PICO: Probe of Inflation and Cosmic Origins

Thematic Area: Space Based Projects

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1 Executive Summary

The Probe of Inflation and Cosmic Origins (PICO) is an imaging polarimeter that will scan the sky for 5 years in 21 frequency bands from 21 to 799 GHz. It will produce full-sky surveys of intensity and polarization with a final combined-map noise level equivalent to 3300 *Planck* missions for the baseline required specifications, and according to our current best-estimate would perform as 6400 *Planck* missions. With these capabilities, unmatched by any other existing or proposed platform:

• PICO could determine the energy scale of inflation and give a first, direct probe of quantum gravity by searching for the signal that arises from gravitational waves sourced by inflation and parameterized by the tensor-to-scalar ratio r. The PICO requirement is to detect $r = 5 \times 10^{-4}\,(5\sigma)$, a level that is 100 times lower than current upper limits, and 5 times lower than limits forecast by any planned experiment. If the signal is not detected, PICO is the only instrument that can exclude at 5σ models for which the characteristic scale in the potential is the Planck scale, a key threshold in inflation physics.

• The mission will measure the minimum expected sum of the neutrino masses with 4σ confidence, rising to 7σ if the sum is near 0.1 eV.

• The measurements will either detect or strongly constrain deviations from the standard model of particle physics by counting the number of light particle species $N_{\rm eff}$ in the early universe with $\Delta N_{\rm eff} < 0.06\,(2\sigma)$.

• PICO will elucidate the processes affecting the evolution of cosmic structures by measuring the optical depth to reionization τ with an error $\sigma(\tau) = 0.002$, limited only by the number of spatial modes available in the largest angular scale cosmic microwave background (CMB) polarization.

• The data will give a full sky map of the projected gravitational potential due to all structures in the Universe with the highest signal-to-noise ratio (SNR) relative to any foreseeable experiment, and it will give a catalog of 150,000 clusters extending to their earliest formation redshift. Each of these datasets will be used in combination with other data to constrain the evolution of the amplitude of linear fluctuations $\sigma_8(z)$ with sub-percent accuracy and thus constrain dark energy and modified gravity models.

• PICO will determine the cosmological paradigm of the 2030's by reducing the allowed volume of uncertainty in an 11-dimensional ΛCDM parameter space by a factor of nearly a billion relative to current *Planck* constraints. Such exquisite scrutiny will either give strong validation of the model or require yet-to-be discovered revisions.

• With 86,000,000 independent polarization measurements across the Milky Way, 2,900 times more than *Planck* had, PICO's data will be used to resolve long-standing questions about our Galaxy including the composition, temperature, and emissivities of Galactic dust, and the relative roles of gas turbulence and magnetic fields in the dynamics of the Galaxy and in the observed low star-formation efficiency.

• The data will constrain generic models of dark matter; enable a search for primordial magnetic fields with sufficient sensitivity to rule them out as the sole source for the largest observed galactic magnetic fields; constrain string-theory-motivated axions; and will give precise tracing of the evolution with z of thermal pressure in the universe.

• PICO's deep, full-sky legacy maps will constrain the early phases of galaxy and cluster evolution; perform a census of cold dust in thousands of low z galaxies; make cosmic infrared background maps due to dusty star-forming galaxies; and map magnetic fields in 70 nearby galaxies.

With its broad frequency coverage, PICO is better equipped than any other current or planned instrument to separate the detected signals into their original sources of emission. This capability is important for many of the science goals, and is key for unveiling the faintest of signals, the telltale signature of inflation, which is already known to be dominated by Galactic foregrounds. PICO's large multiplicity of independent maps and sky surveys, and its stable thermal environment will give control of systematic uncertainties unmatched by any other platform. Mission operations are simple: PICO has a single instrument that surveys the sky with a continuously repetitive pattern. The required technologies have either already been proven by past missions, or are simple extensions of technologies now being used by sub-orbital experiments.

The science PICO will deliver addresses some of the most fundamental quests of human knowledge. Its science advances will enrich many areas of astrophysics, and will form the basis for the cosmological paradigm of the 2030's and beyond. Progress in CMB science requires a scale-up of investment. PICO is the most cost-effective way to achieve this scale-up. It has no competitor in terms of raw sensitivity, and it is the only single-platform instrument with the combination of angular resolution, frequency bands, and control of systematic effects that can deliver the compelling, timely, and broad science.

