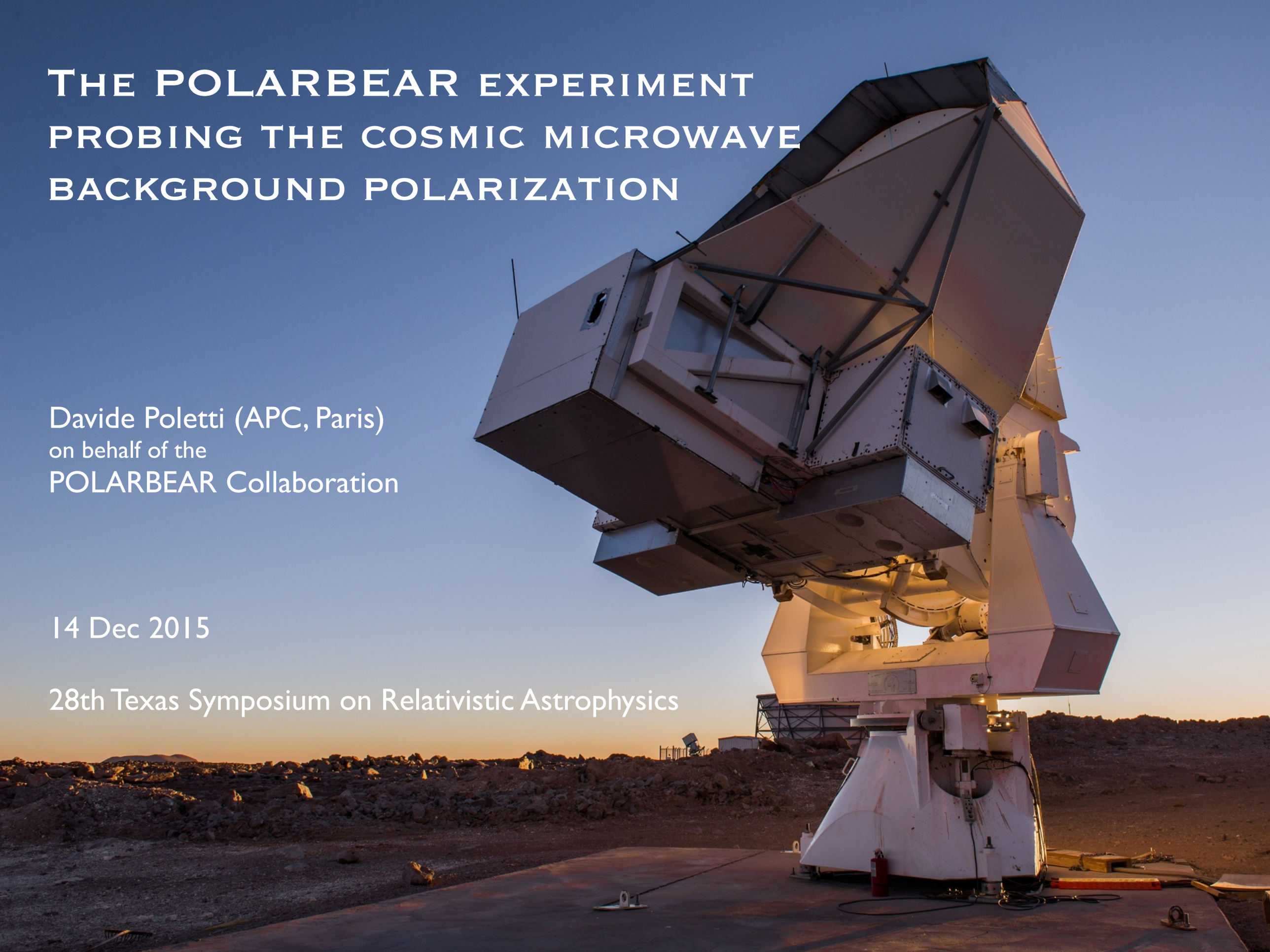
The POLARBEAR experiment probing the cosmic microwave background polarization

Davide Poletti (APC, Paris)
on behalf of the
POLARBEAR Collaboration

14 Dec 2015

28th Texas Symposium on Relativistic Astrophysics



POLARBEAR Collaboration

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

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Suguru Takada

Cardiff University
Peter Ade

NASA Goddard
Nathan Miller

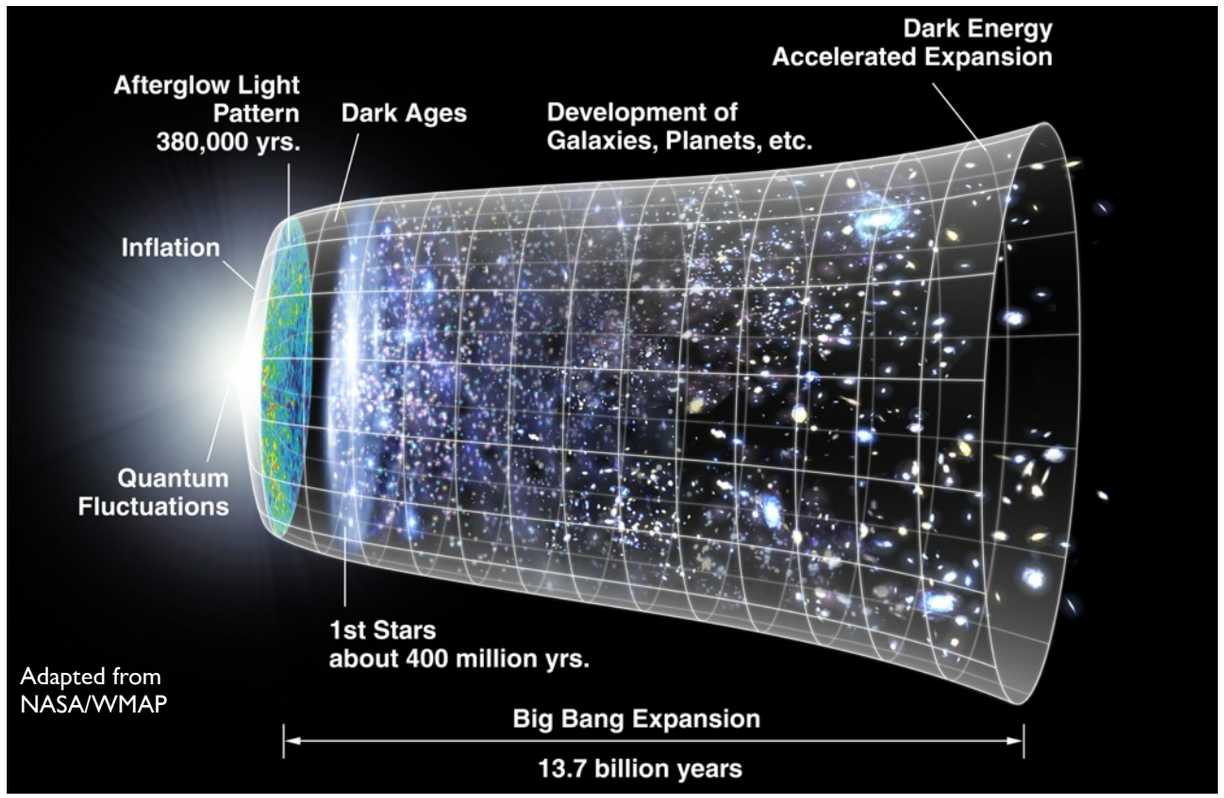
Princeton
Zigmund Kermish

Católica (PUC)
David Boettger
Rolando Dunner

And many more in years past

- B-modes science and measurements
- The POLARBEAR experiment
- First season’s results
- POLARBEAR 2 and Simons array

The Cosmic Microwave Background

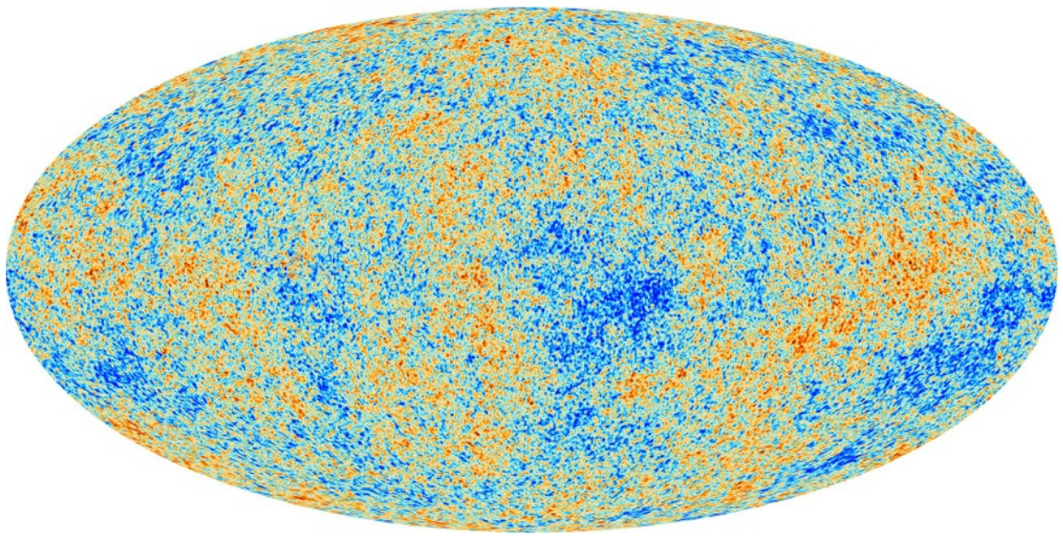


The CMB:

- picture of the 380,000 years old universe
- information on the inflationary phase

Temperature anisotropies:

