Gemini Observatory/AURA artwork by Lynette Cook

# Revisiting Black Hole Scaling Relations


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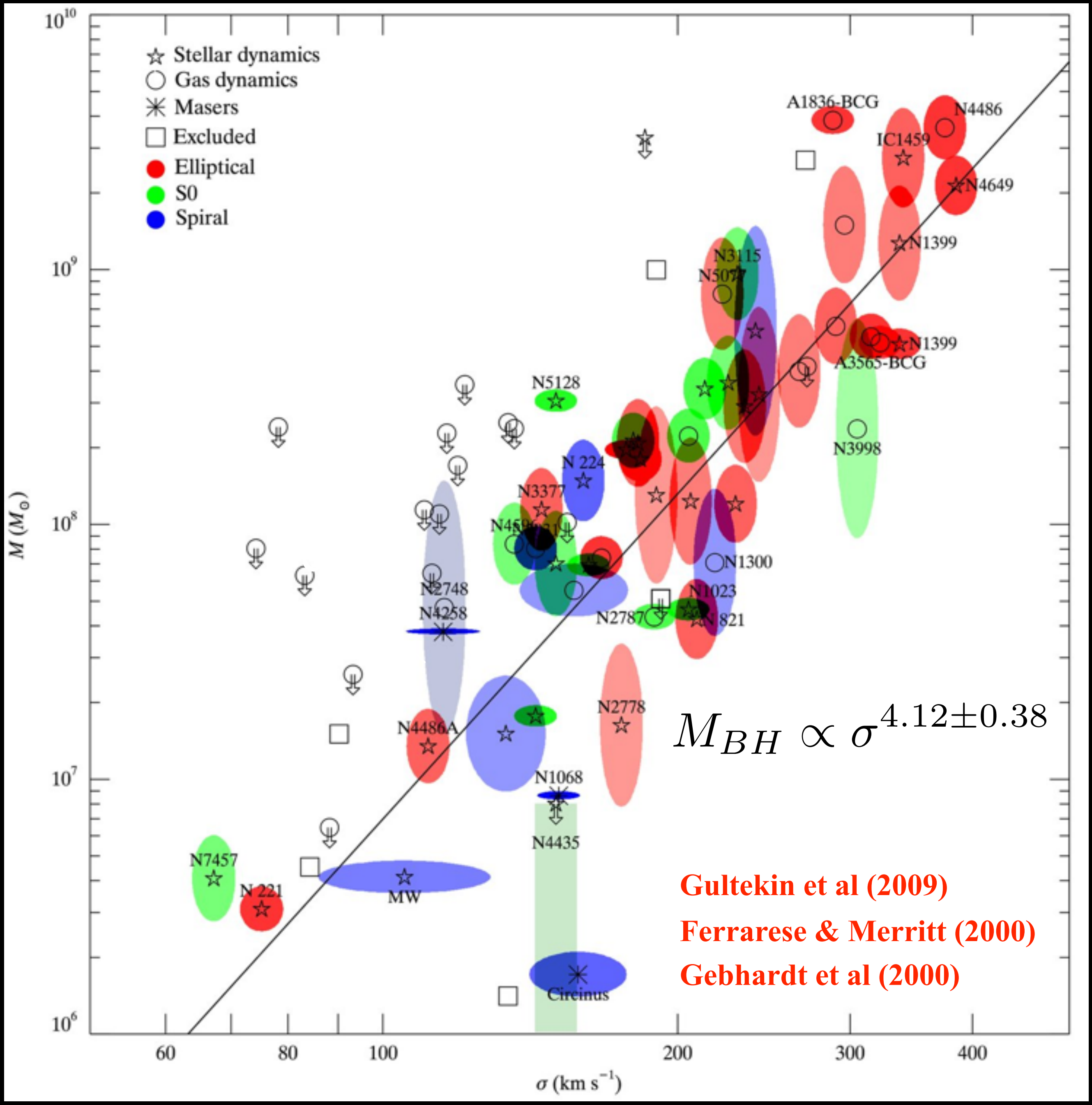
# Local Black Holes

