



# Cosmology and Particle physics with POLARBEAR and Simons Array

ICHEP2016, Aug. 5, 2016  
Masaya Hasegawa (KEK)  
on behalf of POLARBEAR/  
Simons Array collaboration

# *Outline*

- POLARBEAR
  - Motivations : Inflation and  $\nu$  masses
  - Instruments and observation
  - Recent results
- Status & Prospects
  - POLARBEAR2 and Simons Array



# POLARBEAR Collaboration



# What's POLARBEAR ?

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- CMB Polarization Experiment in Chile.



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  - **Inflationary** gravitational waves
  - Gravitational lensing: **Neutrino masses**

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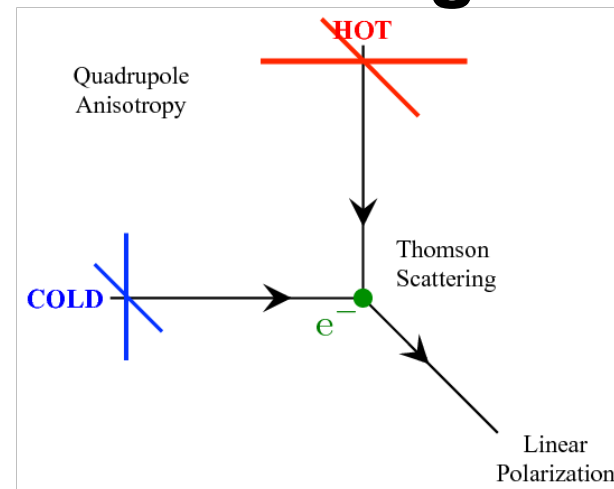
*Shed light on fundamental problems  
in cosmology and particle physics !*



# Science with CMB B-mode

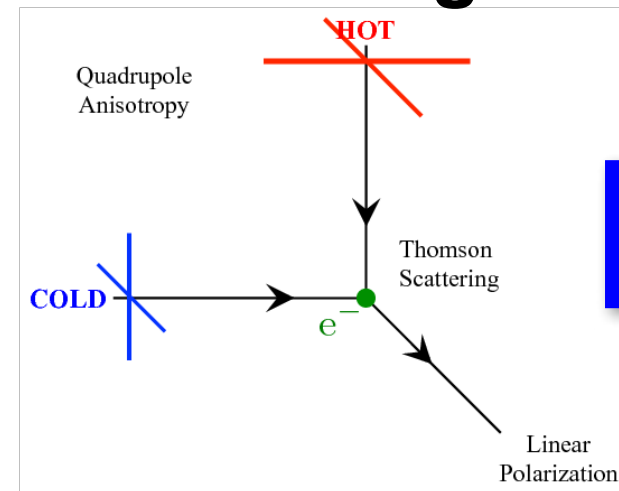
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## Thomson Scattering on LSS

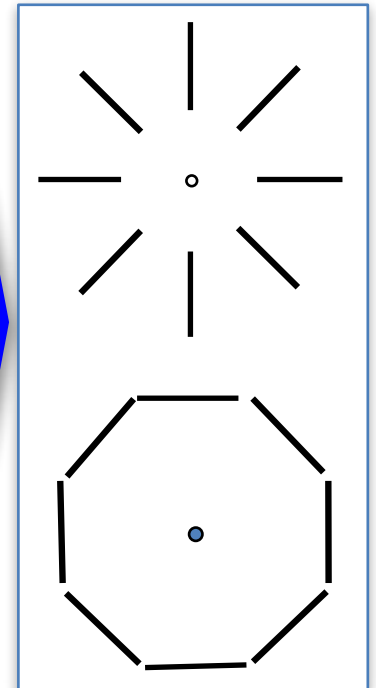


# Science with CMB B-mode

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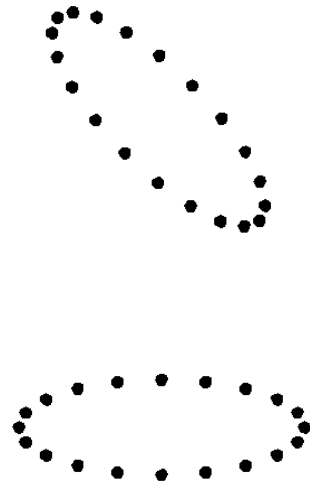
## E-mode



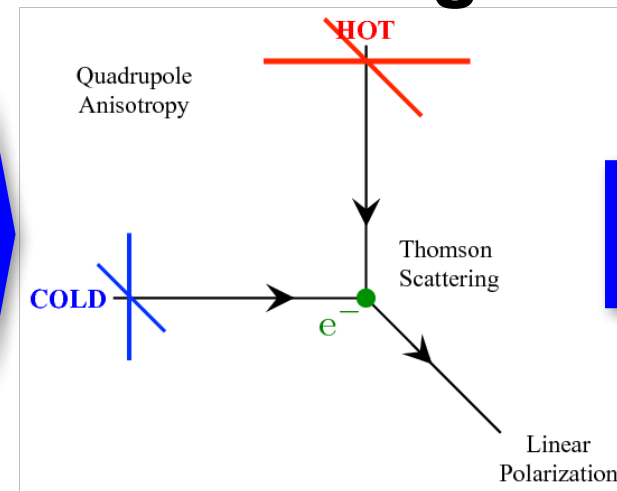


# Science with CMB B-mode

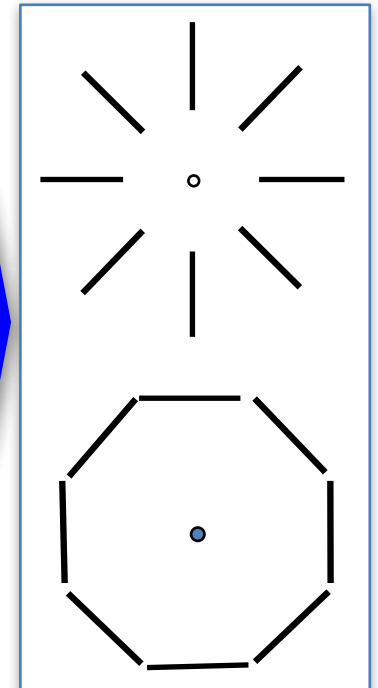
Gravitational  
Wave



Thomson  
Scattering on LSS

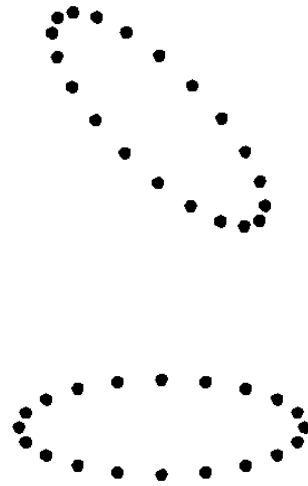


*E*-mode

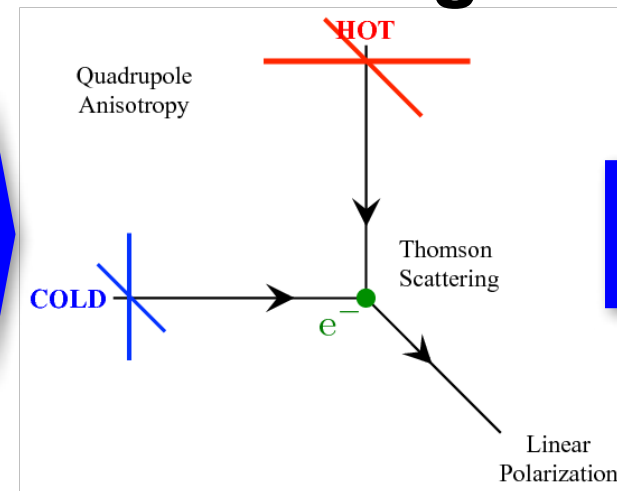


# Science with CMB B-mode

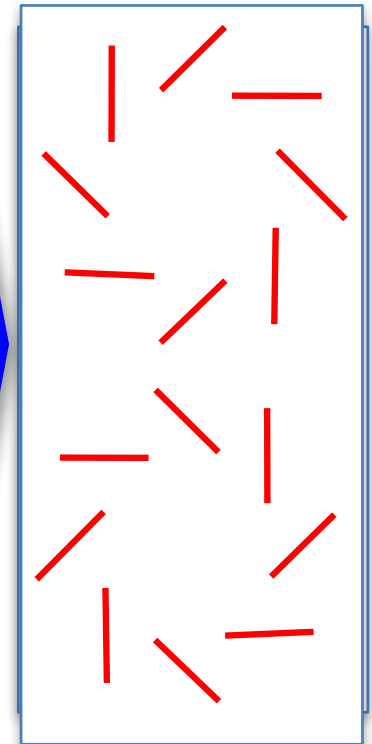
Gravitational  
Wave



Thomson  
Scattering on LSS

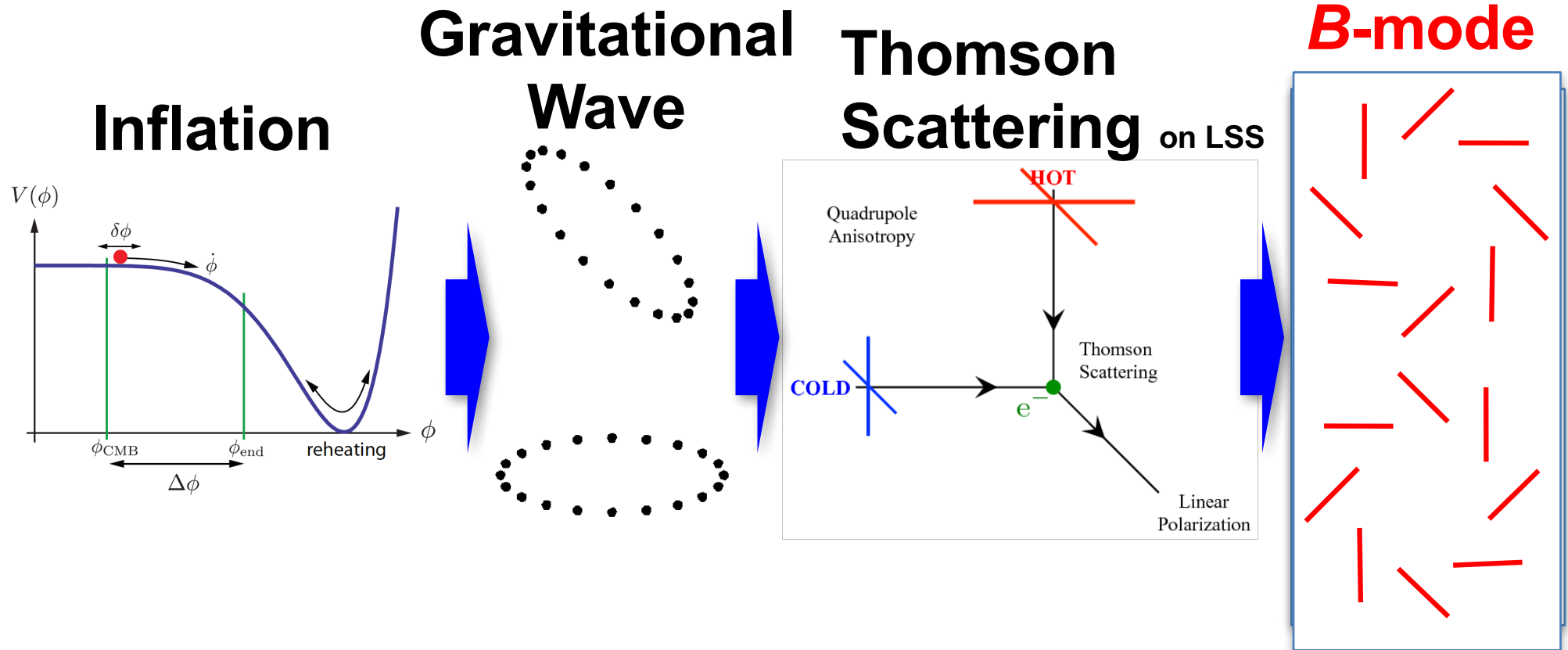


**B-mode**

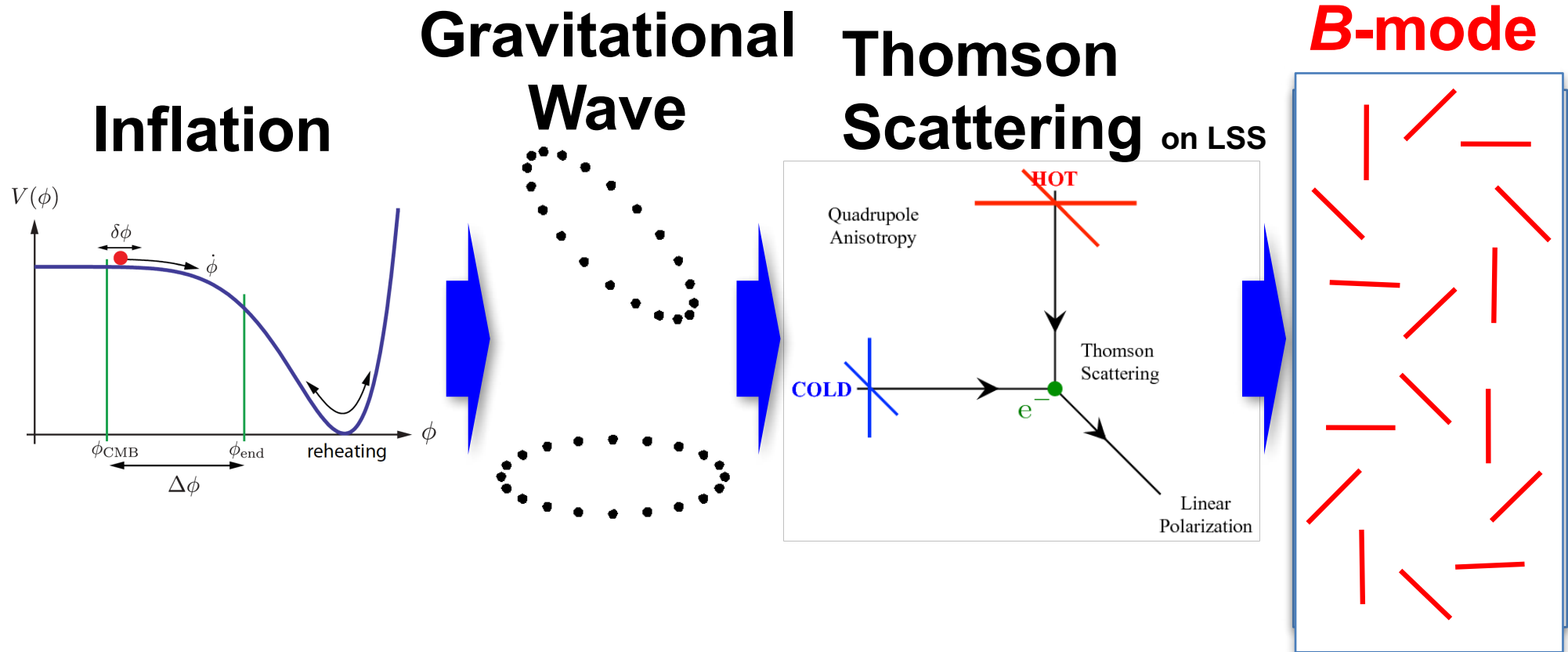




# Science with CMB B-mode



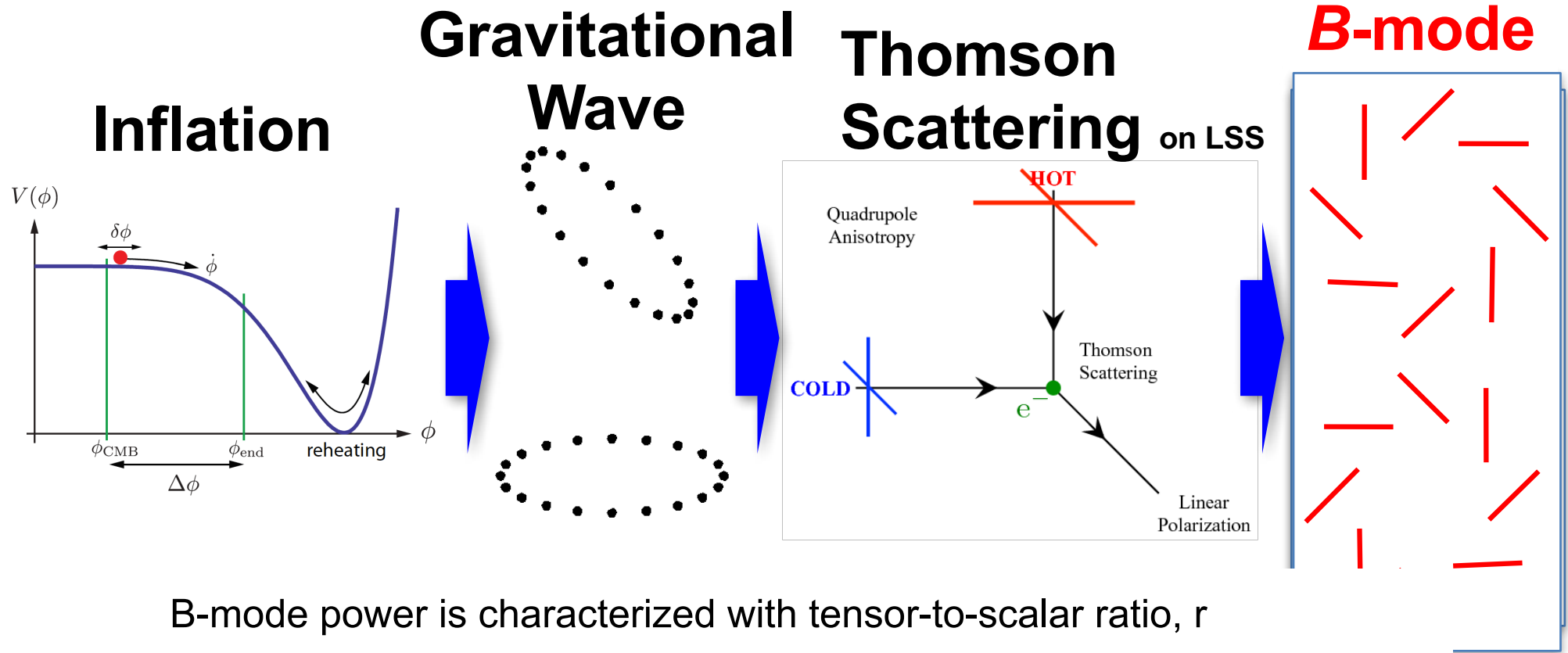
# Science with CMB B-mode



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



# Science with CMB B-mode



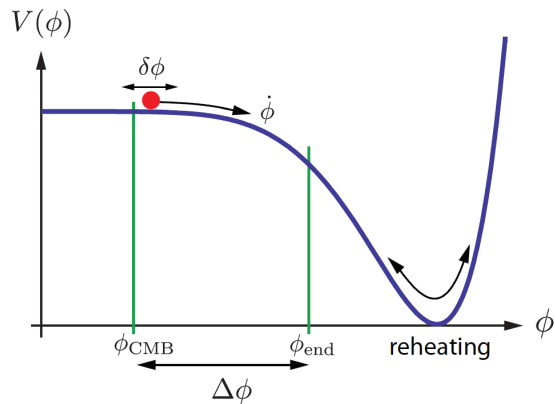
$$V^{1/4} = 1.06 \times 10^{16} \times \left( \frac{r}{0.01} \right)^{1/4} \text{ GeV}$$

