THE ONASSIS FOUNDATION SCIENCE LECTURE SERIES

The 2008 Lectures in Physics: COSMOLOGY: AN ASTROPHYSICAL PERSPECTIVE

Status of the Cosmological Tests: Some Puzzles

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1 July 2008

Three Puzzles

The ΛCDM cosmology passes a demanding network of tests.

But does it have all the physics that will be needed for the observational cosmology and extragalactic astronomy of the 21$^{\rm st}$ century, or is it only the simplest approximation we can get away with at the present — still schematic — level of the evidence?

If ΛCDM differs from reality enough to matter it will become manifest, in anomalies. That is, it is good strategy to operate as if this model were complete until driven to adjust it.

But a proactive approach also can be good strategy: seek puzzles that may prove to be real anomalies. I offer three examples:

- giant galaxies;
- dwarf void galaxies;
- the extended Local Supercluster.

Giant Galaxies as Island Universes

The late merging puzzle. In ΛCDM simulations the most massive galaxies exchange considerable amounts of matter with their surroundings to distances of several megaparsecs.

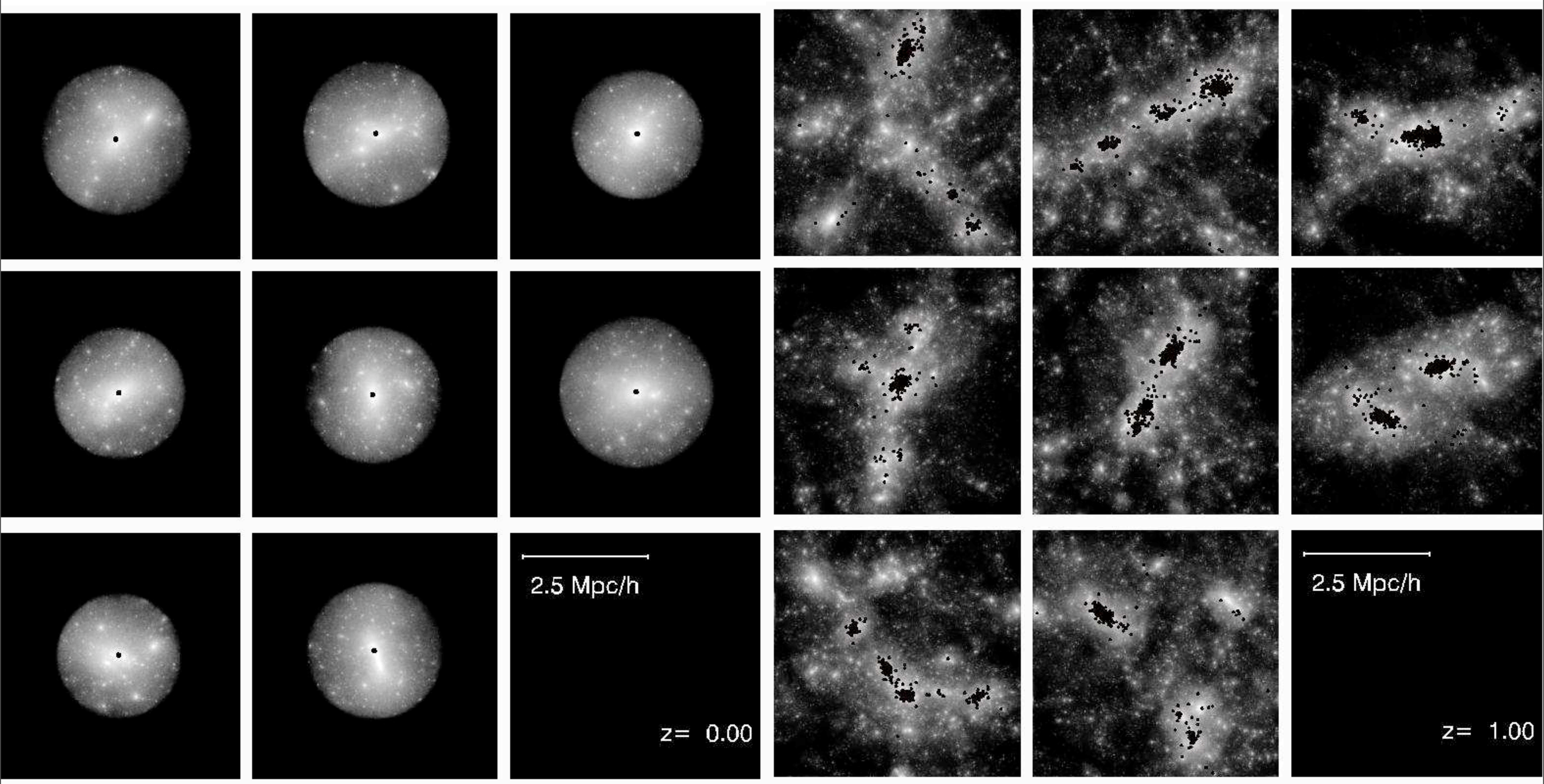
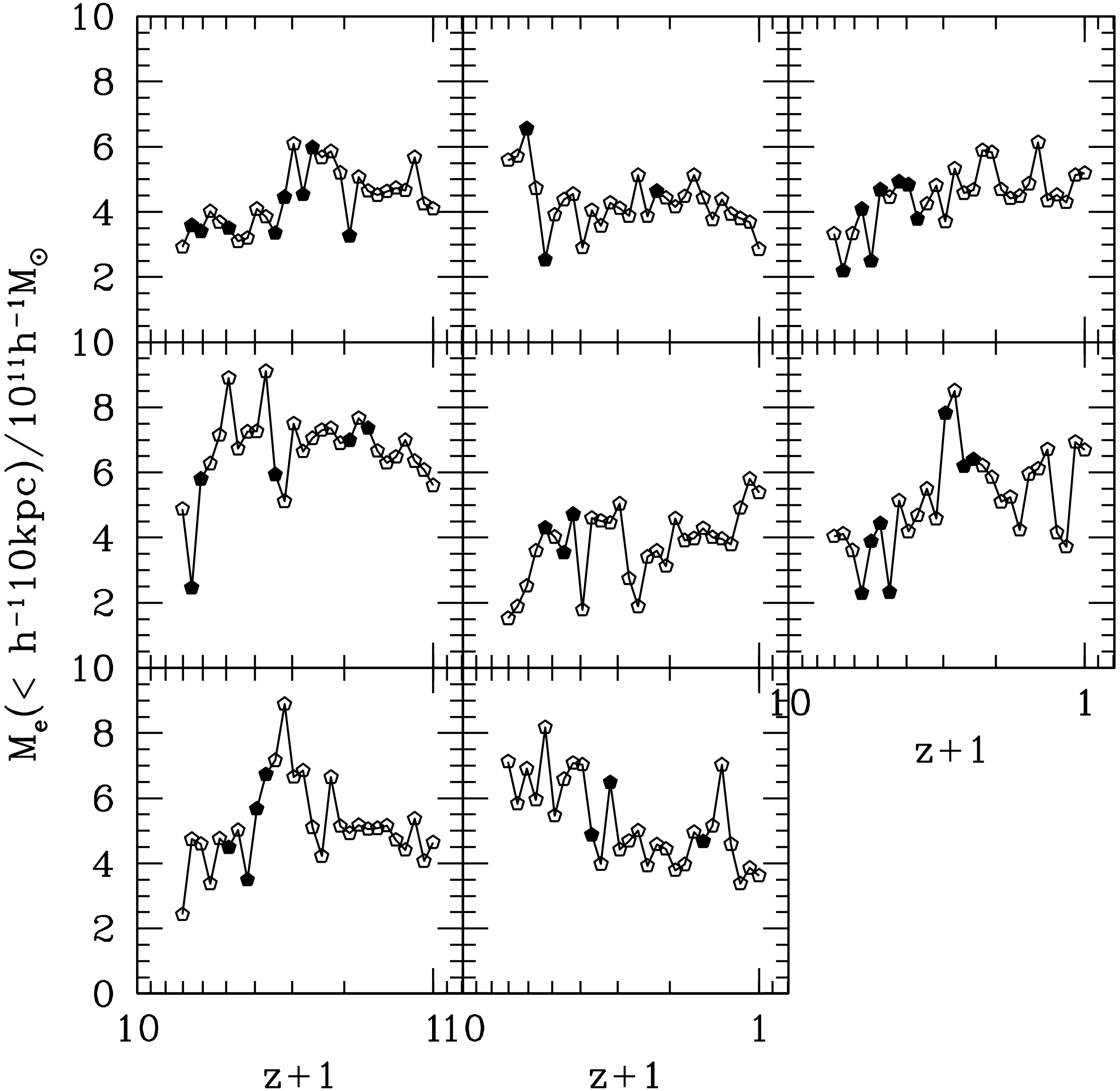


Fig. 2.— Images of the mass distribution at $z = 0, 1$ and 3 in our 8 simulations of the assembly of cluster mass halos. Each plot shows only those particles which lie within r_{200} of halo center at $z = 0$. Particles which lie within $10h^{-1}$ kpc of halo center at this time are shown in black. Each image is $5h^{-1}$Mpc on a side in physical (not comoving) units.

