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Cosmic microwave background cosmology with Planck

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Summary. — Planck is the third-generation space mission aimed at measuring the cosmic microwave background radiation, a relic of the hot Big Bang. Planck *ultimate* measurement of temperature fluctuations in the cosmic microwave background, together with its leading edge observations of polarization, allowed us to perform unprecedented tests of the cosmological model and derive stringent constraints of fundamental physics. The high sensitivity data also enabled us to obtain the most significant measurement to date of the gravitational lensing of the cosmic microwave background. This represents a novel observable for exploring thirteen billion years of structure formation in the universe. In the paper, I discuss some of the main cosmological constraints we obtained so far and their implications for the standard model of cosmology. I also highlight several key aspects in the data analysis process.

1. – Introduction

It has long been recognised that the Cosmic Microwave Background (CMB) is one of the most powerful sources of information about all epochs of the Universe. As such, it played a crucial role in establishing the standard model of cosmology, the so-called ΛCDM. CMB temperature anisotropies, tiny fluctuations of order 10^{-5} the mean temperature $T = 2.725\,\mathrm{K}$, are known to trace the primordial seeds from which cosmic structures originated. They have now been measured with remarkable precision, also thanks to Planck [1], a space mission of the European Space Agency (ESA).

Launched in May 2009, Planck observed the sky for more than four years. With its full sky coverage, high sensitivity at high resolution and broad frequency range, for the first time Planck mapped all the relevant angular scales of the primary anisotropies with a single mission, from the entire sky to arcminute resolution. These measurements allowed us to perform unprecedented tests of the cosmological model, such as a precise census of the constituents of the universe and an accurate determination of its expansion history. For the first time, we have been able to measure the CMB gravitational lensing by the large-scale structure over the whole sky. In addition, although the instruments onboard Planck were not originally designed for polarization studies, and in fact they were adapted to that purpose only in a relatively advanced stage of the mission preparation, the full sky observations of the CMB linear polarization collected by Planck represent already a significant improvement over previous measurements. Polarization carries information that is complementary to temperature, therefore not only it improves the constraining power of the cosmological dataset, but it also offers an internal consistency check.

After briefly introducing the Planck data, I will highlight some key aspects in the data analysis process to extract cosmological information out of the CMB maps. I will then present and compare some of the main cosmological constraints from temperature, polarization and lensing of the CMB, commenting on how they contribute to uphold the ΛCDM model of cosmology.

2. – From maps to science

2˙1. *Sky maps.* – The primary goal of the Planck mission has been to deliver the *ultimate* measurement of the CMB temperature primary anisotropy field. The fundamental requirements to accomplish such a challenge are: a) a coverage of the entire sky; b) high-sensitivity at good enough angular resolution in order to mine all scales at which the CMB primary anisotropies contain information; c) a very broad frequency coverage, to accurately characterize and remove the astrophysical foreground contributions superimposed to the primordial signal. This is done taking advantage of the different frequency dependence of the Galactic and extra-Galactic emissions with respect to the CMB [2]. As a result, Planck observed the whole sky from space in nine channels ranging from 30 to 857 GHz, with an angular resolution of few arcminutes at the highest frequencies, reaching 33 arcminutes in the lowest frequency channel [1]. It also mapped the polarization at the different frequencies, with the exception of the two highest frequency channels.

2˙2. *Angular power spectra.* – One can think of synthesizing the information contained in the Planck maps in terms of their correlation functions on the sphere. A prediction of most cosmic inflation scenarios is that the primordial density perturbations that sourced the structures in the universe, and therefore the CMB anisotropies, are mainly Gaussianly distributed. Such a prediction has been precisely verified with Planck data [3]. As a consequence, almost all of the information contained in the anisotropy field, $\Delta T(\hat{n})$, is actually captured by the two-point correlation function, $C(\theta) \equiv \langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle$, where θ is the angular separation on the sky between the directions of observation $\hat{n}$ and $\hat{n}'$. $\langle \cdot \rangle$ instead indicates the ensemble average over all possible realisations of the sky with the same cosmology. If we expand the anisotropy field into spherical harmonics, which are a natural basis on the sphere, $\Delta T(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{n})$, we find that $C(\theta)$ is proportional to the angular power spectrum $\langle a_{\ell m} a^{*}_{\ell' m'} \rangle = C_{\ell}^{TT} \delta_{\ell \ell'} \delta_{m m'}$, under the assumption that the universe is isotropic. This spectrum gives the power in temperature fluctuations for different multipole moments, $\ell \propto 1/\theta$, *i.e.*, for different angular scales.

