Cluster Evolution
Relativistic Species
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Cosmic Birefringence
PROBE OF INFLATION AND COSMIC ORIGINS
SHAUL HANANY
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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
Textbook Inflation models that naturally explain the spectral index and have super-Planckian mass have:

\[ r \gtrsim 5 \times 10^{-4} \]

PICO requirement:

\[ r < 2 \cdot 10^{-4} \text{ (95\%)}; \quad r = 5 \cdot 10^{-4} \text{ (5\sigma)} \]

Only the PICO exclusion will reject all models with super-Planckian 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)
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If \( r \sim 1 \times 10^{-3} \) - PICO has:
- Systematics control: Highest SNR, most stable thermal platform, simplest design
- Foreground control: Multiple detections in independent patches of the sky

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Can the Foregrounds be Handled

- Fisher forecast that includes correlated foregrounds, foreground separation, 40% sky, and delensing gives $\sigma(r) = 2 \times 10^{-5}$
Can the Foregrounds be Handled

- Map based simulations (PySM + others), $r=0$, 50% of sky, 15% lensing, PICO noise, GNILC foreground removal with 21 bands
- Lowest $\ell$ has x2 bias relative to lensing, x10 lower than $r = 5 \times 10^{-4} (5\sigma)$
- For $\ell=100$, residual is x4 lower
- Results approximately reproduced with other models

Figure: Remazeilles

\[ r = 5 \times 10^{-4} \]
PICO SO3: 4\sigma Detection of Neutrino Mass

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

- Growth of structure is affected by neutrino mass, and the projected gravitational potential - revealed through CMB lensing maps - is a sensitive probe of the growth of structure
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- Sum of neutrino mass requires:
  - Matter density (Baryon acoustic oscillations: DESI/Euclid)
  - Growth of structure (PICO SNR=560; Planck SNR=40)
  - Optical depth to reionization (PICO $\sigma(\tau) = 0.002$)

\[ L_{100} \sim 1 \]
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\[ \Sigma m_\nu = 58 \text{ meV} \]

\[ \sigma(\tau) = 0.002 \]

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- $\sigma (\Sigma m_\nu) = 14$ meV, $(4\sigma = 56$ meV), one of three independent constraints.

Only PICO can provide two of the three inputs within a consistent, self-calibrated dataset.

No other constraint is expected to be tighter.
Light species, beyond 3 neutrinos, could have existed in the early universe and fallen out of thermal equilibrium at high temperature $T_F$.

- CMB spectra are sensitive to the number of light species $N_{\text{eff}}$
- Only 3 neutrinos gives: $N_{\text{eff}} = 3.046$
- Planck + BAO: $2.92 \pm 0.36$ (95%)
- PICO: $\Delta(N_{\text{eff}}) = 0.06$ (95%)

No other constraint is expected to be tighter.
• Milky Way stars form at much lower rate than would be expected from gravitational collapse

• Turbulence + 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 over spatial scales from the diffuse ISM to dense cores?

• Need measurements of magnetic fields over four orders of magnitude: entire galaxy ($10^4$ pc) down to dense cores (0.1-1 pc)
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

Planck (5’)

SOFIA (13”)

Figure: Chuss + Fissel
PICO Science : Galactic Magnetic fields

- Map magnetic fields in 70 external galaxies, with 100 measurements per galaxy (currently 2 are mapped)
- Map 10 nearby clouds with 0.1 pc resolution => scale of cloud cores (currently no data are available to connect magnetic fields in the diffuse ISM to that in cloud cores)

Factor of $10^4$ in spatial scale
Only PICO can generate such a dataset

86,000,000 independent B field measurements x1000 more than Planck
**Science**
- Early galaxy formation and dark matter substructure
- Early cluster formation
- Correlation of dust with galaxy properties
- Physics of jets in radio sources
- Ordering of magnetic fields in external galaxies

**Catalog**
- 4500 strongly lensed galaxies, z~5; (x400)
- 50,000 proto-clusters, z~4.5; (x1000)
- 30,000 galactic dust SEDs, z<0.1; (x10)
- 2000 polarized radio sources; (x10)
- Polarization of few thousand dusty galaxies (x1000);

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
  - $4\sigma$ 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
PICO’s Status

- 50 pg PICO report publicly available (astroph/1902.10541)
- Project paper submitted in 7/2019 (astroph/1908.07495)
- Additional information has been provided to the sub-panel on Electromagnetic Observations from Space II (12/2019)
- Work on PICO will be restarting (initial focus is on foregrounds)
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 best suited to provide this leap.

• 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.

• Next decade ground-based efforts are equivalent in cost to PICO. With more bands, higher sensitivity, better control of systematics, and simpler instrument implementation, PICO is the most cost effective path for progress.
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PICO - community-wide effort + support
213 Authors and Endorsers

https://z.umn.edu/picomission
Hanany et al. arXiv 1902.10541; 1908.07495
Extra Slides