Early Formation and Late Merging of the Giant Galaxies

Liang Gao[1] Abraham Loeb[2] P. J. E. Peebles[3] Simon D. M. White[1] and Adrian Jenkins[4]



The mass in the densest parts of these giant CDM halos within constant physical radius 15 kpc, about the effective radius of a giant galaxy, has been replaced several times by mergers and ejections.

But the mass within 15 kpc stays remarkably close to constant back to redshift $z > 7$.

This means there is no manifest problem with the observation of luminous red galaxies at $z \sim 3$.

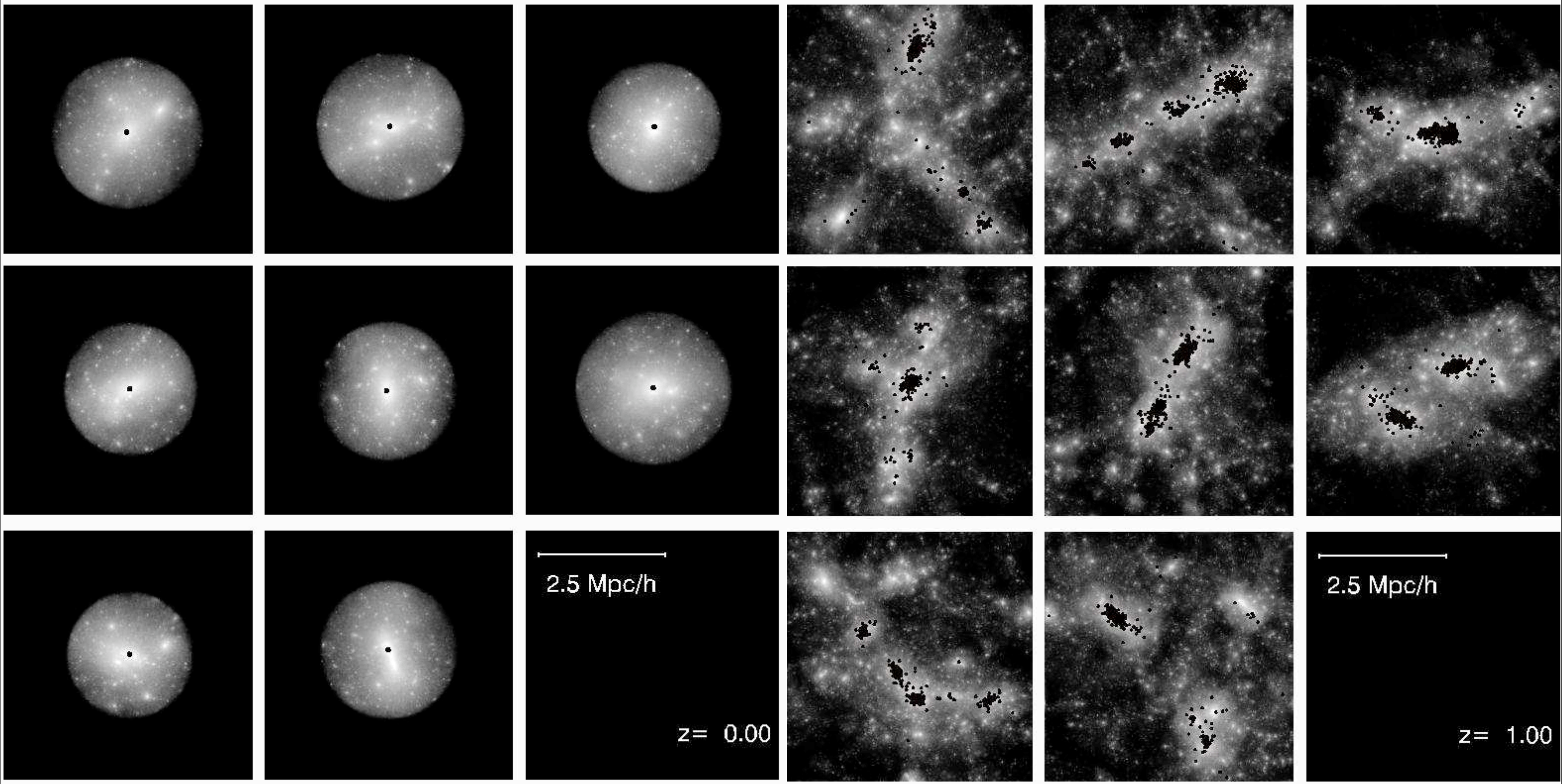
The apparent problem to be discussed is that present-day giants are strikingly insensitive to environment.

Fig. 3.— The total mass within physical distance $10h^{-1}$ kpc of the center of the most massive progenitor of the final halo at each time plotted and for each of our 8 simulations. Symbols switch between filled and open each time the identity of the most massive progenitor changes.

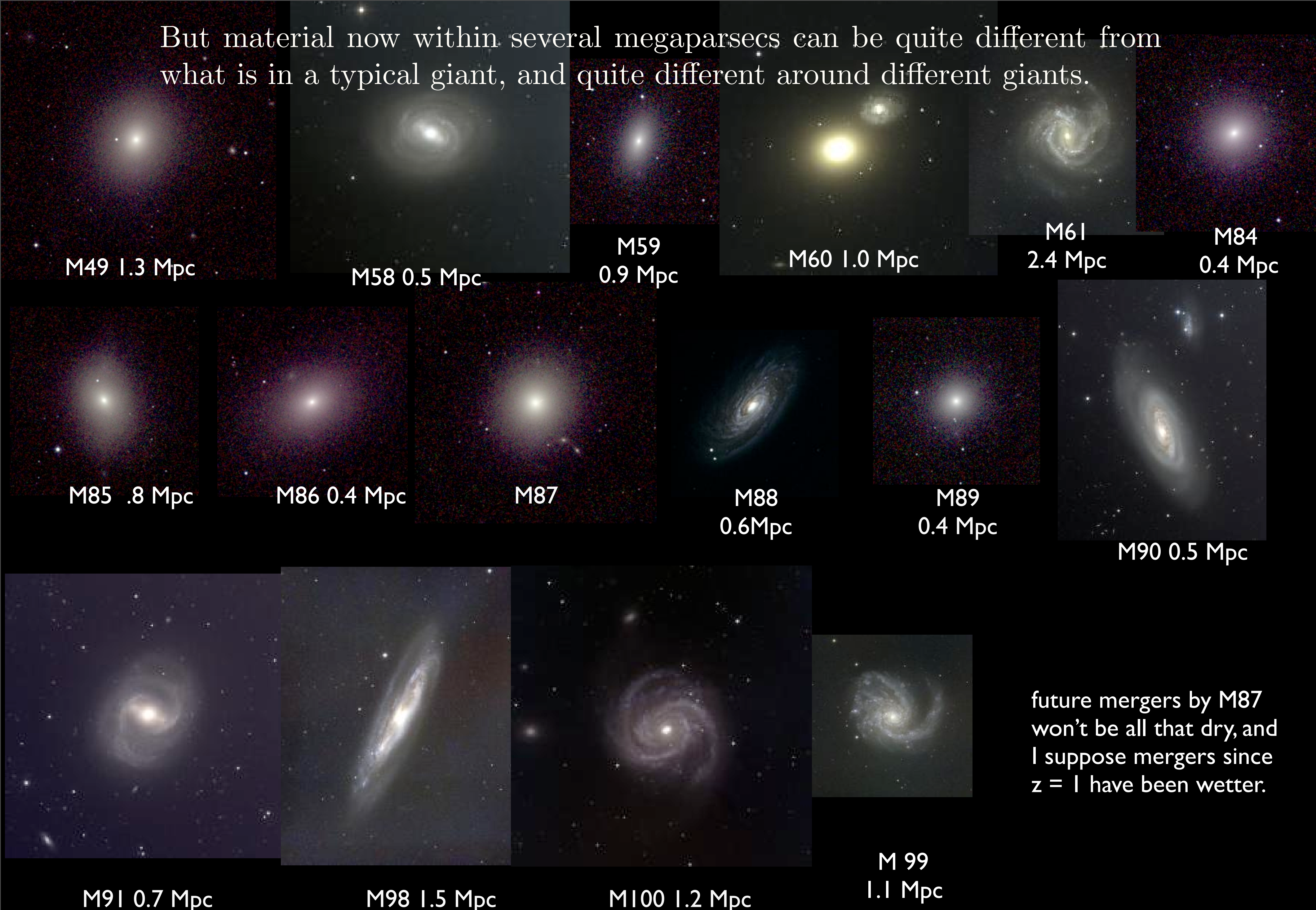
Gao, Loeb, Peebles, White, Jenkins, ApJ 2004

This is a pure CDM simulation. But the evidence is that most stars in a giant galaxy formed at $z > 1$, stars once formed behave like CDM particles, and halo structures are attractors.

