Last Results and Questions From Planck

Silvia Galli

e-mail: gallis@iap.fr

IAP

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Abstract

Planck is an ESA satellite aimed at the observation of the Cosmic Microwave Background. The Planck collaboration has recently published its last legacy release. In this talk I shortly reviewed the main Planck results on cosmological parameters, highlighted some of the curious features present in the data and the Planck point of view on tensions with a few other astrophysical probes, notably with the Hubble constant measurements from local distance measurements.

1 Introduction

One of the main driving forces behind the phenomenal progress of cosmology in the last twenty years has been the observation of the cosmic microwave background (CMB). Europe has played a leading role in CMB science in the last 10 years through the success of ESA's Planck satellite, which provided the ultimate measurement of the CMB temperature anisotropies up to up to multipoles smaller than about $\ell \sim 1500$ [1]. Moreover, Planck has provided powerful measurements of the CMB polarization anisotropies, and the first full-sky measurement of the CMB lensing potential [2]. Furthermore, Figure 1 shows the angular power spectra as measured by Planck.

One of the legacy results of Planck is that the standard model of cosmology, the ΛCDM, works astonishingly well to describe the CMB anisotropies, as well as a large number of other observations. Planck measured cosmological parameters with percent level accuracy, in agreement with other probes, ranging from Baryon Acoustic Oscillations (BAO) to measurements of primordial elements combined with Big-Bang Nucleosynthesis calculations [1]. Nevertheless, the Planck results feature a number of outstanding inconsistencies which might hint towards cracks in this very successful model.

2 The H_0 problem.

In 2019 the ΛCDM model reached a remarkable milestone. The difference between early-time and late-time probes measuring the expansion rate of the universe, i.e. the Hubble constant, reached an unexplained discrepancy of 5.3σ. Indeed, distance-ladder measurements using cepheids and supernovae Ia yield H_0=74.22 ± 1.82 Km/s/Mpc [3]. Combined with data of time delays of multiply imaged strongly lensed quasars, they measure H_0= 73.8±1.1 Km/s/Mpc [4], as also shown in Figure 2. On the contrary, observations of the CMB anisotropies performed by the Planck satellite yield H_0=67.36± 0.54 Km/s/Mpc [1], in agreement with BAO plus primordial deuterium abundance measurements. This difference appeared in the first release of the Planck data at the 2.5σ level, and in

