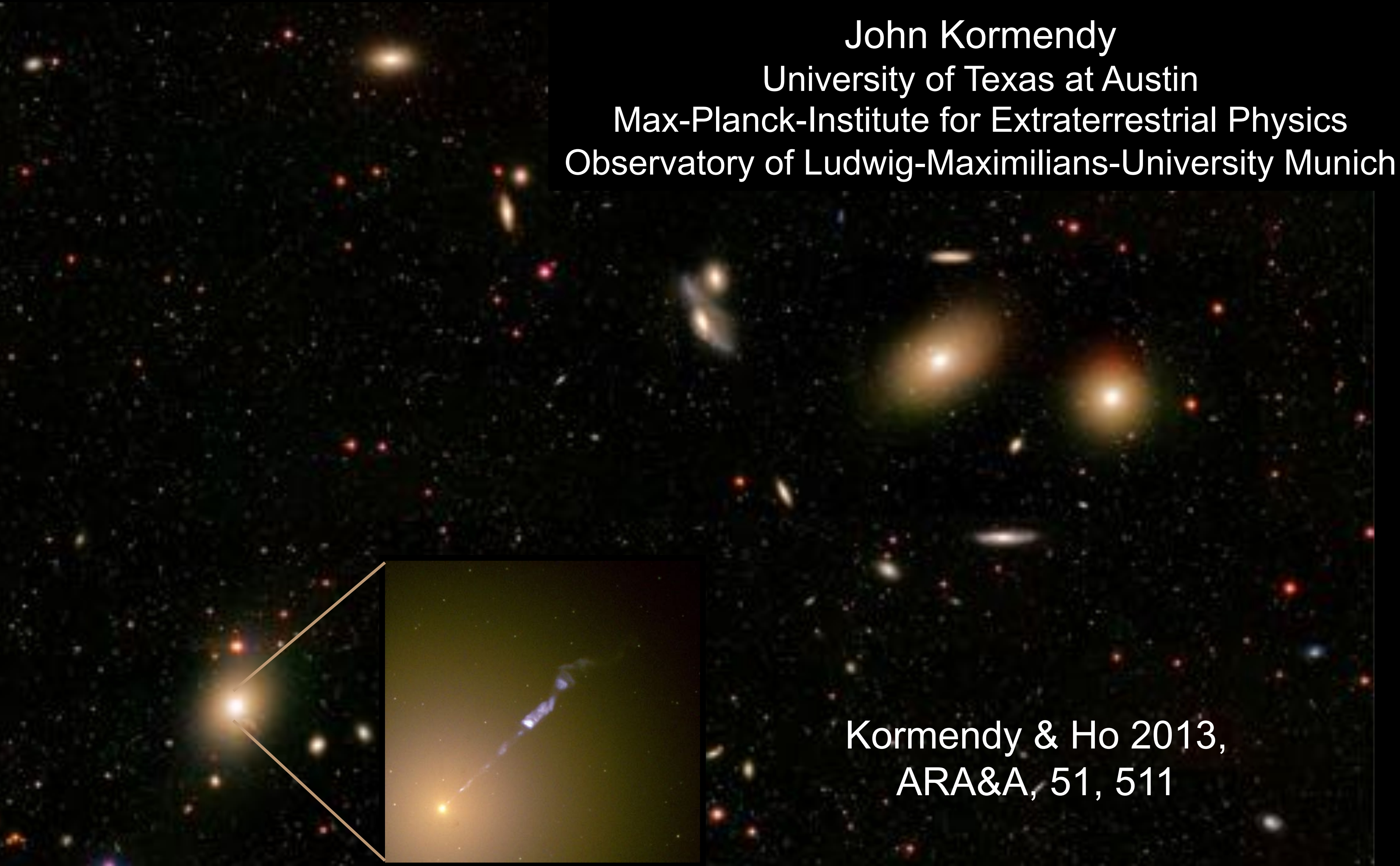
Co-Evolution (Or Not) of Supermassive Black Holes and Host Galaxies



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Kormendy & Ho 2013,
ARA&A, 51, 511

Summary

Almost every elliptical galaxy and many disk galaxies contain a central supermassive BH with mass $10^6 - 10^{10}\ M_\odot$. BHs power energetic nuclear activity (e. g., quasars) when they accrete gas and stars.

BH mass $\mathbf{M_\bullet}$ correlates with bulges+ellipticals but not with disks or pseudobulges or dark matter halos.

BH – host galaxy correlations $\mathbf{M_\bullet} - \mathbf{M_{bulge}}$ and $\mathbf{M_\bullet} - \sigma \Rightarrow$ how BHs and galaxies do (or do not) “coevolve”.

We have a robust picture of star-formation quenching at $z < 1$ (Kormendy 2015, arXiv:1504.03330).

$M_\bullet$—L_{bulge}, $M_\bullet$—M_{bulge}, $M_\bullet$—σ Correlations ➔

CONCLUSION

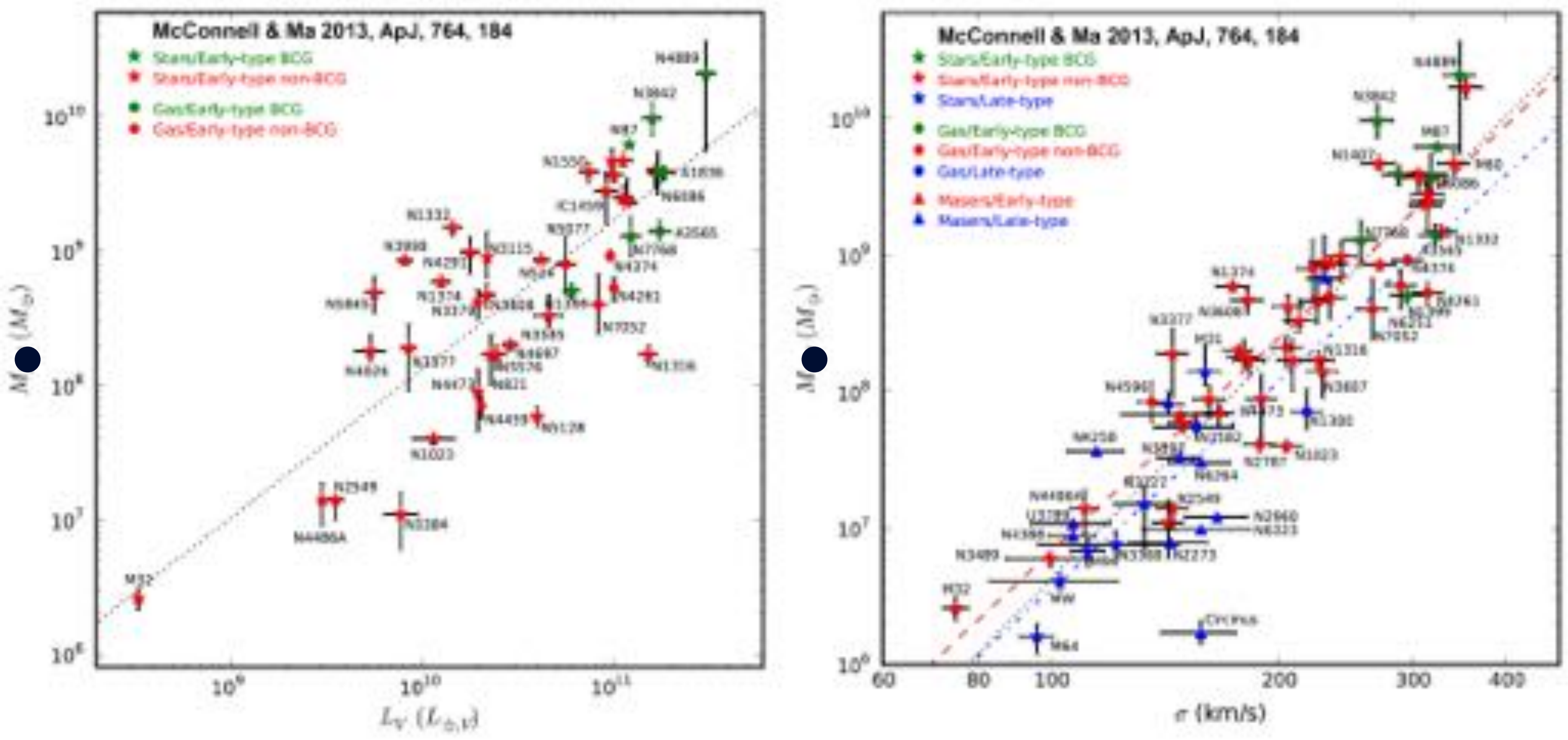
**The formation of bulges and
the growth of their BHs as AGNs
happened together.**

BUT

**Enthusiasm for the idea that
BHs and galaxies control each other’s growth
by AGN feedback is overdone.**

Best M● compilation before Kormendy & Ho 2013:

Gültekin et al. 2009 Gültekin et al. 2009



Problems: Incorrect M● from ionized gas V(r) are included;

: No L_V for late-type bulges; uses L_V instead of L_K;

: No differentiation between classical and pseudo bulges (important);

: No differentiation between old Es and mergers in progress now (important);

: Does not use recently published M● for giant ellipticals that include DM in models.

Therefore (1) scatter is large; (2) zeropoint is wrong, and (3) new conclusions are missed.

Kormendy & Ho 2013 Theme

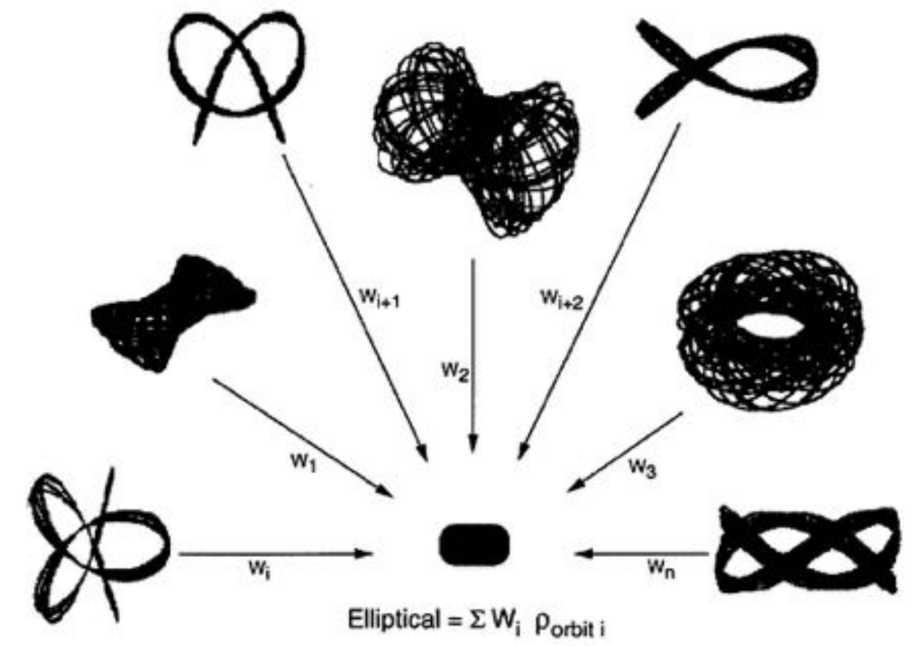
BH masses $M_\bullet$ correlate differently
with different galaxy components
that have different formation histories.

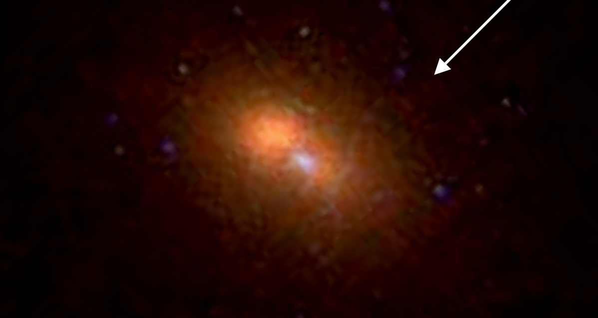
This allows us to refine our picture of BH-galaxy coevolution.

