The Primordial Inflation Explorer

Beyond the Power Spectrum

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B-modes in a Nutshell

**B-Mode Requirements**
- Sensitivity
- Foreground Discrimination
- Systematic Error Rejection
PIXIE Solution: Multi-Moded FTS

Diffraction Limit: $A\Omega = \lambda^2$
Single mode on each of 10,000 detectors

Conserve etendu: $N_{\text{mode}} = A\Omega / \lambda^2$
22,000 modes on each of 4 detectors

Trade angular resolution for frequency coverage and systematic error control

Only possible from space!
PIXIE Nulling Polarimeter

Instrument Isothermal With CMB

Interfere Two Beams From Sky

Beam-Forming Optics

Polarizing Fourier Transform Spectrometer

Multi-Moded Polarizing Detectors

Measured Fringe Pattern Samples Frequency Spectrum of Polarized Sky Emission

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

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

FIRAS With Polarization!
L2 Halo Orbit
- Spin axis 91 deg to sun line
- Precess scan plane to follow sun line
- Full-sky coverage every 6 months

Cryogenic instrument at L2 halo orbit
- Spin at 1 RPM about instrument boresight
- Scan once every 8.5 hours about sun line
Sensitivity the Easy Way
Big Detectors in Multi-Moded Light Bucket

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

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

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

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

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

30x collecting area as Planck bolometers

Sensitivity 70 nK per 1° x 1° pixel

PIXIE polarization-sensitive bolometer
Foregrounds the Easy Way

Phase delay $L$ sets channel width
$\Delta \nu = c/L = 15 \text{ GHz}$

Number of samples sets frequency range
$\nu_i = 15, 30, 45, \ldots (N/2)\Delta \nu$

Example:
24 samples during fringe sweep
12 channels 15 GHz to 180 GHz

But why stop there?
Foregrounds the Easy Way

Phase delay $L$ sets channel width

$$\Delta \nu = \frac{c}{L} = 15 \text{ GHz}$$

Number of samples sets frequency range

$$\nu_i = 15, 30, 45, \ldots \left(\frac{N}{2}\right) \Delta \nu$$

Sample more often: Get more frequency channels!

390 more channels to 6 THz
PIXIE Photon Noise

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

Compute NEP^2 from photon noise
Include CMB, dust, CIB, zodiacal light

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

Contribution to NEP by Frequency

\begin{align*}
\text{NEP}^2 (\text{aW}^2 / \text{Hz}) & \quad \text{Frequency (THz)} \\
\text{Galactic Center} & \quad 10^4 \\
\text{Median Sky} & \quad 10^5 \\
\text{Darkest 10\%} & \quad 10^6
\end{align*}
The Planck mission

Fig. 21. Dust polarization amplitude map, \( P = pQ^2 + U^2 \), at 353 GHz, smoothed to an angular resolution of 100, produced by the di\( \text{use} \) component separation process described in (Planck Collaboration X 2015) using Planck and WMAP data.

Fig. 22. All-sky view of the magnetic field and total intensity of dust emission measured by Planck. The colours represent intensity. The "drapery" pattern, produced using the line integral convolution (LIC, Cabral & Leedom 1993), indicates the orientation of magnetic field projected on the plane of the sky, orthogonal to the observed polarization. Where the field varies significantly along the line of sight, the orientation pattern is irregular and difficult to interpret.

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

No filter on optics:
Increase CMB noise by factor ~2

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

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

Integrated NEP by Frequency

Integrated NEP (aW Hz\(^{-1}/\))
**Planck Collaboration: The Planck mission**

**Fig. 21.** Dust polarization amplitude map, $P = P_0 + U$, at 353 GHz, smoothed to an angular resolution of 10', produced by the diuse component separation process described in (Planck Collaboration X 2015) using Planck and WMAP data.

**Fig. 22.** All-sky view of the magnetic field and total intensity of dust emission measured by Planck. The colours represent intensity. The "drapery" pattern, produced using the line integral convolution (LIC, Cabral & Leedom 1993), indicates the orientation of magnetic field projected on the plane of the sky, orthogonal to the observed polarization. Where the field varies significantly along the line of sight, the orientation pattern is irregular and difficult to interpret.

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**PIXIE Photon Noise**

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

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

Integrated NEP by Frequency

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

Lowpass filter on optics:
Increase CMB noise by ~20%
Why Add THz Channels?

The Usual Prescription

Put a zebra into your sim ... 

... Fit for zebra parameters
Nfeet, NStripes, B/W ratio...
Why Add THz Channels?

