

# The Cosmological Model: an overview and an outlook

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**Abstract.** The Standard Model of Cosmology has emerged from a number of independent lines of evidence, and accounts very well for most large-scale observations of the Universe. I present a brief review of the model, focussing on the underpinning observational data, and commenting on the strengths and weaknesses of each method. I review some of the current implications for inflation, Dark Matter and Dark Energy, and take a look forward to what may be learned from ambitious future cosmological surveys. The future prospects include the possibility of determining definitively whether the Dark Energy is Einstein's cosmology constant or alternatively an evolving scalar field, or even testing whether gravity is not General Relativity, but a manifestation of a higher-dimensional theory based on strings.

## 1. Introduction

Over the last ten years, a number of lines of evidence have pointed towards a consistent picture for the state of the Universe. The observational status is considered by many to be sufficiently strong that the term 'Standard Cosmological Model' is justified as a description of our understanding of the Universe and its contents. The picture which emerges is, however, a curious one, in which the Universe is unexpectedly accelerating, with the vast bulk of its energy density in a form which has not been detected directly on Earth. Indeed, the picture is even more strange, in that the data appear to demand two unknown ingredients, Dark Matter and Dark Energy. However, with the inclusion of these ingredients, a wide variety of quite detailed cosmological observations can be explained, to the extent that the parameters in the theory can be consistently determined with an accuracy typically of a few percent. Confidence in the model is such that the data are increasingly being used for rather detailed examination of the model ingredients. Subtle effects of a number of features, such as the masses and types of neutrinos, the types of interactions of Dark Matter, and the equation of state of the Dark Energy, have been calculated and confronted with theory.

The security of the standard model, and its implications, are such that ambitious plans are being made to probe its ingredients in more detail. With about 75% of the energy budget in Dark Energy, it is perhaps little surprise that this forms the focus for a number of planned observational programmes over the next decade. The main immediate question here is whether the Dark Energy is Einstein's cosmological constant, or a previously undiscovered field with an unusual equation of state which is driving the acceleration of the Universe. More radically, the acceleration may be a manifestation of a breakdown of General Relativity, as may happen if the Universe has extra dimensions. Some string-inspired braneworld models have been investigated

theoretically to the point where confrontation with observation is possible, and we have the intriguing possibility of being able to test such models with future cosmological surveys.

In this short review, I outline the Standard Cosmological Model, and summarise the principal observations underpinning the theory. I discuss the points where the standard model comes under some pressure, and try to give some indications of where the comparison between theory and observation is relatively secure, and where our capability is limited by uncertain physics. I look at the upcoming and planned cosmological surveys, and their capability to measure Dark Energy properties, and to detect beyond-Einstein gravity.

## 2. The Standard Cosmological Model

The notion that there might be Dark Matter in the Universe is very old, dating back to the 1930s when Fritz Zwicky noted that the combined gravity of galaxies in clusters was not sufficient to keep them bound to the cluster, given their large velocity dispersion. The matter cannot be entirely baryonic, since there are stringent limits on the density parameter of baryonic matter,  $\Omega_b = 0.04 \pm 0.004$  (e.g. [1]), arising from the primordial nucleosynthesis of the light elements. This is short of the mass requirements of clusters ( $\Omega_m \simeq 0.2$ ), thus establishing the need for non-baryonic Dark Matter.

The idea that there might also be a cosmological constant (or Dark Energy) component was hinted at by a number of observations, such as the power spectrum of fluctuations in the APM survey of galaxies [2]. However, it is probably fair to say that the idea that the Universe was dominated by such a component only gained wide acceptance when observations of distant supernovae in the late 1990s [3] implied that the Universe was not only expanding, but accelerating. This is quite unexpected, as if it is driven by a source field (rather than a cosmological constant), it requires the field to have a very unusual equation of state, with negative pressure. Specifically, the equation of state parameter  $w \equiv p/(\rho c^2) < -1/3$ . Einstein's cosmological constant is equivalent as far as the expansion of the Universe is concerned with a source field with  $w = -1$ .

