Cosmology from CMB Polarization with POLARBEAR and the Simons Array

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for the POLARBEAR Collaboration
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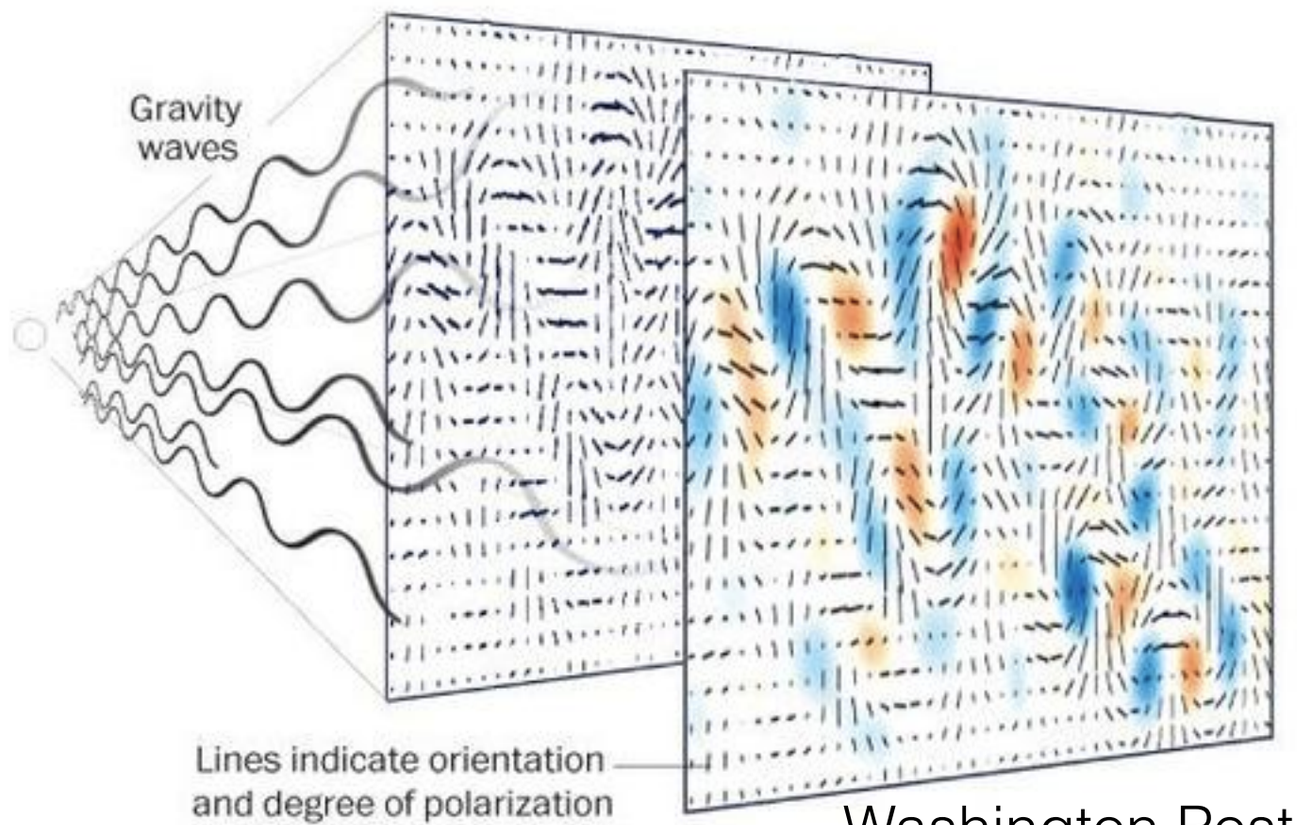
Chamberlain Fellow - Lawrence Berkeley National Lab

Outline

- This talk
  - POLARBEAR instrument and observations
  - Expansion to POLARBEAR-2 and Simons Array
- Next talk (Giulio Fabbian)
  - Data analysis and current results

Cosmology from B-mode Polarization

- Two sources of B-mode polarization in cosmic microwave background
  - **Inflationary signature in primordial CMB**
  - **Energy scale of inflation**
- Gravitational lensing
  - Neutrinos, dark energy



Washington Post

Cosmology from B-mode Polarization

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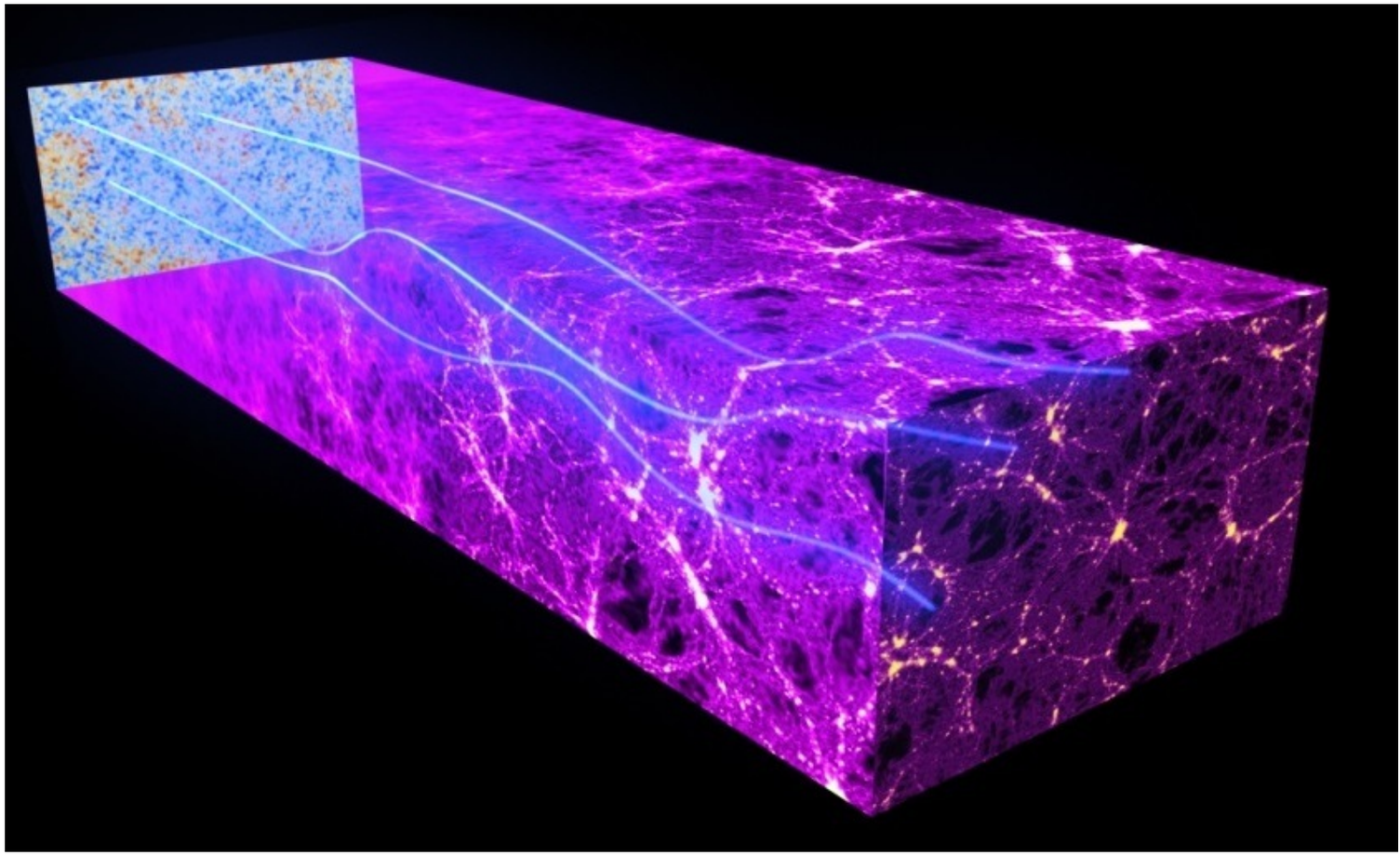

Cosmology from B-mode Polarization

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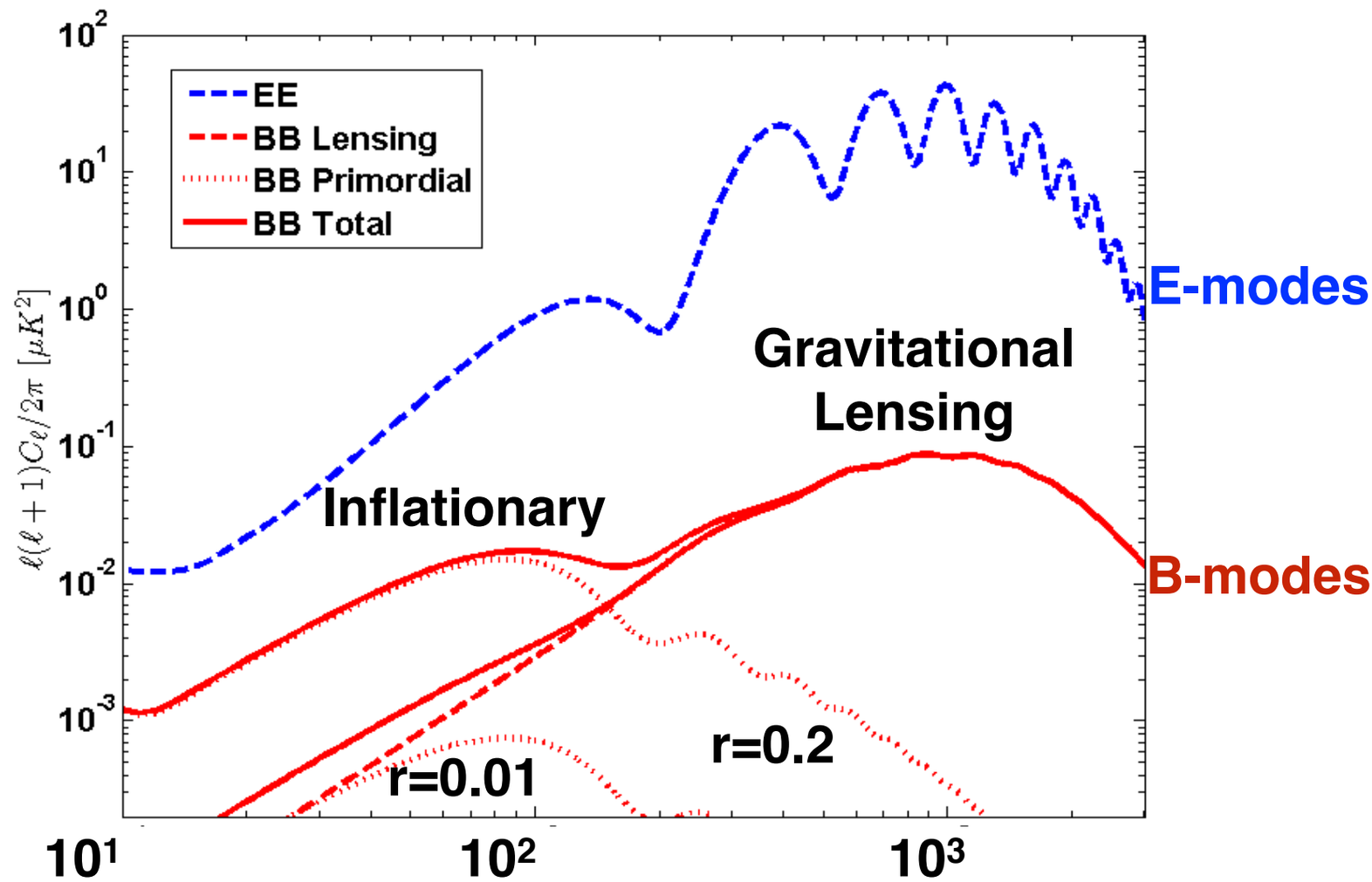
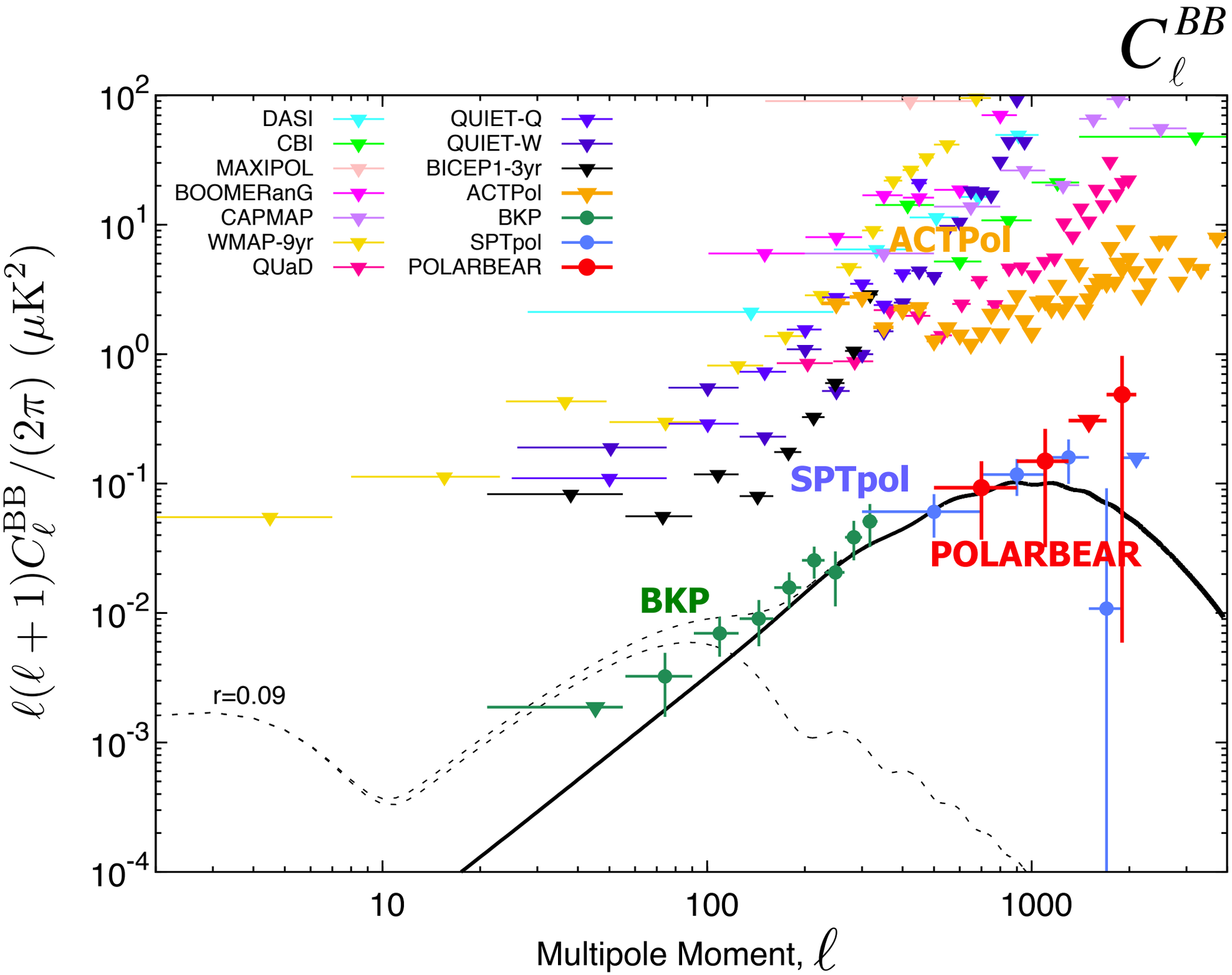
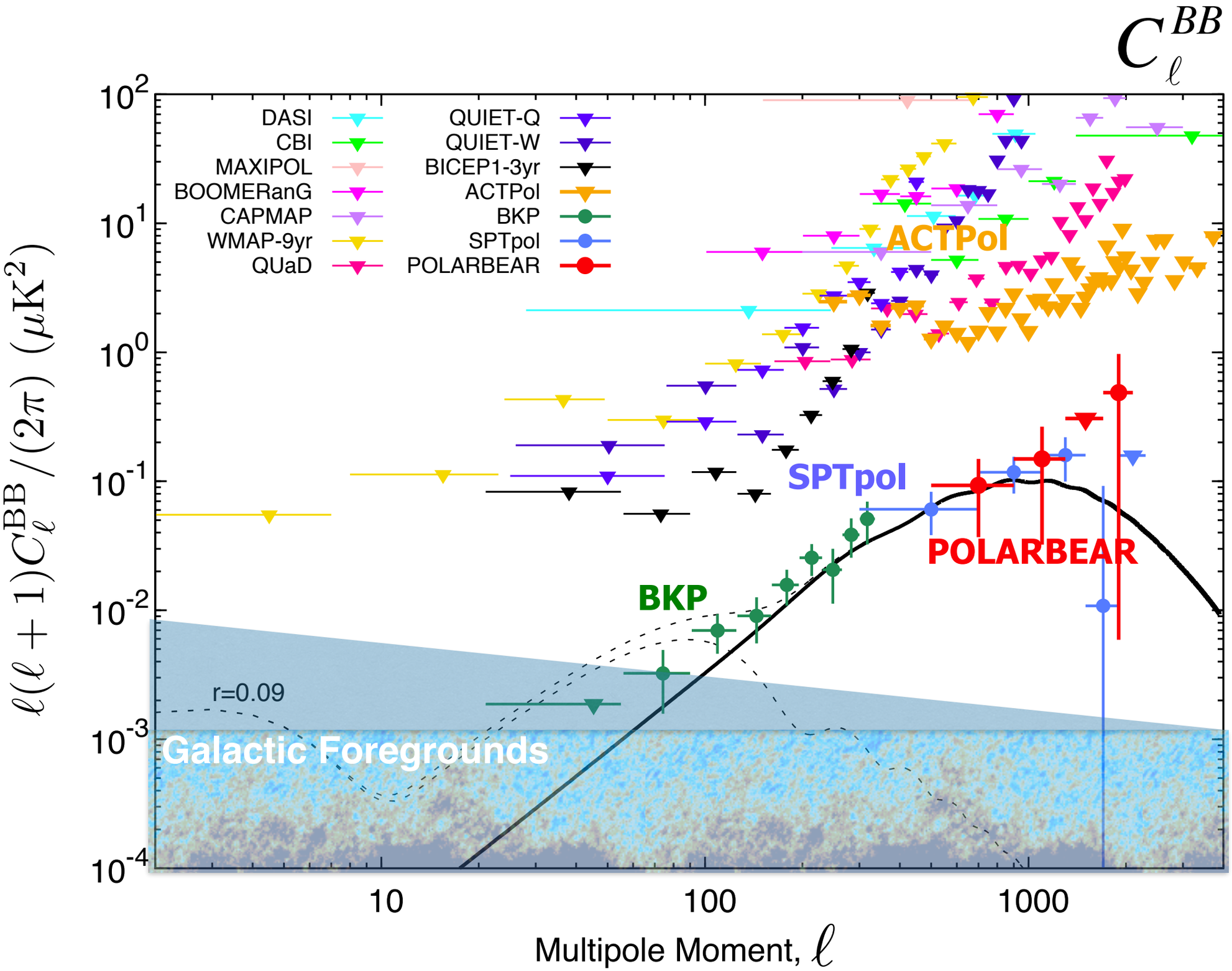


