THE ONASSIS FOUNDATION SCIENCE LECTURE SERIES

The 2008 Lectures in Physics:
COSMOLOGY: AN ASTROPHYSICAL PERSPECTIVE

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

P. J. E. Peebles
30 June 2008

The Cosmological Tests

The web of cosmological tests has grown rich and tight enough to show beyond reasonable doubt that the ΛCDM model is a good approximation to what actually happened back to redshift $z \sim 10^{10}$.

The new goal for the tests becomes to discover how our one viable cosmology might be improved, perhaps by the demonstration that cosmic strings or textures play an observationally significant role, or that the physics of dark matter and dark energy are a little more interesting than that of a perfectly collisionless initially cold gas and a new constant of nature in our universe, or maybe that dimensionless parameters of physics such as the strengths of gravity or electromagnetism are evolving.

And there always is the interesting possibility that we will be led to evidence that forces some deeper adjustment of ideas.

I begin with a survey of the assumptions in the ΛCDM cosmology, and then review the suite of tests of this model. My second lecture presents some ideas on phenomena that might lead us to improvements.

The Cosmological Tests: the ΛCDM Model

A general point to bear in mind is that there are a lot of assumptions in this model.

Some are natural: standard physics, including general relativity theory, but applied on scales of length and time that are enormous compared to the precision tests of the physics.

Many were introduced for the purpose of helping the theory fit the observations.

This means that establishing the ΛCDM Model requires an abundance of independent tests.

The exciting thing is that we at last have arguably more independent tests than free parameters and assumptions.

1. Global Geometry

The ΛCDM cosmology assumes a metric theory of a spacetime that is close to homogeneous and isotropic in the large-scale average. The symmetry requires the Robertson-Walker line element that has one function, $a(t)$, of proper world time t, and one constant, R^{-2},

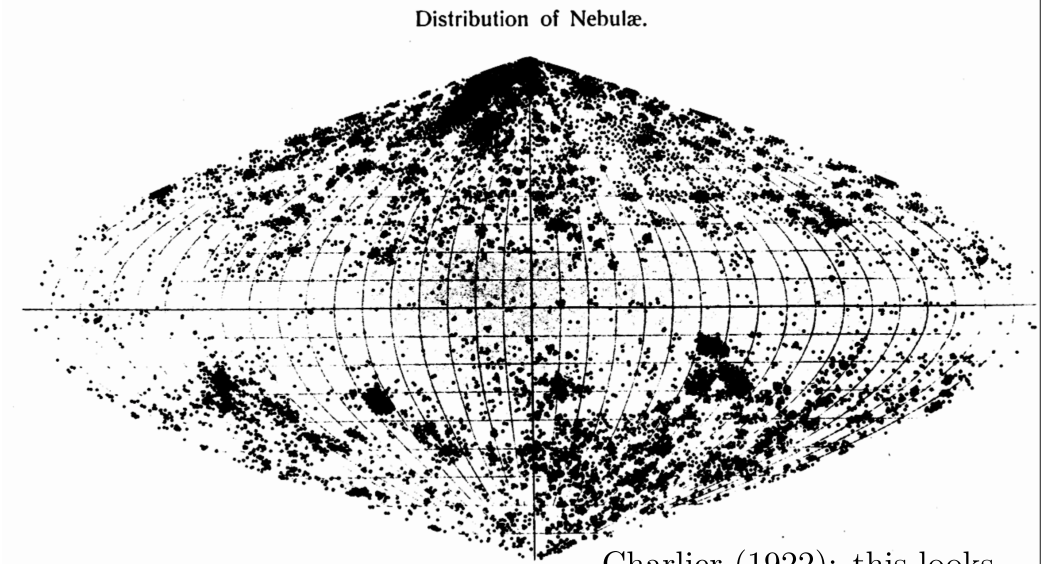
$$ds^2 = dt^2 - a(t)^2\left(\frac{dx^2}{1 - x^2R^{-2}} + x^2(d\theta^2 + \sin^2\theta d\phi^2)\right).$$

An observer at fixed coordinate position x, θ, ϕ sees an isotropic universe. An observer moving relative to this preferred frame sees anisotropic distributions of galaxy redshifts and the 3K background radiation.

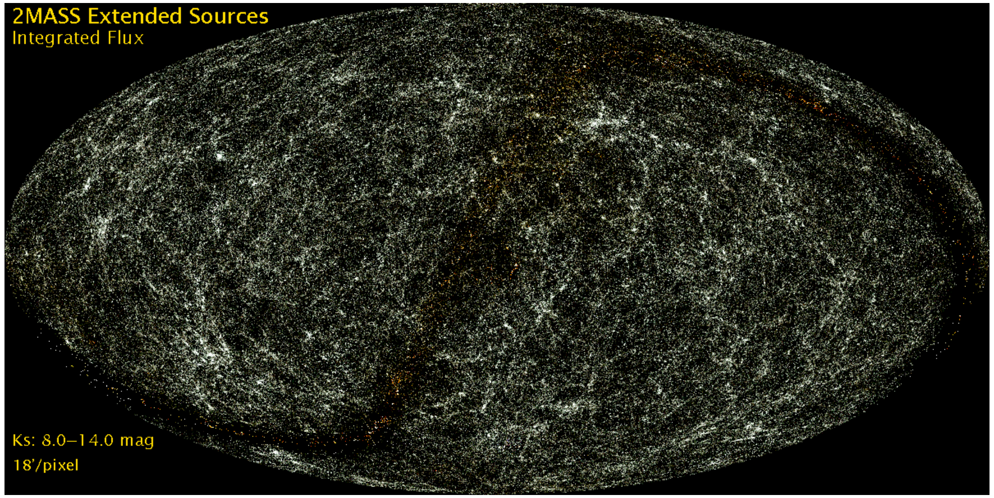
An object with physical size ℓ at coordinate position x appears at angular size $\delta\theta$ to observer at $x = 0$, where

$$\ell = a(t)x\delta\theta.$$

So x is termed the angular size distance.



Charlier (1922): this looks more like a clustering hierarchy — what we would now term a fractal universe.

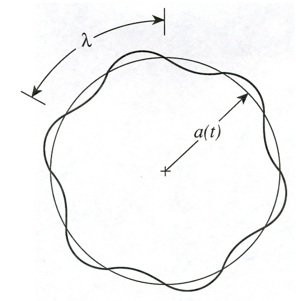


Tom Jarrett (2004): this 1 to 2.2μm galaxy map shows absorption in the plane of the Milky Way, but it looks more like Einstein's proposal of large-scale homogeneity.

2. Expansion and Redshift

In the standard model for the expanding universe the proper — physical — distance between conserved particles is increasing, as $d \propto a(t)$.

To get the cosmological redshift imagine the universe is periodic, and expand a particle wave function into its normal modes. Adiabaticity says a free particle stays in its mode, so its de Broglie wavelength scales with time as the mode wavelength, $\lambda \propto a(t)$, and the momentum scales as $p \propto 1/a(t)$: the peculiar velocity of a free nonrelativistic particle scales as $v \propto 1/a(t)$ and the wavelength of a photon scales as $\lambda \propto a(t)$.



The cosmological redshift z of light emitted by a distant galaxy at wavelength $\lambda_{\rm em}$ and observed at wavelength $\lambda_{\rm obs}$ is

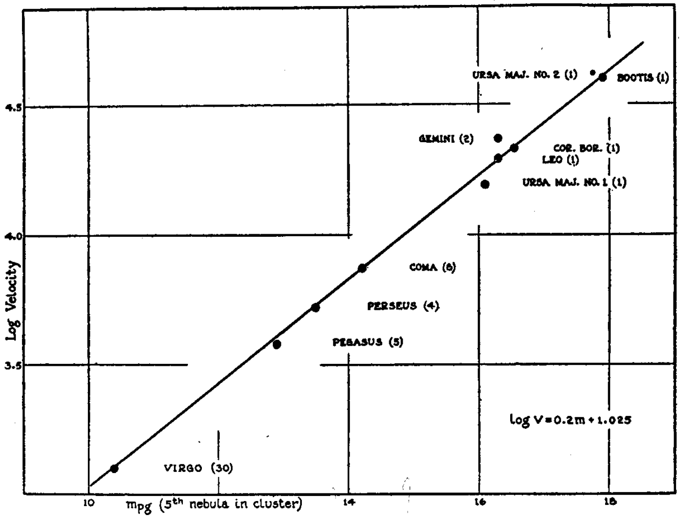
$$1 + z = \frac{\lambda_{\rm obs}}{\lambda_{\rm em}} \simeq \frac{a(t_{\rm obs})}{a(t_{\rm em})}.$$

The first equation is a definition, the second neglects effects of inhomogeneity. It is an interesting exercise to show that, at $z \ll 1$,

$$z = \frac{\dot a}{a} d = H d,$$

where d is physical distance.

This assumes standard local physics, a metric theory, but not GR.



Hubble and Humason ~ 1936

Al Kogut, 2007

3. Fossil Thermal Radiation

Tolman (1931) showed that free thermal radiation in a homogeneous isotropic expanding universe cools but remains blackbody.