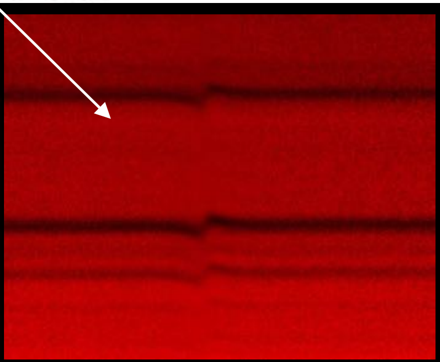
But I have to introduce details about galaxy structure
& implications about galaxy evolution.

We have BH detections in
44 elliptical galaxies +
42 disk galaxies
(21 with classical bulges + 21 with pseudobulges).

Schwarzschild’s (1979, ApJ, 232, 236) Method: Orbit Superposition Models







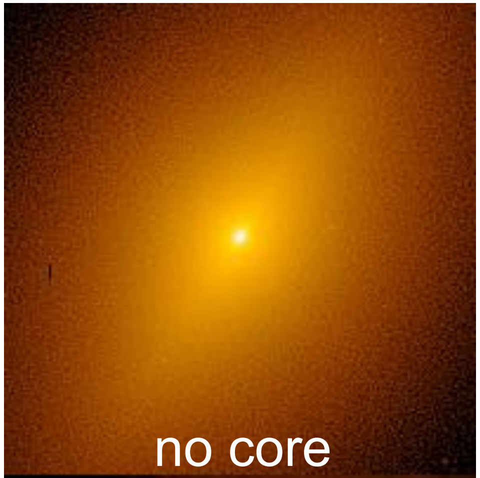
1 – Assume that volume brightness ➜ stellar density ➜ gravitational potential.
2 – Calculate all relevant orbits in this potential and their time-averaged density distrib^{n}.
3 – Make a linear combination of the orbits that fits surface brightnesses and velocities.

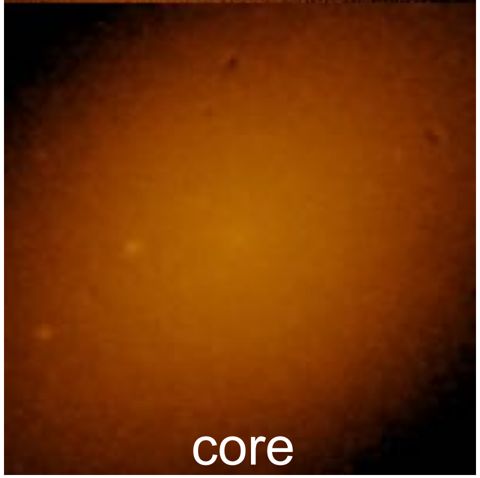
$M_\bullet$ got revised upward in core ellipticals only when we added halo dark matter to dynamical models.

Gebhardt & J. Thomas 2009, ApJ, 700, 1690;
Schulze & Gebhardt 2011, ApJ, 729, 21;
Gebhardt et al. 2011, ApJ, 729, 119;
Rusli et al. 2013, AJ, 146, 45

$M_\bullet = (6.2 \pm 0.4) \times 10^9\ M_\odot$ in M87 does not agree with $(3.8 \pm 0.9) \times 10^9\ M_\odot$ (Macchetto et al. 1997) from ionized gas dynamics ⇒ must include large emission-line widths ($\sigma \sim V$) in dynamical analysis.

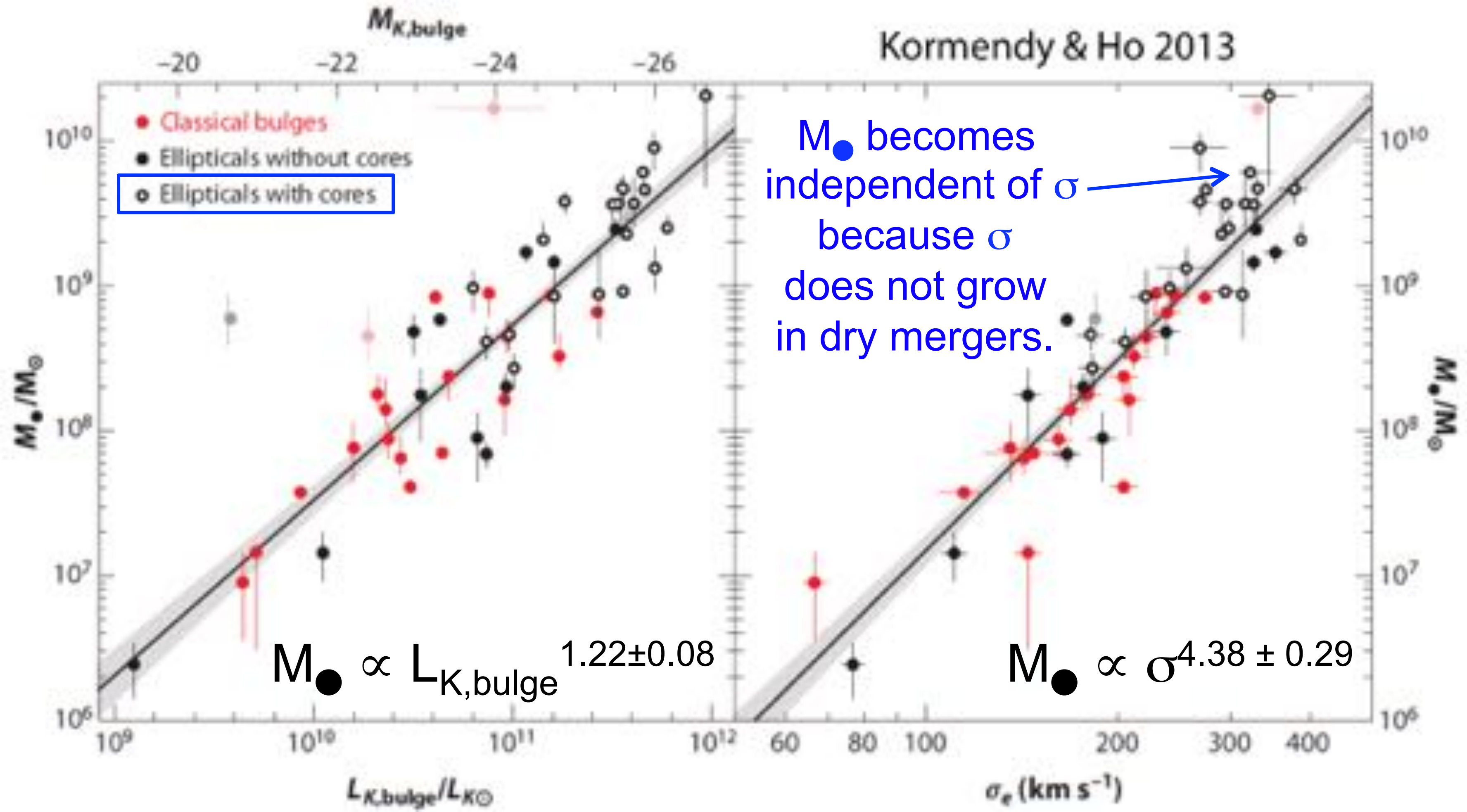
We prune 6 $M_\bullet$ estimates based on rotation curves $V(r)$ of ionized gas for which large emission-line widths ($\sigma \sim V$) were ignored.





The $M_\bullet$ - σ correlation saturates at high σ ...

… only in core galaxies, because Faber-Jackson relation saturates (Kormendy & Bender 2012, ApJ, 769, L5).



$M_\bullet$ becomes independent of σ because σ does not grow in dry mergers.

$M_\bullet \propto L_{K,\mathrm{bulge}}^{1.22\pm0.08}$

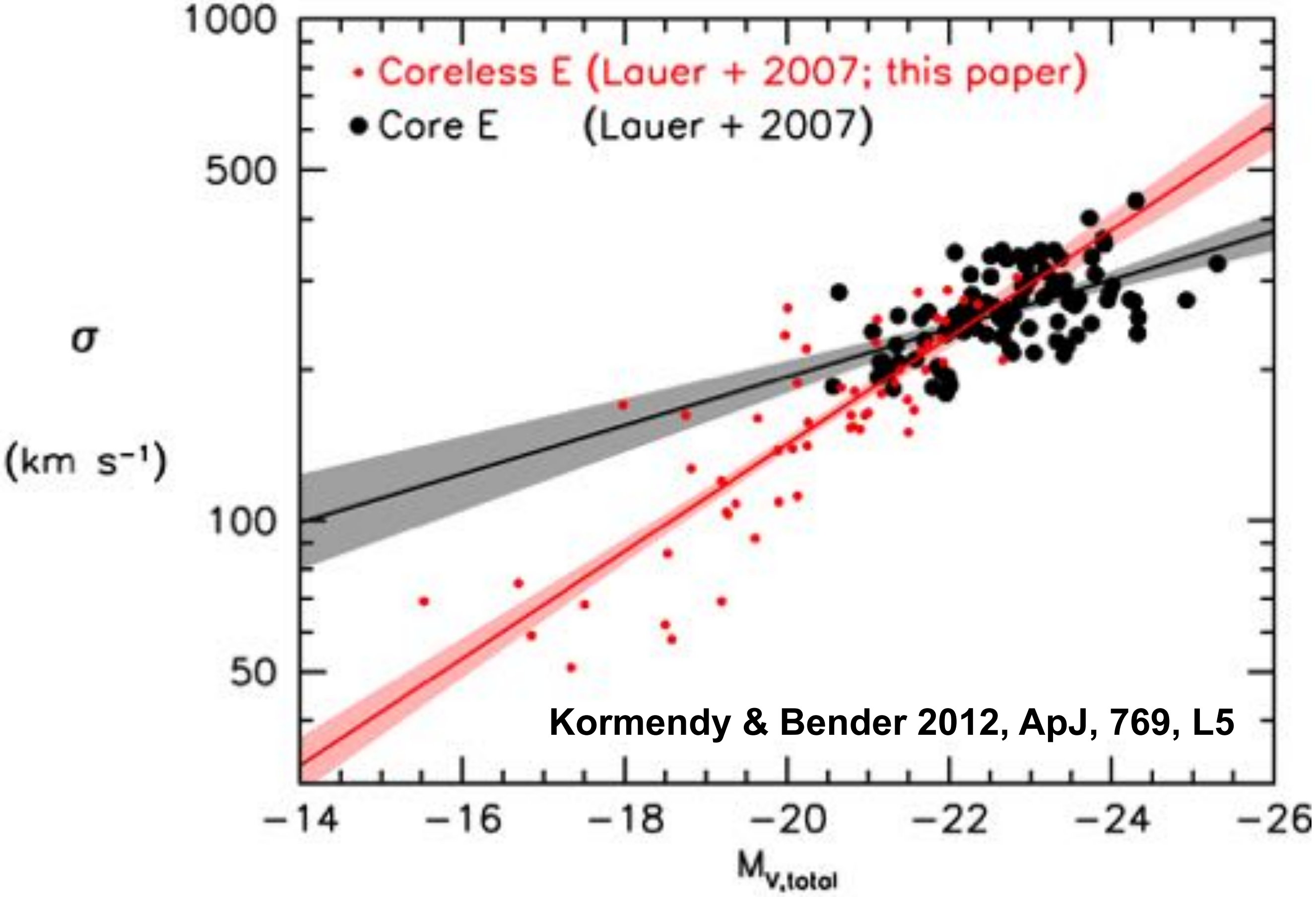
$M_\bullet \propto \sigma^{4.38 \pm 0.29}$

This is a sign that core ellipticals formed via dry mergers.

