The final Planck data release

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Last week the Planck collaboration released their latest and final analyses. The combination of precise measurements with well understood statistical and systematic uncertainties make Planck CMB observations a treasure box for cosmologists, particle and astro-particle physicists. So what does the data release actually contain? And what does it mean for the scientists of the ELUSIVES network?

The Planck satellite was launched in May 2009 and operated continuously between August 2009 and October 2013. During this period it measured the intensity and polarization over the whole sky in nine frequency channels between 25 GHz and 1000 GHz. The main goal of the mission was the measurement of the Cosmic Microwave Background (CMB) radiation - a remnant from the very early universe. Planck was the third-generation space mission to measure the CMB (after COBE and WMAP) and released its data in three major steps: in 2013 from 14 month mission duration and in 2015 from the full mission duration. Since 2015 the analysis pipeline has been updated and improved, especially for polarisation data, and even more consistency check have been carried out. The very recent 2018 release represent the final data analyses by the Planck collaboration.

The CMB follows a black-body spectrum with a temperature of $T_{\rm CMB} = (2.725 \pm 0.002)\,$K and is remarkably homogeneous over the whole sky. However, very small fluctuations in the CMB temperature (at the level of $\Delta T/T \simeq 10^{-5}$!) reveal a lot about the conditions in the early universe. Since the fluctuations are purely statistical they are best described by their two-point correlation function or, in harmonic space, by the power spectrum, shown in Fig. 1. The standard ΛCDM cosmological model is able to predict this correlations structure with remarkable accuracy. It assumes that small quantum fluctuations, created during an inflationary period of accelerated expansion, provided the seeds from which today's large scale structure has grown by gravitational instability. In the ΛCDM model there are five main constituents: dark energy, dark matter, regular atomic matter, the photons of the CMB and three generations of nearly massless neutrinos. The cosmological evolution (and the CMB angular power spectra) depend on six parameters only, of which Planck now constraints five to the sub-percent level! Considering 1-parameter and 2-parameter extensions of ΛCDM, some of which we discuss in the following, the Planck collaboration recognizes no statistical significant preferences for departures from the canonical model.

Planck is also able to test the underlying assumptions of ΛCDM with unprecedented accuracy, such as geometrical flatness ($\Omega_k < 0.0007 \pm 0.0019$), the Gaussian nature of initial fluctuations ($f_{\rm NL} = 2.7 \pm 5.7$), the absence of isocurvature perturbations ($\alpha_{-1} <$

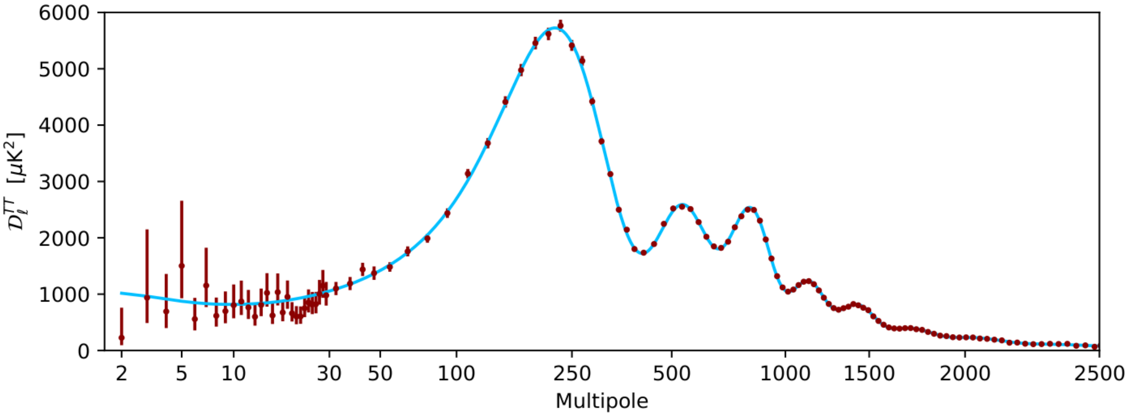

Figure 1: The temperature cross-correlations spectrum as measured by the Planck satellite (red) and the best-fit ΛCDM model (blue).

0.00013 ± 0.000377) and the absence of topological defects ($f < 0.01$), where the latter two refer to cosmic strings. The observations have established a deviation from a scale-invariant primordial spectrum (i.e. $n_s \neq 0$) at more than 8σ. Combined with the Planck measurement of the scalar-to-tensor ratio ($r_{0.002} < 0.07$) this tightly constraints the space for many specific popular models of inflation. Finally the Planck measurements show no significance for a primordial power spectrum departing from a simple power law, implying a featureless, flat inflationary potential.

The baseline cosmological model assumes three neutrino species, whose mass is $\sum m_\nu = 0.06\,\mathrm{eV}$ – the lower bound implied by neutrino oscillations for normal ordering (for inverted ordering the limit would be $\sum m_\nu > 0.1\,\mathrm{eV}$). Heavy neutrinos alter the late-time expansion history of the universe and the shape of the matter power spectrum and hence the neutrino mass can be constrained by from CMB observations. Especially sensitive probe is the lensing potential, inferred from the deflection of CMB photons by the gravitational potentials associated with large scale structure. The Planck collaboration reports an upper limit of $\sum m_\nu < 0.12\,\mathrm{eV}$, very close to the minimum mass allowed within the inverted ordering scheme. If the number of neutrino species departed from three this would as well show up in the CMB data, as additional relativistic degrees of freedom would alter the expansion history of the universe prior to recombination. The effect is parametrized by the effective number of neutrino species N_{eff} as

$$\rho_{\mathrm{rad}} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\,\rho_\gamma \tag{1}$$

where the numerical factors account for the difference in energy density between fermions and bosons and for the neutrino's temperature being lower than that of photons. The standard model predicts $N_{\mathrm{eff}} \simeq 3.046$ in concordance with the Planck measurement $N_{\mathrm{eff}} = 2.99 \pm 0.17$, disfavouring a thermal relic that froze out after the QCD phase transition. Varying N_{eff} and m_ν simultaneously, a 4-th generation thermalized neutrino is excluded at the level of 3σ. Finally, reaching sensitivity the the neutrino's speed of sound and anisotropic stress, Planck is also able to probe non-standard neutrino interactions.

One of the most mysterious ingredients of the ΛCDM model is the cosmological constant Λ: a contribution to the energy density which behaves like vacuum energy, i.e with an equation of state $w = -1$ and drives the late-time accelerated expansion of the universe. However, there is neither a compelling explanation for its value nor a natural mechanism to produce it. Two alternative approaches to account for the accelerated expansion are to propose a dynamical field with effective negative pressure (dark energy) or to propose modifications of gravity from general relativity. With respect to the former option Planck obtained $w_0 = -1.03 \pm 0.03$, consistent with a cosmological constant. Departures from general relativity are probably from the Planck data as well as they would modify the expansion history ot the universe and the evolution of metric perturbations and affect the growth rate of structure and the lensing of CMB photons. However these test are relatively weak compared to those on scales of the solar system.

Although the 2018 data release marks the final word from the Planck collaboration it does not imply the end of CMB physics. Proposed 4th-generation CMB experiments would further improve our measurements. Some discrepancies between Planck measurements and other probes, namely the small value of σ_8 found by the Dark Energy survey and the 3.6σ tension between low-redshift measurements of the Hubble rate, require further attention from the theoretical as well as from the observational side. And of course, the recent data provide us with a powerful opportunity to constrain non-standard cosmological scenarios. A field in which many ELUSIVES members are active as well.