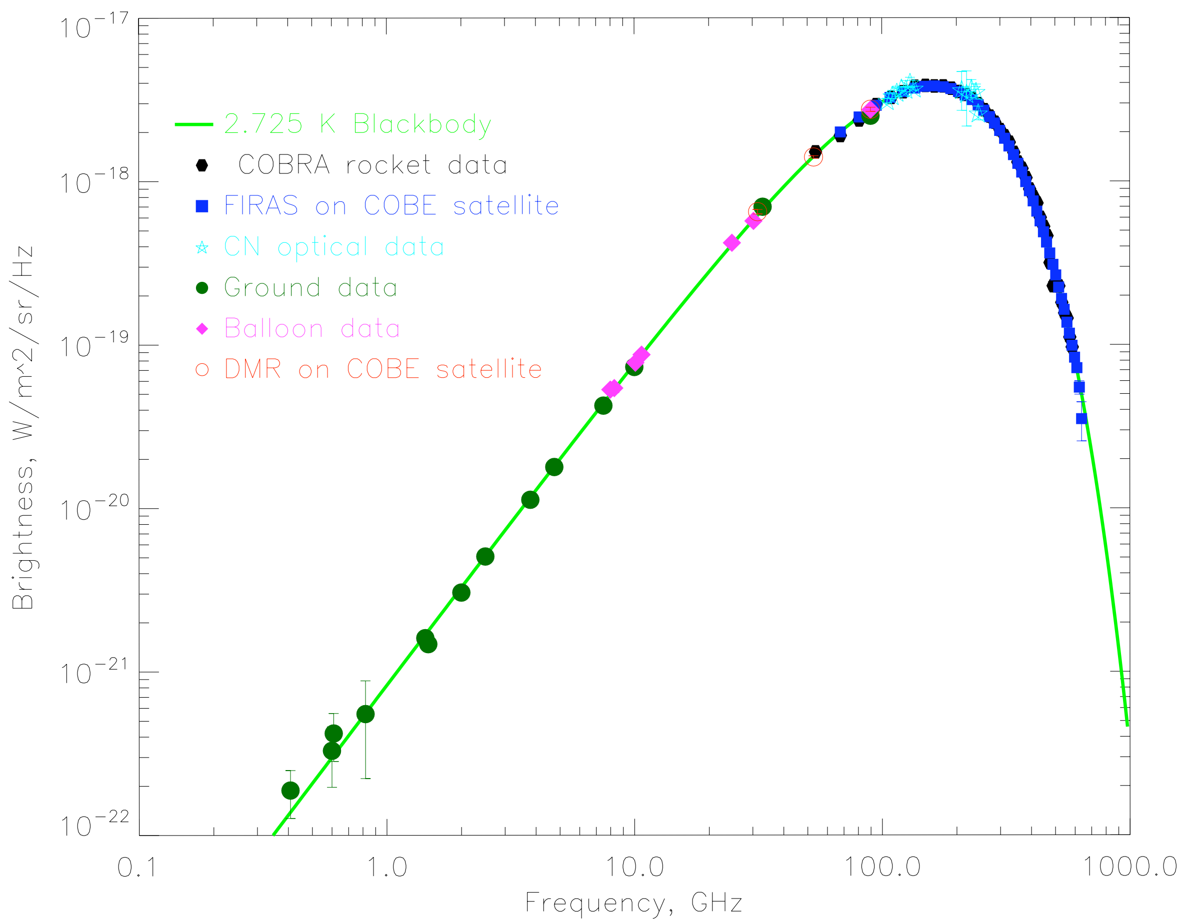
An easy demonstration uses normal modes. Planck's photon occupation number is

$$\mathcal{N} = \frac{1}{e^{h\nu/kT} - 1}.$$

Adiabaticity says $\mathcal{N}$ is conserved. Since $\nu \propto a(t)^{-1}$, $T \propto a(t)^{-1}$, the same for all modes, so the radiation remains thermal.

Again, we did not need GR.

By the same argument a nonrelativistic monatomic gas cools as $T_g \propto a(t)^{-2}$. A comparison of heat capacities of baryons and radiation (at present CBR temperature $\sim$ 3 K and baryon density $\sim 10^{-6}\,\mathrm{cm}^{-3}$) shows why it's hard to disturb the CBR spectrum by energy exchange with the matter.



The universe as it is now can't have forced radiation to relax to this distinctive spectrum: distant objects are observed at these wavelengths. This is tangible evidence our universe evolved from a different state — denser and hotter.

4. Local Energy Conservation

This follows by a similar argument.

In a homogeneous and isotropic universe with mass (energy) density $\rho(t)$ at pressure $p(t)$ imagine a sphere expanding with the general expansion. It has fixed comoving radius x and physical radius $r = a(t)x$. We will require $Hr \ll 1$.

The sphere has volume $V(t) = 4\pi(ax)^3/3$, contains energy $E = \rho V$, and is doing pressure work of expansion $dE/dt = -p dV/dt$. If we can ignore bulk viscosity, we get

$$\dot{\rho} = -3(\rho + p)\dot{a}/a.$$

This is a local energy equation; it does not integrate to global energy conservation.

It assumes standard local physics, and a metric spacetime, but does not require GR.

For matter with negligible pressure, $|p| \ll |\rho|$, $\rho \propto a(t)^{-3}$.

For a radiation-dominated fluid, $p = \rho/3$, $\rho \propto a(t)^{-4}$, which is no surprise since we already have $T \propto a(t)^{-1}$.

5. Friedmann Equation

Spherical symmetry says the acceleration of the radius of the sphere in the preceeding energy calculation is caused by the attraction of the gravitational mass M_g within the sphere, $d^2r/dt^2 = -GM_g/r^2$. This Newtonian expression is valid under local physics if the sphere is small, $Hr \ll 1$.

Now we need GR, which says the active gravitational mass density is $\rho_g = \rho + 3p$, so

$$\frac{\ddot{a}}{a} = -\frac{4}{3}\pi G(\rho + 3p).$$

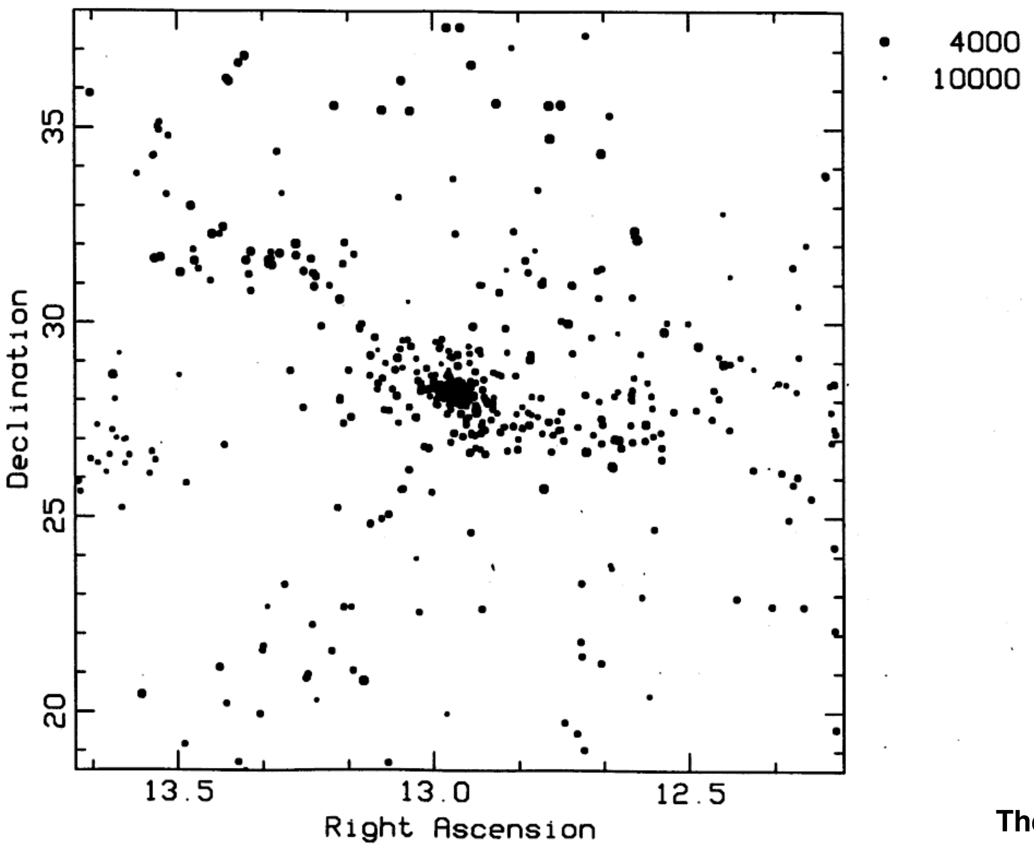
This equation with local energy conservation integrates to

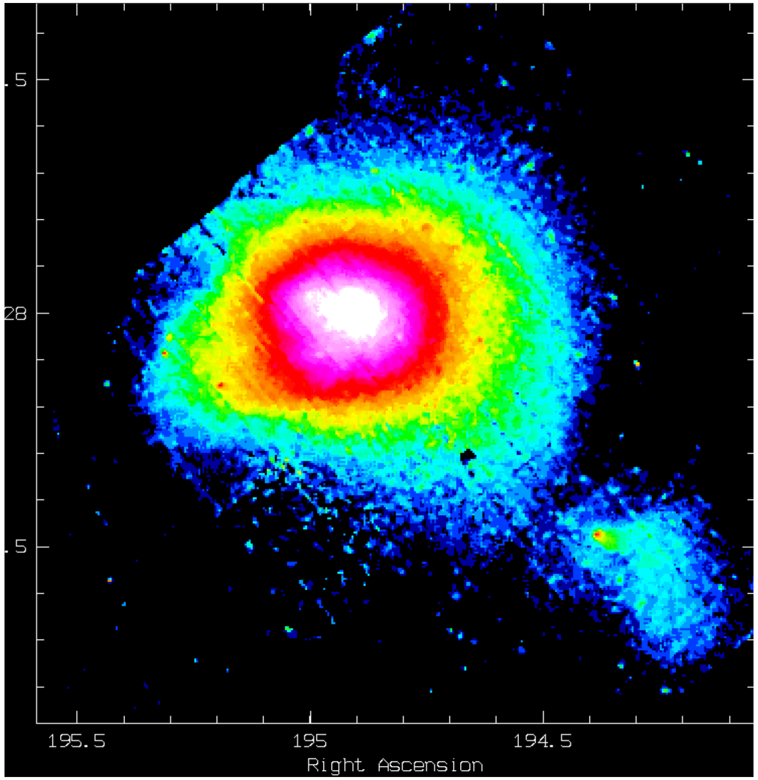
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8}{3}\pi G\rho - (aR)^{-2}.$$

We need GR again to show that the constant of integration R^{-2} is the curvature parameter in the Robertson-Walker line element.

