The POLARBEAR/Simons Array experiments

CMB Foregrounds for B-modes studies
Tenerife, 15 October 2018

Davide Poletti (SISSA)
on behalf of the POLARBEAR/Simons Array collaboration

POLARBEAR Collaboration

MEXT · SIMONS FOUNDATION (Advancing Research in Basic Science and Mathematics) · CONICYT Ministerio de Educación Gobierno de Chile · NSF · NASA

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

UC San Diego
Kam Arnold
Kevin Crowley
Tucker Elleflot
George Fuller
Nicholas Galitzki
Logan Howe
Brian Keating
David Leon
Lindsay Lowry
Martin Navaroli
Gabriel Rebeiz
Max Silva-Feaver
Praween Siritanasak
Grant Teply
Calvin Tsai
Alex Zahn

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

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

Institute D'Astrophysique Spatiale
Giulio Fabbian

U Manchester
Gabriele Coppi
Andrew May
Lucio Piccirillo

UC Irvine
Chang Feng

Cardiff U
Peter Ade

Kavli IPMU
Daisuke Kaneko
Nobuhiko Katayama
Frederick Matsuda
Tomotake Matsumura

U. Melbourne
Federico Bianchini
Christian Reichardt
Anh Pham

SISSA
Carlo Baccigalupi
Nicoletta Krachmalnicoff
Davide Poletti

NASA Goddard
Nathan Miller

Argonne NL
Amy Bender

Imperial College
Andrew Jaffe
Daisy Mak

C Computational Astrophysics
Stephen Feeney

UC Los Angeles
Nathan Whitehorn

Laboratoire Astroparticule & Cosmologie
Dominic Beck
Hamza El Bouhargani
Josquin Errard
Maude Le Jeune
Radek Stompor
Clara Vergès

Laboratoire de l'accélérateur linéaire
Julien Peloton

CU Boulder
Nils Halverson
Greg Jaehnig
Hayley Roberts

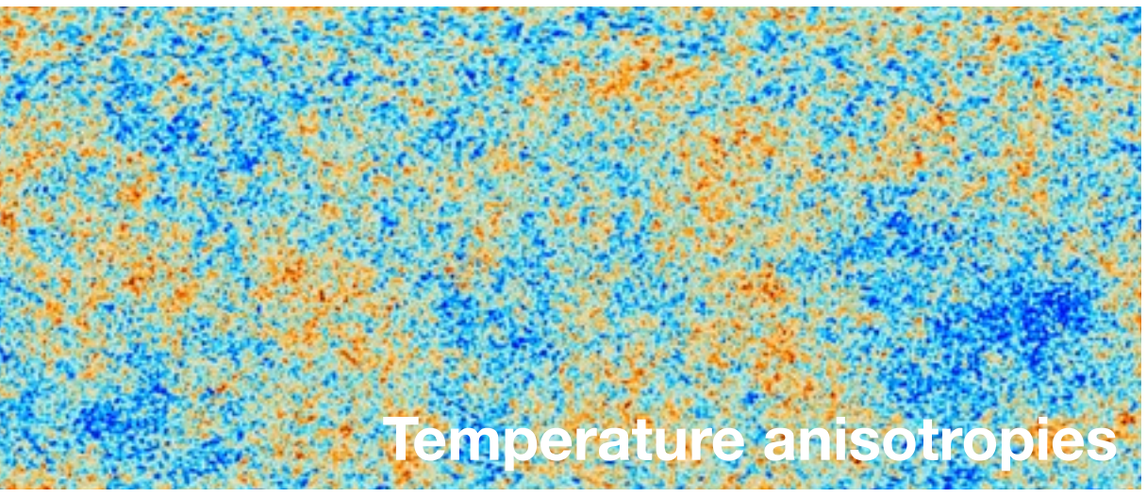
U Chile
Mario Aguilar

Stanford U
Giuseppe Puglisi

Católica (PUC)
David Boettger
Rolando Dunner

And many more in years past…

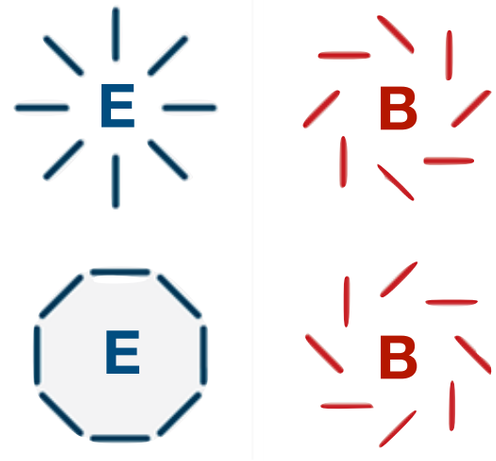
B-mode polarization



Initial conditions:

- compatible with scalar perturbations
- Information in temperature anisotropies already exploited

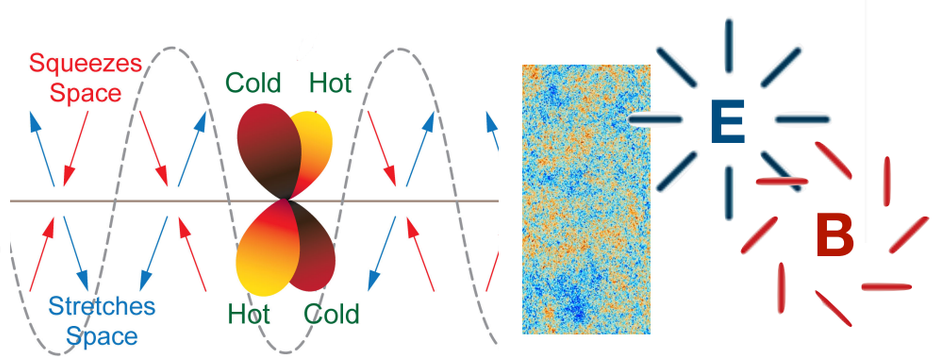
➡ Polarization



Scalar perturbations ➡ E modes

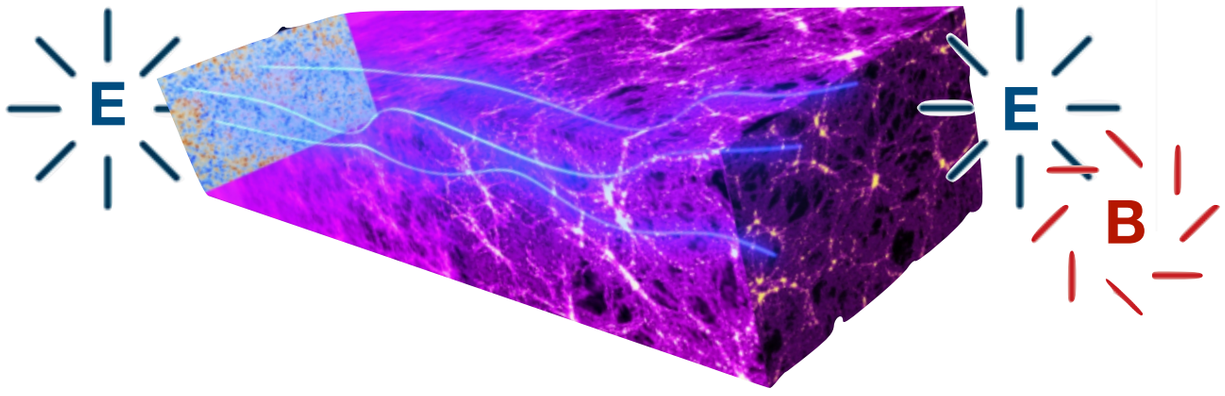
B-modes: clean channel for probing anything else

Tensor perturbations



Primordial B-modes (large scales)

- probe inflation (energy scale, consistency relation…)



Lensing B-modes (small scales)

- probe structure formation (neutrino mass, dark energy)

Many others (e.g. primordial magnetic fields, birefringence)

Image credits: Planck/ESA, Bicep2 (adapted)

