Cosmology from CMB Polarization with POLARBEAR and the Simons Array

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UC Berkeley Space Science Lab
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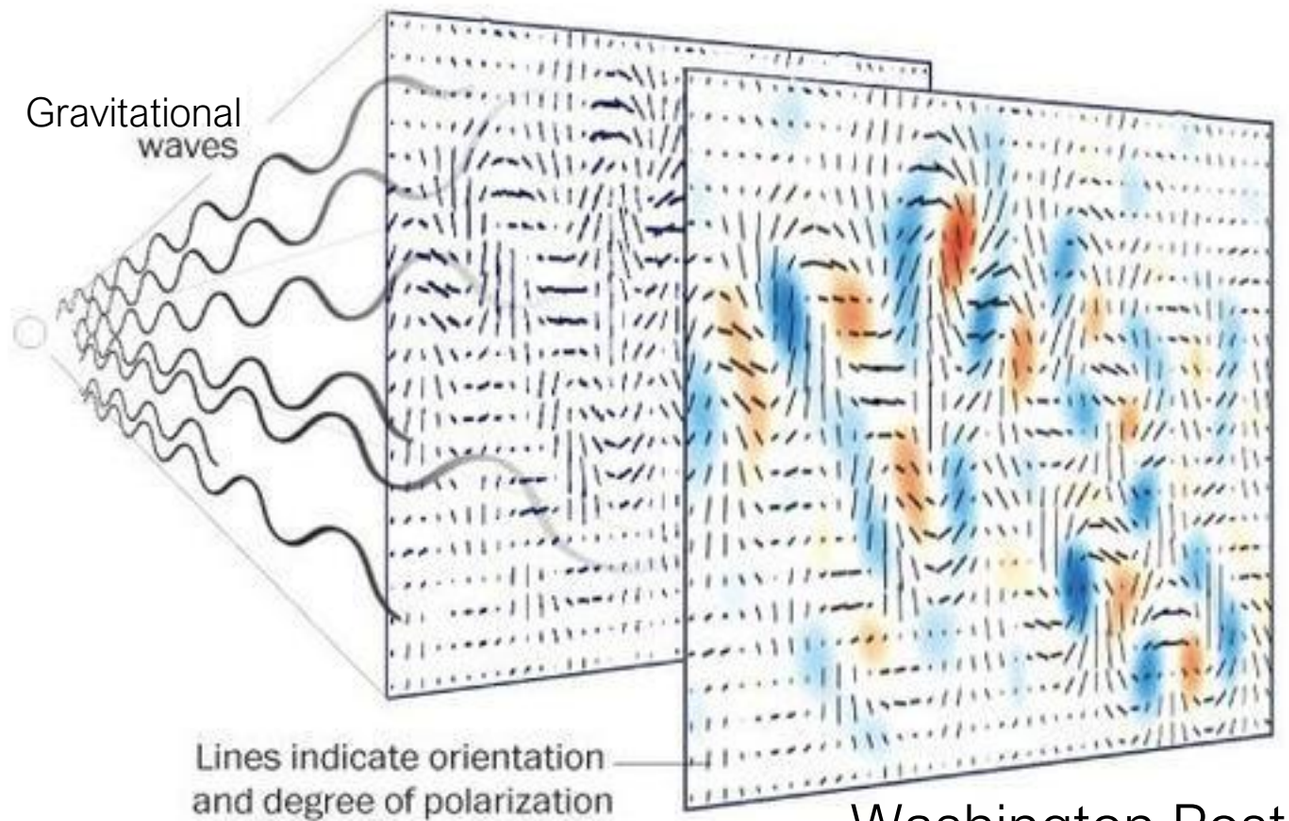
Cosmology from B-mode Polarization

- 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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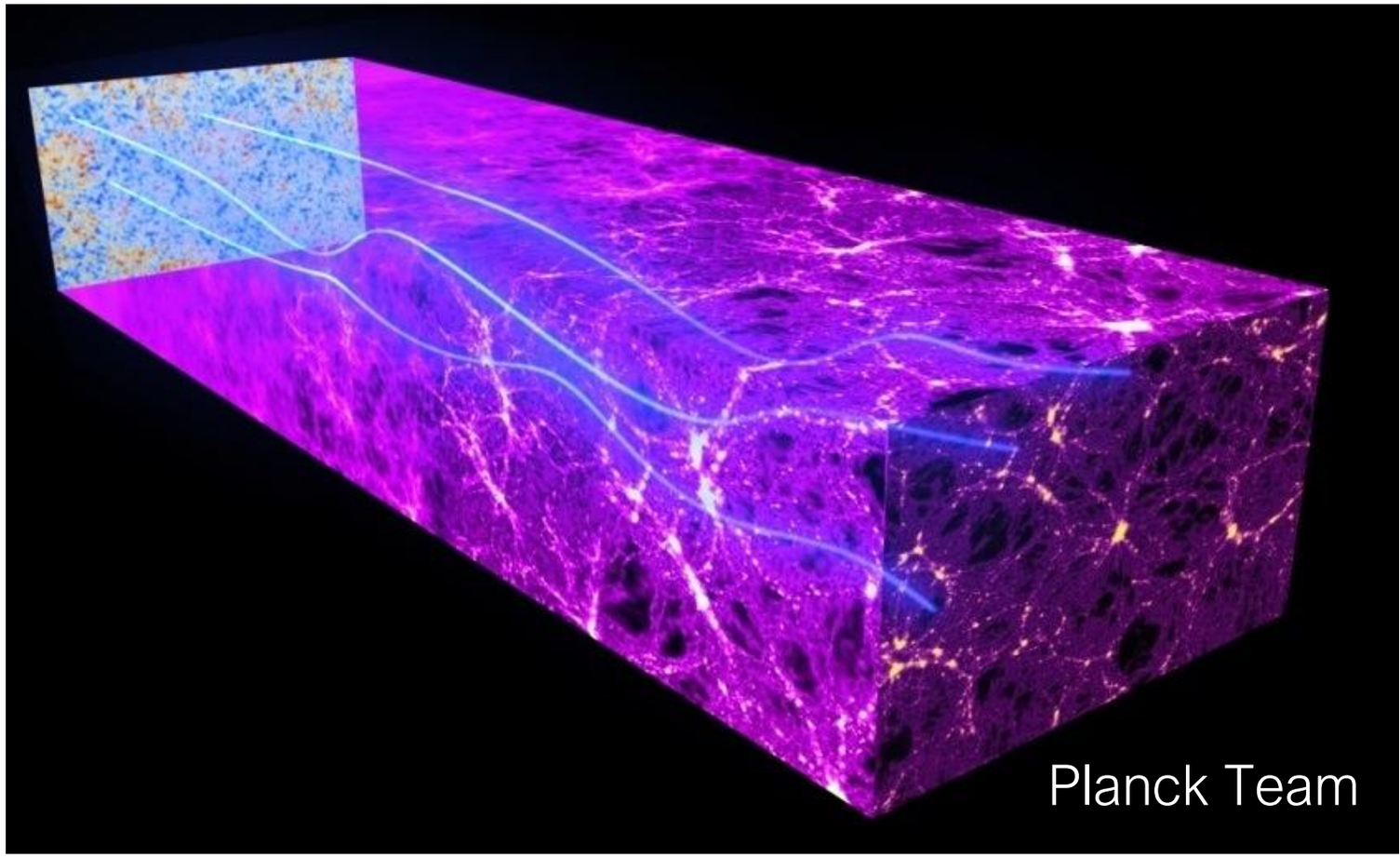

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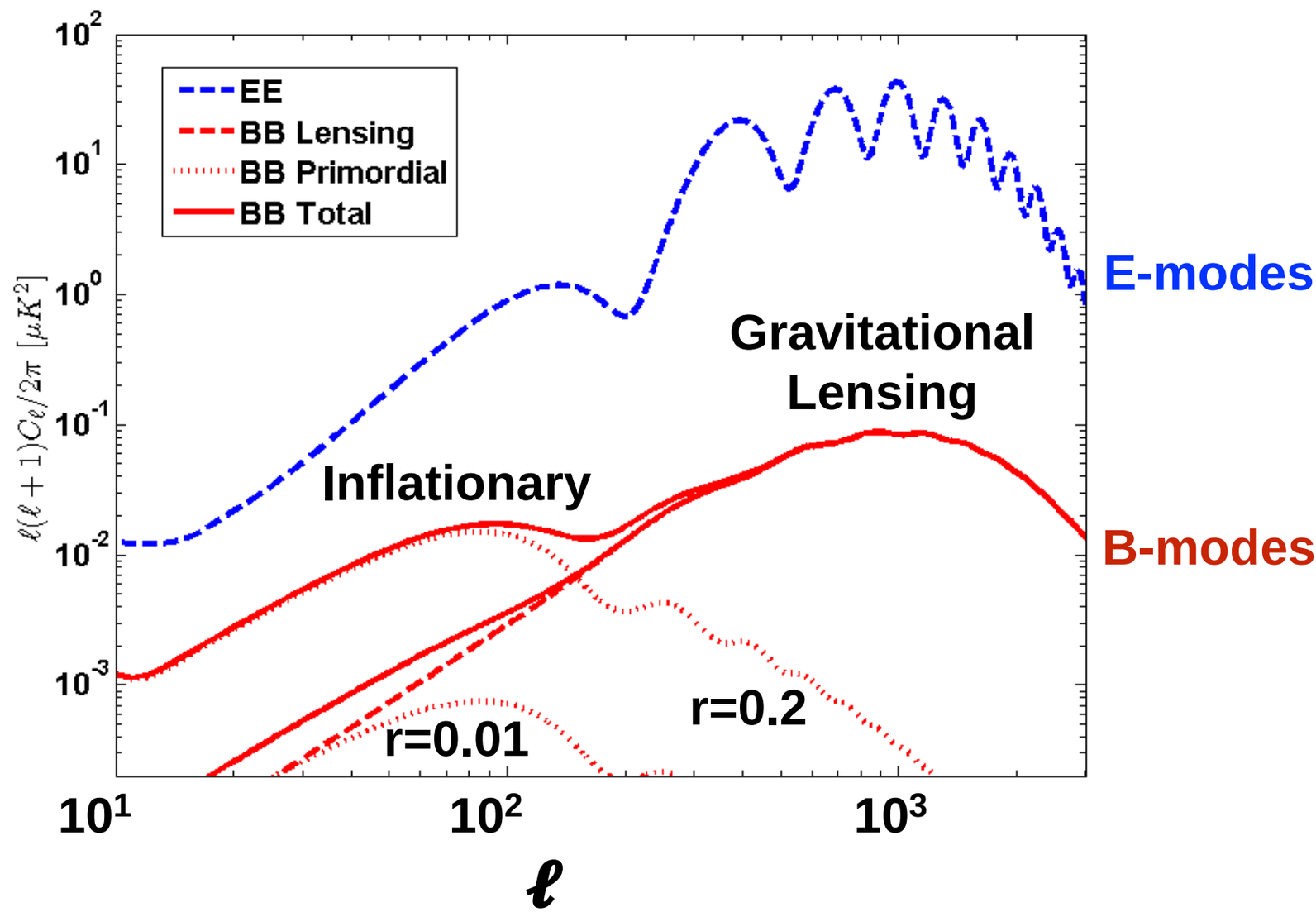