# Science with CMB B-mode

Gravitational Thomson

**B-mode**

Inflation



$W_p$

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

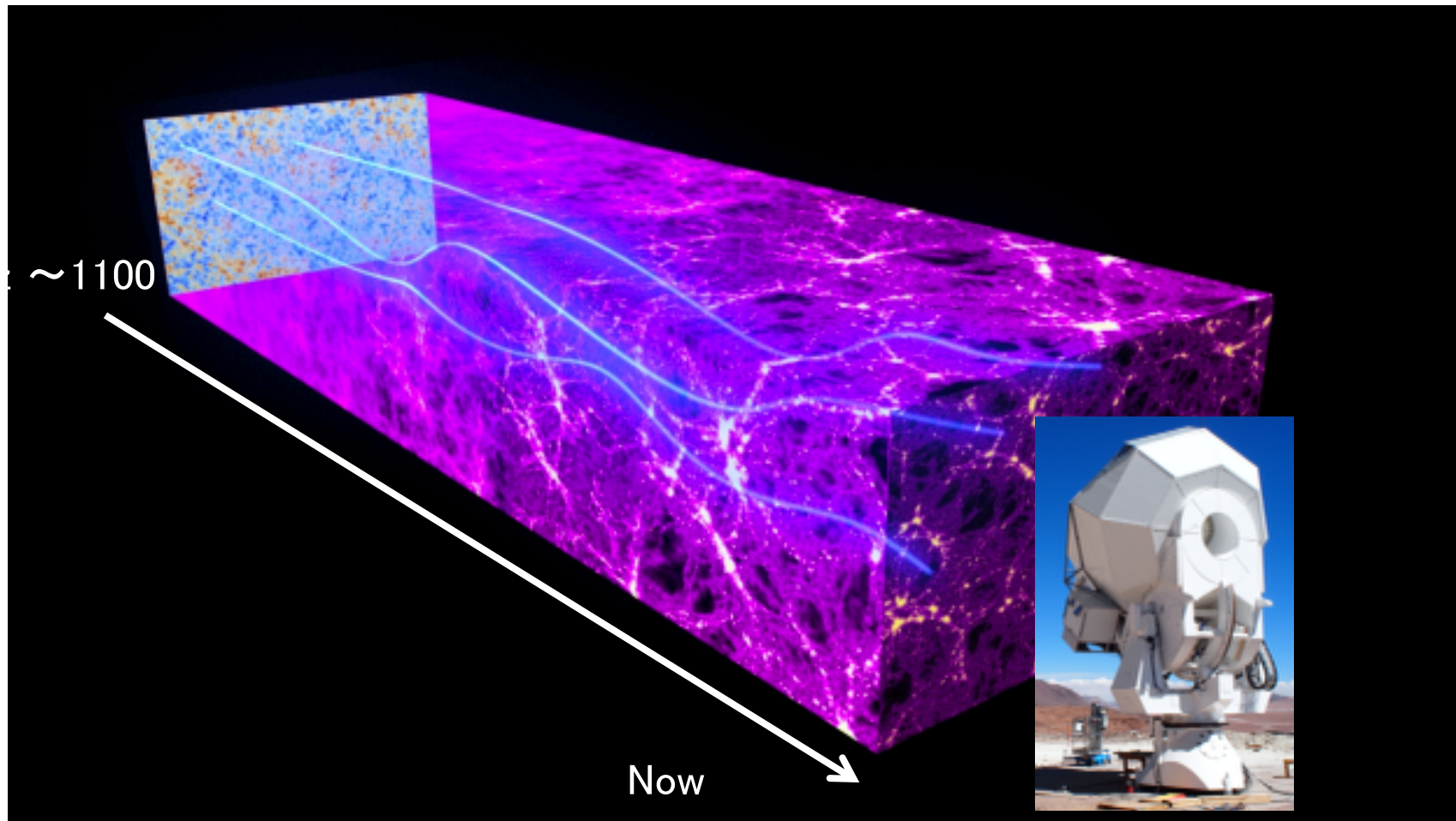
$10^5 \times \text{GZK cut-off (10}^{20}\text{eV)}$

$\rightarrow$  CMB B-mode is a potential window to the **truly-unexplored ultra-high energy phenomenon**

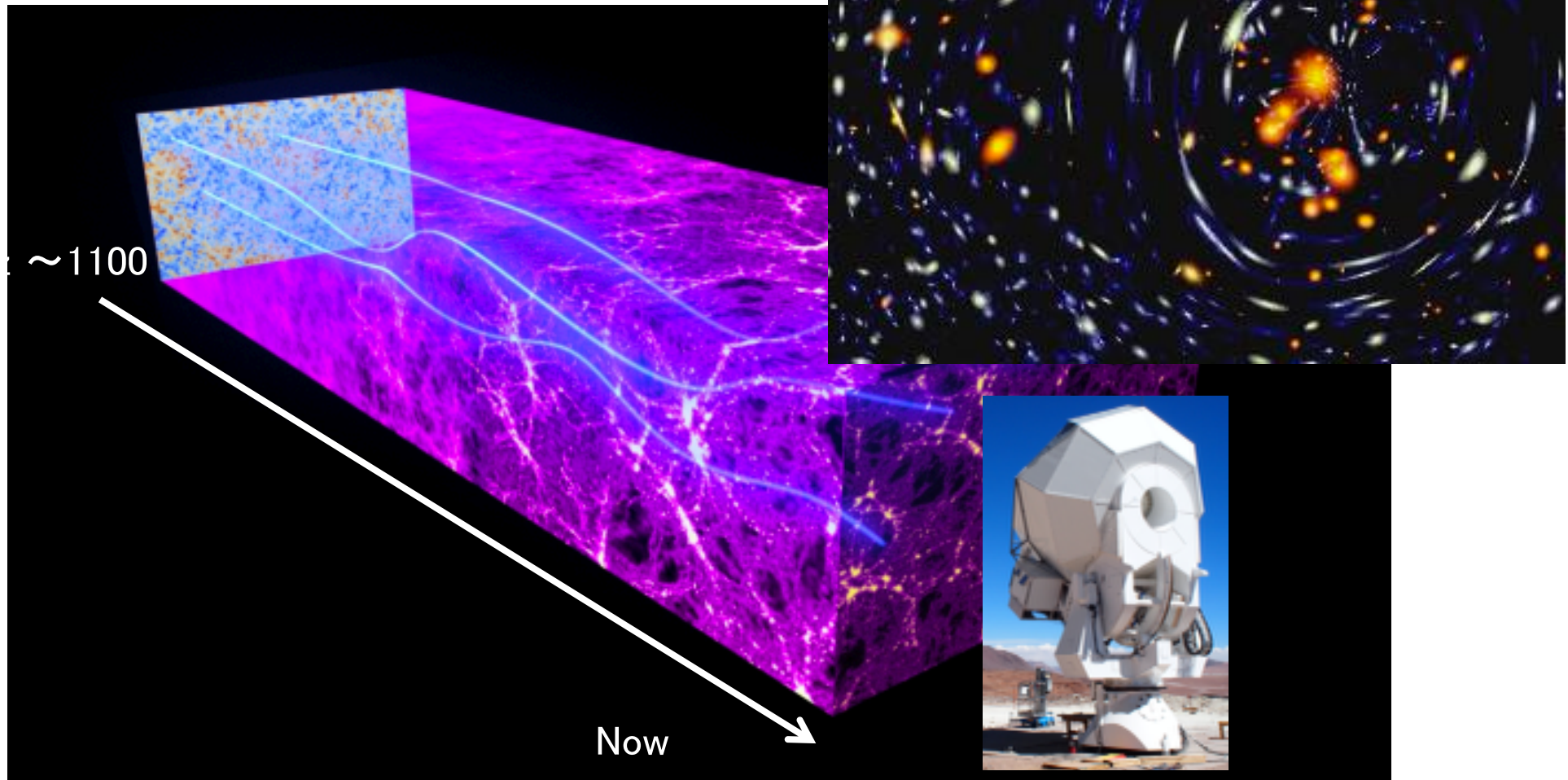
B-mode power is characterized with tensor-to-scalar ratio,  $r$

