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Unlocking cosmic origins: *LiteBIRD*'s quest for inflationary gravitational waves

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Avinash Anand[a,b,*] **for the *LiteBIRD* collaboration**

[a] *Dipartimento di Fisica, Università di Roma Tor Vergata,*
Via della Ricerca Scientifica, 1, 00133, Roma, Italy
[b] *INFN Sezione di Roma2,*
via della Ricerca Scientifica, 1, 00133, Roma, Italy

E-mail: `avinash.anand@roma2.infn.it`

LiteBIRD is a forthcoming space mission dedicated to study the faint B-mode polarization patterns in the cosmic microwave background (CMB) that are believed to be the imprints of the gravitational waves from the period of cosmic inflation. The primary goal of the mission is the measurement of the tensor-to-scalar ratio r, with total uncertainty of $\delta r \sim 0.001$. *LiteBIRD* is planned to be launched in the 2030s to the Sun-Earth Lagrange point L2, where it will perform full-sky CMB measurements for three years. It will cover 15 frequency bands across the 34 to 448 GHz frequency range. The mission will also address key cosmological problems, including a measurement of the optical depth to reionization and constraints on the neutrino mass. With its advanced instrumentation, *LiteBIRD* will mitigate foreground contamination and systematic errors to provide high-fidelity data to improve our understanding of inflation, large-scale anomalies and other fundamental cosmological phenomena.

Frontier Research in Astrophysics – IV (FRAPWS2024)
9-14 September 2024
Mondello, Palermo, Italy

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[*] Speaker

1. Introduction

The cosmic microwave background (CMB) serves as a relic from the early Universe. It carries information about the initial conditions, including the quantum fluctuations that seeded structure formation. In the standard picture, these fluctuations were amplified during a period of exponential expansion, called cosmic inflation, giving rise to the perturbation in the mass-energy density that shaped the Universe we observe today. The theory of inflation predicts that this phase of early expansion not only stretched quantum fluctuations in space, but also generated fluctuations in spacetime itself, producing a homogeneous and isotropic background of primordial gravitational waves. These gravitational waves should leave an imprint on the polarization of the CMB.

The CMB polarization pattern on the sky can be characterized with a polarization tensor using Stokes parameters. The polarization tensor can be represented as the combination of gradient and curl components, referred as E and B modes, respectively. The E modes are generated by scalar cosmological perturbation, whereas the B modes are predicted to arise primarily from the primordial gravitational waves. Since scalar modes do not contribute to the B mode at linear order, this makes B-modes an ideal observable for detecting primordial gravitational waves [1].

Observations of CMB temperature fluctuations have been crucial in establishing the standard Λ cold dark matter (ΛCDM) cosmological model, shedding light on the origin of structure, as well as the densities of matter and dark energy, and other properties of spacetime [2]. While a large amount of information has already been extracted from temperature fluctuations, precise measurements of the fainter CMB polarization anisotropies remain elusive. *LiteBIRD*, the Lite (light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection [3], is a mission designed to map CMB polarization with unprecedented sensitivity. *LiteBIRD*'s mission to study B-mode polarization aims to push technological boundaries, offering insights into fundamental physics at energy scales beyond the reach of current experiments, and providing essential information for understanding the early Universe. Here we present the description of the baseline configuration of LiteBIRD, but the instrument design continues to be investigated to consolidate the flow-down and secure the achievement of the science goals.

2. *LiteBIRD* mission overview

With conceptual studies started in 2008, *LiteBIRD* was selected as JAXA's large-class (L-class) mission in May 2019. It is scheduled to be launched in the 2030s aboard JAXA's H3-22L rocket from the Tanegashima Space Center [3]. The H3 rocket offers three units for the first stage engines (LE-9) and can support zero, two, or four solid rocket boosters (SRB-3) to adjust to different launch requirements [4].