The Usual Prescription

Put a zebra into your sim ...

... Fit for zebra parameters
Nfeet, NStripes, B/W ratio ...

What if Nature had something else in mind?
Why Add THz Channels?

Pick one dust model for simulation input
Fit sim using different dust model

Easy to get non-trivial CMB bias ($\Delta r > 10^{-3}$)
Despite excellent fit to combined sky emission

Need THz data to distinguish dust models

CMB residuals when
Input = transient model
Output = other model
45 channels, 30 to 500 GHz
PIXIE “Forefront Machine”

- Sensitivity plus broad frequency coverage
  - Foreground S/N > 100 in each pixel and freq bin
  - Spectral index uncertainty ±0.001 in each pixel

- Spectral coverage spanning 7+ octaves
  - Polarized spectra from 30 GHz to 6 THz
  - 400 channels with mJy sensitivity per channel

- If PIXIE can’t figure out the foregrounds, it probably can’t be done!
Systematic Error Control

Lesson from FIRAS:
Parts-per-billion measurement requires null measurement plus multiple levels of modulation

The 11th Commandment

XI
THOU SHALT NOT COMMIT SYSTEMATICS
If the sky, calibrator, and instrument are all maintained at the same temperature, then the system can not generate error signal.

**Thermal Physics:**
Blackbody spectrum depends on temperature, and *only* on temperature!

Imager: Telescope at 4 K
ΔT = 1.3 K lever for systematics

PIXIE: Instrument at 2.725 K
ΔT = 0.005 K lever for systematics

*Isothermal operation alone reduces systematic errors by factor 300!*
Systematic Errors II
Chain Multiple Nulls Together

- Maximum $\Delta T$: few mK
- Mirror Emissivity: $\times 0.01$ tens of uK
- Left/Right Asymmetry: $\times 0.01$ few hundred nK
- Swap hot vs cold: $\times 0.01$ few nK

Uncorrected Error: few nK (with blue-ish tinge)
Corrected Error: $\ll 1$ nK

Multiple levels of nulling reduce systematics to negligible levels without relying on any single null.
Symmetry and Systematic Error

20 Ways to Fix An Error

<table>
<thead>
<tr>
<th>Symmetry</th>
<th>Mitigates</th>
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</thead>
<tbody>
<tr>
<td>x vs y Polarization</td>
<td>Pointing</td>
</tr>
<tr>
<td>Left vs Right Detector</td>
<td>Particle Hits</td>
</tr>
<tr>
<td>A vs B Beam</td>
<td>Differential loss</td>
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<tr>
<td>Real vs Imaginary FFT</td>
<td>Detector heat capacity</td>
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<tr>
<td>Forward vs Backward FTS</td>
<td>Microphonics</td>
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<td>Calibrator over A vs B</td>
<td>Calibration, Beam</td>
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<td>Calibrator Hot vs Cold</td>
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<tr>
<td>Ascending vs Descending</td>
<td>Far sidelobes, calibration</td>
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<tr>
<td>Spin m = 2</td>
<td>Electronics</td>
</tr>
<tr>
<td>Spin m = 1, 3 to 12</td>
<td>Beam asymmetries</td>
</tr>
</tbody>
</table>

Multiple nulls combine to reduce systematic errors
- Isothermal instrument: 300x better than FIRAS
- Multiple symmetries: no reliance on any single one
- Estimated systematic errors < 1 nK
PIXIE and Polarization

Sensitivity $r < 2 \times 10^{-4}$ (68% CL)

CMB sensitivity 70 nK per 1° pixel
Test / characterize minimal inflationary models

Cosmic-variance-limited EE spectrum
Characterize astrophysical foregrounds

Complement Ground-Based Efforts
- Large angular scales ($2 < \ell < 300$)
- Legacy dust foreground
- EE to get reionization / tau
- Improve limits on neutrino mass
- Legacy data for mm & sub-mm calibration

Do From Space That Which Can Only Be Done From Space
BUT WAIT, there's more!
Blackbody Calibrator Tests Blackbody Distortions

Calibrator stowed: Polarization only

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

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

Sky Stokes Q

Calibrator deployed: Spectral distortions!