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

# Lensing B-mode

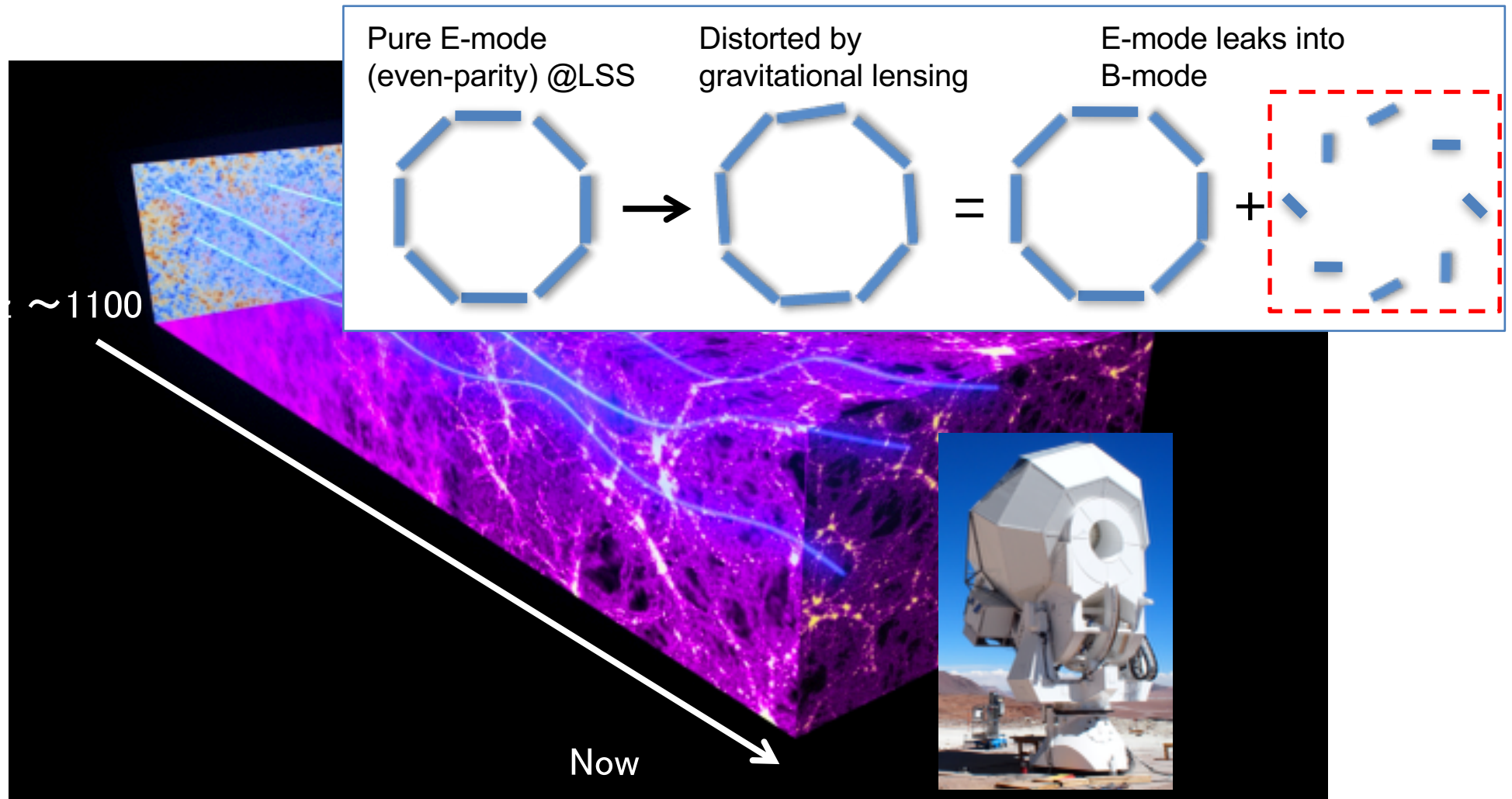


# Lensing B-mode



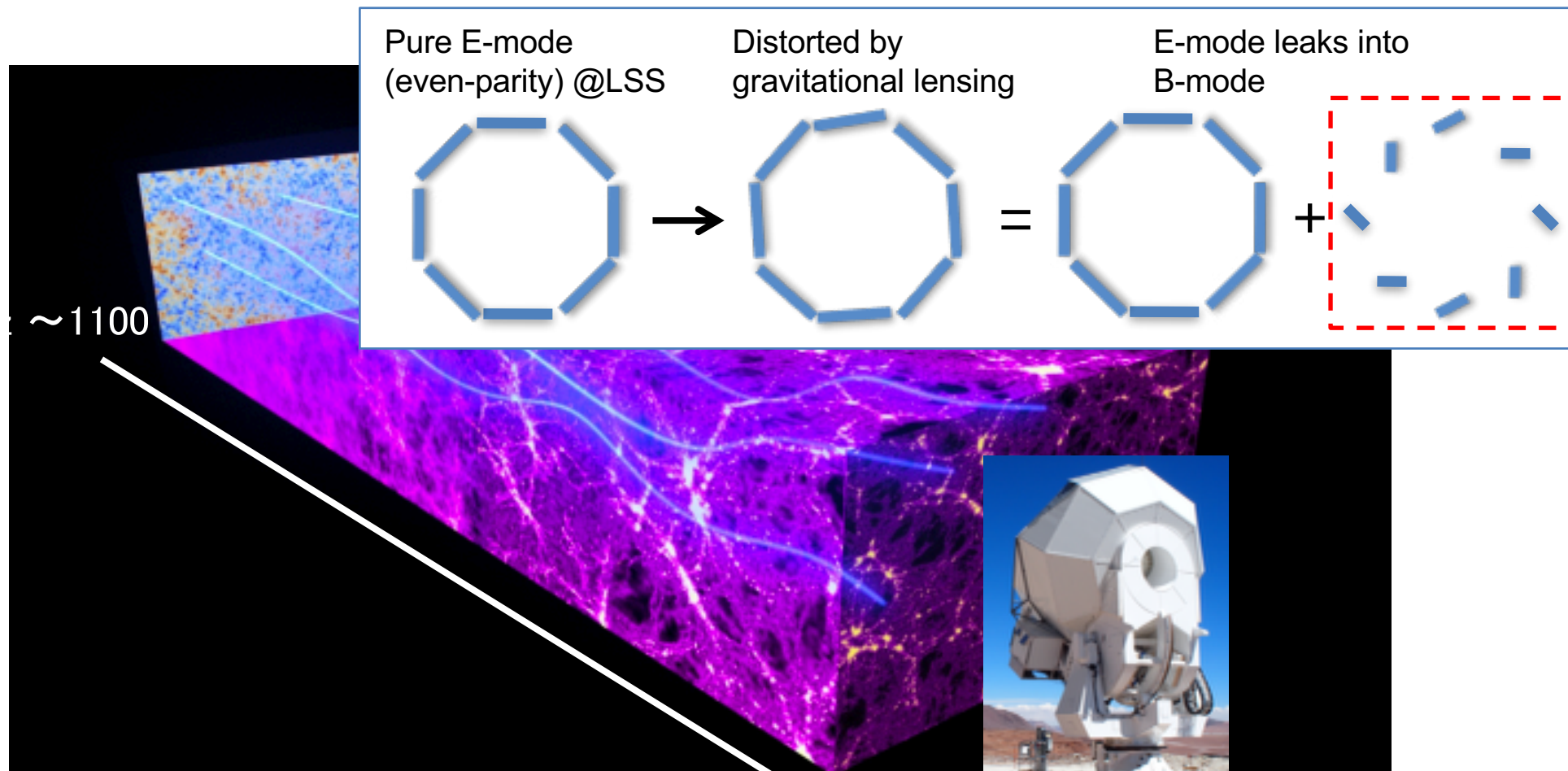


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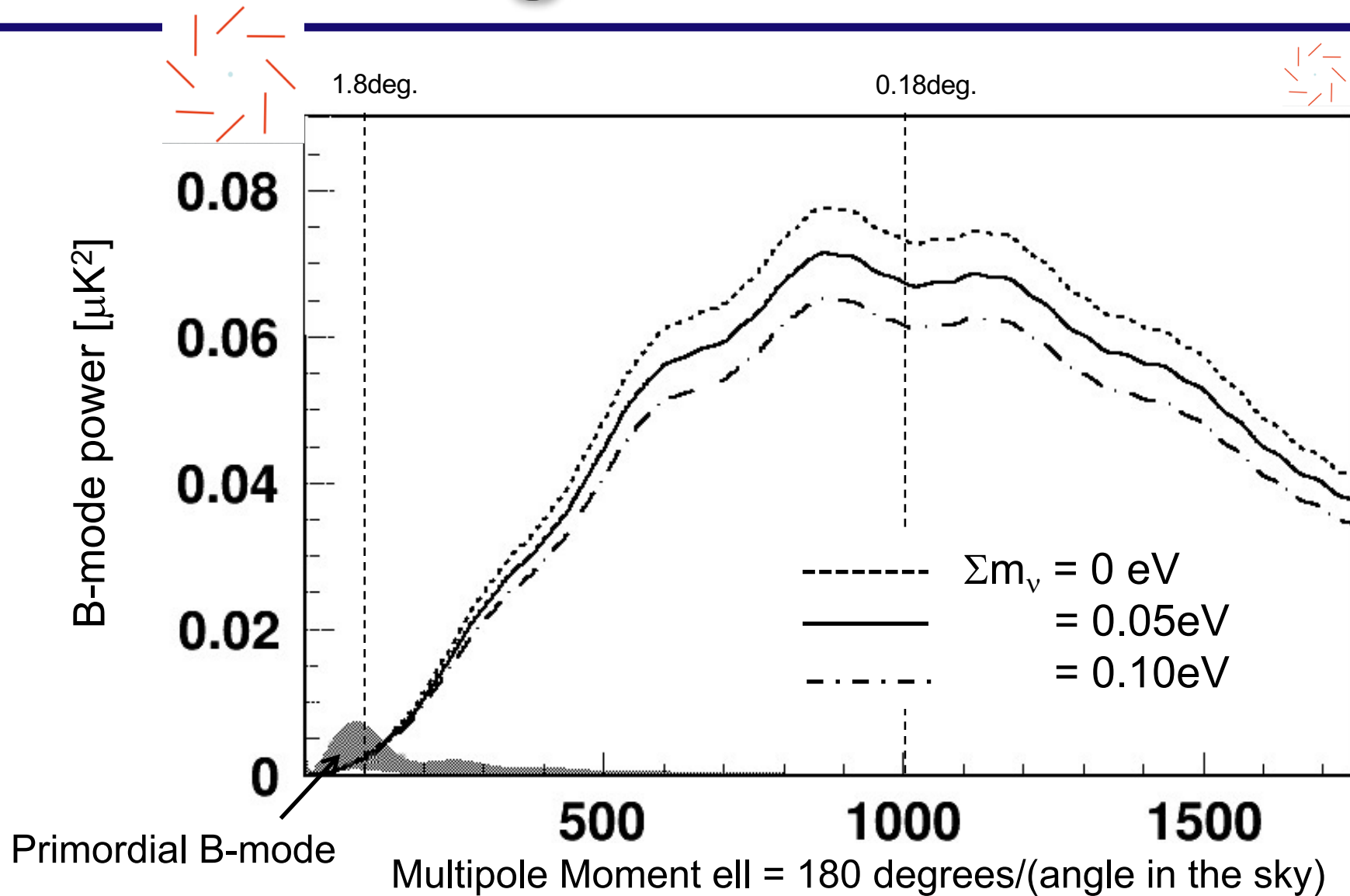


# Lensing B-mode



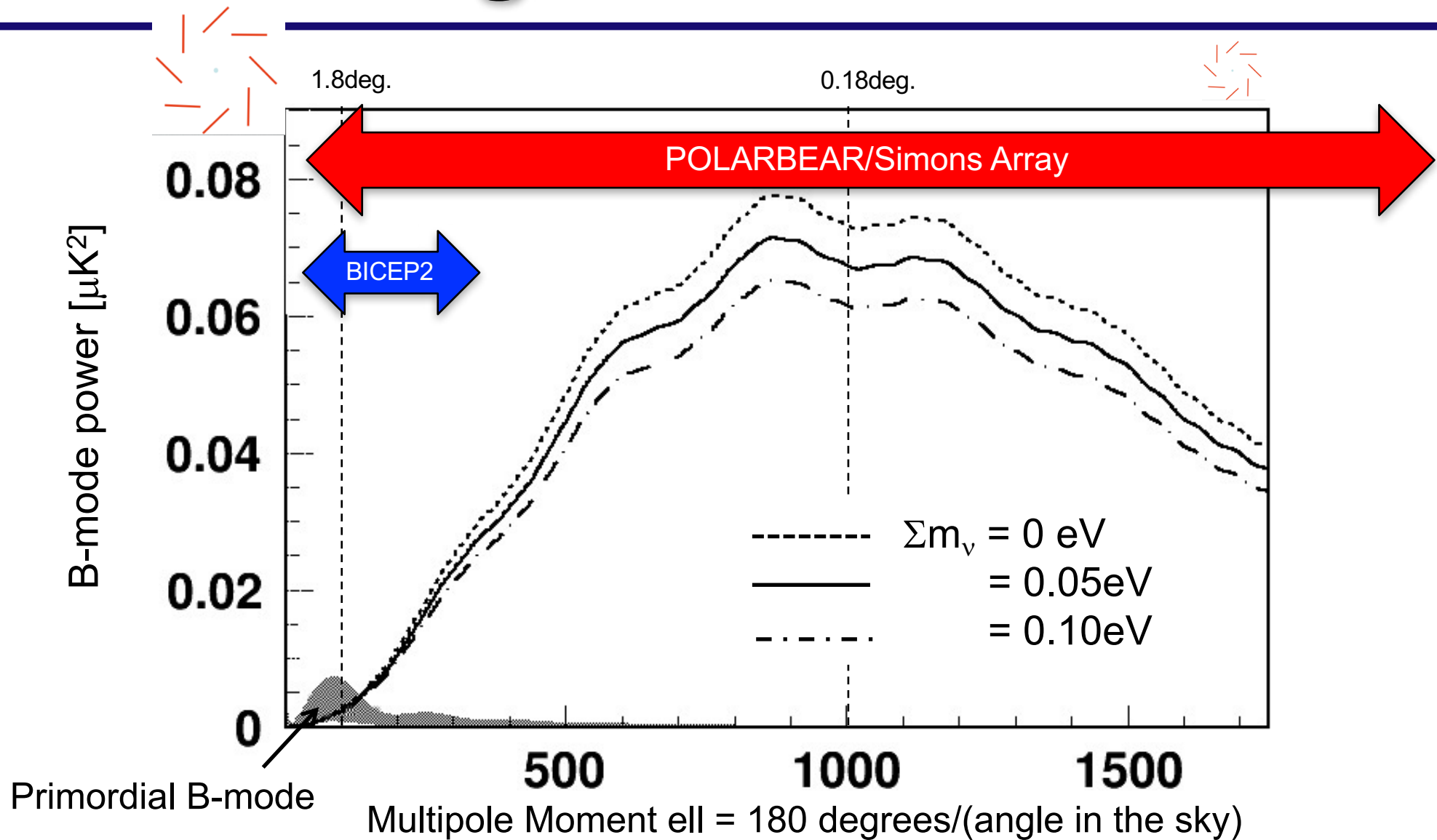
- Small angular scale B-mode is the signature of lensing
- Probe of physics affecting structure growth at  $z \sim 2$ .

# Lensing B-mode Power



The lensing B-mode amplitude is sensitive to  $\Sigma m_\nu$ .

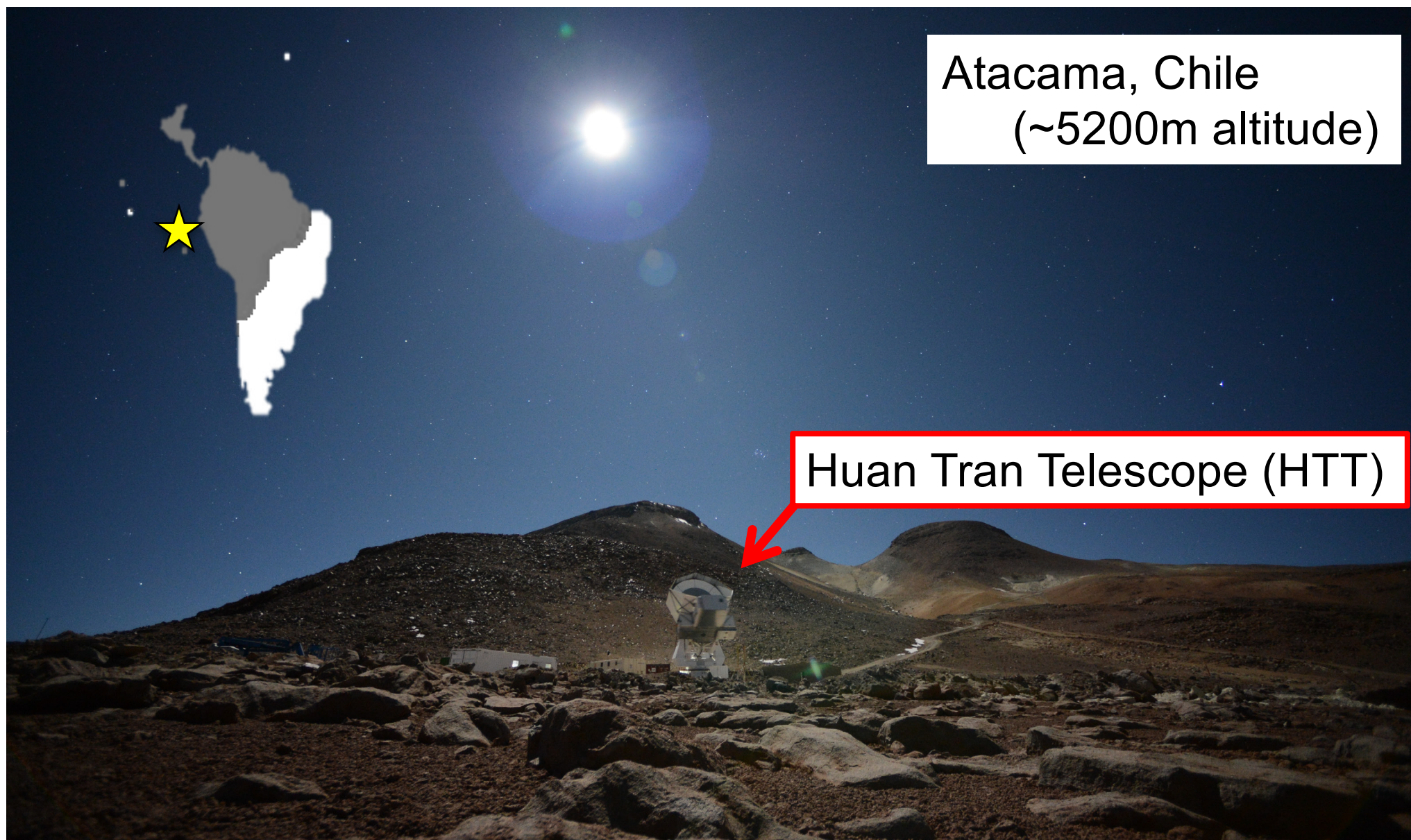
# Lensing B-mode Power



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# POLARBEAR Site

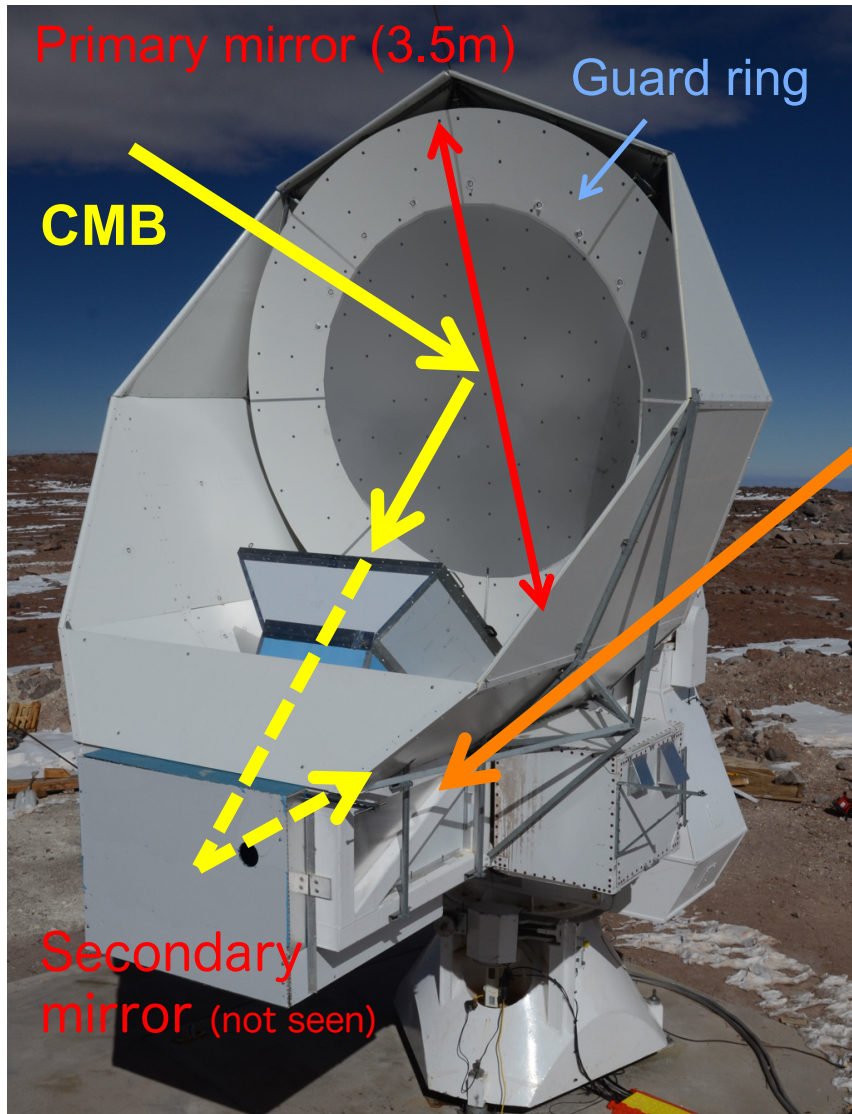


Atacama, Chile  
(~5200m altitude)

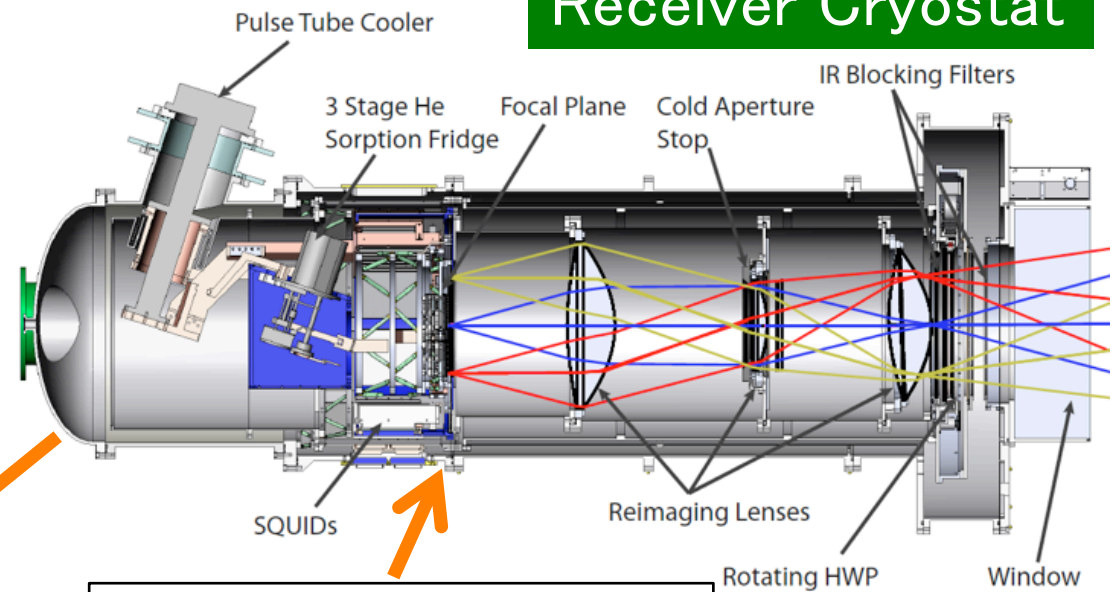
Huan Tran Telescope (HTT)



# POLARBEAR Optics



## Receiver Cryostat



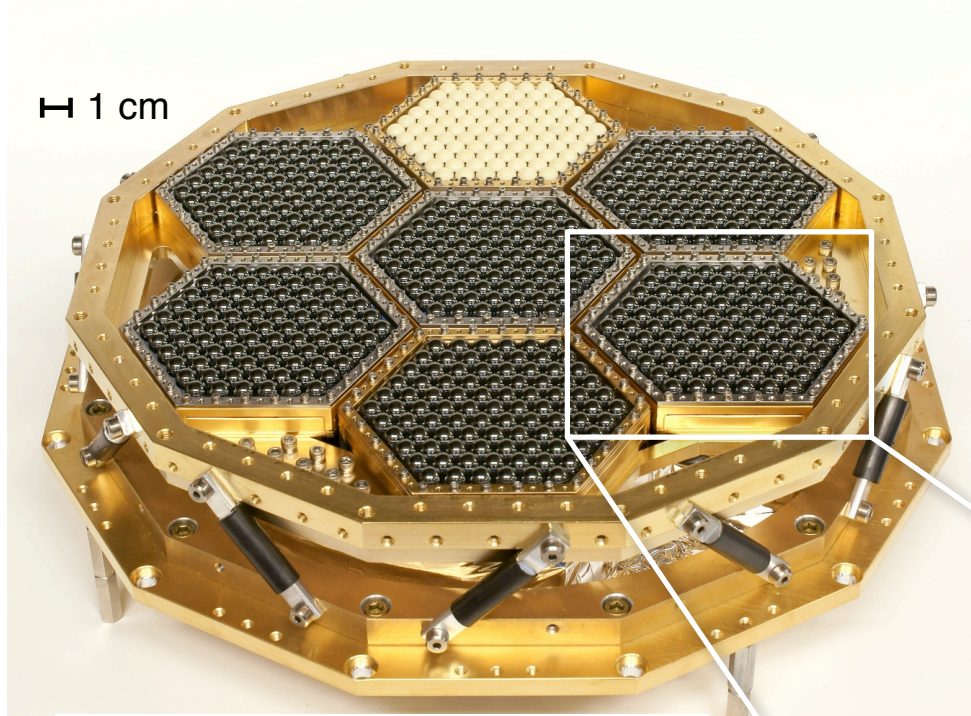
Focal plane (250mK)

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

Angular resolution to measure the lensing B-modes.