CMB B-mode Measurements

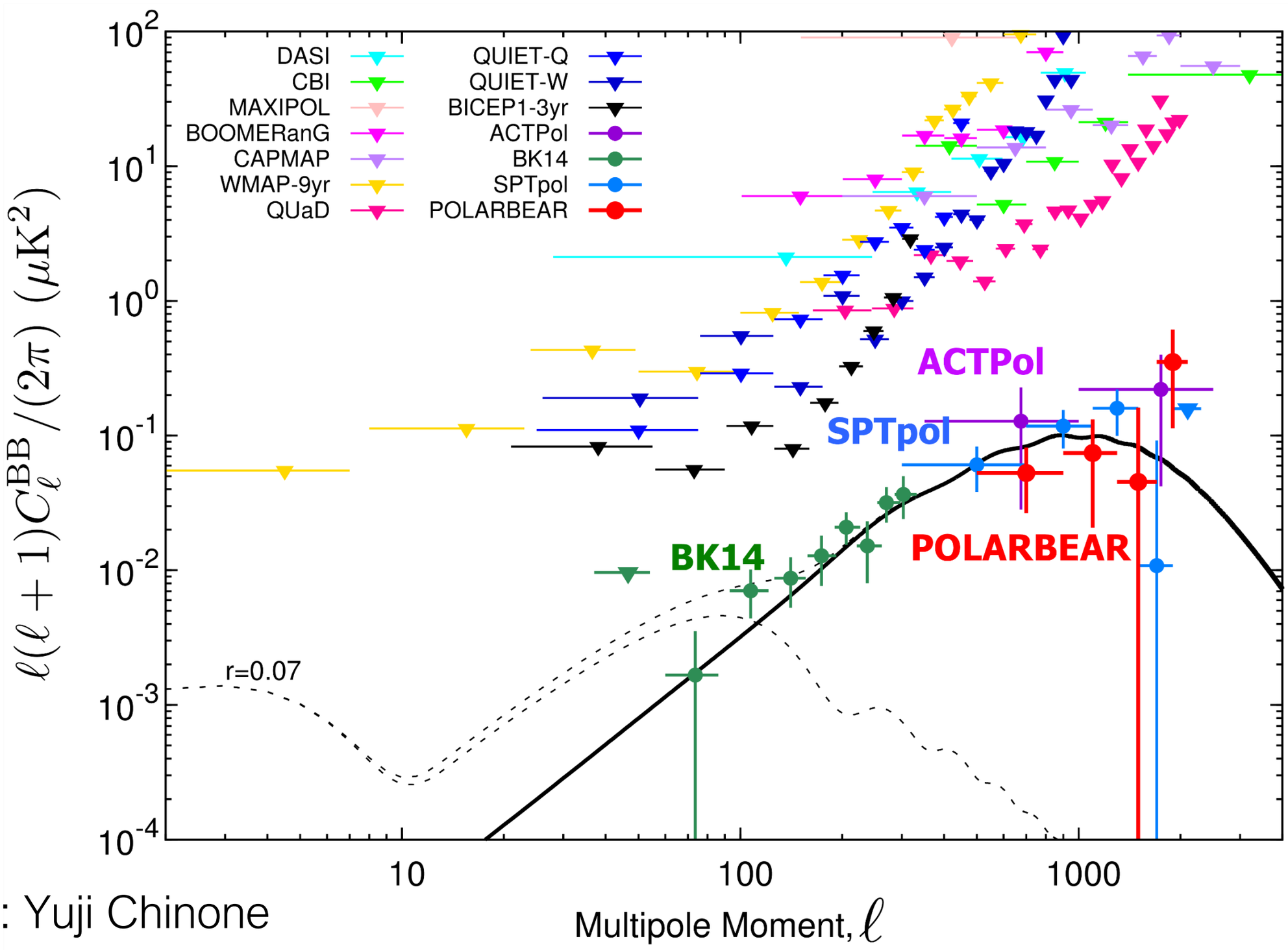


Figure: Yuji Chinone

The POLARBEAR Experiment

- Dedicated CMB polarization experiment designed to measure both inflation and lensing scales
- Located on Cerro Toco at 5200 meters in Atacama desert
- First light January 2012 with POLARBEAR-1
- Expanding to POLARBEAR-2/ Simons Array

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
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
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

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

U. Melbourne
Christian Reichardt
Federico Bianchini
Anh Pham

Imperial College
Andrew Jaffe
Daisy Mak

Institute D'Astrophysique Spatiale
Giulio Fabbian

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
Yuto Minami
Nobuhiko Katayama

SISSA
Carlo Baccigalupi
Nicoletta Krachmalnicoff
Davide Poletti
Giuseppe Puglisi

U Manchester
Gabriele Coppi
Andrew May
Lucio Piccirillo

U of Sussex
Julien Peloton

UC Irvine
Chang Feng

Cardiff University
Peter Ade

NASA Goddard
Nathan Miller

Argonne NL
Amy Bender

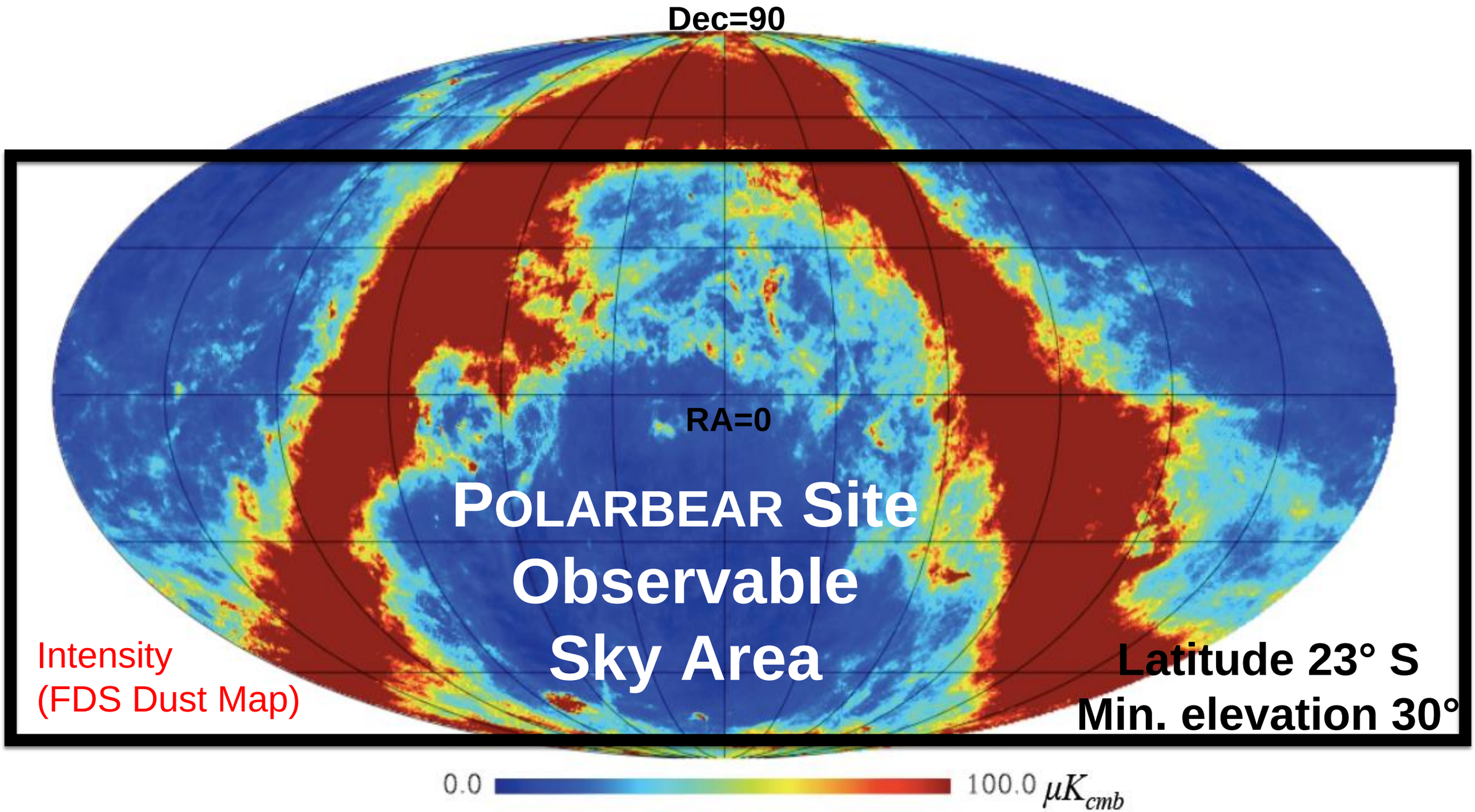
And many more in years past…

POLARBEAR Collaboration

POLARBEAR Observations

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

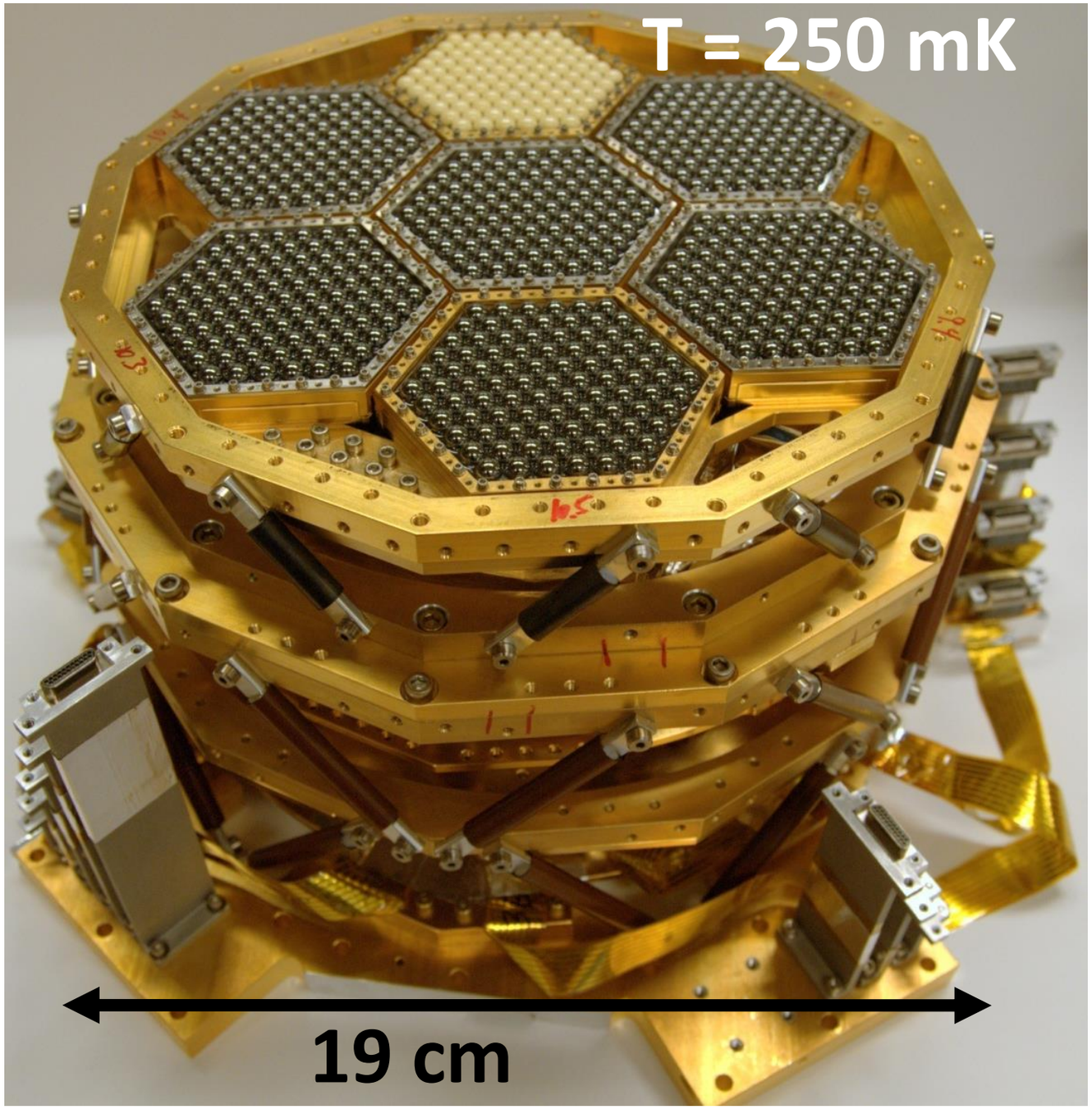
POLARBEAR Observations



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)



