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1 Scientific, Technical, and Management Section

1.1 Executive Summary

We are proposing to study a probe-scale mission to extract the wealth of physical, cosmological, and astrophysical information contained in the spectrum and polarization of the cosmic microwave background (CMB). The CMB Probe will search for the signature of inflationary gravitational waves from the big bang and thus probe quantum gravity. It will constrain the effective number of light particle species, with precision only available to CMB measurements. With its full sky coverage, it will measure the sum of the neutrino masses doubling the significance of detection relative to experiments that measure only smaller portions of the sky. It will probe the nature of dark matter and the existence of new forms of matter at the early universe. It will give new insights on the star-formation history across cosmic times, and it will provide information about the processes that control structure formation. With high sensitivity, access to the entire sky, and the ability to implement broad frequency coverage and exquisite control of systematic effects the Probe is best poised to realize the fidelity of measurements necessary to extract these science goals.

The last US CMB community’s consensus assessment of the case for, and design of a space mission took place 10 years from the time this study will conclude. Since then theoretical considerations, available data from *Planck* and sub-orbital measurements, technology advances, and plans for new sub-orbital experiments have changed the landscape considerably. We propose to provide the 2020 decadal panel with a fresh expert assessment.

The scope of science we envision for the Probe is achievable within the approximate technical envelope of our 2010 baseline mission, which was near \$900M. This scope of science is also targeted by a recently submitted proposal for a European-based mission that has similar cost. Both of these missions have broader science reach than a more focused Japanese-led mission, which is near the \$400M limit. We thus assess that the CMB mission is in the Probe cost window.

The mission study is led by Steering and Executive Committees made up of scientists who built COBE, WMAP, *Planck*, and the leading sub-orbital experiments in the world; by scientists who processed, analyzed, and simulated data from these experiments; and who interpreted the results and put them in a physics and cosmology context. It is open to all member of the CMB community, and will represent hundreds of person years of accumulated knowledge, expertise, and experience.

1.2 Observables and Baselines

Thomson scattering is the source of the polarization of the CMB. It is useful to decompose the polarization field to two modes that are independent over the full sky, E and B modes. Together with the pattern of temperature anisotropy T , the CMB thus gives three auto- and three cross-spectra. The *Planck* satellite and larger aperture ground-based instruments measured the T spectrum to cosmic variance limit for $\ell \leq 1500$. Much information remains encoded in the E and B spectra, whose full exploration has just begun [1, 2, 3, 4, 5]. The B -mode has two contributions: a primordial component at a level that is theoretically characterized using r , and a ‘lensing’ component that is due to gravitational lensing of E -modes by the large scale structure of the Universe; See Figure 1. The current upper limit on r is $r < 0.07$ (95%) [24].

The best measurement of the CMB spectrum – made by COBE/FIRAS approximately 25 years ago – shows the average CMB spectrum is consistent with that of a blackbody to an accuracy of 5 parts in 10^5 [6, 7]. Distortions in this spectrum encode a wealth of new information. The distortion shapes are commonly denoted as μ - and y -types [8, 9]. The μ -distortion arises from energy release in the early universe and can only be produced in the hot and dense environment present at high

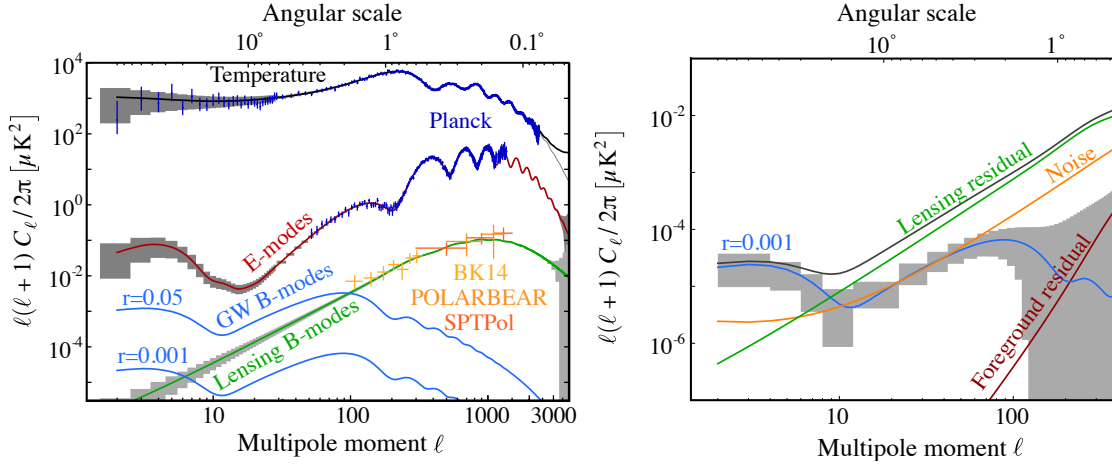


Figure 1: Predicted determination of the CMB power spectra for EPIC-IM (grey boxes) after foreground removal for $r = 0$ (left) and after foreground removal and delensing for $r = 0.001$ (right) overlaid on theoretical predictions (solid lines) and including Planck measurements of the temperature and E modes (dark blue) and of several ground-based measurements of the lensing B modes. The primordial B mode predictions (blue) are shown for two values of r .

redshifts. This makes μ -distortions a novel messenger from a redshift range $z \geq 5 \times 10^4$. The y distortions are caused by energy exchange between CMB photons and free electrons through inverse Compton scattering. These originate at lower redshifts and are sensitive to the evolution of the large scale structure of the universe.

Quantitative predictions in this proposal are based on two current-decade space missions, EPIC-IM and Super-PIXIE [10, 11]. EPIC-IM was presented to the 2010 decadal panel as a candidate CMB imaging polarization mission. It was based on a 1.4 m effective aperture telescope and 11,094 bolometric transition edge sensors. PIXIE is a proposed Explorer-scale mission focused on a measurement of the spectrum and polarization of the CMB on large angular scales. Super-PIXIE is envisioned to be a scaled up, more capable version of PIXIE. It consists of 4 spectrometers, each operating between 30 and 6000 GHz with 400 \sim 15 GHz-wide bands. Improvements in technology by the next decade will enable the design of a mission that is more capable compared to EPIC-IM and Super-PIXIE. Therefore, all quantitative predictions presented in this proposal, which are based on EPIC-IM and Super-PIXIE, represent *minimum* capabilities for the CMB Probe.

1.3 Science Objectives

1.3.1 The Primordial Universe and Cosmic Inflation

The simplest models of inflation, a primordial era of accelerated expansion, predict an as yet unobserved primordial gravitational waves with a nearly scale-invariant spectrum, sourced by quantum fluctuations of the tensor component of the metric. These gravitational waves leave a distinct B -mode imprint on the polarization of the CMB. Any detection of primordial B -mode polarization, whether generated by the gravitational waves of inflation [12, 13] or any other source of vector or tensor perturbations, such as primordial magnetic fields [14, 15, 16, 17] and cosmic strings [18, 19, 20, 21] would reveal completely new information about the early universe. The results would either provide additional confirmation for current models or could overturn them. A detection would also have implications for fundamental physics by providing evidence for a new energy scale near the GUT scale, probing physics well beyond that reachable with terrestrial colliders.

