The Cosmological Tests

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**Abstract.** Recent observational advances have considerably improved the cosmological tests, adding to the lines of evidence, and showing that some issues under discussion just a few years ago may now be considered resolved or irrelevant. Other issues remain, however, and await resolution before the great program of testing the relativistic Friedmann-Lemaître model, that commenced in the 1930s, may at last be considered complete.

1. Introduction

The search for a well-founded physical cosmology is ambitious, to say the least, and the heavy reliance on philosophy not encouraging. When Einstein (1917) adopted the assumption that the universe is close to homogeneous and isotropic, it was quite contrary to the available astronomical evidence; Klein (1966) was right to seek alternatives. But the observations now strongly support Einstein’s homogeneity. Here is a case where philosophy led us to an aspect of physical reality, even though we don’t know how to interpret the philosophy. Other aesthetic considerations have been less successful. The steady-state cosmology and the Einstein-de Sitter relativistic cosmology are elegant, but inconsistent with the observational evidence we have now.

The program of empirical tests of cosmology has been a productive research activity for seven decades. The results have greatly narrowed the options for a viable cosmology, and show that the relativistic Friedmann-Lemaître model passes impressively demanding checks. My survey of the state of the tests four years ago, in a Klein lecture, was organized around Table 1. I discuss here the provenance of this table, and how it would have to be revised to fit the present situation.

The table is crowded, in part because I tried to refer to the main open issues; there were lots of them. Some are resolved, but an updated table would be even more crowded, to reflect the considerable advances in developing new lines of evidence. This greatly enlarges the checks for consistency that are the key to establishing any element of physical science. Abundant checks are particularly important here, because astronomical evidence is limited, by what Nature chooses to show us and by our natural optimism in interpreting it.
### 2. The Classical Tests

#### 2.1. The Physics of the Friedmann-Lemaître Model

The second to the last column in the table summarizes elements of the physics of the relativistic Friedmann-Lemaître cosmological model we want to test.

The starting assumption follows Einstein in taking the observable universe to be close to homogeneous and isotropic. This agrees with the isotropy of the radiation backgrounds and of counts of sources observed at wavelengths ranging from radio to gamma rays. Isotropy allows a universe that is inhomogeneous but spherically symmetric about a point very close to us. I think it is not overly optimistic to consider this picture unlikely, but in any case it is subject to the cosmological tests, through its effect on the redshift-magnitude relation, for example.

It will be recalled that, if a homogeneous spacetime is described by a single metric tensor, the line element can be written in the Robertson-Walker form,

\[ ds^2 = dt^2 - a(t)^2 \left( \frac{dr^2}{1 + r^2/R^2} + r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \right). \]  

This general expression contains one constant, that measures the curvature of sections of constant world time \( t \), and one function of \( t \), the expansion parameter \( a(t) \). Under conventional local physics the de Broglie wavelength of a freely

| Test | Einstein-de Sitter | \( \Omega \sim 0.2 \pm 0.15 \) | Issues for Physics | Issues for Astronomy & Astrophysics |
|------|--------------------|-----------------|------------------|-------------------------------------|
| 1a. Dynamics on scales \( \lesssim 10 \) Mpc | \( \times \) | \( \checkmark \) | \( \checkmark \) | The inverse square law; nature of the dark mass & its effective Jeans length | What's in the voids? |
| 1b. Dynamics on larger scales | \( \times \) | \( \checkmark \) | \( \checkmark \) | | Where and when did galaxies form? |
| 2a. World time \( t(z) \) & ages of stars & elements | \( \times \) | \( \checkmark \) | \( \checkmark \) | Radial displacement-redshift relation | It's the distance scale, stupid |
| 2b. Redshift-angular size relation | \( \checkmark \) | \( ? \) | \( \checkmark \) | Evolution: galaxy merging & accretion; distance \( r(z) \); Lisevitch relation | SNe; ISM & dust; AGN central engines; gravitational lensing objects |
| 2c. Redshift-magnitude relation | \( \checkmark \) | \( ? \) | \( \checkmark \) | \( i \propto (1+z)^{-1} \); deflection of light | |
| 3a. Dynamics on scales \( \gtrsim 10 \) Mpc & clusters of galaxies | \( \times \) | \( \checkmark \) | \( \checkmark \) | BBNS; nature of the primeval departure from homogeneity; near scale-invariant adiabatic Gaussian fluctuations? strings? | The structures of clusters of galaxies; evolution of cluster luminosity, baryon & mass functions; angular & redshift surveys; gravitational lensing processes in the first generations? |
| 3b. Cluster structures \( \rho(r) \) & number density at \( z \ll 1 \) | \( \checkmark \) | \( ? \) | \( \checkmark \) | | |
| 3c. Cluster evolution \( N(z, L, M_\text{h}, z) \) | \( \times \) | \( \checkmark \) | \( \checkmark \) | | |
| 3d. \( \xi_0 (r, z), \xi_0, \xi_0, \xi_0, \xi_0 \) & \( \xi_0 \) | \( \times \) | \( \checkmark \) | \( \checkmark \) | | |
| 3e. Redshifts of assembly of Local clusters, galaxies, QSOs, . . . | \( \checkmark \) | \( ? \) | \( \checkmark \) | | |
| 4. Baryon density \( \Omega_\text{b} \) & the origin of light elements | \( \times \) | \( \checkmark \) | \( ? \) | \( N_\text{e}, m_\text{e}, \mu_\text{e}, s/n_\text{H} \); \( B \)-fields; new physics | What is the present baryon density \( \Omega_\text{b} \)? |
| 5. 3 K CBR spectrum, anisotropy, polarization | \( \times \) | \( \checkmark \) | \( \checkmark \) | All of the above | Effects of reionization & interactions at low \( z \) |