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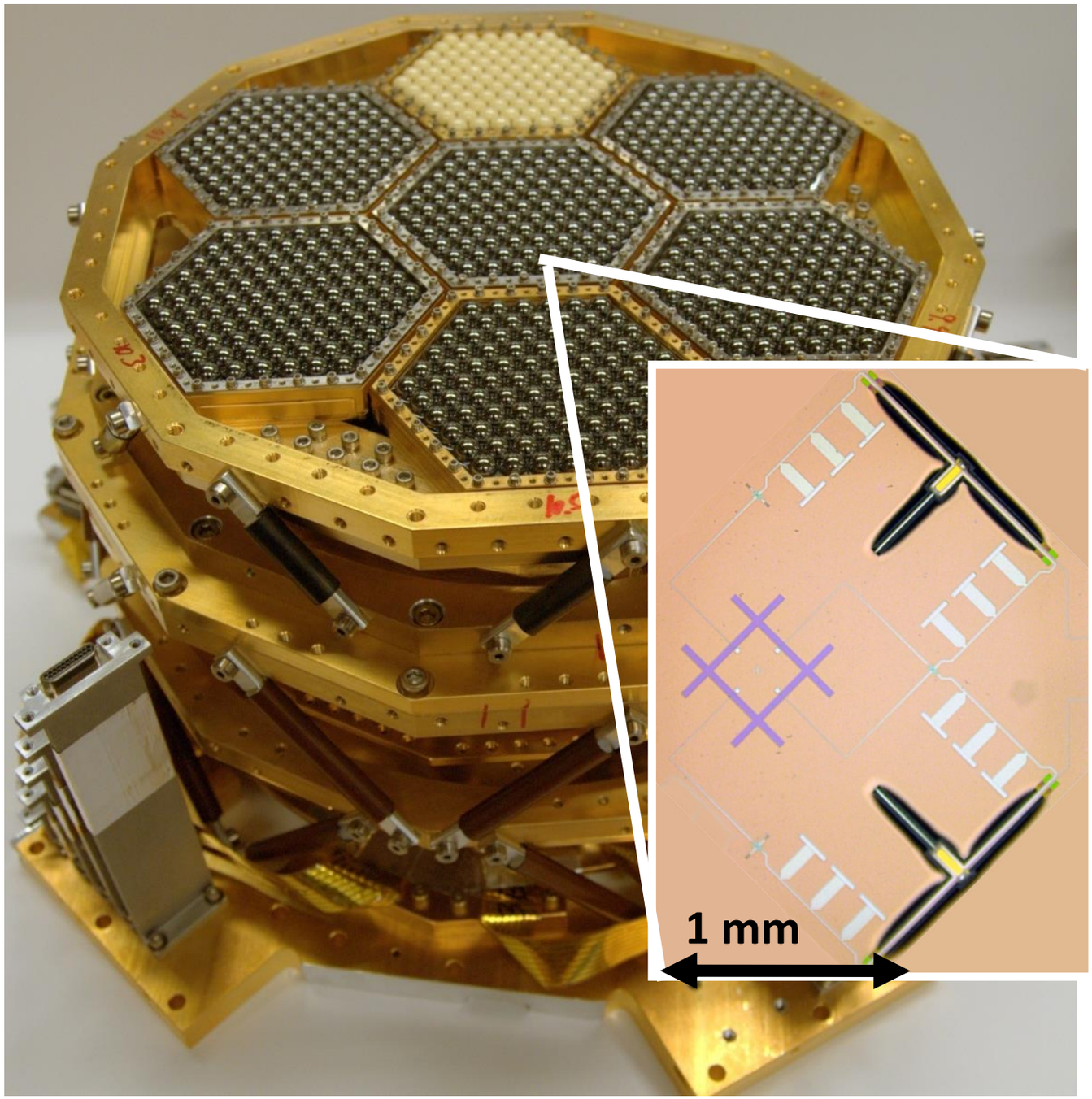
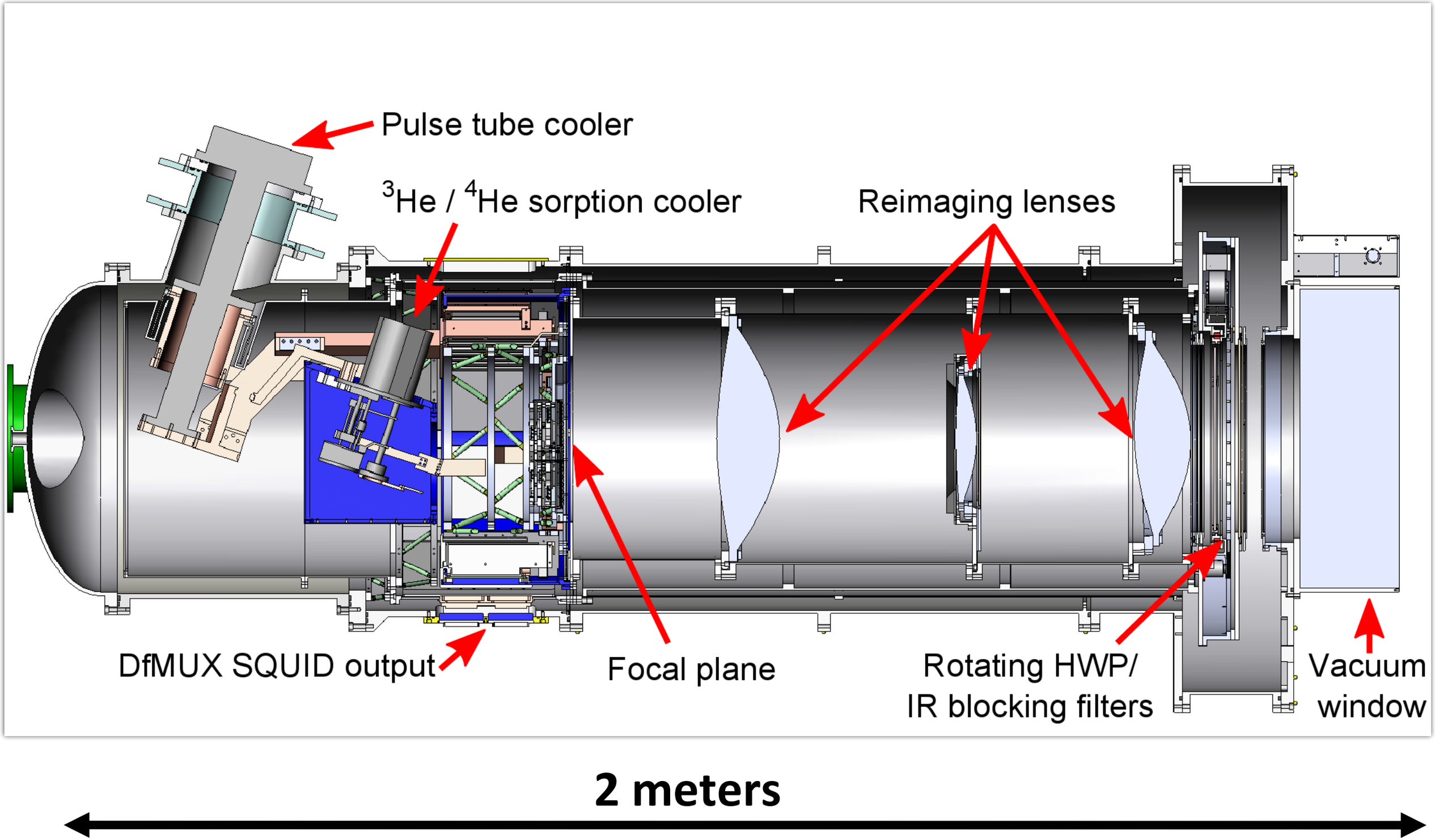


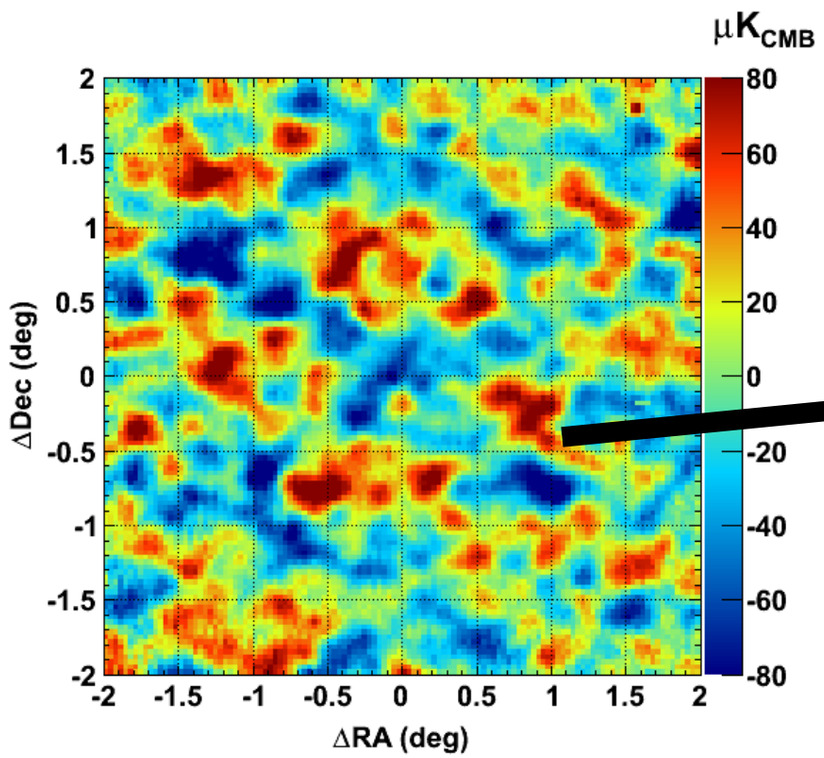
POLARBEAR-1

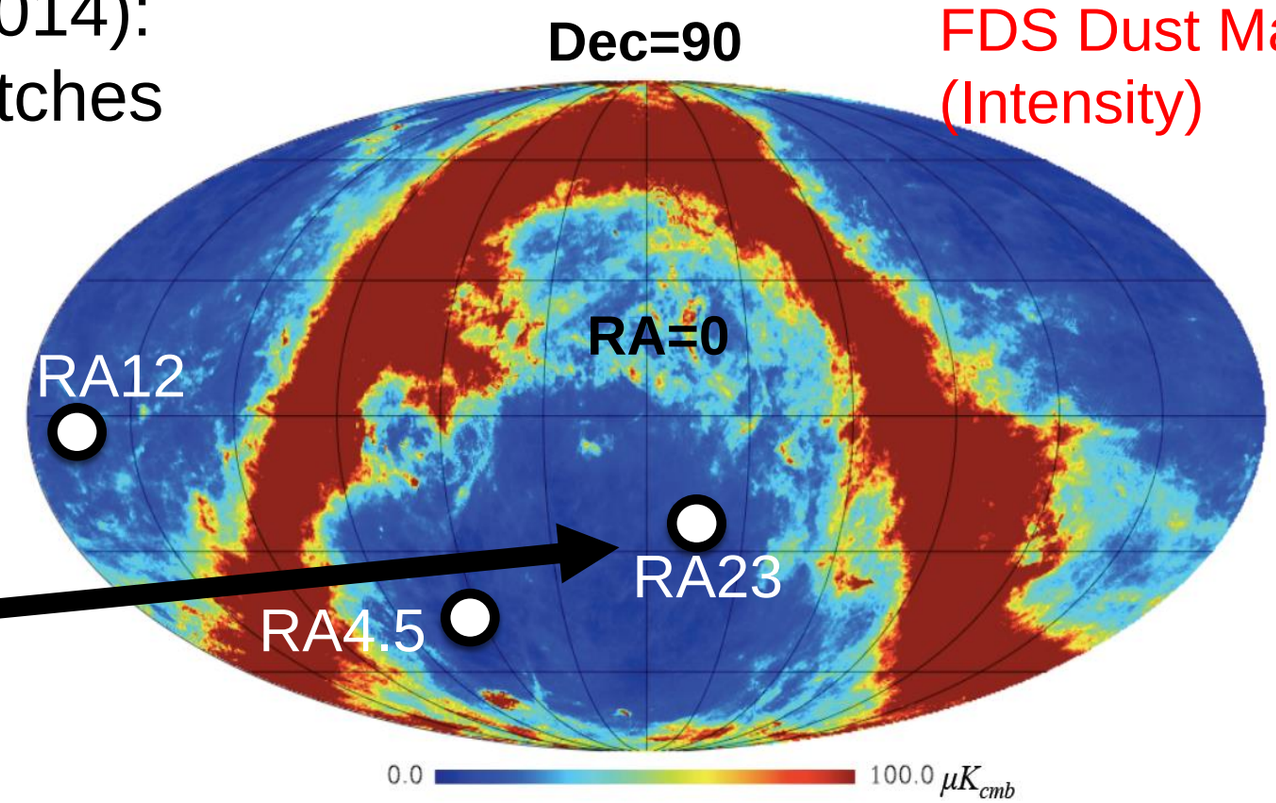
Cryogenic Receiver



POLARBEAR Observations

POLARBEAR-1 Initial survey (2012-2014):
Deep integration on three 3x3 deg. patches
Observations at 150 GHz

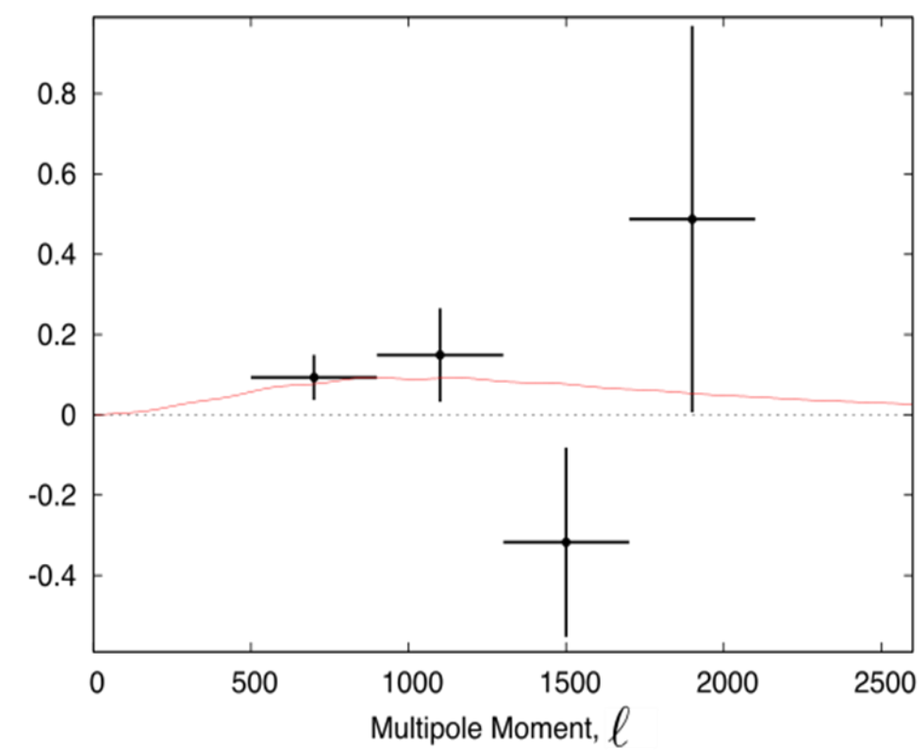




FDS Dust Map
(Intensity)

