1 Executive Summary

The cosmic microwave background (CMB) comes to us from the furthest reaches of the observable Universe, and its photons experience all of cosmic history. Created when the Universe was a hotter, simpler place, CMB photons probe fundamental physics, provide exquisite measurements of the constituents of the cosmos, and tests of relativity. On their journey they feel the impact of the gravitational potentials formed from the assembling cosmic web of superclusters, clusters and galaxies. They interact with the ionized gas in the inter- and circum-galactic medium, gas that eventually fuels star and galaxy formation. Superposed upon the CMB is the emission from multiple extragalactic sources and from our Galaxy. All of this leaves an imprint which sensitive measurements can disentangle so that CMB studies impact every aspect of cosmology and many of astrophysics.

Building upon a long legacy of successful measurements, the next decade holds tremendous potential for new, exciting CMB discoveries. Such discoveries, delivered by the Probe of Inflation and Cosmic Origins (PICO, Fig. 1.1), promise to be revolutionary, affecting physics, astrophysics, and cosmology. PICO is an imaging polarimeter that will scan the sky for 5 years with 21 frequency bands spread between 21 and 799 GHz; see Table 2.1. It will produce 10 independent full sky surveys of intensity and polarization with a final combined-map noise level equivalent to 3250 *Planck* missions for the baseline required specifications, though in our current best-estimate (CBE) it would perform as 6400 *Planck* missions.

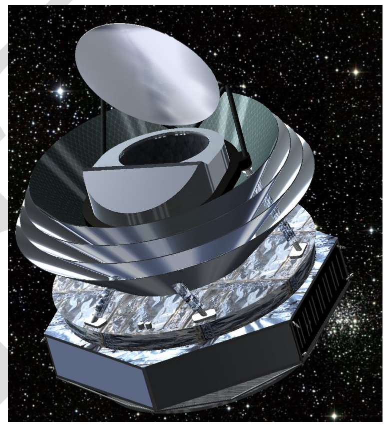

Figure 1.1: The PICO spacecraft

With these capabilities, unmatched by any other existing or proposed platform, PICO will have compelling and broad science deliverables. The mission will respond to seven science objectives (SOs), which are listed in Table 2.2. Delivering this set was the basis for selecting PICO's design and for setting instrument requirements. But PICO's science reach is broader than the baseline set.

PICO could determine the energy scale of inflation and give a first, direct probe of quantum gravity; this is SO1 (§ 2.2). The mission will attempt to detect the signal, which arises from gravitational waves sourced by inflation and parametrized by the tensor to scalar ratio r, at a level of $r = 5 \times 10^{-4}\,(5\sigma)$. This level is 100 times lower than current upper limits, and 10 tens lower than limits forecast by funded foreseeable experiments. If the signal is not detected, PICO will constrain broad classes of inflationary models and exclude at 10σ models for which the characteristic scale in the potential is the Planck scale (SO1 and SO2). The combination of data from PICO and LSST can constrain features in the inflationary potential, the field content during inflation and could rule out all models of slow-roll single-field inflation, marking a watershed in studies of inflation.

The mission will have a deep impact on particle physics by measuring the expected sum of the neutrino masses with 4σ confidence, rising to 7σ if the sum is near 0.1 eV (SO3). Reaching the 4σ level can only be done with an instrument that can measure the polarization of the CMB on the largest angular scales, a measurement optimally done from space, which gives access to the full sky and with a broad band of frequencies to remove foreground contaminants. Cluster counts provided by PICO in combination with followup red-shift measurements, and PICO's map of the projected gravitational potentials along the line of site in combination with LSST gold sample of galaxies, will give two additional independent and equally competitive constraints on the sum of neutrino masses.

The measurements will either detect or strongly constrain deviations from the standard model of particle physics by counting the number of light particle species N_{eff} in the early universe. The constraint of $\Delta N_{eff} < 0.06\,(2\sigma)$ will move the allowed decoupling temperature of a hypothetical new vector particle to temperatures that are 400 times higher than currently determined by *Planck* (SO4). The data will enable a search for the existence of primordial magnetic fields with sufficient sensitivity to rule them out as the sole source for the largest observed galactic magnetic fields; they will improve by $\sim$300 constraints on polarization rotation arising from early universe fields that lead to cosmic birefringence, and will thus constrain string theory-motivated axions; and they will constrain generic models of dark matter candidates.

PICO will elucidate the processes affecting the evolution of cosmic structures. It will measure the optical depth to reionization τ with an error $\sigma(\tau) = 0.002$ limited only by the statistics of the small number of modes available to observe the largest angular scale CMB polarization (SO5). The measurement will be used to constrain models of the formation of the first luminous sources, and is a key input to all astrophysical attempts to improve the determination of the sum of neutrino masses. The data will give a map of the projected gravitational potential due to all structures with a signal-to-noise ratio (SNR) 14 times higher than *Planck*, and a catalog of 150,000 clusters extending to their earliest formation redshfit. Each of these datasets will be used in combination with other data – from LSST and from future optical and infrared surveys - to independently constrain the evolution of the amplitude of linear fluctuations $\sigma_8(z)$, with sub-percent accuracy.

Cross-correlating PICO's map of the thermal Sunyaev–Zel′dovich effect with LSST's gold sample of galaxies, a correlation that is forecast to have an SNR exceeding 1000, will give precise tracing of the evolution of thermal pressure with z. These will be used to place constraints on models of energetic feedback, which are the most uncertain ingredient in models of galaxy formation.

