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The Planck Mission and the Cosmic Microwave Background*

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Abstract. Relevant observations to test cosmological models have increased dramatically in the last fifteen years. The *Planck* space mission for the observation of Cosmic Microwave Background (CMB) has brought a large increase in the accuracy of the maps of its temperature and polarization. These results have confirmed in a spectacular way the ΛCDM model and determined the parameters attached to the present content and dynamics of of our universe with sub percent accuracy. The combination with the baryon acoustic oscillations measurements made these even tighter. The predictions from the inflation paradigm of the early universe physics have been confirmed. The tensor to scalor modes ratio emerging from the early universe is only bounded by an upper limit. Extensions of the model allows to assess the validity of several key assumptions of the ΛCDM and give implications for some parameters of the standard model of particles and interactions. All this constitute now a standard model of cosmology and particle physics which explains a very large body of observations.

1 Introduction: historical perspective on cosmological theories and observations

The big bang theory described by J.-P. Uzan in this seminar has emerged in the first half of the twentieth century. It was made possible by general relativity as the theory of gravity and based on general principles trying to explore the simplest possible models and introduce more complicated models only when observations would impose it. The initial ones were that the universe is, on very large scales,homogeneous, isotropic and stationary. The identification of galaxies similar to the milky way and measurements of their distance and relative velocity allowed Hubble to show that the universe was expanding and to compute a first order of magnitude of the average density of matter in stars. This forced the theoreticians to remove the stationarity hypothesis. The other observational parameter which was key for the theory of the so called big-bang was the universal abundance of Helium with respect to Hydrogen in stars which lead to the hypothesis of primordial nucleosynthesis of Helium and the prediction of the Cosmic Microwave Background (CMB) by Alpher, Bethe, and Gamow (and subsequent work mostly done by Alpher). The discovery of an isotropic microwave background in 1965 by Penzias and Wilson interpreted by Wilkinson et al to be the CMB was a spectacular confirmation of a very daring theoretical prediction considering the observations when it was made. Such a pattern happened a

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*This paper presents the content of the seminar to be given on the 21st of November 2015 and the references to the Planck collaboration papers from which the results are taken. The introductory sections do not have yet a proper bibliography; this will be done for the final version.

number of times in cosmology: theoretical prediction are made, often on the basis of very general considerations of theoretical physics, which are tested and verified much later. We'll show that this is still the case today.

The early observations of Hubble were on the content in baryonic matter and its dynamical behavior (the Hubble expansion) in the nearby universe. In the late 1960s the big bang theory was nowhere near what you would expect from a standard model of cosmology. Zwicky had shown very early that galaxies where much more massive than the mass of stars seen in them. The "missing mass", which is now referred to as dark matter, was also rather obvious observationally as it relied on the well measured rotation velocities of stars and later of interstellar hydrogen in galaxies. It was also see in clusters of galaxies. Nevertheless the nature of the missing mass was not known and an origin in modification of gravity on large scale could not be excluded.

The prediction of the CMB rests on physics taking place in conditions extrapolated backwards in the history of expansion by a fantastic factor of a billion in length scale from those observed by Hubble. This the big bang nucleosyntesis has to happen only a few hundred seconds after the big bang. After the discovery of the CMB it took 25 years before the technology for a cryogenically cooled instrument in space (COBE-FIRAS), permitted to Mather et al 1990 to check that the CMB spectral energy distribution had a very nearly Planckian spectrum with deviations from it less than 10^{-4}. This was the second spectacular verification of a cosmological model prediction done many years earlier.

It was also predicted very soon after the discovery of the CMB that adiabatic inhomogeneities in the energy density distribution could lead to the formation of all observed structure and would lead to acoustic oscillations during the radiation dominated phase of the expansion, and the harmonic modes of these at the time of recombination would leave acoustic parks in the spatial distribution power spectrum observable on the CMB. It was shown that in that case these acoustic peaks would enable to measure the content of the universe with high accuracy [1, 2].

Independantly, Harrison and Zeldovich remarked that the initial spectrum should have be non divergent on either very large or very small scales and that the power law index of inhomogeneities should be close scale invariant (the parameter called n_s in models of the universe around should be 1).

In the early 70s, the origin of the large scale structures was not understood, there was litle evidence about an evolution of galaxies. The large scale geometry of the universe (Euclidean, closed or open) was also unknown and the Hubble constant was known only within a factor of 2 uncertainty. For 30 years, there was no model which could account for the few basic cosmological observations coherently. The development of the observed Large Scale Structures (LSS), especially clusters of galaxies and their number density, was requiring more mass than the baryonic mass observed in form of stars leading to the alternative to assume that most of the baryons in the universe was in diffuse gas. This was shown during this period to be the case in massive galaxy clusters where a hot gas radiating in X-rays dominate the mass. Nevertheless there was no observational evidence for such a large amount of hot gas associated with field galaxies. The possible presence of a dark matter component was one way to solve this problem.

Another experiment on the COBE satellite (COBE-DMR) discovered the anisotropies in the CMB which were needed to explain the creation of structures in the universe from a nearly uniform distribution with small inhomogeneities growing under gravity. The anisotropies detected on very large scale by COBE-DMR were too small if the baryonic matter was the only driver of the structure formation. Non-adiabatic inhomogeneities were considered, for example isocurvature (Peebles). This could be resolved by the introduction of a dark matter with very small coupling to the radiation and baryonic matter but which dominates the matter content.

