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Cosmology with the Cosmic Microwave Background: Latest Results from the PLANCK satellite and the QUIJOTE experiment.

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Abstract

This talk presents an overview of the recent results derived from the observations of the ESA's Planck mission and the QUIJOTE experiment. The Planck 2018 cosmological results correspond to the third (and final) data release from the Planck collaboration. Several improvements in the calibration, the treatment of the polarization data and systematic effects lead to more robust constraints on many parameters. As in previous releases, the base six-parameter ΛCDM model provides an excellent description to the data. I briefly discuss some parameter extensions and the remaining tensions in the data. I also review the current status and first results of the QUIJOTE (Q-U-I JOint TEnerife) experiment, a project with the aim of characterizing the CMB polarization and other Galactic or extra-galactic physical processes that emit in microwaves in the frequency range 10–42 GHz, and at large angular scales (around one degree resolution).

1 Introduction

The study of the anisotropies of the Cosmic Microwave Background (CMB) is one of the most powerful tools in modern cosmology, and has played a crucial role in building our current understanding of the Universe. Here I will review the latest results of two experiments in which the Spanish CMB community has been involved: the ESA's *Planck*[1] satellite and the QUIJOTE experiment[2].

[1] *Planck* is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states (in particular the lead countries France and Italy), with contributions from NASA (USA), and telescope reflectors provided by a collaboration between ESA and a scientific consortium led and funded by Denmark.

[2] QUIJOTE web page: http://www.iac.es/proyecto/cmb/quijote

Planck [31, 12] was a third generation space mission dedicated to measure the CMB temperature and polarization anisotropies over the whole sky with a sensitivity limited by cosmic variance and the ability to remove the astrophysical foregrounds. The satellite was launched in May 2009, and operated without interruptions over three times the initially planned mission duration until October 2013, with a performance exceeding expectations. It observed the microwave sky in 9 frequency bands from 30 to 857 GHz, and with angular resolutions from 5' to 30'. Sect. 2 summarizes the main results of the *Planck* 2018 data release.

The *QUIJOTE* (Q-U-I JOint TEnerife) Experiment is a collaboration between the Instituto de Astrofísica de Canarias, the Instituto de Física de Cantabria, the universities of Cantabria, Manchester and Cambridge (UK), and the IDOM company (Spain). It started operations in November 2012, and consists of two telescopes and three instruments [29, 30] dedicated to measure the polarization of the microwave sky in the frequency range 10–40 GHz, and with angular resolutions from 55' to 16'. Sect. 3 reviews the project status, including the low-frequency maps (10–20 GHz) that will be released in the coming months.

2 Overview of *Planck* 2018 cosmology results

The *Planck* mission had two instruments, with technological performances never achieved in space before. The *Low Frequency Instrument* (LFI) [10, 1, 11] covered three bands at 30, 44 and 70 GHz using low-noise heterodyne amplifiers cooled down to 20 K. The *High Frequency Instrument* (HFI) [8, 13] covered six bands at 100, 143, 217, 353, 545 and 857 GHz with bolometers cooled to 0.1 K. Polarization measurements were obtained in all but the highest two frequency bands [9, 28]. Two data processing centers (DPCs) analyzed and calibrated the data, and made the nine frequency maps of the sky [32, 14].

The scientific results of the mission were presented in various sets of papers and three data releases. The nominal mission data release (PR1) took place in 2013, and the associated results were part of the A&A special issue Vol. 517 [15]. The extended mission data release (PR2) occurred in 2015, and the associated set of papers are part of the A&A special issue Vol. 594 [18]. The third legacy data release (PR3) took place in July 17th, 2018. It contained the series of papers corresponding to the final analysis of the full mission done by the Planck collaboration. Here, I summarize the main results presented in those papers [20, 21, 22, 23, 24, 25, 26, 27]. All the Planck Collaboration papers can be downloaded from here. All the *Planck* data can be downloaded via the Planck Legacy Archive.