LiteBIRD will operate in a Lissajous orbit around the Earth-Sun Lagrange point, L2, which allows for stable observations with minimal interference. The spacecraft will spin around its major axis at a rate of 0.05 rpm (one full rotation every 20 minutes), with a precession of the spin axis. The precision period is set to 3.2058 hours to avoid systematics that may arise through the cross-linking maps. The spin axis of the satellite is inclined at an angle $\alpha = 45°$, and the angle between the telescope boresight and the spin axis is kept as $\beta = 50°$ [3]. This scanning strategy will help to distribute the observations uniformly across the sky, additionally ensuring high thermal stability, short revisit times for each sky pixel, and minimal systematic effects due to cross-linking of maps. A schematic of the *LiteBIRD* scanning strategy is depicted in Fig. 1.

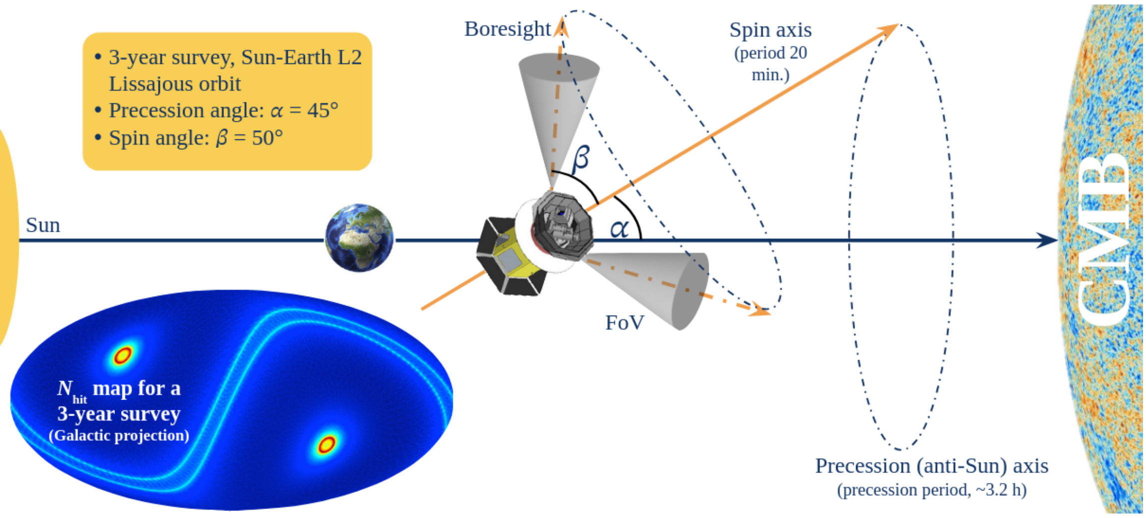

Figure 1: A schematic of the scanning strategy of *LiteBIRD*. With the satellite located along the Sun-Earth axis at Sun-Earth L2 point, it will observe the sky without external interference. The chosen configuration allows the satellite to cover the entire sky uniformly.

The spacecraft is designed to keep bright sources, such as the Earth and Sun, far from the telescope's boresight, thus minimizing the risk of spurious signals from these sources being picked up in the telescope's sidelobes. The spacecraft's axis-symmetric design is optimized for spinning, with the telescopes and solar panels positioned at opposite ends of the satellite (Fig. 2). A high-gain antenna will be placed opposite the instruments to mitigate instrumental interference. The total weight of the spacecraft, including fuel, will be approximately 3,200 kg, with an electrical power requirement of 3.7 kW. *LiteBIRD* will transmit 17.9 GB of scientific and housekeeping data daily, using X-band with a data transfer rate of 10 Mbps [3]. Two JAXA-operated ground stations are being considered for telemetry, command and data downlink, and alternative options are also being explored.

LiteBIRD's mission is primarily to detect B-mode polarization, with a target of achieving $\delta r = 0.001$ for the tensor-to-scalar ratio. To achieve this goal, the satellite will perform a full-sky survey with unprecedented sensitivity, with the objective to produce high-precision maps across a broad frequency range. These maps will cover temperature and polarization data in 15 frequency bands, ranging from 38 to 448 GHz, with an angular resolution up to $30'$ at 100 GHz. *LiteBIRD*'s survey will provide critical data on new physics, complementing ground-based experiments, and will focus on large angular scales that are necessary to distinguish primordial B-mode polarization from the lensing signal, which exists at smaller angular scales.

