Black hole scaling relations

John Magorrian

JENAM, 21 April 2009

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

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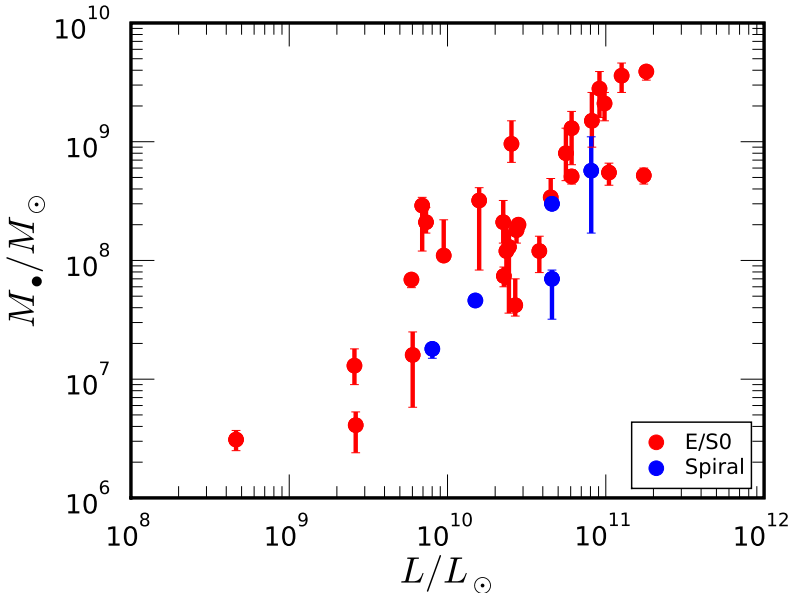

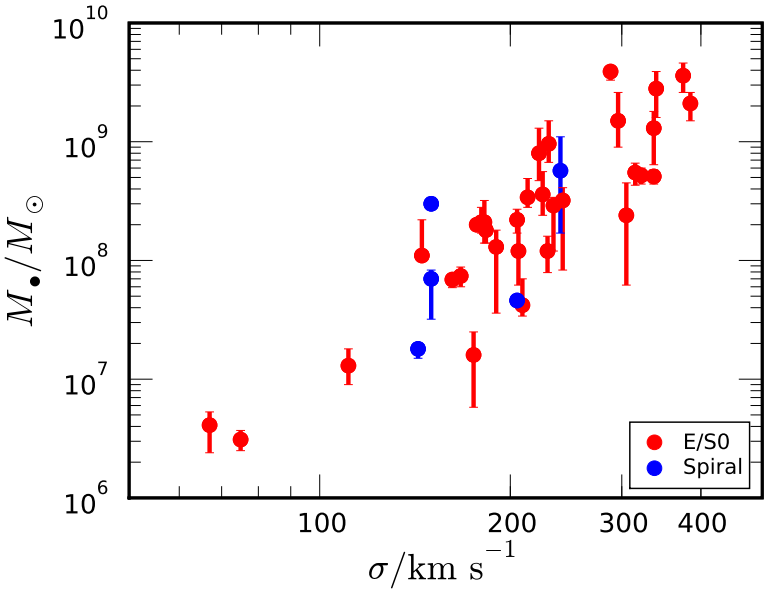

Many more upper bounds (Beifiori, Sarzi et al.).

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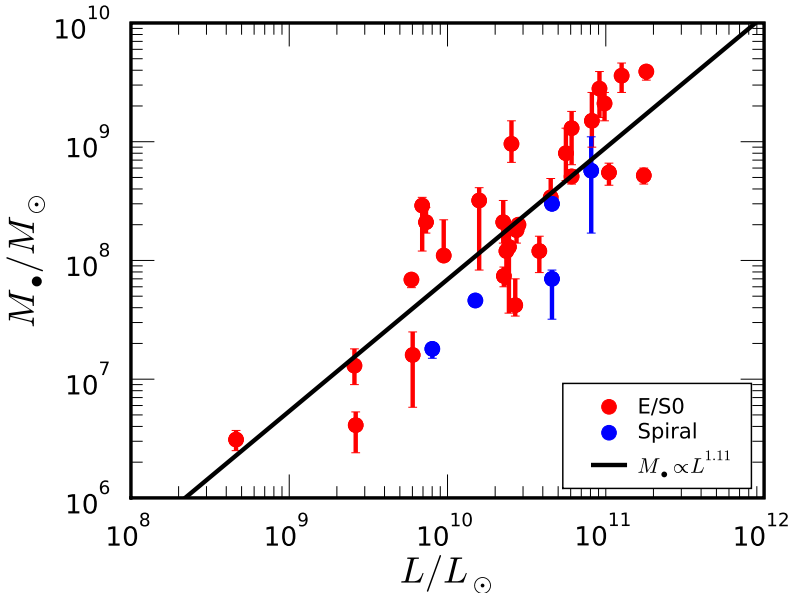

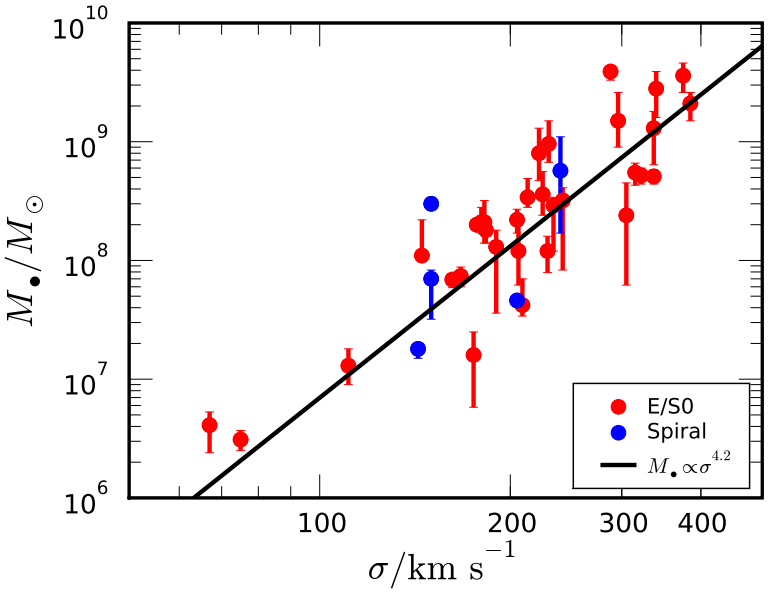

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Motivation

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

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

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

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

In constrast, host scales $\sim 5\mathrm{kpc} \sim 100 r_\bullet$.
$\Rightarrow$ Formation of BH and host intimately linked? Feedback?

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Sombrero Galaxy • M104

Hubble Heritage

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

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σ [km s⁻¹]
R [arcsec]
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Recent history

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($\sigma \sim v_{\rm circ}$ for inhabitants of $\sim$-space.)

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Small scatter $\Rightarrow$ more fundamental than $M_\bullet$–$L_{\rm bulge}$.
Controversy about how to fit straight lines.

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- IMBHs in GCs?
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Present status of BH scaling relations

Host properties
(The x-axes of scaling plots)

Characterize host galaxy by

- $L_{\rm tot}$
- $L_{\rm bulge}$
- $M_{\rm tot}$
- $M_{\rm bulge}$
- $v_{\rm halo}$
- σ
- concentration
- ...

