

Cosmology from CMB Polarization with POLARBEAR and the Simons Array

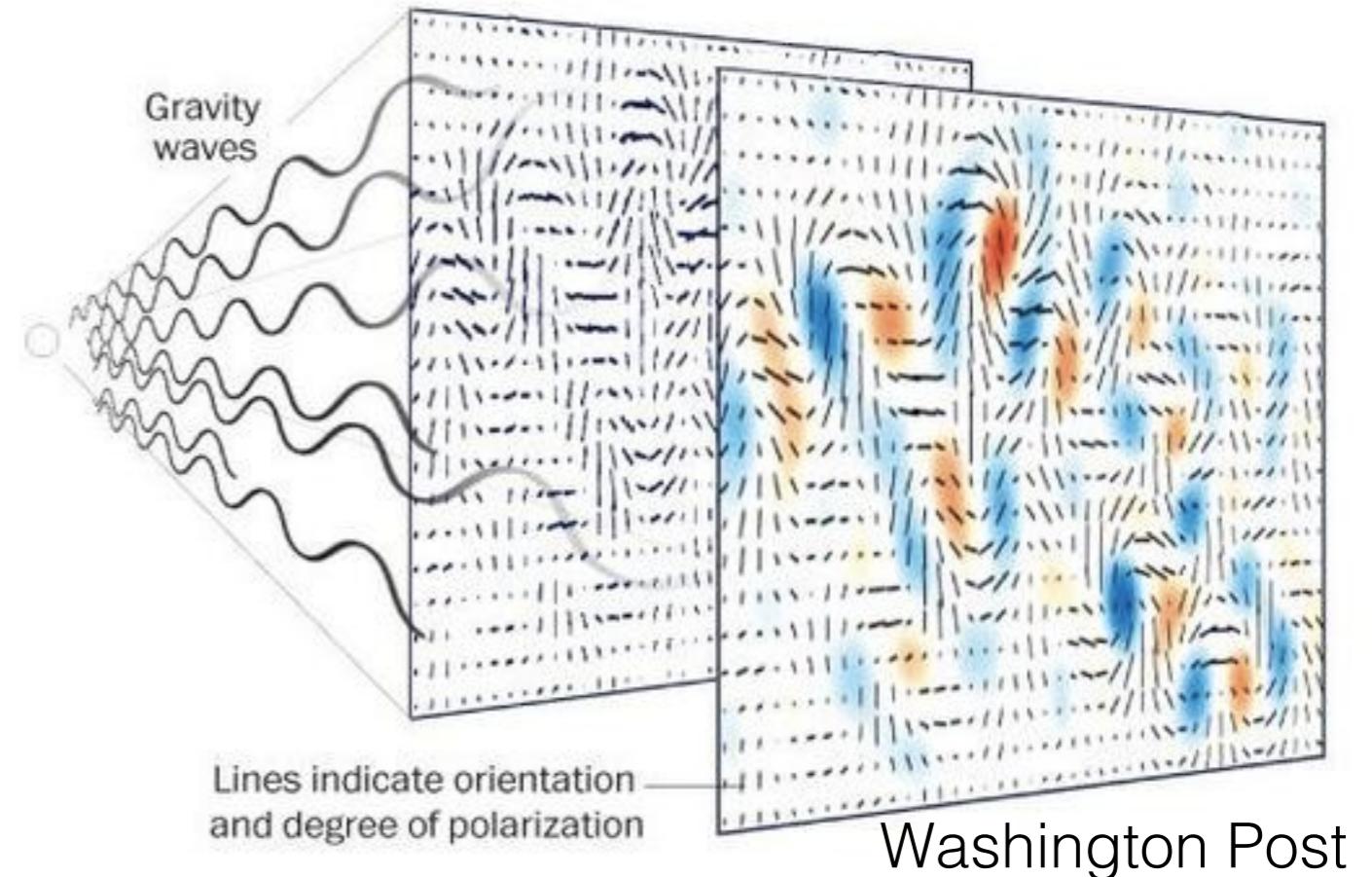
Darcy Barron

NSF Astronomy and Astrophysics Postdoctoral Fellow
UC Berkeley Space Science Lab
Lawrence Berkeley National Lab



