Università degli Studi di Firenze

Coevolution of AGN, BHs and their host galaxies: the observational foundations

Beijing international summer school

"The physics and evolution of AGN"

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Outline of lectures

- Part 1: *Supermassive black holes in galactic nuclei: detections and mass measurements* (2 lectures)
- Part 2: *Scaling relations between black holes and their host galaxies* (2 lectures)
- Part 3: *The cosmological evolution of AGN and BHs* (2 lectures)
- Part 4: *The observational signatures of coevolution* (2 lectures)

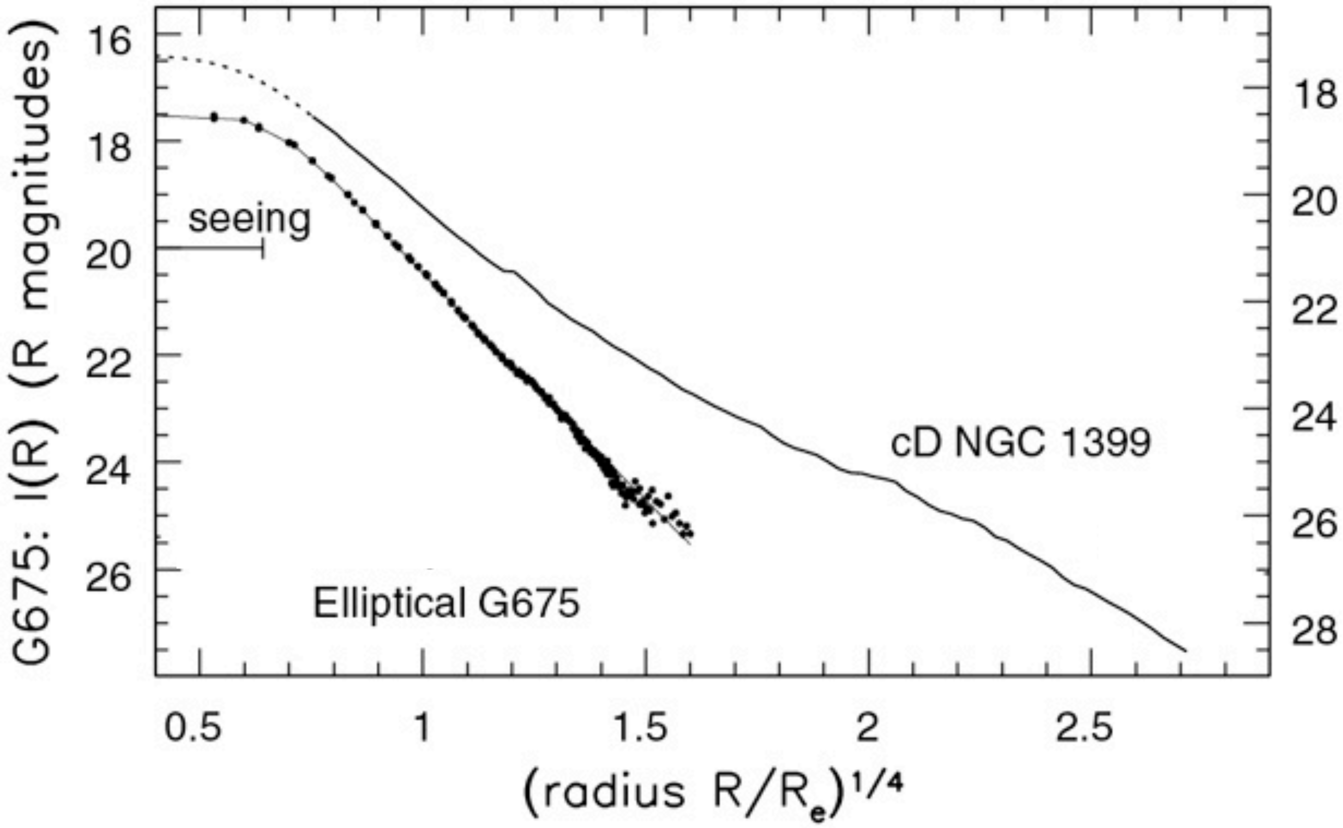
Università degli Studi di Firenze

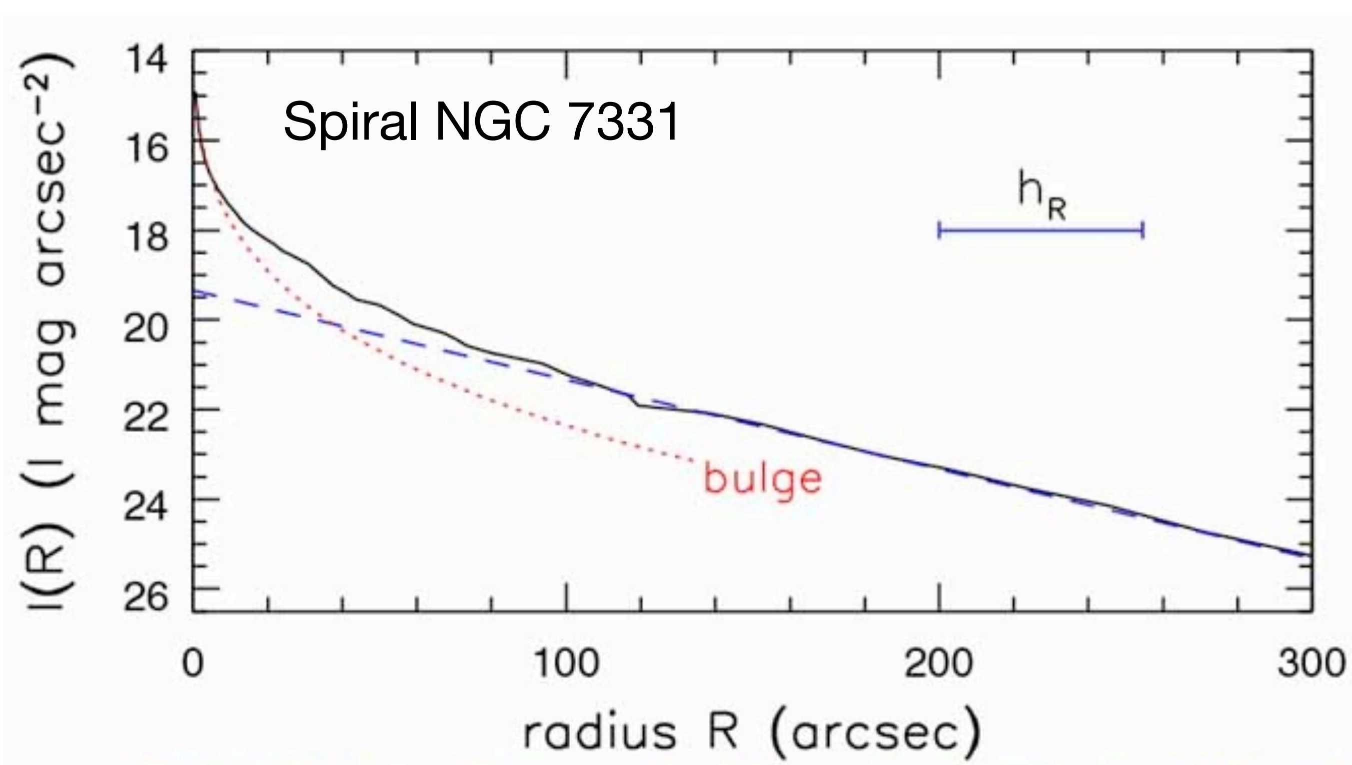
Dipartimento di Fisica e Astronomia
Sezione di Astronomia
Università di Firenze

Part 2: scaling *relations between BHs and host galaxies*

Galaxy structural parameters

Surface brightness profiles of galaxies:





Ellipticals

- Sersic profile

$$\Sigma(R) = \Sigma_e \exp\{-b_n[(R/R_e)^{1/n} - 1]\}$$

Spirals

- Bulge: Sersic profile
- Disk: exponential profile

$$\Sigma_b(R) = \Sigma_e \exp\{-b_n[(R/R_e)^{1/n} - 1]\}$$

$$\Sigma_d(R) = \Sigma_0 \exp\{-(R/h_R)\}$$

Spheroids (Ellipticals or bulges)

- Σ_e, R_e, n are "structural parameters"
- σ_e (L weighted velocity dispersion with R_e), L_e (L within R_e) are another structural parameter

The Fundamental Plane

There exist several relations among scaling parameters like

- ⭐ R_e - Σ_e Kormendy relation
- ⭐ σ_e - L_e Faber-Jackson relation

These relations are just the projection of a 3-variate relation which is called the Fundamental plane of elliptical galaxies (spheroids)

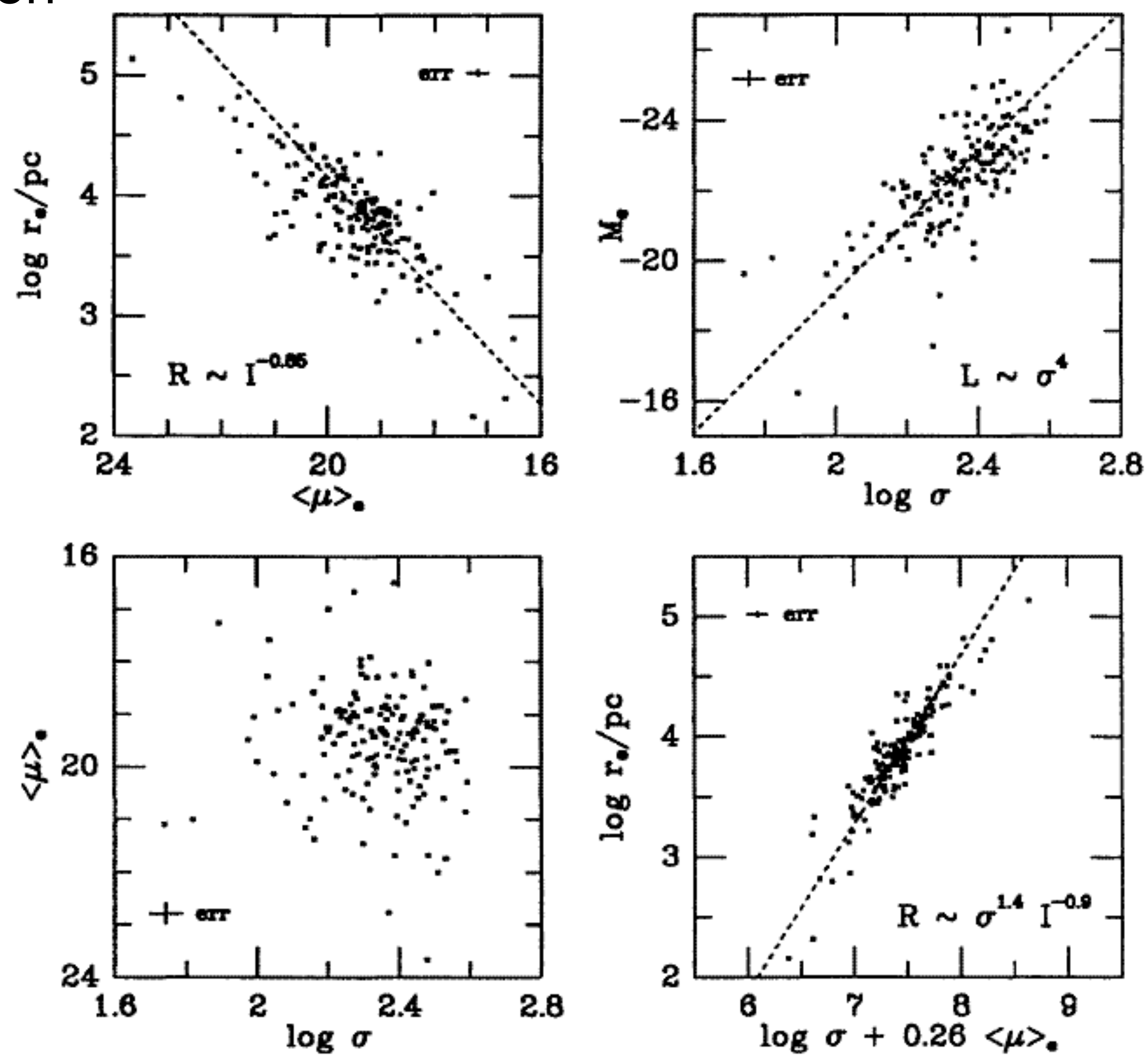
- ⭐ $\log R_e = \alpha \log \sigma_e + \beta \log \Sigma_e$

this is a “plane” in the log space of R_e σ_e Σ_e

Equivalent to

- ⭐ $R_e \sim \sigma_e^{1.4} \Sigma_e^{-0.9}$

Other relations are projection of fundamental plane and have thus larger dispersion



The Fundamental Plane

⭐ $R_e \propto \sigma_e^{1.4} \Sigma_e^{-0.85}$ What is its physical meaning?

Assume spheroids are an homologous family (i.e. same structure):

Virial theorem: $V^2 = G\, M/R_g$

Mass/Light Ratio: $M/L = Y$

Observed quantities are:

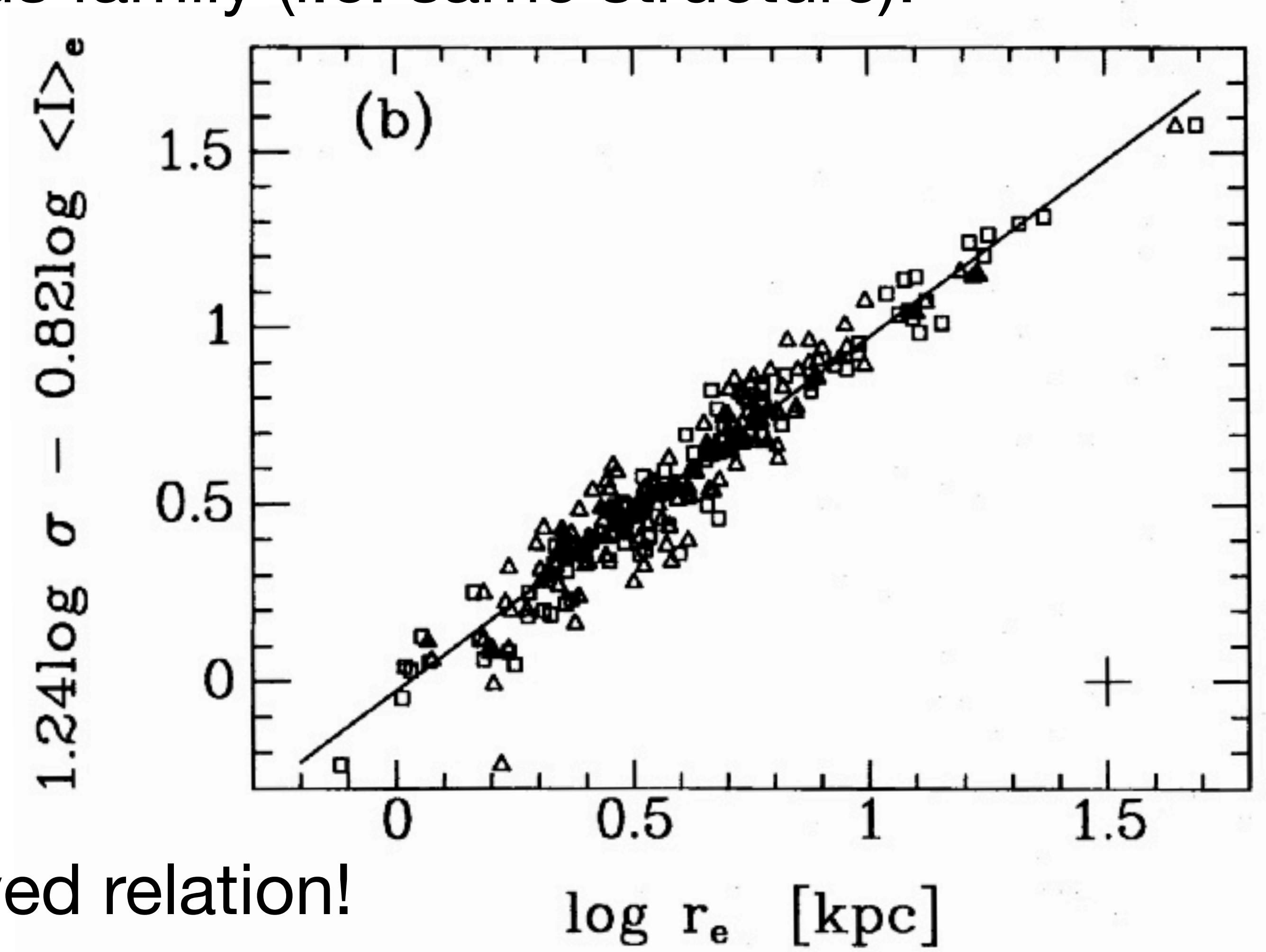
$R_e = k_r\, R_g$

$\sigma^2 = k_v\, V^2$

$\Sigma_e = L/2\ \ (\pi\, R_e^2)^{-1}$

substituting in virial theorem

$R_e = (2\pi\, G\, k_r k_v\, Y\,)^{-1}\, \sigma^2\, \mu_e^{-1}$



⭐ $R_e \propto \sigma_e^2\, \Sigma_e^{-1}$ different from observed relation!

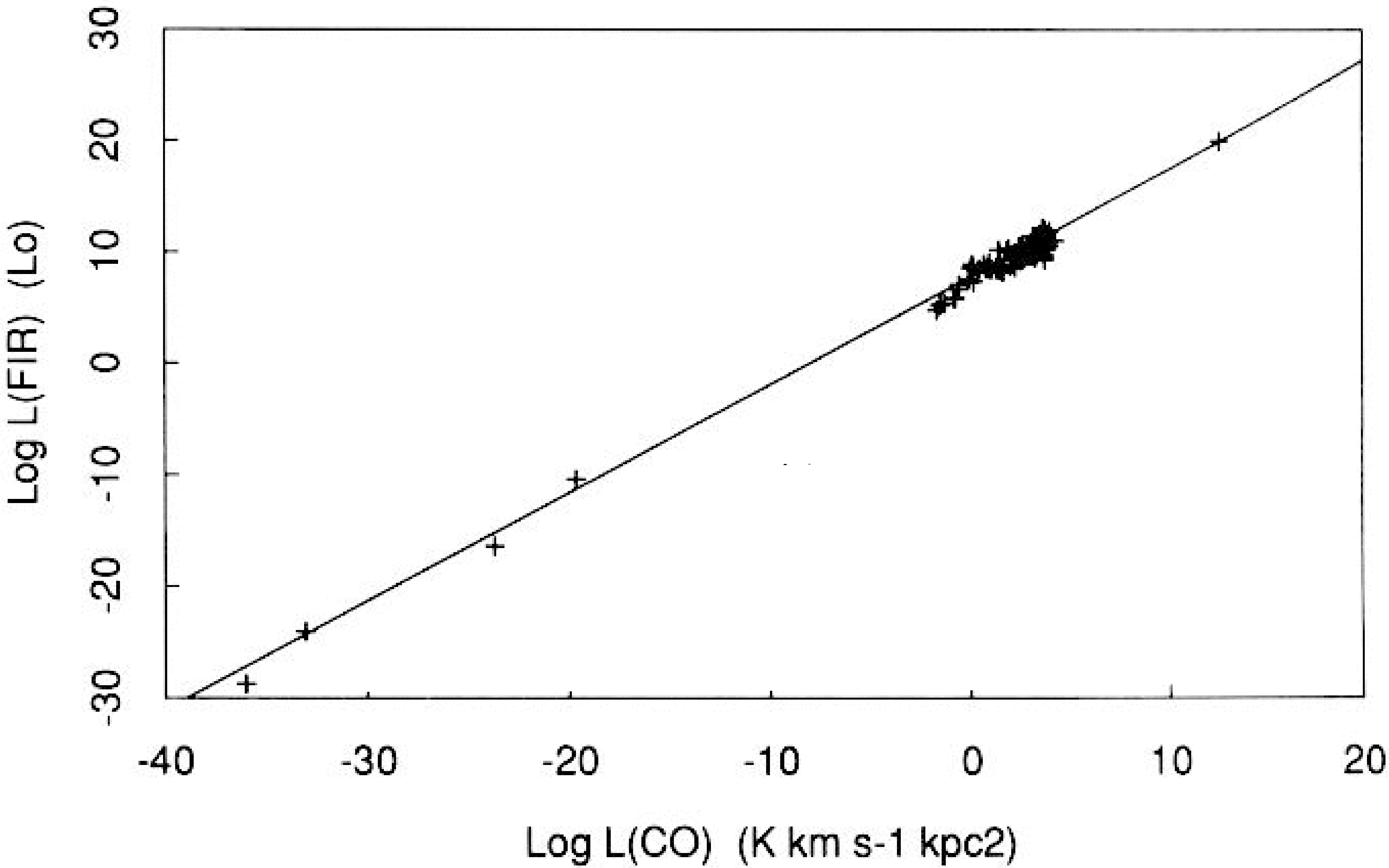
It is then trivial to show that fundamental plane corresponds to

⭐ $R_e \propto \sigma_e^{1.4} \Sigma_e^{-0.85}$ → → $M/L \propto L^{0.2}$

That is M/L depends weakly on luminosity (older and more metal rich stellar populations in more luminous ellipticals).

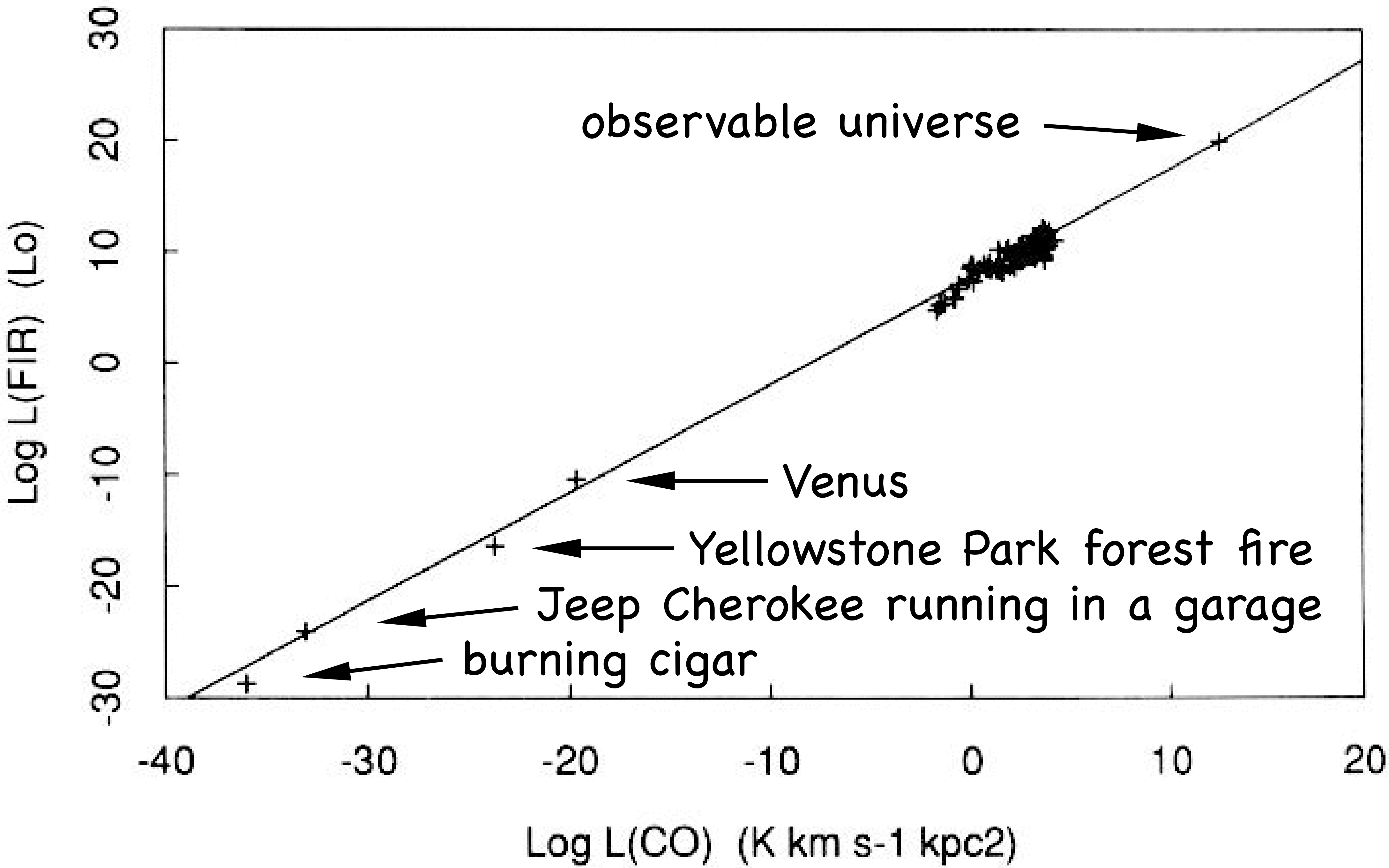
Dependence on $L^{0.2}$ is the "tilt" of the FP with respect to a homologous family (which would have M/L = constant).

Do not abuse of correlations!



Kennicutt 1989

Do not abuse of correlations!

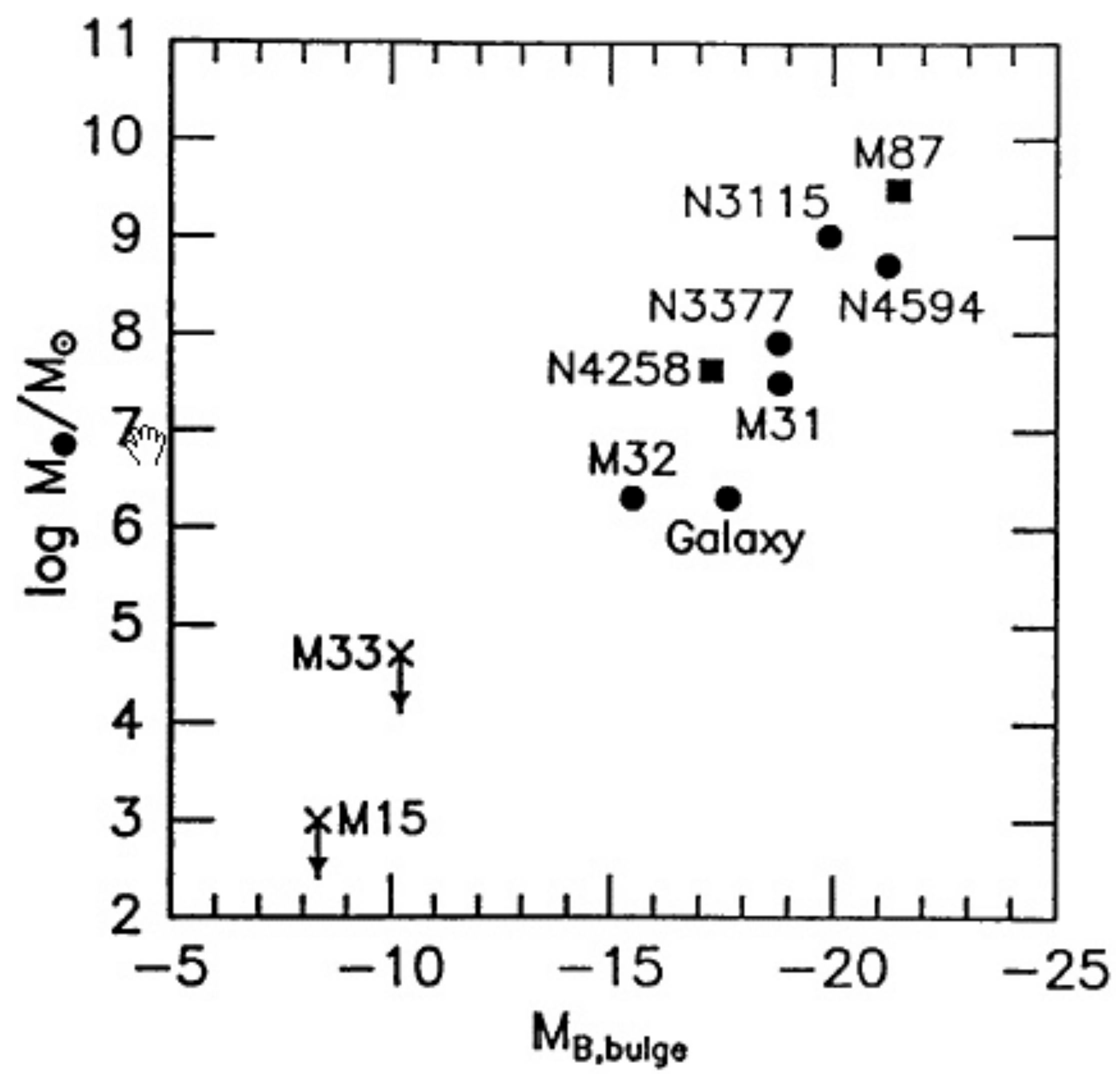


Kennicutt 1989

First hints of BH-galaxy relations

Kormendy & Richstone (1995) suggest the existence of a correlation between the total blue magnitude of the *host spheroid* ($M_{B,bulge}$) and M_{BH}.