E-modes **B-modes**

CMB B-mode Measurements



CMB B-mode Measurements



POLARBEAR Collaboration

MEXT

SIMONS FOUNDATION
Advancing Research in Basic Science and Mathematics

CONICYT Ministerio de Educación Gobierno de Chile

NSF

NASA

UC Berkeley
Brian Barch
Darcy Barron
Yuji Chinone
Ari Cukierman
Tijmen de Haan
Josquin Errard
Neil Goeckner-Wald
John Groh
Grantland Hall
Charles Hill
William Holzapfel
Yasuto Hori
Oliver Jeong
Adrian Lee
Mike Myers
Chris Raum
Paul Richards
Blake Sherwin
Ian Shirley
Bryan Steinbach
Aritoki Suzuki
Nathan Whitehorn
Oliver Zahn

U. Wisconsin - Madison
Kam Arnold

UC San Diego
Chris Aleman
Matt Atlas
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
Brandon Wilson
Amit Yadav
Alex Zahn

CU Boulder
Nils Halverson
Greg Jaehnig
David Schenck

U. Melbourne
Christian Reichardt

KEK
Yoshiki Akiba
Takaho Hamada
Masaya Hasegawa
Kaori Hattori
Masashi Hazumi
Yuki Inoue
Haruki Nishino
Yuuko Segawa
Jun-ichi Suzuki
Osamu Tajima
Satoru Takakura
Sayuri Takatori
Takayuki Tomaru

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Maude Le Jeune
Julien Peloton
Davide Poletti
Radek Stompor

Argonne NL
Amy Bender

Imperial College
Anne Ducout
Stephen Feeney
Andrew Jaffe

McGill University
Matt Dobbs
Adam Gilbert
Josh Montgomery
Graeme Smecher

Dalhousie
Scott Chapman
Colin Ross
Kaja Rotermund
Alexei Tikhomirov

Lawrence Berkeley NL
Julian Borrill
Reijo Keskitalo
Theodore Kisner
Akito Kusaka
Eric Linder

Kavli IPMU
Takuro Fujino
Fumiya Irie
Nobuhiko Katayama
Kuniyoshi Mizukami
Tetsu Yamashita

SISSA
Carlo Baccigalupi
Giulio Fabbian
Giuseppe Puglisi

JAXA
Tomotake Matsumura

UC Irvine
Chang Feng

National Institute for Fusion Science
Suguru Takada

Cardiff University
Peter Ade

NASA Goddard
Nathan Miller

Princeton
Zigmund Kermish

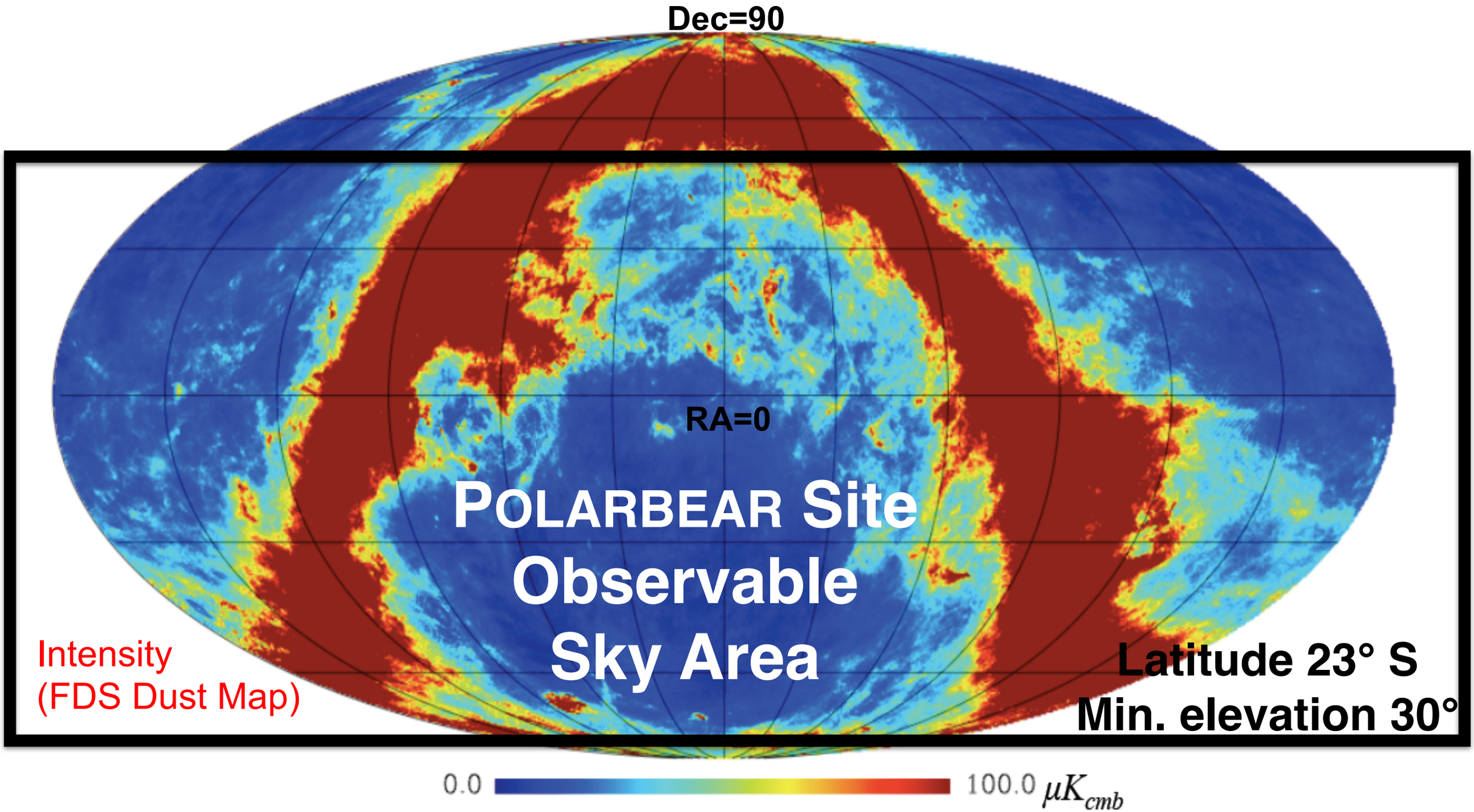
Católica (PUC)
David Boettger
Rolando Dunner

And many more in years past…

The POLARBEAR Experiment

- Dedicated CMB polarization experiment
- Located on Cerro Toco at 5200 meters in Atacama desert
- First light January 2012
- Now in fourth season of observations with POLARBEAR-1
- Two additional telescopes under construction now

POLARBEAR Observations



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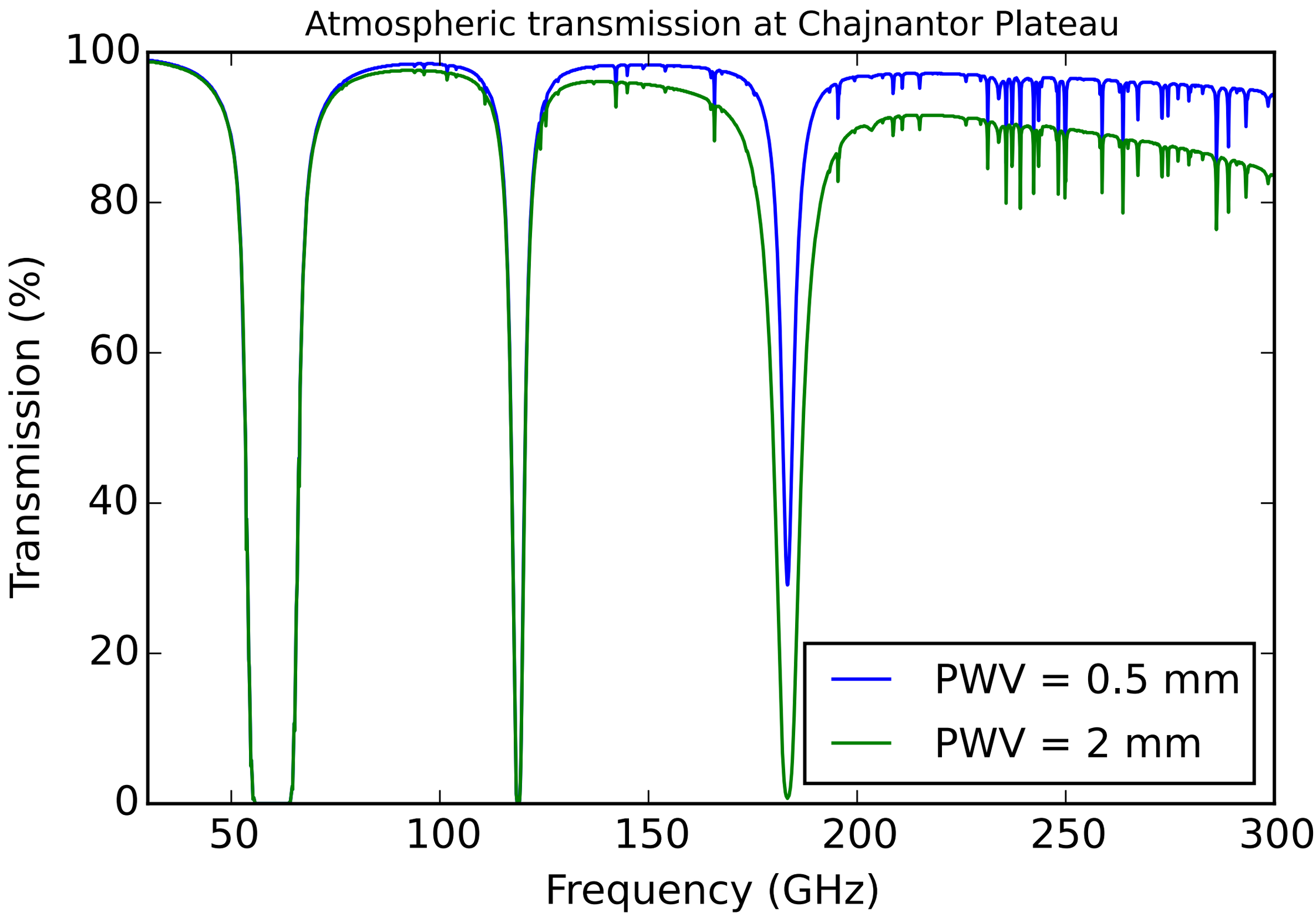


