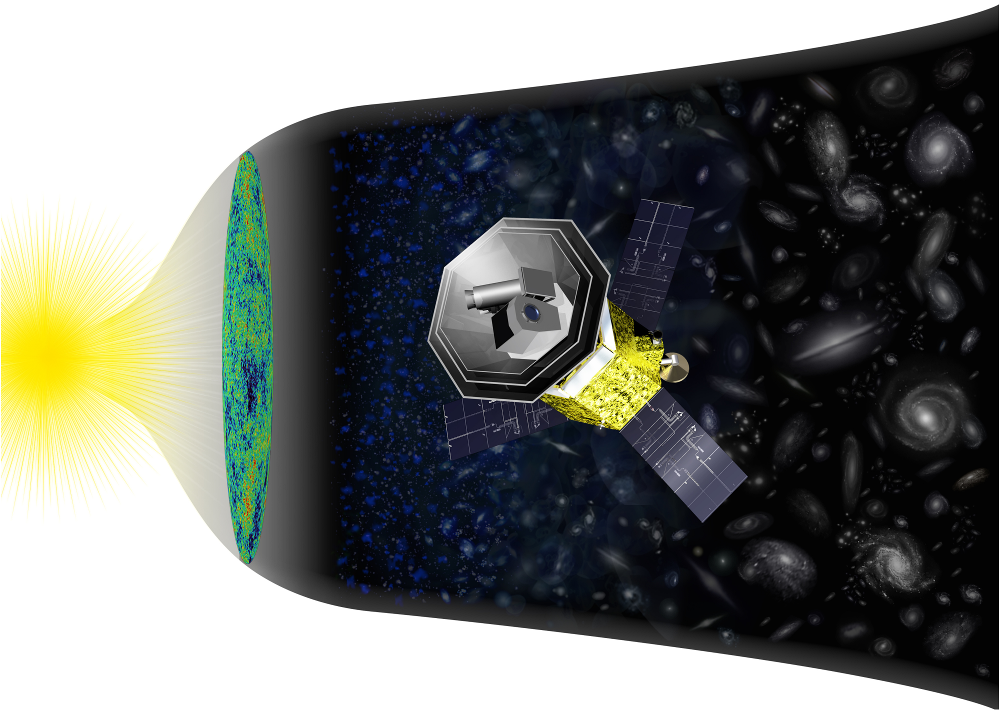
LiteBIRD

Detecting Primordial Gravitational Waves From Inflation



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1 Résumé

LiteBIRD is a Japanese satellite mission for CMB observation that will provide essential clues about the birth of the Universe at a time approximately 10^{-35} sec after the putative Big Bang. LiteBIRD will probe the primordial universe through ultra-precise measurements of the polarization of the cosmic microwave background (CMB) anisotropies on intermediate and large angular scales. This will permit a measurement with unprecedented precision of the B-mode polarization amplitude, thus testing the unique prediction of Cosmic Inflation that the already well mapped scalar cosmological perturbations, which cannot produce a B-mode polarization pattern, were accompanied by a stochastic background of primordial gravitational waves. Cosmic Inflation presently provides the most satisfying theoretical framework for explaining our present Universe through New Physics at energy scales far beyond those of the Standard Model. However, an observational confirmation of this remarkable prediction is as yet lacking. On the time scale of the forthcoming decade, LiteBIRD will be uniquely positioned to achieve this goal, capitalizing on the extremely stable environment at the Sun-Earth L2 point, its exquisite instrumental sensitivity, and its control of instrumental and astrophysical systematic errors.

LiteBIRD will have three telescopes: a Low Frequency Telescope (LFT), a Medium Frequency Telescope (MFT), and a High Frequency Telescope (HFT). LiteBIRD will observe in 15 frequency bands spanning from 35 GHz to 450 GHz and employ state-of-the-art kilo-pixel arrays of multi-chroic detectors with multiple modulations of the polarized signal obtained through an advanced scanning strategy and a continuously rotating polarization modulator (HWP). The resolution of LiteBIRD will range from $18'$ to $70'$ corresponding to the highest and lowest frequency channels, respectively. These features ensure sufficient redundancy and control of systematic effects, which will permit establishing an upper limit on the tensor-to-scalar ratio r of order 10^{-3} (i.e., nearly two orders of magnitude better than current limits or a detection with high significance if r is much higher).

The LiteBIRD design and optimization is driven by B-mode science. Nevertheless, LiteBIRD's impact will be much broader, extending to many other areas of cosmology and astrophysics. LiteBIRD will establish unique constraints on the large angular scale E-mode polarization, and thus will pin down some crucial cosmological parameters such as the optical depth τ, which LiteBIRD will constrain with the precision of $\sigma(\tau) \sim 2 \times 10^{-3}$ (assuming $\tau = 0.055$), limited only by sampling variance. This will considerably helps constraining the neutrino sector breaking the degeneracy with the sum of the neutrino masses. LiteBIRD will also provide unique insights into the large scale structure of the Galactic magnetic field. The full-sky, multi-frequency maps produced by LiteBIRD will constitute a rich and lasting legacy, in particular for the study of the Galactic emissions.

The LiteBIRD satellite is a JAXA 'strategic large mission' with a JAXA budget of 300 M$ selected for a launch in early 2029. In Japan, the project is currently in Phase A (until end of 2023). A US NASA participation is envisaged at the level of 65 M$. The CNES entered into a Phase A in September 2019 until the end of 2021 with the responsibility for the MFT and HFT in collaboration with the European space agencies and the ESA.

The French participation includes strategic hardware contributions to the MFT and the HFT consisting of the sub-Kelvin cooling system, the mechanical structure for the telescopes, the electronics and on-board software and the telescopes calibration. These contributions directly address crucial stages of the detection chain of the LiteBIRD MFT and HFT telescopes, which in turn is critical to the success of the entire project and thus will ensure a high visibility of the French contribution. These participations build on expertise already acquired in France through work on other projects, in particular the Planck HFI, but also Athena, PILOT, and other ground-based or balloon-borne experiments. These instrumental contributions will enable a substantial and highly visible French role in all stages of the data analysis and scientific exploitation of the LiteBIRD data sets.

2 Enjeux scientifiques

Over the past few decades, technological developments and ambitious observational programs have transformed modern cosmology from a data-starved into a data-rich science. New data sets complemented by advanced data analysis techniques and improved theoretical interpretation have converted cosmology into a precision science with an established Standard Model: the hot Big Bang cosmology. This model provides a framework within which to interpret new observational and experimental results. Measurements of the cosmic microwave background (CMB) temperature and polarization anisotropies have played a key role in the rise of modern cosmology. The ultra-precise mapping of the polarization promises to lead to important breakthroughs, as we describe below. Further observational tests of this model and improved constraints on it are essential to improve on our understanding of the big questions concerning the Early Universe. This work also has close connections to fundamental physics. Superstring theory, for example, makes predictions concerning New Physics that cannot be tested in the laboratory. However, the Early Universe provides the extreme conditions needed to test ideas about how the strong, weak, and electromagnetic interactions unify with gravity, presumably somewhere near the Planck scale.

According to the hot Big Bang cosmology, the Universe started in a very dense, hot state, cooling down due to adiabatic expansion and ultimately reaching its present state observed today. It is believed that small initial perturbations assumed to have been generated early on grew owing to their own self-gravity, thus giving rise to the current cosmic structures: filaments, clusters of galaxies, and the galaxies themselves. The initial perturbations also left an imprint of tiny fluctuations on the otherwise homogeneous and isotropic background of primordial photons that we today observe as the CMB. Nearly all current observations can be explained within this model, qualitatively and quantitatively. In its minimal form, this model is referred to as the 'concordance model' and is specified by only six parameters. One of the great challenges now is to understand the origin of these initial perturbations.

