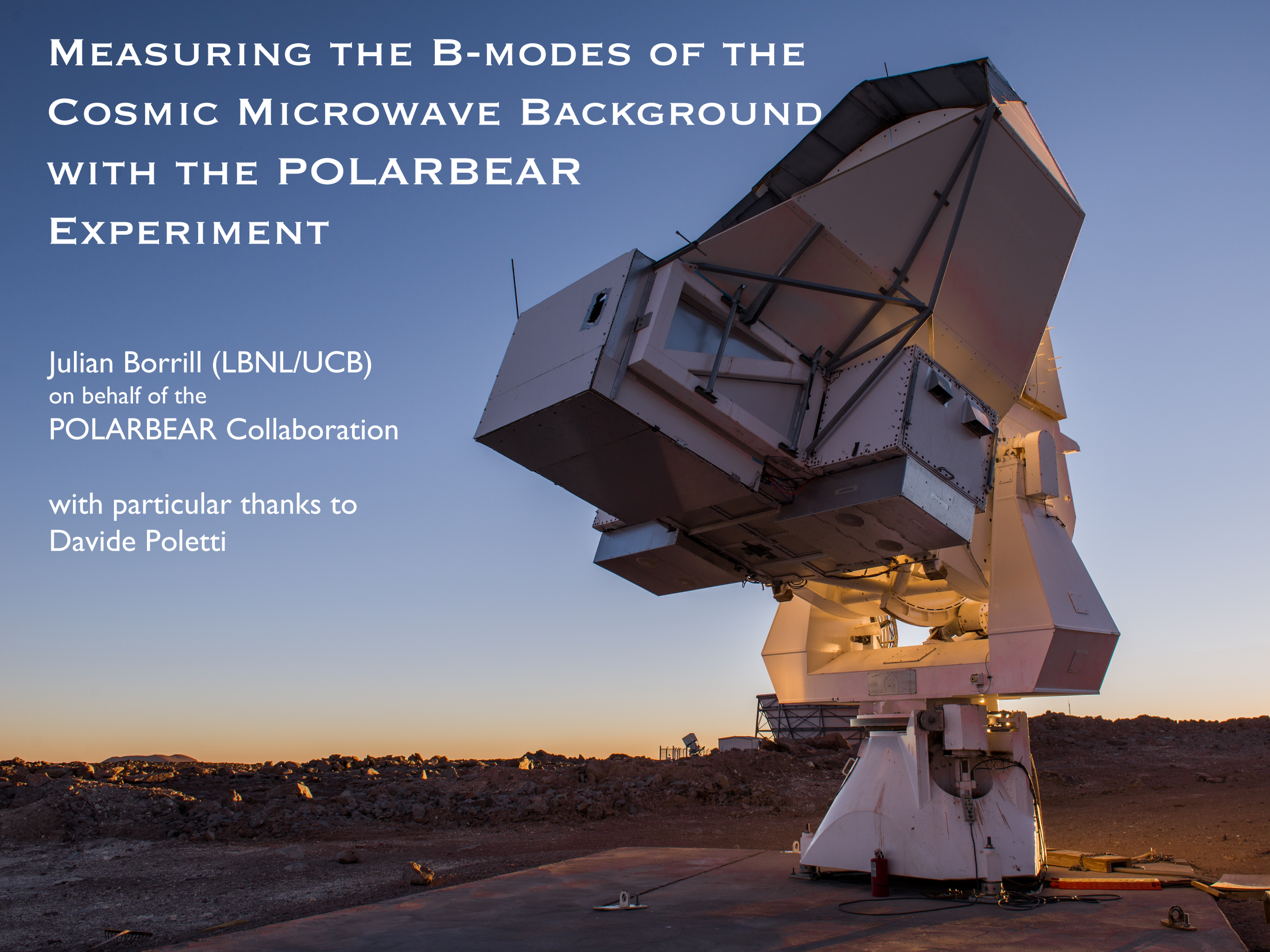
Measuring the B-modes of the Cosmic Microwave Background with the POLARBEAR Experiment

Julian Borrill (LBNL/UCB)
on behalf of the
POLARBEAR Collaboration

with particular thanks to
Davide Poletti



POLARBEAR Collaboration

MEXT · SIMONS FOUNDATION · NSF · NASA

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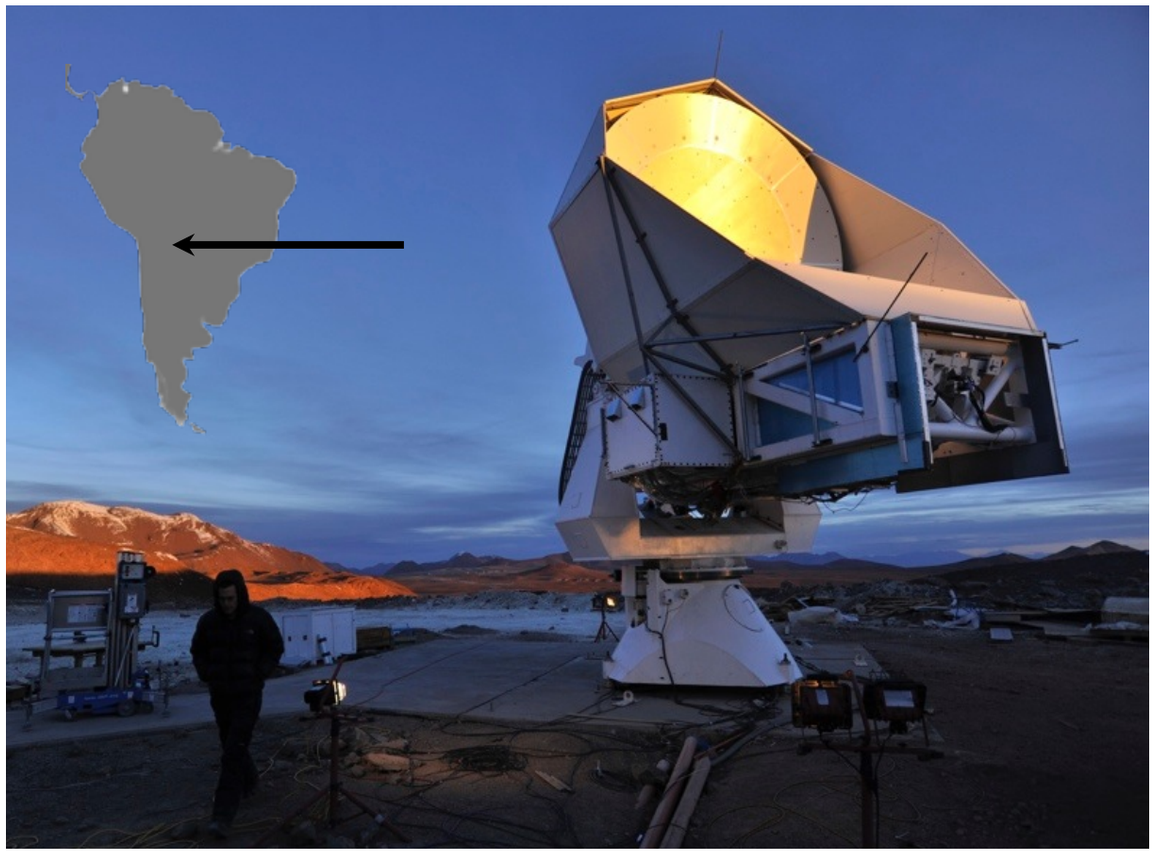
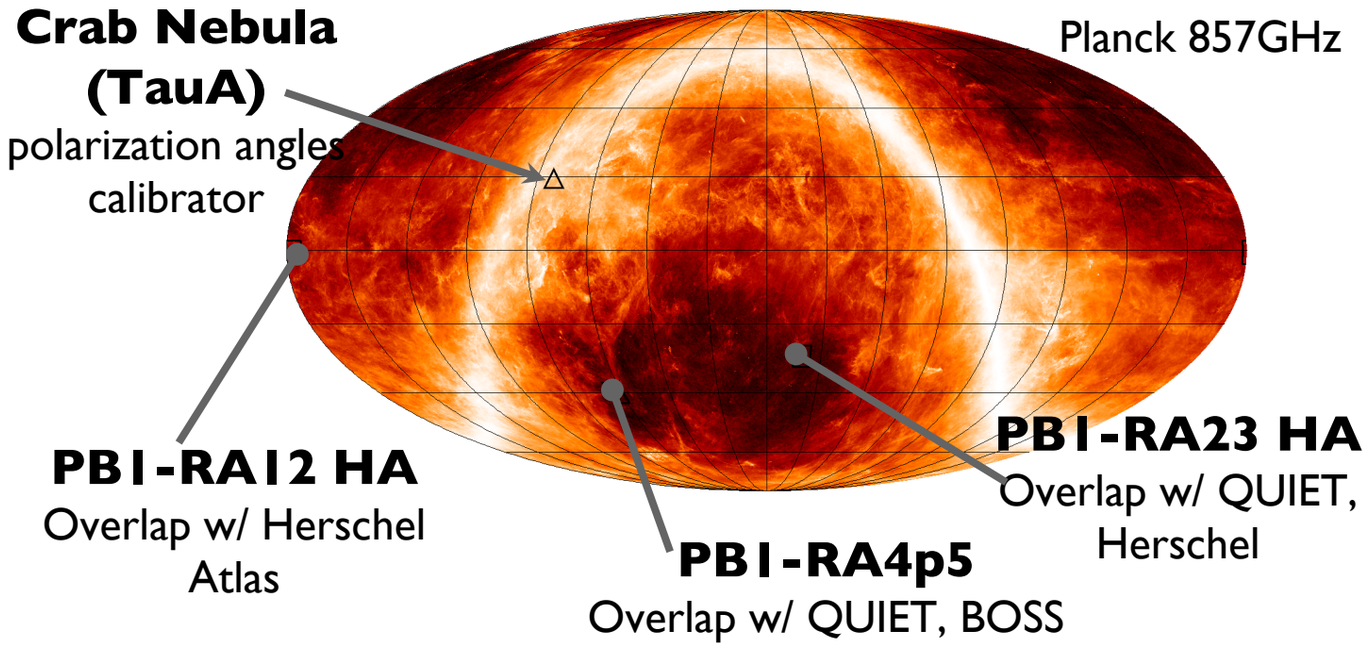
Rolando Dunner

And many more in years past

The POLARBEAR Experiment

- CMB B-modes dedicated experiment
- Atacama desert (~5200 m altitude)
  - Access to 80% of the sky
  - Dry atmosphere
- Targeting both primordial and lensing B-modes