One of the key advantages of space-based missions like *LiteBIRD* is their ability to access a wider range of frequencies than possible with ground-based instruments because of the presence of the atmosphere. This provides the space-based missions with enough frequency coverage to separate the CMB signal from the foreground signals. In addition, the detectors are more sensitive in space compared to the ground, especially at higher frequencies, allowing for better characterization of

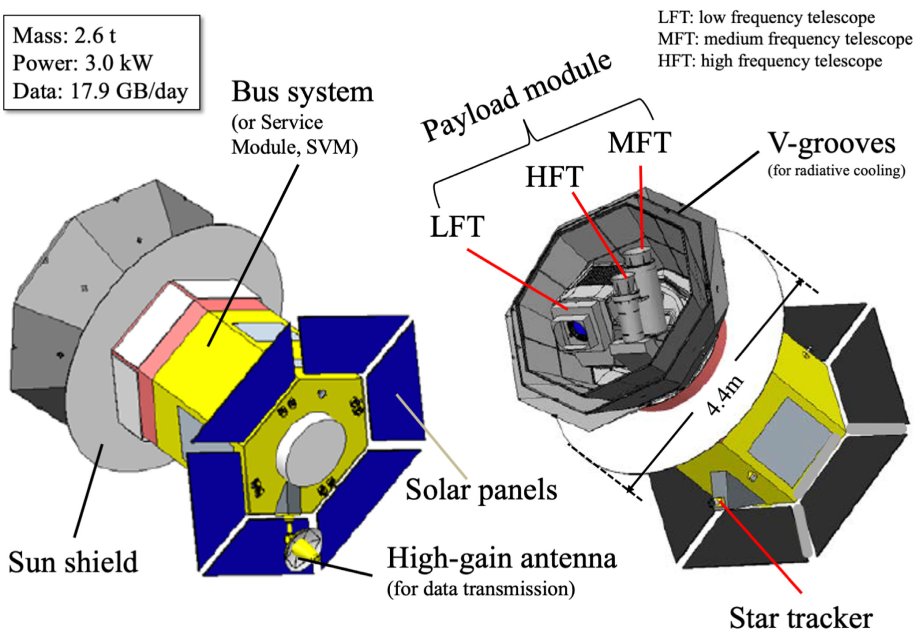

Figure 2: A diagram of the *LiteBIRD* spacecraft illustrating the spatial arrangement of its various instruments and components [3]

Galactic dust emission. Due to full-sky coverage, space-based missions also provide high-quality maps for large angular scales, corresponding to multipoles $2 \leq \ell \leq 30$, where the reionization signature can be detected in E modes.

3. *LiteBIRD* instrument overview

The payload module of the spacecraft will house three telescopes: a low-frequency telescope (LFT); a medium-frequency telescope (MFT); and a high-frequency telescope (HFT). The MFT and the HFT share a common structure, while the LFT will be mounted independently. Each telescope will have their focal planes and cryo-structures cooled down to 100 mK through a global cooling chain, spanning from 300 K to 100 mK. These telescopes will provide the sensitivity needed for the full sky survey, with a combined sensitivity of 2.2 μK-arcmin (Fig. 3). The detectors on *LiteBIRD* will be multi-chroic transition-edge sensor (TES) bolometers, 4508 in number, also cooled to 100 mK [3]. The frequency bands, beam sizes, and the noise-equivalent temperatures (NETs) for each of the 15 frequency channels are determined based on the mission's top-level requirements, as described in the next section. *LiteBIRD*'s observational strategy is focused on large angular scales across the sky, particularly targeting the reionization and recombination peaks in the B-mode power spectrum, which requires exceptional sensitivity at multipoles $2 \leq \ell \leq 200$. This results in a relatively low resolution requirement for telescopes ($< 80'$), while placing significant emphasis on controlling systematics, particularly minimizing $1/f$ noise.

