Supermassive Black Holes: Coevolution (Or Not) of Black Holes and Host Galaxies

John Kormendy
Curtis T. Vaughan, Jr. Centennial Chair in Astronomy
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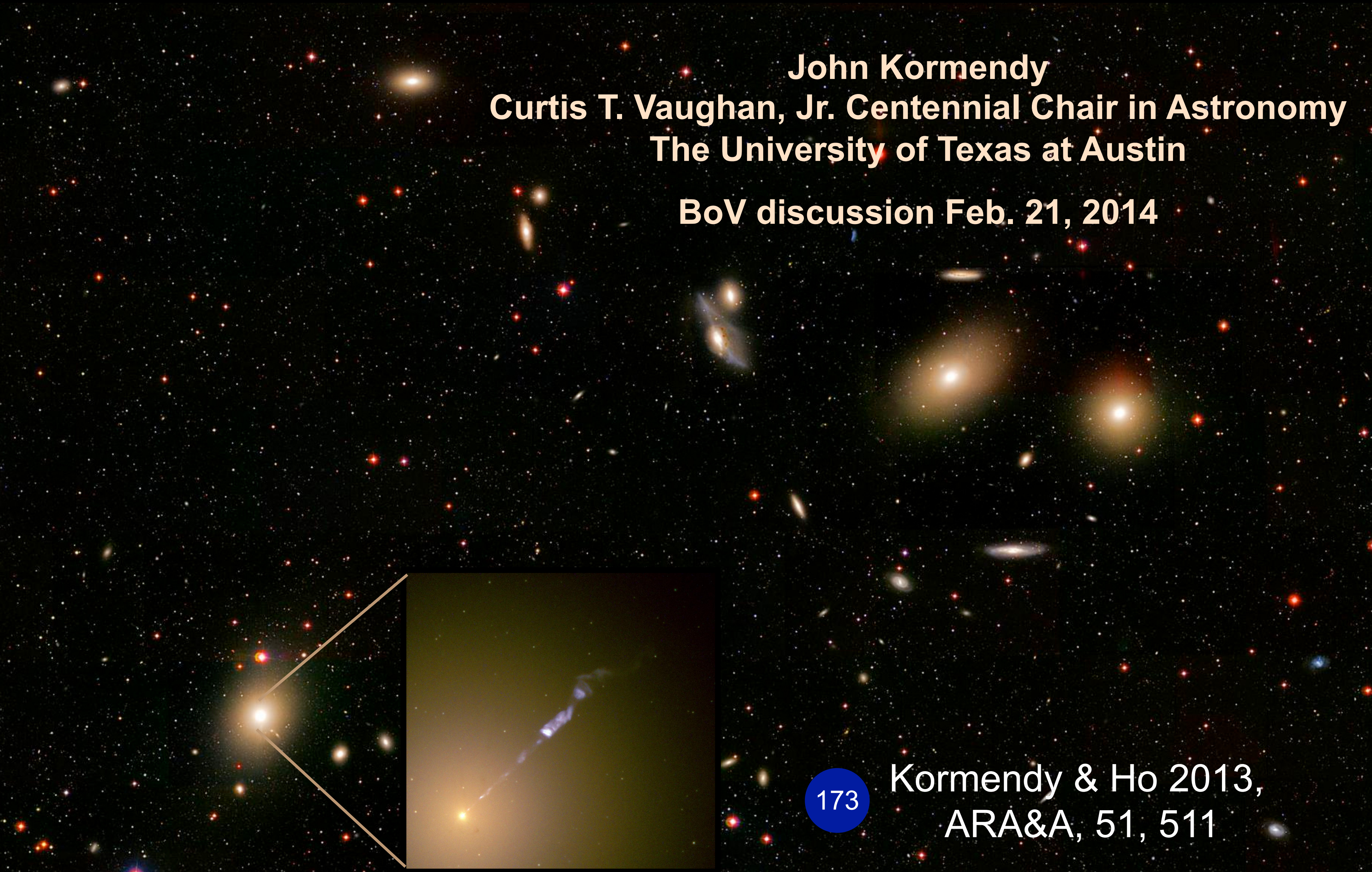
BoV discussion Feb. 21, 2014



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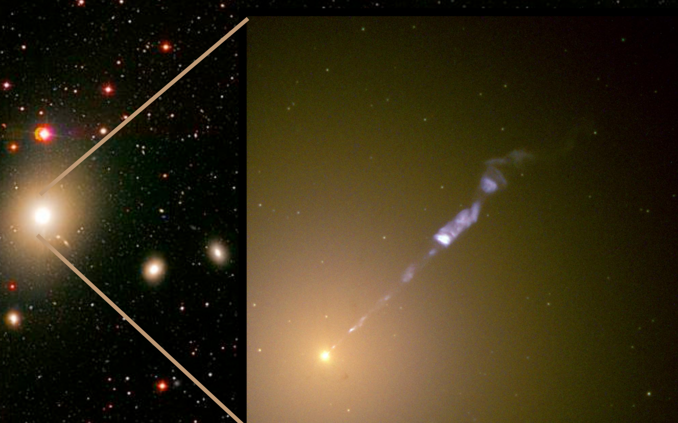
Kormendy & Ho 2013, ARA&A, 51, 511

Supermassive Black Holes:
Coevolution (Or Not) of Black Holes and Host Galaxies

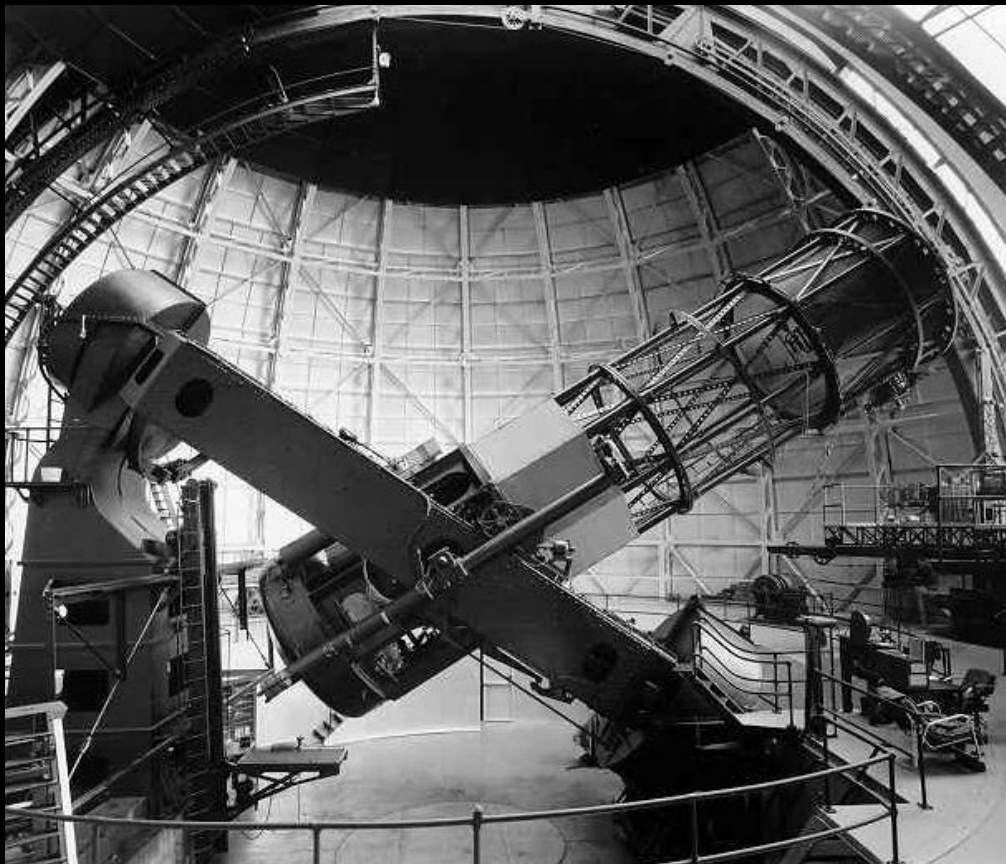
Please help yourself to the compendium of Kormendy et al. review papers in ARA&A on the table near the door.

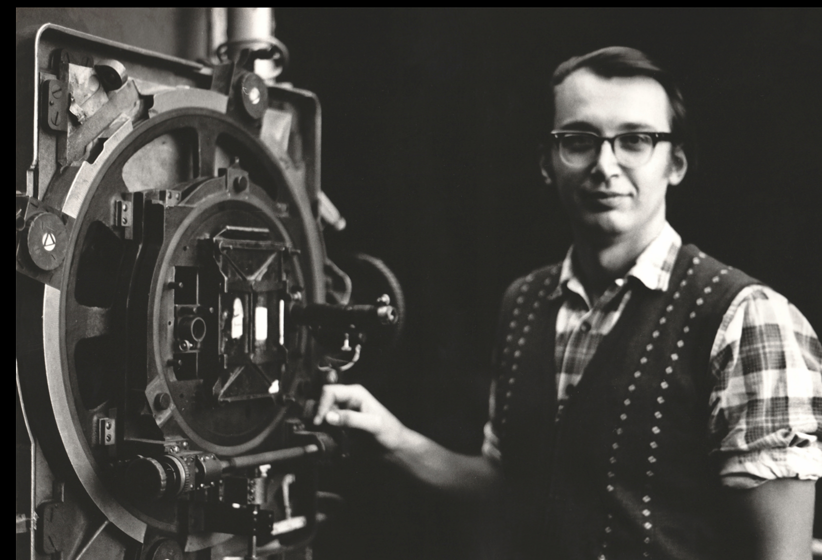
173 ← **These are page numbers in the compendium.**



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

My Caltech PhD research (1970 – 1976) was done at Mt. Wilson & Palomar Observatories, mainly with the Mt. Wilson 100-inch Hooker telescope.





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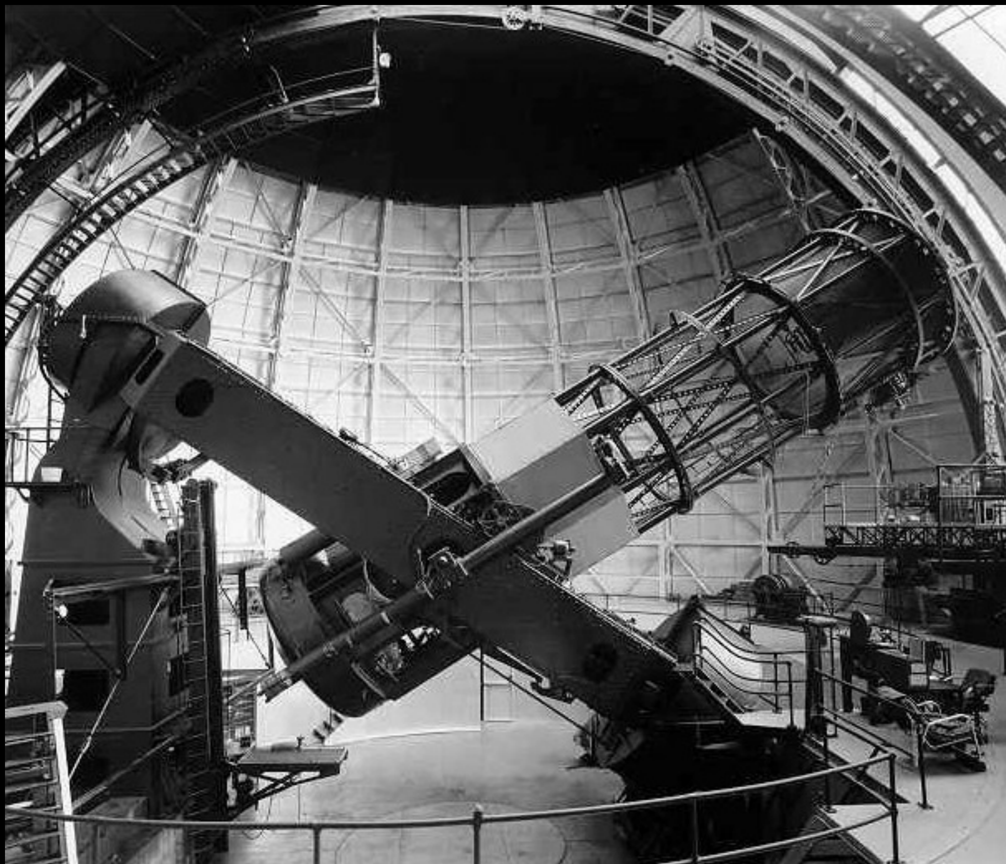
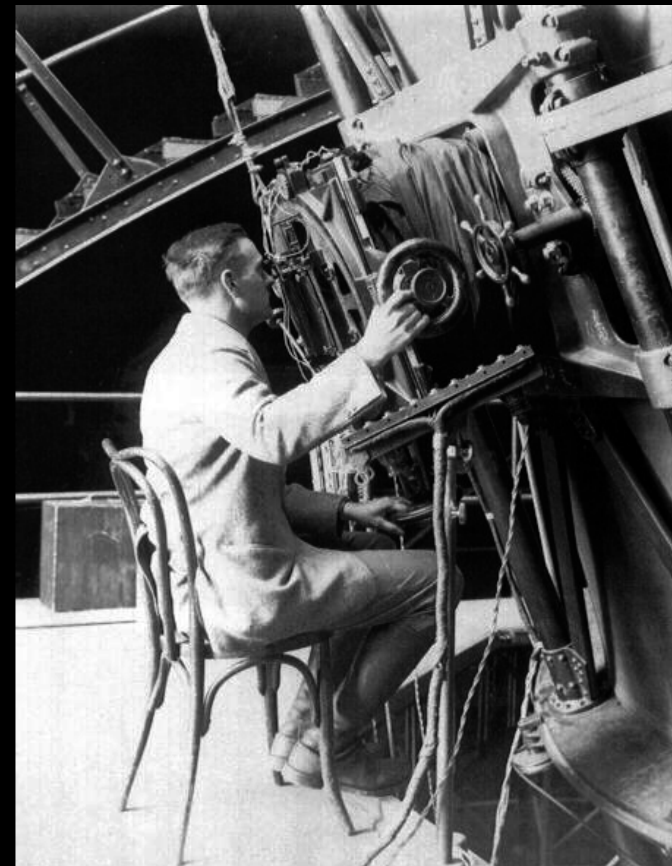




Hubble discovered the expansion of the Universe and developed his galaxy classification scheme largely with the Hooker telescope. I was exceedingly conscious of the historical context into which I was priviledged to step.

My earliest hero:

Allan Sandage
(Mt. Wilson & Palomar Obs.).
He was on my PhD committee,
and he inspired and helped me
early in my career.

I have always had a strong
sense of historical continuity:
It is my job to carry forward
Sandage's work on
galaxy evolution.

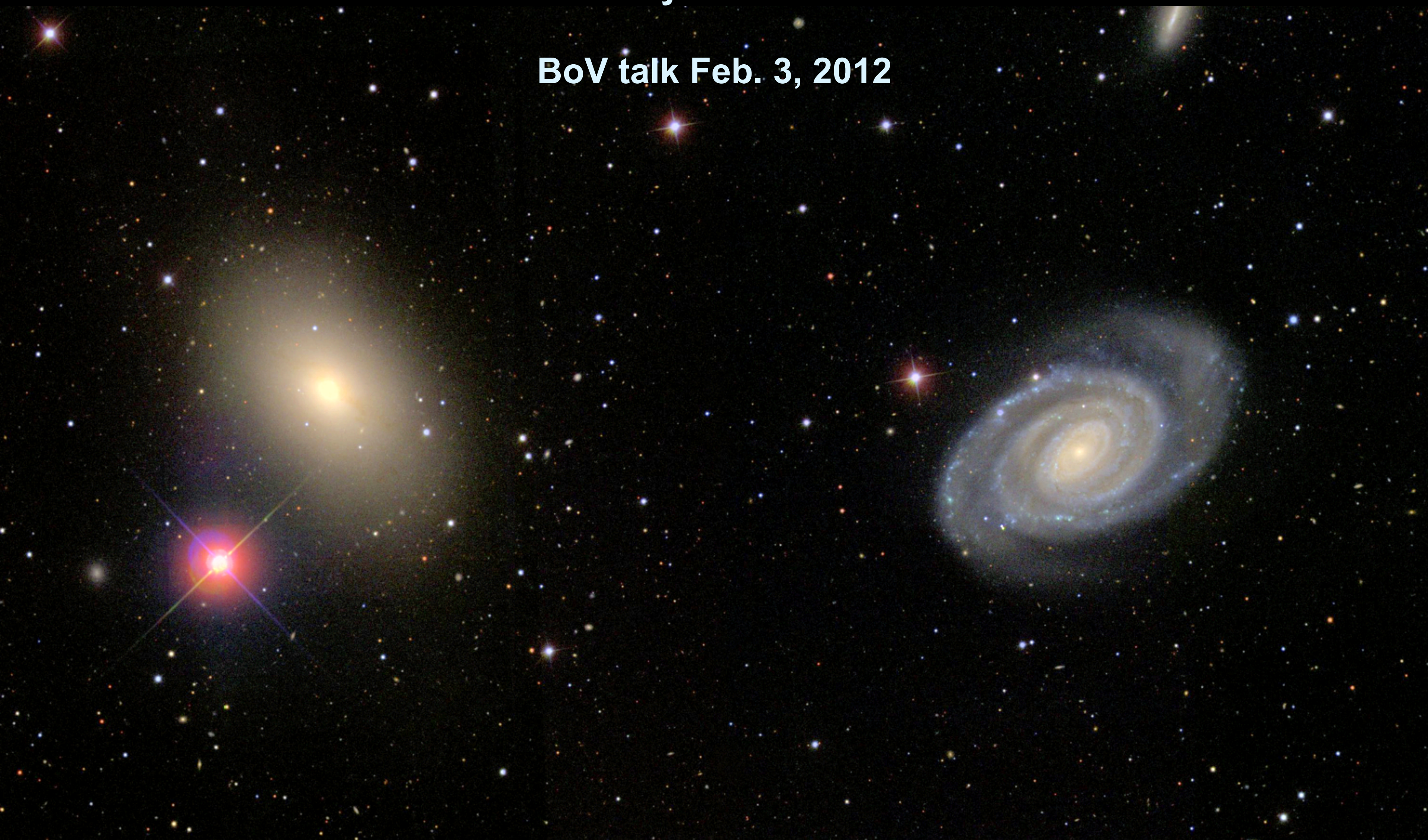
Happy accomplishment:

Sandage apparently accepted
all of the paradigm-changing
contributions that I have made.
For example:

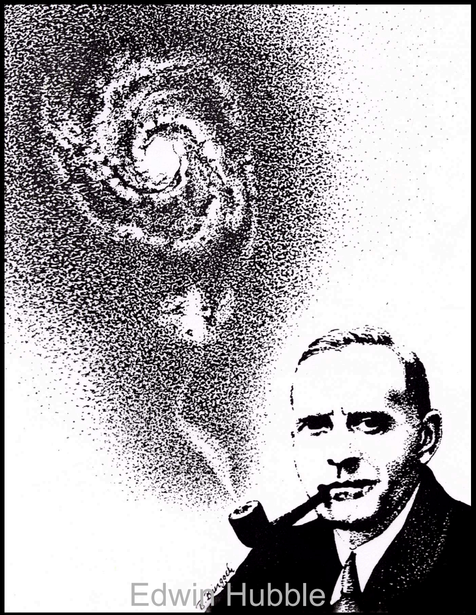
The Stately Dance of Evolution in Spiral Galaxies

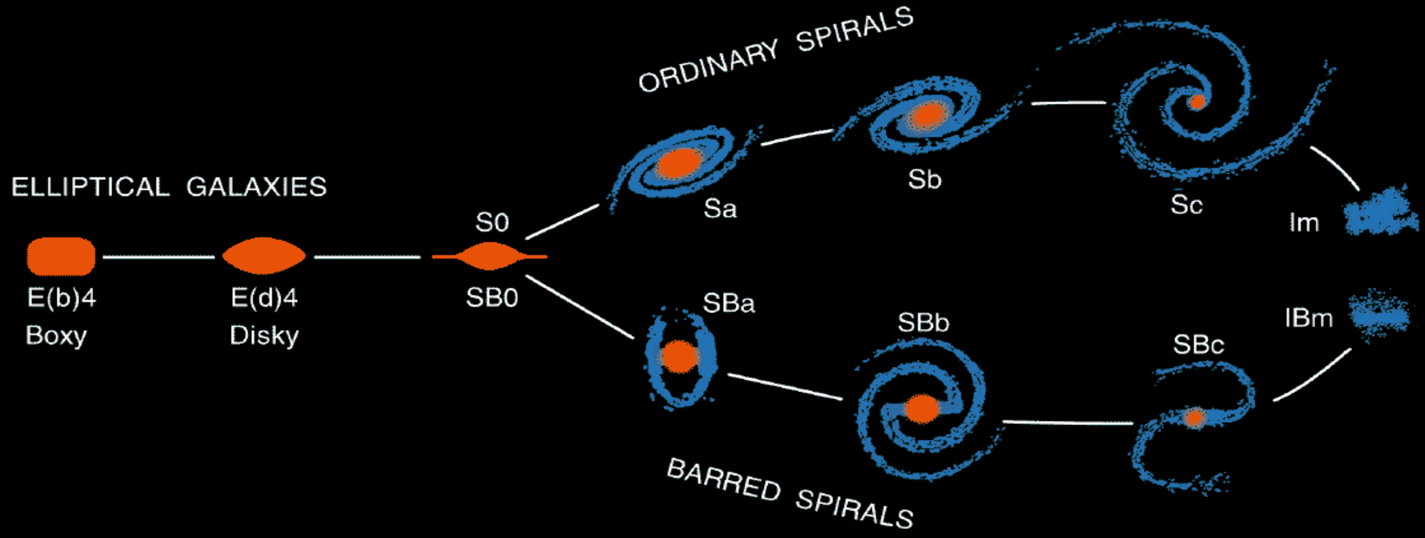
John Kormendy
Curtis T. Vaughan, Jr. Centennial Chair in Astronomy
The University of Texas at Austin

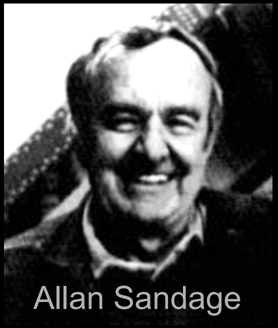
BoV talk Feb. 3, 2012



Important Goal of Extragalactic Astronomy: Explain Hubble Classification





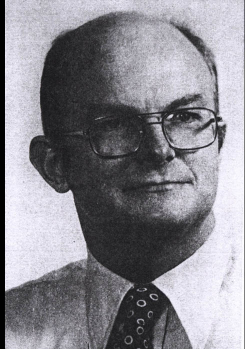


Kormendy & Bender 1996, ApJ, 464, L119

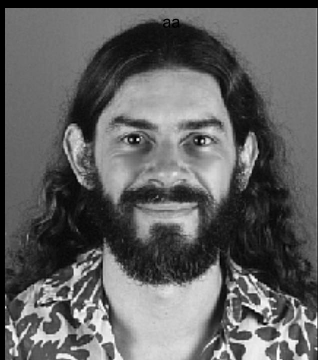
Kormendy & Kennicutt 2004, ARA&A, 42, 681

The Universe is in transition from
early times dominated by
hierarchical clustering and galaxy mergers
to a time when
internal slow ("secular") processes
will dominate galaxy evolution.

At present, both processes are important.



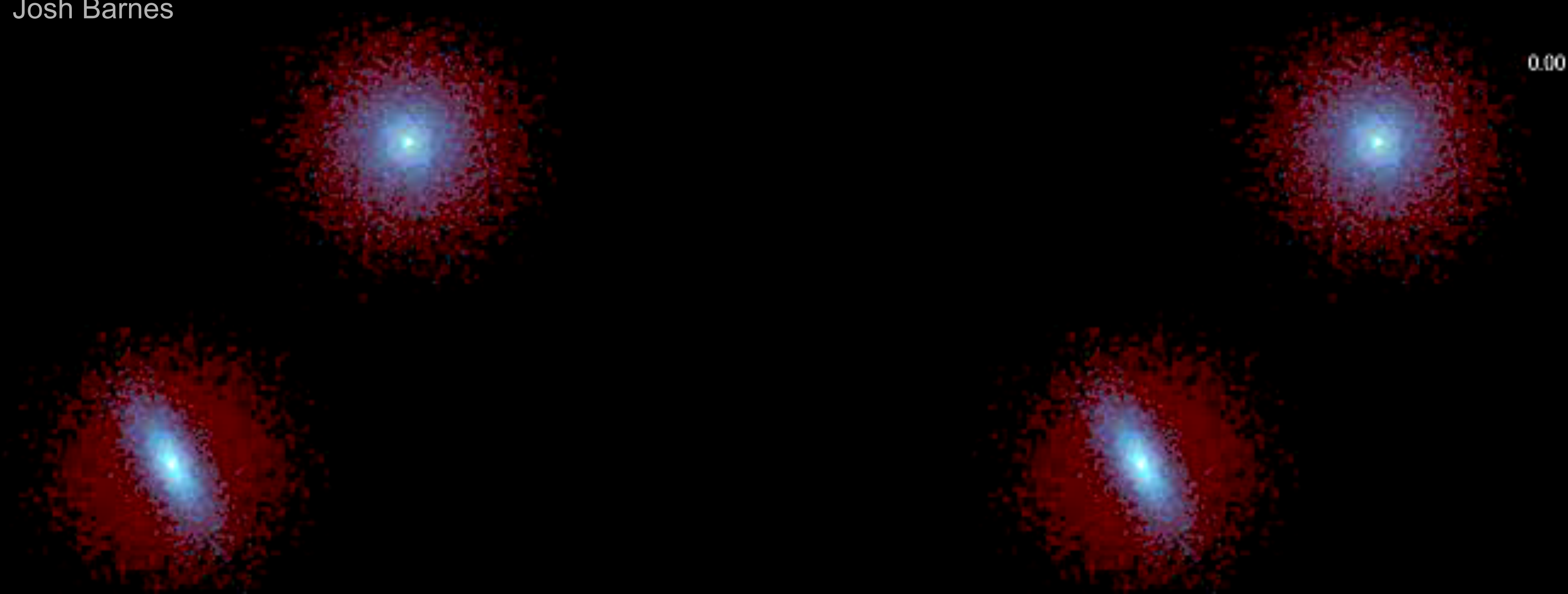
Alar Toomre



Josh Barnes

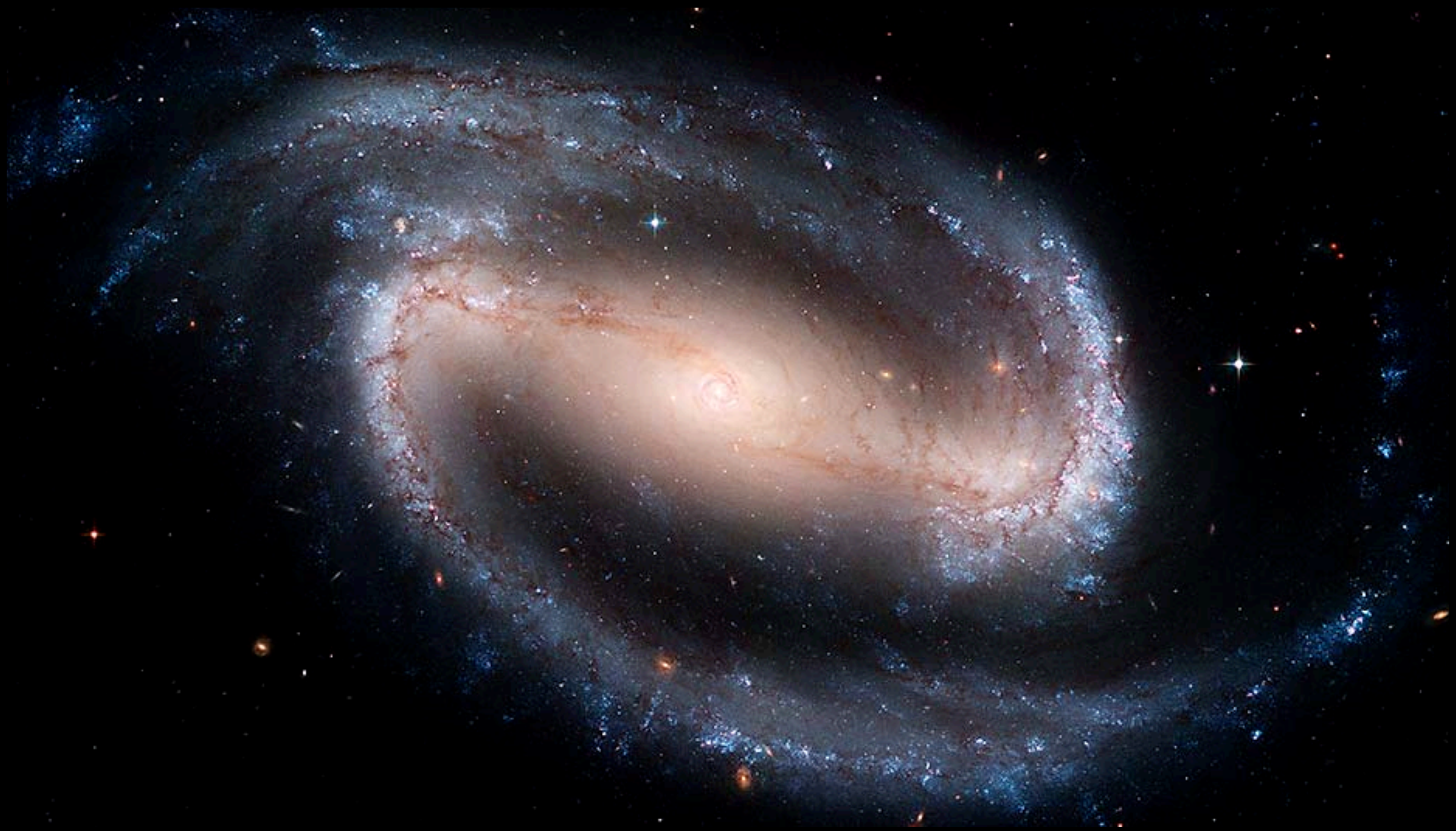
Many galaxies evolve by colliding and merging to make bigger galaxies.