The prediction thus seems clear: the luminous parts of giant galaxies have exchanged considerable material with their surroundings to several megaparsecs distance.



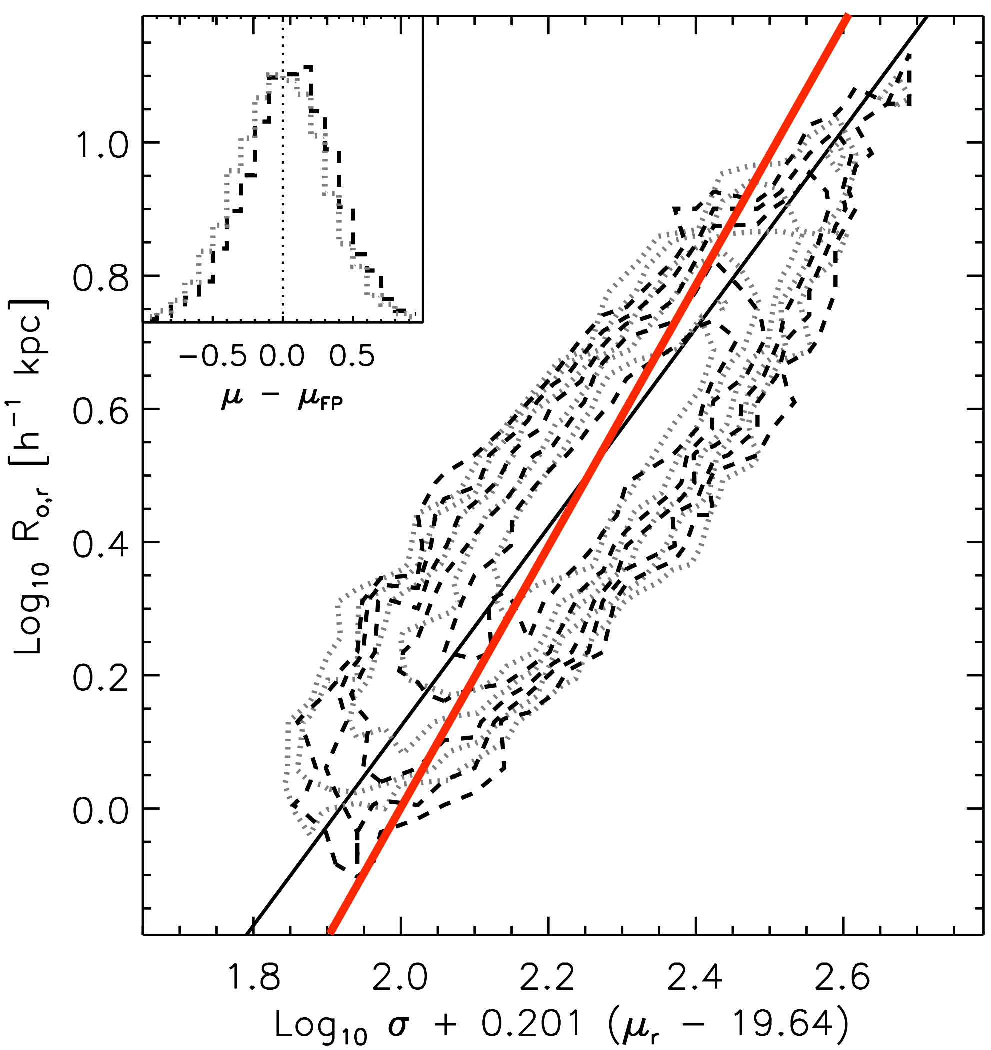
But material now within several megaparsecs can be quite different from what is in a typical giant, and quite different around different giants.



future mergers by M87 won't be all that dry, and I suppose mergers since z = 1 have been wetter.

This shows Nigel Sharp's list of Messier galaxies in the Virgo cluster, with projected distances from M 87.
The images, from NOAO and 2MASS, have a roughly common angular scale, but contrasts can differ.

The late merging puzzle. Large early-type galaxies give the impression of island universes.



M. Bernardi *et al.* (2006) study of the effect of environment on the fundamental plane for SDSS early-type galaxies. Dashed contours: galaxies at higher ambient density; dotted, lower density.

The red line is the relation

$$\log\sigma + 0.2\mu = 0.5\log R + \text{ constant}$$

that follows from the virial theorem if M/L is constant. The scaling indicated by the tilt of the contours relative to the red line,

$$M/L \propto R^{0.3}$$

shows exceedingly little environmental effect.

Late merging puzzle. The line — the early-type red sequence — is insensitive to environment. Again, this is more suggestive of island universes than the considerable exchange of matter with the surroundings predicted by the ΛCDM cosmology.

THE DEPENDENCE ON ENVIRONMENT OF THE COLOR-MAGNITUDE RELATION OF GALAXIES

David W. Hogg,[1] Michael R. Blanton,[1] Jarle Brinchmann,[2] Daniel J. Eisenstein,[3] David J. Schlegel,[4]
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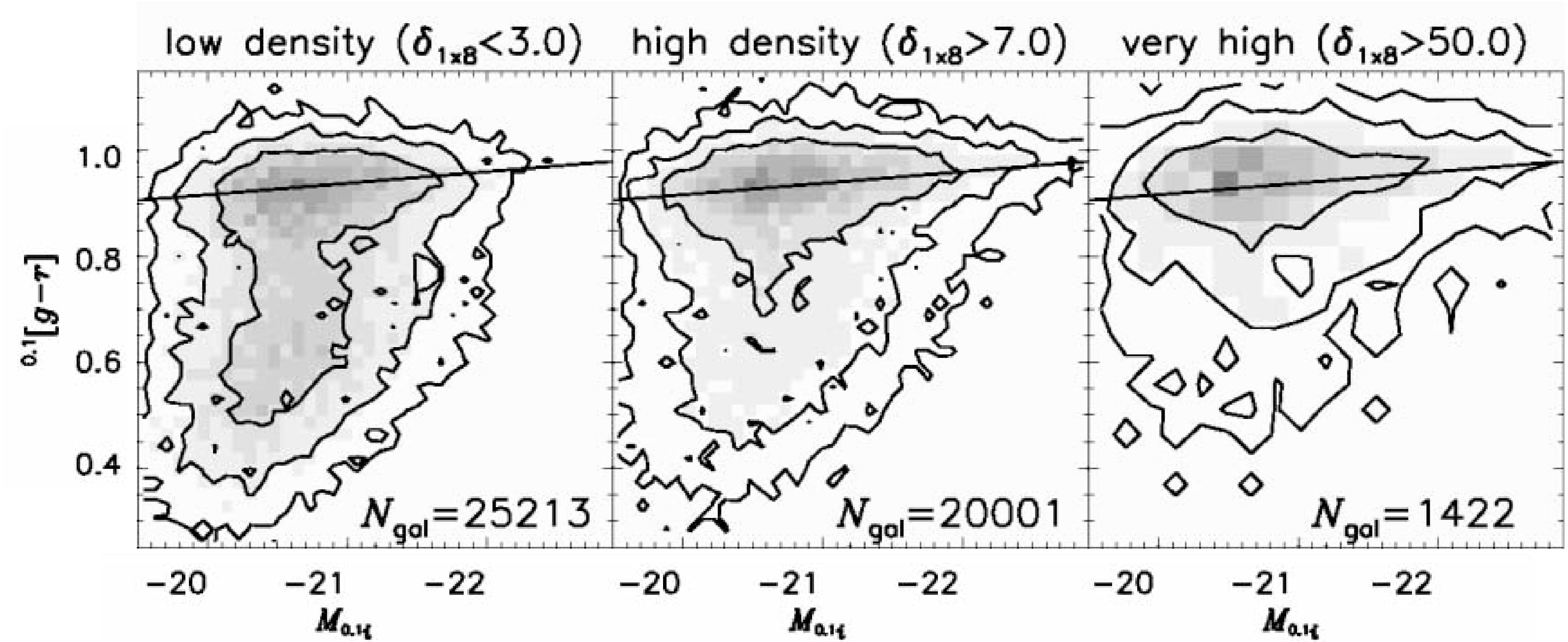
(bowdlerized)



These SDSS colors are measured at about 80% of the nominal Petrosian magnitude, that is, well outside the half-light radius