2 Key Science Goals and Objectives

2.1 Gravitational Waves and Inflation

Measurements of the CMB *BB* angular power spectrum are the only foreseeable way to detect inflationary gravitational waves. The strength of the signal, 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, it reveals the energy scale of inflation. PICO will detect primordial gravitational waves at 5σ significance if inflation occurred at an energy scale of at least 5×10^{15} GeV, or equivalently if $r = 5 \times 10^{-4}$. In a widely endorsed community white paper setting targets for measurements of inflationary gravitational waves in the next decade, Shandera et al. [1] quote two theoretically motivated r rejection targets: (1) $r < 0.01$, and (2) $r < 0.001$. The second threshold is motivated by the goal of rejecting all inflationary models that naturally explain the observed value of the spectral index n_s and having a characteristic scale in the potential that is larger than the Planck scale. Such models are shown in dashed lines in Figure 2.1. They write "If these thresholds are passed without a detection, most textbook models of inflation will be ruled out; and ... the data would then force a significant change in our understanding of the primordial Universe." PICO is the only next-decade experiment with the raw sensitivity to reject both targets at high confidence.

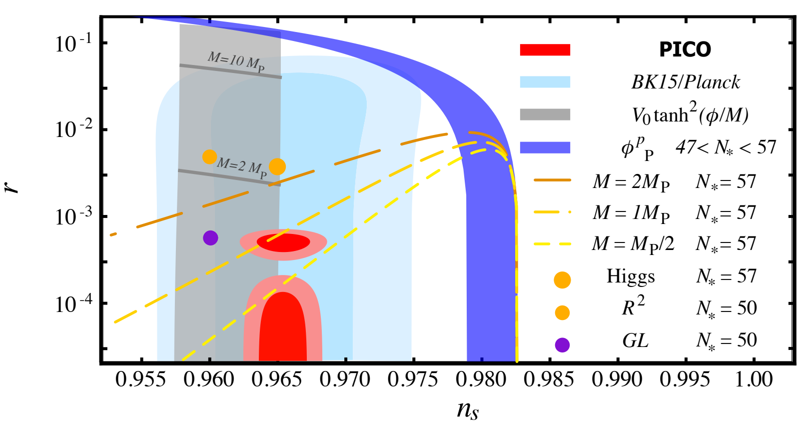

Figure 2.1: PICO will conclusively rule out all Inflation models for which the characteristic scale in the potential is M_p or higher, or will detect $r = 0.0005$ at 5σ (red 1 and 2σ limits and uncertainty ellipses). Current values of σ_r are a factor of 100 higher (cyan). The locus of classes of models and specific ones are shown with dots, solid, and dashed lines.

Uncertainty in the characterization of Galactic foregrounds already limits our ability to constrain r. These foregrounds are anticipated to be nearly 1000 times stronger than next-decade-targeted inflationary B-mode signals at low $\ell \simeq 8$ multipoles. 'Lensing' B-modes, created by gravitational lensing of E-modes, are an additional effective foreground for the higher $\ell \simeq 80$ multipoles. With sufficiently high resolution to remove at least 73% of the lensing effects, and 21 frequency bands to account for foregrounds, PICO is better equipped than all other next-decade experiments to reject intervening signals.

2.2 Fundamental Particles and Fields

• **Light Relics** The effective number of light relic particle species N_{eff} gives information about particle species that are predicted to have existed in the early Universe in extensions of the Standard Model. Light particles beyond the three neutrino families contribute a change ΔN_{eff} that is a function only of the decoupling temperature of the additional species and the spin of the particle. PICO will provide a constraint $\Delta N_{\text{eff}} < 0.06\,(95\%)$ and will either detect new particle species, or constrain the lowest decoupling temperature at which any spin 1 particle could have fallen out of equilibrium by a factor of 400 higher than today's constraint [2]. No next-decade experiment will provide a tighter constraint.

• **Neutrino Mass** The origin, structure, and values of the neutrino masses are among the outstanding questions about the nature of the Standard Model of particle physics. Cosmological measurements of $\sum m_\nu$ relate the amplitudes of the matter power spectrum and the primordial fluctuation power spectrum A_s. Both are limited by degeneracies with other parameters. PICO is the only instrument that will self consistently provide three of the four necessary measurement ingredients: τ, A_s, and the matter power spectrum via CMB lensing. [2, 3]. In combination with DESI and EUCLID data, PICO will give $\sigma(\sum m_\nu) = 14$ meV, giving a $4\,\sigma$ detection of the minimum sum of 58 meV. PICO will measure $\sum m_\nu$ in two additional ways, which will give equivalent constraints.