A key design feature of *LiteBIRD* is a continuously rotating half-wave plate (HWP) as the first optical element in each telescope, at a temperature maintained below 20 K. The rotating HWP modulates the incident signal to $4f$ frequency (where f is the rotation frequency of the HWP),

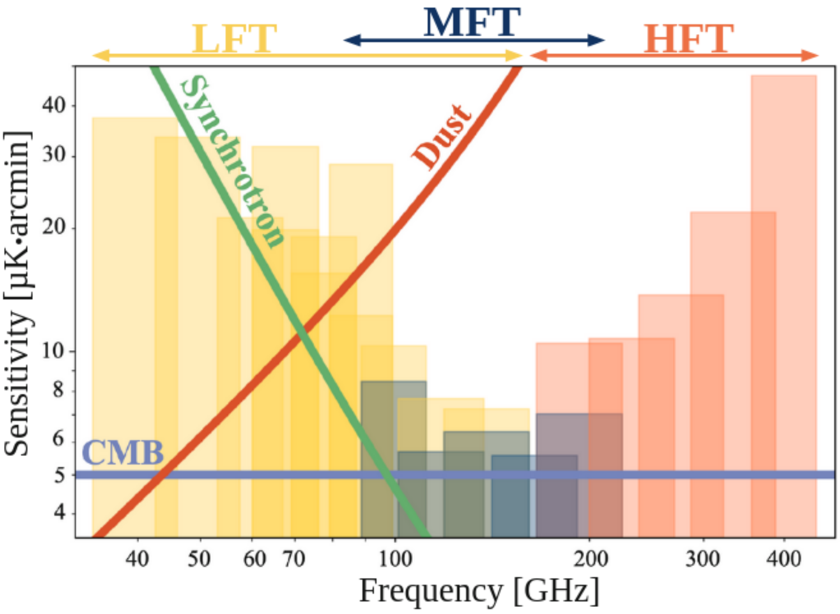

Figure 3: Polarization sensitivity of different frequency channels of *LiteBIRD* in comparison with the CMB, synchrotron, and dust signals.

separating the polarization signals of the instrument and the signal coming from the sky. The rotating HWP also suppresses $1/f$ noise by shifting the sky signal to frequencies higher than the f_{knee} of the $1/f$ noise spectrum, improving the signal quality. The HWP also reduces the temperature-to-polarization leakage, which could otherwise occur when combining data from detectors with orthogonal polarization orientations.

The LFT of *LiteBIRD* will have an aperture diameter of 400 mm and will operate across nine broad frequency bands, ranging from 34 to 161 GHz with angular resolution from 24′ to 71′. The focal plane of LFT will contain a total of 1080 detectors. The telescope's optical design follows a crossed Dragone configuration. The mid- and high-frequency telescopes (MHFT) of *LiteBIRD* will have an aperture diameter of 300 and 200 mm, with 2074 and 1354 detectors, respectively. Both telescopes will cover a 28° diameter field of view with angular resolution less than 30′, and five frequency bands. Specifically, MFT will cover the frequency range 89–224 GHz and HFT will cover 166–448 GHz [3].

Temperature stability is crucial for *LiteBIRD*, as fluctuations in temperature can introduce noise and impact the pointing stability of the telescopes. To minimize these issues, the telescopes are cooled to 4.8 K, reducing the heat load on the focal planes. *LiteBIRD*'s cryogenic cooling system is based on the one developed for the SPICA-SAFARI mission, utilizing a combination of radiative cooling (via V-grooves) to bring the temperature to 30 K, followed by mechanical cryogenic coolers to achieve the final cooling to 4.8 K. This ensures the thermal stability required to achieve the high sensitivity needed for B-mode polarization measurements.

4. Mission requirement flow-down

The requirement flow-down describes the translation of the top-level scientific goals of the mission into detailed specifications for each component of the spacecraft instrument. This defines the expected statistical and systematic uncertainties, guiding the entire design process. Such a structured approach ensures that each component of the spacecraft meets the performance criteria to achieve the final scientific goals with the required precision. The requirement flow-down for *LiteBIRD* is organized into five levels [3] as follows.

Level 1: Scientific requirements that set the overarching goals for the mission.

Level 2: Measurement requirements needed to meet the scientific goals, regardless of specific design choices. This includes 11 sub-requirements related to statistical and systematic uncertainties, scanning strategy, angular resolution, calibration, error budgets, and noise covariance, among others.

Level 3: System requirements, specifying the technical design parameters that must be met to satisfy the Level 2 measurement requirements.

Level 4: Subsystem requirements, which pertain to the specifications for the individual subsystems of the spacecraft.

Level 5: Component-level requirements, detailing the performance criteria for individual components.

