Exhortations

Fourteen billion years ago, in the first fraction of a second of our universe's existence, the most extreme high-energy physics experiment took place. Our ability to use the cosmic microwave background (CMB) to investigate this fantastic event, at energy scales a trillion times higher than can be obtained at the CERN, is at the very core of our quest to understand the fundamental nature of space and time and the physics that drive the evolution of the universe.

The CMB allows direct tests of models of the quantum mechanical origin of all we see in the universe. Subtle correlations in its anisotropy imparted by the interplay of gravitational and quantum physics at high energies contain information on the unification of gravity and quantum physics. Separately, correlations induced on the background at later times encode details about the distribution of all the mass, ordinary and dark, in the universe, as well as the properties of the neutrinos, including the number of neutrino species and types, and their still unknown masses.

Here we describe the scientific case for the next generation ground-based cosmic microwave background experiment, CMB-S4, consisting of dedicated telescopes at the South Pole, the high Chilean Atacama plateau and possibly a northern hemisphere site, all equipped with new superconducting cameras that will provide a dramatic leap forward in cosmological studies, crossing critical thresholds in testing inflation, the number and masses of the neutrinos or the existence of other 'dark radiation', providing precise constraints on the nature of dark energy, and testing general relativity on large scales.

Through the efforts of the CMB experimental groups over the last decade, the technologies needed for CMB-S4 are now in place. There are, however, considerable technical challenges presented by the required scaling up of the instrumentation as well as by the scope and complexity of the data analysis and interpretation. CMB-S4 will require: scaled up superconducting detector arrays with well understood and robust material properties and processing techniques; high throughput mm-wave telescopes and optics with unprecedented precision and rejection of systematic contamination; full characterization of astronomical foreground emission; large cosmological simulations and theoretical modeling with accuracies yet to be achieved; and computational methods for extracting minute correlations in massive, multi-frequency data sets contaminated by noise and a host of known and unknown signals.

The purpose of this document is to set the scientific goals for CMB-S4 and the instrumental configuration required to achieve them. This is of course an iterative process, involving detailed simulations as well as cost considerations. In this chapter we set out the overarching goals for CMB-S4, which are then refined in later chapters. We start with a brief history and the current status of CMB measurements.

0.1 Brief History and Current Status of CMB measurements

From its discovery 50 years ago, measurements of the cosmic microwave background (CMB) have led to spectacular scientific insights into the fundamental workings of space and time, from the quantum mechanical origin of the Universe at extremely high energies in the first moments of the Universe, through the growth of structure and the emergence of the dark energy that now dominates the energy density of the Universe. Studies of the CMB connect physics at the smallest scales and highest energies with the largest scales in the

Universe, roughly 68 orders of magnitude in length scale. They connect physics at the earliest times to the structure that surrounds us now, over 52 magnitudes in time scale.

The deep connections of CMB studies and particle physics predate the discovery of the background, going back to the 1940s when Alpher and Gamow were considering a hot, dense, early Universe as a possible site for nucleosynthesis. To produce the amount of helium observed in the local Universe, they concluded there had to be about 10^{10} thermal photons for every nucleon and predicted that this background of photons would persist to the present day as a thermal bath at a few degrees Kelvin.

The continuing, remarkably successful, story of CMB studies is one driven by the close interplay of theory and phenomenology with increasingly sensitive and sophisticated experiments. The high degree of isotropy of the CMB across the sky, to a part of one in a hundred thousandth, led to the theory of inflation and cold dark matter in the 1980s. It was not until 1992 that COBE discovered the anisotropy, and pinned the level of anisotropy for the following higher angular resolution measurements to characterize. In 2006 the COBE measurements of the background anisotropy and its black-body spectrum were recognized with the second Nobel Prize in physics; the first was awarded in 1978 to Penzias and Wilson for the discovery of the CMB. In the decade after the COBE results, measurements with ground and balloon-based instruments revealed the acoustic peaks in the CMB angular power spectrum, which showed that the Universe was geometrically flat in accord with predictions of inflation and provided strong support for contemporary Type 1a SN based claims for an accelerating Universe, which were recognized with the 2011 Nobel Prize in physics. The early anisotropy measurements also provided an estimate of the universal baryon density and found it to be in excellent agreement with the level estimated at $t \sim 1$ second by BBN calculations constrained to match the observed elemental abundances, and clearly showed that dark matter was non-baryonic. The polarization anisotropy was discovered ten years after COBE at the level predicted from temperature anisotropy measurements. The now standard ΛCDM cosmological model was firmly established.

Two CMB satellites have mapped the entire sky over the last 15 years, first WMAP with moderate angular resolution up to 12 arcminutes, followed by Planck with resolution up to 5 arcminutes. Higher resolution maps of smaller regions of the sky have been provided by ground-based experiments, most notably by the 10m South Pole Telescope (SPT) and the 6m Actacama Cosmology Telescope. The primary CMB temperature anisotropy is now well characterized through the damping tail, i.e., to multipoles $\ell \sim 3000$. The ΛCDM model continues to hold up stunningly well, even as the precision of the CMB determined parameters has increased substantially. Inflationary constraints include limits on curvature constrained to be less than 3% of the energy density, non-Gaussian fluctuations limited to $f_{NL} < 10$, and the departure from pure scale invariance of the primordial fluctuations detected at 5 sigma confidence. Also of interest to particle physics, the effective number of light relativistic species (i.e., neutrinos and any yet identified "dark radiation") is shown to be within one sigma of $N_{eff} = 3.046$, the number predicted by BBN. The sum of the masses of the neutrinos is found to be less than 0.6 eV. Dark matter is shown to be non-baryonic matter at > 40 sigma. Early dark energy models are highly constrained as are models of decaying dark matter.

*** add r and IGW – BICEP etc.

There remains much science to extract from the CMB, including: 1) using CMB B-mode polarization to search for primordial gravitational waves to constrain the energy scale of inflation and to test alternative models, and to provide insights into quantum gravity; 2) obtaining sufficiently accurate and precise determinations of the effective number of light relativistic species (dark radiation) to allow independent and rigorous tests of BBN as well as our understanding of the evolution of the Universe at $t = 1$ sec; 3) a detection of the sum of the neutrino masses, even if at the minimum mass allowed by oscillation experiments and in the normal hierarchy; 4) using secondary CMB anisotropy measurements to provide precision tests of dark energy through its impact on the growth of structure; and 5) testing general relativity and constraining alternate theories of gravity on large scales.

Currently the best cosmological constraints come from analyzing the combination of primary and secondary CMB anisotropy measurements with other cosmological probes, such as baryon acoustic oscillations (BAO) and redshift distortions, weak lensing, galaxy and galaxy cluster surveys, Lyman-alpha forest, Hubble constant, Type 1a SN, and others. The CMB primary anisptropy measurements provide highly complementary data for the combined analysis, in particular by providing a precision measurement of the Universe at $z = 1100$, which will provide a precise prediction for measurements of the late time Universe for any cosmological model and set of parameters – the Hubble constant being an excellent example. Secondary CMB measurements, e.g., CMB lensing, the SZ effects and SZ cluster catalogs, also provide critical late time constraints for the standard cosmological models and extensions to it. The cosmological reach of future cosmological surveys will be greatly extended by **joint analyses** with secondary background measurements, in particular CMB lensing.

0.2 Science reach of CMB-S4

CMB-S4 should be the definitive ground-based CMB project. The key science it should cover, and cover well, are

1. Inflation: CMB-S4 should make the definitive B-mode measurements of the recombination bump at degree angular scales. This includes multiple bands to untangle the foregrounds and degree through arcminute angular scales to measure CMB lensing and E-mode for de-lensing. If it can be demonstrated that foregrounds and atmospheric noise can be mitigated at very low multipoles, CMB-S4 could also target the re-ionization bump. At the lowest multipoles, CMB-S4, balloon and satellite mission would be highly complementary.

   CMB-S4 should answer whether or not large scale slow-roll-single-field inflation models are viable ($r \gtrsim 0.01$) with high significance. If no detection at $r \sim 0.01$, then CMB-S4 should be able to test the currently popular Starobinski model and others by achieving $\sigma(r) < 10^{-4}$ with an ultra deep survey.

   If r is detected before or by CMB-S4, then CMB-S4 should provide a robust cosmic variance limited measure of its value (requiring a large area survey), and set the best possible constraints on n_t (requiring an ultra deep survey).

   CMB-S4 should provide the polarization data to test predictions of models that attempt to explain the low-ell TT power spectrum "anomalies", that may offer clues to inflation. It will be particularly important to achieve accurate $20 < \ell < 100$ EE measurements.

   CMB-S4 will also extend the leverage arm for n_s, particularly in the EE spectrum. It may be possible to extend the primary EE spectrum to multipoles exceeding 10,000 because of the very low level of polarized foregrounds at high ℓ.

   The CMB-S4 data set should be the definitive data set with which any model for the origin of the primordial fluctuations, be it inflationary or an alternative theory, must be consistent with to be viable.

2. Neutrinos and light relativistic species:

   There are two primary areas in which CMB-S4 will provide interesting neutrino constraints.

   a) The first is the effective number of light relativistic species, N_{eff}. This is uniquely probed by the CMB and provides a critical constraint on any model for the neutrinos and their interactions. It is a highly complementary probe to BBN and to sterile neutrino models. Finding consistency with $N_{eff} = 3.046$ at a precision of 0.020 would be an exciting and fundamental achievement linking particle physics and our understanding of the evolution of the first seconds of the Universe. Finding a departure from 3.046 would be even more exciting.

b) The second is the constraint on the sum of the masses of the neutrinos, Σm_ν. Here CMB-S4 will achieve $\sigma(\Sigma m_\nu) = 16$ meV (with DESI BAO prior), with the CMB sensitivity coming primarily through CMB lensing. This will lead to a definite detection of neutrino mass, even at the minimum mass and the normal hierarchy. The sensitivity to the sum of the masses is unique and complementary to terrestrial neutrino experiments.

