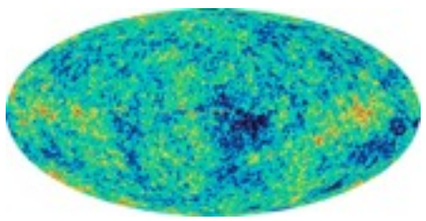
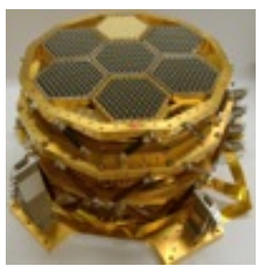
Measuring cosmic microwave background polarization with POLARBEAR

Darcy Barron
UC San Diego

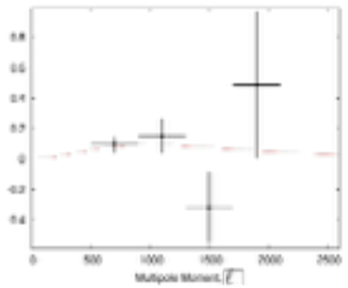
Outline

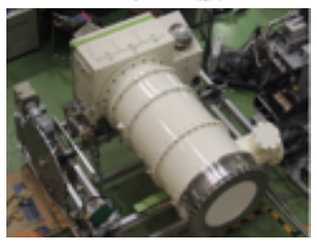


- Scientific motivation



- POLARBEAR-1 instrument





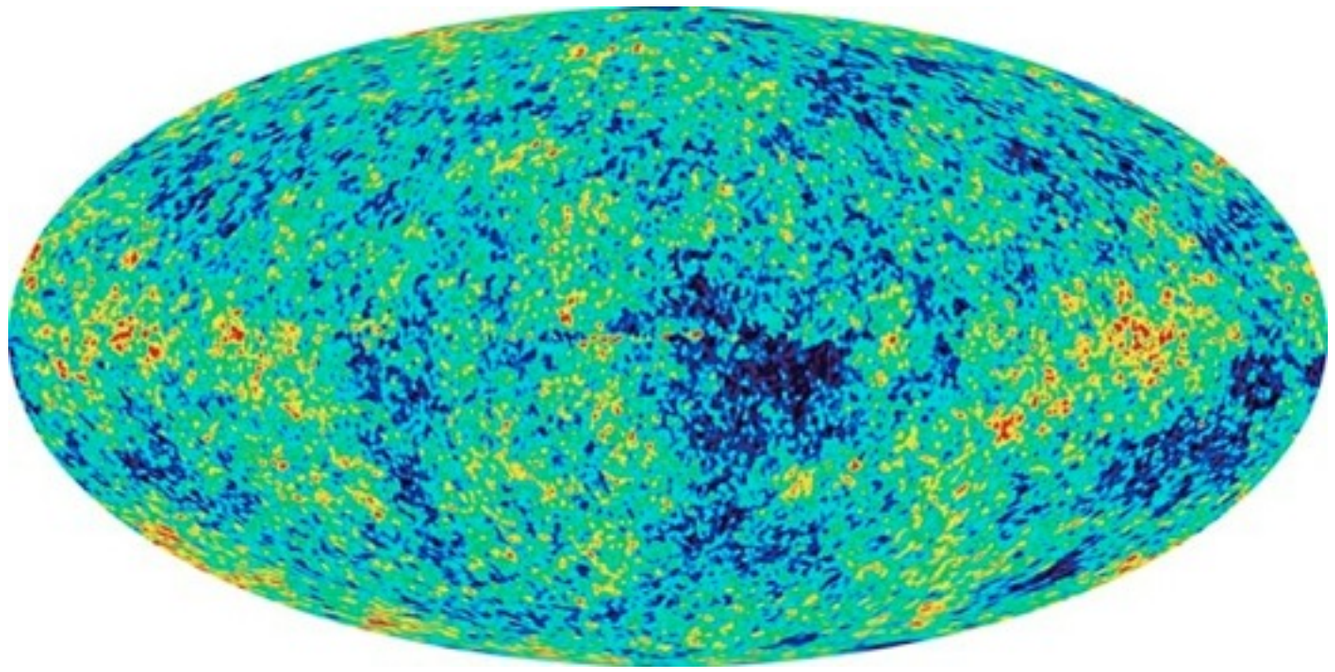
- First season results

- POLARBEAR-2 instrument

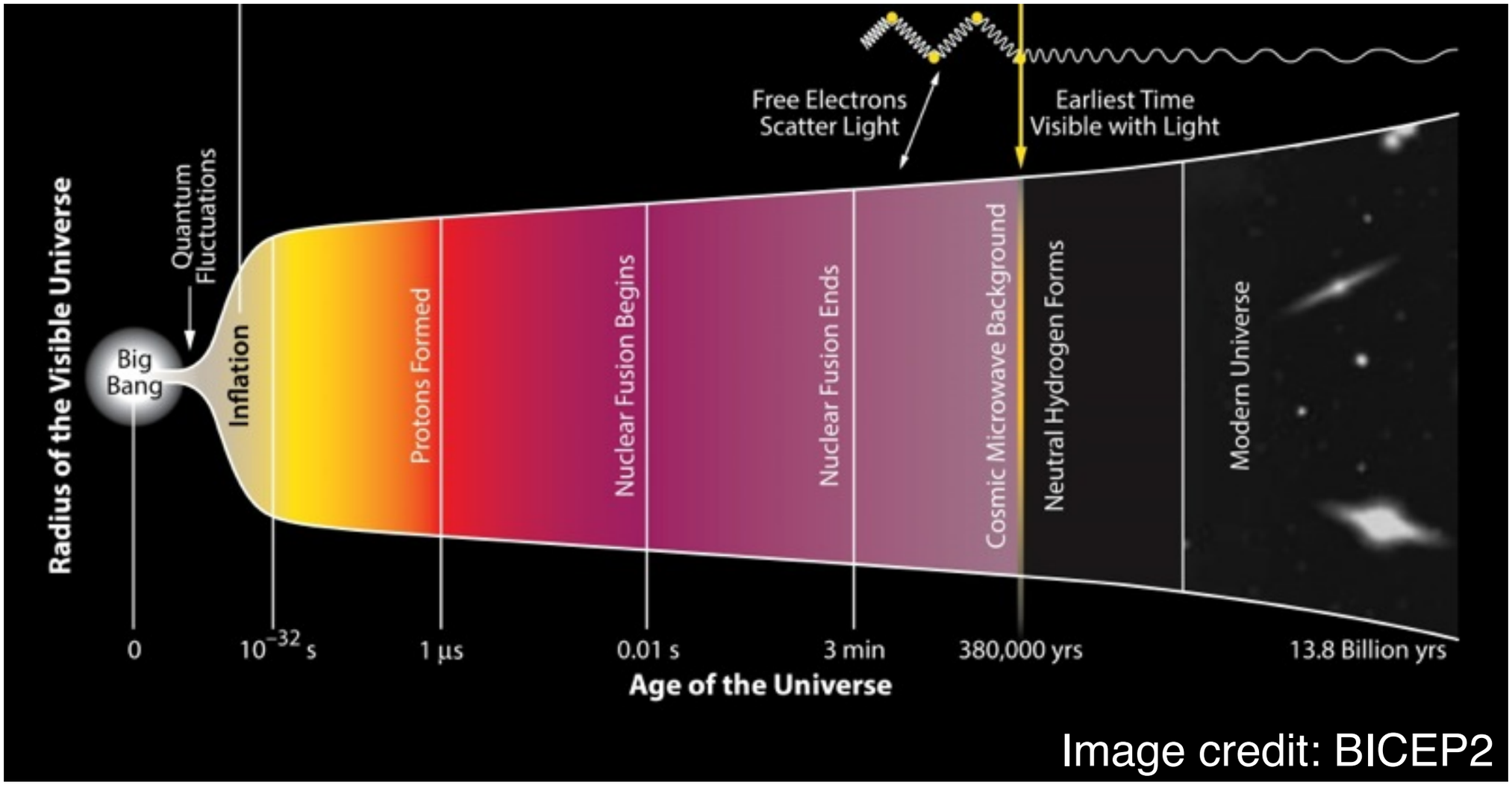
- Simons Array

Scientific motivation:

The cosmic microwave background



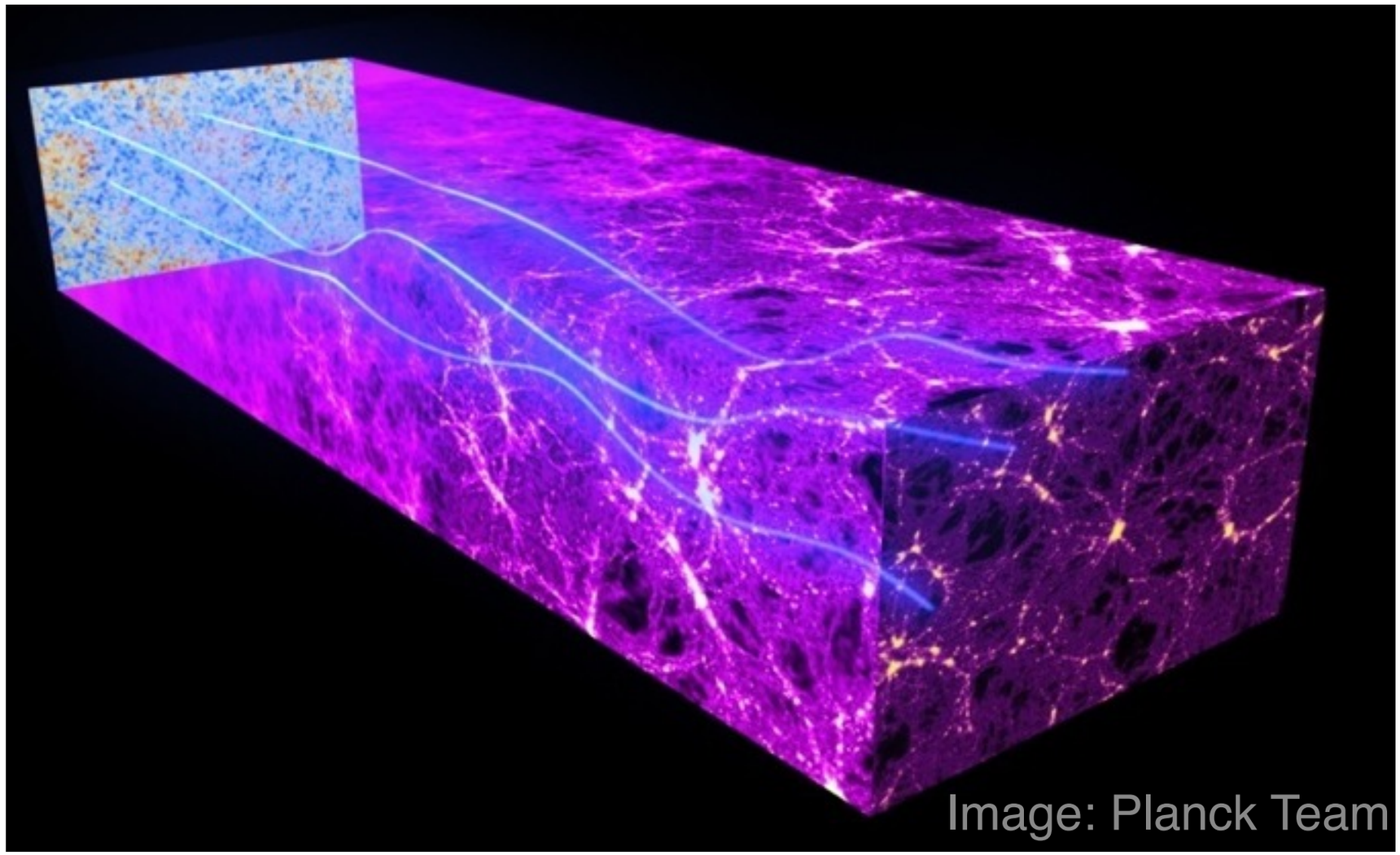
CMB as a snapshot of early universe



Physics of early universe is encoded in the CMB

- Quantum fluctuations during inflation imprint perturbations on the gravitational metric

CMB as a backlight for large-scale structure



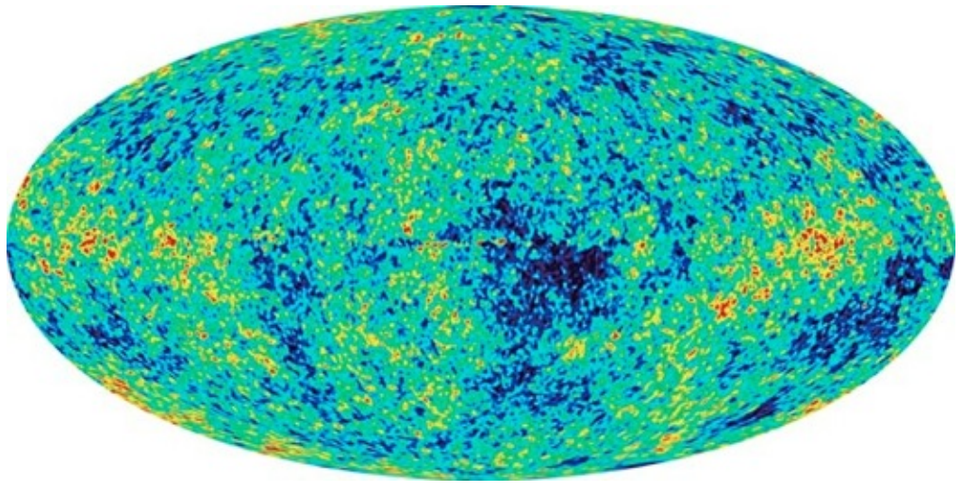
CMB lensing traces all of structure formation history

Lensing Measures:

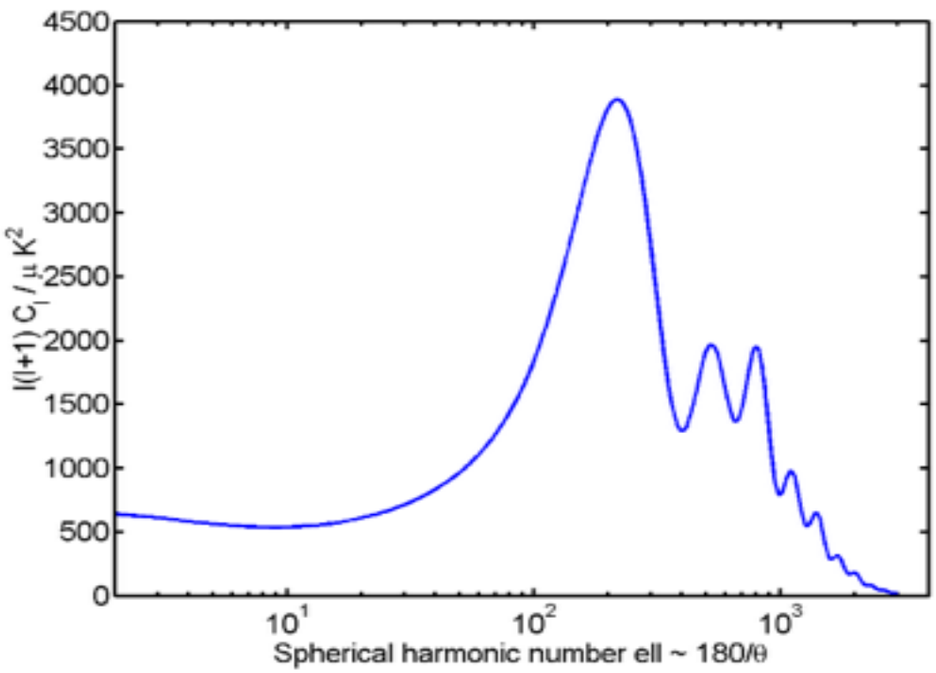
- Influence of dark matter – N_{eff}, sum of the neutrino masses
- Equation of state of dark energy at high redshift

