The relation between supermassive black holes and their host galaxies

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Scaling relations between supermassive black holes and their host galaxies

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Correlations BH - host spheroid

Kormendy & Richstone (1995) suggest $M_{\text{BH}}$ vs $L_{\text{B,spher}}$

Magorrian et al. (1998) find $M_{\text{BH}}$ and $M_{\text{spher}}$ ("Magorrian" relation)
- Low resolution ground based data
- Most mass estimates overestimated (2-1 models)
Two groups independently find tight relation $M_{\text{BH}}$ vs $\sigma$

Big and hot debate about the slope $M_{\text{BH}} \sim \sigma^5$ (FM00) and $M_{\text{BH}} \sim \sigma^4$ (G00)
Where we are now …

- Over 100 mass estimates (stars, gas, masers)
- Differences among galaxy types (early, spirals, pseudo bulges …)
- Many correlations of $M_{\text{BH}}$ (vs $\sigma$, $L$, $R$, $n$, $\text{DM Halo}$, GCs …)

![Graph showing correlations between SMBHs and host galaxies](image)

Review by Kormendy & Ho 2013

De Nicola, AM, Longo 2018

![Graph showing correlations between SMBHs and host galaxies](image)
What’s new since 2000?

BH mass measurements
- Are they really BHs?

Which relations are real?
- Real, observational effects or biases?
- Physical meaning?
- What about the Fundamental plane of spheroids?

Redshift evolution and origin of these relations?
- problems in measuring BH masses (and galaxy properties) at high redshifts
Solid evidence for central ‘dark’ (i.e. non-stellar) mass concentrations in about 80 nearby galaxies has emerged over the past two decades (e.g. Magorrian 1998, Kormendy 2004, Gültekin et al. 2009, Kormendy & Ho 2013, McConnell & Ma 2013) from optical/infrared imaging and spectroscopy on the Hubble Space Telescope (HST) and large ground-based telescopes, as well as from Very Long Baseline radio interferometry (VLBI).

The first truly compelling case that such a dark mass concentration cannot just be a dense nuclear cluster of white dwarfs, neutron stars and perhaps stellar black holes emerged in the mid-1990s from spectacular VLBI observations of the nucleus of NGC 4258, a mildly active galaxy at a distance of 7 Mpc (Miyoshi et al. 1995, Moran 2008, Figure 1). The VLBI observations show that the galaxy nucleus contains a thin, slightly warped disk of H$_2$O masers (viewed almost edge on) in Keplerian rotation around an unresolved mass of 40 million solar masses (Figure 1). The inferred density of this mass exceeds a few $10^9$ solar masses pc$^{-3}$ and thus cannot be a long-lived cluster of ‘dark’ astrophysical objects of the type mentioned above (Maoz 1995).

As we will discuss below, a still more compelling case can be made in the case of the Galactic Center.

Figure 1. Left: Optical and radio image of the active galaxy NGC4258. This disk galaxy exhibits a spectacular curved twin radio and X-ray jet, visible in orange in this picture. Right: (top) Schematic edge-on (left) and face-on (right) views of the almost-edge-on, warped maser disk of NGC 4258 (from Moran 2008) with warp parameters from Herrnstein et al. (2005) and including the inner contours of the radio jet. The relative positions of the receding, near-systemic, and approaching H$_2$O masers are indicated by red, green, and blue spots, respectively. Differences in line-of-sight projection corrections to the slightly tilted maser velocities account for the departures in the high-velocity proper motions of stars Only Milky Way Center Stellar kinematics

- kinematics of stars and (complex) dynamical models

Gas kinematics

- kinematics of gas and simple kinematical models (rotating disks)
- Masers (high spatial resolution from radio interferometry)

Reverberation mapping & Virial Masses

- Talk by Giorgio Calderone

In all case need to resolve BH sphere of influence

$$r_{BH} = \frac{G M_{BH}}{\sigma_*^2} = 10.7 \text{ pc} \left( \frac{M_{BH}}{10^8 M_\odot} \right) \left( \frac{\sigma_*}{200 \text{ km/s}} \right)^{-2}$$

$$\theta_{BH} = 0.11'' \left( \frac{M_{BH}}{10^8 M_\odot} \right) \left( \frac{\sigma_*}{200 \text{ km/s}} \right)^{-2} \left( \frac{D}{20 \text{ Mpc}} \right)^{-1}$$
Impact of AO & 3D spectroscopy

