Cosmic Inflation and Neutrino Masses at POLARBEAR CMB Polarization Experiment

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On behalf of POLARBEAR/ Simons Array Collaboration
POLARBEAR Collaboration

8 countries, 20 institutes, ~100 people

PI : Adrian Lee (UC Berkeley)
Outline

- POLARBEAR Project
  - Motivations: Inflation and $\nu$ masses
  - Instruments and Observation
- Recent achievements
- Status & Prospects
  - POLARBEAR–2/Simons array
- Summary
What’s POLARBEAR?

- POLARBEAR is
  - Ground-based CMB Polarization Experiment
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  • Ground-based CMB Polarization Experiment
  • Aiming the detection/characterization of ‘B-mode (odd-parity)’ polarization pattern originating primordial gravitational wave and gravitational lensing effect.
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Science targets are
  “Inflation” and “Neutrino masses”!
Science with CMB B-mode

Thomson Scattering on LSS

Quadrupole Anisotropy

HOT

COLD

Thomson Scattering

Linear Polarization
Science with CMB B-mode

Thomson Scattering on LSS

\[ E \text{-mode} \]
Science with CMB B-mode

Gravitational Wave

Thomson Scattering on LSS

E-mode
Science with CMB B-mode

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B-mode

- Thomson Scattering
- Quadrupole Anisotropy
- Linear Polarization

Thomson Scattering on LSS
Science with CMB B-mode

Inflation

Gravitational Wave

Thomson Scattering on LSS

B-mode

MASAYA HASEGAWA
B-mode is a smoking gun signature of inflationary universe!
B-mode power is proportional to tensor-to-scalar ratio, $r$

$$V^{1/4} = 1.06 \times 10^{16} \times \left(\frac{r}{0.01}\right)^{1/4} \text{GeV}$$
Inflation

Gravitational

Thomson

W

B-mode

\[ V^{1/4} = 1.06 \times 10^{16} \times \left( \frac{r}{0.01} \right)^{1/4} \text{GeV} \]

B-mode power is proportional to tensor-to-scalar ratio, \( r \)

\( 10^{12} \times \text{LHC (13TeV)} \)

\( 10^5 \times \text{GZK cut-off (10}^{20}\text{eV)} \)

\( \rightarrow \) CMB B-mode is a potential window onto the truly-unexplored ultra-high energy phenomenon
Neutrino Mass

Neutrino Oscillation

$\Delta m^2_{\text{atm}} \sim 10^{-3} \text{ eV}^2$
$\Delta m^2_{\text{sol}} \sim 10^{-5} \text{ eV}^2$

$\rightarrow \Sigma m_\nu > 0.10 \text{ (IH)}$ or $0.05 \text{ eV (NH)}$

- Oscillation experiments confirmed “non-zero neutrino masses”, but its absolute scale is still unknown.
- The region of interest is sub-eV region.

$0.05 \text{ eV} < \Sigma m_\nu < \sim 1.3 \text{ eV}$

Neutrinos are relativistic at LSS.
Neutrino Mass

Probes to sub-eV Neutrino Mass

(Particle physics) Single Beta Decay

• Effective Mass
• KATRIN will reach 200meV sensitivity in ~5 years.

(Particle and Nuclear Physics) 0-ν Double Beta Decay

• Majorana Mass
• Sensitivity below 100 meV in 5 years (KamLAND…)

(Cosmology and Astrophysics) Large Scale Structure

• Sum of ν Masses
• Sensitivity below “oscillation limit” in ~5 years.

Probe \( \Sigma m_\nu \) is complementary to that from particle physics.
Neutrino Mass

Probes to sub-eV Neutrino Mass

(Particle physics)
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Lensing B-mode
Lensing B-mode

Pure E-mode (even-parity) @LSS

Distorted by gravitational lensing

E-mode leaks into B-mode

~1100

Now
B-mode is the signature of lensing, and good tracer of LSS.
The lensing B-mode amplitude is sensitive to $\Sigma m_\nu$. 

