Measuring cosmic microwave background polarization with POLARBEAR

Darcy Barron
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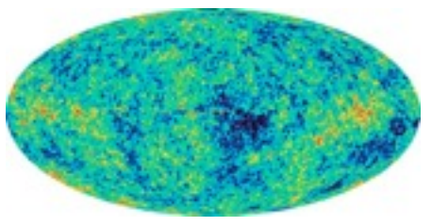
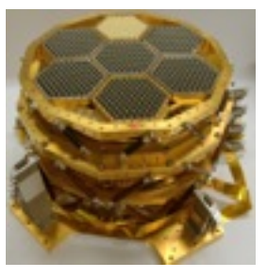
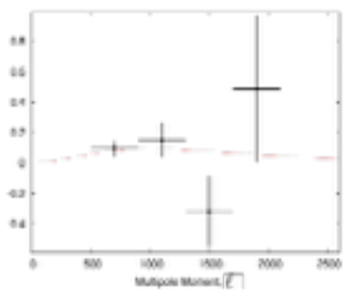
Outline



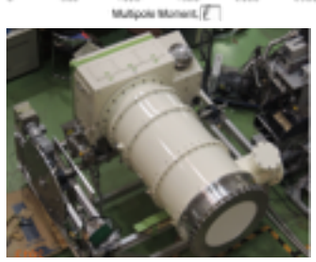
- Scientific motivation



- POLARBEAR-1 instrument



- First season results

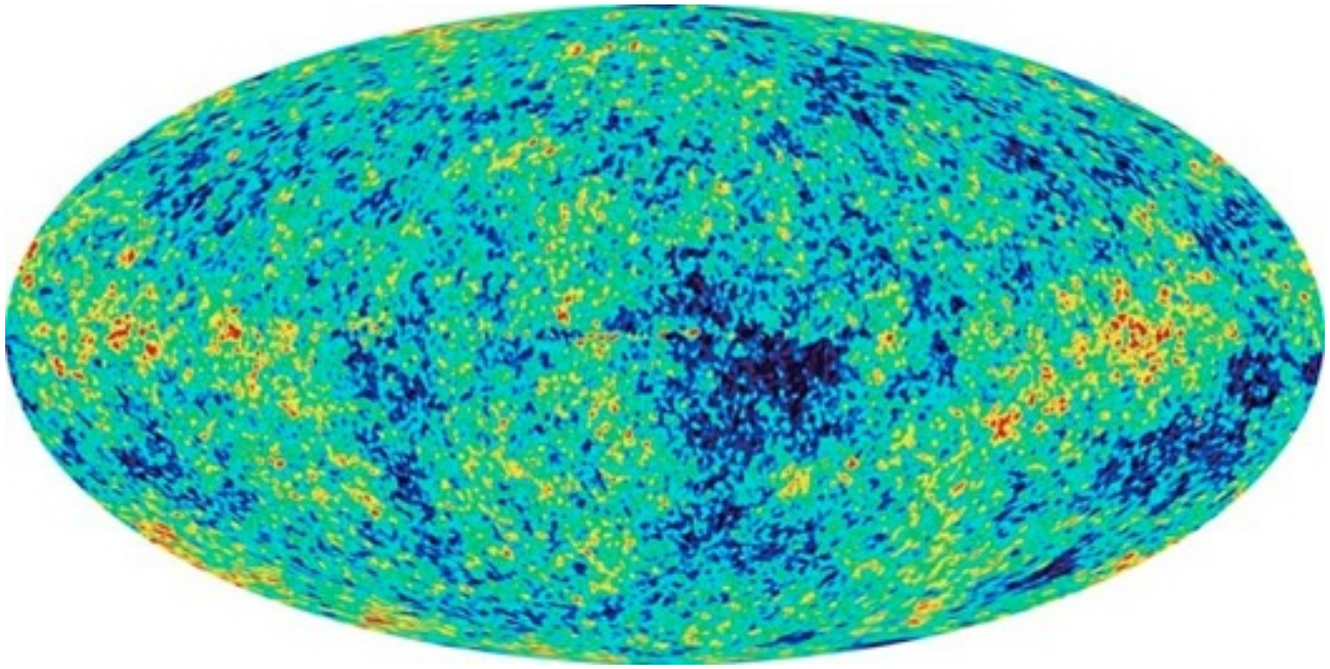


- POLARBEAR-2 instrument

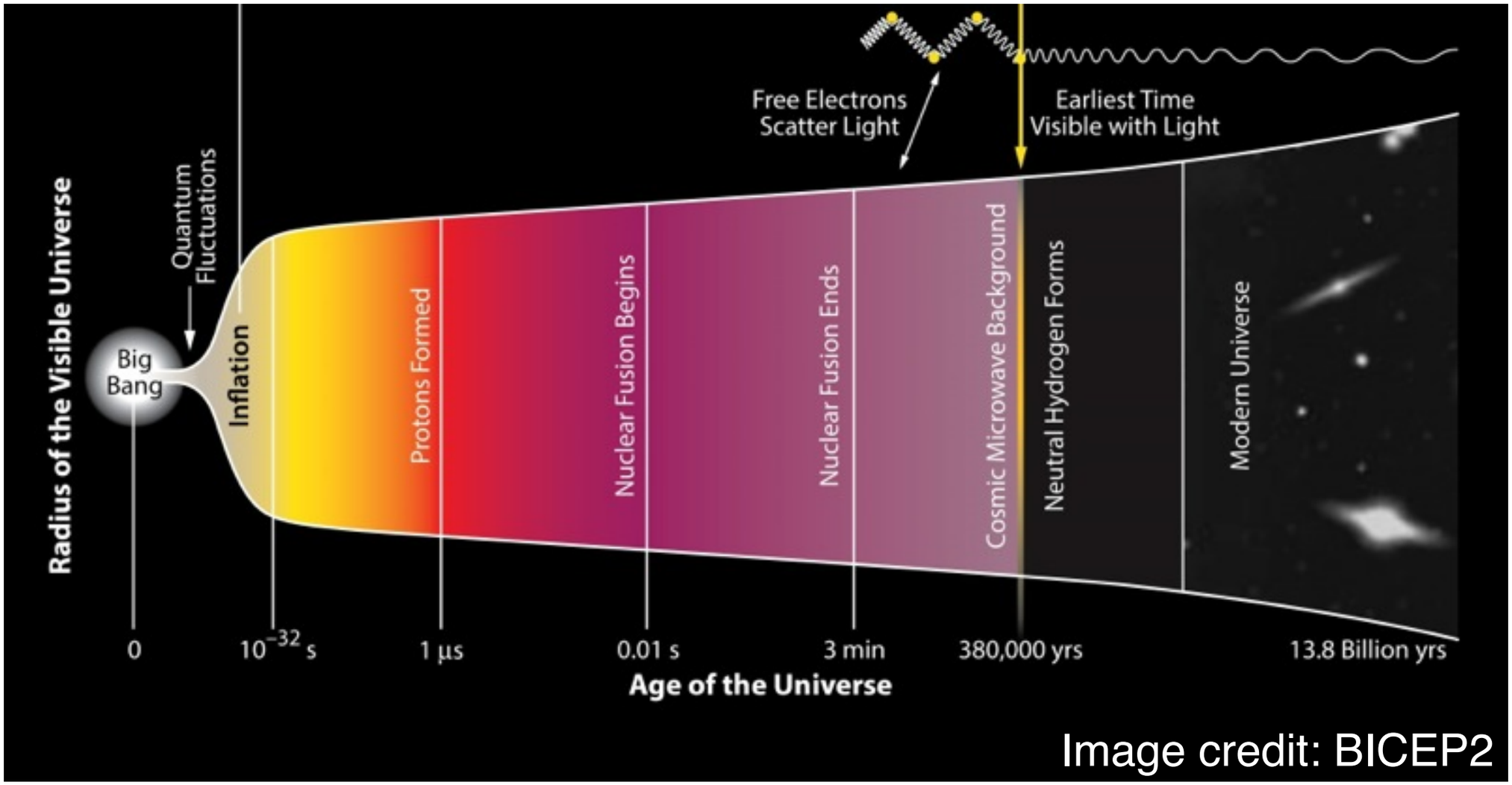
- Simons Array

Scientific motivation:

The cosmic microwave background



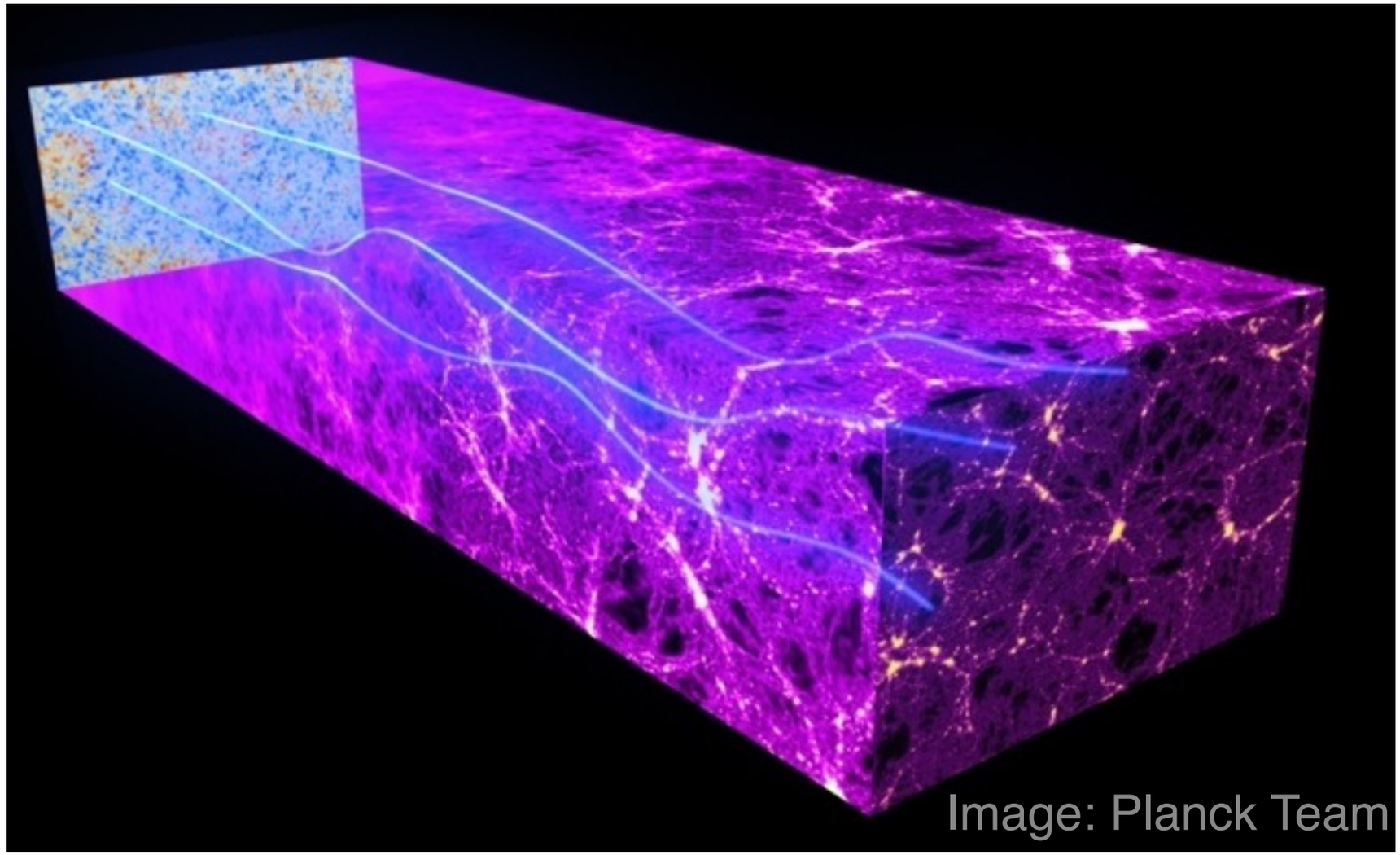
CMB as a snapshot of early universe



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



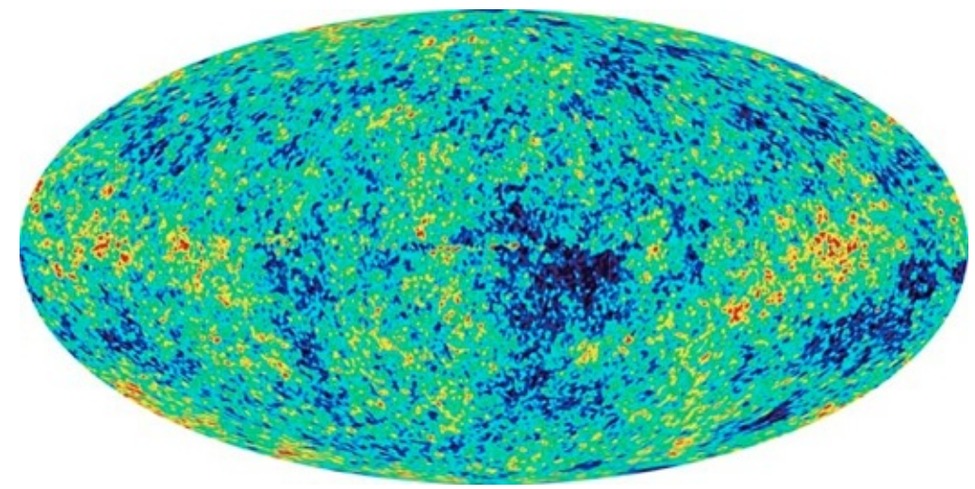
CMB lensing traces all of structure formation history

Lensing Measures:

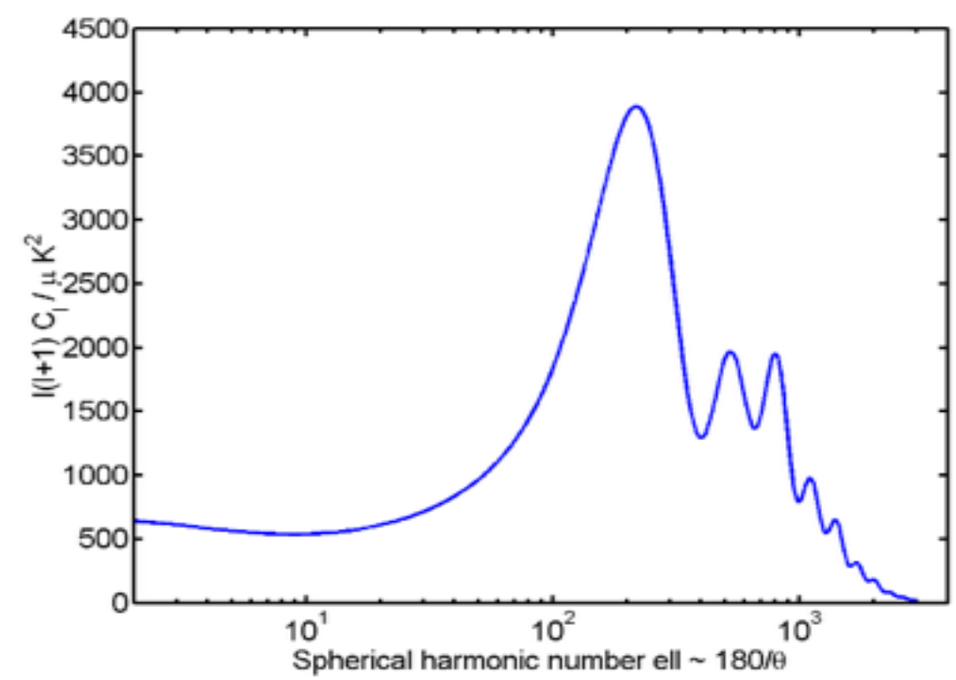
- Influence of dark matter – N_{eff}, sum of the neutrino masses
- Equation of state of dark energy at high redshift

