The Probe of Inflation and Cosmic Origins

A Space Mission Study Report
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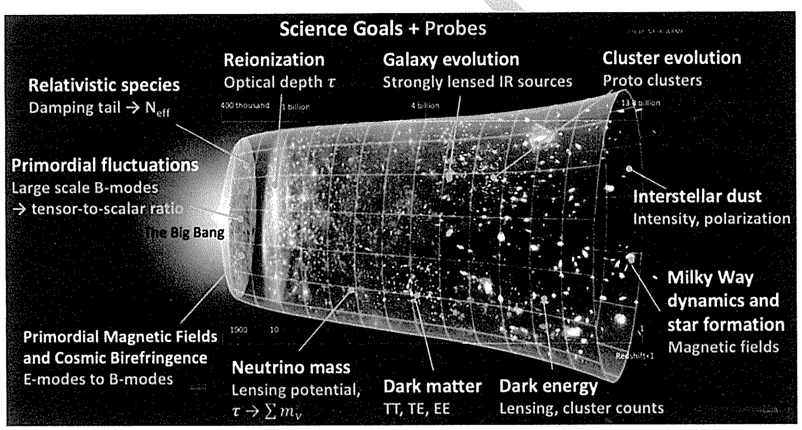

1 Executive Summary

Recent theoretical developments and measurements of the cosmic microwave background (CMB) have uncovered tremendous potential for new exciting discoveries over the next 10 years. The new discoveries, to be delivered by the Probe of Inflation and Cosmic Origins (PICO), are promising to be revolutionary, affecting physics, astrophysics, and cosmology on the most fundamental levels.

PICO is an imaging polarimeter that will scan the sky for 5 years with 21 frequency bands spread between 21 and 800 GHz. It will produce 10 independent full-sky surveys of intensity and polarization with a final combined-map noise level that make it equivalent to 3200 *Planck* missions for the baseline required specifications, and estimated to actually perform as 6400 *Planck* missions. It will produce the first ever full-sky polarization maps at frequencies above 350 GHz, and it will have diffraction-limited resolution, giving it a resolution of 1′ at 800 GHz.

With these unprecedented capabilities, which are unmatched by any other existing or proposed platform, PICO could detect the signature of an inflationary epoch near the big bang, thus determining the energy scale of inflation and giving a first direct probe of quantum gravity. If the signal is not detected it will constrain broad classes of inflationary models, and exclude at [illegible]10σ models for which the characteristic scale of the potential is given by the Planck scale. The combination of data with LSST could rule out slow-roll single-field inflation, which will mark a landmark transition in studies of inflation.

The mission will have a deep impact on particle physics by measuring the expected sum of the neutrino masses in two independent ways, each with at least 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 particles in the early universe at an energy range that is up to 400 times higher than available today. The data will constrain dark matter candidates by pushing *Planck* constraints on the dark matter cross-section by a factor of 25, specifically at low energy scales that are not accessible to direct-detection experiments. The data will probe the existence of cosmic fields that could give rise to cosmic birefringence.

PICO will transform our knowledge of the structure and evolution of the universe. It will measure the redshift at which the universe reionized, strongly constraining physical models describing when and how the first luminous objects formed. It will make a map of the projected matter throughout the volume of the universe with a signal-to-noise ratio exceeding 500. This map will give unprecedented view of the distribution of matter, and will be used to weigh the mass of dark matter halos hosting galaxies, groups, and clusters, with redshifts extending to the formation of the very first such objects. The map will be cross-correlated with other next-decade galaxy surveys, such as LSST, to give strong, sub-percent accuracy constraints on structure-growth parameters. An extraordinary amount of information about the role of energetic feedback on structure formation will come from correlating PICO's map of the thermal Sunyaev-Zeldovich effect with WFIRST and LSST. The correlation – forecast to have a signal-to-noise of 3000 with LSST weak lensing – will enable breaking the analysis down to dozens of tomographic redshift bins, giving extraordinarily detailed information about the evolution of thermal pressure over cosmic time.