POLARBEAR Observations

Huan Tran Telescope

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

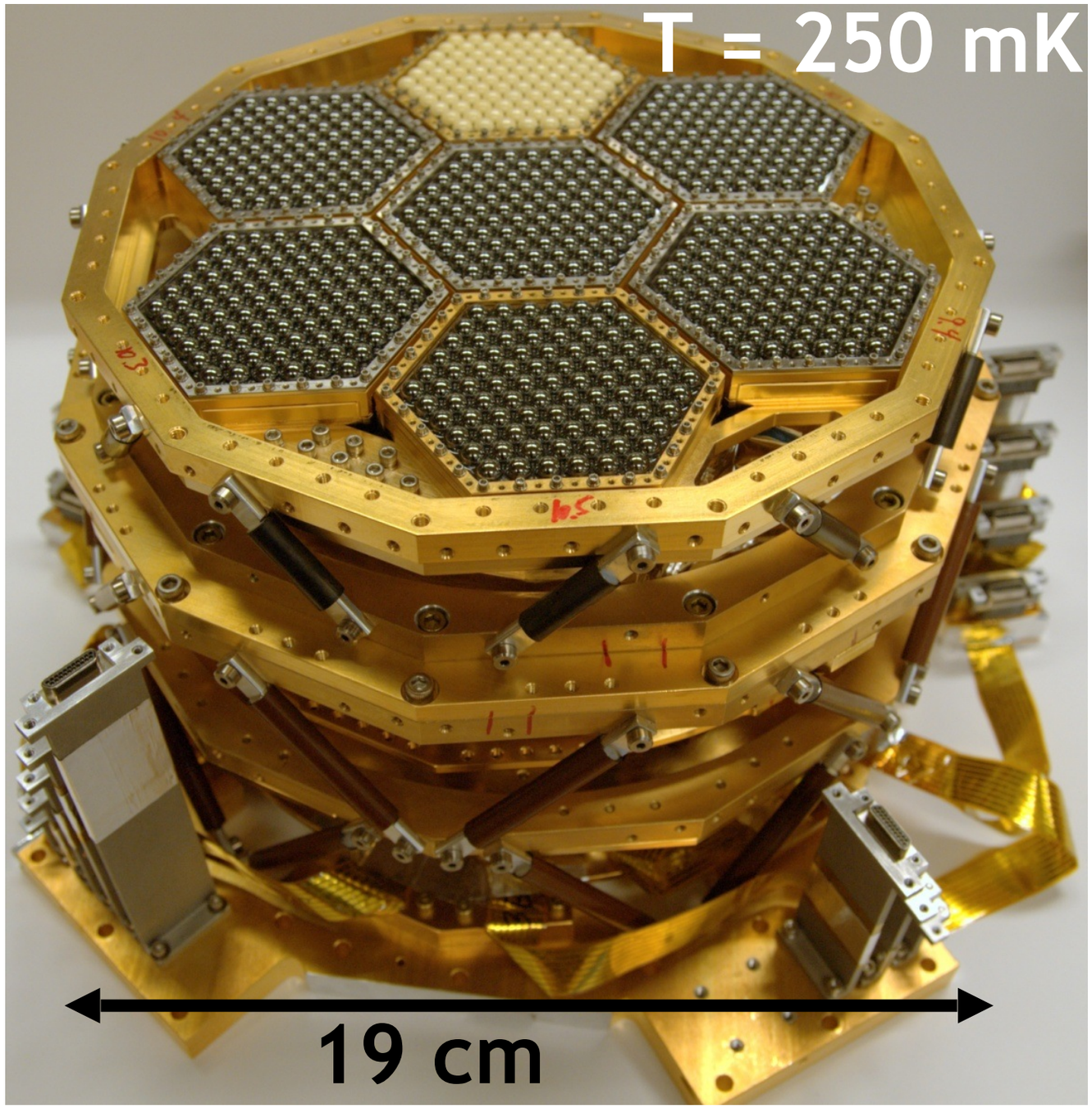
POLARBEAR Observations

- Scan in azimuth at fixed elevation
- Remove “ground template,” fixed in Az-El coordinates
- Modulate CMB Polarization
  - Apparent sky rotation
  - Half-wave plate

POLARBEAR-1

Focal Plane

- 637 dual polarization pixels
- Beam-forming lenslet coupled to each pixel
- 1274 superconducting transition-edge sensor bolometers



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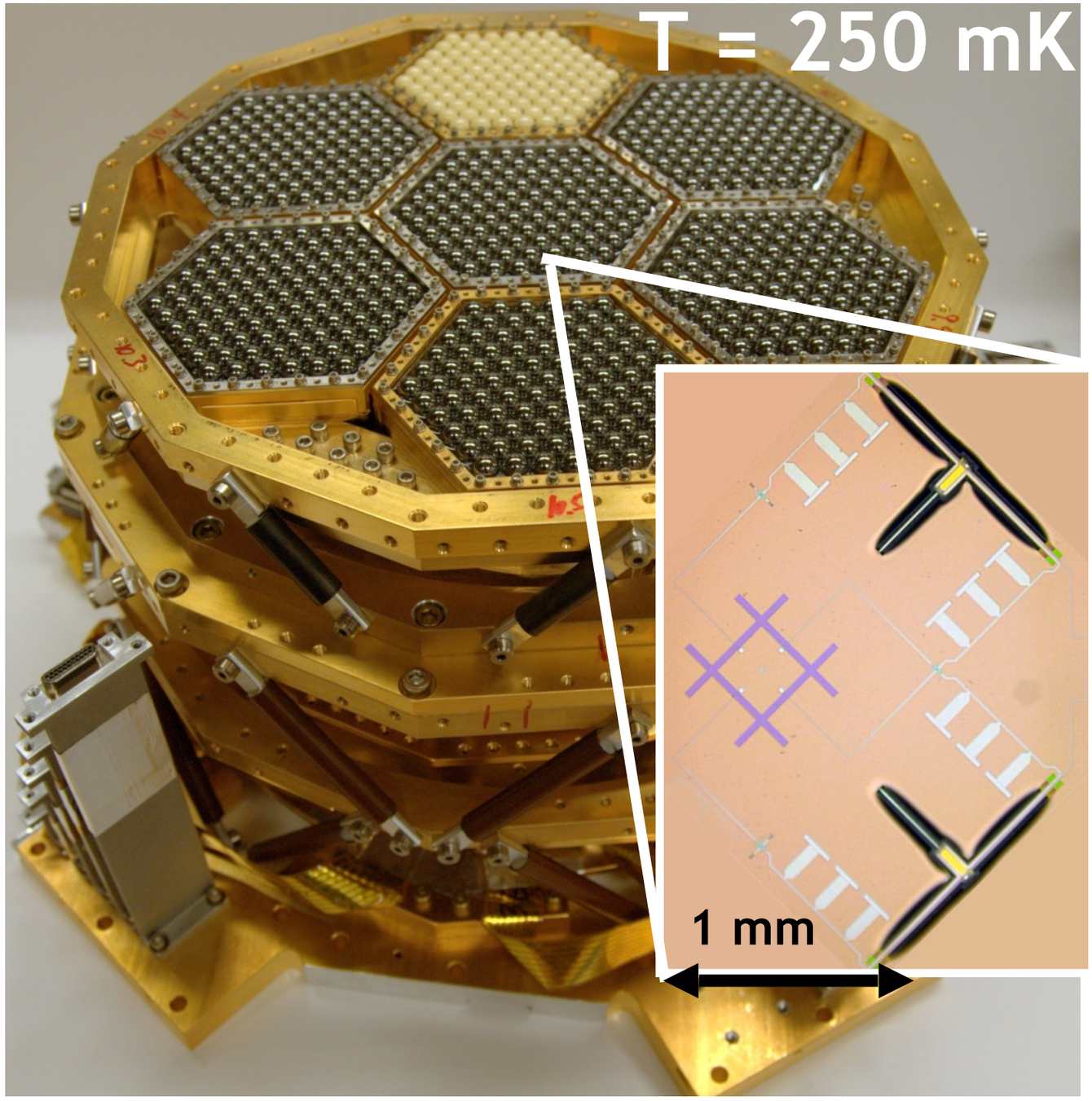
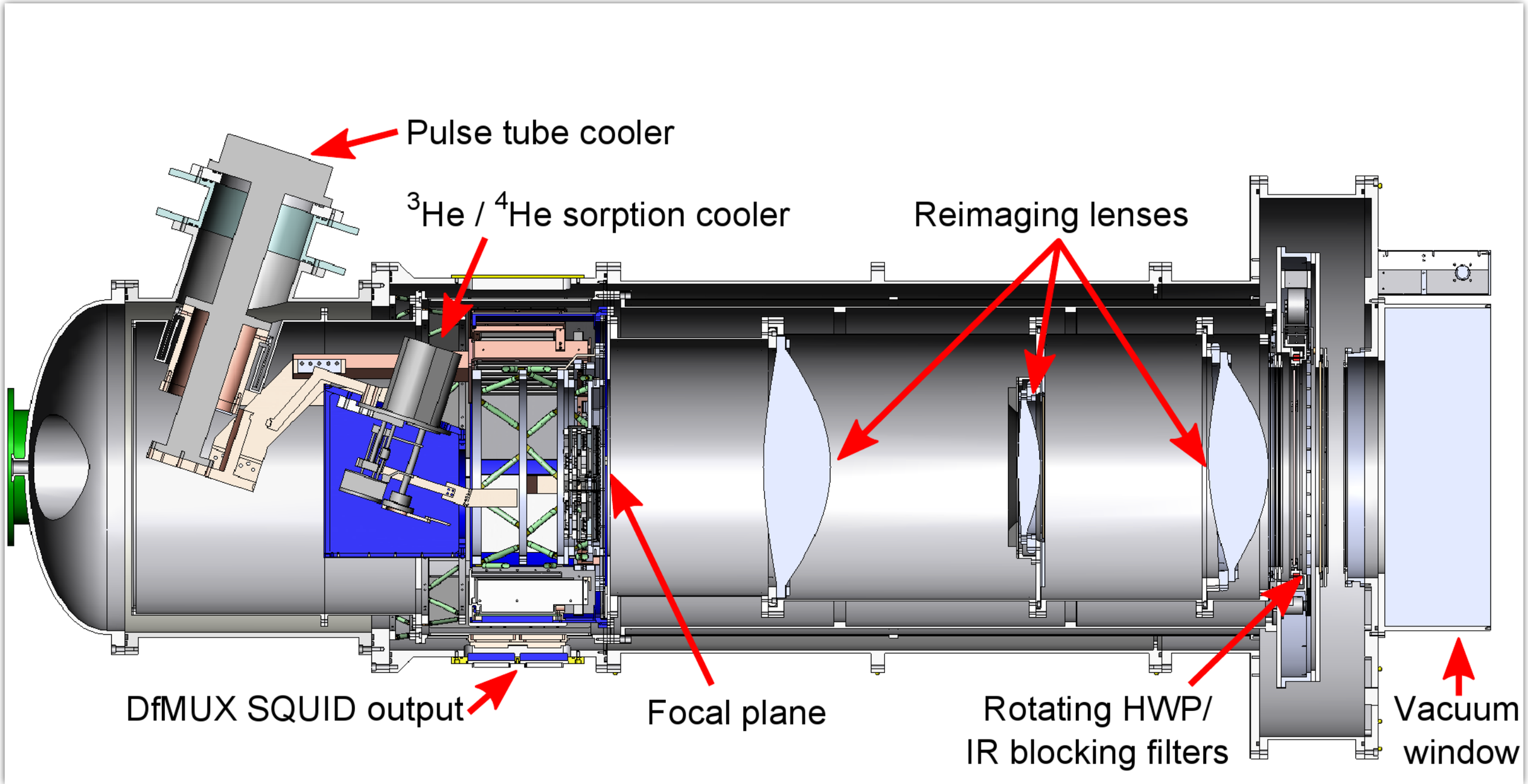