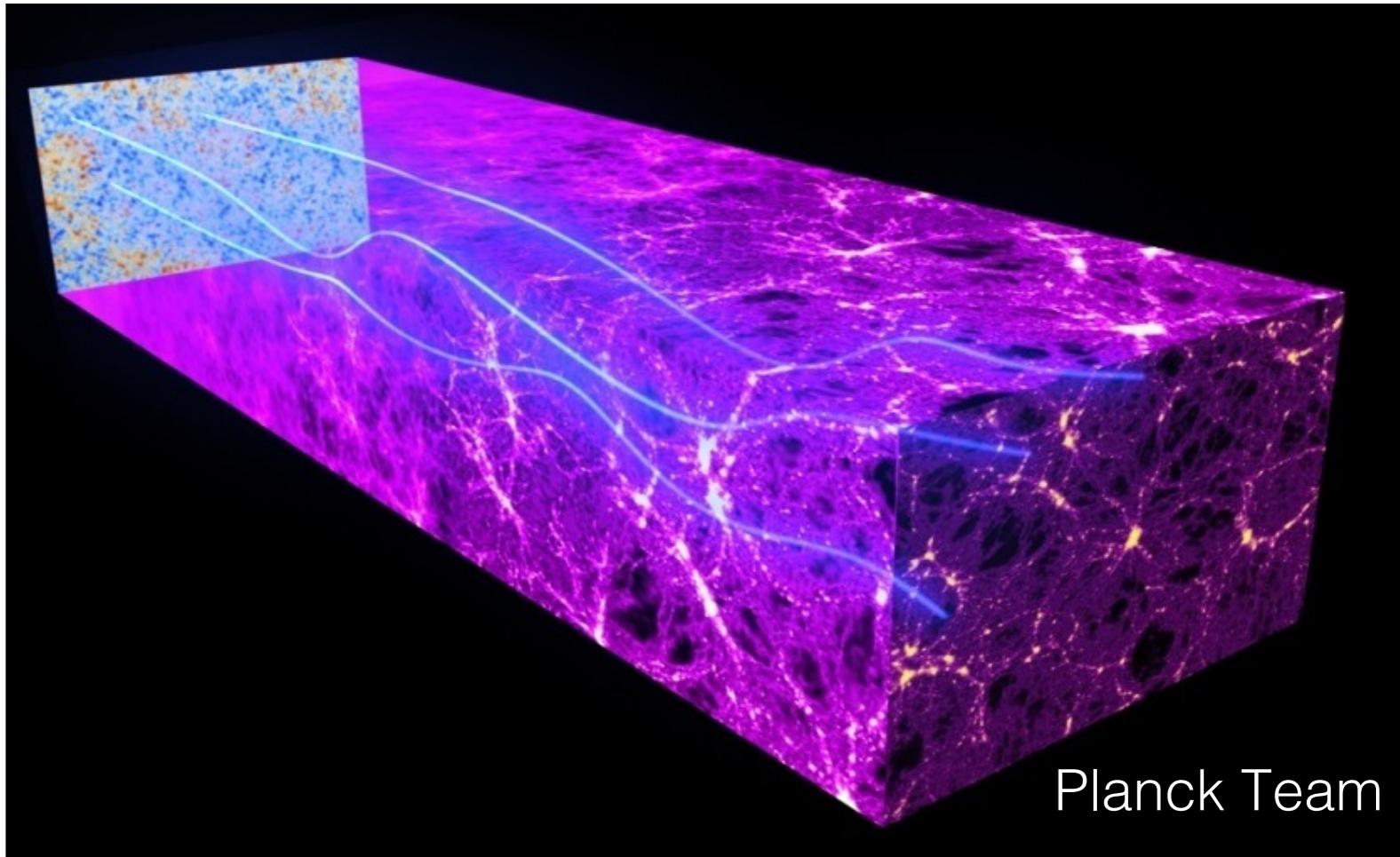
Cosmology from B-mode Polarization

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



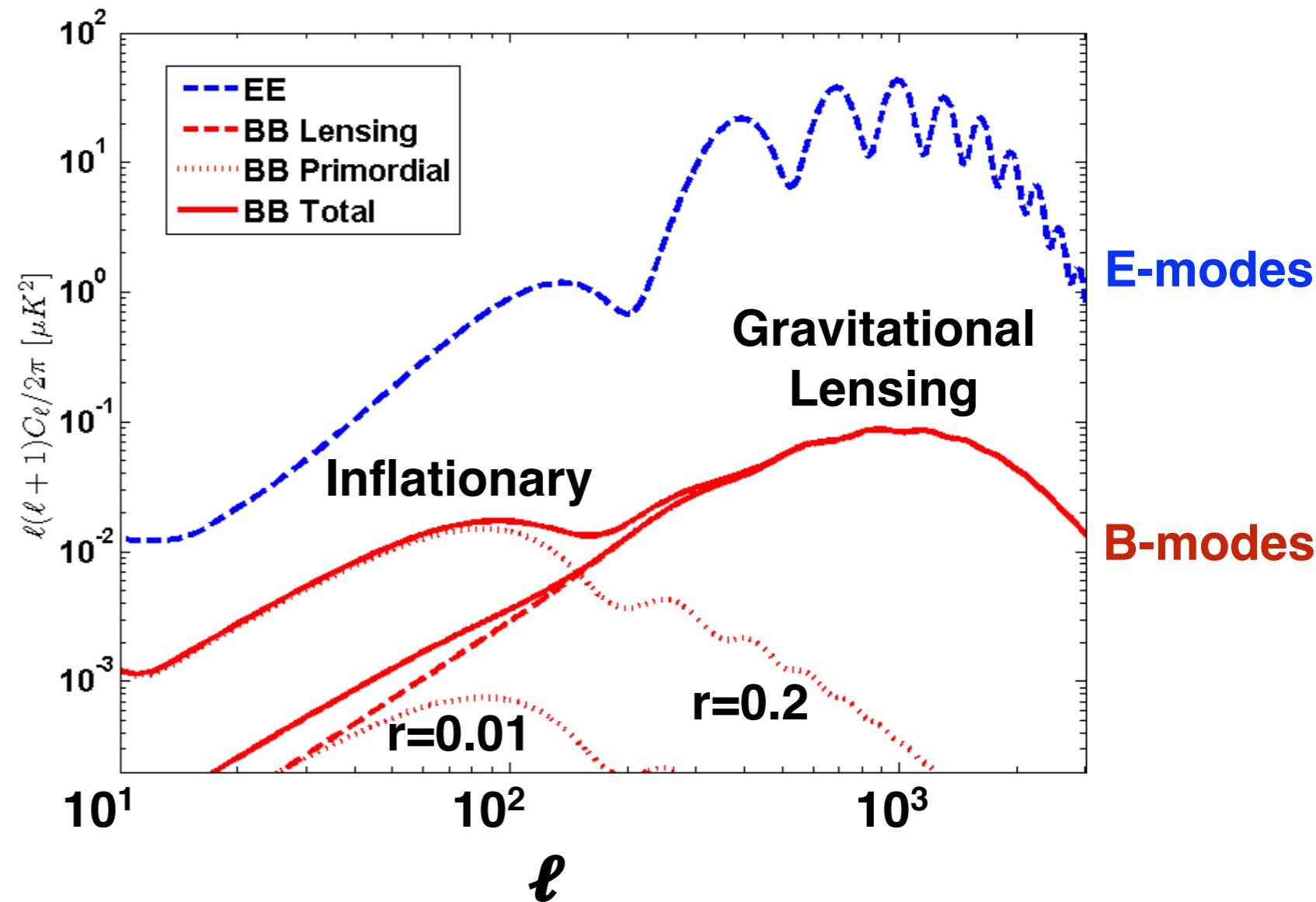
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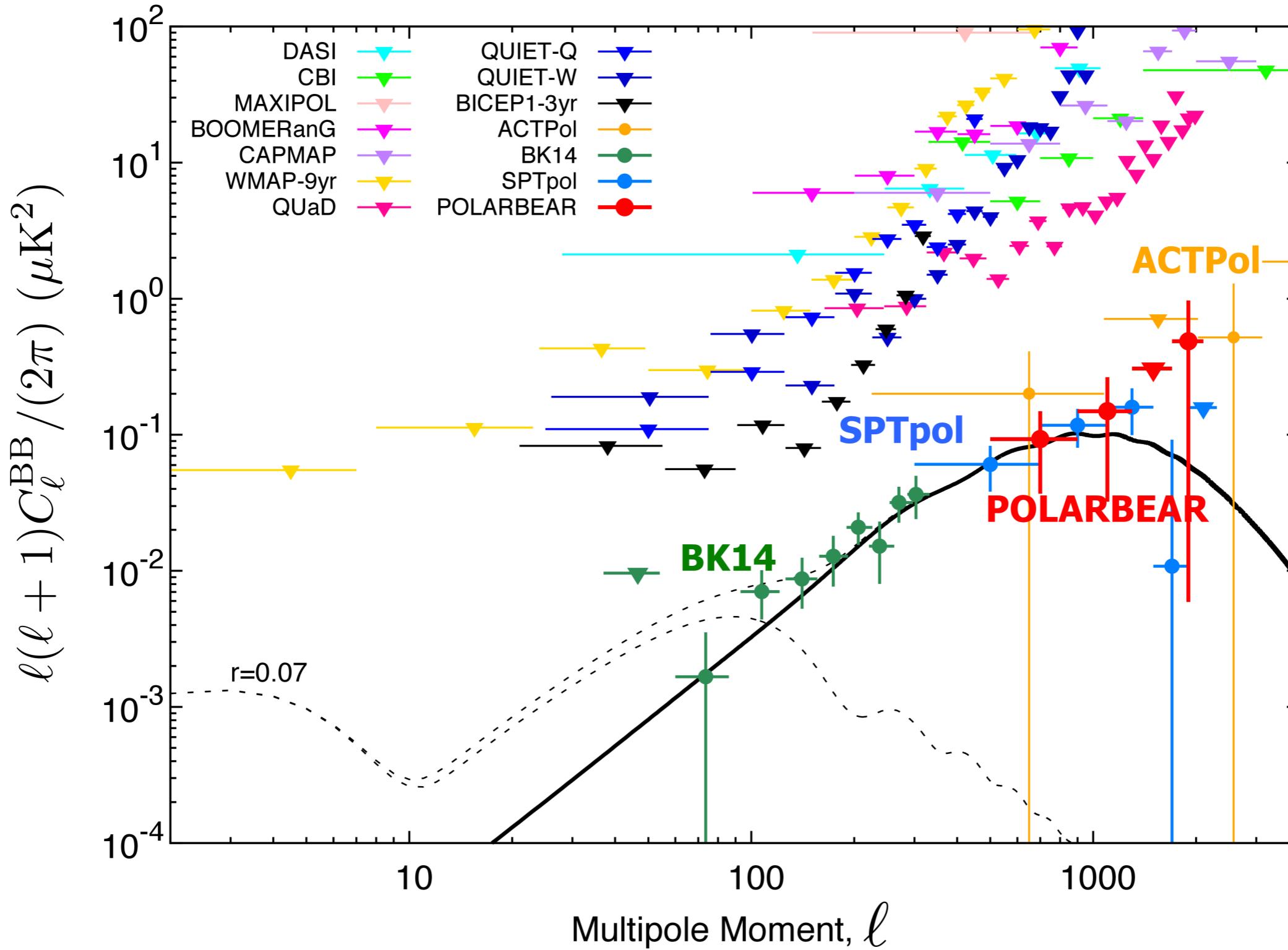


Cosmology from B-mode Polarization

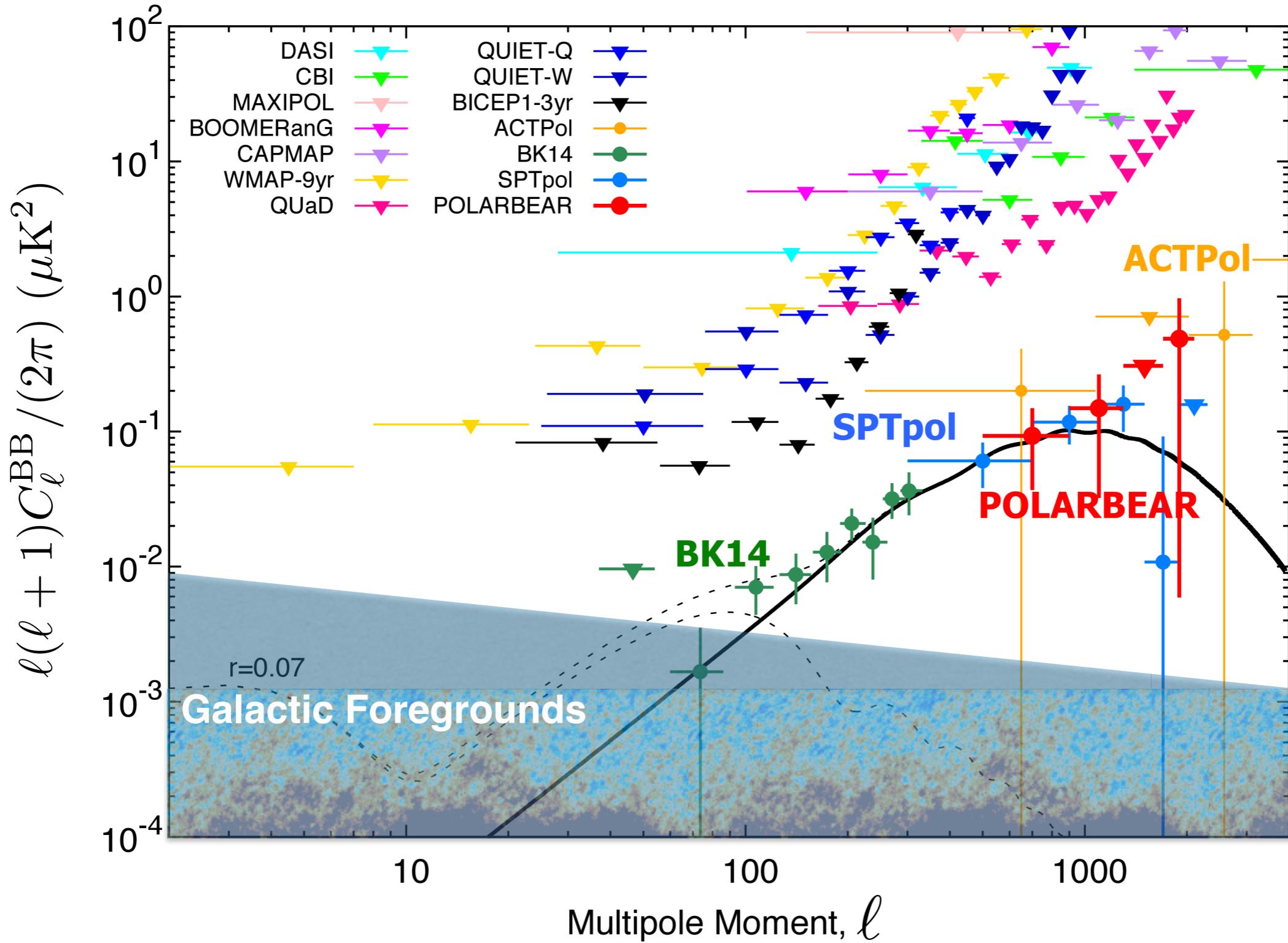
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CMB B-mode Measurements



CMB B-mode Measurements





SIMONS FOUNDATION
Advancing Research in Basic Science and Mathematics

POLARBEAR Collaboration



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



UC San Diego
 Chris Aleman
 Kam Arnold
 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



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



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



Laboratoire Astroparticule & Cosmologie
 Maude Le Jeune
 Julien Peloton
 Davide Poletti
 Radek Stompor



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



Argonne NL
 Amy Bender



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...

