A.D.I.O.N

Association pour le
Développement International de l'Observatoire de Nice

Association reconnue d'utilité publique par décret du 15 septembre 1966

The State of the Cosmological Tests

P. J. E. Peebles, Nice, 2004

Many decades of advances in cosmology have led to the present demanding network of tests.

The results are in strikingly good agreement with the Friedmann-Lemaître ΛCDM cosmology.

But there remains considerable room for improvement, perhaps most notably in the dark sector. I will offer an example.

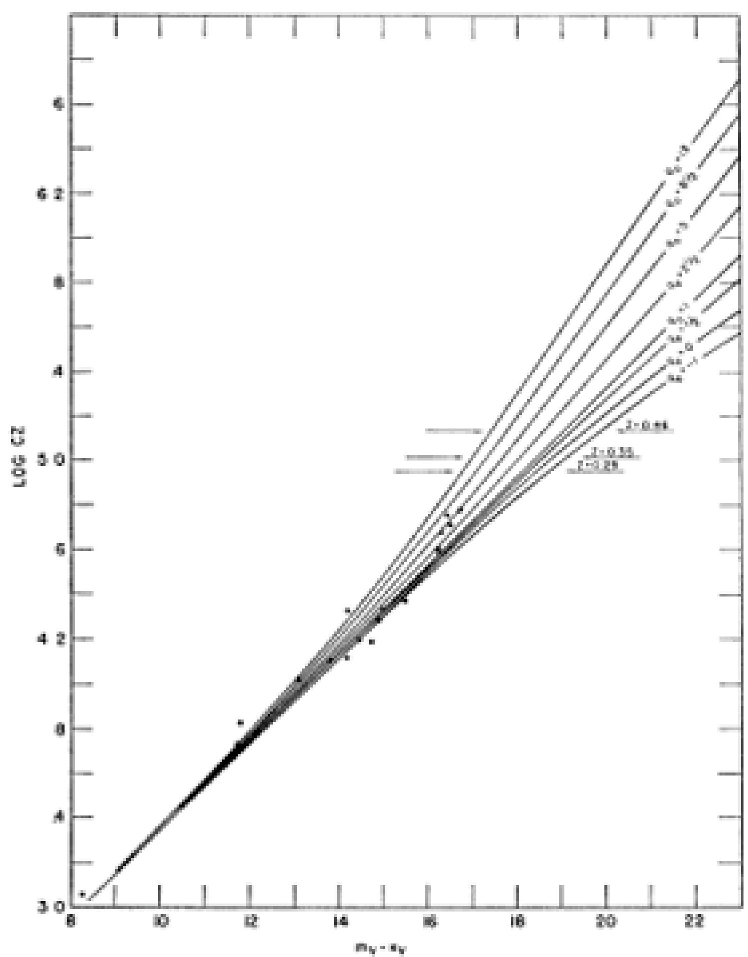
THE ASTROPHYSICAL JOURNAL

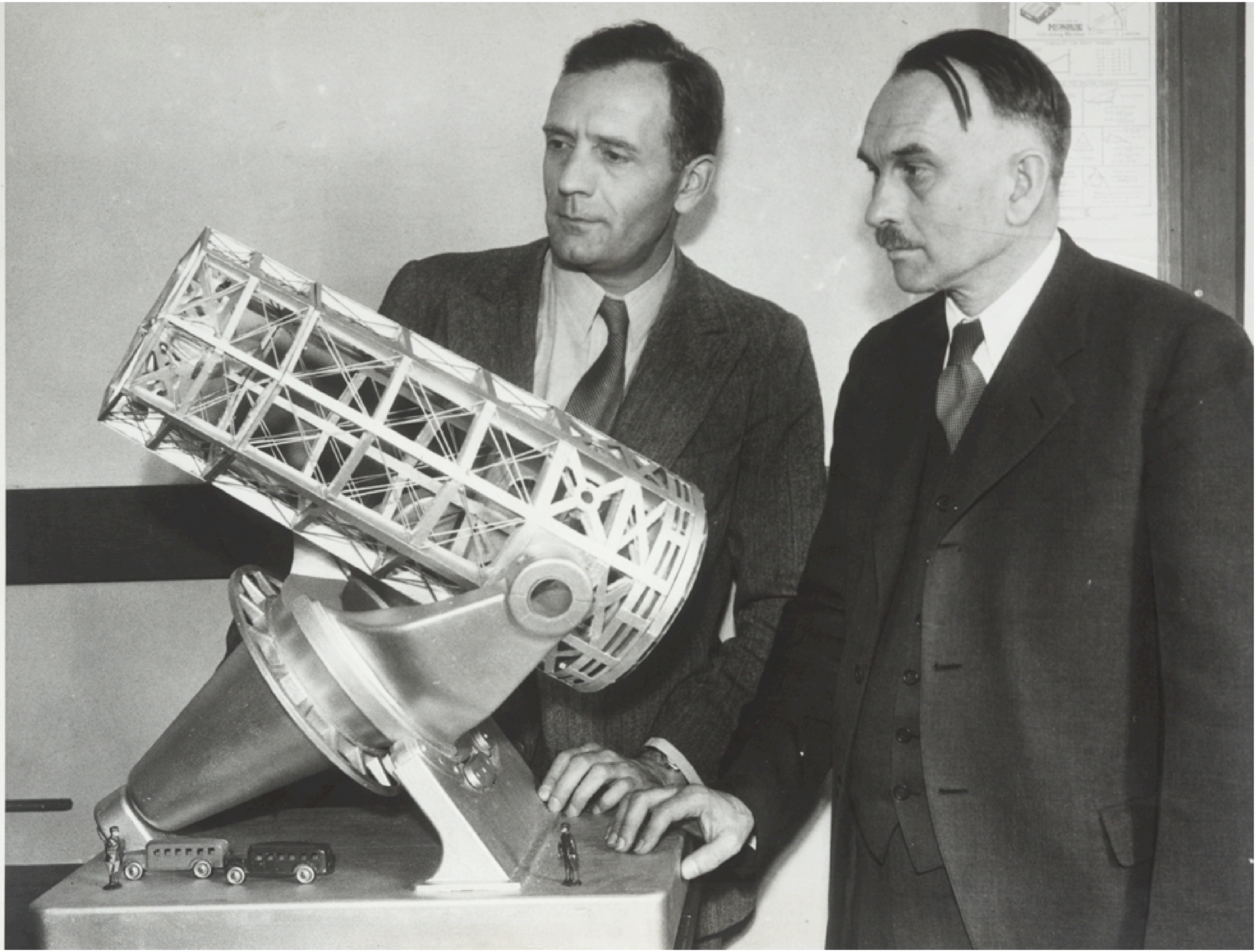
AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 133 MARCH 1961 NUMBER 2

THE ABILITY OF THE 200-INCH TELESCOPE TO DISCRIMINATE BETWEEN SELECTED WORLD MODELS

ALLAN SANDAGE
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology





Edwin Hubble and R. C. Tolman with a model for the Palomar 200 inch telescope, 1931

General Expansion or Tired Light?

Hubble and Tolman discussed a test: in a static tired light cosmology the relation between the surface brightness and redshift of a class of identical galaxies is

$$i \propto (1+z)^{-1},$$

while the relativistic prediction is

$$i \propto (1+z)^{-4}.$$

Tolman showed that homogeneous isotropic expansion preserves the blackbody spectrum of a sea of thermal radiation. This is equivalent to the Hubble-Tolman relation generalized to the spectral surface brightness.

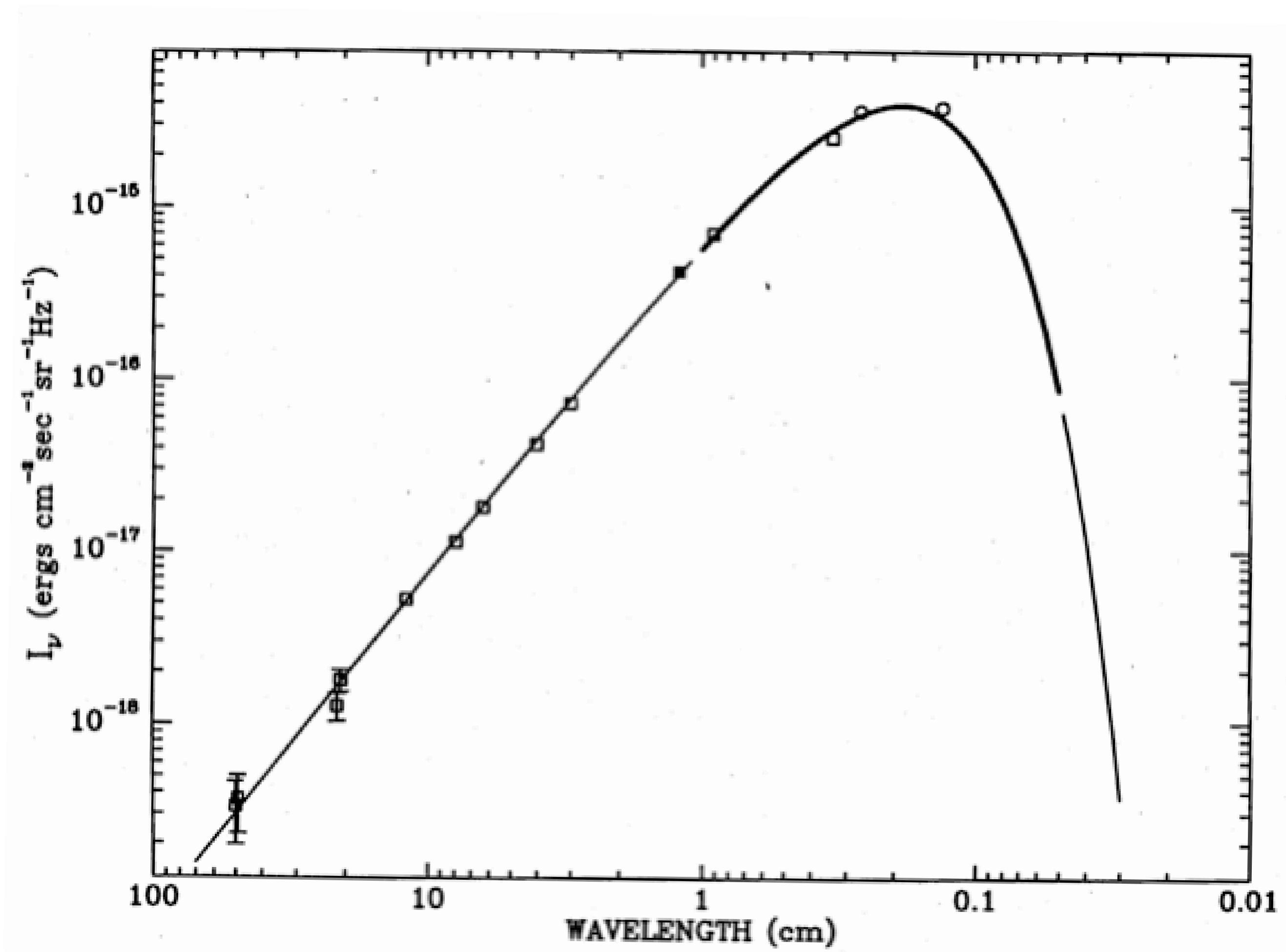
A PRELIMINARY MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE *COSMIC BACKGROUND EXPLORER* (*COBE*)[1] SATELLITE

J. C. MATHER,[2] E. S. CHENG,[2] R. E. EPLEE, JR.,[3] R. B. ISAACMAN,[3] S. S. MEYER,[4] R. A. SHAFER,[2] R. WEISS,[4]
E. L. WRIGHT,[5] C. L. BENNETT, N. W. BOGGESS,[2] E. DWEK,[2] S. GULKIS,[6] M. G. HAUSER,[2] M. JANSSEN,[6]
T. KELSALL,[2] P. M. LUBIN,[7] S. H. MOSELEY, JR.,[2] T. L. MURDOCK,[8] R. F. SILVERBERG,[2] G. F. SMOOT,[9]
AND D. T. WILKINSON[10]

Received 1990 January 16; accepted 1990 February 19

Rocket Measurement of the Cosmic-Background-Radiation mm-Wave Spectrum

H. P. Gush, M. Halpern, and E. H. Wishnow
Department of Physics, University of British Columbia, Vancouver, Canada V6T 2A6
(Received 10 May 1990)



The Standard ΛCDM Cosmological Model

1. The physics of gravity and spacetime is general relativity theory;
2. the observable universe is close to homogeneous and isotropic in the large-scale average;
3. the stress-energy tensor is textbook physics in the visible sector, and dark matter and dark energy – Einstein's cosmological term or something that acts like it – in the dark sector;
4. the universe has expanded from very high redshift;
5. the primeval departures from homogeneity are adiabatic, Gaussian, scale-invariant and growing.

The Cosmological Parameters

The Robertson-Walker line element is

$$ds^2 = dt^2 - a(t)^2 \left(\frac{dx^2}{1 + x^2/R^2} + x^2(d\theta^2 + \sin^2\theta d\phi^2) \right).$$

Hubble's law is $v = H_o r$, where Hubble's constant is the present value of $\dot{a}/a$. The Friedmann equation at low redshift is

$$(\dot{a}/a)^2 = H_o^2[\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda],$$

where

$$1 + z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{a(t_{\text{observed}})}{a(t_{\text{emitted}})}, \quad \Omega_m + \Omega_k + \Omega_\Lambda = 1.$$

THEORY OF RELATIVITY

by

W. PAULI

With Supplementary Notes by the Author

PERGAMON PRESS
NEW YORK · LONDON · PARIS · LOS ANGELES
1958

Einstein† was soon aware of these new possibilities and *completely rejected the cosmological term* as superfluous and no longer justified. I fully accept this new standpoint of Einstein's.‡

THE THEORETICAL ASPECTS OF THE NEBULAR REDSHIFT*

H. P. ROBERTSON
California Institute of Technology, and
Supreme Headquarters, Allied Powers, Europe

DEDICATED TO THE MEMORY OF EDWIN P. HUBBLE

PASP 1955

Of some passing interest is the Einstein–de Sitter model, for which both k and Λ vanish; this model, represented on Figure 3 by the intersection of the dotted and full-line curves, is characterized by

$$\rho_0 = 7.5 \times 10^{-29}\ \mathrm{gm/cm^3}, \qquad t_0 = 3.26 \times 10^9\ \mathrm{yr.} \qquad (14)$$

This density is probably a bit too high, and this age quite a bit too low, to represent the present state of the nebular universe.

for $H_o = 200\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

STEPS TOWARD THE HUBBLE CONSTANT. V. THE HUBBLE CONSTANT FROM NEARBY GALAXIES AND THE REGULARITY OF THE LOCAL VELOCITY FIELD 1975

ALLAN SANDAGE AND G. A. TAMMANN

The local velocity field is as regular, linear, isotropic, and quiet as it can be mapped with the present material. The lack of measurable velocity perturbations, in spite of the observed density inhomogeneities, suggests that the gravitational potential energy is small compared with the kinetic energy of the expansion (provided that there is no high-density, uniform intergalactic medium), and hence that $q_0 < \frac{1}{2}$.

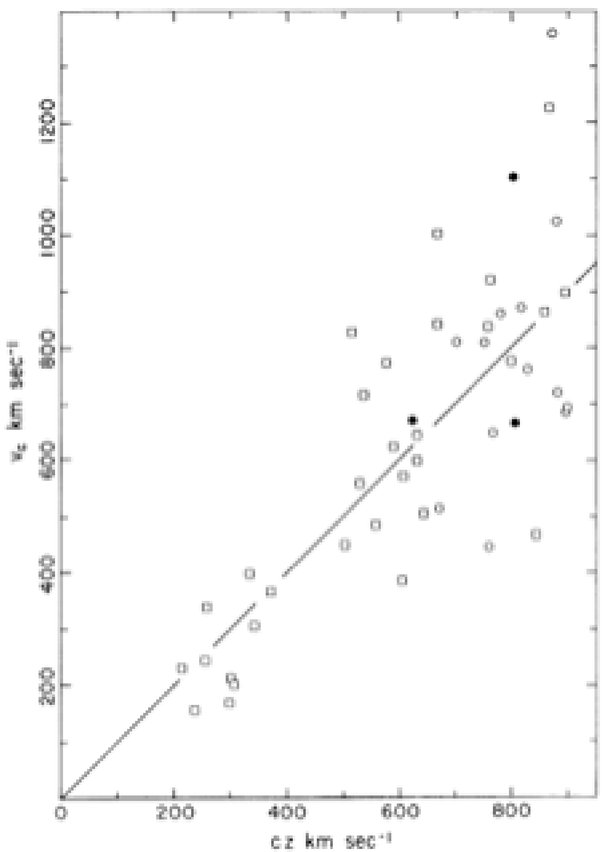


FIG. 1.—The local redshift-distance relation. The distance, cz/H, is estimated from the infrared Tully-Fisher relation. The redshift, v_c, is corrected for the solar motion in the first line of Table 2. The galaxies at distances from the ridge $H|Z_s| < 250$ km s^{-1} are indicated by squares, the galaxies at $HZ_s >$ 250 by filled circles, and the galaxies at $HZ_s < -250$ by open circles. The line is Hubble's law, with slope set by the A86 calibration at distances $cz \sim 4000$–11,000 km s^{-1}.

The local Hubble flow: data from the infrared Tully-Fisher survey by Aaronson, Huchra, Mould, Tully, Fisher, et al. 1982 (Peebles 1988).

Mon. Not. R. astr. Soc. (1975) **172**, *Short Communication*, 23P–26P.