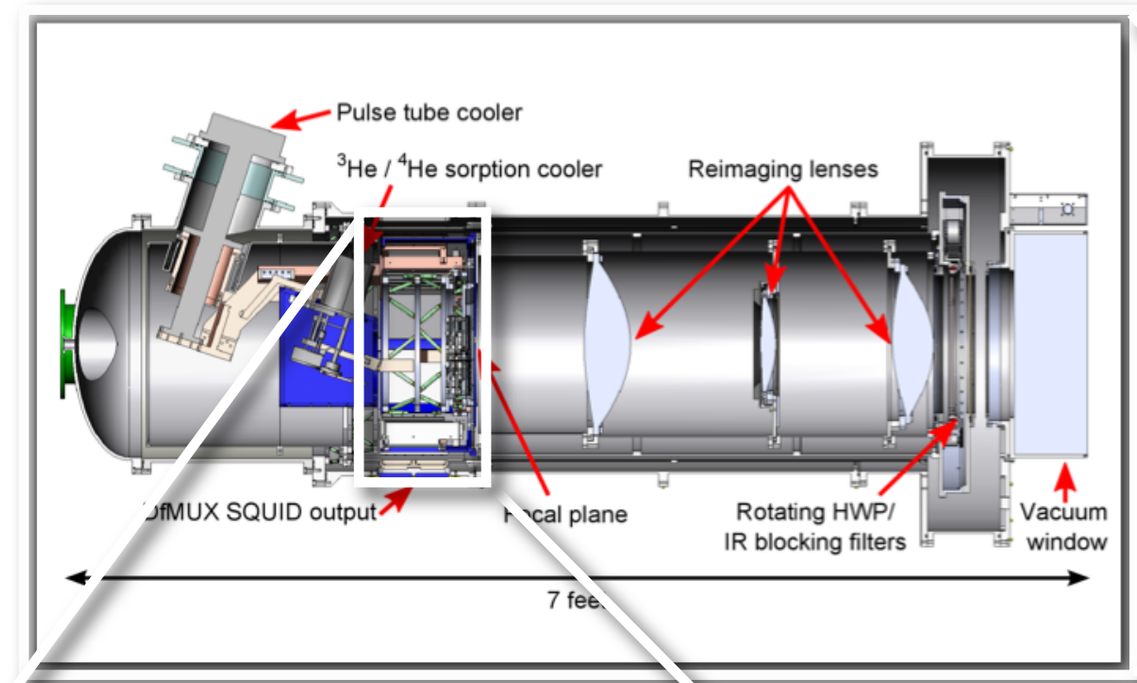


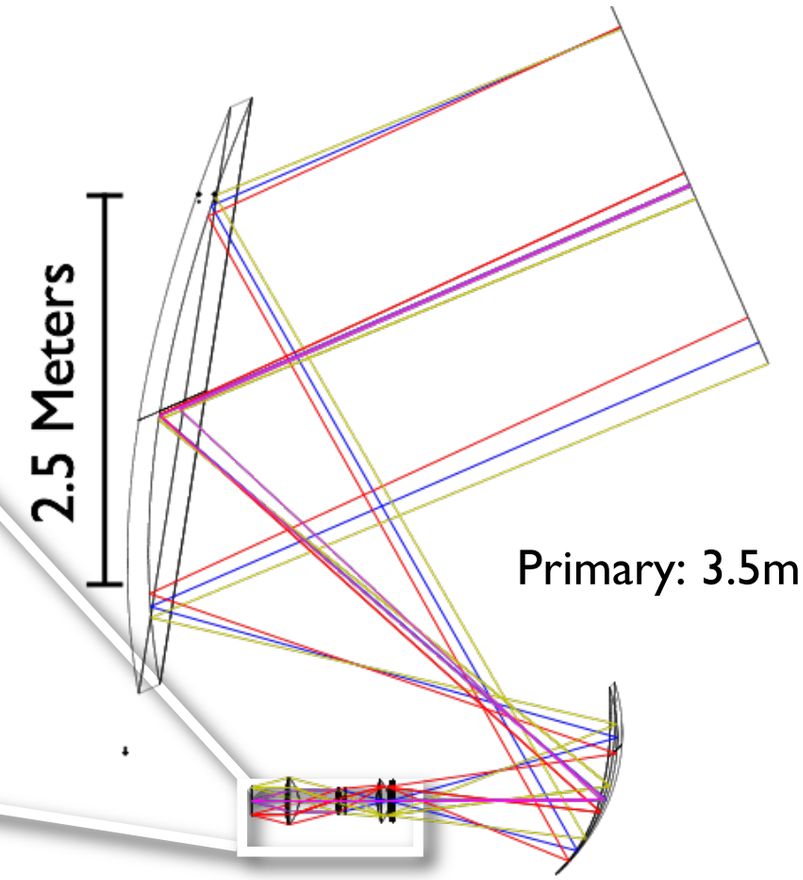


FIRST SEASON

- Period:
  May 2012 to June 2013
- Target:
  deep integration of
  3 patches 8 deg^2

Instrumental Design

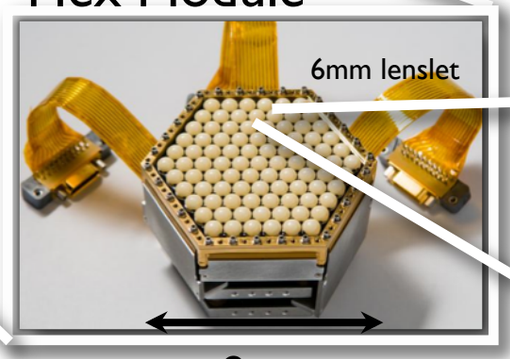




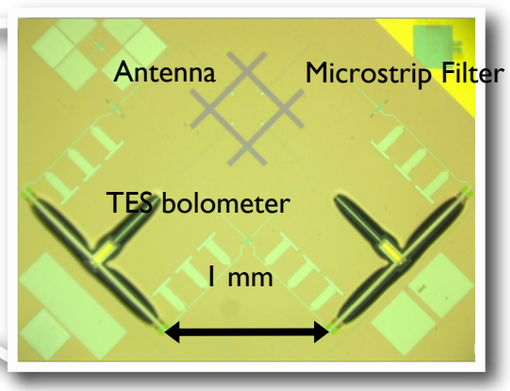
Huan Tran Telescope

1274 bolometers @ 150 GHz
Cooled to 250 mK

Hex Module

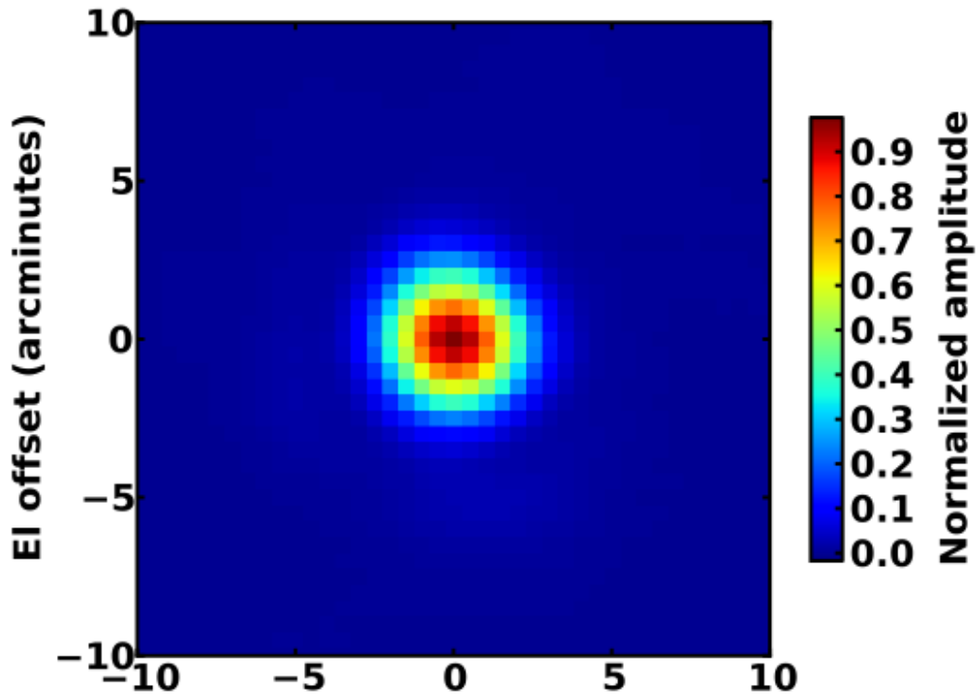


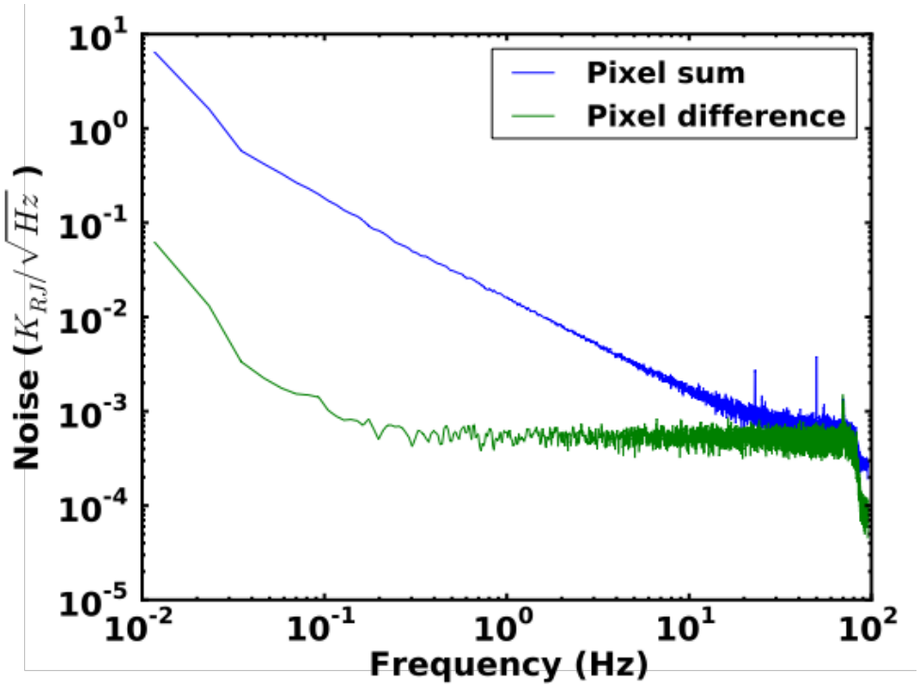
8cm



Instrument Characterization

- Ground based and astrophysical calibrators
  - Beam: Jupiter
  - Polarization angle: Tau A
- 3.5 arcmin beam FWHM
- Ellipticity < 5%, differential ellipticity 1%
- Array NET $23\ \mu K\sqrt{s}$





Map-making and power spectrum

- Filtered map-making

$$\hat{\mathbf{s}} = (\mathbf{A}^\top \mathbf{N}^{-1} \mathbf{A})^{-1} \mathbf{A}^\top \mathbf{F} \mathbf{d}$$