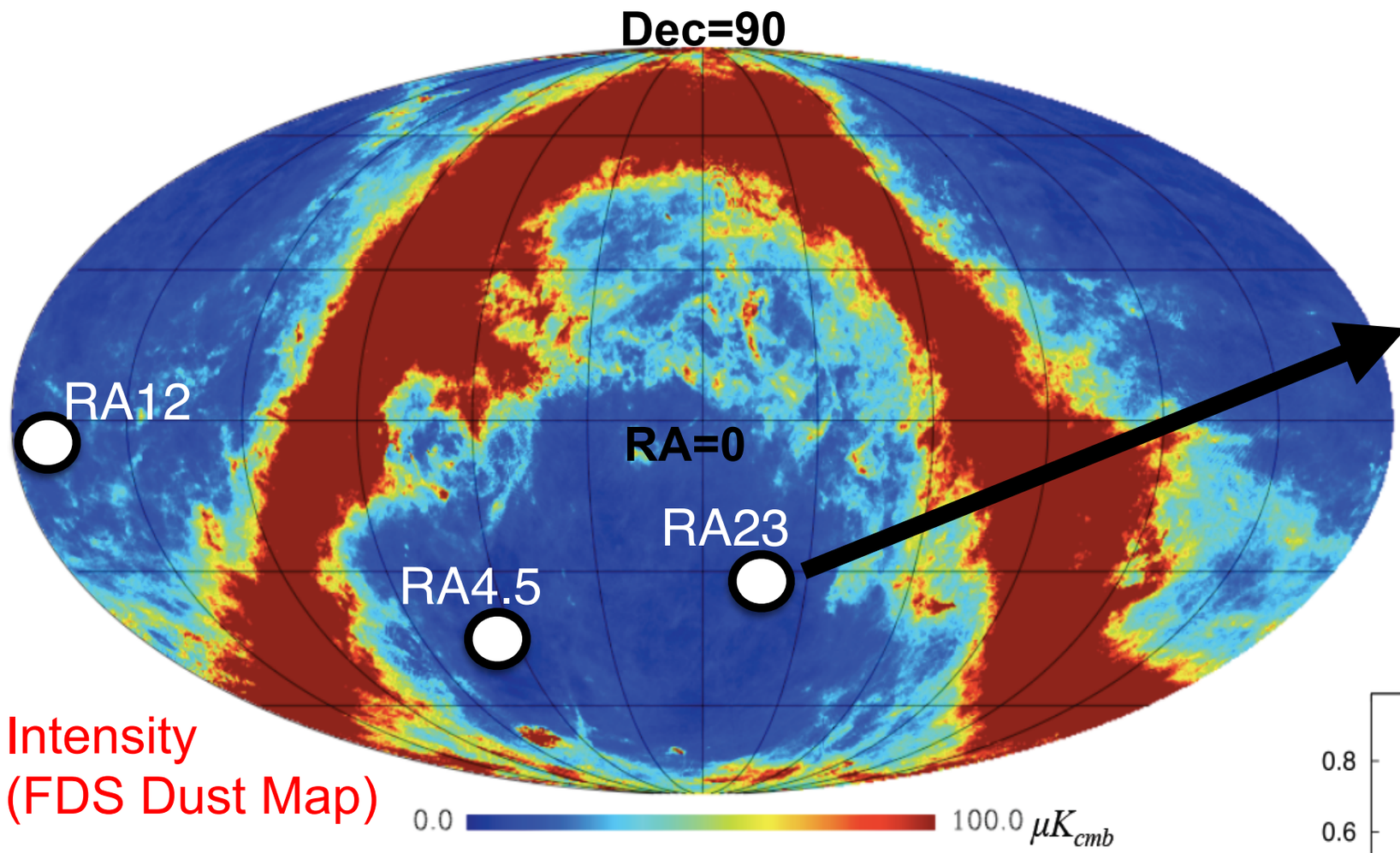
POLARBEAR-1

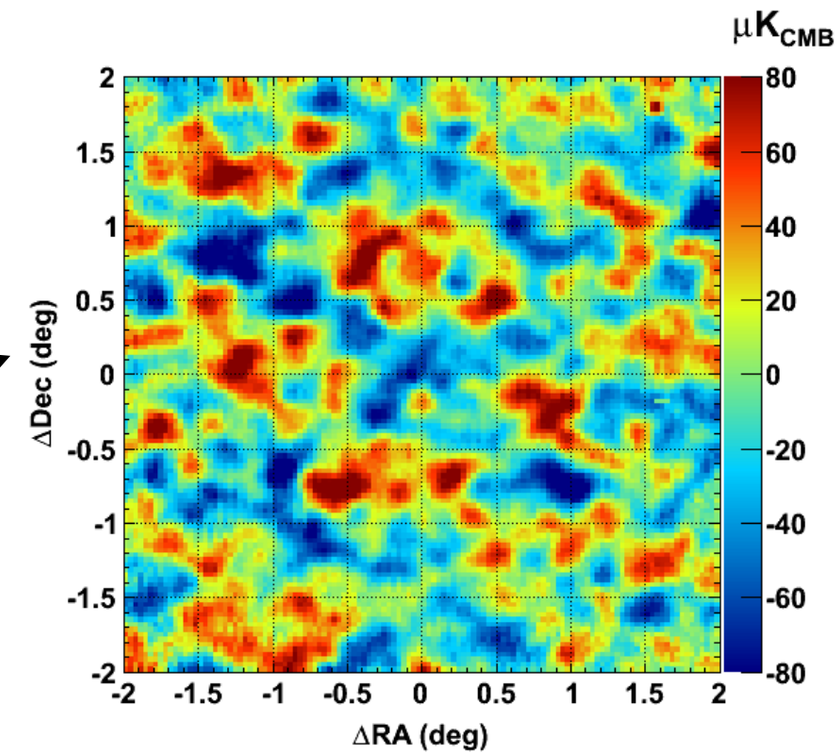
Cryogenic Receiver



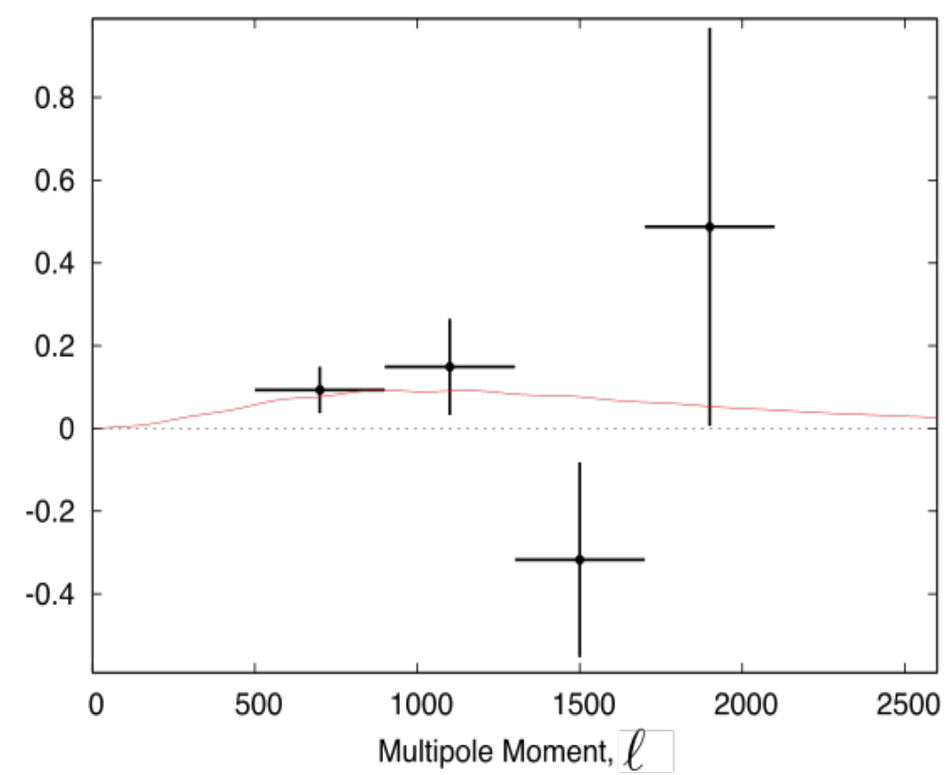
2 meters

POLARBEAR Observations





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

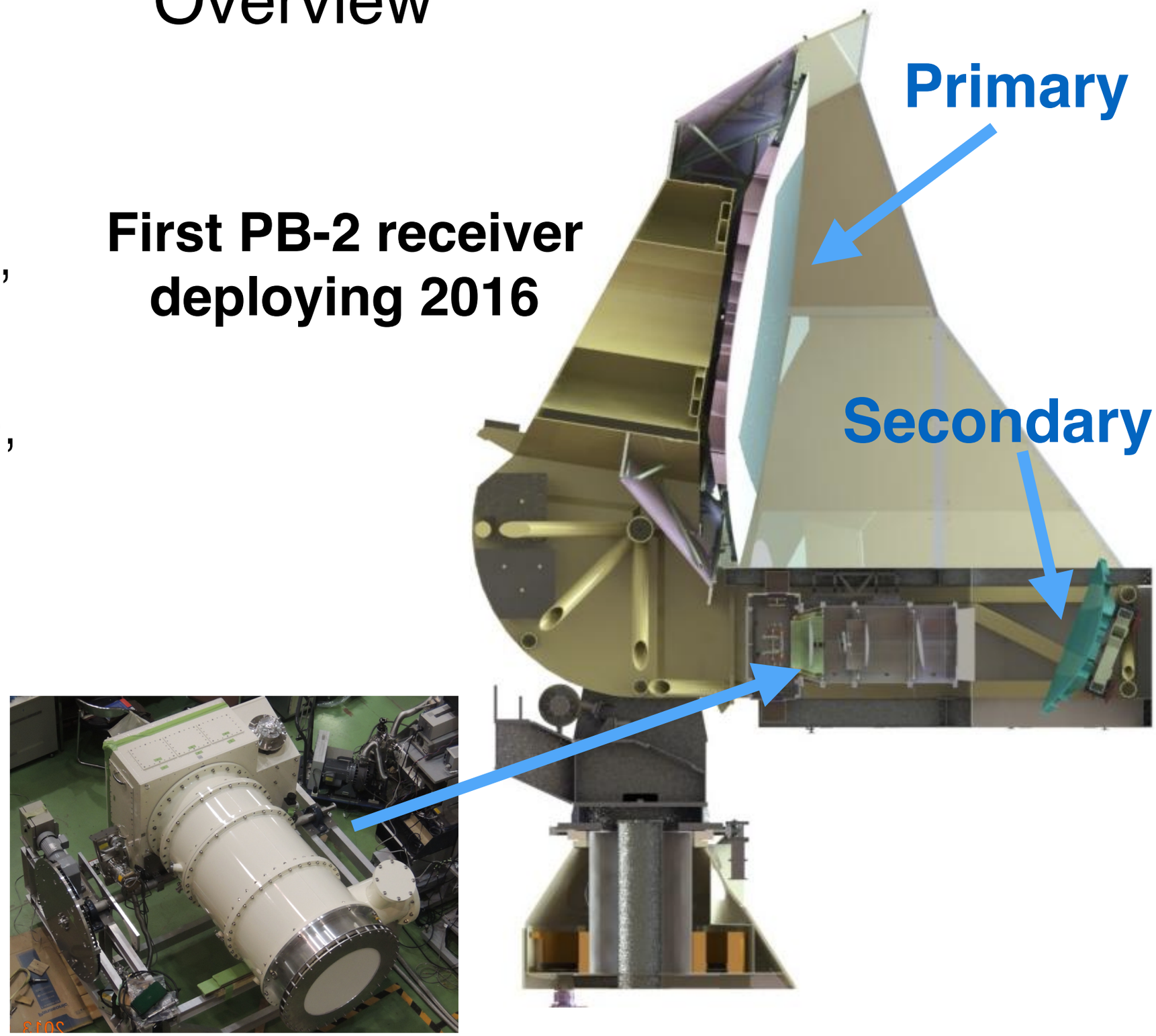


POLARBEAR-2

Overview

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

First PB-2 receiver deploying 2016



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- Larger focal plane, field-of-view
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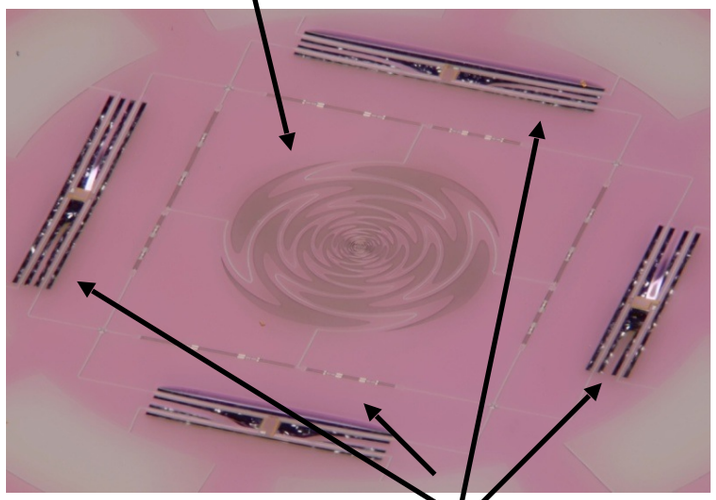
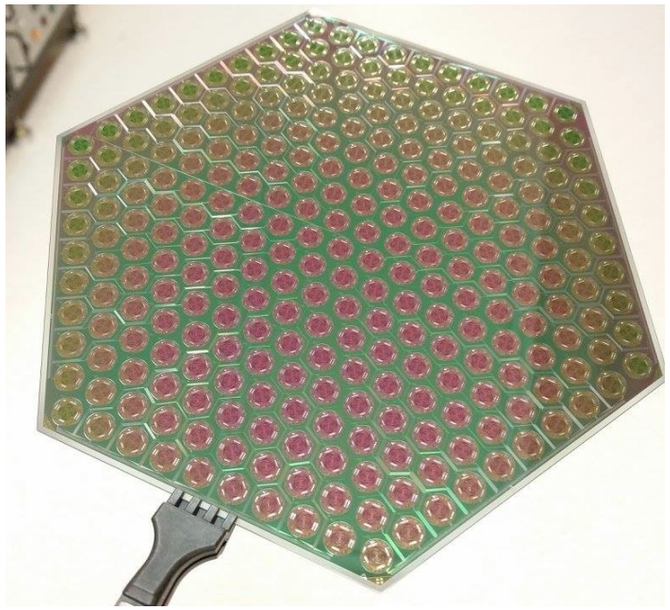
Broadband sinuous antenna



TES bolometers
4 detectors per pixel



271 pixels / wafer

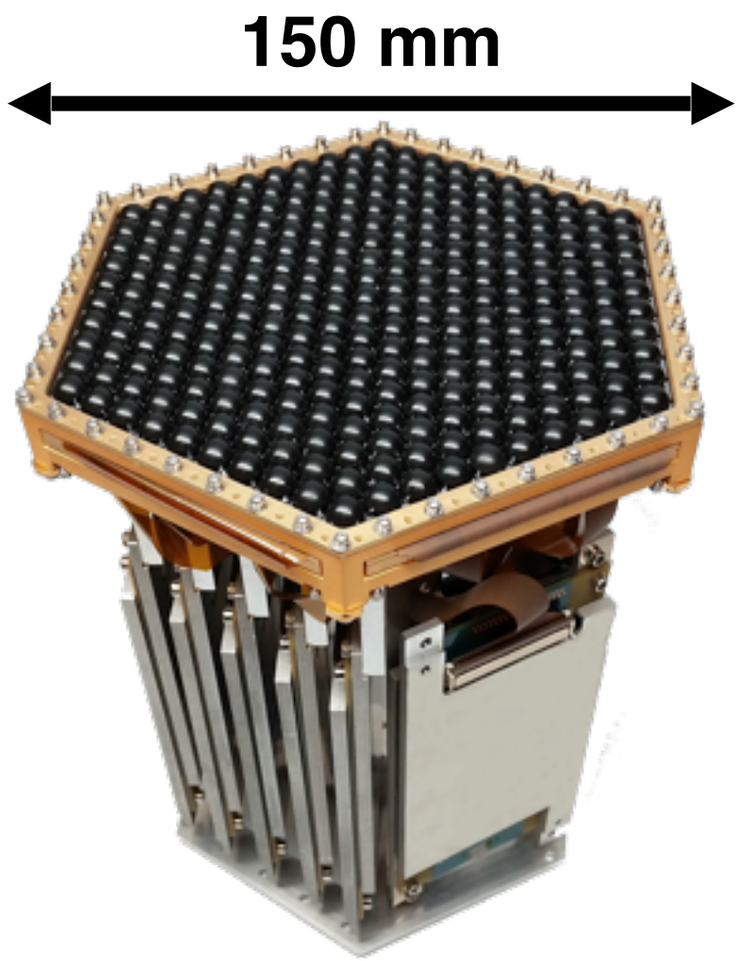
POLARBEAR-2

Overview

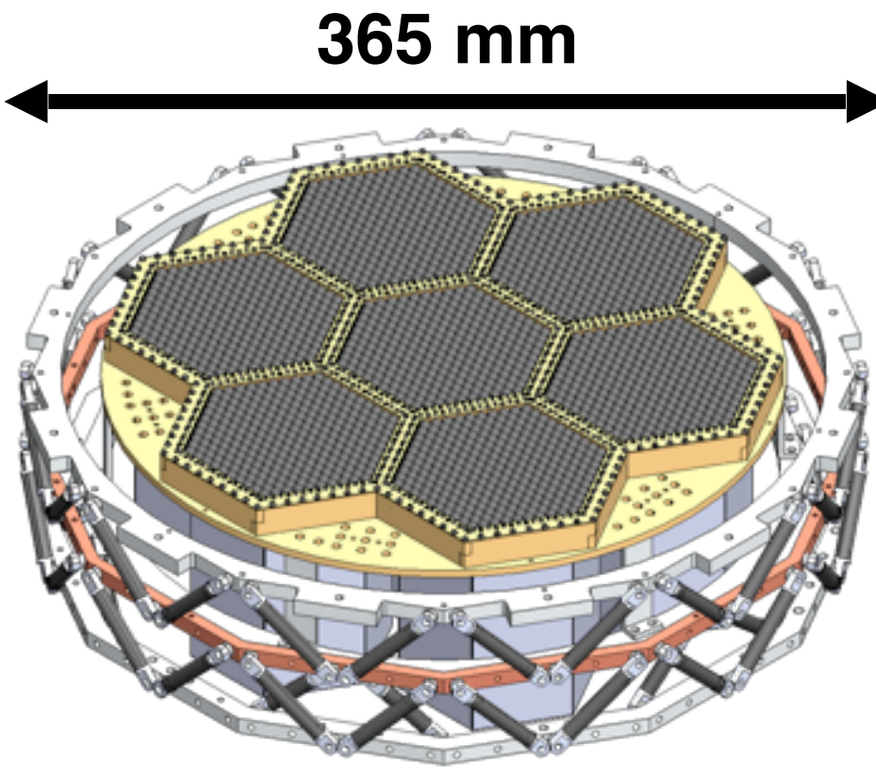
- Next-generation receiver design
- Broadband optics, multi-chroic pixels
- **Larger focal plane**, field-of-view
- $\sigma(\Sigma m_\nu) < 100$ meV