Future
- Optical interferometry (very challenging …)
- JWST (but little improvement…)
- ELT and 30m class telescopes

Nowadays
- use of integral field spectroscopy
- high spatial resolution with AO @ 8m class telescopes
- very high spatial resolution in submm with ALMA

Up to early 2000’s
- measurements with long list spectrographs
- HST provided best spatial resolution

M87 w/ HST, Macchetto, AM, +1997
Stellar dynamics: Schwarzschild models

- New thing: 3D data
- 3-D models
- Inclusion of dark matter haloes (orbits from out to nuclear region)

Images of model orbits (with weights) (Cappellari et al. 2004)

$M_{BH}$, $\Upsilon$, orbital structure

Observed velocity field

Observed galaxy image

Image of orbit on sky

Stellar orbit track

$t$
Stellar dynamics: the case of Centaurus A

Moments of LOSVD →

With AO (3” x 3” FOV)

Data

Model

Seeing limited (8” x 8” FOV)

Data

Model

Cappellari et al. 2009
Gas kinematics

- Assume gas in circularly rotating disk
- Projected velocities and observational effects (e.g. beam smearing)

See A. Pensabene’s Talk
Gas kinematics

- Assume gas in circularly rotating disk
- Projected velocities and observational effects (e.g. beam smearing)

See A. Pensabene’s Talk
Gas kinematics: the case of Centaurus A

Velocity field from H$_2$ (2.12)

$$M_{BH} = 4.5 \times 10^7 \, M_\odot$$  
$$M_{BH} = 0$$  

Warped disk model

Neumayer et al. 2007
Gas kinematics: ALMA

- CO lines in (mostly) spiral galaxies
- ALMA resolution (< 0.01-0.1")
- Molecular gas less dynamically hot than ionised gas

**NGC1332: Barth+2016**

**NGC4697: Davis+2015**
Solid evidence for central 'dark' (i.e. non-stellar) mass concentrations in about 80 nearby galaxies has emerged over the past two decades (e.g. Magorrian 1998, Kormendy 2004, Gültekin et al. 2009, Kormendy & Ho 2013, McConnell & Ma 2013) from optical/infrared imaging and spectroscopy on the Hubble Space Telescope (HST) and large ground-based telescopes, as well as from Very Long Baseline radio Interferometry (VLBI).

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**Masers**

- H$_2$O megamasers in galactic nuclei: “test particles”
- High spatial resolution of radio interferometers
- Possible to measure centripetal acceleration (Herrnstein+99): independent distance!
the dynamic center derived from the fitting of the rotation curve, Fig. 2.—positions are referenced to the strongest systemic feature at 8

\[ \text{Heliocentric Radio Velocity (km s}^{-1}\text{)} \]

\[ \text{Impact Parameter (mas)} \]

\[ \text{LSR Velocity (km s}^{-1}\text{)} \]

\[ \text{Impact Parameter (mas)} \]

\[ \text{North Offset (mas)} \]

\[ \text{East Offset (mas)} \]

NGC1068: Greenhill+1996

Circinus: Greenhill+2001

UGC3789: Reid+2009

NGC5765b: Gao+2016

UGC3789: Zhao+2018
Problems

Stellar dynamics
- Very complex models e.g. black boxes for “others”
- results depend on orbit library (e.g. number of stars)? (e.g. Merritt)
- results do depend on 2-I vs 3-I (e.g. Gebhardt et al., Cappellari et al.)
- results do depend on considering DM Halo (e.g. Gebhardt et al.)
- axisymmetric or triaxial galaxies?
- Jeans modelling reliable? (e.g. Cappellari et al.)

Gas kinematics
- Simple modelling but works only if gas is in circularly rotating thin disk
- Degeneracy $M_{BH}$ - disk inclination
- Gas velocity dispersion: support against gravity and effects on BH mass?
- Effect of non gravitational motions (e.g. outflows)
- Masers: Effect of disk mass? Probably not ($Kuo+18$)
- Masers: only edge on disk observed (strong bias)

- Both gas and stars: errors underestimated?
Galaxies with independent $M_{BH}$ measurements from stars and gas
Discrepancies $\sim$0.2 dex, up to 0.5 dex
Systematic discrepancies at high mass end:
🌟 effect of DM Haloes and 3-I/axysimmetry in stars measures?
🌟 effect of gas velocity dispersion in gas measures?
Are they really BHs?