- ΛCDM confirmed
- Cosmological information exploited

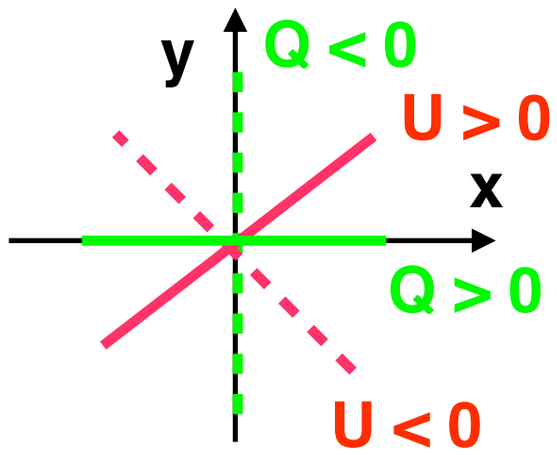


Planck Collaboration

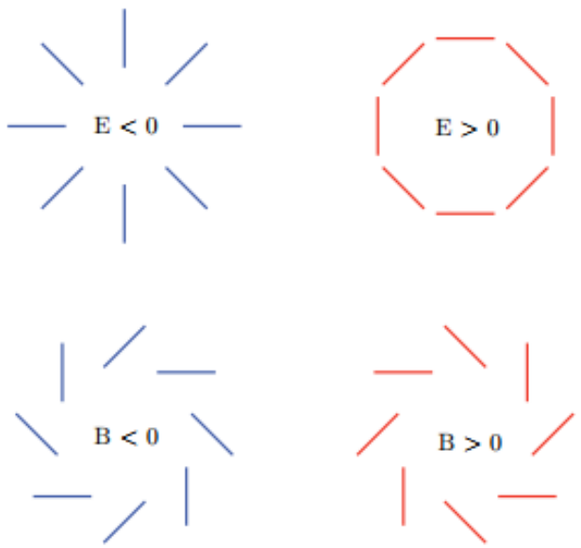
The CMB polarization

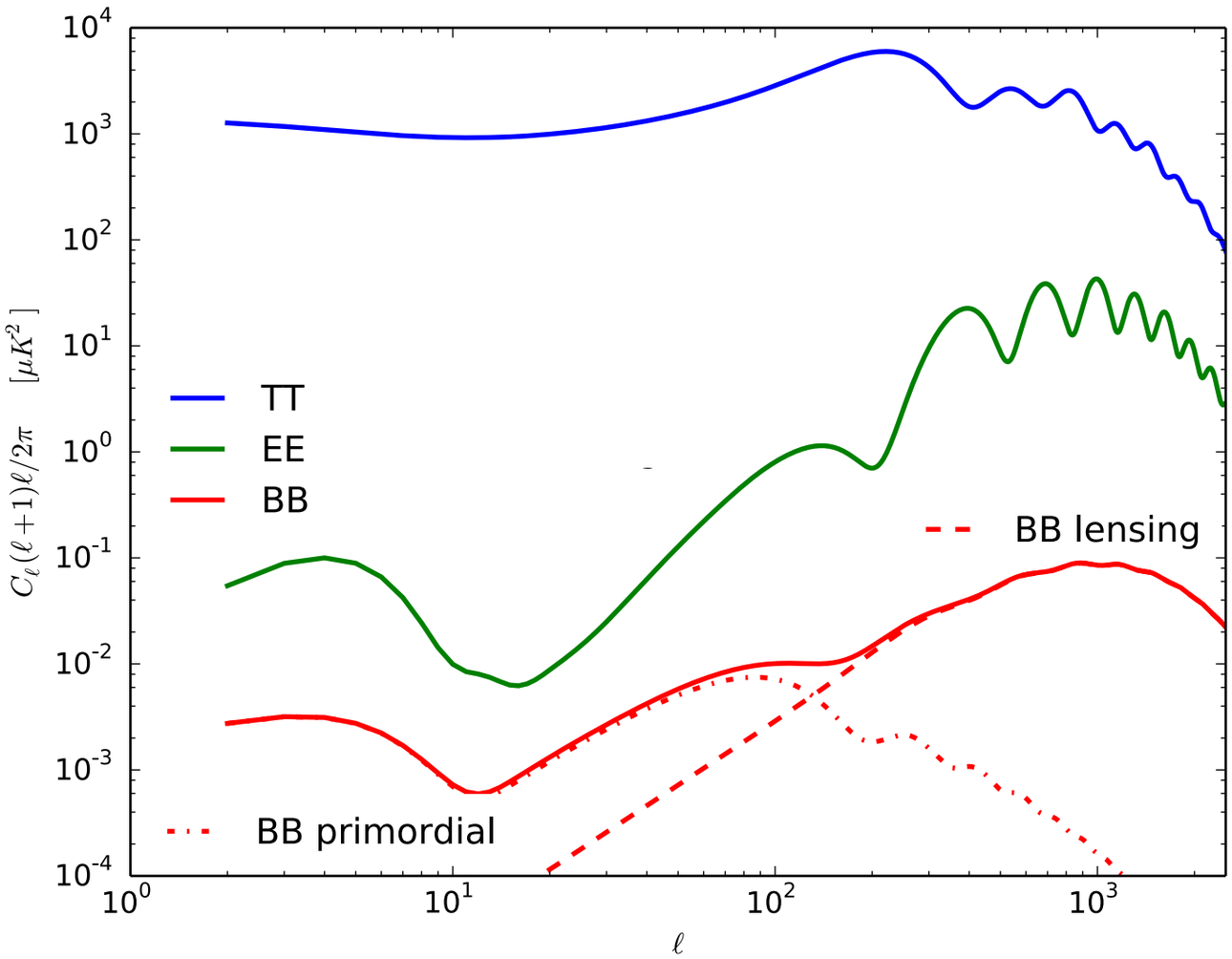
Polarization field

⇨ Q, U Stokes parameters



⇨ Decomposed in E and B modes





Primordial B-modes

Perturbations at the last scattering surface:

- Scalar ⇨ E only (to linear order)
- Tensor ⇨ E and B

Tensor perturbation after inflation:

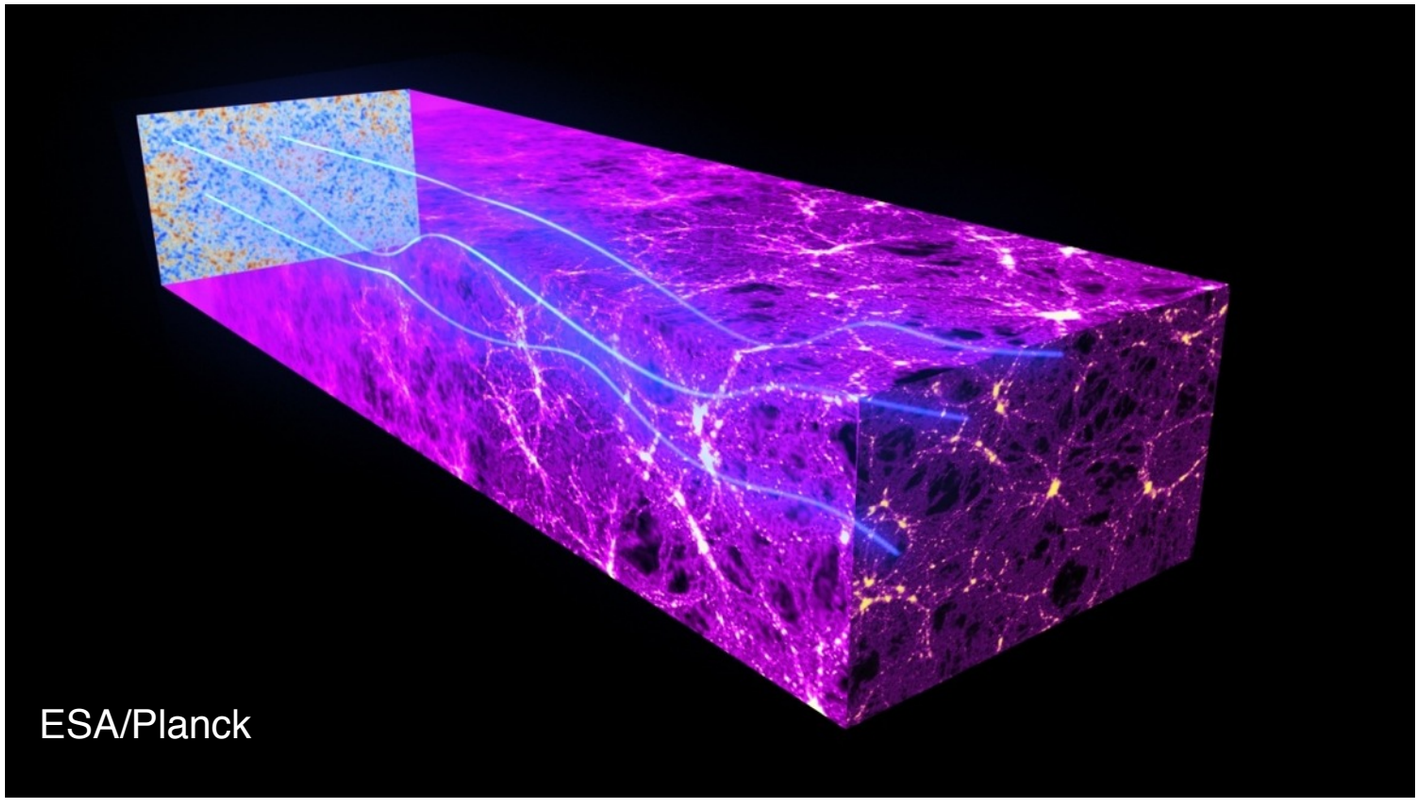
- **r**

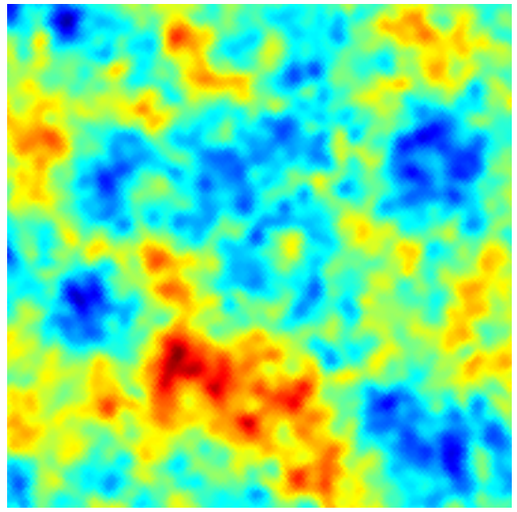
  Energy scale of inflation ($\sim 10^{16}$ GeV for r~0.1)

- **n_t**

  Consistency relation ($r = -8\, n_t$)

Lensing B-Modes





$$\phi(\hat{\mathbf{n}}) = -2\int \mathrm{d}D \frac{D_s - D}{DD_s}\Psi(D\hat{\mathbf{n}}, D)$$

$$\mathbf{d} = \nabla\phi$$

$$\delta E(\mathbf{l};\mathbf{l}') = -[E(\mathbf{l}')\cos 2\varphi_{\mathbf{l}'\mathbf{l}} - B(\mathbf{l}')\sin 2\varphi_{\mathbf{l}'\mathbf{l}}][\mathbf{l}\cdot(\mathbf{l}-\mathbf{l}')]\phi(\mathbf{l}-\mathbf{l}')$$

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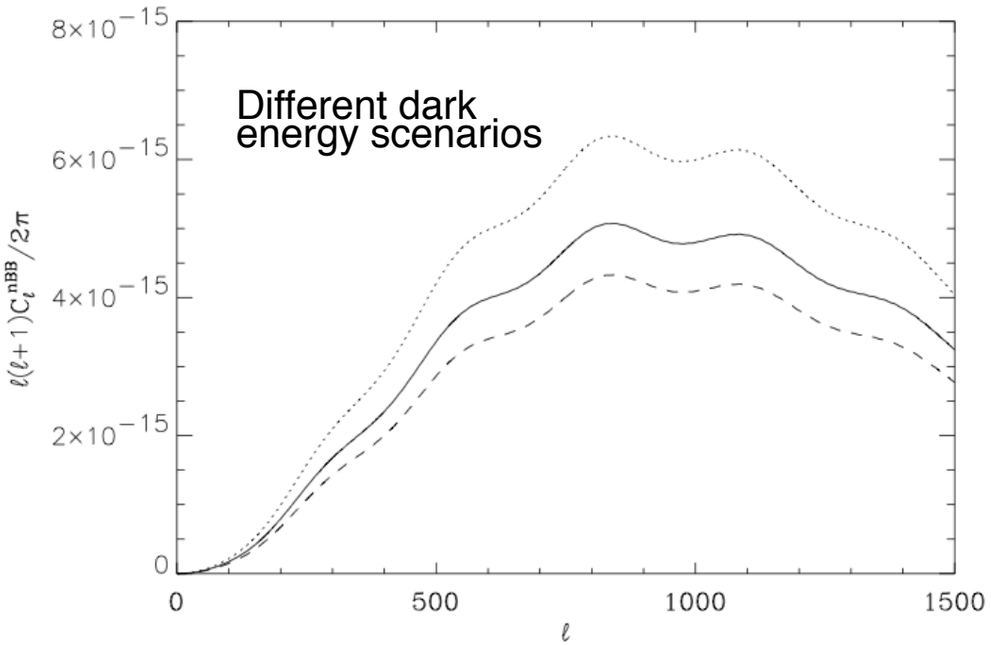
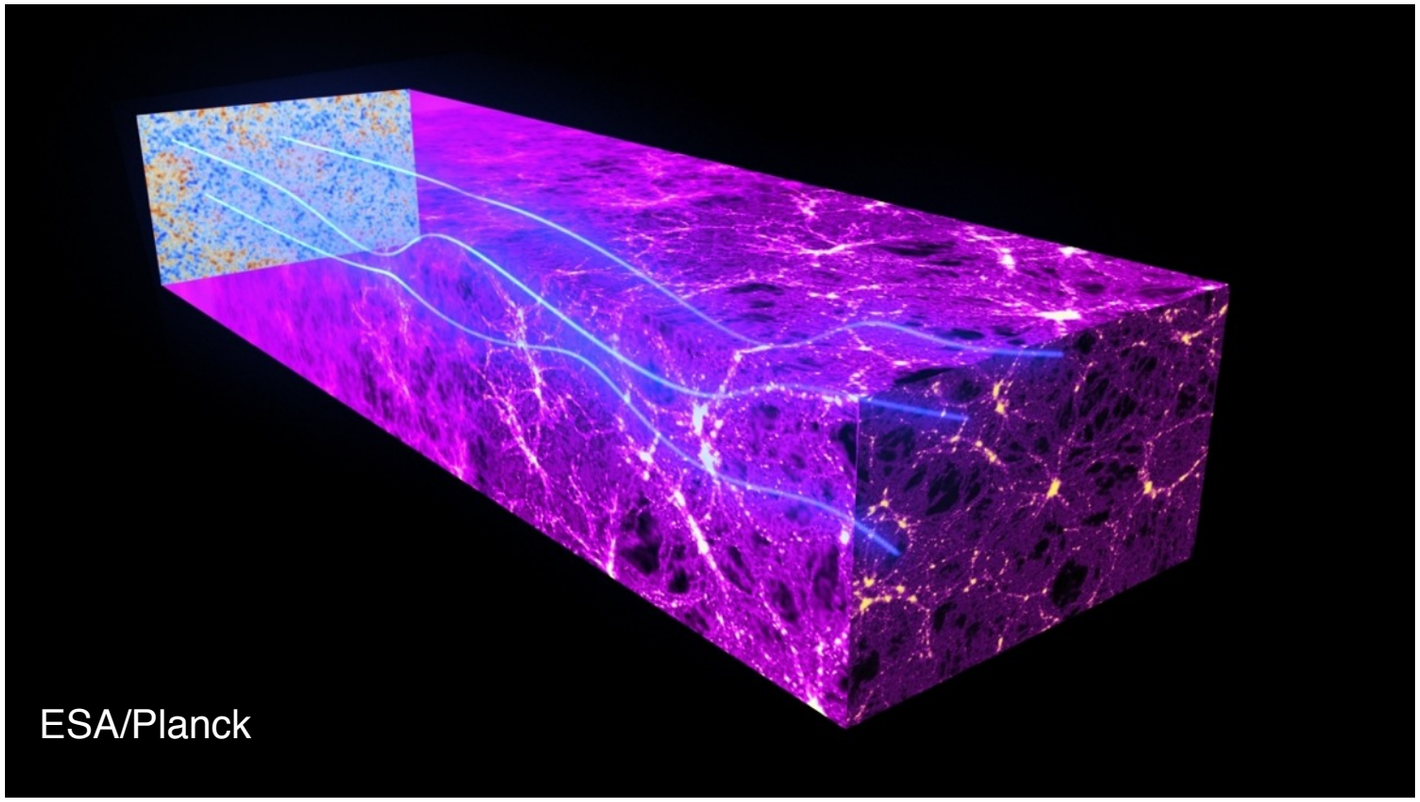
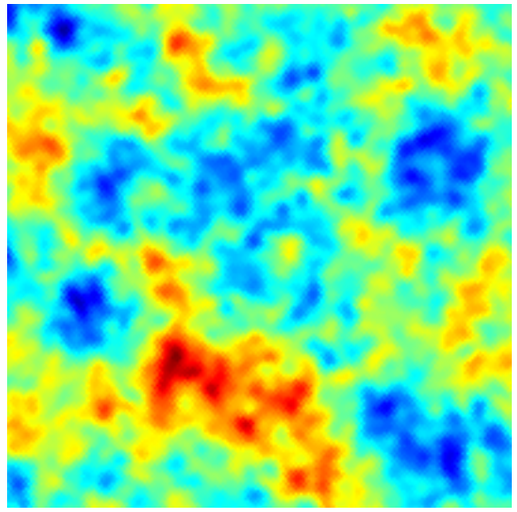
Acquaviva and Baccigalupi (2006)