- ⭐ bulge (spheroid) = entire galaxy in case of an elliptical



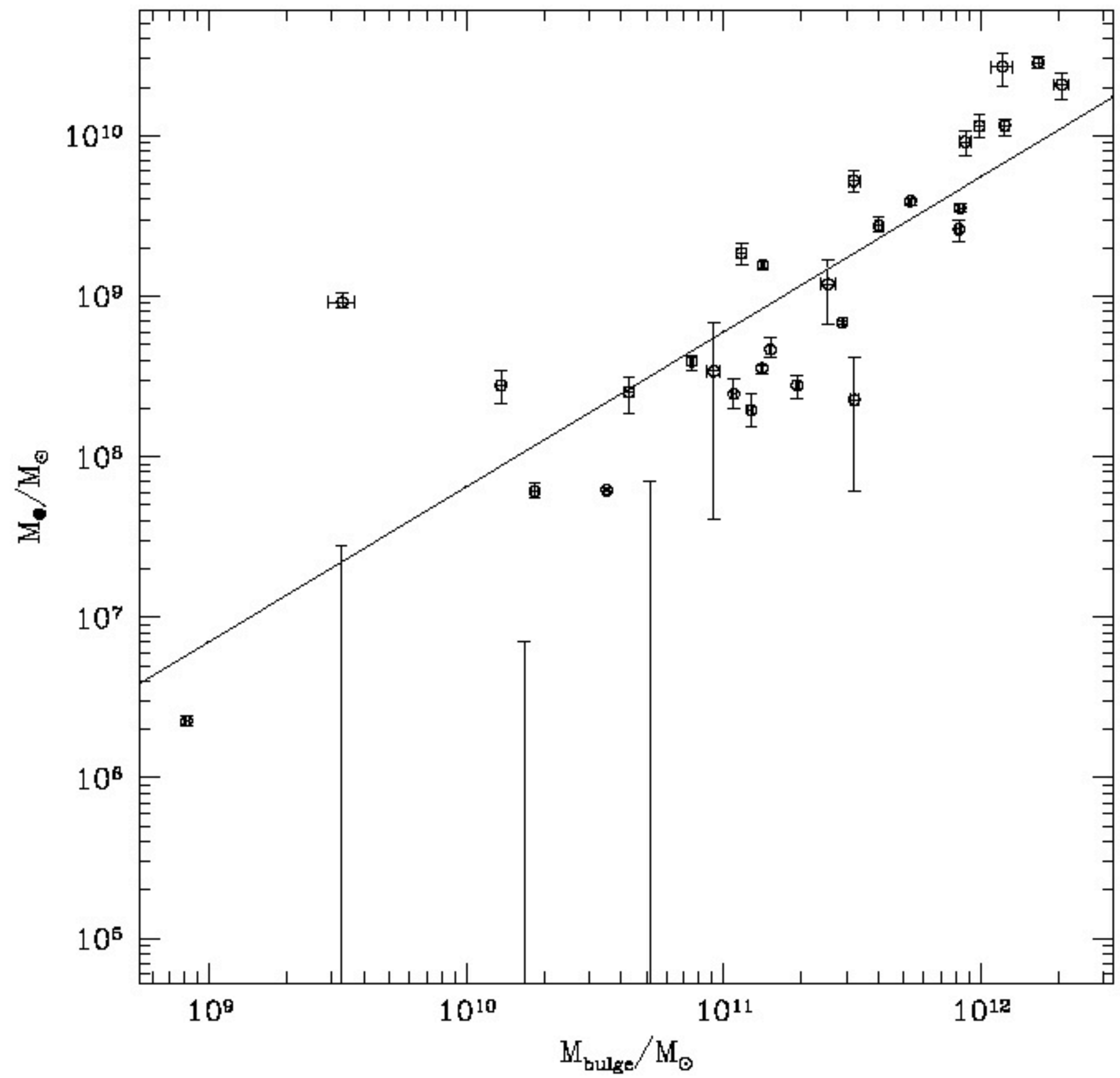
Kormendy & Richstone 1995

More evidence ...

Magorrian at al. (1998) find a correlation between M_{BH} and *bulge* masses ("Magorrian" relation)

- They use mostly low resolution ground based data.
- Use stellar kinematics with axisimmetric 2-I dynamical models.
- They find M_{BH}/M_{bulge}~0.006.

- Most mass estimates have been shown to be much overestimated (use of 2-I models).



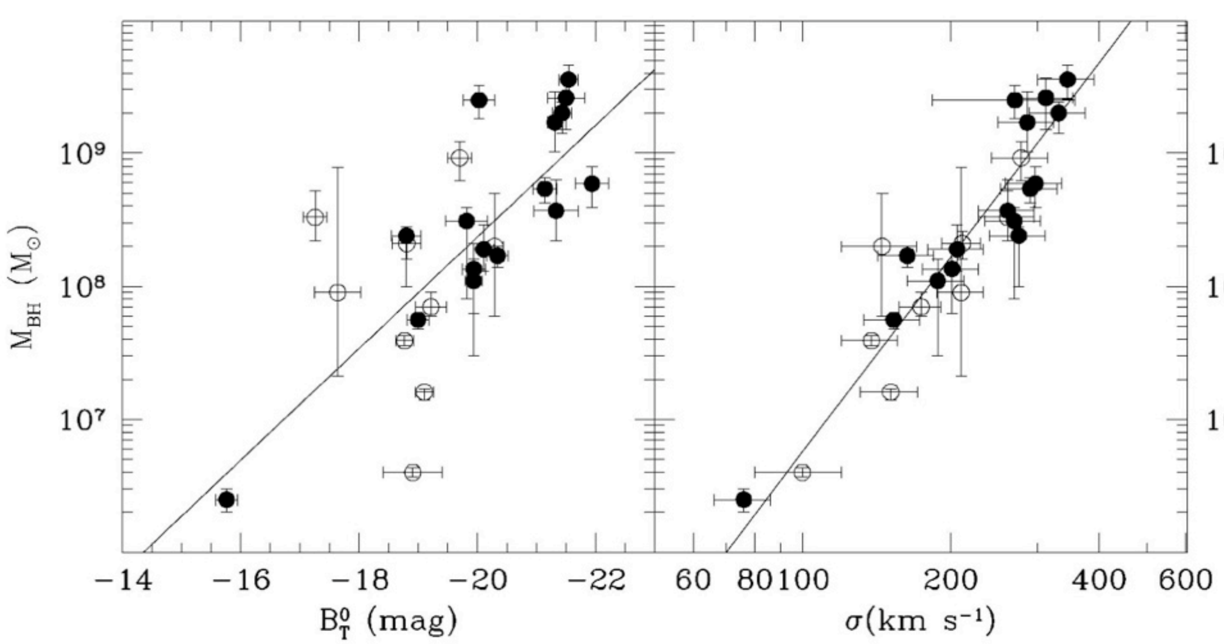
Magorrian at al. 1998

The M_{BH}-σ correlation

Two groups (Ferrarese & Merritt 2000, Gebhardt et al. 2000) independently find a tight relation between M_{BH} and the velocity dispersion of the stars in the galaxy bulge σ (within R_e or R_c=R_e/8)

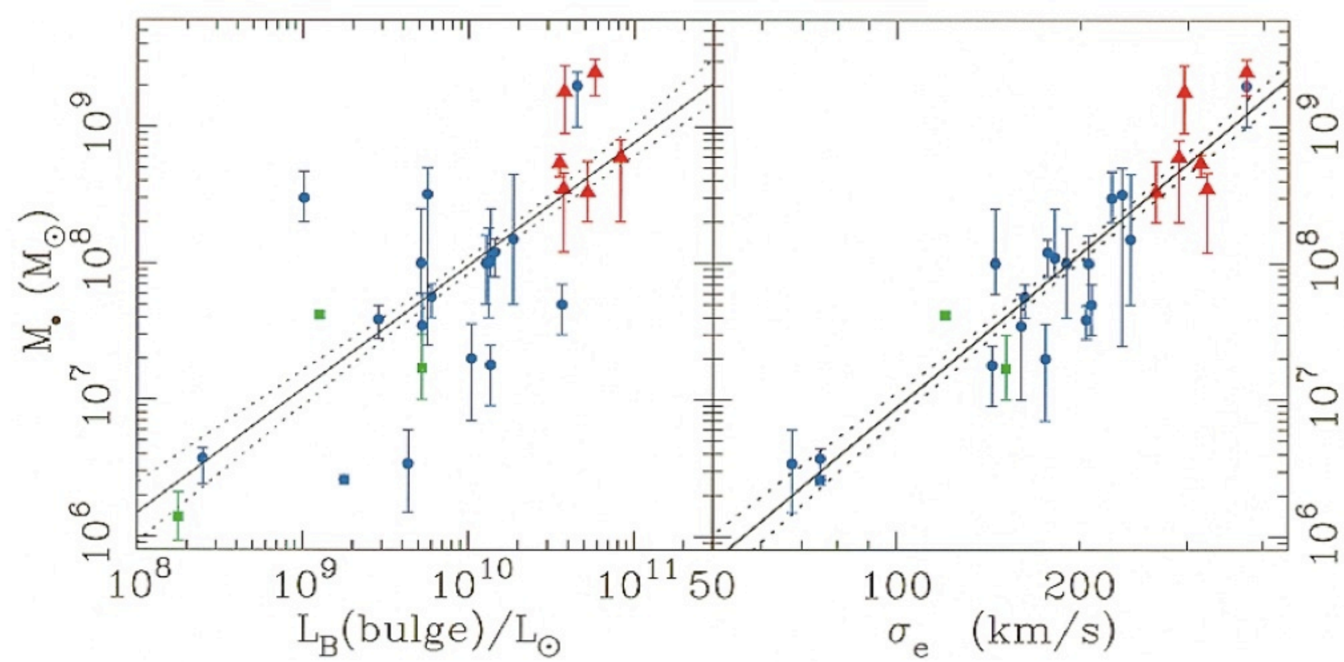
- R_e and R_c much larger than BH sphere of influence, σ should not be affected by BH, only by galaxy grav. potential!
- Big and hot debate about the slope $M_{BH} \sim \sigma^5$ (FM00) and $M_{BH} \sim \sigma^4$ (G00)
- Relation with σ is tighter than relation with B luminosity.

M_{BH}-L_B M_{BH}-σ



Ferrarese & Merritt 2000

M_{BH}-L_B M_{BH}-σ



Gebhardt et al. 2000

What is the meaning of “tight”?

The M_{BH}-σ relation relation is considered the best one because is tighter than the M_{BH}-$M_{B,bulge}$ and M_{BH}-M_{bulge} correlations.

Tightness is related to the intrinsic scatter of M_{BH}-X correlations, i.e. the dispersion in BH masses for given X (eg log σ) beyond measurement errors

- “perfect” relation

$$M = \log M_{\rm BH}$$

$$P(M|V) = \delta(M - a - b\,V)$$

$$V = \log \sigma$$

- with errors on M_{BH} measurement observed scatter is

$$P(M_{obs}|V) = \int P(M_{obs}|M) P(M|V) dM$$

$$P(M_{obs}|V) \frac{1}{\sqrt{2\pi}\sigma_M} \exp\left[-\frac{1}{2}\left(\frac{M_{obs} - a - bV}{\sigma_M}\right)^2\right]$$

Intrinsic scatter

- a possible real (non perfect) relation

$$P(M|V) = \frac{1}{\sqrt{2\pi}\sigma_0}\exp\left[-\frac{1}{2}\left(\frac{M-a-bV}{\sigma_0}\right)^2\right]$$

- observed distribution for given V (σ_M error on M_{obs})

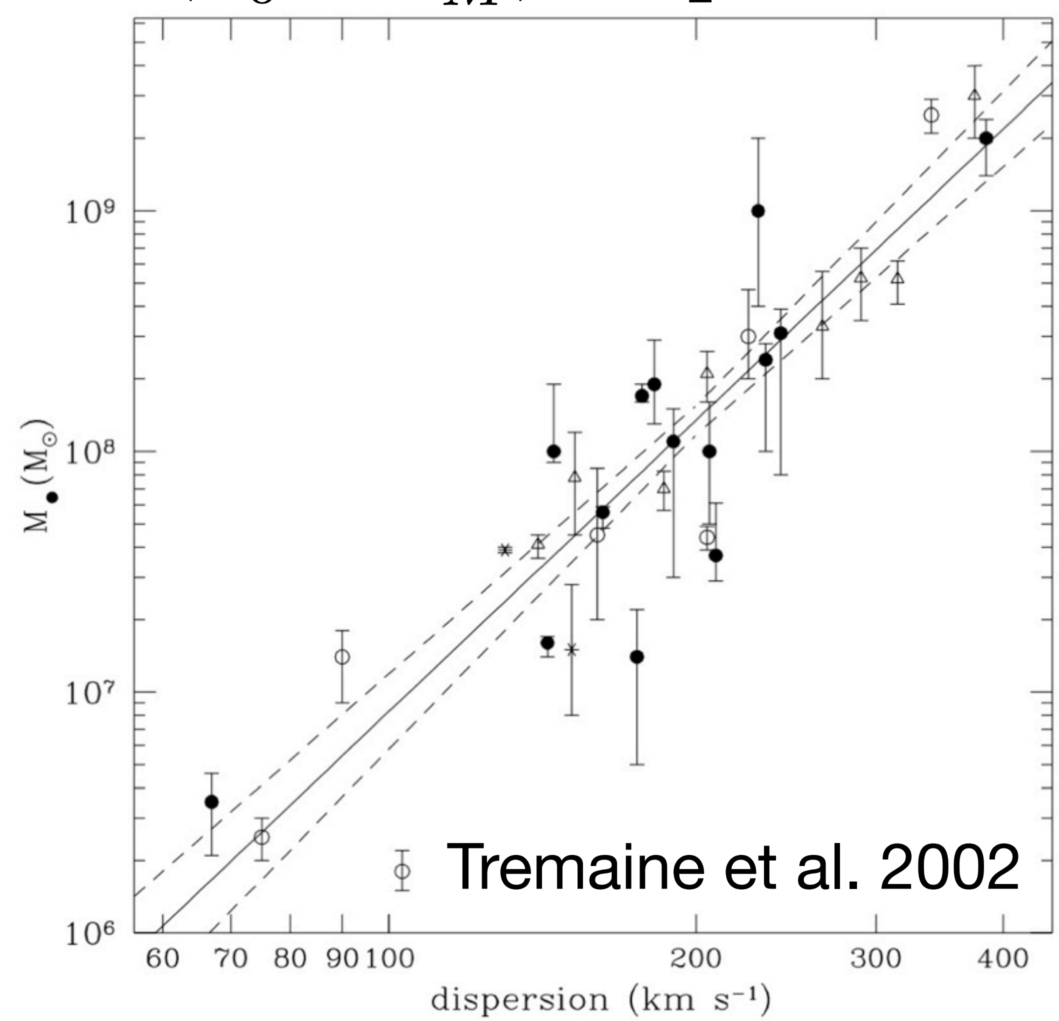
$$P(M_{obs}|V) = \frac{1}{\sqrt{2\pi(\sigma_0^2+\sigma_M^2)}}\exp\left[-\frac{1}{2}\frac{(M_{obs}-a-bV)^2}{(\sigma_0^2+\sigma_M^2)}\right]$$

observed dispersion (scatter, rms of fit residuals) of relation is therefore

$$\sigma_{obs} = \sqrt{\sigma_0^2+\sigma_M^2}$$

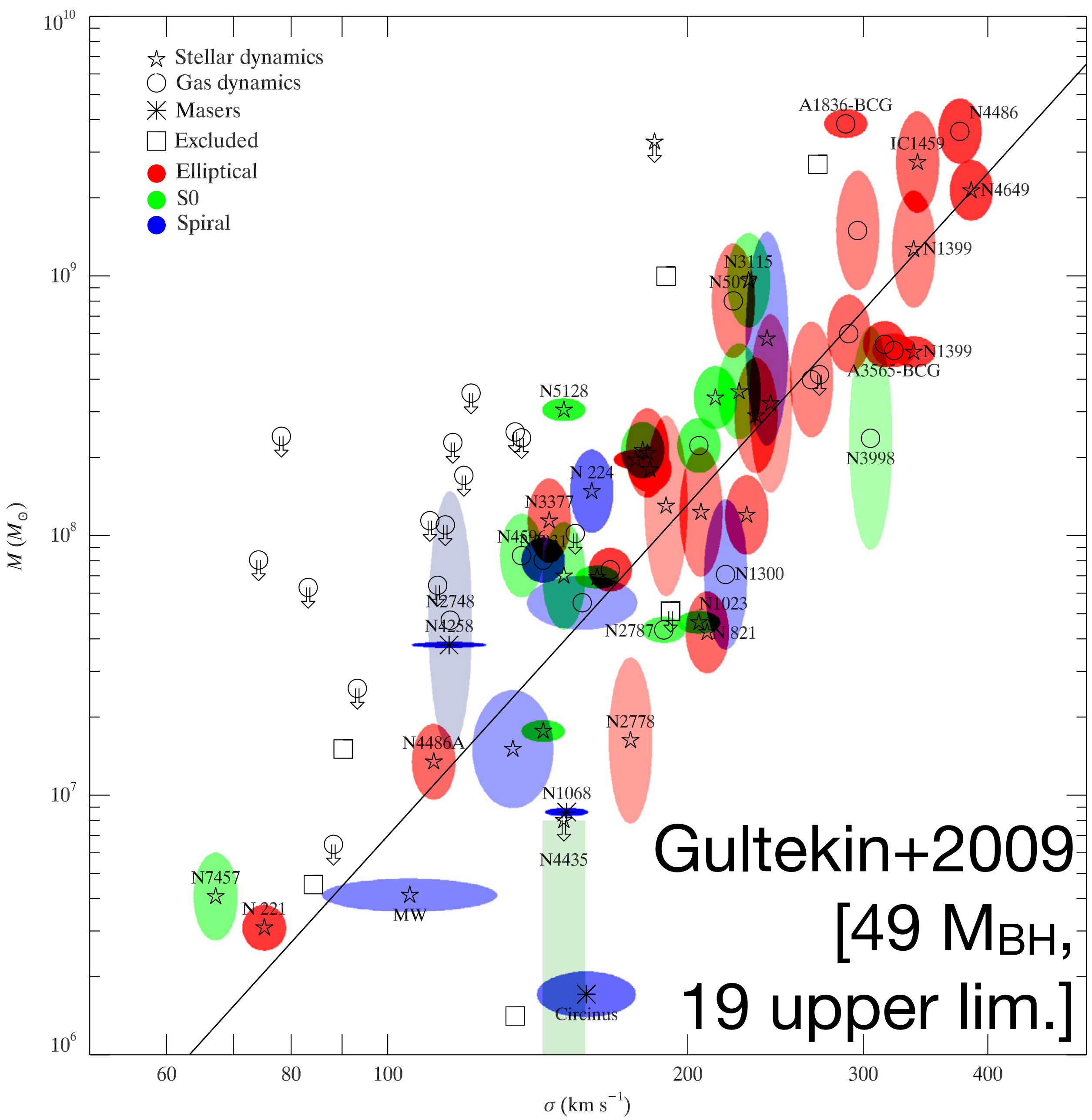
intrinsic scatter of M_{BH}-σ relation is estimated to be ~*0.3-0.4 dex* (factor 2-2.5 dispersion of M_{BH} for given sigma).

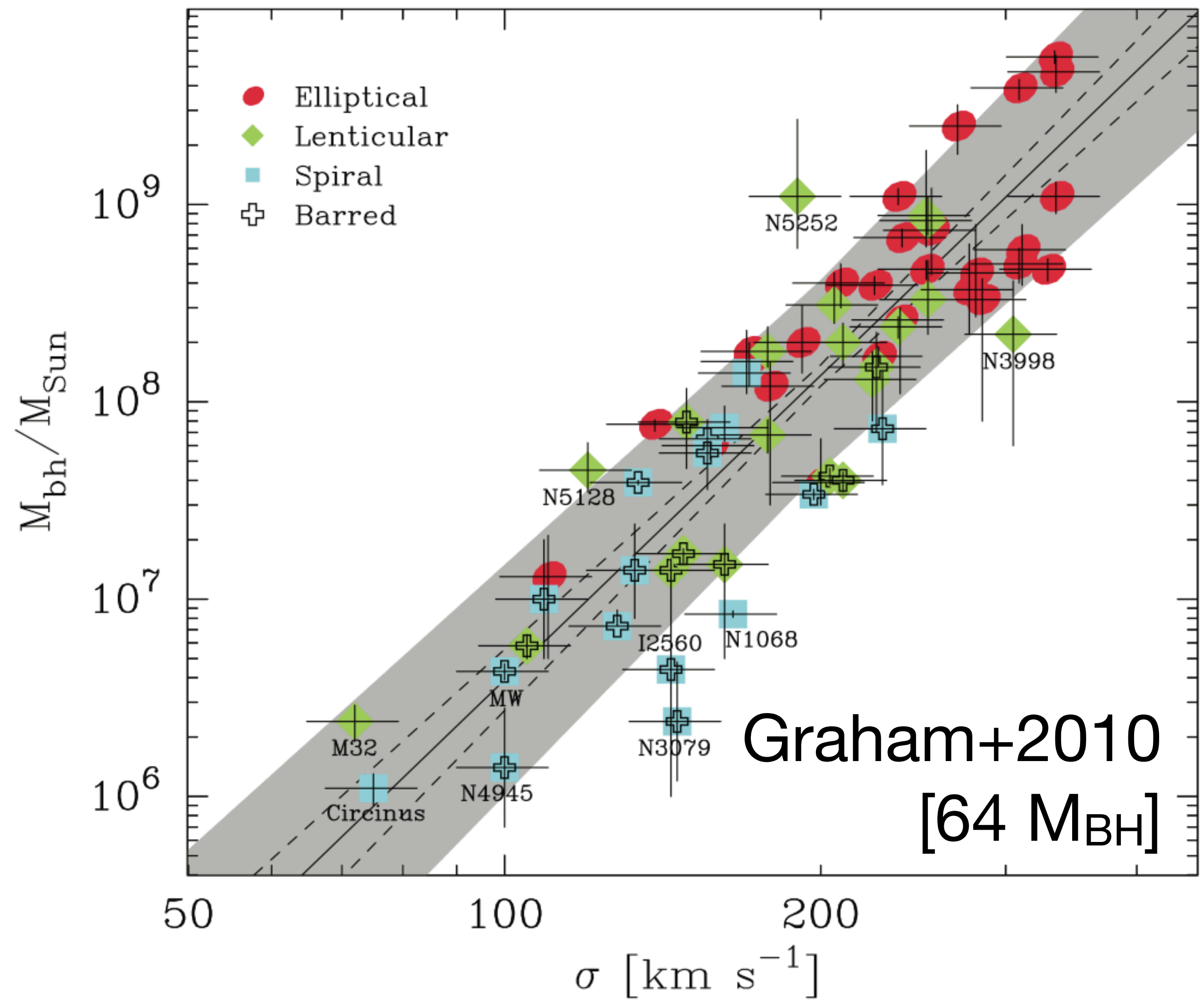
Beware that intrinsic scatter depends critically on the "accuracy" on M_{BH} errors!