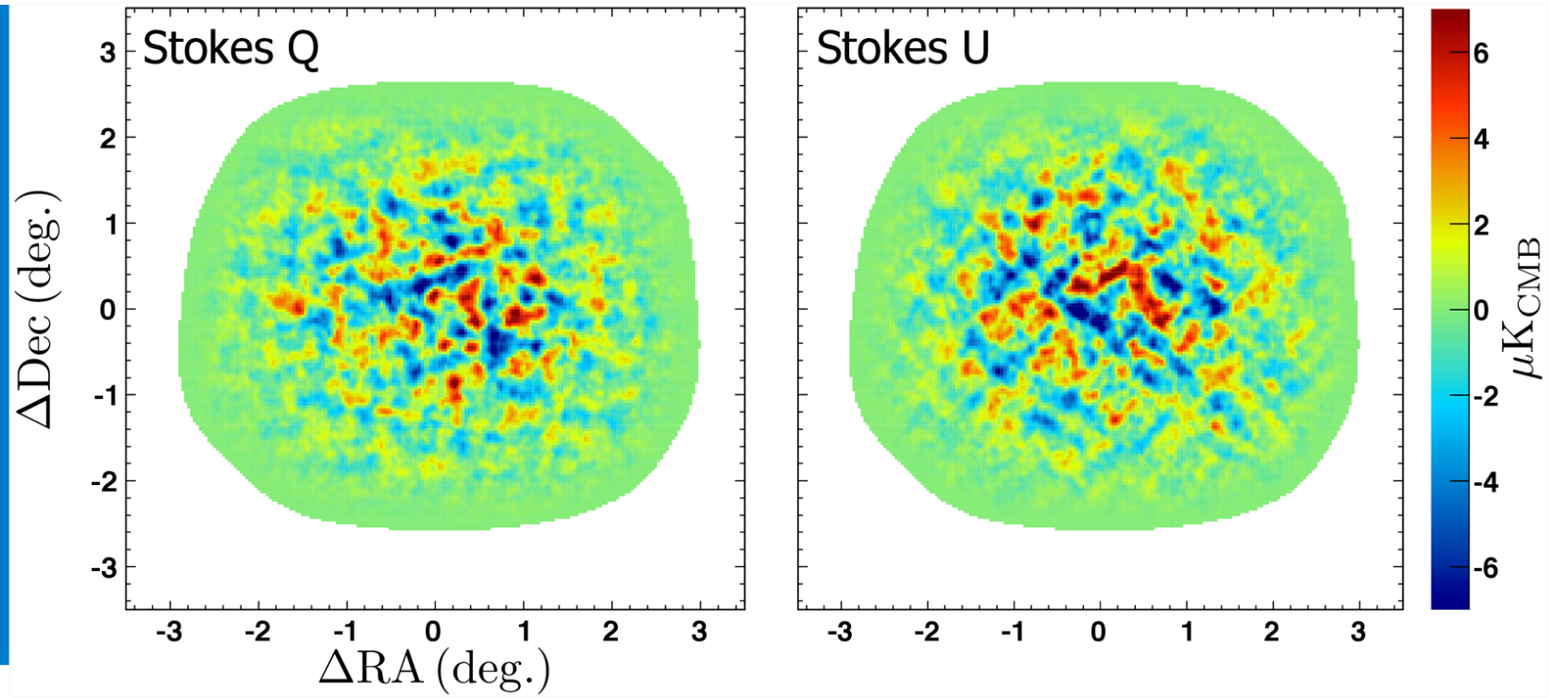
- Flat-sky MASTER power spectrum estimation with daily cross-spectra

Crosscheck and validation

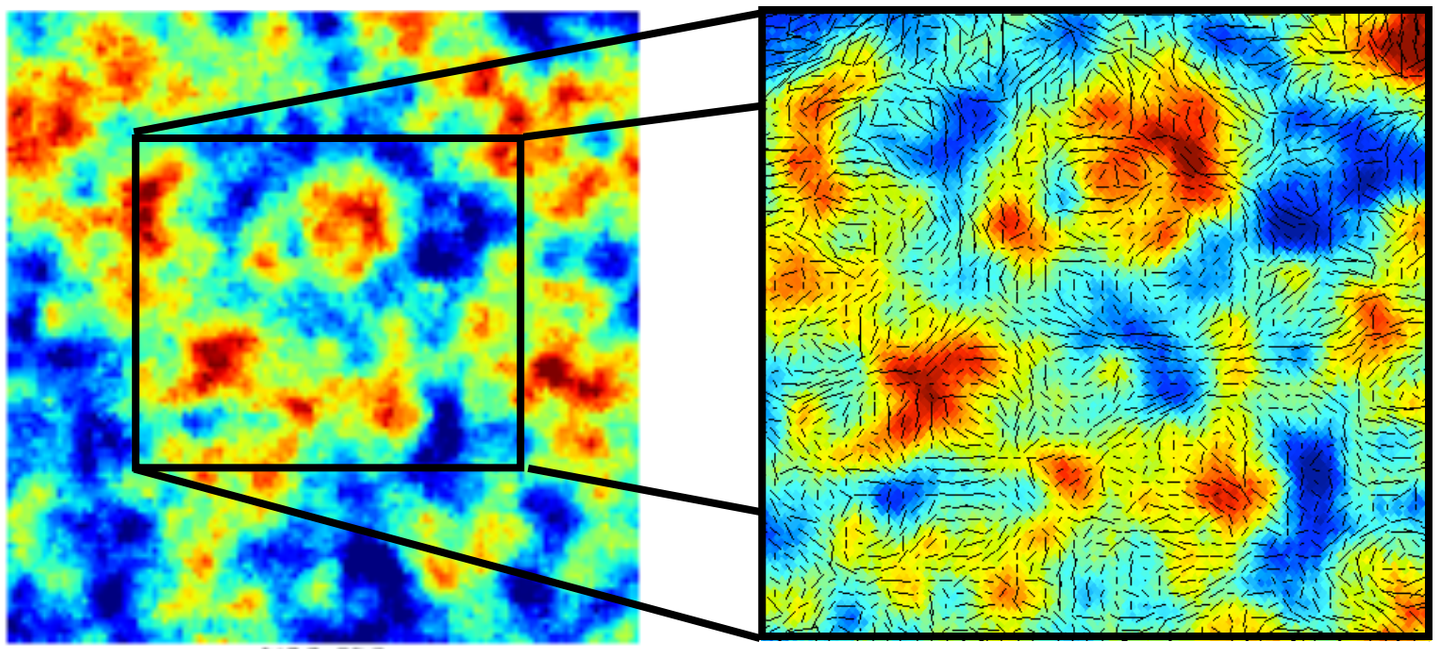
- Unbiased map-making

$$\hat{\mathbf{s}} = (\mathbf{A}^\intercal \mathbf{F} \mathbf{A})^{-1} \mathbf{A}^\intercal \mathbf{F} \mathbf{d}$$

- Curved-sky, pure, pseudo power spectrum estimator



Planck SMICA map



POLARBEAR preliminary

Results: cross-correlation with CIB

Polarization Measurement

$$\kappa = -\frac{1}{2}\nabla \cdot \mathbf{d}$$

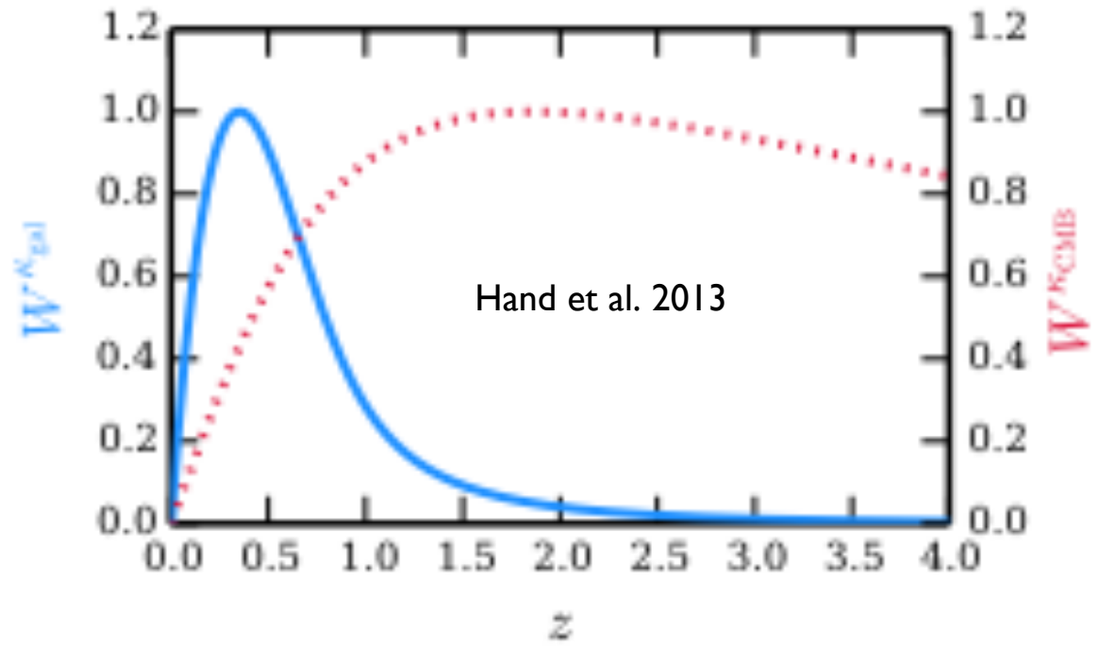
Estimator of κ from POLARBEAR polarization maps

