Contents

1 Scientific, Technical, and Management Section

1.1 Baselines and Observables

We are proposing to study a probe-scale mission to extract the wealth of cosmological information contained in the spectrum and polarization of the cosmic microwave background (CMB). The starting points for our study of this CMB Probe are two current-decade space missions, EPIC-IM and Super-PIXIE [1, 2]. EPIC-IM was presented to the 2010 decadal panel as a candidate CMB imaging polarization space mission. It was based on a 2 m 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.

The best measurements of the CMB spectrum – made by COBE/FIRAS approximately 25 years ago – show that the average CMB spectrum is consistent with that of a blackbody to an accuracy of 4 parts in 10^4 [3, 4]. Distortions in this spectrum encode a wealth of new information. The distortion shapes are commonly denoted as μ- and y-types [5, 6]. 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. 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.

Thomson scattering at the surface of last 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 [7, 8**? ?**].

A future CMB Probe-scale mission will address the physics of the big bang and of quantum gravity; it will measure the sum of the neutrino masses, and constrain the effective number of light particle species and the nature of dark matter; it will probe 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. In addressing these broad array of fundamental questions the Probe firmly fits 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".

1.2 Science Objectives

1.2.1 The Primordial Universe and Cosmic Inflation

The observed temperature and E-mode polarization of the CMB require primordial inhomogeneities in the gravitational potential, providing a remarkable observational link to the dynamics of the Universe near the big bang. Inflation, a primordial era of accelerated expansion, provides a compelling dynamical origin for the observed nearly scale-invariant spectrum of the primordial perturbations [9, 10, 11, 12, 13]. But, inflation also predicts an as yet unobserved spectrum of primordial gravitational waves sourced directly by quantum fluctuations of the tensor component of the metric. These gravitational waves make a distinct B-mode imprint on the polarization of the CMB. Any detection of B-mode polarization, whether generated by the primordial gravitational waves of inflation [14, 15] or by any other source of early time vector or tensor perturbations, would reveal completely new information about the primordial era. The results would provide significant constraints and consistency checks for current models or could perhaps even overturn them. A detection would have implications for fundamental physics by providing evidence for a new energy scale near the GUT scale. In the context of inflation, the relationship is particularly clear: the potential energy V of the inflaton is related to the tensor-to-scalar ratio r at the peak of the spectrum by $V^{1/4} = 3.7 \times 10^{16}\, r^{1/4}$ GeV.

Figure 1 shows current CMB data, B-modes from vacuum fluctuations of the metric during an inflationary era for two values of r, as well as forecasts for the determination of the CMB spectra for EPIC-IM. The most recent constraint on the tensor to scalar ratio gives $r < 0.07\,(95\%)$; see Figure 2 [18]. For testing inflation, the largest scales $\ell \leq 10$ are particularly important because they reveal the presence of B mode correlations on scales that were super-horizon at the time of recombination [16], and because the signal is strongest relative to the B-mode from lensing. No sub-orbital platform has yet produced B-mode measurements at $\ell < 80$, and a satellite is by far the most suitable platform to making the all sky observations necessary to reach the lowest modes, $\ell < 20$. In its recent report New Worlds New Horizons (NWNH), the decadal survey committee strongly endorsed searches for the B-mode signal from inflation saying that "The convincing detection of B-mode polarization in the CMB produced in the epoch of reionization would represent a watershed discovery." [17].