NET bolometer:
360 μK√s

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



Detector Module

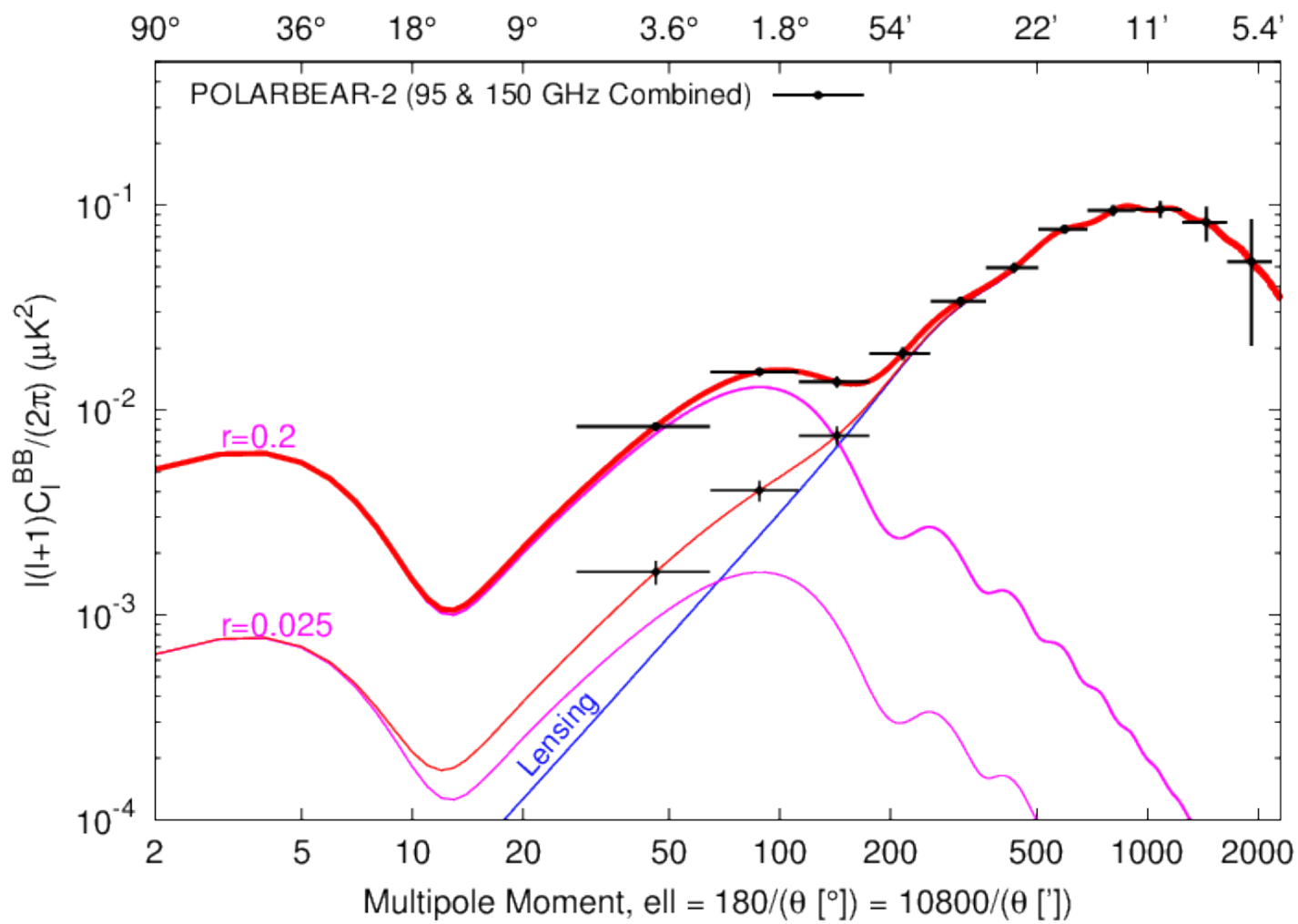


Focal Plane

POLARBEAR-2

Overview

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



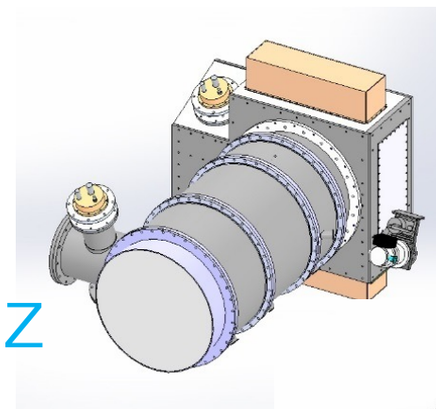
	POLARBEAR-1	**POLARBEAR-2**
Frequency	150 GHz	95 GHz + 150 GHz
Pixels	637	1897
Detectors	1274	7588
Field-of-view	2.3°	4.8°

Simons Array

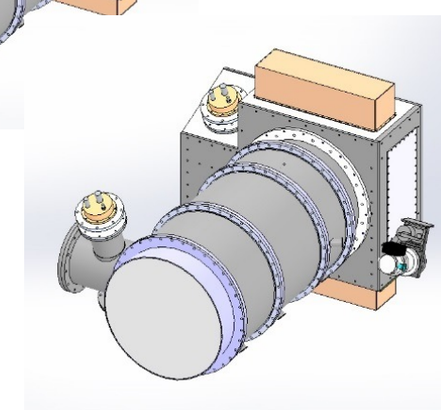
Leverage POLARBEAR experience to rapidly increase sensitivity

- Two telescopes under construction now
  - Install at Chilean site end of 2015

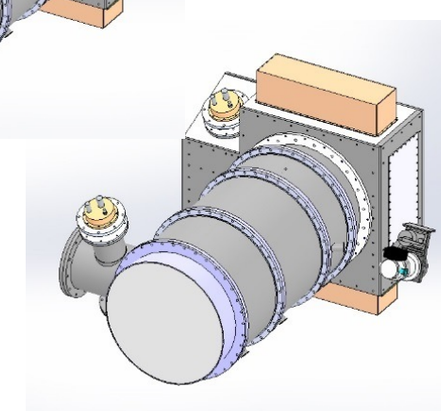
95 GHz / 150 GHz



95 GHz / 150 GHz



150 GHz / 220 GHz



3 receivers (22,764 bolometers) observing at 95,150, 220 GHz
Three-year survey of 65% of sky
Funded by the Simons Foundation, NSF, MEXT

Simons Array

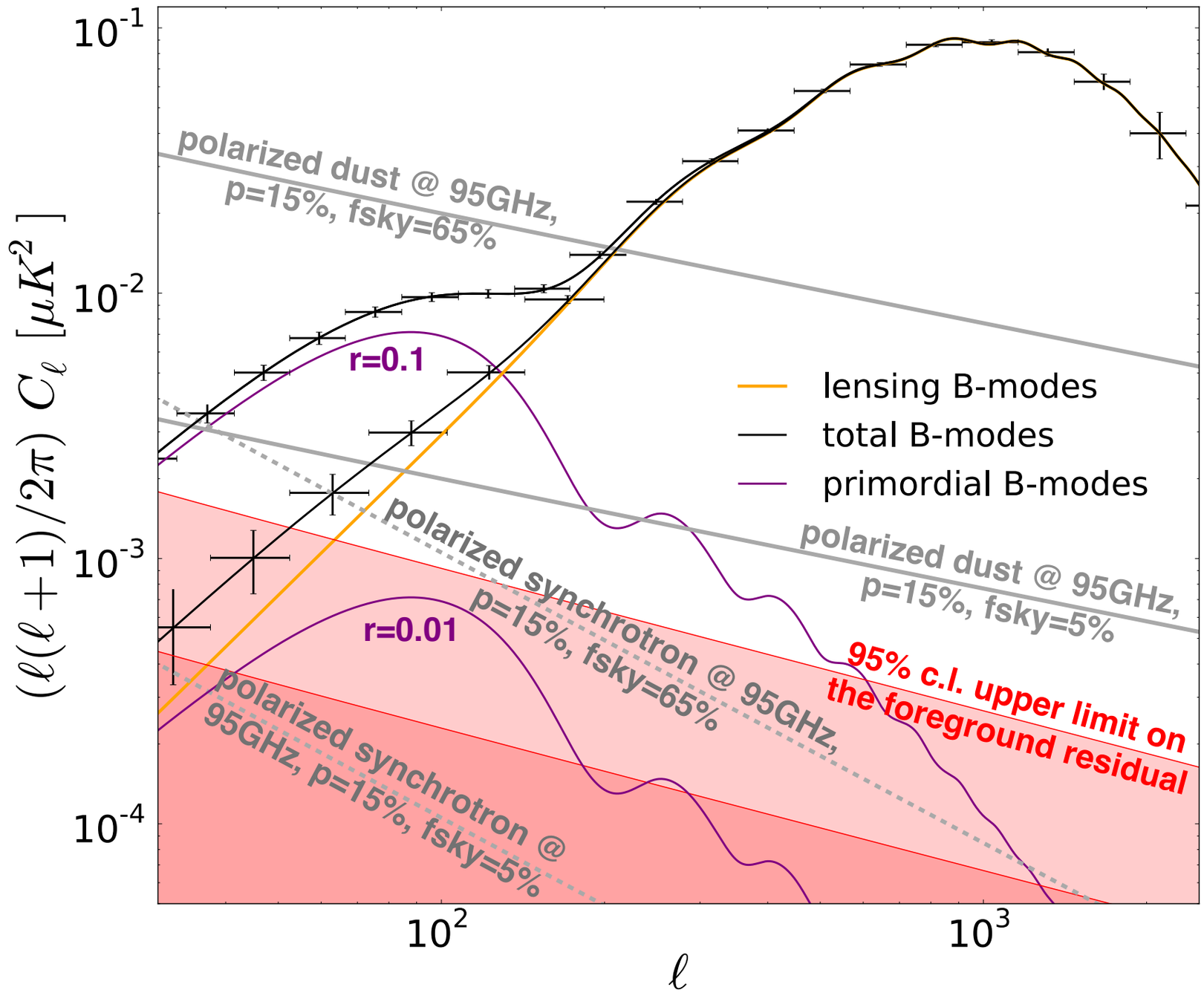
Projected sensitivity

Foreground rejection with multi-frequency Simons Array data

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

w/ DESI BAO, including foreground contamination

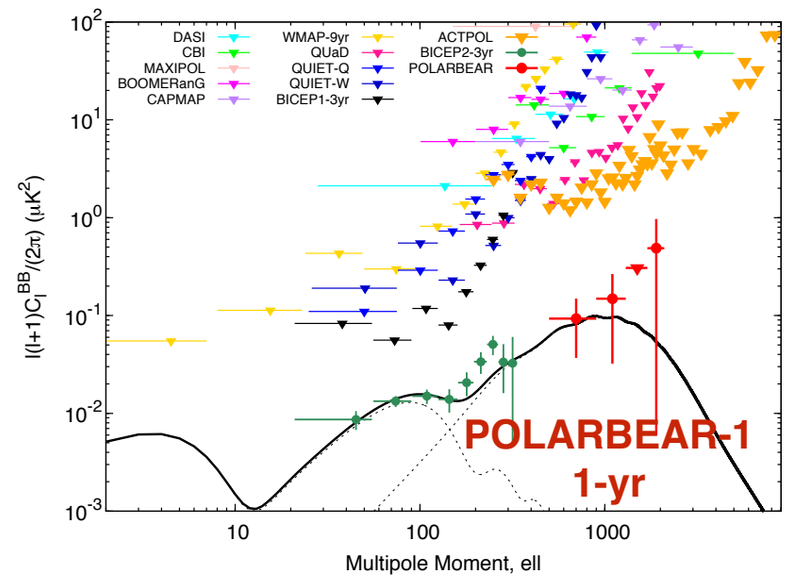
$\sigma(r = 0.1) = 0.006$

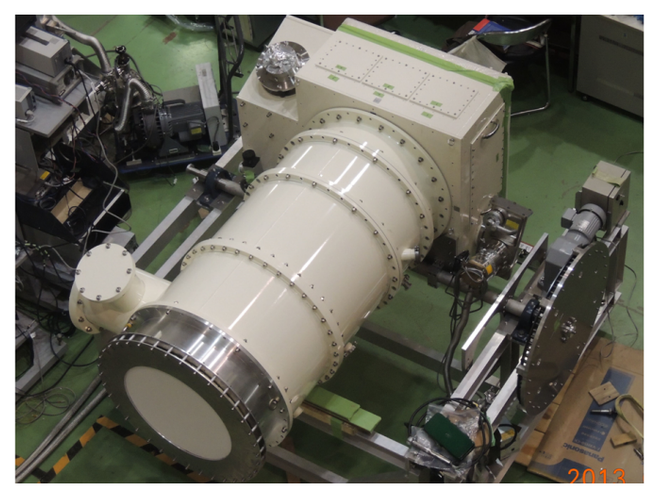


Residual computation method:
Errard et al. 2011, Phys. Rev. D 84, 063005

Thank you

- **POLARBEAR-1** in fourth season of observations
- First-season results with **POLARBEAR-1**:
  - 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 2014, Bender et al SPIE 2014
  - Optics: Inoue et al. SPIE 2014
- **Simons Array** initial survey:
  65% of sky at 3 freqs. (22,764 bolometers)
  - Arnold et al. SPIE 2014



