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Status of Cosmic Microwave Background Observations for the Search of Primordial Gravitational Waves

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Abstract: The cosmic microwave background (CMB) is one of the most powerful tools for cosmology. Its polarization could have imprinted the sign of an inflationary background of gravitational waves, which is supposed to have originated at $10^{-38}/10^{-35}$ seconds after the Big Bang. Detecting this background is extremely difficult because of the weakness of the signal (if any) left on the CMB polarization and because of the need to control the systematic effects. Additionally, the presence of astrophysical foregrounds, the possibility of leakage from curl-free to curl-like components, including gravitational lensing, and the instrumental noise and systematics, require sensitive detectors and smart systematic effect control. We discuss the experimental efforts spent in this field, highlighting the key observational difference and the choice that could lead, in the near future, to the detection of the curl component of the CMB polarization, a clear sign of the inflationary expansion.

Keywords: cosmic microwave background; polarization; gravitational waves; early universe

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1. Introduction

Cosmic inflation is a theory of exponential expansion of the universe invoked in the cosmological standard model to explain some paradoxes and odd coincidences in the way we see our universe. In addition, cosmic inflation makes firm predictions that all cosmologists would like to prove or confute. Inflation predicts a background of gravitational waves that could be detected using the cosmic microwave background (CMB) radiation as a giant antenna consisting of the CMB itself everywhere in the universe. Unfortunately, the amplitude of the gravitational waves' background, which is in turn responsible for polarization of the CMB, is only mildly predicted. The weakness of this prediction arises from the inflationary energy scale being possibly close to the GUT energy scale.

The CMB is in fact an ether of photons that permeates the universe. It can be considered as a relic of the early universe, as it mainly remained unchanged since its origin when the universe was only 380,000 years old, when radiation and matter decoupled. It was discovered in 1965 by Arno Penzias and Robert Wilson, two American physicists working at the Bell Laboratories, during tests and noise measurements on an antenna developed for radio-communications [1]. Penzias and Wilson found a temperature of 3.5 K higher than expected and assigned this excess to the CMB. They were awarded the Nobel prize for Physics in 1978 for this discovery. Curiously enough, the actual first measurement of the CMB was made earlier, in 1941, by the Canadian Andrew McKellar. He measured a temperature of 2.3 K using CN stellar absorption lines [2]. Apparently, McKellar made no connection to the CMB and the significance of this measurement was recognized only after the measurement of Penzias and Wilson.

Soon after its discovery, the study of the fine structures of the CMB was fully recognized to be among the most powerful tools for cosmology. The CMB frequency spectrum was clearly measured for the first time by the FIRAS experiment on board the COBE satellite [3]. This frequency spectrum contains information about the thermal history of the universe. The frequency spectrum is that of a perfect black body, better than one part in ten thousand, at a temperature of 2.72548 ± 0.00057 K [4]. The same COBE satellite actually discovered another feature of the CMB: tiny anisotropies imprinted in its map [5]. Since then, measurements of the CMB anisotropies and the power spectrum that describes their sky distribution have enormously improved until the recent full sky measurements made by the Planck satellite [6]; see, e.g., Figure 1.

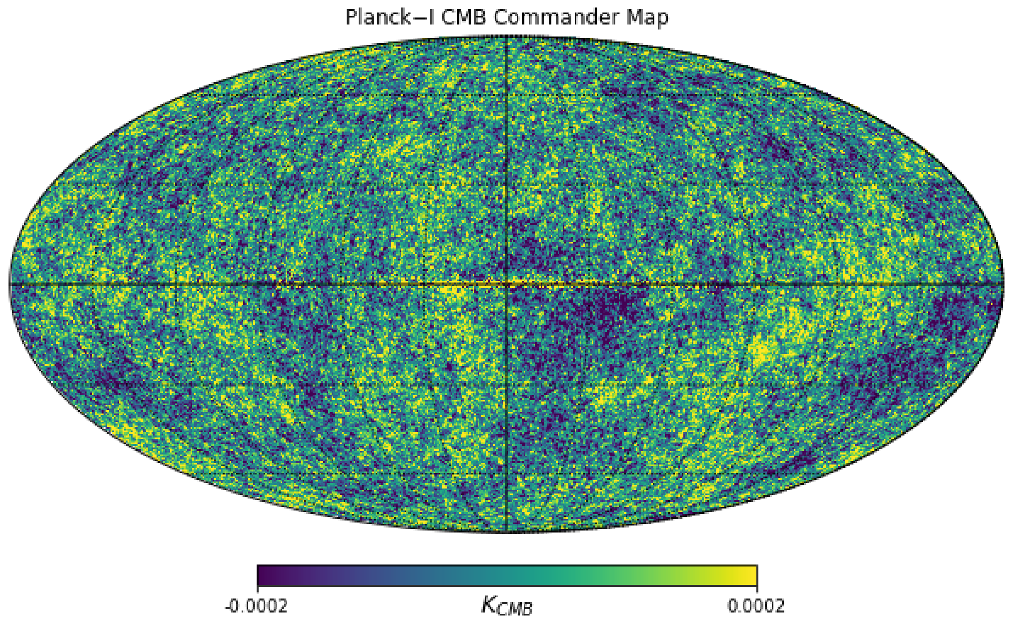

Figure 1. CMB anisotropies map obtained from the Planck satellite analyzed with the commander pipeline.

Another feature in the CMB maps is the presence of a tiny level of polarization. Because of the physics of acoustic oscillations that creates CMB anisotropies (scalar perturbations), a certain degree of polarization is expected, and observed, in the CMB maps [7]. This can be actually observed only if a local quadrupole moment is present in the primordial plasma. Because of the symmetry in the collapsing fluid, a level of polarization is expected to be spatially correlated with primary anisotropies, to have a curl-free polarization pattern with an even parity; these polarization patterns are called E-modes due to their similarity to electric fields, in opposition to the curl components (odd parity), which are called B-modes. B-modes are not expected to originate from the motion of the oscillating primordial fluid. However, a stochastic background of gravitational waves, because of their symmetry properties, could create the conditions in which B-mode polarization is created.

