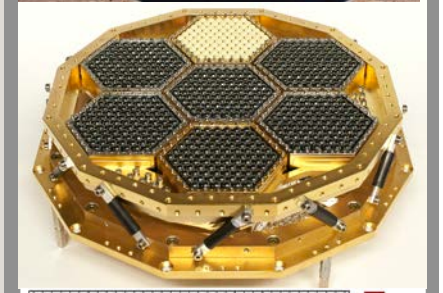
KEK
Inter-University Research Institute Corporation
High Energy Accelerator Research Organization
Institute of Particle and Nuclear Studies

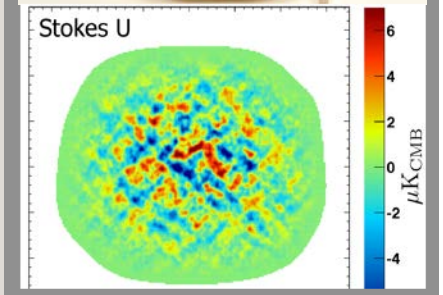
Cosmic Inflation and Neutrino Masses at POLARBEAR CMB Polarization Experiment

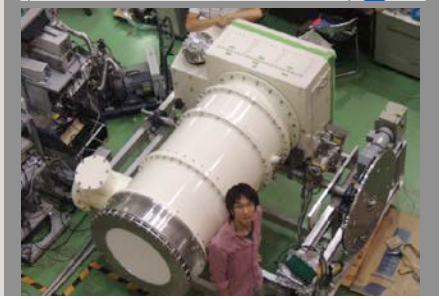
WIN2015, June 12, 2015

Masaya Hasegawa
(KEK)

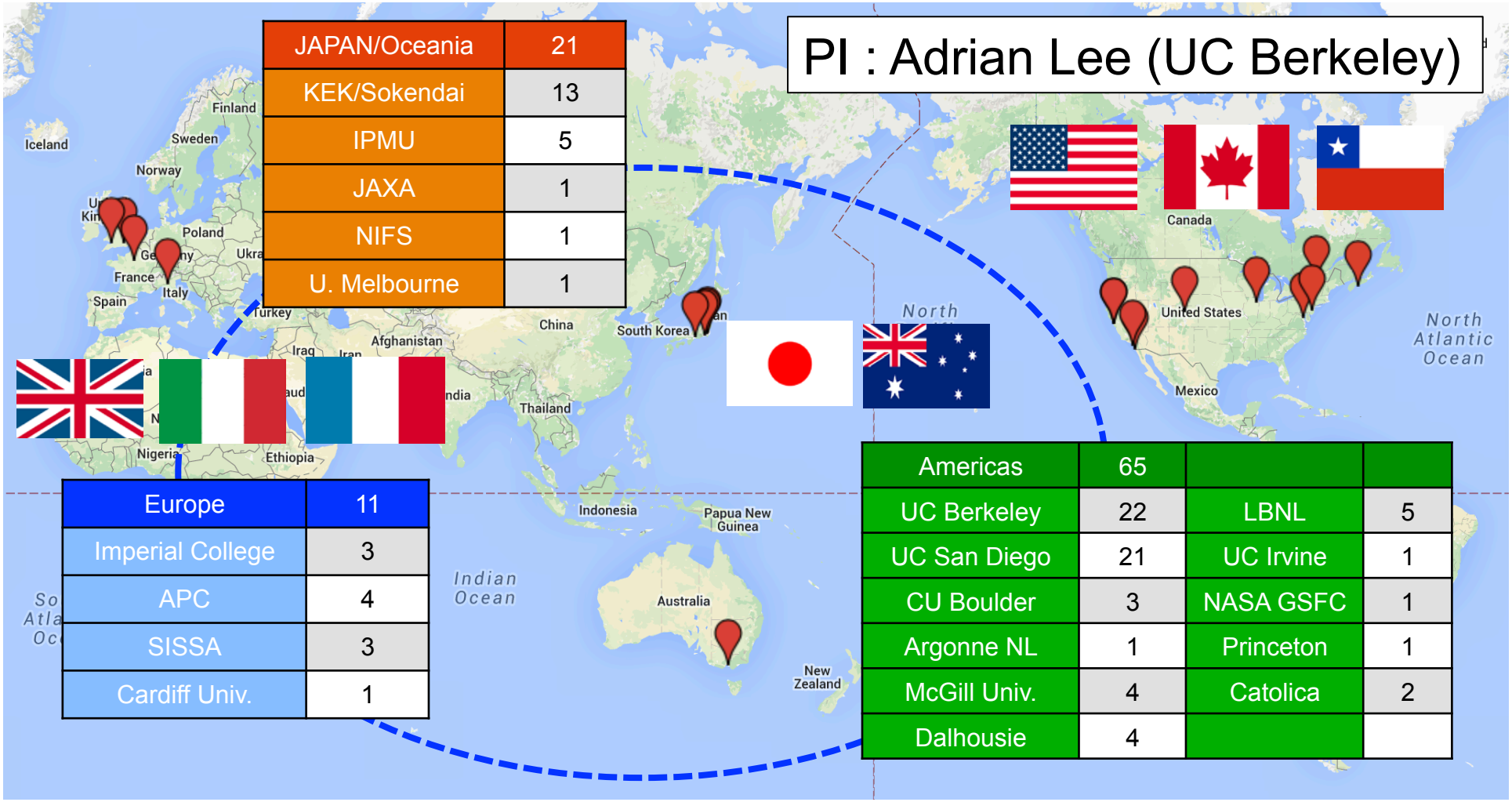
On behalf of POLARBEAR/
Simons Array Collaboration







POLARBEAR Collaboration



JAPAN/Oceania	21
KEK/Sokendai	13
IPMU	5
JAXA	1
NIFS	1
U. Melbourne	1

Europe	11
Imperial College	3
APC	4
SISSA	3
Cardiff Univ.	1

Americas	65		
UC Berkeley	22	LBNL	5
UC San Diego	21	UC Irvine	1
CU Boulder	3	NASA GSFC	1
Argonne NL	1	Princeton	1
McGill Univ.	4	Catolica	2
Dalhousie	4		

8 countries, 20 institutes, ~100 people

KEK

Outline

- POLARBEAR Project
  - Motivations : Inflation and ν 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.

What's POLARBEAR ?

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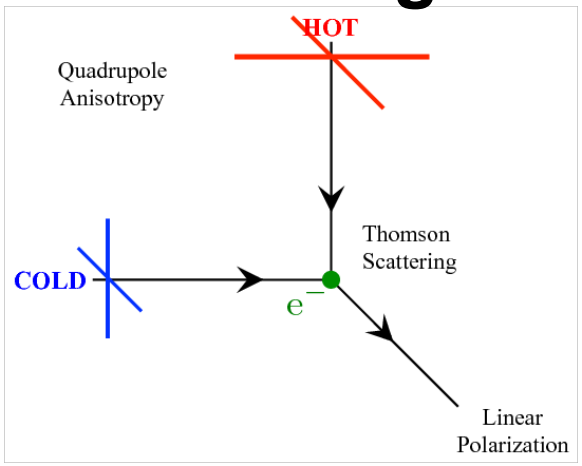
  - Ground-based CMB Polarization Experiment
  - Aiming the detection/characterization of 'B-mode (odd-parity)' polarization pattern originating primordial gravitational wave and gravitational lensing effect.

Science targets are
"Inflation" and "Neutrino masses" !

Science with CMB B-mode

Thomson Scattering on LSS



Science with CMB B-mode

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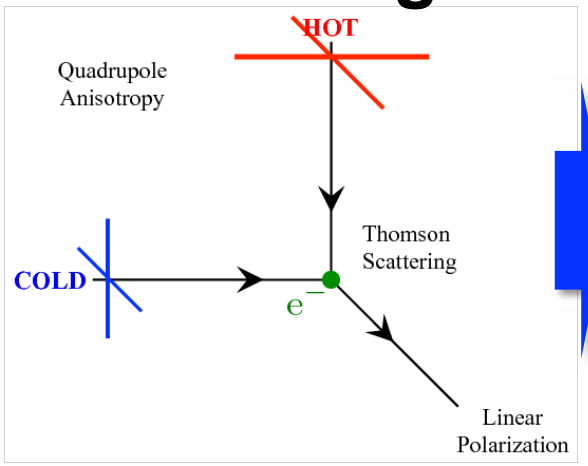
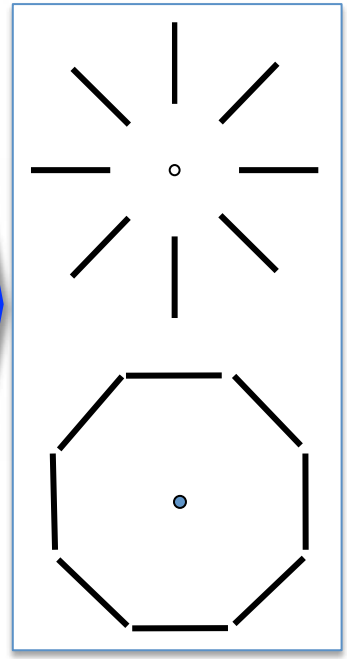


***E*-mode**



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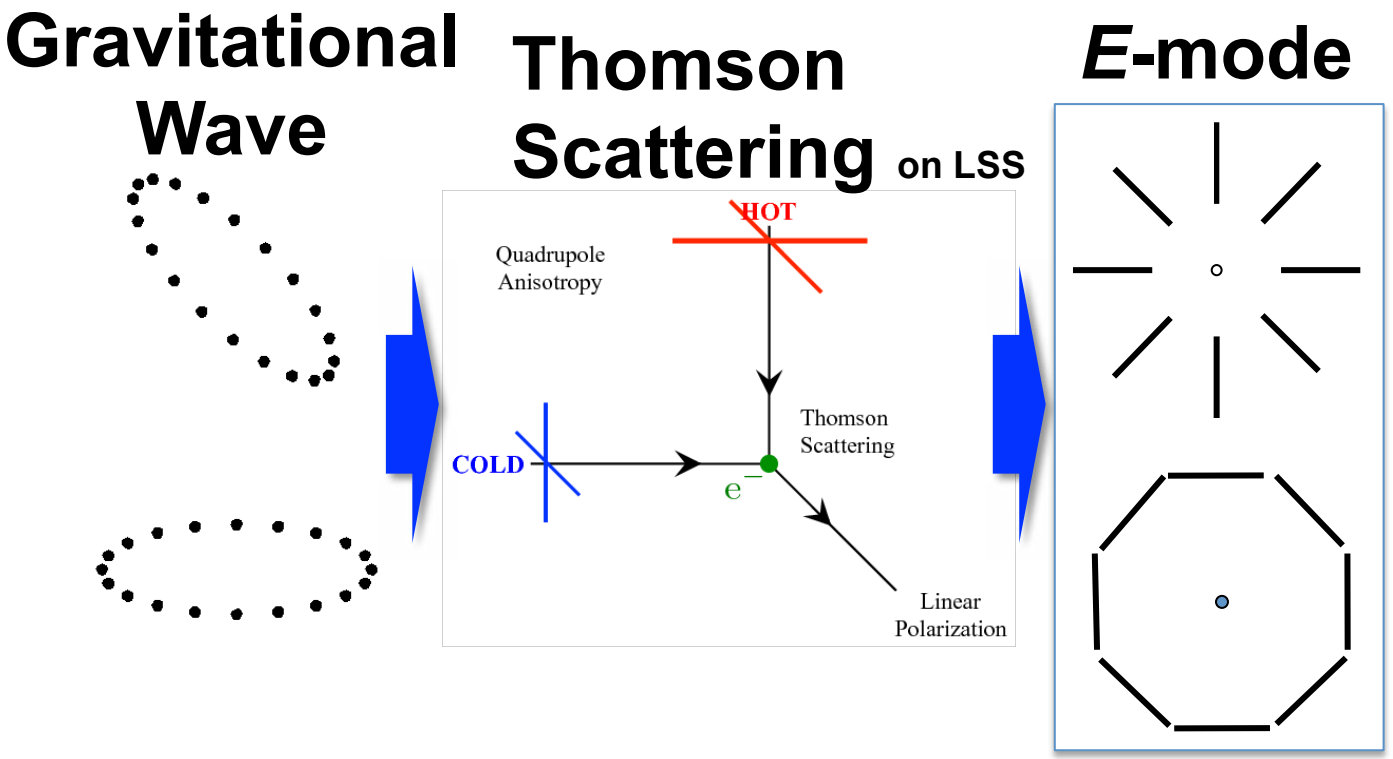

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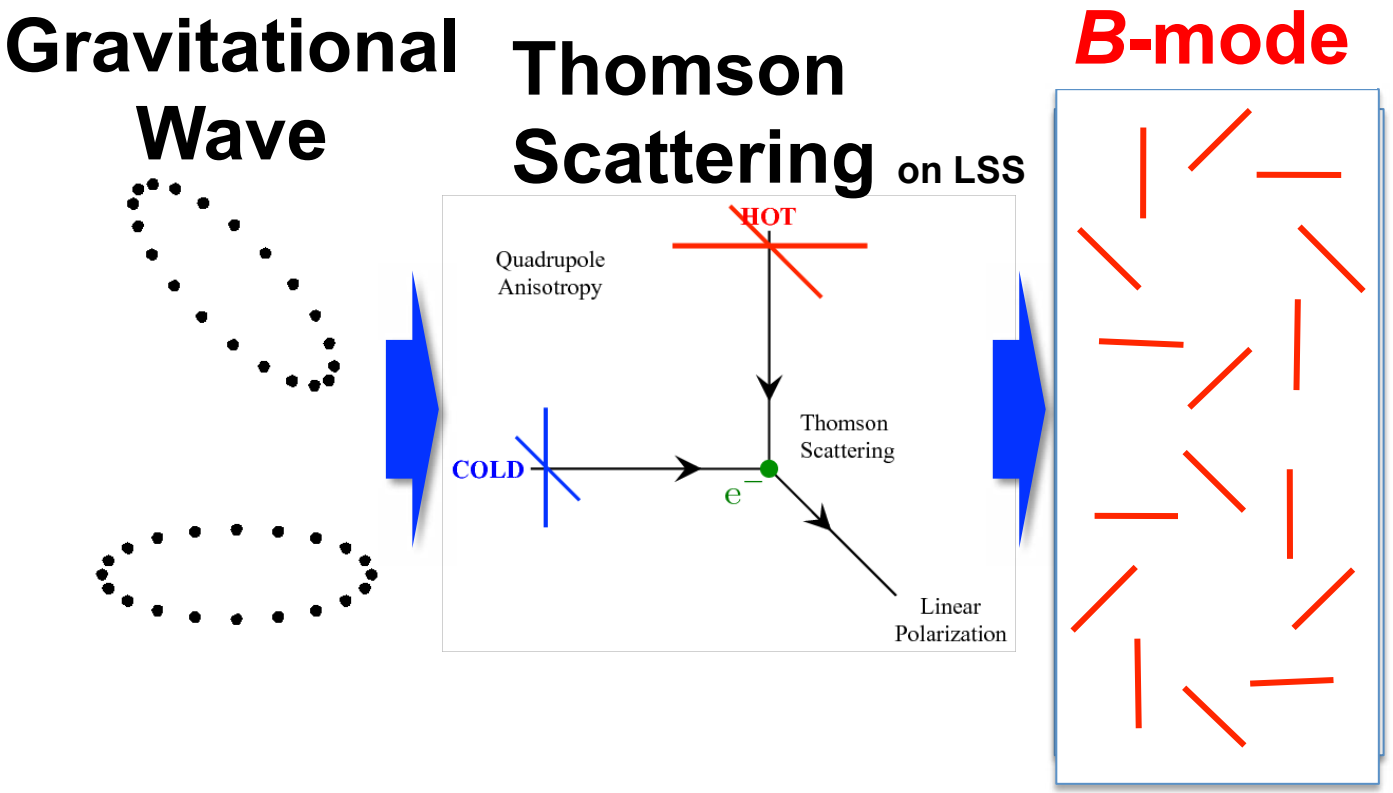

