

The Probe of Inflation and Cosmic Origins

A Space Mission Study Report
December, 2018

Principal Investigator:

Steering Committee:

Executive Committee:

Contributors:

Endorsers:

1 Executive Summary (2 pg, Hanany)

2 Science (31 pages)

48 pages are currently distributed as 29/19: 29 pages for science (including foregrounds and systematics), 19 for instrument, technology, mission, management and cost.

2.1 Introduction (1.5 pgs, Hanany + (??))

NASA suggested table of contents says Science Intro or Landscape section should include: State of the Art in the Field ; Compelling Outstanding Questions; Needed Capabilities for Progress.

2.2 Science Objectives (17.5 pgs)

The PICO Science Traceability Matrix (2pg, Hanany&Trangsrud) will be inserted around here. It is an 11x17 foldout, so it counts as 2 pages, which leaves 15.5 to all the rest in 2.2. Currently allocating 15 pages.

FOR EACH OF THE BELOW SUBSECTIONS:

- Introduce and elaborate on the applicable PICO “Science Objectives” from the STM table (what do they mean and why are they important)
- Observations/Measurements that enable PICO to accomplish each Science Objective (tell the data analysis story that connects the Observations column of the STM to the Science Objective column)
- Contextualize relative to sub-orbital and other space missions. *Emphasize where capabilities are unique to space.*
- Science yield estimate (be quantitative. how well will PICO do at Baseline/Required performance? at Current Best Estimate performance?)
- Include a summary plot or table which demonstrates PICO’s performance against the Science Objective as written (e.g. how it discriminates between different theories)
- Perceived science impact. (The impact isn’t reducing sigma on a parameter. It is about what we will learn about nature.)

2.2.1 Fundamental Physics (6 pgs, Flauger, Green)

To include: Cosmic Inflation, Particle Physics (Neutrinos and Light Relics), primordial EM fields
Gravitational waves and inflation

Measurements of the CMB together with Einstein’s theory of general relativity imply that the observed density perturbations must have been created long before the CMB was released, and rather remarkably even before the universe became filled with a hot and dense plasma of fundamental particles. What generated these perturbations is one of the biggest questions in cosmology.

While the dynamics of the plasma produces some amount of gravitational waves, the amplitude is too small to be detected in existing or planned CMB experiments. So any imprint of gravitational waves on the cosmic microwave background detected by PICO would constitute evidence for gravitational waves from the same primordial period that created the density perturbations. Because the dynamics of gravitational waves is essentially unaffected by the plasma physics, they would be a pristine relic left over from the earliest moments of our universe, and their properties would shed light on the mechanism that created the primordial perturbations that grew into the anisotropies of the CMB and the stars and galaxies around us. Knowledge of the strength of the signal and their statistical properties would transform our understanding of many areas of fundamental physics. Inflation, a period of nearly exponential expansion of the early universe, is the leading paradigm explaining the origin of the primordial density perturbations. It predicts a nearly scale invariant spectrum of primordial gravitational waves originating from quantum fluctuations. Thus, a detection of these gravitational waves would be the first detection of phenomenon associated with quantum gravity. Because the spectrum is scale-invariant, one may hope to detect primordial gravitational waves over a wide range of frequencies including, for example, at LIGO or LISA frequencies. However, as a consequence of the expansion of the universe, the energy density in the gravitational waves rapidly dilutes with increasing frequency, and observations of the CMB provide the easiest, and for the foreseeable future only way to detect these gravitational waves.

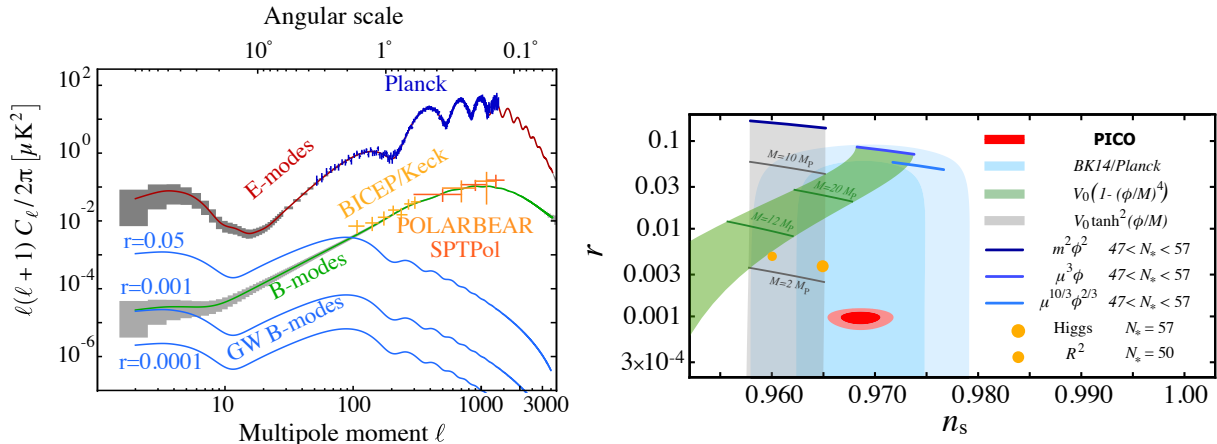


Figure 1: power spectrum place holder

The strength of the signal, often quantified by the tensor-to-scalar ratio r , is a direct measure of the expansion rate of the universe during inflation. Together with the Friedmann equation, this reveals one of the most important characteristics of inflation, its energy scale. PICO will be able to detect primordial gravitational waves if inflation occurred at an energy scale of at least 4×10^{15} GeV. A detection would have profound implications for fundamental physics because it would provide evidence for a new energy scale, and would allow us to probe physics at energies far beyond the reach of terrestrial colliders.

The signal would have two contributions, one on degree angular scales or multipoles of $\ell \sim 80$, typically referred to as the recombination peak, and another contribution for multipoles of $\ell \lesssim 20$ from reionization. The contribution from reionization is expected to be strongest relative to the contribution from weak lensing and instrumental noise. No sub-orbital experiment has meaningfully measured modes at $\ell < 40$ and a satellite like PICO is the most suitable approach to reach the lowest multipoles.

There are two classes of slow-roll inflation that naturally explain the observed value of the spectral index of primordial fluctuations, n_s . The first class is characterized by potentials of the form $V(\phi) \propto \phi^p$. This class includes many of the simplest models of inflation, some of which have already been strongly disfavored by existing observations. If the constraints on the spectral index tighten by about a factor 2 with the central value unchanged, and the upper limits on r improve by an order of magnitude, this class would be ruled out.

The second class is characterized by potentials that exponentially approach a plateau and include R^2 inflation. This model predicts a tensor-to-scalar ratio of $r \sim 0.003$. All models in this class with a characteristic scale in the potential that is larger than the Planck scale predict a tensor-to-scalar ratio of $r \gtrsim 0.001$, and an experiment like CMB-S4 could exclude these scenarios. However, there are models such as the Goncharov-Linde model with a somewhat smaller characteristic scale that predict a tensor-to-scalar ratio of $r \sim 4 \times 10^{-4}$.

In the absence of a detection, PICO would limit the amount of gravitational waves to $r < 10^{-4}$ at 95% CL. This is stronger than current upper limits by three orders of magnitude, and stronger than those expected for the ground-based experiment CMB-S4 by an order of magnitude.

Models of inflation, or the early universe more generally, differ in their predictions for the scalar spectral index n_s and its scale dependence, often referred to as the running of the spectral index n_{run} . With its high resolution and low noise levels, PICO will improve the constraints on n_s and n_{run} by a factor of about two. In addition, PICO will probe the statistical properties of the primordial fluctuations over a wide range of scales with exquisite precision and improve constraints on departures from Gaussianity by a factor 2 – 3.

Light relics

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 [1, 2]. As the universe expands and cools, the particles fall out of equilibrium, leaving observable signatures in the CMB power spectra. Through these effects the CMB is a sensitive probe of neutrino and of other particles' properties.

One particularly compelling target is the effective number of light relic particle species N_{eff} , also called the effective number of neutrinos. The canonical value with three neutrino families is $N_{\text{eff}} = 3.046$. Additional light particles contribute a change to N_{eff} of $\Delta N_{\text{eff}} \geq 0.027 g$ where $g \geq 1$ is the number of degrees of freedom of the new particle [3, 4]. This defines a target of $\sigma(N_{\text{eff}}) < 0.027$ for future CMB observations. Either a limit or detection of ΔN_{eff} at this level would provide powerful insights into the basic constituents of matter.

Forecasts for N_{eff} are shown in Figure 2. The two most important parameters for improving constraints are the fraction of sky observed f_{sky} and the noise. Achieving both larger f_{sky} and lower noise are strengths of PICO 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 $\sigma(N_{\text{eff}}) < 0.025$. 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

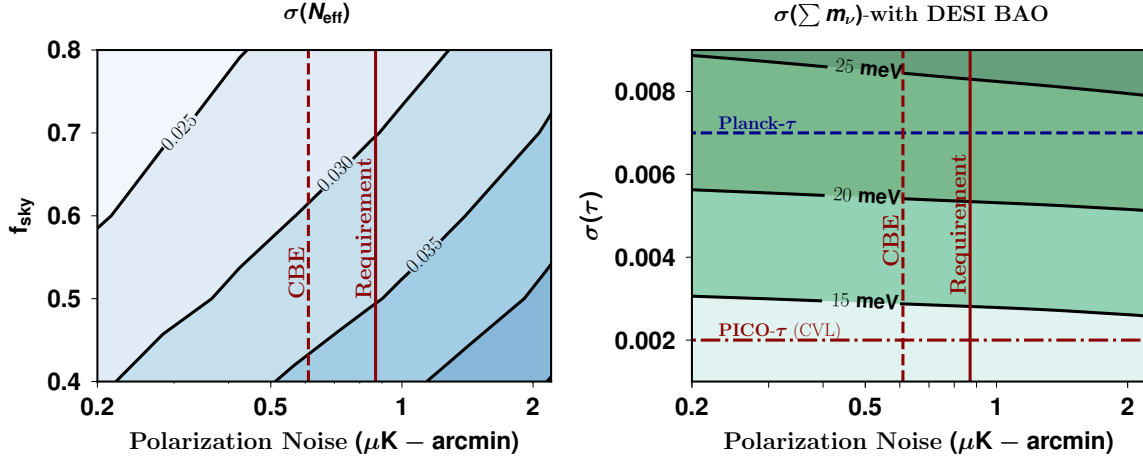


Figure 2: N_{eff} uncertainty as a function of noise and sky fraction (left) and sum of neutrino masses uncertainty as a function of noise and the uncertainty in the measurement of τ , for 0.7 sky fraction (right). The resolution assumed is $5'$. Vertical lines denote the expected performance of the 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 [5], including residual non-Gaussian covariances. The Σm_ν forecasts include DESI BAO.

ratio of N_{eff} to Y_p . PICO'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.

