

New Results from POLARBEAR on CMB Polarization

Masashi Hazumi (KEK)
KEK CMB Group

Brief history of KEK CMB group

- 2007: Established
Joined QUIET experiment
- 2008: Joined POLARBEAR experiment
Proposed LiteBIRD
- 2009: Proposed POLARBEAR-2
- 2010:
- 2011: Published 1st results from QUIET
- 2012: Published 2nd results from QUIET
- 2013: Proposed LiteBIRD to “Master Plan” of Science Council of Japan
1st results from POLARBEAR submitted

For the discovery of primordial gravitational waves predicted by cosmic inflation, and for the tests of quantum gravity

Good progress, beyond my initial expectation to be honest.



Lots of young researchers,
who jumped into this new
enterprise,
are making valuable
contributions !

New Results from POLARBEAR

Accepted by PRL yesterday !

<http://arxiv.org/abs/1312.6645>

Evidence for Gravitational Lensing of the Cosmic Microwave
Background Polarization from Cross-correlation with the Cosmic
Infrared Background

POLARBEAR Collaboration

<http://arxiv.org/abs/1312.6646>

First detection of lensing signals
with CMB polarization alone !

Gravitational Lensing of Cosmic Microwave Background Polarization
POLARBEAR Collaboration

POLARBEAR Collaboration

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Daniel Flanigan



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Zigmund Kermish



Austin College

Peter Hyland



2014/02/24

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Eric Linder
Mike Sholl
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Stephanie Moyerman
Hans Paar
Meir Shimon
Praween Siritanasak
Nathan Stebor
Amit Yadav



Cardiff University

Peter Ade
William Grainger



Dalhousie University

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Colin Ross



KEK

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Yuji Chinone
Masaya Hasegawa
Kaori Hattori
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Yuki Inoue
Yuta Kaneko
Nobuhiro Kimura
Tomotake Matsumura
Hideki Morii
Takahiro Okamura
Akie Shimizu
Jun-ichi Suzuki
Ken-ichi Tanaka
Takayuki Tomaru



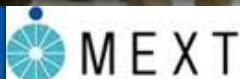
Kavli IPMU

Nobuhiko Katayama
Haruki Nishino



University of Tsukuba

Suguru Takada



POLARBEAR Collaboration Meeting @ KEK, Japan, Mar. 24-28, 2013
"POLARBEAR: New Results from the POLARBEAR CMB
Polarization" Masashi Hazumi (KEK)

Outline

1. Overview of POLARBEAR
2. Gravitational Lensing of CMB Polarization
3. New Results from POLARBEAR
4. Roadmap and Conclusion

1. Overview of POLARBEAR

- Search for inflationary B-modes to $r=0.025$ (95% C.L.) *and detect gravitational lensing B-modes*
- 3.5m primary mirror and large focal plane with 1274 TES bolometers for 150GHz
- First light in Chile in Jan. 2012 and large amount of data already recorded
- Roadmap:
 - 7588 TEses in 2015 (POLARBEAR-2)
 - $r<0.01$ (95% C.L.)
 - >22000 TEses in 2016(Simons Array)



Site

POLARBEAR Site:
Atacama, Chile
(5150m above sea level)





2014/02/24

KEK Physics Seminar "New Results from POLARBEAR on CMB
Polarization"
Masashi Hazumi (KEK)

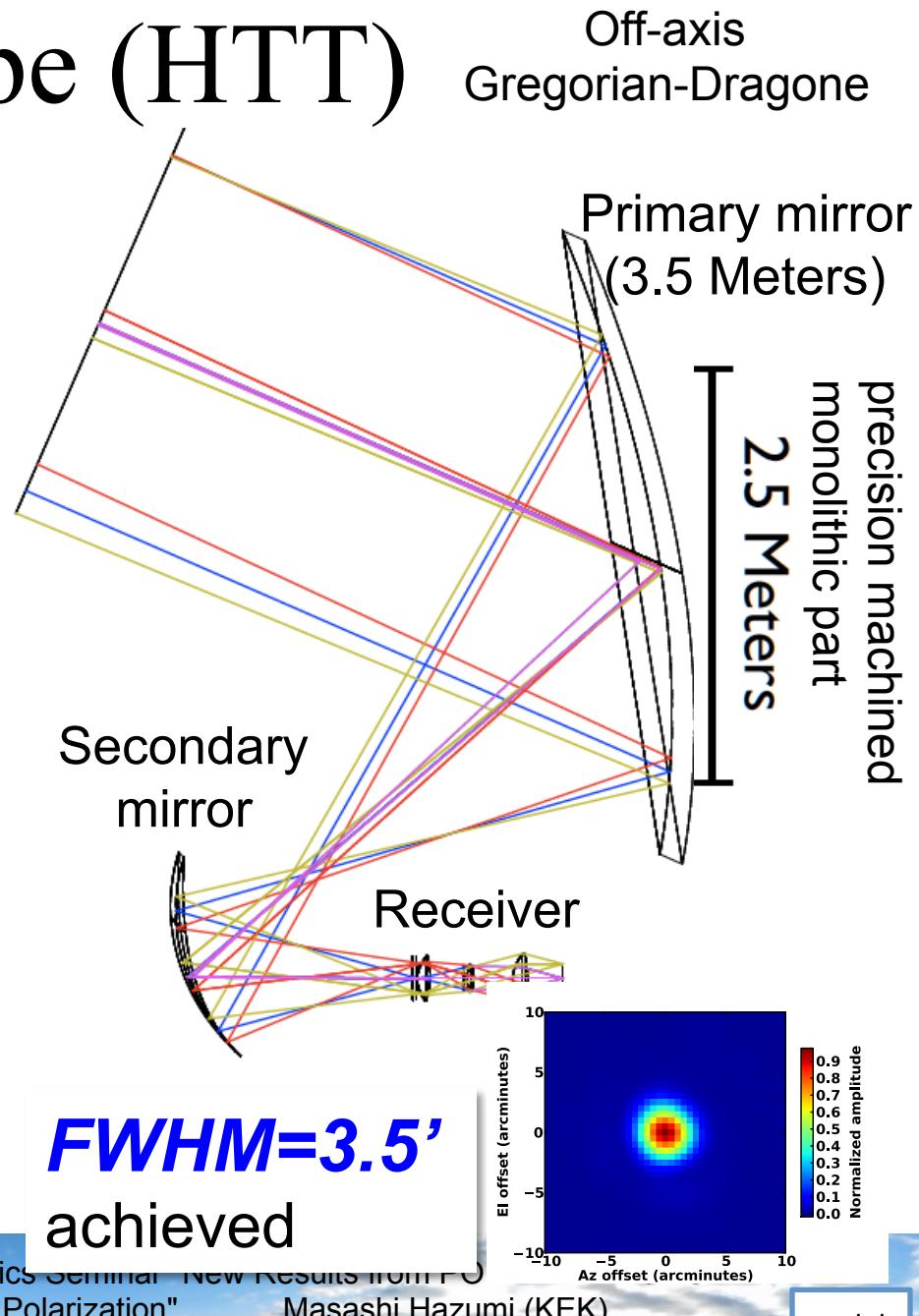
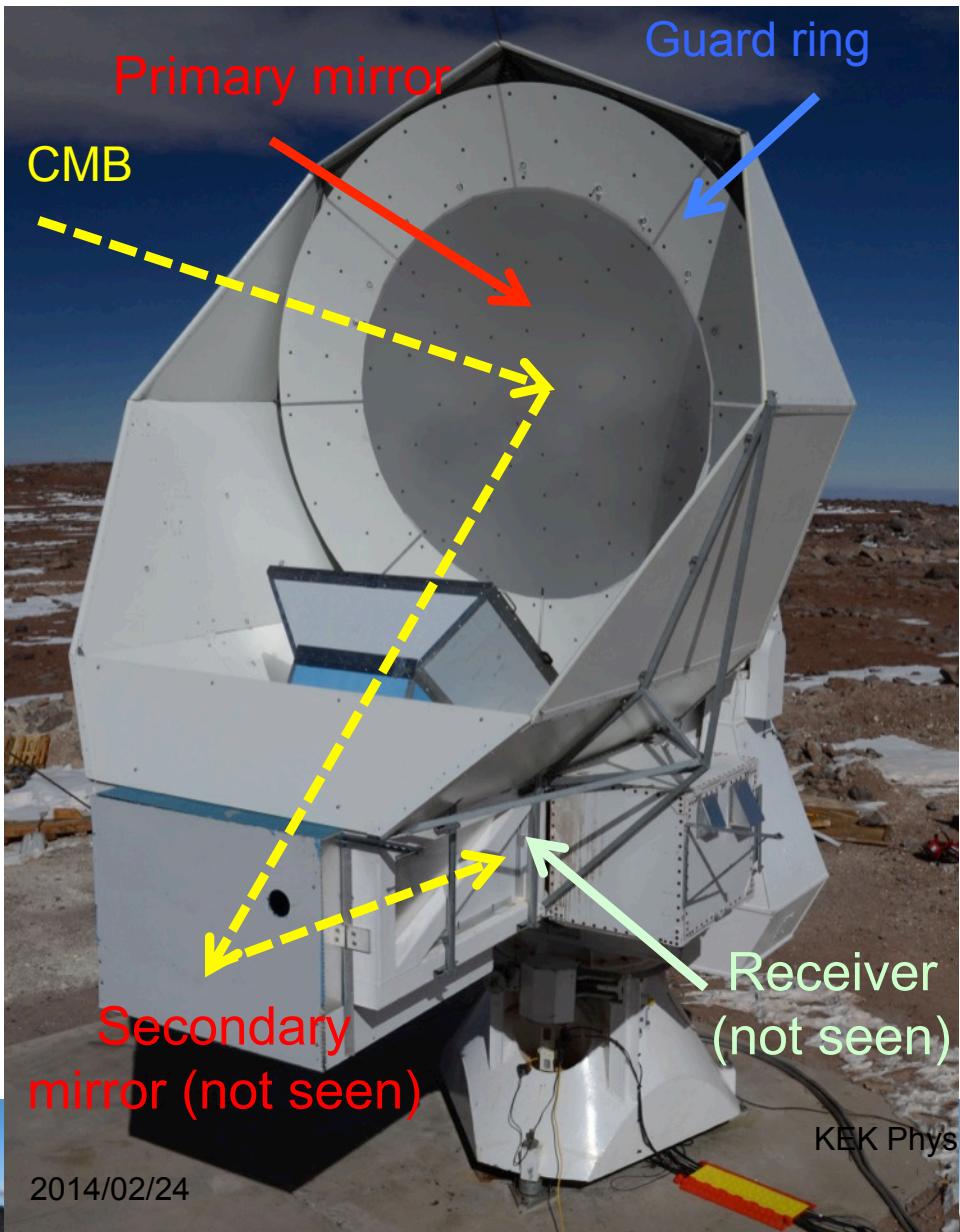
Oxygen tank