Extracting information from the CMB

Primordial CMB is statistically isotropic



Convert maps to angular power spectrum



CMB Temperature power spectrum

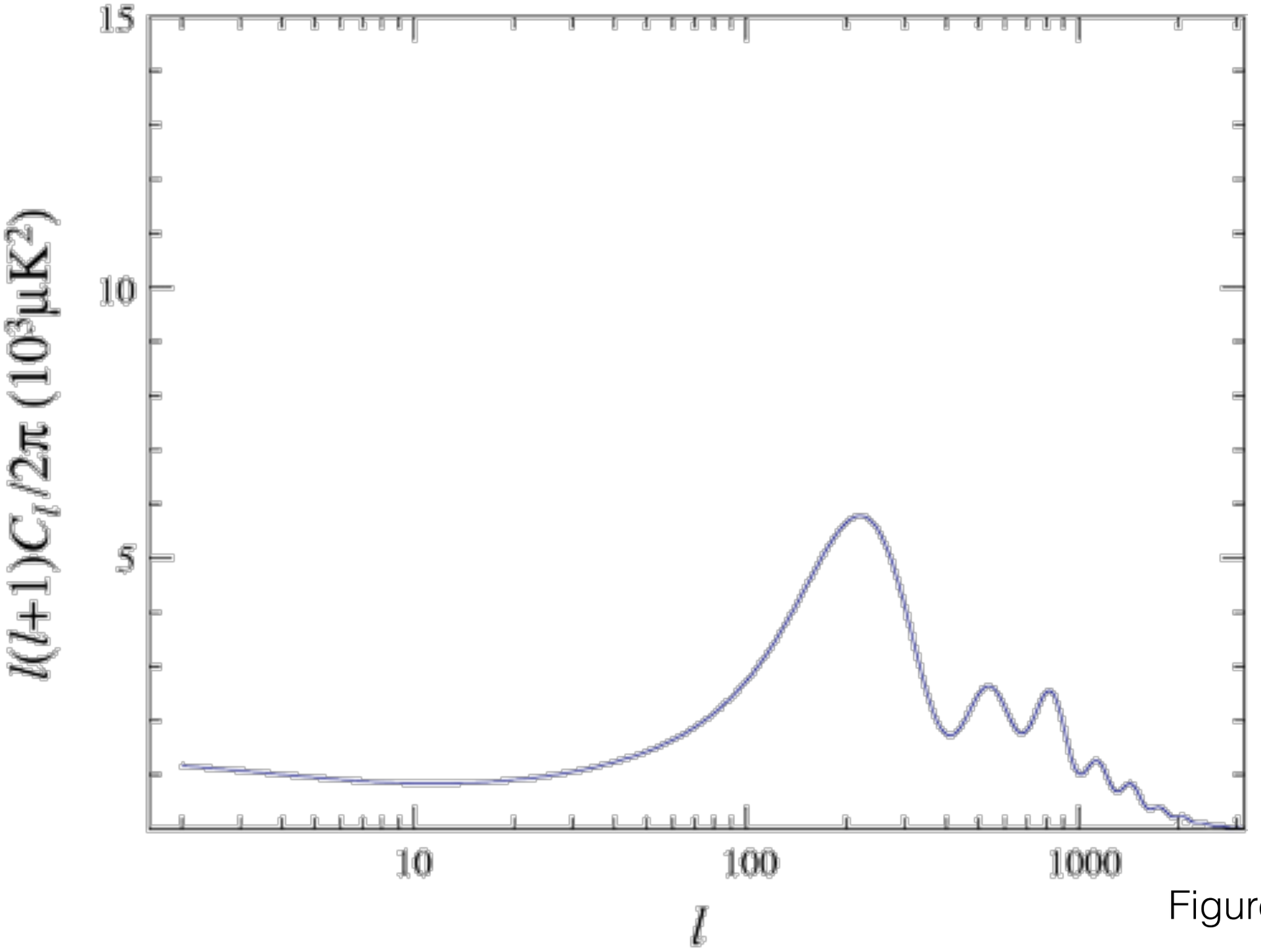
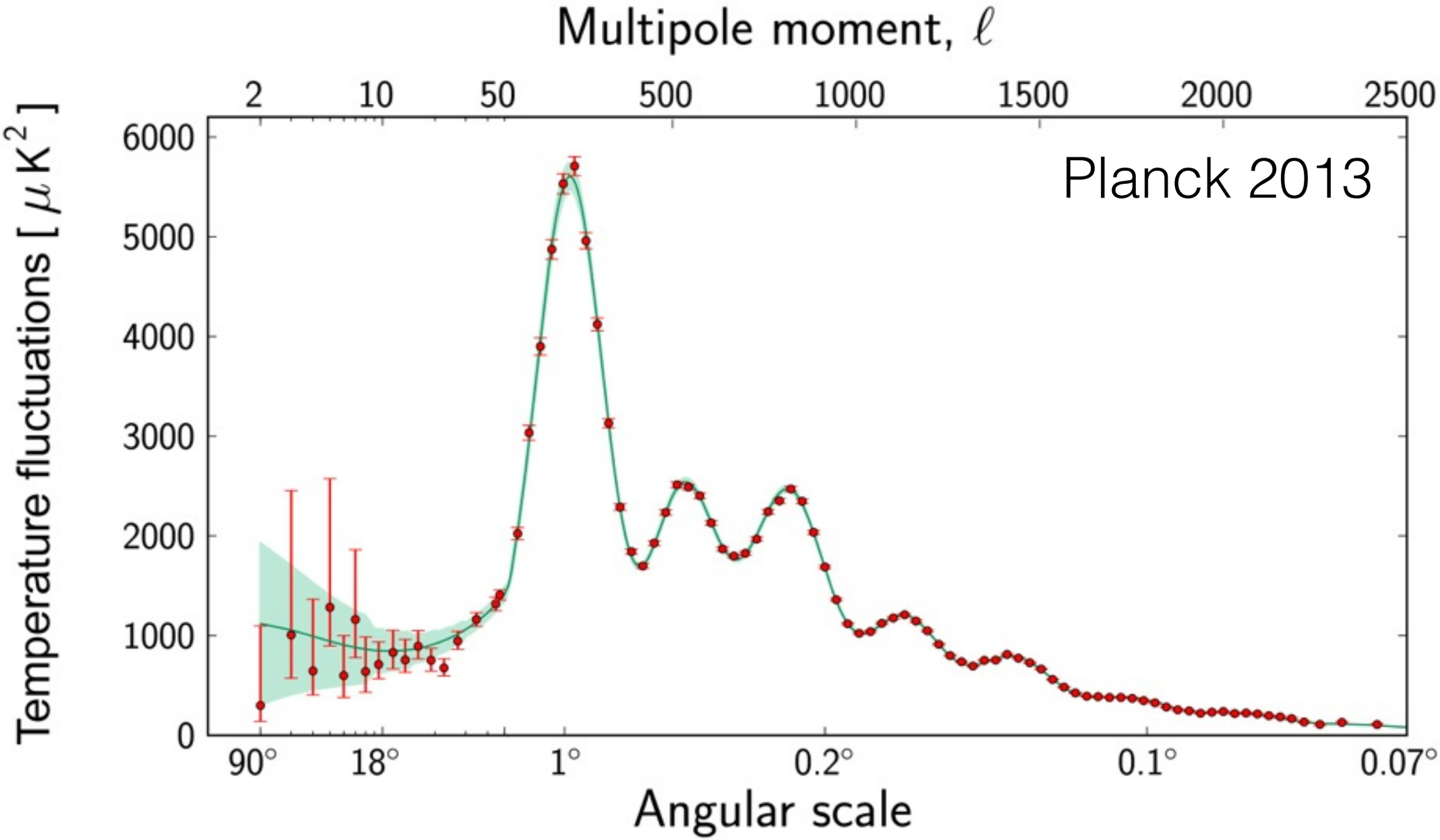
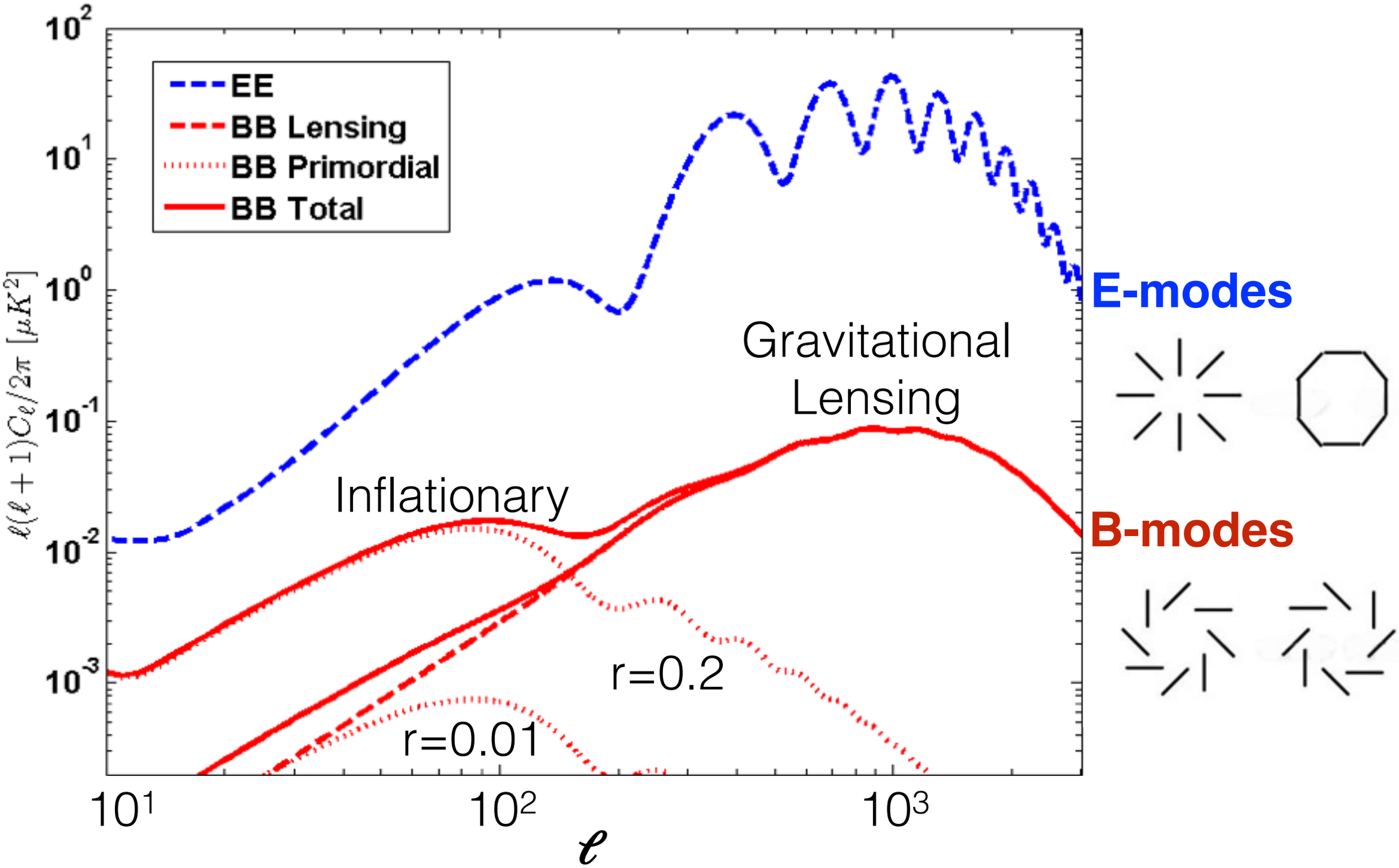


Figure: Wayne Hu

CMB temperature power spectrum

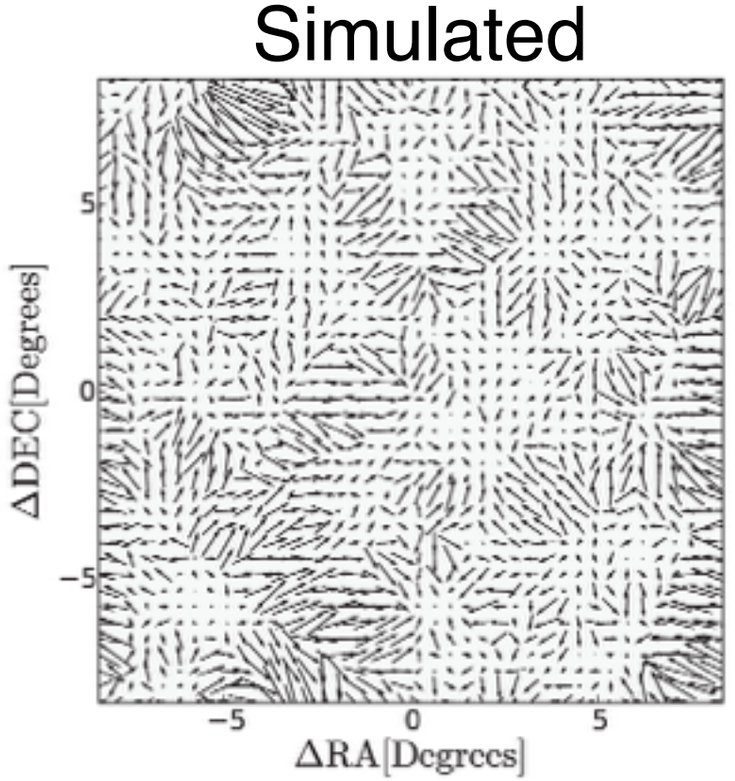


Predicted polarization power spectrum

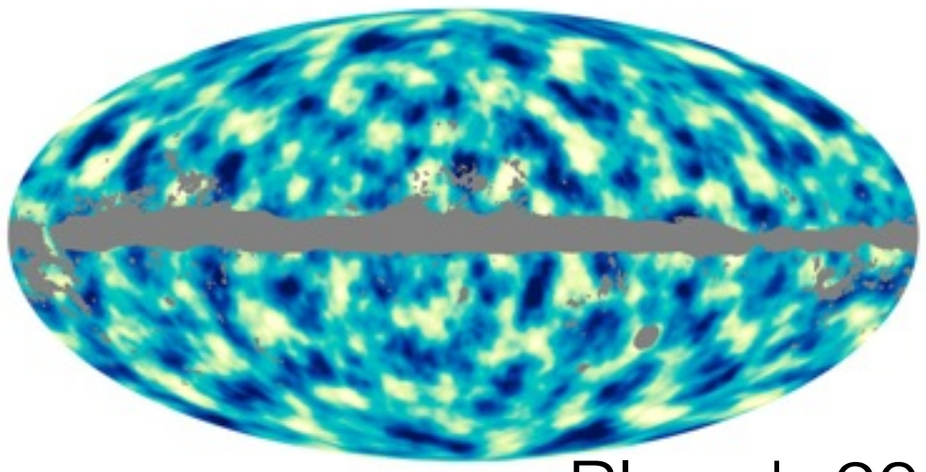


Gravitational lensing of CMB

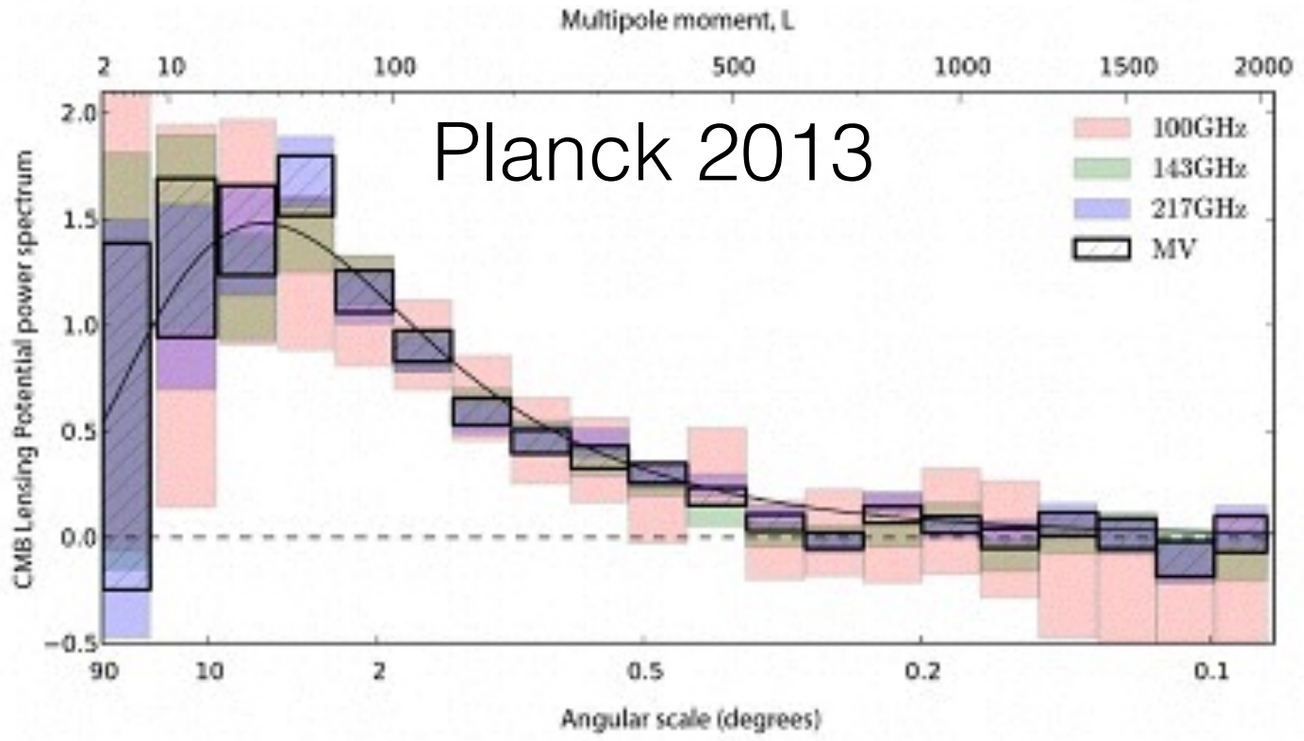
- Lensing deflections are arc minute scale
- Deflections are correlated over degree scales -> tracing large-scale structure
- Create map of the lensing potential, power spectrum



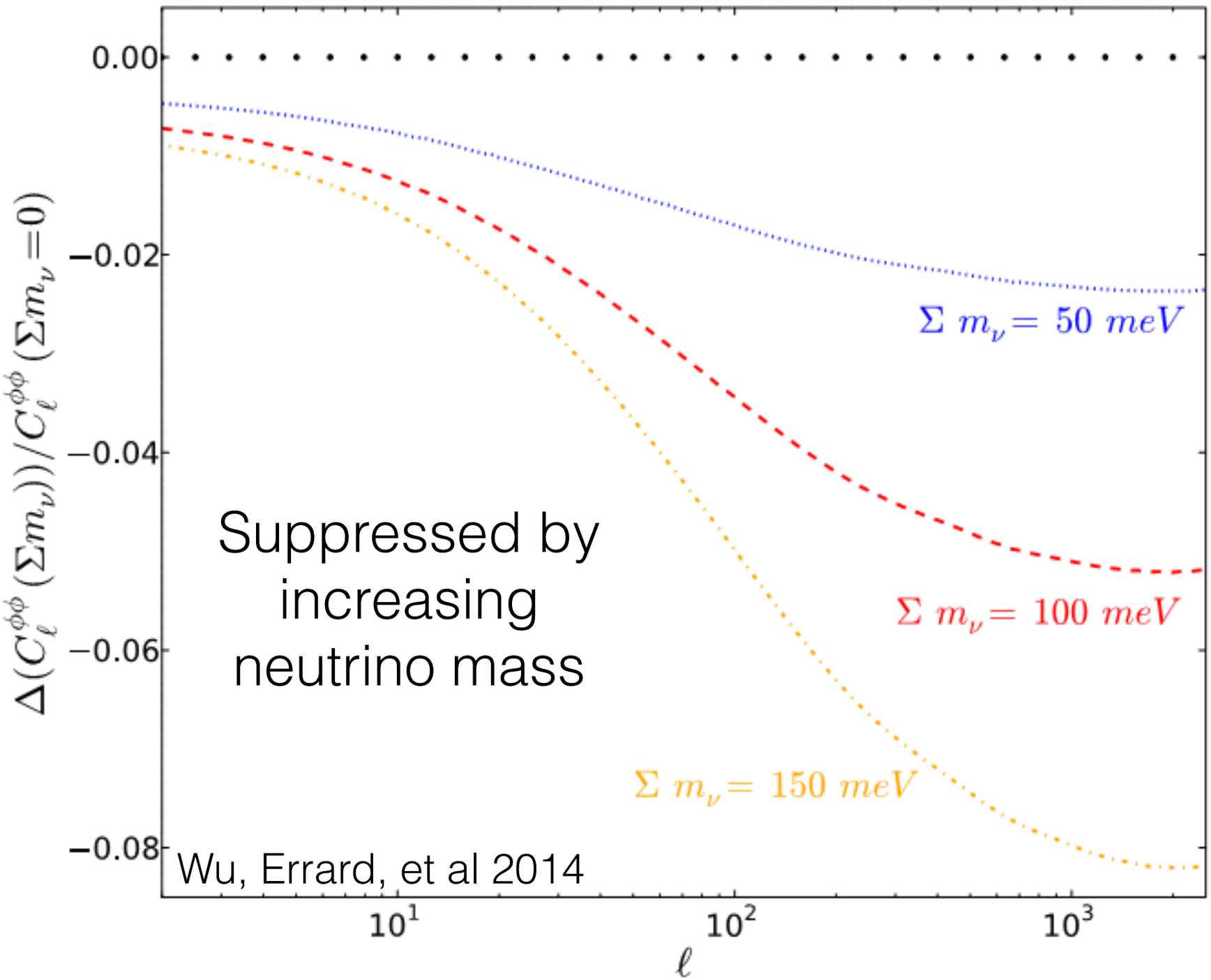
$$\vec{d} = \nabla\phi$$



Planck 2013



Effect of neutrinos on structure formation



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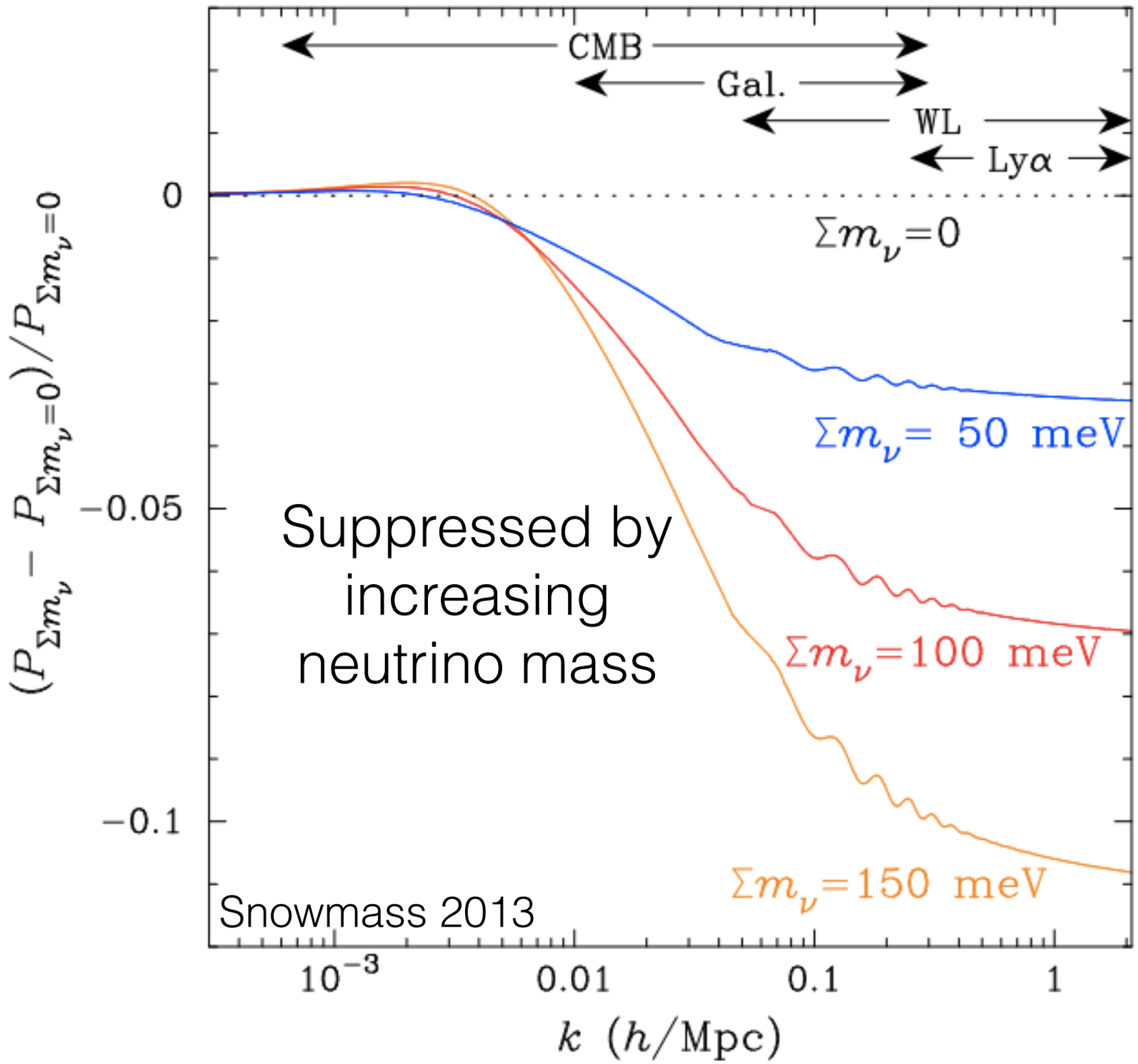