• **Dark Matter** CMB experiments are effective in constraining dark matter candidates in the lower mass range, which is not available for terrestrial direct detection experiments [4–9]. For a spin- and velocity-independent contact interaction between dark matter and protons PICO will improve upon *Planck*'s dark matter cross-section constraints by a factor of 25 over a broad range of candidate dark matter masses. If 2% of the total dark matter content is made of axions in the mass range $10^{-30} < m_a < 10^{-26}$ eV, PICO will detect this species at between 7 and $13\,\sigma$. These constraints are stronger than all other proposed next-decade CMB experiments [10].

• **Primordial Magnetic Fields (PMFs)** PICO is the only experiment that can probe PMFs as weak as 0.1 nG ($1\,\sigma$). Detection of PMFs would be a major discovery because it would signal new physics beyond the Standard Model of particle physics, discriminate among different theories of the early Universe, and explain the puzzling $1-10\ \mu$G fields observed in galaxies. Or it could conclusively rule out a purely primordial (i.e., no-dynamo-driven) origin of the largest galactic magnetic fields [11–21].

• **Cosmic Birefringence** A number of well-motivated extensions of the Standard Model involve fields with parity-violating coupling [22–27]. Their presence may cause cosmic birefringence – a rotation of the polarization of an electromagnetic wave as it propagates across cosmological distances [24, 28, 29]. PICO's constraints on cosmic birefringence are more stringent than any other next-decade experiment [30].

2.3 Cosmic Structure Formation and Evolution

• **The Formation of the First Luminous Sources** Measurements of the optical depth to reionization τ will illuminate the nature of the first luminous sources and the exact history of the reionization epoch, both of which are key missing links in our understanding of structure formation [31]. With full sky coverage, multiple frequency bands, and ample sensitivity to remove foregrounds, PICO is uniquely suited to reach cosmic-variance-limited precision with $\sigma(\tau) = 0.002$. Data from PICO's frequency bands above 400 GHz – which have better than 2 arcmin resolution – will be used to provide clean maps for higher resolution ground-based instruments that can reconstruct the patchy τ field. No other experiment can provide these data.

• **Probing the Evolution of Structures via Gravitational Lensing and Cluster Counts** PICO will give sub-percent constraints on $\sigma_8(z)$, the amplitude of linear fluctuations as a function of redshift, through measurements of gravitational lensing of the CMB photons and independently by using cluster counts. PICO will have an SNR of more than 560 for measurement of $C_L^{\phi\phi}$, the angular power spectrum of the projected gravitational potential ϕ that is lensing the photons. This is the highest of any foreseeable CMB experiment in the range $2 \leq L \lesssim 1500$. When combined with LSST data the measurement will give $\sigma_8(z) < 0.5\%$ in each of six redshift bins for $z > 0.5$ [32]. The mission will find ∼150,000 galaxy clusters, and this catalog will provide $\sigma_8(z) < 1\%$ for each of eight bins in $0.5 < z < 2$, and a neutrino mass constraint $\sigma(\sum m_\nu) = 14$ meV that is independent from the one coming from $C_L^{\phi\phi}$. A significant fraction of the PICO-detected clusters will also be detected by eROSITA, giving an exceptional catalog of multi-wavelength observations for detailed studies of cluster astrophysics. The constraints on σ_8 will translate to constraints on dark energy, modified gravity, baryonic feedback process, and limits on the particle content of the Universe.

• **Constraining Feedback Processes through the Sunyaev–Zeldovich Effect** The thermal SZ (tSZ) effect probes the integrated electron pressure along the line-of-sight. PICO will detect 150,000 clusters through their tSZ signature, the largest catalog of any proposed CMB experiment, including thousands of high-redshift objects that are undetectable via X-ray emission. PICO will also provide the only full-sky, high-SNR tSZ map of any proposed CMB experiment. The cross-correlation of this map with the LSST gold weak-lensing sample (26 gal/arcmin^2 over 40% of the sky) will be detected at SNR=3000, yielding a precise tomographic reconstruction of the evolution of thermal pressure over cosmic time.

2.4 Testing ΛCDM

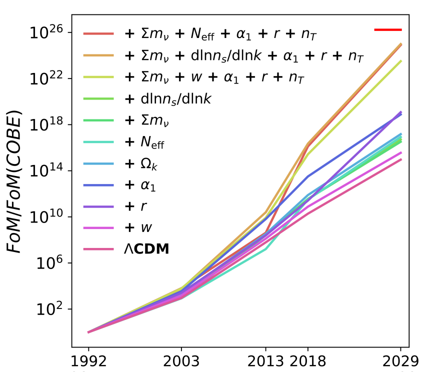

Figure 2.2: The increase in cosmological parameter constraining power using only CMB data since *COBE*. The FoM is the inverse of the uncertainly volume in parameter space. For an 11-parameter set that includes $N_{\rm eff}$ (red increasing line) PICO will improve the FoM by a factor of 0.5×10^9 relative to *Planck*. It will extract nearly the same information as that attainable by a mission with twice higher resolution and nine times lower noise (top right red horizontal bar), that is, PICO's performance on cosmological parameters is equivalent to that of a 'CMB flagship-scale mission'. The constituents of the 11-parameter set are given by Hanany et al. [32].