Magnetic fields thread galaxies and affect their structure and evolution, but the origins of these magnetic fields is a hotly debated question. PICO will resolve the question of whether galactic magnetic fields have been seeded by primordial magnetic fields of cosmic origin. It will map the entire Milky Way in polarization with unprecedented detail at many frequency bands. Such maps are not planned by any other survey, and cannot be produced other than in space. From these unique maps we will map the Galactic magnetic fields structure elucidating the relative roles of turbulence and magnetic fields in the observed low star-formation efficiency, and we will strongly constrain the properties of the diffuse interstellar medium.

By discovering 50,000 proto-clusters with redshift up to 4.5, and 4500 strongly-lensed galaxies with redshift up to 5, PICO will enable a unique view into early galaxy and cluster evolution. These counts are factors of 100 to 1000 larger than available with catalogs today, and the window PICO provides because of its high frequency bands is entirely unique and not available to any other experiment. By discovering 150,000 clusters distributed over cosmic time PICO data, together with future cluster redshift surveys will constrain the dark energy equation of state with constraints similar to other next-decade surveys, and providing an independent constraint on the minimal neutrino mass.

This scientifically ground-breaking mission is based entirely on technologies that are being used actively today by ground- and balloon-based experiments. All the implementation aspects are mature, benefitting from thousands of person-year experience of studying the sky at these wavelengths. These span over more than 50 years of mapping the CMB and include three enormously successful space missions. This combined experience unambiguously shows that the unlimited frequency coverage and thermally benign environment aboard a space-based platform give unparalleled capability to separate the combination of galactic and cosmological signals and to control systematic uncertainties. These qualities, which are critical ingredients for any next-decade experiment, make PICO the optimal platform for a next-generation CMB experiment.

2 Science

2.1 Introduction

The Probe of Inflation and Cosmic Origins (PICO) is an imaging polarimeter designed to survey the entire sky at 21 frequencies between 21 and 800 GHz with a polarization sensitivity that is 57 or 82 times that of the *Planck* mission for the PICO baseline and current best estimate (current best estimate (CBE)) configurations, respectively.

The mission requirements, which define our baseline design, flow down from a small set of key science objectives listed in Table 1. As outlined in this report, this baseline gives rise to a mission that will reach an extraordinarily broad set of science targets, ranging from inflation, to constraints on fundamental particles and fields, to cosmic structure formation and galactic science.

According to inflation, quantum fluctuations in the space-time metric created a background of gravitational waves that imprint a unique signature on the polarization of the CMB. A detection of this inflationary gravity wave (IGW) signal "would be a watershed discovery", a quote from the 2010 decadal panel report [1]. It would be the first observational evidence for quantum gravity. The signal would also give important clues about the nature of inflation, in particular the energy scale at which it occurred. The strength of the signal is commonly parameterized by a parameter commonly labeled r, the tensor-to-scalar ratio. The combination of data from *Planck* and the BICEP/Keck Array give the strongest constraint to date $r < 0.06$ (95%) [2].

Emission within our own galaxy is a source of confusion that must be separated with high fidelity before definitive discovery, or stronger upper limits, can be claimed [3]. For the levels of r targeted in the next decade, PICO has both the frequency coverage and sensitivity to measure and separate sources of foreground confusion and is thus poised to detect or place unprecedented constraints on the physics of inflation. Its measurements of the spectral index of primordial fluctu-

ations will give the strongest constraints yet on specific models of inflation.

A few hundred million years after the Big Bang, the neutral hydrogen gas permeating the Universe was reionized by photons emitted by the first luminous sources to have formed. The nature of these sources (e.g., star-forming galaxies or high-redshift quasars) and the exact history of this epoch are key missing links in our understanding of structure formation. Various measurements, including *Planck*'s measurement of the optical depth to reionization $\tau = 0.054 \pm 0.007$, have indicated that reionization concluded by $z \approx 6$, but its onset at higher redshift is poorly constrained. PICO will yield a breakthrough in this context via a cosmic-variance-limited[1] measurement of τ, with $\sigma(\tau) = 0.002$, which can only be directly measured in large-scale CMB polarization fluctuations (this is SO5). The only proven method to date for measuring this signal, which requires exquisite control of systematics and foreground contamination, is a space-based platform.