P. J. E. Peebles, June 1997  \( \checkmark \) = conditional pass;  \( \times \) = conditional fail

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(1)
moving particle varies as \( \lambda \propto a(t) \). In effect, the expansion of the universe stretches the wavelength. The stretching of the wavelengths of observed freely propagating electromagnetic radiation is measured by the redshift, \( z \), in terms of the ratio of the observed wavelength of a spectral feature to the wavelength measured at rest at the source,

\[
1 + z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{a(t_{\text{observed}})}{a(t_{\text{emitted}})}.
\] (2)

At small redshift the difference \( \delta t \) of world times at emission and detection of the light from a galaxy is relatively small, the physical distance between emitter and observer is close to \( r = c\delta t \), and the rate of increase of the proper distance is

\[ v = cz = H_0 r, \quad H_0 = \dot{a}(t_o)/a(t_o), \] (3)
evaluated at the present epoch, \( t_o \). This is Hubble’s law for the general recession of the nebulae.

Under conventional local physics Liouville’s theorem applies. It says an object at redshift \( z \) with radiation surface brightness \( i_e \), as measured by an observer at rest at the object, has observed surface brightness (integrated over all wavelengths)

\[ i_o = i_e (1 + z)^{-4}. \] (4)

Two powers of the expansion factor can be ascribed to aberration, one to the effect of the redshift on the energy of each photon, and one to the effect of time dilation on the rate of reception of photons. In a static “tired light” cosmology one might expect only the decreasing photon energy, which would imply

\[ i_o = i_e (1 + z)^{-1}. \] (5)

Measurements of surface brightnesses of galaxies as functions of redshift thus can in principle distinguish these expanding and static models (Hubble & Tolman 1935).

The same surface brightness relations apply to the 3 K thermal background radiation (the CBR). Under equation (4) (and generalized to the surface brightness per frequency interval), a thermal blackbody spectrum remains thermal, the temperature varying as \( T \propto a(t)^{-1} \), when the universe is optically thin. The universe now is optically thin at the Hubble length at CBR wavelengths. Thus we can imagine the CBR was thermalized at high redshift, when the universe was hot, dense, and optically thick. Since no one has seen how to account for the thermal CBR spectrum under equation (5), the CBR is strong evidence for the expansion of the universe. But since our imaginations are limited, the check by the application of the Hubble-Tolman test to galaxy surface brightnesses is well motivated (Sandage 1992).

