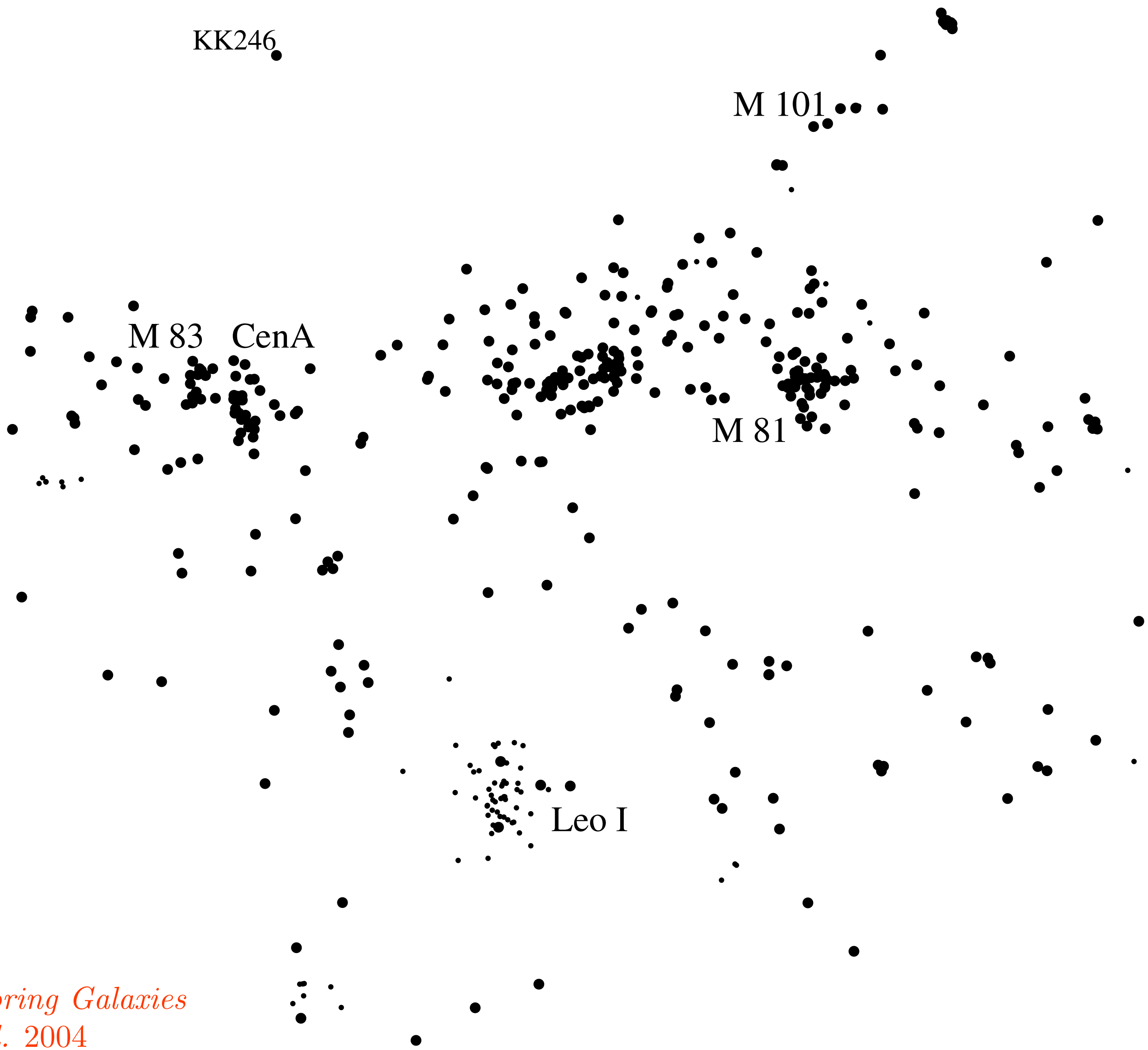
Cosmic Voids

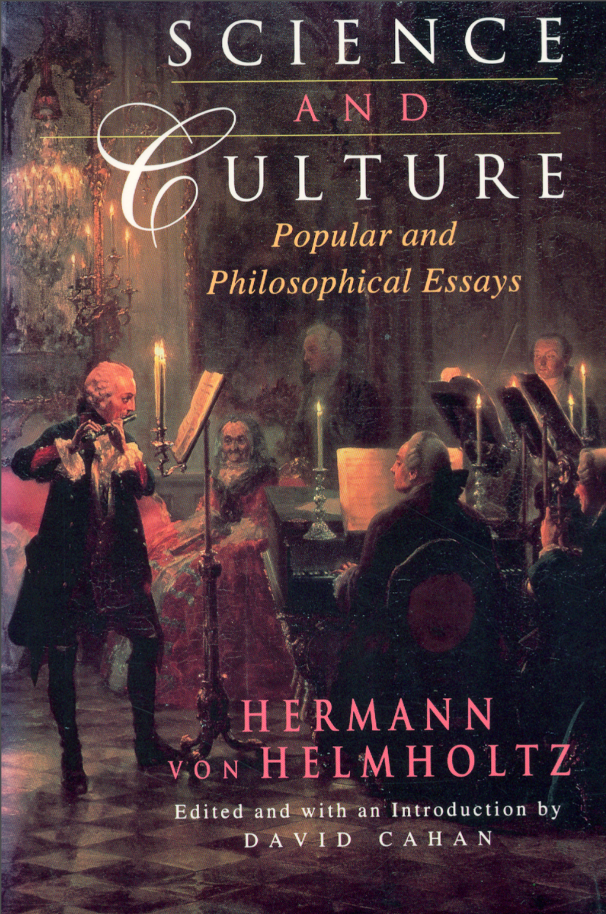
Introductory Comments

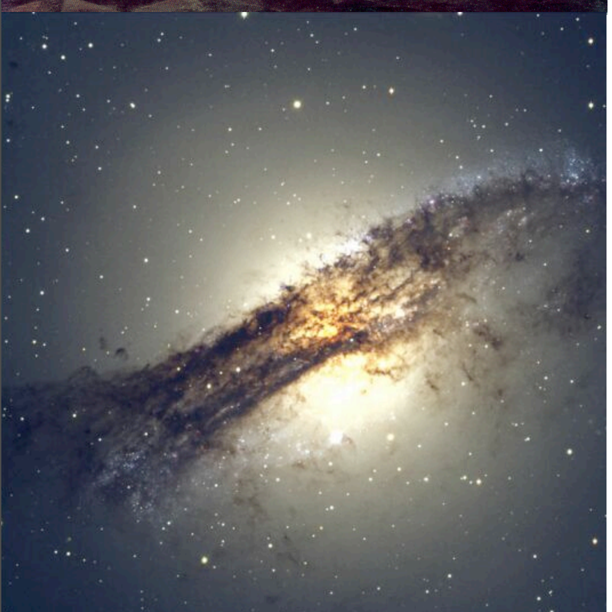
PJE Peebles, Amsterdam, December 2006

Present conditions are sensitive to initial conditions



Catalog of Neighboring Galaxies
Karachentsev *et al.* 2004





Centaurus A Radio Galaxy (VLT KUEYEN + FORS2)

ESO PR Photo 05b/00 (8 February 2000) © European Southern Observatory

The nature of large-scale structure, as we understand the situation, is a product of:

(1) the initial conditions for the Friedmann-Lemaître cosmology;

(2) the interactions of galaxies and the intergalactic medium with their surroundings;

(3) the evolution of galaxies as island universes; and

(4) our belief system.

Factor (1) means we are misled if we don't have excellent understanding of conditions in the very early universe, including the physics.

Factor (4) is a real and proper part of every physical science. Extragalactic astronomy and cosmology is special only in that the bones of our belief system tend to stick out under the thin flesh of the observations.

In this table, I mean by

- *Nature*, initial conditions, or else conditions within about 30 kpc of a protogalaxy when the accumulation of baryon mass within that radius has grown close to the present value;
- *Nurture*, the effect of interactions on scales larger than about 30 kpc, as in the effect of the environment on the evolution of protogalaxies once assembled, and the evolution of the intergalactic medium;
- *Theory*, ideas about what has happened that are more strongly supported by theory than observation.

The assignments in this table are debatable, to be sure, but then we're here to debate the issues.

Phenomenon, real or virtual	*Nature*	*Nurture*	*Theory*
morphology-density relation		$\surd$	
near universal red-sequence color-magnitude relation	$\surd$		
the most luminous galaxies prefer the densest environments, consistent with their strong clustering	$\surd$		
the faintest galaxies & L_* galaxies are similarly distributed, and they avoid common voids	$\surd$	$\surd$	$\surd$
the ΛCDM Cosmic Web defines the voids			$\surd$
inhabitants of voids & low density regions:			
grand-design spirals	$\surd$		
close to normal ellipticals	$\surd$	$\surd$	
low surface density Lyα absorbers		$\surd$	
the warm-hot IGM			$\surd$
baryon-free dwarf DM halos			$\surd$

The morphology-density relation

This has a long history. For example,

Hubble (1936): in clusters all “types of nebulae are represented, but in contrast to the general field, the earlier types, and especially the ellipticals, predominate”;

Spitzer and Baade (1950): “Dense clusters of galaxies, such as the Coma and Corona clusters, contain large numbers of S0 galaxies” which “presumably contain stars only of population type II. It is suggested that collisions between galaxies sweep any interstellar matter out of the galaxies in such clusters, and thereby prevent the appearance of any type I systems”;

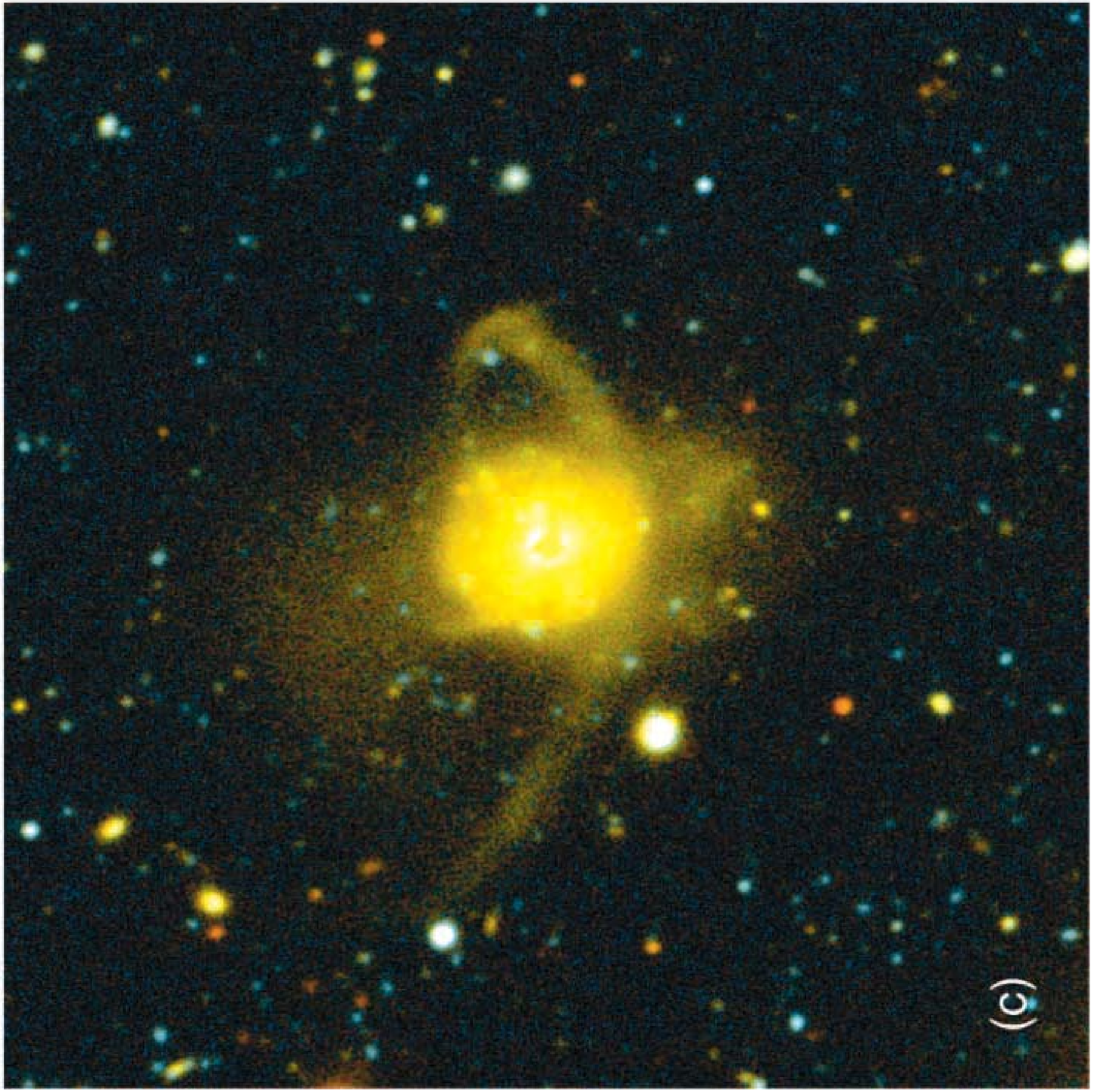
Gunn and Gott (1972): intracluster gas, perhaps indicated by the UHURU X-ray detection of the Coma cluster, might sweep gas out of cluster members; and “the cD galaxies might grow once again at the expense of the intracluster medium;”

van den Bergh (1976): many Virgo cluster spirals “have a rather anemic appearance which is, no doubt, due to the fact that they are forming stars less vigorously than are typical galaxies of the same type in the field”, which “might possibly be understood in terms of the sweeping out of interstellar gas in Virgo spirals by ram pressure.”