Lensing B-Modes





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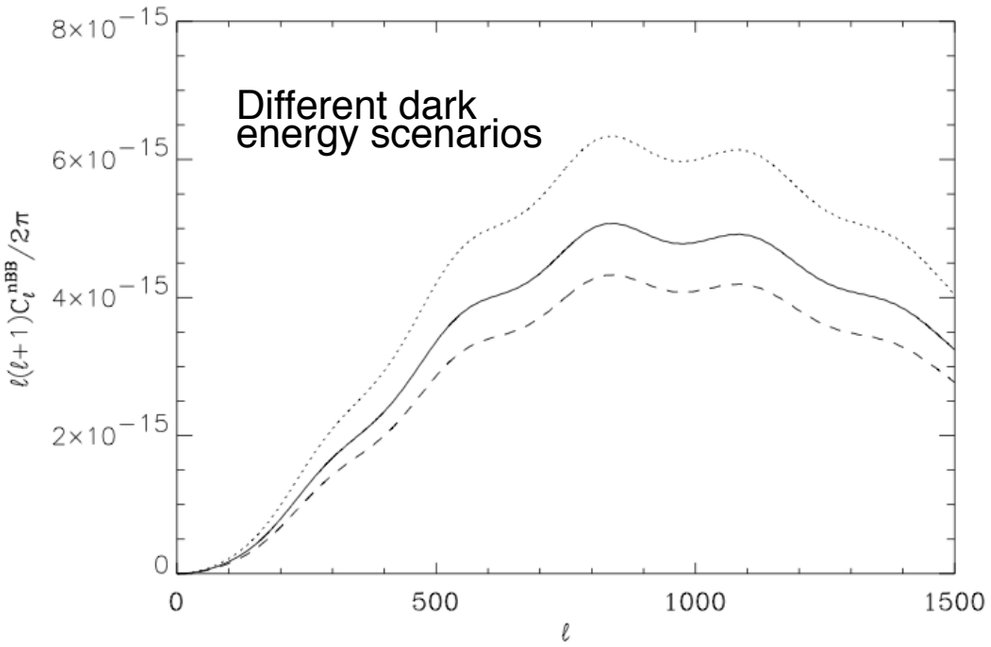
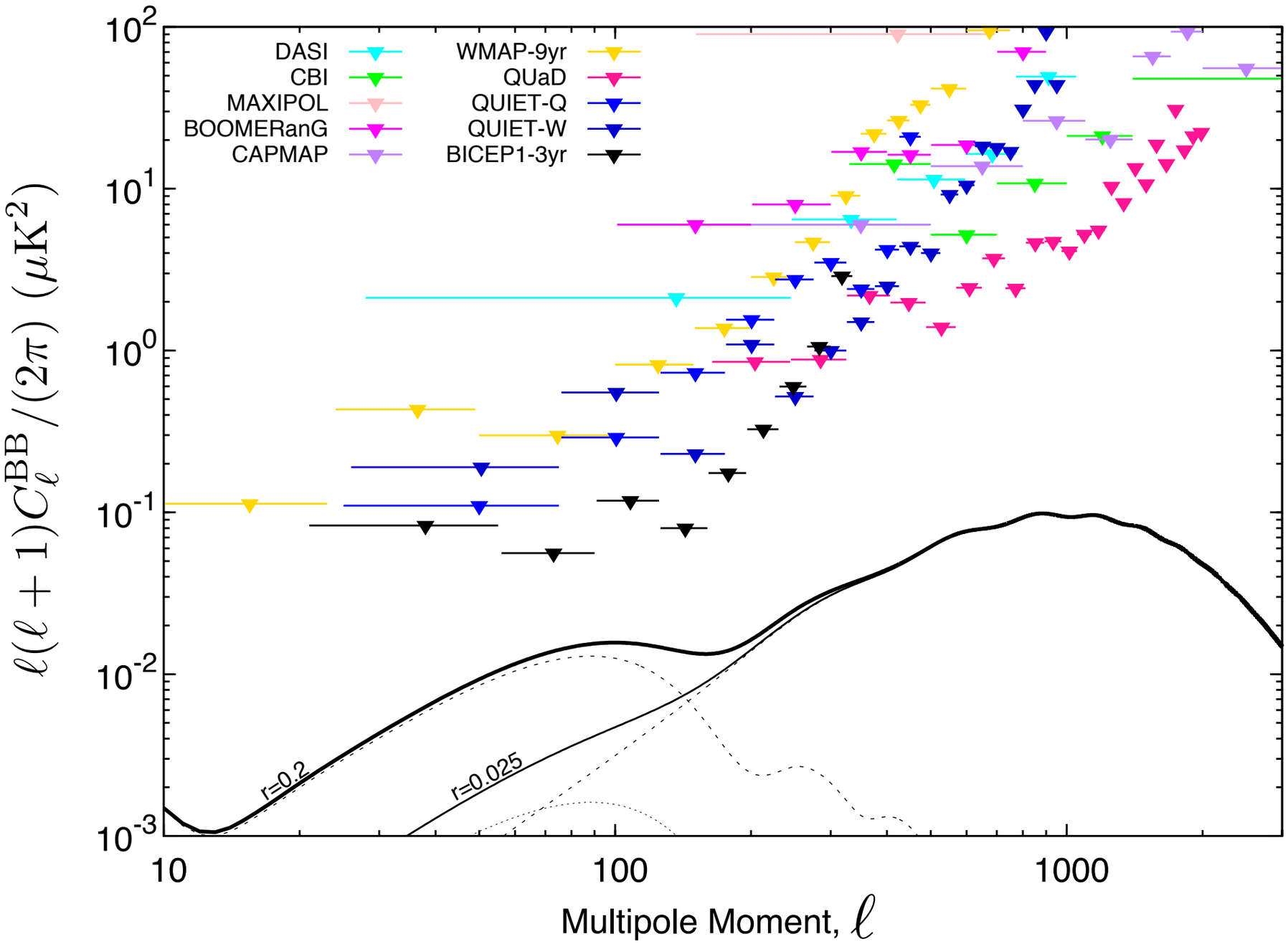


Measurements of the BB power spectrum

Mar 2014 — **2015**



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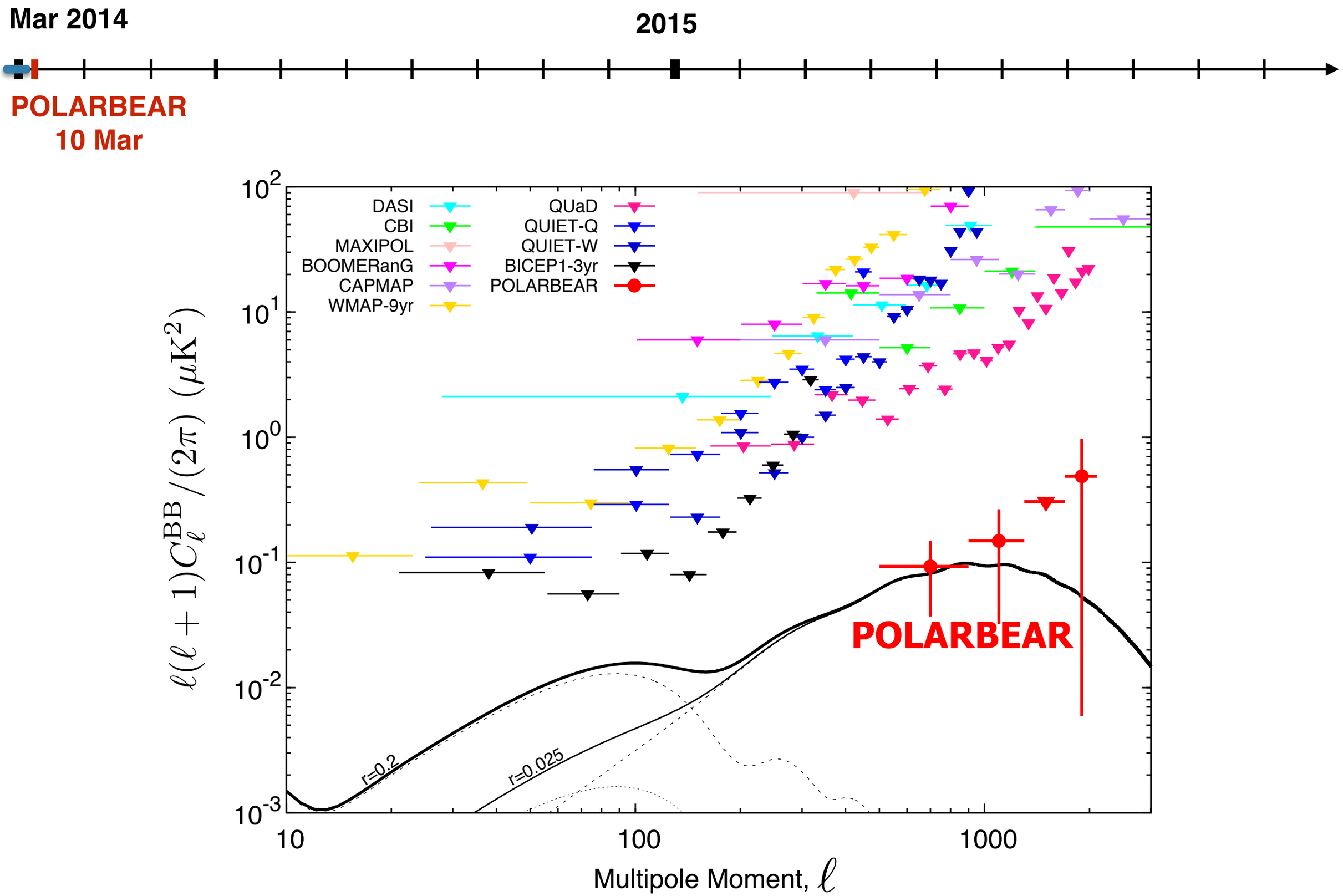