THE SCALE OF GALAXY CLUSTERING AND THE MEAN MATTER DENSITY OF THE UNIVERSE

S. Michael Fall

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energy of random galaxy motion T will grow in accordance with the Layzer–Irvine equation (3)

$$\frac{d}{dt}(T+W)+H(2T+W) = 0 \tag{4}$$

$$W = \tfrac{1}{2}\rho \int_0^R \phi(r)\,\xi(r)\,4\pi r^2\,dr, \quad \phi(r) = -\frac{Gm}{r}$$

With $v \simeq 300\ \mathrm{km\ s^{-1}}$ (8) indicates that

$$0{\cdot}01 \lesssim \Omega \lesssim 0{\cdot}05 \tag{9}$$

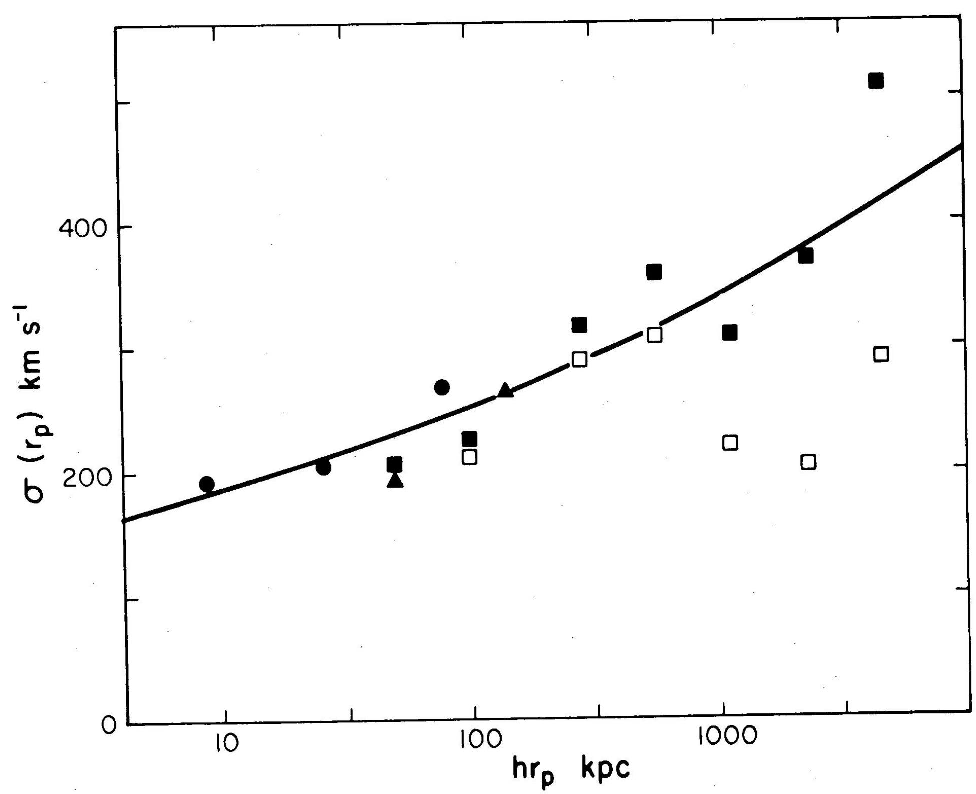
which suggests that, if most matter is distributed as galaxies are, the Universe is unbounded by a large margin. This inequality strengthens the suggestion (4) that the density of matter must be low in order that inhomogeneities do not disrupt the Hubble flow of galaxies more than is observed. The upper limit in (9) coincides nicely with the value favoured by Gott *et al.* (9). This coincidence is remarkable and would seem to provide a more or less independent estimate of the mean matter density of the Universe, although it must be emphasized that the result is subject to several uncertainties.

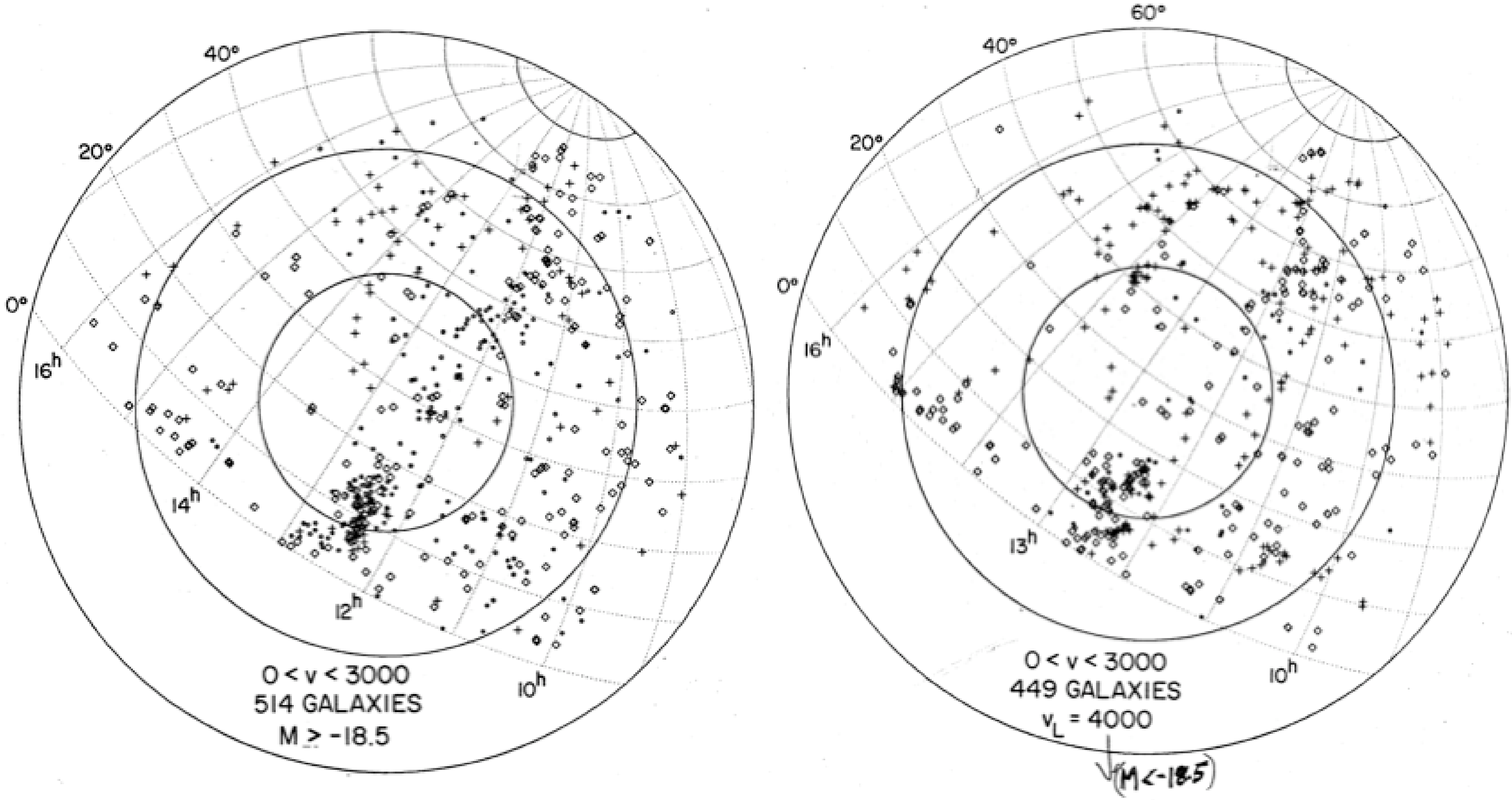
THE ASTROPHYSICAL JOURNAL, 267:465–482, 1983 April 15

A SURVEY OF GALAXY REDSHIFTS. V. THE TWO-POINT POSITION AND VELOCITY CORRELATIONS

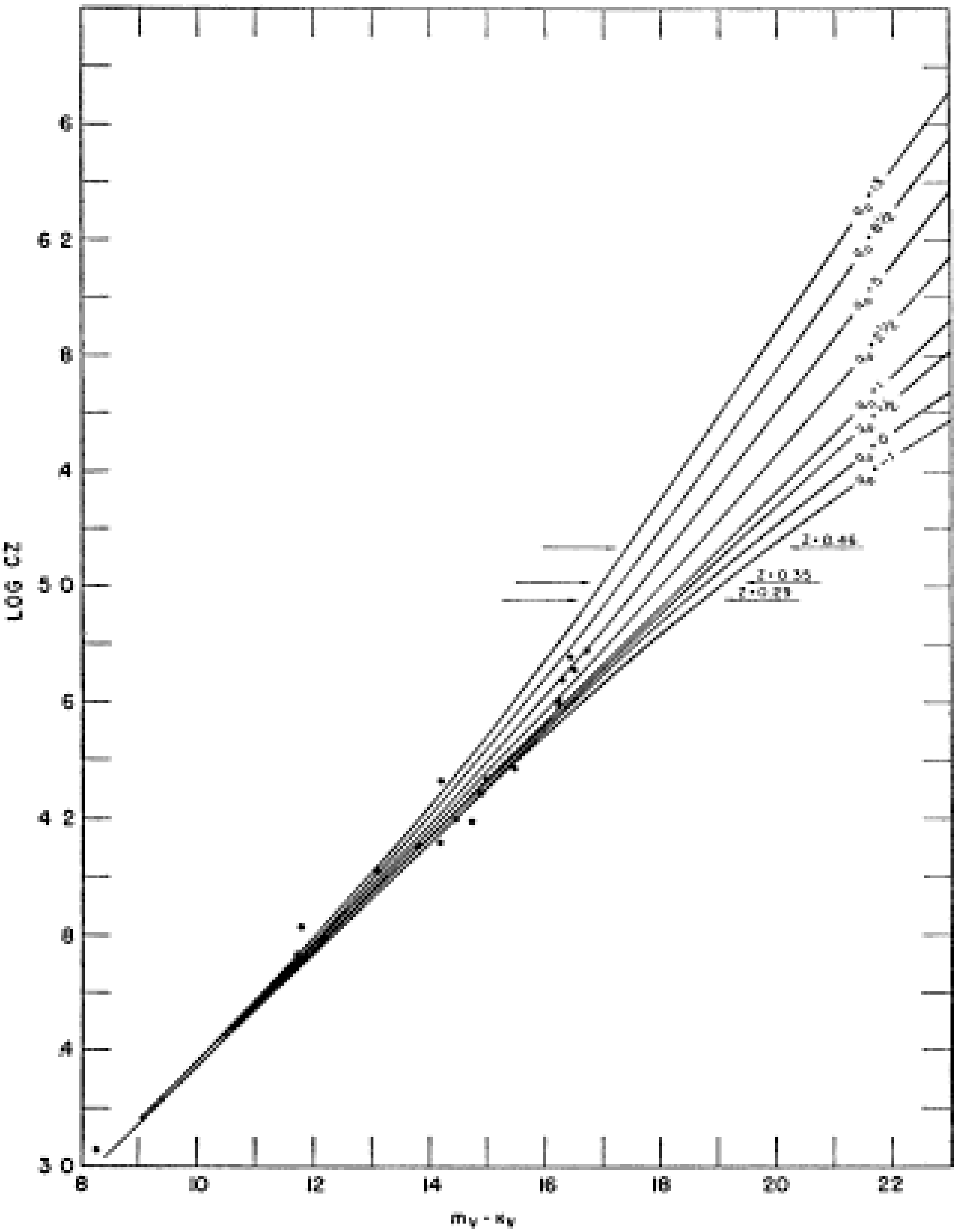
MARC DAVIS
Departments of Astronomy and Physics, University of California
AND
P. J. E. PEEBLES

tends to favor the latter picture. We derive the cosmological density parameter $\Omega = 0.2\, e^{\pm 0.4}$ for the component of matter clustered with the galaxy distribution on scales $\leqslant 1\, h^{-1}$ Mpc.





Davis, Latham, Huchra & Tonry, 1982



LOG CZ
6 2
5 0
4 2
3 0
8
10
12
14
16
18
20
22
$m_V - K_V$
z = 0.46
z = 0.35
z = 0.29

A SURVEY OF GALAXY REDSHIFTS. V. THE TWO-POINT POSITION AND VELOCITY CORRELATIONS

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Received 1982 August 5; accepted 1982 October 12

In redshift space, where the radial distance is cz/H_o, peculiar relative velocities make the galaxy two-point function anisotropic, a function of the separations π and σ parallel and perpendicular to the line of sight.

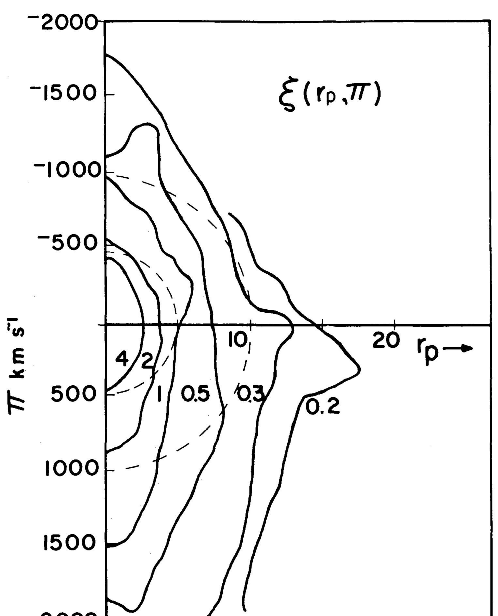
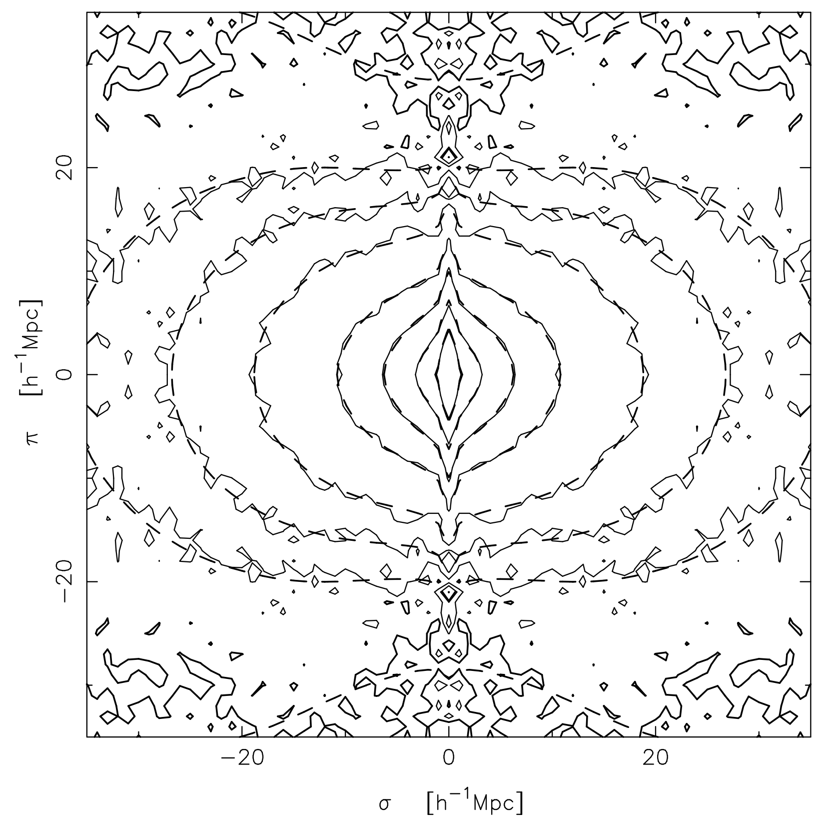


FIG. 4.—The two-point correlation as a function of separations r_p and π perpendicular and parallel to the line of sight. The lines are contours of fixed $\xi(r_p, \pi)$. The dashed semicircles show the expected shape of the contours if peculiar velocities were negligible.



Hawkins *et al.* (the 2dF GRS Team):

$$\Omega_m = 0.30 \pm 0.08.$$

THE ASTROPHYSICAL JOURNAL, 454:15–31, 1995 November 20

ACTION PRINCIPLE SOLUTIONS FOR GALAXY MOTIONS WITHIN 3000 KILOMETERS PER SECOND

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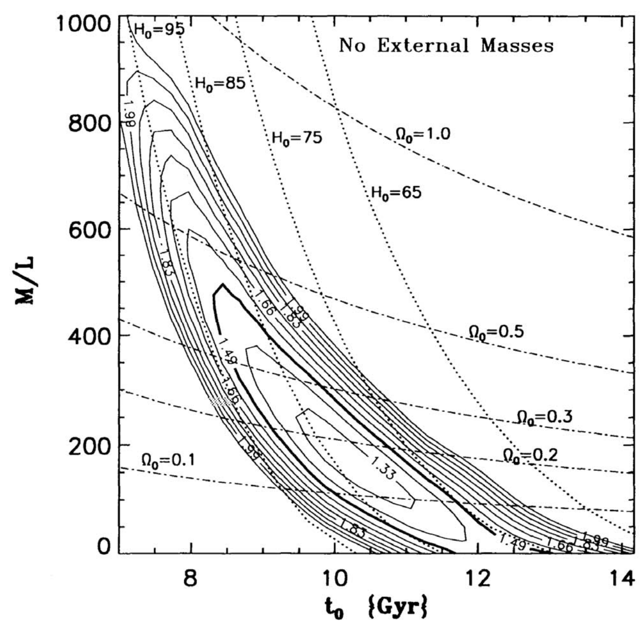

FIG. 6a

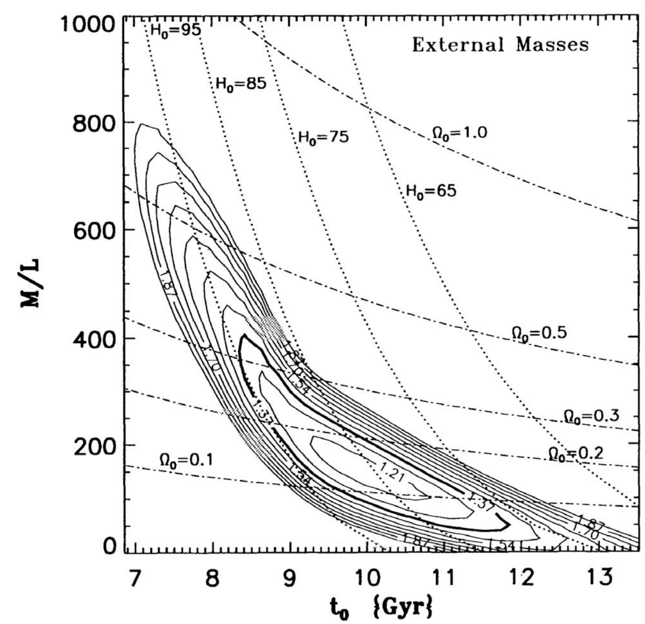

FIG. 6b

FIG. 6.—Contours of χ^2 as a function of the two free parameters M/L and t_0. This reduced χ^2 is calculated from the difference between model and observed distance moduli for 289 galaxies with luminosity–line width distance measurements. The normalization is given by the expected measurement error of $0^m.4$. Contours are at intervals of $0.08 \simeq 1\,\sigma$. The dashed line goes along the bottom of the minimum χ^2 valley. The lines of constant H_0 and Ω_0 are based on the Loveday et al. (1992) luminosity density normalization. (*a*) No external perturbation by masses beyond 3000 km s^{-1} distance. (*b*) External perturbation modeled by the distribution of the great clusters.