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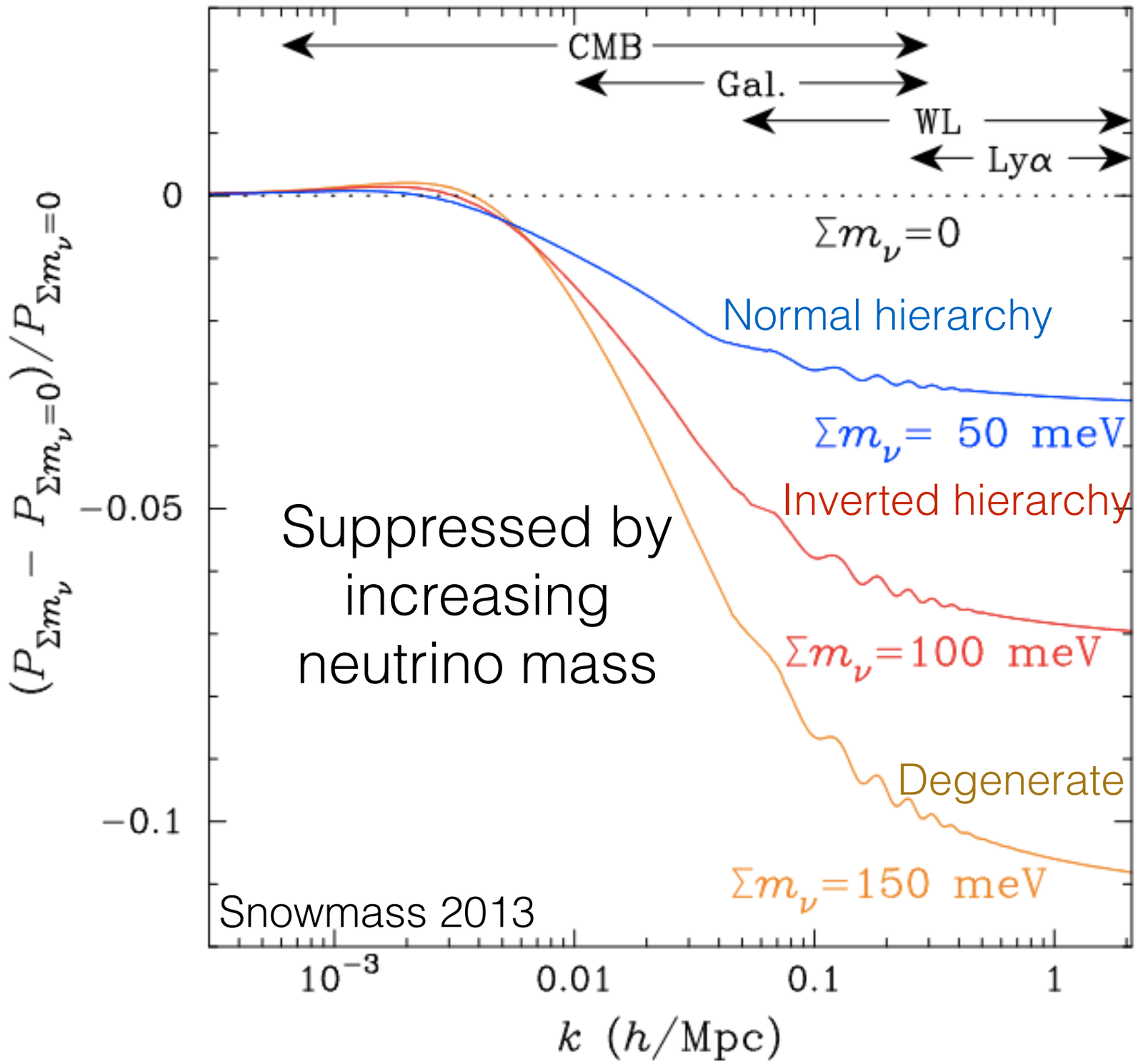
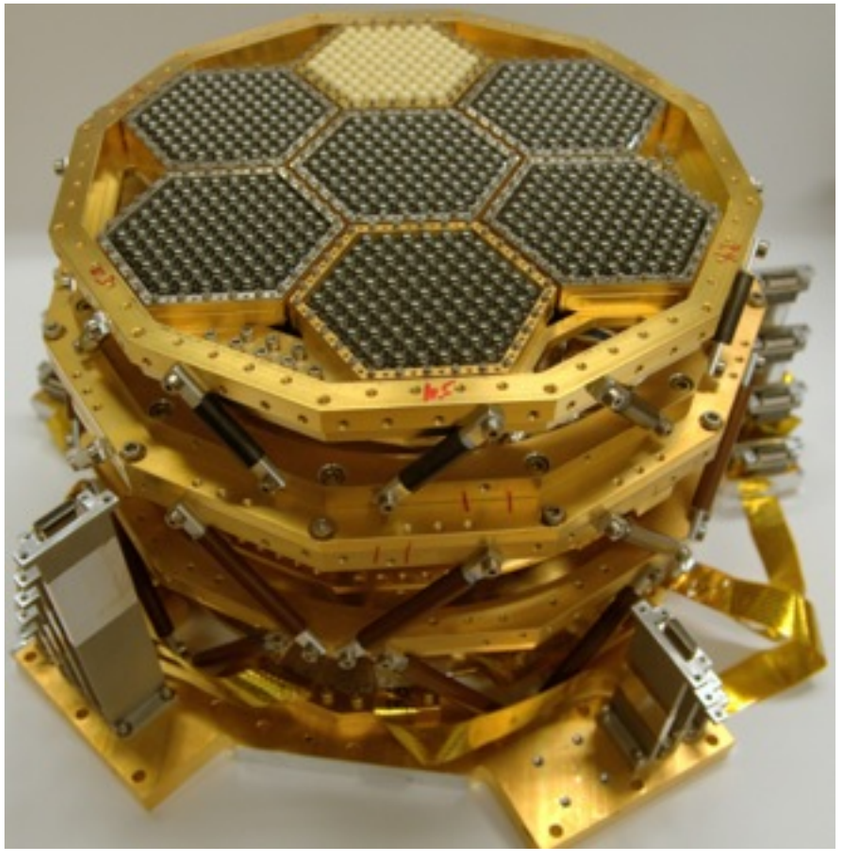


If min. mass (58 meV):

$\Omega_\nu/\Omega_m \sim 0.4\%$

POLARBEAR-1

Instrument Overview



The POLARBEAR Experiment

- Dedicated CMB polarization experiment
- Located on Cerro Toco at 5200 meters in Atacama desert
- First light January 2012
- Now in third season of observations with POLARBEAR-1

POLARBEAR Collaboration

UC Berkeley
Brian Barch
Ari Cukierman
Tijmen de Haan
Josquin Errard
Neil Goeckner-Wald
Charles Hill
William Holzapfel
Yasuto Hori
Oliver Jeong
Adrian Lee
Mike Myers
Christopher Raum
Paul Richards
Blake Sherwin
Ian Shirley
Bryan Steinbach
Nathan Whitehorn
Oliver Zahn

Lawrence Berkeley National Lab
Julian Borrill
Reijo Keskitalo
Theodore Kisner
Akito Kusaka
Eric Linder
Aritoki Suzuki

UC San Diego
Christopher Aleman
Kam Arnold
Matt Atlas
Darcy Barron
Tucker Elleflot
George Fuller
Logan Howe
Jon Kaufman
Kavon Kazemzadeh
Brian Keating
David Leon
Lindsay Lowry
Frederick Matsuda
Martin Navaroli
Hans Paar
Gabriel Rebeiz
Praween Siritanasak
Nathan Stebor
Amit Yadav

Laboratoire Astroparticule & Cosmologie
Maude LeJeune
Julien Peloton
Davide Poletti
Radek Stompor

KEK
Yuji Chinone
Masaya Hasegawa
Kaori Hattori
Masashi Hazumi
Takahiro Okamura
Jun-ichi Suzuki
Osamu Tajima
Satoru Takakura
Takayuki Tomaru

SOKENDAI
Yoshiki Akiba
Yuki Inoue
Yuuko Segawa

Dalhousie
Scott Chapman
Colin Ross
Kaja Rotermund
Alexei Tikhomirov

CU Boulder
Nils Halverson
Greg Jaehnig
David Schenck

McGill University
Matt Dobbs
Adam Gilbert
Josh Montgomery
Graeme Smecher

Kavli IPMU
Fumiya Irie
Nobuhiko Katayama
Kuniyoshi Mizukami
Haruki Nishino

National Institute for Fusion Science
Suguru Takada

Princeton
Zigmund Kermish

UC Irvine
Chang Feng

Imperial College
Anne Ducout
Stephen Feeney
Andrew Jaffe

SISSA
Carlo Baccigalupi
Giulio Fabbian
Giuseppe Puglisi

NASA Goddard
Nathan Miller

Católica (PUC)
David Boettger
Rolando Dunner

JAXA
Tomotake Matsumura

U. Melbourne
Christian Reichardt

Cardiff University
Peter Ade

Argonne NL
Amy Bender

And many more in years past…

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MEXT

POLARBEAR Collaboration

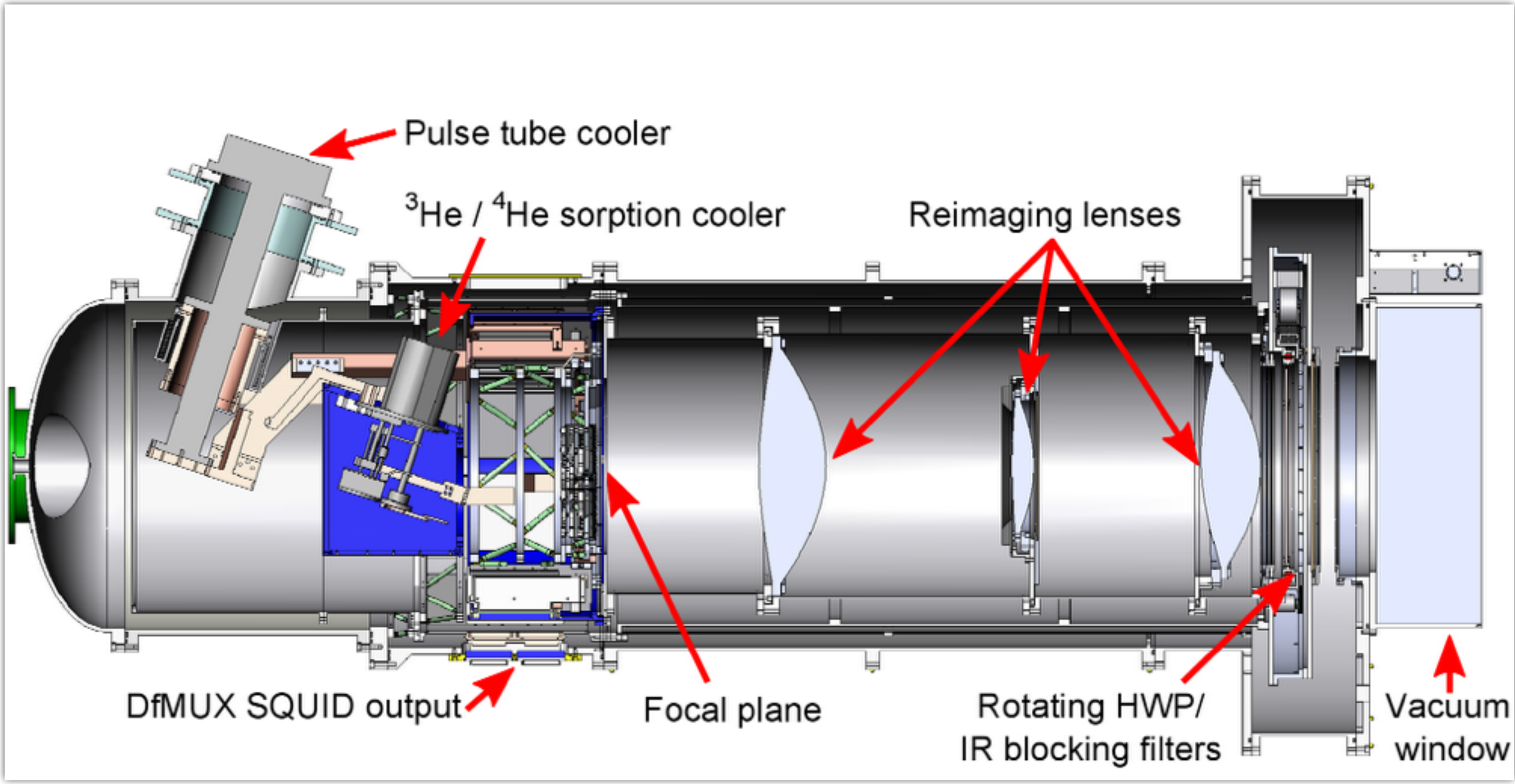
POLARBEAR-1

Huan Tran Telescope

- Off-axis Gregorian-Dragone design
  - Low cross-polarization
  - Large field-of-view
- 3.5’ FWHM beams @ 150 GHz

POLARBEAR-1

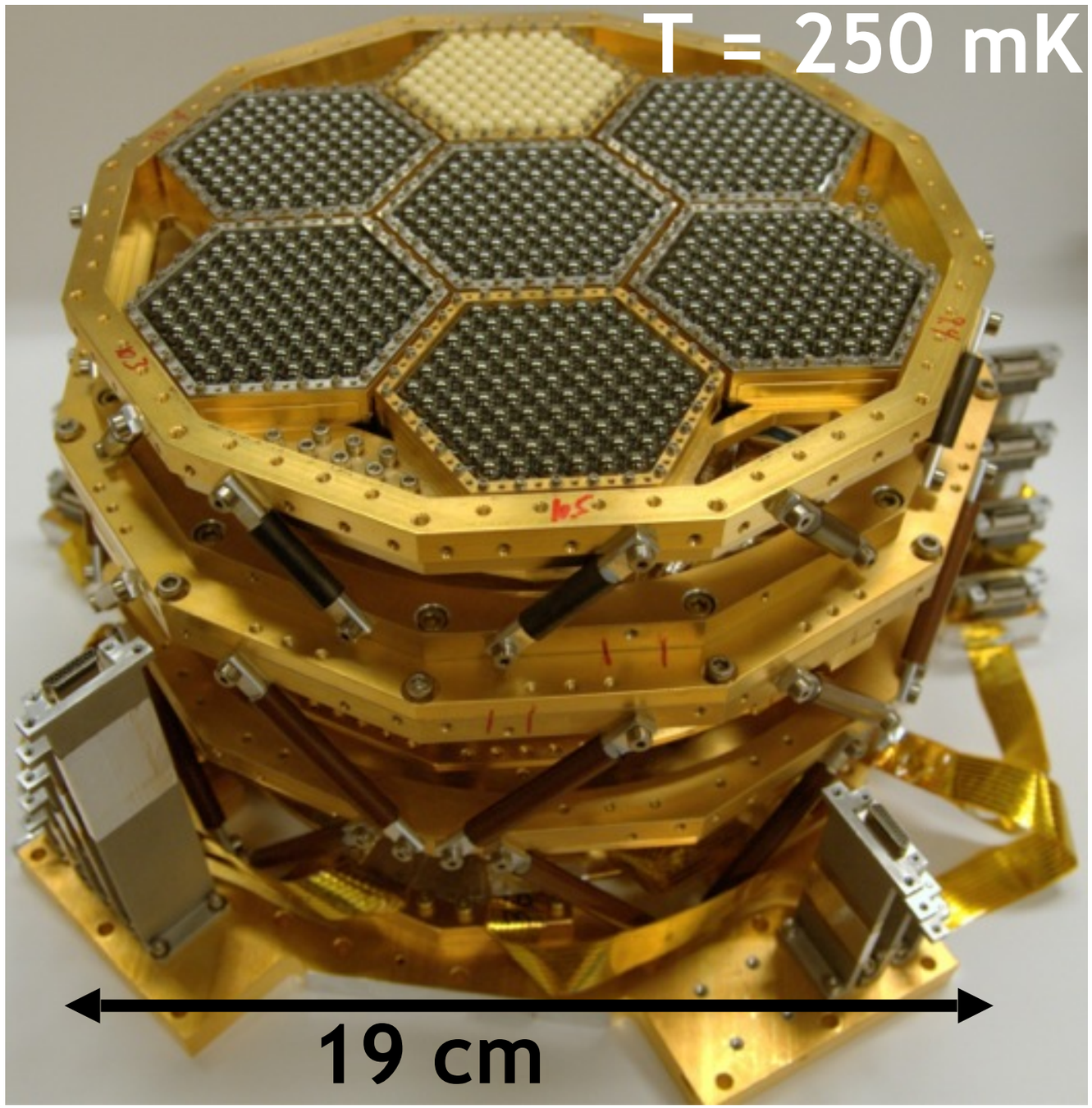
Cryogenic Receiver



2 meters

POLARBEAR-1
Focal Plane

- 637 dual polarization pixels
- Beam-forming lenslet coupled to each pixel
- 1274 superconducting transition-edge sensor bolometers
- Digital frequency-domain multiplexing readout (8x)



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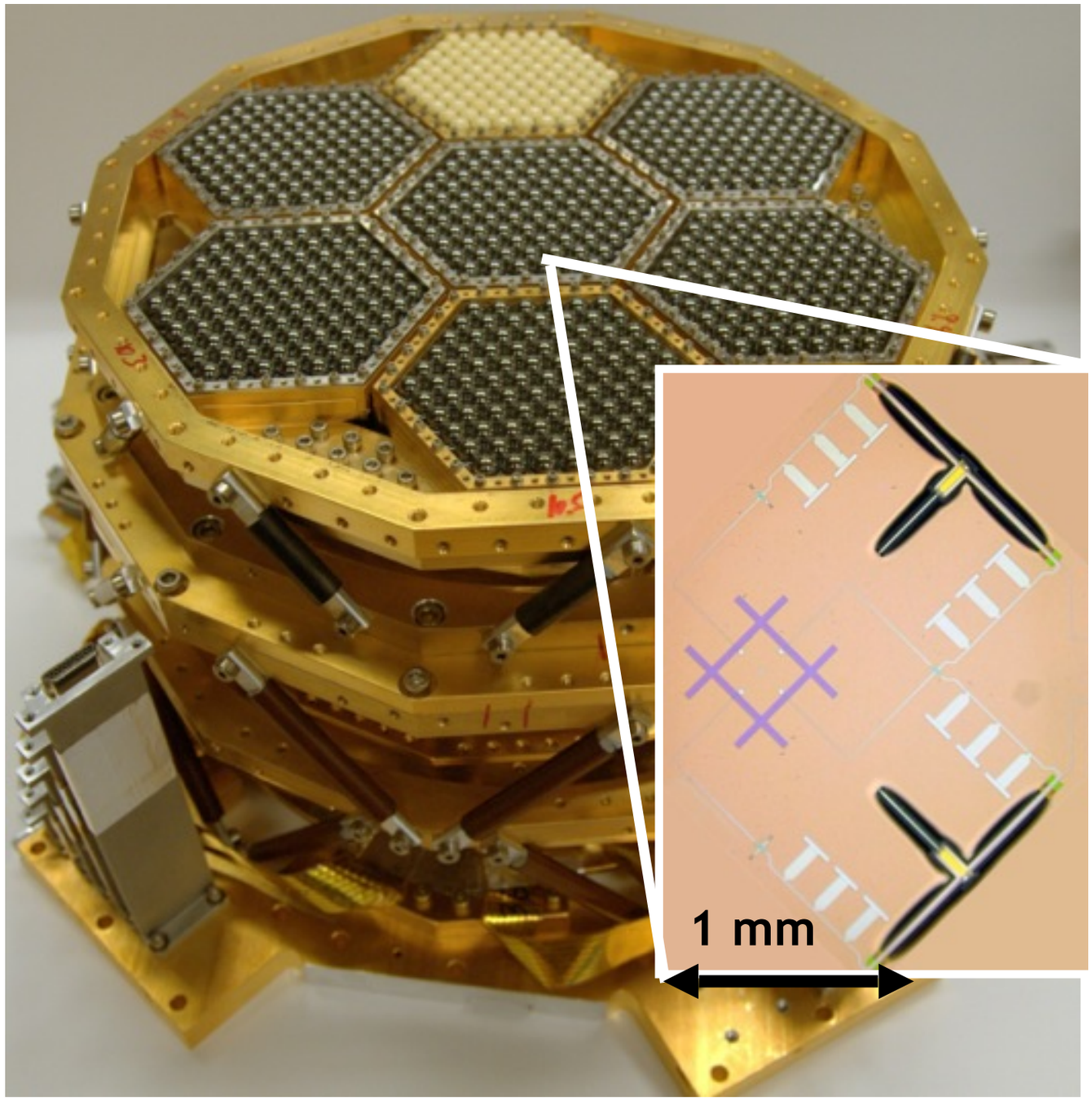