Lensing of the CMB photons by structures as they traverse the Universe provides a projected map of all the matter in the Universe from the epoch of decoupling until today. The non-zero mass of neutrinos affects the clustering of matter and thus can be inferred from maps of the projected matter distribution. The quantity that can specifically be inferred is the sum of the neutrino masses. The current constraint from the combination of *Planck* and large-scale structure data is $\sum m_\nu < 0.12$ eV (95%). This is approaching the minimum summed mass allowed in the inverted neutrino hierarchy of ≈ 0.1 eV and is within a factor of two of the minimal mass allowed in the normal hierarchy of ≈ 0.06 eV. A detection thus appears imminent. However, the precision of determining the neutrino mass scale, using the CMB or *any* other cosmological probe, is limited by knowledge of τ, due to the strong degeneracy between τ and the amplitude of matter fluctuations. PICO's map of the projected matter with signal-to-noise ratio (SNR) exceeding 500 – a result of its low noise and high angular resolution – *and* its own cosmic-variance-limited measurement of τ will give a 4σ detection of $\sum m_\nu$ in the normal hierarchy, rising to 7σ for the inverted hierarchy (see SO3).

The CMB offers a unique window into the thermal history of the Universe, from the time of reheating through today. It is during these eras that the matter and radiation that fill the Universe were produced and evolved to form the structures observed at low redshifts. Measurements of the CMB on small angular scales are sensitive to the many components that make up the Universe including the baryons, cosmic neutrinos, dark matter, and a wide variety of particles motivated by extensions of the Standard Model. The Standard Model of particle physics posits three neutrino families, but it also allows for additional light, relativistic particles, if they existed early enough during the evolution of the Universe. We count the total number light particles thermalized in the early Universe using $N_{\rm eff}$. Light particles thermalized in the early universe leave a universal contribution to $N_{\rm eff}$ that is sensitive to the freeze-out temperature and the spin of the particle. The current *Planck* measurement of $N_{\rm eff} = 2.99 \pm 0.17$ (1σ) is sensitive to particles thermalized after the QCD phase transitions. PICO's measurement with $\sigma(N_{\rm eff}) = 0.03$ (SO4), enabled by low noise levels, high resolution, and full-sky coverage, will reach back to times when the temperature of the Universe was orders of magnitude hotter than we have probed today, and a period that is still largely unexplored. These same experimental features are advantageous not only for $N_{\rm eff}$ but for any new physics with signatures on the CMB. Of particular interest is the nature of dark matter and its interactions. PICO will place constraints that are more than on order of magnitude stronger than *Planck* for a dark matter particle of MeV mass range, which can not be probed by direct detection experiments. PICO will thus reveal important clues to the nature of the fundamental laws and our

[1] The cosmic variance limit is the statistical limit arising from observing a single Universe.

cosmic origins.

Secondary anisotropy in the CMB[2] provide a wealth of information on the growth and evolution of structure in our universe. CMB lensing, the thermal and kinematic Sunyaev-Zel'dovich (SZ) effects, and extragalactic point sources all contribute significantly to the CMB intensity fluctuations on small angular scales (note that lensing is also present in polarization fluctuations). Immense progress in mapping these sources is enabled by PICO's depth, broad frequency coverage, and relatively high resolution. The all-sky, projected mass map reconstructed from CMB lensing that PICO will provide can be correlated with tracers of large-scale structure to tomographically probe the growth of structure at unprecedented SNR levels. The thermal SZ effect provides a map of the integrated free-electron pressure along the line of sight, and the peaks of this map trace the locations of all galaxy clusters in the universe. PICO will find all the massive, virialized, galaxy clusters at any redshift. The epoch of reionization imprints information in the statistical moments of the kinematic SZ signal. The combination of these kSZ statistical moments with the cosmic-variance-limited τ measurement from PICO will provide tight constraints on the global properties of the sources responsible for reionization the universe.