B-mode measurements

First measurements of lensing B-modes since 2014

Primordial B-modes still undetected

Challenges

- Sensitivity
- Atmosphere
- Foregrounds
- Systematics

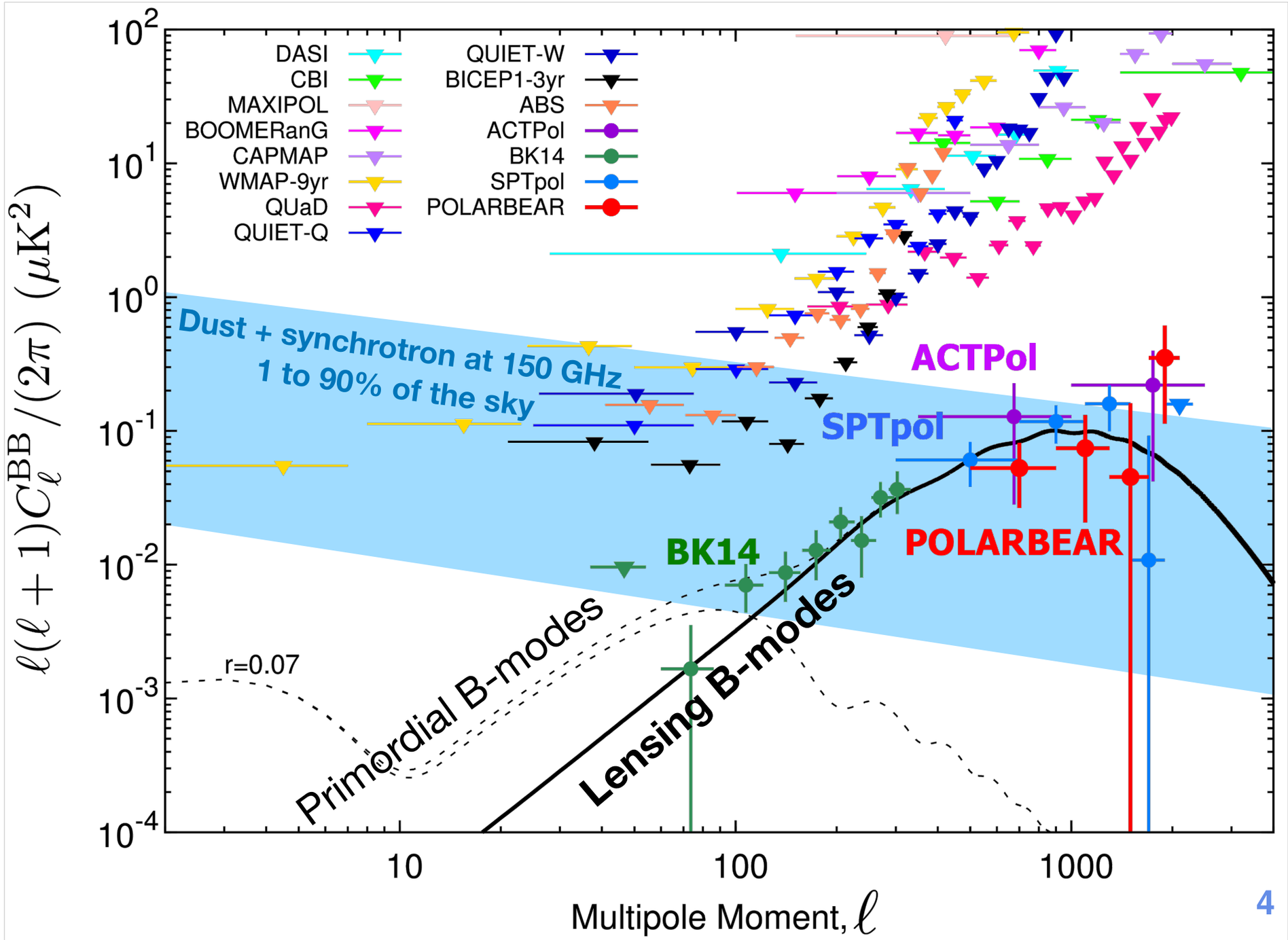
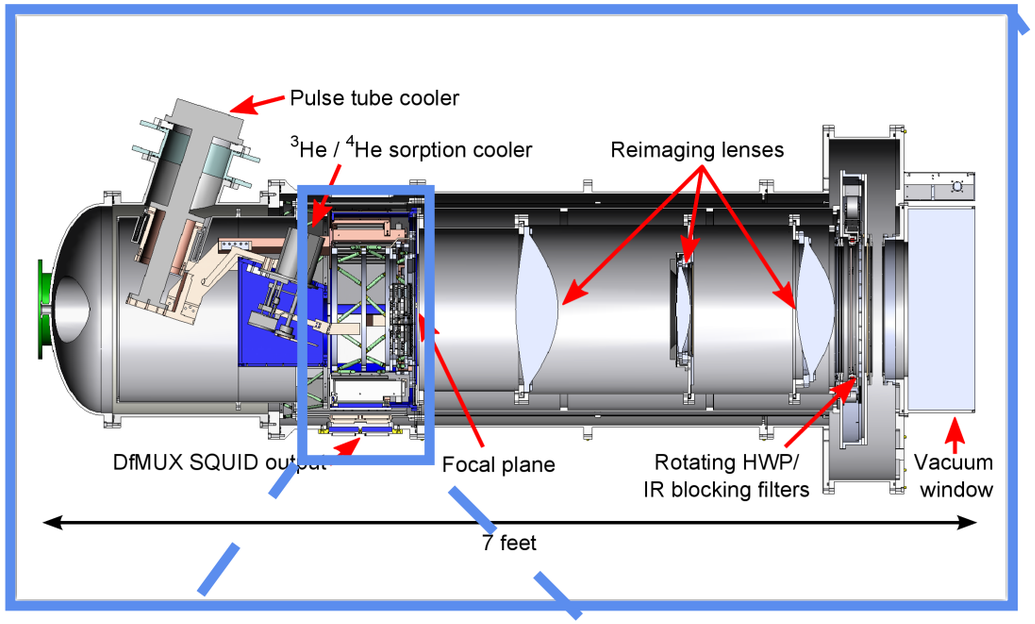
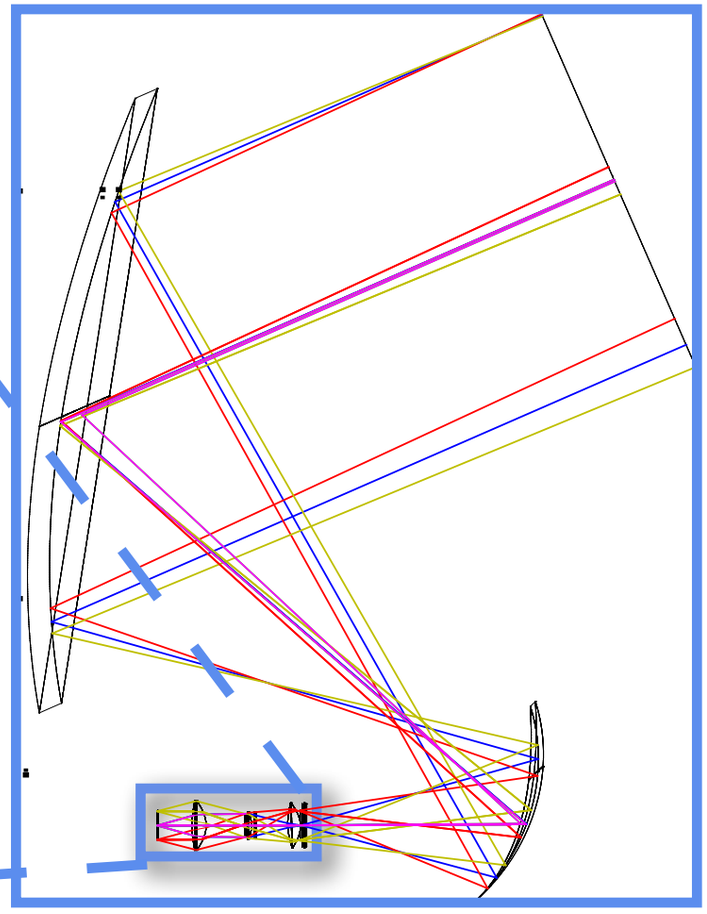
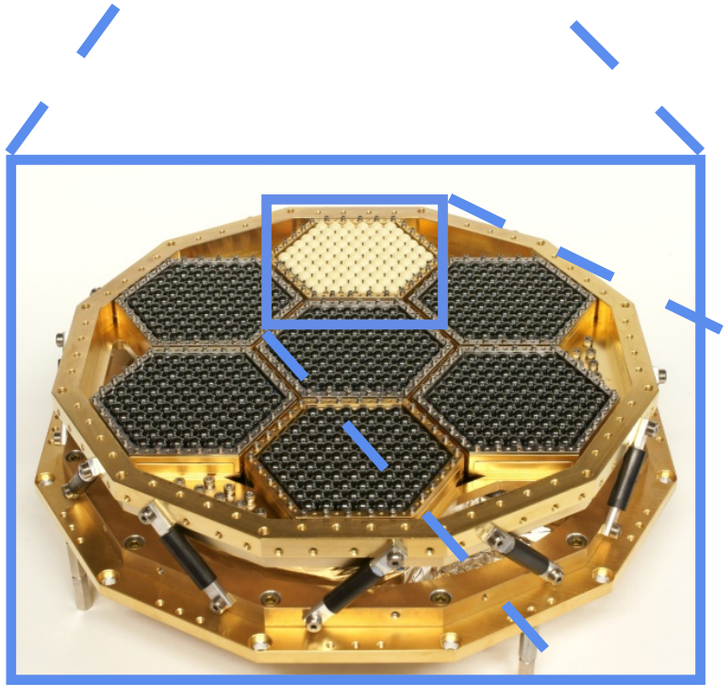


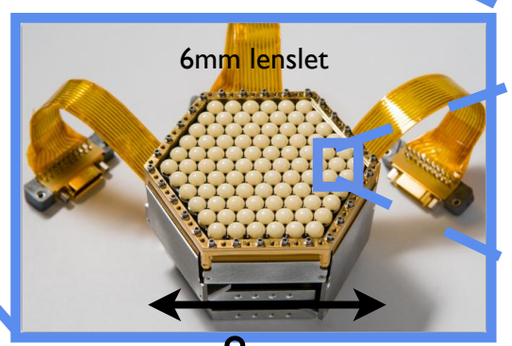
Image by Y. Chinone (adapted)

