PIXIE:
The Primordial Inflation Explorer

Al Kogut
GSFC
History of the Universe

Standard model leaves many open questions

NASA Strategic Guidance:
2010 Astrophysics Decadal Survey

Top Mid-Scale Priorities
#1: Exoplanets (TESS)
#2: Inflation

Use cosmic microwave background as backlight for thermal history of universe
Inflationary Paradigm
Quantum Physics Meets Cosmology

DAWN OF TIME
10^{-32} seconds
inflation
380,000 years
13.7 billion years
Stretched to Cosmic Scales

Quantum Fluctuations ...
Testing Inflation with CMB Polarization

Inflating Space-Time ...

Creates Gravity-Wave Background ...

B-Mode Polarization: “Smoking Gun” Signature of Inflation

Which Sources CMB Polarization

E Modes Even Parity

B Modes Odd Parity
Why Study CMB Polarization?

- **Demonstrate inflation as physical reality**
  - Trace evolution back to single quantum system
  - Oldest information in the universe

- **Measure inflationary energy scale**
  - $10^{16} \text{ GeV}$: Grand Unification theory
  - Trillion (!) times higher energy than Higgs boson

- **Observable “Theory of Everything”**
  - LIGO: Classical gravitational radiation
  - CMB: Proof that gravity obeys quantum mechanics
B-modes in a Nutshell

Requirements for Detection

- Photon-Limited Sensitivity
- Accurate Foreground Subtraction
- Immunity to Instrumental Effects
PIXIE Nulling Polarimeter

Instrument Isothermal With CMB

Beam-Forming Optics

Interfere Two Beams From Sky

Polarizing Fourier Transform Spectrometer for Broad Frequency Coverage

Multi-Moded Detectors for Photon-Limited Sensitivity

Measured Fringe Pattern Samples Frequency Spectrum of Polarized Sky Emission

\[
P_{Lx} = \frac{1}{2} \int \left( E_{Ay}^2 + E_{Bx}^2 \right) + \left( E_{Bx}^2 - E_{Ay}^2 \right) \cos(\frac{z\omega}{c}) \, d\omega
\]

\[
P_{Ly} = \frac{1}{2} \int \left( E_{Ax}^2 + E_{By}^2 \right) + \left( E_{By}^2 - E_{Ax}^2 \right) \cos(\frac{z\omega}{c}) \, d\omega
\]

Stokes Q Polarization

Zero means zero: No fringes if sky is not polarized
Frequency Coverage

Phase delay $L$ sets channel width
\[ \Delta f = \frac{c}{L} = 14.41 \text{ GHz} \]

Number of samples sets frequency range
\[ f_i = [1, 2, 3 \ldots \frac{N}{2}] \times \Delta f \]

400 Frequency Channels across 7 octaves
- 30 GHz to 6 THz
- 14 GHz frequency resolution

Legacy dataset for far-IR astrophysics
PIXIE Observatory

- Spin 1 RPM
- Beams to Sky
- Calibrator
- Fourier Transform Spectrometer
- Sun Shades
- Solar Panels
- Instrument Electronics Module
- Thermal Break
- Spacecraft
PIXIE Mission

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>August 2023</th>
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</thead>
<tbody>
<tr>
<td>Duration</td>
<td>2 years</td>
</tr>
<tr>
<td>Orbit</td>
<td>Sun-Earth L2</td>
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<tr>
<td>Launch Vehicle</td>
<td>AO 3.5m fairing</td>
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</table>
**PIXIE and Polarization**

**Definitive test for large-field inflation**
- CMB sensitivity 70 nK per 1° pixel
- Limit $r < 2 \times 10^{-4}$ for inflation amplitude

**Determine neutrino mass scale**

**Characterize astrophysical foregrounds**

**Complement Ground-Based Efforts**
- Large angular scales ($2 < \ell < 300$)
- Legacy dust foreground
- Legacy data for mm & sub-mm calibration
BUT WAIT, there's more!
Calibrator stowed: Polarization only

Calibrator deployed: Spectral distortions!

