

# Measuring the Cosmic Microwave Background Background B-mode Polarization with the POLARBEAR Experiment

Neil Goeckner-Wald for the POLARBEAR collaboration



# 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  
Ben Westbrook



## 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



## KEK

Yoshiki Akiba  
Takaho Hamada  
Masaya Hasegawa  
Masashi Hazumi  
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  
Aritoki Suzuki



## U. Melbourne

Christian Reichardt  
Federico Bianchini  
Anh Pham



## Imperial College

Andrew Jaffe  
Daisy Mak



## Institute D'Astrophysique Spatiale

Giulio Fabbian



## 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



## UC Los Angeles

Nathan Whitehorn



## CU Boulder

Nils Halverson  
Greg Jaehnig  
Hayley Roberts



## Católica (PUC)

David Boettger  
Rolando Dunner



## Laboratoire Astroparticule & Cosmologie

Dominic Beck  
Josquin Errard  
Maude Le Jeune  
Radek Stompou



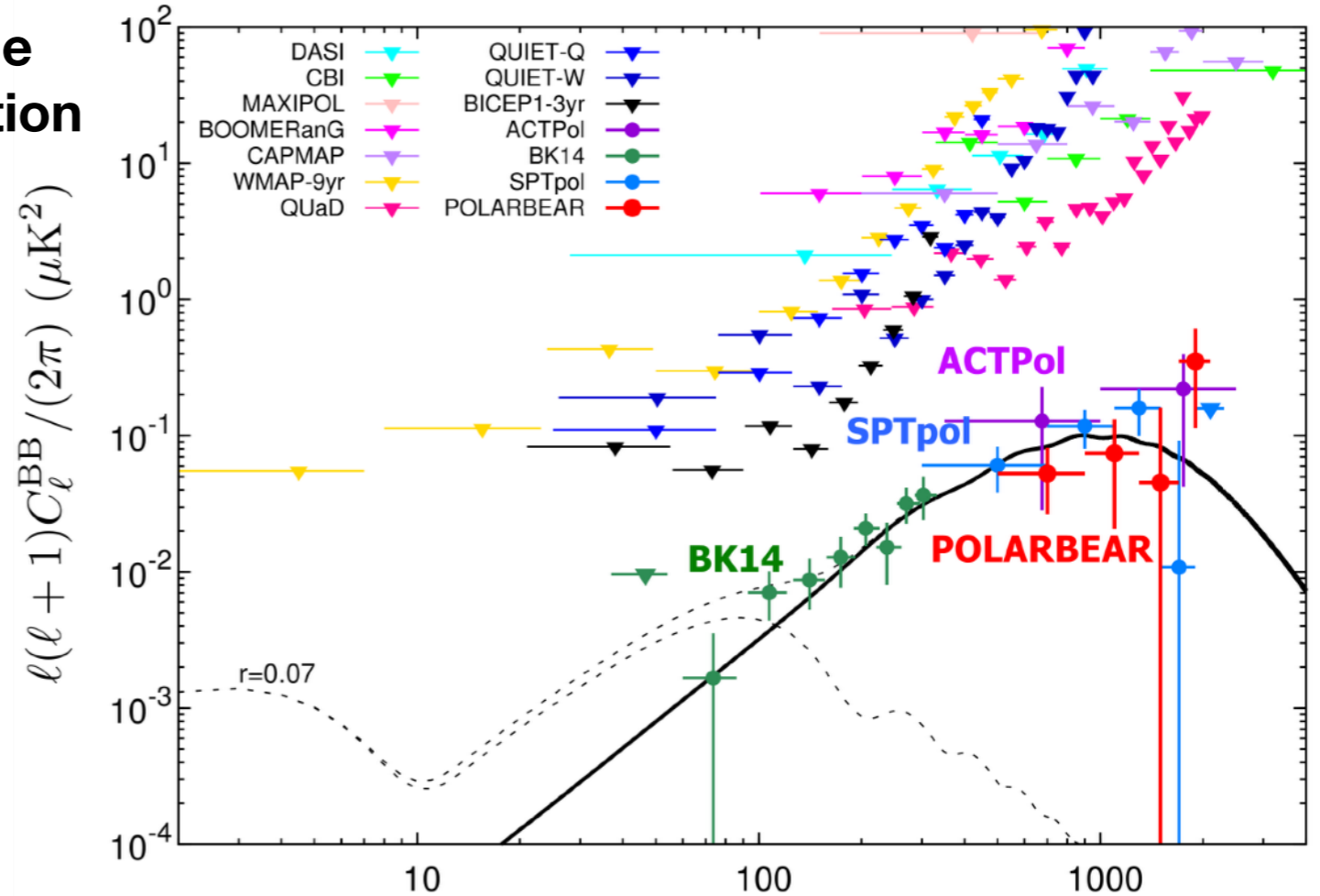
# POLARBEAR Collaboration



# Motivation for POLARBEAR

- Make a precision measurement of CMB B-modes across range of angular scales
- Small angular scales measure gravitational lensing of CMB
  - Science target: **Sum of neutrino masses  $\Sigma m_\nu$**
- Large angular scales constrain theory of cosmic inflation
  - Science target: **Tensor-to-scalar ratio  $r$**

Power in  
B-mode  
polarization



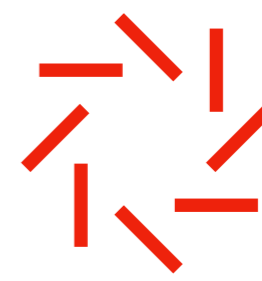
Large angular  
scales,  
inflation science