The basic science goals of the mission are called 'the Level 1 requirements'. For the *LiteBIRD* mission, it is divided into the following two parts [3].

1. **Tensor-to-scalar ratio r measurement sensitivity:** the mission shall measure r with a total uncertainty of $\delta r = 0.001$. This value shall include contributions from instrumental statistical noise fluctuations, instrumental systematics, residual foregrounds, lensing B modes, and observer bias, and shall not rely on future external data sets.

2. **Polarization angular power spectrum measurement capability:** the mission shall obtain full-sky CMB linear polarization maps for achieving $> 5\sigma$ significance using $2 \leq \ell \leq 10$ and $11 \leq \ell \leq 200$ separately, assuming $r = 0.01$. We adopt a fiducial optical depth of $\tau = 0.05$ for this calculation.

Level 1 and Level 2 requirements are collectively referred to as mission requirements. The measurement requirements outlined at Level 2 drive the design choices made at lower levels. For example, the error budget, which is split equally between statistical and systematic uncertainties, is critical in guiding instrument trade-off studies. *LiteBIRD*'s overall error budget allocation, defined as $\sigma_{\text{stat}} = \sigma_{\text{syst}} = 6 \times 10^{-4}$, ensures that the instrument is sensitive enough to detect the faint CMB B modes, while controlling foreground contamination. This is achieved through a detailed understanding of the systematics and through trade-off studies that optimize the design. At the instrumentation level, so far more than 70 different systematic effects have been identified. Each of these are allocated 1% of the total systematic budget, with a target of developing mitigation strategies for each one.

The requirement flow-down from Level 1 to Level 5 provides a clear, structured approach for translating the primary mission goals into the technical specifications. This ensures that every system and component is optimized not only for its stand-alone performance but also for its contribution to the overall scientific goals. For instance – the antisymmetric design of the spacecraft reduces the moment of inertia, the relative position of solar panels and high gain antenna with respect to the scientific instruments, the addition of polarization modulation units – all stem from the need to meet the requirements set in the requirement flow-down.

The data collected by *LiteBIRD* will include the sky signals and pointings of each detector, as well as the housekeeping data of the satellite. Processing of these data will involve calibration, removal of systematic contamination, and production of sky maps at different frequencies with appropriate noise characterization. Calibration and removing the systematics includes dealing with the cosmic ray glitches, and accounting for the non-idealities in the optical and electrical components of the spacecraft. The sky maps obtained at this point are separated into different components, and then CMB maps are used to derive scientific results. This entire pipeline is tightly linked with the mission requirement, since it involves reducing both the systematic and statistical uncertainties in the final scientific products of the mission. Studying the propagation of the systematics from individual spacecraft components to scientific results using dedicated pipelines and its comparison with the Level 2 requirements provides important feedback for the instrument design. The requirement flow-down thus ensures that all components of the mission, including instrument design, data collection, system calibration, systematic mitigation, production of the sky-maps, and the scientific products, work cohesively toward minimizing the uncertainties in the final scientific results.

5. Scientific outcomes

As a first dedicated space-based mission to study the B-mode polarization of CMB, *LiteBIRD* paves the way to explore a wide range of science goals.

Constraints on tensor-to-scalar ratio r: The primary science goal of the *LiteBIRD* mission is the detection of primordial B modes by measuring r. Although there are upper limits on the tensor-to-scalar ratio from the joint analysis of *Planck* and BICEP collaboration [5, 6], these limits are set by the dominance of lensing B modes, which overwhelm the primordial signal at higher multipoles. The next-generation CMB experiments from the ground can observe the B-mode signal from the epoch of recombination, but this is also expected to be dominated by the lensing B-modes (Fig. 4). Therefore, detecting the primordial B-modes requires a focus on the lower multipole range ($\ell < 10$) and a full-sky survey, achievable only from space. With the aim of achieving a precision of $\delta r = 0.001$, *LiteBIRD* will push the upper limits and improve the precision on r, enabling us to confirm or rule out some inflationary models and gain deeper insight into the physics of the early Universe.