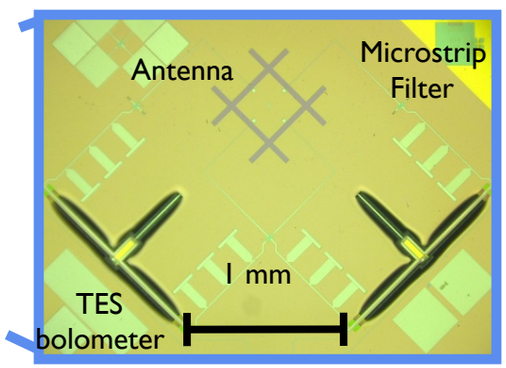
POLARBEAR design







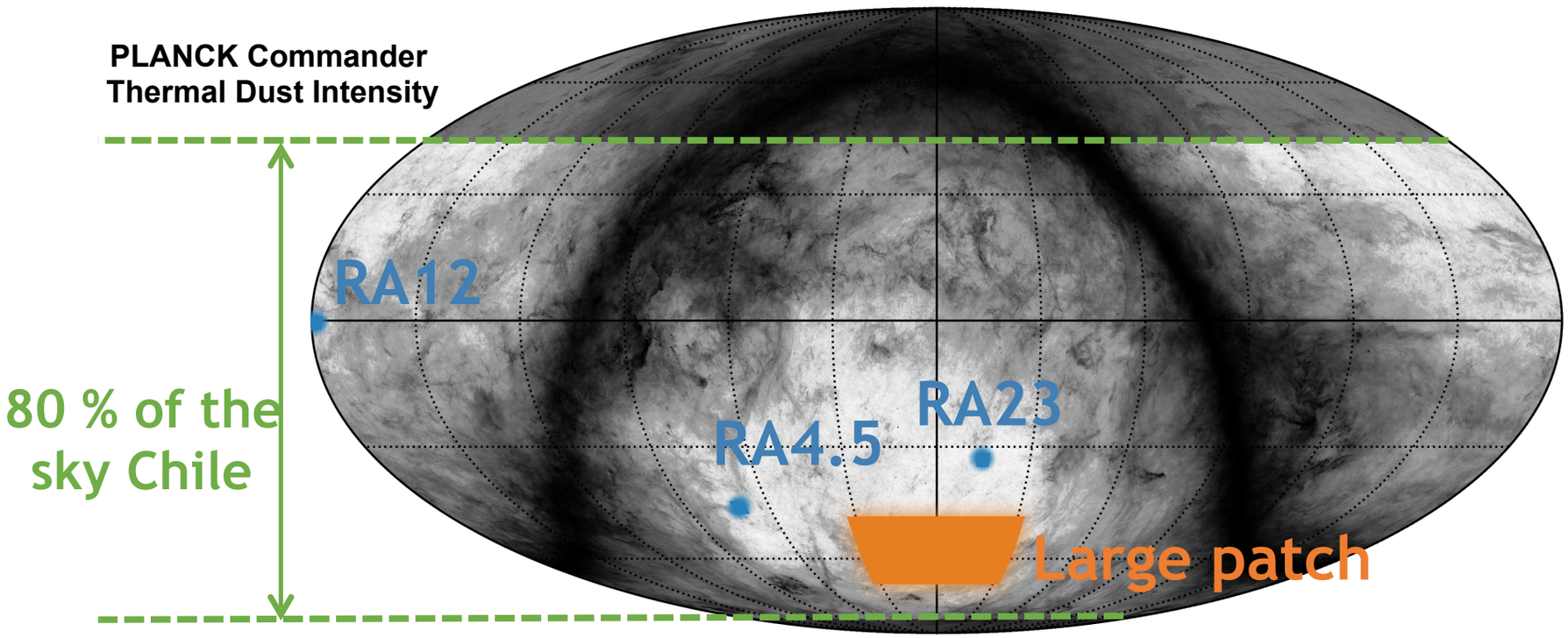


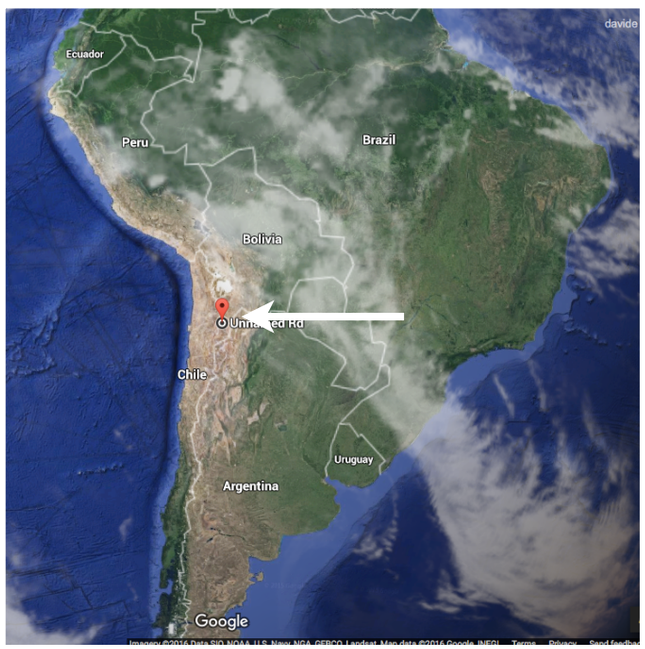


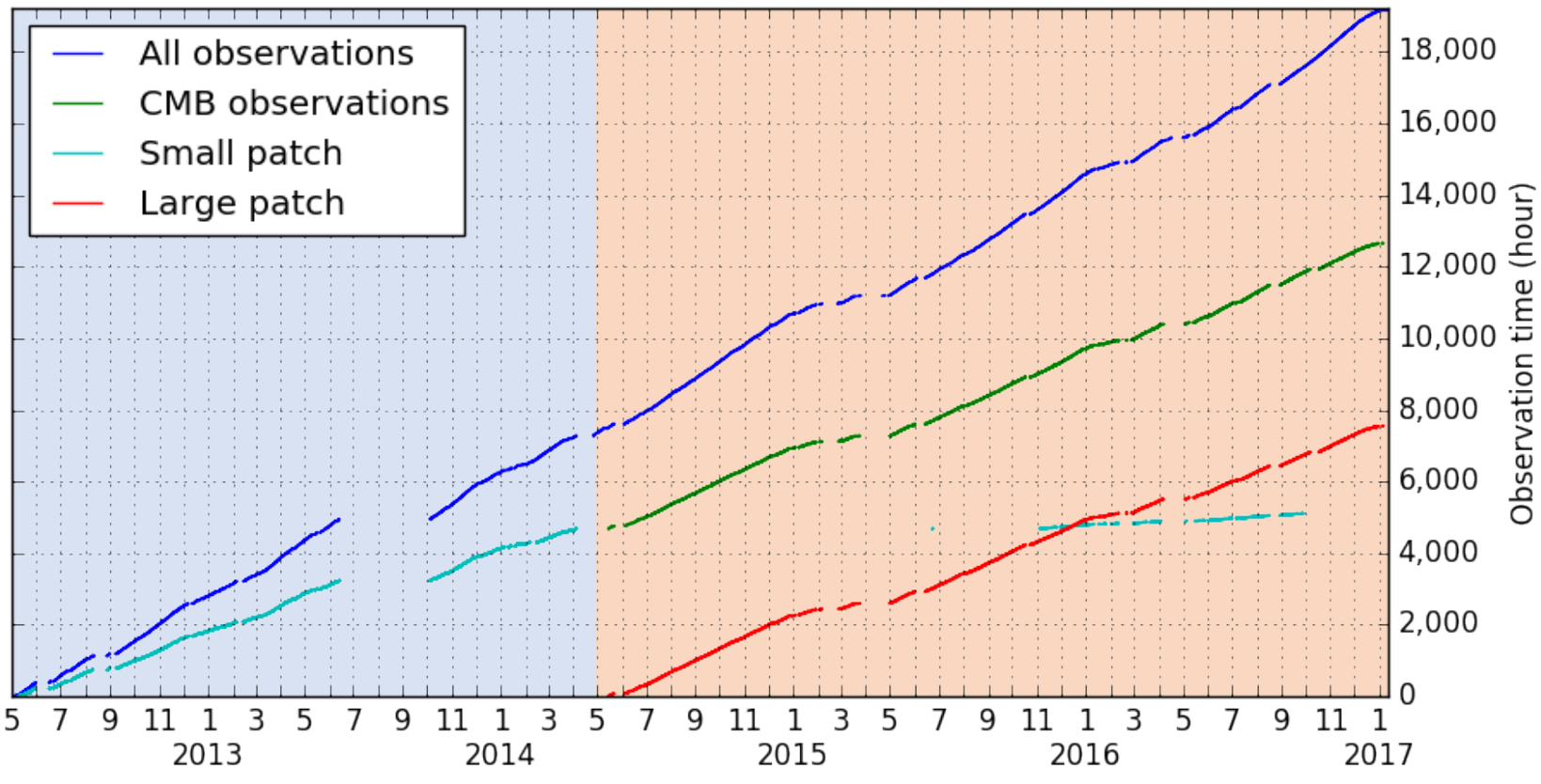
- Off-axis Gregorian-Dragone design
- 2.5 m primary mirror
- 3.5‘ FWHM beam
- Focal plane cooled at 250 mK
- Lenslet-coupled double slot antennas
- 1274 TES bolometers at 150 GHz

For more details
Kermish et al. (2012)
Arnold et al. (2012)

POLARBEAR observational campaigns







Atacama desert (altitude ~5200 m)

- Access to 80% of the sky
- Dry atmosphere

First and second season

- 3 x 10 deg2 patches
- Sub-degree B-modes (lensing)

Third to fifth season

- 20x35 deg patch
- Primordial B-modes

POLARBEAR publications

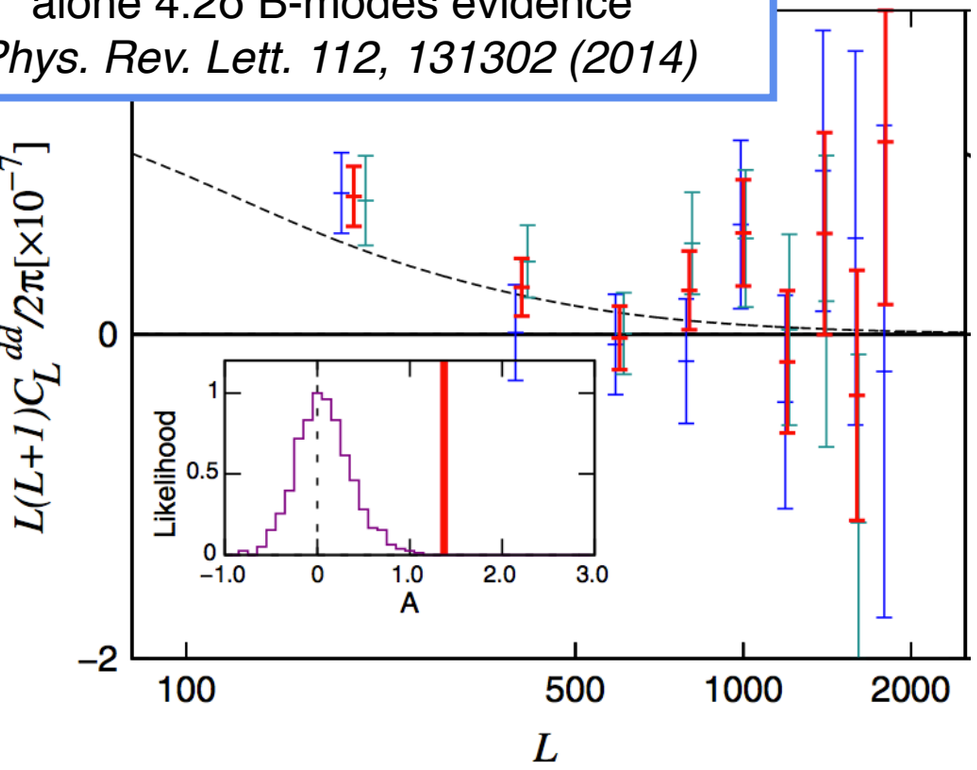
- **Lensing power spectrum** *POLARBEAR Collab. PRL 113, 021301 (2014a)*
- **Cross-correlation galaxy-CMB lensing**
  POLARBEAR Collab. PRL 112, 131302 (2014b)
- **One-year B-mode power spectrum** *POLARBEAR Collab. ApJ 794, 171 (2014c)*
- **Atmospheric emission modelling** *Errard et al, ApJ 809, 63 (2015)*
- **Constraints on cosmic birefringence and primordial magnetic fields**:
  POLARBEAR Collab. PRD 92, 123509 (2015)
- **Unbiased mapmaking technique** *Poletti et al A&A Vol 600 (2017)*
- **Two-year B-mode power spectrum** *POLARBEAR Collab. ApJ 848, 121 (2017)*
- **Continuously rotating HWP demonstration** *Takakura et al, JCAP 05 008 (2017)*
- **Polarization from ice clouds**: *Takakura et al, arXiv:1809.06556 (submitted ApJ)*

In preparation / ongoing analyses

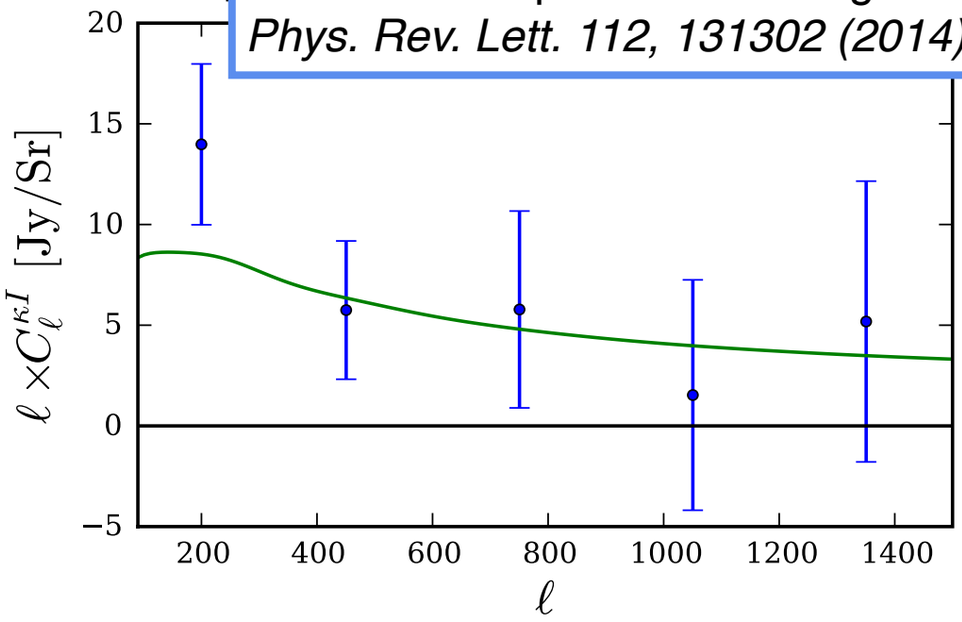
- **Two-season lensing power spectrum**
- **Two-season cross-correlation high-z galaxies-CMB lensing**
- **Cross-correlation galaxy lensing-CMB lensing**
- **Large patch analysis**

First season cosmological results

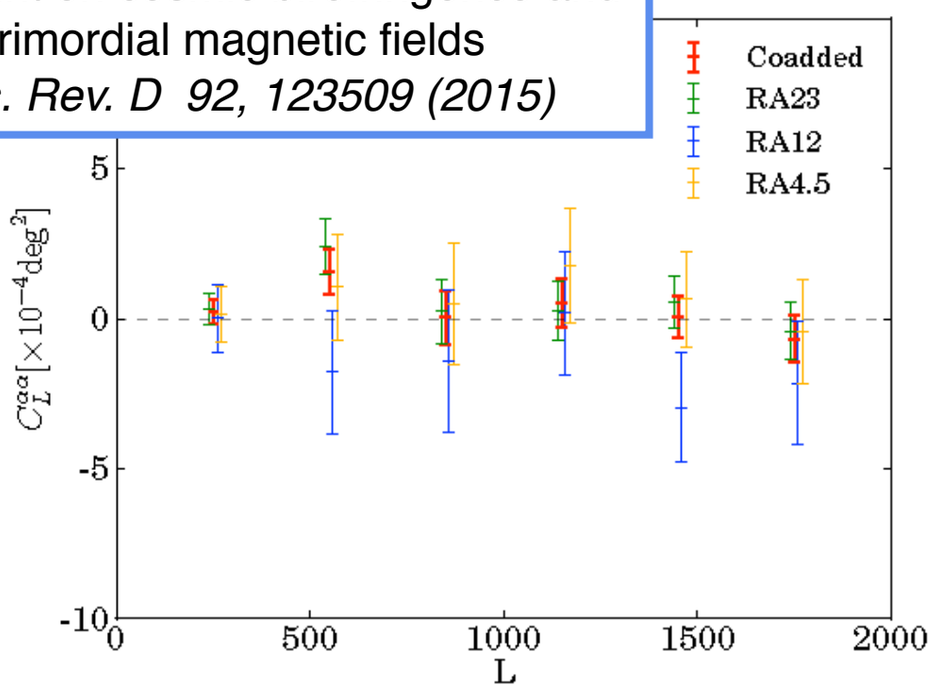
Lensing reconstruction from polarization alone 4.2σ B-modes evidence
Phys. Rev. Lett. 112, 131302 (2014)



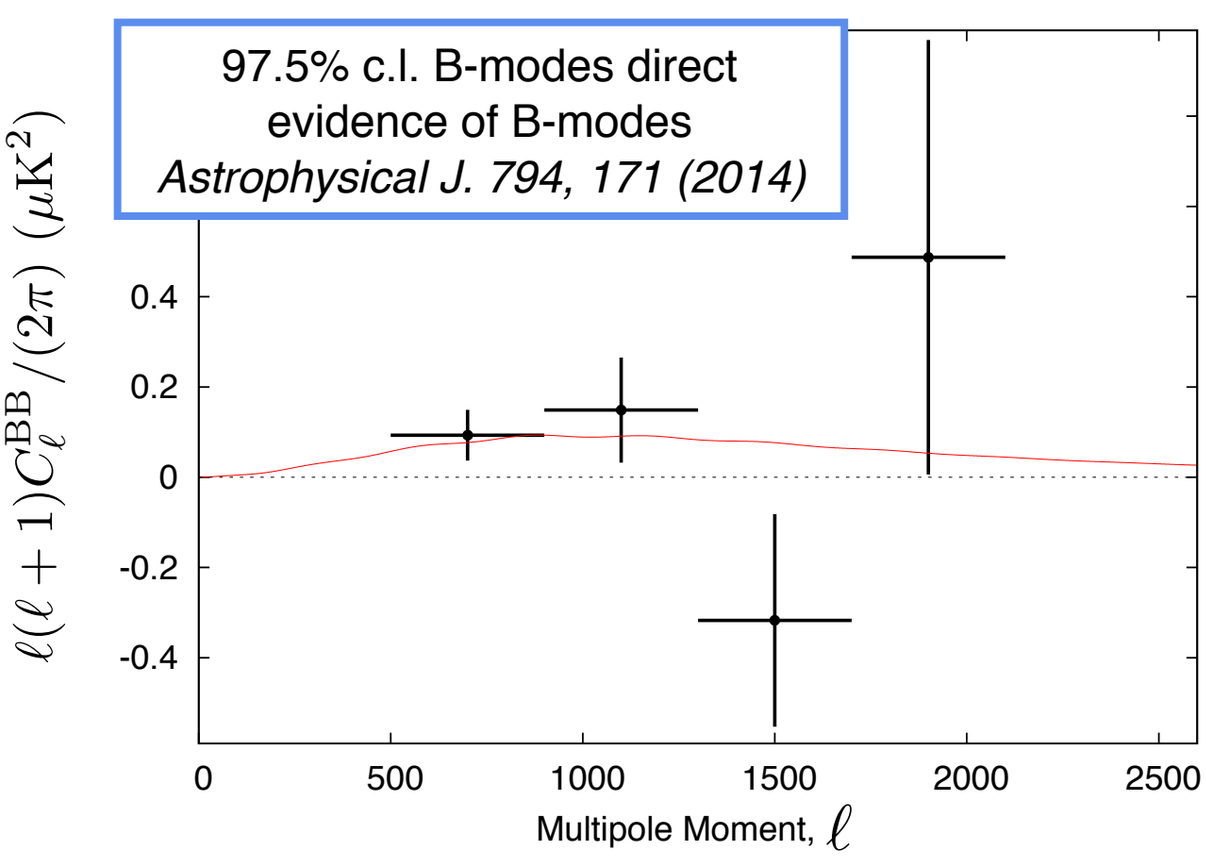
4.0σ polarized lensing
Phys. Rev. Lett. 112, 131302 (2014)



