Neutrino mass measurement in a CMB experiment

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(KEK)

International Symposium on Neutrino Frontier @ Quy Nhon, Vietnam

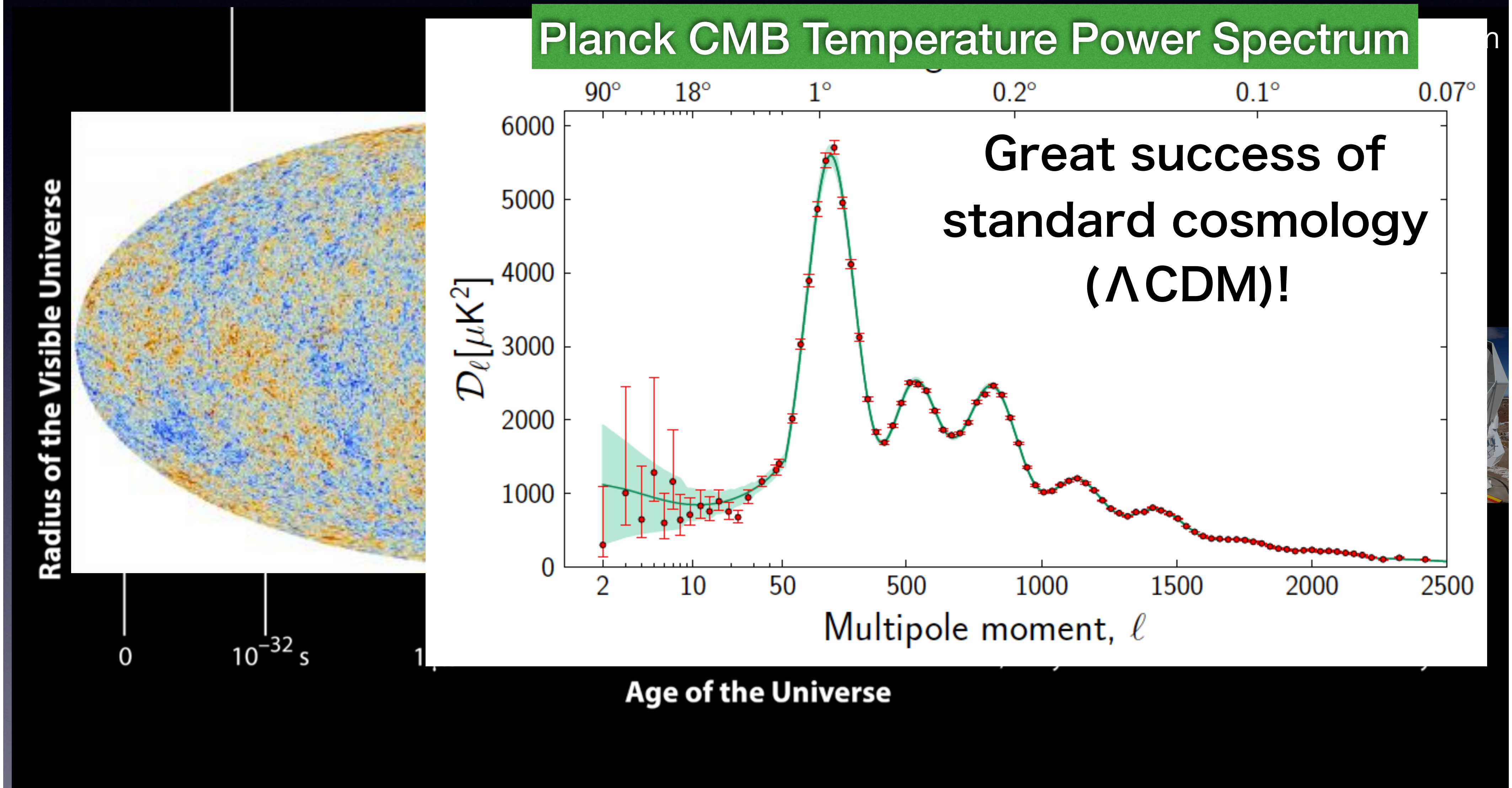
Outline

- Introduction
- CMB and Neutrino mass
- CMB lensing measurements by POLARBEAR
- Next generation experiment: POLARBEAR-2 / Simons Array
- Summary

CMB and Neutrino Mass

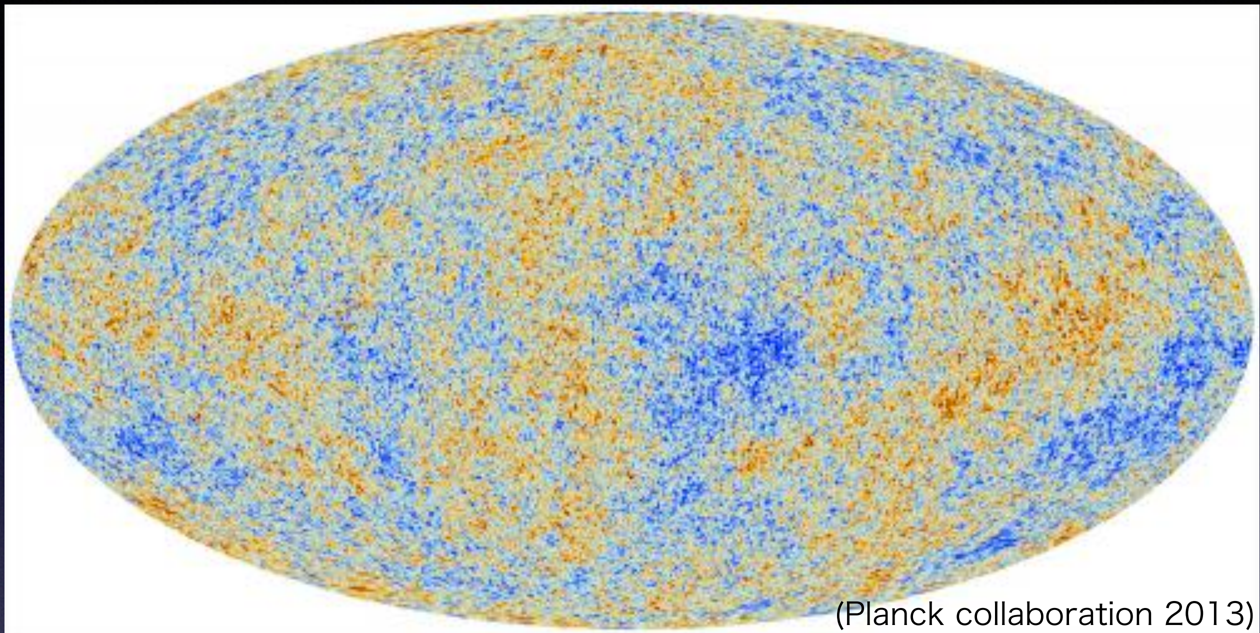
Cosmic Microwave Background

CMB is the oldest observable light coming from the early universe at the age of 380,000 yrs.

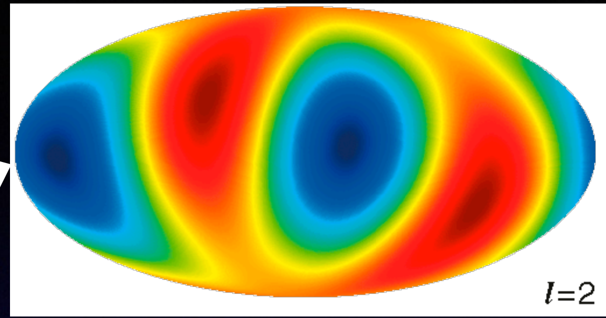


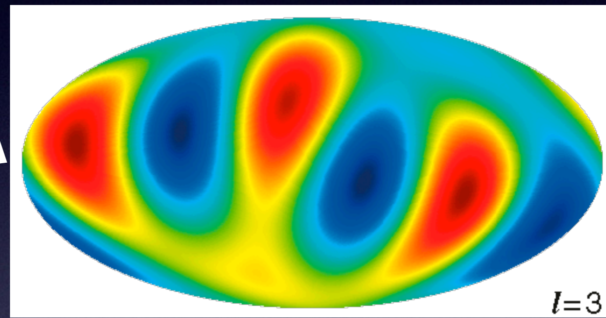
Some Notes about CMB Measurements

What we measure:



(Planck collaboration 2013)





(Fig. from WMAP 7yr, Benett et al.)

and many more higher multipoles…

Decomposition into spherical harmonics

$$T(\boldsymbol{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\boldsymbol{n})$$

$$a_{lm} = \int d\boldsymbol{n} T(\boldsymbol{n}) Y^{*}_{lm}(\boldsymbol{n})$$

Relation b/w angular scale and multipole, ell

$$\theta \sim 180°/l$$

Some Notes about CMB Measurements

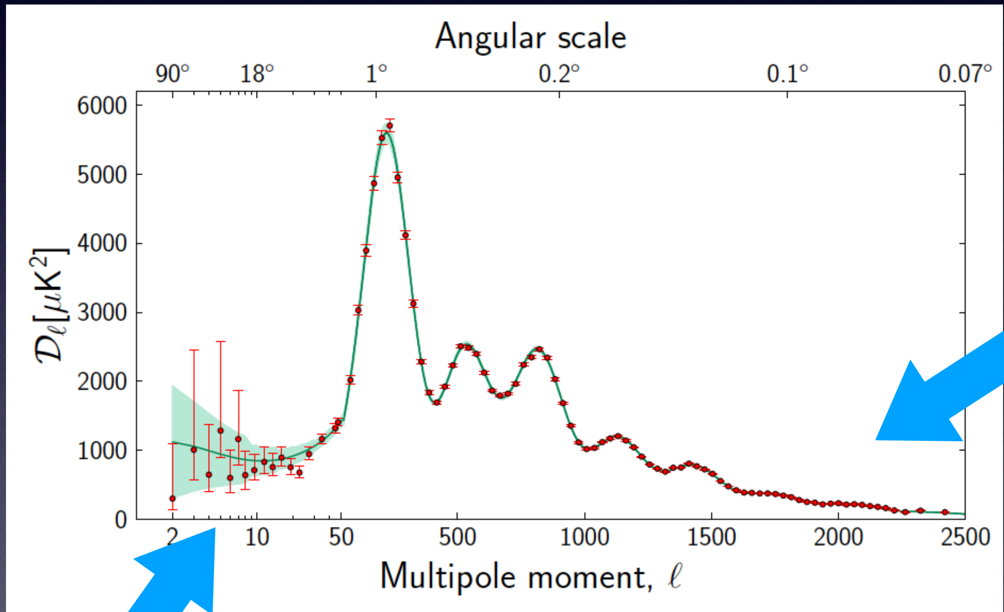
Reconstructed power spectrum, Cl, is
the mean variance of a_{lm} in each multipole

$$C_l = \frac{1}{2l+1}\sum_{m=-l}^{l} |a_{lm}|^2$$

Intrinsic error, cosmic variance
(sample variance)

$$\delta_{int}(C_l) = \sqrt{\frac{2}{(2l+1)f_{sky}}}C_l$$

$$D_l = \frac{l(l+1)}{2}C_l$$



High-ell measurement needs
to be high resolution

$$\delta_{beam}(C_l) \propto e^{l^2\sigma^2}$$

angular resolution

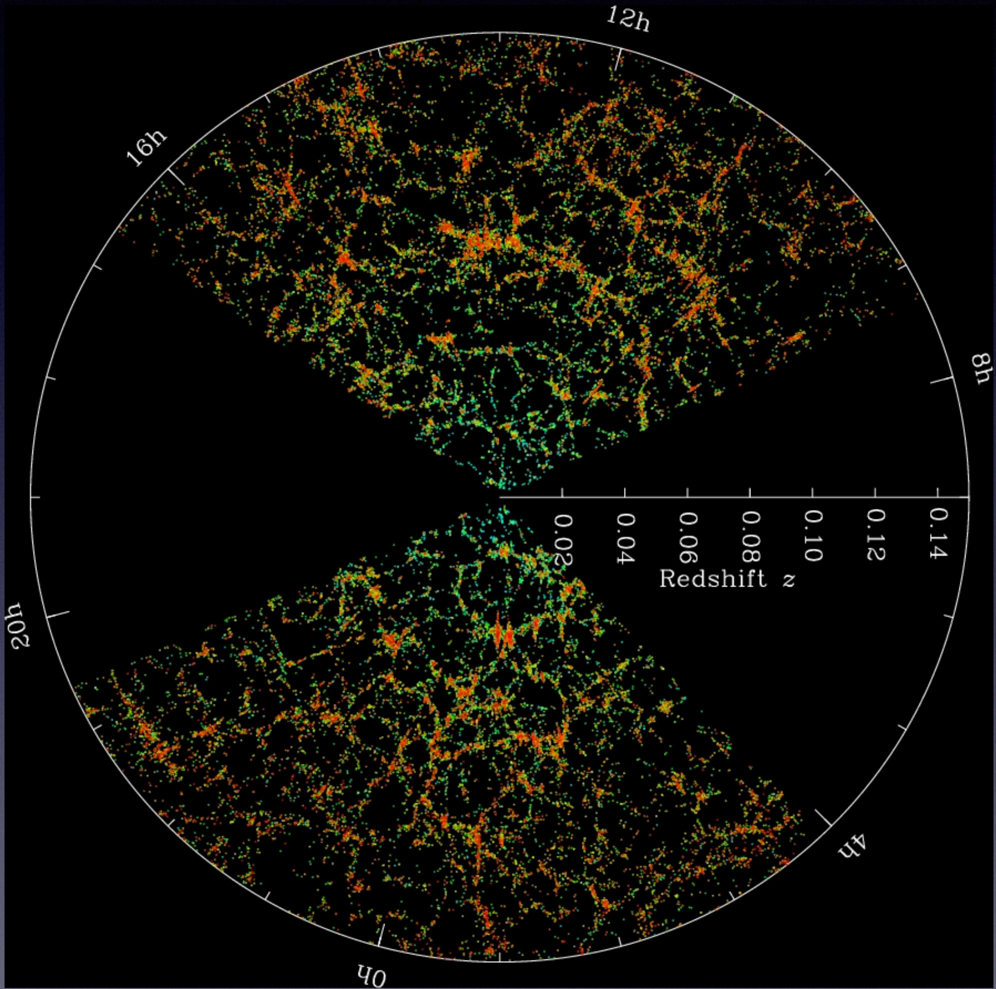
Low-ell measurement needs large
angular scale scans
w/ low 1/f noise (stable detector)