2 Towards a standard model in cosmology

Around the year 2000 the picture changed dramatically with the first evidence from a specific type of supernovae (SNIa) that the universe expansion velocity was increasing at low redshifts instead of decreasing under the influence of the gravity of matter. Such observations are difficult, small statistics and they depend on understanding the possible SNIa luminosity evolution associated for example with the chemical evolution. Soon after, lensing observations lead to the same conclusion.

In cosmology models based on general relativity, this implied that at low redshift a cosmological constant term similar to the one introduced by Einstein to allow a stationary universe is present. This could equivalently be that a large fraction of the stress-energy tensor is made of a dynamical component which has a negative pressure.

If such a term were introduced in the Einstein equation driving the cosmological expansion, the contradictions between the basic observations disappears and this was referred to as the "concordance model". This was still far from a standard model of cosmology analogous to the standard model of particle physics: the number of observation this model was explaining was small and the accuracy was low.

The ΛCDM introduced after 2000 is defined as a spatially flat geometry universe in which the energy density is dominated by a dark energy component (cosmological constant or a dynamical field with an equation of state $P = -E$, the Λ term) and the matter is dominated by a dark matter component (CDM part). The 2.725 K black body radiation completes the description of the present content of the universe. Furthermore initial adiabatic density fluctuations with an initial power spectrum with spectral an index $n_s = 1$ (the Harrison-Zeldovich one) is assumed to give rise to all the structures observed now. The Thompson optical depth of free electrons from the time when the first sources recognized matter to the present time. The physics is described by the standard model of particle physics and gravity by general relativity. This model has 6 free parameters to be measured by observations. With this physics, the dynamics of the universe (from equations derived from general relativity) is set. This is due to the fact that the behavior of these component in the expansion is known for the three component of the energy density as long as the standard model of particle physics and its observations describes it. This present content (relativistic energy density (electromagnetic radiation and as temperature rise leptons and baryons pairs close to thermodynamic equilibrium), baryonic matter, dark matter and dark energy) and associated parameters are needed for a full description of the cosmological evolution as long as the standard model of particles apply and the additional hypothesis of the ΛCDM are understood and fulfilled.

The goal of observational cosmology has been set to check the robustness of the model and measure as accurately as possible all these parameters.

The SNIa observations gives an estimate of the cosmological constant term, estimates of the baryonic matter density from big bang nucleosynthesis and of dark matter from structure formation observations (cluster density and lensing observations and measurement of the present expansion velocity (the Hubble constant) by observations of distant galaxies. Although this introduction of this model was a breakthrough in cosmology, the parameters were not very precisely set and strong hypotheses needed to be tested (flat geometry, adiabatic density fluctuations).The flat space geometry was challenging as a "classical big bang" set by its present content in this model diverges form flat space in the expansion. The initial conditions should thus be extremely close to Euclidean. Furthermore we also need to find a physical source for the initial acceleration of the expansion of the primordial universe and of the adiabatic energy density fluctuations.

In this model, the adiabatic fluctuations are imprinted as the CMB temperature and polarization anisotropies at a redshift of 1100 when the hydrogen in the universe recombines and let the radiation comes to us freely. We thus have a tool to observe the state of the universe at a redshift of 1100 (380 000 years after the big bang). These fluctuations behave as as sound oscillations at times when they are within the horizon and are amplified by gravity when they are at larger scales (see J.-P. Uzan talk in this seminar).

It was predicted after the discovery of the CMB that the power spectrum of the CMB anisotropies reflecting these acoustic modes would be a key observational tool for cosmology if they were present in the microwave sky (Peebles et al, Zeldovich et al).

3 Observations of the Cosmic Microwave Background anisotropies

On scales larger than one degree, these anisotropies reflect the primordial spectrum. At smaller scales they show acoustic peaks which depend on the cosmological parameters. The search for the first acoustic peak was a big topic for observational cosmology in the 1990s. Although marginal detections were done, it finally converged by the two balloon experiments Boomerang and Maxima which showed very clearly the first peak and confirmed spectacularly the flat space of the universe on large scales principle. This was followed by the first year WMAP results which confirmed the power of CMB anisotropies observations for high precision cosmology.

WMAP was a passively cooled experiment at frequencies on the low frequency side of the CMB radiation and using radio astronomy type detection with newly developed high frequency HEMT amplifiers up to 94 GHz. This space mission was built on the short time scale required by the Explorer program.

Planck was selected at the same time and was combining two instruments: one, the Low Frequency Instrument (LFI), was also HEMT based at frequencies comparable to WMAP thus using well established technologies. The other, the High Frequency Instrument (HFI), was using cryogenically cooled bolometers at 100 mK and thus much more ambitious with much better sensitivity and angular resolution but also more risky. The project suffered delays due to the ARIANE 5 first flight failure and was launched in 2009. It became the third generation space mission after COBE and WMAP with a stronger emphasis on polarization of the CMB which is a much weaker signal.

Planck had a number of very new technologies: the space qualified dilution cooler was the main one. It was combined with a very performant passive cooling and two other active coolers at 4K and 20K. This latter was also cooling the LFI HEMT amplifiers which required a high heat lift. This cooler was based on hydrogen sorption with no moving parts leaving only two compressors for the 4K cooler which used a sophisticated vibration damping control to avoid inducing extra noise on the bolometers. Fig. 1 shows the HFI focal plane unit with its different cryogenic stages. The HFI detector chains for the CMB frequencies (100 and 143 GHz) were mostly limited by the fundamental limit set by the photon noise of the cosmic background itself.

