Title: State of the Cosmological Tests

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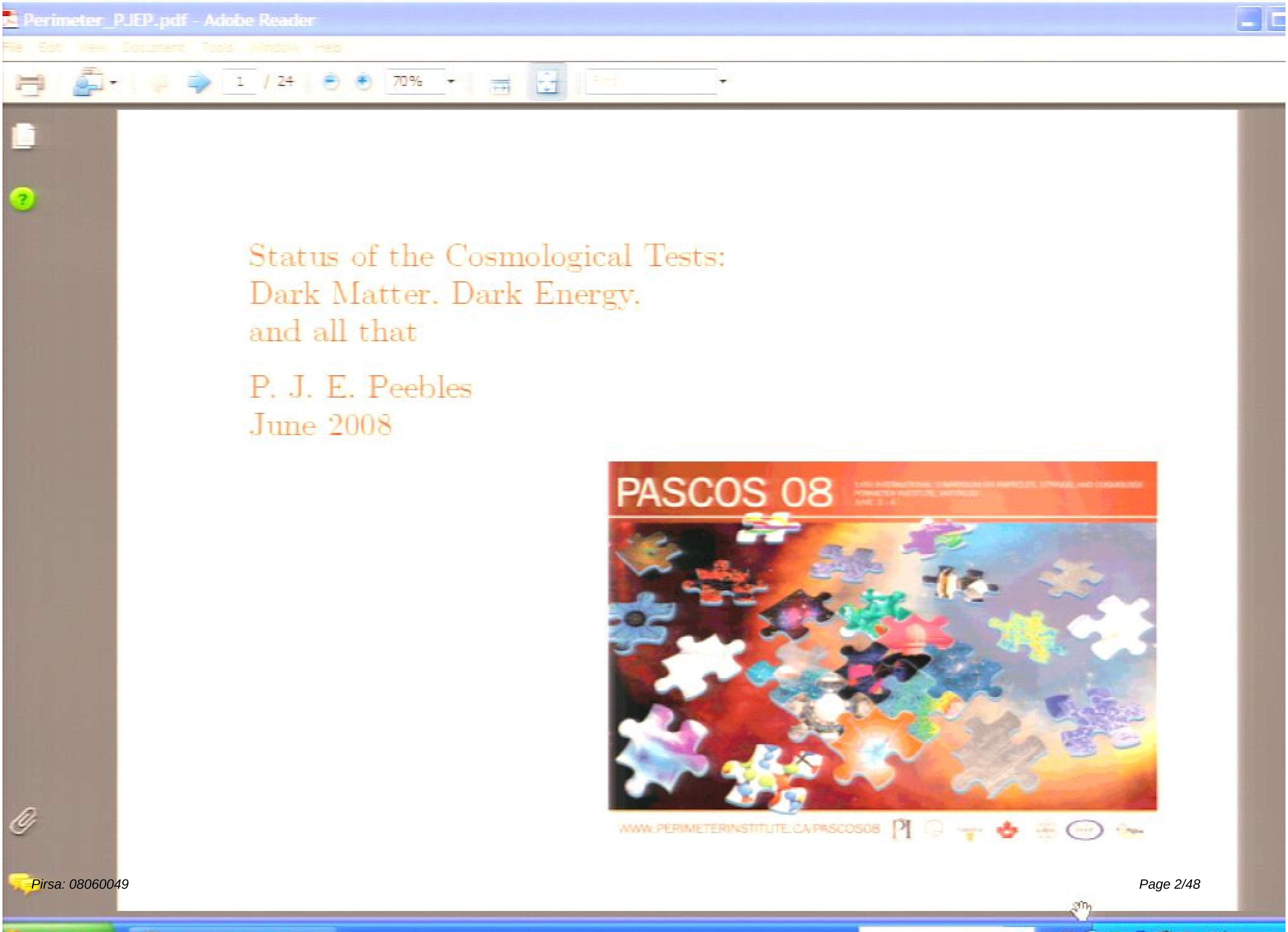
Abstract:



Status of the Cosmological Tests: Dark Matter. Dark Energy. and all that

P. J. E. Peebles
June 2008

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3. The ΛCDM dark sector is vastly simpler than the visible sector. Might this be because the dark sector physics is the simplest approximation we can get away at the present — still exceedingly limited — level of the tests?
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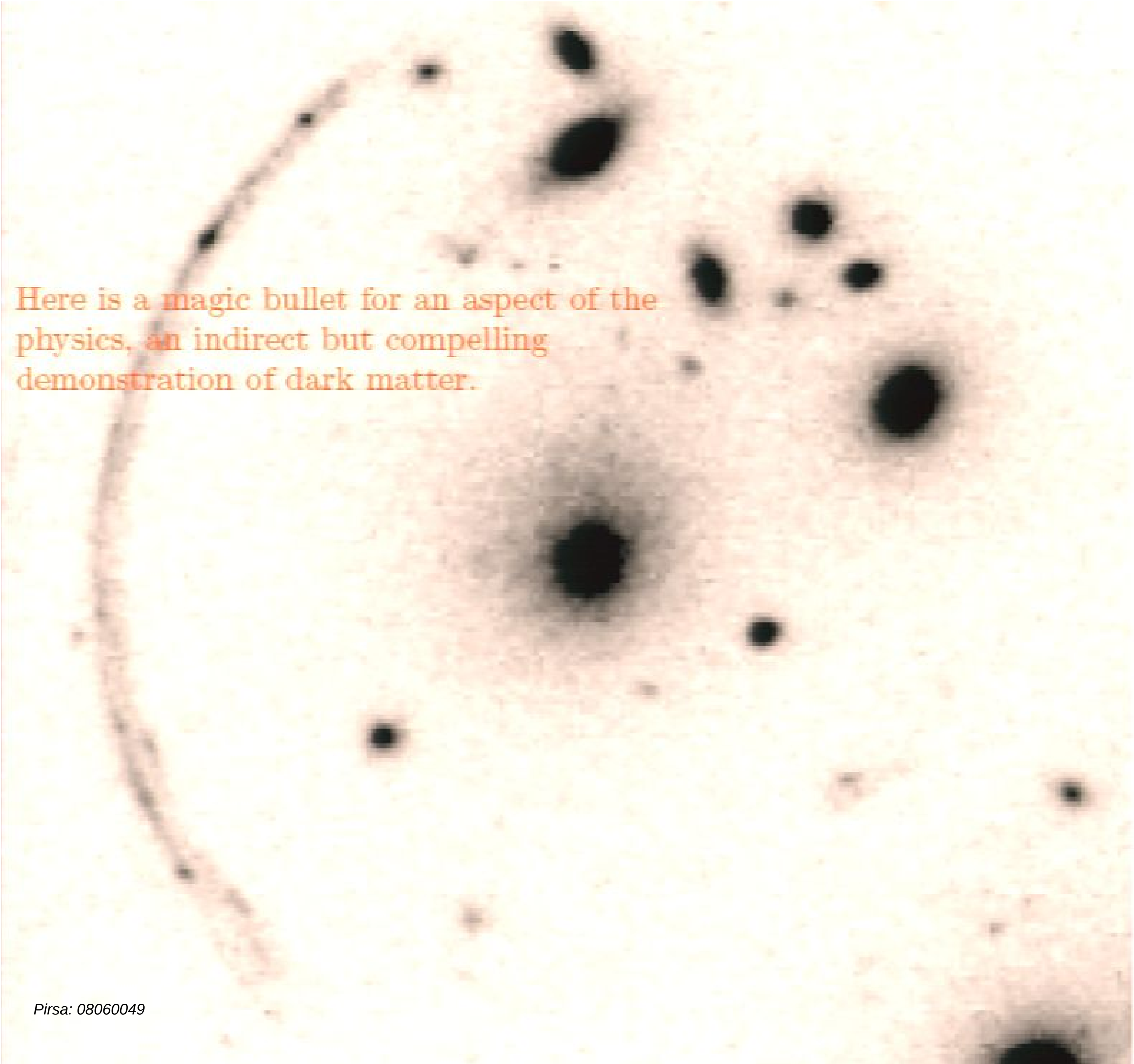

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Smail *et al.* WFPC2 image of the cluster Cl2244-02 at $z = 0.33$.

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But the arc radius is "only" 150 kpc. Might Jupiters fill the inner 100 kpc, and a r^{-1} law explain what happens at 1 Mpc?

We need more tests.

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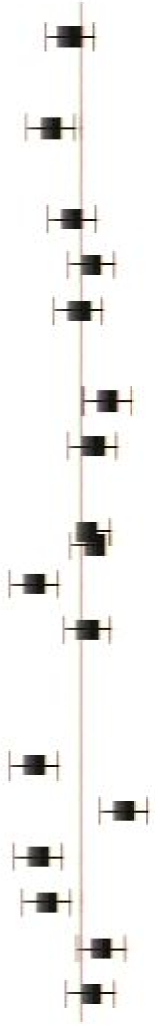

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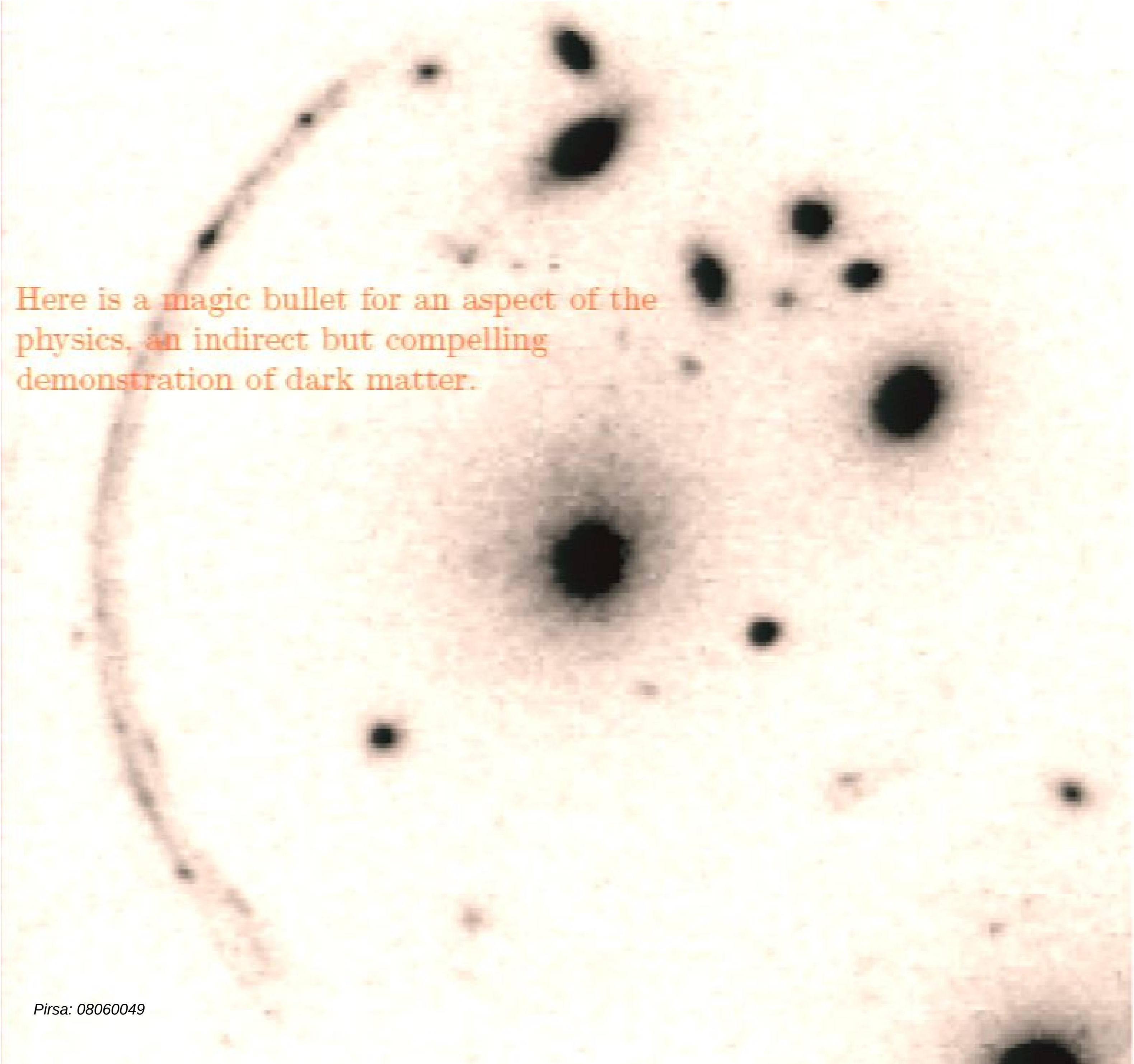

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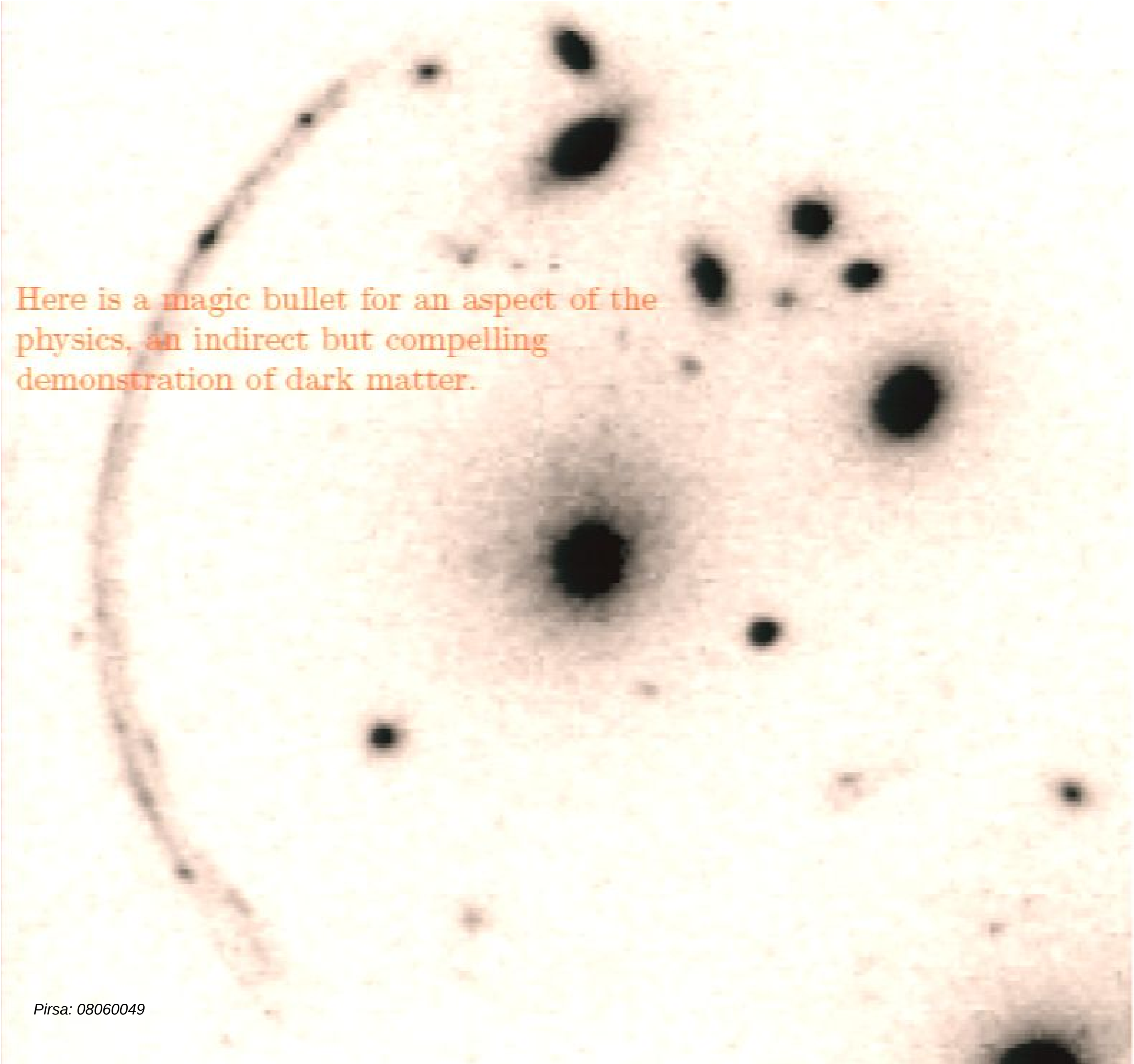

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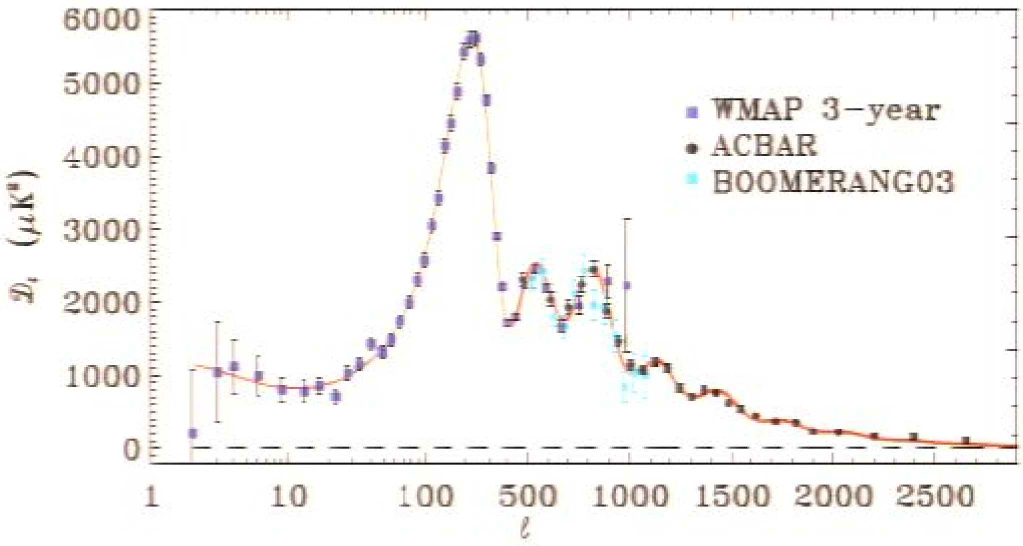


In the spherical harmonic expansion

$$T(\theta,\phi)=\sum a_l^m Y_l^m(\theta,\phi),$$

of the 3 K CBR temperature as a function of position in the sky the variance of the sky temperature per logarithmic interval of angular scale $\delta\theta \sim \pi/l$ is approximately

$$\mathcal{D}_l=\frac{l(l+1)}{2\pi}\langle|a_l^m|^2\rangle.$$

The curve has 7 parameters: distance scale h, densities $\Omega_b h^2$ of baryons, $\Omega_m h^2$ of dark matter, and (constant) $\Omega_\Lambda h^2$ of dark energy, primeval power spectrum power law index n_s and amplitude σ_8, and optical depth σ for scattering at low redshift.