3. Dark Energy and Gravity:

   The CMB can be used to investigate Dark Energy through growth of structure tests, i.e., CMB lensing and SZ clusters, and through testing Gravity on large scales, i.e., though exploiting the kinematic SZ effect to measure the momentum field and large scale flows. The power of these probes is amplified by combining CMB-S4 data with galaxy surveys and Lyman alpha surveys, such as DESI, LSST, Euclid and WFIRST.

   a) CMB lensing maps from CMB-S4 will provide hi-fidelity projected mass maps that will be cross-correlated with optical survey maps. This will increase the reach and precision of the dark energy constraints, as well as provide independent checks. Papers in the literature have quantified the DE FOM improvement of various projects with the addition of CMB lensing. Simulations need to be done to quantify the projected improvements with CMB-S4.

   b) The DE task force pointed out that galaxy cluster evolution had the highest sensitivity of the DE probes considered. However, it also had the largest systematic. The issue is the uncertainty in understanding the mass scaling of the cluster observable. The thermal SZ effect has now been demonstrated to be a low scatter observable with the extraordinary feature of its brightness being redshift independent; an SZ survey probes all redshifts to a limiting mass. However, there still remain large uncertainties in the SZ observable mass scaling. CMB-S4 will be revolutionary in that it is expected to be able to calibrate the mass scaling to better than 1% through CMB lensing. This coupled with a low mass threshold will enable CMB-S4 to identify of order 100,000 clusters, probe the growth of structure to redshifts beyond $z \sim 2.5$, and will allow CMB-S4 to realize the full potential of galaxy clusters as a probe of dark energy. In combination with other Stage-IV baryon acoustic oscillation, supernova, and weak lensing surveys, a Stage-IV cluster survey similar to CMB-S4 would improve the overall dark energy figure of merit to approximately 1250, nearly a factor of two improvement than achieved without clusters.

   c) Testing GR on large scales is important for our understanding of dark energy and the underlying workings of space and matter in general. The kinematic SZ effect allows measurement on the peculiar velocity (departure from Hubble flow) of structures. By measuring the differences in kSZ between pairs of clusters with known redshifts (a synergy of CMB-S4 and optical surveys), gravity can be tested on scales of 100 Mpc and larger. In this way, CMB-S4 paired with a Stage-IV spectroscopic survey would improve constraints on the growth rate predicted by general relativity by a factor of two.

Lastly it would be an oversight not to point out the obvious: there is only one CMB sky. It holds a wealth of information on fundamental physics and the origin and evolution of the Universe. While we have learned a great deal from CMB measurements, including discoveries that have pointed the way to new physics, we have only begun to tap the information contained in CMB polarization, CMB lensing and secondary effects. CMB-S4 should be designed to maximize discovery space by producing high fidelity maps.

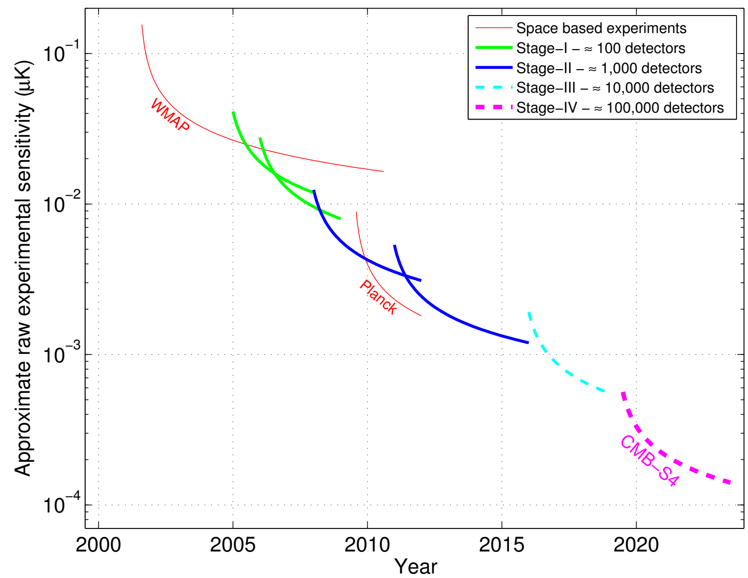

Figure 1. *Plot illustrating the evolution of the raw sensitivity of CMB experiments, which scales as the total number of bolometers. Ground-based CMB experiments are classified into Stages with Stage II experiments having O(1000) detectors, Stage III experiments having O(10,000) detectors, and a Stage IV experiment (such as CMB-S4) having O(100,000) detectors. Figure from Snowmass CF5 Neutrino planning document.*

0.3 From science goals to CMB-S4 design

0.3.1 Conceptual design of CMB-S4

The science goals discussed above leads to a rough conceptual design of CMB-S4.

0.3.1.1 Sensitivity and detector count

The sensitivity of CMB measurements has increased enormously since Penzias and Wilsons discovery in 1965, following a Moores Law like scaling, doubling every roughly 2.3 years. Fig. 4 shows the sensitivity of recent experiments as well as expectations for upcoming Stage 3 experiments, characterized by order 10,000 detectors on the sky, as well as the projection for a Stage 4 experiment with order 100,000 detectors. To obtain many of the CMB-S4 science goals requires of order 1 μK arcminute sensitivity over roughy 70% of the sky, which for a four year survey requires of order 500,000 CMB-sensitive detectors.

To maintain the Moores Law like scaling requires a major leap forward, it requires a phase change in the mode of operation of the ground based CMB program. Two constraints drive the change: 1) CMB detectors are background limited, so more pixels are needed on the sky to increase sensitivity; and 2) the pixel count for CMB cameras are nearing saturation. Even using multichroic pixels and wide field of view optics, CMB telescopes are able to field only tens of thousands of polarization detectors, far fewer than needed to meet the CMB-S4 science goals.

CMB-S4 thus requires multiple telescopes, each with a maximally outfitted focal plane of pixels utilizing superconducting, background limited, CMB detectors. To achieve the large sky coverage and to take advantage of the best atmospheric conditions, the South Pole and the Chilean Atacama sites are baselined, with the possibility of adding a new northern site to increase sky coverage to 100%.

0.3.1.2 Inflationary B-modes: low ℓ sensitivity, foregrounds and atmospheric noise mitigation

At the largest angular scales (low ℓ), the angular scales that must be measured well to pursue inflationary B-modes (as well as critical tests of the E-mode polarization), the CMB polarization anisotropy is highly contaminated by foregrounds. Galactic synchrotron dominates at low frequencies and galactic dust at high frequencies, as recently shown by the Planck and Planck/BICEP/KECK polarization results. Multi-band polarization measurements are required to distinguish the primordial polarized signals from the foregrounds.

Adding to the complexity of low multipole CMB observations is the need to reject the considerable atmospheric noise contributions over the large scans needed to extract the low ℓ polarization. While the spatial and temporal fluctuations of the atmosphere are not expected to be polarized, any mismatches in the polarized beams or detector gains will lead to T-P leakage. These issues can be mitigated by including additional modulations into the instrument design, such as bore-sight rotation or modulation of the entire optics with a polarization modulation scheme in front of the telescope. Implementing such modulations is easier for small telescopes, although they could in principle be implemented on large telescopes as well. The cost of a small aperture telescope is dominated by the detector array, making it feasible to deploy multiple telescopes each optimized for a single band, or perhaps multiple bands within the relatively narrow atmosphere windows.

It is therefore an attractive option for CMB-S4 to include dedicated small aperture telescopes for pursuing low-ℓ polarization. The default plan for CMB-S4 is to target the recombination bump, with E-mode and B-mode polarization down to $\ell \sim 20$. If Stage 3 experiments demonstrate that it is feasible to target the reionization bump from the ground, those techniques may be incorporated into CMB-S4. More likely, however, this is the ℓ range for which CMB-S4 will be designed to be complementary to balloon-based and satellite based measurements.

0.3.1.3 Neutrinos and dark energy: high ℓ sensitivity

At the highest angular resolution (high ℓ), the angular scales needed for de-lensing the inflationary B-modes, constraining N_{eff} and Σm_ν, investigating dark energy and performing gravity tests with secondary CMB anisotropy, the CMB polarization anisotropy is much less affected by both foregrounds and atmospheric noise. In fact, it should be possible to measure the primary CMB anisotropy in E-mode polarization to multipoles a factor of a few times higher than possible in TT, thereby extending the lever arm to measure the spectral index and running of the primordial scalar (density) fluctuations. CMB-lensing benefits from ℓ_{max} of order 5000 and secondary CMB measurements are greatly improved with ℓ_{max} of order 10,000 and higher, requiring large aperture telescopes with diameters of several meters. Owing to the steep scaling of telescope cost with aperture diameter, it is likely not cost-effective to consider separate large aperture telescopes each optimized for a single frequency band.

CMB-S4 is therefore envisioned to include dedicated large aperture, wide field of view telescopes equipped with multi-chroic detector arrays.

0.3.2 Refining the CMB-S4 science case and key performance parameters

The rough conceptual design outlined above clearly needs to be refined. The first priorities are to determine the instrumental specifications to meet each of the science goals. We need to determine: the required resolution and sensitivity; the number of bands to mitigate foreground contamination, which is likely to be function of angular scale; the required sky coverage; the beam specifications (can we tolerate segmented primary reflectors?); the scanning strategy and instrument stability; etc.

Determining these specifications requires simulations, informed by the best available data and phenomenological models. Only when we have these specifications in hand can we design the instrument and answer such basic questions as the number and sizes of the telescopes.

0.4 The Road from Stage 3 to Stage 4

The Stage 2 and 3 experiments are logical technical and scientific stepping stones to CMB-S4. Fig. 5 shows the timeline of the CMB sensitivity and the expected improvement in a few of the key cosmological parameters. The enormous jump in sensitivity with the corresponding improvement in science reach is clear.