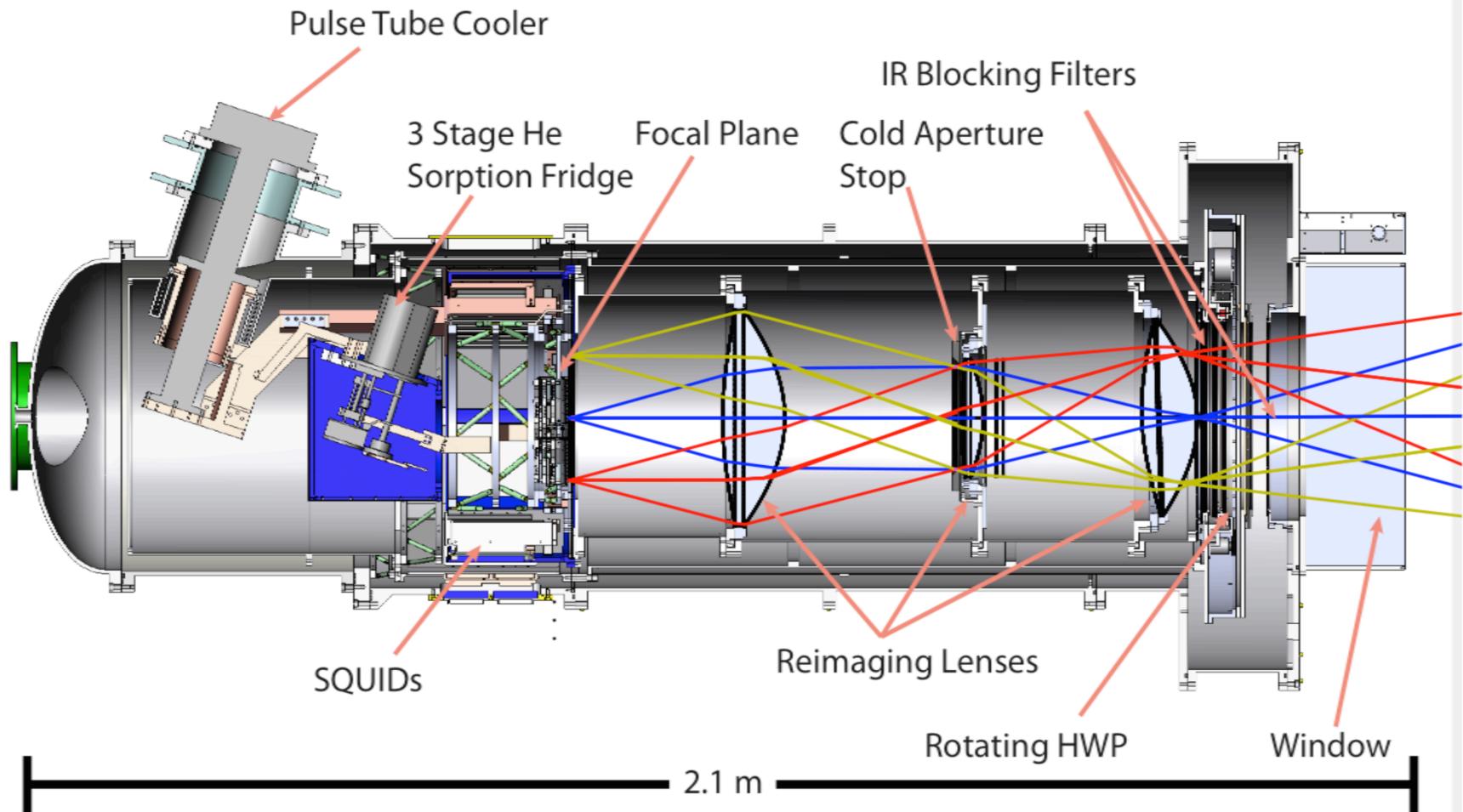
2014/02/24

KEK Physics Seminar "New Results from POLARBEAR on CMB
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Masashi Hazumi (KEK)

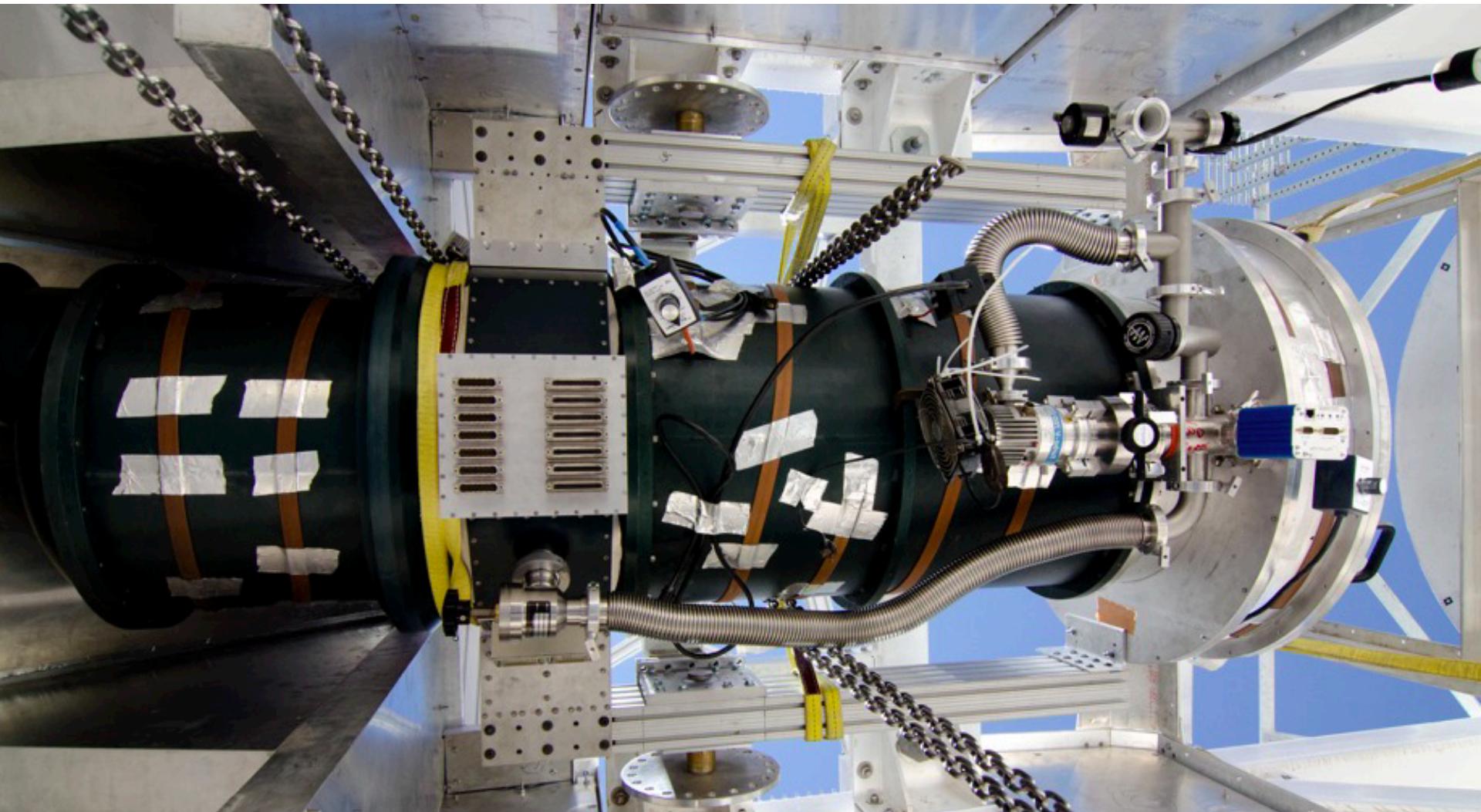
Huan Tran Telescope (HTT)



Receiver System

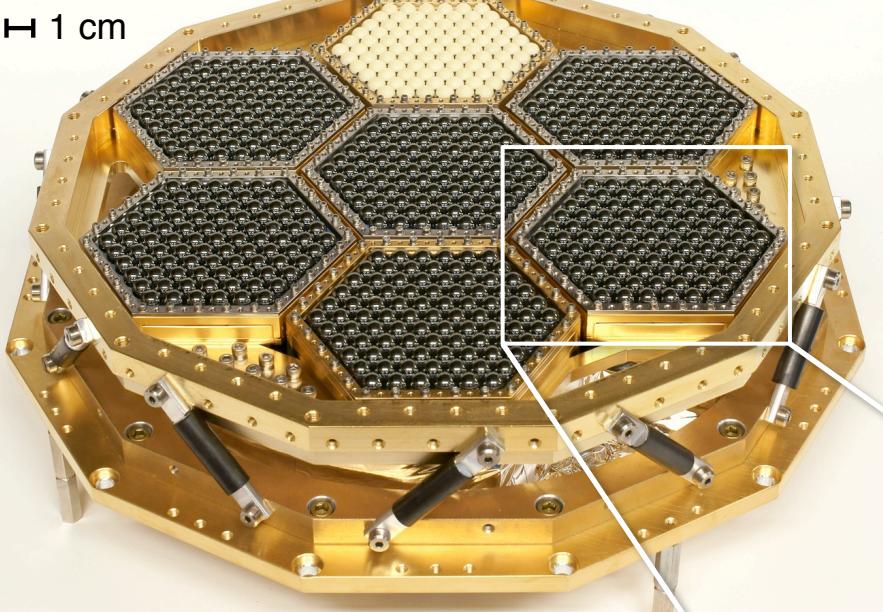


Receiver System

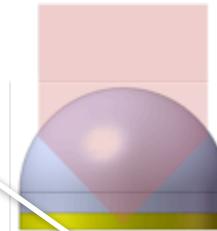


POLARBEAR-1

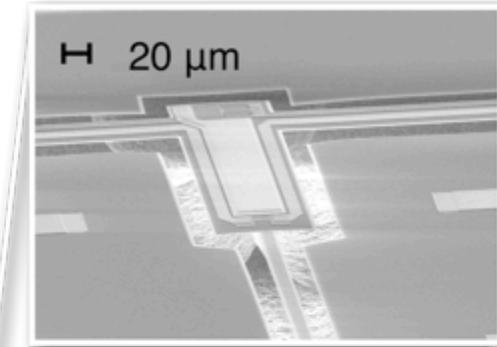
Focal Plane



Lenslet

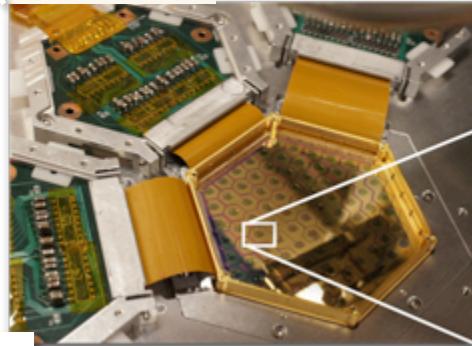


TES

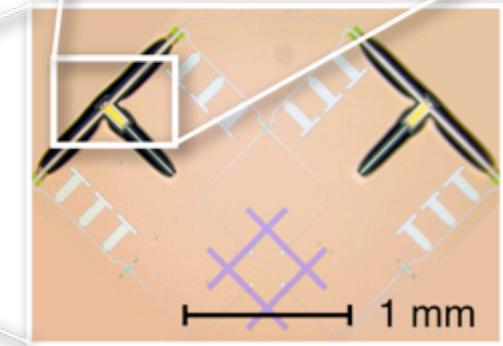


637 pixels
(91 pixels/wafer x 7 wafers)
1274 TES bolometers

21 $\mu\text{K}\sqrt{\text{s}}$ array NET
(achieved typically
during observations)



Wafer module
assembly



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

Readout Electronics

The diagram illustrates the POLARBEAR readout electronics architecture. It starts with a **SQUID** at the bottom, which is connected to a **LPE** (Low-Pass Filter) and then to an **A/D** converter. The **A/D** is part of a **DMFD** (Digital-to-Memory Frame Decoder). Above the DMFD, there are two **D/A** converters: one for the **Carrier DMFS** and one for the **Nulling DMFS**. The Carrier DMFS outputs signals to **Ch 1** through **Ch N**, each consisting of a coil and a resistor (**R_{bol}**). The Nulling DMFS outputs signals to a **SQUID** and a **Nulling loop**. The **Nulling loop** includes a **DC-SQUID** and a **Feedback loop**. Arrows from the text "McGill DfMux motherboard" point to the **DMFD** and the **FPGA** board. Arrows from the text "McGill DfMux motherboard" also point to the **Carrier DMFS** and **Nulling DMFS** sections of the diagram.