2. Inflation

Inflation [8–10] is a theory that was invoked to explain evidence in our universe, otherwise difficult to explain, such as the horizon problem, the absence of magnetic monopoles, and the apparent flatness in the geometry of the universe. Why does our universe consist of many very similar regions that were not causally connected among them? How can the universe be so uniform and its geometry very close to a flat geometry if this would be an unstable solution of the cosmological standard model? Inflation can explain these apparent paradoxes and can in principle be observed by means of the detection of the curl component of the polarization of the CMB, i.e., the B-modes, which originated from a stochastic background of gravitational waves (tensor perturbations) generated during the inflationary exponential expansion of the universe. The search for the signature of an inflationary expansion of the universe is in its very early stage. It is the next milestone in modern cosmology. Inflation should have occurred when the universe was only $\sim 10^{-33}$ s old and should have lasted $\sim 10^{-36}$ s [11]. Inflation is driven by a negative-pressure vacuum energy density. One of the most popular scalar fields responsible for inflation is a slow rolling scalar field that should, among the rest, create the quantum fluctuations at the origin of the scalar perturbations responsible for the primary CMB anisotropies. In other words, the Cosmological Standard Model is self-consistent but fails to explain what has happened at the quantum gravity energy at T > 10^{27} K or E > 10^{14} GeV when the universe was $\sim 10^{-33}$ s old [10].

The energy scale (the potential V) at which inflation took place can be described in terms of the ratio between the amplitude of tensor and scalar fluctuations, i.e., the tensor-to-scalar ratio r [9]:

$$V^{1/4} \approx \left(\frac{r}{0.01}\right)^{1/4} (10^{16}\ \mathrm{GeV}) \tag{1}$$

Since inflation was first proposed, several models were proposed at different energy scales. Given the limits of the energy scale of inflation becoming more and more stringent, most proposed models are not considered anymore. A simple model is the Single-Field Slow-Roll (SFSR). Inflation is associated with the displacement of the scalar field from the minimum of its potential V [12]. A value of r close to 0.01 would imply an energy scale close to what is theoretically foreseen by grand unified theories of fundamental interactions. We stress, however, that there is no firm prediction of the value of r in inflationary models. Additionally, it is unclear what particle drives inflation. The best candidate is a spin-zero field, a boson, and it was proposed that the Higgs boson, under certain circumstances of non-minimal coupling of the Higgs field to gravity, is at the origin of the exponential expansion of the universe and the creation of the background of gravitational waves we are all looking for. It should be stressed, however, that the scalar field responsible for inflation has a value of about the Planck mass. The Higgs mass is $\simeq$125 GeV, a factor 10^{17} smaller, so the connection between the Higgs field and the inflationary field is still unclear.

Another important connection that should be established is the possibility to use multi-messenger astronomy to increase the sensitivity of the search for the gravitational background and have a clearer insight into the physics of inflation. The possibility to cross-correlate gravitational wave data from experiments such as Ligo or Virgo [13] with those of CMB polarization such as Planck [6] is fascinating. This cross-correlation should leverage the power of cross-correlating two datasets, in order to go inside the noise of either the gravitational waves dataset produced by Ligo or Virgo collaborations or the CMB polarization full sky maps, for instance by Planck, in order to extract a primordial gravitational wave background signature. This method could increase the sensitivity and the systematic control of such a search.

3. Cosmic Microwave Background Observations

Observations of the CMB in the last $\simeq$30 years have gone through an enormous improvement in terms of sensitivity, number of detectors and observational techniques, allowing us to enter into the era of so-called precision cosmology. The measurement of the CMB frequency spectrum is probably the only field where no such improvements have been produced, leaving us at similar upper limits for the deviation from a pure black body to those observed by the FIRAS experiment [4]. The reason for this difficulty lies in the extreme difficulty of making monopole (the absolute CMB temperature averaged all over the sky) measurements from the ground as opposed to differential measurements, which more easily remove common mode emissions from the atmosphere. On the other hand, CMB anisotropies have reached an unprecedented level of precision and angular resolution. In Figure 2 we report the observational status on CMB anisotropies obtained from experiments with different frequency and angular resolution capabilities such as the Planck, ACTPol, and SPT experiments. The low-l uncertainties are due to the cosmic variance and not to the experimental noise. This is the uncertainty due to the fact that we can only observe one realization of all the possible realizations of observable universes and it is clearly stronger at large angular scales where this effect gets maximized. At multipoles l up to 500/600, the measurement is dominated by the full-sky maps of the Planck satellite [6], which set the ultimate limit. At higher multipoles, the higher angular resolution of experiments such as the Atacama Cosmology Telescope (ACT [14]) or the South Pole Telescope (SPT [15]) allow us to detect several acoustic peaks of the CMB angular power spectrum. However, observations can still be improved, as only ≃10% of the sky has been observed at high resolution.