# Direct Mass Measurements

**Major updates since Gultekin 09 compilation:**

- **18 new masses**
- **17 updated masses**
- **different slopes**



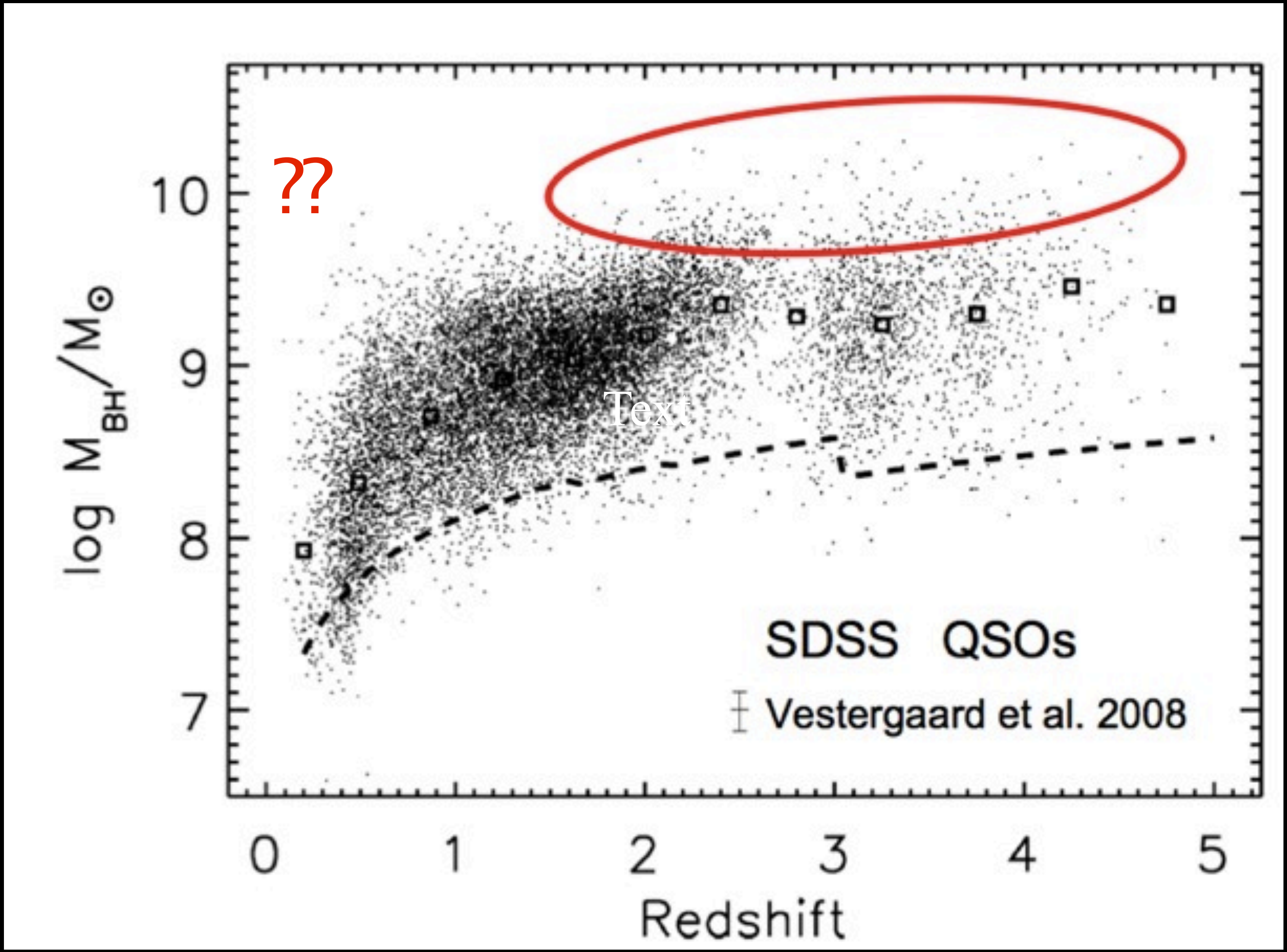

$$M_{BH} \propto \sigma^{4.12 \pm 0.38}$$

Gultekin et al (2009)

Ferrarese & Merritt (2000)

Gebhardt et al (2000)

# High-z QSOs


??
10
9
8
7
log $M_{BH}/M_\odot$
0
1
2
3
4
5
Redshift
Text
SDSS QSOs
Vestergaard et al. 2008

# Why hadn't the biggest galaxies been measured?
## Challenge 1
## Detecting black hole's influence

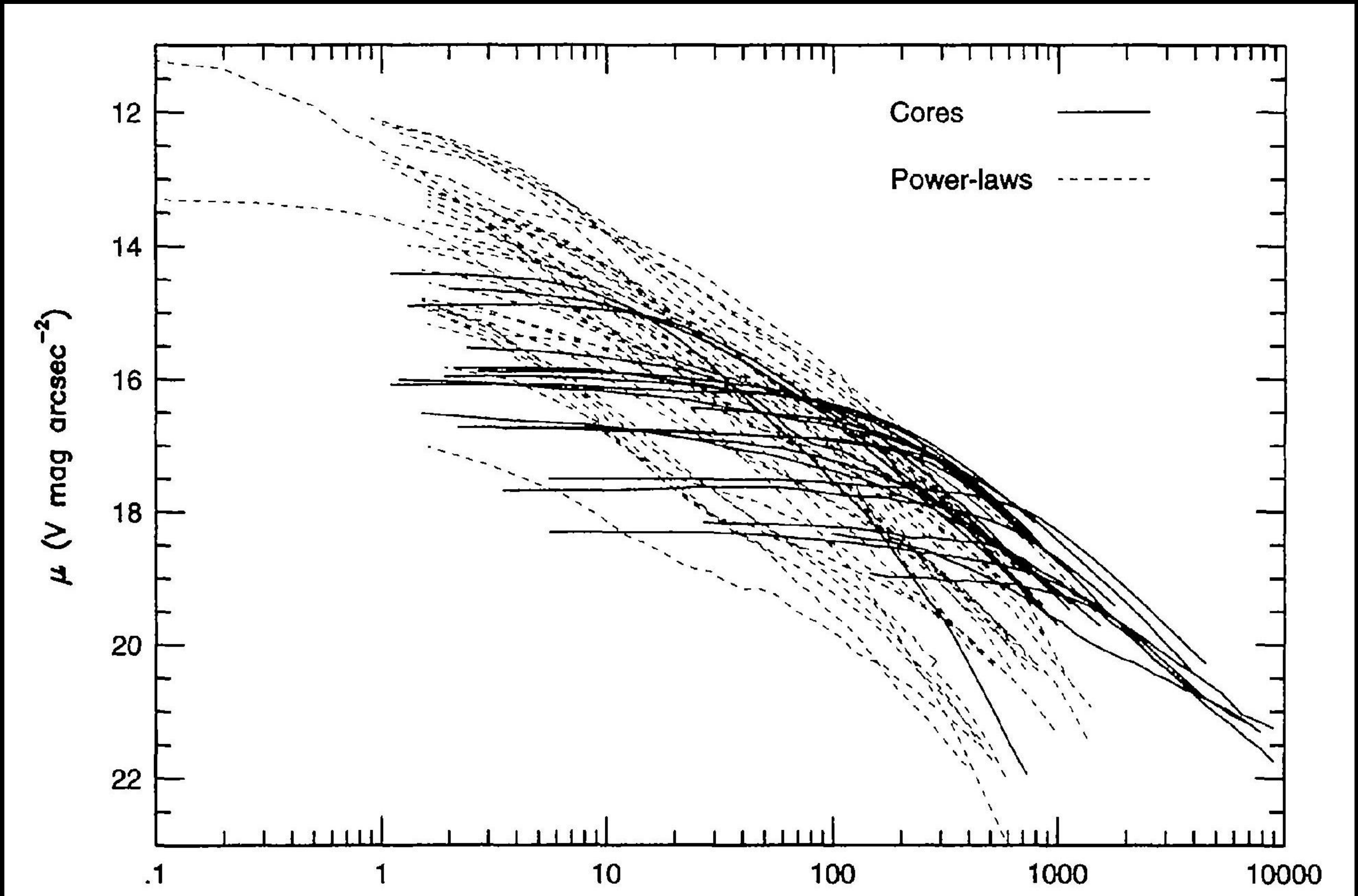
**Massive galaxies are rare. Must go beyond Virgo cluster.**
**(Sauron/ATLAS probes < 40 Mpc)**