Virial theorem:

$$-E_{\rm bind} = \mathrm{KE} = \tfrac{1}{2} M \sigma^2.$$

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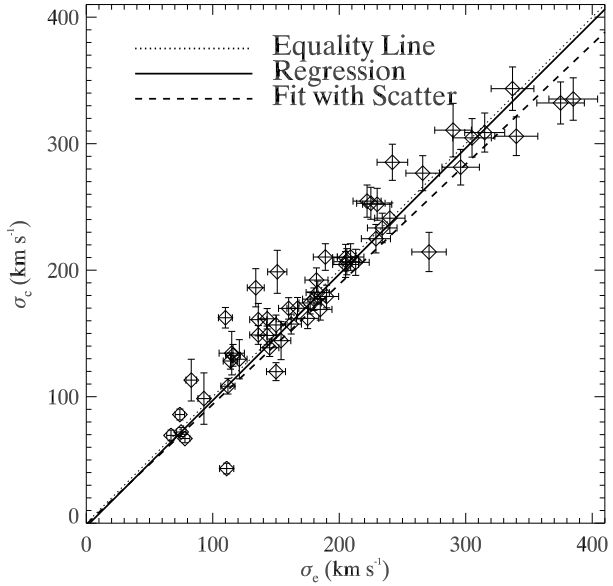


“Black hole” properties
(The y axis)

Recall that $r_{\rm schw} \sim 10^{-4}$ to $10^{-7}\rm pc$.
Observations resolve scales $\gtrsim 1\rm pc$.

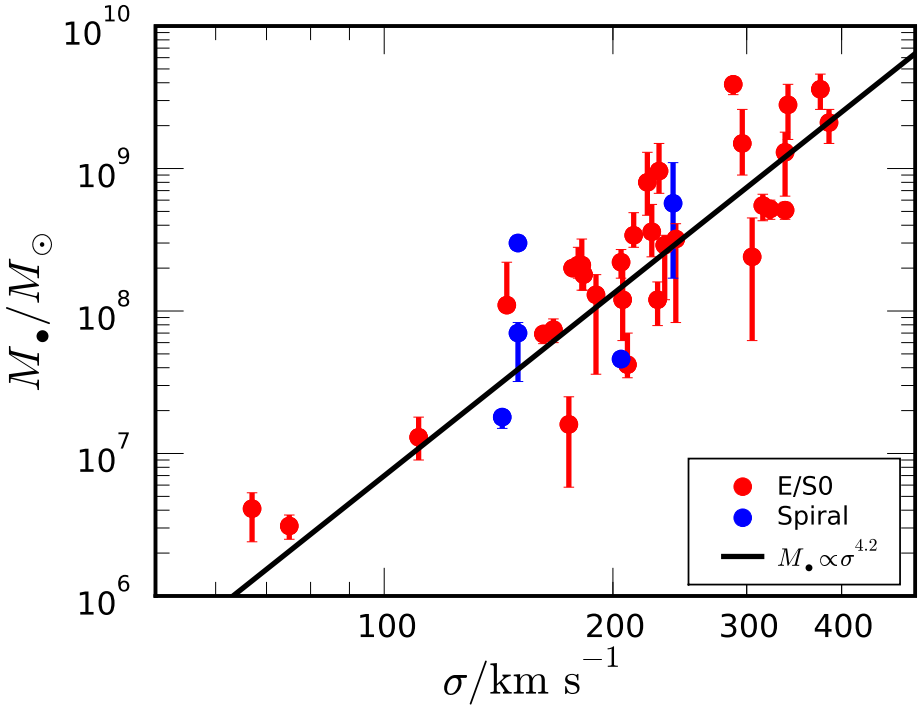
How to find BHs:

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

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

$$\beta = 4.24 \pm 0.41,$$

$$\epsilon_0 = 0.44 \pm 0.06.$$

Restricted to the 25 Es,

$$\beta = 3.96 \pm 0.42$$

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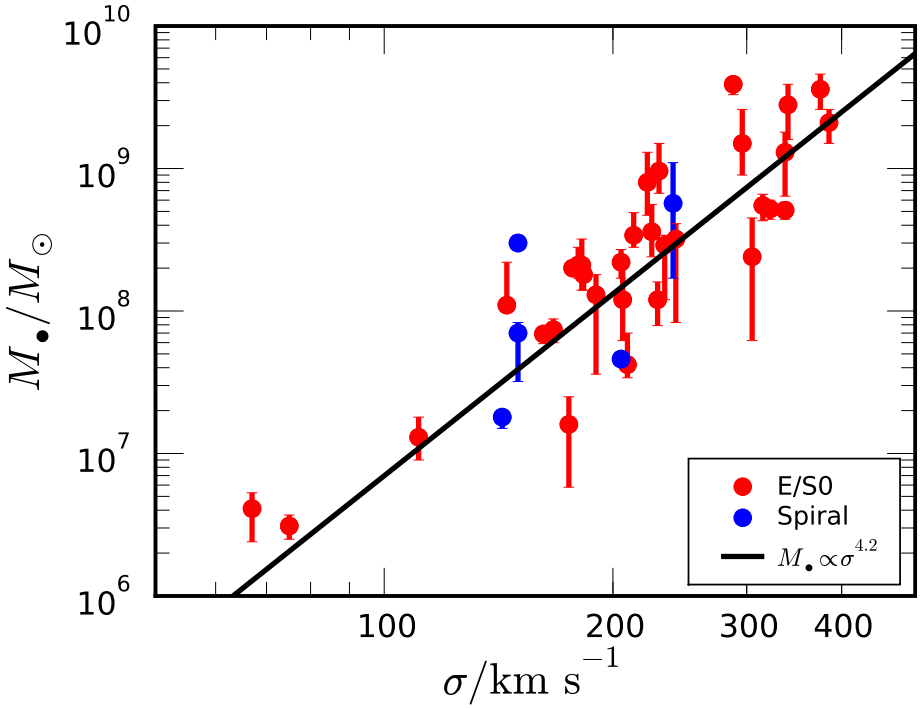

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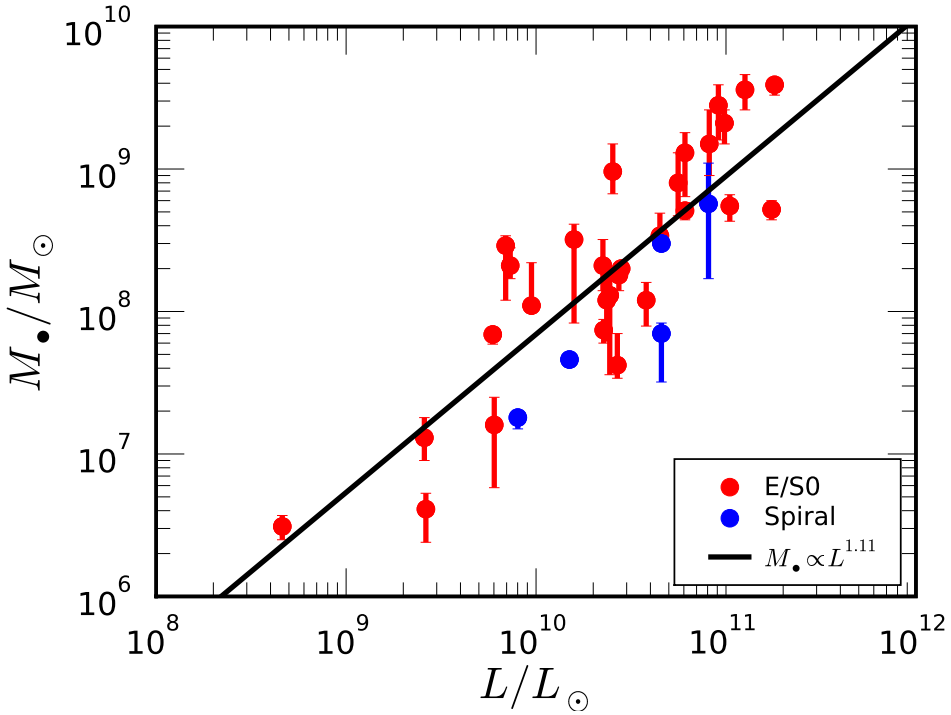

Fitting to 25 Es only,

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

$$\alpha = 1.11 \pm 0.18$$

$$\epsilon_0 = 0.38 \pm 0.09.$$

($M_\bullet \propto M_{\rm bulge}$ from FP.)