Imperial College
 Anne Ducout
 Stephen Feeney
 Andrew Jaffe



U. Melbourne
 Christian Reichardt

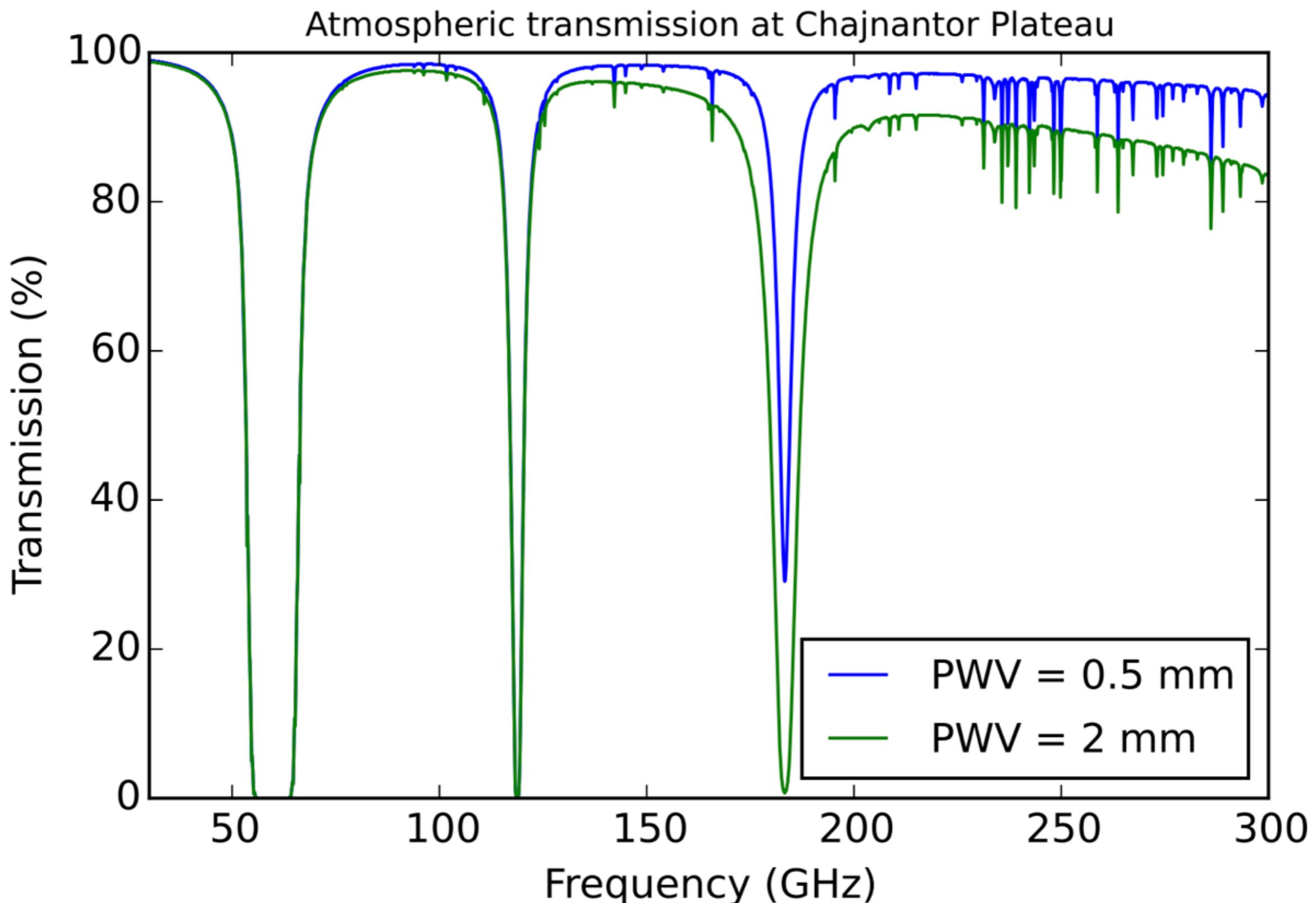


The POLARBEAR Experiment

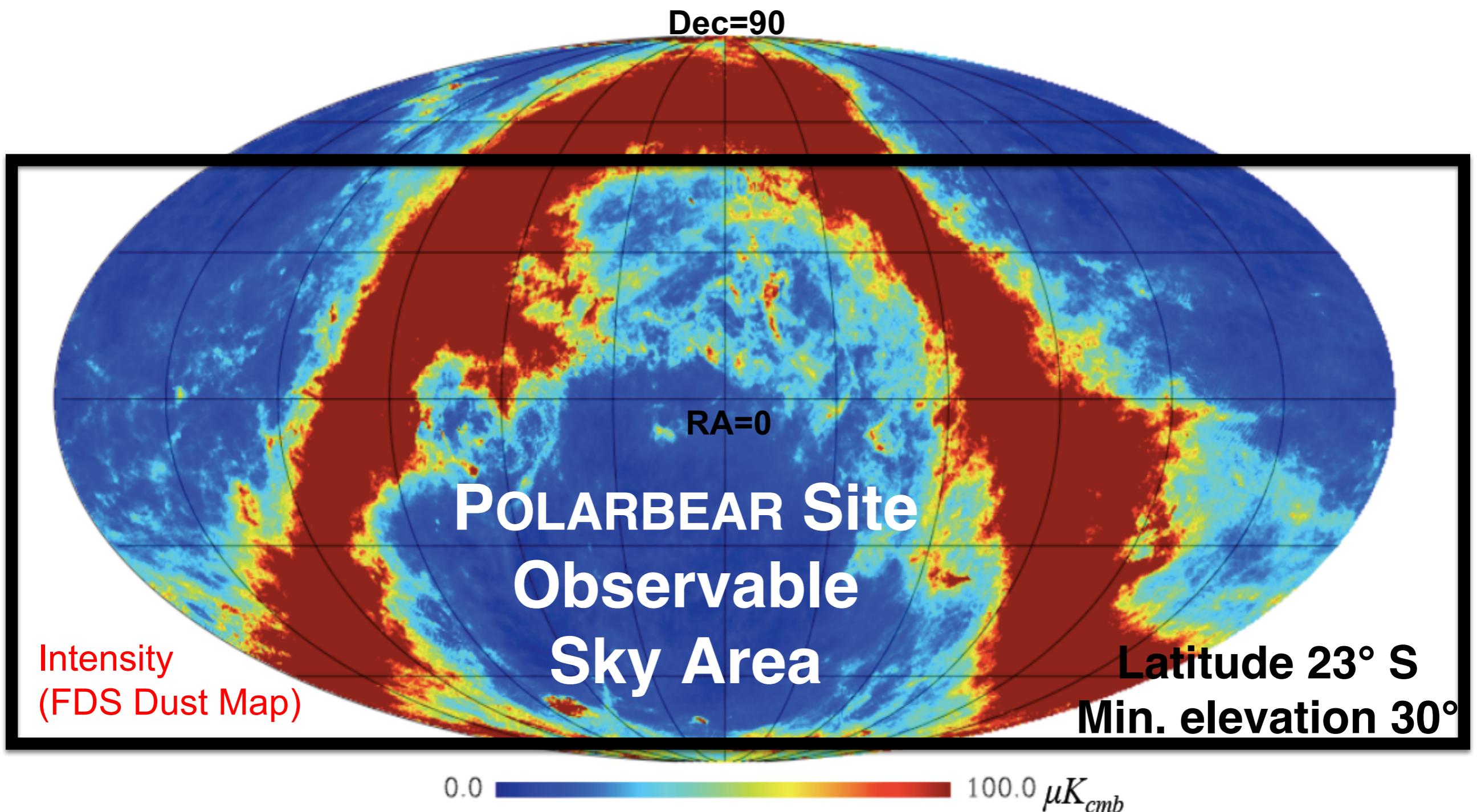
- Dedicated CMB polarization experiment
- Located on Cerro Toco at 5200 meters in Atacama desert
- First light January 2012
- Now in fifth season of observations with POLARBEAR-1
- Expanding to POLARBEAR-2/ Simons Array



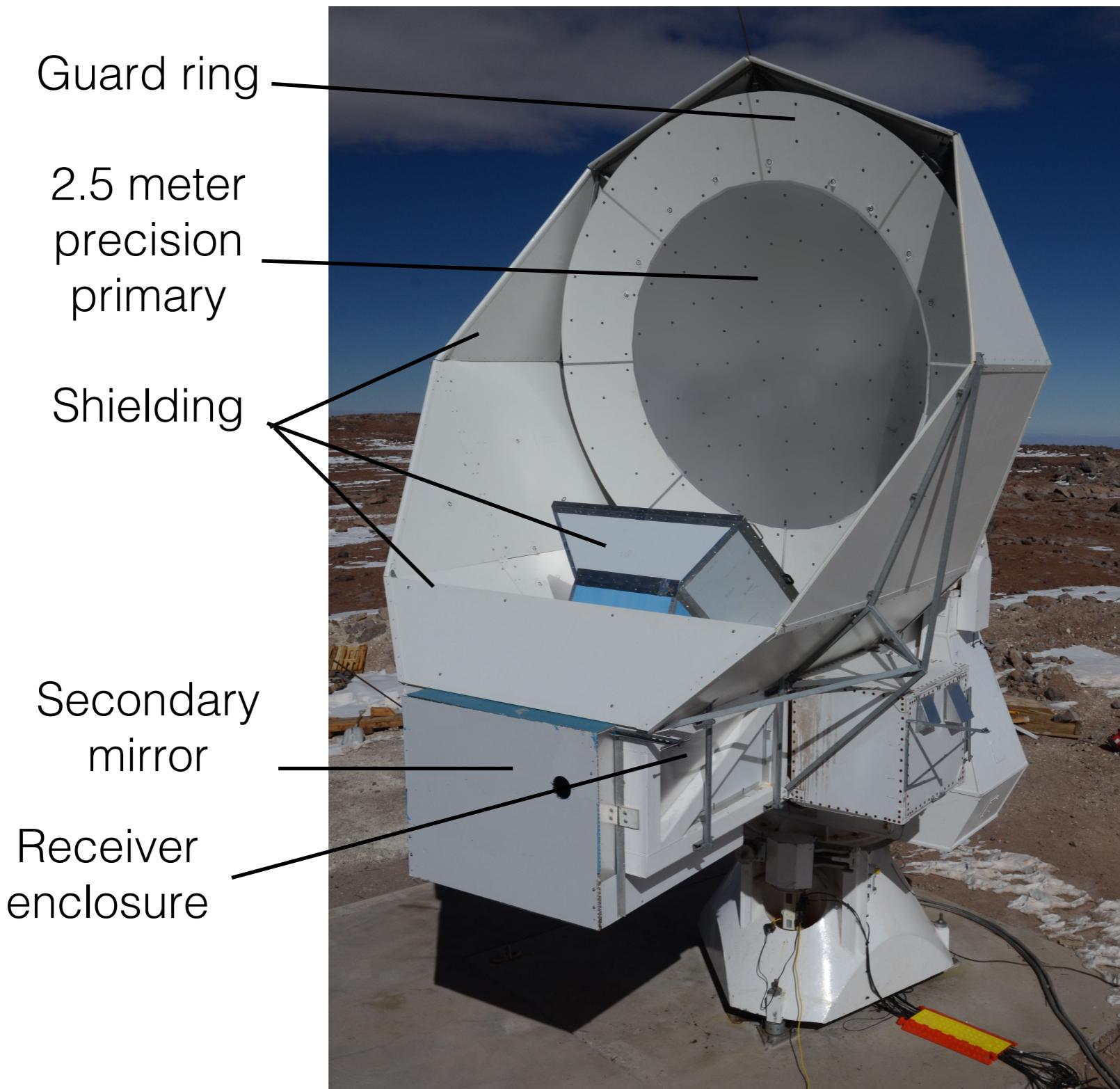
POLARBEAR Observations



POLARBEAR Observations



POLARBEAR Observations

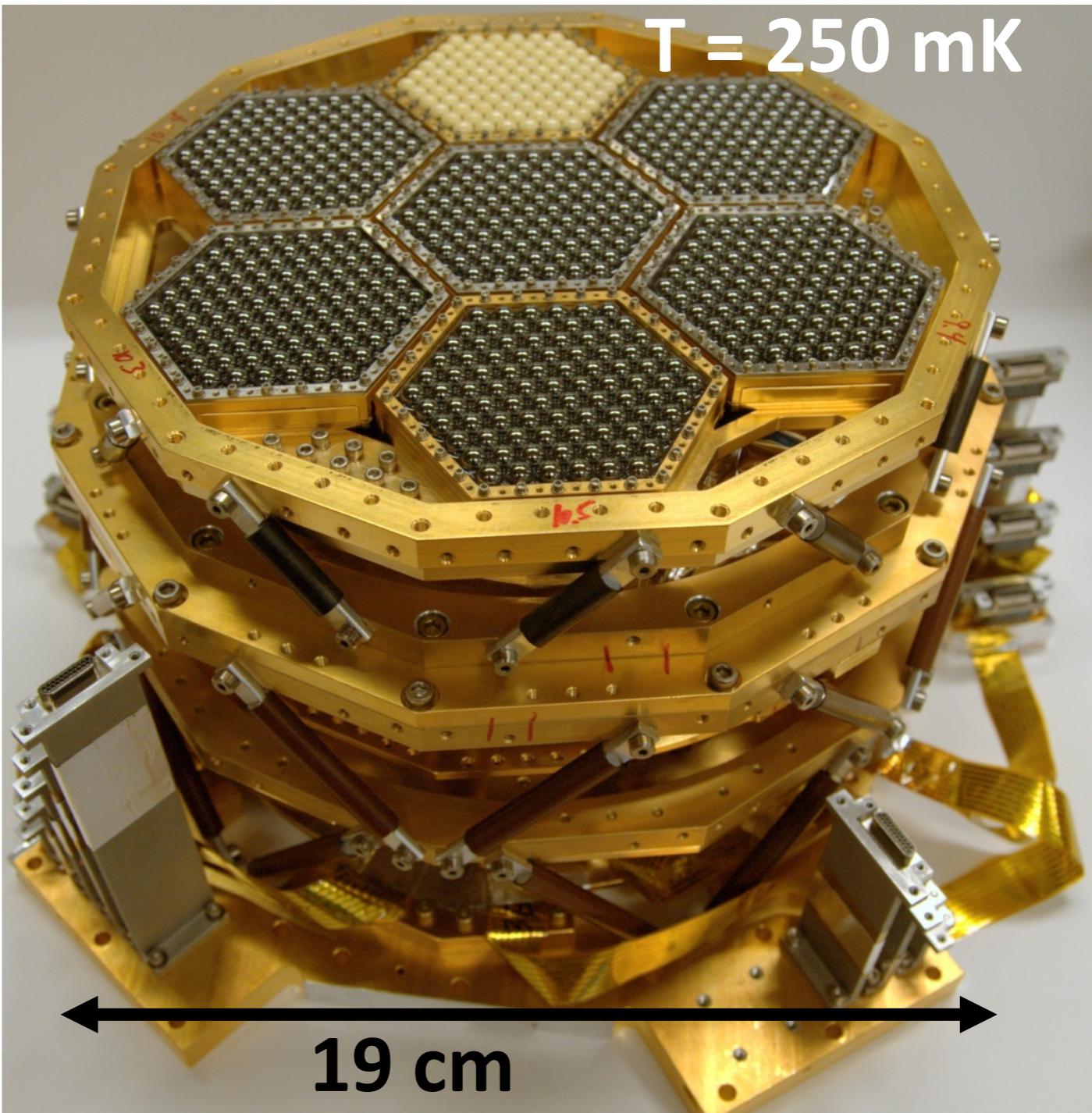


- Off-axis Gregorian-Dragone design
 - Low cross-polarization
 - Large field-of-view
- 3.5' FWHM beams
@ 150 GHz