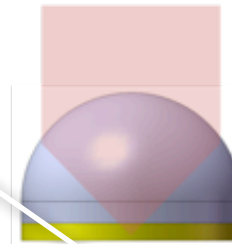


# POLARBEAR-1 Focal Plane

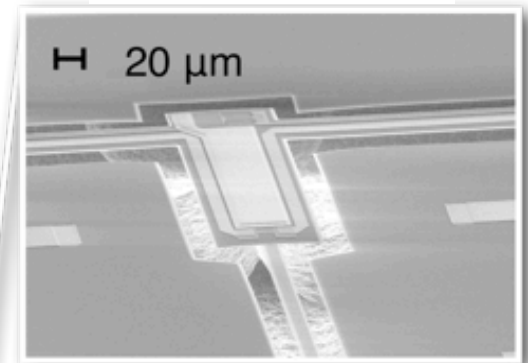


91 pixels (182 bolometers) per wafer under AR-coated lenslet.

Lenslet

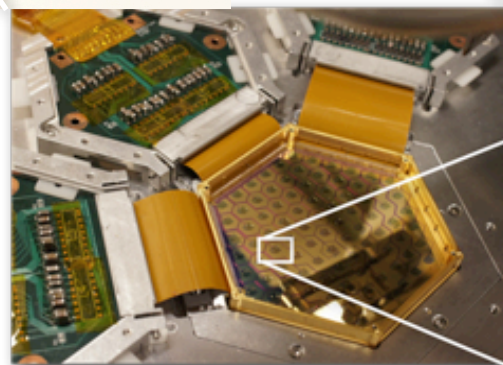


TES bolometer

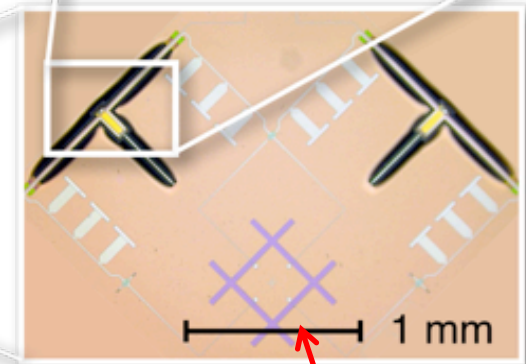


637 pixels  
(91 pixels/wafer x 7 wafers)  
1274 TES bolometers

Array sensitivity :  
 $23 \mu\text{K}\sqrt{\text{s}}$



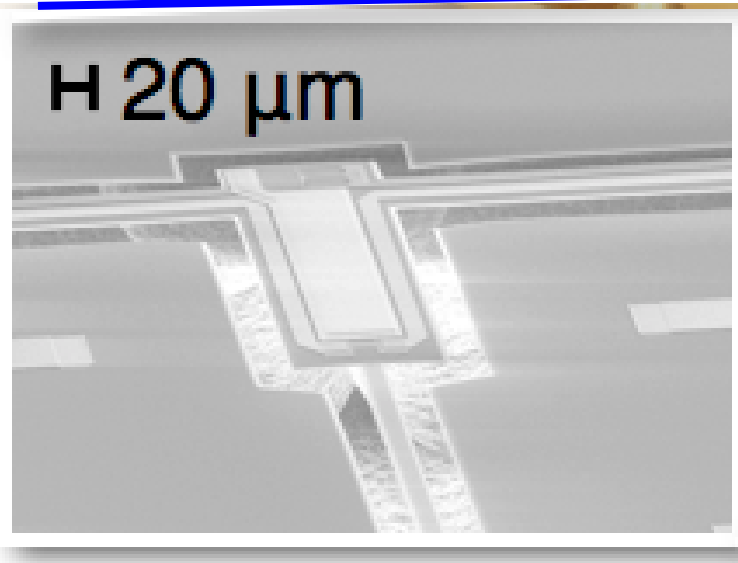
Wafer module



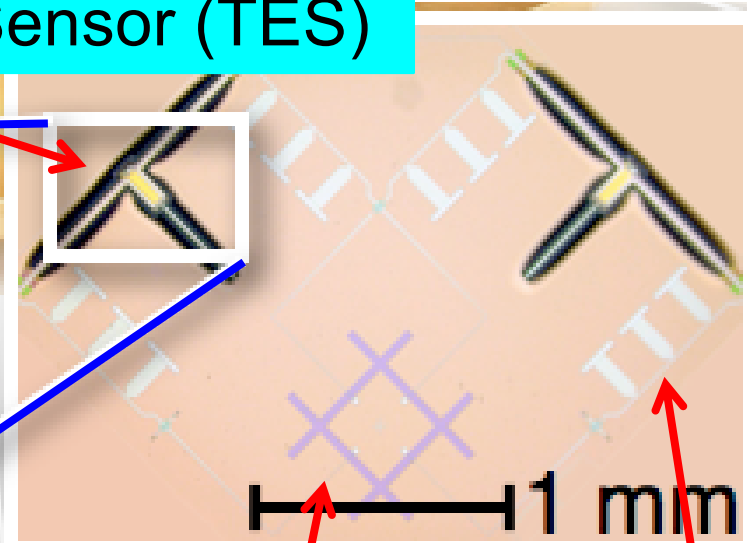
2 TES bolometers/pixel with  
dual-polarization double-slot  
dipole antenna

# 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)

25  $\mu\text{m}$  vs

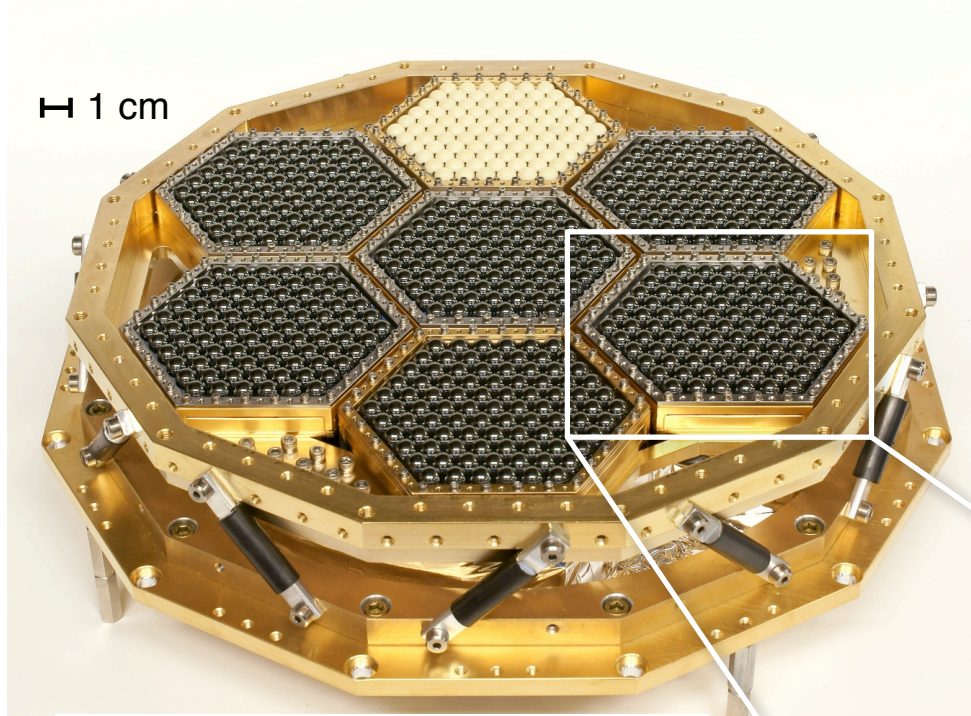
Wafer module



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

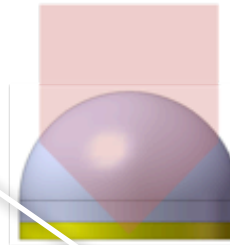


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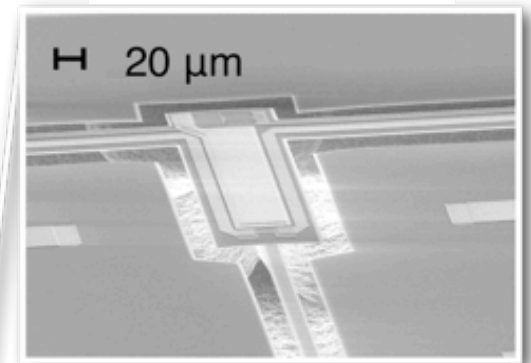


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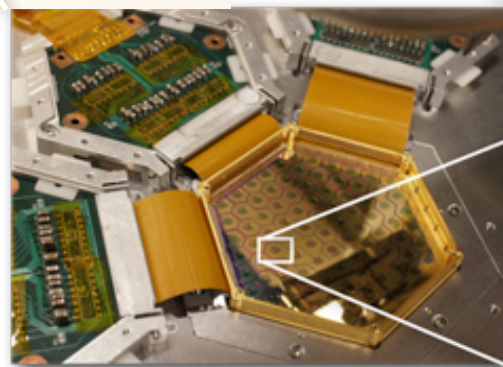


TES bolometer

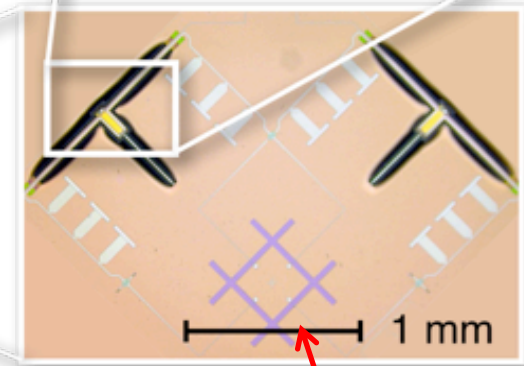


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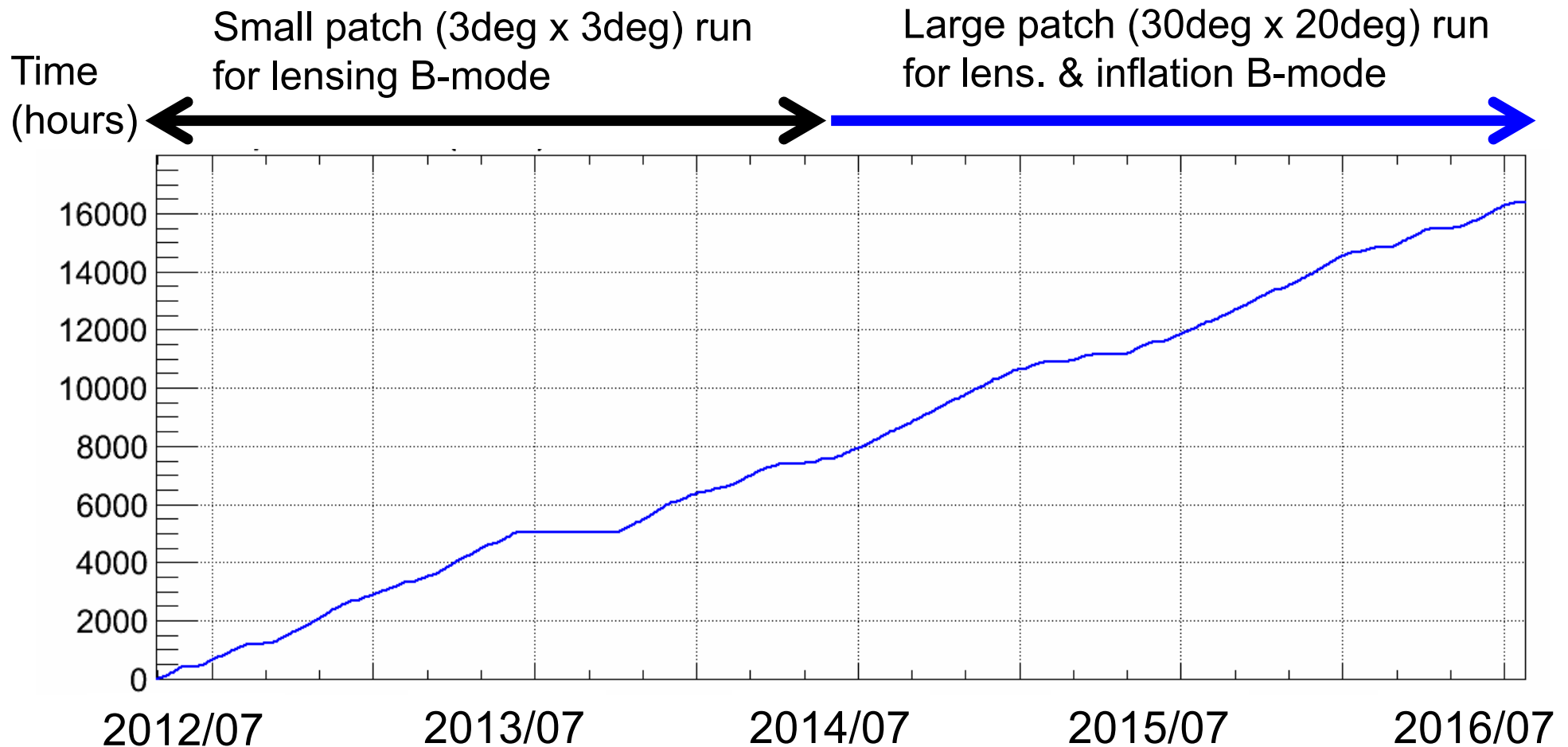