**PIXIE and Absolute Sky Spectra**

On-Board Calibrator Measures Unpolarized Sky Spectrum

\[
P_{Lx} = \frac{1}{2} \int \left( E_{Ay}^2 + E_{Bx}^2 \right) + \left( E_{Bx}^2 - E_{Ay}^2 \right) \cos(z \omega / c) \ d\omega
\]

\[
P_{Ly} = \frac{1}{2} \int \left( E_{Ax}^2 + E_{By}^2 \right) + \left( E_{By}^2 - E_{Ax}^2 \right) \cos(z \omega / c) \ d\omega
\]

**Sky Polarization**

\[
P_{Lx} = \frac{1}{2} \int \left( E_{Cal,y}^2 + E_{Sky,x}^2 \right) + \left( E_{Sky,x}^2 - E_{Cal,y}^2 \right) \cos(z \omega / c) \ d\omega
\]

\[
P_{Ly} = \frac{1}{2} \int \left( E_{Cal,x}^2 + E_{Sky,y}^2 \right) + \left( E_{Sky,y}^2 - E_{Cal,x}^2 \right) \cos(z \omega / c) \ d\omega
\]

[ Calibrator-Sky ]

Spectral Difference

**Calibrator**

Partially-assembled blackbody calibrator

Like COBE/FIRAS, But 1000x More Sensitive!

**Precision Survey for Extragalactic Backgrounds**
Spectral Distortions: Structure Formation

Integrated signal from CMB photons scattering off relativistic electrons

Dominated by intracluster gas in groups and clusters

**High signal-to-noise detection**
- Monopole: 194σ detection
- Relativistic correction: 11σ detection

Mean thermal energy in electrons
Integral constraint on feedback

**Dominated by faint unresolved sources**

Hill et al 2015

Constraints on relativistic electrons

![Graph showing intensity vs. frequency and wavelength](image)

- Y-distortion (Clusters)
- PIXIE Sensitivity (×10)
Spectral Distortions: Dark Matter Annihilation

Chemical potential \( \mu = 1.4 \frac{\Delta E}{E} \)

Annihilation rate \( \sim n^2 \sim z^6 \)

Number density \( n \sim m^{-1} \)

Neutralino mass limit \( m_\chi > 80 \text{ keV} \)

Definitive test for warm dark matter

Dark matter annihilation

PIXIE limit \( \mu < 10^{-8} \)

Neutralino mass limit \( m_\chi > 80 \text{ keV} \)

McDonald et al 2001

de Vega & Sanchez 2010
Cosmic Infrared Background

Measure the frequency spectrum, the power spectrum, and the frequency spectrum of the power spectrum.

Thermal Dust Emission from $z \sim 1-3$
- Monopole: Galaxy Evolution
- Dipole: Bulk Motion
- Anisotropy: Primordial non-Gaussianity

Limits to non-Gaussianity $f_{NL} < 1$

*PIXIE noise is down here!*

Knox et al. 2001
Fixsen & Kashlinsky 2011
Tucci et al 2016
Far-IR Tomography
Intensity Mapping with C+, N+, CO lines

- Low spatial resolution
  Integrated emission from many sources

- Multiple frequency bins
  Multiple redshift slices

- Red-shifted far-IR lines
  C+ 158 um $\rightarrow$ Star formation rate
  CO ladder $\rightarrow$ Cold gas reservoir

Cross-correlate PIXIE with redshift-tagged galaxy surveys
- Track star formation vs redshift
- 5—10% redshift bins at $z=2$—3
- Compare to continuum CIB

BOSS
- Overdensity
  - Single Redshift Slice
  - $0.51 < z < 0.53$

PIXIE
- Single Channel 1245 GHz
  - $k_{\text{Jy/str}}$
  - $7.5$
  - $6.0$
  - $4.5$
  - $3.0$
  - $1.5$
  - $0.0$
  - $-1.5$
Radio Synchrotron

