-dispersion galaxies, ultimately looking to compare to stellar-dynamical determinations.

✦ Detailed investigations of large, carefully selected samples using a homogenous approach is the ideal way to make major progress in the field prior to the next generation of extremely large telescopes.