To test inflation, the largest scales $\ell \leq 10$ are particularly important because they may reveal the presence of B -mode correlations on scales that were super-horizon at the time of recombina-

tion [22], and because on large scales the signal is strongest relative to the lensing B mode and instrumental noise; see Figure 1. In its recent report New Worlds New Horizons (NWNH), the decadal survey committee strongly endorsed searches for B modes from inflation saying, “The convincing detection of B -mode polarization in the CMB produced in the epoch of reionization would represent a watershed discovery.” [23]. No sub-orbital platform has yet produced measurements of B modes at $\ell < 40$, and a satellite is by far the most suitable platform for the all-sky observations necessary to reach the lowest modes, $\ell < 20$.

In slow-roll inflation there are two classes of models that naturally explain the measured value of the spectral index n_s . One is the set of potentials $V(\phi) \propto \phi^p$, which contains many of the canonical inflation models. This set is already under significant observational pressure. If the error bars on the spectral index tighten by a factor of about 2, and the 95% C.L. upper limit on r is pushed to even ~ 0.01 , all such models would be ruled out; see Figure 2.

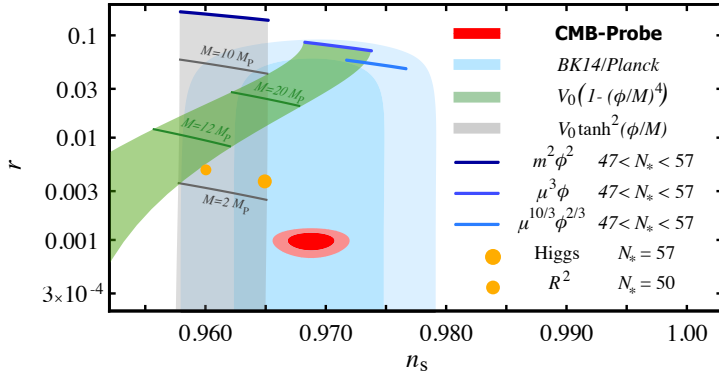


Figure 2: Current 1 and 2σ limits on r and n_s (blue) [24] and forecasted constraints for a fiducial model with $r = 0.001$ for EPIC-IM. Also shown are predictions for the models of the inflaton potential discussed in the text: Chaotic inflation (blue lines); Higgs and R^2 (large and small dots, respectively); quartic hill-top (green band); and a sub-class of α -attractor models [25]

Another class of models includes R^2 and Higgs inflation, which both have $r \sim 0.003$. A future mission capable of reaching $\sigma_r \sim \mathcal{O}(10^{-4})$ would provide significant constraints on virtually all models that naturally explain n_s . EPIC-IM would achieve $\sigma(r) \sim 1.3 \times 10^{-4}$ assuming $r = 0.001$. (This prediction includes subtraction of a galactic dust foreground model with two component power law emissivities, synchrotron emission with a single power law, that all power laws are spatially uniform, and self delensing.)

A detection of B modes consistent with a primordial spectrum of vacuum fluctuations would be the first observation of a phenomenon directly related to quantum gravity. In addition, a Probe mission would allow a high significance detection of any model of large-field inflation. A detection of r would therefore provide motivation to better understand how large-field inflation can be naturally incorporated into quantum gravity [26, 27, 28, 29, 30, 31, 32, 33].

Inflation predicts a B mode spectrum with the shape shown in Figure 1, but there may be additional sources of B -mode polarization either during or after inflation. To be confident of the implications of a detection, the shape and Gaussianity of the B mode spectrum must be characterized. The vast majority of inflation scenarios predict a Gaussian and nearly scale-invariant spectrum for gravitational waves. A target constraint of $\sigma(n_t) < 1$ at $r = 0.01$, easily achievable with a Probe mission, would significantly constrain non-vacuum inflationary sources [34, 35].

Deeper mapping of E -mode polarization will also test inflationary models. Large scale E modes will provide new tests of isotropy, a prediction of most models of inflation; for example, observations with a CMB Probe could reject at 99% confidence models designed to explain the alignment of low multipoles in the temperature maps [36]. Together with continued improvements at high ℓ from the ground, these modes will also improve constraints on the scalar spectral index, its changes with scale, and on primordial non-Gaussianity by factors of about two.

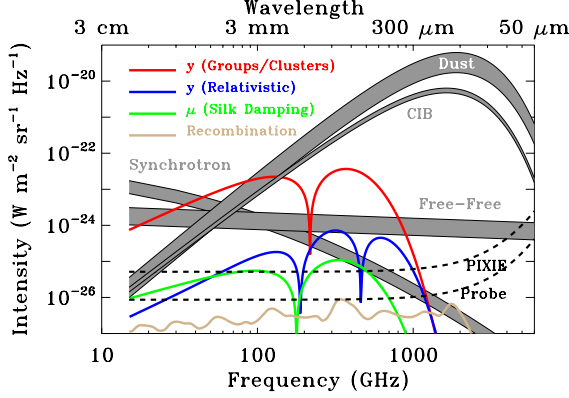


Figure 3: Anticipated y and μ spectral distortions (solid), the signature of resonant recombination lines (solid), and anticipated foreground signal levels relevant for spectral distortion measurements (grey bands). The simplest extension of a proposed Explorer class mission (Probe, dash grey) gives approximately 10 times the Explorer sensitivity (PIXIE). A better optimized Probe may give detections of all anticipated distortions.

Spectral distortion measurements give additional tests of inflation. The dissipation of small-scale perturbations through Silk-damping leads to μ -distortions [37, 38, 39, 40]. In Λ CDM the distortions are predicted at a level of $\mu = (2.0 \pm 0.14) \times 10^{-8}$, a level that is readily accessible to a Probe class mission, see Fig. 3 [40, 41]. A Probe may also give the sensitivity to detect the signature of recombination radiation imprinted by recombination of hydrogen and helium at redshift $z \simeq 10^3 - 10^4$; see Fig. 3 [42, 43]. The detailed physics is sensitive to the values of n_s , which is a direct probe of inflation.

1.3.2 Light Relics and Dark Matter

In the inflationary paradigm, the universe was reheated to temperatures of at least 10 MeV and perhaps as high as 10^{12} GeV. At these high temperatures, even very weakly interacting or very massive particles, such as those arising in extensions of the standard model of particle physics, can be produced in large abundances [44, 45]. As the universe expands and cools, the particles fall out of equilibrium, leaving observable signatures in the CMB power spectra. Through these effects the CMB is a sensitive probe of neutrino and of other particles' properties.

One particularly compelling target is the effective number of light relic particle species N_{eff} , also called the effective number of neutrinos. The canonical value with three neutrino families is $N_{\text{eff}} = 3.046$. Additional light particles contribute a change to N_{eff} of $\Delta N_{\text{eff}} \geq 0.027 g$ where $g \geq 1$ is the number of degrees of freedom of the new particle [46, 47]. This defines a target of $\sigma(N_{\text{eff}}) < 0.027$ for future CMB observations. Either a limit or detection of ΔN_{eff} at this level would provide powerful insights into the basic constituents of matter.