M_{BH}-σ

Countless papers in literature, considered two of the most recent ones!





$$\log(M_{\rm BH}/\,{\rm M}_{\odot}) = (8.12 \pm 0.08) + (4.24 \pm 0.41)\log(\sigma/200\,{\rm km\,s^{-1}})$$

$$\sigma_0 = 0.44 \pm 0.06\, dex$$ Gultekin+2009

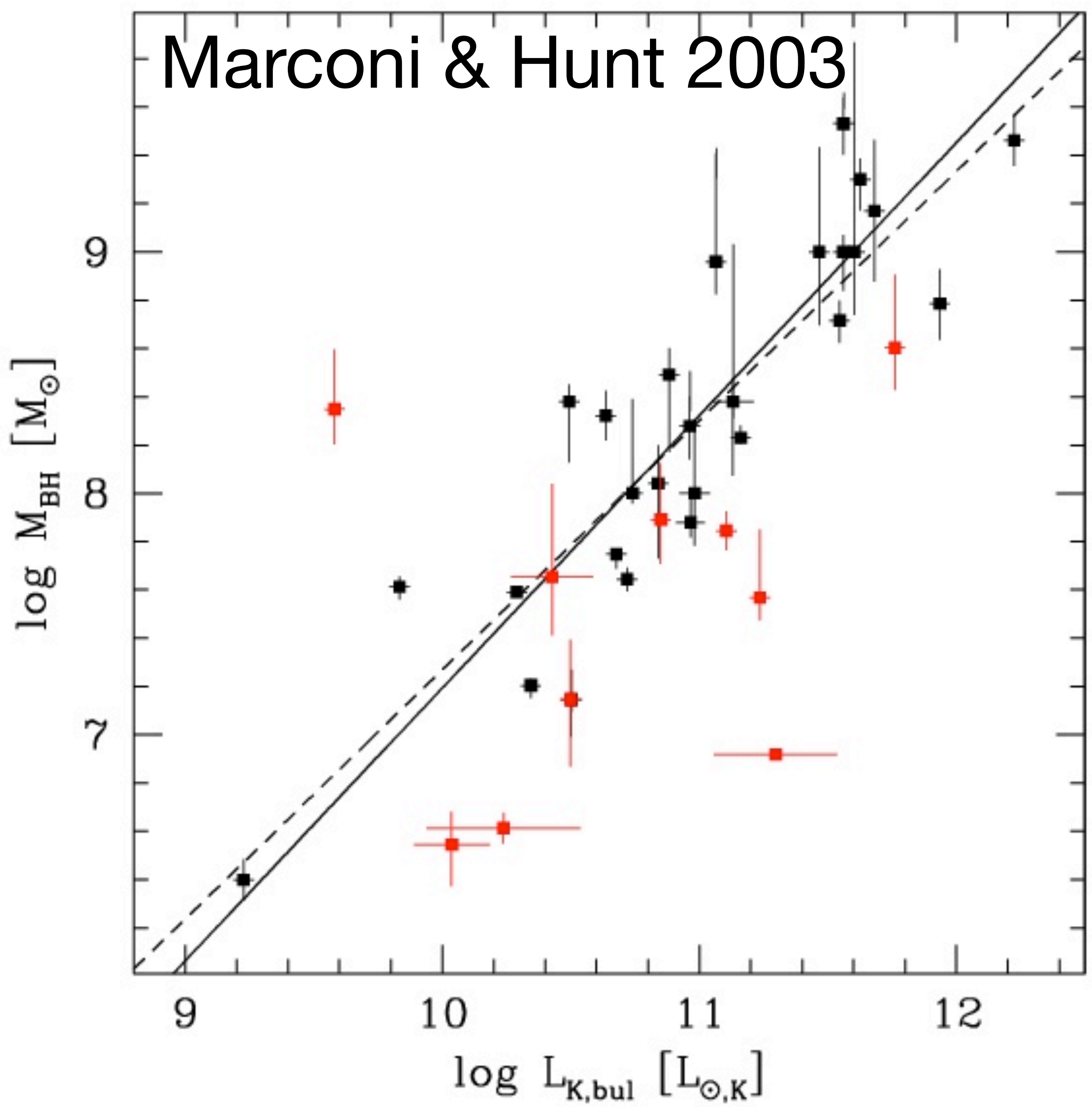
$$\log(M_{\rm BH}/\,{\rm M}_{\odot}) = (8.13 \pm 0.05) + (5.13 \pm 0.34)\log(\sigma/200\,{\rm km\,s^{-1}})$$

$$\sigma_0 = 0.32 \pm 0.05\, dex$$ Graham+2010

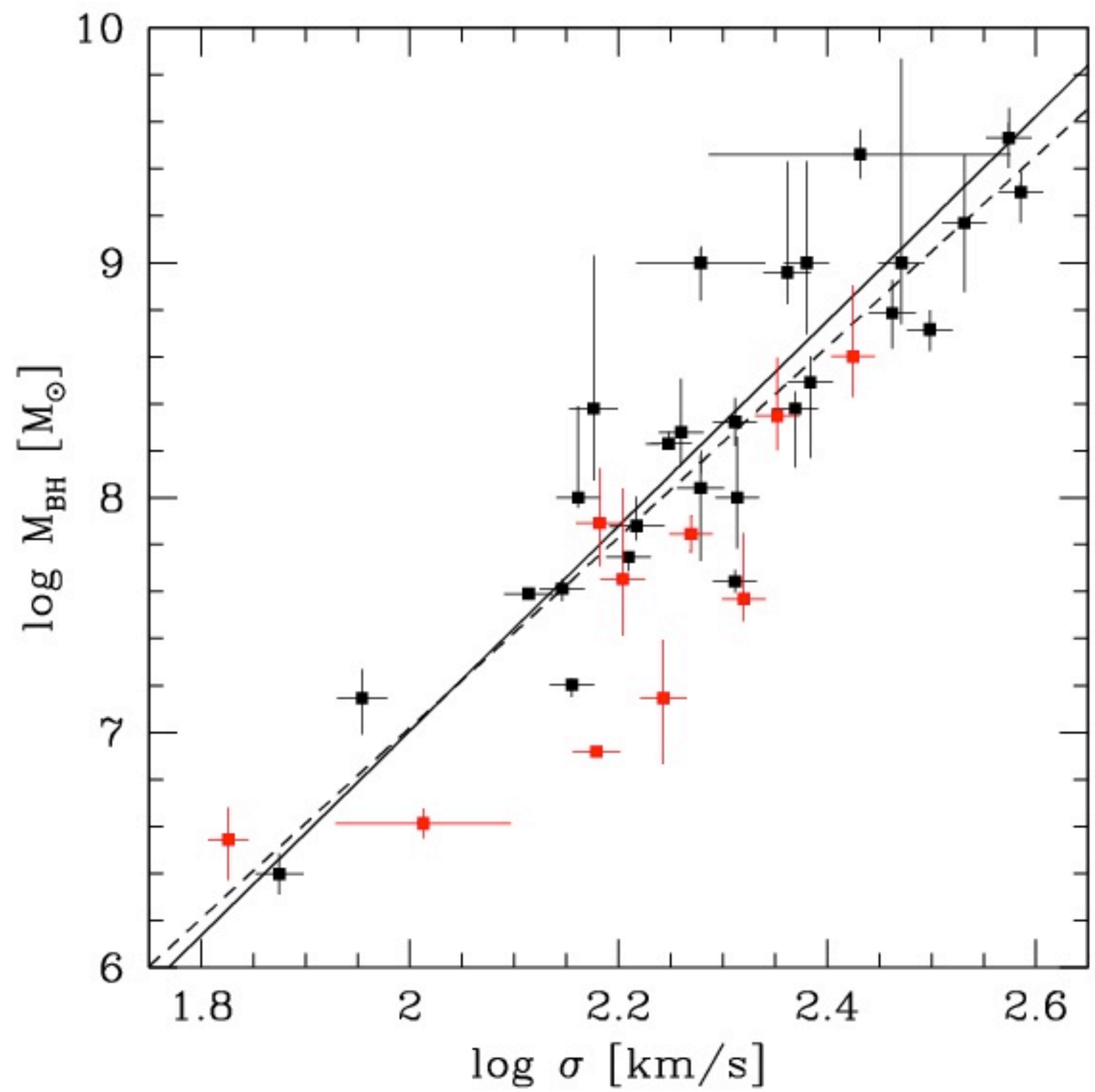
M_{BH}-σ

- Still problems related to sample selection
  (e.g. which BH masses to consider reliable ...)
- adopted fitting methods
  (e.g. how to take into account the intrinsic scatter ...)
- adopted errors in M_{BH} and σ
  - Gultekin takes 5% to σ, Graham takes 10% and this allows steeper slope
  - also smaller error in Gultekin gives larger intrinsic dispersion (0.44 vs 0.32)
- intrinsic scatter increases with increasing samples ... maybe M_{BH}-σ relation is not so tight after all!
- M_{BH}-σ relation with ellipticals only appears to be tighter (i.e. bulges of spiral galaxies define a less tight relation than ellipticals):
  0.31 ± 0.06 vs 0.44 ± 0.06 (Gultekin+09)
  0.27 ± 0.06 vs 0.32 ± 0.06 (Graham+10)

M_{BH} vs Luminosity in the NIR



M_{BH}-$L_{K,bul}$ (rms 0.3 in log M_{BH})

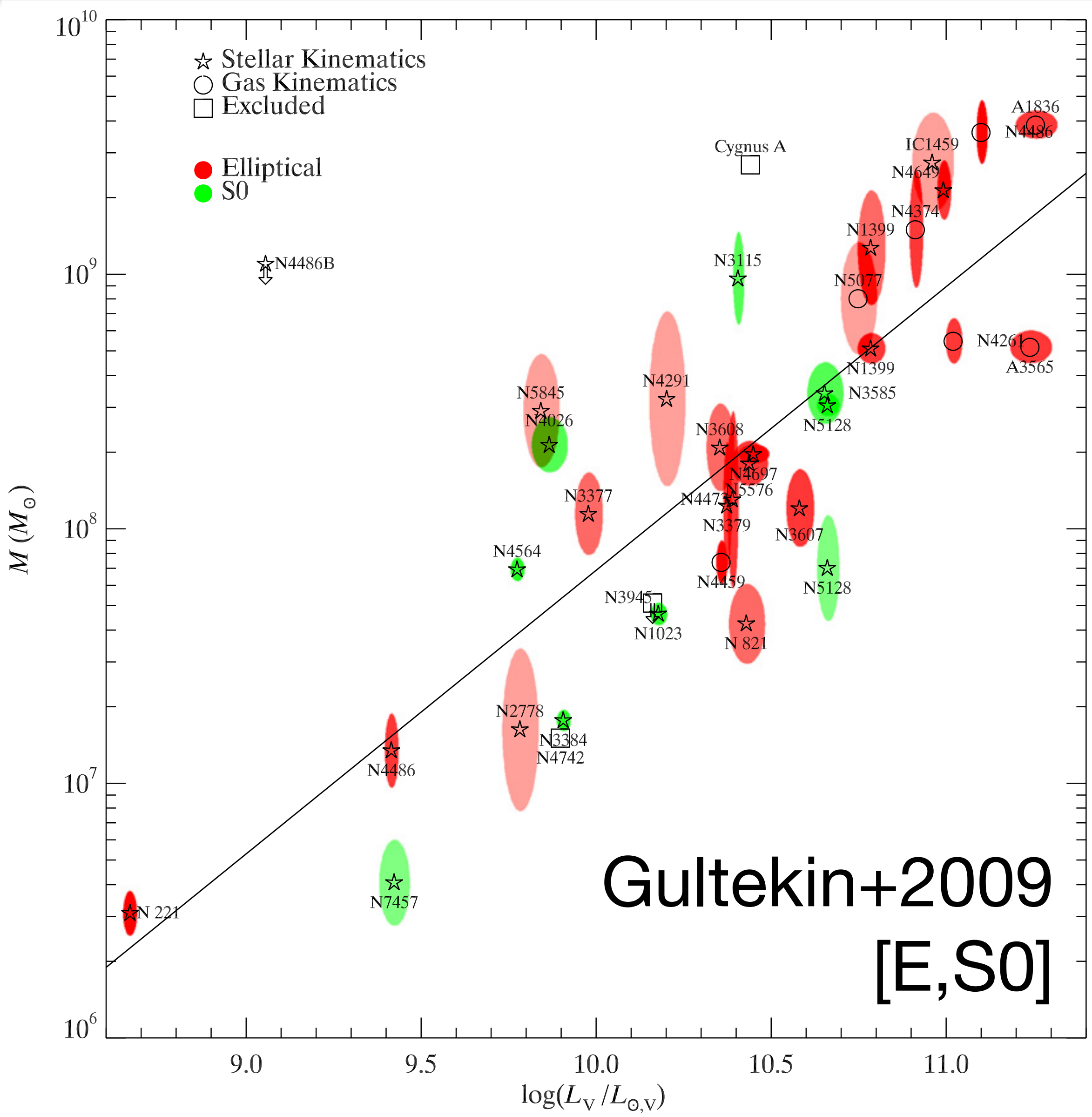


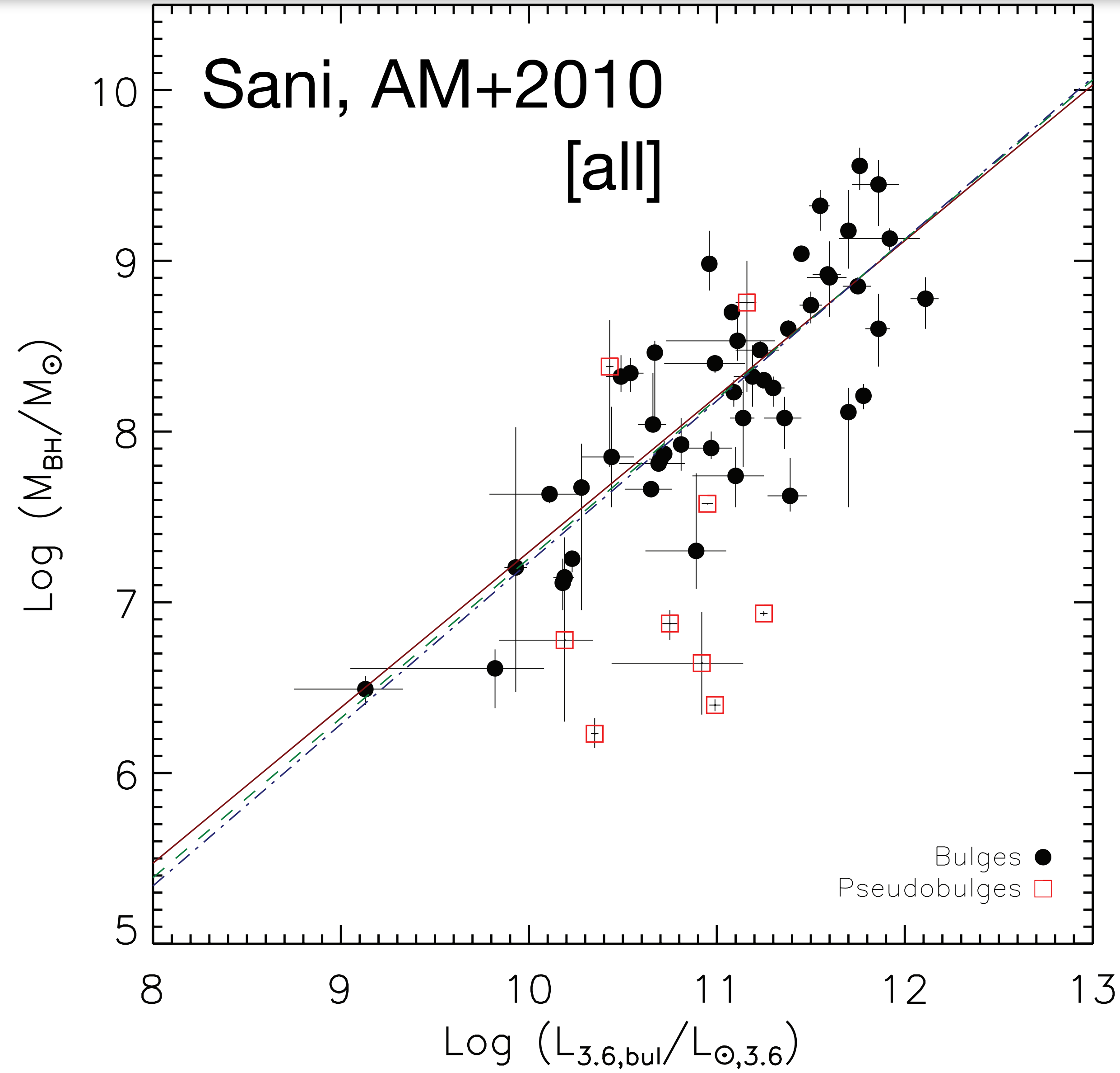
M_{BH}- σ (rms 0.25 in log M_{BH})

Investigate the M_{BH}-L_{bul} relation in the near-IR and consider *only secure* BH masses and galaxy structural parameters.
M_{BH}-L relation is not worse than M_{BH}-σ relation!

M_{BH}-L

Countless papers in literature, considered two of the most recent ones!





$$\log(M_{\rm BH}/\,{\rm M}_\odot) = (8.95 \pm 0.11) + (1.11 \pm 0.18)\log\left(\frac{L_V}{10^{11}\,L_{\odot,V}}\right)$$

$\sigma_0 = 0.38 \pm 0.09\,dex$ Gultekin+2009

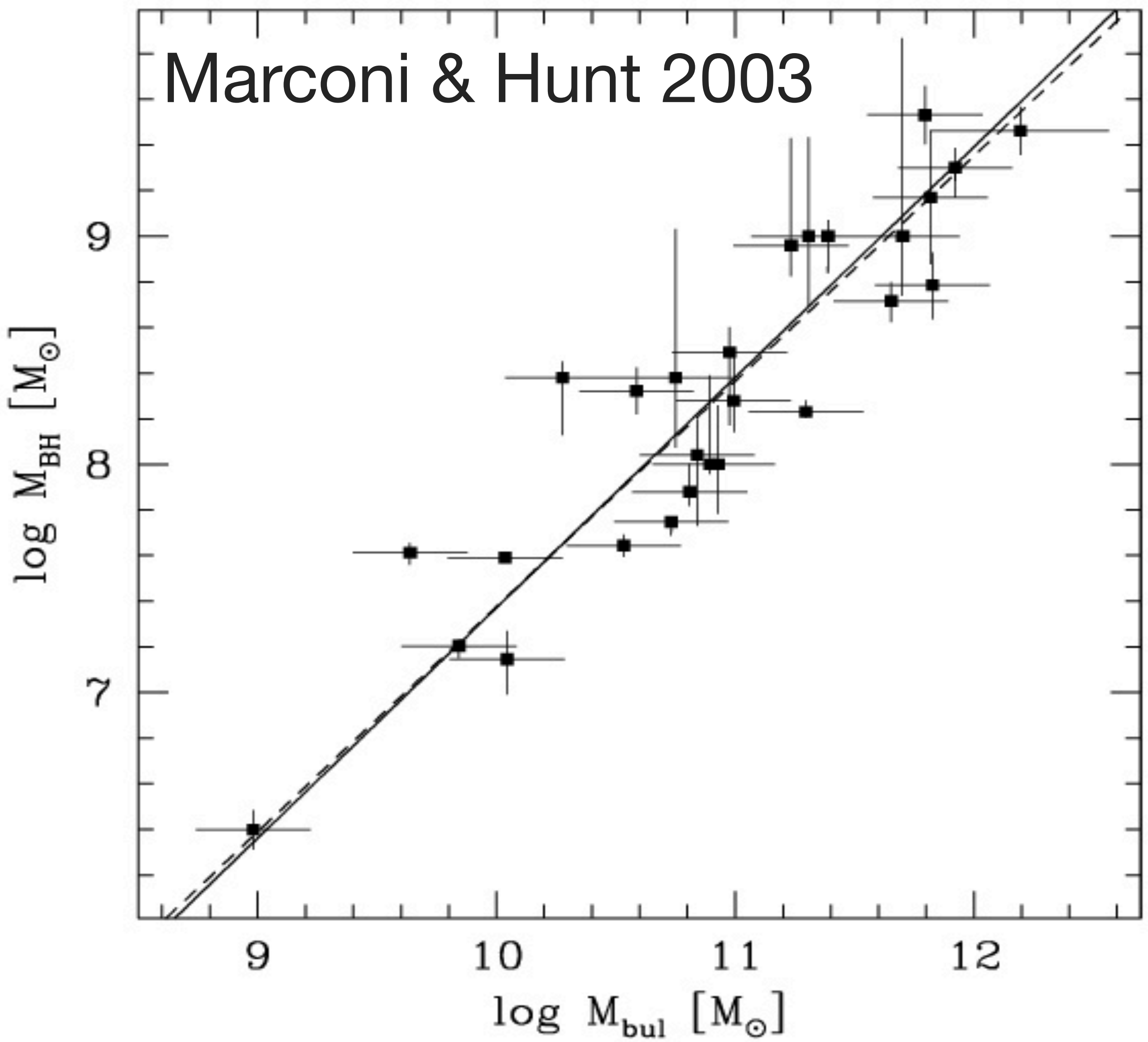
$$\log(M_{\rm BH}/\,{\rm M}_\odot) = (8.19 \pm 0.06) + (0.93 \pm 0.10)\log\left(\frac{L_{3.6\,\mu{\rm m}}}{10^{11}\,L_{\odot,3.6\,\mu{\rm m}}}\right)$$

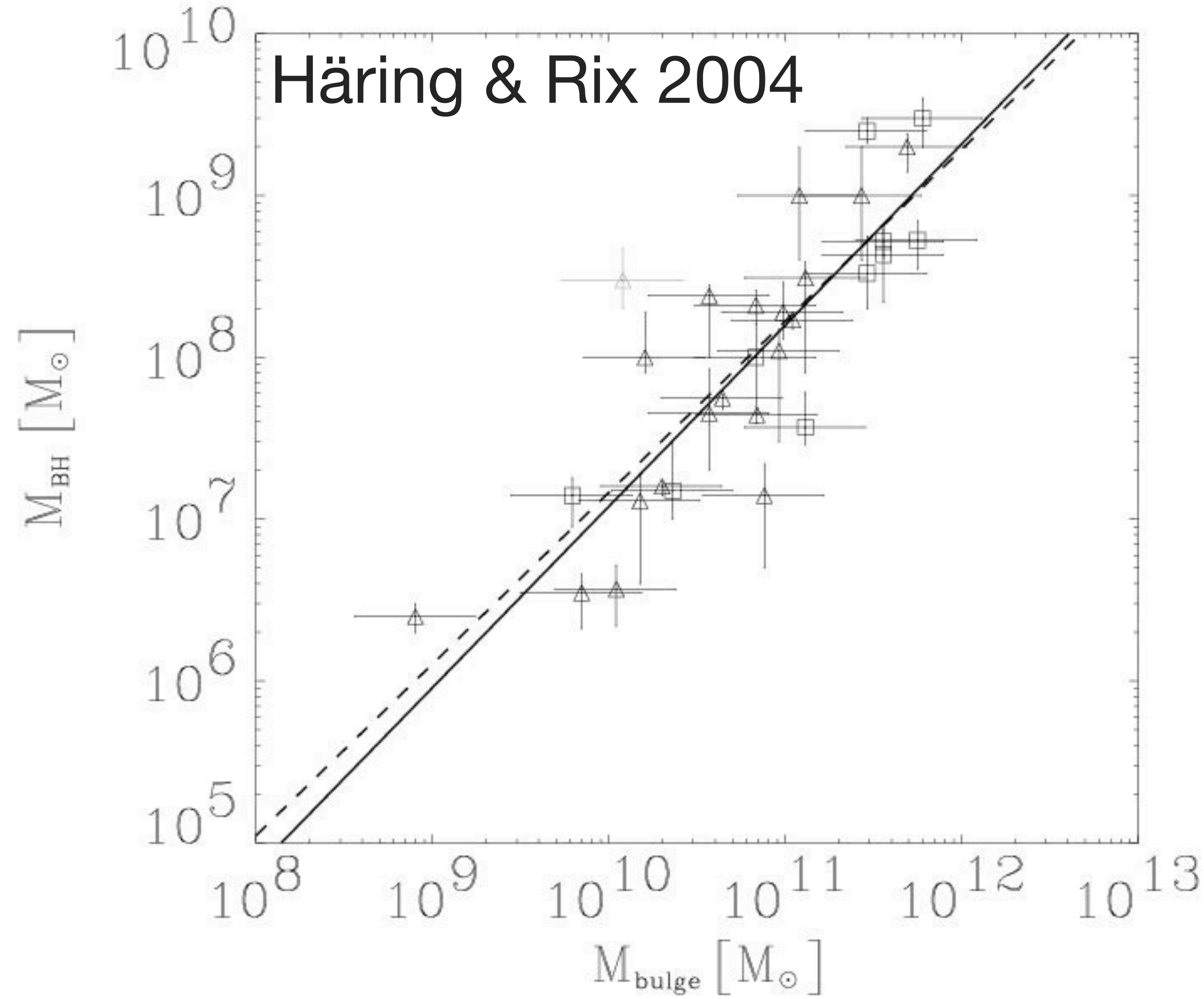
$\sigma_0 = 0.38 \pm 0.05\,dex$ Sani, AM+2010

M_{BH}-L

- Difficulties in accurate decomposition of bulge and disk, especially in later type spirals.
- Similar dispersion as M_{BH}-σ
  0.38±0.09 vs 0.31±0.06 (E+S0, Gultekin+09)
  0.38±0.05 vs 0.33±0.04 (E+S0, Gultekin+09)

M_{BH}-M_{bul}

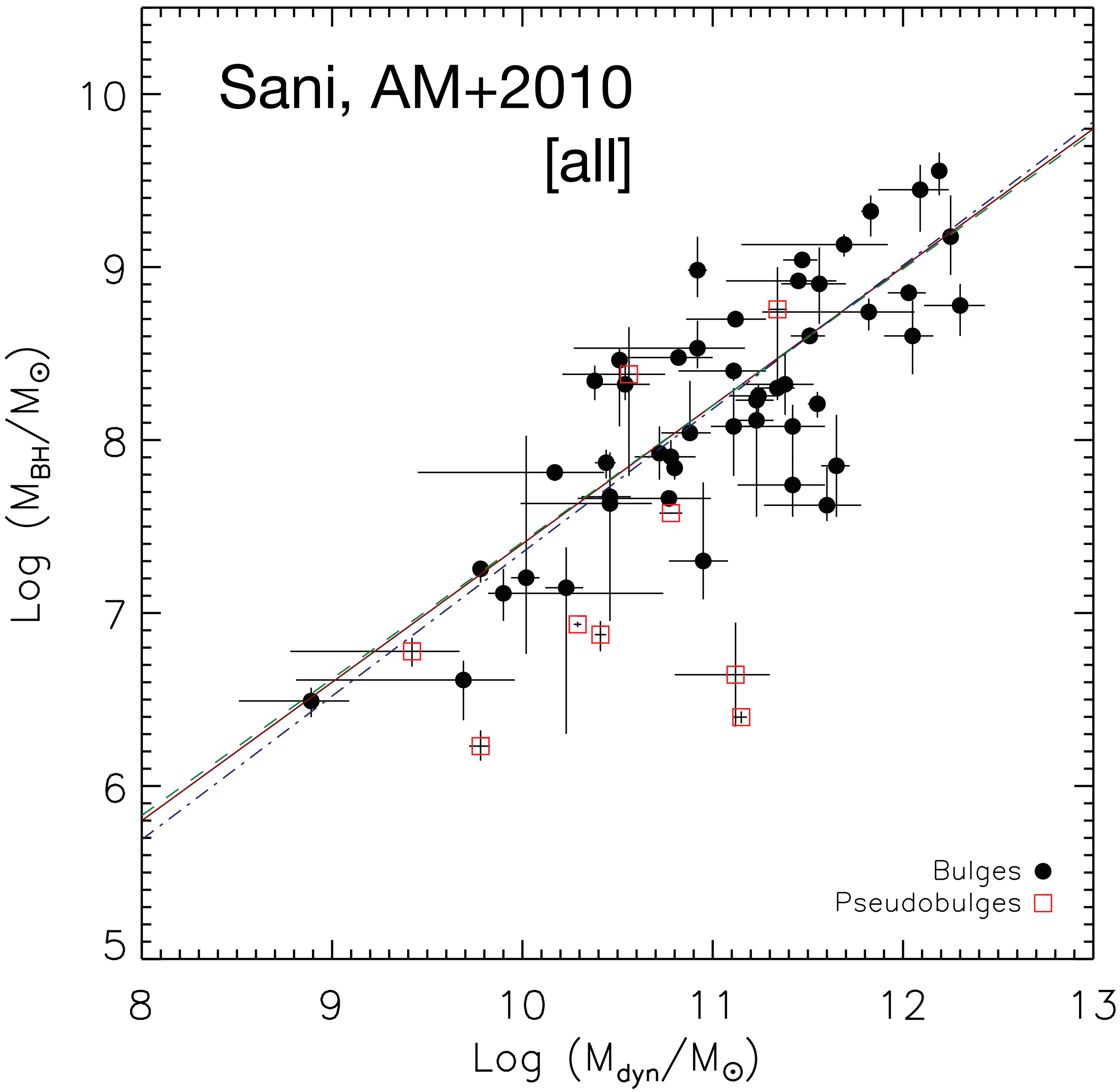




- Tight correlation M_{BH} vs virial bulge mass ($\approx R_e\,\sigma_e^2$) with *intrinsic dispersion* σ_0~0.25.
- Linear slope (0.96+/-0.07), average ratio $M_{BH}/M_{bul} \approx 0.002$.
- Häring & Rix 2004 find σ_0 ~ 0.3 in log M_{BH} with M_{bul} from dynamical models.

M_{BH}-M_{bul}

Countless papers in literature, considered the most recent one!