POLARBEAR-1

Focal Plane

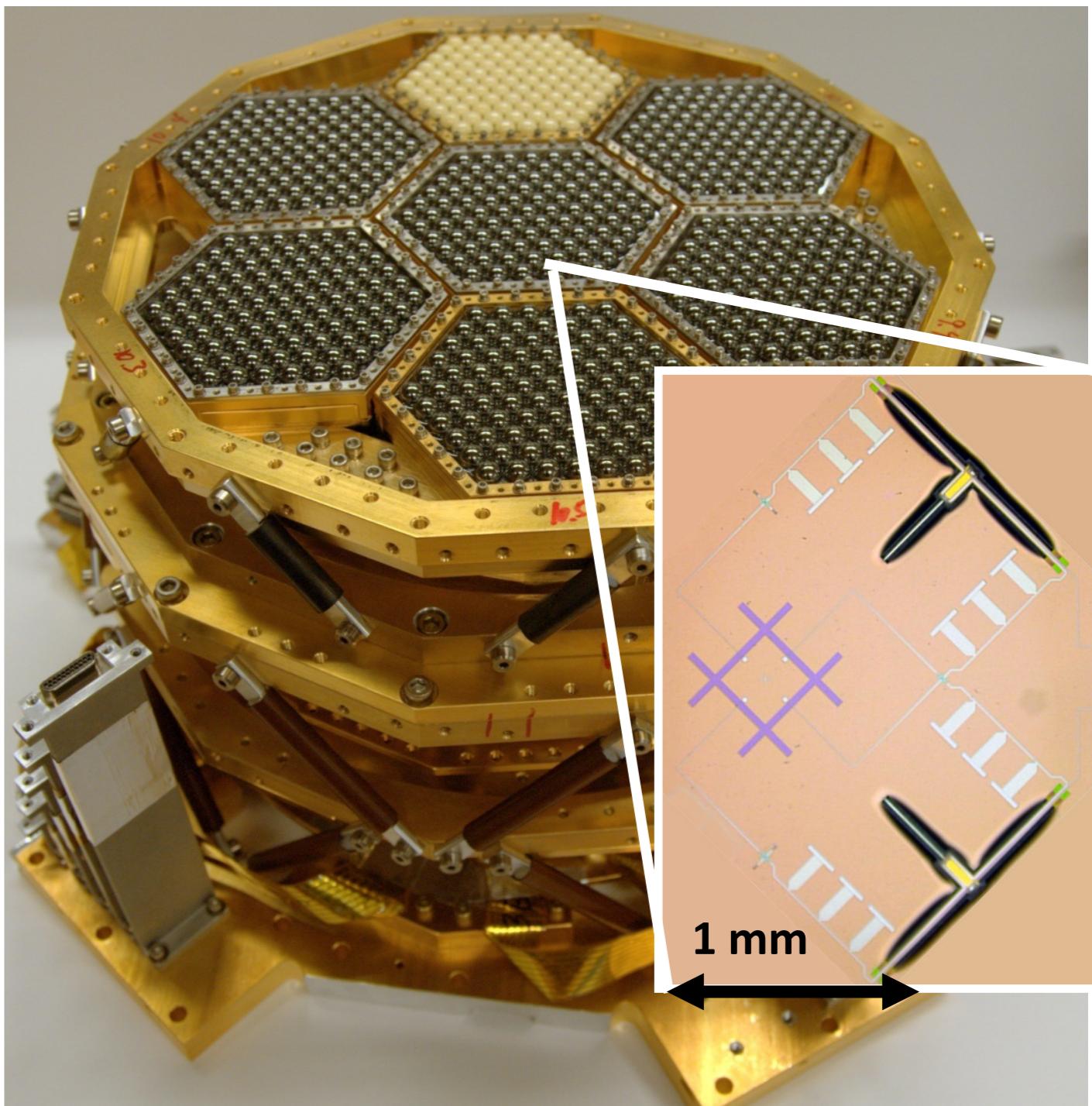
- 637 dual polarization pixels
- Beam-forming lenslet coupled to each pixel
- 1274 superconducting transition-edge sensor bolometers
- Frequency-domain multiplexing readout (8x)



POLARBEAR-1

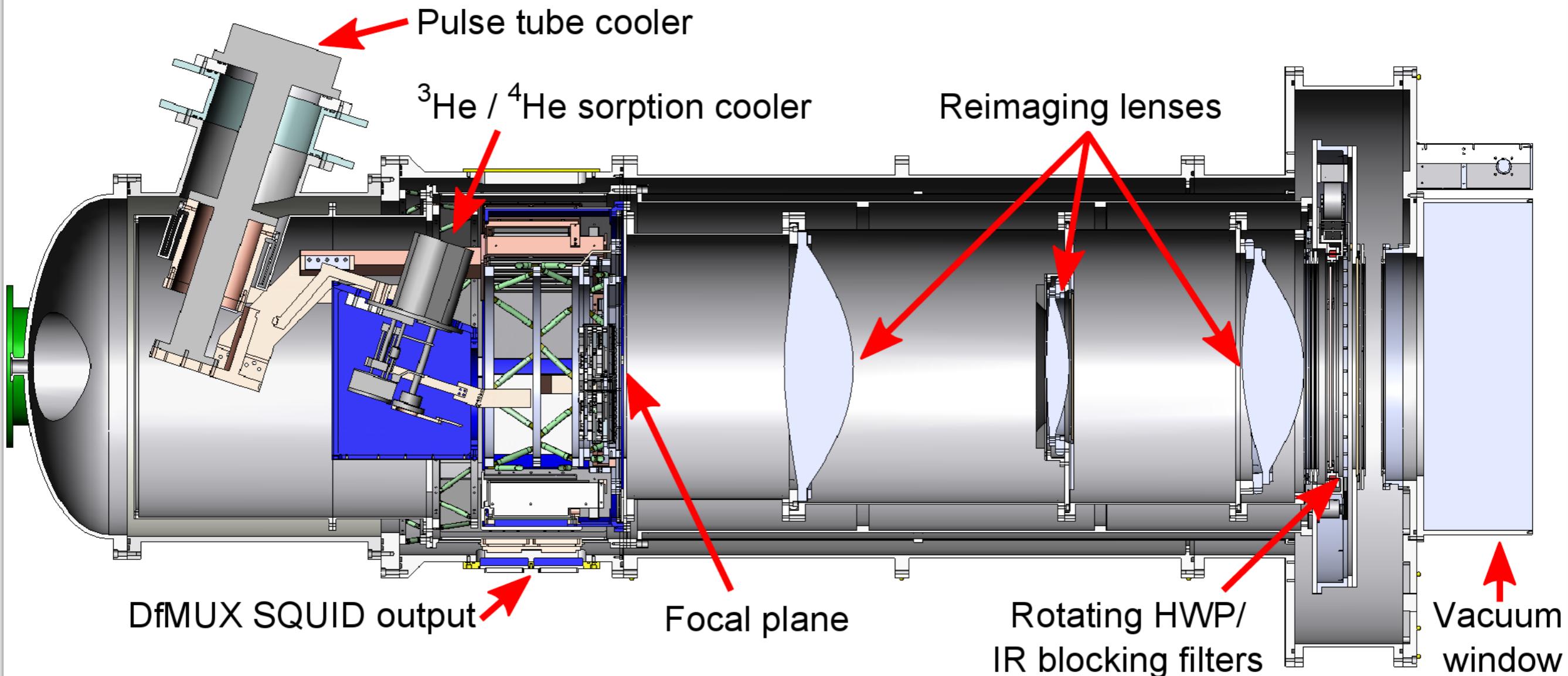
Focal Plane

- 637 dual polarization pixels
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POLARBEAR-1

Cryogenic Receiver



2 meters

POLARBEAR-1

Control of instrumental systematic effects

- Pixel-pair differencing to reject unpolarized atmosphere
- Modulate CMB Polarization with apparent sky rotation
- Scan strategy allows ground template removal