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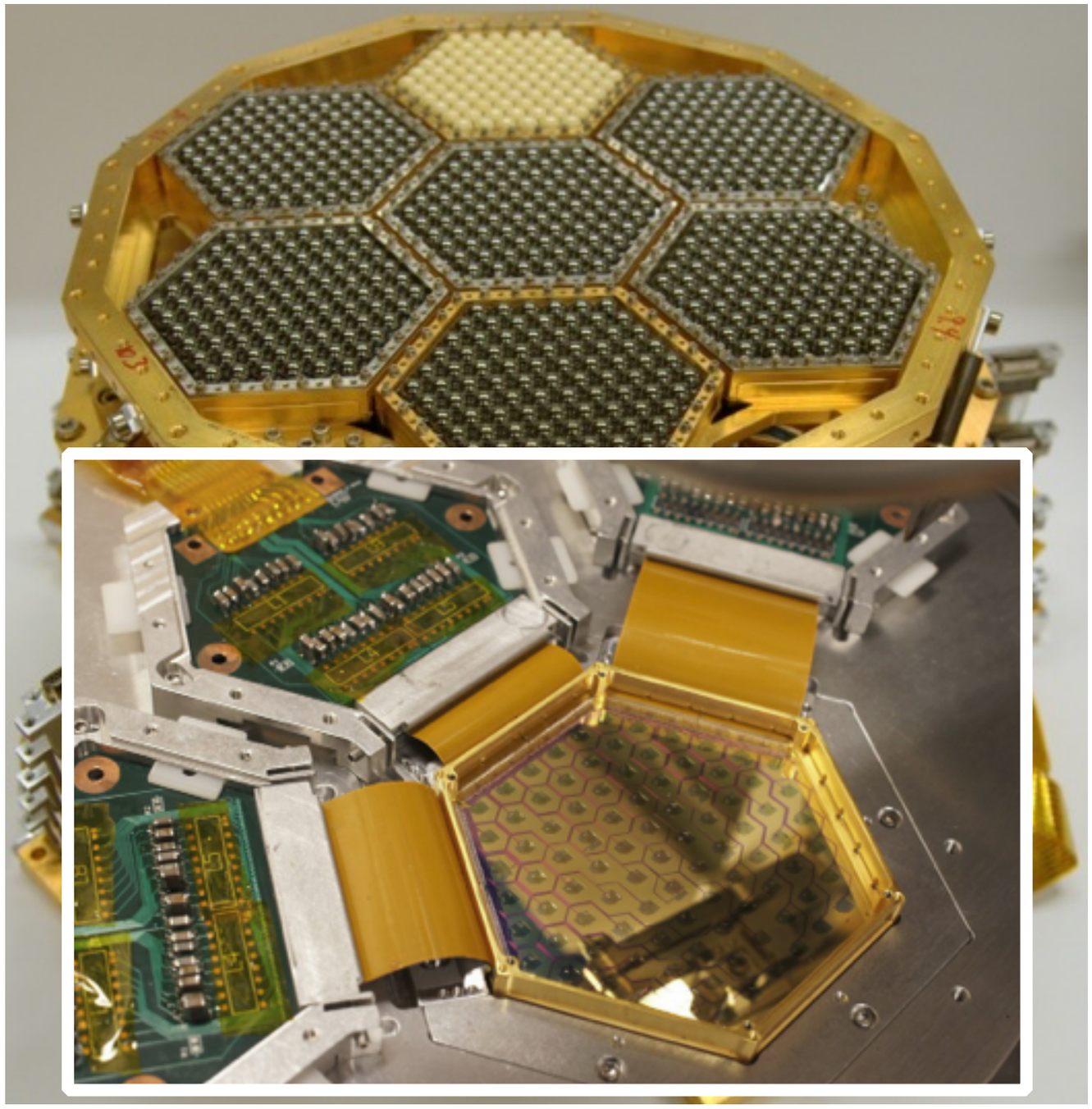
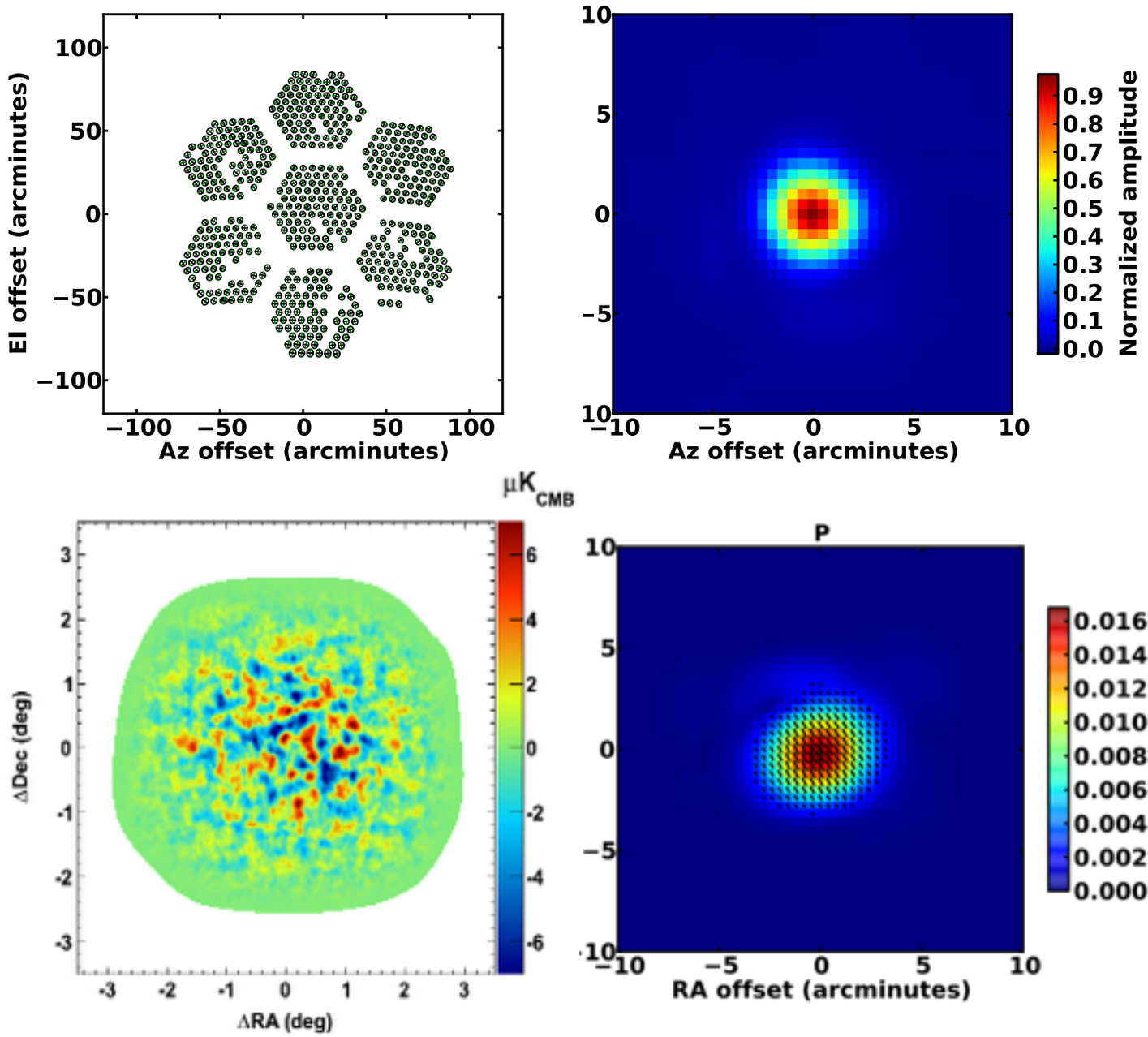


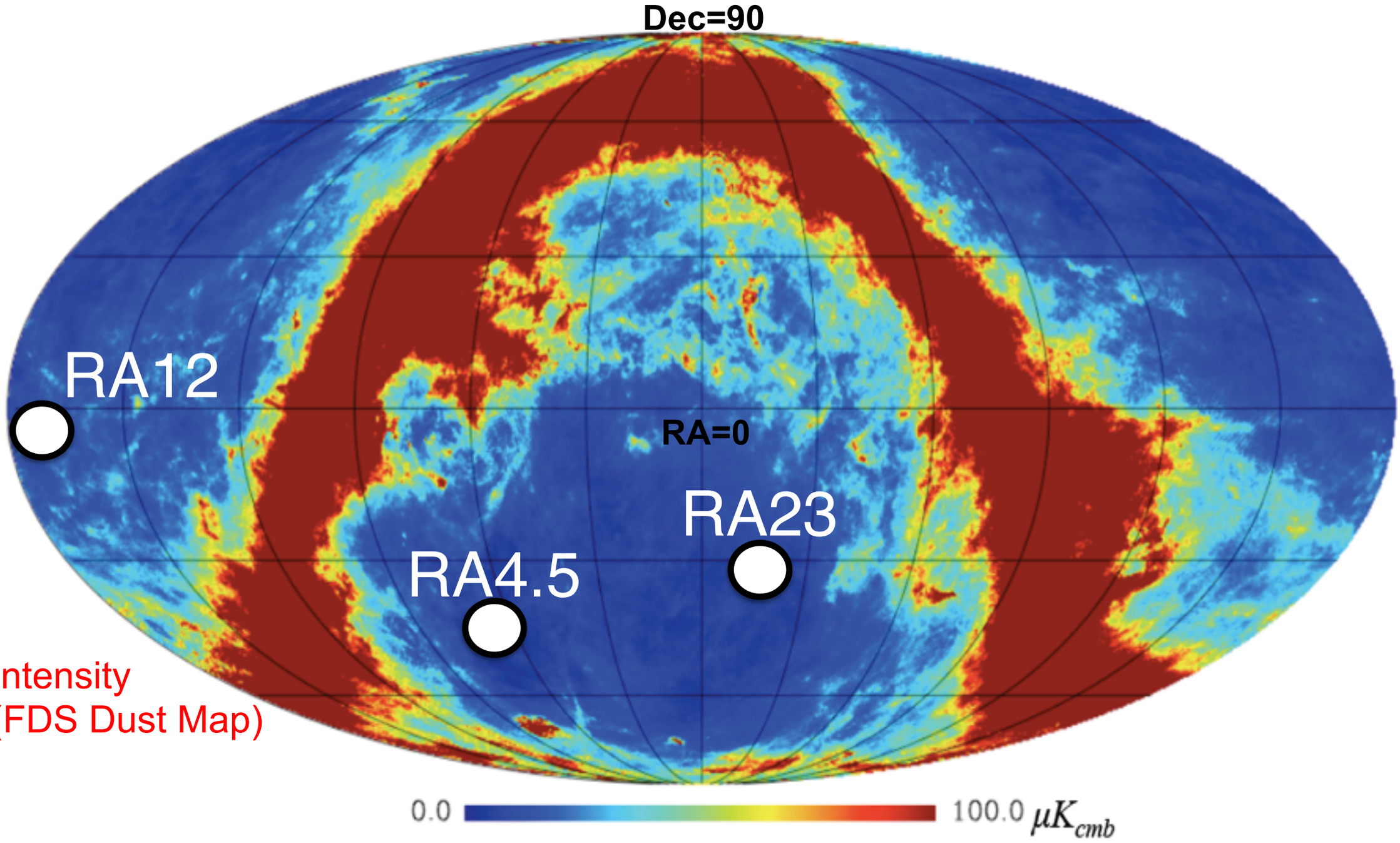
POLARBEAR-1

Instrument performance

- 1015 detectors (80% yield)
- Median NET: 550 μK√s
- First season average instrument NET: 23 μK√s
- ~3.5´ FWHM, ~5% ellipticity
- ~40% optical efficiency

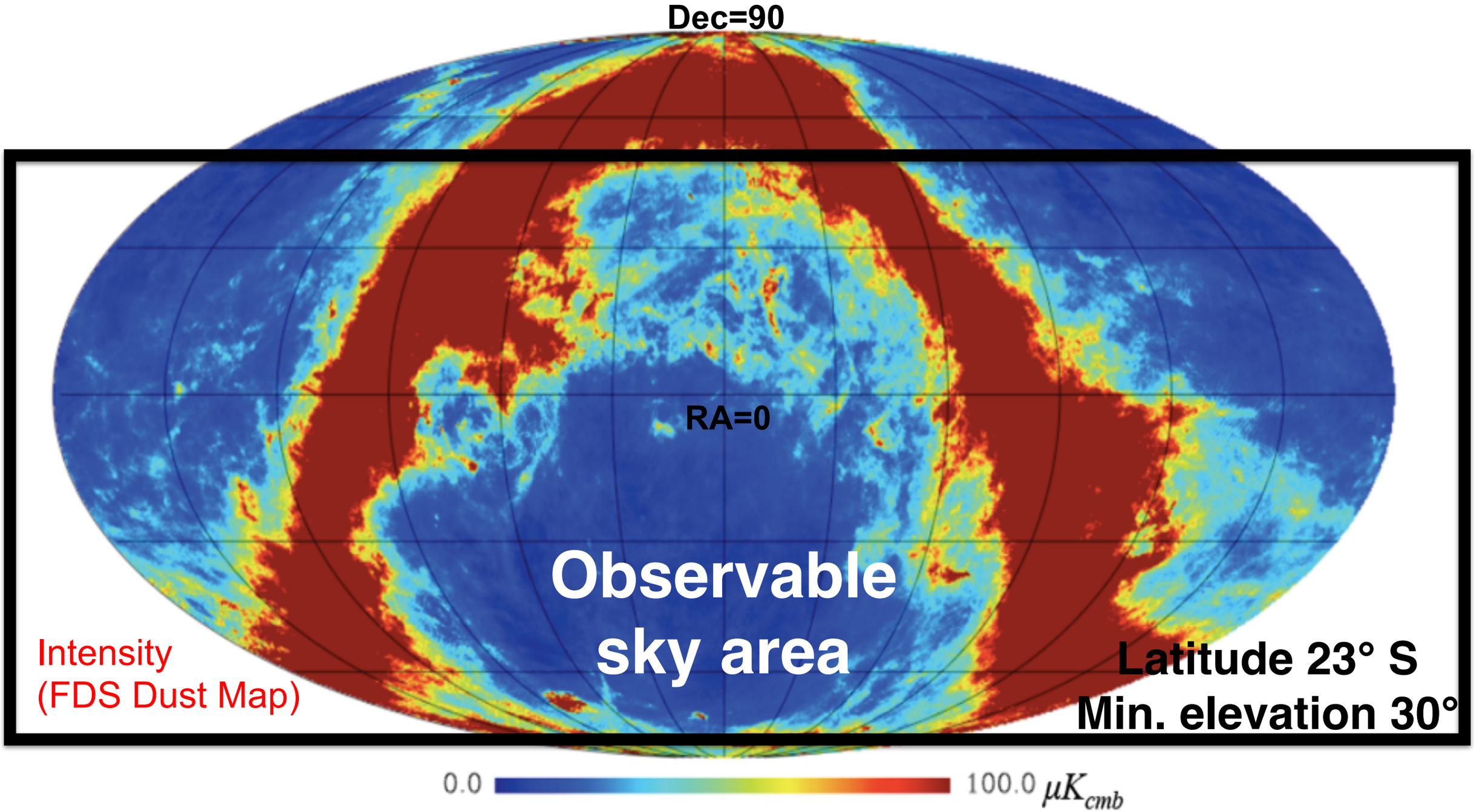


POLARBEAR Observations



PB-1 Initial survey: Deep integration on 3x3 degree patches
Observations at 150 GHz

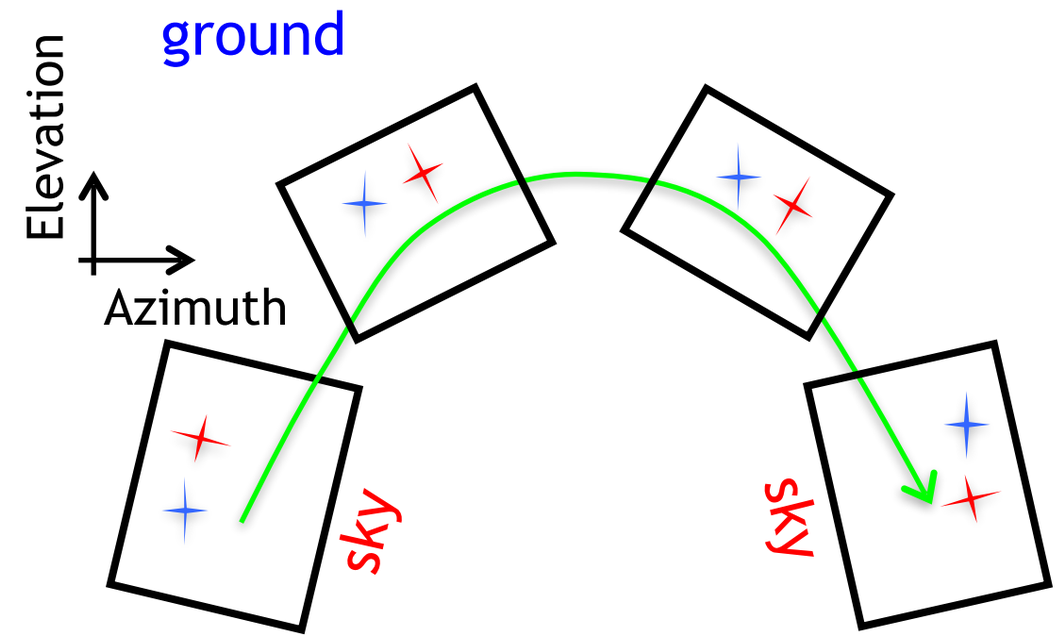
POLARBEAR Observations



POLARBEAR-1

Control of instrumental systematic effects

- Pixel-pair differencing to reject unpolarized atmosphere
- Modulate CMB Polarization with apparent sky rotation
- Co-moving baffling for low sidelobe response
- Scan strategy allows ground template removal



POLARBEAR-1

Control of instrumental systematic effects

- Instantaneous measurement of polarization with each pixel
- Modulation of CMB Polarization:
  - Half-wave plate
  - Apparent sky rotation
- Low sidelobe response
  - Co-moving baffling
  - Scan strategy allows ground removal

POLARBEAR-1

Control of instrumental systematic effects

End-to-end simulations using measured instrument characteristics

Boresight & diff. pointing

Pol. angle

HWP-dependent gain

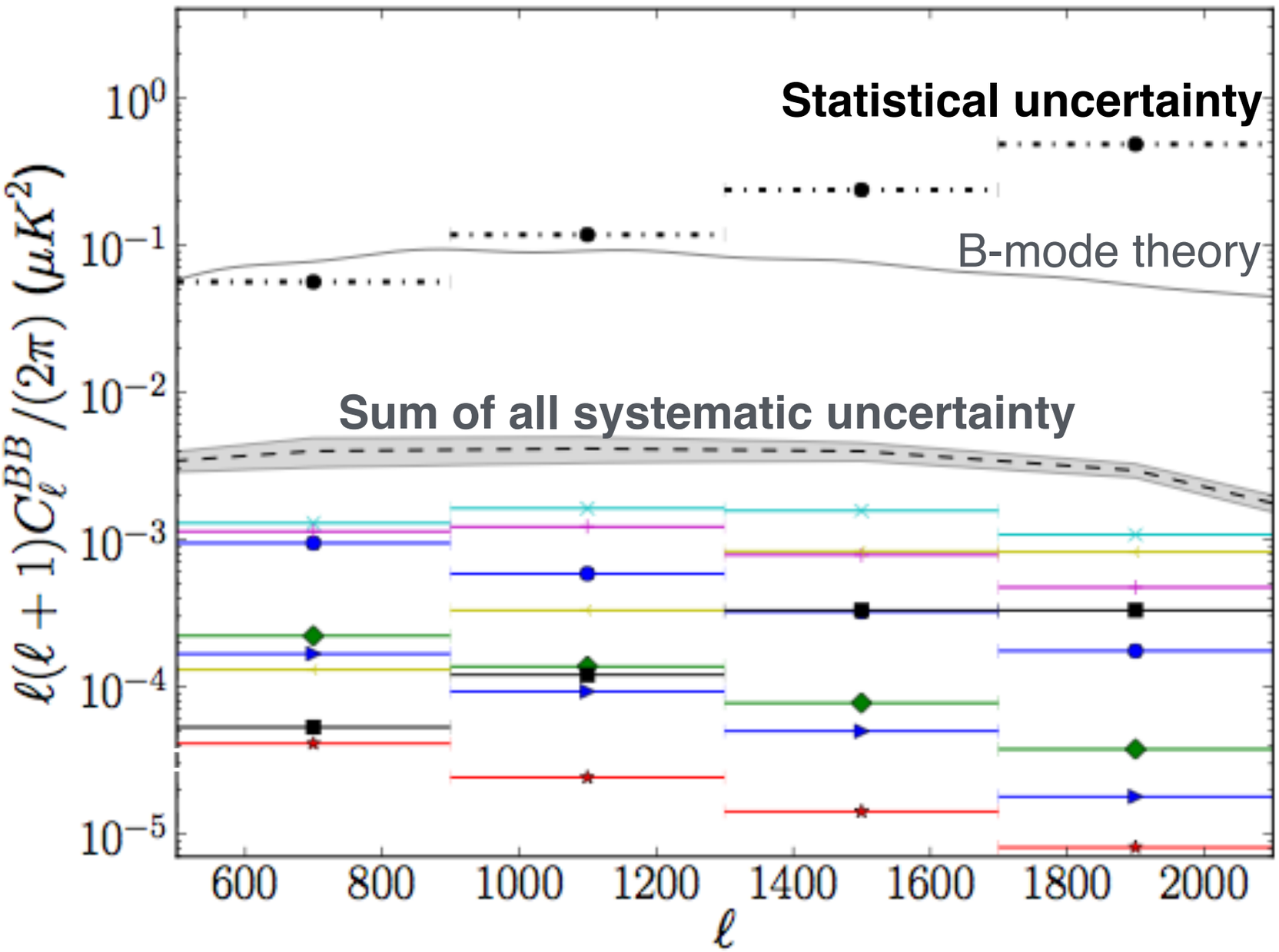
HWP-independent gain

Electrical crosstalk

Differential beamsize

Differential ellipticity

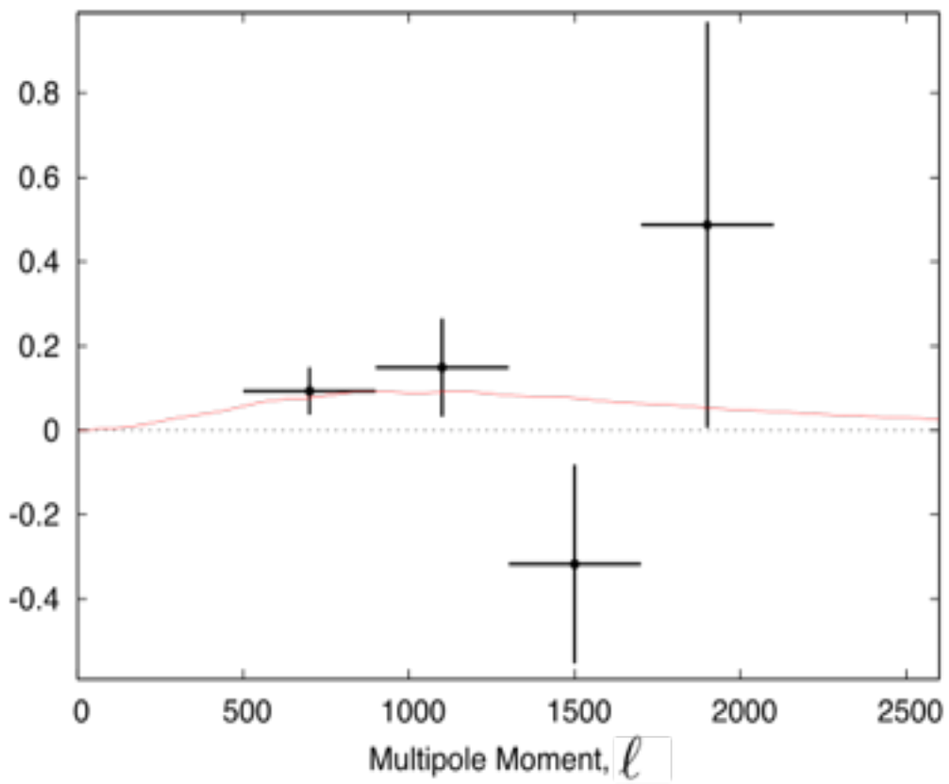
Gain drift



POLARBEAR Collaboration, ApJ 794, 171 (2014)