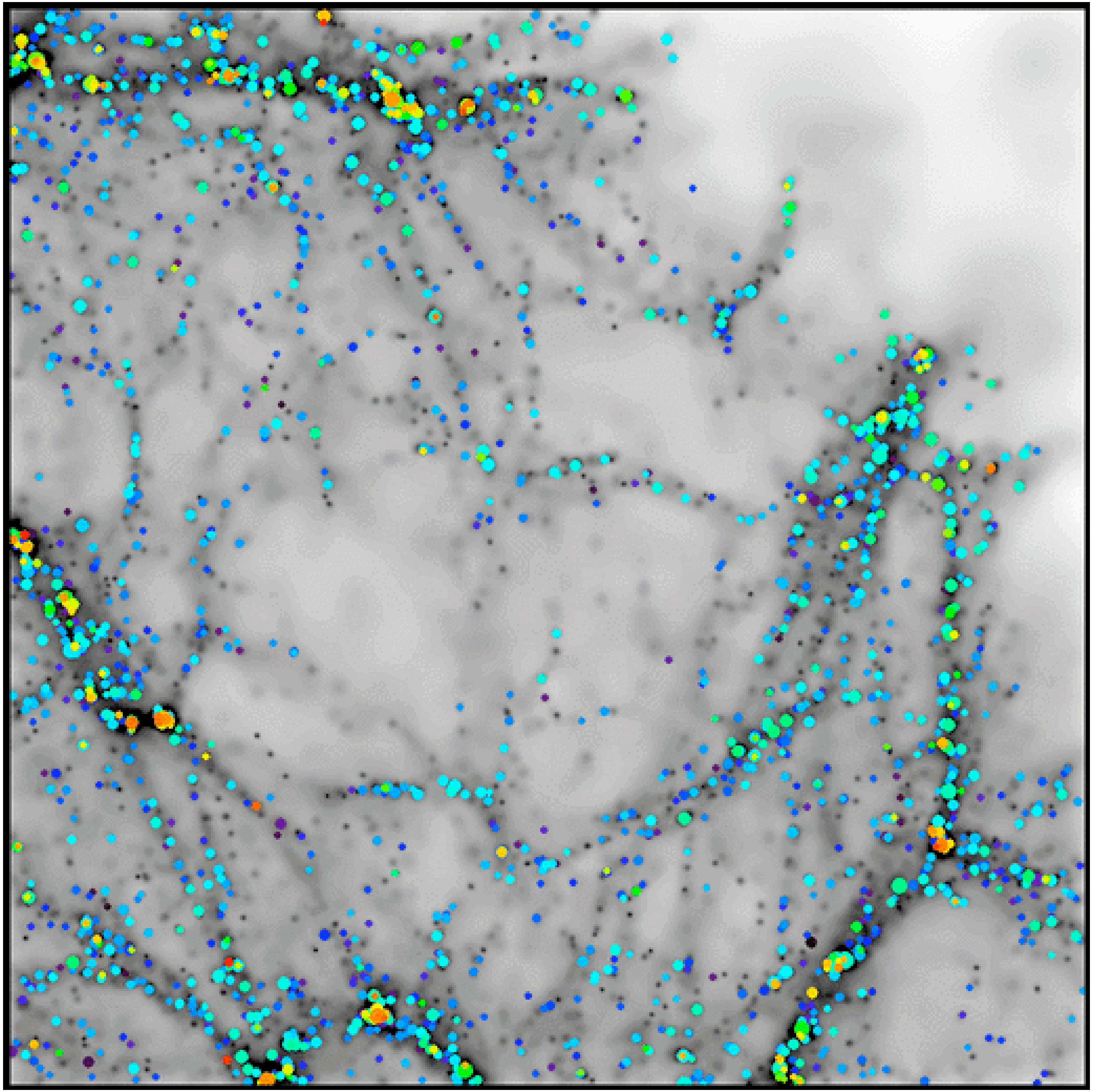
HST image of M87

Late Merging: When galaxies like this merge what happens to their AGNs?

Is the undisturbed appearance of M87 misleading? Should we expect to see examples of large galaxies with displaced or lost massive central compact objects?

Again, advances in observation and theory will be followed with interest: they are going to teach us something of value.

On the Abundance of Extreme Dwarf Galaxies in Voids



Mathis and White 2002

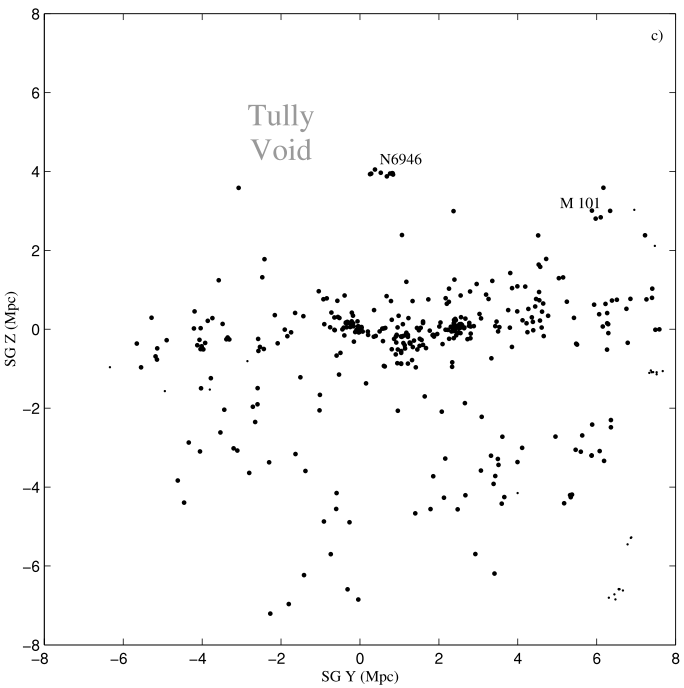
The most massive CDM halos, which would be good homes for the largest galaxies, prefer the densest regions. This is a Good Thing.

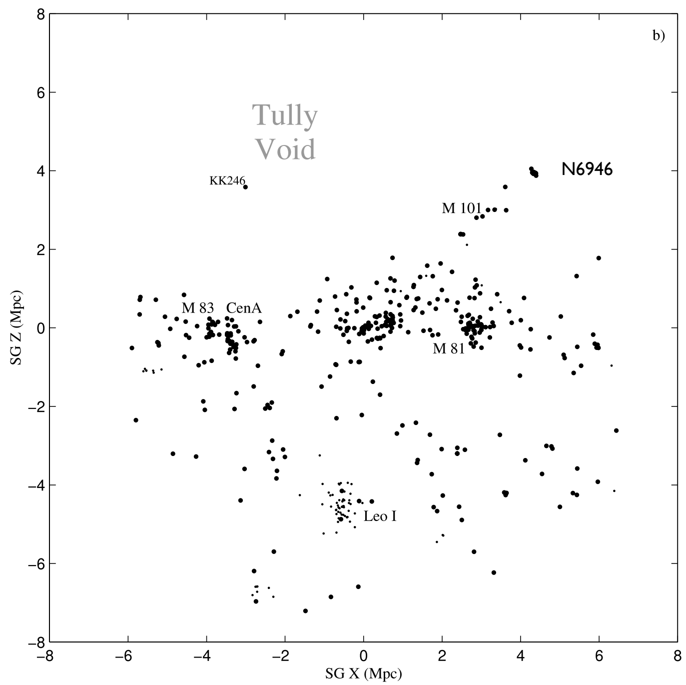
Low mass CDM halos trail into voids defined by more massive halos. This is a Curious Thing.

The seven most luminous galaxies within 8 Mpc (Karachentsev *et al.* 2004)

6. NGC 6946 $M_B = -20.86$
$D = 5.9\,\mathrm{Mpc}$, $Z = 3.7\,\mathrm{Mpc}$

4. M 101, $M_B = -21.23$
$D = 7.4\,\mathrm{Mpc}$, $Z = 2.8\,\mathrm{Mpc}$





It is interesting that the range of luminosities among the seven most luminous is only a factor of two.

It is curious that two edge into the Local Void. Are there signatures of their unusual environment? Do simulations say there ought to be observable signatures?