This converts disks into ellipticals or (if the remnant grows a new disk) into <u>classical bulges</u>.



Slow Evolution of "Isolated" Spiral Galaxies

88 **Noncircular features such as bars <u>permanently</u> rearrange the gas in disks and the stars that form from this gas into outer rings, inner rings, and "pseudobulges".**



NGC 2523 (inner ring)

Gerard de Vaucouleurs

NEARBY SEYFERT GALAXIES

S. M. Simkin, H. J. Su, and M. P. Schwarz

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The Astrophysical Journal, 237:404–413, 1980 April 15

In this "sticky particle" simulation, a tumbling bar rearranges the disk gas into an outer ring, and inner ring, and stuff dumped onto the center.

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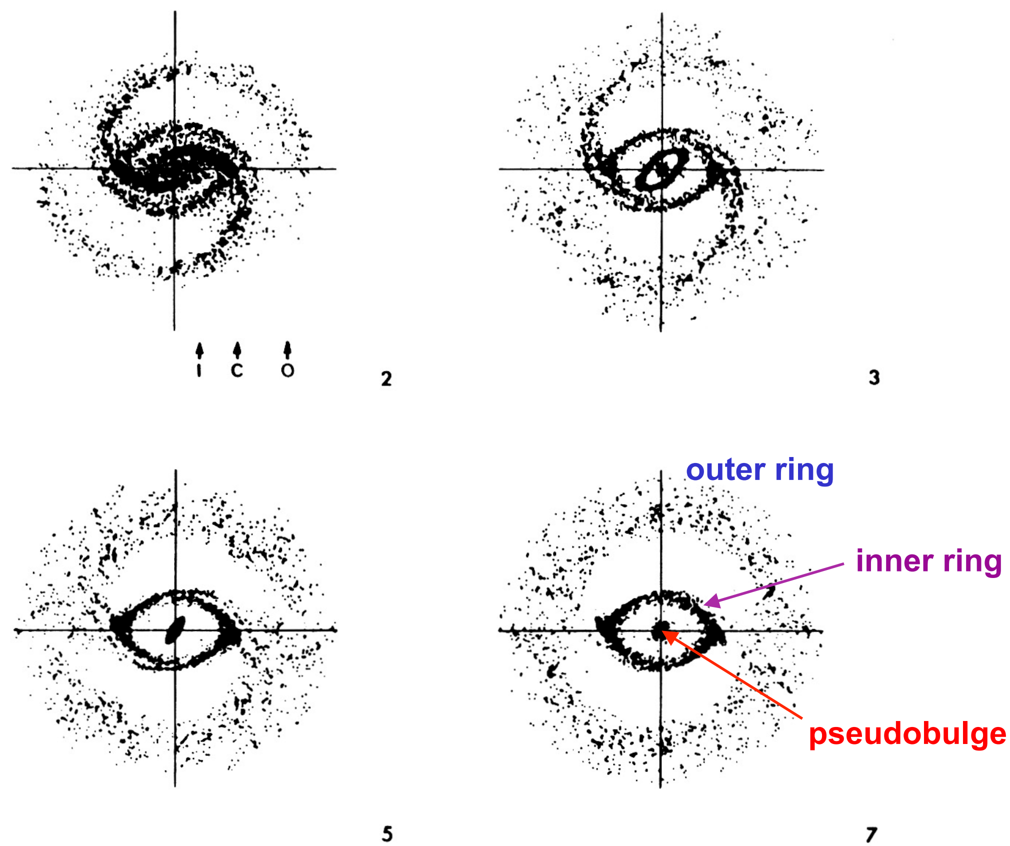
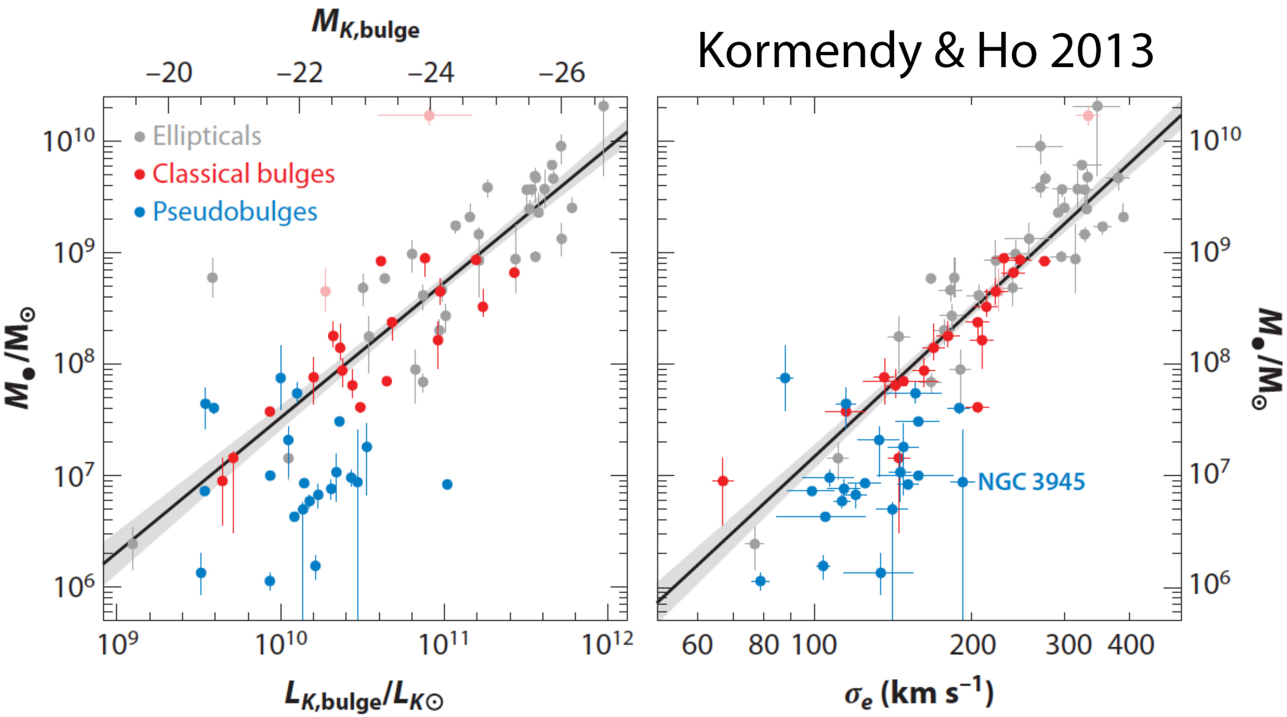


Fig. 3.—Time sequence of the particle distributions for the model described in the text. The arrows indicate the radii of the ILR CR (C), and OLR (O). The time in bar rotation is given in the lower right-hand corner of each frame.



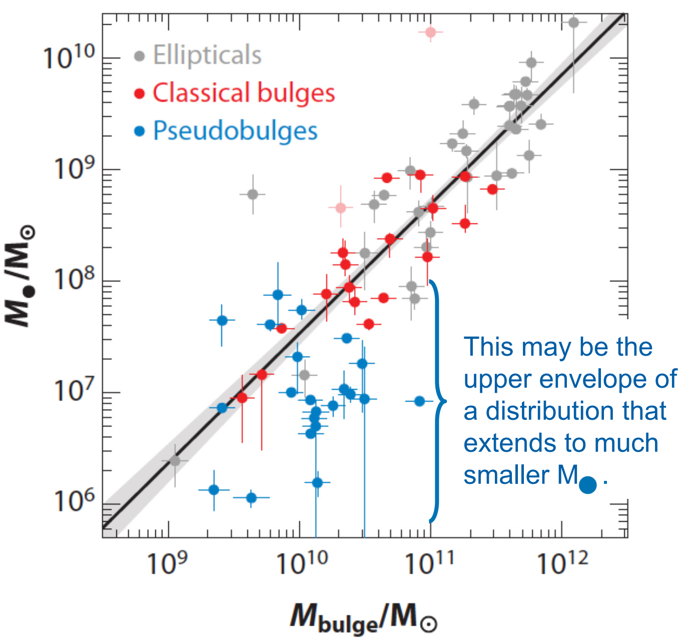
M● correlates little or not at all with pseudobulges ⇒ no coevolution.

Hu 2008, MNRAS, 386, 2242;

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

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

Kormendy & Ho 2013



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NGC 1068: Prototypical Seyfert 1 with a pseudobulge

IMPLICATIONS

Supermassive black holes correlate only with bulges – that is, only with the remnants of major galaxy mergers.

Important success of the secular evolution picture:
Morphological differences divide bulges into two types that correlate differently with black holes implying different formation processes.

BH Correlations With Host Galaxies: Summary

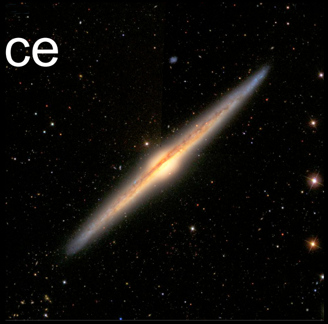
BHs correlate with bulges[1] & ellipticals
but not with disks or
pseudobulges[2] or
dark matter halos.

[1]Classical bulges are made rapidly by galaxy mergers.
[2]Pseudobulges are grown slowly out of disks.

"AGN Feedback" & BH-Galaxy Coevolution

A – No coevolution with galaxy disks or pseudobulges:

Their AGNs are fed locally near the center, and they produce too little energy to affect galaxy evolution.



B – Yes:

1 — Quasar feedback from a bright accretion disk late during wet mergers.
If there is coevolution magic to be engineered, it is here.

2 — Maintenance-mode feedback helps to keep gas hot at highest galaxy masses $M_* > 10^{12}\ M_\odot$.
The effect is negative — it prevents star formation.

3 — The highest-mass galaxies inherit the "magic" from 1.
The tightness of their $M_\bullet - \sigma$ correlation is caused by averaging during dry mergers.

Merger averaging may be the most important process that engineers tight BH-host correlations.

A Brief History of the Black Hole Search

1960s – 1980s: Indirect evidence for BHs from active galactic nuclei ("AGNs") like quasars

1988: Robust detection of M31 BH by Dressler & Richstone (Palomar 200-inch tel.) and by Kormendy (CFHT). More follow (Kormendy & Richstone et lots of al.).
This was the "proof of concept" phase for BHs.

1993 – 1998: Start of BH demographics:

$M_\bullet$ — L_{bulge}, $M_\bullet$ — M_{bulge} correlation suggestive of BH–bulge coevolution
(Dressler, Kormendy, … Magorrian and Nukers, …)

2000 …

$M_\bullet$ — σ Correlation ➔ BH–bulge coevolution!
(Ferrarese & Merritt; Gebhardt and Nukers, …)

The period 1993 – 2011 was a plateau in our understanding of black holes and their relation to host galaxies:
We thought that "one set of $M_\bullet$ correlations rules all".

Kormendy & Ho 2013 review and construct a new and richer picture:
Black holes correlate differently with different kinds of galaxy components that have different formation histories.
Result: Revisions in our picture of BH – host galaxy coevolution.

A Brief History of the Black Hole Search

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**"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 – is an important sign of the developing scientific maturity of this subject.

A Brief History of the Black Hole Search

Kormendy & Ho 2013 review and construct a new and richer picture:
Black holes correlate differently with different kinds of galaxy components that have different formation histories.
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Now let's go back and fill in the details:

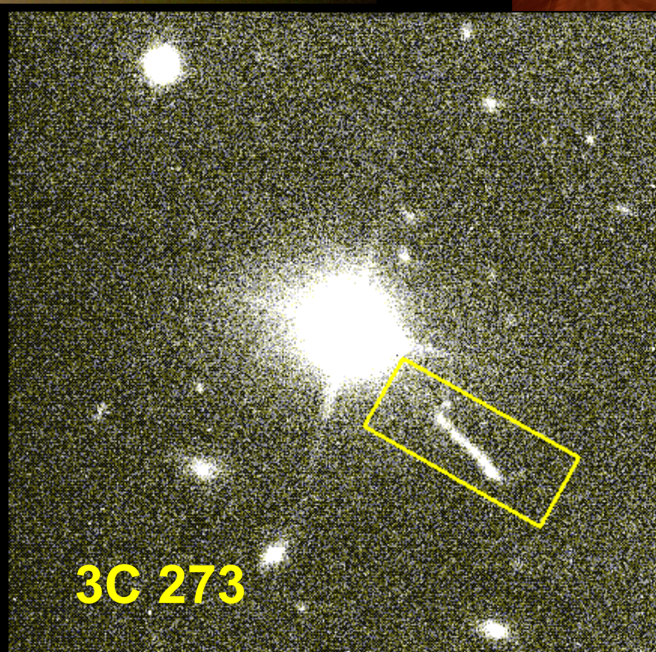
1 – More on the discovery of supermassive black holes

2 – New results in Kormendy & Ho 2013

3 – Implications for galaxy formation:
Which BHs coevolve with their hosts and which ones do not?

4 – Implications for galaxy formation more generally

1 – Supermassive Black Holes in Galaxies: Introduction

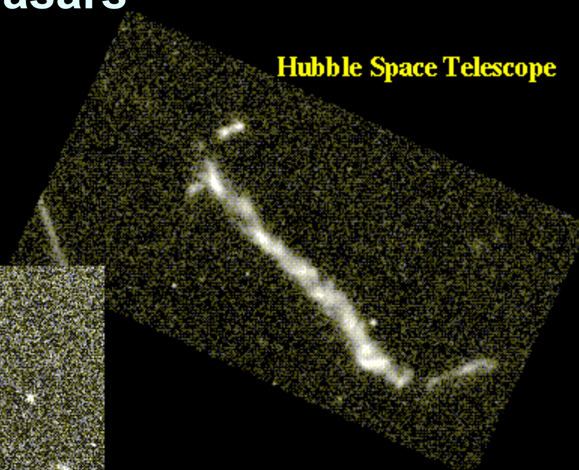


Roughly concurrent discovery of stellar-mass black holes helped to cement this subject.

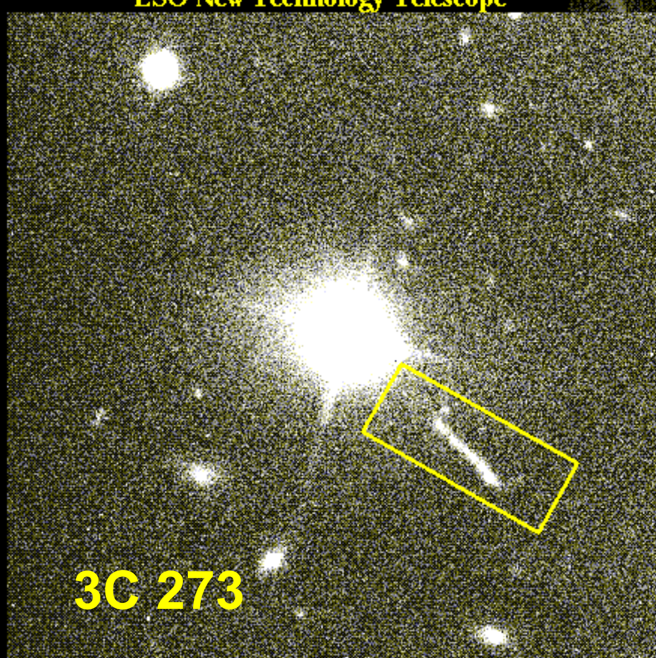
The Discovery of Quasars

Identification (Schmidt 1963, *Nature*, 197, 1040) of the radio source 3C 273 as a "star" with z = 0.158 was a huge shock. Expansion of Universe ➔ 3C 273 was 2nd-most-distant object then known. Rapid variability ➔ quasar engines are tiny: Volumes ≈ size of our Solar System are more luminous than any galaxy.

The energy requirements for powering quasars were the first compelling argument for supermassive black hole engines.

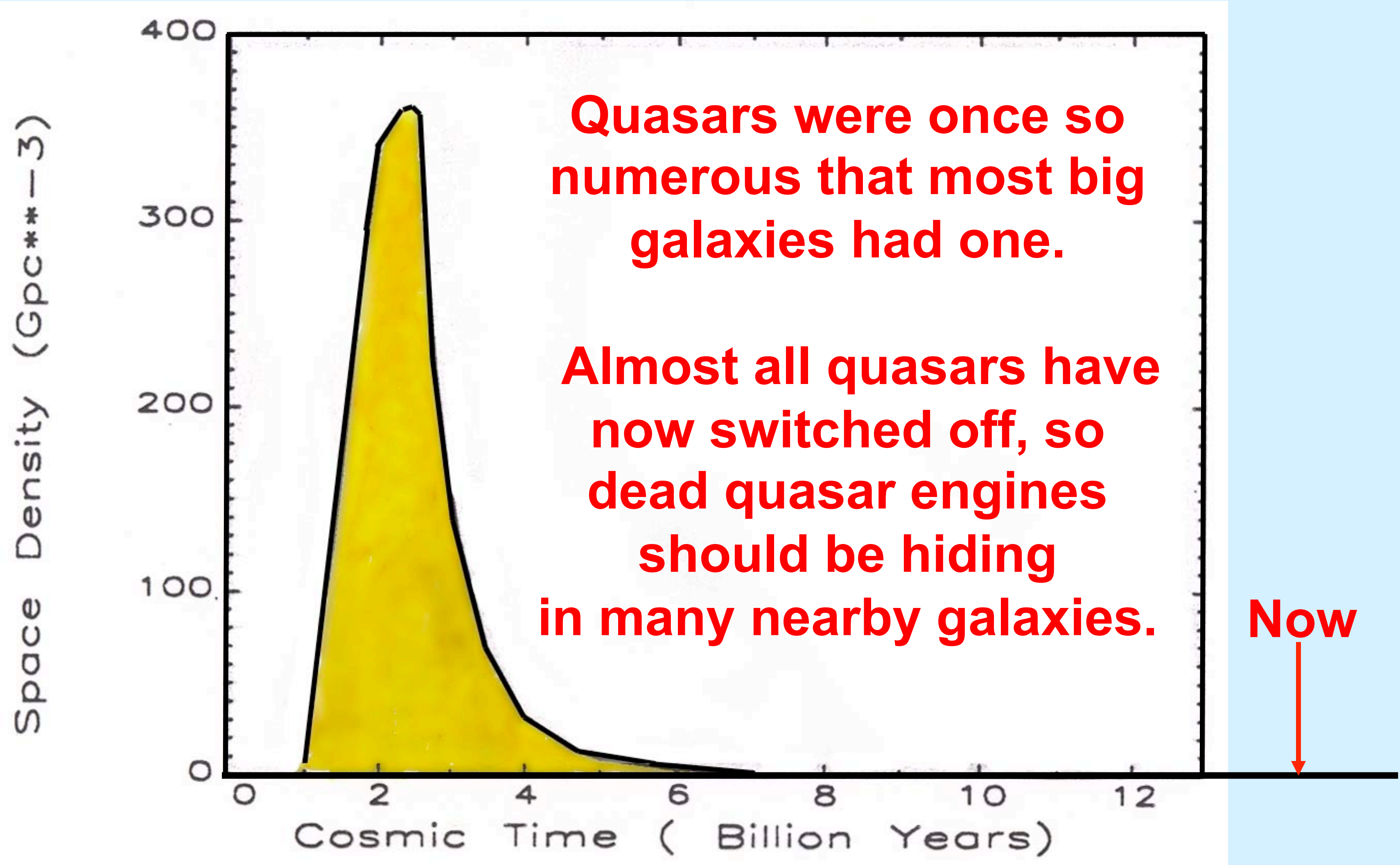


ESO New Technology Telescope



The black hole masses that we find in the nearby universe are just right to explain the energy output of quasars.

The Quasar Era Was >10 Billion Years Ago



The evolution of the universe can be likened to a display of fireworks that has just ended: some few red wisps, ashes, and smoke. Standing on a well-chilled cinder, we see the fading of the suns and try to recall the vanished brilliance of the origin of the worlds.”

Abbé Georges Lemaître (1931)

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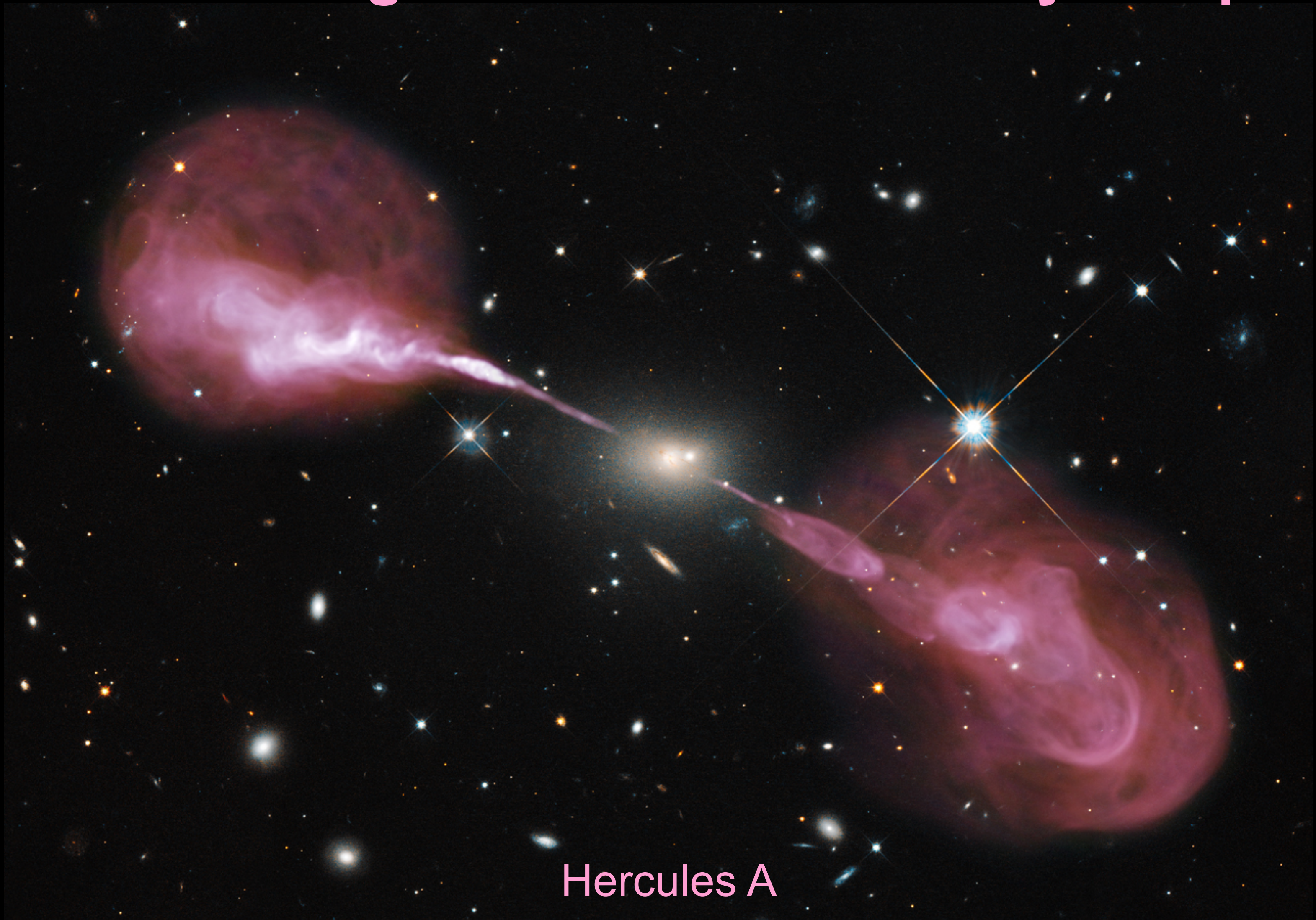
Abbé Georges Lemaître (1931)

The study of black holes is the archaeology of supermassive cinders.

Many radio galaxies and quasars have jets with knot velocities ≈ speed of light.

Therefore: Engines are relativistically compact.



Hercules A

Supermassive Black Holes as Quasar Engines

The huge luminosities and tiny sizes of quasars can be understood if they are powered by black holes with masses of 10^6 to 10^{10} Suns.

Gas near the black hole settles into a hot disk, releasing gravitational energy as it spirals into the hole.

Magnetic fields eject jets along the black hole rotation axis.

PROBLEM

People believe the black hole picture.
Enormous amounts of work are based on it.

But for many years, there was no direct evidence that supermassive black holes exist.

So the search for supermassive black holes became a very hot subject.