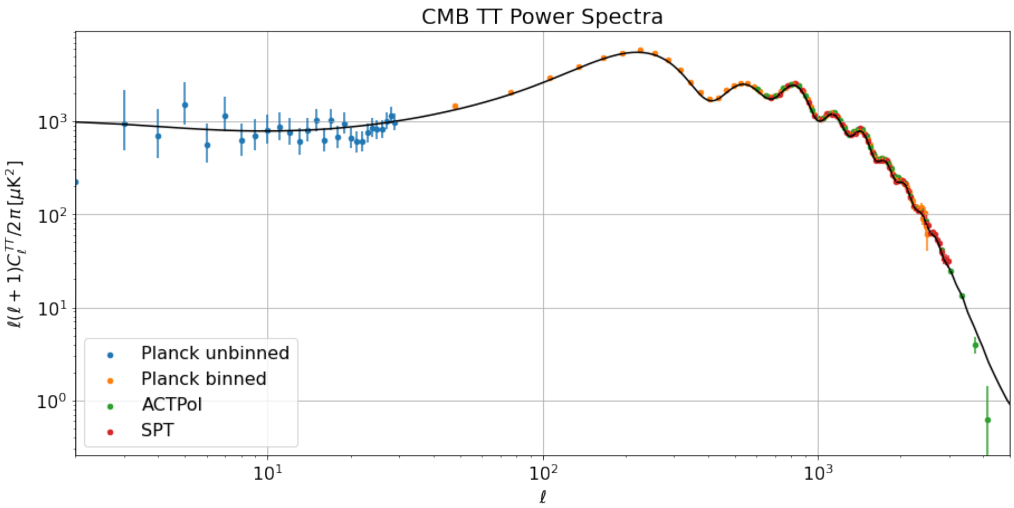

Figure 2. CMB anisotropies power spectrum. Data were obtained from the ACTPol, Planck and SPT experiments. At low multipoles l and large angular scales, Planck data have been left unbinned (not averaged over the multipoles l), whereas at large multipoles l and small angular scales, the data have been binned (averaged) over Δl = 30. Data credit: NASA/LAMBDA Science Team

4. Cosmic Microwave Background Polarization: E-Modes and B-Modes

The CMB is characterized by some degree of polarization. Primary anisotropies are produced by acoustic oscillations of primordial plasma in or out of dense and less dense over-densities [11]. The motion of fluid creates the conditions of a local quadrupole because of Doppler shifts, leading to a net E-modes polarization. A local quadrupole is the condition necessary to drive to a net polarization that otherwise would be averaged out by the isotropy around the last scattering electrons. This type of polarization is correlated with temperature anisotropies [16].

Because of gravitational lensing from cosmic structures, part of the curl-free E-modes convert into curl components, i.e., B-modes [16]. The effect is much larger at small angular scales and can become a problem if the value of the tensor-to-scalar ratio r is below 10^{-2}. This effect is starting to be delineated by high angular resolution experiments such as ACT [14], SPT [15] and Polarbear [17].

The effect of primordial gravitational waves on the CMB is however visible both at medium (≃1°) and at large (several degrees) angular scales. The primordial power spectrum has two characteristic peaks, at multipole $l \simeq 100$ and at lower multipole $l \simeq 4$, this latter due to the re-ionization of the universe and thus of interest at much larger angular scales. The amplitude of these peaks is directly related to the energy scale at which inflation took place, and then to the tensor-to-scalar ratio r as expressed in Equation (1) [16].

Another important point in observational CMB studies is the possibility to de-lens high angular resolution observations so as to be able to infer the primordial recombination peak of the B-modes' power spectrum. Additionally, the complementarity of the experiments in terms of foreground removal capability, spectral coverage, sky coverage and angular resolution is of great importance. Large coverage telescopes may more easily point to the re-ionization bump, although it is more difficult to clean a sky patch from the foreground when single features are not resolved.

From the observational point of view, in fact, it is extremely difficult to find the re-ionization peak because it is necessary to map a large sky patch with good systematic control allowing observations to retrieve large angular scales. Nevertheless, a few experiments have as a goal a large sky fraction map. Among others, we should mention CLASS [18], LSPE [19] and LiteBIRD [20], which will be discussed in the next section.

5. Experimental Effort toward B-Modes Detection

In the following we list several experiments that are now, and since some time, setting the agenda in the field of B-modes detection. This is not an exhaustive list of the existing (or planned) experiments, but it gives an idea of the huge worldwide effort that is being undertaken for this detection. Most of the instruments gather data with transition edge sensor (TES) detectors (see, e.g., [14,15,17–19,21–25]). TESs are superconductor detectors held at their critical temperature between their normal state and their superconducting state. In this way, we have a very steep dependence of the detector resistance on temperature, which makes TESs extremely sensitive thermometers. TESs are the state-of-the-art for millimetric astronomy. However, new techniques have recently started to be developed, such as kinetic inductance detectors [26]. The desire to improve the sensitivity of experiments is a major driver in this field. In order to improve sensitivity, dry and high-altitude sites are selected in order to reduce the effect of atmospheric emissions and fluctuations. Once the detectors are limited by the incoming radiation (photon noise limited), the only way to improve an experiment's sensitivity is to increase the number of detectors and effectively increase the integration time. TESs allow to use large arrays of detectors and, consequently, achieve large fields of view, thanks also to the easiness in multiplexing the SQUIDs that are used to read the TESs. Large cryogenic detector arrays carry the difficulty to read them out, as well as a large thermal input for cryostat. In order to overcome this issue, multiplexing techniques have been developed to reduce the number of wires and thermal input into the coldest stages of a cryostat. Dedicated read-out electronics based on field programmable gate arrays (FPGAs) have been and will be key toward this development.

Another important point is the complementarity of different experiments. Large fractions of the sky need to be mapped to obtain sensitive results; however, only with high angular resolution can one hope to reach large multipoles and remove the foreground from the CMB maps. Large fractions of the sky can be obtained with a dedicated scanning strategy, from particular sites on Earth or from satellites; however, large telescopes, required for high angular resolutions, cannot be sent on a space-borne platform. Many experiments observe the sky from the southern hemisphere but there are few that aim to observe large fractions of the northern hemisphere's sky. In the following, we give specific examples of the interplay between large sky coverage and large telescope aperture.