Finally, in Fig. 3 we show how the scientific findings (yellow), the technical advances (blue) and satellite selections (green) would effect the science goals, survey strategy and possibly the design of CMB-S4. THIS NEEDS TO BE CLEANED UP

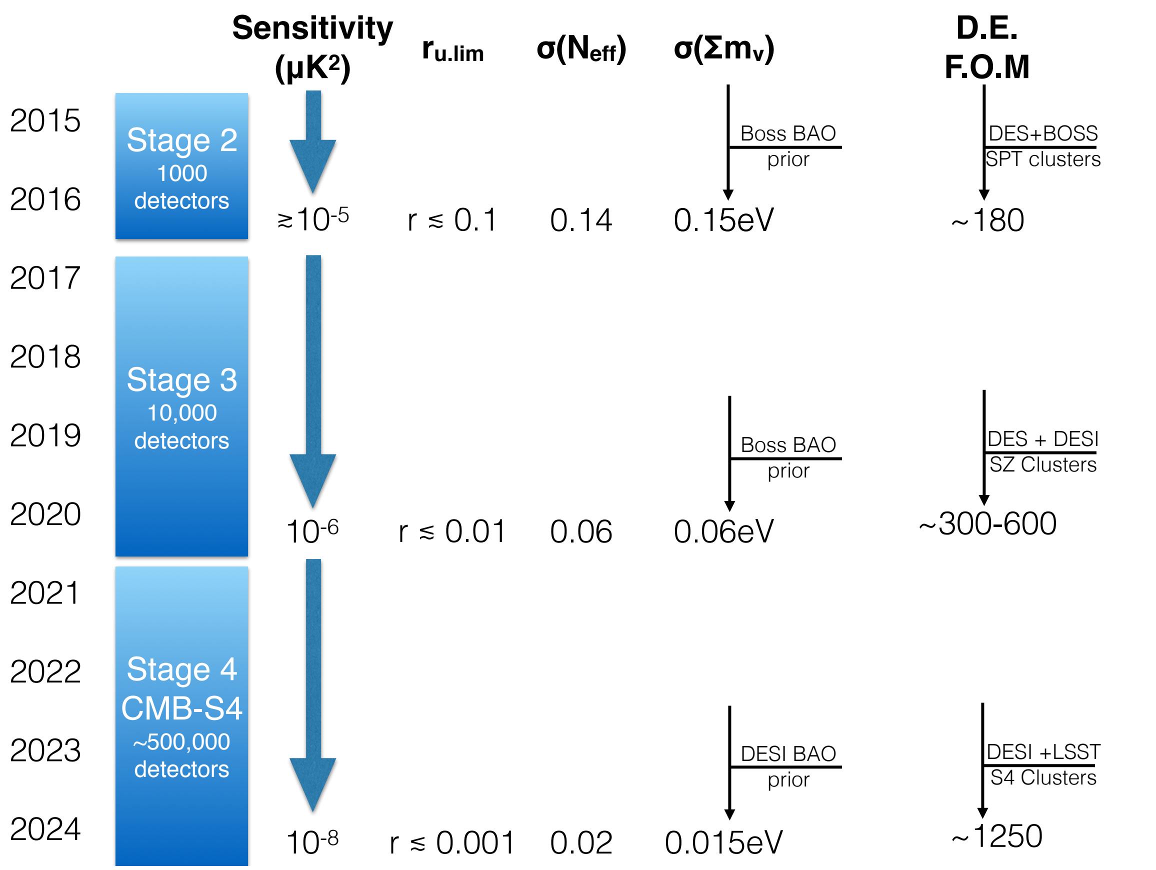

Figure 2. *Schematic timeline of evolution of Stage 3 and CMB-S4 sensitivity in μK^2 and the expected improvement in a few of the key cosmological parameters.*

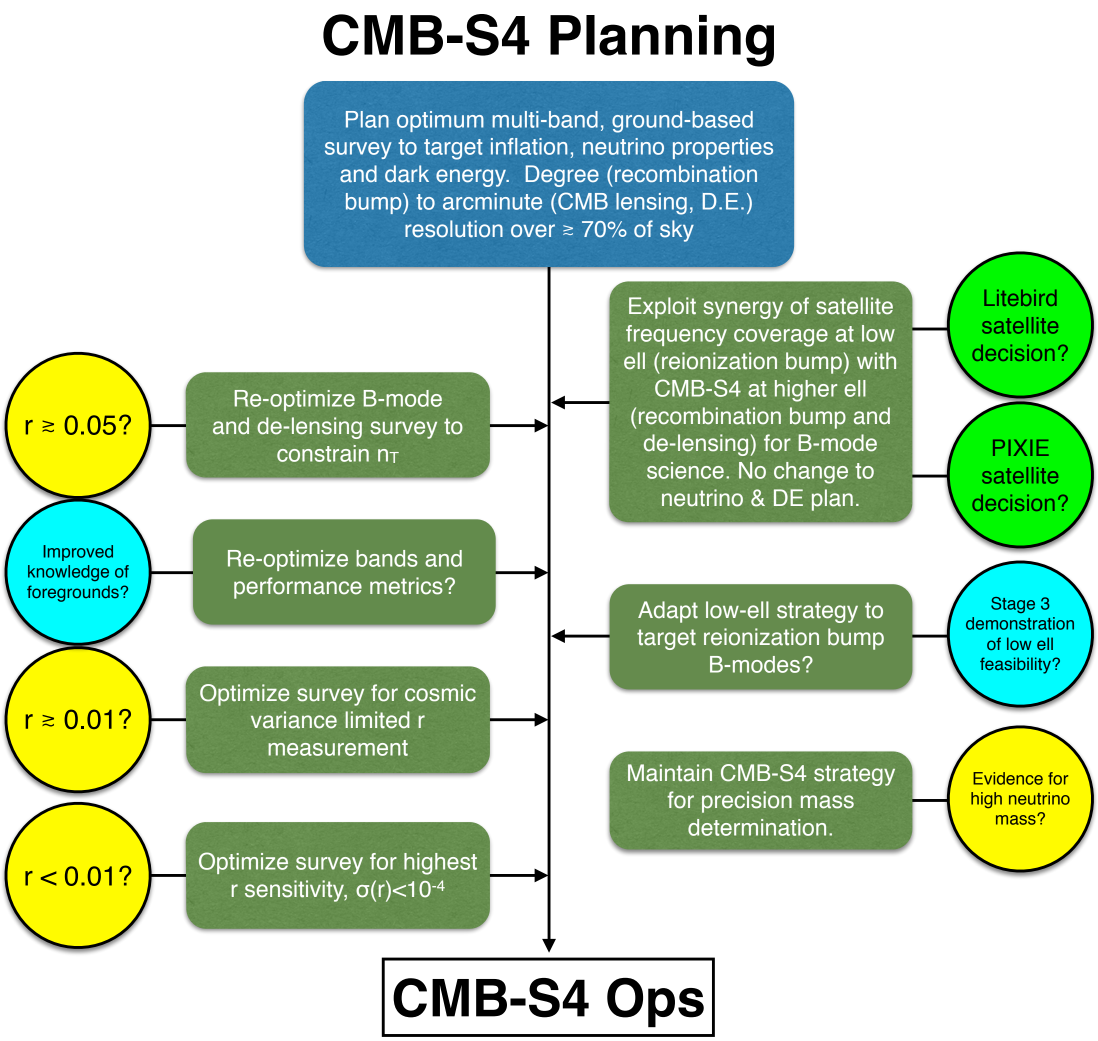

Figure 3. *Schematic flow chart showing how the scientific findings (yellow), the technical advances (blue) and satellite selections (green) would effect the science goals, survey strategy and possibly the design of CMB-S4 (green boxes).*

1

Inflation Physics from the Cosmic Microwave Background

1 Introduction

The study of the polarization of the cosmic microwave background will bring additional information about both the gravitational and matter sectors of the primordial universe. However, for primordial gravitational waves there are clear theoretical thresholds that can be reached with this next generation instrument. We will use the tensor-to-scalar ratio as the primary inflationary science driver for the design.

CMB-S4 can push the constraint on r (the ratio of power in tensor modes to power in scalar modes) nearly two orders of magnitude below the current bound. A detection of primordial gravitational waves in the range accessible to this instrument would:

- Rule out the only currently developed competitor to inflation (ekpyrotic scenario)
- Reveal a new scale of particle physics far above those accessible with terrestrial particle colliders.
- Identify the energy scale of inflation.
- Provide strong evidence for that gravity is quantized, at least at the linear level.
- Provide strong evidence that the complete theory of quantum gravity must accommodate a Planckian field range for the inflaton
- Constrain the mass of the graviton

In the absence of a detection, each factor of 10 improvement in the constraint will reach new and significant thresholds, ruling out major classes of inflation models.

In Section 2 we review in detail what a detection of primordial gravitational waves would mean. Section 3 explains why, in the absence of a detection, a robust upper limit of $r < 0.001$ is the interesting number to push for. Section 4 lays out what is required to achieve that goal. The final two sections describe the significant gains CMB S4 will allow in constraining other aspects of the primordial universe, both standard and more speculative. These include characterizing the scalar power spectrum, constraining curvature, non-Gaussianity, and isocurvature modes, further probes of CMB 'anomalies' and test/constraints of cosmic strings, mass of the graviton, cosmic birefringence, parity violation....?

Recent reviews [2].

2 Implications of a detection of primordial gravitational waves with CMB-S4

The overall evolution of the universe at either early or late times can be well modeled by a Friedmann-Robertson-LeMaitre-Walker metric which is spatially homogeneous and isotropic but possibly evolving in time: $g_{\mu\nu} = -dt^2 + a^2(t)[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2]$ where $k = \pm 1$ allows for open/closed universes and the time evolution is specified by the scale factor, $a(t)$. For much of the rest of the discussion we will for simplicity assume spatial flatness ($k = 0$), although we will return to constraints on the curvature in Section xxx. The Hubble parameter, $H = \dot{a}/a$, gives the rate of expansion of the universe.