1. Andomeda
$M_B = -21.58$
$D = 0.8\,\mathrm{Mpc}$

2. NGC 253
$M_B = -21.37$
$Z = -0.3\,\mathrm{Mpc}$
$D = 3.9\,\mathrm{Mpc}$

3. M 106
$M_B = -21.25$
$D = 7.8\,\mathrm{Mpc}$
$Z = 0.8\,\mathrm{Mpc}$

5. M 81
$M_B = -21.06$
$D = 3.6\,\mathrm{Mpc}$
$Z = -0.04\,\mathrm{Mpc}$

7. Cen A
$M_B = -20.77$
$D = 3.7\,\mathrm{Mpc}$
$Z = -0.3\,\mathrm{Mpc}$

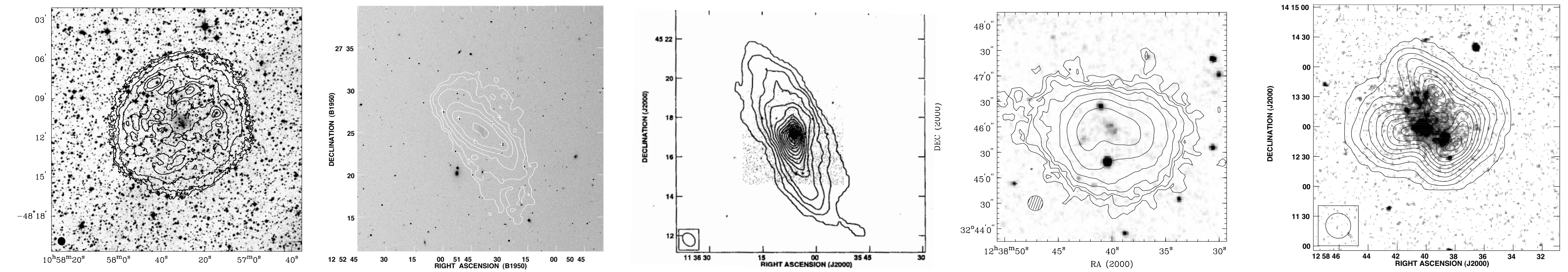
ESO 215, $M_{\rm HI} = 5\times10^{8} m_\odot$ — $M_{\rm HI}/L_B \sim 20,\ v_c \simeq 50\ {\rm km\,s^{-1}}$

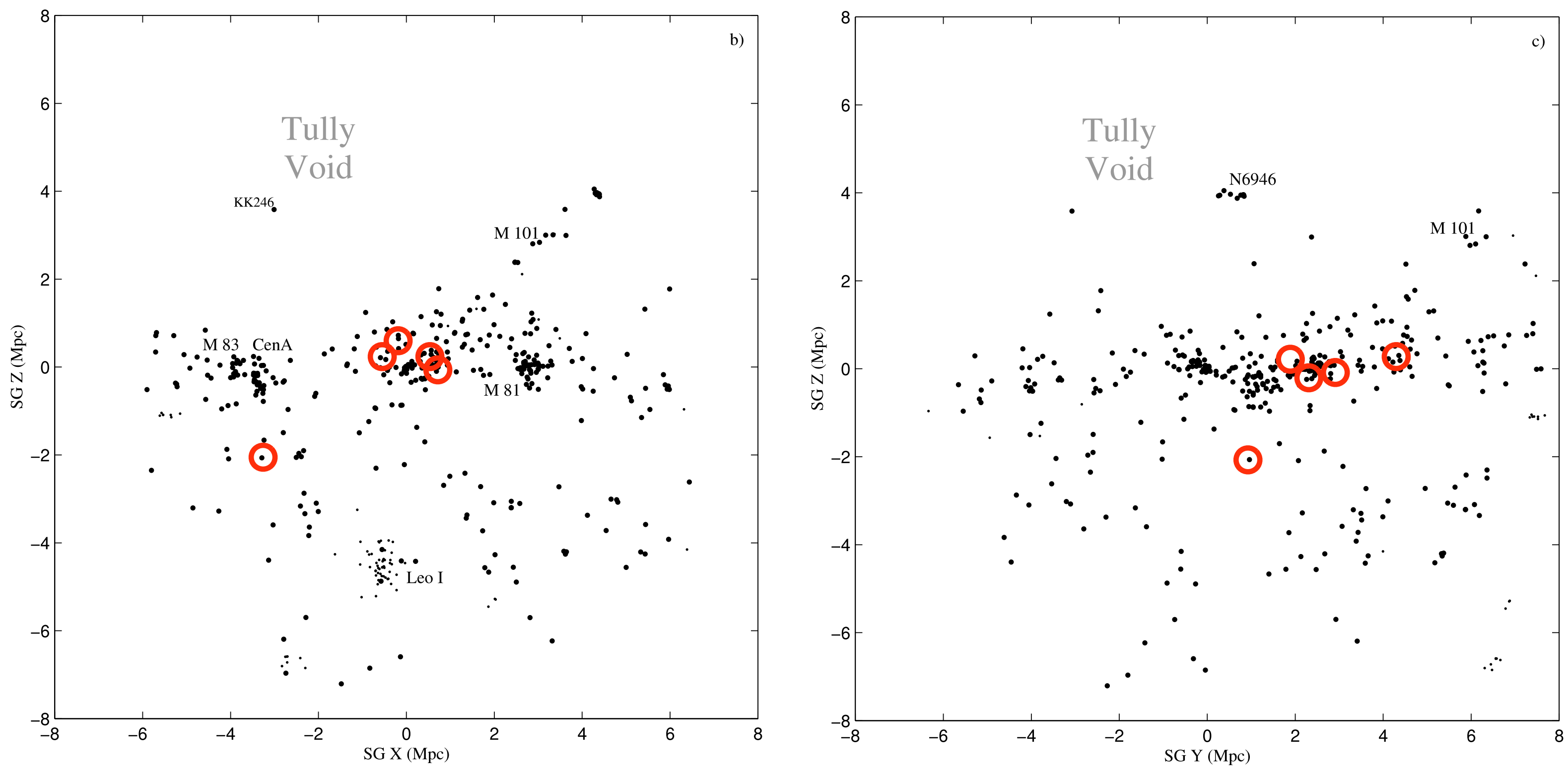
DDO 154, $M_{\rm HI} = 3\times10^{8} m_\odot$ — $M_{\rm HI}/L_B \sim 8,\ v_c \simeq 40\ {\rm km\,s^{-1}}$

NGC 3741, $M_{\rm HI} = 2\times10^{8} m_\odot$ — $M_{\rm HI}/L_B \sim 6,\ v_c \simeq 40\ {\rm km\,s^{-1}}$

UGCA 292, $M_{\rm HI} = 5\times10^{7} m_\odot$ — $M_{\rm HI}/L_B \sim 7,\ v_c \simeq 15\ {\rm km\,s^{-1}}$

DDO 155, $M_{\rm HI} = 1\times10^{7} m_\odot$ — $M_{\rm HI}/L_B \sim 1,\ v_c \simeq 15\ {\rm km\,s^{-1}}$





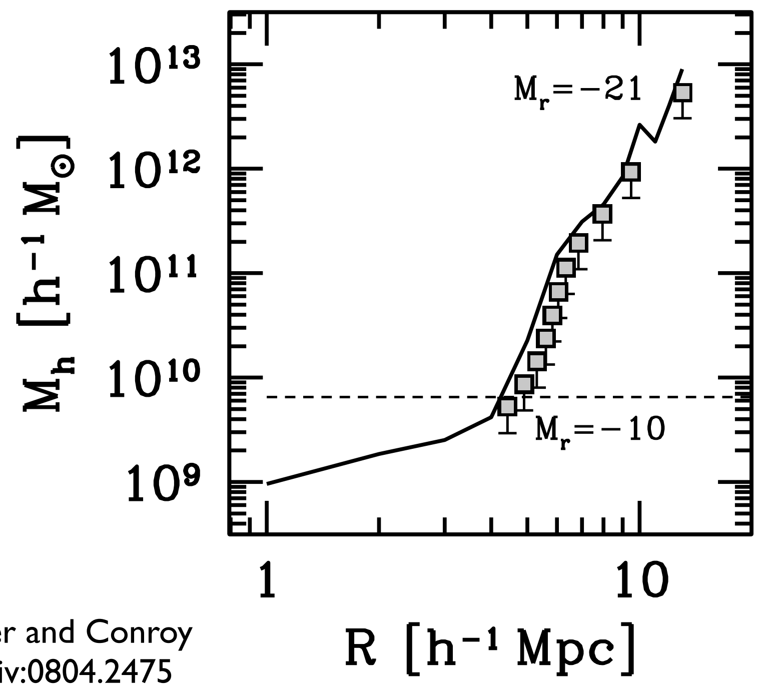
ESO215 DDO154 N3741
DDO 155 U292

ESO215 U292 DDO154
DDO 155 N3741

These gas-rich dwarfs avoid dense regions; they appear to be delicate. But why do they avoid the Local Void?

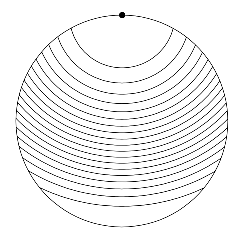
Tinker and Conroy (2008) have an elegant answer: there are DM halos in voids, but none are massive enough to host a visible galaxy.