X

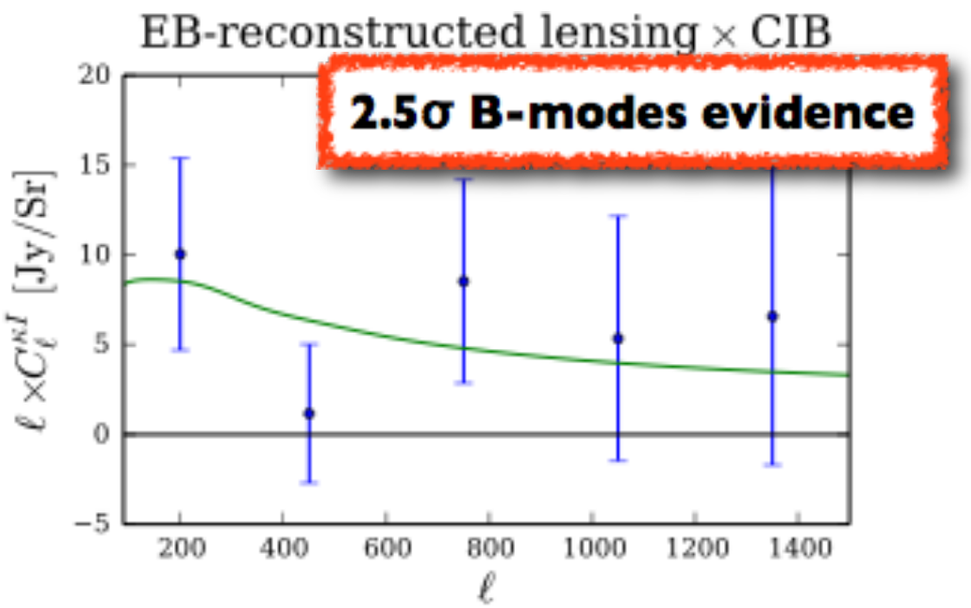
Cosmic Infrared Background

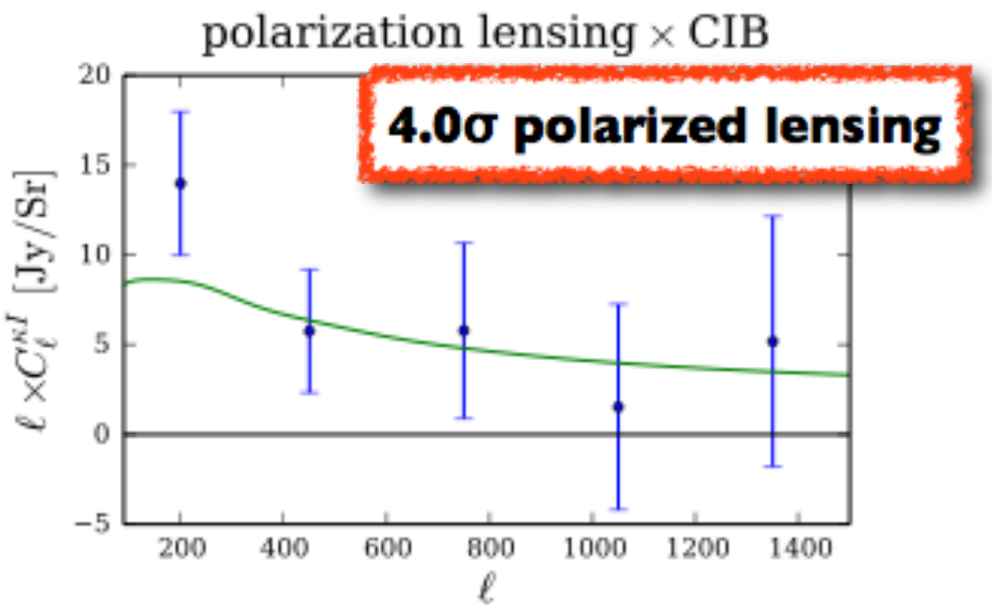
Tracer of density field

CIB map from Hershel



Phys. Rev. Lett. 112, 131302 (2014)
Editors' Suggestion

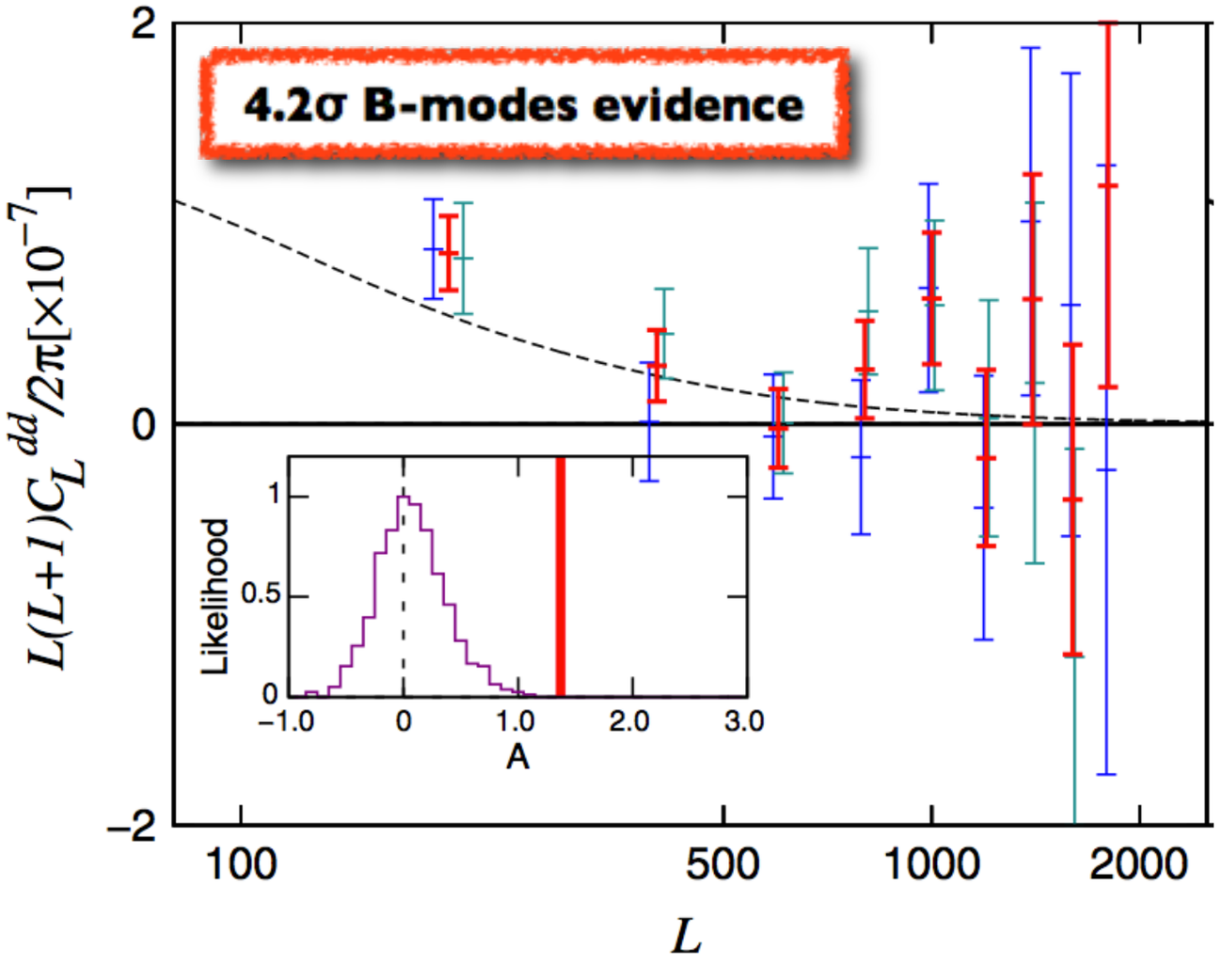




Results: lensing from polarization alone

Polarization lensing Measurement → d estimation → C_ℓ^{dd}

Phys. Rev. Lett. 112, 131302 (2014)
Editors' Suggestion



Results: BB spectrum measurement

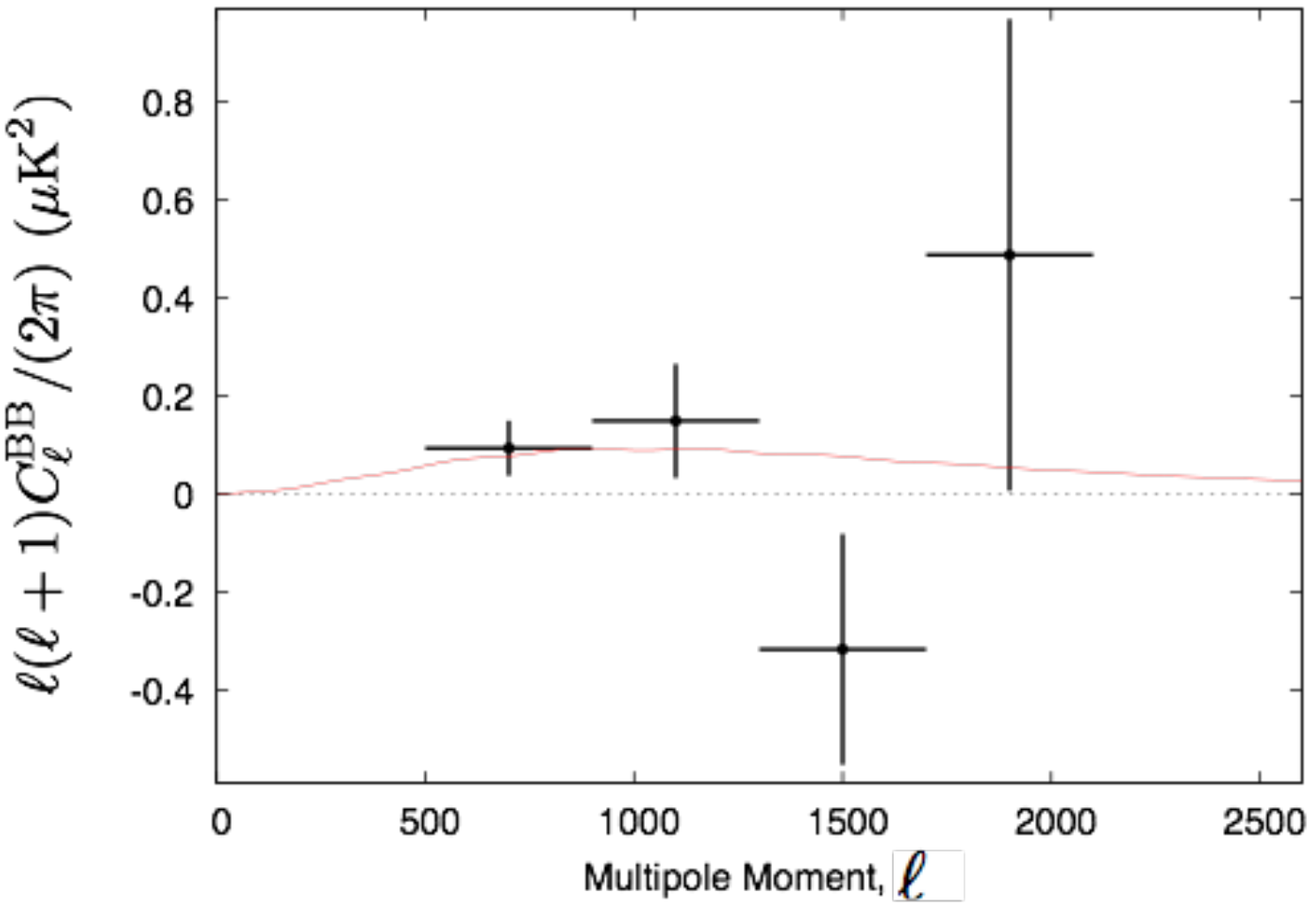
- First direct evidence of lensing B-modes

97.5% c.l. B-modes evidence

- Amplitude of lensing consistent with ΛCDM

Astrophysical J. 794, 171 (2014)