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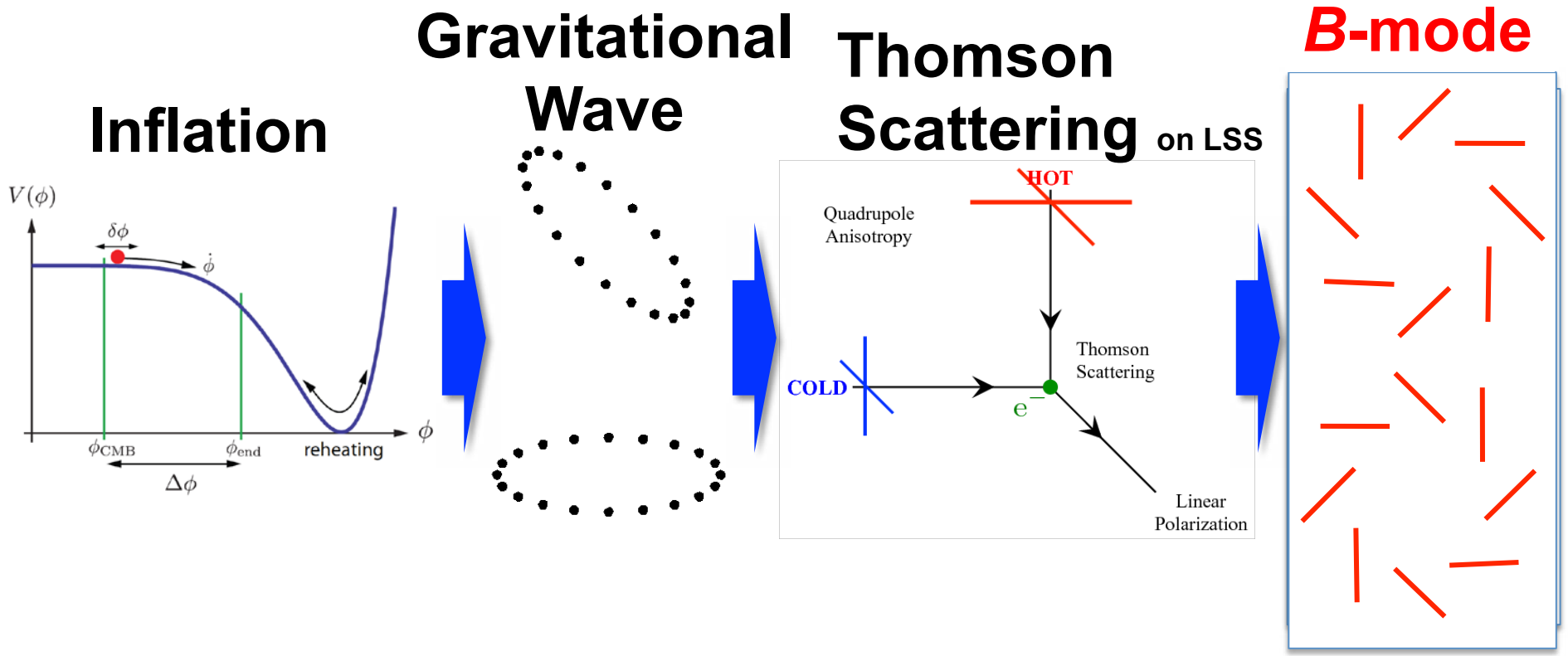

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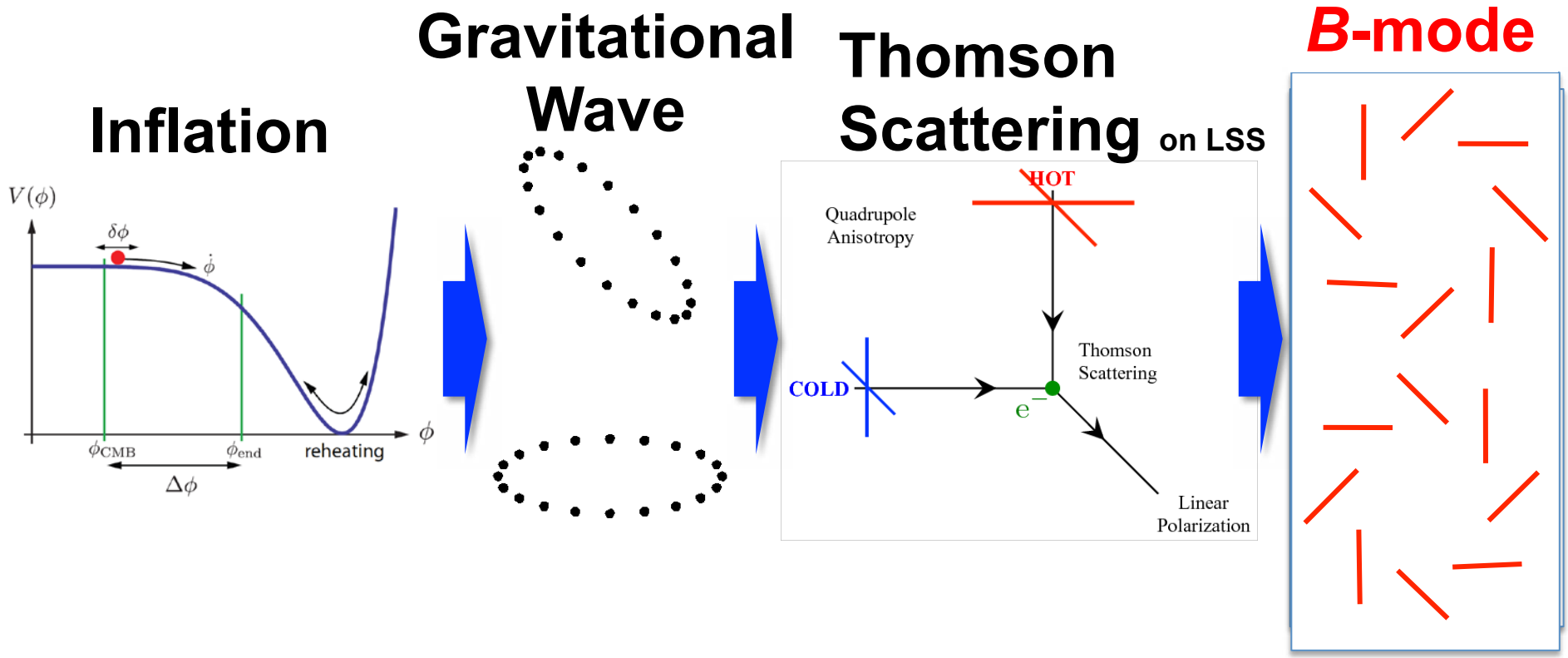
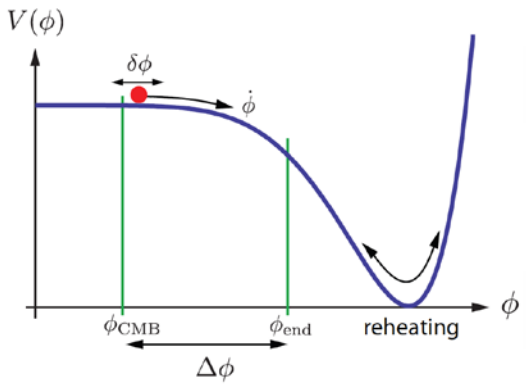


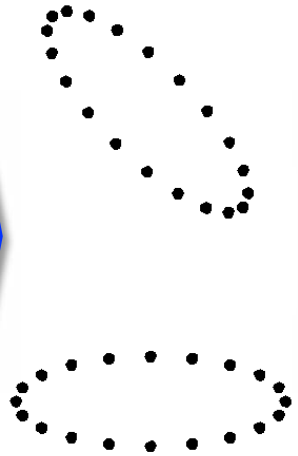
B-mode is a smoking gun signature of inflationary universe!

Science with CMB B-mode

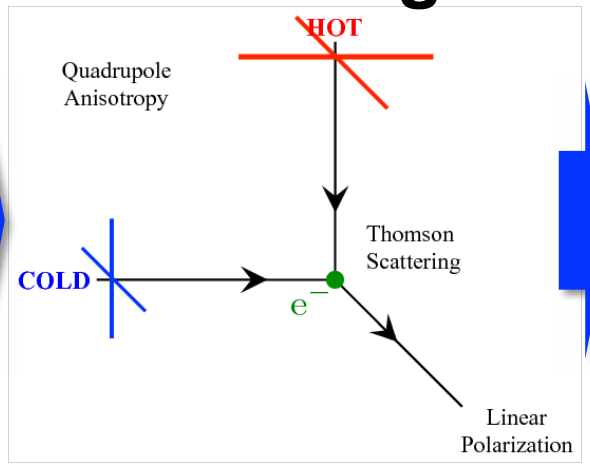
Inflation



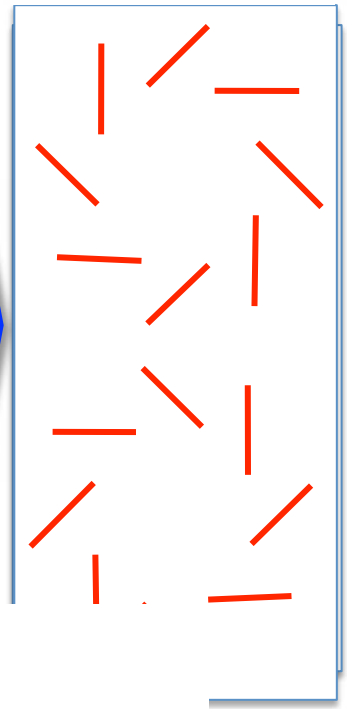
Gravitational Wave



Thomson Scattering on LSS



***B*-mode**

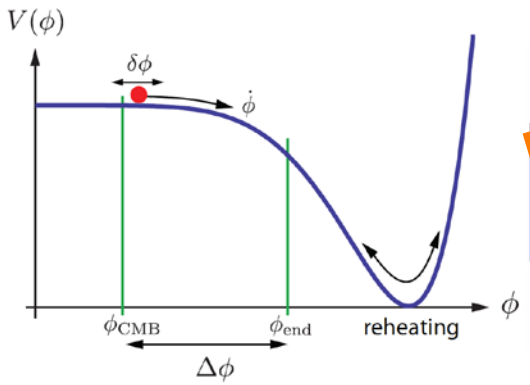


B-mode power is proportional to tensor-to-scalar ratio, r

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

Science with CMB B-mode

Inflation



Gravitational W

Thomson

***B*-mode**

10^{12} x LHC (13TeV)

10^{5} x GZK cut-off (10^{20}eV)

→ CMB B-mode is a potential window onto the truly-unexplored ultra-high energy phenomenon

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

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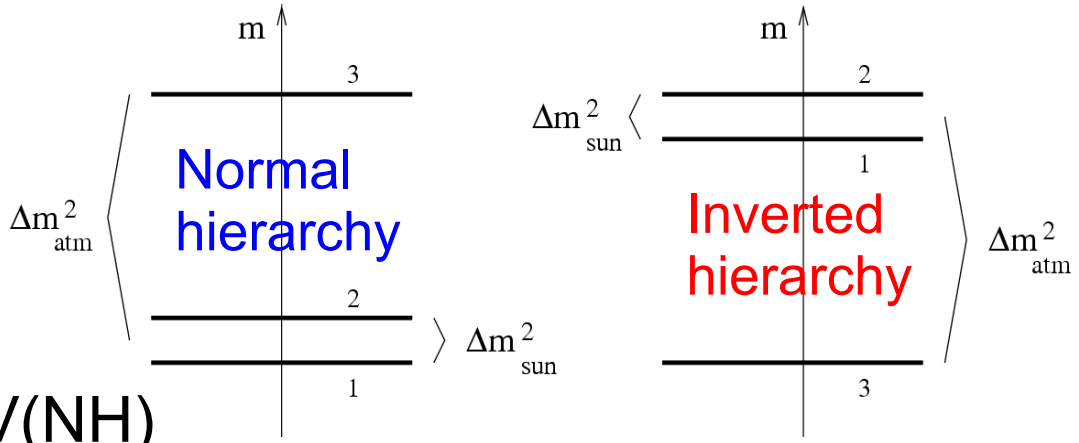
Neutrino Mass

Neutrino Oscillation

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

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

→ $\Sigma m_\nu > 0.10$ (IH) or 0.05eV(NH)



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

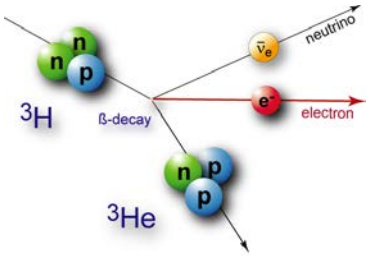
$0.05\ eV < \Sigma\, m_\nu < \sim 1.3\ eV$

Neutrinos are relativistic at LSS.