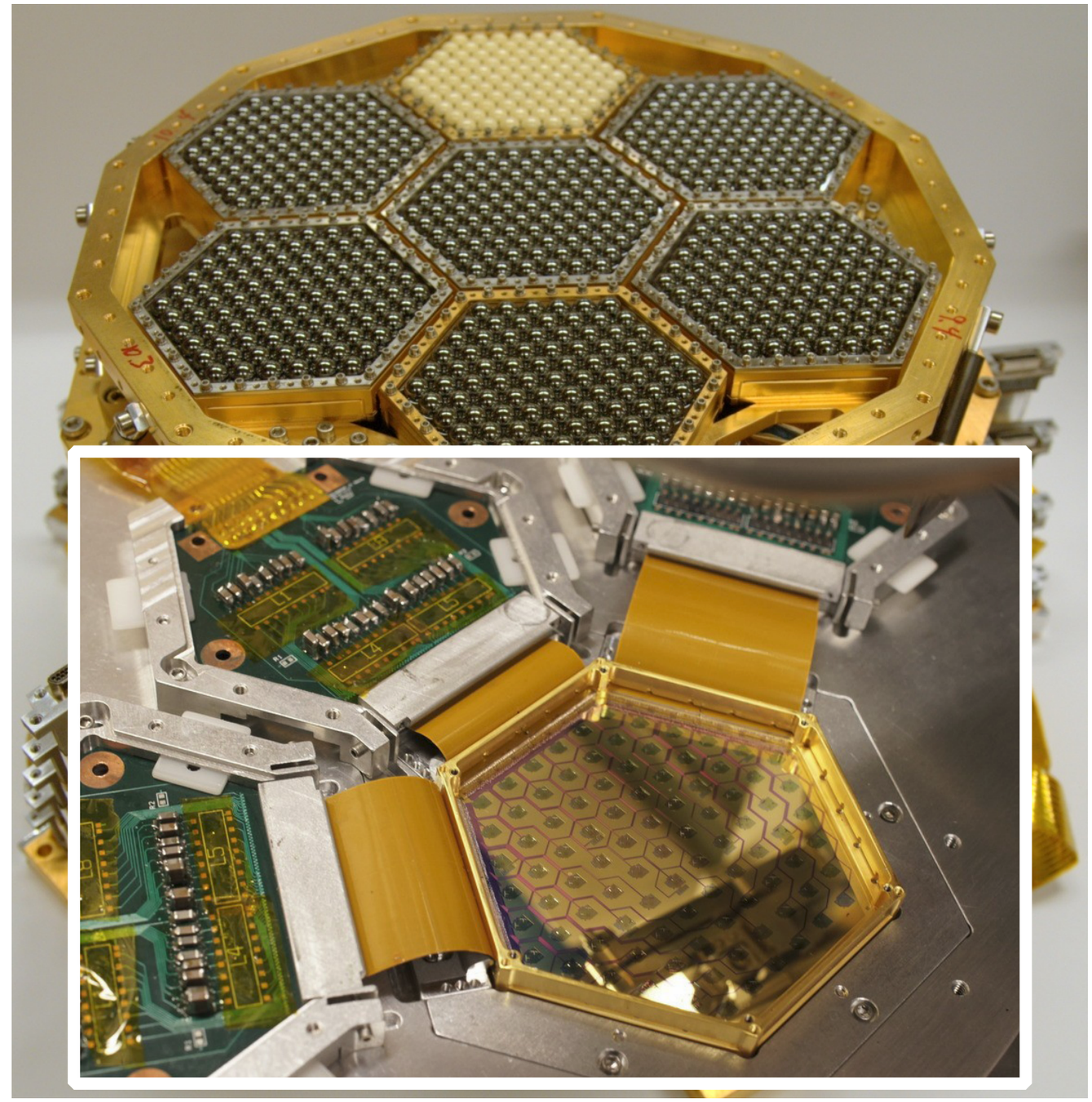


Back-up slides

POLARBEAR-1

Focal Plane

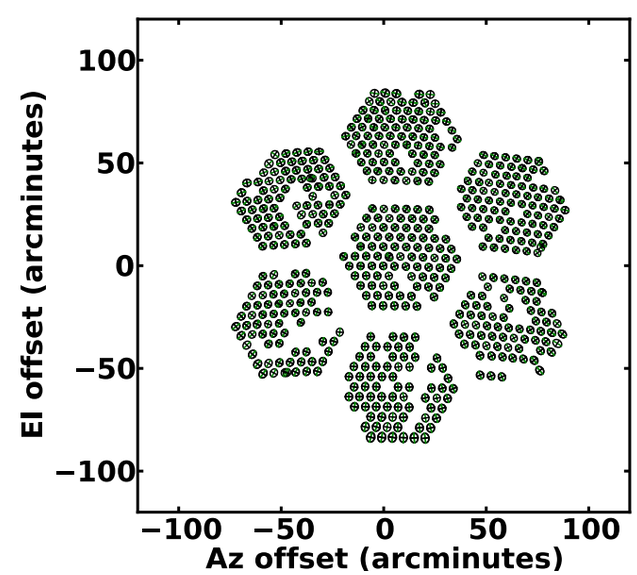
- 637 dual polarization pixels
- Beam-forming lenslet coupled to each pixel
- 1274 superconducting transition-edge sensor bolometers
- Frequency-domain multiplexing readout (8x)

