First Results from CMB Polarization Experiment POLARBEAR

Haruki Nishino (Kavli IPMU) for the POLARBEAR collaboration
Cosmic Microwave Background

CMB is the oldest observable light coming from the early universe at the age of 380,000 yrs.
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Next Frontier... (B-mode) Polarization!
CMB B-mode Polarization (Primordial)

Quantum fluctuations during inflation are predicted to be imprinted as degree-scale curl-like polarization pattern (B-mode)
CMB B-mode Polarization (Primordial)

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Quantum fluctuations during inflation are predicted to be imprinted as degree-scale curl-like polarization pattern (B-mode)
Probing the ultra-high energy scale with B-mode

Inflation Potential:

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

\( r \): tensor-to-scalar ratio

\( \propto \) Amplitude of primordial gravitational waves

\(~2\times10^{16} \text{ GeV}\)

BICEP2 measurement: \( r = 0.2 \)

CMB B-mode can be a probe of physics of ultra-high energy scale!

http://hyperphysics.phy-astr.gsu.edu/ ©C.R. Nave, 2012
- Observed CMB has been deflected by gravitational potentials of Large Scale Structure from $z \sim 1100$ up to now.
- Lensing measurement can be a unique probe of sum of neutrino masses.
CMB B-mode Polarization (Weak Lensing)

Observed CMB polarization

\[(Q + iU)(\hat{n}) = (\tilde{Q} + i\tilde{U})(\hat{n} + d(\hat{n}))\]

\(~:\) primordial CMB deflection

- Typical deflection angle
  - a few arcmin
  - Coherent over \(\sim 2\) deg. scale
- Deflection mixes E and B-mode
  - Producing B-mode at arcminute-scale
- The deflection also induces correlation b/w different multipoles, \(l\) and \(l'\).

\[d_{EE}(L) \propto \sum_{l} E(l) E(l')\]

\[d_{EB}(L) \propto \sum_{l} E(l) B(l')\]

(Hu, Okamoto, 2002)

Simulated Deflection Map

\(\rightarrow: 1\) arc-minute
Upper limits of B-mode power spectrum before March 2014

arXiv:1310.1422

\( r = 0.1 \)

\(~1^\circ\) \quad \(~0.2^\circ\)

Large angular scale \quad Small angular scale
Upper limits of B-mode power spectrum before March 2014

arXiv:1310.1422

~1°

~0.2°

Primordial B-mode

BICEP (r=0.1)

Large angular scale

Small angular scale
Upper limits of B-mode power spectrum before March 2014

arXiv:1310.1422

~1°

~0.2°

BB: 95% confidence upper limits

Lensing B-mode

Primordial B-mode

BICEP (r=0.1)

First season POLARBEAR

Large angular scale

Small angular scale
POLARBEAR Experiment

- Ground-based CMB polarization experiment in the Atacama desert in Chile
- at 5,200m altitude
- Observing since 2012
- Spectral sensitivity at 150 GHz
International collaboration from ~6 countries, ~70 researchers
Atacama Desert is one of the best places (thin and dry atmosphere) on Earth for the CMB observation!
Telescope and Receiver

- Off-axis Gregorian Dragone
- Primary 2.5m precision-machined mirror
  - 3.5 arcmin (FWHM) resolution
- Designed to measure both primordial and lensing B-modes

Huan Tran Telescope @ James Ax Observatory
Focal Plane Detectors

- 2 bolometers in a pixel
- 637 pixels in a array
- 1274 bolometers

Noise level:

\[ 550 \mu \text{K}_{\text{CMB}} \sqrt{s}/\text{bolo} \]
\[ 23 \mu \text{K}_{\text{CMB}} \sqrt{s}/\text{array} \]

Polarization signal appears as a pair-differencing.
1st Season Observing Sky Patches

- Choose low galactic “foreground” regions
- POLARBEAR 1st season: 3 small sky regions (3°x3°) ~ 25deg²
CMB Polarization Maps

\[ Q = E_x^2 - E_y^2 \]

\[ U = E_A^2 - E_B^2 \]

- Filtered map noise level \( \sim 5.5 \) \( \mu \text{K-arcmin} \) (deepest patch)
- \( \sim 10 \) times deeper than Planck
- Deepest map at sub-degree scales
B-mode Power Spectrum from Q and U Maps

Definitions of E and B-modes

\[
\begin{pmatrix}
E(\vec{l}) \\
B(\vec{l})
\end{pmatrix} =
\begin{pmatrix}
\cos 2\phi_l & \sin 2\phi_l \\
-\sin 2\phi_l & \cos 2\phi_l
\end{pmatrix}
\begin{pmatrix}
\tilde{Q}(\vec{l}) \\
\tilde{U}(\vec{l})
\end{pmatrix}
\]

E or B-mode auto power spectrum is obtained as:

\[
C_l^{EE} = \left\langle E(\vec{l}) E(\vec{l})^* \right\rangle
\]

\[
C_l^{BB} = \left\langle B(\vec{l}) B(\vec{l})^* \right\rangle
\]
B-mode Systematic Uncertainties

Polarization can be measured by pair-differencing.

- \( A + B \rightarrow \text{Temperature (unpolarized) measurement} \)
- \( A - B \rightarrow \text{Polarization measurement} \)

However, if there is any mismatch in beams (optical response) of pair detectors...

“Differential beam” effects

- differential size
- differential pointing
- differential ellipticity
- differential gain

These effects can produce spurious polarization signals from (unpolarized) temperature fluctuations.
B-mode Systematic Uncertainties

Polarization can be measured by pair-differencing:

- $A + B$ → Temperature (unpolarized)
- $A - B$ → Polarization measurement

However, if there is any mismatch, these effects can produce spurious polarization signals from (unpolarized) temperature fluctuations.