DANGER

**It is easy to believe that we have proved what we expect to find.
So the standard of proof is very high.**

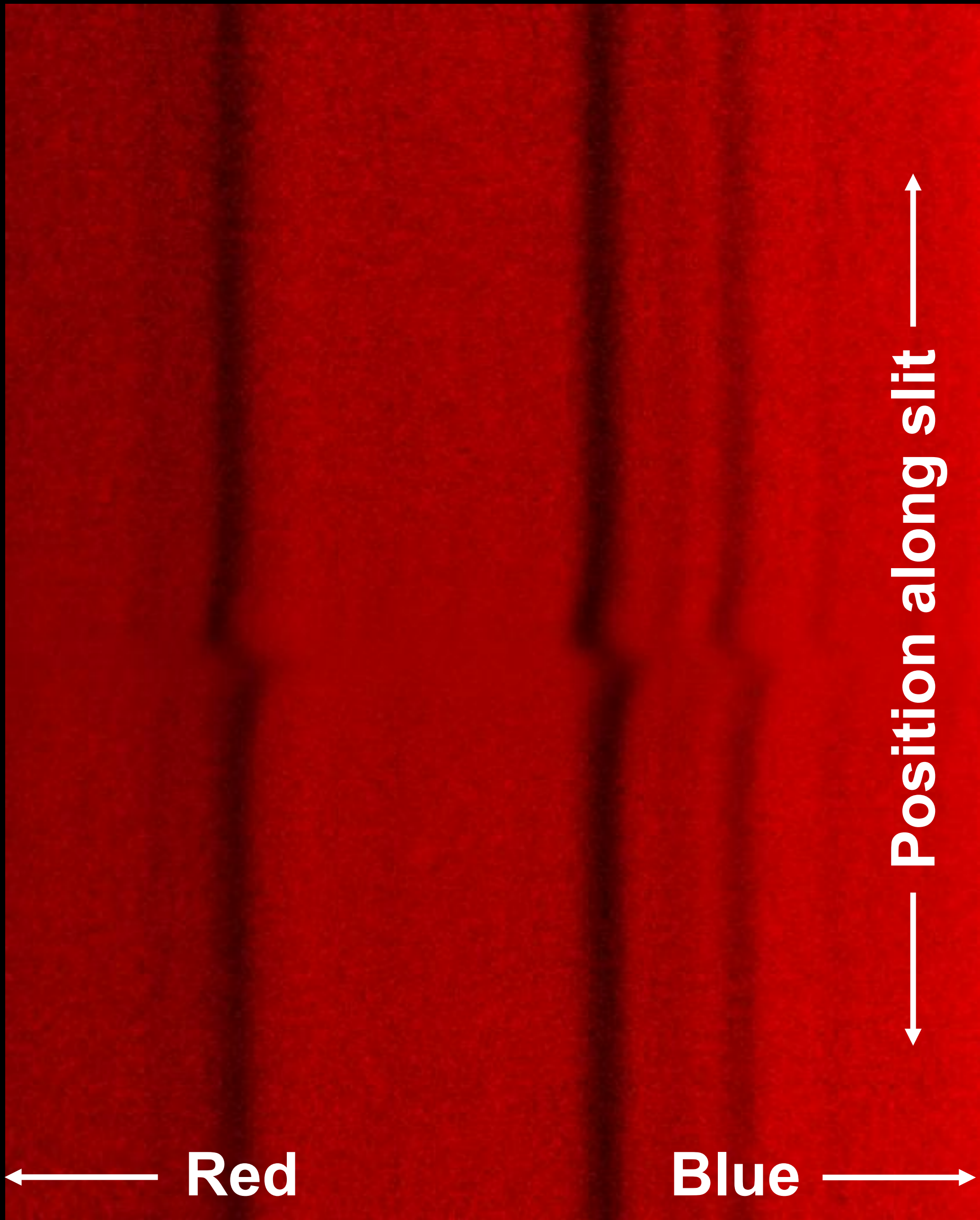
The Search For Supermassive Black Holes

Canada-France-Hawaii-Telescope

M 31: $M_\bullet = 1.4 \times 10^8 M_\odot$

Kormendy 1988, ApJ, 325, 128

M 31 on spectrograph slit

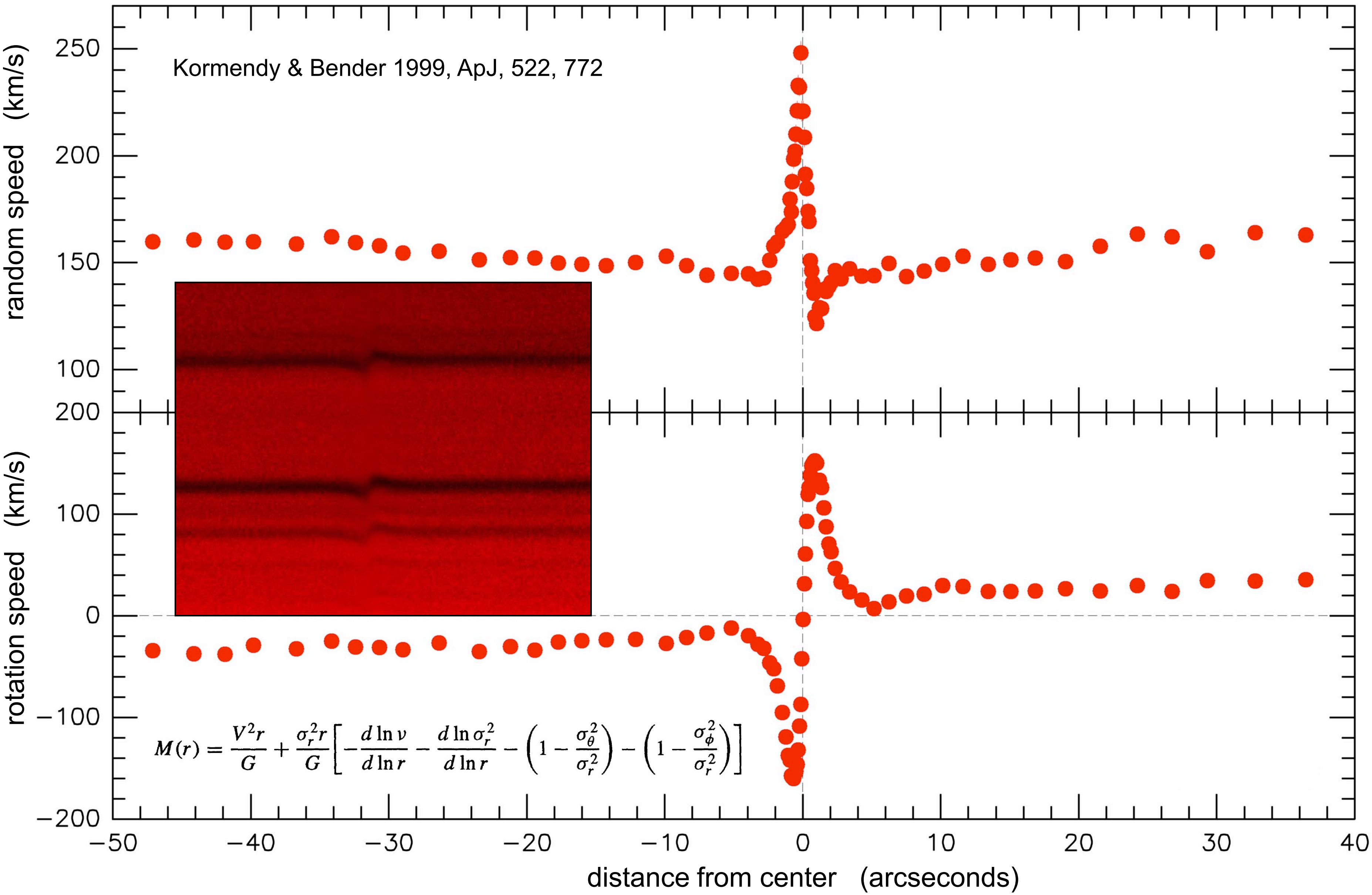


Spectrum of M 31

The brightness variation of the galaxy is divided out.

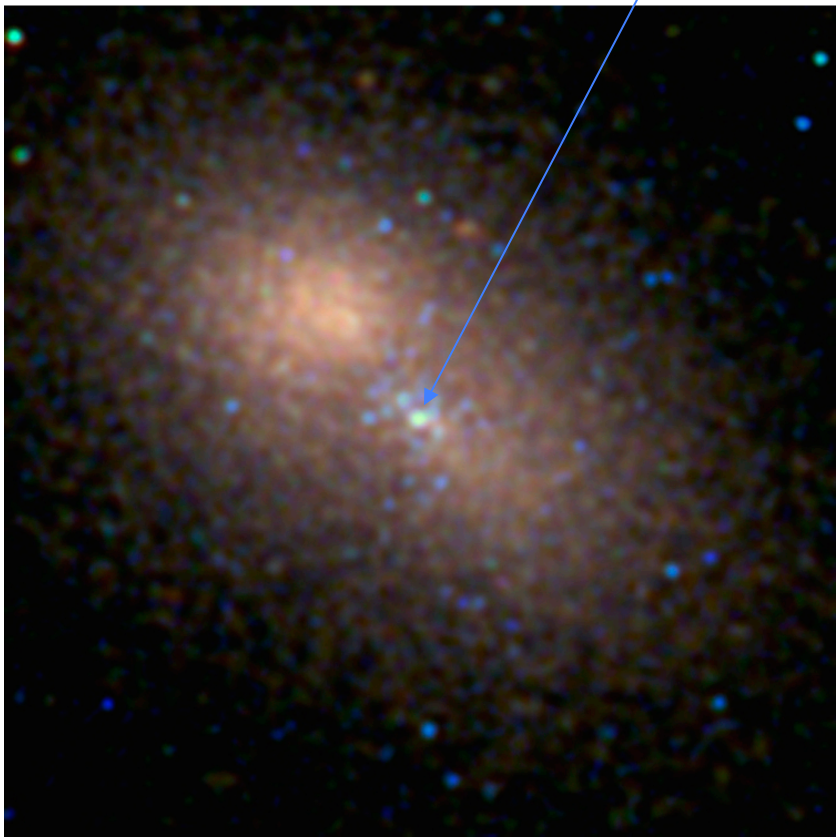
The zigzag in the lines is the signature of the rapidly rotating nucleus and central black hole.

M 31: $M_\bullet = 1.4 \times 10^8\ M_\odot$

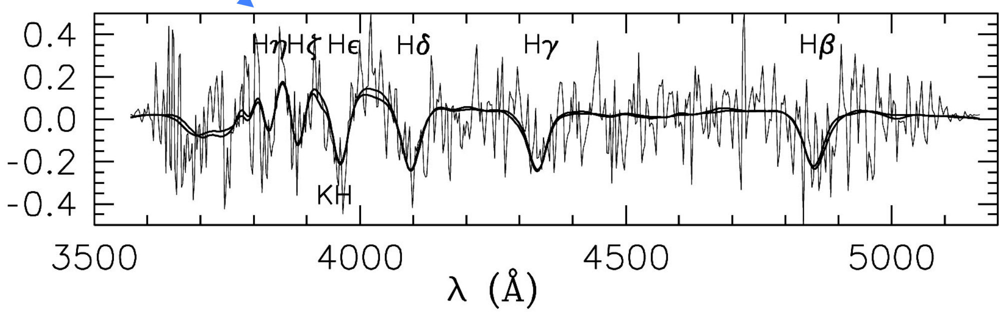


Stars in this blue cluster have LOS velocity dispersion σ = 1183 ± 201 km/s.

The red stars <u>along the same line</u> of sight have σ ~ 250 km/s.



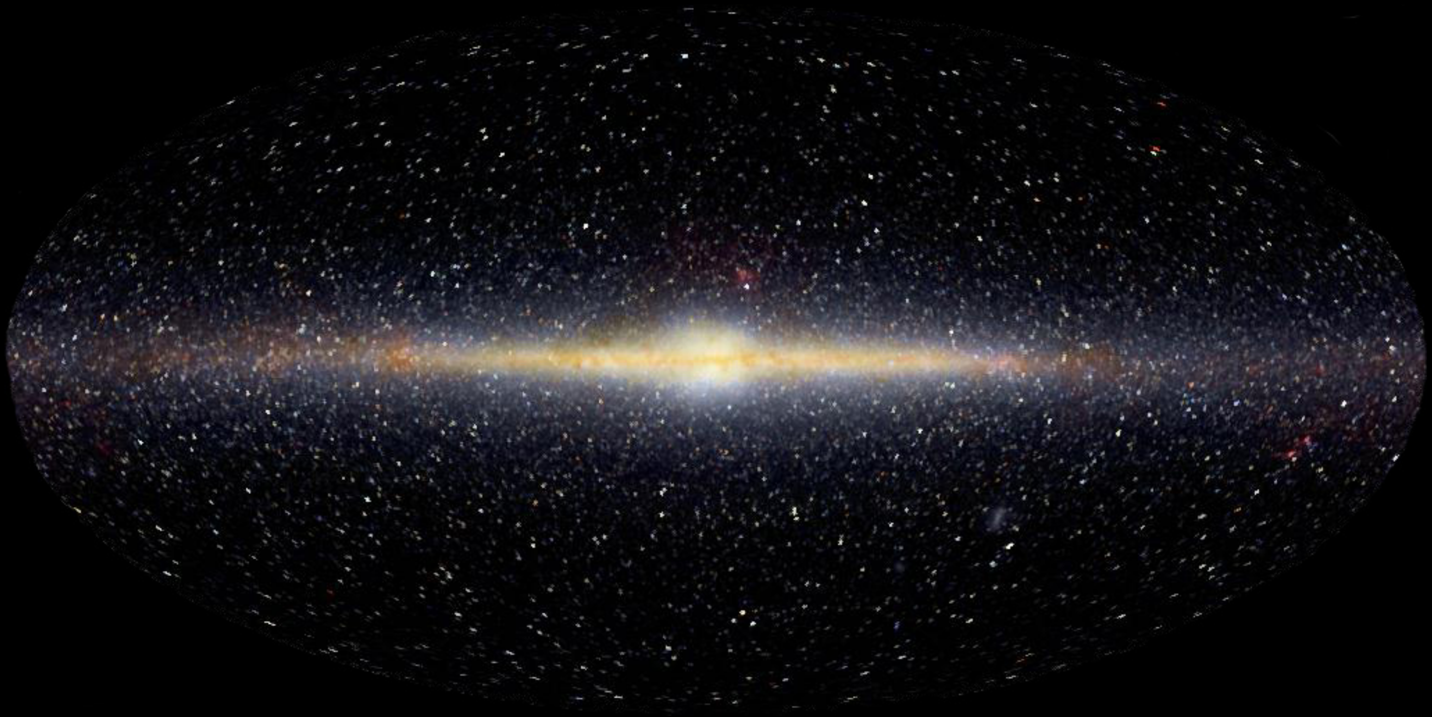
Lauer et al. 2012, ApJ, 745, L121 (HST)



This proves that the black hole is in the blue cluster. Plausible black hole alternatives are ruled out.

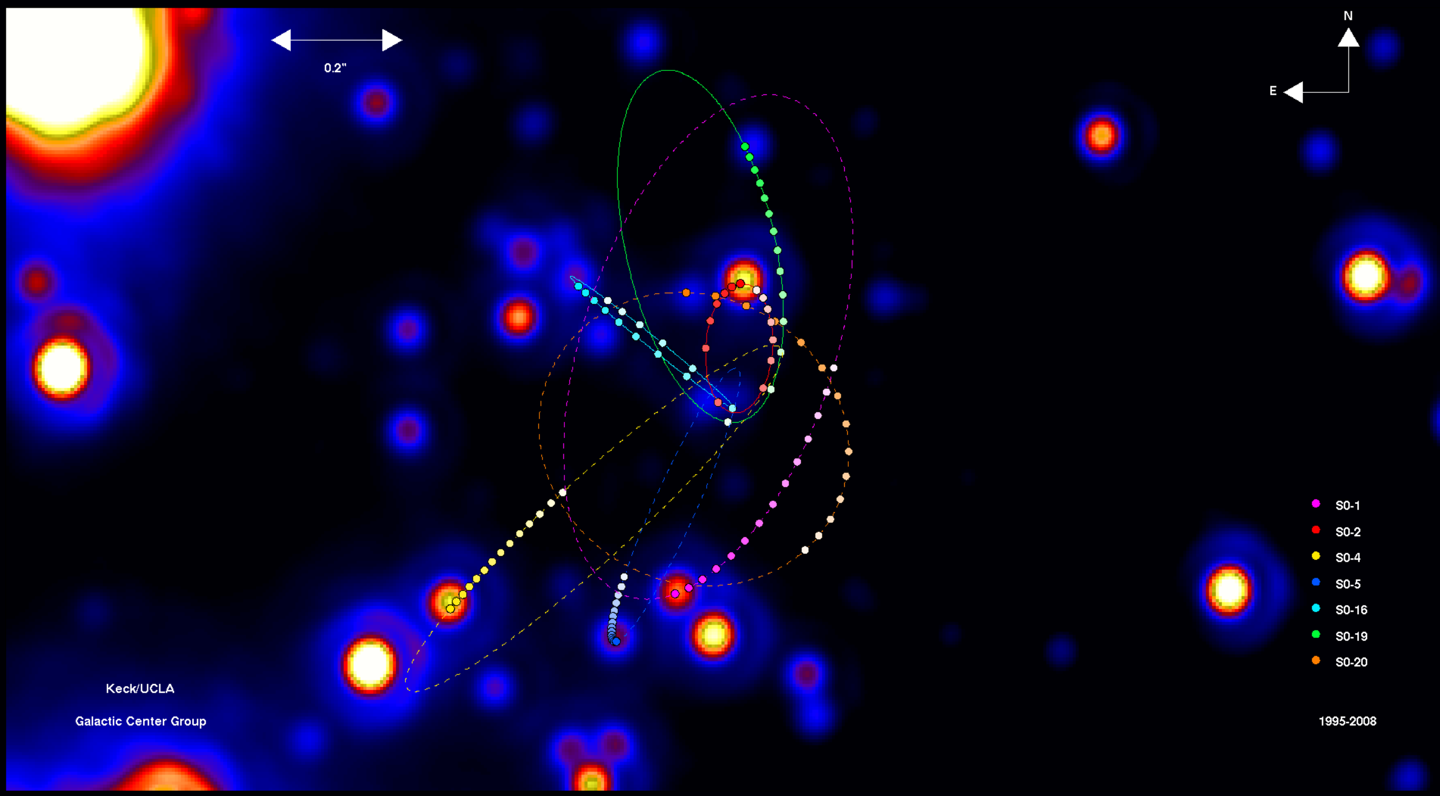
Bender et al. 2005, ApJ, 631, 280;
Kormendy & Bender 1999, ApJ, 522, 772

Our Galaxy: $M_\bullet = 4.3 \times 10^6\ M_\odot$



With adaptive optics working in the infrared (to see through dust)
Reinhard Genzel and Andrea Ghez and their groups
observe individual stellar orbits near the center.
Each orbit independently gives $M_\bullet$.

These stars move as fast as 5000 km/s in orbit around the black hole located at the central radio source Sgr A*.



The dark mass is in such a small volume at the center that alternatives to a black hole (failed stars or dead stars) are ruled out.

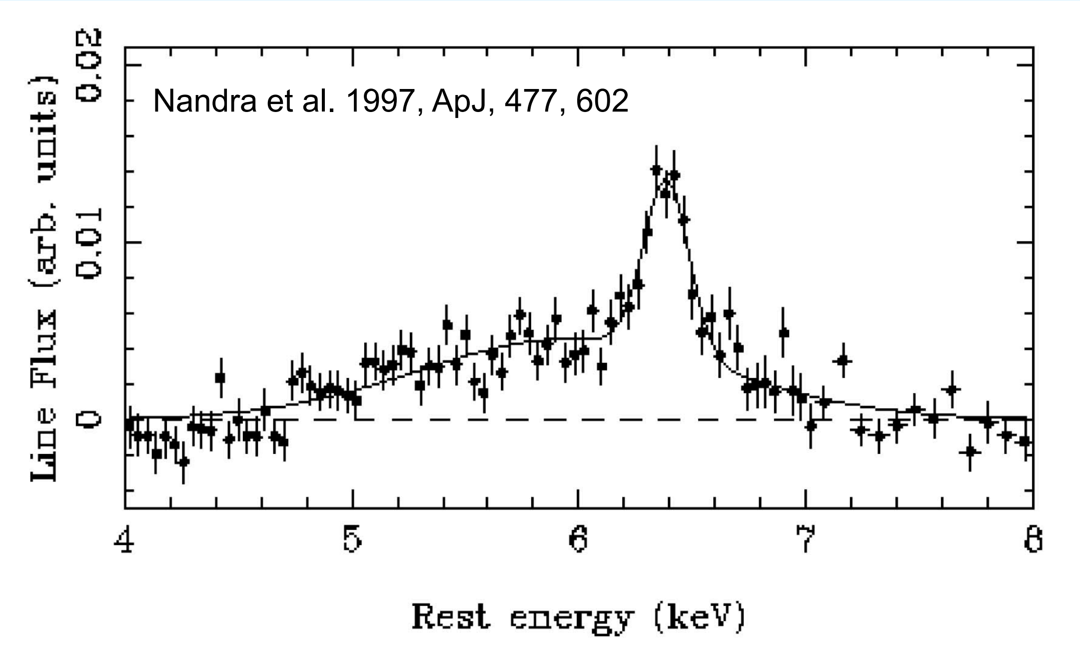
This the best black hole case.

Have we discovered black holes in galactic nuclei?

It's looking good!

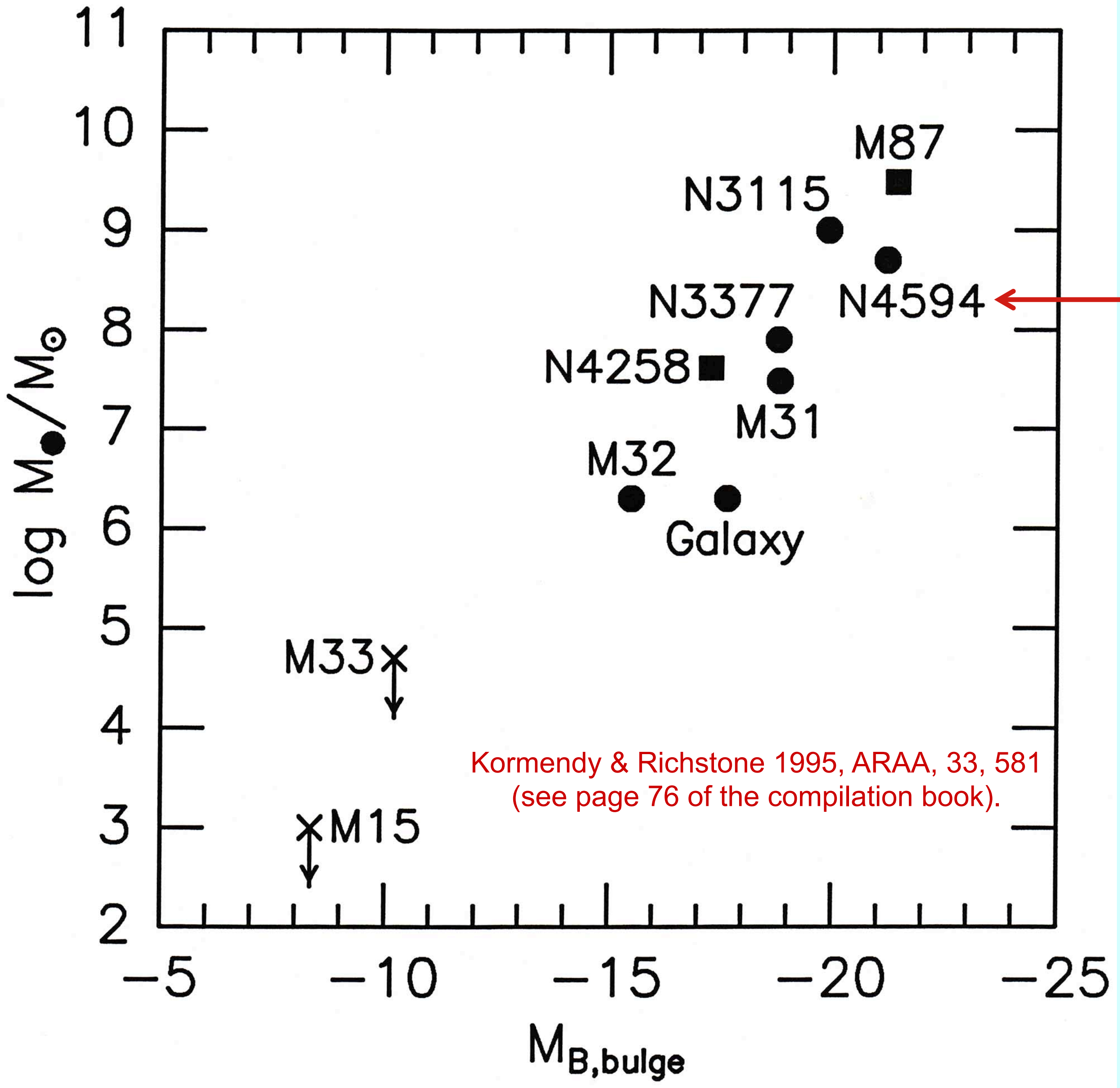
Other alternatives are very implausible.

But: Absolute proof requires that we see velocities of almost the speed of light from near the surface of the black hole.



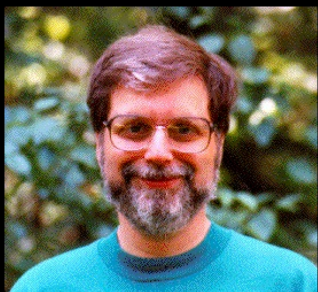
X-ray observations of Seyfert galaxies show that gas near the center moves as fast as 100,000 km/s ~ (1/3) c.

First demographic result (Kormendy 1993; 76 Kormendy & Richstone 1995):
Bigger BHs live in bigger galaxies (specifically: bigger galaxy bulges).



Kormendy & Richstone 1995, ARAA, 33, 581
(see page 76 of the compilation book).

