PICO: mm/submm All Sky Imaging Polarimetric Survey

- PICO will produce the deepest maps of Stokes I, Q, U in 21 frequency bands between 20 and 800 GHz
- Maps will have resolution between 38’ and 1’. 8 maps, >200 GHz: highest resolution, full sky maps
- Ten redundant surveys: stringent control of systematic errors
- 13,000 transition edge sensor bolometers
- 5 year survey from L2
- Noise baseline: 3300 Planck missions (0.87 uK*arcmin)
- Noise Current estimate: 6400 Planck missions (0.61 uK*arcmin)
PICO Implementation: Heritage of Planck

- 2-reflector “Open Dragone” Telescope
- Ambient temperature primary
- 4 K aperture stop
- 4 K secondary reflector
- 0.1 K focal plane (cADR)

PICO technologies are based on extensions of technologies currently used with space and sub-orbital instruments.

Figure: JPL

80 cm; 17 kg

3-color sinuous antenna coupled

center: single color, horn coupled

Coolers, Readout

Telemetry, Flywheels, Power, Radiators

Figure: JPL
Explore How the Universe Began: Inflation

- What is the energy scale of Inflation? What is the physics driving Inflation? Can we directly observe the epoch of quantum gravity?
  - $E_{\text{inf}} = 3.7 \cdot 10^{16} r^{1/4} \text{ GeV}$
  - $B_{80} = 0.08r \mu K^2$
  - Currently $r < 0.06$ (95%) (BKA+Planck)
  - Signal is substantially weaker than Galactic foregrounds and mostly below Lensing foregrounds
  - PICO requirement
    - $r < 2 \cdot 10^{-4}$ (95%); $r = 5 \cdot 10^{-4}$ (5σ)
  - 300 times lower than current constraint

![Graph](image_url)
Textbook Inflation models that naturally explain the spectral index and have superPlanckian mass scale

Only the PICO exclusion will reject all models with superPlanckian scale in the potential with high confidence

“If this threshold is passed without detection, most textbook models of inflation will be ruled out, and the data would force a significant change in our understanding of the primordial Universe”
(Shandera et al. 2019, Community endorsed decadal white paper)
Can the foregrounds be handled?

- Right: one sky model; 21 bands; PICO noise; $n_{side}=512$; analyzed with GNILC; 50% of sky; 85% delensing
- Left: several sky models
- Residual foregrounds are $x5-10$ below $r$ for $\ell=5$; $x3-4$ below $r$ for $\ell=100$

- Bottom left: reconstructing CMB and foregrounds with 21 bands has no $r$ bias ($r=0.001$)
- Bottom right: removing low/high frequencies introduces bias
Explore How Universe Evolves: First Luminous Sources

• What lights up the Universe? Are the first luminous sources star forming galaxies, super-massive black holes, or dark matter annihilation? How long does this period last?
What lights up the Universe? Are the first luminous sources star forming galaxies, super-massive black holes, or dark matter annihilation? How long does this period last?

- Low $\ell$ EE $\rightarrow$ probe of $\tau$, the optical depth to reionization
- PICO: $\sigma(\tau) = 0.002$ (cosmic variance limited)
Determine the Nature of the First Luminous Objects

- What lights up the Universe? Are the first luminous sources star forming galaxies, super-massive black holes, or dark matter annihilation? How long does this period last?

- Low $\ell$ EE $\rightarrow$ probe of $\tau$, the optical depth to reionization

- PICO: $\sigma(\tau) = 0.002$ (cosmic variance limited)

- PICO will determine $z_{re}$
  With kSZ ($\Delta z_{re}$) constrain physical models of reionization

Planck + Stage3
PICO + Stage3
How Does the Universe Evolve: Neutrino Mass

- Only cosmology can determine the absolute mass scale if it is near the minimum allowed \( \Sigma m_\nu = 58 \text{ meV} \)

- Growth of structures is affected by sum of neutrino mass

- Sum of neutrino mass requires
  - Matter density (Baryon acoustic oscillations: DESI/Euclid)
  - Growth of structure (PICO)
  - Optical depth to reionization \( \tau \) (PICO)

- Only PICO can provide both data inputs with a consistent, self-calibrated dataset
At Least 4σ Determination of Neutrino Mass

- Only cosmology can determine the absolute mass scale if it is near the minimum allowed $\Sigma m_\nu = 58$ meV

- Growth of structures is affected by sum of neutrino mass

- Sum of neutrino mass requires
  - Matter density (Baryon acoustic oscillations: DESI/Euclid)
  - Growth of structure (PICO)
  - Optical depth to reionization $\tau$ (PICO)

- Only PICO can provide both data inputs with a consistent, self-calibrated dataset

- $\sigma (\Sigma m_\nu) = 14$ meV, 4σ, one of three independent constraints
Milky Way stars form at much lower rate than would be expected from gravitational collapse.