Extracting information from the CMB

Primordial CMB is statistically isotropic



Convert maps to angular power spectrum



CMB Temperature power spectrum

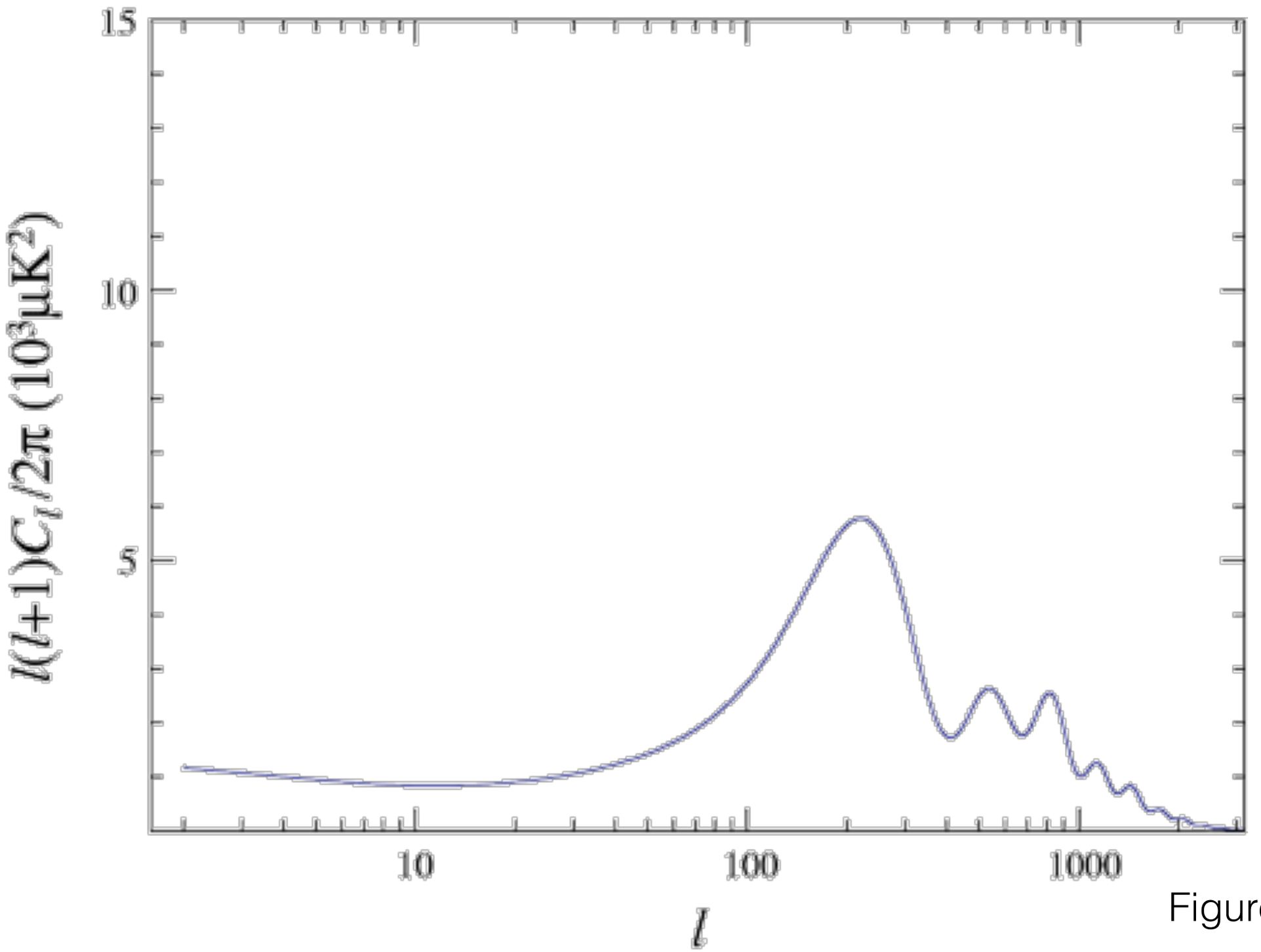
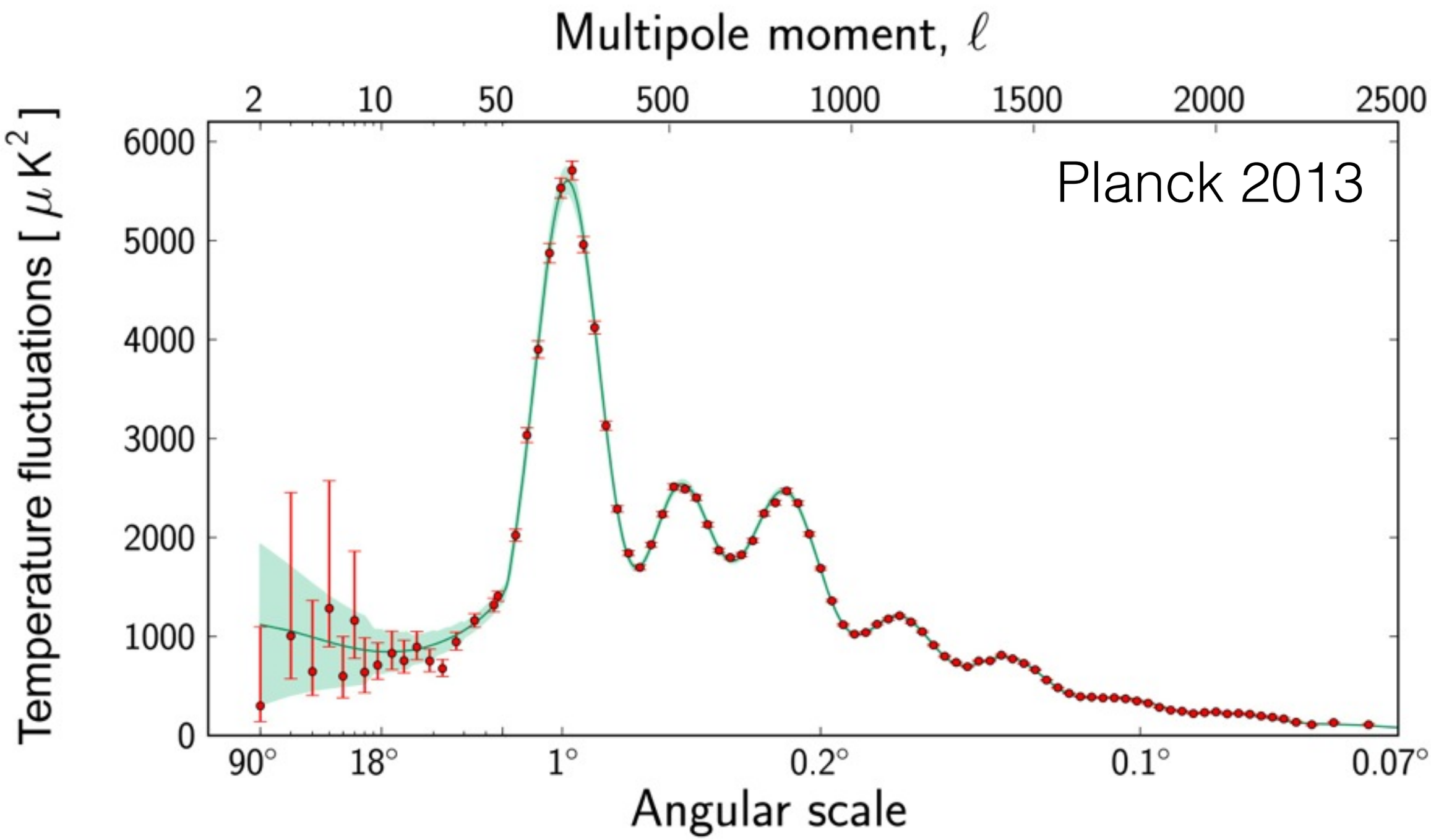
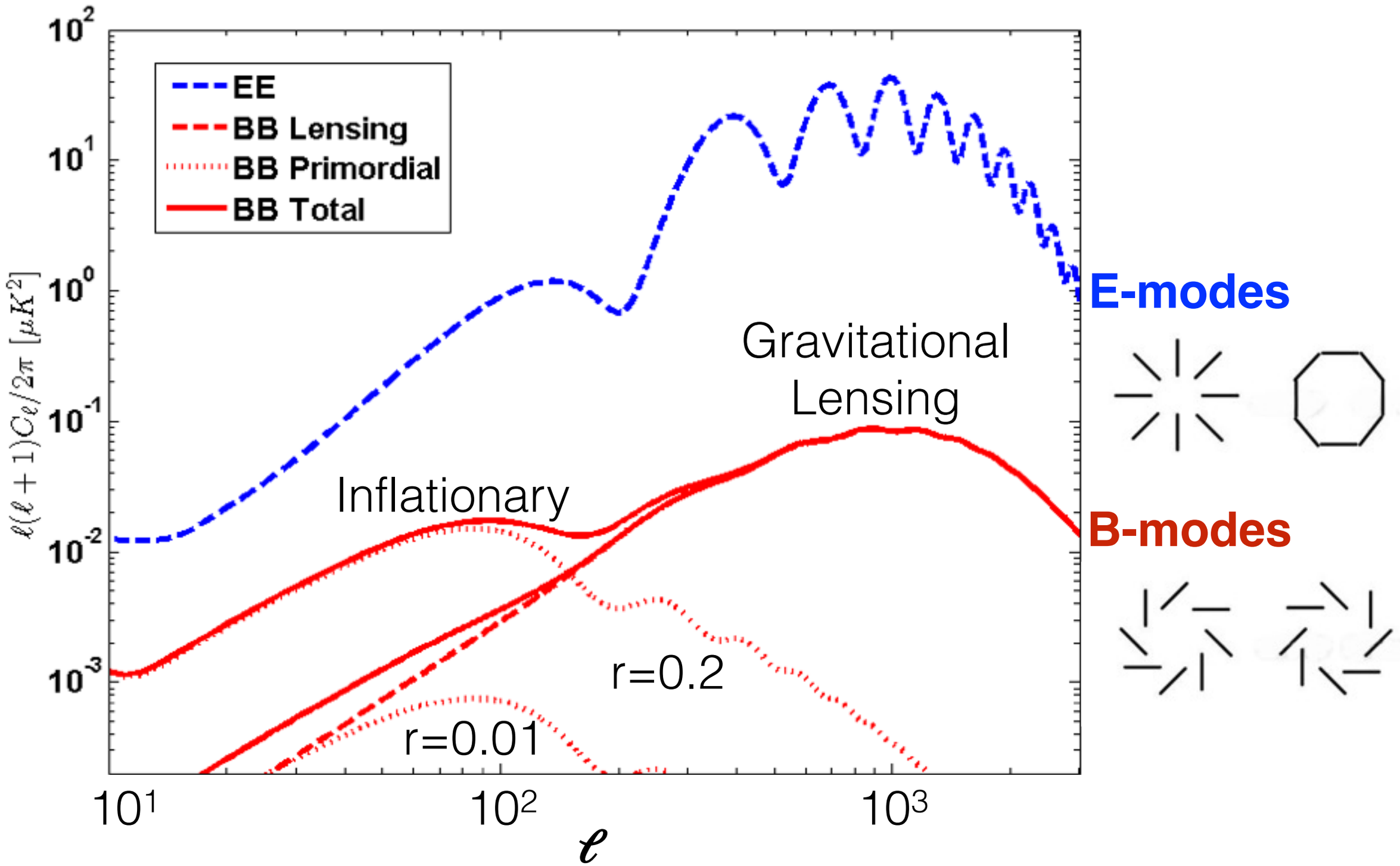