**Black hole's gravity dominates within**
**the sphere of influence**

$$r = \frac{GM_{BH}}{\sigma^2} \approx 50\,\mathrm{pc}\,\frac{M_{BH}}{10^9 M_\odot}\left(\frac{300\,\mathrm{km\,s^{-1}}}{\sigma}\right)^2$$

**0.1 arcsec at 100 Mpc**

# Challenge 2
# Massive galaxies have shallow inner stellar profile




Faber et al (1997)

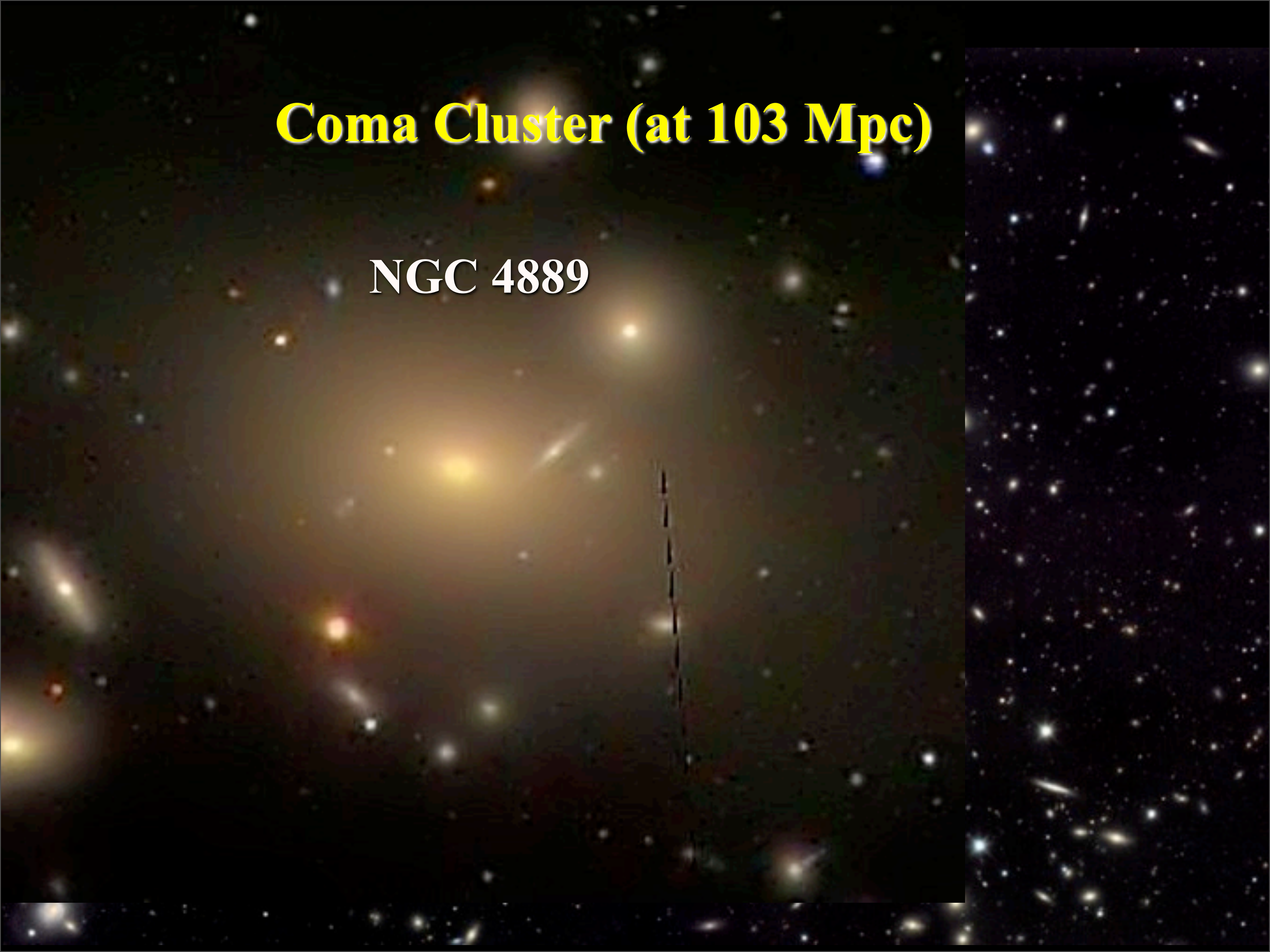
# Integral Field Spectrographs

**Keck OSIRIS** (0.05 to 0.7 arcsec)

**Gemini GMOS-N & S** (0.2 to 3.8 arcsec)

**+ McDonald Mitchell/VIRUS-P** (4 to 35 arcsec)

# Coma Cluster (at 103 Mpc)



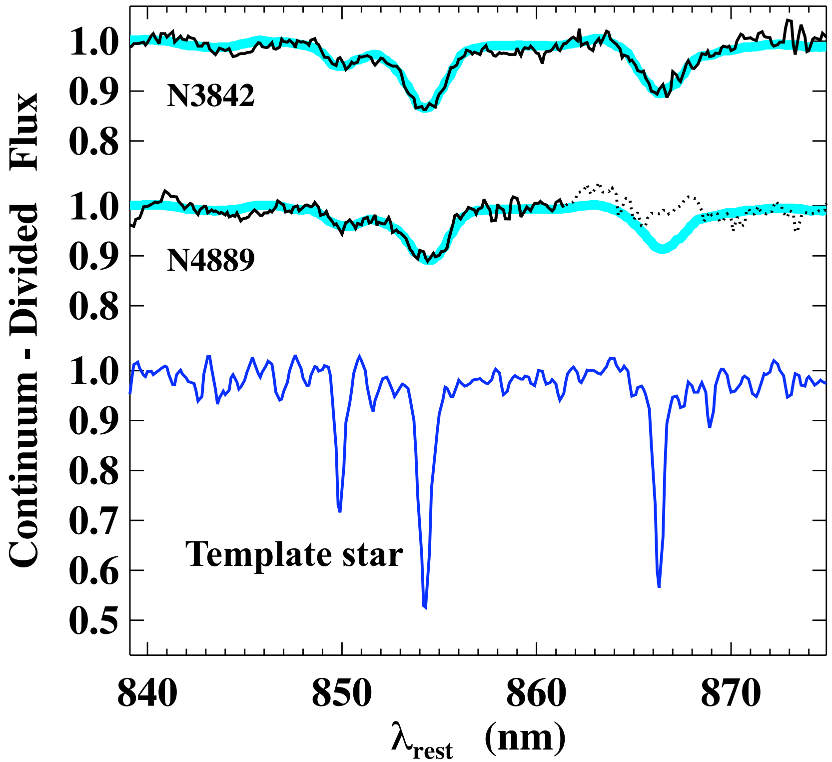
# Ongoing Survey

| Published | BCG | D | σ | Mv | $M_{BH}$ | |
|---|---|---|---|---|---|---|
| NGC 6086 | (A2162) | 139 Mpc | 318 km/s | -23.11 | 3.8e9 | ApJ 2011 |
| NGC 3842 | (A1367) | 98 Mpc | 270 km/s | -23.18 | 9.7e9 | Nature 2011 |