At 1 σ from the minimum of χ^2 the parameters are

$$9.0 < t_0 < 11.5 \text{ Gyr}\,, \quad \Omega_0 = 0.17 \pm 0.10\,.$$

Ann. Rev. Astron. Astrophys. 1983. 21: 109–30

THE ASTROPHYSICAL JOURNAL, **281**: 31–55, 1984 June 1

EVIDENCE FOR LOCAL ANISOTROPY OF THE HUBBLE FLOW

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the mean for Abell clusters, which are considerably richer, we adopt $\delta = 2.2 \pm 0.3$. Then if mass and galaxies have the same coarse distribution, the density parameter derived from Figure 1 is $\Omega = 0.35 \pm 0.15$. It should be

INFALL OF GALAXIES INTO THE VIRGO CLUSTER AND SOME COSMOLOGICAL CONSTRAINTS

R. BRENT TULLY AND EDWARD. J. SHAYA

With virgocentric flow $v_v = 224 \pm 90$ km s^{-1} within the Local Group distance from the Virgo cluster (Bureau, Mould & Stavley-Smith 1996; see also Arronson, Huchra, Mould, Schechter & Tully 1982), and density contrast $\delta N/N = 2.2 \pm 0.3$,

$$\Omega_m = 0.20^{+0.22}_{-0.15},$$

if galaxies trace mass.

AN ESTIMATE OF Ω_m WITHOUT CONVENTIONAL PRIORS

H. Feldman,[1,2] R. Juszkiewicz,[3,4,5] P. Ferreira,[6] M. Davis,[7] E. Gaztañaga,[8] J. Fry,[9] A. Jaffe,[10] S. Chambers,[1] L. da Costa,[11] M. Bernardi,[12] R. Giovanelli,[13] M. Haynes,[13] and G. Wegner[14]

Received 2003 May 6; accepted 2003 August 25; published 2003 September 29

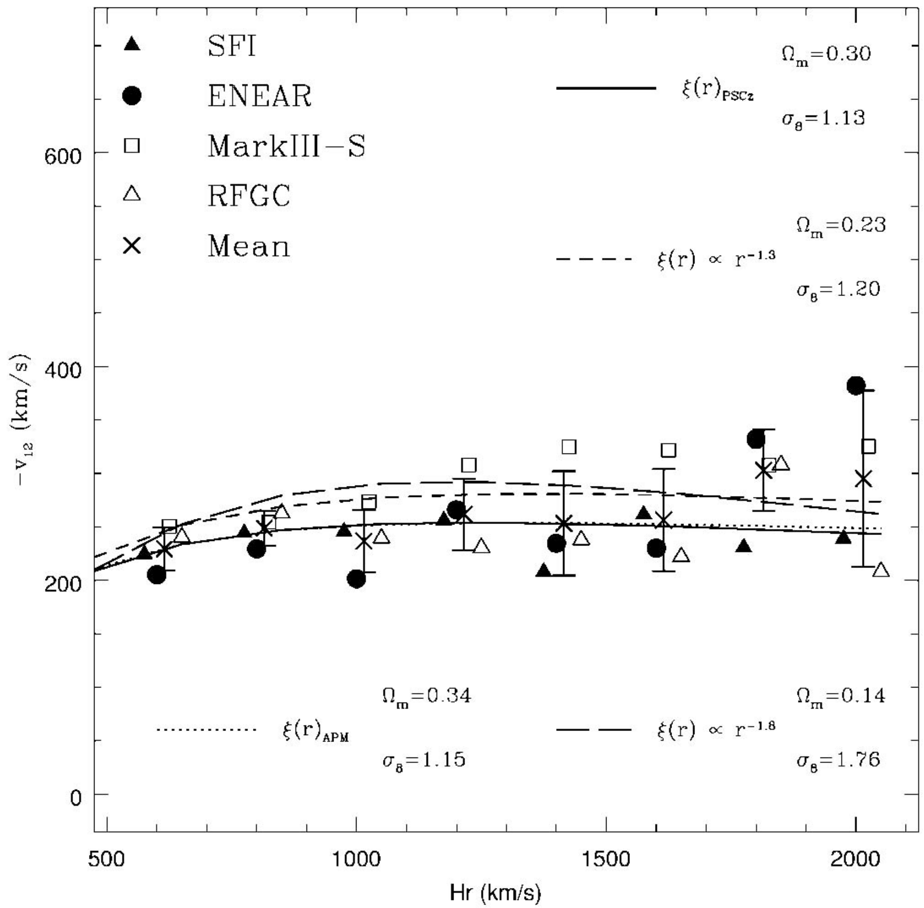


FIG. 3.—Crosses and the associated error bars show the weighted mean pairwise velocity, obtained by averaging over four surveys. Individual survey data points are also shown; we have suppressed their error bars for clarity. These direct measurements of v_{12} are compared to four $v_{12}(r)$ curves, derived by assuming four different models of $\xi(r)$, plotted in Fig. 1. The labels identify best-fit Ω_m and σ_8 parameters.

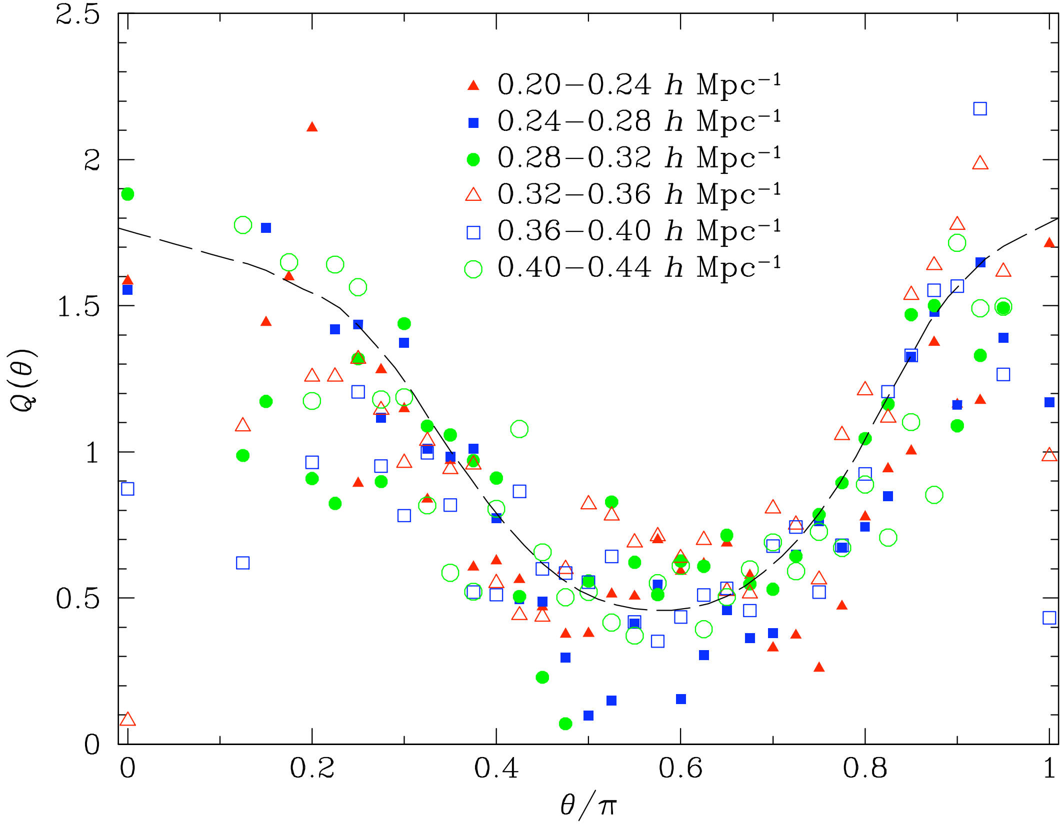
$$\Omega_m = 0.30^{+0.17}_{-0.07}$$

BIASING AND HIERARCHICAL STATISTICS IN LARGE-SCALE STRUCTURE

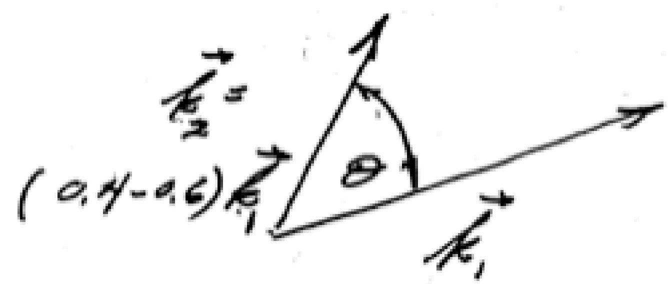
J. N. Fry[1,2] and Enrique Gaztañaga[1,3]

Received 1992 December 18; accepted 1993 February 24

The evidence from the two- and three-point correlation functions is that galaxies are useful mass tracers.



Feldman, Frieman, Fry, and Scoccimarro, 2001



Write

$$\left.\frac{\delta\rho}{\rho}\right._{\rm galaxies} = b_1 \left.\frac{\delta\rho}{\rho}\right._{\rm mass} + \frac{b_2}{2}\left(\frac{\delta\rho}{\rho}\right)^2_{\rm mass} + \ldots .$$

IRAS galaxies – selected at 60 to 100 μ – are moderately biased in the expected direction: dusty galaxies avoid dense regions. Optically selected galaxies are quite good mass tracers: the 2dF survey yields (Verde *et al.* 2002):

$$b_1 = 1.04 \pm 0.11, \quad b_2 = -0.054 \pm 0.08.$$

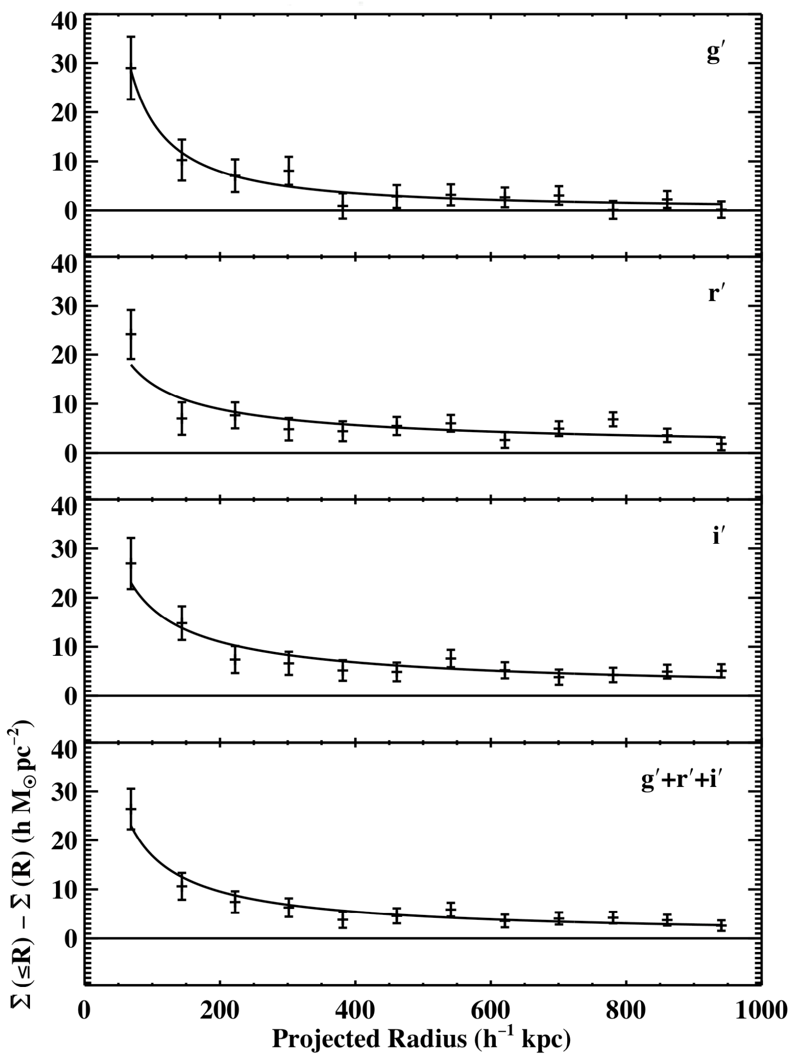


FIG. 7.— Mean density contrast measured as a function of projected radius around ∼31,000 SDSS lens galaxies. The plots are the mean density contrast in g', r', and i' images from the top, with the combined data on bottom. The solid lines are the best-fitting power laws.

The SDSS weak lensing measurement of the mean galaxy surface mass density contrast is (McKay *et al.* 2001)

$$\Sigma(< y) - \Sigma(y) = A(hy/1\ \mathrm{Mpc})^{-\alpha},$$

where

$$A = 2.5^{+0.7}_{-0.8}\, h\, m_\odot\ \mathrm{pc}^{-2}, \quad \alpha = -0.8 \pm 0.2$$

at projected radii

$$70\ \mathrm{kpc} \lesssim y \lesssim 1\ \mathrm{Mpc}.$$

This agrees with the galaxy autocorrelation function shape and value if

$$\Omega_m(\mathrm{weak\ lensing}) = 0.20^{+0.06}_{-0.05}.$$

Weak Gravitational Lensing

If galaxies trace mass the variance of the weak lensing shear averaged within a window of size θ scales with the matter density parameter as

$$\sigma_{\rm lens} \sim \Omega_m^{0.75}.$$

The measured shear (Refregier, Rhodes & Groth 2002, in the HST WFPC2 Groth Strip, and references therein) indicates

$$\Omega_m = (0.27 \pm 0.08)\sigma_8^{-1.7}$$

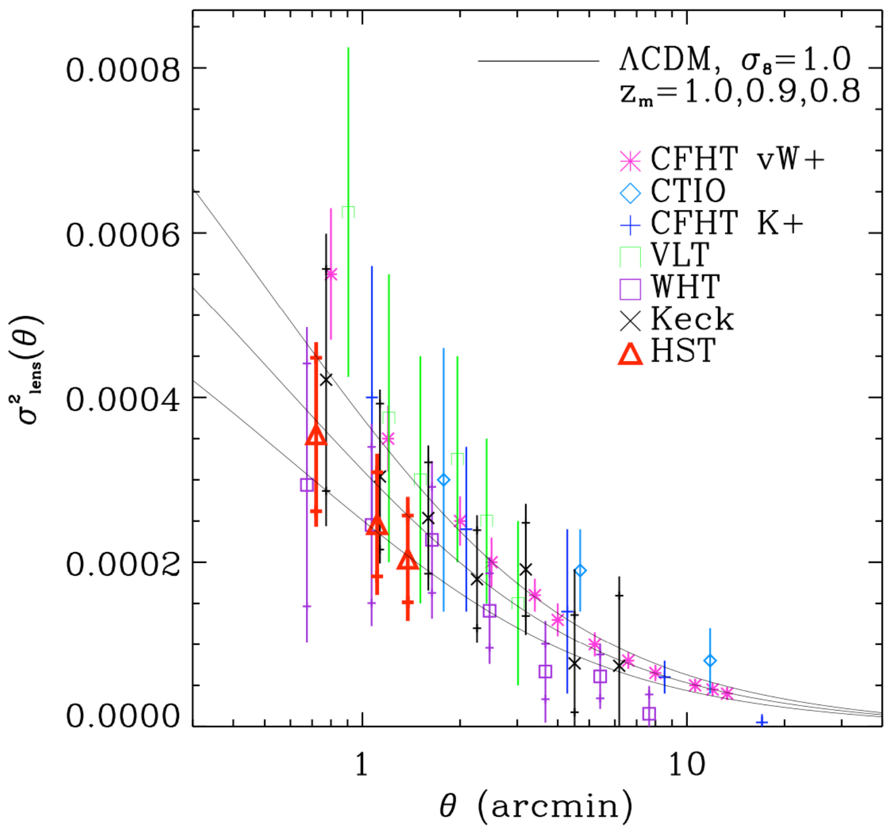
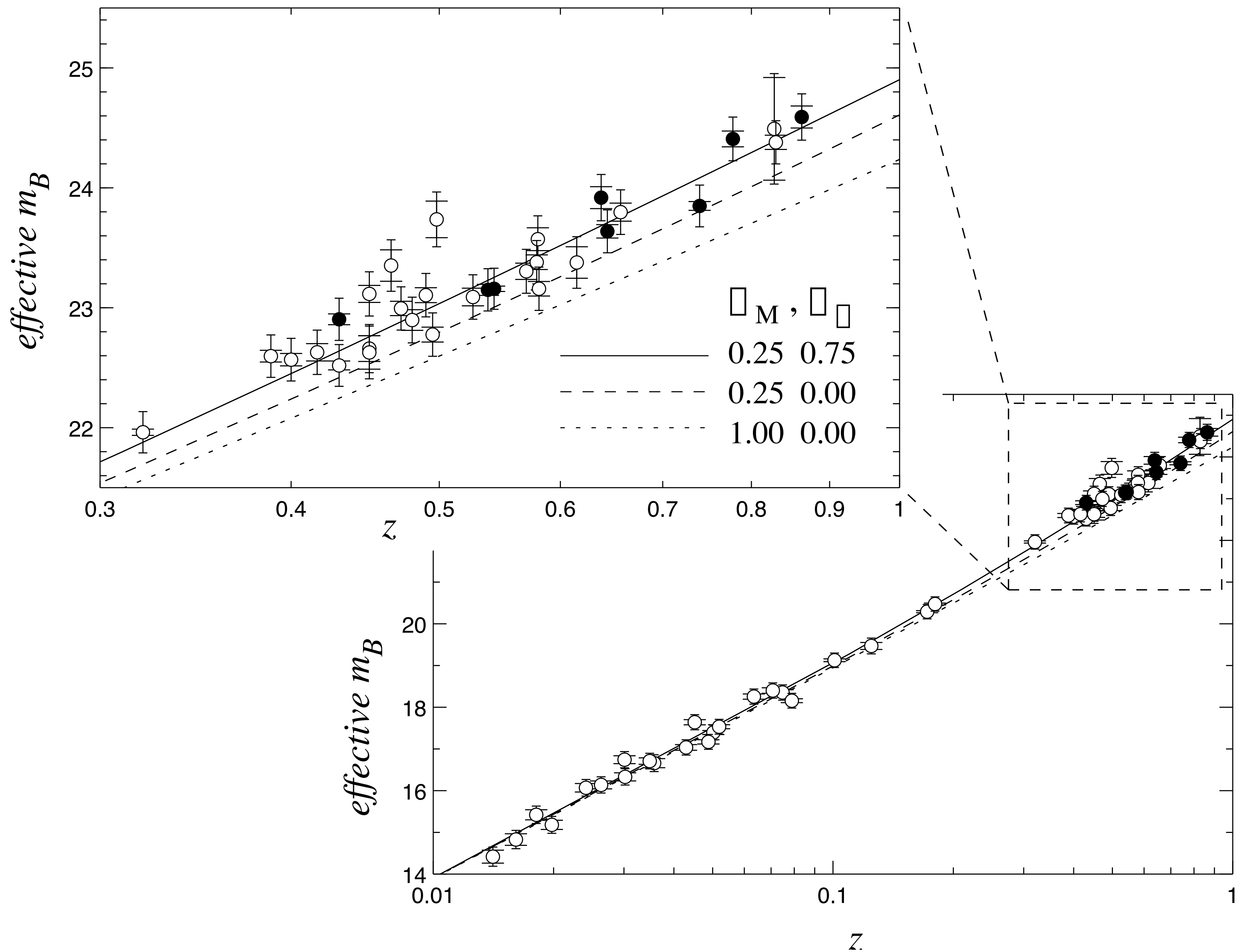
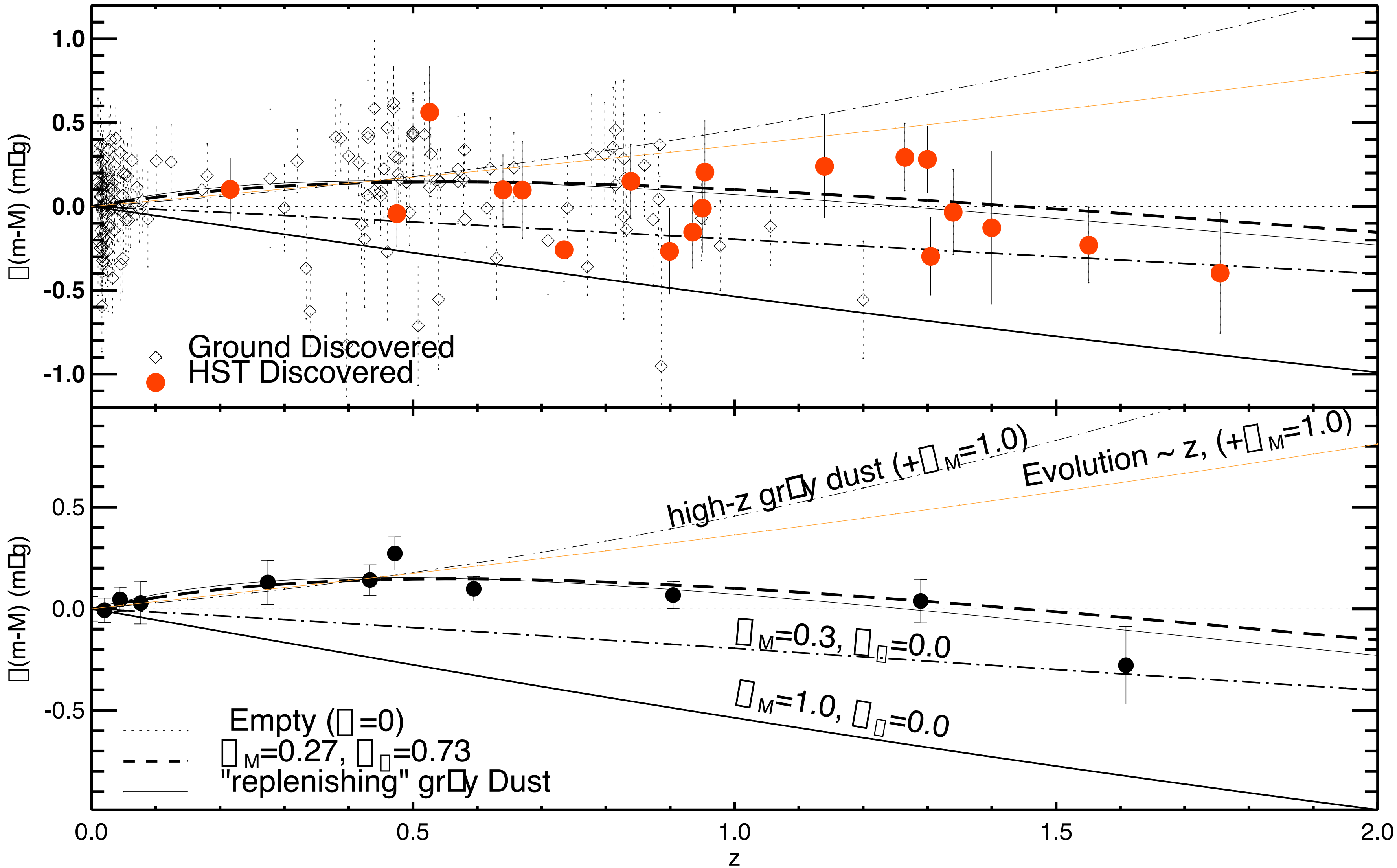