- M_{vir} from virial theorem

$$M_{vir} = 5\frac{R_e \sigma^2}{G}$$

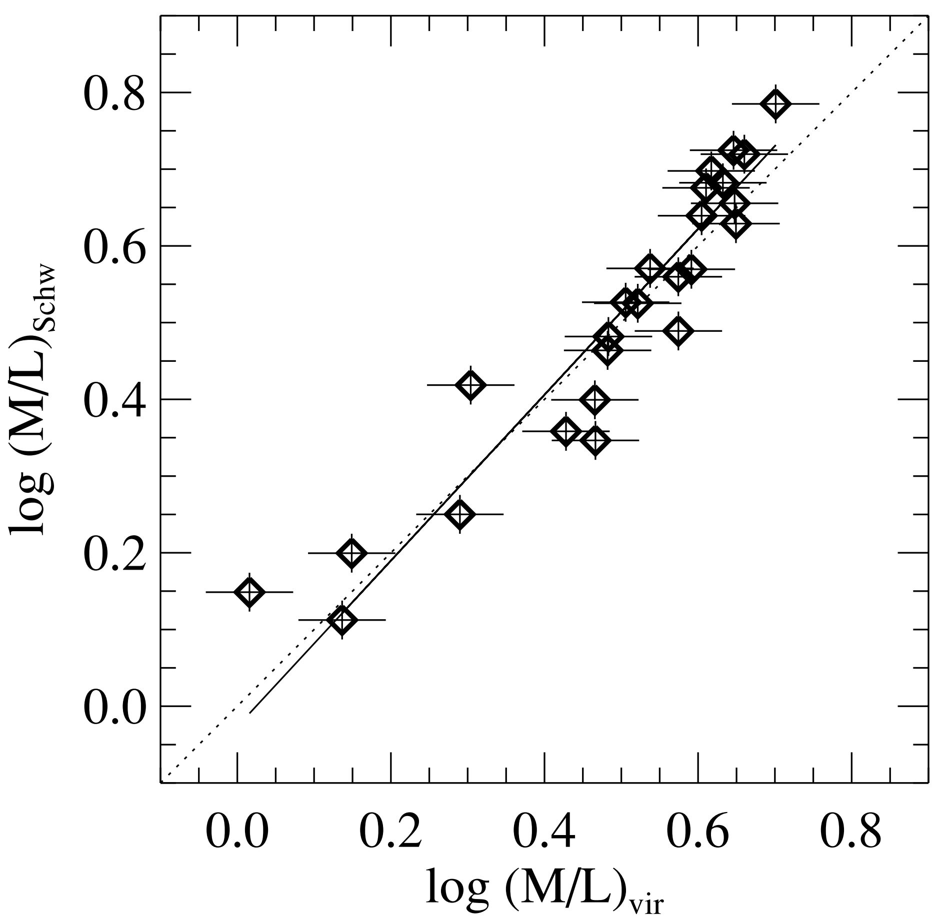
- Similar dispersion as other relations.
- This is really a relation of M_{BH} with a combination of bulge parameters.
- Does M_{vir} really represents bulge mass?

$$\log(M_{\rm BH}/\,{\rm M_\odot}) = (8.20 \pm 0.06) + (0.79 \pm 0.09)\log\left(\frac{M_{vir}}{10^{11}\,{\rm M_\odot}}\right)$$

$$\sigma_0 = 0.37 \pm 0.05\,dex$$

Accuracy of virial bulge mass

- Cappellari et al. 2006 studied a sample of E+S0 galaxies with
  - integral field kinematics (SAURON)
  - HST imaging
  - 3-I Schwarzschild dynamical modeling
- They measured dynamical masses with high accuracy
- They demonstrated that tilt of FP is due to M/L variations, and not to variation in the dynamical structure of galaxies.
- As a by-product they verified the accuracy of virial mass estimates in the central regions of E+S0 galaxies ...



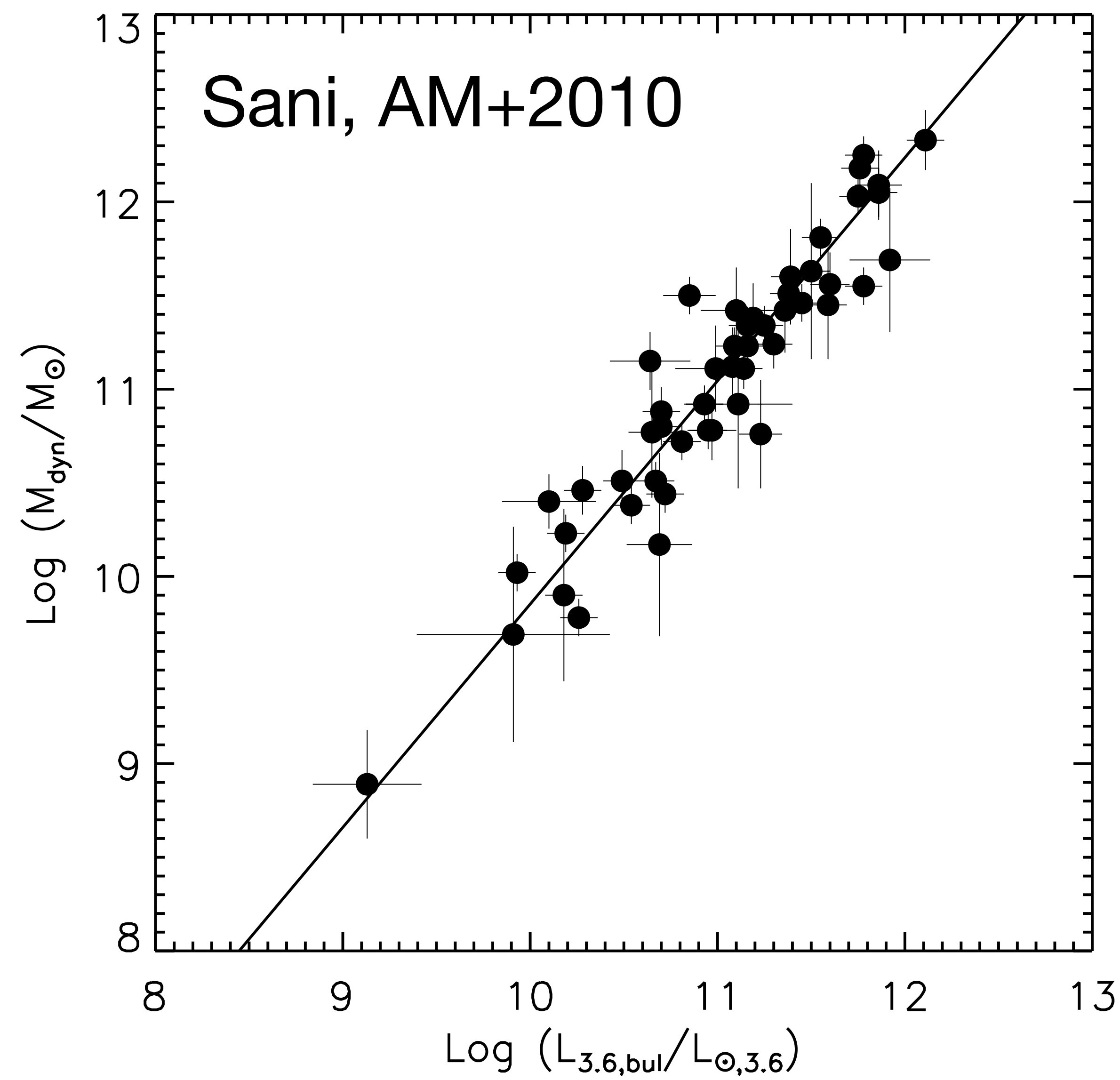
$$\left(\frac{M}{L}\right)_{vir,I} = (5 \pm 1)\frac{R_e \sigma^2}{G\, L_I}$$

$$\sigma_0 \simeq 0.06\, dex$$

M_{vir} is an excellent surrogate of more complex (and expensive) dynamical models!

L vs M_{star}

- Virial masses provide accurate dynamical masses
- Comparing bulge luminosities with dynamical masses, we find that the M_{BH}-L correlation is obviously a correlation with stellar mass (neglecting contributions from dark matter ...)
- Luminosity at 3.6 μm is an excellent tracer of (stellar) mass



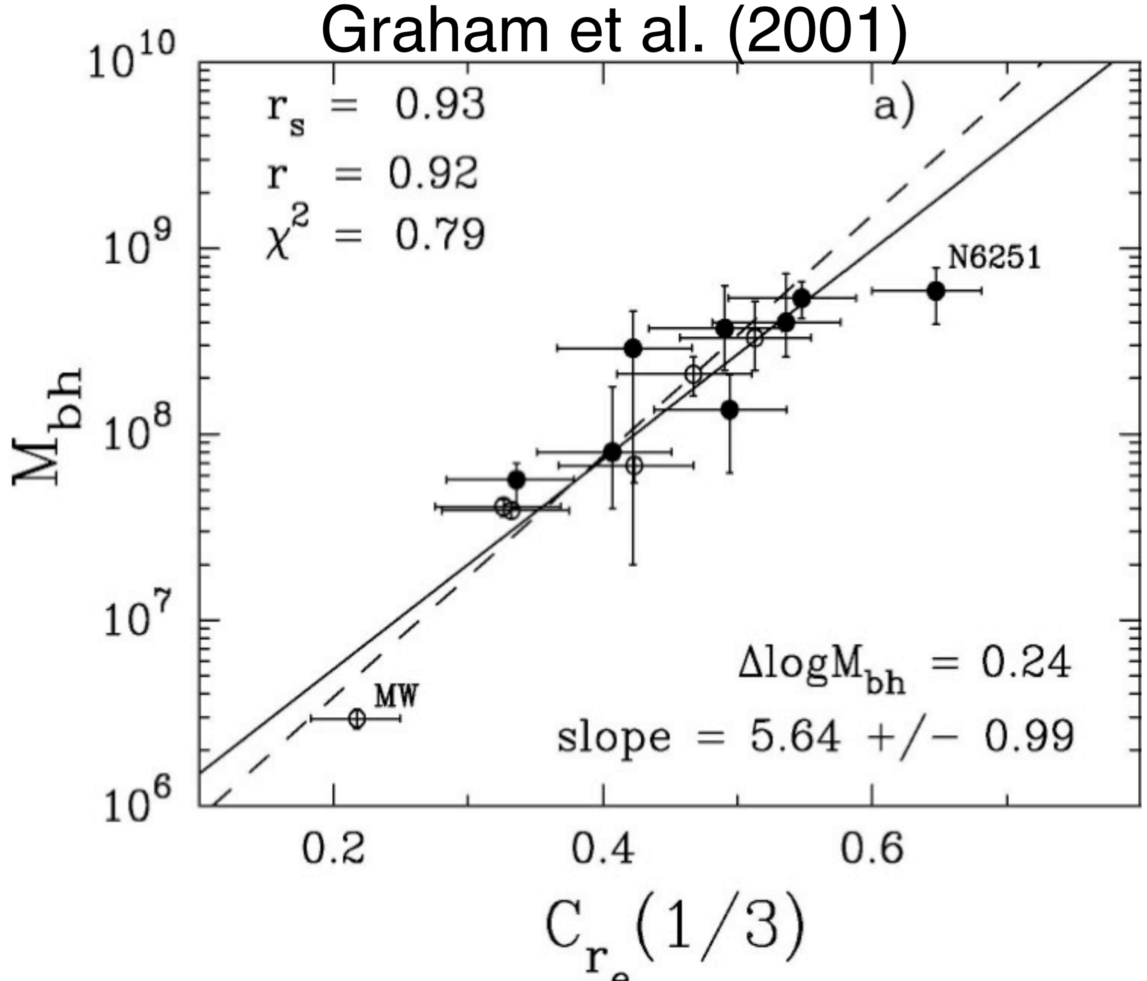
$$\log(M_{vir}/\,\mathrm{M}_\odot) = (11.04 \pm 0.03) + (1.18 \pm 0.07) \log\left(\frac{L_{3.6\,\mu\mathrm{m}}}{10^{11}\,L_{\odot,3.6\,\mu\mathrm{m}}}\right)$$

$$\sigma_0 = (0.13 \pm 0.04)\, dex$$

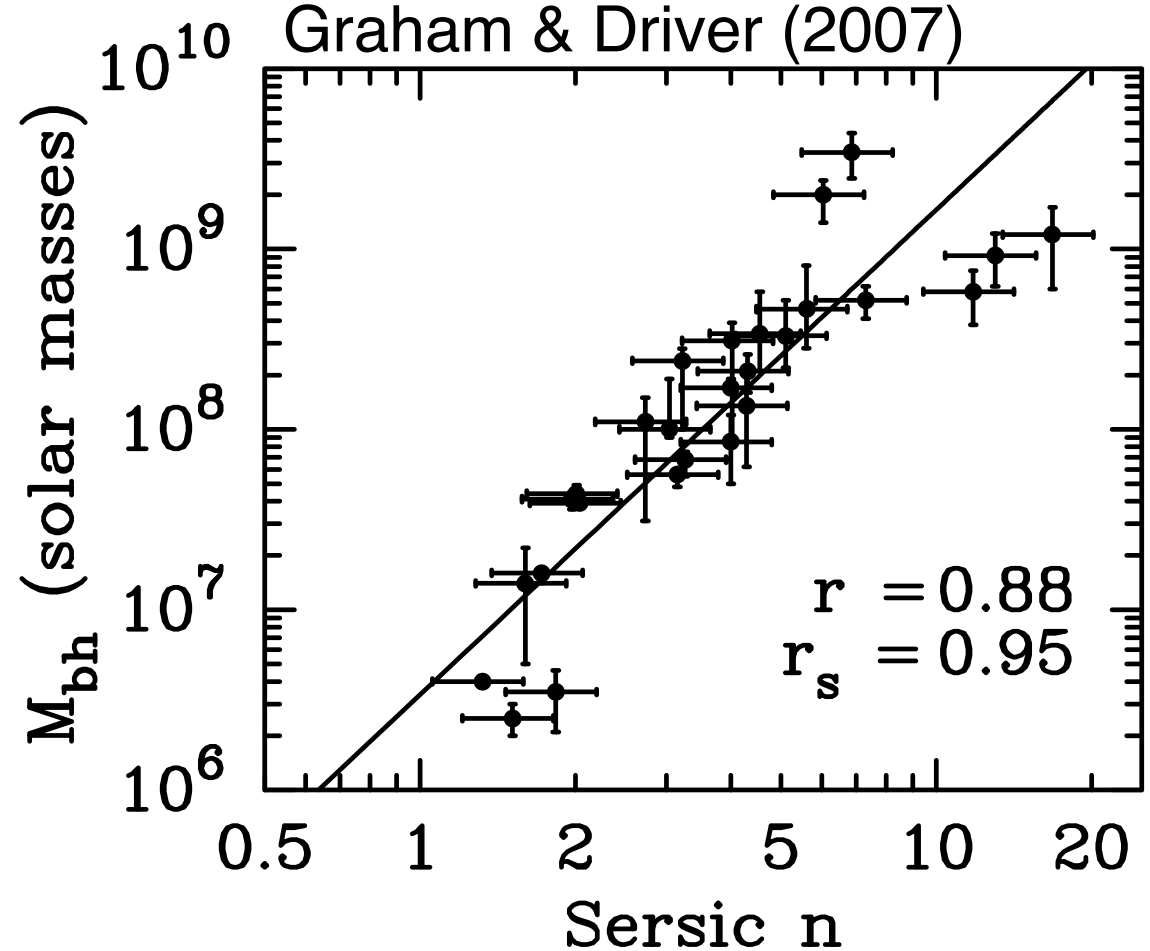
M_{BH} vs bulge light concentration

- Graham et al. (2001) found that M_{BH} is tightly correlated with the concentration index of bulge light [C_{Re} (1/3)= $F(R_e/3)/F(R_e)$]
- BH mass also correlates with Sersic index, $\Sigma(r)\sim\exp(r^{1/n})$, n Sersic index (Graham & Driver 2007)

Graham et al. (2001)

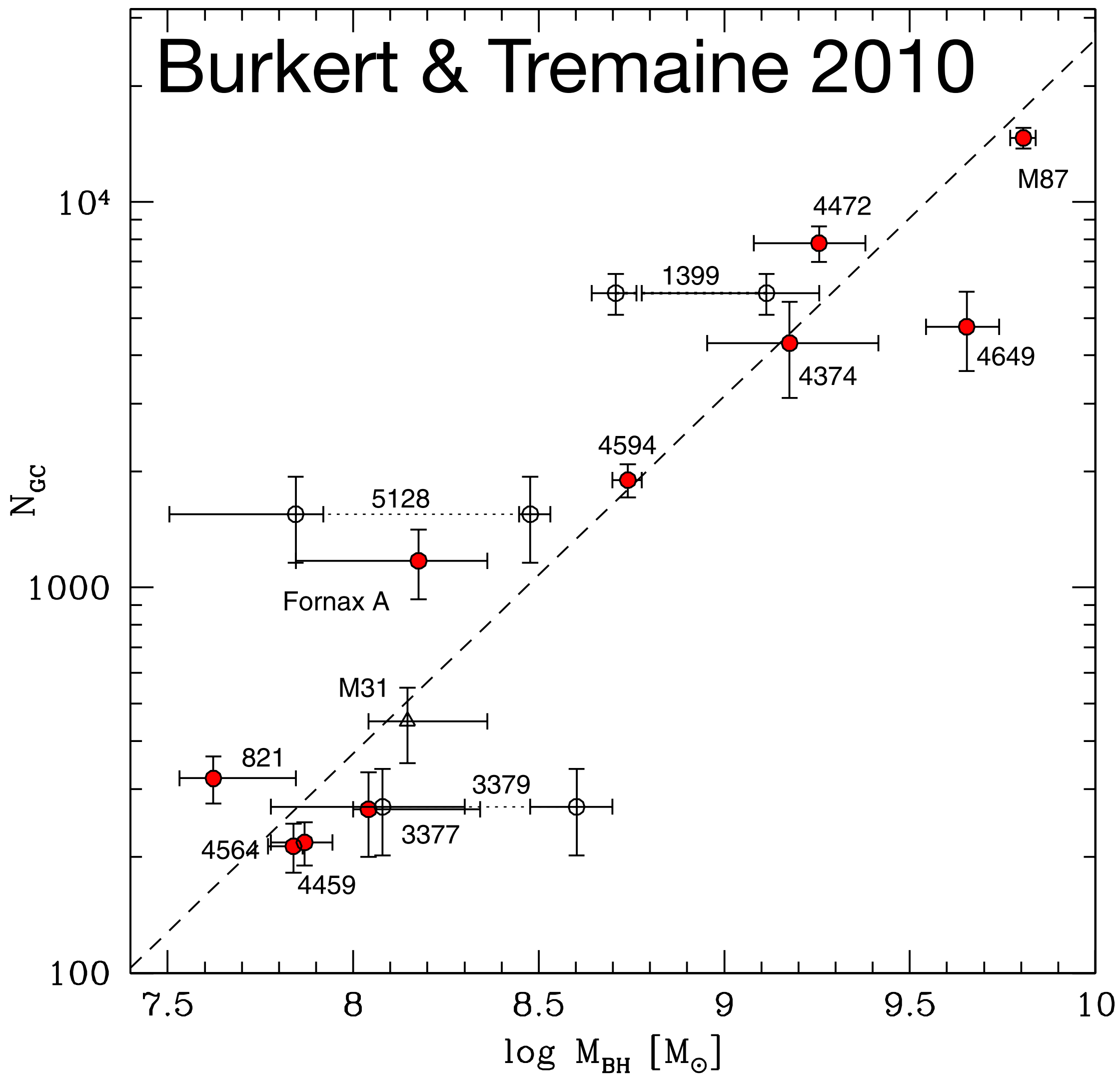


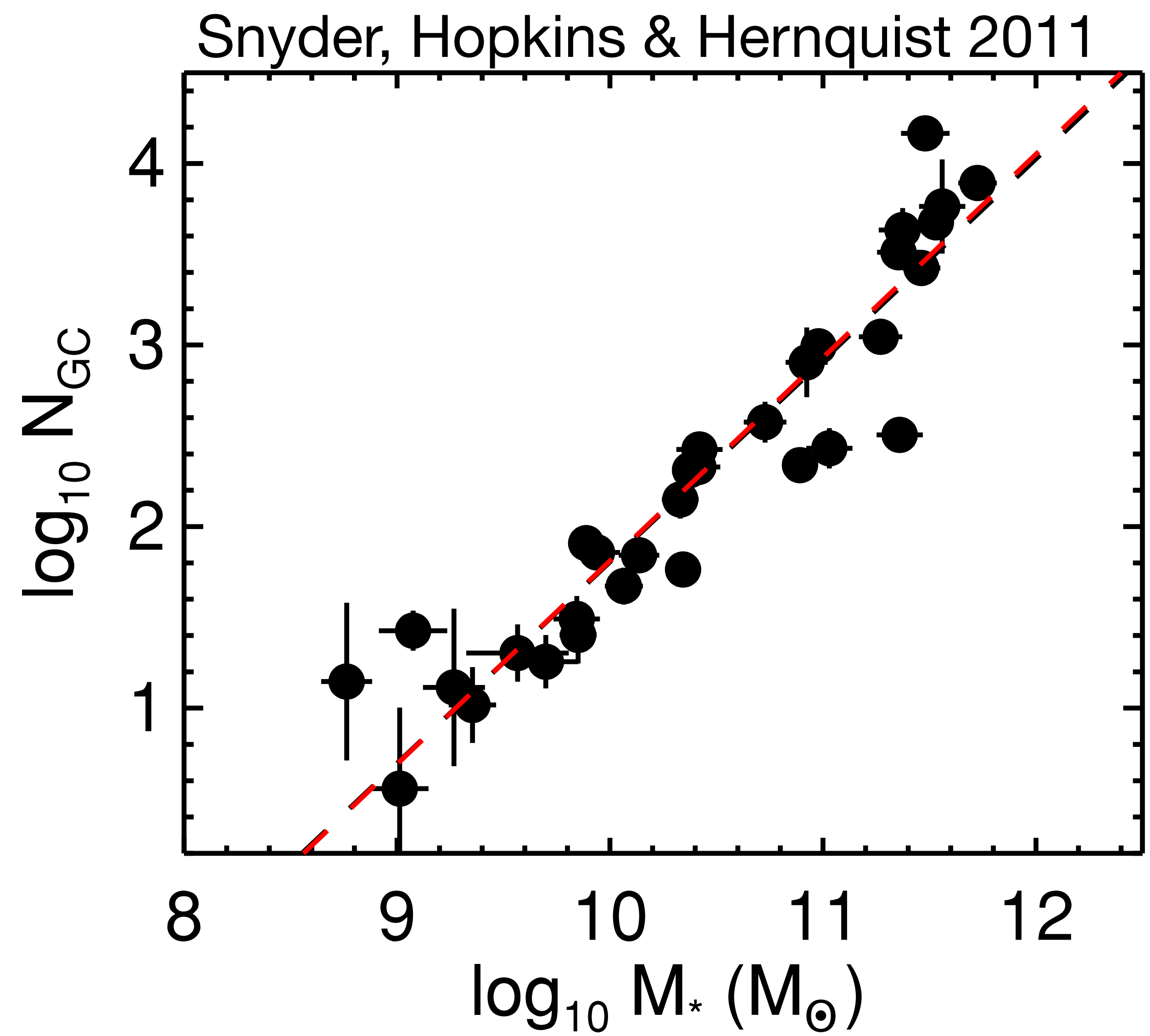
Graham & Driver (2007)



- Kormendy relation (Σ_e-R_e) combined with n-R_e relation (Caon et al. 1993) can be used to explain M_{BH} vs C,n correlation.
- *Sersic index is obviously directly related to other structural parameters of the spheroid and, through them, to M_{BH}.*