The fit is impressive, but consider that

1: if the theoretical spectrum is smooth predictions at neighboring ℓ are not independent, though I know of no way to quantify this;

2: we had a choice of theories — isocurvature; strings, explosions — and chose ΛCDM, with dark matter and dark energy, because it is the most successful: we had more freedom of adjustment than the 7 parameters;

3: at $2.3\,\sigma$ an open CDM model with $\Lambda=0$ fits as well.

Might some brilliant iconoclast find another theory that fits? It is important that we have other tests that make this much more challenging.

Here are 43 statistically independent WMAP3 spectrum measurements with

$$\sum (\mathcal{O} - \mathcal{M})^2/\sigma^2 = 35,$$

as close as one can want to the expected value, 43 − 7, given the freedom to choose

$$\Omega_{\rm CDM} = 0.21, \ \Omega_{\rm b} = 0.044, \ h = 0.72,$$

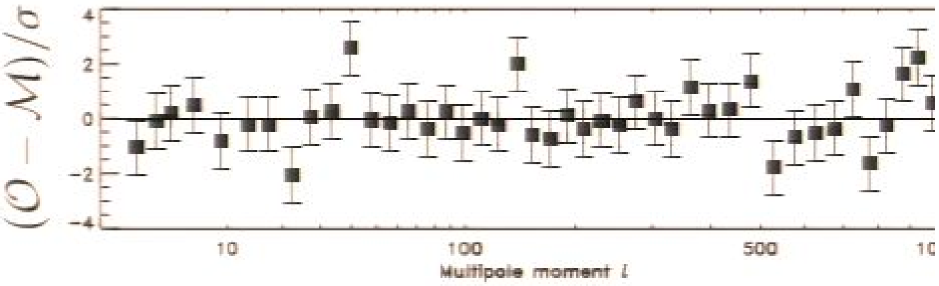
$$n_s = 0.96, \ \sigma_8 = 0.80, \ \tau = 0.09.$$

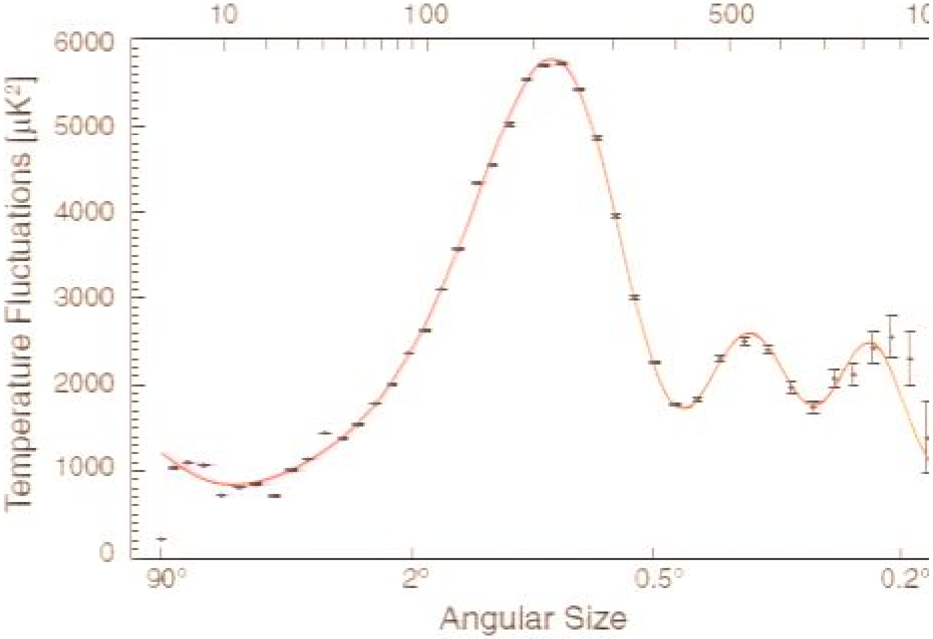
But as we have noted this does not mean ΛCDM has passed 36 independent challenges.

So I propose to consider all the other independent tests one can think of that had a meaningful chance of falsifying this model, reduce each to one or a few numbers, and for each estimate

$$(\mathcal{O} - \mathcal{M})/\sigma.$$

A caution: some standard deviation estimates depend on properties of complex systems such as galaxies whose behavior cannot be fully analyzed from first principles; other estimates are just difficult. You have to deal with judgement calls.





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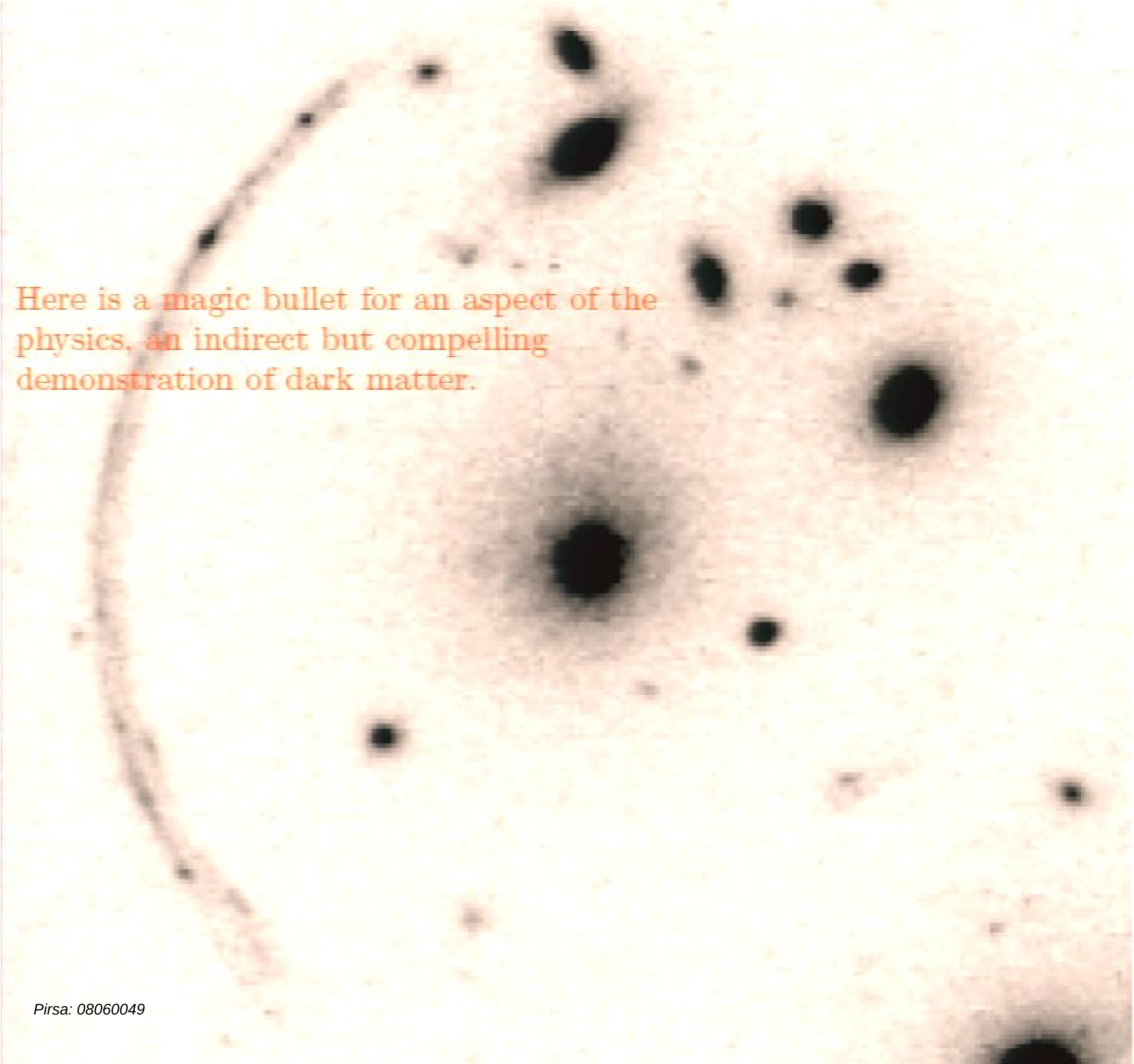

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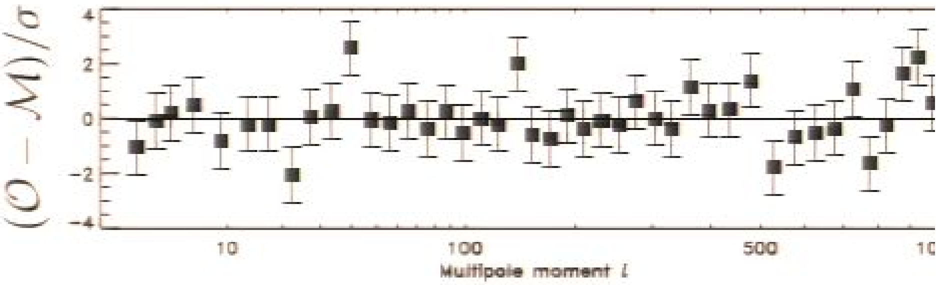

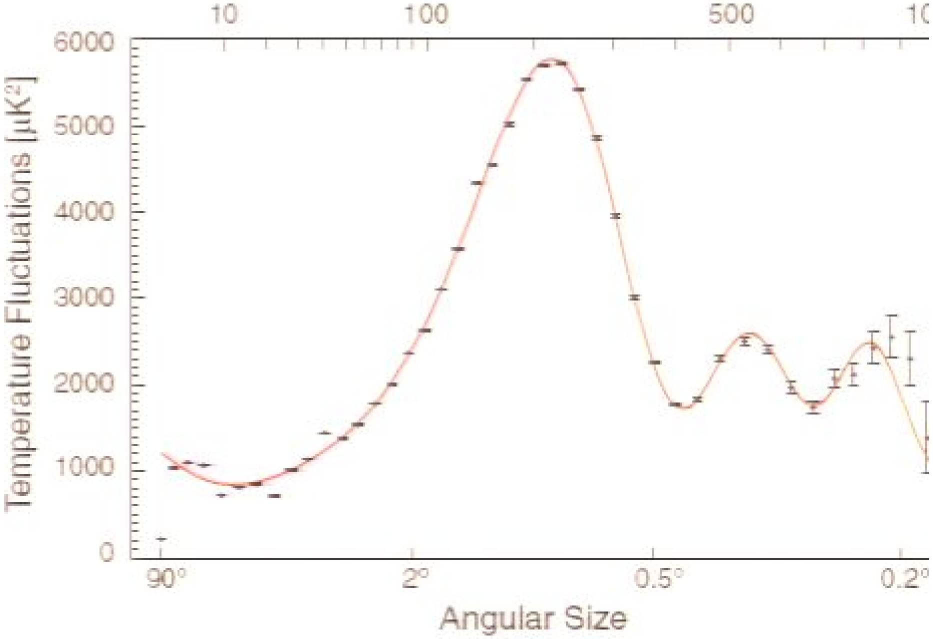

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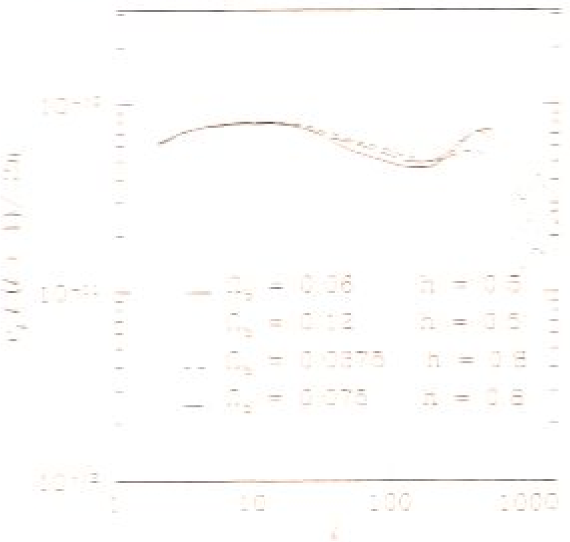
Kaminokowski. Spergel and Sugiyama 1994



WMAPIII:
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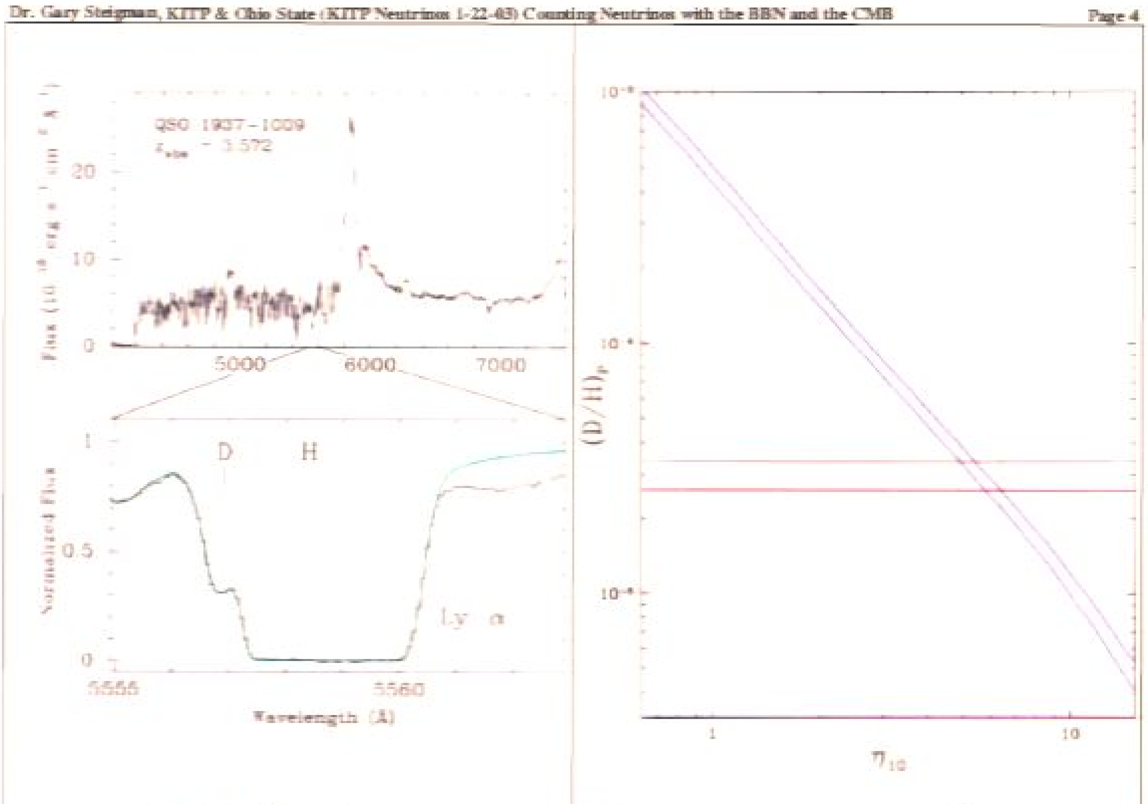
Dr. Gary Steigman, KITP & Ohio State (KITP Neutrinos 1-22-03) Counting Neutrinos with the BBN and the CMB

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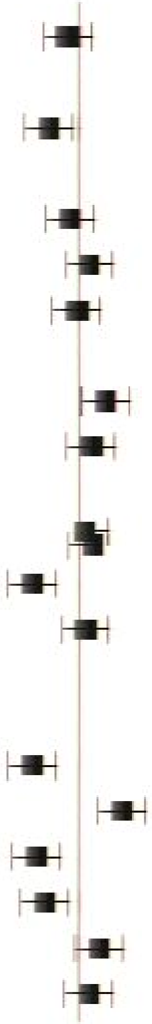

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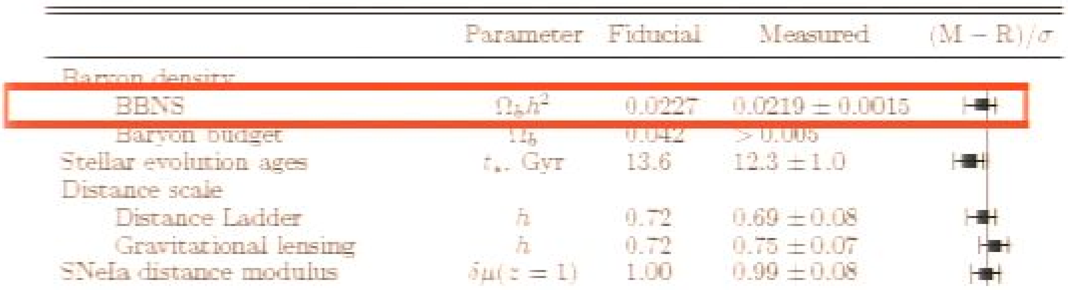