Relation b/w angular scale
and multipole, ell

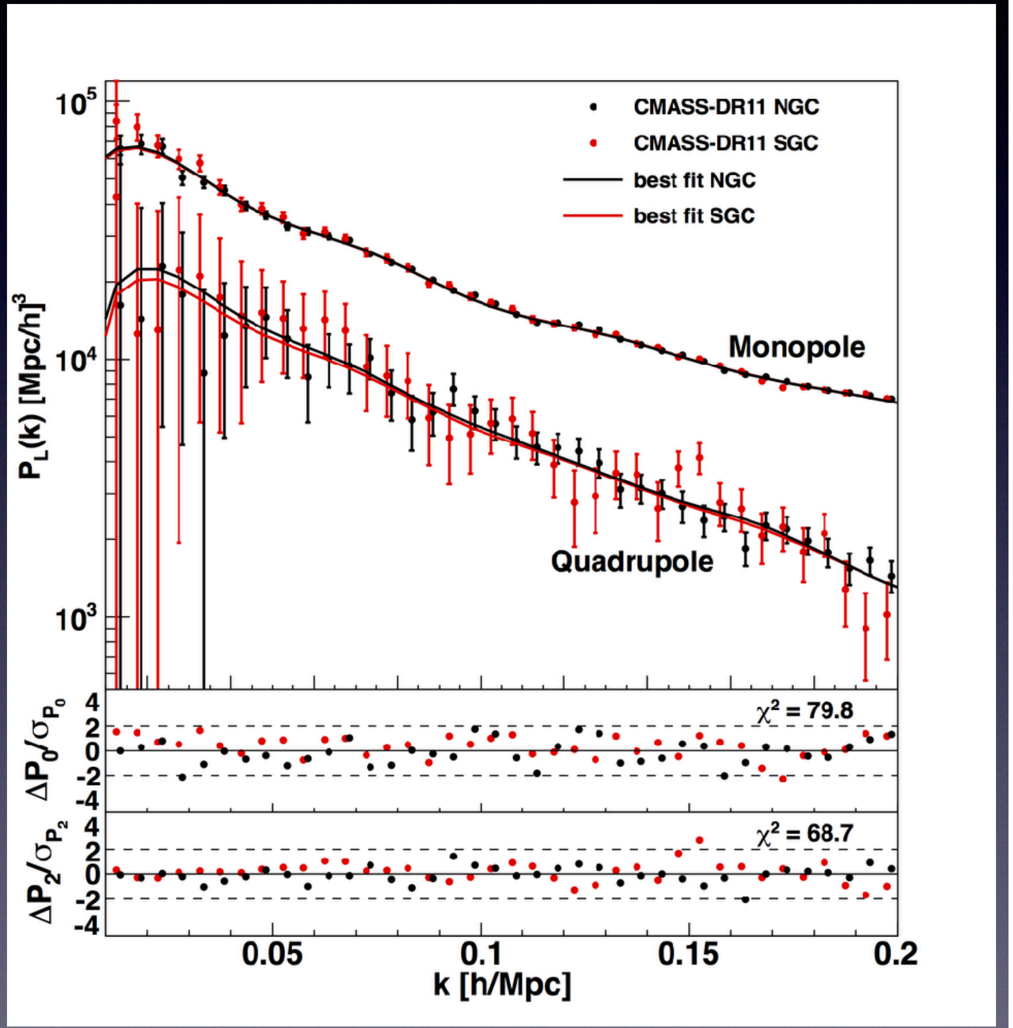
$$\theta \sim 180°/l$$

3-D version example: Matter Power Spectrum

3D map of galaxies by SDSS-III



Matter Power Spectrum



Cosmic Microwave Background

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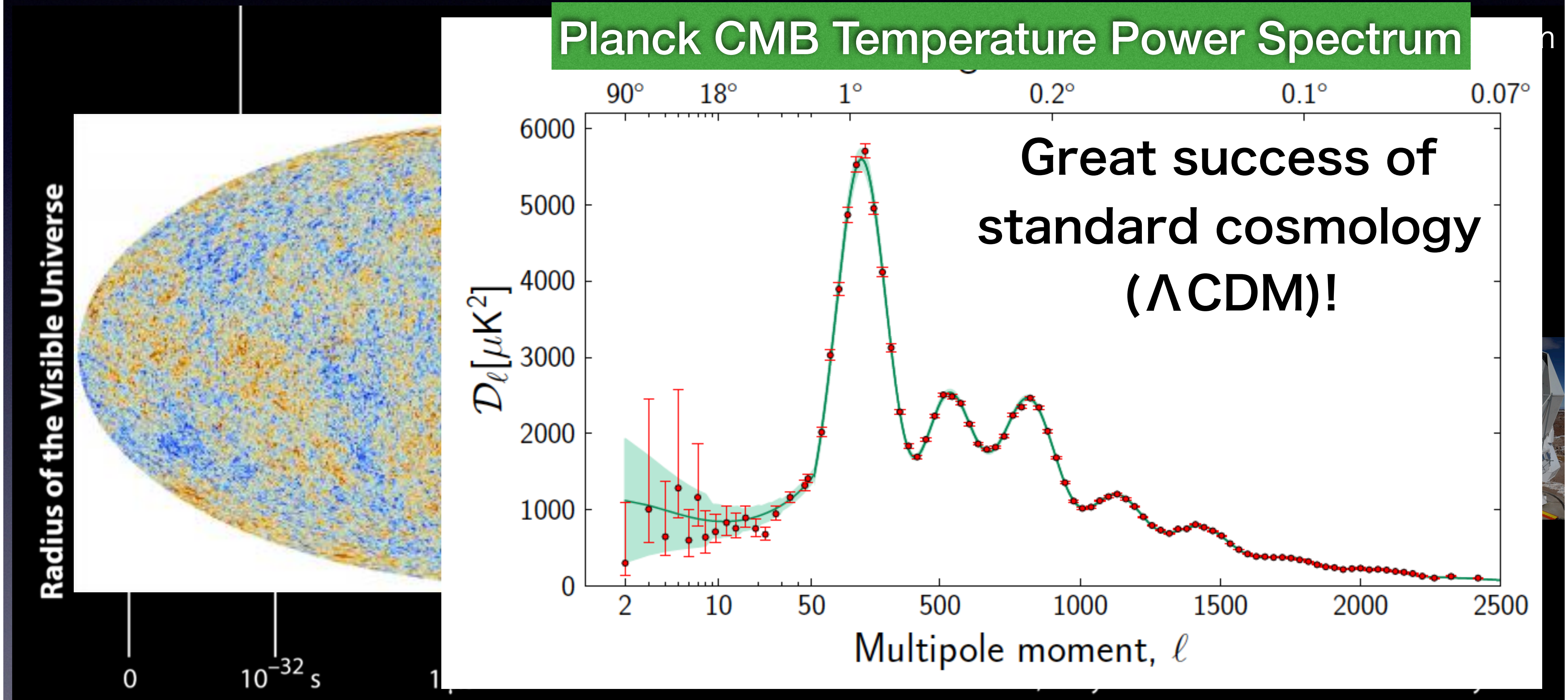
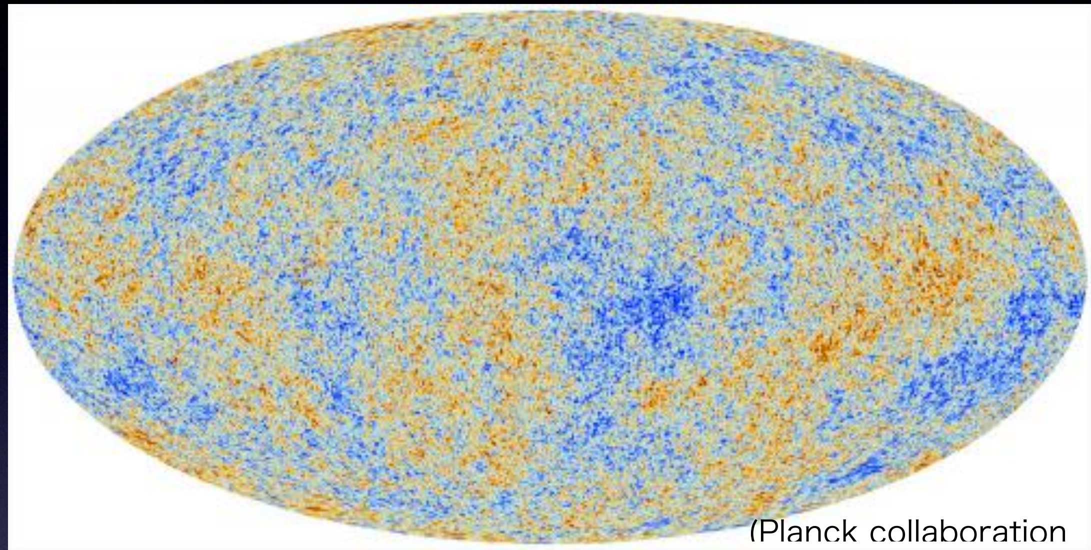


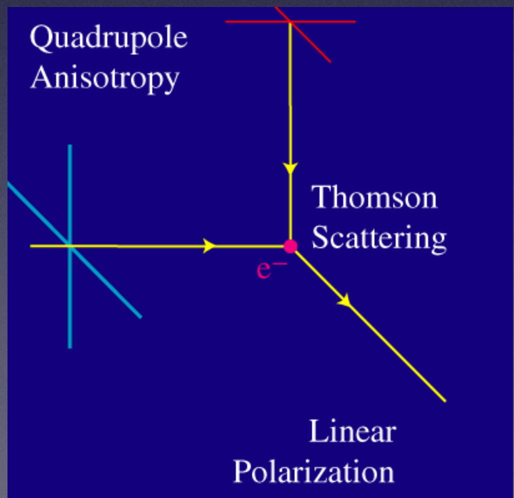
Next Frontier: Polarization!

Another degree of freedom: Polarization

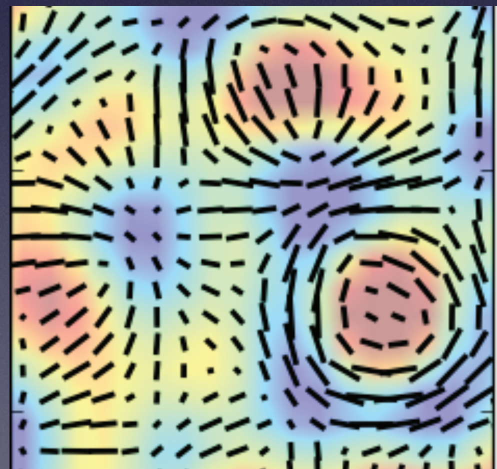
Density perturbations of the very early universe

CMB Temperature fluctuation





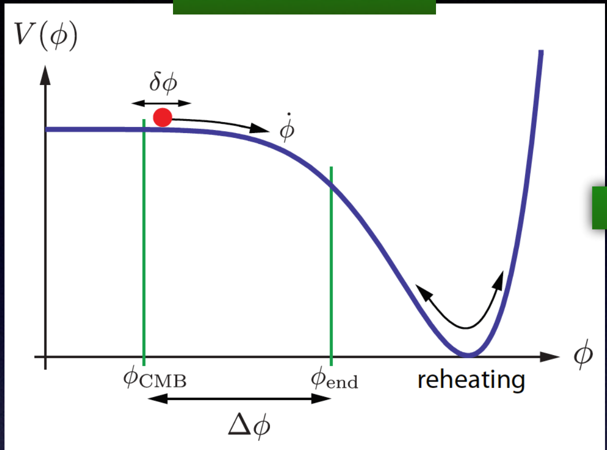
Thomson scattering



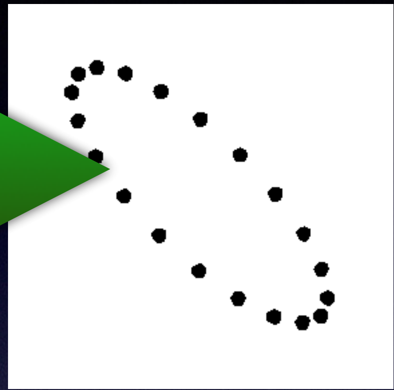
E-mode polarization!
(Even parity)
Detected in 2001

Another degree of freedom: Polarization

Inflation

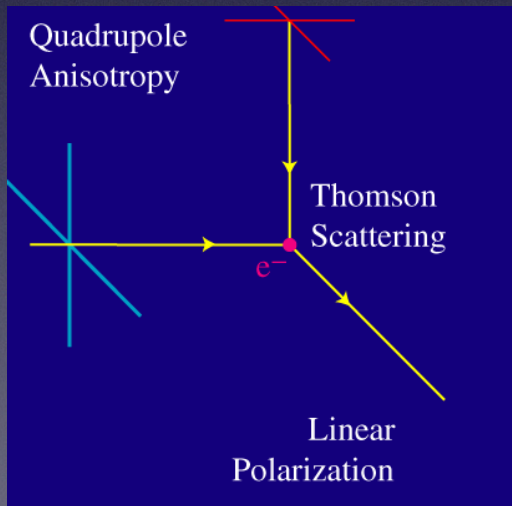


Primordial Gravitational Wave



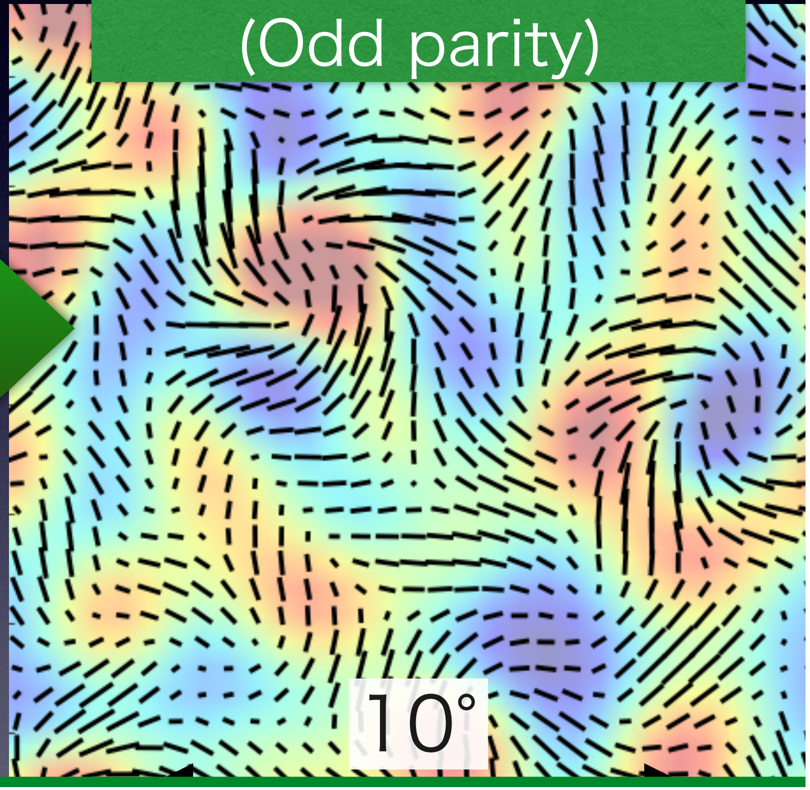
Unique prediction of Inflation:
Inflation generated cosmological-scale gravitational waves from quantum fluctuations

+



Thomson scattering

B-mode Polarization (Odd parity)

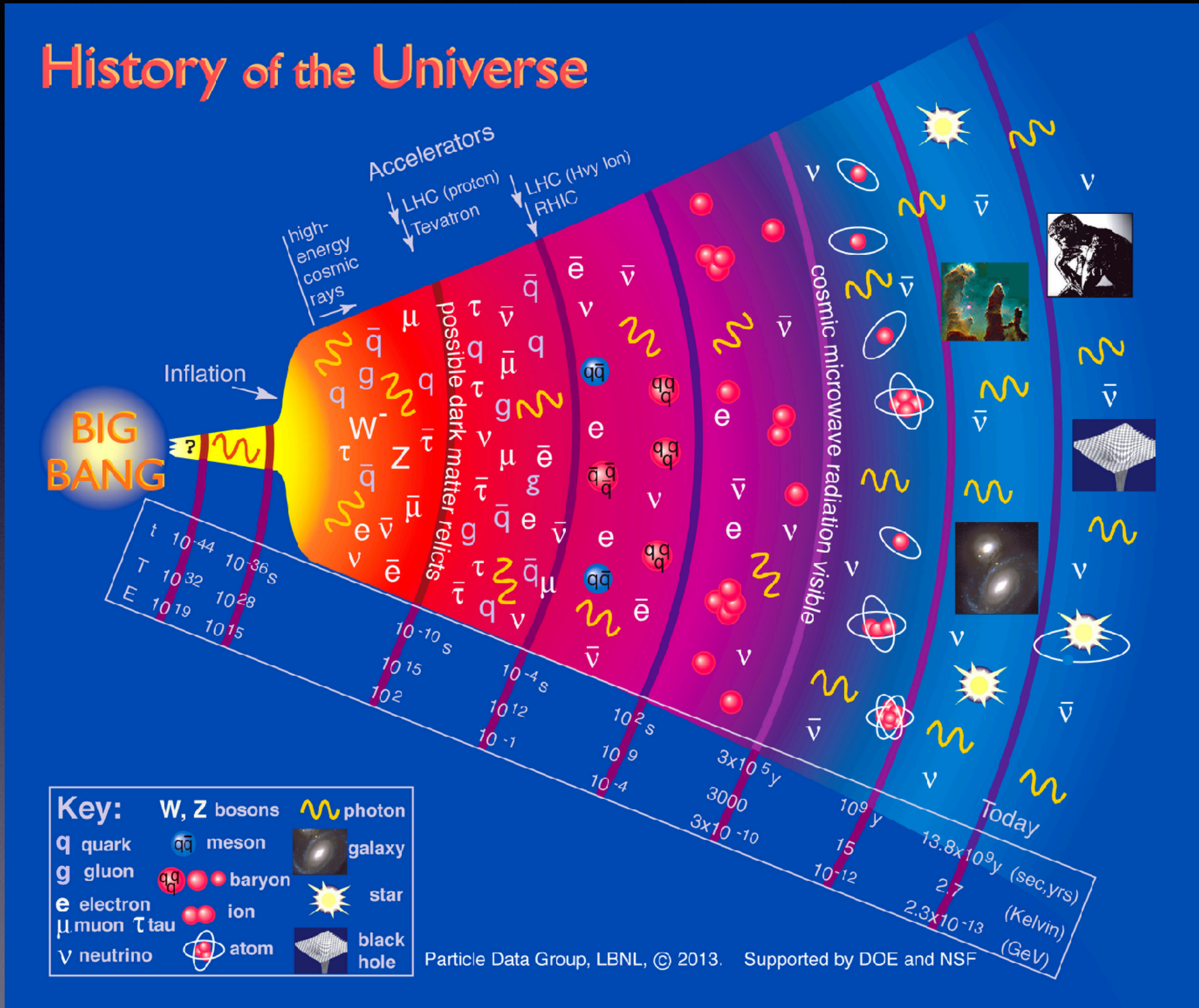


Inflation Potential:

$$V^{1/4} \approx (r/0.01)^{1/4} \times 10^{16}\ \text{GeV}$$

Detecting (degree-scale) B-mode can be a direct evidence for inflation!