Neutrino Mass

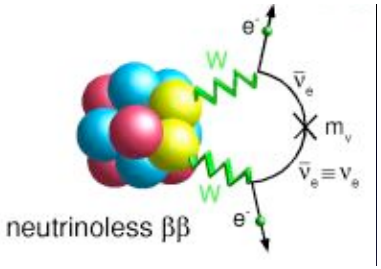
Probes to sub-eV Neutrino Mass

(Particle physics)
Single Beta Decay



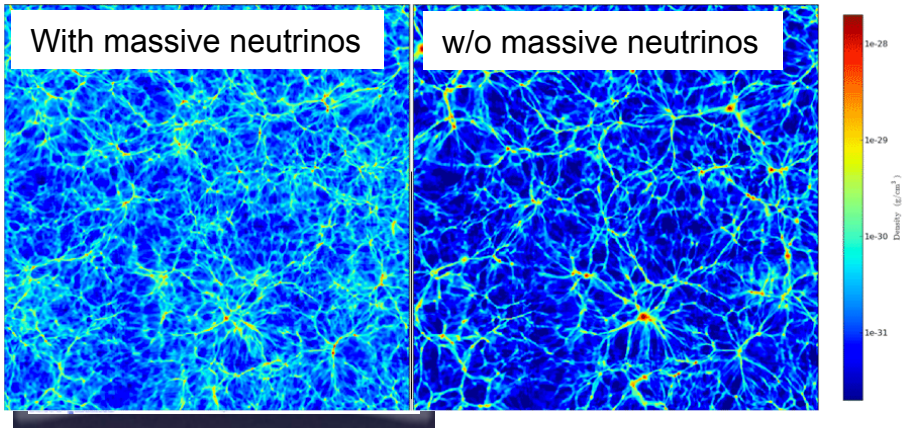
- Effective Mass
- KATRIN will reach 200meV sensitivity in ~5 years.

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



- Majorama Mass
- Sensitivity below 100 meV in 5 years (KamLAND…)

(Cosmology and Astrophysics)
Large Scale Structure



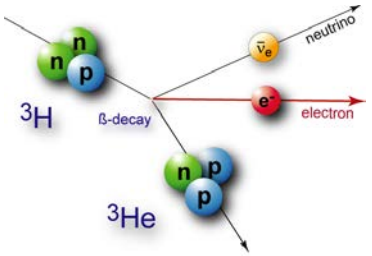
- Sum of ν Masses
- Sensitivity below "oscillation limit" in ~5 years.

Probe Σm_ν is complementary to that from particle physics.

Neutrino Mass

Probes to sub-eV Neutrino Mass

(Particle physics)
Single Beta Decay



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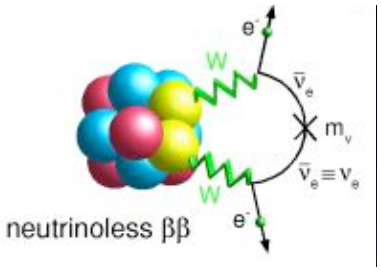

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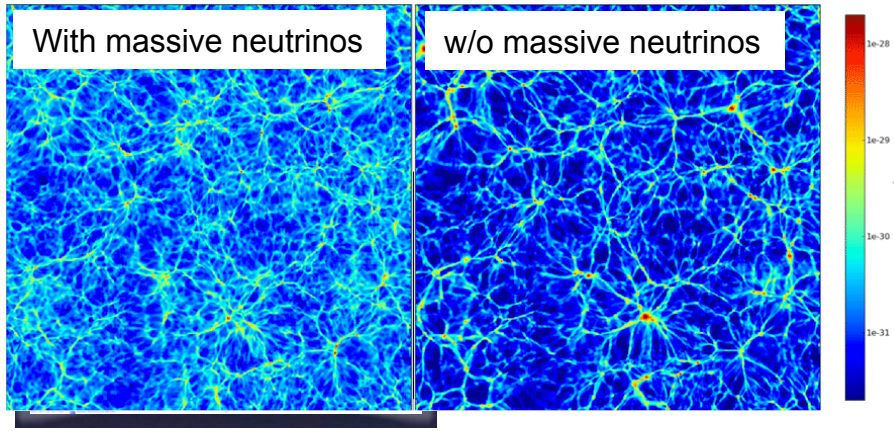

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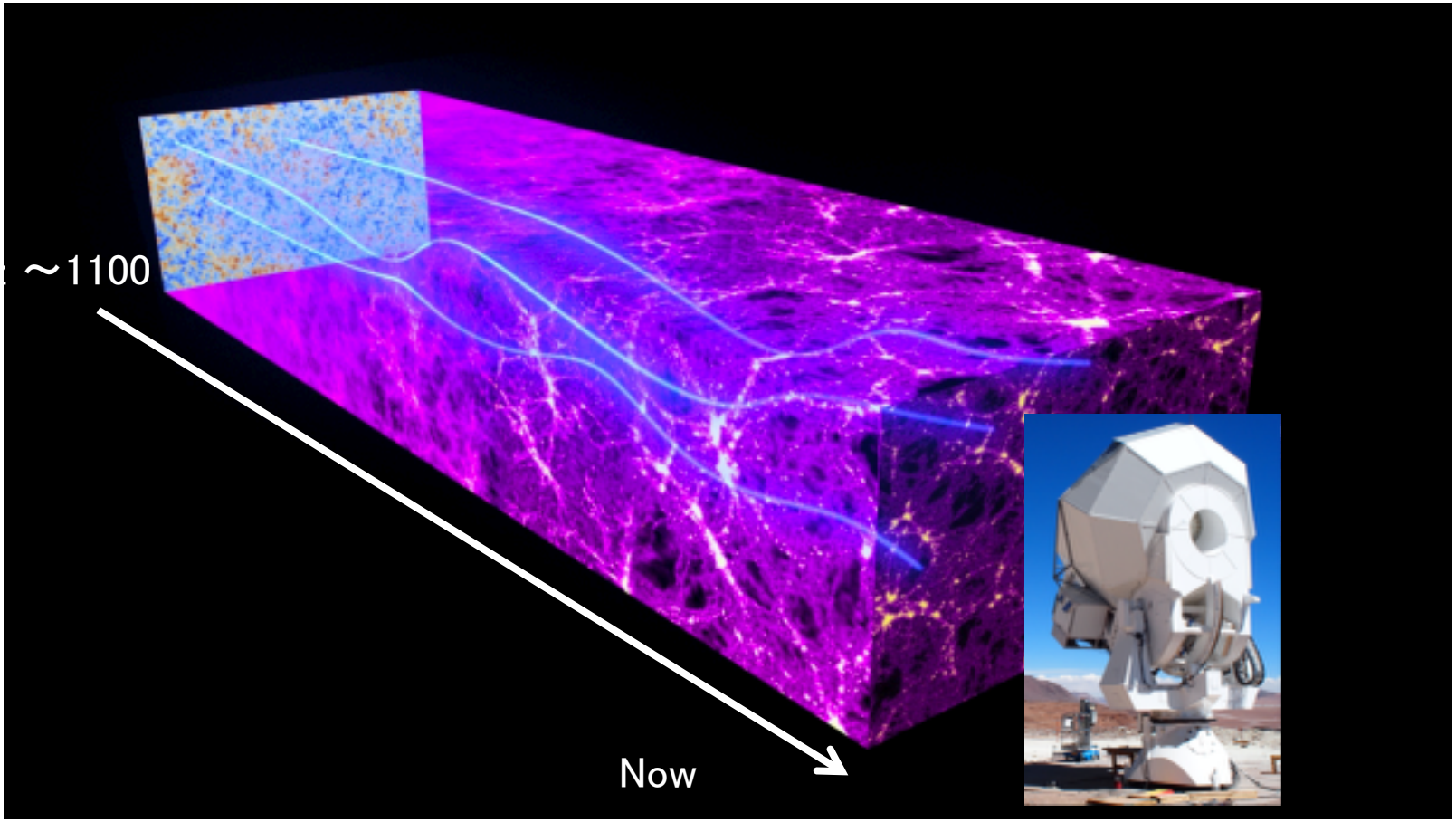
Lensing B-mode



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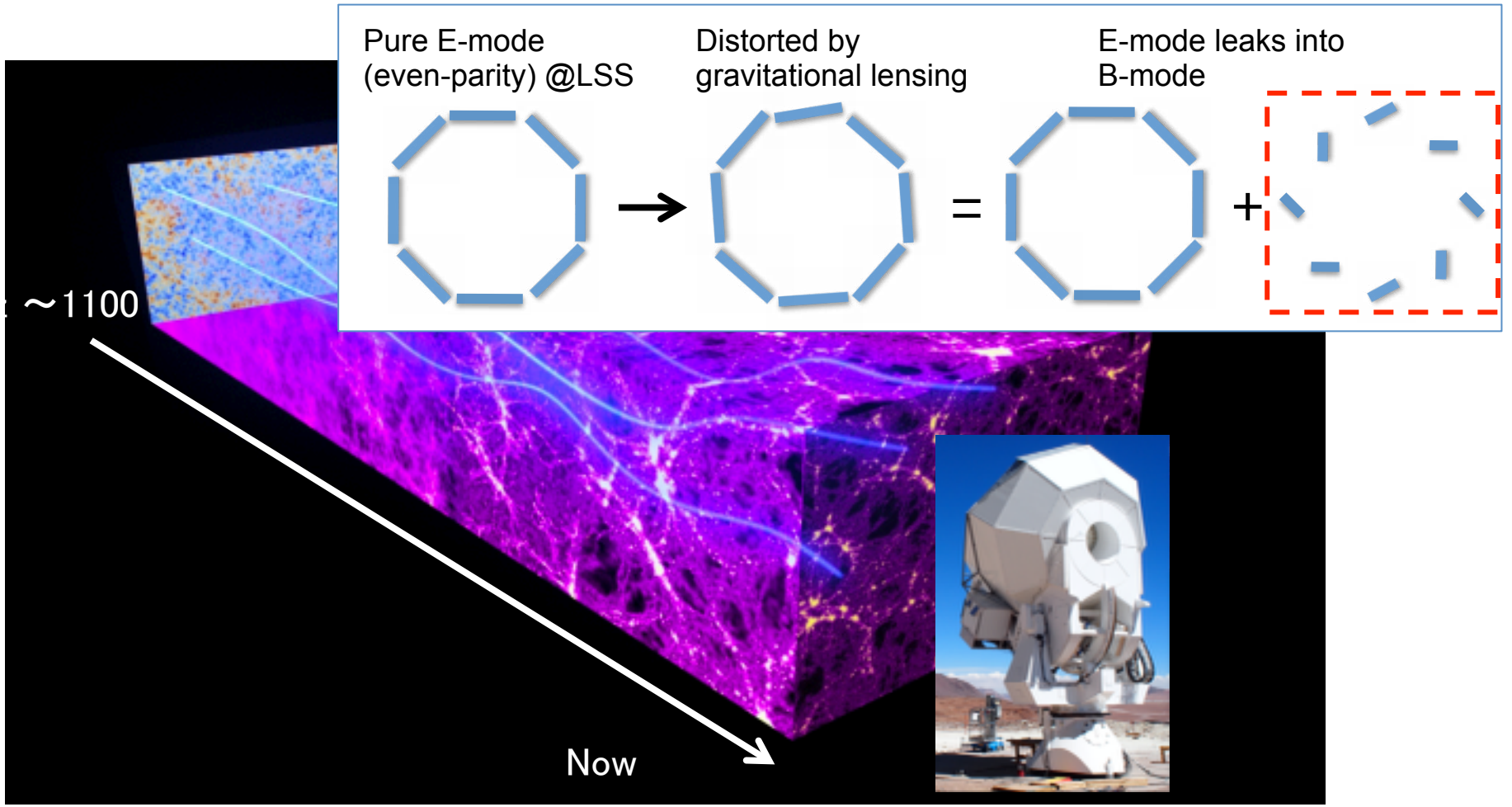