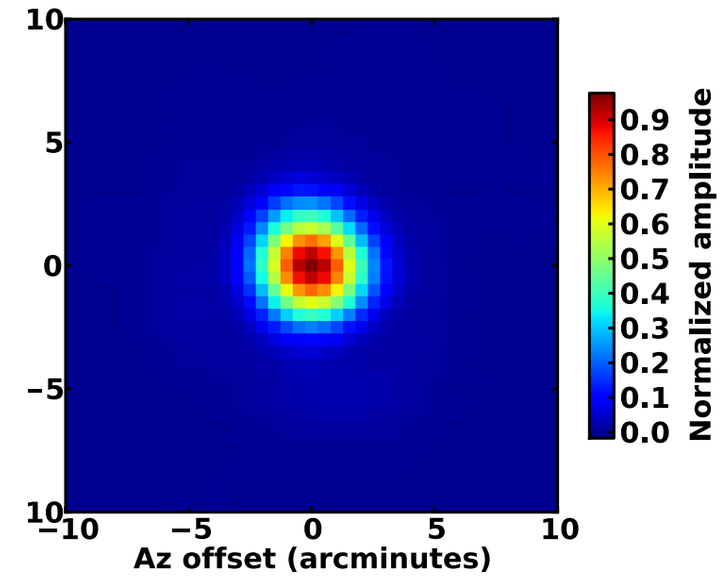


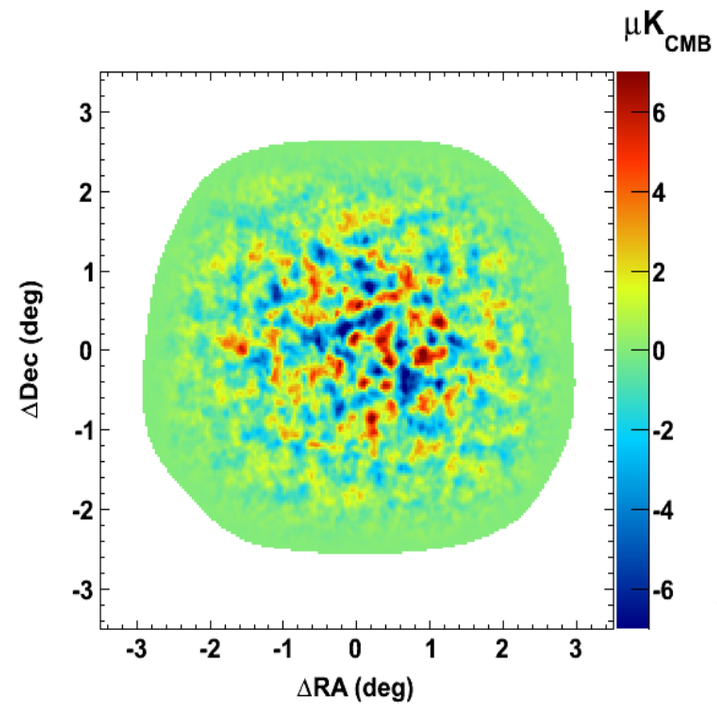
POLARBEAR-1

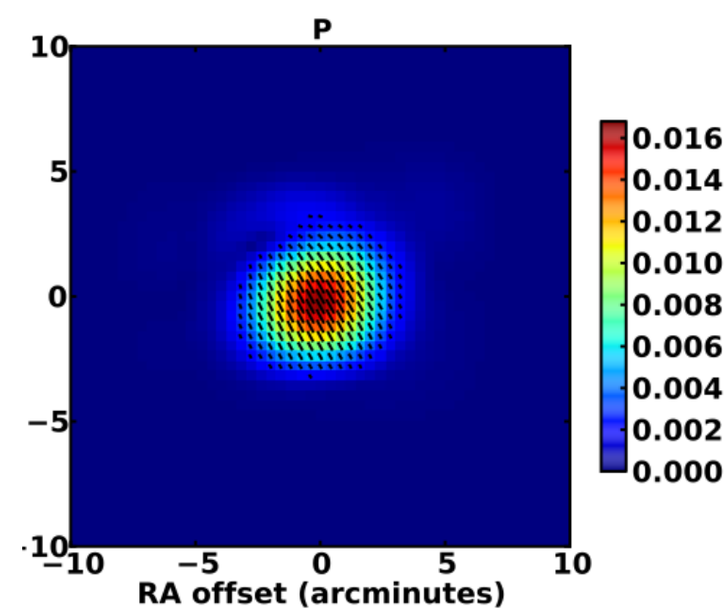
Instrument performance

- 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



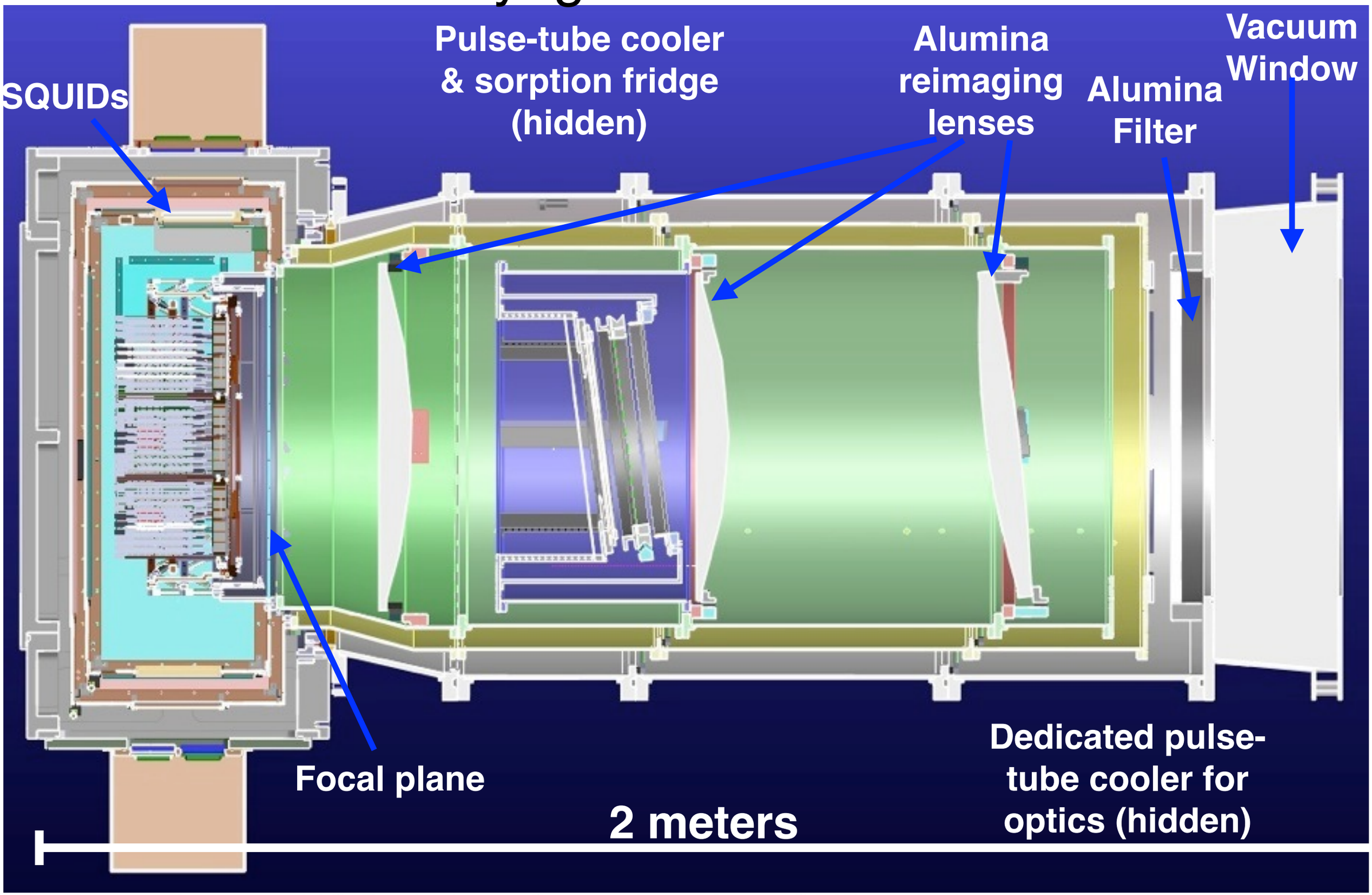






POLARBEAR-2

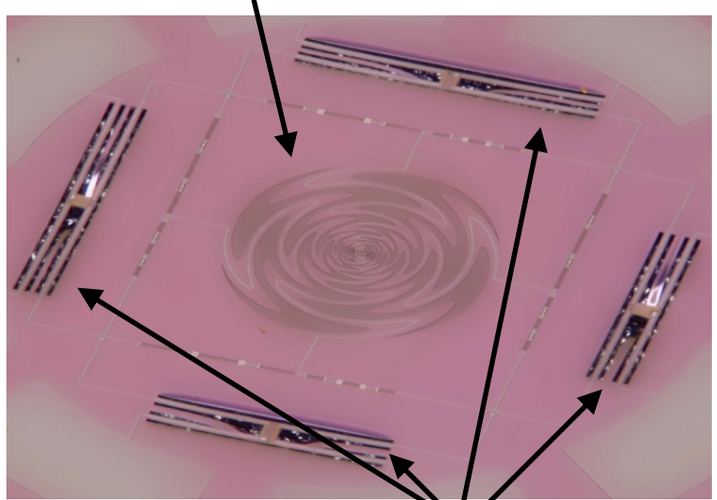
Cryogenic Receiver



POLARBEAR-2

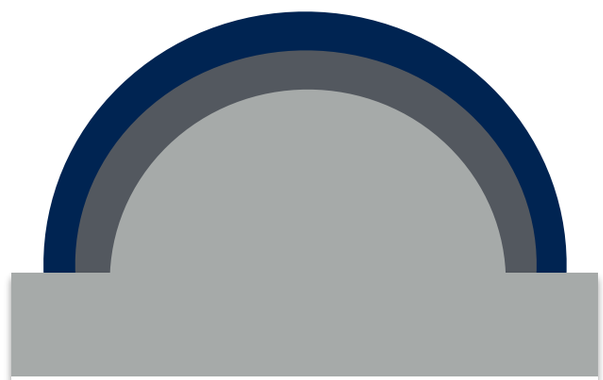
Focal Plane

Broadband sinuous antenna



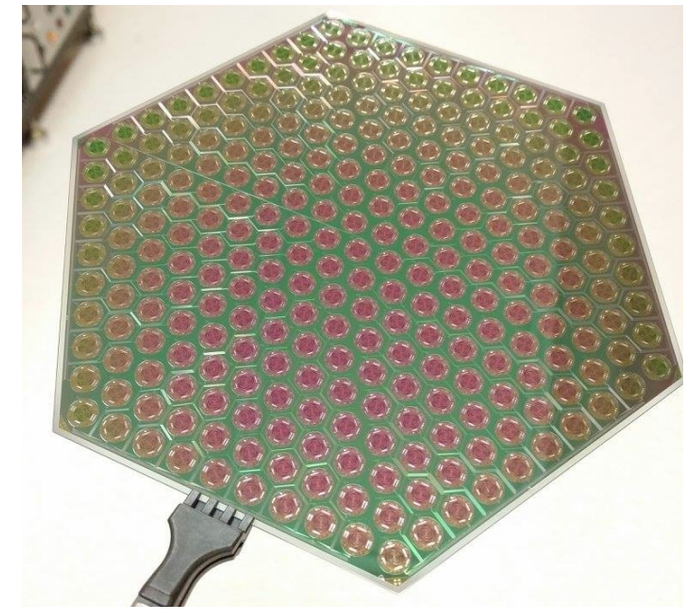
TES bolometers

4 detectors per pixel

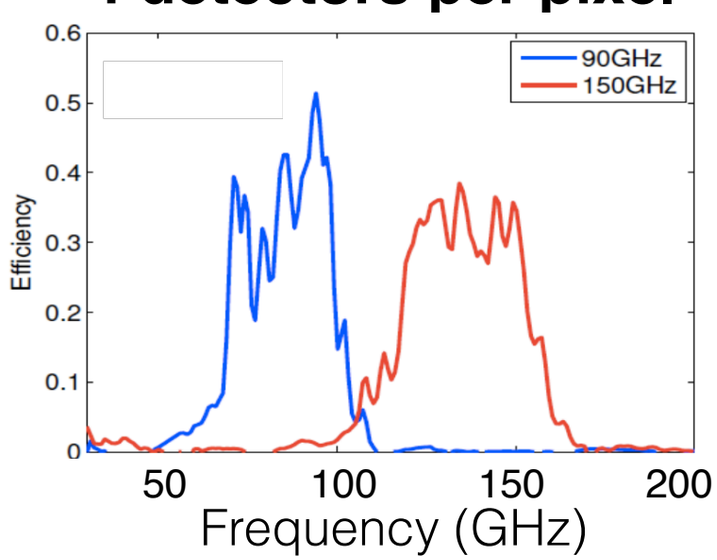


Beam-forming silicon lenslet w/ 2-layer AR coating

AR-coated lenslets on seating wafer



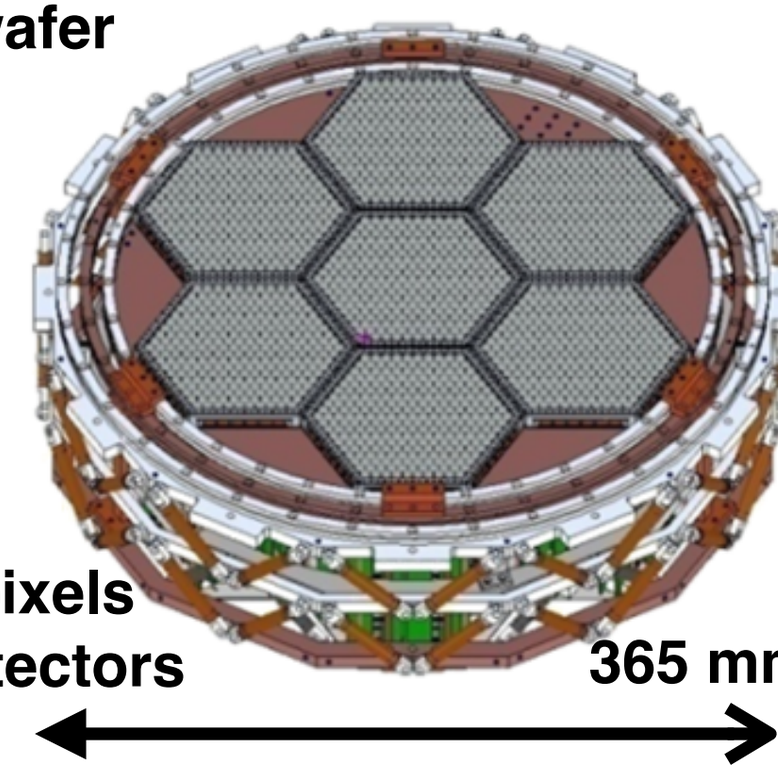
271 pixels / wafer



Freq. band measurement

NET bolometer:
360 μK√s

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



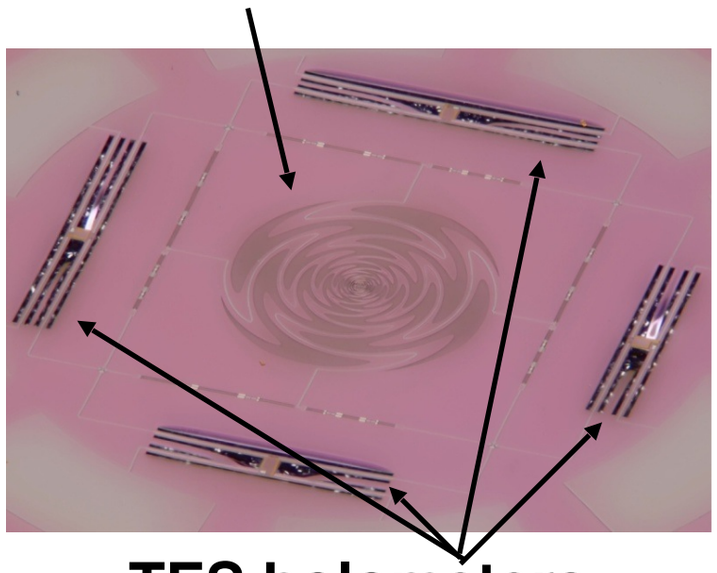
1897 pixels
7588 detectors

365 mm

POLARBEAR-2

Detector Pixel

Broadband sinuous antenna



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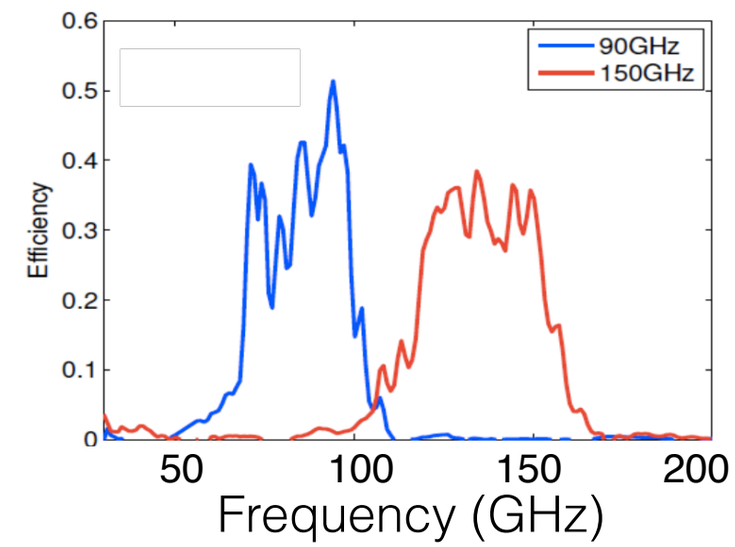

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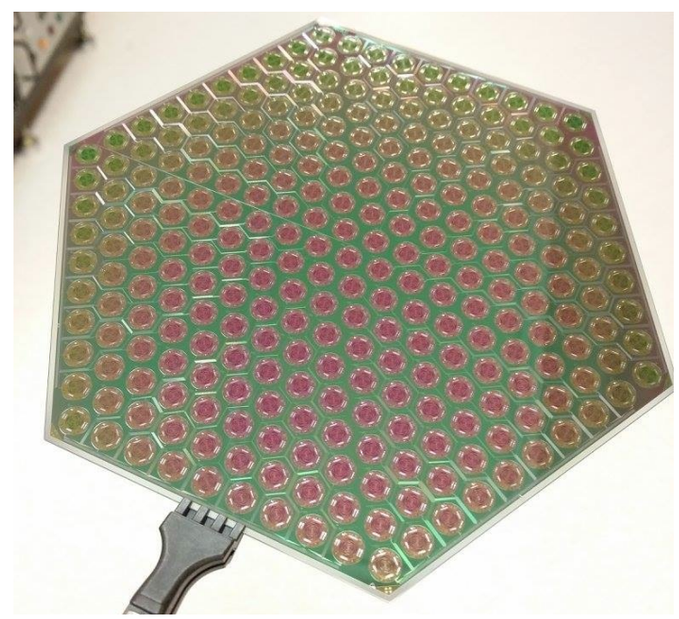