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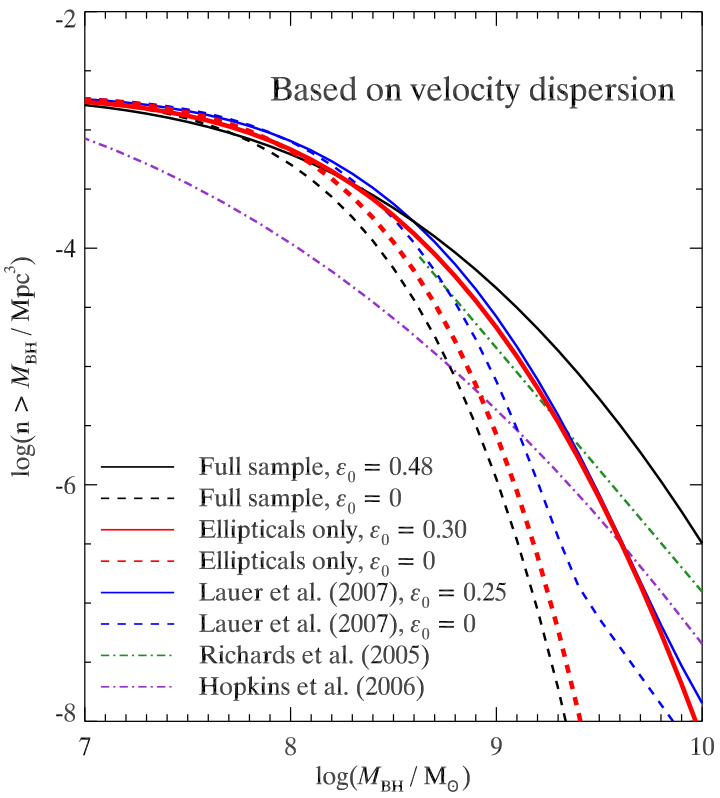
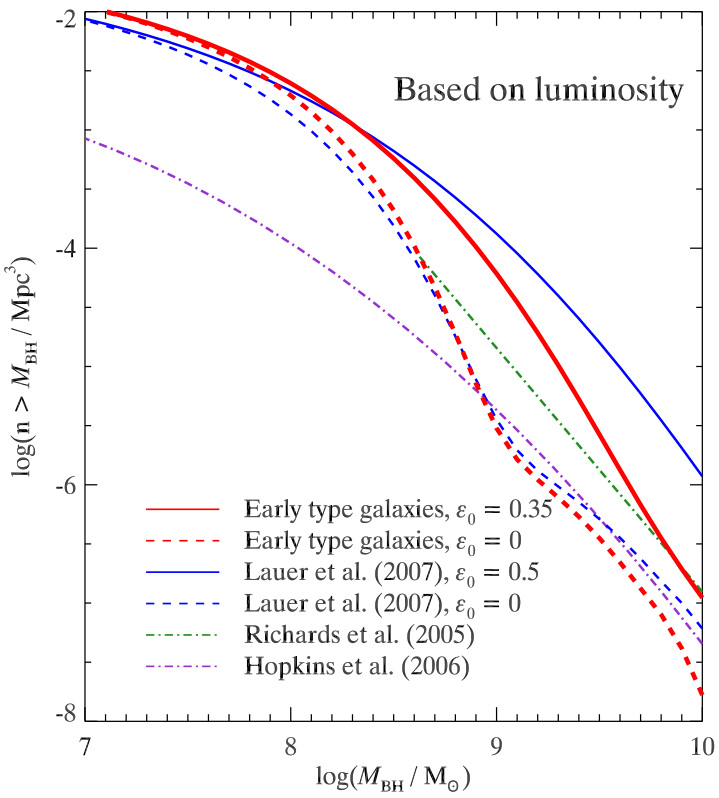
Crude summary of G+09

- Choice of sample matters
- $M_\bullet$–σ relation has only marginally less scatter than $M_\bullet$–$M_{\rm bulge}$ for Es

Differences between the two relations
(Lauer+nuk 2007, Gültekin+nuk 2009)

Cumulative BH mass functions:



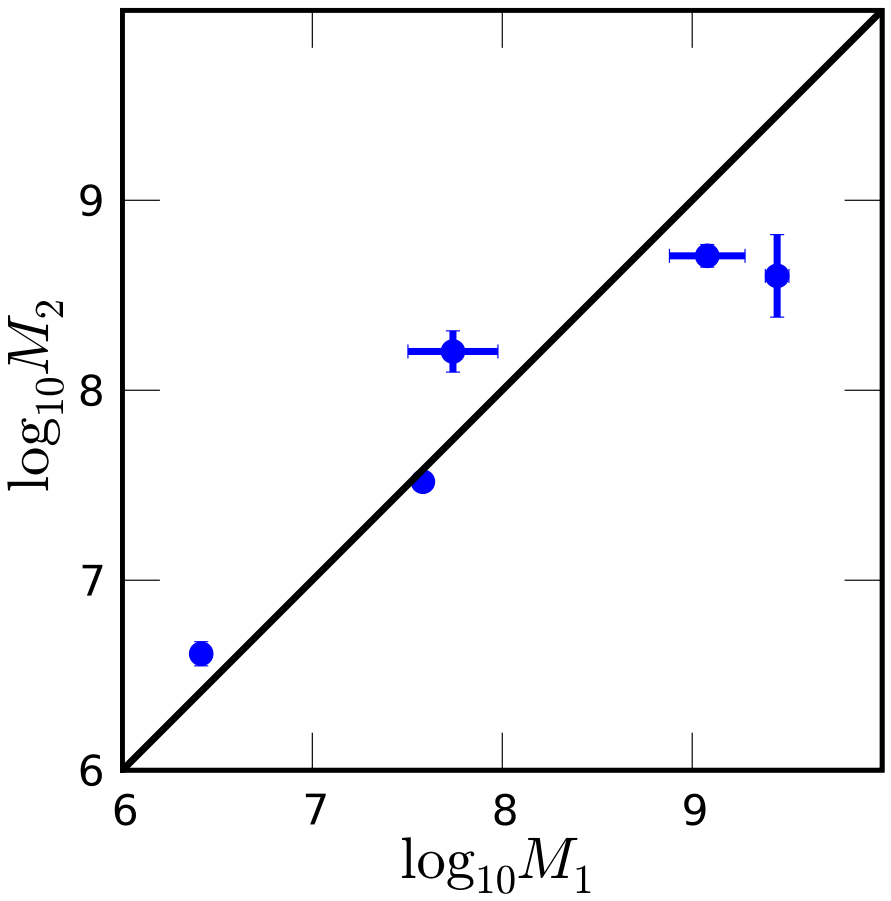


- Use green curve as reference for L versus σ relations.
- Compare dashed vs solid red curves for ϵ_0.