The constant \( R^{-2} \) and function \( a(t) \) in equation (1) are measurable in principle, by the redshift-dependence of counts of objects, their angular sizes, and their ages relative to the present. The metric theory on which these measurements are based is testable from consistency: there are more observable functions than theoretical ones.
The more practical goal of the cosmological tests is to over-constrain the parameters in the relativistic equation for $a(t)$,

$$
\left( \frac{\dot{a}}{a} \right)^2 = \frac{8}{3} \pi G \rho_t \pm \frac{1}{a^2 R^2} = H_o^2 [\Omega_m (1 + z)^3 + \Omega_\Lambda + (1 - \Omega_m - \Omega_\Lambda)(1 + z)^2]. \tag{6}
$$

The total energy density, $\rho_t$, is the time-time part of the stress-energy tensor. The second line assumes $\rho_t$ is a sum of low pressure matter, with energy density that varies as $\rho_m \propto a(t)^{-3} \propto (1+z)^3$, and a nearly constant component that acts like Einstein’s cosmological constant $\Lambda$. These terms, and the curvature term, are parametrized by their present contributions to the square of the expansion rate, where Hubble’s constant is defined by equation (3).

### 2.2. Applications of the Tests

When I assembled Table 1 the magnificent program of application of the redshift-magnitude relation to type Ia supernovae was just getting underway, with the somewhat mixed preliminary results entered in line 2c (Perlmutter et al. 1997). Now the supernovae measurements clearly point to low $\Omega_m$ (Reiss 2000 and references therein), consistent with most other results entered in the table.

The density parameter $\Omega_m$ inferred from the application of equation (6), as in the redshift-magnitude relation, can be compared to what is derived from the dynamics of peculiar motions of gas and stars, and from the observed growth of mass concentrations with decreasing redshift. The latter is assumed to reflect the theoretical prediction that the expanding universe is gravitationally unstable. Lines 1a and 1b show estimates of the density parameter $\Omega_m$ based on dynamical interpretations of measurements of peculiar velocities (relative to the uniform expansion of Hubble’s law) on relatively small and large scales. Some of the latter indicated $\Omega_m \sim 1$. A constraint from the evolution of clustering is entered in line 3c. The overall picture was pretty clear then, and now seems well established: within the Friedmann-Lemaître model the mass that clusters with the galaxies almost certainly is well below the Einstein-de Sitter case $\Omega_m = 1$. I discuss the issue of how much mass might be in the voids between the concentrations of observed galaxies and gas clouds in §4.1.

All these ideas were under discussion, in terms we could recognize, in the 1930s. The entry in line 2e is based on the prediction of gravitational lensing. That was well known in the 1930s, but the recognition that it provides a cosmological test is more recent. The entry refers to the multiple imaging of quasars by foreground galaxies (Fukugita & Turner 1991). The straightforward reading of the evidence from this strong lensing still favors small $\Lambda$, but with broad error bars, and it does not yet seriously constrain $\Omega_m$ (Helbig 2000). Weak lensing — the distortion of galaxy images by clustered foreground mass — has been detected; the inferred surface mass densities indicate low $\Omega_m$ (Mellier et al. 2001), again consistent with most of the other constraints.

The other considerations in lines 1 through 4 are tighter, but the situation is not greatly different from what is indicated in the table and reviewed in Lasenby, Jones & Wilkinson (2000).
3. The Paradigm Shift to Low Mass Density

Einstein and de Sitter (1932) argued that the case $\Omega_m = 1$, $\Omega_\Lambda = 0$, is a reasonable working model: the low pressure matter term in equation (6) is the only component one could be sure is present, and the $\Lambda$ and space curvature terms are not logically required in a relativistic expanding universe.

Now everyone agrees that this Einstein-de Sitter model is the elegant case, because it has no characteristic time to compare to the epoch at which we have come on the scene. This, with the perception that the Einstein-de Sitter model offers the most natural fit to the inflation scenario for the very early universe, led to a near consensus in the early 1990s that our universe almost certainly is Einstein-de Sitter.

The arguments make sense, but not the conclusion. For the reasons discussed in §4.1, it seems to me exceedingly difficult to reconcile $\Omega_m = 1$ with the dynamical evidence.

The paradigm has shifted, to a low density cosmologically flat universe, with

$$\Omega_m = 0.25 \pm 0.10, \quad \Omega_\Lambda = 1 - \Omega_m. \quad (7)$$

There still are useful cautionary discussions (Rowan-Robinson 2000), but the community generally has settled on these numbers. The main driver was not the dynamical evidence, but rather the observational fit to the adiabatic cold dark matter (CDM) model for structure formation (Ostriker & Steinhardt 1995).

I have mixed feelings about this. The low mass density model certainly makes sense from the point of view of dynamics (Bahcall et al. 2000; Peebles, Shaya & Tully 2000; and references therein). It is a beautiful fit to the new evidence from weak lensing and the SNeIa redshift-magnitude relation. But the paradigm shift was driven by a model for structure formation, and the set of assumptions in the model must be added to the list to be checked to complete the cosmological tests. I am driven by aspects of the CDM model that make me feel uneasy, as discussed next.