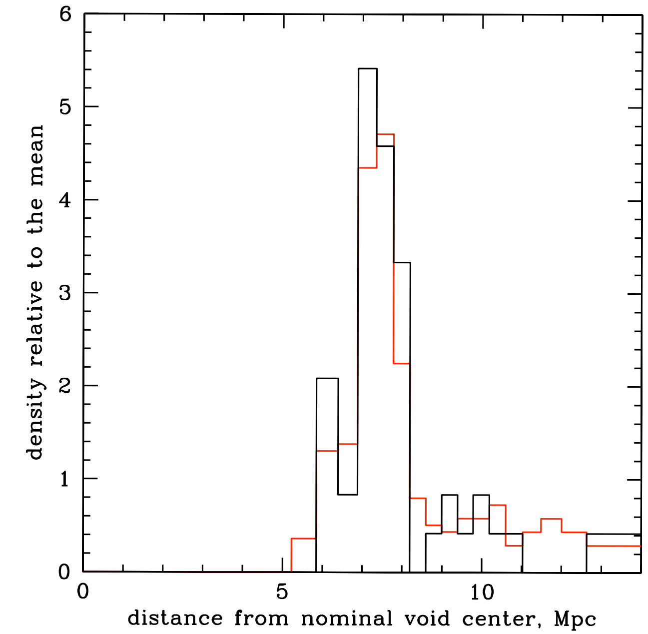
But the answer may not yet be quite complete. At DM halo mass $10^{10} M_\odot$ the Tinker-Conroy excluded region is 5 Mpc inside the excluded region for L_* galaxies, which would be well inside the Local Void. I am bothered by the absence of dwarfs trailing off in to the Local Void.



Tinker and Conroy
arXiv:0804.2475

FIG. 5.— The maximum halo mass within voids as a function of distance from the void center. The solid curve represents mean of the largest three voids in the 96 h^{-1} Mpc simulation. The points represent $M_{\rm min}$ as a function of magnitude, placed along the curve to demonstrate how large the void would be at each luminosity. The dashed curve is the critical mass from Hoeft et al. (2006), below which star formation in void halos is significantly attenuated due to delayed formation histories of void halos.





The Local Void: black: $M_B < -17$; red: $M_B > -17$

And consider the situation at $z = 10$, when the mass density in a present void was becoming noticeably less than the mean, and halo formation and merging in voids would have started to taper off.

Consider halos at $z = 10$ with mass and comoving number density

$$M = 10^8 h^{-1} M_\odot, \quad n(> M) = 1h^3 \text{ Mpc}^{-3}, \quad Mn(> M) \simeq 1 \times 10^{-3} \bar{\rho}.$$

The mass fraction is somewhat larger than $Mn(> M)$, small but not negligible.

The Local Void has volume $\sim 10^3$ Mpc^3. If its density is 10% of the mean it contained some

$$0.1 \times 10^3 \text{ Mpc}^3 \times 1h^3 \text{ Mpc}^{-3} \sim 30$$

of these halos.

The virial scaling relation, $M \sim 200\rho_o(1 + z)^3 R^3$, with normalization from Evrard *et al.* (2008), indicates the typical velocity dispersion, temperature and baryon density in one of these halos are

$$\sigma \sim 20 \text{ km s}^{-1}, \quad T = \bar{m}\sigma^2/k \simeq 20,000 \text{ K}, \quad n_b \sim 0.05 \text{ cm}^{-3}.$$

This works out to cooling time and expansion time $\sim$ collapse time

$$\tau = 3kT/\Lambda n_b \sim 3 \times 10^{12} \text{ s}, \qquad t \simeq 2 \times 10^{16} \text{ s}.$$

Feedback may well temper collapse. But it seems reasonable to expect that halos at $z \gtrsim 10$ would have left stars in the Local Void. The diminished accretion and merging in voids might favor preservation of HI mini-disks, but that requires closer analysis.

Two points:

1. I don't know of an isolated gas cloud detected in H I ($\Sigma \gtrsim 10^{19}$ cm^{-2}) that has no starlight and is further than about 100 kpc from an optical galaxy. (Nearer clouds exist but could be ejecta.) Apparently a galaxy with this surface density has to have formed some stars to support itself in its DM halo.

2. There is considerable mass more than 1.5 Mpc from the nearest L_* galaxy in plasma with no starlight, detected at much lower surface density by the Lyα resonance absorption line. This is in effect — maybe really — the remnants of the Lyα forest. The cloud heavy element abundances are low (Stocke *et al.* 2007).

I don't know of any observational evidence that these void plasma clouds are attached to DM halos.

The Theory and Observation of Extreme Dwarfs in Voids

1. Conditions for survival of an H I-rich dwarf seem to be

a. isolation, to avoid mergers and tidal disruptions (gas-rich dwarfs tend to be $\gtrsim 300\,\mathrm{kpc}$ from the nearest $L \gtrsim L_*$ galaxy),

b. surface density $\Sigma_{HI} \gtrsim 10^{18}\,\mathrm{cm}^{-2}$ and circular velocity $v_c \gtrsim 20\,\mathrm{km\,s}^{-1}$, apparently sufficient to resist ionization and evaporation;

2. so theoretical issues are

a. at $z \sim 10$, when protovoids were just becoming noticeable, the predicted number density of DM halos with potential wells deep enough to bind photoionized plasma, which absent merging translates to comoving number density about one tenth that in a low redshift void with density $\sim 10\%$ of the mean,

b. the rate of formation of dwarf void DM halos at $z < 10$, which I suppose is low,

c. the rate of loss of void dwarfs by merging and harassment, which likely has much less effect on void dwarfs than on dwarfs in halos of L_* galaxies;

3. and observational issues are

a. the present abundance of gas-rich void dwarfs, prominent in H I but hard to find, a challenge Arecibo ALFALFA is addressing,

b. the present abundance of void early-type extreme dwarfs, certainly rare in the Local Void, but worth deeper checks.

On the Curious Preference of Clusters and AGNs for the Extended Plane of the Local Supercluster

Gérard and Antoinette de Vaucouleurs in Paris, 1962.