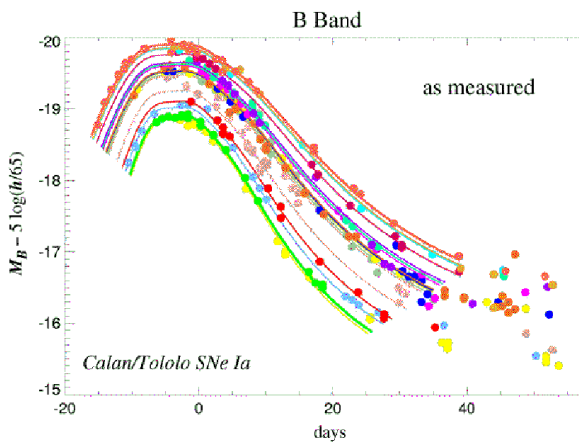
The Standard Cosmological Model therefore consists of the following: the Universe began with the Big Bang, went through a period of near-exponential inflation at early times ( $\sim 10^{-35}s$ ), and has expanded ever since, under gravitational influence described by General Relativity. The expansion rate is controlled by its contents, which are baryonic matter (and electrons) with density parameter  $\Omega_b \simeq 0.04$ , photons at 2.73K and neutrinos (with negligible energy density), cold Dark Matter with  $\Omega_m \simeq 0.26$  (0.22 in CDM), and Dark Energy, with  $\Omega_{DE} \simeq 0.74$ ). The current expansion rate is described by a present-day Hubble parameter  $H_0 \equiv 100h \simeq 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . Errors on these quantities are a few percent. It is spatially flat, or very nearly so, and structure grew from adiabatic fluctuations with a near-scale-invariant spectrum, with a primordial power spectrum,  $P(k) \propto k^n$  with  $n \simeq 1$ , generated during inflation. The present-day amplitude of fluctuations is characterised by a parameter  $\sigma_8 \simeq 0.75$  and the optical depth by  $\tau \simeq 0.08$ . A flat model with 6 free parameters ( $\Omega_m h^2$ ,  $\Omega_B h^2$ ,  $h$ ,  $n$ ,  $\tau$ ,  $\sigma_8$ ) provides a good fit to most observations, but extensions to this model, where  $n$  varies with scale, or neutrinos have a significant non-zero mass. This relatively simple model accounts for nearly all cosmological observables, including geometrical measurements of the Universe, the power spectrum of fluctuations, and the light element abundances arising from primordial nucleosynthesis. In the simplest model, the Dark Energy is simply Einstein's cosmological constant  $\Lambda$ .

### 2.1. Probes of geometry: supernovae

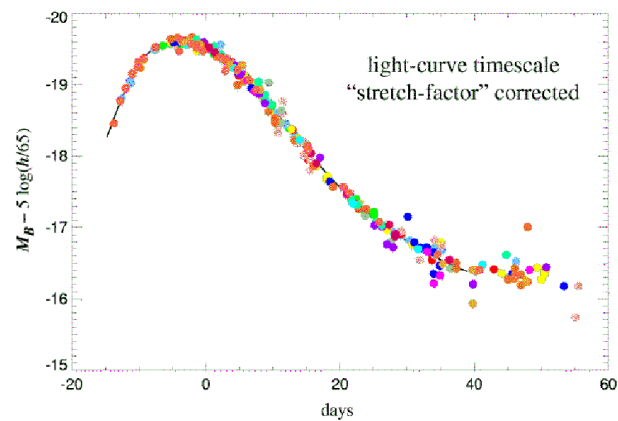
The Cosmological Model can be tested by probing the distance-redshift relation  $r(z)$ . Type 1a supernova have roughly the same intrinsic brightness and can therefore be used as standard candles to measure the luminosity distance,  $D_L \equiv (1+z)r(z) = c(1+z) \int_0^z dz'/H(z')$ .

Geometrical measures like this essentially constrain the Hubble parameter vs redshift, which depends on several of the cosmological parameters, including  $\Omega_m$ ,  $\Omega_{DE}$  and  $w$ .

Use of the luminosity distance requires objects of known brightness, and Type 1a supernovae are good standardisable candles for this purpose. They are thought to arise from the collapse of a stellar core which for reasons of mass transfer reaches the Chandrasekhar limit. In principle one might expect these to be identical, but in practice there is some variation in the peak luminosity of the supernovae, leading to a scatter which is half a magnitude or more. The variations are, however, correlated with the colour and the decay lifetime of the lightcurve, and empirical corrections can be made which reduce the scatter to around 0.13 magnitudes (about 13%; fig. 2). The supernova Hubble diagram (Fig. 3) can then be used to confront theory with observations.