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 [? ? ?]. *Planck* currently excludes WIMPs with mass $m_{\text{dm}} < 16$ GeV and a future CMB mission could reach $m_{\text{dm}} < 45$ GeV for $f_{\text{sky}} = 0.8$. The CMB provides the most stringent constraints on the dark matter annihilation cross section for dark matter in this mass range.

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 [6]. These couplings affect the evolution of fluctuations and ultimately the T and E spectra. The current limits of $\sigma \lesssim 10^{-31} - 10^{-34} \text{ cm}^2 \times (m_{\text{dm}}/\text{MeV})$ can be competitive with direct detection for sub-GeV masses. More exotic dark sectors that include long-range forces can produce an even richer phenomenology in the CMB and in the large-scale structure without necessarily producing an associated signature in direct detection experiments or indirect searches (e.g. [7, 8, 9]).

$\sigma \simeq 10^{-39} - 10^{-35} \text{ cm}^2$ [?].

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., ? ? ? ? ?].

Neutrino mass

The origin and structure of the neutrino masses is one of the great outstanding questions about the nature of the Standard Model particles. Measurements of neutrinos in the lab have revealed much about the masses differences and mixing angles. Cosmology compliments the ongoing effort in the

lab by offering a measurement of the sum of the neutrino masses, $\sum m_\nu$, through the gravitational influence of the non-relativistic cosmic neutrinos (confirmed by the measurement of N_{eff}). The best current constraint arises from a combination of Planck and BOSS BAO to constraint $\sum m_\nu < 0.12$ eV (95%).

Cosmological measurements are primarily sensitive to the suppression of power on small scales after the neutrinos become non-relativistic, which can be measured via CMB lensing or weak lensing in a galaxy survey. However, these measurements are limited by our knowledge of the primordial amplitude, A_s . In practice, CMB observations most directly constrain $A_s e^{-2\tau}$ and thus do not provide a high precision measurement of A_s or τ .

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* [10]. Forecasts for a CMB measurement of $\sum m_\nu$ using the lensing B mode [11] are shown in Figure 2. 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 PICO 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 [12]. 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 PICO.

Using a PICO measurement of τ to achieve $\sigma(\tau) < 15$ meV, implies that either PICO would be capable of detecting $\sum m_\nu > 0$ at greater than 4σ or would exclude the inverted hierarchy ($\sum m_\nu > 100$ meV) at 95% confidence, depending on the central value of the measurement.

2.2.2 Cosmic Structure Formation and Evolution (4 pgs. Hill, Battaglia (& Alvarez))

Physics of Reionization

The reionization of the Universe imprints multiple signals in the CMB, in both temperature and polarization. In polarization, the most important reionization signal is the large-scale E -mode power sourced by the scattering of the temperature quadrupole during this epoch. This signal allows a direct measurement of the optical depth, τ , with very little degeneracy with other parameters (and, to some extent, a measurement of the reionization history itself). In contrast, inference of τ from the TT power spectrum is hindered by its direct degeneracy with the scalar fluctuation amplitude. Thus, large-scale EE power spectrum measurements are a unique and crucial observable to constrain this parameter. If measurements of τ are not improved beyond the current uncertainties from *Planck*, inference of several new aspects of cosmological physics (e.g., neutrino mass) will be severely hindered. PICO is the ideal experiment to make this measurement. Its noise level and frequency coverage permit a cosmic-variance-limited constraint on τ , i.e., $\sigma(\tau) \approx 0.002$. **Does this projected error bar need to be derived from the foreground simulations that are being used for r forecasting? Or is it obvious that if we can reach the $\sigma(r)$ target, this $\sigma(\tau)$ value can easily be achieved?**

In temperature, the most important small-scale imprint is that sourced by the “patchy” kinematic Sunyaev-Zel’dovich (kSZ) effect, due to the peculiar velocities of free electron bubbles around ionizing sources (e.g., galaxies or quasars). The total kSZ power spectrum receives contributions from both the patchy reionization signal and “late-time” sources, e.g., the intergalactic and intracluster media. The reionization and late-time signals are expected to have comparable amplitudes [? ? ?

]. With constraints on the late-time contribution from other information (e.g., cross-correlations), effective small-scale foreground removal, and with the primary CMB TT power spectrum constrained by inference from the EE power spectrum, it is possible to extract reionization constraints from the small-scale kSZ power spectrum [?].

In addition to these signals, reionization also leaves specific non-Gaussian signatures in the CMB. In particular, patchy reionization induces non-trivial 4-point functions in both temperature [?] and polarization [?]. The temperature 4-point function can be used to separate reionization and late-time kSZ contributions. Combinations of temperature and polarization data can be used to build quadratic estimators for reconstruction of the patchy τ field, analogous to CMB lensing reconstruction. **Are we planning to try to forecast these here?**

FIGURE: τ constraint, kSZ power spectrum constraints, perhaps patchy τ reconstruction constraints? I assume the four-point estimator does not look promising given the relatively low resolution of PICO, but we can check the Smith papers. This will essentially be an analog of Fig. 39 of the SO forecasting paper (Nick and Marcelo have the relevant code).

The Sections below need to be rearranged to match other Science Objective(s) from the STM, but to also relay the breadth of science reachable by PICO, even if those goals are not in the STM.

Structure Formation via Gravitational Lensing

- CMB lensing map and auto-power spectrum: figure with signal and quadratic estimator noise curve(s)
- Delensing and neutrino mass constraints assumed to go in fundamental physics chapter
- Cross-correlations: what to focus on here?
- CMB halo lensing: cluster mass calibration

Physics of Galaxy Formation via the Sunyaev-Zel'dovich (SZ) Effects

- Thermal SZ Effect
 - Cluster count forecast
 - y -map and tSZ auto-power spectrum: figure with signal and NILC noise curve(s) [M. Remazeilles]
 - Cross-correlations: forecast S/N with LSST, Euclid, DESI
- Kinematic SZ Effect
 - Cross-correlations: forecast S/N with LSST, Euclid, DESI
 - Constraints on ICM models: figure with gas pressure and density profile plots, error bars
 - Late-time kSZ power spectrum?

2.2.3 Galactic Structure and Star Formation (3 pgs, Chuss & Fissel)

Galactic Molecular Clouds

Stars form out of dense, gravitationally unstable subregions within molecular clouds. The efficiency of this conversion from molecular gas to stars is very low, as a result of the balance between

turbulence, magnetic fields, feedback from young stars, and gravity over many scales in size and density [?]. Magnetic fields may play an important role in slowing the star formation process, by inhibiting motions of gas in the direction perpendicular to the field. However the degree to which magnetic fields reduce star formation efficiency is poorly constrained because of the difficulty of making detailed maps of magnetic fields over a large sample of molecular clouds. With PICO we will answer the question of **how do the magnetic fields that thread clouds inhibit the formation of dense, gravitationally unstable sub-structures within molecular clouds, and how does magnetic regulation affect the efficiency with which stars form?**

PICO will measure dust polarization over the entire sky, and since dust grains are known to align perpendicular to their local magnetic field [? ?], these observations will be used to create detailed maps of magnetic field morphology. With a best 1.1' FWHM beam size PICO will be able to map all molecular clouds at better than 1 pc resolution out to 3.4 kpc. The BoloCam Galactic Plane Survey found 700 molecular clouds, recovering distances for approximately half their sample while covering roughly a third of the Galactic Plane [?]. PICO can therefore be expected to make highly detailed magnetic field maps of thousands of molecular clouds with thousands to hundreds of thousands of independent measurements per cloud, a huge improvement over the 10 nearby clouds mapped to the same level of detail with the *Planck* Satellite [?].

Our goal is to use the PICO observations to measure:

- *The Balance between Gravity and Magnetic Support.* This is parameterized by the mass-to-flux ratio $\mu = M/M_B$, comparing M , the mass of a gas cloud to $M_\Phi = \Phi/2\pi G^{1/2}$, the maximum mass that can be supported by the magnetic flux (Φ) through the cloud. Where $\mu > 1$ the cloud cannot be supported by the magnetic field alone. Current observations suggest that the envelopes of clouds can be supported against gravity by magnetic fields ($\mu < 1$), but higher density structures such as cores and filaments are supercritical ($\mu > 1$) and can thus collapse to form stars [?]. PICO will determine whether this model is true for all clouds and make detailed observations of the density scale magnetic flux is lost.
- *The Balance between Turbulence and Magnetic Fields.* Turbulence also plays a crucial role in star formation. The turbulent gas motions will determine the initial range of gas density within the molecular cloud. The balance between turbulent and magnetic fields, is characterized by the Alfvén Mach number $\mathcal{M}_A = \sigma_k/v_A$, where σ_k is the turbulent velocity width and $v_A = |B|/\sqrt{4\pi\rho}$ is the Alfvén velocity. If $\mathcal{M}_A < 1$ then the magnetic field is strong enough to significantly influence gas motions. Recent Planck observations of ten nearby clouds have shown that low column density cloud structures statistically tend to align parallel to the magnetic field [?], while high column density cloud structures have either no preferred alignment or in many cases align perpendicular to the magnetic field [?]. These observations can only be reproduced in simulations if the large-scale magnetic field within molecular clouds is as strong or stronger than turbulence [? ? ?]. PICO will determine whether the “strong field” case is true for molecular clouds of different ages and masses, and will measure the scale at which the cloud transitions from magnetic to turbulence and/or gravity dominated.