| NGC 4889 | (Coma) | 103 Mpc | 347 km/s | -23.73 | 2.1e10 | Nature 2011 |
| NGC 7768 | (A2666) | 120 Mpc | 313 km/s | -23.01 | 1.3e9 | ApJ 2012 |
| NGC 2832 | (A0779) | 97 Mpc | 334 km/s | -23.76 | < 9.0e9 | ApJ 2012 |

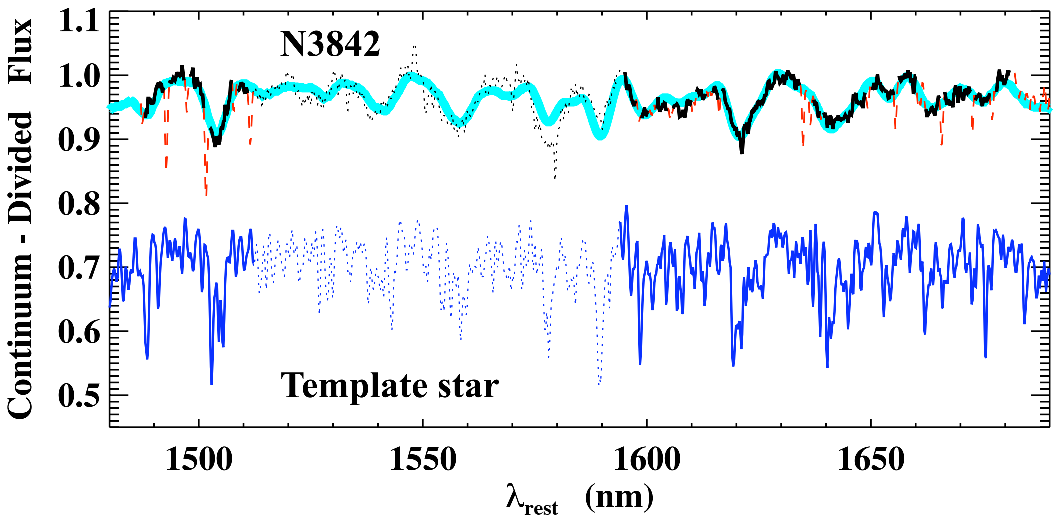
**Analyzing**

| | | | | | |
|---|---|---|---|---|---|
| NGC 4552 | (M89) | 15 Mpc | 254 km/s | -21.60 | GMOS, VP |
| NGC 4365 | (in Virgo) | 20 Mpc | 256 km/s | -22.20 | GMOS, VP |
| NGC 4696 | (A3526) | 40 Mpc | 254 km/s | -24.30 | GMOS-S |
| NGC 4751 | | 24 Mpc | 349 km/s | -20.80 | GMOS-S |
| NGC 910 | (A0347) | 81 Mpc | 249 km/s | -22.79 | OSIRIS, NIFS, GMOS,VP |
| NGC 7578 | (A2572) | 172 Mpc | 214 km/s | -23.41 | OSIRIS, VP |
| U9767 | (A2040) | 176 Mpc | 223 km/s | -23.46 | OSIRIS, GMOS, VP |
| NGC 6166 | (A2199) | 129 Mpc | 307 km/s | -23.80 | GMOS |