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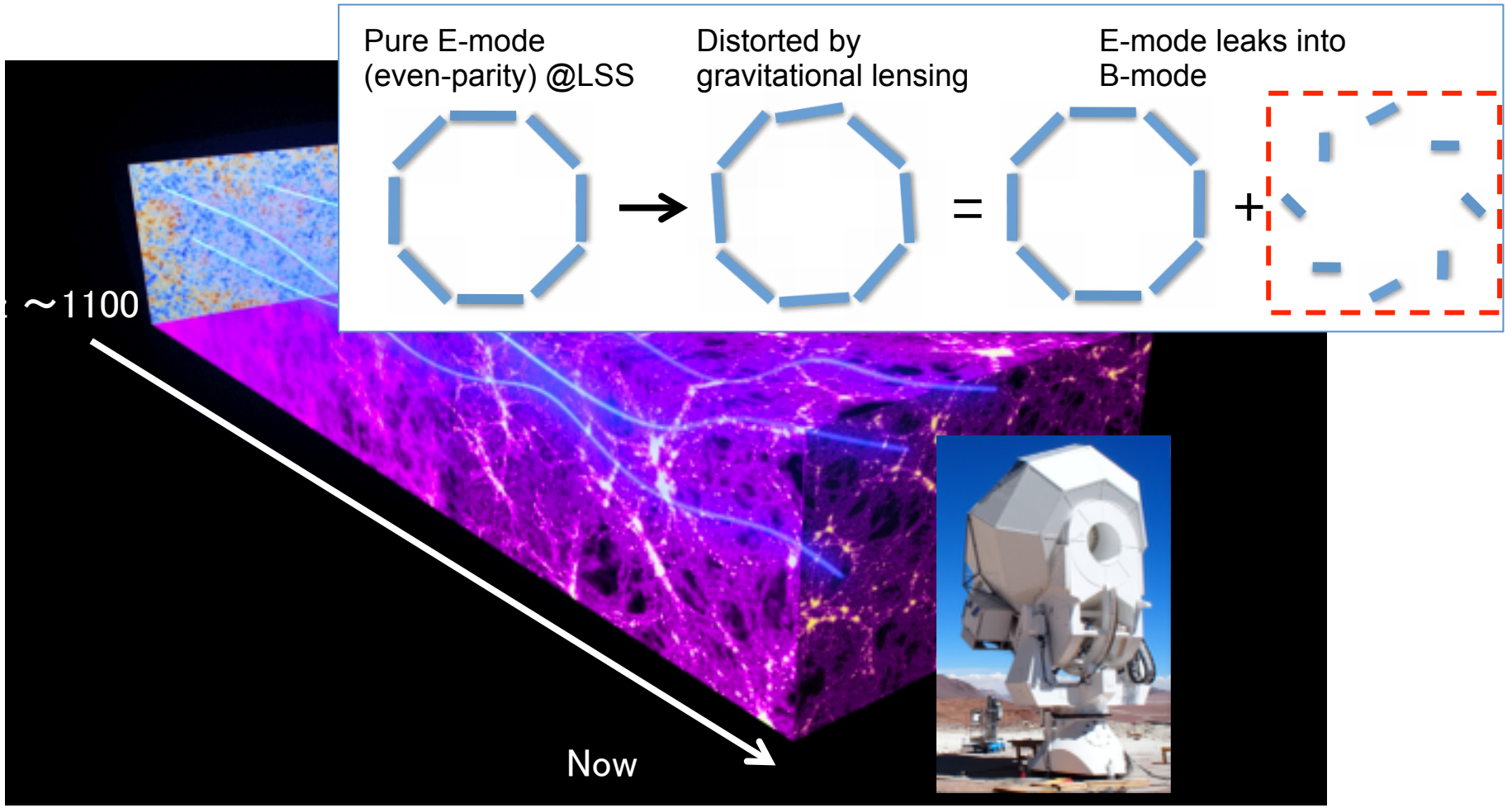
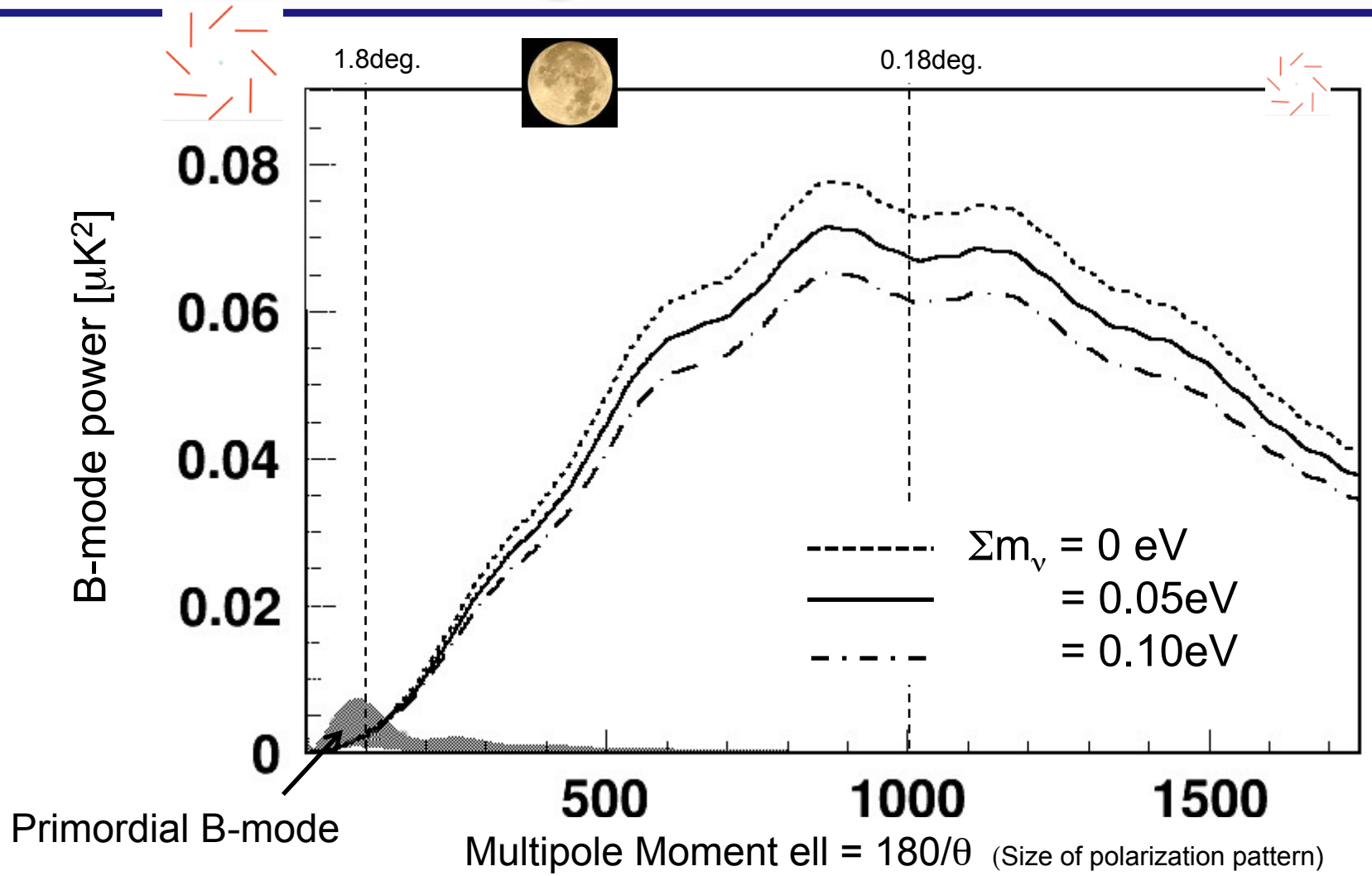


B-mode is the signature of lensing, and good tracer of LSS.

Lensing B-mode Power



The lensing B-mode amplitude is sensitive to Σm_ν.

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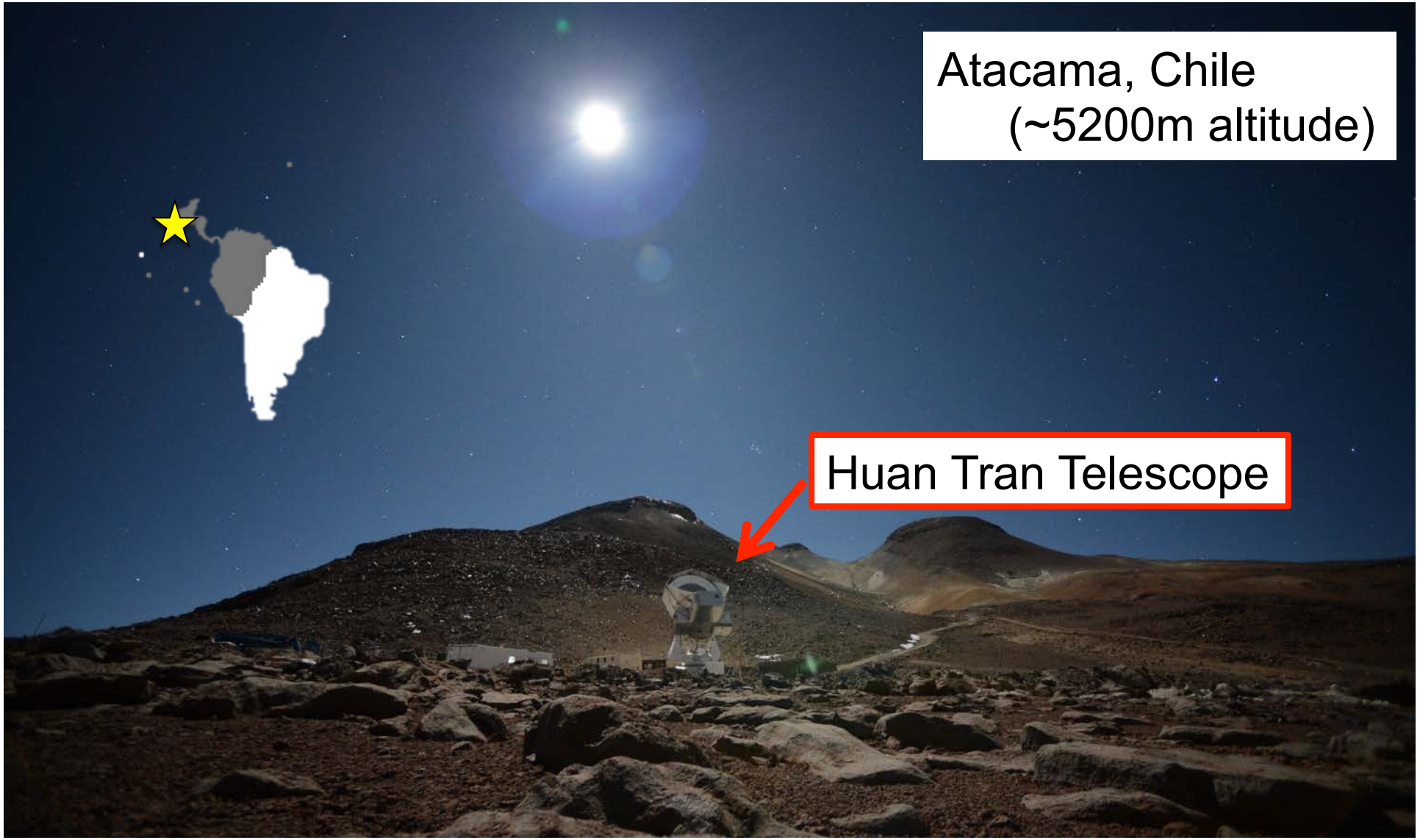
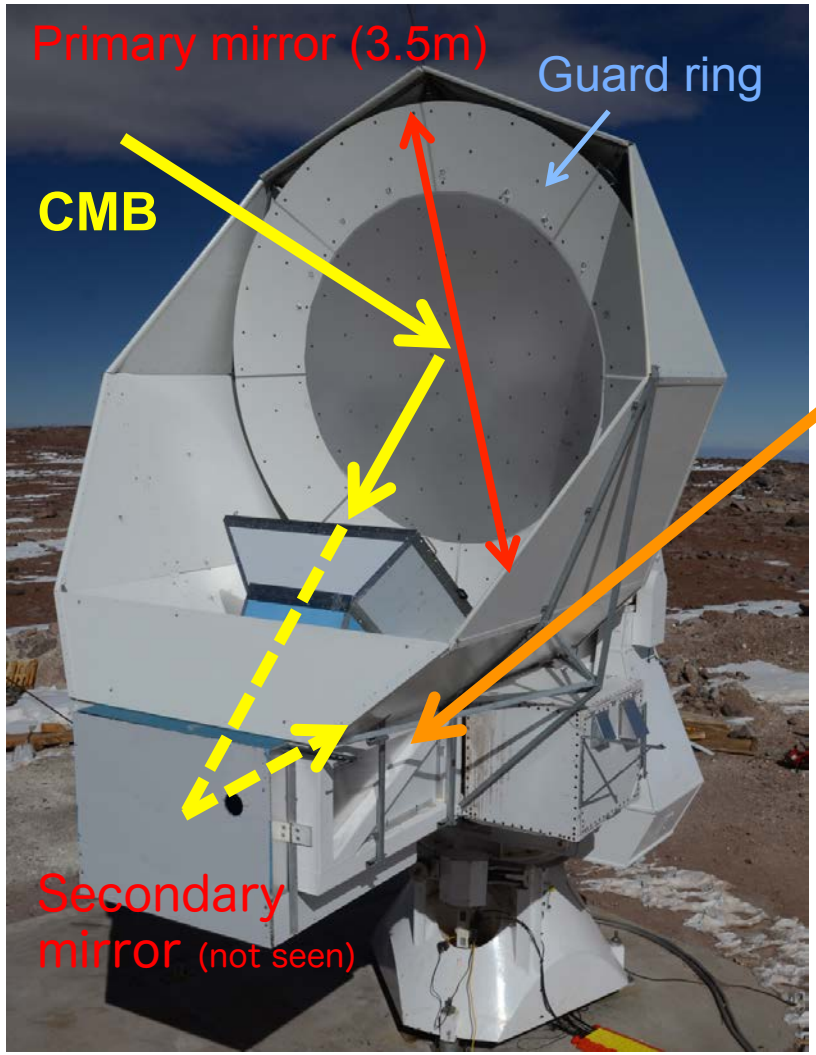
POLARBEAR Experiment

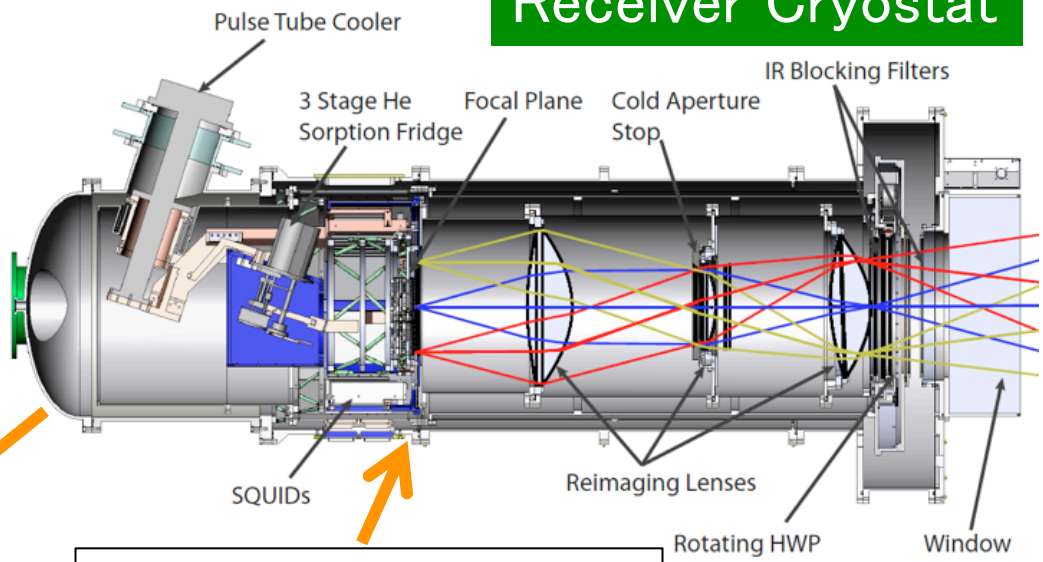
POLARBEAR Site



Huan Tran Telescope (HTT)