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

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

[ Calibrator-Sky ]

Spectral Difference

Like FIRAS, But 1000x More Sensitive!
Spectral Distortion from Energy Release

Optically thin case: Compton $y$ distortion

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(x) - 1} \left[ 1 + \frac{yx \exp(x)}{\exp(x) - 1} \left( \frac{x}{\tanh(x/2) - 4} \right) \right]$$

$$y = \int \frac{kT_e}{mc^2} ncs_oT \, dt$$

Optically thick case: Chemical potential distortion

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(\frac{h\nu}{kT} + \mu) - 1}$$

$$\mu = 1.4 \frac{\Delta E}{E}$$

Distortion to blackbody spectrum proportional to integrated energy release
PIXIE Spectral Capability

- Improve COBE by factor of 1000
  \[|\mu| < 10^{-8}\]
  \[|y| < 2 \times 10^{-9}\]

- Expect significant detections
  - 1500σ for cluster \(y\) distortion
  - 95σ for reionization \(y\) distortion
  - 3σ for inflation \(\mu\) distortion

- Open new discovery space
  - Dark matter annihilation
  - Exotic physics

- Bring spectral distortions to same precision as B-mode polarization
Planck measures thermal SZ effect

Monopole floor: $y > 5.4 \times 10^{-8}$

**PIXIE 50-sigma detection**

**Contribution from unresolved sources**

**Total monopole**: $y = 1.6 \times 10^{-6}$

**PIXIE 1500-sigma detection**

- **Dipole**: Compare to CMB at $z=1000$
  Gravitational accelerations

- **Cross-correlate vs redshift surveys**
  Growth of structure
Spectral Distortions: Inflation

Energy release at $10^4 < z < 10^6$

Chemical potential $\mu = 1.4 \frac{\Delta E}{E}$

PIXIE limit $\mu < 10^{-8}$

PIXIE 3-sigma detection

Spectral distortions extend tests of inflation by 4 orders of magnitude in physical scale

- Scalar index and running
- Non-Gaussian $f_{\text{NL}}$
- Tensor index and running

Test inflation at solar-mass scales!

Daly 1991
Hu, Scott, & Silk 1994
Chluba, Erickcek, & Ben-Dayan 2012
Sunyaev & Khatri 2013

Triple the number of e-folds from inflation
**Spectral Distortions: Dark Matter Annihilation**

Dark matter annihilation

- **PIXIE limit** $\mu < 10^{-8}$
- **Neutralino mass limit** $m_\chi > 80$ keV
- **Definitive test for warm dark matter**

**Chemical potential**

$$\mu = 1.4 \frac{\Delta E}{E}$$

**Annihilation rate**

$$\sim n^2 \sim z^6$$

**Number density**

$$n \sim m^{-1}$$

Derivation:

$$m_\chi > 80 \text{ keV} \left[ f \left( \frac{\mu}{5 \times 10^{-8}} \right) \left( \frac{\sigma v}{6 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}} \right) \left( \frac{\Omega_\chi}{0.112} \right)^2 \right]^{1/2}$$

**Graphical Representation**

- **Frequency (GHz)**
- **Wavenumber (cm\(^{-1}\))**
- **Power Spectral Density**
  - $y = 1 \times 10^{-8}$
  - $\mu = 5 \times 10^{-8}$

*McDonald et al 2001*
*de Vega & Sanchez 2010*
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 $6 \times 10^{-26}$ W m$^{-2}$ sr$^{-1}$ Hz$^{-1}$
- CMB sensitivity 70 nk RMS per pixel

Legacy Archive for far-IR Astrophysics

Multiple Science Goals
- Polarization / inflation
- Tau / neutrino mass
- Spectral distortions / growth of structure
- ISM and Dust Cirrus

B-mode: $r < 2 \times 10^{-4}$ (1σ)
Distortion $|\mu| < 10^{-8}$, $|y| < 5 \times 10^{-9}$

\[
\text{Angular Scale (Deg)} \quad \begin{array}{cccccc}
90 & 30 & 10 & 3 & 1 & 0.3 \\
\end{array}
\]

\[
\text{Multipole } \ell \quad \begin{array}{cccccc}
1 & 10 & 100 & 1000 \\
\end{array}
\]

\[
\text{B-Mode Power } C_{\ell} (\mu K^2) \quad \begin{array}{cccccc}
10^0 & 10^{-2} & 10^{-4} & 10^{-6} \\
\end{array}
\]

\[
\text{Inflation } (r=0.01) \\
\text{Planck} \\
\text{PIXIE Sensitivity} \\
\text{Lensing} \\
\text{SPT} \\
\text{POLARBEAR} \\
\text{BICEP2} \times \text{Planck}
\]

\[
\text{Intensity } (W \text{ m}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}) \\
\text{Frequency (GHz)} \quad \begin{array}{cccccc}
10 & 100 & 1000 \\
\end{array}
\]

\[
\text{Y-distortion (Clusters)} \\
\text{Y-Distortion (Reionization)} \\
\text{Mu-Distortion (Inflation)} \\
\text{Dust} \\
\text{Synchrotron} \\
\text{PIXIE Sensitivity}
\]
Small PI-led missions
- 22 full missions proposed Feb 2011
- $200M Cost Cap + launch vehicle