An overview of the main 2018 results, as well as the cosmological legacy of *Planck* is given in [20]. The data processing pipelines and calibration procedures used for both instruments LFI and HFI are described in [21] and [22], respectively. For the LFI, several improvements have been made with respect to previous releases, especially in the calibration process and in the correction of instrumental features such as the effects of nonlinearities in the response of the analogue-to-digital converters. For the HFI, major improvements in the map-making, the calibration process and in the treatment of the polarization data and systematic effects have been achieved since the previous 2015 release. An extensive series of

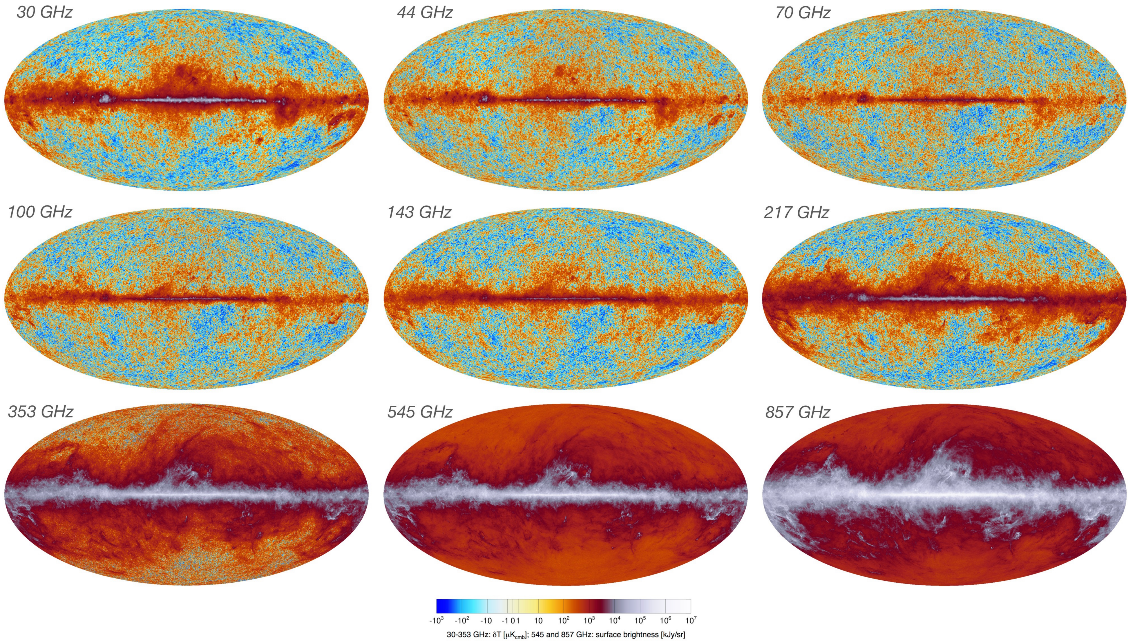

Figure 1: Total intensity emission in each of the nine *Planck* 2018 frequency bands, after removal of a common dipole component. The first seven maps are expressed in equivalent CMB temperature units, while the two highest frequencies, monitoring the dust emission, are expressed in brightness units. Courtesy of ESA and the Planck Collaboration, taken from [20].

null tests dedicated to check the consistency of the maps is also provided [21, 22].

Fig. 1 and 2 show the sky as seen by *Planck* in intensity and polarization, respectively. Each panel in Fig. 1 represents one of the nine Planck's frequency channels, displayed in Galactic coordinates. Similarly, Fig. 2 shows the linear polarization maps (Stokes Q and U parameters) measured by Planck at its lowest seven frequency channels.

2.1 CMB maps and power spectra

As in previous *Planck* data releases, four different component separation methods were used and optimized to produce CMB maps based on *Planck* data alone (Commander, NILC, SEVEM, and SMICA). Those CMB maps and accompanying simulations are the basic input for all analyses of homogeneity, stationarity, and Gaussianity of the CMB fields [25]. Figure 3 shows the intensity map obtained with the SMICA method (left panel), and also the polarization field smoothed on scales of 5°. In addition to the CMB component separation, three methods (Commander, GNILC, and SMICA) were used to extract astrophysical components, i.e. foregrounds. The component separation methodology is described in detail in [23].