To measure these quantities we will apply established polarization analysis techniques:

- *Magnetic Field Dispersion:* Both [?] and [?] showed that in the interstellar medium the dispersion in magnetic field direction angles can be used to estimate the magnetic field

strength, if the turbulent velocity dispersion is known. With PICO we will use the modern variations of this method [? ? ?] by fitting a model polarization angle dispersion power spectrum in order to constrain the projected magnetic field strength ($|B_{POS}|$), turbulent to magnetic field ratio (\mathcal{M}_A), and magnetized turbulence power spectrum .

- *Polarization Modeling:* Measuring the statistical properties of the fraction of dust emission that is polarized and how this polarization level correlates with column density and magnetic field angle dispersion, can be used to constrain whether the field is strong or weak, where in the cloud is the magnetic field best traced, and how inclined the magnetic field is with respect to the plane of the sky [? ? ?].
- *Comparing Polarization and Velocity Gradients:* Gradients in spectral line velocity for atomic and molecular gas have recently been shown to align perpendicular to the magnetic field [? ? ?]. These gradients change from perpendicular to parallel to the magnetic field where the cloud becomes self-gravitating. Most PICO target clouds have already been observed with Galactic plane molecular line surveys such as CHAMP, ThRUmms, MALT-90, and SEDGISM, so by comparing PICO maps the velocity structure we can determine where the energy balance between gravity and magnetic fields change.
- *Cloud Structure Alignment the Magnetic Field:* *Planck* and BLASTPol observations have shown a statistically significant change in relative alignment of low (parallel) to high density (perpendicular) gas with respect to the magnetic field [? ? ?]. As discussed above, this is consistent with cloud formation simulations where $\mathcal{M}_A \leq 1$, or where the magnetic field is equal or stronger than the turbulent gas motions. The column density where the transition occurs seems to depend on both the degree of magnetization (\mathcal{M}_A), and formation history of the cloud [? ? ?].

Each of the above analysis methods has different uncertainties and limitations. However, by applying all four techniques to both PICO observations and synthetic polarization maps made from “observing” simulations of molecular clouds in models we will quantitatively compare theory and observations, strongly constraining both the magnetic field strength, Alfven Mach number, mass-to-flux ratio. Once the magnetization parameters are determined by PICO, we can then compare the magnetization to the efficiency of star formation, measured from near and far-IR observations of protostars with *Herschel*, *Spitzer*, and *JWST*.

PICO’s ability to map thousands of clouds, is not possible with any other current or proposed polarimeter. This large sample size is crucial, because dust polarization observations are sensitive to only the magnetic field projected on the plane of the sky. Polarization maps, and therefore inferred magnetic field morphology will look very different for clouds of with different viewing angles, and also for young clouds versus clouds that have already formed stars that may provide radiative feedback. **Observing a large sample size of clouds will allow PICO to study the role of magnetic fields in star formation as a function age, mass, while accounting for statistically for different viewing angles.**

Dust Physics - Grain Alignment

The association of interstellar polarization with elongated dust grains aligned by the interstellar magnetic field is well established [? ? ? ?]. For a review see [?]. Without a quantitative theory

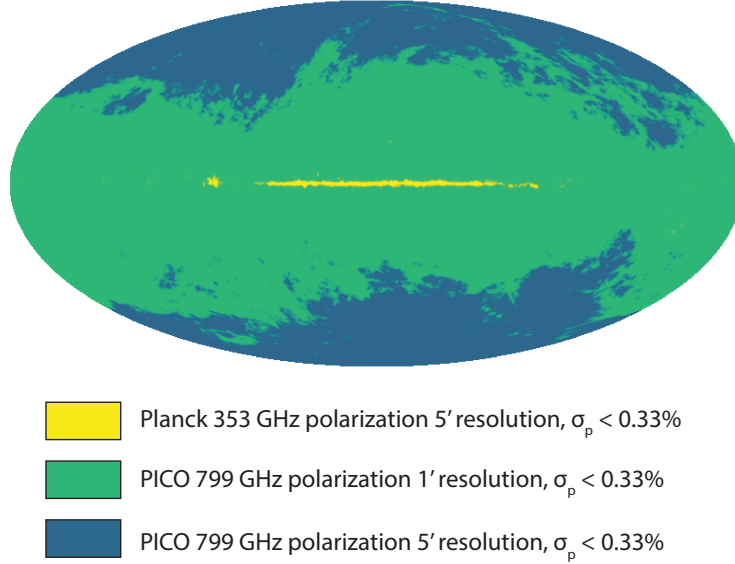


Figure 3: Caption

of grain alignment, it is impossible to properly model the magnetic field in the ISM using interstellar polarization observations. The last decade has been marked by significant advancements in developing the quantitative theory of grain alignment. In particular, the analytical model of grain alignment by radiative torques [?] has been developed with some of its predictions successfully confirmed [? ?]. However, a number of key questions remain unanswered and this hinders the further progress of quantitative interpretation of the rich polarimetric data in relation to magnetic fields in the ISM.

In particular, the efficiency of radiative torque alignment depends on whether the grains have enhanced magnetic susceptibility [? ?] and whether the grain randomization is enhanced by magnetic turbulence [?]. Observational testing of the theoretical predictions, in particular, at the extremes of low and high density lines of sight, can finally provide the community with comprehensive theory of grain alignment. PICO with its high sensitivity and resolution is ideally suited to make these key observations.

Very low density lines of sight through dust near very luminous stars can be used to explore the transition in RAT from alignment with respect to the radiation, to alignment with respect to the magnetic field. This transition depends strongly on the grain magnetic susceptibility. PICO can explore grain alignment near hot stars with a strong UV continuum as well as cool stars, such as red giants and supergiants with much redder continua. These lines of sight will be very difficult to observe from balloon or airborne FIR and sub-mm polarimeters due to the low surface brightness and lack of all sky coverage.

At the other extreme, very high density lines of sight contain dust that is shielded from the interstellar radiation field, and show evidence for loss of grain alignment [?](Jones et al. 2015). PICO will not be able to fully spatially resolve all of these dense, molecular cloud cores, but it will be able to measure fractional polarization and column depth for thousands of cores. The many contributing factors influencing measurements of grain alignment in dense cores, such as the local field direction (as determined by the surrounding position angles), level of turbulence (as seen in the surrounding polarimetry), direction and proximity to luminous infrared sources, presence of an

embedded YSO (which may provide Mid-Infrared flux to align grains), and the type of embedded YSO (luminosity and SED) can be separated statistically with this large sample, an impossible task for ground based observations. These observations will provide a comprehensive assessment of grain alignment in dense molecular clouds. **What measurements are necessary for this? Do we compare directions of polarization with magnetic fields measured in other ways? with radiation field directions? Are there critical complementary observations that we will assume/know we will have?**

Dust Physics - Composition

Spectroscopic features observed in both dust extinction and emission reveal the materials that compose interstellar dust. Strong extinction features at 9.7 and $18\ \mu\text{m}$ indicate much of the dust is in the form of amorphous silicates while features at $2175\ \text{\AA}$, $3.3\ \mu\text{m}$, and $3.4\ \mu\text{m}$ attest to abundant hydrocarbons. It is unknown, however, whether the silicate and carbonaceous materials coexist on the same grains (for instance, in a core-mantle structure) or whether they are segregated into distinct grain populations. If there are indeed multiple grain species, this will induce additional challenges for modeling the emission from interstellar dust in both total intensity and polarization at levels relevant for B-mode science [?].

Polarimetry allows clear discrimination between these scenarios. Spectropolarimetry of dust extinction features have yielded a robust polarization signal in the $9.7\ \mu\text{m}$ silicate feature [e.g., ?], indicating that the silicate grains are aligned with the interstellar magnetic field. In contrast, searches for polarization in the $3.4\ \mu\text{m}$ carbonaceous feature have yielded only upper limits, even along sightlines where silicate polarization is observed [? ?]. These data suggest that the silicate and carbonaceous materials cannot exist on the same grains. However, these studies are limited to only a few highly-extincted sightlines that may not typify the diffuse ISM.

Measuring polarized dust emission with PICO will provide a much more definitive test of these scenarios that extends to the most diffuse sightlines. If multiple dust species are contributing to the total dust emission, it is unlikely that they will all have identical SEDs, and therefore the fractional contribution of each grain type will vary with frequency. Likewise, it is unlikely that every grain type will have an identical intrinsic polarization fraction, and thus the total dust polarization fraction will vary with frequency. In contrast, the polarization fraction from compositionally homogeneous dust will be frequency-independent.

At odds with the spectropolarimetric evidence from dust extinction, current measurements of the polarization fraction of the dust emission with *Planck* [?] and BLASTPol [?] betray little to no frequency dependence across the full PICO frequency range (see Figure). While some models with multiple dust species are ruled out by these data, many models still fall within the current uncertainties. In addition, the current data at $\nu > 353\ \text{GHz}$ are from sightlines with much higher densities than the diffuse ISM, and thus may not be representative.

In addition to silicon and carbon, dust grains are a reservoir for most of the interstellar iron, some of which may be in the form of superparamagnetic inclusions [?]. The enhanced magnetic susceptibility from such inclusions results in the alignment from radiative torques becoming independent of the angle between the magnetic field and the radiation anisotropy [? ?], unlike for ordinary paramagnetic grains for which there is an explicit predicted dependence [?]. Thus, measuring grain alignment in the vicinity of bright stars with PICO, where the radiation direction is well-known, will provide a robust test for the presence of magnetic inclusions. Additionally, the emission from these inclusions will be polarized orthogonally to the electric dipole emission from the grain, lead-

ing to a decline in the polarization angle at low frequencies ($\nu \lesssim 100$ GHz) and possibly a reversal in the polarization direction [?]. Thus, PICO will also place direct constraints on the presence of magnetic inclusions through measurements of the dust polarization fraction.