Our understanding of magnetic fields is rooted in observations of the very local universe: the Milky Way and nearby galaxies. Magnetic fields are observed to be a foremost agent of the Milky Way's ecology. Understanding magnetic field is crucial for making progress on some exciting issues in the astrophysics of galaxies: the dynamics and energetics of the multiphase interstellar medium, the efficiency of star formation, the acceleration and propagation of cosmic rays, and the impact of feedback on galaxy evolution. Through its detailed high-resolution polarization measurements of galactic dust emission, PICO will produce an unprecedented data set, mapping galactic magnetic fields and providing answers to these questions (SO6 and 8).

Magnetic fields are not only critical for understanding the dynamics and evolution of galaxies. The very origin of magnetic fields in galaxies, and their possible evolution from primordial, early-universe cosmic magnetic fields is a topic of intense debate. PICO is poised to provide definitive answer as to whether early universe magnetic fields could provide the seeds for most current galaxies.

The magnetized ISM in the Solar Neighborhood presents a challenge for the investigation of cosmological signals. Cosmological signals of interest, such as CMB B-mode polarization, CMB spectral distortions, and 21cm line emission from the cosmic dawn and the reionization epoch are obscured by galactic dust and synchrotron emission that can be orders of magnitude brighter. PICOs detailed mapping of these signals will strongly constrain the physical properties of the ISM and thus models of dust-grain composition, temperature, and emissivities (SO7).

The PICO deep and high resolution maps will yield a treasure trove of point source that will be mined for years. The mission will provide a full-sky catalog of tens of thousands of extragalactic millimeter and sub-millimeter point sources, which are beacons for active galactic nuclei (in the radio) and dust emission from vigorously star-forming galaxies at $z \gtrsim 2$ and earlier (in the far-IR).

2.2 Science Objectives

2.2.1 Fundamental Physics

Inflation and Gravitational waves

Measurements of the CMB together with Einstein's theory of general relativity imply that the ob-

Table 1: Science Traceability Matrix (STM)