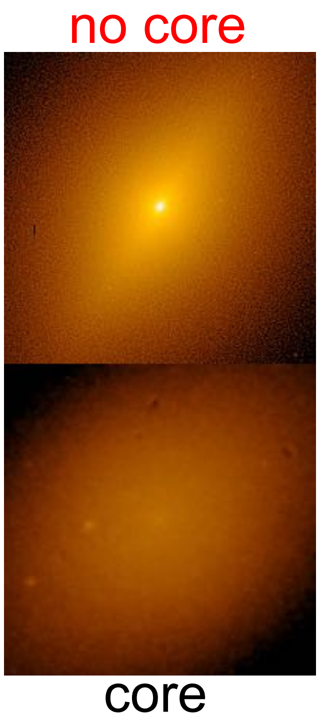
NOTE: Both correlations have the same intrinsic scatter of 0.28 dex in $M_\bullet$.

Faber-Jackson (1976) relation ($\sigma \propto L^{0.27}$ for coreless ellipticals) "saturates" for elliptical galaxies with cores: $\sigma \propto L^{0.12}$ or* $\sigma \propto M^{0.09}$.

*We used $M/L \propto L^{0.32}$ (Cappellari et al. 2006).



Kormendy & Bender 2012, ApJ, 769, L5



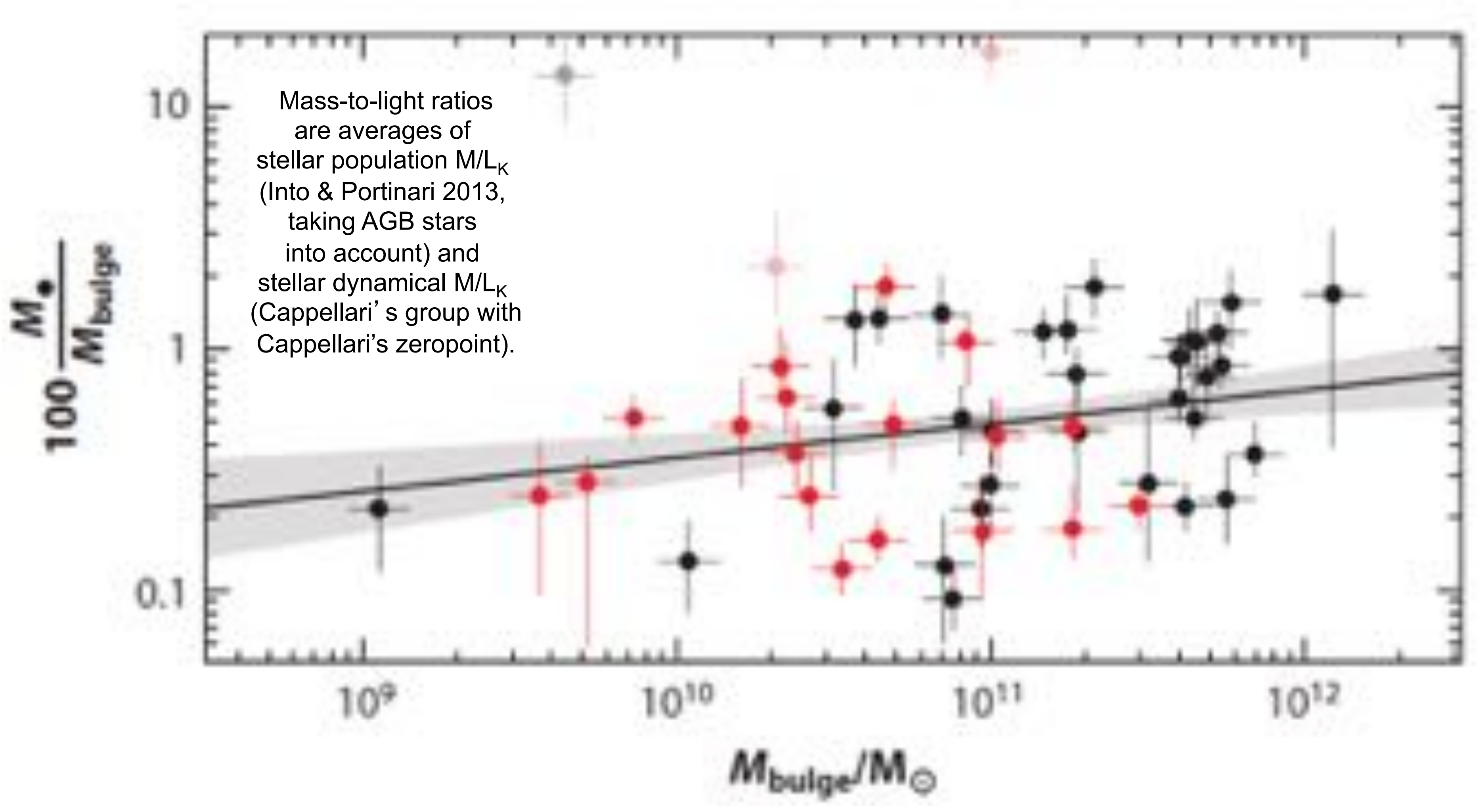
This is evidence that core Es formed via dry mergers:

N-body simulations also get a shallow $\sigma \propto M^{0.15}$ for major, dry mergers (Hilz et al. 2012).

Contrast: Minor mergers imply that $\sigma \propto M^{-0.05}$.

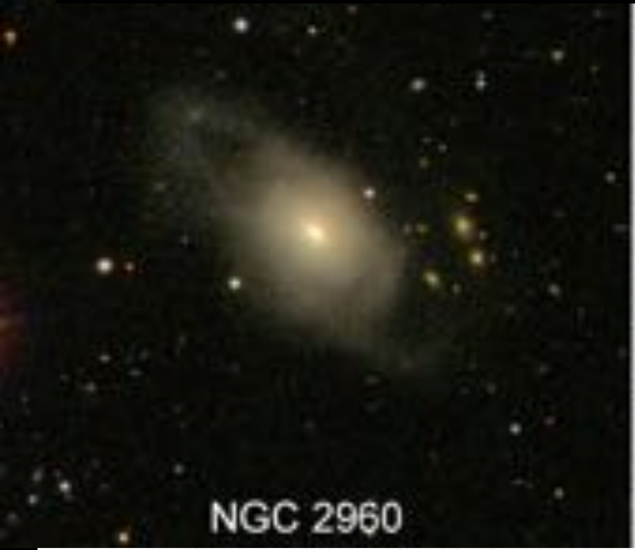
The canonical BH mass fraction is 0.5 %. This is ~ 4 times bigger than we thought.

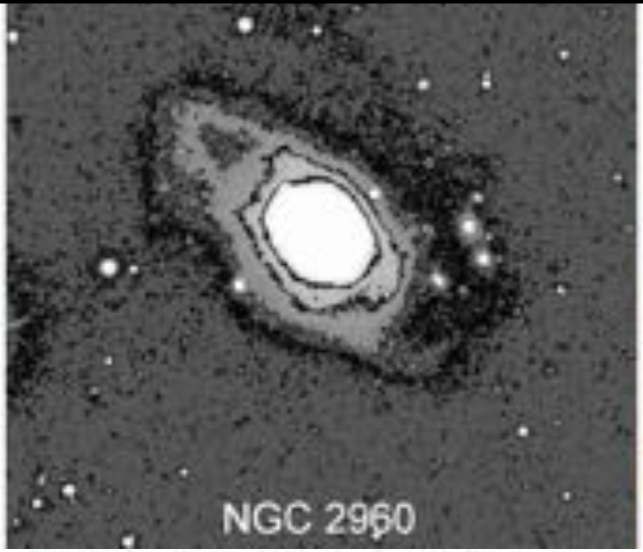
BH mass fractions scatter between 0.1 % and 2 %.

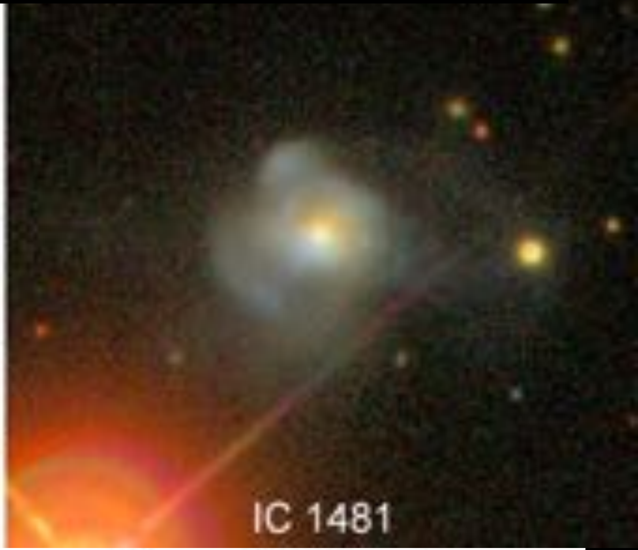


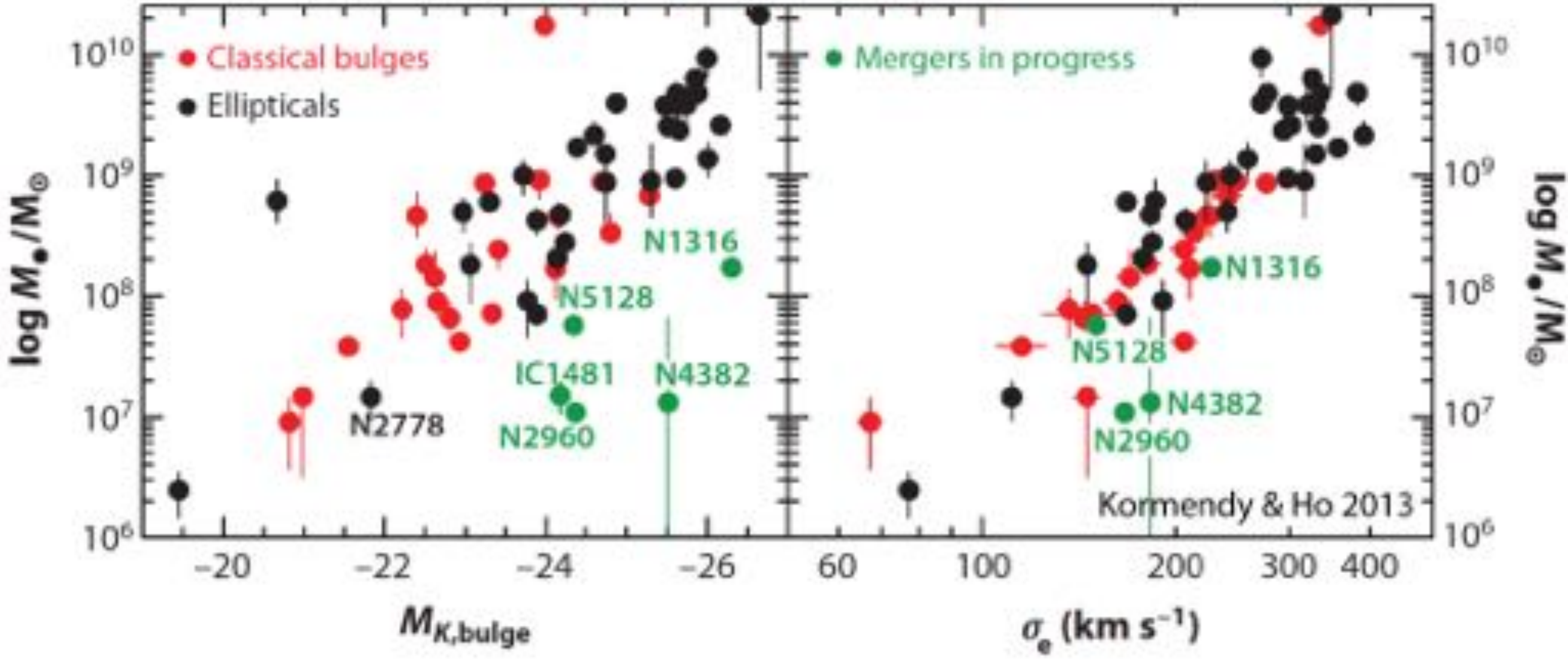
Mass-to-light ratios
are averages of
stellar population M/L_K
(Into & Portinari 2013,
taking AGB stars
into account) and
stellar dynamical M/L_K
(Cappellari's group with
Cappellari's zeropoint).