Cosmological initial conditions surely played a direct and important role in establishing the density-morphology relation. For example, cD's likely mark the positions of exceptionally large primeval density fluctuations.

But the role of environment is clear too, as in van den Bergh's (1976) anemic Virgo spirals and van Dokkum's (2005) dry mergers in ellipticals.

So I am inclined to assign the dominant role in determining the density-morphology relation to *Nurture*.



Pieter van Dokkum (2005)

Phenomenon, real or virtual	*Nature*	*Nurture*	*Theory*
morphology-density relation		$\surd$	
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the ΛCDM Cosmic Web defines the voids			$\surd$
inhabitants of voids & low density regions:			
grand-design spirals	$\surd$		
close to normal ellipticals	$\surd$	$\surd$	
low surface density Lyα absorbers		$\surd$	
the warm-hot IGM			$\surd$
baryon-free dwarf DM halos			$\surd$

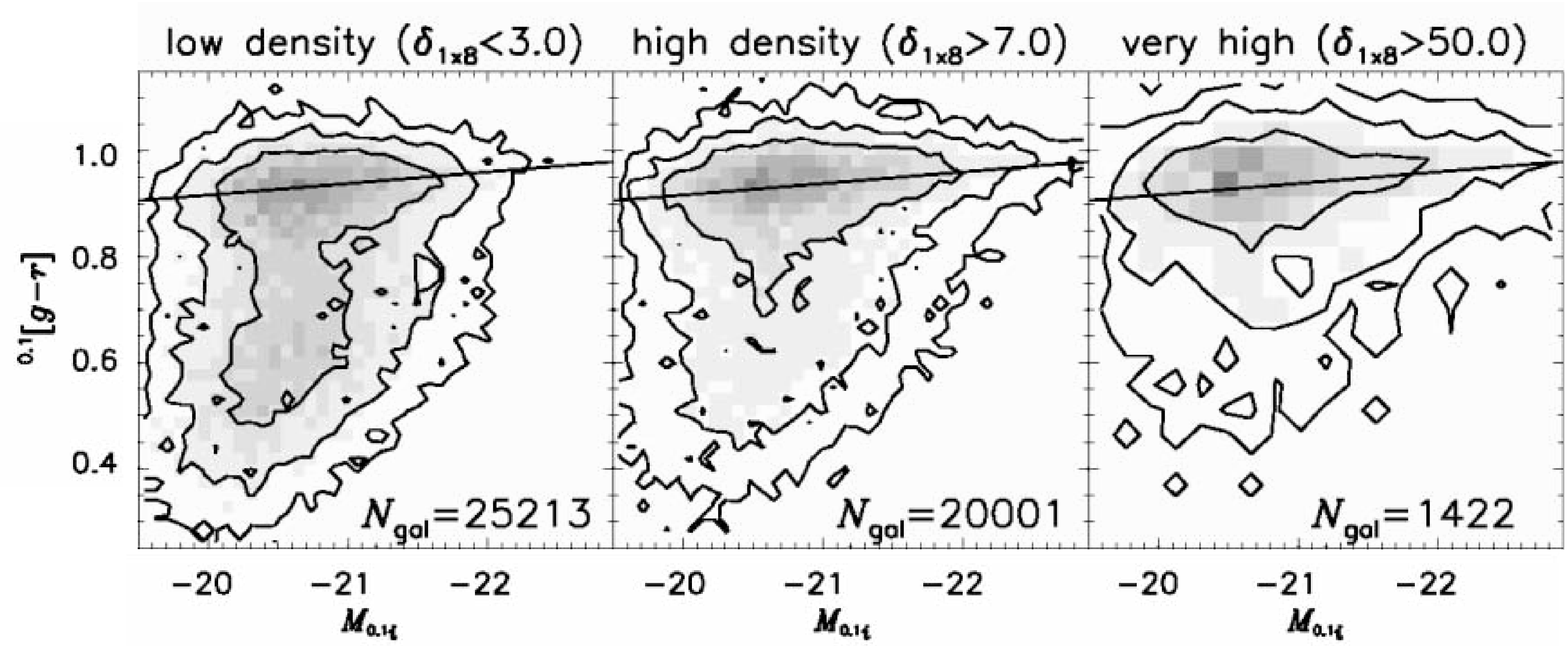
The red edge of the color-magnitude-density diagram

The red edge of the color-magnitude-density diagram

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]
James E. Gunn,[4] Timothy A. McKay,[5] Hans-Walter Rix,[6] Neta A. Bahcall,[4]
J. Brinkmann,[7] and Avery Meiksin[8]
Received 2003 July 11; accepted 2003 December 2; published 2004 January 16

(bowdlerized)

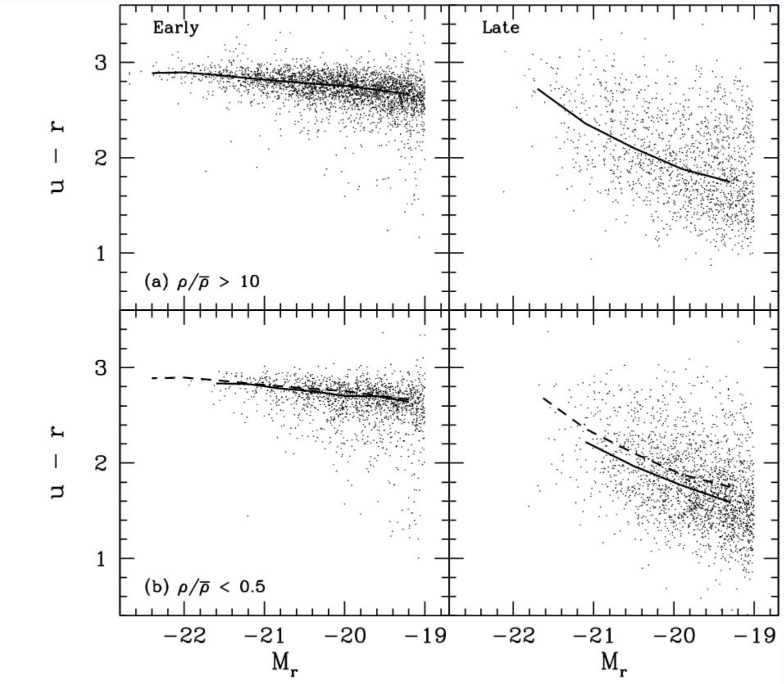


The local number density contrast is the average within a cylinder of radius $1h^{-1}$ Mpc and half-length $8h^{-1}$ Mpc in redshift space.

The SDSS magnitudes and colors are measured at $\sim 80\%$ of the nominal Petrosian magnitude, that is, well outside the half-light radius.

The red edge of the color-magnitude-density diagram

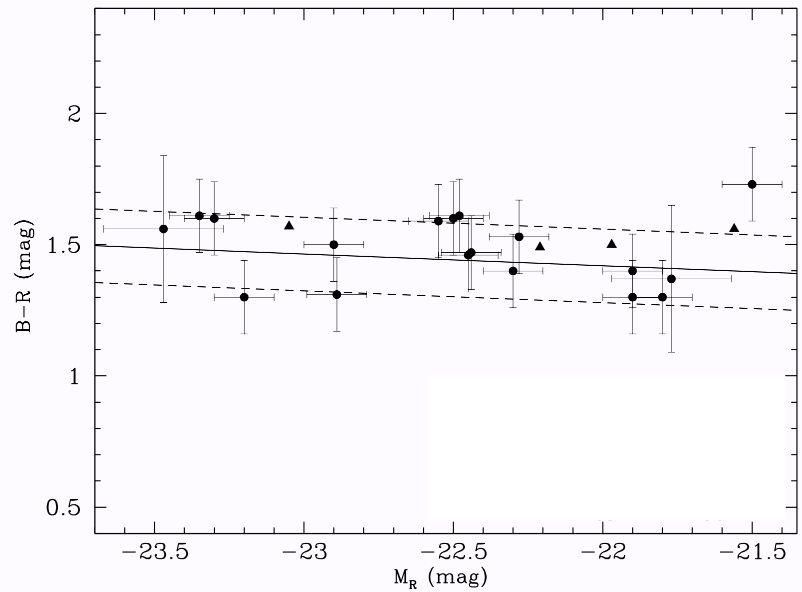
Park and the SDSS Collaboration



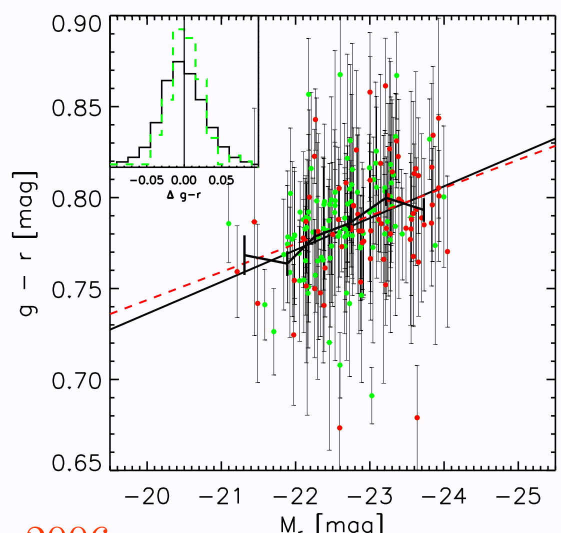
The local density, ρ, is the number density within a shaped smooth window in redshift space that contains 20 $L > L_*$ galaxies.

The curves are modes; the dashed curves in the lower panel, $\rho/\langle\rho\rangle < 0.5$, are the high density cases shown in the upper panels.

Reda, Forbes and Hau 2005



Circles with error bars are Reda *et al.* isolated ellipticals. Solid line is the Coma cluster CMR.



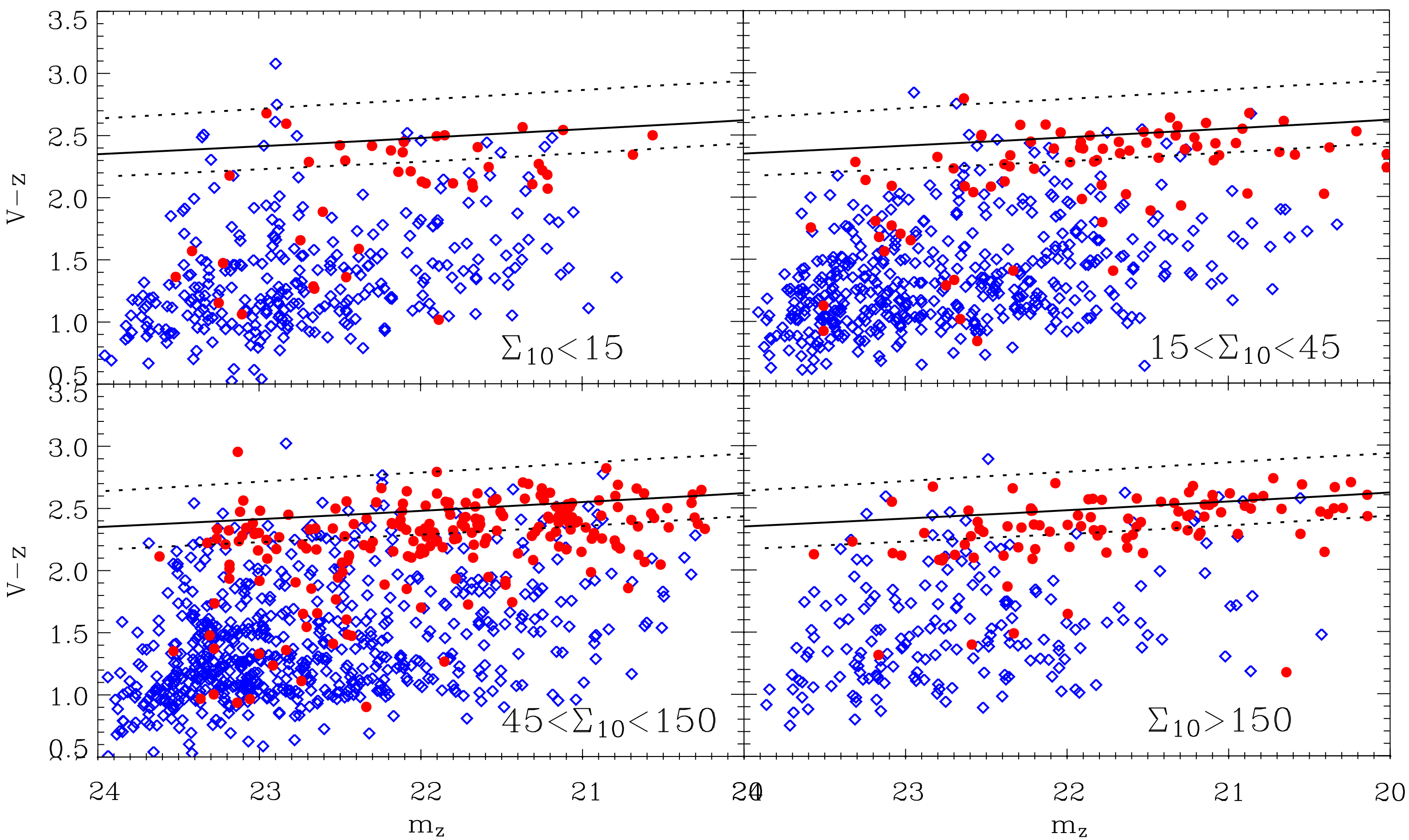
Bernardi *et al.* 2006

Fig. 8.— Location of C4 BCGs (symbols) with respect to the color-magnitude relation defined by the bulk of the early-type galaxy population (solid line). Dashed line shows a linear fit of color as a function of absolute magnitude, and jagged line with error bars shows the mean color in a few bins in luminosity. Inset shows that BCGs are not offset from the relation defined by the bulk of the popula-

The red edge of the color-magnitude-density diagram

The Cosmic Evolution Survey (COSMOS): The morphological content and enviromental dependence of the galaxy color-magnitude relation at $z \sim 0.7$

P. Cassata[1,2], L. Guzzo[3], A. Franceschini[2], N. Scoville[4,5], P. Capak[4], R. S. Ellis[4], A. Koekemoer[6], H. J. McCracken[7], B. Mobasher[6], A. Renzini[8], E. Ricciardelli[2], M. Scodeggio[1]
Y. Taniguchi[9], D. Thompson[10,4]



With thanks to Paolo Cassata and Gigi Guzzo for permission to show their pre-publication result.