6. Dark Matter

Hypothetical matter required to gravitationally bind stars and gas in the outer parts of galaxies, and the galaxies and plasma in clusters of galaxies.

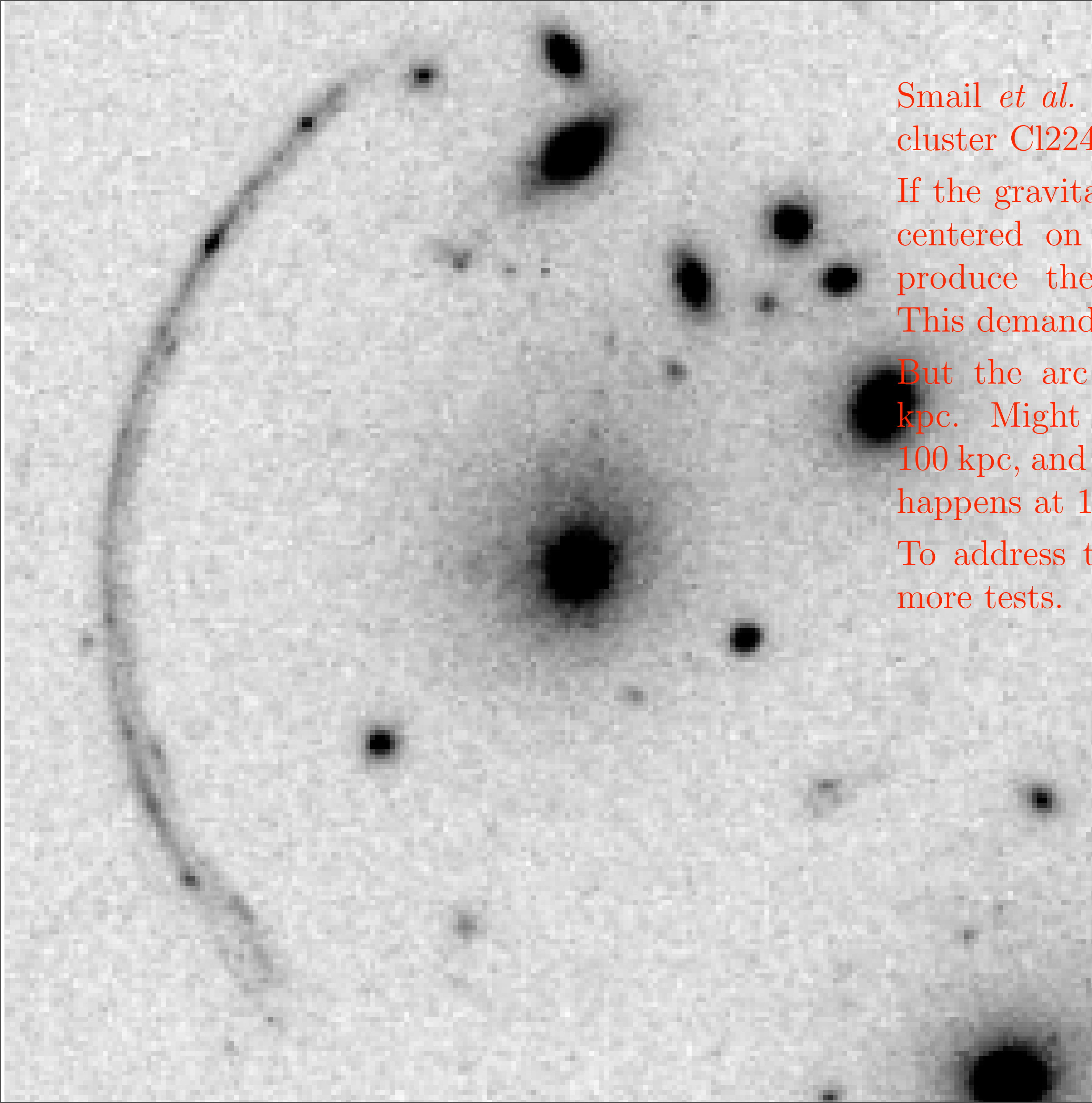




The dynamical state of the Coma cluster with XMM-Newton

D. M. Neumann[1], D. H. Lumb[2], G. W. Pratt[1], and U. G. Briel[3]

It is good science to ask, with Milgrom, whether the binding might result instead from a gravitational force law that decreases more slowly than r^{-2} under suitable conditions. Here is a compelling case for dark matter:

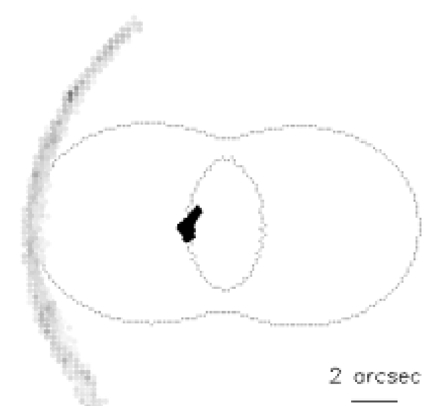


Smail *et al.* WFPC2 image of the cluster Cl2244-02 at $z = 0.33$.

If the gravitational attraction were centered on the light it couldn't produce the smooth arc image. This demands dark matter.

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?

To address that question we need more tests.



7. Dark Energy

In the 1917 paper introducing the cosmological constant Einstein rewrote his field equation as $R_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T)$.

Lemaître (1932) noticed that if we put the cosmological constant on the other side of the equation (and rearrange the trace term) we get

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = -\kappa T_{\mu\nu} - \lambda g_{\mu\nu}.$$

For an isotropic fluid at rest with energy density ρ and pressure p, $T_{\mu\nu}$ is diagonal, ρ, p, p, p. We see that Einstein's new term placed as a part of the source has the role of a fluid with energy density and pressure

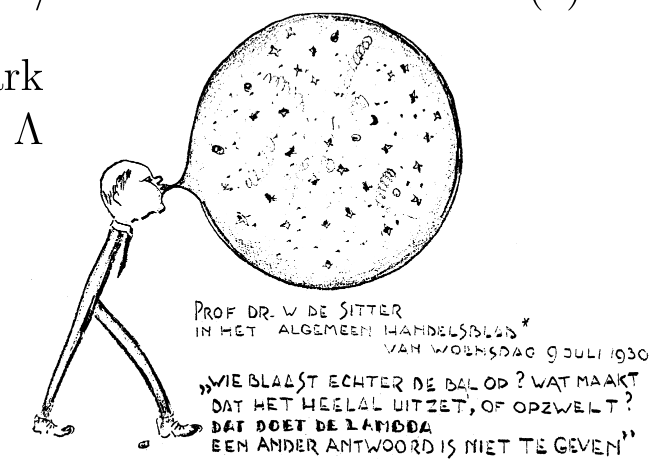
$$\rho_\lambda = \lambda/\kappa, \qquad p_\lambda = -\lambda/\kappa. \tag{1}$$

The modern advances: we have a new name, dark energy, a new symbol, Λ, and evidence that Λ really is a significant actor.

Equation (1) in Friedmann's equation gives

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3}G(\rho + 3p - 2\rho_\Lambda),$$

where ρ and p exclude DE. When DE dominates the expansion accelerates.



8. Redshift-Magnitude Relation

Liouville's theorem says the density of photons in single-particle phase space is constant along the photon path. It's an interesting exercise to check that that says the radiation surface brightness — energy flow per unit area, steradian and logarithmic frequency interval — scales as $\nu i_\nu \propto (\nu_o/\nu_e)^4$, for emitted frequency ν_e and observed frequency ν_o.