Figure: Wayne Hu

CMB temperature power spectrum



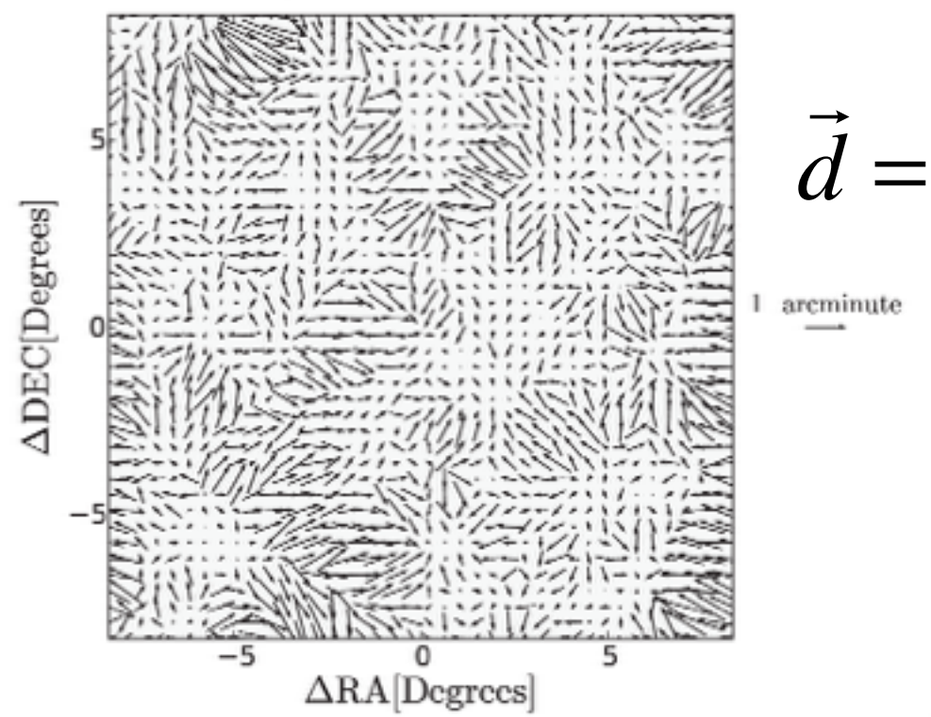
Predicted polarization power spectrum



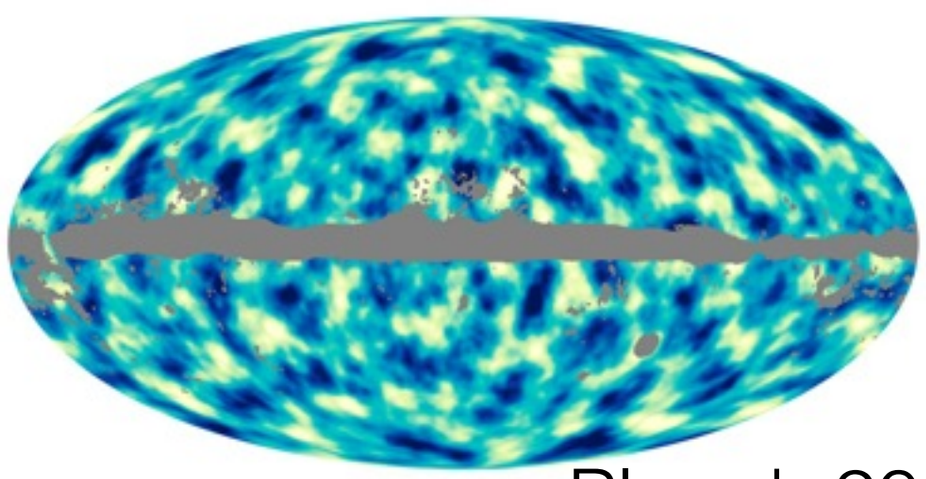
Gravitational lensing of CMB

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

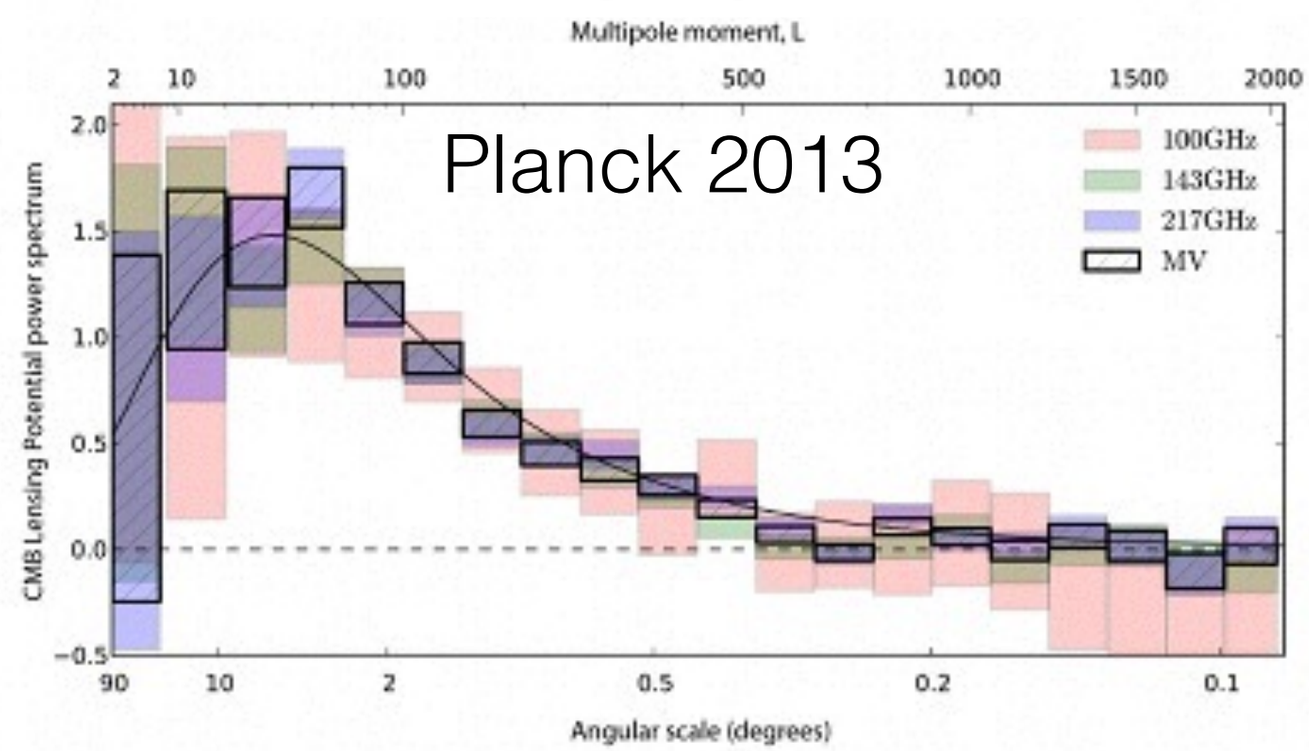
Simulated



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

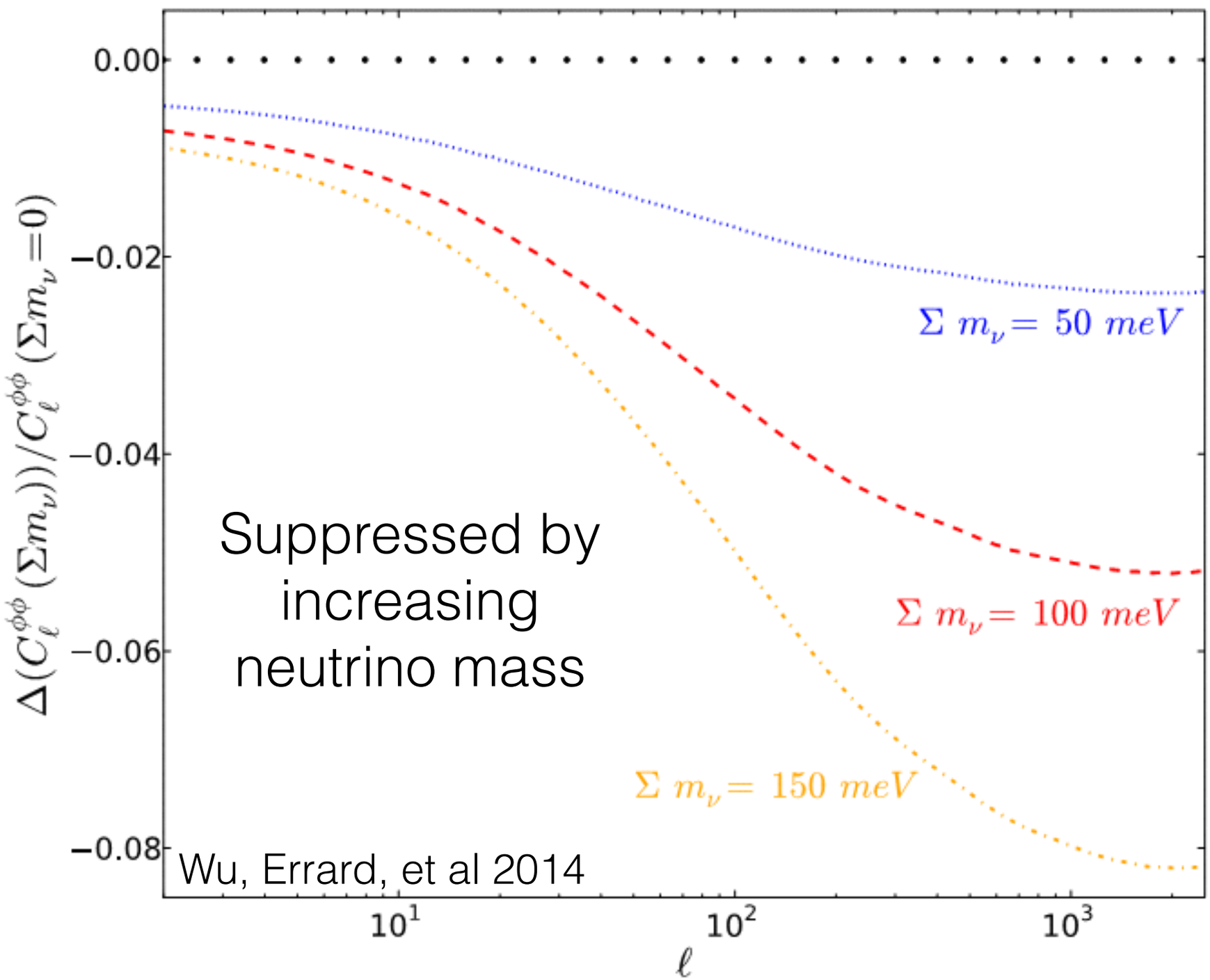


Planck 2013

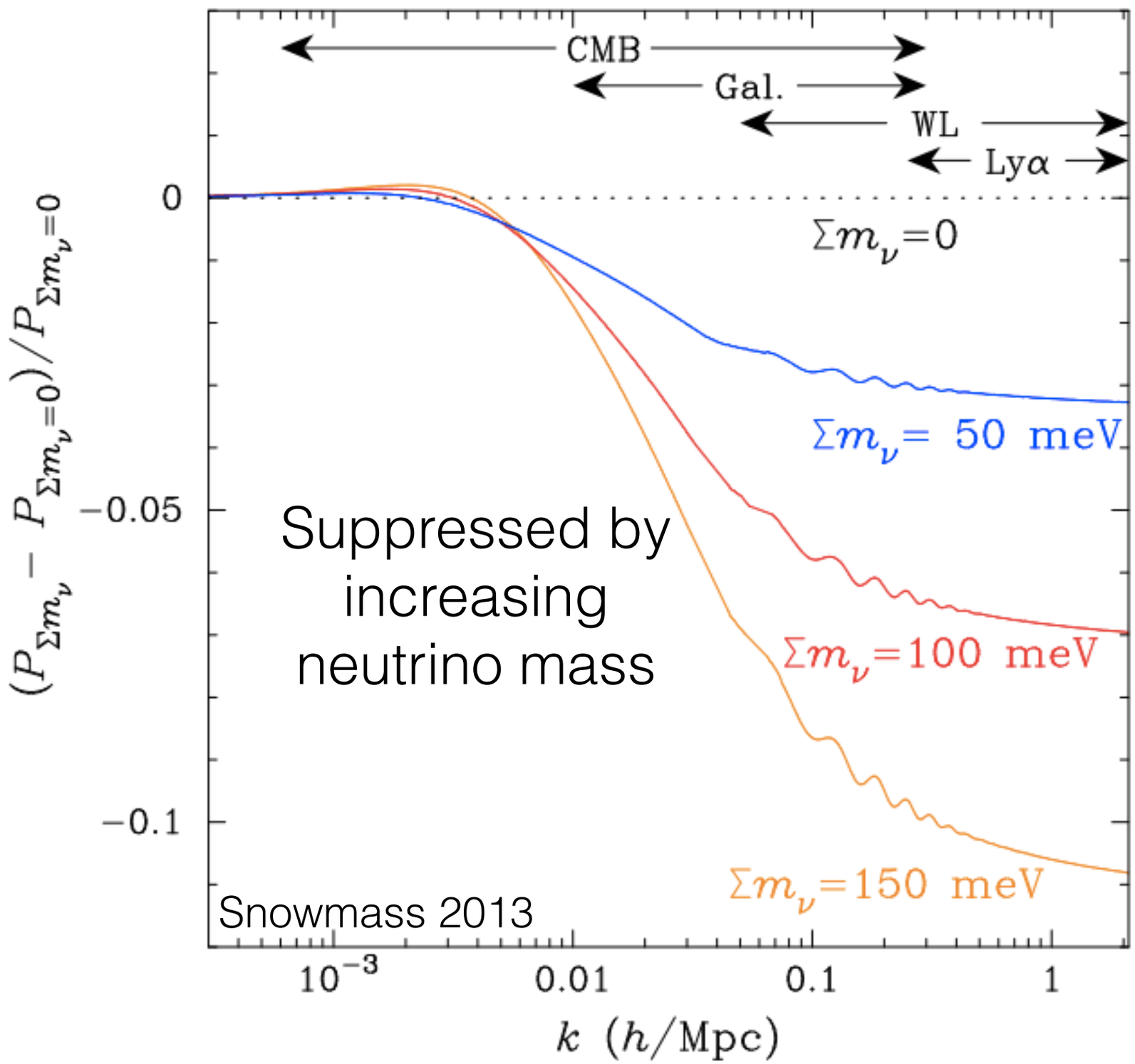


Planck 2013

Effect of neutrinos on structure formation



Effect of neutrinos on structure formation



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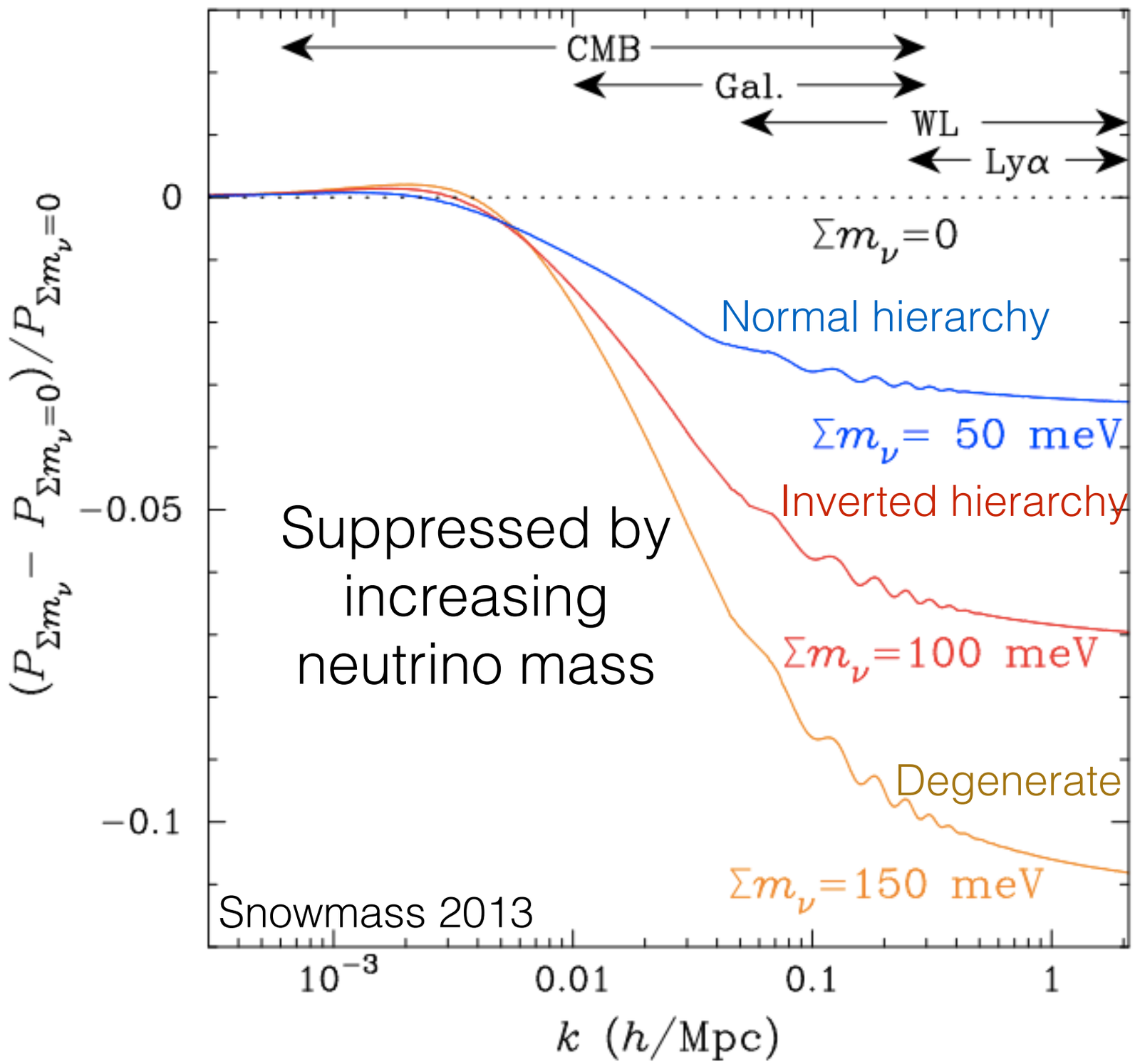
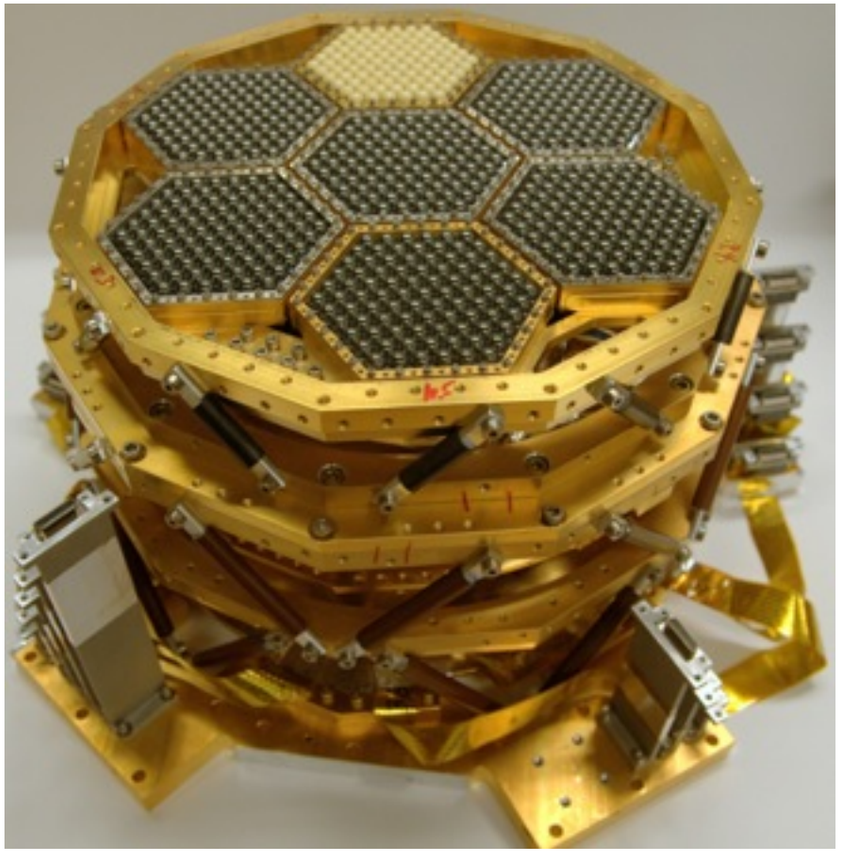


If min. mass (58 meV):

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

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

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Giuseppe Puglisi

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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

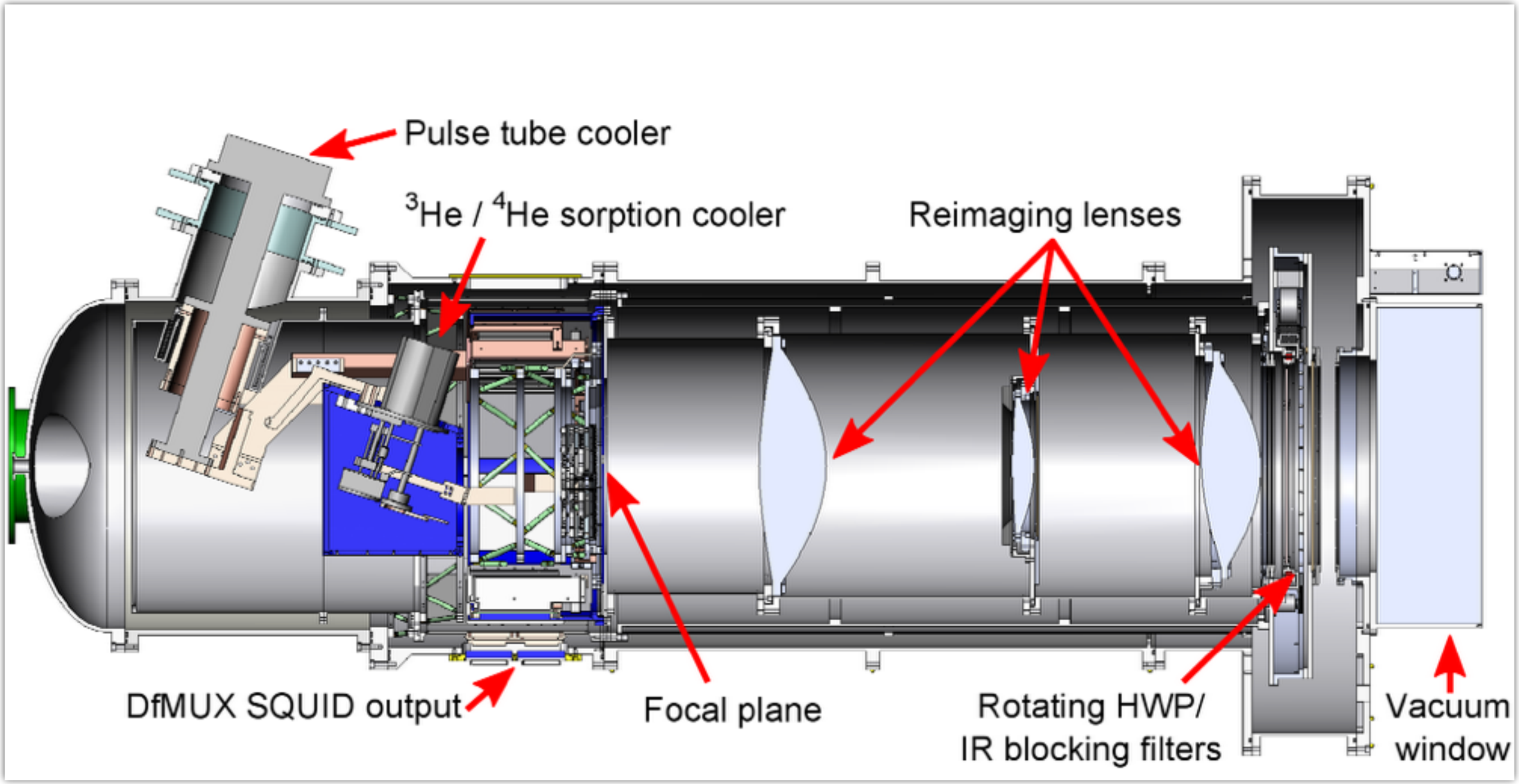
POLARBEAR-1

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

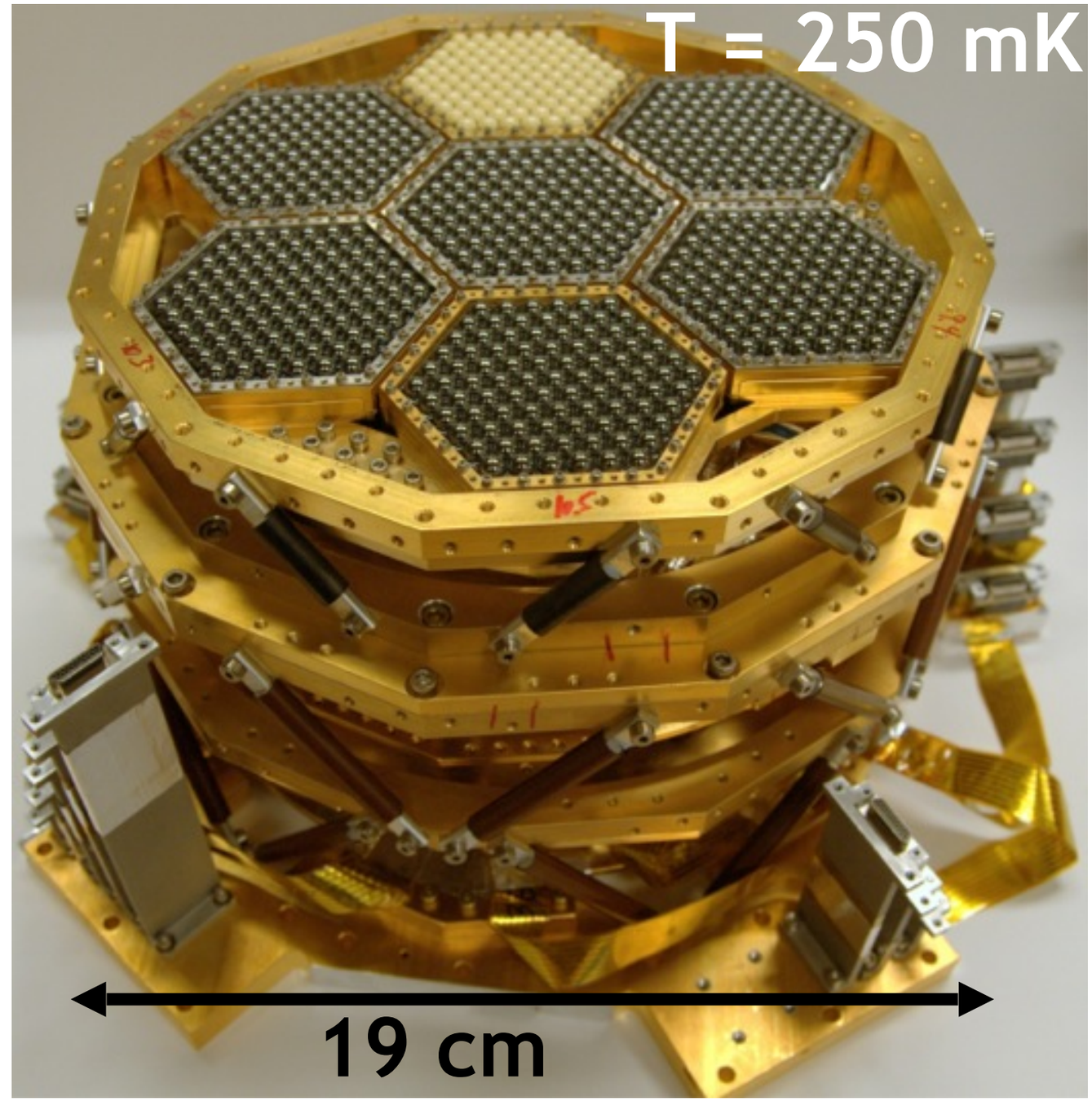


2 meters

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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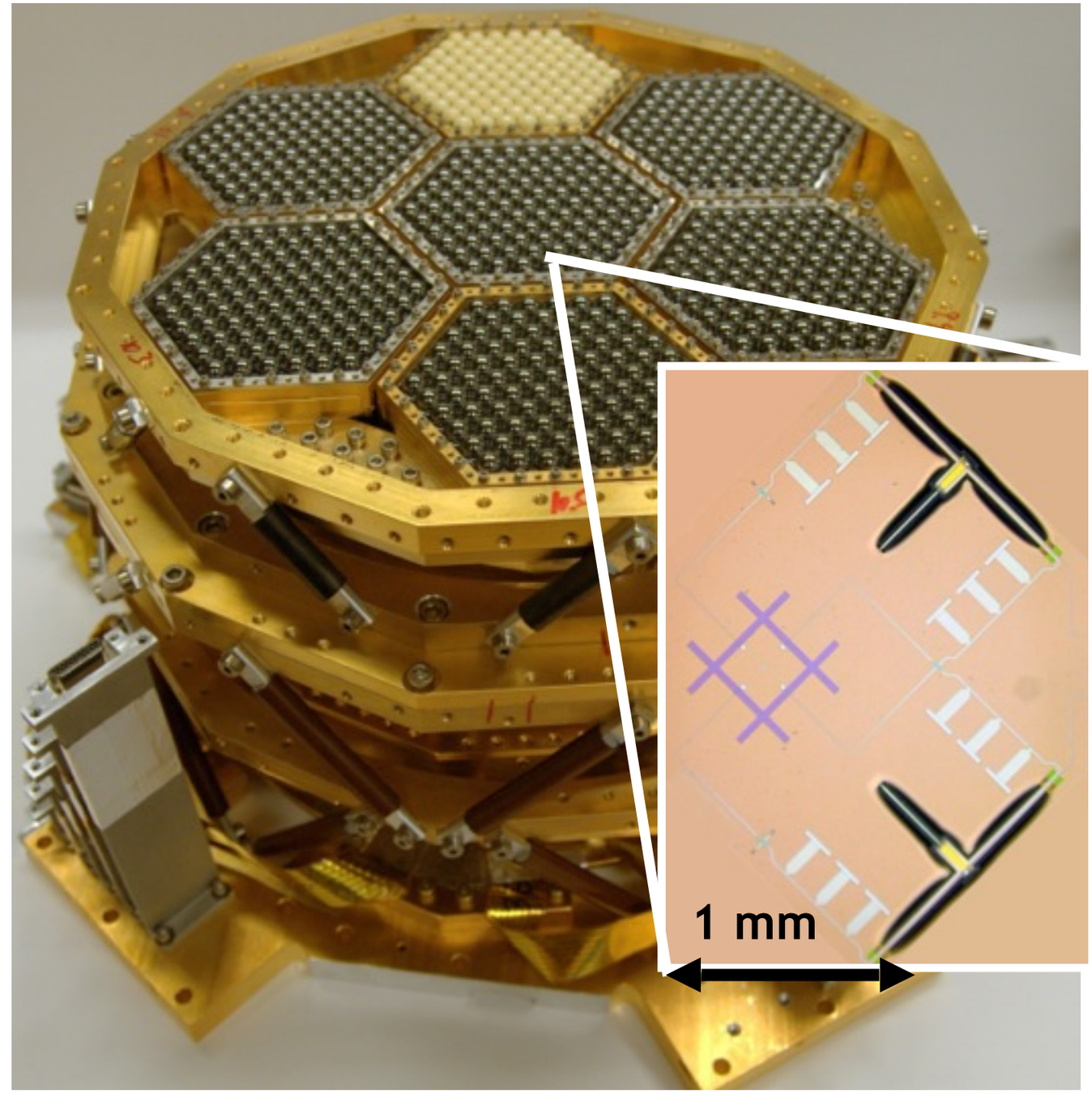