The foreground-subtracted, frequency-averaged, cross-half-mission intensity (TT) and

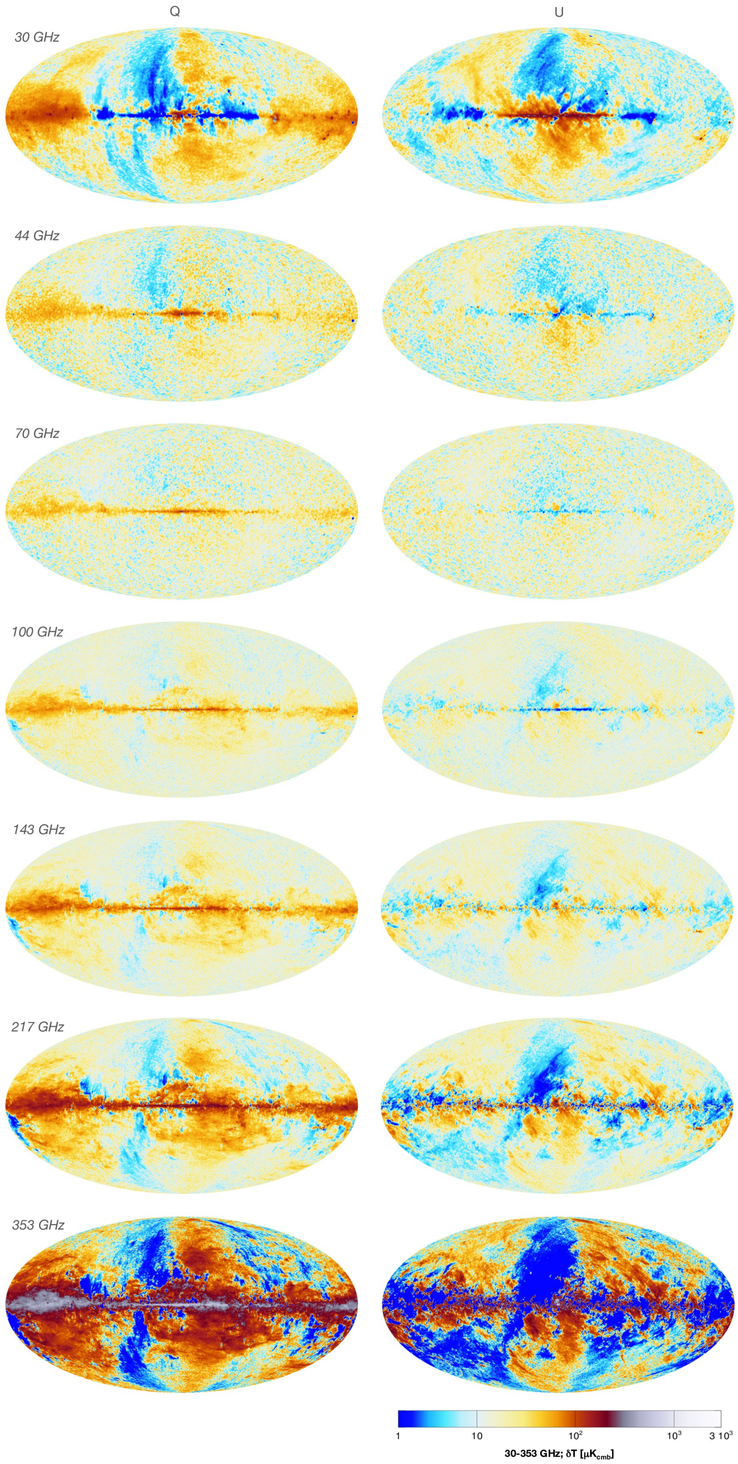

Figure 2: The seven sky polarization maps of Planck 2018. The first two columns show the Q and U Stokes parameters measuring linear polarization, and the last column presents the polarized intensity, $P = \sqrt{Q^2 + U^2}$. Courtesy of ESA and the Planck Collaboration, taken from [20].