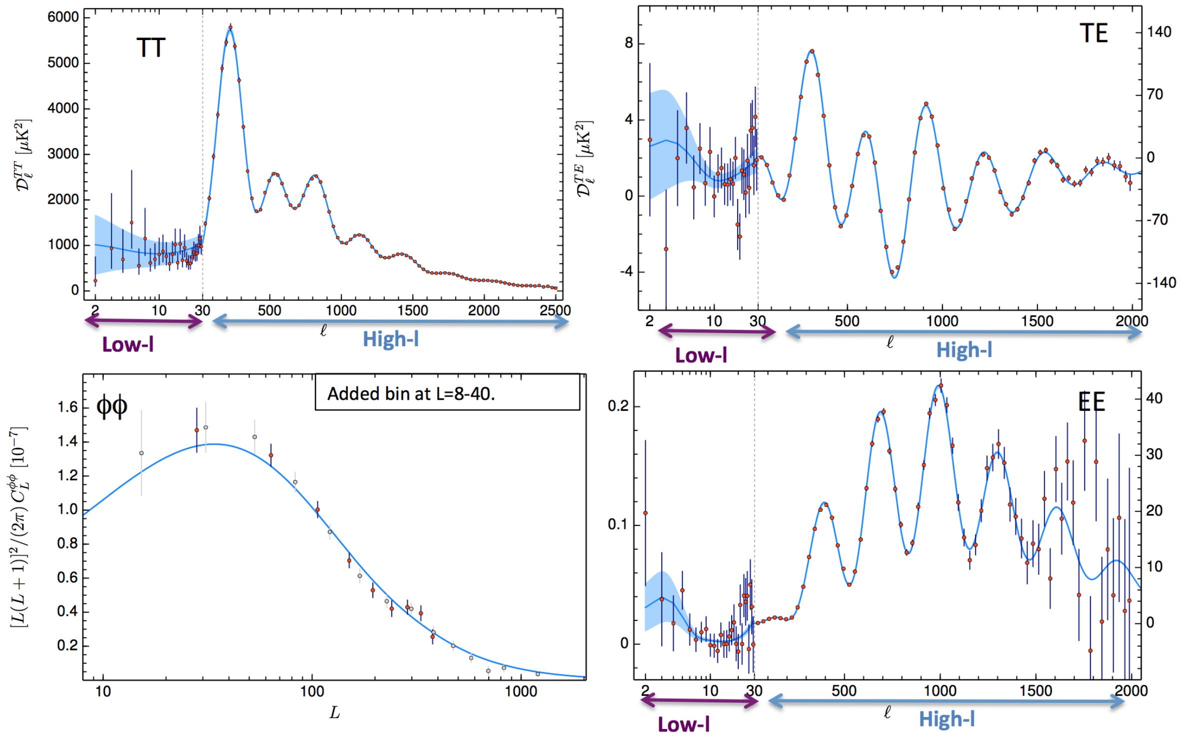

Figure 1: Planck angular power spectra for intensity (TT), E-mode polarization (EE), temperature polarization cross-correlation (TE) and the lensing reconstruction (PP). The red points are the data, while blue lines are the best-fit spectra assuming a ΛCDM model. Taken from [1]

spite of all of the efforts trying to identify systematic effects which could explain it, it has only grown in statistical significance over the years. Recently, distance-ladder measurements using the tip of the red giant branch to calibrate supernovae Ia provided measurements which are for the moment consistent with both, as well as other probes [5]. If one could completely exclude statistical and systematic effects as the source of such a discrepancy, the implications of this tension could potentially be revolutionary. In effect, distance-ladder measurements are direct, i.e. they directly test the local expansion of the universe today. Conversely, CMB and BAO are indirect, i.e. they are probes which require a model in order to infer the Hubble rate today. Thus, the most fascinating hypothesis is that the solution of this tension lies in a change of the cosmological model, implying evidence for the existence of new physics [6]. As of today, a number of possible extensions of the ΛCDM model has been proposed to solve this issue, although none of them are so-far able to completely explain it. Most of these focus on changing the physics of the early universe, in particular the calculation of the sound horizon [6]. Examples are models with new physics in the neutrino sector [7] or early dark energy [8]. On the other hand, changing the physics of the universe at late-times such as e.g. with dark energy, decaying dark matter or interacting dark matter-dark energy was already proved to be in disagreement with current data.

3 The σ_8 and beyond the standard model problem.

The H_0 problem is not the only one related to the Planck measurements. There is a series of inconsistencies at lower statistical significance, and likely all related to each other. These have triggered a huge interest in the cosmology community due to their potentially pivotal consequences.