Dirty laundry

Sanity checks

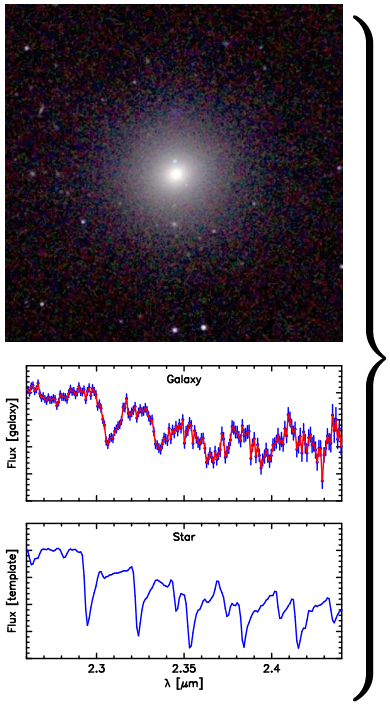
Galaxies with two or more independent measurements of $M_\bullet$:



Errorbars underestimated?

What's going wrong?
(Magorrian 2006, Houghton et al 2006, in prep)

Most $M_\bullet$ come from stellar dynamics:



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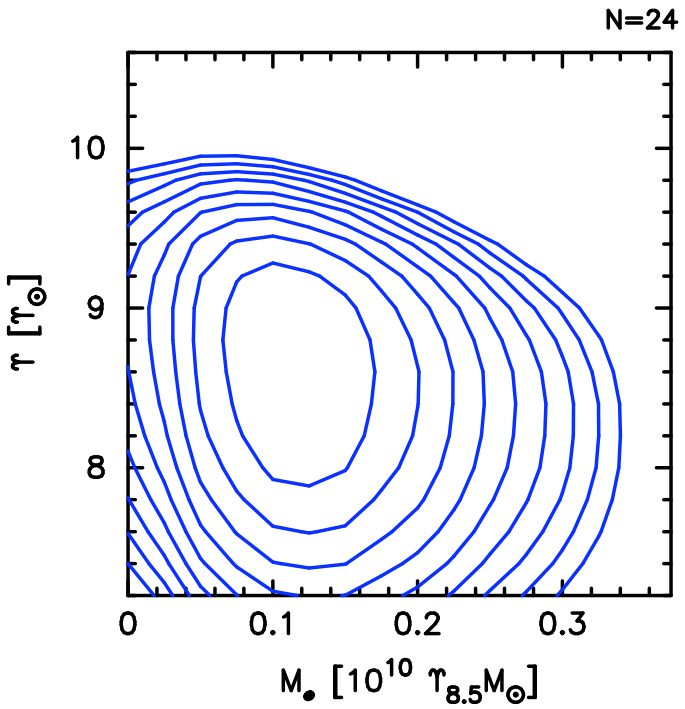

Pitfalls

- Template mismatch, continuum subtraction, ...
- Assumptions in modelling (symmetry, OS method...)
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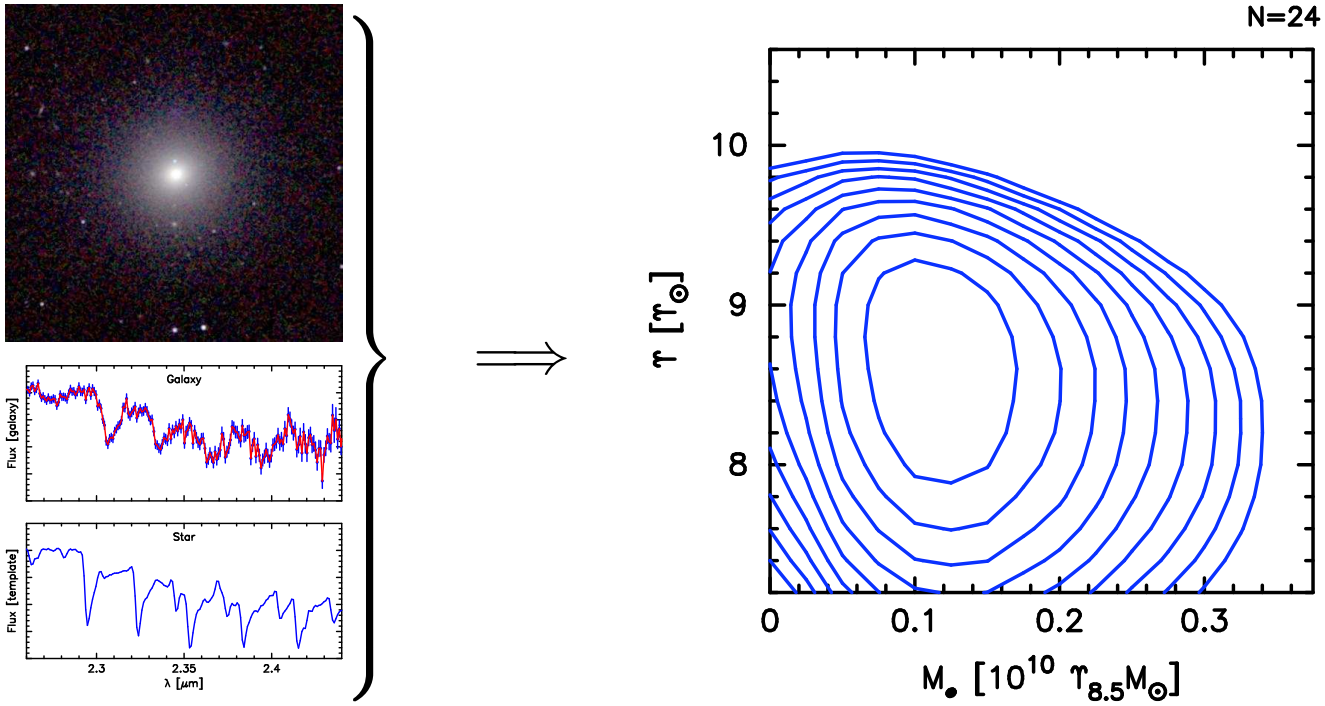

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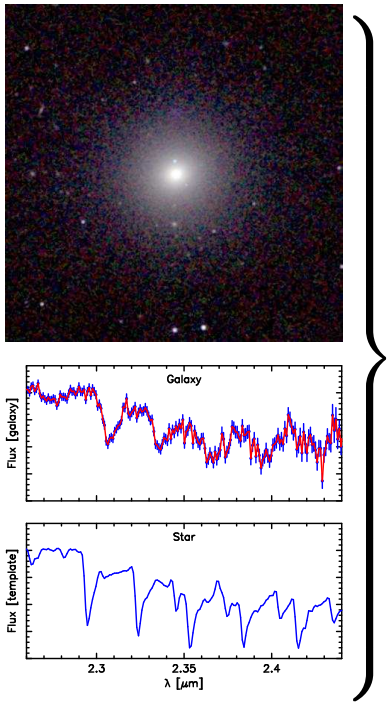