Cosmic Inflation currently offers the best framework for explaining the origin of these initial conditions as opposed to accepting them as an *ad hoc* boundary conditions without any deeper explanation. Cosmic inflation is a remarkably successful family of theories for the new physics beyond the Standard Model of particle physics. Inflation provides the initial conditions for the hot Big Bang cosmology theory. First proposed in the early 80s, inflation succeeded in remedying a number of shortcomings of the hot big bang cosmological model (e.g., the flatness, smoothness, monopole, and horizon problems) in a particularly economical and elegant way. Inflation has been also shown to provide a predictive mechanism for generating the initial departures from perfect homogeneity and isotropy with well-defined and calculable statistical properties. Many of these predictions regarding the 'scalar' cosmological perturbations, namely the nearly perfect Gaussianity and the approximately scale-invariant spectral shape, have already been tested at modest precision by previous observational efforts, in particular by the observations made by the ESA Planck space mission. While compelling evidence in favor of inflation has been accumulating, as of today no decisive proof of inflation has been found.

Perhaps the most striking prediction of inflation is that these 'scalar' perturbations should be accompanied by a stochastic background of gravitational waves also generated during inflation. This prediction has not yet been tested. Unlike the gravitational waves recently detected by LIGO, which arise from local sources and are of relatively short wavelength, the gravitational waves from inflation have a very 'red' spectrum, and their typical amplitude on large scales is quantified by the so-called tensor-to-scalar ratio r. The current upper limit on r is 0.07 (95% c.l.). This means that no more than 7% of the primordial power is due to primordial gravitational waves, or tensor modes. However, the precise value of r matters! Detecting r, and in particular setting a very tight limit on its value, would have transformational consequences for cosmology. A detection would provide invaluable clues about the laws of fundamental physics at energies more than 12 orders of magnitude beyond what could eventually be probed with Large Hadron Collider—and also on length scales more than 12 orders of magnitude larger than the future LISA space mission, and thus not accessibly in any man-made laboratories in the foreseeable future.

Although these gravitational waves leave their trace on all CMB temperature and polarization anisotropies, the B mode of the CMB polarization offers the most sensitive way to detect large-wavelength primordial gravitational waves of the sort generated during inflation. This is because the ordinary 'scalar' perturbations cannot excite the B mode at linear order, and thus any confusion in the primordial gravitational wave detection can come only due to the B-mode signal generated through the higher-order corrections (such as from gravitational lensing). These are not only readily calculable but demonstrated to be very small on large angular scales. The large angular scales, $\gtrsim 1^\circ$ therefore provide a unique and direct window onto the primordial, gravitational-wave generated B-mode signal, in principle permitting constraints on r nearly two orders of magnitude better than current limits. The statistical weight of the primordial B-mode signal is concentrated in two windows: the reionization bump, on very large angular scales; and the recombination bump, on scales slightly exceeding 1 degree, at least for sufficiently large values of r. Detecting both these features would unequivocally demonstrate the primordial nature of the detected signal. To resolve the recombination bump requires only a modest resolution of $\sim 30'$.

In contrast, on smaller, subdegree scales, the B-mode signal is dominated by lensing-generated contributions and thus not directly useful for setting limits on r. This small scale information however can be used to remove the lensing signal on both small and large angular scales. If such 'delensing' can be realized, an even better constraint on r will be possible. The gain from delensing is most important for very low values of $r \lesssim 10^{-3}$. Measuring both large and small angular scales would also constrain the slope of the gravitational wave spectrum n_T. While there is no doubt that having high $\lesssim 5'$ resolution from space would be desirable, it sets formidable requirements for the instrument itself that have to be weighed carefully against the expected overall performance improvement and its impact on the targeted science, given the instrumental noise and the presence of anticipated systematic errors. In contrast, the case for a medium-resolution mission is robust and scientifically very appealing. It is based on four main pillars. These are:

Inflation. Cosmic inflation can be realized within different theoretical frameworks. One of the major challenges is to understand how inflation could be realized within the framework of an underlying theory. Indeed, there is a large number of inflationary models to be confronted with observational data. These models include those arising from GUT and string theories, which despite their theoretical appeal lack convincing experimental evidence. To test these models, headway can be made with a detection or a tight upper limit on r. Given the multiplicity of the inflationary models there is no unique prediction for r, but essentially a continuum of predictions extending all the way to values compatible with zero. Nevertheless, a precision on r of order 10^{-3} seems to stand out, permitting a robust detection of the 'next-order', 'natural' expectation for r, and would entail important repercussions for a number of existing models. For instance, setting an upper limit on r of order $\mathcal{O}(10^{-3})$ would falsify large-field models as well as the popular Starobinsky model, as shown in Fig 1. Luckily, this is also the level that can be reached given our current state of detector technology and knowledge of astrophysical contaminants. Not surprisingly, nearly all past and recent CMB satellite proposals (EPIC, BPOL, CORE, PIXIE, LiteBIRD, ...) have targeted this value. Among these LiteBIRD is the only mission that could feasibly realize this goal within the next decade. LiteBIRD will be capable of capitalizing on synergies with the complementary ground-based initiative CMB-S4, which aims to perform high-resolution ground-based observations on a similar time scale (see Sect. 4).

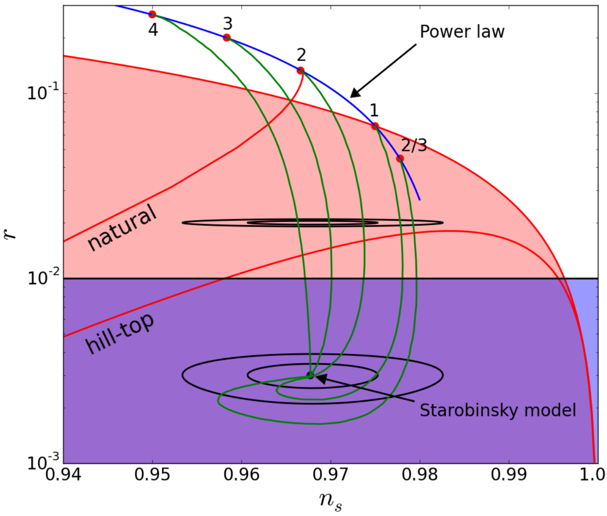

Figure 1: LiteBIRD constraint forecasts on two key inflationary parameters: the tensor-to-scalar ratio r and the spectral tilt of the primordial spectrum of density perturbations n_s, for two cosmological scenarios with $r = 0.02$ and $r = 0.002$. Solid lines show predictions for different families of inflationary models. LiteBIRD will reject many popular models of inflation. Figure taken from NASA MO proposal.

A reliable and convincing detection of primordial gravity waves would constitute a revolutionary break-through discovery having a major impact on our understanding of the origins of the Universe. Such a discovery would also have a major impact on other areas of fundamental physics. Achieving the scientific objective described above will require an exquisitely stable environment and an instrument with access to the full sky across a broad range of wavelengths, and an outstanding control of systematic effects matching its raw sensitivity. These conditions have only been demonstrated in space.

Large-angular scale CMB E-mode polarization. LiteBIRD will also provide a measurement of large-scale E-mode polarization of the CMB, which will yield a cosmic-variance-limited constraint on the value of the optical depth τ. Aside from its inherent interest as a way to probe the reionization history of the Universe, a measurement of the optical depth τ is indispensable in order to break existing parameter degeneracies with the overall amplitude of the primordial cosmological perturbations. In particular, this large scale measurement will have important consequences on the estimation of neutrino mass through lensing potential reconstruction. Although not directly performed by LiteBIRD, this latter is and will be achieved by high resolution ground-based experiments, such as CMB-S3/4, likely in combination with other data sets coming from LSST, Euclid and DESI. Therefore, through the measurement of τ, LiteBIRD enables the use of smaller angular scale data to determine the neutrino masses or the equation state of dark energy. Planck data are dominated by instrumental noise and also contain residuals from a combination of instrumental and astrophysical effects. No other data is expected to become available before LiteBIRD.

Multi-frequency polarized sky maps. High precision large-scale measurements of the CMB polarized anisotropies taken in multiple frequency bands will constitute the true legacy of LiteBIRD. Exploiting these full-sky polarization maps will provide important clues about the physics of Galactic foregrounds, which will directly inform Galactic model building, in particular concerning large-scale magnetic fields. Such measurements will also set limits on possible distortion of the energy spectrum from the perfect blackbody form, producing high-fidelity maps of the μ and y parameters and thus constraining energy generation by exotic process as well as the physics of the cosmological reionization. In models where the dark matter consists of axions, the conversion of CMB photons into axions by a magnetic field can also imprint a recognizable spectral distortion, turning the large angle CMB sky into a probe of dark matter. As the relevant information is distributed over a broad range of scales, a higher resolution means typically more information. Nonetheless, full-sky maps with a resolution of order a degree or larger will already constitute a unique data set, with a potentially high impact on these science areas.