Gas turbulence and magnetic fields slow collapse from the diffuse ISM to molecular clouds to star forming regions.

What is the ratio of energy stored in the magnetic field to that stored in turbulent motion? How does this ratio vary over spatial scales from the diffuse ISM to dense cores, which host star formation?

Need measurements of magnetic fields over scales of galaxy down to dense cores.

Millimeter-wave polarimetry gives magnetic field parameters.
Solve Puzzle of Low Star Formation Efficiency

86,000,000 independent B field measurements; x1000 more than Planck

Planck 353 GHz polarization 5’ resolution, $\sigma_p < 0.67\%$

PICO 799 GHz polarization 1’ resolution, $\sigma_p < 0.67\%$

Orion Region

Figure: Chuss + Fissel
### Legacy Surveys Available only with PICO Data

<table>
<thead>
<tr>
<th>Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Early galaxy formation and dark matter substructure</td>
</tr>
<tr>
<td>• Early cluster formation</td>
</tr>
<tr>
<td>• Correlation of dust with galaxy properties</td>
</tr>
<tr>
<td>• Physics of jets in radio sources</td>
</tr>
<tr>
<td>• Ordering of magnetic fields in external galaxies</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Catalog</th>
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</thead>
<tbody>
<tr>
<td>• 4500 strongly lensed galaxies, z~5; (x400)</td>
</tr>
<tr>
<td>• 50,000 proto-clusters, z~4.5; (x1000)</td>
</tr>
<tr>
<td>• 30,000 galactic dust SEDs, z&lt;0.1;(x10)</td>
</tr>
<tr>
<td>• 2000 polarized radio sources; (x10)</td>
</tr>
<tr>
<td>• Polarization of few thousand dusty galaxies (x1000);</td>
</tr>
</tbody>
</table>

Data will be mined for years by astrophysicists in many sub-disciplines
Set Cosmological Paradigm for the 2030s

- 6-parameter \( \Lambda \)CDM describes the Universe well
- But tensions exist
  - 3.4\( \sigma \) between supernovae and CMB measurements of \( H_0 \)
  - 2\( \sigma \) in measurements of \( \sigma_8 \) (amplitude of fluctuations)
- What is most of the Universe made of?
- Constraint on 6-parameter \( \Lambda \)CDM:
  - PICO/Planck = 50,000 (Planck/WMAP9 = 300)
- Constraint on 11-parameter \( \Lambda \)CDM+:
  - PICO/Planck = 1.2\( \times 10^8 \)

\( \Lambda \)CDM will either survive this stringent scrutiny, or a new cosmological paradigm will emerge
Why PICO, Why Now

- Transformative science; Much of the science can only be done from space

- Further progress with CMB requires a leap in sensitivity, foreground characterization, and systematic control. Space is the most cost-effective approach.

- PICO is the only instrument with the combination of sky coverage, resolution, frequency bands, and sensitivity to achieve all of the science with one platform.

- A space mission is best suited to provide the level of control of systematic uncertainties necessary.

- PICO relies on current technologies or straightforward extensions.
Cluster Evolution
Relativistic Species
Dark Matter
Galaxy Evolution
Inflation and Quantum Gravity
Dark Energy
Neutrino Mass
Primordial Magnetic Fields
Interstellar Dust
Cosmic Birefringence
Milky Way Dynamics and Star Formation
First Luminous Sources

PROBE OF INFLATION AND COSMIC ORIGINS
SHAUL HANANY
UNIVERSITY OF MINNESOTA

PICO has strong community support

213 Authors and Endorsers

Authors
Macedo Alvarez
Emmanuel Amsel
Peter Ashdown
Jonathan Aumont
Kazushi Arai
Ranajoy Banerji
R. Beine
James G. Biretta
Sourish Banerjee
Nick Batalha
Jana Beletic
Kimberly K. Boddy
Marco Bonnet
Julian Borlum
Franogan Bouchet
Francois Bouchet
Philippe Bourdin
Jay Bunkar
Jose Chabas
David Chais
Susan R. Chiang
Joelle Coopermand

Endorsers
Maximilien Abgrall
Zhezhen Ahmad
David Albert
Matthias A. Arin
Adam Anderson
James Annis
Janos Audren
Carlo Baglaferini
Daniele Barron
Ritabh Basu Thaker
Ella Barrienta
Danilo Barmasse
Karin Behera
Bradford Benson
Pedro Bernal
Rafael Bernal
Manuel Bernal
Federico Bianchini
Daniel Bittermann

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https://z.umn.edu/picomission
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