Constraints on the inflationary models: Single-field slow-roll inflation predicts a gravitational wave background that is nearly scale invariant, nearly Gaussian, and respects parity symmetry. Any deviations from these predictions could point to non-minimal couplings of the

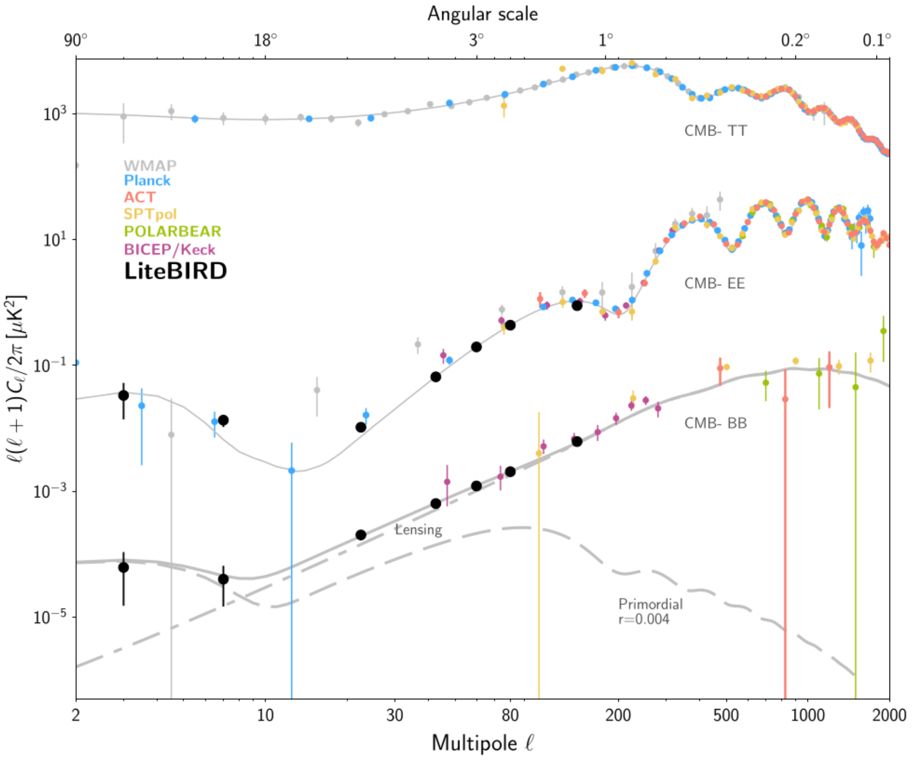

Figure 4: The angular power spectra of CMB along with the measurements from the previous experiments and forecast for *LiteBIRD* [3]

inflaton field or the presence of additional fields during inflation. *LiteBIRD* can explore these possibilities by measuring the cross-correlation between different modes and by measuring the bispectrum to detect potential non-Gaussianity.

Probing the epoch of reionization: The epoch of reionization (EoR) introduces a bump in the B-mode signal around $\ell{\sim}10$, that can be distinguished from the primordial B-mode even for $r{\sim}0.001$ [3]. The spectrum of *LiteBIRD*'s B-mode signal, even in the absence of primordial gravitational waves, will provide stringent constraint on the optical depth at EoR and will help breaking the degeneracies between different cosmological parameters, which have been difficult to resolve in other measurements.

Cosmic birefringence: Cosmic birefringence refers to the rotation of the polarization plane of light as it travels through the Universe. Cosmic birefringence could be a signature of new physics, such as the presence of axion-like particles or other exotic fields. By measuring the TB and EB cross-power spectra, *LiteBIRD* will search for evidence of cosmic birefringence, helping to probe fundamental physics beyond the standard model.

Primordial magnetic fields: The primordial magnetic fields (PMFs), which may have originated in the early Universe, may have left their imprints on the CMB through their effect on the polarization pattern. *LiteBIRD*'s multi-frequency survey will allow it to distinguish between the magnetic field-induced B modes and those generated by inflation, providing new constraints on the amplitude of PMFs and their impact on the early Universe.

Large-scale anomalies: *LiteBIRD* will also contribute to addressing several anomalies that have been observed in the CMB, such as the cold-spot and large-scale hemispherical asymmetries. These anomalies, identified in the *WMAP* [7] and *Planck* [2, 8] data, could indicate new physics or simply represent statistical fluctuations. To explore the origins of these anomalies, a precise measurement of the E-mode signal would be necessary. *LiteBIRD*'s full-sky polarization maps will provide an opportunity to test these anomalies more rigorously, with improved precision in data largely independent of the temperature anisotropies, to potentially resolve the discrepancies in our understanding of the large-scale structures.