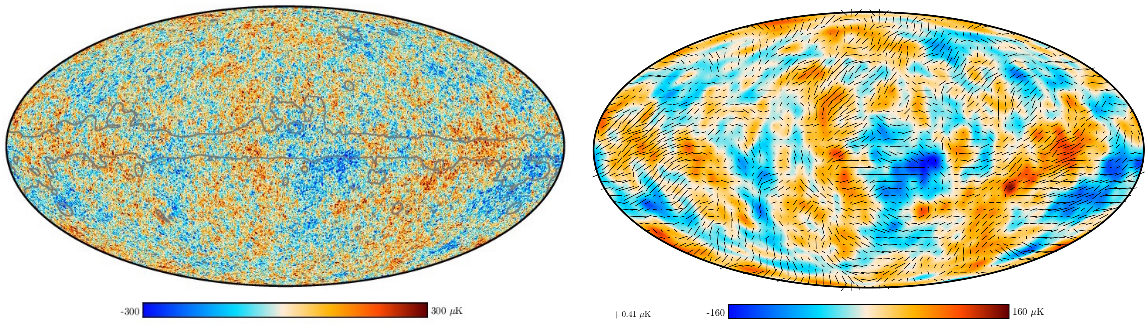

Figure 3: CMB maps obtained with the *Planck* 2018 data release. Left panel: reconstructed SMICA temperature map. Right panel: linear polarization field represented as rods of varying length, superimposed on the temperature map, when both are smoothed at 5° scales. Both CMB maps have been masked and inpainted in regions where residuals from foreground emission are significant. That mask is delineated by a grey line in the left figure, and covers mostly the Galactic plane. Courtesy of ESA and the Planck Collaboration, taken from [20].

polarization (TE and EE) spectra are plotted in Fig. 4, together with the Commander power spectrum at multipoles $\ell < 30$. The blue-line in the figure shows the best-fit base-ΛCDM theoretical spectrum fitted to the combination of temperature, polarization and lensing data. The intensity TT spectrum (top panel) constitutes an extremely precise measurement over three decades in multipole range, allowing to characterize seven acoustic peaks in detail. The uncertainties of that plot are dominated by sampling variance, rather than by instrumental noise or foreground residuals, at all scales below multipole $\ell = 1800$. The polarization power spectra (TE and EE) have improved significantly with respect to previous releases at low multipoles, thanks to the inclusion of the HFI low-ℓ data. The measured TE spectrum has about the same constraining power (in terms of final error bars on the cosmological parameters) as the TT one, while the EE spectrum still has a sizeable contribution from noise. Moreover, the excellent agreement of the TE and EE polarization spectra with the prediction of the ΛCDM theoretical spectrum fitted to the temperature data only constitutes one of the most important consistency tests for the cosmological model.

The bottom-right panel in Fig. 4 shows the power spectrum of the lensing potential. On small angular scales, the primordial CMB anisotropies are distorted by gravitational lensing, primarily sourced by the large-scale structure of the Universe at relatively high redshifts (peaking at $z \sim 2$). The 2018 result represents the highest signal-to-noise ratio detection of CMB lensing to date, exceeding 40σ [25] using intensity and polarization, and with a polarization lensing detection at 9σ. The inclusion of this information in the cosmological analyses breaks some parameter degeneracies inherent to the CMB anisotropies alone.

2.2 *Planck* 2018 Cosmological Parameters

As in the two previous data releases, the *Planck* 2018 measurements of the CMB anisotropies and lensing-potential power spectra are very well described by a standard spatially-flat six