The Nuker Team



Doug Richstone

Sandra Faber

Karl Gebhardt

John Kormendy

Scott Tremaine

Tod Lauer

Ralf Bender

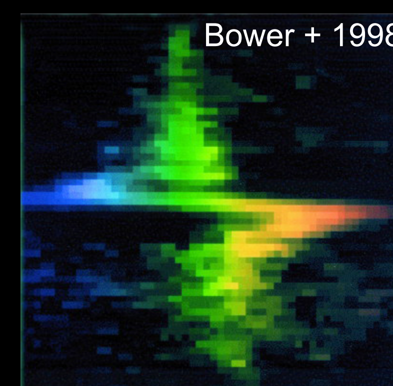
Alan Dressler

Alex Filippenko

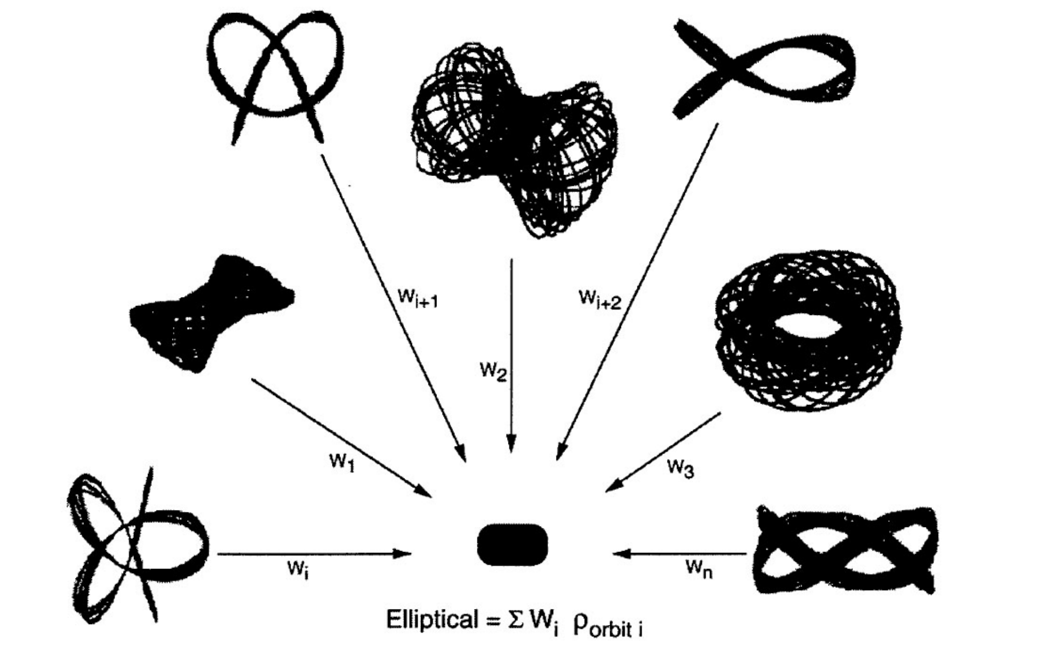
Richard Green

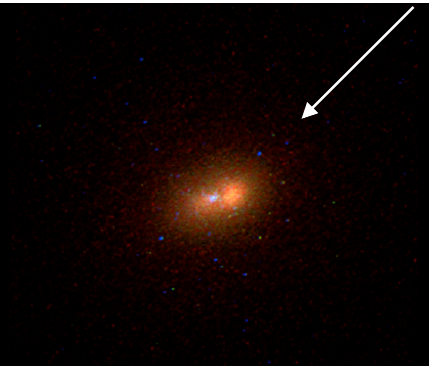
Additional Nukers
Gary Bower
Carl Grillmair
Kayhan Gültekin
Luis Ho
John Magorrian
Jason Pinkney
Christos Siopis

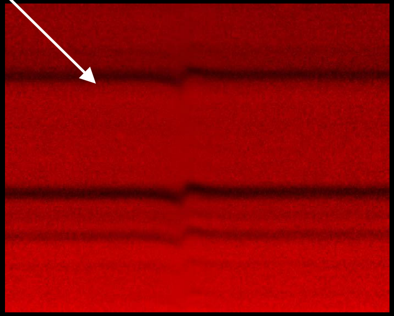
Iconic emission spectrum of NGC 4374 ⇒ $M_\bullet = (9\pm1) \times 10^8 M_\odot$

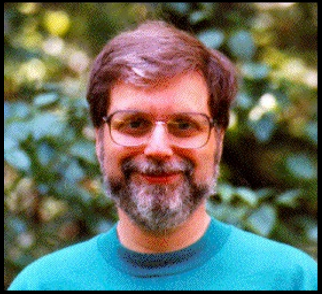


Martin Schwarzschild's (1979, ApJ, 232, 236) Method: Orbit superposition models are now standard.









Doug Richstone

Karl Gebhardt (UT)

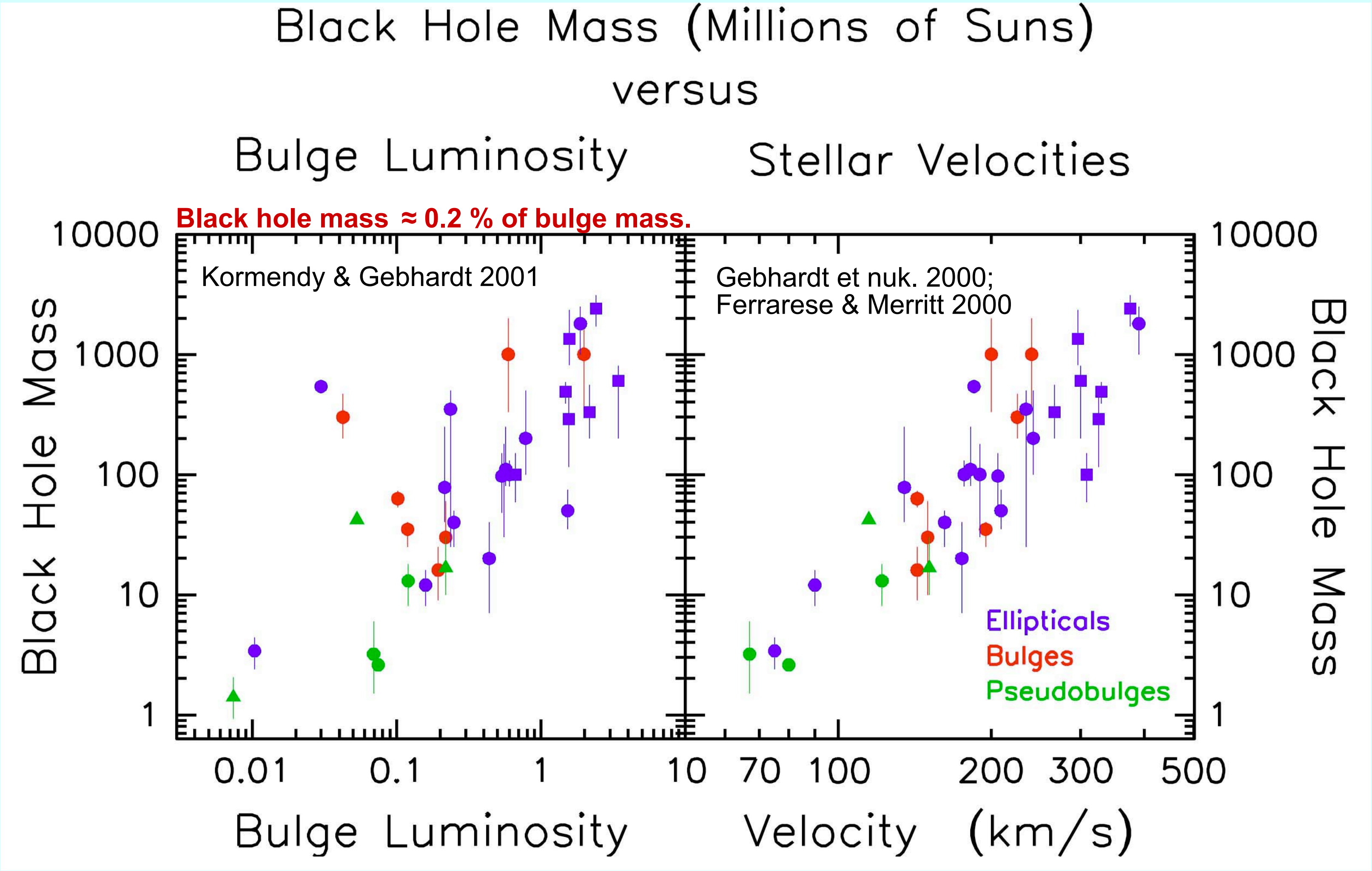
Scott Tremaine

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

Measured $M_\bullet$ values have remained stable despite dramatic improvements in spatial resolution, data analysis, and modeling techniques.

Galaxies do not use their freedom to indulge in perverse orbit structure.

Why? Physics of galaxy formation limits possibilities.



Bigger BHs live in bigger bulges (2001 version).

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

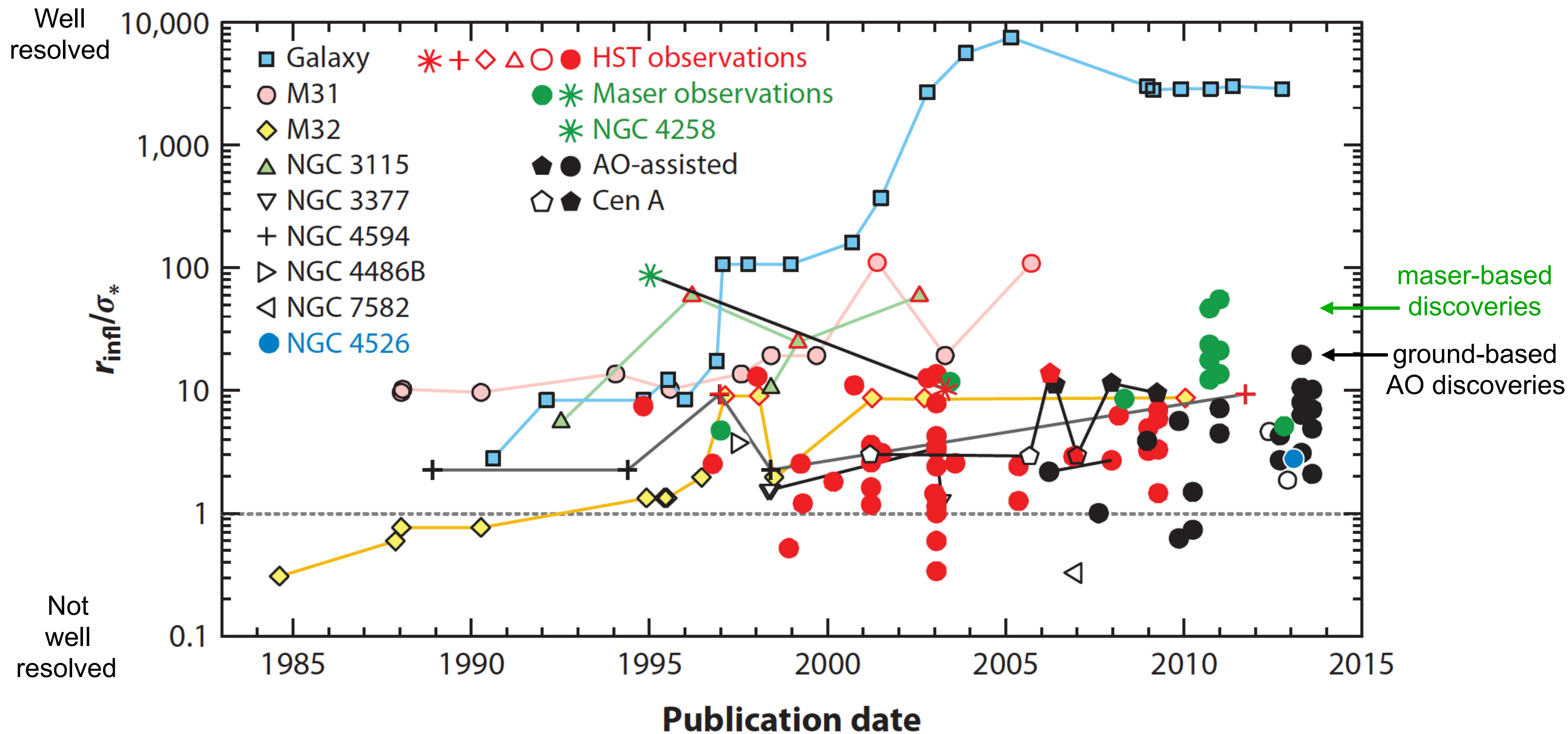
CONCLUSION

The formation of bulges and
the growth of their BHs as "quasars"
happened together.

BUT

Enthusiasm for the idea that
BHs and galaxies regulate each other's growth
by quasar energy feedback is overdone.
We need a course correction.

How well do BH discovery observations resolve the radius $r_{infl} \approx GM_\bullet/\sigma^2$ influenced by the BH?



The heyday of HST BH discoveries is over.

Ground-based adaptive optics (AO) infrared observations and radio interferometry of masers are taking over.

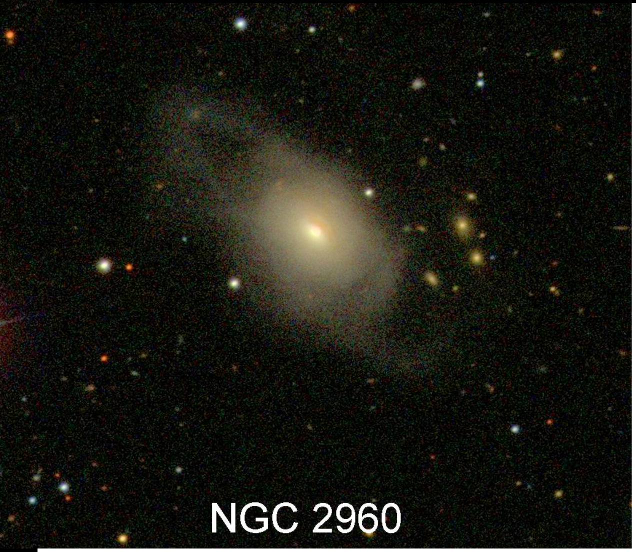
2 – New Results in Kormendy & Ho (2013)

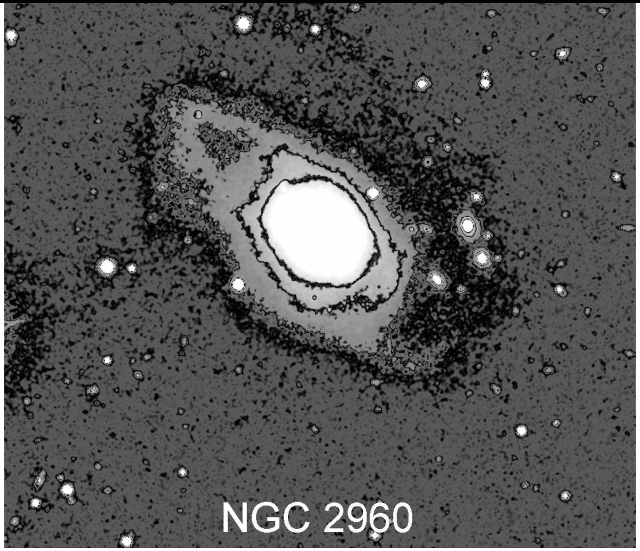
BH masses $M_\bullet$ correlate differently
with different kinds of galaxy components
that have different formation histories. This is good news.

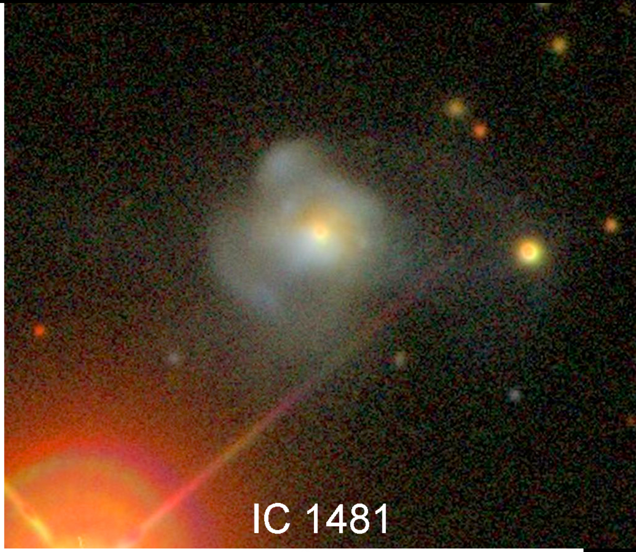
But I have to introduce many details about galaxy structure
and their implications about galaxy evolution.

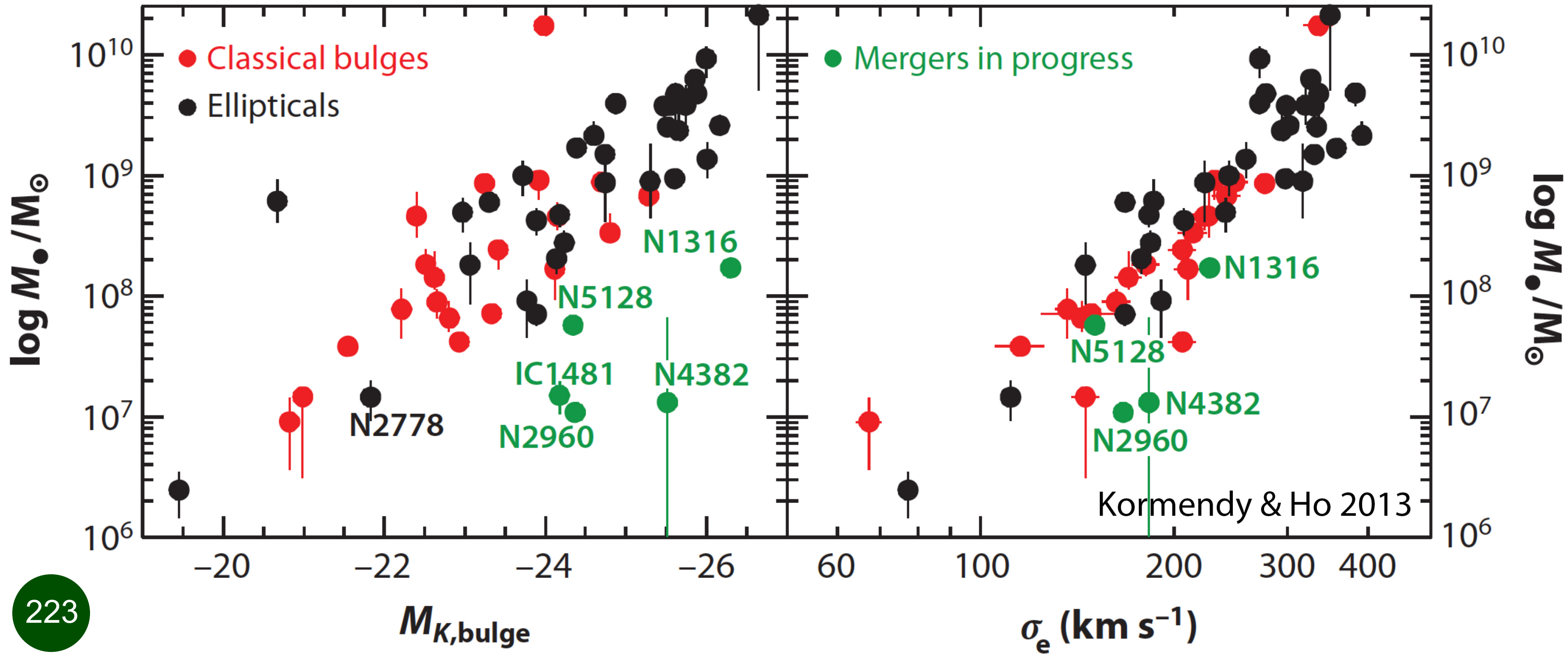
We have BH detections via spatially resolved dynamics
in
44 elliptical galaxies
and
41 disk galaxies
(20 with classical bulges + 21 with pseudobulges).

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



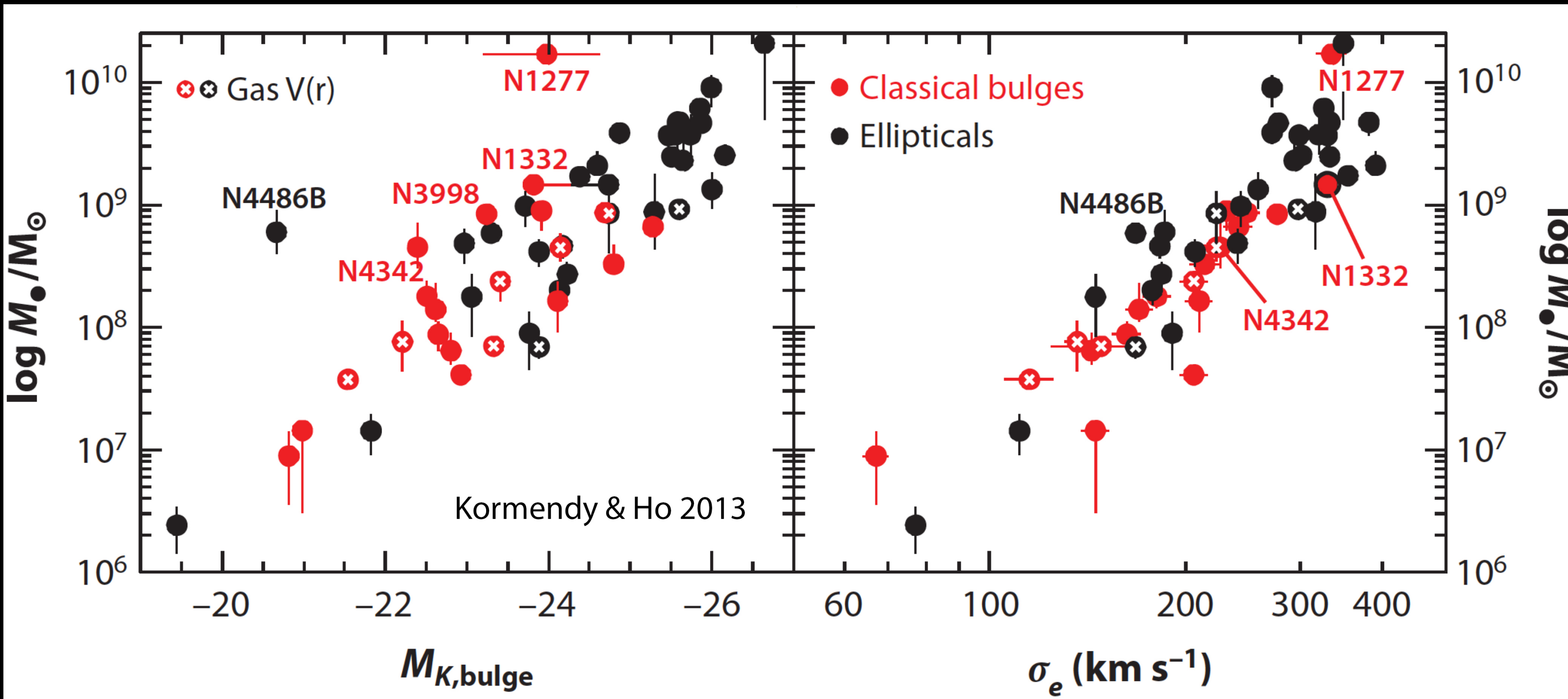






Rare galaxies contain BH monsters.

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

Revised BH–Host Galaxy Correlations

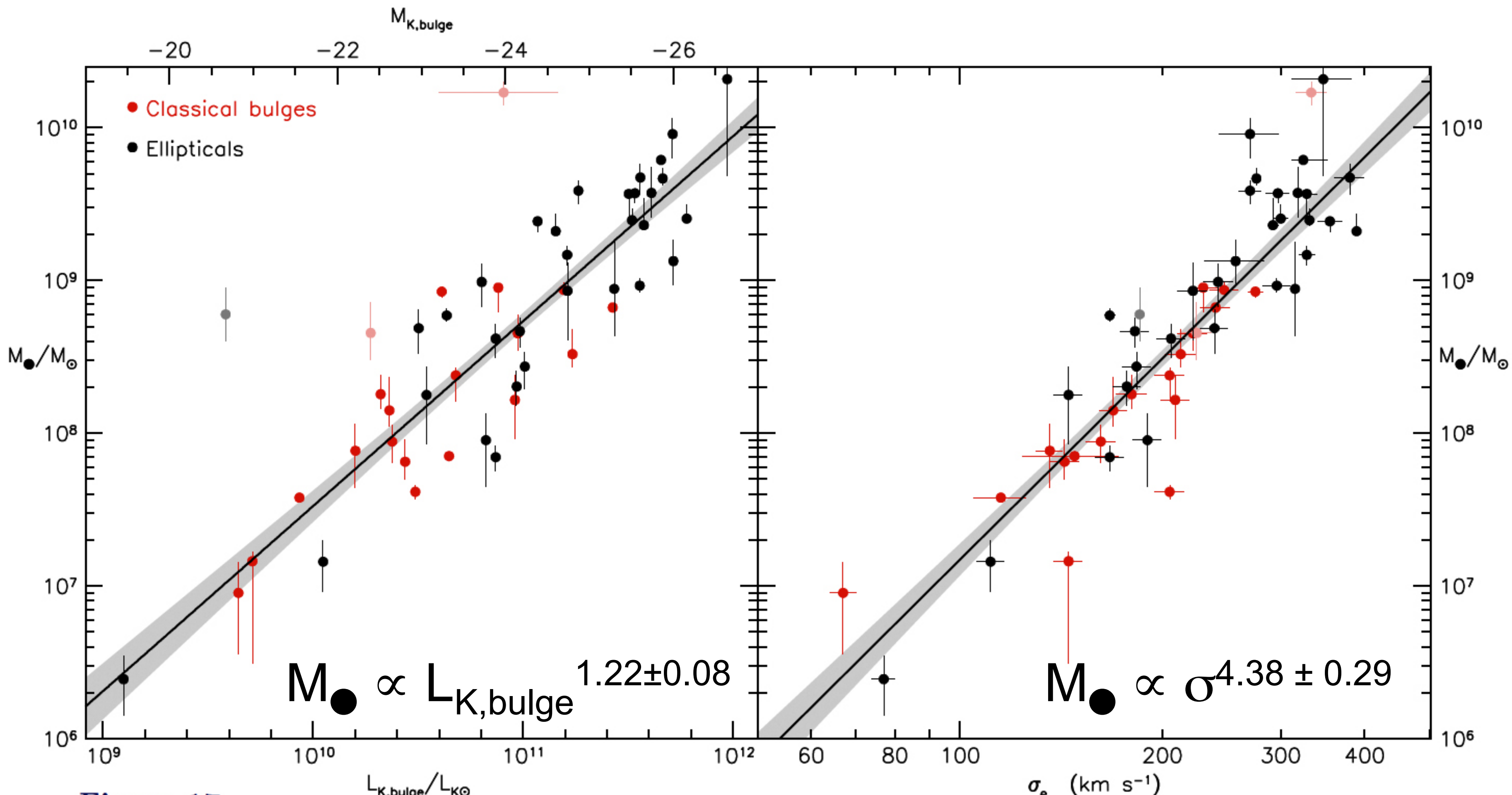


Figure 17

The $M_\bullet$–$M_{\mathrm{K,bulge}}$ and $M_\bullet$–σ_e correlations with symmetric (Tremaine et al. 2002) least-squares fits (Equations 2 and 3) and the 1σ range of the fits (*gray shading*). Here we give equal weight to all the points. Fits that use the individual $M_\bullet$ measurement errors (Equations 4 and 5) are almost identical. Among the plotted points, all fits omit the BH monsters (*points in light colors*), $M_\bullet$ values determined from ionized gas rotation curves without taking line widths into account (NGC 4459 and NGC 4596), and the two highest-$M_\bullet$ ellipticals (NGC 3842 and NGC 4889).

Revised BH–Host Galaxy Correlations

$$\frac{M_\bullet}{10^9\,M_\odot} = \left(0.544^{+0.067}_{-0.059}\right)\left(\frac{L_{K,\mathrm{bulge}}}{10^{11}\,L_{K\odot}}\right)^{1.22\pm0.08} \quad \text{intrinsic scatter} = 0.30\ \text{dex}$$

$$\frac{M_\bullet}{10^9\,M_\odot} = \left(0.310^{+0.037}_{-0.033}\right)\left(\frac{\sigma}{200\,\mathrm{km\,s^{-1}}}\right)^{4.38\pm0.29} \quad \boxed{\text{intrinsic scatter} = 0.28\ \text{dex}}$$

$$\frac{M_\bullet}{10^9\,M_\odot} = \left(0.49^{+0.06}_{-0.05}\right)\left(\frac{M_\mathrm{bulge}}{10^{11}\,M_\odot}\right)^{1.17\pm0.08}; \quad \boxed{\text{intrinsic scatter} = 0.28\ \text{dex.}}$$

Note that the $M_\bullet$–M_{bulge} correlation has the same intrinsic scatter as the $M_\bullet$–σ correlation.