M_{BH} vs number of GCs

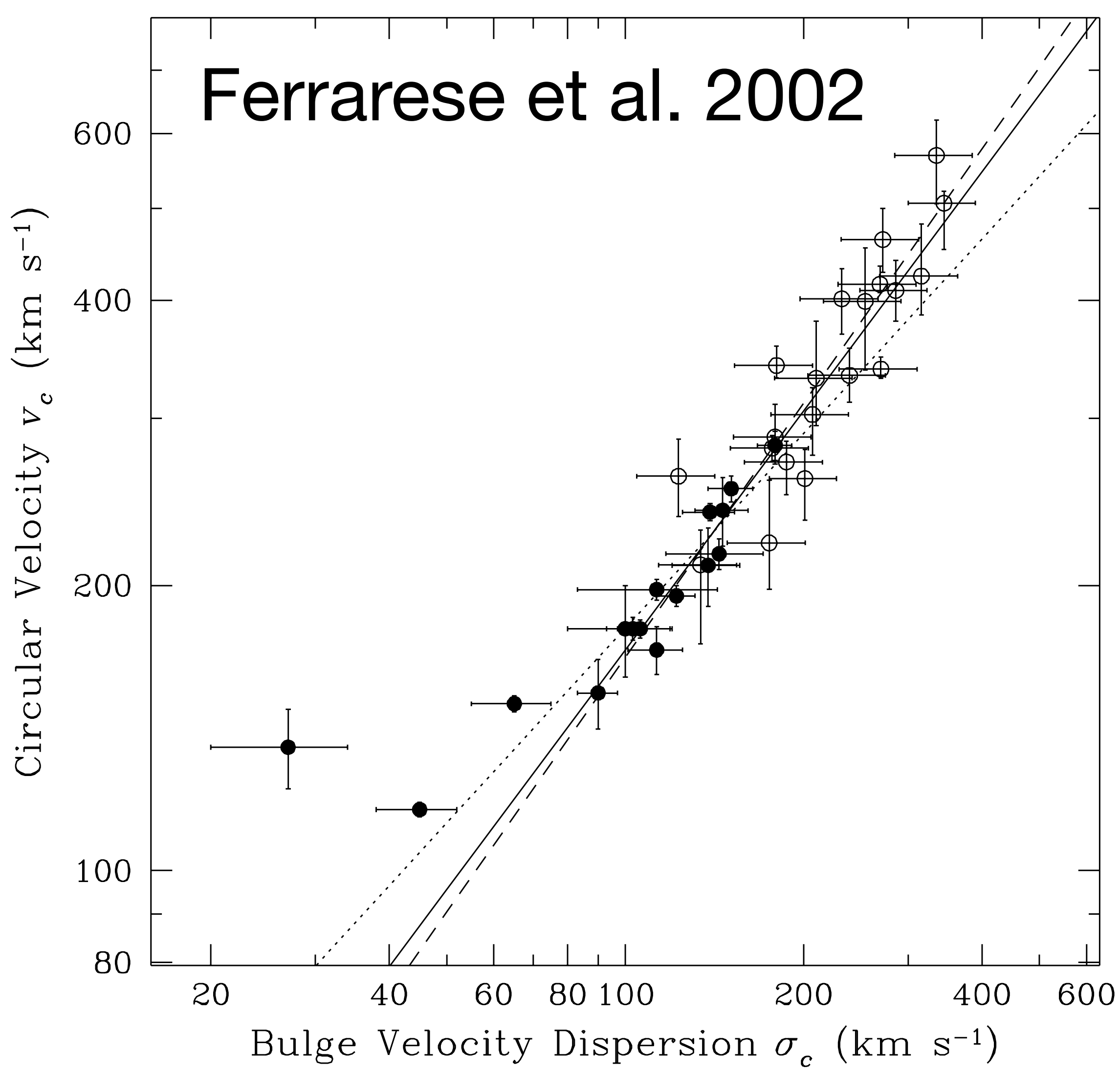


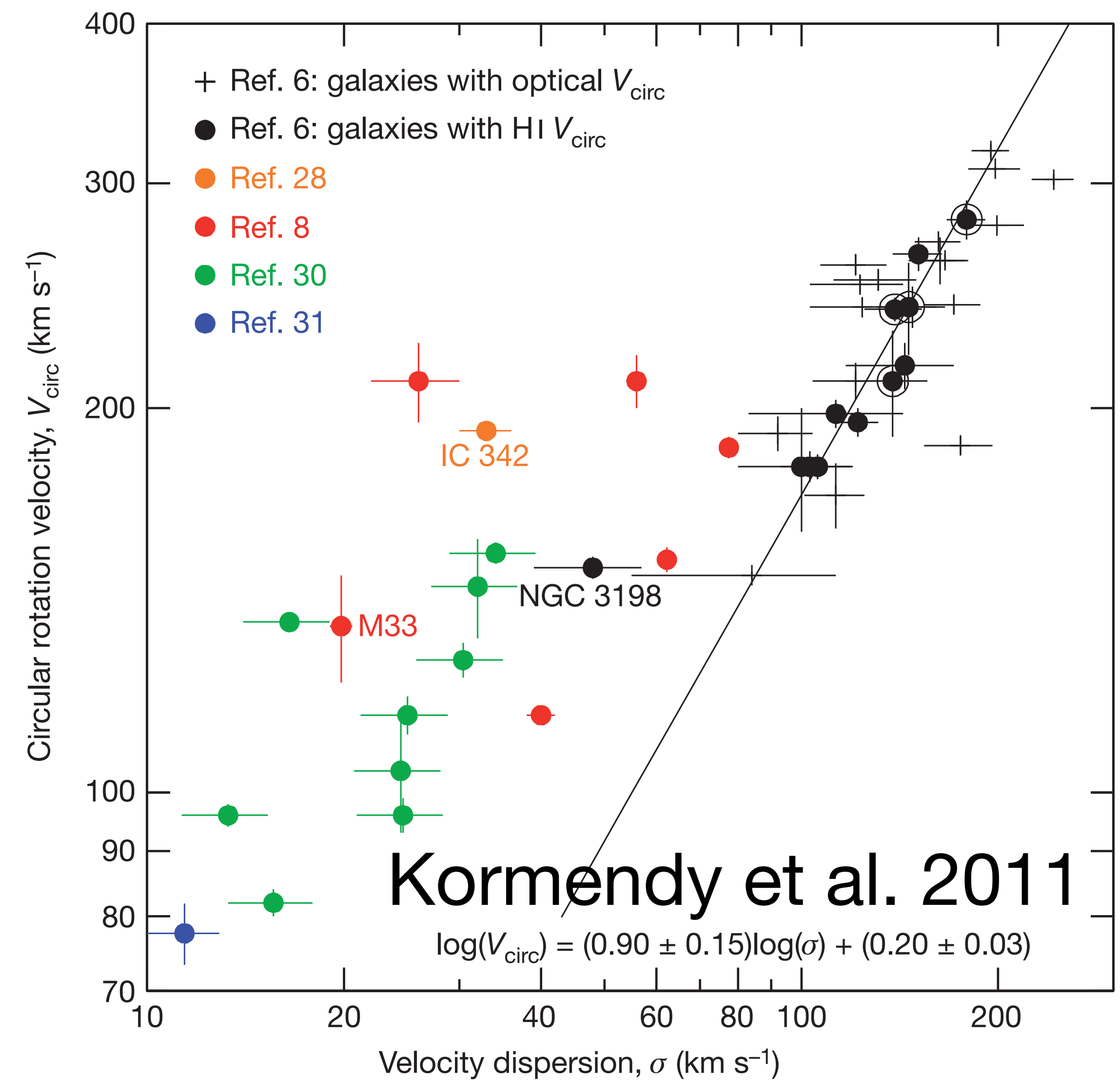


- Burkert & Tremaine (2010) presented a correlation between M_{BH} and number of Globular Clusters implying M_{BH} ~ total mass in GCs
- Snyder et al. (2011) show that there is not a direct "physical" correlation between M_{BH} and N_{GC}, but that
  N_{GC} is directly linked to M_{star} and σ, and through them, to M_{BH}

M_{BH}-dark matter halo

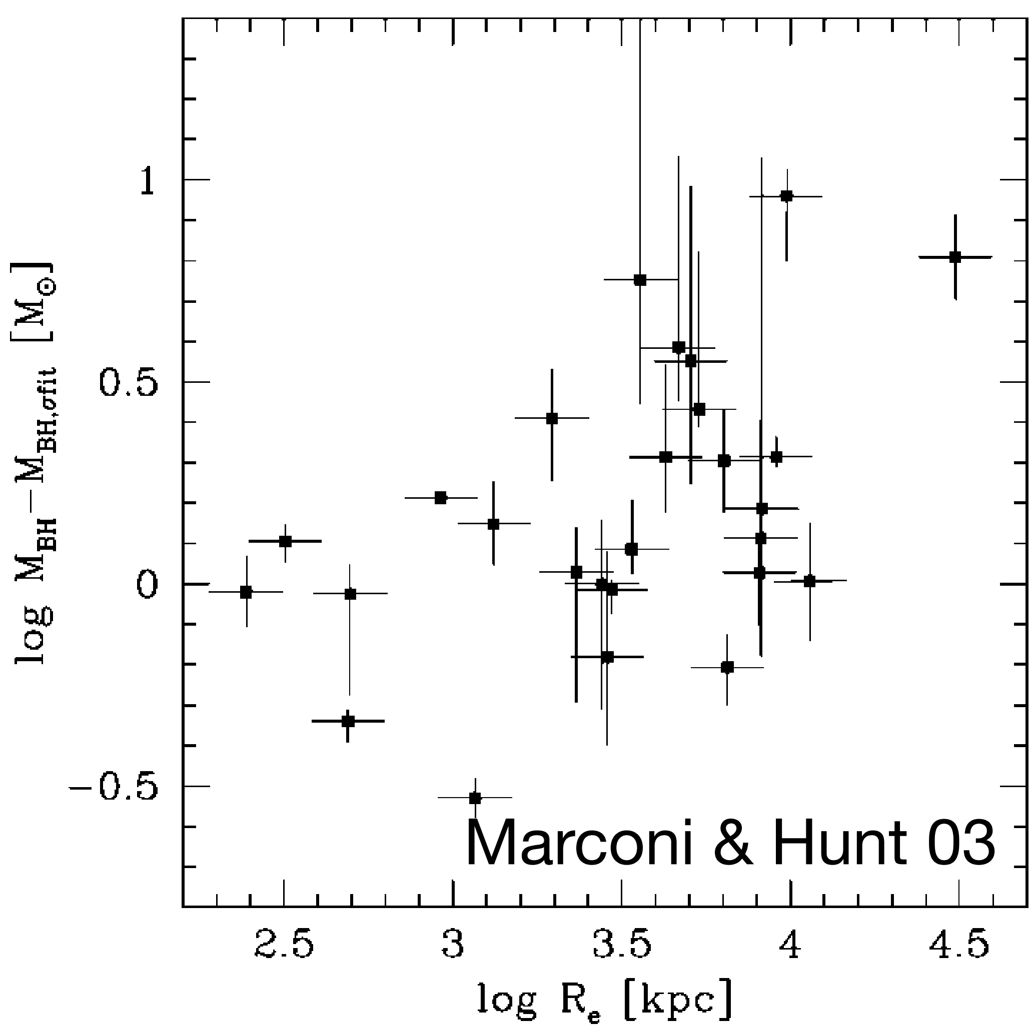
- Ferrarese et al. 2002 find a tight correlation between σ and the galaxy circular velocity V_c measured where rotation curve is flat
- Since σ is related to M_{BH}, and V_c is related to M_{DM} (mass of dark matter halo), this implies a non-linear relation M_{BH}-M_{DM} ($M_{BH}/M_{DM} \sim 10^{-4} - 10^{-5}$)
- Recently questioned by Kormendy et al. 2011.
- No correlation at all or does it break down at small σ?
- In any case, is it a real relation, or a “secondary” one like for *n* and N_{GC}?

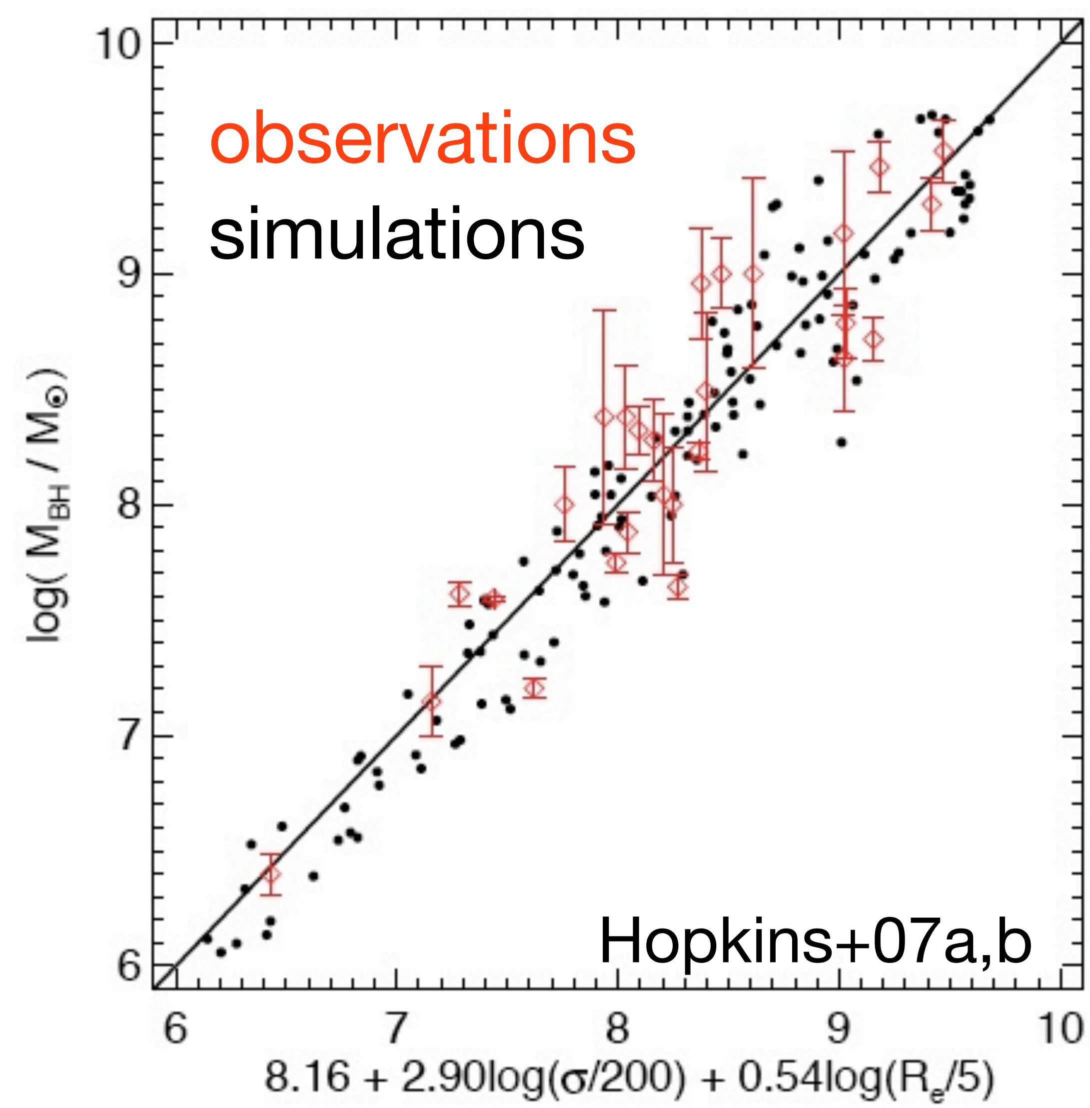




BH fundamental plane

- Correlation of M_{BH} with virial bulge mass (~ $R_e\sigma^2$) suggests that M_{BH} might correlate with combination of R_e, σ
- Indeed residuals of M_{BH}-σ (weakly) correlate with R_e (Marconi & Hunt 2003)
- Hopkins et al. (20007a,b)propose a "fundamental plane" for M_{BH} found *both in data and from models* (see also Barway & Kembhavi 07, Aller & Richstone 07, Feoli & Mancini 2009).





BH fundamental plane

- The BH fundamental plane is in practice a correlation of BH mass with gravitational binding energy (Hopkins et al. 2007, Aller & Richstone 2007, Feoli & Mancini 2009)

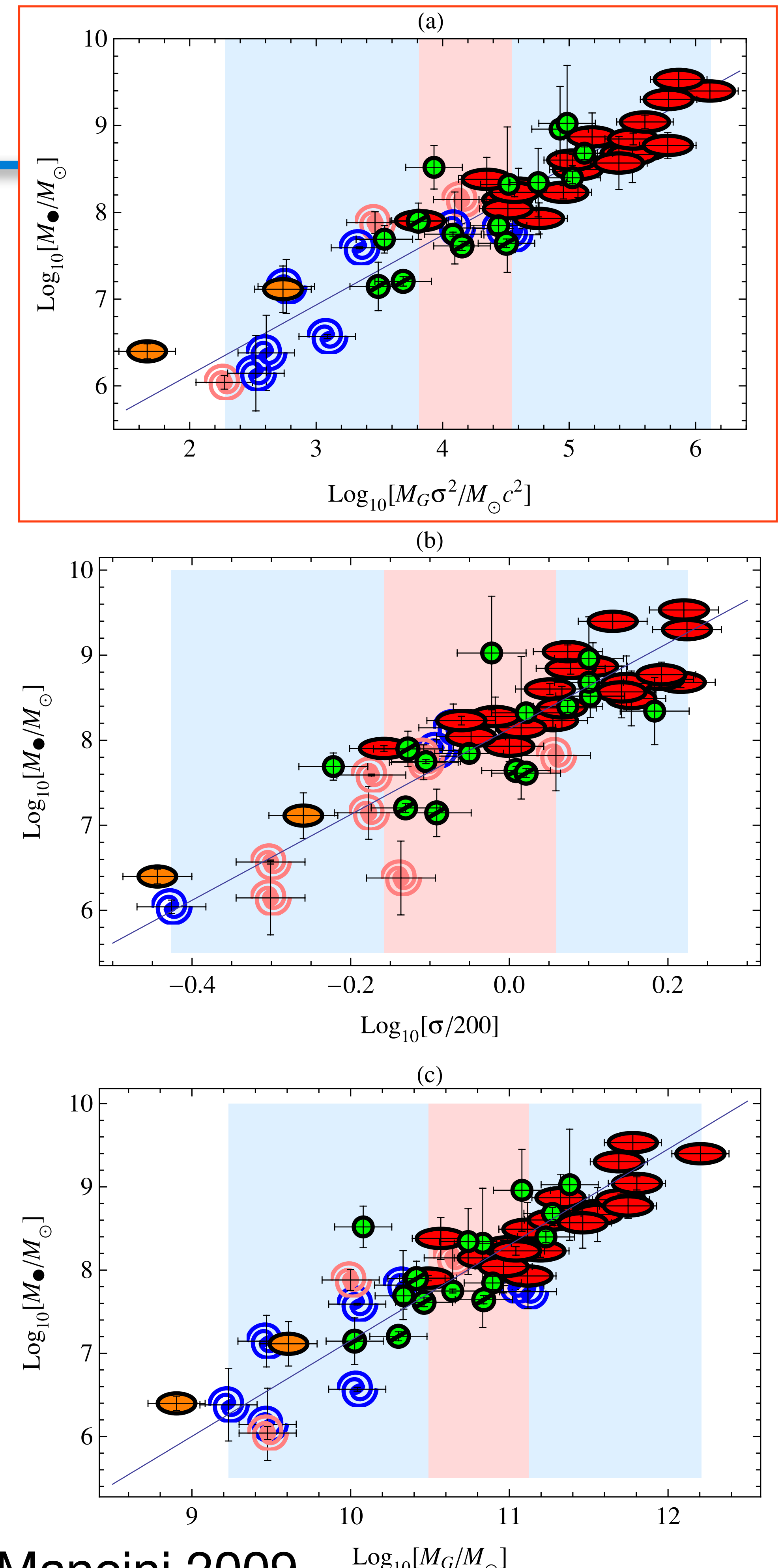
$$M_{\rm BH} \sim (M_{vir}\,\sigma^2)^{0.7-0.8}$$

- Virial theorem (K kinetic energy, W gravitational binding energy) states

$$W + 2K = 0$$

hence

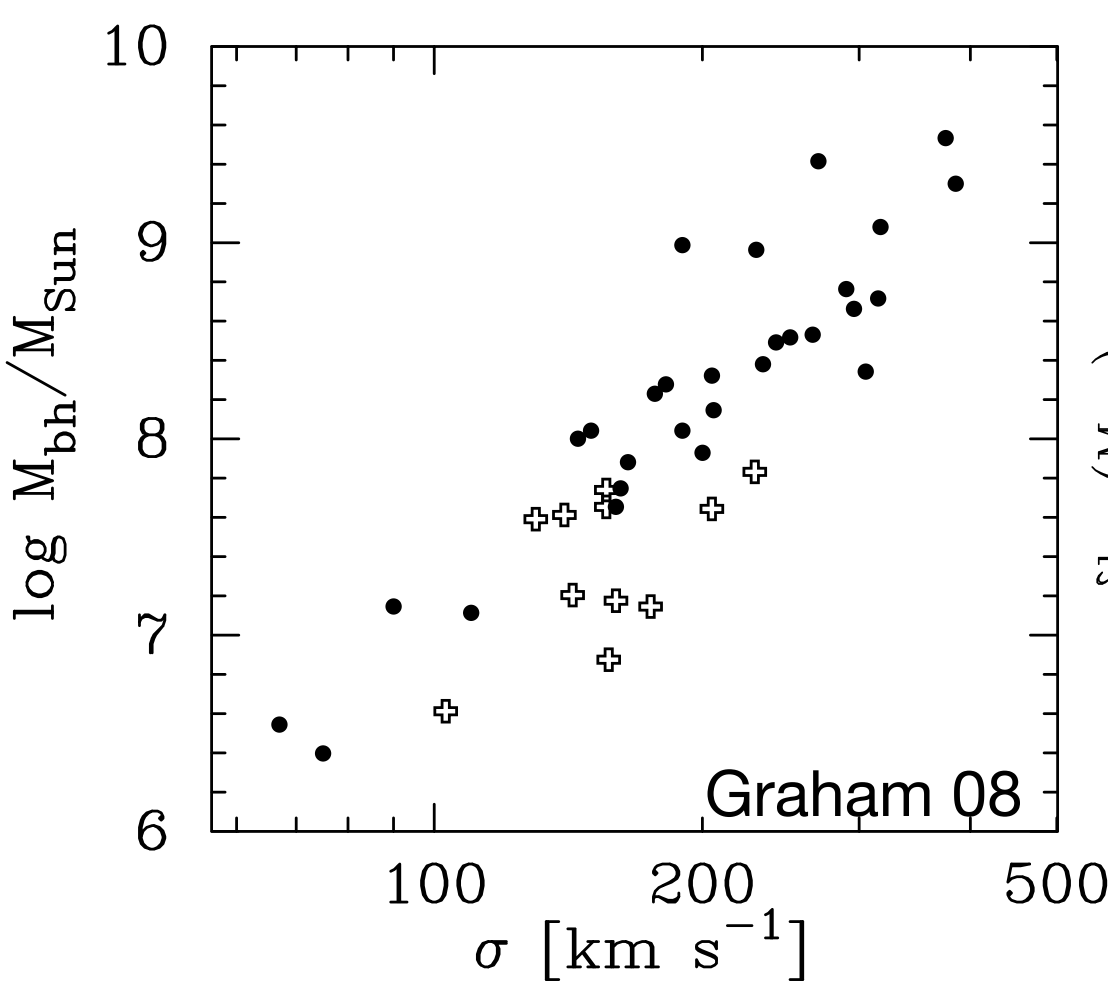
$$|W| = 2K = M\sigma^2 \sim M_{vir}\sigma^2 \propto R_e\sigma^4$$

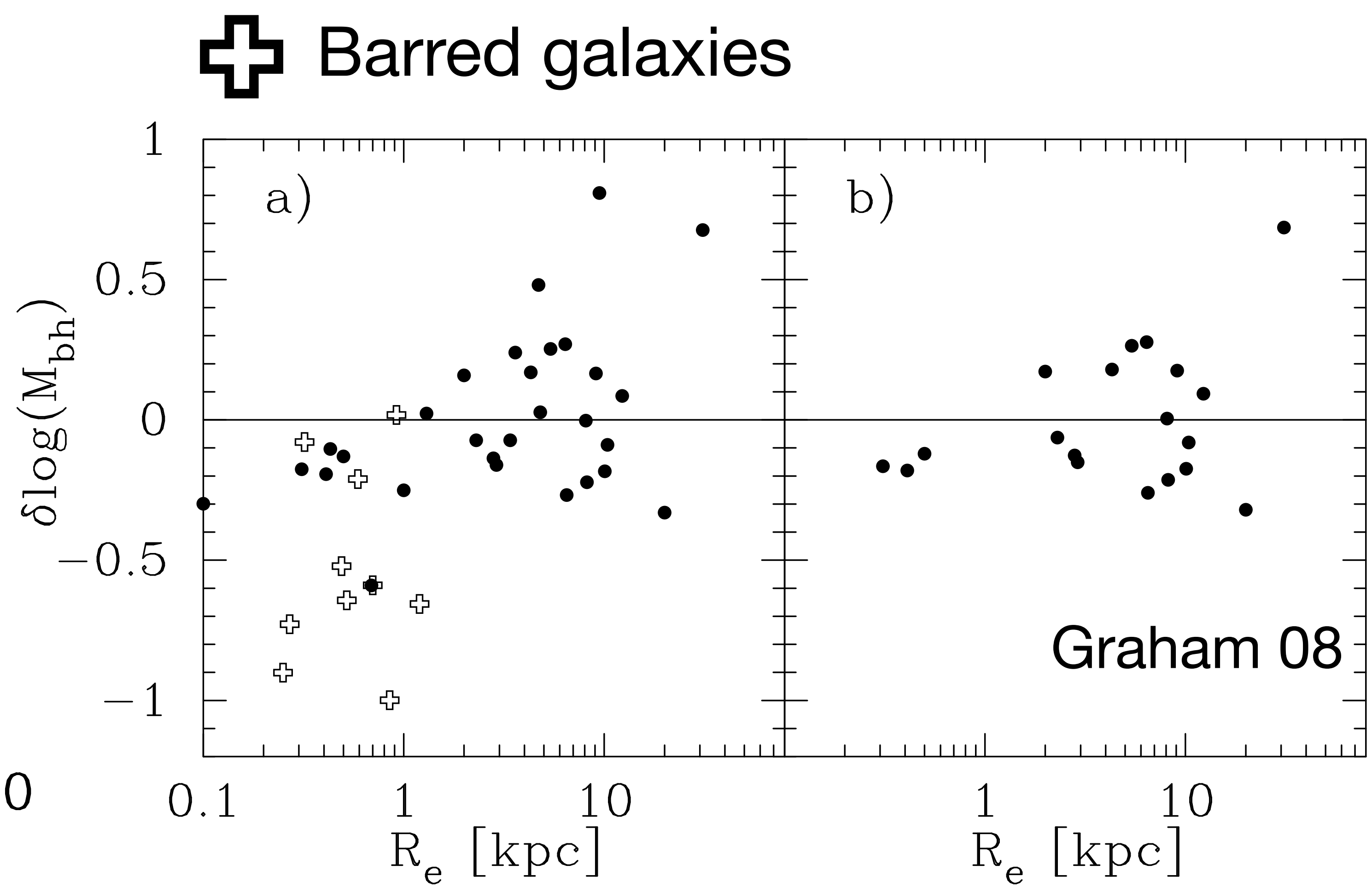


Feoli & Mancini 2009

BH fundamental plane?