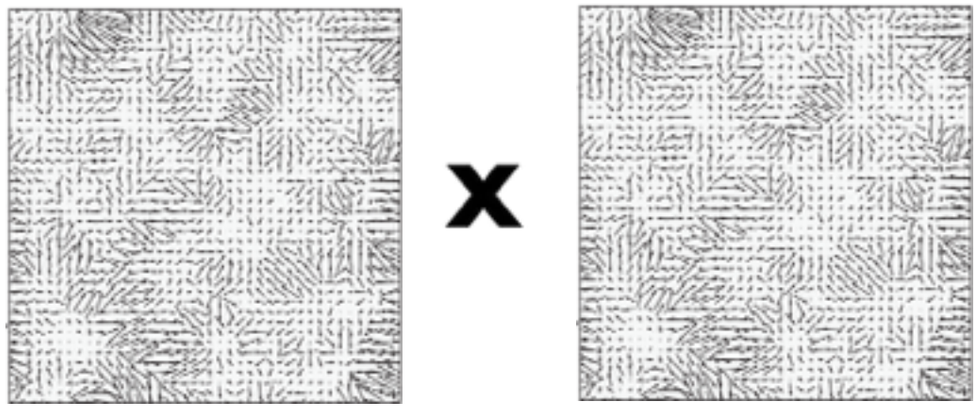
POLARBEAR

First season results

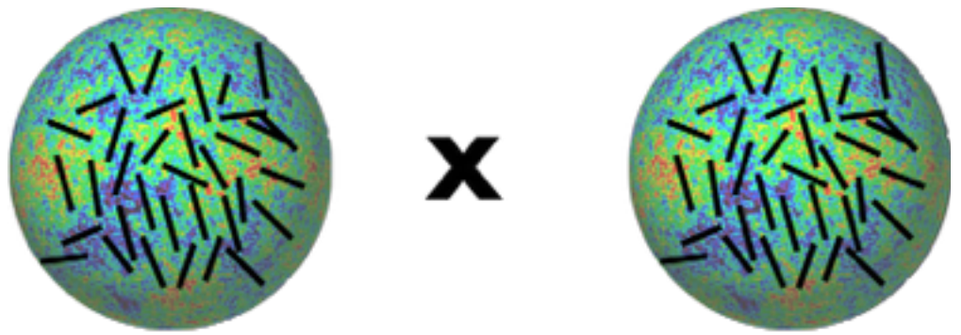


POLARBEAR First Season Results: Three B-mode Analyses

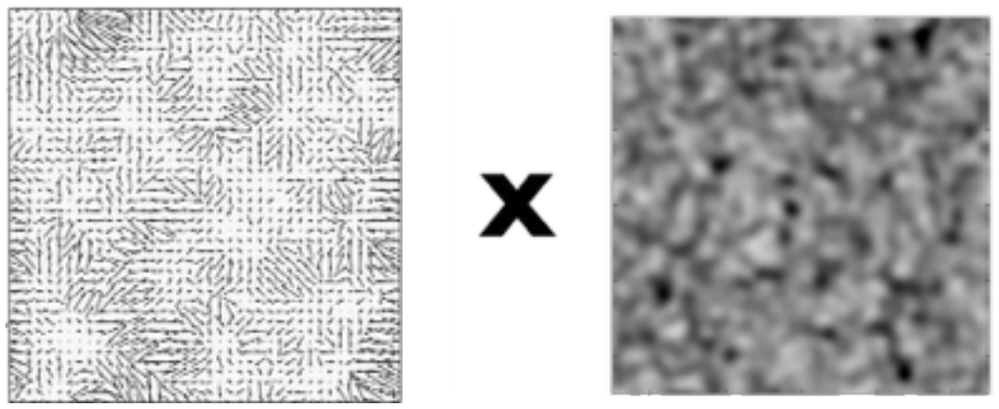
Deflection power spectrum:
CMB-only polarized lensing deflection power
PRL 113, 021301 (2014)



Angular power spectrum:
C_ℓ^{BB}
ApJ 794, 171 (2014)



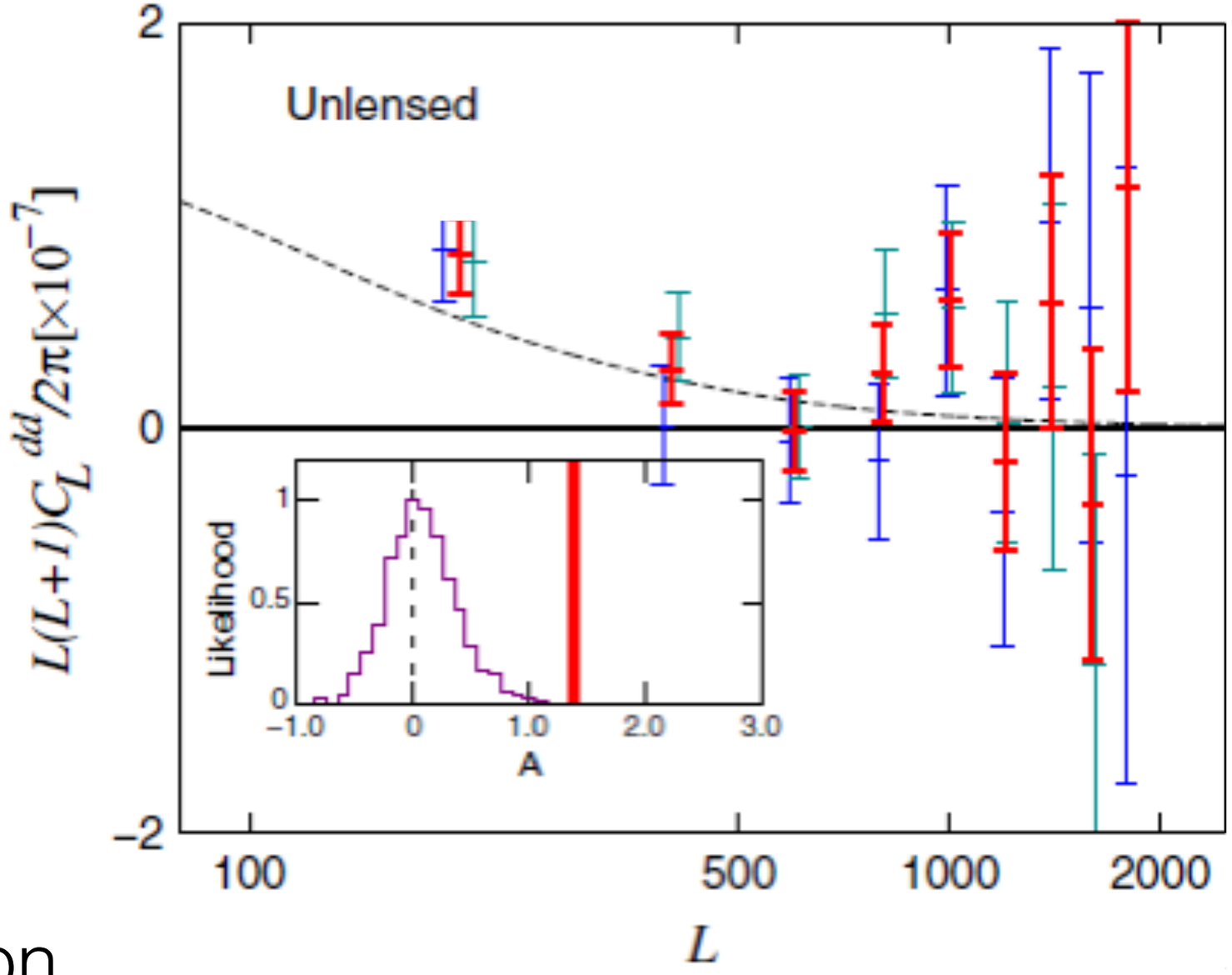
Galaxy cross-correlation:
CMB deflection measurements
cross-correlated with luminous
tracers of dark matter
PRL 112, 131302 (2014)



Combined 4.7 sigma rejection of no lensing B-modes from CMB alone
All spectra available on NASA LAMBDA site

POLARBEAR First Season Results: Deflection power spectrum

- CMB-polarization only
- 4.2 sigma rejection of "no lensing B-modes"
- Polarization will be most sensitive measure of C_L^{dd}
- Groundwork for neutrino masses, dark energy



POLARBEAR Collaboration
PRL 113, 021301 (2014)

Green: $< EBEB >$

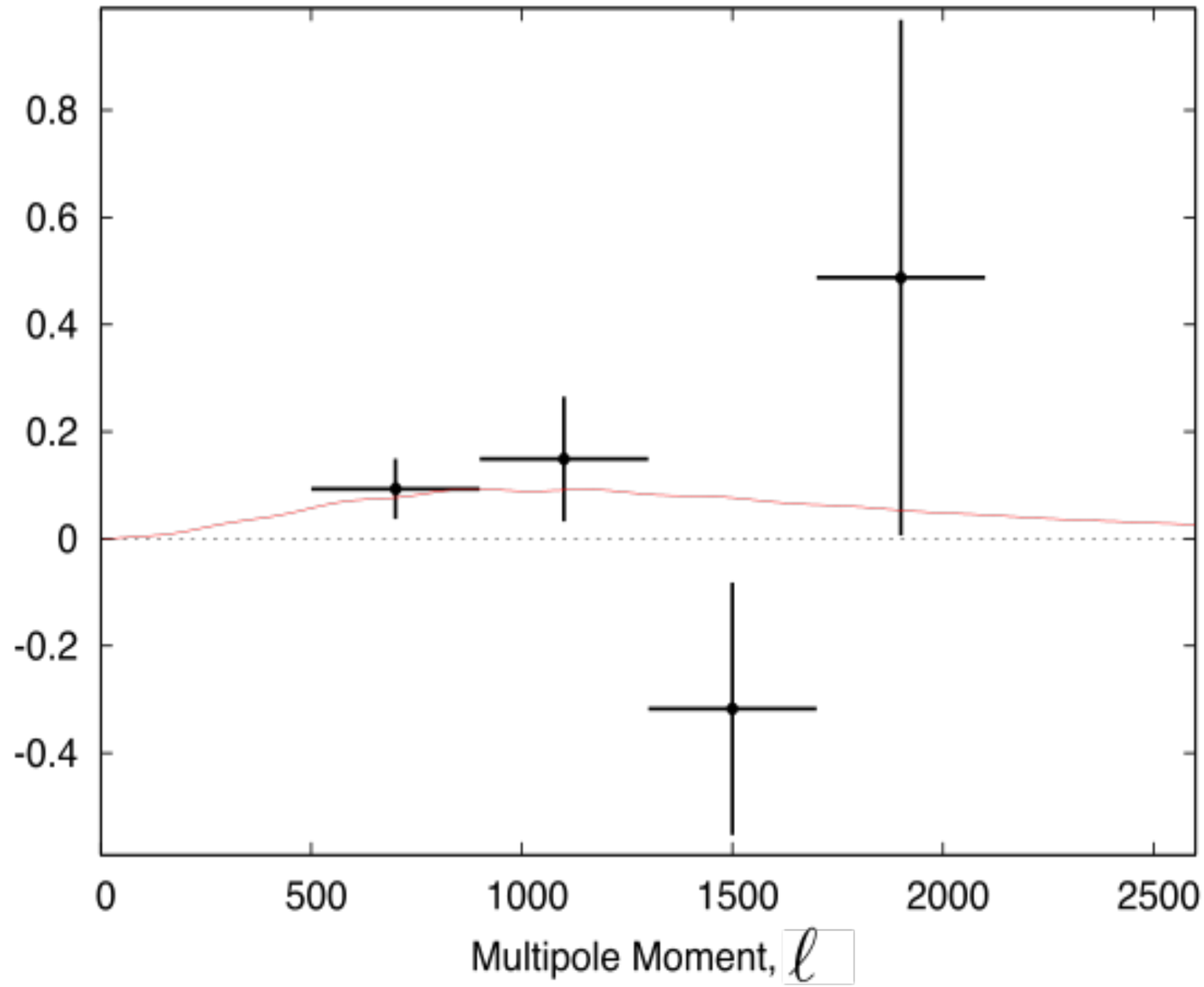
Blue: $< EEEB >$

Red: Combined

POLARBEAR First Season Results: Angular power spectrum

97.2% rejection of "no lensing B-modes"

- Including possible systematic instrumental biases
- Including estimate of foreground bias



Amplitude of lensing compared to ΛCDM:

$$1.12 \pm 0.61\ (stat)\ ^{+0.04}_{-0.12}\ (sys) \pm 0.07\ (mult)$$

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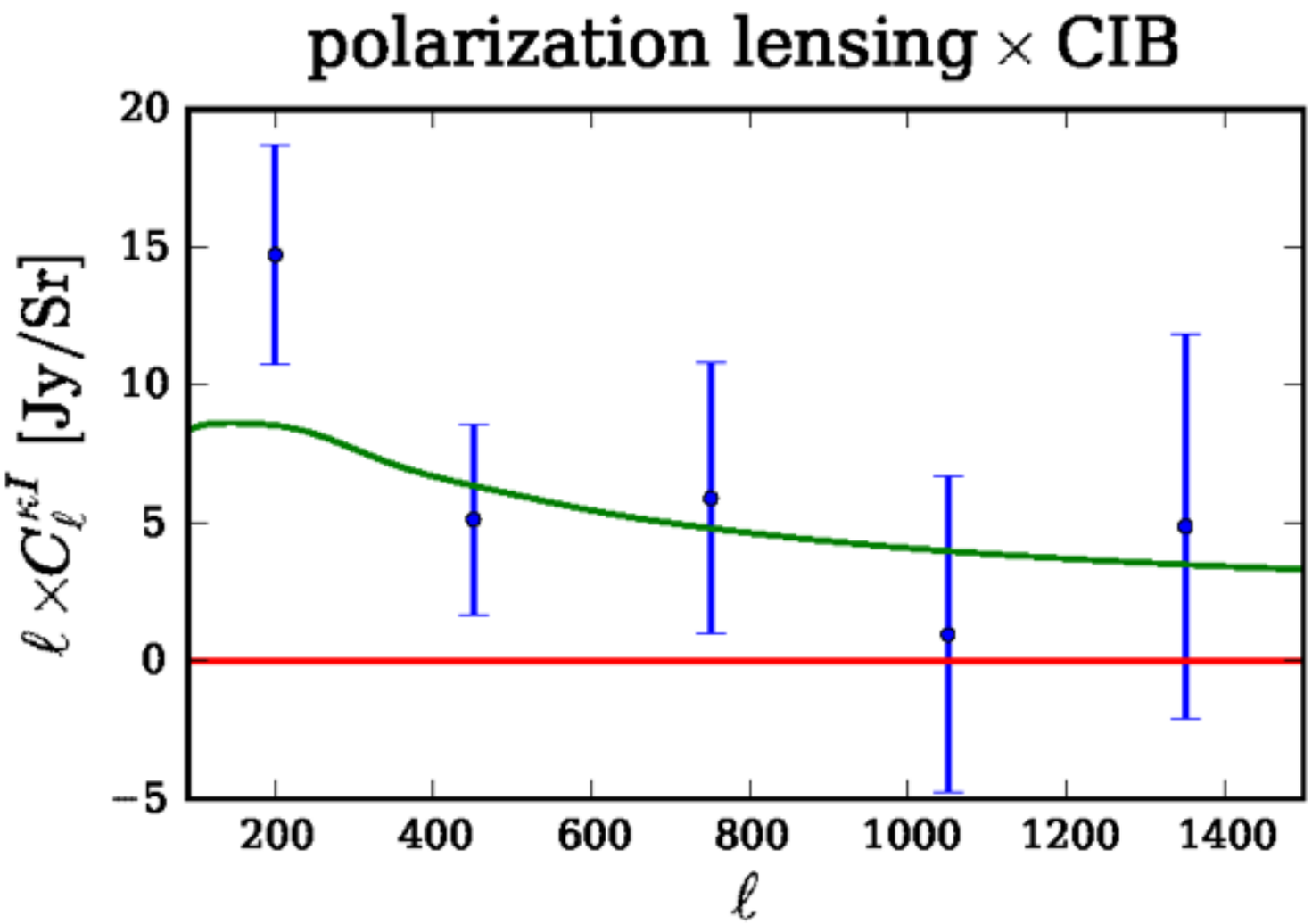
ApJ 794, 171 (2014)

POLARBEAR First Season Results: Galaxy cross-correlation

- Cross-correlation with cosmic infrared background (CIB)
  - Herschel-ATLAS data
- 4.0 sigma rejection of "no lensing"



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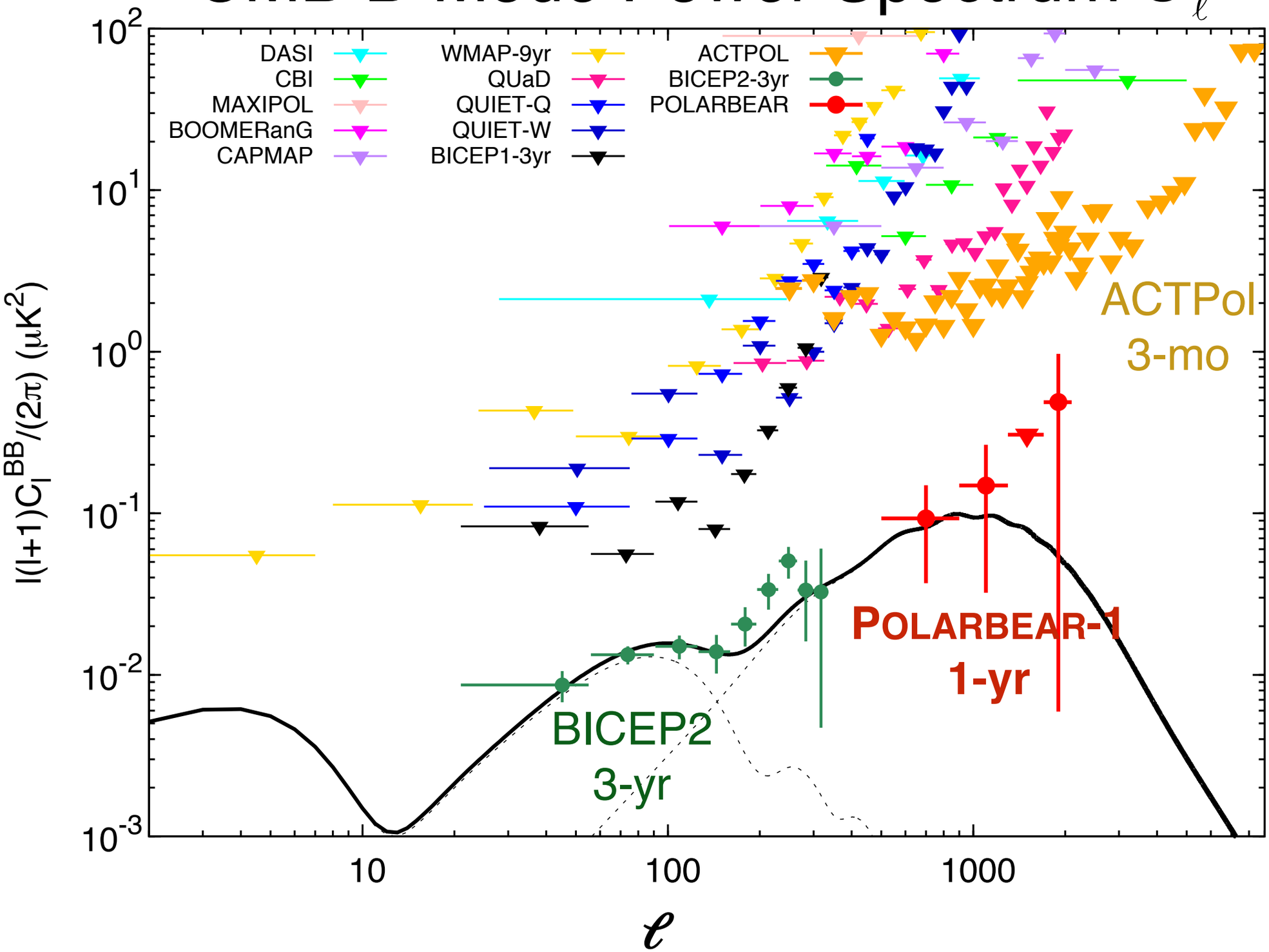
PRL 112, 131302 (2014)