Receiver Cryostat

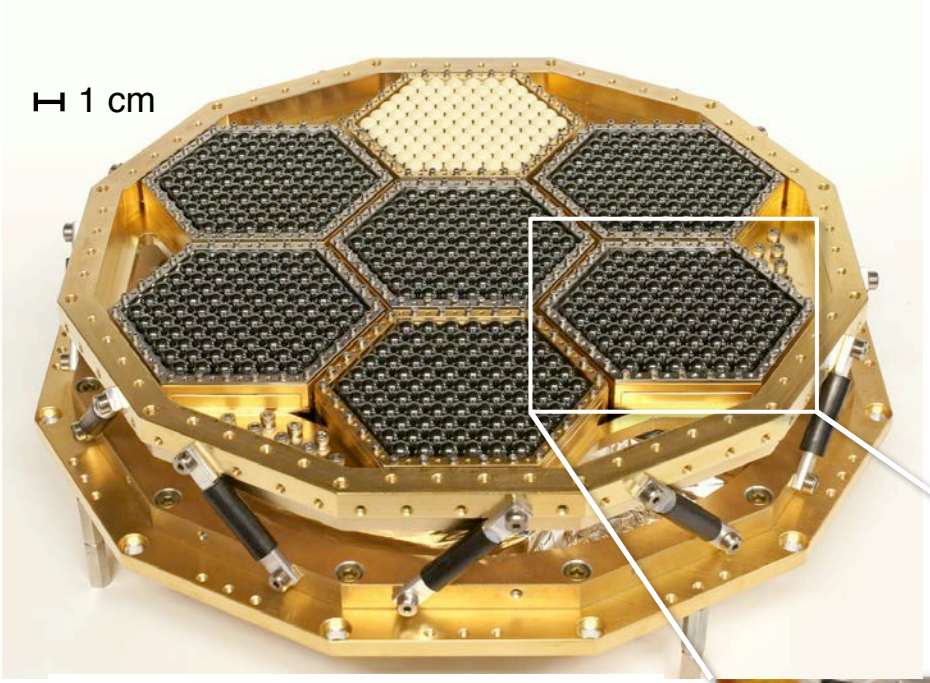


Focal plane (250mK)

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

Good enough angular resolution to measure the lensing B-mode signal

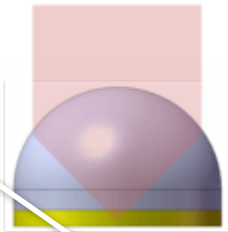
POLARBEAR-1 Focal Plane

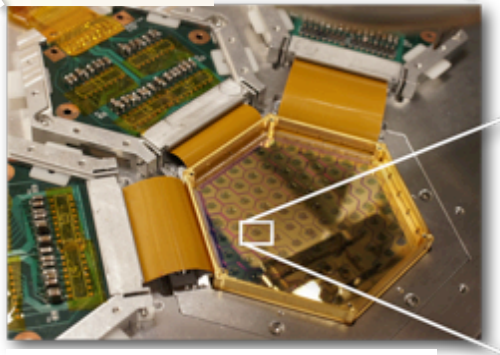


637 pixels
(91 pixels/wafer x 7wafers)
1274 TES bolometers

Array sensitivity : 23μK√s

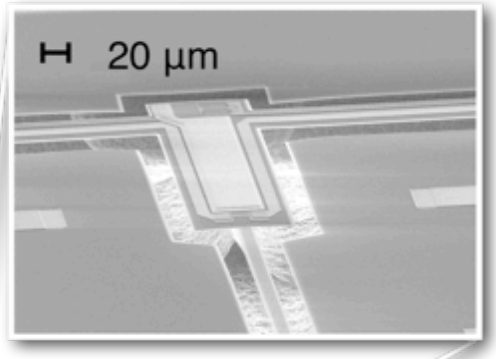
Lenslet

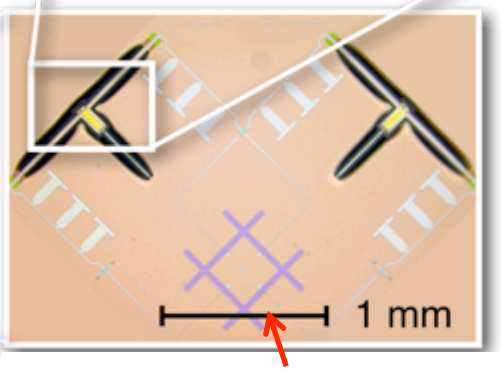




Wafer module

TES bolometer

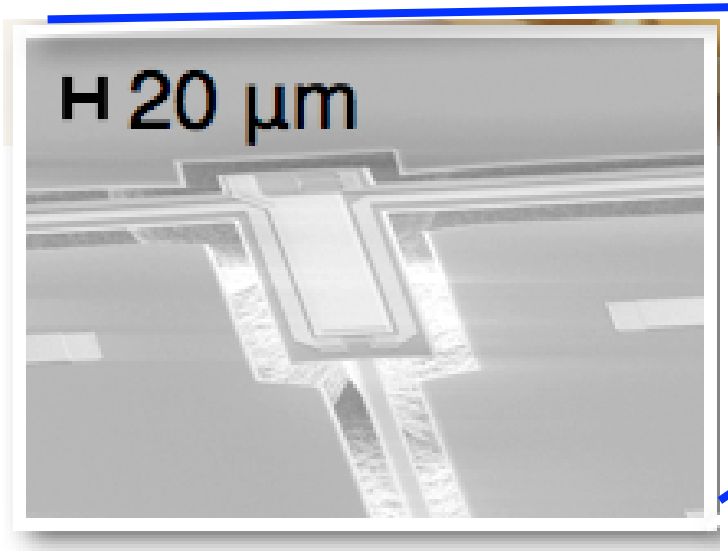


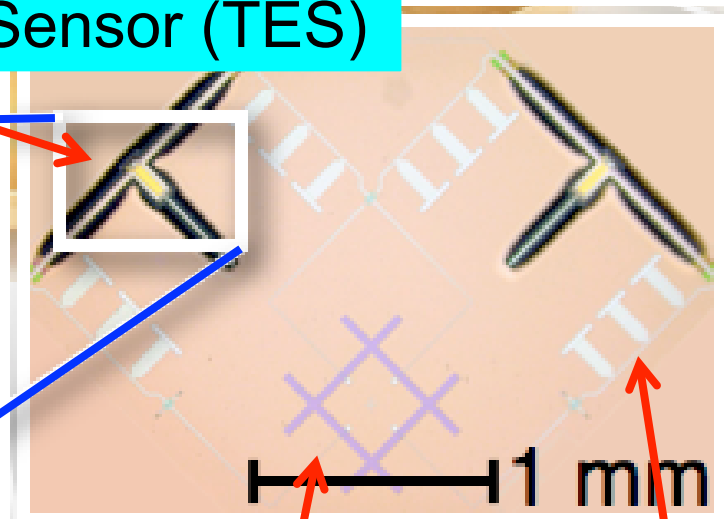


2 TES bolometers/pixel with dual-polarization double-slot dipole antenna

POLARBEAR-1 Focal Plane

Superconducting Transition Edge Sensor (TES)





Antenna (dual-polarization double-slot dipole antenna)

Polarization is measured by pair-differencing

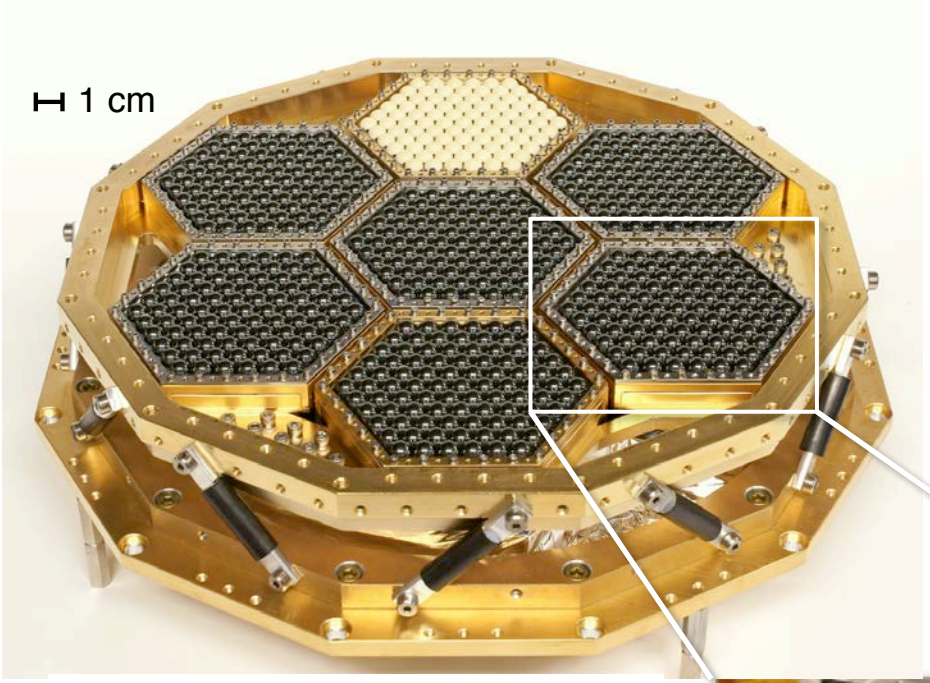
Micro strip filter (150GHz)

25μK√s

water module

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

POLARBEAR-1 Focal Plane



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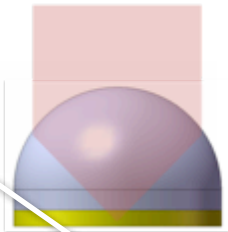
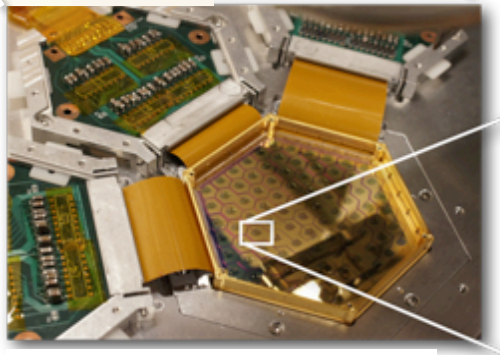
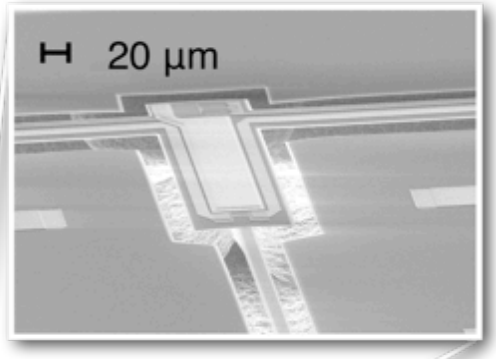
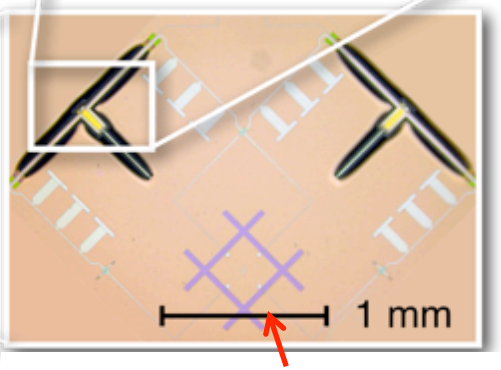