Forecasts for N_{eff} are shown in Figure 4. The two most important parameters for improving constraints are the fraction of sky observed f_{sky} and the noise. Achieving both larger f_{sky} and lower noise are strengths of the CMB Probe compared to other platforms. Our baseline mission nearly reaches the target constraint with $g = 1$, and a newly designed mission is could reach $\sigma(N_{\text{eff}}) < 0.027$. A high precision measurement of the CMB in temperature and polarization is the only proven approach capable of reaching this important threshold.

Many light relics of the early universe are not stable. They decay, leaving faint evidence of their past existence on other tracers. The relics with sufficiently long lifetime to survive few minutes, past the epoch of light element synthesis, leave a signature on the helium fraction Y_p . If they decay by the time of recombination, their existence through this period is best measured through the ratio of N_{eff} to Y_p . The Probe's cosmic variance limited determination of the E mode power spectra will improve current limits for these quantities by a factor of five thus eliminating sub-MeV mass thermal relics. Spectrum distortion measurements give additional constraints on the lifetime and abundance of such relics [49, 50, 51, 52]. A future Probe's μ -distortion constraint gives a two

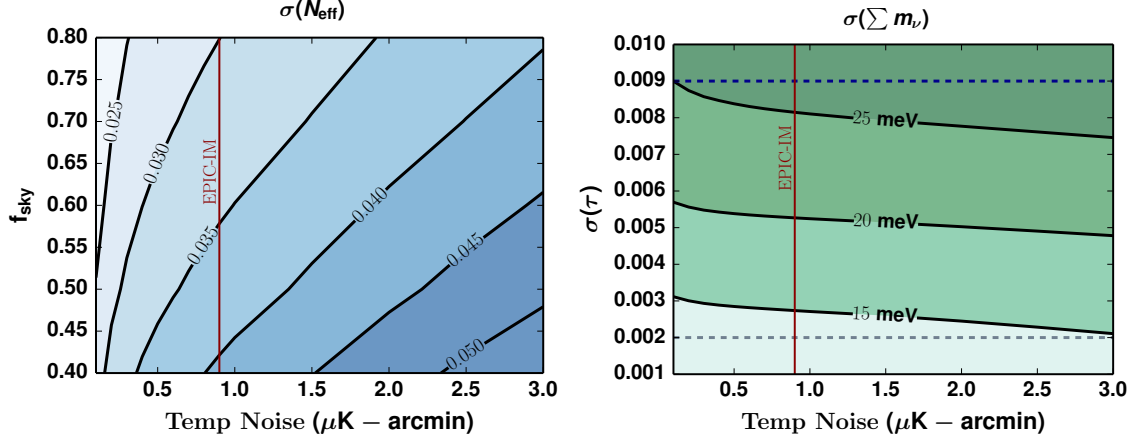


Figure 4: N_{eff} as a function of noise and sky fraction (left) and Neutrino mass constraints as a function of uncertainties in measurement of τ , noise, and sky fraction of $f_{\text{sky}} = 0.7$. The resolution assumed is $5'$. Vertical lines denote the expected performance of EPIC-IM. The blue dashed line is the current *Planck* limit; the grey dashed line is the limit from cosmic variance measurement of τ . All forecasts assume internal delensing of the T and E -maps [48], including residual non-Gaussian covariances. The $\sum m_\nu$ forecasts include DESI BAO.

orders of magnitude improvement on the abundance and lifetime of early universe relics [53, 54] compared to current constraints derived from measurements of light element abundances [55, 56].

Cosmological measurements have already confirmed the existence of one relic that lies beyond the Standard Model: dark matter. For a conventional WIMP candidate, the CMB places very stringent constraints on its properties through the signature of its annihilation on the T and E spectra [57, 58, 59]. *Planck* currently excludes WIMPs with mass $m_{\text{dm}} < 16$ GeV and a future CMB mission could reach $m_{\text{dm}} < 45$ GeV for $f_{\text{sky}} = 0.8$. The CMB provides the most stringent constraints on the dark matter annihilation cross section for dark matter in this mass range. The CMB is complimentary to direct detection experiments which probe the scattering cross-section of dark matter with standard model particles.

A particle-independent approach is to constrain dark matter interactions that would affect the evolution of the effective dark matter fluid and its interactions with baryons or photons. The simplest example is to constrain the baryon-dark matter cross section through its effective coupling of the two fluids [60]. These couplings affect the evolution of fluctuations and ultimately the T and E spectra. The current limits of $\sigma \lesssim 10^{-31} - 10^{-34} \text{ cm}^2 \times (m_{\text{dm}}/\text{MeV})$ can be competitive with direct detection for sub-GeV masses. More exotic dark sectors that include long-range forces can produce an even richer phenomenology in the CMB and in the large-scale structure without necessarily producing an associated signature in direct detection experiments or indirect searches (e.g. [61, 62, 63]).

Interactions of dark matter with standard model particles can also be constrained through measurements of spectral distortions [64]. Current constraints from FIRAS are most sensitive to small dark matter mass, $m_X \lesssim 0.2$ MeV, but these could be extended to $m_X \lesssim 1$ GeV with a Probe-class mission, testing DM interaction down to cross-sections $\sigma \simeq 10^{-39} - 10^{-35} \text{ cm}^2$ [64]. This provides new constraints on the low mass end, $m_X \lesssim 10$ MeV and improve existing limits [65, 66] by up to a factor of $\simeq 50$. Distortion measurements furthermore open a new avenue for testing dark matter-proton interactions [64].

A host of other physical phenomena including the existence and properties of axions, primordial

magnetic fields, and superconducting strings, leave signatures on the spectrum of the CMB and can therefore be constrained by the sensitive measurements of a future Probe [e.g., 67, 68, 69, 70, 71].

1.3.3 Neutrino Mass

Cosmology is uniquely capable of measuring the sum of neutrino masses, $\sum m_\nu$, directly through the suppression of the growth of structures in the universe on small scales. However, all cosmological measurements of $\sum m_\nu$ are fundamentally limited by our uncertainty in τ due to the strong degeneracy between τ and A_s . Although many surveys hope to detect $\sum m_\nu$ at high significance, any detection of the minimum value expected from particle physics $\sum m_\nu = 58$ meV at more than 2σ will require a better measurement of τ . The best constraints on τ come from E modes with $\ell < 20$ which require measurements over the largest angular scales. To date, the only proven method for such a measurement is from space, including the current limit from *Planck* of $\sigma(\tau) = 0.009$ [72]. Forecasts for an internal CMB measurement of $\sum m_\nu$ via CMB lensing [73] are shown Figure 4. With the current measurement of τ one is limited to $\sigma(\sum m_\nu) \gtrsim 25$ meV, with similar conclusions holding for other types of cosmological measurements. The CMB Probe will reach the cosmic variance limit of $\tau \sim 0.002$ and will therefore reach $\sigma(\sum m_\nu) < 15$ meV when combined with DESI’s measurements of baryon acoustic oscillations [74]. Robustly detecting neutrino mass at $> 3\sigma$ in any cosmological setting is only possible with an improved measure of τ like one one achievable with the CMB Probe.