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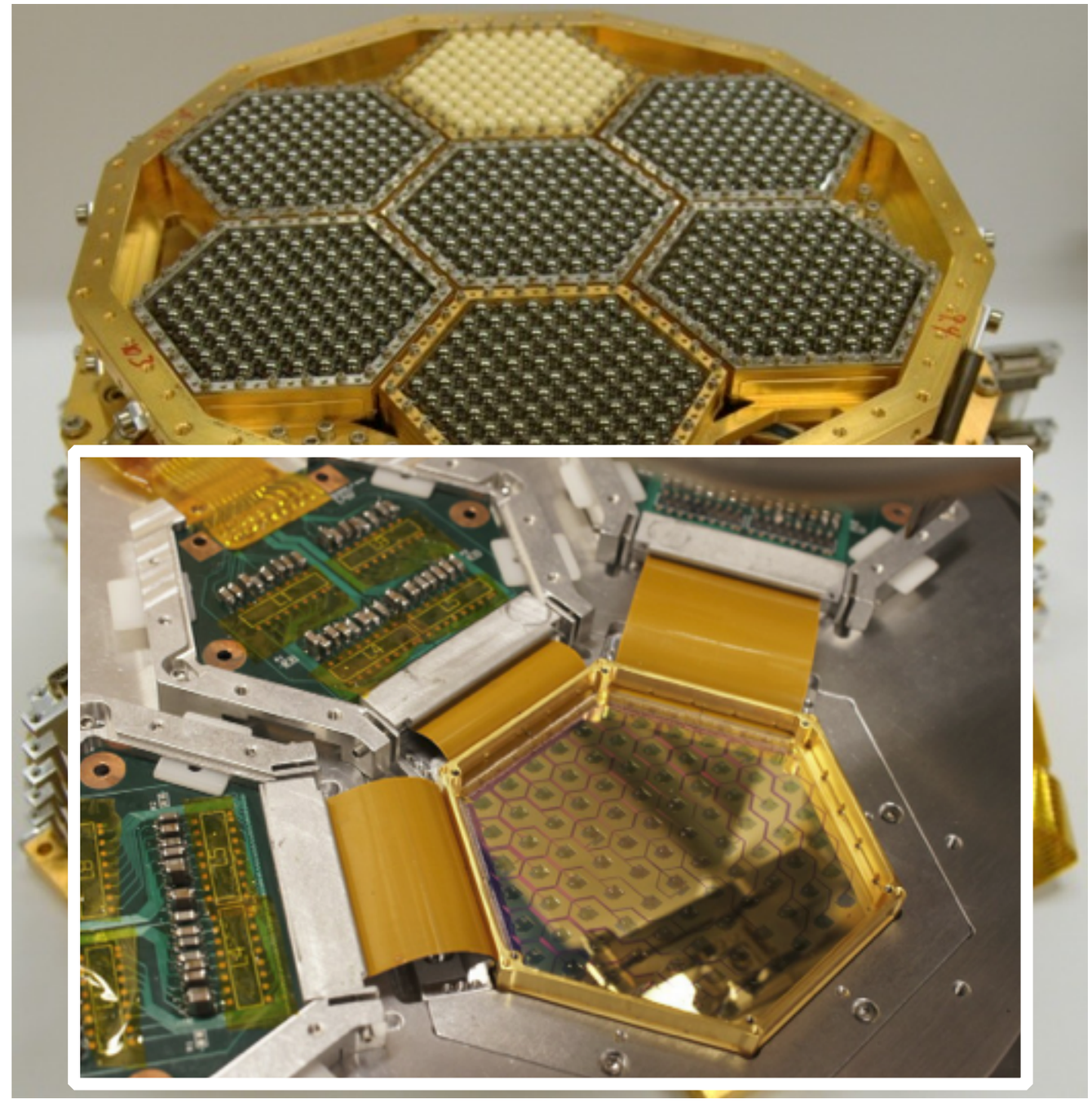
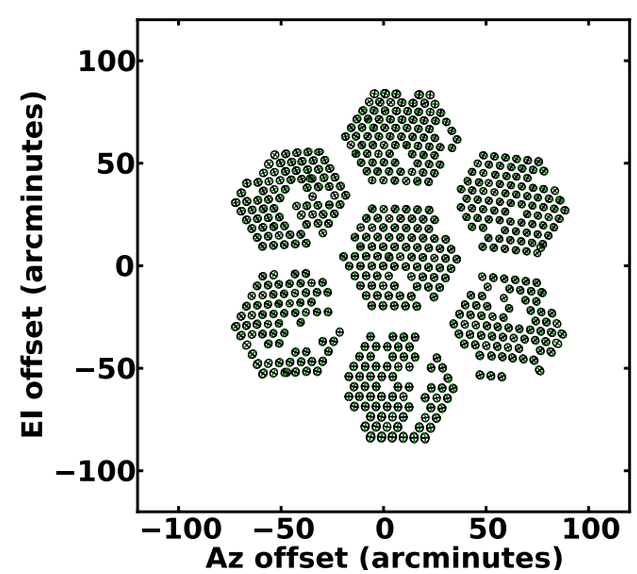
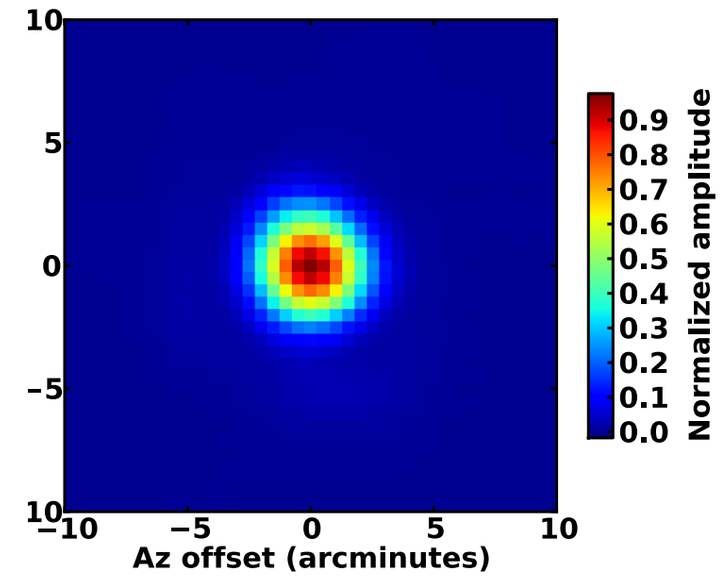


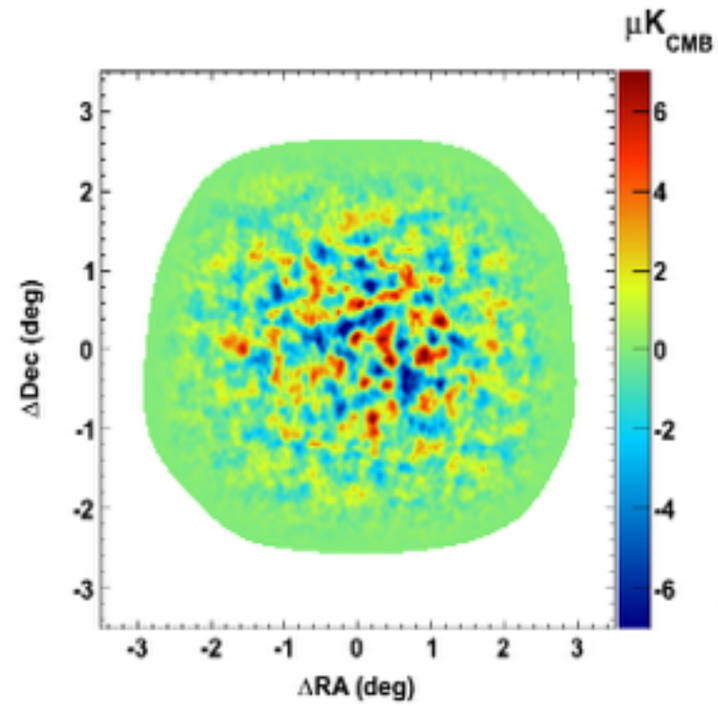
POLARBEAR-1

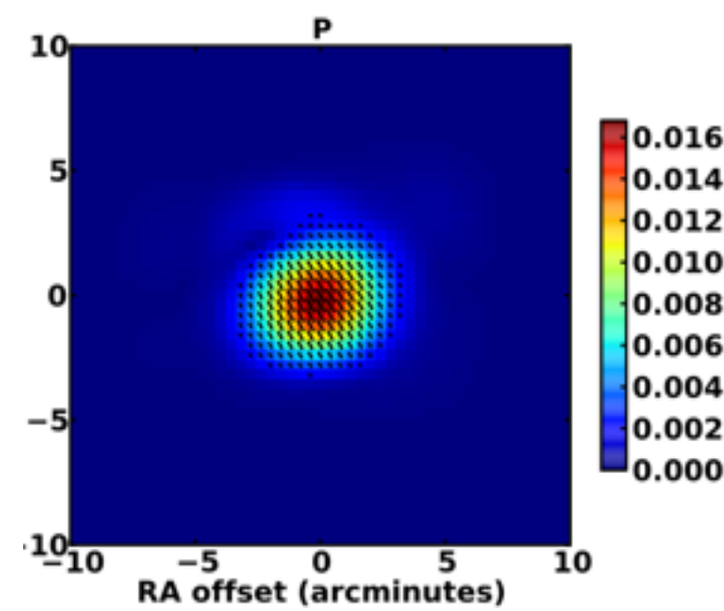
Instrument performance

- 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

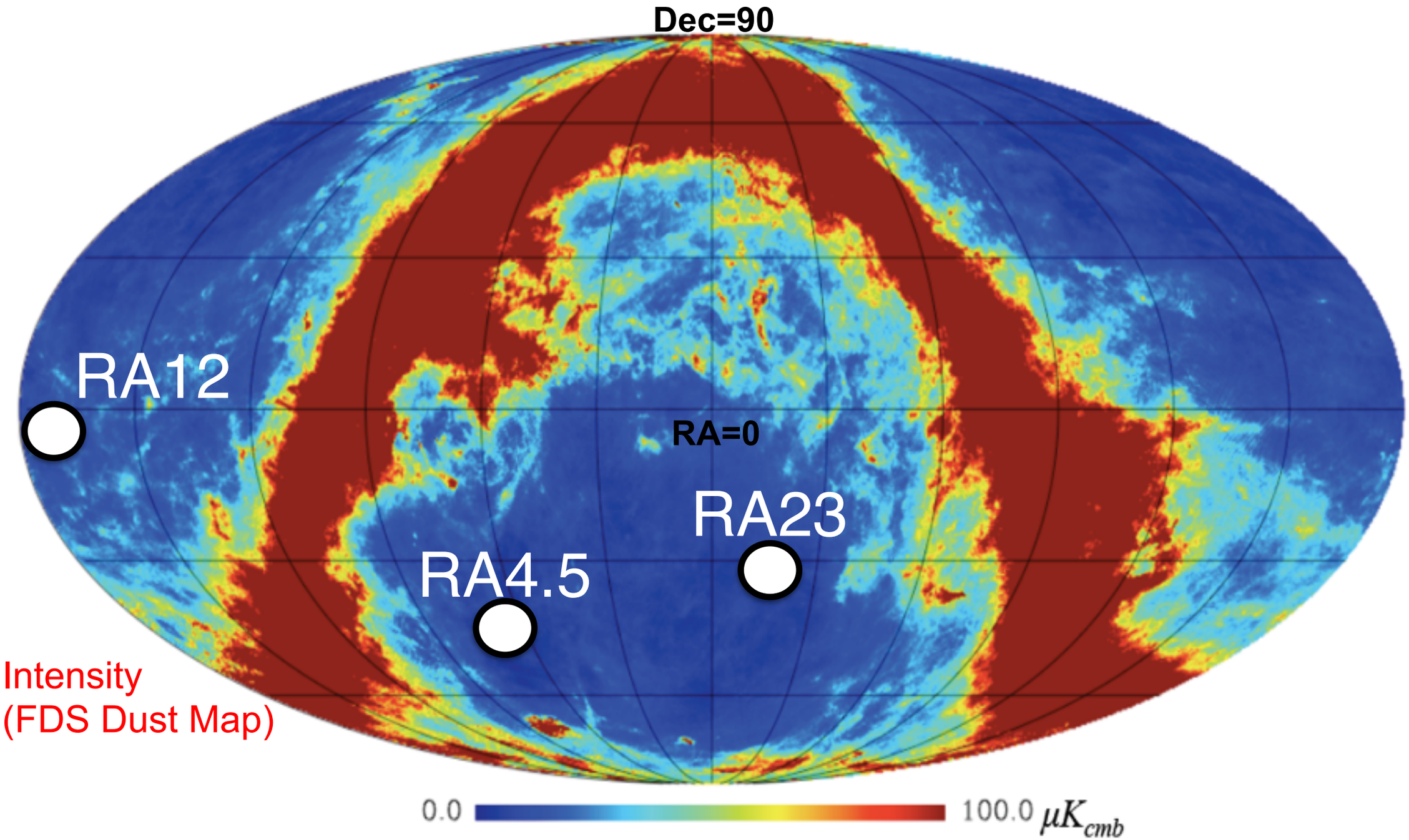






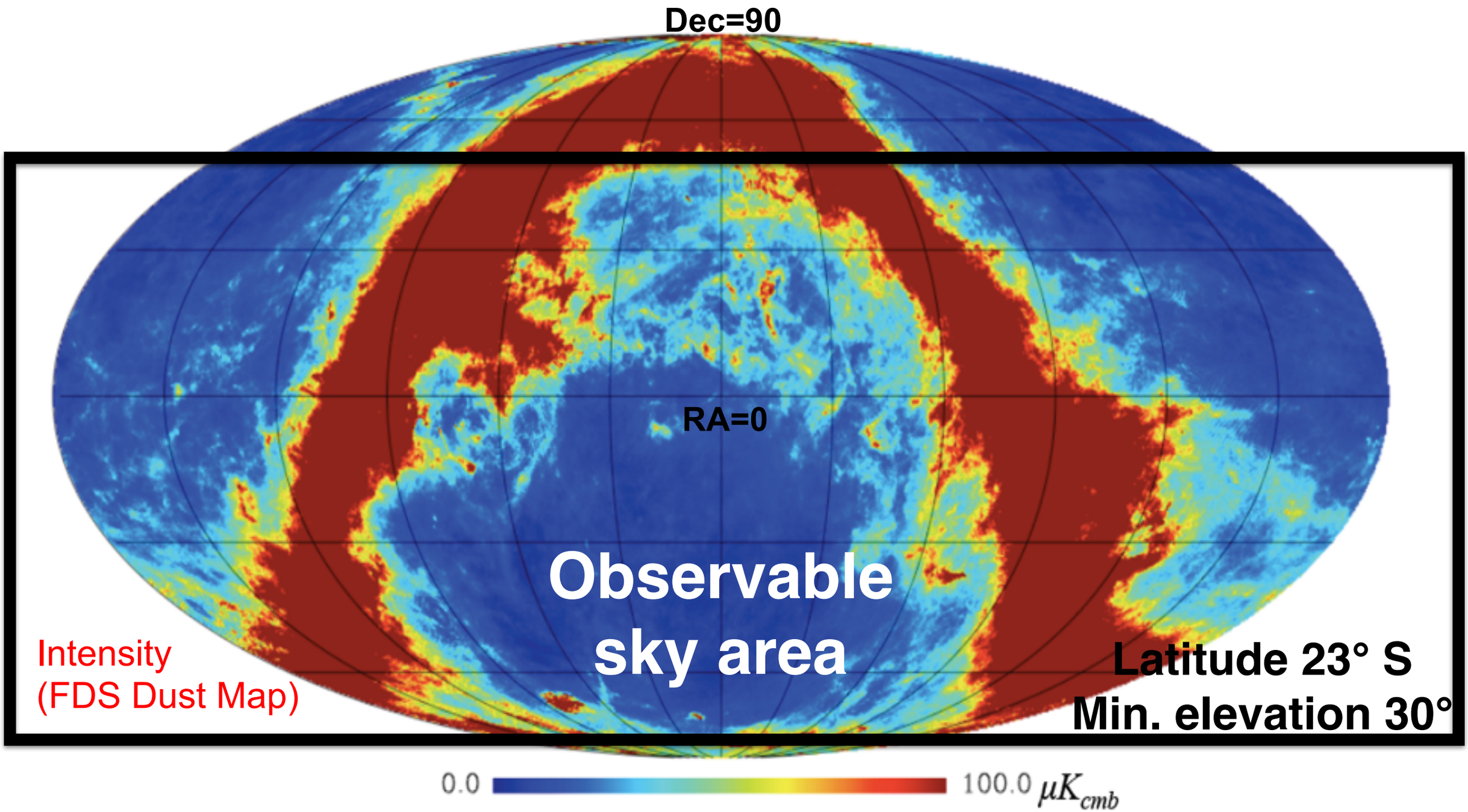


POLARBEAR Observations



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

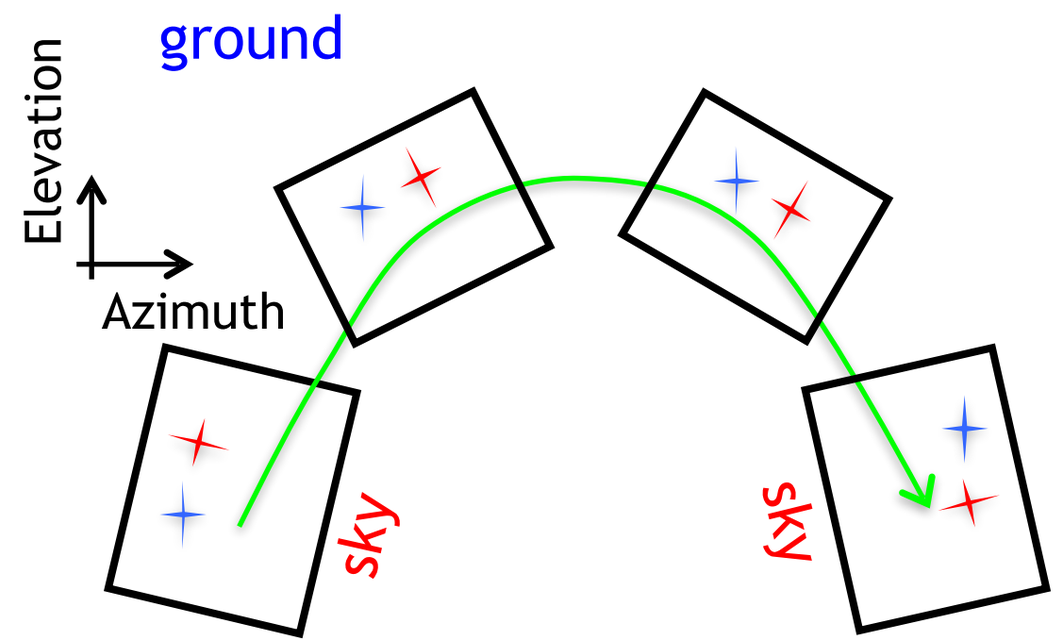
POLARBEAR Observations



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

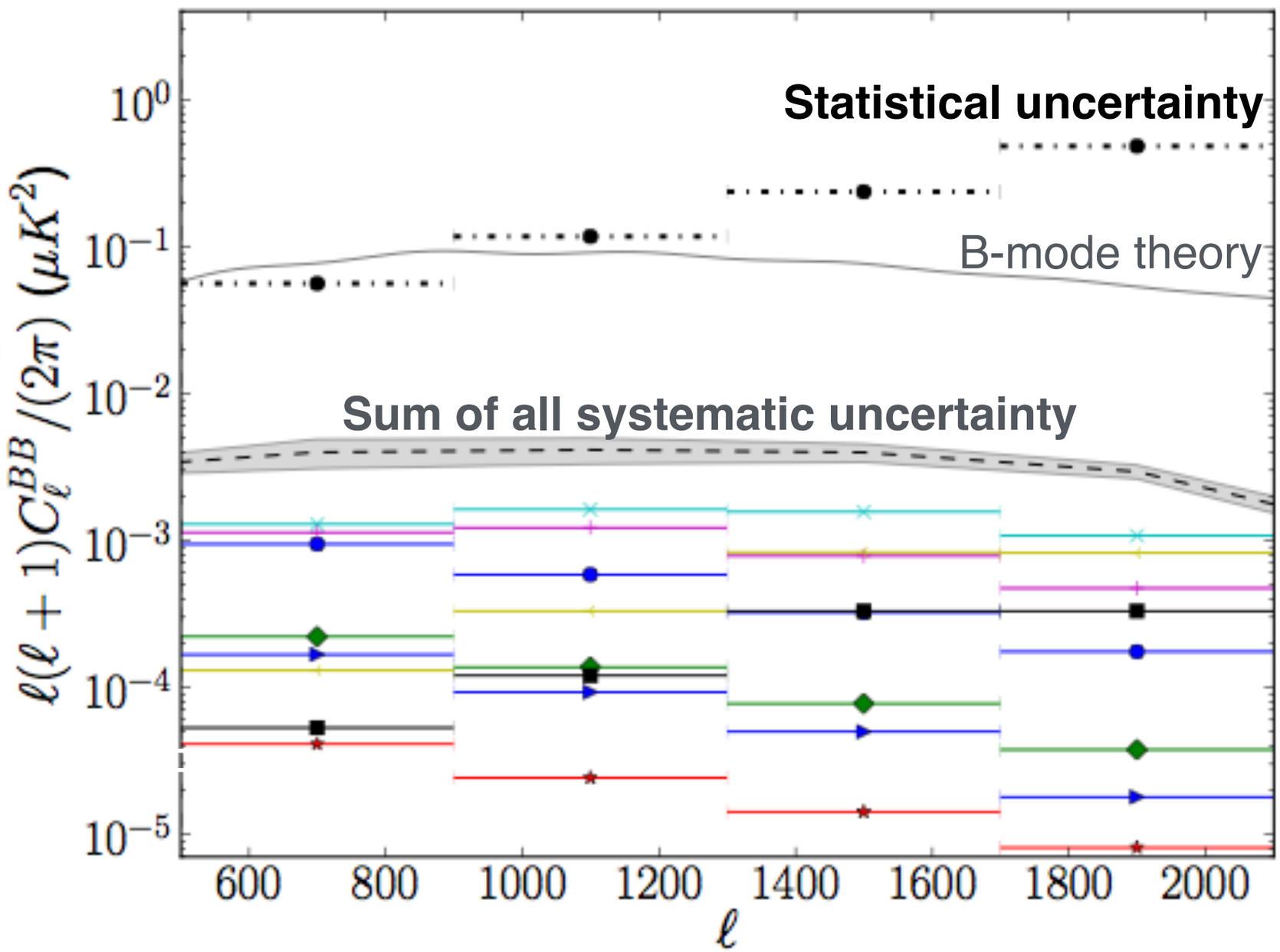
HWP-independent gain

Electrical crosstalk

Differential beamsize

Differential ellipticity

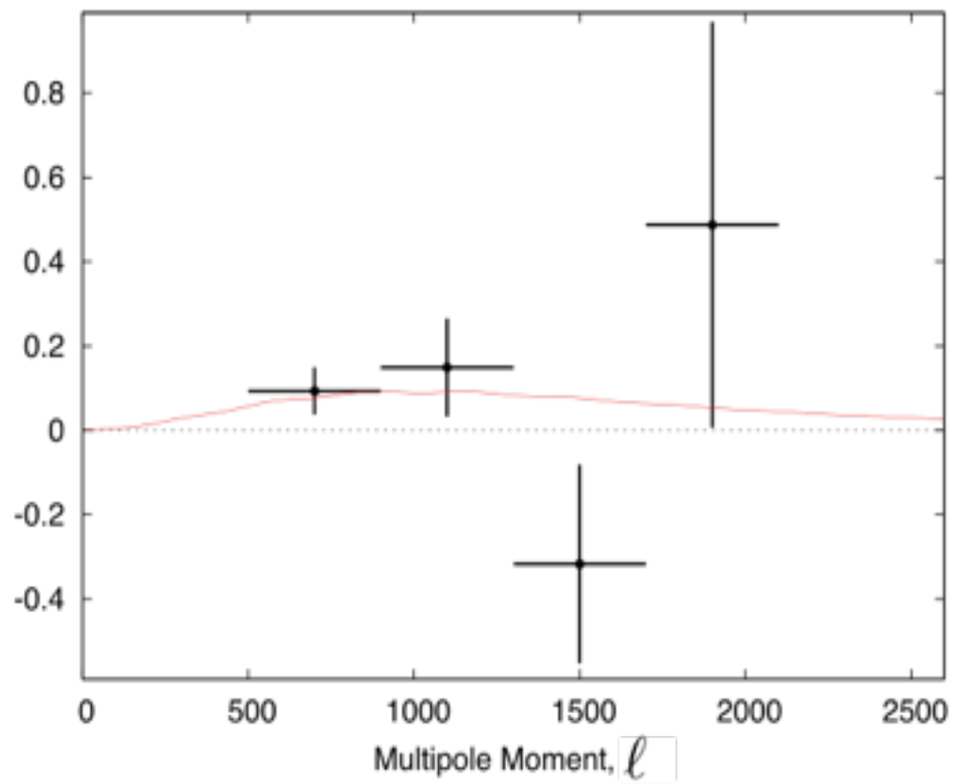
Gain drift



POLARBEAR Collaboration, ApJ 794, 171 (2014)