Science Goals from NASA Science Plan	Science Objectives	Scientific Measurement Requirements			Instrument (single instrument, single mode)		Mission Functional Requirements
		Model Parameters	Physical Parameters	Observables	Functional Requirements	Projected Performance	
Explore how the universe began (Inflation)	SO1. Probe the physics of the big bang by detecting the energy scale at which inflation occurred if it is above 4×10^{15} GeV, or place an upper limit if it is below (§2.2.1)	Tensor-to-scalar ratio r^a: $\sigma(r) = 1 \times 10^{-4}$ at $r = 0$; $r < 5 \times 10^{-4}$ at 5σ confidence level	CMB polarization BB power spectrum for modes $2 < l < 300$ to cosmic variance limit, and CMB lensing power spectrum for modes $2 < l < 1000$ to cosmic variance limit	Linear polarization across $60 < \nu < 300$ GHz over entire sky; Foreground separation requires $20 < \nu < 800$ GHz	Frequency coverage: ν_c from 20 to 800 GHz.	Frequency coverage: See Table 3.2. 21 bands with ν_c from 21 to 799 GHz. Frequency resolution: $\Delta\nu/\nu_c = 25\%$. Sensitivity: See Table 3.2. Combined instrument weight of $0.43\,\mu K_{CMB}\sqrt{s}$. Angular resolution: See Table 3.2. FWHM = $6.2' \times (155\,GHz/\nu_c)$; $1.1'$ for $\nu_c = 799$ GHz. Sampling rate: See Table 3.1. $(3/BeamFWHM) \times (336'/s)$	Sun-Earth L2 orbit with Sun-Probe-Earth $< 15°$. 5 yr survey with $\geq 95\%$ survey efficiency. Full sky survey: Spin instrument at 1 rpm; Boresight 69° off spin axis; Spin axis 26° off anti-Sun line, precessing 360° / 10hr. Pointing control: Spin axis $60'$ (3σ, radial). Spin 1 ± 0.1 rpm (3σ) Pointing stability: Drift of spin axis $< 1'/1$ min (3σ, radial); Jitter $< 20''/20$ ms (3σ, radial). Pointing knowledge (telescope boresight): $10''$ (3σ, each axis) from spacecraft attitude 1'' (3σ, each axis) final reconstructed Return and process instrument data: 1.5 Tbits/day (after 4x compression) Thermally isolate instrument from solar radiation and from spacecraft bus
	SO2. Probe the physics of the big bang by excluding classes of potentials as the driving force of inflation (§2.2.1, Figure 2)	Spectral index (n_s) and its derivative (n_{run}): $\sigma(n_s) < 0.0015$; $\sigma(n_{run}) < 0.002$	CMB polarization BB power spectrum for modes $2 < l < 1000$ to cosmic variance limit	Intensity and linear polarization across $60 < \nu < 220$ GHz over the entire sky; Foreground seperation enveloped by SO1 and less driving	Frequency resolution: $\Delta\nu/\nu_c = 25\%$. Sensitivity: See Table 3.2. Combined instrument weight of $< 0.87\,\mu K_{CMB}\sqrt{s}$. Angular resolution [for delensing and foreground separation]: FWHM = $6.2' \times (155\,GHz/\nu_c)$. Sampling rate: $(3/BeamFWHM) \times (336'/s)$.		
Discover how the universe works (Neutrino mass and N_{eff})	SO3. Determine the sum of neutrino masses. (§2.2.1, Figure 4)	Sum of neutrino masses[b] (Σm_ν): $\Sigma m_\nu < 15$ meV with DESI or Euclid	CMB polarization BB power spectrum for modes $2 < l < 4000$ to cosmic variance limit; CMB intensity maps (to give Compton Y map from which we extract clusters)				
	SO4. Tightly constrain the thermalized fundamental particle content of the early Universe (§2.2.1, Figure 3)	Number of neutrino effective relativistic degrees of freedom (N_{eff}): $\sigma(N_{eff}) < 0.03$	CMB temperature and EE polarization power spectra $2 < l < 4000$ to cosmic variance limit				
Explore how the universe evolved (reionization)	SO5. Distinguish between models that describe the formation of the earliest stars in the universe (§2.2.2, Figure 5)	Optical depth to reionization (τ): $\sigma(\tau) < 0.002$	CMB polarization EE power spectrum for modes $2 < l < 20$ to cosmic variance limit	Linear polarization across $60 < \nu < 300$ GHz over entire sky; Foreground separation enveloped by SO1 and less driving			
Explore how the universe evolved (Galactic structure and dynamics)	SO6. Determine if magnetic fields are the dominant cause of low Galactic star formation efficiency (§2.2.3)	Ratio of cloud mass to maximum mass that can be supported by magnetic field ('Mass to flux ratio' μ); Ratio of turbulent energy to magnetic energy (Alfven Mach number $\mathcal{M}_A$) on scales 0.05–100 pc	The turbulence power spectrum on scales 0.05–100 pc; Magnetic field strength (B) as a function of spatial scale and density; Hydrogen column density; Gas velocity dispersion	Intensity and linear polarization with < 1 pc resolution for thousands of molecular clouds and with < 0.05 pc for the 10 nearest molecular clouds; Maps of polarization with 1' resolution over the entire sky	Enveloped by SO1–4, except: Angular resolution: $\leq 1.1'$ (at highest frequency) Sensitivity at 800 GHz: 27.4 kJy/sr		
	SO7. Constrain the temperatures and emissivities characterizing the Milky Way's interstellar diffuse dust (§2.2.3)	Intrinsic polarization fractions of the components of the diffuse interstellar medium to accuracy better than 3% when averaged over $10'$ pixels	Fractional polarization and intensity as a function of frequency	Intensity and linear polarization maps in 12 frequency bands between 108 and 800 GHz			

[a] The values include internal delensing and an ILC foreground separation using the 21 frequency bands.
[b] Using the PICO BB lensing power spectrum and τ with BAO from DESI; or independently using PICO cluster counts and LSST data.

[2]Secondary anisotropy arise from sources other than primordial density and GW fluctuations

served 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. Understanding the mechanism generating these perturbations, which evolved to fill the universe with structures, is one of the most important open questions in cosmology.

PICO's precision measurements of temperature and E-mode polarization anisotropy would provide additional information about the statistical properties of the primordial density perturbations generated during this epoch. In addition, PICO would be exquisitely sensitive to the faint imprint gravitational waves present during recombination leave on the polarization of the CMB. Unlike density perturbations, they not only generate primordial temperature and E-mode polarization but primordial B-mode polarization [4, 5]. Any detection of primordial B-mode polarization by PICO would constitute evidence for gravitational waves from the same primordial period that created the density perturbations and open a new window on this early epoch.