1.3.4 Cosmological structure formation

Understanding the evolution of cosmological structures from small density perturbations through the formation of the first stars to present day galaxies and clusters is a key goal of cosmology.

In particular, to understand the details of reionization – the transition of the universe from dominated by neutral to ionized hydrogen – and to establish a connection between the history of reionization and our knowledge of galaxy evolution is an open frontier. When did the epoch of reionization start? How long did it last? Are early galaxies enough to reionize the entire universe or is another population required?

Measurements of the CMB E mode power spectrum over large angular scales are sensitive to the optical depth to reionization τ , a key parameter for all reionization models that attempt to answer these questions. The *Planck* team reported recently a value of $\tau = 0.055 \pm 0.009$ [72, 76]. The level is lower than previous estimates and reduces the tension between CMB-based analyses and constraints from other astrophysical sources [?]. The CMB Probe’s cosmic variance limited measurement of E -mode polarization will improve the 1σ error by a factor of 4.5 to reach a cosmic variance limited measurement of τ , thus setting stringent constraints on models of the reionization epoch.

In addition to constraining the reionization epoch, the anisotropies in the cosmic infrared background (CIB) produced by dusty star-forming galaxies in a wide redshift range, are an excellent probe of both the history of star formation and the link between galaxies and dark matter across cosmic time. The *Planck* collaboration derived values of the star formation rate up to redshifts $z \sim 4$ and are complementary to number counts measurements ([77, 78, 79]). By measuring CIB anisotropy with $\simeq 100$ times higher signal-to-noise ratio and at multiple frequencies, the CMB Probe will dramatically improve this approach. Specifically, it will constrain the star formation rate with one tenth of *Planck*’s uncertainty. For example, a key parameter in simulations of the angular power spectrum of the CIB is M_{eff} , the galaxy halo mass that is most efficient in producing star formation activity. Comparing measurements of the power spectrum to simulations constrains

this parameter, which informs structure formation models. Current models and measurements find $M_{\text{eff}} \sim 10^{12}$ solar masses with about 10% uncertainty. The CMB Probe will constrain this parameter at the percent level.

Reionization of the universe and the onset of structure formation inject energy into the sea of CMB photons. This injection is detectable through a distinct spectral distortion. This is the largest expected distortion – marked ‘ y Groups/Clusters’ in Figure 3 – and will be clearly detected by the CMB Probe. A detection will give information about the total energy output of the first stars, AGNs, and galaxy clusters, an important parameter in structure formation models. Group-size clusters that have masses $M \simeq 10^{13} M_{\odot}$ contribute significantly to the signal. With temperature $kT_e \simeq 1$ keV these are sufficiently hot to create a relativistic temperature correction to the large y -distortion. This relativistic correction, denoted ‘ y relativistic’ in Figure 3, will also be detected with high signal-to-noise ratio by the CMB Probe, and will be used to constrain the currently uncertain feedback mechanisms used in hydrodynamical simulations of cosmic structure formation [80].

The CMB spectrum varies spatially across the sky. One source of such anisotropic distortion is due to the spatial distribution clusters of galaxies and has already been measured by Planck [81]. A combination of precise CMB imaging and spectroscopic measurements will allow observing the relativistic temperature correction of individual SZ clusters [82, 83, 84], which will calibrate cluster scaling relations and inform our knowledge of the dynamical state of the cluster atmosphere.

Resonant scattering of the CMB photons during and post last scattering leads to spectral-spatial signals that can be used to constrain the abundance of metals in the dark ages and therefore the make-up of the first, and subsequent generations of stars [85, 86, 87, 88, 89].

1.4 The Challenges: Foregrounds and Systematics

The search for primordial B modes poses the most stringent requirements on foreground removal and control of systematic effects. A tentative target for the CMB Probe is to constrain the tensor-to-scalar ratio with an uncertainty that is a factor of 50-100 smaller than the current upper limit $r < 0.07$ at 95% CL, that is, to reach $\sigma(r) \lesssim 0.0005$ in the presence of foregrounds and accounting for systematic effects. According to data from *Planck* and sub-orbital experiments, foregrounds already dominate the signal. The large reduction in the size of the final error will require exquisite measurements and modeling of foregrounds.

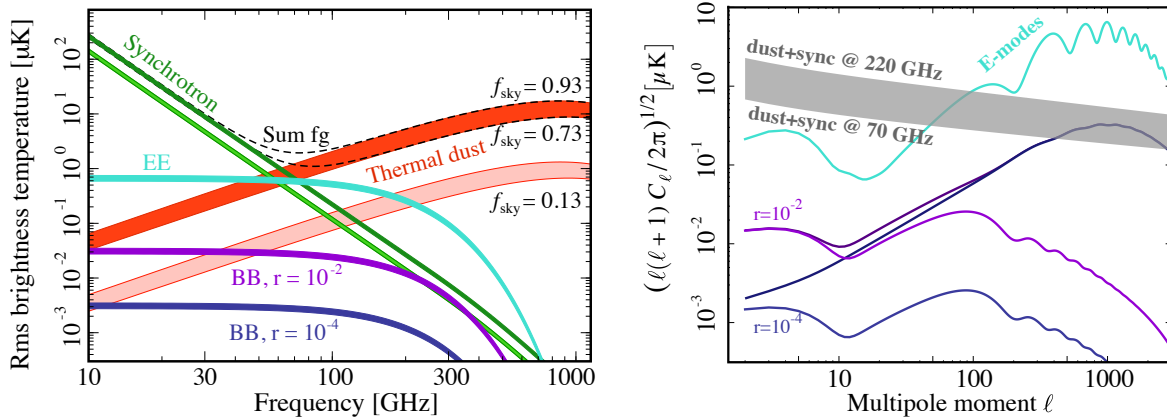


Figure 5: *Left:* Brightness temperature as function of frequency for the polarized CMB (cyan, purple, blue) and Galactic foreground signals: dust (red) and synchrotron (green). The darker bands correspond to sky fractions between 73% and 93%; the lighter bands to the cleanest 13%, with the width indicating the uncertainty. *Right:* Angular power spectrum for E - and B -mode polarization for two values of r , and for foreground emission between 70 and 220 GHz.

To ascertain that the uncertainty on the measurement of r is dominated by statistical rather than systematic error, the mission design, execution, and data analysis will have to be dominated by the need to control systematic uncertainties to unprecedented, not yet demonstrated levels.

1.4.1 Foregrounds

Whereas the CMB temperature anisotropy signal dominates Galactic sources of emission over much of the sky, this is not the case for polarization. Figure 5 compares the expected RMS brightness temperature of polarized emission from Galactic sources to E and B modes as a function of frequency and gives the expected signal levels as a function of angular scale ℓ .

The conclusions are that:

- over the largest angular scales (lowest ℓ s), which are crucial for a range of science goals and where inflationary B modes would be largest relative to those from lensing and instrument noise, foreground sources of confusion will need to be measured and subtracted to a level better than 1 part in 10 for E and in 100 for B ;
- foregrounds dominate the potential inflationary B mode signal on *all* angular scales by an order of magnitude or more.