5.1. High Angular Resolution CMB Polarimeters

The possibility to detect CMB anisotropies and their polarization with high enough angular resolution (i.e., o[1′]) opens great possibility, among others, to effectively perform the de-lensing activity necessary for an effective B-modes detection. Gravitational structures, in fact, act to smooth the acoustic peaks in temperature and E-mode CMB polarization power spectra, in addition to converting part of the E-modes into B-modes. Additionally, if telescopes are designed with a large enough field of view, they can definitely search for a primordial recombination bump in the B-modes power spectrum. Among other instruments, we should cite the Atacama Cosmology Telescope (ACT [14]), the South Pole Telescope (SPT [15]) and PolarBear ([17]).

From 2008, ACT, a 6 m telescope fielded in the Atacama Desert at 5200 m a.s.l., has been gathering data with three instruments: the first, a Millimeter Bolometer Array Camera (MBAC [14]), had three independent sets of optics with filled arrays of detectors, cooled to 300 mK, at frequencies of 148, 218 and 277 GHz, and was not sensitive to polarization. The second, ACTPol ([25]), started gathering data in 2013 and has used feedhorn-coupled, polarization-sensitive detectors and 100 mK cryogenics with continuous cooling: two arrays centered at 148 GHz and one array operating at both 97 and 148 GHz. The third instrument, AdvACT, gathers data in five frequency bands, from 27 to 230 GHz: one high-frequency

150/230 GHz and two mid-frequency 90/150 GHz feedhorn-coupled, polarization-sensitive multichroic detectors, with low-frequency 27/39 GHz arrays that recently replaced one 90/150 GHz array for synchrotron monitoring. ACT uses TES with the time domain multiplexing technique.

The SPT is a 10 m telescope gathering data from the South Pole station in Antarctica. It also has fielded three generations of instruments: SPT-SZ, SPTpol and SPT-3G [27]. With a 1.2′ FWHM beam at 150 GHz, the SPT can reach high multipole with its 2690 dual-polarization detectors, with triple frequency capability. SPT-3G currently has about 16,000 TES readouts using frequency-domain multiplexing readout.

The Polarbear experiment measures CMB polarization using 1274 TES cooled to 0.3 K through lenslet-coupled double-slot dipole antennas working at 150 GHz. Polarbear uses frequency-domain multiplexing to read its TES [28].

These three experiments are carrying out very precise measurements, which are allowing and will allow soon to measure or set upper limits in the B-modes power spectrum, especially for the lensing part at large multipoles, as shown in Figure 3. Further improvements are than expected from data of these three experiments in addition to experiments such as Simons Observatory [29] and Stage 4 [30], whose experimental efforts start from the aforementioned experiments (see later for details).

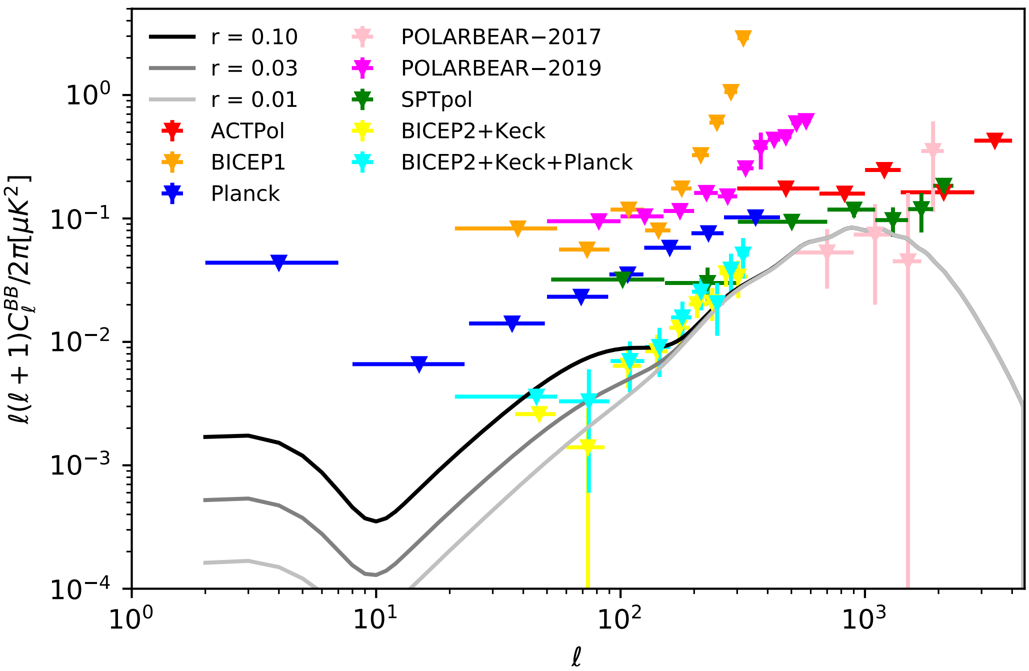

Figure 3. Some observed B-mode powers from CMB experiments. The x-axis is a logarithmic scale of the multipoles l, whereas the y-axis reports the temperature fluctuations of B-modes. The factor $l(l+1)$ ensures that $l(l+1)C_l$ is constant at low ls for a nearly scale-invariant spectrum of density perturbations. Data with error bars on the y-axis are significant detections, while the remaining are 95% upper limits. Data were taken from the NASA/LAMBDA website. Theoretical curves for $r = 0.1$ and $r = 0.01$ are shown respectively with black and grey lines.