Wafer module



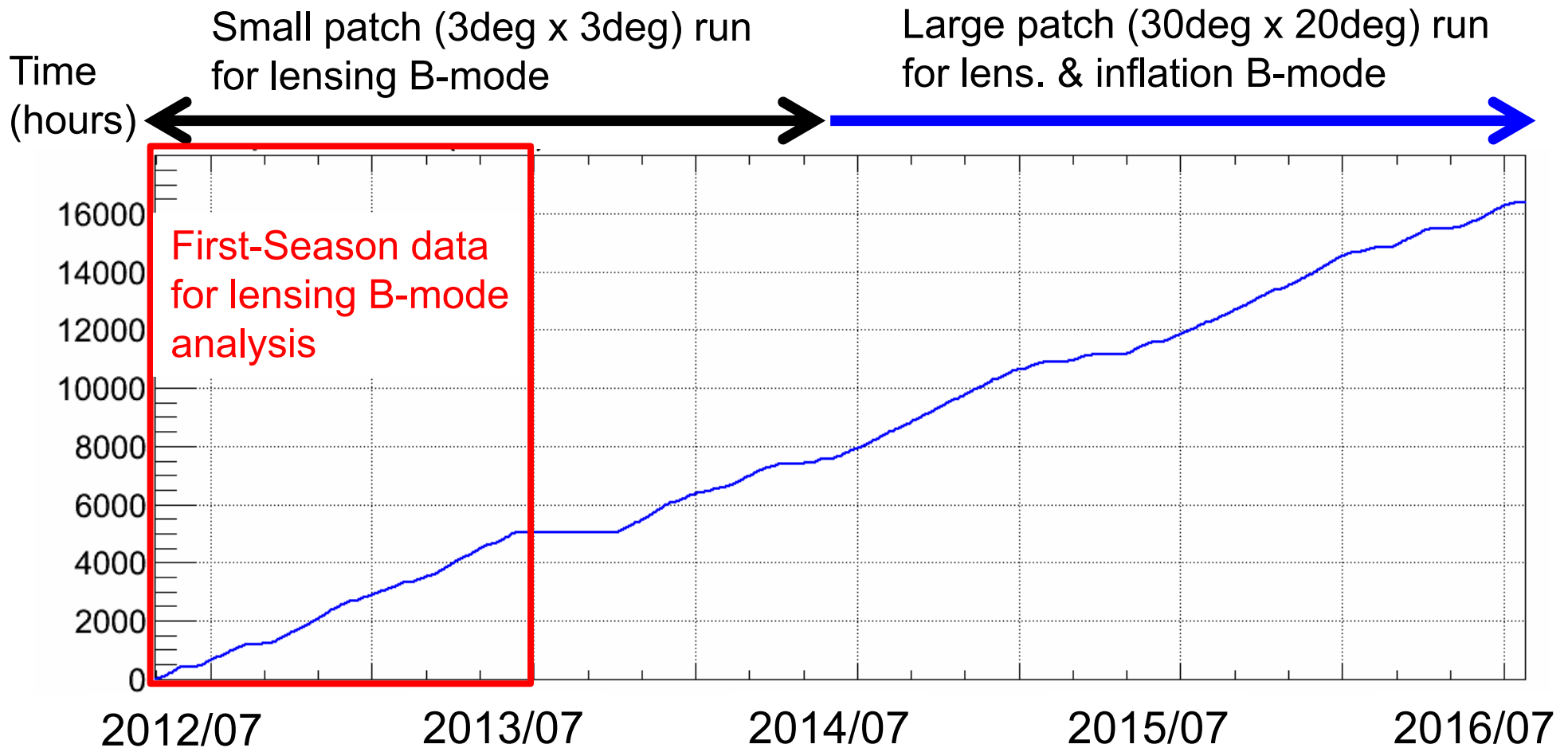
2 TES bolometers/pixel with  
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dipole antenna

# Observation



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

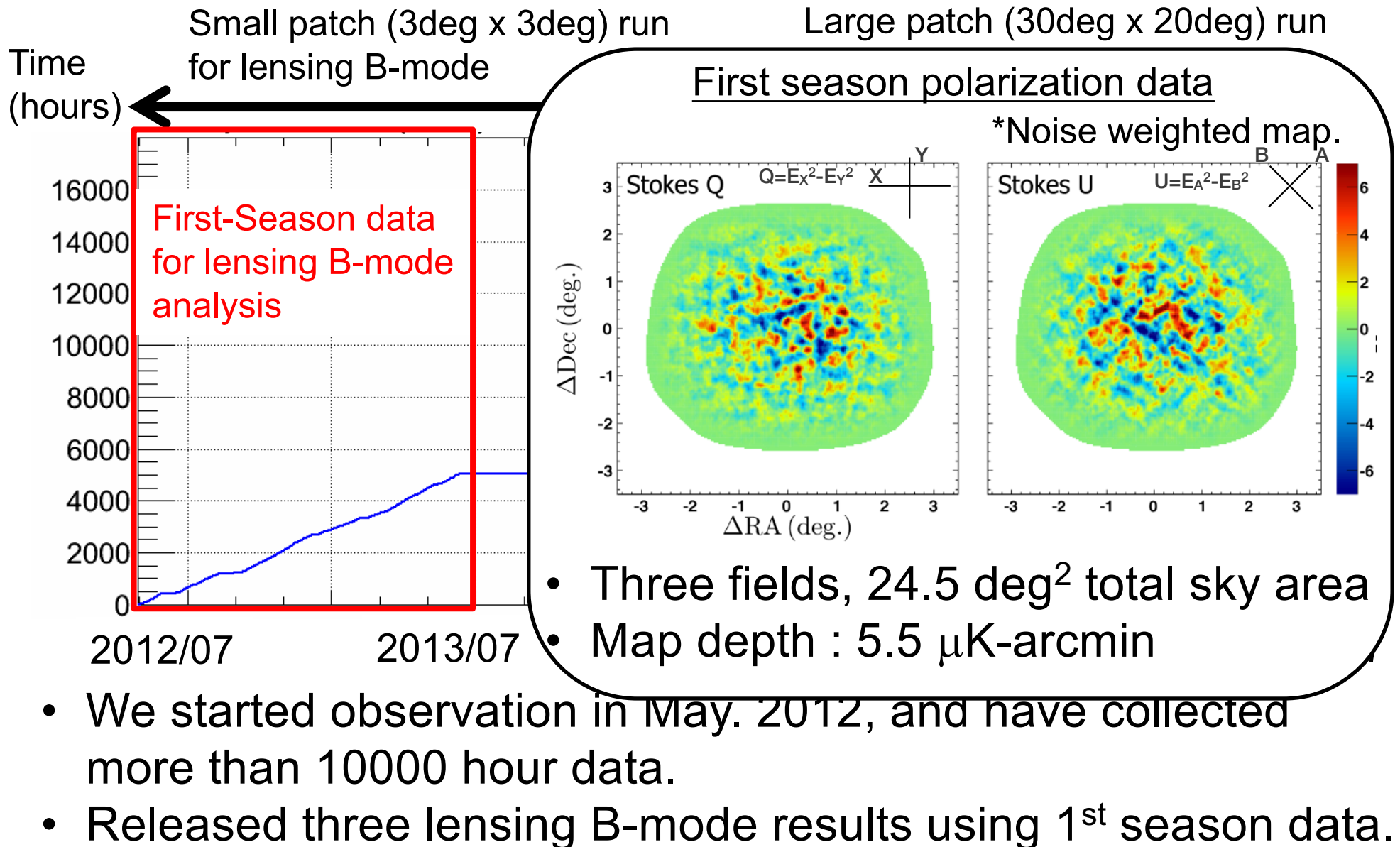
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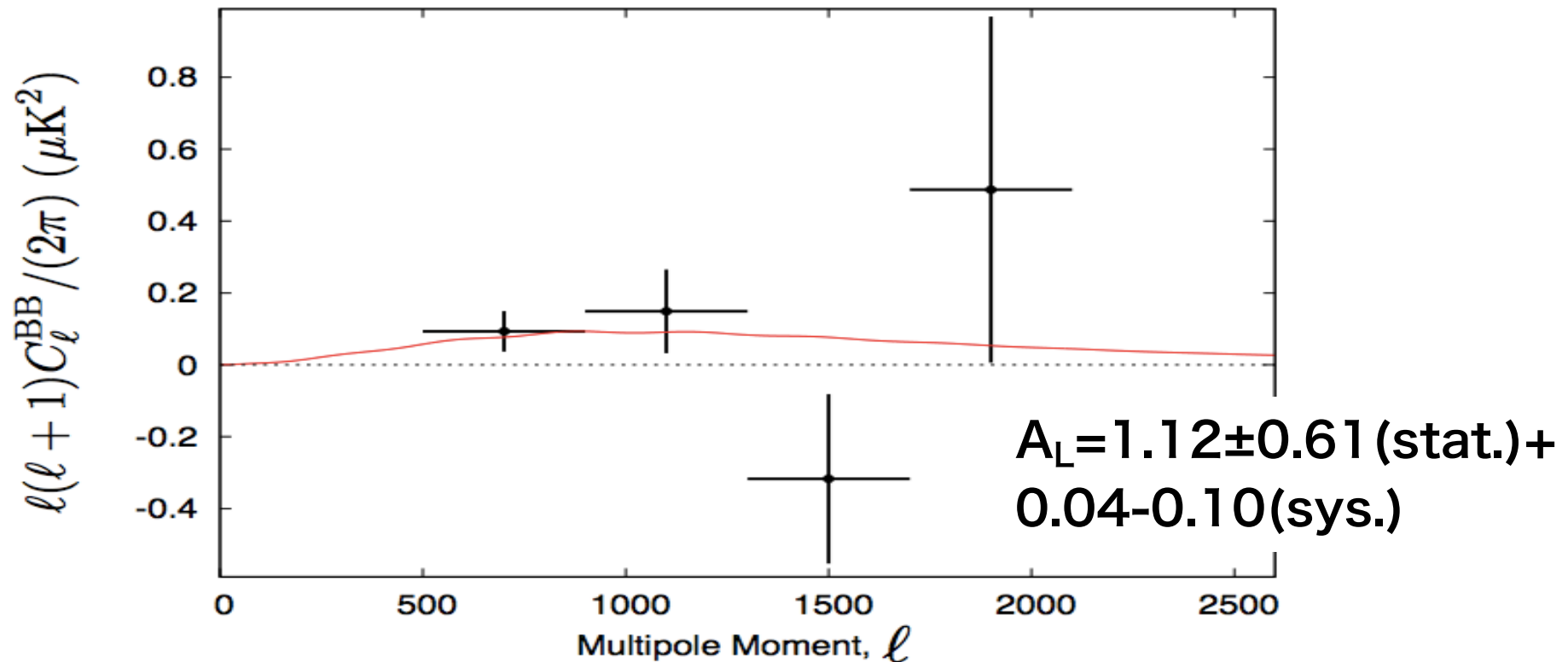
# Observation



# First-season POLARBEAR Results

## BB Power Spectrum

Astrophys. J. 794, 171 (2014)



- First measurement of lensing B-mode spectrum
  - 97.2% rejection of “no lensing B-mode” ( $4.7\sigma$  including  $C_{\ell}^{dd}$ )
  - Amplitude is consistent with  $\Lambda$ CDM expectation

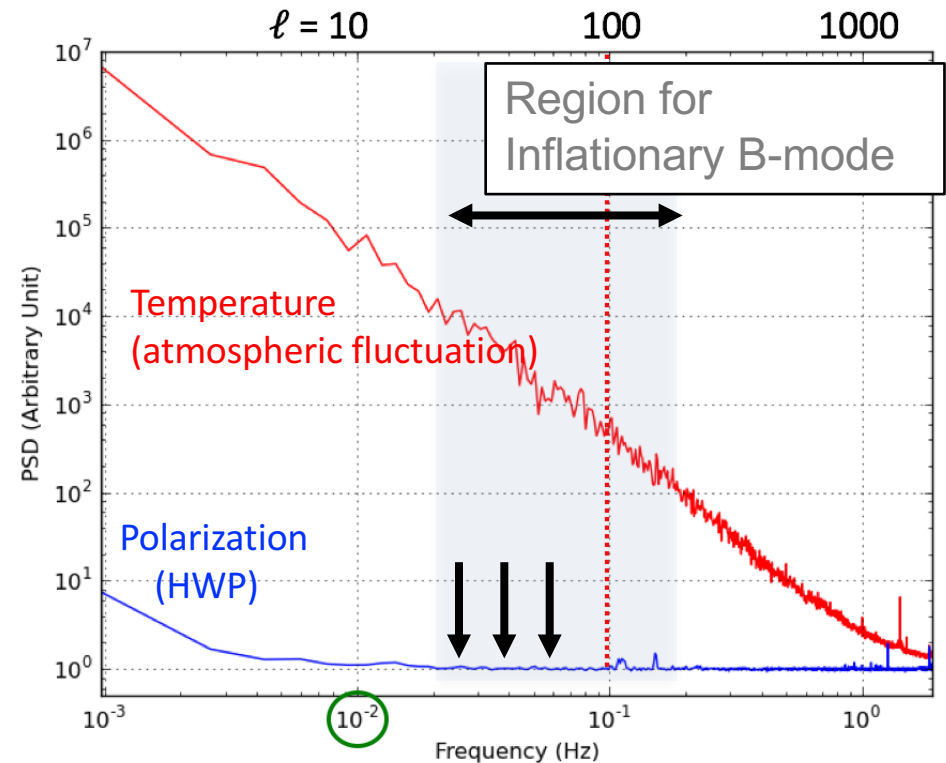
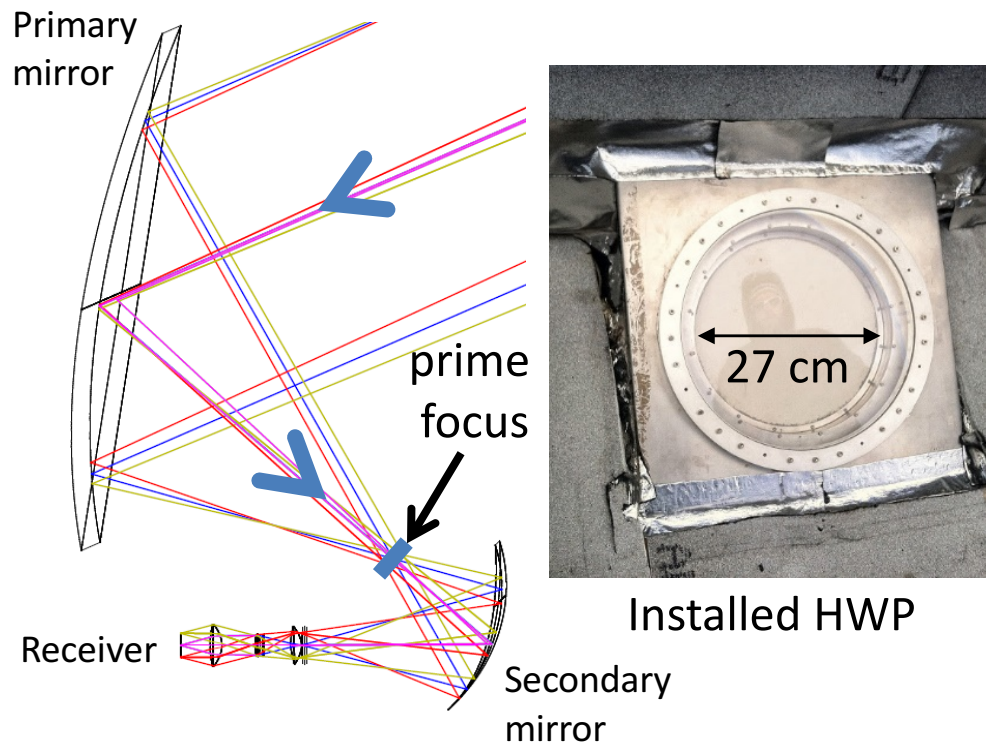
# Recent papers with 1<sup>st</sup> season data

Topic	Journal	
Cross correlation of lensing deflection with Cosmic Infrared Background	PRL 112, 131302 (2014)	Editor's suggestion
Lensing deflection power spectrum	PRL 113. 021301 (2014)	Editor's suggestion
CMB B-mode auto power spectrum	ApJ 794, 2 (2014)	
Modeling of atmospheric emission	ApJ 809, 63 (2015)	
Cosmic Birefringence and Primordial Magnetic Field	PRD 92, 123509 (2015)	Editor's suggestion
Map-making algorithm	Submitted	

} Lensing-Bmode

- POLARBEAR continues timely publication of high profile results.
- More results (with 2<sup>nd</sup> season data) will come.

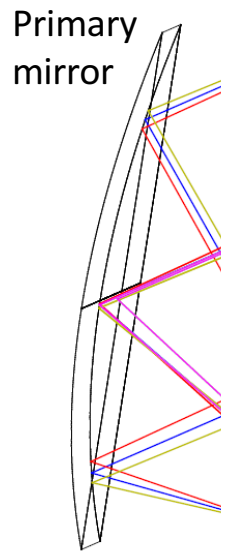
# Large patch observation



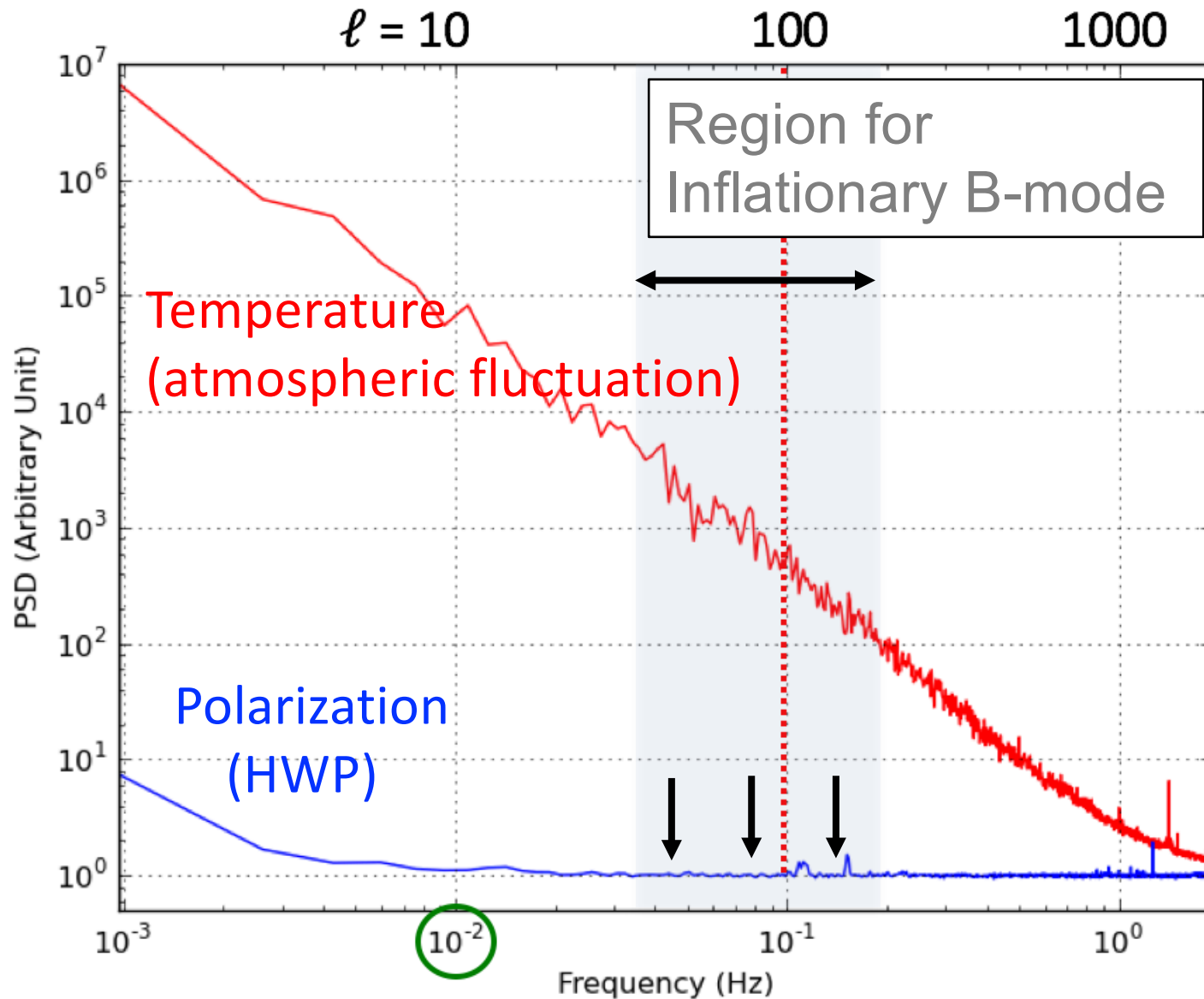
- We have observed larger ( $30 \times 20 \text{ deg}^2$ ) patch to access lower  $\ell$  region.
- Mitigate  $1/f$  noise with continuously rotating HWP.