Constraint on cosmic birefringence and primordial magnetic fields
Phys. Rev. D 92, 123509 (2015)



97.5% c.l. B-modes direct evidence of B-modes
Astrophysical J. 794, 171 (2014)

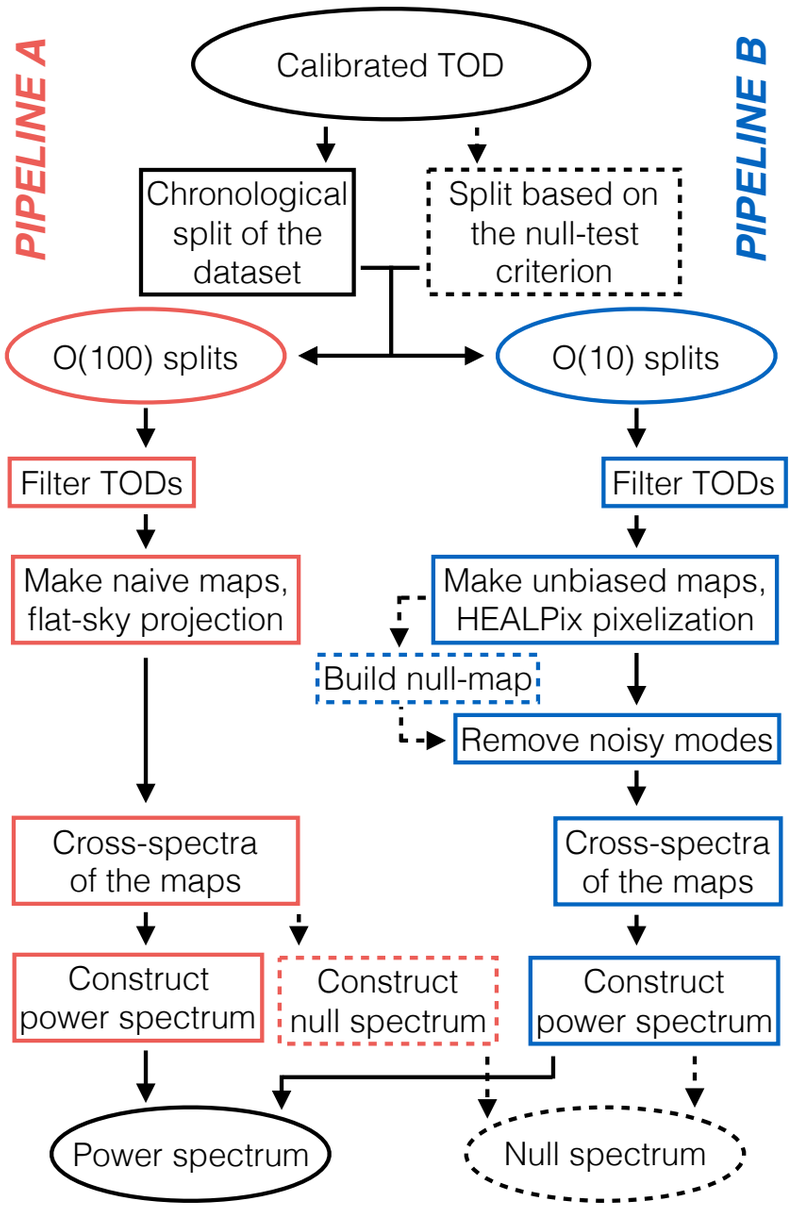


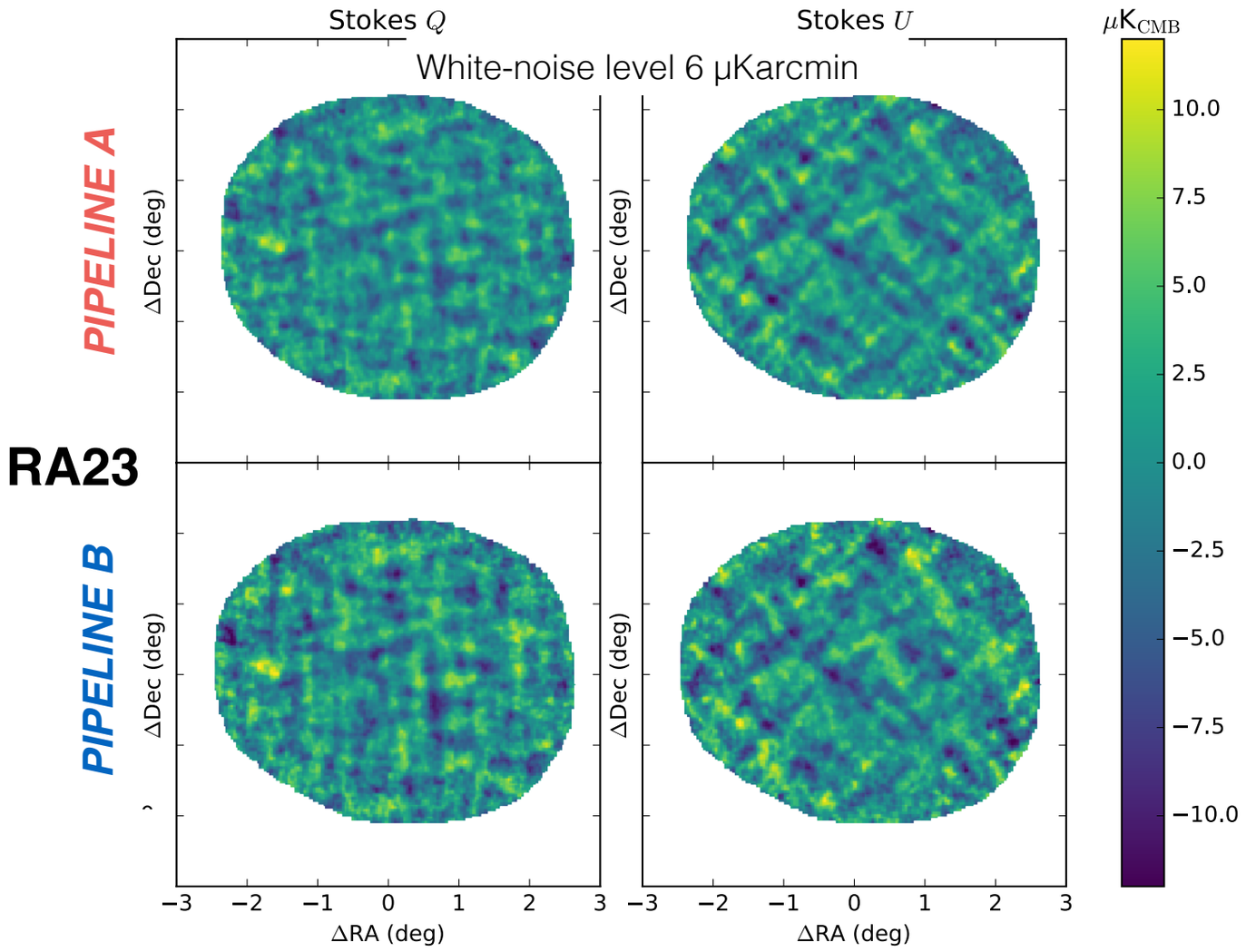
POLARBEAR Second Season Results

POLARBEAR Collaboration ApJ 848, 121 (2017)

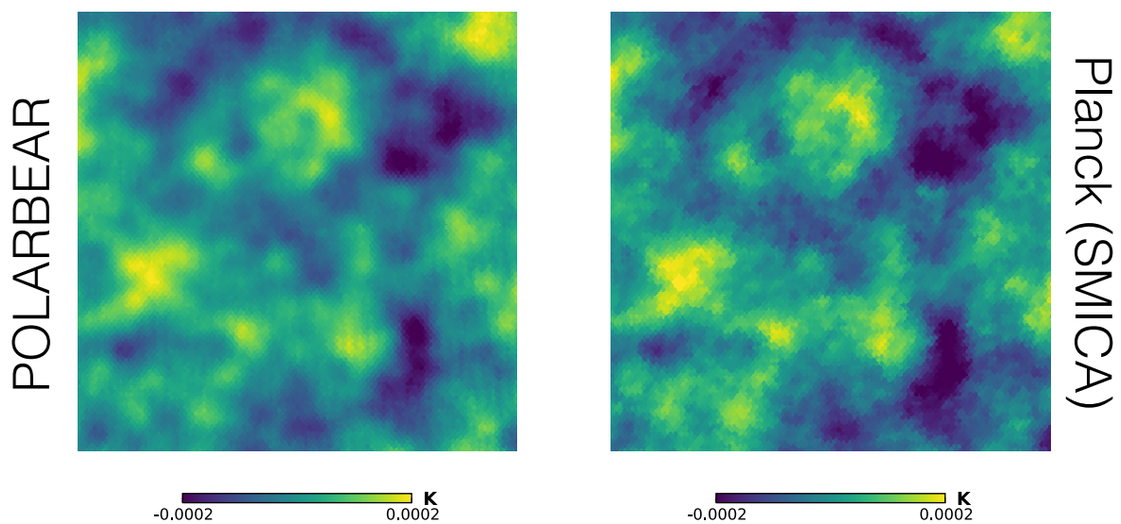
Compared to first season results:

- 61% more data
- Improved calibration
- New independent pipeline *(Poletti et al, 2017)*





RA23
Stokes T
3° x 3°
center



Validation

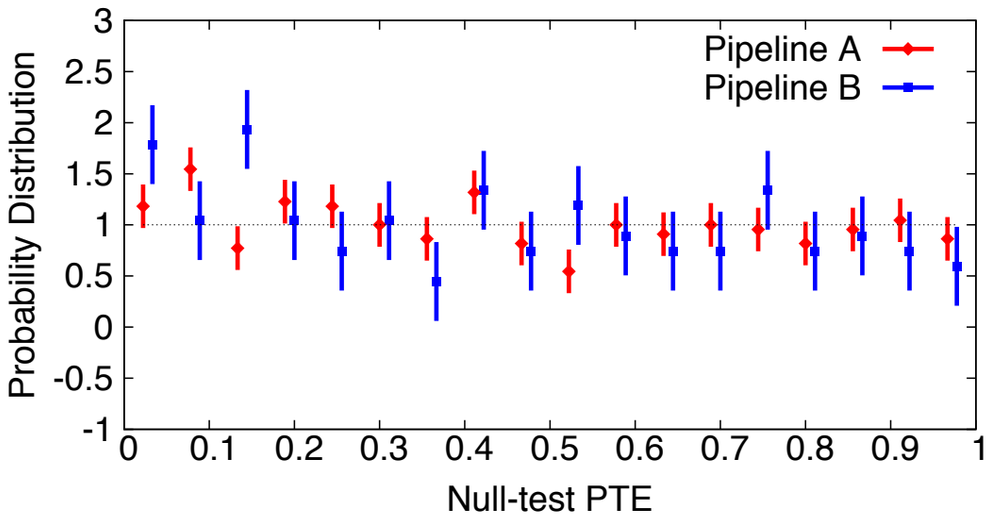
POLARBEAR Collaboration ApJ 848, 121 (2017)