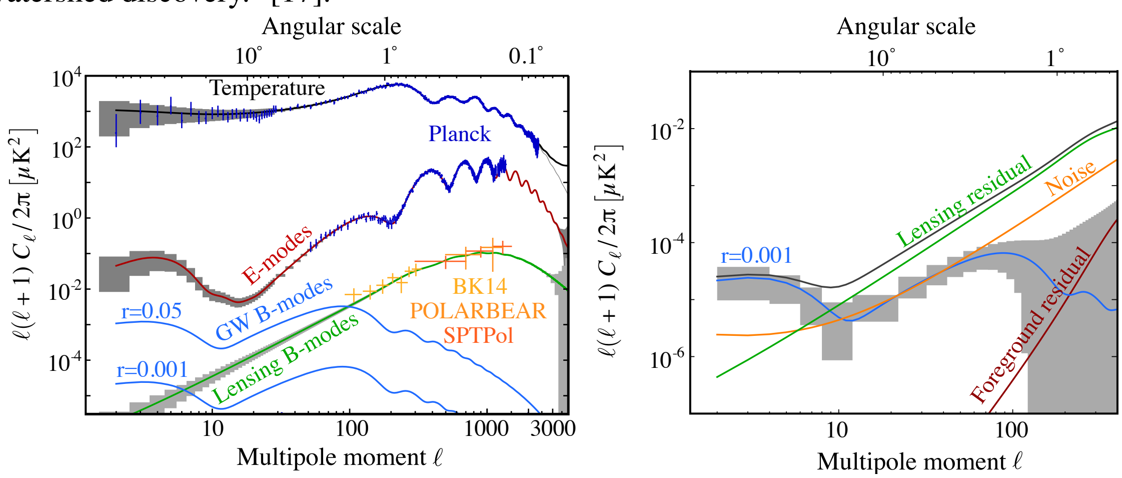

Figure 1: Predicted determination of the CMB power spectra for EPIC-IM (grey boxes) overlaid on theoretical predictions (solid lines) and including Planck measurements of the temperature and E modes (blue) and of several ground-based measurements of the lensing B-modes. The tensor B-mode predictions (blue) are shown for two representative values of the tensor-to-scalar ratio: $r = 0.001$ and $r = 0.05$.

In slow roll inflation there are just two observationally viable 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. The other class of models includes Starobinsky 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 nearly every currently favored inflation model. For a simple foreground model with spatially uniform spectral dependence assuming that synchrotron emission is well described by a power law and that dust emission is well characterized by a two-component model, EPIC-IM would achieve $\sigma(r) \sim 1.3 \times 10^{-4}$ assuming $r = 0.001$ and delensing with data from EPIC-IM itself.

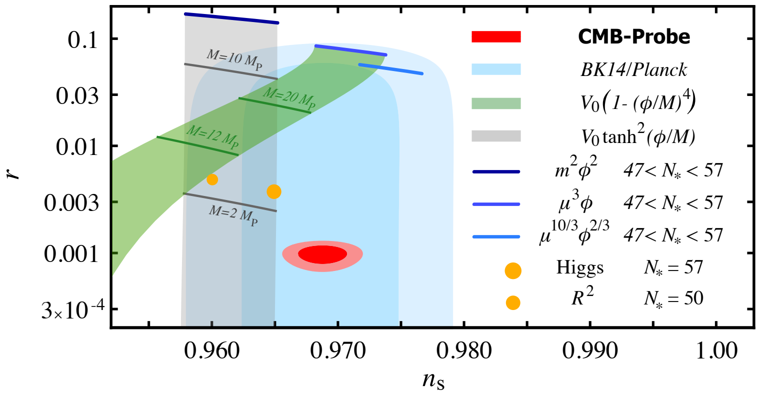

Figure 2: Current 1 and 2σ limits on r and n_s (blue) and forecasted constraints for a fiducial model with $r = 0.001$ for EPIC-IM [18]. Also shown are predictions for the models of the inflaton potential discussed in the text: Chaotic inflation for a range of $N_\star$ values (blue lines); Higgs and R^2 (large and small dots, respectively); quartic hilltop (green band); and a sub-class of α-attractor models [19]

A detection of B-modes consistent with a primordial spectrum of vacuum fluctuations would be the first observation of a phenomena directly related to quantum gravity. In addition, any detection with a next generation satellite would be evidence for *large-field* inflation [20], in which a smooth potential that supports inflation extends over a distance in field space $\Delta\phi \gtrsim M_p$. Quantum gravity studies of inflation give a generic expectation $\Delta\phi \lesssim M_p$ [21, 22, 23, 24], although there are some mechanisms to realize large-field inflation [25, 26, 27, 28]. A detection of r would therefore provide strong motivation to better understand how large-field inflation can be naturally incorporated into quantum gravity.

All inflation models predict a B-mode spectrum with the shape shown in Figure 1, but inflation need not be correct [29, 30, 31] and does not preclude 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 an extremely Gaussian and nearly scale-invariant spectrum for gravitational waves. A target constraint of $\sigma(n_\mathrm{t}) < 1$ at $r = 0.01$, driven by the information in the reionization bump, would significantly constrain non-vacuum inflationary sources [32, 33] and rule out physics completely inconsistent with inflation.