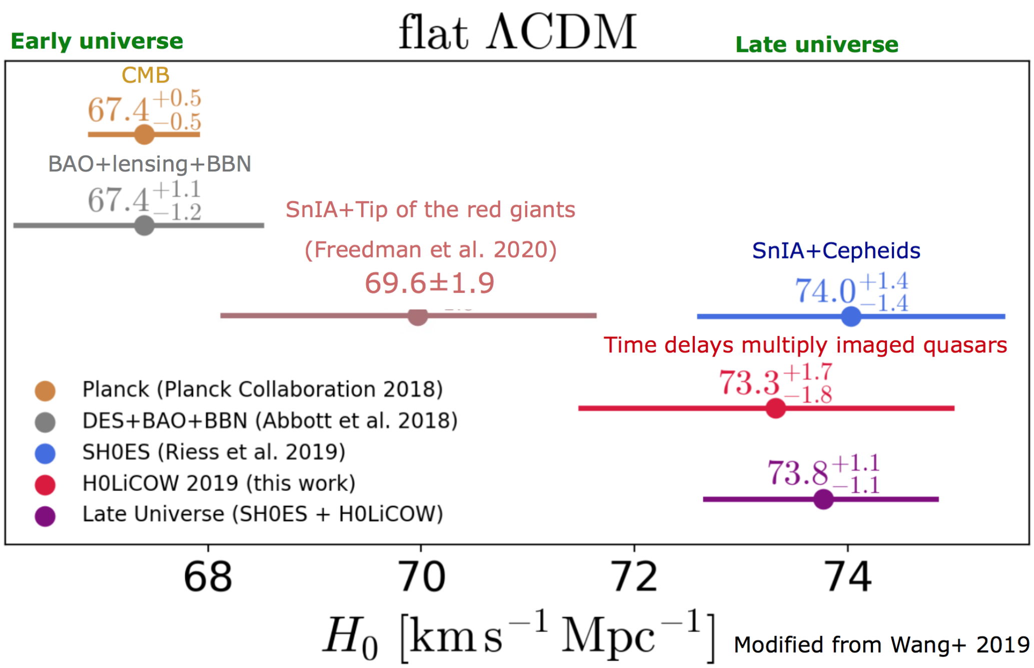

Figure 2: Measurements of the Hubble constant from different probes. Modified from [4]

3.1 The σ_8 problem

There is a long-standing, persistent discrepancy on combinations of the amplitude of matter density perturbations today, σ_8, and matter density, ω_m, as measured by Planck on the one hand or by counts of galaxy clusters and weak lensing observations [9] on the other hand. The latest Planck CMB data yield e.g. σ_8=0.8111±0.0060 (Planck TT,TE,EE+lowE+lensing, ΛCDM) [1], while late-time probes measure values lower by 2-3σ (with error bars typically 3 times larger than Planck). This subject has triggered a large literature, investigating the possibility that part of this discrepancy might be due to astrophysical uncertainties in the lower-redshift probes (e.g. the hydrodynamical mass-bias of galaxy clusters). However, the possibility that this could also be due to something unusual in the CMB spectra, either it be statistical, systematic or physical, is still viable, and requires a deeper investigation.

3.2 Extensions of the vanilla ΛCDM model

Models beyond the vanilla one, such as those with large non-zero curvature of the universe or modified gravity, which increase the predicted amplitude of lensing in the CMB power spectra, provide marginally better fits to the Planck CMB anisotropy data at the 2-3σ level [1]. However, such findings are in disagreement with the observed amplitude of the reconstructed CMB lensing potential as measured e.g. by Planck itself, and BAO data. The discrepancies on the measurement of these extensions between different probes suggest that if these are indeed signs of new physics, the existing models are unlikely to provide the correct answer yet.

3.3 Planck inconsistencies

The Planck data marginally passes two internal consistency tests. The first evaluates cosmological parameters from two ranges of multipoles, the low ones (ℓ800) and the high ones (ℓ800), finding ΛCDM parameters which are different at the $\sim 2\sigma$ level [10]. The second measures the amplitude of lensing as measured in the anisotropy power spectra via the phenomenological lensing parameter A_L, which is expected to be equal to unity in the standard model of cosmology. Unexpectedly, Planck measures this parameter to be higher, $A_L = 1.180 \pm 0.065$ (68% confidence level, Planck TT,TE,EE+lowE) [1]. However, it is already known this cannot be the sign of an anomalous, physical excess of lensing in the universe. In fact, while this effect is measured at $\sim 15\sigma$ in the anisotropy spectra, it is much better measured (at $\sim 33\sigma$ when marginalizing over uncertainties of the theoretical model) by the lensing potential reconstructed from the non-gaussian signatures it leaves in the CMB maps. The reconstructed CMB lensing from Planck itself does not show an equivalent excess in amplitude. All these three families of anomalies and inconsistencies are likely sourced by the same features of the Planck power spectra. These look like a preference for an extra-smoothing of the peaks and troughs of the small scale Planck CMB temperature anisotropy power spectrum at $\ell \sim 1000$, and a preference for lower power at large scales (at $\ell 30$), as shown in [10]. This is also shown in Figure 3, where we plot the Planck residuals of the TT temperature power spectrum with respect to the ΛCDM model, together with extended models which can better fit the remaining residuals. We underline here that although these models provide marginally better chi-squares, the ΛCDM is already an excellent fit to the data.