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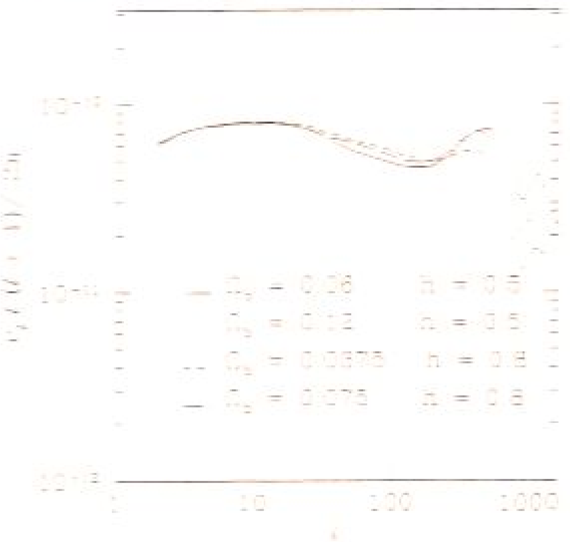

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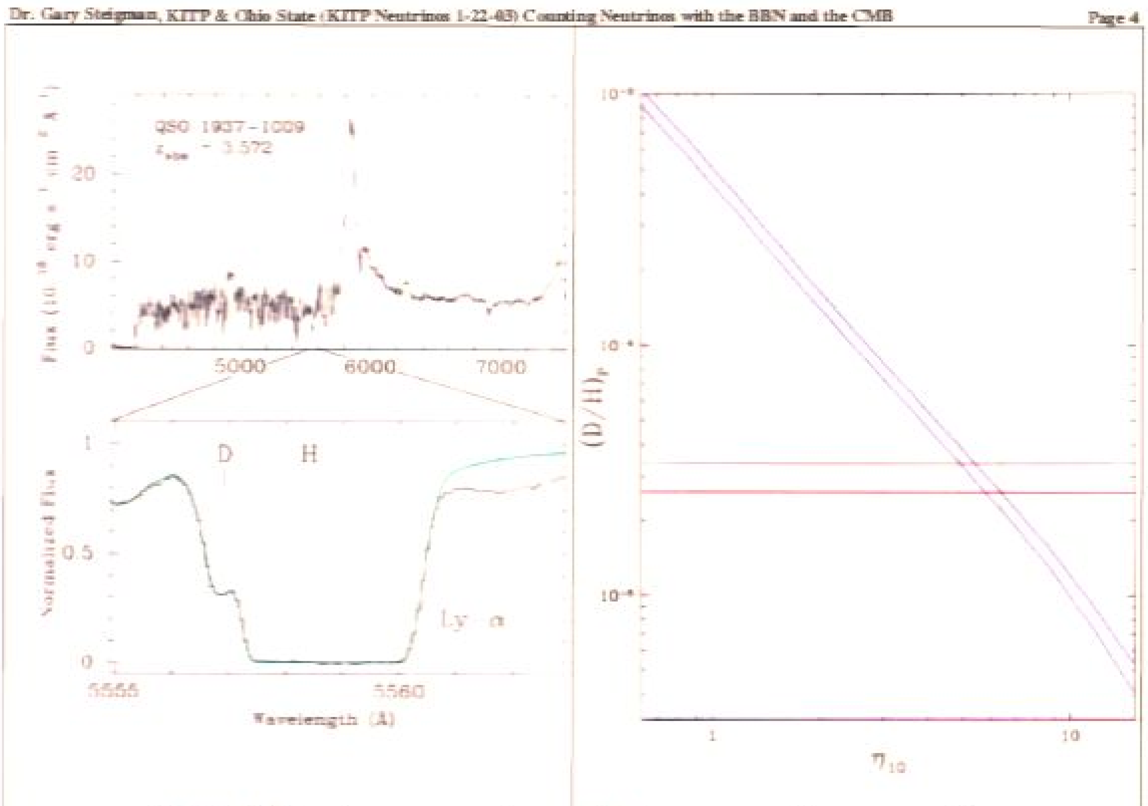

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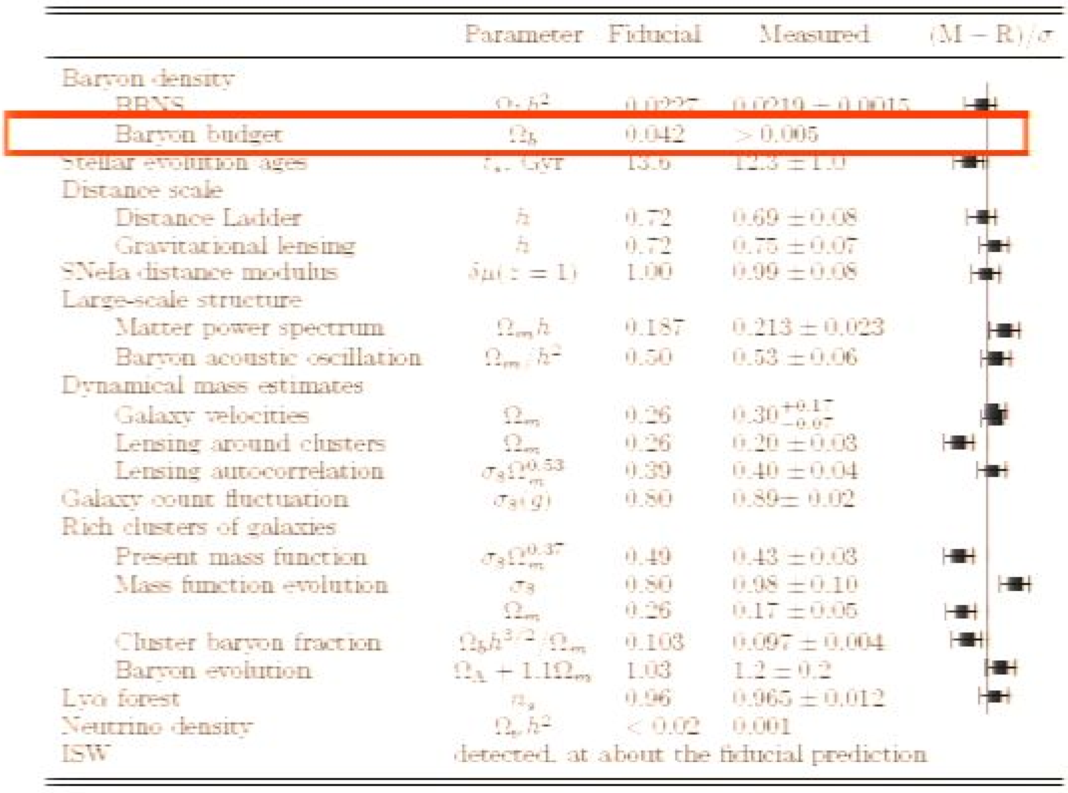

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The observed baryons add up to ten percent of the total density in the standard model. But the measurement is worth listing: the observations could have falsified the model.

some detected in H
resonance absorptio
line clouds, but larg
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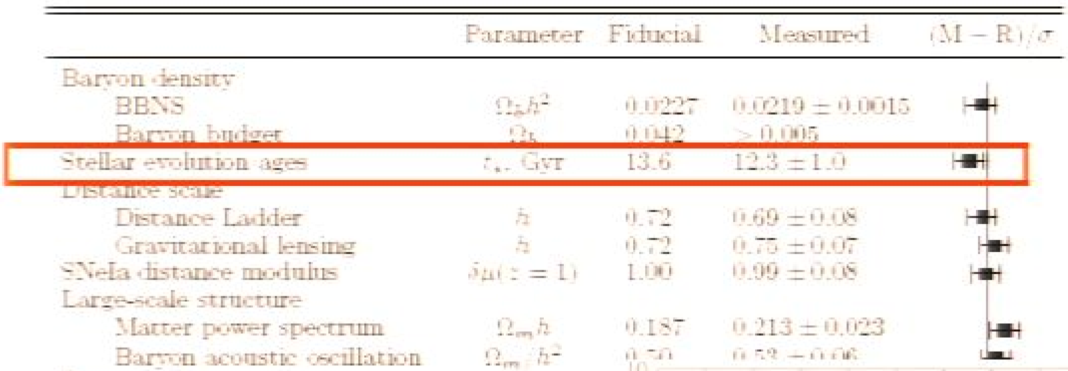
3	Baryon rest mass:			0.045 ± 0.003
3.1	Warm intergalactic plasma		0.040 ± 0.003	
3.1a	Virialized regions of galaxies	0.024 ± 0.005		
3.1b	Intergalactic	0.016 ± 0.005		
3.2	Intracluster plasma		0.0018 ± 0.0007	
3.3	Main-sequence stars: spheroids and bulges		0.0015 ± 0.0004	
3.4	Main-sequence stars: disks and irregulars		0.00055 ± 0.00014	
3.5	White dwarfs		0.00036 ± 0.00008	
3.6	Neutron stars		0.00005 ± 0.00002	
3.7	Black holes		0.00007 ± 0.00002	
3.8	Substellar objects		0.00014 ± 0.00007	
3.9	H I + He I		0.00062 ± 0.00010	
3.10	Molecular gas		0.00016 ± 0.00006	
3.11	Planets		10^{-6}	
3.12	Condensed matter		$10^{-5.6 \pm 0.3}$	
3.13	Sequestered in massive black holes		$10^{-5.4}(1 + \epsilon_n)$	

From Fukugita and Peebles 2004



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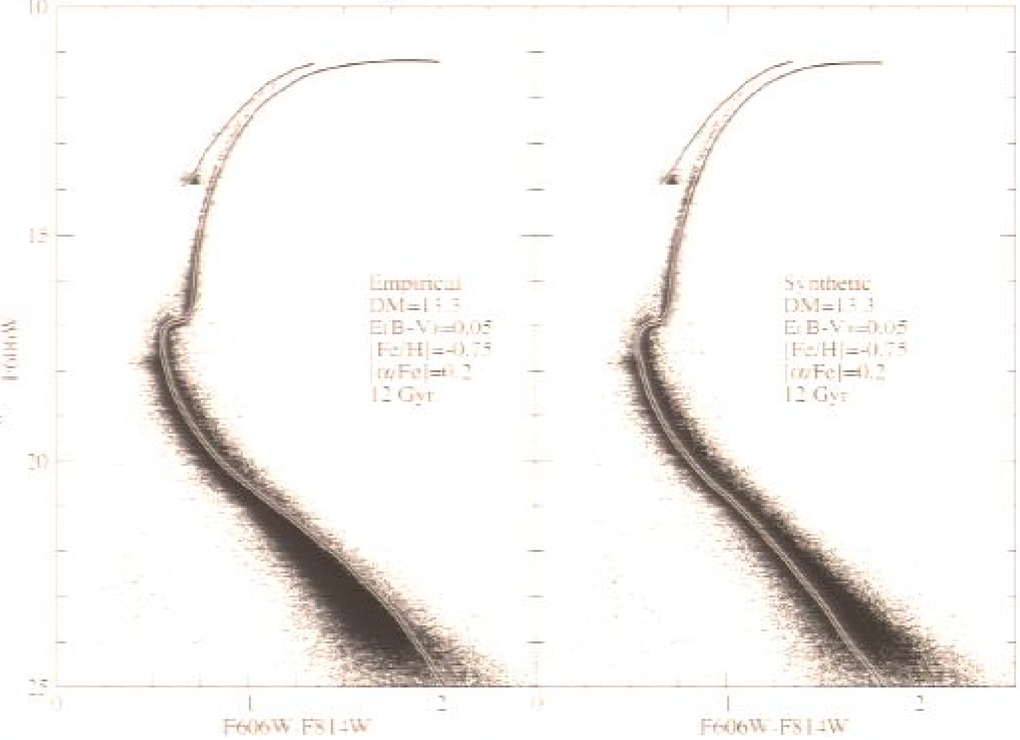
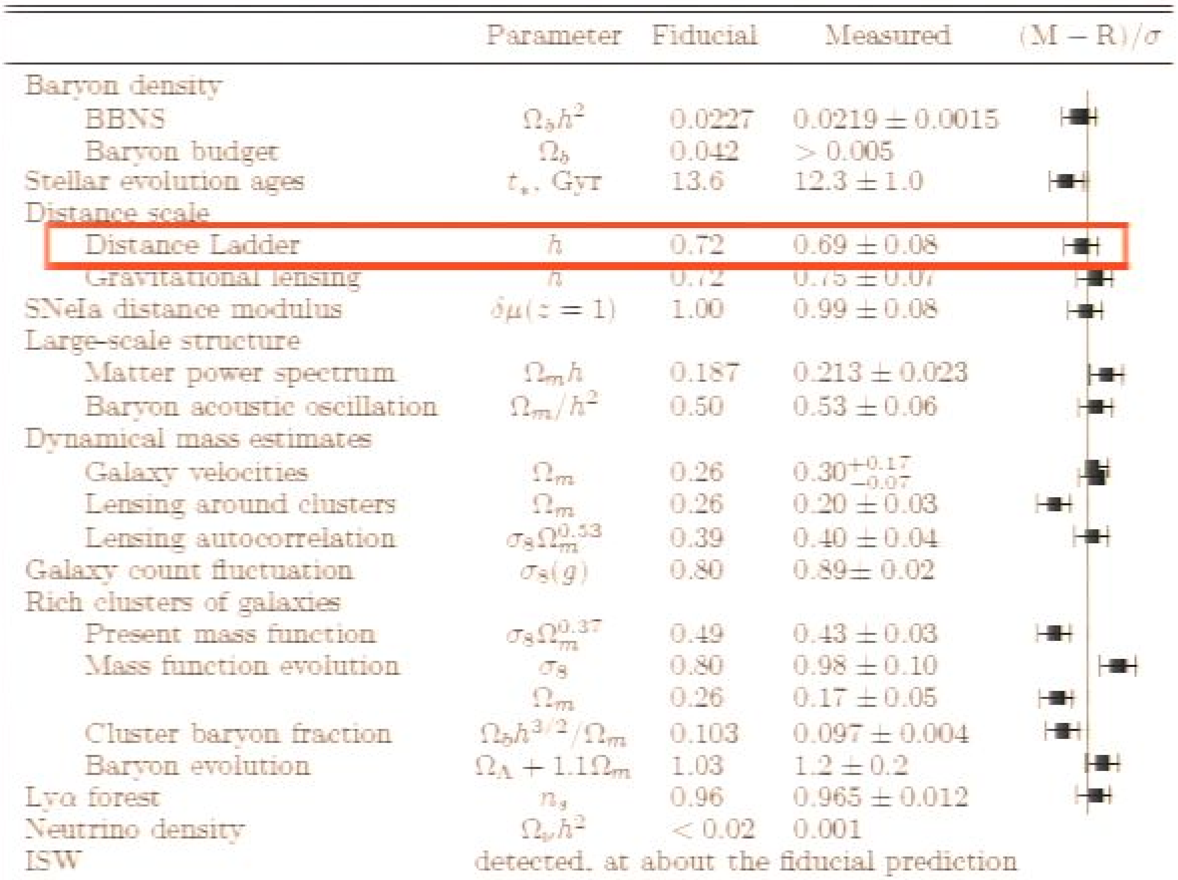


Fig. 12.— ACS data from 47 Tuc compared to isochrones with both empirical (*left*) and synthetic (*right*) color transformations. Details are listed on each panel. Data are from Sarajedini et al. (2007). The fiducial line from the metal-rich SHB model of § 4.4 (Fig. 6) is plotted alongside both isochrones. [*See the electronic edition of the Journal for a color version of this figure.*]

Distances and ages of NGC 6397, NGC 6752 and 47 Tuc*

R. G. Gratton[1], A. Bragaglia[2], E. Carretta[2], G. Clementini[2], S. Desidera[1], F. Grundahl[3], and S. Lucatello[1,4]