The Extended Local Supercluster

EVIDENCE FOR A LOCAL SUPERGALAXY

By GÉRARD DE VAUCOULEURS

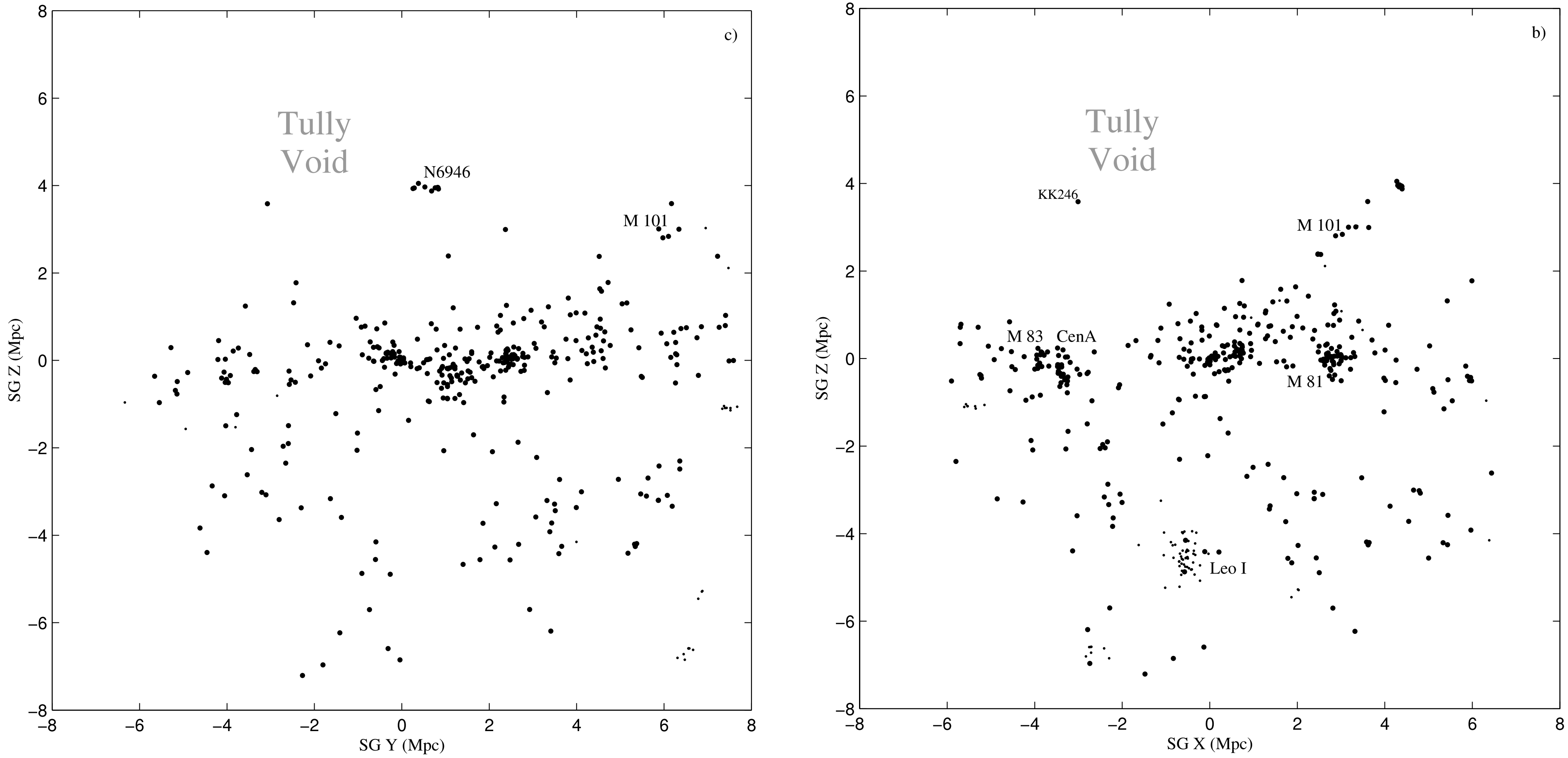
Astrophysical Journal 1953

From an analysis of the radial velocities of about a hundred galaxies within 4 megaparsecs Mrs. V. Cooper Rubin recently found evidence for a differential rotation of the inner metagalaxy.[1] The pole of the rotational plane of the system was placed at $l = 14°$, $b = +10°$.

An investigation of the spatial distribution of the galaxies in the Shapley-Ames Catalogue[2] gives independent evidence of the existence of a local cloud of galaxies, or supergalaxy, within which our own galaxy is situated. The strong flattening of the system supports the assumption of a general rotation.

The accompanying diagram (Fig. 1) gives a schematic interpretation of the apparent clustering of nebulae brighter than the 13th magnitude in both galactic hemispheres, the objects of the nearby Local Group being excluded. Although some of the features are probably spurious and due to chance fluctuations in the general field, there is nevertheless quite independent of any subjective interpretation of the data definite evidence of a strong concentration of the nebulae towards and along a great circle of the sphere crossing almost at right angles to the galactic equator at longitudes $l = 105°$ and $l = 285°$, (possibly 110°–290° in the southern galactic hemisphere.)

The nearby galaxies, at distances $< 8\,\mathrm{Mpc}$, prefer the plane of the de Vaucouleurs Local Supercluster.



Catalog of Neighboring Galaxies Karachentsev *et al.* 2004

The Extended Local Supercluster

P. A. Shaver, Australian J. Phys (1991)

At distances $\sim 80\,\mathrm{Mpc}$ galaxies in general are not noticeably concentrated toward the Local Supercluster, but the powerful radio galaxies tend to be close to this plane.

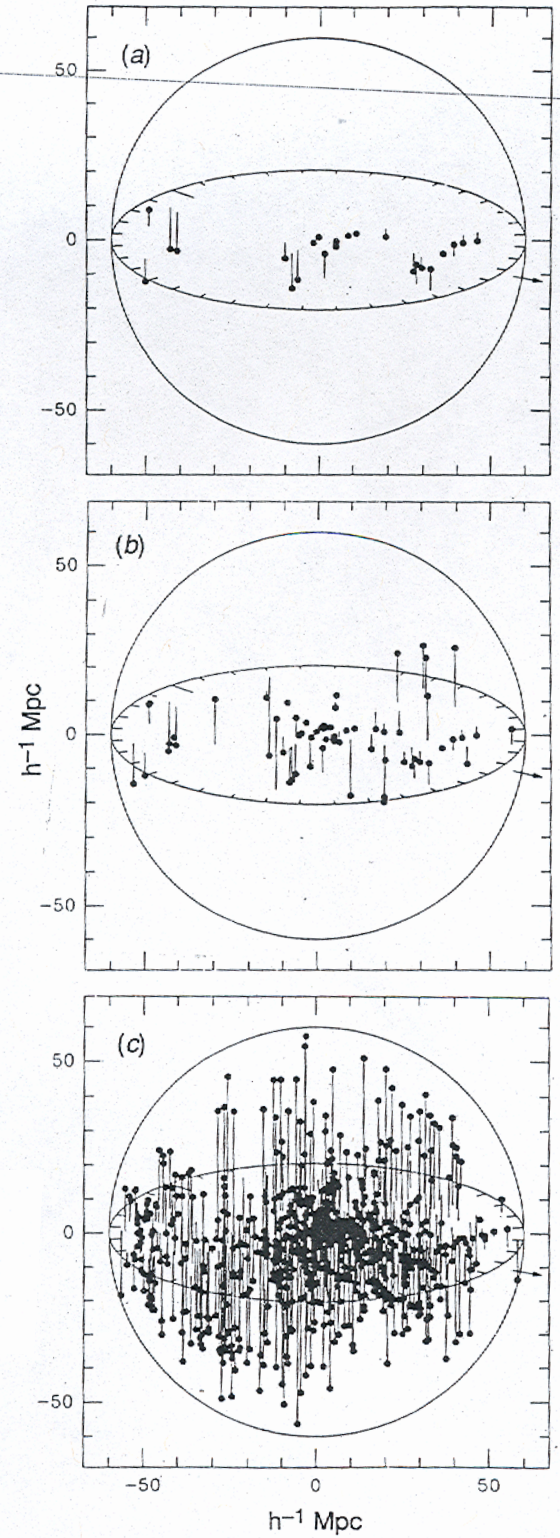
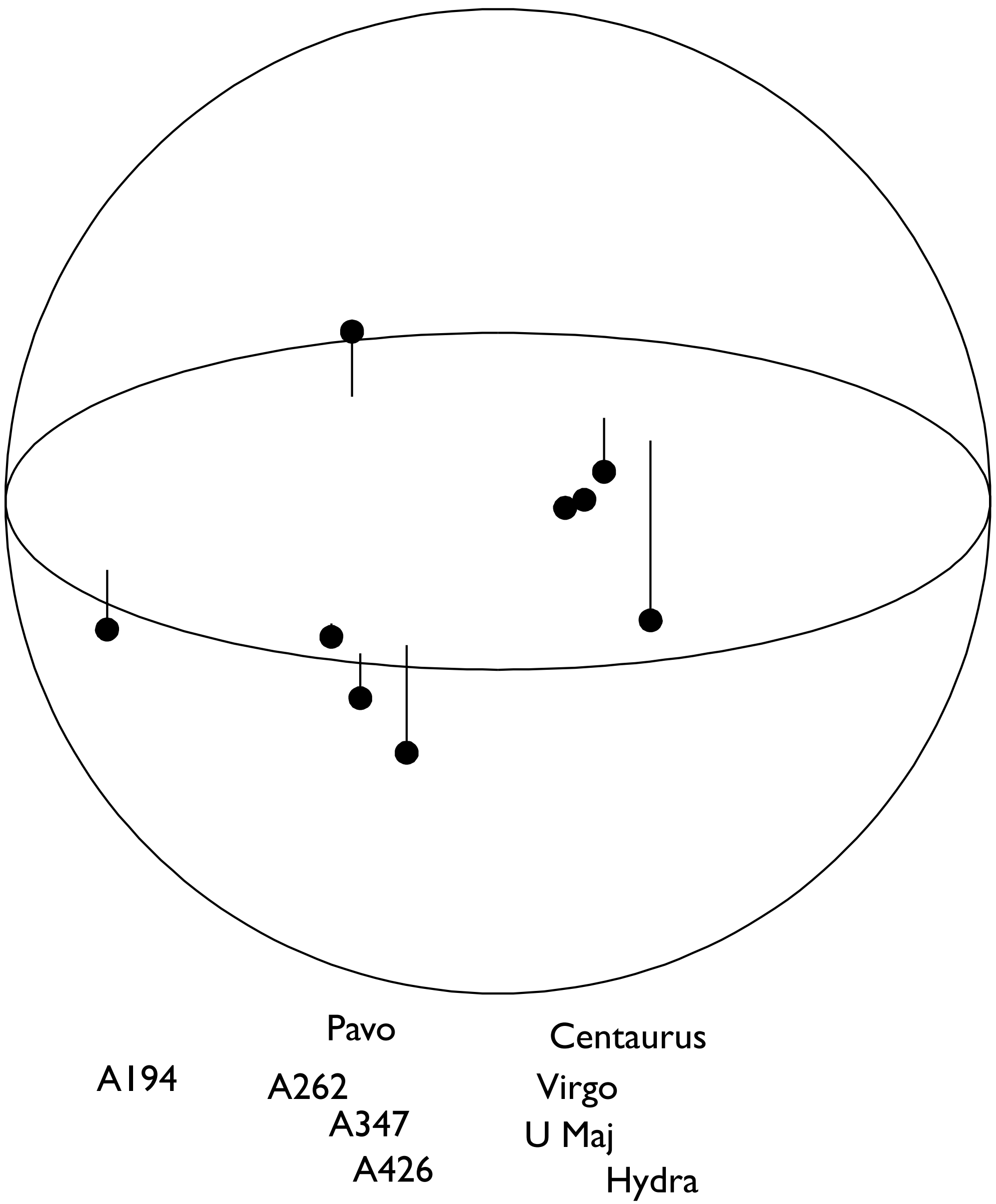