Deeper mapping of E-mode polarization will also contribute to testing inflationary models. Large scale E-modes will provide new tests of isotropy, a prediction of most models of inflation; for example, the observations can reject at 99% confidence models in which low multipoles are aligned in the temperature maps [34]. Together with continued improvements at high ℓ from the ground, these modes will also improve constraints on the scalar spectral index and its changes with scale 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 to a Probe class mission, see Fig. 3 [38, 39].

A better optimized probe may also give the sensitivity to detect the signature of recombination radiation imprinted by cosmological recombination of hydrogen and helium at redshift $z \simeq 10^3 - 10^4$; see Fig. 3 [40, 41]. The detailed physics is sensitive to the values of n_s, which is a direct probe of inflation.

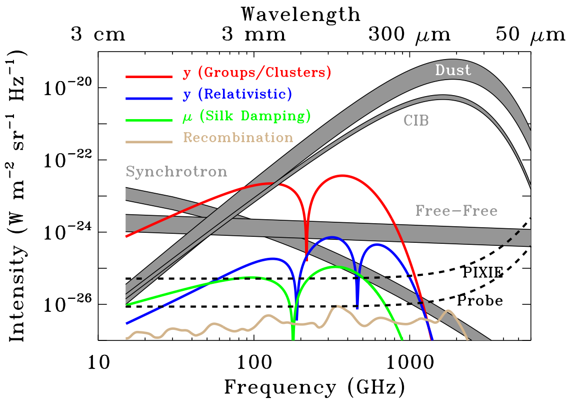

Figure 3: Anticipated y and μ spectral distortions (solid), the signature of resonant recombination lines (solid), and anticipated foreground signal levels relevant for spectral distortion measurements (grey bands). The simplest extension of a proposed Explorer class mission (Probe, dash grey) gives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

1.2.2 Light Relics and Dark Matter

After inflation, the universe was reheated to temperatures of at least 10 MeV and perhaps as high as 10^{10} 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 and leave 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 a powerful insight 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 $g = 1$, already exceeding constraints from other astrophysical probes and planned CMB observations. A newly designed mission is likely to reach $\sigma(N_{\rm eff}) < 0.027$ with high signal-to-noise ratio.

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 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 [47, 48, 49, 50]. A future Probe's μ-distortion constraint gives a two orders of magnitude improvement on the abundance and life time of early Universe relics [51, 52] compared to current constraints derived from measurements of light element abundances [53, 54].

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 [55, 56, 57]. Planck currently excludes WIMPs with mass $m_{\rm dm} < 16$ GeV and a future 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. The

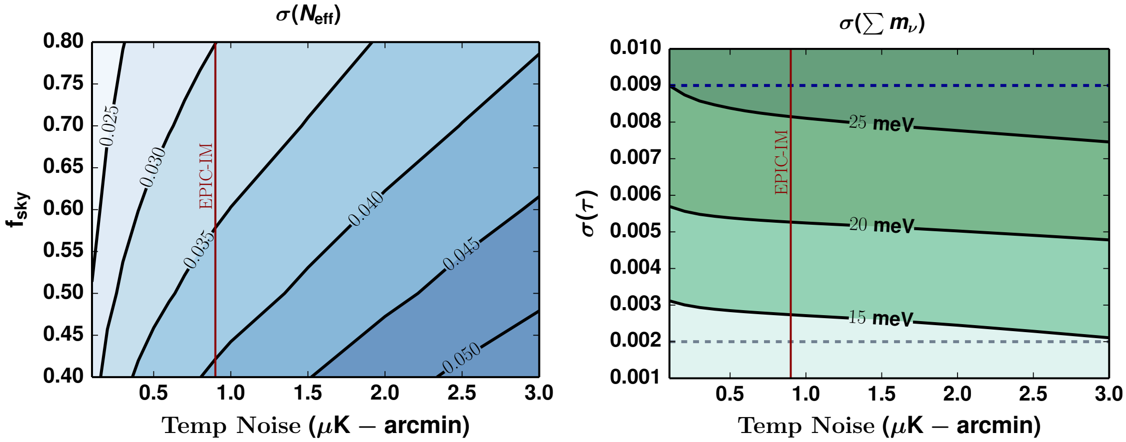

Figure 4: $N_{\rm eff}$ as a function of noise and sky fraction (left) and Neutrino mass constraints as a function of uncertainties in measurement of τ, noise, and sky fraction of $f_{\rm sky} = 0.7$. The resolution assumed is 5'. Vertical lines denote the expected performance of EPIC-IM. The blue dashed 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 [46], including residual non-Gaussian covariances. The $\sum m_\nu$ forecasts includes DESI BAO.