	Parameter	Fiducial	Measured	$(\mathrm{M}-\mathrm{R})/\sigma$
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BBNS	$\Omega_b h^2$	0.0227	0.0219 ± 0.0015	
Baryon budget	Ω_b	0.042	> 0.005	
Stellar evolution ages	t_*, Gyr	13.6	12.3 ± 1.0	
Distance scale				
Distance Ladder	h	0.72	0.69 ± 0.08	
Gravitational lensing	h	0.72	0.75 ± 0.07	
SNeIa distance modulus	$\delta\mu(z=1)$	1.00	0.99 ± 0.08	
Large-scale structure				
Matter power spectrum	$\Omega_m h$	0.187	0.213 ± 0.023	
Baryon acoustic oscillation	Ω_m / h^2	0.50	0.53 ± 0.06	
Dynamical mass estimates				
Galaxy velocities	Ω_m	0.26	$0.30^{+0.17}_{-0.07}$	
Lensing around clusters	Ω_m	0.26	0.20 ± 0.03	
Lensing autocorrelation	$\sigma_8 \Omega_m^{0.53}$	0.39	0.40 ± 0.04	
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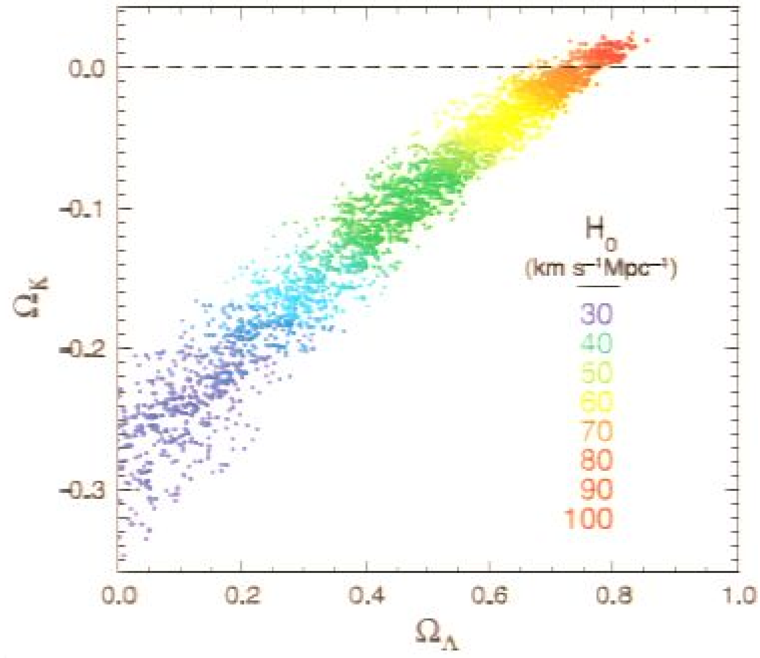
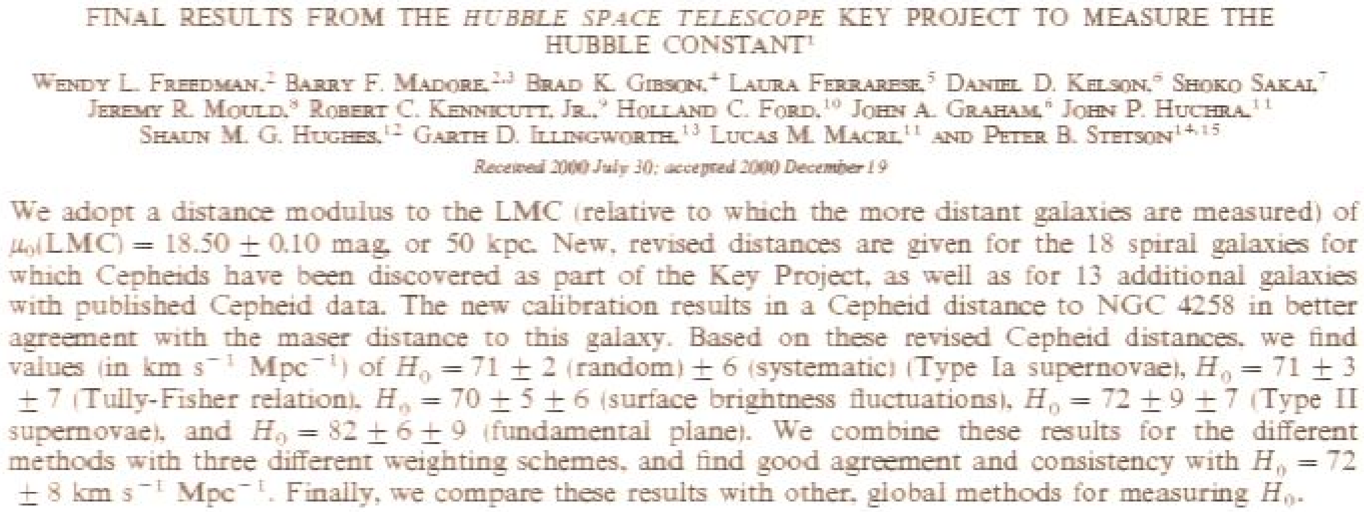
Baryon evolution	$\Omega_\Lambda + 1.1\Omega_m$	1.03	1.2 ± 0.2	
Lyα forest	n_s	0.96	0.965 ± 0.012	
Neutrino density	$\Omega_\nu h^2$	< 0.02	0.001	
ISW	detected, at about the fiducial prediction			



Dunkley *et al.* WMAPIII

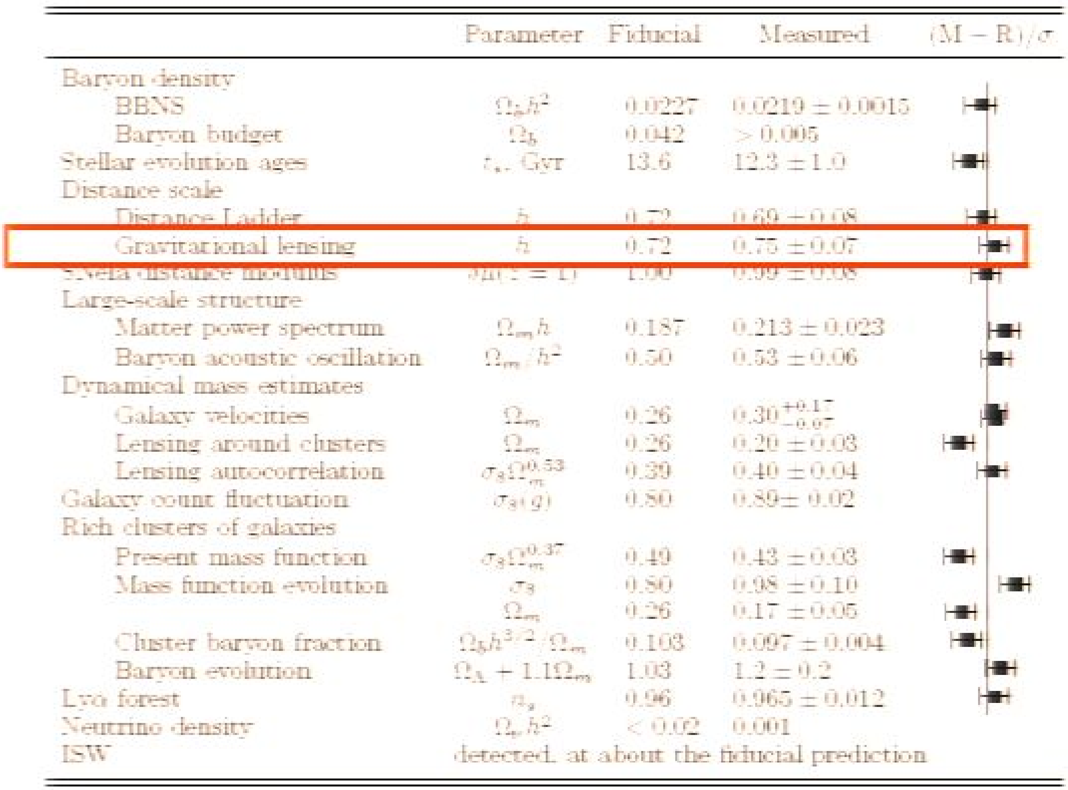


FINAL RESULTS FROM THE *HUBBLE SPACE TELESCOPE* KEY PROJECT TO MEASURE THE HUBBLE CONSTANT[1]

Wendy L. Freedman,[2] Barry F. Madore,[2,3] Brad K. Gibson,[4] Laura Ferrarese,[5] Daniel D. Kelson,[6] Shoko Sakai,[7]
Jeremy R. Mould,[8] Robert C. Kennicutt, Jr.,[9] Holland C. Ford,[10] John A. Graham,[6] John P. Huchra,[11]
Shaun M. G. Hughes,[12] Garth D. Illingworth,[13] Lucas M. Macri,[11] and Peter B. Stetson[14,15]

Received 2000 July 30; accepted 2000 December 19

We adopt a distance modulus to the LMC (relative to which the more distant galaxies are measured) of $\mu_0(\mathrm{LMC}) = 18.50 \pm 0.10$ mag, or 50 kpc. New, revised distances are given for the 18 spiral galaxies for which Cepheids have been discovered as part of the Key Project, as well as for 13 additional galaxies with published Cepheid data. The new calibration results in a Cepheid distance to NGC 4258 in better agreement with the maser distance to this galaxy. Based on these revised Cepheid distances, we find values (in km s^{-1} Mpc^{-1}) of $H_0 = 71 \pm 2$ (random) $\pm$ 6 (systematic) (Type Ia supernovae), $H_0 = 71 \pm 3 \pm 7$ (Tully-Fisher relation), $H_0 = 70 \pm 5 \pm 6$ (surface brightness fluctuations), $H_0 = 72 \pm 9 \pm 7$ (Type II supernovae), and $H_0 = 82 \pm 6 \pm 9$ (fundamental plane). We combine these results for the different methods with three different weighting schemes, and find good agreement and consistency with $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1}. Finally, we compare these results with other, global methods for measuring H_0.



	Parameter	Fiducial	Measured	$(M-R)/\sigma$
Baryon density				
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Baryon budget	Ω_b	0.042	> 0.005	
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Distance scale				
Distance Ladder	h	0.72	0.69 ± 0.08	
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Large-scale structure				
Matter power spectrum	$\Omega_m h$	0.187	0.213 ± 0.023	
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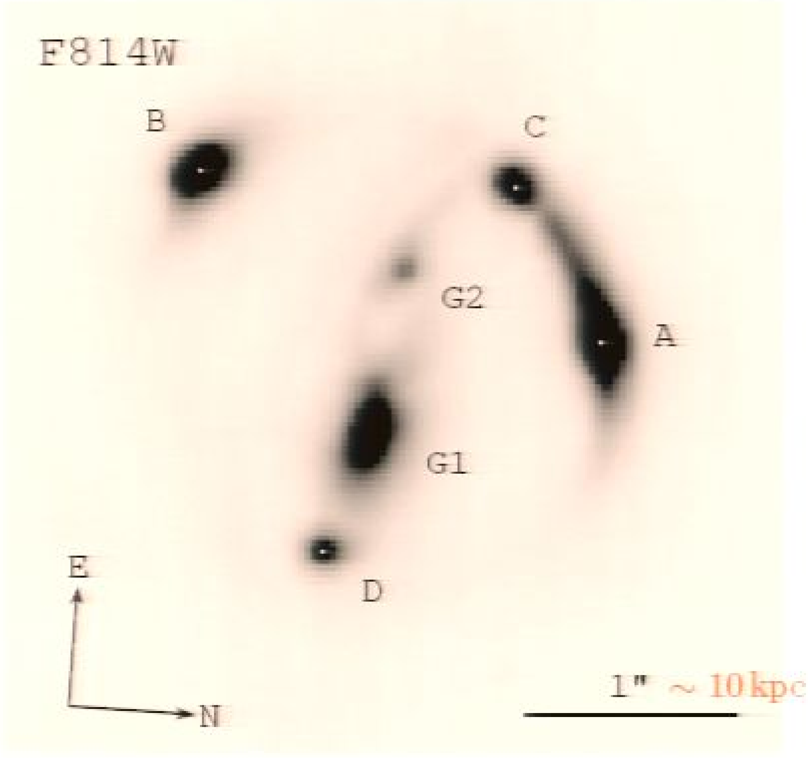
Dynamical mass estimates				
Galaxy velocities	Ω_m	0.26	$0.30^{+0.17}_{-0.07}$	
Lensing around clusters	Ω_m	0.26	0.20 ± 0.03	
Lensing autocorrelation	$\sigma_8 \Omega_m^{0.53}$	0.39	0.40 ± 0.04	
Galaxy count fluctuation	$\sigma_8(g)$	0.80	0.89 ± 0.02	
Rich clusters of galaxies				
Present mass function	$\sigma_8 \Omega_m^{0.37}$	0.49	0.43 ± 0.03	
Mass function evolution	σ_8	0.80	0.98 ± 0.10	
	Ω_m	0.26	0.17 ± 0.05	
Cluster baryon fraction	$\Omega_b h^{3/2} / \Omega_m$	0.103	0.097 ± 0.004	
Baryon evolution	$\Omega_\Lambda + 1.1\Omega_m$	1.03	1.2 ± 0.2	
Lyα forest	n_s	0.96	0.965 ± 0.012	
Neutrino density	$\Omega_\nu h^2$	< 0.02	0.001	
ISW	detected, at about the fiducial prediction			

The G1,2 lens redshift is $z_l = 0.63$.

The source redshift is $z_s = 1.39$.

There are three measured radio arrival time differences for the source images A, B, C, D.

This merits an independent entry because it is based on gravitational lensing — applied on scales ten orders of magnitude larger than the precision tests on the scale of the Solar System and smaller.



DISSECTING THE GRAVITATIONAL LENS B1608+656: LENS POTENTIAL RECONSTRUCTIO

S. H. Suyu[2,3,4], P. J. Marshall[5], R. D. Blandford[2,3], C. D. Fassnacht[6], L. V. E. Koopmans[7], J. P. McKean[6,8], and T. Treu[5,9]

Table 5.3. *Cosmological Tests*

	Parameter	Fiducial	Measured	$(M-R)/\sigma$
Baryon density				
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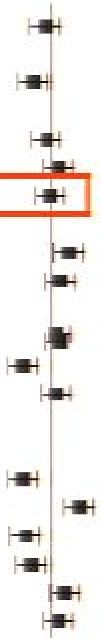
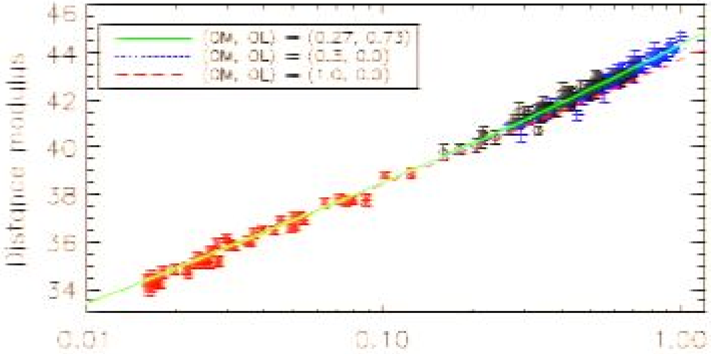
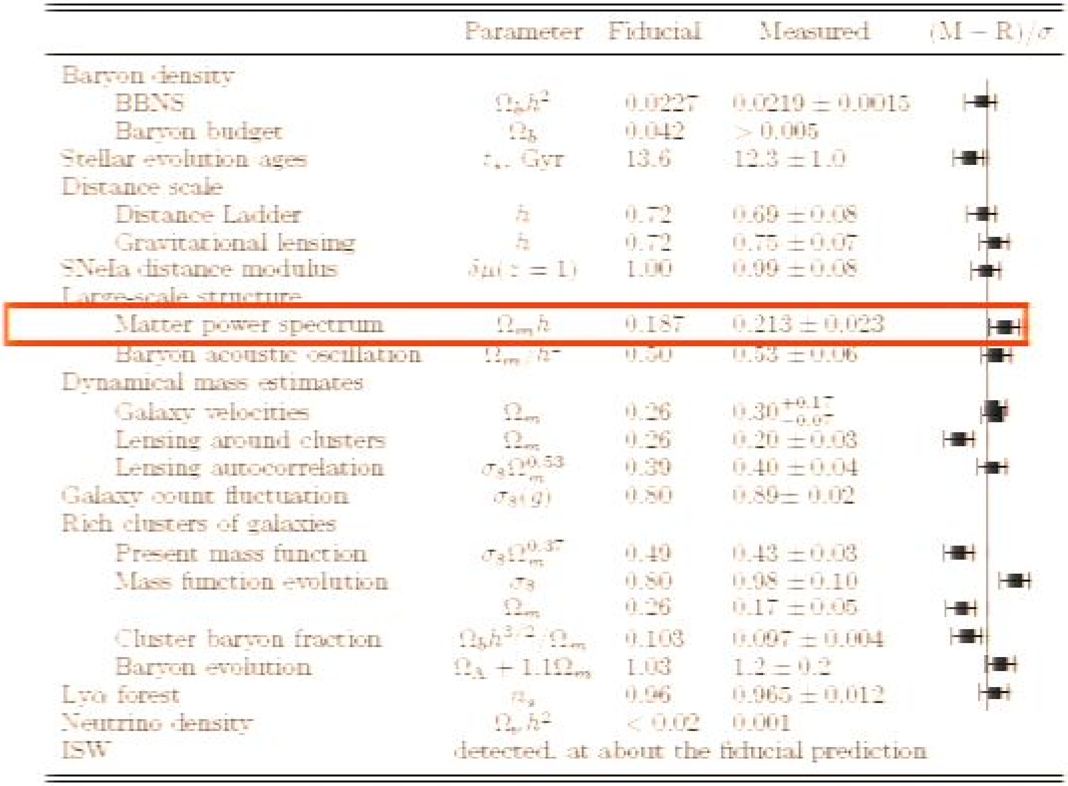




Observational Constraints on the Nature of Dark Energy: First Cosmological Results from the ESSENCE Supernova Survey

W. M. Wood-Vasey[1], G. Miknaitis[2], C. W. Stubbs[1,3], S. Jha[4,5], A. G. Riess[6,7],
P. M. Garnavich[8], R. P. Kirshner[1], C. Aguilera[9], A. C. Becker[10], J. W. Blackman[11],
S. Blondin[1], P. Challis[1], A. Clocchiatti[12], A. Conley[13], R. Covarrubias[10], T. M. Davis[14],
A. V. Filippenko[4], R. J. Foley[4], A. Garg[1,3], M. Hicken[1,3], K. Krisciunas[8,16],
B. Leibundgut[17], W. Li[4], T. Matheson[18], A. Miceli[10], G. Narayan[1,3], G. Pignata[12],
J. L. Prieto[19], A. Rest[9], M. E. Salvo[11], B. P. Schmidt[11], R. C. Smith[9], J. Sollerman[14,15],
J. Spyromilio[17], J. L. Tonry[20], N. B. Suntzeff[9,16], and A. Zenteno[9]

$$\begin{aligned}
\delta\mu &= 5\log y(1+z)/z, \\
y &= H_o a_o r \\
&= \int_0^{\infty} \frac{dz}{\sqrt{\Omega_m(1+z)^3 + 1 - \Omega_m}}
\end{aligned}$$



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The cosmological constant and cold dark matter