Arguably the most significant discrepancy between the predictions of a generic hot big bang model and our observed sky is the horizon problem: the measured average CMB temperature and the statistics of the measured anisotropies are the same over regions that share no causal history. Models for the primordial universe attempt to give a causal (and ideally also a 'natural') explanation for the observed homogeneity in scales greater than a couple degrees by postulating an early era where the co-moving Hubble radius, $(aH)^{-1}$ is decreasing with time. Inflation puts large scales in causal contact by an era of accelerated expansion, $\ddot{a} > 0$, with nearly (but not exactly) constant Hubble parameter. The matter field that sources this expansion should have equation of state $w \approx -1$, which is minimally provided by a single scalar field whose energy density is predominately determined by its potential.

The remarkable feature of inflation is that once an evolving scalar field is invoked to source the background accelerated expansion, quantum fluctuations during inflation inevitably generate post-inflationary metric perturbations. The perturbed metric can be described in the ADM formalism by

$$\begin{aligned} ds^2 &= -N^2 dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt) \\ h_{ij} &= a^2(t)[e^{2\zeta}\delta_{ij} + \gamma_{ij}] \end{aligned} \tag{1.1}$$

Here the equations of motion for N (the lapse) and N^i (the shift) are the Hamiltonian and momentum constraints, while ζ ($= -\mathcal{R}$ of *Planck convention*) and γ_{ij} contain the dynamical scalar and tensor degrees of freedom. (In scenarios with matter sources other than a scalar field there may also be vector perturbations. These are generally irrelevant unless they are being actively sourced by, eg, cosmic strings in the post-inflationary universe.

The link between the CMB and other tracers of primordial inhomogeneities and the primordial era is a statistical representation of the metric fluctuations after inflation and reheating. Observations today constrain these parameters at early times, which we can compare to calculations from any theory for the primordial era (and reheating). To an excellent approximation, the observed scalar fluctuations are statistically homogeneous, isotropic, and Gaussian so they are well characterized by a power spectrum that is only a function of wavenumber $|\vec{k}|$. Assuming that the same is true for any tensor fluctuations (as is predicted by inflation), we characterize the amplitude and scale dependence of fluctuations by

$$\begin{aligned} \langle \zeta(\vec{k})\zeta(\vec{k}')\rangle &= (2\pi)^3\delta^3(\vec{k}+\vec{k}')\frac{2\pi^2}{k^3}\mathcal{P}_\zeta(k) \\ \mathcal{P}_\zeta(k) &\equiv A_s\left(\frac{k}{k_*}\right)^{n_s-1+\frac{1}{2}(dn_s/d\,\ln k)\ln(k/k_*)+\ldots} \\ \langle \gamma_s(\vec{k})\gamma_{s'}(\vec{k}')\rangle &= (2\pi)^3\delta_{ss'}\delta^3(\vec{k}+\vec{k}')\frac{2\pi^2}{k^3}\frac{1}{2}\mathcal{P}_t(k) \end{aligned}$$

$$\mathcal{P}_t(k) \equiv A_t \left(\frac{k}{k_*}\right)^{n_t + \frac{1}{2}(dn_t/d\ \ln k)\ln(k/k_*) + \ldots} \tag{1.2}$$

where the factor of 1/2 in the second to last line accounts for the fact that the measured power includes (presumably equal) contributions from each of the two graviton polarizations. The tensor-to-scalar ratio, r is the relative power in the two types of fluctuations at a chosen pivot scale k_* accessible by the CMB:

$$r = \frac{P_T(k_*)}{P_\zeta(k_*)} \tag{1.3}$$

2.1 A new scale of particle physics

Basic equations, address potential caveats that the new scale is also exactly the scale of inflation:

- Models that also generate a significant amplitude of gravitational waves from particle sources are also constrained by signatures in the scalar fluctuations (especially non-Gaussianity). [6, 7] find that at most $\sim x\%$ or so (get the exact number) could be from sources other than the de Sitter quantum fluctuations. New proposed scenarios where all could be [8]. How much room is there? Do improved constraints on NG, etc, remove this window?
- Should we address these papers at all: 1410.8845, rebutted in 1508.01527, re-rebutted in 1510.06759, (different author) 1510.07956?

2.2 Large r, inflaton field range, symmetries

Although the spectrum of tensor fluctuations depends only on the Hubble parameter during inflation, the scalar power depends also depends on the evolution of the homogeneous field sourcing inflation. This means that the tensor-to-scalar ratio, r, is related to the inflaton field range in Planck units [9]

$$\frac{\Delta\Phi}{M_p} = \int_0^{\mathcal{N}_{\rm end}} d\mathcal{N} \left(\frac{r}{8}\right)^{1/2} \tag{1.4}$$

where $\mathcal{N}$ is the total number of e-folds needed to put the largest observed scales in causal contact during inflation. The tensor to scalar ratio, r is in general not a constant during inflation. It is perhaps useful to define an effective number of e-folds

$$\mathcal{N}_{\rm eff} = \int_0^{\mathcal{N}_{\rm end}} d\mathcal{N} \left(\frac{r}{r_{\rm CMB}}\right)^{1/2} \tag{1.5}$$

where $r_{\rm CMB}$ is the value of the tensor-to-scalar ratio at large scales ($k = 0.05\ Mpc^{-1}$). Then the relationship between field range and the tensor-to-scalar ratio becomes algebraic:

$$\frac{\Delta\Phi}{M_p} = \left(\frac{r_{\rm CMB}}{8}\right)^{1/2} \mathcal{N}_{\rm eff} \tag{1.6}$$

Since r is just the ratio of tensor and scalar power, we can write $d\ln r/d\mathcal{N} = n_T - (n_s - 1)$. For canonical single-field inflation we can use the consistency relation between r and n_T to write $d\ln r/d\mathcal{N} = -(n_s - 1) + \frac{r}{8}$.

The total number of e-folds needed to put the largest scales in causal contact depends on the reheating temperature. Furthermore, there is model-dependence in how parameters vary during inflation.

Some example model to illustrate further...probably need a plot.

Can ϵ vary non-monotonically in such a way that r is large but field range was sub-Planckian? There are several papers claiming this, for example [**?**, 10]. Raphael suggested some (all?) had a numerical error...We should comment.

So, upshot is that small field models have $\Delta\Phi/M_p \ll 1$, and so r unobservable with CMB-S4. Large field models, where $\Delta\Phi/M_p \gtrsim \mathcal{O}(1)$ are detectable with this instrument. As effective field theories, large field inflation is perfectly reasonable [11, 12, 13, 14, 15] (that is, the approximate shift symmetry ensures that quantum corrections from the inflaton and graviton will not spoil the potential even over a super-Planckian range). However, it is still an important question whether or not large field inflation can be obtained from a UV complete theory. String theory is the best developed candidate for the theory of quantum gravity, and there have been several proposals for large-field inflation [16, 17, 18, 19, 20, 21, 22]. While these constructions are very promising, there is also interesting current discussion of whether at least some apparent means to achieve large field inflation (via multiple axions) may be incompatible with basic principles of quantum gravity [23, 24, 25, 26]. A detection of r, with a robust conclusion that it is from quantum fluctuations, would provide the only data point for the foreseeable future that weighs in on quantum gravity.

2.3 Other probes allowed by a detection

If the amplitude of gravitational waves is large enough, it becomes more reasonable to hope we might measure some other things

- how large is large enough that we could hope to say something about n_T, in conjunction with futuristic direct GW detection?
- any scenarios, even wild where, ie, $\langle\zeta\zeta h\rangle$ or other correlators could be large and somehow accessible?

3 Constraining the amplitude of primordial gravitational waves

3.1 What we learn from the $r < 0.01$

- models that live here have field ranges that are super-Planckian

3.2 What we learn from the constraint $r < 0.001$

models that live here: Starobinsky and friends

4 CMB data products and simulations required to achieve goals for PGW

5 Improved constraints on the particle content of the primordial universe

- Scalar power spectrum: running, wiggles
- non-Gaussianity (three point function, four point function) **text from Joel Meyers, so far just copied from wiki except tex-ified**

  The present best constraints on local non-Gaussianity come from the Planck 2015 analysis and give $f_{\rm NL} = 0.8 \pm 5.0$ (68% CL) [Planck2015 - 1502.01592]. A noise-free cosmic variance limited CMB experiment is expected to produce constraints on $f_{\rm NL}$ with 1σ error bars of about 3 [astro-ph/0005036]. Therefore the best that can be expected of CMB Stage-IV is slightly less than a factor of two improvement on the current best limits.

  A detection of local non-Gaussianity would have far reaching theoretical implications, since any significant detection of local $f_{\rm NL}$ would rule out all models of single clock inflation [astro-ph/0407059]. In the absence of a detection, however, it is important to ask what can be learned from improved constraints on $f_{\rm NL}$. Though not firm, nor entirely robustly defined, it can be argued that a natural theoretical threshold where qualitatively new general conclusions about the physics of the early universe can be drawn would come from constraints on $f_{\rm NL} < \mathcal{O}(1)$, see for example [1412.4671] for a fuller discussion. In order to achieve this level of constraint, it seems necessary to move beyond the cosmic microwave background to study other data sets, such as large scale structure. Despite the fact that CMB Stage-IV is not expected to reach this threshold, it is worth asking what can be gleaned from an improved constraint on $f_{\rm NL}$ from the CMB.

  There do exist some well motivated models for the origin of fluctuations in the early universe which predict local non-Gaussianity at a level where CMB Stage-IV could either hint toward, or slightly disfavor at around the level of 2σ. These models include the simplest modulated reheating scenario [astro-ph/0306006] and ekpyrotic cosmology [0906.0530], both of which predict $f_{\rm NL} \sim 5$.

  In the modulated reheating scenario, the field which drives inflation Φ decays to the particles of the standard model with a rate γ which is determined by the value of a second field σ which remains light throughout inflation. The quantum fluctuations in σ result in a spatially modulated reheating surface resulting in the curvature perturbations that we observe in the CMB and large scale structure. The process by which the fluctuations in the light field are converted into curvature fluctuations naturally results in local non-Gaussianity given by $f_{\rm NL} = 5(1 - \Gamma\Gamma''/\Gamma'^2)$, where this formula holds in the case that Φ oscillates about a quadratic minimum after inflation and the fluctuations in Φ make a negligible contribution to the observed power spectrum.