*Ready to target inflation B-mode !*

# Large patch observation

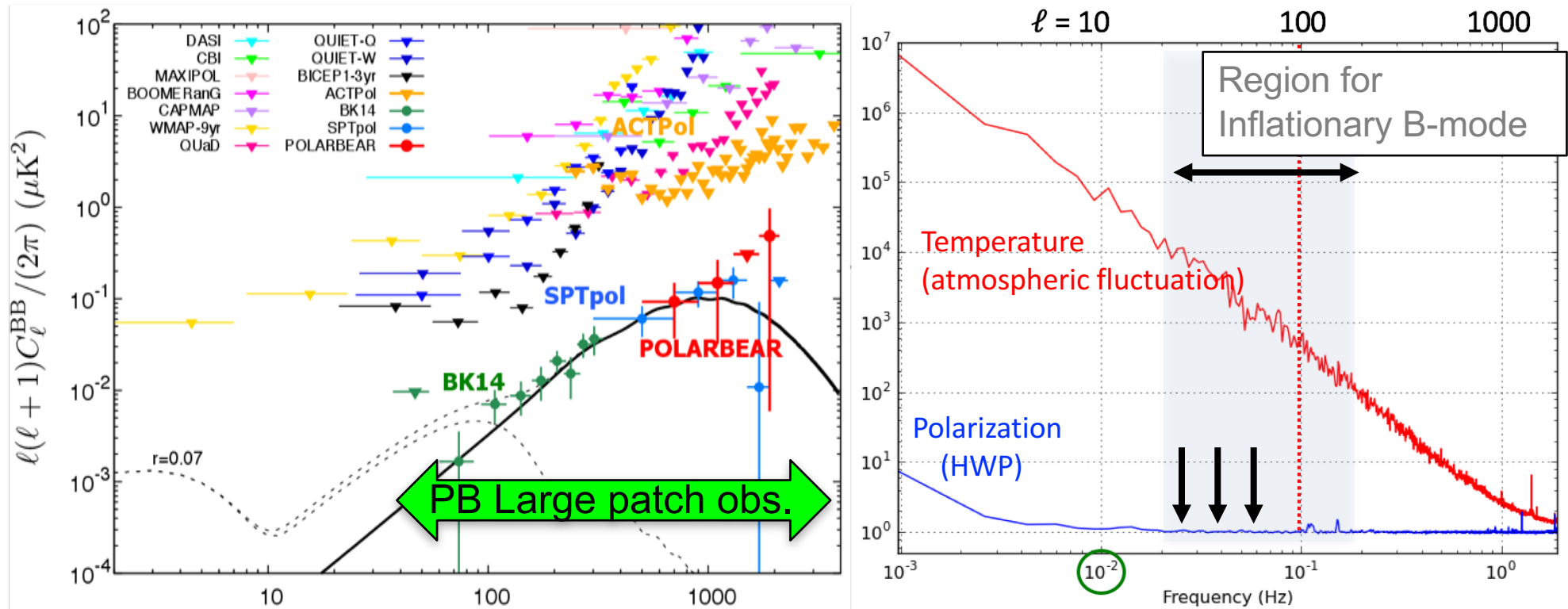


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ode !

# Large patch observation



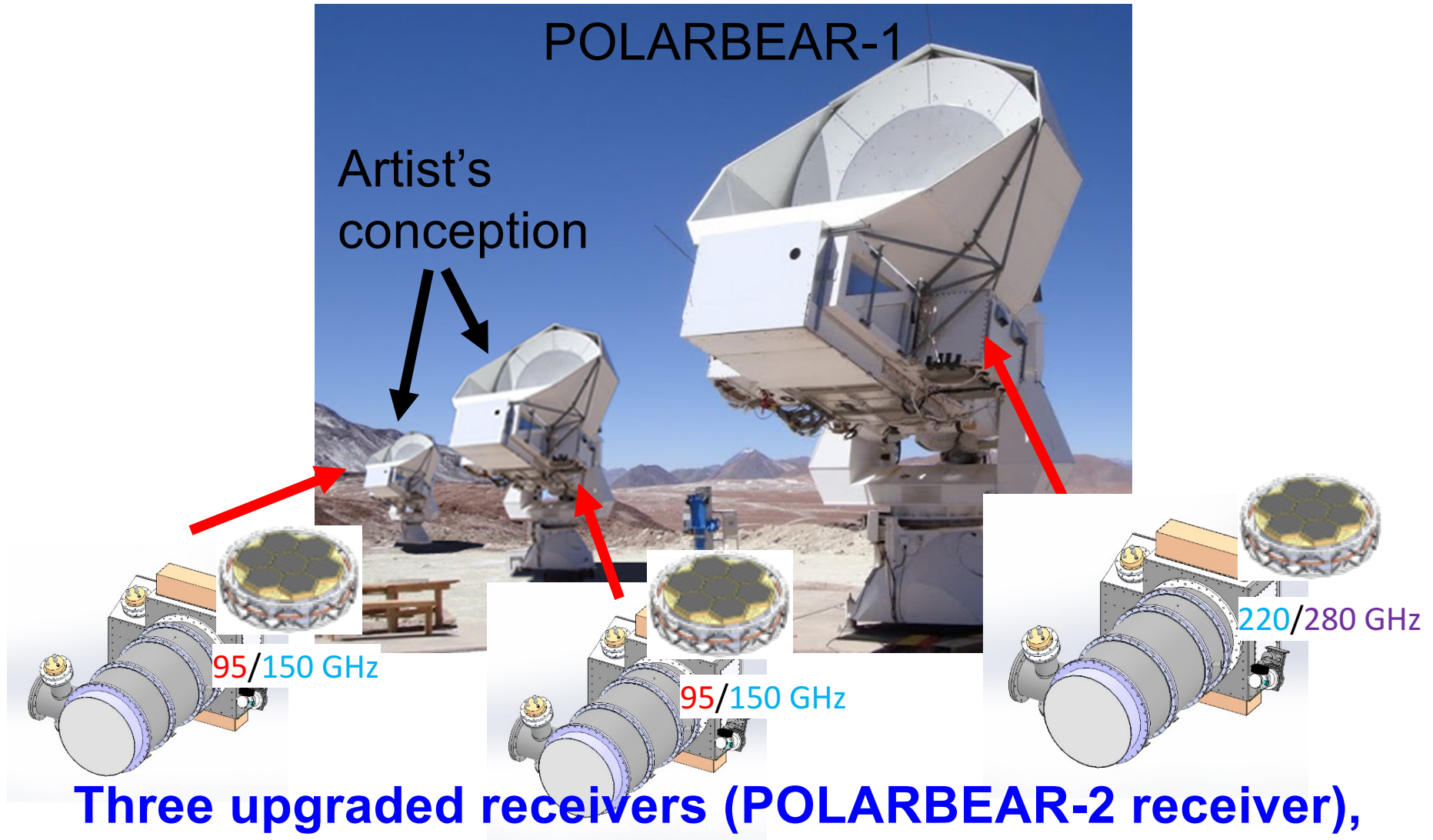
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# The Simons Array

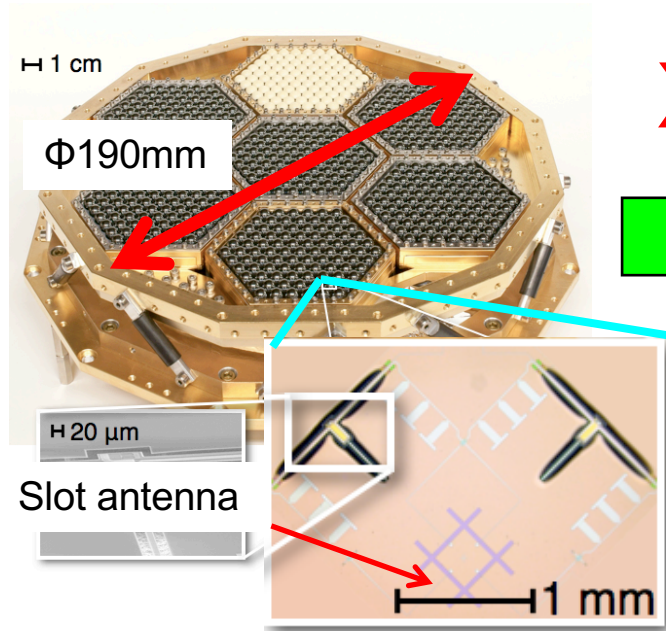
Expanding POLARBEAR to three multi-chroic telescopes



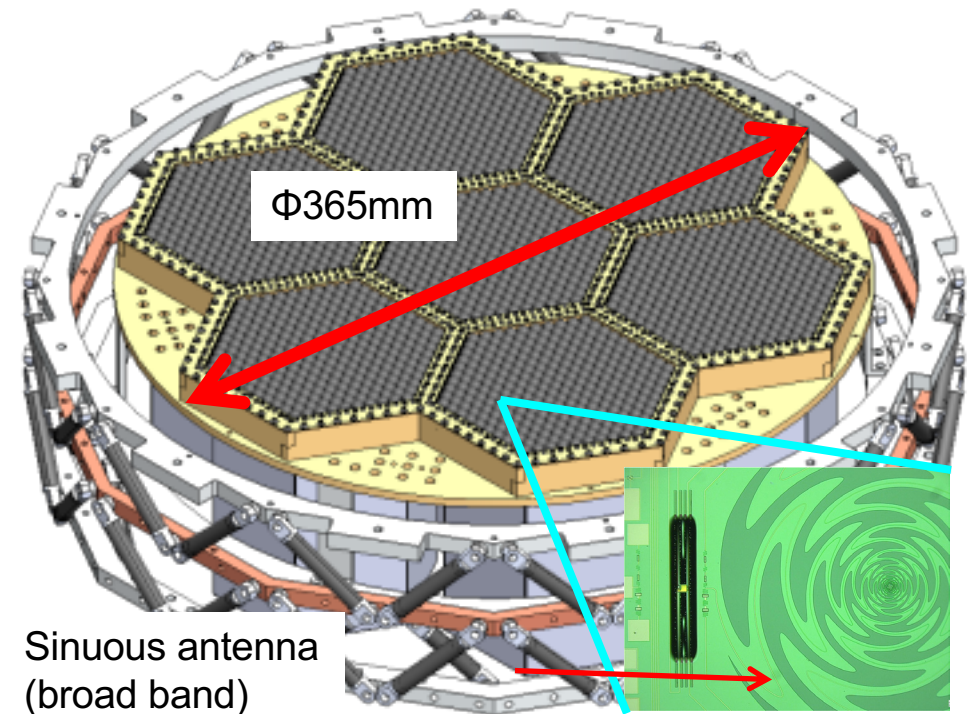
Three upgraded receivers (POLARBEAR-2 receiver),  
observing at 95, 150, 220, 280 GHz

# POLARBEAR to Simons Array

POLARBEAR-1  
1274 detector array



POLARBEAR-2 focal plane

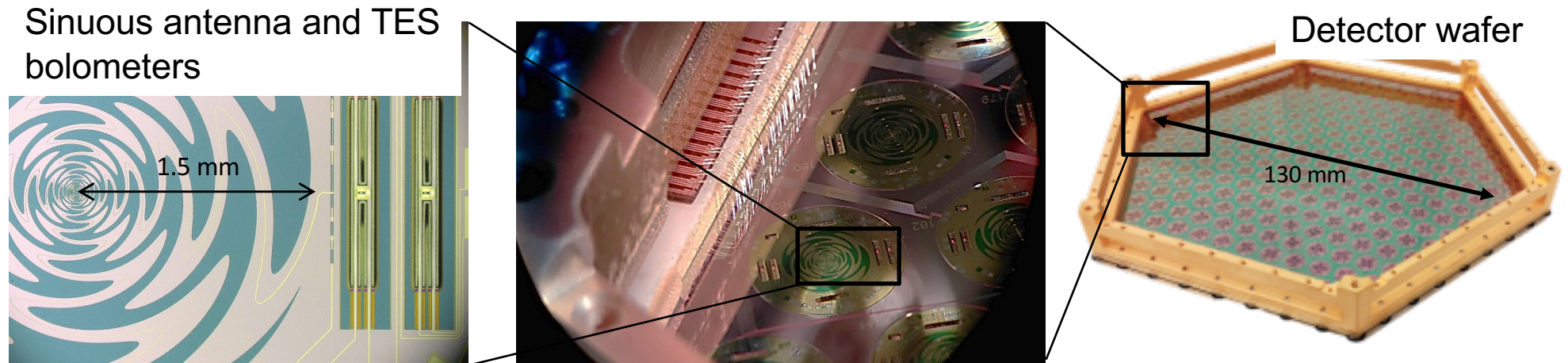


- Three larger focal plane (7588 TES / focal plane)
- Multi-chroic pixels with 95/150, 220/280GHz frequency coverage.