The red edge of the color-magnitude-density diagram

Galaxies relax to the red when star formation is sufficiently suppressed. But that can't be the whole story: the tilt of the C-M relation requires correlation of luminosity with some combination of stellar age, metallicity and/or chemistry.

The red edge of the color-magnitude diagram is not sensitive to density, indicating this is an effect of *Nature*: these red galaxies remind me of island universes.

So why classify morphology-density as an effect of *Nurture*? It's a good question.

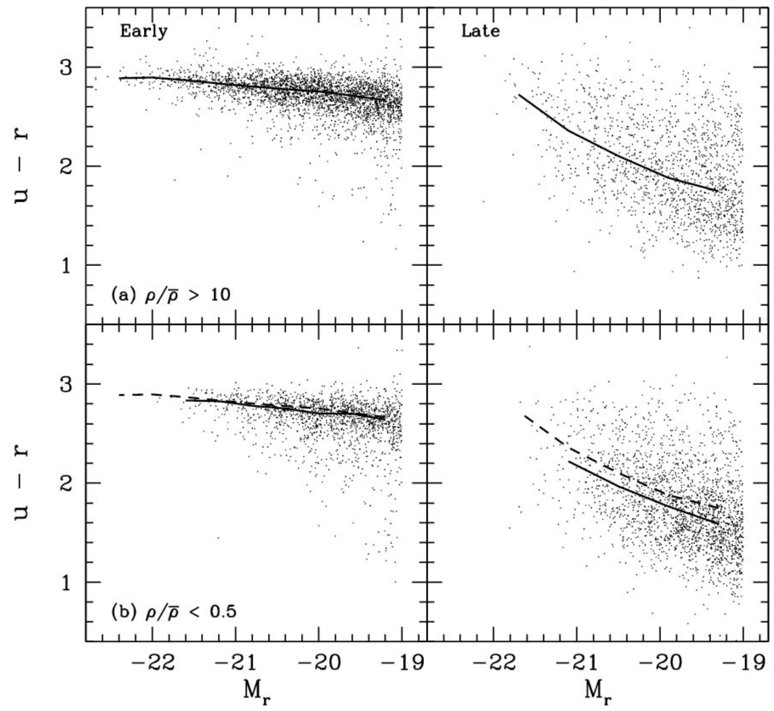
Phenomenon, real or virtual	*Nature*	*Nurture*	*Theory*
morphology-density relation		$\surd$	
→ near universal red-sequence color-magnitude relation	$\surd$		
the most luminous galaxies prefer the densest environments, consistent with their strong clustering	$\surd$		
the faintest galaxies & L_* galaxies are similarly distributed, and they avoid common voids	$\surd$	$\surd$	$\surd$
the ΛCDM Cosmic Web defines the voids			$\surd$
inhabitants of voids & low density regions:			
grand-design spirals	$\surd$		
close to normal ellipticals	$\surd$	$\surd$	
low surface density Lyα absorbers		$\surd$	
the warm-hot IGM			$\surd$
baryon-free dwarf DM halos			$\surd$

The luminosity-density relation

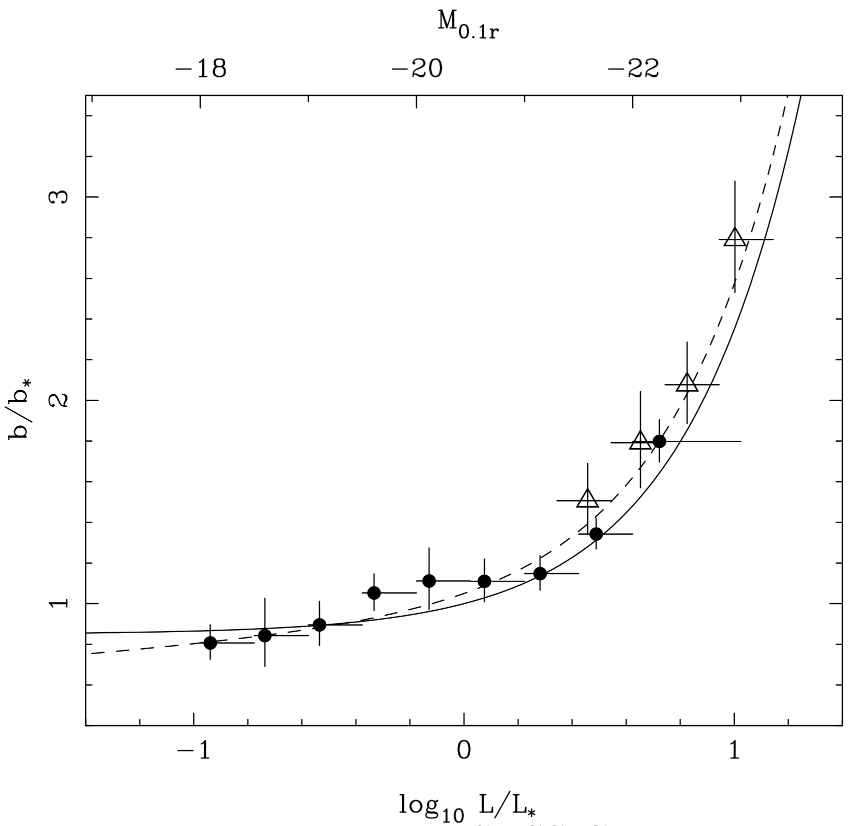
The luminosity-density relation

The most luminous galaxies, at $L \simeq 10$ times that of the Milky Way, favor the densest environments. Consistent with that, the spatial autocorrelation function is largest for the largest galaxies, and at $L \simeq 10L_*$ it is comparable to that of rich clusters of galaxies.

Cannibalism aids the density-luminosity relation, and argues for *Nurture*, but the conventional and sensibile wisdom is that the most luminous galaxies mark the largest primeval density fluctuations, an example of *Nurture* (in my terminology).



Park and the SDSS Collaboration



Percival and the SDSS Collaboration

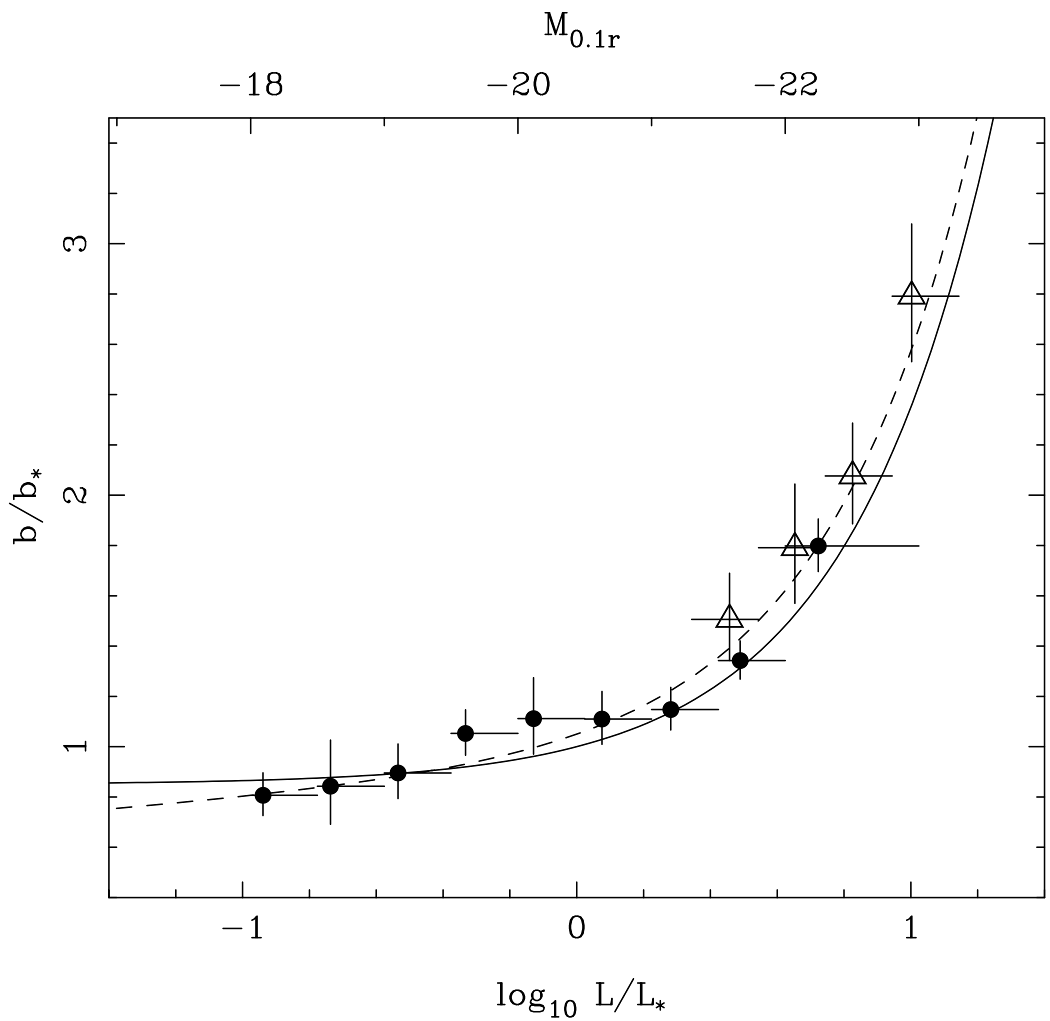
The relative distributions of L_* galaxies and the least luminous known galaxies

The faintest galaxies are distributed in pretty much in the same way as the L_* galaxies.

In this figure the "bias" varies as the square root of the two-point correlation function, I think here evaluated at 2.5 Mpc.

The strong clustering at $L = 10L_*$ is prominent and important.

Equally striking — and equally important — is the small variation of the clustering amplitude at $0.1L_* < L < 3L_*$. This second point is illustrated by the map of nearby galaxies discussed next.

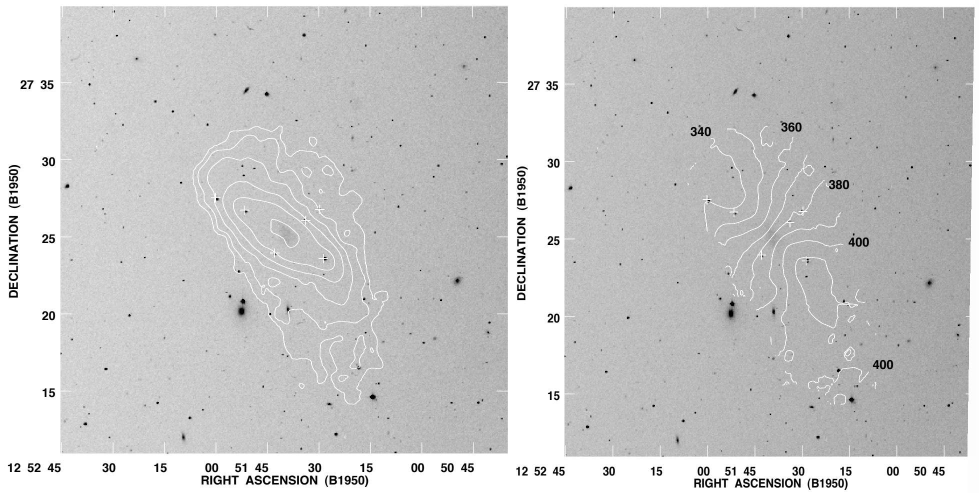


THE SHAPE OF THE SDSS DR5 GALAXY POWER SPECTRUM

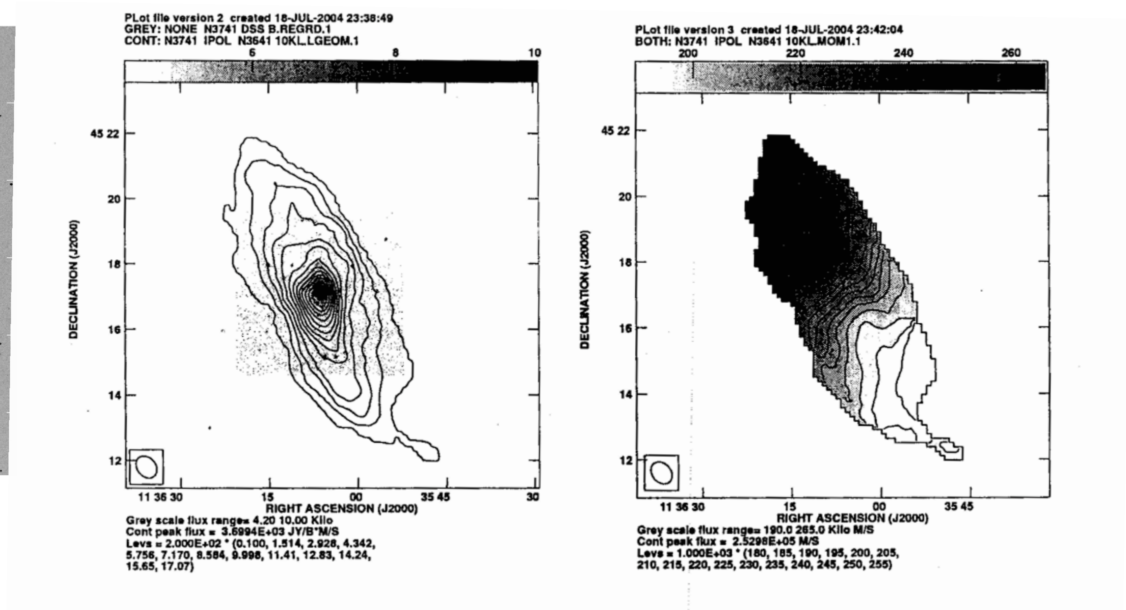
Will J. Percival[1], Robert C. Nichol[1], Daniel J. Eisenstein[2], Joshua A. Frieman[3,4], Masataka Fukugita[5], Jon Loveday[6], Adrian C. Pope[7,8], Donald P. Schneider[9], Alex S. Szalay[7], Max Tegmark[10], Michael S. Vogeley[11], David H. Weinberg[12], Idit Zehavi[13], Neta A. Bahcall[14], Jon Brinkmann[15], Andrew J. Connolly[16], Avery Meiksin[17],