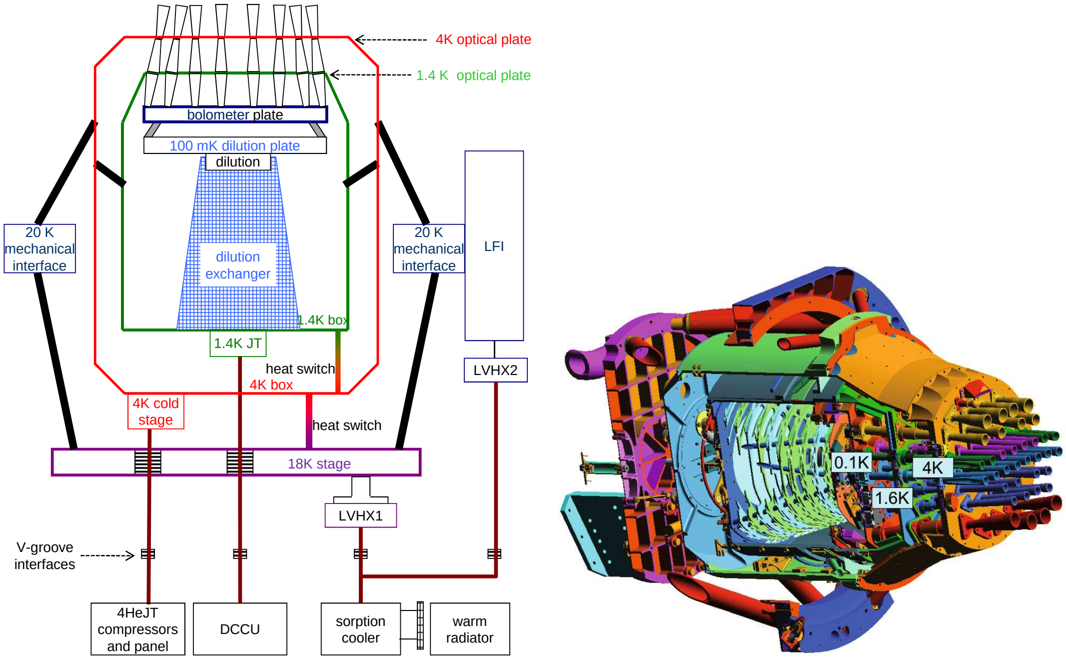


Figure 1: The Planck-HFI instrument: on the left the thermal design schematics and on a view on the right showing the 4K box holding the feed horns collecting the radiation from the telescope, the 1.6 K bos holding the filters and the 100 mK plate holding the bolometers. (Ref. [5].)

The LFI and HFI combination was covering a very broad range of frequencies (30 GHz to 1 THz) and thus controlling very well the galactic and extragalactic foregrounds due to synchrotron emission on the low frequency side and dust emission on the high frequency side. The main CMB channels are concentrated near the minimum of the foregrounds at 70, 100 and 143 GHz. The *Planck* satellite was orbiting the L2 Lagrange point of the sun-earth system (were WMAP was also) which allows a very good rejection of the thermal radiation from the sun, the earth and the moon. It worked extremely well and provided results with the predicted goal sensitivity for 2.5 years for HFI (limited by the amount of ^{3}He carried for the dilution cooler) and 4 years for the LFI.

4 Determination of the ΛCDM cosmological model parameters

The CMB all sky map (Fig. 2) is extracted from the frequency maps using all the frequencies to remove the galactic and extragalactic foregrounds.

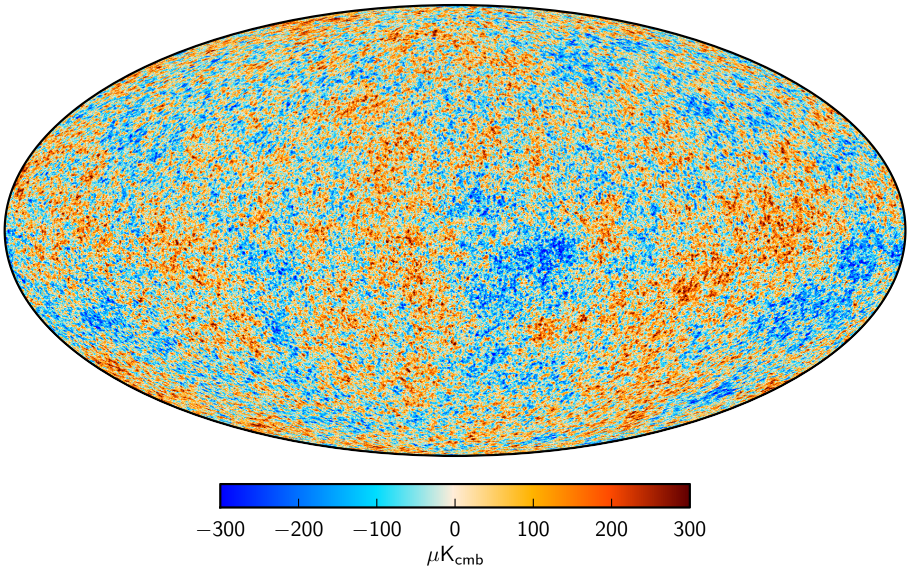


Figure 2: The CMB temperature all sky map in galactic coordinates. (Ref. [6].)