Known signals can be accounted for and removed with multi-frequency observations even if their amplitude is large. But the best measurements to date, from *Planck*, fall far short of the fidelity envisioned for the Probe. This is visually demonstrated by Figure 6, which compares the level of B modes at low ℓ for $r = 0.001$ to the *Planck* 353 GHz noise, extrapolated to 150 GHz, a frequency band in which the inflationary signal is among the strongest.

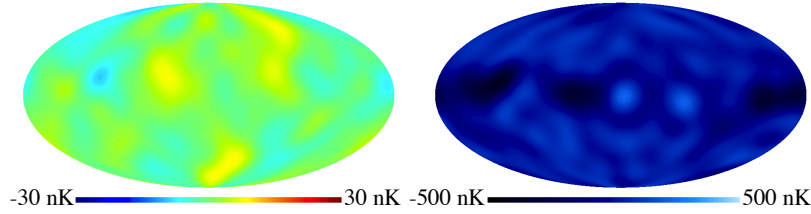


Figure 6: *Left*: Stokes Q for inflationary B modes for $\ell < 12$ and $r = 0.001$. *Right*: Noise in the *Planck* 353 GHz map of Stokes Q for $\ell < 12$ extrapolated to 150 GHz assuming the (sky average) spectral properties of dust. Note the color scales.

Removal of foregrounds based on multi-frequency data in a number of frequency bands relies on extrapolations between frequencies based on an assumed spectral dependence. At the current level of precision a power law dependence for synchrotron radiation and a modified black body spectrum for dust emission provide a reasonable fit to CMB data. At the level of precision required for a probe mission, this description will no longer be sufficient. The complex composition of dust leads to departures from a simple modified black body spectrum because different components may emit at different temperatures. The different components are in general not perfectly correlated with each other, leading to decorrelation between frequency bands. Furthermore, the spectral dependence of synchrotron and dust emission is spatially varying. The spectral dependence must ultimately be measured with the Probe mission. The challenge is to design the frequency coverage to do so optimally.

While the search for primordial B modes leads to the strictest constraints on foreground residuals, exquisite control of foregrounds is also necessary for the other science objectives. Detailed information about the reionization history, available by a cosmic variance limited measurement of the E power spectrum, is buried below the foregrounds at $\ell < 10$. In addition, one must understand the foreground requirements to successfully delens the data at the required level. Recovering *all* of the spectral distortions signals from the raw data will require proper accounting for emission by dust grains, synchrotron emission from electrons spiraling in the Galactic magnetic field, Coulomb

scattering of charged particles (‘free-free’) (see Figure 3), as well as anomalous microwave emission and CO emission.

1.4.2 Systematic Errors

The latest experience with *Planck* points to the following systematic error categories likely to be important for the CMB Probe, or for that matter, for any instrument striving to map the polarization over large portions of the sky to the levels targeted by the CMB Probe [72]: 1) Intensity-to-polarization leakage, 2) stability, and 3) straylight. Each of these is considered in light of polarimetry measurements through differencing the signals of two detectors that are sensitive to orthogonal polarization states.

Leakage. The CMB anisotropy signal is a factor of 1000 larger than the strongest possible inflationary B modes (see for example Fig. 1). Therefore instrumental effects that can leak even a small fraction of an intensity fluctuation into spurious polarization and must be understood and controlled. The main effects are differences between gains of detectors, their frequency bandpass mismatch, their differential pointing on the sky, and their differential antenna patterns. Currently, the most sensitive sub-orbital experiments have shown control of systematics at a level of $r \lesssim 0.006$; approximately half of the contribution was from intensity to polarization leakage [90]. These differential effects need to be controlled, through instrument design, characterization, and data analysis to levels that are another factor of 10-100 more stringent so that the contributions of systematic uncertainties to the Probe’s total error budget is negligible.

Leakage-related effects will drive requirements on the optical system, the uniformity of the bandpass of each polarimeter, calibration requirements on the level of cross-polar leakage and its angle, and measurements of the beam shape as a function of source spectrum. These systematic effects can potentially be mitigated by modulation of the sky signal in such a way that allows complete reconstruction of the polarized sky signal using each photometer, for example, using a half-wave plate.

Stability. The reconstruction of deep, full sky polarization maps involves a combination of measurements made at times separated by months, requiring stability of the response of the instrument on corresponding time scales. Random deviations from stability are a source of noise; systematic deviations are a source of systematic error. These types of systematic errors require control of thermal drifts of spacecraft temperatures to mitigate thermal emissivity changes and thermoelastic deformation of telescope structures. The cryogenic operating temperatures of detectors or reference calibration loads must be controlled adequately as well. Careful design of the scan strategy can shorten the time scales needed for stringent stability, for example *Planck*’s scan strategy traced out great circles which overlapped on 1 minute timescales, giving a shorter effective time scale for stability requirements.

The spacecraft’s ambient radiation environment is modulated by the solar activity and can introduce temperature drifts in the cryogenic stages and lead to correlated transients in detectors and readout electronics. For example, cosmic ray energy deposition in the *Planck*/HFI focal plane was a source of correlated noise between detectors and created a factor ~ 5 additional noise at $\ell=2$ [72]. The design of the instrument must account for these effects.

Straylight. When the brightest sources in the sky – the Sun, Moon, planets, and Galaxy – are passing through the far sidelobes of the telescope they create a spurious polarization signal. If they are passing in repeated, scan synchronous pattern, the spurious signal becomes a source of systematic error. This far sidelobe response can be reduced through careful optical design and baffling, but will always be present at a non-trivial level. Detailed modeling of the *Planck*

telescope, convolved with sky sources, gave a predicted sidelobe contamination at a detectable level of tens of micro-Kelvin in the 30 GHz maps. This contamination has been observed in *Planck* difference maps. As a result an estimate of the sidelobe contamination was removed from some of the *Planck* time ordered data as part of the mapmaking process. The more stringent requirements for CMB-probe will necessitate at least this level of mitigation.

1.5 The CMB Probe in Context

1.5.1 Current and Forthcoming Sub-Orbital Efforts

The remarkable forthcoming scientific yield has motivated significant agency investments in current and future sub-orbital experiments which are designed to realize the full potential of this unique probe of fundamental physics and astrophysics. These experiments are designed to exploit the comparative advantages of the sub-orbital platforms, while providing the design heritage and experience necessary to maximize the probability of success of an orbital mission.

For the ground-based efforts, these include combinations of *i)* provision for large apertures and therefore high angular resolution, *ii)* flexibility to rapidly deploy new technologies, and *iii)* allowance for detector formats that are relatively unconstrained by mass and power limitations. To date, these have demonstrated low noise measurements of small and intermediate angular scale E and B polarization structures over less than 2% fractional areas of the sky.

The balloon-borne missions *i)* extend the frequency reach of the ground based telescopes, *ii)* enable high fidelity measurements on larger angular scales than can be probed from the ground, and *iii)* grant access to an environment with similar requirements and constraints as in orbit, providing heritage for future space missions as well as experience in dealing with the analysis of data that are representative of a space mission. In this way, the sub-orbital programs complement and multiply the scientific return of the proposed orbital mission, while reinforcing its technical preparedness.

