POLARBeaR
POLARization of the Background Radiation

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Introduction
Gravitational waves from inflation → probe the first instant of the Universe

design → ratio tensor-to-scalar \( r \sim 0.025 \)

High fidelity detection of E-modes

B-modes have not been detected yet

Probe the B-modes from gravitational lensing
→ constraint on the total neutrino mass
→ early action of dark energy

4' beams → entire angular scale

from Bicep 2 years, Chiang et al., 2009.
POLARBeaR concept

sensitivity

→ 1274 TES bolometers @ 150 GHz

→ Switch focal plane for 90, 220 GHz

systematic errors control

→ small beam: reduced beam systematics

→ Multiple Polarization Modulations using Sky Rotation (Chile) and Half Wave Plate (HWP)

→ Low sidelobe optics

→ Sky Patches Coordinated with QUIET

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POLARBeaR deployment

→ telescope assembly done

→ lab tests for the cryostat (check for detector performance, NET measurement, etc.)

→ Spring 2010 : testing phase at Cedar Flat, California

→ November 2010 : Chile deployment
POLARBeaR design

- Primary mirror
- Primary guard ring
- Inner ground shield
- Receiver
- Secondary mirror
- Azimuth bearing
- Elevation bearing

3.6 m
POLARBeaR design

- Cryogenics (use of pulse-tube cooler)
- Cold reimaging optics
- Focal plane
- Rotating HWP (sapphire modulating the incoming polarization)
POLARBeaR focal plane

→ 2 Wafers at Cedar Flat California

→ 7 Hexagonal wafers in Chile

→ 637 Pixels/1274 bolometers @ 150 GHz

→ NEQ/U = 20 K s^{1/2}

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POLARBeaR focal plane

Bias and readout wires

2 wafers for Cedar Flat, California
POLARBeaR pixel

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POLARBeaR
Dfmux readout

capacitors/inductors

FPGA-based Oscillator-Demodulators

squids

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POLARBeaR HWP

Single plate Sapphire
AR coated
~70K
Designed for both continuous and stepped rotation
Ball bearing
Belt driven / stepper motor
Optical encoder readout
~ arcsec repeatability for stepped HWP

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\[ TOD(t) = C \left[ I - \epsilon Q \cos(4\rho(t) - 2\alpha) + \epsilon U \sin(4\rho(t) - 2\alpha) \right] \]
POLARBeaR groundshielding

Goal: Ground must be suppressed by $\sim 10^9$
- Cylindrically symmetric
- Curved panels
- Extra tall to shield mountains

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POLARBeaR systematic errors control

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POLARBeaR systematic errors

- Foregrounds
- Ghost reflections
- Band mismatch
- HWP Synchronous Signals
- Array temperature stability
- Atmosphere
- Polarization calibration
- Ground/sidelobes
- Telescope flexure
- Beam distortions
- Choice of observed patches, multifrequency
- Simulation/subtraction routines
- Lab calibration, polarized objects on the sky (crab nebula)
- Scan strategy
- HWP
- Small beam size
- Beam measurement
POLARBeaR scan strategy

Each hour:
- EL1 → EL2
- Scan in AZ, fixed EL ~ 1 hour
- Re-center scan each hour
- Choose centers for uniformity
- Choose HWP stepping scheme
- Scans of Planets (Jupiter, Mars) and sky
dips for calibration
Foregrounds and Scan Regions

→ Scan is targeted at low dust contrast regions as low as ~2μK intensity

→ 90, 150 & 220 GHz bands

→ Patches coordinated with QUIET
conclusion
# POLARBeaR Chile version summary

<table>
<thead>
<tr>
<th>Frequencies</th>
<th>90/150/220 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular resolutions</td>
<td>7' : 90 GHz</td>
</tr>
<tr>
<td></td>
<td>4' : 150 GHz</td>
</tr>
<tr>
<td></td>
<td>2.7' : 220 GHz</td>
</tr>
<tr>
<td>Field centers and sizes</td>
<td>Coord w/ QUIET</td>
</tr>
<tr>
<td></td>
<td>1000 deg$^2$ total</td>
</tr>
<tr>
<td>Detector type</td>
<td>Bolometer/TES</td>
</tr>
<tr>
<td>Instrument NEQ/U</td>
<td>360/\sqrt{1288/4} = 20 K s$^{1/2}$</td>
</tr>
<tr>
<td>Telescope type</td>
<td>Gregorian/lenses</td>
</tr>
<tr>
<td>Polarization Modulations</td>
<td>HWP, sky rotation</td>
</tr>
<tr>
<td>Location</td>
<td>Atacama</td>
</tr>
<tr>
<td>Observation start date</td>
<td>2010</td>
</tr>
<tr>
<td>Planned observing time</td>
<td>1000/250 elapsed/effective days</td>
</tr>
<tr>
<td>Projected limit on $r$</td>
<td>0.025 95% c.l.</td>
</tr>
</tbody>
</table>
Thank you for your attention
STOP
POLARBeaR design