POLARBEAR-1

Control of instrumental systematic effects

End-to-end simulations
using measured
instrument
characteristics

Boresight & diff. pointing
Pol. angle

HWP-dependent gain

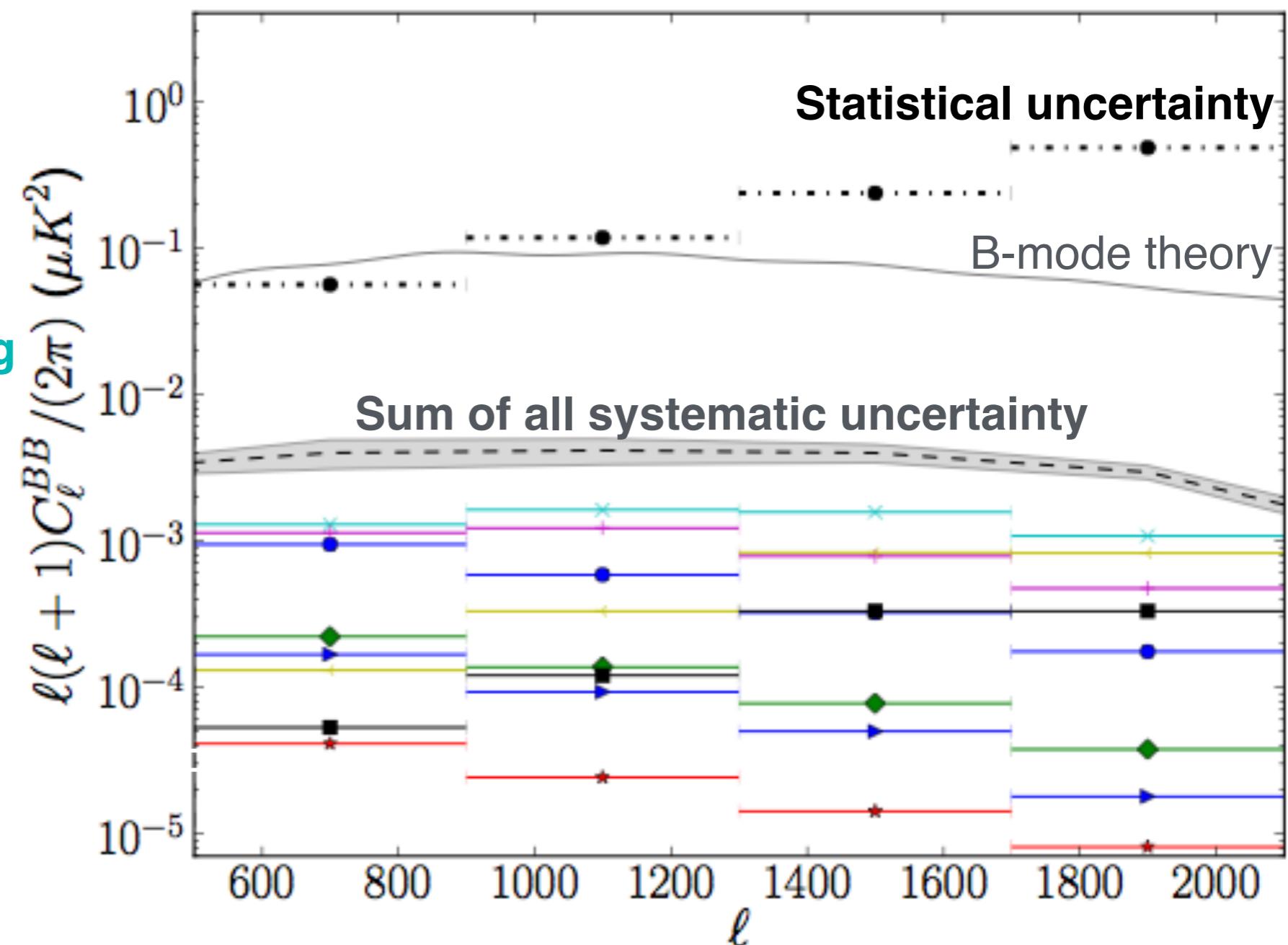
HWP-independent gain

Electrical crosstalk

Differential beamsize

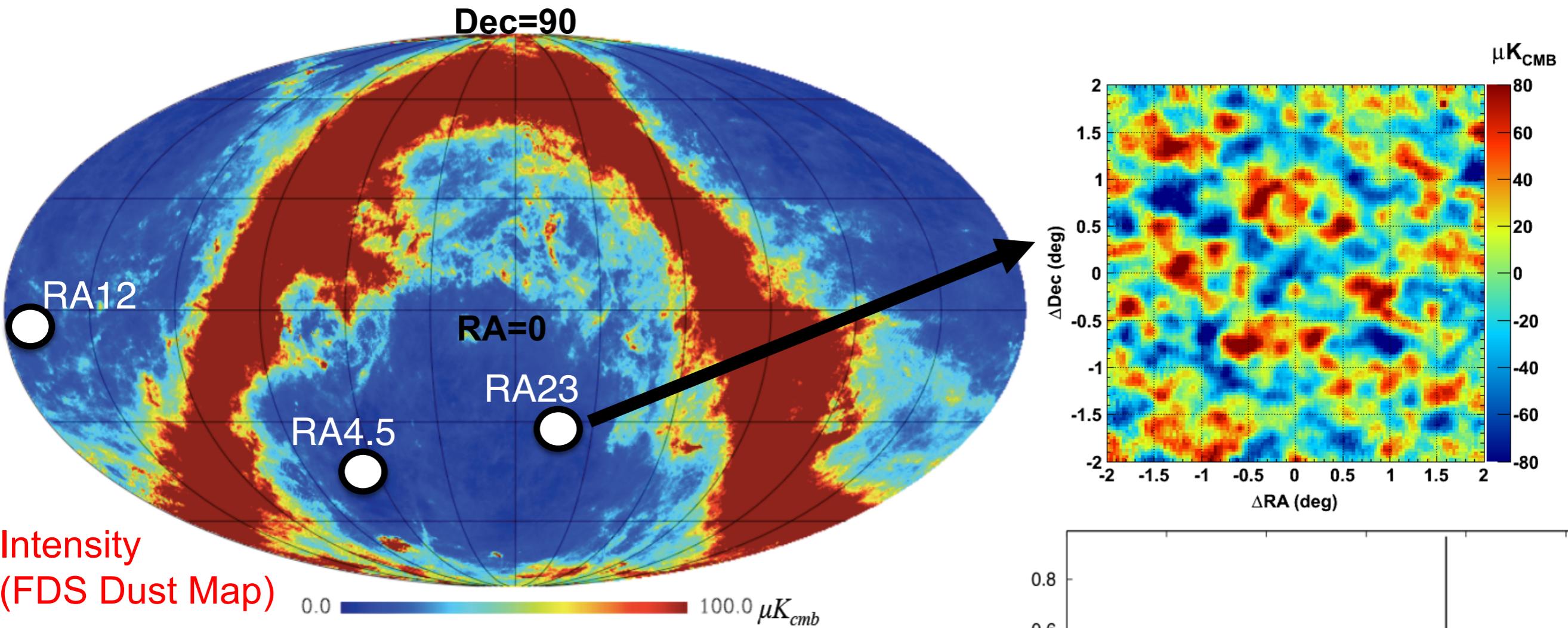
Differential ellipticity

Gain drift



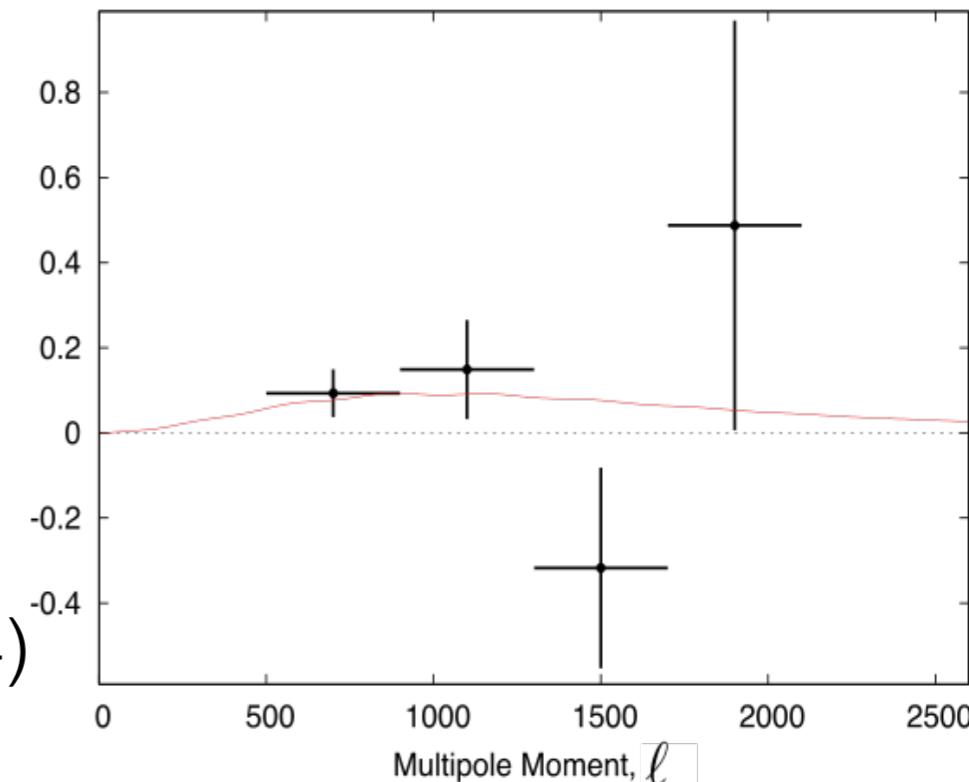
POLARBEAR Collaboration, ApJ 794, 171 (2014)

POLARBEAR Observations



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

Angular power spectrum: ApJ 794, 171 (2014)
Deflection power spectrum: PRL 113, 021301 (2014)
Galaxy cross-correlation: PRL 112, 131302 (2014)

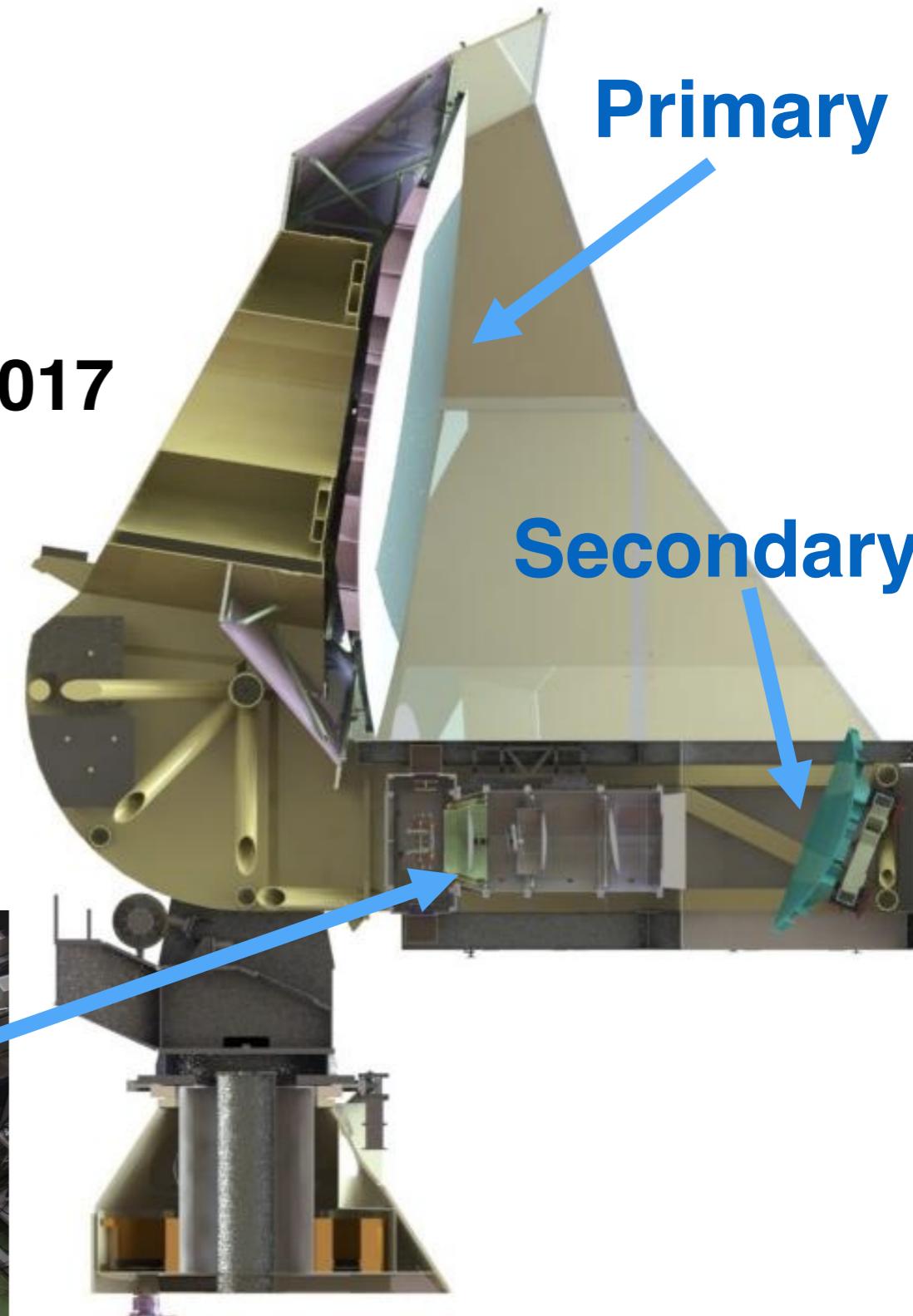
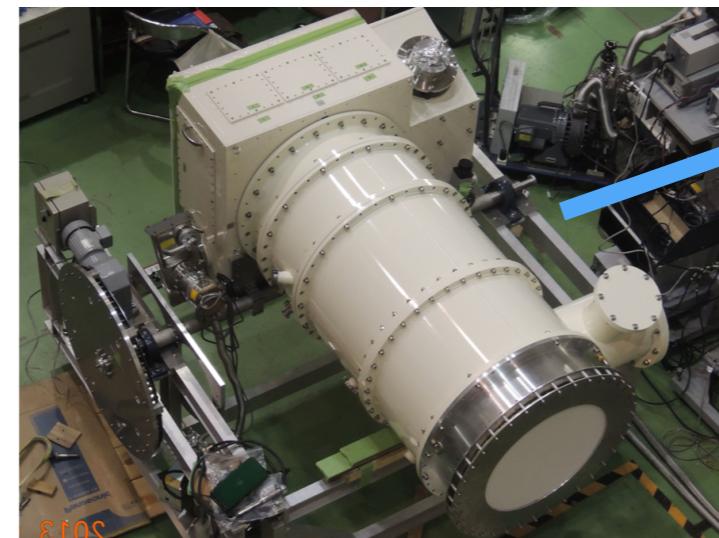