History of the Universe (Particle Physics ver.)



Cosmological number density of neutrinos (per flavour):

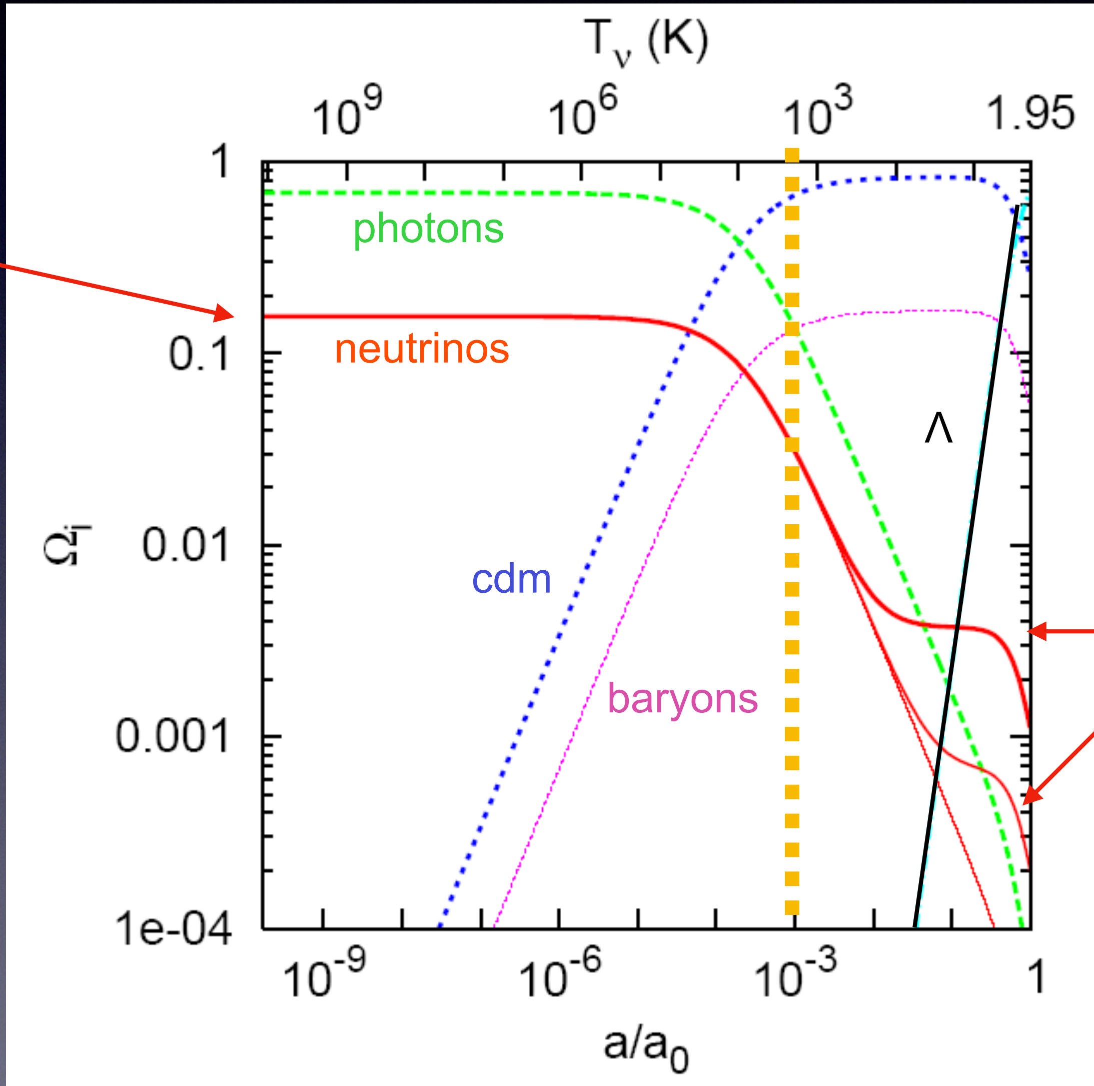
$$n_\nu = \frac{3}{11} n_\gamma$$ ← photon

$$\sim \frac{113}{a^3} \ \text{cm}^{-3}$$

Neutrinos in the Energy Densities of the Universe

Neutrinos are massive!

Relativistic in the early Universe!



Significant fraction of energy density should have significant effect on the evolution of the Universe

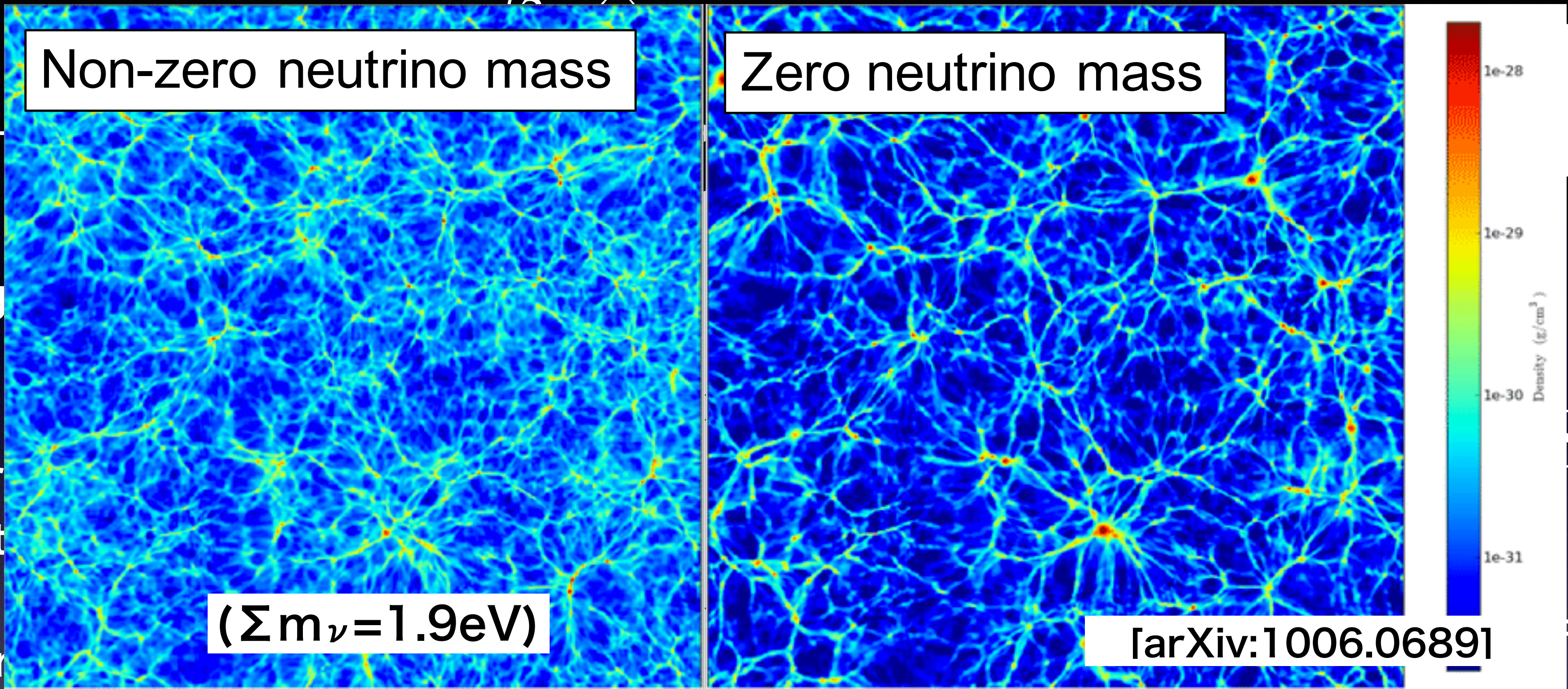
Becoming non-relativistic matter in the later time

$$\Omega_\nu h^2 \sim \frac{\sum m_\nu}{93 \text{ eV}}$$

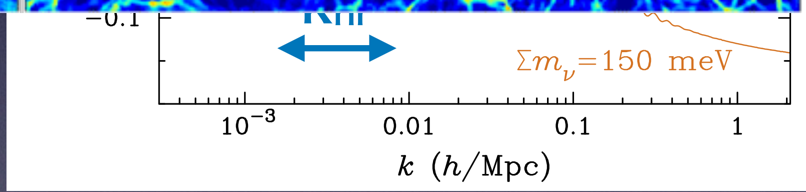
(today)

[Lesgourgues & Pastor, 2012]

Neutrino Free-Streaming Effect



Neutr
growt
scale
strea
density still contributes to the expansion rate of the Universe.



$8f_\nu$

$= \frac{\Omega_\nu}{\Omega_m}$

Abazajian et al. (2015)

Neutrino mass effect appears for smaller scale than the free-streaming scale of neutrinos transitioning into non-relativistic region.

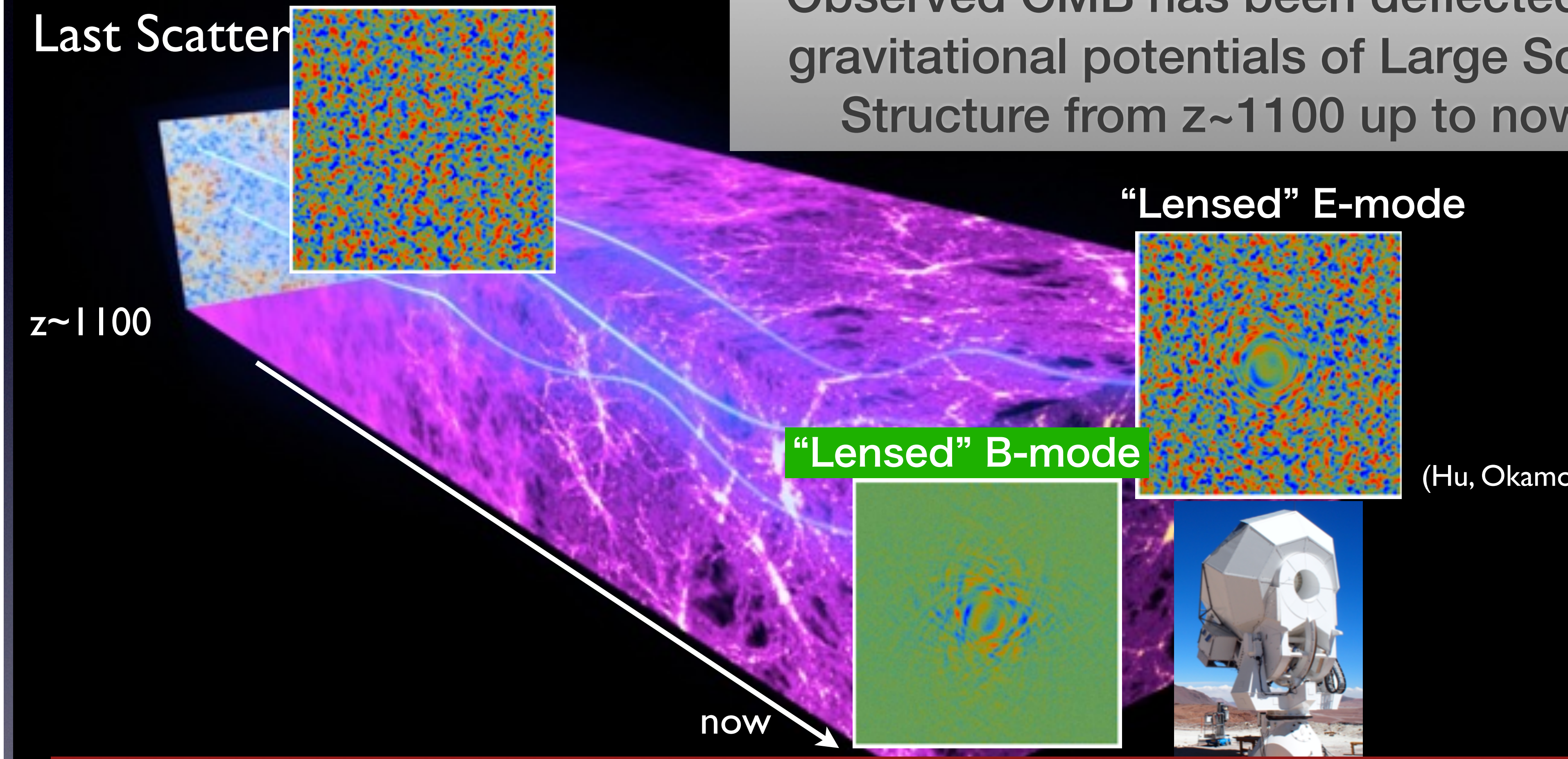
$$k > k_{\rm nr} \sim 0.003 \left(\frac{\Omega_m}{0.3}\frac{m_\nu}{0.05\,\rm eV}\right)^{1/2} h/\rm Mpc$$

Large-scale structure and CMB lensing

Weak lensing effect appears as a secondary effect on CMB.