Synergy with ground-based experiments: *LiteBIRD* will complement and enhance the capabilities of future ground-based CMB experiments, such as CMB-S4 [9]. While ground-based experiments will focus on smaller angular scales (such as the recombination peak at $\ell{\sim}80$), *LiteBIRD* will provide critical measurements on large angular scales ($\ell{\sim}10$), where the primordial gravitational waves from reionization and inflation are expected to dominate. The combination of these complementary data sets will significantly improve cosmological measurements, including the sum of neutrino masses.

6. Conclusions

LiteBIRD mission represents a significant leap toward our understanding of the early Universe, particularly to detect the signatures of inflationary primordial gravitational waves imprinted in the CMB. *LiteBIRD*'s highly sensitive observations, combined with advanced data analysis techniques will enable us to produce high-fidelity CMB E- and B-mode power spectra that will serve as an unprecedented probe of cosmic inflation. By targeting the B-mode polarization signal, *LiteBIRD* will push the current upper limit on the tensor-to-scalar ratio r that will test the key prediction of the single-field slow-roll inflation and potentially probe physics beyond the standard model.

In addition to its primary goal of detecting primordial gravitational waves, *LiteBIRD* will also place stringent constraints on key cosmological parameters, including the optical depth at reionization and the sum of neutrino masses. Furthermore, the mission will offer new insights into the nature of primordial magnetic fields, cosmic birefringence, and other potential exotic phenomena.

Acknowledgments

This work is supported in Japan by ISAS/JAXA for Pre-Phase A2 studies, by the acceleration program of JAXA research and development directorate, by the World Premier International Research Center Initiative (WPI) of MEXT, by the JSPS Core-to-Core Program of A. Advanced Research Networks, and by JSPS KAKENHI Grant Numbers JP15H05891, JP17H01115, and JP17H01125. The Canadian contribution is supported by the Canadian Space Agency. The French *LiteBIRD* phase A contribution is supported by the Centre National d'Etudes Spatiale

(CNES), by the Centre National de la Recherche Scientifique (CNRS), and by the Commissariat à l'Energie Atomique (CEA). The German participation in *LiteBIRD* is supported in part by the Excellence Cluster ORIGINS, which is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy (Grant No. EXC-2094 – 390783311). The Italian *LiteBIRD* phase A contribution is supported by the Italian Space Agency (ASI Grants No. 2020-9-HH.0 and 2016-24-H.1-2018), the National Institute for Nuclear Physics (INFN) and the National Institute for Astrophysics (INAF). Norwegian participation in *LiteBIRD* is supported by the Research Council of Norway (Grant No. 263011) and has received funding from the European Research Council (ERC) under the Horizon 2020 Research and Innovation Programme (Grant agreement No. 772253 and 819478). The Spanish *LiteBIRD* phase A contribution is supported by MCIN/AEI/10.13039/501100011033, project refs. PID2019-110610RB-C21, PID2020-120514GB-I00, PID2022-139223OB-C21 (funded also by European Union NextGenerationEU/PRTR), and by MCIN/CDTI ICTP20210008 (funded also by EU FEDER funds). Funds that support contributions from Sweden come from the Swedish National Space Agency (SNSA/Rymdstyrelsen) and the Swedish Research Council (Reg. no. 2019-03959). The UK *LiteBIRD* contribution is supported by the UK Space Agency under grant reference ST/Y006003/1 – 'LiteBIRD UK: A major UK contribution to the LiteBIRD mission – Phase1 (March 25)'. The US contribution is supported by NASA grant no. 80NSSC18K0132. A.A. is supported by Italian Research Center on High Performance Computing, Big Data and Quantum Computing (ICSC), project funded by European Union - NextGenerationEU - and National Recovery and Resilience Plan (NRRP) - Mission 4 Component 2 within the activities of Spoke 3 (Astrophysics and Cosmos Observations). A.A. is also supported by the InDark and *LiteBIRD* INFN projects.

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