POLARBEAR-2

Overview

- Next-generation receiver design
- Larger focal plane, field-of-view
- Broadband optics, multi-chroic pixels
- $\sigma(\Sigma m_v) < 100 \text{ meV}$

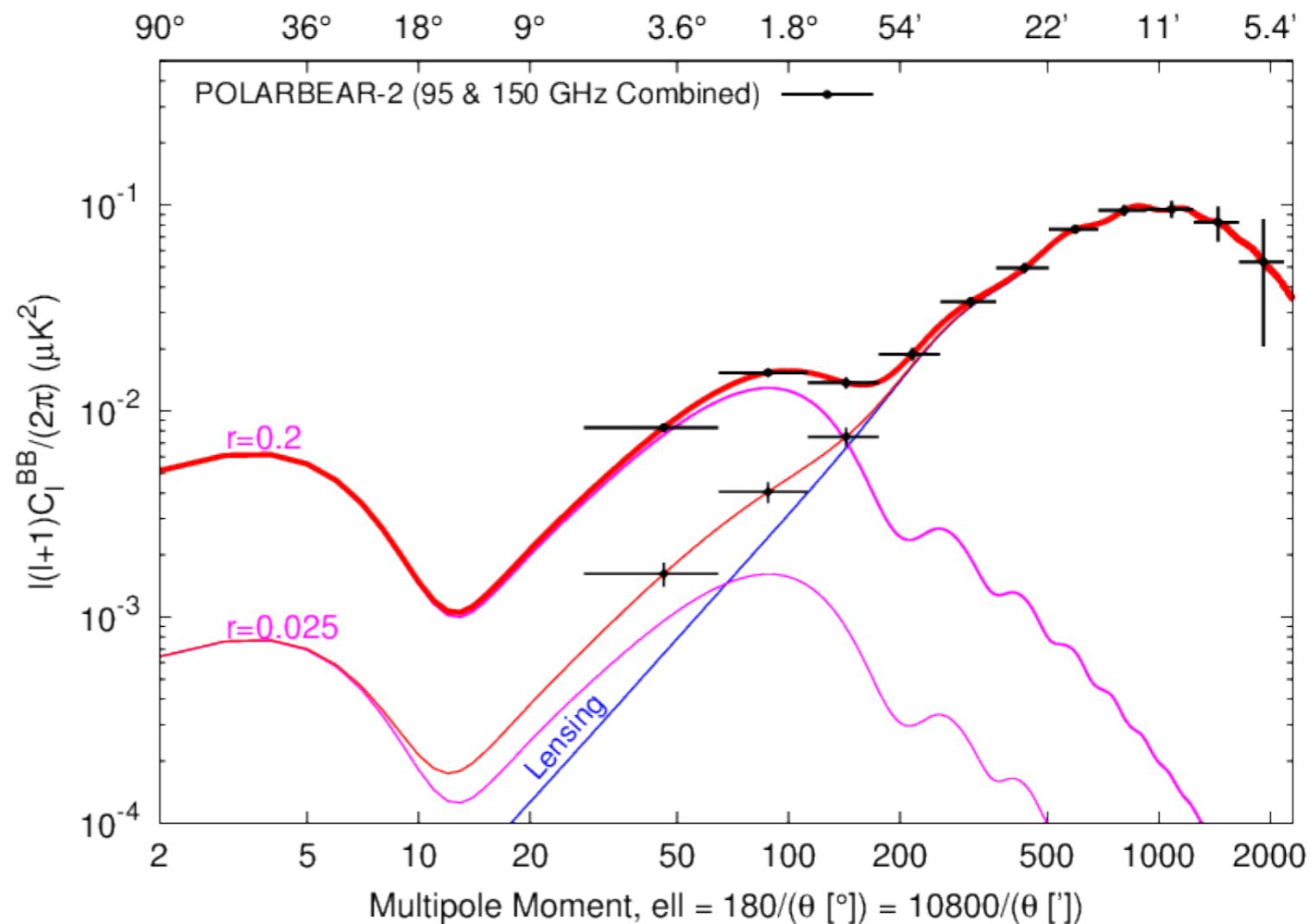
**PB-2a
deploying 2017**



POLARBEAR-2

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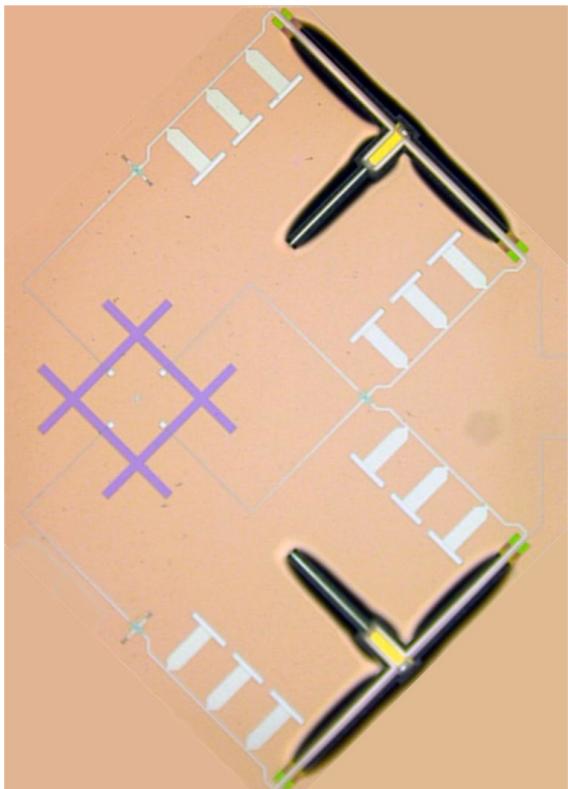


	POLARBEAR-1	POLARBEAR-2
Frequency	150 GHz	95 GHz + 150 GHz
Pixels	637	1897
Detectors	1274	7588
Field-of-view	2.3°	4.8°