PICO will set the cosmological paradigm for the 2030's and beyond by measuring the six parameter ΛCDM with 50,000 times more constraining power compared to *Planck*; see Figure 2.2 (the improvement between WMAP and *Planck*was by 300). For an 11-parameter set that includes r, $N_{\rm eff}$, and $\Sigma(m_\nu)$, the improvement is by a factor of 0.6×10^9. These improvements will test ΛCDM stringently. If it survives such scrutiny its dominance as the prevailing paradigm will strengthen. If tensions deepen to become discrepancies, it would be exciting to have a new cosmological model emerge.

2.5 Galactic Structure and Star Formation

PICO will produce 21 polarization maps of Galactic emission, all much deeper than *Planck*'s seven maps. At 799 GHz PICO will have five times finer resolution than *Planck*. Such a dataset can only be obtained by a space mission like PICO. These data will complement a rich array of other polarization observations forthcoming in the next decade, including stellar polarization surveys to be combined with Gaia astrometry, and Faraday rotation measurements from observations at radio wavelengths with the Square Kilometer Array (SKA) and its precursors.

• **Test models of the composition of interstellar dust** Less than a few μm in size, dust grains are intermediate in the evolution from atoms and molecules to large solid bodies such as comets, asteroids, and planets. Through vastly improved spectral characterization of Galactic polarization, the PICO data will validate or reject state-of-the-art dust models [e.g. *33*, *34*], test for the presence of additional dust grain species with distinct polarization signatures, such as magnetic nanoparticles [*35*], and will be used as an input for the foreground separation necessary to extract cosmological E- and B-mode science.

• **Determine how magnetic fields affect molecular cloud and star formation** Stars are formed through interactions between gravitational and magnetic fields, turbulence, and gas over more than four orders of magnitude of spatial scales, which span the diffuse ISM (kpc scale), molecular clouds (10 pc), and molecular cloud cores (0.1 pc). However, the role magnetic fields play in the large-scale structure of the diffuse interstellar medium (ISM) and in the observed low star-formation efficiency has been elusive, owing to the dearth of data. With 1.1 arcmin resolution PICO will expand the number of independent magnetic field measurements across the sky from *Planck*'s 30,000 to 86,000,000, a factor of 2900. The data will robustly characterize turbulent properties like the Alfvén Mach number across a previously unexplored regime of parameter space.

2.6 Legacy Surveys

PICO will generate a rich and unique catalog of hundreds of thousands of new sources serving astrophysicists across a broad range of interests including in galaxy and cluster evolution, correlations of cold galactic dust with galactic properties, the physics of jets in active galactic nuclei, and the properties of the cosmic infrared background. This information will be embedded in catalogs including 50,000 proto-clusters extending to $z \simeq 4.5$, 4,500 strongly lensed galaxies extending to $z \simeq 5$, 30,000 galaxies with $z \leq 0.1$, polarization data for few thousand radio sources and dust galaxies, and the deepest maps of the CIB with resolution as high as 1 arcmin .

2.7 Foregrounds and Systematics

Properly modeling, detecting, and separating foregrounds and systematic effects are key for the success of any experimental endeavor striving to achieve $\sigma(r) \lesssim 1 \times 10^{-3}$.

• PICO has the highest sensitivity of any next-decade CMB experiment, and the most frequency bands compared to any imaging instrument. It is thus more suitably equipped to handle foreground complexities. Higher sensitivity will translate to higher SNR of systematic effects.

• Hanany et al. [*32*] have shown that frequencies above 400 GHz may be essential for removing large angular scale foregrounds. They have also shown that for several realistic sky models PICO should be able to satisfy its r detection requirement.

• Relative to other platforms, a space-based mission provides the most thermally stable platform, a prerequisite for improved control of systematic effects. PICO's orbit at L2 is among the most thermally stable of possible orbits.