Results with first season dataset

Angular power spectrum: ApJ 794, 171 (2014)
Deflection power spectrum: PRL 113, 021301 (2014)
Galaxy cross-correlation: PRL 112, 131302 (2014)
Constraints on cosmic birefringence and primordial magnetic fields: Phys. Rev. D 92, 123509 (2015)



POLARBEAR Observations

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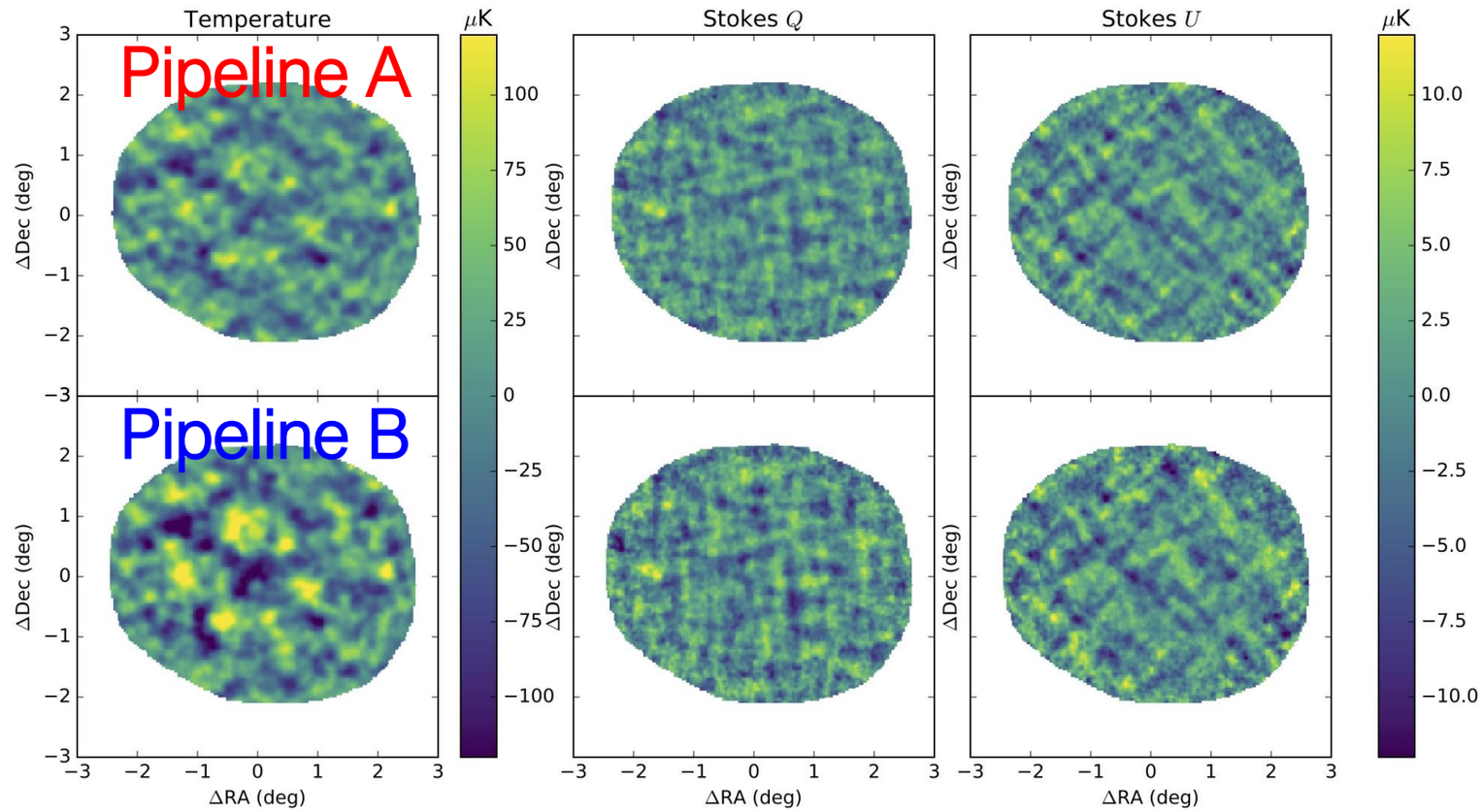
Deep integration on three 3x3 deg. patches
Observations at 150 GHz

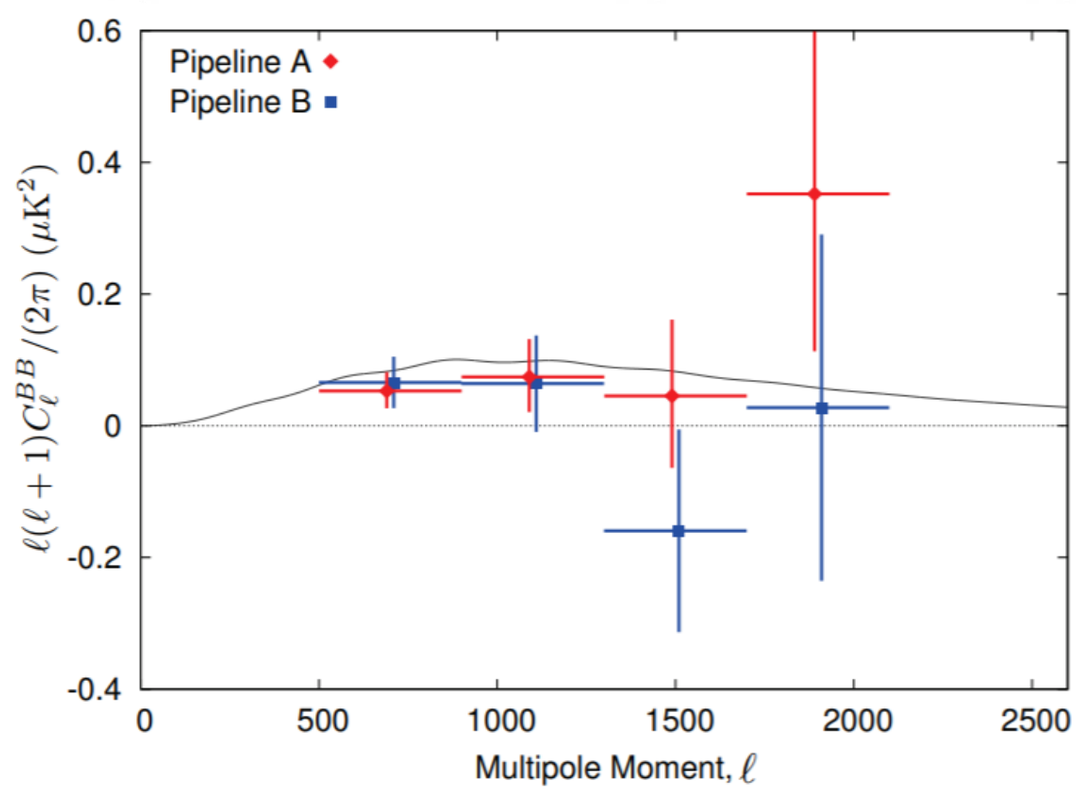
New results with two-year dataset

Angular power spectrum:
arXiV: 1705.02907 (2017)

Reduced band-power uncertainty by factor of two

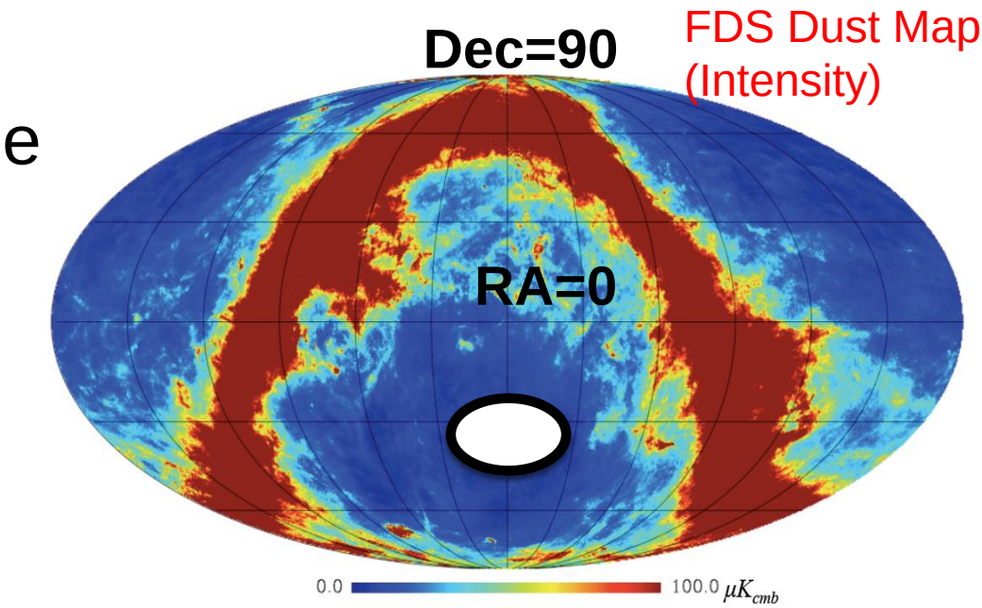
Two independent pipelines performed analysis from calibrated time-ordered-data (TOD) to maps and power spectrum estimate