In temperature, the power spectrum has been measured over large portions of the sky by the satellite missions COBE [4] and WMAP [5], though with only a modest angular resolution. A better angular resolution has been achieved by balloon- and ground-based experiments, which however can just observe very small patches of the sky (*e.g.* [6, 7]). With Planck data, instead, we have been able to map the primary temperature anisotropy field on all the relevant angular scales, across three decades in multipoles, as illustrated in fig. 1, covering regimes where different physical effects come into play, see for example [8].

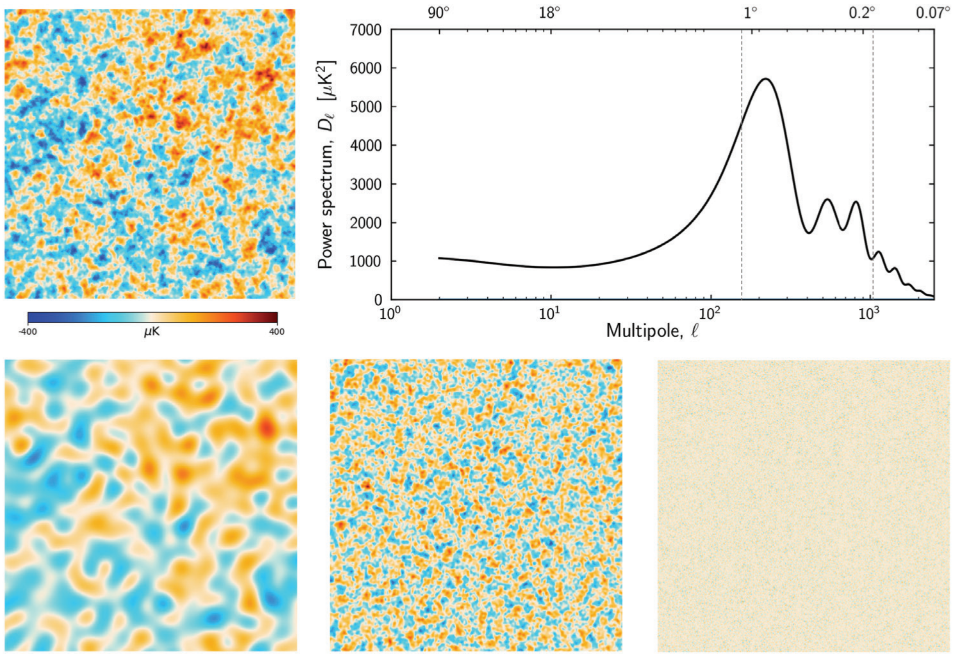

Fig. 1. – The upper left panel shows a $30^\circ \times 30^\circ$ patch extracted from the Planck CMB temperature anisotropy map. The visible pattern is a superposition of anisotropies on several angular scales. In order to isolate the different contributions, the lower panels show filtered versions of the same patch. In the leftmost panel, the filter leaves the largest angular scales unaltered while removing the smaller scales. In the middle panel a band-pass filter has been applied to the data, while in the rightmost panel the filtering only keeps the smallest angular scales. These filtered maps correspond to three different regimes in the angular power spectrum $D_\ell = \ell(\ell+1)/(2\pi)C_\ell$ (upper right panel), which are governed by different physical processes.