- PICO's sky scan pattern gives strong data redundancy, which enables numerous cross-checks. Each of the 12,996 detectors makes independent maps of the I, Q, and U Stokes parameters enabling many comparisons within and across frequency bands, within and across sections of the focal plane, and within and across bolometers that have either the same or different polarization sensitivities. Half the sky is scanned every two weeks, and the entire sky is scanned in 6 months.
- The scan pattern gives almost continuous scans of planets and large amplitude ($\geq$ 4 mK) CMB dipole signals [36]. These features result in continuous, high SNR calibration and antenna-pattern characterization.

We direct the reader to the mission study report for more details on our work on foreground rejection and characterization of systematic effects for PICO [32].

3 Technical Overview

PICO meets all of its science-driven instrument requirements with a single instrument: an imaging polarimeter with 21 logarithmically spaced frequency bands centered between 21 and 799 GHz (Table 3.1). The instrument has a two-reflector Dragone-style telescope; see Figure 3.1. The focal plane is populated by transition-edge-sensor (TES) bolometers and read out using a time-domain multiplexing scheme. The instrument has both passive and active cooling stages. PICO operates from the Earth-Sun L2 and employs a single science observing mode, providing highly redundant coverage of the full sky. A full description of the reference design is given by Hanany et al. [32].

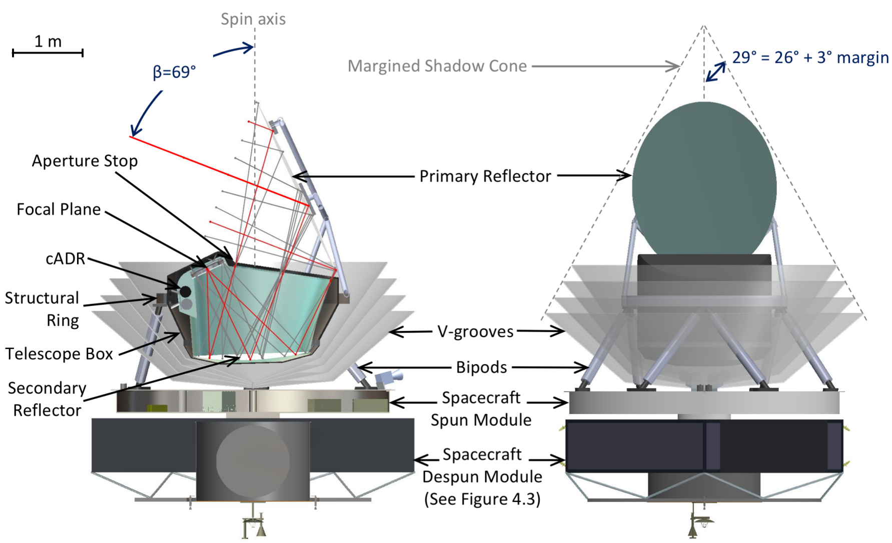

Figure 3.1: PICO overall configuration in side view and cross section (left), and front view with V-Groove assembly shown semi-transparent (right). The mission consists of a single science instrument mounted on a structural ring. The ring is supported by bipods on a stage spinning at 1 RPM relative to a despun module. Only power and digital information pass between the spun and despun stages.

3.1 Telescope, Detectors, and Readout

The PICO 1.4 m aperture, two-mirror telescope gives a large diffraction-limited field of view, sufficient to support approximately 10^4 detectors; arcminute resolution at 800 GHz; low instrumental and cross-polarization; and low sidelobe response. There are no moving parts in the PICO optical system, reducing mission risk. There are no lenses, eliminating absorption and reflection losses and obviating the need for developing broad-band anti-reflection coatings. The primary mirror is passively cooled to $\sim$20 K. An aperture stop and a secondary mirror are actively cooled to 4.5 K.

The PICO focal plane has a total of 12,996 TES detectors, 175 times the number flown aboard *Planck*. The required full-sky, 5-year survey depth is 0.87 μK arcmin; the current best estimate performance is 0.61 μK arcmin, offering 40% noise margin. PICO is the most sensitive CMB experiment proposed for the next decade. To achieve similar raw sensitivity, a ground-based instrument would require $\gtrsim$50 times the number of detectors.

There is broad flexibility in the detailed implementation of the PICO focal plane. In the baseline design we employ three-color sinuous antenna/lenslet pixels [37] for the 21–462 GHz bands and single color, feedhorn-coupled, polarization sensitive bolometers for the three higher frequency bands. PICO can also achieve its required performance with two-color pixels [?] (for 21–462 GHz) with a total of 19 bands and the same noise margin, or even with single-color pixels at all 21 bands [?] and 17% noise margin. Current Ground-based instruments use all three technologies at a narrower range of frequencies. There are development programs in place to adapt the technologies to a broader ranger of frequencies and to space applications.