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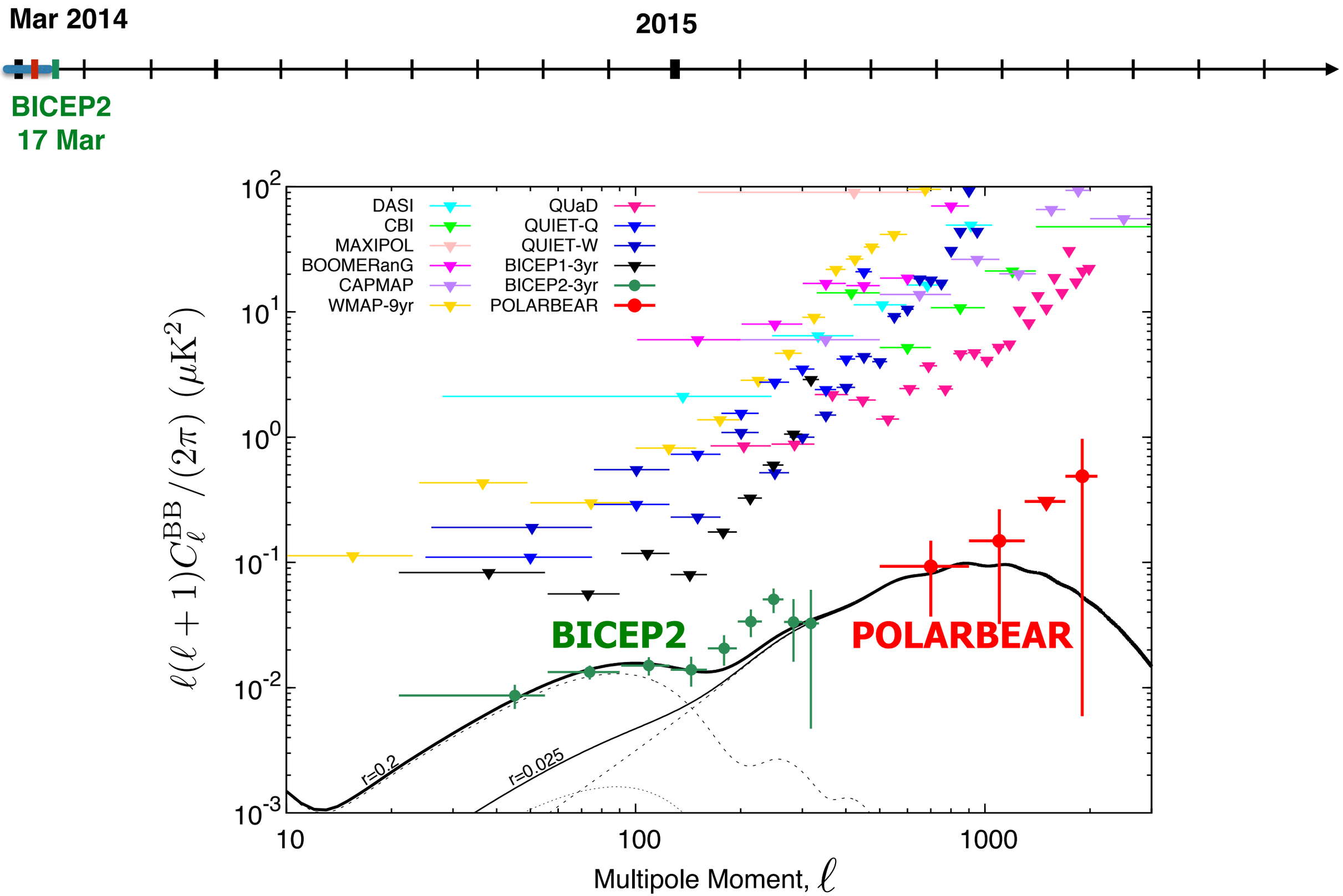

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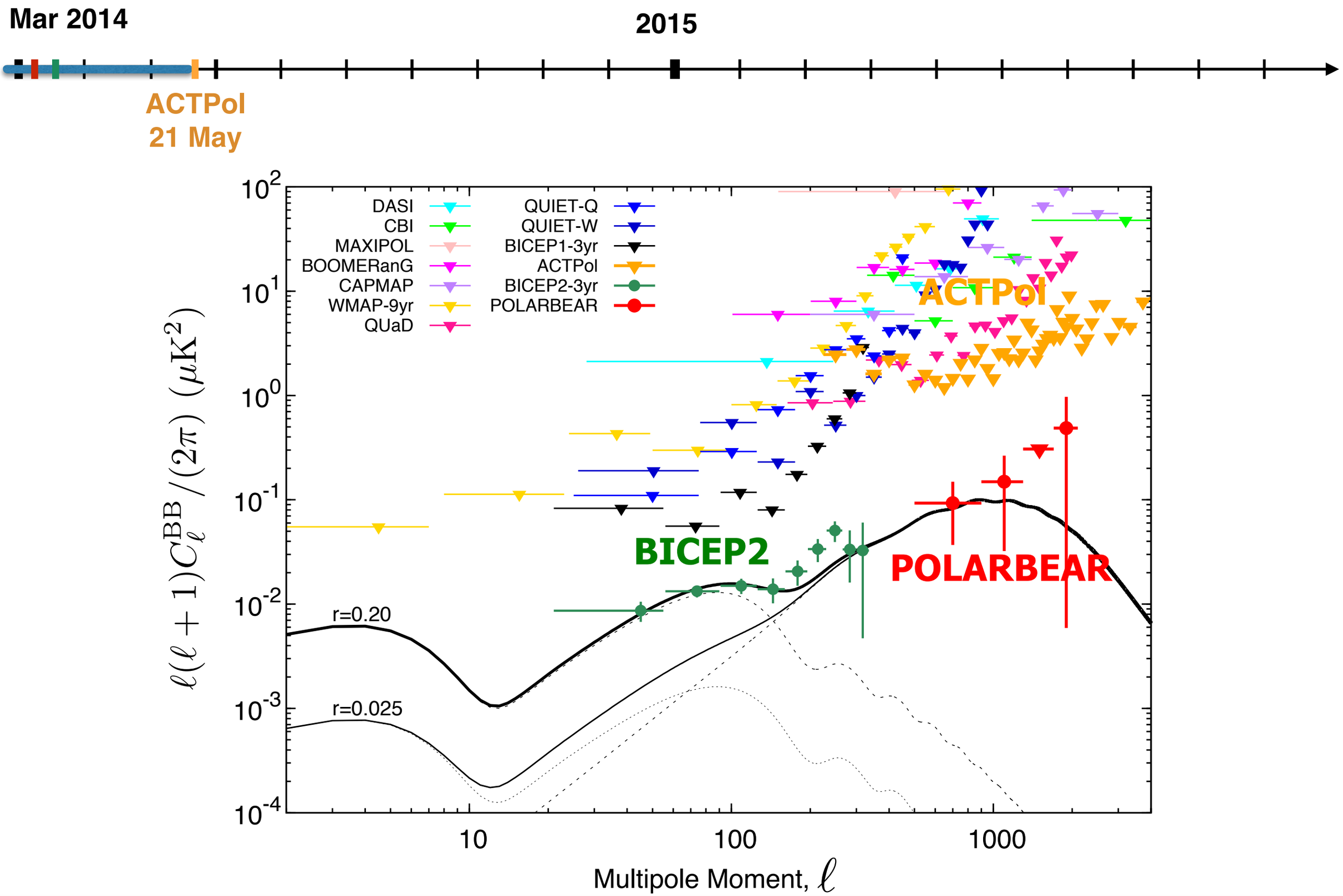
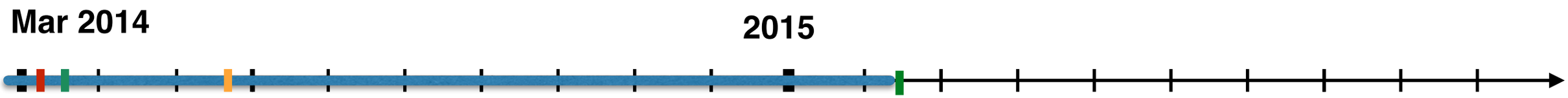
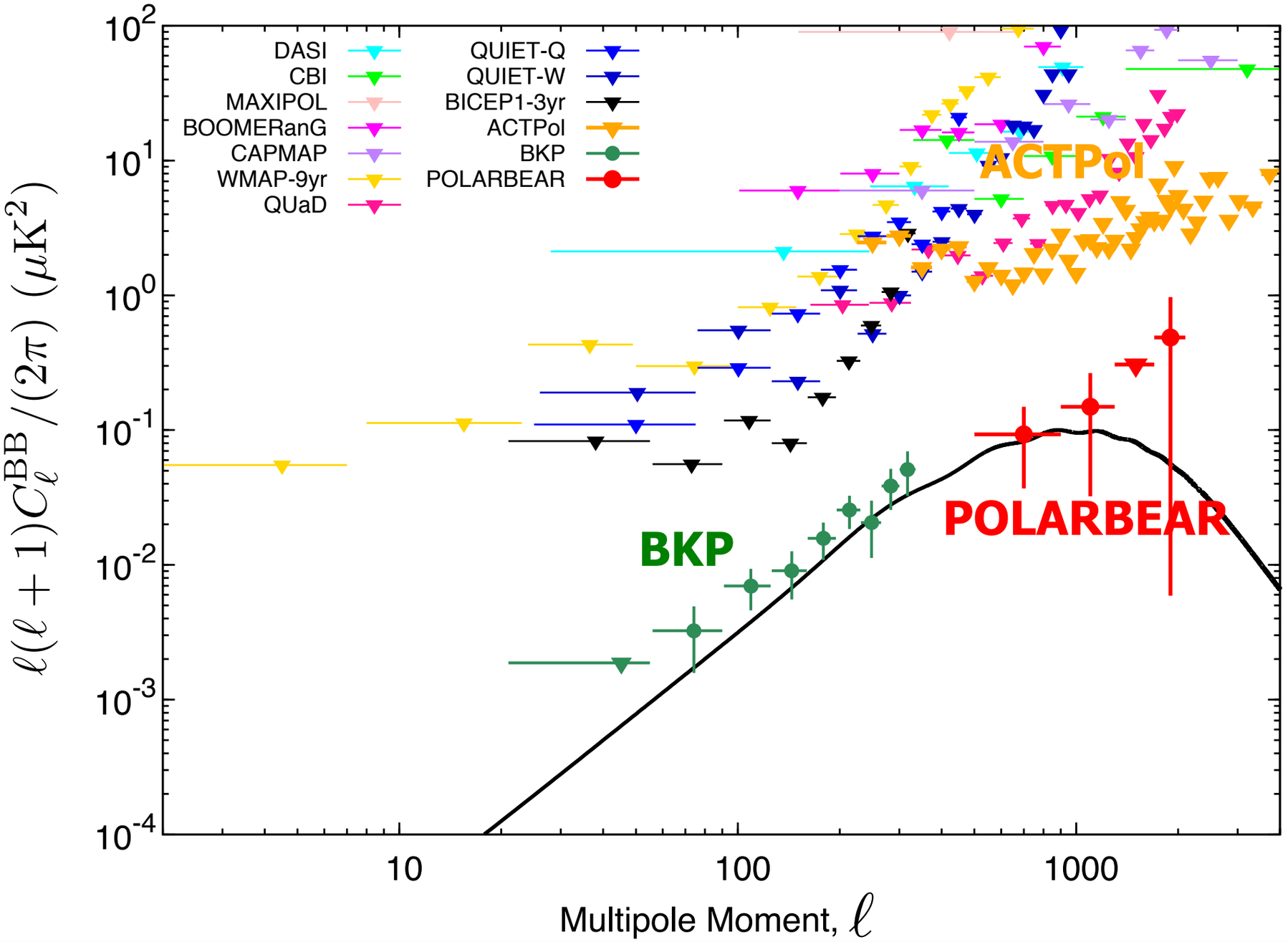