4. Issues of Structure Formation

A decade ago, at least five models for the origin of galaxies and their clustered spatial distribution were under active discussion (Peebles & Silk 1990). Five years later the community had settled on the adiabatic CDM model. That was in part because simple versions of the competing models were shown to fail, and in part because the CDM model was seen to be successful enough to be worthy of close analysis. But the universe is a complicated place: it would hardly be surprising to learn that several of the processes under discussion in 1990 prove to be significant dynamical actors, maybe along with things we haven’t even thought of yet. That motivated my possibly overwrought lists of issues in lines 3a to 3e in the table.

I spent a lot of time devising alternatives to the CDM model. My feeling was that such a simple picture, that we hit on so early in the search for ideas on how structure formed, could easily fail, and it would be prudent to have backups. Each of my alternatives was ruled out by the inexorable advance of the measurements, mainly of the power spectrum of fluctuations in the temperature
of the CBR. The details can be traced back through Hu & Peebles (2000). The experience makes me all the more deeply impressed by the dramatic success of the CDM model in relating observationally acceptable cosmological parameters to the measured temperature fluctuation spectrum (Hu et al 2000 and references therein).

This interpretation is not unique. McGaugh (2000) presents a useful though not yet completely developed alternative, that assumes there is no nonbaryonic dark matter — \( \Omega_{\text{baryon}} = \Omega_m \sim 0.04 \) — and assumes a modification to the gravitational inverse square law on large scales — following Milgrom (1983) — drives structure formation. But the broad success of the CDM model makes a strong case that this is a good approximation to what happened as matter and radiation decoupled at redshift \( z \sim 1000 \). An update of Table 1 would considerably enlarge entry 5.

If the CDM model really is the right interpretation of the CBR anisotropy it leaves considerable room for adjustment of the details. I turn now to two issues buried in the table that might motivate a critical examination of details.

### 4.1. Voids

The issue of what is in the voids defined by the concentrations of observed galaxies and gas clouds is discussed at length in Peebles (2001); here is a summary of the main points.

The familiar textbook, optically selected, galaxies are strongly clustered, leaving large regions — voids — where the number density of galaxies is well below the cosmic mean. Galaxies with low gas content and little evidence of ongoing star formation prefer dense regions; gas-rich galaxies prefer the lower ambient density near the edges of voids. This is the morphology-density correlation.

The CDM model predicts that the morphology-density correlation extends to the voids, where the morphological mix swings to favor dark galaxies. But the observations require this swing to be close to discontinuous. A substantial astronomical literature documents the tendency of galaxies of all known types — dwarfs, irregulars, star forming, low surface brightness, and purely gaseous — to avoid the same void regions. There are some galaxies in voids, but they are not all that unusual, apart from the tendency for greater gas content.

The natural interpretation of these phenomena is that gravity has emptied the voids of most galaxies of all types, and with them drained away most of the low pressure mass. This is is not allowed in the Einstein-de Sitter model. If the mass corresponding to \( \Omega_m = 1 \) were clustered with the galaxies the gravitational accelerations would be expected to produce peculiar velocities well in excess of what is observed. That is, if \( \Omega_m = 1 \) most of the mass would have to be in the voids, and the morphology-density correlation would have to include the curious discontinuous swing to a mix dominated by dark galaxies in voids. That is why I put so much weight on the dynamical evidence for low \( \Omega_m \).

At \( \Omega_m = 0.25 \pm 0.10 \) (eq. [7]) the mass fraction in voids can be as small as the galaxy fraction. That would neatly remove the discontinuity. But gravity does not empty the voids in numerical simulations of the low density CDM model. In the simulations massive dark mass halos that seem to be suitable homes for ordinary optically selected galaxies form in concentrations. This is
good. But spreading away from these concentrations are dark mass halos that
are too small for ordinary galaxies, but seem to be capable of developing into
dwarfs or irregulars. This is contrary to the observations.

The consensus in the theoretical community is that the predicted dark mass
clumps in the voids need not be a problem, because we don’t know how galaxies
form, how to make the connection between dark mass halos in a simulation and
galaxies in the real world. The point is valid, but we have some guidance, from
what is observed. Here is an example.

