Available online at www.sciencedirect.com

ScienceDirect

Nuclear and Particle Physics Proceedings 265–266 (2015) 48–51

www.elsevier.com/locate/nppp

Precision Measurements of the Cosmic Microwave Background

P. de Bernardis

Dipartimento di Fisica, Sapienza Universitá di Roma

Abstract

Fifty years after the first detection, we are now in the era of precision measurements of the Cosmic Microwave Background (CMB). The spectrum, anisotropy and polarization of the CMB have been measured with outstanding precision. The results support the hot big bang theory, and the adiabatic inflationaly scenario for the formation of large-scale structures in the Universe, with cold dark matter and dark energy. This is a short report on the latest experimental results, with mention of their impact on fundamental physics, and in particular on neutrino physics, the subject of this conference. We focus on spaceborne experiments, aimed at measuring the finest details of the CMB with final precision and accuracy.

Keywords: cosmic microwave background, experiments, cosmology

1. Introduction

The CMB is a faint background of meV photons, with accurate blackbody spectrum (T=2.725K). Their density is $\sim 400\gamma/cm^3$ everywhere in the Universe. This density outnumbers the density of matter by almost 10 orders of magnitude, and is believed to be produced a few μs after the big bang, from a slight matter-antimatter asymmetry.

The CMB is an important tool of cosmology and fundamental physics in several ways.

a) the CMB provides us with a direct view of the primeval plasma (380 kyr after the big-bang, and 13.7 Gyr ago) and its small inhomogeneities (the seeds of the large-scale structures) resulting in faint anisotropy of the CMB brightness (temperature); the precise shape of the angular power spectrum of CMB anisotropy depends on the geometry of the universe, on its composition in terms of neutrinos (number of species and masses), cold dark matter, dark energy, and on the properties of primordial density inhomogeneities, i.e. on the physics of cosmic inflation.

b) the CMB provides us with an indirect view of the first split-second after the big-bang, when the typical energy of matter was 12 orders of magnitude larger than the highest energy studied at accelerators, and cosmic inflation is believed to happen. Quantum fluctuations present in the pre-inflation phase result in scalar (density) and tensor (gravitational waves) fluctuations in the post-inflation era. The former provide an origin for the density inhomogeneities generating cosmic structures, and provide intensity fluctuations and a faint irrotational pattern of linear polarization in the CMB; the latter produce an additional irrotational *and* rotational pattern (B-modes) of linear polarization. From the power spectrum of B-mode polarization it is in principle possible to investigate the potential of the inflaton, i.e. constrain physics at the 10^{16} GeV scale. The inflation-generated density fluctuations are expected to be Gaussian and scale-invariant to first order, with very slight deviations which also constrain the inflation model [1, 2].

c) the CMB is a diffuse backlight illuminating *from behind* the structures present in the universe. CMB photons are inverse-Compton scattered in hot cosmic plasmas (e.g. in clusters of galaxies) and this effect (the Sunyaev-Zeldovich effect) has been used to discover a large number of clusters of galaxies (see e.g. [3, 4, 5]).

http://dx.doi.org/10.1016/j.nuclphysbps.2015.06.013

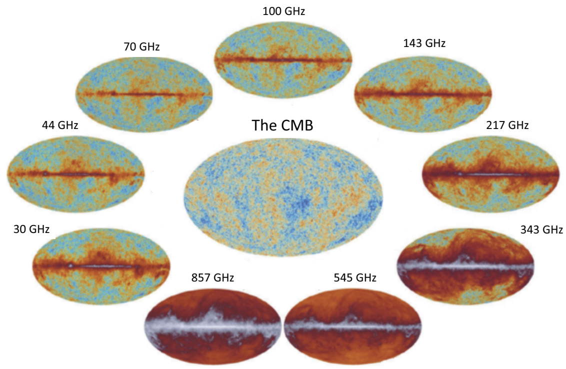

Figure 1: Full-sky maps obtained from Planck at the 9 operating frequencies, and the CMB map obtained from the components separation process. For high quality figures and data see the Planck Legacy Archive http://pla.esac.esa.int/pla/.