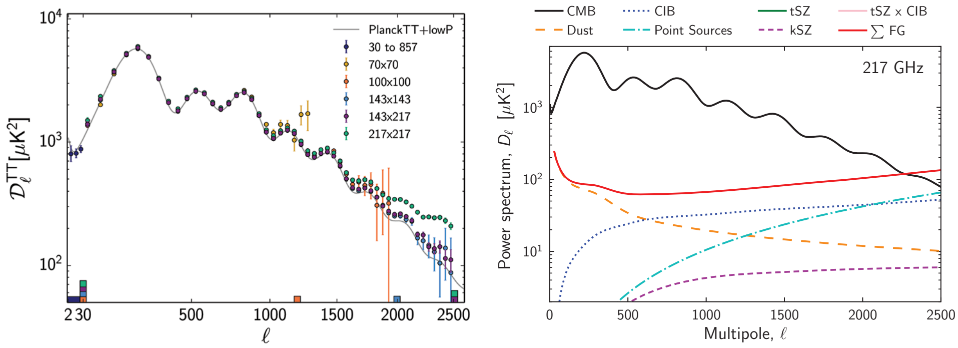

Fig. 2. – Left panel: Planck angular power spectra not corrected for foregrounds. The coloured squares on the x-axis indicate the data selection, in terms of ℓ-range, included in the Planck likelihood [11]. The grey solid line indicates the best-fit theoretical ΛCDM spectrum. Right panel: small-scale foreground (FG) templates at 217 GHz, compared to the CMB best-fit theoretical spectrum. Note that at this frequency the tSZ effect described in the text is null.

Also the polarization field can be described in terms of angular power spectra. Because linear polarization is identified by both an amplitude and an orientation, it can in turn be decomposed into two coordinate-independent quantities with different dependence on cosmology [9]. In this paper we focus on the curl-free component, the so-called E mode, which is determined by almost the same physics as the temperature. The E mode is also taken to be an isotropic Gaussian random field and it is correlated with the temperature. Thus, we expect to be able to measure C_ℓ^{EE} and C_ℓ^{TE} power spectra.

2˙3. *Small-scale foreground modeling.* – The empirical temperature angular power spectra estimated from Planck data are shown in fig. 2. While the CMB power spectrum is uniquely determined by the underlying cosmological model and its parameters, it is evident how spectra at different frequencies are affected by distinct amounts of foreground contamination. Thus, in order to reliably estimate the cosmology, we need to provide an accurate statistical description of all the known uncertainties, both instrumental and astrophysical in nature, associated to the empirical spectra. This is done by means of the Planck CMB likelihood function [10, 11], which I will not describe here. However, I wanted to draw the reader's attention on how this task requires a deep interconnection with astrophysics. In particular, at small angular scales, the strongest foregrounds that are detected in the maps, both in the form of diffuse emission and compact extragalactic objects, are actually masked before estimating the spectra. Therefore, when fitting for the parameters of the cosmological model, we use the likelihood function to also marginalise over physically motivated templates of the *residual* foregrounds. These account for: diffuse emission from dust that resides in our own Galaxy; shot noise from unresolved galaxies; the cosmic infrared background (CIB), *i.e.* emission from high-redshift dusty star forming galaxies that trace the large-scale structure of the universe; the thermal (tSZ) and kinetic (kSZ) Sunyaev-Zel'dovich effect from re-scattering of CMB photons off the hot gas in galaxy clusters; the correlation between the tSZ and CIB sources ($\mathrm{tSZ} \times \mathrm{CIB}$) expected to arise because both signals trace the large scale structures in the universe. Examples of these templates fitted at the 217 GHz channel are shown in fig. 2. Once the foreground models are fitted and subtracted from the data, the CMB angular power spectra estimated at different frequencies agree with each other with high accuracy.

3. – The ΛCDM: A successful model

3˙1. *Cosmological parameters from temperature and polarization anisotropies.* – According to the standard model of cosmology, we live in a spatially flat, expanding Universe, whose dynamics are governed by General Relativity and whose constituents are cold dark matter, a cosmological constant Λ, baryons and radiation (photons plus three neutrino species). The primordial seeds of cosmic structures are Gaussian-distributed fluctuations with an almost scale-invariant spectrum generated by inflation, $P(k) = A_s(k/k_0)^{n_s-1}$, where we choose $k_0 = 0.05\,\mathrm{Mpc}^{-1}$. Such a model is fully described by six parameters, given in table I, most of which we have determined with Planck at better than percent precision [12], improving on previous constraints by a factor 1.5–2 [13].