5.2. Hunting the Recombination Bump from Ground

The best sites on Earth for performing sensitive CMB measurements are those with a low content of precipitable water vapor. The most sensitive experiments are located in the Atacama Desert and in the Antarctic continent. In the Amundsen–Scott base, at the South Pole in Antarctica, the BICEP–Keck collaboration has been installing instruments since 2008 [22]. The BICEP–Keck instruments are expressly and uniquely devoted to the B-modes search. They are giving the most stringent upper limit nowadays on the value of the tensor-to-scalar ratio r. The BICEP2, Keck Array and BICEP3 instruments recently released their ultimate upper limit, joining the data from the BICEP2, Keck Array and BICEP3, up to 2018, with those of Planck and WMAP. BICEP/Keck Array results reach depths of 2.8, 2.8 and 8.8 μK_{cmb}/arcmin at 95, 150 and 220 GHz over an area of $\simeq$600 square degrees at 95 GHz and $\simeq$400 square degrees at 150 and 220 GHz. They set an upper limit of $r < 0.036$, which is so far the most stringent limit on r.

On the Argentinian site of the Atacama Desert, an international collaboration is installing a new experiment that is devoted to the search for the B-modes: the Q and U Bolometric Interferometer for Cosmology (QUBIC [24,31–37]). QUBIC is a novel instrument that combines the sensitivity of TES bolometers with the high control of systematics that only interferometers can have. It will gather data at 150 and 220 GHz and it is now undergoing diffuse calibration. QUBIC will gather data with 2048 TES at the two frequencies with 128:1 time domain multiplexing technology based on 128 SQUIDs cooled to 1 K. With three years of integration, simulations show that QUBIC can achieve a statistical sensitivity to the effective tensor-to-scalar ratio of $\sigma(r) = 0.015$. This is another example of complementarity. Besides the sensitivity that QUBIC will be able to reach, it will be a unique experiment for efficiently removing systematic effects and, thanks to its spectral capability, which is another feature intrinsic to interferometry [35], will allow more efficiently to disentangle CMB from foregrounds.

5.3. Searching for the Recombination Bump in the Stratosphere

Since the Boomerang experiment [38], and probably even earlier [39], the stratosphere has been recognized to be a good place to make CMB measurements. A long duration balloon (LDB) experiment has the advantage of being substantially outside the atmosphere (LDBs fly at $\simeq$40 km altitude in the stratosphere) with the cost of the instrument being similar to that of a ground experiment, and much lower than that of a satellite. In addition, LDBs can field new technology relaxing the mandatory requirements for space-borne experiments concerning the readiness level of new technologies. The request for appropriate sub-orbital technological readiness level is still a driver but is not as stringent as for space-borne experiments, and this allows the scientific community to also make progress in the readiness levels.

The SPIDER experiment [21] flew from Antarctica in 2015 with different arrays of TES bolometers in two different frequencies: 815 TES at 150 GHz and 675 TES at 95 GHz. SPIDER set an upper limit on B-modes at a level of $r < 0.11$. SPIDER uses time domain multiplexing and dedicated electronics to read its detectors [40].

The Primordial Inflation Polarization Explorer (PIPER [23]) is another balloon-borne experiment that aims at measuring the B-modes of the CMB from the stratosphere. It consists of two telescopes cooled to 1.7 K thanks to a liquid helium bucket dewar with no windows between the LHe-cooled telescope and the ambient environment. Each telescope uses a pair of 32×40 TESs in the range of four frequency bands: 200, 270, 350 and 600 GHz. Through a series of conventional balloon flights, the PIPER collaboration aims to measure the primordial tensor-to-scalar ratio at a level of $r < 0.007$ at 95% CL.

5.4. Re-Ionization Bump

Another possibility to detect the inflationary gravitational wave background is to try and measure the re-ionization bump at a large angular scale, i.e., $l < 10$ (see Figure 3). This bump originates from gravitational waves interacting with ionized matter at later times and thus is a signal that characterizes a large portion of the sky.

The Large Scale Polarization Explorer (LSPE [19]) is another B-modes experiment composed of a ground-based coherent receiver, STRIP [41], and a balloon-borne experiment, SWIPE [42], which will map a large portion of the sky. STRIP takes advantage of its observational location at Tenerife (latitude 28° North), allowing it to use the earth's rotation to map a large fraction of the sky. SWIPE scans the sky by rotating the entire experiment flying from the northern hemisphere during winter. In this way, LSPE can perform the observations without interference from the sun entering the field of view. In order to enlarge the radiation modes reaching the detectors, SWIPE employs multimoded TES, which increases the modes of radiation (and thus the sensitivity) of the detectors while paying the price of reduced angular resolution. This happens because the amount of radiation sums coherently with the number of modes, while noise sums incoherently, so the net effect is an increase of the S/N ratio and the square root of the number of modes. This is an alternative way to improve the sensitivity of an experiment.

The Cosmology Large Angular Scale Surveyor (CLASS [18]) has been operational in the Atacama Desert since 2016, and since 2019 with four frequency bands: 40, 90, 150 and 220 GHz, the last two frequency bands employing dichroic detectors. CLASS takes advantage of its geographical position in the Atacama Desert, at latitude $\simeq 23^\circ$ South, to use the earth's rotation to make a large map of the sky. In this way, CLASS is the only ground-based experiment to be able to address both the re-ionization peak and the primordial peak. CLASS recently presented calibration and on-sky performance using the moon and planets [18].

5.5. Large Ground-Based Efforts toward Inflationary B-Modes

The weakness of the signal to be detected requires a joint venture of the various ground base experiments we have mentioned so far. Two efforts have been funded or partially funded to try to use the different capabilities of the aforementioned experiments: they are the Simons Observatory, located in the Atacama Desert, and the CMB Stage4 effort, which will be distributed in the Atacama Desert and in Antarctica.

The Simons Observatory (SO [29]) is a large effort that is being built to gather data from the Atacama Desert, in the same location where ACT and PolarBear are observing the sky. It will gather data within six bands: 27, 39, 93, 145, 225 and 280 GHz. SO will have three small-aperture telescopes of 0.5 m and one large-aperture telescope of 6 m. It will gather data with 60,000 bolometers. The small aperture telescopes will have a large sky coverage and will thus hunt the largest angular scales with a high mapping speed. Their forecast predicts a sensitivity level in r on the order of $\sigma(r) = 0.003$.