The 2010 Decadal Panel strongly recommended supporting sub-orbital efforts in preparation for a possible space mission to follow sub-orbital detections of inflationary gravitational waves. As a result, the US has clear leadership in the field, both in terms of ground- and balloon-based experiments and results.

This leadership will continue into the foreseeable future. In aggregate, funded, now-being-built ‘Stage 3’ CMB experiments will deploy approximately 100,000 detectors on various sub-orbital experiments within the next 3-5 years. Ground-based experiments plan to extend measurements from few percent of the sky to few tens, although in a limited frequency range between 30 and 300 GHz. Balloon-borne payloads operating at even higher frequencies strive to cover even larger fractions.

1.5.2 Proposed Efforts: LiteBIRD, CORE, and CMB-S4

Japan, in collaboration with NASA, is now considering whether to proceed with LiteBIRD, a space mission designed to search for B modes from inflation. The US Team has submitted its Phase A report to NASA; Phase A in Japan will conclude in about a year. LiteBIRD is a smaller, more focused mission compared to the CMB Probe. It is an imager based on a 0.4 m aperture telescope. Its reach in ℓ space is 2.5-4 times lower compared to the 1-1.5 m aperture we are considering for the Probe making the science available at ℓ ’s above few hundred in both E and B modes unreachable. It has no spectroscopic capabilities and thus not sensitive to any of the spectral distortion science goals.

A collaboration of scientists in Europe has just recently proposed CORE to ESA as part of the M5 round of space mission proposals. The team includes a number of US collaborators; the PI of

this proposal is a member of CORE’s Executive Board. CORE is a CMB polarization imager that is based on a 1.2 m aperture telescope and thus intended to reach 3 times the resolution of LiteBIRD. It will reach a resolution of 5-10 arcmin in the 100-200 GHz bands. CORE targets similar breadth of science as the CMB Probe. Selection of missions for Phase A studies is expected in June 2017, and end of Phase A in summer 2019.

The US CMB community has proposed, and the Particle Physics Project Prioritization Panel (P5) has recommended to the DOE, the establishment of a 4th generation CMB experiment called CMB-S4. This is an ambitious program to field approximately 5 times the number of detectors fielded by Stage 3 experiments. If and when funded, CMB-S4 will enable unprecedented sensitivity at frequency bands accessible from the ground, and with telescopes that enable high resolution.

1.5.3 Why Study a CMB Probe?

Learning from the successes of COBE/FIRAS, COBE/DMR, WMAP, and *Planck*, a CMB Probe is the single most suitable vehicle to deliver complete sky coverage and therefore information on the largest angular scales, comprehensive frequency coverage, and exquisite control of systematic effects. Some of the science goals described in Section 1.3 are reachable only through mapping of the largest angular scales. No sub-orbital experiment has yet produced any polarization results on more than 2% of the sky, let alone on scales requiring 70% of the sky. The broad frequency coverage of the space mission is best suited to mitigate the foregrounds expected on a broad range of angular scales, including those important for removing the effects of *B* modes from lensing. The mission will provide a single self-consistent and self-calibrated data set; and it will provide legacy maps at many frequency bands that will become the basis for hundreds of new papers.

If the inflationary signal is detected by sub-orbital experiments any time soon, a space mission to characterize the signal in full detail is equally compelling. The existence of ambitious sub-orbital programs is a complementary strength. How to make the best use of this complementarity is an explicit goal of our study; see Section 1.7.

1.5.4 Does the CMB Probe Fit Within the Cost Window?

The total cost estimate for the EPIC-IM mission, as generated by JPL’s Team X, was \$920M in 2009 [10]. The mission had a 1.4 m effective entrance aperture, a telescope that was maintained at 4 K, and focal plane with 11,094 TES detectors operating at 0.1 K. The CORE mission, that had just been proposed to ESA, has an aperture of 1.2 m, a telescope operating between 40 and 77 K, and a focal plane with few thousand bolometric detectors operating at 0.1 K. It was estimated by the proposing team to have a total cost of ~\$750M, which includes an ESA contribution of \$610M and the rest is from member countries. LiteBIRD has a 0.4 m aperture telescope feeding one of two focal planes. The telescope is cooled to 4 K; the second focal plane is coupled to the sky without reflectors. Both focal planes are cooled to 0.1 K and contain few thousand detectors. LiteBIRD is within JAXA’s \$300M class and the US contribution is \$65M.

The science goals we are envisioning for the CMB Probe, the effective aperture size, between 1 and 1.5 m, and the telescope and focal plane temperatures are most akin to EPIC-IM and CORE. While the relation between these parameters and total cost will be analyzed during this mission study, these past exercises suggest that an imager fits within the \$400M - \$1000M class.

PIXIE, which consists of a single spectrometer, is being proposed as an Explorer class mission. Super-PIXIE, consisting of four spectrometers, but sharing the same spacecraft should fit within the Probe cost bracket. Whether a scientifically compelling mission that has a combined imager/spectrometer instruments can be constructed within the Probe cost cap is one of the ques-

tions we will address during the study.

1.5.5 This Study in the Context of Previous Mission Studies

The EPIC-IM summary paper and a report to the decadal panel from a NASA mission study, both from 2009, represent the US community’s most recent view of the anticipated science reach and the path to implementation of a possible future US space mission. The landscape has changed since. Theoretical advances and progress in physics and astrophysics gave updated goals for the fidelity of measurements of E and B modes, including measurements of inflationary gravitational waves, the properties of light relics, and structure formation in the universe. A slew of sub-orbital experiments together with the *Planck* mission have transformed our view of the mm-wave polarized sky, highlighting the requirement on thorough understanding of the foregrounds. Advances in detector technologies, multiplexed readouts, and optical components now enable a significantly more capable mission than the one envisioned ten years ago. And the community has vastly more experience with designs of polarimeters and the control of their systematic uncertainties. A new study, based on this accumulated information and experience, is timely; this is the study we are proposing here.

The US LiteBIRD team has proposed participation in LiteBIRD and recently generated its Phase A report. The proposal and report were conducted by a subset of the community for the purpose of supporting a specific mission design, within specific cost caps, that match JAXA plans.

Work on our proposal, and the subsequent mission study, represent a collaborative effort by all interested members of the CMB community, including US members of the LiteBIRD team. We have also reached out to our international partners and invited them to participate. The final report will present a consensus view of the US CMB community. This would be the proper input for the deliberations of the next US decadal panel.

1.6 State of Technologies

The imager version of the probe consists of the following main technical elements: a telescope with an effective aperture size of $\lesssim 1.5$ m, a focal plane consisting of thousands of detectors, coolers that provide a focal plane temperature between 0.1 and 0.3 K, and a multiplexed readout system with which a handful of wires are used to readout hundreds or thousands of detectors. Additional elements could include filters and potentially lenses and polarization modulators. The spectrometer version is also a cryogenic mission, and has two main elements: the spectrometer, and the cold load that provides its absolute calibration. Both versions have the standard complement of spacecraft bus features to provide pointing control and sensing, telemetry, and power.