Exotic physics and non-standard models. In addition to these primary science objectives, a clean map of the primordial CMB polarization on large scales will also shed light on more exotic physics possibly at play in the primordial universe, on departures from the standard paradigm, and on new phases in the early universe, which are poorly constrained. These maps will allow new searches for non-Gaussianity, possible couplings of the inflaton to a spectator field (including EB correlations, letpon and baryon asymmetry, etc.), parity violation (either at a fundamental level or through primordial magnetogenesis), and constraints on the physics of post-inflationary reheating.

As we explain below, only with a dedicated satellite mission can these science objectives be achieved. The LiteBIRD satellite has been optimized to carry out this science program in a reliable and economical manner.

3 Projet

3.1 Mission goals

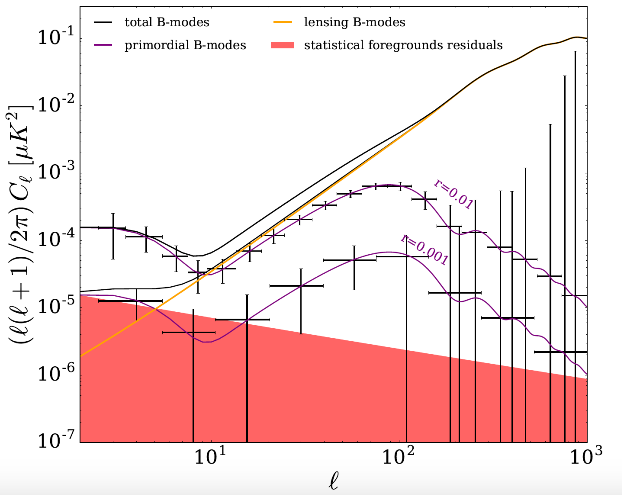

Figure 2: Projected LiteBIRD constraints on the primordial CMB B-mode spectra with $r = 0.01$ and 0.001 are shown with black crosses. The uncertainty involves cosmic variance of the primordial and lensing signals, noise, and residual foregrounds. This shows that LiteBIRD will be capable of detecting two bumps of the primordial spectrum if r is high and of setting marginal constraints on r as low as $r \approx 0.001$. The red shaded area depicts the 1σ uncertainty on the level of foreground residual remaining after a typical component separation.

LiteBIRD is a satellite mission currently under Phase-A study in Japan. LiteBIRD's design will permit achieving the science goals described in Sect. 2 focusing on those aspects of the B-mode science, that can be reliably delivered only from space and that can be achieved without a removal of the small-scale lensing signal.

The primary science objective of LiteBIRD is the discovery of primordial gravitational waves predicted to have been generated during the epoch of Cosmic Inflation. This objective is the driving principle behind its design. LiteBIRD will be capable of constraining with high precision the total B-mode spectrum in the multipole number range up to $\ell \sim 200$ and setting an upper limit on r of $\approx 10^{-3}$, including statistical and systematic uncertainties, or detect r with high significance if r happens to be larger. (See Fig. 2.) Indeed, LiteBIRD's constraint on the total B-mode spectrum will be cosmic variance limited up to $\ell \approx 200$ independently on the value of r with a potential exception of the lowest multipoles, which will be affected by extra uncertainty due to the foreground removal, in particular if r is low. These levels of sensitivity are certain to shed new light on our understanding of physics of the very early Universe in general and of inflation in particular. They will also start to restrict significantly parameter space available for viable models of inflation as shown in Fig. 1 and discussed in Sect. 2.

In order to achieve the required performance, LiteBIRD will observe the sky in multiple frequency channels deeply enough to produce foreground-cleaned maps of the CMB polarization over the full sky with a noise level of $\sim 2.5\,\mu$K·arcmin. This sensitivity, taken at face value, would let LiteBIRD set an upper limit on r on the order of (few) $\times 10^{-4}$ due to the statistical uncertainty of the noise and sample variance. This value, however, increases up to $\sim 10^{-3}$ if also systematic effects due to residual emissions and instrumental effects are conservatively incorporated. Even in this case, LiteBIRD will set constraints on the B-mode spectrum within a range of angular scales sufficiently broad to detect both reionization and recombination bumps of the B-mode primordial spectrum, Fig. 2. This double detection would confirm the primordial nature of the observed signal. Indeed, for $r = 0.01$ both bumps will be detected by LiteBIRD on 5σ level.

These forecasts include extra uncertainty due to gravitational lensing induced B-modes present on the large angular scales, demonstrating that **LiteBIRD can achieve its stated science goals without any delensing**. However, LiteBIRD will be well matched to the next generation of the ground efforts as planned for the next decade, allowing for follow up and joint analyses, which will further extend LiteBIRD's impact and its legacy. Whether this will be warranted or not will depend on the level of non-statistical uncertainties as found in the actual data and efficiency of still to be devised, practical delensing techniques. We discuss this in more detail in Sect. 4.

While striving for its main science objective, LiteBIRD will address many other science goals requiring large or intermediate resolution, as mentioned in the previous section. Notably, this will include mapping the E modes of the CMB polarization with exquisite precision. At low ℓ, the measurement of E modes by LiteBIRD will be limited only by unavoidable cosmic variance, thus constraining the reionization optical depth with unprecedented accuracy of $\sigma(\tau) = 2\times10^{-3}$ (where the Planck value $\tau = 0.055$ is assumed), Fig. 3.

This measurement will not only provide constraints on reionization models but will also greatly reduce the degeneracies in determining the cosmological parameters from the CMB, in particular removing the degeneracies in the overall amplitude of the B-mode lensing signal, and thus help to enable absolute neutrino mass determinations, see Table 1.

LiteBIRD will also produce full-sky microwave polarization maps in multiple frequency bands with sensitivities more than an order of magnitude better than the maps delivered by the Planck satellite. These maps will have lasting legacy value and help us map the Galactic magnetic field and understand the physics of the Galactic dust.

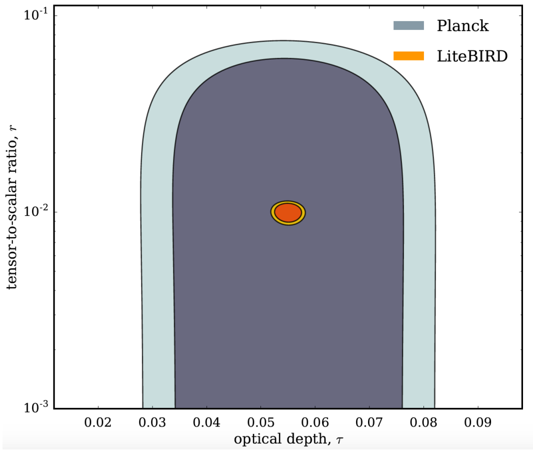

Figure 3: LiteBIRD constraint forecasts on the tensor-to-scalar ratio r and the optical depth τ as compared to the current Planck results. The assumed fiducial value of τ is set to the Planck value 0.055 while r is assumed to be 0.01. The 1σ and 2σ regions are shown. No instrumental systematics are accounted for. LiteBIRD will deliver cosmic variance limited constrain on τ.

3.2 Experimental approach

A reliable detection of the B-mode signal poses numerous outstanding challenges for the instrument, its operations as well as data analysis, which a successful experiment will have to address. LiteBIRD has been specifically designed to overcome them in order to deliver the science goals defined in the previous Section. Here we outline some of the main challenges facing the CMB B-mode experiments and LiteBIRD's approach to tackling them.

