Big galaxies have big black holes
(Kormendy & Richstone 1995; Gebhardt et al. 2001; Ferrarese & Merritt 2001)

Caricature

1. All galaxies have BHs.
2. The bigger the galaxy, the bigger the BH.
Big galaxies have big black holes
(Kormendy & Richstone 1995; Gebhardt et al. 2001; Ferrarese & Merritt 2001)

Caricature

1. All galaxies have BHs.
2. The bigger the galaxy, the bigger the BH.

Evidence: BHs detected in $\sim 50$ nearby galaxies.

Many more upper bounds (Beifiori, Sarzi et al.).
Big galaxies have big black holes
(Kormendy & Richstone 1995; Gebhardt et al. 2001; Ferrarese & Merritt 2001)

**Caricature**

1. All galaxies have BHs.
2. The bigger the galaxy, the bigger the BH.

**Evidence:** BHs detected in $\sim 50$ nearby galaxies.

Many more upper bounds (Beifiori, Sarzi et al.).
1 Motivation

2 Present state of scaling relations

3 Health warning

4 Things to look forward to

5 Summary
**Motivation**

**Obvious connection to QSOs:** (Sołtan 1982)
Energy density $u$ of QSO light implies BH mass density

$$\rho_\bullet = \epsilon u/c^2 \sim 10^5 \, M_\odot \, \text{Mpc}^{-3}. $$

**Deeper connection to galaxy formation**
Two natural length scales associated with BH:

$$r_{\text{schw}} = \frac{2GM_\bullet}{c^2} \sim 10^{-4}\, \text{pc}$$
$$r_\bullet = \frac{GM_\bullet}{\sigma^2} \sim 10\, \text{pc} \sim 1''$$

for M104.

In contrast, host scales $\sim 5\, \text{kpc} \sim 100r_\bullet$.

$\Rightarrow$ Formation of BH and host intimately linked? Feedback?
**Motivation**

**Obvious connection to QSOs:** (Sołtan 1982)
Energy density $u$ of QSO light implies BH mass density

$$\rho_\bullet = \epsilon u/c^2 \sim 10^5 M_\odot \text{Mpc}^{-3}.$$  

**Deeper connection to galaxy formation**
Two natural length scales associated with BH:

$$r_{\text{schw}} = \frac{2GM_\bullet}{c^2} \sim 10^{-4}\text{pc}$$

$$r_\bullet = \frac{GM_\bullet}{\sigma^2} \sim 10\text{pc} \sim 1'' \right \text{for M104.}$$

In contrast, host scales \(\sim 5\text{kpc} \sim 100r_\bullet\).  
⇒ Formation of BH and host intimately linked? Feedback?
Motivation

**Obvious connection to QSOs:** (Soltan 1982)
Energy density $u$ of QSO light implies BH mass density

$$\rho_\bullet = \epsilon u/c^2 \sim 10^5 M_\odot \text{Mpc}^{-3}.$$ 

**Deeper connection to galaxy formation**
Two natural length scales associated with BH:

$$r_{\text{schw}} = \frac{2GM_\bullet}{c^2} \sim 10^{-4} \text{pc} \quad \left\{ \begin{array}{l} 
    r_\bullet = \frac{GM_\bullet}{\sigma^2} \sim 10\text{pc} \sim 1'' 
  \end{array} \right. \text{ for M104.}$$

In contrast, host scales $\sim 5\text{kpc} \sim 100r_\bullet$.

⇒ Formation of BH and host intimately linked? Feedback?
Sombrero Galaxy • M104
Sombrero Galaxy • M104

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC03-28
Sombrero Galaxy • M104

NASA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC03-28
Recent history


1998: Silk & Rees (1998) predict $M_\bullet \sim \sigma^5$. Also Fabian 1999. ($\sigma \sim v_{\text{circ}}$ for inhabitants of $\sim$-space.)

2001: $M_\bullet - \sigma$ relation found observationally. Small scatter $\Rightarrow$ more fundamental than $M_\bullet - L_{\text{bulge}}$. Controversy about how to fit straight lines.

Since then:
- Explanations for $M_\bullet - \sigma$; predictions at low and high ends.
- Other correlations proposed ($v_{\text{halo}}$, concentration, ...)
- IMBHs in GCs?
- High-$z$ BH scaling relations.
**Recent history**

**1995:** Kormendy & Richstone (1995) notice $M_\bullet \sim L_{\text{bulge}}$.

**1998:** Silk & Rees (1998) predict $M_\bullet \sim \sigma^5$. Also Fabian 1999. ($\sigma \sim v_{\text{circ}}$ for inhabitants of $\sim$-space.)