Relative to *Planck*, which was the last CMB imaging cryogenic mission, the most significant advances have been made in developing detector and readout technologies, and in optical components. While *Planck* had 54 polarization sensitive detectors, sub-orbital experiments now routinely implement thousands. Aided by large throughput optical systems, and large lenses Stage3 experiments will implement tens of thousands. By the time the Probe flies a focal plane with tens of thousands of detectors, in which few electrical lines readout thousands of detectors will be standard, well-tested technology. A key technical question for the implementation of the probe is whether the need to reject systematic uncertainties will require the implementation of an active polarization modulator.

Arrays of Detectors Currently bolometric transition edge sensor detectors have the highest TRL. Arrays with thousands of elements have flown on balloon-borne instruments. Ground-based instruments using this technology have fielded new technologies including multi-chroic detectors,

several new optical coupling schemes with horns and planar antennas, and Kinetic Inductance DetectorS (KIDS). We will study the systematics, sensitivity, cryogenic requirements, and mass of a focal plane suitable for the probe mission.

Readouts Currently the CMB field uses two families of readout technologies: frequency domain multiplexing (fMUX) and time domain multiplexing (TDM). Both offer 64 channels per readout module and have mature TRLs from being flown on sub-orbital missions. Emerging technologies include code-division multiplexing (based on TDM) which could substantially reduce the power requirements for the readout electronics; and microwave fMUX which promises to incorporate > 1000 channels of TES detectors or KIDS per multiplexing module, greatly simplifying focal plane integration and reducing the cryogenic load on the cold stage. We will study the noise, power, and mass implications of these solutions and identify the best approach for the probe mission.

Optical Components and Polarization Modulators Filters, Lenses, and Polarization Modulators are rapidly maturing technologies that have the potential to improve sensitivity, reduce focal plane mass, manage thermal loads, and mitigate important systematic effects. Antireflection (AR) coatings on silicon lenses with up to 3:1 ratio bandwidth have been deployed, similar lenses will soon be flown on balloons, and coatings on larger alumina lenses will soon be fielded on the ground. These AR coating approaches and metal-mesh metamaterials have lead to new realizations of broad-band half-wave plate (HWP) modulators which complement other approaches including variable phase polarization modulators. Continuous and stepped HWPs have been flown on sub-orbital missions to mitigate systematics. Deployed filters include metal-mesh, AR coated crystals, plastic layers and hybrids of these approaches. We will study mission configurations that include these technologies and optimize the system to minimize mass, cooling requirements, maximize sensitivity, and identify methods for control of systematic effects with and without a polarization modulator.

Cryogenics: An open cycle dilution refrigerator was flown on Planck and a continuous adiabatic demagnetization refrigerator will soon be flown on a balloon. We will study the requirements and tradeoffs of these mature cooling technologies in a mission plan.

Spectrometer The spectrometer is comprised of an array of 4 polarizing Fourier transform spectrometers, each with an absolute reference calibrator. Each spectrometer has an aperture less than 0.5 m feeding 4 detectors in an integrating cavity. The spectrometer builds on the COBE/FIRAS mission using mature technology (TRL 6 or higher). Multi-moded optics, concentrators, detectors, and calibrators have been demonstrated; detector readout is copied from the successful Hitomi design. We will study the instrument configuration and evaluate systematics, sensitivity, risks and requirements for this configuration.

1.7 Mission Study and Management Plan

1.7.1 Study Plan

The mission study is open to the entire CMB community and includes 75 scientists. To gain maximum benefit from *Planck*, LiteBIRD, and CORE we invited international members to participate. The work is organized into Working Groups (WG); see Figure 7. Working groups are led by members of the study's Executive Committee, as listed in the Figure. Although Figure 7 suggests distinct boundaries between the WGs we expect and encourage significant overlap and feedback. It is not practical to enumerate all the interdependencies.

The study will be carried out through intra- and inter-WG teleconferences; mission design teleconference with JPL engineers; mission design meetings at JPL; and a community workshop that is described in more detail below. A central activity that cross-cuts across several of the

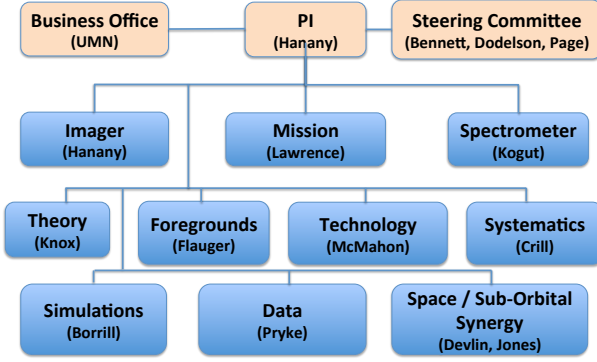


Figure 7: Management structure of the CMB Probe. A steering committee advises the PI. The study is led by the PI through an Executive Committee. Each member of the committee is in charge of a specific Working Group (blue boxes). Significant overlap and feedback is expected between the working groups. Participation in the Working Groups is open to all members of the CMB community.

WGs is the development and use of a ‘Mission Performance Simulator’. The mission performance simulator takes as input a particular instrument configuration (e.g number of detectors, frequencies, resolutions), sky observing pattern, models of sky emission (including CMB and foregrounds), and systematic effects. It generates detector timestreams that are used to make maps. The maps can be analyzed for their astrophysical content.

We now describe the work of each of the WGs and, where appropriate, lay out responsibilities for elements of the mission performance simulator.

- **Theory (Knox)** This WG will survey, summarize, and prioritize the set of science goals for the Probe. Given input on target frequency bands, assumptions about foregrounds, instrument systematics, and instrument noise levels the group will generate forecasts for the impact of the Probe’s products and their significance to physics and astrophysics. This group will also investigate which other astrophysical data sets are most suitable for cross-correlation analysis with the Probe’s data.
- **Mission and connection with JPL (Lawrence)** The Mission WG is responsible for defining the overall mission architecture including telescope implementation, cooling, telemetry, mass, power, and cost. We are requesting that engineering and costing session be conducted with JPL. Charles Lawrence, Chief Scientist of the Astronomy, Physics, and Space Technology Directorate at JPL, and the *Planck* US PI, will lead this WG.
- **Imager (Hanany) and Spectrometer (Kogut)** The imager and spectrometer WGs will translate the science goals to mission requirements and to nominal designs. The designs will include telescopes of various configurations, focal planes with several candidate detector technologies and readout schemes, optical elements, and cooling strategies. These groups will similarly consider the options for spectrometers. Both groups will interact frequently with JPL the Mission WG. The WG will consider an imager-only design, a spectrometer-only design, and a combined instrument. This group will provide focal plane configurations for the mission performance simulator.
- **Technology (McMahon)** to be completed
- **Space / Sub-Orbital Synergy (Devlin, Jones)** By the time the CMB probe is likely to fly, significant advances will have been made on the ground. This is true regardless of the state of the proposed CMB-S4 effort, and even more so should funding for S4 becomes available soon. This WG will assess and recommend the most appropriate design parameters such that the data sets from the Probe and sub-orbital measurements complement each other. Pertinent questions include: to what extent should the aperture size of the Imaging Probe rely on delensing capabilities provided by high resolution measurements from the ground? What is the optimal resolution of a space-based mission from the point of view of providing foreground subtraction capabilities to sub-orbital missions? What is an optimal overlap in ℓ -space coverage? Does the design of a spectrometer depend on the specifics of data available from sub-orbital measurements? We are planning a community

workshop to address these question, including forming a community consensus on the question of the need for a space mission if CMB-S4 is funded.