SENSITIVITY. The expected amplitude of the primordial B-mode signal is very small. To detect B modes an experiment must achieve a sufficient sensitivity. The noise of modern CMB detectors is limited by the intrinsic fluctuations of incident photons, which generate noise many orders of magnitude higher than the sought after signal. The required sensitivity can only be reached using a large number of detectors observing the sky simultaneously over an extended period of time, covering the sky as uniformly as possible.
▷ LiteBIRD will employ state-of-the-array kilo-pixel arrays of very sensitive detectors. These will operate in a very low background environment of the Sun-Earth L2 point and benefit from the cooling of the LiteBIRD mirrors down to 5K. These will ensure high instantaneous sensitivity of the LiteBIRD focal planes. LiteBIRD's operations over 3 years will result in a uniform sky coverage ensuring the required on-the-sky sensitivity of $\sim 2.5\,\mu$K·arcmin (more than an order of magnitude deeper than Planck-HFI).

LONG-TERM TRENDS. The long observation times require a very stable instrument as well as a very stable operating environment. The time drifts and long-term correlations are particularly relevant for observations of large-angular scales, which can be scanned only over long time periods.
▷ LiteBIRD's vantage point at L2 provides the most stable environment accessible for CMB observations. Furthermore, LiteBIRD's one-axis stabilized satellite permits complex scanning strategies, which will be optimized to mitigate any residual long term drifts and correlations, ensuring that any beam-size pixel will be revisited on multiple time-scales and crossed from different directions. LiteBIRD's active polarization modulator, a half-wave plate (HWP), will move the polarized sky signals to frequencies sufficiently high that any contributions from long-term effects will be negligible.

INSTRUMENTAL EFFECTS. The B-mode signal has to be detected in the presence of much larger signals, such as total intensity and E-mode polarization of the CMB itself. Any spurious B-mode like contribution resulting from conversion of these signals via instrumental effects is likely to dominate the primordial signal. Controlling these and other instrumental effects to sufficient, and indeed excellent, precision is necessary. The relevant effects include intensity-to-polarization or cross-polar leakages typically incurred in the optics of the instruments, but also beam asymmetries or side lobes. Other instrumental effects which need to be exquisitely controlled are detector band-passes as well as their relative calibration. These are crucial in order to permit separation of non-cosmological contributions.
▷ LiteBIRD's HWP placed as the first optical element will permit a robust differentiation of the spuri-

ous polarization generated by the instruments optics. The HWP will also facilitate the reconstruction of the sky signal separately from the data of each LiteBIRD detector, minimizing the effects due to beam or band-pass mismatches between the detectors. LiteBIRD optics will be designed to minimize the stray-light using high quality lenses, anti-reflection coating and proper shielding. The LiteBIRD instrument will be carefully calibrated both on the ground and in-flight capitalizing on polarized and unpolarized astrophysical sources. Advanced models of the LiteBIRD instruments developed and tested against the data during those campaigns will be later used to correct for remaining unwanted effects during the data analysis.

Non-cosmological signals. CMB detectors due to their extraordinary sensitivity are prone to detecting, alongside the sought-after signals, contaminations of non-cosmological origins. These include signals emitted by our instrument, the environment, or the Galaxy. A successful experiment will have to be either capable of shielding off undesired signals or to possess sufficient redundancy to distinguish and remove their contributions. In particular, the Galactic emissions are recognized as one of main limiting factors in the quest for the primordial B-mode signals as they can not be effectively shielded off. In spite of the significant progress achieved in this area, most recently thanks to the Planck satellite, these so called foregrounds are poorly known in particular as far as their polarization is concerned. One has to rely on either their frequency scaling being different from that of the CMB or differences in morphology between the two signals. The instruments have to be designed carefully with sufficient redundancy to allow capitalizing on such differences. As ultimately the extraction of the genuine CMB signal from the data will have to rely on novel data analysis techniques, a careful assessment is required to decide what has to be addressed through hardware requirements and what can be dealt with later in software.
▷ LiteBIRD will capitalize on the flexibility of the satellite and the scanning strategy and careful shielding to avoid radiation from the Sun, the Earth and the Moon. To remove the Galactic emissions LiteBIRD will use 15 frequency bands spanning broad range of frequencies which will permit separating signals of a different origin using variety of different and complementary data analysis techniques. The optimization of the frequency bands of LiteBIRD as well as the per band sensitivities is an on-going process, where progressively more complex Galactic emission models as well as data analysis techniques are developed and applied to forecasting (see Fig. 4).

Cosmic rays. Cosmic rays can have potentially big impact on the quality of data collected by a space mission. This has been one of the lessons learned from the Planck HFI mission and if not accounted for can pose an even bigger problem for more sensitive experiments involving large arrays of the detectors.
▷ LiteBIRD detectors will be specifically designed and tested to ensure that the heat and phonons deposited by cosmic rays are quickly dissipated minimizing their impact on the detector arrays overall performance.

pointing and global calibration. A direction of the observations for any collected sample as well as the orientation of the polarization sensitive detectors with respect to the sky need to be reconstructed with high precision to prevent leakages of the much higher E-mode signal into B or generating spurious EB correlations. The latter if real would constitute evidence in favor of parity violations in the early Universe, e.g., due to primordial magnetics fields or axions coupled to photons.
▷ LiteBIRD will employ high-quality star cameras to reconstruct the pointing and use astrophysical sources to characterize the beams and calibrate the orientations of the polarizers.

3.3 Design

As currently designed [1], LiteBIRD will observe the sky in 15 overlapping frequency bands spanning the range from 34 GHz up to 448 GHz (Fig. 4). The frequency range is achieved using three side-by-side telescopes each actively cooled to 5K: a Low-Frequency reflecting Telescope (LFT) and two refractive telescopes a Medium-Frequency Telescope (MFT) and a High-Frequency Telescope (HFT). Significant overlap is ensured between the frequency of the three focal planes (100, 119, and 140 GHz will be common to LFT and MFT while the 195 GHz channel will be common between MFT and HFT). LiteBIRD will include 4508 transition edge sensors (TES) deployed on the two telescopes cooled to 100mK.

Each LiteBIRD telescope will have a separate continuously rotating half-wave plate (HWP) as the first ele-

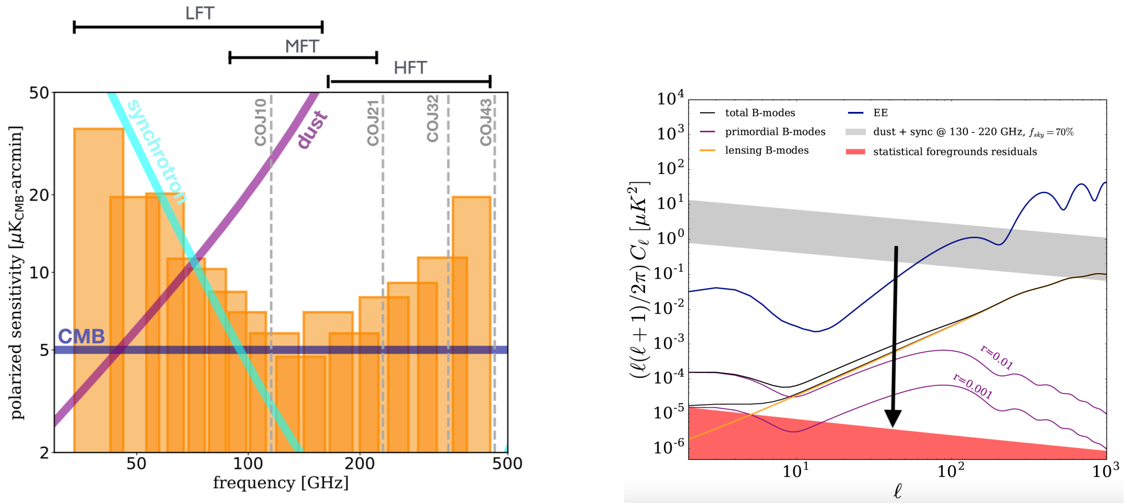

Figure 4: Left panel: Frequency bands and their sensitivity (units on the left vertical axis) in the current LiteBIRD baseline design, compared with the main diffuse foregrounds emissions (units on the right vertical axis). Frequency bands and associated sensitivity are optimized to ensure a good signal-to-noise across frequencies, therefore ensuring the best performance in cleaning the astrophysical components and extracting the primordial signals. Right panel: Foreground amplitude in the CMB channels prior, gray shaded area, and after component separation assuming LiteBIRD's frequency channels as in the left panel. These are contrasted against the sought after CMB B-mode signals. The foreground signal is suppressed by nearly five orders of magnitude and mostly below the targeted levels as marked by the black arrow. The red area shows statistical residual only, 1σ, and no systematic effects have been accounted for.

ment of its optical chain to modulate the polarization. This choice ensures a measurement of polarized signal for each individual detector on all sky position, without requiring for scanning redundancy, by suppressing the $1/f$ noise and mitigating systematic errors (including beam and polarization non-ideality, gain variation, and bandpass mismatch).