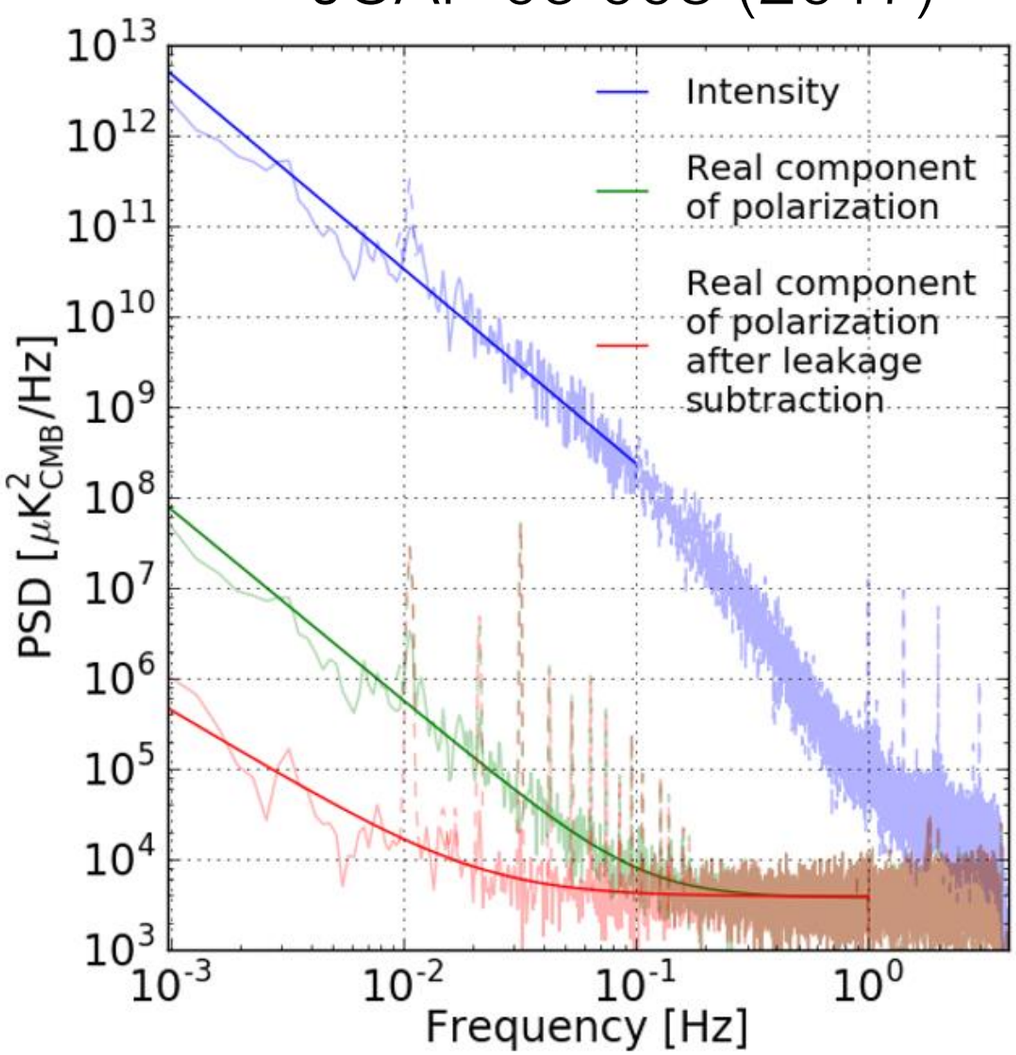


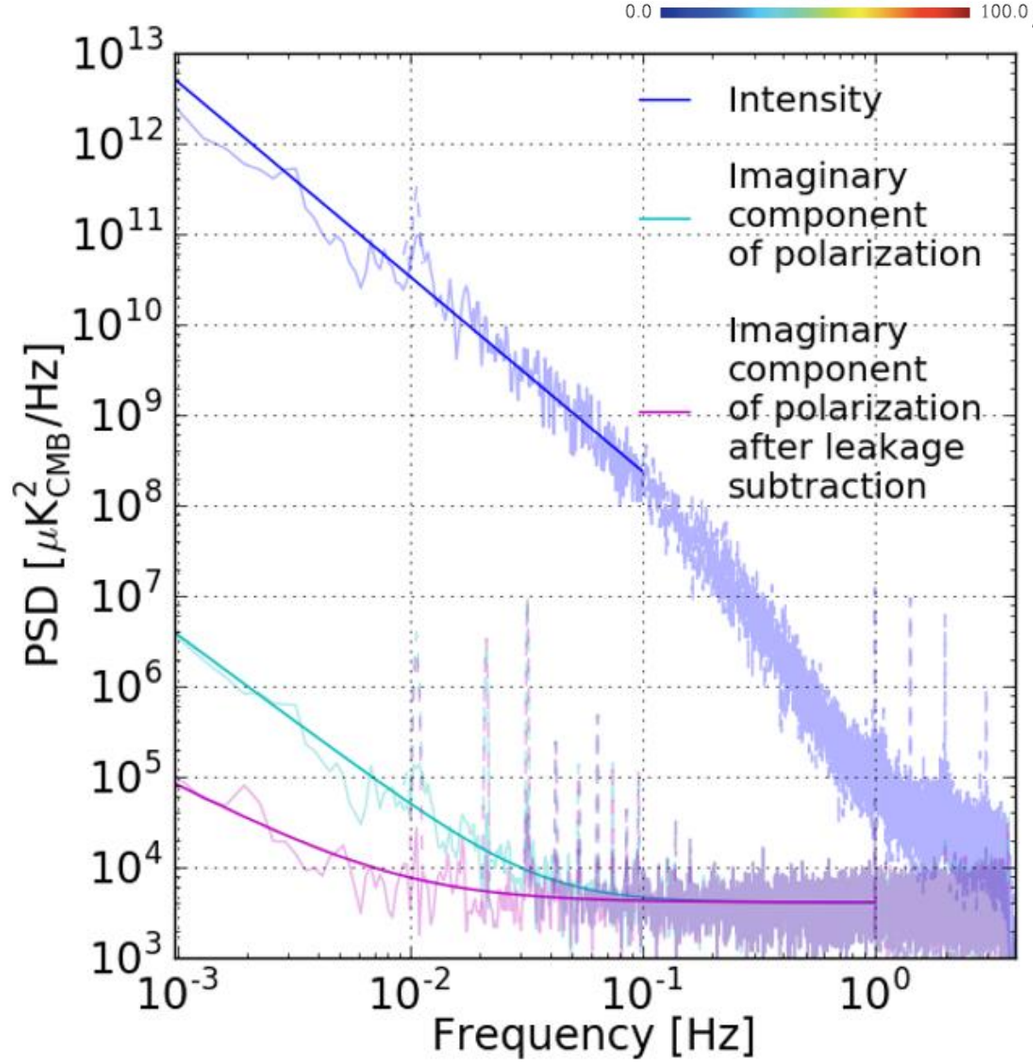


POLARBEAR Observations

POLARBEAR-1 Wide survey (2014-current):
Observing larger sky area in southern Galactic hole
Polarization modulation with
continuously rotating half-wave plate
Performance of CRHWP on sky:
Takakura et al. (PB collaboration)
JCAP 05 008 (2017)





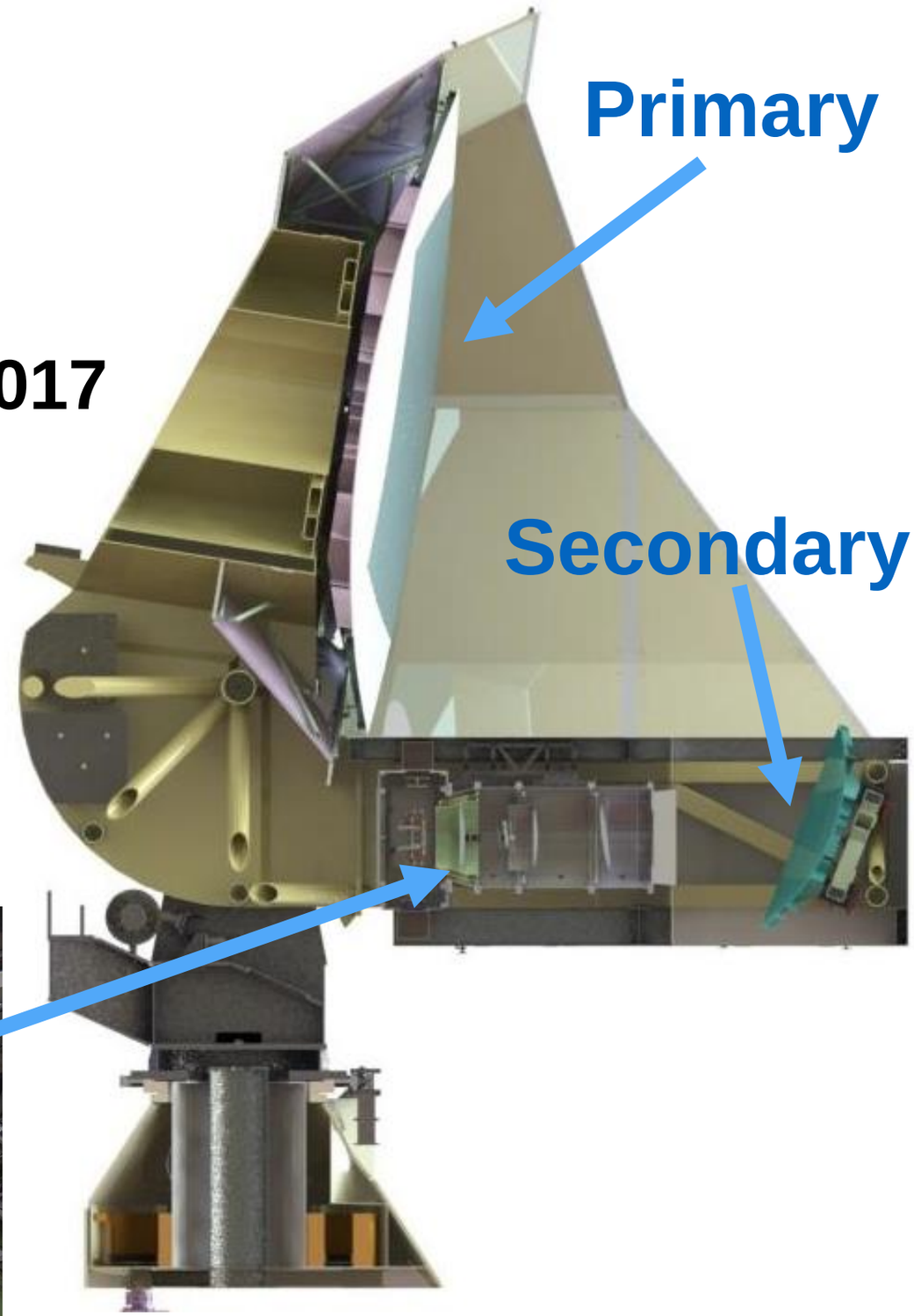


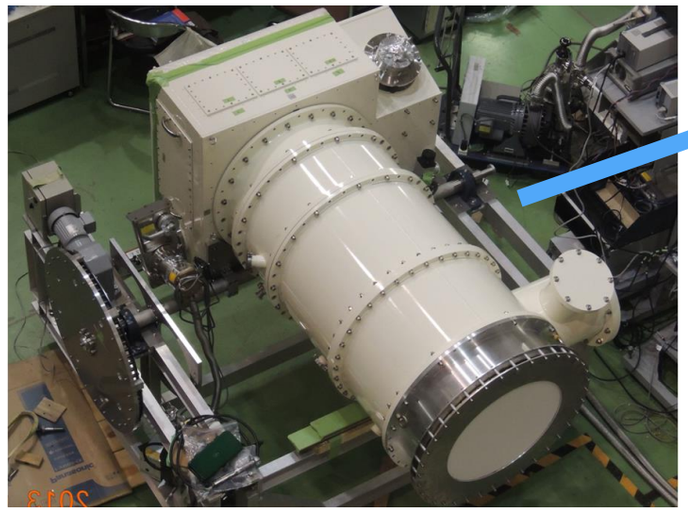
POLARBEAR-2

Overview

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

PB-2a deploying 2017





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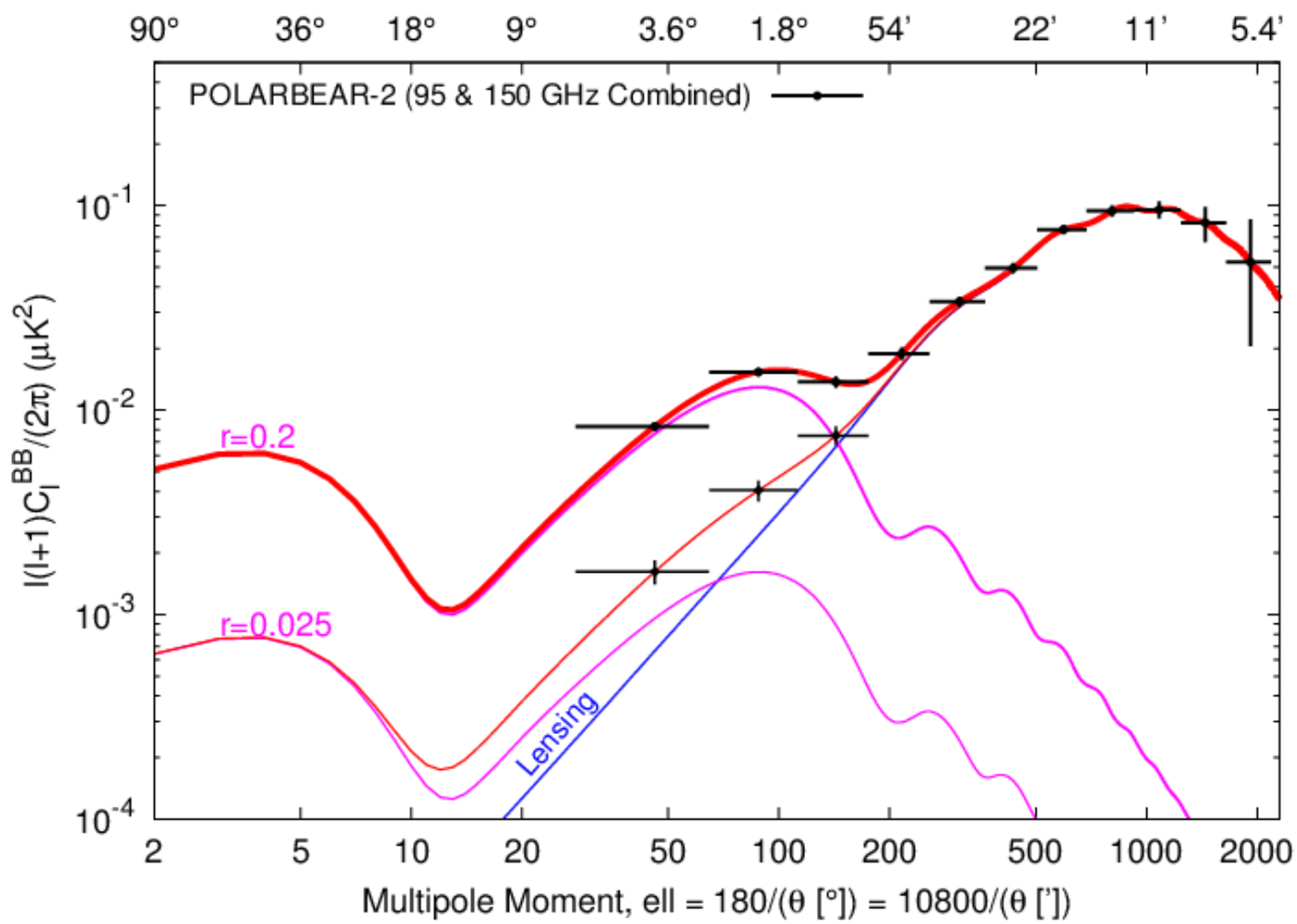
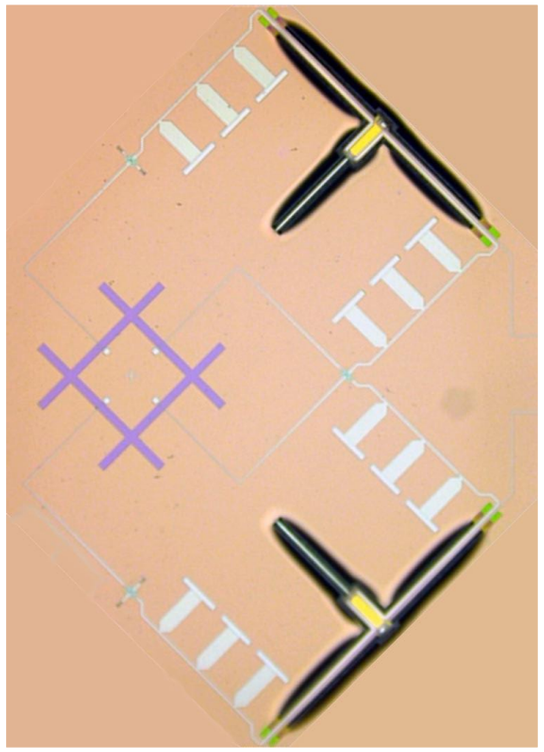