- **Data Analysis and Exploitation (Pryke)** The full sky nature, the broad frequency coverage, and the high sensitivity of the CMB-Probe will generate a legacy data set surpassing that of *Planck*'s. This WG will plan for the extraction of cosmological and astrophysical products from the Probe's data. This includes exploring optimal implementation of component separation techniques, of combining sub-orbital CMB data with the Probe's, and of cross-correlating with data at other wavelengths. The WG will assess whether specific synergies suggest preferring some mission parameter values over others. The group will use outputs of the mission performance simulator.

- **Systematics (Crill)** This WG will identify sources of systematic effects, evaluate their approximate magnitude, and will construct the tools to integrate the these systematic effects into the mission performance simulator. Examples include frequency band mismatches, differential gains, and sidelobes. The WG will explore mitigation of systematic errors by design, for example implementing modulation schemes and modulator technologies, and mitigation by analysis techniques.

- **Foregrounds (Flauger)** This WG will construct foregrounds models that encompass all the known and expected emission complexities. The models will be informed by data and physical inputs and will include, for example, spatial variations of the spectral dependence, decorrelation between frequencies, and departures from a simple modified black body law for Galactic dust [91, 92, 93, 94, 95, 96]. The models will be used as part of the Mission Performance Simulator. The WG will also study, develop, test, and recommend methods for component separation including those used with *Planck* [97].

- **Simulations (Borrill)** This WG will be in charge of building and running the mission performance simulator. It is based on the massively parallel tools built for the Planck Full Focal Plane simulations [98]. The simulations will use the high performance computing resources available to the CMB community at the DOE's National Energy Research Scientific Computing (NERSC) Center at Lawrence Berkeley National Laboratory.

1.7.2 Mission Study Timeline

The study will be conducted in three broad phases with several months overlap to allow for the non-linear nature of the progression: Mission Definition; Mission Implementation; Report Writeup.

Mission Definition: 3/2017 - 12/2017 The primary output of this period is a set of mission requirements that will feed into the Mission Implementation phase. To achieve a set of mission requirements we will use the mission performance simulator to iterate over various angular resolutions, focal plane configurations, detector noise properties and progressively more complex foreground and systematic effect models. Having extracted astrophysical information from the resulting multifrequency maps we will have determined the necessary e.g. focal plane sensitivity, or the number of frequency bands. The set of these parameters is the mission requirements.

During the middle of this period, in summer of 2017, we are planning to hold the community workshop. The goal for the workshop is to generate consensus about the complementarity between the data from the space mission and from sub-orbital experiments. This consensus will inform the design parameters of the mission.

Mission Implementation: 9/2017 - 6/2018 This is the period This is the period during which baseline instrument parameters become a space mission. We will finalize the detector and readout technologies, or identify several acceptable options. We will investigate the impact of target telescope size and temperature on cooling resources, and cost. Readout technologies will also have

impact on cooling resources – because of the number of wires reaching the focal plane – and on power budget. The preferred scan strategy has consequences on maneuvering the spacecraft and on attitude reconstruction. The large number of detectors will impose constraints on the telemetry.

By the beginning of 2018 we will define a point design for the mission and a relevant exploration space around it. The session with JPL's TeamX is scheduled for 3/2018. This timing will allow for digesting the results and finalizing the mission implementation.

Report Writeup: 3/2018 - 9/2018

1.7.3 Study Team

The study consists of more than 50 scientists representing hundreds of years of experience with CMB theory, data analysis, and measurements on all platforms including satellite missions that have already flown (COBE, WMAP, and *Planck*) and the two proposed (LiteBIRD and CORE). The PI Hanany, who has more than 20 years of CMB ballooning experience, co-led MAXIMA and Archeops, was the PI of MAXIPOL and EBEX, and is a member of CORE's Executive Board, will have ultimate responsibility for the study. He is advised by a Steering Committee – Bennett (Johns Hopkins), Dodelson (Chicago), and Page (Princeton) – and assisted by a business office at the University of Minnesota. An Executive Committee (EC) is in charge of the daily operation of the collaboration. The members of the Steering and Executive Committees led and are leading operating CMB experiments that have produced the most compelling CMB polarization results. They include leaders and members of the WMAP, US *Planck*, US LiteBIRD, and US CORE teams. They include initiators and implementors of new millimeter-wave technologies, and of recognized experts in data analysis and theory.

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2 Curriculum Vitae

3 Summary of Work Effort

4 Current and Pending Support

5 Letters of Support

6 Budget Details - Narrative

6.1 Team, and Work Effort

6.1.1 Funded Team Members

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6.2 Costing Principles

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6.3.4 Other Direct Costs

Publications and Teleconferencing

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7 Budget Sheets

ACS attitude control system

ADC analog-to-digital converters

ADS attitude determination software

AHWP achromatic half-wave plate

AMC Advanced Motion Controls

ARC anti-reflection coatings

ATA advanced technology attachment

BRC bolometer readout crates

BLAST Balloon-borne Large-Aperture Submillimeter Telescope

CANbus controller area network bus

CIB cosmic infrared background

CMB cosmic microwave background

CMM coordinate measurement machine

CSBF Columbia Scientific Balloon Facility

CCD charge coupled device

DAC digital-to-analog converters

DASI Degree Angular Scale Interferometer

dGPS differential global positioning system

DfMUX digital frequency domain multiplexer

DLFOV diffraction limited field of view

DSP digital signal processing

EBEX E and B Experiment

EBEX2013 EBEX2013

ELIS EBEX low inductance striplines

ETC EBEX test cryostat

FDM frequency domain multiplexing

FPGA field programmable gate array

FCP flight control program

FOV field of view

FWHM full width half maximum

GPS global positioning system

HDPE high density polyethylene

HIM high index materials

HWP half-wave plate

IA integrated attitude

IP instrumental polarization

JSON JavaScript Object Notation

LDB long duration balloon

LED light emitting diode

LCS liquid cooling system

LC inductor and capacitor

LZH Lazer Zentrum Hannover

MCP multi-color pixel

MSM millimeter and sub-millimeter

MLR multilayer reflective

MAXIMA Millimeter Anisotropy eXperiment IMaging Array

NASA National Aeronautics and Space Administration

NDF neutral density filter

PCB printed circuit board

PE polyethylene

PME polarization modulation efficiency

PSF point spread function

PV pressure vessel

PWM pulse width modulation

RMS root mean square
SLR single layer reflective
SMB superconducting magnetic bearing
SQUID superconducting quantum interference device
SQL structured query language
STARS star tracking attitude reconstruction software
SWS sub-wavelength structures
TES transition edge sensor
TDRSS tracking and data relay satellites
TM transformation matrix
UHMWPE ultra high molecular weight polyethylene
UMN University of Minnesota