**10 more scheduled (Gemini)**



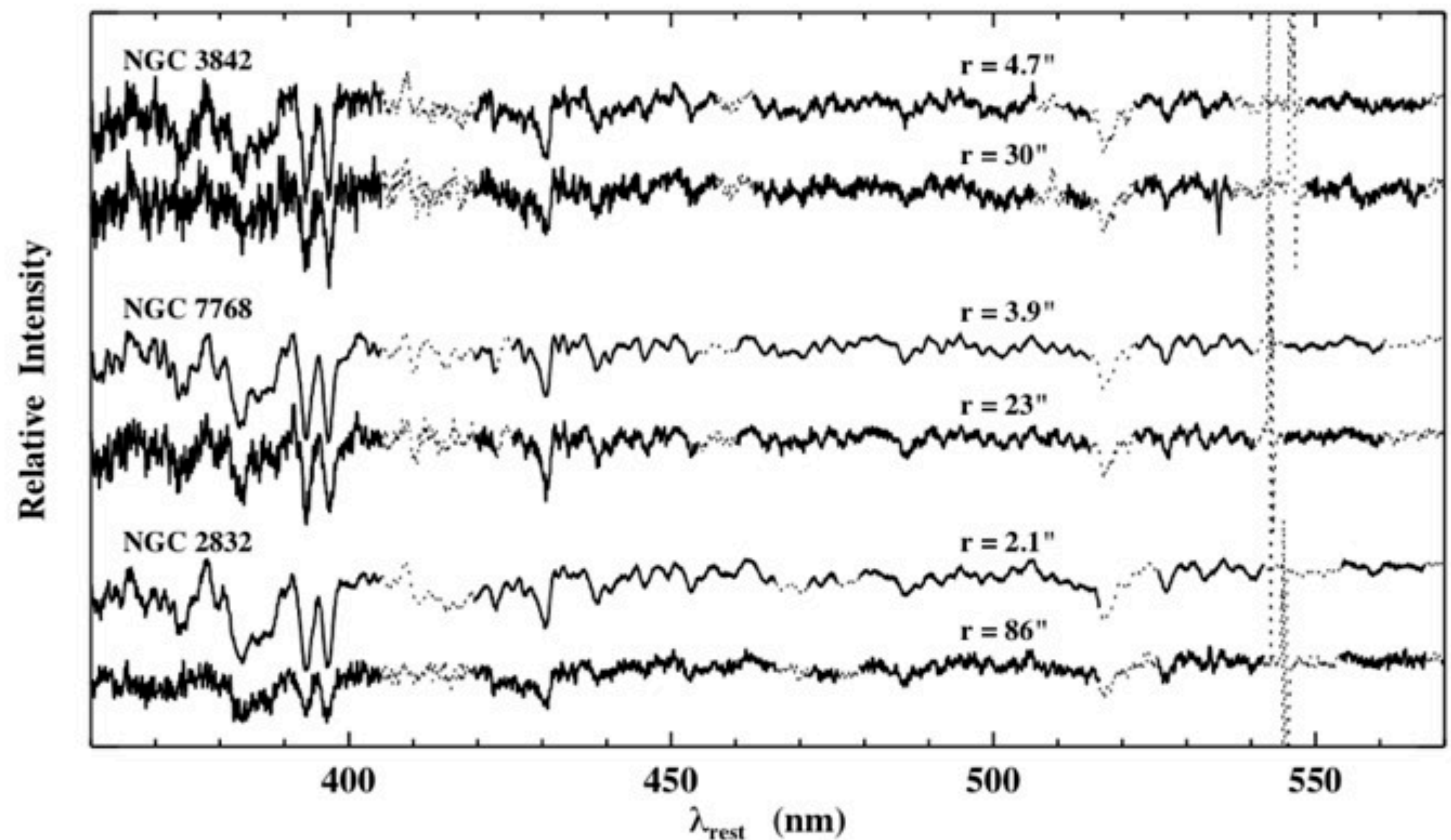

**GMOS Spectra**
**(r<0.25 arcsec)**
**CaII triplet**




**OSIRIS Spectra**
**CO band heads**

**McConnell et al (2011)**

# VIRUS-P Spectra




McConnell et al (2012)

# Stellar Orbit Modeling

e.g. Schwarzschild (1979); Gebhardt et al (2003)

1. Assume a black hole mass $M_{BH}$ and stellar mass-to-light ratio ($\Upsilon = M^*/L$)

2. Generate stellar orbits in gravitational potential

$$\rho = M_{BH}\,\delta(r) + \Upsilon\,\rho^* + \rho_{dm}$$

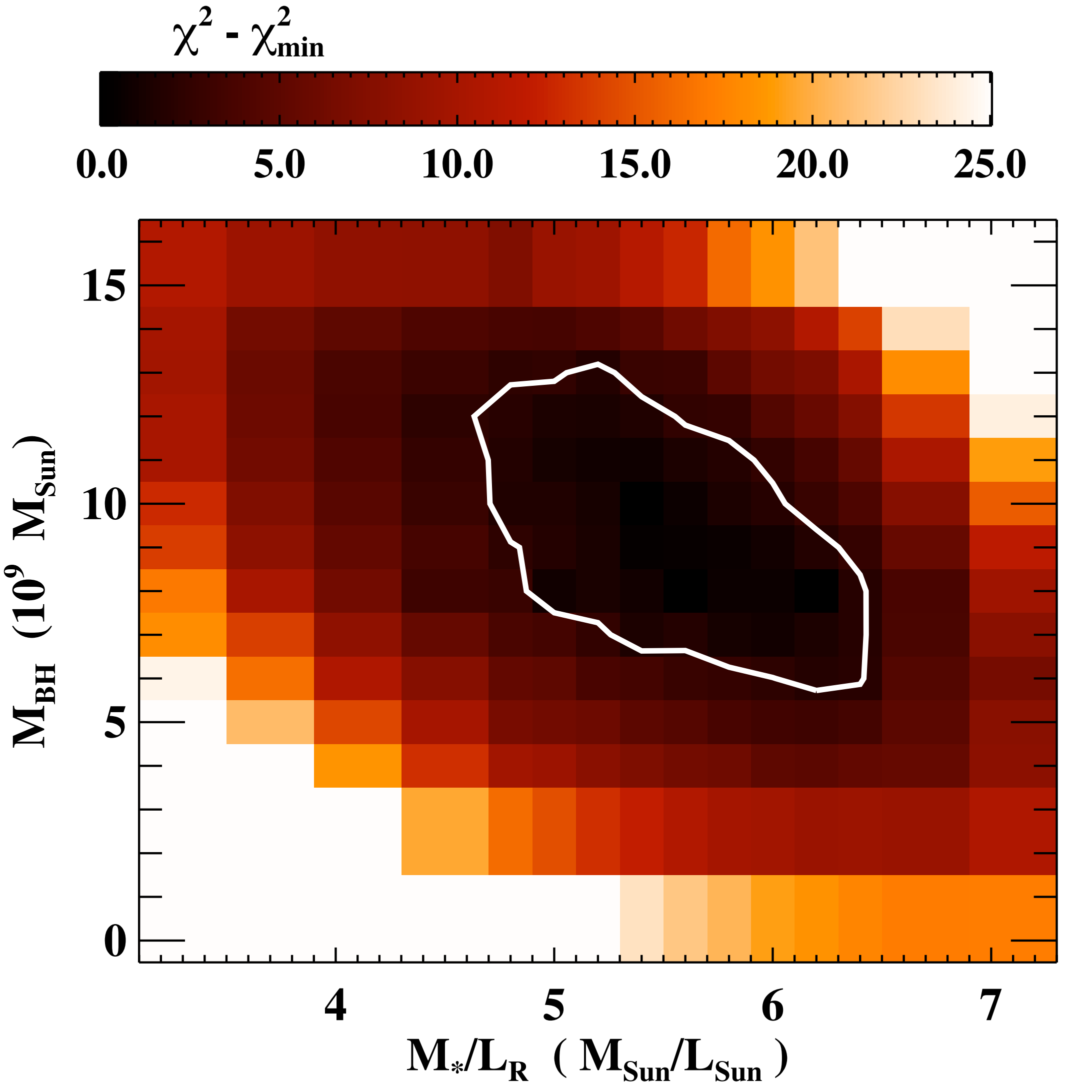
3. For a $M_{BH}$ and $\Upsilon$, determine the combination of orbits that (a) reproduces the observed light profile $\rho^*$
   (b) best fits the LOS velocity distributions derived from spectra at multiple spatial points