In the ΛCDM model scalar primordial fluctuations are assumed Gaussian and thus all the information is contained in the power spectrum. The *Planck* measurement of these power spectra in temperature and E modes polarization can be seen in Fig. 3. The parity invariant part of the polarization map is refereed as the E modes and the part changing sign under parity the B modes part by analogy with the electric and magnetic fields.

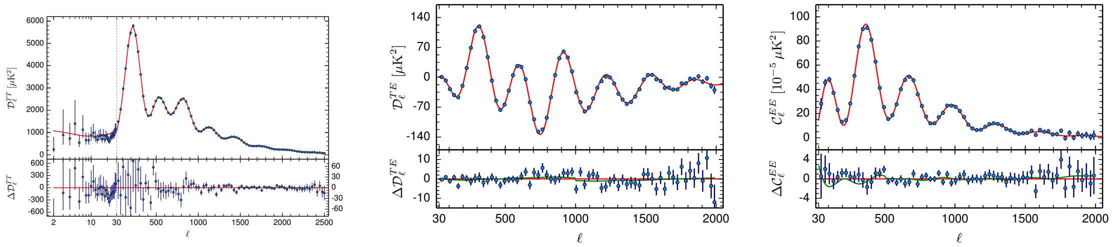


Figure 3: CMB power spectra. The power for temperature (left panel), temperature-E modes polarization cross spectrum, (center panel), E-modes spectra (right panel). The residuals between observations and the Planck best model are shown in the bottom panels. (Ref. [3].)

These power spectra are plotted as a function of multipoles of the spherical harmonics l after summing over the m parameter and the plotted quantity is $Dl = C_l \times l \times (l+1)/2\pi$ for TT and TE. For EE the C_l is shown. In each of these figures the bottom panel shows the residuals between the data and the ΛCDM model with the *Planck* parameters. In temperature the uncertainties are dominated by the cosmic variance of the signal measured itself for l less than about 1500, above that value they are dominated by the noise. In polarization (Fig. 3) the noise dominates for $l > 500$. Note that the units are μK^2 for left and central panels involving temperature but

$10^{-5}\mu K^2$ for the right panel for the E modes power spectrum.

The accuracy of the determination of all the ΛCDM parameters is limited when using only the CMB power spectra because of the degeneracies between parameters. Among these, a major one is the geometric degeneracy. Figure 4 illustrates that point. The points represent the prediction of the model in the plane $\Omega_\Lambda - \Omega_m$, and are color coded as function of the Hubble parameter. It can be seen that these falls close to the dotted line representing $\Omega_\Lambda + \Omega_m = 1$ which is the flat space geometry condition. In the ΛCDM model the assumption on the geometry removes this degeneracy. The lensing has a smoothing effect on the acoustic peaks which helps limiting the geometric degeneracy with the very high *Planck* sensitivity.

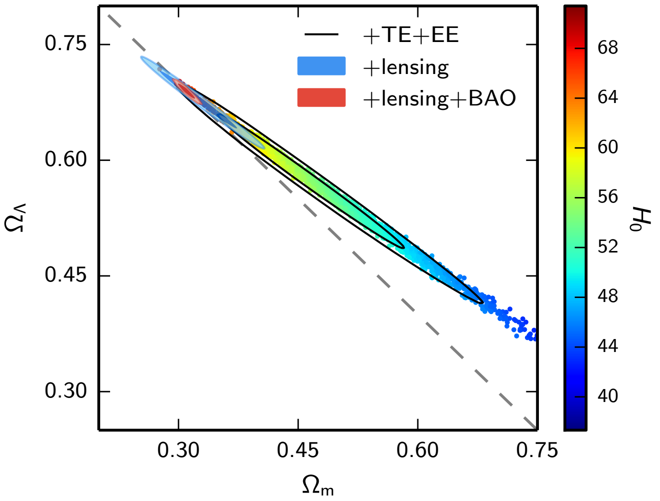


Figure 4: Constraints in the $\Omega_\Lambda - \Omega_m$ plane from the Planck 2015 release (black contours). The blue contours show the breaking of the geometrical degeneracy from the introduction of the lensing data and the blue contours when BAO measurements are introduced [3]. The top panels show the power epectrum over two different ranges of multipoles. The bottom panels show the difference between the data and the theory band power. (Ref. [3].)

Using the flat space assumption was the condition for WMAP to get the cosmological parameters. Using the value of the Hubble constant measured from measurements of radial velocity and distance of galaxies is another way. The measurement of the Hubble constant is a notoriously difficult one as it requires a chain of astronomy distance indicators going from the geometrical parallax of stars to the distance of galaxies which are more and more difficult when the galaxies are more distant. The *Planck* data are accurate enough to observe the gravitational lensing of the CMB signal by the Large Scale Structures in the universe at low redshift which is a very small signal but a non-Gaussian one. It can thus be detected by higher correlations than the two points correlation and the associated power spectrum if the accuracy of the measurements is good enough. Figure 5 shows that indeed these higher order correlation are giving power spectra in agreement with the best ΛCDM model.