Draft version October 5, 2006

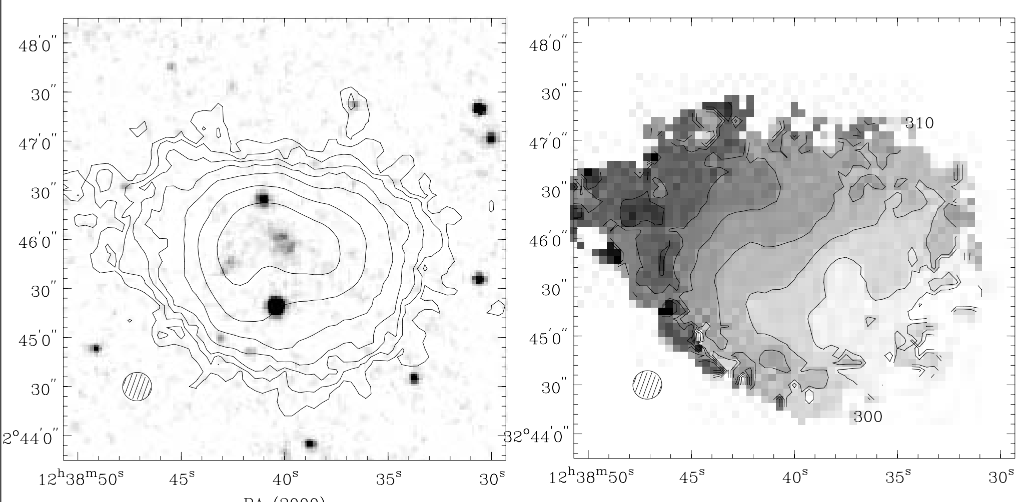
So where are these really faint galaxies relative to the normal galaxies?



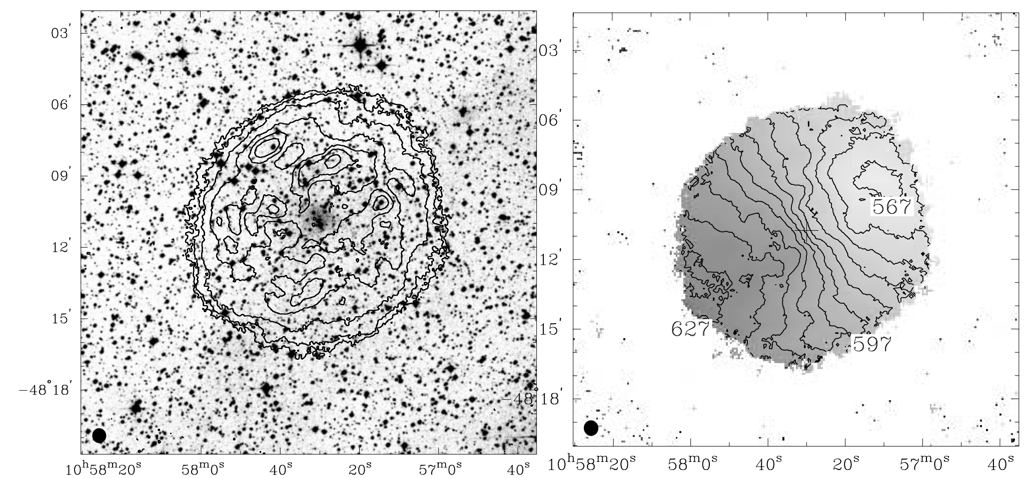
DDO 154 Carignan & Purton (1998)
$\mathcal{M}_{\rm stars} = 10^{7.6}\mathcal{M}_\odot$, $\mathcal{M}_{\rm HI} = 10^{8.4}\mathcal{M}_\odot$
$\mathcal{M}_{\rm dark} = 10^{9.5}\mathcal{M}_\odot$ within $r \sim 8$ kpc
escape velocity ~ 60 km s^{-1} from 8 kpc



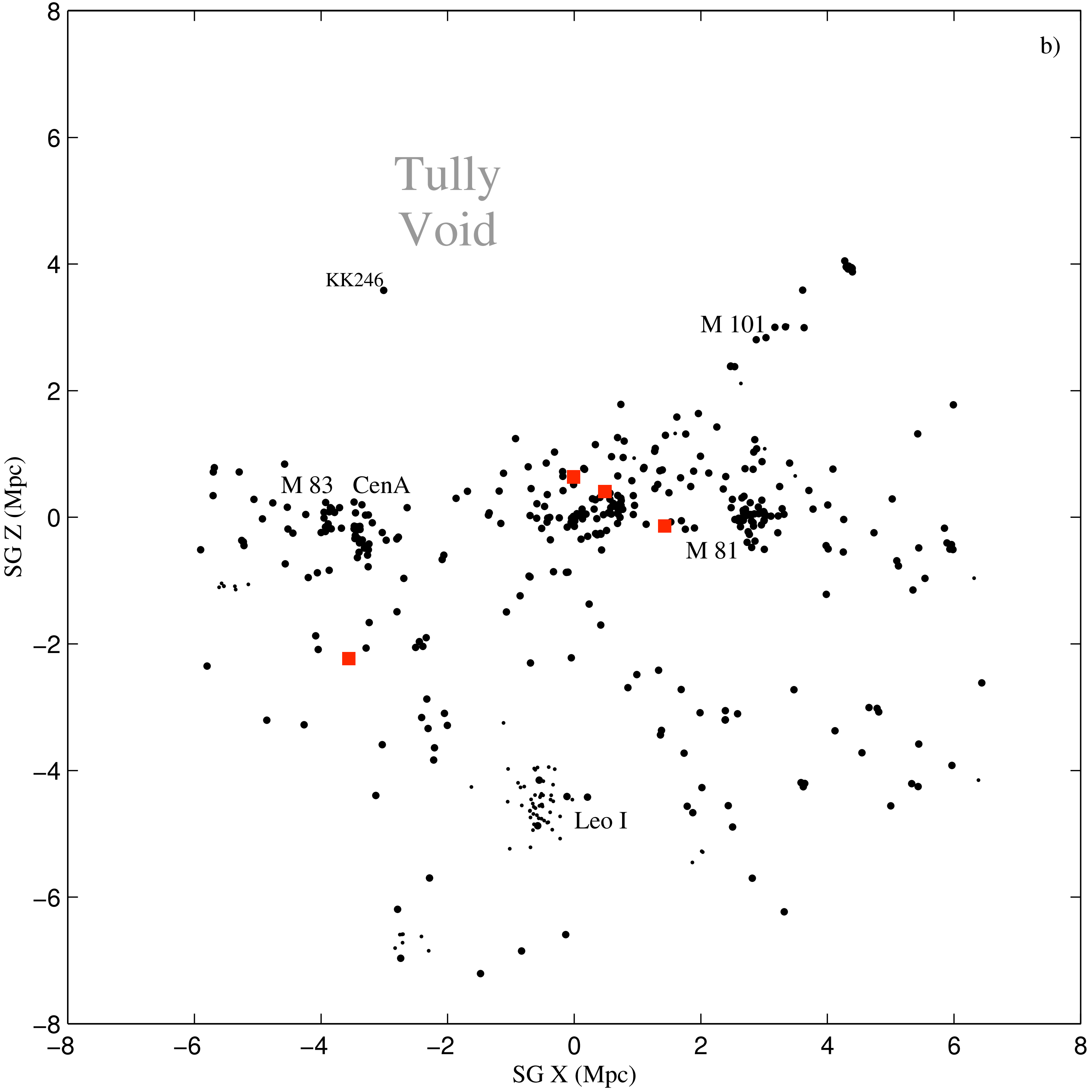
NGC 3741, Igor Karachentsev *et al.*, GMRT



UGCA 292, Young *et al.* ApJ 592, 111 (2003)
$\mathcal{M}_{\rm HI} = 10^{7.7}\mathcal{M}_\odot$, $\mathcal{M}_{\rm HI}/\mathcal{L}_{\rm B} \sim 7\mathcal{M}_\odot/\mathcal{L}_\odot$



ESO 215-G?009, Warren *et al.* AJ, 128, 1152 (2004)
$\mathcal{M}_{\rm HI}/\mathcal{L}_{\rm b} = 20\mathcal{M}_\odot/\mathcal{L}_\odot$, $\mathcal{M}_{\rm HI} = 10^{8.7}\mathcal{M}_\odot$
$\mathcal{M}_{\rm dark} = 10^{9.6}\mathcal{M}_\odot$ within $r \sim 7$ kpc, $v_{\rm escape} \gtrsim 70$ km s^{-1}



The Karachentsev *et al.* (2004) *Catalog of Neighboring Galaxies.* The larger circles show the galaxies at $v_{\rm LG} < 550$ km s^{-1}. The smaller circles show concentrations of galaxies just outside this sphere.

The red squares, left to right are the gas dwarfs
ESO 215-G?009
DDO 154
UGCA 292
NGC 3741

The gas dwarfs seem to avoid dense regions, as seems reasonable because one imagines they are readily tidally disrupted. Less easily explained — to me — is their avoidance of the local void.

“Our choice of a working definition for voids is simple: they are empty (Fairall et al. 1991). As the Local Void so clearly demonstrates, there is no population of low luminosity galaxies filling the voids.”

A.P. Fairall, D. Turner, M.L. Pretorius, M. Wiehahn, V. McBride, G. de Vaux and P.A. Woudt

Department of Astronomy, University of Cape Town, Private Bag, Rondebosch 7700, South Africa

In the ΛCDM cosmology voids contain large numbers of DM halos with masses $< 10^{10} M_\odot$.

I showed examples of galaxies that appear to have halo masses less than about $10^{10} M_\odot$. They are observed in the optical *and* at 21 cm.

No such objects are observed in nearby voids.

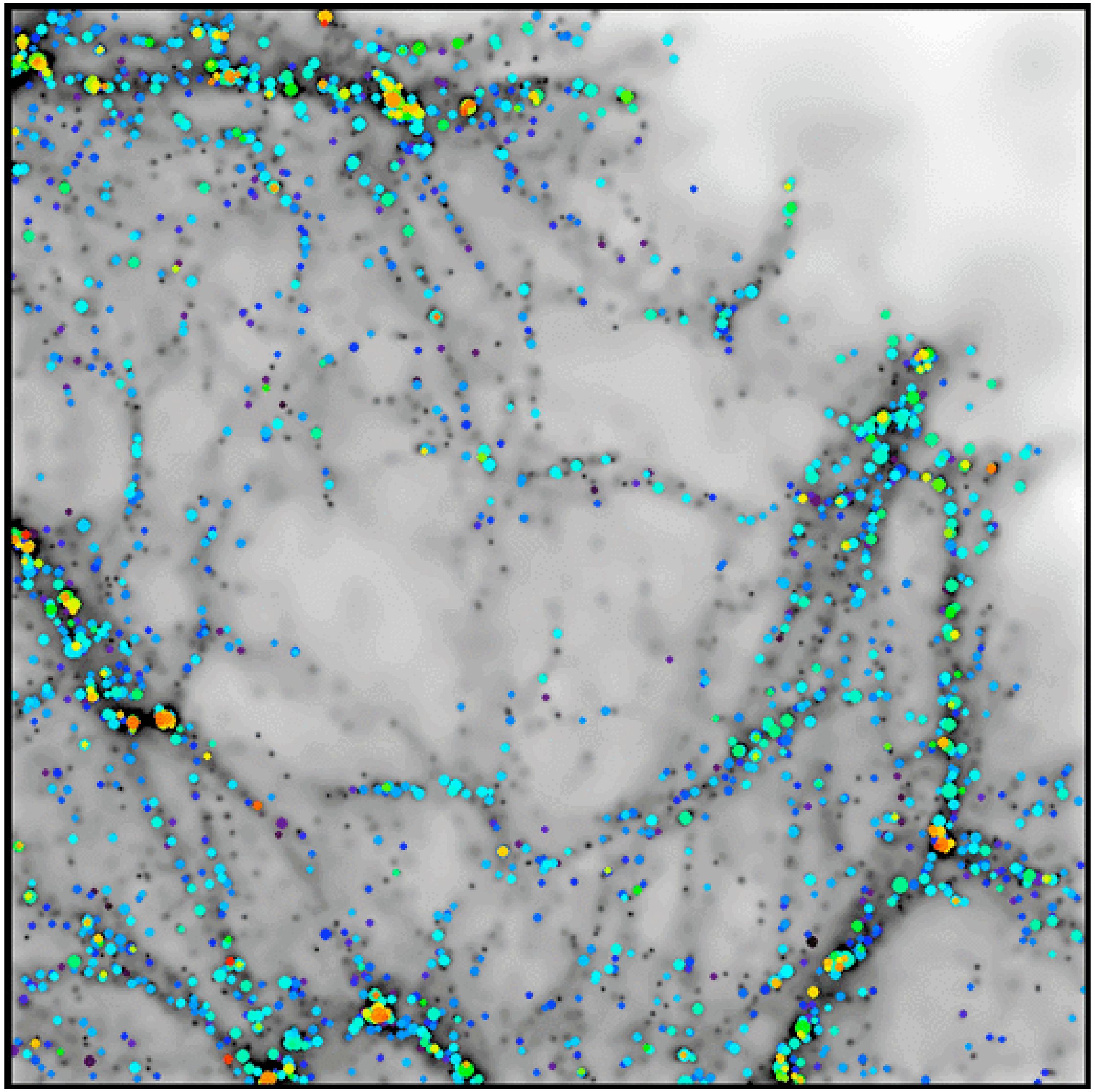
The conventional interpretation is that void halos are not like known dwarfs: almost all have to have much lower ratios of starlight and HI to total mass.