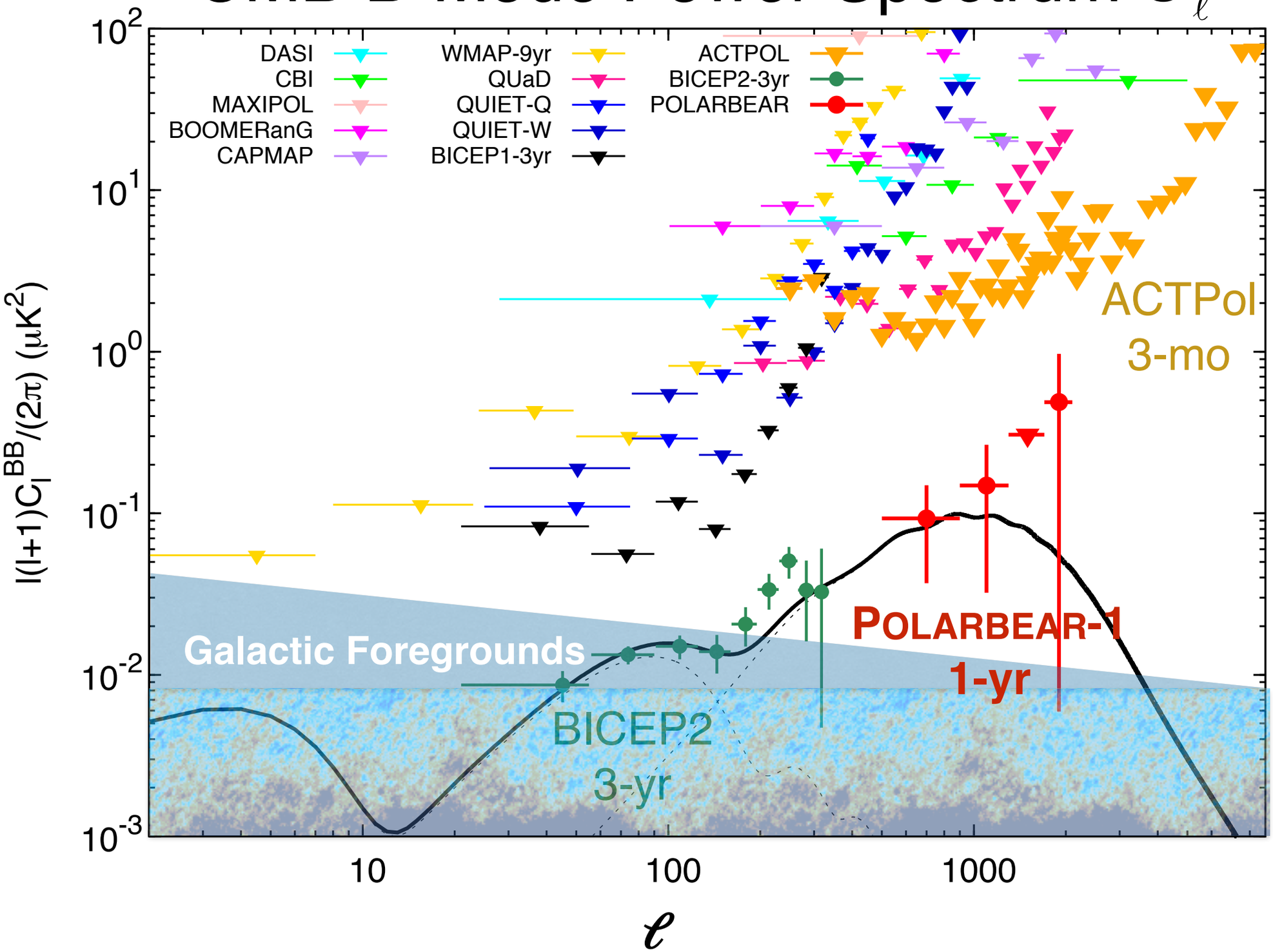
POLARBEAR-1

CMB B-Mode Power Spectrum C_ℓ^{BB}



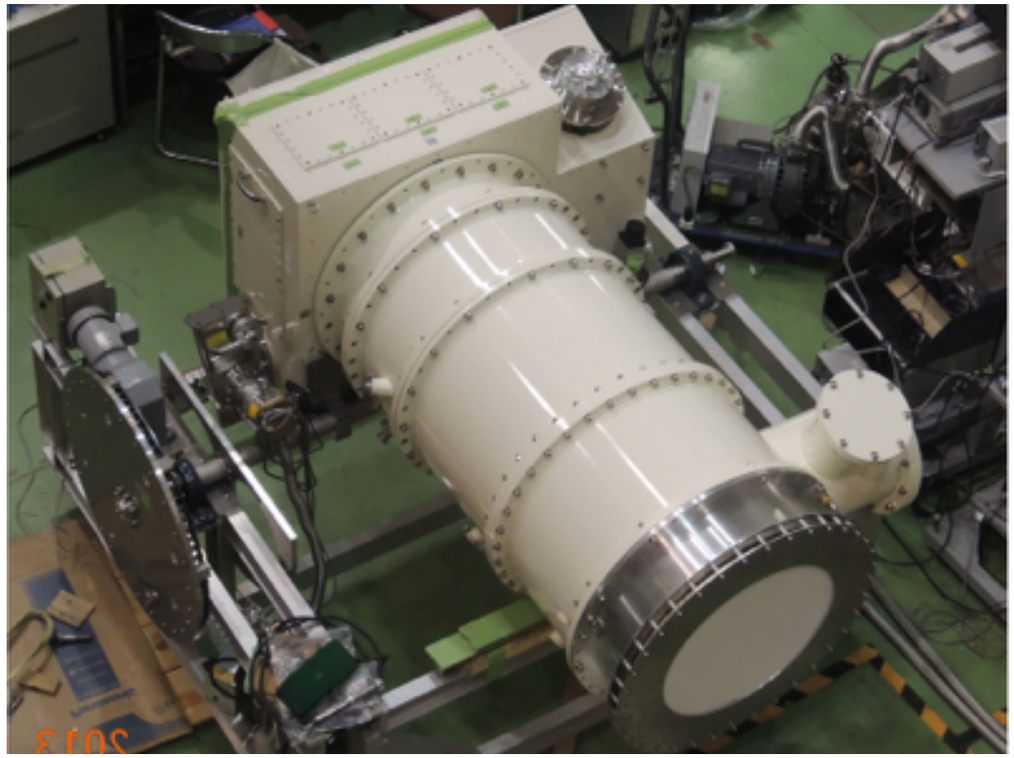
POLARBEAR-1

CMB B-Mode Power Spectrum C_ℓ^{BB}



POLARBEAR-2

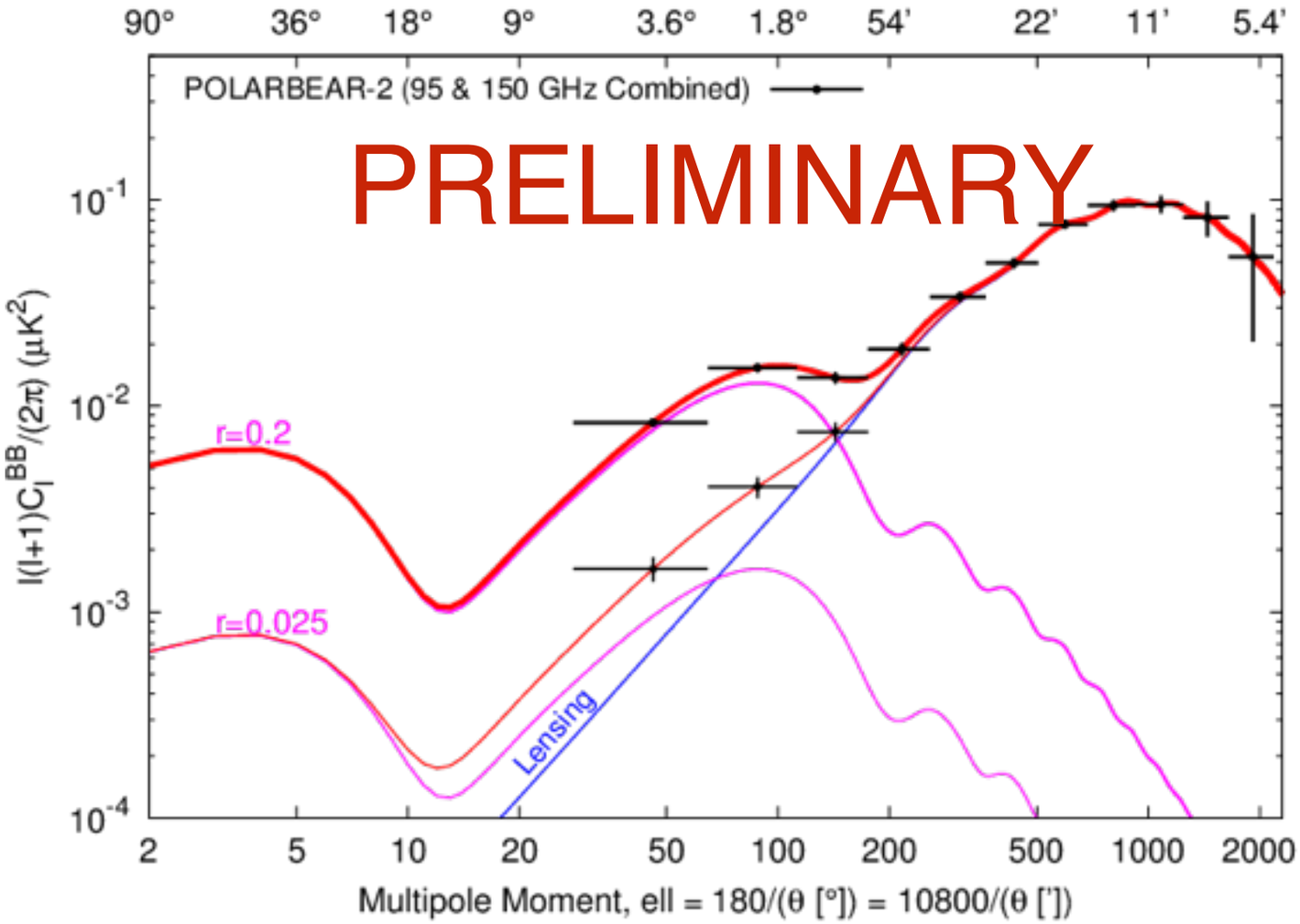
Instrument overview



POLARBEAR-2

Overview

- Next-generation receiver design
- Larger focal plane, field-of-view
- Broadband optics, multi-chroic pixels
- **$\sigma(\Sigma m_\nu) < 100$ meV**



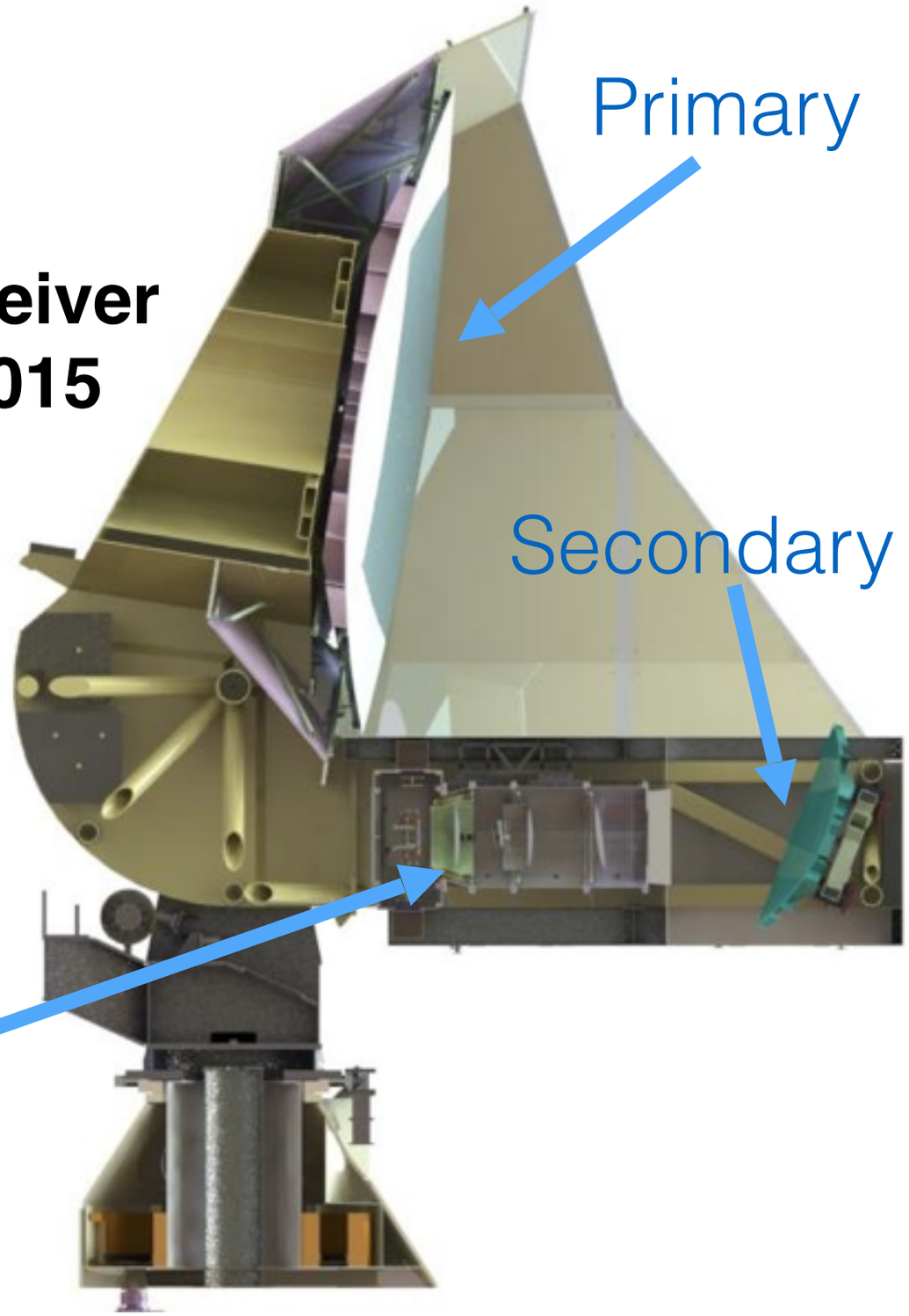
	POLARBEAR-1	POLARBEAR-2
Frequency	150 GHz	95 GHz + 150 GHz
Pixels	637	1897
Detectors	1274	7588
Field-of-view	2.3°	4.8°

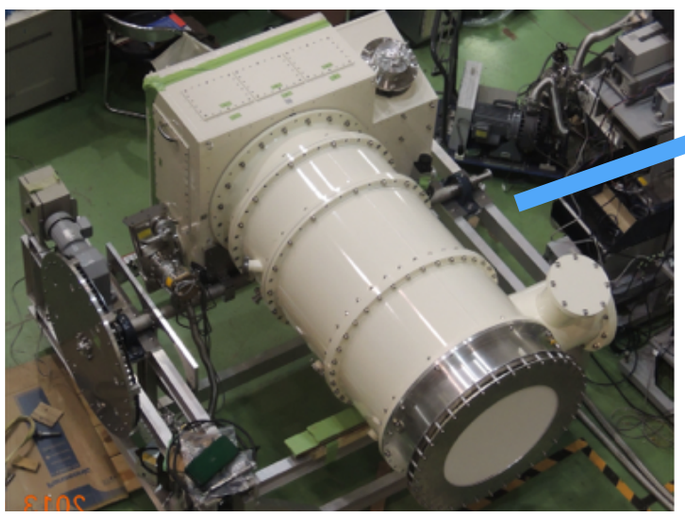
POLARBEAR-2

Overview

- Next-generation receiver design
- Larger focal plane, field-of-view
- Broadband optics, multi-chroic pixels
- **$\sigma(\Sigma m_\nu) < 100$ meV**