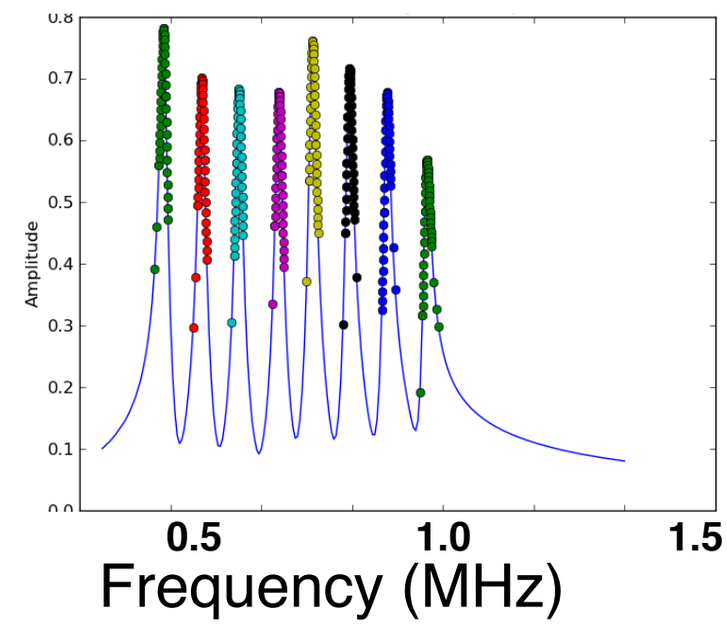
271 pixels / wafer

POLARBEAR-2

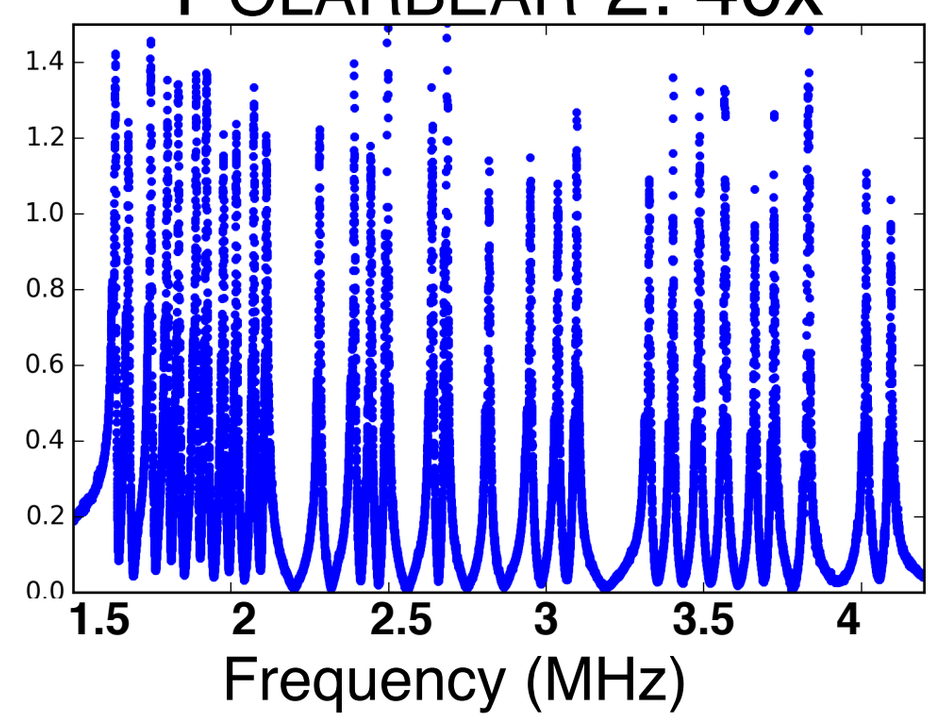
Readout

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

POLARBEAR-1: 8x



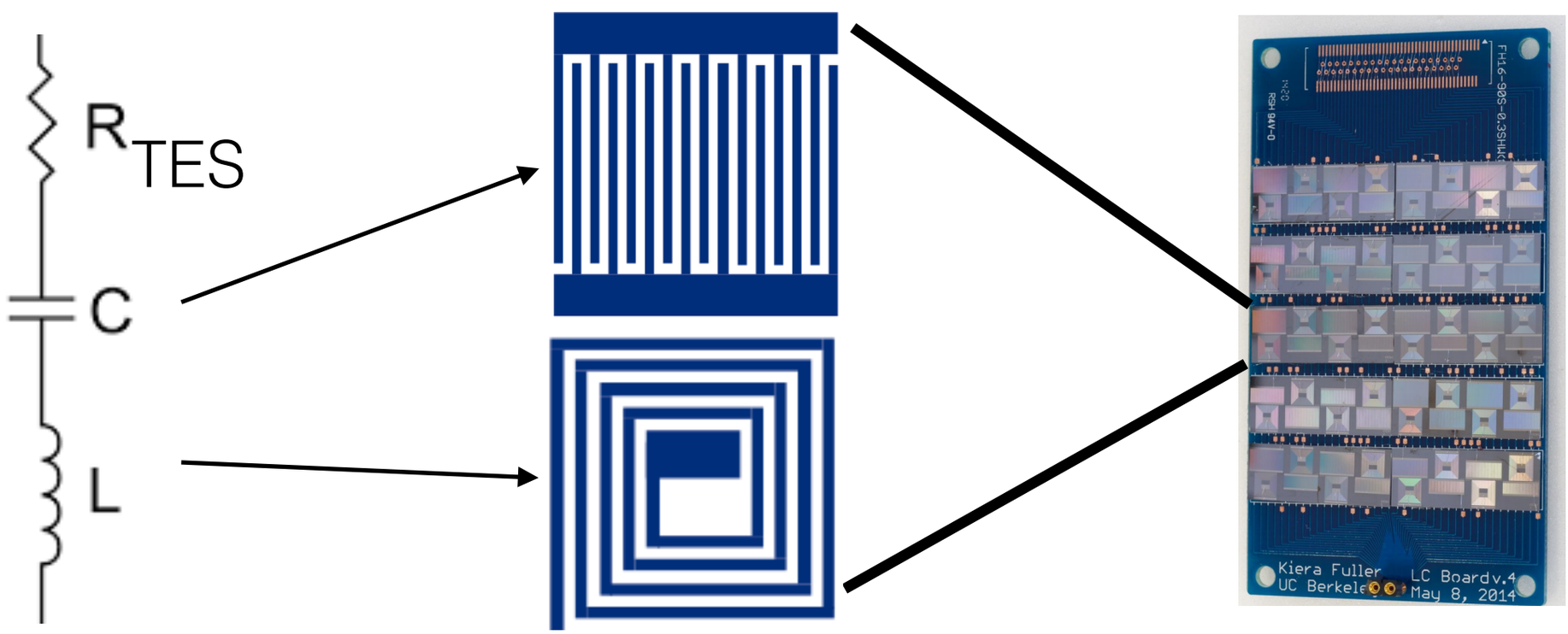
POLARBEAR-2: 40x



POLARBEAR-2

Readout

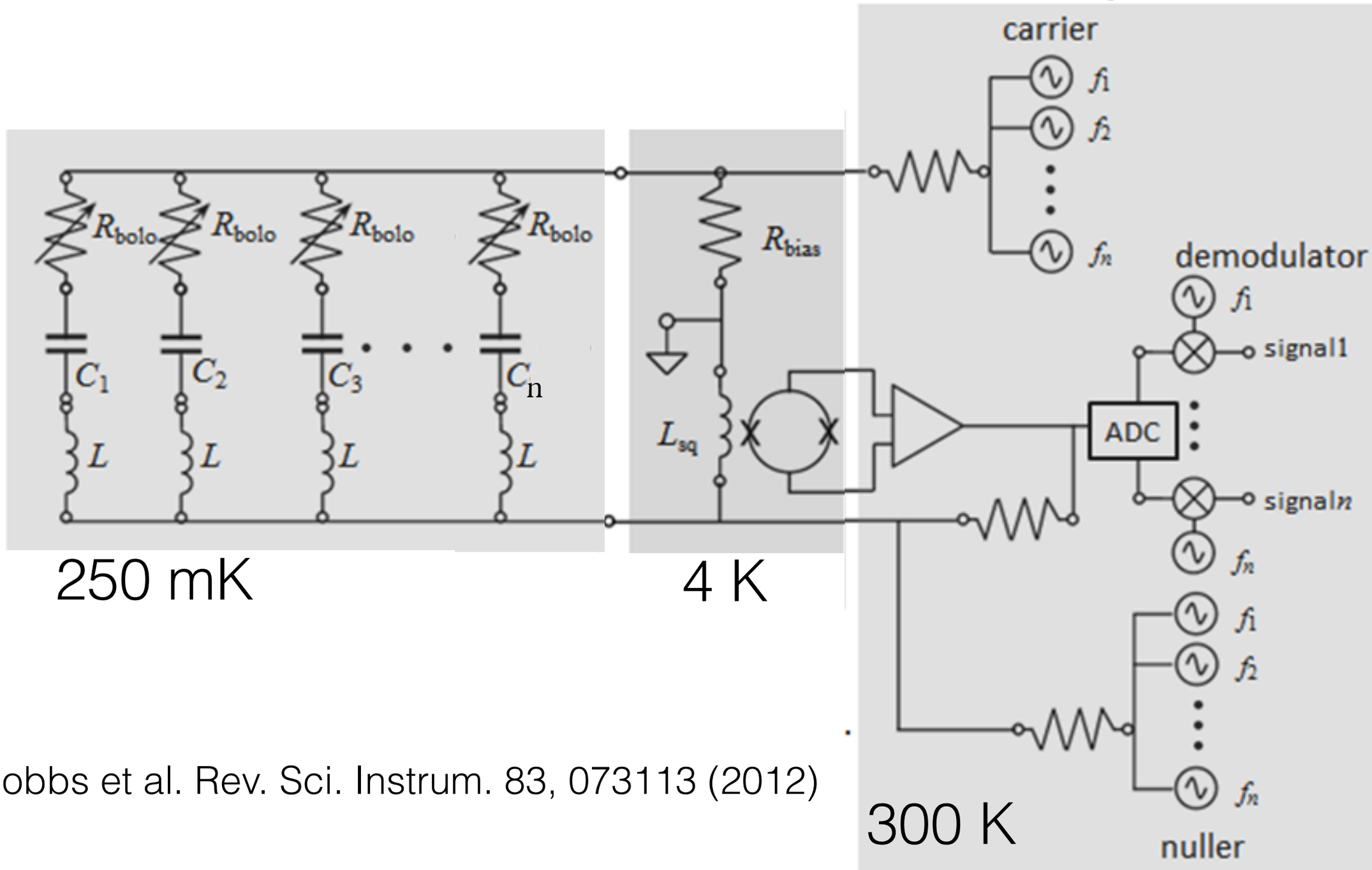
- PB-2 focal plane has 6x as many detectors as PB-1
  - Increase from 8x to 40x
  - Achieved with closer frequency spacing, increased SQUID readout bandwidth
- Requirements
  - Low-loss interdigitated capacitors
  - Low-inductance cold wiring



POLARBEAR-2

Readout

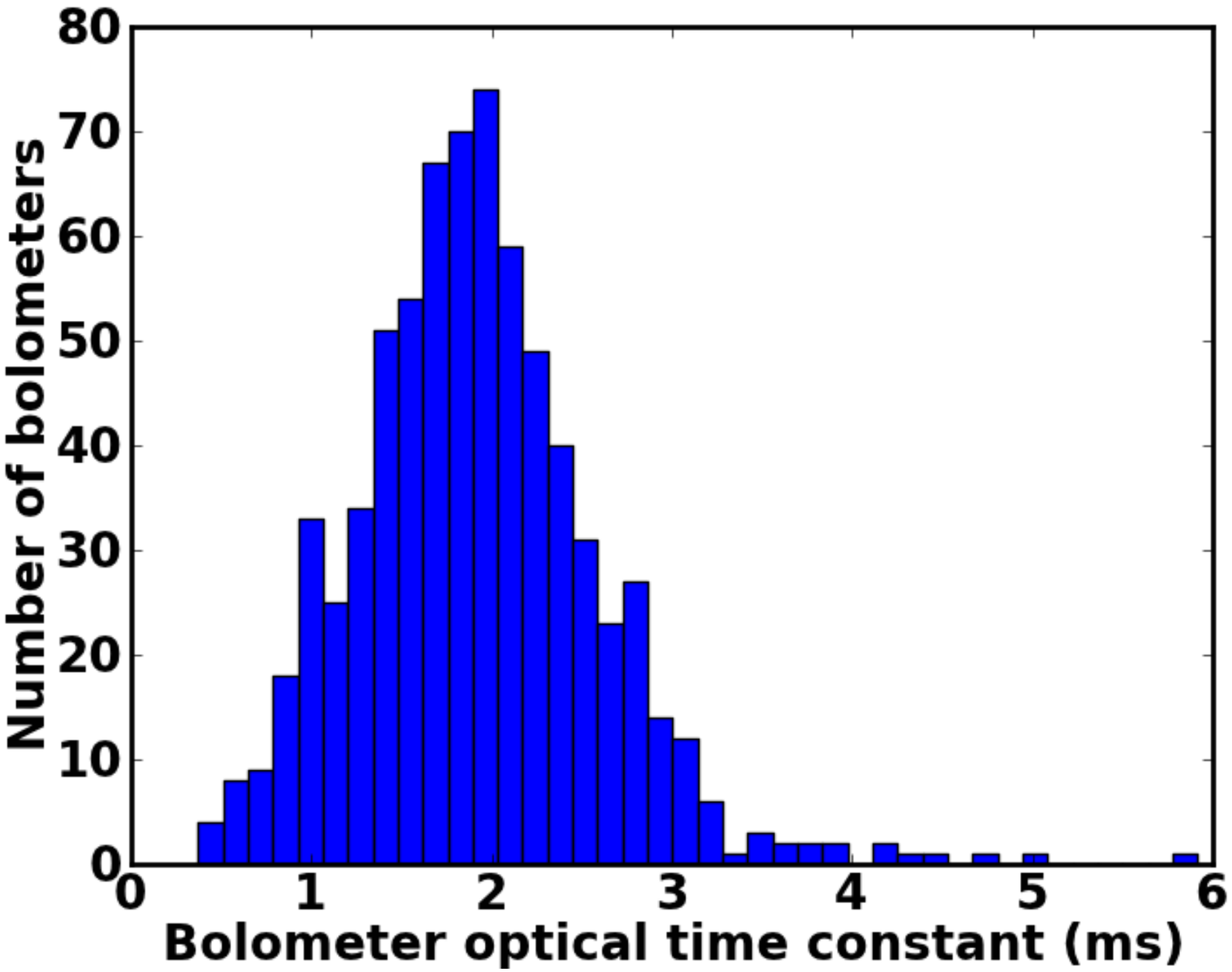
Frequency domain multiplexing



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

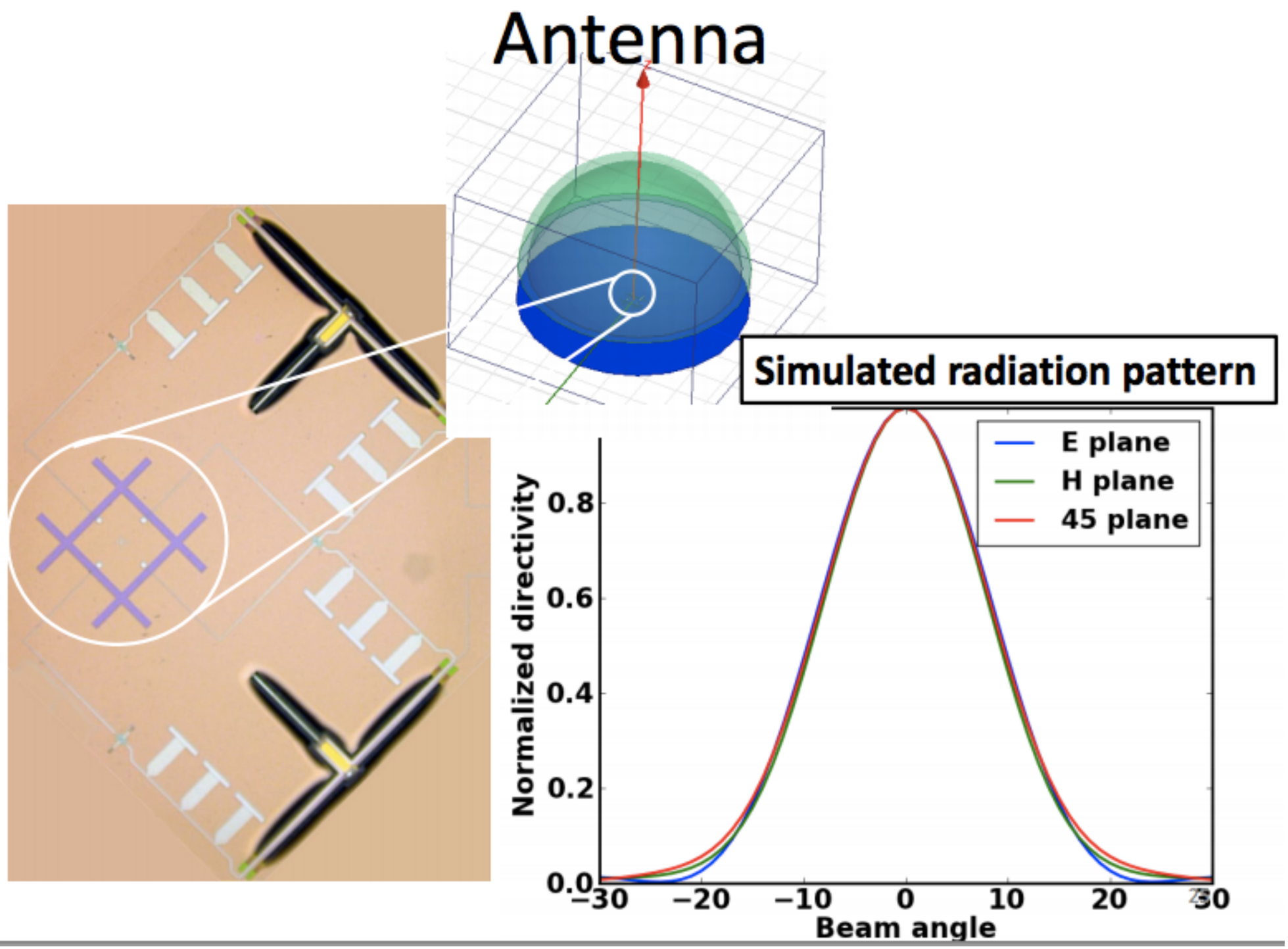
X

Optical time constants



- Measured while observing
- 1.9 ms time constant (85 Hz 3dB freq)
- Detectors fast enough to resolve all CMB signals

Lenslet-coupled dual-slot dipole antennas



The Next Generation of CMB Instruments

- Higher sensitivity
  - Reduce noise variance
- Spectral information
  - Characterize and remove polarized foregrounds
- Large sky coverage
  - Reduce sample variance
- Beamsize < 4’
  - Characterize lensing and de-lens