Wafer module

TES bolometer





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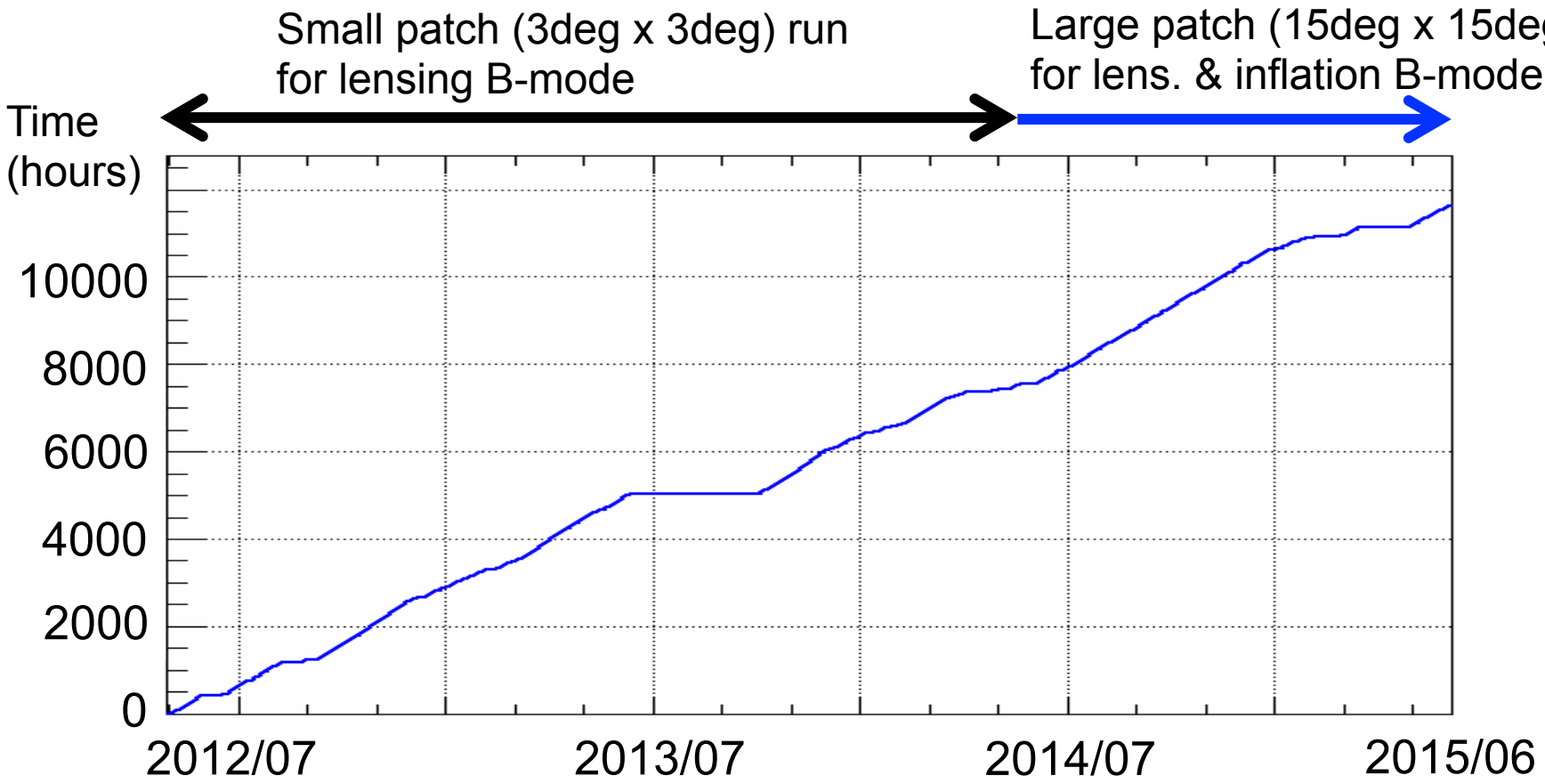
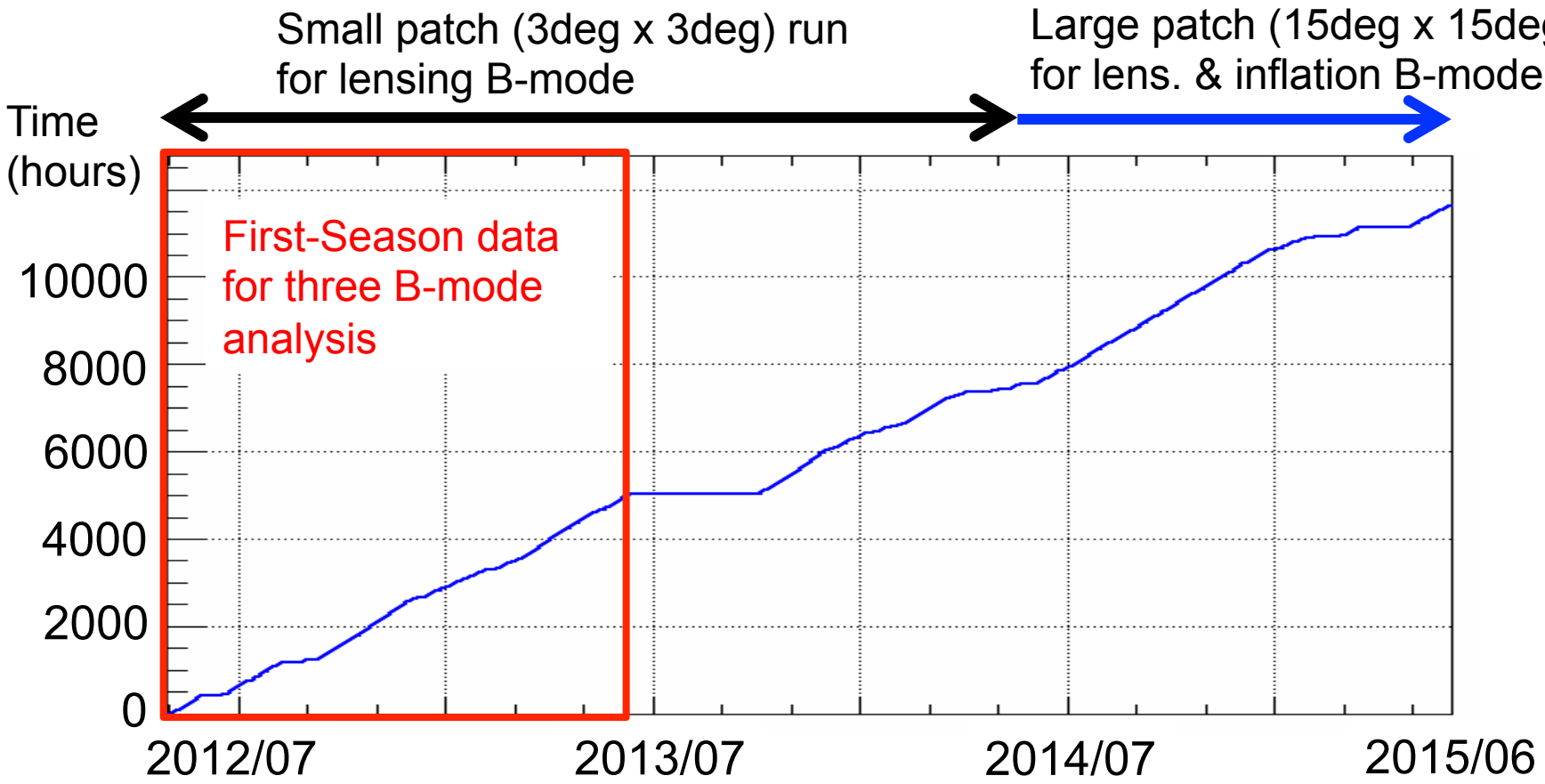
Observation



- We started observation in May. 2012, and have collected more than 10000 hour data.
- Released three lensing B-mode results using 1st season data.

Observation



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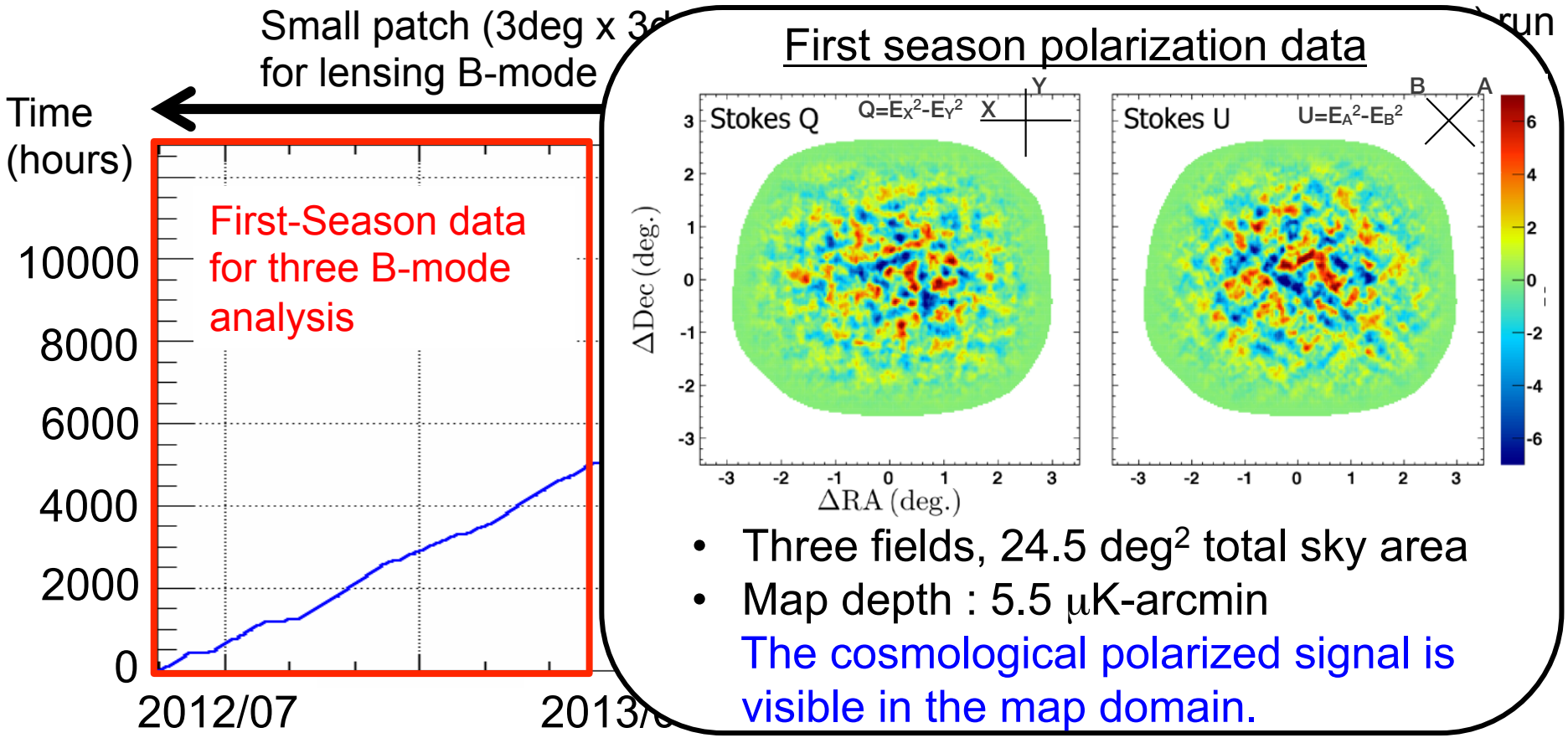

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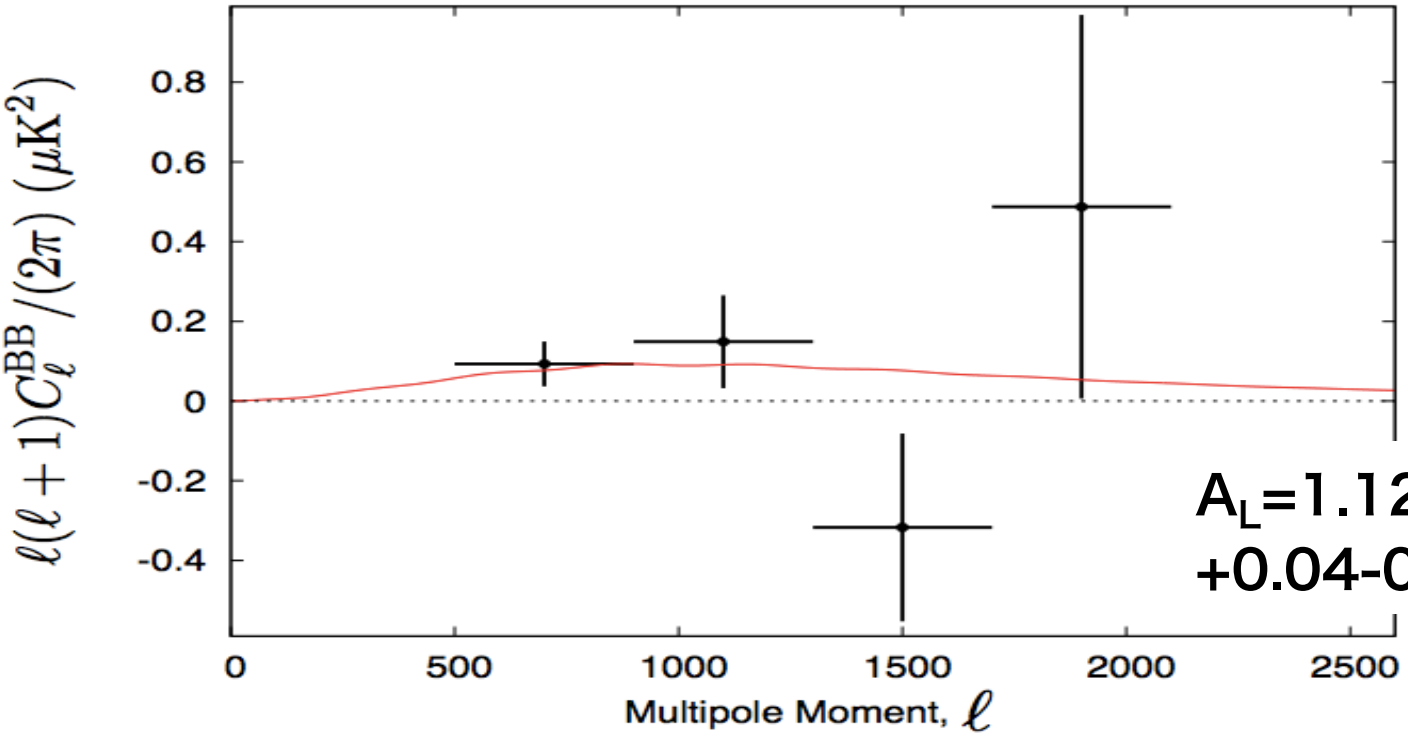
First-Season POLARBEAR Results

(1) BB Power Spectrum

Astrophys. J. 794, 171



A_L=1.12±0.61(stat.)
+0.04-0.10(sys.)

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

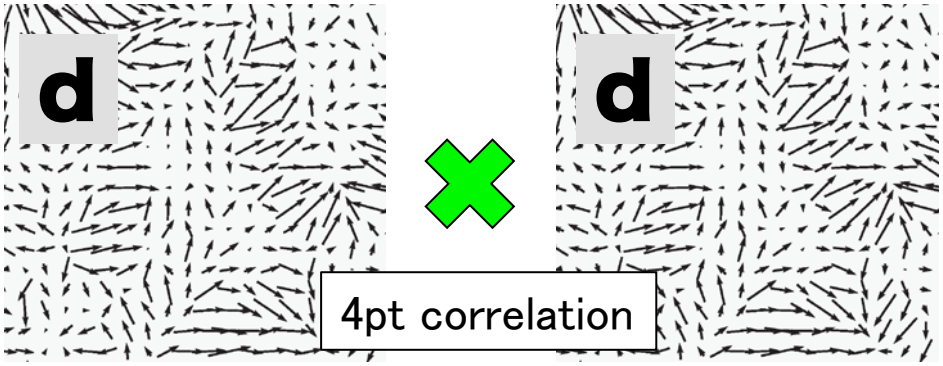
First-Season POLARBEAR Results

(2) Lensing deflection power spectrum

$$d_{EE}(\mathbf{L}) \propto \sum_{\mathbf{l}} E(\mathbf{l})E(\mathbf{l}')$$

$$d_{EB}(\mathbf{L}) \propto \sum_{\mathbf{l}} E(\mathbf{l})B(\mathbf{l}')$$

(Hu, Okamoto, 2002)



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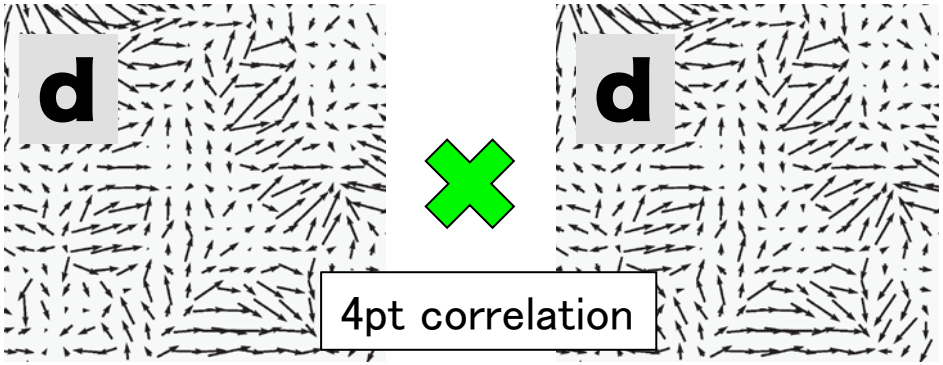
$$d_{EB}(\mathbf{L}) \propto \sum_{\mathbf{l}} E(\mathbf{l})B(\mathbf{l}')$$