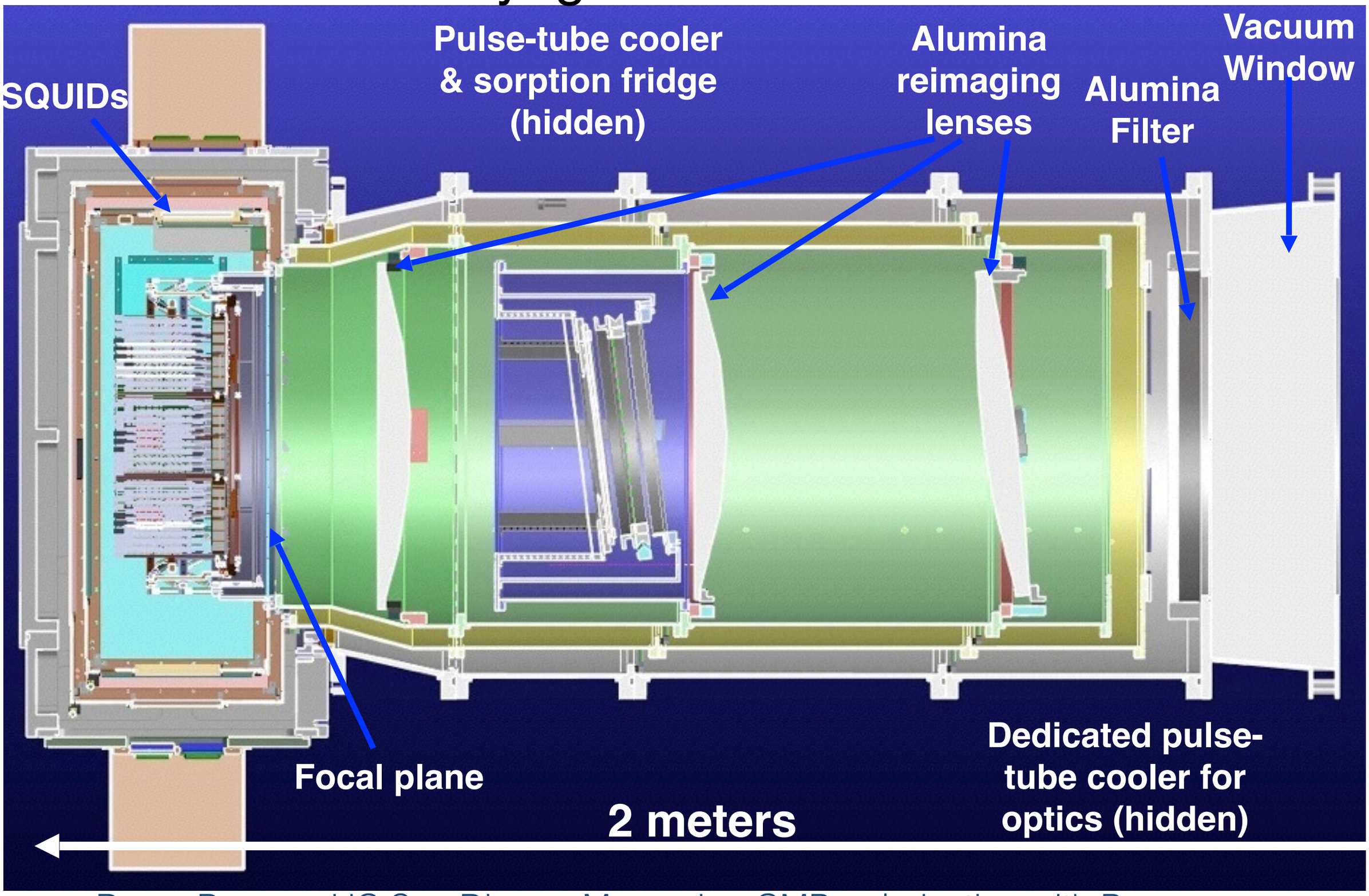
First PB-2 receiver deploying 2015





POLARBEAR-2

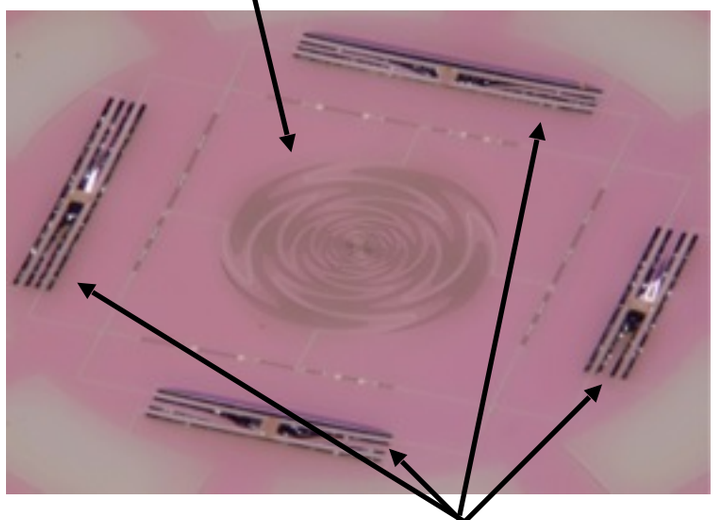
Cryogenic Receiver



POLARBEAR-2

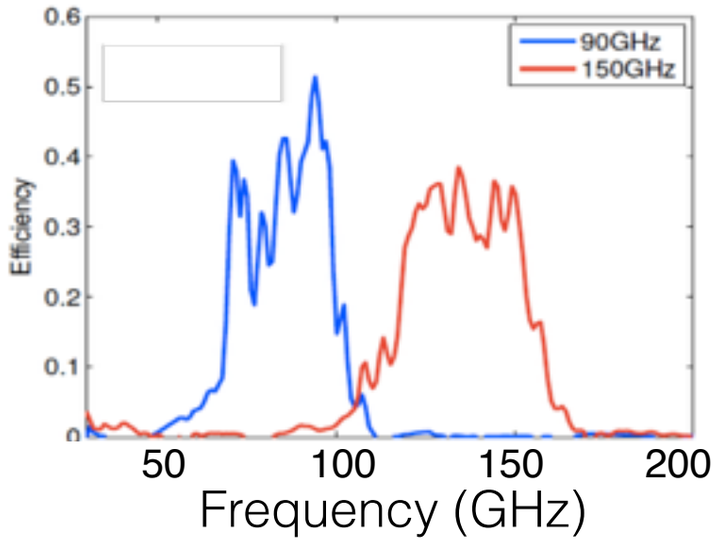
Focal Plane

Broadband sinuous antenna

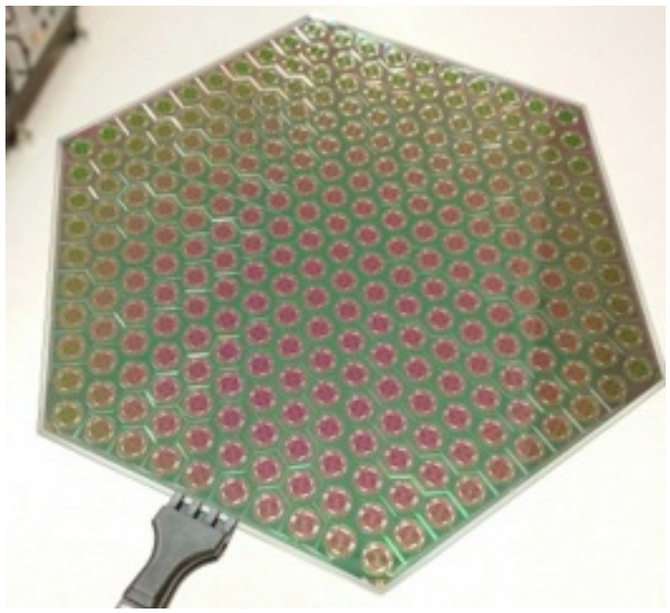


TES bolometers

4 detectors per pixel



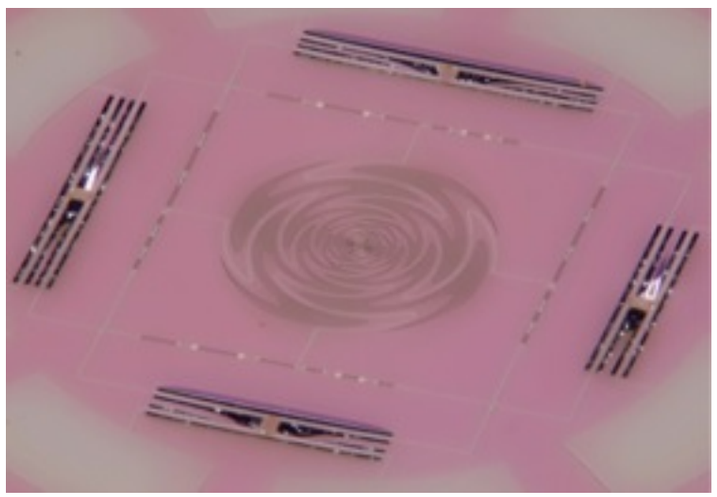
Freq. band measurement



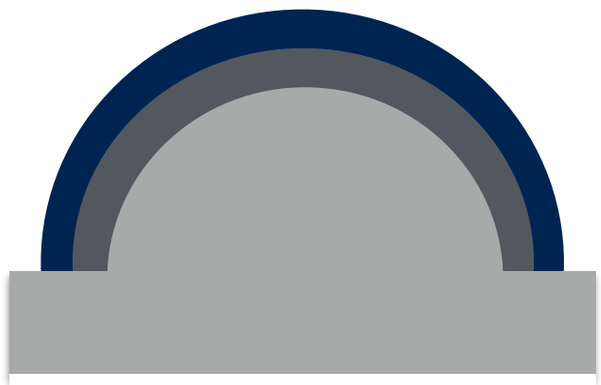
271 pixels / wafer

POLARBEAR-2

Focal Plane



Dichroic pixel

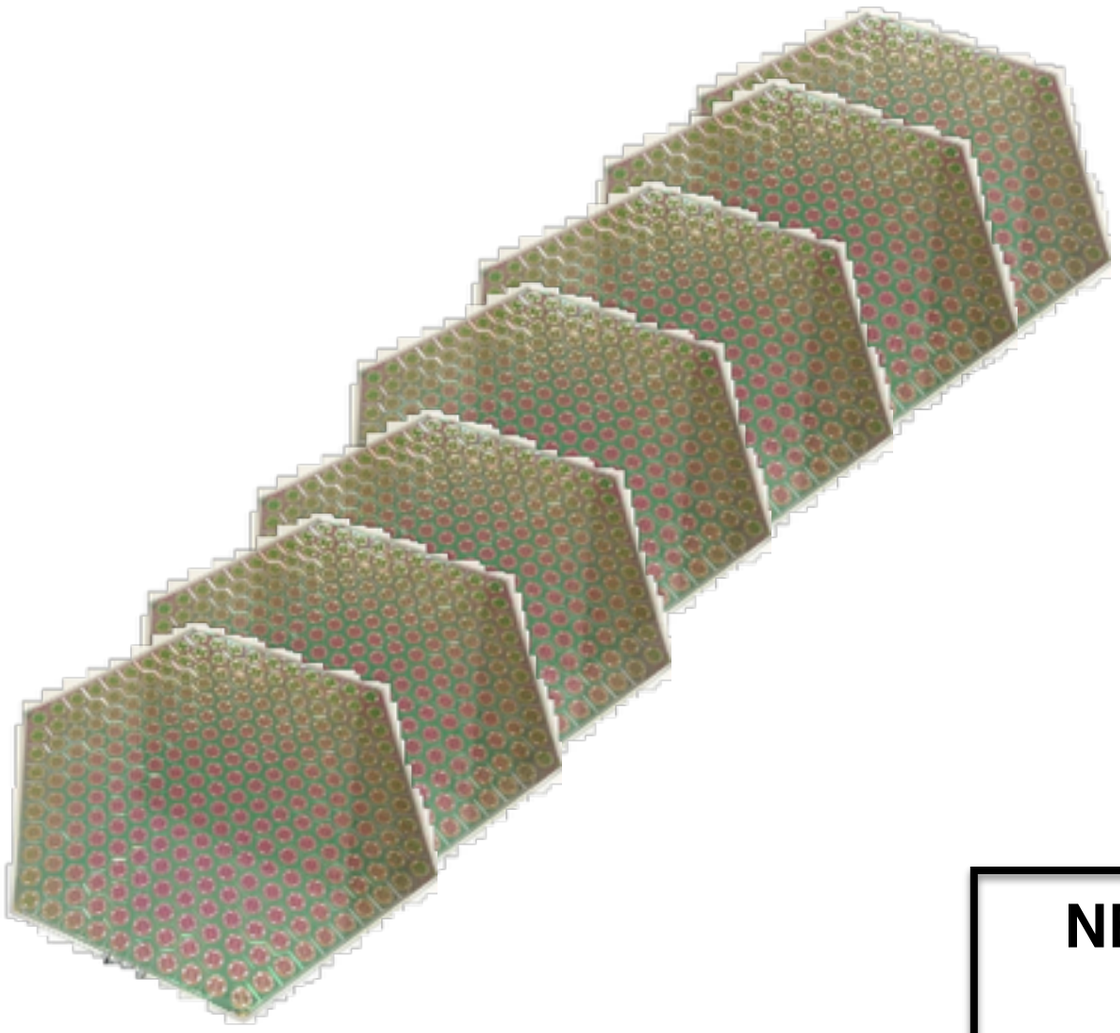


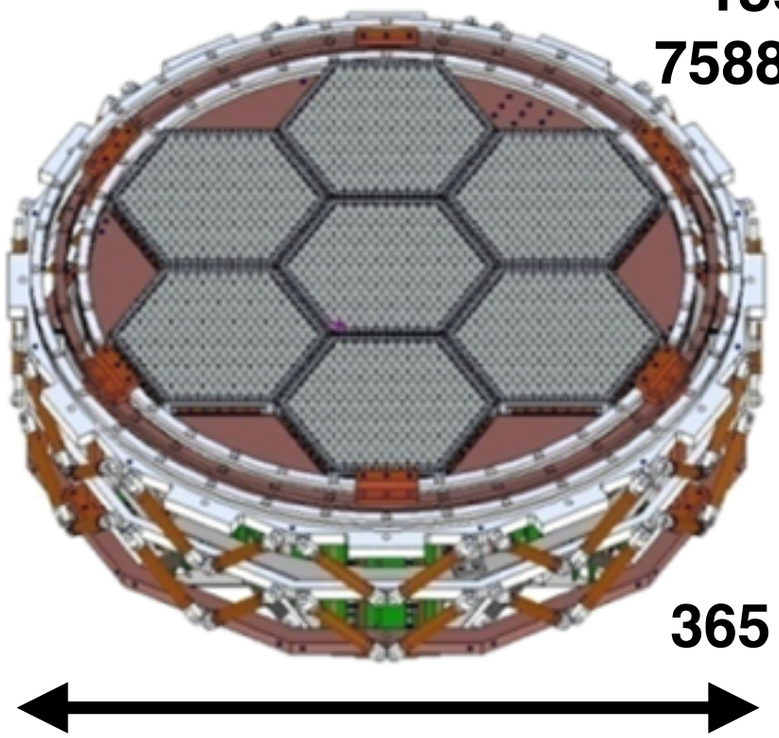
Beam-forming silicon lenslet w/ 2-layer AR coating

AR-coated lenslets on seating wafer

POLARBEAR-2

Focal Plane





1897 pixels
7588 detectors

365 mm

NET bolometer:
360 μK√s

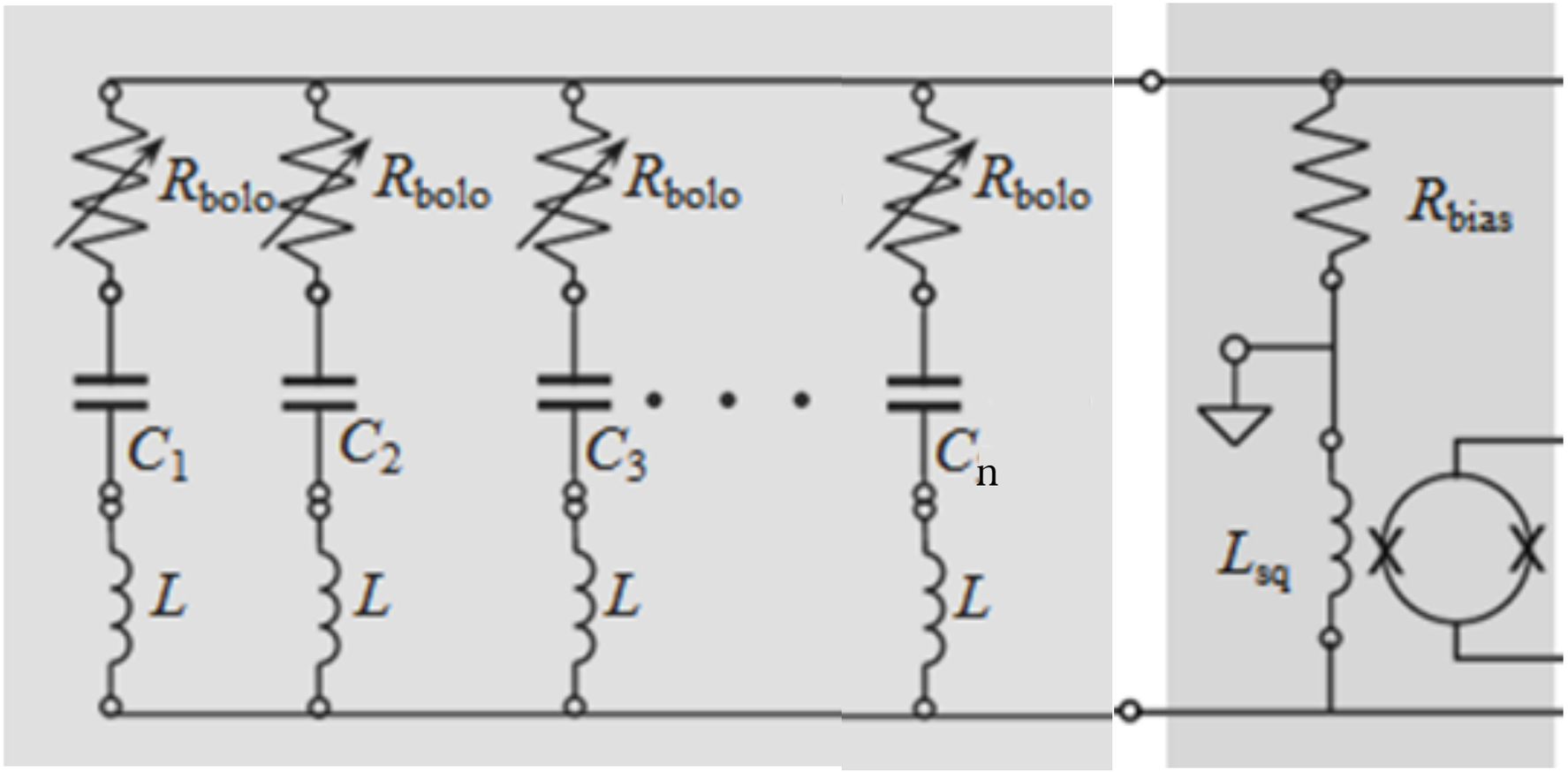
NET array:
4.1 μK√s
(95 GHz + 150 GHz)

POLARBEAR-2

Readout

Frequency domain multiplexing

Dobbs et al. Rev. Sci. Instrum. 83, 073113 (2012)

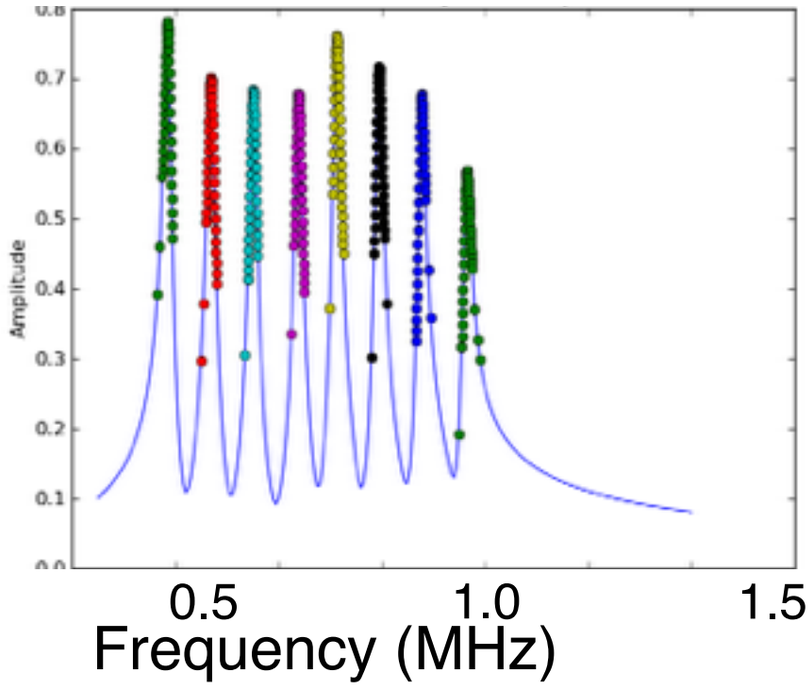


POLARBEAR-2

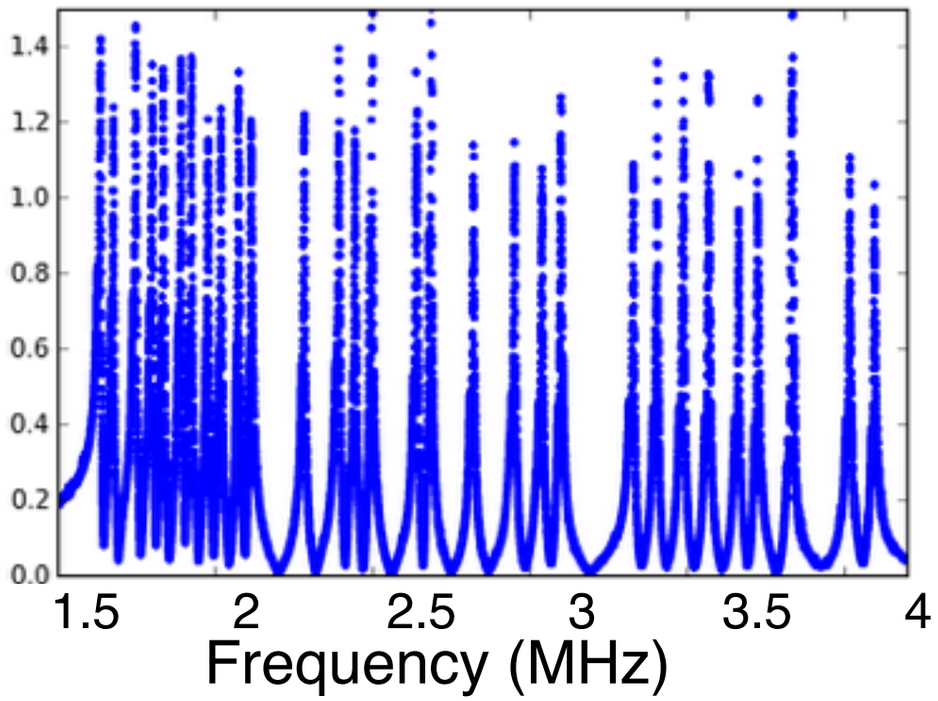
Readout

- PB-2 focal plane has 6x as many detectors as PB-1
  - Increase from 8x to 40x
  - Achieved with closer frequency spacing, increased SQUID readout bandwidth

POLARBEAR-1: 8x



POLARBEAR-2: 40x

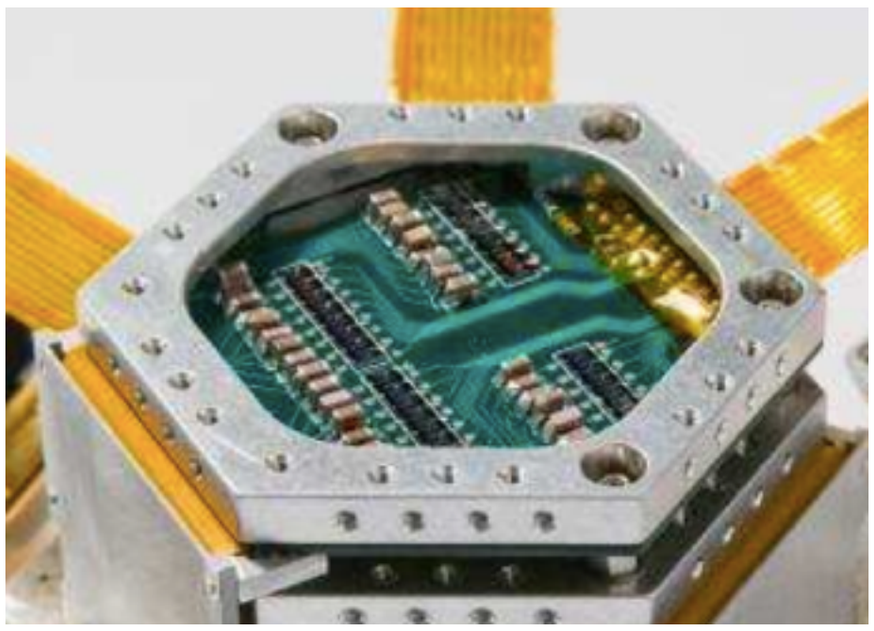


POLARBEAR-2

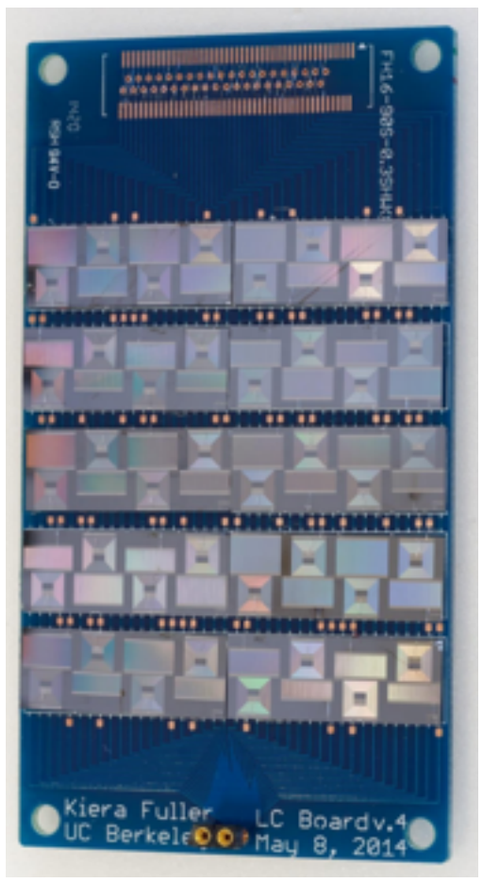
Readout

- PB-2 focal plane has 6x as many detectors as PB-1
  - Increase from 8x to 40x
  - Achieved with closer frequency spacing, increased SQUID readout bandwidth