Small angular  
scales,  
lensing science



E-mode  
polarization



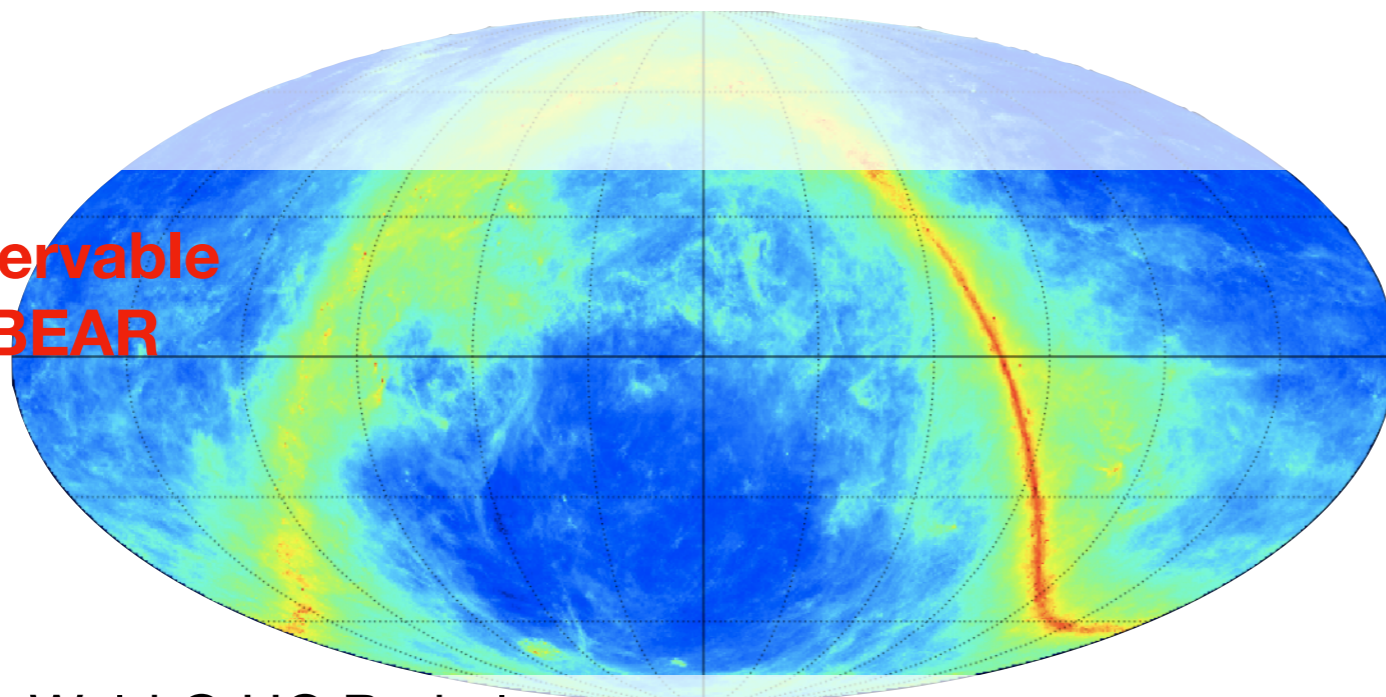
B-mode  
polarization

# POLARBEAR-1

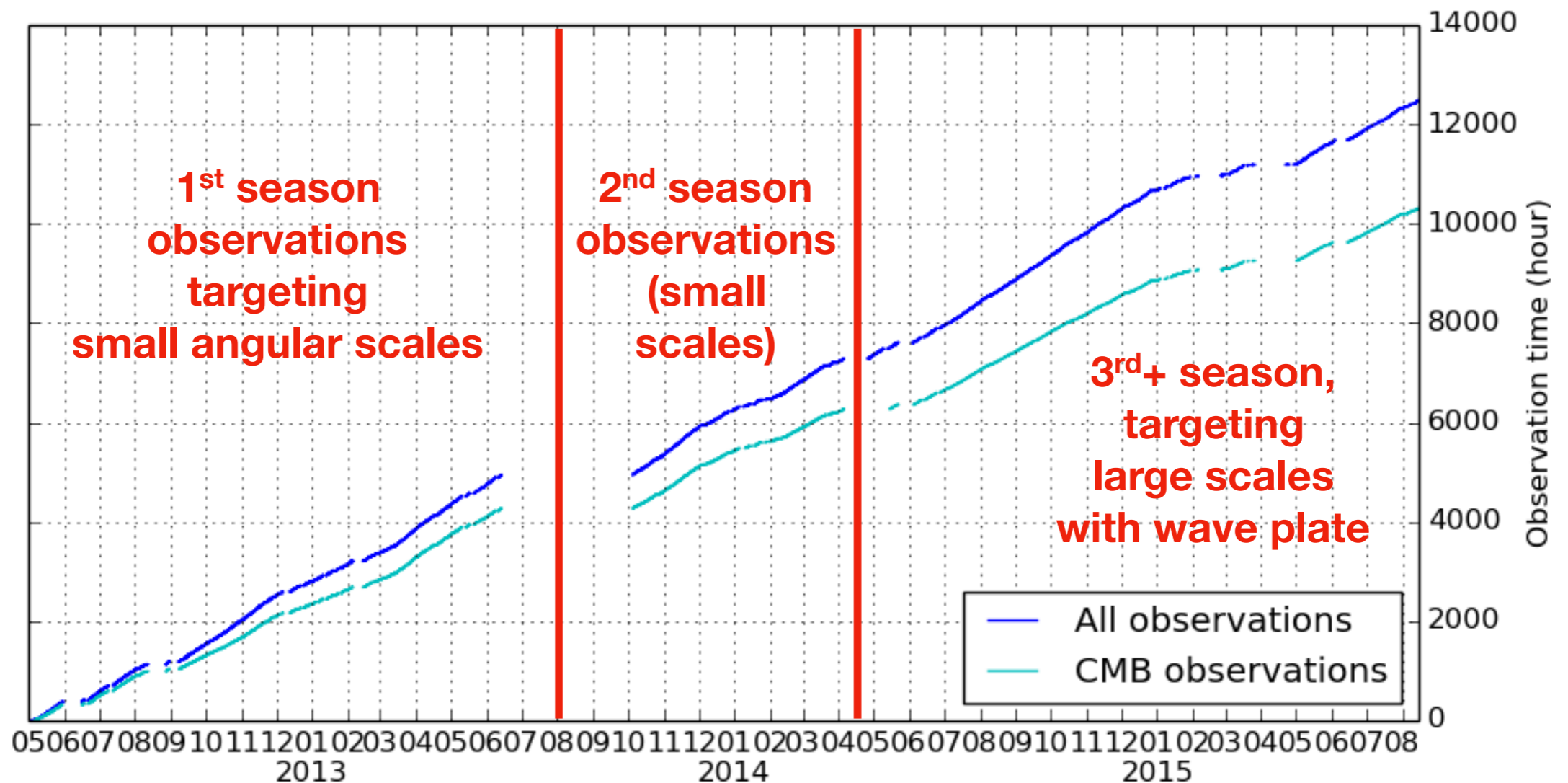
- First light in 2012
- 2.5 m off-axis Gregorian telescope gives 3.5' beams at 150 GHz
- Located at 5200m on Cerro Toco in Atacama desert
- Transparent atmosphere in mm wavelengths



**80% sky observable  
by POLARBEAR**

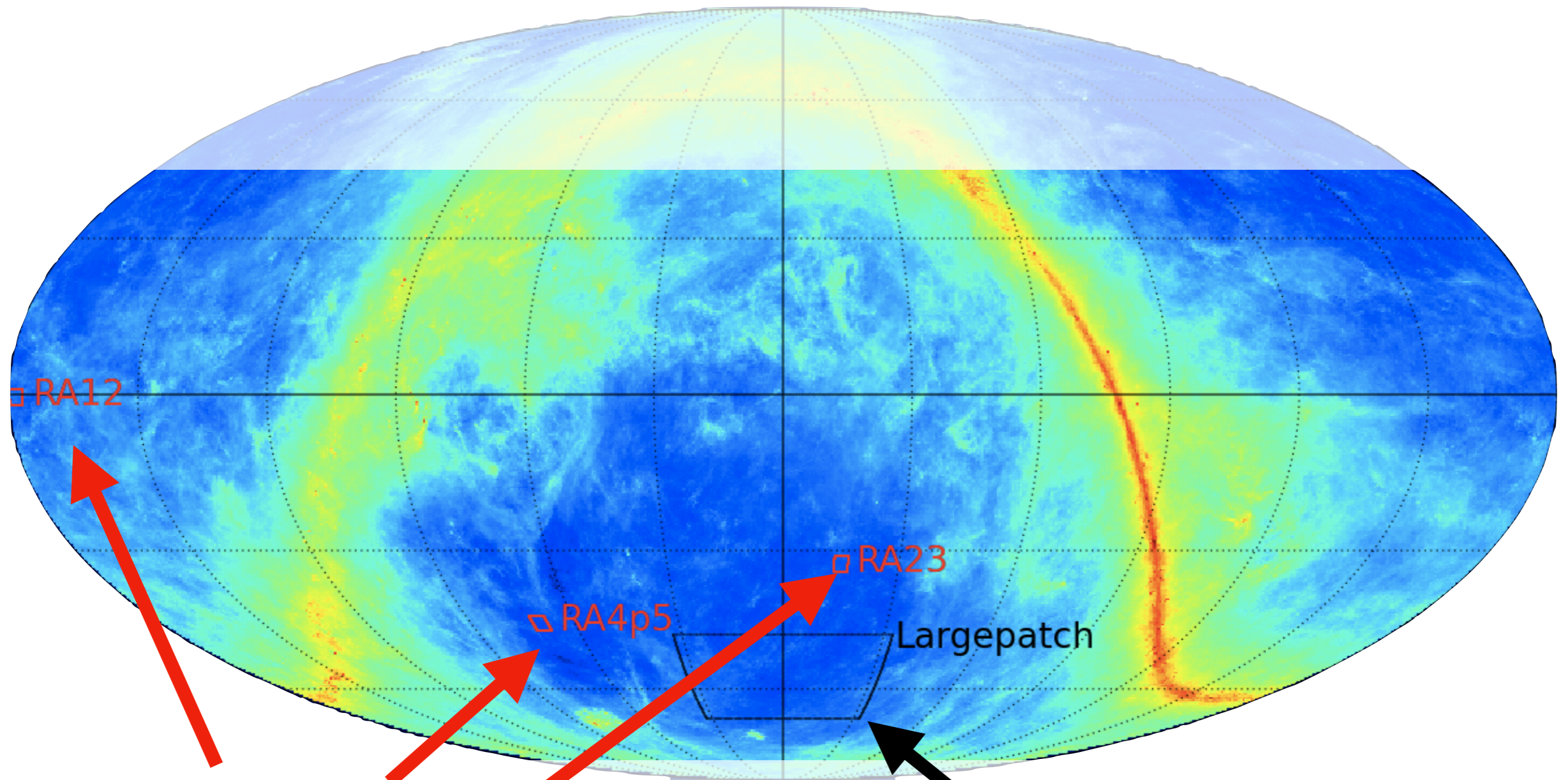


# POLARBEAR-1 Observations



- Two observation modes: small angular scale (high- $\ell$ ) and large angular scale (low- $\ell$ )
- Installed continuously rotating half wave plate (HWP) in May 2014 to improve sensitivity to large angular scales