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 [58]. These couplings affect the evolution of fluctuations and ultimately the T and E spectra. The current limits of $\sigma \gtrsim 10^{-31} - 10^{-34}\,{\rm cm}^2 \times (m_{\rm dm}/{\rm MeV})$ 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. [59, 60, 61]).

Interactions of dark matter with standard model particles can also be constrained through measurements of spectral distortions [62]. Current constraints from FIRAS 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, testing DM interaction down to cross-sections $\sigma \simeq 10^{-39} - 10^{-35}\,{\rm cm}^2$ [62]. This provides new constraints on the low mass end, $m_{\rm X} \lesssim 10\,{\rm MeV}$ and improve existing limits [63, 64] by up to a factor of $\simeq 50$. Distortion measurements furthermore open a new avenue for testing dark matter-proton interactions [62].

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., 65, 66, 67, 68, 69].

1.2.3 Neutrino Mass

One of the last unknowns of the Standard model of particle physics is the absolute mass scale of the neutrinos. Cosmology presents a unique opportunity to measure the sum of neutrino masses $\sum m_\nu$ through the suppression of the growth of structures in the Universe on small scales. The sensitivity to $\sum m_\nu$ from suppression of power is limited by our knowledge of the primordial amplitude of fluctuations A_s, which is strongly degenerate with the optical depth τ. The current limit on τ from *Planck* of $\sigma(\tau) = 0.009$ [] limits $\sigma(\sum m_\nu) \gtrsim 25$ meV. Forcasts for an internal CMB measurement of $\sum m_\nu$ via CMB lensing [70] are shown Figure 4 but the conclusion is the same for any proposed cosmological probe. Therefore, a cosmological 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 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 [71]. A detection of $\sum m_\nu$ at this level is not possible with any other existing survey.

1.2.4 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 cluster is a key goal of cosmology [72]. Cosmological reionization, the transition of the Universe from dominated by neutral to ionized hydrogen, is a cornerstone of this evolution because it encodes information about the star formation history and the physical processes that formed the galaxies of various luminosities and masses we see today. But when did the epoch of reionization start? How long did it last? Are early galaxies enough to reionize the entire Universe or is another source 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 $\tau = 0.055 \pm 0.009$ [**?** **?**]. The level is significantly 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.

The anisotropy 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 that, at redshifts z$\sim$ 3, are three times larger than constraints from number counts measurements ([73, 74, 75]). The new mission probe, By measuring CIB anisotropy with 100 times higher signal-to-noise ratio the CMB Probe will shed light on this intriguing discrepancy. Specifically, it will constrain the star formation rate with one tenth of *Planck*'s uncertainty.

A key parameter in simulations of the angular power spectrum of the CIB is $M_{\rm eff}$, the galaxy hallo 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 $M_{\rm eff} \sim 10^{12}$ solar masses with about 10% uncertainty. The CMB Probe will constrain this parameter at the percent level.

The transition to reionized 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 $kT_{\rm e} \simeq 1\,{\rm keV}$ 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 CMB Probe, and will be used to constrain the currently uncertain feedback mechanisms used in hydrodynamical simulations of cosmic structure formation [76].

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 [77]. A combination of precise CMB imaging and spectroscopic measurements will allow observing the relativistic temperature correction of individual SZ clusters [78, 79, 80], 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 [81, 82, 83, 84, 85].

1.3 The Challenges: Foregrounds and Systematics

The search for primordial B-modes sets 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 100 smaller than the current upper limit $r < 0.07$, that is, to reach $\sigma(r) < 0.0007$. According to data from *Planck* and sub-orbital experiments foregrounds currently already dominate the signal. A 100-fold improvement on the final error will require exquisite measurement and accounting for foreground sources of confusion.

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 controlling systematic uncertainties to unprecedented, and not yet achieved, levels.

1.3.1 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 the level of E and B mode signals as a function of frequency and gives the expected signal levels as a function of angular scale ℓ.