The proposed 300 K - 4.8 K cryogenic chain for LiteBIRD is based on the architecture developed as part of the SPICA SAFARI mission. It combines radiative cooling with mechanical cryocoolers to provide cooling to temperatures down to about 4.8 K. In its current definition, a 15 K pulse tube cooler associated with 3 V-groove radiators, respectively at 160 K, 90 K and 30 K, intercept part of the thermal loads. Then, one helium Joule Thomson loops (4 K JT, 4He), pre-cooled by 2 two-stage Stirling coolers (100 K / 20 K). Both MFT and HFT have intermediate cold stages at 1.8 K and 0.3 K between their mechanical enclosure at 4.8 K and the detectors at 0.1 K. The 2 K cooler is based on three ADR stages in parallel to provide a continuous cooling at 1.7 K. The controlled heat rejection of the 2 K cooler operation will be used to damp the 4.8 K stage thermal oscillations. The Sub-Kelvin cooler is made of two ADR stages in parallel to provide a stable and continuous cooling at 0.3 K combined with two other ADR stages in parallel for the 0.1 K stage.

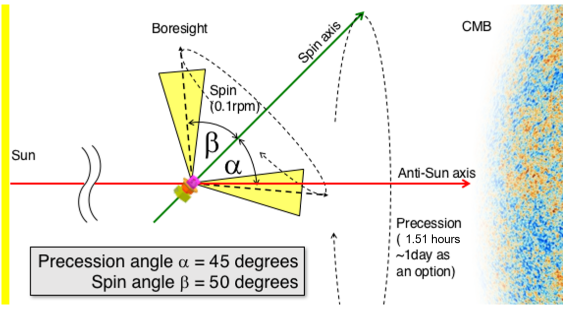

Figure 5: LiteBIRD's scan strategy will involve both precession and spin, while the satellite follows a Lissajous orbit around L2, which in turn orbits around the Sun. [Adapted from JAXA proposal.]

LiteBIRD will operate over 3 years, observing the full sky multiple times. Its scanning strategy will combine multiple simultaneous motions of the telescopes, each with a different characteristic time scale (Fig. 5), capitalizing on the flexibility of the one-axis stabilized spacecraft.

4 Etat de l'art

The CMB is a very active field of research with many dedicated experiments currently on line or planned that will observe the CMB from ground-based and balloon-borne platforms. LiteBIRD is the only project planned for the next decade that will be able to benefit from the unique advantages offered by space. Space is particularly conducive to CMB observations because it provides an extremely stable, low background environment, while simultaneously permitting observations of the entire sky via highly redundant, well cross-linked sky scans. Both are crucial for providing reliable constraints on the largest angular scales, where exquisite control of the long term trends is essential. Space also offers unrestricted access to the entire frequency range, thus allowing for the best possible removal of Galactic contaminations.

LiteBIRD will be a dominant force in the quest for the primordial B-mode signals on the time scale of the next 10-15 years. Historically, every CMB satellite mission from COBE to WMAP and Planck has resulted in a leap forward in our understanding of the Universe, crowning years of important albeit more incremental efforts from balloons and the ground, and moving the field to the next level of precision and robustness. LiteBIRD will continue this tradition. We note that if the amplitude of the primordial gravitational waves r happens to be large enough to be detectable by one of the future sub-orbital experiments, LiteBIRD will provide a high precision measurement and high signal-to-noise characterization over a broader range of angular scales, which will be crucial for setting constraints on inflationary models and physics, thus addressing the main science question, which the mission is designed for. If r is low, LiteBIRD will be in a unique position to either detect it or set the most restrictive upper limit. In either case LiteBIRD is bound to have fundamental impact on our understanding of the early Universe, delivering all of its key science goals single-handedly.

On the time scale of LiteBIRD, the CMB ground community is considering the deployment of an 'ultimate' ground-based CMB observatory called CMB-S4, which is planned to observe a significant fraction of the sky (around 40%) using $\mathcal{O}(500,000)$ polarized sensitive detectors in 5-10 frequency bands [2, 3] covering all available atmospheric windows between ~ 30 to ~ 280GHz. CMB-S4 is anticipated to include multiple telescopes with a range of apertures. These will include large aperture telescopes for lensing-related science goals (e.g., neutrino masses, dark energy, combination with optical measurements, etc). These telescopes will produce complementary data sets particularly suitable for the joint analysis with LiteBIRD data. However, any other sufficiently powerful ground data set may be considered here as well.

Because the LiteBIRD design focuses on those aspects of the CMB signal that are only accessible or best carried out from space, it is naturally complementary to high-resolution ground-based efforts. **A joint analysis of LiteBIRD and ground-based data set of sufficient resolution could further improve the constraints produced by the mission better LiteBIRD's stated target**. This is illustrated in Table 1, where for definiteness we assume that the CMB-S4 data cover the multipole range from $\ell = 30$ to $3,000$, the white noise level in map-domain after component separation is $\sim 1.5\mu$K.arcmin over a sky fraction $f_{sky} = 0.4$ and that the noise correlations are characterized by $\ell_{knee} \approx 60$. These specifications are clearly ambitious and are used here merely for the illustrative purposes.

Typically in such a combination, the CMB-S4 ground observatory provides the intermediate and high resolution to be combined with the large-scale information from LiteBIRD. When analyzed together these data sets will improve constraints on key cosmological parameters. In particular, we find that under these assumptions up to 60% of the lensing signal can be removed with help of the internal delensing, where the lensing potential is estimated internally from the same ground data set. This level is similar to the 50% delensing level potentially achievable via delensing based on some external data, e.g., of the cosmic infrared background [4]. Consequently, the derived constraints would be similar in both cases. Whether such a level of delensing can be achieved needs to be confirmed by a more detailed investigation accounting for instrumental and other systematic effects in a more realistic way. In this example, the significant level of delensing explains the large overall improvement of the constraints on r and spatial spectral index of the tensor perturbations, n_T, obtained from the joint analysis as compared to the LiteBIRD alone results as shown in the Table. The improvement on the constraint of the total mass of neutrinos is due to the addition of the small scales from CMB-S4. However LiteBIRD's tight limit on the optical depth τ is very important in determining the

parameter	fiducial value	LiteBIRD	LiteBIRD +'CMB-S4'	Planck
tensor-to-	$r = 0.01$	0.00086	0.00031	$r \leq 0.07^{(a)}$ (95%)
scalar ratio	$r = 0.001$	0.00058	0.00017	$r \leq 0.07^{(a)}$ (95%)
tensor index ($r = 0.01$)	$n_T = -0.00125$	0.17	0.10	-
scalar amplitude	$\ln(10^{10} A_S) = 3.064$	0.0042	0.0033	$0.024^{(c)}$
scalar index	$n_S = 0.9667$	0.0030	0.0013	$0.0044\ ^{(c)}$
total neutrino mass	$\sum m_\nu = 60\text{meV}$	117meV	38meV	589meV $^{(c,d)}$
optical depth	$\tau = 0.055$	0.0020	0.0018	$0.013\ ^{(c)}$

$^{(a)}$ from Planck+BICEP2+Keck Array; $^{(b)}$ $\simeq$ 11meV if DESI included; $^{(c)}$ from Planck 2015 results. XIII. Cosmological parameters; $^{(d)}$ from TT+TE+EE+lensing. Constraint on total neutrino mass becomes $<$ 194meV for TT+TE+EE+lensing+ext+BAO+JLA+H_0.

