Contents

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 primordial 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 a 2σ detection reachable by 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 in 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 on all scales, from clusters of galaxies to the collapse of a protostellar core. With high sensitivity, access to the entire sky, 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 8 years ago. 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

It is useful to decompose the polarization field of the CMB 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 $r < 0.07\,(95\%)$ [6].

The best measurement of the CMB spectrum – made by COBE/FIRAS approximately 25 years ago – shows that the average CMB spectrum is consistent with that of a blackbody to an accuracy of 5 parts in 10^5 [7, 8]. Distortions in this spectrum encode a wealth of new information. The distortion shapes are commonly denoted as μ- and y-types [9, 10]. 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 redshifts $z \geq 5 \times 10^4$. The y distortions are caused by energy exchange between

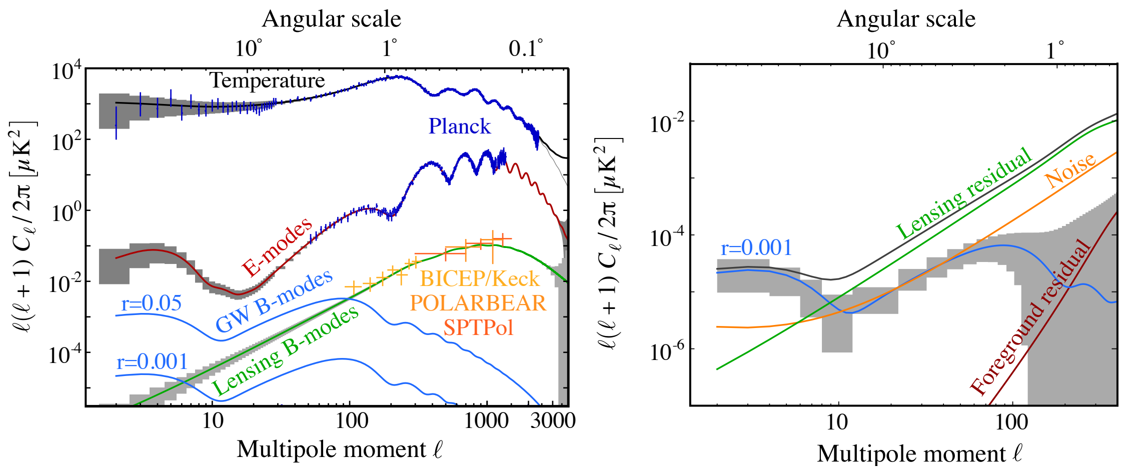

Figure 1: Predicted determination of the CMB power spectra for EPIC-IM (grey boxes) after foreground removal for $r = 0$ (left) and after foreground removal and delensing for $r = 0.001$ (right) overlaid on theoretical predictions (solid lines) and including *Planck* measurements of the temperature and 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.

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 performance assessments in this proposal are based on two current-decade mission designs, EPIC-IM and Super-PIXIE [11, 12]. 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 version consisting of 4 spectrometers, each operating between 30 and 6000 GHz with 400 ∼15 GHz-wide bands. The two designs are our starting point for consideration of a future Probe; they are generically referred to as 'baselines'. We will show that the Probe will require higher sensitivity than the baseline; the requirement will be determined during the study. Improvements in technology by the next decade will enable the design of a mission that is much more capable compared to the baselines.

1.3 Science Objectives

The broad array of fundamental questions the CMB Probe will address, as describe in this section, firmly fit into NASA's strategic plan as articulated by its Strategic Goal 1 "Expand the frontiers of knowledge", and specifically Objective 1.6 "Discover how the universe works, [and] explore how it began and evolved".

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 [13, 14] or any other source of vector or tensor perturbations, such as primordial magnetic fields [15, 16, 17, 18] and cosmic strings [19, 20, 21, 22] 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 recombination [23], and because on large scales the signal is strongest relative to the lensing B mode and instrumental noise; see Figure 1. 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 of primordial fluctuations $n_{\rm s}$. 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.