Table 3.1: **Frequency Bands, Resolution, and Noise Level**

Frequency	FWHM	Polarization map depth	
		Baseline	CBE
[GHz]	[arcmin]	[μK_{CMB}][a]	[μK_{CMB}][a]
21	38.4	23.9	16.9
25	32.0	18.4	13.0
30	28.3	12.4	8.7
36	23.6	7.9	5.6
43	22.2	7.9	5.6
52	18.4	5.7	4.0
62	12.8	5.4	3.8
75	10.7	4.2	3.0
90	9.5	2.8	2.0
108	7.9	2.3	1.6
129	7.4	2.1	1.5
155	6.2	1.8	1.3
186	4.3	4.0	2.8
223	3.6	4.5	3.2
268	3.2	3.1	2.2
321	2.6	4.2	3.0
385	2.5	4.5	3.2
462	2.1	9.1	6.4
555	1.5	45.8	32.4
666	1.3	177	125
799	1.1	1050	740

[a] For units in [Jy/sr] see Hanany et al. [32].

Polarimetry is achieved by measuring the signals from pairs of two co-pointed bolometers within a pixel that are sensitive to two orthogonal linear polarization states. Half the pixels in the focal plane are sensitive to the Q and half to the U Stokes parameters of the incident radiation, providing sensitivity to the Stokes I, Q, and U parameters. Two layouts for the distribution of the Q and U pixels on the focal plane have been investigated [38]; both satisfy mission requirements.

The current baseline for PICO is to use a time-domain multiplexer (TDM), because to date this scheme uses the least power consumption and dissipation at ambient temperatures. The thermal loading on the cold stages from the wire harnesses is subdominant to conductive loading through the mechanical support structures. In the PICO TDM implementation a row of 102 detectors are read out simultaneously, and 128 such rows are read out sequentially. SQUIDs will be used as current amplifiers. All the technologies elements necessary for implementing this readout have already been demonstrated [32]. Only packaging for space is required. Suborbital experiments have developed techniques to shield the SQUIDs from Earth's magnetic field [39]. PICO will use these demonstrated techniques to shield SQUID readout chips from the ambient magnetic environment, which is 20,000 times weaker than near-Earth.

3.2 Thermal

The PICO thermal system does not require cryogenic consumables, permitting consideration of significant mission extension beyond the prime mission. The system, consisting of V-groove radiators for passive cooling, mechanical coolers to achieve 4.5 K, and a continuous adiabatic demagnetization refrigerator (cADR), meets all thermal requirements with robust margins [32] .

The cADR maintains the focal plane at 0.1 K and the surrounding enclosure, filters, and readout components at 1 K. Heat loads in the range of 30 μW at 0.1 K and 1 mW at 1 K (time-average) are within the capabilities of current cADRs developed by GSFC [40, 41] and flown on suborbital balloon flights. The PICO sub-kelvin heat loads are estimated at less than half of this capability.

A cryocooler system similar to that used on JWST to cool the MIRI detectors [42, 43] backs the cADR and cools the aperture stop and secondary reflector to 4.5 K. Both Northrop Grumman Aerospace Systems (NGAS, which provided the MIRI coolers) and Ball Aerospace have developed such coolers under the NASA-sponsored Advanced Cryocooler Technology Development Program [44]. The NGAS project has completed PDR-level development, and is expected to reach CDR well before PICO begins Phase-A. The projected performance of this cooler will give more than 100 % heat lift margin relative to PICO's requirements [32].

3.3 Design Reference Mission

The PICO concept of operations is similar to that of the successful *WMAP* [45] and *Planck* [46] missions. After launch, PICO cruises to a quasi-halo orbit around the Earth–Sun L2 Lagrange point. A two-week decontamination period is followed by instrument cooldown, lasting about two months. After in-orbit checkout is complete, PICO begins its science survey, depicted in Figure 3.2. This survey ensures that each sky pixel is revisited along many orientations, which is optimal for polarimetric measurements. Over the 5 year duration, PICO executes 10 independent full sky surveys, giving high redundancy for identifying systematic uncertainties.