**Figure 1.** Light curves of Type 1a supernovae before empirical corrections [4].

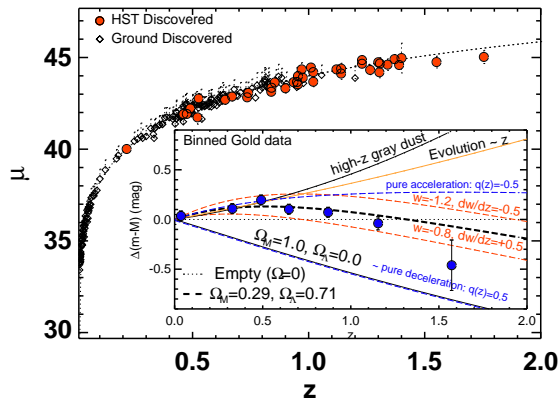


**Figure 2.** Light curves of Type 1a supernovae after empirical corrections [4].

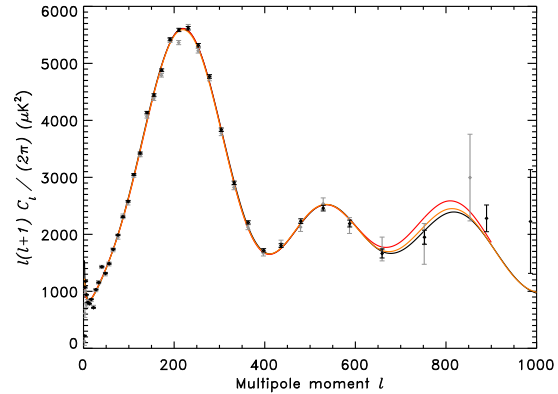
The most remarkable implication of the diagram is the evidence that the Universe is accelerating, which is not expected in simple models of Big Bang evolution, and is indicative of an effectively repulsive gravity component, which may be provided by the cosmological constant, or Dark Energy with a sufficiently negative pressure. Of particular interest is that the supernovae are now being detected at sufficiently high redshift that they probe an earlier era before the Universe started its current acceleration. Interpreting the data in terms of the standard model with a cosmological constant (or Dark Energy as a genuine vacuum energy with  $w = -1$ ) indicates a positive Dark Energy density. One caveat to bear in mind is that the analysis assumes that type 1a supernovae are standard candles (after correction) at all redshifts, and there is increasing evidence that there are at least two types of progenitors for these supernovae, associated with a young population [7] (perhaps as young as 75 Myr [8]) and an old (probably several Gyr) population. The proportions of the two types of progenitor must change with cosmic time, and it is not known yet whether the corrections apply equally to both types, at least sufficiently accurately to use these as detailed cosmological probes of the Dark Energy equation of state parameter.

## 2.2. Cosmic Microwave Background observations

The cosmic microwave background (CMB) gives us the most robust cosmological constraints, due to a combination of a very firm theoretical footing, and high-quality data. Theoretical understanding is very sound because the principal processes are interactions between photons and matter which formed an almost uniform density fluid close to thermal equilibrium. Linear perturbation theory describes the Universe at the time of emission to high accuracy, and there



**Figure 3.** The supernova Hubble diagram [5].



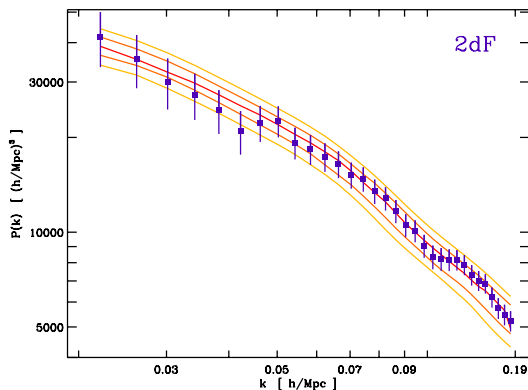
**Figure 4.** The WMAP angular power spectrum [6].

were no astrophysical objects to confuse the issue. The main uncertainties are foreground effects, such as dust and synchrotron radiation from the Milky Way galaxy and other sources. With observations at many frequencies these foregrounds seem able to be subtracted to high accuracy over much of the sky. The WMAP satellite currently provides by far the most powerful dataset.