This is possible, to be sure. But it is a vivid example of the power of a belief system.

Phenomenon, real or virtual	*Nature*	*Nurture*	*Theory*
morphology-density relation		$\surd$	
near universal red-sequence color-magnitude relation	$\surd$		
the most luminous galaxies prefer the densest environments, consistent with their strong clustering	$\surd$		
the faintest galaxies & L_* galaxies are similarly distributed, and they avoid common voids	$\surd$	$\surd$	$\surd$
the ΛCDM Cosmic Web defines the voids			$\surd$
inhabitants of voids & low density regions:			
grand-design spirals	$\surd$		
close to normal ellipticals	$\surd$	$\surd$	
low surface density Lyα absorbers		$\surd$	
the warm-hot IGM			$\surd$
baryon-free dwarf DM halos			$\surd$

The ΛCDM Cosmic Web

The Cosmic Web

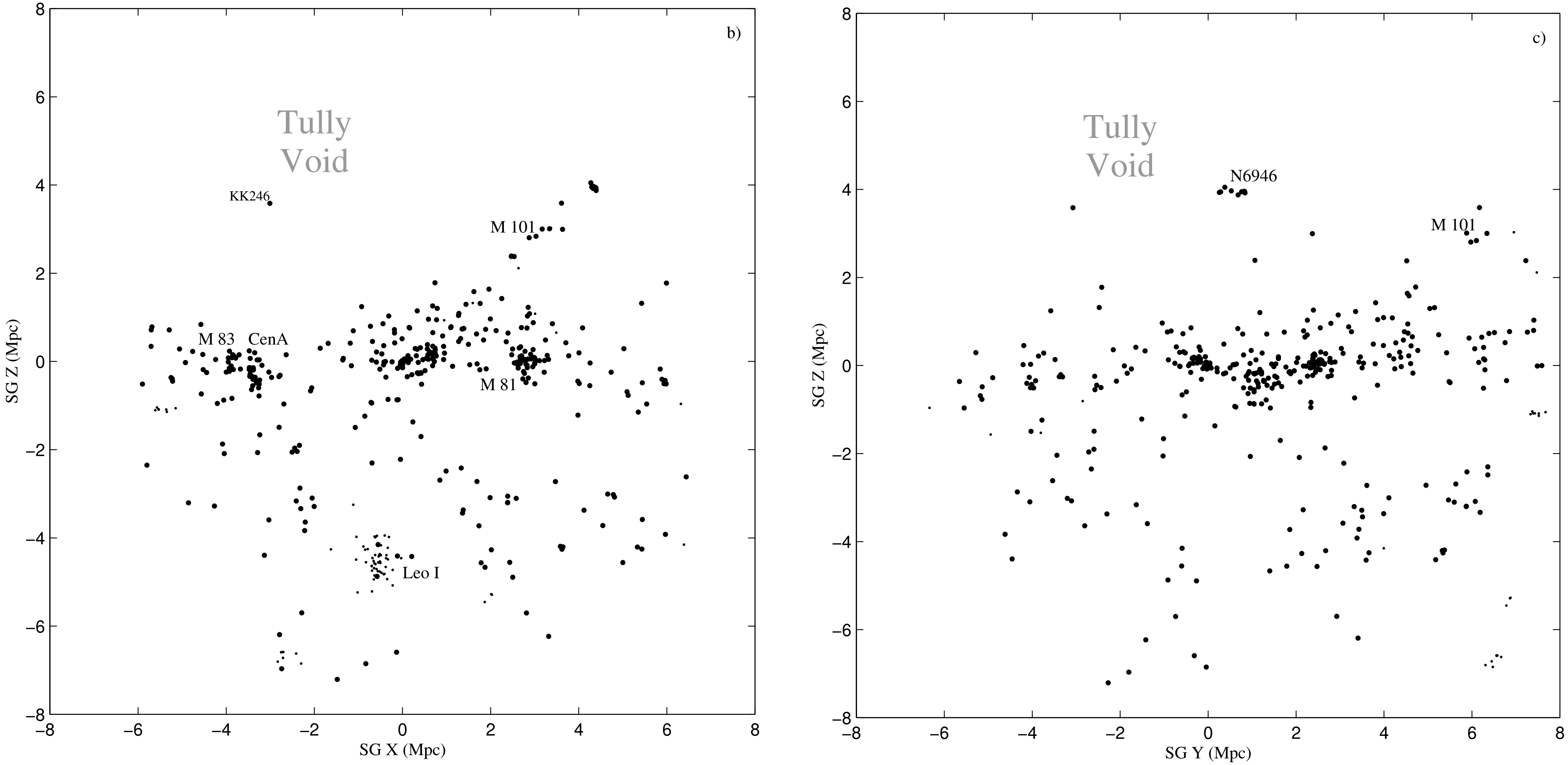


$50 \times 50 \times 15 h^{-1}$ Mpc

H. Mathis & S. D. M. White, MN 337, 1193, 2002

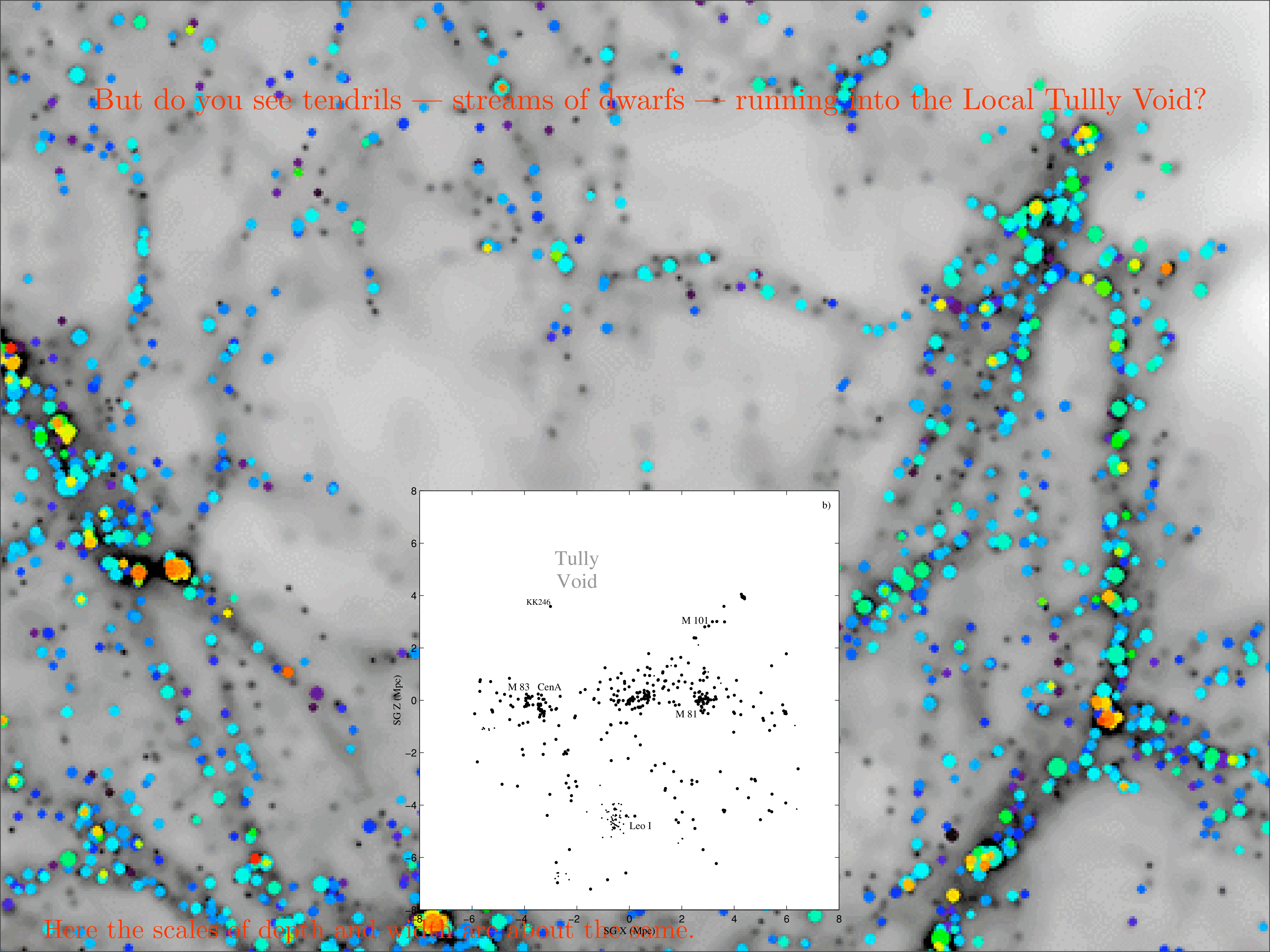
The Cosmic WEB paradigm is well motivated by the ΛCDM cosmology, which has passed demanding tests.

And the Web has proved to be a powerful organizing concept: the galaxy distribution does resemble a sponge.

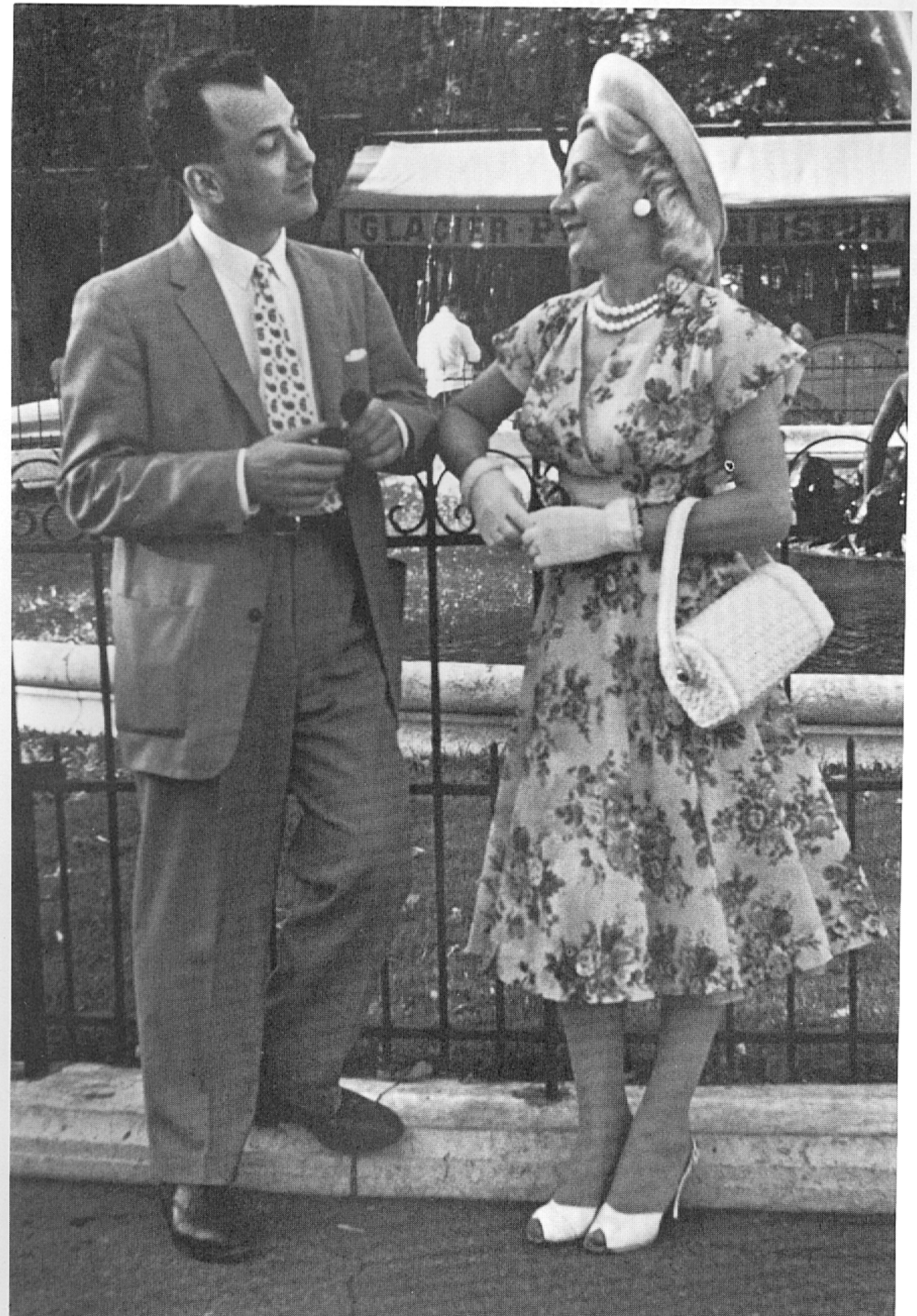


Catalog of Neighboring Galaxies Karachentsev *et al.* 2004

But do you see tendrils — streams of dwarfs — running into the Local Tullly Void?