(image credit: ESA)

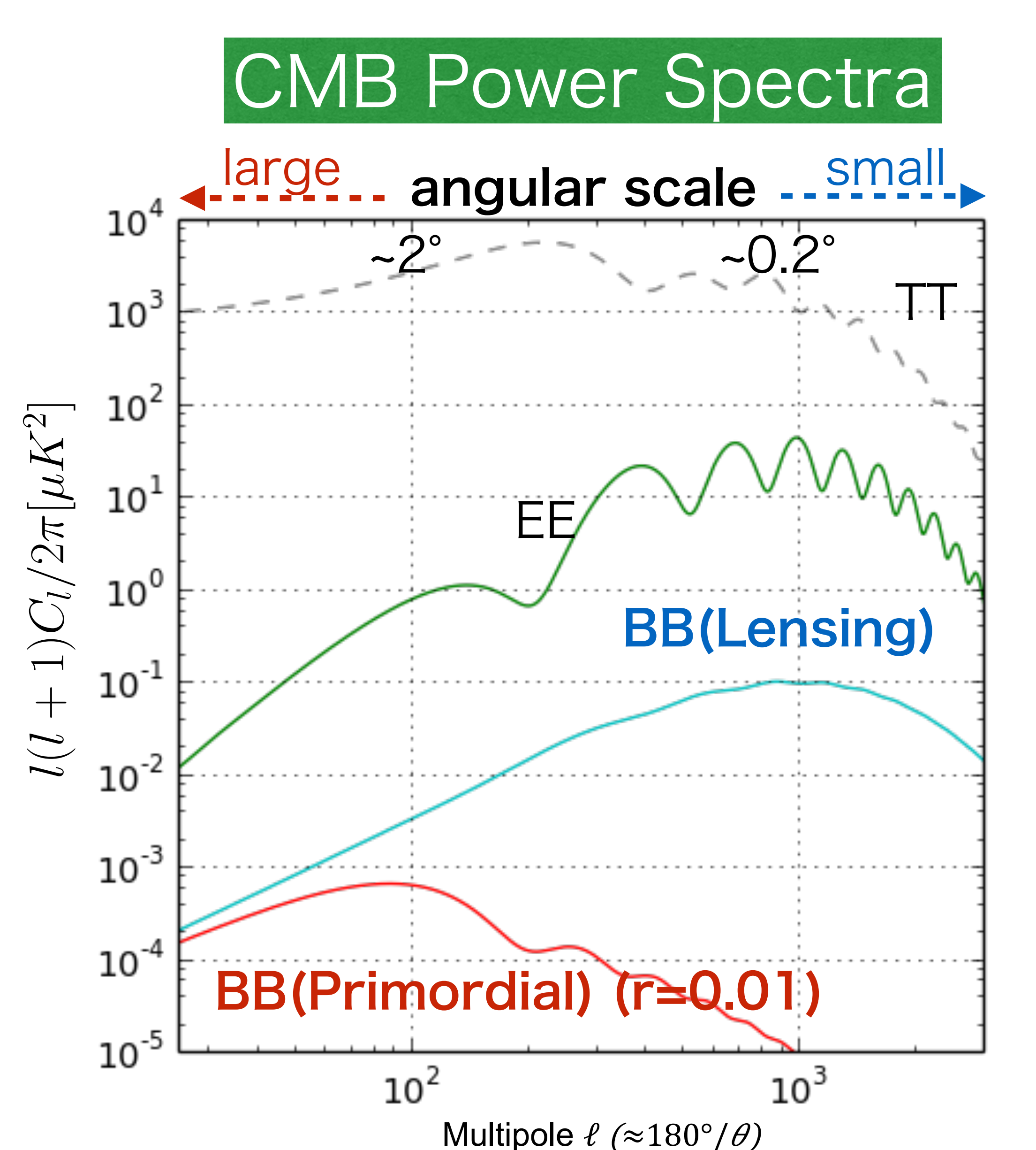
Observed CMB has been deflected by gravitational potentials of Large Scale Structure from z~1100 up to now.



(Hu, Okamoto 2002)

At sub-degree scale, weak lensing signal can be a dominant signal source for CMB B-mode polarization.

CMB B-mode Power Spectrum by Weak Lensing

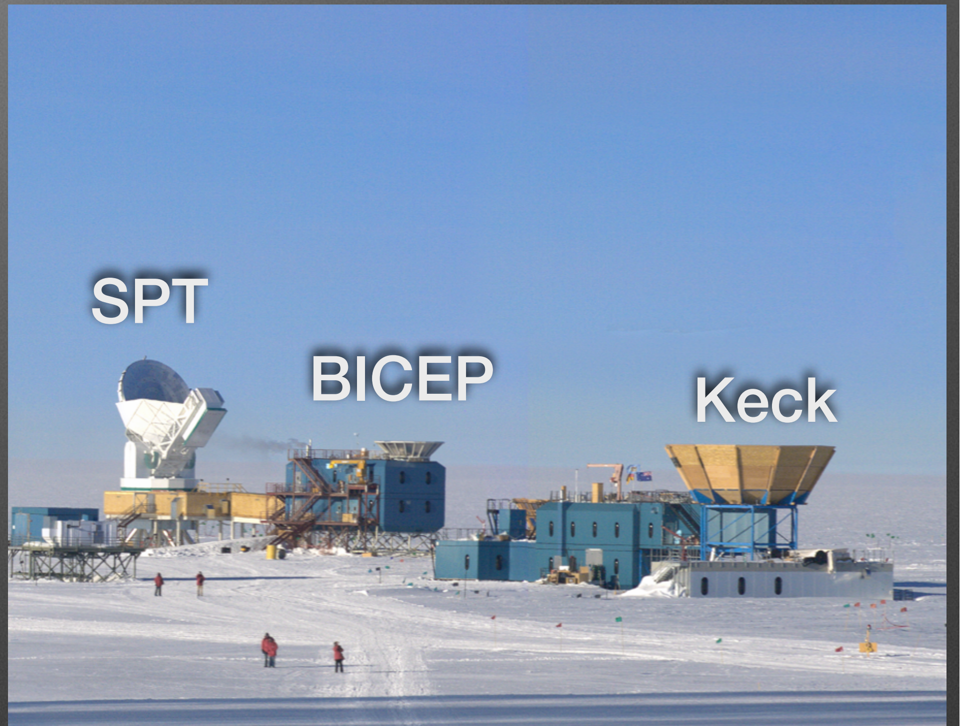


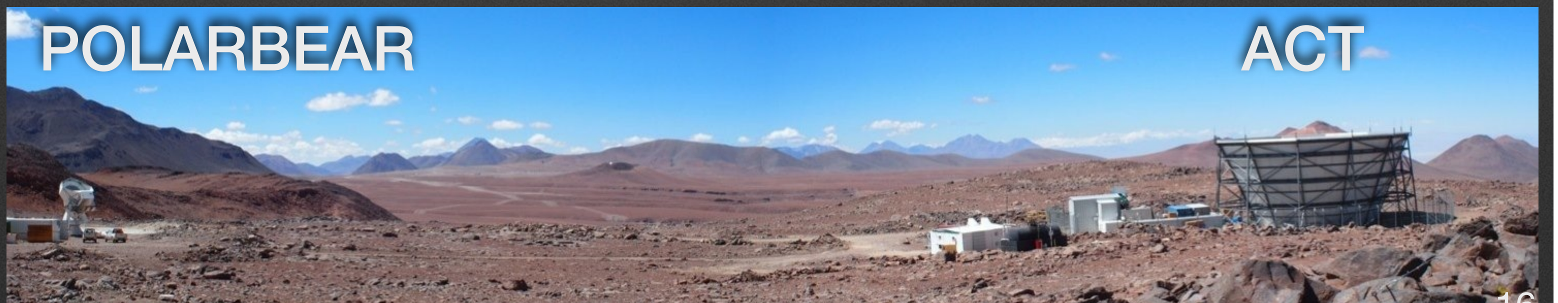
- **Lensing signal is the primary signal at sub-degree scale for B-modes.**
  - **Measurement by CMB temperature is already limited by cosmic variance up to very high-multipole.**
  - **Potentially, B-mode measurement can do much better lensing measurement by improving SNR.**
- To measure lensing, we need a high angular resolution optics

Polarized, high SNR and high angular resolution experiment is needed for a better measurement of neutrino mass by CMB!

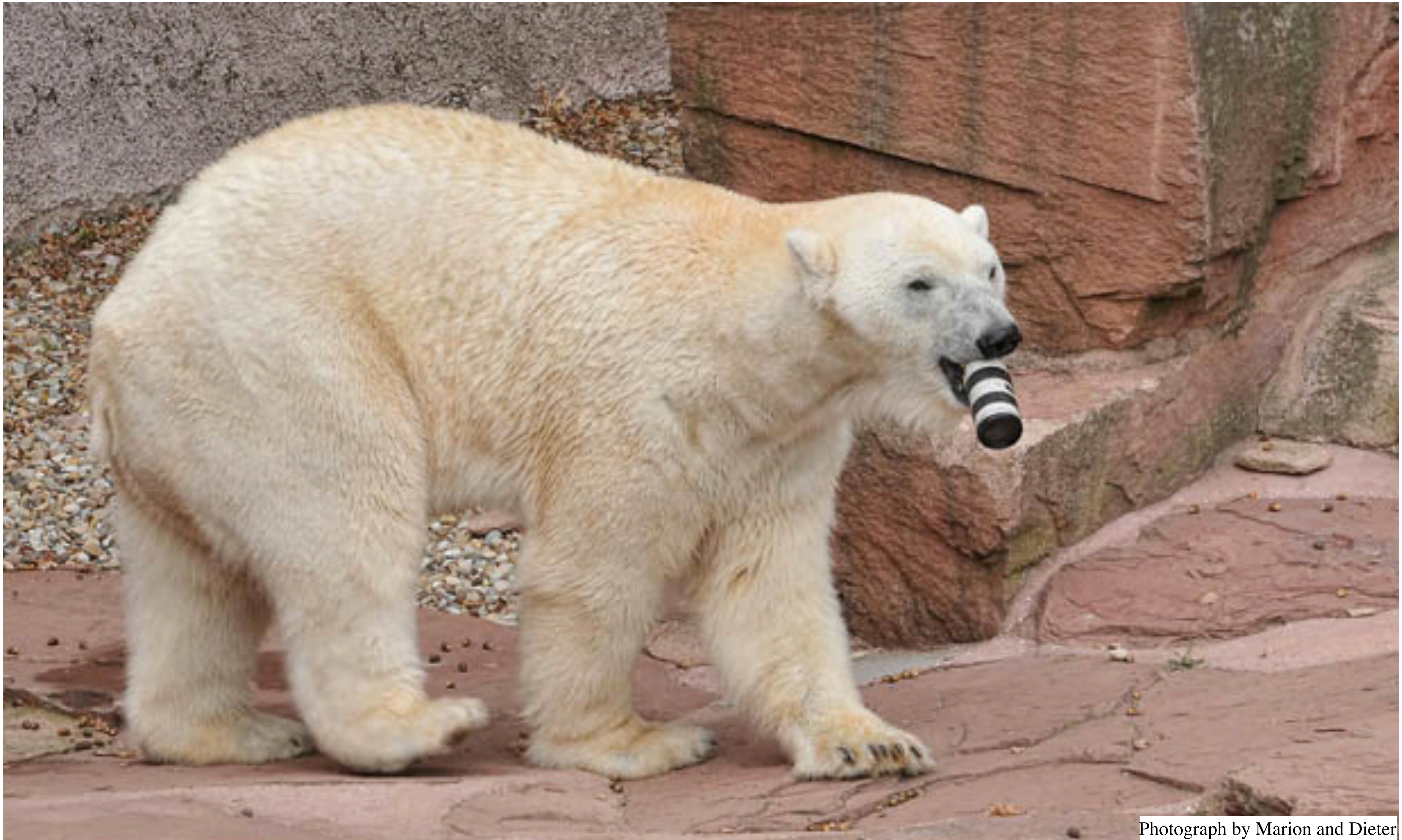
CMB polarization experiments

- Satellite: PLANCK
- Balloon-borne: EBEX, SPIDER
- South Pole
  - BICEP and Keck Array
  - SPTpol → SPT-3G
- Atacama Desert, Chile
  - POLARBEAR → Simons Array
  - ACTPol → Advanced ACTPol
  - CLASS





CMB lensing measurement by POLARBEAR



Photograph by Marion and Dieter

POLARBEAR Experiment is...

- A ground-based CMB polarization experiment in the Atacama desert in Chile
  - at 5,200m altitude
- Observing since 2012
- Has spectral sensitivity at 150 GHz

POLARBEAR Collaboration

International collaboration from ~8 countries, ~100 researchers

POLARBEAR Collaboration

UC Berkeley
Shawn Beckman
Darcy Barron
Yuji Chinone
Ari Cukierman
Tijmen de Haan
Neil Goeckner-Wald
John Groh
Charles Hill
William Holzapfel
Oliver Jeong
Adrian Lee
Dick Plambeck
Chris Raum
Paul Richards
Aritoki Suzuki
Ben Westbrook

UC Los Angeles
Nathan Whitehorn

CU Boulder
Nils Halverson
Greg Jaehnig
Hayley Roberts

Católica (PUC)
David Boettger
Rolando Dunner

UC San Diego
Kam Arnold
Kevin Crowley
Tucker Elleflot
George Fuller
Nicholas Galitzki
Logan Howe
Brian Keating
David Leon
Lindsay Lowry
Frederick Matsuda
Martin Navaroli
Gabriel Rebeiz
Max Silva-Feaver
Praween Siritanasak
Grant Teply
Calvin Tsai
Alex Zahn

Laboratoire Astroparticule & Cosmologie
Dominic Beck
Josquin Errard
Maude Le Jeune
Radek Stompor

U Chile
Mario Aguilar

KEK
Yoshiki Akiba
Takaho Hamada
Masaya Hasegawa
Masashi Hazumi
Yuto Minami
Haruki Nishino
Yuuko Segawa
Satoru Takakura
Sayuri Takatori
Daiki Tanabe
Takayuki Tomaru

Kyoto U.
Shunsuke Adachi
Osamu Tajima

U. Melbourne
Christian Reichardt
Federico Bianchini
Anh Pham

SISSA
Carlo Baccigalupi
Nicoletta Krachmalnicoff
Davide Poletti
Giuseppe Puglisi

U of Sussex
Julien Peloton

McGill University
Matt Dobbs
Adam Gilbert
Josh Montgomery

Dalhousie
Scott Chapman
Colin Ross
Kaja Rotermund
Alexei Tikhomirov

Lawrence Berkeley NL
Julian Borrill
Reijo Keskitalo
Theodore Kisner
Akito Kusaka
Eric Linder
Alex Madurowicz
Blake Sherwin
Raymond Tat