The error contours given by the black contours are from *Planck* temperature and polarization power spectra only. The blue patch, sitting nearly on the dotted line, shows the reduction of the errors brought by using jointly the lensing power spectrum with the temperature and polarization ones. It removes mostly the geometric degeneracy. Finally the smaller red patch shows the additional reduction of the uncertainties which is obtained by adding another geometric measurement on galaxies showing the Baryonic Acoustic Oscillations (BAO) reflecting at low redshift the acoustic peak seen at red shift of 1100 in the CMB.

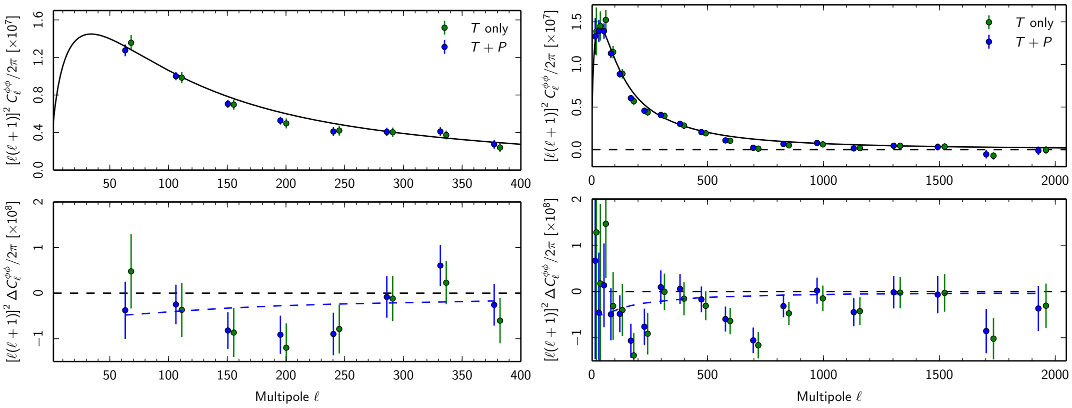
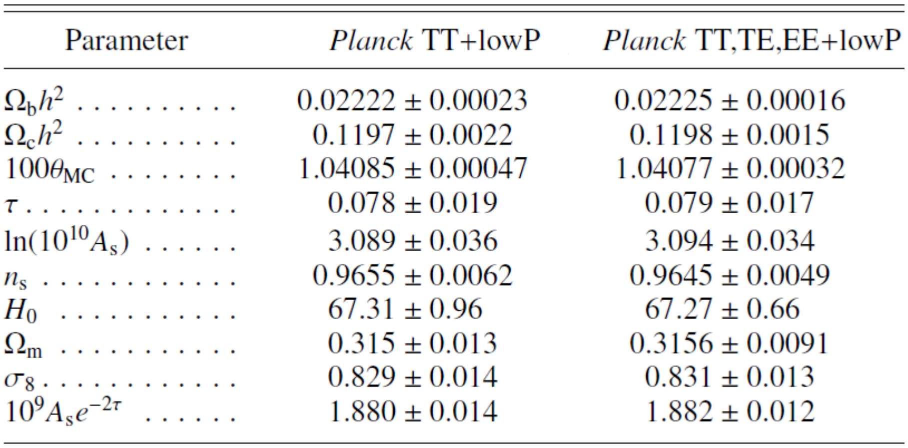


Figure 5: Planck measurements of the lensing power spectrum compared to predictions of the best fitting base ΛCDM model. The lower panels show the difference with the model. (Ref. [3].)

This is a spectacular illustration of a trend shown in the last release of the *Planck* data. The addition of the polarization, the lensing and of other geometric measurements independent of astrophysical uncertainties comfort the cosmological model and reduces the uncertainties of the parameters within the ones obtained by the CMB temperature only data.

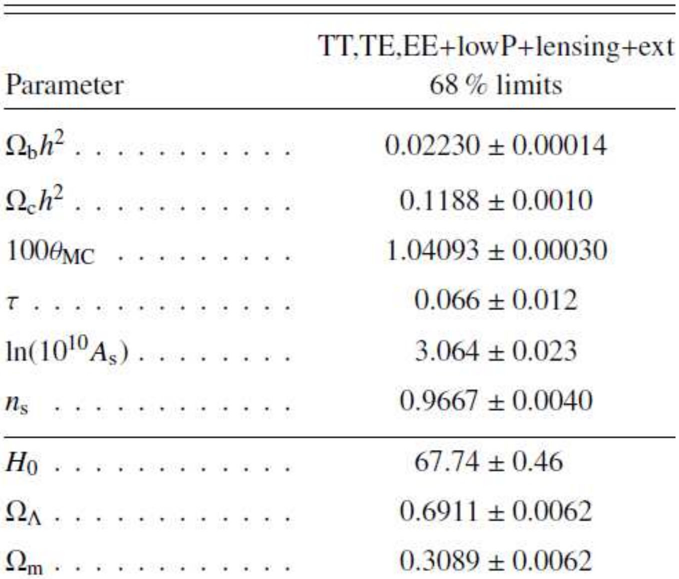
Figure 6 illustrates the improvement due to the polarization data.



Parameter	*Planck* TT+lowP	*Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.3156 ± 0.0091
σ_8	0.829 ± 0.014	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.882 ± 0.012

Figure 6: The table gives the parameters of the base ΛCDM model from the temperature only data (left column) and combined with the polarization data. (Ref. [3].)