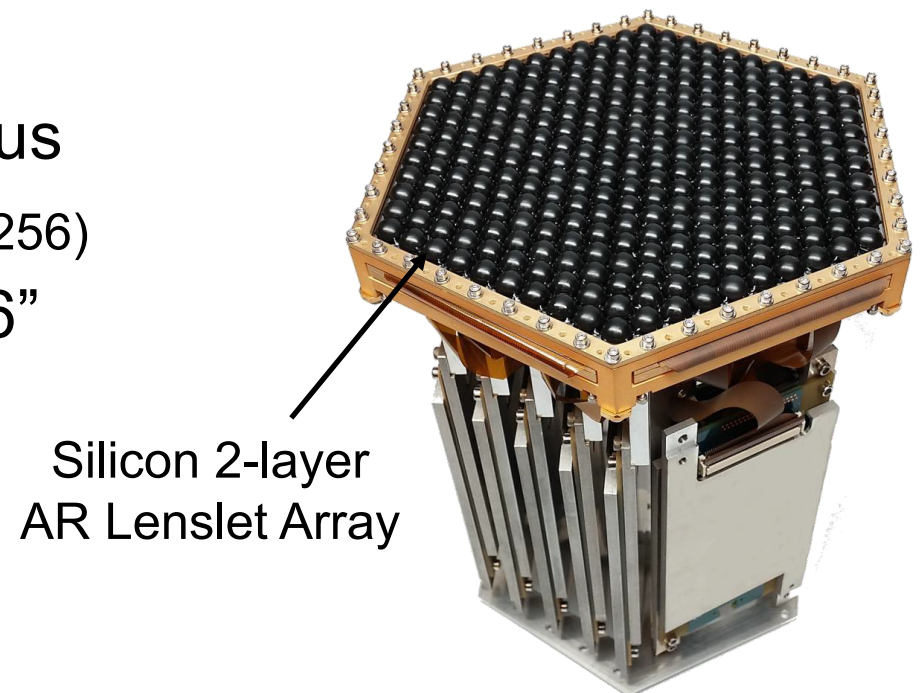
*x18 leap with multi-chroic pixels*



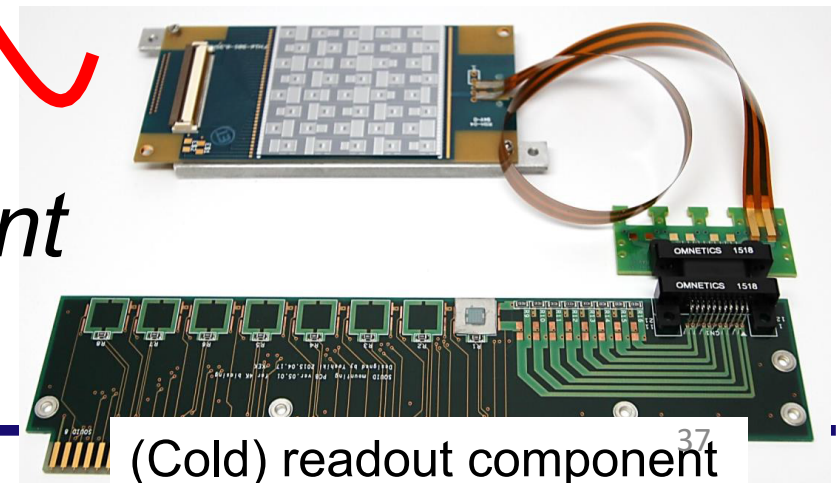
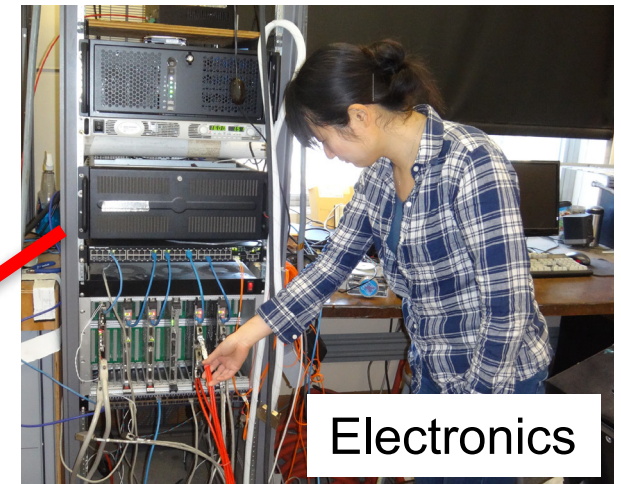
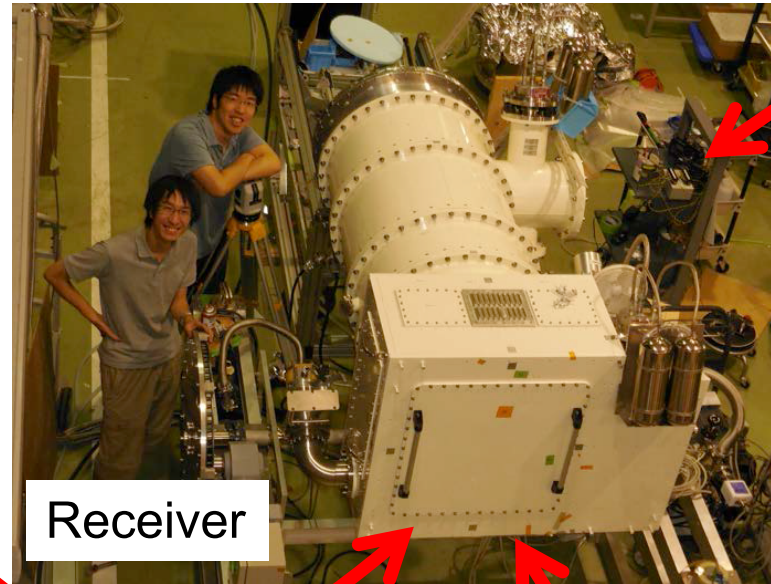
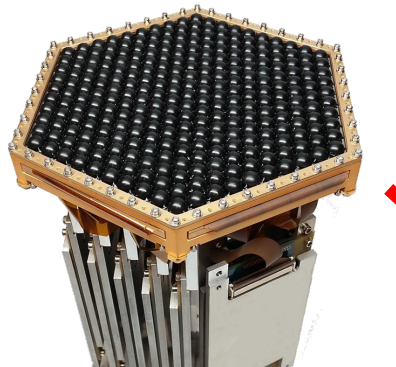
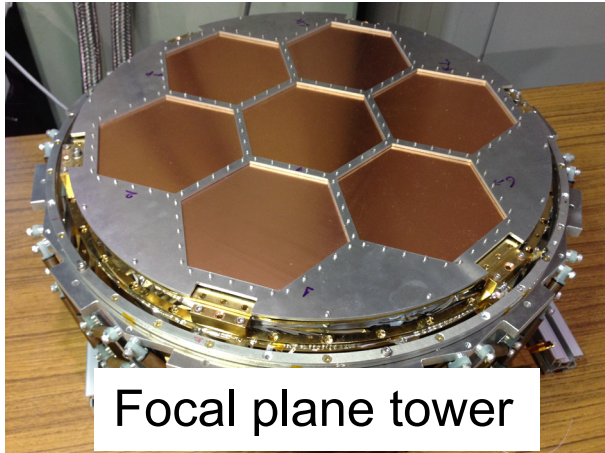
# POLARBEAR-2 Detector



- TES bolometer w/ 2-band sinuous detector design (Suzuki et al, 1210.8256)
- Detector fabrication at UCB on 6" silicon wafers
- 1084 bolometers per wafer
- 40x frequency MUX readout

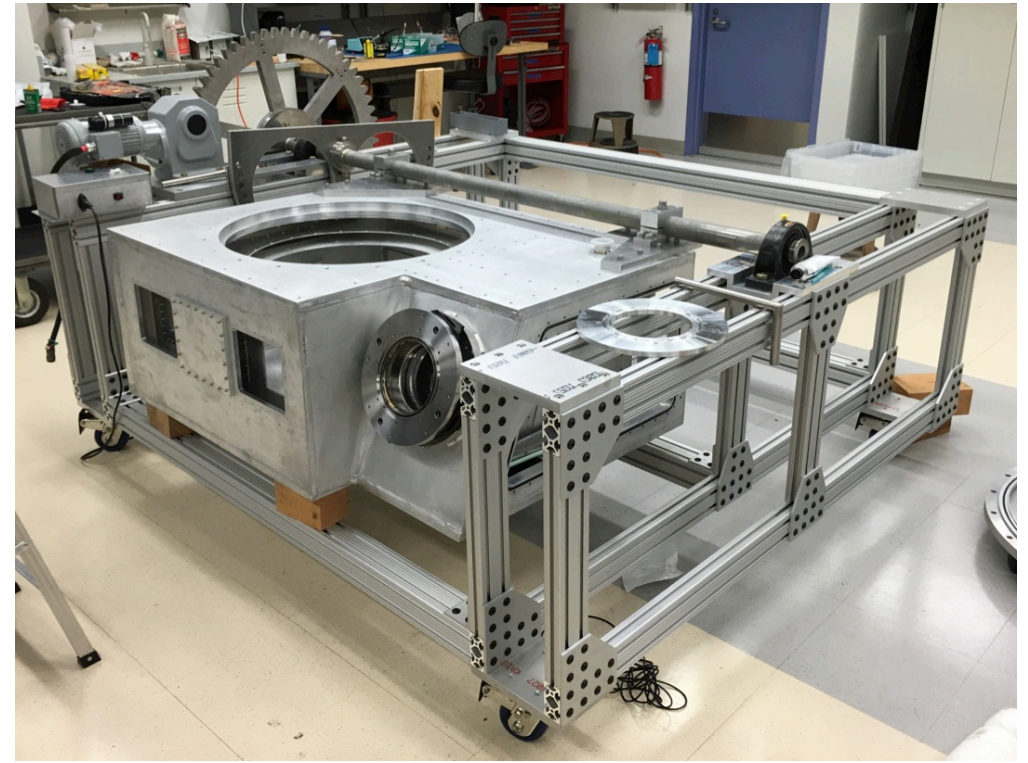


# 1st receiver assembly at KEK



*Lab. testing with full equipment  
will be started soon.*





- 2<sup>nd</sup> and 3<sup>rd</sup> receiver backends are being constructed in UCSD.



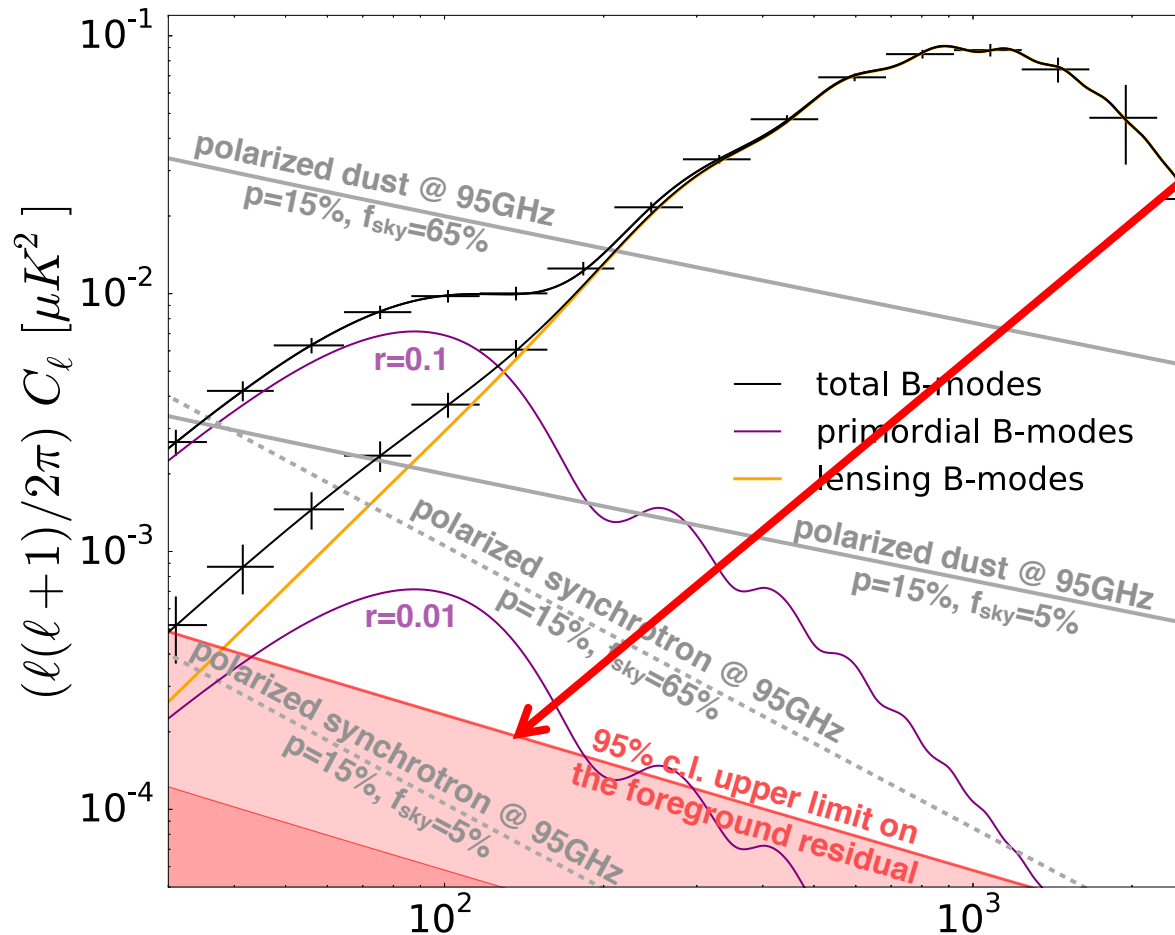
Photo taken by Nate Stebor (UCSD)

Two new telescopes (HTT-2 & HTT-3)

POLARBEAR-1  
telescope (HTT-1)

Assembly of 2 telescopes will be completed soon.  
Simons Array (1.3k  $\rightarrow$  23k detectors) will start in 2018.

# Simons Array (projected) sensitivity



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

Inflation

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

Neutrino mass

- $\sigma(\Sigma m_\nu) = 40$  meV  
(19 meV (stat))

w/ DESI BAO

***Simons Array can contribute to cosmology and particle physics significantly.***



# Future : Simons Observatory

SIMONS OBSERVATORY

\$40 Million Grant Establishes Simons Observatory, a New Investigation into the Formation of the Early Universe



Current member :  
ACT +  
Simons Array

The [Simons Foundation](#) has awarded a \$38.4 million grant to establish the [Simons Observatory](#), a new astronomy facility in Chile's Atacama Desert that will merge and expand existing efforts to explore the evolution of the universe from its earliest moments to today. An additional \$1.7 million of support is being provided by the [Heising-Simons Foundation](#). The project is a collaboration among Princeton University, The University of California at San Diego, The University of California at Berkeley, The University of Pennsylvania, and the Lawrence Berkeley National Laboratory, all of which are also providing financial support. [Read More...](#)

on 20th April 2016

<https://www.simonsobservatory.org>

- Five year program (\$45M) to establish observatory for key CMB science, and advancing technology.
- Important step towards CMB-S4



# Summary

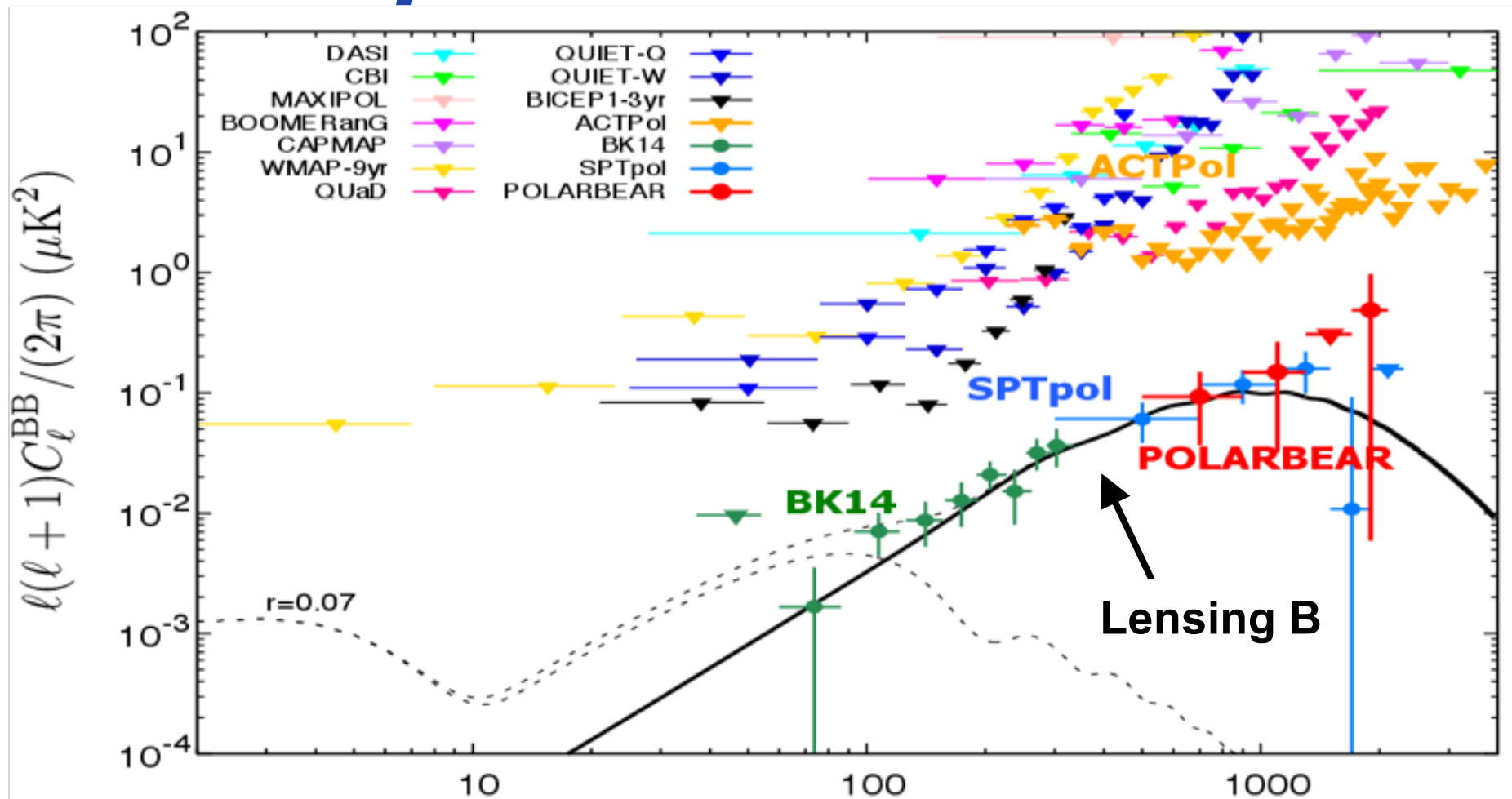
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- POLARBEAR is a ground-based CMB polarization experiment, aiming to reveal the inflationary universe and neutrino absolute mass scale.
- POLARBEAR-1 : the first measurement of lensing B-mode signal at  $4.7\sigma$  with CMB data alone, and large patch observation started for inflationary B-mode.
- POLARBEAR-2/Simons Array is being prepared.

Stay Tuned !