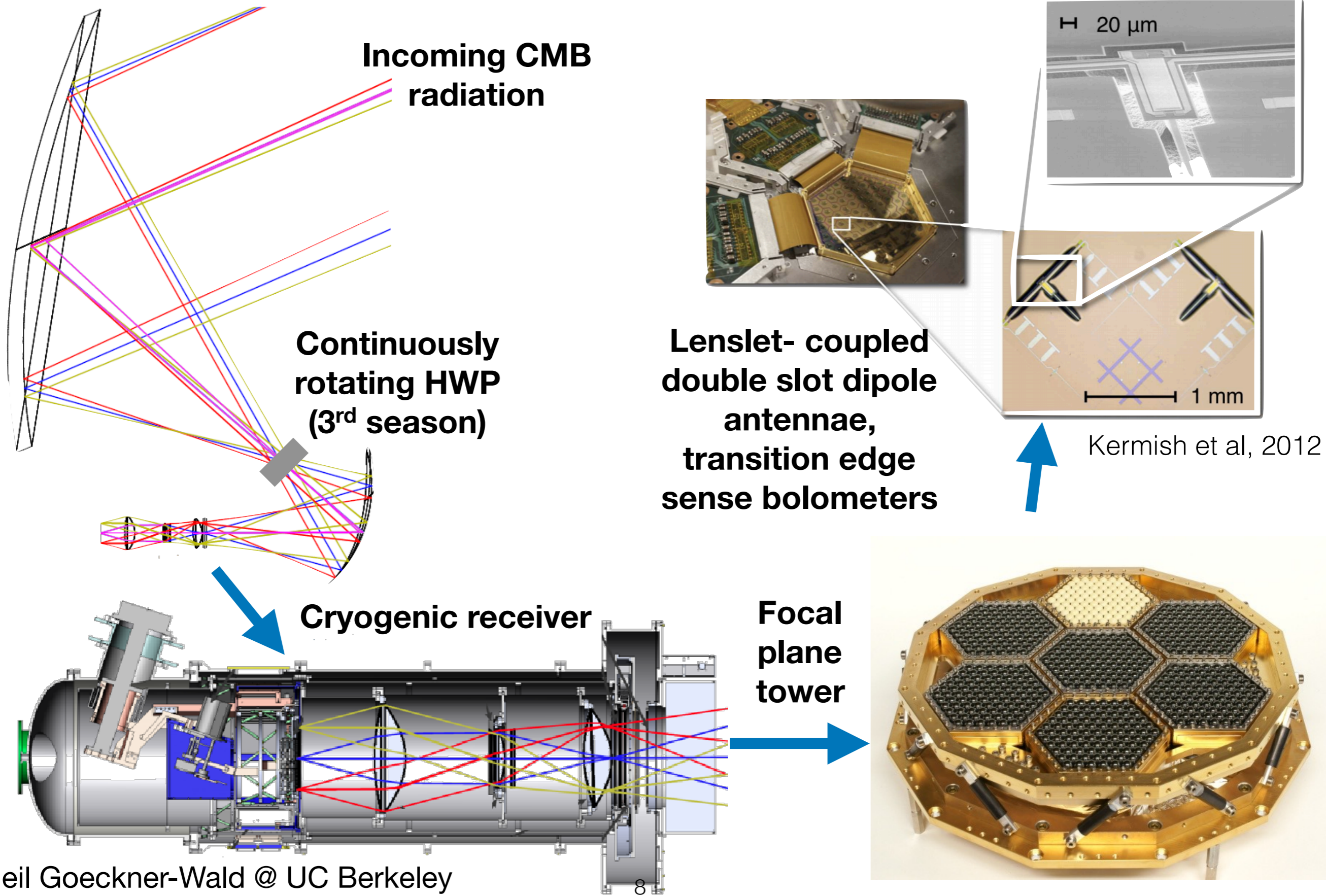
# POLARBEAR-1 Patches



**First two seasons  
3° x 3° patches for  
lensing science,  
combined 24 hour availability**

**Third season  
single 20° x 35° patch  
for inflation science,  
13 hour availability**

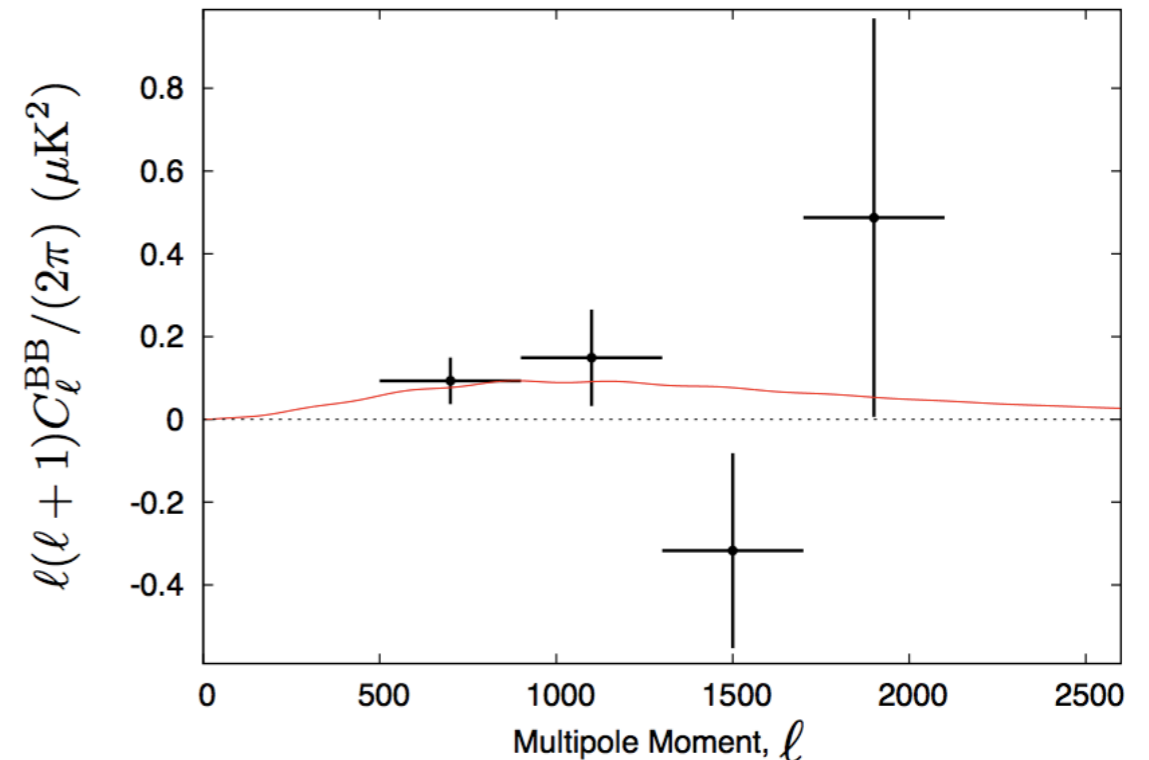
# POLARBEAR-1 Instrument



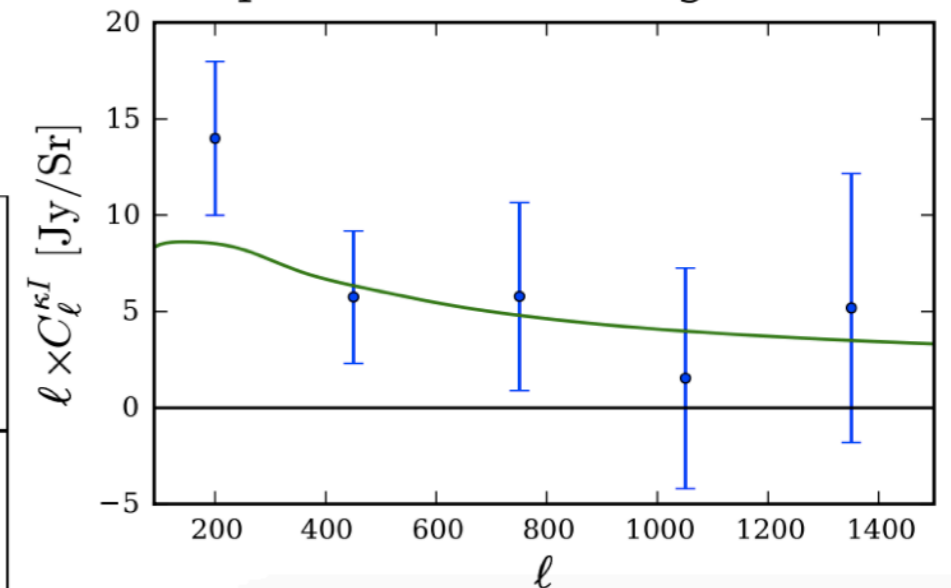


# Initial Science Results

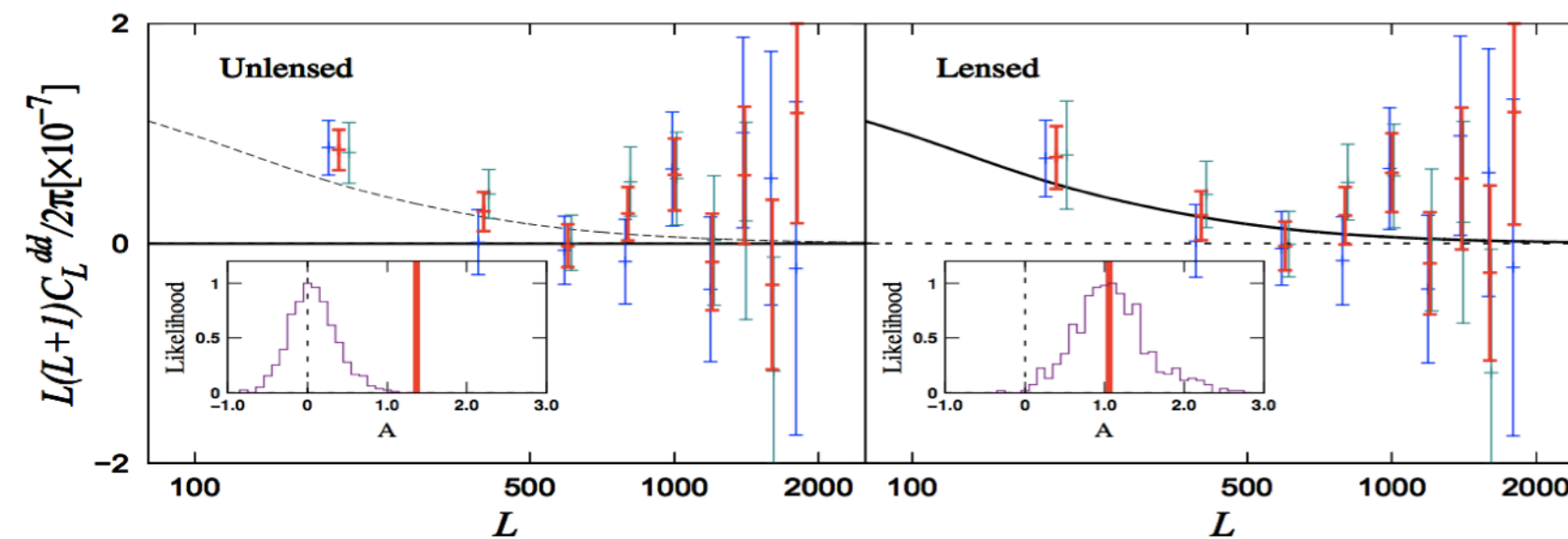
- **Reject null B-mode spectrum at 97.2% confidence level** [POLARBEAR collaboration 2014]