Figure 7 shows the further improvements obtained with the lensing, the geometrical measurements and the constraints on the Hubble constant done on galaxies.



Parameter	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02230 ± 0.00014
$\Omega_c h^2$	0.1188 ± 0.0010
$100\theta_{MC}$	1.04093 ± 0.00030
τ	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.064 ± 0.023
n_s	0.9667 ± 0.0040
H_0	67.74 ± 0.46
Ω_Λ	0.6911 ± 0.0062
Ω_m	0.3089 ± 0.0062

Figure 7: The table illustrates the improvement brought by the introduction of observations data from galaxy surveys (BAO, JLA, H_0). (Ref. [3].)

Figure 8 shows the excellent agreement between the prediction for the Acoustic scale distance ratio from the *Planck* base ΛCDM model as a function of redshift and the BAO measurements. especially the best and most recent one (BOSS CMASS).

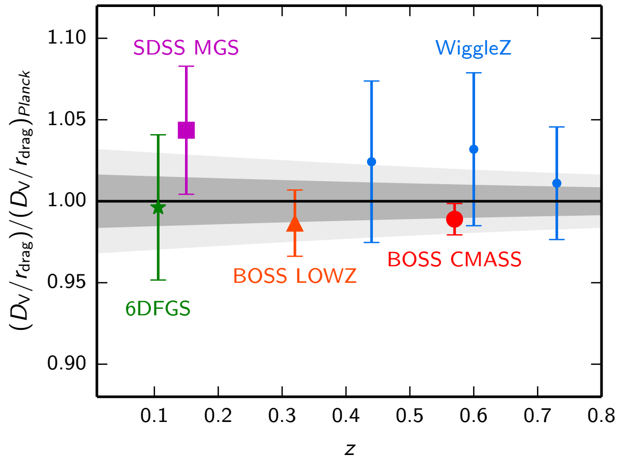


Figure 8: Acoustic-scale distance ratio in the base ΛCDM model divided by the mean distance ratio from *Planck*. (Ref. [3].)

One parameter of the ΛCDM model which is not measured accurately yet. This is the reionization parameter which measures the Thompson optical depth of the free electrons from the time at which the first sources recognized the universe to the present time. The best measurement of this parameter is expected to be from the EE modes of the CMB polarization data at very low multipoles ($l = 3 - 10$). Such measurement are very difficult. In *Planck* systematic effects prevented the use of the high sensitivity HFI data for this measurements so far. Figure 9 shows the 2015 situation in the form of posterior distribution of τ values for different data sets.

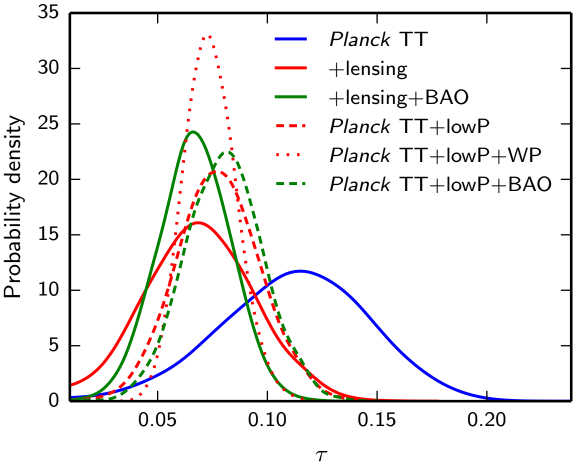


Figure 9: Marginalized constraints on the reionization optical depth in the base ΛCDM model for various combination of data. This parameter is not yet very well constrained. (Ref. [3].)

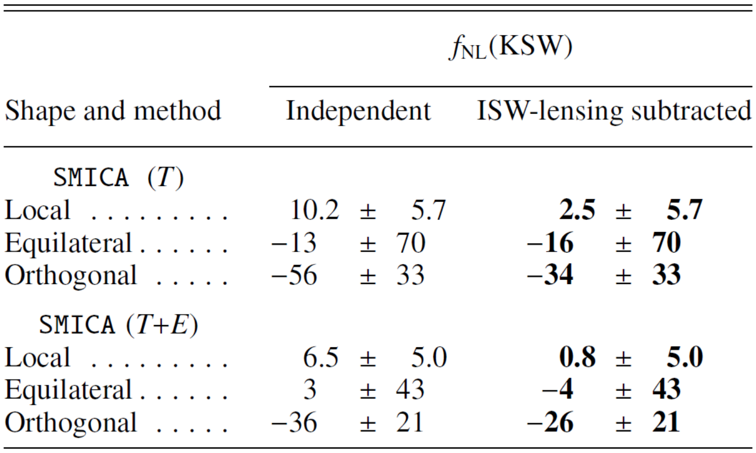
The value of this parameter in Figure 7 using the *Planck* data and the BAO measurements is 0.0066 ± 0.012. The best WMAP measurement using the *Planck* data to remove the dust foreground is 0.089 ± 0.014 (Bennet et al 2013). Using the *Planck* EE spectra at very low multipoles is now possible thanks to the understanding and removal of the last systematic effects. It will be published soon in a forthcoming publication. It confirms and extend the trend toward lower values of τ.