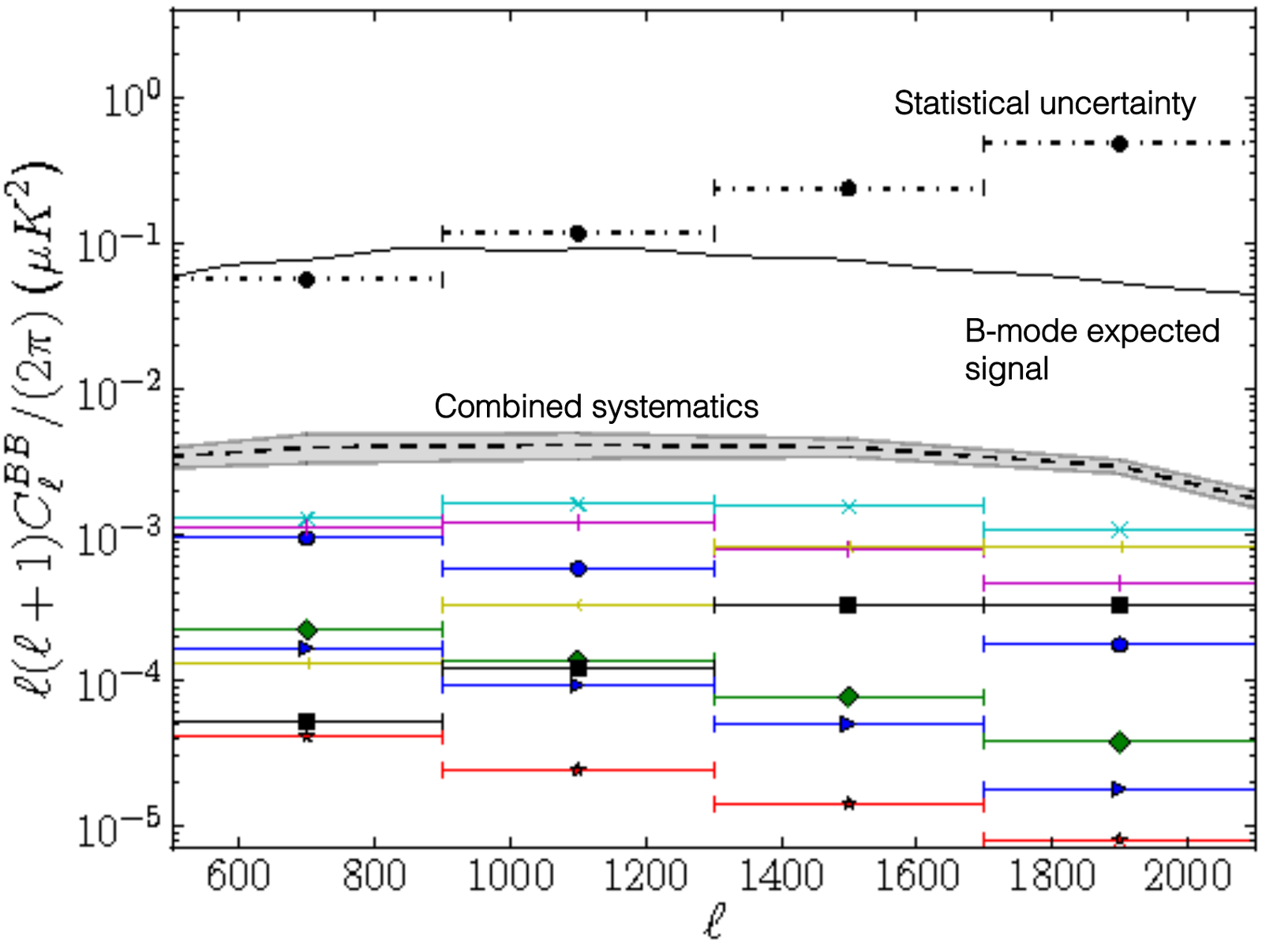
- Negligible contamination from astrophysical foregrounds
- Negligible contamination from systematic effects



Control of the systematics

- Systematics pipeline:
  systematic injection and propagation through the whole science pipeline

⇨ Residual systematics are negligible



Most notably:

Boresight and differential pointing

Differential beam size

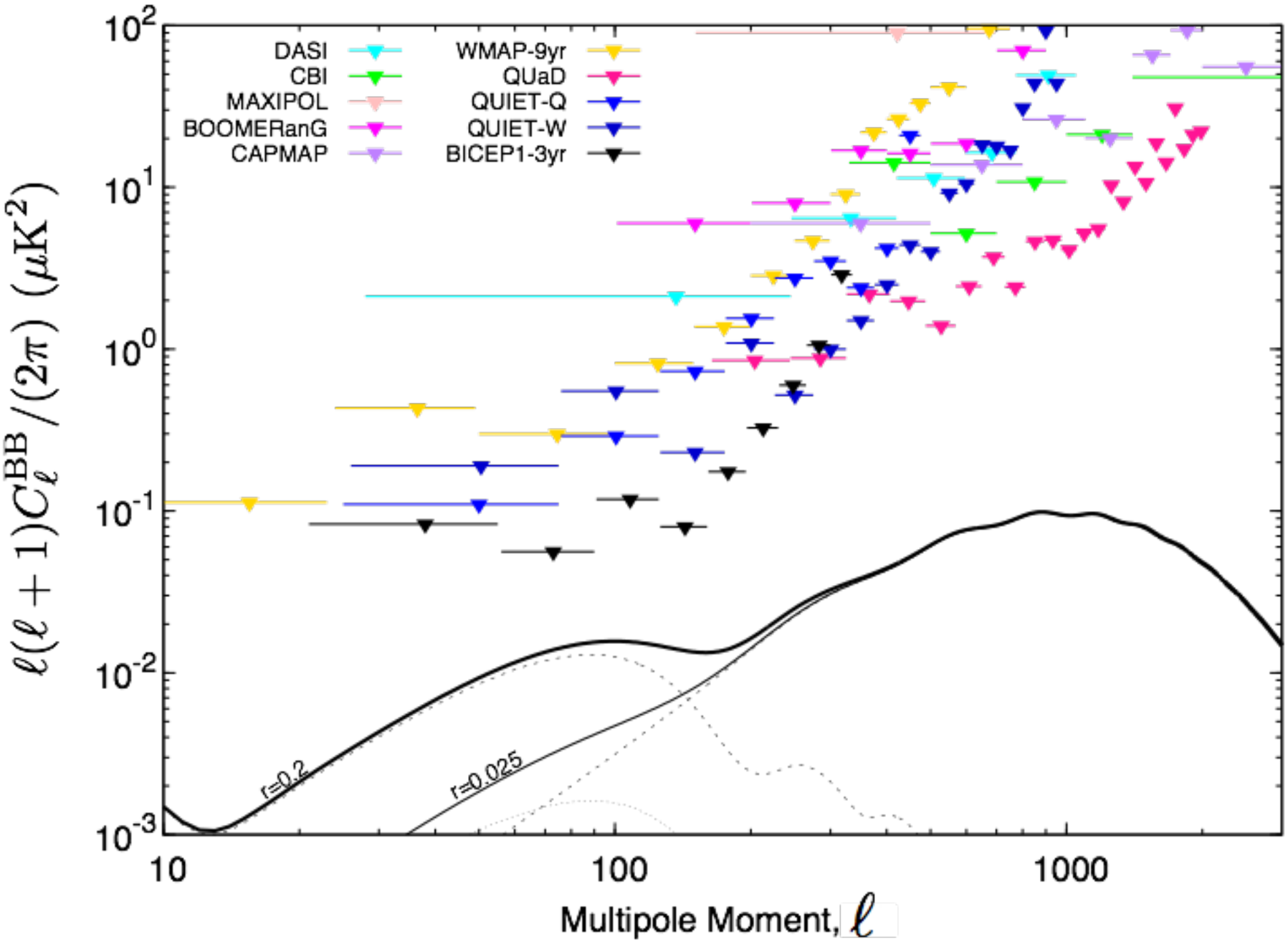
Polarization angle

Differential beam ellipticity

HWP dependent gain

A very active field

Mar 2014 — 2015



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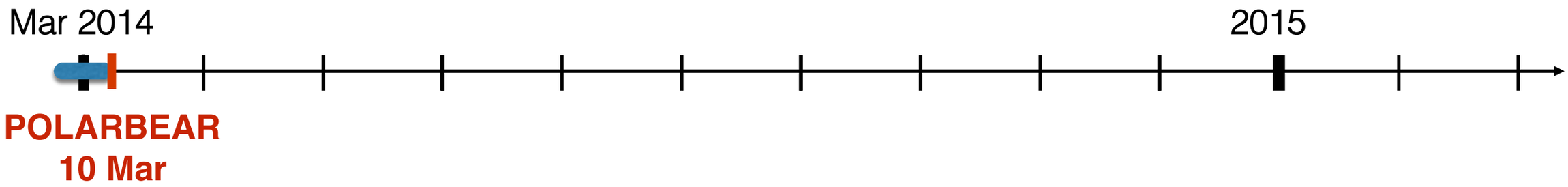
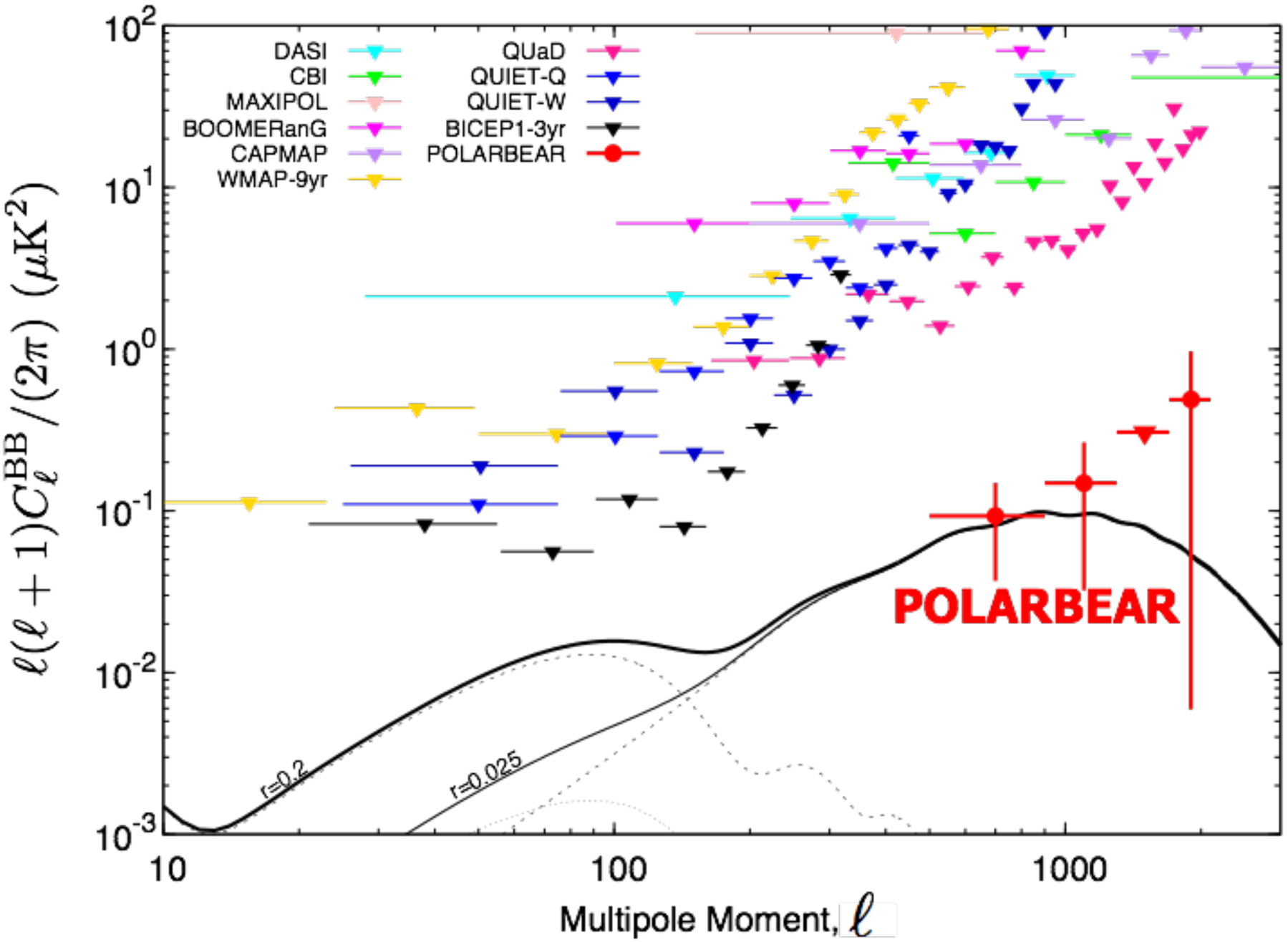