🌟 Sometimes measurements “marginally” resolve BH sphere of influence
🌟 Affects reliability of mass measurement

2. PROGRESS IN BH DETECTION TECHNOLOGY. I. IMPROVEMENTS IN SPATIAL RESOLUTION

Figure 1 shows the history of $M^\bullet$ measurements for all galaxies that have BH detections based on observations of spatially resolved dynamics. Multiple measurements for each galaxy are joined by straight line segments to show how the available spatial resolution has improved with time. For BHs found with HST, only the discovery observations are shown; these have not been superseded. The individual measurements for our Galaxy, M31, and M32 are listed in Table 1. Spatial resolution is parameterized by the ratio of the radius $r_{\text{infl}}$ of the sphere of influence of the BH to the effective Gaussian dispersion radius $\sigma^\bullet$ of the point-spread function (PSF) (see notes to Table 1).

2.1. Early Ground-Based BH Discoveries

Kormendy & Richstone (1995) review the seven ground-based BH detections and one based on HST available in 1995. The first dynamical BH discovery was in M32 (Tonry 1984, 1987). It was made with barely enough resolution to be reasonably secure (Kormendy 2004) (Section 2.2.1). It is typical of a subject with urgent expectations and much at stake that the first discovery is made as soon as it becomes barely feasible and at a time when the result still has only modest significance.

Galaxy

<table>
<thead>
<tr>
<th></th>
<th>M31</th>
<th>M32</th>
<th>NGC 3115</th>
<th>NGC 3377</th>
<th>NGC 4594</th>
<th>NGC 4486B</th>
<th>NGC 7582</th>
<th>NGC 4526</th>
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<tbody>
<tr>
<td>HST observations</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
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<td>▲</td>
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<tr>
<td>Maser observations</td>
<td>▲</td>
<td>▲</td>
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<td>▲</td>
<td>▲</td>
<td>▲</td>
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</tr>
<tr>
<td>NGC 4258</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
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</tr>
</tbody>
</table>

10,000

1,000

100

10

1

0.1

0.01


Publication date

Kormendy & Ho 2013
Are they really BHs?

Observations find: dark mass confined within spatial resolution element

Unambiguous proof of BH: motions close to Schwarzschild radius

At lower confidence: density of possible cluster so high that it must collapse to BH in short time (Maoz+1998)

Very far from $R_{\text{SCHW}}$ scales

<table>
<thead>
<tr>
<th>Method &amp; Telescope</th>
<th>Scale ($R_S$)</th>
<th>No. of SBH Detections</th>
<th>$M_\bullet$ Range ($M_\odot$)</th>
<th>Typical Densities ($M_\odot$ pc$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe Kα line (XEUS, ConX)</td>
<td>3–10</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Reverberation mapping (Ground based optical)</td>
<td>600</td>
<td>36</td>
<td>$10^6$–$4 \times 10^8$</td>
<td>$\gtrsim 10^{10}$</td>
</tr>
<tr>
<td>Stellar proper motion (Keck, NTT, VLT)</td>
<td>1000</td>
<td>1</td>
<td>$4 \times 10^6$</td>
<td>$4 \times 10^{16}$</td>
</tr>
<tr>
<td>H$_2$O megamasers (VLBI)</td>
<td>$10^4$</td>
<td>1</td>
<td>$4 \times 10^7$</td>
<td>$4 \times 10^9$</td>
</tr>
<tr>
<td>Gas dynamics (optical) (Mostly HST)</td>
<td>$10^6$</td>
<td>11</td>
<td>$7 \times 10^7$–$4 \times 10^9$</td>
<td>$\sim 10^5$</td>
</tr>
<tr>
<td>Stellar dynamics (Mostly HST)</td>
<td>$10^6$</td>
<td>17</td>
<td>$10^7$–$3 \times 10^9$</td>
<td>$\sim 10^5$</td>
</tr>
</tbody>
</table>

Ferrarese & Ford 2005

In most cases survival time scales of clusters $>>$ age of universe

Nuclear star clusters exist: are we overestimating BH masses?

adapted from Maoz 1998
Additional ~40 galaxies with less reliable measurements or upper limits