5 Extensions of the base ΛCDM and constraining early universe physics

The extensions of the ΛCDM model can be of different kinds. Some assumptions of the ΛCDM model are not driven by the physics we associate with it. Neither the flatness of space nor the primordial gaussian adiabatic fluctuations derive directly from general relativity and the standard model of particle physics.

The first kind of extensions explores early universe physics. In the base line ΛCDM model there are only two parameters describing the initial conditions. The amplitude of the initial fluctuations A_s is associated with τ with which it is strongly correlated in the combination $10^9 A_s \times \exp(-2\tau)$. The other one is the spectral index of the power law spectrum describing the primordial fluctuations n_s. The inflation paradigm of an exponential acceleration of the expansion associated with quantum fluctuations gives a natural common origin to these assumptions. Quantum fluctuations being at the origin of the energy density fluctuations is very appealing (no other has been proposed). In this paradigm, inflation has to end with a reheating phase where the particles and fields are generated. If the end of inflation is not sudden it implies that the index n_s is somewhat smaller than 1 the difference is of order $1/N$ where N is the number of e-foldings between the end of inflation and the time our present day Hubble scale crossed the inflation Horizon. N should be between 50 and 60. This leads to values $n_s \sim 1 - 1/N = 0.96 - 0.97$. This deviation from scale invariance in the ΛCDM parameters is shown by *Planck* to be present with a 7 sigma confidence level.

Testing the Gaussianity uses three point correlations after removing the expected part from the two point correlations and also the ISW and lensing contributions. The values for the different geometries of the three points are given in Figure 10. These are only upper limits and are very low and getting close to values which would not give much clues on the primordial universe physics.



	$f_{\rm NL}$(KSW)	
Shape and method	Independent	ISW-lensing subtracted
`SMICA` (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
`SMICA` (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**

Figure 10: Limits of the f_{NL} non-Gaussianity parameter from temperature only (top) and combined with Polarization (bottom). The right column shows the results after subtraction of the ISW and lensing effects. This leaves upper limits on the primordial non-Gaussianity. (Ref. [4].)

It is possible to introduce other parameters related to primordial physics in the *Planck* analysis. Inflation models predict a fraction r of the energy density fluctuations in form of tensor fluctuations (gravity waves) which would imprint B modes polarization on the CM. Figure 11 shows the constraints from Planck for the allowed regions in the $r - n_s$ plane together with the predictions of models and classes of inflation models. The tightest B-modes constraint on r come from th Bicep2-Keck-*Planck* (BKP) analysis following an early claim for detection of the primordial B modes around $l = 100$ by assuming no dust contribution. The 353 GHz *Planck* data shows evidence for an interstellar dust contribution close to the observed leven of the BICEP2 measurement. The combined of *Planck* and BKP gives $r_{0.002} < 0.08$ with 95% confidence limit.

The flat space geometry is the first one and has been discussed in the previous section. The best value for the residual contribution of curvature to the total energy density is Ω_K is 0.000 ± 0.005 (95 % confidence level).

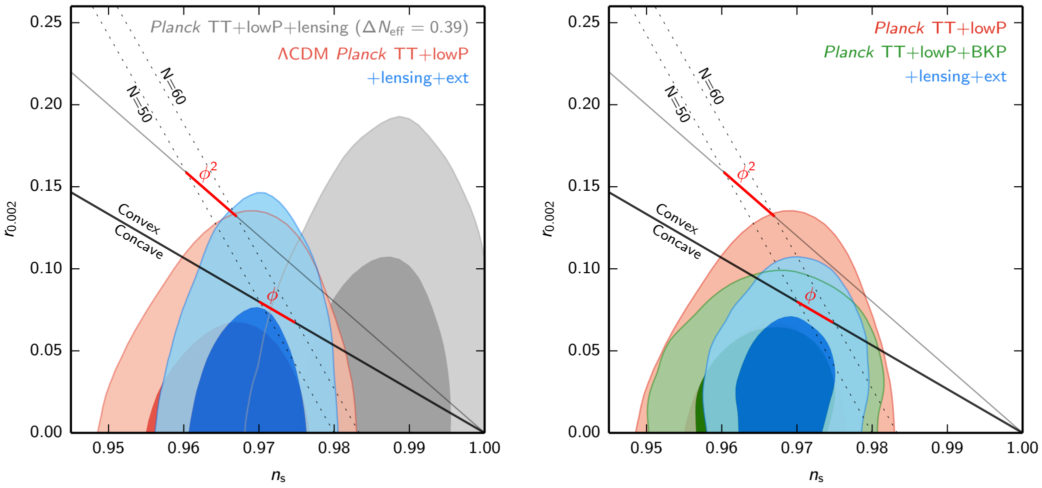


Figure 11: Plots of non excluded regions in the plane $n_s - r$. Positions of classes of inflation models are also shown. The grey area shows the feet of relaxing the effective number of neutrinos species. (Ref. [3].)

A potential curvature of the primordial spectrum is another extension which allows to explore more complicated models. Planck finds a low upper limit: $dn_s/d\ln k = 0.0065 \pm 0.0076$.

The adiabaticity of the fluctuations can be tested by putting an upper limit on the isocurvature fluctuations which had been one model explored before ΛCDM. The fraction can be described by a parameter $\alpha = 0.0003 \pm 0.0016$.

The dark energy equation of state in the ΛCDM model is the one given by a cosmological constant. We can open the parameters of the dark energy component w_0 and w_a. Figure 12 shows no evidence for deviation away from the cosmological constant values.