Primordial B-mode $(r=0.24)$

Lensing B-mode
B-mode Systematic Uncertainties

Polarization can be measured by pair-differencing:

- \( \Delta A + \Delta B \) → Temperature (unpolarized)
- \( \Delta A - \Delta B \) → Polarization measurement

However, if there is any mismatch

Primordial B-mode \((r=0.24)\)

These effects can produce spurious polarization signals from (unpolarized) temperature fluctuations.
Expected B-mode

Estimated spurious B-mode from systematics

Achieved good leakage mitigation by...
- sky rotation
- small beam (high res.)
- polarization modulation by half-wave plate.

pointing
differential beam size
differential ellipticity
relative gain (HWP dependent)
relative gain
electrical crosstalk
gain drift

Confirmed all systematic uncertainties are much smaller than the level of expected B-mode signal.
First Results from POLARBEAR

Cross correlation of lensing deflection with Cosmic Infrared Background

Evidence for gravitational lensing, consistent with SPTpol (Hanson et al. 2013)

Lensing deflection power spectrum

First evidence for gravitational lensing with CMB polarization data alone

CMB B-mode auto power spectrum

First direct measurement of B-mode auto-power spectrum in sub-degree angular scale

Measurement of lensing B-modes with three independent methods
Cross-correlation of lensing deflection with Cosmic Infrared Background (CIB)

\[ \ell \times C_\ell^{\text{F}} [\text{Jy}/\text{Sr}] \]

- CIB: Herschel/SPIRE
  \[ \sim 500 \mu \text{m} \]
- CIB is a good tracer for the matter distribution in \( z=1-3 \)
- Expected to correlate with CMB lensing

Reject null hypothesis at 4.0 \( \sigma \)
Consistent with SPTpol (Hanson et al, 2013)
A_L = 1.37 ± 0.30 (stat.) ± 0.13 (sys.)

(A_L = 1: WMAP-9yr Λ CDM)

Rejection of null hypothesis at 4.2 σ

First evidence for gravitational lensing with CMB polarization alone
B-mode Power Spectrum

\[ l(l+1)C_{l}^{BB} / (2\pi) (\mu K^2) \]

Multipole Moment, \( \ell \)

\[ A_{BB} = 1.12 \pm 0.61 \text{(stat.)} ^{+0.04}_{-0.10} \text{(sys.)} \]

(\( A_{BB} = 1 \): WMAP-9yr \( \Lambda \) CDM)

Rejection of null hypothesis at 97.5\% C.L.

4.7 \( \sigma \) evidence for lensing B-mode when combined with \( C_{l}^{dd} \) measurement
B-mode Power Spectrum
B-mode Power Spectrum

POLARBEAR is starting large sky patch observations for primordial B-mode measurement.
What are needed for next generation CMB experiments?

- **Higher sensitivity**
  - Reduce noise variance
  - Current gen. ~1K pixels
    - $\rightarrow$ >10K pixels
- **Spectral information**
  - Characterize and remove polarized foregrounds
- **Large sky coverage**
  - Reduce sample variance
  - More accessible sky from Atacama than from South Pole
- **Resolution < 4 arcmin**
  - cf. BICEP2 beam: ~30 arcmin
  - Characterize lensing effect and de-lense.
Upgrade Plans: POLARBEAR-2 & Simons Array

**POLARBEAR-2: New Receiver**

- More statistics: 7,588 bolometers
  - Noise level: $4.1 \mu K_{\text{CMB}} \sqrt{s}/\text{array}$
  - Multi-chroic: 95 and 150 GHz

- Will be mounted on a new telescope.

**Simons Array**

- Three 3.5m telescopes
  - 22,764 bolometers
  - Two 95 / 150GHz receivers
  - One 150 / 220GHz receiver

- 2 new telescopes (Funded)

Will be deployed 2015

Details in the poster by M. Hasegawa (July 4)
POLARBEAR-2 & Simons Array: Science Prospects

- Sum of neutrino masses: 19 meV at 3 identical 3.5m telescopes
- Simons Array is an expansion of POLARBEAR-1
- Core Detector wafer (542 TESs)
- Polarization signal can be separated
- Polarisers (modes of zero divergence)
- Beam (angular response)
- Matsumura, N. Miller, H.

Expected Sensitivity for B-mode

- Multipole Moment, $\ell = 180/(\theta [^\circ]) = 10800/(\theta [^\prime])$
- $\sigma (r: \text{tensor-to-scalar ratio}) = 0.002$
- $\sigma (\Sigma m_\nu) = 19 \text{ meV with Planck+DESI BAO}$

Expected Sensitivity for $\Sigma m_\nu$ and $\Omega_m$

- Planck (no lensing) + DESI
- Simons Array CMB
- Simons Array + DESI BAO

[Graphs and data plots showing expected sensitivities and measurements]
Summary

- POLARBEAR reported the first results from the 1st season observations.
  - First evidence for gravitational lensing with CMB polarization data alone.
  - First measurement of B-mode power spectrum at sub-degree scale using CMB alone
  - 4.7 $\sigma$ evidence for weak lensing B-mode Polarization
- POLARBEAR-2 & Simons Array will dramatically improve the sensitivity with...
  - New receivers with 7,588 bolometers each
  - Three telescopes, for a total of 22,764 bolometers
  - Three observation frequencies (95 GHz +150 GHz + 220 GHz)