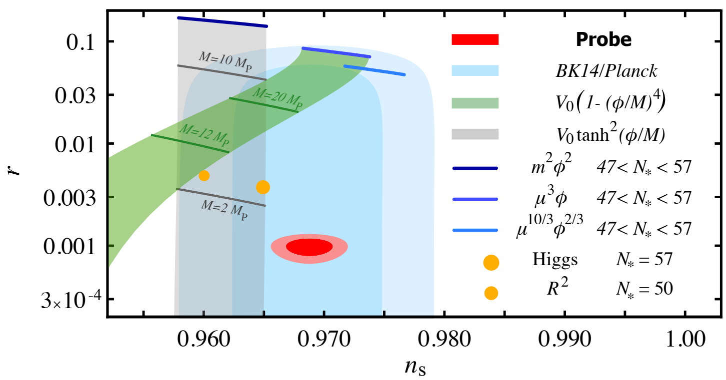

Figure 2: Current 1 and 2σ limits on r and $n_{\rm s}$ (blue) [6] and forecasted constraints for a fiducial model with $r = 0.001$ for the baseline probe. Also shown are predictions for the models of the inflaton potential discussed in the text.

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 $n_{\rm s}$. The baseline probe 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 [24, 25, 26, 27, 28, 29, 30, 31].

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 $\sigma(n_{\rm t}) < 1$ at $r = 0.01$, easily achievable with a Probe mission, would significantly constrain non-vacuum inflationary sources [32, 33].

Deeper mapping of 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 [34]. Cosmic variance limited measurement of these modes will also improve constraints on n_s, its changes with scale, and on primordial non-Gaussianity by factors of about two.

Spectral distortion measurements give additional tests of inflation. The dissipation of small-scale perturbations through Silk-damping leads to μ-distortions [35, 36, 37, 38]. In ΛCDM the distortions are predicted at a level of $\mu = (2.0 \pm 0.14) \times 10^{-8}$, a level that is readily accessible

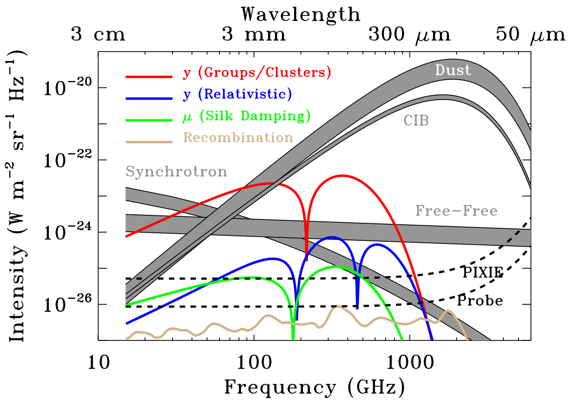

Figure 3: Anticipated y and μ spectral distortions (solid), the signature of resonant recombination lines (solid), and anticipated foreground signal levels relevant for spectral distortion measurements (grey bands). The simplest baseline spectrometer (Probe, dash) gives approximately 10 times the Explorer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

to a Probe class mission, see Figure 3 [38, 39]. 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 Figure 3 [40, 41]. The detailed physics is sensitive to the values of $n_{\rm s}$, 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 [42, 43]. 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 $N_{\rm eff}$, also called the effective number of neutrinos. The canonical value with three neutrino families is $N_{\rm eff} = 3.046$. Additional light particles contribute a change to $N_{\rm eff}$ of $\Delta N_{\rm eff} \geq 0.027\, g$ where $g \geq 1$ is the number of degrees of freedom of the new particle [44, 45]. This defines a target of $\sigma(N_{\rm eff}) < 0.027$ for future CMB observations. Either a limit or detection of $\Delta N_{\rm eff}$ at this level would provide powerful insights into the basic constituents of matter.

Forecasts for $N_{\rm eff}$ are shown in Figure 4. The two most important parameters for improving constraints are the fraction of sky observed $f_{\rm sky}$ and the noise. Achieving both larger $f_{\rm sky}$ and lower noise are strengths of the CMB Probe compared to other platforms. Our baseline mission nearly reaches the target constraint with $g = 1$. A newly designed mission with only 10 times higher sensitivity will reach $\sigma(N_{\rm eff}) < 0.025$. A high precision measurement of the CMB in temperature and polarization is the only proven approach to reach 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 $N_{\rm eff}$ 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. The Probe's μ-distortion measurement gives a two orders of magnitude improvement on the abundance and lifetime of early universe relics compared to current constraints derived from measurements of light element abundances [47, 48, 49, 50].