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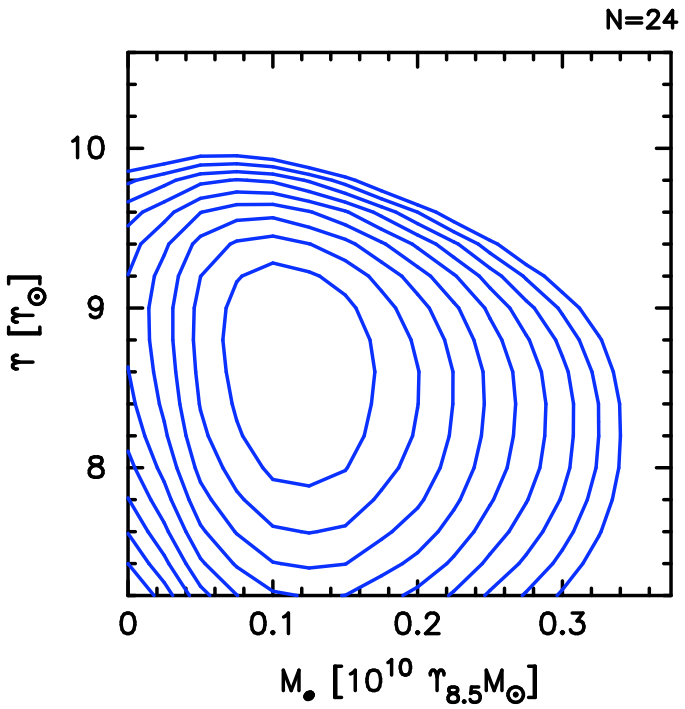

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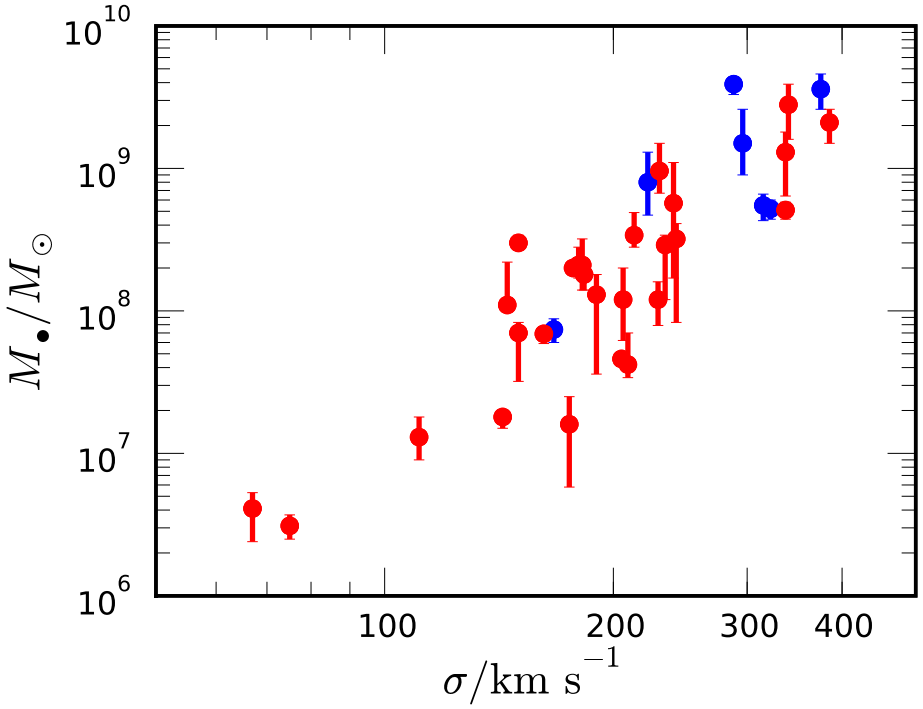
Gas has a different set of problems.
Measurements of $M_\bullet$ from gas versus stars:



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

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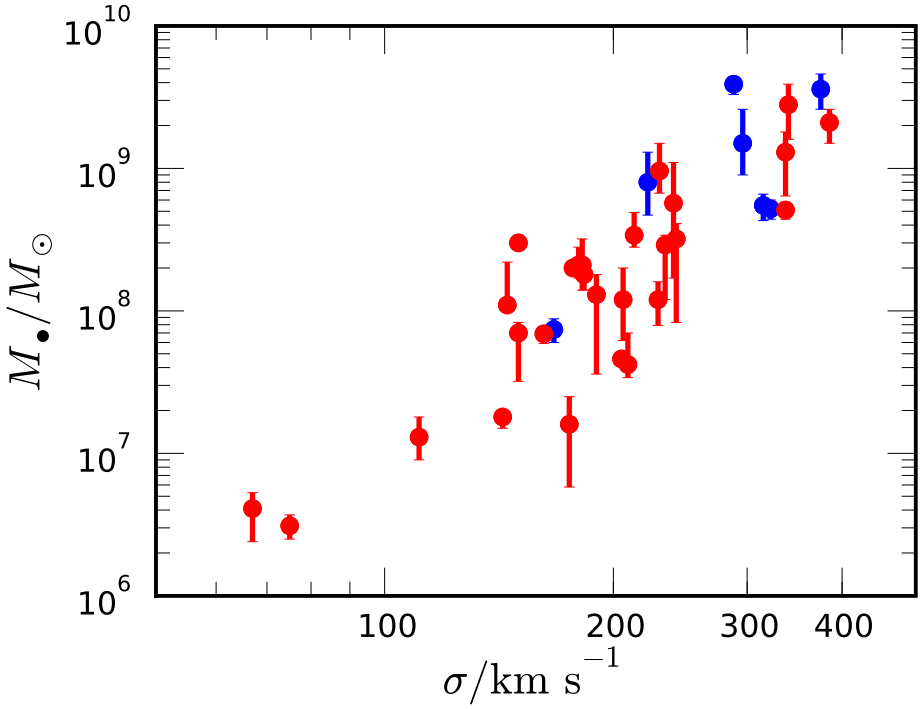

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Things to look forward to

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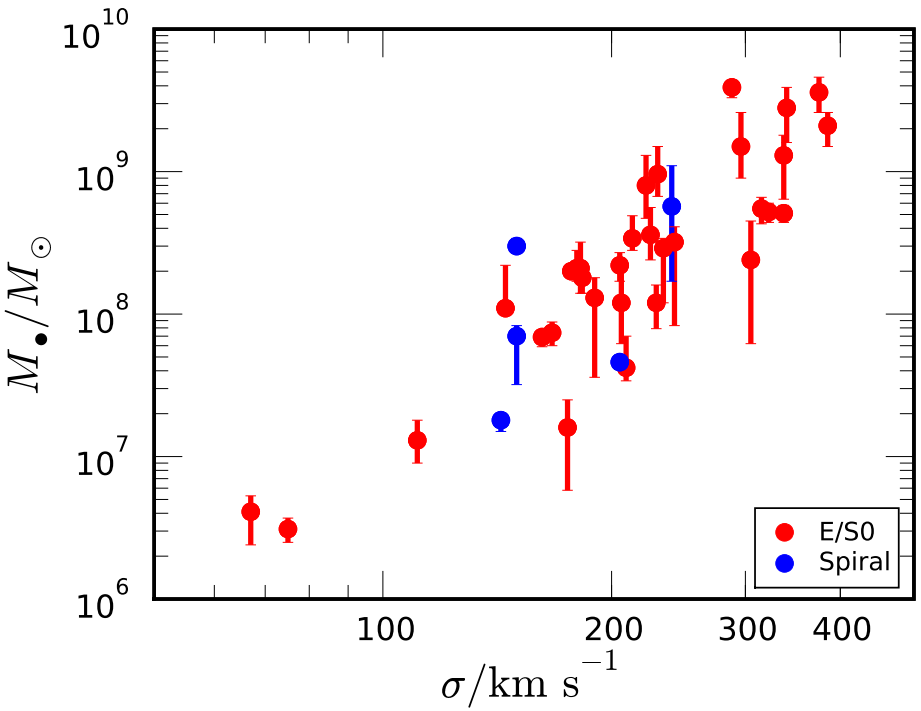

Present sample is deficient in spirals.