In summary, PICO will dramatically improve the constraints on the properties of polarized dust emission and provide a definitive test of multi-component grain models, including the presence of magnetic inclusions. These insights will be directly inform modeling efforts in component separation

Meisner and Finkbeiner (2015) have determined a revised 2-component model for the diffuse Galactic thermal dust emission in the far-infrared.

$$I_\nu \propto 8570 \left(\frac{\nu}{\text{GHz}} \right)^{1.63} B_\nu(9.75\text{K}) + 1.49 \left(\frac{\nu}{\text{GHz}} \right)^{2.82} B_\nu(15.7\text{K}) \quad (1)$$

Assuming an independent polarization for each of the components, a simple model for the polarization can be articulated.

$$p = \frac{p_1 \times 8570 \left(\frac{\nu}{\text{GHz}} \right)^{1.63} B_\nu(9.75\text{K}) + p_2 \times 1.49 \left(\frac{\nu}{\text{GHz}} \right)^{2.82} B_\nu(15.7\text{K})}{8570 \left(\frac{\nu}{\text{GHz}} \right)^{1.63} B_\nu(9.75\text{K}) + 1.49 \left(\frac{\nu}{\text{GHz}} \right)^{2.82} B_\nu(15.7\text{K})} \quad (2)$$

Applying the noise estimates from PICO, 1000 simulations were run for each combination of polarization values for the two temperature components. Only frequency channels 107 GHz and above are used, and the simulated data are binned to the 7.9 arcminute beam of PICO's 107 GHz channel. The uncertainties in each of the resulting polarization fractions were estimated from the variance of the simulation results. The resulting uncertainty of the warmer component is expected to be 1.7% and that of the colder component is expected to be 1.3%.

Diffuse Interstellar Medium

The diffuse ISM fills most of the volume of the Milky Way. It is a multi-phase medium, with magnetic fields, cosmic rays, and turbulence in rough energy equipartition [e.g., ?]. As the material that condenses to form molecular clouds, and eventually stars, and the material into which supernovae explode, the diffuse ISM is sculpted by a range of physics over many scales. Despite its importance, a comprehensive understanding of the diffuse ISM is challenging because of its diverse composition, its sheer expanse, and the multi-scale nature of the physics that shapes it. PICO is poised to revolutionize this field. With the unprecedented dynamic range summarized in Figure 3, PICO will drastically expand our ability to study the diffuse ISM both as a function of environment and as a function of physical scale. Here we detail a few of the scientific areas where PICO will answer major open questions.

Diffuse Interstellar Medium - Structure Formation

Recent high-resolution observations of the diffuse ISM have revealed a wealth of complex structure, deeply influenced by the structure of the ambient magnetic field. The structure of the cold neutral medium (CNM) in particular is highly anisotropic, largely organized into filamentary structures that are aligned with the magnetic field [?]. Alignment between linear ISM structures and the magnetic field traced by dust polarization has recently been measured in both neutral hydrogen [? ?] and dust emission [?]. The statistical properties of the density-magnetic field correlations can be described by cross-correlating the dust temperature (T) with the dust polarization field, decomposed into the rotationally invariant E - and B -modes. These measurements were made for the

first time with *Planck*, with several unexpected results. There is a positive TE correlation in the diffuse ISM, as well as a nonunity ratio of E -mode to B -mode polarization ($EE/BB \sim 2$). These correlations are currently thought to be caused by the preferential elongation of density structures along the magnetic field [? ?]. How do these quantities depend on scale and Galactic environment? The sensitivity and dynamic range of PICO will enable us to answer this question, which may in turn constrain properties of interstellar turbulence [e.g., ? ?].

Perhaps even more surprisingly, the final *Planck* data release reported a nonzero TB correlation across a range of scales in the diffuse ISM [?]. Such a correlation implies that the density-polarization correlation is not parity invariant. PICO will make a much higher-fidelity measurement of the TB correlation, and will either confirm or refute the *Planck* detection. PICO will also constrain the EB correlation value across the sky: EB was found to be zero within *Planck* uncertainty, but positive TE and TB correlations imply that at least a weak EB correlation should exist. The origin of the TB correlation is unknown. It has been speculated that the TB correlation could be due to nonzero magnetic helicity, or some other parity-violating MHD property, or that the low-multipole TB correlation may be related to the structure of the local large-scale magnetic field. PICO will test parity violation in the diffuse ISM, constrain models of magnetic helicity, and test models of the local Galactic magnetic field. **Is this an opportunity for a figure showing how much better PICO will do for power spectra? Or maybe the cosmology sections have this covered** Structure formation in the diffuse ISM is a key area of study motivating observations across the electromagnetic spectrum. PICO's observations will complement recently completed high dynamic range neutral hydrogen (HI) surveys, such as HI4PI [?] and GALFA-HI [?], as well as planned surveys of interstellar gas, most prominently with the Square Kilometer Array (SKA) and its pathfinders. One of the open questions in diffuse structure formation is how gas flows within and between phases of the ISM. A planned all-sky absorption line survey with SKA-1 will increase the number of measurements of the ISM gas temperature by several orders of magnitude [?]. Quantitative comparisons of the ISM temperature distribution from SKA-1 and estimates of the magnetic field strength and coherence length scale from PICO will elucidate the role of the magnetic field in ISM phase transitions.

2.3 Legacy Surveys (2 pgs, de Zotti)

Describe science that we get for free.

2.3.1 Point extragalactic sources in the PICO frequency range

As illustrated by the left panel of Fig. 4, at $\lambda \gtrsim$ few mm the dominant extragalactic population are blazars (flat-spectrum radio quasars, FSRQs, and BL Lacs), typically at $z \gtrsim 1$; the solid blue line shows an example. At shorter wavelengths dusty galaxies take over. The brightest sources in this spectral range are nearby star-forming galaxies like M 61. PICO will also see the brightest high- z sub-mm sources which, due to the “magnification bias”, are those whose flux density is boosted by strong gravitational lensing.

Herschel surveys have shown that, at $500 \mu\text{m}$ (600 GHz), about 20% of galaxies at the PICO detection limit are strongly lensed (right panel of Fig. 4). This is an extraordinary selection efficiency: for comparison, the fraction of strongly lensed galaxies is of $\sim 10^{-3}$ in all other frequency bands where searches have been carried out. Also, these galaxies have sub-mm colors substantially different from those of the other extragalactic populations and are therefore very easily singled out

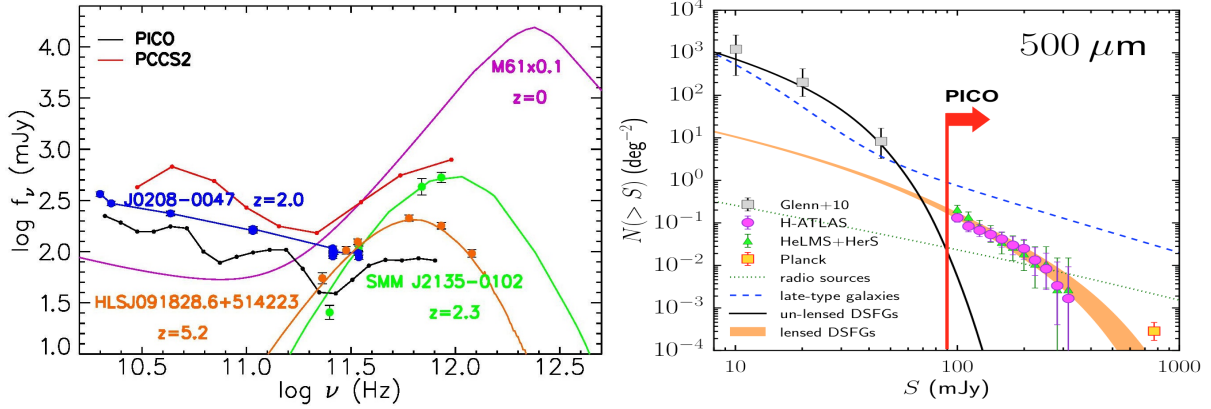


Figure 4: **Left panel.** Examples of SEDs of extragalactic sources detectable by PICO, compared with its point source detection limits (solid black line). The SED of M61 has been scaled down by a factor of 10. The 90% completeness limits of the Second *Planck* Catalogue of Compact Sources (PCCS2; [13]) are also shown. **Right panel.** Integral counts of the various populations of extragalactic sources at $500 \mu\text{m}$ as determined by *Herschel* surveys. The vertical red line shows the estimated PICO detection limit.

[14].

PICO will detect several thousands strongly lensed galaxies. Objects like the $z = 4$ source HLSJ091828.6 + 514223 (left panel of Fig. 4; [15]) would be detectable by PICO up to extreme redshifts ($z > 10$).

The availability of thousands of strongly lensed galaxies opens exciting prospects both on the astrophysical and on the cosmological side (cf., e.g., ref. [16]). Compared to searches in other wavebands, PICO detections will extend to much higher redshift sources [most optically-selected strongly lensed galaxies are at $z < 1$, cf. Fig. 7 of ref. 16] and will pick up the rare most extreme amplifications, thanks to its all sky coverage: the magnification factors, μ , of “*Planck* dusty GEMS” are estimated to be of up to 50 [17].

Sub-mm lensing allows us to probe the most active star-formation phases, hardly visible in the optical. The gravitational flux boosting is accompanied by a stretching of images. Thus follow-up with ALMA can achieve an effective resolution of several milli-arcsec, i.e. can measure galactic structures at $z \simeq 3$ down to the astounding level of $\sim 50 - 60$ pc, much smaller than the sizes of Galactic giant molecular clouds [18]. This provides unique direct information on the mechanisms driving the star-formation and on the shapes, sizes and surface brightnesses of star-formation regions.

The detection of several thousands of galaxies at redshifts $\gtrsim 1$ and up to $z > 5$ allows a substantial progress towards a complete census of the dust-enshrouded star-formation history of the universe, i.e. towards tracking the buildup of stellar mass over cosmic time, in particular over epochs of most intense star formation.

The high redshifts of magnified galaxies imply high redshifts of foreground lenses. Optical follow-up will allow us to investigate the total (visible and dark) mass of the lensing galaxies, their density profiles, dark matter sub-structures in a much higher redshift range than in the case of optical selection [19].