Mergers in progress have unusually small $M_\bullet$.



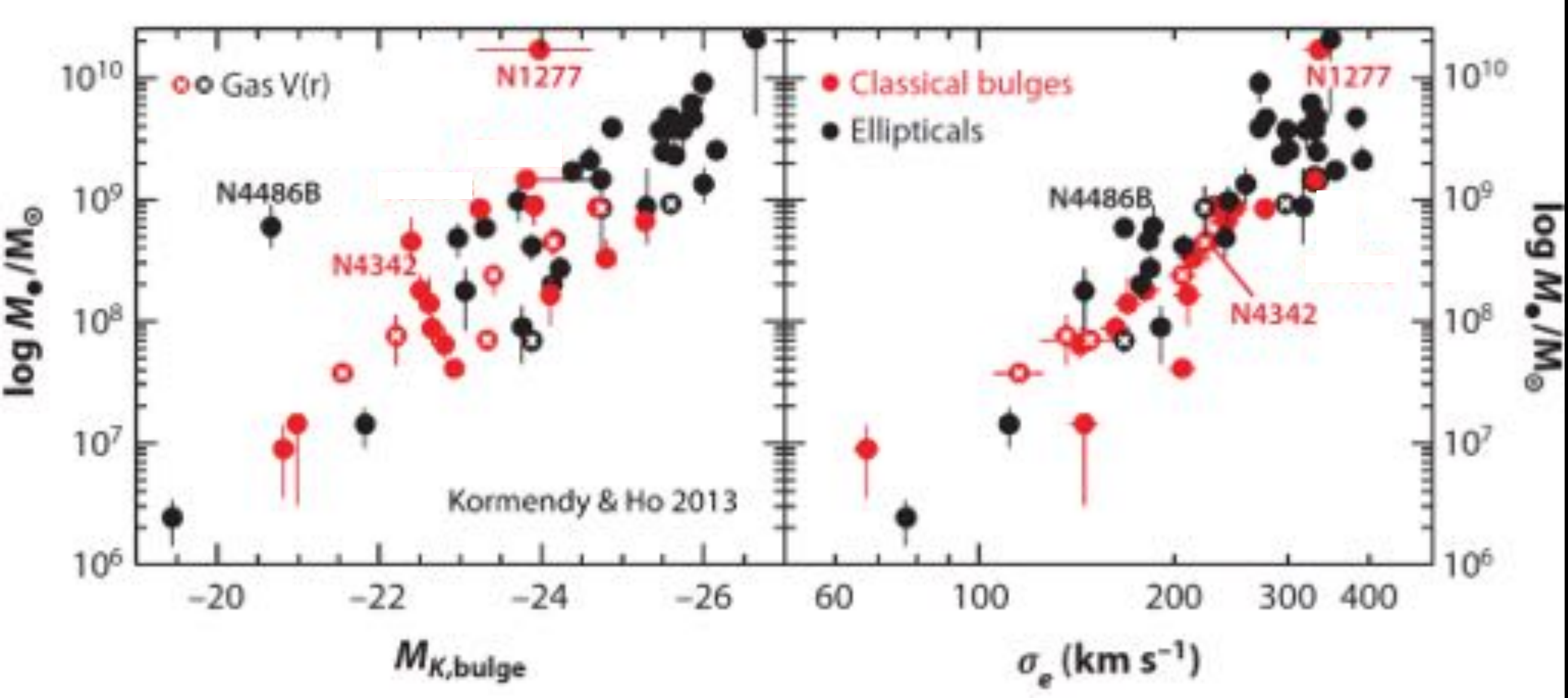






Rare galaxies contain BH monsters.

Relics of a time before the BH-host correlations were engineered?



NGC 4486B: Kormendy et nuk. 1997, ApJ, 482, L139

NGC 4342: Cretton & F. van den Bosch 1999, ApJ, 514, 704

NGC 1277: R. van den Bosch, Gebhardt, et al. 2012, Nature, 491, 729

NGC 4642 UCD: Seth et al. 2014, Nature, 513, 398 More to come!

Bulge Definition:

Alvio Renzini, following Allan Sandage:

“A bulge is nothing more nor less than an elliptical galaxy that happens to live in the middle of a disk.”

Bulge Definition:

Astrophysical paraphrase:

“A <u>classical bulge</u> is the remnant of a major galaxy merger.”

Includes: mergers of clumps that form in high-z, gas-rich disks.

Secular Evolution of “Isolated” Spiral Galaxies

Noncircular features such as bars and ovals permanently rearrange gas in disks and stars that form from the gas into outer rings, inner rings, and “pseudobulges”.

Kormendy & Kennicutt 2004, ARA&A, 42, 603;
Kormendy 2013, 23rd Canary Islands Winter School review, arXiv:1311.2609

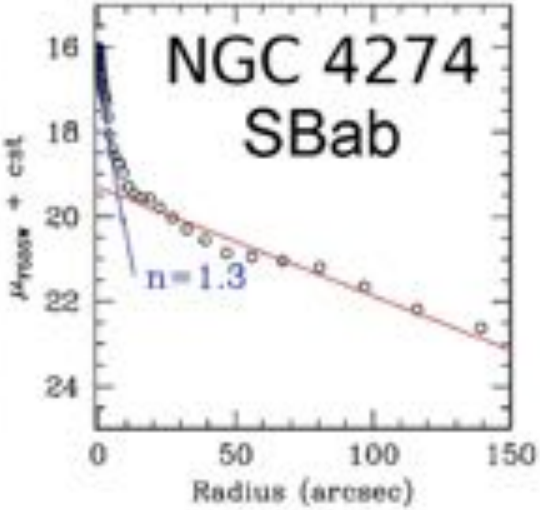
Self-gravitating systems evolve by spreading — they form a denser core and a more diffuse halo.

Systems that are supported by random motions evolve by transporting energy outward.

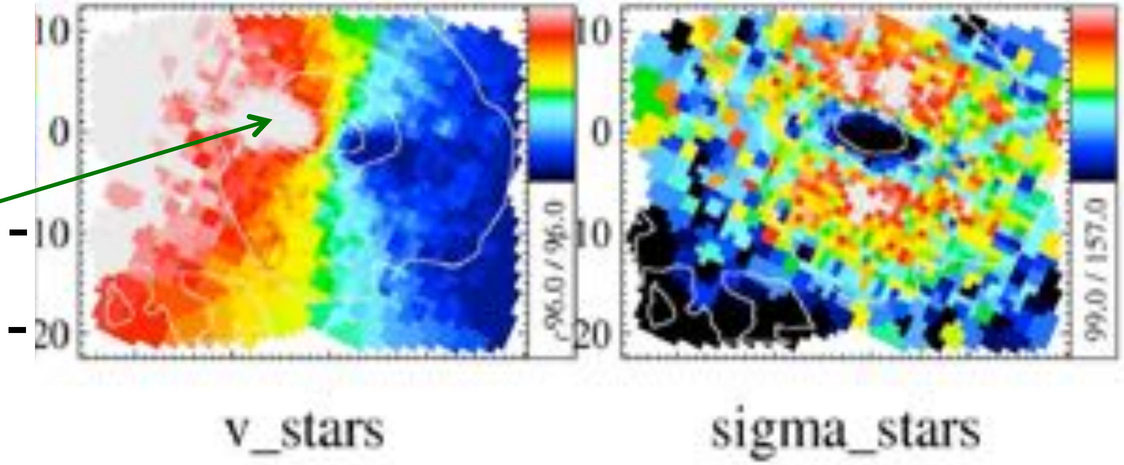
Systems that are supported by rotation evolve by transporting angular momentum outward.
Growth of pseudobulge from a galaxy disk ~ growth of star from a protostellar disk
~ growth of black hole from a quasar accretion disk.

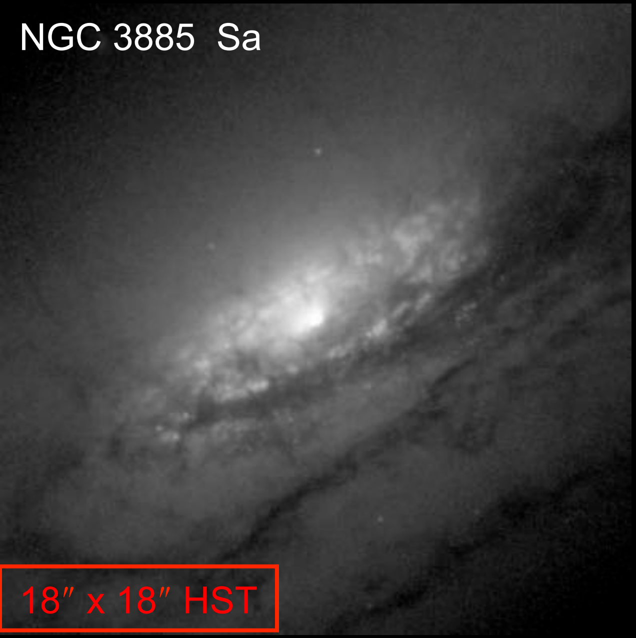
High-Surface-Brightness Center ≡ "Bulge" Is Disky: Cold & Rapidly Rotating

Falcón-Barroso et sauron 2006, MNRAS, 369, 529
Peletier et sauron 2008, IAU Symposium 245



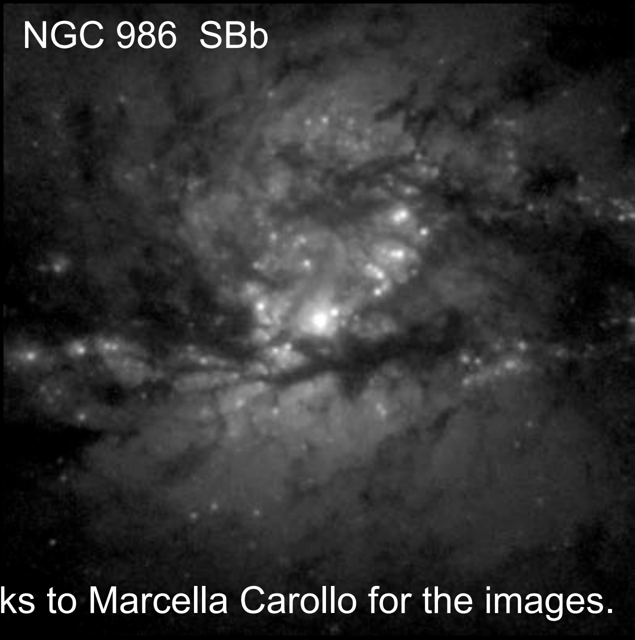
This is a typical disky pseudobulge.