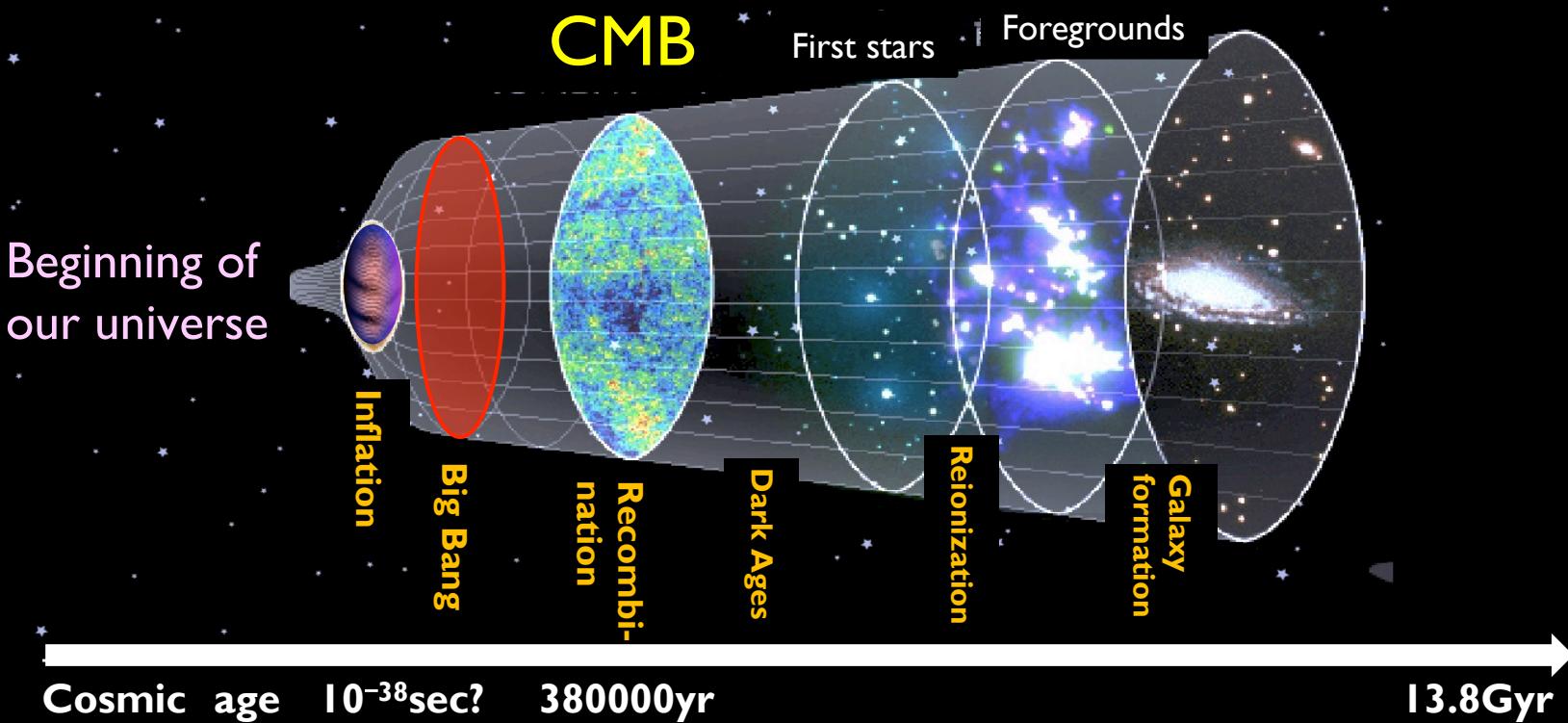
Frequency-domain multiplexing (8 to 1)
SQUIDs (NIST) and room-temp.
electronics (McGill)

1/f knee ~ 100mHz
w/ pixel difference

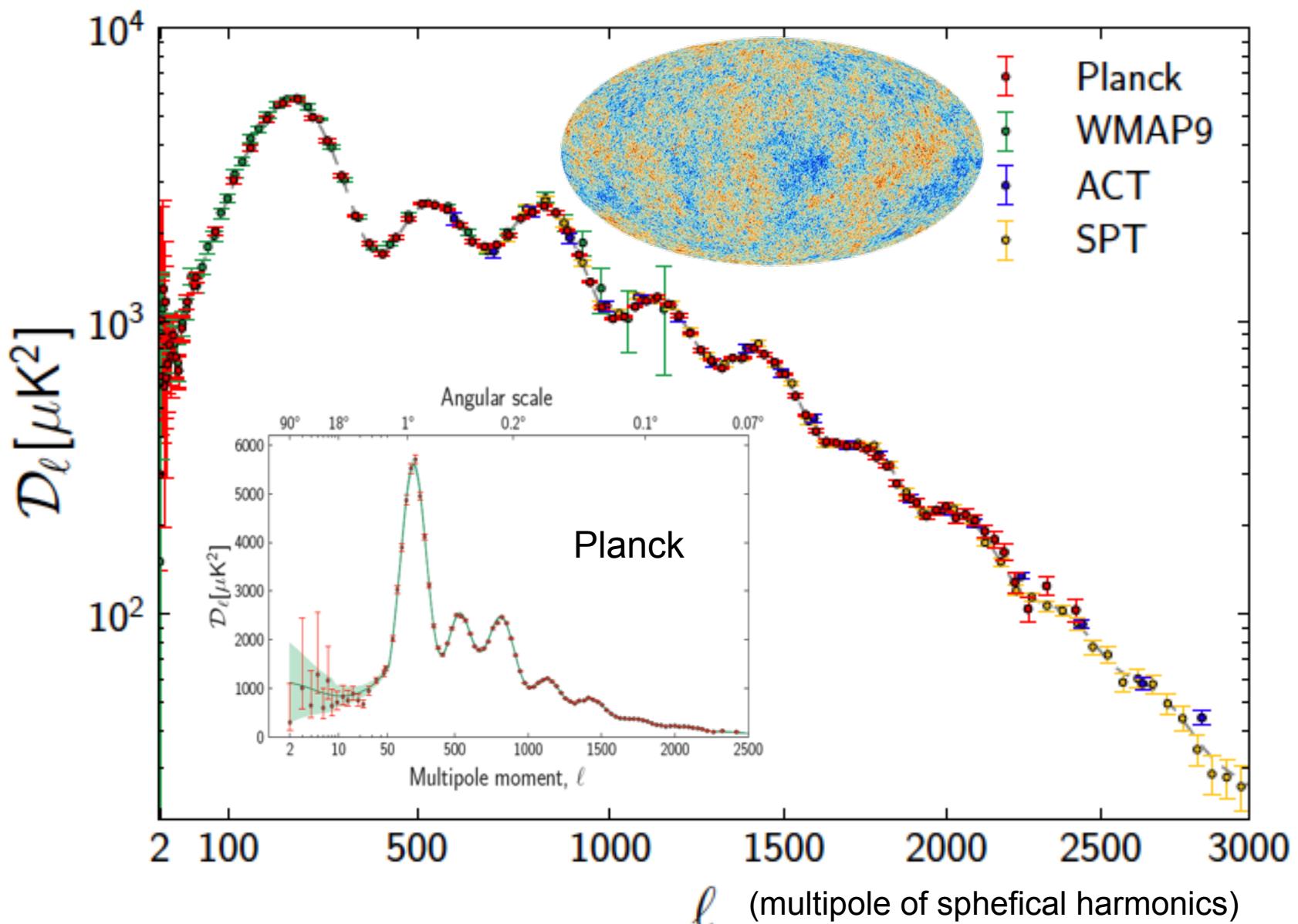
This log-log plot shows the noise spectrum for the **Pixel sum** (blue line) and **Pixel difference** (green line) methods. The y-axis is labeled **Noise (K_{RJ}/\sqrt{Hz})** and ranges from 10^{-5} to 10^1 . The x-axis is labeled **Frequency (Hz)** and ranges from 10^{-2} to 10^2 . The blue line for the **Pixel sum** shows a clear **1/f** noise knee around 100 mHz. The green line for the **Pixel difference** shows significantly lower noise levels across the entire frequency range, indicating better performance.

2. Gravitational Lensing of CMB Polarization

Cosmic History



CMB temperature power spectrum



KEK物理学シリーズ

3

宇宙物理学



高エネルギー加速器研究機構

著者
小玉英雄
井岡邦仁
郡和範

共立出版

拡大

[拡大画像\(ズームで\)を表示](#)

[自分のイメージを掲載する](#)

[出版社・著者の方へ「なか見!検索」で書籍を紹介しませんか?](#)

宇宙物理学 (KEK物理学シリーズ 3) [単行本]

小玉英雄 (著), 井岡邦仁 (著), 郡和範 (著), 高エネルギー加速器研究機構 (監修)
[カスタマーレビューを書きませんか?](#)

価格: **¥ 4,200** 通常配送無料 [詳細](#)

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[会員登録](#)でもれなく1,000ポイント キャンペーン実施中。

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Amazonプライム会員に適用。注文手続きの際に申し込んでください。 [詳細はこちる](#)

[ほしい物リストに追加する](#)

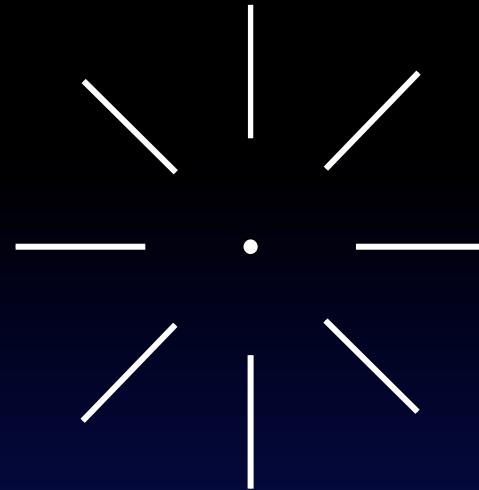
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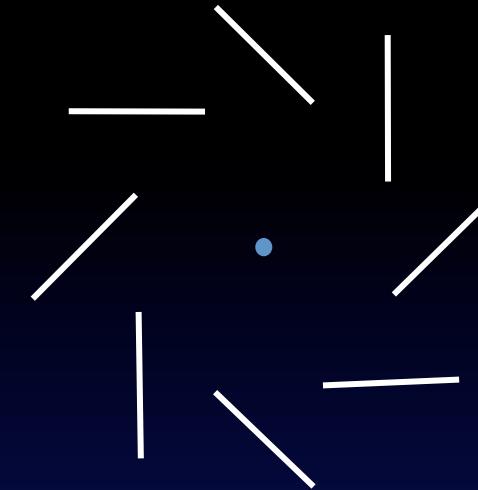
CMB Polarization: E-mode and B-mode

E-mode



Divergence,
even parity

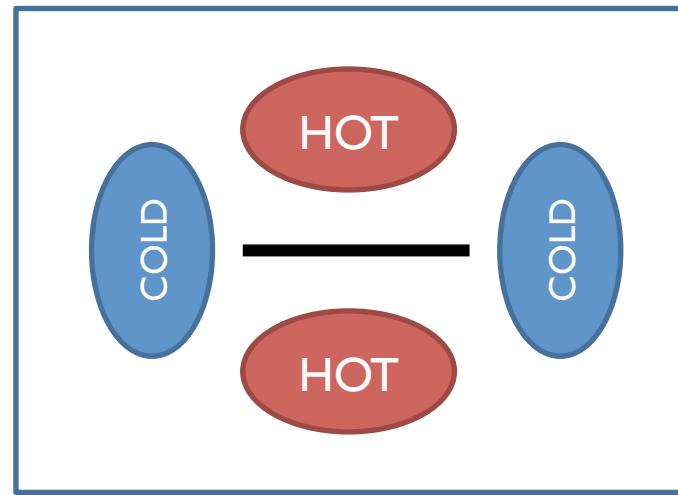
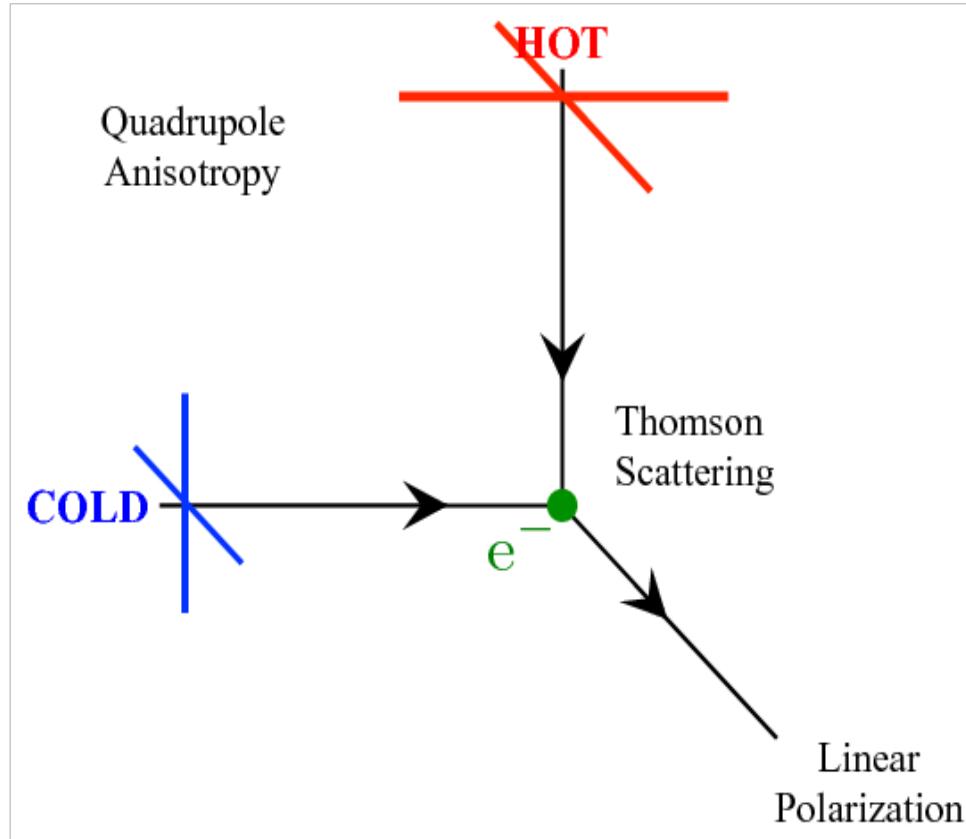
B-mode



Curl,
odd parity

Polarization map is decomposed into E-mode and B-mode.