PIXIE not selected; urged to re-propose
- Top (Category I) science rating
- Broad recognition of science appeal

Re-propose to next MIDEX AO (2016)
- Technology is mature
- Launch early next decade

"PIXIE's spectral measurements alone justify the program"
-- NASA review panel
Coming Soon From a Spacecraft Near You!
Spectral Distortions: Reionization

E-mode optical depth $\sim$ Electron density $n$

**Same scattering for both signals**

Combine to get $n$ and $T_e$

- $T_e$ probes ionizing spectrum
- Distinguish Pop III, Pop II, AGN

Determine nature of first luminous objects

Spectrum: $y$ distortion $\sim$ Electron pressure $\int n k T_e$

- PIXIE limit $y < 5 \times 10^{-9}$
- Signal $y \sim 10^{-7}$

PIXIE 95-sigma detection (but buried under IGM)
Cosmic Infrared Background

Thermal Dust Emission from $z \sim 1--3$
- Monopole: Galaxy Evolution
- Dipole: Bulk Motion
- Anisotropy: Matter power spectrum

Frequency coverage over CIB peak
- Complement Herschel, Planck

Measure the frequency spectrum, the power spectrum $C_\ell$, and the frequency spectrum of the $C_\ell$

**PIXIE noise is down here!**

Knox et al. 2001
Fixsen & Kashlinsky 2011
Spectral Line Emission

400 Spectral Maps
Stokes I, Q, U
$\Delta \nu = 15$ GHz

Extremely Rich Data Set!

Continuum Emission
- Synchrotron, Dust

Line Emission
- CO, C+, N+, O, …

Dust Physics
- Silicate vs carbonaceous dust
- Large-scale magnetic field

Diffuse ISM
- Temperature, Density
- Energy Balance
- Metallicity
Foreground Comparison

Polarized Foregrounds

Unpolarized Foregrounds
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
PIXIE Nulling Polarimeter

Measured Fringe Pattern
Samples Frequency Spectrum of Polarized Sky Emission

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

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

Stokes \( Q \)

Nulling Polarimeter: Zero = Zero
Demonstrate multi-moded single-polarization photon-limited detectors
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>Blackness (30 to 300 GHz)</td>
<td>&lt; -60 dB</td>
<td>-65 dB</td>
<td></td>
</tr>
<tr>
<td>Blackness (&gt; 300 GHz)</td>
<td>&lt; -20 dB</td>
<td>-50 dB</td>
<td></td>
</tr>
<tr>
<td>Temperature Range (Body)</td>
<td>2.6 - 3.5 K</td>
<td>2.6 - 3.5K</td>
<td></td>
</tr>
<tr>
<td>Temperature Range (Single Cone)</td>
<td>2.6 - 20 K</td>
<td>2.6 - 20 K</td>
<td></td>
</tr>
<tr>
<td>Temperature Gradient</td>
<td>&lt; 3 μK</td>
<td>&lt; 1 μK</td>
<td></td>
</tr>
</tbody>
</table>
Instrument Cryogenics

**Fully cryogenic instrument**
- Cryo-cooler to 4.5 K
- ADR to 2.7 K (instrument body)
- ADR to 0.1 K (detectors)

**Tolerant thermal design**
- Robust design/performance margins
- Active thermal control for all optical surfaces
- Thermal “backbone” tolerant vs temperature excursions

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**Instrument 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>
</tr>
</thead>
<tbody>
<tr>
<td>Stirling (Upper Stage)</td>
<td>68</td>
<td>2362</td>
<td>4613</td>
<td>95%</td>
</tr>
<tr>
<td>Stirling (Lower Stage)</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>iADR</td>
<td>2.6</td>
<td>6</td>
<td>12</td>
<td>100%</td>
</tr>
<tr>
<td>dADR</td>
<td>0.1</td>
<td>0.0014</td>
<td>0.03</td>
<td>2043%</td>
</tr>
</tbody>
</table>

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**PIXIE Instrument Heat Flow**

- Heat flow values in mW.

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