An object with luminosity $\nu_e L_{\nu_e}$ and physical size ℓ has surface brightness $\nu_e i_{\nu_e} \propto \nu_e L_{\nu_e}/\ell^2$ at the source, and at angular size distance x it subtends solid angle $\delta\Omega \propto (\ell/a_e x)^2$, so the observed energy flux density is

$$\nu f_\nu \propto \frac{\nu_e L_{\nu_e}}{\ell^2}\left(\frac{\nu_o}{\nu_e}\right)^4\left(\frac{\ell}{a_e x}\right)^2 \propto \frac{\nu_e L_{\nu_e}}{(a_o x)^2(1+z)^2},$$

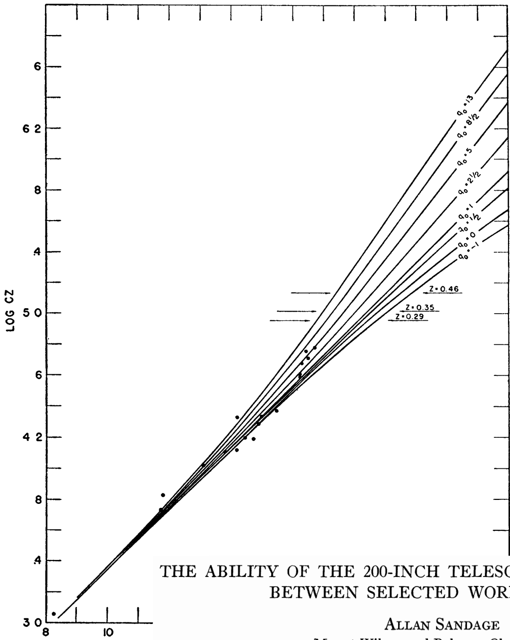
To get x as a function of z use GR:

$$\int \frac{dt}{a(t)} = \int \frac{dx}{\sqrt{1 - x^2 R^{-2}}}.$$

It's standard to write Friedmann's equation for this integral as

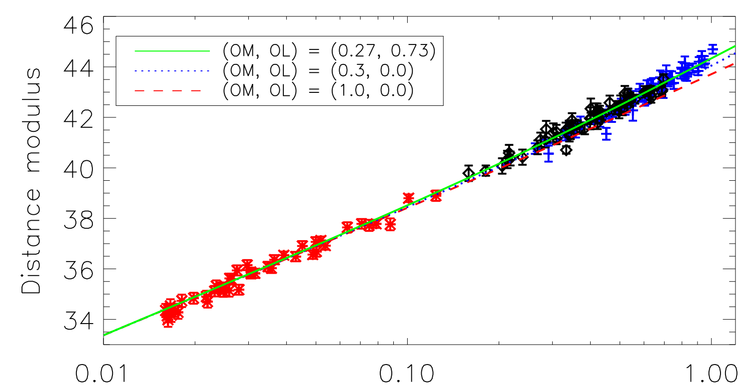
$$(\dot{a}/a)^2 = H_o^2[\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda],$$

where H_o is Hubble's constant and the Ω's are the density parameters for radiation, matter, space curvature, and dark energy.



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
Received October 14, 1960; revised November 5, 1960



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]

9. Initial Conditions

"Neoclassical" cosmological tests probe behavior of departures from homogeneity.

In GR the expanding universe is gravitationally unstable: small departures from homogeneity grow larger. The flow of oil in a pipeline is unstable too, but with the difference that the flow grows to turbulence that forgets initial conditions.

Large-scale structure, as galaxies and clusters of galaxies, is sensitivity to initial conditions. One way to see why is to note that the standard cosmology does not give us a characteristic time to define exponential growth. Thus in the early universe where $p = \rho/3$ we get the power law growth,

$$\frac{\delta\rho}{\rho} \equiv \delta(\vec{x}, t) \propto t.$$

Though the early mass distribution had to have been very close to smooth the primeval mass fluctuations produce significant curvature fluctuations. A simple way to see this: in the radiation-dominated early universe $G\rho \propto t^{-2}$, as expected from dimensional analysis, and since $\rho \propto a^{-4}$ for radiation we're not surprised that $a \propto t^{1/2}$. That produces curvature perturbation

$$\Phi \sim G\delta M/r \propto G\bar{\rho}\,\delta\,(ax)^2 \sim \text{constant}.$$

In the standard model the early universe had slight permanent wrinkles.

9. Initial Conditions

In the standard model the primeval departure from homogeneity is adiabatic, Gaussian and close to scale-invariant.

The first condition, homogeneous entropy per conserved particle, means roughly that the ratios of local number densities of photons, baryons and DM particles are constant (with adjustments for annihilation of the electron-positron sea and so on).

Gaussianity means the mass fluctuations are fixed by the power spectrum.

Near scale-invariance is characterized by the curvature fluctuations. The mass density is $\rho(\vec{x},t) = \bar{\rho}(t)(1+\delta(\vec{x},t))$, the mass correlation function is

$$\xi(x) = \langle \delta(\vec{x}+\vec{y})\delta(\vec{y})\rangle,$$

the mass fluctuation power spectrum $\mathcal{P}(k)$ is defined by

$$\xi(x) = \int d^3k\, \mathcal{P}(k) e^{i\vec{k}\cdot\vec{x}}, \quad \langle \delta^2\rangle = \xi(0) = \int d^3k\, \mathcal{P}(k) = \int 4\pi k^3 \mathcal{P}(k)\, d\ln k.$$

The mean square value — the variance — of the density contrast is $\langle \delta^2\rangle$. One sees that the variance per logarithmic interval of the wavenumber k, or wavelength $\lambda = 2\pi/k$, is $4\pi k^3\mathcal{P}(k)$. So the variance in curvature per logarithmic interval of length scales as

$$\Phi^2 \propto \delta^2 x^4 \propto \mathcal{P}(k)k^3 \times k^{-4} \propto k^{n_s-1}.$$

The scale-invariant case is $n_s = 1$. The evidence is that n_s is slightly below unity, though I understand that that is not yet to be considered convincingly established.

Initial Conditions: Acoustic Oscillations

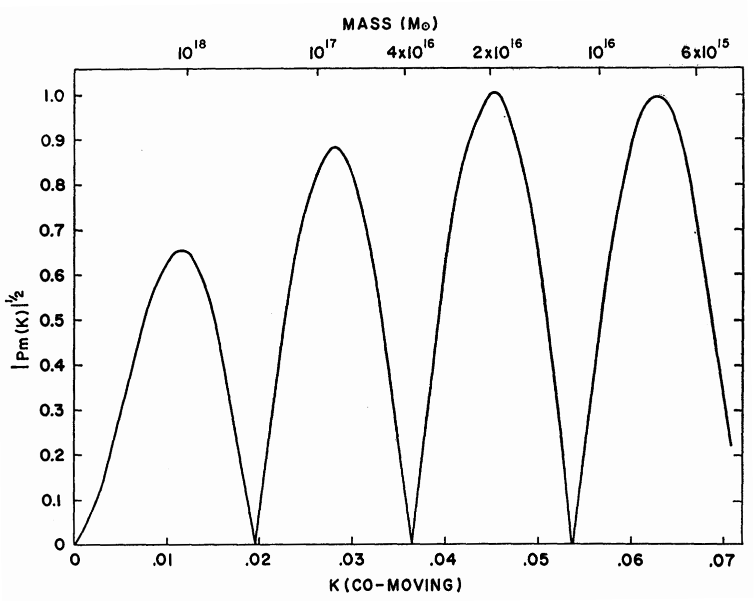
At redshift $z \gtrsim 1000$, temperature $T \gtrsim 3000\,\mathrm{K}$, baryonic matter is thermally ionized. Thomson scattering by the free electrons causes plasma and radiation to act as a single viscous fluid. Baryons and radiation are decoupled at $z \simeq 1000$ when the plasma combines to atomic hydrogen and H_2 — with trace residual ionization.

Adiabaticity requires that the primeval fluctuations in the baryon distribution are accompanied by fluctuations in the radiation.

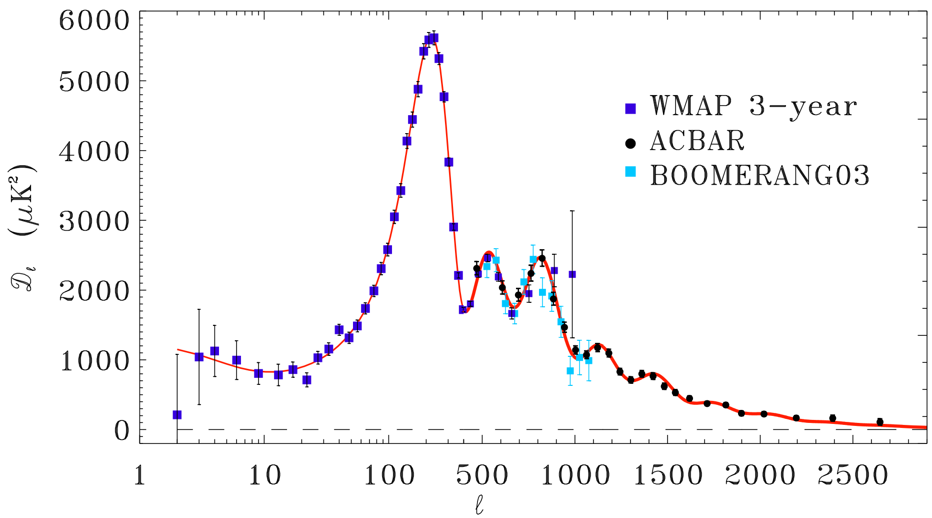
The radiation pressure requires that the Fourier amplitude $\delta_{\vec{k}}(t)$ in the plasma-radiation distribution oscillates.

The condition that the universe is growing clumpy requires that each Fourier component of the primeval distribution starts growing as $\delta_{\vec{k}}(t) \propto t$ in the early universe.

The phasing means that the power spectrum of the baryon and radiation distribution at decoupling is an oscillating function of wavenumber, as in this 1970 computation (before dark matter).



Acoustic Oscillations and the CMB Anisotropy Spectrum



In the spherical harmonic expansion

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

of the 3 K CMB 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 deeply 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 was seen to help fit the measurements: 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.