- Graham 08 shows
  - Barred galaxies are systematically offset from M_{BH}-σ relation (but not from M_{BH}-L)
  - the need of FP is driven by "barred" galaxies. The bar affects σ and a combination of σ, R_e gives a tighter relation.
- Hu 08 notices the offset nature of "pseudobulges" (from mostly barred galaxies) in M_{BH}-σ relation





Pseudobulges

A pseudobulge is a bulge with disk-like properties and therefore is different from a "classical" bulge (see review by Kormendy & Kennicutt 2004)

- has a flatter, more disk-like shape than a classical bulge
- is mostly rotation supported (i.e. V_{rot}/σ larger than in bulges)
- is deviant in L-σ (Faber-Jackson) relation for having small σ
- can show spiral structure or nuclear bars (within the bulge part of profile)
- nearly exponential surface brightness profiles (e.g. $n < 2$)
- has star formation and younger stellar populations than classical bulges

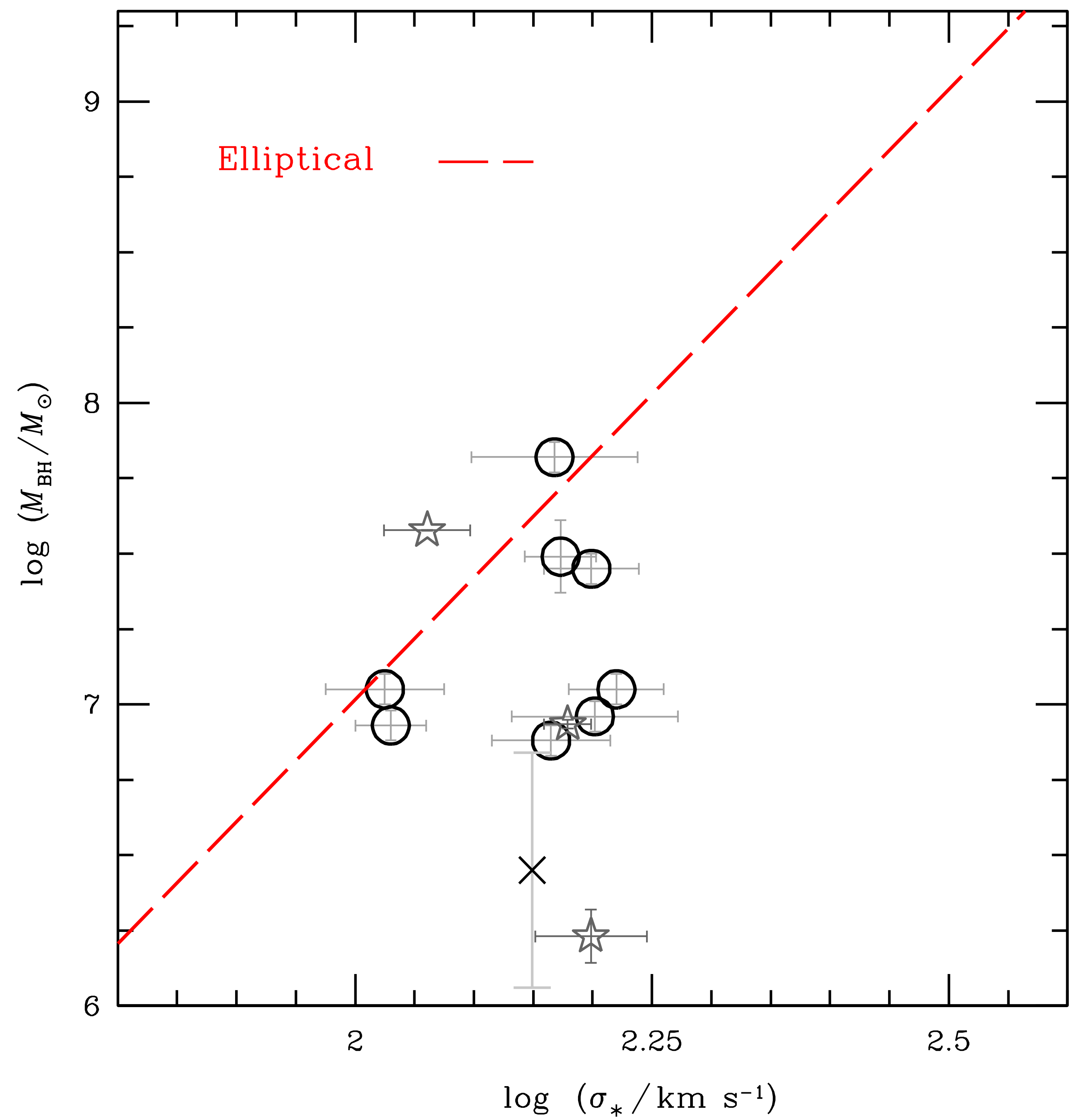
☆ *Pseudobulges resides mostly in barred and oval galaxies (pseudobulges ← → barred galaxies)*

☆ Classical bulges are believed to be the result of the merger driven galaxy formation process, same structural properties as elliptical galaxies

☆ *Pseudobulges are believed to be the result of secular processes in the disk driven by non-axisymmetries in the potential: a bar can build a concentration of gas and stars in the center of a galaxy which then becomes a pseudobulge*

Pseudobulges

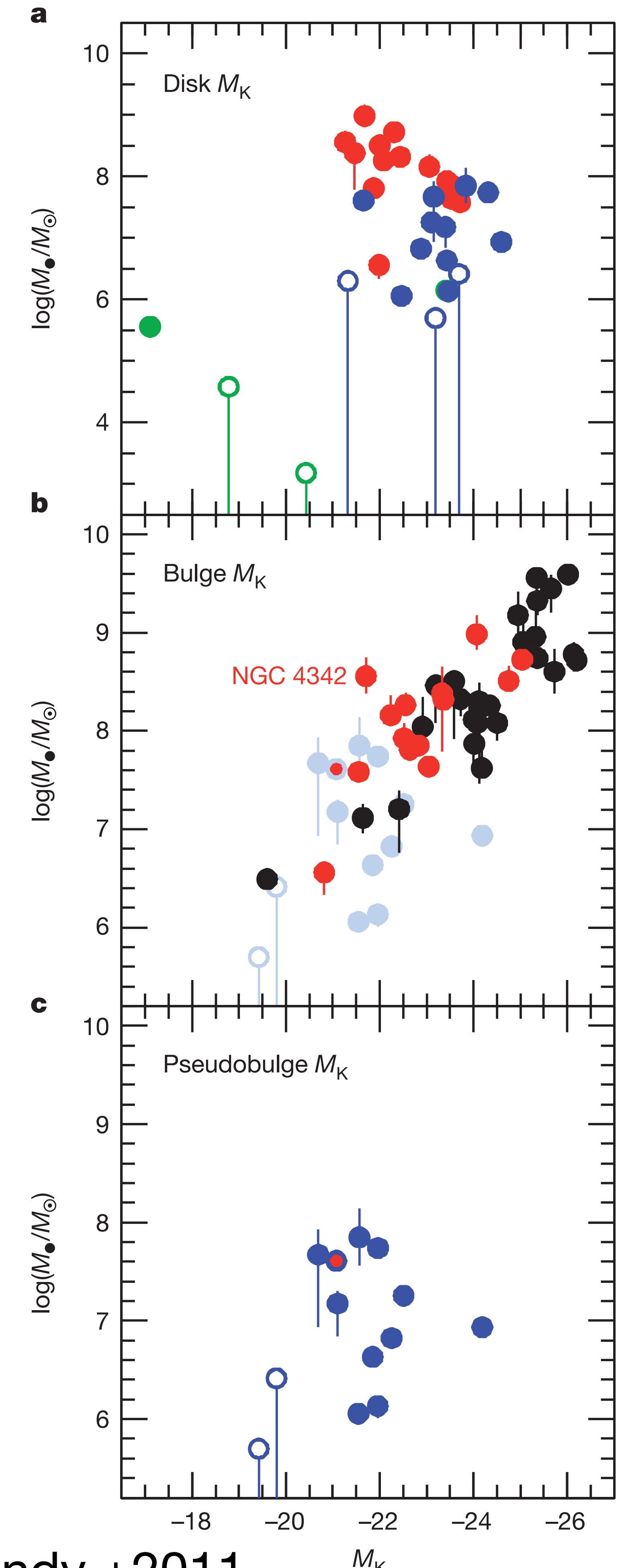
- Accurate M_{BH} measurements from H_2O masers are offset w.r.t. relation for Elliptical galaxies (Greene et al. 2010)
- *At least 7 out of 9 masers galaxies have pseudobulges.*
- Does this really indicate a different relation for pseudobulges, or a different M_{BH}-σ relation in general?



Greene et al. 2010

Pseudobulges

- "Secure" correlations are between M_{BH} and structural parameters of *ellipticals and classical bulges*
- There is no correlation with disks (e.g. Kormendy et al. 2011)
- Barred galaxies and pseudobulges appear deviant from M_{BH}-galaxy relations
  - it is very likely that a barred galaxy hosts a pseudobulge, likely same phenomenon
- Do pseudobulges or barred galaxies define a different correlation or no correlation at all?
  - offset correlation with larger scatter (Hu 2008)
  - no correlation at all (Kormendy +2011)
- What is the origin of the offset nature?
  - different BH growth?
  - dynamical effects of bar seen as *larger* σ?



Kormendy +2011

A much needed summary ...

We have many correlations with spheroid (bulge) structural parameters

- M_{BH}-σ
- M_{BH}-L (M_{star})
- M_{BH}-M_{dyn}
- M_{BH}-n
- M_{BH}-N_{GC}
- M_{BH}-M_{DM}
- M_{BH} "fundamental plane": $M_{BH} \sim \sigma^{\alpha} R^{\beta}$
- There might be different correlations for bulges and pseudobulges
- M_{BH} does not correlate with disk properties

- Is there a fundamental relation?
- Are they reliable?
- What is the physical origin of these correlations?

Is there a fundamental relation?

- M_{BH}-σ
- M_{BH}-L (M_{star})
- M_{BH}-M_{dyn}
- M_{BH}-n *likely indirect relation*
- M_{BH}-N_{GC} *likely indirect relation*
- M_{BH}-M_{DM} *likely indirect relation*
- M_{BH} "fundamental plane": $M_{BH} \sim \sigma^{\alpha} R^{\beta}$
- There might be different correlations for bulges and pseudobulges

  focus on elliptical galaxies and classical bulges only ...
- M_{BH} does not correlate with disk properties

  forget about disks ...

Are these relations independent?

Assume the basic correlation is $M_{BH} \sim M_{bulge}$

Combine with galaxy scaling relations:

☆ $M_{BH} \sim L_{bulge}^{1.1}$ consistent with $M_{BH} \sim M_{bulge}$ if $(M/L)_{bulge} \sim L_{bulge}^{0.1}$ (consistent with fundamental plane)

☆ Faber-Jackson $L \sim \sigma^4$ implies $M_{BH} \sim (\sigma^4)^{1.1} \sim \sigma^{4.4}$

All M_{BH}-galaxy correlations can be explained as the result of a fundamental relation (e.g. $M_{BH} \sim M_{bulge}$) combined with galaxy scaling relations.

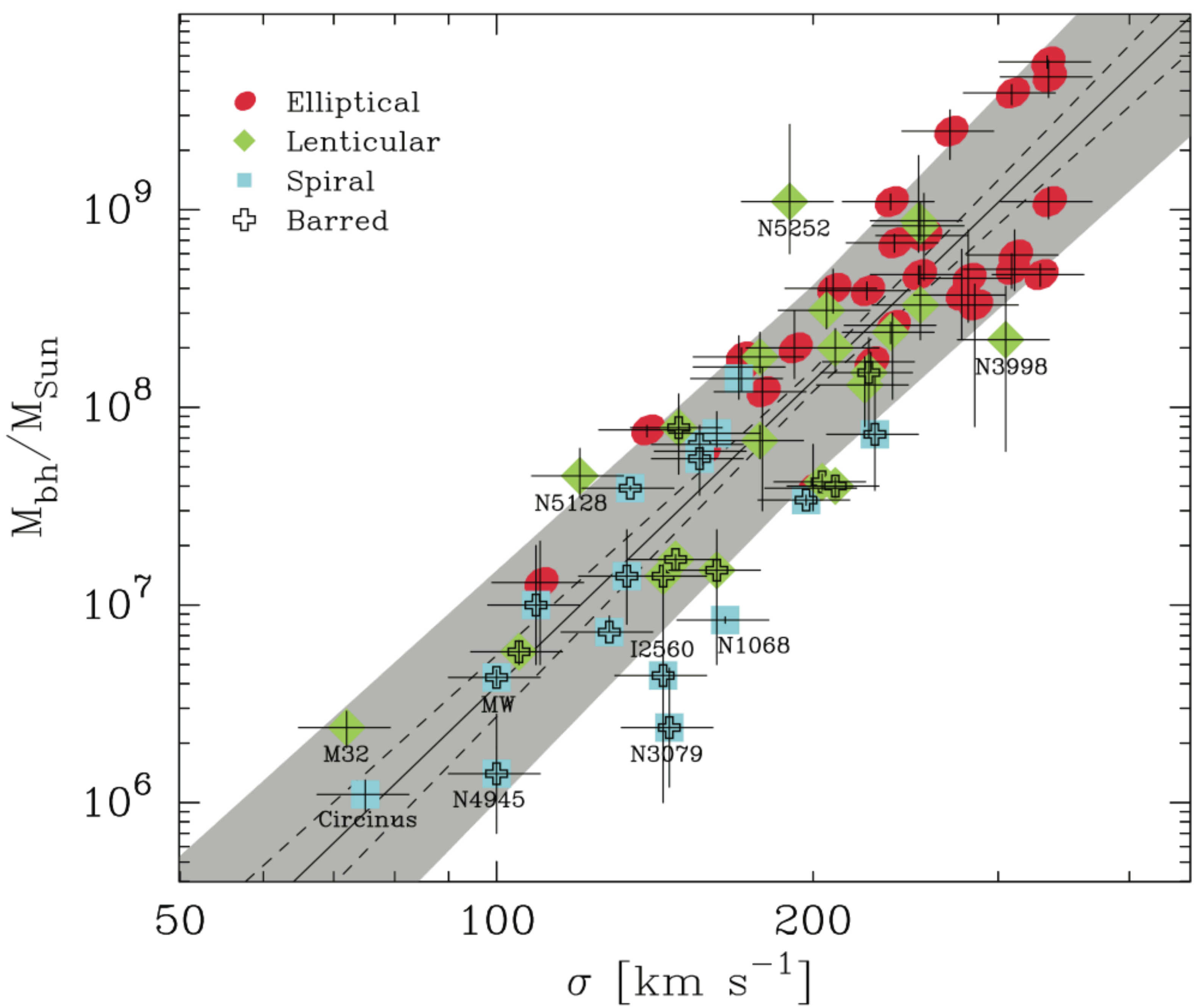
Big Black Holes are in big galaxies!

This argument is too simple, does not take into account intrinsic scatters but indicate that one must take into account the intrinsic relations among the various parameters (eg. Fundamental Plane of elliptical galaxies).

Observational biases

Recall the $R_{BH}=\Delta\theta$ for BH detection, then maximum distance at which a BH can be detected is

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



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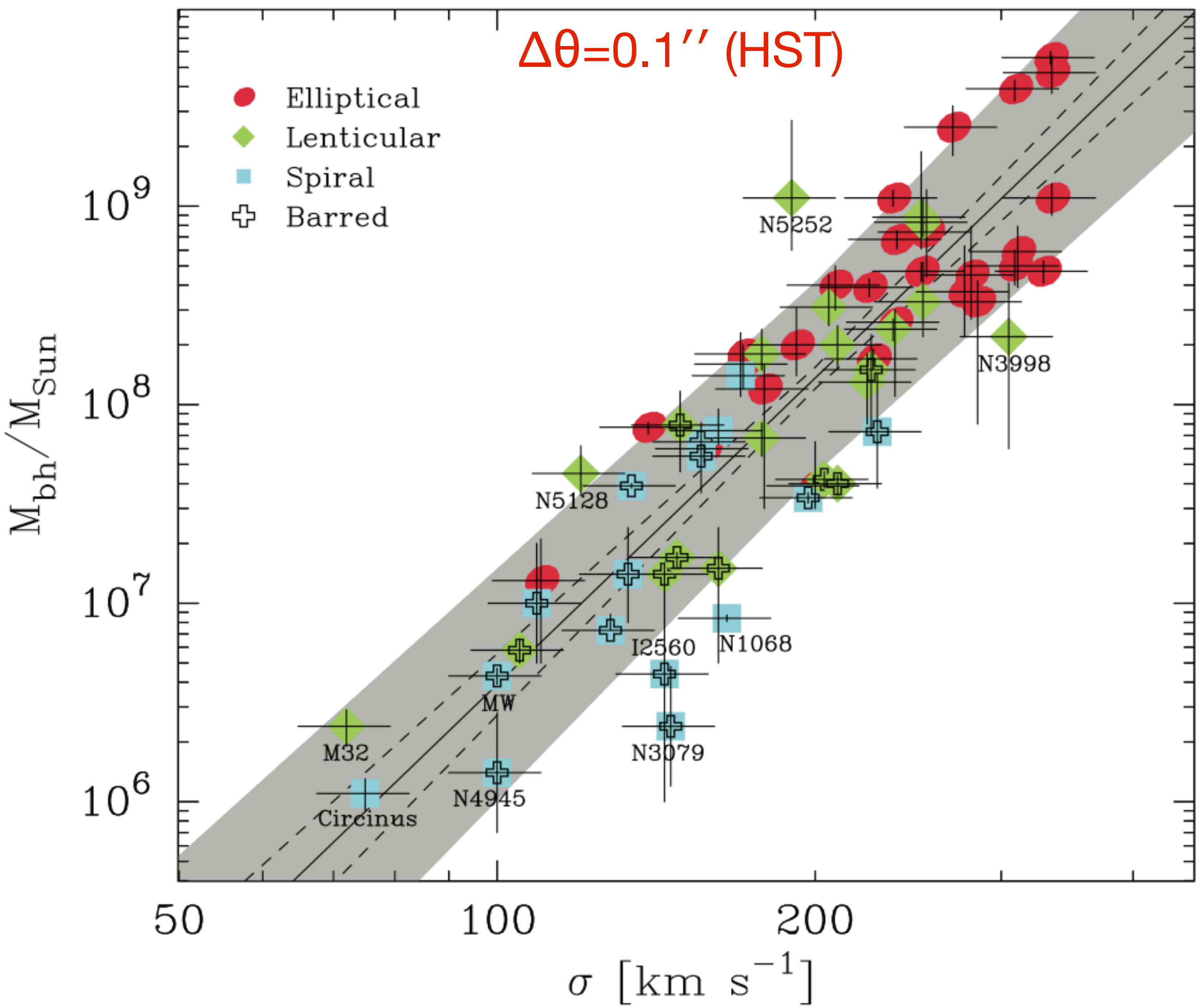

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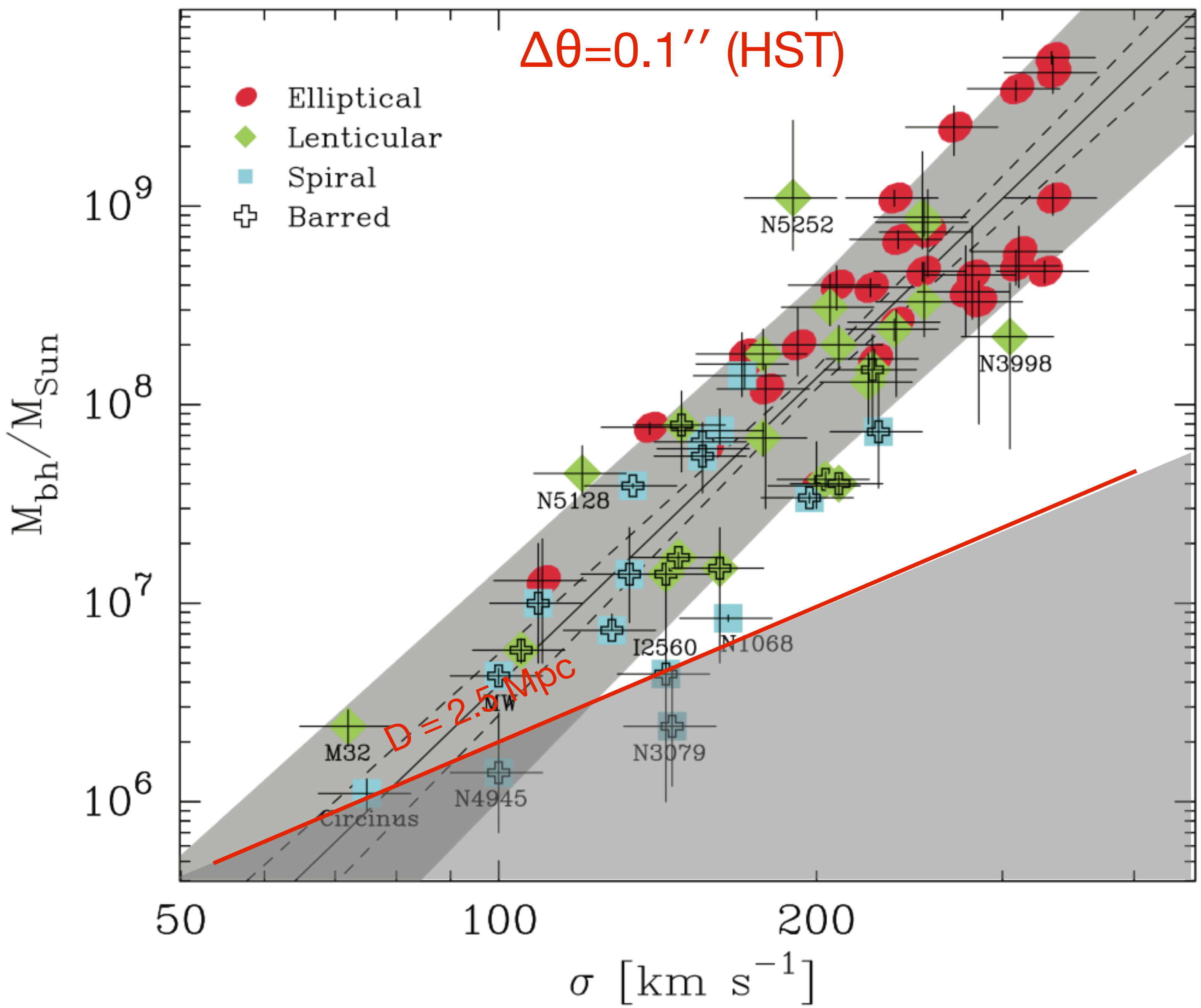

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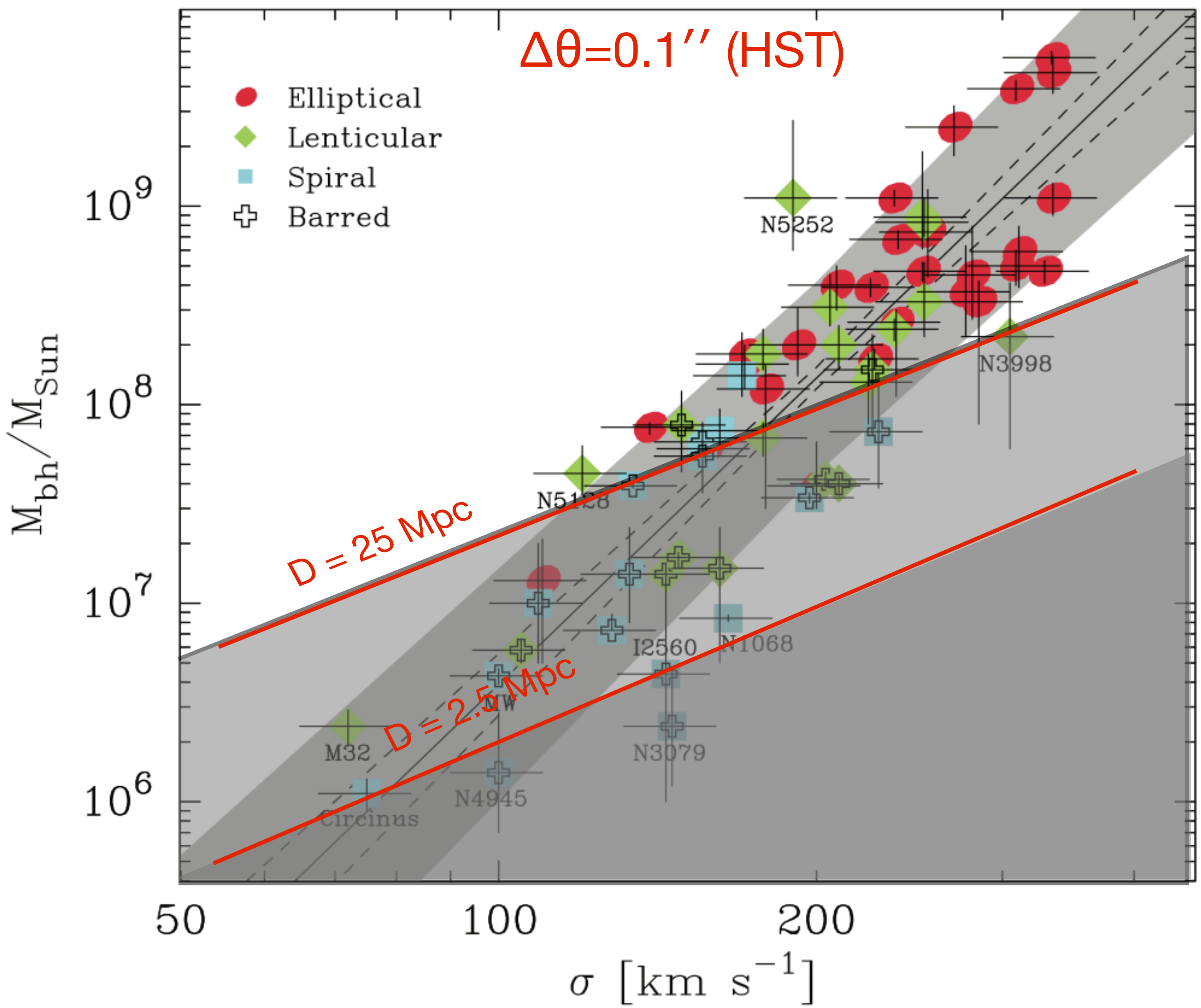

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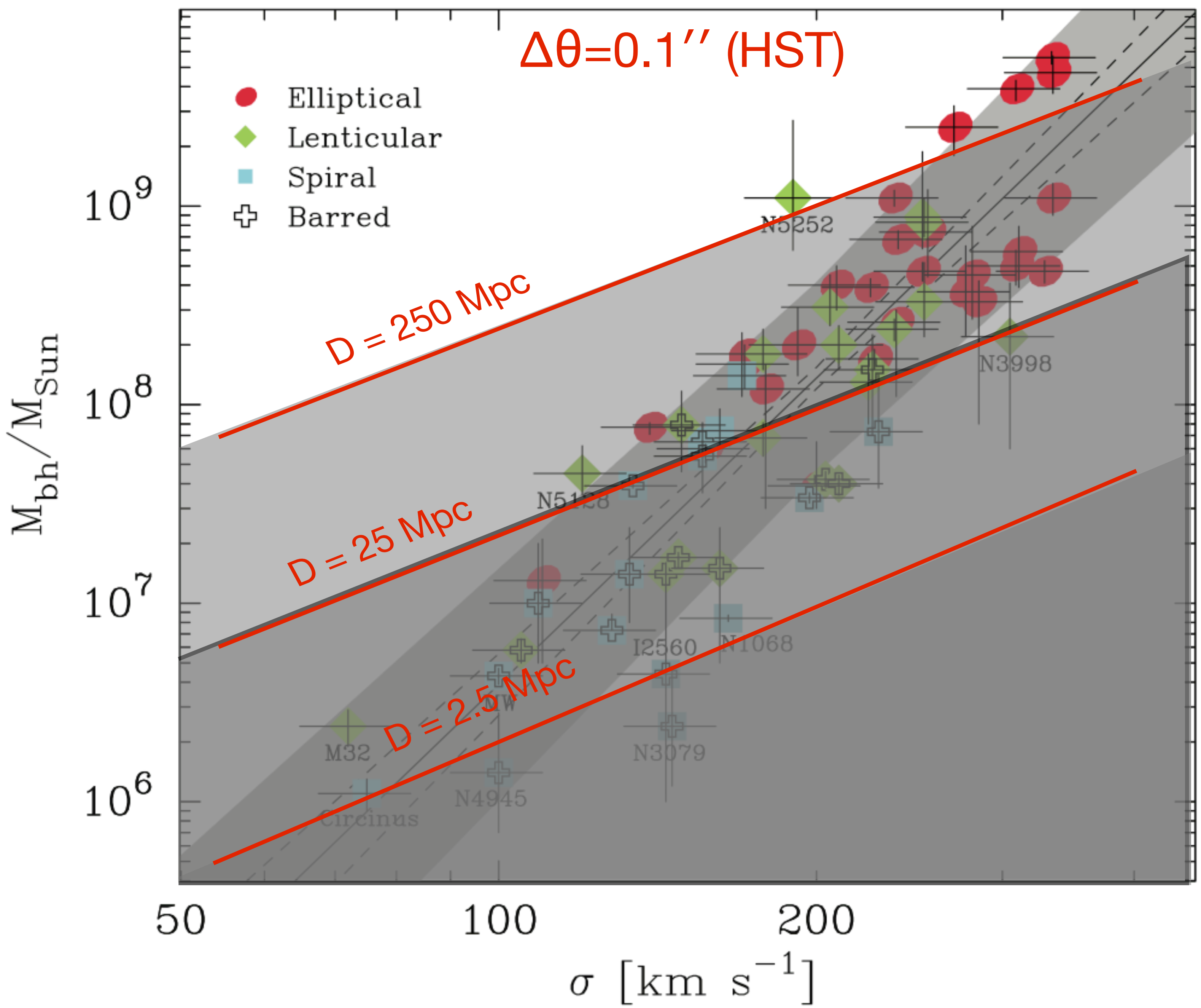