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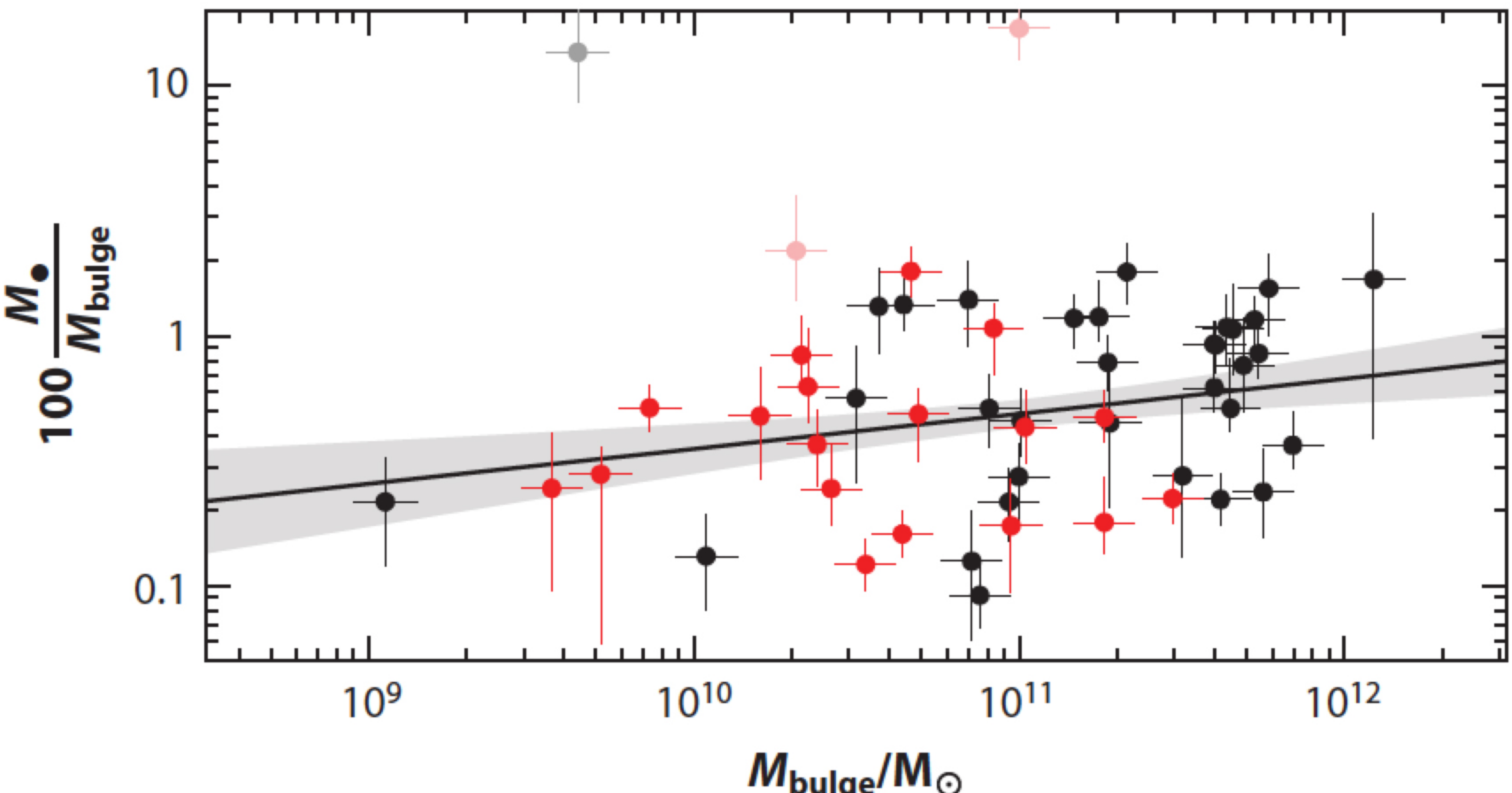
The canonical BH mass fraction is 0.5 %.
This is about 4 times bigger than we thought.

BH mass fractions scatter between 0.1 % and 2 %.

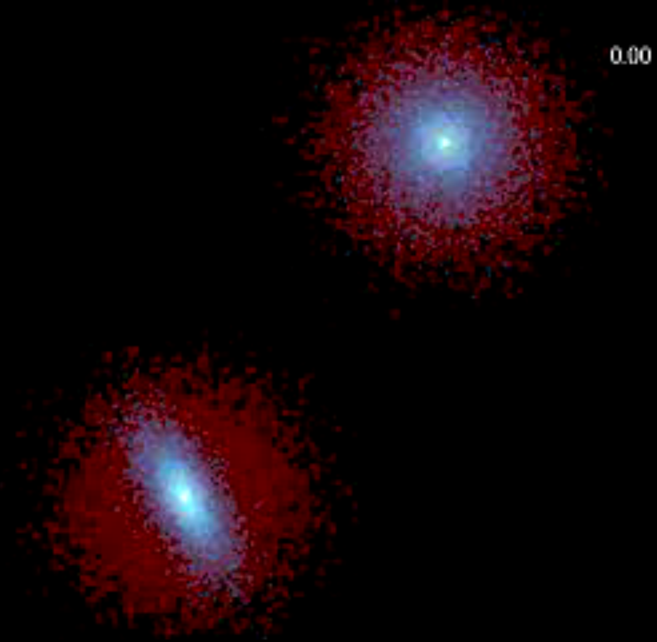


Bulge Definition:

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."

The physics that underlies the formation of black holes & the evolution of disks is very general (Lynden-Bell, Tremaine):

Self-gravitating objects spread because their heat capacity is negative.

(Kormendy & Fisher 2005, RevMexA&A, 23, 101)

Temperature $T \propto \overline{v^2}$;

Virial theorem 2KE + PE = 0. Total E ≡ KE + PE = -KE.

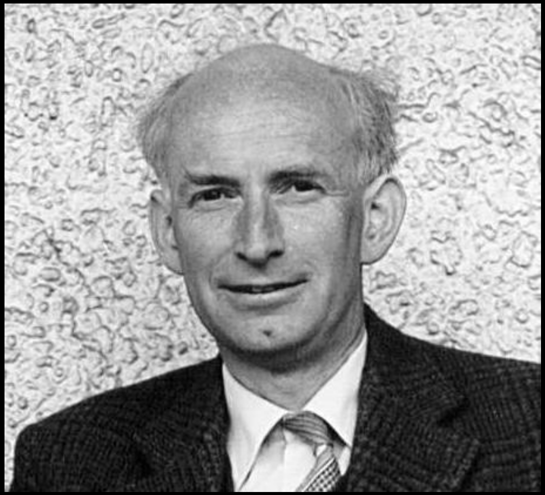
Therefore heat capacity ≡ $dE/dT \propto d[\,-Nm\overline{v^2}/2\,]/d[\,\overline{v^2}\,] < 0$.

Therefore, if the system loses energy, it gets hotter.

If the center of the system gets slightly hotter than the outside, then heat flows outward, the center gets hotter, and this promotes more heat flow.

The system spreads — it forms a dense core by expanding a diffuse halo — if some mechanism efficiently transports energy outward.

Orbits are donkeys.



Donald Lynden-Bell

That is: If you push an orbiting object forward to make it go faster, it will climb to a higher orbit and end up going slower. And vice versa.

Self-gravitating disks spread because outward angular momentum transport minimizes total energy.

Kormendy & Fisher 2005, RevMexA&A, 23, 101
Kormendy 2007, IAU Symposium 245

Tremaine (1989) provides a transparent summary of an argument due to Lynden-Bell & Kalnajs (1972) and to Lynden-Bell & Pringle (1974). A disk is supported by rotation, so evolution is by angular momentum transport. The 'goal' is to minimize the total energy at fixed total angular momentum. A rotationally supported ring at radius r in a fixed potential $\Phi(r)$ has specific energy $E(r)$ and specific angular momentum $L(r)$ given by

$$E(r) = \frac{r}{2}\frac{d\Phi}{dr} + \Phi \quad \text{and} \quad L(r) = \left(r^3 \frac{d\Phi}{dr}\right)^{1/2} .$$

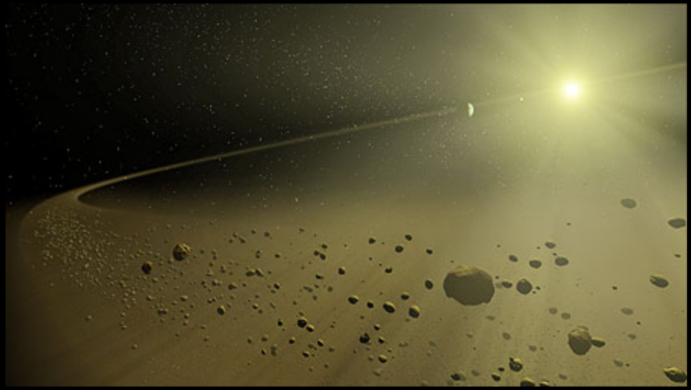
Then $dE/dL = \Omega(r)$, where $\Omega = (r^{-1}d\Phi/dr)^{1/2}$ is the angular speed of rotation. Disks spread when a unit mass at radius r_2 moves outward by gaining angular momentum dL from a unit mass at radius $r_1 < r_2$. This is energetically favorable: the change in energy,

$$dE = dE_1 + dE_2 = \left[-\left(\frac{dE}{dL}\right)_1 + \left(\frac{dE}{dL}\right)_2\right] dL = \left[-\Omega(r_1) + \Omega(r_2)\right] dL\,,$$

is negative because $\Omega(r)$ usually decreases outward. 'Thus disk spreading leads to a lower energy state. In general, disk spreading, outward angular momentum flow, and energy dissipation accompany one another in astrophysical disks' (Tremaine 1989).

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

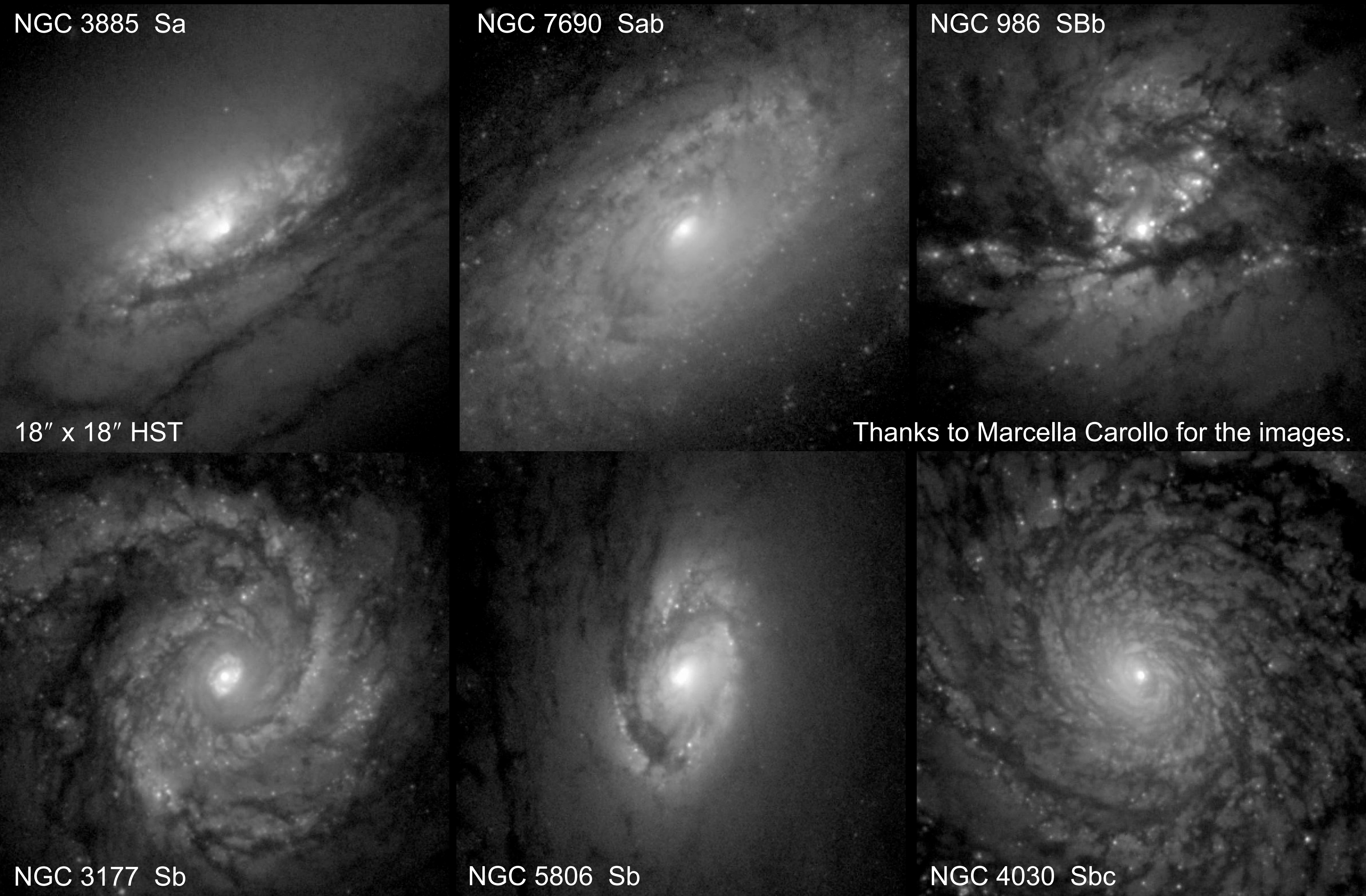
Systems that are supported by random motions evolve by transporting energy outward.



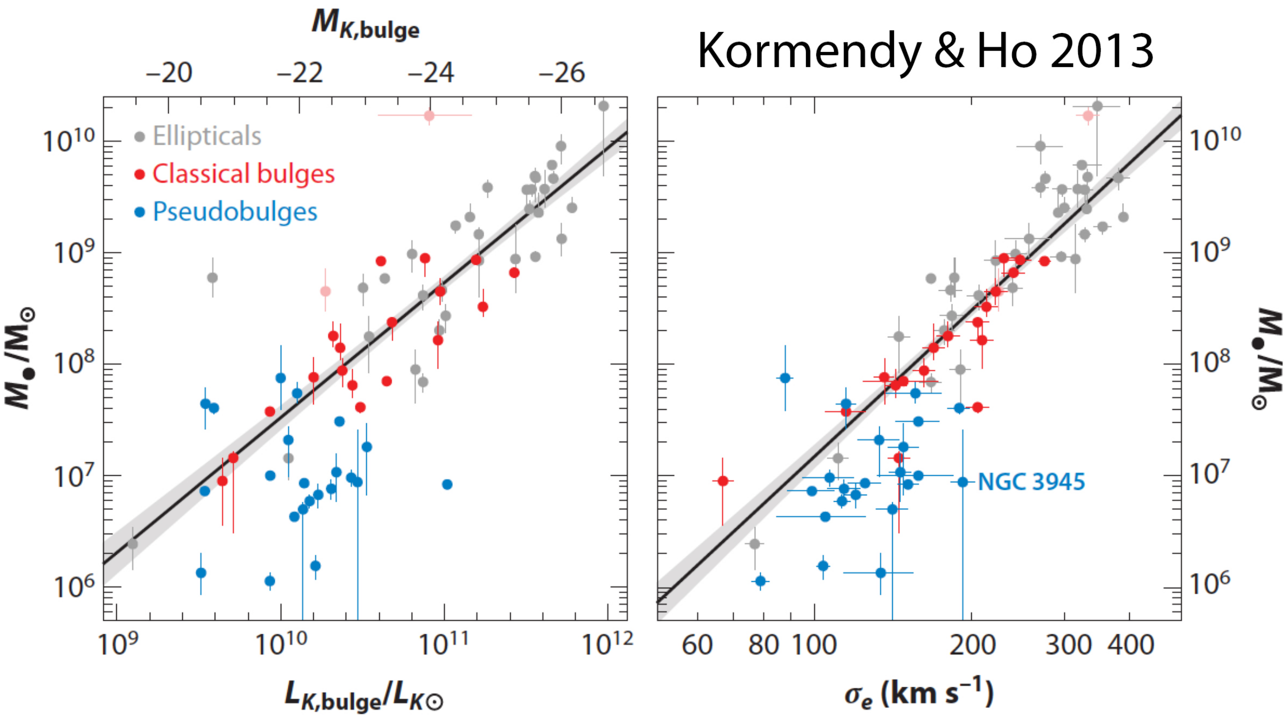
Systems that are supported by rotation evolve by transporting angular momentum outward.

<u>Pseudobulge growth in a galaxy disk is analogous to growth of a star from a protostellar disk and growth of a black hole from a quasar accretion disk.</u>

Examples of Pseudobulges



Based on these, we would never invent a folklore that bulges are elliptical galaxies that live in the middle of a disk!



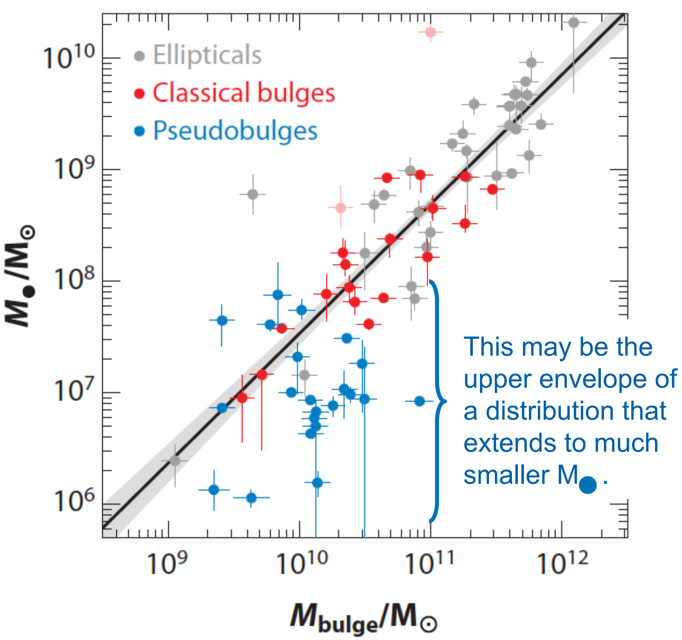
$M_\bullet$ correlates little or not at all with pseudobulges ⇒ no coevolution.

Hu 2008, MNRAS, 386, 2242;

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

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

Kormendy & Ho 2013



NGC 1068: Prototypical Seyfert 1 with a pseudobulge

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

The M33 nucleus has tiny velocity dispersion σ = 20 ± 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).

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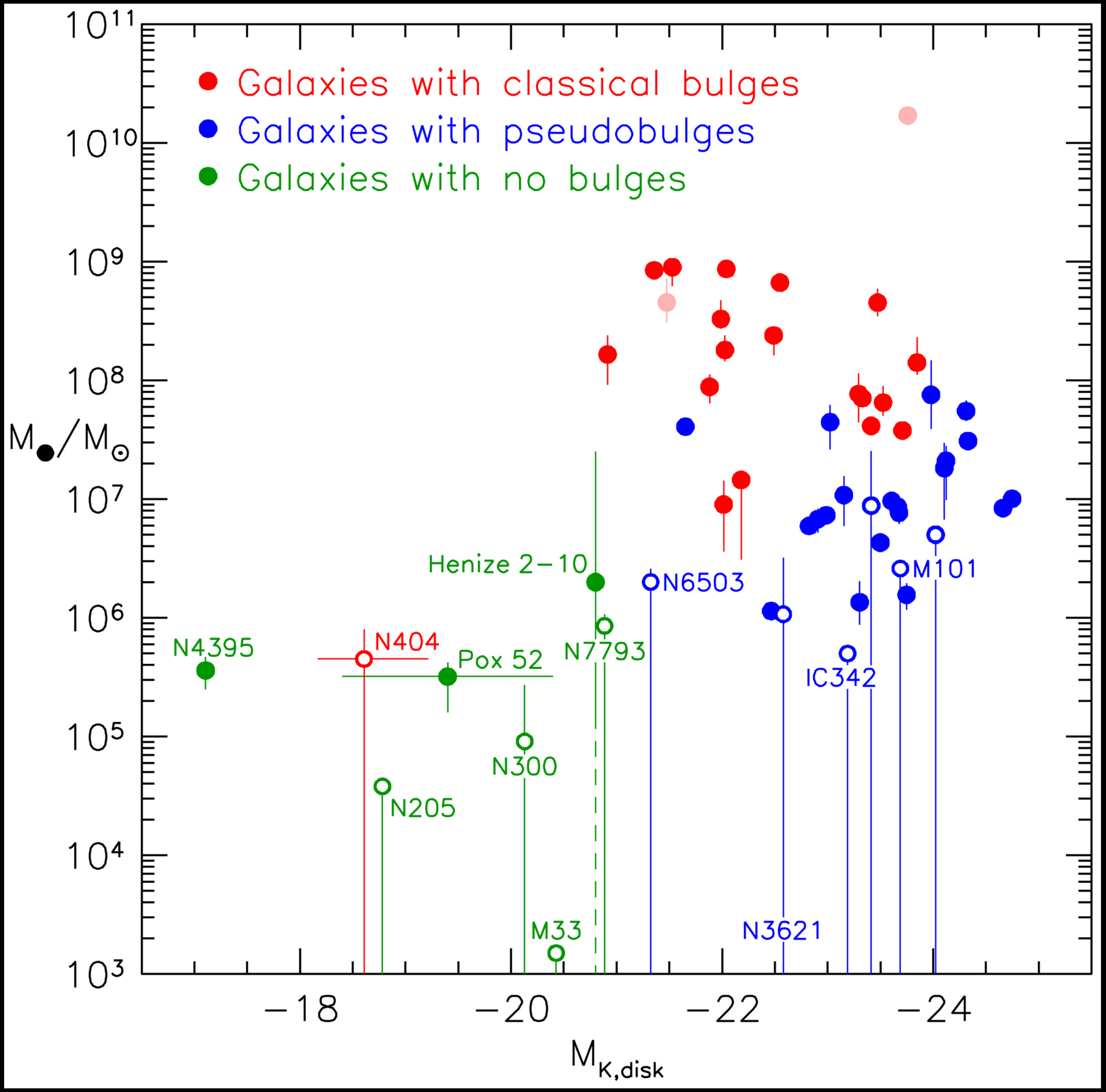
BHs do not correlate with galaxy disks.

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



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).

Conclusion

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

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

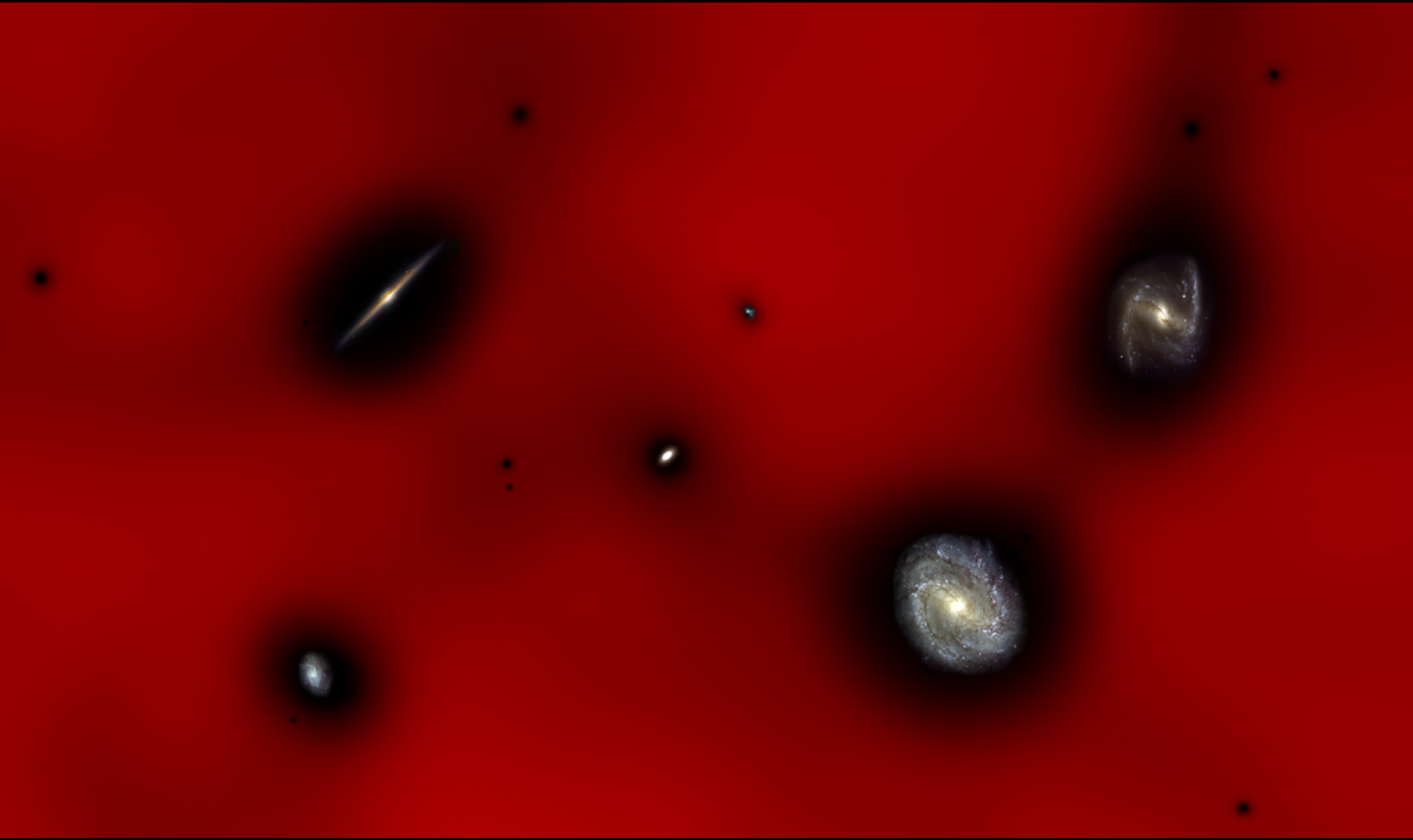
The biggest BHs grow rapidly to high mass, coevolving with bulges via mergers and quasar AGNs,

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.

The latter BHs are seeds for the former BHs.

Do Black Holes Correlate With Dark Matter Halos?



Do Black Holes Correlate With Dark Matter Halos?

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

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

Test: Does $M_\bullet$ correlate tightly with M_{DM} (i. e., with $V_{\mathbf{circ}}$) in the absence of a bulge?

Answer = "No!"