Fig. 2.— Shear variance $\sigma^2_{\rm lens}$ as a function of the radius θ of a circular cell. Our observed value (HST) as well as that observed by other groups: van Waerbeke et al. (2001, CFHT vW+), Wittman et al. (2000, CTIO), Kaiser, Wilson & Luppino (2000, CFHT K+), Maoli et al. (2000, VLT), Bacon et al. (2002, WHT and Keck). For our measurement, the inner error bars correspond to noise only, while the outer error bars correspond to the total error (noise + cosmic variance). The errors for the measurements of Maoli et al. (2000) and van Waerbeke et al. (2001) do not include cosmic variance. The measurements of Hämmerle et al. (2001) and Hoekstra et al. (2002) are not displayed but are consistent with the other measurements. Also displayed are the predictions for a ΛCDM model with $\Omega_m = 0.3$, $\sigma_8 = 1$, and $\Gamma = 0.21$. The galaxy median redshift was taken to be $z_m = 1.0, 0.9$, and 0.8, from top to bottom, respectively.



Robert Knop and the Supernova Cosmology Project team, ApJ, 598, 102, 2003

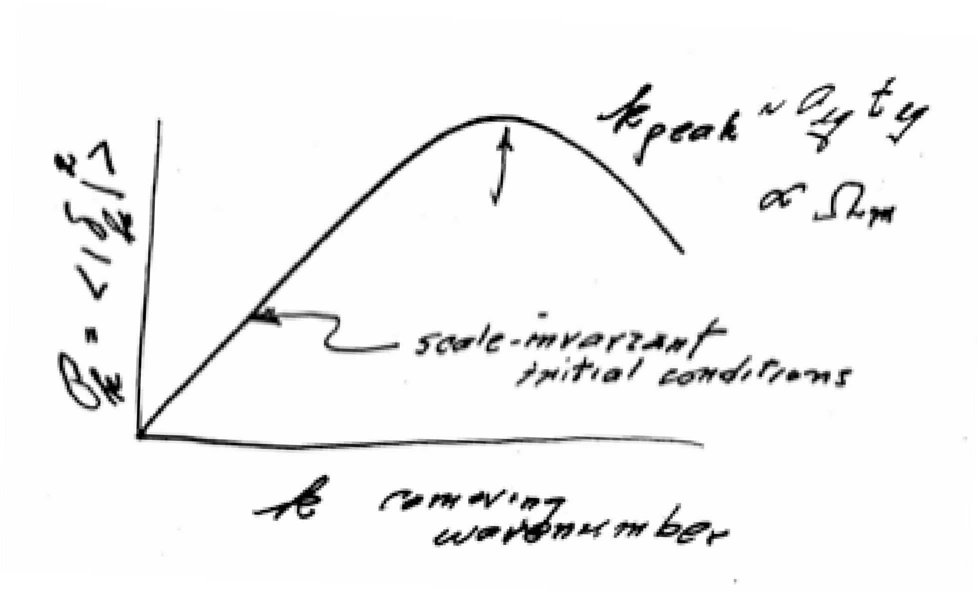


courtesy Adam Riess; see also Riess et al., astro-ph/0402512

The cosmological constant and cold dark matter

G. Efstathiou, W. J. Sutherland & S. J. Maddox (1990)

Department of Physics, University of Oxford, Oxford OX1 3RH, UK



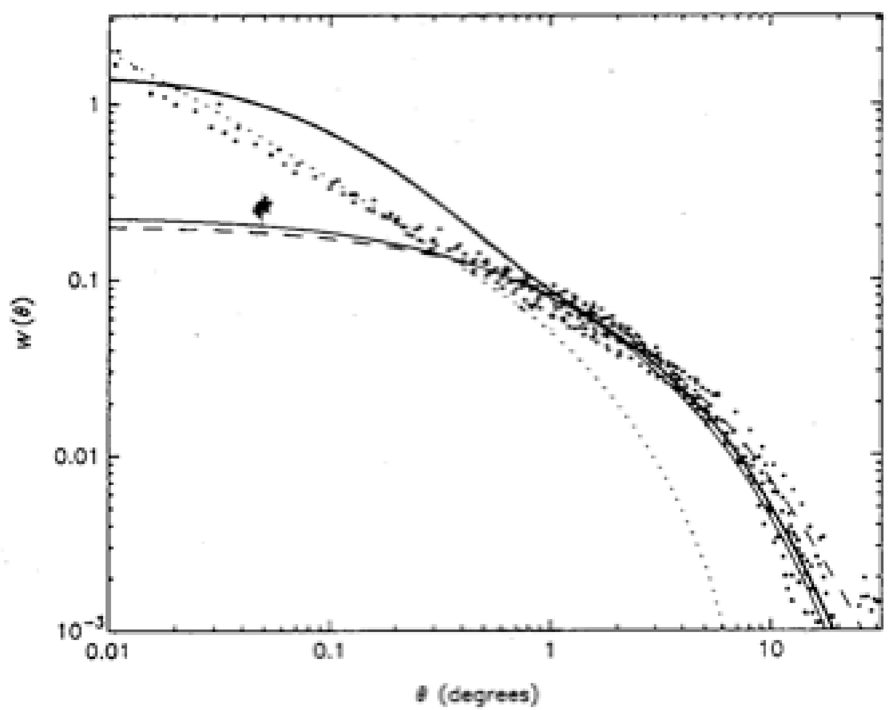


FIG. 1 The dots show estimates of the angular correlation function $w(\theta)$ for galaxies in the APM galaxy survey (see ref. 5 for details). These estimates have been scaled to the depth of the Lick galaxy catalogue where 1° corresponds to a spatial scale of $\sim 5h^{-1}$ Mpc. The dotted line shows the predictions of the $\Omega=1$ CDM model (from ref. 5). The thin solid and dashed lines show the results of the linear theory for $\Omega_0=0.2$ scale-invariant CDM models with $h=1$ and 0.75, respectively. The thick solid line shows N-body results for $\Omega=0.2$ and $h=0.9$; the flattening of this curve at angular scales $\leq 0.1°$ is an artefact of the resolution of the computer code, but the excess between 0.1° and 1° is real (see Fig. 2).

Will Percival, 2004: the 2dF GRS gives

$$\Omega_m = 0.23 \pm 0.03$$

for $h = 0.7$.

Looking for □Cosmologic□ Const□nt with the Rees-Sci□m□Effect

Robert G. Crittenden □nd Neil Turok
Joseph Henry L□bor□ory, Princeton University, Princeton, New Jersey 08544

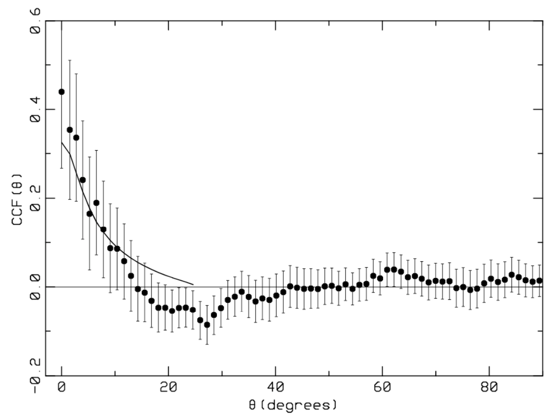


Fig. 1. The cross-correlation function of the WMAP ILC CMB maps with the *HEAO1 A2* 2-10 *keV*, hard X-ray map. The error bars were determined from Monte Carlo calculations and are highly correlated. The solid curve is the predicted ISW effect from the standard ΛCDM cosmological model and is not a fit to the data. The units are $\mu K\ TOT\ counts\ s^{-1}$ where $1\ TOT\ count\ s^{-1} \sim 1 \times 10^{-5} erg\ s^{-1} cm^{-2} sr^{-1}$.

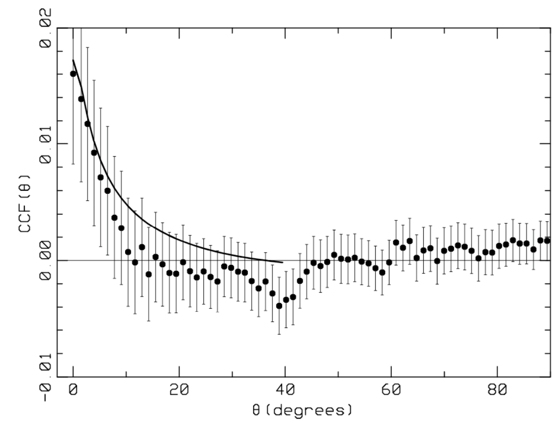


Fig. 2. The cross-correlation function of the WMAP ILC CMB maps with the NVSS 1.4 GHz radio survey. The error bars were determined from Monte Carlo calculations and are highly correlated. The solid curve is the predicted ISW effect from the standard ΛCDM cosmological model and is not a fit to the data. The units are $mK\ counts$ where the counts are number of radio sources per 1.3×1.3 degree pixel.

Boughn \& Crittenden 2004

The Integrated Sachs-Wolfe effect:

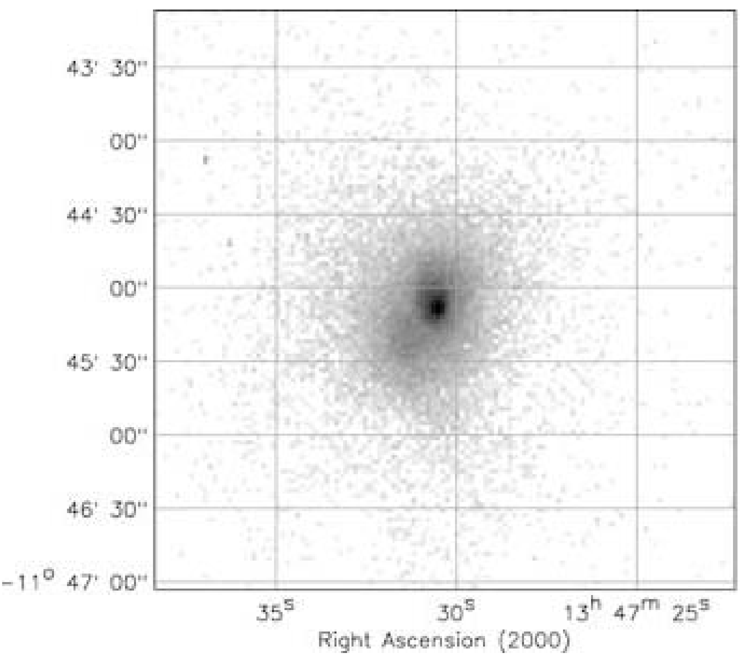
$$\frac{\delta T}{T} = -\int \frac{\partial \phi}{\partial x^\alpha} dx^\alpha.$$

where $\nabla^2 \phi = 4\pi G a(t)^2 \delta\rho$. In the Einstein-de Sitter model the mass density contrast in linear perturbation theory varies as $\delta\rho/\rho \propto t^{2/3} \propto a(t)$, so the potential $\phi \sim G\delta\rho(ax)^2$ is independent of time. In a low density model ϕ varies with time, so the integral gets a contribution from low redshift, and the CBR angular distribution is correlated with the mass distribution at low redshift.

Mon. Not. R. Astron. Soc. **335,** 256–266 (2002)

Chandra observations of RX J1347.5−1145: the distribution of mass in the most X-ray-luminous galaxy cluster known

S. W. Allen,* R. W. Schmidt and A. C. Fabian
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA



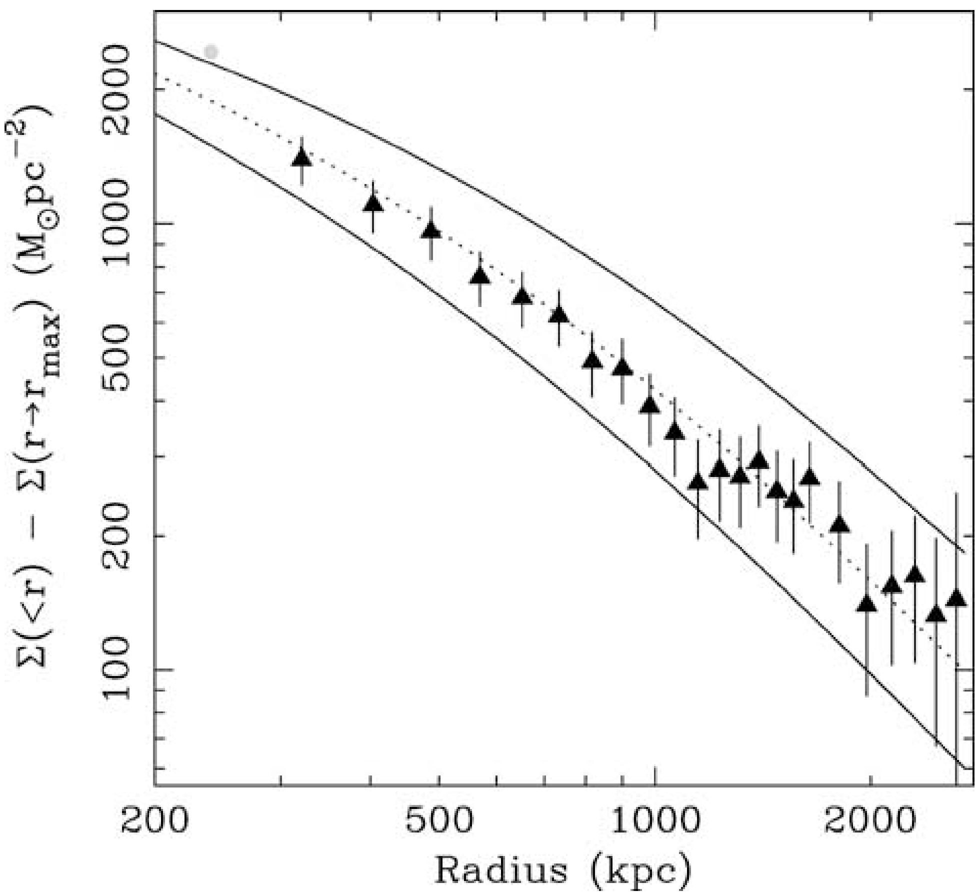


Figure 8. A comparison of the projected surface mass density contrast determined from the *Chandra* X-ray data (Section 5) with the weak lensing results of Fischer & Tyson (1997 solid triangles) and the strong lensing result from Section 6.2 (grey circle). The best-fitting NFW X-ray mass model for the relaxed regions of the cluster and 1σ confidence limits (the maximum and minimum values at each radius for all NFW models within the 68 per cent confidence contour shown in Fig. 6) are shown as the dotted and full curves, respectively. The strong lensing point is marked with a grey circle. Note that the strong lensing point should lie above the X-ray results, which exclude the regions of the cluster affected by the second mass clump. We adopt $r_{\rm max} = 2.72$ Mpc as in Fischer & Tyson (1997).