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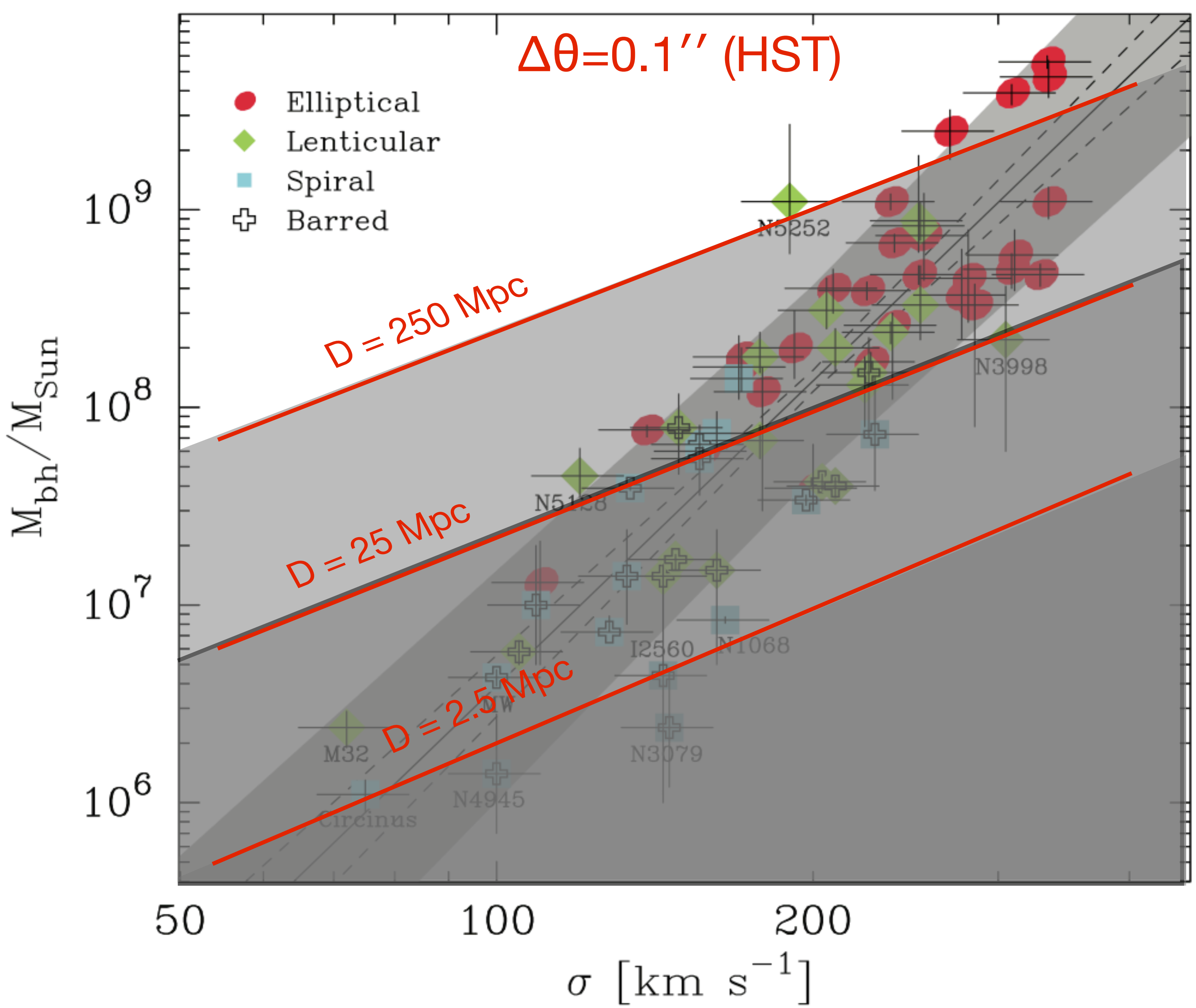


NO detection areas on M_{BH}-σ diagram for given Δθ, D:

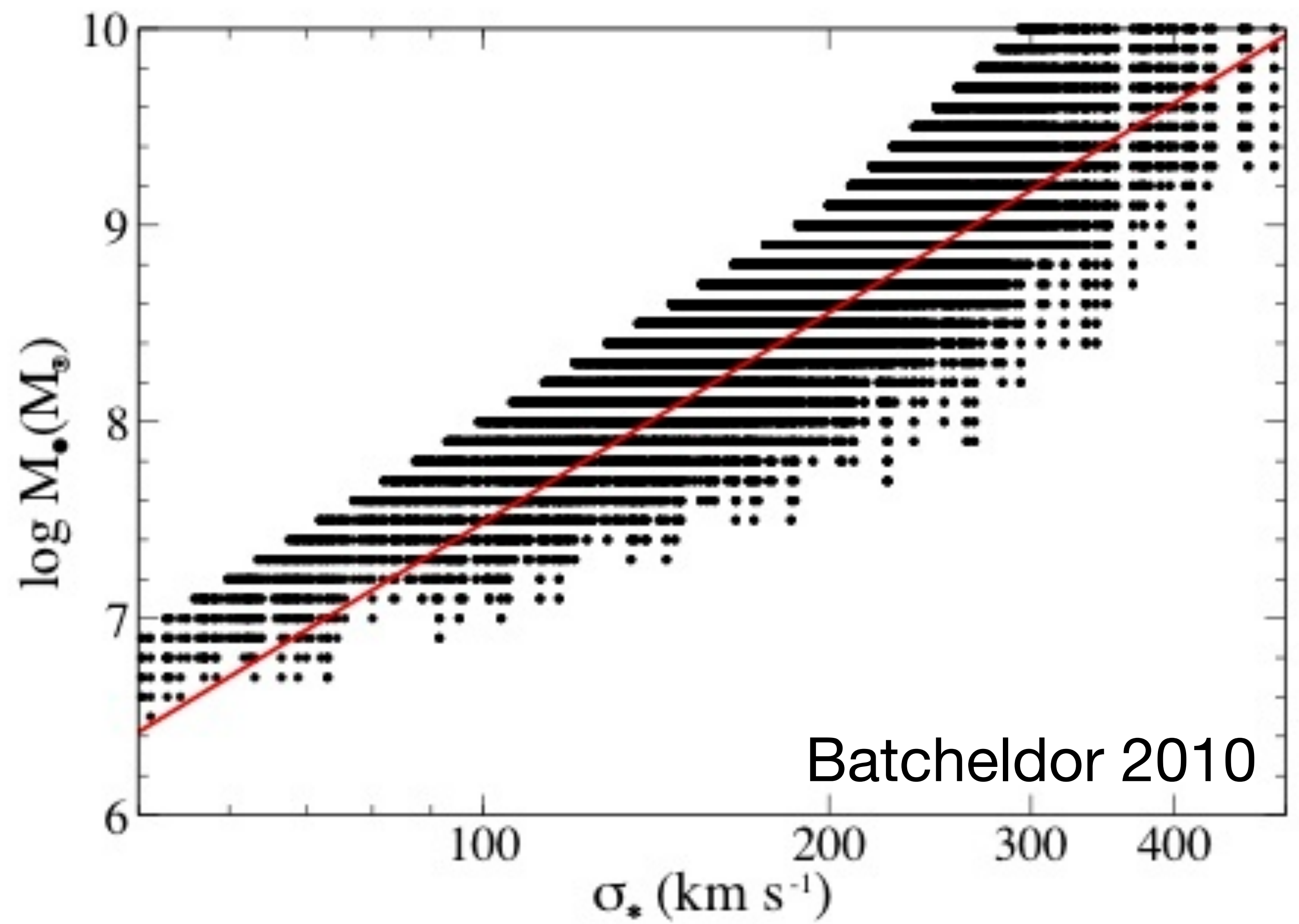
- Direct M_{BH} measures are limited to the local universe (D~250 Mpc)
- There are definitely no BHs above the correlation (big BHs in small galaxies)
- The area below the correlation is 'biased' and cannot be explored (small BHs in big galaxies?)

An upper envelope?

M_{BH}-σ an "upper envelope"?

Batcheldor (2010):

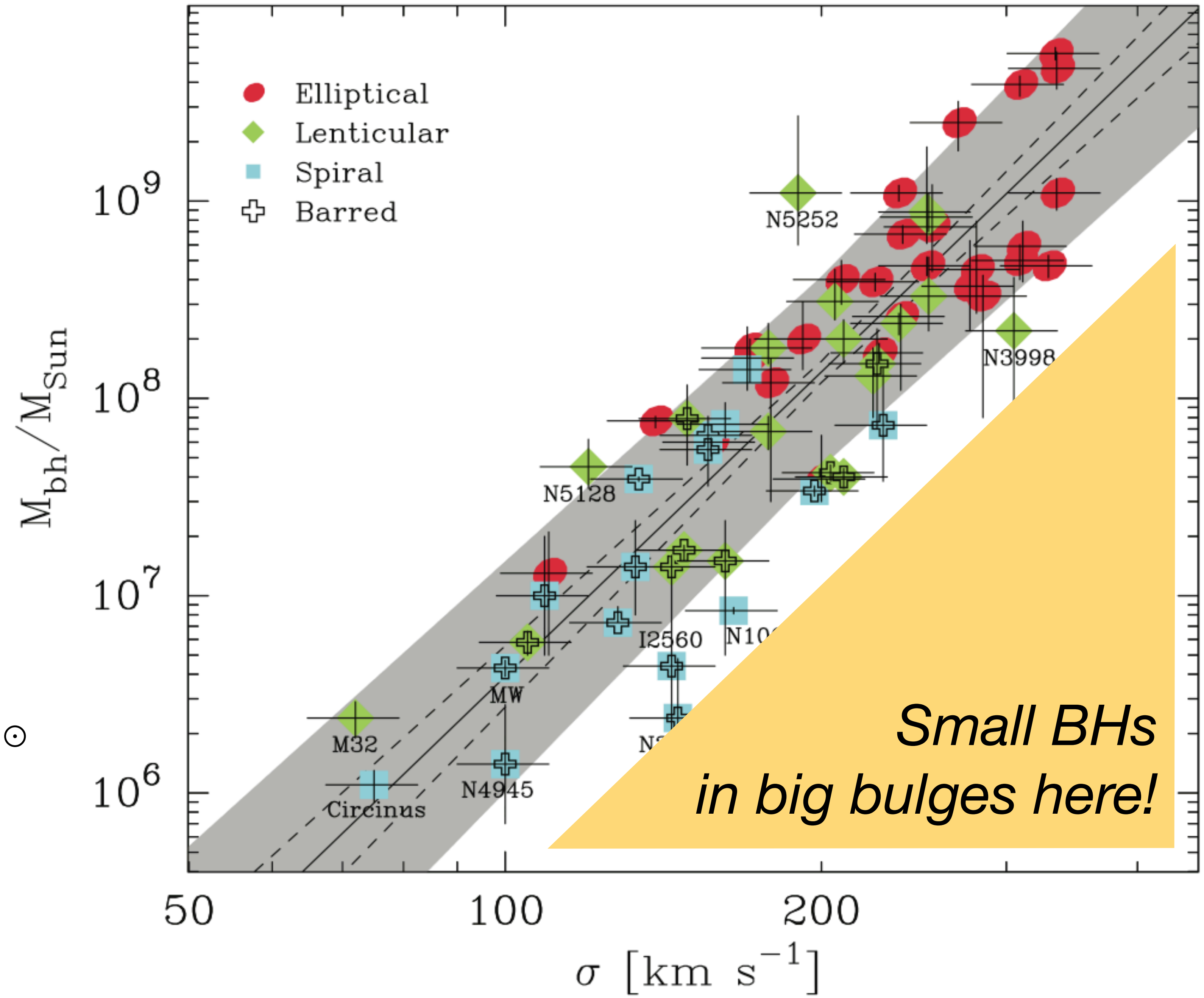
- Take all galaxies with σ from Leda database and assign them random M_{BH} within 0-M_{BH}(σ)
- cut away those objects for which R_{BH} < 0.1" (max spatial resolution with HST)
- Observed M_{BH}-σ with correct slope and scatter is reproduced!



- We are missing small BHs in large galaxies (if they exist).
- *M_{BH}-σ might be an upper envelope!*
- *However analysis by Gultekin et al. 2011 suggests this is not possible (at least in Early types) because we have too many detections already ...*

Problems and open issues

Graham+2010



Problems and open issues (beyond those on M_{BH}):

- 64 galaxies with M_{BH} (Graham+2010)
- difficult to assess the reliability and accuracy of all points;
- few points at low/high mass ends
  - #9 $10^6 < M_{BH} < 10^7 M_\odot$
  - #7 $10^9 < M_{BH} < 5\ 10^9 M_\odot$
- mostly E/S0, few spirals
  - #48 E+S0
  - #16 Spirals
- is there really a BH fundamental plane?
- do all galaxies follow the same correlation?
- are there small BHs in massive galaxies (e.g. M_{BH}-galaxy relations an upper envelope)?

What is the physical origin?

How does the BH know about its host galaxy and galaxy about its BH?

Radius of BH sphere of gravitational influence: $$R_{BH} = \frac{GM_{BH}}{\sigma_\star^2}$$

Observed correlation:

$$M_{BH} \simeq 10^{-3} M_{sph}$$

Spheroid virial mass:

$$M_{sph} \simeq 5 \frac{\sigma_\star^2 R_{sph}}{G}$$

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Spheroid virial mass:

$$M_{sph} \simeq 5 \frac{\sigma_\star^2 R_{sph}}{G}$$

$$R_{BH} = \frac{GM_{\rm BH}}{\sigma_\star^2} \simeq 5 \times 10^{-3} R_{sph}$$

$$V_{BH} \simeq 1.3 \times 10^{-7} V_{sph}$$

The volume under the BH influence is only ~10^{-7} of the total volume.

No gravitational “exchange” of information!

BH-galaxy coevolution

If BH grown by accretion, the energy released during growth is

$$L = \varepsilon \dot{M}_{acc} c^2$$

$$\dot{M}_{BH} = (1-\varepsilon)\dot{M}_{acc}$$

$$E_{grow} = \frac{\varepsilon}{1-\varepsilon} M_{BH} c^2$$

The gravitational binding energy of the virialized spheroid is

$$E_{grav} \simeq M_{sph}\sigma_\star^2$$

$$\frac{E_{grow}}{E_{grav}} \simeq \frac{\varepsilon}{1-\varepsilon}\left(\frac{M_{BH}}{M_{sph}}\right)\left(\frac{\sigma_\star}{c}\right)^{-2} = 250\left(\frac{\sigma_\star}{200\,km\,s^{-1}}\right)^{-2}$$

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Energy released by accreting BH (i.e. AGN) can affect galaxy structure and can unbind, eg, gas in the galaxy.

AGN feedback can let the galaxy know about the BH!

By regulating the feeding to the BH the galaxy can let the BH know about it!

The need for AGN feedback (eg King 2010)

- Assume AGN emit (close) to the Eddington ratio and that there is a radiation driven outflow from the AGN: can explain M_{BH}-σ
- Two relevant cases for $\dot{m} = \dot{M}/\dot{M}_{Edd}$
  - $\dot{m} \sim 1$ momentum driven outflow which sweeps ISM in a shell. This shell recollapses unless M_{BH} has reached critical value

$$M_{\rm BH} = \frac{f_g \sigma_T}{\pi m_p G^2} \sigma^4 = 3.7 \times 10^8 \, {\rm M}_\odot \left(\frac{\sigma}{200\,{\rm km}} \right)^4$$

~OK

  - $\dot{m} \gg 1$ energy driven outflow which sweeps ISM gas in a shell; imposing expansion work equal to E injection rate (Silk & Rees 1998)

$$M_{\rm BH} = \frac{f_g \sigma_T}{\pi m_p G^2 c} \sigma^5 = 2.4 \times 10^5 \, {\rm M}_\odot \left(\frac{\sigma}{200\,{\rm km}} \right)^5$$

too small!

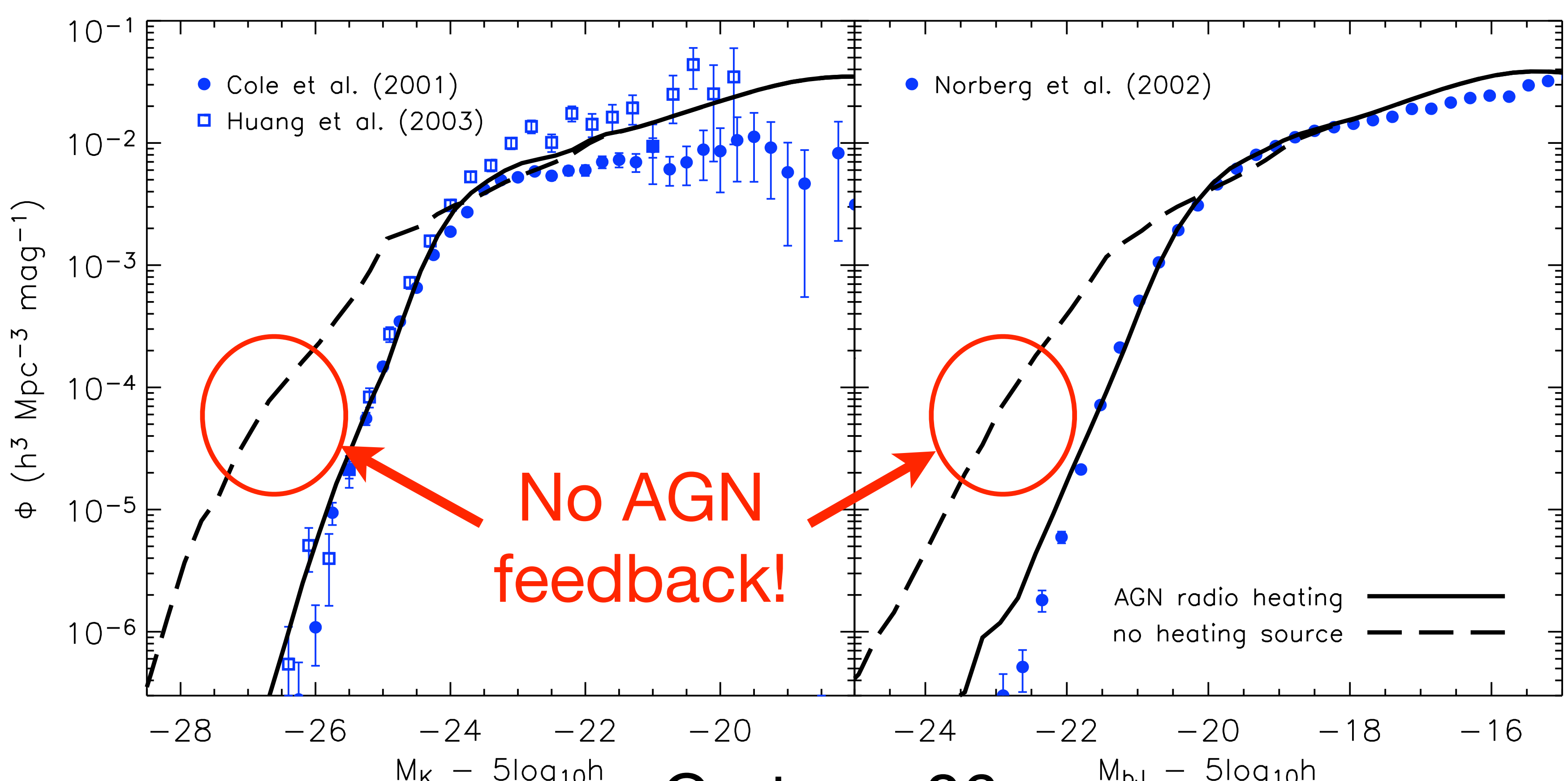
- Slope and normalization different in the two cases
- No free parameters, the energy driven case does not seem to appear in nature (bubble blown in energy driven case should break up for Rayleigh-Taylor instability due to large density contrast in shock)

The need for AGN feedback

AGN feedback (i.e. BH growth) can affect galaxy growth and explain M_{BH}-galaxy relation →**Cedric's lectures**

But AGN feedback is also needed to explain observed galaxy properties (e.g. apparent anti-hierarchical behaviour of galaxy evolution, red colors of ellipticals, steepness of optical luminosity function).

*AGN phases are **fundamental** in the evolution of galaxies.*



Croton +06

The ultimate goal...

Several models can explain M_{BH}-galaxy relations with various "flavours" of AGN feedback on the host galaxy.

Silk & Rees 98, Kauffman & Haehnelt 00, Cavaliere & Vittorini 00, Granato+ 04, 06, Murray +04, Di Matteo+05, Cattaneo+ 05, Miralda-Escudè & Kollmeier 05, Monaco & Fontanot 05, Croton +06, Hopkins +06, Malbon +06, Marulli +08

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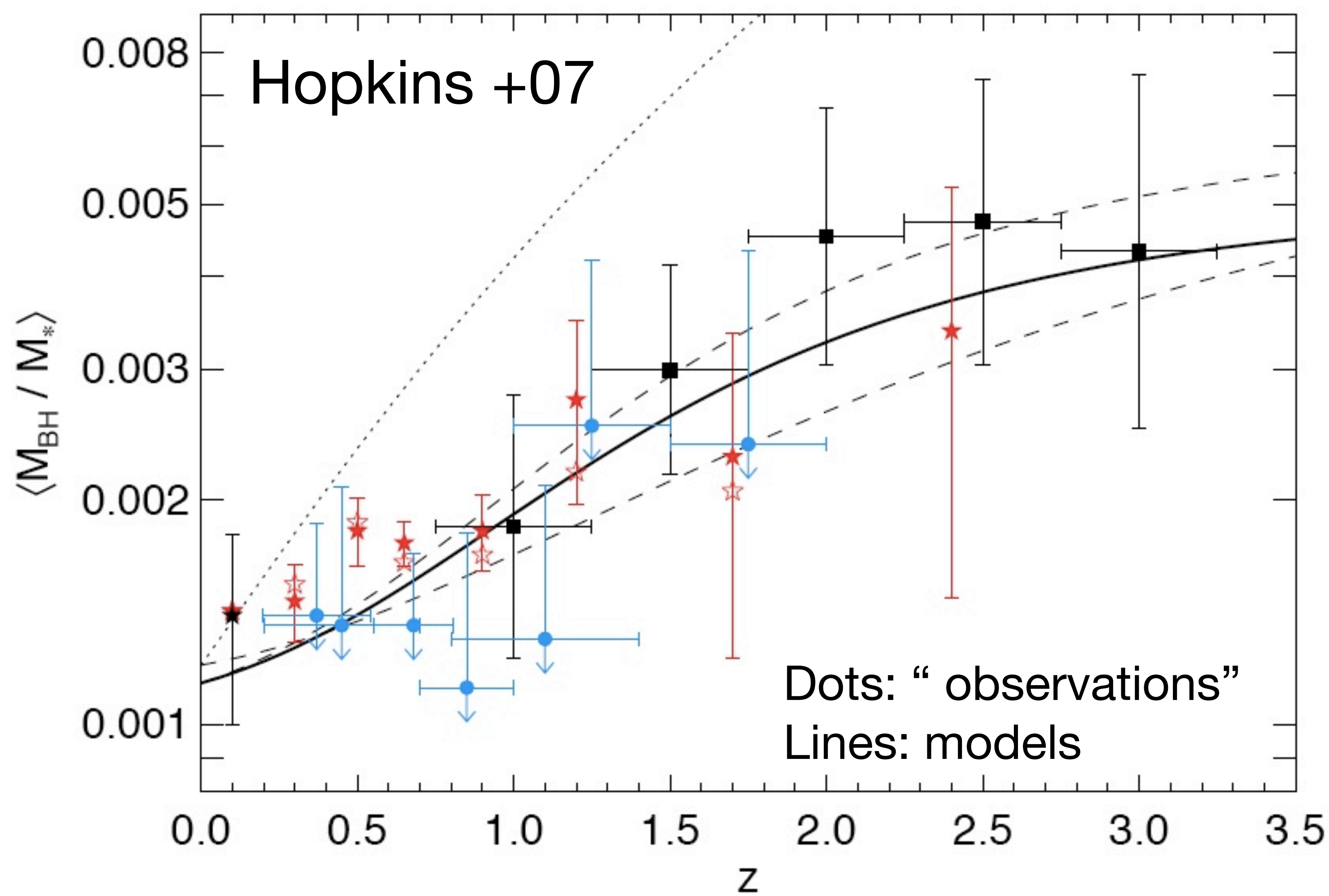
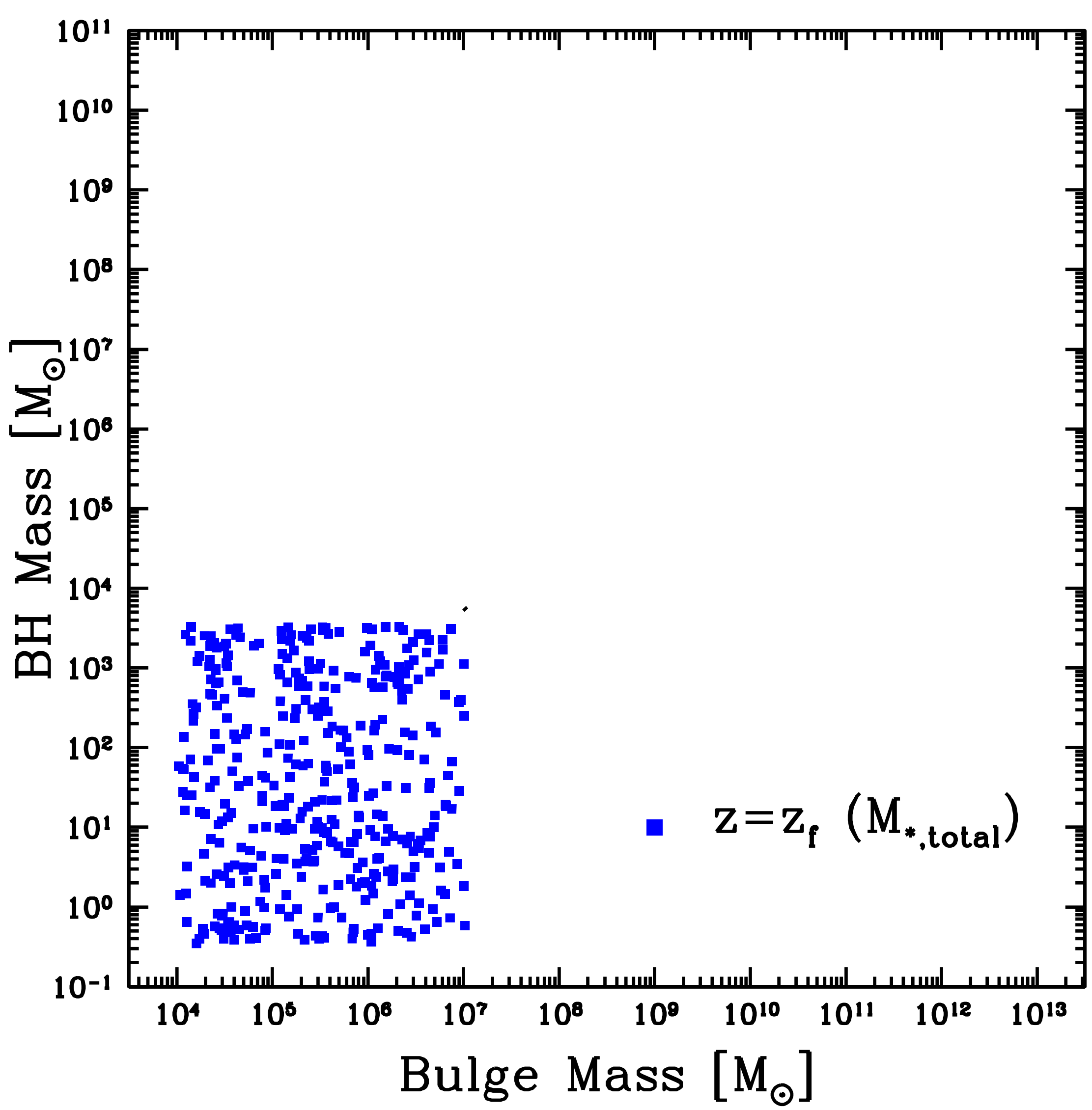
Redshift evolution of M_{BH}-galaxy relations can constraint BH growth and galaxy evolutionary models.