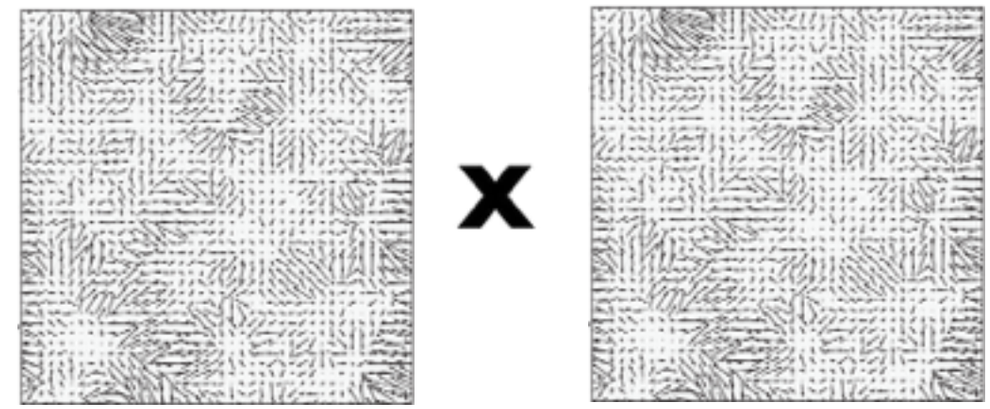
POLARBEAR

First season results

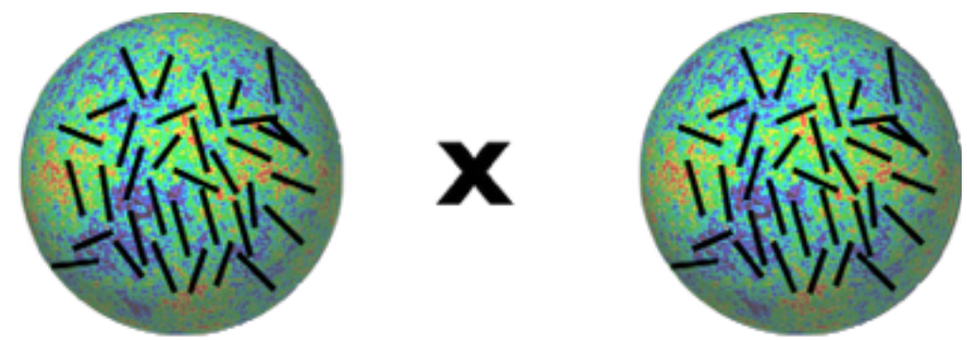


POLARBEAR First Season Results: Three B-mode Analyses

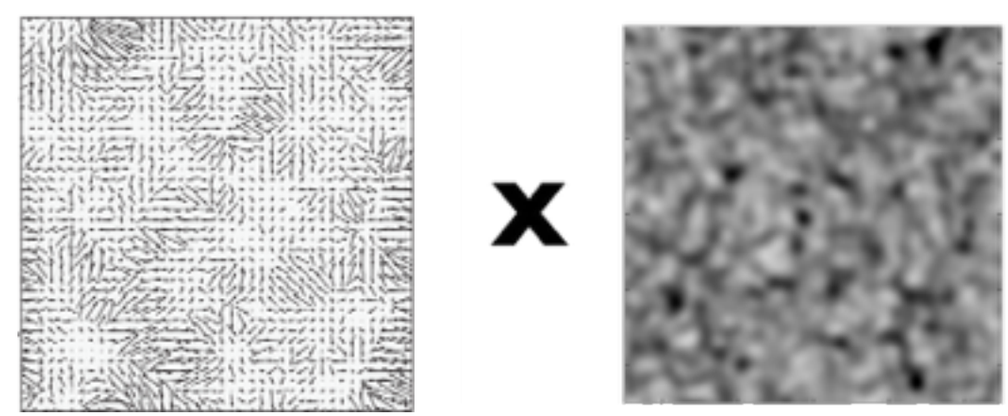
Deflection power spectrum:
CMB-only polarized lensing deflection power
PRL 113, 021301 (2014)



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



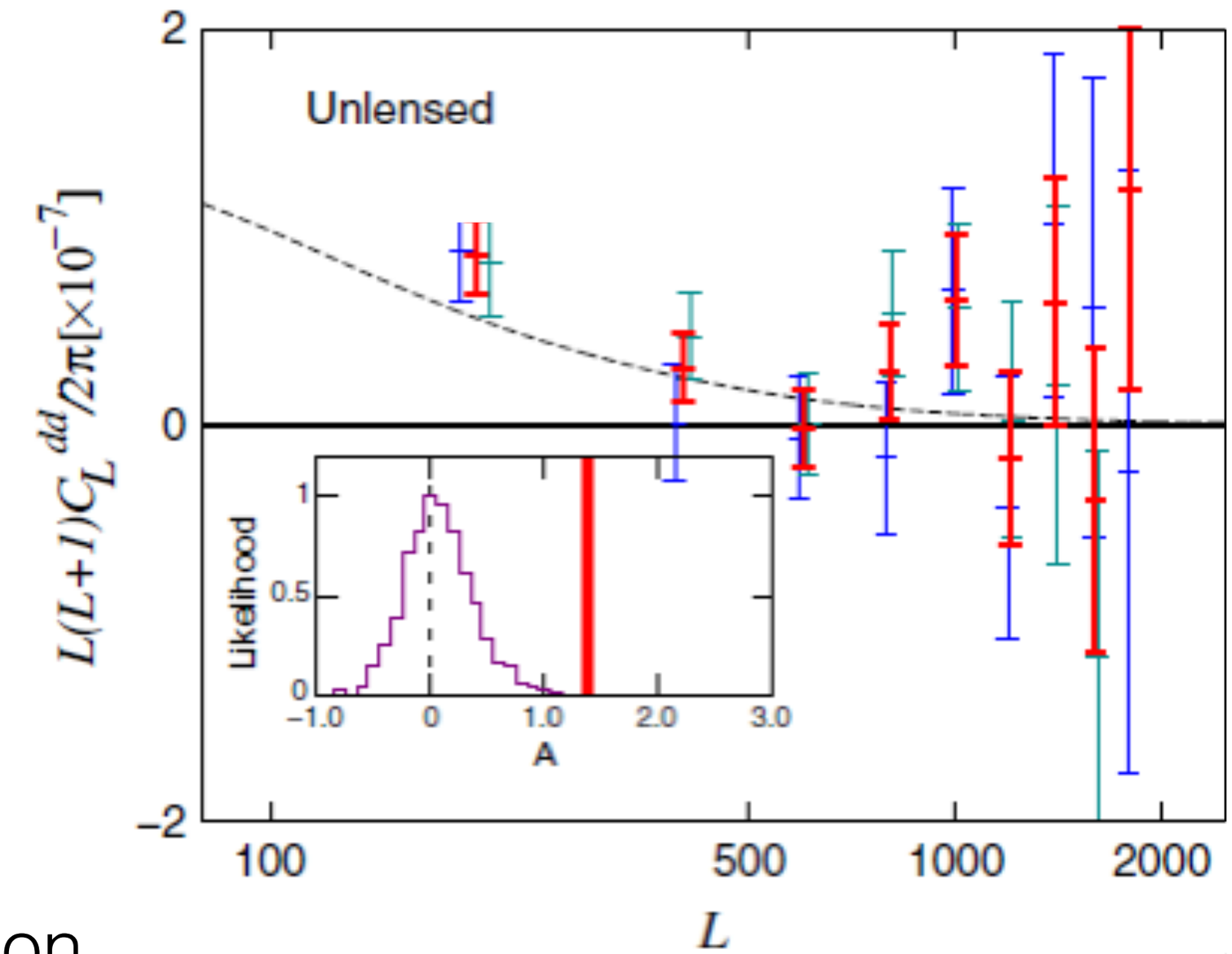
Galaxy cross-correlation:
CMB deflection measurements cross-correlated with luminous tracers of dark matter
PRL 112, 131302 (2014)



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: $< EBEB >$

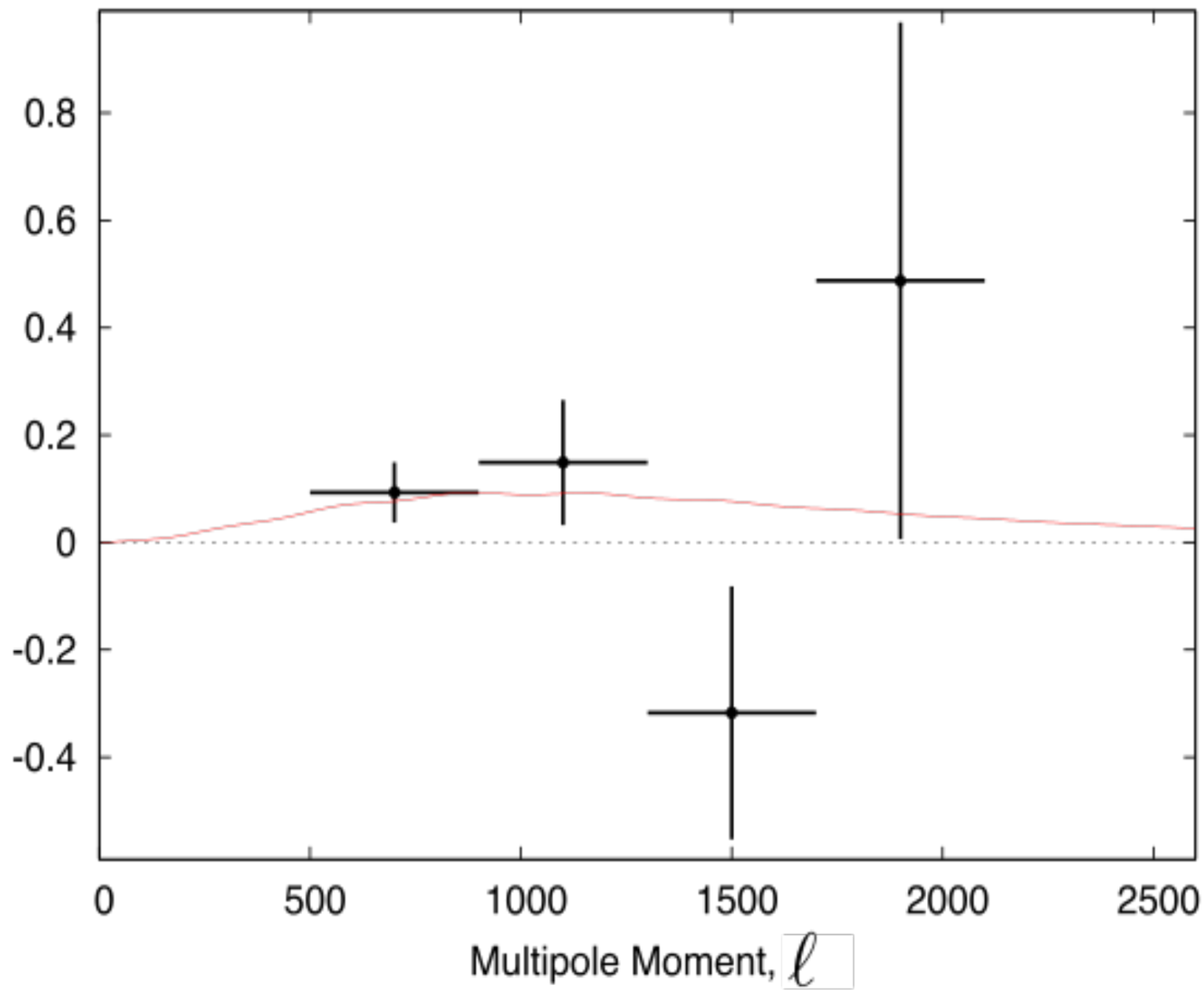
Blue: $< EEEB >$

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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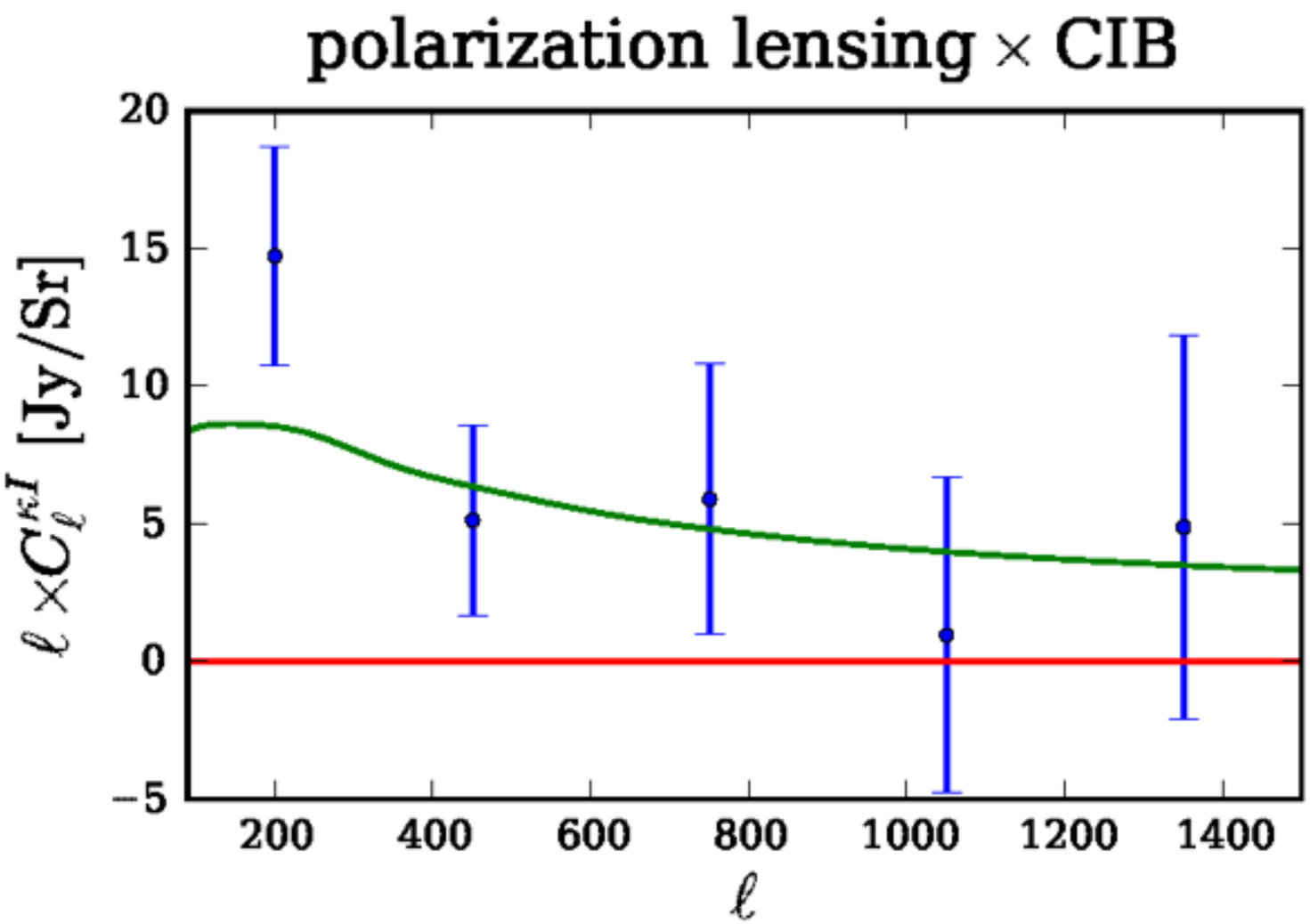
ApJ 794, 171 (2014)

POLARBEAR First Season Results: Galaxy cross-correlation

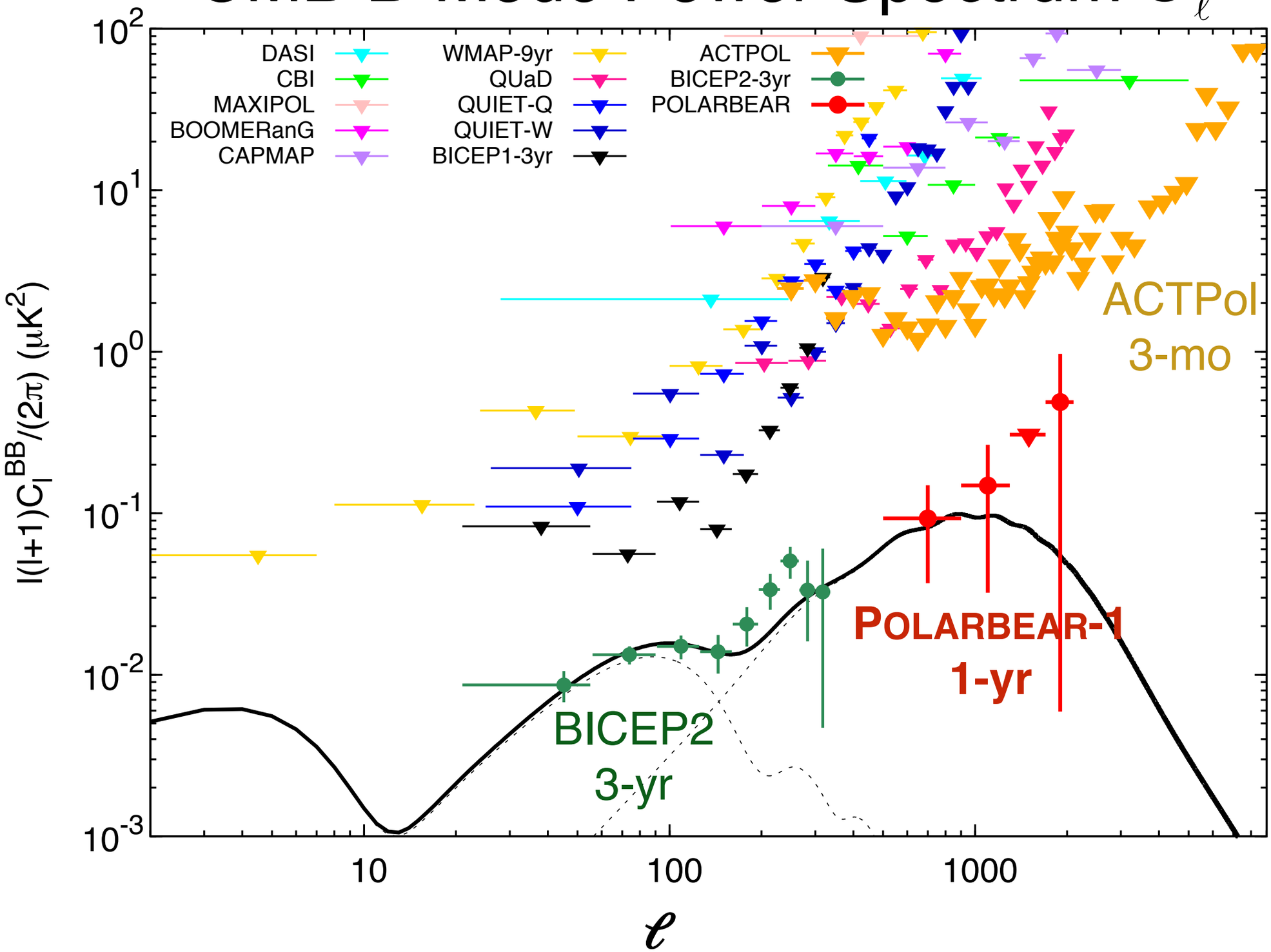
- Cross-correlation with cosmic infrared background (CIB)
  - Herschel-ATLAS data
- 4.0 sigma rejection of "no lensing"