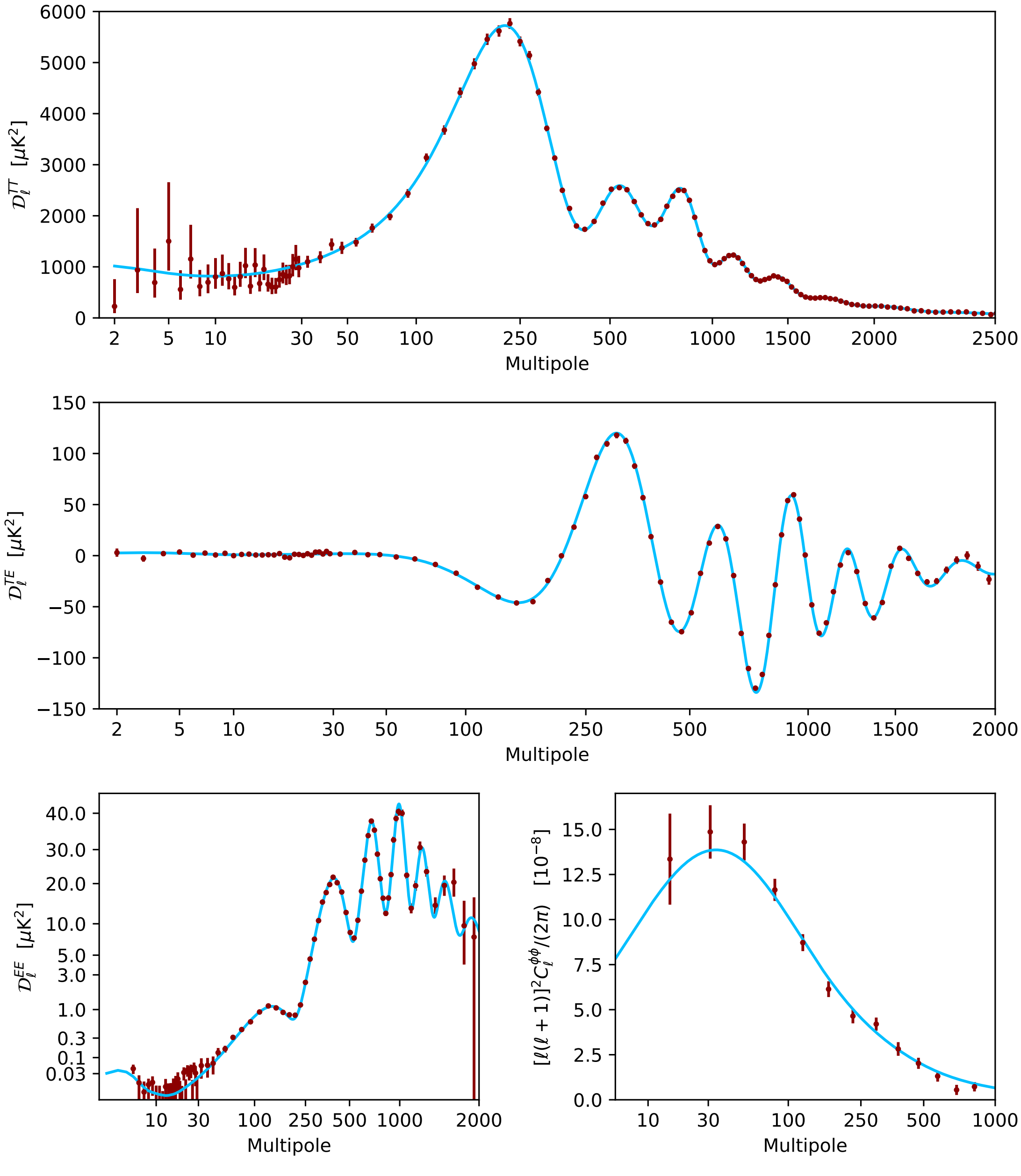

Figure 4: Planck 2018 CMB power spectra. These are foreground-subtracted, frequency-averaged, cross-half-mission angular power spectra for temperature (top), the temperature-polarization cross-spectrum (middle), the E mode of polarization (bottom left) and the lensing potential (bottom right). The blue lines show the best-fitting ΛCDM model. Courtesy of ESA and the Planck Collaboration, taken from [20].

Table 1: Parameter confidence limits derived from the *Planck* CMB temperature, polarization and lensing power spectra, and with the inclusion of BAO data. Error bars in all cases correspond to 68 % confidence limits. The first set of values corresponds to the six base ΛCDM parameters. The remaining parameters shown below the line are derived from those six. More details can be found in [24].

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_{\rm b}h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_{\rm c}h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{\rm MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10}A_{\rm S})$	3.044 ± 0.014	3.047 ± 0.014
$n_{\rm S}$	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 (km s^{-1} Mpc^{-1})	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
$\Omega_{\rm M}$	0.3153 ± 0.0073	0.3111 ± 0.0056
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060

parameter ΛCDM model with adiabatic scalar perturbations [24]. This consistency helds either fitting all the power spectra separately or in combination. The derived values for the six parameters of this base model, together with some derived parameters, are summarized in Table 1. Except for the reionization optical depth, the other five base parameters are measured with sub-percent accuracy. In particular, the CDM component is measured at 100σ, the angular acoustic scale to 0.03 % precision, and $n_{\rm S}$ is found to be 8σ away from scale invariance ($n_{\rm S} = 1$).

All parameters remained quite consistent across the different analyses (2013, 2015, 2018) [16, 19, 24]. Compared to the 2015 results [19], the improved measurements of the large-scale polarization allow the reionization optical depth to be measured with higher precision, which in turn leads to a better precision for other correlated parameters. Moreover, the improved modeling of the small-scale polarization also leads to more robust constraints on many parameters, with residual modeling uncertainties estimated to affect them only at the 0.5σ level.