  This can be contrasted with the simplest curvaton scenario, where a field ? which remains light during inflation comes to dominate the energy density of the universe after the field which drives inflation Φ decays. The fluctuations in the energy density of ? then determine the curvature perturbations that are observed today. The local non-Gaussianity in this simple model is predicted to be $f_{\rm NL} = -5/4$ [hep-ph/0110002], which is unfortunately a few times smaller than the expected error bar from CMB Stage-IV.

  Absent a significant detection of local non-Gaussianity (which is unlikely given the current constraints from Planck), CMB Stage-IV can provide useful constraints or tantalizing hints about particular models of the early universe, though it will unfortunately be unable to reach the level of constraint at which broader conclusions can be drawn.

- isocurvature

6 Improved constraints on spatial curvature, anomalies, birefringence, . . .

References

[1] K. Abazajian, K. Arnold, J. Austermann, B. Benson, C. Bischoff, *et al.*, "Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure," `arXiv:1309.5383 [astro-ph.CO]`.

[2] M. Kamionkowski and E. D. Kovetz, "The Quest for B Modes from Inflationary Gravitational Waves," `arXiv:1510.06042 [astro-ph.CO]`.

[3] D. Bessada and O. D. Miranda, "CMB Polarization and Theories of Gravitation with Massive Gravitons," *Class. Quant. Grav.* **26** (2009) 045005, `arXiv:0901.1119 [gr-qc]`.

[4] S. Dubovsky, R. Flauger, A. Starobinsky, and I. Tkachev, "Signatures of a Graviton Mass in the Cosmic Microwave Background," *Phys. Rev.* **D81** (2010) 023523, `arXiv:0907.1658 [astro-ph.CO]`.

[5] D. Bessada and O. D. Miranda, "CMB anisotropies induced by tensor modes in massive gravity," *JCAP* **0908** (2009) 033, `arXiv:0908.1360 [astro-ph.CO]`.

[6] M. Mirbabayi, L. Senatore, E. Silverstein, and M. Zaldarriaga, "Gravitational Waves and the Scale of Inflation," *Phys. Rev.* **D91** (2015) 063518, `arXiv:1412.0665 [hep-th]`.

[7] O. zsoy, K. Sinha, and S. Watson, "How Well Can We Really Determine the Scale of Inflation?," *Phys. Rev.* **D91** no. 10, (2015) 103509, `arXiv:1410.0016 [hep-th]`.

[8] R. Namba, M. Peloso, M. Shiraishi, L. Sorbo, and C. Unal, "Scale-dependent gravitational waves from a rolling axion," `arXiv:1509.07521 [astro-ph.CO]`.

[9] D. H. Lyth, "What would we learn by detecting a gravitational wave signal in the cosmic microwave background anisotropy?," *Phys.Rev.Lett.* **78** (1997) 1861–1863, `arXiv:hep-ph/9606387 [hep-ph]`.

[10] A. Chatterjee and A. Mazumdar, "Bound on largest $r \lesssim 0.1$ from sub-Planckian excursions of inflaton," *JCAP* **1501** no. 01, (2015) 031, `arXiv:1409.4442 [astro-ph.CO]`.

[11] A. D. Linde, "Particle physics and inflationary cosmology," *Contemp. Concepts Phys.* **5** (1990) 1–362, `arXiv:hep-th/0503203 [hep-th]`.

[12] N. Kaloper, A. Lawrence, and L. Sorbo, "An Ignoble Approach to Large Field Inflation," *JCAP* **1103** (2011) 023, `arXiv:1101.0026 [hep-th]`.

[13] C. Csaki, N. Kaloper, J. Serra, and J. Terning, "Inflation from Broken Scale Invariance," *Phys. Rev. Lett.* **113** (2014) 161302, `arXiv:1406.5192 [hep-th]`.

[14] D. E. Kaplan and R. Rattazzi, "A Clockwork Axion," `arXiv:1511.01827 [hep-ph]`.

[15] K. Choi and S. H. Im, "Realizing the relaxion from multiple axions and its UV completion with high scale supersymmetry," `arXiv:1511.00132 [hep-ph]`.

[16] E. Silverstein and A. Westphal, "Monodromy in the CMB: Gravity Waves and String Inflation," *Phys.Rev.* **D78** (2008) 106003, `arXiv:0803.3085 [hep-th]`.

[17] L. McAllister, E. Silverstein, and A. Westphal, "Gravity Waves and Linear Inflation from Axion Monodromy," *Phys.Rev.* **D82** (2010) 046003, `arXiv:0808.0706 [hep-th]`.

[18] M. Berg, E. Pajer, and S. Sjors, "Dante's Inferno," *Phys. Rev.* **D81** (2010) 103535, `arXiv:0912.1341 [hep-th]`.

[19] E. Palti and T. Weigand, "Towards large r from [p, q]-inflation," *JHEP* **04** (2014) 155, arXiv:1403.7507 [hep-th].

[20] L. McAllister, E. Silverstein, A. Westphal, and T. Wrase, "The Powers of Monodromy," *JHEP* **09** (2014) 123, arXiv:1405.3652 [hep-th].

[21] F. Marchesano, G. Shiu, and A. M. Uranga, "F-term Axion Monodromy Inflation," *JHEP* **09** (2014) 184, arXiv:1404.3040 [hep-th].

[22] R. Blumenhagen, C. Damian, A. Font, D. Herschmann, and R. Sun, "The Flux-Scaling Scenario: De Sitter Uplift and Axion Inflation," arXiv:1510.01522 [hep-th].

[23] A. de la Fuente, P. Saraswat, and R. Sundrum, "Natural Inflation and Quantum Gravity," *Phys. Rev. Lett.* **114** no. 15, (2015) 151303, arXiv:1412.3457 [hep-th].

[24] T. C. Bachlechner, C. Long, and L. McAllister, "Planckian Axions and the Weak Gravity Conjecture," arXiv:1503.07853 [hep-th].

[25] B. Heidenreich, M. Reece, and T. Rudelius, "Weak Gravity Strongly Constrains Large-Field Axion Inflation," arXiv:1506.03447 [hep-th].

[26] K. Kooner, S. Parameswaran, and I. Zavala, "Warping the Weak Gravity Conjecture," arXiv:1509.07049 [hep-th].

2

Neutrino Physics from the Cosmic Microwave Background

1 Introduction

Direct interactions between neutrinos and observable matter effectively ceased about one second after the end of inflation. Nevertheless, the total energy density carried by neutrinos was comparable to other matter sources through today. As a result, the gravitational effect of the neutrinos is detectable both at the time of recombination and in the growth of structure at later times [1].

2 Neutrino Mass

2.1 Theory Review

2.2 Observational Signatures and Target

Massive neutrinos contribute to the crical density as

$$\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{93\,\mathrm{eV}} \ . \tag{2.1}$$

2.2.1 CMB Power Spectra (TT, EE, Lensing Potential)

2.2.2 SZ Cluster Abundance

2.2.3 Cross-correlations with External Datasets

2.3 Forecasts

2.4 Relation to Lab Experiments

Relation between lab measurements of neutrino masses and the cosmological measurements.

3 Effective Number of Neutrinos

3.1 Theory Review

The *effective* number of neutrinos defined to be

$$N_{eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_R - \rho_\gamma}{\rho_\gamma} \ , \tag{2.2}$$

where ρ_R is the total energy density in radiation and ρ_γ is the energy density in photons.

Status of calculations in the Standard Model – (Contribution expected from G. Fuller)

3.2 Observational Signatures and Target

Status of current observations – Planck has provided a strong constraint on $N_{eff} = 3.15 \pm 0.23$ when combining both temperature and polarization data.

3.3 Forecasts

3.4 Thermal History and Big Bang Nucleosynthesis

4 Sterile Neutrinos

4.1 Theory and Motivation

4.2 Cosmological Implications

4.3 Relation to Lab Experiments

5 Other Targets

5.1 Axion-like Particles

5.2 Energy Injection and Particle Decays

5.3 Connections to BBN and Spectral Distortions

References

[1] K. Abazajian, K. Arnold, J. Austermann, B. Benson, C. Bischoff, *et al.*, "Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure," arXiv:1309.5383 [astro-ph.CO].

[2] M. Kamionkowski and E. D. Kovetz, "The Quest for B Modes from Inflationary Gravitational Waves," arXiv:1510.06042 [astro-ph.CO].

[3] D. Bessada and O. D. Miranda, "CMB Polarization and Theories of Gravitation with Massive Gravitons," *Class. Quant. Grav.* **26** (2009) 045005, arXiv:0901.1119 [gr-qc].

[4] S. Dubovsky, R. Flauger, A. Starobinsky, and I. Tkachev, "Signatures of a Graviton Mass in the Cosmic Microwave Background," *Phys. Rev.* **D81** (2010) 023523, arXiv:0907.1658 [astro-ph.CO].

[5] D. Bessada and O. D. Miranda, "CMB anisotropies induced by tensor modes in massive gravity," *JCAP* **0908** (2009) 033, arXiv:0908.1360 [astro-ph.CO].

[6] M. Mirbabayi, L. Senatore, E. Silverstein, and M. Zaldarriaga, "Gravitational Waves and the Scale of Inflation," *Phys. Rev.* **D91** (2015) 063518, arXiv:1412.0665 [hep-th].

[7] O. zsoy, K. Sinha, and S. Watson, "How Well Can We Really Determine the Scale of Inflation?," *Phys. Rev.* **D91** no. 10, (2015) 103509, arXiv:1410.0016 [hep-th].

[8] R. Namba, M. Peloso, M. Shiraishi, L. Sorbo, and C. Unal, "Scale-dependent gravitational waves from a rolling axion," arXiv:1509.07521 [astro-ph.CO].