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

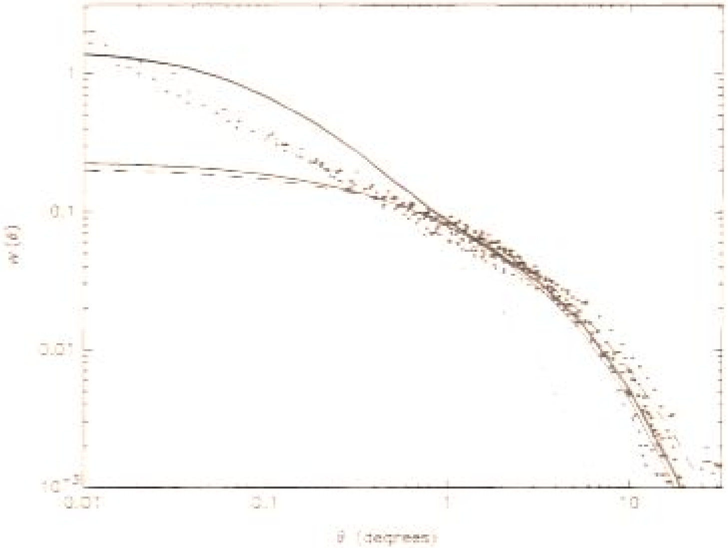
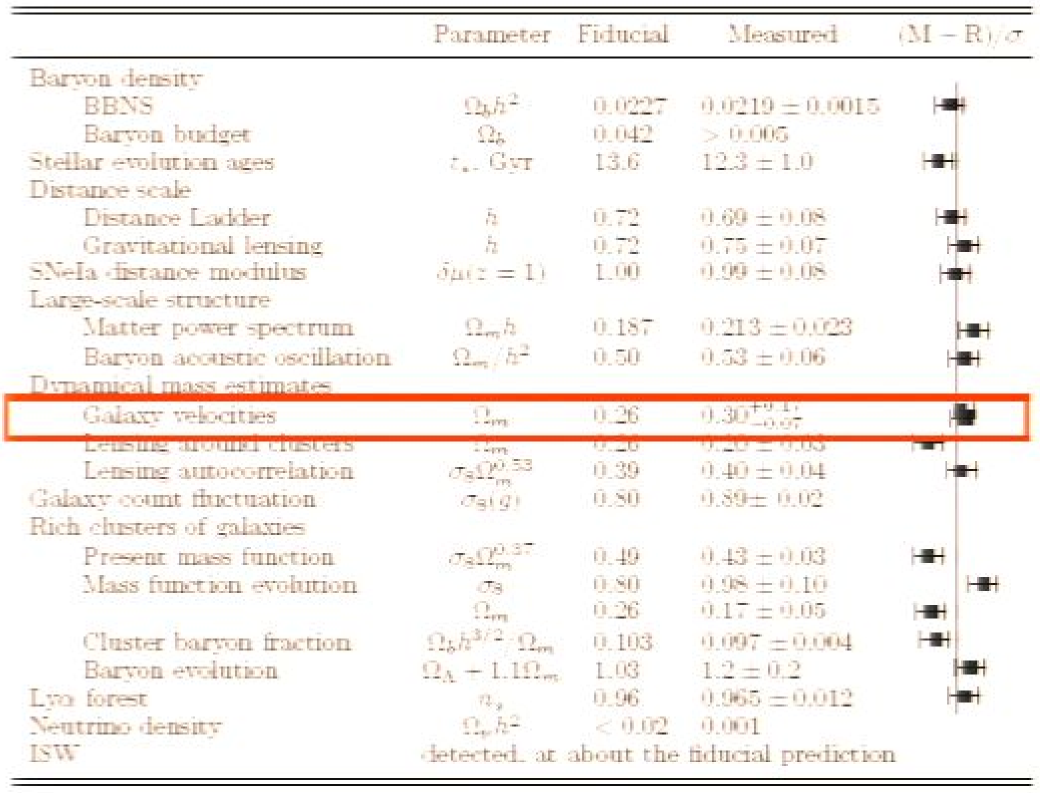


FIG. 1 The dots show estimates of the angular correlation function $w(\theta)$ for galaxies in the APM galaxy survey (see ref. 5 for details). These estimates have been scaled to the depth of the Lick galaxy catalogue where 1° corresponds to a spatial scale of $\sim 5h^{-1}$ Mpc. The dotted line shows 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 $n = 1$ 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 $\lesssim 0.1°$ is an artefact of the resolution of the computer code, but the excess between 0.1° and 1° is real (see Fig. 2).



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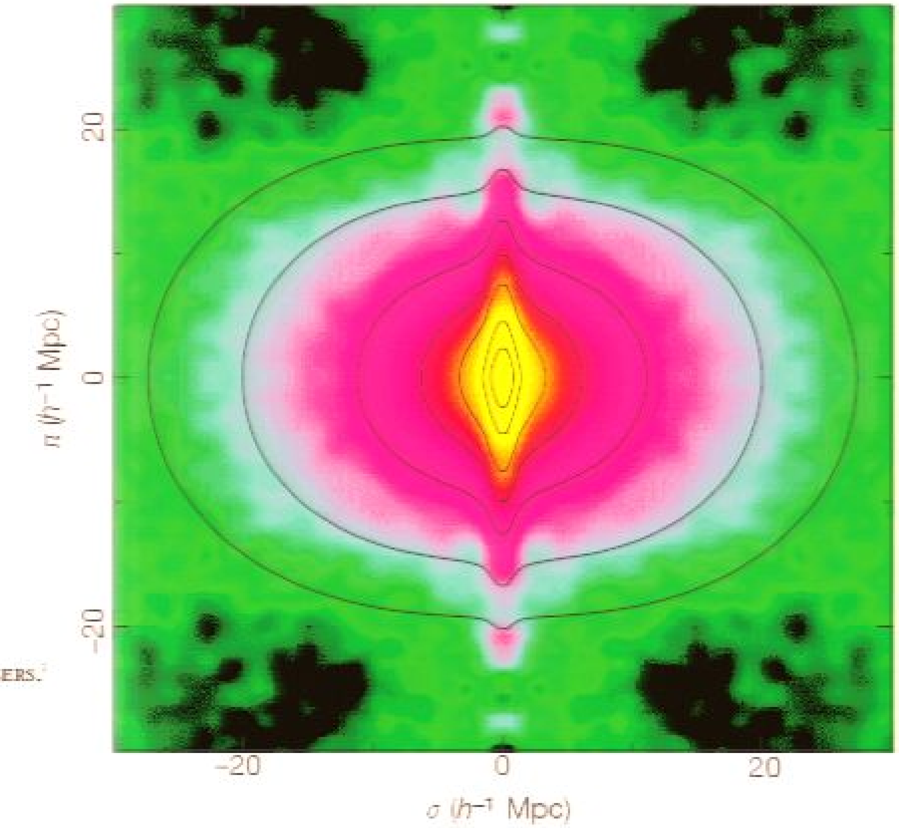
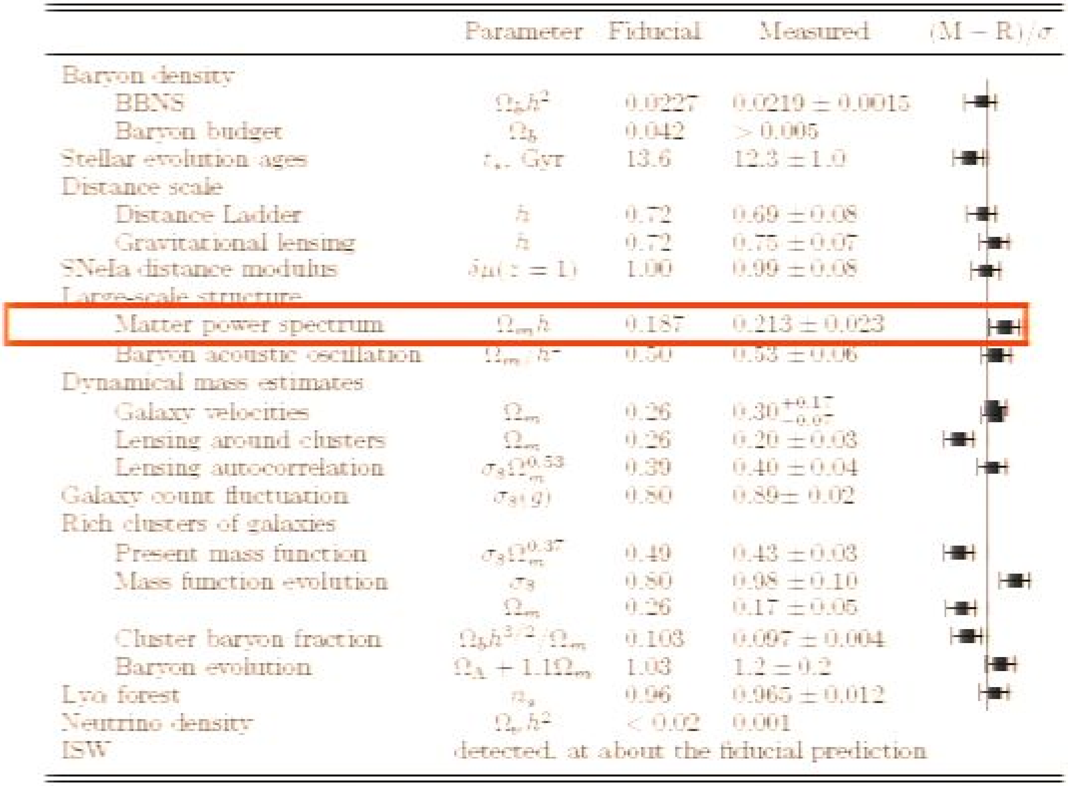
AN ESTIMATE OF Ω_m WITHOUT CONVENTIONAL PRIORS

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,[7]
L. da Costa,[11] M. Bernardi,[12] R. Giovanelli,[13] M. Haynes,[13] and G. Wegner[14]



A measurement of the cosmological mass density from clustering in the 2dF Galaxy Redshift Survey



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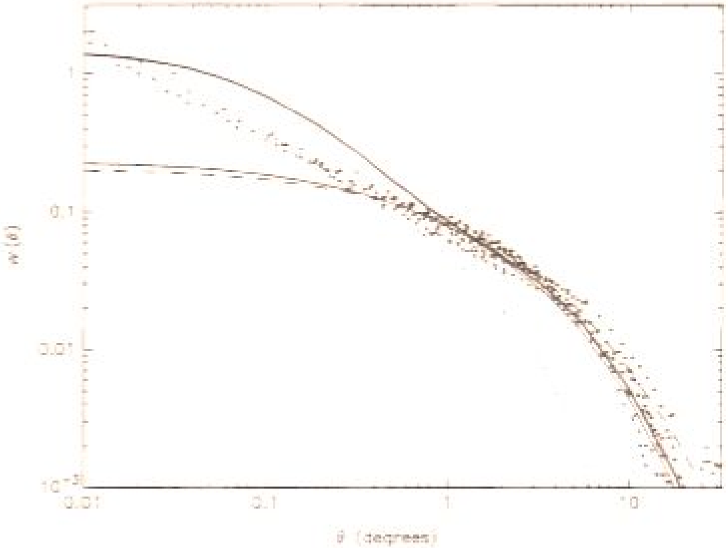

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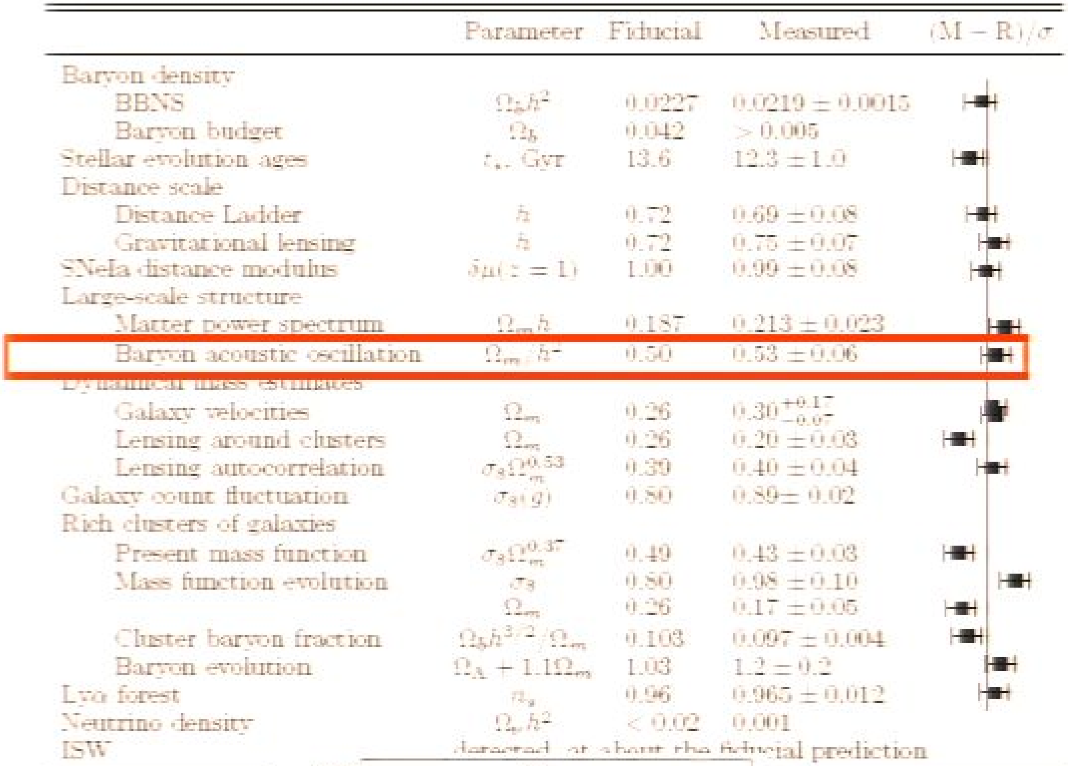

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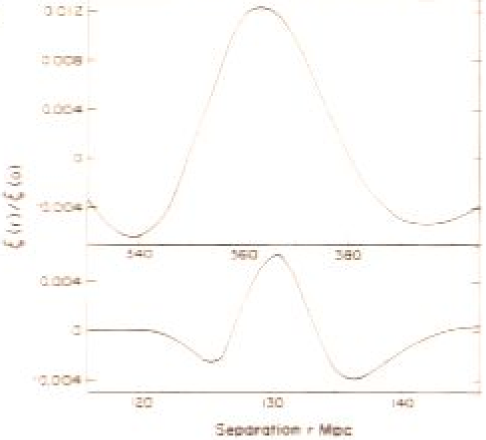
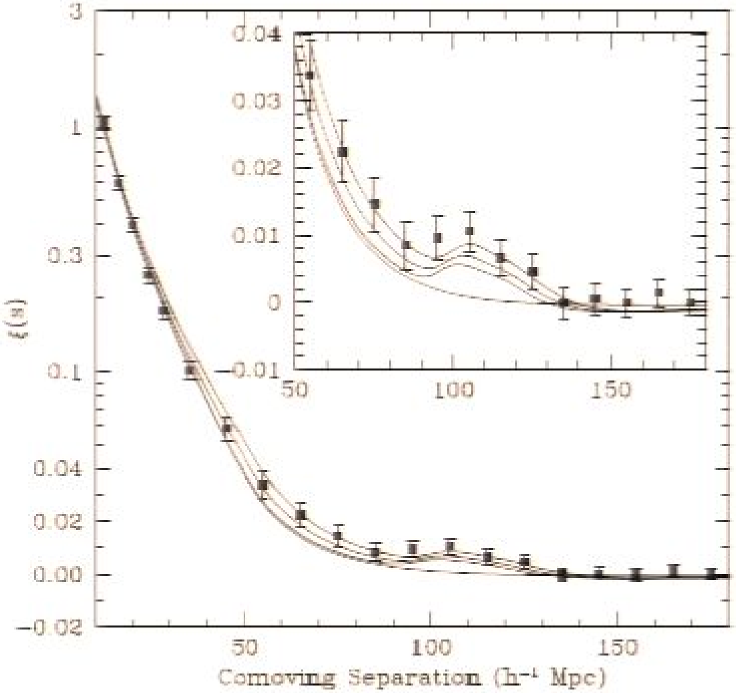


PRIMEVAL ADIABATIC PERTURBATIONS: CONSTRAINTS FROM THE MASS DISTRIBUTION

P. J. E. Peebles
Joseph Henry Laboratories, Physics Department, Princeton University

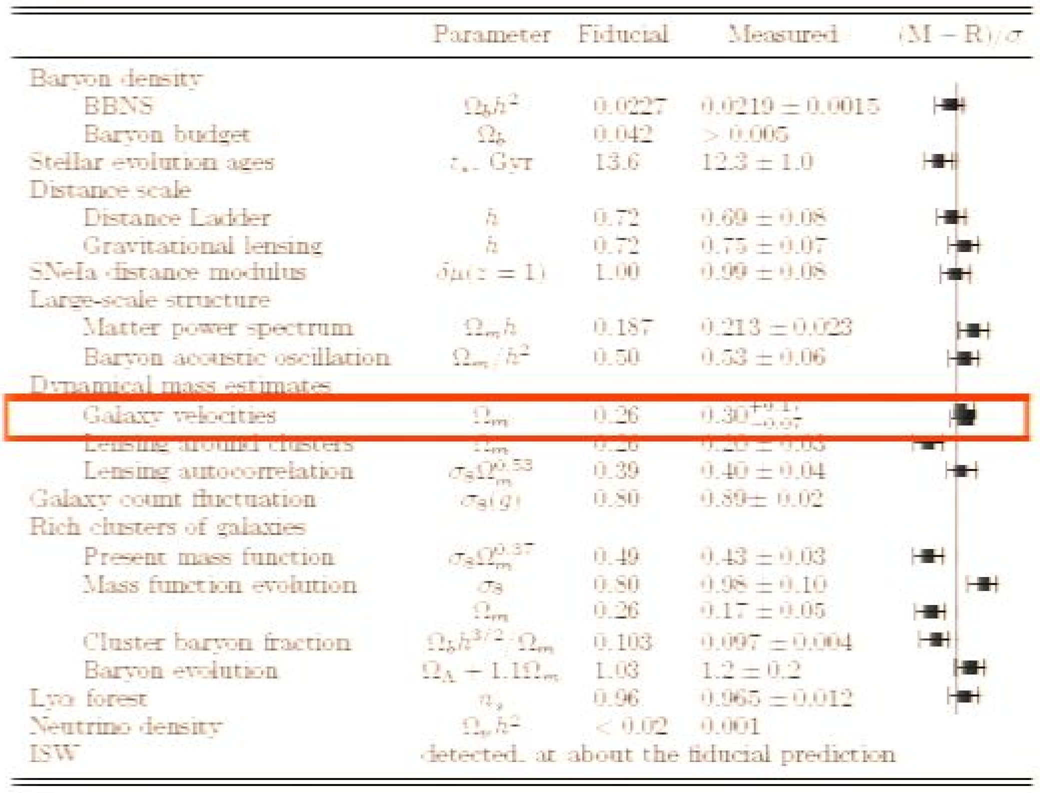
Received 1981 February 9; accepted 1981 March 27



DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION
FUNCTION OF SDSS LUMINOUS RED GALAXIES

Daniel J. Eisenstein,[1,2] Idit Zehavi,[1] David W. Hogg,[3] Roman Scoccimarro,[3] Michael R. Blanton,[3] Robert C. N
Ryan Scranton,[8] Hee-Jong Seo,[1] Max Tegmark,[6,7] Zheng Zheng,[1] Scott F. Anderson,[9] Jim Annis,[10] Neta Bahc
Jon Brinkmann,[12] Scott Burles,[7] Francisco J. Castander,[13] Andrew Connolly,[8] Istvan Csabai,[14] Mamoru D
Masataka Fukugita,[16] Joshua A. Frieman,[10,17] Karl Glazebrook,[18] James E. Gunn,[11] John S. Hendry,[10]
Gregory Hennessy,[19] Zeljko Ivezic,[9] Stephen Kent,[10] Gillian R. Knapp,[11] Huan Lin,[10] Yeong-Shang Loh,[2
Robert H. Lupton,[11] Bruce Margon,[21] Timothy A. McKay,[22] Avery Meiksin,[23] Jeffrey A. Munn,[19]
Adrian Pope,[18] Michael W. Richmond,[24] David Schlegel,[25] Donald P. Schneider,[26]
Kazuhiro Shimasaku,[27] Christopher Stoughton,[10] Michael A. Strauss,[11]
Mark SubbaRao,[17,28] Alexander S. Szalay,[18] István Szapudi,[29]
Douglas L. Tucker,[10] Brian Yanny,[10] and Donald G. York[17]

Received 2004 December 31; accepted 2005 July 15



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AN ESTIMATE OF Ω_m WITHOUT CONVENTIONAL PRIORS

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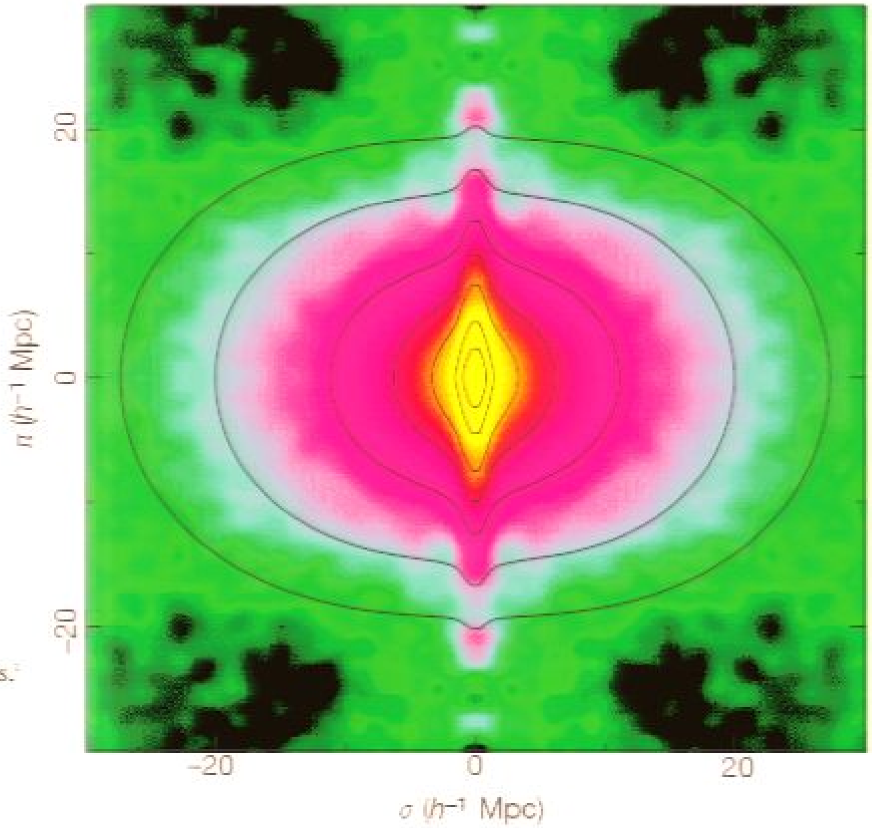
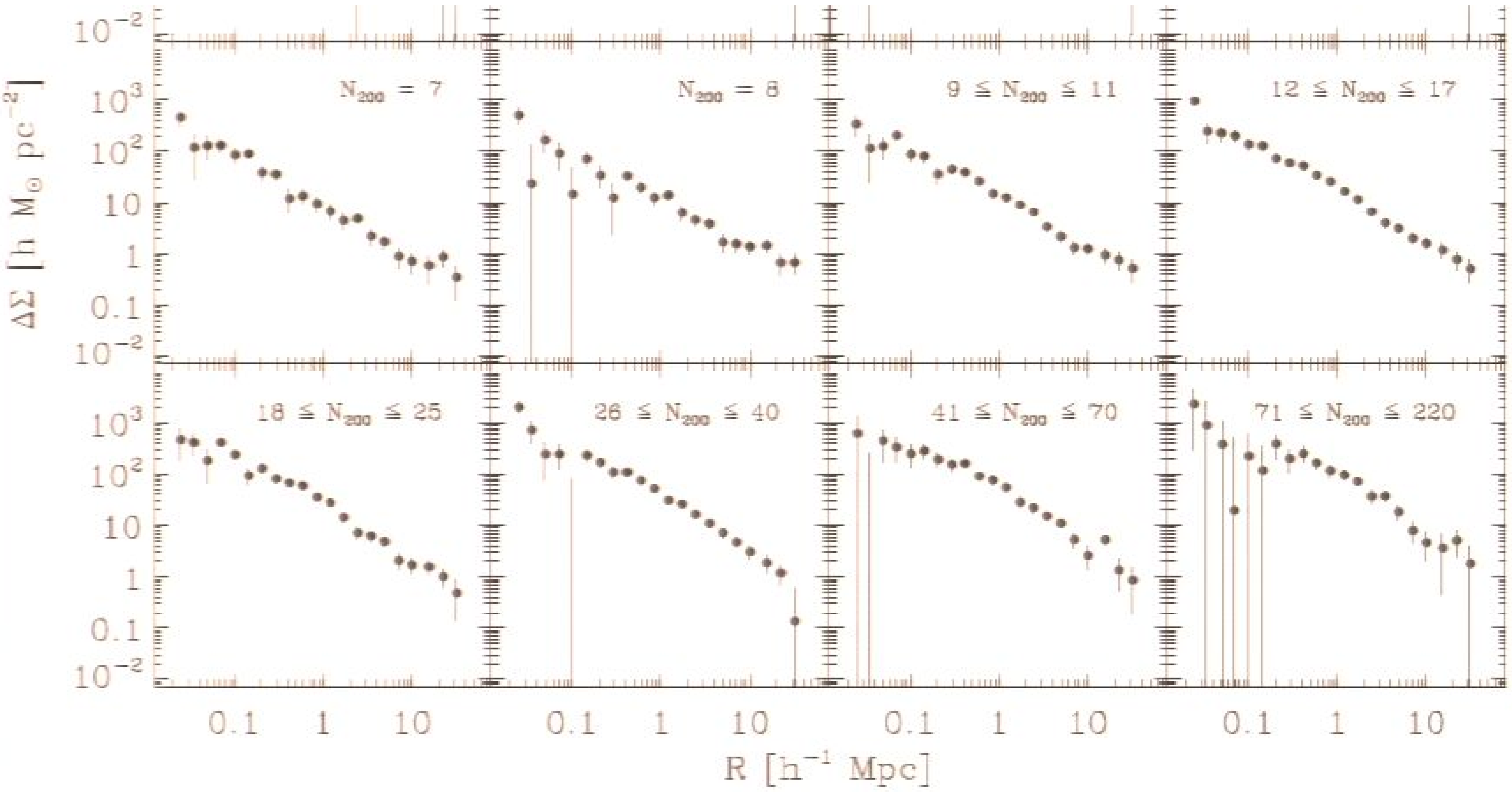
L. da Costa, M. Bernardi, R. Giovanelli, M. Haynes, and G. Wegner

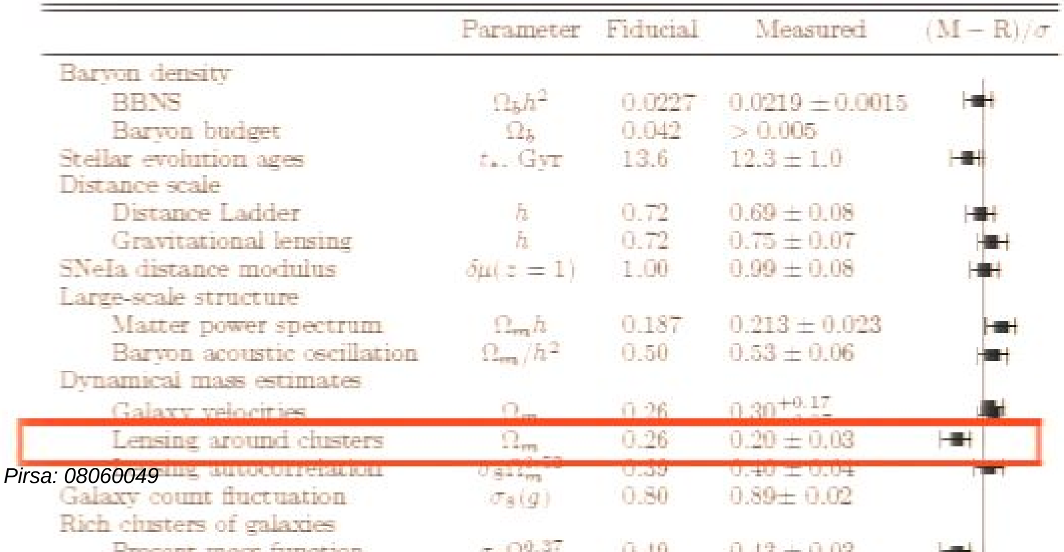


A measurement of the cosmological mass density from clustering in the 2dF Galaxy Redshift Survey

[illegible]



Cluster-mas
correlation
function fro
SDSS weak
lensing,
Sheldon *et*
al. (2007)



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Gravitational lensing by the mass in and around clusters radially distorts background galaxies by an amount

$$\propto \Delta\Sigma = -R d\Sigma/dR/2,$$

where Σ is the mean mass per unit area within distance R of a cluster.

If galaxies trace mass on these large scales measurement of the concentration of light give the mean mass density.

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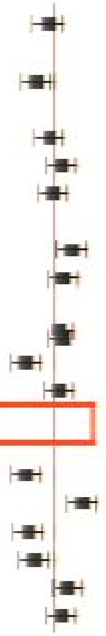

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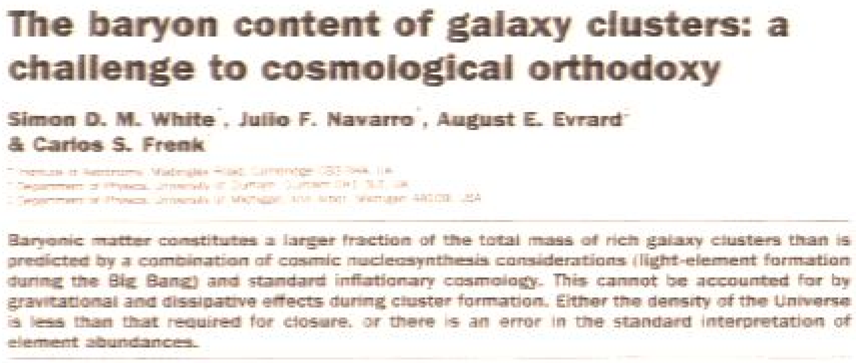

The baryon content of galaxy clusters: a challenge to cosmological orthodoxy

Simon D. M. White, Julio F. Navarro, August E. Evrard & Carlos S. Frenk

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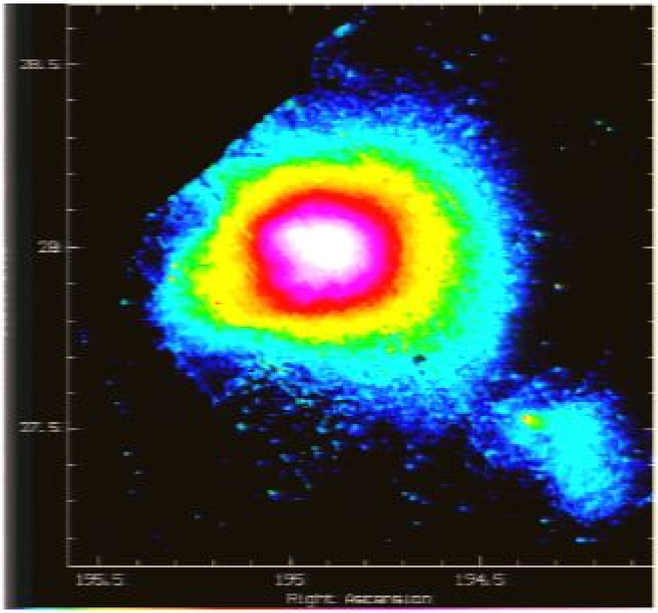

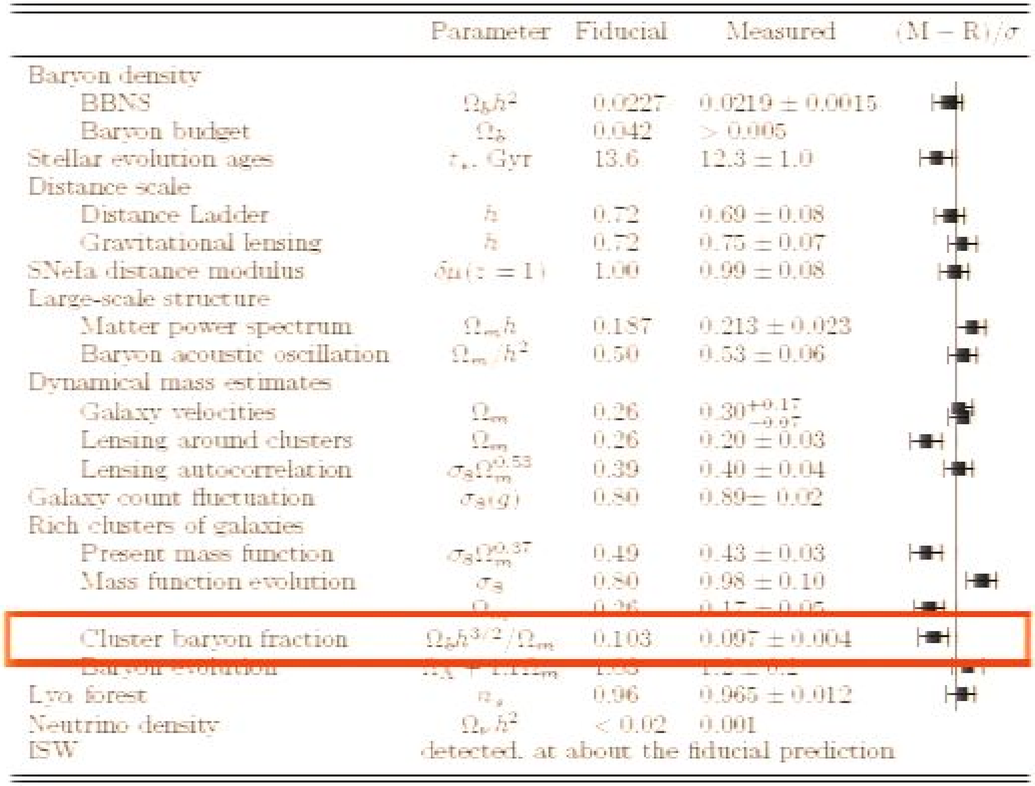

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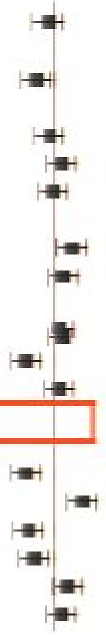

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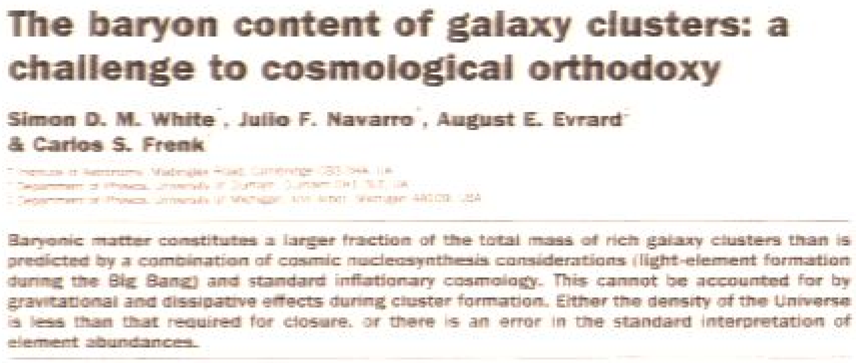

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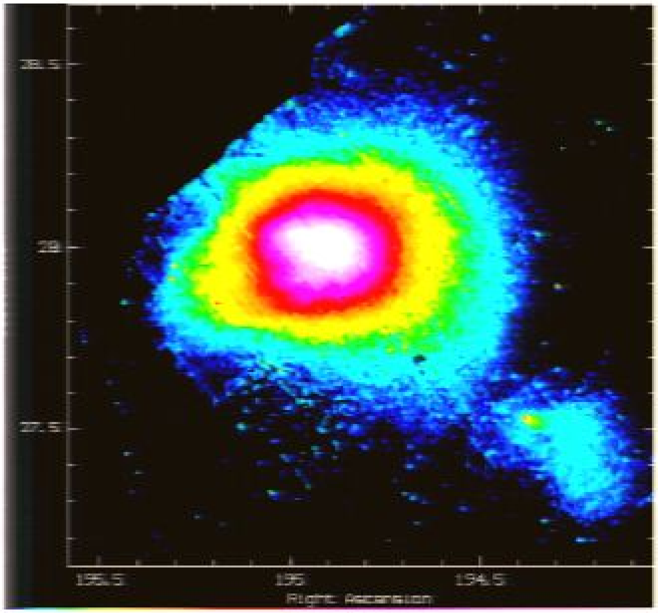