Measurements of the BB power spectrum



BICEP2 - Keck Array - Planck
2 Feb



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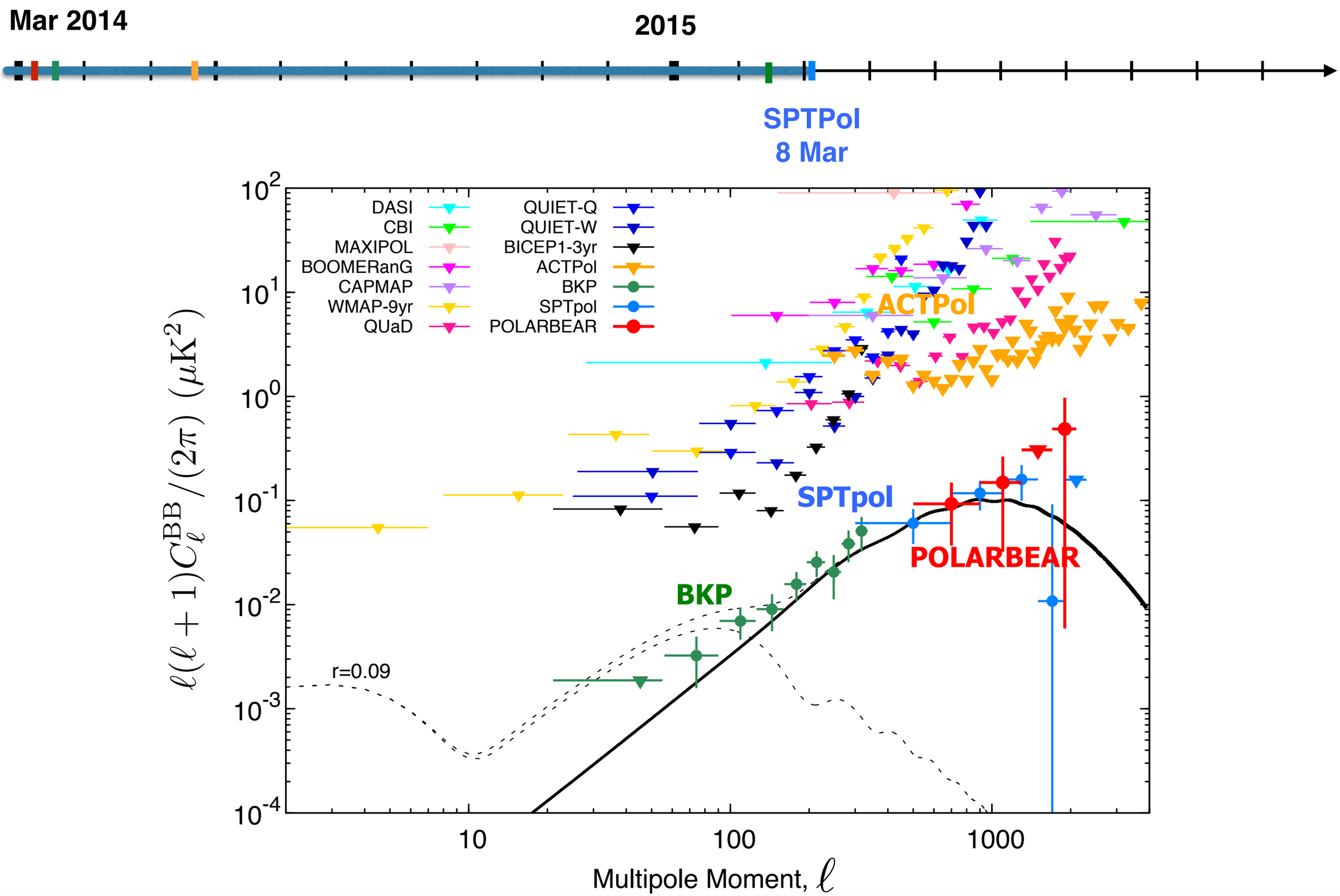

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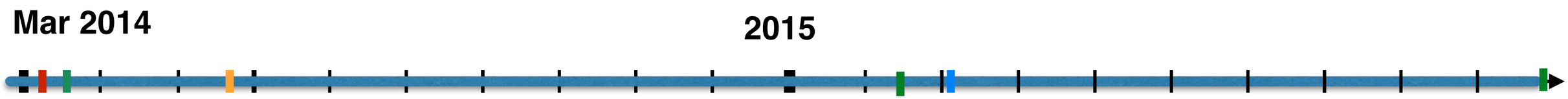

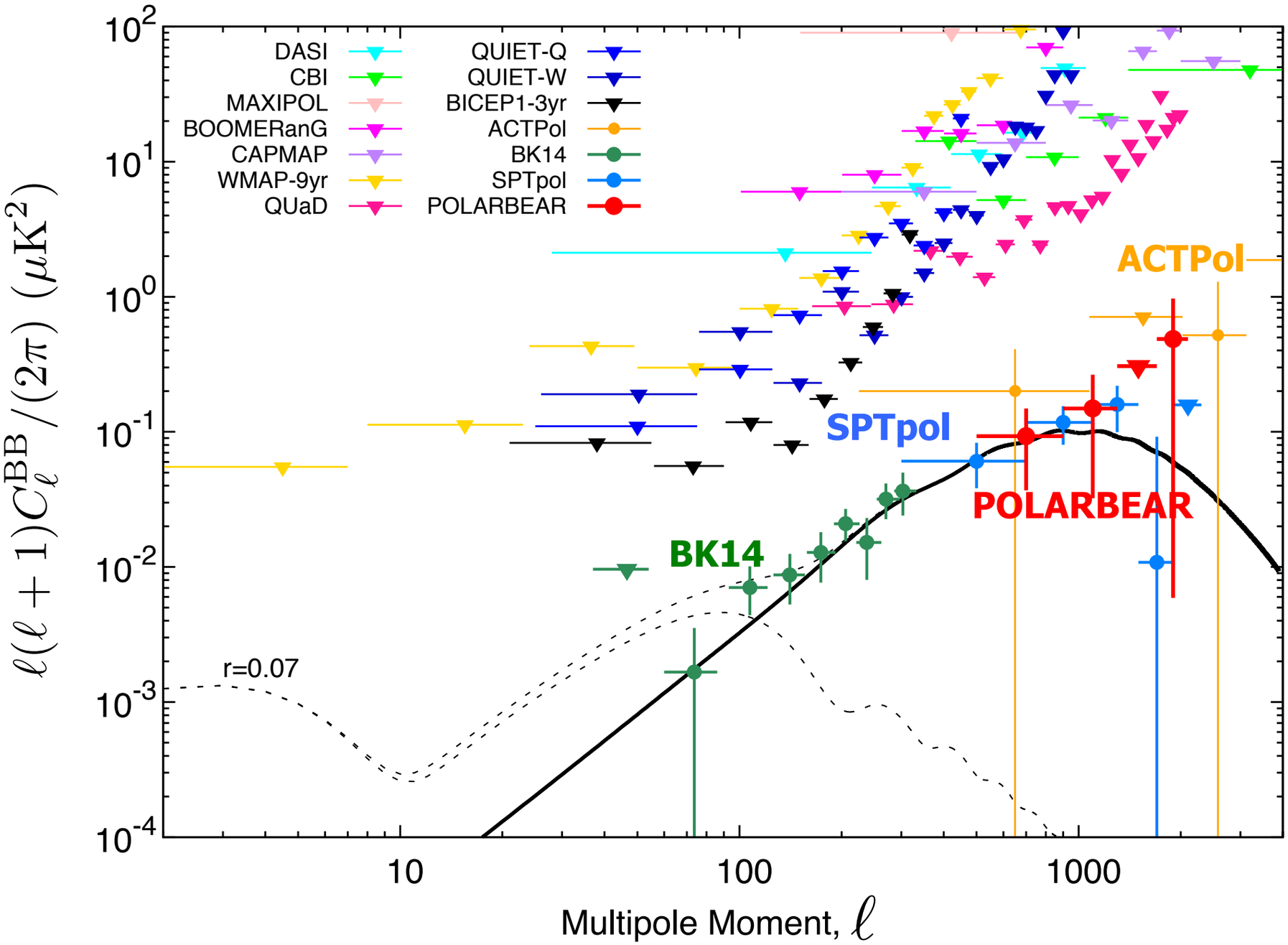

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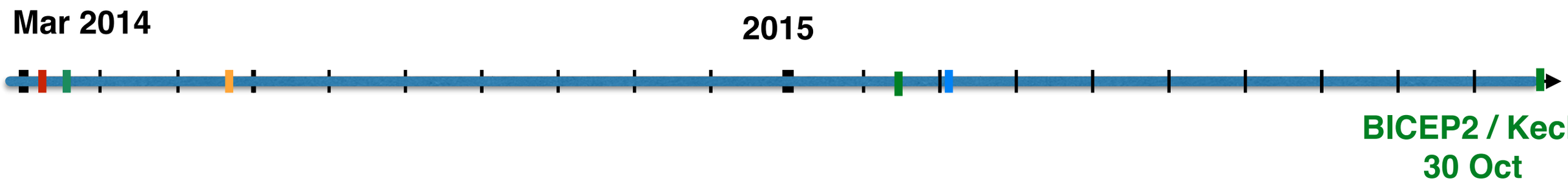
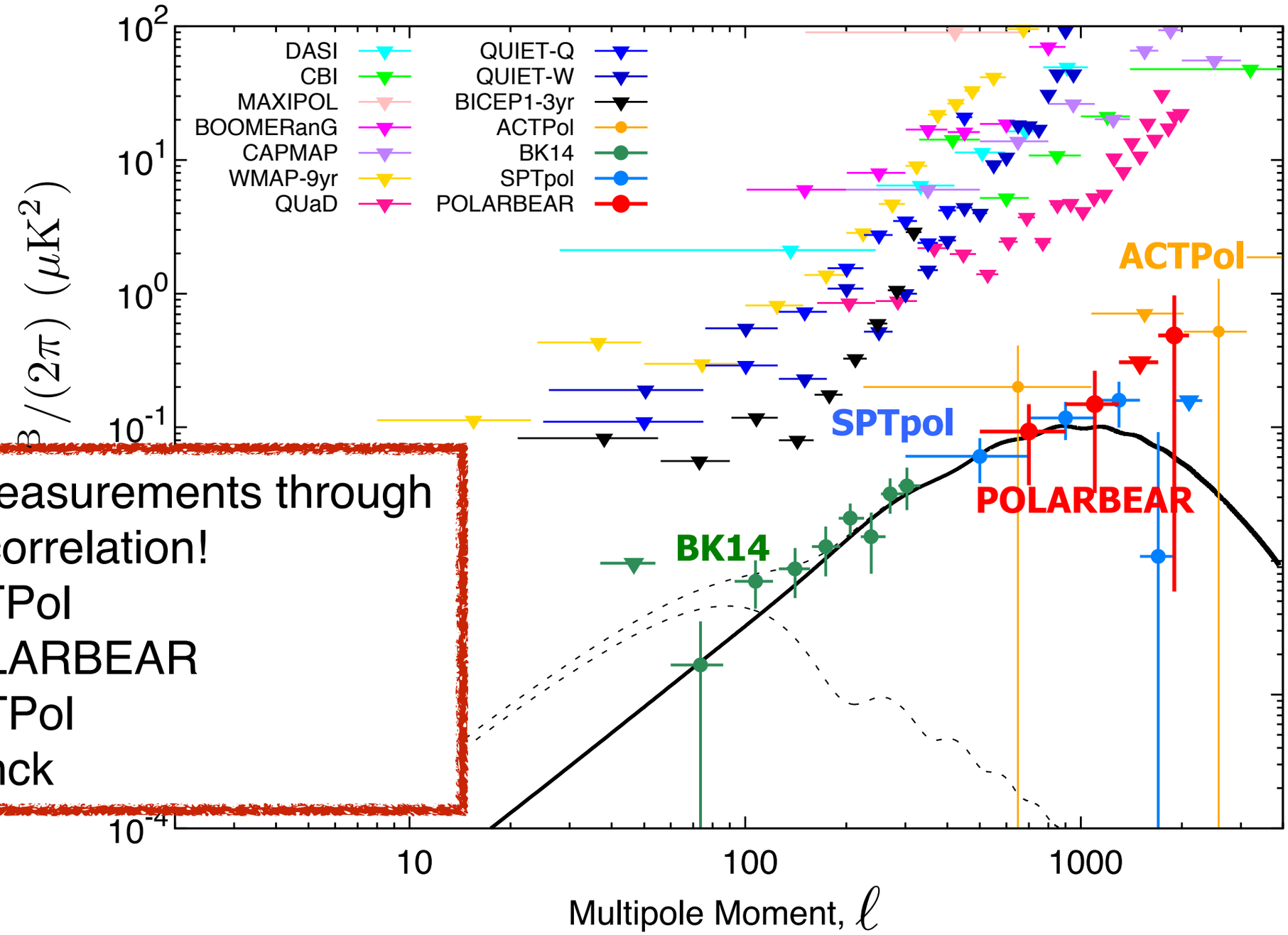