The CMB Stage4 (CMB-S4, [30]) is a project that aims at unifying the large effort already being carried out for ground observation of the CMB. It is the next-generation experiment and is formed of a series of telescopes located both in the Atacama Desert and in the South Pole. It intends to be the definitive ground-based CMB polarization experiment. CMB-S4 plans to measure the sky with 500,000 detectors over seven years using fourteen small aperture telescopes and one "delensing" telescope. CMB-S4 is predicted to see a tensor-to-scalar ratio r greater than 0.003 at more than 5σ and, in the absence of a detection, to place an upper limit of $r < 0.001$ at 95% CL.

5.6. Hunting B-Modes from Space

LiteBIRD ([20]) is the next CMB space mission after COBE, WMAP and Planck. It was selected by the Japan Aerospace Exploration Agency (JAXA) in May 2019. LiteBIRD will orbit around the Sun–Earth Lagrangian point L2 and will measure the CMB using three telescopes. It is a reflective telescope for the lower frequencies (low frequency telescope, LFT) with a 400 mm aperture and angular resolution ranging from 24 to 71 arcminutes. The LFT will gather data in nine frequency bands spanning from 34 to 161 GHz in order to be able to detect both CMB and synchrotron radiation. Two refractive telescopes have been designed for the medium and high frequency ranges (MHFT). The frequency band is divided into 89 to 224 GHz for the medium and frequency telescope (MFT), and 166 to 448 GHz for the high frequency telescope (HFT). LiteBIRD will reach an unprecedented total sensitivity to CMB polarization with a typical angular resolution of 0.5°. LiteBIRD will gather data with 1030 multi-chroic pixels for a total of 4508 TES, distributed over the three telescopes. The TES will be read out using a frequency domain multiplexing scheme borrowing from a scheme already in use with the SPT or PolarBear.

Forecasts predict that LiteBIRD will reach a tensor-to-scalar ratio limit of $r < 0.001$. This would be done probing both the recombination bump and the re-ionization. This sensitivity will either detect primordial gravitational waves or rule out inflationary models within the currently predicted scenarios. Favorable scenarios predict models with $r \simeq 0.01$ [16]. In this case, LiteBIRD would detect them with more that 10 σ precision.

6. Conclusions

As we have seen, the hunt for B-modes is in its greatest development thanks to balloon-borne, ground-based and satellite experiments that are planned and gathering data. Optical design, polarization modulators, and cryogenic techniques have been increasingly matured but the field that is probably giving the strongest impulse to the field is the design of detectors. Progress on detector sensitivity is impressive and improved technologies are being developed and deployed in addition to the standard TES technology, which is the one that for the moment is filling the instruments' focal planes. Detectors need to reach a sensitivity of a few $10^{-18}W/\sqrt{Hz}$. Focal planes are saturated so we need multiple telescopes and/or parallel processing or a multimoded approach. TES is the most mature technology but kinetic inductance detectors (KIDs) promise substantial development thanks to their ease of building and multiplexing.

Predictions affirm that Stage 3 experiments (those that are now gathering data) will probably reach a sensitivity of $\sigma(r) \simeq 0.01$. We have to wait until SO and Stage 4 to reach a sensitivity of $\sigma(r) \simeq 0.001$. In this context, we should ask ourselves: will the systematic control be able to catch up? We need a fiducial model that would include multiple components such as thermal dust, synchrotron, and anomalous microwave emission (AME). In fact, thermal dust and synchrotron polarized emission can be orders of magnitude larger than CMB B-modes depending on the frequency and on the sky portion observed. For instance, in a particularly clean region of the sky, at the minimum of their summed emission (i.e., $\simeq$70 GHz), synchrotron and thermal dust emission can be a few μK while B-modes can be a few tens of nK for $r = 0.01$. On the other hand, AME is still an emission that lacks predictability. It will have to be understood and monitored especially if it is found to be polarized. If there are departures from the fiducial model, then AME will be a problem for B-modes detection [43]. Additionally, will the data-analysis effort follow?

The quest for B-modes is clearly very challenging. So far, no single experiment could lead to a detection but only upper limits could be established. A possibility to amplify experiments' sensitivity would be to use the aforementioned cross-correlation between CMB polarimeters and gravitational wave experiments. Once a full sky map of gravitational waves will be available, this still unexplored technique could start producing results in separate work. In any case, the joint effort of several different experiments could lead to a significant improvement of the sensitivity but another important point is the capability to control f the systematics, especially when this is carried out with different observational techniques. An example of this is the bolometric interferometry that QUBIC is implementing. Additionally, the spectral capability and the wide number of bands is going to be key to disentangling CMB B-modes from foreground signals.