After fitting for foreground and cosmological parameters, we derive the maximum likelihood temperature power spectrum estimated from Planck temperature data shown in fig. 3. This spectrum is cosmic variance limited up to $\ell = 1600$ and it has been estimated over a large fraction of the sky, ranging from 40 to 93%. This means that no

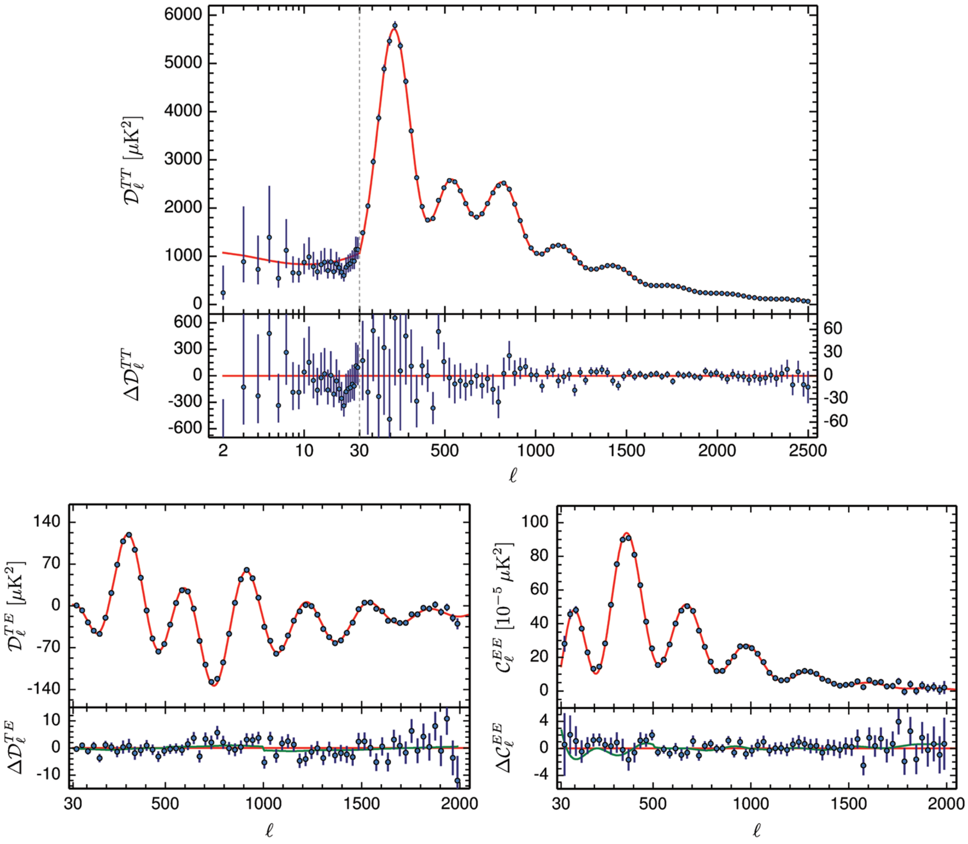

Fig. 3. – Top: maximum likelihood frequency-averaged temperature power spectrum. The solid red line is the best-fit base ΛCDM theoretical spectrum fitted to the Planck TT+lowP dataset (table I). Residuals with respect to this model are shown in the lower panel. Bottom: maximum likelihood frequency-averaged TE and EE polarization power spectra. The solid red line is the best-fit theoretical model from temperature data. Residuals with respect to this theoretical model are shown in the lower panel in each plot. The green lines in the lower panels indicate the temperature-to-polarization leakage model, showing how contributions from residual systematic errors are expected to be at a low level, only few $(\mu\mathrm{K})^2$.

other experiment can do better in this range of angular scales, as the measurement is not limited by the instrument capabilities. This power spectrum measurement is therefore the best one can have for cosmological parameters studies. We find it to be an excellent fit to the ΛCDM model, with an associated $\chi^2 = 2545$ for 2479 degrees of freedom, which corresponds to a probability to exceed of 17%.

The ΛCDM is a highly predictive model. Given the cosmological parameters obtained from temperature data, one can predict the theoretical angular power spectra in polarization, as shown in fig. 3. We find that polarization power spectra measured by Planck are in very good agreement with expectations. Moreover, polarization data are accurate enough to allow for an independent determination of the cosmological parameters, which we find to be in good agreement with the temperature. A joint analysis of temperature and polarization allows to tighten the overall constraints as reported in table I.