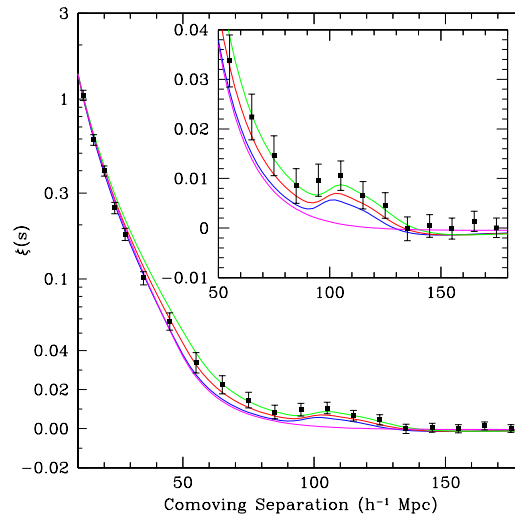
Although the analysis is not quite done this way, the confrontation with theory is most easily illustrated by comparing the angular power spectrum of CMB fluctuations with theory, as shown in Fig. 4. The agreement is quite remarkable. Perturbations which enter the Hubble radius before recombination will soon oscillate as the sound speed is roughly  $c/\sqrt{3}$  which means the Jeans length is comparable to the Hubble radius. The first peak corresponds to the smallest waves which don't oscillate; the second peak to those waves which enter before recombination, compress and then reach maximum expansion at recombination. Subsequent peaks have similar interpretations. The features in the power spectrum are dependent on a number of factors, but the first peak corresponds roughly to a pre-recombination Jeans' length fluctuation, of a more-or-less fixed physical size. It acts like a standard ruler, so its angular size (or wavenumber  $\ell$ ) measures the geometry of the Universe - flat or curved. For a flat Universe, the peak should be at  $\ell \simeq 200$ , as observed.

### 2.3. Large-scale structure

The power spectrum of matter fluctuations emerging after recombination can also be computed with high confidence. Following the growth of these fluctuations, the power spectrum can be compared with structures today. This involves two complications. One is that the fluctuations do not remain small, so numerical simulations are required to evolve the matter power spectrum. This is relatively well understood. Potentially more difficult is that we do not observe matter directly in large-scale structure, but luminous baryonic matter in the form of galaxies. The connection between the galaxy distribution and the matter distribution is often referred to as *bias* and represents a significant source of systematic uncertainty, especially on small scales. The power spectrum of galaxies from the 2dF galaxy redshift survey is shown in Fig. 5, along with theoretical curves with cosmological parameters which fit the WMAP CMB Data. The agreement is reassuring. Details in the power spectrum, such as baryon acoustic oscillations



**Figure 5.** Power spectrum of 2dF galaxies from [9], along with expected power spectrum with best fit parameters from WMAP, with errors [6].



**Figure 6.** BAOs in SDSS [10].

(BAOs), remnants of the oscillations present in the CMB, may be used as probes of geometry, as they act as more-or-less standard rulers. BAOs have been detected in both the 2dFGRS and the SDSS (Fig. 6). The main uncertainty is bias, and how the positions of the peaks may shift when the field becomes nonlinear.

#### 2.4. Weak gravitational lensing

Weak gravitational lensing avoids the problems with bias by probing the matter density directly. Fluctuations in the matter distribution perturb the paths of light from background galaxies, whose images get distorted. The very appealing aspect of lensing is that the physics is simple and well-understood. The distortions are, however, rather small ( $\sim 1\%$ ) and control of systematics in optics is challenging. Results of cosmological weak lensing measurements have been reported since 2000, and provide complementary constraints on cosmological parameters. Latest results [11] have reduced the previous tension with the CMB, and are now in agreement with WMAP. The main change is a better estimate of the redshift distribution of the lensed sources. The clean physics involved makes this a very promising probe for future surveys, with the main physical source of systematic error being a possible correlation between orientations of foreground galaxies and distorted background images [12].

#### 2.5. Lyman $\alpha$ forest and neutrino masses

Absorption of light from bright distant quasars by systems containing neutral hydrogen gas can be used to probe the clustering of matter on smaller scales than can be probed by galaxy surveys. It is also possible (indeed necessary) to do this at high redshift, which has the advantage of investigating the evolution of clustering, and it also probes the Universe at a time when it was less clustered, which reduces uncertainties. On the downside, the relationship between the matter density and the characteristics of the absorption rely on rather complex physics, and it is fair to say that the connection between observables and theory is harder for this probe than the others considered here. In principle, the Ly $\alpha$  forest can put strong constraints on the sum of the neutrino masses, as non-zero masses alter the shape of the power spectrum at large wavenumbers. Currently the strongest limit claimed is  $\sum m_\nu < 0.17$  eV [13], using Ly $\alpha$  forest clustering statistics. The most conservative limit restricts analysis to the well-understood

CMB, which puts a much weaker limit of 1.8 eV [6]. This limit is secure; a middle course is to include galaxy clustering statistics, which are independent of the complex Ly $\alpha$  physics, but which could be affected by scale-dependent bias. Combining WMAP and large-scale structure from 2dF/SDSS gives an upper limit of  $\sum m_\nu = 0.66eV$  [6].