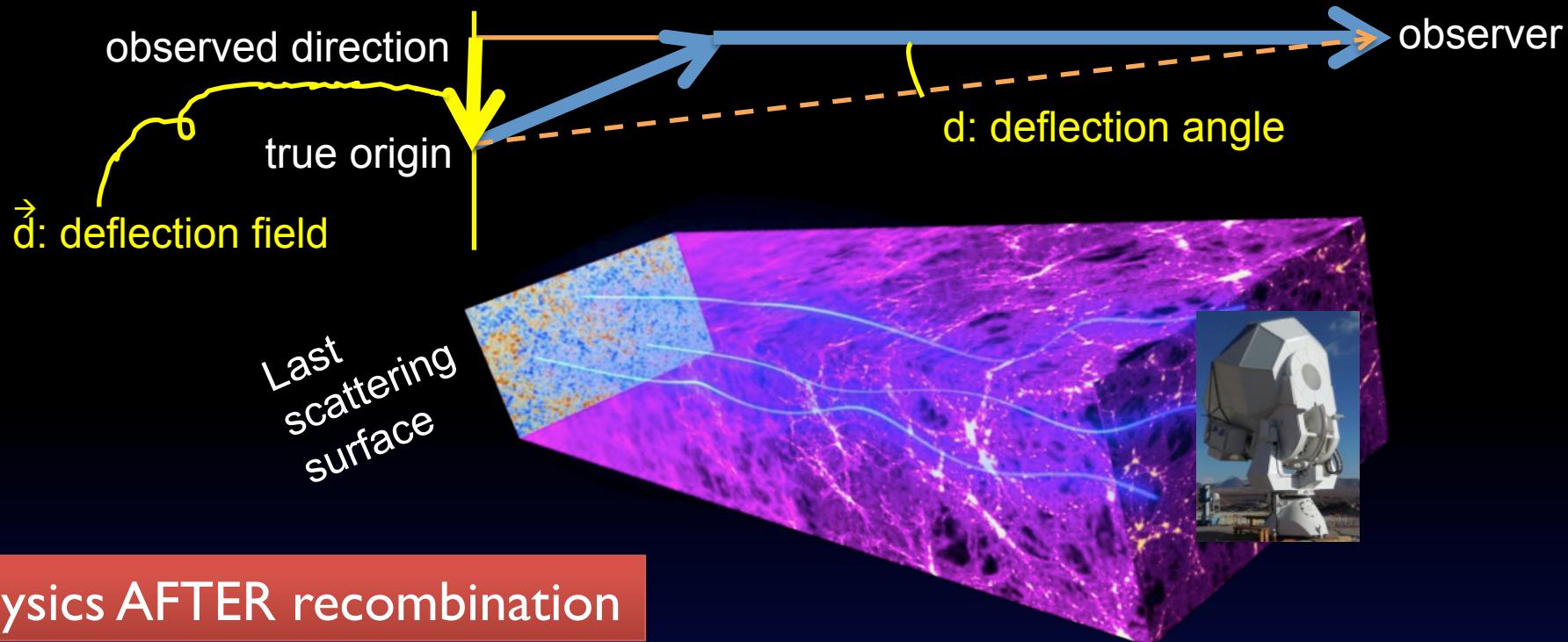
Physics at recombination



Local quadratic anisotropy
in photon density
around electrons results in
CMB polarization E-mode.

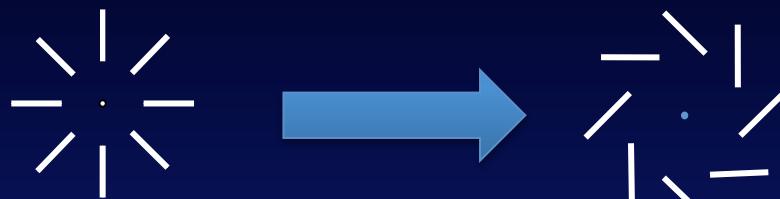
This is just text-book physics + CMB temperature anisotropy.

Lensing B-mode

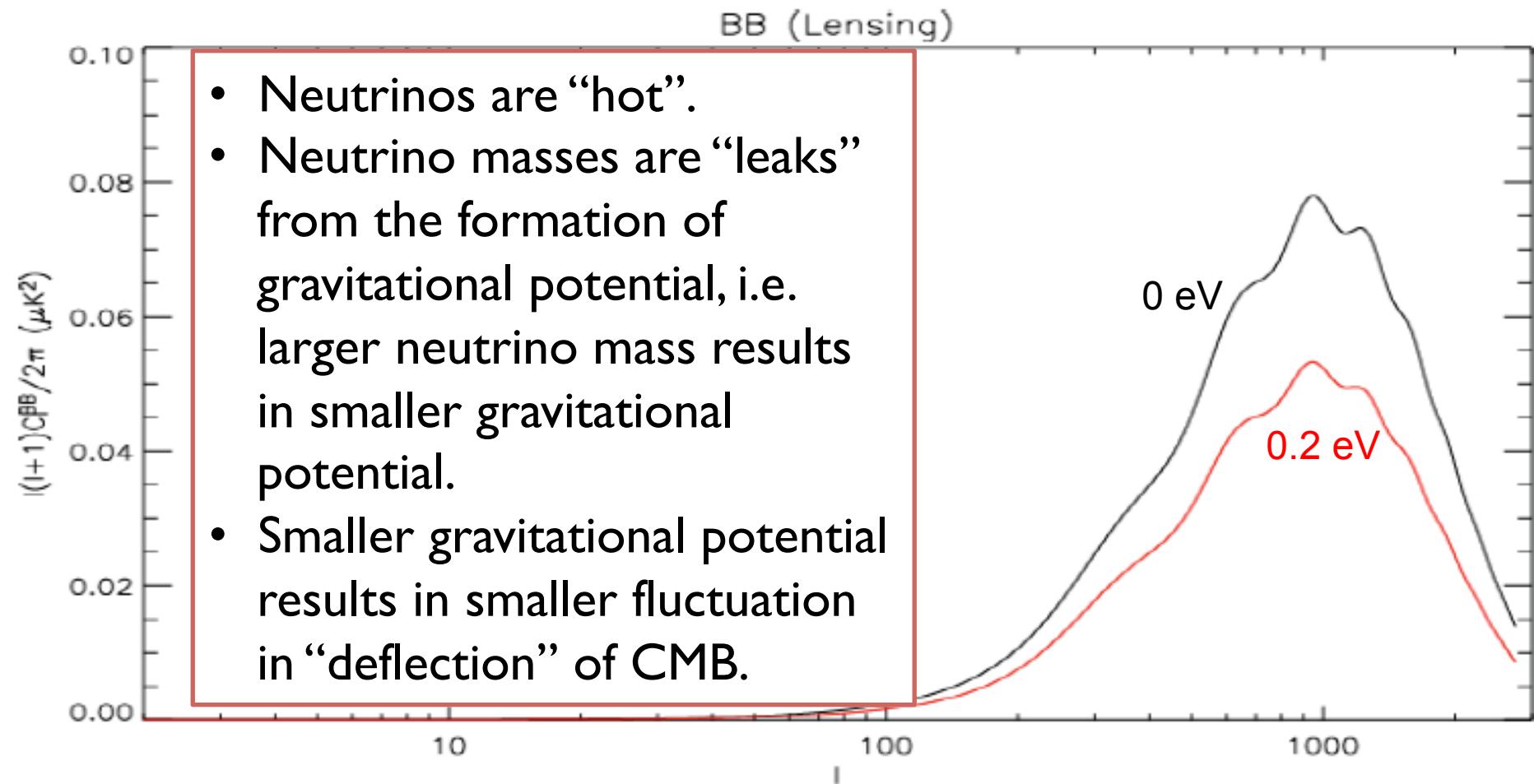


Physics AFTER recombination

- Gravitational potentials along the line of sight distort original CMB map
- E-mode leaks into B-mode
- Valuable in its own right: sensitive to sum of neutrino masses, and any energy density from physics beyond the standard model
- Lensing centered at $z \sim 2$, deflection angle $\sim 2\text{arcmin}$ with 2deg. coherence

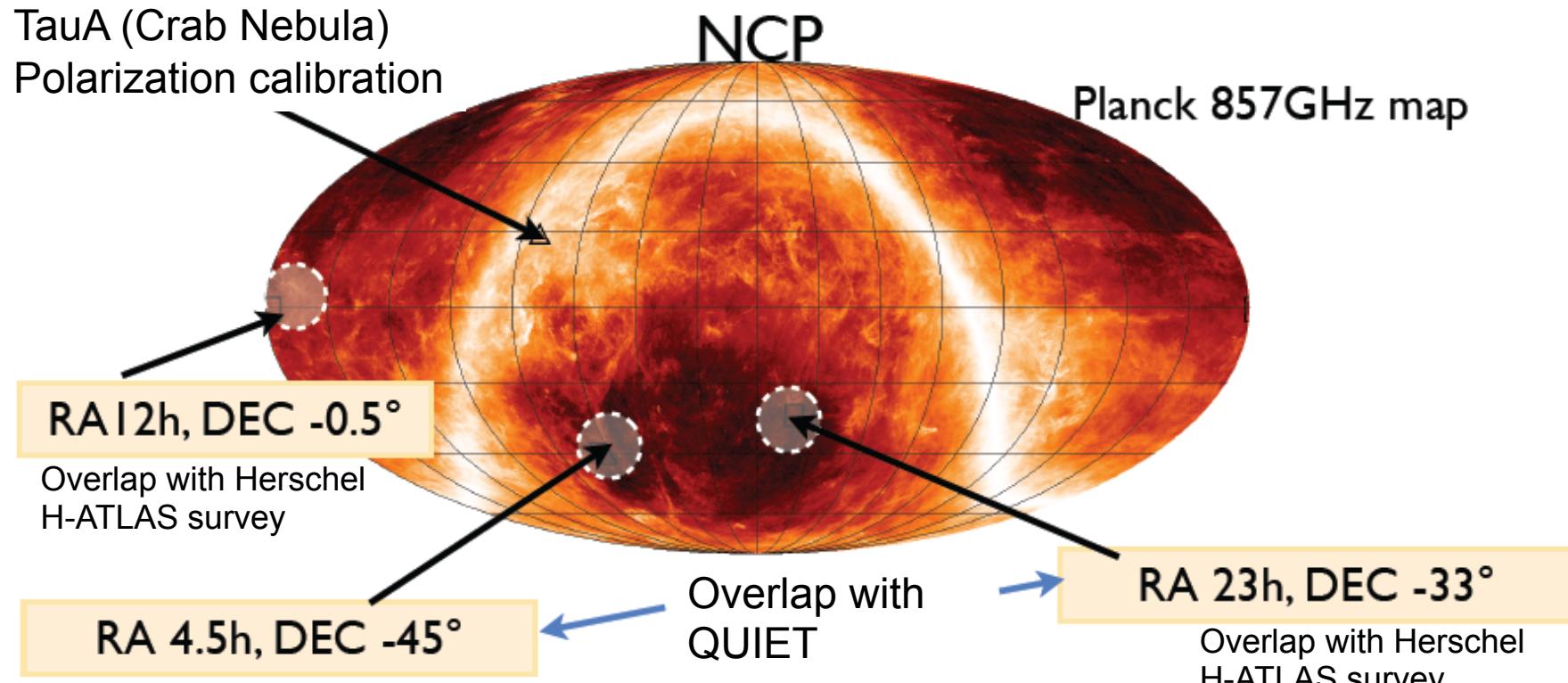


Effects of neutrino masses on B mode



3. New Results from POLARBEAR

Observation



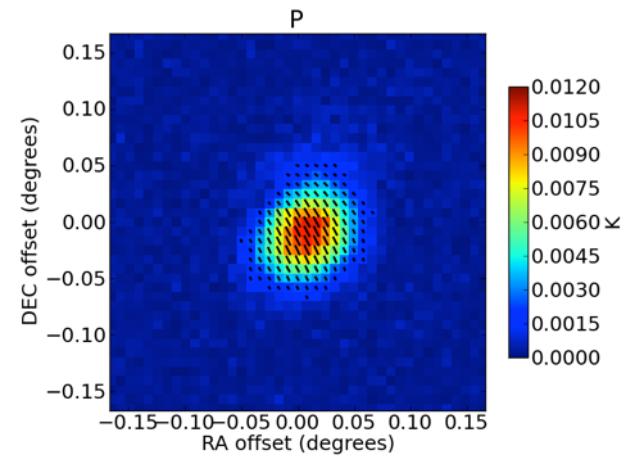
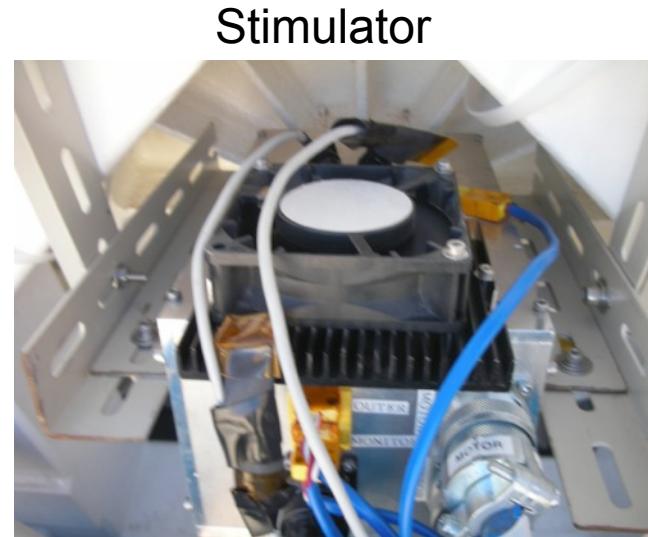
- Small dust components
- Overlap with Hershel CIB and QUIET CMB
- 3deg x 3deg in first season (May 2012 – June 2013, >4000h)