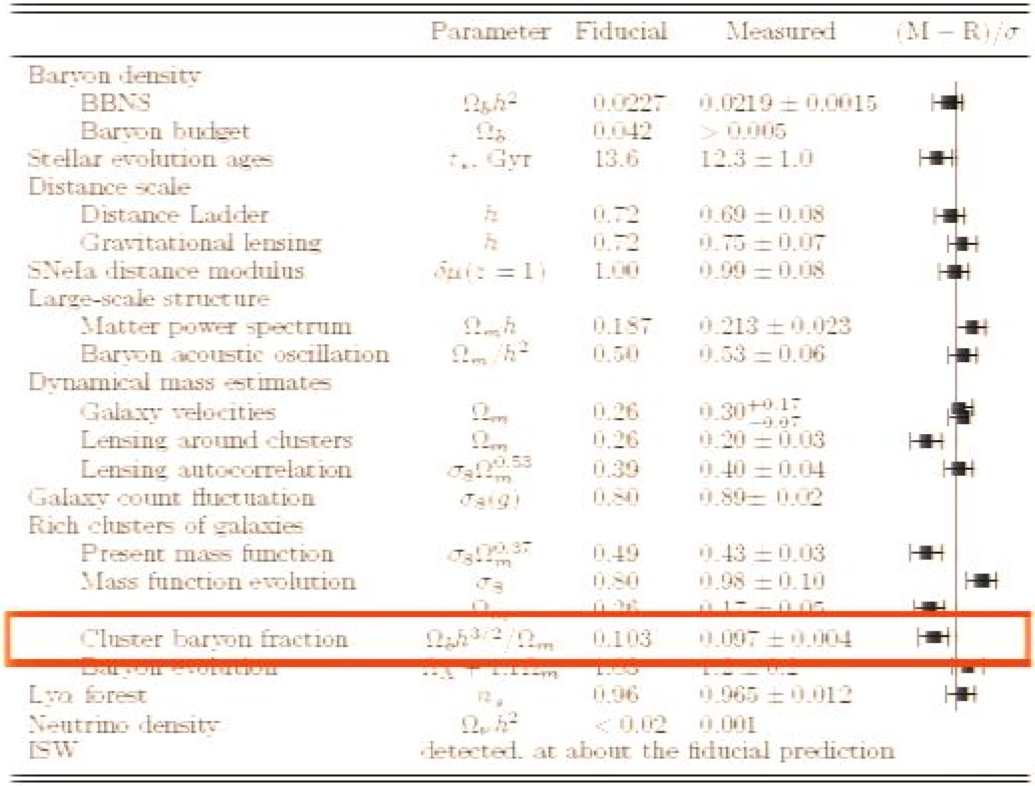

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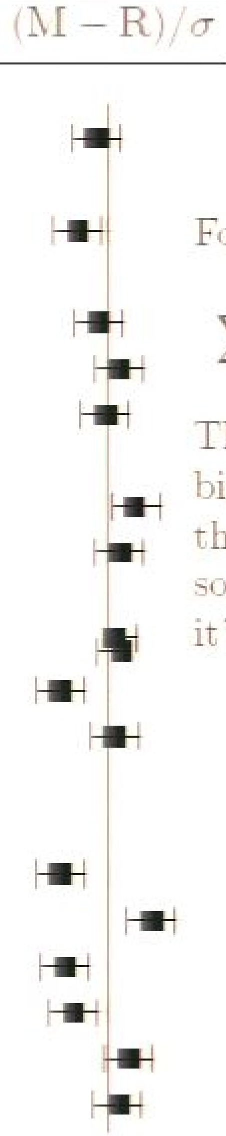


For these 16 measure

$$\sum \frac{(\mathcal{O} - \mathcal{M})^2}{\sigma^2} = 26$$

This is formally t
big, but considerin
the dicey estimates
some of the σ's I thi
it's remarkably good

The ΛCDM cosmology passes an impressive number of independent challenges: it proves to be a good approximation to reality.

But as I said, one may wonder whether the sector of dark matter and dark energy really is so vastly simpler than physics in the visible sector.

If the dark sector of ΛCDM is only the simplest approximation we can get away with at the present level of the evidence then anomalies might point to something better.

There are problems reconciling the theory and observations of galaxies. Might some indicate new dark sector physics rather than the complications of the physics we have now? I offer an example that fascinates me.

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

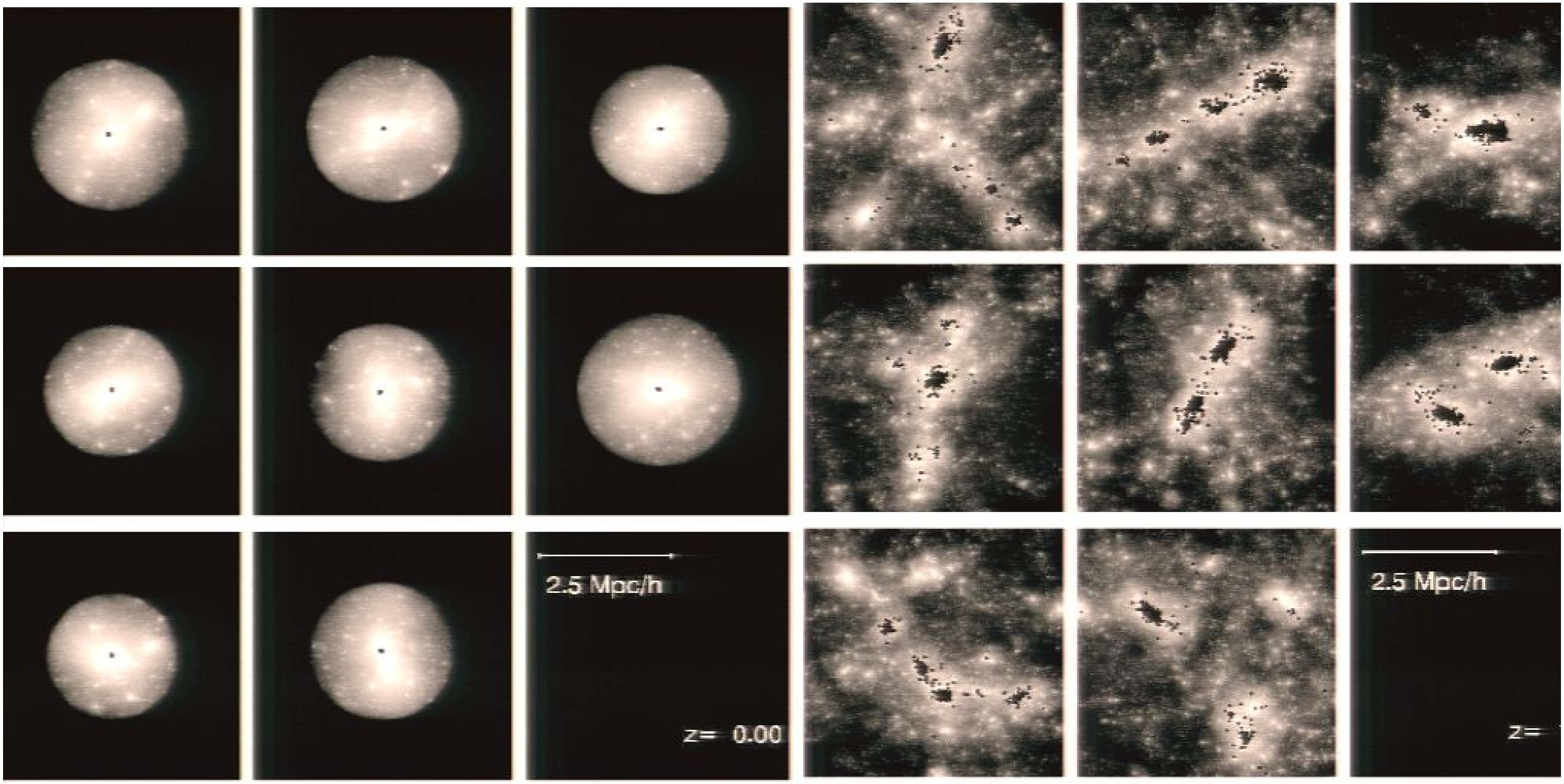
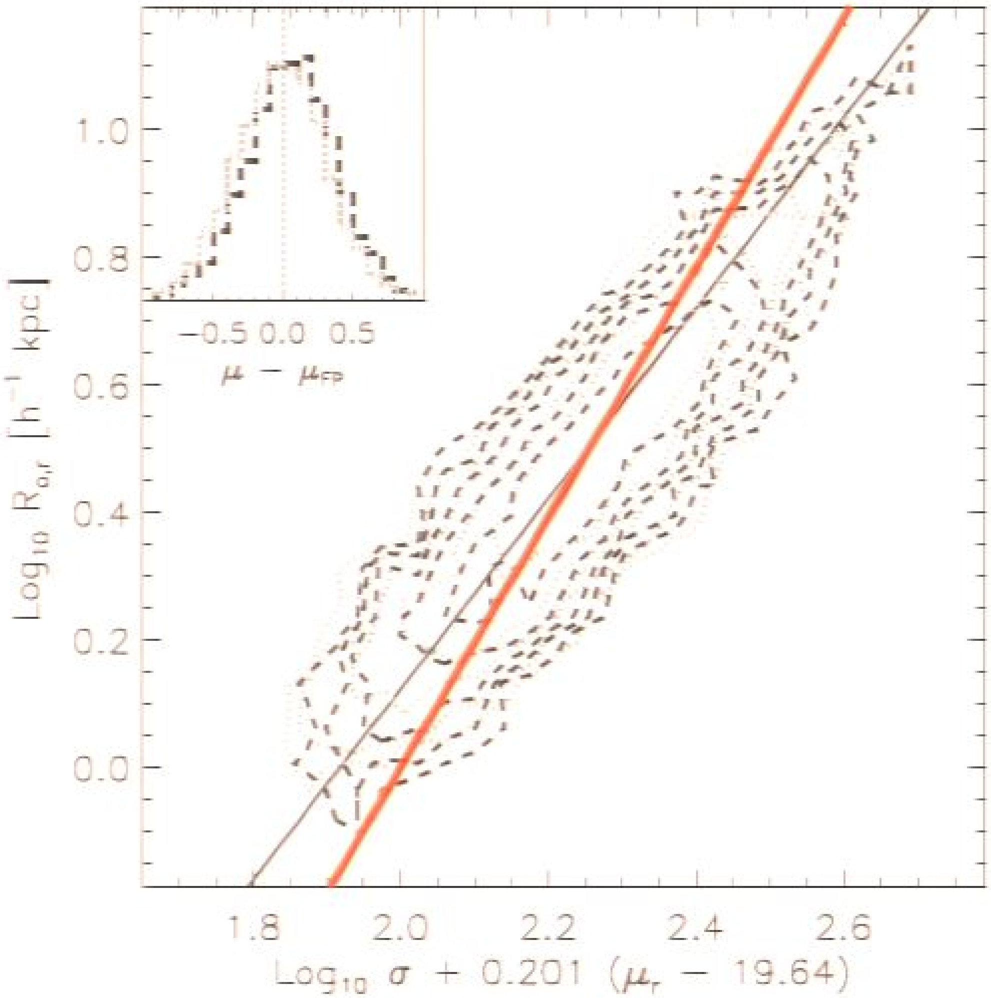


Fig. 2.— Images of the mass distribution at $z = 0.1$ and 3 in our 8 simulations of the assembly of cluster mass halos. Each plot shows only those particles which lie within r_{200} of halo center at $z = 0$. Particles which lie within $10h^{-1}$ kpc of halo center at this time are shown in black. Each 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

The late merging puzzle. But 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, which again 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

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Received 2003 July 11; accepted 2003 December 2; published 2004 January 16

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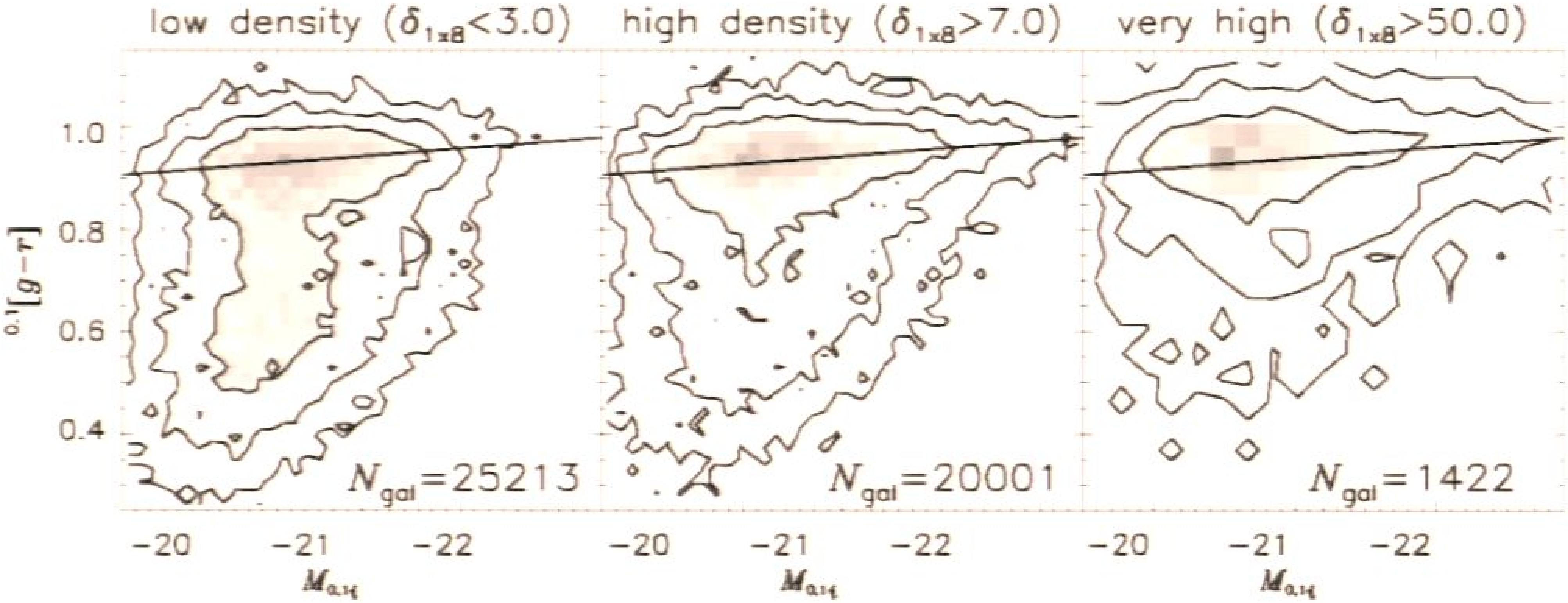

These SDSS colors are measured at about 80% of the nominal Petrosian magnitude, that is, well outside the half-light radius

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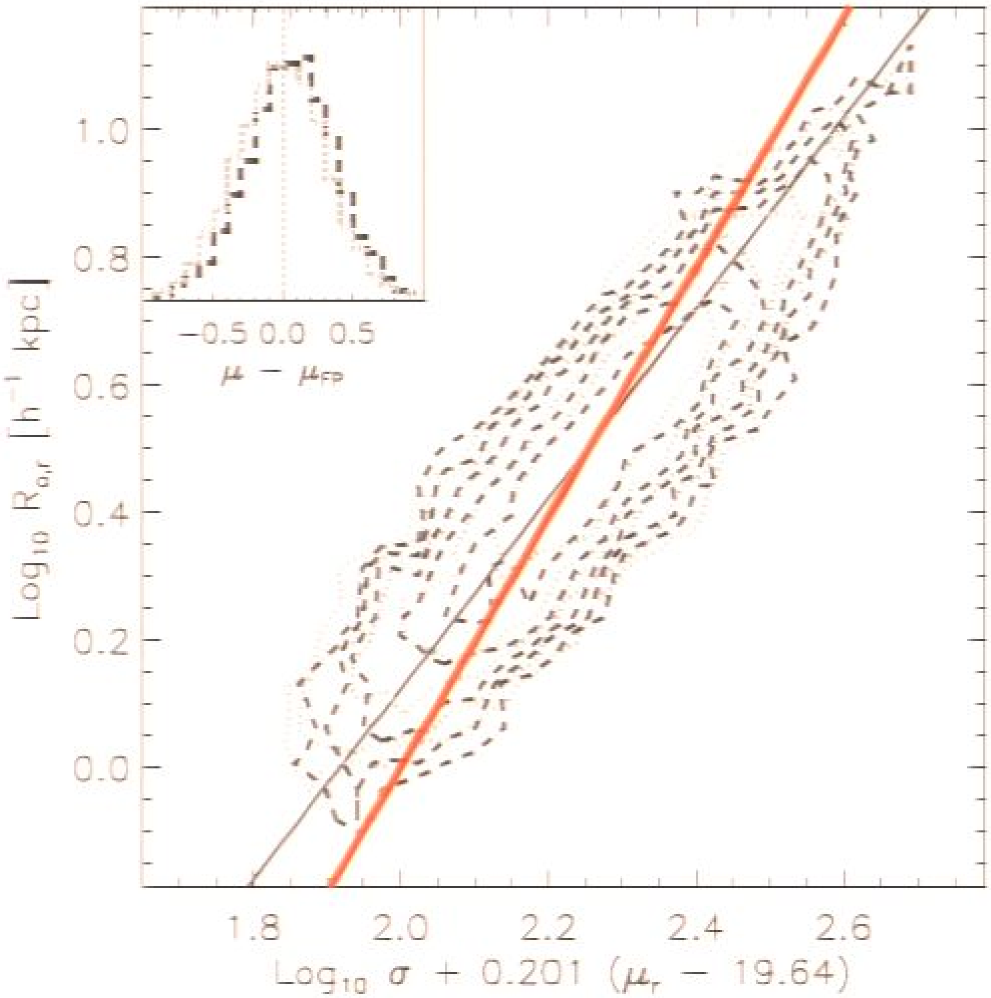