Table 1: Key 68% C.L. constraints from LiteBIRD alone or combined with a putative CMB-S4-like experiment and compared with the current limits from Planck. We include statistical errors from synchrotron+dust cleaning and assume iterative internal delensing for the combined constraints [7]. The CMB-S4-like experiment adopted here is described in Sect. 4. Foregrounds properties are allowed to vary on a typical angular scale of $\sim$ 15 deg [8]. We note that more complex sky models may lead to degradation of some of the quoted constraints and may require more advanced component separation methods [9, 10]. These issues are actively being studied as part of the LiteBIRD preparatory work.

combined constraint in particular if other cosmological probes, e.g., baryon acoustic oscillations (BAO), are also used [5, 6].

Moreover, LiteBIRD will provide invaluable pieces of information for the small-scale science adding value to the science outcome of the suborbital efforts. Most notably, LiteBIRD will complement the frequency bands accessible from the ground, in particular by providing high frequency maps needed to trace the Galactic dust.

We conclude that standalone or in a combination with other data sets available within a decade from now, LiteBIRD will define the standard for the CMB research and cosmology for the decades following the mission, ensuring its lasting legacy and long-term impact on the field.

5 Génèse et calendrier

LiteBIRD is a Japanese strategic large satellite with the maximum budget for the JAXA contribution set at the equivalent of approximately 300 Million US dollars. The launch is scheduled for 2029. A US NASA contribution of 65 Million USD is envisaged. Contribution from the CSA (Canadian Space Agency) is under consolidation. On the Japanese side, LiteBIRD has undergone a Japanese Phase A study to be completed in March 2023. The US Phase A study has just been completed, and NASA has awarded a substantial amount for further technology development, which could allow the NASA and JAXA Phase B studies to become aligned.

The French involvement in LiteBIRD dates back to early 2015. Just after the first contact, the JAXA did propose to Europe to take in charge the highest frequencies of the instrument through a separate telescope (ending up in two telescopes after the ESA CDF in march-June 2018). After the Concurrent Design Facility (CDF), ESA decided not to take the lead of this part of the instrument but is still considering a substantial participation to the mission. The French collaborators proposed a mission of opportunity to CNES which accepted to start a Phase A2 in late 2019. **The decision to further continue in Phase B will depend on the selection of the Medium size mission at ESA (M5). This will occur by mid-2021.**

The CNES Phase A2 is for the study of the responsibility for the delivery of the medium- and high-frequency telescopes of LiteBIRD. The aim of the study phase is to work with the Japanese and US partners to converge on the design and to define constraints on the various sub-systems. The goal will also be to reach the appropriate Technical Readiness Level for each sub-system according to the project requirements. If then selected for Phase B, the CNES will be in charge of delivering the various models of the instruments to JAXA.

2017 - 2019	JAXA pre-Phase A
May 2019	Class-L Mission Selection
09/2019 - 03/2022	JAXA Phase A1
End 2021	System Requirement Review
03/2022 - 03/2023	JAXA Phase A2
03/2023 - 06/2024	Phase B (Preliminary design)
01/2024 - 09/2025	Phase C (EM development and tests)
09/2025 - 12/2028	Phase D (FM production and tests)
early 2029	Launch
2029 - 2032	Mission Operation

Table 2: JAXA calendar

The CNES schedule is consistent with the main milestones of the Japanese and US plans. Actually, the JAXA schedule (Table 2) has been revised after the Hitomi failure. The LiteBIRD project, which is actually in Phase A1, will switch into a Phase A2 starting in March 2022 and lasting 1 year, up to March 2023.

After CNES Phase A2, we plan a more substantial implication of our team into the development and the tests of the Engineering Model (EM) during Phase C, and then into the production and the characterization of the Flight Model (FM) during Phase D. The current target launch is year 2029.

LiteBIRD is supported by the french community in France. It was recommended as high priority in the CMB roadmap[1] in 2018. In 2019, an endorsement letter with more than 140 signatures was sent to CNES together with the organisation of a ”LiteBIRD-day” in July 2019 (at APC).

IN2P3 was involved since the early times in the discussions for a European participation to the LiteBIRD project. The researchers of the institute actively participated to the discussions with CNES and the two proposals sent in 2017 and 2018. They played an important role in the ESA CDF (in particular in the thermo-mechanical design and the calibration plan). LiteBIRD has been presented at the labs Conseil Scientifique (LAL in October 2018 and APC in March 2020). Both recommend a strong support to the respective hardware involvement together with a support of the activity in the data analysis and science exploitation. It is an IN2P3 master-project since late 2019.

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[1] CMB roadmap available here

6 Organisation du projet

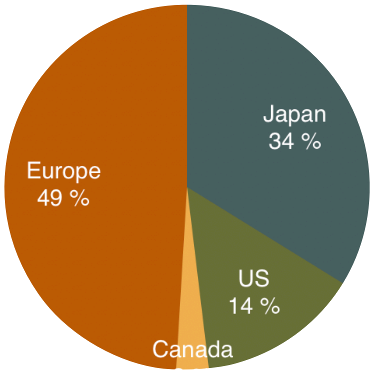

Figure 6: Distribution of the LiteBIRD collaborators.

The LiteBIRD international collaboration currently includes more than 200 researchers from Japan, North America and Europe (see Fig 6). The collaboration is managed through an Interim Governance Board (IGB) which members are nominated from Japan, Europe and North America. It is in charge of the management of the Joint-Study-Groups (JSG) as well as other sub-committees for specific tasks. The IGB is actually composed of 40 members including 7 French collaborators (4 from IN2P3: Sophie Henrot-Versillé, Guillaume Patanchon, Radek Stompor, Matthieu Tristram).

Design and forecasting studies are done within the Joint Study Groups (JSG). They are four of them: the systematic JSG, the foregrounds JSG, the calibration JSG and the Payload-module JSG. The international organisation also includes a Data Management Group, a simulation team, and a performance team. Bylaws for the Phase A are under currently being voted.

At the European level, we have set up a LiteBIRD-Europe steering committee with 9 country members, which are: France, Italy, UK, Germany, Spain, Denmark, the Netherlands, Ireland, and Sweden. Currently, the steering committee is made of 10 representatives: two for partners with important contributions on both instrumental and science aspects (France, Italy and UK), and one for the others (notice that Sweden and Ireland do not have any representative in the steering committee yet, since they integrated the collaboration only very recently). The members of the European Steering committee for France are: L. Montier (IRAP, INSU) and R. Stompor (APC, IN2P3). The LiteBIRD-Europe collaboration has regular meetings, on a trimestrial basis, which complements the bi-annual face-to-face (becoming screen-to-screen) meetings of the whole LiteBIRD collaboration, including Japan, US, Canada and Europe.

Since CNES took the lead of the MHFT for a Phase A2 in late 2019, France plays a key role in the European organisation, since L. Montier is the European Spokesperson. The coordination of the MHFT will be done by the CNES project manager (Thierry Maciaszek) with a project office which is under construction. The current version of the task-sharing for the hardware contribution (Fig. 7) will be proposed to CNES for validation at the Comité Inter-Organisme in October 2020. The corresponding European management plan for the collaboration is under redefinition.

The LiteBIRD-France organisation is supervised by the MHFT Principal Investigator: Ludovic Montier (IRAP). We hold regular phone meetings each week and have a dedicated wiki accessible on the web[2]. At this time the LiteBIRD-France team is composed of more than 50 researchers and 12 engineers from 13 laboratories covering 4 institutes (IN2P3, INSU, CEA, INP). This team is representative of the French CMB community and demonstrates the level of interest and the support of the community for the project. The ultimate composition of the LiteBIRD-France team will be decided when agencies will commit at the end of Phase A and will depend on the level of funding as well as our responsibilities within the project. This will be defined in a discussion with our partners in Europe, Japan, and the US and likely will involve a Memorandum Of Understanding (MOU) between all partners.

It is LiteBIRD's policy that full members of the collaboration, thus including all agreed LiteBIRD-France members, will have access to entire data set as collected by all telescopes LFT, MFT, and HFT. Details are currently define in the LiteBIRD collaboration policies.