	POLARBEAR-1	**POLARBEAR-2a**
Frequency	150 GHz	95 GHz + 150 GHz
Pixels	637	1897
Detectors	1274	7588
Field-of-view	2.3°	4.8°

POLARBEAR-2

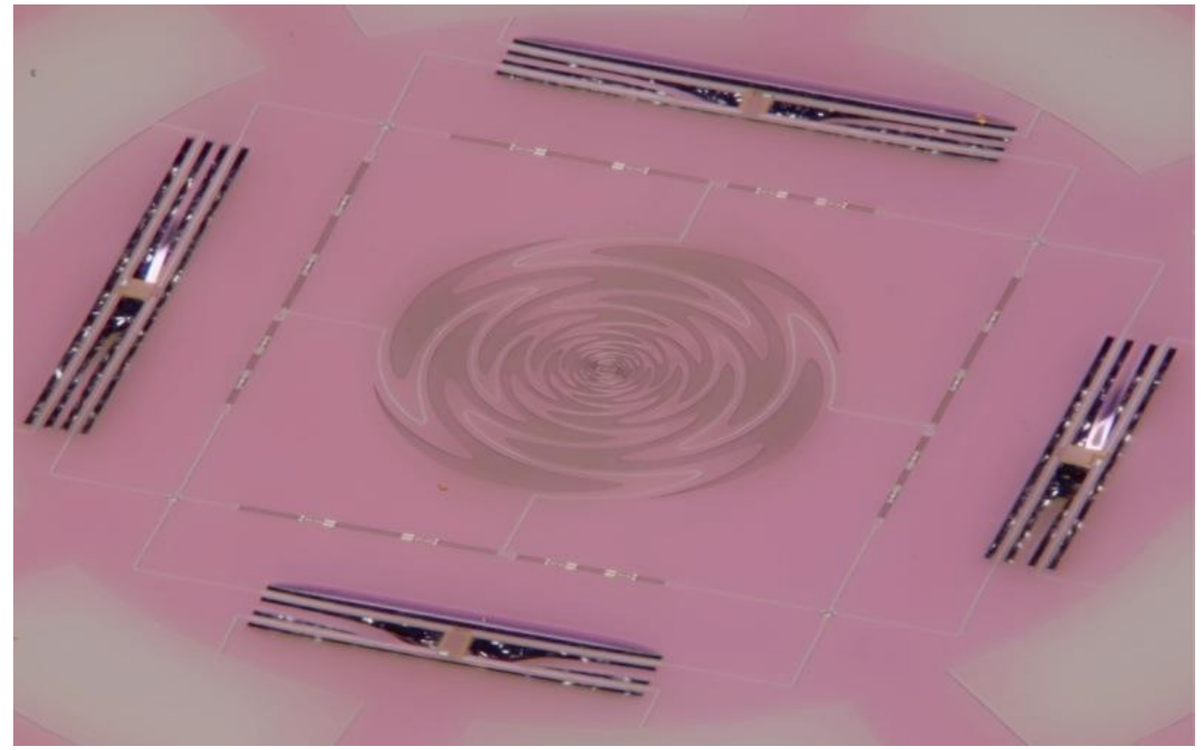
Focal Plane

POLARBEAR-1
Double-slot dipole



Myers PhD Thesis 2010
Arnold et al. SPIE 2012

POLARBEAR-2
Broadband sinuous antenna



O'Brient PhD Thesis 2010
A. Suzuki et al. JLTP Jan. 2014

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Focal Plane

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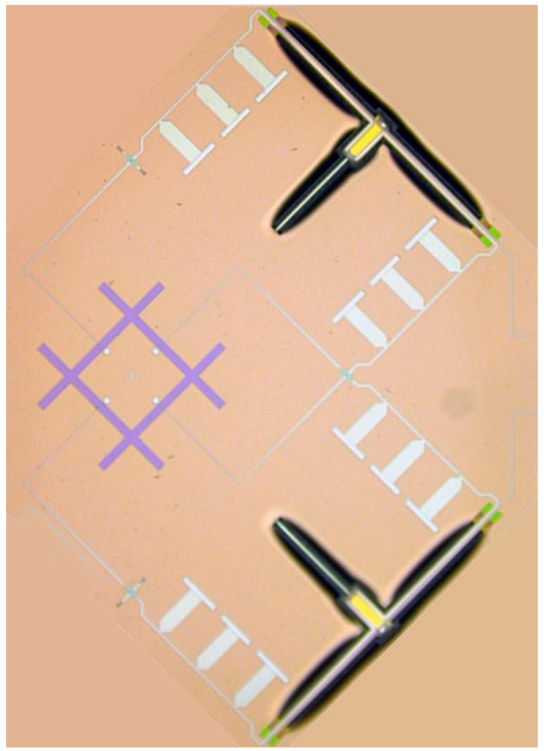
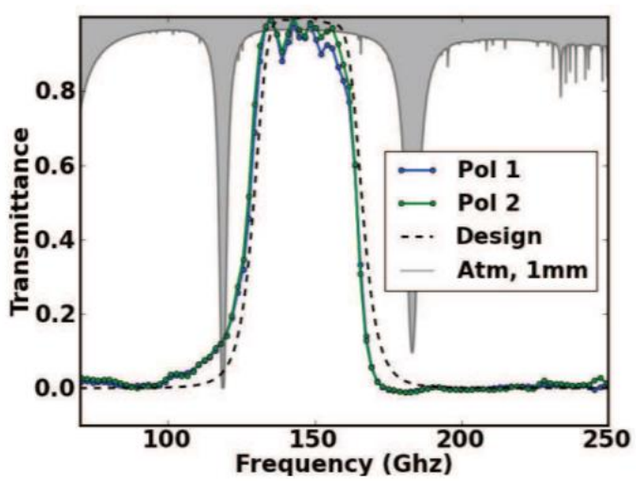
Double-slot dipole





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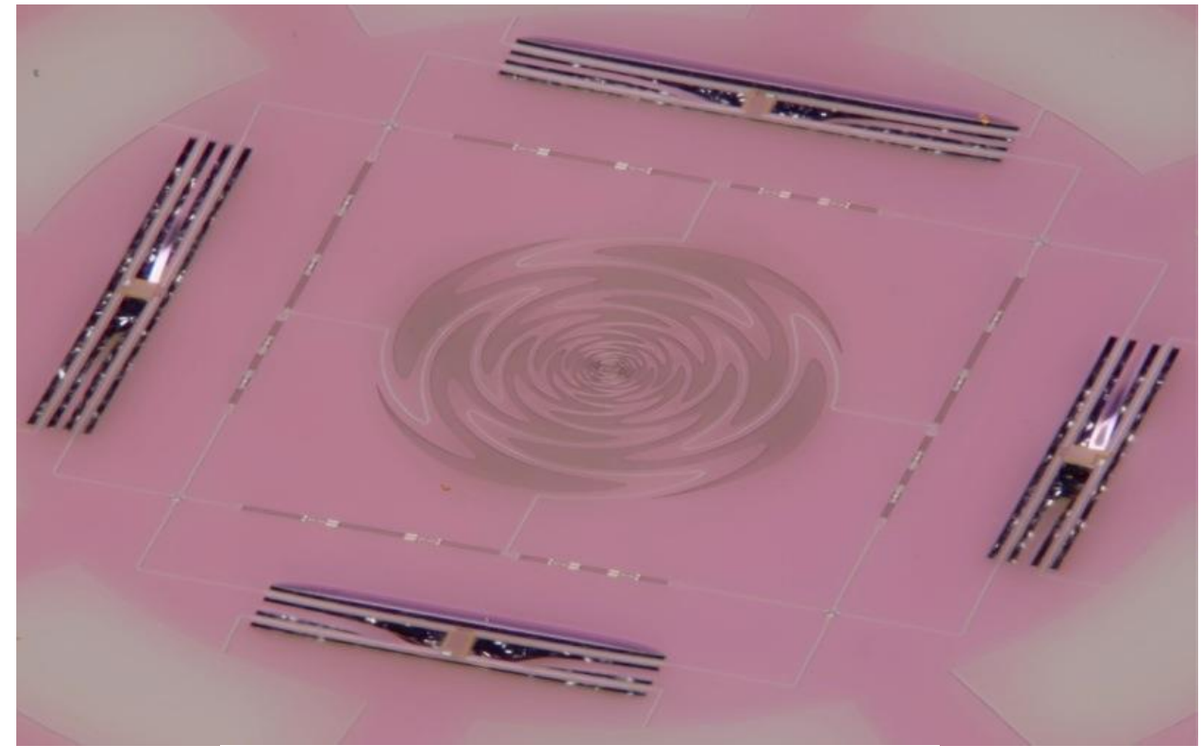
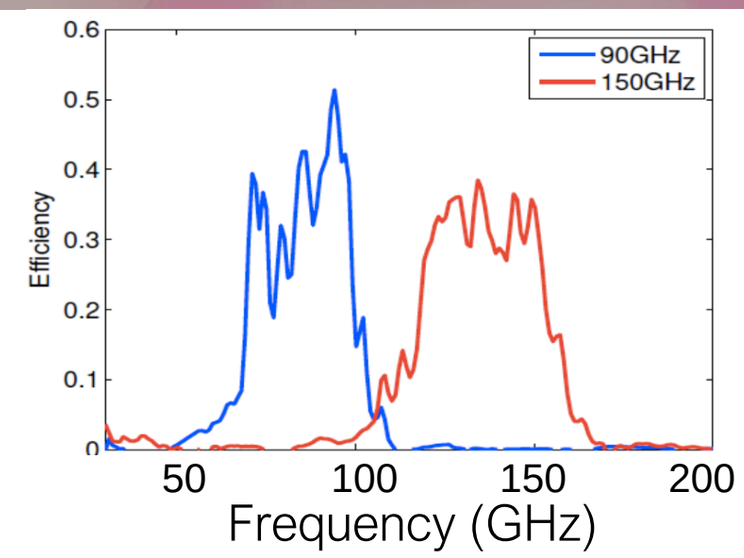
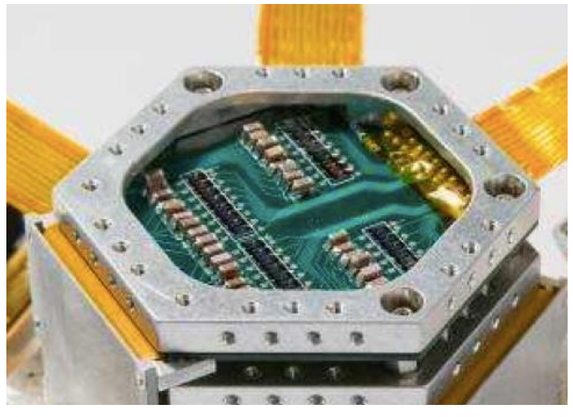