The baryon content of galaxy clusters: a challenge to cosmological orthodoxy

Simon D. M. White*, Julio F. Navarro†, August E. Evrard‡ & Carlos S. Frenk† (1993)

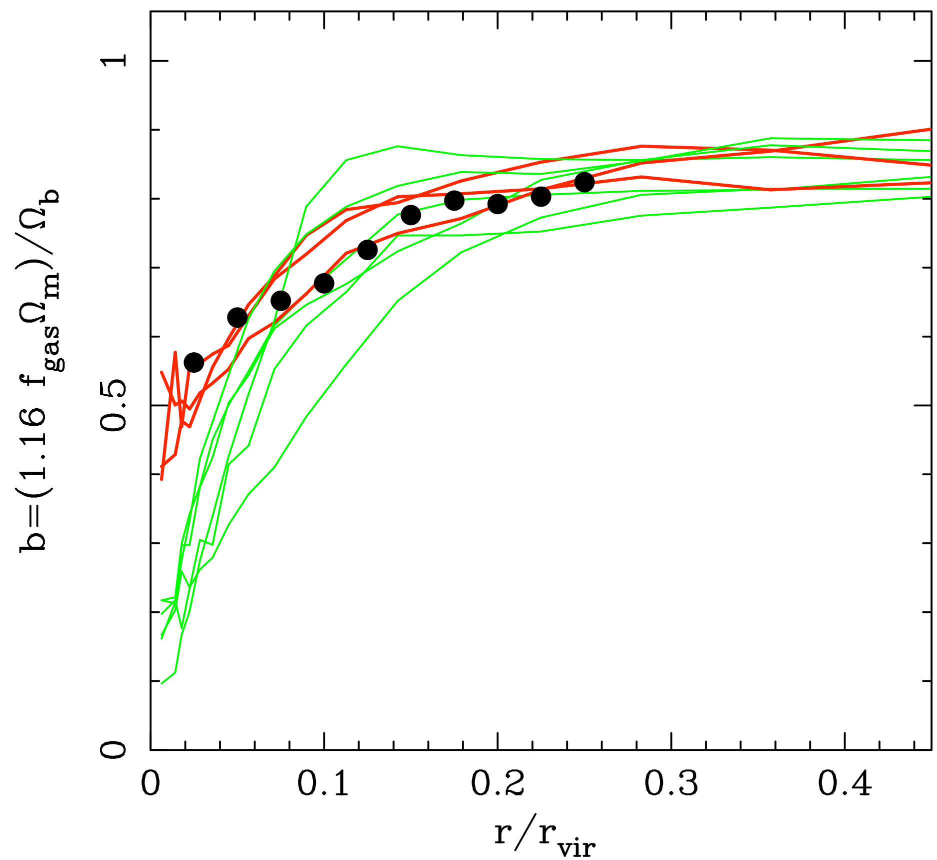
Because rich clusters of galaxies have a large escape velocity one might expect they contain a fair sample of baryonic and dark matter,

$$f_{\rm baryon} = \frac{M_{\rm baryon}}{M_{\rm total}} \simeq \frac{\Omega_{\rm baryon}}{\Omega_m}.$$

$\Omega_{\rm baryon}$ is well constrained by light element abundances.

Chandra X-ray observations (Allen *et al.* 2004) indicate $f_{\rm plasma} = 0.117$. With $f_{\rm stars} = 0.16 f_{\rm plasma}$, and a modest 20% fudge factor for loss of baryons during cluster assembly (from numerical simulations),

$$\Omega_m = 0.26 \pm 0.04$$



Steve Allen et al., astro-ph/0405340

CONSTRAINING Ω WITH CLUSTER EVOLUTION

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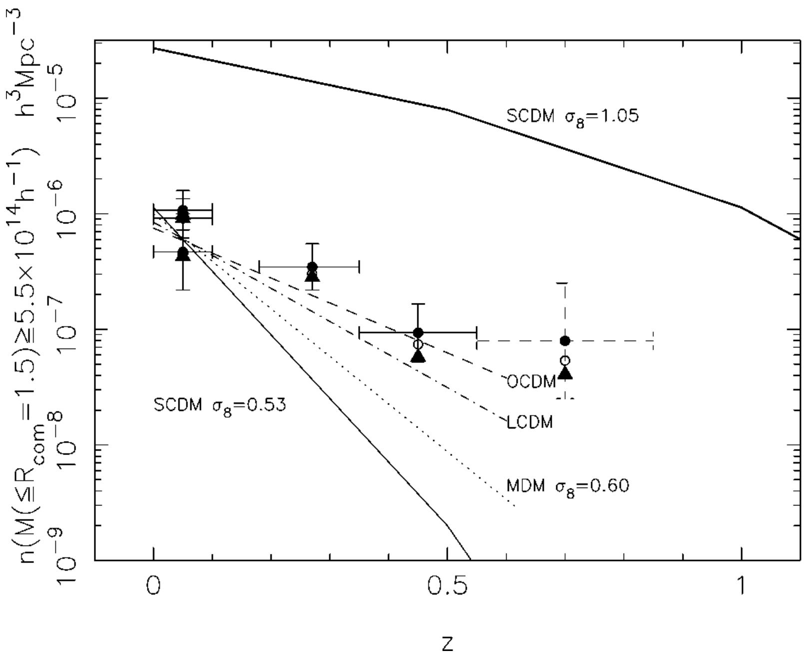


FIG. 2.—Observed vs. model cluster abundance as a function of redshift for clusters with mass $M(\leq R_{com} = 1.5\ h^{-1}\ \mathrm{Mpc}) \geq 5.5 \times 10^{14}\ h^{-1}\ M_\odot$. The observed abundances at $z \sim 0$ are from Bahcall & Cen (1993), Mazure et al. (1996), and Henry & Arnaud (1991). The data at $z \sim 0.27$ and 0.45 are from the CNOC survey (Carlberg et al. 1997), and the data at $z \sim 0.7$ are from Luppino & Gioia (1995). The different symbols represent the observed number densities for $\Omega = 1$ (*filled circles*), $\Omega = 0.35$, $\Lambda = 0$ (*open circles*), and $\Omega = 0.4$, $\Lambda = 0.6$ (*triangles*).

Within the standard cosmology we have two free parameters, Ω_m and the bias b_1 of the clustering of galaxies relative to mass, to fit two constraints, the abundance of rich clusters at low redshift and at $z \sim 1$.

Bahcall & Bode (2003) find

$$\Omega_m = 0.17 \pm 0.05, \quad b_1 = 1.0 \pm 0.1,$$

at one standard deviation and $h = 0.72$.

Mass Density Measurements[a]

	Ω_m
peculiar velocities	
rms relative velocity, 30 kpc $\lesssim hr \lesssim$ 300 kpc	$0.20e^{\pm 0.4}$
redshift space anisotropy 10 Mpc $\lesssim hr \lesssim$ 30 Mpc	0.30 ± 0.08
numerical action 1 Mpc $\lesssim hr \lesssim$ 30 Mpc	0.17 ± 0.10
virgocentric flow $hr \sim$ 10 Mpc	$0.20^{+0.22}_{-0.15}$
mean relative velocities 10 Mpc $\lesssim hr \lesssim$ 20 Mpc	$0.30^{+0.17}_{-0.07}$
weak gravitational lensing: galaxy-mass	$0.20^{+0.06}_{-0.05}$
mass-mass	0.27 ± 0.08
SNeIa redshift-magnitude relation	$0.29^{+0.05}_{-0.03}$
shape of the mass fluctuation power spectrum	0.23 ± 0.02
integrated Sachs-Wolfe effect	~ 0.3
cluster baryon mass fraction	0.26 ± 0.04
cluster mass function as a function of redshift	0.17 ± 0.05

[a] for $h = 0.7$ and $\sigma_8 = 1$.

This is not precision cosmology: the constraint is $0.15 < \Omega_m < 0.3$*, and the assumption galaxies trace mass has to be crude. But we do have a good case that it is accurate cosmology, that is, the constraint is believable.*

The Void Phenomenon

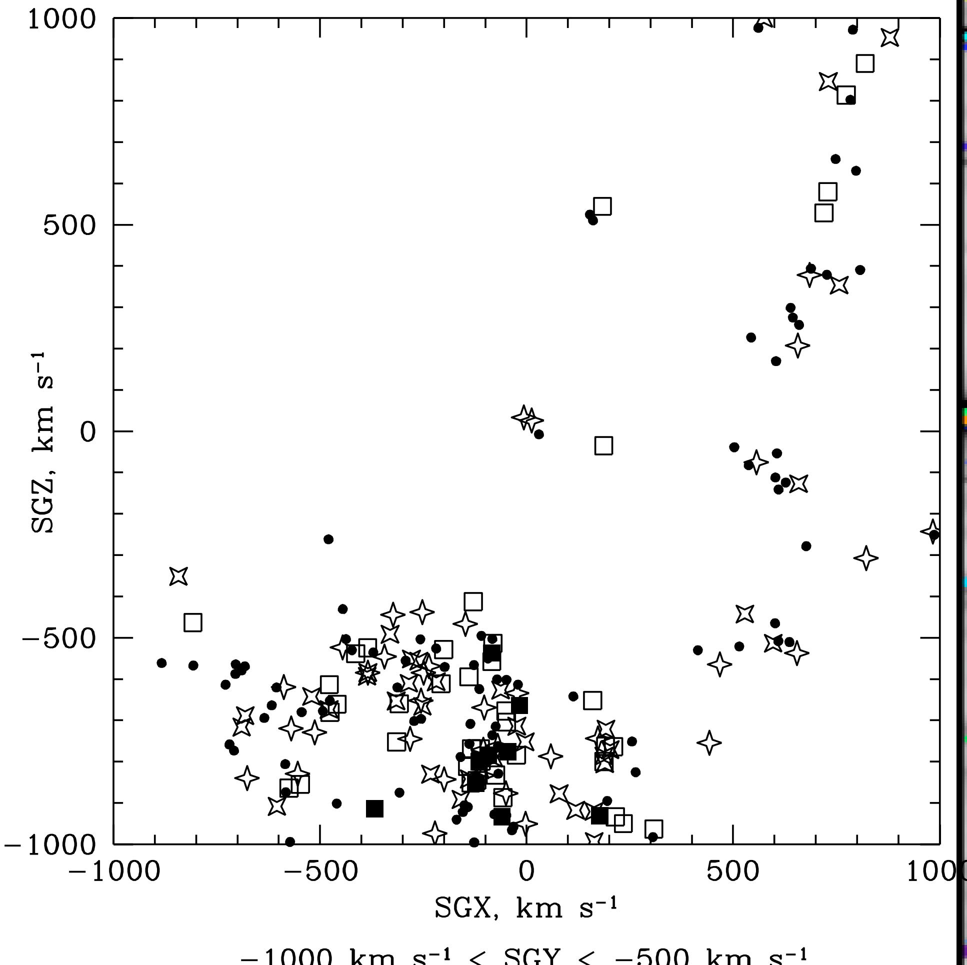
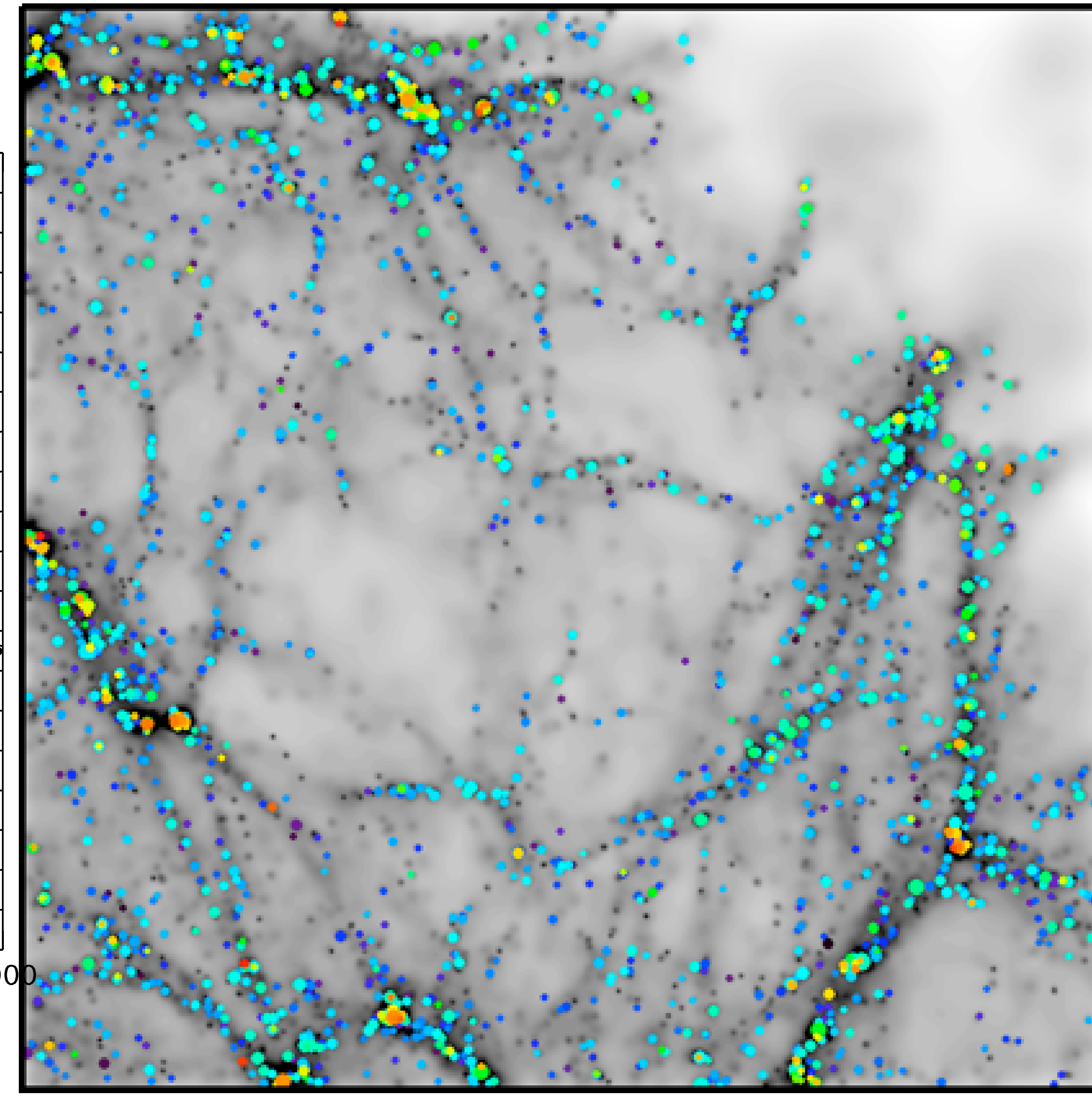


FIG. 2.—Map of ORS galaxies in a slice in redshift space. The normal to the slice points in the direction of the Virgo Cluster, from the opposite side of the Milky Way. Filled squares are elliptical galaxies, open squares are S0 galaxies, crosses are Sa–Sc galaxies, plus signs are later spiral types, and filled circles are dwarfs and irregulars.



Mathis & White, MNRAS 337, 2002

DDO 154: A "DARK" GALAXY?

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Received 1988 May 3; accepted 1988 June 3

DDO 154 = NGC 4789A
SGL = 90°, SGB = 7°
distance = 3.2 Mpc
1 arc min $\simeq$ 1 kpc

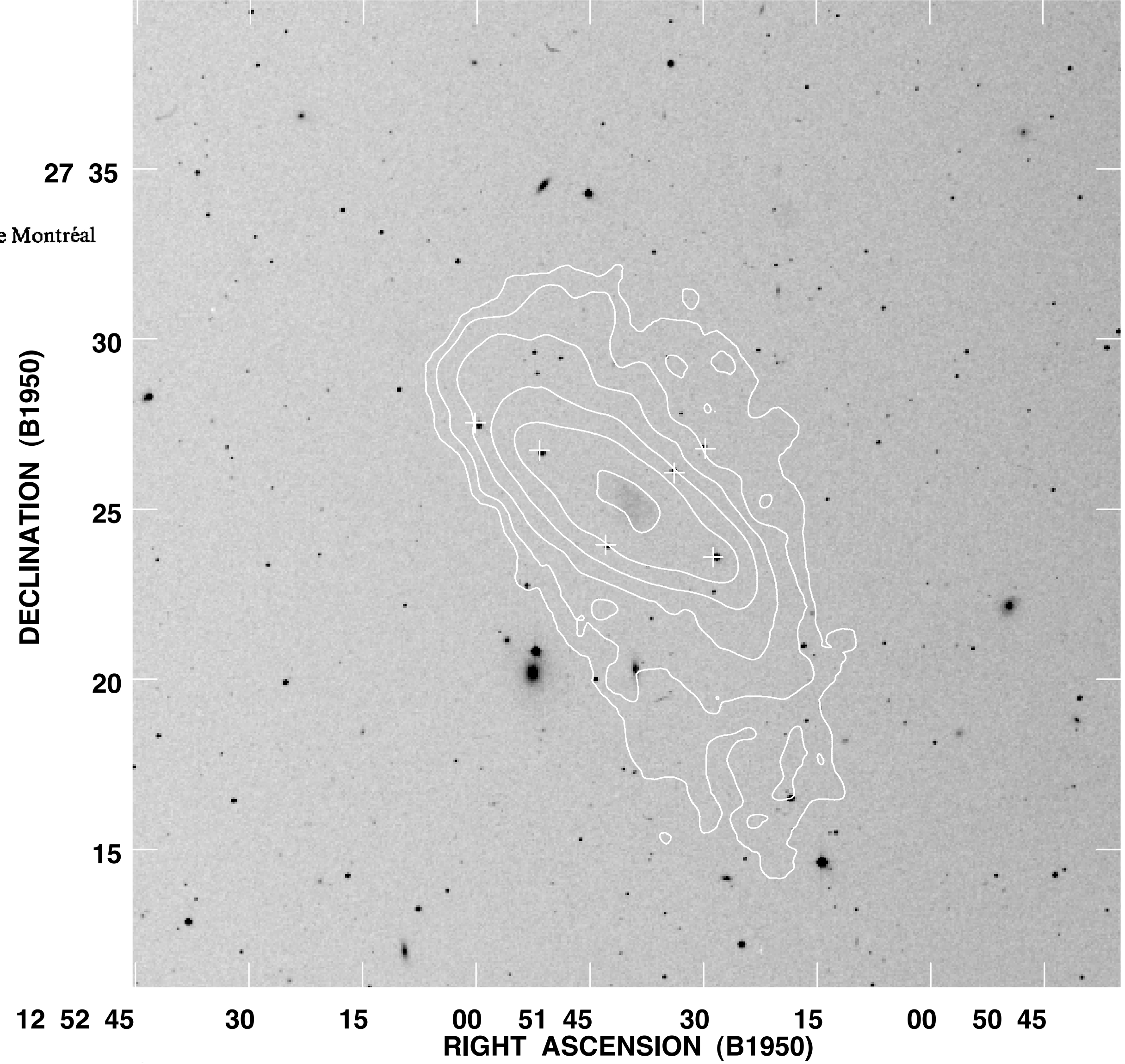


FIG. 3.—Total H I map superposed on the optical for the combined VLA + DRAO data. The contours are 0.5, 1, 2, 4, 8, and 16 × 10^{20} cm^{-2}. The circula
beam size is 1′

However, looking in Tully's (1988) Nearby Galaxies Catalog, the nearest neighbors are NGC 4826 and UGC 7698, both at more than 350 kpc away, which allows us to consider that DDO 154 is a fairly well isolated system.