Also PICO will explore essentially the entire Hubble volume for the most intense hyperluminous

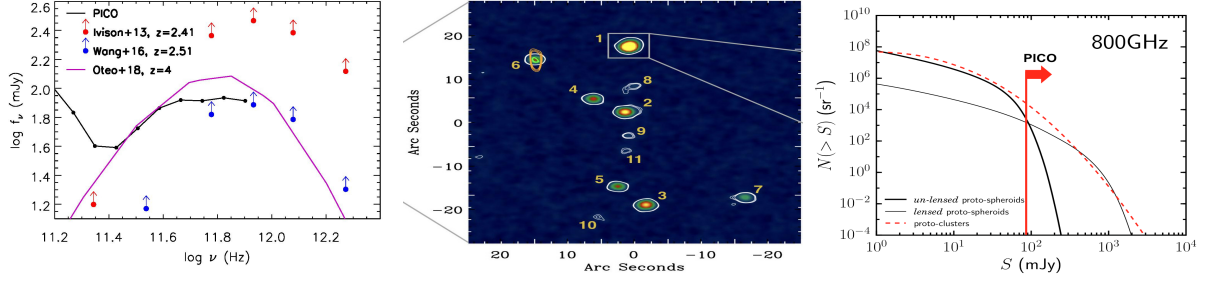


Figure 5: **Left panel.** SEDs of the cores of two proto-clusters of starbursting galaxies discovered by [22] at $z = 2.41$, by [23] at $z = 2.506$ and by [24] at $z = 4.0$. The first two SEDs include only the contributions of proto-cluster members within $10''$, i.e. over an angular size below the PICO resolution, corresponding to physical radii $\simeq 80$ kpc, substantially smaller than the effective proto-cluster sizes. The reported flux densities are therefore lower limits to those that will be measured by PICO. The SED of the $z = 4.0$ proto-cluster correspond to a SFR of $6500 M_\odot \text{ yr}^{-1}$, estimated by [24] summing the contributions of galaxies detected by ALMA within a radius of $\simeq 25''$; again this is likely a lower limit to what PICO will measure. The solid black line shows the PICO detection limits. **Central panel.** ALMA image of the $z = 4.0$ proto-cluster discovered by [24], extracted from Fig. 1 of their paper. **Left panel.** Counts of proto-clusters at 800 GHz predicted by the model of ref. [25]. The vertical red line corresponds to the PICO detection limit.

starbursts, testing whether there are physical limits to the star-formation rates of galaxies.

The right panel of Fig. 4 also shows that PICO will detect tens of thousands star forming galaxies in the nearby universe, reaching a surface density about a factor of two higher than that of the IRAS satellite at its $60 \mu\text{m}$ completeness limit [20]. The IRAS wavebands are relatively insensitive to low temperature dust emission, a significant and largely unexplored component of many nearby galaxies [21]. PICO will provide a full characterization of this component, complementing IRAS data to establish well calibrated dust SEDs as a function of galaxy morphology, luminosity, dust and gas mass, etc..

2.3.2 Early phases of cluster evolution

PICO will open a new window for the investigation of early phases of cluster evolution, when their member galaxies were actively star forming and before the hot IGM was in place. In this phase traditional approaches to cluster detection (X-ray and SZ surveys, searches for galaxy red sequences) work only for the minority of evolved objects; indeed they have yielded only a handful of confirmed proto-clusters at $z \gtrsim 1.5$ [26]¹.

SEDs of spectroscopically confirmed sub-mm-bright proto-clusters detectable by PICO are shown in the left panel of Fig. 5). *Planck* has demonstrated the power of low-resolution surveys for the study of large-scale structure [27] but its resolution was too poor to detect individual proto-clusters [25]. As illustrated by the central panel of Fig. 5, the typical sizes of high- z proto-cluster cores are of $\sim 1'$ (cf. also ref. [28]), nicely matching the PICO FWHM at the highest frequencies.

CMB Probe will detect many tens of thousands of these objects (right-hand panel of Fig. 5) up to $z \gtrsim 4$ (left panel). This will allow a real breakthrough in the observational validation of the forma-

¹More high- z proto-clusters have been found targeting the environment of tracers of very massive halos, such as radio-galaxies, QSOs, sub-mm galaxies. These searches are however obviously biased.

tion history of the most massive dark matter halos, traced by clusters, a crucial test of models for structure formation. Follow-up observations will characterize the properties of member galaxies, probing the galaxy evolution in dense environments and shedding light on the complex physical processes driving it.

2.3.3 Radio sources

PICO will increase by orders of magnitude the number of blazars selected at sub-mm wavelengths and will determine the SEDs of many hundreds of them up to 800 GHz. The most luminous high- z FSRQs were found to host black holes (BHs) with the largest masses, up to $\sim 4 \times 10^{10} M_{\odot}$ (S5 0014+813, at $z = 3.366$; see ref. [29]). Such objects have particularly hard mm-wave spectra; thus PICO surveys are well suited to detect them. Objects like S5 0014 + 813 are detectable by PICO up to $z > 5$.

Blazar searches are the most effective way to sample the most massive BHs at high z because of the Doppler boosting of their flux densities. Since the flux boosting occurs for jets closely aligned with the line of sight ($\theta < 1/\Gamma$, $\Gamma \sim 15$ being the bulk Lorentz factor), for each FSRQ there are other $2\Gamma^2$ (i.e. hundreds) sources of similar intrinsic properties but pointing elsewhere.

Very large BH masses at high- z challenge models because it is very hard to grow a seed BH from stellar mass to $> 10^9 M_{\odot}$ in the limited age of the universe. It is even more so for jetted quasars because jets are likely associated with rapidly spinning BHs whose radiative efficiency is large so that the mass growth is slow. Yet at least 4 FSRQs has been discovered at $z > 5$ (up to $z = 5.48$; [30]). One (SDSS J013127.34032100.1 at $z = 5.18$) has estimated BH mass of $\sim 10^{10} M_{\odot}$ [31].

The PICO surveys of the largely unexplored mm/sub-mm spectral region will also offer the possibility to discover new transient sources [32] or events, such as blazar outbursts.

2.3.4 Source polarization

PICO will make a giant leap forward in the determination of polarization properties of both radio sources and of dusty galaxies over a frequency range where ground based surveys are impractical or impossible. Thanks to its high sensitivity, it will detect in polarization both populations over a substantial flux density range, determining directly, for the first time, number counts in polarized flux density.

Mm/sub-mm polarimetry of radio sources provides unique information on the magnetic field configuration (geometry and degree of order) in the innermost, unresolved regions of the jets, close to the active nucleus. Polarimetry of dusty galaxies as a function of their inclination is informative on the structure and on the ordering of their large-scale magnetic fields.

2.4 Complementarity with Other Surveys and with Sub-Orbital Measurements (1 pg, Lawrence, Schmittfull)

Should describe complementarity with other astrophysics surveys (both space and ground) and with sub-orbital CMB measurements. For the astrophysical surveys, this is summary text of text that is presumably sprinkled elsewhere in the proposal; please cross-reference.

2.4.1 Complementarity with Astrophysical Surveys in the 2020s

For cosmological constraints on the sum of neutrino masses, there is no known way to achieve $\sigma(\sum m_\nu) < 25 \text{ meV}$ without improving measurements of the optical depth τ over *Planck*'s low- ℓ polarization constraint (see the neutrino mass section above). In particular, this applies to all methods that rely on comparing low-redshift structure with the amplitude of the CMB at high redshift, such as galaxy clustering, weak lensing, or cluster counts. (Should add a sentence on ongoing work that attempts to get around τ : still not possible to do better than 25meV even with LSST and CMB-S4.) Improving τ and therefore $\sigma(\sum m_\nu)$ is only possible by improved observations of low- ℓ E modes, which are only possible from space. With its improved τ measurement PICO would therefore directly improve neutrino mass constraints when combined with late-time probes, reaching $\sigma(\sum m_\nu) < 15 \text{ meV}$. PICO therefore complements all efforts that probe the late time structure of the Universe to constrain the sum of neutrino masses, and combining PICO with these low-redshift observations enables more than any cosmological experiment could achieve on its own.

Reconstructing the CMB lensing convergence on very large angular scales, $L_\kappa < 20$, requires exquisitely systematic control over a large sky fraction as well as high angular resolution to perform the lensing reconstruction. A space mission like PICO would provide that, complementing ground-based CMB lensing reconstructions that typically observe smaller sky fraction (or at least have different observation noise in different areas of the sky due to scanning strategy), which makes it difficult to reconstruct lensing on the largest scales. Indeed, PICO could robustly measure the lensing signal with a power spectrum signal-to-noise ratio of more than 100 per mode on very large scales (based on Alex Van Engelen noise plot from PICO meeting; is this still up to date?). Such high-significance CMB lensing measurements on the very largest scales can be useful when combined with measurements of galaxy clustering to search for local primordial non-Gaussianity via its scale-dependent effect on galaxy bias. In an idealized forecast, we find $\sigma(f_{\text{NL}}) \simeq 0.5$ for $L_{\text{min}}^{\kappa\kappa, \kappa g, gg} = 4$, and $\sigma(f_{\text{NL}}) \simeq 0.9$ for $L_{\text{min}}^{\kappa\kappa, \kappa g, gg} = 20$, assuming optimistic LSST galaxy clustering with 60 arcmin^{-2} galaxies and with high-redshift dropout galaxies. This would be a notable improvement over the best current constraint $\sigma(f_{\text{NL}}) = 5$ from *Planck*. Such a measurement would ultimately likely be limited by limitations of LSST on the very largest scales, but space based observations of galaxy clustering with Euclid or SPHEREx could help in this regard.

2.4.2 Complementarity with Sub-Orbital Measurements

Since the first measurements that recognized the existence of the CMB were made in 1964, important observations have been made from the ground, from balloons, and from space. The question for the future is what should the roles be of these three types of experimental approaches? To answer this question, start by considering the advantages and disadvantages of each location (Table ?).