2.3 Cosmological parameters: beyond the base model

As in previous releases, several one-parameter extensions to the base (six-parameter) model have been explored [24]. However, the main conclusion of those analyses is that we do not find any compelling evidence for any of the considered extensions. For example, when considering spatial curvature, the joint constraints with baryon acoustic oscillation (BAO) measurements provides consistency with a flat universe, finding $\Omega_{\rm K} = 0.0007 \pm 0.0019$. There is no evidence for additional relativistic degrees of freedom, beyond the Standard Model prediction ($N_{\rm eff} = 3.046$). When combining *Planck* 2018 with BAO, we find $N_{\rm eff} = 2.99 \pm 0.17$.

In the neutrino sector, we find that sum of the neutrino masses is tightly constrained to $\Sigma m_\nu < 0.12\,\mathrm{eV}$, again in combination with BAO measurements. In addition, we find no evidence for dynamical dark energy; combining with Type Ia supernovae (SNe), the dark-energy equation of state parameter is measured to be $w_0 = -1.03 \pm 0.03$, consistent with a cosmological constant. Finally, we find no evidence for deviations from a purely power-law primordial spectrum, and combining with data from BAO, BICEP2, and Keck Array data, we place a limit on the tensor-to-scalar ratio of $r_{0.002} < 0.07$.

2.4 Tensions

The *Planck* base-ΛCDM parameters shown in Table 1 are in good agreement with BAO, SNe, standard big-bang nucleosynthesis predictions for the helium and deuterium abundances, and with some galaxy lensing observations. However, they are in slight tension with the Dark Energy Survey's combined-probe results including galaxy clustering (which prefers lower fluctuation amplitudes or matter density parameters), with the cluster number counts and the Sunyaev-Zeldovich Comptonization maps (although the lower value of τ slightly alleviates the tension) [17], and in significant tension with local measurements of the Hubble constant (which prefer a higher value) [24]. Simple model extensions that could in principle partially resolve those tensions are not favored by the data. As in previous releases, the CMB spectra continue to prefer higher lensing amplitudes than predicted in base ΛCDM at over 2σ. However, this is not supported by the lensing reconstruction or the BAO data.

2.5 The legacy of *Planck*

Planck has measured the properties of our Universe to percent-level fidelity, and has been used to test our understanding of the cosmological model to high precision. Here there is a list of topics in which the mission has provided an important legacy: it gave the most precise picture of the universe (6-parameter ΛCDM model); the best characterization of the isotropy and statistics of the CMB anisotropies; the most stringent constraints on inflation physics and primordial non-Gaussianity; constraints on fundamental physics (including neutrino physics, dark energy, modified gravity and primordial magnetic fields); a map of the lensing potential; very rich SZ science (including two catalogs of galaxy clusters with 1653 detections, a full sky SZ map, and the detection of peculiar velocities); a measurement of the ISW effect; maps of the CIB; important studies of extra-galactic sources, both in radio (quasars and radio galaxies) and infrared (dusty star-forming galaxies); a detailed information on the space-frequency distribution of the diffuse Galactic components (synchrotron, free-free, thermal dust, spinning dust emission, magnetic field,…); galactic sources (cold cores, HII regions and young star-forming regions); and the best determination of the Solar Dipole.

3 The *QUIJOTE* experiment

The theoretical framework where we can accommodate all these cosmological results is the ΛCDM cosmology together with inflation, a period of accelerated expansion at the early in-