**2001:** $M_\bullet-\sigma$ relation found observationally. Small scatter $\Rightarrow$ more fundamental than $M_\bullet-L_{\text{bulge}}$. Controversy about how to fit straight lines.

**Since then:**
- Explanations for $M_\bullet-\sigma$; predictions at low and high ends.
- Other correlations proposed ($v_{\text{halo}}$, concentration, ...)  
- IMBHs in GCs?
- High-z BH scaling relations.
Recent history


1998: Silk & Rees (1998) predict $M_\bullet \sim \sigma^5$. Also Fabian 1999. ($\sigma \sim v_{\text{circ}}$ for inhabitants of $\sim$-space.)

2001: $M_\bullet - \sigma$ relation found observationally. Small scatter $\Rightarrow$ more fundamental than $M_\bullet - L_{\text{bulge}}$. Controversy about how to fit straight lines.

Since then:
- Explanations for $M_\bullet - \sigma$; predictions at low and high ends.
- Other correlations proposed ($v_{\text{halo}}$, concentration, ...)
- IMBHs in GCs?
- High-z BH scaling relations.

1998: Silk & Rees (1998) predict $M_\bullet \sim \sigma^5$. Also Fabian 1999. ($\sigma \sim v_{\text{circ}}$ for inhabitants of $\sim$-space.)

2001: $M_\bullet - \sigma$ relation found observationally.
Small scatter $\Rightarrow$ more fundamental than $M_\bullet - L_{\text{bulge}}$.
Controversy about how to fit straight lines.

Since then:
- Explanations for $M_\bullet - \sigma$; predictions at low and high ends.
- Other correlations proposed ($v_{\text{halo}}$, concentration, ...)
- IMBHs in GCs?
- High-$z$ BH scaling relations.
Present status of BH scaling relations
Host properties
(The $x$-axes of scaling plots)

Characterize host galaxy by

- $L_{\text{tot}}$
- $L_{\text{bulge}}$
- $M_{\text{tot}}$
- $M_{\text{bulge}}$
- $v_{\text{halo}}$
- $\sigma$
- concentration
- ...

Virial theorem:

$$-E_{\text{bind}} = KE = \frac{1}{2} M \sigma^2.$$

$\sigma$ is velocity dispersion measured through a large aperture:
Host properties
(The x-axes of scaling plots)

Characterize host galaxy by
- $L_{\text{tot}}$
- $L_{\text{bulge}}$
- $M_{\text{tot}}$
- $M_{\text{bulge}}$
- $v_{\text{halo}}$
- $\sigma$
- concentration
- ...

Virial theorem:

$$-E_{\text{bind}} = KE = \frac{1}{2} M \sigma^2.$$ 

$\sigma$ is velocity dispersion measured through a large aperture:
Host properties
(The x-axes of scaling plots)

Characterize host galaxy by
- $L_{\text{tot}}$
- $L_{\text{bulge}}$
- $M_{\text{tot}}$
- $M_{\text{bulge}}$
- $v_{\text{halo}}$
- $\sigma$
- concentration
- ...

Virial theorem:

$$-E_{\text{bind}} = KE = \frac{1}{2} M \sigma^2.$$  

$\sigma$ is velocity dispersion measured through a large aperture:
Recall that $r_{\text{schw}} \sim 10^{-4}$ to $10^{-7}$ pc.
Observations resolve scales $\gtrsim 1$ pc.

**How to find BHs:**

1. Use kinematics of stars/gas to look for evidence of massive dark object (MDO)
   - still need to resolve $\sim$ BH sphere of influence, $\sim$ pc scales.
   - Only feasible for nearest galaxies.

2. Indirect arguments $\Rightarrow$ MDO is BH (Maoz 1998).
   - But MDO could often also be BH + dark cluster or BH binary.
Scaling relations as of today
(Gültekin+nuk 2009, arXiv:0903.4897)

49 BH detections and 18 upper limits**

Use ML technique to find best-fit power-law relation between $M_\bullet$ and host, allowing for intrinsic scatter.