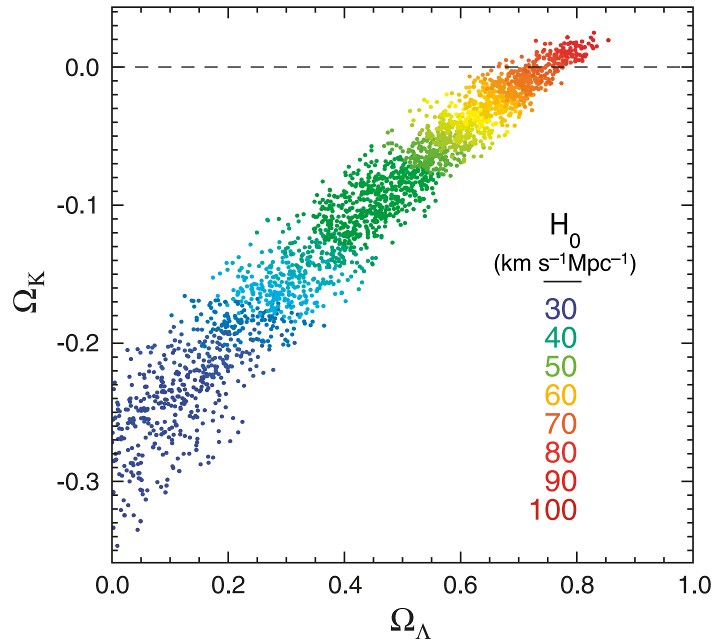
A fit without dark energy

The density parameters $\Omega_b h^2$ for baryons and $\Omega_m h^2$ for dark matter, with the present CMB temperature $T_o = 2.725\,\mathrm{K}$, and the primeval power spectrum power law index n_s and amplitude, closely fix the evolution of fluctuations in the distributions of baryons and radiation up to $z \sim 1000$ when they decouple.

Any combination of distance scale $h = H_o/100$ km s^{-1} Mpc^{-1} and space curvature that produces the same angular size distance back to $z = 1000$ gives very nearly the same CBR anisotropy spectrum.

This allows a fit to the WMAP5 anisotropy measurements in a model with no dark energy. It is important that we have constraints within the fit — the $\Lambda = 0$ fit requires an exceedingly dicey distance scale — and we have quite independent evidence, as from the redshift-magnitude relation.

But it suggests the question: might some brilliant iconoclast find some other way to eliminate dark energy, some other theory that fits? The key point is that we have many other tests that all together make this a considerable challenge.



Dunkley *et al.* WMAPIII

This Illustrates a Way to Organize the Suite of Cosmological Tests

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

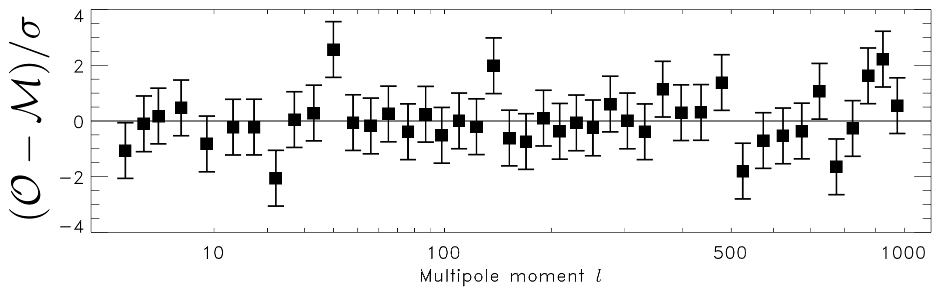
$$\Omega_{\rm CDM} = 0.21,\ \Omega_{\rm b} = 0.044,\ h = 0.72,$$

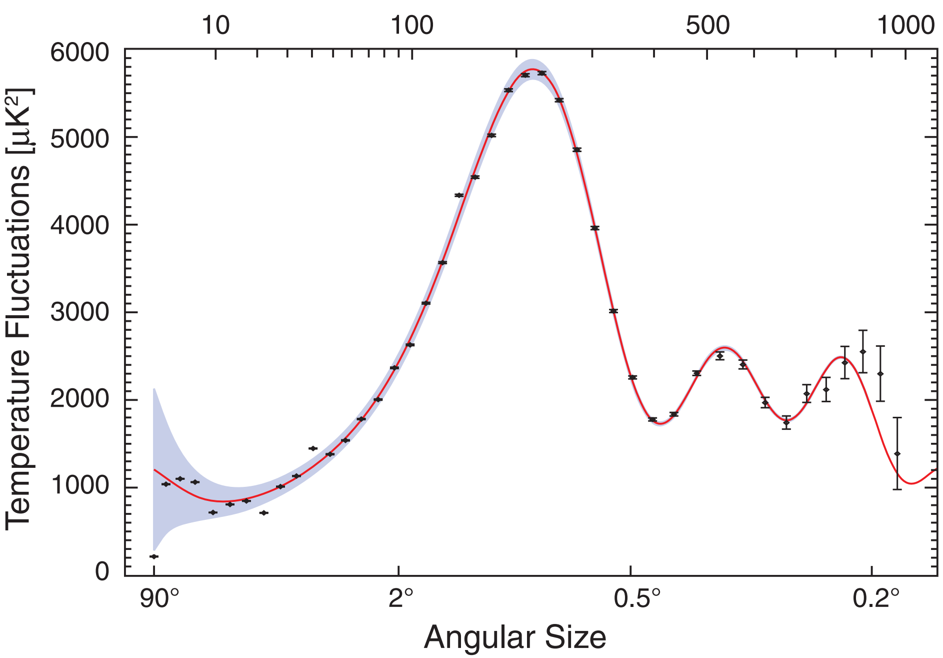
$$n_s = 0.96,\ \sigma_8 = 0.80,\ \tau = 0.09.$$

As we have noted this does not mean this ΛCDM has passed 36 independent challenges; we need more tests.

So let us consider every other independent test that had a meaningful chance of falsifying this particular model, reduce each to one or a few numbers, and for each estimate the statistic

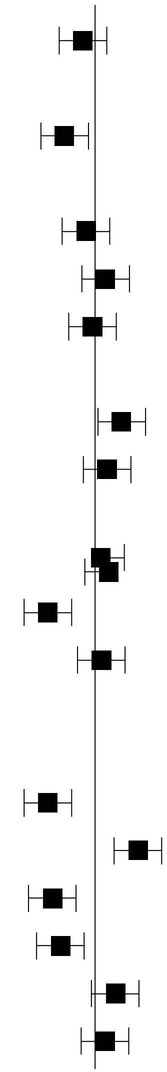
$$(\mathcal{O} - \mathcal{M})/\sigma.$$





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.

	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	
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			



From *Finding the Big Bang*, Peebles, Page and Partridge

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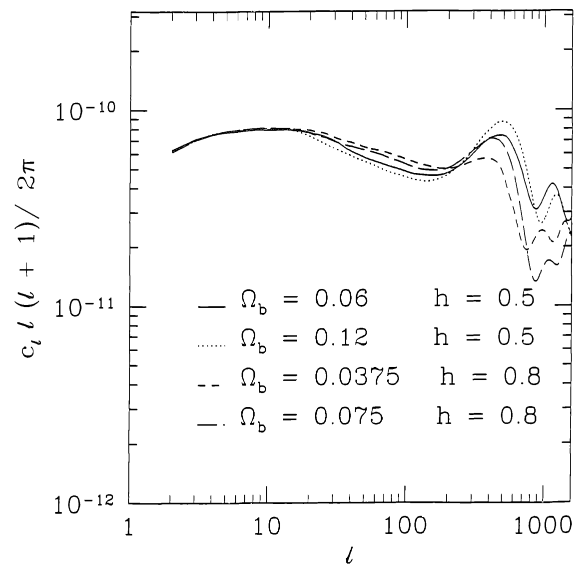
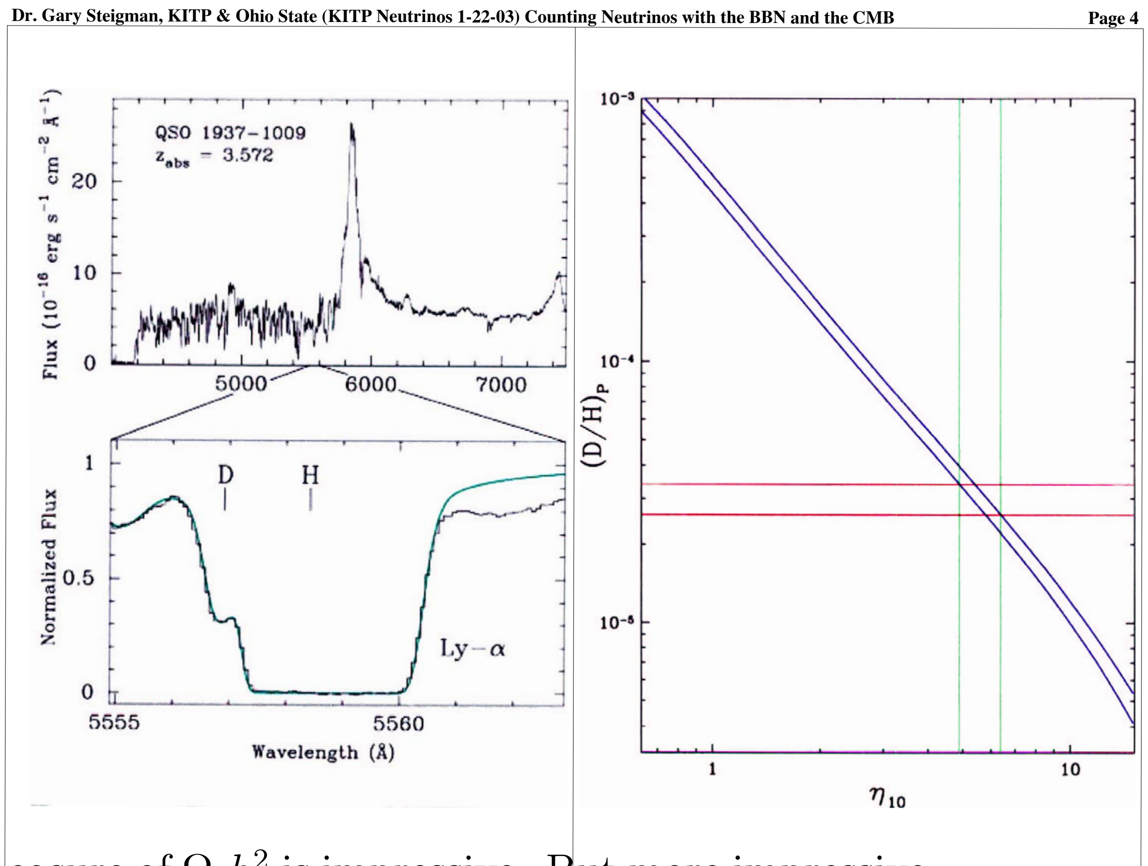
Kaminokowski, Spergel and Sugiyama 1994



WMAPIII:
$\Omega_b h^2 = 0.02273 \pm 0.00062$



The precision of the WMAPIII measure of $\Omega_b h^2$ is impressive. But more impressive is the consistency of measures of $\Omega_b h^2$ from such very different phenomena.