Constant Elevation Scan

Video

Calibration

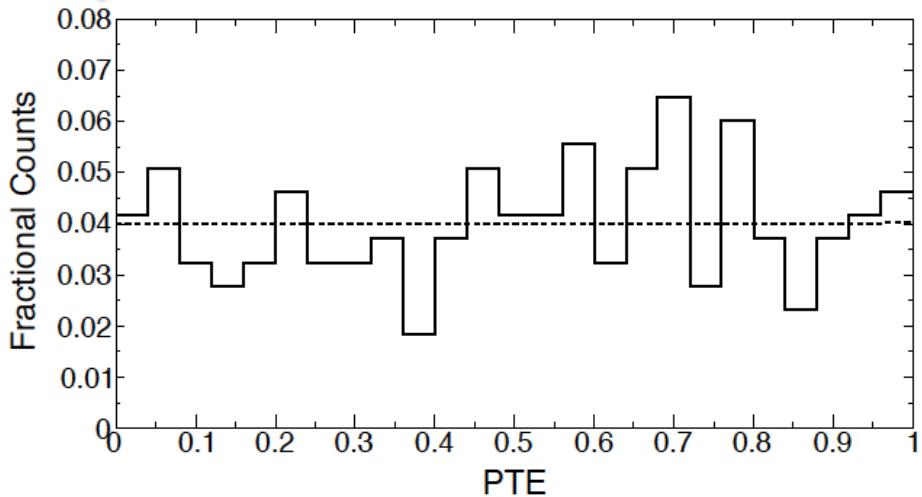
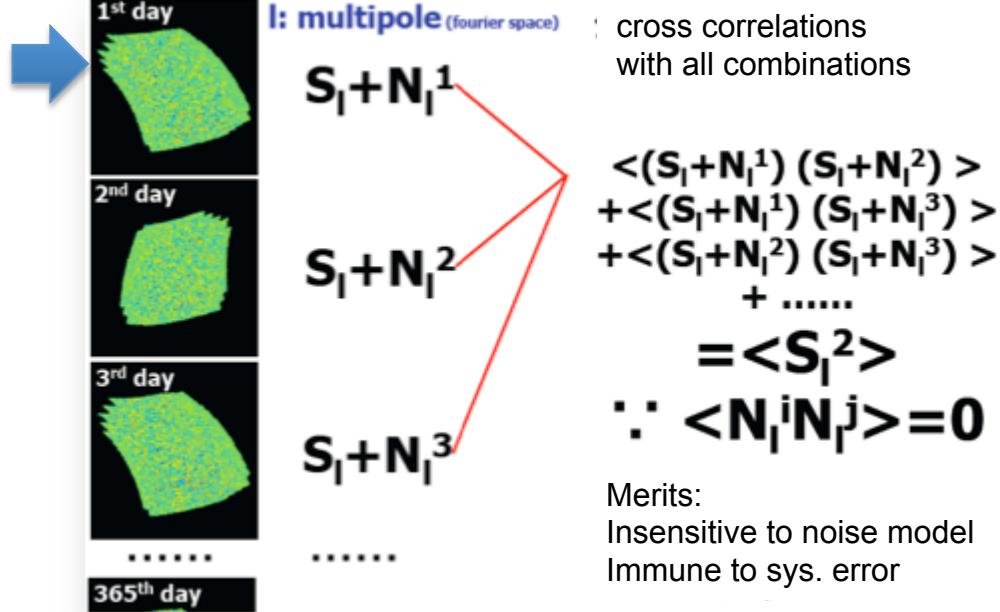
- Beam
 - Planets (Jupiter, Saturn, Venus)
- Absolute Gain
 - WMAP9 Temperature Anisotropy
- Relative Gain
 - Stimulator (thermal source)
- Absolute Polarization Angle
 - C_{EB}
- Relative Polarization Angle
 - TauA (Crab Nebula)



Data analysis

2–4 from HEP culture

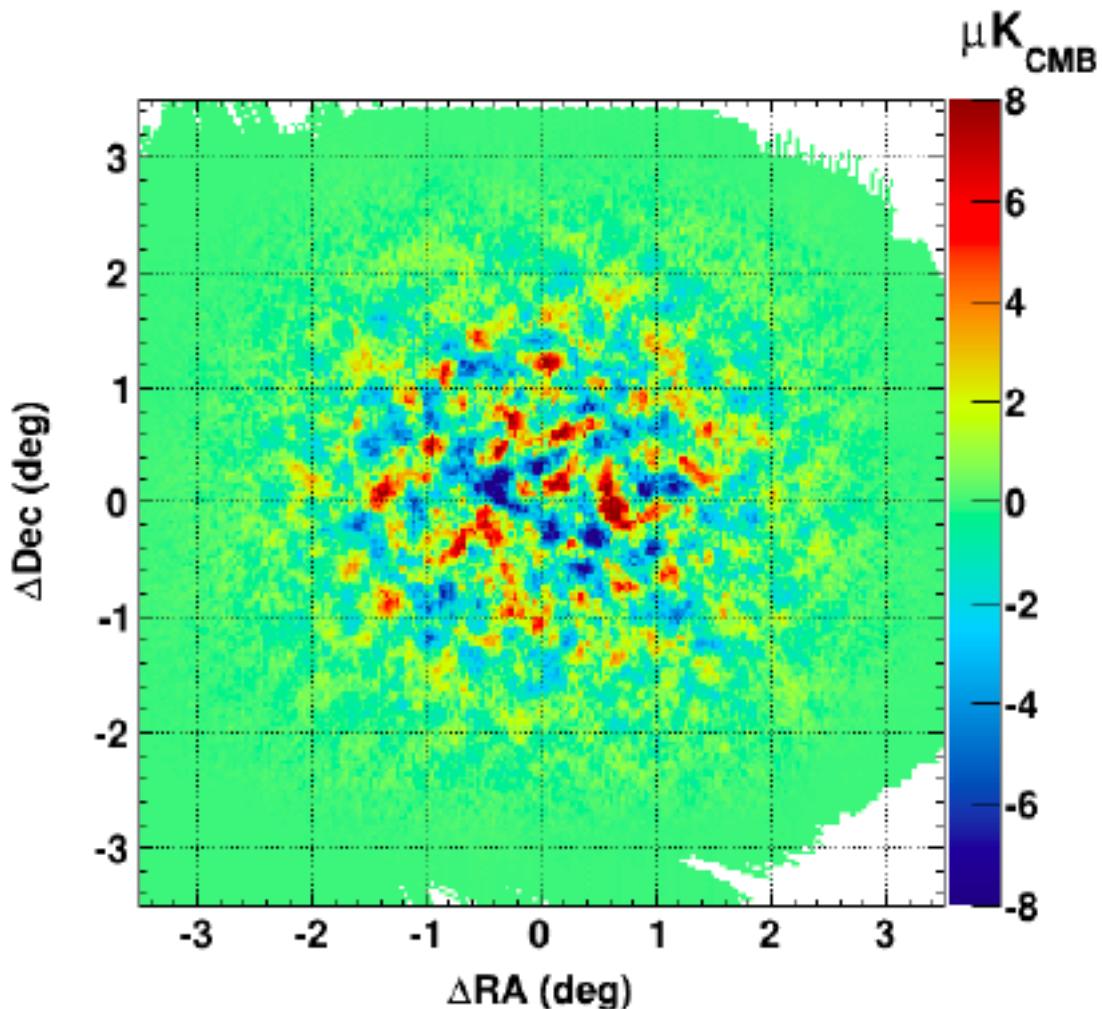
1. Day-by-day cross correlation
2. Blind Analysis
 - Open the results only after 3. and 4.
3. Thorough systematic error check
4. Thorough Data Validation



Probability To Exceed (PTE)
of null tests for
 Cl^{BB} , Cl^{EB} power spectra

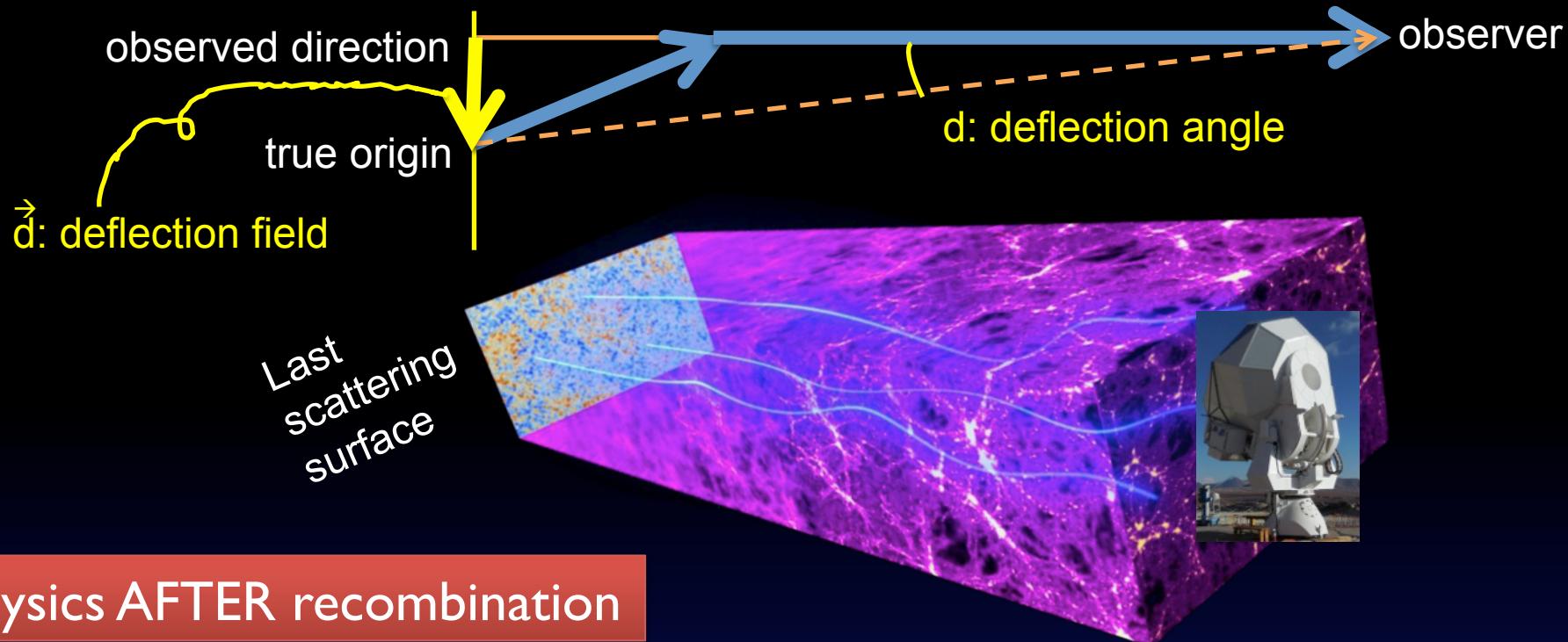
POLARBEAR-1 (First year of data)

E-mode polarization



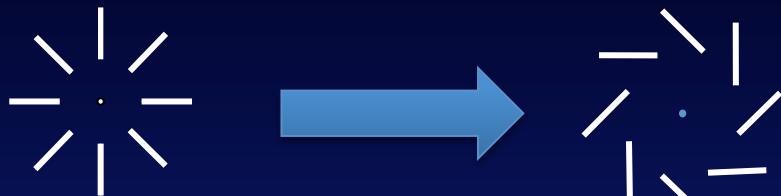
About 10 times
as deep as
Planck data

Lensing B-mode



Physics AFTER recombination

- Gravitational potentials along the line of sight distort original CMB map
- E-mode leaks into B-mode
- Valuable in its own right: sensitive to sum of neutrino masses, and any energy density from physics beyond the standard model
- Lensing centered at $z \sim 2$, deflection angle $\sim 2\text{arcmin}$ with 2deg. coherence



<http://arxiv.org/abs/1312.6646>

First detection of lensing signals
with CMB polarization alone !