Variable galaxy morphological types

Galaxy Morphology A Distance$^a$ $M_20^a$ $r_e$ $L_2$ $R_e$ B

NGC224 Sb 2 0.77 ± 0.03 8.15 ± 0.16 22.3 ± 0.02 10.34 ± 0.10 -0.19 ± 0.02 1
NGC4472 E2 0 17.14 ± 0.59 9.40 ± 0.04 2.08 ± 0.01 11.86 ± 0.06 0.05 ± 0.01 1
NGC4831 Sb 2 3.60 ± 0.13 7.81 ± 0.13 2.12 ± 0.02 10.43 ± 0.31 -0.24 ± 0.02 1
NGC4374 E1 0 18.51 ± 0.60 8.97 ± 0.05 2.47 ± 0.02 11.64 ± 0.25 0.07 ± 0.01 1
NGC4486 E1 0 16.68 ± 0.72 9.68 ± 0.04 2.51 ± 0.03 11.64 ± 0.25 0.05 ± 0.02 1
NGC4594 Sa 2 9.87 ± 0.82 8.82 ± 0.04 2.38 ± 0.02 10.79 ± 0.25 -0.03 ± 0.01 1
NGC3379 E1 0 10.70 ± 0.54 8.62 ± 0.11 2.31 ± 0.02 10.96 ± 0.25 0.02 ± 0.02 1
NGC221 E2 1 0.80 ± 0.03 6.39 ± 0.19 1.89 ± 0.02 9.12 ± 0.04 -0.90 ± 0.02 1
Cygnaus E 0 242.70 ± 24.27 9.42 ± 0.12 2.92 ± 0.05 12.19 ± 0.10 0.46 ± 0.04 0
NGC1271 SB0 2 80.00 ± 8.00 9.48 ± 0.15 2.45 ± 0.01 11.07 ± 0.08 0.34 ± 0.07 0
NGC1275 E 1 73.80 ± 8.00 8.90 ± 0.23 2.39 ± 0.08 11.84 ± 0.08 0.15 ± 0.04 0
NGC1600 E 0 64.00 ± 6.40 10.23 ± 0.04 2.47 ± 0.02 11.86 ± 0.08 1.08 ± 0.04 0
NGC3706 E 0 46.00 ± 4.00 8.78 ± 0.06 2.51 ± 0.01 11.58 ± 0.08 0.80 ± 0.04 0
NGC2552 S0 2 92.00 ± 9.20 8.98 ± 0.23 2.29 ± 0.02 11.49 ± 0.09 0.88 ± 0.06 0
NGC4339 E 1 16.00 ± 1.60 7.63 ± 0.36 1.98 ± 0.02 10.26 ± 0.25 0.37 ± 0.04 0
NGC4444 E 1 22.80 ± 2.24 7.85 ± 0.15 1.99 ± 0.02 10.28 ± 0.25 0.30 ± 0.04 0
NGC4578 E 1 16.30 ± 1.63 7.28 ± 0.22 2.03 ± 0.02 10.53 ± 0.25 0.49 ± 0.04 0
NGC4762 E 1 22.60 ± 2.26 7.36 ± 0.14 2.13 ± 0.02 11.05 ± 0.25 1.06 ± 0.04 0

$^a$ BH Database as of “today”

De Nicola, AM, Longo 2018
Many BH-galaxy relations

BH masses correlate with almost every property of the host spheroid

- L, σ (e.g. K&H 13, Mc Connell & Ma+13, Van Den Bosch 16)
- Sersic index (e.g. Savorgnan, Graham+13)

(Stellar) mass (e.g. Sani+11, K&H13, Reines & Volonteri 15)

Effective radius (e.g. De Nicola+18)
Many BH-galaxy relations

- Ferrarese (2002) galaxies with optical $V_{\text{circ}}$
- Ferrarese (2002) galaxies with HI $V_{\text{circ}}$
- Böker et al. (1999) nuclei
- Kormendy et al. (2010) nuclei
- Walcher et al. (2005) nuclei
- Ho & Flippenko (1996) nuclei

**Figure 3.** Pitch angle of spiral arms (e.g. Davis+17)

**DM Halo mass**
(see Kormendy & Ho 13)

**Table 2.**

<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
<th>Column 5</th>
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<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

**Number of globular clusters** (Burkert & Tremaine 11)
Our view has further changed in recent years

- Different BH-galaxy relations for different “bulges”, disks do not correlate

- Classical bulges: Form after merger events, feedback is important

- Pseudo bulges: Form by secular processes, no feedback required

E.g., Kormendy & Ho 2013

But there are BHs in bulgeless galaxies …

More complex than we previously thought …
Different relations for late & early types?