Carignan & Purton, 1998

Physics in the Dark Sector

Since the dark and visible sectors interact largely, or maybe totally, through gravity, which is a blunt probe, how can we be sure physics in the dark sector is not more complicated than the standard ΛCDM cosmology?

If the dark sector physics differs from ΛCDM enough to matter the signature will be anomalies — by definition.

There are anomalies; the challenge is to decide whether they are real or only apparent.

A possibly interesting generalization of the ΛCDM model adds a long-range scalar dark matter interaction. This has a long history.

Nordström's (1913) scalar gravity theory for point-like particles with mass $m = \kappa\phi$ can be written as the action

$$S = \int d^4x \, \phi_{,i}\phi^{,i}/2 - \sum \int \kappa\phi ds \, .$$

The field equation, $\phi_{,i}^{,i} + \kappa n = 0$ for nonrelativistic particles, requires $\bar{n} = 0$, but this was before Einstein's cosmological principle.

In the 1950s and 1960s Jordan, Dicke and others applied a variant of this action to a scalar-tensor gravity theory.

I think Damour, Gibbons & Gundlach (1990) were the first to note that the tight constraints in the visible sector allow a substantial role for a scalar interaction in the dark sector.

Other recent discussions of long-range scalar interactions in the dark and/or visible sectors include Casas, Garcia-Bellido & Quiros (1992); Damour & Polyakov (1994); Wetterich (1995); Anderson & Carroll (1997); Bean (2001); Amendola (2000); Amendola & Tocchini-Valentini (2002); França & Rosenfeld (2002); Damour, Piazza & Veneziano (2002); Comelli, Pietroni & Riotto (2003); and Amendola, Gasperini & Piazza (2004).

The variant to be considered here is based on work with Glennys Farrar and Steve Gubser in astro-ph/0307316, hep-th/0402225 & hep-th/0407097.

The point that is new — though there are earlier analogues — and maybe essential is that a "charge neutrality" can eliminate the scalar force on scales larger than nonlinear clustering, so the cosmological tests are largely unaffected.

Superstring theorists nowadays are much taken with scalar fields, but question whether any can avoid acquiring a mass that is unacceptable for our purpose. Gubser, in hep-th/0407097, argues why this need not be a showstopper.

Superstring scenarios suggest we consider a Lagrangian density for the dark matter that looks like

$$\begin{aligned}\mathcal{L} = \phi_{,i}\phi^{,i}/2 + i\bar{\Psi}_{+}\gamma\partial\Psi_{+} + i\bar{\Psi}_{-}\gamma\partial\Psi_{-} + \\ - m_o e^{\beta_{+}\phi/m_{\rm pl}}\bar{\Psi}_{+}\Psi_{+} - m_o e^{-\beta_{-}\phi/m_{\rm pl}}\bar{\Psi}_{-}\Psi_{-}\,.\end{aligned}$$

In the limit of small de Broglie and Compton wavelengths, and assuming ϕ is held close to the minimum of its potential, which we can shift to $\phi \equiv 0$, the action is a generalization of the Nordström form,

$$S = \int\sqrt{-g}\, d^4x\, \phi_{,i}\phi^{,i}/2 - \sum_a \int (m_{+} + y_{+}\phi) ds_a - \sum_b \int (m_{-} - y_{-}\phi) ds_b .$$

In Minkowski spacetime the field equation is

$$\nabla^2\phi - \ddot{\phi} = y_+\langle\sqrt{1-v_+^2}\rangle n_+(\vec{r},t) - y_-\langle\sqrt{1-v_-^2}\rangle n_-(\vec{x},t).$$

I think $\langle\phi\rangle$ moves masses and hence velocities so that the spatial mean of the rhs vanishes; but $\langle\phi\rangle$ is stabilized as well by the curvature of the potential in the exponential model.

In the quasi-static limit the field equation and force law are

$$\nabla^2\phi = y_+ n_+(\vec{x},t) - y_- n_-(\vec{x},t), \qquad \vec{f} = -\nabla m_a = \mp y_\pm \nabla\phi.$$

This is electrostatics, but with the opposite sign. The sum of the gravitational and scalar force between dark matter particles is

$$\begin{aligned}
F_{++} &= -\frac{Gm_+^2}{r^2}\left(1 + \frac{y_+^2}{4\pi G m_+^2}\right), \\
F_{+-} &= -\frac{Gm_+m_-}{r^2}\left(1 - \frac{y_+y_-}{4\pi G m_+m_-}\right), \\
F_{--} &= -\frac{Gm_-^2}{r^2}\left(1 + \frac{y_-^2}{4\pi G m_-^2}\right).
\end{aligned}$$

Emptying Voids

Suppose there are two dark matter species, with $y_+ = y_- = y$ and $n_+ = n_-$, and

$$m_+ \gg m_- \,, \qquad \frac{y^2}{4\pi G m_+^2} \sim 1 \,.$$

Since we want $\rho_{\rm baryons} \ll \rho_+$, in linear perturbation theory the density contrasts $\delta = \delta n/\bar{n}$ satisfy

$$\begin{aligned}
\frac{\partial^2 \delta_+}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta_+}{\partial t} &= 4\pi G\bar{\rho}\left[\delta_+ + \frac{y^2}{4\pi G m_+^2}\left(\delta_+ - \delta_-\right)\right] \\
\frac{\partial^2 \delta_-}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta_-}{\partial t} &= 4\pi G\bar{\rho}\left[\delta_+ + \frac{y^2}{4\pi G m_+ m_-}\left(\delta_- - \delta_+\right)\right], \\
\frac{\partial^2 \delta_{\rm baryon}}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta_{\rm baryon}}{\partial t} &= 4\pi G\bar{\rho}\delta_+ .
\end{aligned}$$

The $(-)$ dark matter settles where the mass density, ρ_+, is least, and pushes the remnant massive dark matter, but not loose baryons, out of the protovoids.

This could be a Good Thing.

The Void Phenomenon

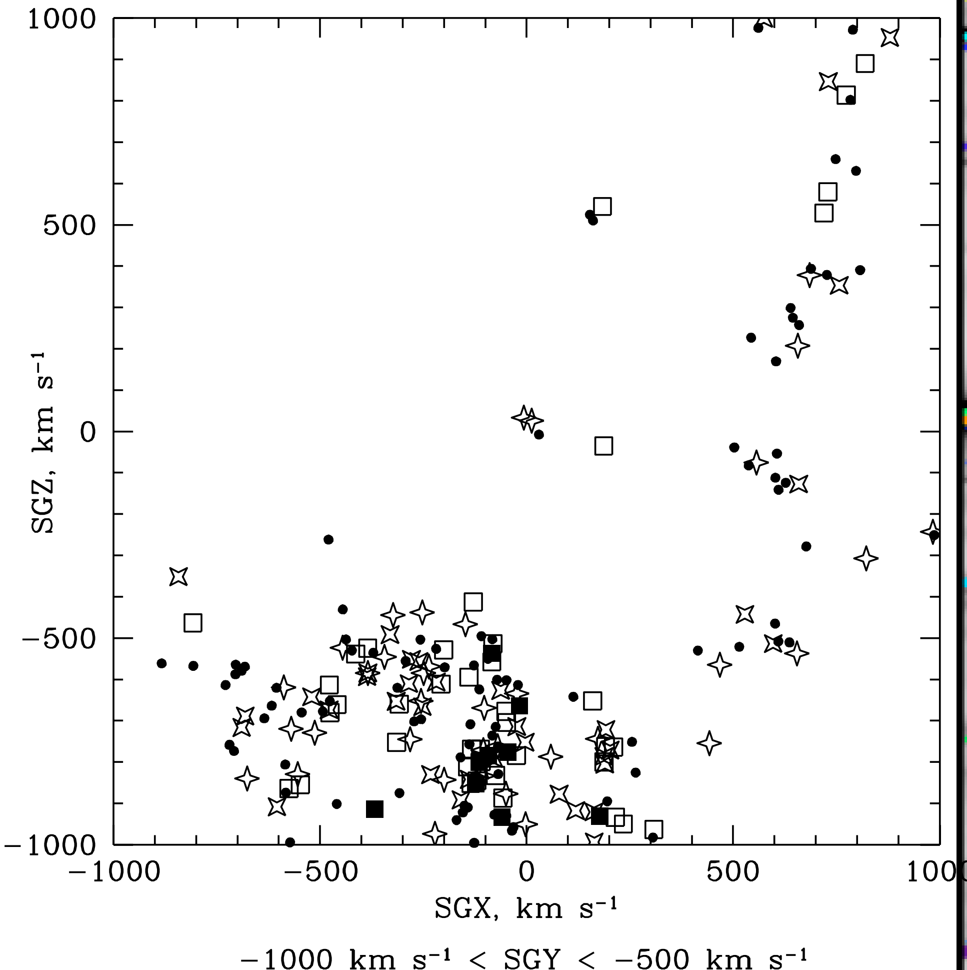
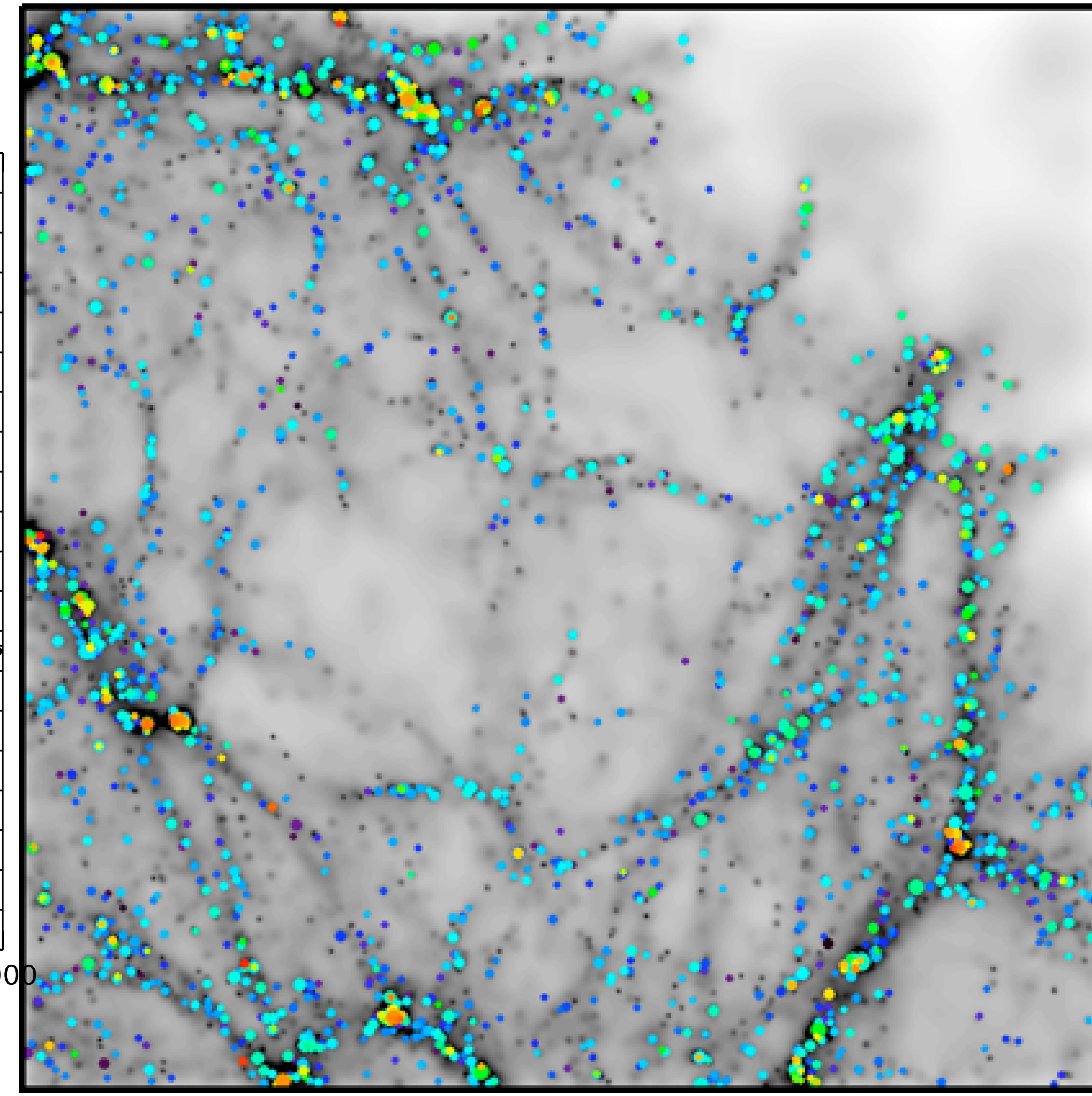


FIG. 2.—Map of ORS galaxies in a slice in redshift space. The normal to the slice points in the direction of the Virgo Cluster, from the opposite side of the Milky Way. Filled squares are elliptical galaxies, open squares are S0 galaxies, crosses are Sa–Sc galaxies, plus signs are later spiral types, and filled circles are dwarfs and irregulars.



Mathis & White, MNRAS 337, 2002

Under close to adiabatic initial conditions charge neutrality eliminates the scalar force in linear perturbation theory, so this model passes most of the cosmological tests as well as ΛCDM.

Neal Dalal is looking into numerical N-body simulations of the nonlinear development of charge separation. I think it is clear that we can choose parameters to get satisfactorily empty voids; the big issue is whether there are unintended consequences – perhaps earlier formation and greater masses of rich clusters — and if so whether positive or negative.

Let us consider now another issue: the merging of galaxies at low redshifts.

I will argue that the ΛCDM cosmology seems to predict unacceptably pronounced merging of galaxies at redshifts $z < 1$, and that this might be remedied by a scalar force in the dark sector, with parameters that differ from — or maybe complement — the parameters that could remedy the void problem.

A HIGH MERGER FRACTION IN THE RICH CLUSTER MS 1054−03 AT z = 0.83: DIRECT EVIDENCE FOR HIERARCHICAL FORMATION OF MASSIVE GALAXIES[1,2]

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Received 1999 March 17; accepted 1999 June 1; published 1999 June 25