Gravitational Lensing of Cosmic Microwave Background Polarization POLARBEAR Collaboration

Lensing B-mode detection with CMB 4-point correlations

$$\begin{aligned} \text{Cl}^{\text{dd}} &= \langle d_{\text{EB}} d_{\text{EB}} \rangle = \langle \text{EBEB} \rangle \\ &= \langle d_{\text{EE}} d_{\text{EB}} \rangle = \langle \text{EEE} \text{B} \rangle \end{aligned} \quad \text{d for deflection field}$$

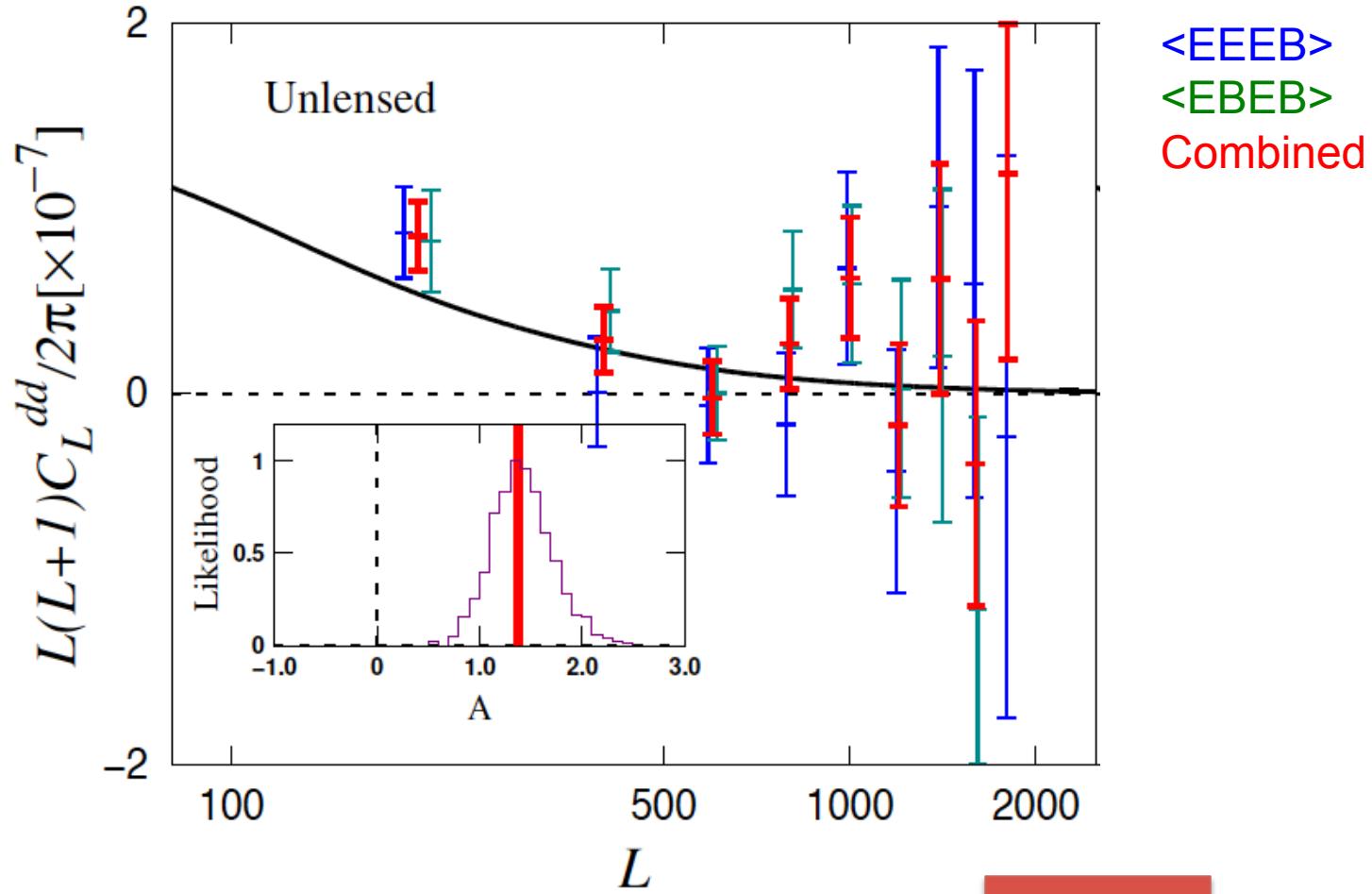
- E leaks into B due to gravitational lensing.
 - symmetric pattern viewed through a distorted lens
- Many wave numbers of B created
- E-B correlation between different wave numbers : $E(l)B(l') \neq 0$

$$d_{\text{EB}}(\mathbf{L}) = \frac{A_{\text{EB}}(L)}{L} \int \frac{d^2 l}{(2\pi)^2} E(l) B(l') \frac{\tilde{C}_l^{EE} \mathbf{L} \cdot \mathbf{l}}{C_l^{EE} C_{l'}^{BB}} \sin 2\phi_{ll'}$$

New !

POLARBEAR 2013 C_L^{dd}

<http://arxiv.org/abs/1312.6646>



Amplitude = $1.37 \pm 0.30(\text{stat}) \pm 0.13(\text{syst})$

4.2σ

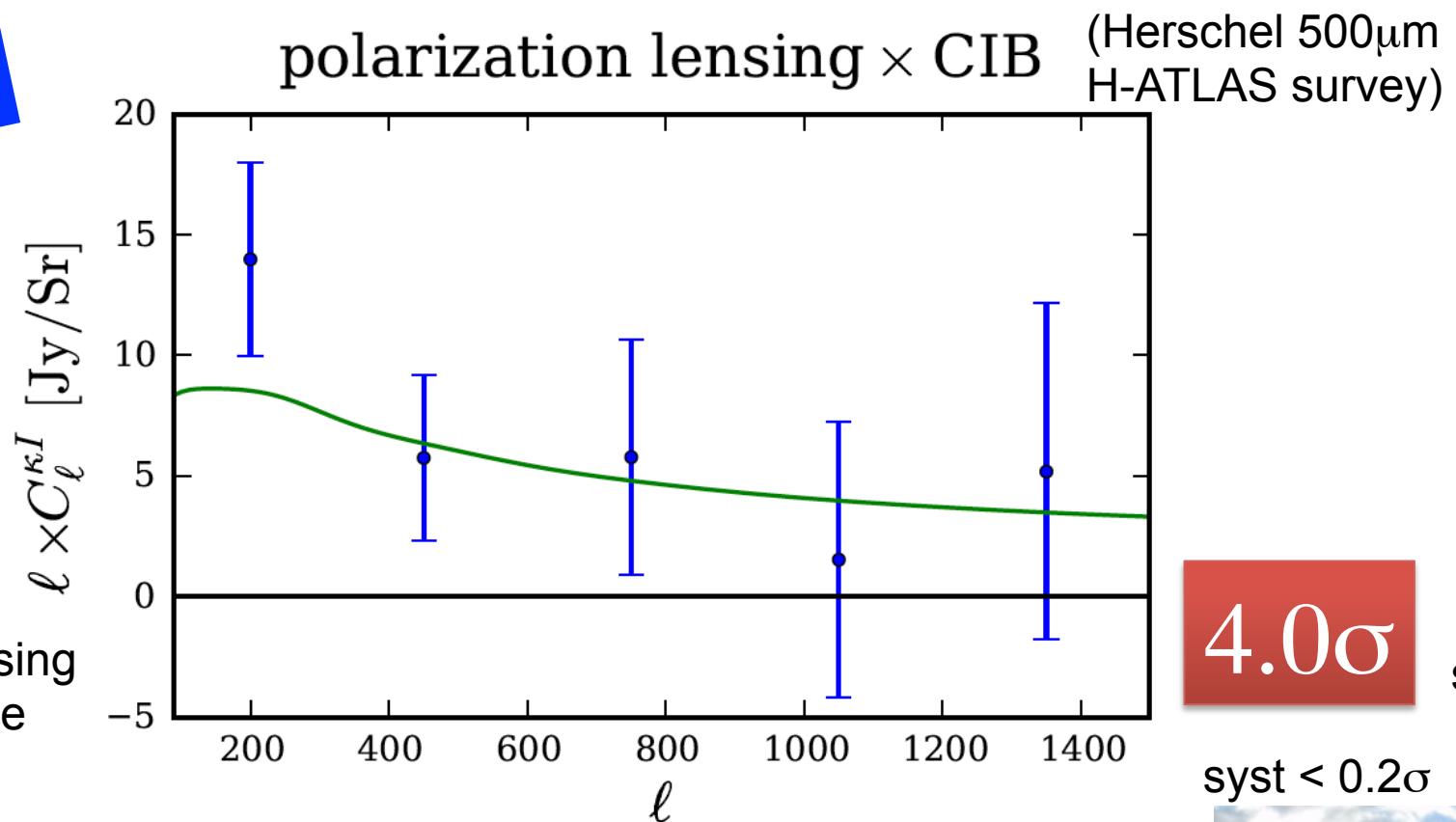
stat & syst
combined

<http://arxiv.org/abs/1312.6645>

Evidence for Gravitational Lensing of the Cosmic Microwave Background Polarization from Cross-correlation with the Cosmic Infrared Background

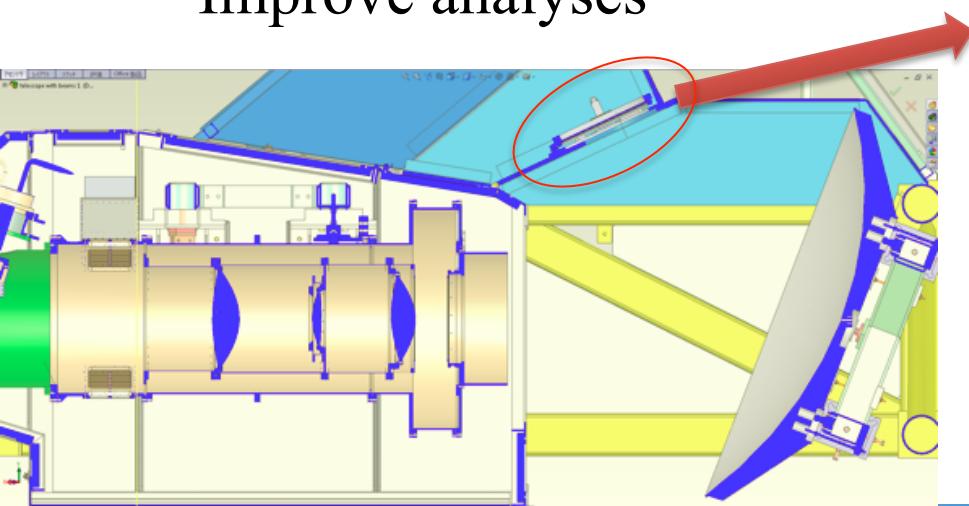
POLARBEAR Collaboration

New !