- **Lensing power spectrum at 4.2  $\sigma$**  [POLARBEAR collaboration 2013b]
- **Lensing power spectrum with cross correlation with cosmic infrared background HERSCHEL-ATLAS at 4.0  $\sigma$**  [POLARBEAR collaboration 2013a]



polarization lensing  $\times$  CIB



CCW from left: Polarbear lensing power spectrum, cross correlation with CIB, BB autospectrum



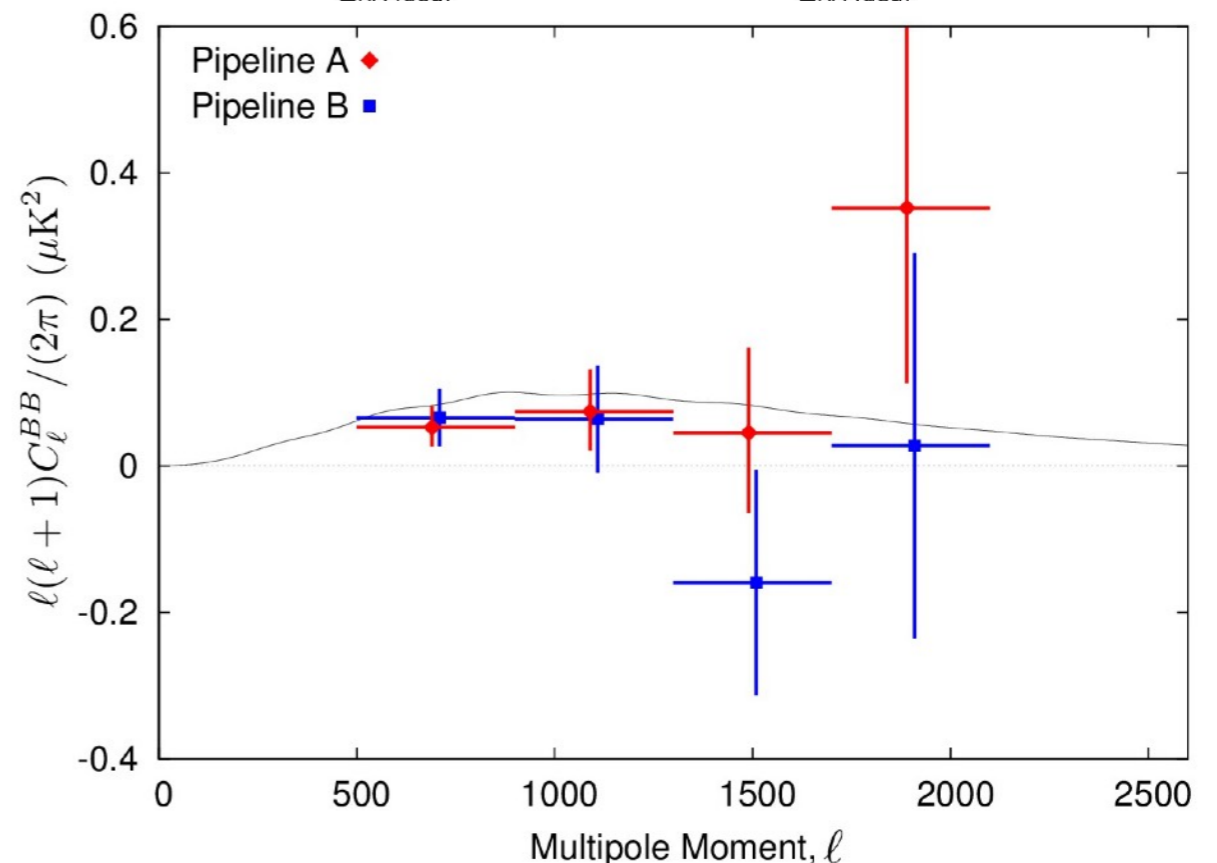
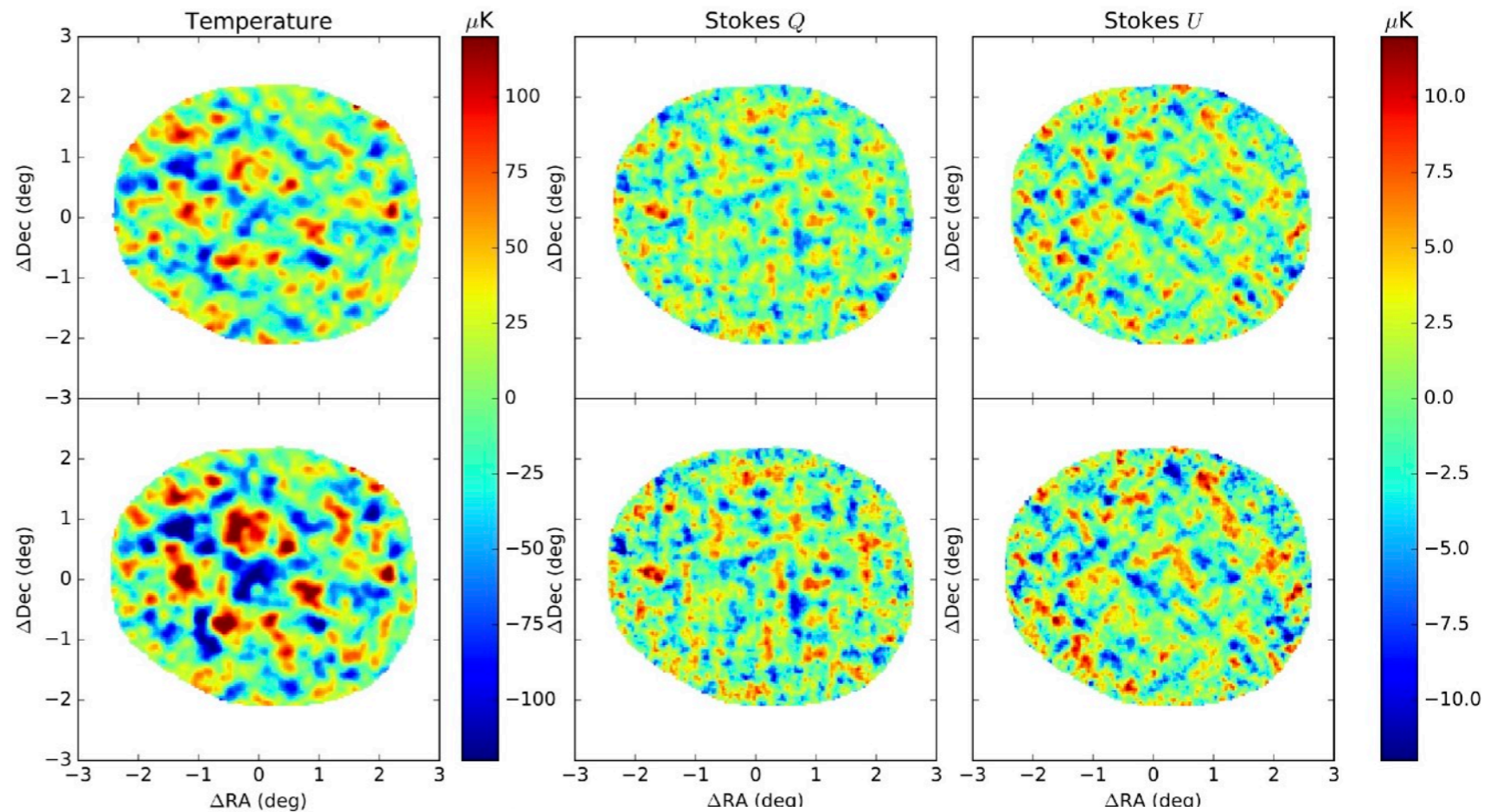
# Second Season Results