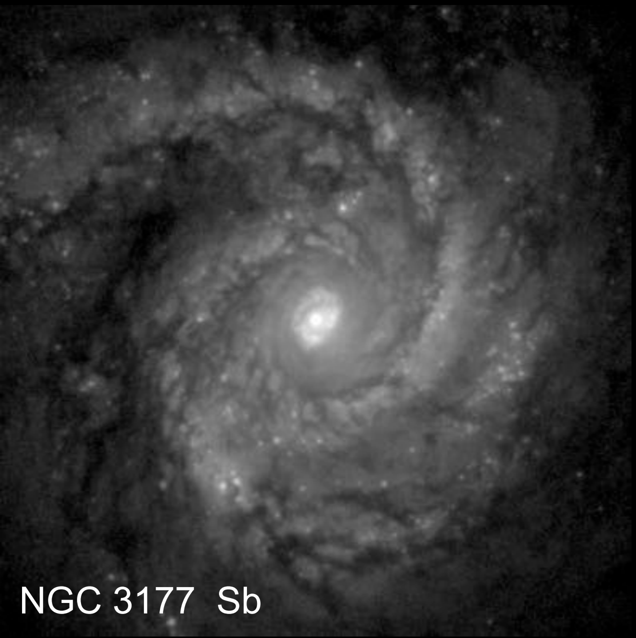

NGC 3885 Sa

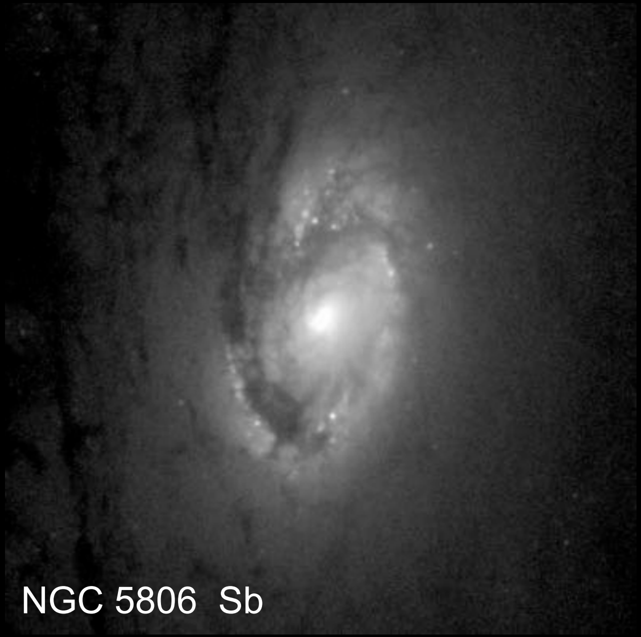
18″ x 18″ HST

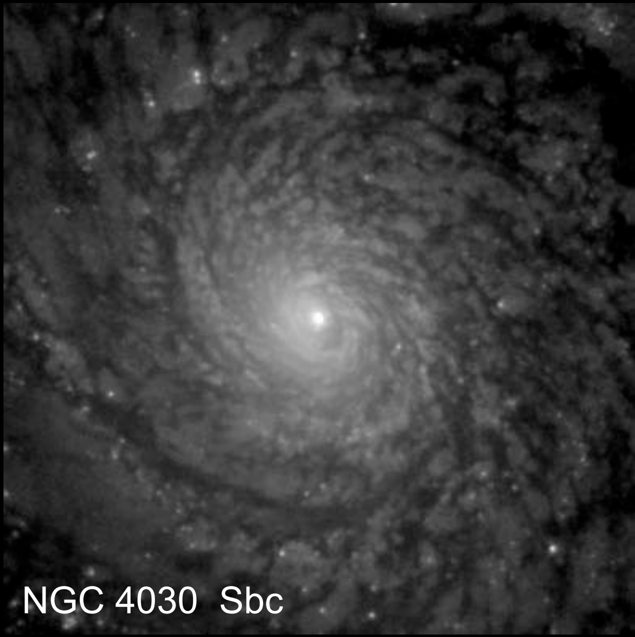

NGC 7690 Sab


NGC 986 SBb

Thanks to Marcella Carollo for the images.

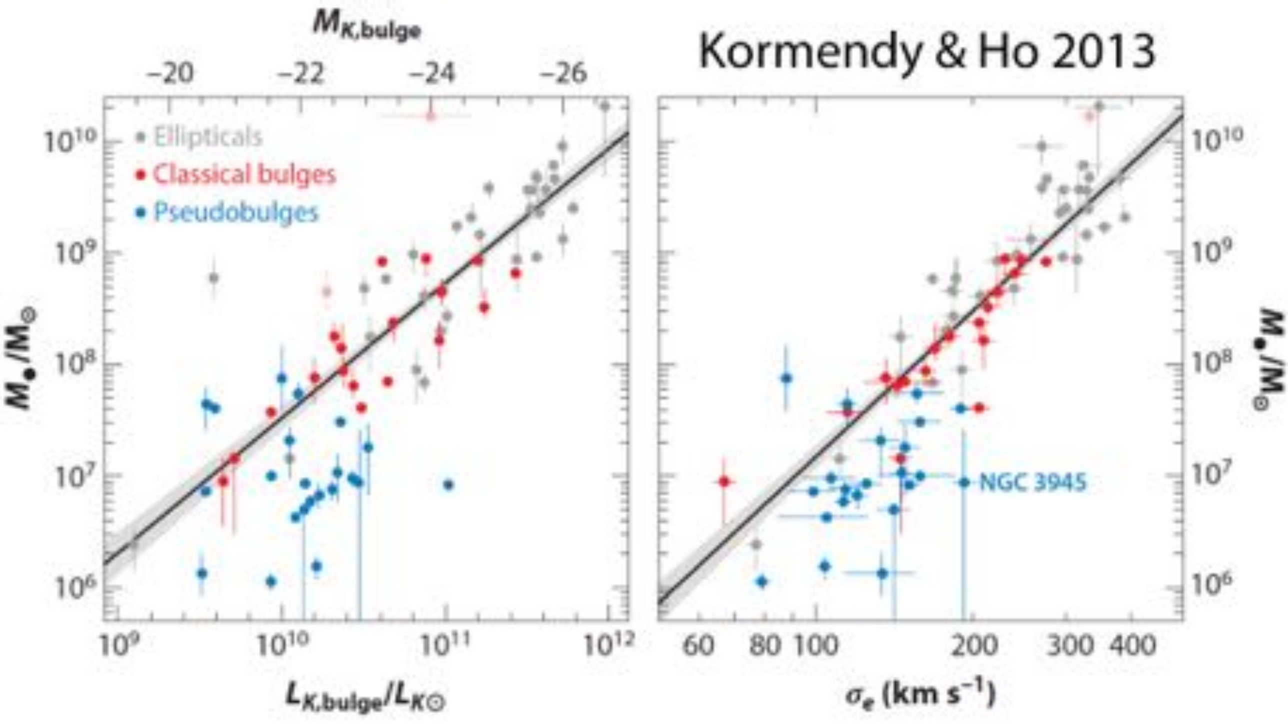

NGC 3177 Sb


NGC 5806 Sb


NGC 4030 Sbc

Pseudobulges are not “like ellipticals that live in the middle of a disk.”

$M_\bullet$ correlates little or not at all with pseudobulges ⇒ no coevolution.

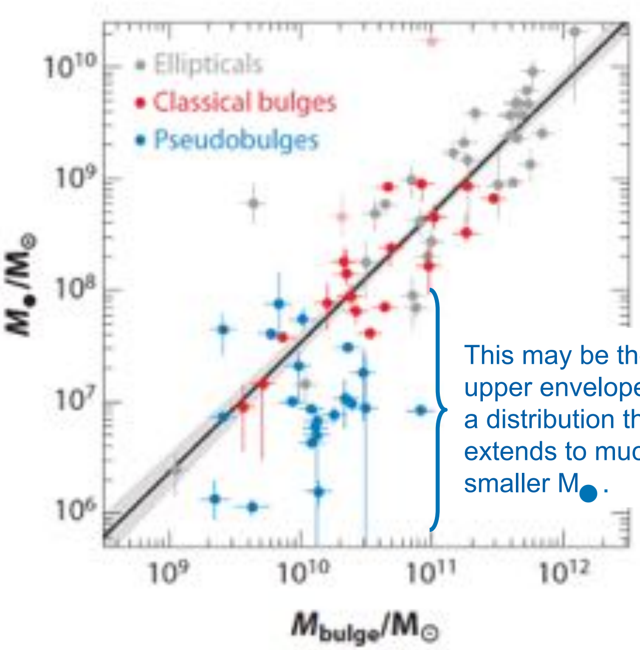


Hu 2008, MNRAS, 386, 2242;

Greene et al. 2010, ApJ, 721, 26;

Kormendy, Bender, Cornell 2011, Nature, 469, 374;

Kormendy & Ho 2013



This may be the upper envelope of a distribution that extends to much smaller $M_\bullet$.

NGC 1068: Prototypical Seyfert 1 with a pseudobulge

Conclusion

(Kormendy et al. 2011, Nature, 469, 374).

There are 2 fundamentally different evolution channels for supermassive black holes (BHs):

The biggest BHs grow rapidly to high mass,
coevolving with bulges via mergers and quasar AGNs,

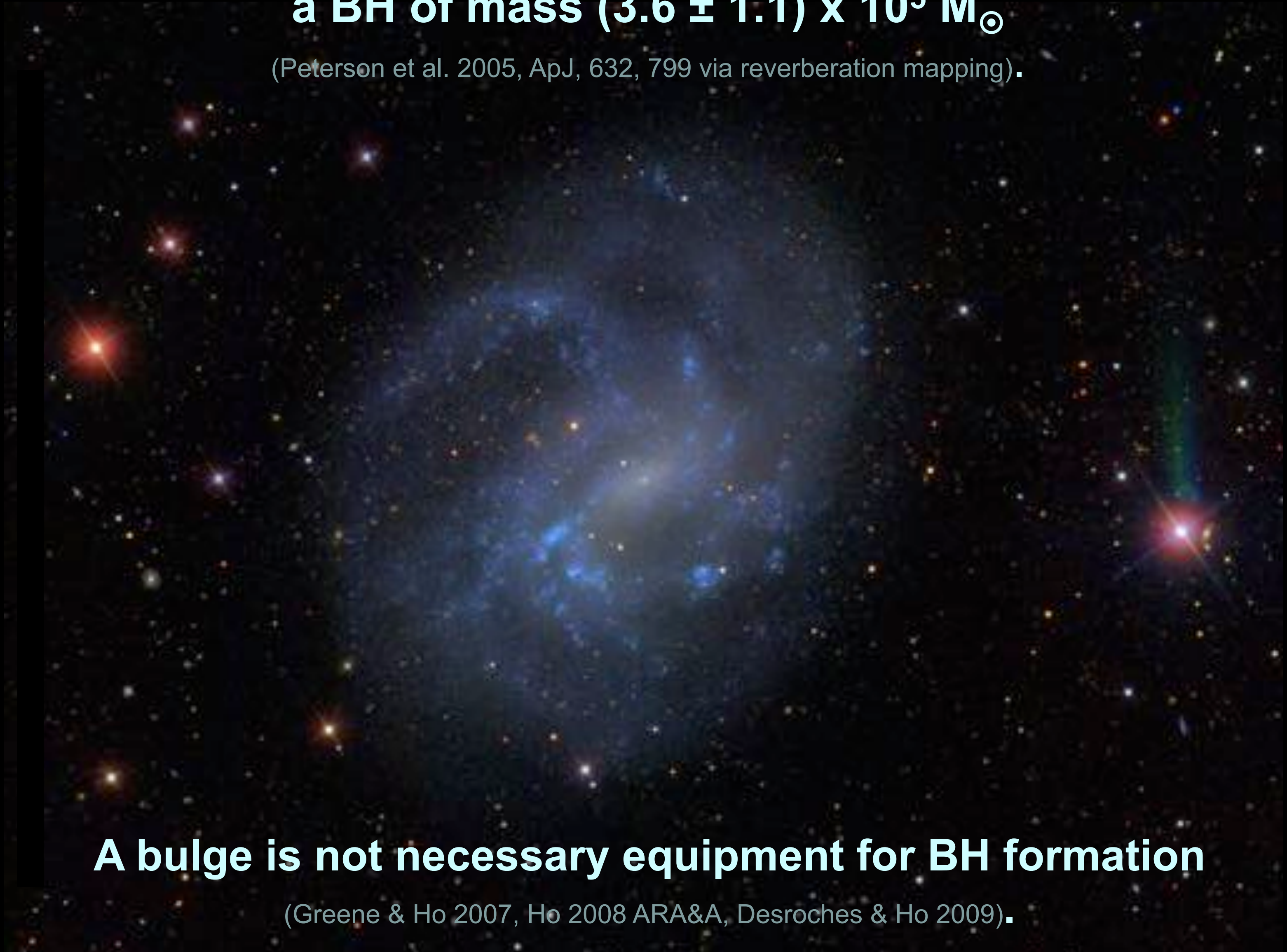
and

small BHs grow slowly & stay mostly intermediate-mass
via low-L Seyfert activity in largely bulgeless galaxies.
They do not correlate (i. e., coevolve) with host disks.