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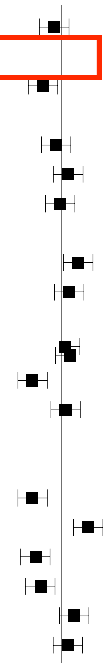
Baryon acoustic oscillation	Ω_m/h^2	0.50	0.53 ± 0.06	
Dynamical mass estimates				
Galaxy velocities	Ω_m	0.26	$0.30^{+0.17}_{-0.07}$	
Lensing around clusters	Ω_m	0.26	0.20 ± 0.03	
Lensing autocorrelation	$\sigma_8 \Omega_m^{0.53}$	0.39	0.40 ± 0.04	
Galaxy count fluctuation	$\sigma_8(g)$	0.80	0.89 ± 0.02	
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	
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 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 HI resonance absorption line clouds, but largely hypothetical dark baryons

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

	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		
Dynamical mass estimates				
Galaxy velocities	Ω_m	0.26		
Lensing around clusters	Ω_m	0.26		
Lensing autocorrelation	$\sigma_8\Omega_m^{0.53}$	0.39		
Galaxy count fluctuation	$\sigma_8(g)$	0.80		
Rich clusters of galaxies				
Present mass function	$\sigma_8\Omega_m^{0.37}$	0.49		
Mass function evolution	σ_8	0.80		
	Ω_m	0.26		
Cluster baryon fraction	$\Omega_b h^{3/2}/\Omega_m$	0.103		
Baryon evolution	$\Omega_\Lambda + 1.1\Omega_m$	1.03		
Lyα forest	n_s	0.96		
Neutrino density	$\Omega_\nu h^2$	< 0.02		
ISW	detected, at about the			

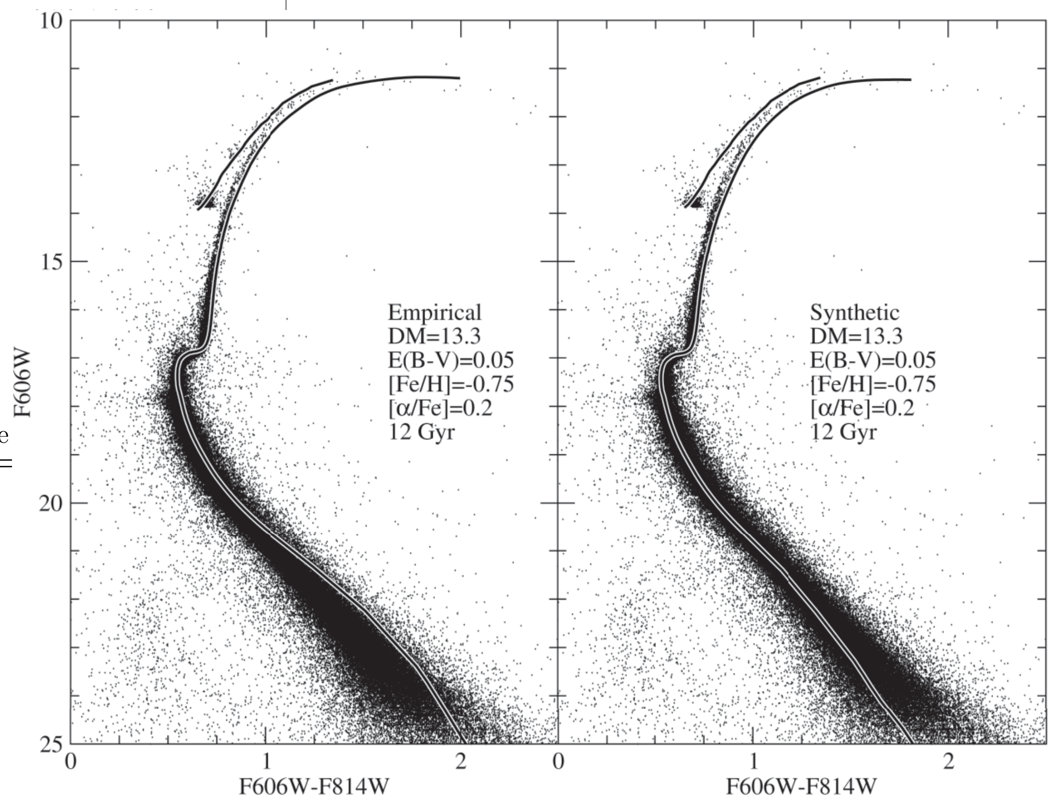


Fig. 12.—ACS data from 47 Tuc compared to isochrones with both empirical (*left*) and synthetic (*right*) color transformations. Details are listed on each panel. Data are from Sarajedini et al. (2007). The fiducial line from the metal-rich SHB model of § 4.4 (Fig. 6) is plotted alongside both isochrones. [*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[1], G. Clementini[2], S. Desidera[1], F. Grundahl[3], and S. Lucatello[1,4]

	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	
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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	
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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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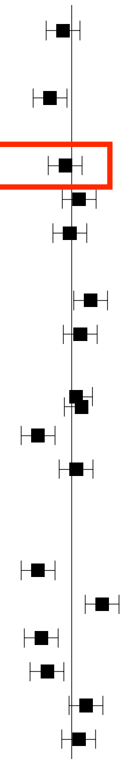
Lyα forest	n_s	0.96	0.965 ± 0.012	
Neutrino density	$\Omega_\nu h^2$	< 0.02	0.001	
ISW	detected, at about the fiducial prediction			



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 μ_0(LMC) = 18.50 ± 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) ± 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	$(\mathrm{M}-\mathrm{R})/\sigma$
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	
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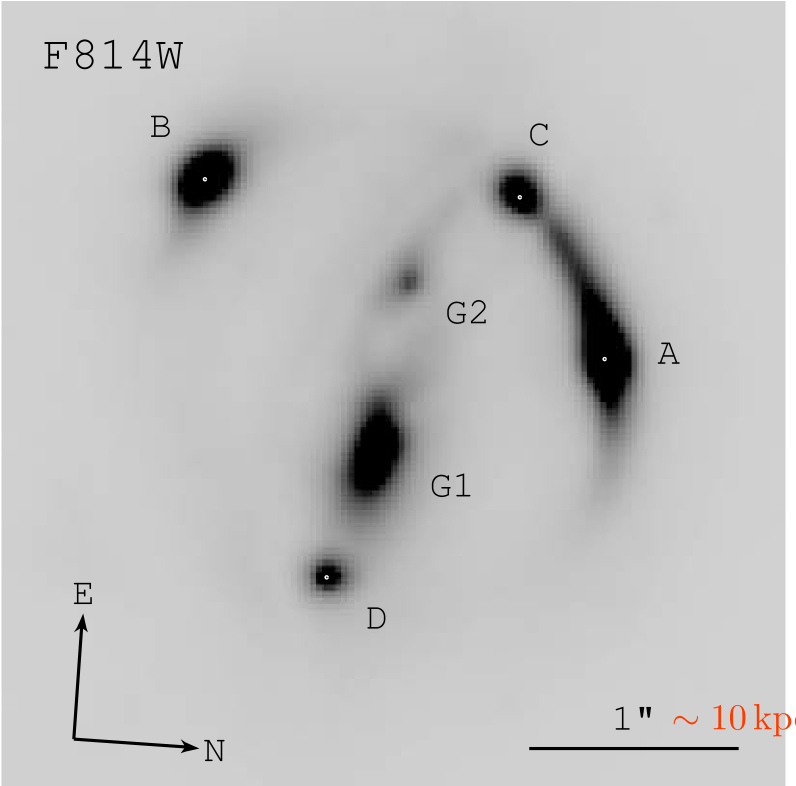
SNeIa distance modulus	$\delta\mu(z=1)$	1.00	0.99 ± 0.08	
Large-scale structure				
Matter power spectrum	$\Omega_m h$	0.187	0.213 ± 0.023	
Baryon acoustic oscillation	Ω_m/h^2	0.50	0.53 ± 0.06	
Dynamical mass estimates				
Galaxy velocities	Ω_m	0.26	$0.30^{+0.17}_{-0.07}$	
Lensing around clusters	Ω_m	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	
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.