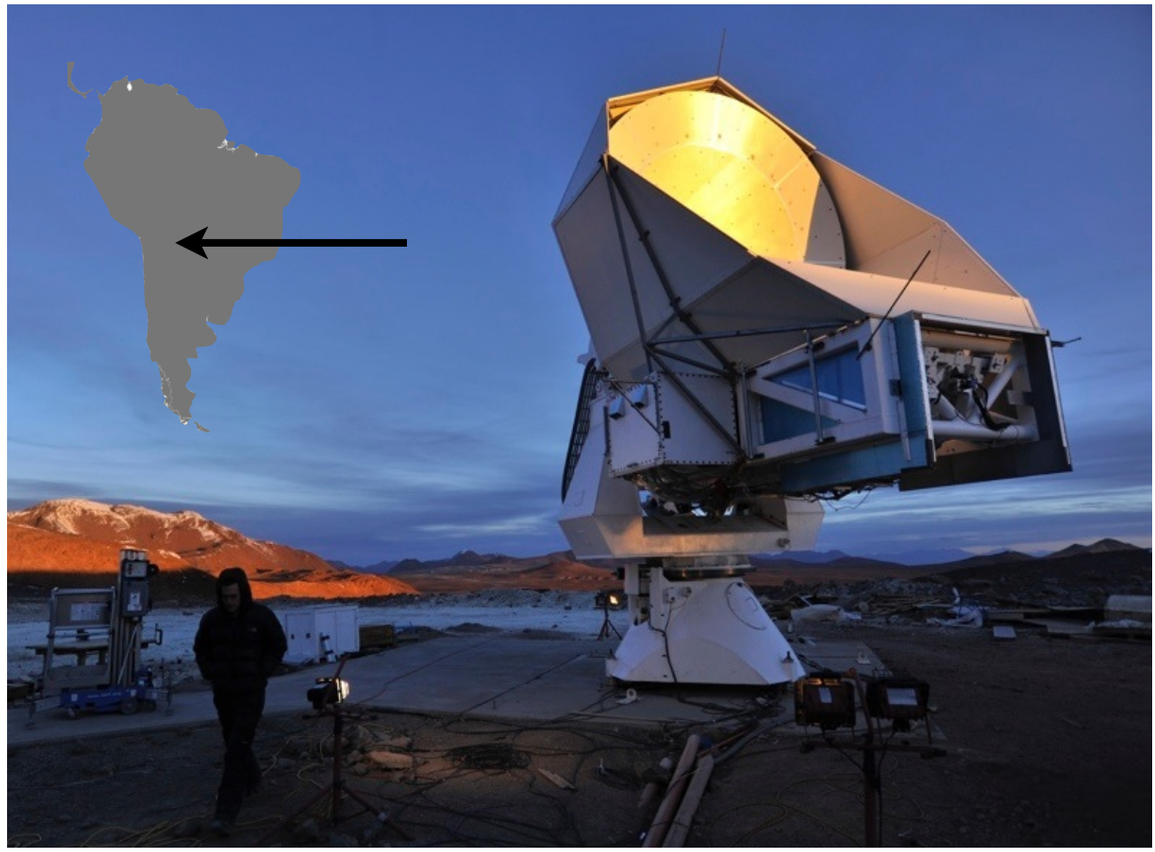
Plus measurements through cross-correlation!

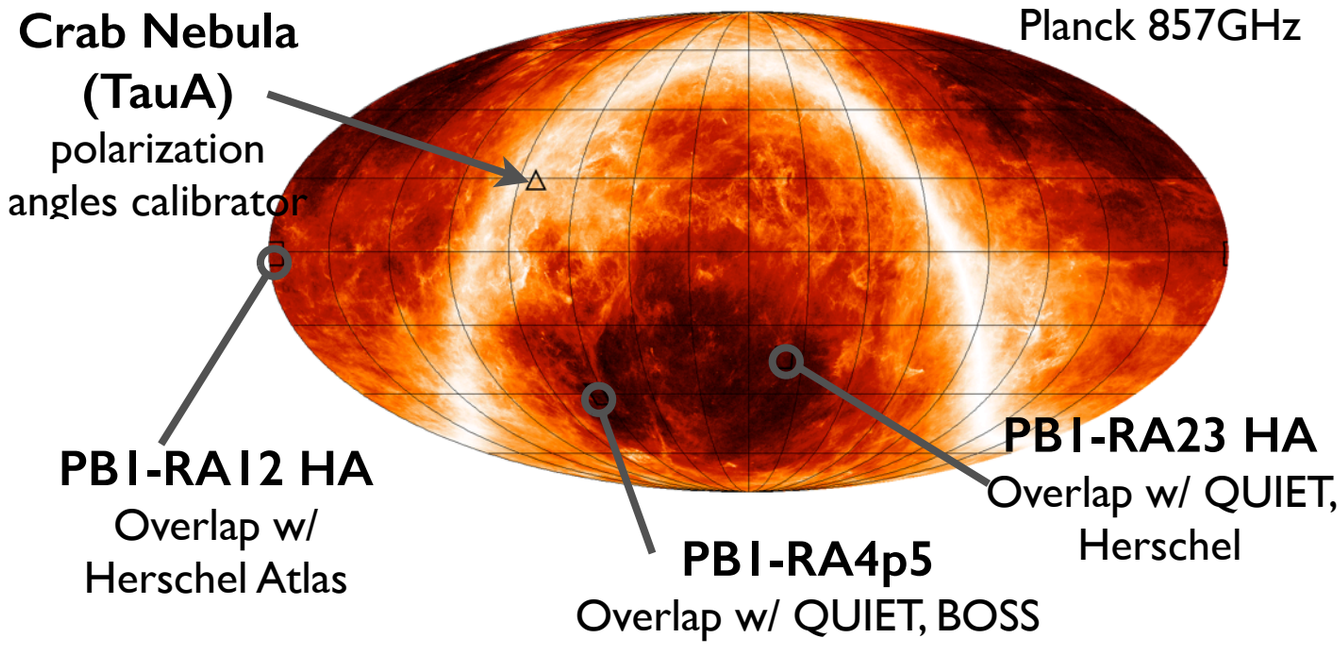
- SPTPol
- POLARBEAR
- ACTPol
- Planck

- B-modes science and measurements
- **The POLARBEAR experiment**
- First season’s results
- POLARBEAR 2 and Simons array

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

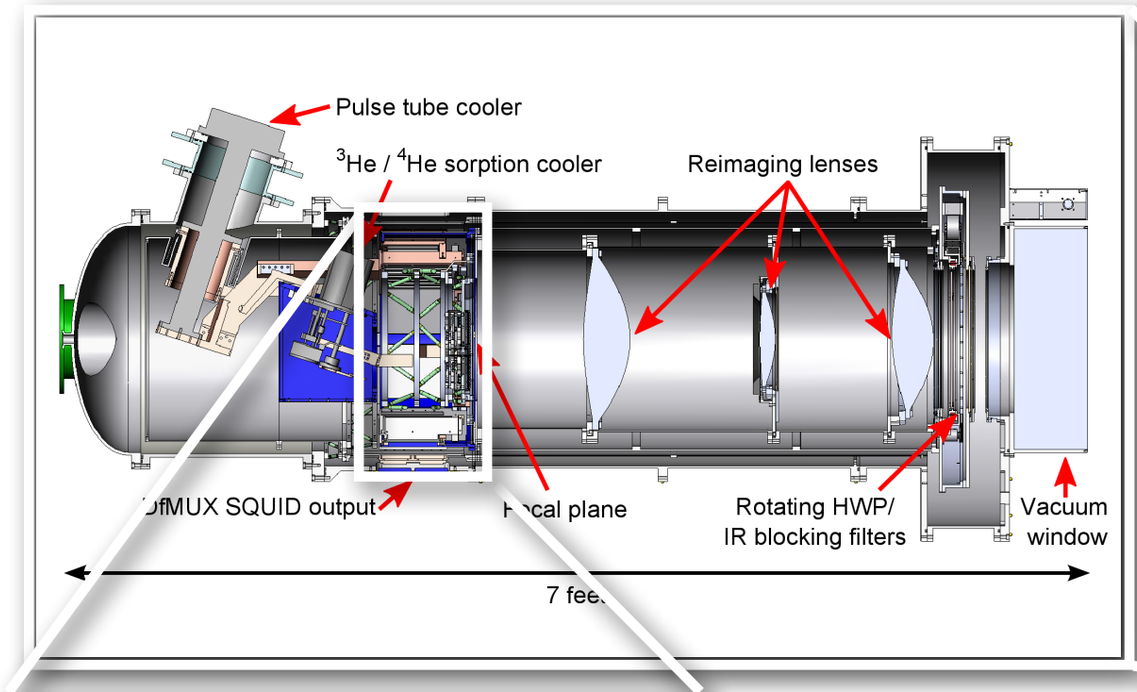


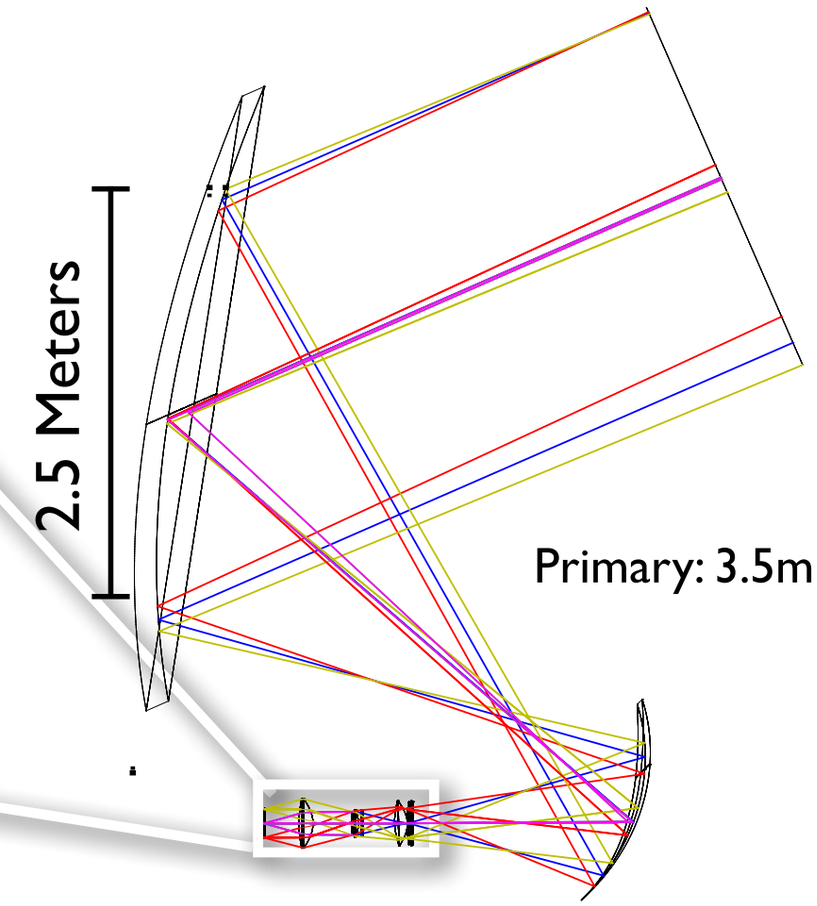


FIRST SEASON

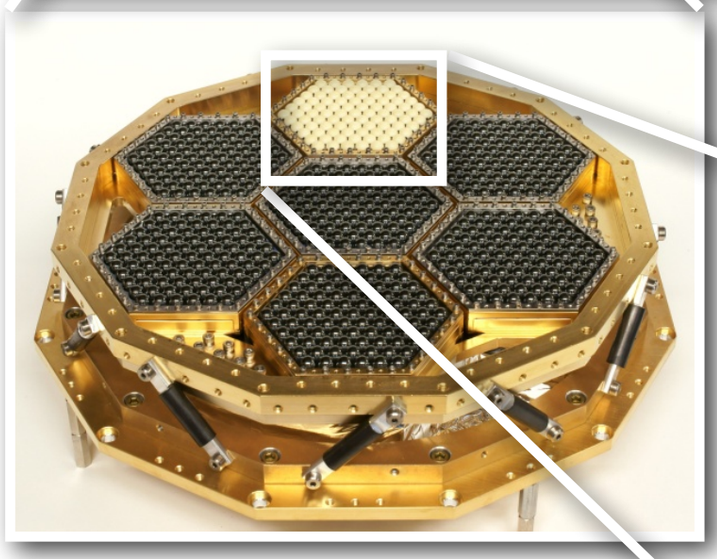
- Period:
  May 2012 to June 2013
- Target:
  deep integration of
  3 patches 5 deg x 5 deg