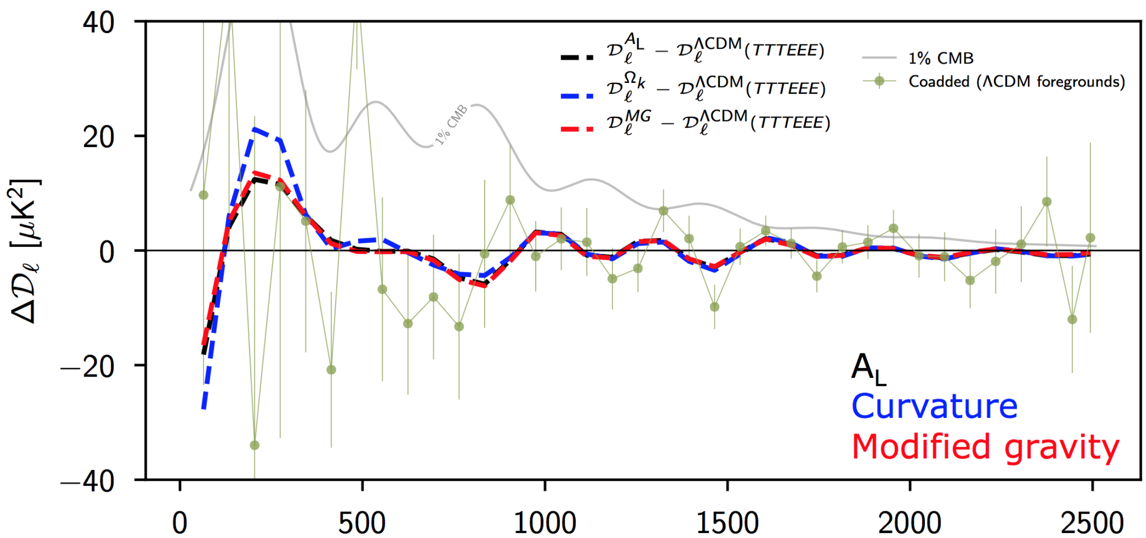

Figure 3: Figure 2: Residuals of the Planck TT CMB anisotropy power spectrum with respect to the ΛCDM best-fit (gray data points). The dashed lines show extended ΛCDM models which marginally better fit the data at the $2 - 3\sigma$ level, and which all fit the same features in the power spectra. We show the case of extra-lensing, (ΛCDM+A_L green), curvature (ΛCDM+Ω_k, blue), modified gravity (ΛCDM+MG, red [1]) and electron mass (ΛCDM+ m_e, green, [11]).

We showed that as-of-today there is no evidence that these residuals can be caused by a known systematic (see summary in Section 3.10 of [12],. Thus, these anomalies, whether they are due to a statistical fluctuation, unknown systematics or the signature of new physics, still lack a correct interpretation, despite many years of intense scrutiny. If further confirmed, they would impact the interpretation of some of the most interesting fundamental physics parameters that only cosmology can provide, including the curvature of the universe, the sum of the neutrino masses, dark energy and modified gravity.

4 Conclusions

The Planck results have marked a milestone in our knowledge of the universe. They have demonstrated that the ΛCDM model is a remarkably good fit to the current data. However, they have also opened new questions. The most remarkable one is about the value of the Hubble constant, which Planck measures to be in disagreement with more direct observations at more than the 4σ level. Future observations of the CMB at high resolution in polarization, as well as of plenty of other probes, will certaily shed new light on these issues, possibly confirming or refuting the need of a new paradigm in the standard model of cosmology.

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