- Recent work with careful bulge/disk decomposition from 3.6 μm Spitzer images (Savorgnan & Graham 2015)
- Accurate BH-galaxy relations: no difference between bulges and pseudo-bulges, apparently due to different relations for early type galaxies spheroids (red sequence) and spiral galaxy bulges / spheroids (blue cloud)

Savorgnan, Graham, AM, Sani 2015

De Nicola, AM, Longo 18
An observational bias?

Maximum distance at which a BH can be detected ($R_{BH}$ spatially resolved)

$$D = 22 \, \text{Mpc} \left( \frac{M_{BH}}{10^8 \, M_\odot} \right) \left( \frac{\sigma_*}{200 \, \text{km/s}} \right)^{-2} \left( \frac{\Delta \theta}{0.1''} \right)^{-1}$$

e.g. Batcheldor 2010 but see Gultekin+11
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\]

\(\Delta \theta = 0.1''\) (HST)

e.g. Batcheldor 2010 but see Gultekin+11
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NO detection areas on $M_{\text{BH}}$-$\sigma$ diagram for given $\Delta \theta$, $D$:

- ★ Direct $M_{\text{BH}}$ measures are limited to the local universe ($D \sim 250$ Mpc)
- ★ There are definitely no BHs above the correlation (big BHs in small galaxies)
- ★ The area below the correlation is ‘biased’ and cannot be explored (small BHs in big galaxies?)

e.g. Batcheldor 2010 but see Gultekin+11
Correlations are biased to higher Mass/Velocity dispersion galaxies

⭐ Normalization of $M_{BH}$-$\sigma$ relation increased by factor $\sim 3$
Which is the “fundamental” relation?

- Relations with M, L, σ, R and other parameters suggest existence of “fundamental” BH-galaxy relation
- Proposal of BH “Fundamental plane” $M_{\text{BH}} \sim \sigma^\alpha R^\beta$ (e.g. Hopkins+2007)
  - Hopkins+ find $M_{\text{BH}} \sim \sigma^{3.0} R^{0.4}$ ($-E_{\text{grav}} \sim 2 E_{\text{kin}} \sim \sigma^{4.0} R$)
- In general $M_{\text{BH}}$-$\sigma$ considered “fundamental” because it has smaller intrinsic scatter

What about the well-known fundamental plane of elliptical galaxies?
- Almost never taken into account …

- Van den Bosch+16 finds
  - $M_{\text{BH}} \sim (L_K/R_e)^{3.8}$
  - with same scatter as
  - $M_{\text{BH}} \sim \sigma^{5.4}$
  - consistent with FP Projection
- $M_{\text{BH}}$-$\sigma$ main relation, other relations are combination with FP

Data from Saglia+97, Wegner+99
### BH Database as of “today”

- About 80 galaxies with “secure” BH masses
- Additional ~40 galaxies with less reliable measurements or upper limits
- Various galaxy morphological types

De Nicola, AM, Longo (2018) combine “secure” BH masses with photometry from Spitzer 3.6um or K band (good tracers of stellar mass)
FP of galaxies with BH Masses

All galaxies follow FP, also pseudo bulges seem to

\[ L = \epsilon_0 + \epsilon_1 \cdot V + \epsilon_2 \cdot R + \epsilon_3 \]

\[ \epsilon_z = 0.13 \]

De Nicola, AM, Longo 2018
A BH fundamental plane?

$$M_{BH} = (-0.21 \pm 0.33)L + (0.56 \pm 0.33)R + (4.10 \pm 0.39)V$$

L, R, V, logs

★ Main dependence on $V = \log \sigma$, small dependence on $R = \log R_e$, no dependence on $L = \log L_{sph}$,

★ Intrinsic scatter not decreased w.r.t. $M_{BH}-\sigma$

Hyperplane is not the fundamental relation!

To disentangle FP from $M_{BH}-L, \sigma, R$ relations

★ Assume BH fundamental relation

$$M_{BH} = \alpha L + \beta R + \gamma V + \Sigma \ (\Sigma \ \text{int. scatter})$$

★ Model FP as a trivariate Gaussian distribution $\phi(L, R, V)$

★ Slopes and intrinsic scatters of all $M_{BH}-L, \sigma, R$ can be computed analytically as a function of $\alpha, \beta, \gamma, \Sigma$

★ We conclude that $M_{BH} \sim \sigma^{4.0} R^{0.4}$ is best relation (fundamental?)