Kavli IPMU
Daisuke Kaneko
Nobuhiko Katayama
Tomotake Matsumura

Institute D'Astrophysique Spatiale
Giulio Fabbian

U Manchester
Gabriele Coppi
Andrew May
Lucio Piccirillo

UC Irvine
Chang Feng

Cardiff University
Peter Ade

NASA Goddard
Nathan Miller

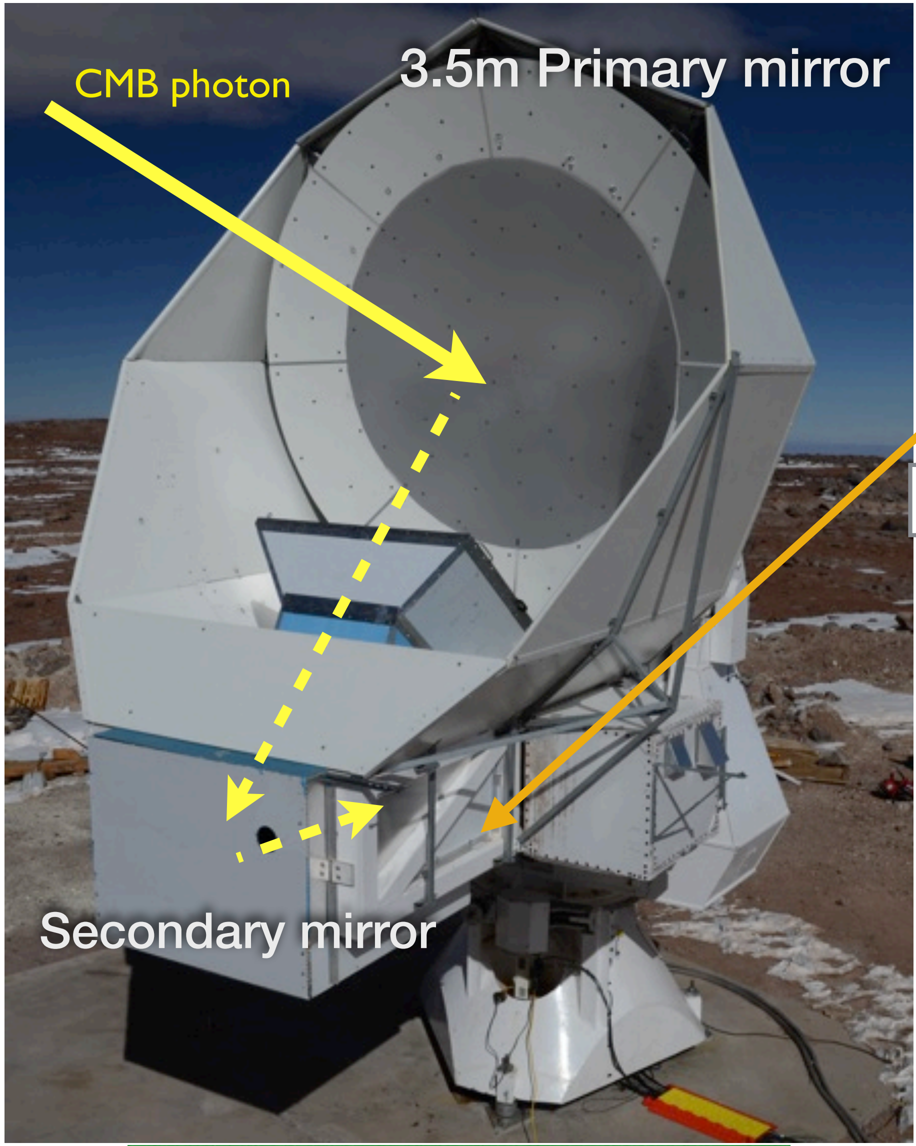
Argonne NL
Amy Bender

Imperial College
Andrew Jaffe
Daisy Mak

C Computational Astrophysics
Stephen Feeney

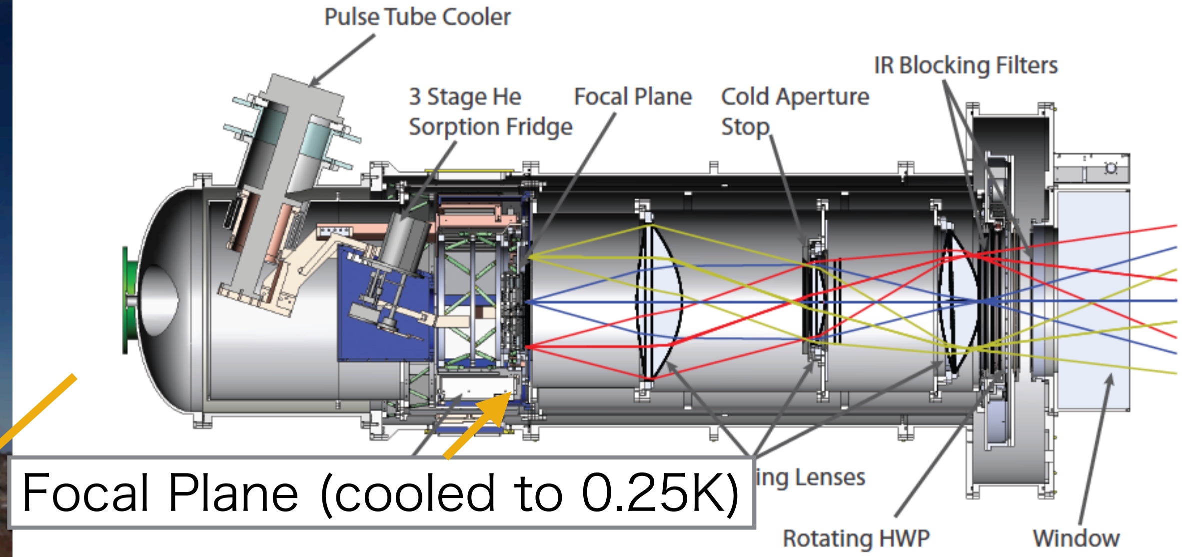
And many more in years past…

Telescope and Receiver



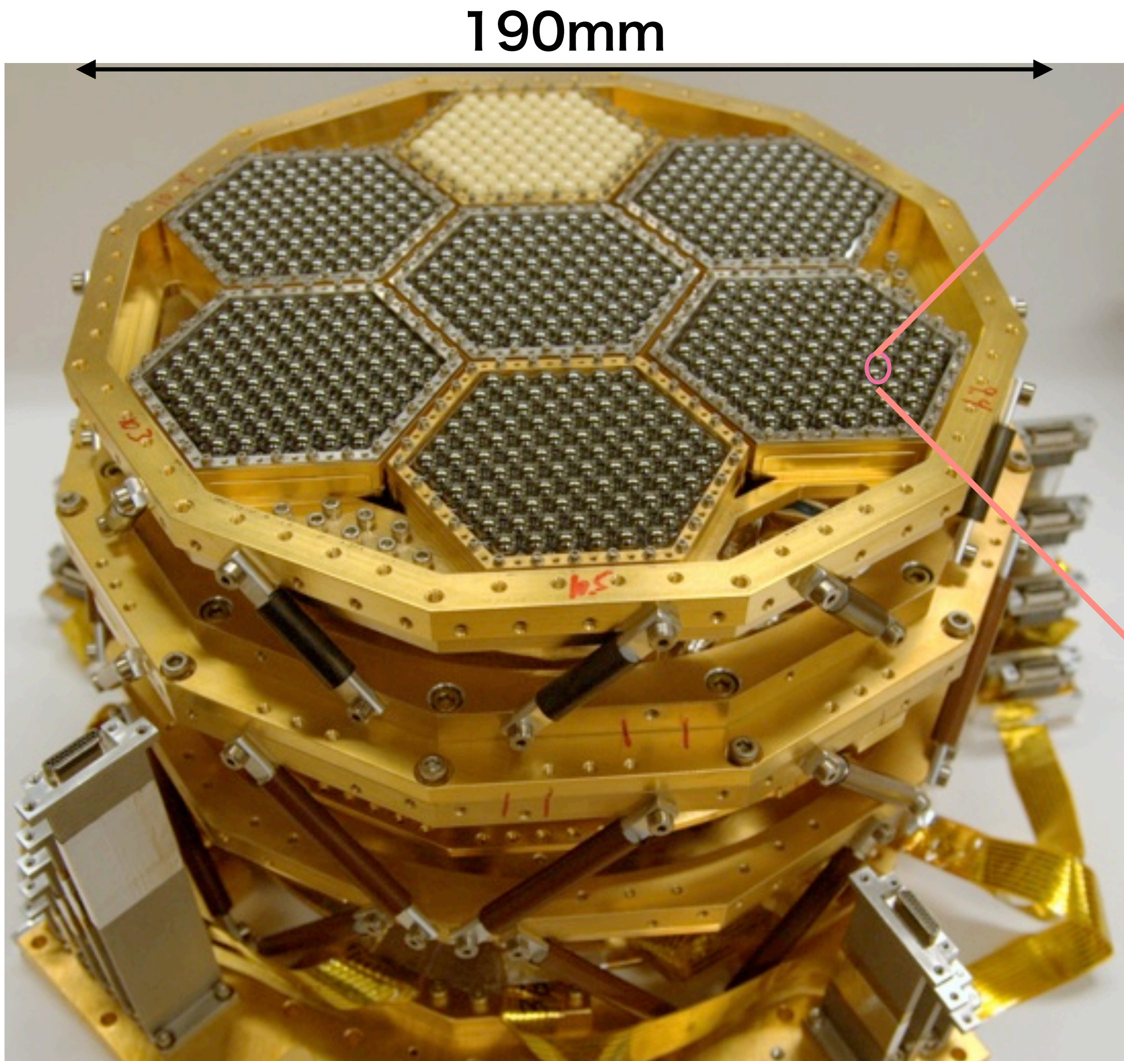
Huan Tran Telescope

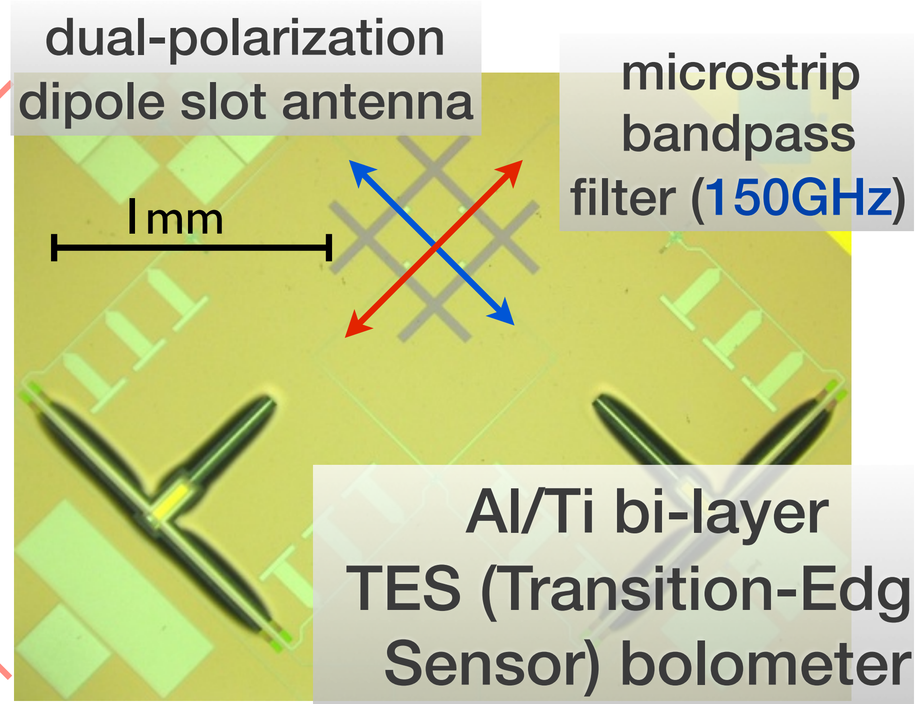
Receiver cryostat

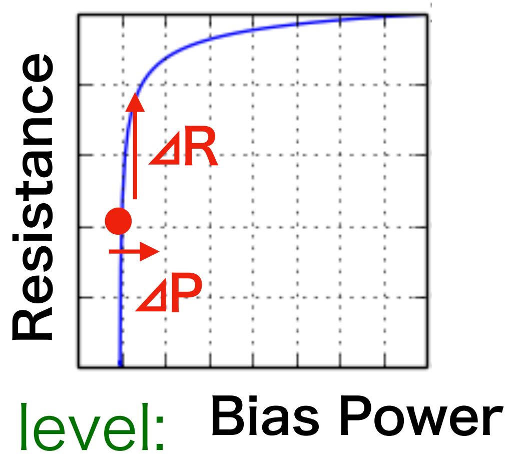


- Primary 2.5m precision-machined mirror
- 3.5 arcmin (FWHM) resolution
- **Designed to measure both primordial and lensing B-modes**

Focal Plane Detectors







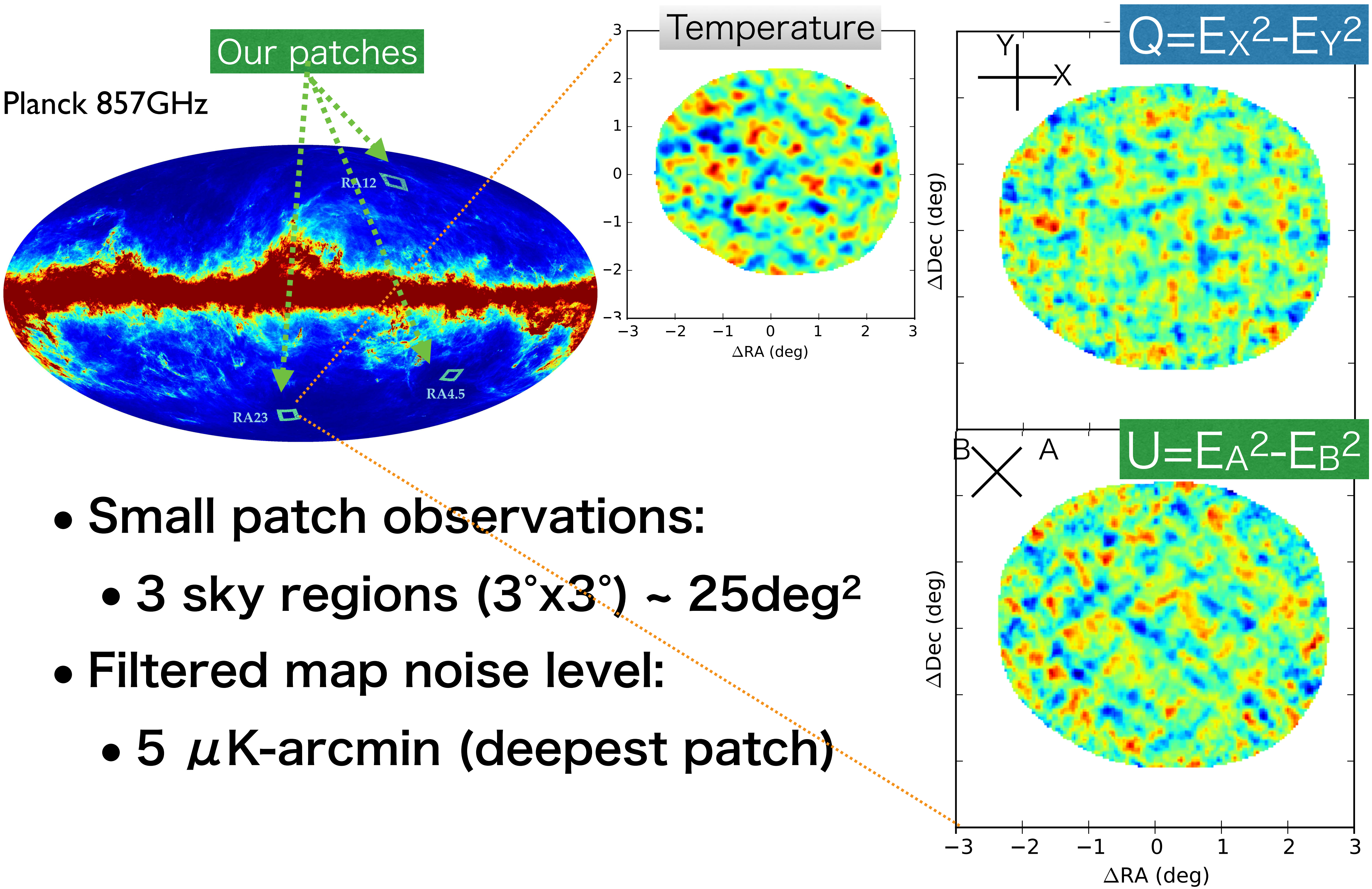
- 2 bolometers in a pixel
- 637 pixels in a array
- 1274 bolometers

Noise level:

$550\mu K_{CMB}\sqrt{s}$ (per bolometer)

$23\mu K_{CMB}\sqrt{s}$ (per array)

1st+2nd Season Observing Sky Patches



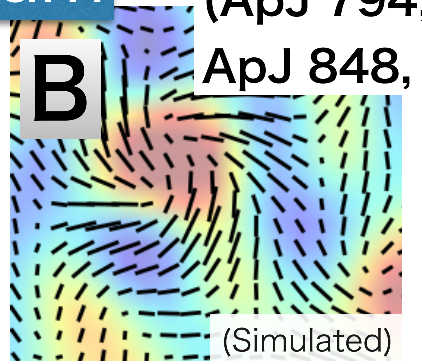
- Small patch observations:
  - 3 sky regions (3°x3°) ~ 25deg^2
- Filtered map noise level:
  - 5 μK-arcmin (deepest patch)

CMB lensing measurements w/ POLARBEAR

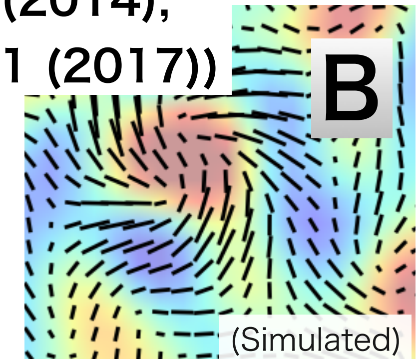
CMB B-mode auto power spectrum

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

(ApJ 794, 2 (2014), ApJ 848, 121 (2017))



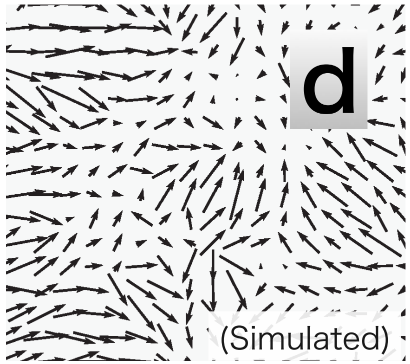
X



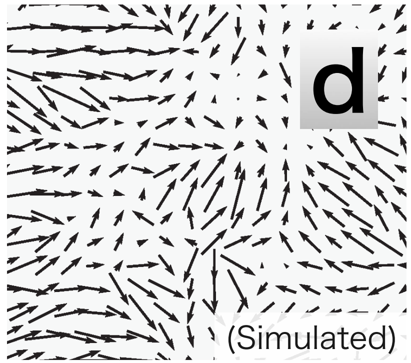
Lensing deflection power spectrum

First evidence for gravitational lensing with CMB polarization data alone

(PRL 113, 021301 (2014))