CMB measurements are also quite powerful in constraining extensions to the base

Table I. – *Base ΛCDM cosmology parameters constraints (68% CL). The baseline data combination uses Planck temperature data (TT) and polarization at large angular scales (lowP). The extended analysis includes also polarization data at small angular scales (TE, EE)* [12].

Parameter	Definition	TT+lowP	TT, TE, EE+lowP
$\Omega_b h^2$	baryon density today	0.02222 ± 0.00023	0.02225 ± 0.00016
$\Omega_c h^2$	cold dark matter density today	0.1197 ± 0.0022	0.1198 ± 0.0015
$100\,\theta_*$	sound horizon at recombination	1.04105 ± 0.00046	1.04096 ± 0.00032
n_s	scalar perturbations spectral index	0.9655 ± 0.0062	0.9645 ± 0.0049
τ	optical depth due to reionization	0.078 ± 0.019	0.079 ± 0.017
$\ln(10^{10} A_s)$	density perturbations log power	3.089 ± 0.036	3.094 ± 0.034

Table II. – *Constraints on extensions to the ΛCDM model (95% CL). The* `Baseline` *data combination includes Planck temperature with measurements of the polarization at large angular scales, whereas* `ext` *refers to Supernovae Ia and BAO data, as described in the text* [12].

Parameter	Definition	$\texttt{Baseline}$	$\texttt{Baseline} + \texttt{lensing} + \texttt{ext}$
Ω_k	curvature parameter today	$-0.052^{+0.049}_{-0.055}$	$-0.0001^{+0.0054}_{-0.0052}$
Y_P	helium abundance	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.035}_{-0.036}$
$\mathrm{d}n_s/\mathrm{dln}k$	running of the spectral index	-0.008 ± 0.016	$-0.003^{+0.015}_{-0.014}$
w	dark energy equation of state	$-1.54^{+0.62}_{-0.50}$	$-1.006^{+0.085}_{-0.091}$
$\sum m_\nu$	sum of neutrino masses	$< 0.715\,\mathrm{eV}$	$< 0.234\,\mathrm{eV}$
N_{eff}	number of relativistic species	$3.13^{+0.64}_{-0.63}$	$3.15^{+0.41}_{-0.40}$

ΛCDM model. As evident from table II, we find that Planck data do not favour an extended model. This conclusion is even reinforced when we combine Planck to other cosmological datasets, such as to Baryonic Acoustic Oscillations (BAO), Type-Ia supernovae (from the Joint Light-curve Analysis compilation) and the current direct Hubble constant estimate [12]. Specifically, estimates of the helium abundance are in agreement with Big Bang Nucleosynthesis predictions. The dark energy equation of state is compatible with a cosmological constant ($w = -1$). Moreover, there is no indication of extra relativistic degrees of freedom other than the three neutrino species.

3·2. *Gravitational lensing.* – As CMB photons propagate freely across the universe from the last scattering surface, the gravitational tug of the intervening large scale structure distorts their paths. This effect, known as gravitational lensing, induces deflections on characteristic scales of about two arcminutes, which are however coherent over two degrees wide regions. For example, in propagating through a large overdense clump of matter on the line of sight, CMB anisotropies get magnified appearing bigger on the sky. This is a subtle effect, but it may be measured statistically with high angular resolution, low-noise observations of the CMB anisotropy field, like those collected by Planck [14].

First of all, lensing has an impact on the CMB temperature angular power spectrum, specifically it smooths its peaks and troughs. This tiny effect has been detected at the $10\,\sigma$ level with Planck. Secondly, the deflections induce a distinctive non-Gaussianity in the distribution of the anisotropies that can be used to reconstruct the integrated mass

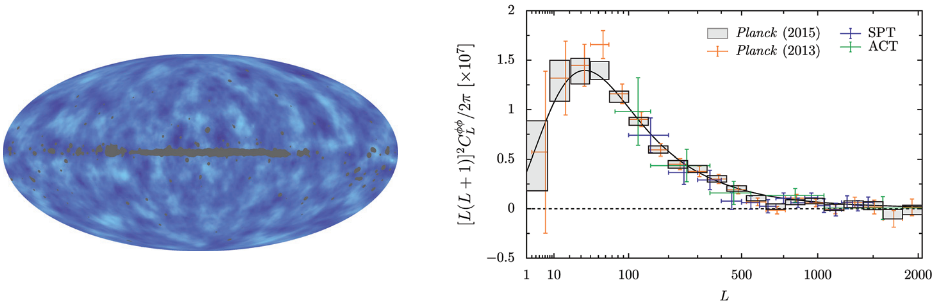

Fig. 4. – Left: map of the lensing potential estimated from Planck 2015 data. Right: angular power spectrum of the lensing potential from Planck data, compared to estimates from the South Pole Telescope and the Atacama Cosmology Telescope [14]. The black solid line is the fiducial ΛCDM theory power spectrum based on parameters from the temperature analysis.