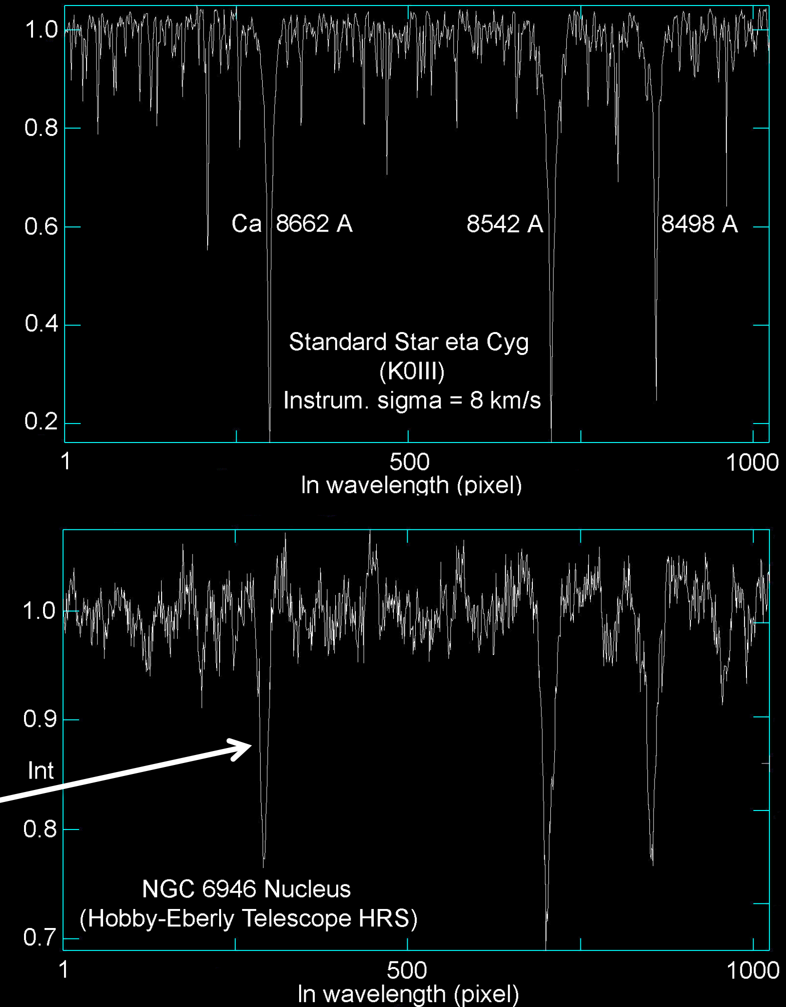
Kormendy, Drory, Bender, & Cornell 2010, ApJ, 723, 54:

Measure stellar velocities σ in the central clusters of the biggest bulgeless disk galaxies using HET HRS.

NGC 6946 (Scd)

V_{circ} = 191 ± 10 km s^{-1} but σ = 56 ± 2 km s^{-1}

⇒ No merger-built bulge



Spectral lines in the NGC 6946 nucleus are <u>almost as narrow</u> as in the single standard star η Cygni.

⇒ stellar velocities at the center of NGC 6946 are small.

M101 (Scd)

V_{circ} = 202 ± 13 km s^{-1} but σ = 24 ± 4 km s^{-1}

(Ho et al. 2009; Kormendy et al. 2010)

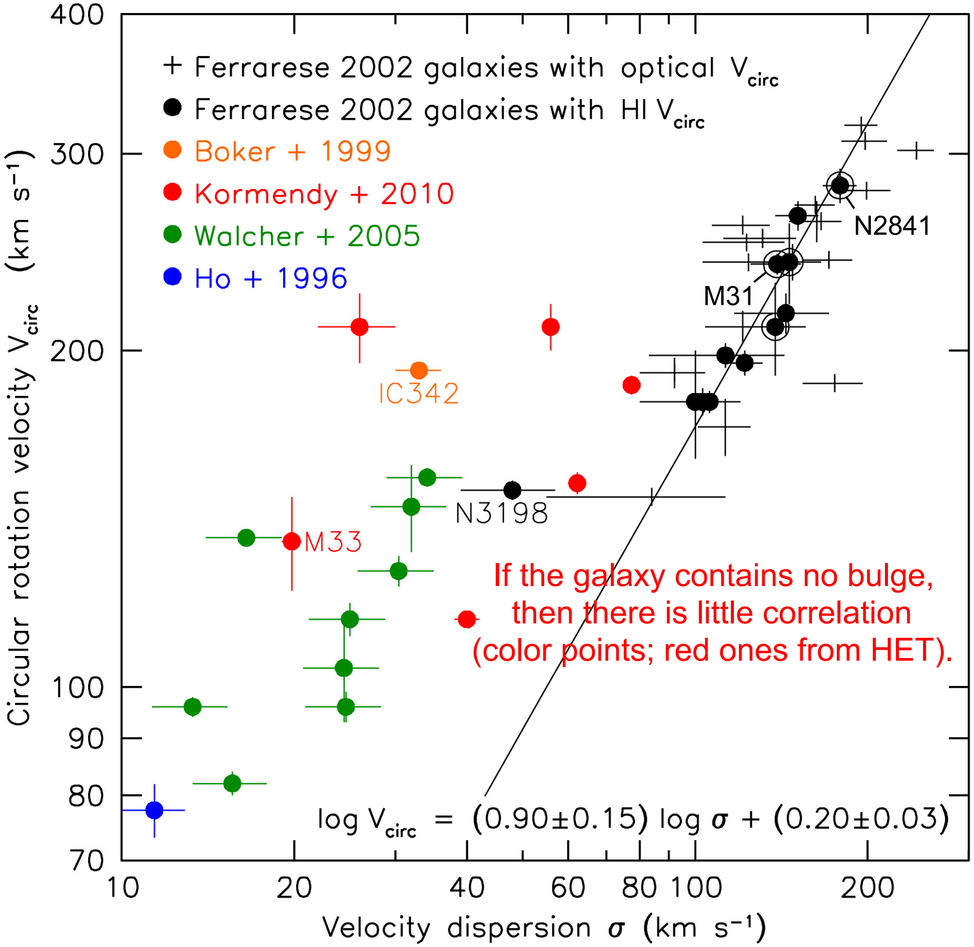
⇒ No merger-built bulge

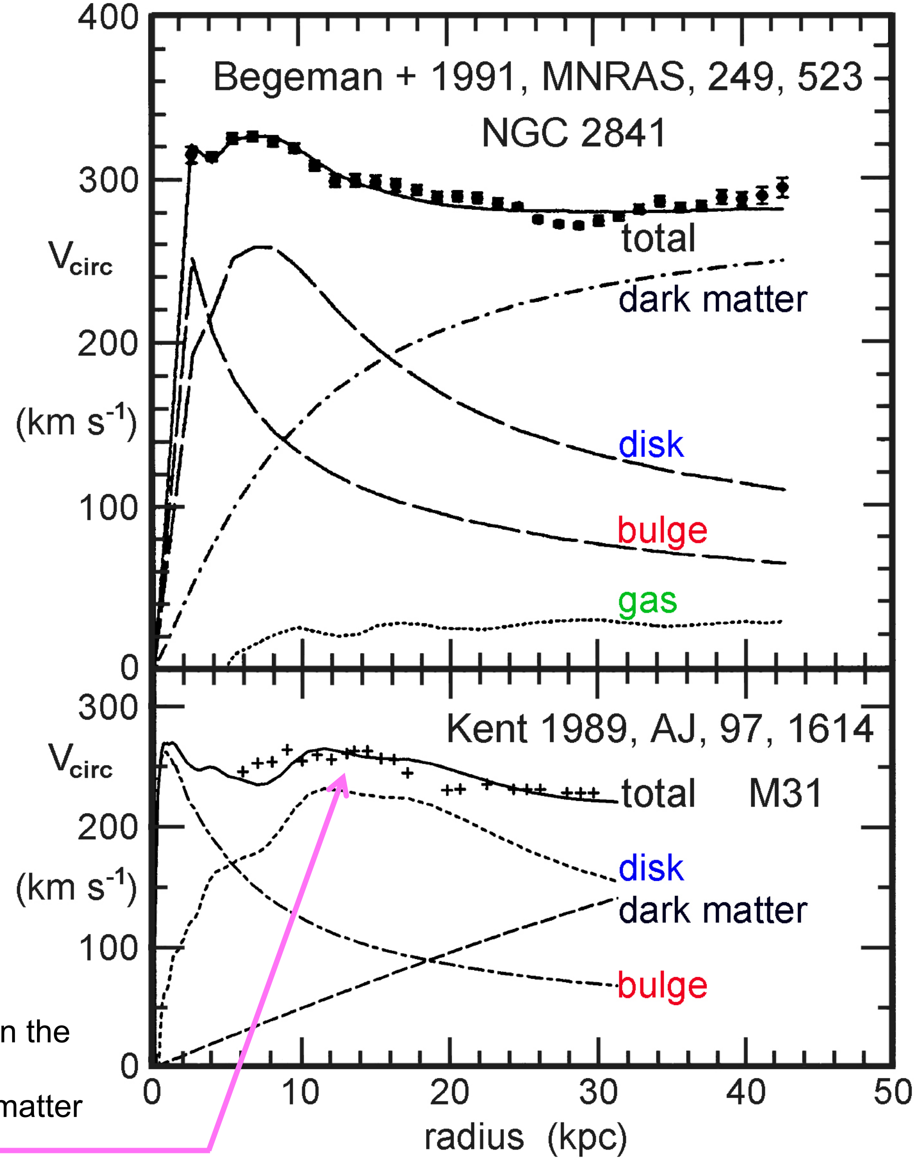
Pseudobulge/T = 2.7 % ;
Nucleus/Total = 0.03 %
in K band.

Most giant galaxies in the local (radius = 8 Mpc) volume are pure disks.
We do not know how these galaxies form (Kormendy et al. 2010; Fisher & Drory 2011).

Supermassive black holes do not correlate with dark matter halos of galaxies

(Kormendy & Bender 2011, Nature, 469, 377).





If $\sigma \Leftrightarrow M_\bullet$ for classical bulges (◉) but not for pseudobulges (●), then the $V_{circ} - \sigma$ correlation is not a $M_\bullet$ – DM correlation.

Suggest: It is caused by the "conspiracy" between visible and dark matter to make almost-flat, featureless rotation curves. Like this:

BH Correlations With Host Galaxies: Summary

BHs correlate with bulges[1] & ellipticals
but not with disks or
pseudobulges[2] or
dark matter halos.

[1]Classical bulges are made rapidly by galaxy mergers.
[2]Pseudobulges are grown slowly out of disks.

Section 3 – Do BHs and Galaxies Coevolve ?

That is,

Do BH growth and galaxy evolution regulate each other ?

276 Reigning Bandwagon = AGN Feedback

Energy argument (e. g., Silk & Rees 1998; Ostriker & Ciotti 2005):

– BH binding energy » galaxy binding energy

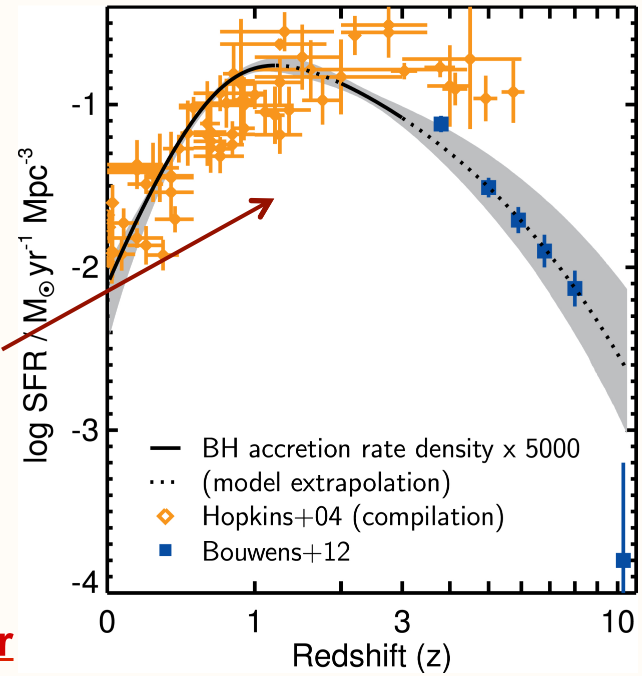
➔ if a few % of AGN energy couples to gas, then all gas can be expelled.

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

BH demographics:

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

The history of the growth of BHs as quasars and the history of star formation in the Universe are similar.



Aird et al. 2010, MNRAS, 401, 2531

➔ **The idea that BHs and galaxies coevolve,**

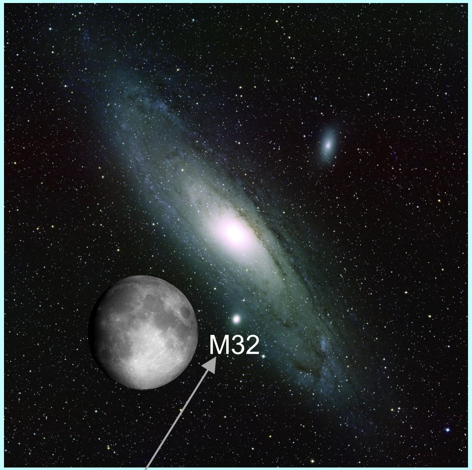
that is,

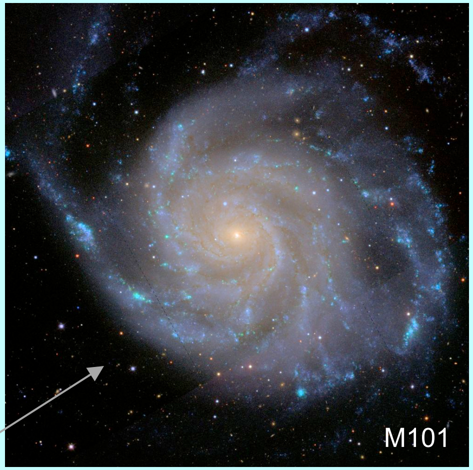
that BH growth and galaxy evolution regulate each other has become VERY popular.

Problem:

AGN feedback depends on galaxy mass, 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.

Kormendy & Ho 2013 results:

8.1 Four Regimes of AGN Feedback: An Introduction

The conclusion that BHs correlate differently with different galaxy components allows us to refine our ideas on coevolution. Section 8 reviews evidence for the "punch line" conclusions of this paper. We present the case that there are four regimes of AGN feedback in three different kinds of galaxies.

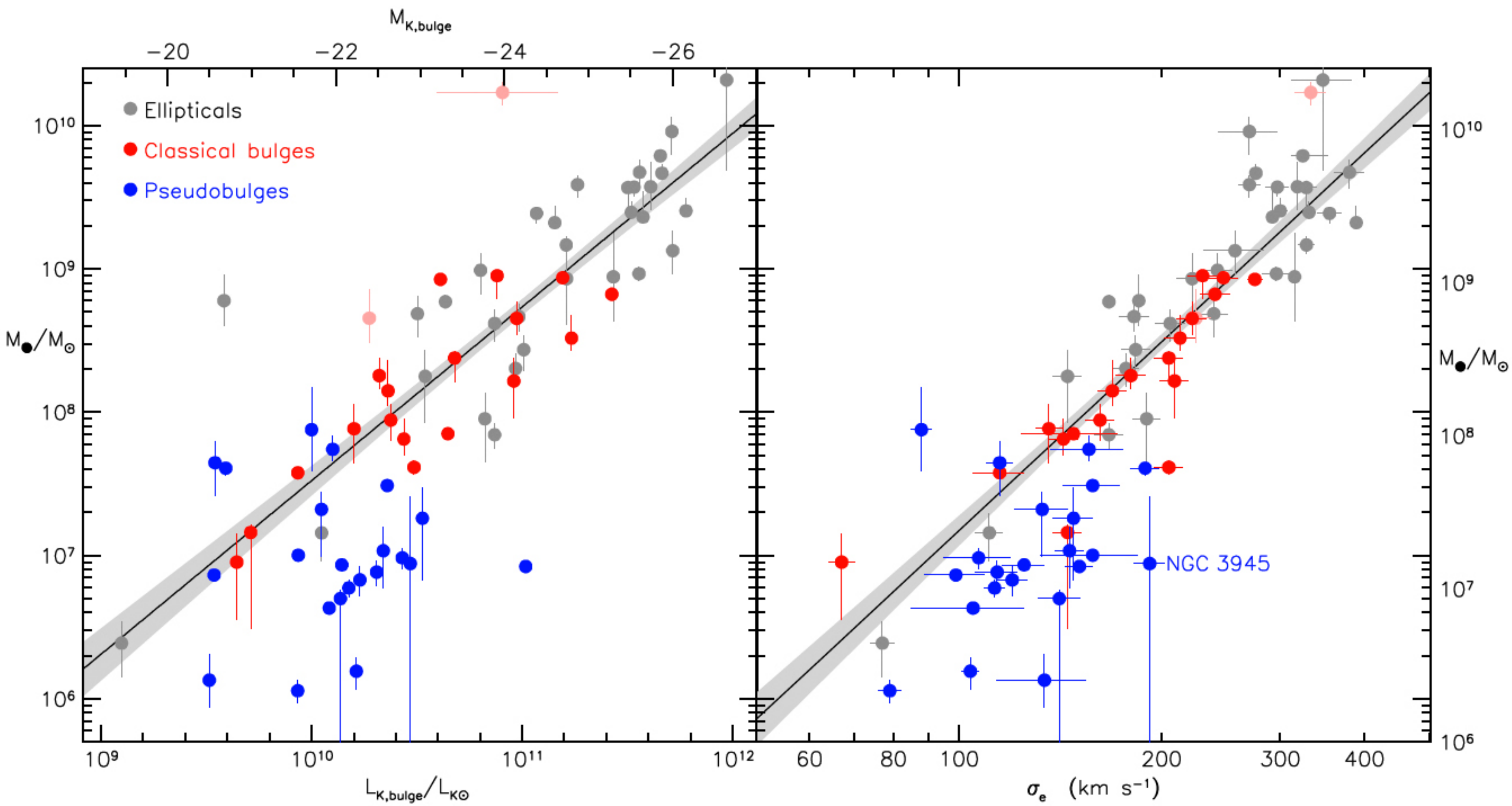
(1) **Galaxies that lack dominant classical bulges** can contain BHs, but these grow by low-level AGN activity that involves too little energy to affect the host galaxy (Section 8.3).

(2) Feedback may help to establish $M_\bullet$–host relations during dissipative ("wet") major mergers that make **classical bulges and low- to moderate-luminosity elliptical galaxies**. The jury is still out and the physics remains obscure. But if this is to work, it must work mostly at high z (Section 8.6).

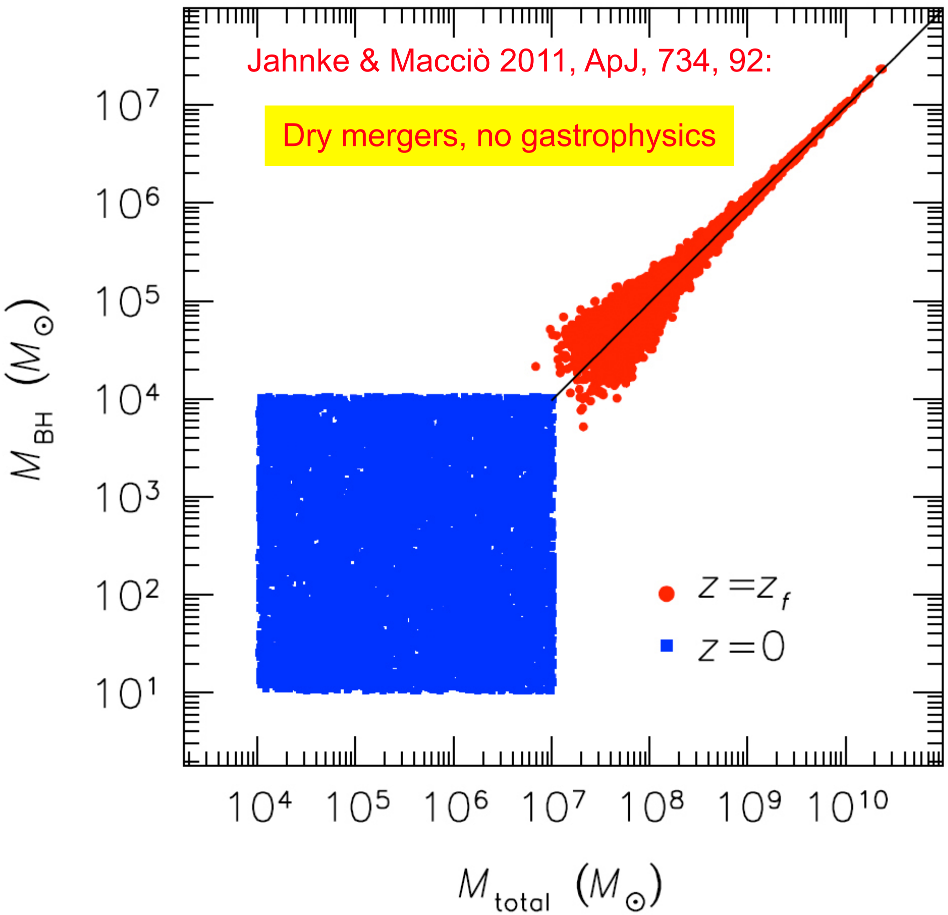
(3) **The highest-mass ellipticals have cores** and otherwise are recognizably different from their lower-mass counterparts. We review evidence that they form in dissipationless ("dry") mergers. These giant ellipticals inherit any feedback effects from (2). In them, AGN feedback plays the essentially negative role of keeping galaxy formation from "going to completion" by keeping baryons locked up in hot gas.

(4) **Averaging inherent in galaxy and BH mergers may be the most important effect that leads to BH–host-galaxy correlations.** Then the central limit theorem ensures that the scatter in BH correlations with their hosts decreases as $M_\bullet$ increases (Section 8.5).

M●–host-galaxy correlations have larger scatter at smaller M●.



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



If you start with any two blue points (that is, with no correlation between BH mass and host mass) and you merge the galaxies and their BHs, then the scatter gets smaller.

Do this again and again and you get the correlation of the red points.

This involves no “magic physics”; it is just a consequence of adding numbers from a log-log plot.

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.

8.1 Four Regimes of AGN Feedback: An Introduction

The conclusion that BHs correlate differently with different galaxy components allows us to refine our ideas on coevolution. Section 8 reviews evidence for the "punch line" conclusions of this paper. We present the case that there are four regimes of AGN feedback in three different kinds of galaxies.

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(3) **The highest-mass ellipticals have cores** and otherwise are recognizably different from their lower-mass counterparts. We review evidence that they form in dissipationless ("dry") mergers. These giant ellipticals inherit any feedback effects from (2). In them, AGN feedback plays the essentially negative role of keeping galaxy formation from "going to completion" by keeping baryons locked up in hot gas. Here the controlling point is that these galaxies are massive enough to hold onto hot, X-ray-emitting gas. "Maintenance-mode AGN feedback" helps to keep the hot gas hot and to prevent late star formation and BH accretion (Section 8.4).

(4) **Averaging inherent in galaxy and BH mergers may be the most important effect that leads to BH–host-galaxy correlations.** Then the central limit theorem ensures that the scatter in BH correlations with their hosts decreases as $M_\bullet$ increases (Section 8.5).

"Cores" are explained on the next slide.

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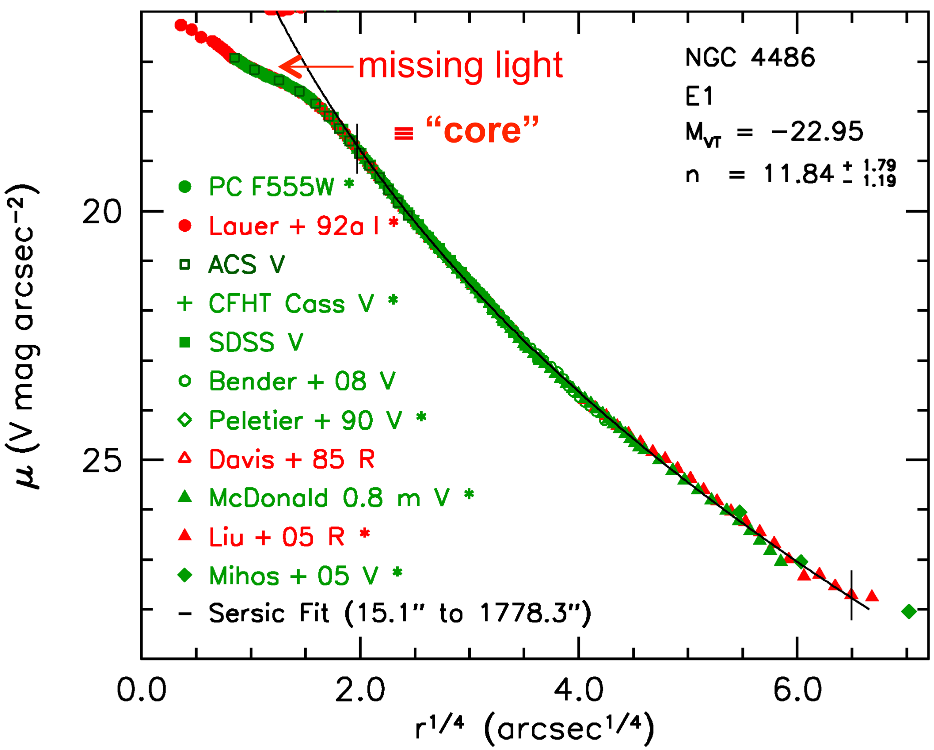
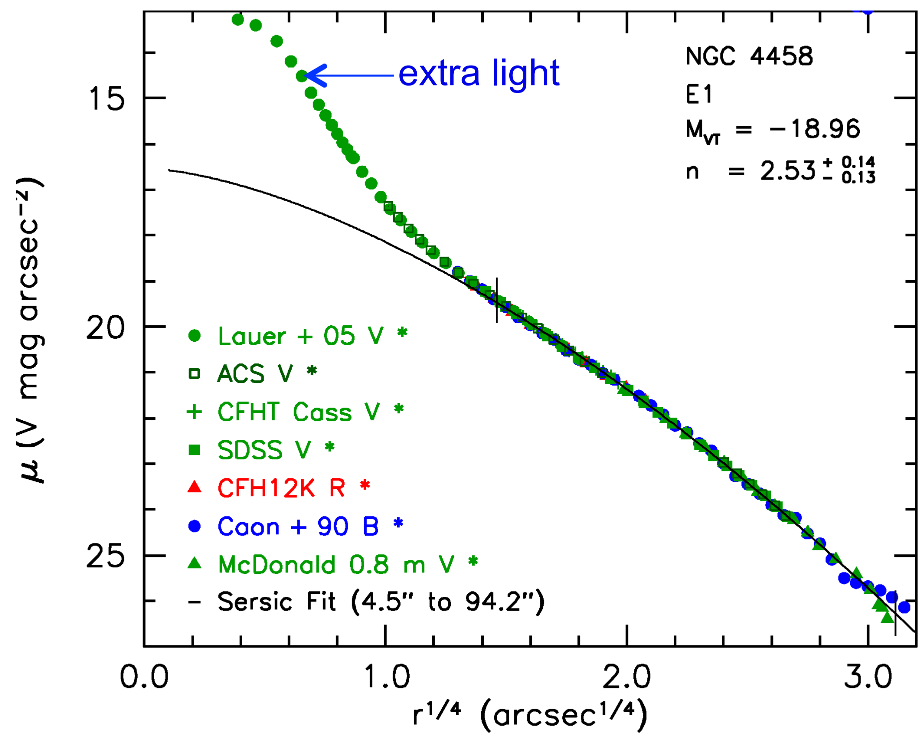
Kormendy et al. 2009, ApJS, 182, 216 ⇒

Two kinds of elliptical galaxies:

with "cores" ≡ "missing light" and with "extra light" @ center.