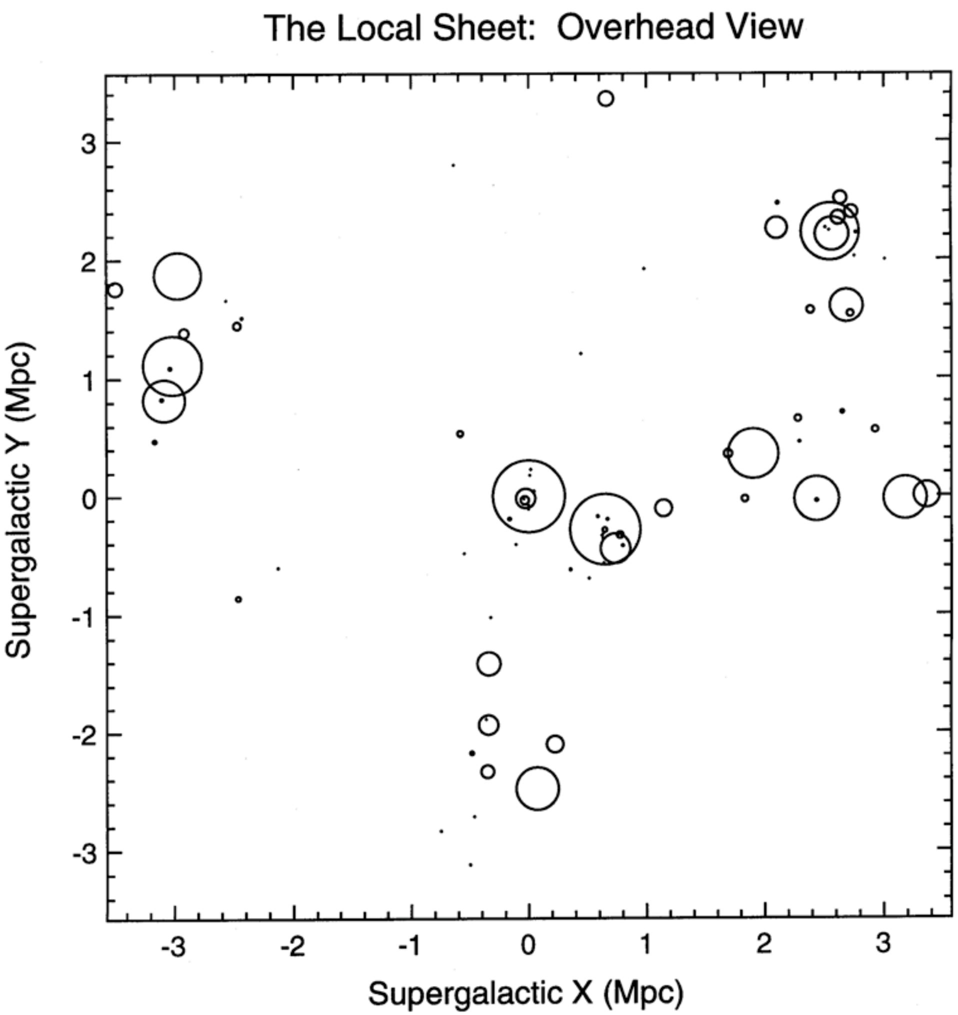


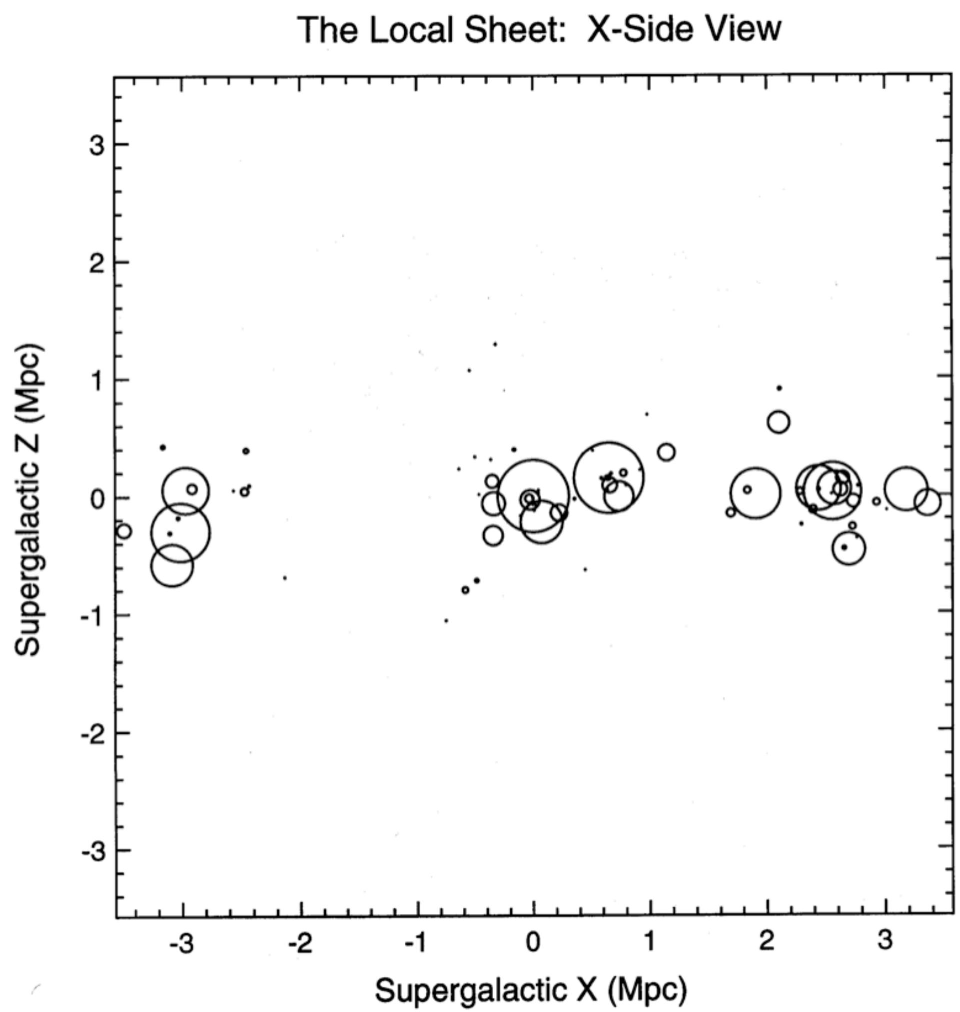
Here the scales of depth and width are about the same.



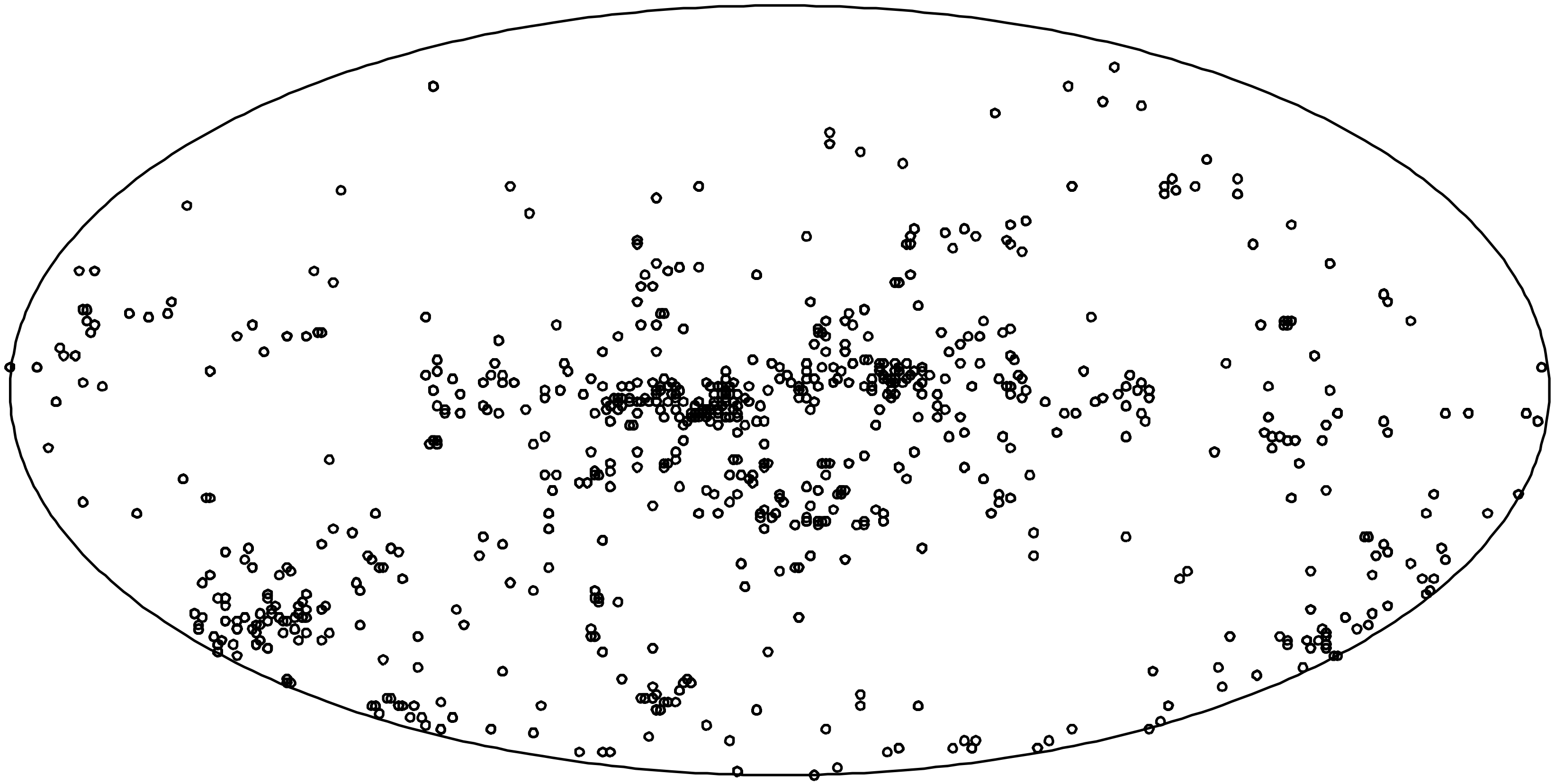
Gérard and Antoinette de Vaucouleurs in Paris, 1962.

These people found a web of another sort.





Marshall L. McCall, York University
Preliminary Map of the Local Sheet
of Nearby Galaxies, 1999



The de Vaucouleurs Local Supercluster

IRAS PSCz galaxies, $cz_{\mathrm{LG}} < 1500$ km s^{-1}

Will Saunders *et al.* (2000)