Suggest: the latter BHs are seeds for the former BHs.
They are the most numerous BHs in the nearby Universe.

NGC 4395 is a bulgeless Sm galaxy that contains a BH of mass $(3.6 \pm 1.1) \times 10^5\ M_\odot$

(Peterson et al. 2005, ApJ, 632, 799 via reverberation mapping).



A bulge is not necessary equipment for BH formation

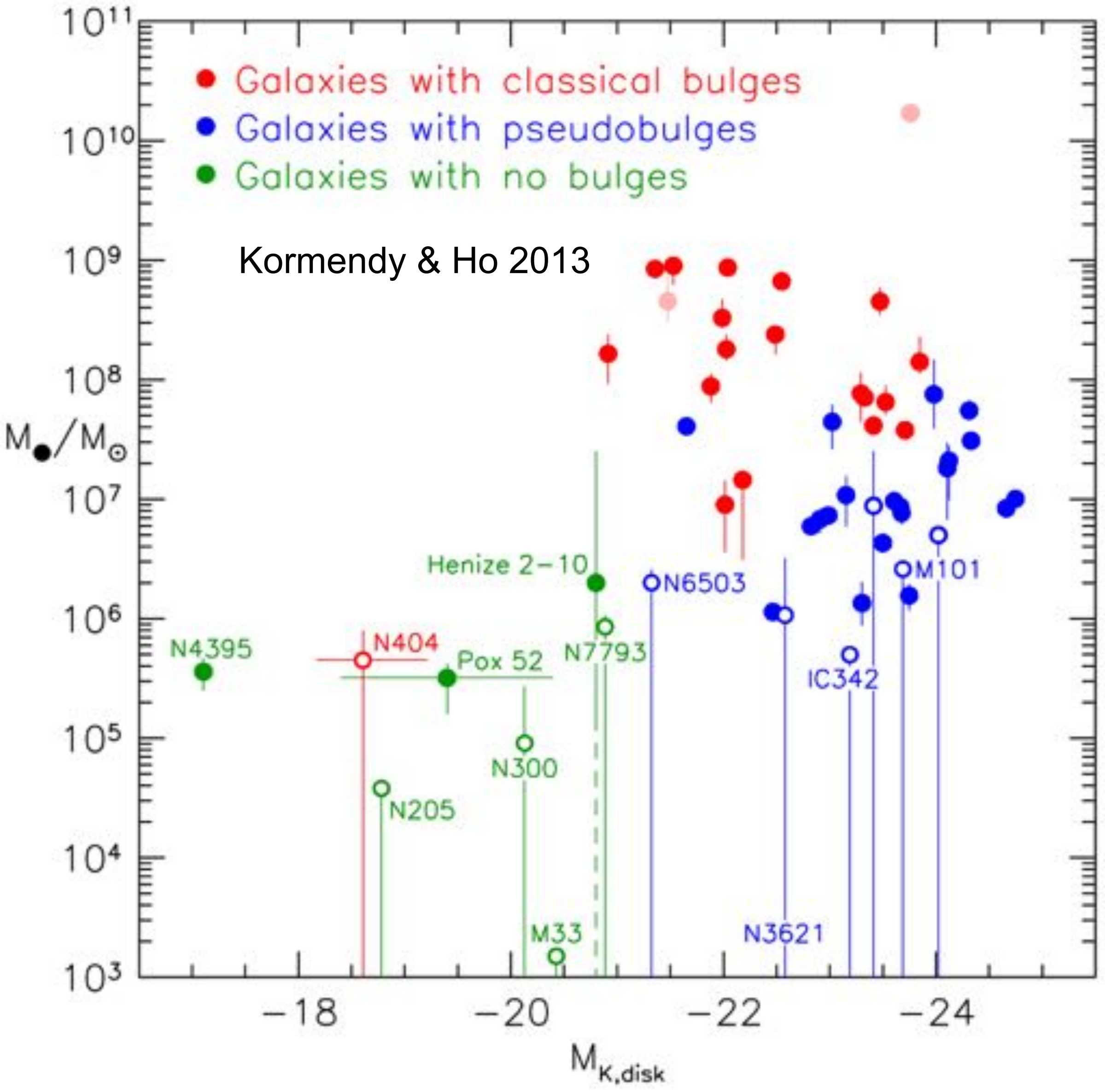
(Greene & Ho 2007, Ho 2008 ARA&A, Desroches & Ho 2009).

But BHs in bulgeless galaxies do not correlate with their hosts

(see also Greene + 2008, 2010).

BHs do not correlate with galaxy disks.

(Kormendy & Gebhardt 2001, 20th Texas Symp., AIP, 363 ; Kormendy et al. 2011, Nature, 469, 374).



Kormendy & Ho 2013

The bulgeless galaxy M 33 does not contain a black hole.

The nucleus of M 33 has $\sigma = 20 \pm 1$ km/s

(Kormendy et al. 2010, ApJ, 723, 54).

Any black hole must be less massive than ~ 1500 $M_\odot$

(Merritt et al. 2001, Science, 293, 1116 ; Gebhardt et al. 2001, AJ, 122, 2469).

Do Black Holes Correlate With Dark Matter Halos?

Ferrarese 2002, Baes et al. 2003 and others suggest that the fundamental correlation is between $M_\bullet$ and halo dark matter. This is based on a "tight correlation" between σ and $V_{\mathbf{circ}}$.

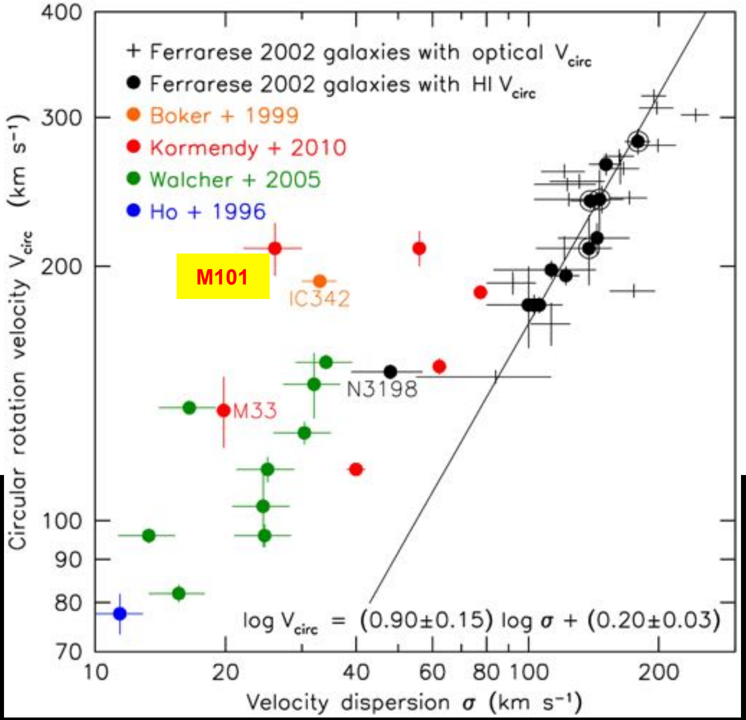
$M_\bullet / M_{DM}$ ↓ at $V_{\mathbf{circ}} < 150\ \mathrm{km\ s^{-1}}$.

Is $M_\bullet$–M_{DM} correlation more fundamental than $M_\bullet$–M_{bulge} correlation?

Test:

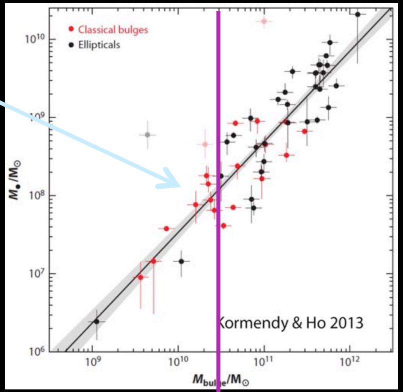
Does $M_\bullet$ (or σ) correlate tightly with $V_{\mathbf{circ}}$ in the absence of a bulge?

Answer = "no".



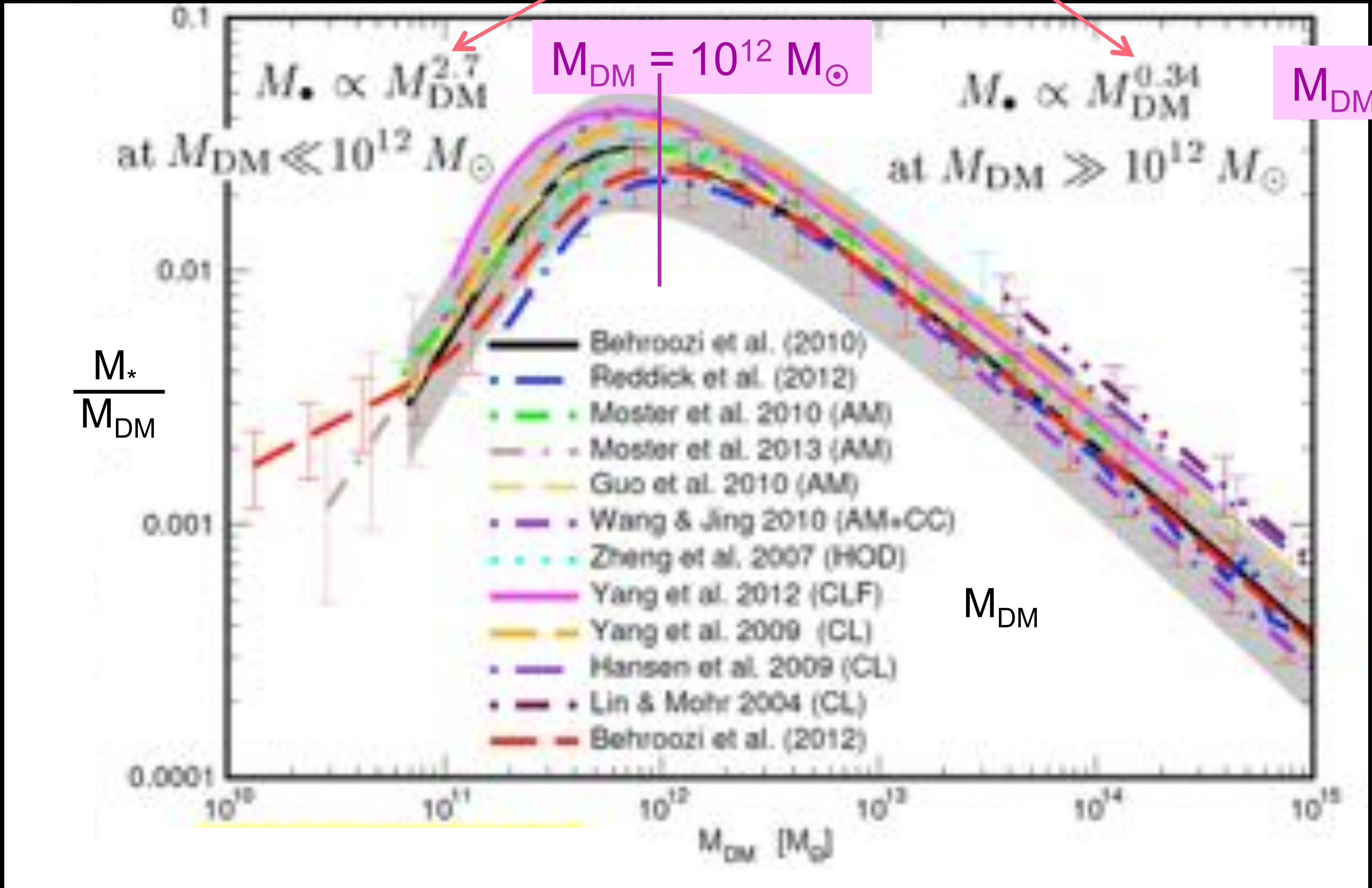
Here, I discuss 3 of 7 independent arguments in Kormendy & Ho 2013.