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<table>
<thead>
<tr>
<th>Systematic</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crosspolar beam</td>
<td>E ↔ B</td>
</tr>
<tr>
<td>Polarization angle errors</td>
<td>E ↔ B</td>
</tr>
<tr>
<td>Pointing errors (on Q/U)</td>
<td>E ↔ B</td>
</tr>
<tr>
<td>Main beam asymmetry (before differencing)</td>
<td>dT ↔ B</td>
</tr>
<tr>
<td>Sidelobes</td>
<td>dT ↔ B</td>
</tr>
<tr>
<td>Instrumental polarization</td>
<td>dT ↔ B</td>
</tr>
<tr>
<td>Relative calibration errors</td>
<td>dT ↔ B</td>
</tr>
<tr>
<td>Pointing errors before differencing</td>
<td>T ↔ B</td>
</tr>
<tr>
<td>Gain drift before differencing</td>
<td>T ↔ B</td>
</tr>
<tr>
<td>Optics and spillover T variations</td>
<td>dT_{opt} ↔ B</td>
</tr>
<tr>
<td>Scan modulated cold stage variations</td>
<td>dT_{cs} ↔ B</td>
</tr>
<tr>
<td>Band shape errors, including modulator effects</td>
<td>foregrounds ↔ B</td>
</tr>
<tr>
<td>Others?</td>
<td>?</td>
</tr>
</tbody>
</table>
Comment l'Univers a commencé ? Avec une période d'inflation ?

- curvature \( \sim 0 \)
- Universe is isotropic
- Origine for the big structures in the Universe
- magnetic monopoles
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\[
\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{8\pi} \left| \vec{\epsilon} \cdot \vec{\epsilon}' \right|^2
\]

Density, Vorticity, Gravity Waves

Quadrupole Anisotropy

Thomson Scattering

Linear Polarization
Gravitational waves
( + lensing + systematics + ...)

Symmetry break \( \rightarrow \) \( \text{rot}(B) \neq 0 \)

E-mode

B-mode
\[ \Theta \equiv \frac{\Delta T}{T} (\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_l^m (\theta, \phi) \]

<table>
<thead>
<tr>
<th>100% Q</th>
<th>100% U</th>
<th>100% V</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ +Q ]</td>
<td>[ +U ]</td>
<td>[ +V ]</td>
</tr>
<tr>
<td>[ y ]</td>
<td>[ y ]</td>
<td>[ y ]</td>
</tr>
<tr>
<td>[ x ]</td>
<td>[ x ]</td>
<td>[ x ]</td>
</tr>
<tr>
<td>[ Q &gt; 0; U = 0; V = 0 ] [ (a) ]</td>
<td>[ Q = 0; U &gt; 0; V = 0 ] [ (c) ]</td>
<td>[ Q = 0; U = 0; V &gt; 0 ] [ (e) ]</td>
</tr>
<tr>
<td>[ Q &lt; 0; U = 0; V = 0 ] [ (b) ]</td>
<td>[ Q = 0, U &lt; 0, V = 0 ] [ (d) ]</td>
<td>[ Q = 0; U = 0; V &lt; 0 ] [ (f) ]</td>
</tr>
</tbody>
</table>

\[ Q(\hat{n}) + iU(\hat{n}) = \sum_{lm} (2a_{lm} \ Y_{lm}(\hat{n})) \]

\[ Q(\hat{n}) - iU(\hat{n}) = \sum_{lm} (-2a_{lm} \ Y_{lm}(\hat{n})) \]

\[ E a_{lm} = -\frac{2a_{lm} + \frac{-2a_{lm}}{2}}{2} \]

\[ B a_{lm} = \frac{i \ Y_{lm} - \frac{-2a_{lm}}{2}}{2} \]

\[ \langle E a_{lm} E a_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_{l}^{EE} \]

\[ \langle a_{lm} E a_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_{l}^{TE} \]

\[ \langle B a_{lm} B a_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_{l}^{BB} \]

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POLARBeaR performance

\( (l+1)C_l/2\pi (\mu K^2) \)

- Synchrotron
- Dust
- Noise
- 150 GHz
- 220 GHz

\( l \) vs. \( \log_{10} C_l \)

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POLARBEAR Detector performance

**Polarization Purity**

- Polarizer Angle (degrees)
- Response to chopped load (arb)
- Fit: $(1+\delta) \cdot A \cdot \cos^2(\pi/180(\text{angle} - q)) + h$
- $A, q$ depend on setup
- $\delta = 0.019$

**Receiver Spectrum**

- Frequency (GHz)
- Transmittance
- Atmosphere
- Design
- Measured

**Beam map**

- $\tan(\theta) \cos(\phi)$
- $\tan(\theta) \sin(\phi)$
- E-Plane
An example of **POLARBeaR** systematic error: the atmosphere contamination.

**Kolmogorov turbulences**

\[(L_0, L_i, \ldots)\]

**Wind**

(wind speed, profile)

**Water vapor distribution**

\((C_0, T_0, z_0, \ldots)\)

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