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References

1. Penzias, A.A.; Wilson, R.W. A Measurement of Excess Antenna Temperature at 4080 Mc/s. *Astrophys. J.* **1965**, *142*, 419–421. [CrossRef]
2. McKellar, A. Molecular Lines from the Lowest States of Diatomic Molecules Composed of Atoms Probably Present in Interstellar Space. *Publ. Dom. Astrophys. Obs.* **1941**, *251*, 32–58.
3. Mather, J.C. et al. [COBE-FIRAS Collaboration]. Measurement of the Cosmic Microwave Background Spectrum by the COBE FIRAS Instrument. *Astrophys. J.* **1994**, *420*, 439. [CrossRef]
4. Fixsen, D.J. The Temperature of the Cosmic Microwave Background. *Astrophys. J.* **2009**, *707*, 916–920. [CrossRef]
5. Smoot, G.F.; Bennett, C.L.; Kogut, A.; Wright, E.L.; Aymon, J.; Boggess, N.W. Structure in the COBE differential microwave radiometer first-year maps. *Astrophys. J.* **1992**, *396*, L1–L5. [CrossRef]
6. Aghanim, N. et al. [Planck Collaboration] Planck 2018 results I: Overview and the cosmological legacy of Planck. *Astron. Astrophys.* **2020**, *641*, A1. [CrossRef]
7. Kovac, J.; Leitch, E.M.; Pryke, C.; Carlstrom, J.E.; Halverson, N.W.; Holzapfel, W.L. Detection of Polarization in the Cosmic Microwave Background using DASI. *Nature* **2002**, *420*, 772–787. [CrossRef]
8. Guth, A.H. The inflationary universe: A possible solution to the horizon and flatness problems. *Phys. Rev. D* **1981**, *23*, 347. [CrossRef]
9. Linde, A.D. A new inflationary universe scenario: A possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems. *Phys. Rev. D* **1982**, *108*, 389–393. [CrossRef]
10. Starobinsky, A.A. Spectrum of relict gravitational radiation and the early state of the universe. *JETP Lett.* **1980**, *30*, 682–685.
11. Hu, W.; White, M. A CMB Polarization Primer. *New Astron.* **1997**, *2*, 323. [CrossRef]
12. Tristram, M.; Banday, A.J.; Górski, K.M.; Keskitalo, R.; Lawrence, C.; Andersen, K.J.; Barreiro, R.B.; Borrill, J.; Eriksen, H.; Fernandez-Cobos, R.; et al. Planck constraints on the tensor-to-scalar ratio. *Astron. Astrophys.* **2021**, *647*, A128. [CrossRef]
13. Abbott, B.P. et al. [LIGO Scientific Collaboration and Virgo Collaboration] GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs. *Phys. Rev. X* **2019**, *9*, 031040.
14. Swetz, D.; Ade, P.A.; Amiri, M.; Appel, J.; Battistelli, E.; Burger, B.; Chervenak, J.; Devlin, M.; Dicker, S.; Doriese, W.; et al. Overview of the atacama cosmology telescope: Receiver, instrumentation, and telescope systems. *Astrophys. J. Suppl. Ser.* **2011**, *194*, 41. [CrossRef]
15. Carlstrom, J.; Ade, P.A.; Aird, K.; Benson, B.; Bleem, L.; Busetti, S.; Chang, C.; Chauvin, E.; Cho, H.-M.; Crawford, T.; et al. The 10 Meter South Pole Telescope. *Publ. Astron. Soc. Pac.* **2011**, *123*, 568. [CrossRef]
16. Kamionkowski, M.; Kovetz, E.D. The Quest for B Modes from Inflationary Gravitational Waves. *Ann. Rev. Astron. Astrophys* **2016**, *54*, 227. [CrossRef]
17. Ade, P.; Akiba, Y.; Anthony, A.; Arnold, K.; Atlas, M.; Barron, D.; Boettger, D.; Borrill, J.; Chapman, S.; Chinone, Y.; et al. A Measurement of the Cosmic Microwave Background B-Mode Polarization Power Spectrum at Sub-Degree Scales with POLARBEAR. *Astrophys. J.* **2014**, *794*, 171. [CrossRef]
18. Dahal, S.; Appel, J.W.; Datta, R.; Brewer, M.K.; Ali, A.; Bennett, C.L.; Bustos, R.; Chan, M.; Chuss, D.T.; Cleary, J.; et al. Four-year Cosmology Large Angular Scale Surveyor (CLASS) Observations: On-sky Receiver Performance at 40, 90, 150, and 220 GHz Frequency Bands. *Astrophys. J.* **2022**, *926*, 33. [CrossRef]
19. Addamo, G. et al. [The LSPE Collaboration] The large scale polarization explorer (LSPE) for CMB measurements: Performance forecast. *J. Cosmol. Astropart. Phys.* **2021**, *2021*, 008. [CrossRef]
20. Sugai, H.; Ade, P.; Akiba, Y.; Alonso, D.; Arnold, K.; Aumont, J.; Austermann, J.; Baccigalupi, C.; Banday, A.J.; Banerji, R.; et al. Updated Design of the CMB Polarization Experiment Satellite LiteBIRD. *J. Low Temp. Phys.* **2020**, *199*, 1107. [CrossRef]
21. Ade, P.A.R. et al. [Spider Collaboration] A Constraint on Primordial B-modes from the First Flight of the SPIDER Balloon-borne Telescope. *Astrophys. J.* **2022**, *927*, 174. [CrossRef]
22. Ade, P.A.R. et al. [BICEP Keck Collaboration] BICEP/Keck XIII: Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season. *Phys. Rev. Lett.* **2021**, *127*, 151301. [CrossRef]
23. Kogut, A.; Ade, P.; Baildon, T.; Bellis, N.; Benford, D.; Bennett, C.; Chuss, D.; Datta, R.; Eimer, J.; Fixsen, D.; et al. The Primordial Inflation Polarization Explorer (PIPER): Science Goals. *Bull. Am. Astron. Soc.* **2020**, *52*, 3.
24. Piat, M. et al. [QUBIC Collaboration] QUBIC IV: Performance of TES bolometers and readout electronics. *J. Cosmol. Astropart. Phys.* **2022**, *2022*, 37. [CrossRef]
25. Thornton, R.; Ade, P.; Aiola, S.; Angile, F.; Amiri, M.; Beall, J.; Becker, D.; Cho, H.; Choi, S.; Corlies, P.; et al. The atacama cosmology telescope: The polarization-sensitive actpol instrument. *Astrophys. J. Suppl. Ser.* **2016**, *227*, 21. [CrossRef]
26. Paiella, A.; Ade, P.; Battistelli, E.; Castellano, M.; Colantoni, I.; Columbro, F.; Coppolecchia, A.; D'Alessandro, G.; de Bernardis, P.; De Petris, M.; et al. In-Flight Performance of the LEKIDs of the OLIMPO Experiment. *J. Low Temp. Phys.* **2020**, *199*, 491–501. [CrossRef]
27. Sobrin, J.; Anderson, A.; Bender, A.; Benson, B.; Dutcher, D.; Foster, A.; Goeckner-Wald, N.; Montgomery, J.; Nadolski, A.; Rahlin, A.; et al. The Design and Integrated Performance of SPT-3G. *Astrophys. J. Suppl. Ser.* **2022**, *258*, 2. [CrossRef]
28. Adachi, S.; Faúndez, M.A.; Arnold, K.; Baccigalupi, C.; Barron, D.; Beck, D.; Beckman, S.; Bianchini, F.; Boettger, D.; Borrill, J.; et al. A Measurement of the Degree-scale CMB B-mode Angular Power Spectrum with Polarbear. *Astrophys. J.* **2020**, *897*, 1.