BHs do not correlate with DM beyond the BH–bulge correlation.



$M_\bullet \propto M_{\rm bulge}^{1.17}$ for all $M_{\rm bulge}$,

but $M_\bullet$ depends on $M_{\rm DM}$ in a complicated way.



$M_{\rm DM} = 10^{12}\ M_\odot$

BH Correlations With Host Galaxies:
Summary

BHs correlate with bulges+ellipticals
but not with disks or
pseudobulges or
dark matter halos.

AGN feedback: Popular idea that BH growth and galaxy evolution regulate each other

1 – Silk & Rees 1998; Ostriker & Ciotti 2005:

– BH binding energy » galaxy binding energy

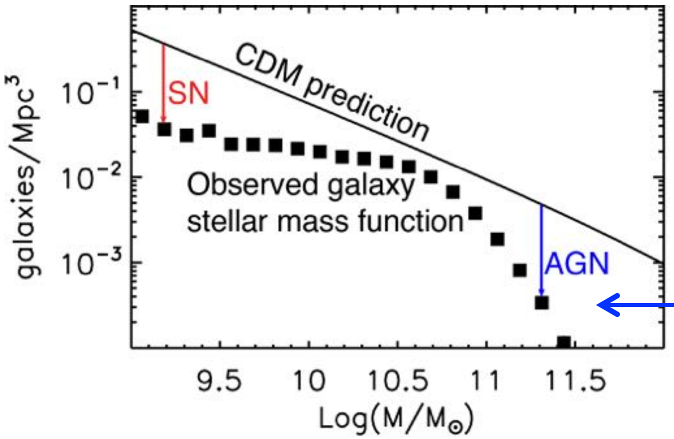
➔ if a few % of AGN energy couples to gas, then all gas can be expelled.

➔ BH growth may be self-limiting & AGN feedback can affect galaxy formation.

2 – $M_\bullet$–σ correlation ➔ close connection between BH growth & galaxy formation.

3 – The history of AGN growth of BHs ∝ history of star formation in the Universe.

4 – Solves puzzle: Why is the galaxy mass function so steep at high masses?

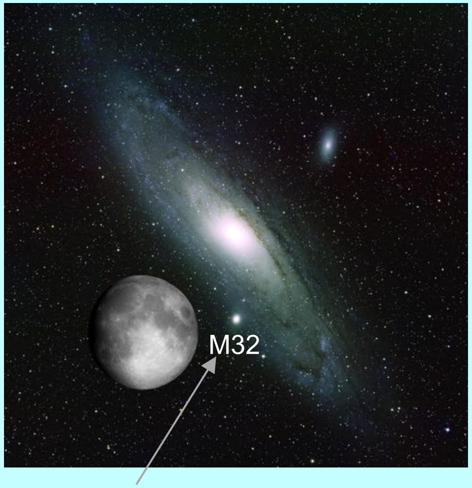


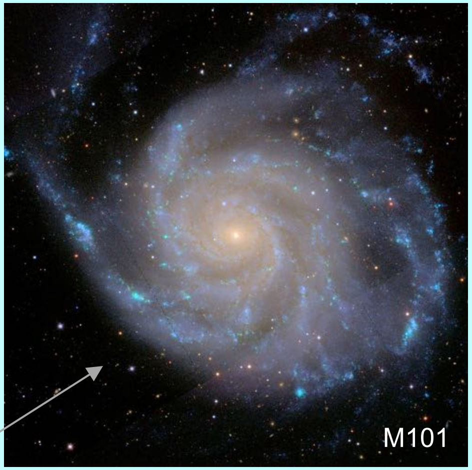
Keep baryons locked in hot gas.

Problem:

AGN feedback depends on M_{galaxy}, roughly independently of host morphology.

But BHs correlate only with bulges+ellipticals
and not with disks or
pseudobulges or
dark matter halos.



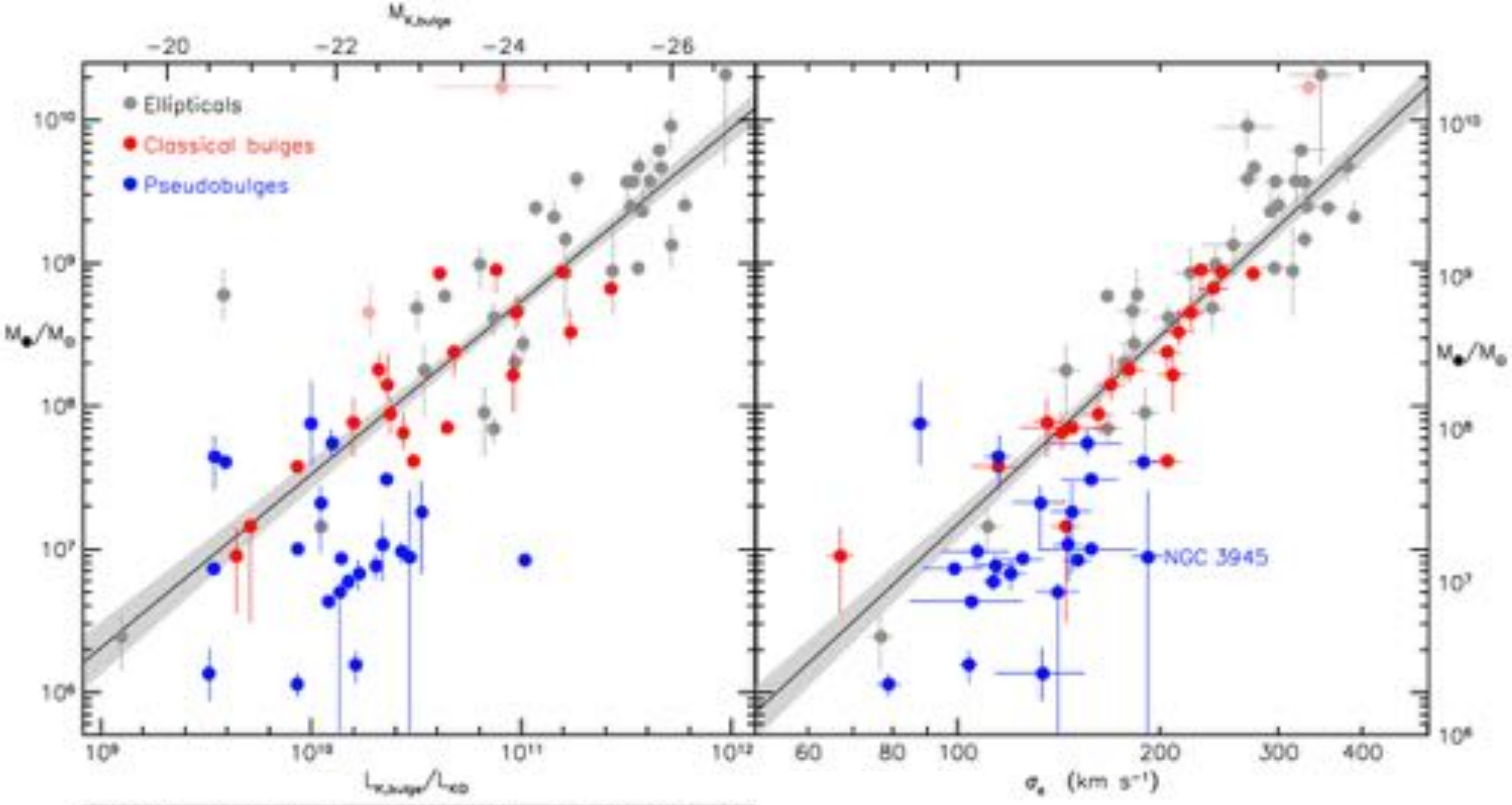


E. g., small Es participate in “coevolution”; giant pure disks do not.

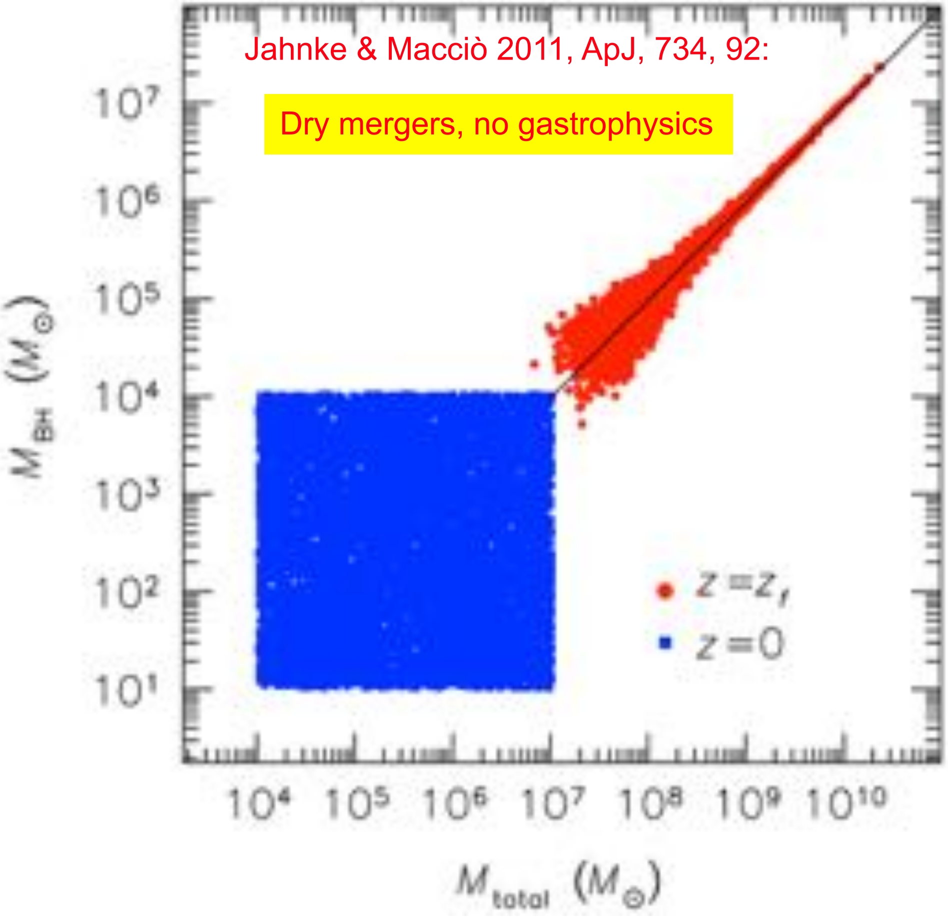
Conclude: Coevolution is not only (or even mainly) about mass.
Coevolution is about major mergers.

More evidence for this conclusion:

$M_\bullet$–host-galaxy correlations have larger scatter at smaller $M_\bullet$.



Do BH–host-galaxy correlations acquire their small scatter via the averaging produced by mergers?


Jahnke & Macciò 2011, ApJ, 734, 92:

Dry mergers, no gastrophysics

Similar conclusions:

Peng 2007, ApJ, 671, 1098;

Gaskell 2010, AIPC, 1294, 261;

Hirschmann et al. 2010, MNRAS, 407, 1016

The central limit theorem may be most of the story.

Coevolution (Or Not) of BHs and Host Galaxies

1 – Small BHs in pseudobulges & disks do not coevolve with (i. e., influence) hosts.

2 – Quasar mode AGN feedback helps to quench star formation during starbursts driven by wet mergers that make coreless-disky-rotating Es.

3 – Radio mode AGN feedback keeps X-ray gas hot in core-boxy-nonrotating Es and prevents further star formation (“M_{crit} quenching”).