Characteristic	Ground	Balloon	Space
Performance			
Sky coverage	Partial from single site	Partial from single flight	Full. Scan strategy not limited by atmosphere or ground. Large fractions of the sky can be observed nearly simultaneously with the same detectors.
Frequency coverage	Limited to atmospheric “windows”, which get increasingly opaque at higher frequencies. The frequency range where astronomical foregrounds are minimum is inaccessible from the ground, and frequencies above 300 GHz are unusable.	Better than ground. Fore-ground-minimum frequencies still unusable.	Unrestricted
Angular resolution	Telescope cost a function of size, but arcminute resolution possible.	Restricted to small telescopes. Arcminute resolution effectively impossible.	Telescope cost a steep function of size. Arcminute resolution very expensive.
Backgrounds and noise	Hundreds of K loading of detectors from atmosphere and ground, plus direct noise. Individual detector sensitivity reduced substantially, with $250 \mu\text{K s}^{-1/2}$ the practical limit for a single direct detector.	Atmospheric loading much less than from ground, but still greater than from space.	Only CMB, CIB, and Galactic backgrounds. Individual direct-detector sensitivities roughly an order of magnitude better.
Integration time	Limited by Sun, weather.	Severely limited by flight time. To date, tens of days per flight.	Continuous observations for years.
Practicalities			
Accessibility, repairability	Good	None. Multiple flights sometimes possible.	
Mass	Not a big issue	Big issue	Big issue

In every respect affecting performance, space has the advantage, and there can be no argument that space will be required to reach the ultimate limits set by astronomical foregrounds. But the advantages of space come at a high cost, in both time and money, and an essential question is how much can be done from the ground and balloons first? The answer depends on the specific requirements of the science questions being addressed, which we discuss below. However, some general guidelines can be given. When the entire sky is needed, as for fluctuations on the largest angular scales, space is necessary. The difficulties of controlling systematic errors and foregrounds over the whole sky at a level significantly below what has been achieved by Planck are simply too great to overcome on the ground. Progress on the reionization bump ($2 \leq \ell \leq 12$), whether for τ or for r , requires space. Significant progress can surely be made from the ground on the

recombination bump ($30 \leq \ell \leq 300$), and the $r \approx 10^{-3}$ goal of the “ultimate” ground-based experiment CMB-S4 looks to be both bold and achievable. For r , the confusing signal from large-scale-structure lensing of CMB E -modes into B -modes must be measured and removed, and this requires observations on sub-degree scales over a wide frequency range (because of foregrounds) that especially at the lower frequencies is a challenge from space.

The PICO r goal of 10^{-4} is beyond the reach of ground observations. The limited frequency range observable from the ground is not enough to separate foregrounds to the necessary level, and at 10^{-4} there is no room to give up any advantage on systematics. For science requiring higher angular resolution, however, such as observations of galaxy clusters at 1 arcmin resolution, the ground has a clear advantage.

(need more in here)

Balloon observations have been valuable in the past, but the severe limitations on observing time must be recognized. Even the ultra-long-duration balloons that have been on the horizon for more than two decades but have not yet flown for any astrophysics experiment offer only 10^2 days per flight, 5–10% of the duration of the Planck mission (depending on instrument), and 3% of the duration of WMAP. Both WMAP and Planck showed the essential power of repeated observations in identical conditions in revealing and controlling systematics. This will never be possible with balloon experiments. Reaching 10^{-4} will require vigorous exploitation of *every* possible advantage. There is nevertheless still an important role for balloon experiments, in demonstrating new technologies, and in training of students.

2.5 Foregrounds (4 pgs, Jacques and Clem)

Contamination of CMB observations by astrophysical foreground emission of various origins is one of the major challenges that future observations of CMB polarization must face. Polarized emission in the PICO frequency range is known to be dominated by synchrotron emission from the galactic interstellar medium in our own galaxy and by thermal emission from interstellar dust. Although much has been learnt about these polarized foregrounds with WMAP and Planck observations, their exact properties are not known at the level that would be needed to guarantee that they can be separated out from the CMB using known component separation techniques. In particular neither the exact form one should assume for the frequency scaling of their emission (if any), nor the variation of these emission laws across the sky or along the line of sight, nor the small-scale distribution of emission, are known at the required level of detail. Whether other processes emit at a level that can contaminate PICO observations significantly is also not known at present.

The many frequency channels of PICO can be used to learn from the PICO observations themselves the properties of these foregrounds, and to identify the CMB contribution in the multifrequency data using its unique spectral signature. To be robust against our uncertainty about the foregrounds, we assess the feasibility of foreground cleaning for different models of foreground emission of varying complexity, from optimistic to pessimistic, and for various component separation methods.

2.5.1 PSM sky simulations at $N_{\text{side}} = 16$

The PSM (Planck Sky Model) [33] is a simulation software developed by the *Planck* Collaboration to model sky emissions at submillimetre to centimetre wavelengths based on the state-of-the-art observations of the *Planck* satellite mission and earlier surveys. We use the PSM to simulate all-sky polarization maps at the 21 frequency bands of *PICO* (21 to 800 GHz). The simulated

components of emission include CMB E- and B-mode polarization, polarized Galactic synchrotron and thermal dust foreground emissions. The CMB template map is generated from CAMB [34] through CMB E- and B-mode power spectra by assuming an optical depth to reionization of $\tau = 0.06$ and a tensor-to-scalar ratio of $r = 10^{-3}$, as well as gravitational lensing effects. Galactic dust Q and U polarization maps are generated from the *Planck* GNILC dust intensity all-sky map at 353 GHz, in which cosmic infrared background (CIB), CMB, and noise have been filtered out, and assuming average polarization fractions of 5-10%. Galactic synchrotron Q and U maps are based on the *WMAP* polarization observations at 23 GHz [35].

The thermal dust Q and U template maps are extrapolated across *PICO* frequencies through a modified blackbody energy spectrum having variable spectral index and temperature over the sky, using the *Planck* GNILC dust spectral index and temperature maps for which $\beta_d = 1.6 \pm 0.1$ and $T_d = 19.4 \pm 1.3$ K, respectively. The synchrotron Q and U template maps are extrapolated across *PICO* frequencies through a curved power-law spectrum, with a variable spectral index over the sky of $\beta_s = -3 \pm 0.06$ based on the synchrotron index map from [35], and a constant curvature of $C_s = 0.3$ [36] to account for different populations of cosmic ray electrons and possible AME polarization [37]. The CMB, dust, and synchrotron component maps in each *PICO* frequency are then co-added, and instrumental white noise is added to each sky map using the sensitivities per frequency quoted by *PICO*. The PSM simulations are generated at a pixel resolution of HEALPix [38] $N_{\text{side}} = 16$ ($2 \leq \ell \leq 47$), therefore assuming spectral variations of the foregrounds across $N_{\text{side}} = 16$ pixels.

2.5.2 *PICO* forecasts with COMMANDER

We have applied the COMMANDER algorithm [39] to the set of PSM $N_{\text{side}} = 16$ sky simulations for *PICO*. COMMANDER is a Bayesian parametric fitting method which has been thoroughly used by the *Planck* Collaboration for the separation of CMB and foreground components [40, 41]. Using MCMC Gibbs sampling in each pixel, the COMMANDER algorithm allows to fit simultaneously the amplitudes of CMB and foreground components, their spectral parameters, and the CMB E- and B-mode power spectra in a self-consistent Bayesian framework. A Blackwell-Rao estimator applied to the Gibbs samples allows in particular to reconstruct the statistical (chi-square) distribution of the CMB B-mode power spectrum at each multipole, and the posterior distribution of the tensor-to-scalar ratio [42, 43]. Such a Bayesian method performs end-to-end propagation of all foreground uncertainties towards the tensor-to-scalar ratio, while providing a chi-square goodness-of-fit in each pixel which allows to revise the parametric model or readjust the galactic mask a posteriori. The *PICO* sky maps are processed by COMMANDER using a Galactic mask leaving a 50% fraction of the sky, and forecasts on r are computed using the range of low multipoles $2 \leq \ell \leq 47$.

First considering *PICO* sky simulations *without foregrounds*, but just CMB and noise in the *PICO* frequency bands, we recover the tensor-to-scalar ratio with $\sigma(r = 10^{-3}) = 0.40 \times 10^{-3}$ significance: this provides the minimum uncertainty on $r = 10^{-3}$ that can be achieved by *PICO* from low multipoles $2 \leq \ell \leq 47$ in the absence of foregrounds on 50% of the sky. In the presence of foregrounds (full simulation), with variable spectral indices over the sky, the COMMANDER results on r are of similar quality due to the broad frequency range of *PICO* (21 -800 GHz), with $\sigma(r = 10^{-3}) = 0.41 \times 10^{-3}$ for *PICO*v2-1.4 and $\sigma(r = 10^{-3}) = 0.36 \times 10^{-3}$ for *PICO*v3 (increased sensitivities per channel) after foreground cleaning. Assuming now that 60% delensing in power has been achieved (modified PSM simulation with only 40% of the lensing B-mode power left in the CMB map realisation), the uncertainty on $r = 10^{-3}$ is improved by more than 30%, with

$\sigma(r = 10^{-3}) = 0.24 \times 10^{-3}$ for *PICO*v3 after foreground cleaning and 60% delensing. Finally, we note that discarding low- and high-frequency bands, resulting in a descoped version of *PICO* with a narrower frequency range of 43-462 GHz, the COMMANDER results are degraded by 75%, with an uncertainty increasing from $\sigma(r = 10^{-3}) = 0.4 \times 10^{-3}$ to $\sigma(r = 10^{-3}) = 0.7 \times 10^{-3}$ after foreground cleaning. The main reason for the degradation is a lack of constraining power on the dust temperature variations over the sky when discarding frequencies above 462 GHz, which translates into a degradation of the fitted CMB B-mode power spectrum by extrapolation towards central frequencies.

[MR: I can add a figure on COMMANDER C_ℓ^{BB} results with *PICO*, if needed]

We are working in parallel on COMMANDER2, a new version of the algorithm operating in harmonic space, thus allowing to perform the parametric fit at full resolution and to further reduce the uncertainty on r by the increase of information / modes.