☐ This result takes into account FP

De Nicola, AM, Longo 2018
Physical meaning of BH-galaxy relations

Huge topic with hundreds/thousands of papers … a few key points:

- Relation $M_{\text{BH}}$-galaxy properties implies a physical link between BH and host galaxy (Coevolution BH-galaxy)
- BH sphere of influence very small: $V_{\text{BH}}/V_{\text{gal}} \sim 10^{-7}$ → no gravitational link
- Energy released to grow BH $\gg$ gravitational binding energy → \textbf{AGN feedback} (Talks by M. Brusa, R. Maiolino tomorrow)

Possibilities to establish $M_{\text{BH}}$-galaxy relations:

- AGN feedback on host galaxy (also needed to stop galaxy growth)
- BH self-regulation (i.e. feedback on small scales $< 1$ kpc)
- Random growth → central limit → big BHs in big galaxies

but scatter too large?
A very simple model ...

Model by A. King and collaborators:

- for $L/L_{\text{Edd}} \sim 1$ fast wind accelerated close to AGN
- wind creates a bubble which sweeps the gas in host galaxy ISM
- shock forms at the interface between wind and swept ISM
- post shock material is Compton-cooled by AGN up to $\sim$kpc scales → wind is momentum driven
- wind falls back until $M_{\text{BH}} \sim M_{\text{BH}}(\sigma)$
- then expands beyond $\sim$kpc scales, Compton-cooling no more effective → outflow becomes energy driven
A very simple model ...

★ model prediction

\[ M_{BH} = \frac{2f_g \sigma T}{\pi m_p G^2} \sigma^4 = 4.6 \times 10^8 M_\odot \left( \frac{\sigma}{200 \text{ km}} \right)^4 \]

★ no free parameters, excellent agreement with observations!

★ Extremely simple: spherical symmetry, ISM with uniform density, galaxy as isothermal sphere but ...

★ agreement with observations tells us that the basic physics is probably there
**M$_{BH}$-galaxy relations vs z**

Review by Kormendy & Ho up to 2013

- Signs of evolution at $z<2$ disappear when whole galaxy is considered
- Increased $M_{BH}/M_{Gal}$ weakens evidence for evolution at lower $z$

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![Diagram of MBH-galaxy relations](image)

- $z = 0.1$–$1.0$ AGNs
- $z = 1.0$–$2.0$ QSOs
- $z = 2.0$–$4.0$ QSOs
- $z = 4.0$–$7.0$ QSOs
- $z \approx 2$ RGs
- $z \approx 2$ SMGs

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Häring & Rix 2004

Kormendy & Ho 2013

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Obscured
dust-reddened quasars and other obscured AGNs appear to have preferentially undermassive BHs, the most extreme being the submillimeter galaxies (SMGs). Less massive hosts are mostly disk-like, spiral galaxies at $z \lesssim 2$; they show a larger scatter in $M_{BH}-M_{*,bulge}$ like that of pseudobulges at $z \approx 0$. (c) Offset of log $M_{BH}$ with respect to the local $M_{BH}-M_{*,bulge}$ relation derived by Häring & Rix (2004, dashed line) and here in Section 6.6 (solid line). The black points at $z \approx 0$ are our sample of (left to right) ellipticals, classical bulges, and pseudobulges with dynamically detected BHs (Tables 2 and 3; objects are slightly offset from $z = 0$ for clarity). Adapted from Ho (2013).
Review by Kormendy & Ho up to 2013