[9] D. H. Lyth, "What would we learn by detecting a gravitational wave signal in the cosmic microwave background anisotropy?," *Phys.Rev.Lett.* **78** (1997) 1861–1863, arXiv:hep-ph/9606387 [hep-ph].

[10] A. Chatterjee and A. Mazumdar, "Bound on largest $r \lesssim 0.1$ from sub-Planckian excursions of inflaton," *JCAP* **1501** no. 01, (2015) 031, arXiv:1409.4442 [astro-ph.CO].

[11] A. D. Linde, "Particle physics and inflationary cosmology," *Contemp. Concepts Phys.* **5** (1990) 1–362, arXiv:hep-th/0503203 [hep-th].

[12] N. Kaloper, A. Lawrence, and L. Sorbo, "An Ignoble Approach to Large Field Inflation," *JCAP* **1103** (2011) 023, arXiv:1101.0026 [hep-th].

[13] C. Csaki, N. Kaloper, J. Serra, and J. Terning, "Inflation from Broken Scale Invariance," *Phys. Rev. Lett.* **113** (2014) 161302, arXiv:1406.5192 [hep-th].

[14] D. E. Kaplan and R. Rattazzi, "A Clockwork Axion," arXiv:1511.01827 [hep-ph].

[15] K. Choi and S. H. Im, "Realizing the relaxion from multiple axions and its UV completion with high scale supersymmetry," arXiv:1511.00132 [hep-ph].

[16] E. Silverstein and A. Westphal, "Monodromy in the CMB: Gravity Waves and String Inflation," *Phys.Rev.* **D78** (2008) 106003, arXiv:0803.3085 [hep-th].

[17] L. McAllister, E. Silverstein, and A. Westphal, "Gravity Waves and Linear Inflation from Axion Monodromy," *Phys.Rev.* **D82** (2010) 046003, arXiv:0808.0706 [hep-th].

[18] M. Berg, E. Pajer, and S. Sjors, "Dante's Inferno," *Phys. Rev.* **D81** (2010) 103535, arXiv:0912.1341 [hep-th].

[19] E. Palti and T. Weigand, "Towards large r from [p, q]-inflation," *JHEP* **04** (2014) 155, `arXiv:1403.7507 [hep-th]`.

[20] L. McAllister, E. Silverstein, A. Westphal, and T. Wrase, "The Powers of Monodromy," *JHEP* **09** (2014) 123, `arXiv:1405.3652 [hep-th]`.

[21] F. Marchesano, G. Shiu, and A. M. Uranga, "F-term Axion Monodromy Inflation," *JHEP* **09** (2014) 184, `arXiv:1404.3040 [hep-th]`.

[22] R. Blumenhagen, C. Damian, A. Font, D. Herschmann, and R. Sun, "The Flux-Scaling Scenario: De Sitter Uplift and Axion Inflation," `arXiv:1510.01522 [hep-th]`.

[23] A. de la Fuente, P. Saraswat, and R. Sundrum, "Natural Inflation and Quantum Gravity," *Phys. Rev. Lett.* **114** no. 15, (2015) 151303, `arXiv:1412.3457 [hep-th]`.

[24] T. C. Bachlechner, C. Long, and L. McAllister, "Planckian Axions and the Weak Gravity Conjecture," `arXiv:1503.07853 [hep-th]`.

[25] B. Heidenreich, M. Reece, and T. Rudelius, "Weak Gravity Strongly Constrains Large-Field Axion Inflation," `arXiv:1506.03447 [hep-th]`.

[26] K. Kooner, S. Parameswaran, and I. Zavala, "Warping the Weak Gravity Conjecture," `arXiv:1509.07049 [hep-th]`.

3

Dark Energy / Gravity / Dark Matter

1 Introduction

Here is an intro.

4

CMB Lensing

1 Introduction to CMB Lensing

2 Measuring Neutrino Masses with the Lensing Auto Spectrum

2.1 Bias Subtraction

3 Delensing

3.1 Neff from Delensing E-modes

3.2 Primary Gravity Waves from Delensing B-modes

3.3 Method

4 Halo Lensing

4.1 Modified Estimator

4.2 Forecasts

5 Cross-correlations

5.1 CMB Lens x Optical Lens

5.2 CMB Lens x Galaxy Redshift Survey

6 Systematic Effects and Mitigation

6.1 Astrophysical Foregrounds

6.2 Instrumental Effects

7 Instrument, Survey, and Simulation Requirements

References

[1] K. Abazajian, K. Arnold, J. Austermann, B. Benson, C. Bischoff, *et al.*, "Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure," arXiv:1309.5383 [astro-ph.CO].

[2] M. Kamionkowski and E. D. Kovetz, "The Quest for B Modes from Inflationary Gravitational Waves," arXiv:1510.06042 [astro-ph.CO].

[3] D. Bessada and O. D. Miranda, "CMB Polarization and Theories of Gravitation with Massive Gravitons," *Class. Quant. Grav.* **26** (2009) 045005, arXiv:0901.1119 [gr-qc].

[4] S. Dubovsky, R. Flauger, A. Starobinsky, and I. Tkachev, "Signatures of a Graviton Mass in the Cosmic Microwave Background," *Phys. Rev.* **D81** (2010) 023523, arXiv:0907.1658 [astro-ph.CO].

[5] D. Bessada and O. D. Miranda, "CMB anisotropies induced by tensor modes in massive gravity," *JCAP* **0908** (2009) 033, arXiv:0908.1360 [astro-ph.CO].

[6] M. Mirbabayi, L. Senatore, E. Silverstein, and M. Zaldarriaga, "Gravitational Waves and the Scale of Inflation," *Phys. Rev.* **D91** (2015) 063518, arXiv:1412.0665 [hep-th].

[7] O. zsoy, K. Sinha, and S. Watson, "How Well Can We Really Determine the Scale of Inflation?," *Phys. Rev.* **D91** no. 10, (2015) 103509, arXiv:1410.0016 [hep-th].

[8] R. Namba, M. Peloso, M. Shiraishi, L. Sorbo, and C. Unal, "Scale-dependent gravitational waves from a rolling axion," arXiv:1509.07521 [astro-ph.CO].

[9] D. H. Lyth, "What would we learn by detecting a gravitational wave signal in the cosmic microwave background anisotropy?," *Phys.Rev.Lett.* **78** (1997) 1861–1863, arXiv:hep-ph/9606387 [hep-ph].

[10] A. Chatterjee and A. Mazumdar, "Bound on largest $r \lesssim 0.1$ from sub-Planckian excursions of inflaton," *JCAP* **1501** no. 01, (2015) 031, arXiv:1409.4442 [astro-ph.CO].

[11] A. D. Linde, "Particle physics and inflationary cosmology," *Contemp. Concepts Phys.* **5** (1990) 1–362, arXiv:hep-th/0503203 [hep-th].

[12] N. Kaloper, A. Lawrence, and L. Sorbo, "An Ignoble Approach to Large Field Inflation," *JCAP* **1103** (2011) 023, arXiv:1101.0026 [hep-th].

[13] C. Csaki, N. Kaloper, J. Serra, and J. Terning, "Inflation from Broken Scale Invariance," *Phys. Rev. Lett.* **113** (2014) 161302, arXiv:1406.5192 [hep-th].

[14] D. E. Kaplan and R. Rattazzi, "A Clockwork Axion," arXiv:1511.01827 [hep-ph].

[15] K. Choi and S. H. Im, "Realizing the relaxion from multiple axions and its UV completion with high scale supersymmetry," arXiv:1511.00132 [hep-ph].

[16] E. Silverstein and A. Westphal, "Monodromy in the CMB: Gravity Waves and String Inflation," *Phys.Rev.* **D78** (2008) 106003, arXiv:0803.3085 [hep-th].

[17] L. McAllister, E. Silverstein, and A. Westphal, "Gravity Waves and Linear Inflation from Axion Monodromy," *Phys.Rev.* **D82** (2010) 046003, arXiv:0808.0706 [hep-th].

[18] M. Berg, E. Pajer, and S. Sjors, "Dante's Inferno," *Phys. Rev.* **D81** (2010) 103535, arXiv:0912.1341 [hep-th].

[19] E. Palti and T. Weigand, "Towards large r from [p, q]-inflation," *JHEP* **04** (2014) 155, `arXiv:1403.7507 [hep-th]`.

[20] L. McAllister, E. Silverstein, A. Westphal, and T. Wrase, "The Powers of Monodromy," *JHEP* **09** (2014) 123, `arXiv:1405.3652 [hep-th]`.

[21] F. Marchesano, G. Shiu, and A. M. Uranga, "F-term Axion Monodromy Inflation," *JHEP* **09** (2014) 184, `arXiv:1404.3040 [hep-th]`.

[22] R. Blumenhagen, C. Damian, A. Font, D. Herschmann, and R. Sun, "The Flux-Scaling Scenario: De Sitter Uplift and Axion Inflation," `arXiv:1510.01522 [hep-th]`.

[23] A. de la Fuente, P. Saraswat, and R. Sundrum, "Natural Inflation and Quantum Gravity," *Phys. Rev. Lett.* **114** no. 15, (2015) 151303, `arXiv:1412.3457 [hep-th]`.

[24] T. C. Bachlechner, C. Long, and L. McAllister, "Planckian Axions and the Weak Gravity Conjecture," `arXiv:1503.07853 [hep-th]`.

[25] B. Heidenreich, M. Reece, and T. Rudelius, "Weak Gravity Strongly Constrains Large-Field Axion Inflation," `arXiv:1506.03447 [hep-th]`.

[26] K. Kooner, S. Parameswaran, and I. Zavala, "Warping the Weak Gravity Conjecture," `arXiv:1509.07049 [hep-th]`.