distribution across the sky back to the last-scattering surface and its associated gravitational potential. Planck data allow to constrain the amplitude of the gravitational potential power spectrum to 2.5% precision. In fig. 4 we show both the reconstructed gravitational potential map and its angular power spectrum, where the black solid line is not a fit to the data but a prediction of the model given the cosmological parameters derived from the temperature power spectrum analysis of sect. **3**˙1. The excellent agreement between data and predictions is a powerful test of the ΛCDM model, because it tells us that the clustering of matter at redshift $z = 2$, where CMB lensing is most efficient, is consistent with that predicted from the statistics of the CMB fluctuations at $z = 1100$.

Because of its sensitivity to the late-time evolution of the universe, gravitational lensing provides a cosmological probe complementary to CMB. It helps breaking degeneracies and improving cosmological constraints, in particular for the quantities most affected by the large-scale structure evolution, such as the amplitude of matter fluctuations, the dark energy parameters, and the neutrino masses. Also, given the consistency with ΛCDM, lensing measurements constrain some extensions tightly, most notably the curvature of space time (Ω_k). Passing from the CMB power spectra constraint, to the joint constraint, the improvement in error bar is dramatic, providing a remarkable measurement of curvature from the CMB alone at sub-percent precision,

$$\begin{aligned} \Omega_\mathrm{k} &= -0.052^{+0.03}_{-0.02} \quad (\mathrm{PlanckTT} + \mathrm{lowP}, 68\%\ \mathrm{CL}) \\ \Omega_\mathrm{k} &= -0.005^{+0.009}_{-0.007} \quad (\mathrm{PlanckTT} + \mathrm{lowP} + \mathrm{lensing}, 68\%\ \mathrm{CL}). \end{aligned} \tag{1}$$

4. – Final remarks

This paper provides a short overview of some key cosmological results from the Planck mission. I highlighted in which sense Planck provided the *ultimate* measurement of the CMB temperature anisotropy field, and how we used that to perform stringent tests of the cosmological model. We estimated the parameters of the model with an unprecedented, in most cases sub-percent, precision. Thanks to the high quality of the measurements also the science related to secondary effects, like the gravitational lensing of the CMB radiation, has flourished. Moreover, first results from polarization have already been pioneering in providing an independent check of the cosmological model. It is worth noticing that an improved characterization of the polarization measurements is among the main features of the new version of the data, which was released to the public by the Planck Collaboration in July 2018. This constitutes the final, so-called "legacy", release from Planck, and it is not discussed in this paper. With the standard six-parameter model of cosmology as a foundation, we are now using the CMB to explore new elements of the theory. Interesting tests of fundamental physics have been possible, which are already complementary and competitive to those attainable in laboratories, *e.g.* for what concerns the characterization of the neutrino sector.

Overall, our results show that the Inflationary Standard Model of Cosmology is very successful in explaining Planck temperature, polarization and gravitational lensing data. Furthermore, it is worth stressing that, besides being internally consistent, Planck results are also in agreement with those from other CMB experiments, BAO and Type Ia SN data, and with Big Bang Nucleosynthesis predictions. These conclusions pose a challenge to forthcoming cosmological observations and bring even into sharper focus the fundamental theoretical issues that the model poses and that are still awaiting a solution.

Although not discussed in this paper, it is interesting to mention that Planck measurements of the present universe expansion rate and the amplitude of linear matter fluctuations have been found to be in tension with those derived by some low redshift probes, *e.g.* [15, 16]. The causes of these tensions are still debated and will be the subject of intense investigation over the coming years. Mainly because if they are not due to flukes in the observations, they might hint to an inconsistency in the otherwise very successful standard ΛCDM model.

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