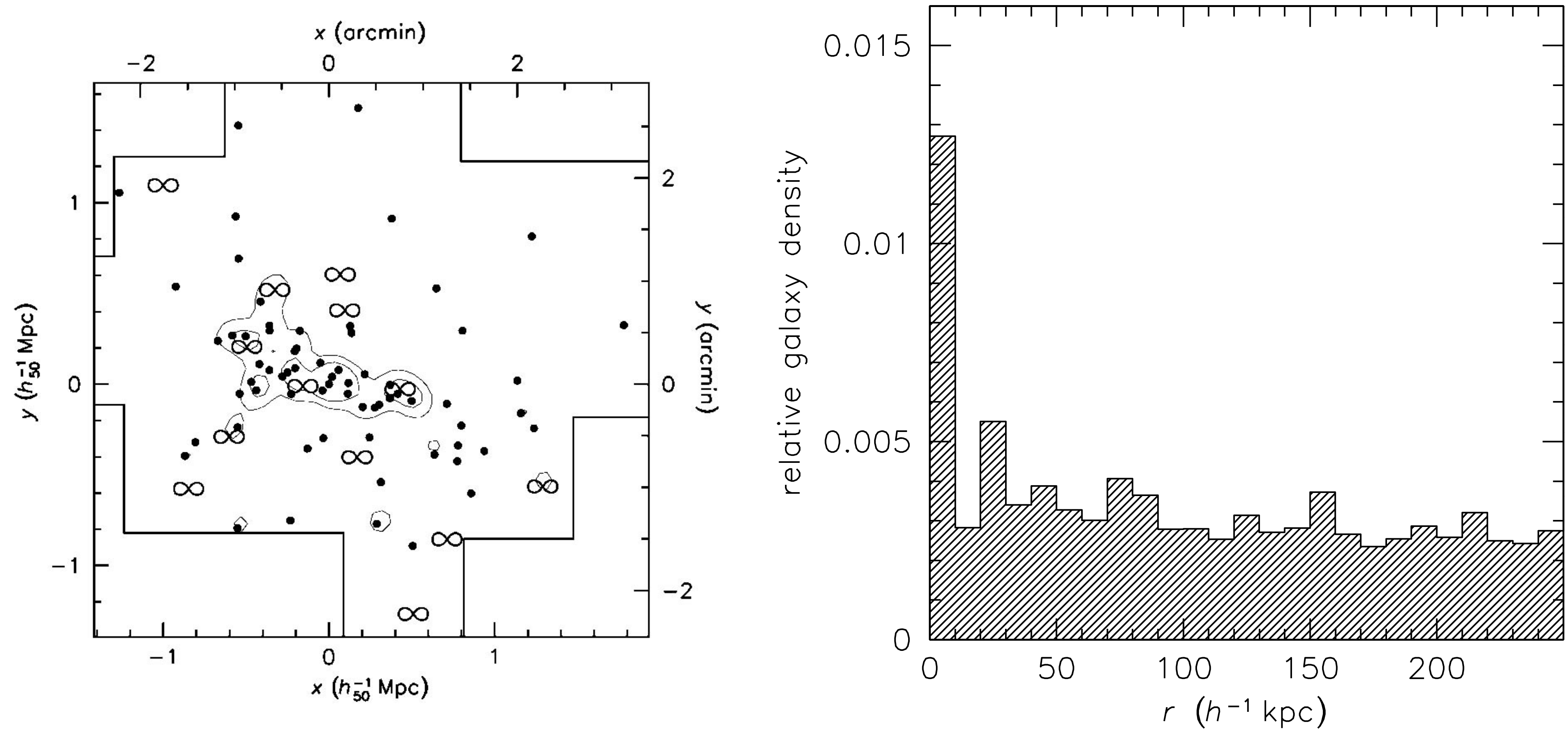
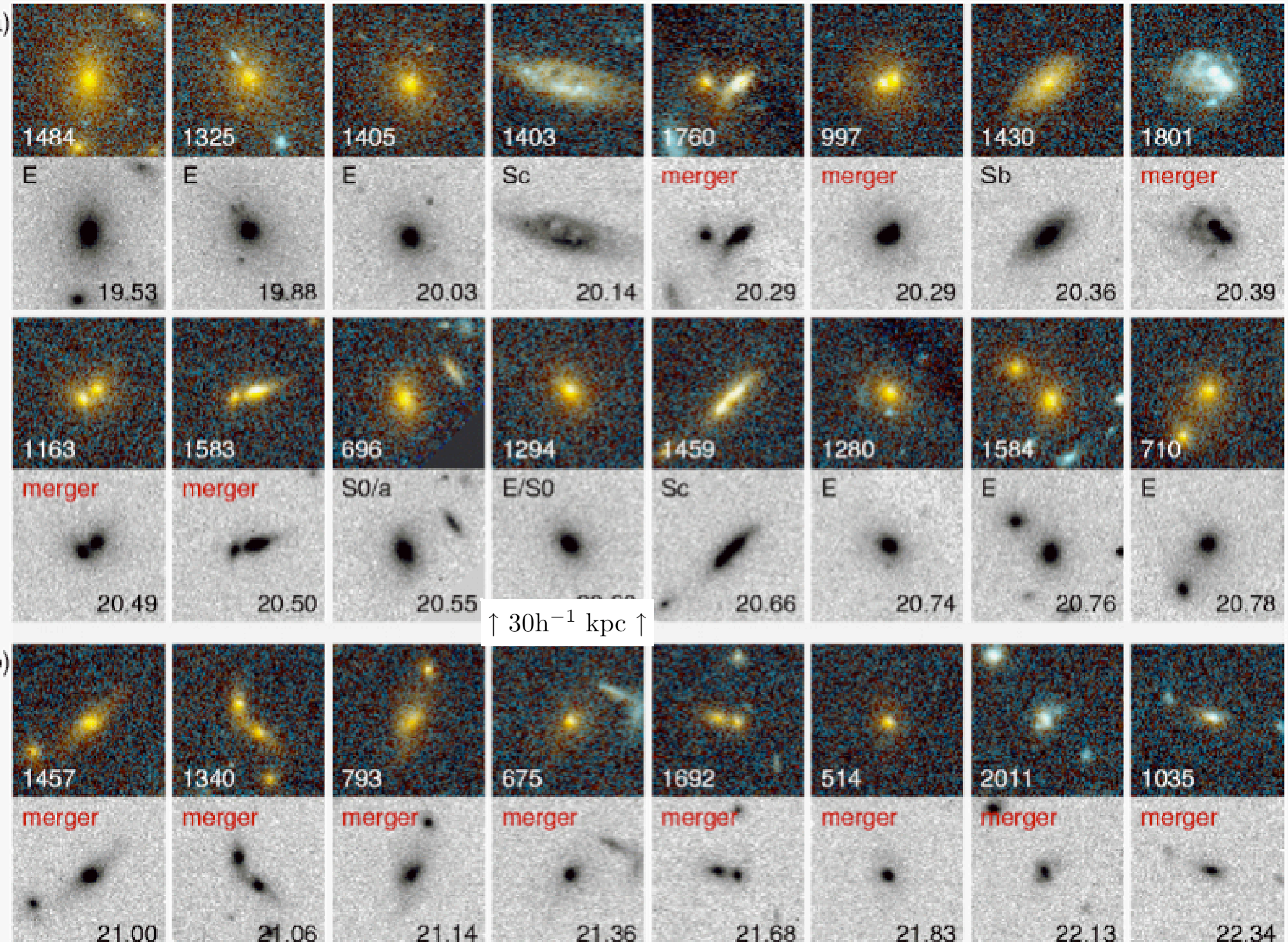


FIG. 2.– Spatial distribution of confirmed cluster members in MS 1054−03. Isodensity contours indicate the distribution of red galaxies in the *HST* data. Note the filamentary galaxy distribution. Mergers are indicated by infinity symbols. The mergers are preferentially found in the outskirts of the cluster, indicating they probably reside in cold infalling clumps.



1484
E
19.53
1325
E
19.88
1405
E
20.03
1403
Sc
20.14
1760
merger
20.29
997
merger
20.29
1430
Sb
20.36
1801
merger
20.39
1163
merger
20.49
1583
merger
20.50
696
S0/a
20.55
1294
E/S0
1459
Sc
20.66
1280
E
20.74
1584
E
20.76
710
E
20.78
↑ 30h^{-1} kpc ↑
1457
merger
21.00
1340
merger
21.06
793
merger
21.14
675
merger
21.36
1692
merger
21.68
514
merger
21.83
2011
merger
22.13
1035
merger
22.34

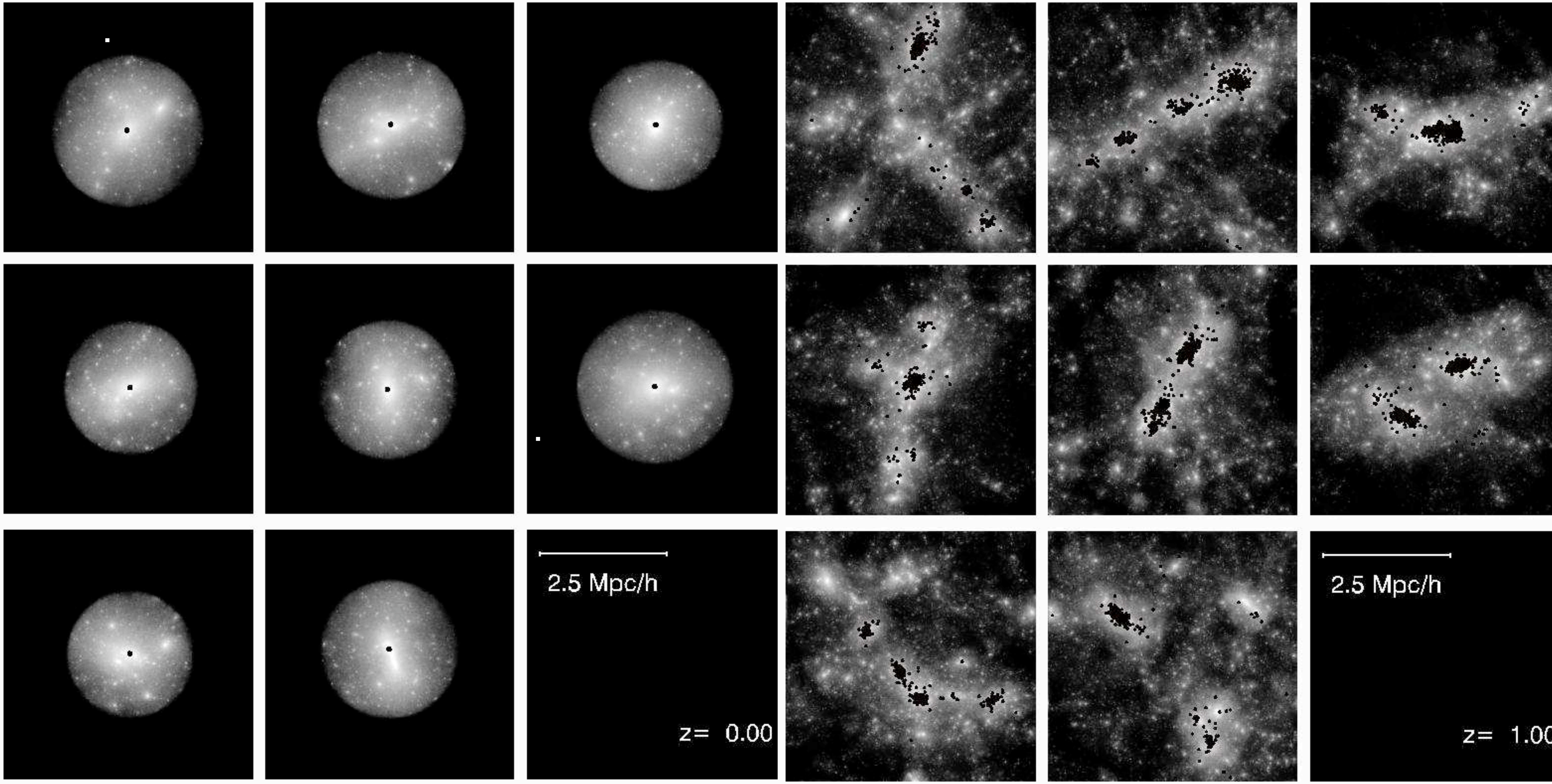


Fig. 2.— Images of the mass distribution at $z = 0, 1$ and 3 in our 8 simulations of the assembly of cluster mass halos. Each plot shows only those particles which lie within r_{200} of halo center at $z = 0$. Particles which lie within $10h^{-1}$ kpc of halo center at this time are shown in black. Each 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]

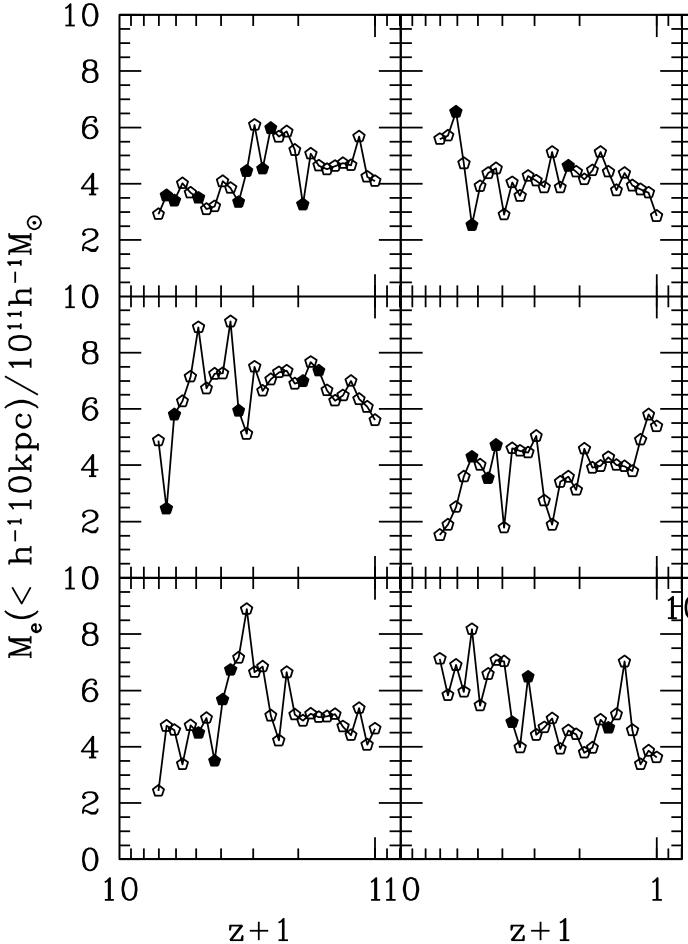


Fig. 3.— The total mass within physical distance $10h^{-1}$ kpc of the center of the most massive progenitor of the final halo at each time plotted and for each of our 8 simulations. Symbols switch between filled and open each time the identity of the most massive progenitor changes.

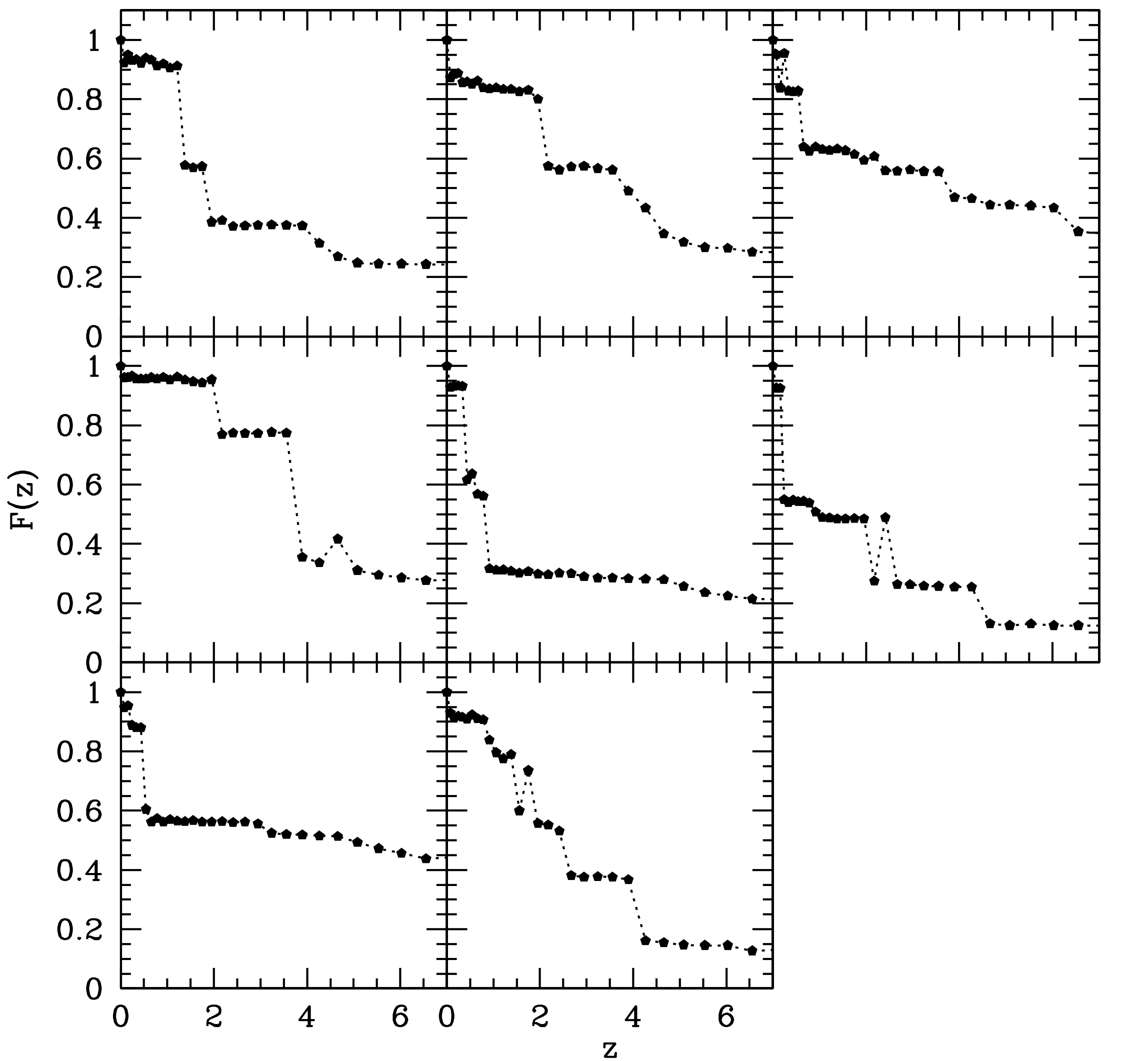


Fig. 4.— History of addition of the matter now in the central parts of massive halos. Th black curves show the fraction of the particles at $r < 10h^{-1}$ kpc at $z = 0$ which lie withi $100h^{-1}$ kpc (physical) distance from the center of their main concentration at each earlie redshift z.

Gao, Loeb, Peebles, White, Jenkins, astro-ph/0312499

These simulations seem to indicate that in the ΛCDM cosmology on average about one third of the matter now within the half-light radius of the central cD in a rich cluster was at $z = 1$ spread over a few megaparsecs.

This pronounced late merging is in line with the large number of binary galaxies in MS 1054,

but is it consistent with the apparently relaxed morphologies and modest evolution of the giant cDs at $z < 1$, and with their old stellar ages: how could the cDs know to accrete only early-type objects?

THE DETAILED FUNDAMENTAL PLANE OF TWO HIGH REDSHIFT CLUSTERS: MS 2053–04 AT Z=0.58 AND MS 1054–03 AT Z=0.83

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astro-ph/0312236

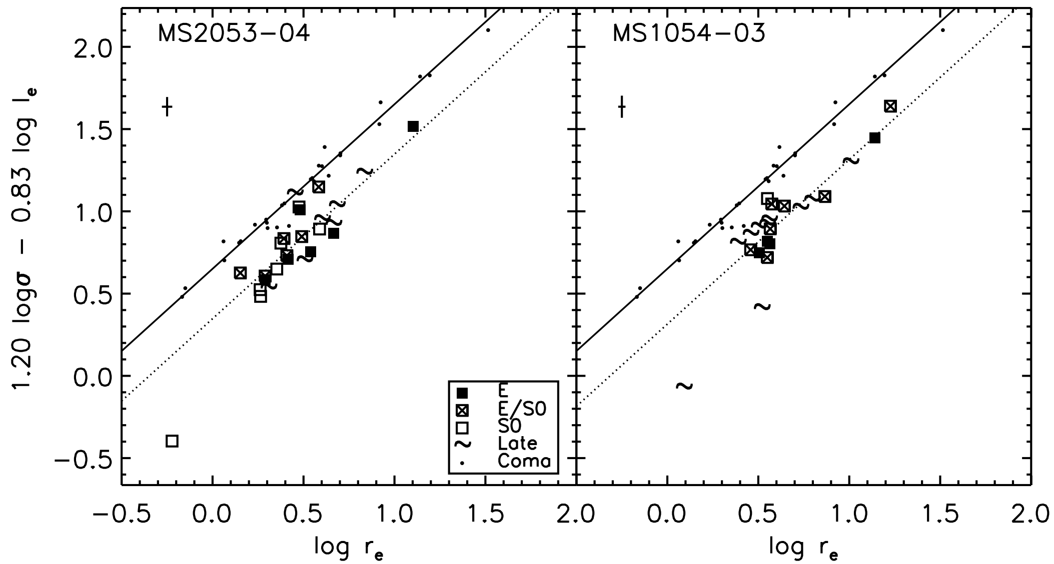
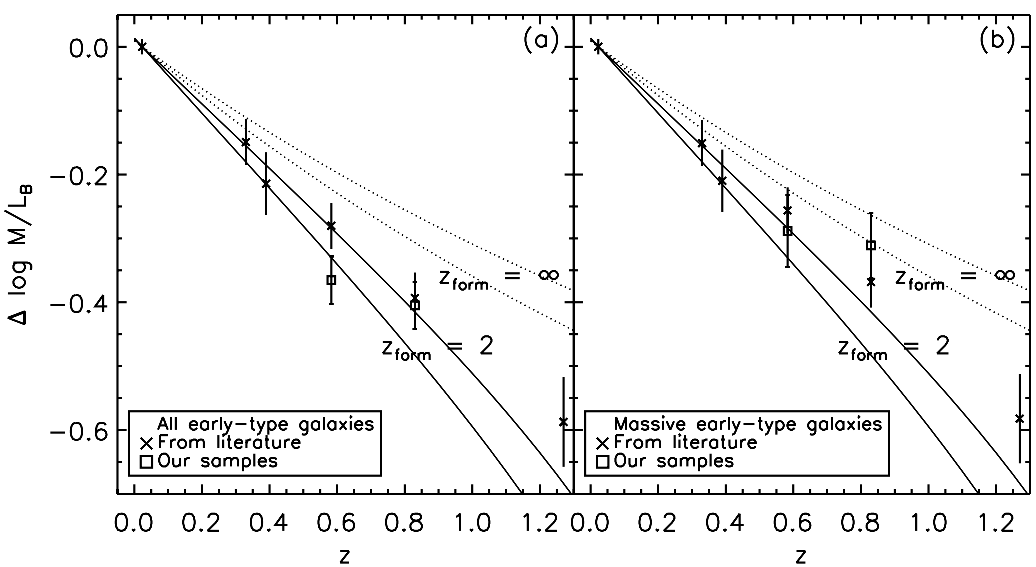


FIG. 5.— The fundamental plane of clusters MS 2053–04 (z=0.583) and MS 1054–03 (z=0.83). The Coma FP is drawn for reference. Typical error bars are plotted in the upper left corner. Cluster galaxies in the higher redshift clusters follow the FP scaling relation, but with an offset with respect to Coma. Galaxies with early-type morphologies show a larger scatter than in the local universe.