Would like to have more giant Es.

2.2m HST (optical) → 8m VLT (NIR).

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

Already underway! (NGC 1399 + Cen A + following talk)

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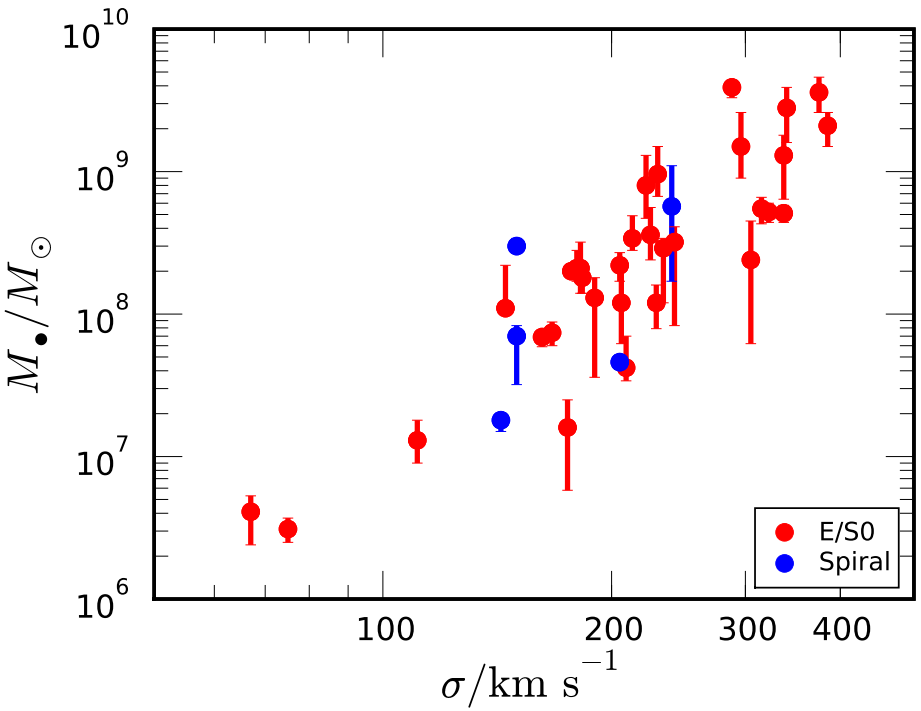

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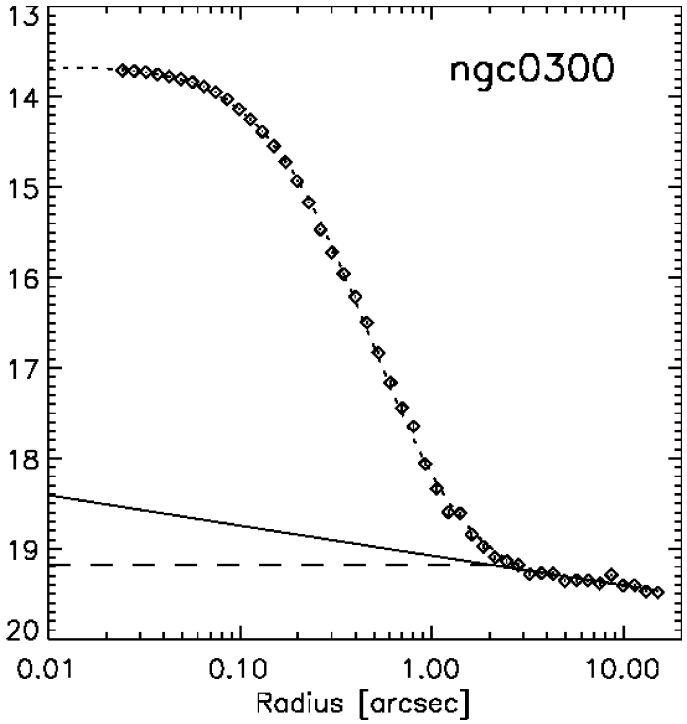
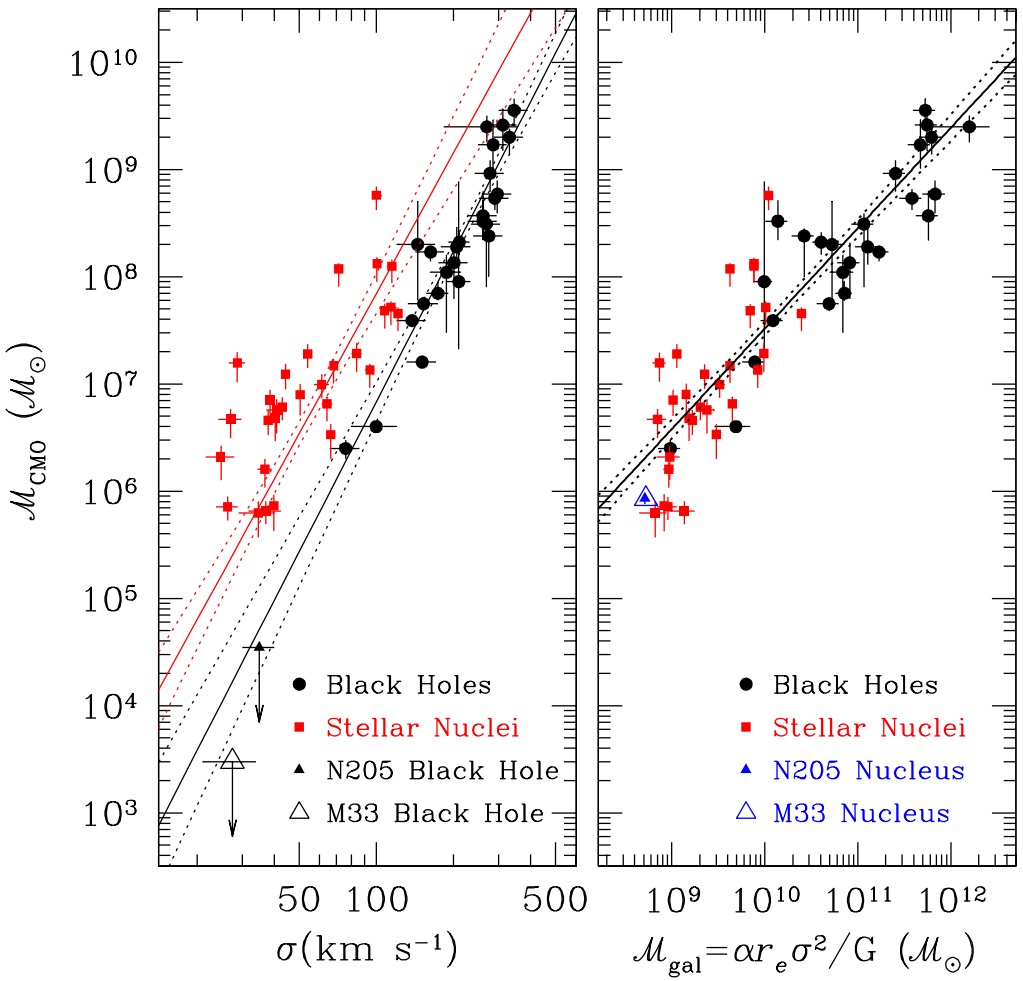
Future: 2 – Nuclear star clusters
(e.g., van der Marel et al. 2007)



$> \frac{1}{2}$ 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.)