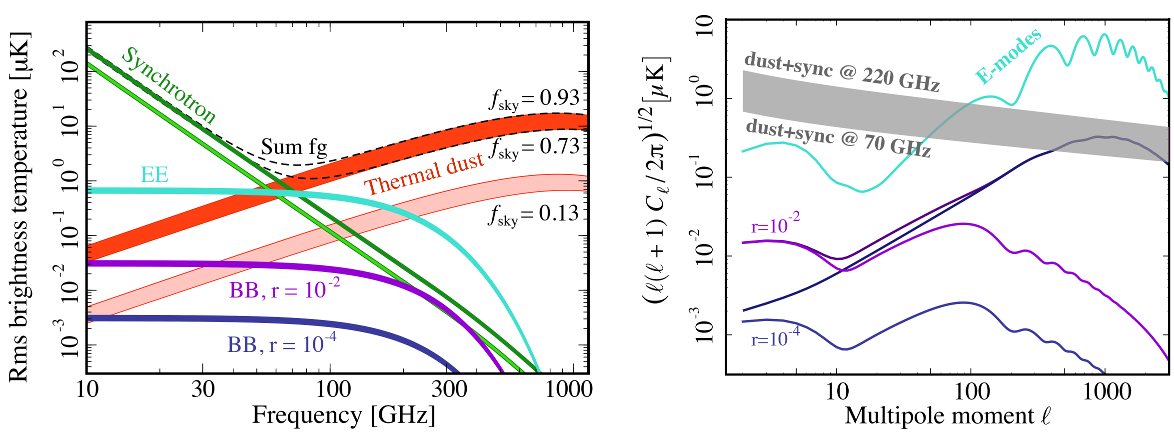

Figure 5: *Left:* Brightness temperature as function of frequency for the polarized CMB (cyan, purple, blue) and galactic foreground signals: dust (red) and synchrotron (green). The darker bands correspond to sky fractions between 73% and 93%; the lighter bands to the cleanest 13%, with the width indicating the uncertainty. *Right:* Angular power spectrum for B-mode polarization for $r = 10-2$ and $r = 10-4$, and for foreground emission between 70 and 220 GHz.

The conclusions, some of which are also borne out by *Planck* measurements, are that:

- over the largest angular scales (lowest ℓs), which are crucial for a range of science goals and where an inflationary B mode signal would be largest relative to that 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 shorter than needed for the fidelity envisioned for the Probe. This is visually demonstrated by Figure 6, which compares the level of B mode signal at low ℓ for $r = 0.001$ to the *Planck* 353 GHz noise, extrapolated to 150 GHz, a frequency band in which the signal is among the strongest.

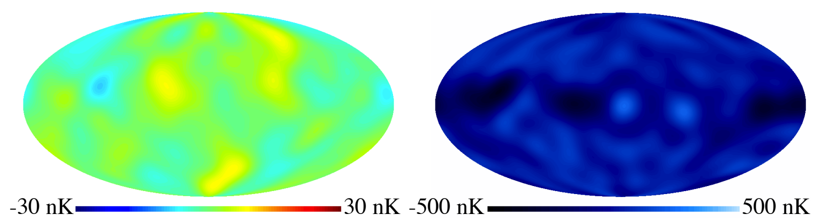

Figure 6: *Left:* Stokes Q for inflationary B-modes for $\ell < 12$ and $r = 0.001$. *Right:* Noise in the $Planck$ 353 GHz map of Stokes Q for $\ell < 12$ extrapolated to 150 GHz assuming the sky average spectral properties of dust.

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 precision a power law dependence for synchrotron radiation and a modified black body spectrum for dust 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 be 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. The critical measurements of τ, available by a cosmic variance limited measurement of the E power spectrum, are 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, and Coulomb scattering of charged particles ('free-free'); see Figure 3.

1.3.2 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 [**?**]: 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-mode signal (see for example Fig. 1). Therefore instrumental effects that can 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 1 part in 10^4 to give a negligible contribution for $\sigma(r) < 0.001$. This level of control represents a factor of 100 improvement on *Planck*'s performance [**?**].

Leakage-related effects will drive: requirements on the optical system, and 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. This type of systematic error puts requirements on 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 as well as introducing 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$10 additional noise at 0.016 Hz, corresponding to multipole ℓ=1 [**?**]. 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.