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[2] http://litebird.in2p3.fr

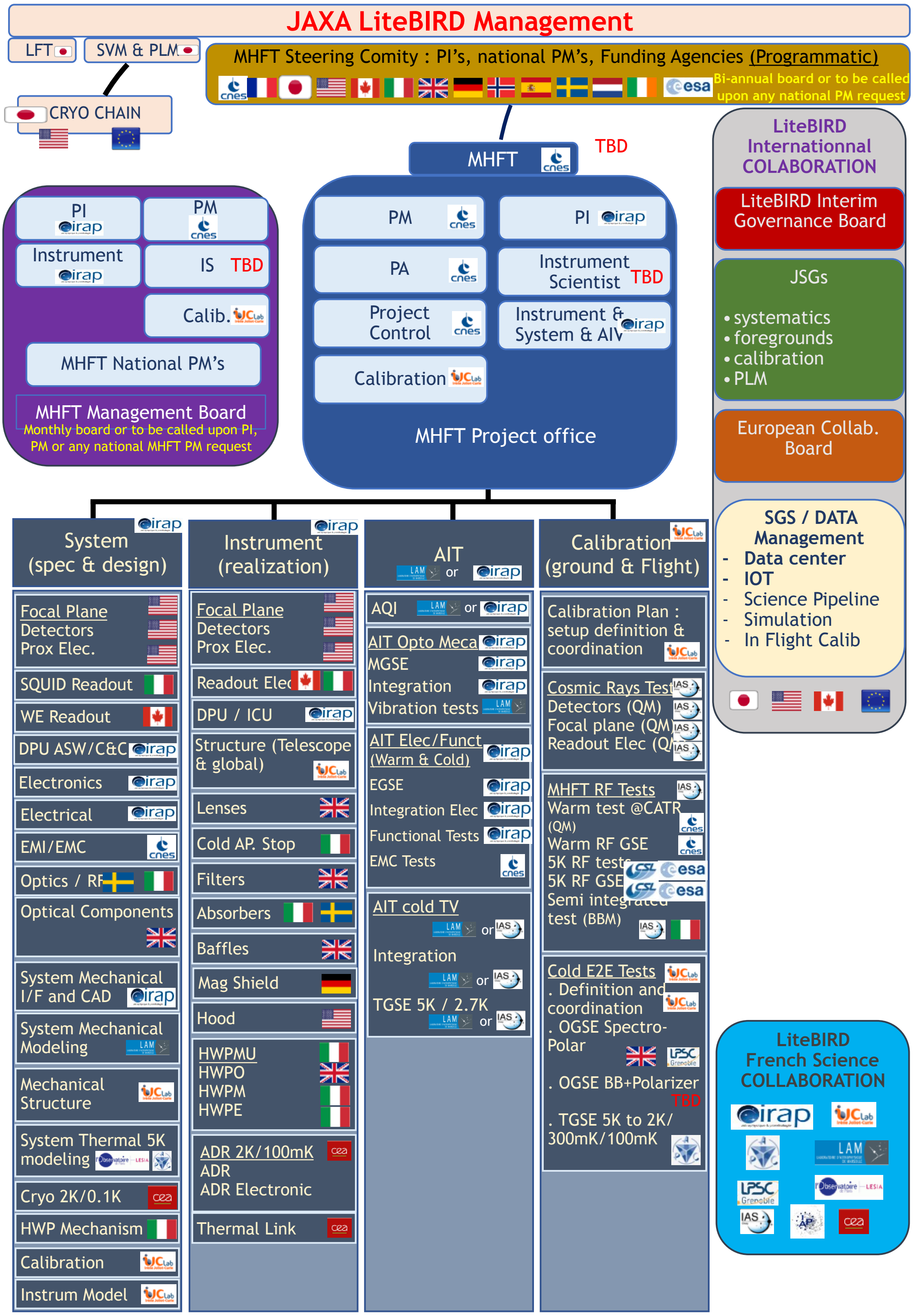

Figure 7: Current version of the task-sharing for MHFT that will be proposed to CNES at the next CIO.

7 Ressources et moyens

7.1 Team IN2P3

Currently at IN2P3, 3 laboratories are involved in the LiteBIRD master-project (APC, IJClab and LPSC) with 13 staff researcher and 8 engineers.

APC: Martin Bucher (DR,10%), Josquin Errard (CR,50%), Ken Ganga (DR,5%), Jean-Christophe Hamilton (DR,10%), Guillaume Patanchon (MdC,50%), Michel Piat (Prof,20%), Radek Stompor (DR,40%)
Laurent Grandsire (IR, 20%), Jean-Pierre Thermeau (IR, 40%), Fabrice Voisin (IR, 20%)

IJClab: Xavier Garrido (MdC,10%), Sophie Henrot-Versillé (DR,70%), Thibaut Louis (CR,30%), Matthieu Tristram (CR,80%)
Didier Auguste (AI, 80%), Julien Bonis (IR, 30%), Denis Douillet (IR, 70%), Greg Iaquaniello (IE, 50%), Julien Peloton (IR, 10%)

LPSC: Juan Francisco Macias-Perez (DR, 15%), Andrea Catalano (CR, 15%)

They are taking part in the instrumental effort (with technical contributions described in Sect. 8) as well as having a leading role in the forecasting of performances and scientific preparation within the international collaboration (Sect. 9). As is their custom, LPSC will work in close collaboration with Institut Néel (INP) for their technical responsibilities (See Sect. 8). We expect the FTE to progressively increase with the project development. Support for Post-doc and PhD students is crucial for data analysis and science exploitation (see Sect. 9).

Laboratory	**Researcher**	**Engineer**
APC	7 (1.85 FTE)	3 (0.8 FTE)
IJClab	4 (1.9 FTE)	5 (2.5 FTE)
LPSC	2 (0.3 FTE)	–
Total	13 (4.05 FTE)	8 (3.3 FTE)

Table 3: Human Ressources at IN2P3

The IN2P3 team possesses a very broad expertise in all aspects of the CMB research acquired over the last 20 years and recognized within the community worldwide, in general and within the LiteBIRD team in particular. The relevant instrumental expertise has been mainly gained through the work on the space missions like Planck-HFI and Athena, the balloon-borne experiments (such as Archeops and PILOT), and the ground-based instruments such as NIKA (1 and 2) and QUBIC as well as dedicated R&D programs.

In the area of data analysis and science exploitation, the IN2P3 scientists played significant and leading roles in all aspects of the Planck satellite data analysis. Moreover, some of the collaborators have been members of ground-based CMB experiments, including some of the most successful current B-mode efforts (POLARBEAR, Simons Observatory, CMB-S4) in which they played leading and coordinating roles. The expertise of the team covers every stage of the data analysis: from time-ordered, raw data processing, systematics studies in intensity and polarization especially at large angular scales, map-making, constraints on cosmological models, and understanding of the astrophysical emissions.

7.2 Budget

The overall budget for Phase A2 is above 1 M€ for more than one year without human cost. It represents the cost for hardware development and travel expenses. It covers the French hardware contribution including the cryogenic system, the instrument design, the construction of a prototype for the end of Phase A2, the electronics and on-board software, the definition of the calibration setup and measurements, and the preparation to the data analysis. **It is entirely covered by CNES.**

Actually, the hardware developments takes advantage of some already funded packages such as the development of the CCDR for TRL5 qualification (funded by CNES R&T), the cryostat for the CR tests (funded by CNES) and the VNA and the source for calibration (funded by DIM-ACAV). **If selected at the end of the Phase A2 (end 2021), the project will require more funding from CNES.** Given the current baseline, we expect the total French contribution (including human costs) to be between 50-100 M€.

8 Réalisations techniques

In addition to the launch, the operations and the spacecraft, LiteBIRD JAXA deliverables include the LFT telescope and the mechanical coolers. The three focal planes (for the LFT, MFT, and the HFT) will be provided by NASA together with the SQUID amplifiers and cold-electronics in collaboration with Canada. The CNES is responsible for the study of the MFT and HFT in collaboration with the other European agencies. These include Italy, the United Kingdom, Germany, the Netherlands, Spain, Denmark, and Sweden. The participation of the ESA is still to be defined.