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- Detections of $M_\bullet$ in ~ 50 galaxies
  - mostly big, bright, early-type
- Many more upper bounds
  - mostly late-type S
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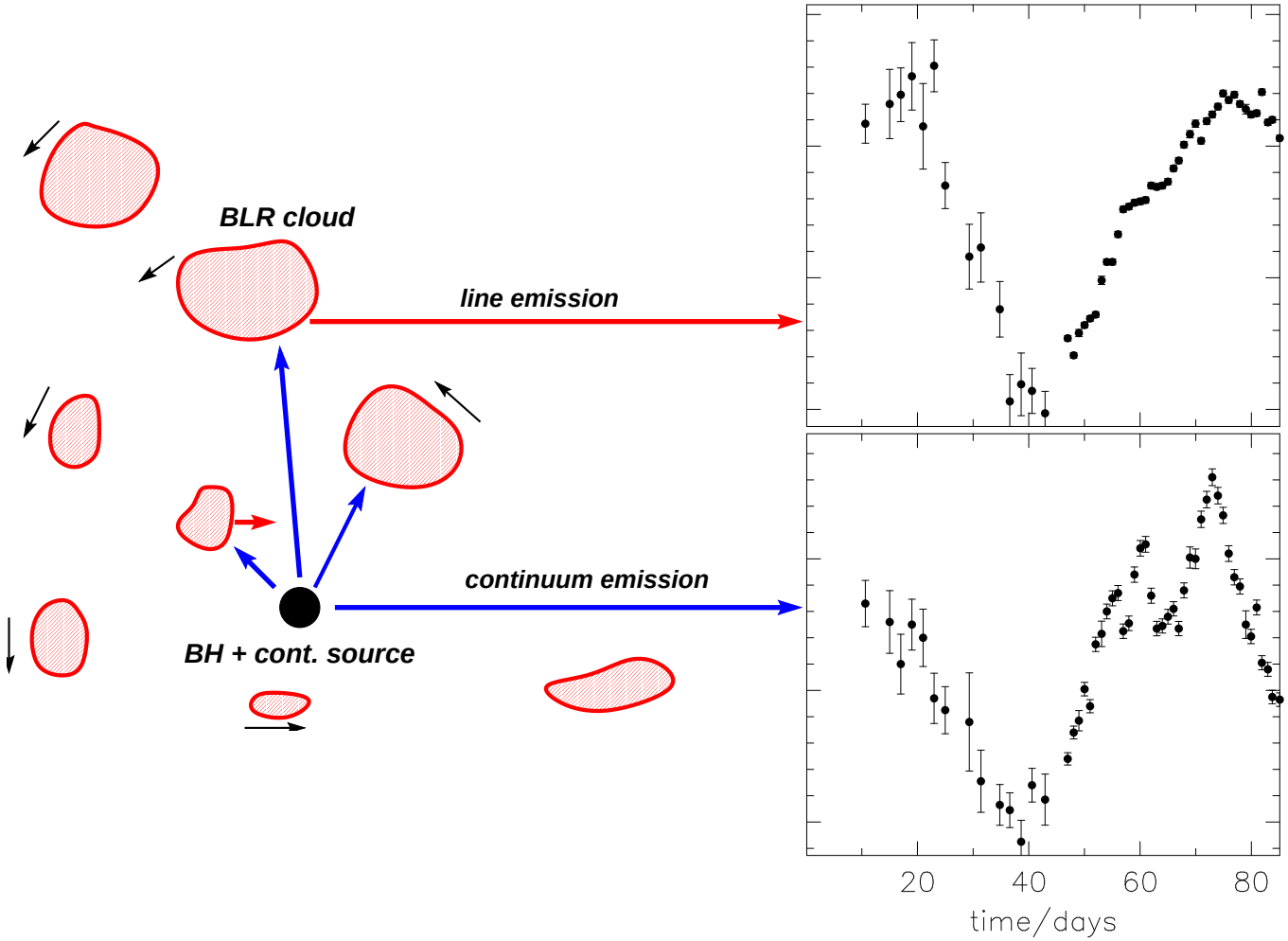
$M_\bullet$ from reverberation mapping?



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For each ion,

$$\mathcal{L}(v,t) = \int \Psi(v,\tau)\mathcal{C}(t-\tau)\,\mathrm{d}\tau, \qquad (\star)$$

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,

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

with fudge factor $f \sim 1$.

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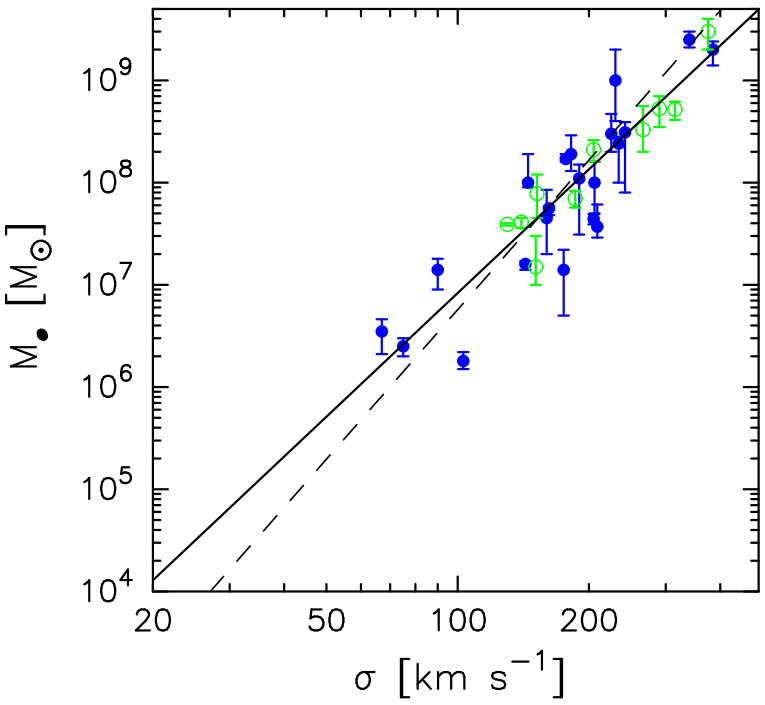