↔ Boxy isophotes ↔ Disky isophotes





Core E ≡ dry merger remnant; BH binaries scour cores by flinging stars away from the center. **Why dry?**

Extra light E = wet merger remnant; Extra light made by merger starburst.

How AGN feedback solves the problem of episodic energy input:

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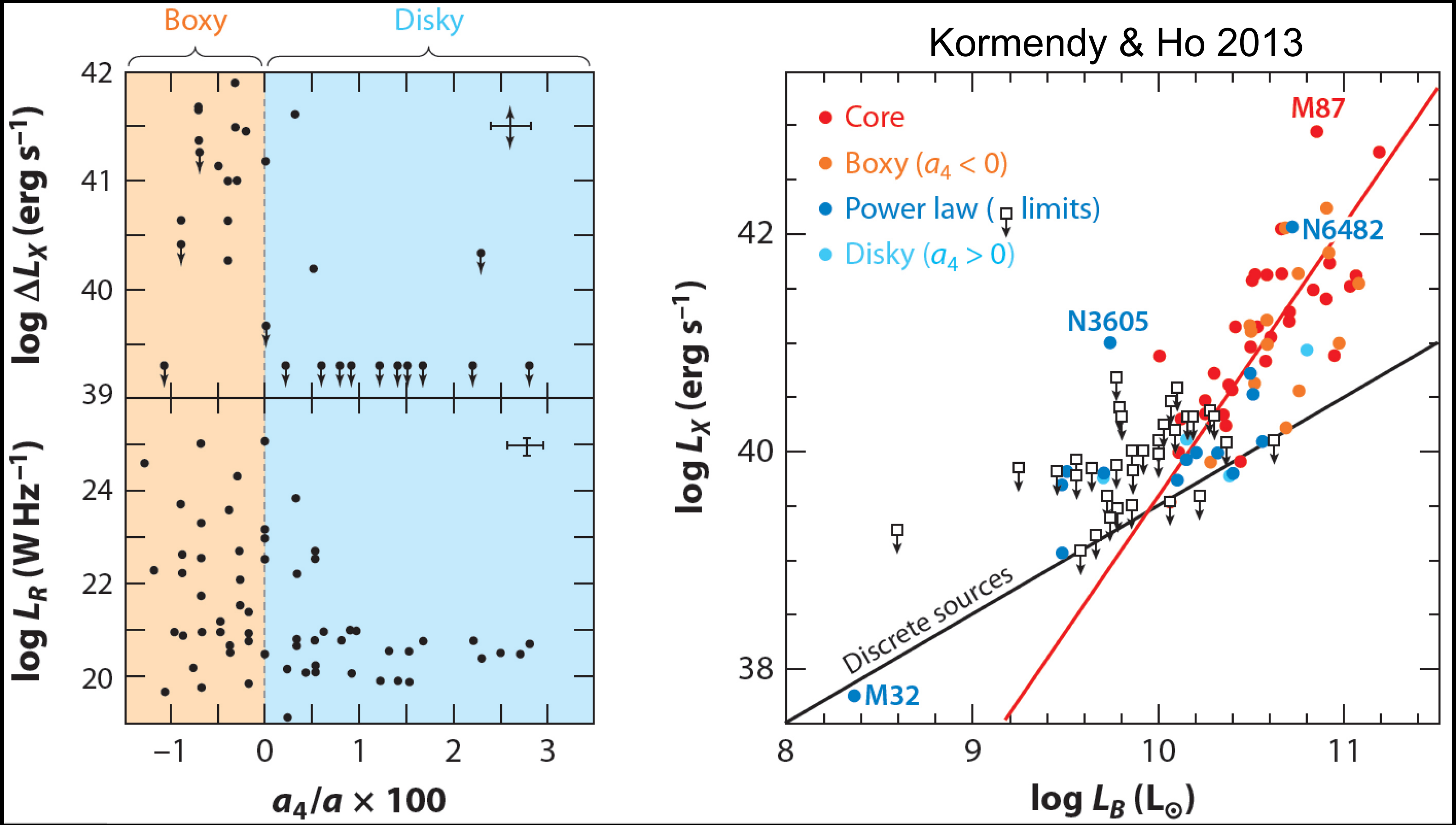
Essential new idea: hot gas = energy storage medium.

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

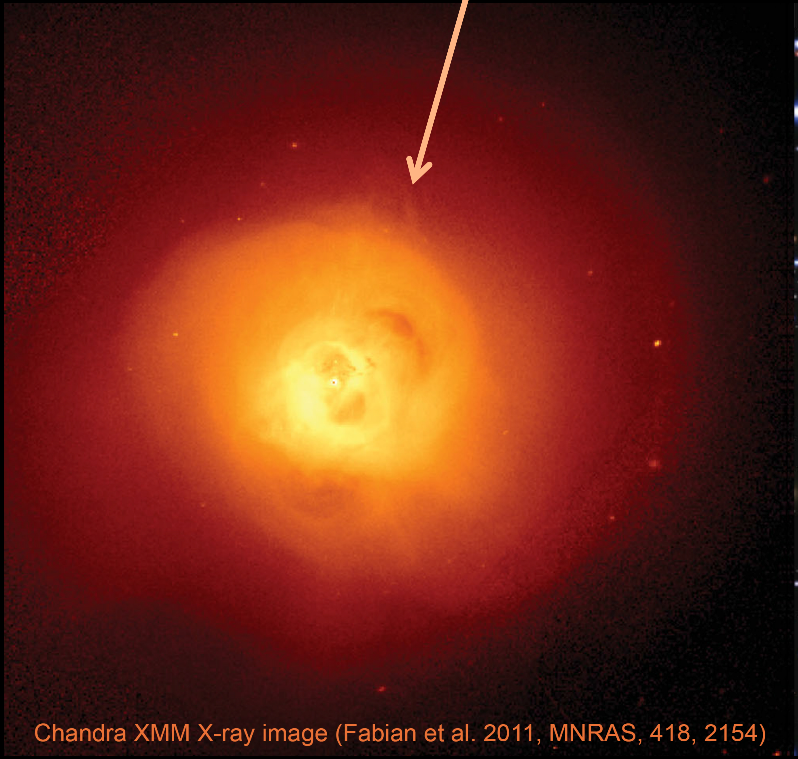


We suggest that AGN feedback into X-ray gas only in giant-boxy-core galaxies and their progenitors quenches star formation and makes dry mergers dry.

AGN feedback needs a "working surface" = X-ray-emitting gas in giant Es and clusters

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

This hot, X-ray-emitting gas permeates the Perseus cluster and prevents any cold gas in galaxies that fall into the cluster from making new stars. This is the meaning of "dry merger".


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.

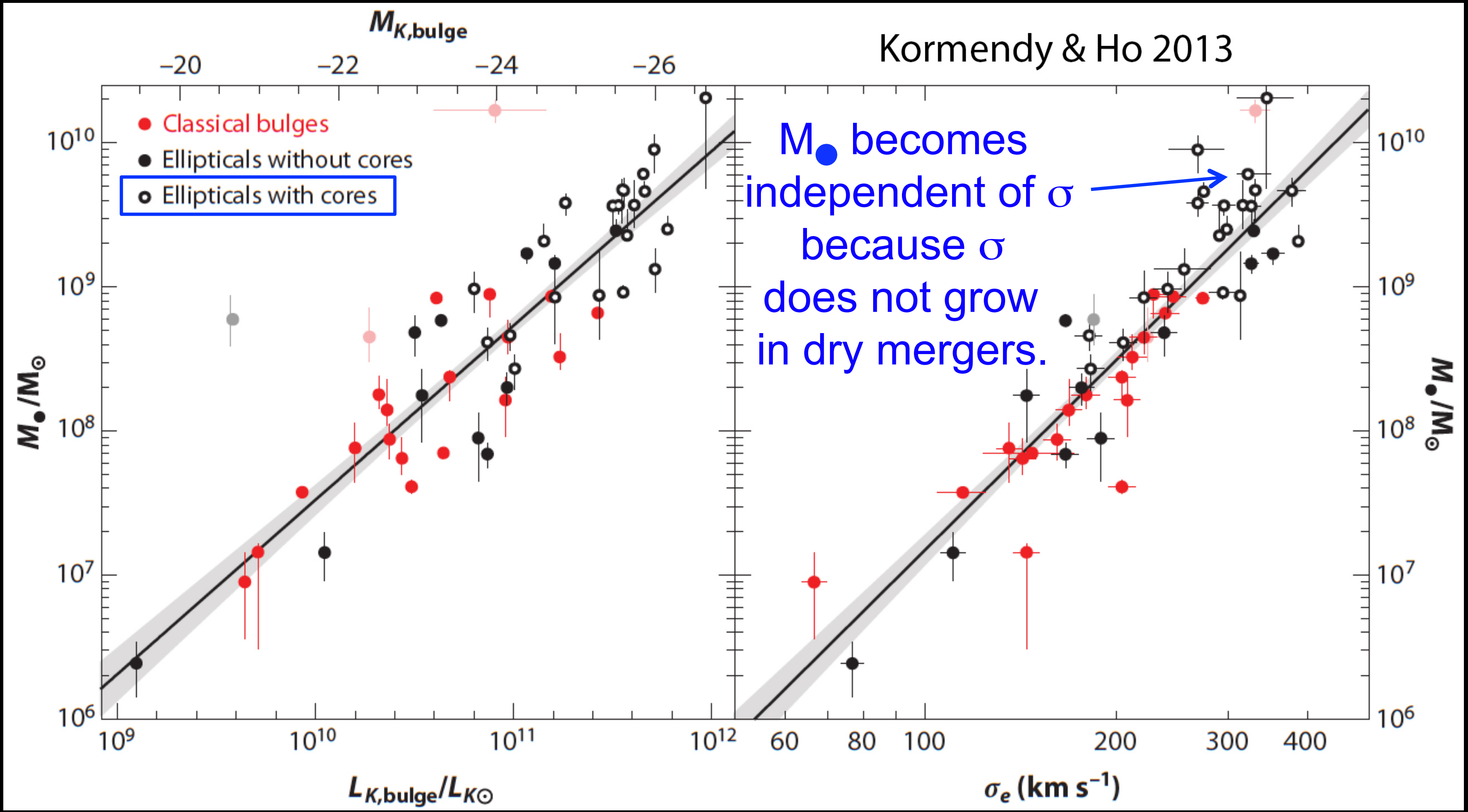
Any combination of heating mechanisms is OK:

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

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

... only in core galaxies (Kormendy & Bender 2012, ApJ, 769, L5).



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

(Early hints: Lauer + 2007, ApJ, 662, 808; McConnell + 2011, 2012)

BH Coevolution ? – Summary

AGN Feedback & BH-Galaxy Coevolution – 1 – No

BHs do not correlate closely enough to imply coevolution with

1 — galaxy disks;

2 — pseudobulges;

3 — dark matter halos.

Suggest: These BHs are fed episodically and slowly by local processes that result in no coevolution.

They are the most numerous (but not the most massive) BHs in the universe.

AGN Feedback & BH-Galaxy Coevolution – 2 – Yes

Distinguish between 2 modes of feedback:

1 — Quasar-mode feedback from a bright accretion disk late during a dissipative merger (Hopkins et al. 2006, ApJS, 163, 1).
If there is coevolution magic to be engineered, it is here.

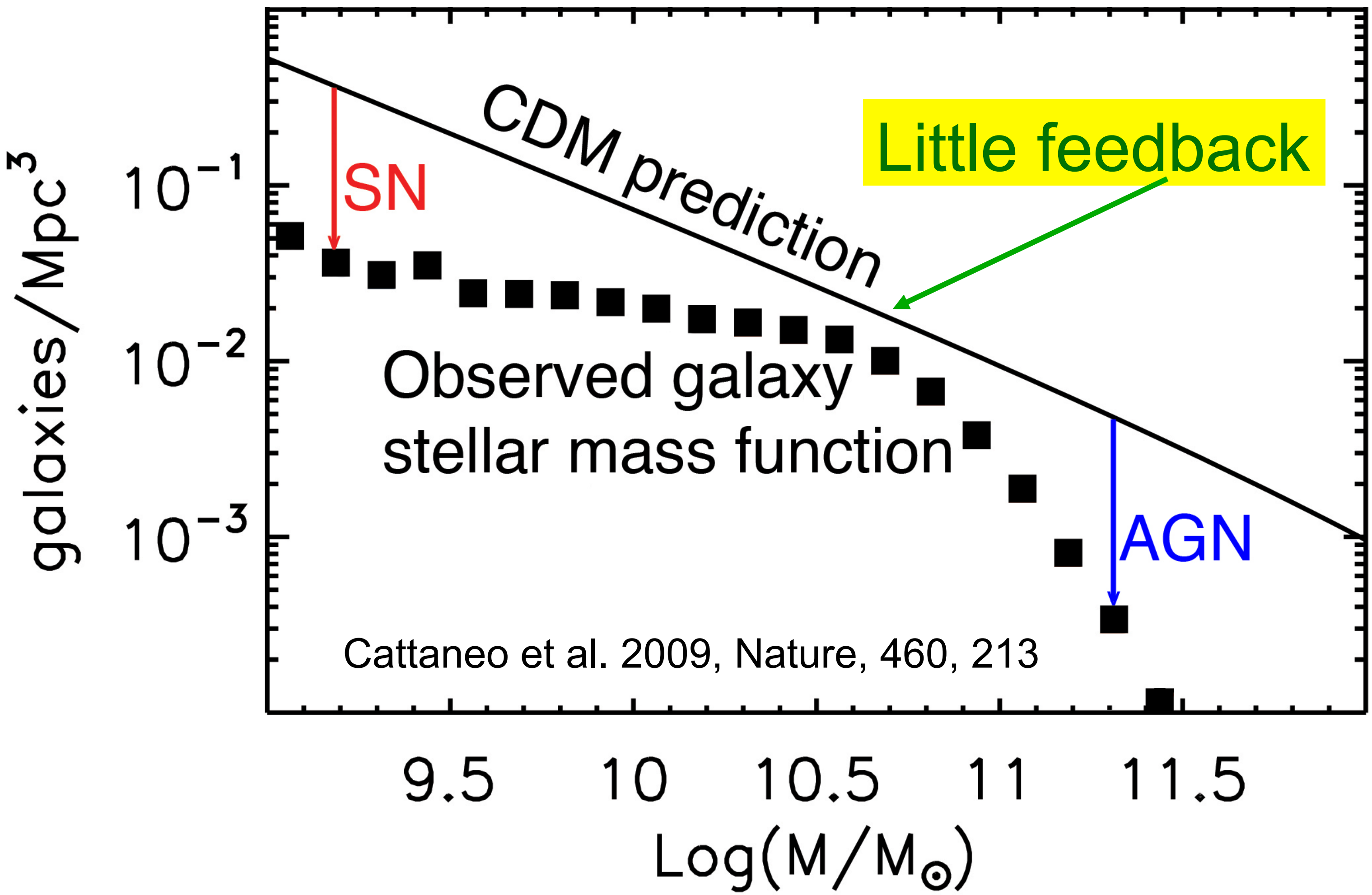
2 — Maintenance-mode feedback helps to keep gas hot at galaxy $M_* > 10^{12}\ M_\odot$.
Effect is mainly negative — to prevent star formation.

3 — The highest-mass galaxies inherit the "magic" from 1.
The tightness of their $M_\bullet - \sigma$ correlation is caused by averaging during dry mergers.

Merger averaging may be the most important process that engineers tight BH-host correlations.

Helps to solve problem of stellar mass function of galaxies:

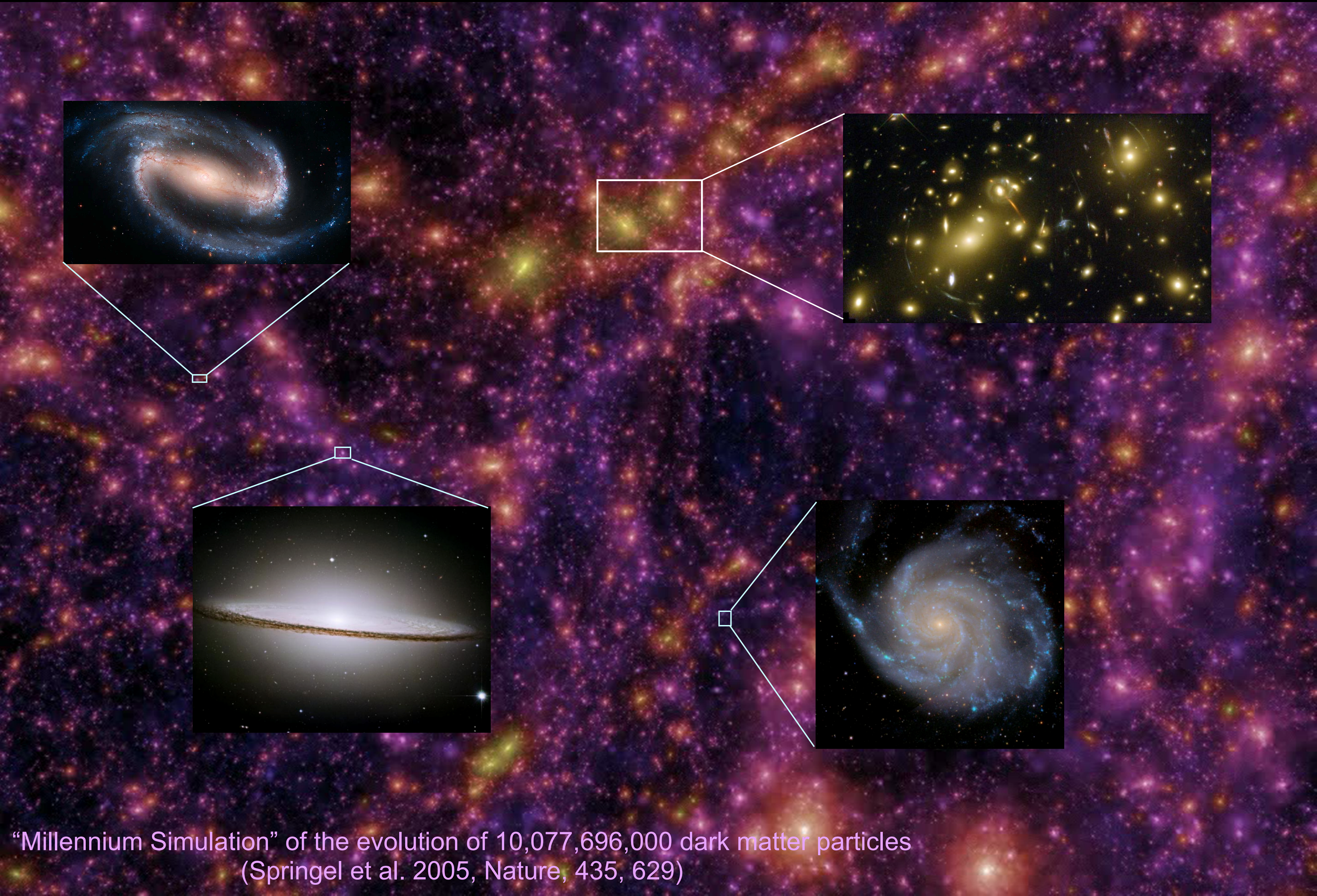
The galaxy mass function may be whittled by
SN at the low-mass end and by
AGN feedback at the high-mass end.



A little cooling of the X-ray gas feeds galaxy BHs and turns them temporarily into active galactic nuclei (AGNs). They then reheat the gas and switch off the BH feeding. Many cycles like this help to keep the hot gas hot. This in turn prevents any further growth of galaxies by star formation. And that's why the number of galaxies per unit volume falls below the prediction (the line) from models of cold dark matter (CDM).

In other words:
AGN feedback keeps the baryons suspended in hot gas and keeps galaxy formation from finishing.

4 – A Brief Introduction to Galaxy Formation



“Millennium Simulation” of the evolution of 10,077,696,000 dark matter particles
(Springel et al. 2005, Nature, 435, 629)

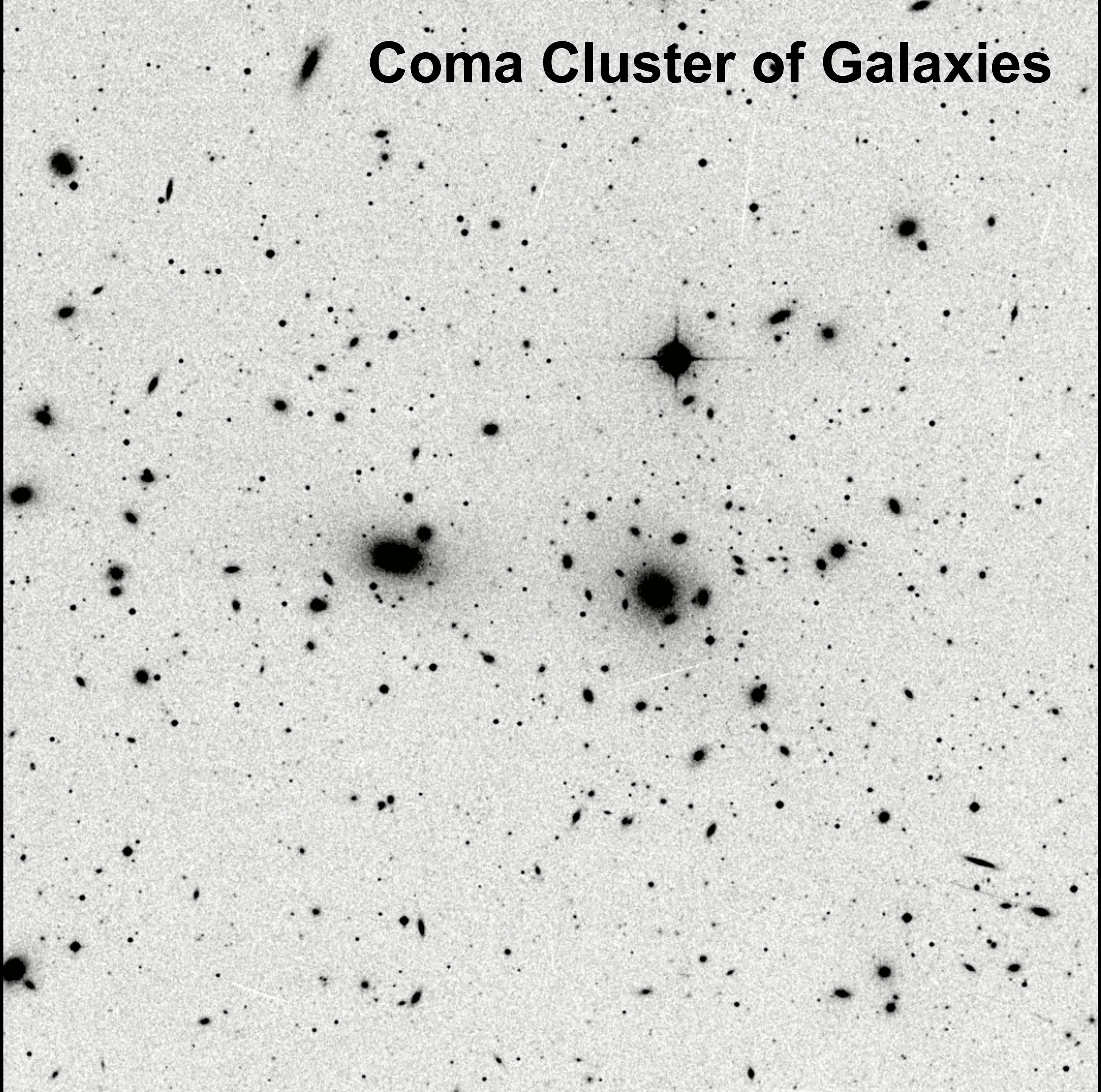
It is impossible to remove the problem of galaxy formation from its cosmological context of hierarchical clustering.

Bernard Jones (1992)

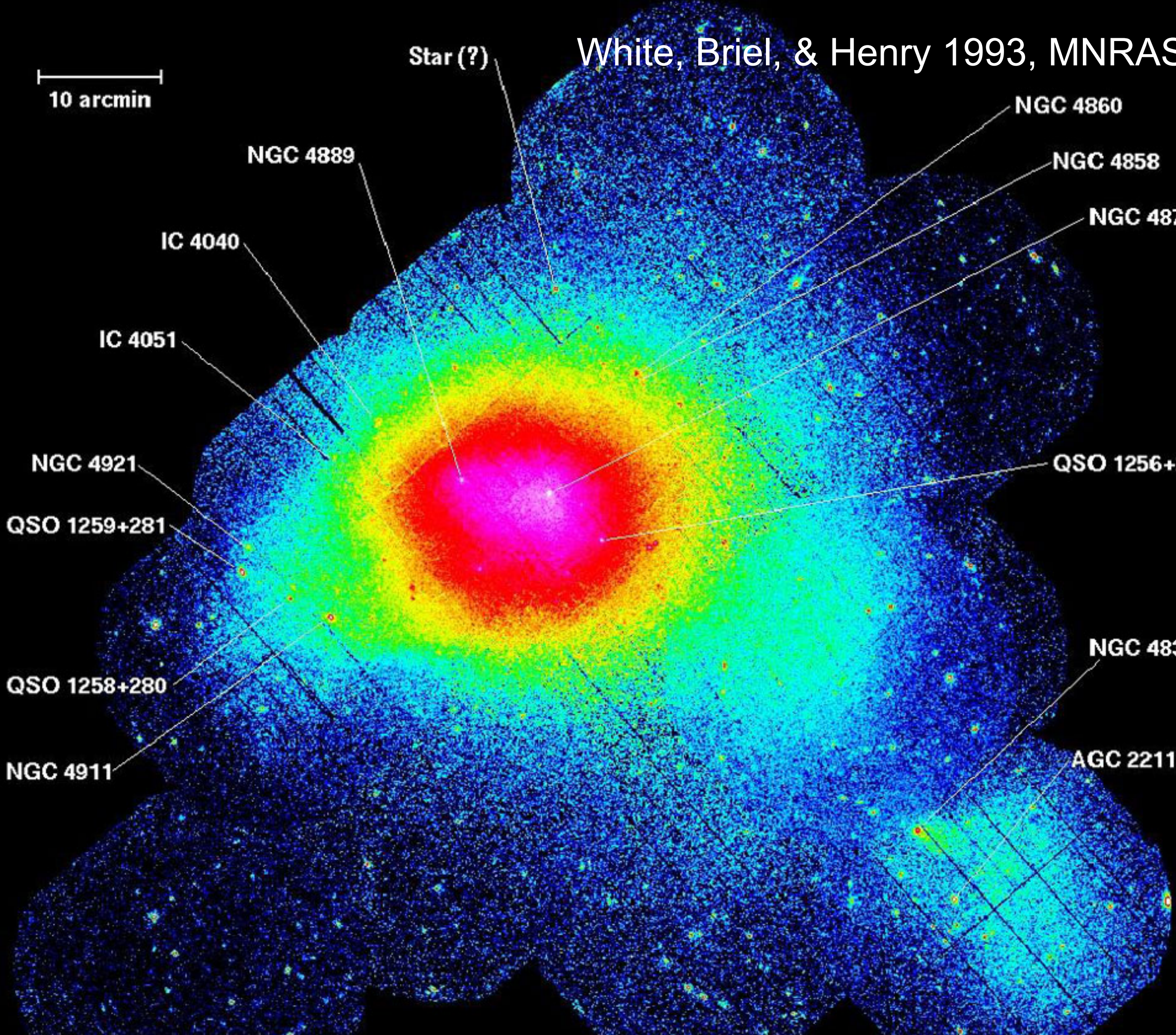
Cold Dark Matter theory has now reached the point at which it should be admitted as a Candidate Member to the Academy of Established Theories, so that it can sit alongside the established theories of Maxwell, Einstein, and Heisenberg.