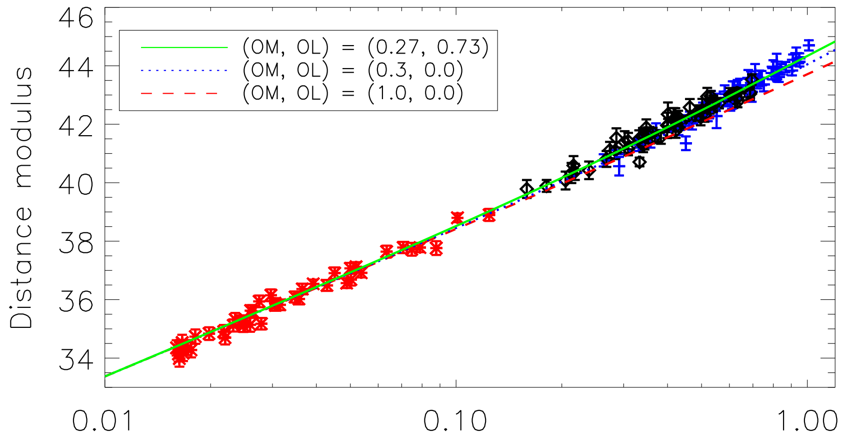
DISSECTING THE GRAVITATIONAL LENS B1608+656: LENS POTENTIAL RECONSTRUCTION[1]

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*

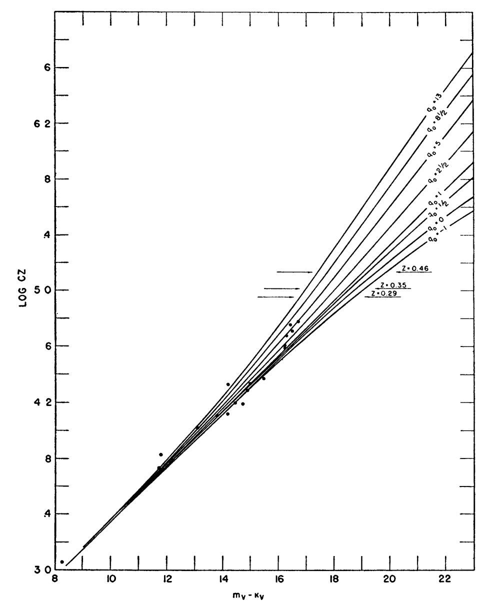
	Parameter	Fiducial	Measured	$(\mathrm{M}-\mathrm{R})/\sigma$
Baryon density				
BBNS	$\Omega_b h^2$	0.0227	0.0219 ± 0.0015	
Baryon budget	Ω_b	0.042	> 0.005	
Stellar evolution ages	t_*, Gyr	13.6	12.3 ± 1.0	
Distance scale				
Distance Ladder	h	0.72	0.69 ± 0.08	
Gravitational lensing	h	0.72	0.75 ± 0.07	
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	
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			

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



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]



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

Received October 14, 1960; revised November 5, 1960

	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	
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 cosmological constant and cold dark matter

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

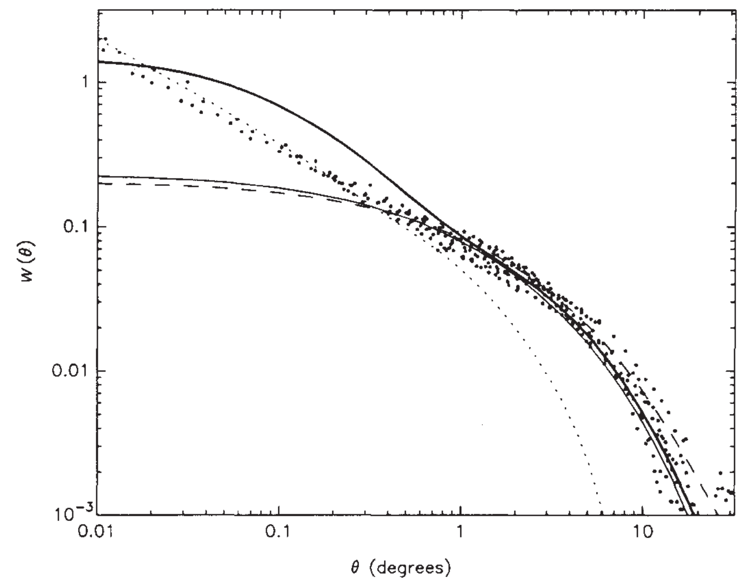


FIG. 1 The dots show estimates of the angular correlation function $w(\theta)$ for galaxies in the APM galaxy survey (see ref. 5 for details). These estimates have been scaled to the depth of the Lick galaxy catalogue where 1° corresponds to a spatial scale of $\sim 5h^{-1}$ Mpc. The dotted line shows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

	Parameter	Fiducial	Measured	$(\mathrm{M}-\mathrm{R})/\sigma$
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	
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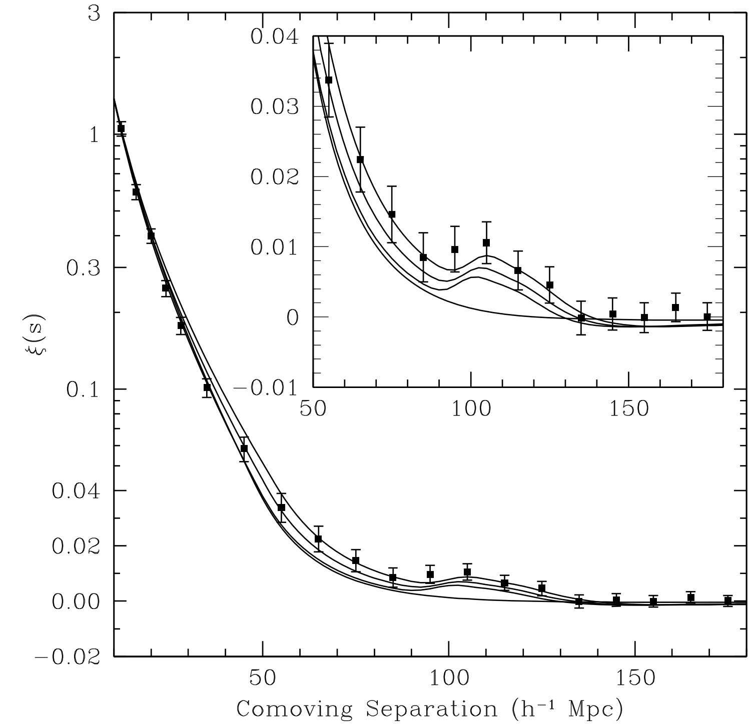
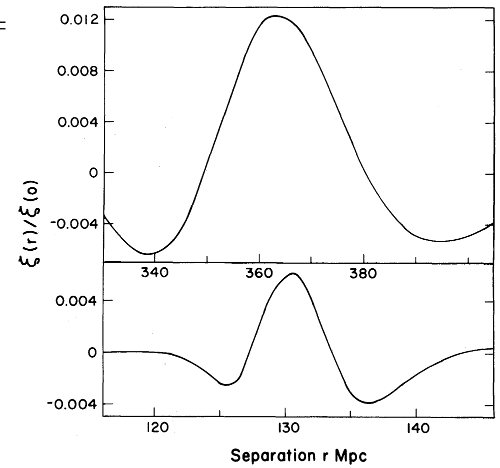


DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

Daniel J. Eisenstein,[1,2] Idit Zehavi,[1] David W. Hogg,[3] Roman Scoccimarro,[3] Michael R. Blanton,[3] Robert C. Nichol,[4] Ryan Scranton,[5] Hee-Jong Seo,[1] Max Tegmark,[6,7] Zheng Zheng,[8] Scott F. Anderson,[9] Jim Annis,[10] Neta Bahcall,[11] Jon Brinkmann,[12] Scott Burles,[7] Francisco J. Castander,[13] Andrew Connolly,[5] Istvan Csabai,[14] Mamoru Doi,[15] Masataka Fukugita,[16] Joshua A. Frieman,[10,17] Karl Glazebrook,[18] James E. Gunn,[11] John S. Hendry,[10] Gregory Hennessy,[19] Zeljko Ivezić,[9] Stephen Kent,[10] Gillian R. Knapp,[11] Huan Lin,[10] Yeong-Shang Loh,[20] Robert H. Lupton,[11] Bruce Margon,[21] Timothy A. McKay,[22] Avery Meiksin,[23] Jeffery 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



PRIMEVAL ADIABATIC PERTURBATIONS: CONSTRAINTS FROM THE MASS DISTRIBUTION[1]

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

Received 1981 February 9; accepted 1981 March 27

	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				
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Large-scale structure				
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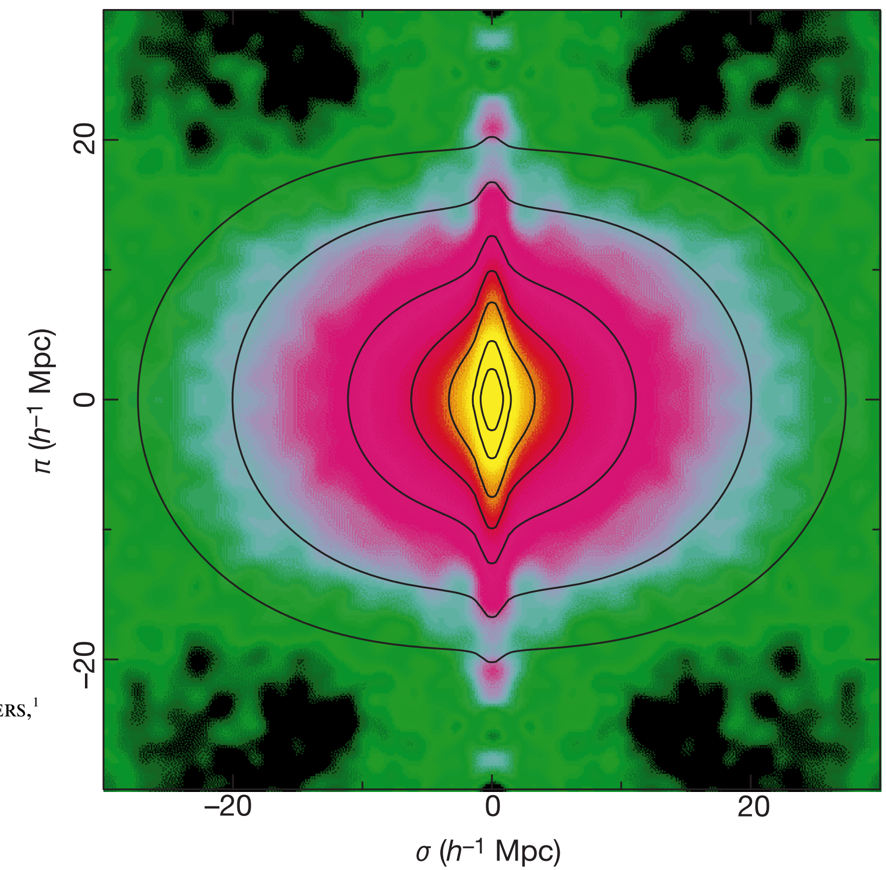
Neutrino density	$\Omega_\nu h^2$	< 0.02	0.001	
ISW	detected, at about the fiducial prediction			