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**Lensing B-mode Power**

![Graph showing the B-mode power against multipole moment](image)

- $\Sigma m_\nu = 0$ eV
- $\Sigma m_\nu = 0.05$ eV
- $\Sigma m_\nu = 0.10$ eV
POLARBEAR Experiment
POLARBEAR Site

Atacama, Chile (~5200m altitude)

Huan Tran Telescope
Huan Tran Telescope (HTT)

- Off-axis Gregorian-Dragone
- 2.5m primary precision machined mirror $\rightarrow$ FWHM $= 3.5'$ achieved

Good enough angular resolution to measure the lensing B-mode signal
POLARBEAR-1 Focal Plane

637 pixels
(91 pixels/wafer x 7 wafers)
1274 TES bolometers

Array sensitivity : $23\mu K\sqrt{s}$
POLARBEAR-1 Focal Plane

Superconducting Transition Edge Sensor (TES)

Polarization is measured by pair-differencing

Antenna (dual-polarization double-slot dipole antenna)

Micro strip filter (150GHz)

23µK vs

Array sensitivity : 23 µK√s

91 pixels (182 bolometers) per wafer under AR-coated lenslet.

Total: 7 wafers = 637 pixels (1274 bolometers)

2 TES bolometers/pixel with dual-polarization double-slot dipole antenna

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POLARBEAR-1 Focal Plane

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Observation

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- Released three lensing B-mode results using 1st season data.
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First season polarization data

- Three fields, 24.5 deg² total sky area
- Map depth : 5.5 μK-arcmin

The cosmological polarized signal is visible in the map domain.
First-Season POLARBEAR Results

(1) BB Power Spectrum

- First measurement of lensing-B mode spectrum.
- 97.2% rejection of “no lensing B-mode”
- Amplitude is consistent with $\Lambda$CDM expectation

$A_L = 1.12 \pm 0.61 \text{(stat.)} + 0.04 - 0.10 \text{(sys.)}$

Astrophys. J. 794, 171
First-Season POLARBEAR Results

(2) Lensing deflection power spectrum

\[
\begin{align*}
\delta_{EE}(L) &\propto \sum_{l} E(l) E(l') \\
\delta_{EB}(L) &\propto \sum_{l} E(l) B(l')
\end{align*}
\]

(Hu, Okamoto, 2002)

4pt correlation
First-Season POLARBEAR Results

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Observed direction

\( \mathbf{d} \): deflection field

True direction

4pt correlation

POLARBEAR

observer
First-Season POLARBEAR Results

(2) Lensing deflection power spectrum

4.2σ rejection of “no lensing B-modes”

“First measurement of polarization lensing” with CMB data alone


(Editor’s suggestion)

[Diagram showing observed and true directions, labeled with "d : deflection field" and "observed direction" vs "true direction" and "observer"]
First-Season POLARBEAR Results

(2) Lensing deflection power spectrum

4.2σ rejection of “no lensing B-modes”

“First measurement of polarization lensing” with CMB data alone


(3) Cross correlation with Cosmic Infrared Background

(Herschel/SPIRE)
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4.0σ evidence of gravitational lensing of CMB polarization

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We successfully measure the lensing B-mode with CMB data alone.


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4.2σ rejection of “no lensing B-modes”

We successfully measure the lensing B-mode with CMB data alone.

(3) Opening the new era of “B-mode” cosmology!

(Editor’s suggestion)
Next: POLARBEAR-2

POLARBEAR-1
1274 detector array

POLARBEAR-2 focal plane

• Larger focal plane (Φ365)
  • 7588 bolometers (~6x increase in mapping speed)
• Multi-chroic pixels with 95/150GHz frequency coverage.
PB2 receiver assembly @ KEK

250mK focal plane
(6x the PB1 bolometers)

Re-imaging lenses(4K), IR filter(50K)

The receiver will be shipped to Chile next spring.
(Start taking data in early summer next year)
Simons Array

Simons Array (= 3 x PB2)

- 22,764 bolometers
- Resolution : 3.5’ @150GHz
- 3 frequency bands
  (95/150/220GHz)
- Wide sky survey (f_{sky}=65%)

Measurement of B-mode spectrum with unprecedented precision.

Leverage POLARBEAR experience to rapidly increase sensitivity
Simons Array (projected) sensitivity

Foreground rejection with 95/150/220 GHz, Planck, & C-BASS data

Inflation
- $\sigma(r=0.1) = 6 \times 10^{-3}$
- $\sigma(\Sigma m_\nu) = 40$ meV

Neutrino mass
- $\sigma(\Sigma m_\nu) = 19$ meV

w/ DESI, BAO

Simons array can contribute to cosmology and particle physics significantly.
Summary

• POLARBEAR is a ground-based CMB polarization experiment, aiming to reveal the inflationary universe and neutrino absolute mass scale.

• POLARBEAR-1: the first measurement of lensing B-mode signal at $4.7\sigma$ with CMB data alone, and successfully laid the groundwork for neutrino mass measurement.

• POLARBEAR-2/Simons Array is being prepared. Stay Tuned!