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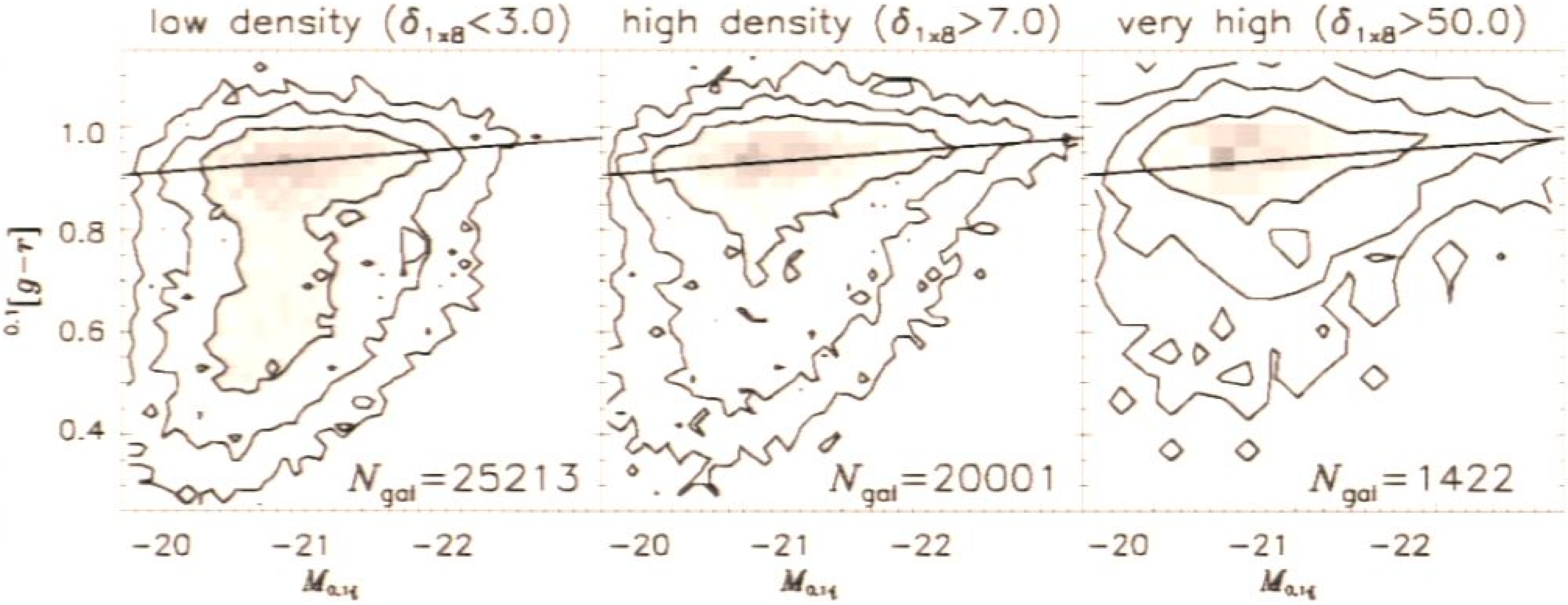

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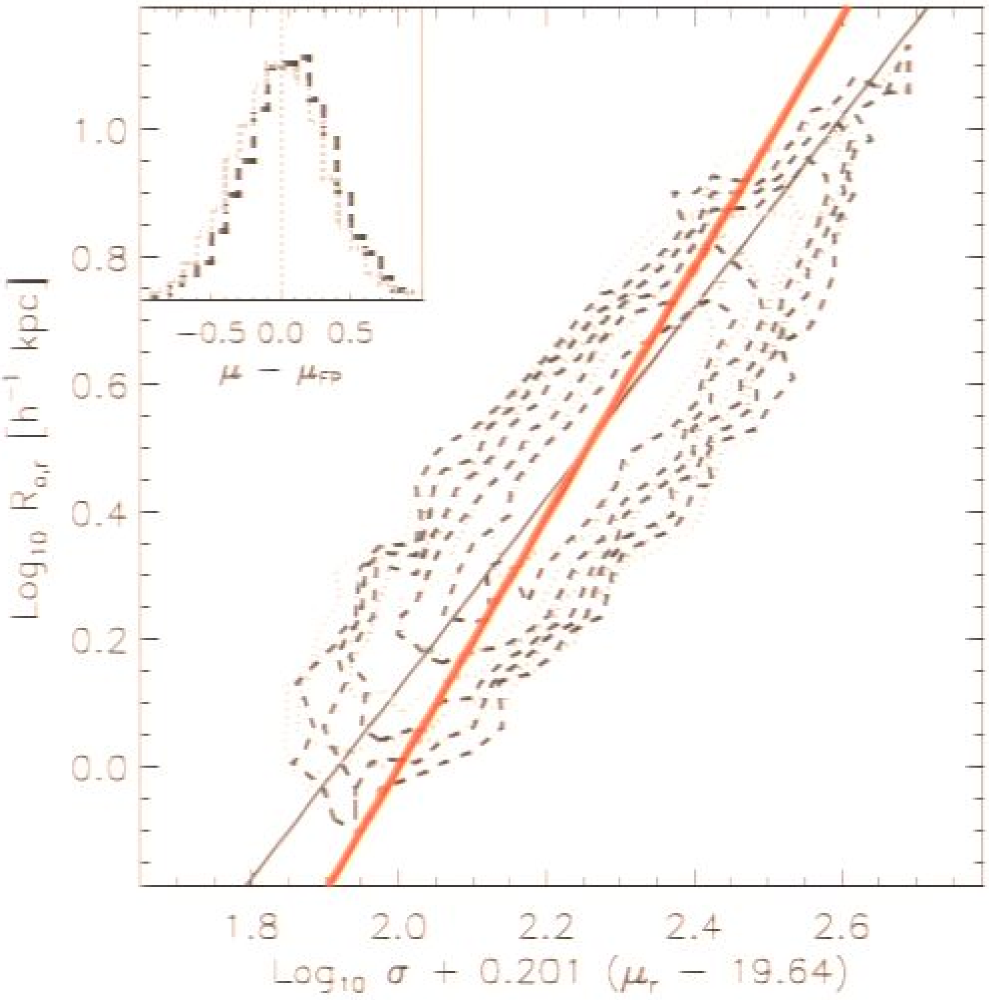

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Late merging puzzle. The line — the early-type red sequence — is insensitive to environment. which again is more suggestive of island universes than the considerable exchange of matter with the surroundings predicted by the ΛCDM cosmology.

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

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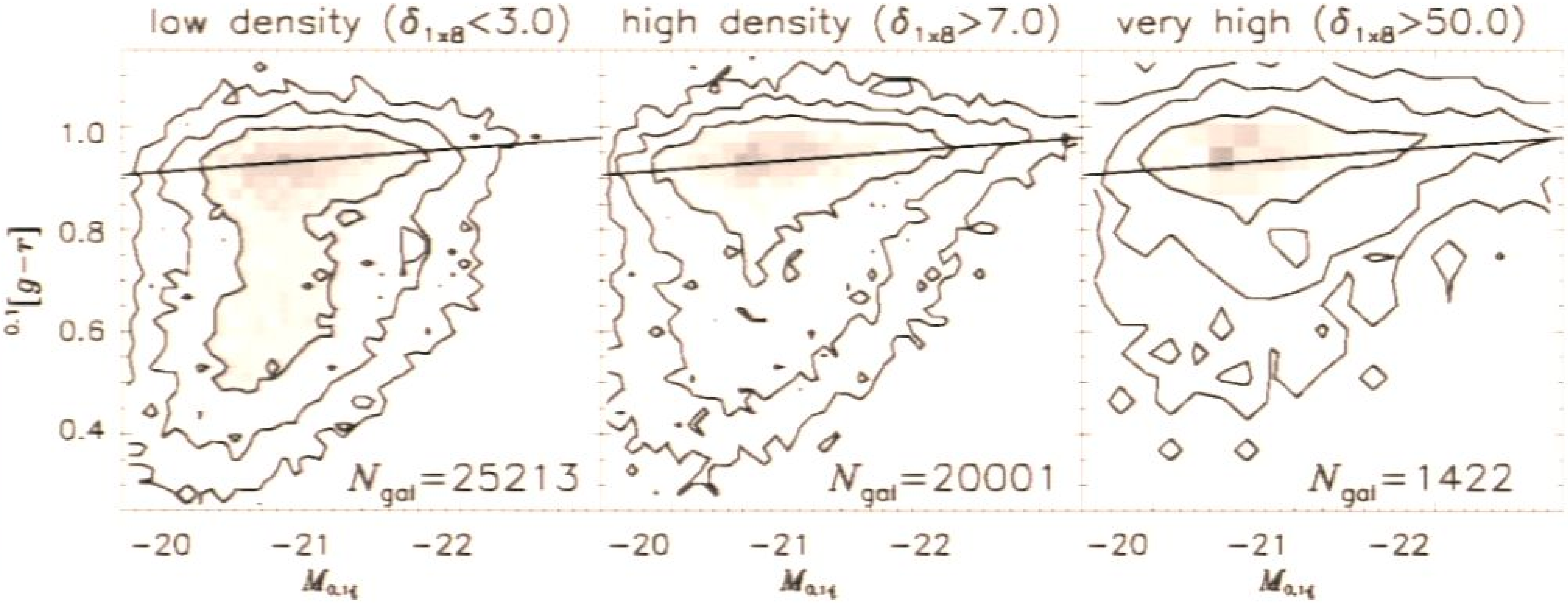

These SDSS colors are measured at about 80% of the nominal Petrosian magnitude, that is, well outside the half-light radius

I offer the island universe puzzle to illustrate the point that there is no shortage of interesting problems in cosmology at modest redshift.

A problem assignment: determine whether this puzzle points to new physics, maybe in the dark sector, or to the complexity of the physics we already have.

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

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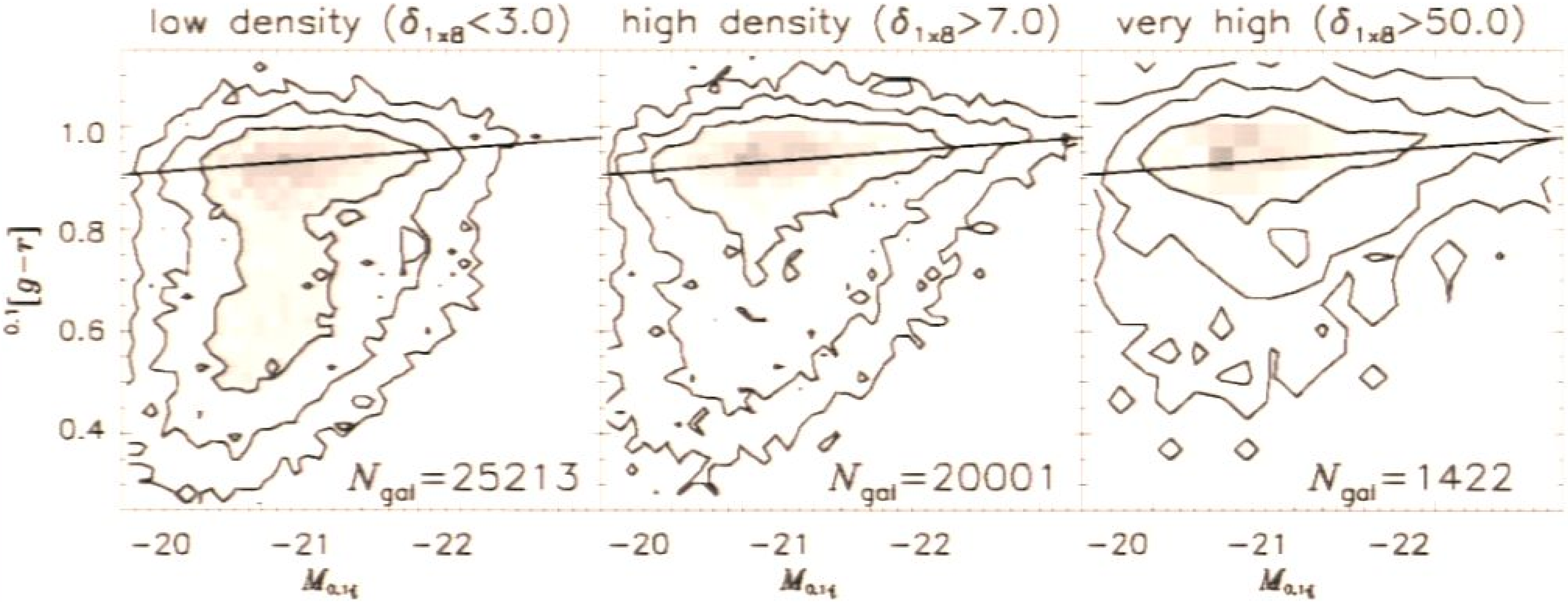

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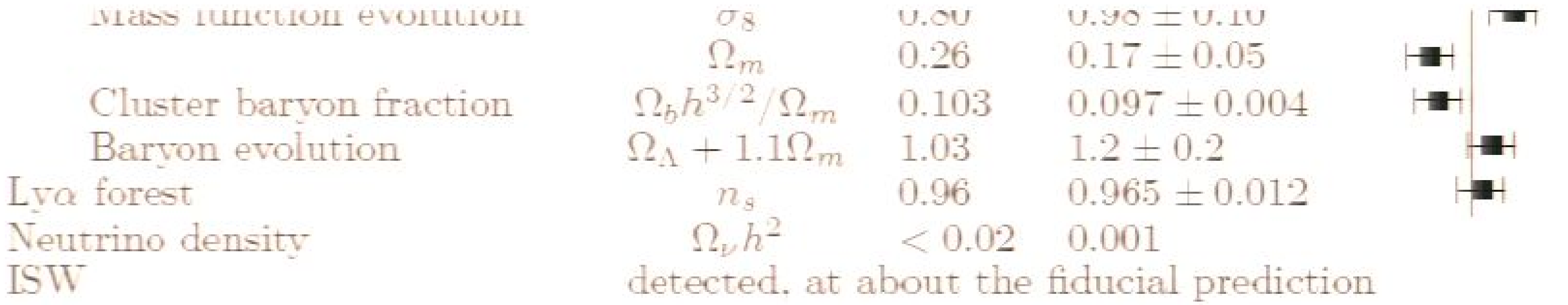
The ΛCDM cosmology passes an impressive number of independent challenges: it proves to be a good approximation to reality.

But as I said, one may wonder whether the sector of dark matter and dark energy really is so vastly simpler than physics in the visible sector.

If the dark sector of ΛCDM is only the simplest approximation we can get away with at the present level of the evidence then anomalies might point to something better.

There are problems reconciling the theory and observations of galaxies. Might some indicate new dark sector physics rather than the complications of the physics we have now? I offer an example that fascinates me.



Mass function evolution	σ_8	0.80	0.98 ± 0.10
	Ω_m	0.26	0.17 ± 0.05
Cluster baryon fraction	$\Omega_b h^{3/2}/\Omega_m$	0.103	0.097 ± 0.004
Baryon evolution	$\Omega_\Lambda + 1.1\Omega_m$	1.03	1.2 ± 0.2
Lyα forest	n_s	0.96	0.965 ± 0.012
Neutrino density	$\Omega_\nu h^2$	< 0.02	0.001
ISW	detected, at about the fiducial prediction		

	Parameter	Fiducial	Measured	(M − R)/σ
Baryon density				
BBNS	$\Omega_b h^2$	0.0227	0.0219 ± 0.0015	
Baryon budget	Ω_b	0.042	> 0.005	
Stellar evolution ages	t_*, Gyr	13.6	12.3 ± 1.0	
Distance scale				
Distance Ladder	h	0.72	0.69 ± 0.08	
Gravitational lensing	h	0.72	0.75 ± 0.07	
SNeIa distance modulus	$\delta\mu(z = 1)$	1.00	0.99 ± 0.08	
Large-scale structure				
Matter power spectrum	$\Omega_m h$	0.187	0.213 ± 0.023	
Baryon acoustic oscillation	Ω_m / h^2	0.50	0.53 ± 0.06	
Dynamical mass estimates				
Galaxy velocities	Ω_m	0.26	$0.30^{+0.17}_{-0.07}$	
Lensing around clusters	Ω_m	0.26	0.20 ± 0.03	
Lensing autocorrelation	$\sigma_8 \Omega_m^{0.53}$	0.39	0.40 ± 0.04	
Galaxy count fluctuation	$\sigma_8(g)$	0.80	0.89 ± 0.02	
Rich clusters of galaxies				
Present mass function	$\sigma_8 \Omega_m^{0.37}$	0.49	0.43 ± 0.03	
Mass function evolution	σ_8	0.80	0.98 ± 0.10	
	Ω_m	0.26	0.17 ± 0.05	
Cluster baryon fraction	$\Omega_b h^{3/2} / \Omega_m$	0.103	0.097 ± 0.004	
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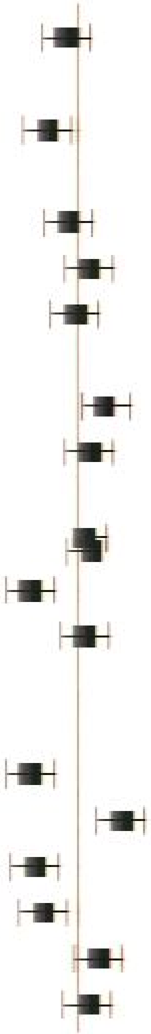

For these 16 measure

$$\sum \frac{(\mathcal{O} - \mathcal{M})^2}{\sigma^2} = 26$$

This is formally to big, but considerin the dicey estimates some of the σ's I thin it's remarkably good