Blind policy

Data selection and quality assessment before inspecting the BB power spectrum

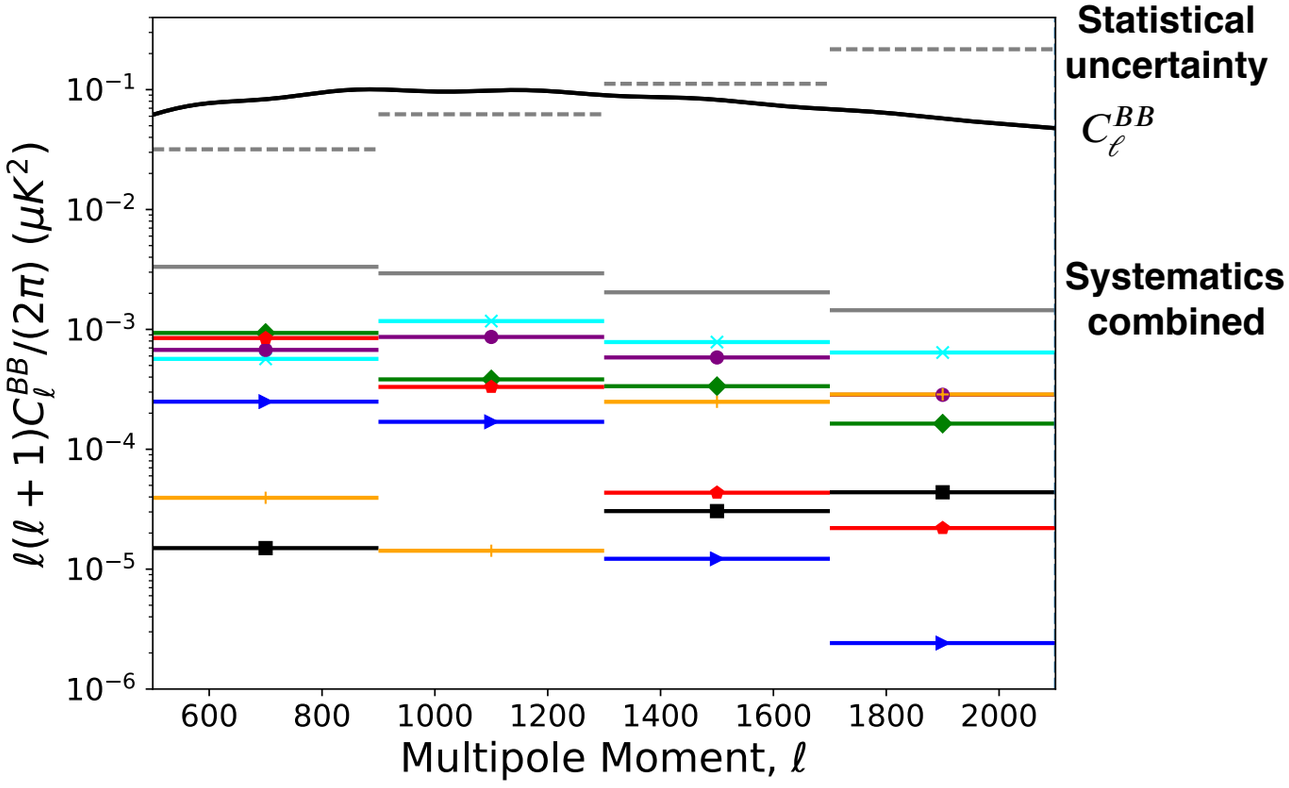
NULL TESTS

Systematics control and error-bars validation.
(temporal, weather, scan direction, calibration, sun or moon location…)



Compatible with flat distribution (i.e. the null spectra are compatible with the noise model)

INSTRUMENTAL EFFECTS



End-to-end propagation of systematics.

Polarization angle

Pointing

Gain drifts

Differential gain

Readout crosstalk

Differential **beam ellipticity** and **shape**.

Foregrounds

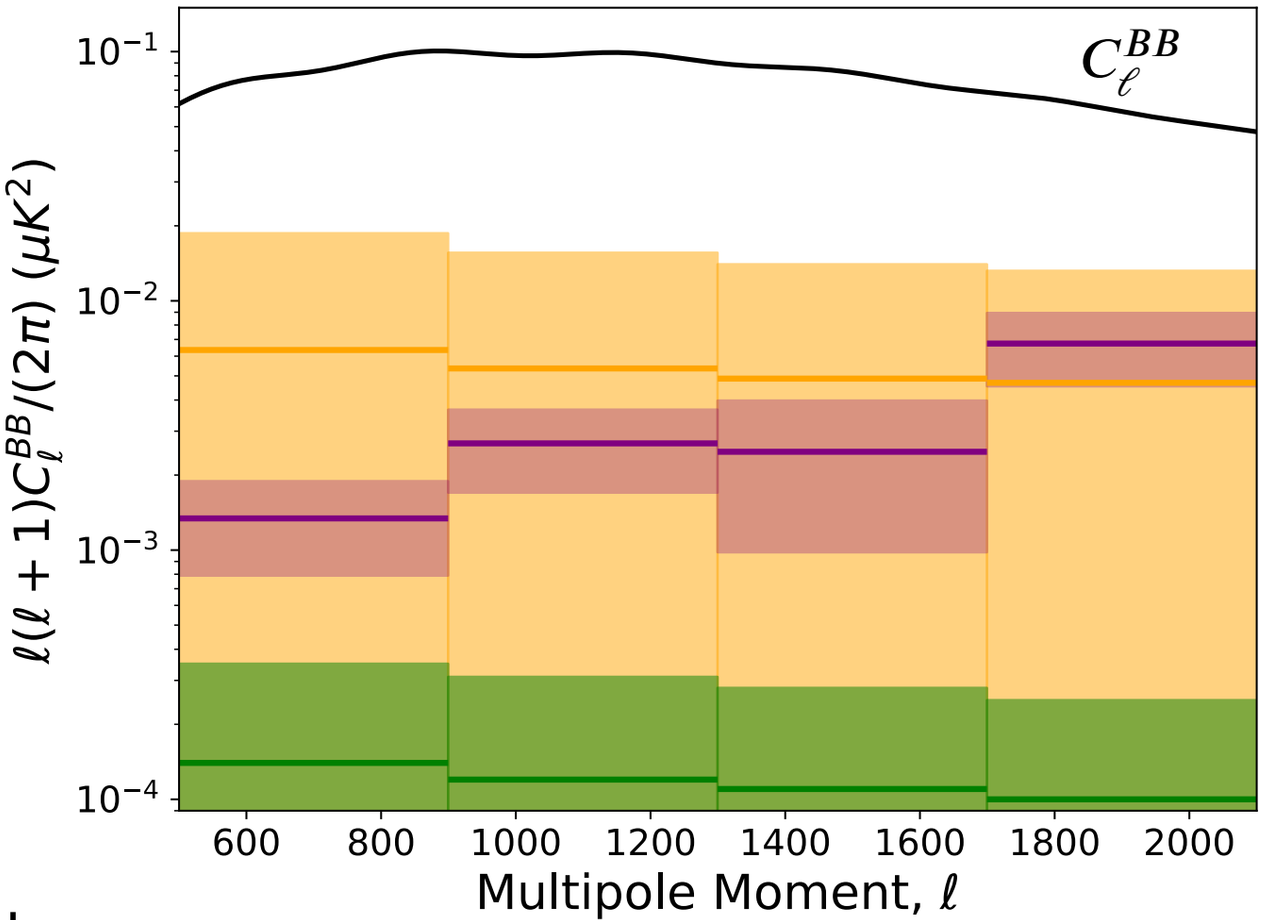
POLARBEAR Collaboration ApJ 848, 121 (2017)

Diffuse foregrounds

Dust and **synchrotron** are evaluated using Planck 353 GHz and 30 GHz and WMAP K-band polarization maps.

- Extend the patches
- Measure foregrounds power at large scales ($\ell = 80$)
- Extrapolate the power spectrum to PB angular scales and frequency