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. Knowledge of the strength of the signal and its statistical properties would transform our understanding of many areas of fundamental physics.

Inflation, a period of nearly exponential expansion of the early universe [6–9], is the leading paradigm explaining the origin of the primordial density perturbations [10–14]. It predicts a nearly scale-invariant spectrum of primordial gravitational waves originating from quantum fluctuations [15]. In this sense a detection of primordial B-modes would be the first observation of a phenomenon associated with quantum gravity [16].

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.

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's goal is to detect primordial gravitational waves if inflation occurred at an energy scale of at least 4×10^{15} GeV, or equivalently a tensor-to-scalar ratio of $r = 3 \times 10^{-4}$. A detection would have profound implications for fundamental physics because it would provide evidence for a new energy scale tantalizingly close to the energy scale associated with grand-unified theories, and would allow us to probe physics at energies far beyond the reach of terrestrial colliders.

Even in the absence of a detection PICO's measurements would contain invaluable information about the early universe. There are only two classes of slow-roll inflation in agreement with current data 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 (see the right panel of Figure 1). 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. Select models in this class are shown as blue lines in Figure 2.

The second class is characterized by potentials that approach a constant as a function of field

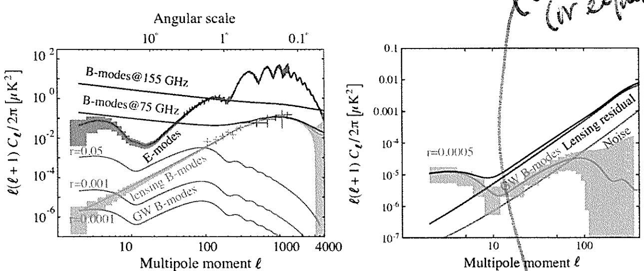

Figure 1: *Left panel: EE* (red) and lensing *BB* (green) angular power spectra and their measurement uncertainties predicted for PICO (gray), as well as the *BB* power spectrum produced by IGW with different values of r. Also shown are measurements of lensing from current experiments (orange) and *Planck* measurements of the E mode (dark blue) [17–21]. The *BB* spectra of Galactic emission on the cleanest 60% of the sky at 75 and 155 GHz (purple) dominate the cosmological signals except at $\ell \gtrsim 1000$ and over a narrow frequency band. *Right panel:* Predicted uncertainties for a detection of primordial gravitational waves with $r = 0.0005$ for PICO (gray), together with the signal (blue), the instrumental noise (orange), and the lensing residual after internal delensing (red).

value, either like a power law or exponentially. Two representative examples in this class are shown as the green and gray bands in Figure 2. This class also include R^2 inflation, which predicts a tensor-to-scalar ratio of $r \approx 0.004$. 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 $r \gtrsim 0.001$. Different values of characteristic scales are indicated by the darker lines in Figure 2. Many microphysical models in this class possess a characteristic scale that is super-Planckian, but there are models such as the Goncharov-Linde model with a somewhat smaller characteristic scale that predict a tensor-to-scalar ratio of $r \approx 4 \times 10^{-4}$ [22].

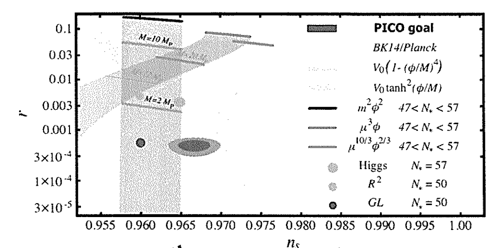

Figure 2: Current 1 and 2σ limits on r and n_s (blue) and forecasted constraints for a fiducial model with $r = 0.0005$ for PICO. Also shown are predictions for the selected models of inflation discussed in the text.

In the absence of a detection, PICO would limit the amount of gravitational waves to $r < 10^{-4}$ at 95% CL and would exclude all these models.

Let us now take a closer look at the signal. As shown in Figure 1, it has two contributions, one