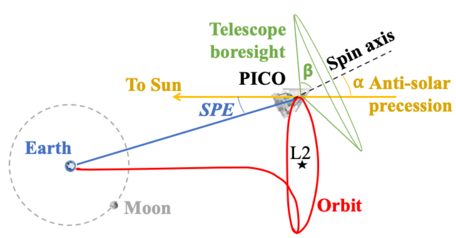

Figure 3.2: PICO surveys the sky by spinning the instrument about the spacecraft's symmetry axis at 1 RPM. The telescope boresight is tilted by $\beta = 69^{\rm o}$ from that axis. The symmetry axis precesses around the anti-sun direction with a period of 10 hours; $\alpha = 29^{\rm o}$. Nearly 50% of the sky is surveyed every two weeks. The entire sky is covered in 6 months.

Instrument data are compressed and stored on-board, then returned to Earth in daily 4-hr Ka-band science downlink passes (concurrent with science observations). High data-rate downlink to the Deep Space Network (DSN) is available from L2 using near-Earth Ka bands. We assumed a launch with the Falcon 9. Its capability for ocean recovery exceeds PICO's 2147 kg total launch mass (including contingency) by a 50 % margin.

The PICO spacecraft bus is Class B and is designed for a minimum lifetime of 5 years in the L2 environment. Mission-critical elements are redundant. The aft end of the spacecraft (the "de-spun module") is comprised of six equipment bays that house standard components. The instrument and V-grooves are mounted on bipods from the spacecraft's "spun module," which contains the 4 K cooler compressor and drive electronics, the sub-K cooler drive electronics, and the detector warm readout electronics. A motor drives the spun module at 1 rpm. Only power and data (digital) lines pass between the spun and de-spun modules. Reaction wheels on the despun module cancel the angular momentum of the spun module and provide three-axis control.

4 Technology Drivers

The remaining technology developments required to enable the PICO baseline design are:

- extension of three-color antenna-coupled bolometers down to 21 GHz and up to 462 GHz;
- construction of high-frequency direct absorbing arrays and laboratory testing;
- beam line and 100 mK testing to simulate the cosmic ray environment at L2; and
- expansion of time-domain multiplexing to support 128 switched rows per readout column.

All of these developments are straightforward extensions of technologies already available and

Table 4.1: PICO technologies can be developed to TRL 5 prior to a 2023 Phase A start using the APRA ("A") and SAT ("S") programs, requiring an estimated total of $13M.

Task	Current status	Milestone A	Milestone B	Milestone C	Current funding	Required funding	Date TRL5 achieved
1a. Three-color arrays $\nu < 90\,\mathrm{GHz}$	2-color lab demos $\nu > 30\,\mathrm{GHz}$	Field demo of 30–40 GHz (2020)	Lab demos 20–90 GHz (2022)	—	A & S	$2.5M over 4 yr (1 A + 1 S)	2022
1b. Three-color arrays $\nu > 220\,\mathrm{GHz}$	2-color lab demos $\nu < 300\,\mathrm{GHz}$	Field demo of 150–270 GHz (2021)	Lab demos 150-460 GHz (2022)	—	A & S	$3.5M over 4 yr (2 Ss)	2022
2. Direct absorbing arrays $\nu > 50\,\mathrm{GHz}$	0.1–5 THz unpolarized	Design & prototype of arrays (2021)	Lab demo of 555 GHz (2022)	Lab demo 799 GHz (2023)	None	$2M over 5 yr (1 S)	2023
3. Cosmic ray studies	250 mK w/ sources	100 mK tests with sources (2021)	Beamline tests (2023)	—	A & S	$0.5–1M over 5 yr (part of 1 S)	—
4a. Fast readout electronics	MUX66 demo	Electronics Engineering and Fab (2020)	Lab demo (2021)	Field demo (2023)	No direct funds	$4M over 5 yr (1 S)	2023
4b. System engineering; 128× MUX demo	MUX66 demo	Design of cables (2020)	Lab demo (2021)	Field demo (2023)	No direct funds	—	—

used today by sub-orbital and orbital experiments. We recommend APRA and SAT funding to complete the development through the milestones described in Table 4.1 and by Hanany et al. [*32*].

5 Organization, Partnerships, and Current Status

PICO is the result of an 18-month mission study funded by NASA (total grant = $150,000). The study was open to the entire mm/sub-mm community. Seven working groups were led by members of PICO's Executive Committee, which had a telephone conference weekly, led by the PI. A three-member steering committee, composed of two experimentalists experienced with CMB space missions, and a senior theorist gave occasional advice to the PI. More than 60 scientists, international- and US-based, participated in-person in each of two community workshops (November 2017 and May 2018). The study report has been submitted by NASA to the decadal panel, and it is available on the arXiv and on the PICO website [*32*, *47*]. It has contributions from 82 authors, and has been endorsed by additional 131 members of the community.