➡ Contamination compatible with zero

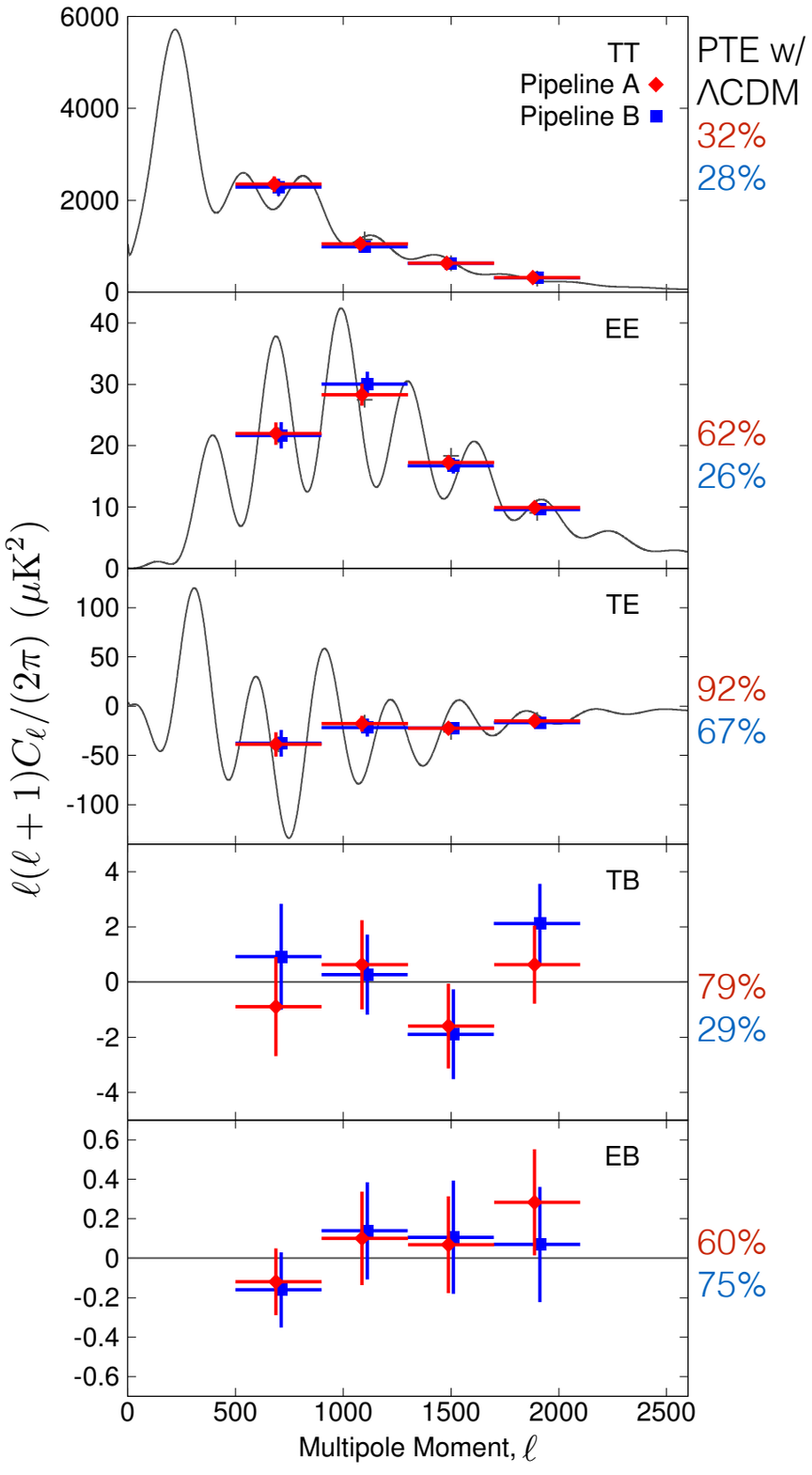


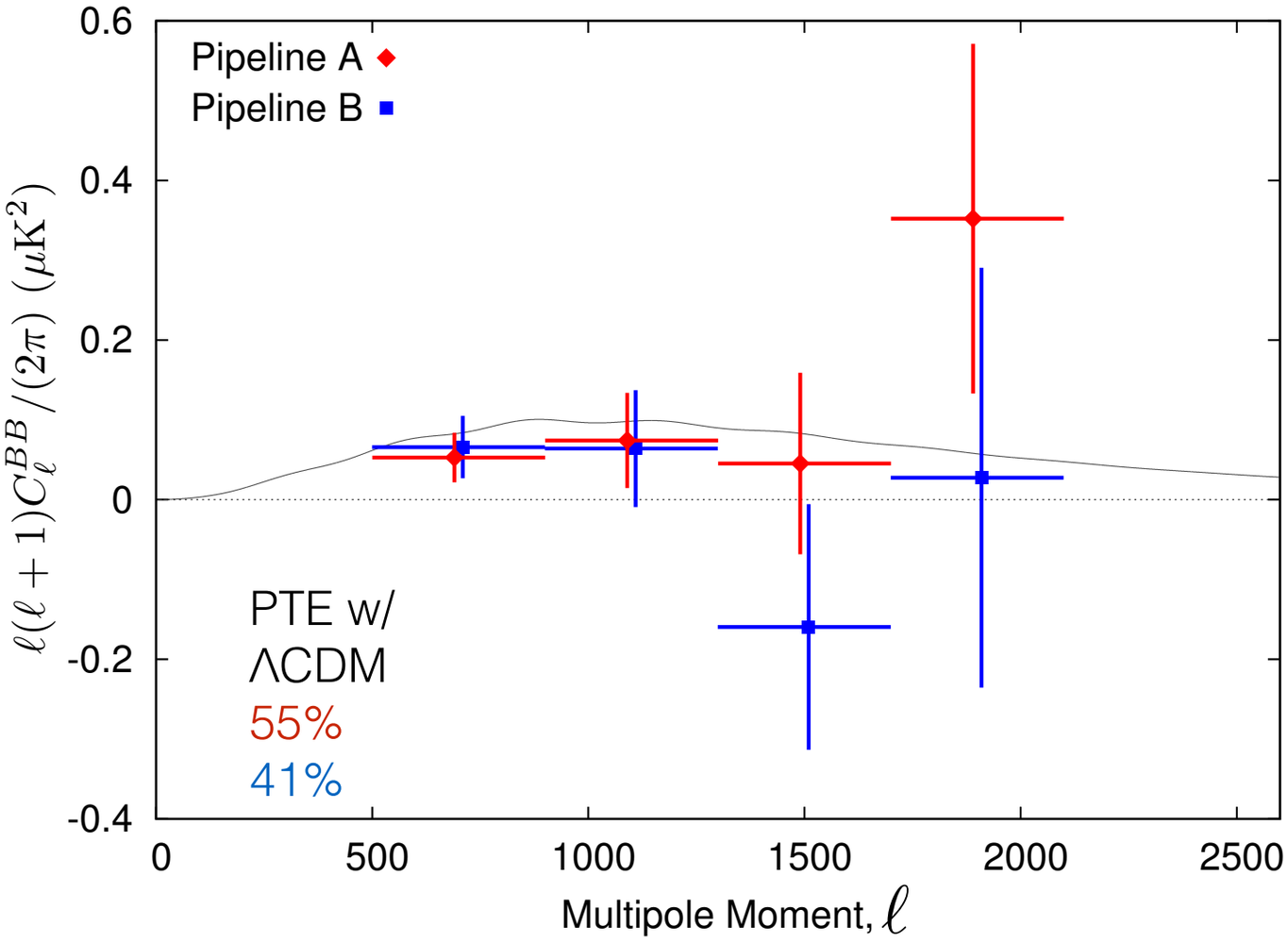
Dusty and radio galaxies

Set of simulated galaxies with distribution, intensity and polarization fraction modelled after observation *(De Zotti et al, 2005; George et al, 2015; Bonavera et al, 2017)*

POLARBEAR Second Season Results

POLARBEAR Collaboration ApJ 848, 121 (2017)



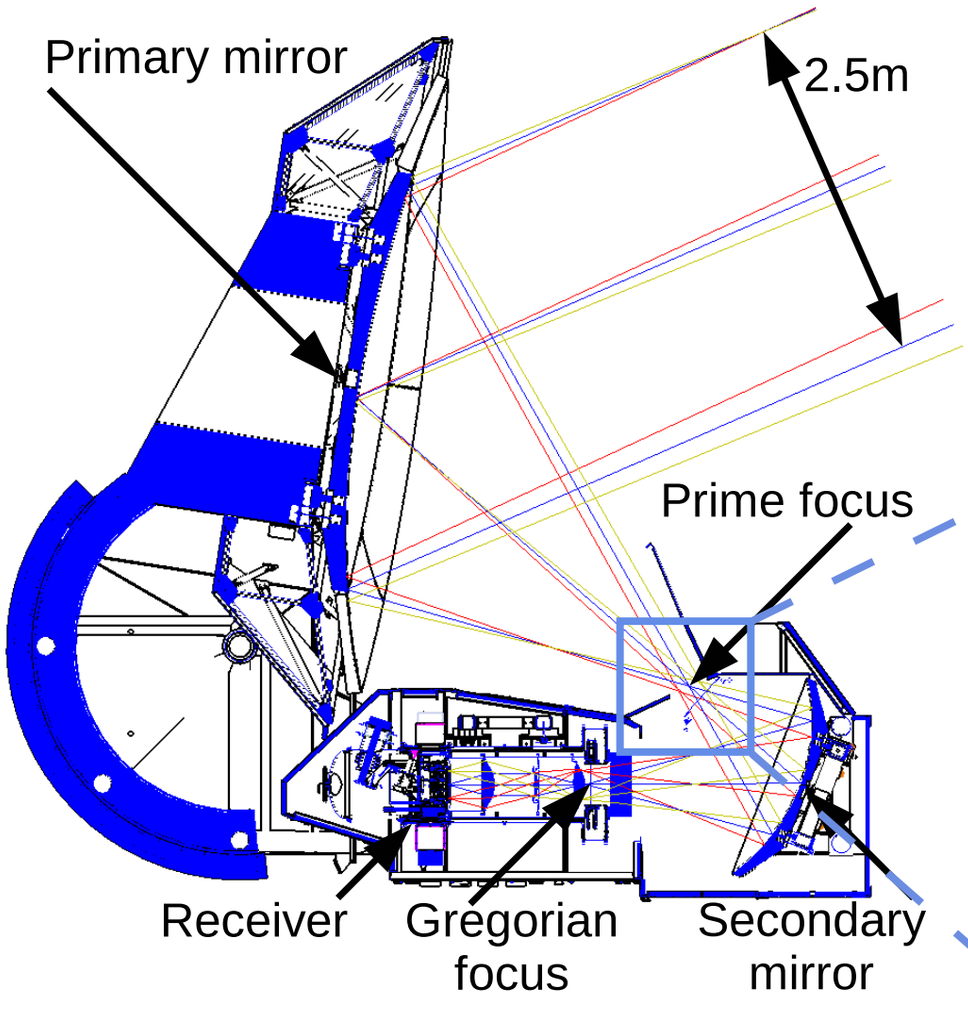


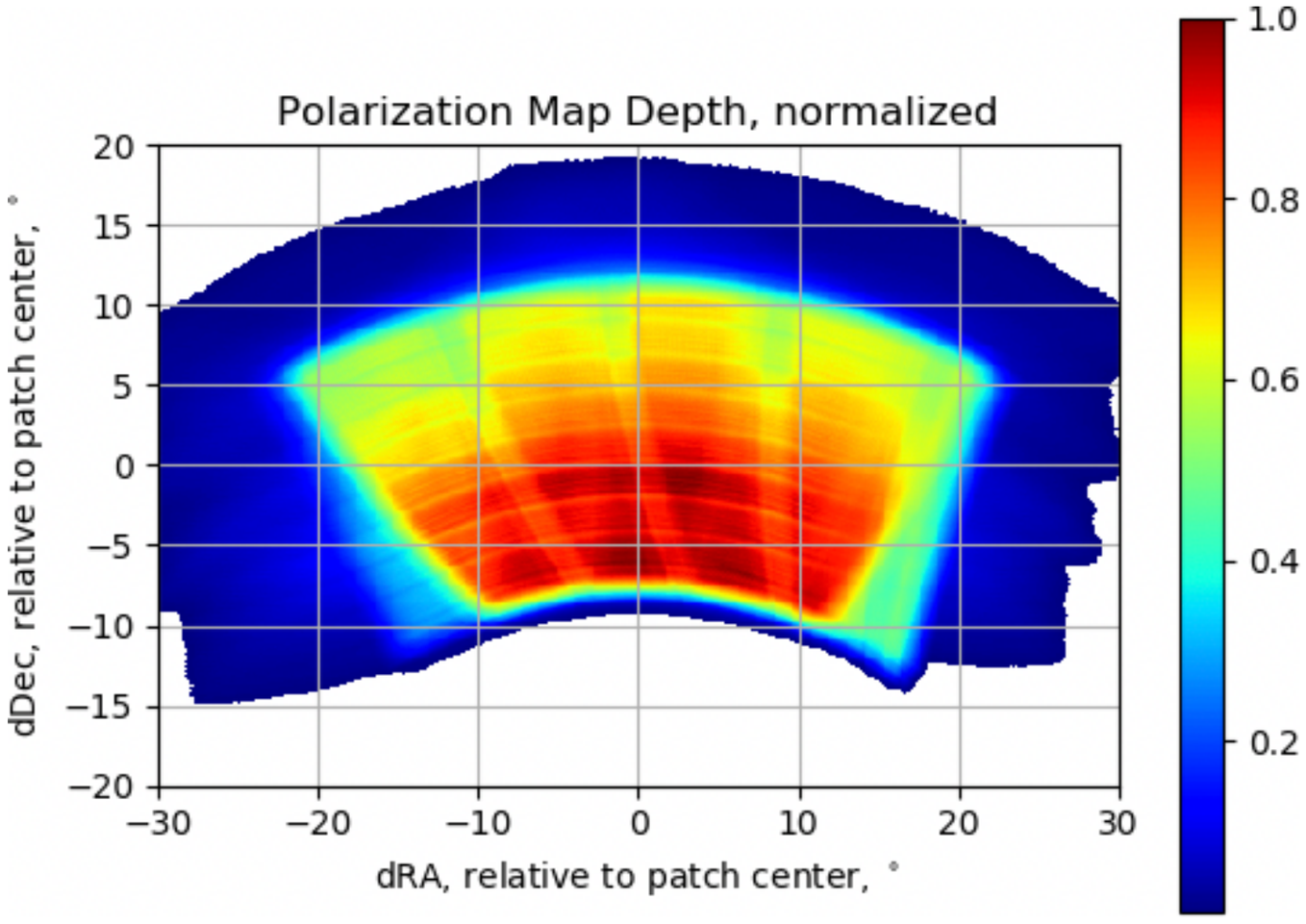
- All spectra are compatible with ΛCDM and between the pipelines (28% pte)
- 3.1σ rejection of no B-modes
- Measured amplitude of lensing B-modes

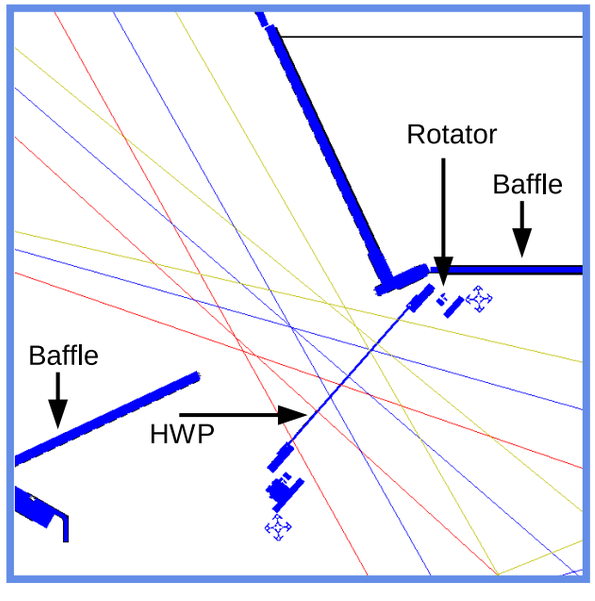
$$A_L = 0.60^{+0.26}_{-0.24}(\text{stat})\ ^{+0.00}_{-0.04}(\text{inst}) \pm 0.14(\text{foreground}) \pm 0.04(\text{mult})$$

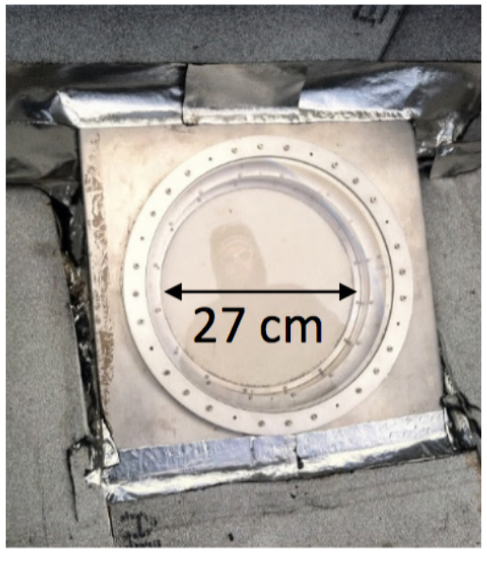
Towards primordial B-modes

- After second season: Observation of a 700 deg^2 patch
- Continuously rotating half-wave plate (CRHWP) installed at the prime focus