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 [51, 52, 53]. *Planck* currently excludes WIMPs with mass $m_{\rm dm} < 16$ GeV and a future

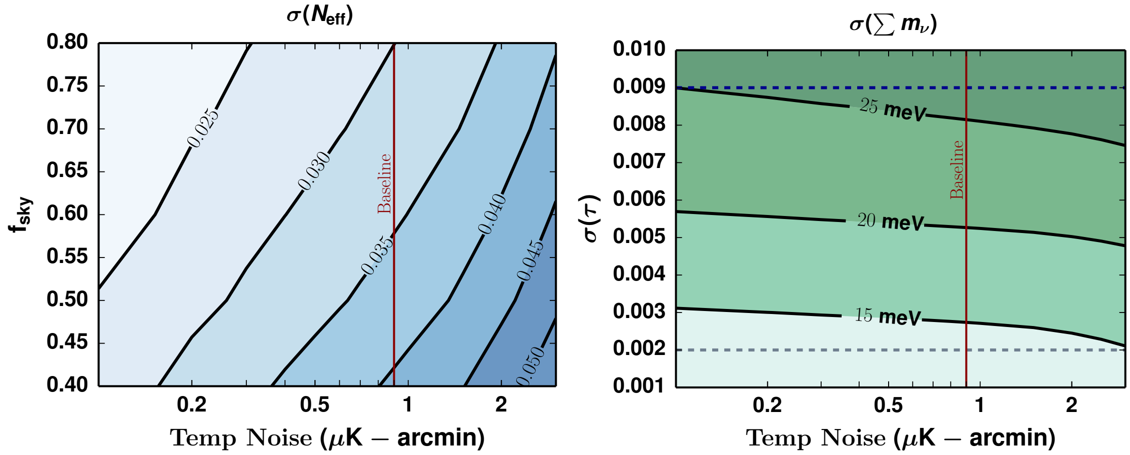

Figure 4: $N_{\rm eff}$ uncertainty as a function of noise and sky fraction (left) and sum of neutrino masses uncertainty as a function of noise and the uncertainty in the measurement of τ, for 0.7 sky fraction (right). The resolution assumed is 5'. Vertical lines denote the expected performance of the baseline mission. The upper blue dashed line is the current *Planck* limit; the lower grey dashed line is the limit from cosmic variance limited measurement of τ. All forecasts assume internal delensing of the T and E-maps [46], including residual non-Gaussian covariances. The $\sum m_\nu$ forecasts include DESI BAO.

CMB mission could reach $m_{\rm dm} < 45$ GeV for $f_{\rm sky} = 0.8$. The CMB provides the most stringent constraints on the dark matter annihilation cross section for dark matter in this mass range.

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 [54]. These couplings affect the evolution of fluctuations and ultimately the T and E spectra. The current limits of $\sigma \lesssim 10^{-31} - 10^{-34}\,{\rm cm}^2 \times (m_{\rm dm}/{\rm MeV})$ 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. [55, 56, 57]).

Current constraints from FIRAS's spectrum measurement are most sensitive to small dark matter mass, $m_{\rm X} \lesssim 0.2\,{\rm MeV}$, but these could be extended to $m_{\rm X} \lesssim 1\,{\rm GeV}$ with a Probe-class mission, thus testing DM interaction down to cross-sections $\sigma \simeq 10^{-39} - 10^{-35}\,{\rm cm}^2$ [58]. Spectral distortion measurements also open a new avenue for testing dark matter-proton interactions [58].

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., 59, 60, 61, 62, 63].

1.3.3 Neutrino Mass

Cosmology is uniquely capable of measuring the sum of neutrino masses, $\sum m_\nu$, 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 the optical depth to reionization τ and the amplitude of the primordial perturbation power spectrum A_s. Although many surveys hope to detect $\sum m_\nu$, 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. The current limit of $\sigma(\tau) = 0.009$ is from *Planck* [64]. Forecasts for a CMB measurement of $\sum m_\nu$ using lensing B modes [65] are shown in Figure 4. With the current uncertainty in τ one is limited to $\sigma(\sum m_\nu) \gtrsim 25$ meV; no other survey or cosmological probe would improve this constraint. But 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 [66]. Robustly detecting neutrino mass at $> 3\sigma$ in any cosmological setting is only possible with an improved measurement of τ like the 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. An open frontier in this quest is to discover 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. 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. The *Planck* team reported recently a value of $\tau = 0.055 \pm 0.009$ [64, 67]. The level is lower than previous estimates and reduces the tension between CMB-based analyses and constraints from other astrophysical sources [68]. The CMB Probe's measurement of E-mode polarization will improve $\sigma(\tau)$ by a factor of 4.5, reaching the cosmic variance limit and setting stringent constraints on models of the reionization epoch.