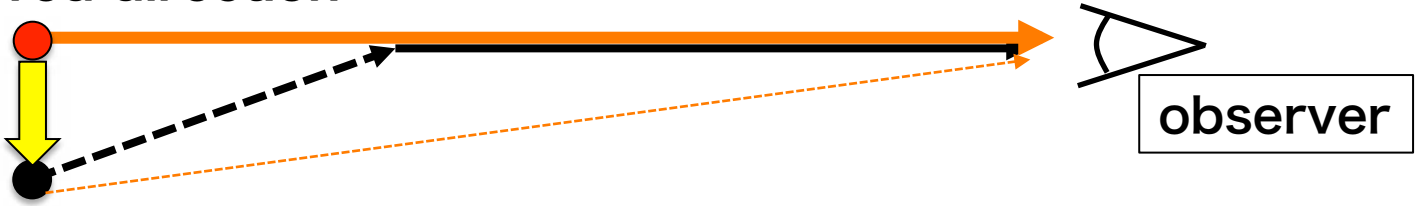
(Hu, Okamoto, 2002)



POLARBEAR

Observed direction

$\vec{d}$:deflection field



True direction

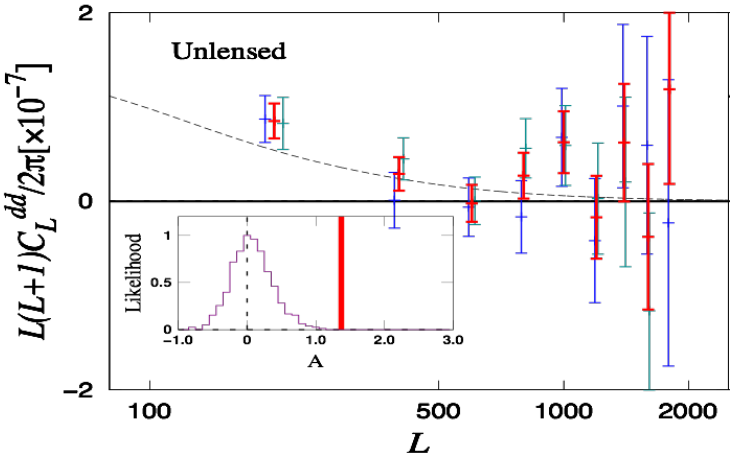
First-Season POLARBEAR Results

(2) Lensing deflection power spectrum

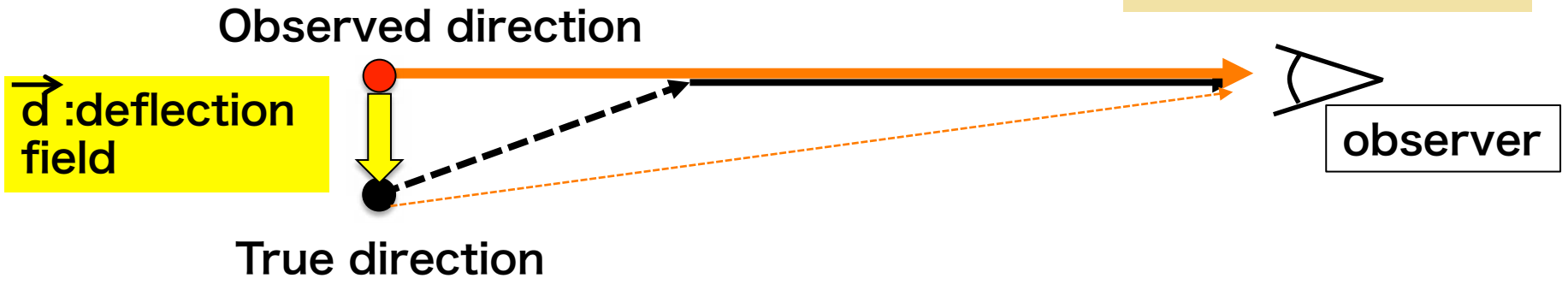
4.2σ rejection of "no lensing B-modes"

"First measurement of polarization lensing" with CMB data alone

PRL 112, 021301 (2014).
(Editor's suggestion)



POLARBEAR



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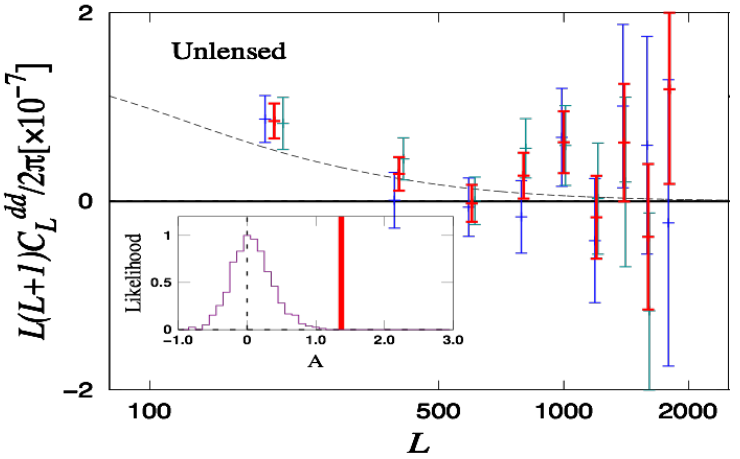
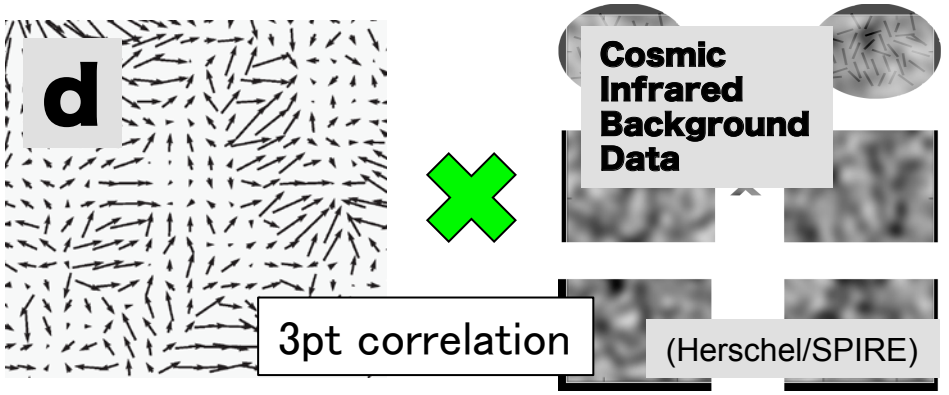


(3) Cross correlation with Cosmic Infrared Background



First-Season POLARBEAR Results

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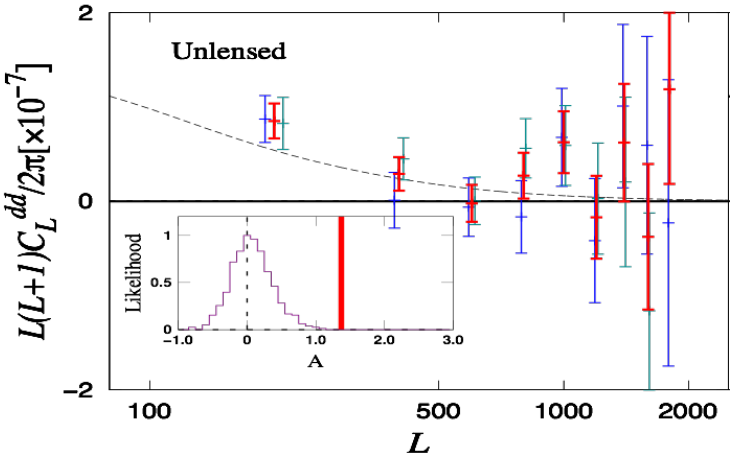

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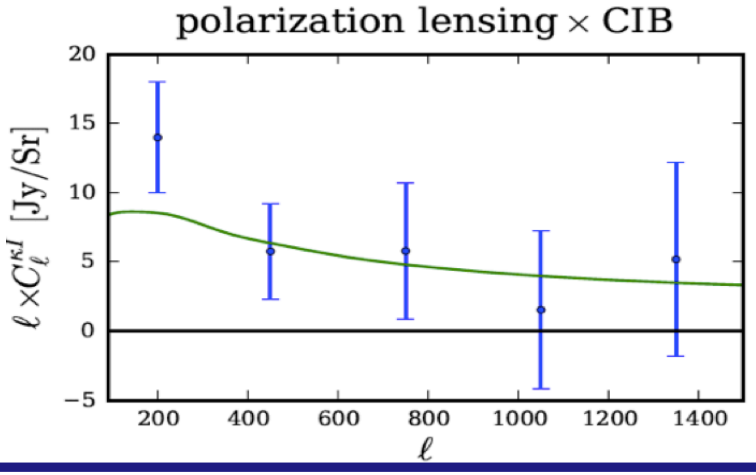
4.0σ evidence of gravitational lensing of CMB polarization

PRL 112, 131302 (2014).
(Editor's suggestion)



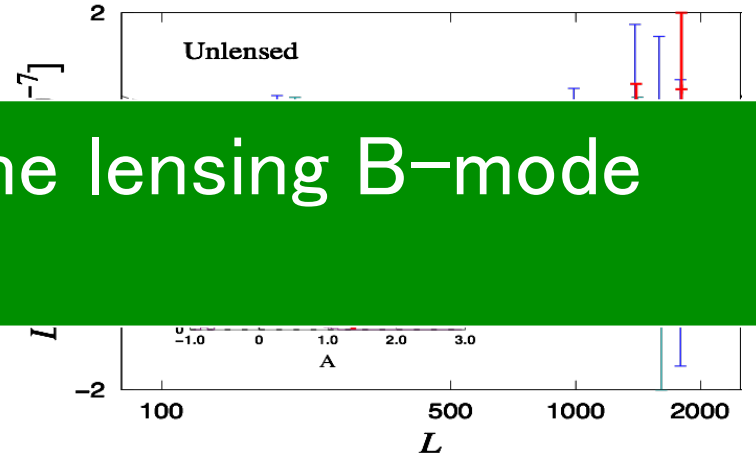
First-Season POLARBEAR Results

(2) Lensing deflection power spectrum

4.2σ rejection of "no lensing B-modes"

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

PRL 112, 131302 (2014).
(Editor's suggestion)



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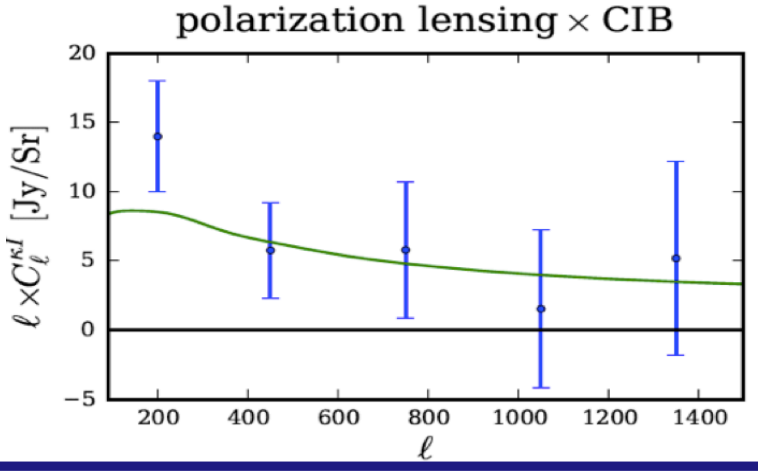

First-Season POLARBEAR Results

(2) Lensing deflection power spectrum

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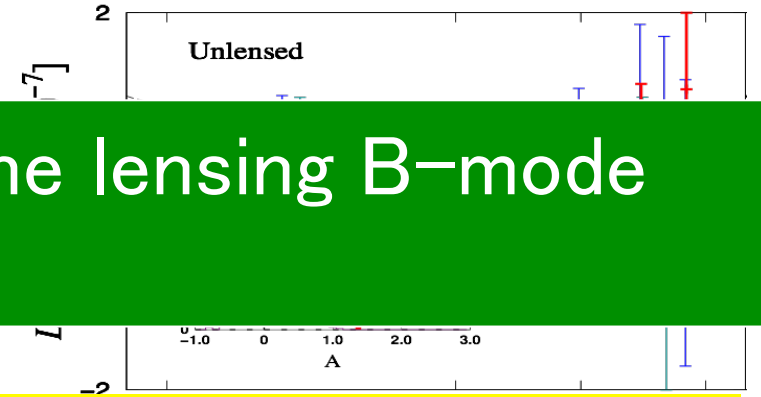
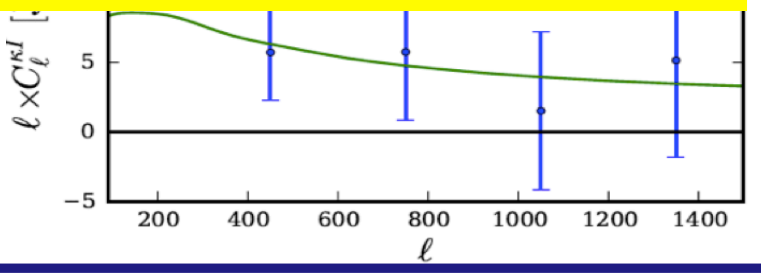


We successfully measure the lensing B-mode with CMB data alone.