- Signs of evolution at $z<2$ disappear when whole galaxy is considered
- Increased $M_{\text{BH}}/M_{\text{Gal}}$ weakens evidence for evolution at lower $z$

\[ M_{\text{BH}} \text{-galaxy relations vs } z \]

\[ \Delta \log M_\bullet (\text{bulge}) \]

\[ \Delta \log M_\bullet \text{ (bulge)} \]

\[ \Delta M_\bullet = M_\bullet (\text{bulge}) - M_\bullet (\text{spheroid}) \]

\[ \Delta \log M_\bullet (\text{bulge}) = \log M_\bullet (\text{bulge}) - \log M_\bullet (\text{spheroid}) \]

\[ M_\bullet (\text{bulge}) \approx 10^{2.0-4.0} \quad \text{QSOs} \]

\[ M_\bullet (\text{spheroid}) \approx 10^{0.1-1.0} \quad \text{AGNs} \]

\[ M_\bullet (\text{total}) = M_\bullet (\text{bulge}) + M_\bullet (\text{spheroid}) \]

\[ M_\bullet (\text{total}) = M_\bullet (\text{disk}) + M_\bullet (\text{spheroid}) \]

\[ M_\bullet (\text{total}) = M_\bullet (\text{bulge}) + M_\bullet (\text{disk}) \]

\[ M_\bullet (\text{total}) = M_\bullet (\text{bulge}) + M_\bullet (\text{spheroid}) + M_\bullet (\text{disk}) \]

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Kormendy & Ho (this paper)

Häring & Rix 2004
**M\(_{BH}\)-galaxy relations vs z**

- Average M\(_{BH}/M_{gal}\) larger than in local universe at z <1-3 (Peng+06, Treu+04,07, Woo+06,08, Bennert+10,11, Decarli+09,10, Alexander+09, Merloni+10)

- M\(_{BH}/M_{gal}\) increases at higher z (Wu+07, Ho+07, Maiolino+09, Walter+09): M\(_{BH}\) up to ~10% of M\(_{gal}\)!

- Large M\(_{BH}/M_{gal}(\text{star})\) might be due to selection effects (e.g. Lamastra+10) or biases (e.g. Lauer+07)

- The ALMA revolution: extension to very high redshift with “dynamical” M\(_{gal}\) (e.g. Maiolino+05, Walter+09, Wang+13, 16, Willott+13,15, Venemans+12,16,17, Banados+15, Decarli+17, Trakhtenbrot+17)
MBH-galaxy relations vs z

- Average $M_{BH}/M_{gal}$ larger than in local universe at $z<1-3$ (Peng+06, Treu+04,07, Woo+06,08, Bennert+10,11, Decarli+09,10, Alexander+09, Merloni+10)

- $M_{BH}/M_{gal}$ increases at higher $z$ (Wu+07, Ho+07, Maiolino+09, Walter+09): $M_{BH}$ up to ~10% of $M_{gal}$!

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- The ALMA revolution: extension to very high redshift with “dynamical” $M_{gal}$ (e.g. Maiolino+05, Walter+09, Wang+13,16, Willott+13,15, Venemans+12,16,17, Banados+15, Decarli+17, Trakhtenbrot+17)

See talk by Antonio Pensabene!
Virial masses $M_{\text{BH}} = f V^2 R / G$

- **Only in type 1 AGN**
- **Calibration i.e. f**
  - based on assumption that AGN follow same relation as quiescent galaxies
  - what if BHs are under/overmassive?
  - inclination effect not considered

**The BH mass ladder (→ Peterson 2004)**

1. Spatially resolved
   - Gas & stellar kinematics correlations
   - Local universe (< 250 Mpc)
   - Calibration (Onken +04)
   - $M_{\text{BH}}$ $\sim 5 \text{ dex}$

2. Reverberation mapping (RM)
   - $M_{\text{BH}} = f V^2 R_{\text{BLR}} / G$
   - Time expensive
   - R$_{\text{BLR}}$-L relation
   - (Kaspi +00, Bentz +09)
   - Calibration (Vestergaard & Peterson 06)
   - $M_{\text{BH}}(\text{SE}) / M_{\text{BH}}(\text{RM}) \sim 0.4 \text{ dex}$

3. Single Epoch (SE)
   - $M_{\text{BH}} = \tilde{f} V^2 L^\alpha$

**Figure 32**

- BH–host-galaxy correlations for active galactic nuclei (AGNs) with BH masses derived from reverberation mapping (RM) and from single-epoch spectroscopy of broad AGN emission lines.

- (a) AGNs (colored points) show considerably larger scatter in the $M_{\text{BH}}$–$\sigma$ relation than inactive galaxies (black points). Moreover, the scatter increases toward lower BH masses; most of these galaxies contain pseudobulges. Adapted from Xiao et al. (2011).