The evolution of the fundamental planes for these two clusters is consistent with pure passive evolution from star formation at $z_f \sim 2$ to 3.

If these galaxies had enjoyed significant growth by merging at $z \sim 1$ it had to have been merging selectively with stellar systems that were already old,

and merging must not have substantially affected the central dark matter mass fraction,

unless the two fortuitously cancel.

MULTIPLICITY OF THE FIRST BRIGHTEST GALAXY IN A CLUSTER VERSUS BAUTZ-MORGAN TYPE

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University of British Columbia
Received 1979 January 22; accepted 1979 March 29

	BM = I	I-II	II	II - III	III
All *D*:					
Multiple...........	15	13	39	59	33
Single.............	43	51	194	315	921
% *M*/100..........	.26	.20	.17	.16	.03

The time scale for merger by tidal energy transfer can be estimated from application of basic dynamical principles first outlined in a different context by Spitzer (1958). We find t (tidal) $\sim 3 \times 10^8$ yr.

The theoretical time scales for merger of a few times 10^7 yr (or 10^8 yr) are extremely small. Binary supergiant galaxies are predicted to coalesce forming single supergiant galaxies in 10^{-3} (or 10^{-2}) of the age of the universe. Why, then, do we see so many of them? As a

Bautz-Morgan type I has a central cD

DYNAMICALLY CLOSE GALAXY PAIRS AND MERGER RATE EVOLUTION IN THE CNOC2 REDSHIFT SURVEY

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Received 2001 July 23; accepted 2001 September 25

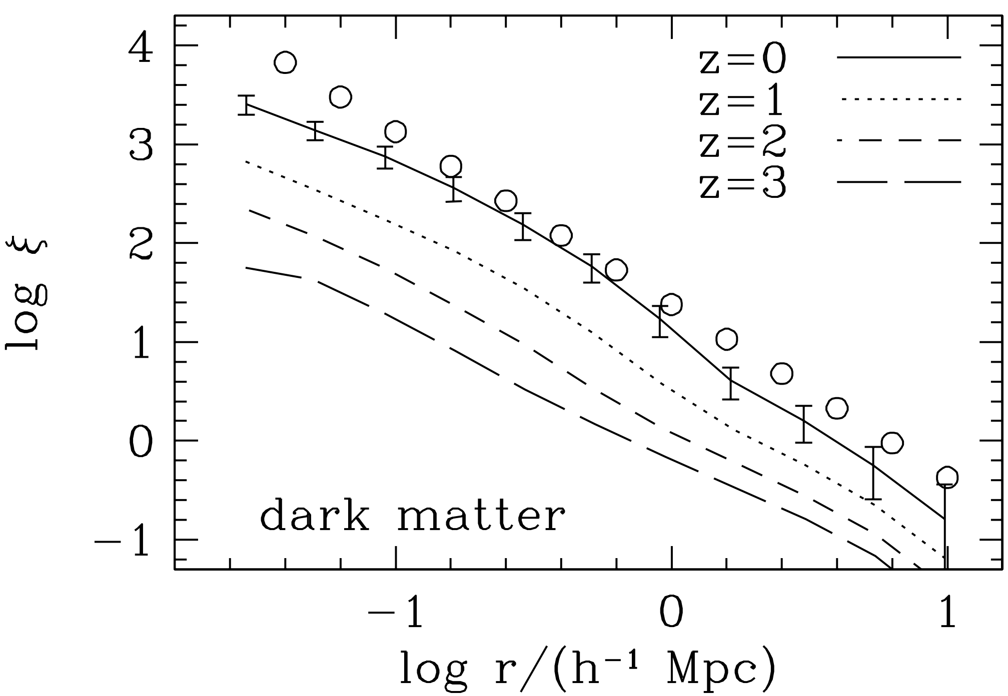
kpc and comparing with the low-redshift SSRS2 pair sample, we infer evolution in the galaxy merger and accretion rates of $(1 + z)^{2.3 \pm 0.7}$ and $(1 + z)^{2.3 \pm 0.9}$, respectively. These are the first such estimates to be made using only confirmed dynamical pairs. When combined with several additional assumptions, this implies that approximately 15% of present epoch galaxies with $-21 \leq M_B \leq -18$ have undergone a major merger since $z = 1$.

Mergers certainly happen.
but what is the rate?

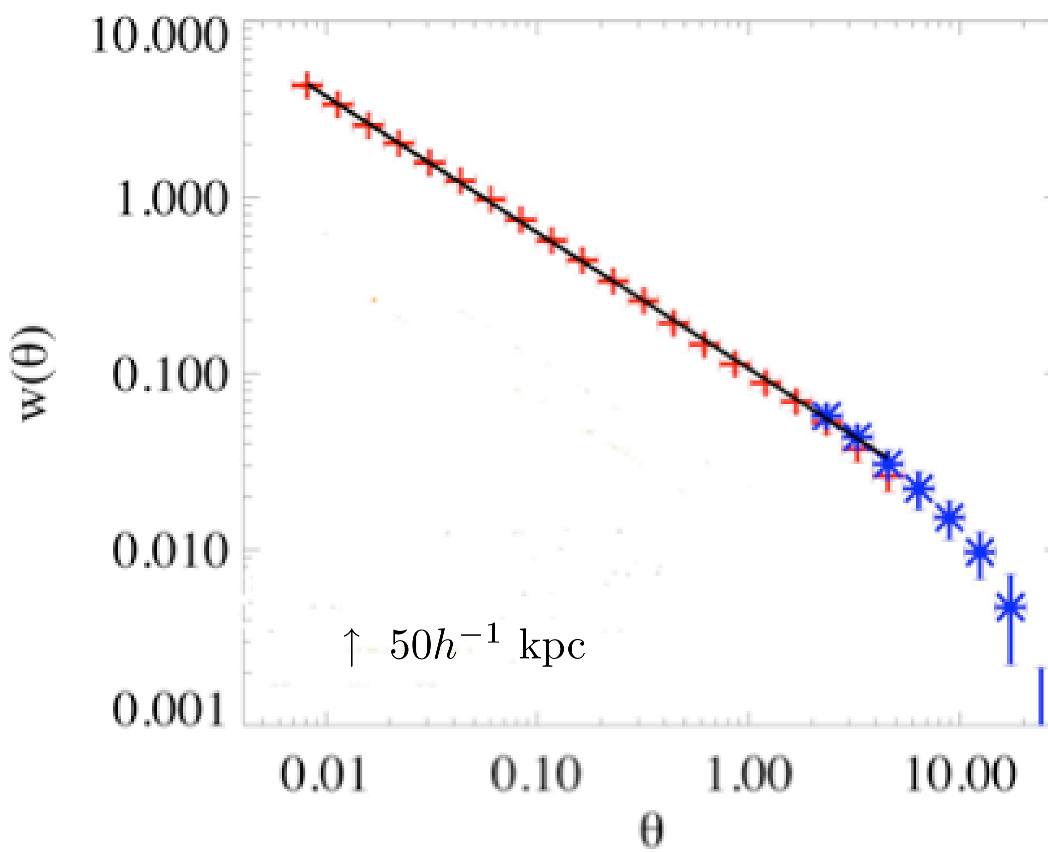
Estimates of the galaxy merger rate from the abundance of close pairs of galaxies assume bound systems of galaxies at separations $\lesssim 100$ Mpc merge in a Hubble time.

This is sound if the dark matter is well approximated as a gas of particles that interact only with gravity, and the indicated merger rate seems reasonable or even modest compared to what one sees in the simulations.

But it would imply that the power law form of the galaxy two-point correlation function is a cruelly misleading accident.

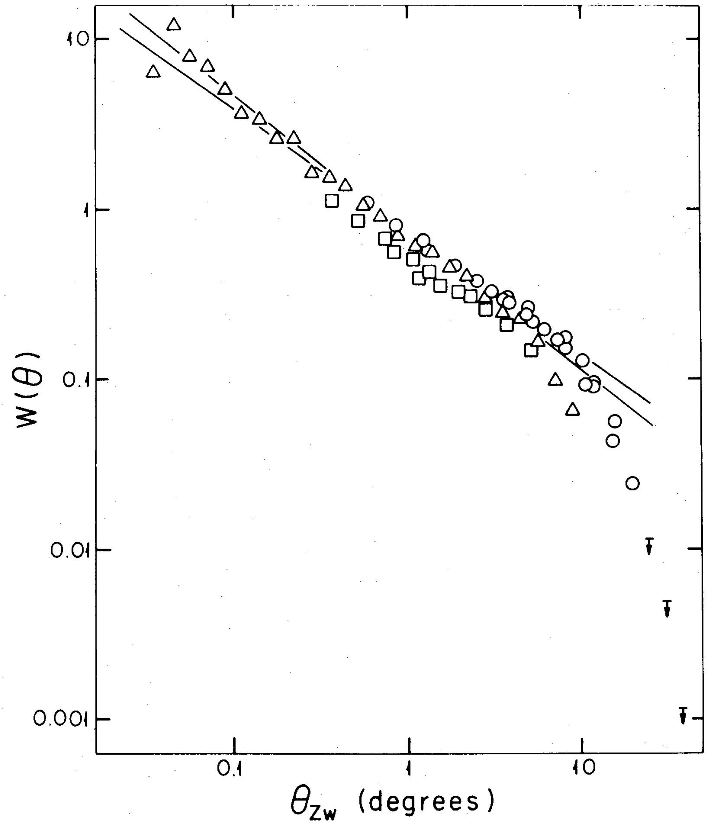


Weinberg et al. 2004

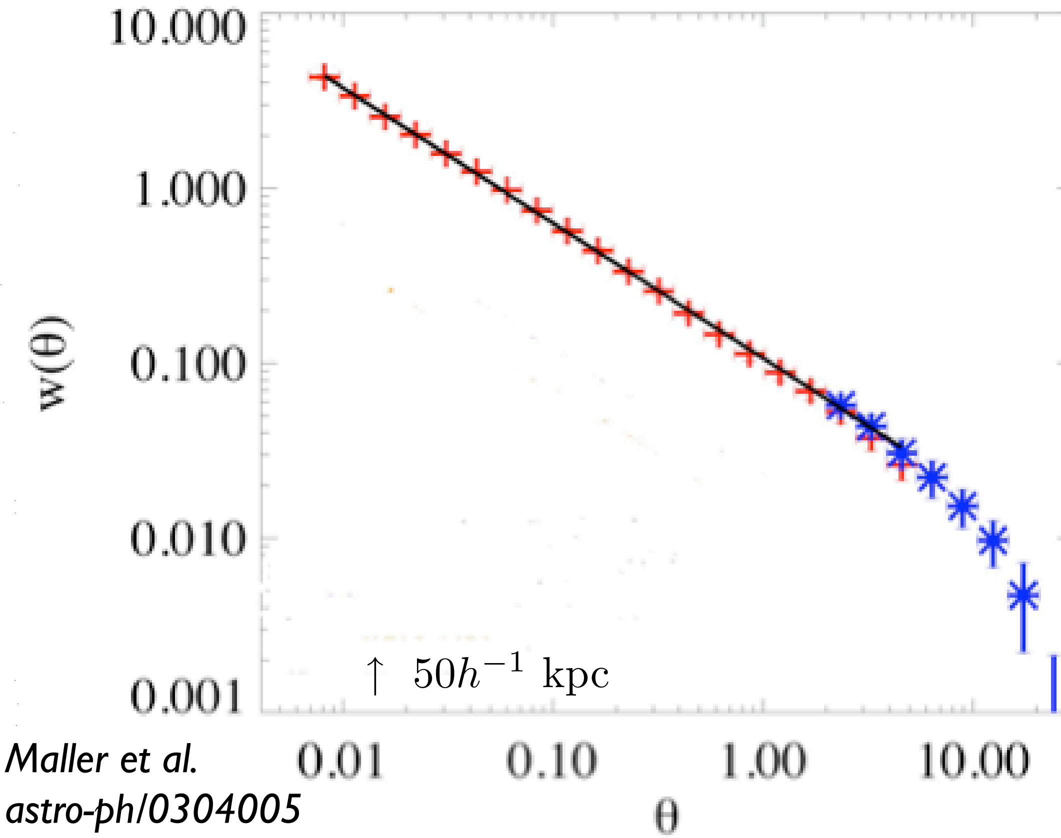


Maller, et al. astro-ph/0304005 analysis of SDSS

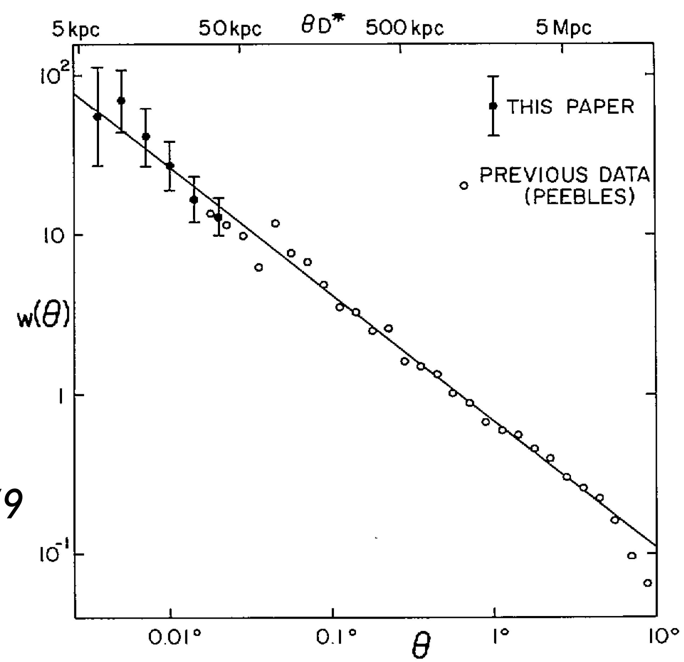
Groth & Peebles 1977; various catalogs



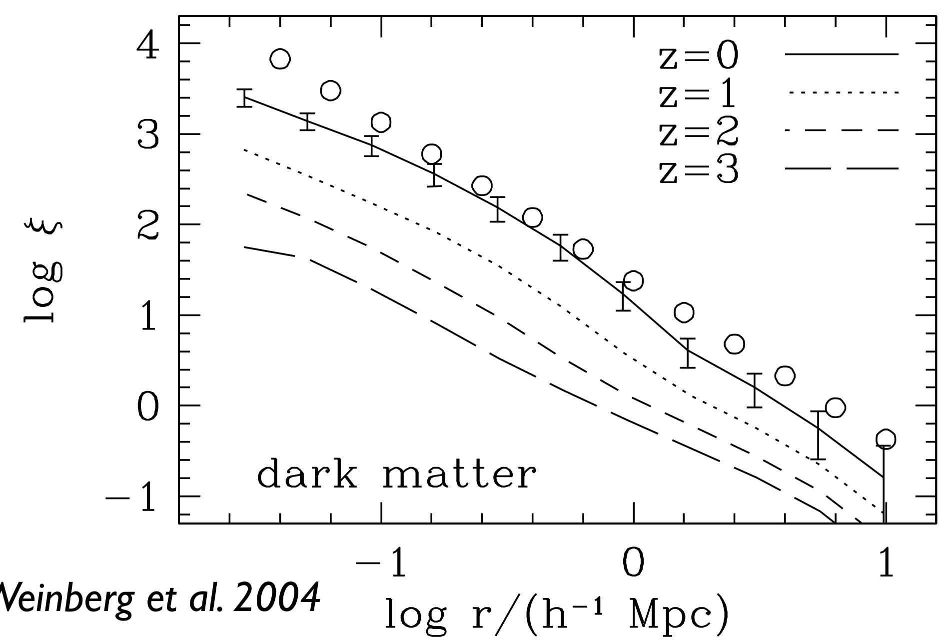
Maller et al. astro-ph/0304005



Turner & Gott 1979



Weinberg et al. 2004



Merging and a Scalar Force in the Dark Sector

If $\bar{n}_+ = \bar{n}_-$, $y_+ = y_- = y$ and $m_+ \simeq m_- = m$ the force law is

$$F_{++} = F_{--} = \frac{Gm^2}{r^2}(1+\beta), \quad F_{+-} = \frac{Gm^2}{r^2}(1-\beta), \quad \beta = \frac{y^2}{4\pi Gm^2}.$$

If $\beta = 1$ then in a binary with massive halos of opposite charge the dark matter particles in one halo see only the baryons in the other, and the relative acceleration of the two galaxies is

$$g \sim \frac{GM_{\rm stars}}{r^2},$$

down from the standard cosmology by $M_{\rm stars}/M_{\rm halo}$.

This could be a Good Thing.

If $\beta \gtrsim 1$ and initial conditions are close to adiabatic then I expect

1. massive halos have single scalar charges;
2. more rapid nonlinear development of charged halos produces more tightly bound halos at higher redshift; and
3. the relative acceleration of oppositely charged halos is reduced or reversed.

To be studied in N-body simulations is whether, relative to the ΛCDM model,

a. cDs exhibit more tranquil evolution at low redshift;

b. dumbell galaxies — with opposite charges —are more common;

c. the structures of cluster-scale halos are any better approximations to the structures of clusters of galaxies;

d. the mass autocorrelation function is more like the galaxy function.