James Binney (2004)
Career Iconoclast

Coma Cluster of Galaxies



White, Briel, & Henry 1993, MNRAS, 261, L8



The Coma Cluster is filled with hot, X-ray-emitting gas
(observations by XMM-Newton satellite (0.3 – 2.0 keV, 22.6 Ksec exposure)

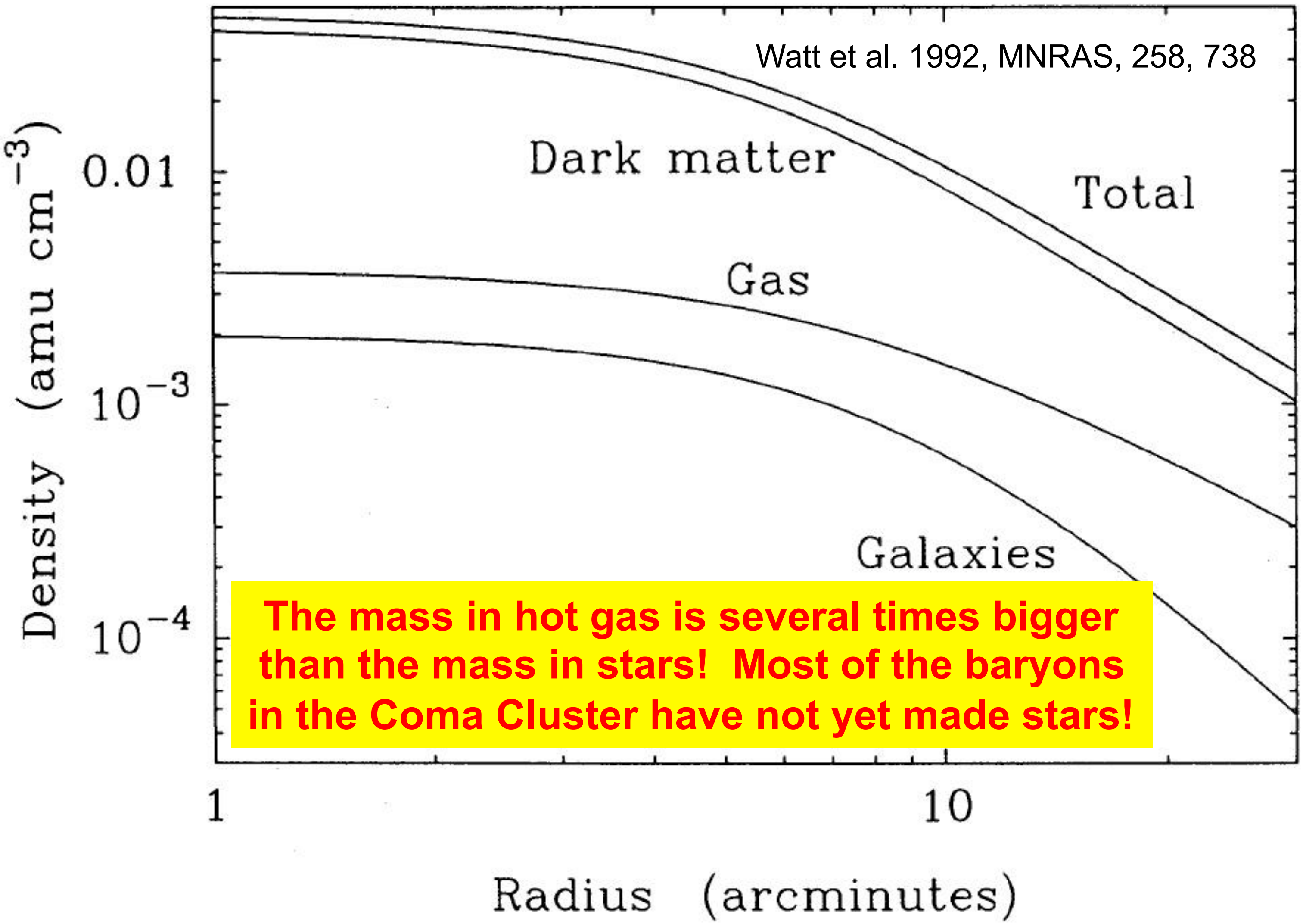


Figure 9. Density profile of the major contributors to the mass of the cluster. The gravitating and gas mass profiles are derived in the present work, and the galaxy mass density is from the data of Kent & Gunn (1982) assuming $M/L_V = 5(M_\odot/L_\odot)$.

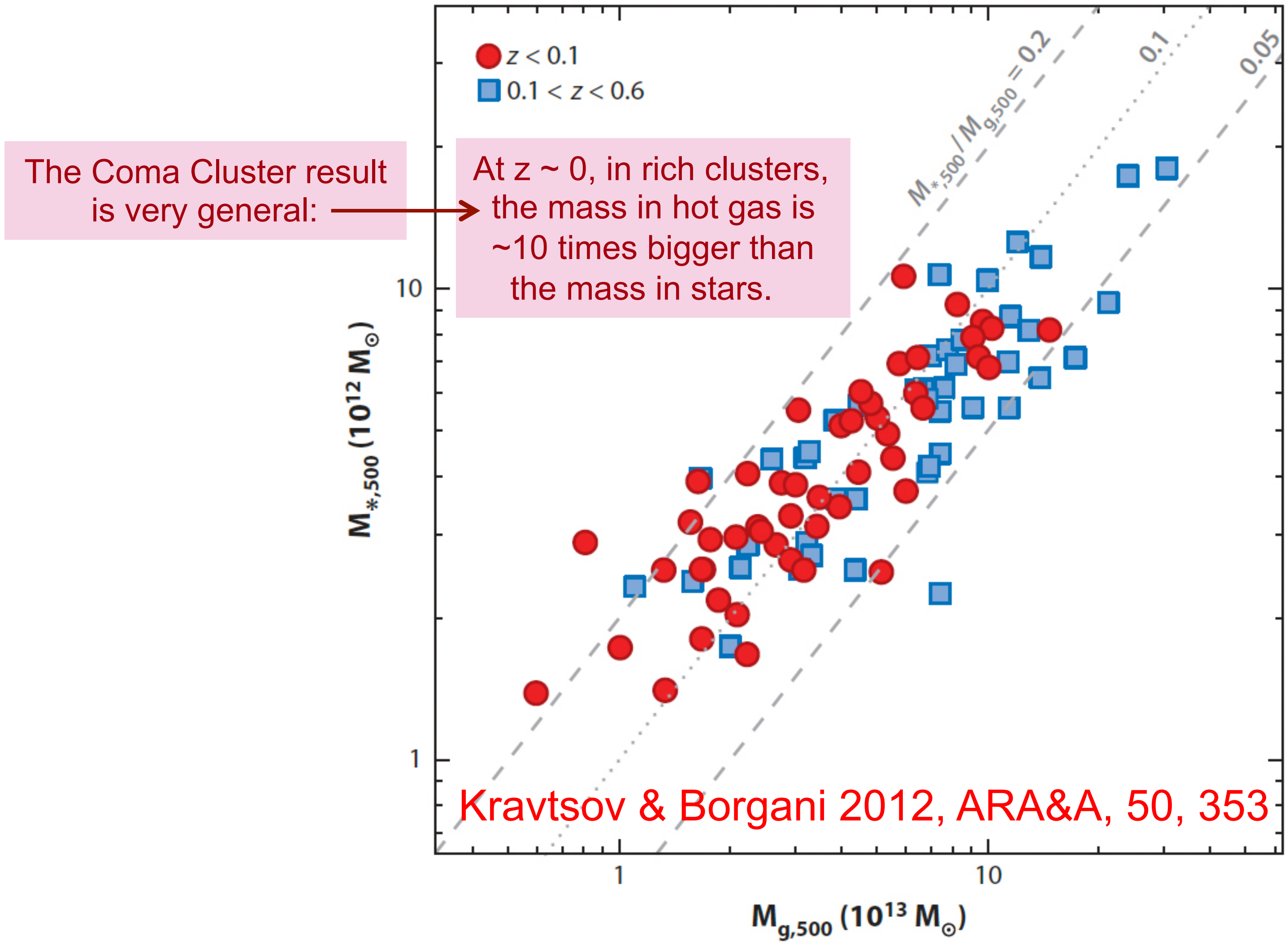


Figure 2

The mass in stars versus the mass of hot, X-ray emitting gas. Both masses are measured within the radius R_{500} estimated from the observationally calibrated $Y_X - M_{500}$ relation, assuming flat ΛCDM cosmology with $\Omega_m = 1 - \Omega_\Lambda = 0.26$ and $h = 0.71$. Red circles show local clusters located at $z < 0.1$, whereas blue squares show higher redshift clusters: $0.1 < z < 0.6$ (see Lin et al. 2012 for details). The dotted line corresponds to the constant stellar-to-gas mass ratio $M_{*,500}/M_{g,500} = 0.1$, whereas the dashed lines correspond to the values of 0.05 and 0.2 for this ratio.

The baryonic mass function of galaxies

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Phil. Trans. R. Soc. London, A363, 2693 (2005)

Where are the baryons in the nearby Universe?

Answer:

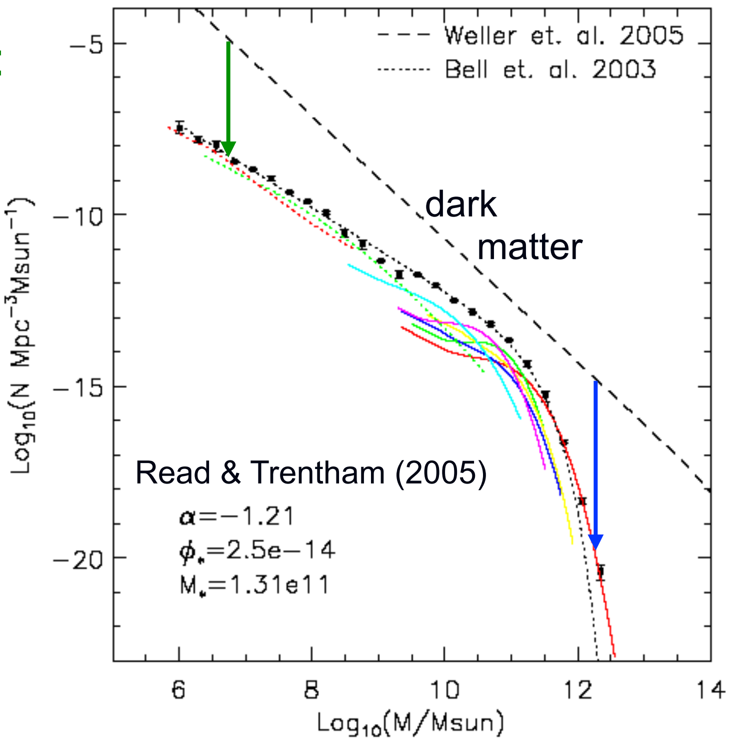
About 1/3 are in stars;

about 1/3 are in a "warm-hot intergalactic medium" (WHIM), and

about 1/3 are in hot, x-ray-emitting gas.

Most ($\sim$ 90%) of the baryons in the Universe are not in galaxies. They probably exist in a warm/hot intergalactic medium. Searching for direct observational evidence and deeper theoretical understanding for this will form one of the major challenges for astronomy in the next decade.

Reason at low mass:
feedback from
supernovae
in small galaxies.



Reasons at high mass:

1 – energy input
from cosmological infall
&
from AGNs
keeps baryons hot
(x-ray temperatures ≥ 10^6 K).

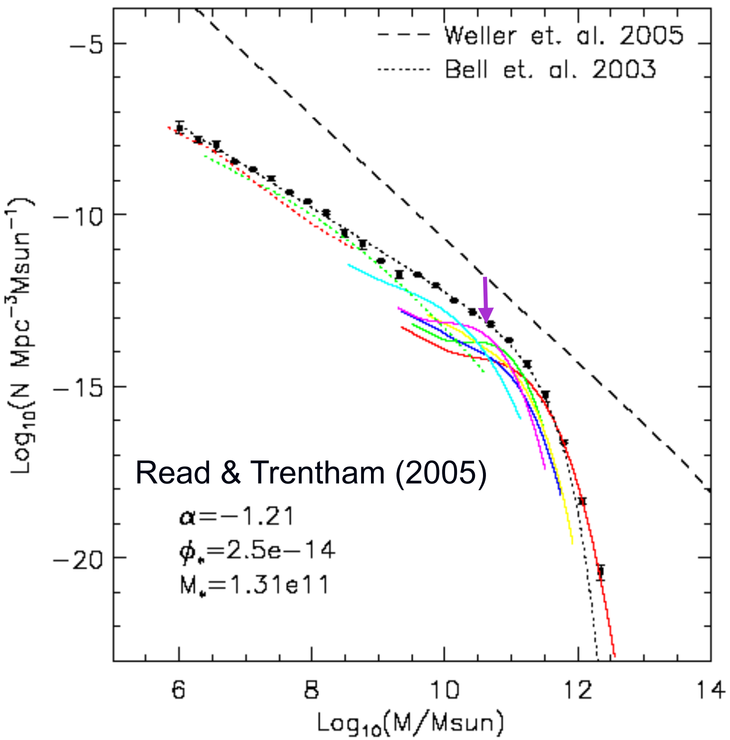
2 – The biggest halos contain
clusters of galaxies,
not individual galaxies.

Figure 4. The field galaxy baryonic mass function. The data points are for all galaxies, while the lines show spine fits by Hubble Type. The lines are as in figure 2. The CDM mass spectrum from the numerical simulations of Weller et al. (2004) is also shown. Overlaid are parameters for a Schechter fit to the total mass function.

Cold dark matter theory predicts the dark matter halo mass function (dashed line).

This is not a scaled version of the observed baryonic mass function of galaxies.

There is a deficit of galaxies at both high and low masses.



Even at intermediate masses,
~ 80 % of the baryons
are not yet in galaxies.

We believe that they are in a
"warm-hot intergalactic medium"
(WHIM)
which is very hard to detect*
(Davé et al. 2001, ApJ, 552, 473)

*except by Im galaxies
that turn into Sphs?

Figure 4. The field galaxy baryonic mass function. The data points are for all galaxies, while the lines show spine fits by Hubble Type. The lines are as in figure 2. The CDM mass spectrum from the numerical simulations of Weller et al. (2004) is also shown. Overlaid are parameters for a Schechter fit to the total mass function.

Take-home message:

We like to think that galaxies are "mature" objects and that
our job is to study galaxy evolution to see how they got that way.

But: Galaxy formation is much less "finished" than we like to think!

Dai, Bregman, Kochanek, & Rasia 2010, ApJ, 719, 119

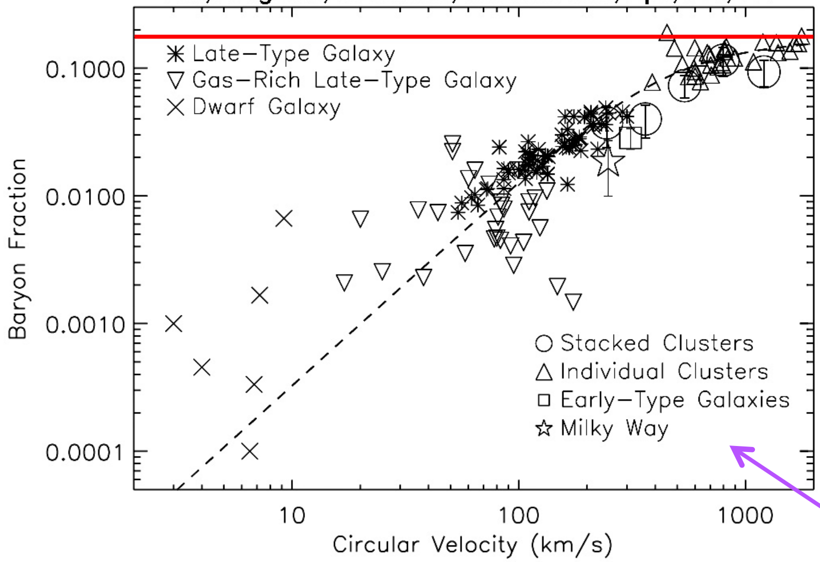


Figure 4. Baryon fractions as a function of potential well depth from dwarf galaxies to rich clusters. The circles are our stacked groups and clusters, the triangles are individual groups and clusters (Vikhlinin et al. 2006; Sun et al. 2009), the square is the ensemble of early-type lens galaxies (Gavazzi et al. 2007), asterisks are late-type galaxies (McGaugh 2005), upside-down triangles are gas-rich, late-type galaxies (Stark et al. 2009), crosses are dwarf galaxies (Walker et al. 2007), and the five-angle star is the Milky Way (Sakamoto et al. 2003; Flynn et al. 2006). The red line is the cosmic baryon fraction. The data points can be fit by a broken power-law model (dashed line) with the break at $V_c \sim 440$ km s^{-1}. The scatter of the data points around the mean relation is relatively small, which indicates that baryon fractions are largely set by the depths of a system's potential well.

Allen, Evrard, & Mantz 2011, ARA&A, 49, 409

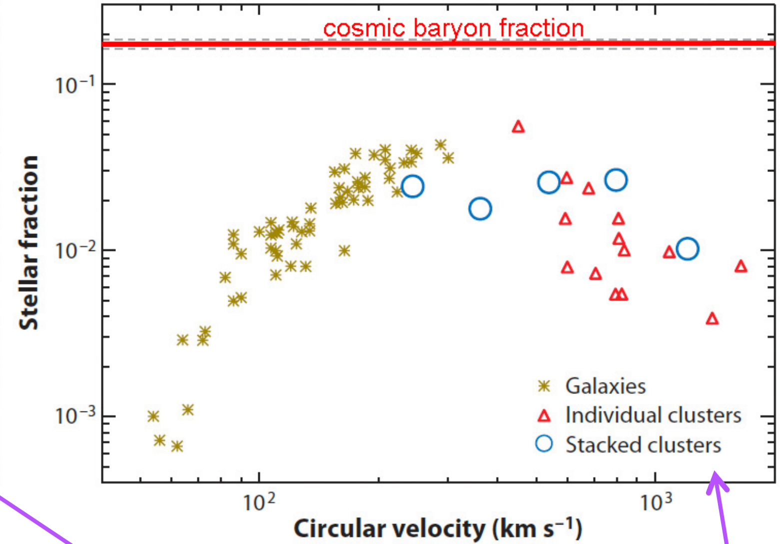


Figure 2

The observed stellar mass fraction as a function of halo circular velocity for systems ranging from galaxies to rich clusters indicates that star-formation efficiency peaks in halos of mass $\sim 10^{13}\ h^{-1}\ M_\odot$. From Dai et al. (2010).

The left plot shows the baryon fraction (not the fraction of mass in stars). Note that we can account for a bigger fraction of the baryons in bigger objects with bigger circular velocities. That is, the baryons in clusters of galaxies with equivalent circular velocity ~ 1000 km/s are not missing. They are just not in stars. They remain suspended in hot gas because AGN feedback and continued gas infall from larger scales prevents the hot gas from cooling.

Only at small velocities are baryons missing. They have been ejected from galaxies into the "Warm-Hot Intergalactic Medium" (WHIM).

Take-home message:

Very little AGN feedback keeps hot gas hot for a very long time.

Cooling and star formation of all gas and "finishing" galaxy formation will take a long time.

About 1/3 of the baryons in the local Universe are thought to be in the WHIM – in cosmic filaments of gas that are far away from visible galaxies.

Davé et al. 2001, ApJ, 552, 473

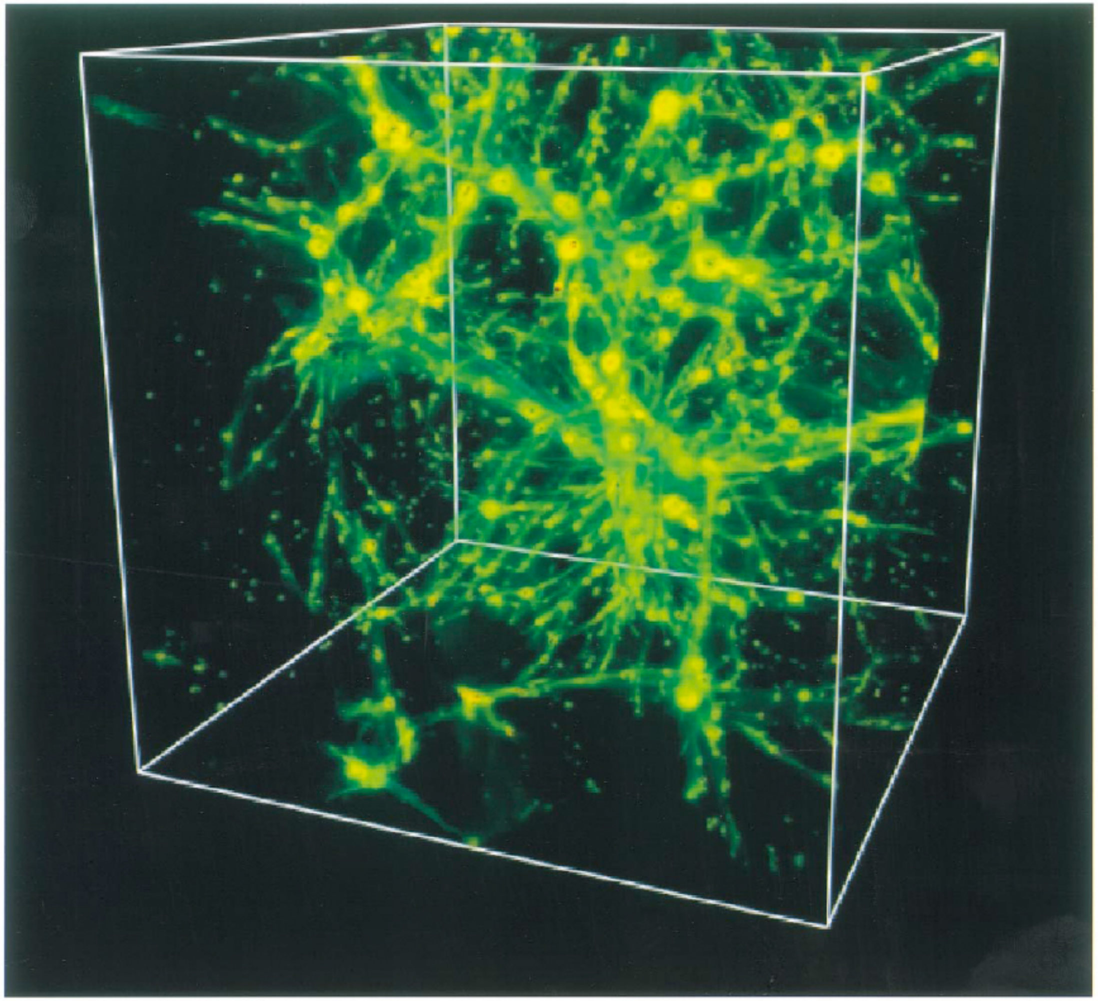


FIG. 3.—WHIM gas in simulation C2. Contours are color-coded by overdensity; green represents overdensity $\delta \sim 10$, while red shows $\delta \sim 10^4$.

6. SUMMARY

We study the warm-hot intergalactic medium (WHIM), defined as all the gas in the universe with temperature $10^5 < T < 10^7$ K, in six cosmological hydrodynamic simulations with widely varying spatial resolutions, volumes, code algorithms, and input physics. In each simulation, the WHIM contains $\approx$30–40% of all baryons in the present-day universe. As a rule of thumb, our simulations predict that the fractions of baryons in the warm-hot phase, the diffuse phase, and gravitationally bound systems are roughly comparable at the present epoch.

Our simulations predict that the majority of WHIM gas is far away from galaxies and clusters, residing in the diffuse IGM. A promising avenue to detect this more typical WHIM gas is via absorption, as continuing observations with STIS aboard the *Hubble Space Telescope* will detect many more O VI absorbers.

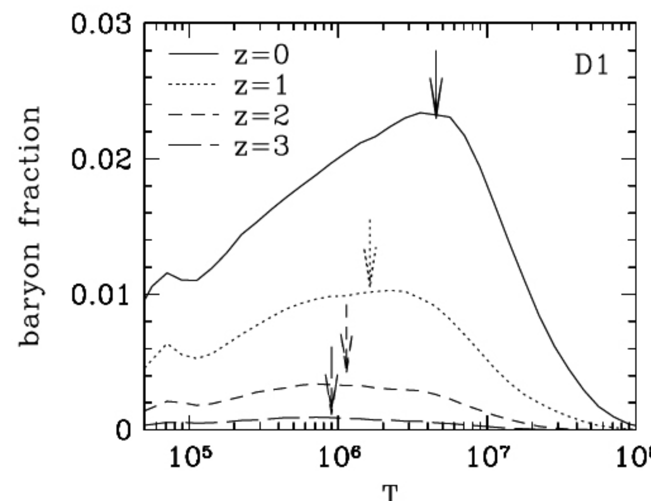


FIG. 5.—Mass fraction of baryons as a function of temperature in simulation D1, at $z = 0$ (*solid line*), $z = 1$ (*dotted line*), $z = 2$ (*short-dashed line*), and $z = 3$ (*long-dashed line*). The arrows indicate the predicted peak temperature from gravitational shock heating at various z, from eq. (2).

The evolution of the universe can be likened to a display of fireworks that has just ended: some few red wisps, ashes, and smoke. Standing on a well-chilled cinder, we see the fading of the suns and try to recall the vanished brilliance of the origin of the worlds.

Lemaître 1931

Future of Galaxy Formation

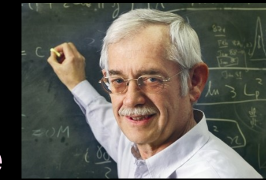
The evolution of the universe can be likened to a display of fireworks that has just ended: some few red wisps, ashes, and smoke. Standing on a well-chilled cinder, we see the fading of the suns and try to recall the vanished brilliance of the origin of the worlds.

Lemaître 1931

The fireworks of youth may be over,
but middle age is going to last a
long, long, long, long,
LONG,
long time.

A final comment about supermassive and stellar-mass black holes:

Hawking Radiation from Black Holes



Jacob Bekenstein (1972) and Stephen Hawking (1974) explored the thermodynamics of BHs and suggested that:

Black holes effectively radiate energy consistent with $T \propto 1/M_\bullet$.

Carried to extremes (small BH masses), this has led to a violent contradiction between general relativity and quantum mechanics.

However:

Time scale for BH evaporation = 2.66×10^{-24} $(M_\bullet / \text{kg})^3$ yr.

A 200,000 kg BH evaporates in 1 second as a 5 million megaton TNT explosion.

However, BHs with $M_\bullet$ > mass of Earth's Moon are now in equilibrium with the cosmic microwave background radiation and have not started to evaporate yet.

A dead star BH with $M_\bullet \approx 3M_\odot$ has an evaporation time of 6×10^{68} yr.

Supermassive BHs evaporate $10^6 – 10^{10}$ times more slowly.

We know natural ways to make dead star and supermassive BHs.
But we have no slightest inkling that the Universe has ever made smaller BHs.

Therefore the BHs whose quantum effects get our theories into trouble involve physics that our Universe, with age = 13.7×10^9 yr, very likely has not "invented" yet.