### 3. Problems with the Standard Cosmological Model

The main challenges to the standard model come from small scales. Numerical simulations show that many small-mass haloes are expected, but far fewer satellite galaxies of the Milky Way have been found. SDSS has recently found more low-mass galaxies [14], but there is still a deficit. One possibility is that the comparison has not been done fairly - the full halo circular velocity may not be achieved until beyond the visible outer radii of the dwarf galaxies [15]. However, in the end it is likely that feedback processes from star formation hold the key - the potential wells are very shallow, and observed dwarf galaxies have very low baryon fractions, so probably there is a population of even fainter dwarfs with few stars. The other point of tension is the inner profile of the Dark-Matter dominated dwarfs, which are shallower than theory predicts. This is to a certain extent an open issue, but there are possible resolutions with bars or triaxial haloes. Self-interacting Dark Matter can remove the theoretical cusps [16], but the cross-section required may already be almost ruled out (see next section).

### 4. Constraints on inflation, Dark Matter, and modified Gravity

There are consistency relations which inflation imposes on the tensor-to-scalar ratio and the slope of the power spectrum. Space constraints here preclude a full discussion, but the CMB and large-scale structure data are beginning to constrain inflationary potentials. Constraints on the number of coupled neutrinos can be obtained from their influence on the growth of perturbations, with current data favouring none [17].

A very interesting object which puts a number of interesting constraints is the bullet cluster, which shows two clusters post-collision [18]. X-ray emission shows that the hot gas is left between the two concentrations of galaxies, which have passed through each other with little direct interaction. Most interestingly, gravitational lensing analysis provides a ‘convergence’ map with peaks at the positions of the galaxy centres, not the (dominant baryonic) x-ray emitting gas. In General Relativity, the convergence is proportional to the surface density, so the conventional interpretation is that there is a dominant Dark Matter component which is more-or-less collisionless. This puts severe pressure on gravity models such as MOND and TeVeS, which explore whether one can do away with Dark Matter. One caveat here is that in such models the convergence is not simply proportional to the surface density, but it will be a challenge for these models to account for the convergence peaks at the galaxy concentrations. Within the standard model, the separation of the Dark Matter concentrations puts constraints on the Dark Matter cross-section of  $\sigma/m < 0.12 \text{ m}^2 \text{ kg}^{-1}$  [19].

### 5. Prospects for the Future

We can expect major improvements in data on several fronts. In the CMB, Planck promises measurements of the power spectrum to smaller scales than WMAP, as well as wider frequency coverage which should aid foreground subtraction. CMB polarisation experiments, of which many are underway or planned, can in principle detect gravitational waves from inflation, which would be a significant validation of the theory. In weak lensing, the Pan-STARRS 1 survey of up to 3/4 of the sky promises a huge leap in statistical accuracy over the  $\sim 100$  square degrees of the largest optical surveys to date. Further ahead, more powerful photometric surveys are envisaged from space or the ground (DUNE, SNAP, LSST, Pan-STARRS 4). Many galaxy surveys motivated by BAOs are planned, both with spectroscopic redshifts (WFMOS, MegaMOS, ADEPT etc) and with photometric redshifts, some using a very large number of

filters (PAU). Many of the multi-band photometry surveys would also obtain supernova samples in large numbers out to high redshifts ( $z \sim 1.7$ ).

What can we expect to know in 2020? Dark Energy constraints should be very tight, with weak lensing in combination with Planck potentially achieving sub-1% accuracy on  $w$ , and useful constraints on its evolution. Currently  $w$  is known to  $w = -1.04 \pm 0.06$ , assuming that it does not vary [13]. Future errors will be dominated by systematics, and the requirements are demanding [20]. BAOs and supernovae on their own are somewhat less powerful, but the systematics in each technique are sufficiently complex that it is vitally important to pursue all viable methods and seek independent verification.

Neutrino masses and properties could potentially be measured with high accuracy, with claimed achievable limits on the sum of  $0.06\text{eV}$  from Ly $\alpha$  forest [21],  $0.05\text{eV}$  from weak lensing [22], and  $0.025\text{eV}$  from high- $z$  clustering [23]. Here, the physics is complex in all methods (including weak lensing, because of baryonic physics on small scales), so one would demand consistent measurement from multiple probes.

One intriguing possibility is to test General Relativity itself. Methods which probe both the geometry and the growth rate, which both depend on  $H(z)$  in General Relativity can look for an inconsistency. Large weak lensing surveys from space, of the size and depth proposed for DUNE and SNAP, could theoretically find strong evidence for gravity theories arising from extra dimensions, such as proposed by string-based braneworlds [24].

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