The anisotropy of the cosmic infrared background (CIB), produced by dusty star-forming galaxies in a wide redshift range, is 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~ 4 [69, 70, 71]). By measuring CIB anisotropy with $\simeq 100$ times higher signal-to-noise ratio at multiple frequencies, the CMB Probe will constrain the star formation rate with one tenth of *Planck*'s uncertainty. Similar improvement will be achieved in constraining $M_{\rm eff}$, the galaxy halo mass that is most efficient in producing star formation activity.

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 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 $kT_{\rm e} \simeq 1\,{\rm keV}$ 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 Probe. It will be used to constrain the currently uncertain feedback mechanisms used in hydrodynamical simulations of cosmic structure formation [72].

The CMB spectrum varies spatially across the sky. One source of such anisotropic distortion is due to the spatial distribution of clusters and has already been measured by *Planck* [73]. A combination of precise CMB imaging and spectroscopic measurements will allow observing the relativistic temperature correction of individual SZ clusters [74, 75, 76], 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 [77, 78, 79, 80, 81].

1.3.5 Galactic Magnetic Fields and The Star Formation Process

Magnetohydrodynamic turbulence is a key regulator of the star-formation process. It acts over a range of spatial scales extending from the the largest eddies in the diffuse interstellar medium down to the scales of protostellar cores, envelopes, disks, outflows, and jets. Despite extensive work on observing density, velocity, and magnetic field structure, key questions remain open. For example, we don't yet know the characteristic magnetic field strength in molecular clouds, nor do we know the scales and mechanisms for dissipation of magnetized turbulence. Recent years have witnessed the development of sophisticated high-resolution 3-d simulations of magnetized turbulence, allowing us to constrain both the field structure and the associated grain alignment parameters via statistical comparisons between observed and simulated submillimeter-wave polarization maps. Our proposed probe-scale mission will provide tens of millions of independent magnetic field measurements, covering the missing spatial scales not recoverable via interferometric polarimetry with the Atacama Large Millimeter-Submillimeter Array, and thereby characterizing definitively the magnetic links between protostellar structures and the Galactic ISM.

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 $r < 0.07\,(95\%)$, that is, to reach $\sigma(r) \lesssim 0.0005$ limited by foreground uncertainties. Foregrounds already dominate the signal. The large reduction in the size of the final error will require exquisite measurements and modeling of their properties.

To ascertain that the uncertainty on the measurement is dominated by statistics, or foreground uncertainties, rather than systematic errors, the contribution due to instrumental systematic effects should be $\sigma(r) \lesssim 0.0001$. To achieve these unprecedented levels the mission design, execution, and data analysis will be driven by control of systematic uncertainties.