29. Ade, P.A.R. et al. [Simons Observatory Collaboration] The Simons Observatory: Science goals and forecasts. *J. Cosmol. Astropart. Phys.* **2019**, *2*, 56.
30. Abazajian, K.; Addison, G.; Adshead, P.; Ahmed, Z.; Allen, S.W.; Alonso, D.; Alvarez, M.; Anderson, A.; Arnold, K.S.; Baccigalupi, C.; et al. CMB-S4 Science Case, Reference Design, and Project Plan. *arXiv* **2019**, arXiv:1907.04473.
31. Cavaliere, F. et al. [QUBIC Collaboration] QUBIC VII: The feedhorn-switch system of the technological demonstrator. *J. Cosmol. Astropart. Phys.* **2022**, *2022*, 04.
32. D'Alessandro, G. et al. [QUBIC Collaboration] QUBIC VI: Cryogenic half wave plate rotator, design and performance. *J. Cosmol. Astropart. Phys.* **2022**, *2022*, 39. [CrossRef]
33. Hamilton, J.-C. et al. [QUBIC Collaboration] QUBIC I: Overview and science program. *J. Cosmol. Astropart. Phys.* **2022**, *2022*, 34. [CrossRef]
34. Masi, S.; Battistelli, E.; de Bernardis, P.; Chapron, C.; Columbro, F.; d'Alessandro, G.; De Petris, M.; Grandsire, L.; Hamilton, J.-C.; Marnieros, S.; et al. QUBIC V: Cryogenic system design and performance. *J. Cosmol. Astropart. Phys.* **2022**, *2022*, 38. [CrossRef]
35. Mousset, L. et al. [QUBIC Collaboration] QUBIC II: Spectral polarimetry with bolometric interferometry. *J. Cosmol. Astropart. Phys.* **2022**, *2022*, 35. [CrossRef]
36. O'Sullivan, C. et al. [QUBIC Collaboration] QUBIC VIII: Optical design and performance. *J. Cosmol. Astropart. Phys.* **2022**, *2022*, 41. [CrossRef]
37. Torchinsky, S.; Hamilton, J.-C.; Piat, M.; Battistelli, E.; Chapron, C.; d'Alessandro, G.; de Bernardis, P.; De Petris, M.; Lerena, M.; González, M.; et al. QUBIC III: Laboratory characterization. *J. Cosmol. Astropart. Phys.* **2022**, *2022*, 36. [CrossRef]
38. de Bernardis, P.; Ade, P.A.; Bock, J.J.; Bond, J.; Borrill, J.; Boscaleri, A.; Coble, K.; Crill, B.; De Gasperis, G.; Farese, P.; et al. A flat Universe from high-resolution maps of the cosmic microwave background radiation. *Nature* **2000**, *404*, 955. [CrossRef]
39. De Bernardis, P.; De Luca, A.; De Petris, M.; Epifani, M.; Gervasi, M.; Maoli, R.; Masi, S. The ARGO project: Scientific targets, first results and future perspectives. *Il Nuovo C. C* **1992**, *15*, 993–1011. [CrossRef]
40. Battistelli, E.; Amiri, M.; Burger, B.; Halpern, M.; Knotek, S.; Ellis, M.; Gao, X.; Kelly, D.; Macintosh, M.; Irwin, K.; et al. Functional Description of Read-out Electronics for Time-Domain Multiplexed Bolometers for Millimeter and Sub-millimeter Astronomy. *J. Low Temp. Phys.* **2008**, *151*, 908–914. [CrossRef]
41. Franceschet, C.; Del Torto, F.; Villa, F.; Realini, S.; Bongiolatti, R.; Peverini, O.; Pezzotta, F.; Viganó, D.; Addamo, G.; Bersanelli, M.; et al. The LSPE-Strip feed horn array. *J. Instrum.* **2022**, *17*, P01029. [CrossRef]
42. Columbro, F.; Madonia, P.; Lamagna, L.; Battistelli, E.; Coppolecchia, A.; de Bernardis, P.; Gualtieri, R.; Masi, S.; Paiella, A.; Piacentini, F.; et al. SWIPE Multi-mode Pixel Assembly Design and Beam Pattern Measurements at Cryogenic Temperature. *J. Low Temp. Phys.* **2020**, *199*, 312–319. [CrossRef]
43. Dickinson, C.; Ali-Haïmoud, Y.; Barr, A.; Battistelli, E.; Bell, A.; Bernstein, L.; Casassus, S.; Cleary, K.; Draine, B.T.; Génova-Santos, R.; et al. The State-of-Play of Anomalous Microwave Emission (AME) research. *New Astron. Rev.* **2018**, *80*, 1–28. [CrossRef]