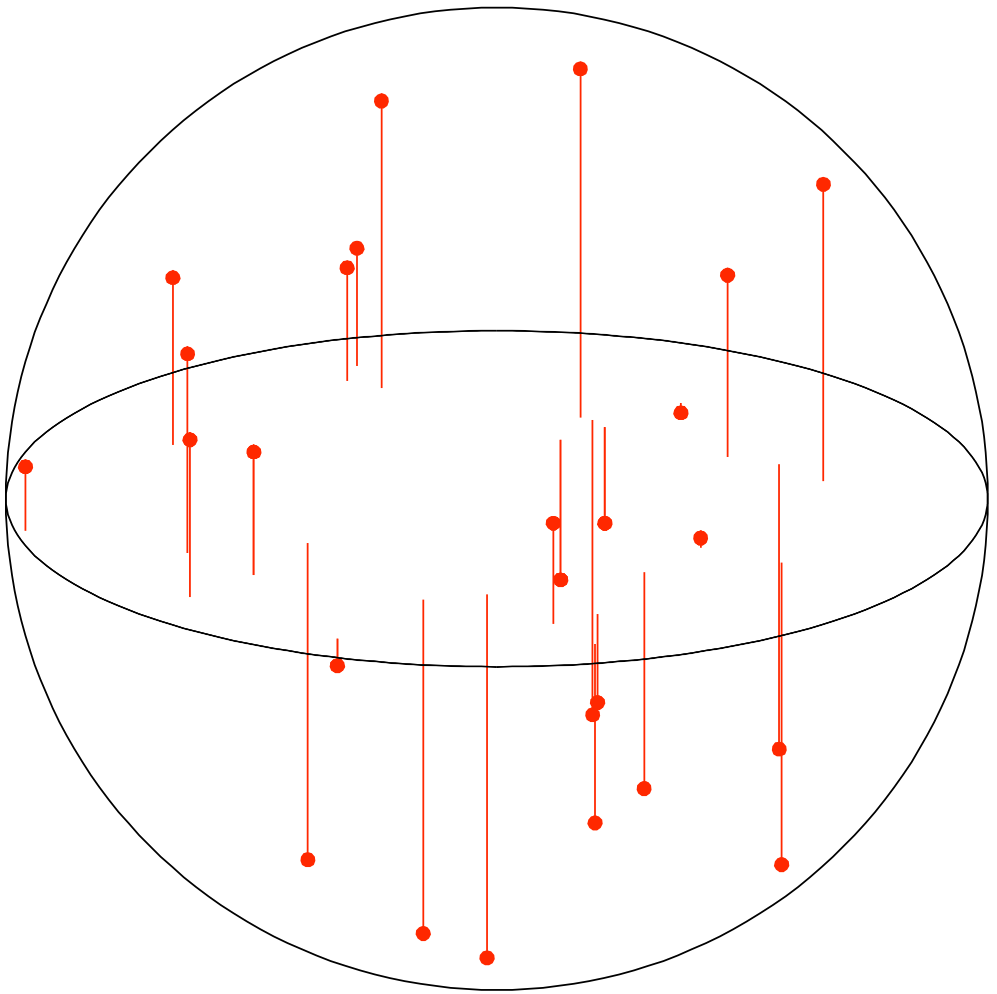
Fig. 5. Space distributions of the complete radio and optical galaxy samples out to $z = 0 \cdot 02$: (*a*) radio galaxies with $S_{408} > 4$ Jy, (*b*) radio galaxies with $S_{408} > 1$ Jy, and (*c*) the optical galaxies. Orientation and symbols as in Fig. 4*a*. The arrows show the 'Great Attractor' direction.

More recent illustrations of Shaver's effect

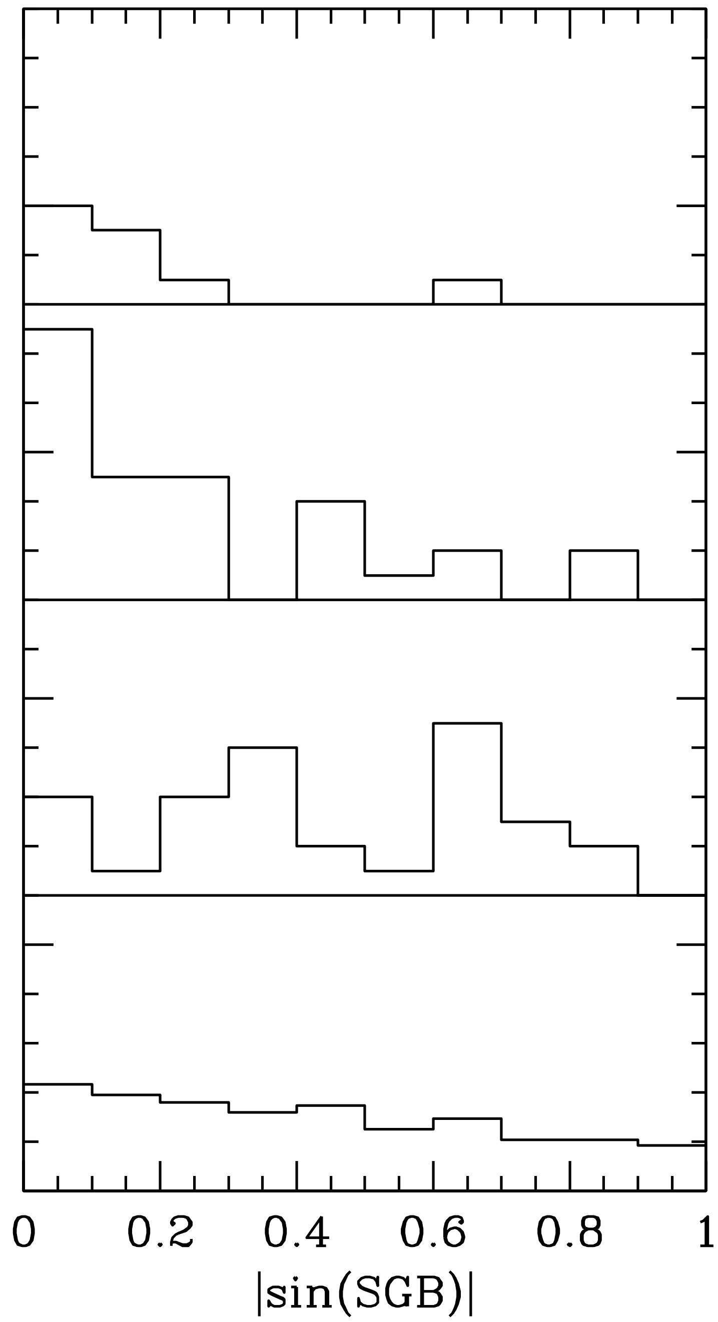
The nine clusters of galaxies at $z < 0.02$ prefer the plane of the Local Supercluster.

The 30 PSCz galaxies at $z < 0.02$ and most luminous at 60 μm are much less concentrated.





Distributions in supergalactic latitude B for objects at redshift $z < 0.02$



The nine clusters of galaxies. The mean of $|\sin \mathrm{B}|$ is 0.18, or 3.3σ low for a uniform Poisson distribution.*

The 30 Veron AGNs most luminous at 20 cm. The mean of $|\sin \mathrm{B}|$ is 0.26, or 4.5σ low.*

The 30 PSCz galaxies most luminous at 60 μm.

The 3000 PSCz galaxies most luminous at 60 μm.

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*This neglects clustering, but the two-point function for the projected distribution at 80 Mpc is pretty small.

The Enigmatic Extended Local Supercluster

We have seen that

1. at $D < 8$ Mpc the observed galaxies show a distinct preference for the plane of the Local Supercluster,
2. and at $D < 80$ Mpc

    a. the nine clusters of galaxies show a pretty distinct preference for the same plane,

    b. as do the 30 AGNs that are most luminous at 20 cm (of which I count only two or three in the clusters),

    c. while the galaxies that are luminous and dusty enough to make it into the PSCz catalog show a statistically real but much more subtle preference for this plane.

So is this curious arrangement

1. an insignificant accident?
2. to be expected in ΛCDM?
3. or maybe a hint of physics to be added to ΛCDM?

Conclusion: there is no lack of fascinating problems in the phenomenology of extragalactic astronomy and cosmology.