The Large-Scale Supercluster

P. A. Shaver, Australian J. Phys. **44**, 759 (1991)

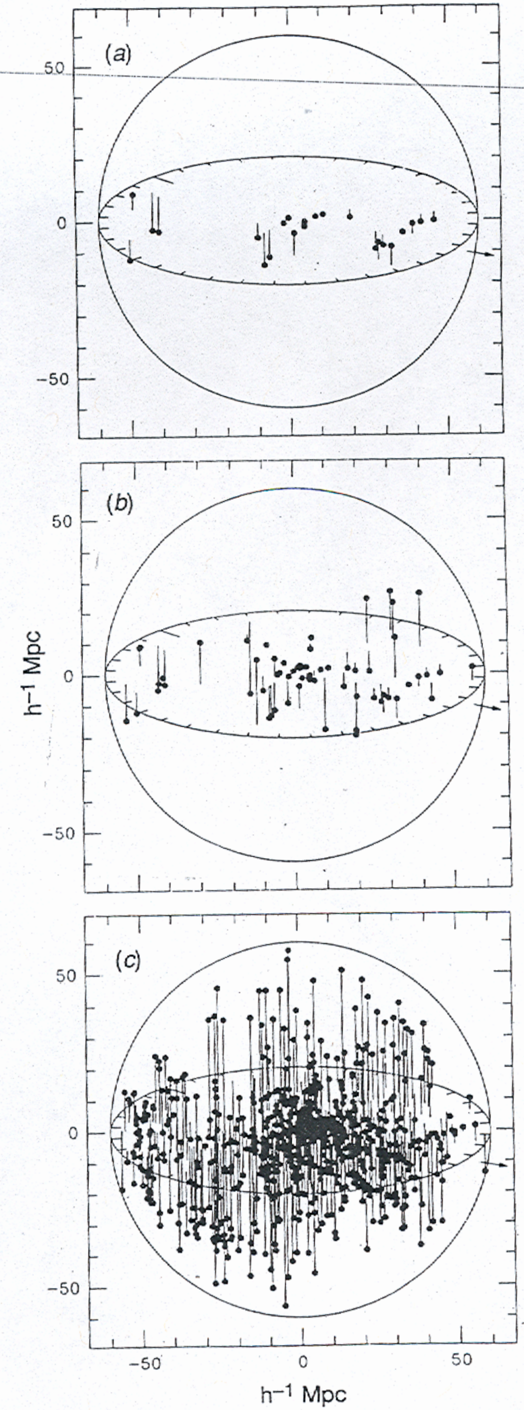
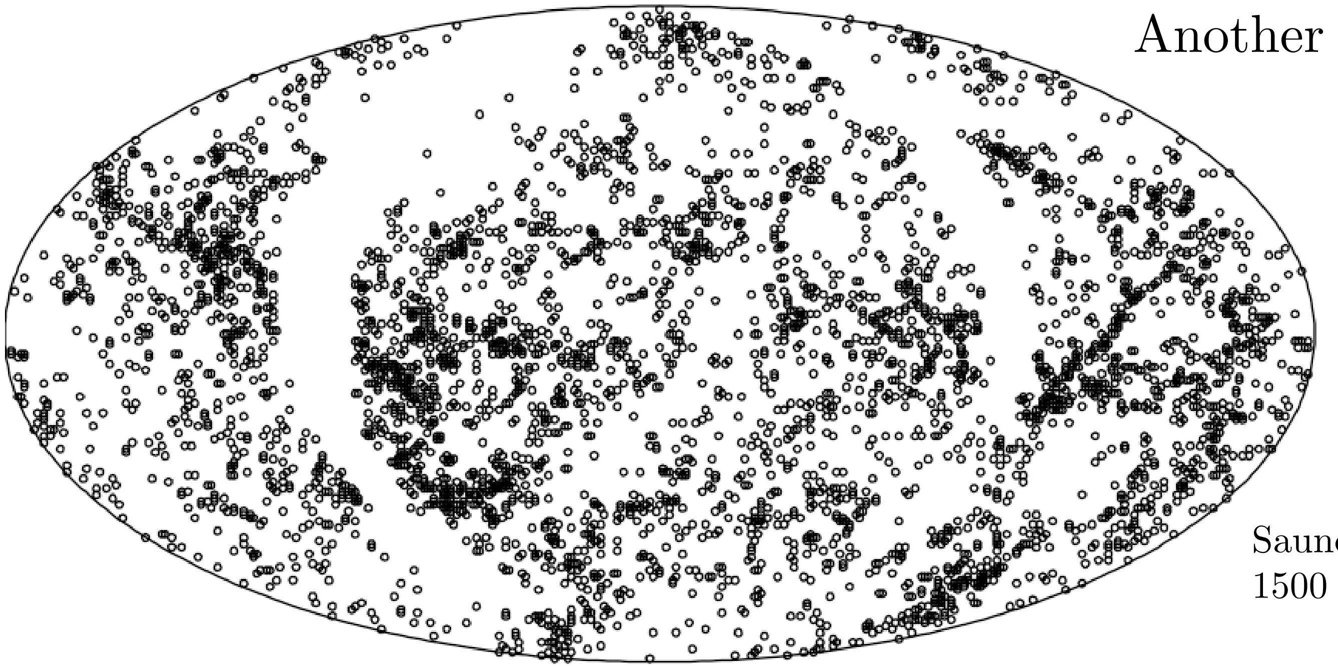
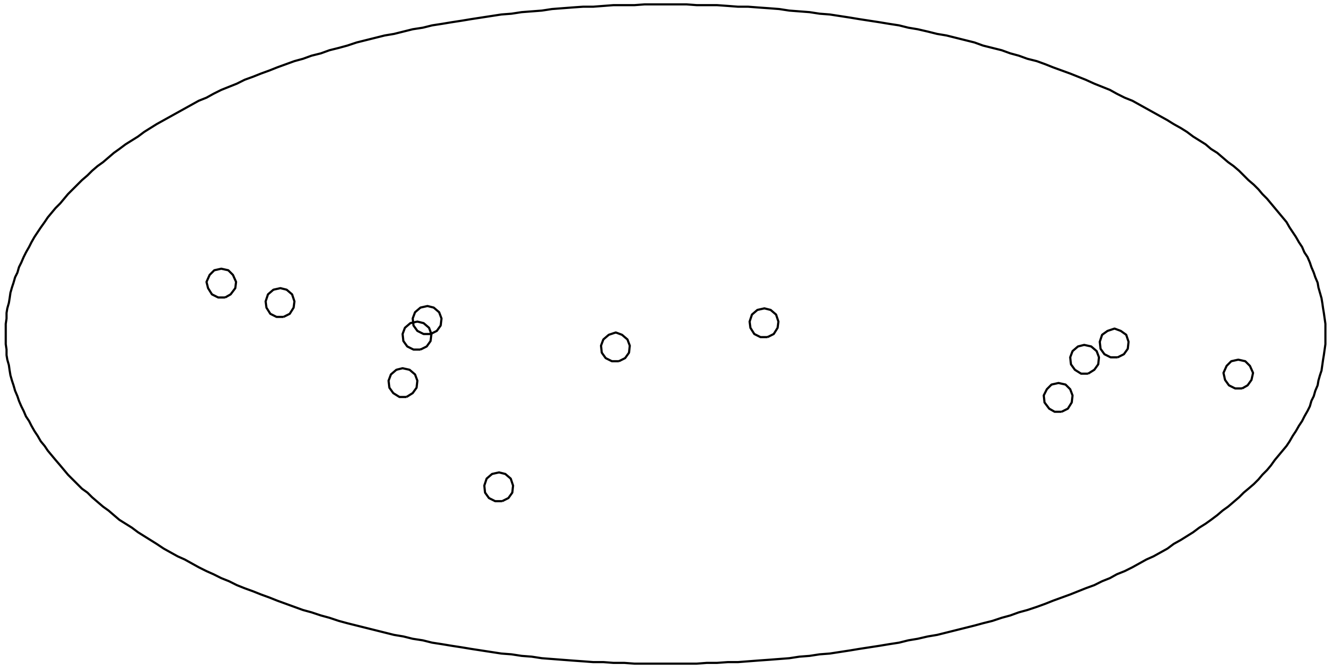


Fig. 5. Space distributions of the complete radio and optical galaxy samples out to $z = 0 \cdot 02$: (*a*) radio galaxies with $S_{408} > 4$ Jy, (*b*) radio galaxies with $S_{408} > 1$ Jy, and (*c*) the optical galaxies. Orientation and symbols as in Fig. 4*a*. The arrows show the 'Great Attractor'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

Another look at the Shaver effect:



Saunders *et al.* (2000) PSCz galaxies at $1500 < v_{\rm LG} < 6000$ km s^{-1}



Abell-Corwin-Olwin clusters with Struble-Rood (1999) redshifts $1000 < cz_{\rm lg} < 6000$ km s^{-1}

Galaxies at distances $\lesssim 3$ Mpc are aligned with the de Vaucouleurs Local Supercluster at distance ~ 20 Mpc.

At distances $20 \lesssim r \lesssim 100$ Mpc clusters and AGNs are aligned with the Local Supercluster, but the general galaxy population shows little evidence of it.

If these observations are not just curious accidents, but rather physically significant, then we may ask

- how did this Web of AGNs avoid entangling the general galaxy population?
- how does this Web of AGNs relate to the Cosmic Web of the ΛCDM cosmology?

The observers' Cosmic Web is operational and well established.

The theorists' ΛCDM Cosmic Web is an established part of the community belief system, with good reason. But I have not yet seen the evidence that would promote it to an established part of physical reality.

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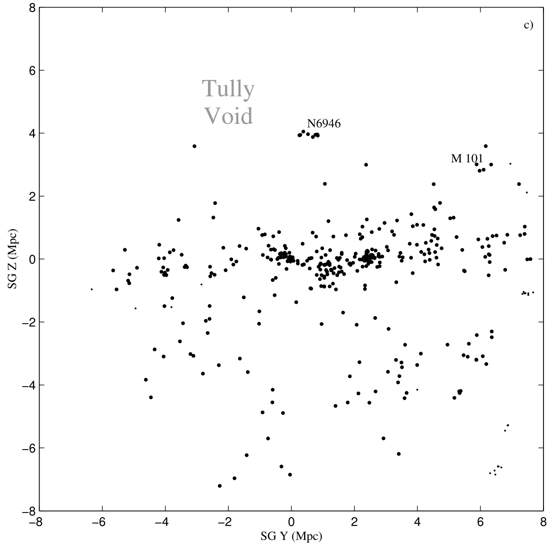
inhabitants of voids & low density regions:			
grand-design spirals	$\surd$		
close to normal ellipticals	$\surd$	$\surd$	
low surface density Lyα absorbers		$\surd$	
the warm-hot IGM			$\surd$
baryon-free dwarf DM halos			$\surd$

Inhabitants of the Voids

Void inhabitants: a grand design spiral NGC 6946

Adam Block/NOAO/AURA/NSF



Catalog of Neighboring Galaxies
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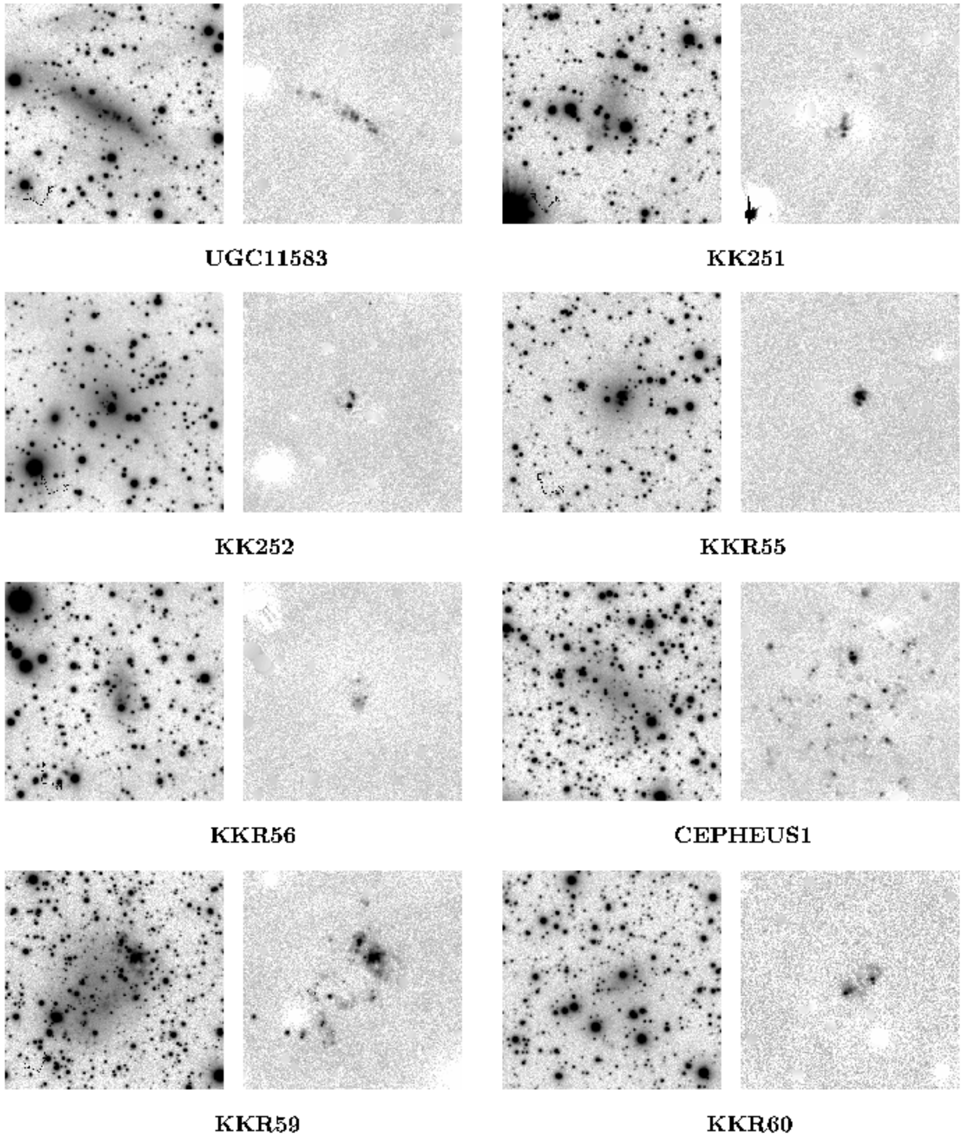


Hα and continuum-free images of the eight dwarf irregular companions of NGC 6946 (Karachentsev et al. 2005)

Void inhabitants: a grand design spiral NGC 6946

Might the low density around NGC 6946 have suppressed growth of an extended DM halo?

Carignan *et al.* (1990) find a close to flat 21-cm rotation curve with

$$v_c = 160 \text{ km s}^{-1} \text{ at } R < 20 \text{ kpc}.$$

The Hα curve extends to about the same radius.

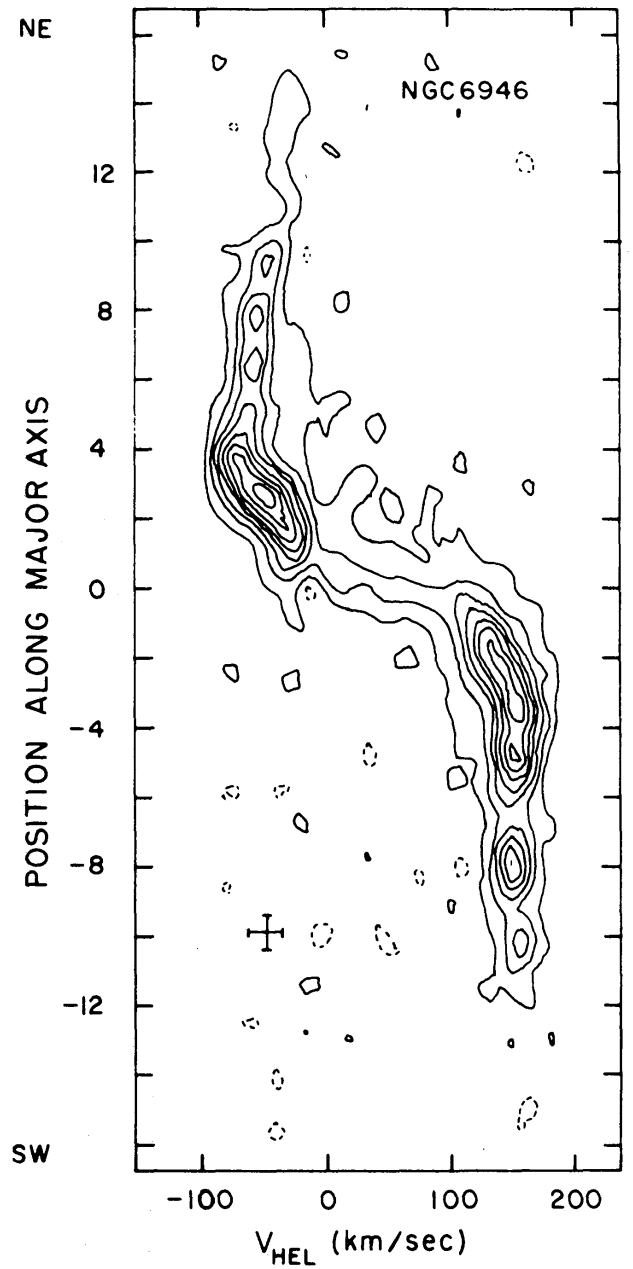
At the luminosity of NGC 6946, $L_B = 3\times10^{10}L_\odot$, I think its circular velocity is below the template.