POLARBEAR Collaboration
PRL 112, 131302 (2014)

POLARBEAR-1

CMB B-Mode Power Spectrum C_ℓ^{BB}



POLARBEAR-1

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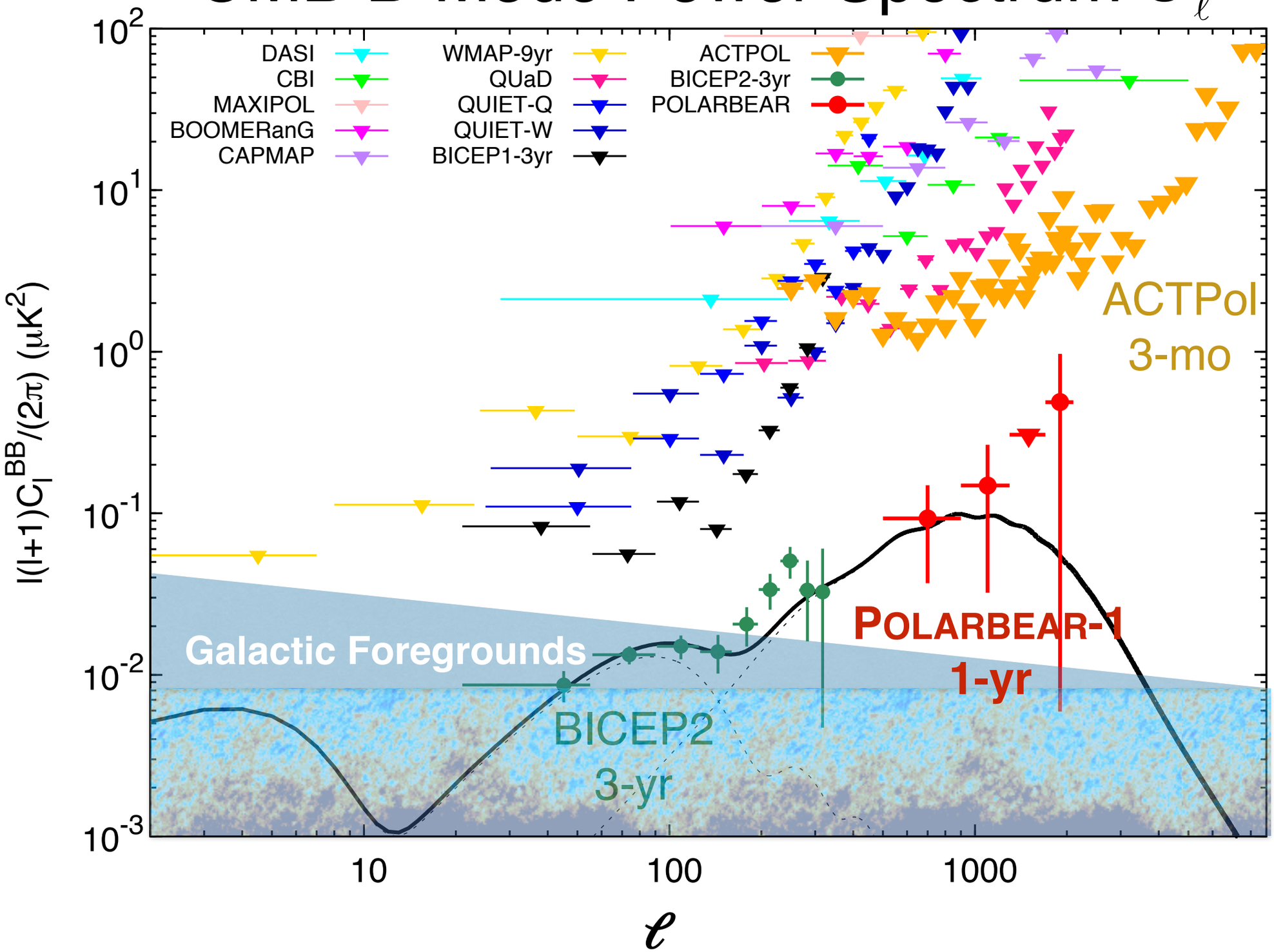
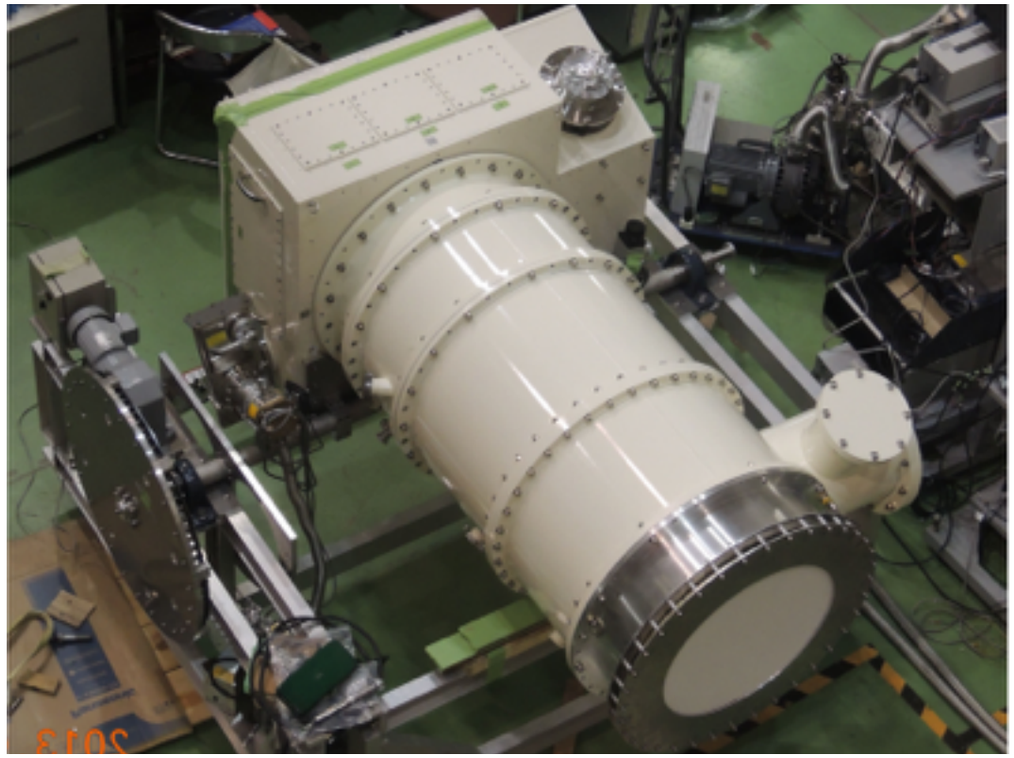


POLARBEAR-2

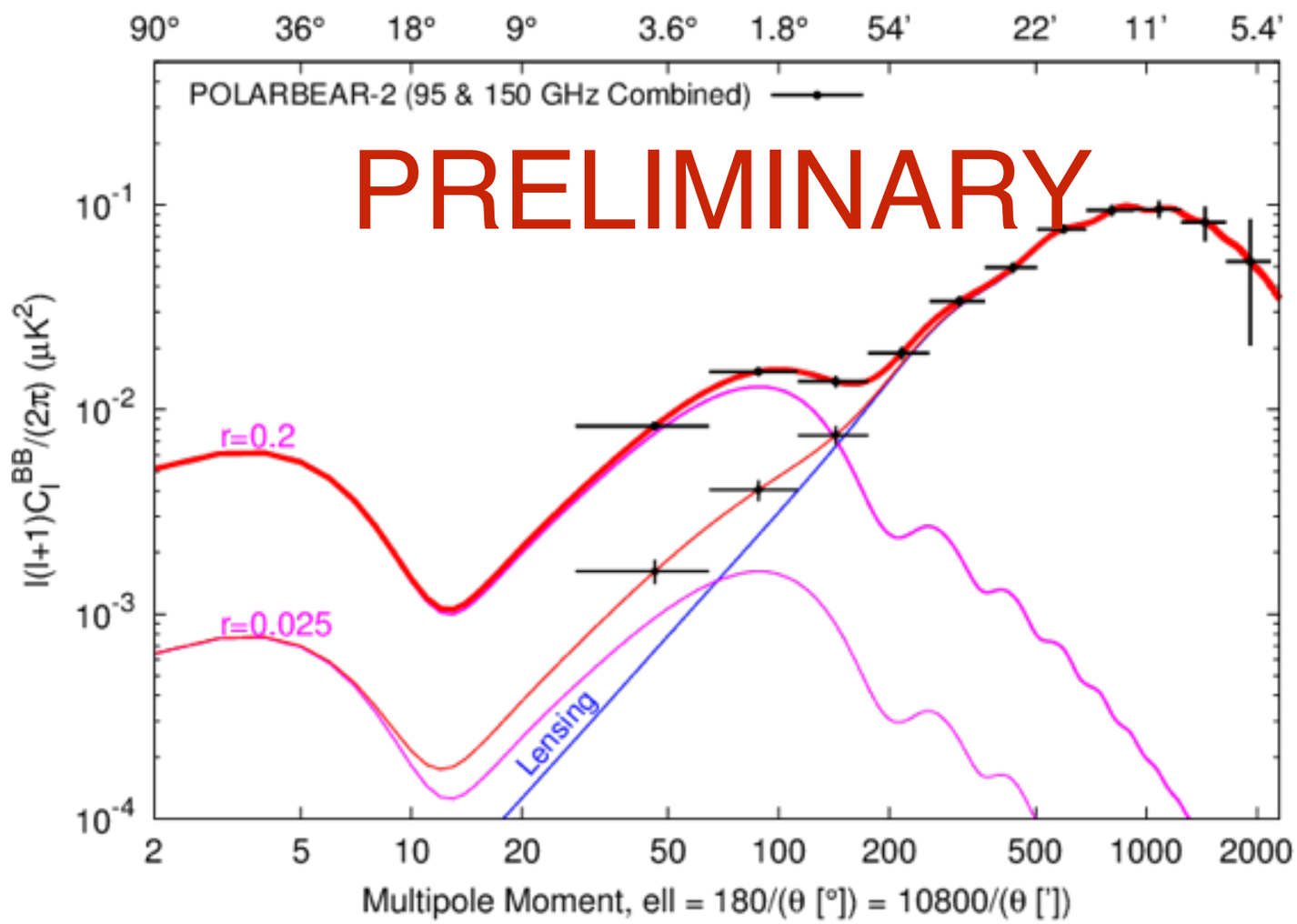
Instrument overview



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
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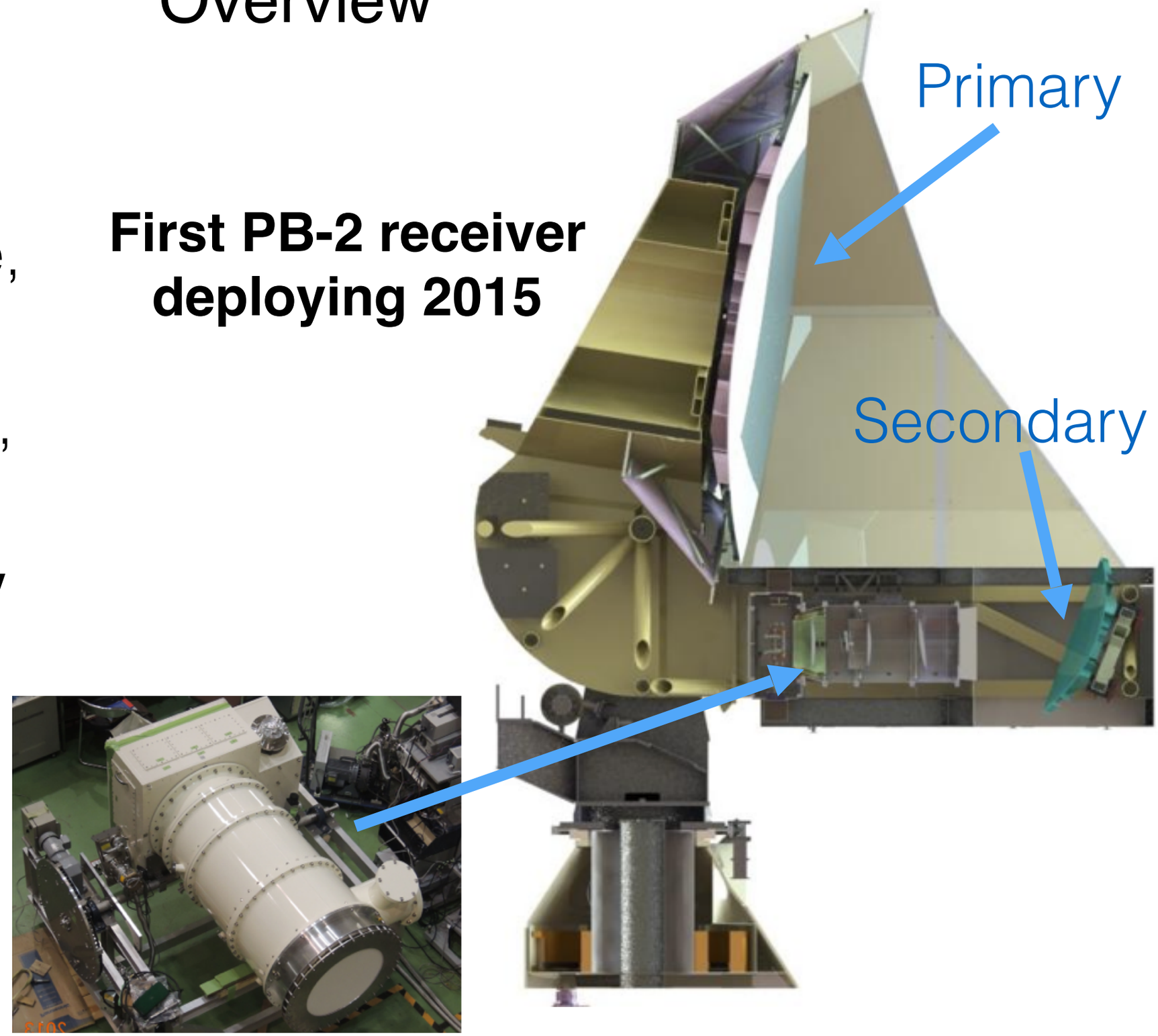
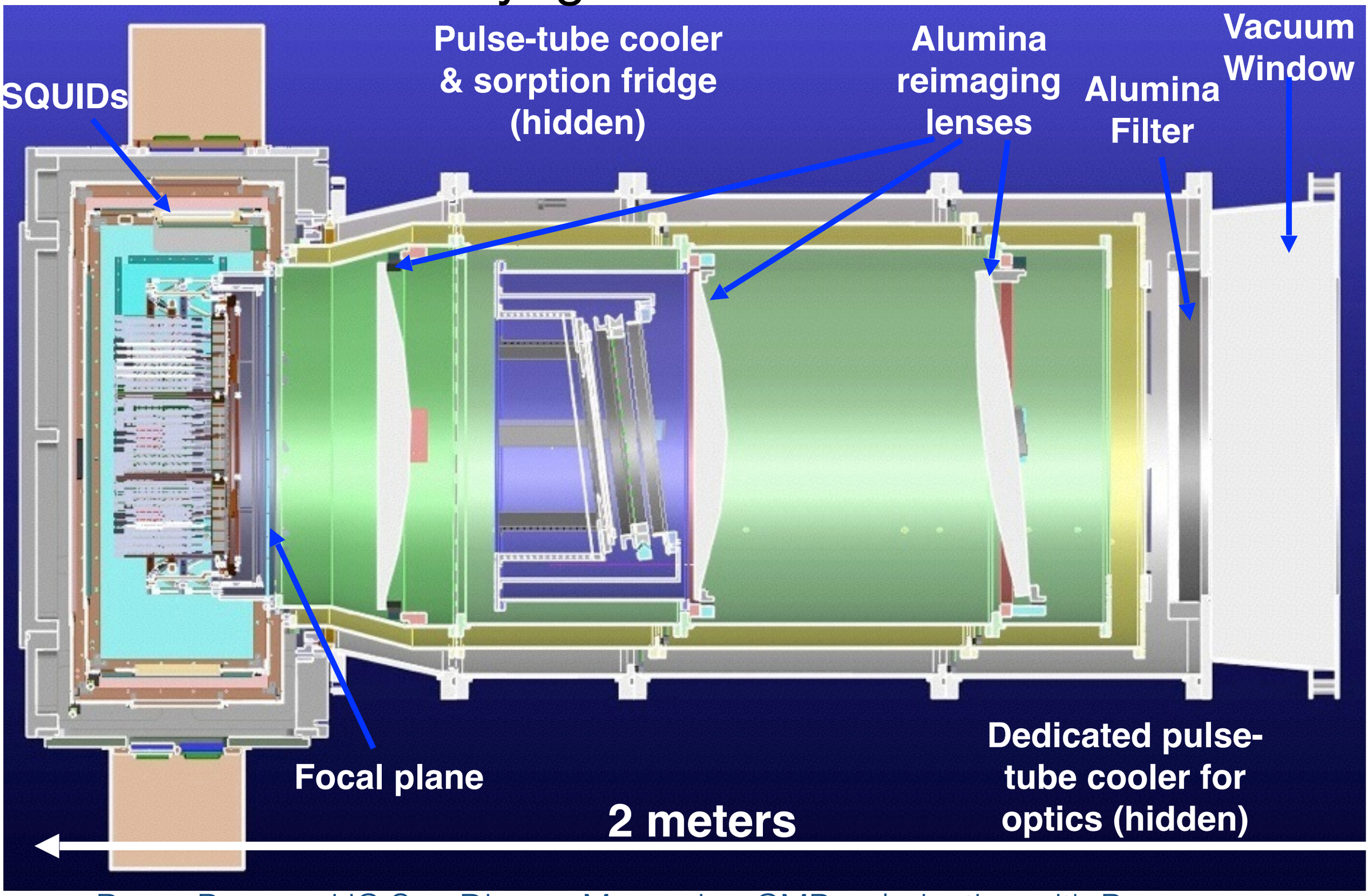
- Broadband optics, multi-chroic pixels
- **$\sigma(\Sigma m_\nu) < 100$ meV**