4. Compute $\chi^2$ for the best-fit orbits

5+. Repeat for different $M_{BH}$ and $M^*/L$

N. Minimize $\chi^2$ to obtain best-fit $M_{BH}$ and $M^*/L$

# NGC3842




$$M_{BH} = (9.7 \pm 2.5) \times 10^9 M_\odot$$
$$M_*/L_R = (5.2 \pm 0.8)\, M_\odot/L_\odot$$

# $M_{BH} - \sigma$ Relation

$$\log M_{BH} = \alpha + \beta \log(\sigma/200\mathrm{km/s})$$

**All 65 galaxies**

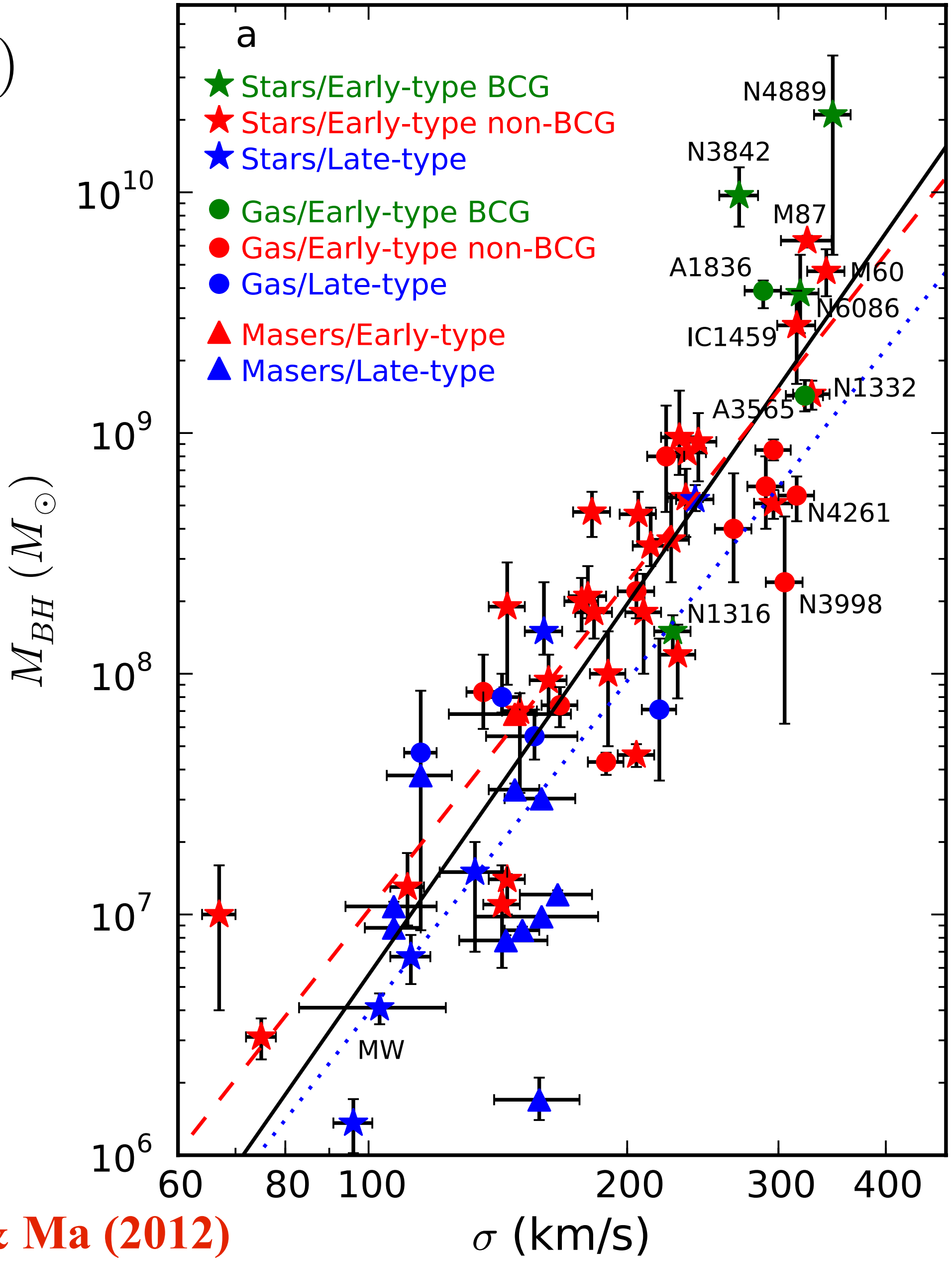
$$\beta = 5.48 \pm 0.34 \quad (\epsilon_0 = 0.38)$$
$$\alpha = 8.29 \pm 0.05$$