POLARBEAR
10 Mar



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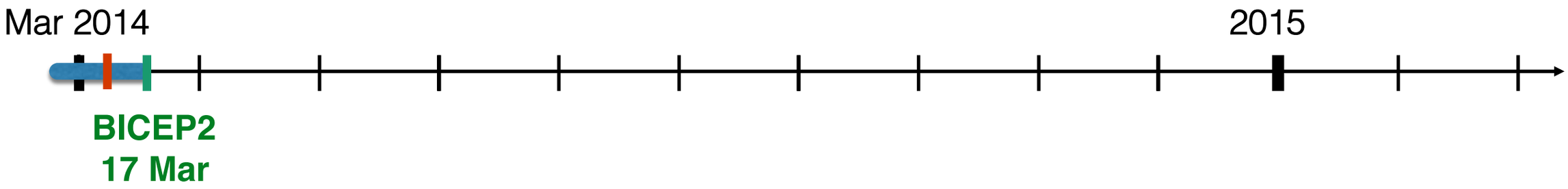

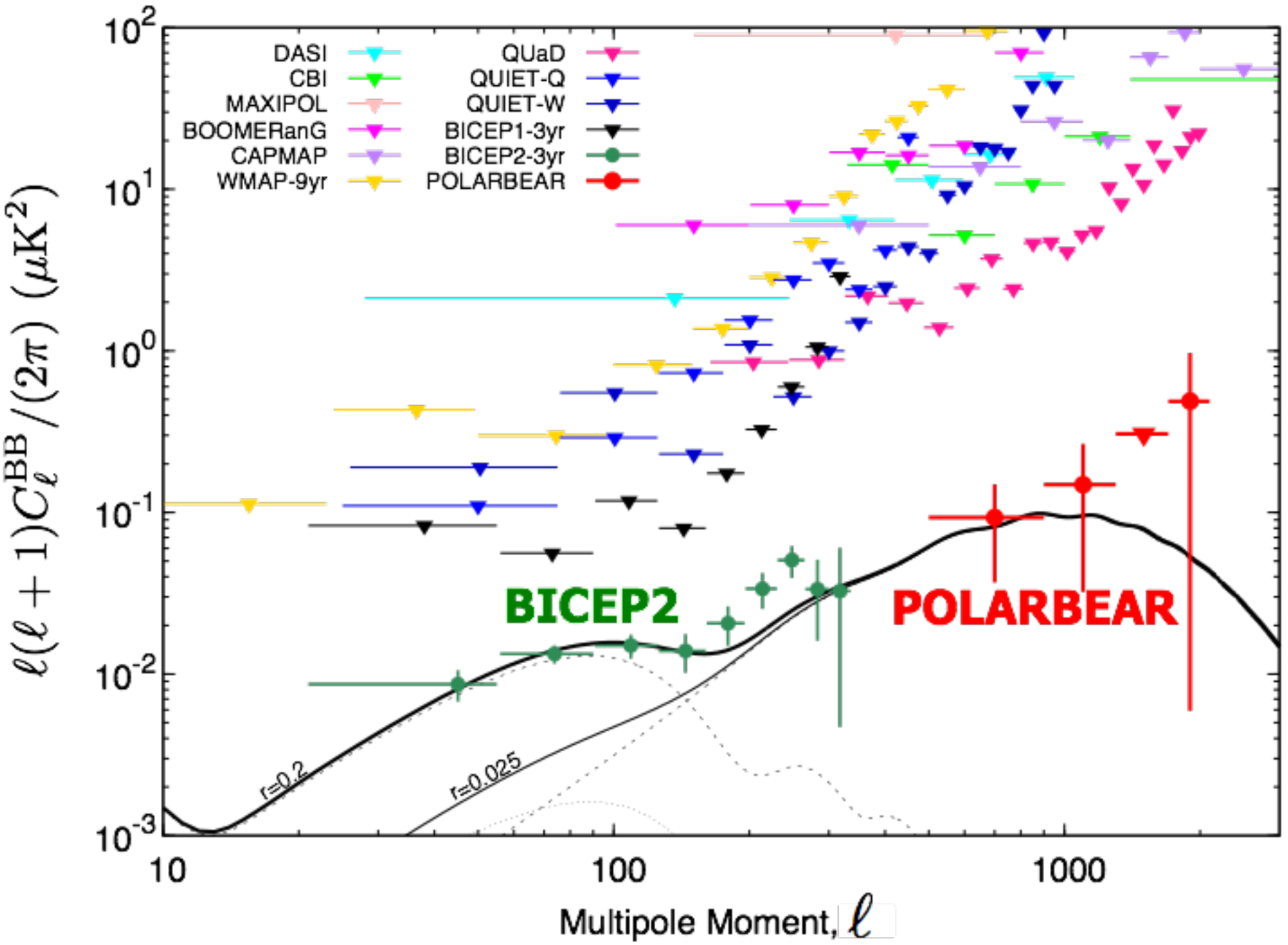

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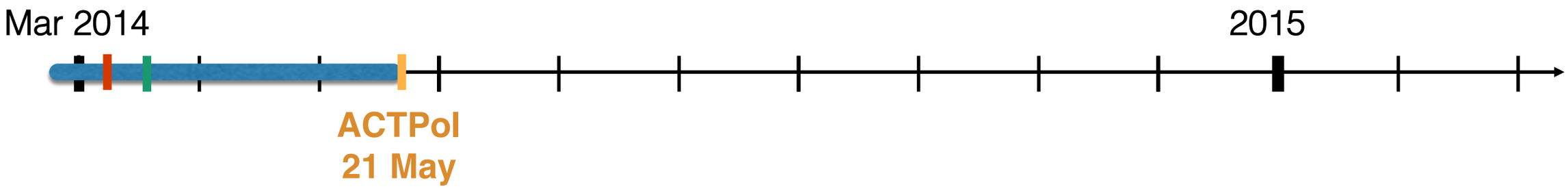
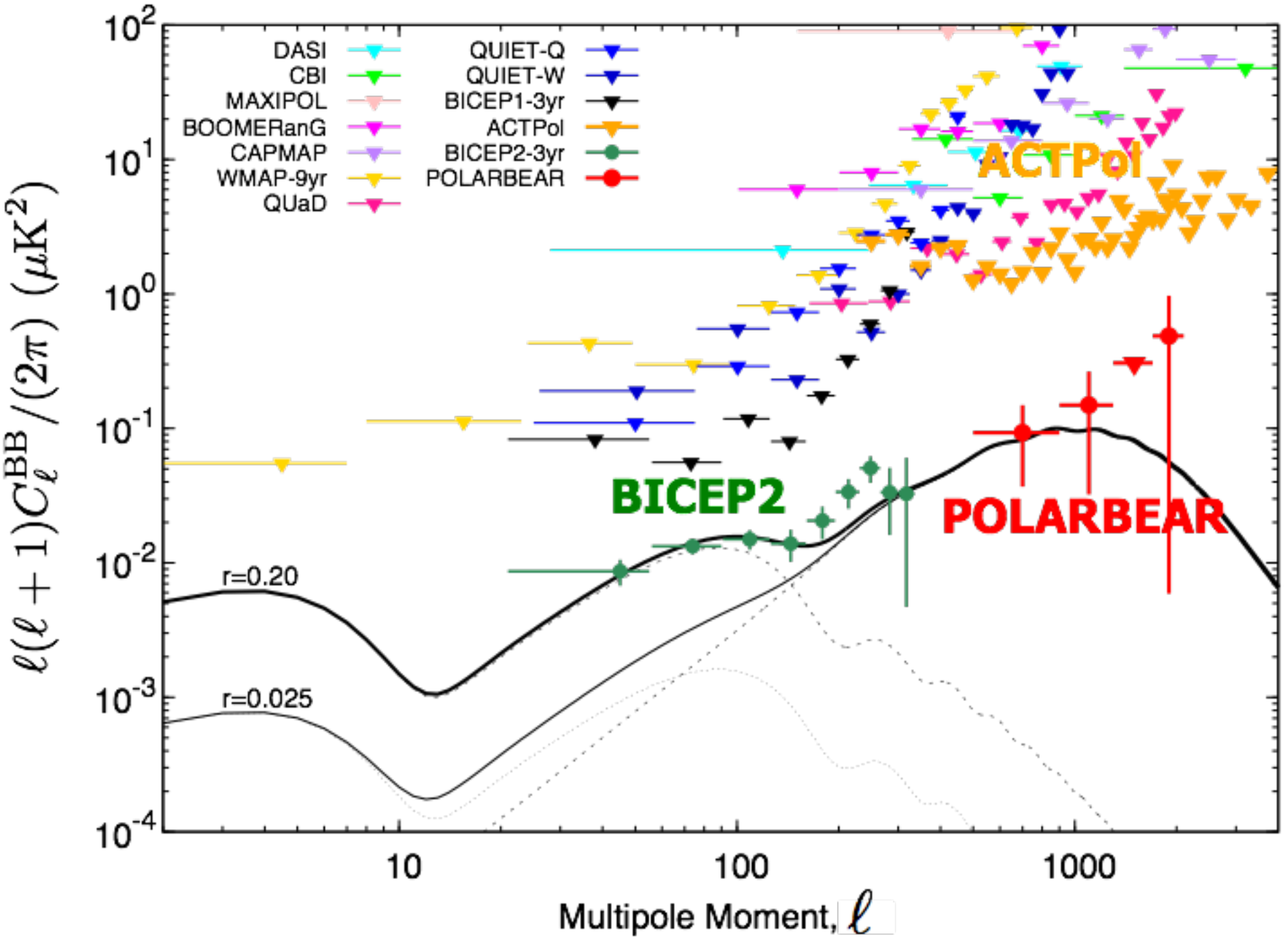