2.6 Systematic Errors (3 pgs, Crill)

Aside from control of foregrounds, the most compelling reason to observe the CMB from space is the opportunity for excellent control of systematic errors that affect CMB measurements from any platform. The L2 environment offers excellent stability as well as the ability to observe large fractions of the sky on many time scales without interference from the Sun, Earth, or Moon. The redundancy of observations allows the checking of consistency of results and an improved ability to calibrate and to correct systematic errors in post-processing analysis.

As of today, there is a clear path to demonstrate that state-of-the-art technology and data processing can take advantage of the L2 environment and control systematic errors to a level that enables the science goals of *PICO*.

A rich literature investigates the types of systematic errors due to the environment, the instrumentation, observation strategies, and data analysis that confound the polarization measurement by creating a bias or an increased variance[44, 45, 46]. Every measurement to date has reached a systematic error limit, and have advanced many sophisticated techniques to mitigate systematics, finding both new technological solutions and new analysis techniques. As an example, the BICEP's systematics limited it to $r=0.1$ [?] while through additional effort within the program, BICEP2 achieved a systematics limit of $r=6 \times 10^{-3}$ [47]). In the near term, the ground based and suborbital CMB community will continue to develop new techniques in handling systematics, particularly in developing the CMB-S4 project.

All prior on-orbit measurements of CMB polarization were limited by systematic errors until an in-depth study of the systematics was performed and the post-processing data analysis suppressed them[10, 48, 49]. Particularly we note Fig. 3 of the Planck legacy paper which indicates Planck's systematic error limits on the polarization power spectral measurements. Recently studied space missions, such as EPIC-IM, LiteBird and *CORE*, have placed systematic error mitigation at the forefront of the case for their mission and have developed tools and strategies for estimating and mitigating these[50, 51, 52].

End-to-end simulation of the experiment is an essential tool, including realistic instabilities and non-idealities of the spacecraft, telescope, instrument and folding in data post-processing techniques used to mitigate the effects. Systematics are coupled with the spacecraft scan strategy, and the details of the data analysis pipeline.

2.6.1 List of Systematics

The systematic errors faced by PICO can be categorized into three broad categories: 1) Intensity-to-polarization leakage, 2) stability, and 3) straylight and are listed in Table 1. These were prioritized for further study using a risk factor assessed by the working group. The risk factor incorporates the working group's assessment of how mission-limiting the effect is, how well these effects are understood by the community and whether mitigation techniques exist.

The working group's three highest risk systematic errors were studied further and are discussed in subsections below. The PICO team used simulation and analysis tools developed for Planck[53] and *CORE*, adapting them for PICO.

We note that many of the systematics could be mitigated further through the use of polarization modulation such as a half-wave plate or a variable phase delay modulator. For the purposes of the cost constraints of PICO, we investigated mitigation techniques that do not require a modulator.

2.6.2 Absolute polarization angle calibration

The rotation of the CMB polarization can have different causes, including 1. a birefringent primordial Universe, or a Faraday rotation due a primordial magnetic field [57], 2. birefringent foregrounds, or interaction with the Galactic magnetic field, 3. systematic effects in the instrument, and in particular an error on the actual direction of polarization measured by each detector. While the first two sources create a rotation that may depend on scale, position and/or frequency, the latter depends mainly on the detector considered.

A rotation α of the direction of polarization mixes the Q and U Stokes parameters via $Q \pm iU \rightarrow e^{\mp i2\alpha}(Q \pm iU)$ and thus mixes the the power spectra and their correlations as illustrated in Fig. 6.

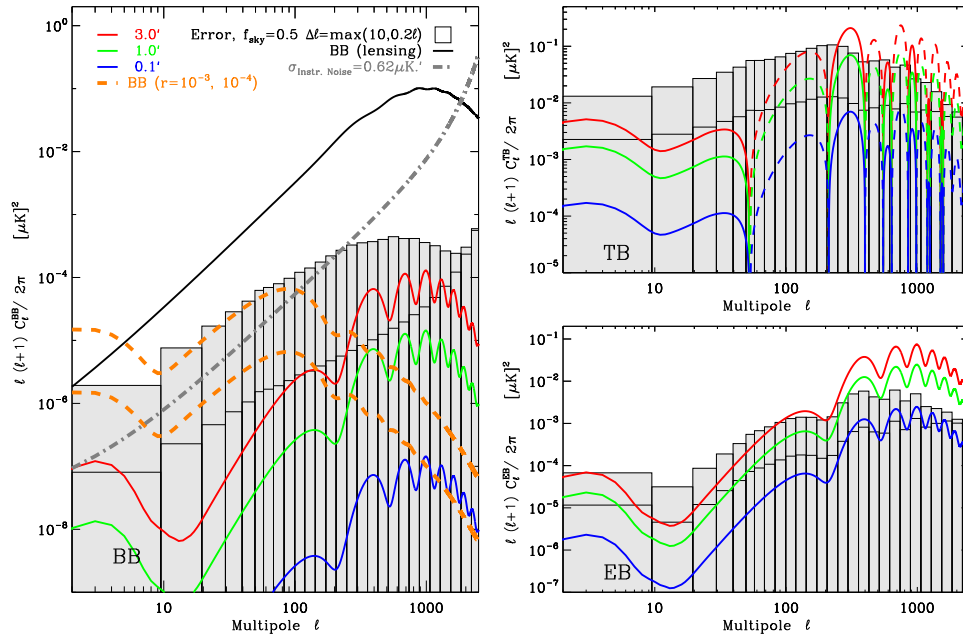


Figure 6: Effect of a rotation of the angle of polarization, assuming the Planck 2018 Λ -CDM best fit model [58] with $\tau = 0.054$ and expected PICO noise performance, assuming perfect delensing.

In Planck, the ground measurements of the detectors orientation had an error of $\pm 0.9^\circ$ (rel.) $\pm 0.3^\circ$

Name	Risk	Description	State-of-the-art	Additional Mitigation Needed
Leakage				
Polarization Angle Calibration.....	5	Uncertainty in polarization calibration leaks $E \rightarrow B$.	Knowledge of astrophysical calibrators to 0.3° (author?) [54]; ground measurement to 0.9° reconstruction to 0.2° using TB and EB demonstrated by <i>Planck</i> ?	See Sect. 2.6.2 for discussion.
Bandpass Mismatch.....	4	Edges and shapes of the the spectral filters vary from detector to detector. leaks $T \rightarrow P$, $P \rightarrow P$ if the source's bandpass differs from calibrator's bandpass?	Precise bandpass measurement[?]; SROll algorithm[?]; filtering technique[?]; additional component solution (see Banerji& Delabrouille in prep).	State-of-the-art meet requirements.
Beam mismatch.....	4	Beam shapes differ between detectors that are combined to reconstruct polarization; leaks $T \rightarrow P$, $P \rightarrow P$	See Sect. 2.6.2	State-of-the-art meet requirements.
Time Response Accuracy and Stability.....	4	Uncertainty of detector in time constants (measurement errors, time variability) biases polarization angle, pointing and beam size. In a constant spin-rate mission (PICO) is degenerate with the beam shape. leaks $T \rightarrow P$, $P \rightarrow P$	On-orbit reconstruction of time response to 0.1% across a wide signal band[55], residuals corrected as part of beam and map-making algorithm[?].	State-of-the-art meet requirements.
Readout Cross-talk.....	4	Power in one detector leaks into other detectors	<i>Planck</i> 's high-impedance bolometers with crosstalk measured at the level of 10^{-3} did not impact CMB polarization science[?]. Cross-talk low-impedance bolometers measured at XXX.	State-of-the-art meets requirements.
Chromatic beam shape.....	4	Beam shape is a function of source SED: measured using a planet, used to build a window function to correct CMB power spectrum.	<i>Planck</i> simulations and parameterization as part of the likelihood.	Should be further investigated in Phase A of a mission using physical optics simulations.
Gain mismatch.....	3	Relative gain between detectors that are combined to reconstruct polarization; error leaks $T \rightarrow P$	mission-average relative calibration demonstrated to 10^{-4} to 10^{-5} level [?]	State-of-the-art measurement of mission-average gain meets requirements; Sect. 2.6.3 describes effects of stability in time in relative gains.
Cross-polarization.....	3	$Q \rightarrow U$ rotation by the optical elements of the instrument.	Degenerate with polarization gain calibration.	State-of-the-art meets requirements.
Stability				
Gain Stability.....	5	Time-variation of detector gain due to time variability of detector heat sink temperature variations and optical loading.	Reconstruction of time variability of gain to 0.2% in <i>Planck</i> [?].	See Sect. 2.6.3; Gain fluctuations in PICO on the level of XXX% on time scales of YYY can be corrected in post-processing.
Pointing jitter.....	3	Random pointing error mixes T, E and B at small angular scale	Pointing reconstruction in <i>Planck</i> to XXX arcsec.	State-of-the-art meets requirements.
Straylight				
Far Sidelobes.....	5	Pickup of Galactic signals at large angles from the main beam axis; Spillover can be highly polarized.	<i>Planck</i> validated straylight model in anechoic chamber to -80 dBi[56].	Design of optical system and baffling, informed by telescope straylight simulations. See Sect. 2.6.4 for a study of beams calculated with a physical optics code for the PICO telescope and simulated Galactic pickup during the reference mission.
Other				
Residual correlated cosmic ray hits.....	3	detectors experience correlated cosmic ray hits below detection threshold resulting in misestimated noise covariance.	<i>Planck</i> /HFI found the 5% percent noise correlation due to this effect did not impact results[?].	State-of-the-art detector design to reduce cosmic ray cross-section; State-of-the-art analysis techniques (accounting for correlated noise) meet requirements.

Table 1: Systematic errors expected in PICO's measurement of CMB polarization. The risk level was scored from 1 to 5 based on the study team's assessment. Those systematic errors found to be most likely to impact PICO are described further in the text.

(abs.) [59].

The most recent constraints on cosmological birefringence (or systematic rotation) was set in (author?) [60], looking for residual signal in TB and EB spectra, but are dominated by the uncer-

tainties on the detector orientations.