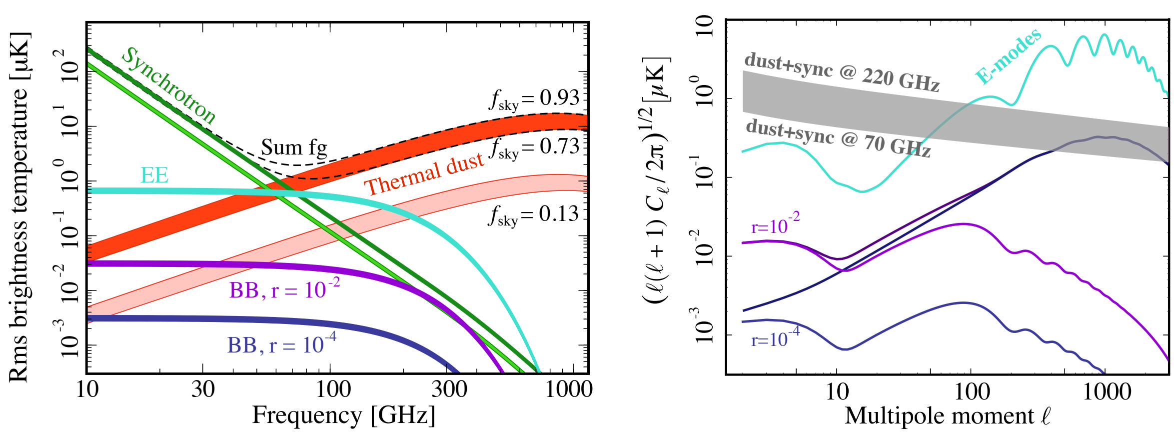

Figure 5: *Left:* Brightness temperature as function of frequency for the polarized CMB (cyan, purple, blue) and Galactic foreground signals: dust (red) and synchrotron (green). The darker bands correspond to sky fractions between 73% and 93%; the lighter bands to the cleanest 13%, with the width indicating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

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 ℓs), 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 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 inflationary B-mode signal on *all* angular scales by an order of magnitude or more.

Known signals can be accounted for and removed even if their amplitude is large. But the best measurements to date, from *Planck*, have uncertainties that fall far short of the goals 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.

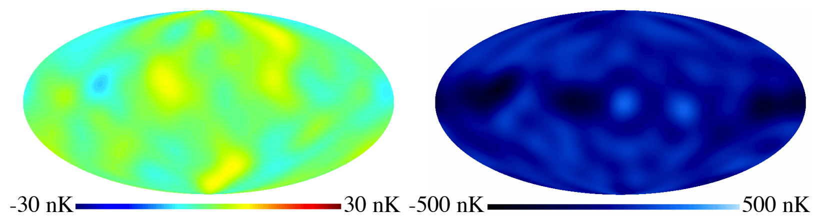

Figure 6: *Left:* Stokes Q for inflationary B modes for $\ell < 12$ and $r = 0.001$. *Right:* Noise in the *Planck* 353 GHz map of Stokes Q for $\ell < 12$ extrapolated to 150 GHz assuming the (sky average) spectral properties of dust. Note the color scales.

Removal of foregrounds based on multi-frequency data 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 spatially uniform modified black body spectrum for dust emission give a reasonable fit to the data. But the complex composition of Galactic dust – for example, the grains' size distribution, the different materials, and different radiative envirnoments – suggests that this simple phenomenological description would no longer be valid at higher precision levels. One expects departures from a modified black body spectrum, and the emission properties are expected to vary spatially. The details of foreground emission, at every point on the sky, must ultimately be measured with the Probe itself. The challenge is to design the frequency coverage to do so optimally.

For $r < 0.01$ the inflationary signal is at or below the lensing B mode; see Figure 1. Using high resolution polarization measurements, it is possible to reconstruct the lensing field and 'delens' and thus remove the effect of lensing. But for low r values significant delensing is required, and it is an open question at which point foregrounds will become the limiting factor.

Good 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 $\ell < 10$. And recovering the spectral distortions signals will require proper accounting of 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 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 Probe [64]: 1) Intensity-to-polarization leakage, 2) stability, and 3) straylight. Each of these is considered below in light of polarimetry measurements through differencing the signals of two detectors that are sensitive to orthogonal polarization states. Currently, the most sensitive sub-orbital experiments have shown control of systematics at a level of $r \lesssim 0.006$ ($r \lesssim 0.001$ with a polarization modulator on the main beam pattern) on small (1%) sky fractions [82, 83].

Leakage The CMB temperature anisotropy signal is a factor of 1000 larger than the strongest possible inflationary B modes. Therefore instrumental effects that leak even a small fraction of an intensity fluctuation into spurious polarization 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. 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.

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 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.

The spacecraft's ambient radiation environment is modulated by the solar activity and can introduce temperature drifts in the cryogenic stages, leading 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 $\sim$5 additional noise at ℓ=2 [64]. 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 the Probe will necessitate a much stronger level of mitigation.

1.5 The CMB Probe in Context

1.5.1 Current and Forthcoming Sub-Orbital Efforts

The remarkable scientific yield has motivated significant agency investments in current and future sub-orbital experiments. 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 efforts 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.

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 are important in their own right and are critical preparation for a space mission.