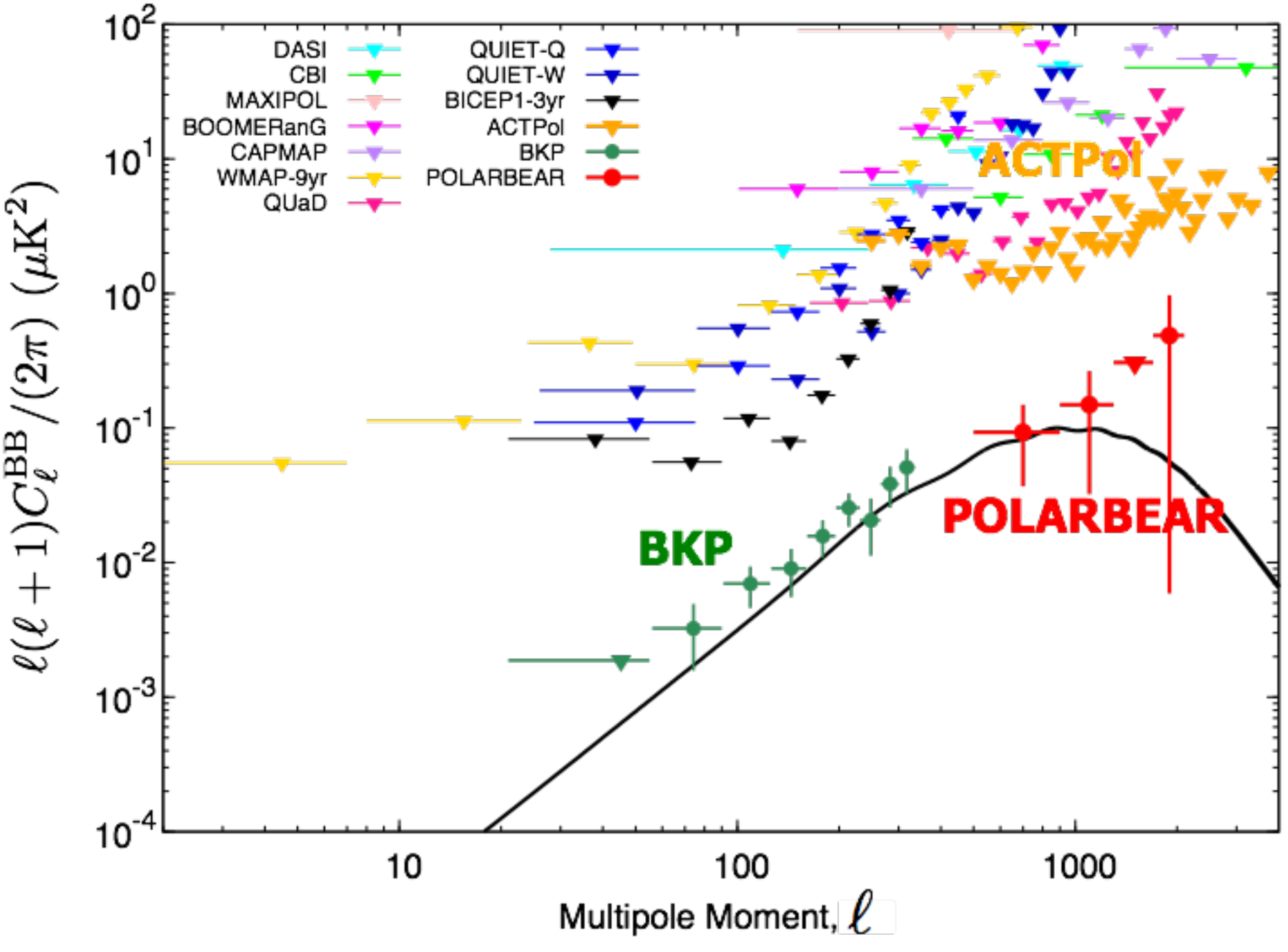


A very active field

Mar 2014

2015

BICEP2 - Keck Array - Planck
2 Feb



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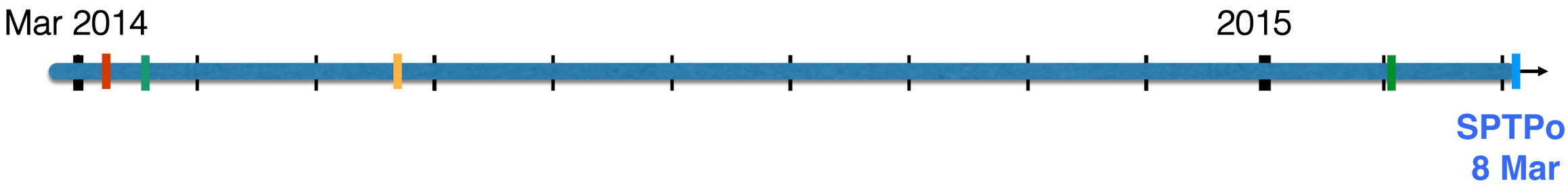