Another type of extension is possible by assuming decay rates of the dark matter. It has been shown that *Planck* rules out the interpretation of the FERMI-Pamela gamma ray excesses in term of dark matter annihilation.

The last kind of extensions is to check the consistency of the physics used in the model. Big bang nucleosynthesis which lead to the prediction of the existence of the CMB is an obvious one to test. Big band nucleosynthesis predictions of Helium and Deuterium abundances as a function of baryon abundance can be compared with astrophysical measurements and with the baryon abundance found by Planck Taking the effective number of neutrino species from the standard model ($N_{eff} = 3.04$) there is full g-agreement with the best abundances astrophysical measurements. In fact the accuracy of the Planck predictions gives is much better than the astrophysical measurements for Helium.

The nucleosynthesis is affected by the number of species of neutrinos. The constraints on neutrino species is

$$N_{eff} = 3.04 \pm 0.18 \ (\textit{Planck}\ \text{TT, TE, EE+low P+BAO})$$

and neutrino masses upper limits

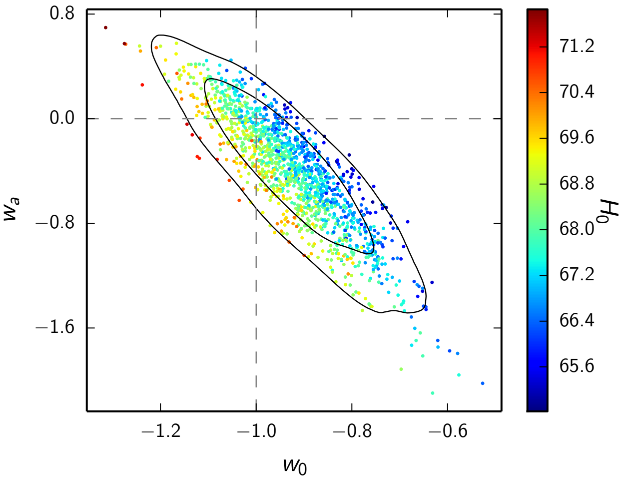


Figure 12: The sample distribution in the $w_0 - w_a$ plane of the dark energy parameters are shown color coded as a function of H_0. The contour are the 68% and 95% limits. Dashed gray lines intersect at the point corresponding to a cosmological constant. (Ref. [3].)

$$\sum m_\nu < 0.17\,\mathrm{eV}\ (\textit{Planck}\ \mathrm{TT,\ TE,\ EE{+}low\ P{+}BAO}).$$

Finally, interesting extensions are possible to show the overall consistency of the emerging standard cosmological model with some rate of physics relevant to cosmology.

One can ignore the COBE measurement of the CMB temperature (2.725 K) and leaves this temperature to be fitted on the Planck anisotropy data with the other parameters. The temperature affects the recombination history and thus the acoustic peaks. We find

$$T = 2.718 \pm 0.021\,\mathrm{K}\ (\textit{Planck}\ \mathrm{TT,\ TE,\ EE{+}low\ P{+}BAO}).$$

The atomic physics rate of the forbidden transition 2s-1s of the hydrogen atom important for recombination can also be extracted from the CMB anisotropies Planck data as shown in Fig. 13.

A last example is in the nuclear physics critical for big bang nucleosynthesis. The nuclear rate $d(p,\gamma)^3He$ rate is controlling the Deuterium abundance. We can extract a probability distribution for this rate compared to the rate used. We find 1.109 ± 0.058 suggesting that the rates might have been underestimated by 10%.

In conclusion, these examples show that the we now have a standard cosmological model based on the CMB measured with Planck and the BAO, JLA and H_0 observations which is encompassing not only a large number of cosmological observations but also is now constraining some of the underlying physics.

This makes the standard particles physics and cosmology models an ensemble which accounts for many observations and experimental results. They also both need to be extended coherently beyond their present form to resolve common questions (nature of dark energy and dark matter, supersymetry, physics near the Planck scale...).

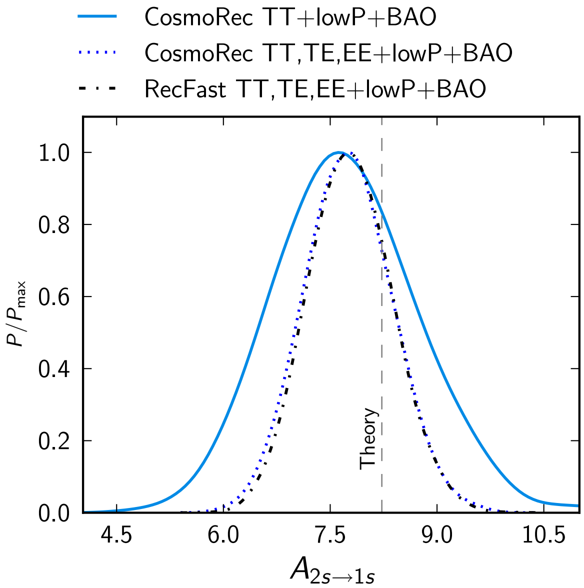


Figure 13: The marginalized posterior distribution are shown for A_{2s-1s} with different theoretical CMB codes and data combinations. The theoretical value is shown by the dashed line. (Ref. [3].)

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