The 2010 Decadal Panel strongly recommended supporting sub-orbital efforts in preparation for a possible space mission that would make a definitive and high quality measurement of primordial 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 primordial B modes. 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 CMB Probe. It is an imager based on a 0.4 m aperture telescope. Its reach in ℓ space is 2.5-4 times less compared to the 1-1.5 m aperture we are considering for Probe making the science at ℓ's above a few hundred in E and B modes unreachable. It has no spectroscopic capabilities and thus not sensitive to 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 have 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, comprehensive frequency coverage, and exquisite control of systematic effects. No sub-orbital experiment has yet produced any polarization results on more than 2% of the sky, let alone on scales requiring $> 70\%$, which are crucial for achieving some of the science goals described in Section 1.3. The broad frequency coverage of the space mission is best suited to mitigate the foregrounds expected on a broad range of angular scales. 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 [11]. 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 has just been proposed to ESA, has an aperture of 1.2 m, a telescope cooled to 40 K or less, 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 and has a continuously rotating polarization modulator. The second focal plane is coupled to the sky without reflectors; it has a second continuously rotating polarization modulator. Both focal planes are cooled to 0.1 K and contain few thousand detectors. LiteBIRD is estimated to be 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 study, these past exercises suggest that a polarization 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 questions we will address during the study.

1.5.5 This Study in the Context of Previous Mission Studies

The US CMB community's most recent view of the anticipated science reach and the path to implementation of a possible future US space mission were summarized in an unpublished report to the 2010 decadal panel. That report drew upon the EPIC-IM mission design, which is nearly 10 years old. The landscape has since changed. Theoretical advances in physics and astrophysics give updated science goals, and therefore new targets for the fidelity of measurements of E and B modes. Existing and forthcoming data, from new astrophysical surveys and particle physics experiments, present opportunities for new synergies and complementarities. 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.

The US LiteBIRD team has proposed participation in LiteBIRD and recently submitted its Phase A report. The proposal and report were conducted by a subset of the community for the purpose of supporting a mission design that matches JAXA's plans and its cost caps.

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: a 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.

Planck, which was the last CMB imaging cryogenic mission, had 65 polarization sensitive detectors. The most significant advances since *Planck* have been in developing detector and readout technologies, and optical components. The baseline imager, enjoying technologies of a decade ago, had $\sim$30 times the sensitivity of *Planck*. As the paragraphs below describe, a mission with today's technologies would already be more powerful than the baseline mission. The CMB Probe promises to be orders of magnitude more sensitive than *Planck*.

Arrays of Detectors Most modern sub-orbital experiments use TES bolometers, with thousands of detectors with TRL≥ 5. HEMT amplifiers, which are a competitive technology below 100 GHz, also have high TRL. The bolometric arrays have been successfully implemented with a variety of optical coupling schemes such as horns, contacting lenslets, and antenna arrays. Some instruments have deployed newer technology with arrays of 'muti-chroic pixels'. With this technology several frequency bands are detected through the same focal plane pixel. As of now, arrays with up to 3 bands and 6 detectors per pixel are being used. A new detector technology using kinetic inductance inductors (KIDs) is emerging, which may have benefits in simplicity of fabrication and scalability to arrays with hundreds of thousands of elements.

Readout Two families of readout technologies are in use: frequency- and time-domain multiplexing, FDM, and TDM, respectively. Both offer 64 channels per readout module and have mature TRLs having been flown on balloon payloads. Increasing the multiplexing factor, a goal in both approaches, decreases the heat load due to wiring on the focal plane. The microwave FDM is an emerging technology which promises to incorporate $\gtrsim 500$ channels of TES detectors or KIDs per multiplexed module. It is attractive because there is no dissipation at the coldest stage, but there is increased dissipation at ~ 4 K and further development is required to reduce the ambient temperature power consumption. Currently the ambient temperature power consumption of TDM systems is $\times 2-3$ lower, but development is necessary to reduce the higher power consumption at the coldest stage.

Polarization Modulators and Other Optical Components A polarization modulator presents an attractive means to reject a host of systematic uncertainties. Some sub-orbital experiments have used modulators and experience with their operation, efficacy, and the systematic errors they present, is growing. For use with the Probe, the modulators will need to have high polarization efficiency over a broad bandwidth. A fractional bandwidth of $\sim$100% has been demonstrated. Optical systems that incorporate refractive elements can realize higher throughput than reflectors alone; the use of refractors – or a modulator – requires broad-band anti-reflection coatings. Groups have developed specialized sprays and techniques to fabricate sub-wavelength structures. Most of these technologies have TRL$\geq$5.