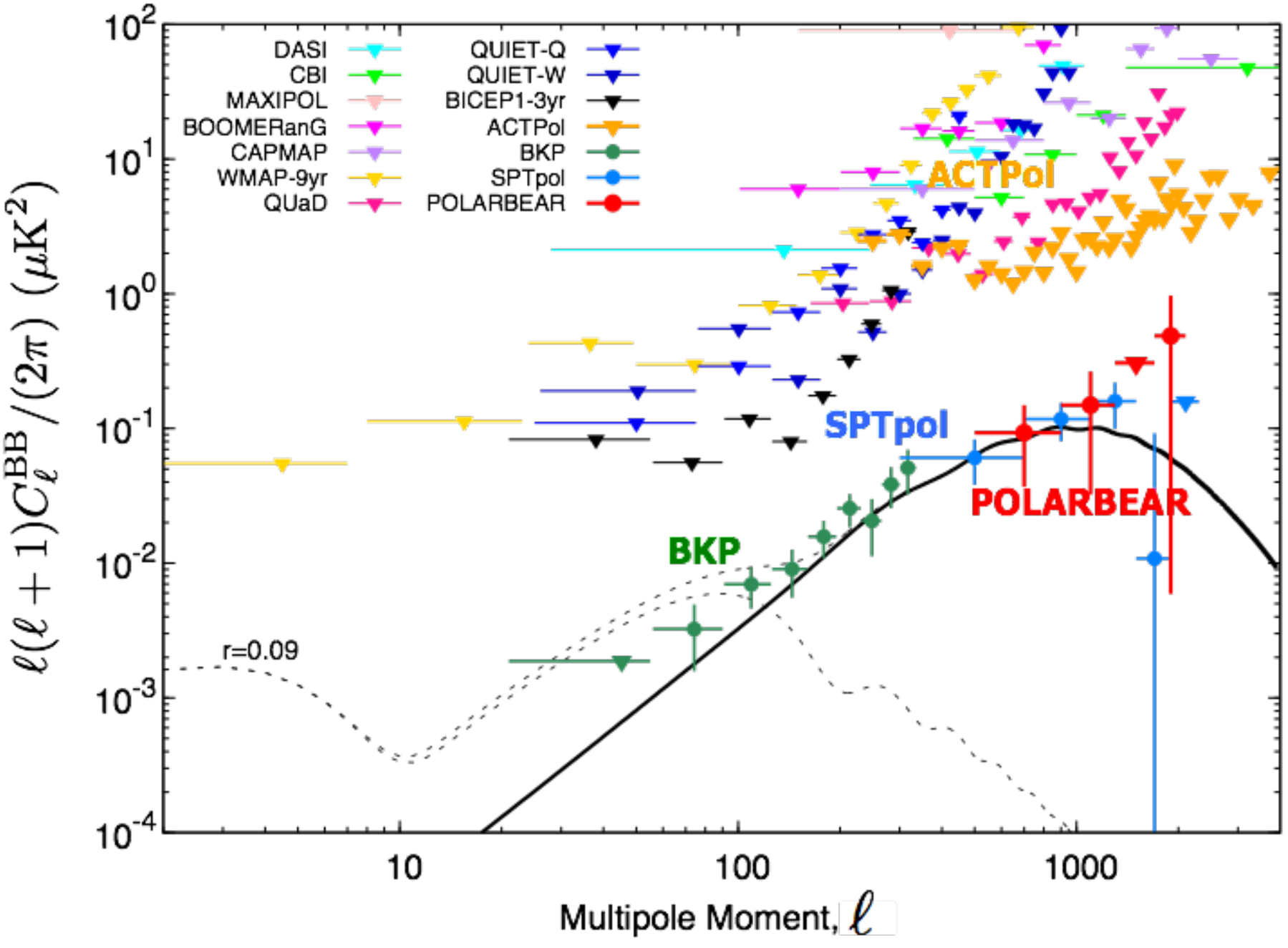

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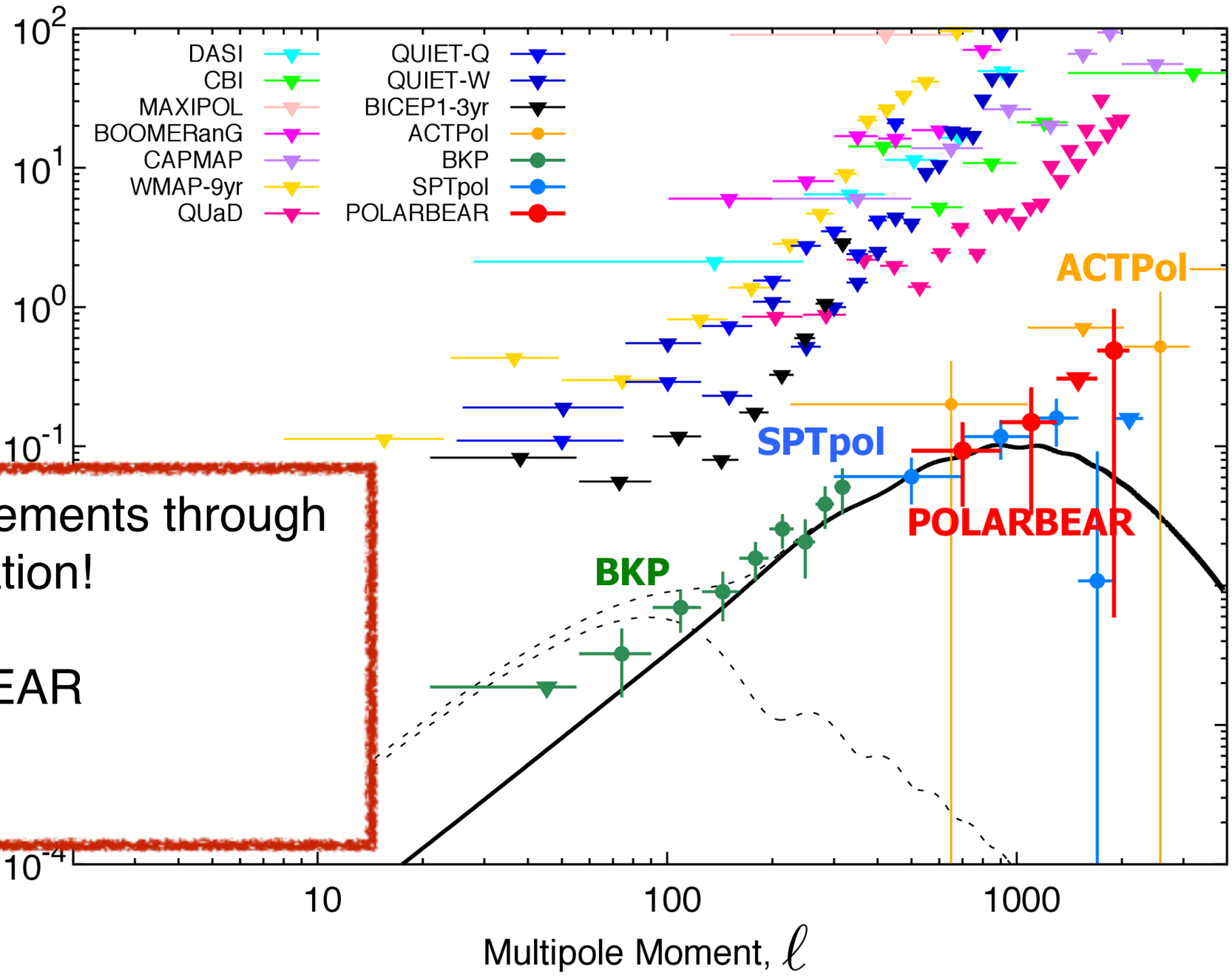


Plus measurements through cross-correlation!

- SPTPol
- POLARBEAR
- ACTPol
- Planck

Current Status

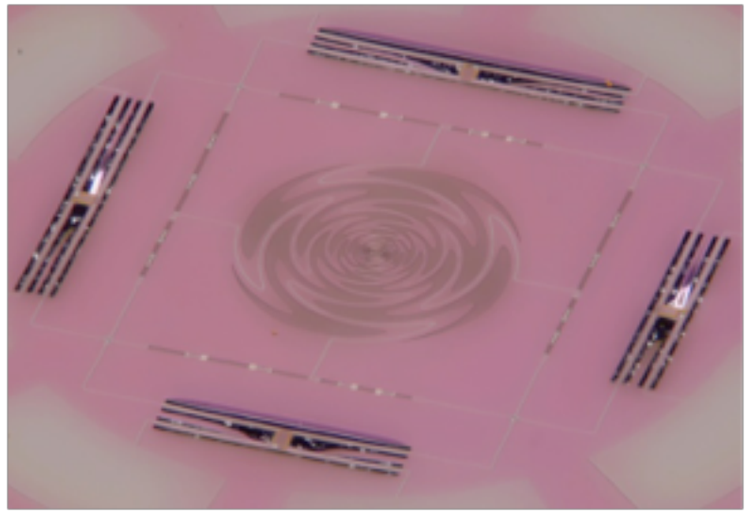
- Season I successfully probed small scales
- Systematics: under control
- Sensitivity: close to lensing B-modes level
- BICEP2 and Planck: foregrounds dominate large scales

The Future: POLARBEAR 2 and Simons Array

2016: POLARBEAR 2

new telescope and receiver

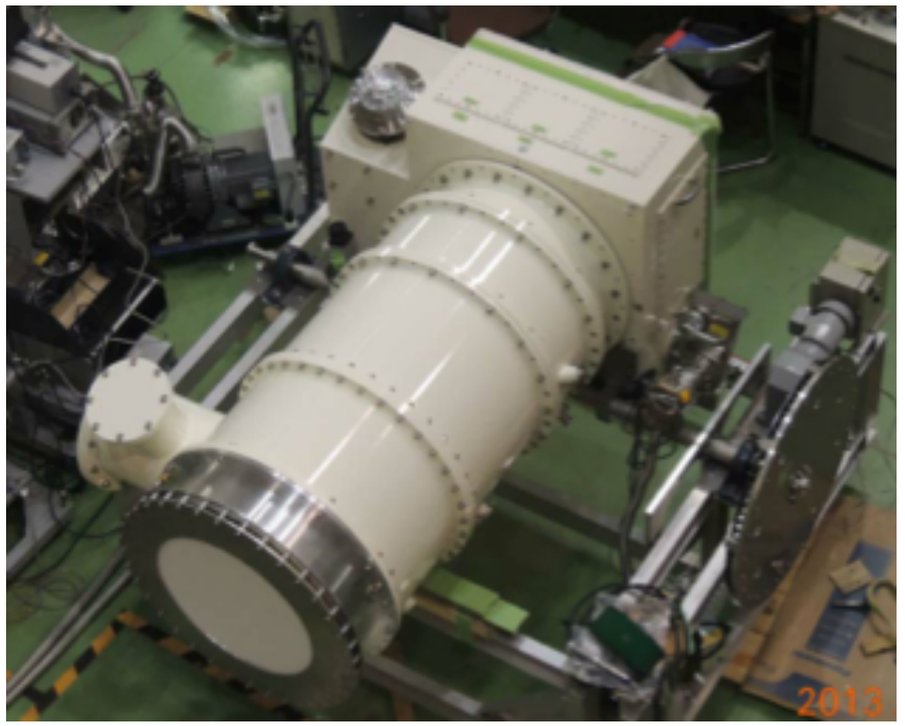
- 7,588 detectors
- Dichroic pixels (95/150 GHz)



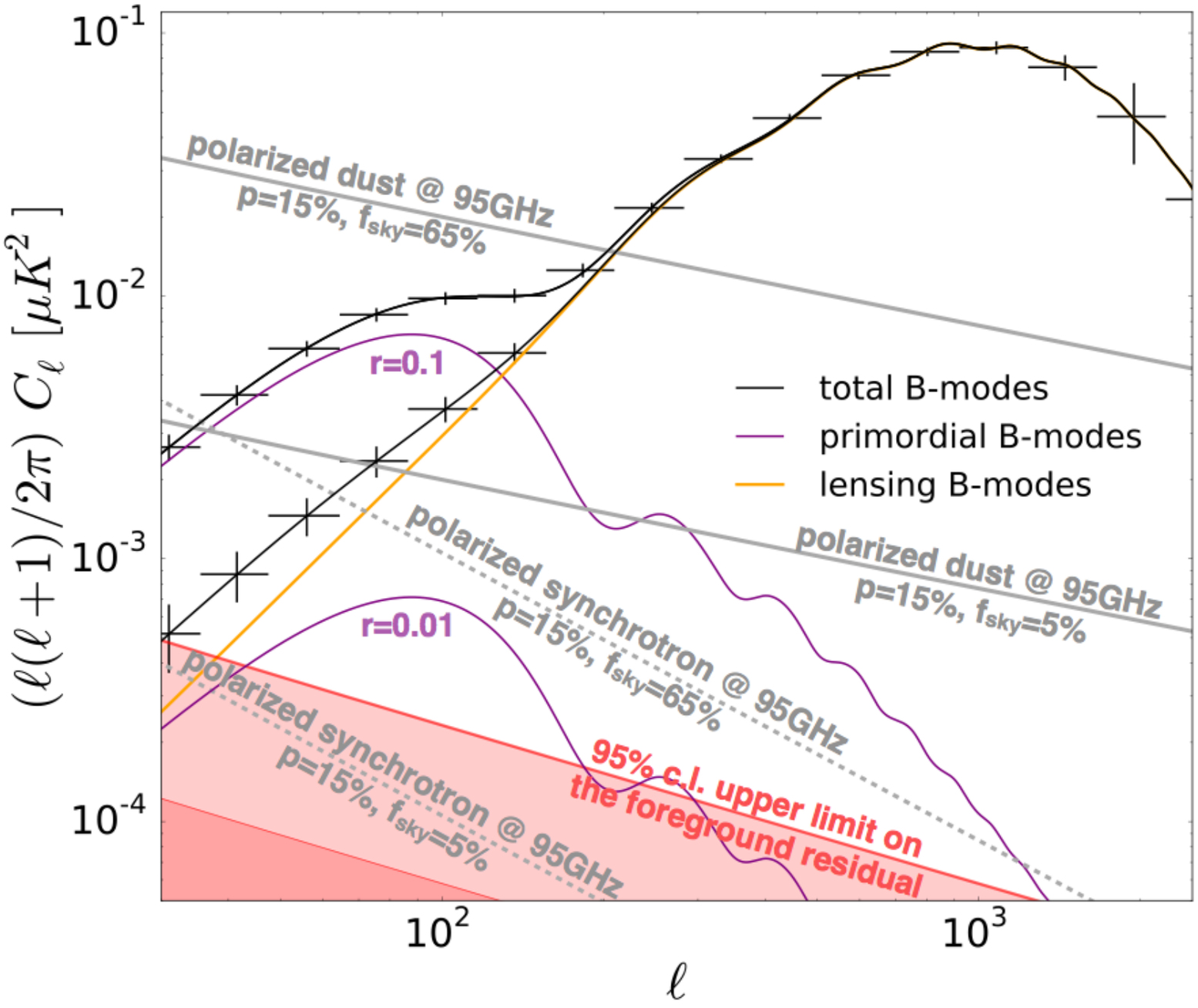
2017: Simons Array

new telescopes, 2 new PB2-like receivers

- 22,764 detectors
- 220 GHz channel



Simons Array: sensitivity and foreground rejection



Simons Array
90/150/220 GHz
combined with
Planck and C-Bass

$$\sigma(r = 0.1) = \begin{matrix} 6 \cdot 10^{-3} \\ (4 \cdot 10^{-3}) \end{matrix}$$

$$\sigma(\Sigma m_\nu) = \begin{matrix} 40\ \text{meV} \\ (19\ \text{meV}) \end{matrix}$$

Combined with DESI BAO

$r < 0.09$ Planck 2015 XIII

$\Sigma m_\nu < 0.15$ eV

Palanque-Delabrouille et al (2015)

*Dust level: Planck Intermediate XXX

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

Summary

- B-mode era has begun and accuracy is rapidly increasing
- POLARBEAR: probing CMB B-Modes from the Atacama desert
- SEASON 1: first measurement of lensing B-modes using the CMB alone, validated with the CIB cross-correlation
- SEASON 1: Analysis ongoing.
- FUTURE: probing both lensing and primordial B-Modes with POLARBEAR 2 and Simons Array. High sensitivity and foreground rejection with multi-frequency coverage.