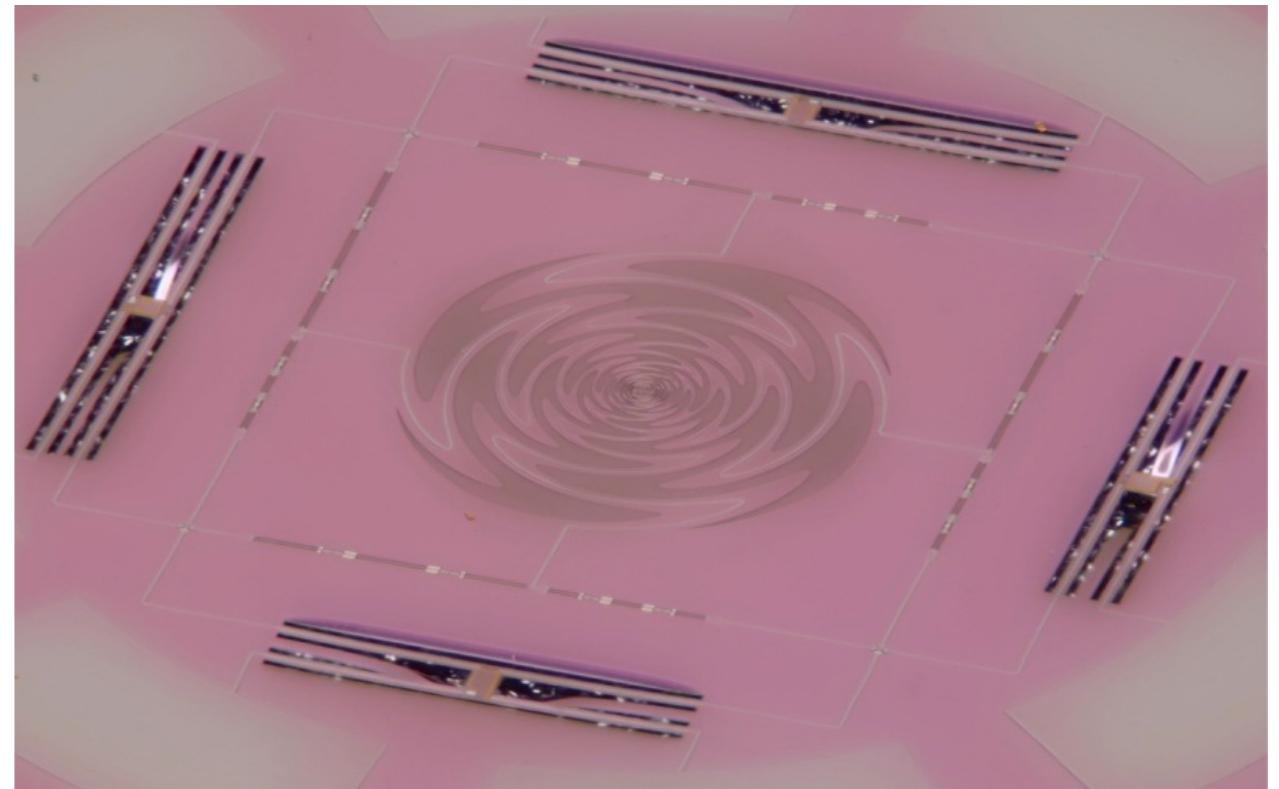
POLARBEAR-2

Focal Plane

POLARBEAR-1
Double-slot dipole



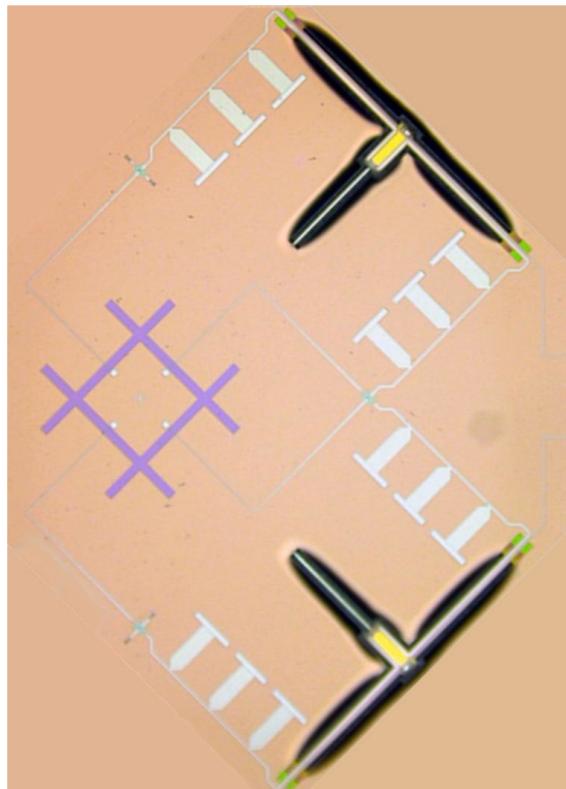
POLARBEAR-2
Broadband sinuous antenna



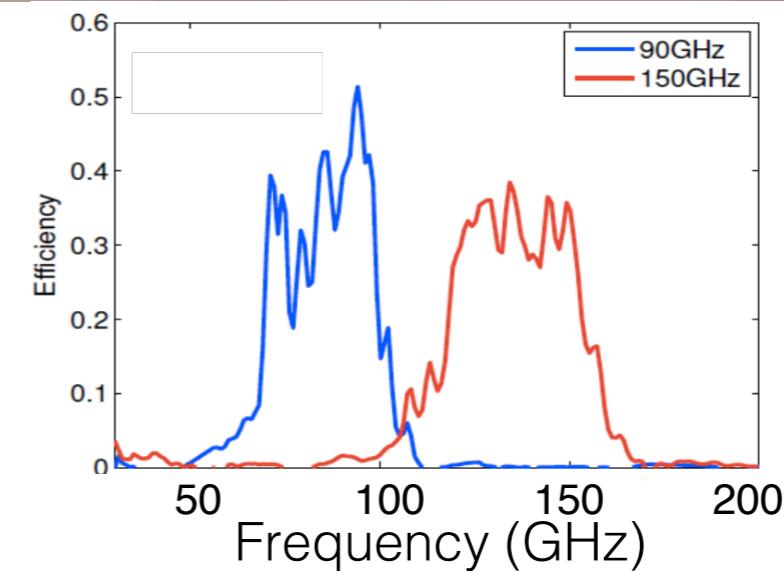
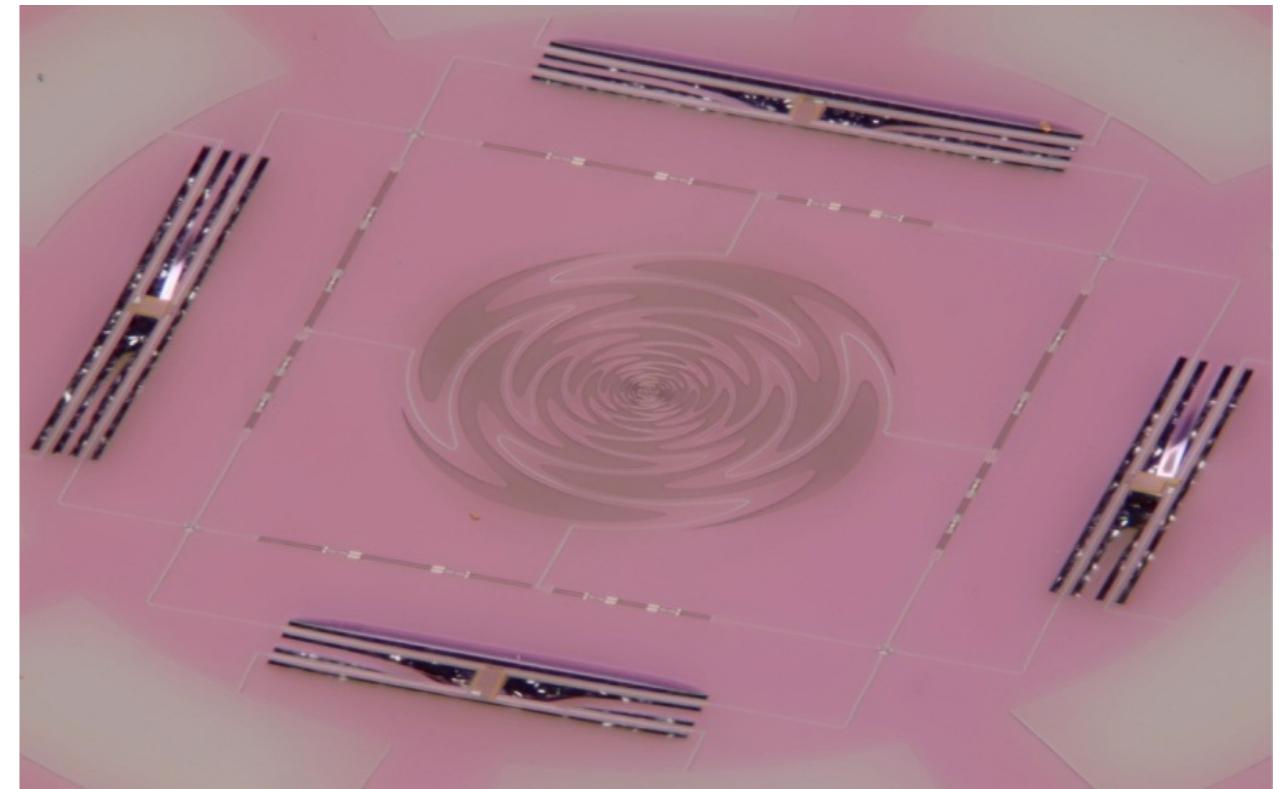
POLARBEAR-2

Focal Plane

POLARBEAR-1
Double-slot dipole



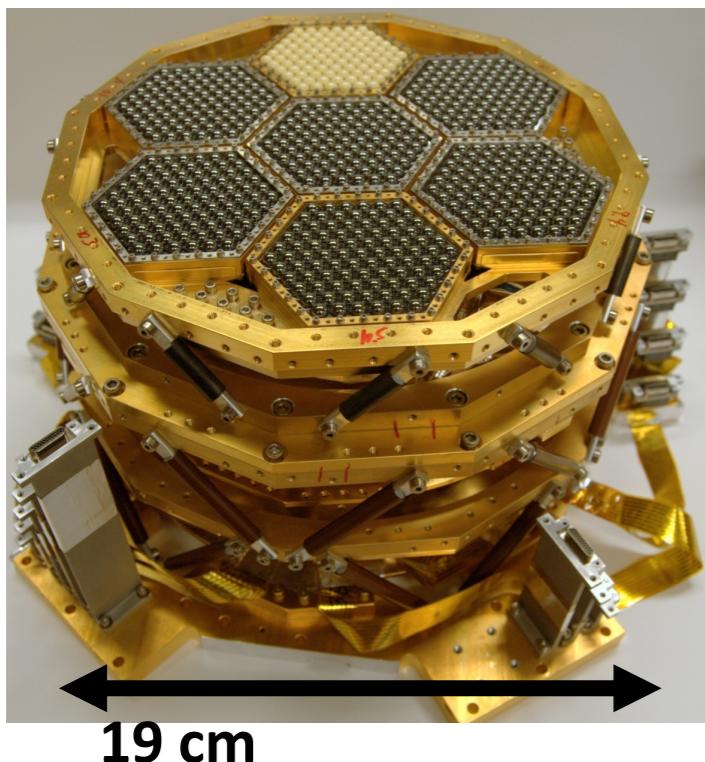
POLARBEAR-2
Broadband sinuous antenna



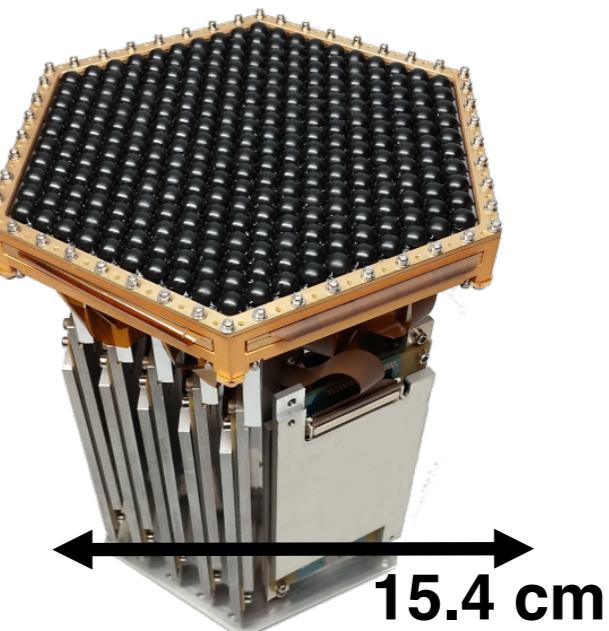
POLARBEAR

Focal Plane

POLARBEAR-1
Seven 4-inch wafers
1274 bolometers



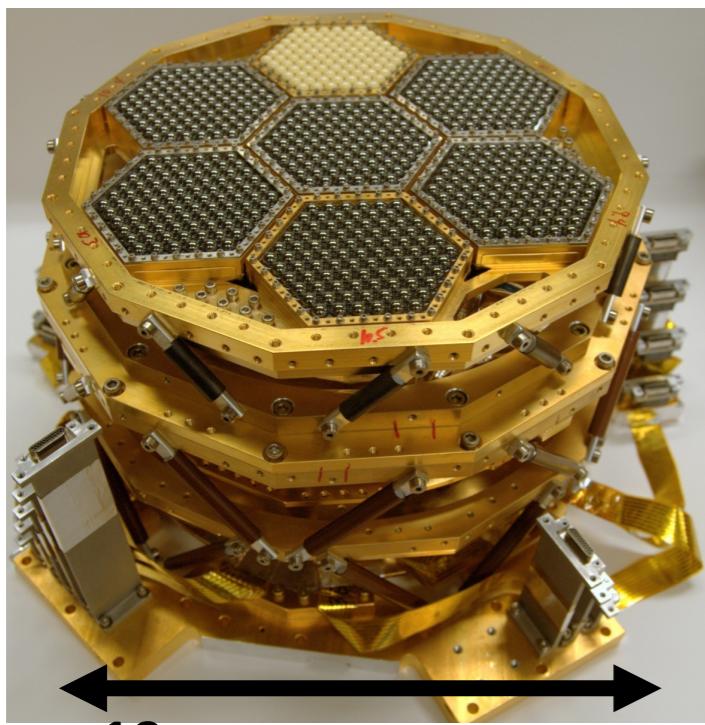
POLARBEAR-2
Detector module
Six-inch wafer with
1084 bolometers