Pipeline A

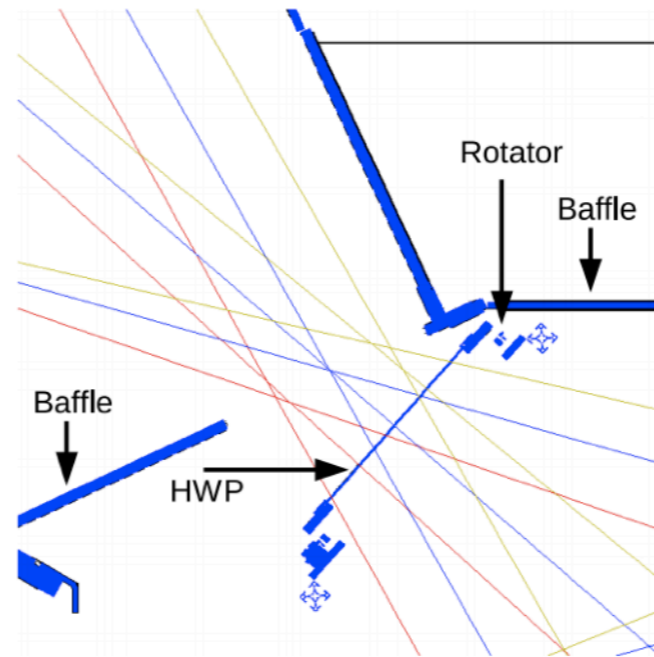
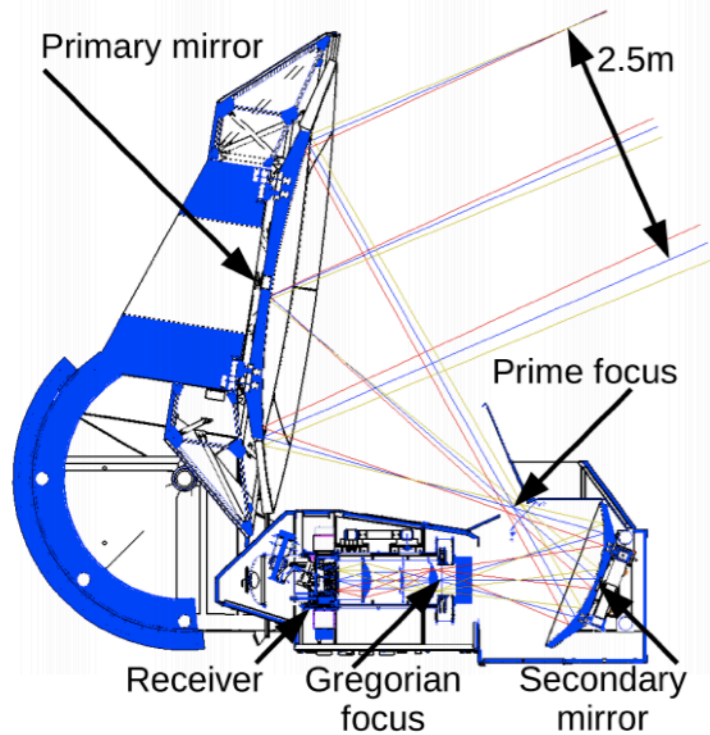
Pipeline B

Two analysis pipelines convert time ordered data to maps and power spectra

- New results with two seasons of data [POLARBEAR 2017]
- Two independent pipelines for more robust result
- Reduced band-power uncertainties by factor of two
- Lensing power spectrum in preparation!