The Local Group of galaxies contains two large spirals, our Milky Way and
the somewhat more massive Andromeda Nebula. There many smaller galaxies,
most tightly clustered around the two spirals. But some half dozen irregular
galaxies, similar to the Magellanic clouds, are on the outskirts of the group.
These irregulars have small velocities relative to the Local Group. Since they
are not near either of the large galaxies they are not likely to have been spawned
by tidal tails or other nonlinear process. Since they are at ambient densities close
to the cosmic mean their first substantial star populations would have formed
under conditions not very different from the voids at the same epoch. In short,
these objects seem to prove by their existence that observable galaxies can form
under conditions similar to the voids in CDM simulations. Why are such galaxies
so rare in the voids?

4.2. The Epoch of Galaxy Formation

Numerical simulations of the CDM model indicate galaxies were assembled rel-
atively recently, at redshift \( z \sim 1 \) \citep[e.g.][]{cen00}. For definiteness in
explaining what bothers me about this I adopt the density parameter in equa-
tion (7) and Hubble parameter \( H_o = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

The mass in the central luminous parts of a spiral galaxy is dominated by
stars. The outer parts are thought to be dominated by nonbaryonic dark matter.
The circular velocity \( v_c \) of a particle gravitationally bound in a circular orbit
in the galaxy varies only slowly with the radius of the orbit, and there is not
a pronounced change in \( v_c \) at the transition between the luminous inner part
and the dark outer part. The value of the mean mass density \( \rho(<r) \) averaged
within a sphere of radius \( r \) centered on the galaxy relative to the cosmic mean
mass density, \( \bar{\rho} \), is

\[
\frac{\rho(<r)}{\bar{\rho}} = \frac{2}{\Omega_m} \left( \frac{v_c}{H_o r} \right)^2 \sim 3 \times 10^5, \quad \text{at} \quad r = 15 \text{ kpc.} \tag{8}
\]

At this radius the mass of the typical spiral is thought to be dominated by
nonbaryonic dark matter. Why is the dark mass density so large? Options are
that

1. at formation the dark mass collapsed by a large factor,

2. massive halos formed by the merging of smaller dense clumps, that formed
   at high redshift, when the mean mass density was large, or

3. massive halos themselves were assembled at high redshift.
To avoid confusion let us pause to consider the distinction between interpretations of large density contrasts in the luminous baryonic central regions and in the dark halo of a galaxy. If the baryons and dark matter were well mixed at high redshift, the baryon-dominated central parts of the galaxies would have to have been the result of settling of the baryons relative to the dark matter. Gneddin, Norman, and Ostriker (2000) present a numerical simulation that demonstrates dissipative settling of the baryons to satisfactory stellar bulges. The result is attractive — and hardly surprising since gaseous baryons tend to dissipatively settle — but does not address the issue at hand: how did the dark matter halos that are thought to be made of dissipationless matter get to be so dense?

We have one guide from the great clusters of galaxies. The cluster mass is thought to be dominated by nonbaryonic matter. A typical line-of-sight velocity dispersion is \( \sigma = 750 \, \text{km s}^{-1} \). The mean mass density averaged within the Abell radius, \( r_A = 2 \, \text{Mpc} \), relative to the cosmic mean, is

\[
\frac{\rho(<r_A)}{\rho} = \frac{4}{\Omega_m} \left( \frac{\sigma}{H_o r_A} \right)^2 \sim 300. 
\] (9)

Clusters tend to be clumpy at the Abell radius, apparently still relaxing to statistical equilibrium after the last major mergers, but they are thought to be close to dynamic equilibrium, gravity balanced by streaming motions of the galaxies and mass. This argues against the first of the above ideas: here are dark matter concentrations that have relaxed to dynamical support at density contrast well below the dark halo of a galaxy (eq. [8]).

The second idea to consider is that a dense dark matter halo is assembled at low redshift by the merging of a collection of dense lower mass halos that formed earlier. This is what happens in numerical simulations of the CDM model. Sometimes cited as an example in Nature is the projected merging of the two Local Group spirals, the Milky Way and the Andromeda Nebula. They are 750 kpc apart, and moving together at 100 km s\(^{-1}\). If they moved to a direct hit they would merge in another Hubble time. But that would require either wonderfully close to radial motion or dynamical drag sufficient to eliminate the relative orbital angular momentum. Orbit computations indicate masses that would be contained in \( \rho \propto r^{-2} \) dark halos truncated at \( r \sim 200 \, \text{kpc} \), which seems small for dissipation of the orbital angular momentum. The computations suggest the transverse relative velocity is comparable to the radial component (Peebles, Shaya & Tully 2000). That would say the next perigalacticon will be at a separation \( \sim 300 \, \text{kpc} \), not favorable for merging. Thus I suspect the Local Group spirals will remain distinct elements of the galaxy clustering hierarchy well beyond one present Hubble time. If the Local Group is gravitationally bound and remains isolated the two spirals must eventually merge, but not on the time scale of the late galaxy formation picture.