Near Future

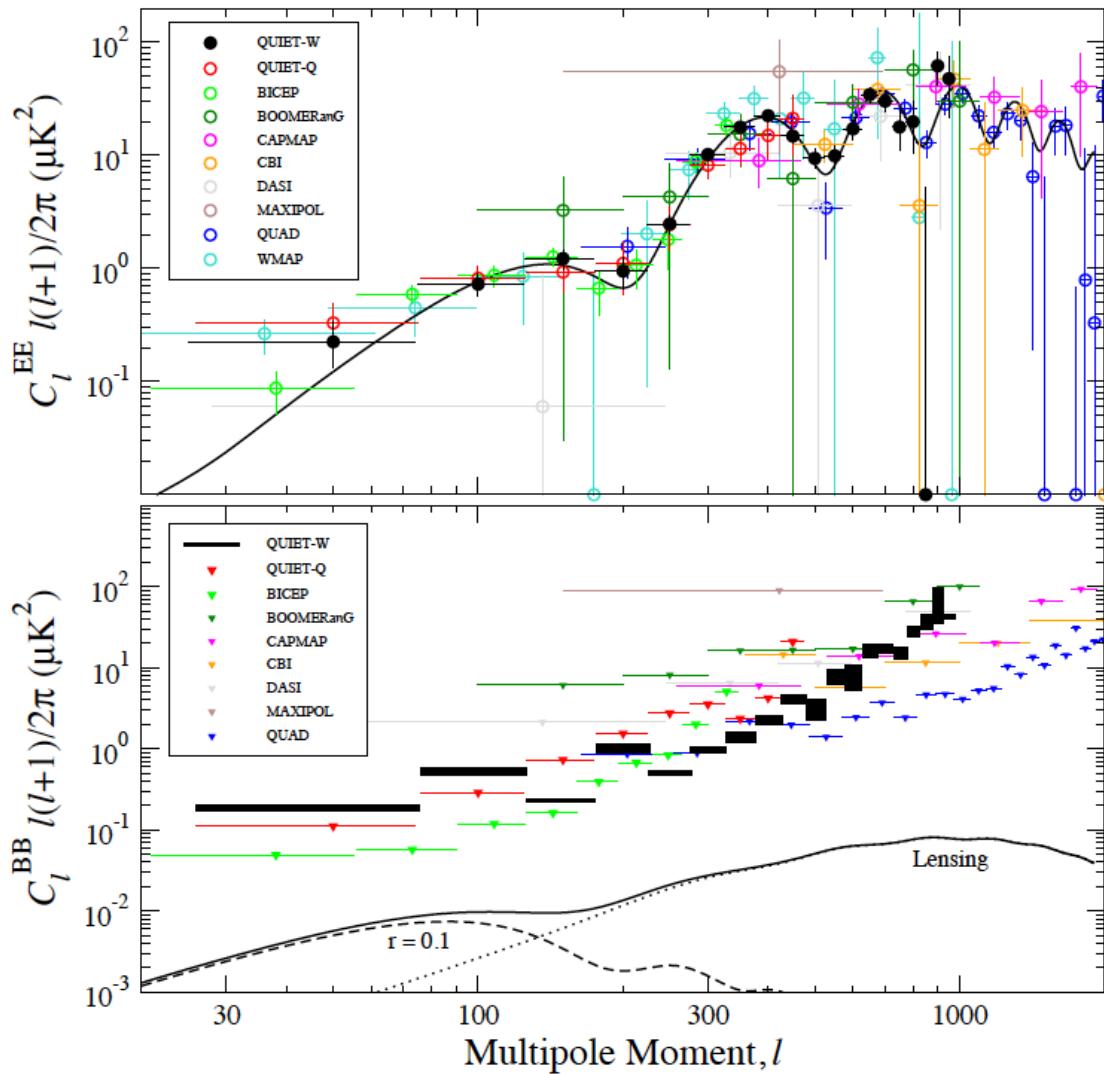
- Cl_{BB} results in preparation
- POLARBEAR-1 will go for 15deg x 15deg observations to search for primordial gravitational waves.
- Need to further mitigate systematics and 1/f noise. Such efforts are on-going
 - Additional angle calibrator
 - additional half-wave-plate
 - Improve analyses



2014/02/24

KEK Physics Seminar "New Results from POLARBEAR on CMB
Polarization"
Masashi Hazumi (KEK)

Current Status of polarization measurements



E-mode

- Observed
- Consistent with ΛCDM

B-mode

- Not observed yet
- Best limit on r from B-mode is $r < 0.7$ (95% C.L.) by BICEP (3yr data, preliminary)

若手の活躍

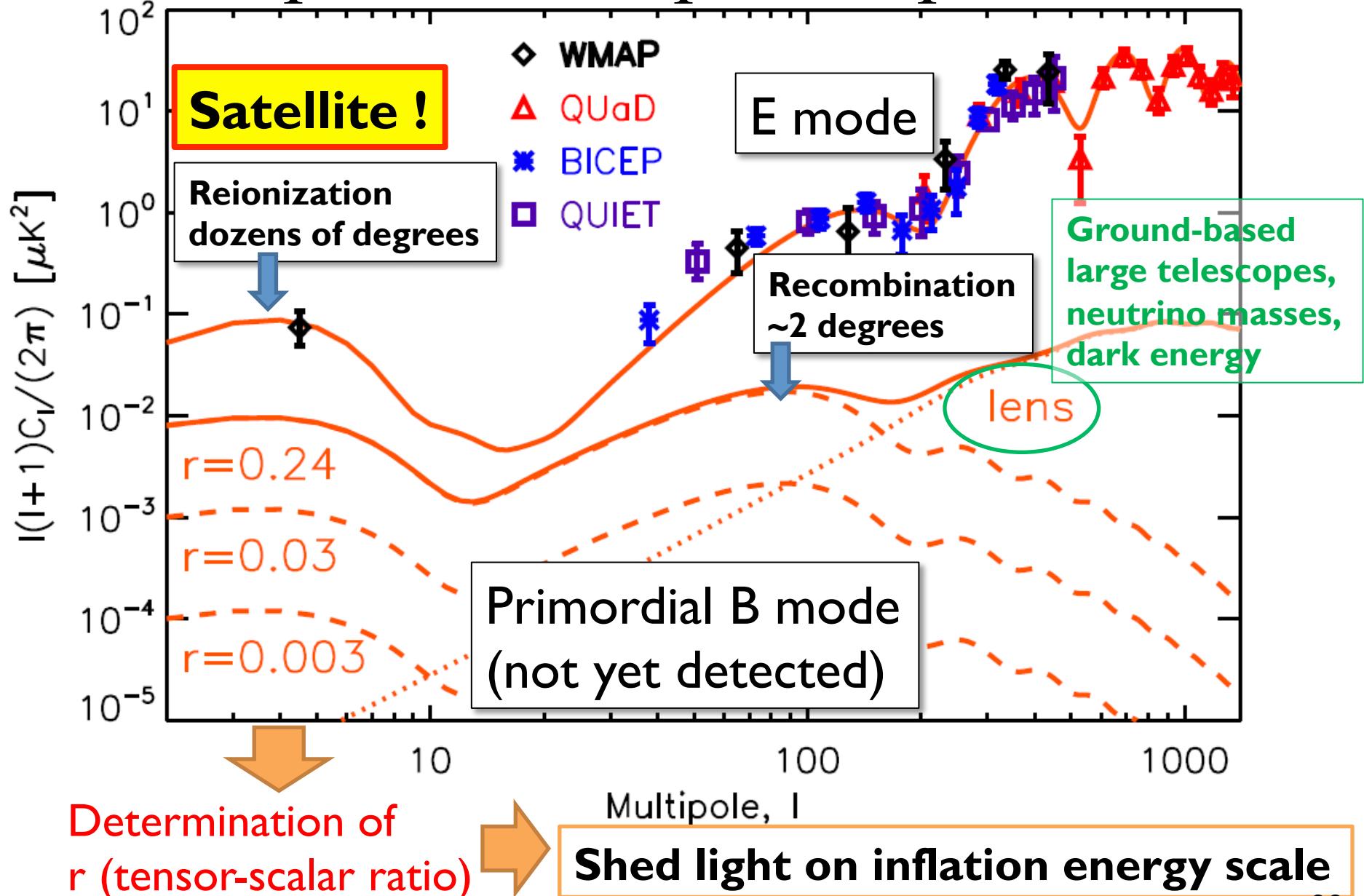
- 都丸(較正源開発、受信機開発)
 - 長谷川(データ較正)
 - 松村(スキャンストラテジー等)
 - 西野(データ解析、オンライン系)
 - 茅根(データ解析)
 - 高倉(データ解析)
-
- 観測・運用は全員でがんばった
(上記+服部、森井、堀、清水、
井上、秋葉)

Cl^{BB}(いわゆるBモード)の
結果発表に向けて奮進中



4. Roadmap and Conclusion

CMB polarization power spectra



Two Major Goals

- Search for primordial CMB B-mode
 - arising from primordial gravitational waves during cosmic inflation
 - Ultimate goal is to reach $r \sim 0.001$
- Precision measurements of sum of neutrino masses
 - Ultimate goal is to reach $\sum m_\nu \sim 20\text{meV}$

Grand Roadmap

$r=0.001$

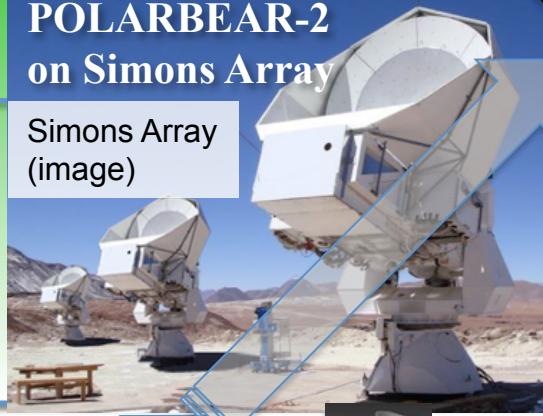
$r=0.01$

$r=0.1$

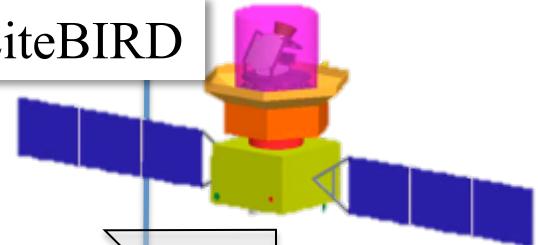
$r=1$

Large-single-field
slow-roll models

POLARBEAR-2
on Simons Array
Simons Array
(image)