For PICO, the relative rotation of the detectors, could be measured with a good accuracy (a few $0.1'$?, [†\[refs?\]](#)) on the CMB, but the overall rotation is difficult to determine. Known polarized sources, such as the Crab Nebula, could be used to do that but [\(author?\)](#) [54] show that the current uncertainty of $0.33^\circ = 20'$ on the Crab polarization orientation, obtained when combining all the available measurements, would not the measurement of tensorial B modes below $r \sim 0.01$ (assuming everything else to be nominal), far from PICO's target.

In the absence of other systematics and foregrounds, an unaccounted polarization rotation α of $10'$ increases the error bar of r by 30%, while EB , TB and BB spectra can measure a rotation α at 3σ when $\alpha \sim 0.07, 0.2$ and $0.9'$ respectively on perfectly delensed maps, and $0.25, 0.9$ and $4.5'$ on raw maps.

In principle, the technique of using the TB and EB spectra can detect and measure a global polarization rotation error at levels ($0.1'$) well below those affecting r measurements in BB ($> 1'$). However, a future mission should include additional aspects of the measurements of CMB polarization, such as delensing, the interaction with foregrounds, and $1/f$ noise in simulating and assessing the impact of an angle calibration error.

2.6.3 Gain Stability

Photometric calibration is the process of converting the raw output of the receivers into a physically-meaningful quantity, such as thermodynamic temperature or brightness. As CMB receivers are usually linear, this process reduces to the characterization of the *gain factor* G :

$$y(t) = G(t) \times T(\vec{x}(t)) + n(t), \quad (3)$$

where $y(t)$ is the timestream of raw samples produced by the detector, $G(t)$ is the gain factor (which we allow to vary with time), T is the sky temperature observed along direction $\vec{x}(t)$ (which varies with time as the spacecraft spins), and $n(t)$ is a noise term that includes both uncorrelated and correlated noise. It is assumed that the timescale of variation in G (G/\dot{G}) is much longer than the typical timescale of variations in T : in the case of Planck, this was of the order of several days. In the case of space CMB experiments, the characterization of $G(t)$ is commonly done using the signal caused by the motion of the spacecraft with respect to the rest frame of the CMB itself. This signal is commonly called the *dipole*, as its most significant contribute is at multipole $\ell = 1$. For the PICO concept study, we evaluated the impact of noise in the estimation of $G(t)$ using the tools developed for the Planck/LFI instrument and the CORE mission proposal. The quality of the estimate depends on the noise level of the receiver, but also on the details of the scanning strategy. The Planck/LFI experiment, because of a poor choice of the scanning strategy parameters (namely, a too slow precession motion), was forced to avoid using one year out of four in the 2015 data release [REF]. We can anticipate that this problem is not expected in PICO, thanks to the significantly faster precession envisaged.

In order to test the impact of calibration uncertainties, we have run the following analysis:

1. We simulated the observation of the sky, assuming four receivers and the nominal scanning strategy. We included both white noise and $1/f$ noise. The sky only contained CMB anisotropies, plus the CMB dipole.
2. We ran the calibration code to fit the dipole against the raw data simulated during step 1.

3. We simulated again the observation of the sky, but this time we used the values of G computed during step 2, which contain errors due to the presence of $n(t)$ and the CMB signal in Eq. (3). The noise in the output map is therefore the sum of the noise in the error on G and the term n .

The presence of foregrounds in the sky signal would cause a bias in the estimation of the calibration constants, due to the presence of large scale features in the Milky Way at microwave frequencies. A full data analysis pipeline for PICO should pair the calibration step with the component separation step, following a schema similar to what has been done by the Planck/LFI team for the 2018 data release [CITATION]: the application of the calibration code should be followed by a component separation analysis, and these two steps should be iterated until the result converge to a solution. In this analysis we assume to study the calibration at the last iteration, when the components have already been properly separated.

Results of the simulation are shown in Figures XXX and YYY. The scanning strategy employed by PICO allows for a much better calibration than in the case of Planck's, thanks to the much faster precession.

2.6.4 Far Sidelobe Pickup

The main beam (within a few degrees of the axis of beam response) in a CMB mission can be measured to high precision using the planets as compact sources. Measurement of each detector's response to signals more than a few degrees off axis, which tends to be at a very low level (more than -80dB less than the peak response) but spread over a very large solid angle, is difficult to do pre-launch, and may not be done accurately after launch. Nonetheless, this far sidelobe can couple bright Galactic signal from many tens of degrees off-axis and confuse it with polarized signal from the CMB off the Galactic plane.

To evaluate this systematic error, GRASP software² was used to compute the PICO telescope's pickup over the full sky. This full-sky beam was convolved with a polarized Galactic signal and a full PICO mission scan using the simulation pipeline. The far sidelobe pickup was estimated to contribute less than XXX to the B-mode angular power spectrum and thus an error in r of YYY. In a real mission due to the difficulties of measuring this beam, physical optics simulation capabilities must be maintained and validated as well as possible with on-orbit data.

2.6.5 Key Findings

Properly modeling, engineering for, and controlling the effects of systematic errors in a next-generation CMB probe is critical. In particular we note:

- The raw sensitivity of the instrument should include enough margin that data subsets can independently achieve the science goals. This allows testing of the results in the data analysis and additional data cuts, if needed.
- NASA's support of ground-based and suborbital CMB missions will mitigate risk to a future space mission as PICO by continuing to develop analysis techniques and technology for mitigation of systematic errors.

²<https://www.ticra.com>

- In a PICO mission’s phase A, a complete end-to-end system-level simulation software facility would be developed to assist the team in setting requirements and conducting trades between subsystem requirements while realistically accounting for post-processing mitigation. Any future CMB mission is likely to have similar orbit and scan characteristics to those of PICO, thus there is an opportunity for NASA and the CMB community to invest in further development of this capability now.

2.7 Measurement Requirements (2 pgs, Hanany & Trangsud)

The combination of PICO’s diverse science goals are achievable using a single instrument that executes one, continuous, simple observing pattern of the entire sky. This pattern integrates noise down to unprecedented levels, and provides for multiple checks of possible systematic errors in the data analysis.

• **Depth** We quantify survey depth in terms of the RMS fluctuations that would give a signal-to-noise ratio of 1 on a sky pixel that is 1 arcminute on a side. Depth in any frequency band is determined by detector sensitivity, the number of detectors in the focal plane, the sky area covered, and the duration of the mission. The science objective driving the depth requirement is SO1, the search for the IGW signal which requires a depth of $0.87 \mu\text{K} \cdot \text{arcmin}$. This requirement is a combination of the low-level of the signal, the need to separate the various signals detected in each band, and the need to detect and subtract systematic effects to the required levels. • **Sky Coverage** There are several science goals driving a full sky survey for PICO. The term ‘full sky’ refers to the entire area of sky available after separating other astrophysical sources of confusion. In practice this implies an area of 50-70% of the full sky for probing non-Galactic signals, and the rest of the sky for achieving the Galactic science goals.

(1) Probing the optical depth to the epoch of reionization (STM SO5) requires full sky coverage as the signal peaks in the EE power spectrum on angular scales of 20 to 90 degrees. Measuring this optical depth to limits imposed by the statics of the small number of available ℓ modes is crucial for minimizing the error on the neutrino mass measurement.

(2) If $r \neq 0$, the BB power spectrum due to IGW (STM SO1) also has a local maximum in the same range of angular scales (20 to 90 degrees). For $r \gtrsim 0.001$ (CHECK) this local maximum is at a higher level than the BB lensing spectrum, making this range of scales appealing to survey, as there is no need to separate the signatures of two cosmological signals.

(3) The PICO constraint on N_{eff} (STM SO4) requires a determination of the EE power spectrum to limits imposed by the statics of available ℓ modes. Full sky coverage is required to achieve this limit. (4) PICO’s survey of the Galactic plane and regions outside of it is essential to achieving its Galactic structure and star formation science goals (SO6, 7, 8).

• **Frequency Bands** The multitude of astrophysical signals that PICO will characterize determine the frequency range and number of sub-bands that PICO uses. The IGW signal peaks in the frequency range between 30 and 300 GHz. However, Galactic signals, which are themselves signals PICO strives to characterize, are a source of confusion for the IGW. The Galactic signals and the IGW are separable using their spectral signature. Simulations indicate that 21 bands, each with $\sim 25\%$ bandwidth, that are spread across the range of 20 - 800 GHz can achieve the separation at the level of fidelity required by PICO.

Characterizing the Galactic signals, specifically the make up of Galactic dust (SO7), requires spectral characterization of galactic dust in frequencies between 100 and 800 GHz. [Aren’t there synchrotron questions that are answerable with spectral information?](#)

• **Resolution** Several science objectives require an aperture of 1.5 m and the resolution listed in Table ???. To reach $\sigma(r) = ??$ we will need to 'delens' the E- and B-mode maps that PICO will generate; see Section ??. Delensing is enabled with a map that has a native resolution of 2-3 arcminutes at frequencies between 100 and 300 GHz. Similar resolution is required to achieve the constraints on the number of light relics (SO??), which will be extracted from the EE power spectrum at multipoles $100 \lesssim \ell \lesssim 2500$. The process of delensing may be affected by other signals, primarily the signal due to Galactic dust. It is thus required to map Galactic dust to at least the same resolution as at 300 GHz. Higher resolution is mandated by science objectives 6,7, and 8, which require resolution of 1 arcminute at 800 GHz. We have thus chosen to implement diffracted limited resolution between 20 and 800 GHz.

3 Instrument (6 pgs, Hanany & Trangsud)

Telescope (Hanany / Young), focal plane (Hanany / Young), cooling (Trangsud), readout (O'Brient)
Review: Bock, Hubmayr, Suzuki,

4 Mission (5 pgs, Trangsud)

To be included: mission architecture, spacecraft and subsystems, orbit, attitude control and determination (Trangsud)

5 Technology Maturation (4 pgs, O'Brient & Trangsud)

Requirements, planned activities, schedules and milestones, estimated cost (O'Brient?)
For each technology include:

- Requirements
- Planned activities
- Schedule and Milestones
- Estimated Cost

6 Management, Risk, Heritage, and Cost (4 pgs, Trangsud)

cost, risk, heritage (Trangsud)

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