My doubts are reenforced by the failure to observe precursors of galaxies. Galaxy spheroids — elliptical galaxies and the bulges in spirals that look like ellipticals — are dominated by old stars. Thus it is thought that if present-day spheroids were assembled at \( z \sim 1 \) it would have been by the merging of star clusters. These star clusters might have been observable at redshift \( z > 1 \), as a strongly clustered population, but they are not.
That leaves the third idea, early galaxy assembly. I am not aware of any conflict with what is observed at \( z < 1 \). The observations of what happened at higher redshift are rich, growing, and under debate.

5. Concluding Remarks

If the models for cosmology and structure formation on which Table 1 is based could be taken as given, the only uncertainties being the astronomy, the constraints on the cosmological parameters would be clear. The long list of evidence for \( \Omega_m = 0.25 \pm 0.10 \), in the table and the new results from the SNeIa redshift-magnitude relation and weak lensing, abundantly demonstrates that we live in a low density universe. The CBR demonstrates space sections are flat. Since \( \Omega_m \) is small there has to be a term in the stress-energy tensor that acts like Einstein’s cosmological constant. The SNeIa redshift-magnitude result favors a low density flat universe over low density with open geometry (\( \Lambda = 0 \)), at about three standard deviations. That alone is not compelling, considering the hazards of astronomy, but it is an impressive check of what the CBR anisotropy says.

But we should remember that all this depends on models we are supposed to be testing. The dynamical estimates of \( \Omega_m \) in lines 1a and 1b assume the inverse square law of gravity. That is appropriate, because it follows from the relativistic cosmology we are testing. We have a check on this aspect of the theory, from consistency with other observations whose theoretical interpretations depend on \( \Omega_m \) in other ways. The CDM model fitted to observed large-scale structure requires a value of \( \Omega_m \) that agrees with dynamics. This elegant result was an early driver for the adoption of the low density CDM model. But we can’t use it as evidence for both the CDM model and the inverse square law; we must turn to other measures. We have two beautiful new results, from weak lensing and the redshift-magnitude relation, that agree with \( \Omega_m \sim 0.25 \). The latter does not exclude \( \Omega_m = \Omega_{\text{baryons}} \sim 0.04 \); maybe MOND accounts for flat \( v_c(r) \) but does not affect equation (6) (McGaugh 2000). And if we modified local Newtonian dynamics we might want to modify the physics of the gravitational deflection of light.

There are alternative fits to the CBR anisotropy, with new physics (McGaugh 2000), or conventional physics and an arguably desperate model for early structure formation (Peebles, Seager & Hu 2000). They certainly look a lot less elegant than conventional general relativity theory with the CDM model, but we’ve changed our ideas of elegance before.

In §4 I reviewed two issues in structure formation that I think challenge the CDM model. They may in fact only illustrate the difficulty of interpreting observations of complex systems. It’s just possible that they will lead us to some radical adjustment of the models for structure formation and/or cosmology. I don’t give much weight to this, because it would mean the model led us to the right \( \Omega_m \) for the wrong reason. Relatively fine adjustments are easier to imagine, of course. With them we must be prepared for fine adjustments of the constraints on parameters such as \( \Lambda \).

This is quite a tangled web. Progress in applying the many tests, including the mapping the CBR temperature and polarization, will be followed with close attention.
We have an impressive case for the Friedmann-Lemaître cosmology, from the successful fit to the CBR anisotropy and the consistency of the evidence for \( \Omega_m \sim 0.25 \) from a broad range of physics and astronomy. But the cosmological tests certainly are not complete and unambiguous, and since they depend on astronomy the program is not likely to be closed by one critical measurement. Instead, we should expect a continued heavy accumulation of evidence, whose weight will at last unambiguously compel acceptance. We are seeing the accumulation; we all look forward to the outcome.

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