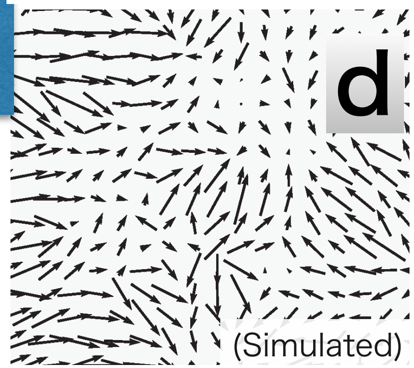
X



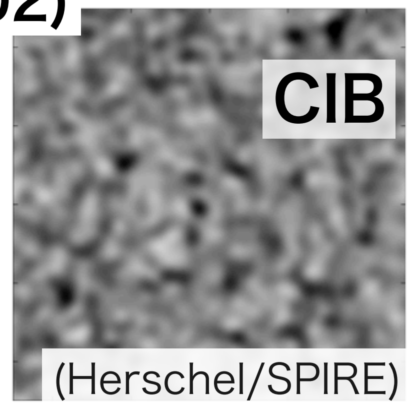
Cross correlation of lensing deflection with Cosmic Infrared Background

Rejection of null-lensing hypothesis at 4.0σ

(PRL 112, 131302)

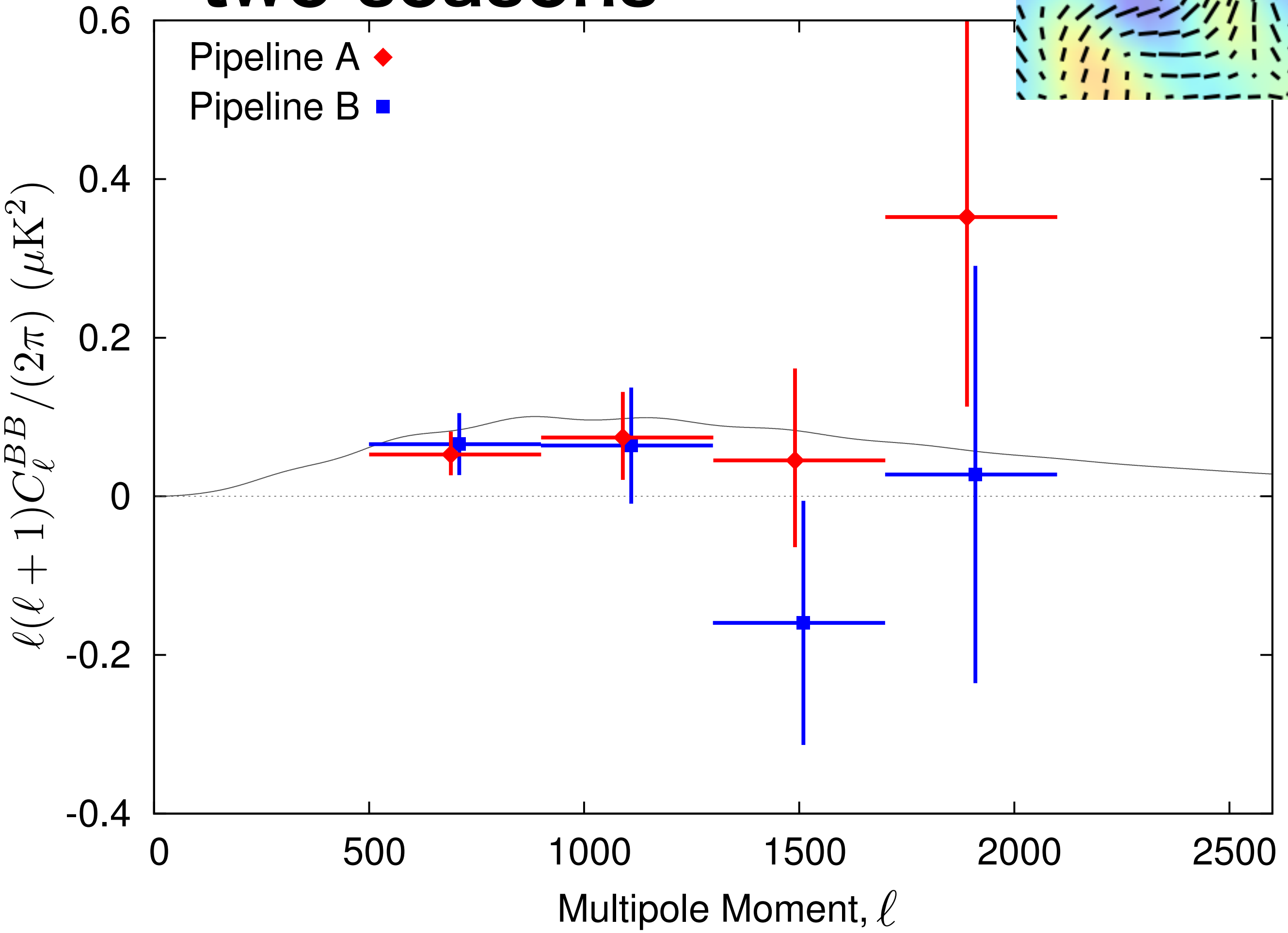


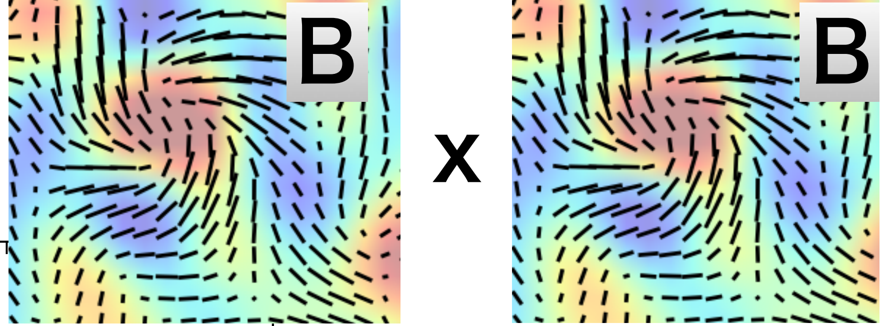
X



Measurement of lensing B-modes with three different methods

Cl_{BB} result from the first two seasons

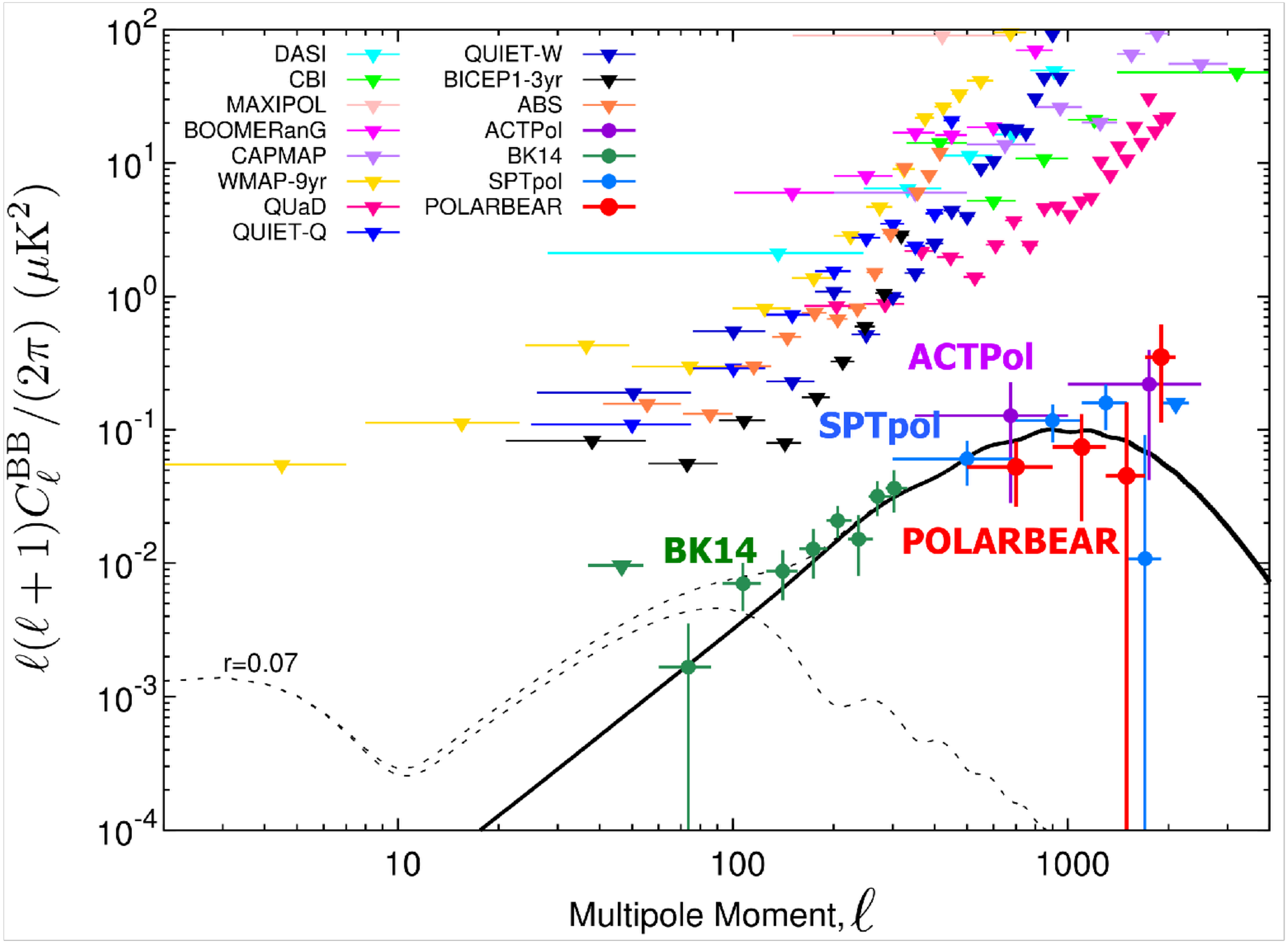




ApJ 848, 121 (2017)

- **3.1 σ rejection of no B-mode hypothesis**
- Lensing amplitude (relative to Planck 2015 best-fit model prediction):
  - $A_L = 0.60^{+0.26}_{-0.24}$ (stat.)$^{+0.00}_{-0.04}$ (inst. sys.) ± 0.14 (foreground) ± 0.04 (multi.)

Current status of CMB B-mode measurements



(Figure by Y. Chinone)

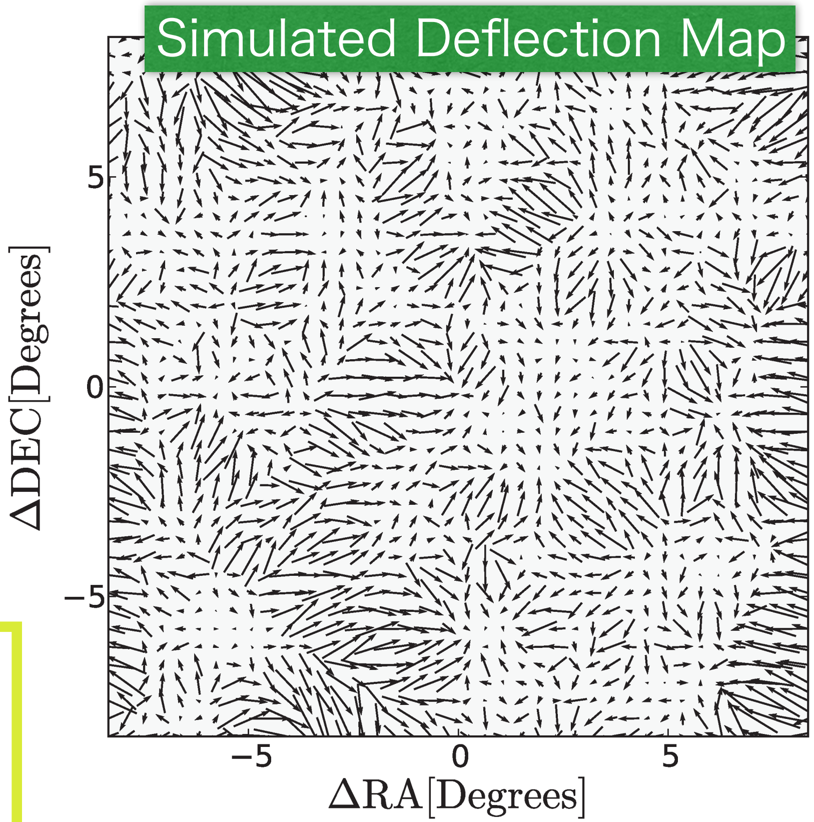
Another method to measure weak lensing

Observed CMB polarization

$$(Q+iU)(\hat{\mathbf{n}}) = (\tilde{Q}+i\tilde{U})(\hat{\mathbf{n}}+\mathbf{d}(\hat{\mathbf{n}}))$$

~: primordial CMB deflection

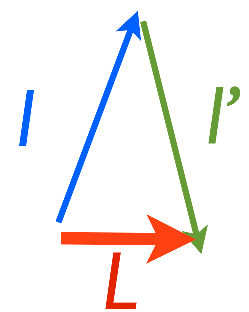
- Typical lensing deflection angle
  - a few arcmin
  - Coherent over ~2 deg. scale
- Deflection mixes E and B-mode
  - Producing B-mode at arcminute-scale
- **The deflection also induces correlation b/w different multipoles, l and l'.**



→ : 1 arc-minute

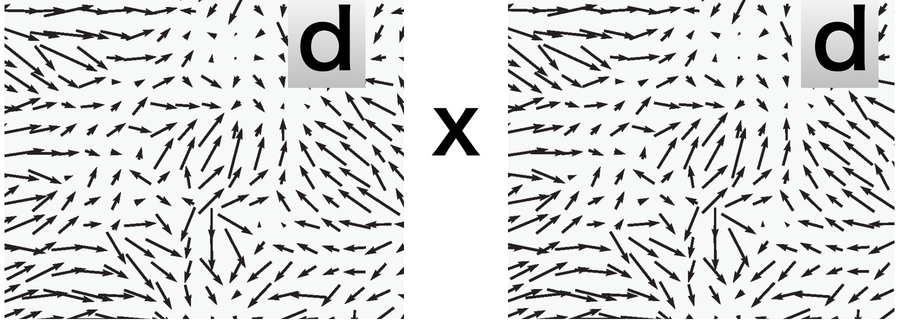
$$d_{EE}(\mathbf{L}) \propto \sum_{\mathbf{l}} E(\mathbf{l})E(\mathbf{l}')$$