**46 early-type galaxies**

$$\beta = 5.01 \pm 0.38 \quad (\epsilon_0 = 0.33)$$
$$\alpha = 8.35 \pm 0.06$$

**19 late-type galaxies**

$$\beta = 5.02 \pm 1.18 \quad (\epsilon_0 = 0.46)$$
$$\alpha = 8.05 \pm 0.22$$




**McConnell & Ma (2012)**

# $M_{BH} - \sigma$ Relation

$$\log M_{BH} = \alpha + \beta \log(\sigma/200\mathrm{km/s})$$

**All 65 galaxies**

$$\beta = 5.48 \pm 0.34$$
$$\alpha = 8.29 \pm 0.05$$
$(\epsilon_0 = 0.38)$

**46 early-type galaxies**

$$\beta = 5.01 \pm 0.38$$
$$\alpha = 8.35 \pm 0.06$$
$(\epsilon_0 = 0.33)$

**22 core galaxies**

$$\beta = 5.08 \pm 0.88$$
$$\alpha = 8.44 \pm 0.13$$

**19 power-law galaxies**

$$\beta = 4.43 \pm 0.75$$
$$\alpha = 8.22 \pm 0.09$$

**19 late-type galaxies**

$$\beta = 5.02 \pm 1.18$$
$$\alpha = 8.05 \pm 0.22$$
$(\epsilon_0 = 0.46)$

**McConnell & Ma (2012)**

# $M_{BH} - \sigma$ Relation

$$\log M_{BH} = \alpha + \beta \log(\sigma/200\text{km/s})$$

**All 65 galaxies**

$$\beta = 5.48 \pm 0.34$$
$$\alpha = 8.29 \pm 0.05$$
$(\epsilon_0 = 0.38)$

**Add 92 upper limits**

$$\beta = 5.29 \pm 0.30$$
$$\alpha = 8.09 \pm 0.05$$

**Use σ (0 - $r_{eff}$)**

$$\beta = 5.29 \pm 0.32$$
$$\alpha = 8.26 \pm 0.05$$

**46 early-type galaxies**

$$\beta = 5.01 \pm 0.38$$
$$\alpha = 8.35 \pm 0.06$$
$(\epsilon_0 = 0.33)$

**19 late-type galaxies**

$$\beta = 5.02 \pm 1.18$$
$$\alpha = 8.05 \pm 0.22$$
$(\epsilon_0 = 0.46)$

**Gultekin et al (2009)**

$$\beta = 4.12 \pm 0.38$$
$$\alpha = 8.19 \pm 0.06$$
$(\epsilon_0 = 0.39)$

**McConnell & Ma (2012)**

# $M_{BH} - L$ Relation

$$\log M_{BH} = \alpha + \beta \log(L/10^{11} L_\odot)$$

**40 early-type galaxies**

$$\beta = 1.24 \pm 0.15$$
$$\alpha = 9.18 \pm 0.12$$
$(\epsilon_0 = 0.55)$

**Gultekin (2009)**

$$\beta = 1.17 \pm 0.12$$
$$\alpha = 9.01 \pm 0.10$$
$(\epsilon_0 = 0.36)$

**Beifiori (2012)**

$$\beta = 1.14 \pm 0.40$$
$$\alpha = 8.69 \pm 0.22$$
$(\epsilon_0 = 0.52)$

**McConnell & Ma (2012)**

# $M_{\rm BH} - M_{\rm bulge}$ Relation

$$\log M_{\rm BH} = \alpha + \beta \log(M_{\rm bulge}/10^{11} M_\odot)$$

**34 galaxies**
**($M_{bulge}$ from dynamical models)**

$$\beta = 1.07 \pm 0.12$$
$$\alpha = 8.42 \pm 0.08$$
$(\epsilon_0 = 0.33)$

**Beifiori (2012)**
**(19 galaxies: $M_{bulge} \sim r_e \sigma^2/G$)**

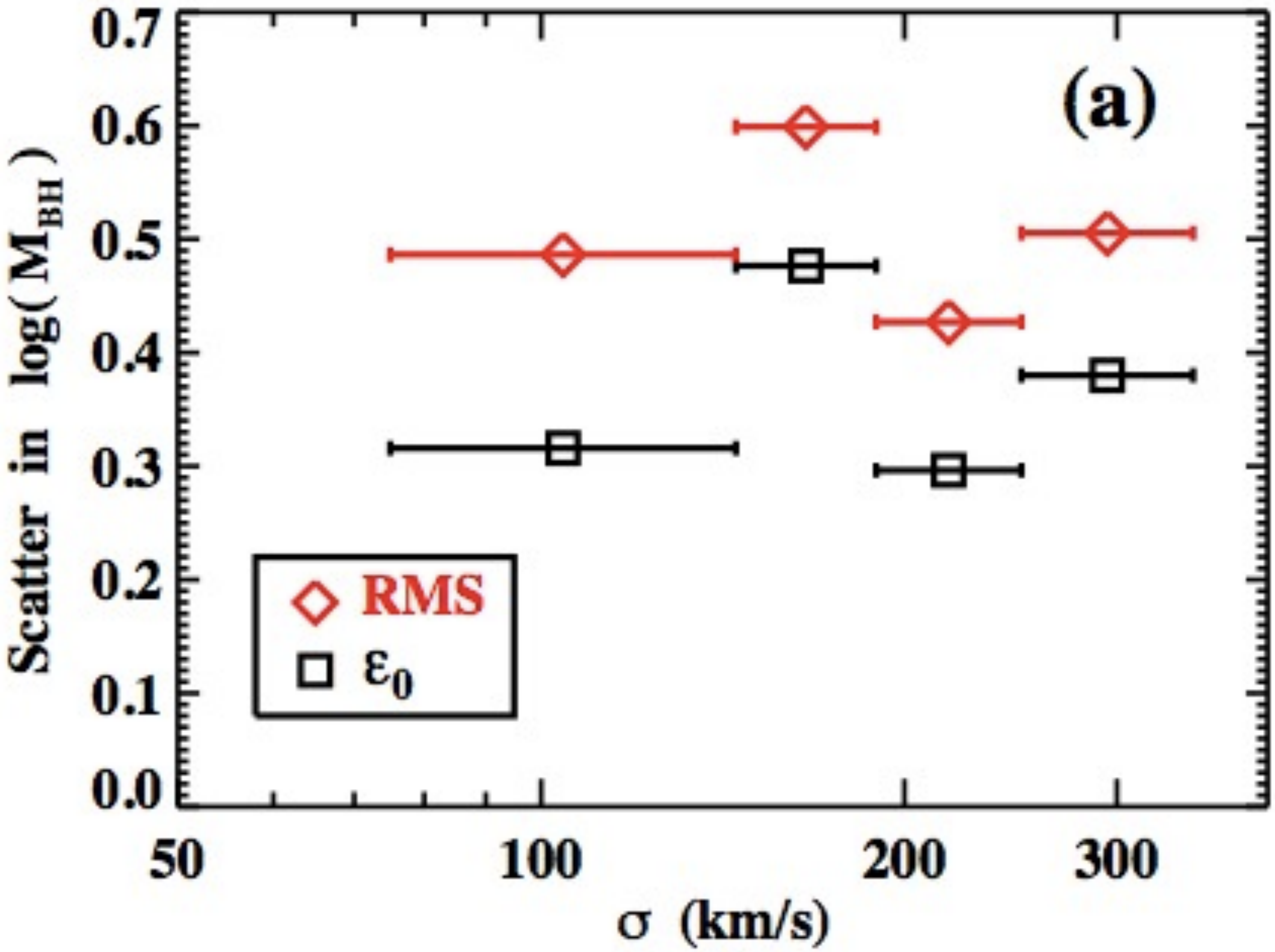
$$\beta = 0.79 \pm 0.26$$
$$\alpha = 8.25 \pm 0.13$$
$(\epsilon_0 = 0.47)$