2. The status of the art of CMB measurements

We are seeing a real boost of CMB measurements nowadays, dominated by the results of the Planck satellite and those of ground-based telescopes using large arrays of bolometric detectors.

Working from deep space (L2) the Planck satellite has produced high resolution, multi-frequency maps of the mm-wave sky, with unprecedented precision and accuracy. The multifrequency approach is the key to obtain an unbiased measurement of the map of the CMB. In fact, the brightness received from a given line of sight is the sum of a number of components: galactic, extragalactic, cosmological. Even if measured with negligible noise, this brightness must be cleaned from contaminating emissions (foregrounds) to provide an accurate estimate of the faint brightness fluctuations of the CMB. The only handle we have to solve the problem is the fact that different foregrounds have spectra and angular distributions very different from those of the CMB. A number of methods has been invented to efficiently separate the components of the measured brightness (see e.g. [6] and references therein), but for sure the number of different frequencies to be observed must be larger than the number of components to be separated. As foregrounds we can list galactic synchrotron, galactic free-free, interstellar dust (thermal and anomalous), extragalactic sources, each with a different spectrum and in principle also with spectral variations in different areas of the sky. Among these, interstellar dust and galactic synhcrotron are significantly polarized. From this list it is clear that the set of 9 frequencies (30, 44, 70, 100, 143, 217, 343, 545, 857 GHz) observed by Planck (figure 1) is a tremendous improvement with respect to ground based experiments, which can observe only the low frequency sky ($f \lesssim 240$GHz) even in the coldest and driest sites on Earth, and cannot achieve full-sky coverage. From the Planck CMB map a high precision, well calibrated angular power spectrum of temperature anisotropy TT has been obtained, which is consistent with the expectation of the adiabatic inflationary model, and allows the precise determination of cosmological parameters [7, 8].

Despite of the remarkable overall consistency, one cannot avoid noting that small deviations at low multipoles are present (and were already detected in the WMAP data), and currently unexplained.

Planck is also very sensitive to CMB polarization, as demonstrated in [9]. The complete analysis will be published in early 2015.

The TT spectrum is affected by neutrino masses mainly due to gravitational lensing. Increasing the sum of neutrino masses suppresses clustering within the horizon at the non-relativistic transition, so that the CMB lensing potential is suppressed. In the Planck TT data this results in an upper limit $\sum m_\nu < 0.66eV$ at 95% CL. The other important effect of neutrino masses on TT is through the angular-diameter distance, which is contrained by the position of the first acoustic peak. This effect is degenerate with Ω_Λ and H_o, so TT data must be combined with independent cosmological data. From a combination of TT (Planck + WMAP + high ℓ measurements) and Baryonic Acoustic Oscillations data, and assuming flatness, the upper limit is $\sum m_\nu < 0.23eV$ at 95% CL. Relaxing flatness, $\sum m_\nu < 0.32eV$ at 95% CL.

The number of neutrino species affects the energy density of radiation when the species are relativistic. This is parametrized by the N_{eff} parameter, and affects the expansion rate before recombination, and consequently the age of the universe at recombination and thus the sound horizon. The TT spectrum from Planck + high ℓ + WMAP polarization measurements constrains $N_{eff} = 3.36 \pm 0.66$ at 95% CL, which is fully consistent with the standard lore. For a thorough discussion, see [8].

While the power spectrum of E-modes in the linear pattern of CMB polarization (EE) and the cross correlation ET have been exhaustively measured by several experiments, and found to be fully consistent with what we expect to be produced by the same density inhomogeneities generating the TT spectrum, a convincing measurement of cosmological B-modes has not been obtained yet. As a matter of facts, after years of steadily improving upper limits, the BICEP2 experiment has re-