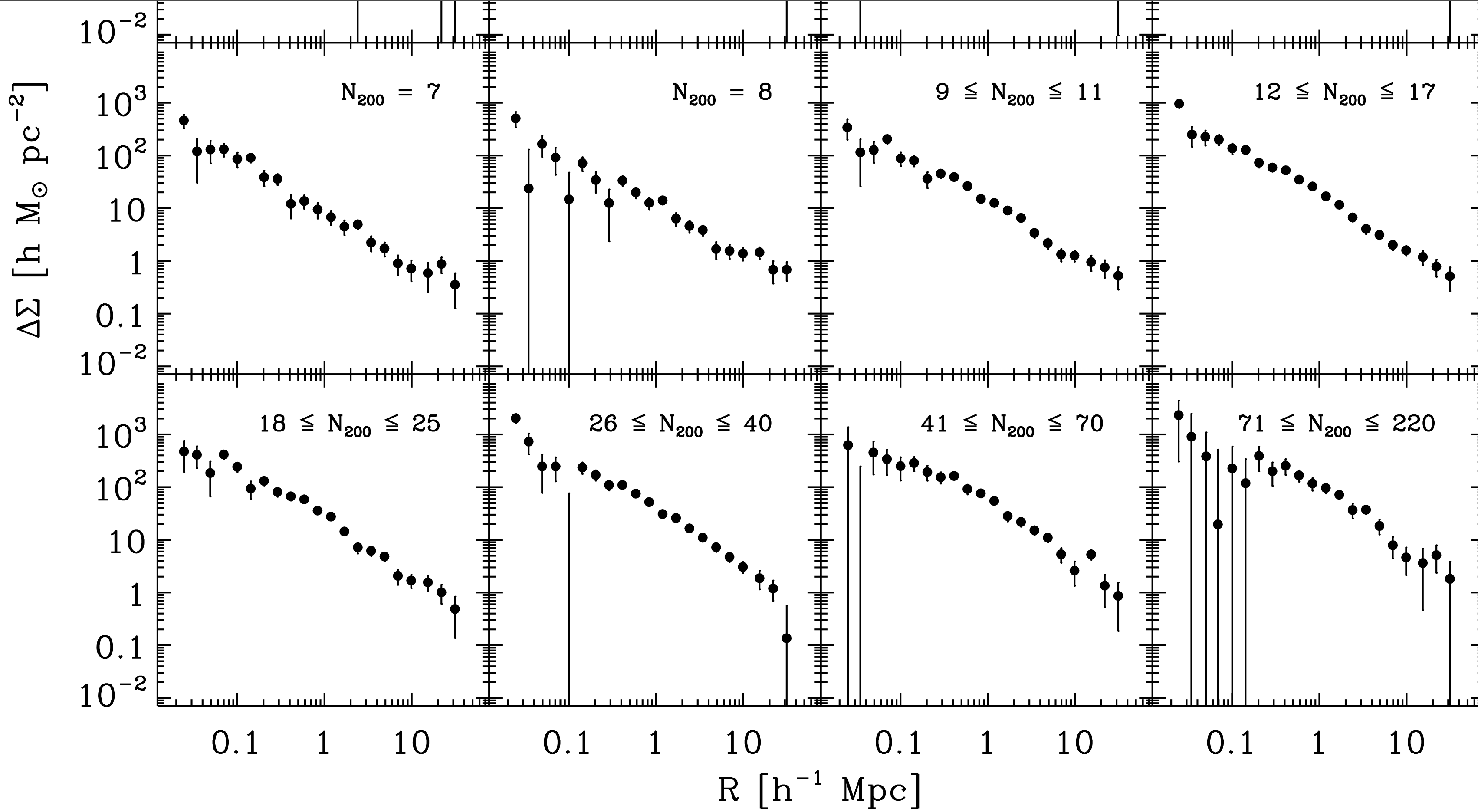
AN ESTIMATE OF Ω_m WITHOUT CONVENTIONAL PRIORS

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]



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

John A. Peacock[1], Shaun Cole[2], Peder Norberg[2], Carlton M. Baugh[2], Joss Bland-Hawthorn[3], Terry Bridges[3], Russell D. Cannon[3], Matthew Colless[4], Chris Collins[5], Warrick Couch[6], Gavin Dalton[7], Kathryn Deeley[6], Roberto De Propris[6], Simon P. Driver[8], George Efstathiou[9], Richard S. Ellis[9,10], Carlos S. Frenk[2], Karl Glazebrook[11], Carole Jackson[4], Ofer Lahav[9], Ian Lewis[3], Stuart Lumsden[12], Steve Maddox[13], Will J. Percival[1], Bruce A. Peterson[4], Ian Price[4], Will Sutherland[1,7] & Keith Taylor[3,10]



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

	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	

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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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			

This checks consistency of the measured large-scale mass fluctuations with what is needed to fit the measured fluctuations of the CMB temperature.

The statistic is the rms fractional mass fluctuation

$$\sigma_8(m) = \langle (m - \langle m \rangle)^2 \rangle^{1/2} / \langle m \rangle$$

in randomly placed spheres of radius $8h^{-1}$ Mpc. The surrogate is the rms fractional fluctuation $\sigma_8(g)$ in galaxy counts on the same scale.

Since stars and DM are segregated we can only expect $\sigma_8(m)$ and $\sigma_8(g)$ are about the same. The significance of the test is your judgement call.

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

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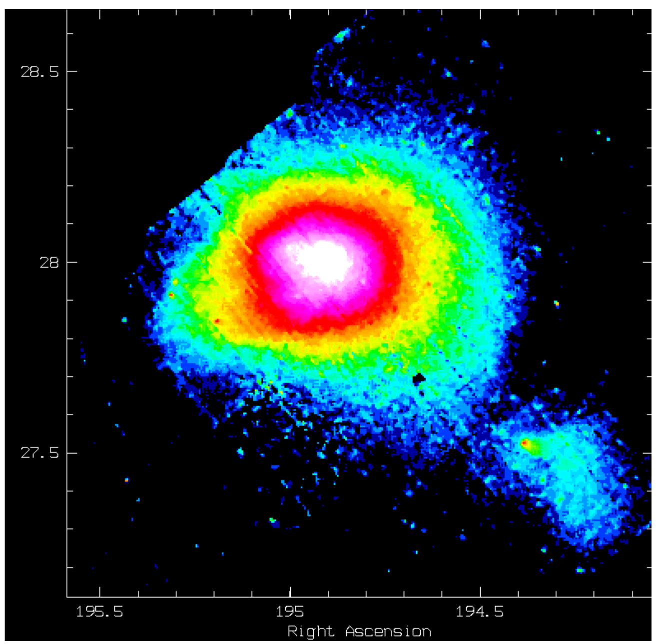
Baryonic matter constitutes a larger fraction of the total mass of rich galaxy clusters than is predicted by a combination of cosmic nucleosynthesis considerations (light-element formation during the Big Bang) and standard inflationary cosmology. This cannot be accounted for by gravitational and dissipative effects during cluster formation. Either the density of the Universe is less than that required for closure, or there is an error in the standard interpretation of element abundances.



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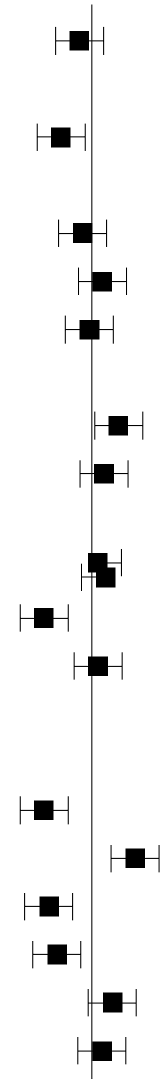

For these 16 measures

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

This is formally too big, but considering the dicey estimates of some of the σ's I think it's remarkably good.

The Cosmological Tests: A Summary

The ΛCDM cosmology has passed a considerable variety of independent challenges, each of which could have falsified the model. We have looked at the universe from many sides now and found that this cosmology fits what is observed.

That does not mean ΛCDM is realty; we make progress by successive approximations.

And we are drawing exceedingly big conclusions from what still is very limited evidence.

These considerations lead me to expect that ΛCDM will continue to be a good approximation to the improving observations, but that it would not be surprising to find that it has to be adjusted, as in more complicated physics in the dark sector, or maybe something completely different.

In my second lecture I'll discuss three phenomena that seem puzzling and may — just possibly — point to some adjustment.