PIXIE Improvements to Synchrotron Model
- Polarization amplitude in faint regions
- Zero level for intensity + polarization

Test for local-bubble synchrotron model
Multiple Decadal Goals in One MIDEX Mission

<table>
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<th>Science Goal</th>
<th>PIXIE Measurement</th>
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<tr>
<td>Inflation</td>
<td>Polarization B-modes</td>
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<tr>
<td>Neutrino Mass</td>
<td>Polarization E-modes</td>
</tr>
<tr>
<td>Reionization</td>
<td>Polarization E-modes</td>
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<td>Dark Matter</td>
<td>Spectral Distortion (γ)</td>
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<tr>
<td>Large-Scale Structure</td>
<td>Spectral Distortion (μ)</td>
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<td>Star Formation History</td>
<td>Far-IR Intensity Mapping</td>
</tr>
<tr>
<td>Radio Background</td>
<td>Synchrotron intensity + polarization</td>
</tr>
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</table>
Unique Science Capability

Full-Sky Spectro-Polarimetric Survey
- 400 frequency channels, 30 GHz to 6 THz
- Stokes I, Q, U parameters
- 49152 sky pixels each 0.9° × 0.9°
- Pixel sensitivity 6 × 10^{-26} W m^{-2} sr^{-1} Hz^{-1}
- CMB sensitivity 70 nk RMS per pixel

Legacy Archive for far-IR Astrophysics

Multiple Science Goals
- Inflation
- Neutrino Mass
- Galaxy Evolution
- Interstellar Medium

95% CL Limits:
- B-mode: r < 4 × 10^{-4}
- Distortion |μ| < 10^{-8}, |γ| < 5 × 10^{-9}
Now how much would you pay?
A Non-Cosmological Problem

Will a future Congress fund a $1B Inflation Probe?
Low-cost alternative within existing NASA budget line
NASA Explorer Program

Small PI-led missions
• 11 full missions proposed Dec 2016
• $250M Cost Cap + launch vehicle

PIXIE submitted with mature technology
• All technology TRL 6 or higher
• Cost & schedule based on flight missions

Step-1 proposal submitted Dec 2016
• Phase A down-select "Summer 2017"
• Phase B down-select late 2018
• Launch 2023
Sensitivity the Easy Way
Big Detectors in Multi-Moded Light Bucket

\[
\text{NEP}_{\text{photon}}^2 = \frac{2A\Omega (kT)^5}{e^2 \hbar^3} \int \alpha \epsilon f \frac{x^4}{e^x - 1} \left(1 + \frac{\alpha \epsilon f}{e^x - 1}\right) dx
\]

\[
\delta I_\nu = \frac{\delta P}{A\Omega \Delta \nu (\alpha \epsilon f)}
\]

Photon noise \(\sim (A\Omega)^{1/2}\)
Big detector: Negligible phonon noise

Signal \(\sim (A\Omega)\)
Big detector: S/N improves as \(\sim (A\Omega)^{1/2}\)

30x collecting area as Planck bolometers

PIXIE: \(A\Omega = 4 \, \text{cm}^2 \, \text{sr}\)

Sensitivity 70 nK per 1° x 1° pixel

See P. Nagler detector talk Thursday afternoon (9914-47)
Demonstrate multi-moded single-polarization photon-limited detectors
PIXIE Photon Noise

\[
\text{NEP}^2_{\text{photon}} = \frac{2A \Omega (kT)^5}{c^2 h^3} \int \frac{x^4}{e^x - 1} \left(1 + \frac{\alpha \epsilon f}{e^x - 1}\right) dx
\]

Compute \(\text{NEP}^2\) from photon noise
Include CMB, dust, CIB, zodiacal light