Fitting full sample,

$$M_\bullet = M_{200} \left( \frac{\sigma}{200 \text{ km s}^{-1}} \right)^\beta,$$

$$\beta = 4.24 \pm 0.41, \quad \epsilon_0 = 0.44 \pm 0.06.$$

Restricted to the 25 Es,

$$\beta = 3.96 \pm 0.42, \quad \epsilon_0 = 0.31 \pm 0.06.$$
Scaling relations as of today
(Gültekin+nuk 2009, arXiv:0903.4897)

49 BH detections and 18 upper limits***.

Use ML technique to find best-fit power-law relation between $M_\bullet$ and host, allowing for intrinsic scatter.

Fitting full sample,

$$M_\bullet = M_{200} \left( \frac{\sigma}{200 \text{km s}^{-1}} \right)^\beta,$$

$$\beta = 4.24 \pm 0.41,$$
$$\epsilon_0 = 0.44 \pm 0.06.$$

Restricted to the 25 Es,

$$\beta = 3.96 \pm 0.42$$
$$\epsilon_0 = 0.31 \pm 0.06.$$
49 BH detections and 18 upper limits.

Use ML technique to find best-fit power-law relation between $M_\bullet$ and host, allowing for intrinsic scatter.

Fitting to 25 Es only,

$$M_\bullet = M_{11} \left( \frac{L_{\text{bulge}}}{L_\odot, V} \right)^{\alpha}$$

$$\alpha = 1.11 \pm 0.18$$

$$\epsilon_0 = 0.38 \pm 0.09.$$
49 BH detections and 18 upper limits.

Use ML technique to find best-fit power-law relation between $M_\bullet$ and host, allowing for intrinsic scatter.

**Crude summary of G+09**

- Choice of sample matters
- $M_\bullet - \sigma$ relation has only marginally less scatter than $M_\bullet - M_{\text{bulge}}$ for Es
Differences between the two relations
(Lauer+nuk 2007, Gültekin+nuk 2009)

Cumulative BH mass functions:

- Use green curve as reference for $L$ versus $\sigma$ relations.
- Compare dashed vs solid red curves for $\epsilon_0$. 
Dirty laundry
Sanity checks

Galaxies with two or more independent measurements of $M_\bullet$:

![Graph showing log$_{10}$ $M_1$ vs. log$_{10}$ $M_2$ with errorbars.]

Errorbars underestimated?
What’s going wrong?
(Magorrian 2006, Houghton et al 2006, in prep)

Most $M_\bullet$ come from stellar dynamics:

Pitfalls

- Template mismatch, continuum subtraction, ...
- Assumptions in modelling (symmetry, OS method...)
- Not bringing model to data.
What’s going wrong?
(Magorrian 2006, Houghton et al 2006, in prep)

Most $M_*$ come from stellar dynamics:

Pitfalls

- Template mismatch, continuum subtraction, ...
- Assumptions in modelling (symmetry, OS method...)
- Not bringing model to data.
What’s going wrong?
(Magorrian 2006, Houghton et al 2006, in prep)

Most $M_*$ come from stellar dynamics:

Pitfalls
- Template mismatch, continuum subtraction, ...
- Assumptions in modelling (symmetry, OS method...)
- Not bringing model to data.
Good news...

Gas has a different set of problems.
Measurements of $M_\bullet$ from gas versus stars:

An accident? A malicious conspiracy?
What do we really know about scatter in $M_\bullet$–host relations?
Good news...

Gas has a different set of problems.
Measurements of $M_*$ from gas versus stars:

An accident? A malicious conspiracy?
What do we really know about scatter in $M_*$–host relations?
Things to look forward to
Future: 1 – Reduce biases in existing BH sample

Present sample is deficient in spirals.

Would like to have more giant Es.

2.2m HST (optical) \(\rightarrow\) 8m VLT (NIR).

IFU \(\rightarrow\) dynamics of central regions, not just \(M_\bullet\).

Already underway! (NGC 1399 + Cen A + following talk)
Future: 1 – Reduce biases in existing BH sample

Present sample is deficient in spirals.

Would like to have more giant Es.

2.2m HST (optical) $\rightarrow$ 8m VLT (NIR).

IFU $\Rightarrow$ *dynamics of central regions*, not just $M_\bullet$.

Already underway! (NGC 1399 + Cen A + following talk)
\( \frac{1}{2} \) of early- and late-type spirals and intermediate-\( L \) Virgo Es have central compact stellar clusters. Only “hot” component in late-type spirals.
Scaling – NCs in early-type Virgo galaxies (e.g., Wehner & Harris 2006; Ferrarese & Côté)

Red points show (photometric) NC masses. $L \sim 10^6 L_\odot$, $r \propto L^{0.5}$

Extended SF histories.