- (b) Inactive classical bulges and Es along with reverberation-mapped AGNs with $M_{\text{BH}} \gtrsim 10^7 M_\odot$ (green points). Low-mass AGNs, on the other hand, along with inactive BHs in pseudobulges, fall notably below the correlation for classical bulges and ellipticals. Adapted from Jiang, Greene & Ho (2011).

**Masses.** The correlation between BH mass and (pseudo)bulge luminosity is more complicated to interpret. The Greene-Ho objects lie significantly below the fiducial $M_{\text{BH}}$–$L_{\text{bulge}}$ relation for inactive galaxies: (Pseudo)bulges are overluminous at a fixed BH mass (Greene, Ho & Barth 2008; Jiang, Greene & Ho 2011) or the BHs are undermassive at fixed (pseudo)bulge mass (Section 6.8). Part of this offset can be ascribed to younger stellar populations in pseudobulges. But that is not the whole story, as the $M_{\text{BH}}$–$M_{\text{bulge}}$ relation in Figure 21 makes clear. Similarly, a significant offset remains after applying an $M_{\text{BH}} / L$ correction and even after replacing the (pseudo)bulge luminosity with its dynamical mass computed using the measured velocity dispersion and effective radius (Jiang, Greene & Ho 2011) (Figure 32b). Therefore Figure 32b is consistent with Section 6.8.

**7.3. A BH in the Starbursting Dwarf Galaxy Henize 2-10**

The “poster child” for BH discovery using the radio–X-ray–fundamental plane (Merloni, Heinz & Di Matteo 2003; Gültekin et al. 2009a) is Henize 2-10, illustrated in Figure 33. Reines et al. (2011) present a good case that the galaxy contains a BH, based on the observation of an X-ray point source with 2–10-keV luminosity $L_X \sim 10^{39}$ erg s$^{-1}$ and a radio core with 4.9-GHz and 8.5-GHz luminosities of $L_R \approx 10^{35}$ erg s$^{-1}$. Careful astrometry implies that they are the same.
Virial masses $M_{\text{BH}} = f V^2 R / G$

⭐ CIV: used for very high redshift (with optical spectra) but reliability questioned by many authors

☐ CIV probably affected by outflows

☐ Denney 13 shows that CIV average line profile are different than $r.m.s.$ ones: existence of non-BLR extended component (outflow?) strongly affects line width estimate

Denney 13
Virial masses $M_{\text{BH}} = f V^2 R / G$

⭐ **Radiation pressure**
- May affect BH mass estimates (partially cancel gravitational force; Marconi+08, +09)
- Still an open issue

- If all incident ionising photons absorbed by a BLR cloud (must be to have MgII emission ...)

\[
F = \frac{L_{\text{ion}}}{4\pi r^2 c} \Delta A \quad F_{\text{grav}} = \frac{G M(r) m_p N_H \Delta A}{r^2}
\]

\[
\frac{F_{\text{rad}}}{F_{\text{grav}}} = \frac{L_{\text{ion}}}{4\pi G c m_p M(r) N_H} \approx 5
\]

\[
L_{\text{ion}} = 10^{13} L_\odot, M(r) = M_{\text{BH}} = 10^9 M_\odot, N_H = 10^{23} cm^{-2}
\]
Virial masses in (luminous) AGN

★ Galaxy properties difficult to measure (galaxy difficult to “see” with AGN emission)

★ Selection effects: sampling objects at specific time of their evolution (e.g. Lamastra+10)

★ ALMA revolution: it is possible to measure dynamical galaxy masses up to high redshift

- Same challenges as in BH mass measurement form gas (galaxy sizes at high z, similar to nuclear disk sizes i.e. < 1”)

- Usually galaxy masses are simple virial estimates

- Dynamical masses are total masses within a few kpc

\[ \text{Pensabene+18} \]
Conclusions

BH mass measurements
- There are open issues on gas and stellar kinematical measurements
- We still not have the unambiguous proof that we detect BHs (except for Milky Way) but considering AGN they most likely are …

Which relations are real?
- We still need to probe the low BH in big bulge regime
- Existence of correlations imply coevolution BH-galaxy
- There is a fundamental correlation (e.g. $M_{\text{BH}} - \sigma$ or $M_{\text{BH}} - \sigma, R$) the rest result from combination with galaxy structure (e.g. FP)

Redshift evolution and origin of these relations?
- At high redshift BH seem over massive compared to host galaxies
- limited to type 1 AGN for virial BH masses
- need to properly measure galaxy dynamical masses