Instrumental design



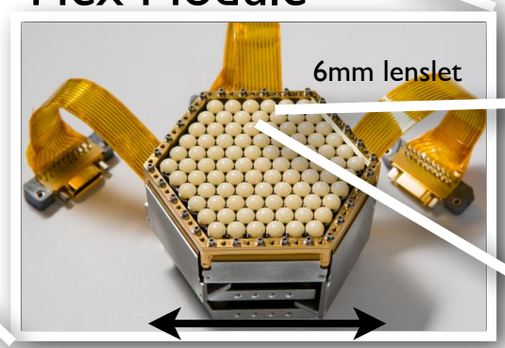


Huan Tran Telescope

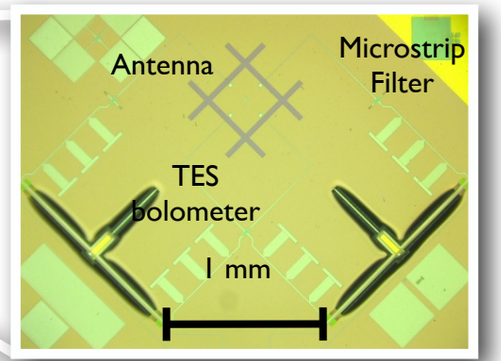


1274 bolometers @ 150 GHz
Cooled to 250 mK

Hex Module

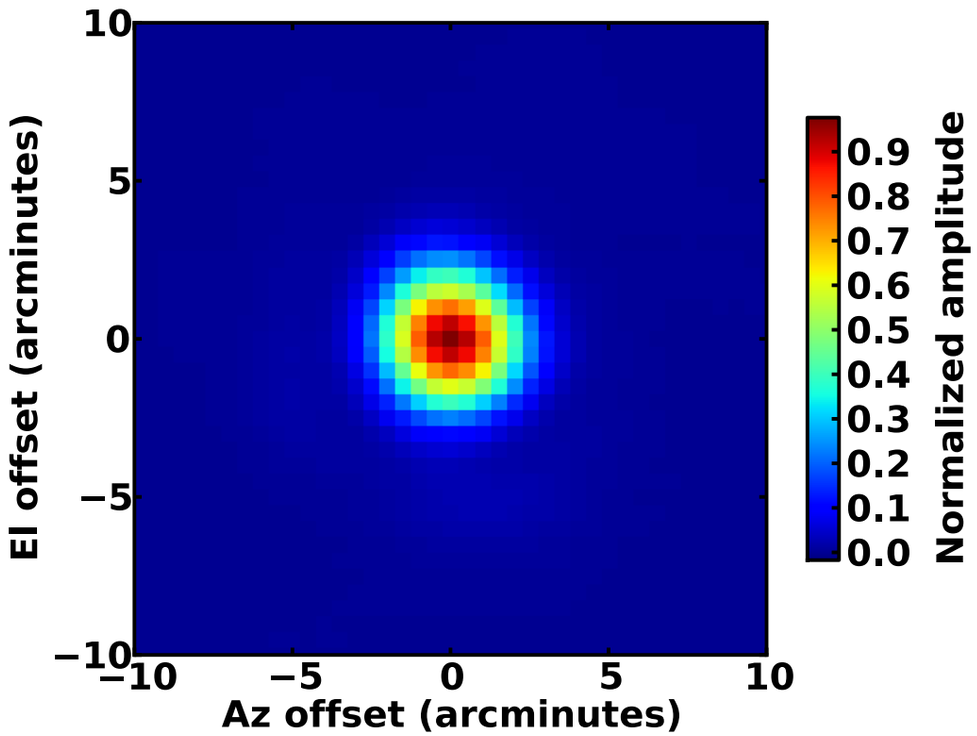


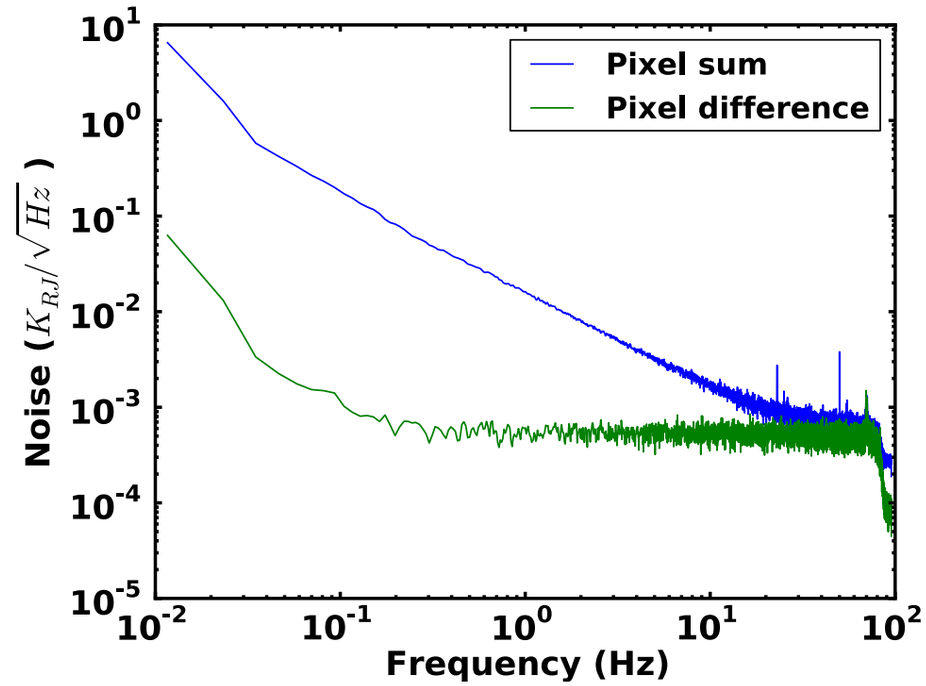
$$
\begin{aligned}
d^t(t) &= g_{top}\left[I(\hat{n}(t)) + Q(\hat{n}(t))\cos(2\psi(t)) + U(\hat{n}(t))\sin(2\psi(t))\right] \\
d^b(t) &= g_{bot}\left[I(\hat{n}(t)) - Q(\hat{n}(t))\cos(2\psi(t)) - U(\hat{n}(t))\sin(2\psi(t))\right]
\end{aligned}
$$



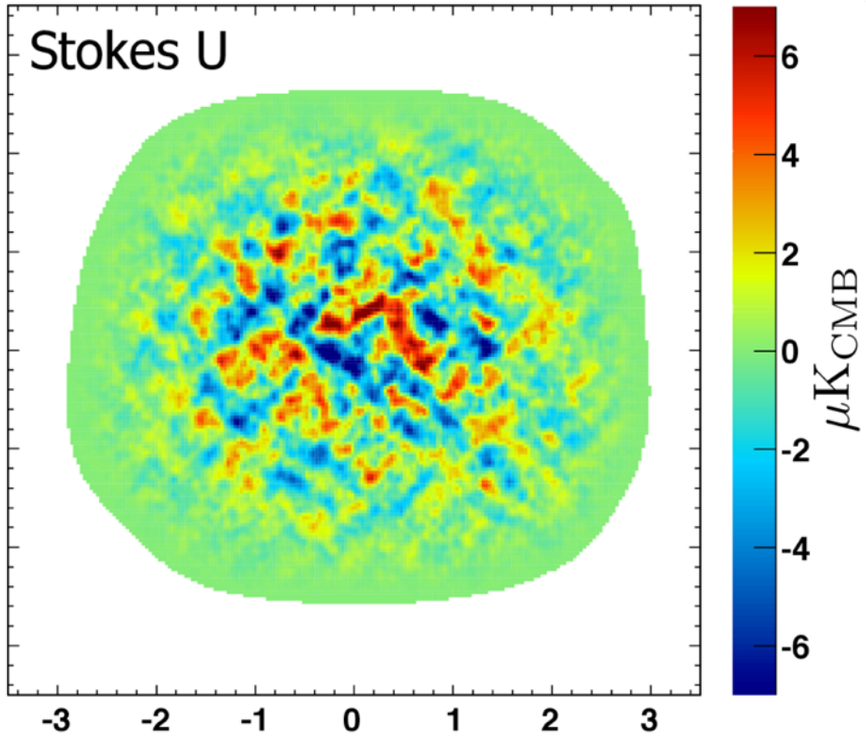
Instrument characterization

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



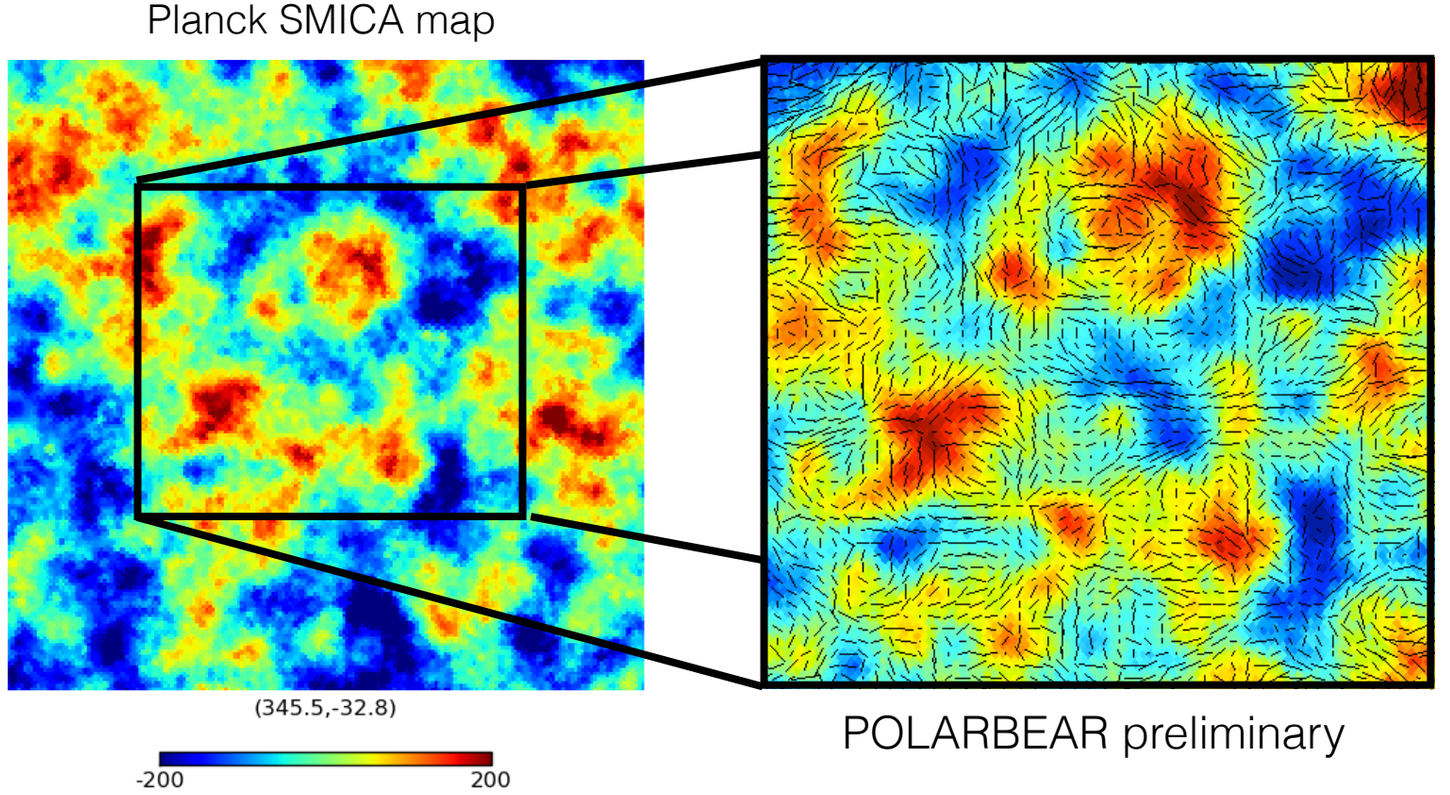


Map and power spectrum



- Filtered mapmaking:
  $\hat{\mathbf{s}} = (\mathbf{A}^\top \mathbf{N}^{-1} \mathbf{A})^{-1} \mathbf{A}^\top \mathbf{F} \mathbf{d}$
- Very fast