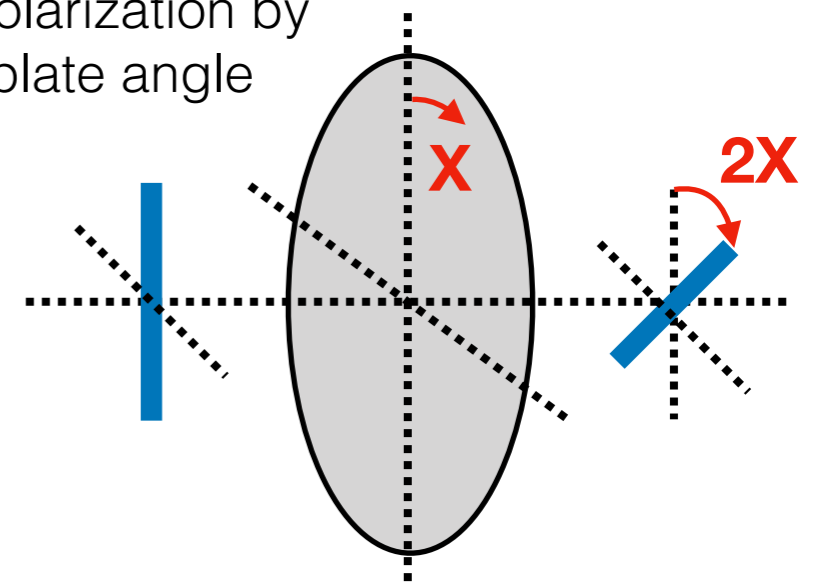


# Polarization modulation with a HWP

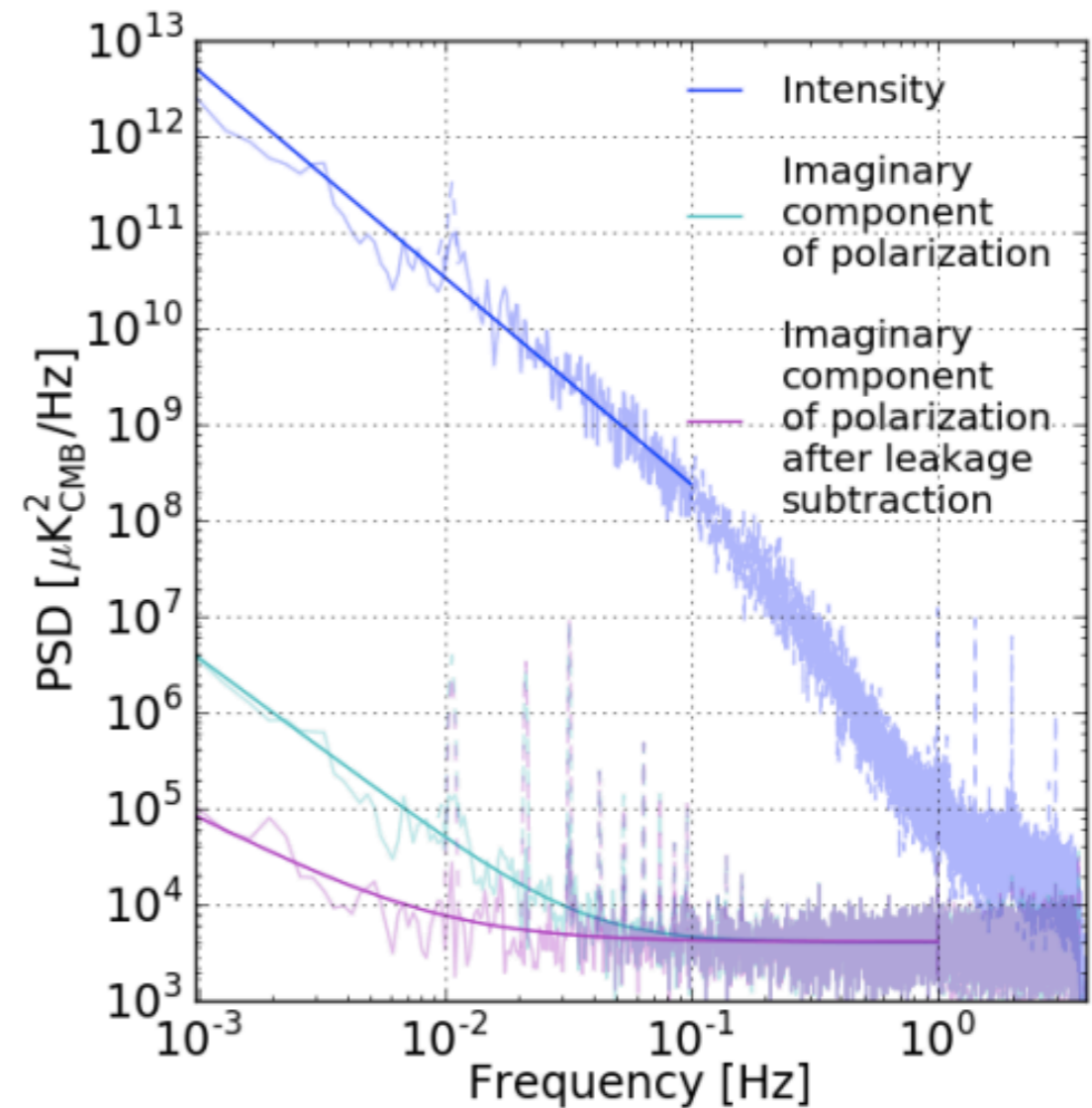
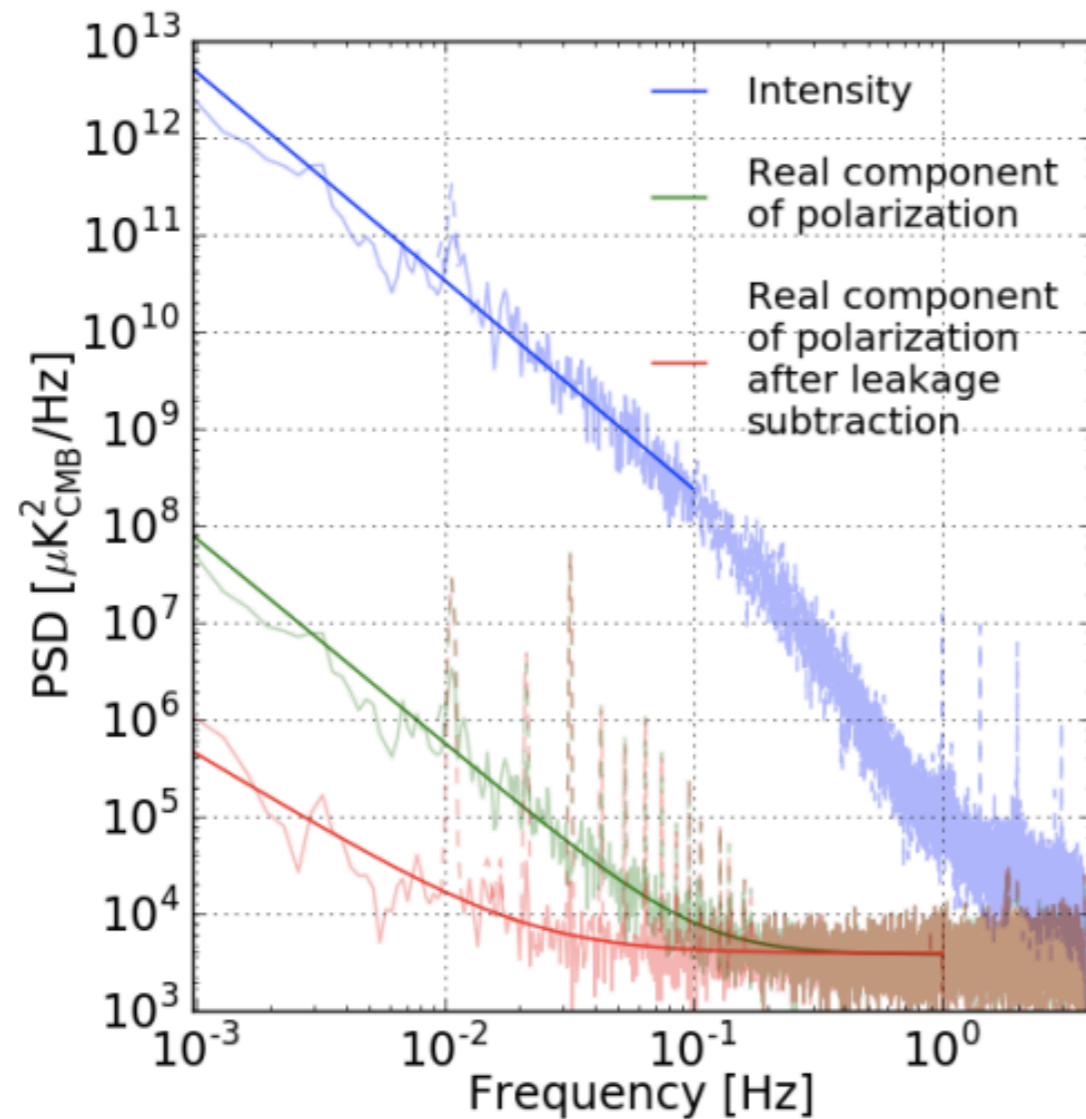


- Rotating HWP at prime focus installed after second season of observations
- Continuous rotation modulates sky polarization at  $4f_{\text{HWP}}$  (8Hz)
- Demodulation in analysis recovers sky polarization signal