First PB-2 receiver deploying 2015



POLARBEAR-2

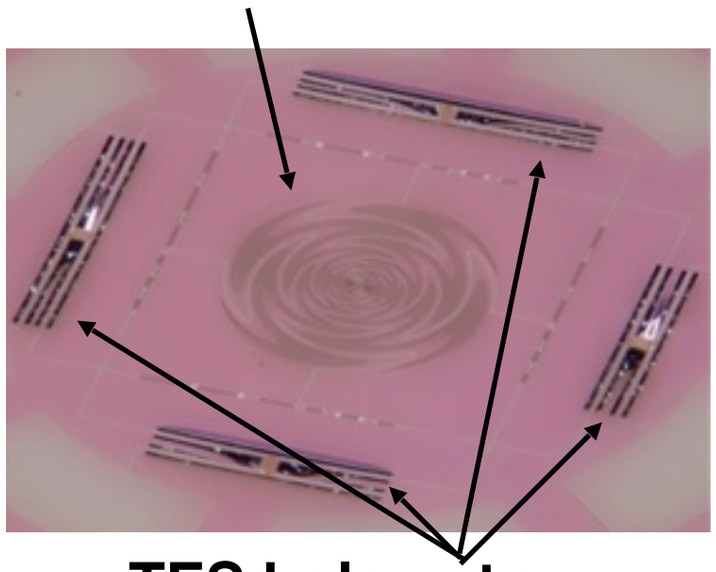
Cryogenic Receiver



POLARBEAR-2

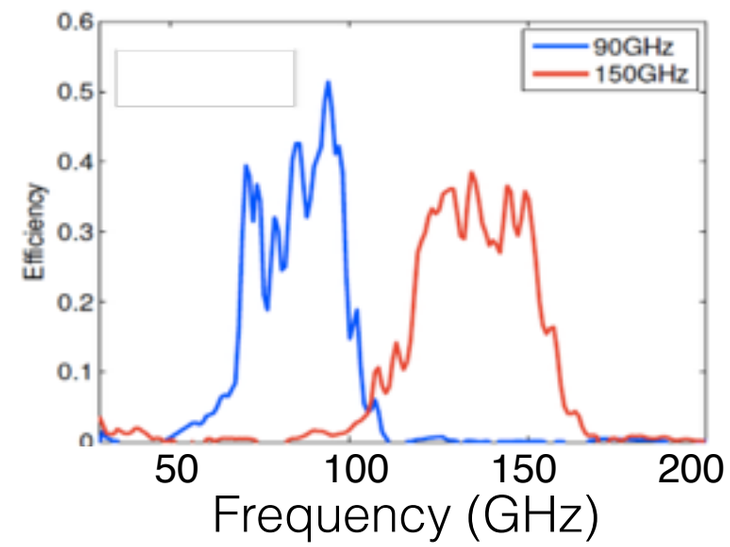
Focal Plane

Broadband sinuous antenna

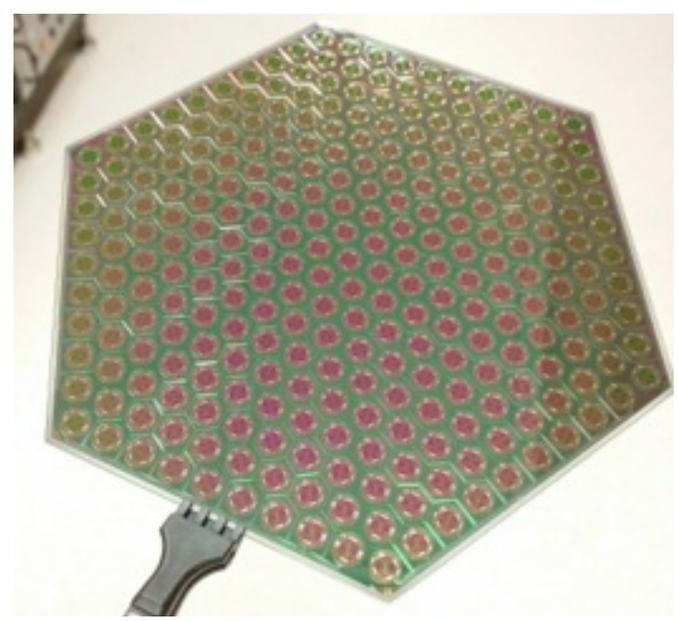


TES bolometers

4 detectors per pixel



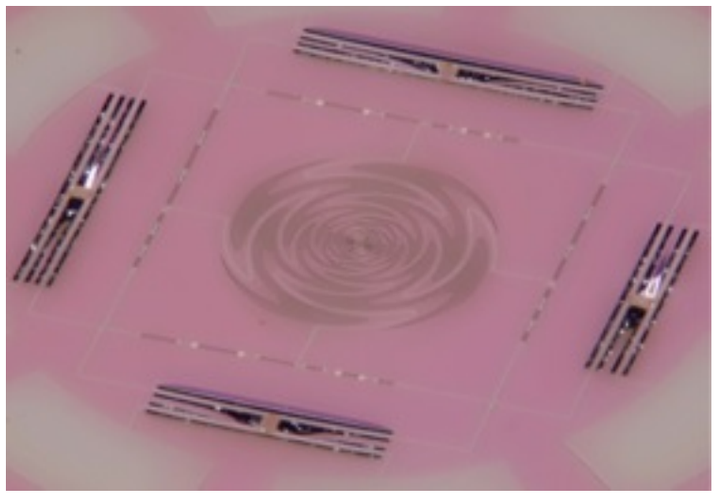
Freq. band measurement



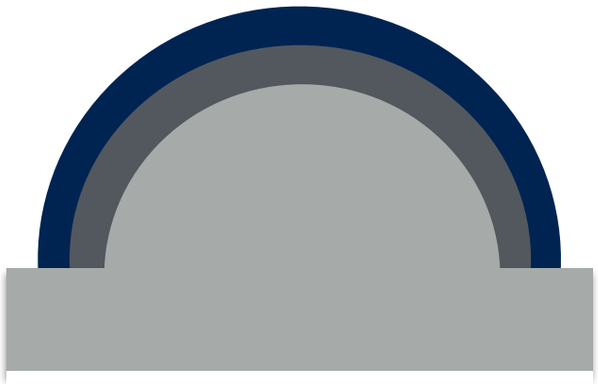
271 pixels / wafer

POLARBEAR-2

Focal Plane



Dichroic pixel

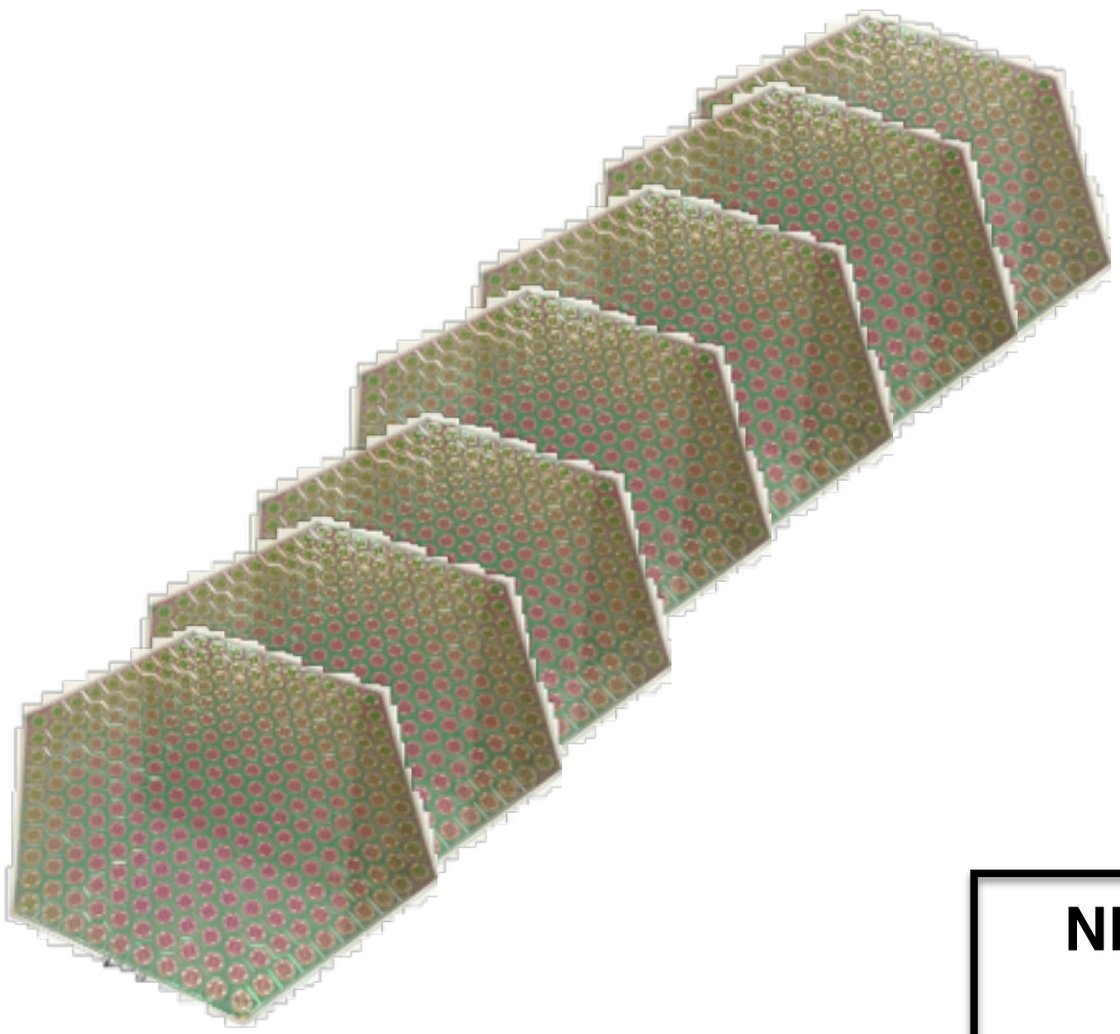


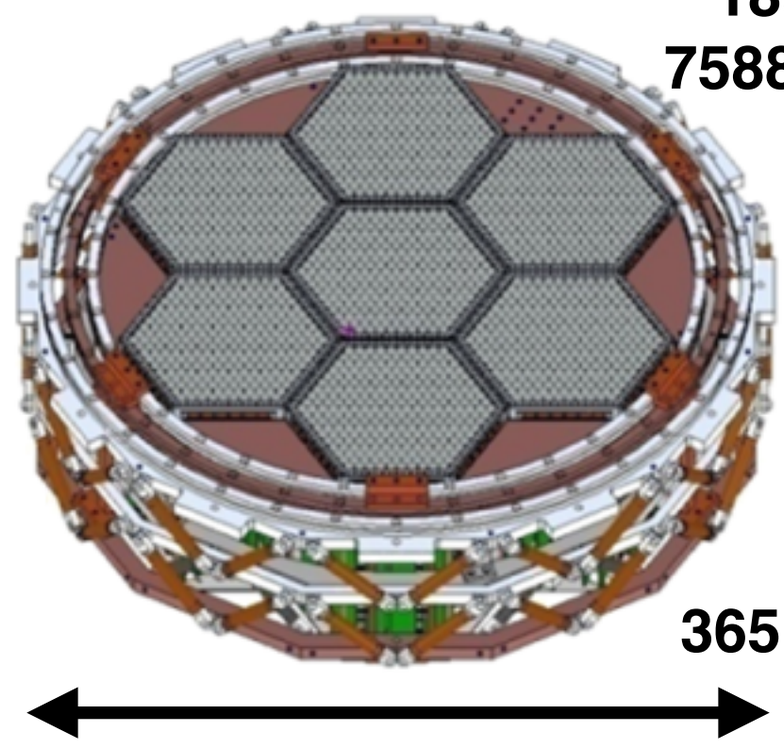
Beam-forming silicon lenslet w/ 2-layer AR coating

AR-coated lenslets on seating wafer

POLARBEAR-2

Focal Plane





1897 pixels
7588 detectors

365 mm

NET bolometer:
360 μK√s

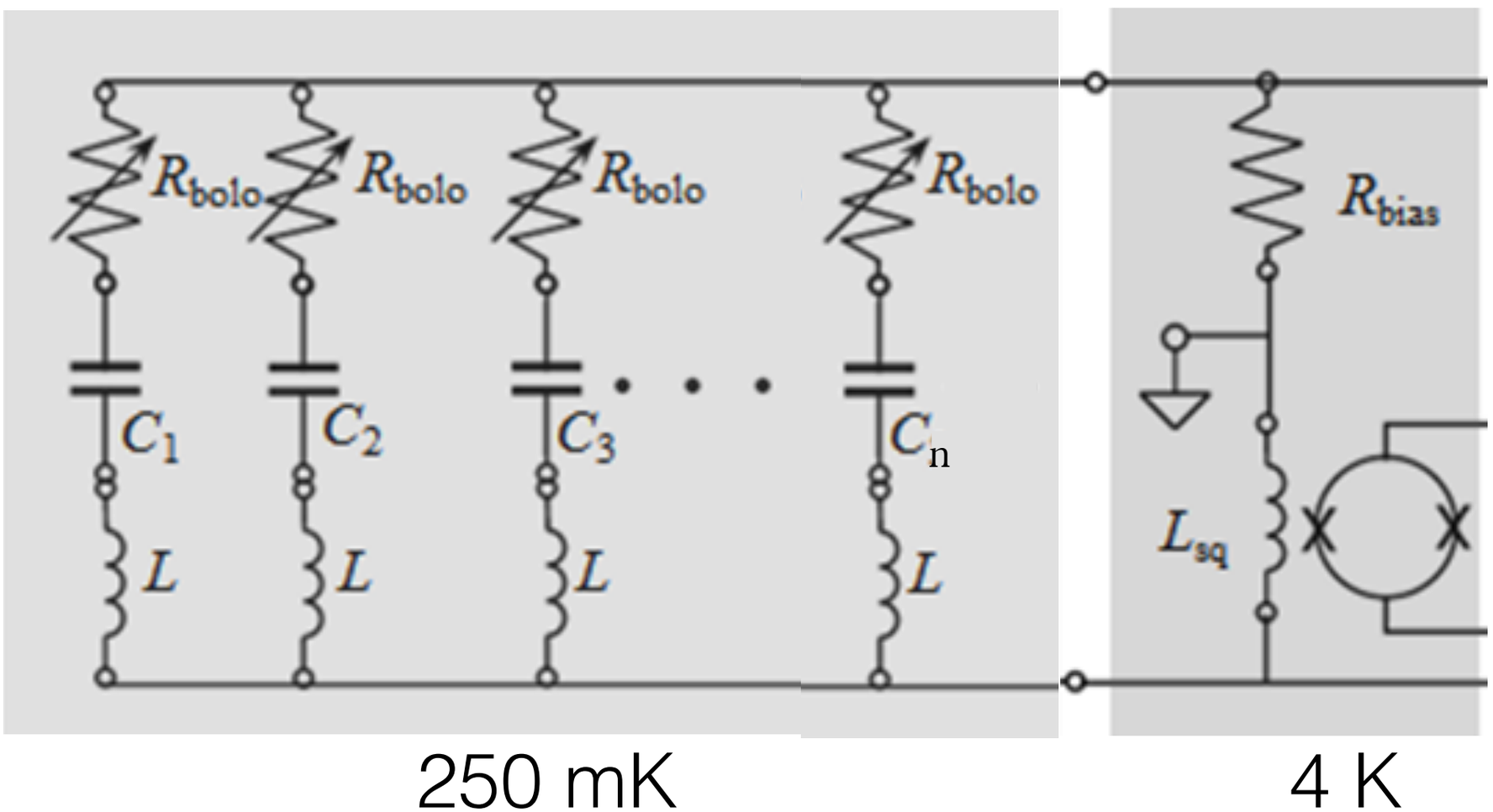
NET array:
4.1 μK√s
(95 GHz + 150 GHz)

POLARBEAR-2

Readout

Frequency domain multiplexing

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

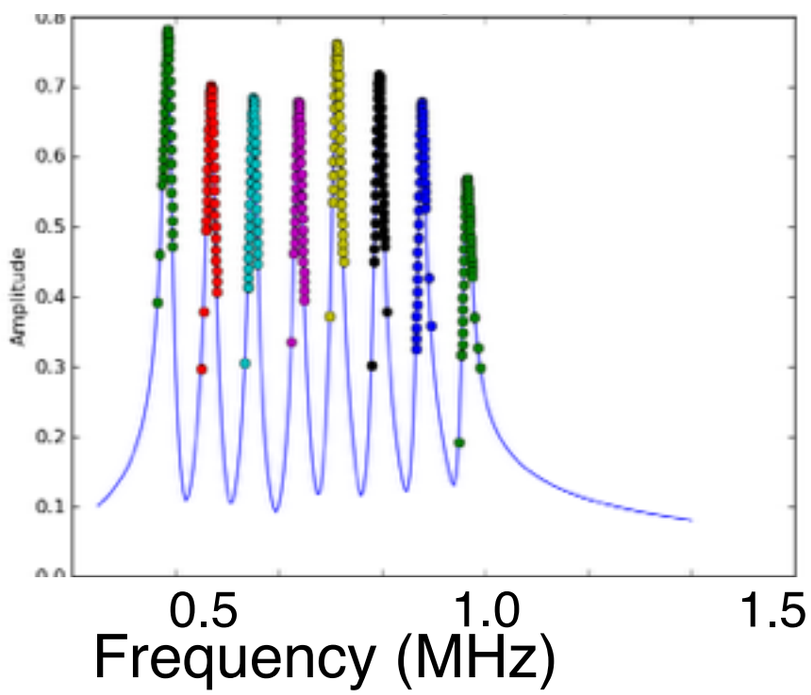


POLARBEAR-2

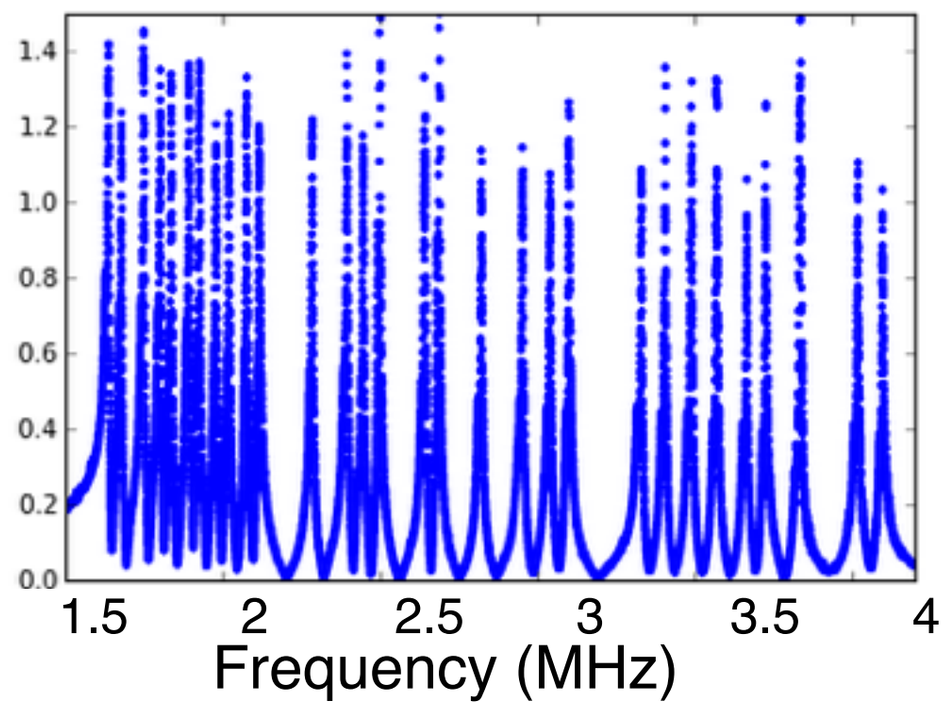
Readout

- 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

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  - Increase from 8x to 40x
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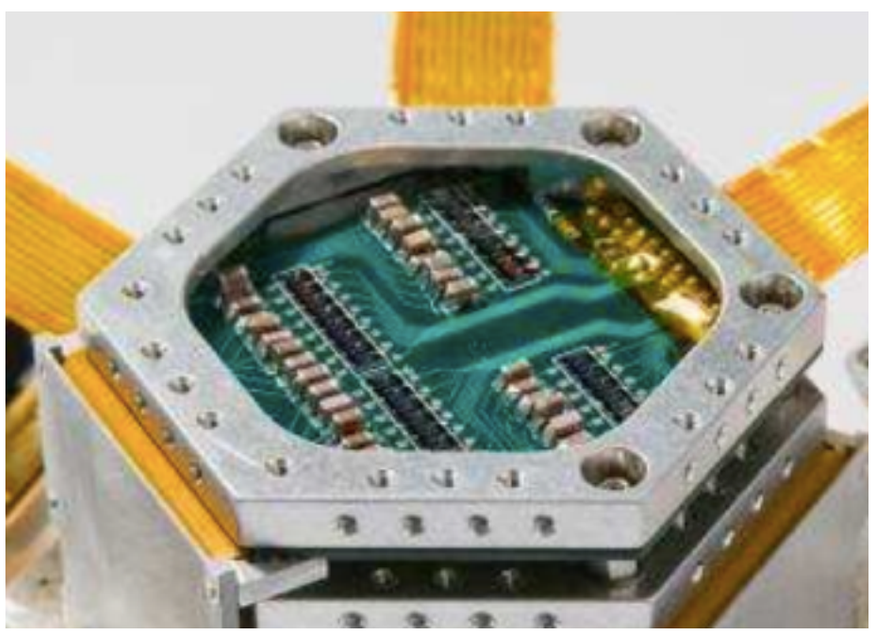
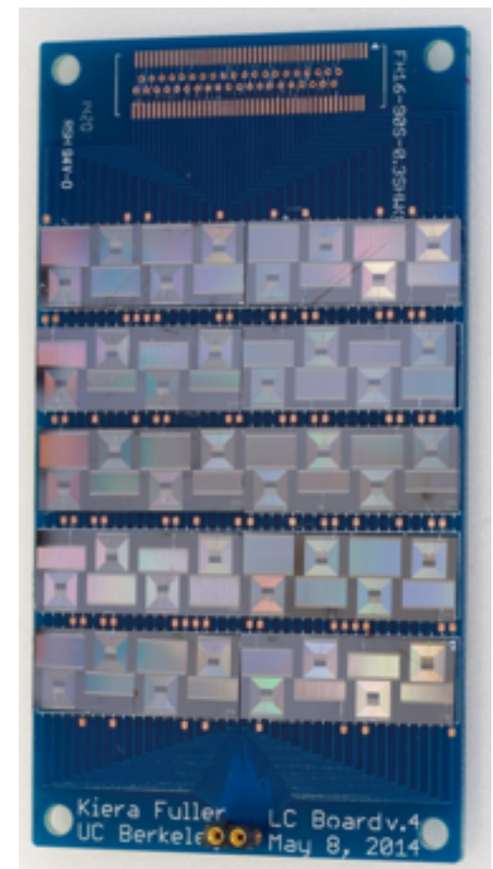
POLARBEAR-1: 8x