5

Experimental Approach

1 Introduction

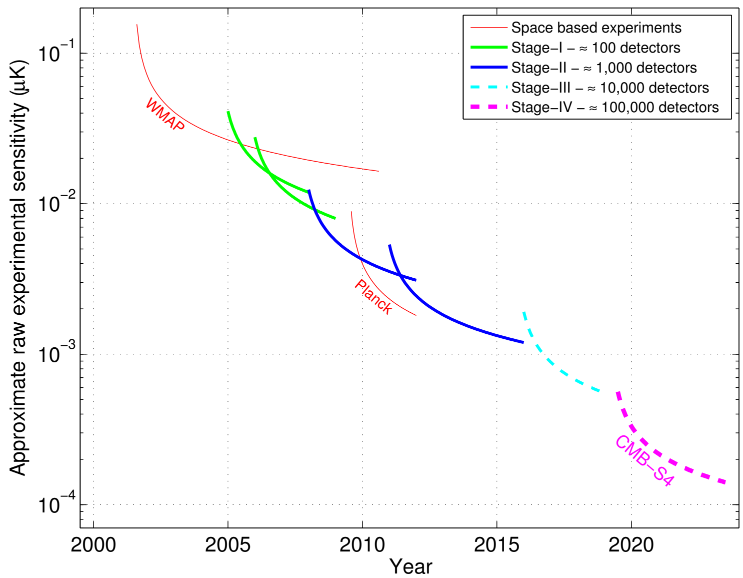

Figure 4. *Plot illustrating the evolution of the raw sensitivity of CMB experiments, which scales as the total number of bolometers. Ground-based CMB experiments are classified into Stages with Stage II experiments having O(1000) detectors, Stage III experiments having O(10,000) detectors, and a Stage IV experiment (such as CMB-S4) having O(100,000) detectors. Figure from Snowmass CF5 Neutrino planning document.*

Experiment design from science goals

- depth

- sky area

- resolution

- ell space coverage

-frequency coverage

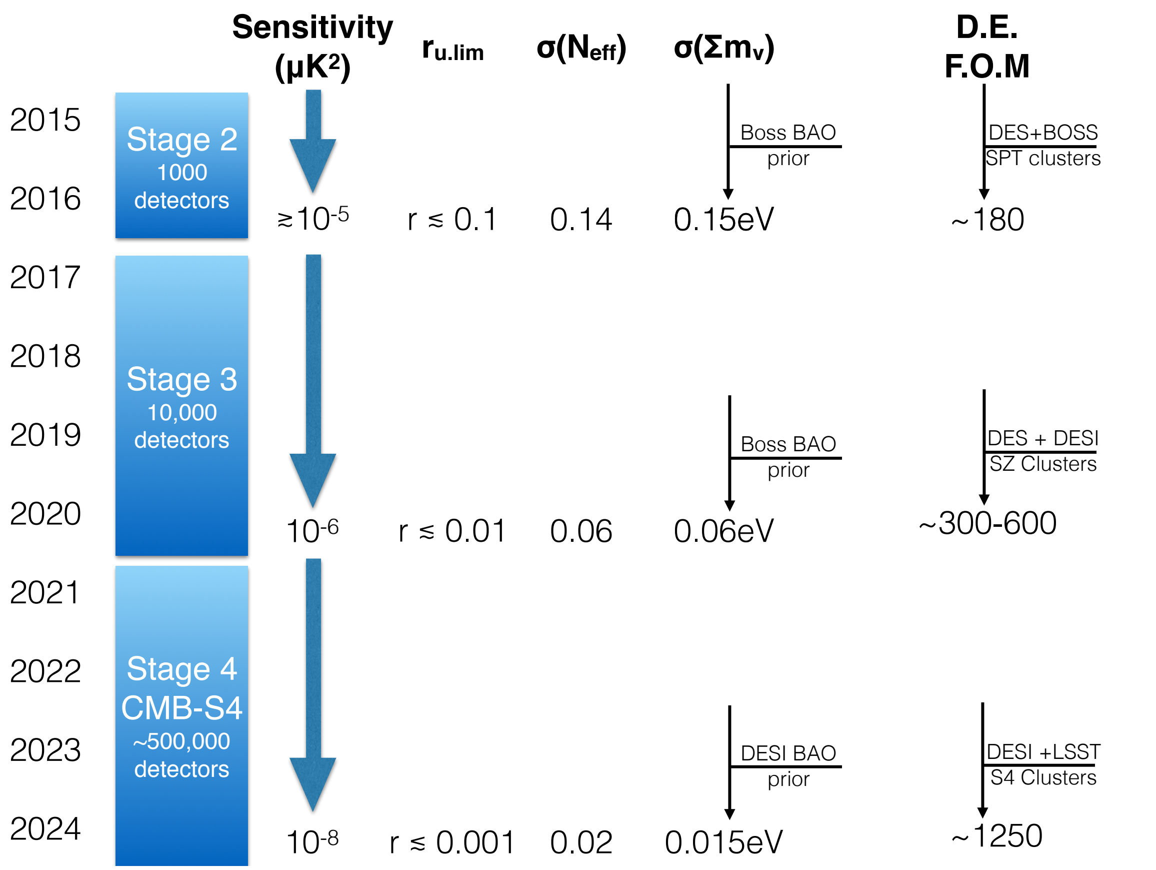

Figure 5. *Schematic timeline of evolution of Stage 3 and CMB-S4 sensitivity in μK^2 and the expected improvement in a few of the key cosmological parameters.*

2 Complementarity of Ground and Space

3 Detector Arrays

- Superconducting Arrays

- TES

4 Multiplexer technologies

5 Telescopes and Optics

- Polarization modulators

6 Sites

- Chile + Pole

- Northern Site

6

Simulations and Data Analysis

1 Introduction

Overview of simulations and data analysis elements motivating the subsequent division into 5 blocks.

1.1 Data Analysis

A sequence of S/N enhancing data compressions via domain transformations - time samples (red) to sky pixels (blue) to map multipoles (green) to physical parameters (yellow).

An iterative process, with each domain exposing different systematic effects to be mitigated.

A full analysis requires propogating not just the data but also their covariance between domains. The size of the full pixel covariance now precludes exact methods except in certain special cases.

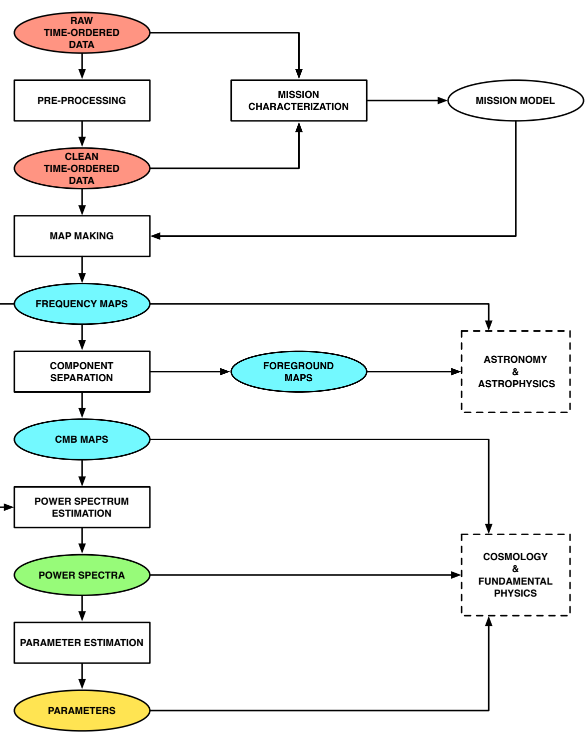

Figure 6. *The CMB data analysis pipeline*

1.2 Simulation

Needed for

- Mission design and development (both instrument and observation)
- Validation and verification of analysis tools
- Absent a full covariance matrix, Monte Carlo based uncertainty quantification and debiasing.

From top to bottom, there is an inevitable trade-off between the computational cost of generating the simulation and its realism and accuracy.

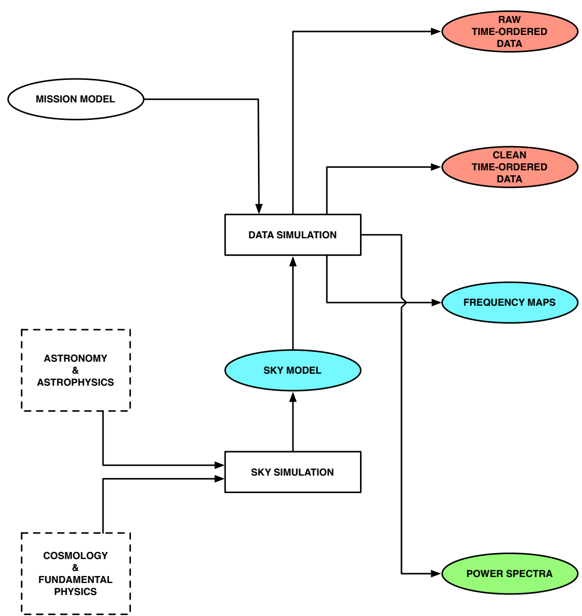

Figure 7. *The CMB simulation pipeline*

1.3 Coupling Simulation and Data Analysis

The overall simulation and data analysis pipeline runs both as a top-down data reduction and a wrap-around refinement of mission and sky characterization and modeling.

It can be subdivided into 5 blocks based on the challenges faced and expertise required to address them.