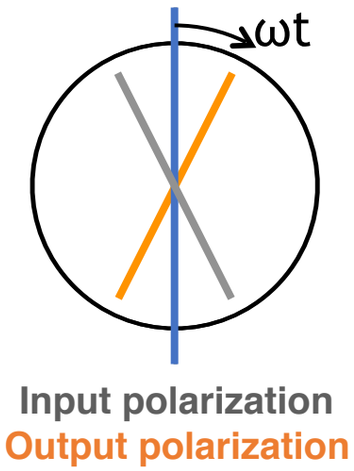
Images: Takakura et al (2017), N.Goeckner-Wald

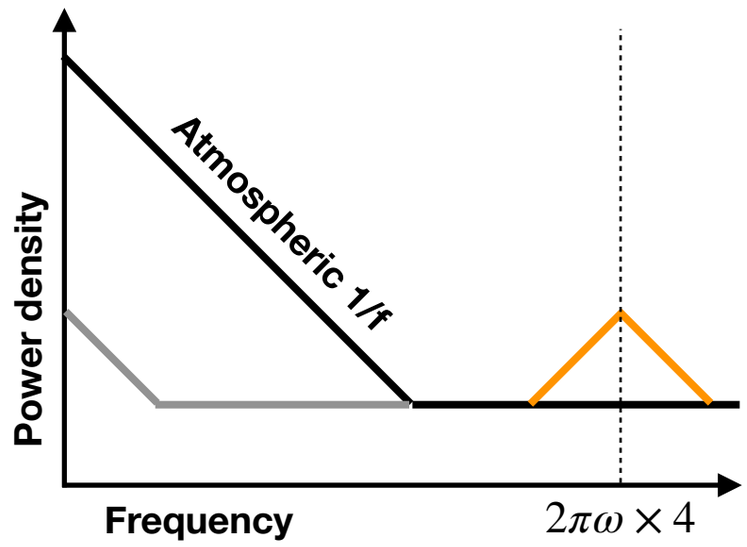
On-sky performance of the CRHWP

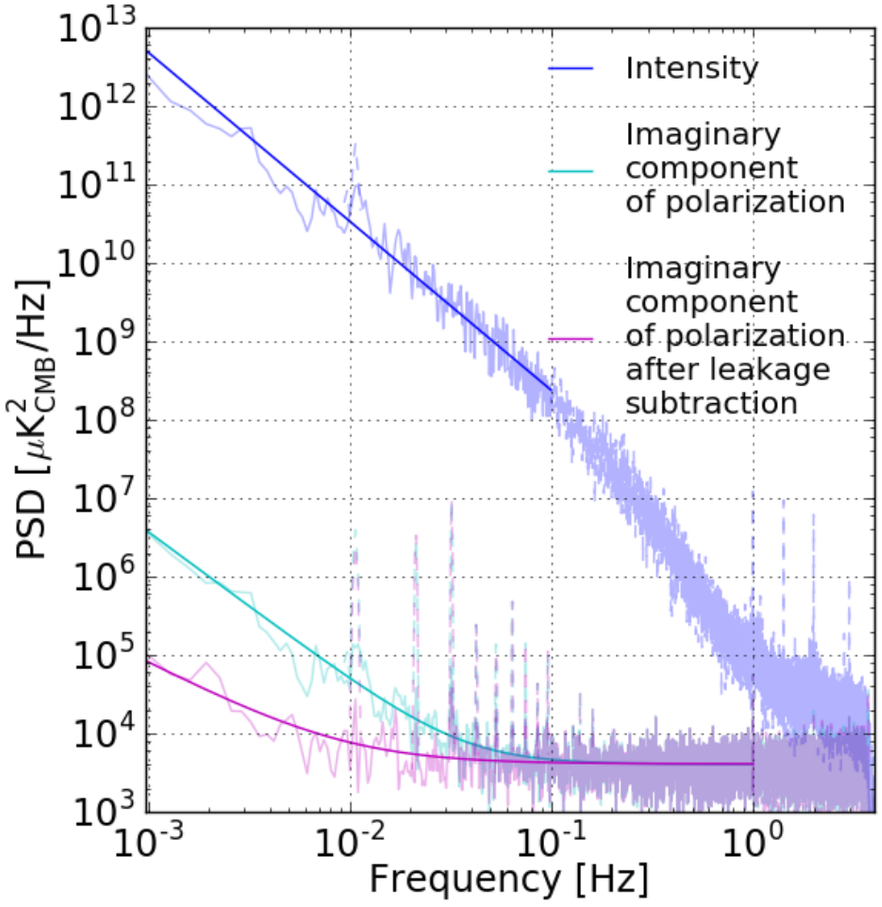
Takakura et al, JCAP 05 008 (2017)

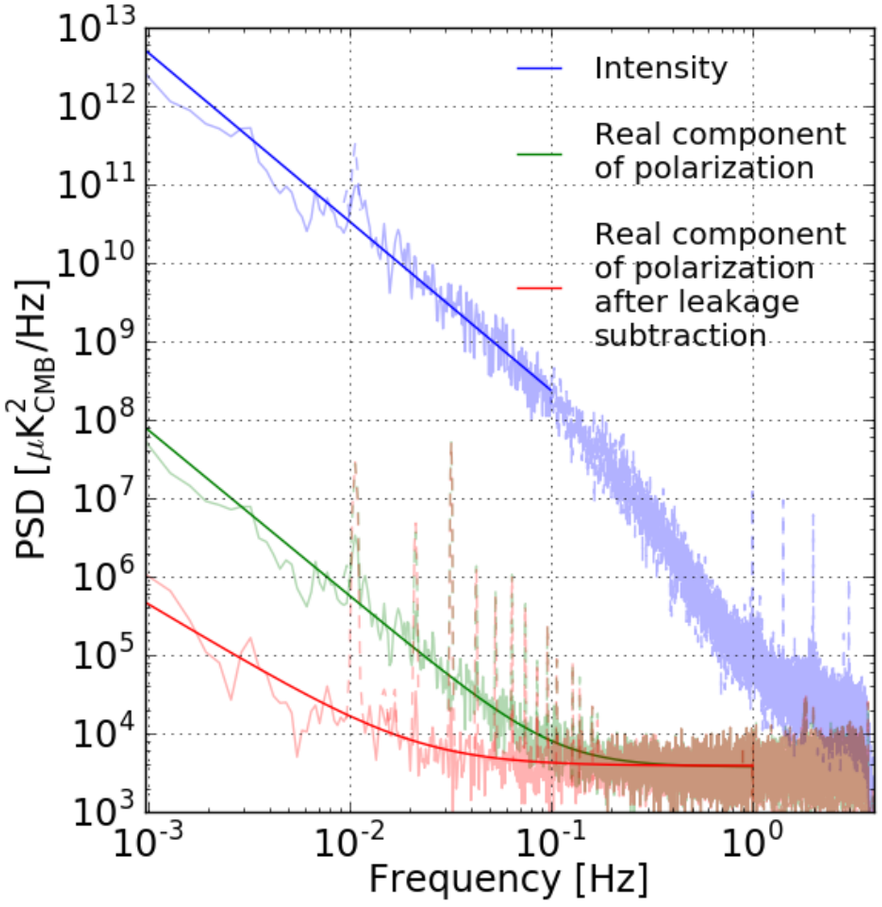
- Atmospheric signal has strong 1/f component
- CRHWP spinning at 2 Hz

  ➡ Polarization modulated at 8Hz
- 1/f knee 32 mHz ($\ell \sim 39$)









Large patch analysis

POLARBEAR Collaboration, in preparation

- Effective sky area: 700 deg2
- Three season data
- Analysis ongoing, stay tuned

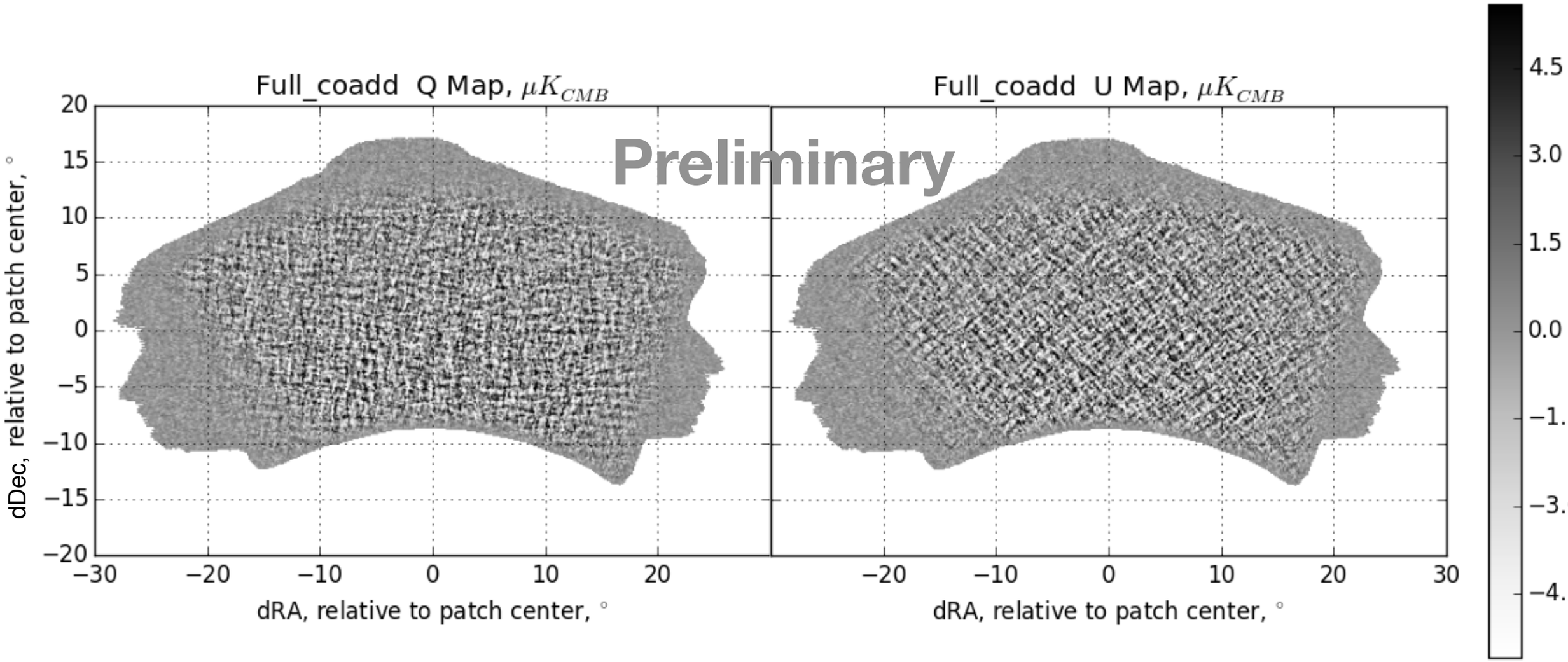
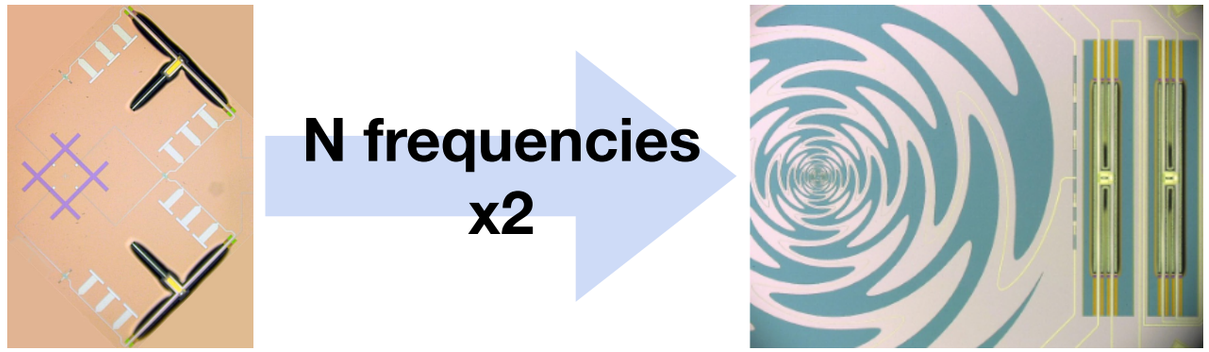
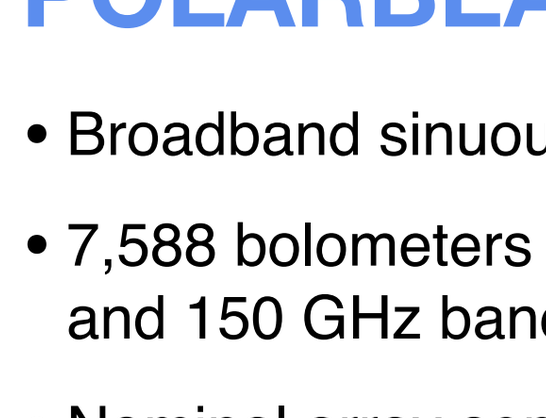