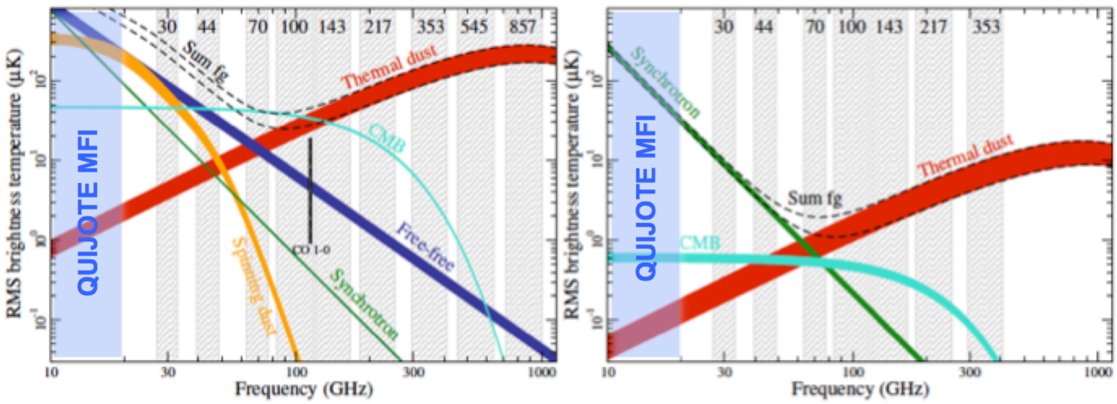

Figure 5: Estimated frequency dependence of the different astrophysical foregrounds in the microwave domain, both in intensity (left) and polarization (right panel). The figure on the right assumes no polarization for the AME. The locations of the *Planck* and *QUIJOTE-MFI* frequency bands are indicated using grey and blue bands, respectively. Adapted from [18].

stants after the Big-Bang. All basic inflationary predictions have been confirmed by *Planck* (i.e. a spatially flat Universe, with nearly scale-invariant spectrum of density perturbations, which is almost a power-law, dominated by adiabatic Gaussian scalar perturbations). However, there is still an inflationary prediction not yet verified. According to the inflationary paradigm, quantum fluctuations in the space-time metric created a background of gravitational waves that imprinted a unique signature on the polarization maps of the CMB: B-modes at large angular scales.

The main scientific driver of *QUIJOTE* is to carry out observations of the CMB polarization, to constrain the primordial B-mode signal down to the level of $r = 0.05$. In addition, another important goal is to characterize the low-frequency polarized foregrounds. One of the main legacy results of *Planck* is the demonstration that foreground signals, and in particular, the polarized emission from our galaxy, will be a major limiting factor of the possible constraints on the existence of B-modes. In this context, the *QUIJOTE* maps in the 10–20 GHz band provide a complementary window to the *Planck* data, bringing valuable information in an almost unexplored frequency domain (see Fig. 5), and providing the essential information to properly correct for the Galactic synchrotron and the anomalous microwave emissions (AME). This legacy information from *QUIJOTE* will be essential for future sub-orbital or satellite experiments.

The *QUIJOTE* project has two phases. In the first phase, we installed the first QUIJOTE telescope unit (QT1) together with the multi-frequency instrument (MFI) [6] at the Teide Observatory. The MFI covers four frequency bands at 11, 13, 17 and 19 GHz, and started operations in November 2012. The second phase includes a second QUIJOTE telescope (QT2) installed in July 2014, and two additional instruments. The thirty-gigahertz instrument (TGI) consists of 31 receivers at 30 GHz [7], while the forty-gigahertz instrument (FGI) has also 31 receivers at 42 GHz. At this moment, we are in the commissioning phase of a hybrid-instrument covering 30 and 42 GHz simultaneously, with half TGI receivers and the other half with FGI ones, but sharing the same cryostat. More information on the *QUIJOTE* instruments and telescopes can be found in [30] and references therein.

3.1 *QUIJOTE-MFI* preliminary results: the wide survey

The *QUIJOTE-MFI* instrument has been operating for almost six years. After this period, we have accumulated $\sim 24,000$ h of data, corresponding to approximately 50 % observing efficiency. As described in [30], the observations carried out with the MFI are of two types: either deep integrations using a raster scan mode at constant elevation in selected sky areas (e.g. Galactic regions, calibrators or cosmological fields), or a wide survey mode using continuous 360° azimuth scans at constant elevation.

Scientific results have been presented for some of the deep observations in a few Galactic regions, as the Perseus molecular complex [4], the W43, W44 and W47 area [5], or the Taurus molecular complex. Here, I discuss the status of the MFI wide Galactic survey, that will be published soon. This wide survey covers around 20,000 deg^2 every day, aiming for a final aggregated sensitivity of $\sim 30\,\mu$K/deg in polarization (Stokes Q and U maps) in the four MFI bands. To date, we have accumulated around 10,000 h of data in this so-called "nominal mode". The preliminary maps have sensitivities around 40–55 μK/deg.