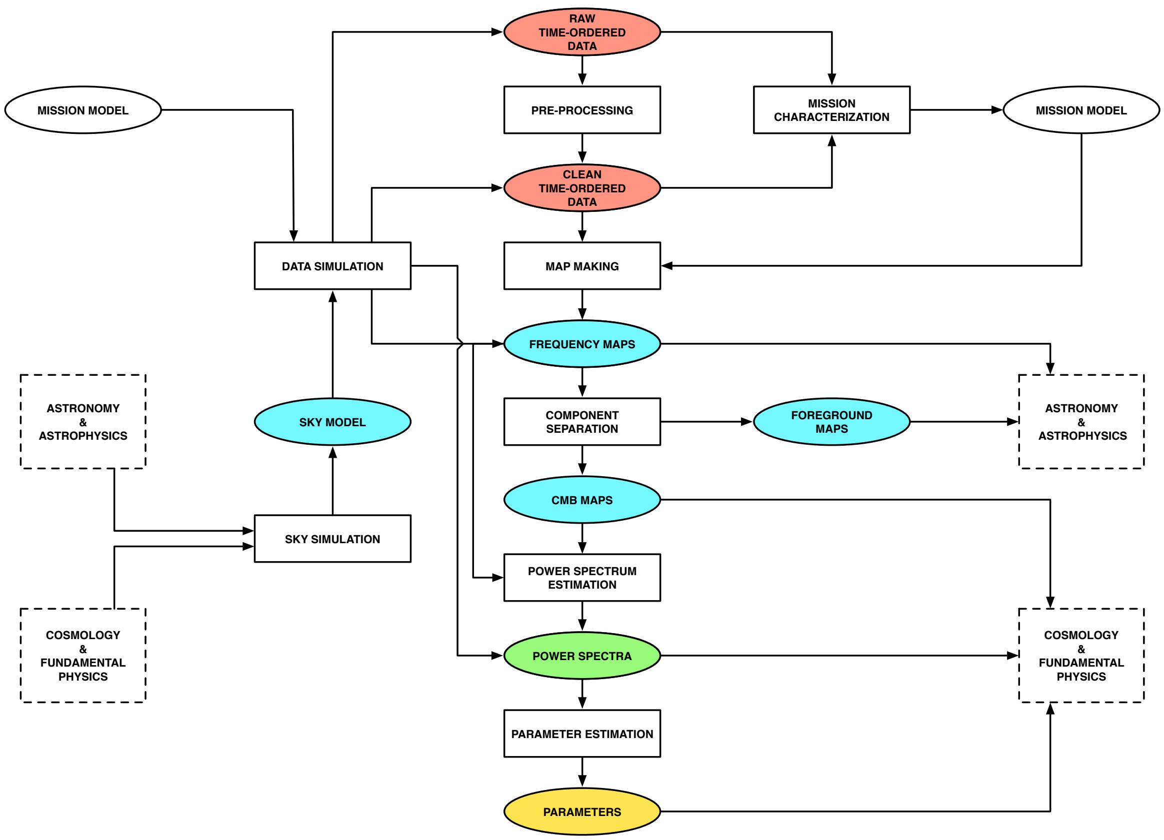

Figure 8. *The full CMB simulation/data analysis pipeline*

2 Forecasting

Key challenges:

- capturing sufficient complexity in multipole-domain sky and mission models.

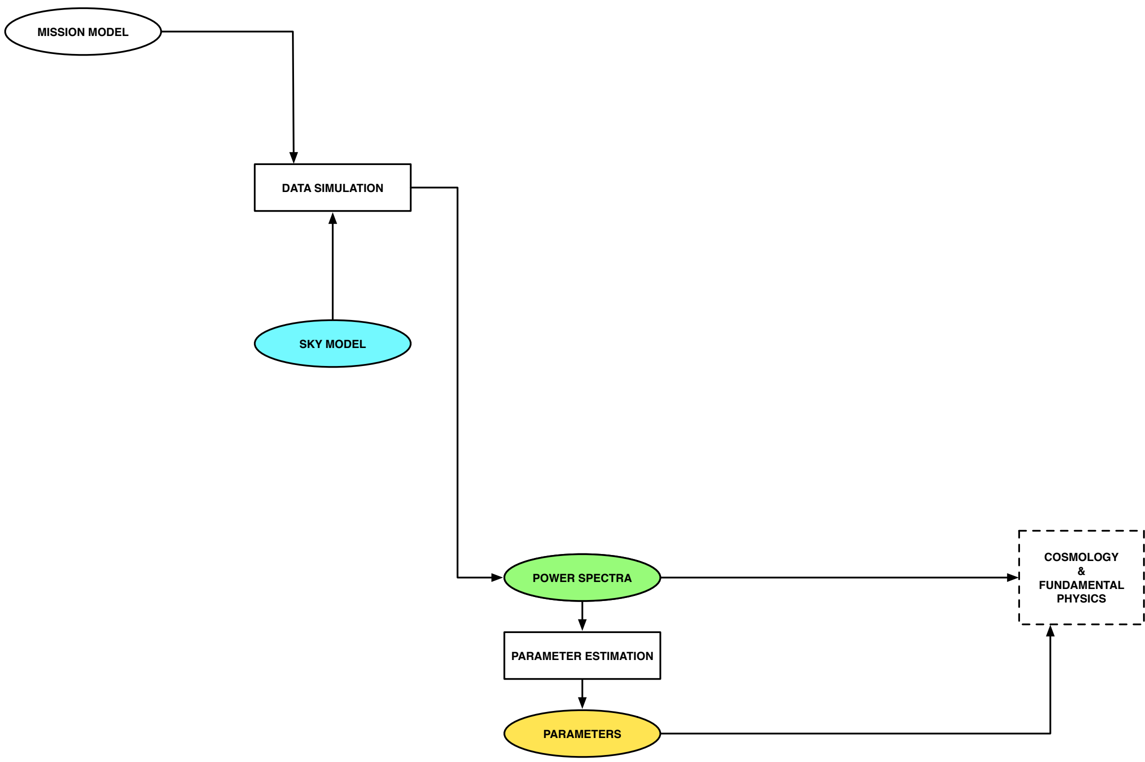

Figure 9. *The forecasting pipeline*

3 Sky Modeling

Key challenges:

- reliability of models based on noisy, bandpassed, beam-convolved observations, including Planck
- self-consistency of CMB secondaries and extra-Galactic foregrounds
- usability/software engineering

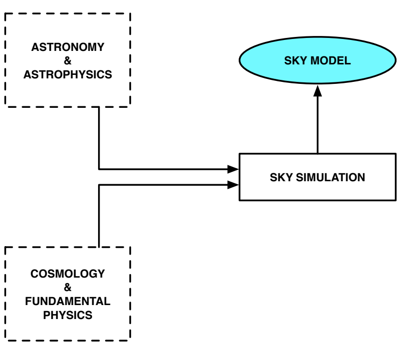

Figure 10. *The sky modeling pipeline*

4 Time-Ordered Data Processing

Key challenges:

- computational tractability due to data volume and complexity of next-generation supercomputers
- mitigating raw data systematics and developing sufficient mission and data models

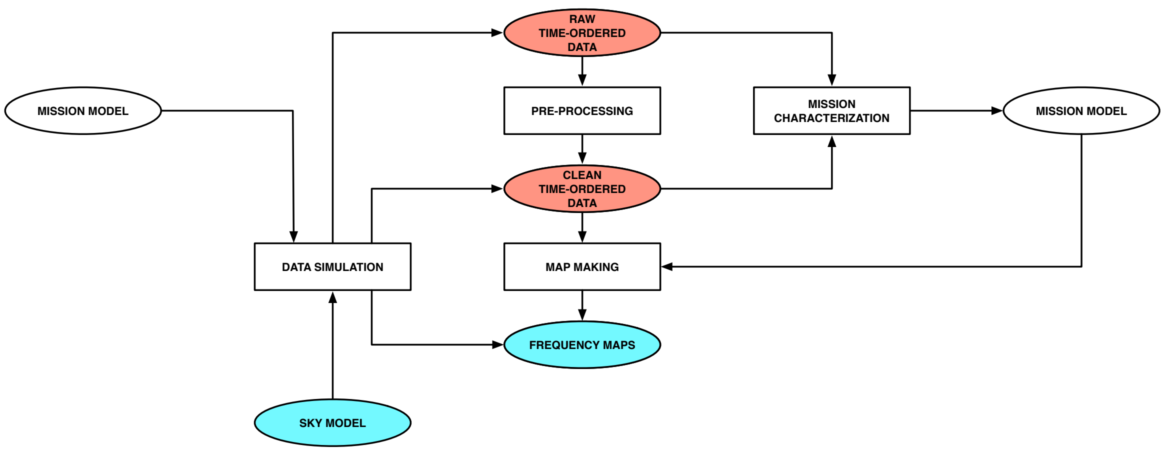

Figure 11. *The time-ordered data processing pipeline*

5 Component Separation

Key challenges:

- validation - are we using the right algorithms for the (as yet unknown) real foregrounds
- verification - are these algorithms right given our (as yet flawed) simulations

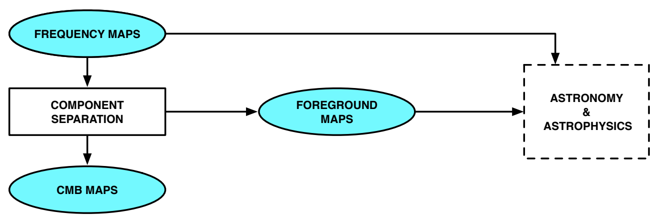

Figure 12. *The component separation pipeline*

6 Statistics and Parameters

Key challenges:

- are our approximations to the full data covariance sufficient?

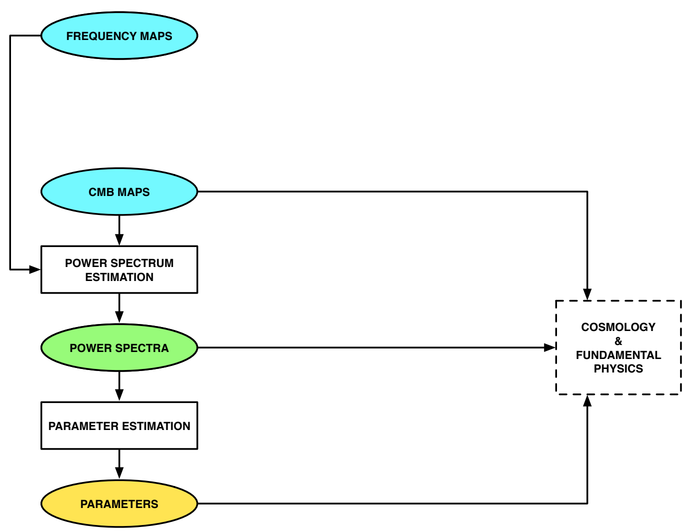

Figure 13. *The statistics and parameters pipeline*