**Haring & Rix (2004)**

$$\beta = 1.12 \pm 0.06$$
$$\alpha = 8.20 \pm 0.10$$

McConnell & Ma (2012)

# Scatter in $M_{bh}$ does not decrease at high σ




McConnell & Ma (2012)

# Black Hole Data Website

html address TBA: see McConnell & Ma 2012

**Black Hole Data**
Test

| Galaxy | $M_{BH}$ (+,-) ($M_{sun}$) | sigma (km/s) | log($L_V$) | $M_V$ | log($L_{3.6}$) | $M_{3.6}$ | $M_{bulge}$ ($M_{sun}$) | $R_{inf}$ (arcsec) | $R_{eff}$ V-band (arcsec) | $R_{eff}$ I-band (arcsec) | $R_{eff}$ 3.6mu (arcsec) | Distance (Mpc) | Morph | BH Mass Method | BH Mass Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Milky Way | 4.1 (0.6,0.6) e6 | 103 ± 20 | – | – | – | – | – | 43.02 | – | – | – | 0.008,– | S | stars | Ghez 2008, Gillessen 2009 |
| A1836-BCG | 3.9 (0.4,0.6) e9 | 288 ± 14 | 11.26 ± 0.06 | -23.35 | – | – | – | 0.27 | – | 17.61 | – | 157.5,– | E (C) | gas | Dalla Bonta 2009 |
| A3565-BCG ^b | 1.4 (0.3,0.2) e9 | 322 ± 16 | 11.24 ± 0.06 | -23.30 | – | – | – | 0.22 | – | – | – | 54.4,- | E (C) | gas | Dalla Bonta 2009 |
| Circinus | 1.7 (0.4,0.3) e6 | 158 ± 18 | – | – | 10.31 ± 0.016 | -22.53 | – | 0.02 | – | – | 10.83 | 4.0,– | S | masers | Greenhill 2003 |
| IC1459 ^c | 2.8 (1.1,1.2) e9 | 315 ± 16 | 10.96 ± 0.06 | -22.51 | 11.82 ± 0.12 | -26.30 | 3.09e11 | 0.81 | 29.82 | – | 61.08 | 30.9,– | E (C) | stars | Cappellari 2002 |
| N221 (M32) | 2.92 (0.56,0.56) e6 | 75 ± 3 | 8.66 ± 0.02 | -16.85 | 9.09 ± 0.252 | -19.47 | 8.32e8 | 0.57 | 38.65 | – | 28.78 | 0.86,0.81 | E (I) | stars | Verolme 2002 |
| N224 (M31) | 1.37 (0.8,0.3) e8 | 160 ± 8 | – | – | – | – | 3.98e10 | 6.52 | – | – | – | 0.80,0.73 | S | stars | Bender 2005 |
| N524 | 8.62 (0.8, 0.4) e8 | 235 ± 12 | 10.60 ± 0.04 | -21.85 | 11.23 ± 0.076 | -24.83 | – | 0.57 | – | – | 26.83 | 23.3,24.2 | S0 (C) | stars | Krajnovic 2009 |
| N821 | 1.65 (0.73, 0.73) e8 | 209 ± 10 | 10.43 ± 0.05 | -21.28 | 11.35 ± 0.104 | -25.13 | 2.09e11 | 0.14 | 29.37 | 35.01 | 63.58 | 25.5,23.4 | E (I) | stars | Schulze 2011 |
| N1023 | 3.99 (0.43,0.43) e7 | 205 ± 10 | 10.18 ± 0.11 | -20.53 | 10.79 ± 0.072 | -23.71 | 8.32e10 | 0.08 | – | – | 24.04 | 12.1,10.5 | S0 (pl) | stars | Bower 2001 |
| N1194 ^(b,d) | 6.8 (0.3, 0.3) e7 | 148 ± (26.22) | – | – | – | – | – | 0.05 | – | – | – | 55.5,– | S0 | masers | Kuo 2011 |

# Summary

Major update to Gultekin 09 compilation. See our BH website.

Gemini + IFU + AO make it feasible to extract $M_{BH}$ and stellar populations at centers of nearby massive galaxies.

BCGs can host massive black holes >~ 10 billion solar masses.
NGC 3842 and 4889 are new record holders.
Remnants of massive high-z QSOs?
Expect tens more new measurements

Time to move beyond a single global fit to scaling relations of $M_{BH}$ with galaxy properties.
e.g. Late vs early type     Core vs power-law

$M_{BH} - \sigma$ relation. Which $\sigma$? Modelers pay attention to $\sigma$.
Scatter does not decrease at high mass - some models ruled out.