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

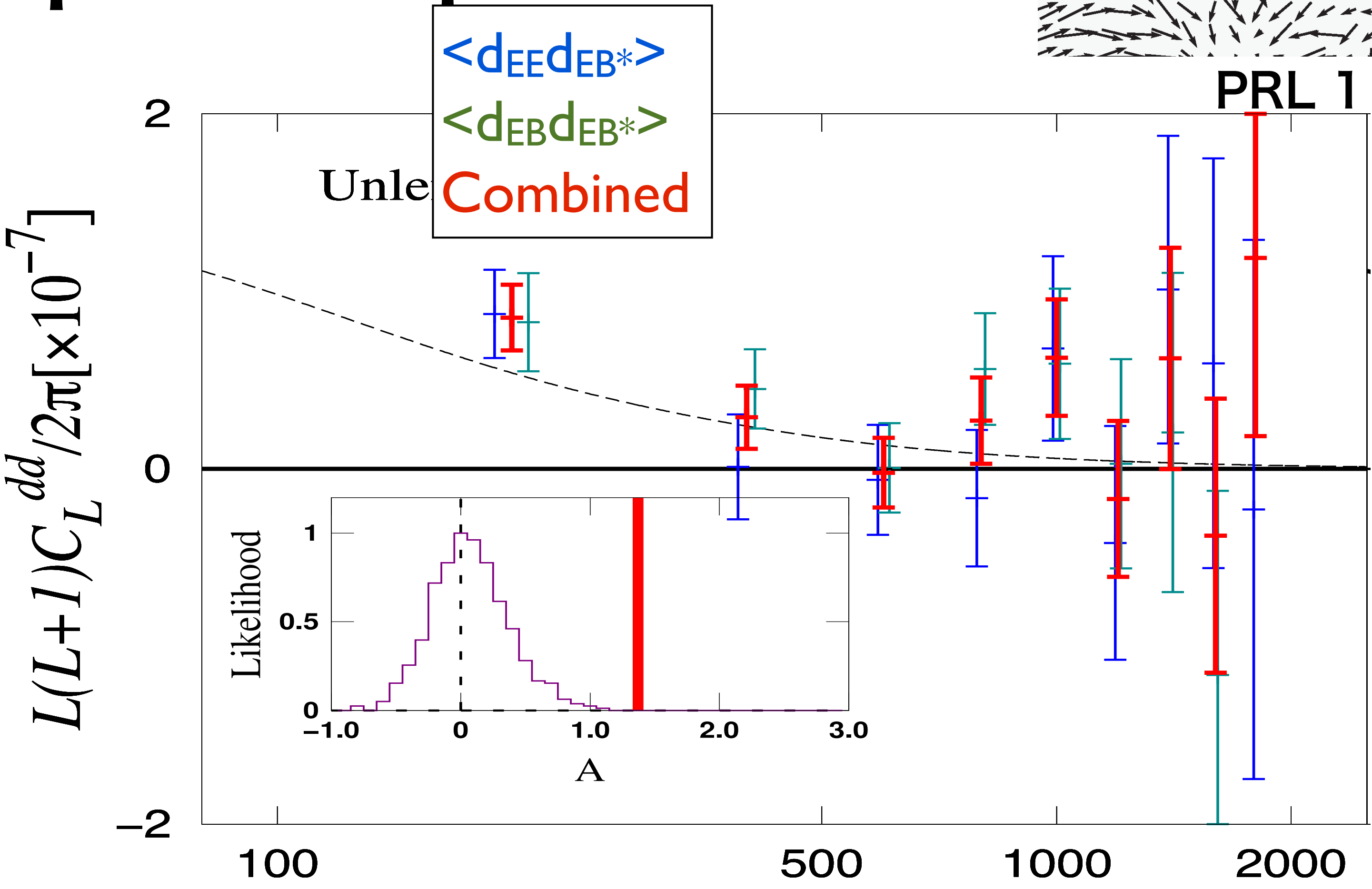


(Hu, Okamoto, 2002)

Lensing deflection power spectrum



PRL 113, 021301 (2014)



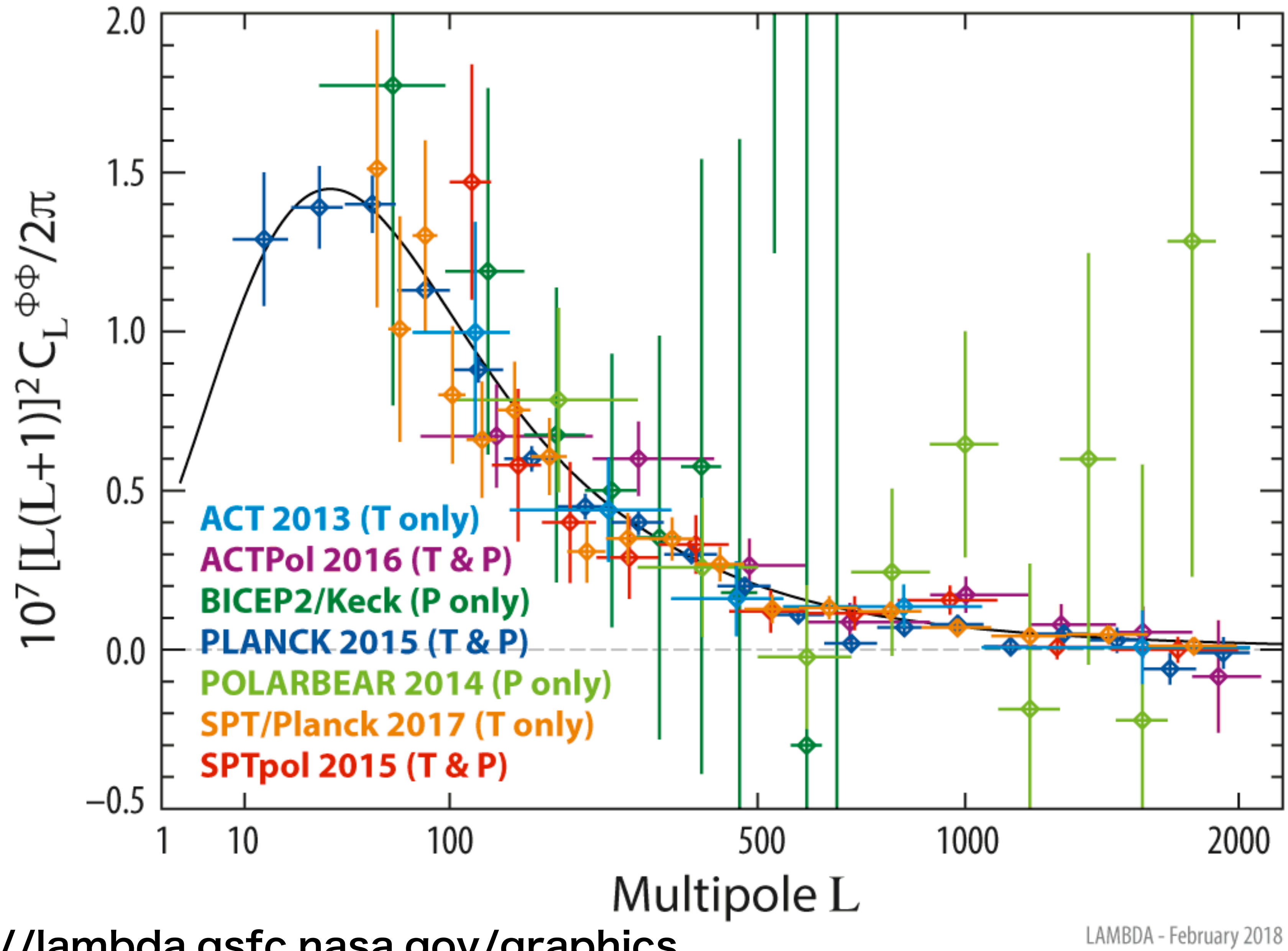
$A_L = 1.37 \pm 0.30(\text{stat.}) \pm 0.13(\text{sys.})$

(A_L = 1: WMAP-9yr ΛCDM)

Rejection of null hypothesis at 4.2σ

First evidence (in 2014) for gravitational lensing with CMB polarization alone

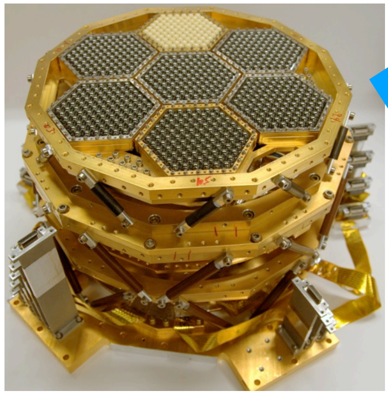
Current status of CMB lensing measurements

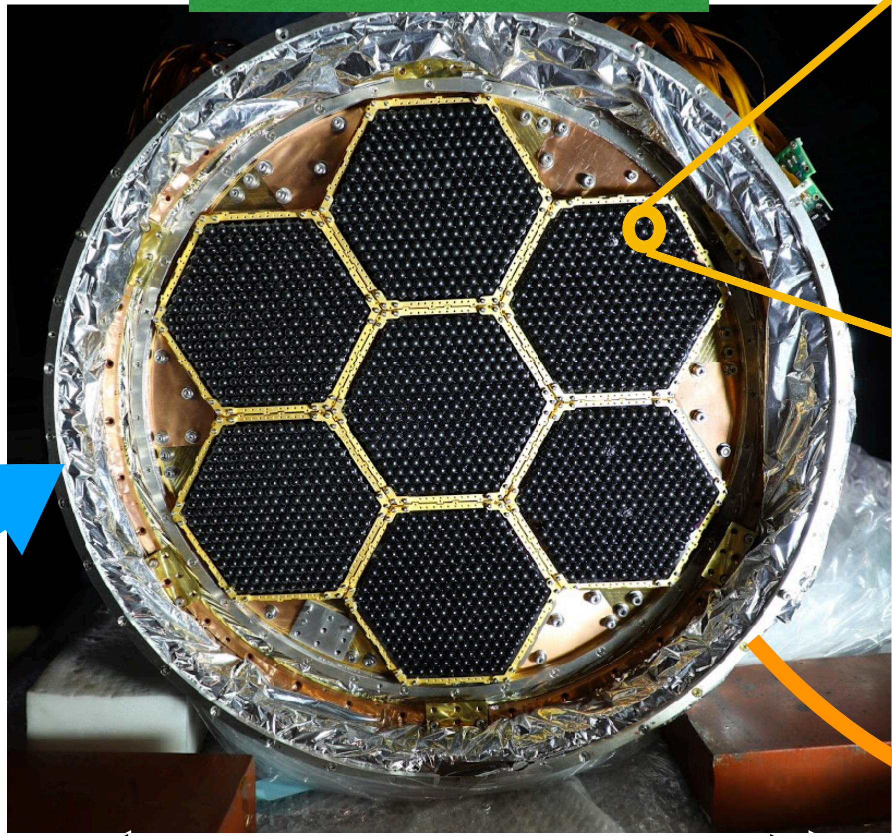


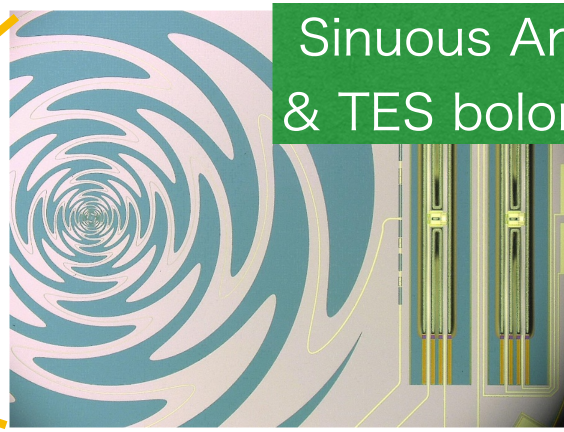
https://lambda.gsfc.nasa.gov/graphics

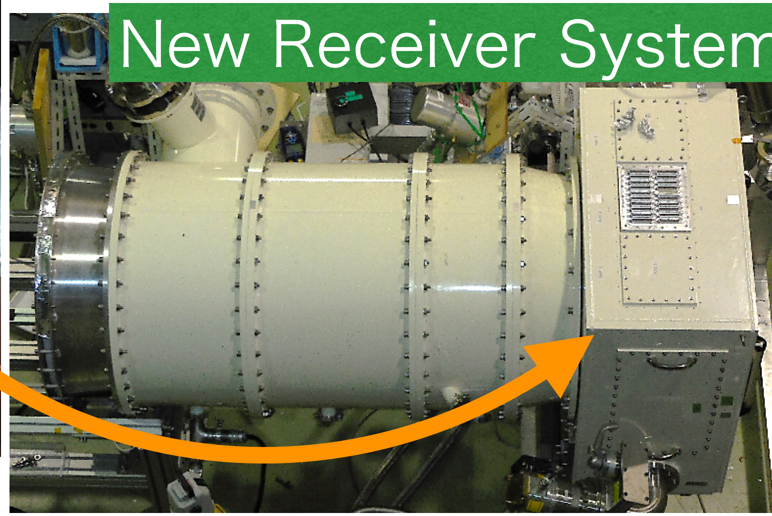
Next Generation Experiment: POLARBEAR-2 & Simons Array

POLARBEAR-2: New Generation Receiver







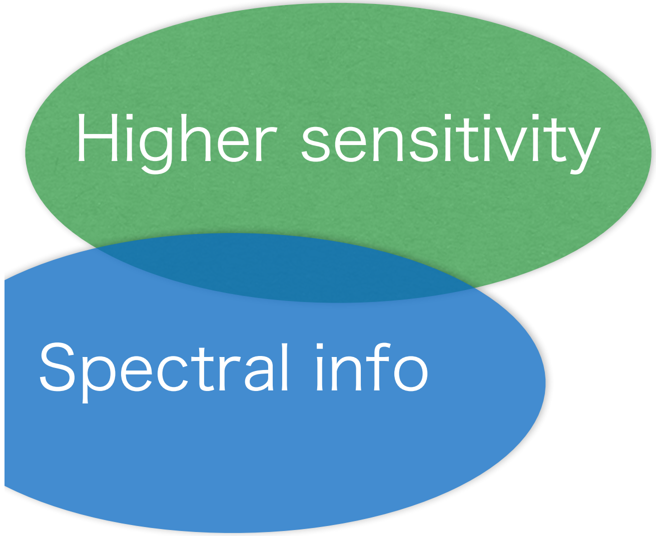


Higher sensitivity

Spectral info

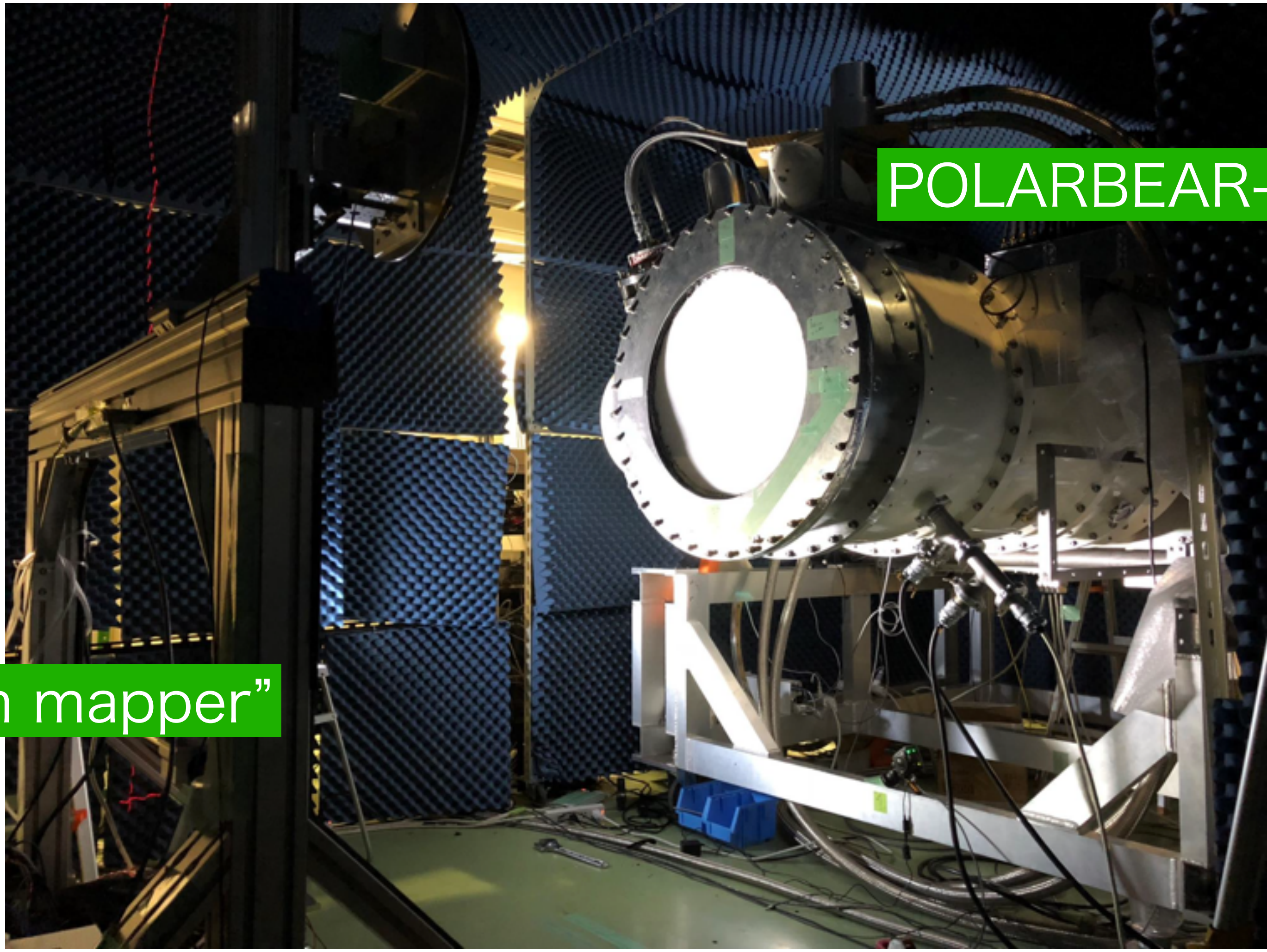
- 7,588 bolometers, 6 times more bolometers on a larger focal plane
- Di-chroic detector:
  - 90+150GHz for the first receiver
- Integration testings in progress