Fundamental to measure M_{BH} at ALL redshifts!

Do we really need feedback?

- Populate dark halo merger trees with uncorrelated BH and M_{star}
- Follow evolution with recipes for star formation and BH accretion that reproduce what is globally observed (see later) but without any coupling of the two for individual galaxies (*no feedback*).
- It is possible to recreate the M_{BH}-M relation at z=0 with correct slope!
- *M_{BH}-M can also be the result of random merging events (Peng 2007)*



Jahnke & Macciò 2010

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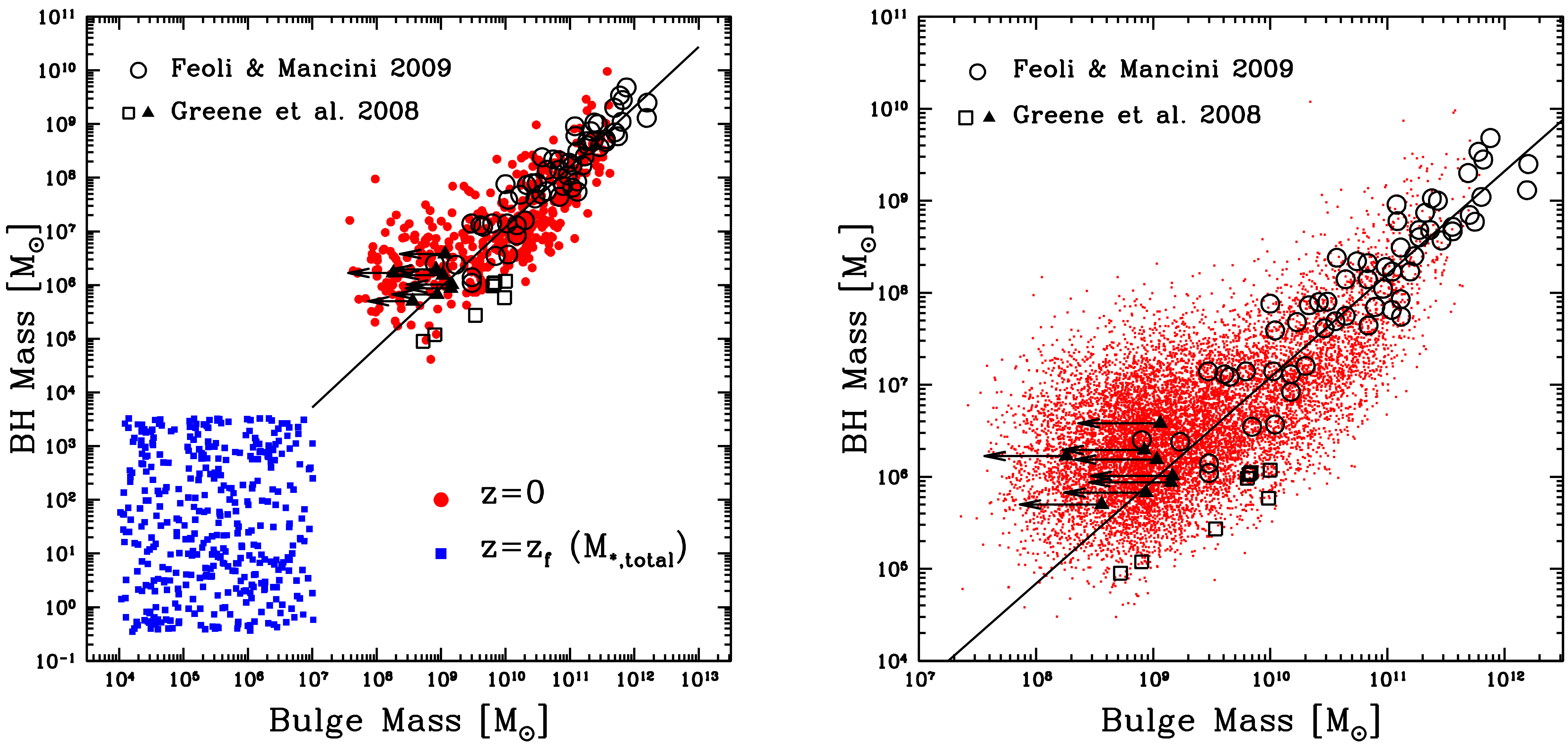

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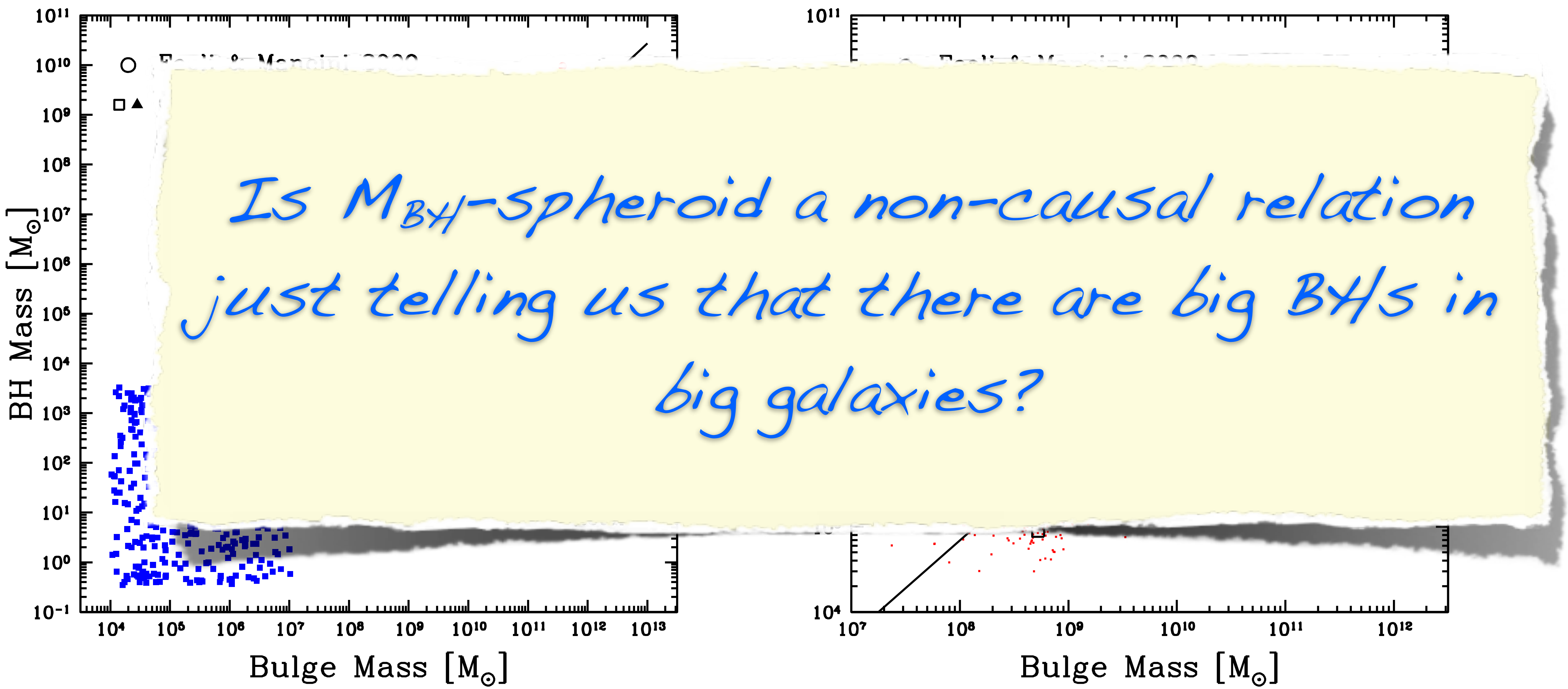


Is M_{BH}-spheroid a non-causal relation just telling us that there are big BHs in big galaxies?

Jahnke & Macciò 2010

Demography of local black holes

The following ingredients allow a demography of BHs in the nearby universe:

- assume BHs resides in the nuclei of ***all*** nearby galaxies
- assume *all* BHs follow the scaling relations with host spheroid (bulge): M_{BH}-σ,L
- combine with the luminosity- or σ- function of spheroids
- obtain the mass function on BHs in the local universe

Demography of local black holes

$$dN = \phi(M_{\rm BH})dM_{\rm BH}$$

number of BHs per unit volume with mass in M_{BH}, $M_{BH}+dM_{BH}$ range

$$\phi(M_{\rm BH}) = \int_0^{+\infty} P(M_{\rm BH}|L_{\rm sph})\phi(L_{\rm sph})dL_{\rm sph}$$

$$\phi(M_{\rm BH}) = \int_0^{+\infty} P(M_{\rm BH}|\sigma_e)\phi(\sigma_e)d\sigma_e$$

$\phi(L_{sph})$, $\phi(\sigma_e)$ are L_{sph}, σ_e functions of spheroids
$P(M_{BH}|L_{sph})$, $P(M_{BH}|\sigma_e)$ are the scaling relations written as conditional probabilities

$$\rho_{\rm BH} = \int_0^{+\infty} M_{\rm BH}\phi(M_{\rm BH})dM_{\rm BH}$$

BH mass density

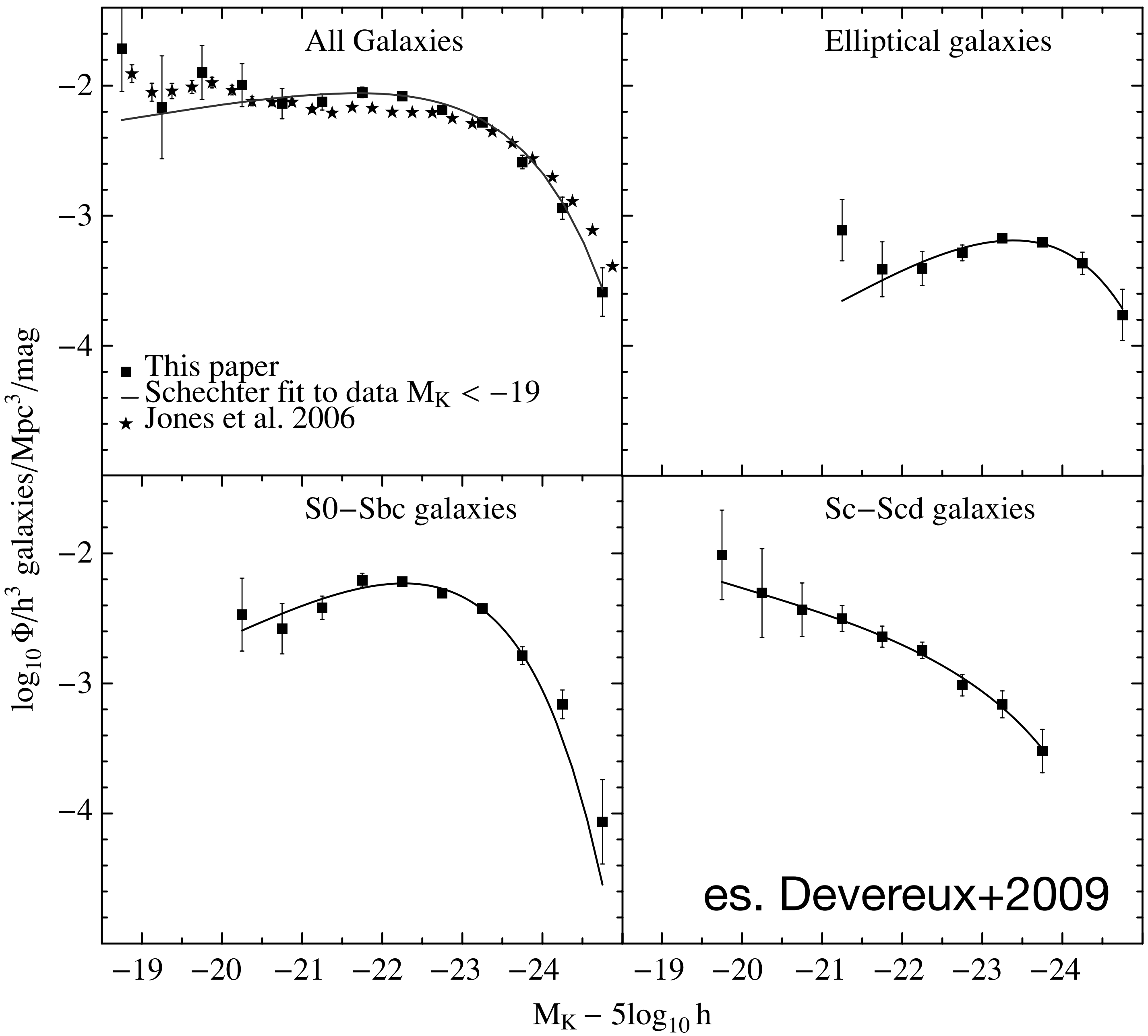
For example:

$$P(M_{\rm BH}|\sigma_e) = \exp\left[-\frac{1}{2}\left(\frac{\log(M_{\rm BH}/\,{\rm M}_\odot) - a - b\log(\sigma_e/200\,{\rm km\,s^{-1}})}{\sigma_0}\right)^2\right]$$

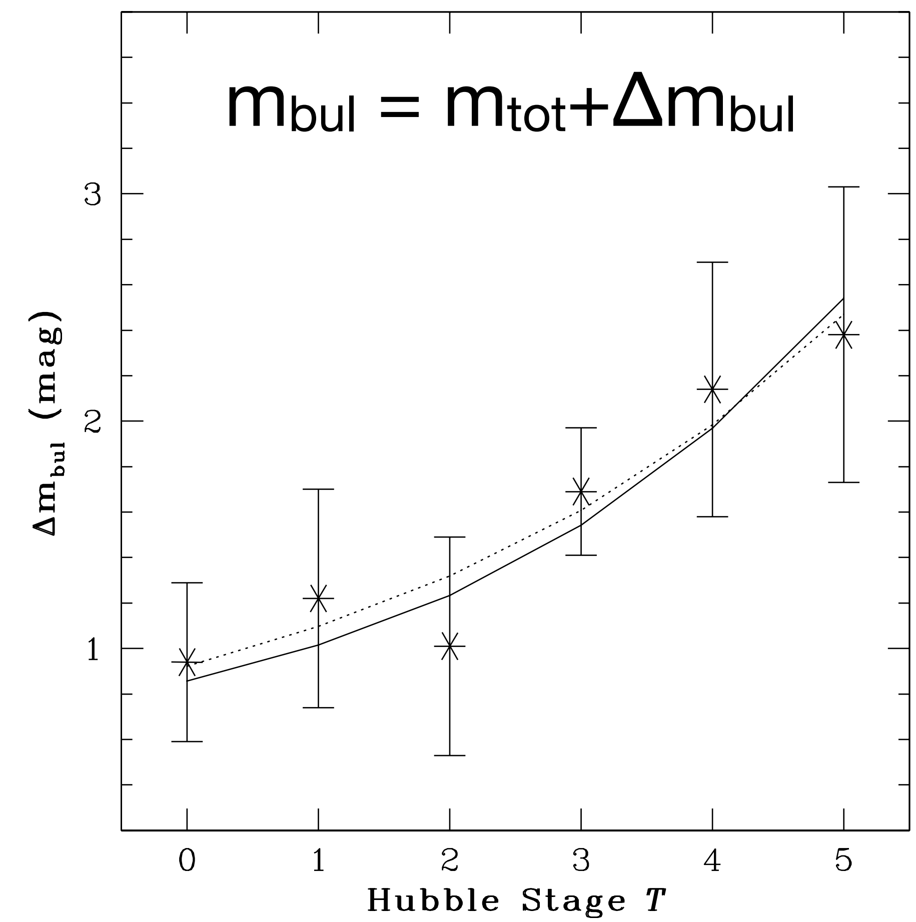
is the M_{BH}-L_{sph} relation with intrinsic scatter σ_0 (assumed normally distributed).

Luminosity function of spheroids

- To obtain the luminosity function of spheroids, one has to apply a bulge/total correction (B/T=1 for ellipticals).
- B/T depends on the morphological type
  → *need LF per morphological type*



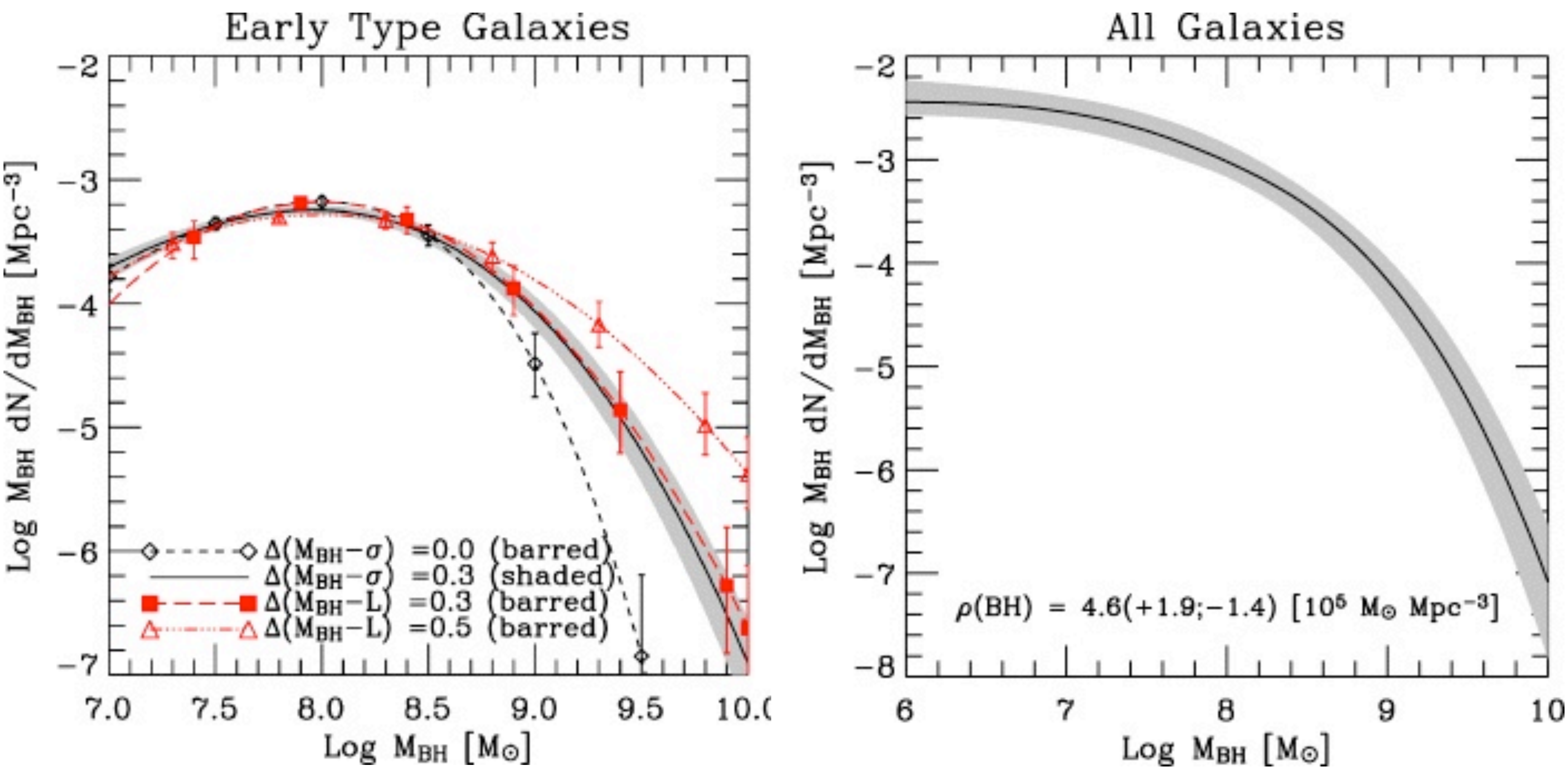
es. Devereux+2009



es. Dong & De Robertis 2006

Local BH mass function

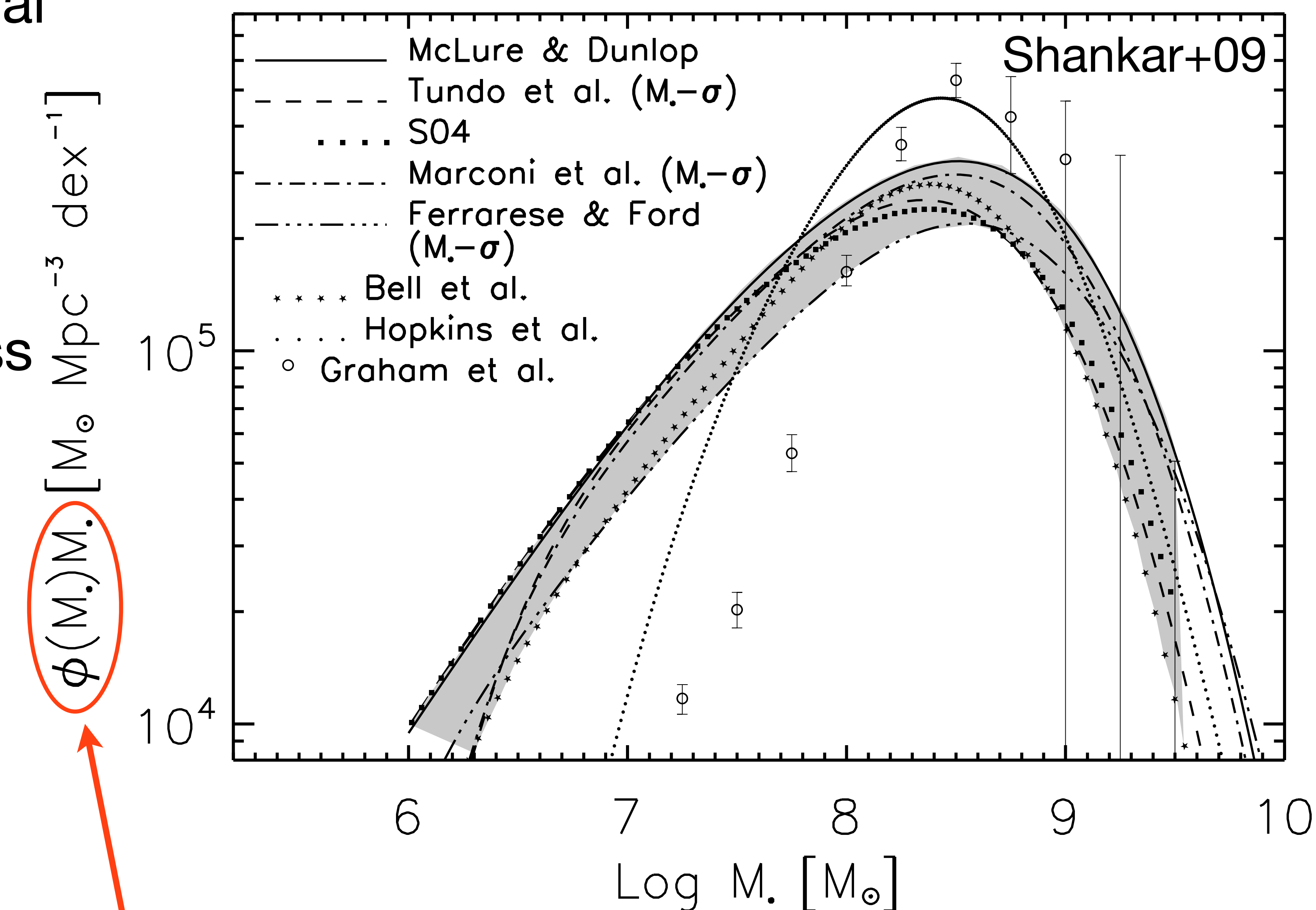
For 0 intrinsic dispersion, the BH mass function is just the L/σ function rescaled: $P(M_{BH}|L_{sph})$ is a Diracs's δ function.
The intrinsic dispersion significantly affects the high mass tail of the BH mass function.



Marconi et al. 2004

Local BH mass function

- Overall there is a general agreement (or not so large disagreement) among estimates from different authors.
- The integrated BH mass density is $\rho_{BH} \simeq 3.5\text{-}5.5 \times 10^5\ M_\odot\ Mpc^{-3}$
- Uncertainty are mostly due to M_{BH}-galaxy relations!
- ρ_{BH} depends mostly on the zero points of the correlations

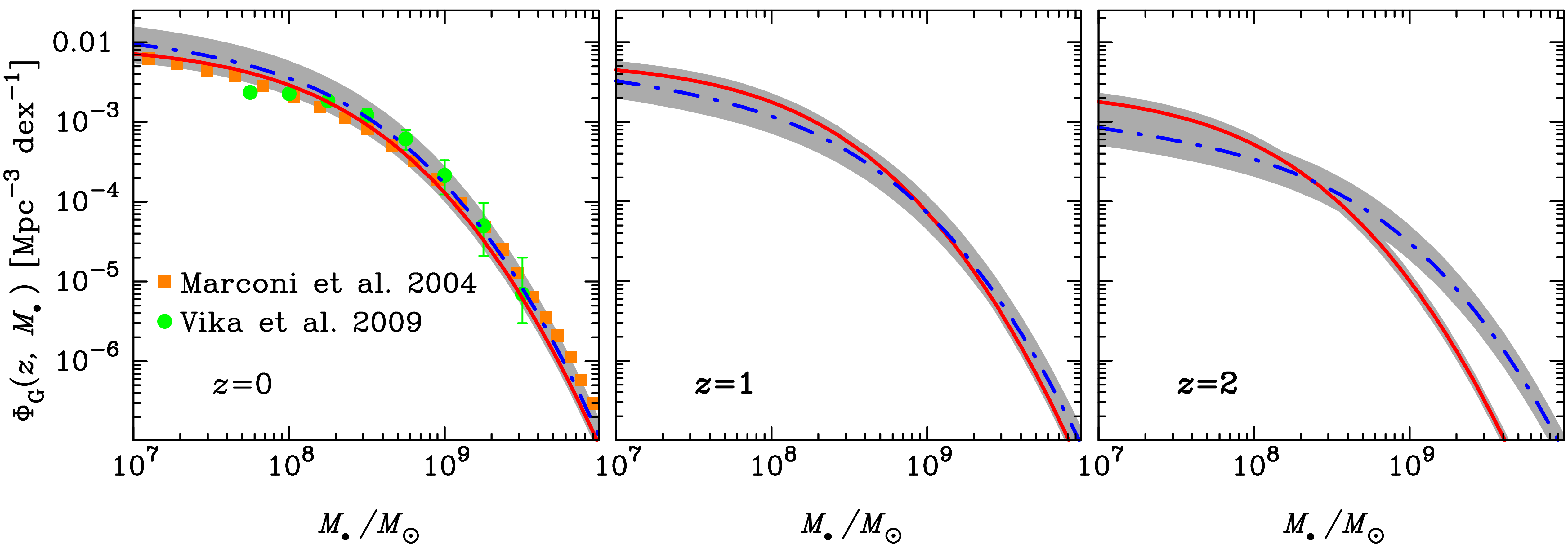


$\phi(M)\, M$ is directly the contribution to ρ_{BH}

Salucci +99, Yu & Tremaine 02, Marconi +04, Shankar +04, Tamura+06, Tundo +07, Hopkins +07, Graham +07, Shankar +08, Vika+09 et many al.

Local BH mass function

Li+11 has estimated the BHMF up to z~2, using the MBH-Mstar relation (and its redshift evolution, see last lecture) and phi(Mstar).
Their nice work matches previous results at z=0, indicating that the estimates of the BHMF and BH mass density appear to be robust.



Li, Ho & Wang, 2011