Spectrometer The polarizing Fourier transform spectrometer builds on the COBE/FIRAS mission using mature technology with TRL $\geq$6. The baseline spectrometer we have assumed here is comprised of a number of individual spectrometers, each with its own absolute reference calibrator, Multi-moded optics, concentrators, detectors, and calibrators have been demonstrated. The detector readout is copied from the that used for the Hitomi mission. But the Probe version may combine multiple spectrometer beams within a single telescope. How to achieve that will be part of this study.

Cryogenics For providing an operating temperature of 0.1 K: an open cycle dilution refrigerator, a European technology, was flown on *Planck*. A closed cycle version is under development (also in Europe) and has TRL 3-4. A Goddard continuous adiabatic demagnetization refrigerator (ADR) will soon be flown on a balloon payload. The Hitomi spacecraft operated a staged version of such an ADR. For higher operating temperatures, refrigerator technologies are standard, but suitability for the mission thermal loads will be assessed during the study.

1.7 Mission Study and Management Plan

1.7.1 Study Plan

The mission study is open to the entire CMB community and includes more than 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.

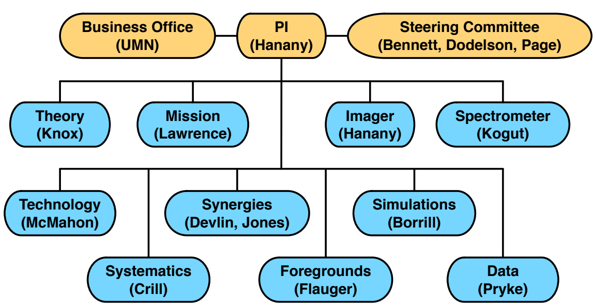

Figure 7: Management structure of the CMB Probe. A steering committee advises the PI. The study is led by the PI through an Executive Committee. Each member of the committee is in charge of a specific Working Group (blue boxes). Significant overlap and feedback is expected between the working groups.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

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.

By the time the CMB probe is likely to fly, significant advances will have been made with sub-orbital efforts. This is true regardless of the state of the proposed CMB-S4 effort, and even more so should funding for S4 become available soon. A central study activity will be to investigate and clarify the complementarity between the space mission and sub-orbital efforts. The workshop is dedicated to discussing this topic. Pertinent topics include: the extent to which the aperture size of the imaging probe relies on delensing capabilities provided by high resolution measurements from the ground; the optimal resolution of a space-based mission from the point of view of providing foreground information to sub-orbital missions; the optimal overlap in ℓ-space; the relation between the design of a spectrometer and forthcoming sub-orbital measurements; and the necessity for a space mission in the era of sub-orbital experiments with 500,000 detectors.

Another central activity that cuts across several of the 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 are 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 Probes 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)** This working group will provide technical input to the team designing the mission and instruments. It will assess the most appropriate technologies given the implementation of the mission and identify technologies that are in need of development. A central topic of assessment will be the technical readiness and possible implementation of a polarization modulator.

• **Space / Sub-Orbital Synergy (Devlin, Jones)** This WG will coordinate the study of complementarity between the Probe and sub-orbital efforts. It will also prepare, organize, and run the community workshop, and will be in charge of summarizing the conclusions.

• **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 [84, 85, 86, 87, 88, 89]. 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* [90].

• **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.

• **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 [91]. 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.

• **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.

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 gives the set of mission requirements.

In summer of 2017 we are planning to hold the community workshop. The conclusions from the workshop, regarding the complementarity between the Probe and sub-orbital experiments, will inform the design parameters of the mission.

Mission Implementation: 9/2017 - 6/2018 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. This is the period during which we will have defined a nominal design for the mission and a relevant exploration space around it. These will be the basis for the design session with JPL's Team X, and for the 'report about findings' as prescribed by NASA.

Report Writeup: 3/2018 - 9/2018 Writing the final report.

1.7.3 Study Team

The study consists of more than 75 scientists representing hundreds of person 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 to date. They include leaders and members of the WMAP, US *Planck*, US LiteBIRD, and US CORE teams; the leader of the PIXIE spectrometer proposal; initiators and implementors of new millimeter-wave technologies; and of recognized experts in data analysis and theory.

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