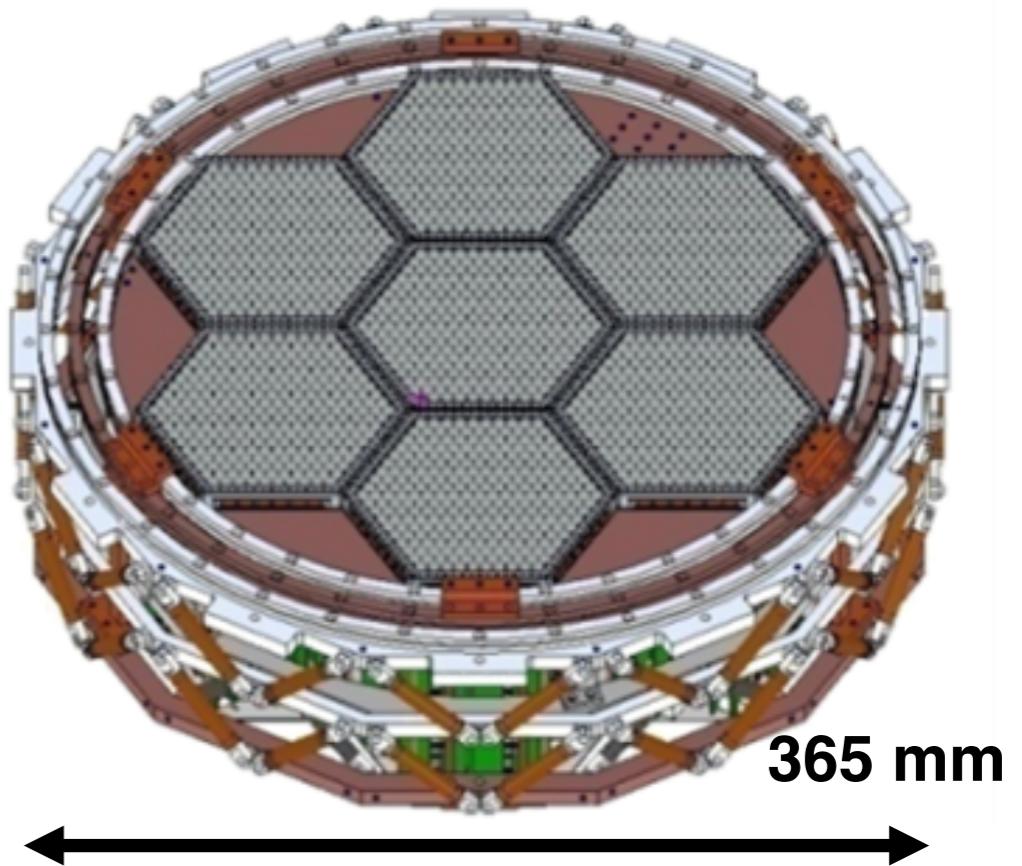
POLARBEAR

Focal Plane

POLARBEAR-1
Seven 4-inch wafers
1274 bolometers



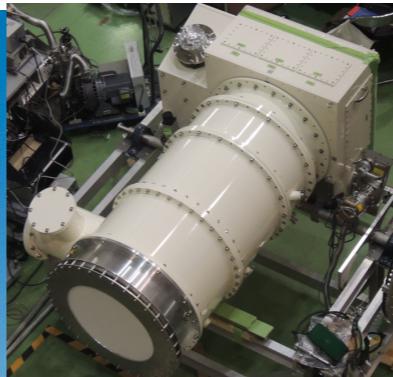
POLARBEAR-2
Seven 6-inch wafers
7588 bolometers



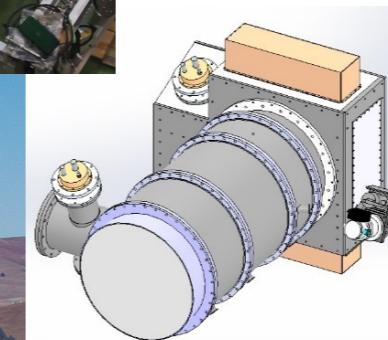
Simons Array

Leverage POLARBEAR experience to rapidly increase sensitivity

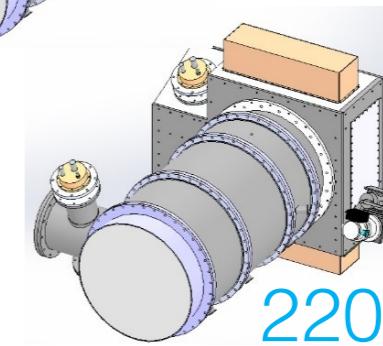
- Two new telescopes installed at Chilean site
- First new receiver will deploy in 2017



95 GHz / 150 GHz



95 GHz / 150 GHz



220 GHz / 280 GHz

3 receivers (22,764 bolometers) observing at 95, 150, 220, 280 GHz
Hardware funded by the Simons Foundation, NSF, MEXT

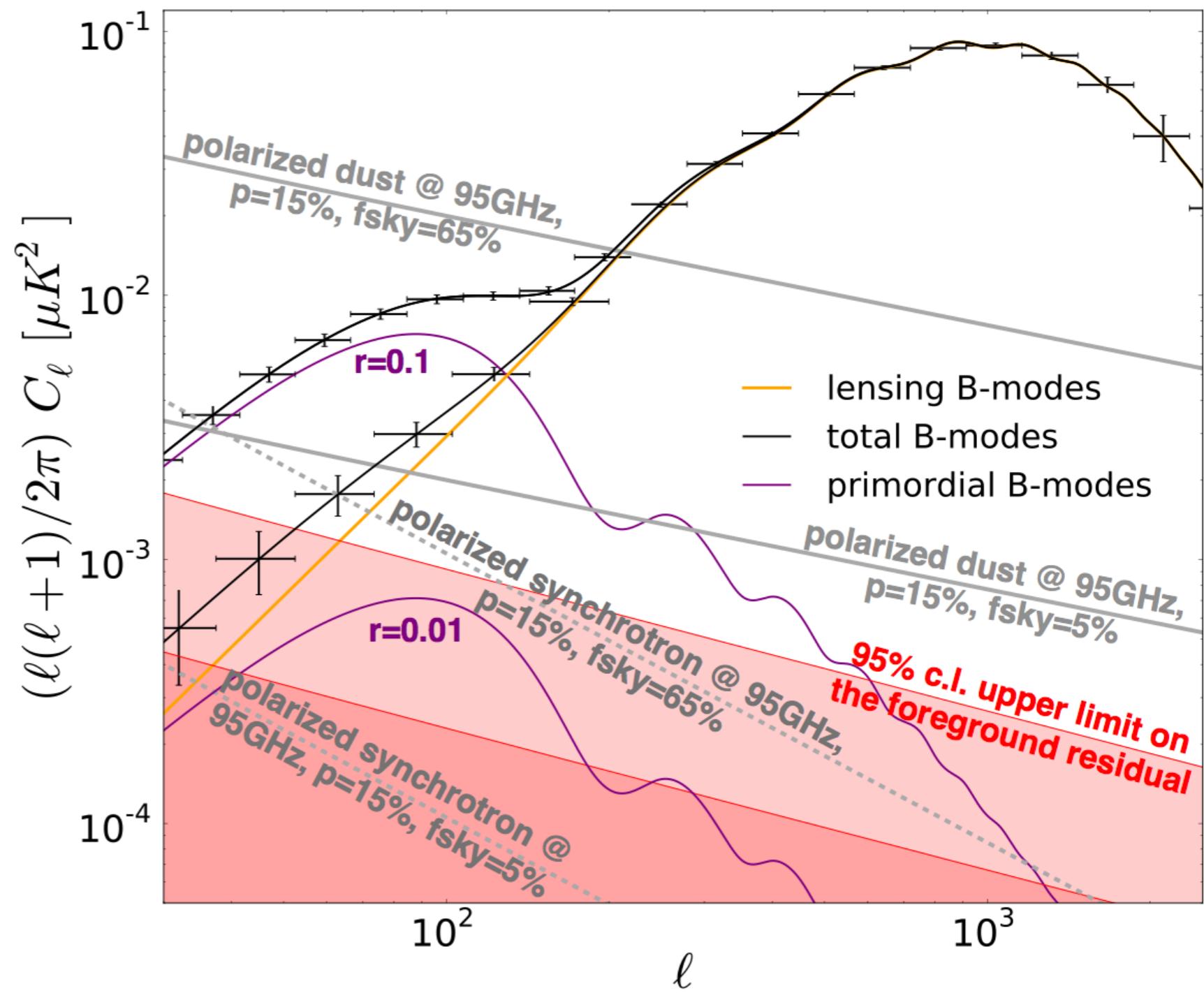
Simons Array

Projected sensitivity

Foreground rejection
with multi-frequency
Simons Array data

$\sigma(\Sigma m_v) = 40 \text{ meV}$
w/ DESI BAO,
including foreground
contamination

$\sigma(r = 0.1) = 0.006$

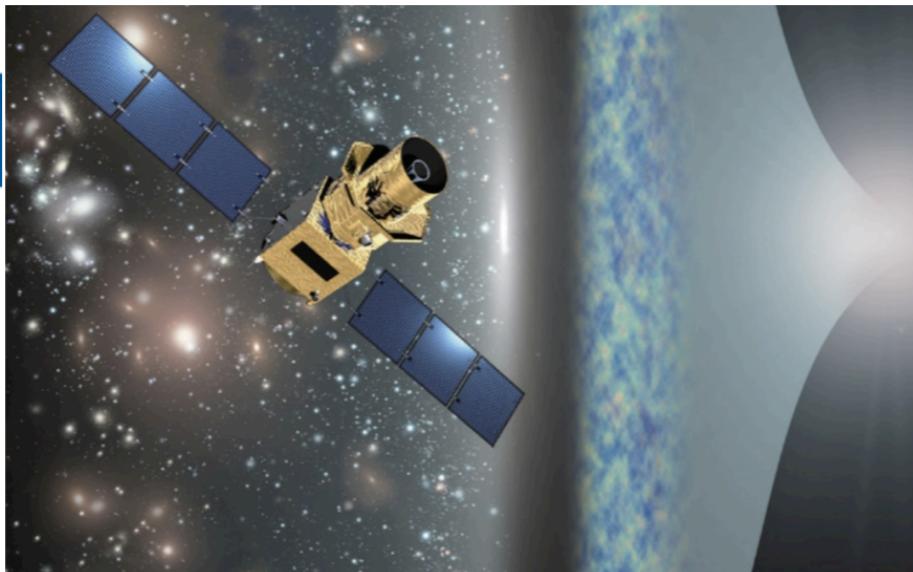


What's next?

Future CMB polarization experiments

- Want to extract the wealth of cosmological information in the presence of complex foregrounds
- Planning complementary measurements from ground and space

LiteBIRD



CMB-S4



What's next?

Future CMB polarization experiments

- CMB-S4: “the ultimate ground-based CMB polarization experiment”
 - Proposed in Snowmass documents (2013) as input to Particle Physics Project Prioritization Panel (P5), recommended by P5 report
- **Goal:** Map CMB polarization across the sky to the sensitivity and resolution needed to reach lensing B-mode signal and beyond
 - Massive scaling up of current efforts
 - 50k detectors deploying by ~2018
 - S4 plans are ~ 500k detectors ~ 2025
 - Will require coordinated effort of entire CMB community
- Science Book published this summer (arXiv:1610.02743)
- Instrument white papers coming soon



The Simons Observatory

<http://simonsobservatory.org>

A five year, \$45M+ program to pursue key Cosmic Microwave Background science targets, and advance technology and infrastructure in preparation for CMB-S4.

- Merger of the ACT and POLARBEAR/Simons Array teams.

Tentative plans include:

- Major site infrastructure
- Technology development (detectors, optics, cameras)
- Demonstration of new high throughput telescopes.
- CMB-S4 class receivers with partially filled focal planes.
- Data analysis

POLARBEAR/Simons Array

ACT



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Thank you

- **POLARBEAR-1** in fifth 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 2016
 - Optics: Inoue et al. SPIE 2016
- **Simons Array**: expands POLARBEAR to 3 telescopes, 4 bands, 22,764 bolometers
 - Stebor et al. SPIE 2016
- **Simons Observatory**: funding and initial study phase started Sept. 2016