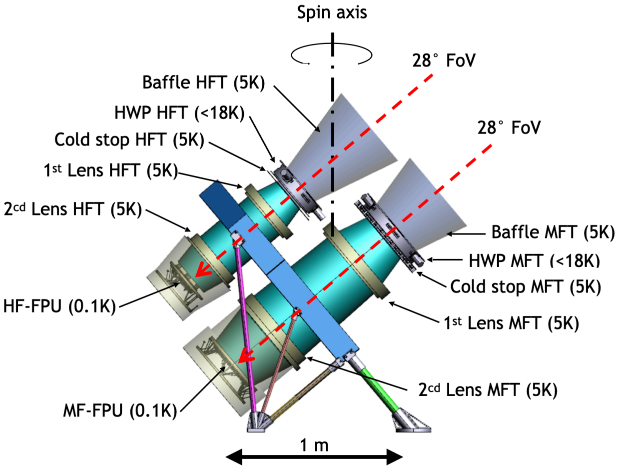

Figure 8: Design of the MFT and HFT telescopes.

The current baseline designs of the Medium- and High-Frequency Telescopes includes 10 spectral bands split in two focal planes: MFT (5 spectral bands from 89 to 224 GHz) and HFT (5 spectral bands from 166 to 448 GHz). The detectors are di- or tri-chroic sensitive assembled on wafers containing from 254 up to 488 TES bolometers, ending in a total of 2074 detectors for the MFT and 1354 for the HFT. To modulate the polarization, a rotating Half Wave Plate (HWP) is located as the first element of the optical chain, at the aperture of the telescope, thus enabling the control of the polarization systematics. The optical design is still under discussion. We consider the options of using either a refractive or a reflective optical system. In the current baseline, the detectors are located on two focal-planes at the focus of two refractive telescopes with transmissive HWPs of 200 mm and 300 mm aperture diameters, respectively. A possible backup solution is also envisaged with a single reflective cross-dragon optical telescope with a $10^\circ \times 20^\circ$ field of view.

In order to lower thermal emissions from the optical elements, the telescopes are cooled down to 5 K (Fig. 8). An aperture stop of 300 mm diameter suppresses the thermal loading due to the spillover at the entrance pupils.

During the last years, efforts have been made in each European country to identify its potential implication. Discussions happened to resolve possible overlaps and share the responsibilities while addressing all the steps of building, integrating, and testing the whole MFT and HFT. **These discussions lead to a task-sharing that will be proposed to CNES during the Comité Inter-Organisme (CIO) in October 2020.**

Among the hardware deliverable, France will be in charge of providing the sub-Kelvin cooling system (CEA), the mechanical structure (IN2P3), the electronics and on-board software (INSU) and some part of the Ground Segment Equipements (INSU and IN2P3). CNES will be responsible for the delivery of the integrated MFT and HFT.

The IN2P3 teams were involved in the ESA CDF for the Working Package on AIT/Calibration as well as for the design of the thermo-mechanical structure of the telescopes. Since 2018, the researcher and engineers at

IN2P3 were actively involved to propose a design and a task sharing. In the current proposal to the CNES management the key roles of IN2P3 labs are the following:

Mechanical Structure: IJClab is responsible for the design and delivery of the mechanical structure (including the telescope tubes and the structure at 5K to maintain the tubes). For the Phase A2, this includes the delivery of a the mechanical structure of a prototype of a refractive telescope on which we will be able to perform the first optical tests. This prototype would be fabricated at the IJClab. In case of selection, the IJClab would be in charge of delivering the mechanical structure for the different models from the Engineering Model (EM) to the Flight Model (FM). This design will be made in collaboration with APC involved in the thermal modelling.

System Thermal Modeling: APC is deputy thermal architect for the global thermal modeling of the telescopes (MFT and HFT).

Calibration & Ground Segment Equipment (GSE) The GSEs include all specific hardware components needed for the calibration phase. APC is in charge of the thermal GSE for the cold stages (5K–2K–100mK) and LPSC is involved in the Optical GSE for spectral polarization. The institute will also take a leading role in the organisation and management of the ground pre-flight calibration phase (leader S. Henrot-Versillé).

The hardware responsibilities have been discussed with each lab and agreed according to their own schedule and duties. It is part of the task-sharing document that will be proposed to CNES during the CIO in October 2020. The manpower for each lab has been identified and estimated and is realistic given their respective responsibilities. Support will be requested to the institute and the CNES for expertise on Quality Assurance specific to space missions.

These contributions will offer the IN2P3 an important role within the LiteBIRD project. **It will allow for a raise of the experimental expertise in space missions which can be translated into new responsibilities in the future.** These instrumental contributions will enable a substantial and highly visible role in all stages of the data analysis and scientific exploitation of the LiteBIRD data sets.

9 Implication Scientifique

The scientific and analysis studies are conducted within the Joint Study Groups (JSG) and other sub-groups for specific studies within the international collaboration. They are currently focused on the forecasting of the performances and the study of the impact of the instrumental and astrophysical systematic uncertainties.

The IN2P3 scientists are largely involved in those groups:

The JSG Systematics is in coordinating the studies on LiteBIRD systematics. In close connection with the instrumentalists, it provides the tools for simulating the instrumental effect as well as methods to mitigate their impact on the science extraction. G. Patanchon (APC) is co-leading.

The JSG Foregrounds is in charge of developping tools to perform the component separation / foreground subtraction to derive CMB maps from frequency measurements. The APC team is particularly active in this group.

The JSG calibration is coordinating the calibration plan including the definition of the measurements to be performed and the derivation of the Ground Segment Equipments required to satisfy the science requirements. S. Henrot-Versillé (IJClab) is co-leading.

The Performance team is forecasting the LiteBIRD performances taking into account the impact of instrumental noise, systematic effects, and foreground subtraction. J. Errard (APC) is co-leading.

The Data Management Group is in charge of the coordination of the data analysis and data management. This includes the definition of the data flows, the development of the analysis infrastructure for the data processing and the simulations. M. Tristram (IJClab) is co-chairing this group.

Researchers from IN2P3 also organised meetings to discuss LiteBIRD science and workshops with theoreticians to further investigate the various Inflation models and the impact of a potential primordial gravitational wave detection on the history and evolution of the Universe. Taking advantage of our experience on the Planck mission, we also want to develop the studies based on the E-mode of polarization which can constrain the history of the reionization phase after the dark ages of the Universe.

In order to keep an important impact on the data analysis and science exploitation, we need to increase our manpower rapidly. Concerning the manpower, the CNES is not providing any direct support. **We are thus looking for other source of fundings for Post-doc and PhD students (ANR, ERC, IN2P3, open calls at CNES, ...).**

References

[1] H. Sugai et al. Updated Design of the CMB Polarization Experiment Satellite LiteBIRD. Journal of Low Temperature Physics, 199(3-4):1107–1117, January 2020.

[2] K. N. Abazajian, P. Adshead, Z. Ahmed, S. W. Allen, and et al. CMB-S4 Science Book, First Edition. ArXiv e-prints, October 2016.

[3] M. H. Abitbol, Z. Ahmed, D. Barron, R. Basu Thakur, and et al. CMB-S4 Technology Book, First Edition. ArXiv e-prints, June 2017.

[4] B. D. Sherwin and M. Schmittfull. Delensing the CMB with the cosmic infrared background. Phys. Rev. D, 92(4):043005, August 2015.

[5] K. N. Abazajian, K. Arnold, J. Austermann, B. A. Benson, and et al. Neutrino physics from the cosmic microwave background and large scale structure. Astroparticle Physics, 63:66–80, March 2015.

[6] R. Allison, P. Caucal, E. Calabrese, J. Dunkley, and T. Louis. Towards a cosmological neutrino mass detection. Phys. Rev. D, 92:123535, Dec 2015.

[7] J. Errard, S. M. Feeney, H. V. Peiris, and A. H. Jaffe. Robust forecasts on fundamental physics from the foreground-obscured, gravitationally-lensed CMB polarization. JCAP, 3:052, March 2016.

[8] B. Thorne, J. Dunkley, D. Alonso, and S. Næss. The Python Sky Model: software for simulating the Galactic microwave sky. MNRAS, 469:2821–2833, August 2017.

[9] R. Stompor, J. Errard, and D. Poletti. Forecasting performance of CMB experiments in the presence of complex foreground contaminations. Phys. Rev. D, 94(8):083526, October 2016.

[10] M. Remazeilles, A. J. Banday, C. Baccigalupi, and for the CORE collaboration. Exploring Cosmic Origins with CORE: B-mode Component Separation. ArXiv e-prints, April 2017.