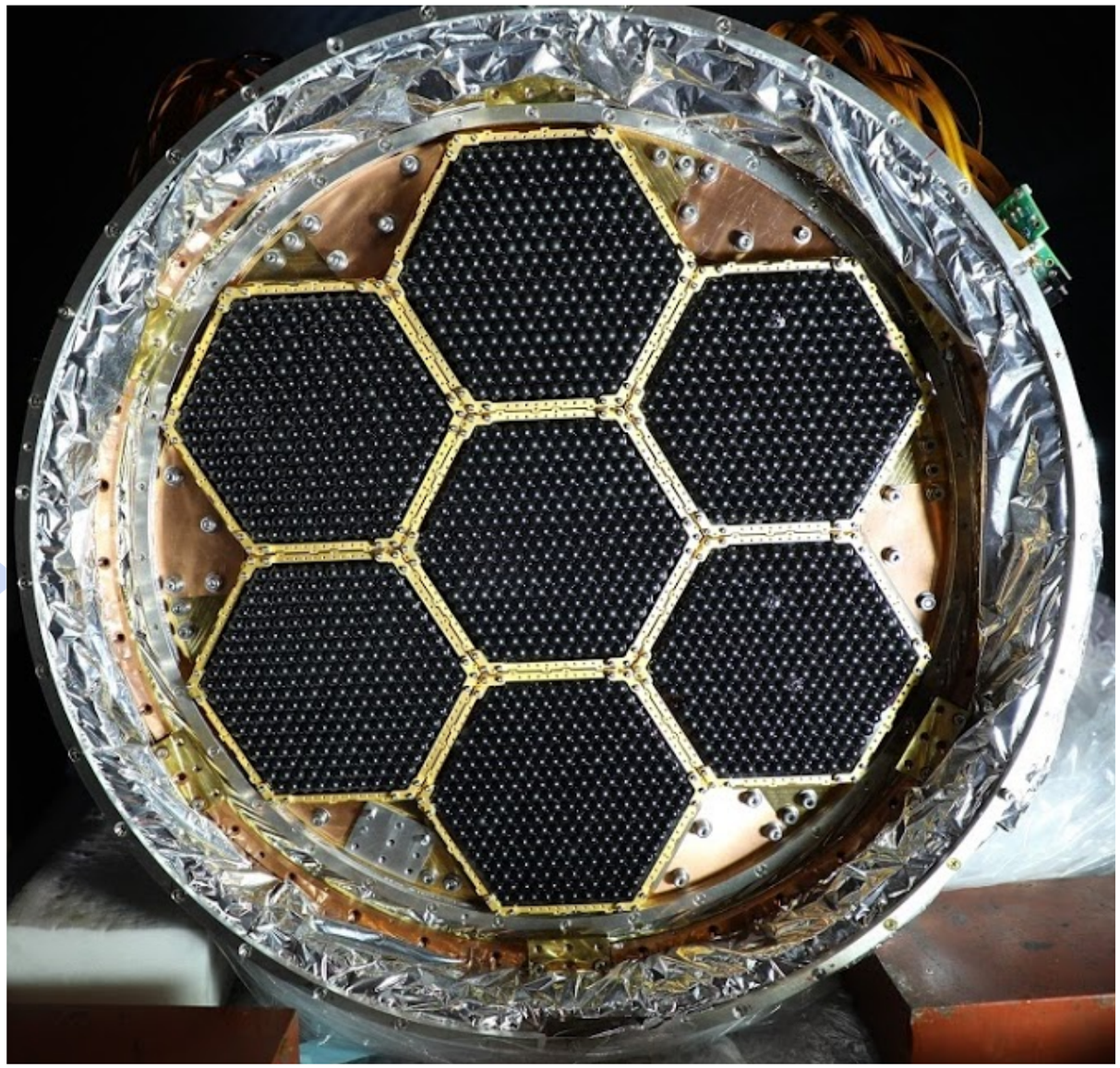
Image by N.Goeckner-Wald

POLARBEAR-2A receiver

- Broadband sinuous antennas
- 7,588 bolometers observing in 95 GHz and 150 GHz band
- Nominal array sensitivity at 150 GHz
  $5.8\ \mu K_{\mathrm{CMB}}\sqrt{s}$ *(Suzuki et al, 2015)*
- Broadband HWP at secondary focus *(Hill and Beckman et al, 2016)*
- First light by the end of 2018







Simons Array

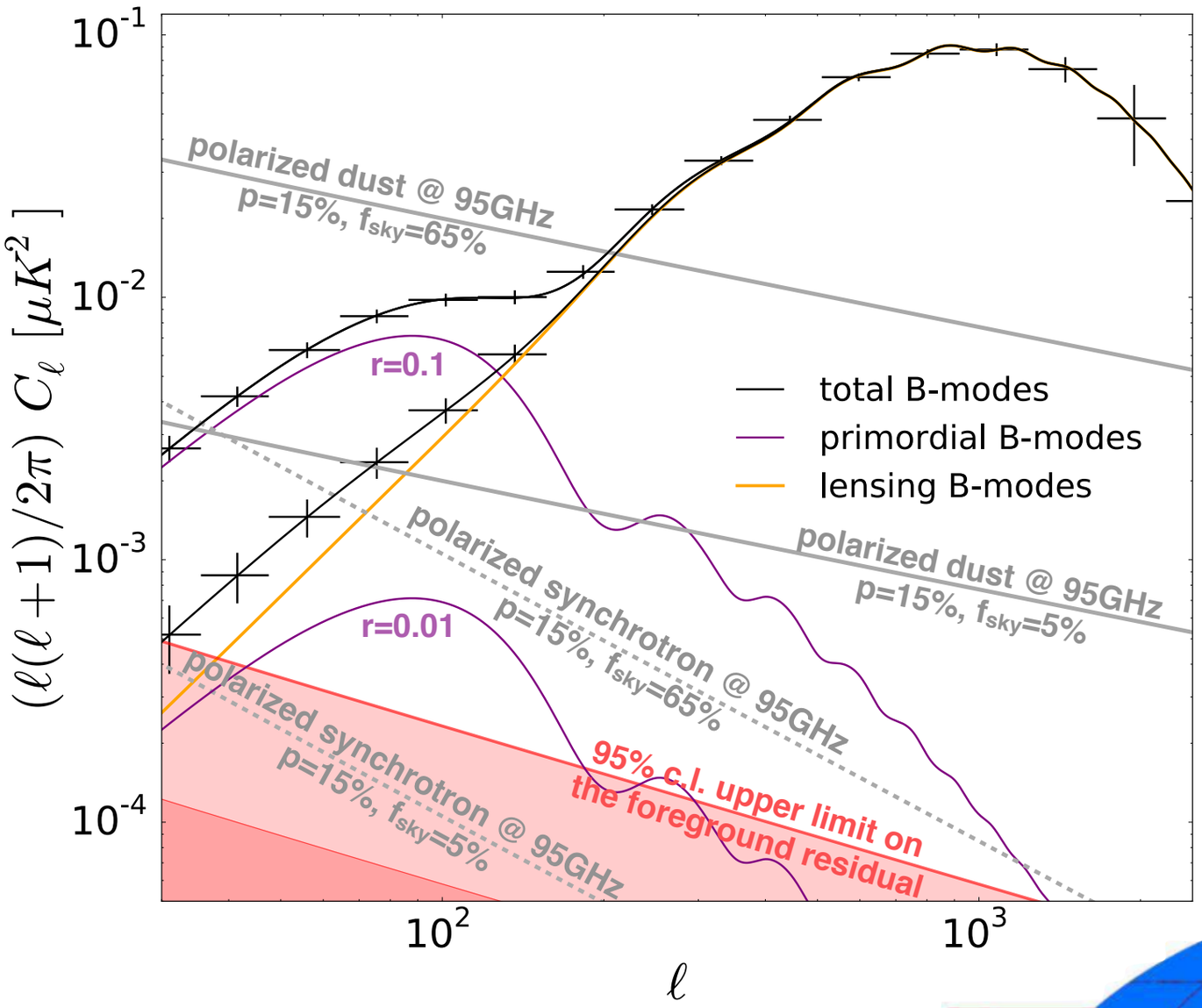
- 3 telescopes
- 22,764 bolometers total
- Frequency bands: 95 / 150 / 220 / 270 GHz
- Full array projected sensitivity $2.5\ \mu K_{\mathrm{CMB}}\sqrt{s}$

POLARBEAR-2A
95 / 150 GHz
(end of 2018)

POLARBEAR-2B
95 / 150 GHz
(2019)

POLARBEAR-2C
220 / 270 GHz
(2019)

Simons array



Expected constraints after foreground cleaning on the **tensor-to-scalar ratio**

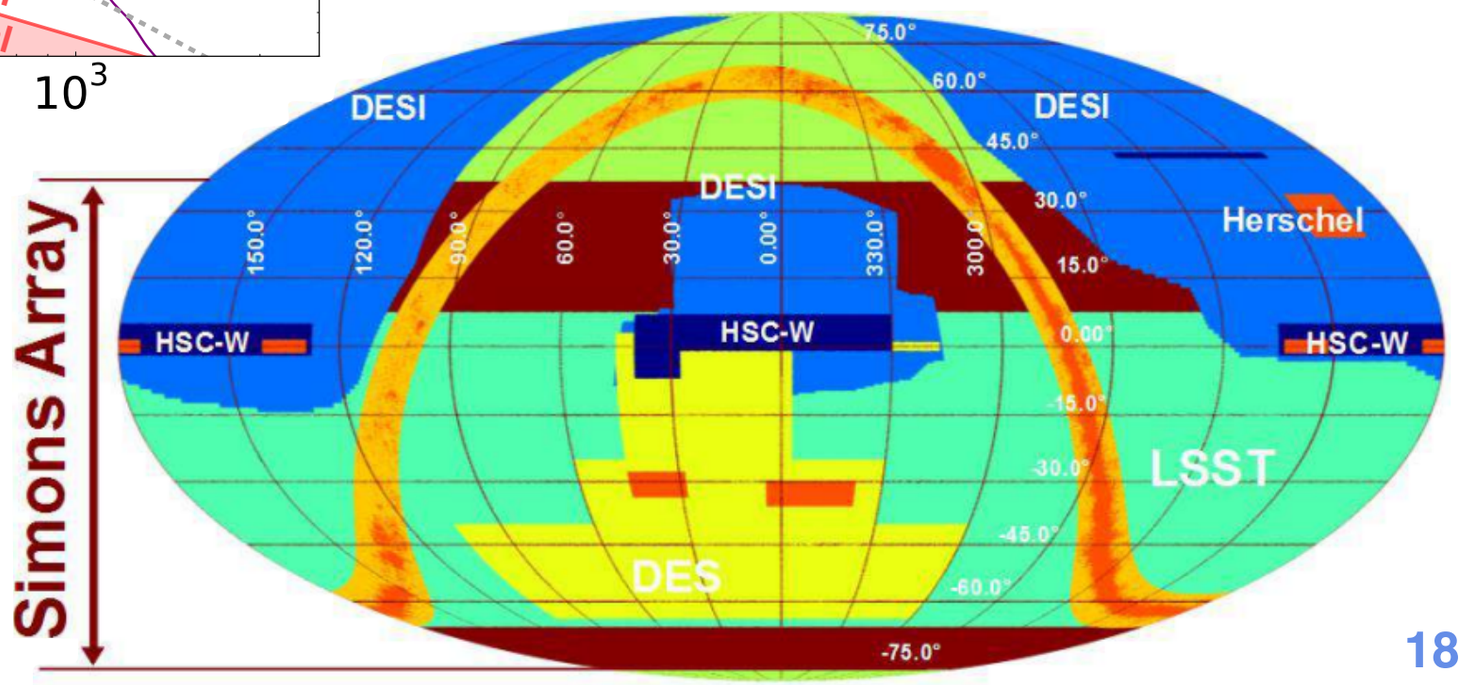
$$\sigma(r = 0.1) = 6 \cdot 10^{-3}$$

and on the **total neutrino mass** (when cross-correlated with galaxy surveys)

$$\sigma(\Sigma\, m_\nu) = 40\ \mathrm{meV}$$

(Stebor et al, 2016)

⇨ Constrain inflation, neutrino mass hierarchy, primordial magnetic fields and more...



Conclusions

Polarbear probing B-modes from the Atacama desert

First and second season
Important contributions to CMB sub-degree polarization science, in particular for B-modes

Third to fifth seasons
Focus on degree scale with large patch and CRHWP

Polabear 2 and Simons Array
Increased sensitivity and frequency coverage coming very soon

Simons Observatory…wait a few minutes

Thanks