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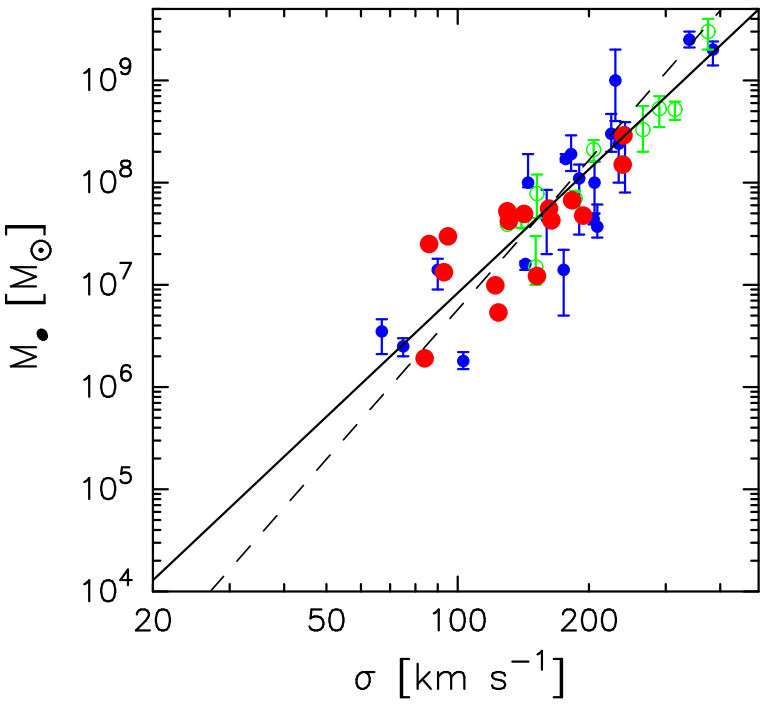
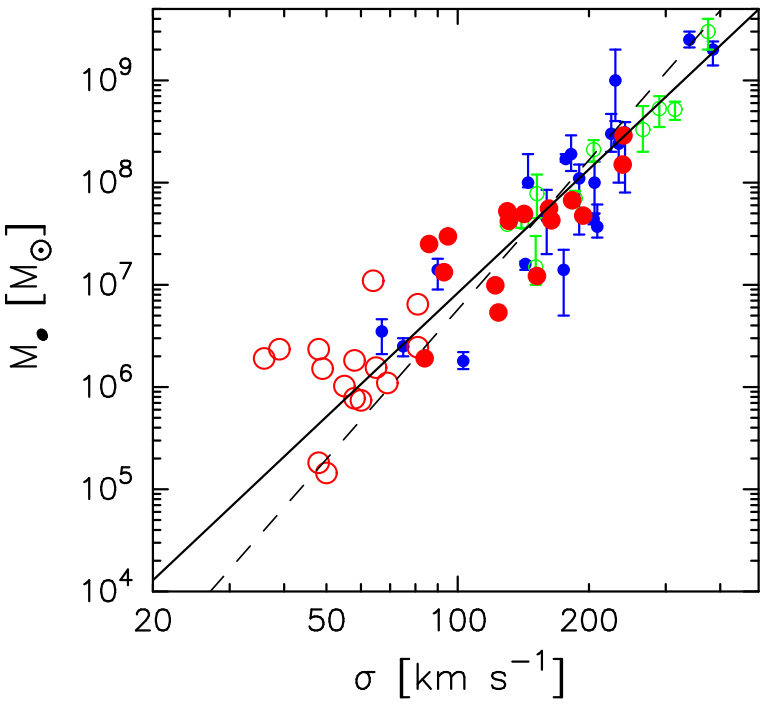


Active galaxies: $M = f\frac{rv^2}{G}$,
with r from reverberation mapping (Onken et al.)

Leaps of faith

BH masses estimates for AGN:



Active galaxies: $M = f\frac{rv^2}{G}$,

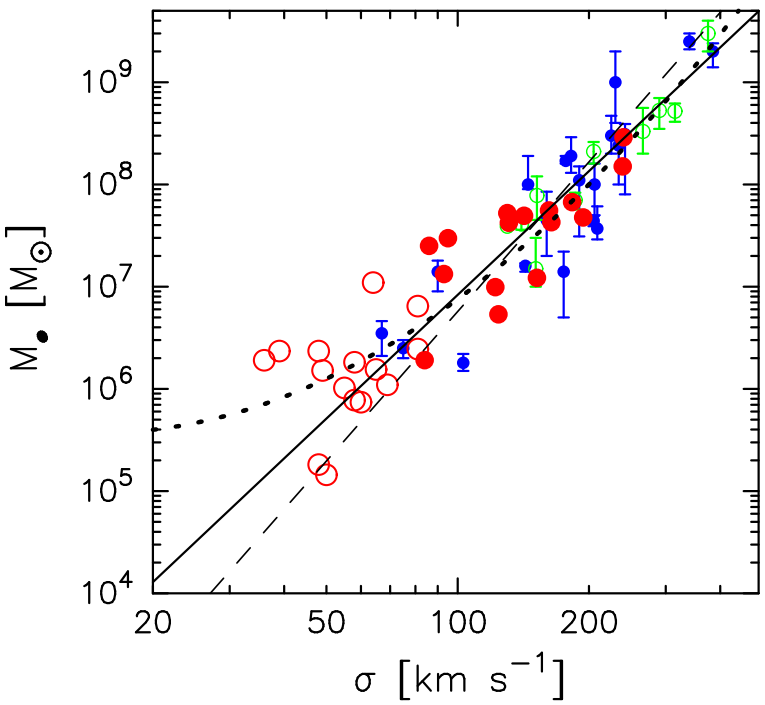
with r from reverberation mapping (Onken et al.)

or using $r = f' L^\lambda$ (Barth, Greene, Ho)

Becomes shallower at low masses?

Leaps of faith

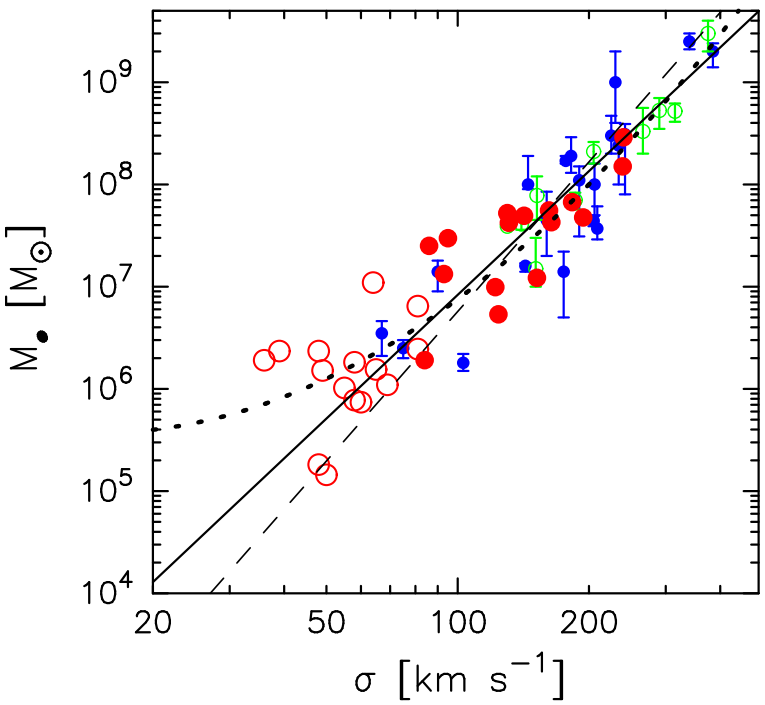
BH masses estimates for AGN:



Wyithe's log-quadratic fit to *direct* $M_\bullet$

Leaps of faith

BH masses estimates for AGN:



Wyithe's log-quadratic fit to *direct* $M_\bullet$

Remember: AGN masses are indirect.