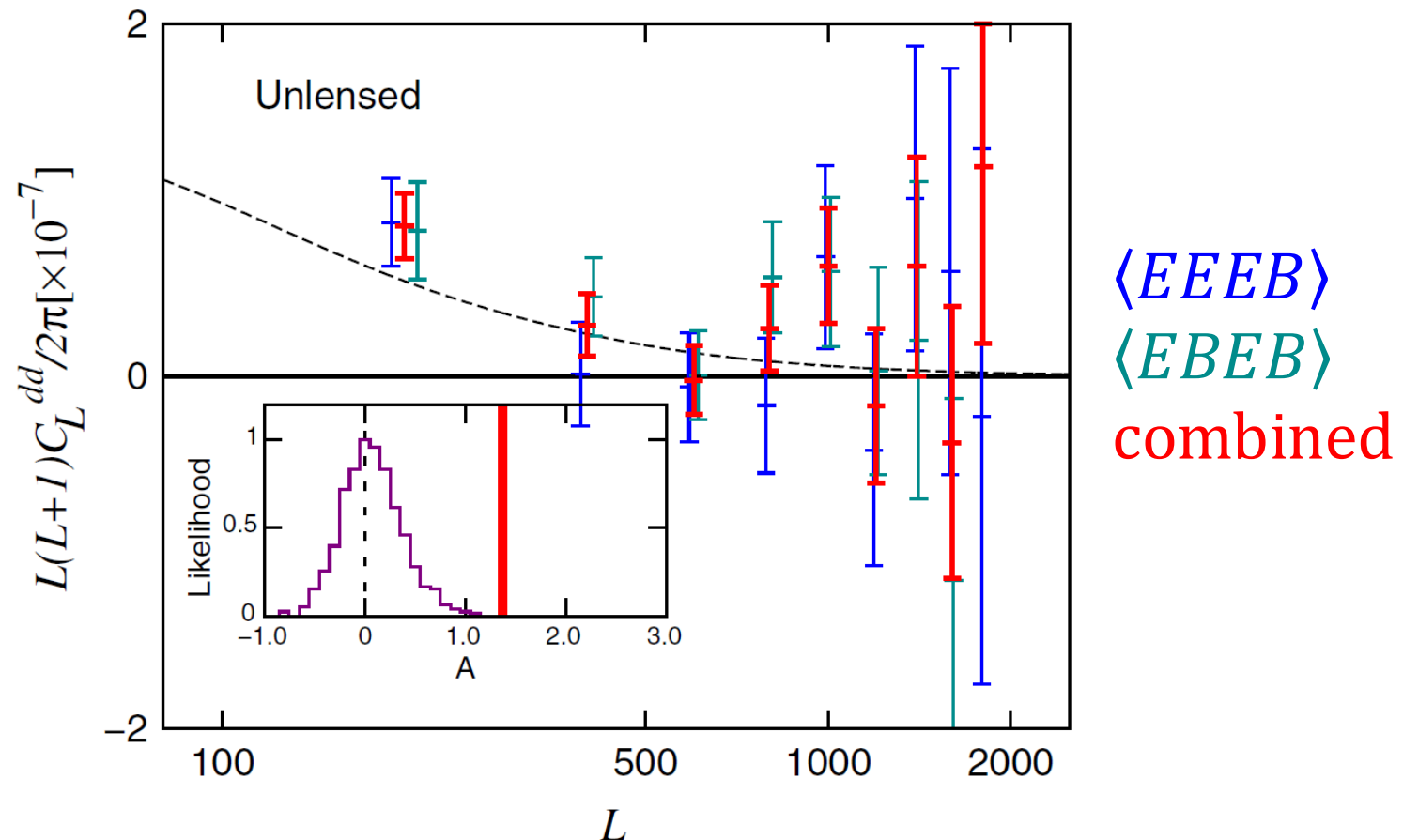
# Supplements

# Experimental status



- Lensing B-mode has been detected by a several groups (1<sup>st</sup> detection was made by PB).
- No clear evidence is found for inflation B-mode.

# 1. Lensing CMB polarization measurement from CMB polarization

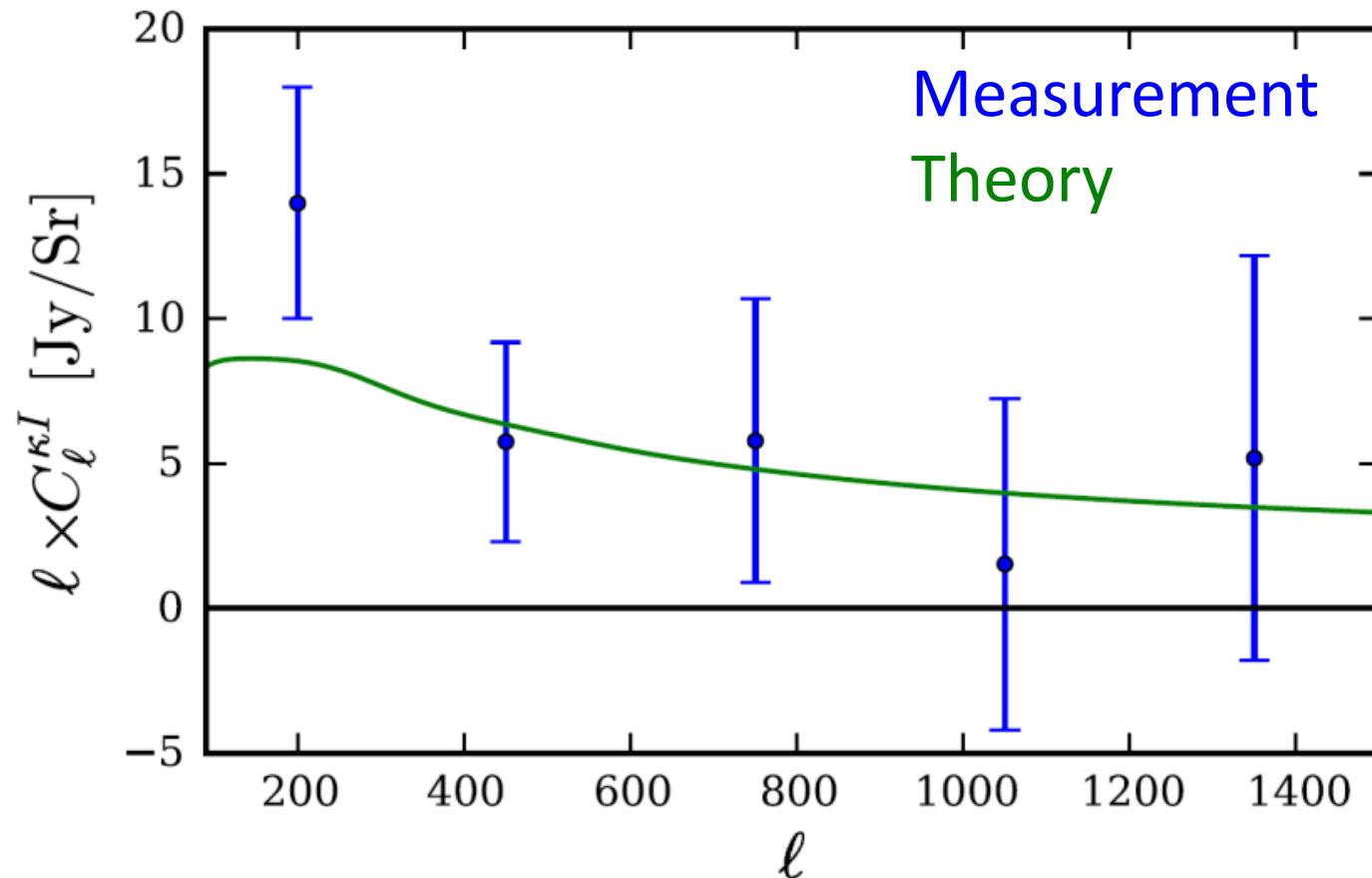


- Power spectrum of lensing diffraction field estimators reconstructed from our CMB polarization data.

**4.2  $\sigma$  detection of lensing B-mode**

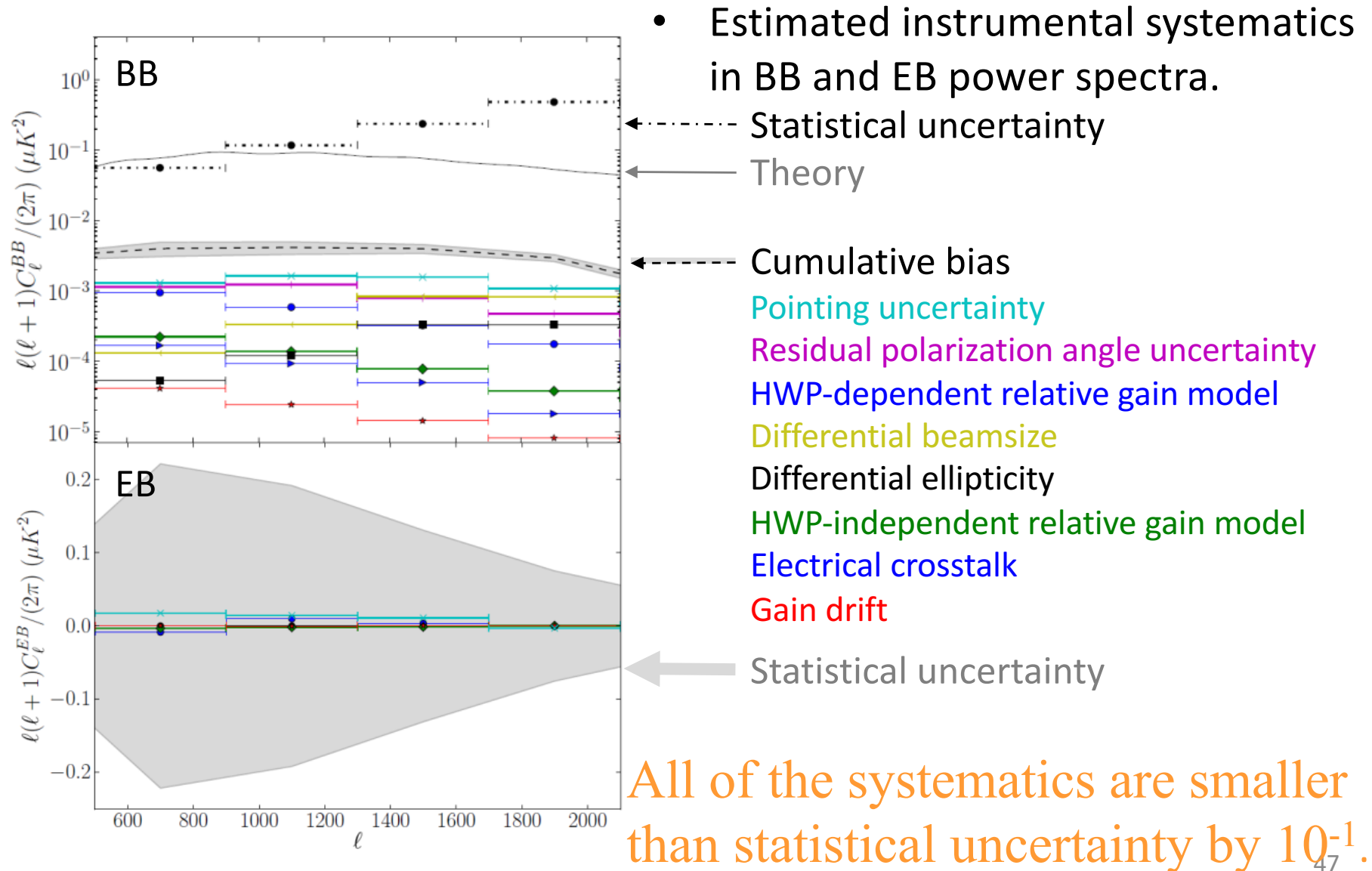


## 2. Lensing CMB polarization measurement from cross correlation with CIB

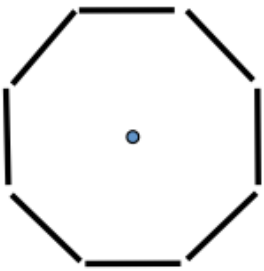


- Cross-power spectrum of CMB polarization lensing and 500  $\mu\text{m}$  Herschel CIB map.  
**4.0  $\sigma$  detection of lensing B-mode**

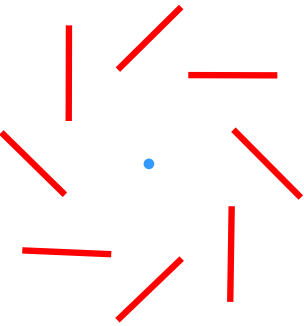
# Systematics evaluation



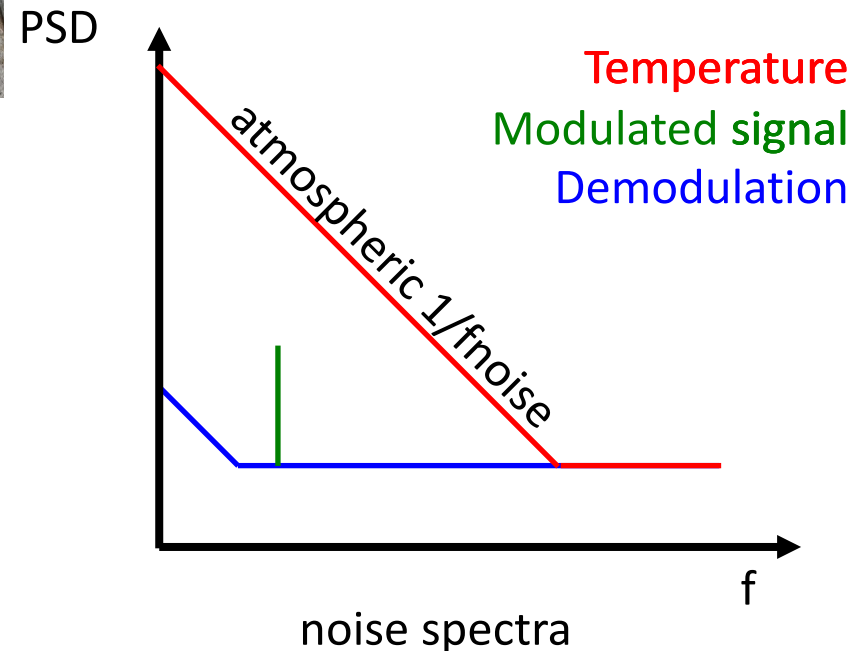
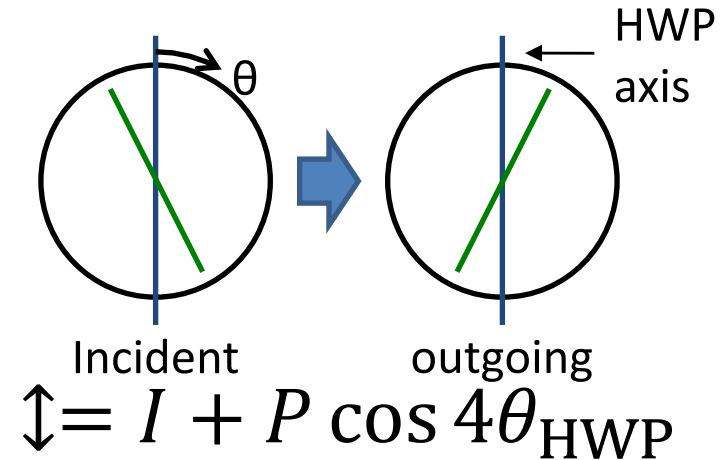
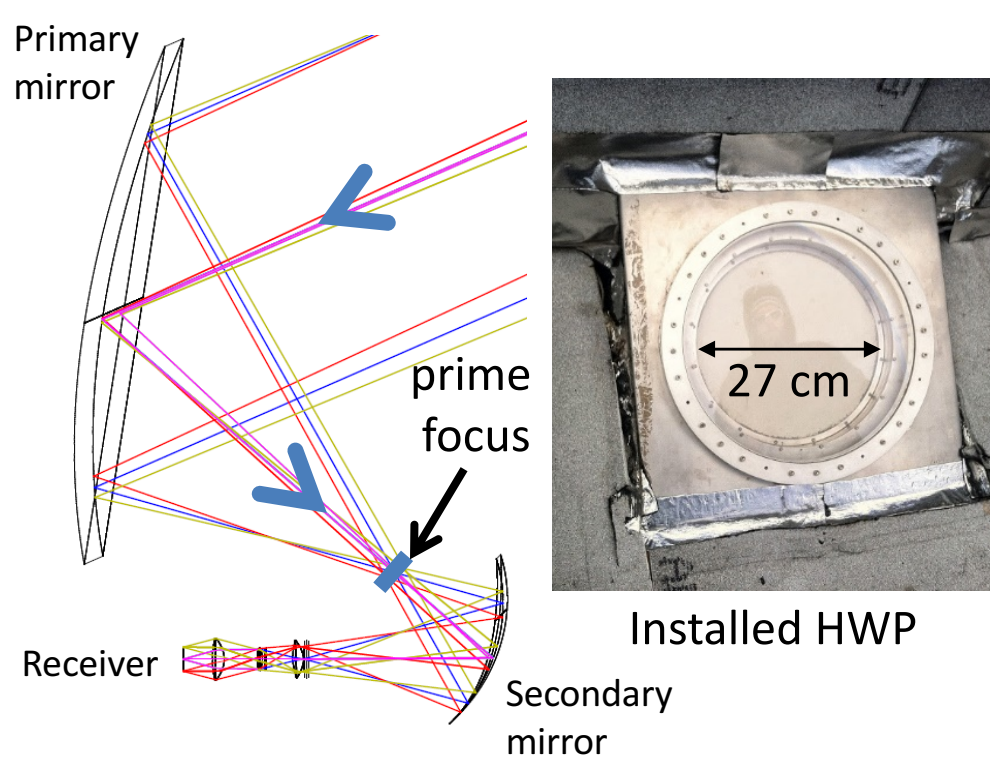
E-mode



B-mode



# Large patch observation



- We installed continuously rotating warm half-wave plate (HWP) at prime focus.