PICO's maps of the Milky Way will be used to resolve long-standing questions about our own Galaxy. Galactic interstellar dust grains are a link between atoms and molecules and planetary objects, yet their composition and their role in Galactic chemistry is still under debate. Galactic magnetic fields are known to play a key role in the dynamics of gas in the Galaxy, and in determining the efficiency of star formation, but their quantitative contribution relative to turbulence is yet to be determined. With the mission's Galactic dust polarization maps we will constrain dust properties, including composition, temperature, and emissivities (SO6). The derived, detailed $1'$ resolution maps of magnetic field will be used to quantify the relative roles of turbulence and magnetic fields in the dynamics of the Galaxy and in the observed low star formation efficiency (SO7).

PICO will give 21 full-sky maps of intensity and polarization, each much deeper compared to *Planck*'s seven; five will have polarization information in frequencies between 385 and 800 GHz that *Planck* did not have. At 385 GHz PICO's noise is 100 times lower than *Planck*'s at 353 GHz. And PICO's highest resolution is five times finer than *Planck*'s. Only PICO will provide such full sky legacy maps. Six are at frequencies not accessible to ground-based experiments, with which we will: constrain the early phases of galaxy evolution by discovering 4500 strongly lensed dusty galaxies with z up to 5; investigate the early phases of cluster evolution by discovering 50,000 proto-clusters out to $z \sim 4.5$; give census of cold dust in 30,000 low z galaxies; give cosmic infrared background maps of the anisotropies due to dusty star-forming galaxies; map magnetic fields in 70 nearby galaxies; and, with 3,000-fold increase relative to *Planck* in the number of independent measurements of magnetic field in our own Galaxy, study how magnetic fields are generated through a combination of turbulence and large scale gas motion.

With its broad frequency coverage PICO is better equipped than any other current or foreseeable instrument to separate the detected signals to their original sources of emission. This capability is most important for the faintest of signals, the telltale of inflation, which is already known to be dominated by Galactic foregrounds. Our simulations indicate that PICOs combination of low noise and multitude of bands is sufficient to separate the inflationary signal from the foregrounds at the required level. But current uncertainties on the parameters characterizing Galactic foregrounds are large and we recommend support for (1) modeling, simulation, and algorithm development for effective foreground separation, and (2) improved Galactic emission measurements with sub-orbital experiments.

Similar to its successful predecessors, WMAP and *Planck*, PICO will conduct observations from L2, a location that ensures stable thermal environment. It will execute 10 redundant, full-sky surveys, each complete within 6 months. The sky scan pattern, which is optimized for control of polarimetric systematic uncertainties, ensures that the measured I, Q, and U Stokes parameters can be reconstructed by each of the 12,996 polarization sensitive detectors. The combination of large multiplicity of independent maps, sky surveys, and stable environment will give control of systematic uncertainties unmatched by any other platform. We recommend support for more detailed studies of systematic effects, specifically through end-to-end simulations.

The mission has a single instrument that surveys the sky with the same repeated pattern. The telescope is a 1.4 m entrance-aperture, two-reflector system, with ambient temperature primary, and 4.5 K actively cooled aperture-stop and secondary. The 0.1 K cooled focal plane is based on 3-color pixels coupling the incident radiation to transition edge sensor bolometers that are read out using a time-domain multiplexed system. All of these technologies are either already in use by sub-orbital experiments, or are simple extensions to higher or lower frequency bands. We recommend continued support for technology development and maturation in the laboratory and by sub-orbital experiments.

The science PICO will deliver is compelling, timely, and broad. There is long heritage of successful space and sub-orbital measurements, and technologies are mature. PICO is the only instrument with the combination of sensitivity, angular resolution, frequency bands, and control of systematic effects that can deliver the compelling and broad science we have described using a single platform. We recommend a start for the mission in the next decade, support for continued technology development and sub-orbital experiments, and support for studying and simulations of the effects of foreground removal and of systematic effects.

2 Science

2.1 Introduction

The Probe of Inflation and Cosmic Origins (PICO) has seven science objectives (SOs) that derive from NASA's three science strategic goals: to explore how the Universe began; to discover how the Universe works; and to explore how the Universe evolved. The SOs, which include probing the inflationary epoch near the big bang, constraining the properties of fundamental particles, probing the structure and evolution of the Universe, and understanding the structure of our own Galaxy, require measurements in and around frequency bands in which the cosmic microwave background is most intense. The SOs and the measurement requirements derived from them are given in Table 2.2 and define the PICO 'baseline design'. This design gives rise to a mission that delivers a much broader set of science deliverables. This report describes the broad array of science deliverables, but focuses primarily on the primary SOs listed in the Table.

The PICO mission consists of a single instrument: an imaging polarimeter that surveys the entire sky at 21 frequency bands spread between 21 and 799 GHz. The telescope has an aperture of 1.4 meter giving diffraction limited resolution between $38'$ and $1'$. The instrument incorporates a 0.1 K-cooled focal plane that hosts 12,996 transition edge sensor (TES) bolometric detectors. The baseline design contains a margin of 40% in detector noise. Experience with past space missions, most recently with *Planck*, shows that pre-mission calculated detector performance is in fact achieved in space [1, 2]. We therefore include throughout this report performance estimates that are based also on our current estimate for the actual performance. Those are labeled current best estimate (CBE). Table 2.1 gives the frequency bands, resolution, both baseline and CBE noise levels, as well as other key mission parameters.

Mission operations throughout the 5-year duration of the mission are simple. PICO executes one specific sky scan pattern that repeats itself for the entire duration of the mission. With this scan pattern the entire sky is scanned every 6 months giving 10 independent full-sky maps of intensity and polarization, giving the three Stokes parameters T, Q and U of the detected electromagnetic radiation. The scan pattern is optimized for polarization measurements as each sky pixel is scanned along multiple orientations. Therefore full-sky maps of the Stokes parameters can be reconstructed from the data of each of the 12,996 polarization sensitive