(Editor's suggestion)

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

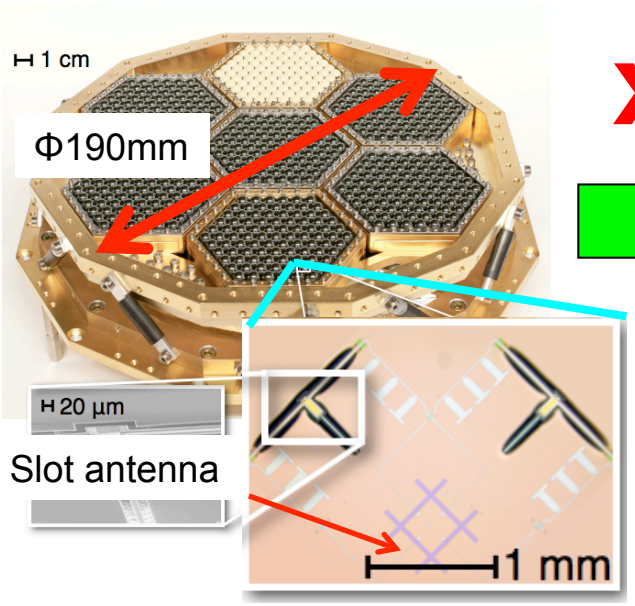
4.0
len



PRL 112, 131302 (2014).
(Editor's suggestion)

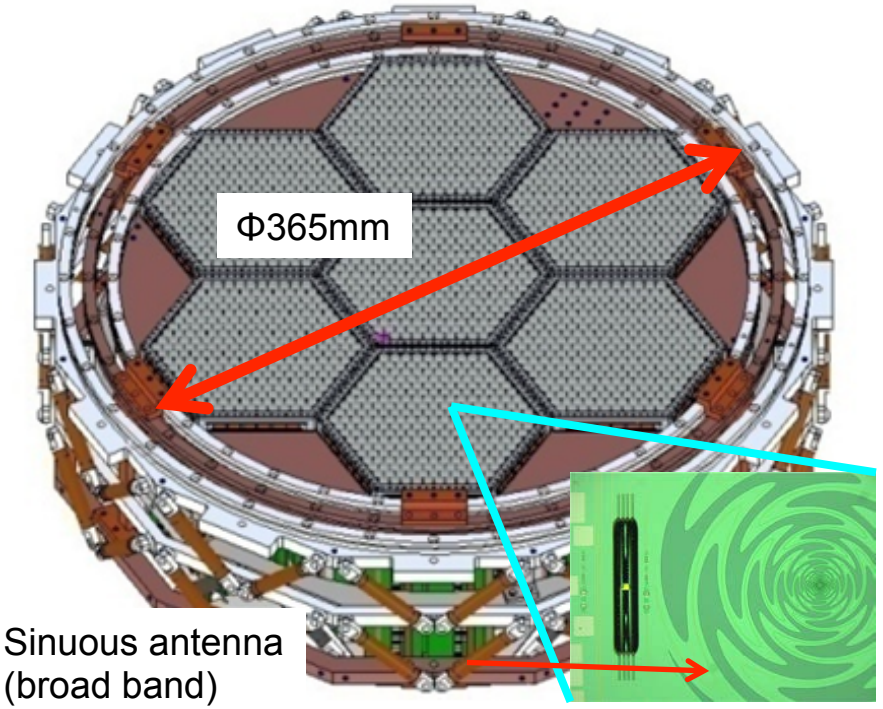
Next: POLARBEAR-2

POLARBEAR-1
1274 detector array



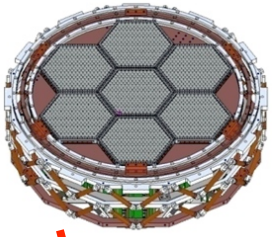
x6

POLARBEAR-2 focal plane

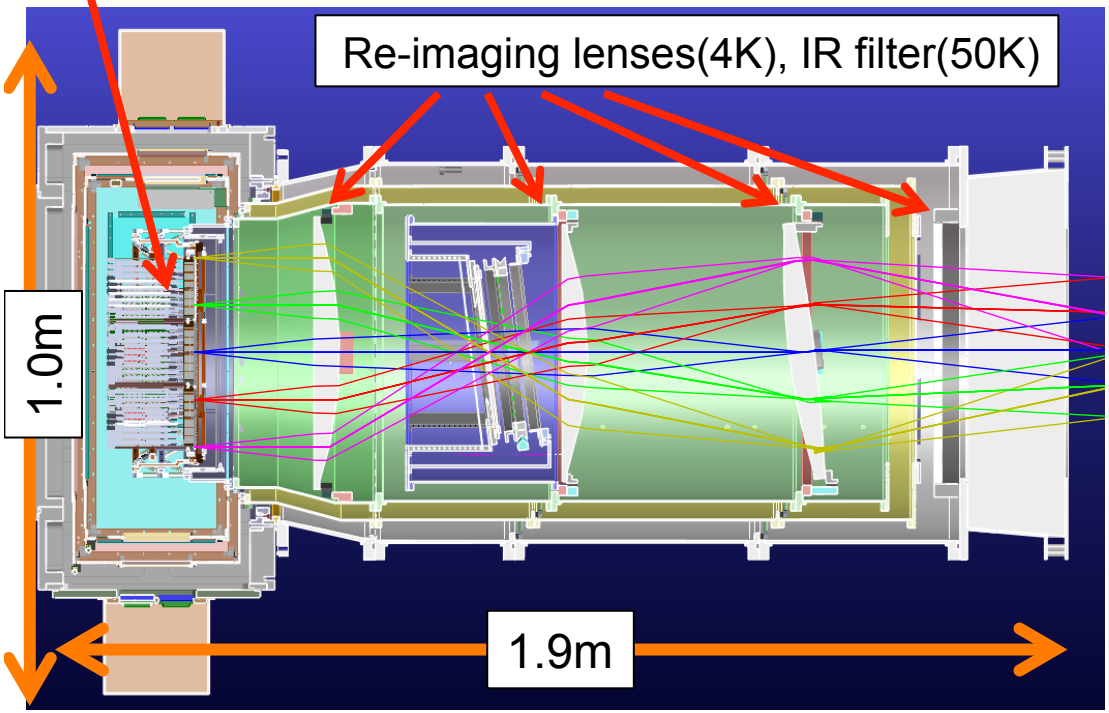


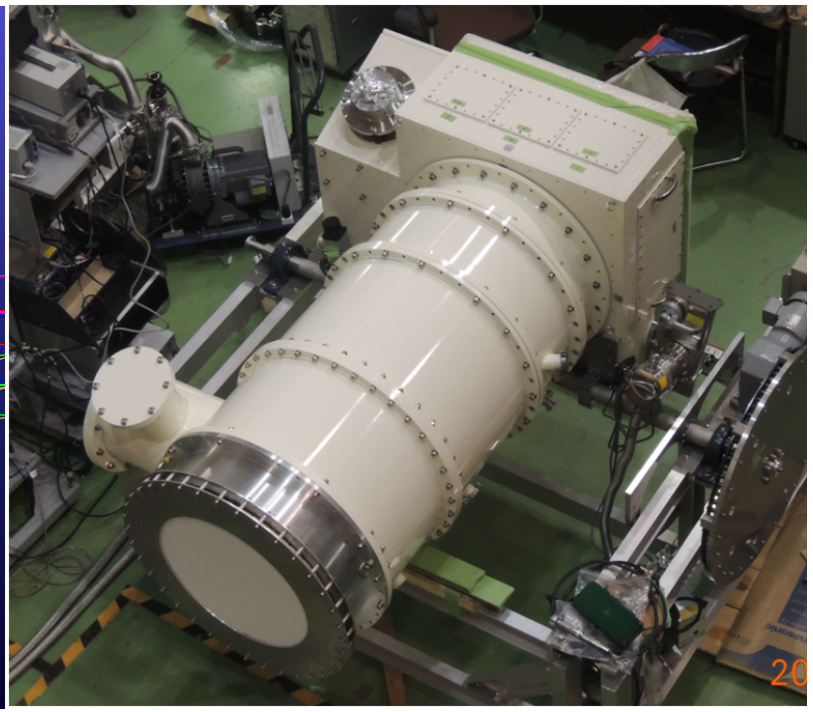
- Larger focal plane (Φ365)
  - 7588 bolometers (~6x increase in mapping speed)
- Multi-chroic pixels with 95/150GHz frequency coverage.

PB2 receiver assembly @ KEK



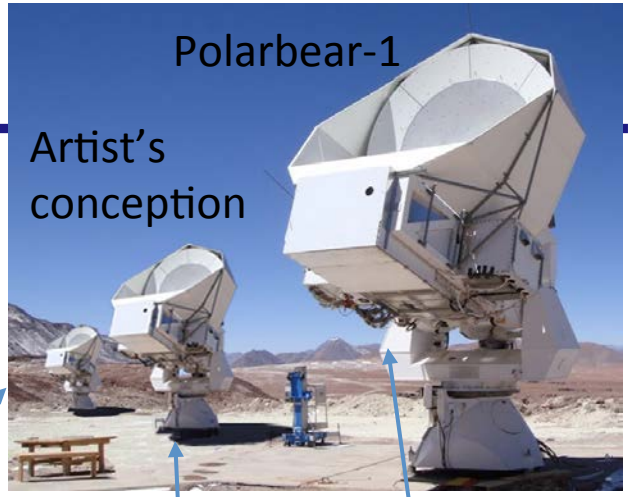
250mK focal plane
(6x the PB1 bolometers)





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

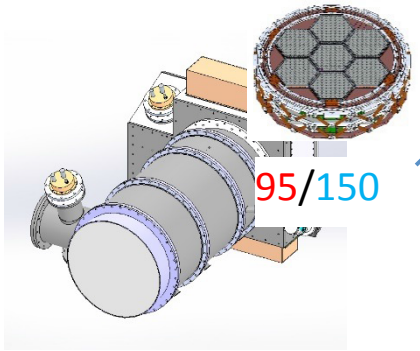
Simons Array



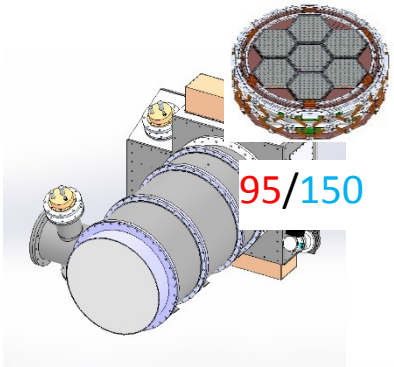
Simons Array (= 3 x PB2)

Leverage POLARBEAR experience to rapidly increase sensitivity

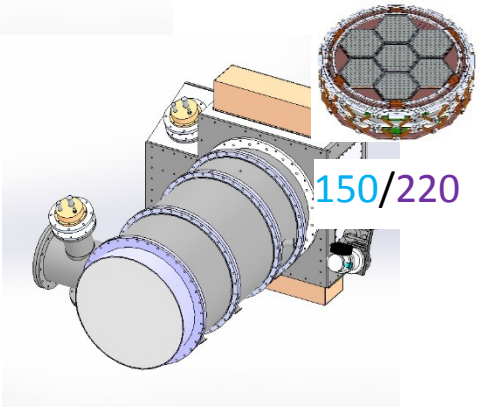
- 22,764 bolometers
- Resolution : 3.5' @150GHz
- 3 frequency bands (95/150/220GHz)
- Wide sky survey (f_{sky}=65%)



2016



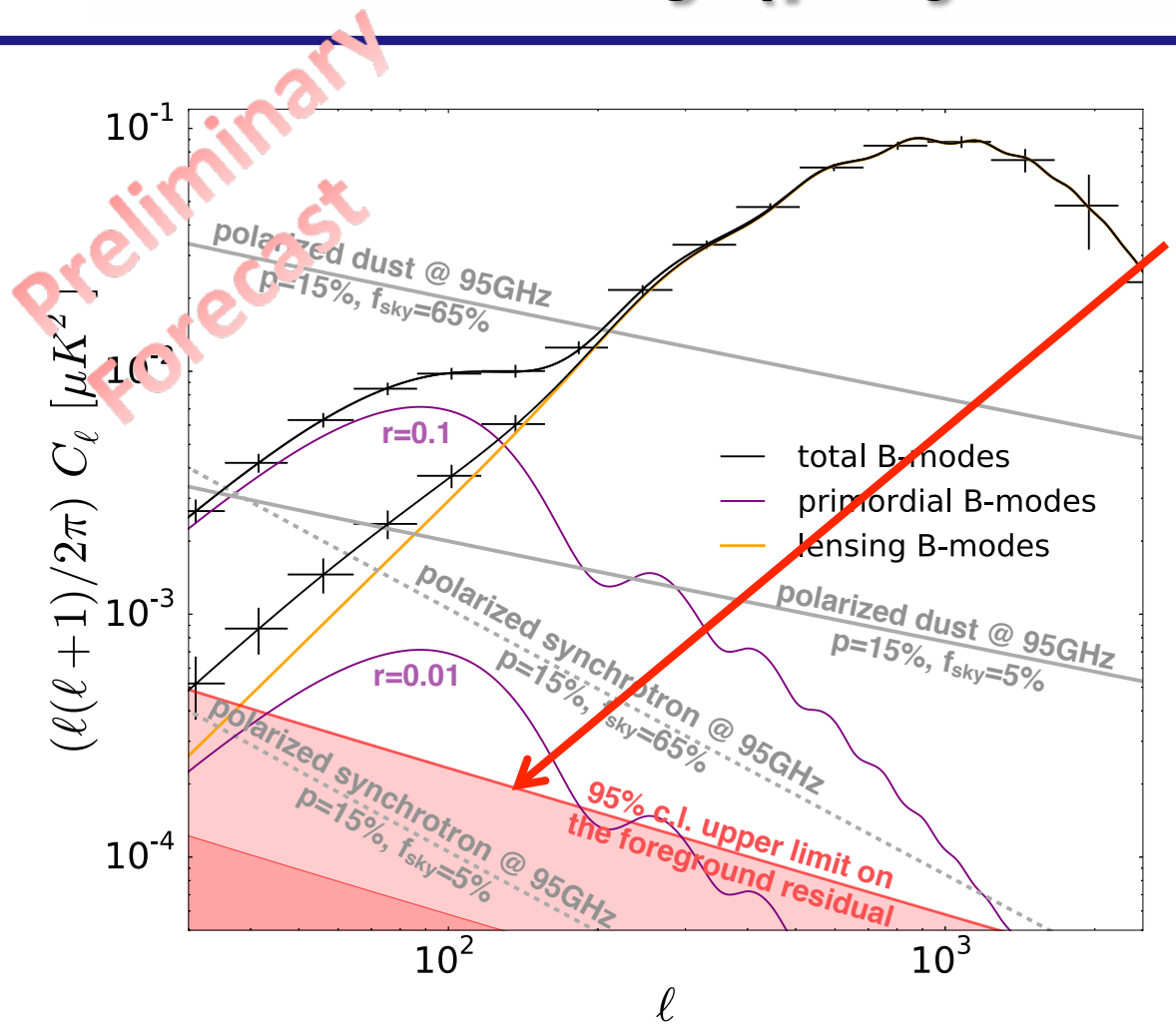
2017



2017

Measurement of B-mode spectrum with unprecedented precision.

Simons Array (projected) sensitivity



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

Inflation

- $\sigma(r=0.1) = 6\times10^{-3}$ (4×10^{-3})

Neutrino mass

- $\sigma(\Sigma m\nu) = 40$ meV (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 4.7σ with CMB data alone, and successfully laid the groundwork for neutrino mass measurement.
- POLARBEAR-2/Simons Array is being prepared.

Stay Tuned !