HWP rotates polarization by twice wave plate angle

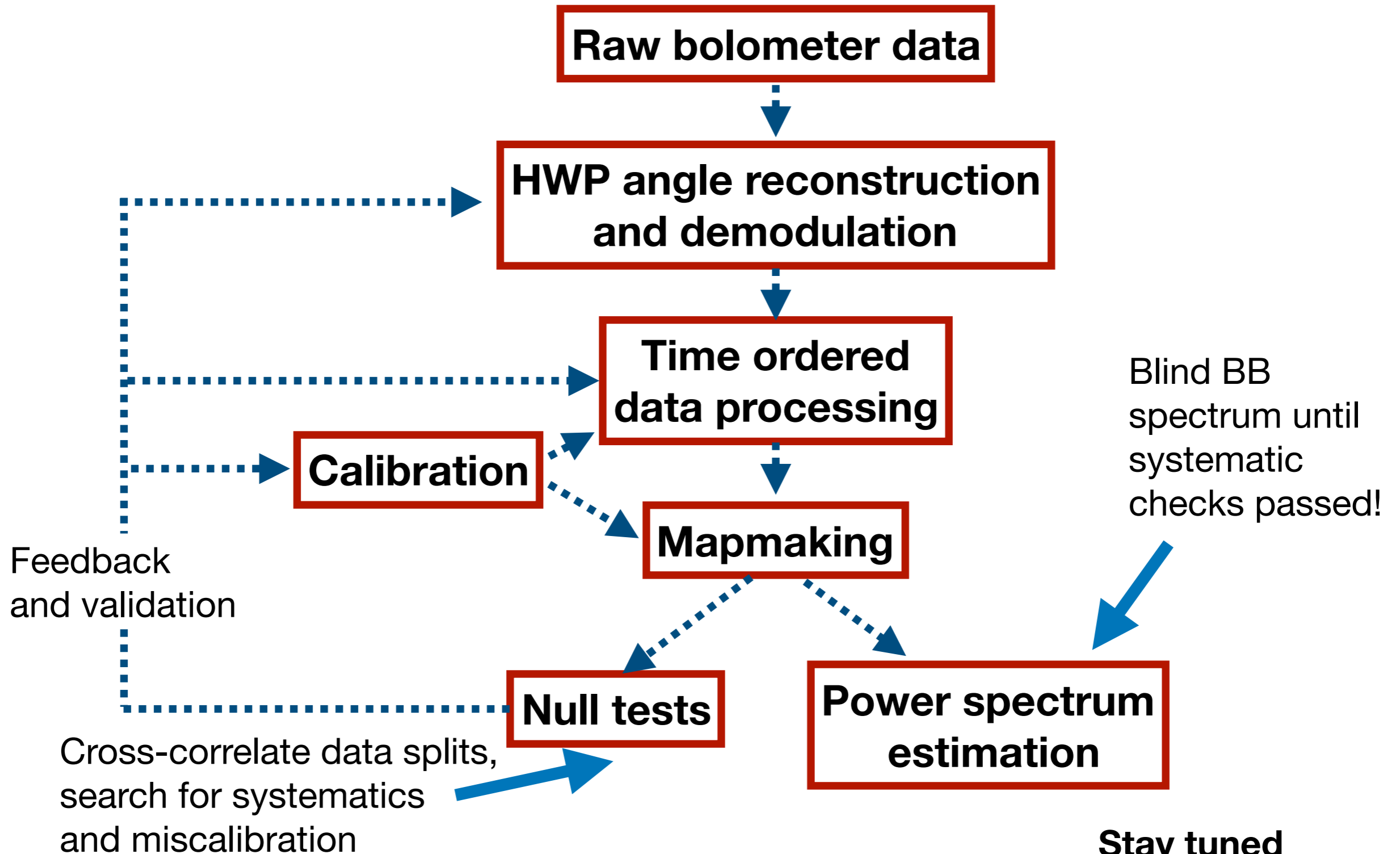


# On-sky HWP performance



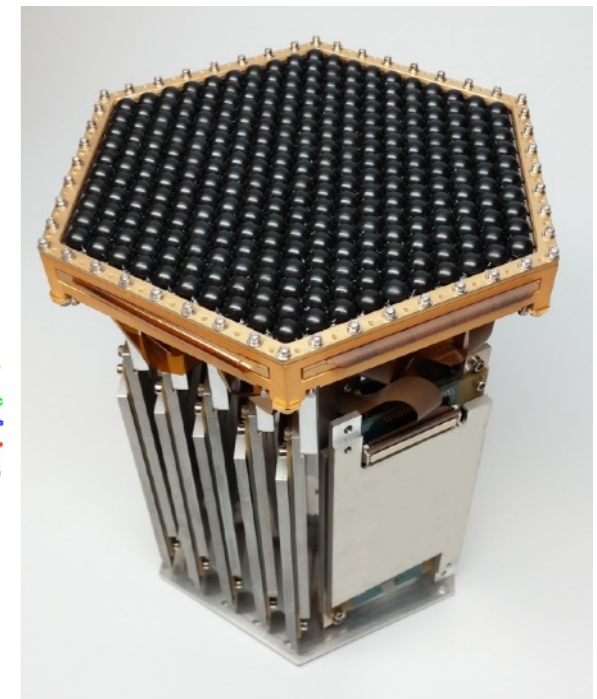
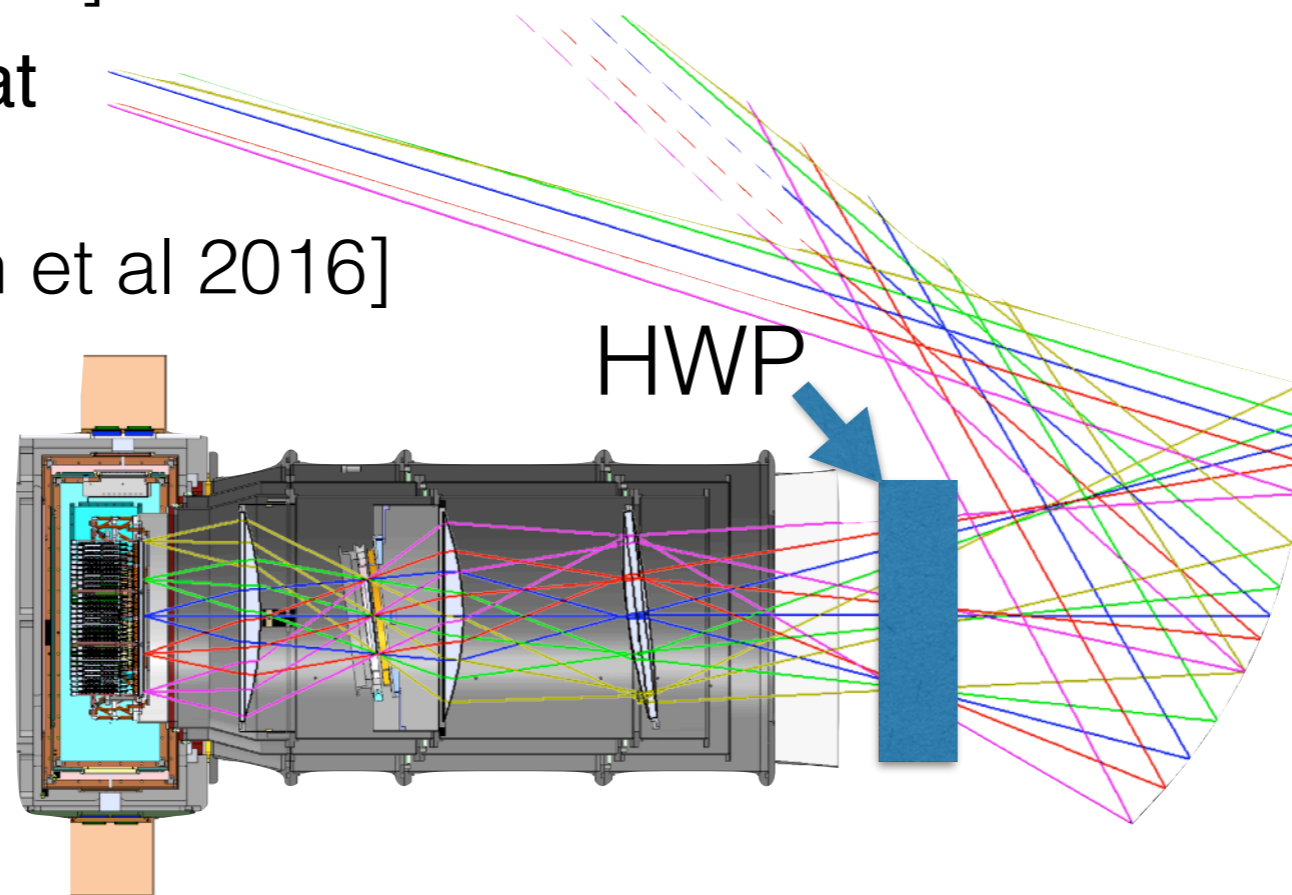
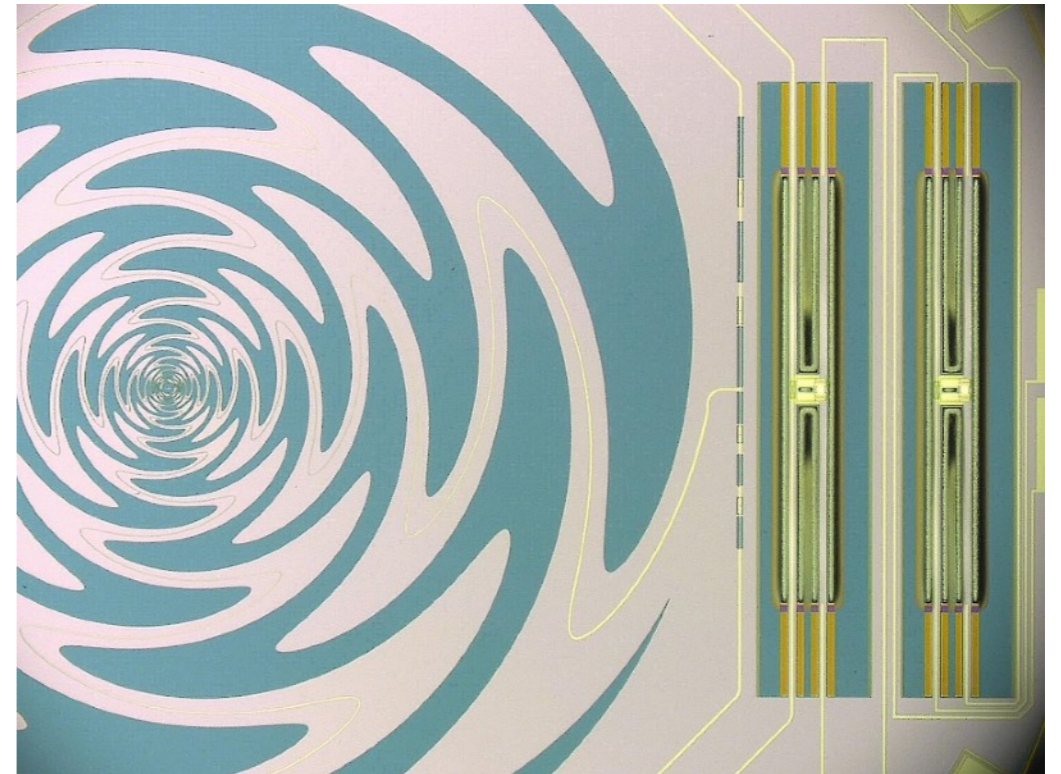
- Temperature to polarization leakage seen due to optics and non-linearity
- After subtraction, demonstrated  $1/f$  suppression necessary for inflation science! [Takakura et al 2017]