Contribution to NEP by Frequency

Galactic plane is bad for cosmology
Rest of sky is not so bad
PIXIE Photon Noise

Galactic plane is bad for cosmology
Rest of sky is not so bad

Lowpass filter on optics:
Increase CMB noise by ~20%

Integrated NEP by Frequency

\[
\text{NEP}_{\text{photon}}^2 = \frac{2A\Omega (kT)^5}{c^2 \hbar^3} \int \alpha \epsilon f \frac{x^4}{e^x - 1} \left(1 + \frac{\alpha \epsilon f}{e^x - 1}\right) dx
\]

Compute NEP\(^2\) from photon noise
Include CMB, dust, CIB, zodiacal light
Systematic Error Control
Multiple Instrumental Symmetries

Spacecraft spin imposes amplitude modulation of entire fringe pattern

Same information 4x per stroke with different time/space symmetries

Multiple Redundant Symmetries Allow Clean Instrument Signature
Multiple levels of nulling reduce systematics to negligible levels without relying on any single null
Blackbody Calibrator

Based on successful ARCADE calibrator

Note: Not To Scale

<table>
<thead>
<tr>
<th>XCal Requirements</th>
<th>Parameter</th>
<th>Requirement</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blackness (30 to 300 GHz)</td>
<td>&lt; -60 dB</td>
<td>-65 dB</td>
</tr>
<tr>
<td></td>
<td>Blackness (&gt; 300 GHz)</td>
<td>&lt; -20 dB</td>
<td>-50 dB</td>
</tr>
<tr>
<td></td>
<td>Temperature Range (Body)</td>
<td>2.6 - 3.5 K</td>
<td>2.6 - 3.5 K</td>
</tr>
<tr>
<td></td>
<td>Temperature Range (Single Cone)</td>
<td>2.6 - 20 K</td>
<td>2.6 - 20 K</td>
</tr>
<tr>
<td></td>
<td>Temperature Gradient</td>
<td>&lt; 3 μK</td>
<td>&lt; 1 μK</td>
</tr>
</tbody>
</table>
Mirror Transport Mechanism

Translate $\pm 2.54$ mm at 0.5 Hz
Optical phase delay $\pm 1$ cm
Repeatable cryogenic position

Demonstrated performance exceeds requirement by factor of ten

Engineering prototype

![Diagram showing position error vs mirror position]
**Cryogenics**

**Moonshine Thermal Gradient**
- Barrel Azimuth

**Barrel Height**

**Multi-Stage Cryogenic Design**
- Passive Sun Shades (not shown)
- 4.5 K Cryo-cooler
- 2.7 K ADR
- 0.1 K ADR

**Cryo-Cooler Compressor (280 K)**

**J-T Cold Head (4.5 K)**

**Thermal Lift Budget**

<table>
<thead>
<tr>
<th>Cooler Stage</th>
<th>Stage Temp (K)</th>
<th>CBE Loads (mW)</th>
<th>Derated Capability (mW)</th>
<th>Contingency &amp; Margin</th>
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<tbody>
<tr>
<td>Stirling (Upper)</td>
<td>68</td>
<td>2362</td>
<td>4613</td>
<td>95%</td>
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<tr>
<td>Stirling (Lower)</td>
<td>17</td>
<td>132</td>
<td>278</td>
<td>111%</td>
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<tr>
<td>Joule-Thomson</td>
<td>4.5</td>
<td>20</td>
<td>40</td>
<td>100%</td>
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<tr>
<td>ADR</td>
<td>2.6</td>
<td>6</td>
<td>12</td>
<td>100%</td>
</tr>
<tr>
<td>ADR</td>
<td>0.1</td>
<td>0.0014</td>
<td>0.03</td>
<td>2043%</td>
</tr>
</tbody>
</table>
Foreground Comparison

Unpolarized Foregrounds

Polarized Foregrounds

Intensity (W m^2 sr^-1 Hz^-1)

Frequency (GHz)

Wavelength

3 cm 3 mm 300 μm 50 μm

3 10 100 1000

Dust

CMB Unpolarized

CMB E-Mode

CMB B-Mode

PIXIE Sensitivity

Synch