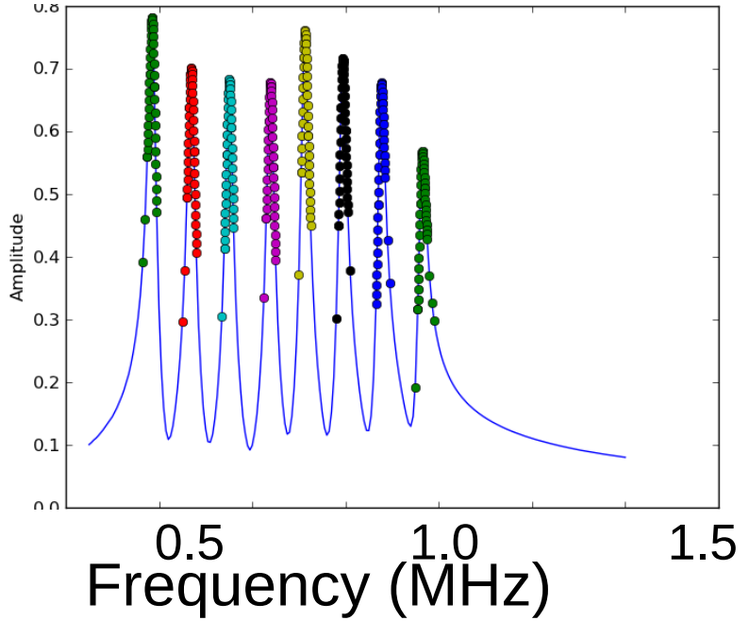


POLARBEAR-2

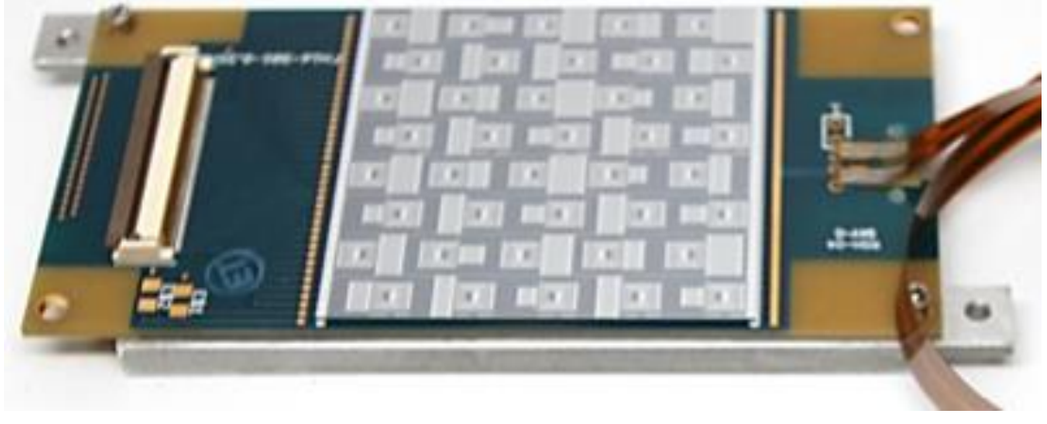
Readout

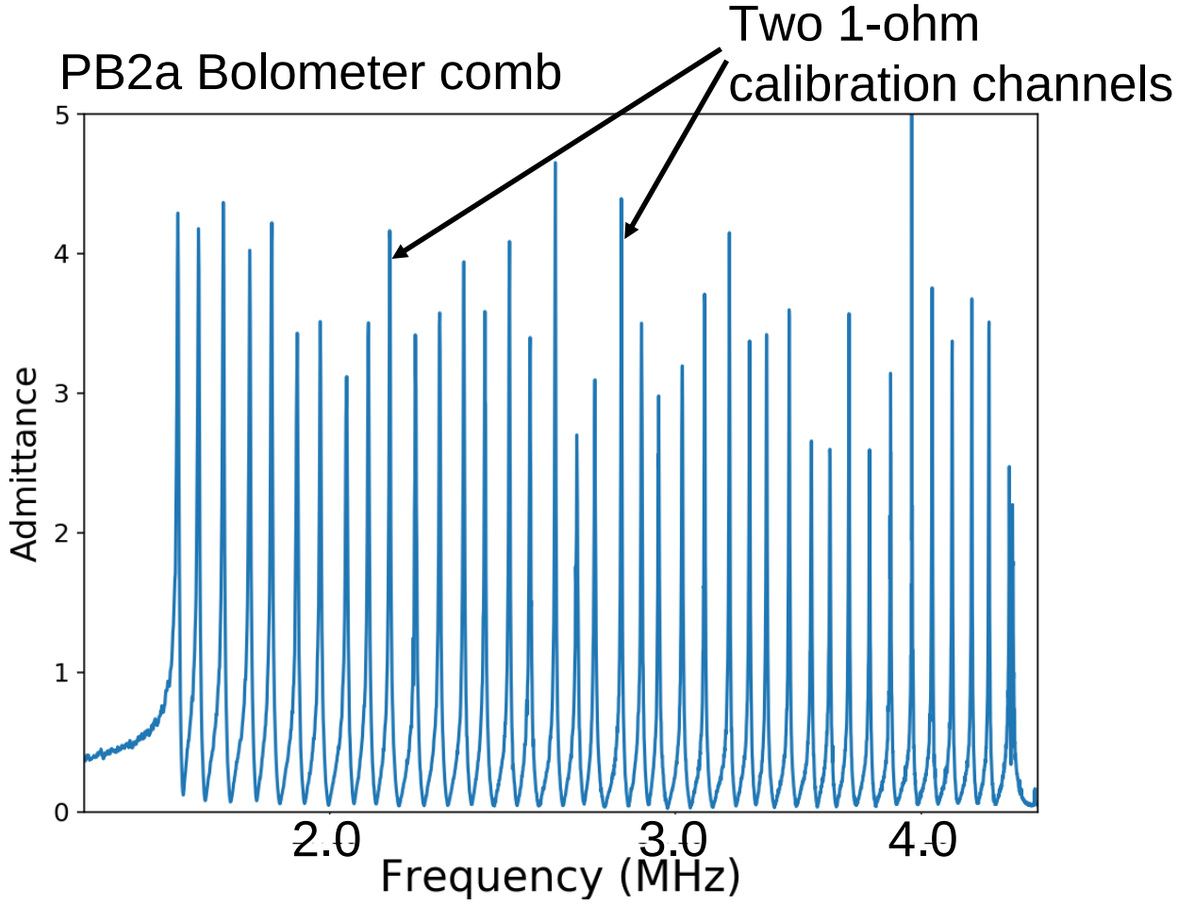
POLARBEAR-1
8x freq. division multiplexing





POLARBEAR-2
40x freq. division multiplexing



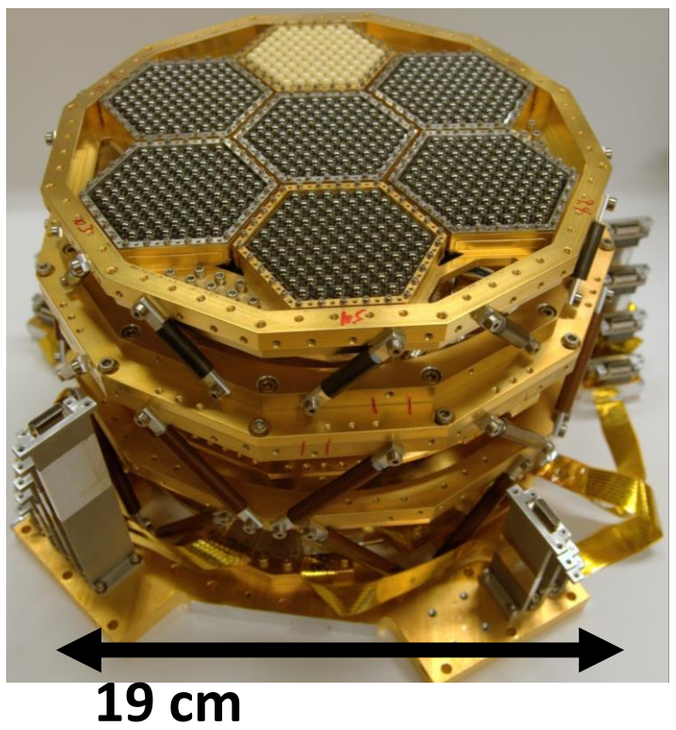


Dfmux: Dobbs et al., Rev. Sci. Inst. Vol 83 7 (2012)
Digital active nulling: de Haan et al., Proc. SPIE 2012
Planar Lithographed Superconducting LCs:
Rotermund et al., JLTP Vol 184, 1–2 (2016)
CMB-S4 Technology Book arxiv:1706.02464

POLARBEAR

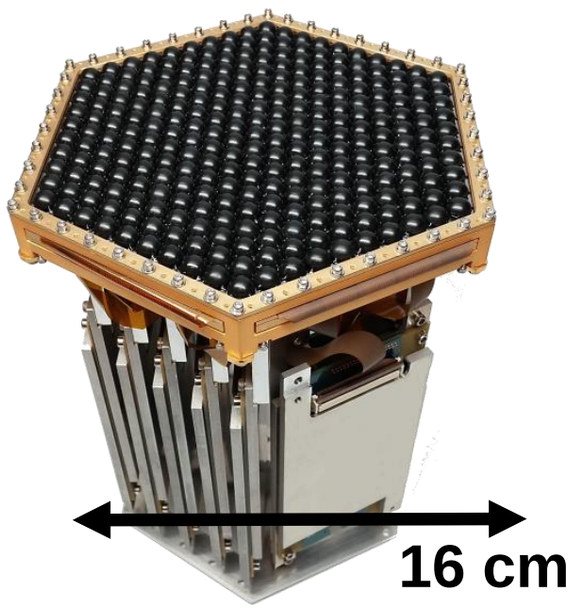
Focal Plane

POLARBEAR-1
Seven 4-inch wafers
1274 bolometers



Arnold et al., Proc. SPIE Vol 8452 (2012)

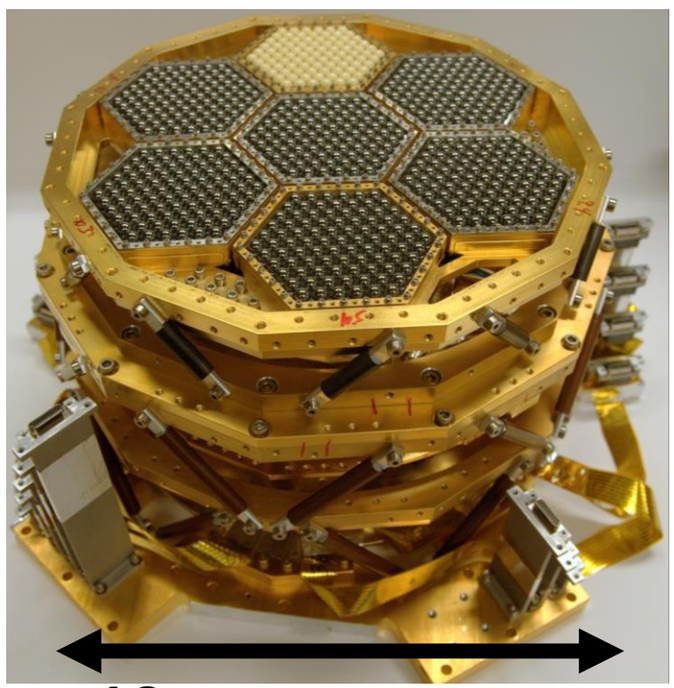
POLARBEAR-2
Detector module
Six-inch wafer with
1084 bolometers