4 – Mass averaging in major mergers helps to reduce $\mathbf{M_{\bullet} - M_{bulge}}$ scatter.

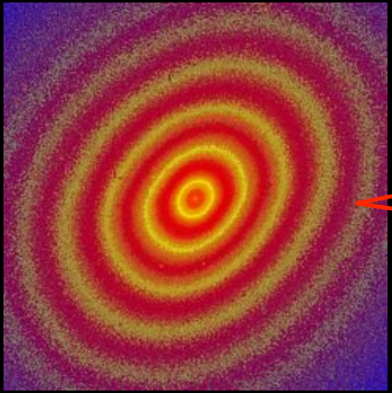
Modes 2 and 3 control the formation of the two different types of ellipticals:

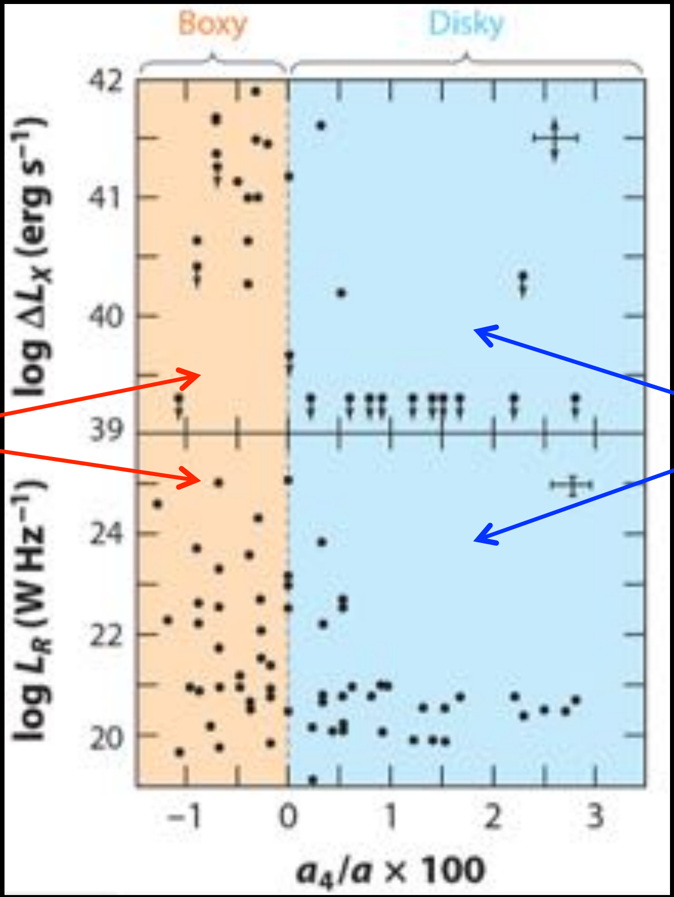
X-ray gas causes “M_{crit} quenching” of star formation

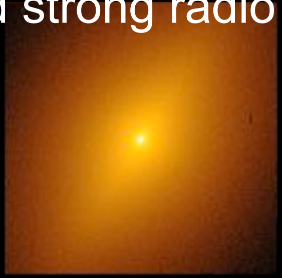
(e. g., Cattaneo + 2006, 2008, 2009; Faber + 2007; Kormendy et al. 2009, ApJS, 192, 216 = “KFCB”).

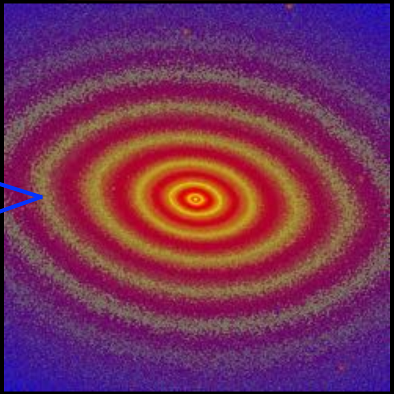
Requirement: Mass > $M_{crit} \approx 10^{12}\ M_{\odot}$ in order to hold X-ray gas.

Bender et al. (1989): Only core/boxy Es have both X-ray gas and strong radio sources:









Core-boxy-nonrotating ellipticals are remnants of dry mergers.

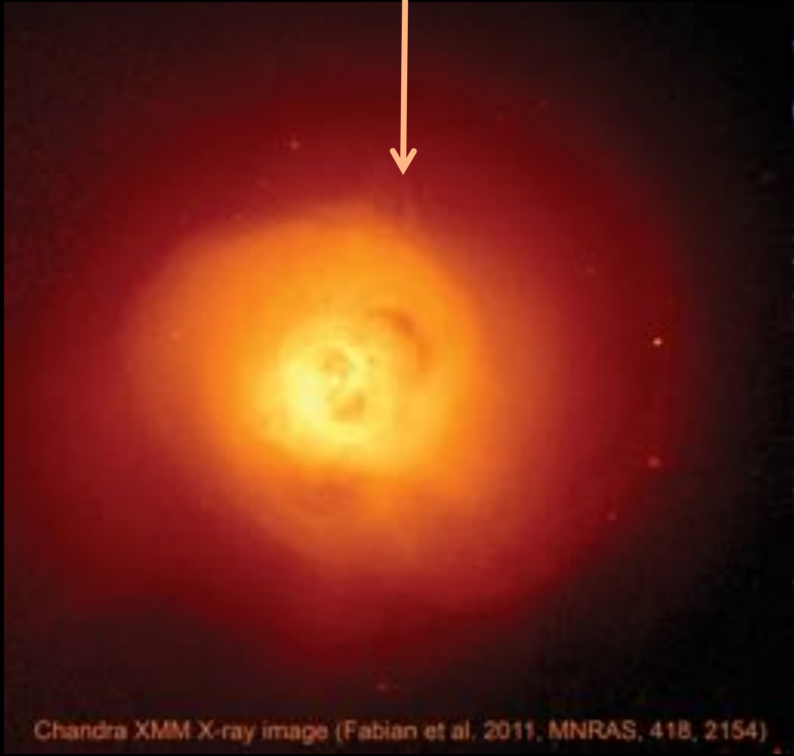
Coreless-disky-rotating ellipticals are remnants of wet mergers that include cold gas dissipation and a central starburst.

KFCB suggest that AGN feedback into X-ray gas only in giant-boxy-core galaxies and their progenitors helps to quench star formation and to make mergers dry.

AGN feedback needs a “working surface” = X-ray-emitting gas in giant ellipticals and clusters

Chandra X-Ray Observatory ⇒ In Perseus Cluster and elsewhere, jet energy is redistributed more isotropically via bubbles, compression waves, …

Hot, X-ray-emitting gas permeates the Perseus cluster and prevents cold gas in galaxies that fall into the cluster from making stars. So any mergers are “dry”.



Chandra XMM X-ray image (Fabian et al. 2011, MNRAS, 418, 2154)

Optical image of the Perseus Cluster and NGC 1275

X-ray gas makes dry mergers dry and allows core scouring by BH binaries to happen.

Any combination of heating mechanisms is OK:

AGN energy feedback*,
cosmological gas infall**,
recycling of gas from old stars***.

*Fabian 2012, ARAA, 50, 455
**Dekel & Birnboim 2006, MNRAS, 368, 2
***Jerry Ostriker

Many lines of research converge on a consistent picture of the quenching of star formation at $z < 1$.

E. g., Peng, Lilly, et al. 2010, ApJ, 721, 193 suggest that the "red sequence" of star-formation-quenched galaxies is caused by 3 processes:

(1) M_{crit} mass quenching by X-ray-emitting gas,
(2) environmental quenching, and
(3) quenching via mergers and bulge formation.

$$M_{crit} = M_{DM} \sim 10^{12}\ M_{\odot}$$

Kormendy & Ho 2013 agree:

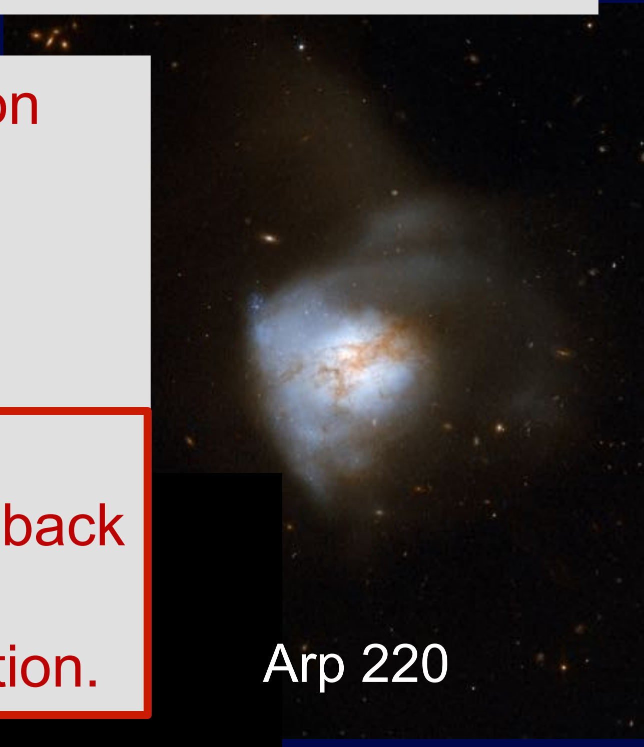
Mass quenching is the same process as environmental quenching:

In M_{crit} "mass quenching", the X-ray gas
that does the work belongs to your DM halo.

"Environmental quenching" is just M_{crit} mass quenching
where the X-ray gas belongs to
somebody else's DM halo
(i. e., the halo of your parent galaxy or cluster).

An additional way to quench star formation
is necessary to explain
sub-M_{crit}, "red and dead" S0 galaxies
that do not live in galaxy clusters.

These have big bulges. Suggest:
"Merger quenching" is begun by energy feedback
from wet-merger starbursts and
finished by energy feedback from BH accretion.

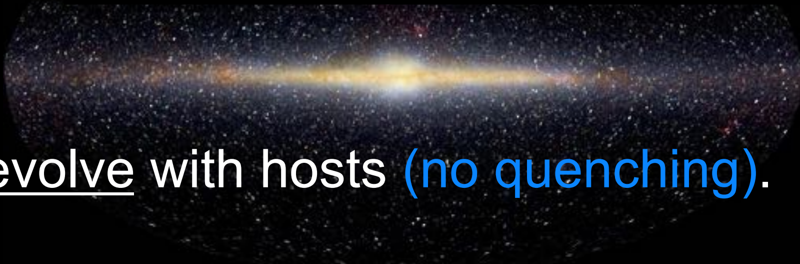


Arp 220

Summary

BHs correlate with bulges+ellipticals but not with disks or
pseudobulges or
dark matter halos.

BH $\mathbf{M_\bullet}$ − σ and $\mathbf{M_\bullet - M_{bulge}}$ **correlations** ⇒ coevolution?



1 – BHs in pseudobulges and disks do not coevolve with hosts (no quenching).

2 – Quasar mode AGN feedback helps to quench starbursts in wet mergers that make disky-rotating Es (merger quenching).

3 – Radio mode AGN feedback keeps X-ray gas hot in boxy-nonrotating Es and prevents further star formation (M_{crit} mass quenching and M_{crit} environmental quenching).

4 – The highest-mass BHs inherit coevolution "magic" from 1. Then:
Mass averaging in major mergers further reduces the $\mathbf{M_\bullet - M_{bulge}}$ scatter.

Kormendy & Ho 2013, ARA&A, 51, 511

New, richer picture:
Black holes correlate differently with different kinds of galaxy components
that have different formation histories.

Result = refinement of our picture of BH – host galaxy coevolution.

> **“When we try to pick out anything by itself,**
> **we find it hitched to everything else in the Universe.”**
>
> **John Muir**
> **My First Summer in the Sierra (1911)**

The rapidly growing interconnections between different subjects –
between BH studies and a variety of work on galaxy evolution –
are a sign of the developing maturity of this subject.