LiteBIRD



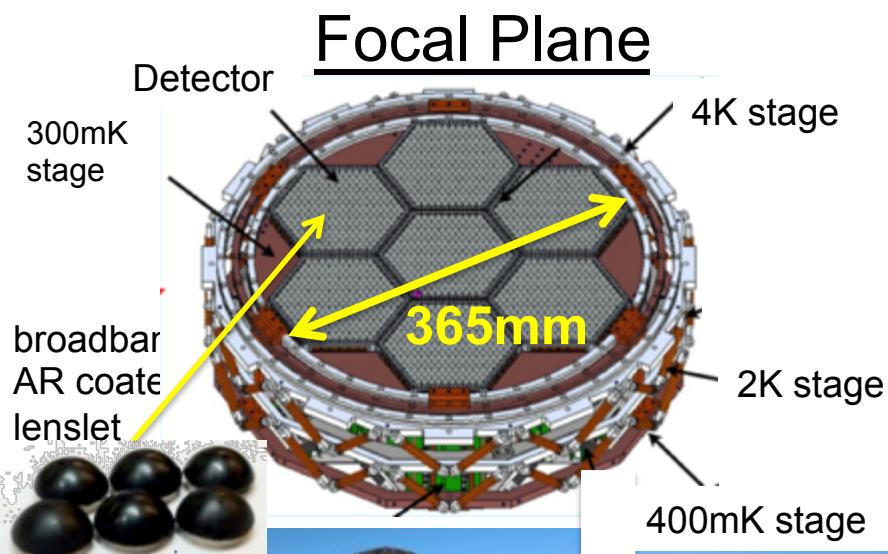
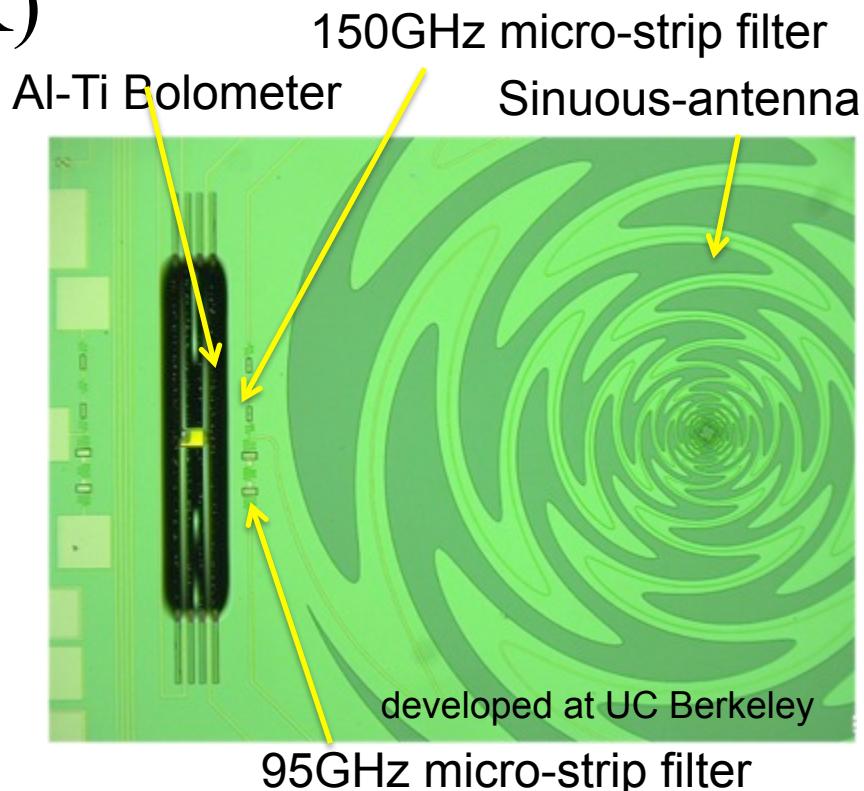
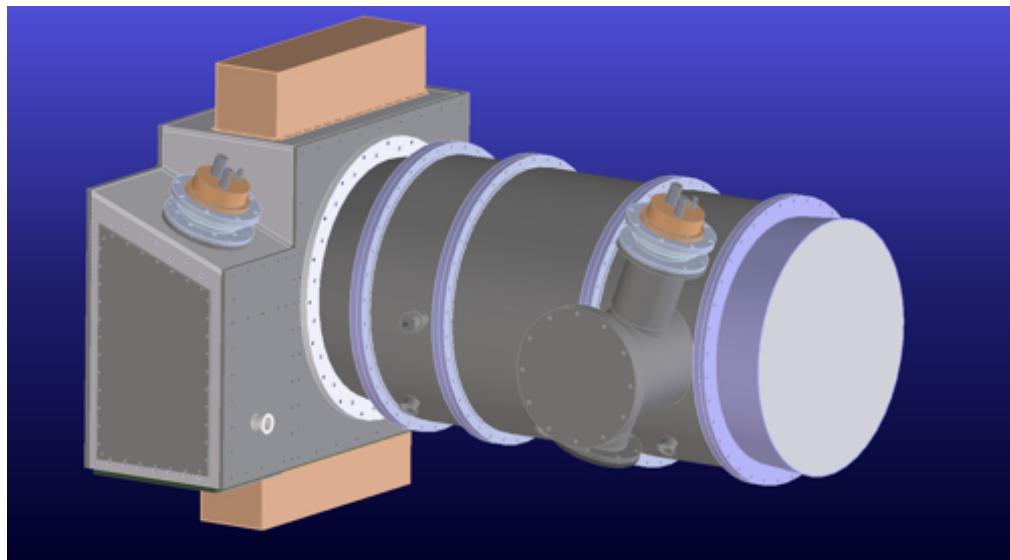
2005

2010

2015

2020

POLARBEAR-2 (led by KEK)



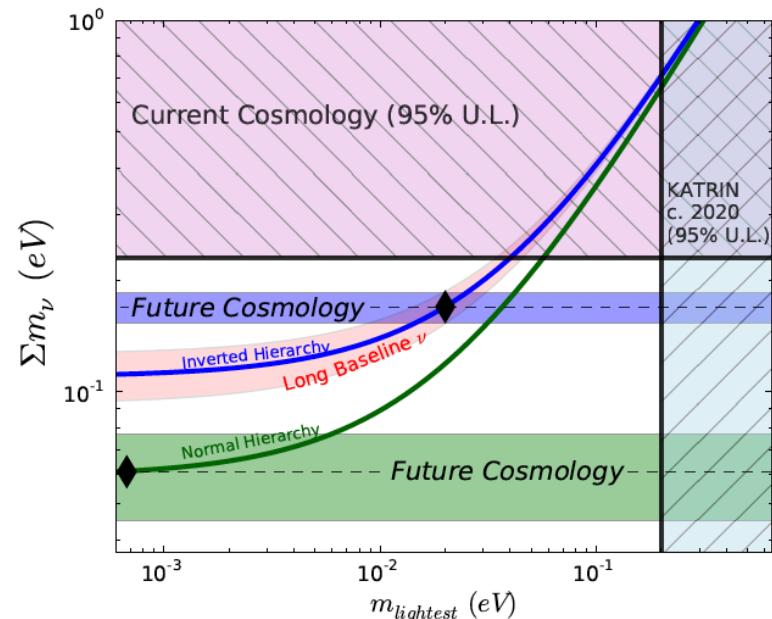
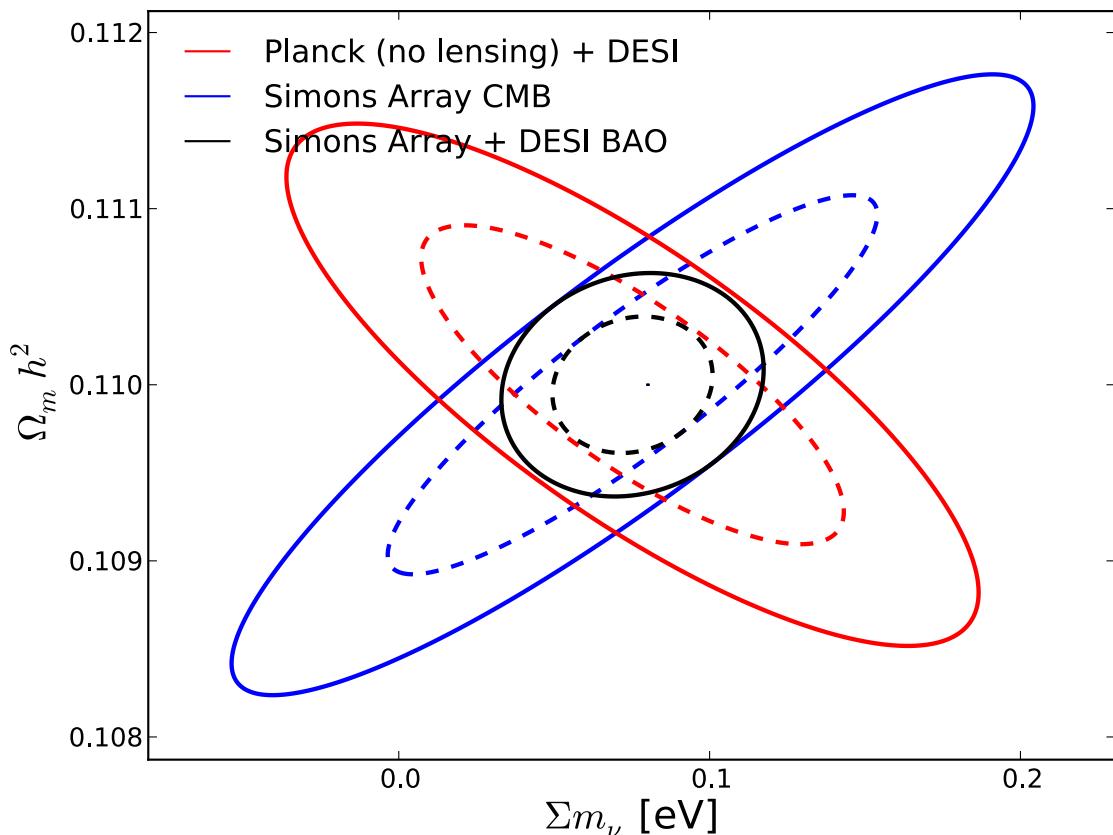
2014/02/24

- 7588 TES bolometers
- 95GHz and 150GHz
- $r < 0.01$ @ 95% C.L.
- $\sigma(\Sigma m_v) = 65\text{meV}$ (w/ Planck)

POLARBEAR-2
receiver system at KEK

2013.09.02

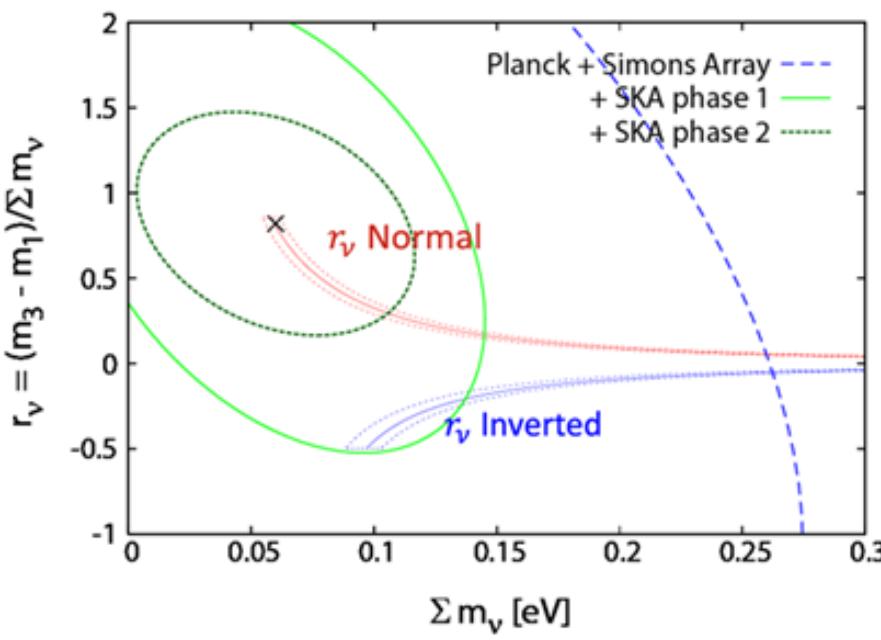
Expectation: Sum of neutrino masses



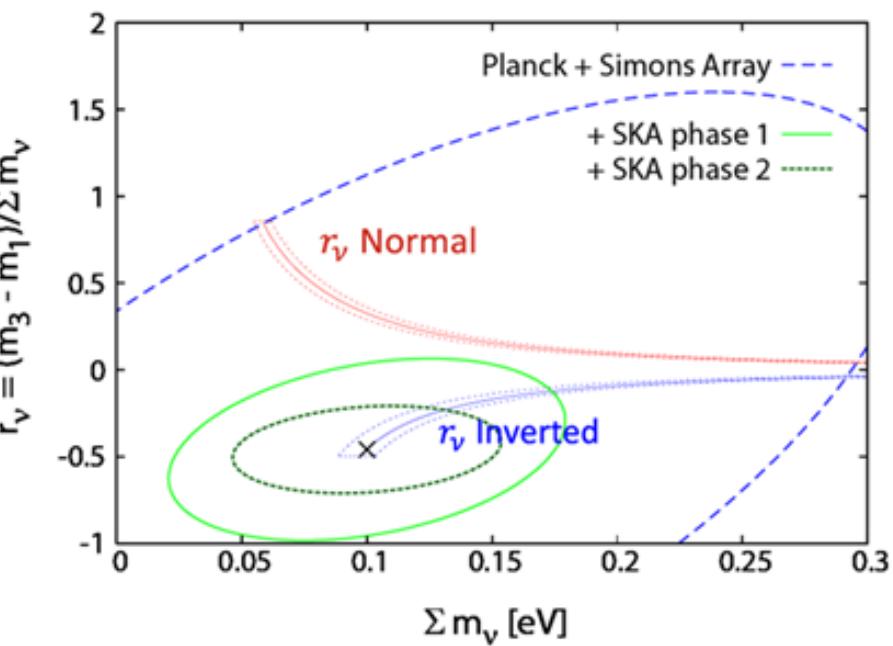
total error ~ 18 meV with 3 POLARBEAR-2 receivers,
project named Simons Array

Further (futuristic) constraints

Normal hierarchy



Inverted hierarchy



Oyama-Kohri-Hazumi 2014 in preparation

Conclusion

- First results from POLARBEAR
 - detected gravitational lensing for the first time with CMB polarization data alone
 - Important milestone !
- We are ready to do precision cosmology with CMB polarization !
- POLARBEAR-1,-2 and Simons Array guarantee fruitful results in cosmology. Stay tuned !