POLARBEAR

Focal Plane

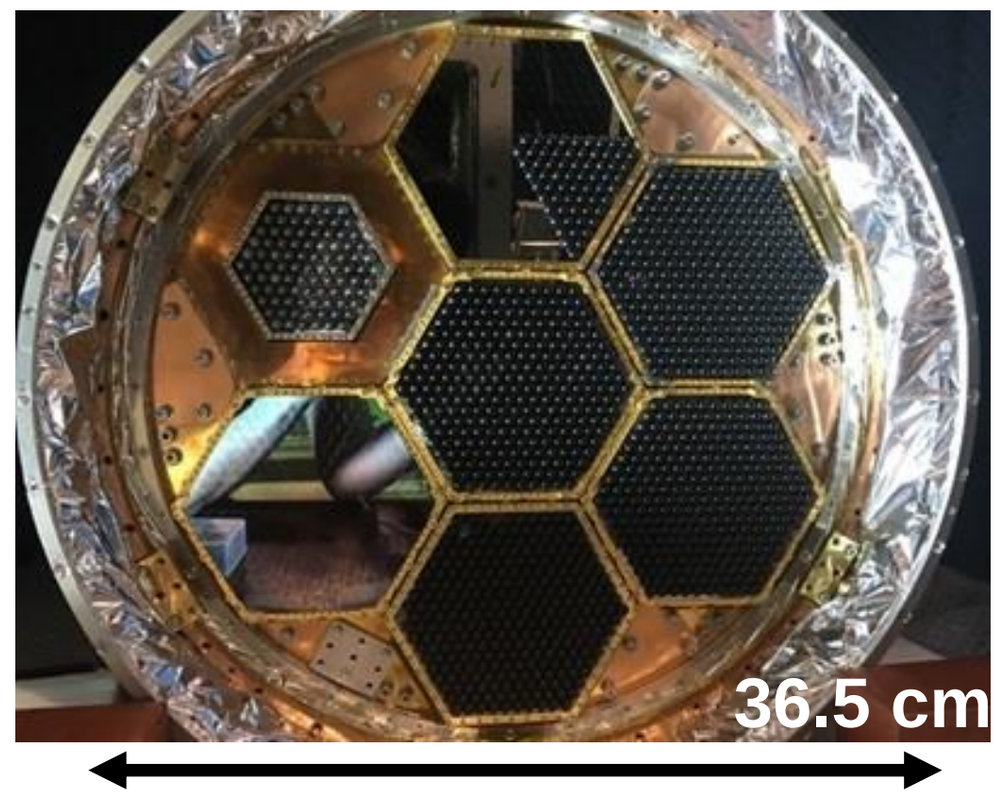
POLARBEAR-1
Seven 4-inch wafers
1274 bolometers



19 cm

Arnold et al., Proc. SPIE Vol 8452 (2012)

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 later this year

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

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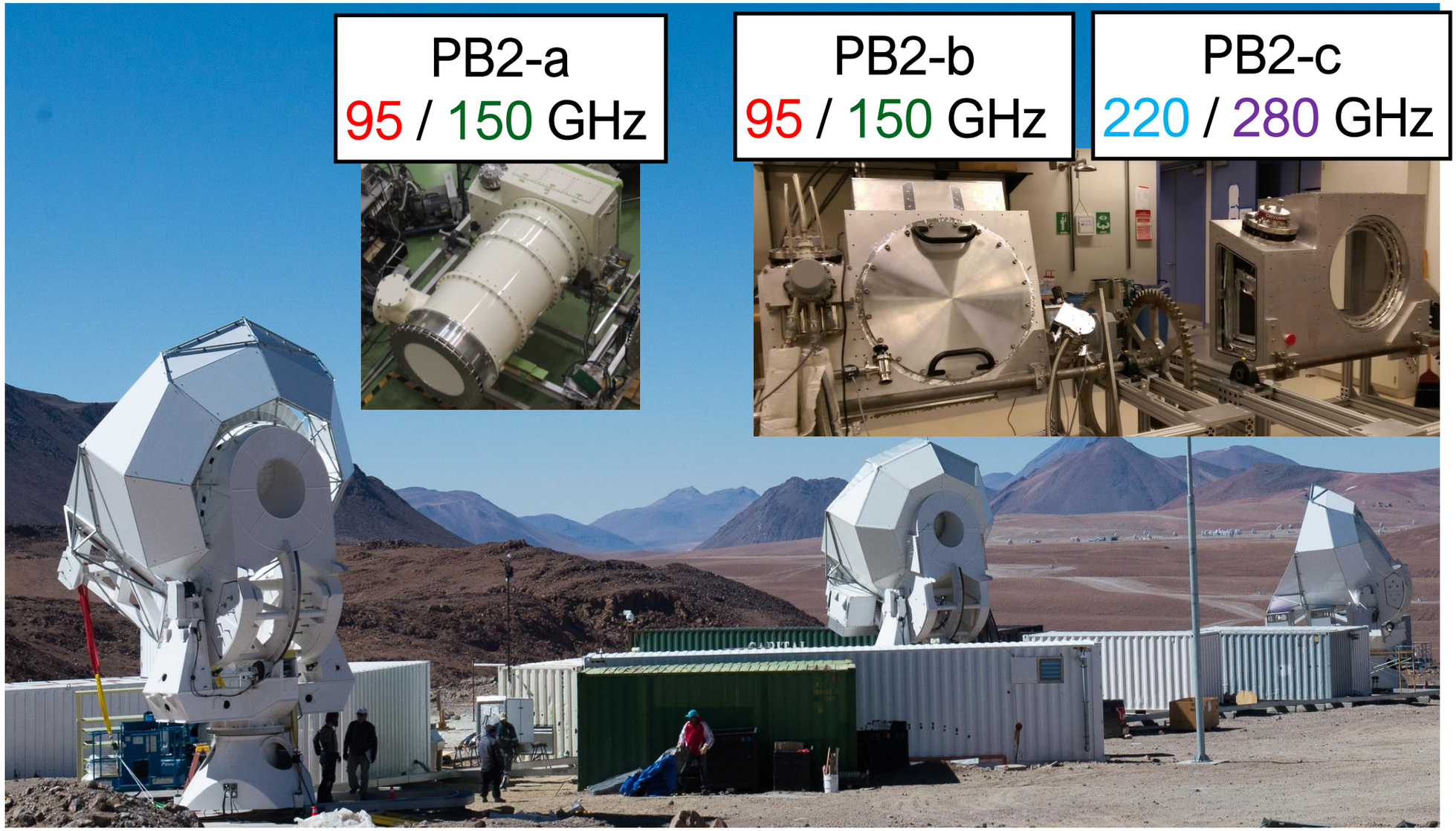

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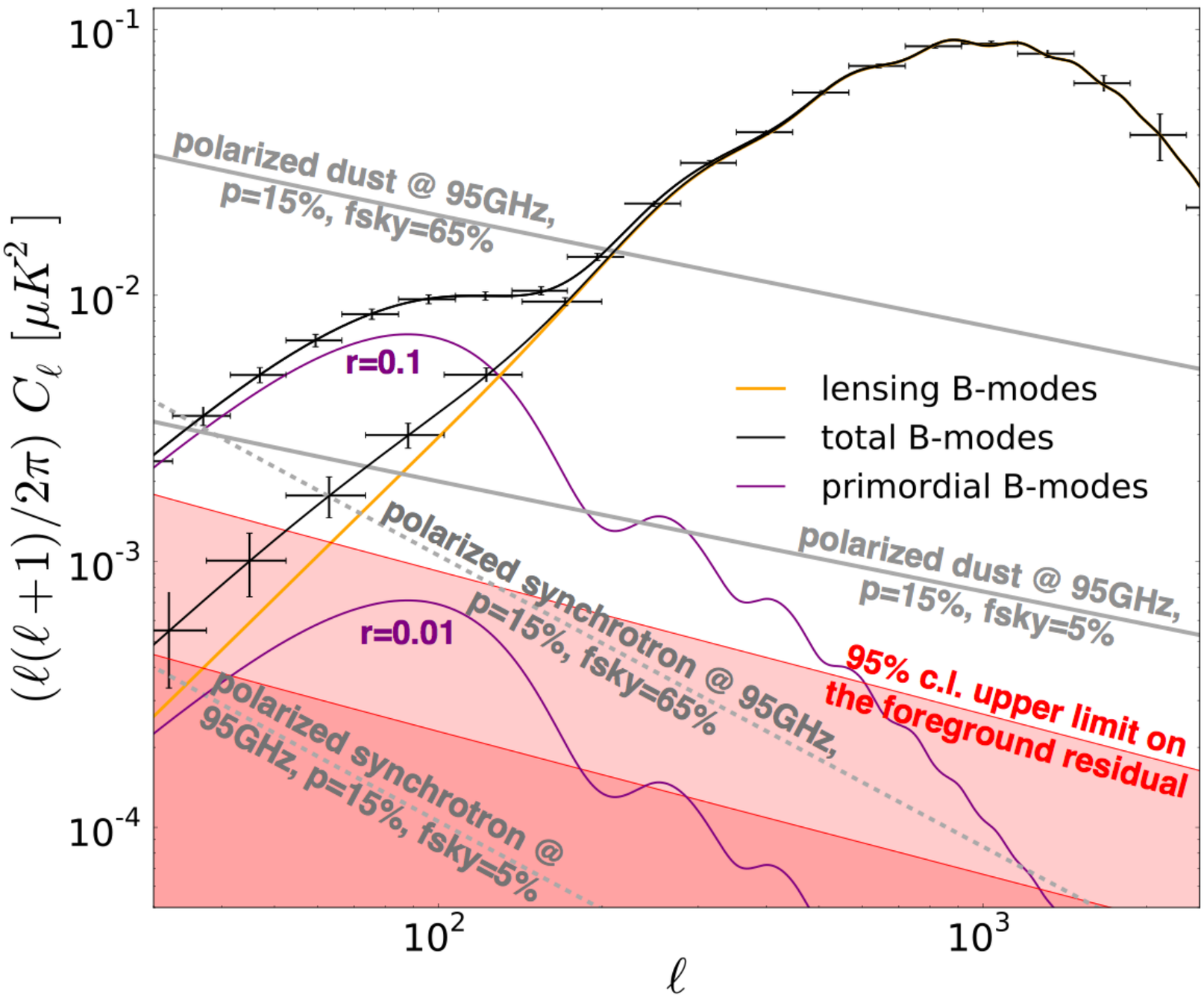
Simons Array
Projected sensitivity

Foreground rejection with multi-frequency Simons Array data

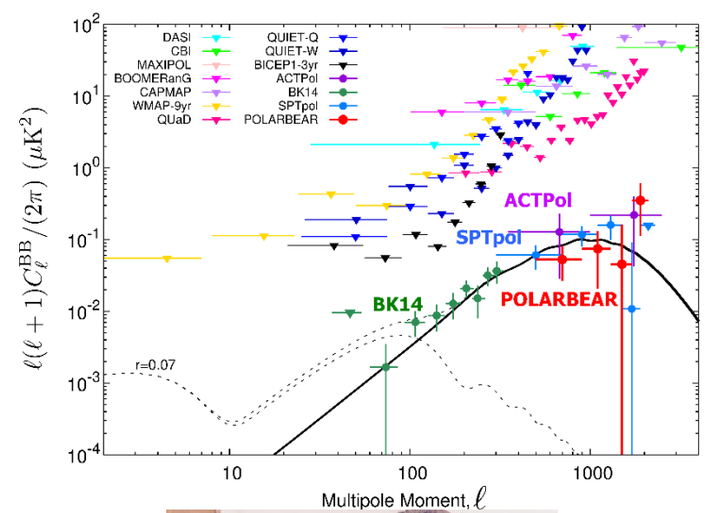
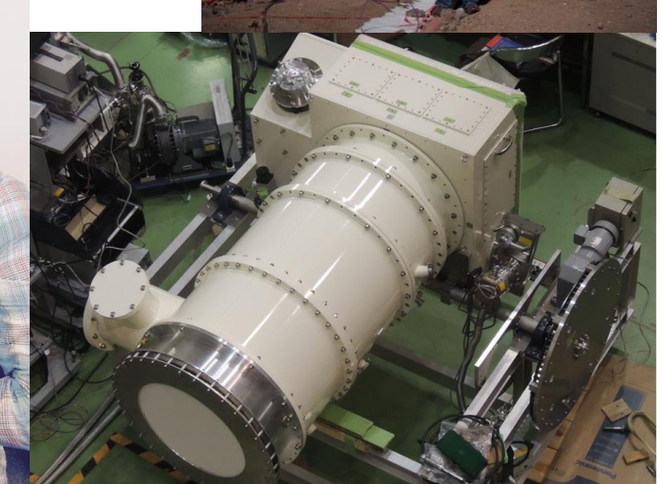
$\sigma(\boldsymbol{\Sigma m}_\nu)$ = 40 meV
w/ DESI BAO, including foreground contamination

$\sigma(\boldsymbol{r}$ = 0.1) = 0.006

Stebor et al., Proc. SPIE 2016



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

Thank you

- 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)
  - Constraints on cosmic birefringence and primordial magnetic fields:
    POLARBEAR Collab. PRD 92, 123509 (2015)
  - Mapmaking technique:
    Poletti et al. A&A Vol 600 (2017)
  - Two-year combined results:
    POLARBEAR Collab. arXiV: 1705.02907 (2017)
  - Continuously rotating HWP demonstration:
    Takakura et al. JCAP 05 008 (2017)
- **POLARBEAR-2 / Simons Array** designed for increased sensitivity, foreground mitigation
  - Technology development and future prospects described in CMB-S4 Technology book arXiV:1706.02464
  - POLARBEAR-2: Inoue et al. SPIE 2016
  - Simons Array: Stebor et al. SPIE 2016
  - Many more LTD17 proceedings coming this year