POLARBEAR-1: 8x



POLARBEAR-2: 40x



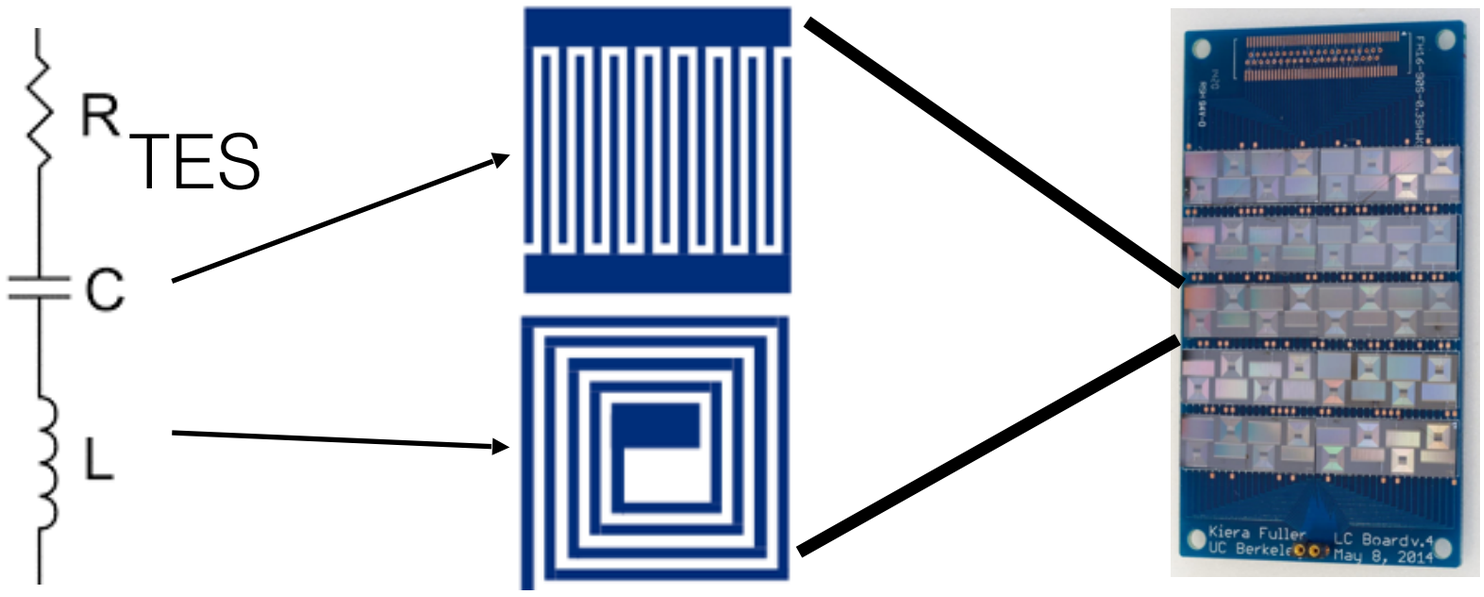
POLARBEAR-2

Readout

Requirements for 40x multiplexing

- Low-loss interdigitated capacitors
- Low-inductance cold wiring
- Digital feedback on SQUID
  - Digital Active Nulling, de Haan et al. 2014
- High-performance analog signal cable

NbTi stripline



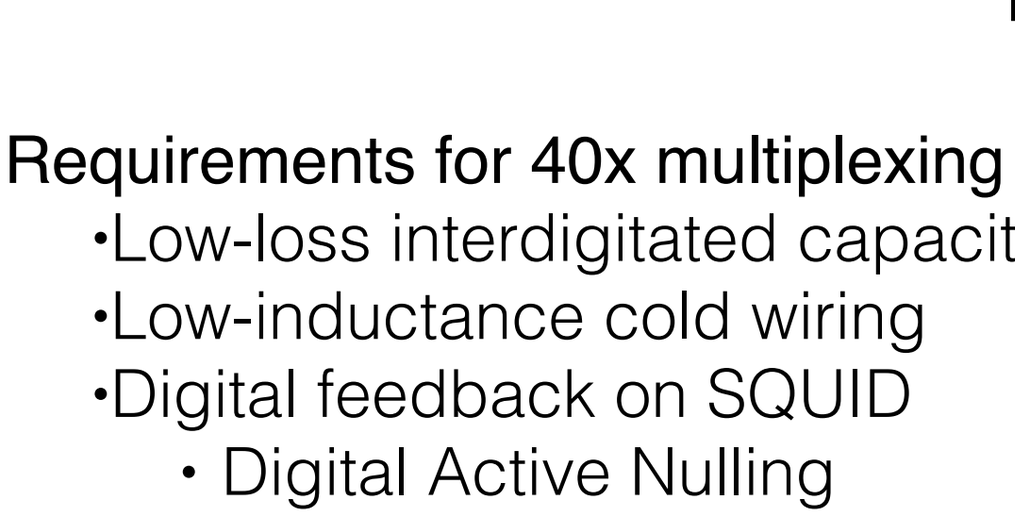
Signal cable

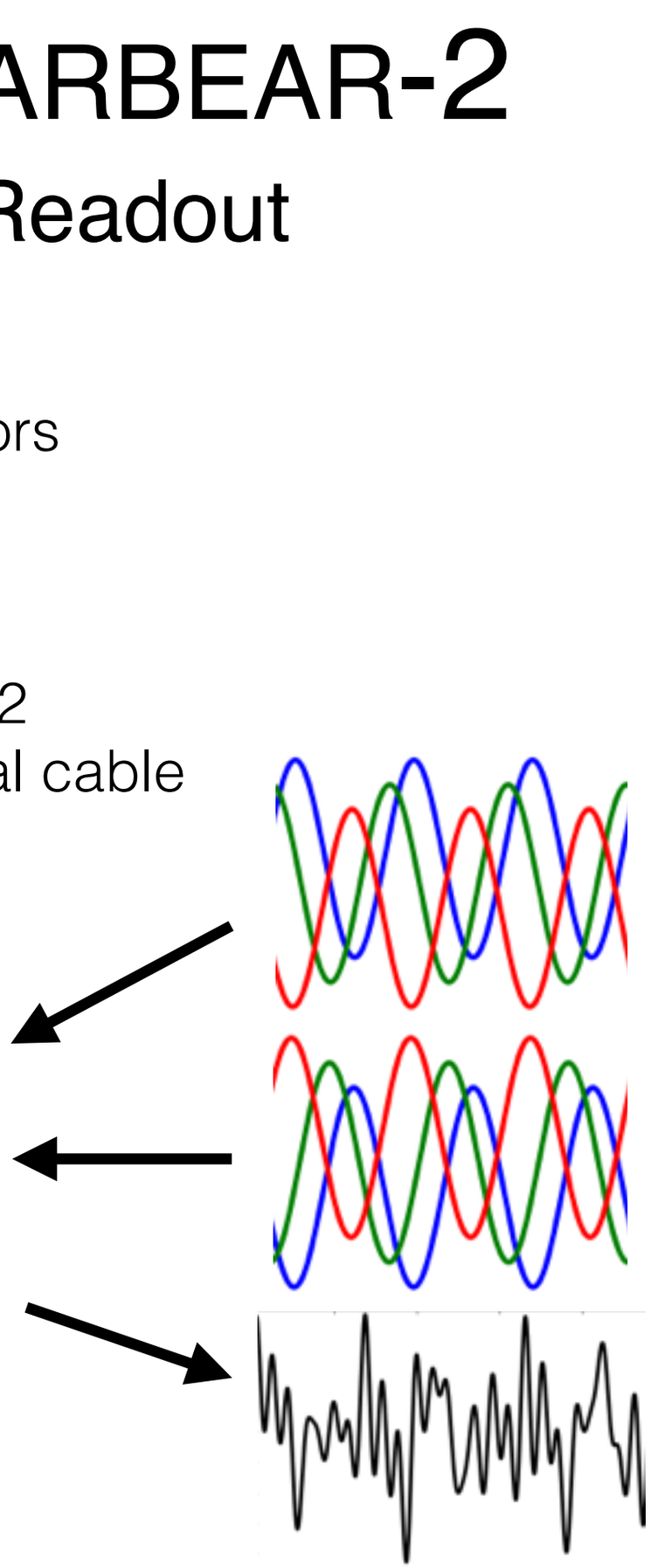
POLARBEAR-2

Readout

Requirements for 40x multiplexing

- Low-loss interdigitated capacitors
- Low-inductance cold wiring
- Digital feedback on SQUID
  - Digital Active Nulling
  - de Haan et al. SPIE ATI 2012
- High-performance analog signal cable





Signal cable

Simons Array

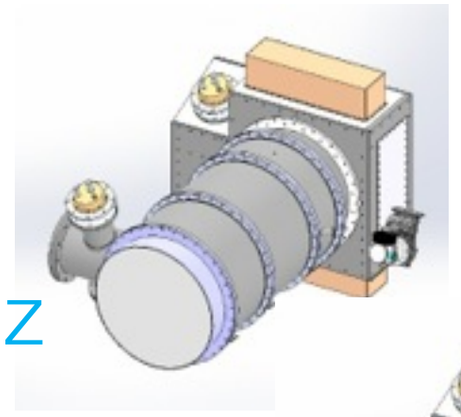
Overview

Simons Array

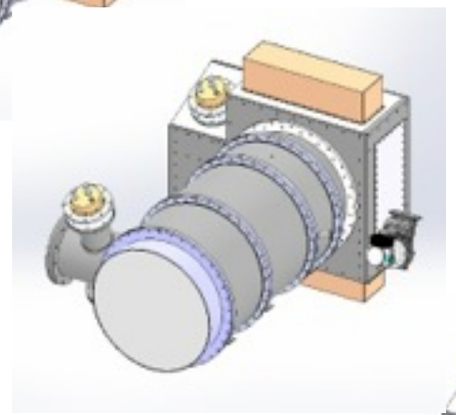
Leverage POLARBEAR experience to rapidly increase sensitivity

- Initial survey: Three-year survey of 65% of sky
- Two telescopes under construction now
  - Installation in 2015

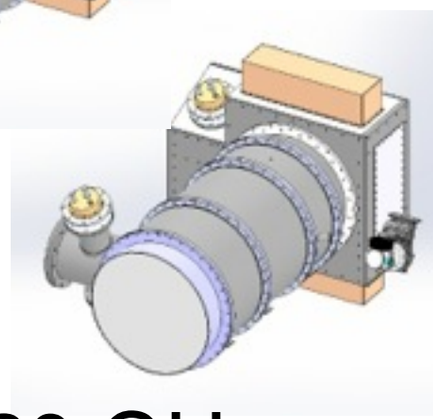
95 GHz / 150 GHz



95 GHz / 150 GHz



150 GHz / 220 GHz



3 receivers (22,764 bolometers) observing at 95,150, 220 GHz

Hardware funded by the Simons Foundation, NSF, MEXT

Simons Array

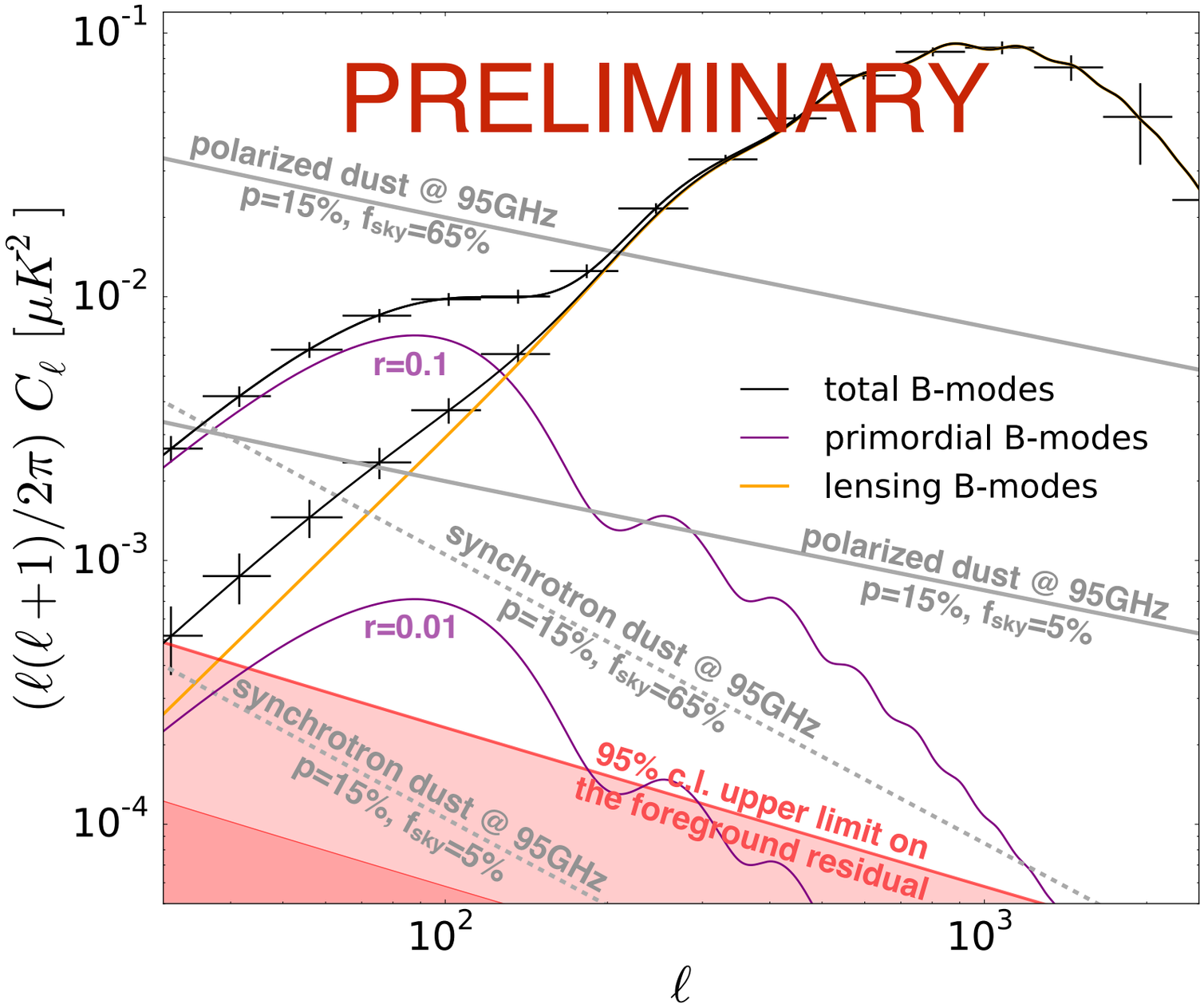
Projected sensitivity

Foreground rejection with multi-frequency Simons Array data

$\sigma(\Sigma m_\nu) = 40$ meV

(w/ DESI BAO)

$\sigma(r = 0.1) = 0.006$



Residual computation method:
Errard et al. 2011, Phys. Rev. D 84, 063005

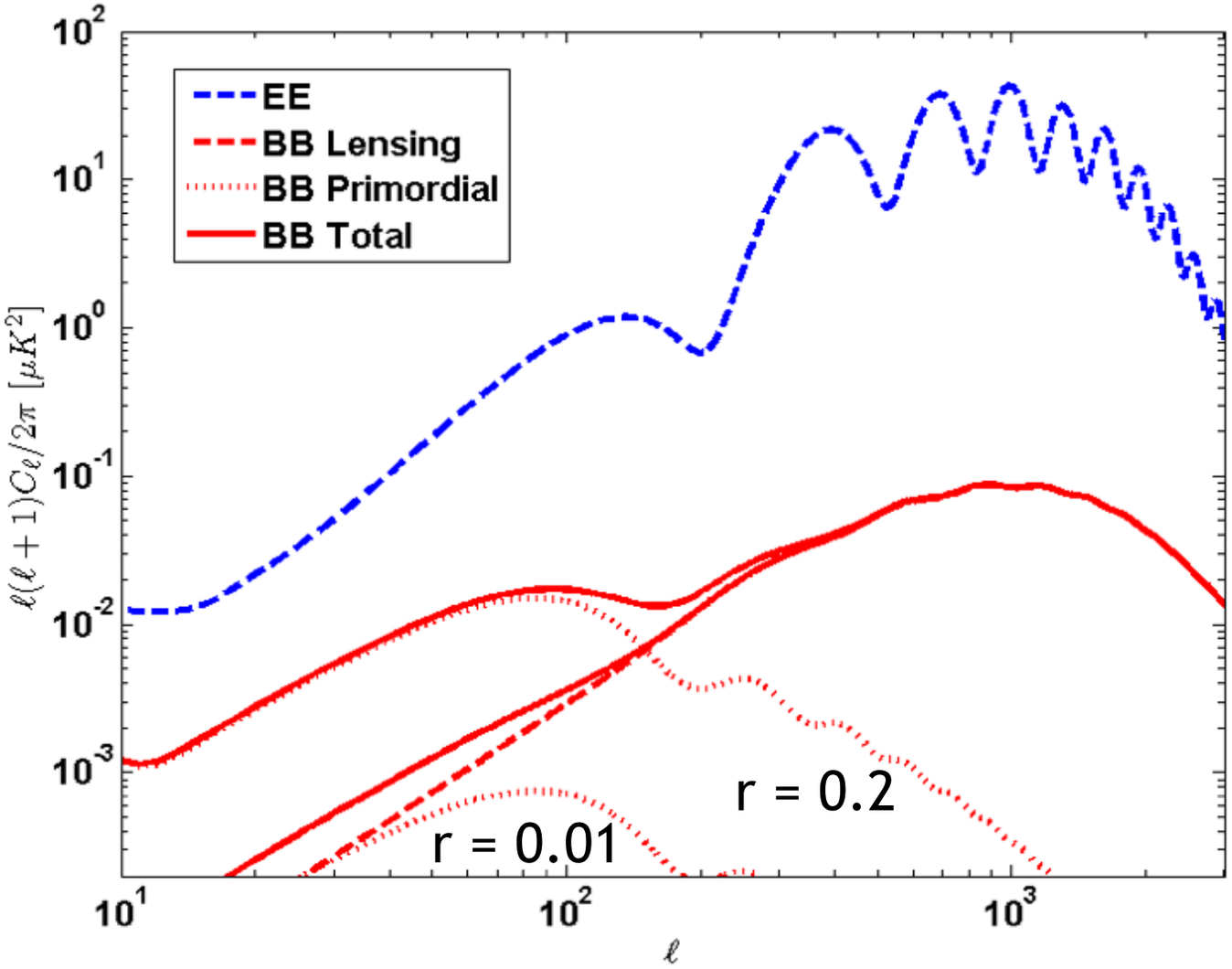
The next generation

- The “ultimate” ground based CMB polarization experiment
  - “CMB-Stage 4”
- Goals:

  $\sigma(\boldsymbol{\Sigma m_\nu}) = 16$ meV

  $\sigma(\boldsymbol{r}) = 0.001$

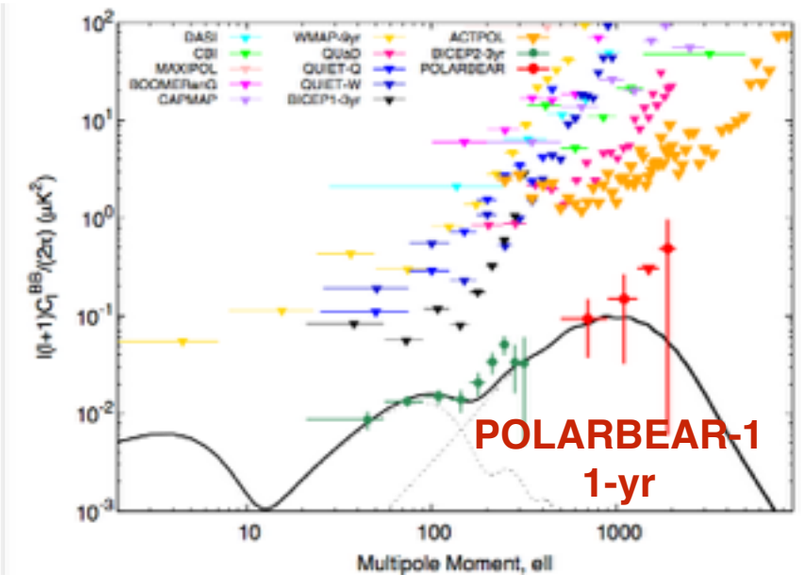
- Instrument:
  - ~100x as many detectors as current generation
  - Frequency range 40 - 240 GHz
  - Survey 50% of sky to ~1 uK-arcmin depth
  - < 3 arcmin resolution

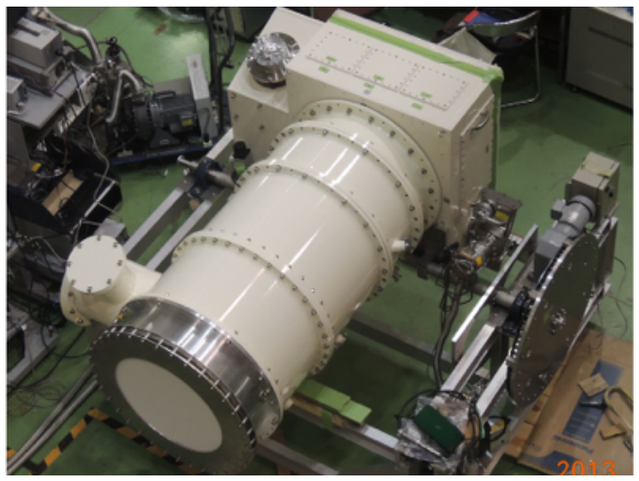


Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381

Thank you

- POLARBEAR-1 in third season of observations
- First-season results with POLARBEAR-1: three analyses showing CMB B-modes
- 4.7σ rejection of no lensing B-modes from CMB
  - Deflection power spectrum:
    POLARBEAR Collab. PRL 113, 021301 (2014)
  - Galaxy cross-correlation:
    POLARBEAR Collab. PRL 112, 131302 (2014)
  - Angular power spectrum:
    POLARBEAR Collab. ApJ 794, 171 (2014)
- POLARBEAR-2 designed for increased sensitivity, foreground mitigation (deploying soon!)
  - Dichroic pixel:
    A. Suzuki et al. JLTP Jan. 2014
  - Readout: Barron et al. SPIE ATI 2014, Bender et al. SPIE ATI 2014, Hattori et al. SPIE ATI 2014
  - Optics: Inoue et al. SPIE ATI 2014
- Simons Array initial survey:
  65% of sky at 3 freqs. (22,764 bolometers)
  - Arnold et al. SPIE ATI 2014





Backup slides