# Analysis Formalism



# POLARBEAR-2

- Broadband sinuous antennas and optics
- 7588 bolometers split between 95GHz and 150 GHz bands
- Nominal array sensitivity of
  - $5.8 \mu\text{K}_{\text{CMB}} \sqrt{\text{s}}$  @ 150 GHz
  - $5.8 \mu\text{K}_{\text{CMB}} \sqrt{\text{s}}$  @ 95 GHz[Suzuki et al 2015]
- Broadband HWP at secondary focus [Hill and Beckman et al 2016]



CCW from left: PB2 receiver showing location of HWP, detector module, broadband sinuous antenna

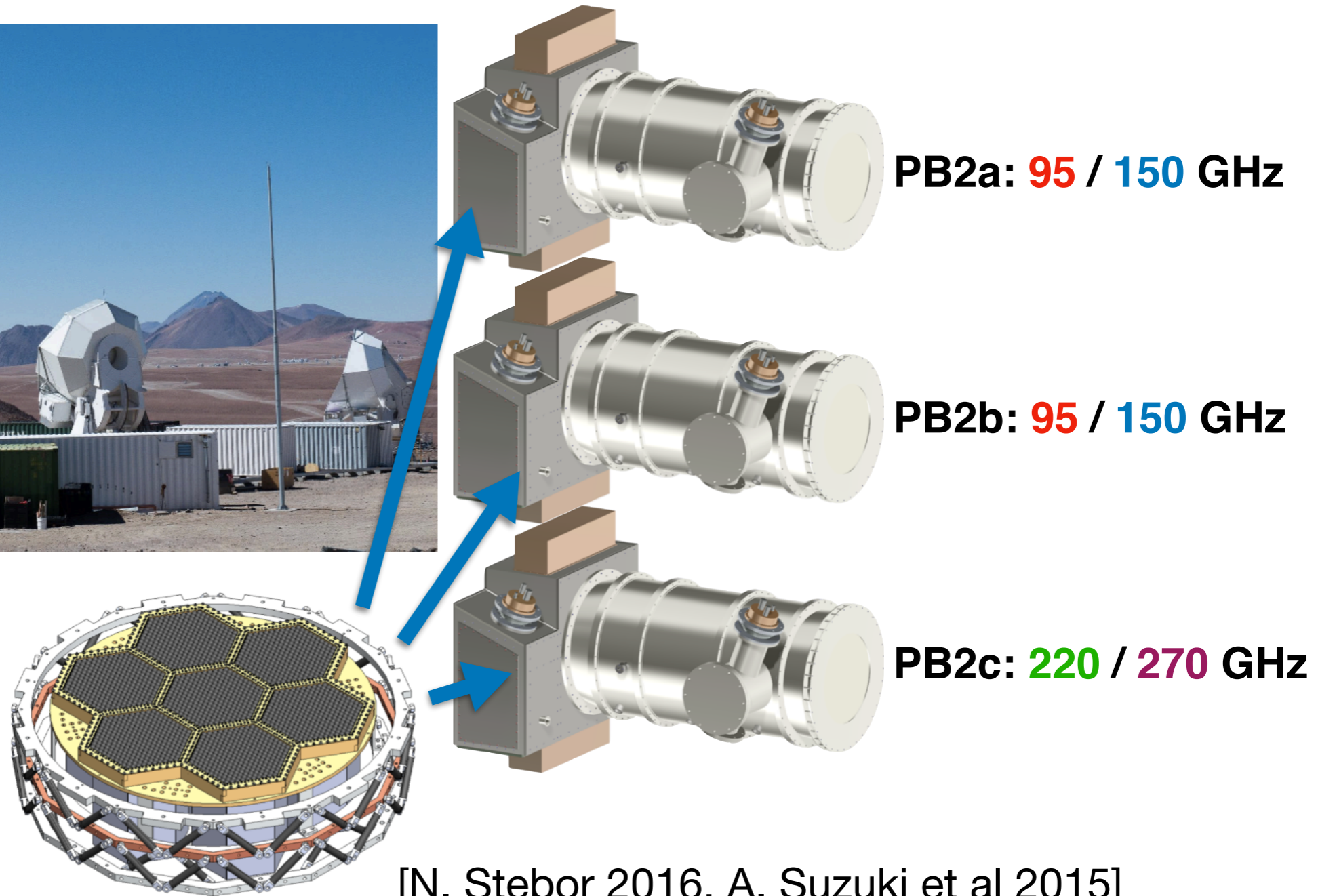
# Simons Array

- Full array projected to achieve  $\sim 2.5 \mu\text{K}_{\text{CMB}} \sqrt{s}$ 
  - Constrain  $\sigma(r=0) = 6e-3$  with Planck and foregrounds
  - Constrain  $\sigma(\Sigma m_\nu) = 40 \text{ meV}$  with DESI BAO and foregrounds



Simons Array telescopes  
being installed in Chile

**3x**



[N. Stebor 2016, A. Suzuki et al 2015]

# Conclusions

## POLARBEAR-1 Publications

- **POLARBEAR 1 experiment** Proceedings of SPIE Volume 8452
- **First season B mode power spectrum** Ap. J., 794:171, 2014.
- **Lensing power spectrum** Phys. Rev. Lett. (Editors' Suggestion), 113:2, 2014.
- **Lensing by cross-correlation with CIB** Phys. Rev. Lett.(Editors' Suggestion), 112:13, 2014.
- **Constraints on cosmic birefringence** Phys. Rev. D 92, 123509 (2015)
- **Explicit mapmaking technique** A&A 600, A60 (2017)
- **On-sky performance of PB1 HWP** JCAP 05 (2017) 008
- **B mode power spectrum from two seasons of data** [arxiv.org/abs/1705.02907](https://arxiv.org/abs/1705.02907)

## POLARBEAR-2 Publications

- **POLARBEAR-2 and the Simons Array Experiments.** JLTP, 2015.
- **Development of PB2 Half Wave Plate** Proc. of SPIE, Volume 9914, Number 99142U-1

and many more to come...



# Backup: Analysis Pipelines