POLARBEAR-2: 40x



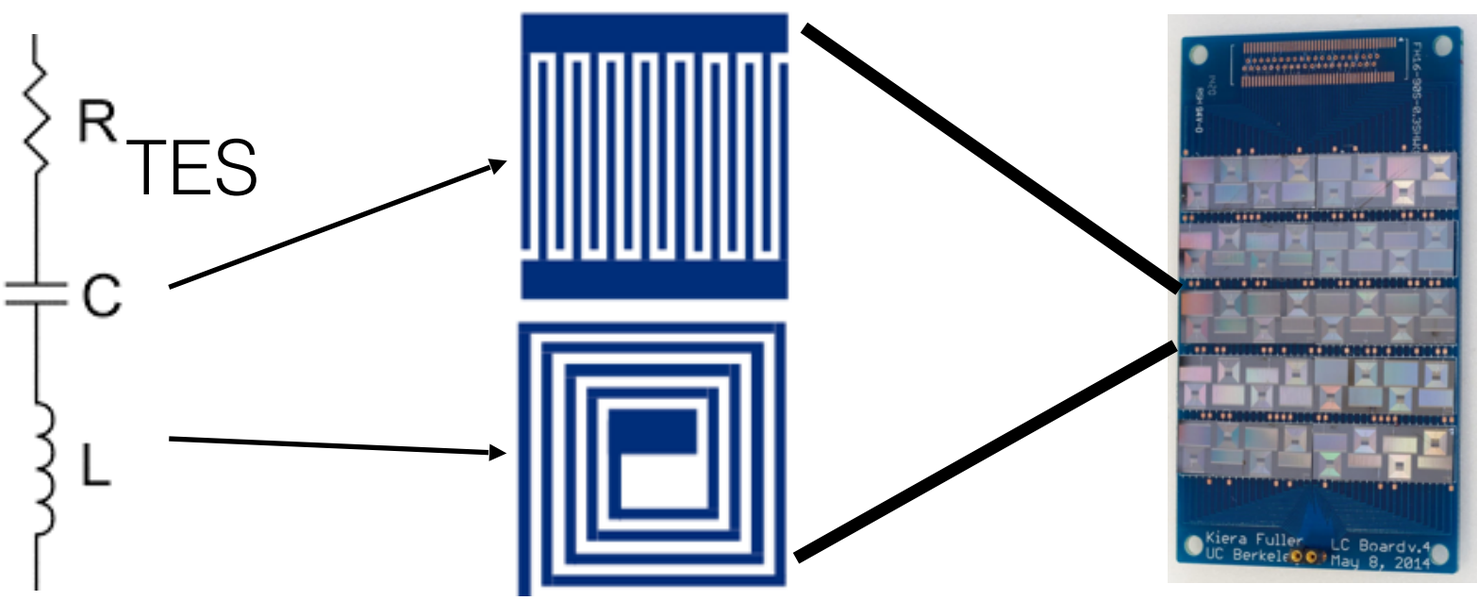
POLARBEAR-2

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



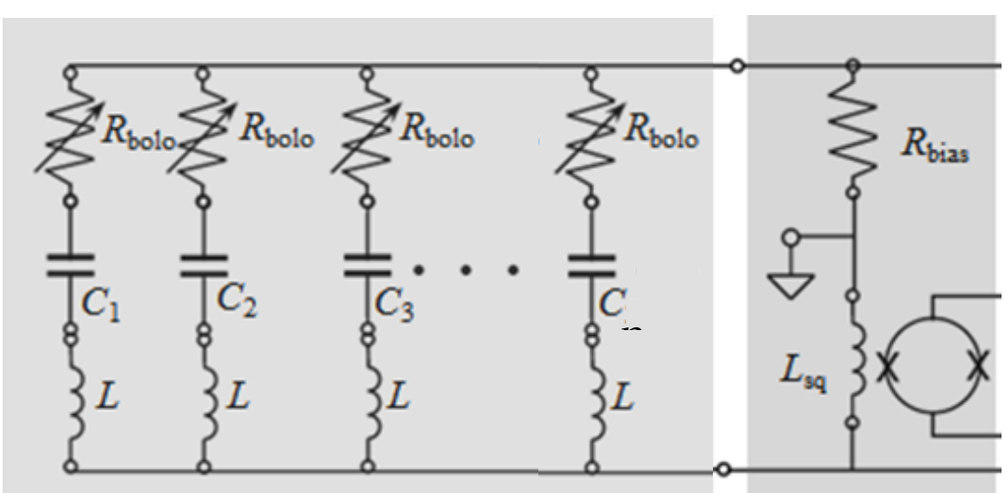
Signal cable

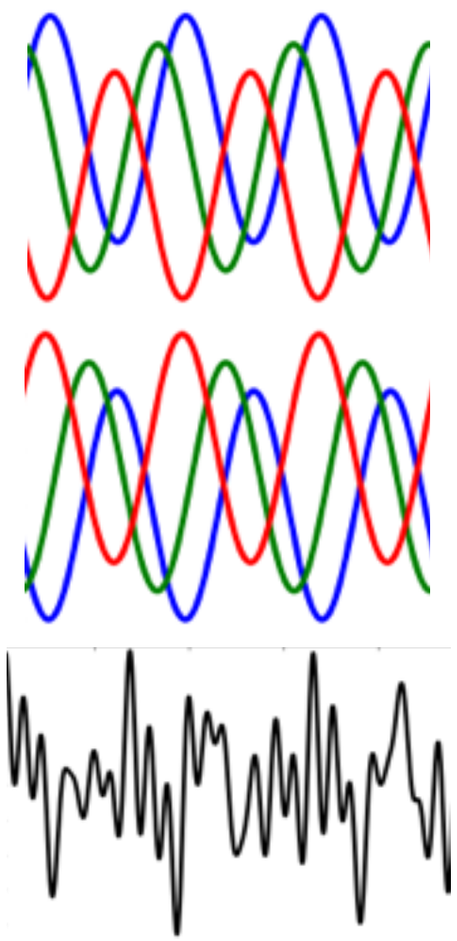
POLARBEAR-2

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

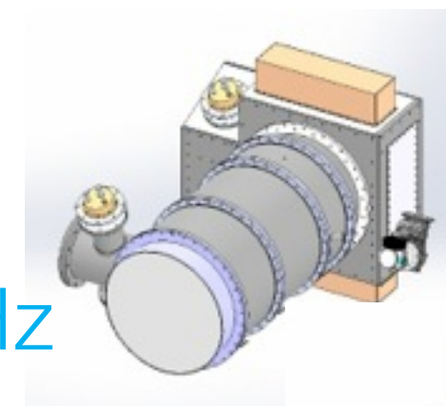
Overview

Simons Array

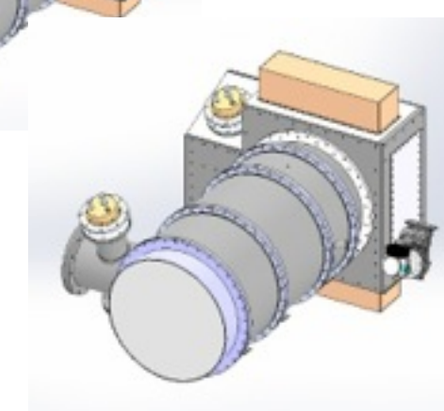
Leverage POLARBEAR experience to rapidly increase sensitivity

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

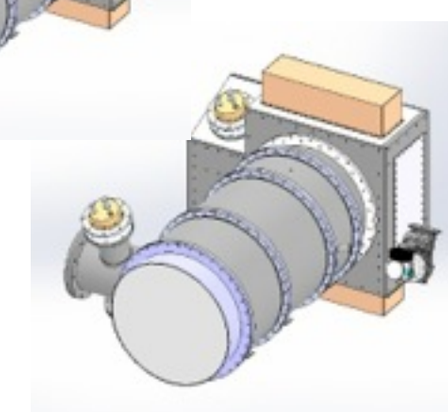
95 GHz / 150 GHz



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

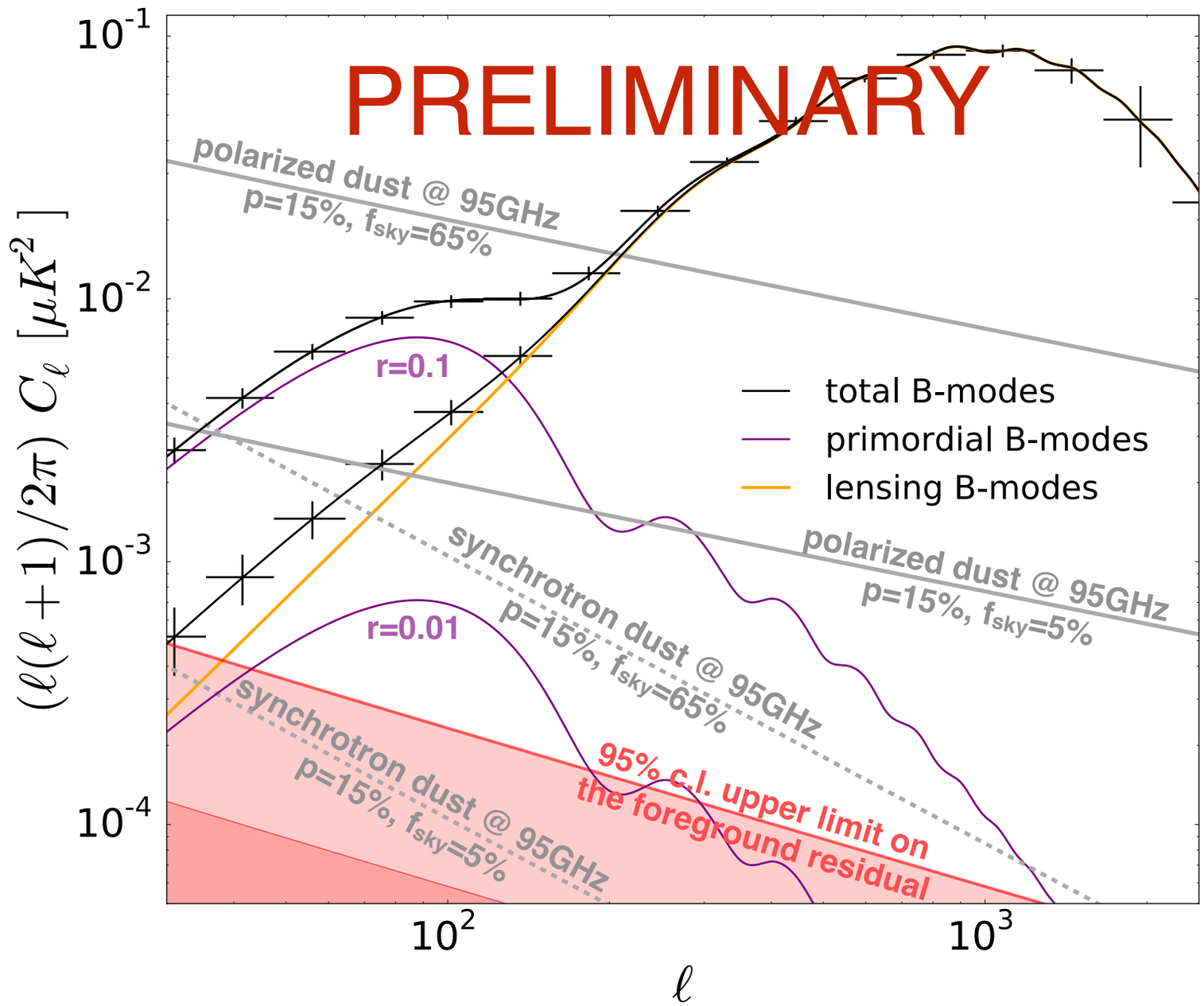
Projected sensitivity

Foreground rejection with multi-frequency Simons Array data

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

(w/ DESI BAO)

$\sigma(r = 0.1) = 0.006$



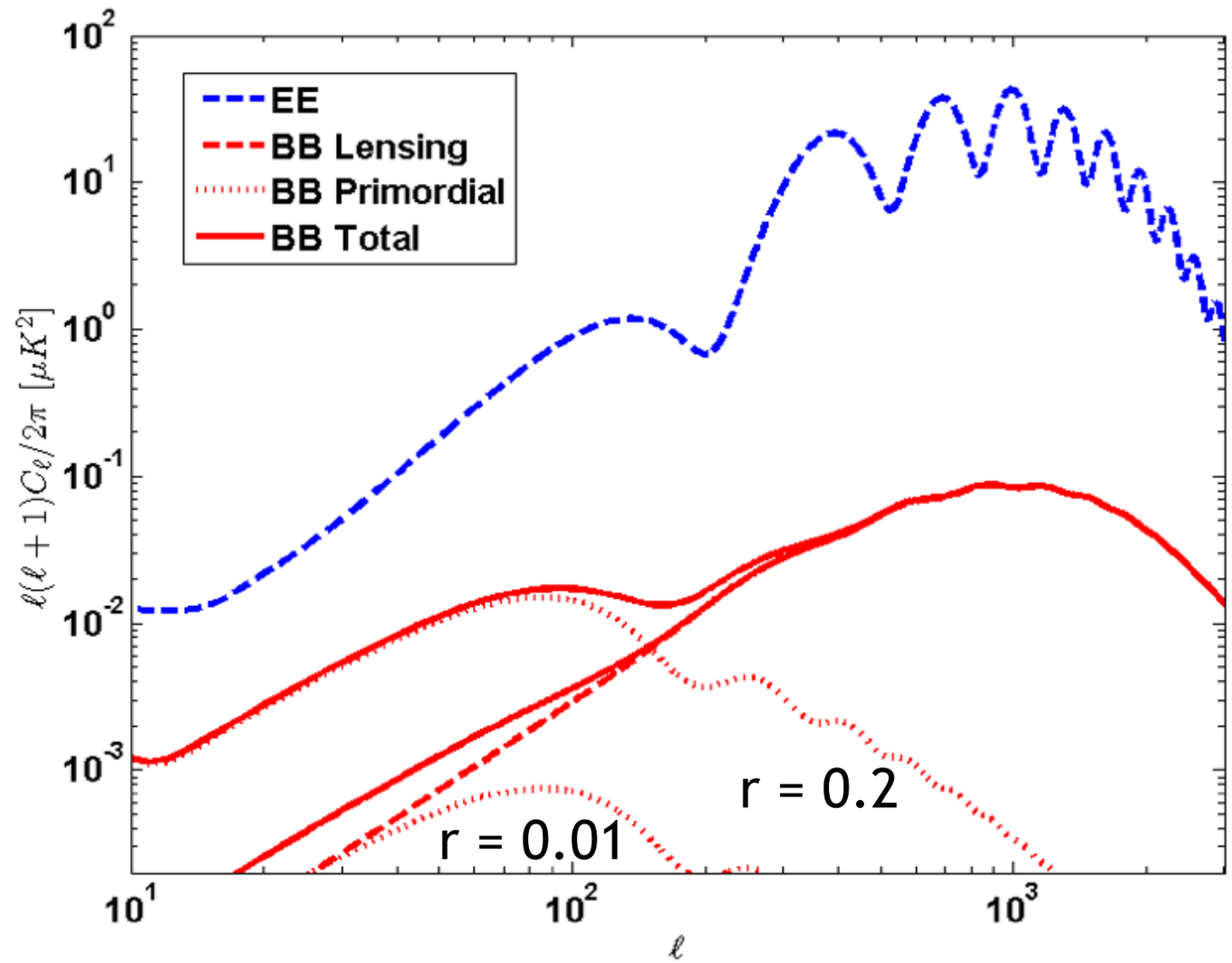
Residual computation method:
Errard et al. 2011, Phys. Rev. D 84, 063005

The next generation

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

  $\sigma(\Sigma m_\nu)$ = 16 meV

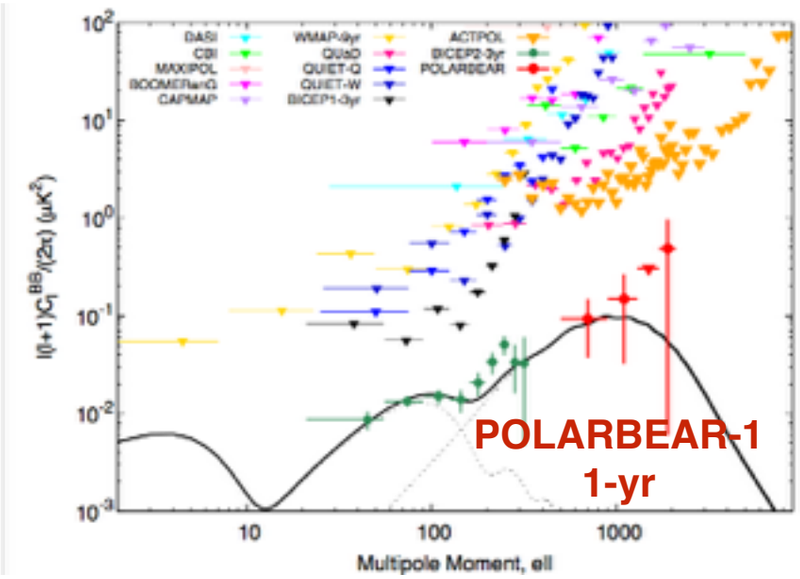
  $\sigma(r)$ = 0.001
- Instrument:
  - ~100x as many detectors as current generation
  - Frequency range 40 - 240 GHz
  - Survey 50% of sky to ~1 uK-arcmin depth
  - < 3 arcmin resolution

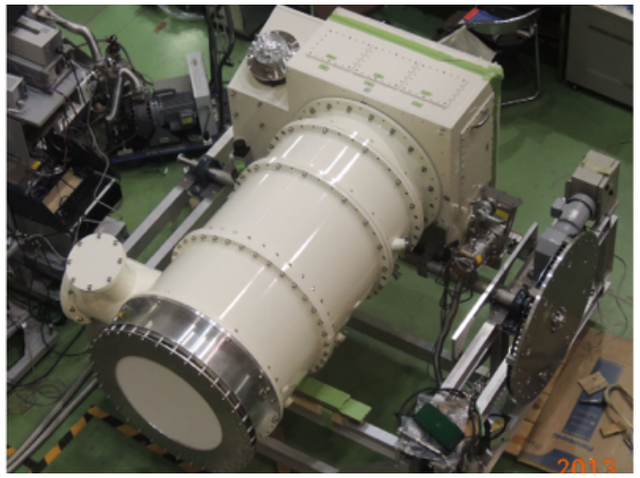


Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381

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