The rms line-of-sight velocity dispersion of the eight dwarf satellites relative to NGC 6946 is $\sigma =$ 70 km s^{-1}, which indicates circular velocity

$$v_c \simeq 100 \text{ km s}^{-1} \text{ at } R \simeq 100 \text{ kpc},$$

which again seems low.

What is the best probe for more clues to the mass structure: deep 21-cm or Hα? imaging searches for more satellites? weak lensing?



Void inhabitants: a grand design spiral NGC 6946

What produced the angular momentum of the isolated spiral NGC 6946? Under the tidal torque picture, ideas are

- the dwarf companions? but they seem very small;
- massive dark companions? but how could a massive neighbor have remained dark?
- massive protogalaxies that were nearby at high redshift, before the void opened up? but in the standard model voids don't open up so much as fail to produce visible galaxies.

Again, more clues to dynamics at larger radii could be very interesting.

Void inhabitants: early-type galaxies

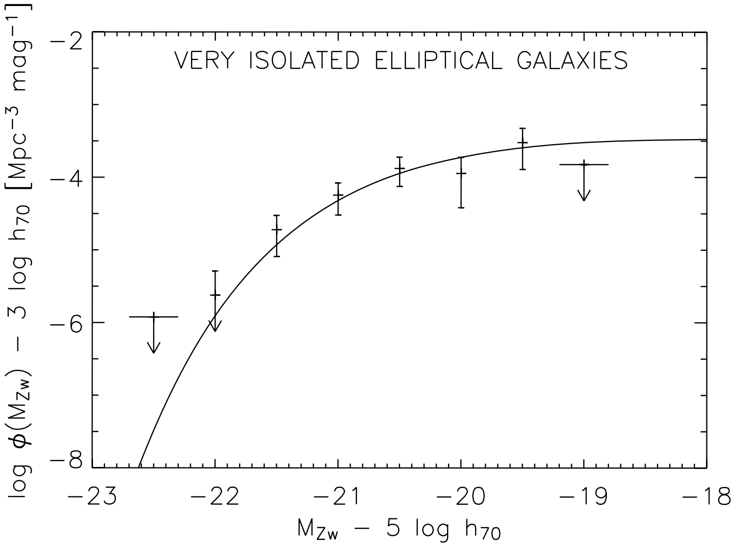


FIG. 1.—Luminosity function of the elliptical galaxy sample (26 members), vertically scaled to match the Marzke et al. (1994b) normalization. The solid line is the Schechter function fit to the Marzke et al. (1994b) data. The magnitude bins are 0.5 mag wide and the vertical error bars indicate $\sqrt{N}$ statistics for each bin.

VERY ISOLATED EARLY-TYPE GALAXIES

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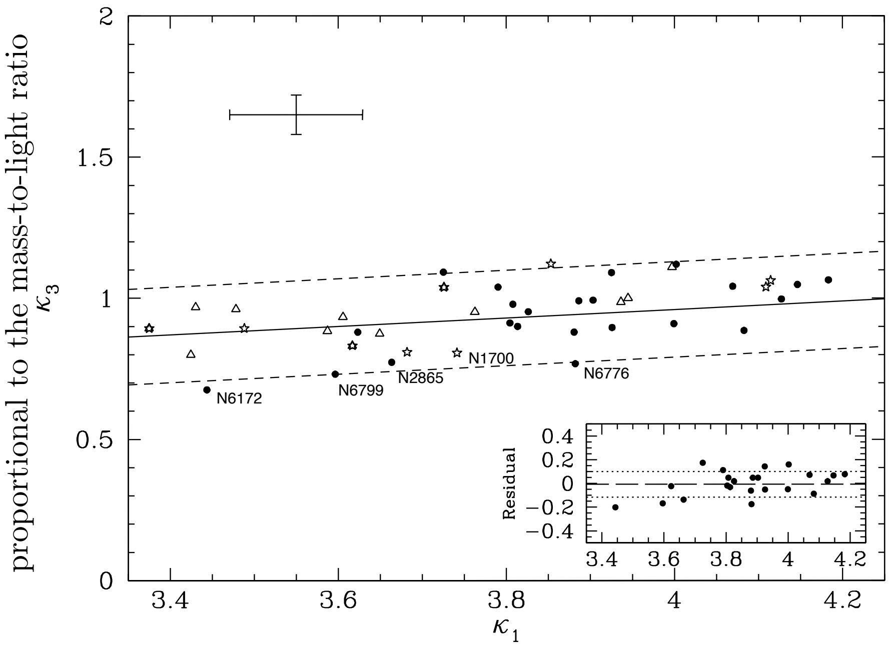

filled circles: Reda *et al.* isolated early types
triangles: Hickson compact group members
stars: loose group members
solid line: Virgo cluster galaxy FP

The fundamental plane of isolated early-type galaxies

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Void inhabitants: early-type galaxies

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Evidence for evolving spheroidals in the *Hubble Deep Fields* North and South

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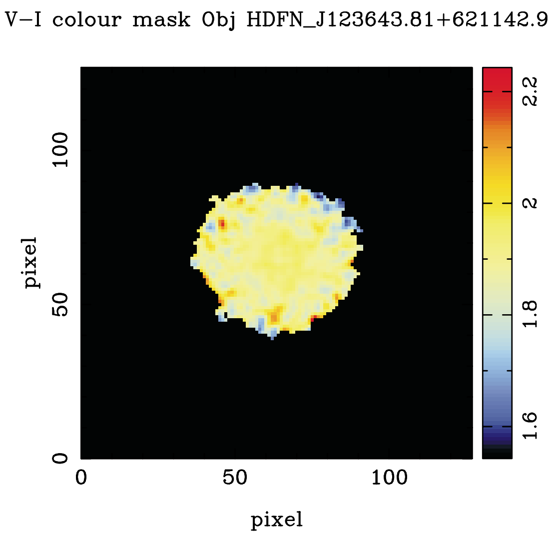
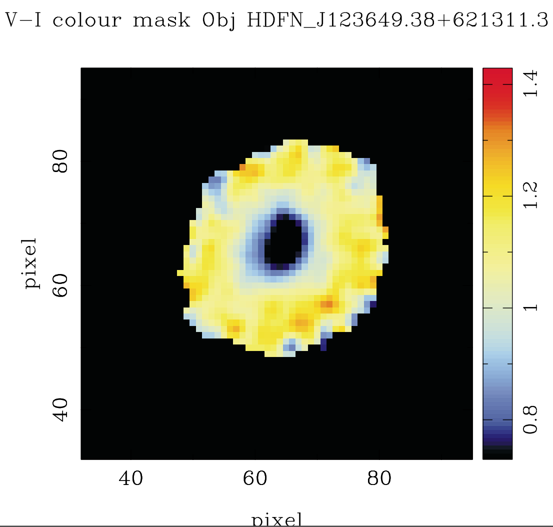
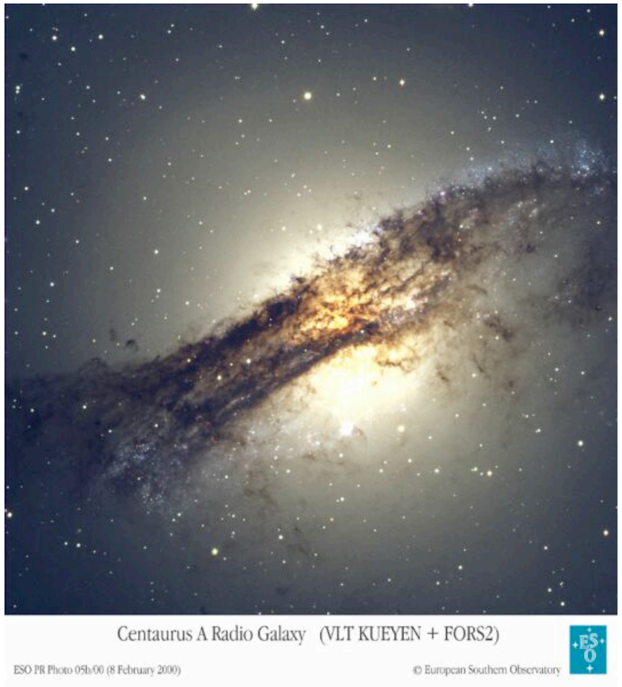




Some ellipticals outside rich clusters have blue cores. I gather that it's generally agreed that this is largely due to young stars in the core. The star formation surely is fueled in part by accretion. But I gather the young stars have high heavy element abundances, which I suppose indicates recycling of gas shed by stars in the galaxy.



Void inhabitants: early-type galaxies

These elliptical galaxies likely aren't as isolated as NGC 6946, but they do sample lower density regions.

They show effects of environment — some Reda *et al.* early-type galaxies are over-luminous for their masses, and some ellipticals have blue cores — but am I wrong to be impressed by the modest extent of these effects?

Phenomenon, real or virtual	*Nature*	*Nurture*	*Theory*
morphology-density relation		$\surd$	
near universal red-sequence color-magnitude relation	$\surd$		
the most luminous galaxies prefer the densest environments, consistent with their strong clustering	$\surd$		
the faintest galaxies & L_* galaxies are similarly distributed, and they avoid common voids	$\surd$	$\surd$	$\surd$
the ΛCDM Cosmic Web defines the voids			$\surd$
inhabitants of voids & low density regions:			
→ grand-design spirals	$\surd$		
→ close to normal ellipticals	$\surd$	$\surd$	
low surface density Lyα absorbers		$\surd$	
the warm-hot IGM			$\surd$
baryon-free dwarf DM halos			$\surd$

The void inhabitants: Lyα absorbers, but not detectable 21-cm emitters

I understand that 21-cm sources not arguably associated with a galaxy or a system of galaxies are exceedingly rare.

McLin, Stocke *et al.* (2002) show there are void Lyα absorbers, at

$$10^{12.5} < N_{\rm HI} < 10^{14.5} \mathrm{cm}^{-2},$$

that show no conspicuous association with galaxies.

So how did the process of formation of these absorbers avoid producing appreciable numbers of clouds at the higher surface densities and areas that would be detectable as isolated 21-cm sources?

And how are these absorbers related to the Lyα forest at $z \sim 3$, which (I think I remember) shows strikingly few voids?

Void Inhabitants: the warm-hot intergalactic medium

Plasma at $T = 10^{6\pm1}$ K is detected in and around groups of galaxies.

I suppose the Cen & Ostriker (1999) shock-heating of the IGM tends not to happen in voids, but that plasma heated elsewhere could flow into voids, depending on how strongly the plasma is gravitationally bound to the DM.

Might this flow produce void DM-free Lyα absorbers? Might that fit the observations?

Void Inhabitants: DM Halos

A standard mass density in dwarf DM halos in voids, $\rho_{\rm void} \simeq 0.1\bar{\rho}$, suggests voids have expanded by about twice the global factor.

The void dwarf DM halo population is pretty well established in the community belief system. Is it real?

Or might the void expansion factor have been significantly larger than that? Might the voids be as empty as they look?

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Astronomy & Astrophysics

Disturbed isolated galaxies: indicators of a dark galaxy population? *(Research Note)*

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ABSTRACT

We report the results of our search for disturbed (interacting) objects among very isolated galaxies. The inspections of 1050 northern isolated galaxies from KIG and 500 nearby, very isolated galaxies situated in the Local Supercluster yielded five and four strongly disturbed galaxies, respectively. We suggest that the existence of "dark" galaxies explains the observed signs of interaction. This assumption leads to a cosmic abundance of dark galaxies (with the typical masses for luminous galaxies) that is less than ~1/20 the population of visible galaxies.

Key words. galaxies: interactions

Phenomenon, real or virtual	*Nature*	*Nurture*	*Theory*
morphology-density relation		$\surd$	
near universal red-sequence color-magnitude relation	$\surd$		
the most luminous galaxies prefer the densest environments, consistent with their strong clustering	$\surd$		
the faintest galaxies & L_* galaxies are similarly distributed, and they avoid common voids	$\surd$	$\surd$	$\surd$
the ΛCDM Cosmic Web defines the voids			$\surd$
inhabitants of voids & low density regions:			
grand-design spirals	$\surd$		
close to normal ellipticals	$\surd$	$\surd$	
low surface density Lyα absorbers		$\surd$	
the warm-hot IGM			$\surd$
baryon-free dwarf DM halos			$\surd$

Summary

1. Some correlations of galaxy properties with environment seem to be largely inheritance from the cosmological initial conditions, as in the density-maximum luminosity relation. (Cannibalism surely enhanced this effect, but if dominant how are we to understand the near universality of the C-M red sequence?)

2. Clear evidence of physical interactions among galaxies and their environments includes

a. anemic spirals, tidal tails in spirals, red streams in ellipticals;

b. hot plasma in clusters, the WHIGM, and maybe Lyα absorbers in voids.

3. The effects of physical interactions on galaxies seem strikingly modest, as in the near universal red edge of the color-magnitude plot, and not obviously what one might have expected in the ΛCDM cosmology.

4. Maybe an even more pressing challenge is the apparent disconnect between the theory and observation of dwarf void galaxies.