- How do NCs form?
- Do NCs harbour BHs?

Something for EELT!
(Along with IMBHs in GCs, dEs.)
All galaxies have BHs.

The bigger the galaxy, the bigger the BH.

- Detections of $M_\bullet$ in $\sim 50$ galaxies
  - mostly big, bright, early-type
- Many more upper bounds
  - mostly late-type S
- Biases in sample being reduced thanks to AO+NIR
- No-one understands errors on individual $M_\bullet$ (JM 2006)
- Easy to get overexcited about minimizing scatter in $M_\bullet$–host relations.
Summary

Caricature

1. All galaxies have BHs.
2. The bigger the galaxy, the bigger the BH.

- Detections of $M_*$ in $\sim 50$ galaxies
  - mostly big, bright, early-type
- Many more upper bounds
  - mostly late-type S

- Biases in sample being reduced thanks to AO+NIR
- No-one understands errors on individual $M_*$ (JM 2006)
- Easy to get overexcited about minimizing scatter in $M_*$–host relations.
Summary

Caricature

1. All galaxies have BHs.
2. The bigger the galaxy, the bigger the BH.

- Detections of $M_\bullet$ in $\sim 50$ galaxies
  - mostly big, bright, early-type
- Many more upper bounds
  - mostly late-type S
- Biases in sample being reduced thanks to AO+NIR
- No-one understands errors on individual $M_\bullet$ (JM 2006)
- Easy to get overexcited about minimizing scatter in $M_\bullet$–host relations.
Summary

Caricature

1. All galaxies have BHs.
2. The bigger the galaxy, the bigger the BH.

- Detections of $M_\bullet$ in $\sim 50$ galaxies
  - mostly big, bright, early-type
- Many more upper bounds
  - mostly late-type S
- Biases in sample being reduced thanks to AO+NIR
- No-one understands errors on individual $M_\bullet$ (JM 2006)
- Easy to get overexcited about minimizing scatter in $M_\bullet$–host relations.
Summary

Caricature

1. All galaxies have BHs.
2. The bigger the galaxy, the bigger the BH.

- Detections of $M_*$ in $\sim 50$ galaxies
  - mostly big, bright, early-type
- Many more upper bounds
  - mostly late-type S
- Biases in sample being reduced thanks to AO+NIR
- No-one understands errors on individual $M_*$ (JM 2006)
- Easy to get overexcited about minimizing scatter in $M_*$–host relations.
Future: 3 – active galaxies

$M_*$ from reverberation mapping?
For each ion,

\[ \mathcal{L}(v, t) = \int \psi(v, \tau) C(t - \tau) \, d\tau, \]  

(\star)

with \( \psi(v, \tau) \) determined by the geometry and kinematics of the BLR.

Instead of solving (\star), can obtain characteristic BLR

- size, \( r \), by cross correlating light curves, and
- velocity, \( v \), from FWHM of emission lines.

Together they give an immediate BH mass estimate,

\[ M_\bullet \approx f \frac{r v^2}{G}. \]

with fudge factor \( f \sim 1 \).
For each ion,

\[ \mathcal{L}(v, t) = \int \psi(v, \tau)C(t - \tau)\,d\tau, \]

with \( \psi(v, \tau) \) determined by the geometry and kinematics of the BLR.

Instead of solving (⋆), can obtain characteristic BLR
- size, \( r \), by cross correlating light curves, and
- velocity, \( v \), from FWHM of emission lines.

Together they give an immediate BH mass estimate,

\[ M_\bullet \approx f \frac{rv^2}{G}. \]

with fudge factor \( f \sim 1. \)
BH masses estimates for AGN:
BH masses estimates for AGN:

Active galaxies: $M = f \frac{rv^2}{G}$,
with $r$ from reverberation mapping (Onken et al.)
Leaps of faith

BH masses estimates for AGN:

Active galaxies: \( M = f \frac{r v^2}{G} \),
with \( r \) from reverberation mapping (Onken et al.)
or using \( r = f' L^\lambda \) (Barth, Greene, Ho)
Becomes shallower at low masses?
BH masses estimates for AGN:

Wyithe’s log-quadratic fit to direct \( M_\bullet \).
BH masses estimates for AGN:

Wyithe’s log-quadratic fit to direct $M_\bullet$.
Remember: AGN masses are indirect.