Figure 6 shows the status of the maps for the two lowest MFI frequency bands (11 and 13 GHz). The polarization maps have sensitivities of around 50–55 μK/deg, and provide a high signal-to-noise detection of the polarized synchrotron emission at these frequencies, including the diffuse emission in North-Polar Spur or the Fan regions. The *QUIJOTE* maps are now being used to constrain the spectral behavior of the polarized synchrotron emission, in combination with the WMAP and *Planck* frequency bands. Our preliminary results provide a synchrotron spectral index with an average value of $\beta_{\mathrm{s}} = -3.00 \pm 0.05$, and with an average synchrotron-dust correlation of $\sim 20\,\%$ at large scales, but with significant spatial variations in those properties. Other studies based on these *QUIJOTE* maps, as component separation analyses, the study of multiple AME regions, the characterization of radio-sources in the maps, or the diffuse emission in the north polar spur and the Fan region are in preparation, and will be presented in the coming months.

These analyses are partially funded by the RADIOFOREGROUNDS[3] project (2016-2018), a H2020-COMPET-2015 program aiming to provide the best possible description of the synchrotron emission and AME in our Galaxy in the Northern sky, by adding the information contained in the *QUIJOTE-MFI* frequencies to the *Planck* maps. The associated data products will be made publicly available at the end of the project.

3.2 Future plans

The commissioning phase of the combined TGI/FGI instruments is now taking place. The observing plan is to conduct a cosmological survey during 3 effective years, and to combine

[3] RADIOFOREGROUNDS web: http://www.radioforegrounds.eu.

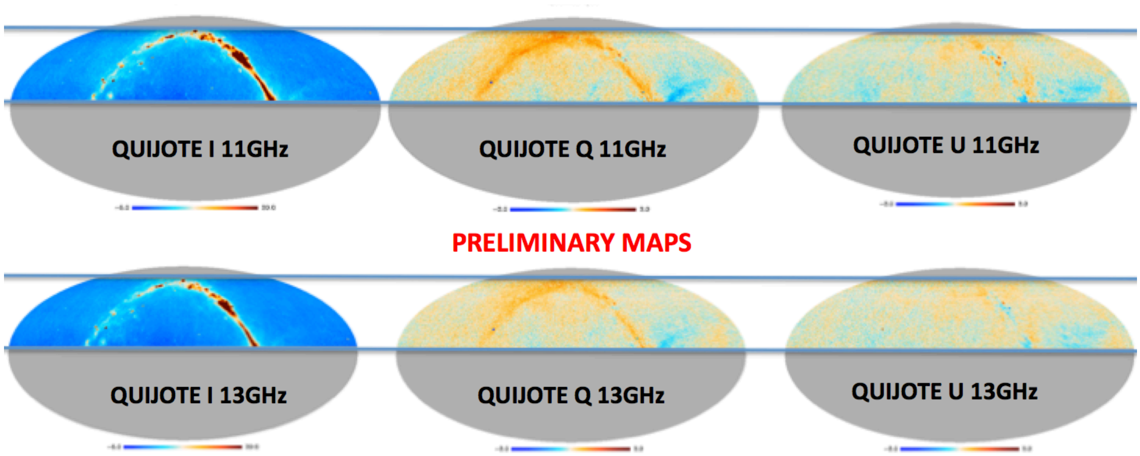

Figure 6: Preliminary maps of the *QUIJOTE-MFI* wide survey, displayed in equatorial coordinates. We show the 11 GHz (first row) and 13 GHz (second row) maps for Stokes I (left), Q (center) and U (right) parameters. The horizontal lines define the declination band between $\delta = 5°$ and $\delta = 80°$. We note that the Stokes Q and U parameters are referred to the Galactic coordinate system, although they are displayed in equatorial coordinates.

these data with the MFI maps. In addition to *QUIJOTE*, two new CMB polarization experiments will be installed soon at the Teide Observatory (Tenerife): Groundbird and STRIP. GroundBird [2] is a MKIDs array to study the CMB polarization in two bands centered at 145 and 220 GHz. It is a collaboration formed by RIKEN, KEK, NAOJ, and Saitama, Kyoto and Tohoku universities in Japan, the Korea University and the IAC. The installation is planned for early 2019. STRIP [3] is part of LSPE, a combined program of ground-based and balloon-borne polarization observations. STRIP will operate in the 42 and 90 GHz bands, and will be installed at the Teide Observatory in mid 2019. Altogether, *QUIJOTE*, STRIP and Groundbird will constitute an unique microwave polarization observatory in the Northern hemisphere, with ten frequency bands covering from 10 to 240 GHz.

Acknowledgments

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