The PICO team designed an entirely US-based mission, so that the full cost of the mission can be assessed. We excluded contributions by other space agencies, despite expression of interest by international scientists. The PICO concept has wide support in the international community. If the mission is selected to proceed, a path that would be scientifically and financially optimal relative to other options, it is reasonable to expect that international partners would participate and thus reduce the US cost of the mission.

6 Schedule and Cost

• **Schedule** NASA-funded Probe studies including PICO assume a Phase A start in October 2023. PICO development phases B-D are similar in duration to recent comparably sized NASA missions such as Juno and SMAP. PICO is a cryogenic mission similar to *Planck*, but the cryo-

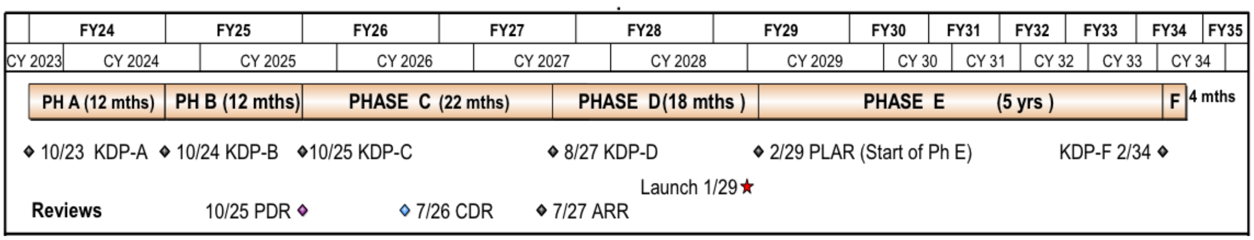

Figure 6.1: PICO development and operations schedule.

genic design is simpler because all of PICO's detectors are maintained at 0.1 K (some of *Planck*'s detectors were maintained at 0.1 K, and some at 20 K). We used experience from *Planck* and from current implementations of ground-based kilo-pixel arrays to allocate appropriate time for integration and testing. The baseline mission lifetime is 5 years.

The PICO instrument does not have cryogenic consumables (as *Planck* did) permitting mission extension beyond the prime mission duration.

• **Cost** We estimate PICO's total Phase A–E lifecycle cost between \$870M and \$960M, including the \$150M allocation for the Launch Vehicle (per NASA direction). These cost estimates include 30 % reserves for development (Phases A–D) and 13 % reserves for operations (Phase E). Table 6.1 shows the JPL Team X and the PICO team mission cost breakdown. Team X estimates are generally model-based, and were generated after a series of instrument and mission-level studies. The PICO team adopted the Team X estimates, but also obtained a parametrically estimated cost range for the Flight System and Assembly, Test, and Launch Operations from Lockheed Martin Corporation to represent the cost benefits that might be realized by working with an industry partner. After adding estimated JPL overhead the PICO team cost is in-family with but lower than the Team X cost.

Table 6.1: PICO mission costs

<table>
<tr><th rowspan="3">Project Phase</th><th colspan="2">Estimate by</th></tr>
<tr><th>JPL</th><th>PICO</th></tr>
<tr><th>Team X</th><th>Team</th></tr>
<tr><td>Development (Phases A–D) including 30% reserves</td><td>$ 724M</td><td>$ 634–677M</td></tr>
<tr><td>Operations (Phases E–F) including 13% reserves</td><td colspan="2">$ 84M</td></tr>
<tr><td>Launch Vehicle</td><td colspan="2">$ 150M</td></tr>
<tr><td>Total Cost (FY18$)</td><td>$ 958M</td><td>$ 868–911M</td></tr>
</table>

Science team costs are assessed by Team X based on PICO science team estimates of the numbers and types of contributors and meetings required for each year of PICO mission development and operations. These workforce estimates are informed by recent experience with the *Planck* mission. PICO's spacecraft cost reflects a robust Class B architecture. Mission-critical elements are redundant. Appropriate flight spares, engineering models and prototypes are included. Mission operations, Ground Data Systems, and Mission Navigation and Design costs reflect the relatively simple operations: PICO has a single instrument and a single, repetitive science observing mode.

The active cooling system (the 0.1 K cADR and 4 K cryocooler) comprises nearly half of the payload cost. The cADR cost for this study is an estimate from Goddard Space Flight Center. The 4 K cryocooler cost for this study is based on the NASA Instrument Cost Model (NICM) VIII CER Cryocooler model [48], assuming a commercial build. Based on JPL experience, 18 % of the instrument cost is allocated for integration and testing (I&T). More details on the cost of PICO are available in the full PICO report [32].

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