Simons Array: POLARBEAR-2x3



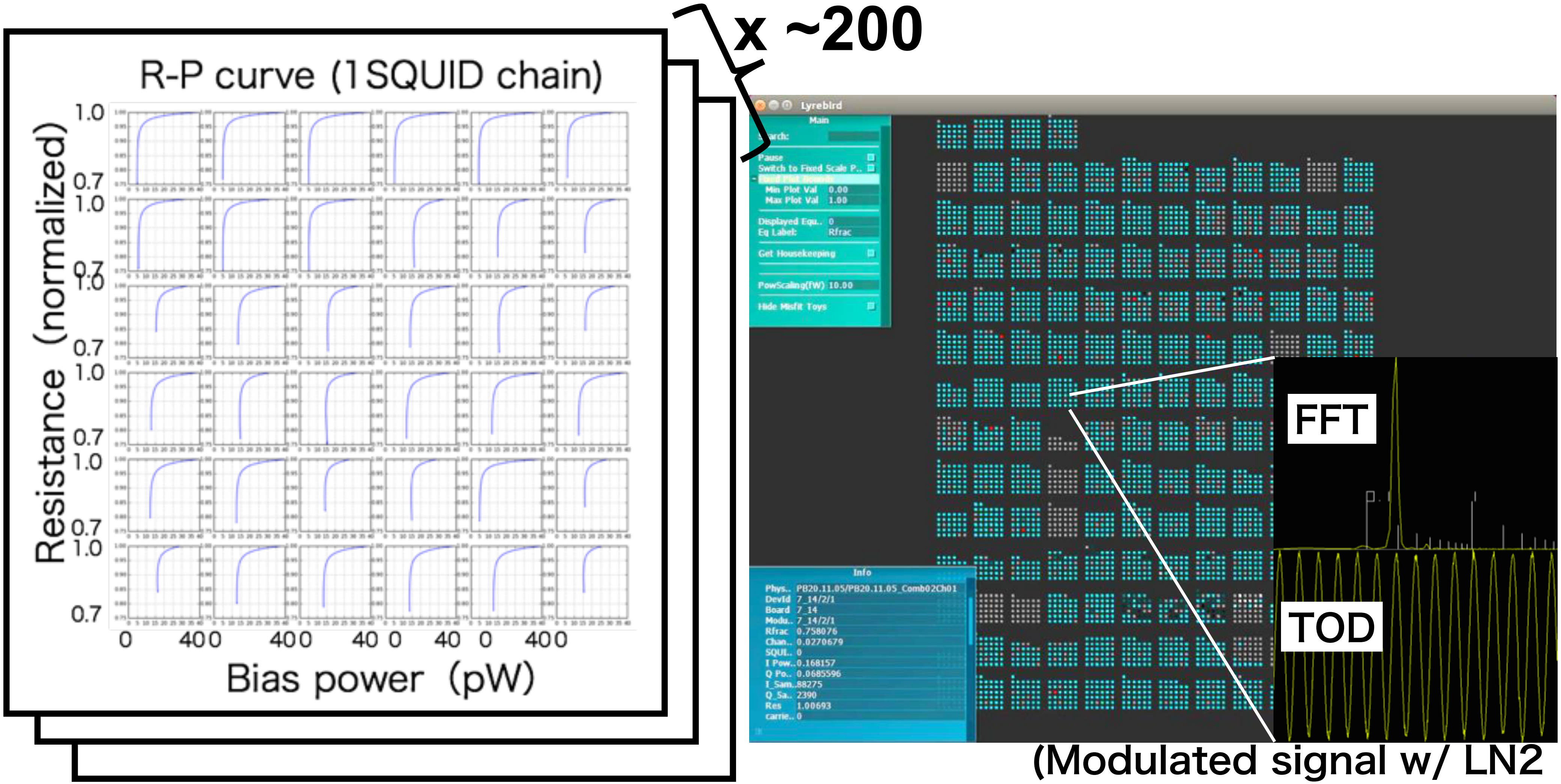
- Simons Array is a funded upgrade experiment of POLARBEAR.
- Constructed two new telescopes. Three telescopes in total.
- **4 frequency bands, ~22,000 bolometers in total**

POLARBEAR-2 Integration Testings in the KEK lab



- POLARBEAR-2 receiver system end-to-end integration testing is underway in the KEK lab in Japan.
- We are in the final stage of validation/characterization of the integrated system of detectors, readout, receiver optics, DAQ, etc.

POLARBEAR-2 receiver system is working

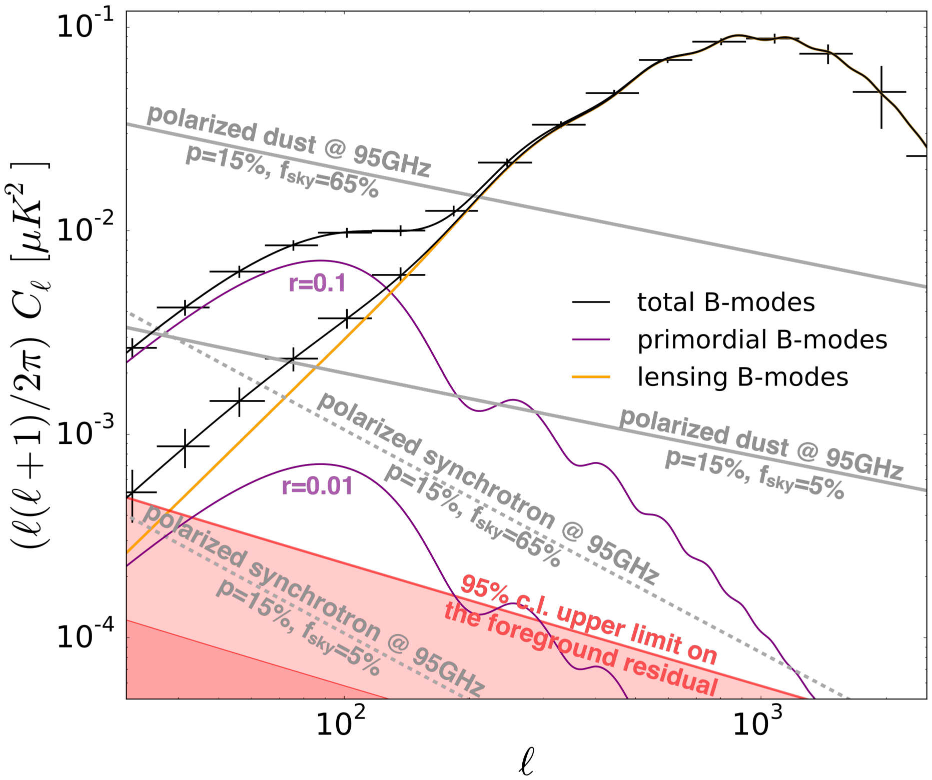


(Modulated signal w/ LN2 and a wire grid.)

- Successful operation of full-array scale detector and readout, observing clear responses from modulated optical signals.
- 1st receiver deployment in Chile in late this year.

Simons Array: Prospects for Sensitivity

B-mode Power Spectrum w/ Expected Foreground Level



- Three year Simons Array observation (w/ foreground subtraction by PLANCK 353GHz and C-BASS 5GHz)
  - **Primordial gravitational wave: $\sigma(r=0.1) \sim 6\times10^{-3}$**
  - **Sum of neutrino mass: $\sigma(\Sigma m_\nu)$=40meV (combined w/ DESI BAO)**

Current status of Cosmological Neutrino Mass Constraints

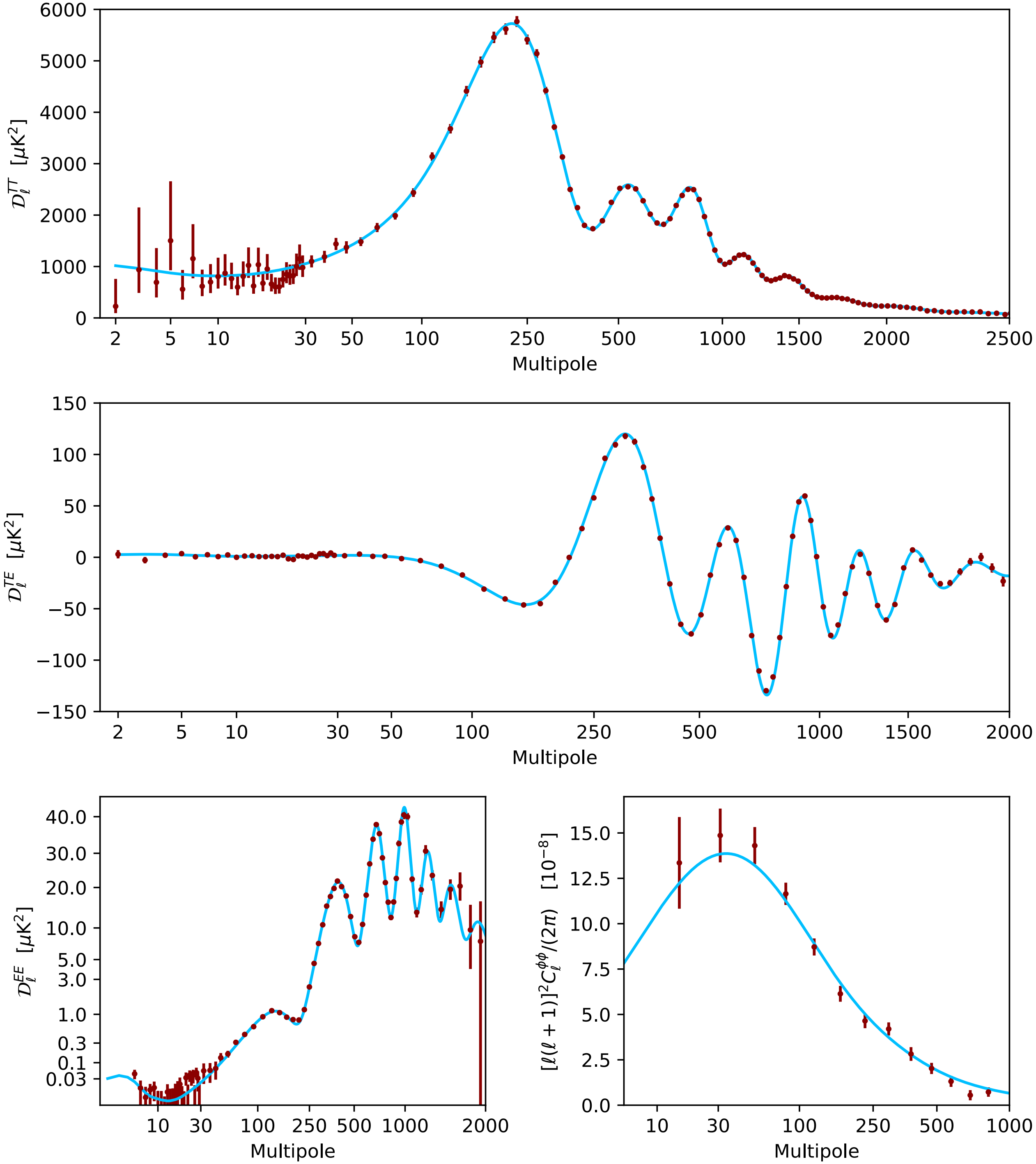
	Model	95% CL (eV)
CMB alone		
Pl15[TT+lowP]	ΛCDM+$\sum m_\nu$	< 0.72
Pl15[TT+lowP]	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.73
Pl16[TT+SimLow]	ΛCDM+$\sum m_\nu$	< 0.59
CMB + probes of background evolution		
Pl15[TT+lowP] + BAO	ΛCDM+$\sum m_\nu$	< 0.21
Pl15[TT+lowP] + JLA	ΛCDM+$\sum m_\nu$	< 0.33
Pl15[TT+lowP] + BAO	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.27
CMB + probes of background evolution + LSS		
Pl15[TT+lowP+lensing]	ΛCDM+$\sum m_\nu$	< 0.68
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.25
Pl15[TT+lowP] + $\rm P(k)_{DR12}$	ΛCDM+$\sum m_\nu$	< 0.30
Pl15[TT,TE,EE+lowP] + BAO+ $\rm P(k)_{WZ}$	ΛCDM+$\sum m_\nu$	< 0.14
Pl15[TT,TE,EE+lowP] + BAO+ $\rm P(k)_{DR7}$	ΛCDM+$\sum m_\nu$	< 0.13
Pl15[TT+lowP+lensing] + Lyα	ΛCDM+$\sum m_\nu$	< 0.12
Pl16[TT+SimLow+lensing] + BAO	ΛCDM+$\sum m_\nu$	< 0.17
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+Ω_k	< 0.37
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+w	< 0.37
Pl15[TT+lowP+lensing] + BAO	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	< 0.32
Pl15[TT,TE,EE+lowP+lensing]	ΛCDM+$\sum m_\nu$+5-params.	< 0.66

- Important to combine multiple cosmological probes to solve parameter degeneracies
- Combining next generation CMB and BAO measurements is expected to achieve sub-100meV sensitivity, which might make some interesting implications for the mass-hierarchy.

Planck team just released the final(?) results two days ago…

Summary table from PDG2018

Final data release from Planck!



No B-mode (auto-)power spectra are shown (yet).

Current status of Cosmological Neutrino Mass Constraints

	Model	95% CL (eV)
CMB alone		
Planck2018 (TT+ lowE)	ΛCDM+$\sum m_\nu$	< 0.54
Pl15[TT+lowP]	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	
Pl16[TT+SimLow]	ΛCDM+$\sum m_\nu$	< 0.59
Planck2018 (TT+TE+EE lowE)		< 0.26
Planck2018 (TT+TE+EE+lowE+BAO)	ΛCDM+$\sum m_\nu$	< 0.21
	ΛCDM+$\sum m_\nu$	< 0.13
	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	
CMB + probes of background evolution + LSS		
Planck2018 (TT+TE+EE+lowE+BAO+lensing)	m_ν	< 0.68
	m_ν	< 0.12
	m_ν	
	m_ν	< 0.14
Pl15[TT,TE,EE+lowP] + BAO+ P(k)$_{\rm DR7}$	ΛCDM+$\sum m_\nu$	< 0.13
Pl15[TT+lowP+lensing] + Lyα	ΛCDM+$\sum m_\nu$	< 0.12

Message from Planck team:
“95% limit of Σm_ν<0.12eV starts to put pressure on the inverted mass hierarchy”

- Important to combine multiple cosmological probes to solve parameter degeneracies
- Combining next generation CMB and BAO measurements is expected to achieve sub-100meV sensitivity, which might make some interesting implications for the mass-hierarchy.

Summary table from PDG2018

Summary

- CMB and Neutrino mass
  - Because of non-zero mass and significant abundances in the Universe, neutrinos should have made characteristic effects in the evolution of the Universe.
  - The observation of CMB have been one of the most important cosmological tools to measure those signatures.
  - (Sum of) neutrino mass sensitivity by CMB weak lensing can be improved by the next generation CMB polarization experiments and is expected to reach below 100 meV level.
  - Latest results from Planck w/ BAO: 0.12 eV (95% C.L.)
- CMB lensing measurements by POLARBEAR
  - B-mode from weak lensing has been measured by several experiments including POLARBEAR.
- Next generation experiment: POLARBEAR-2 / Simons Array
  - Will deploy late this year. Stay tuned.