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



- Unbiased mapmaking: $\hat{\mathbf{s}} = (\mathbf{A}^\intercal \mathbf{F} \mathbf{A})^{-1} \mathbf{A}^\intercal \mathbf{F} \mathbf{d}$
- Fast, iterative estimator
- Accurate, explicit estimator

- Curved-sky, pure, pseudo power spectrum estimator

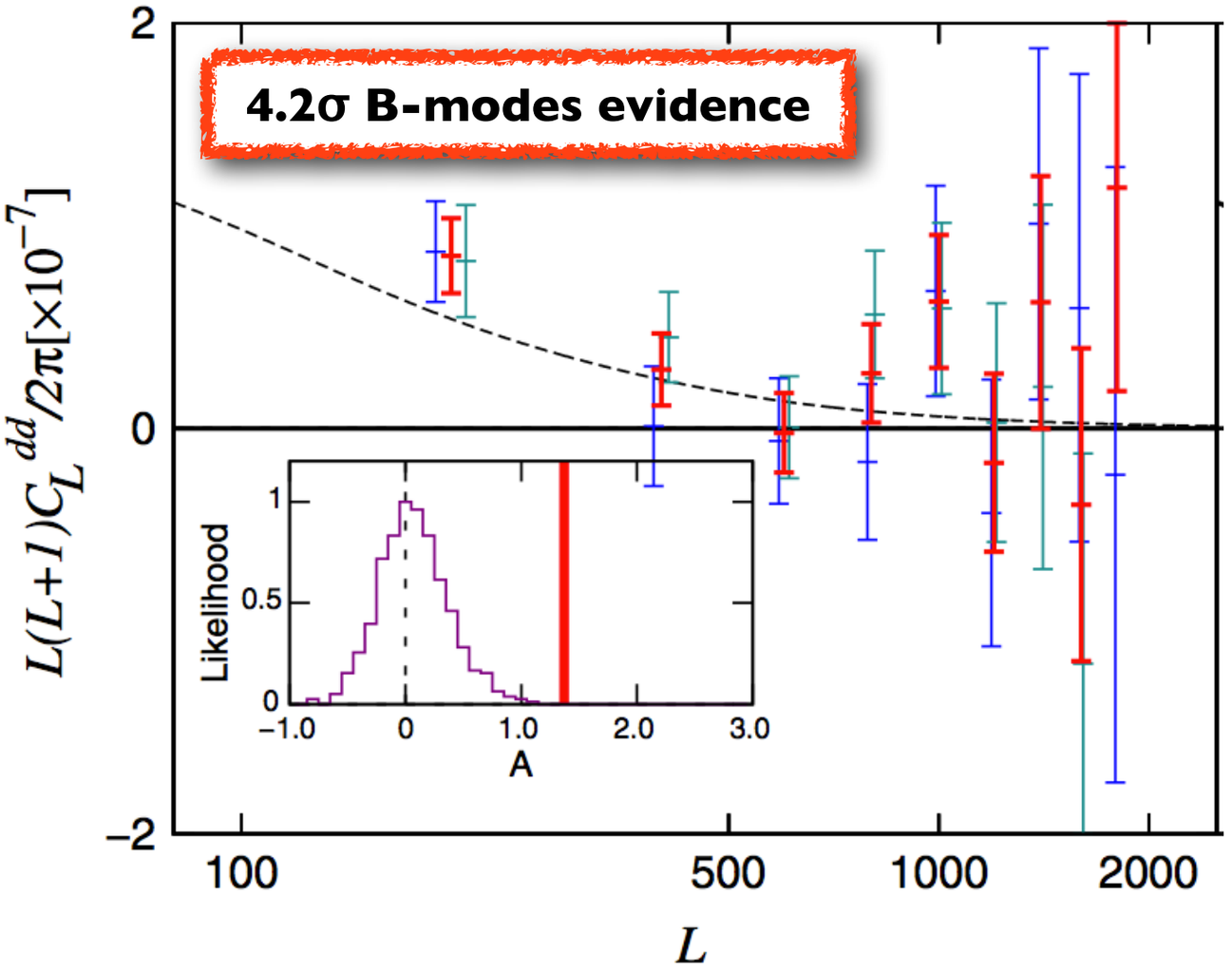
Cross-check and validation

- B-modes science and measurements
- The POLARBEAR experiment
- **First season's results**
- POLARBEAR 2 and Simons array

Results: lensing from polarization alone

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

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



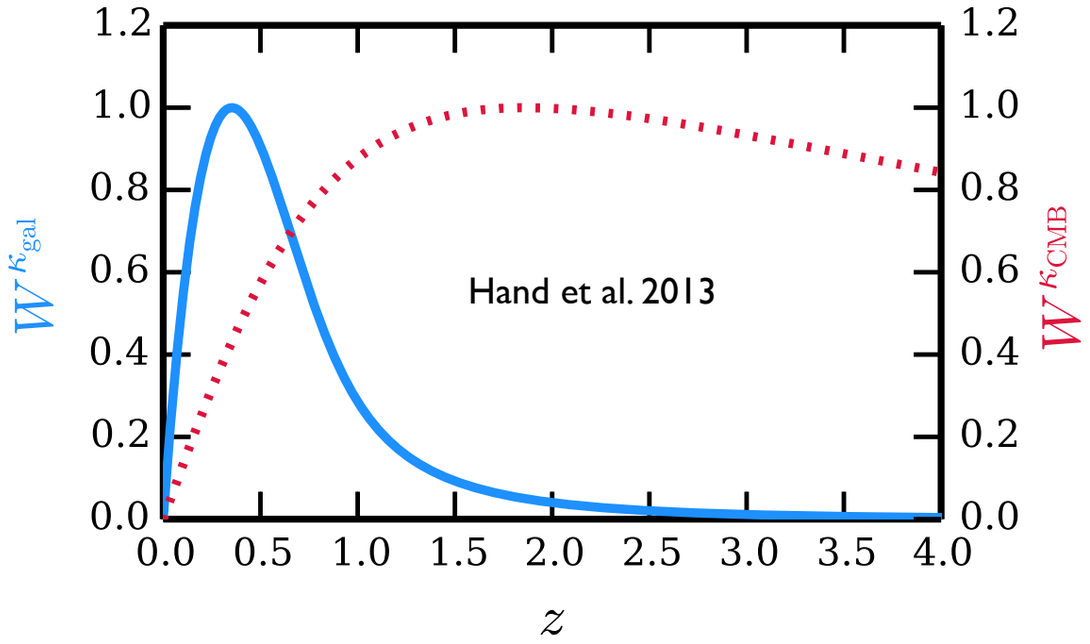
Results: cross-correlation with CIB

Polarization Measurement

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

Cosmic Infrared Background

Tracer of density field



Estimator of κ from POLARBEAR polarization maps **X** CIB map from Hershel

Phys. Rev. Lett. 112, 131302 (2014)
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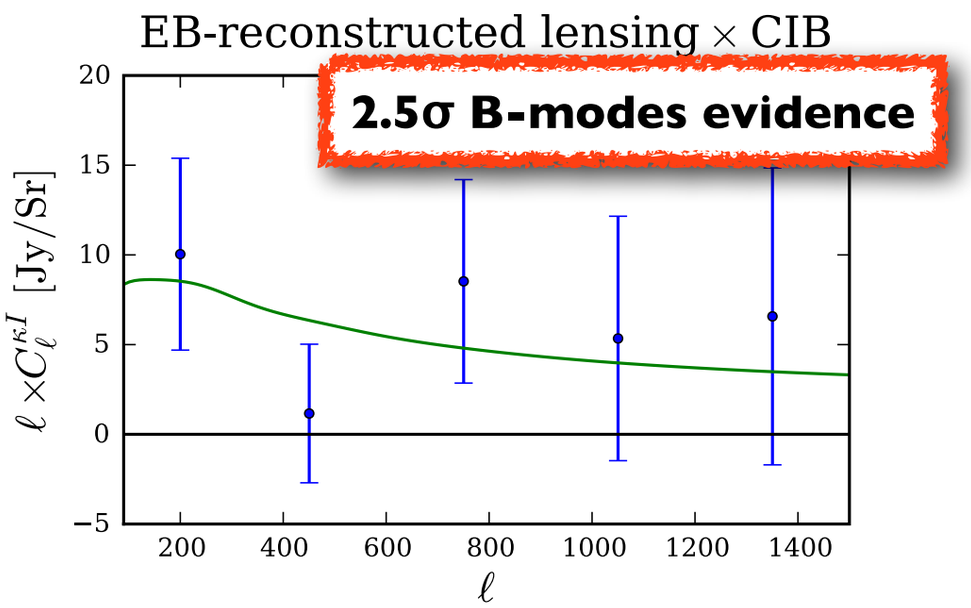
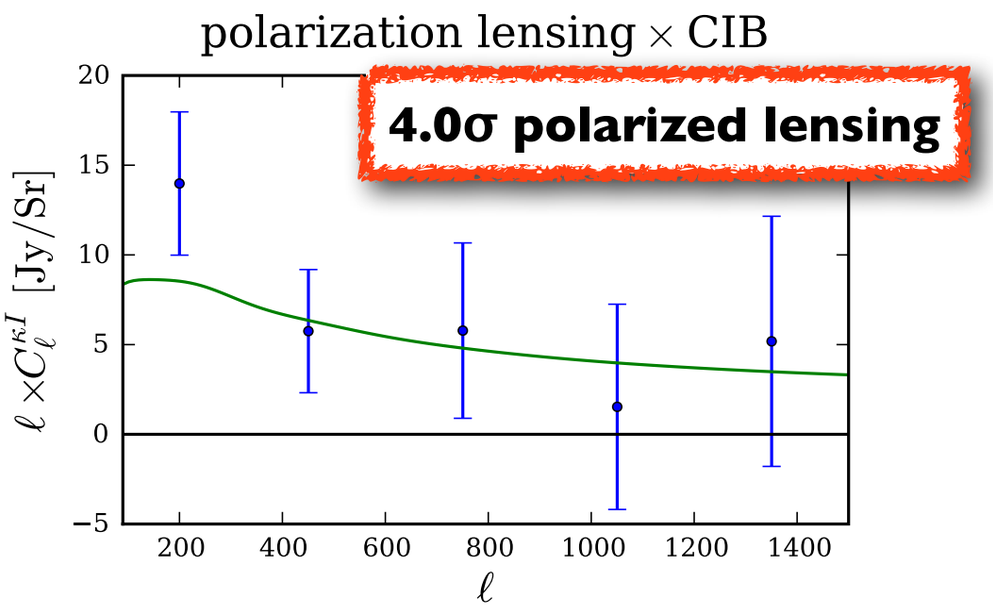




Results: BB spectrum measurement

- First direct evidence of lensing B-modes

97.5% c.l. B-modes evidence

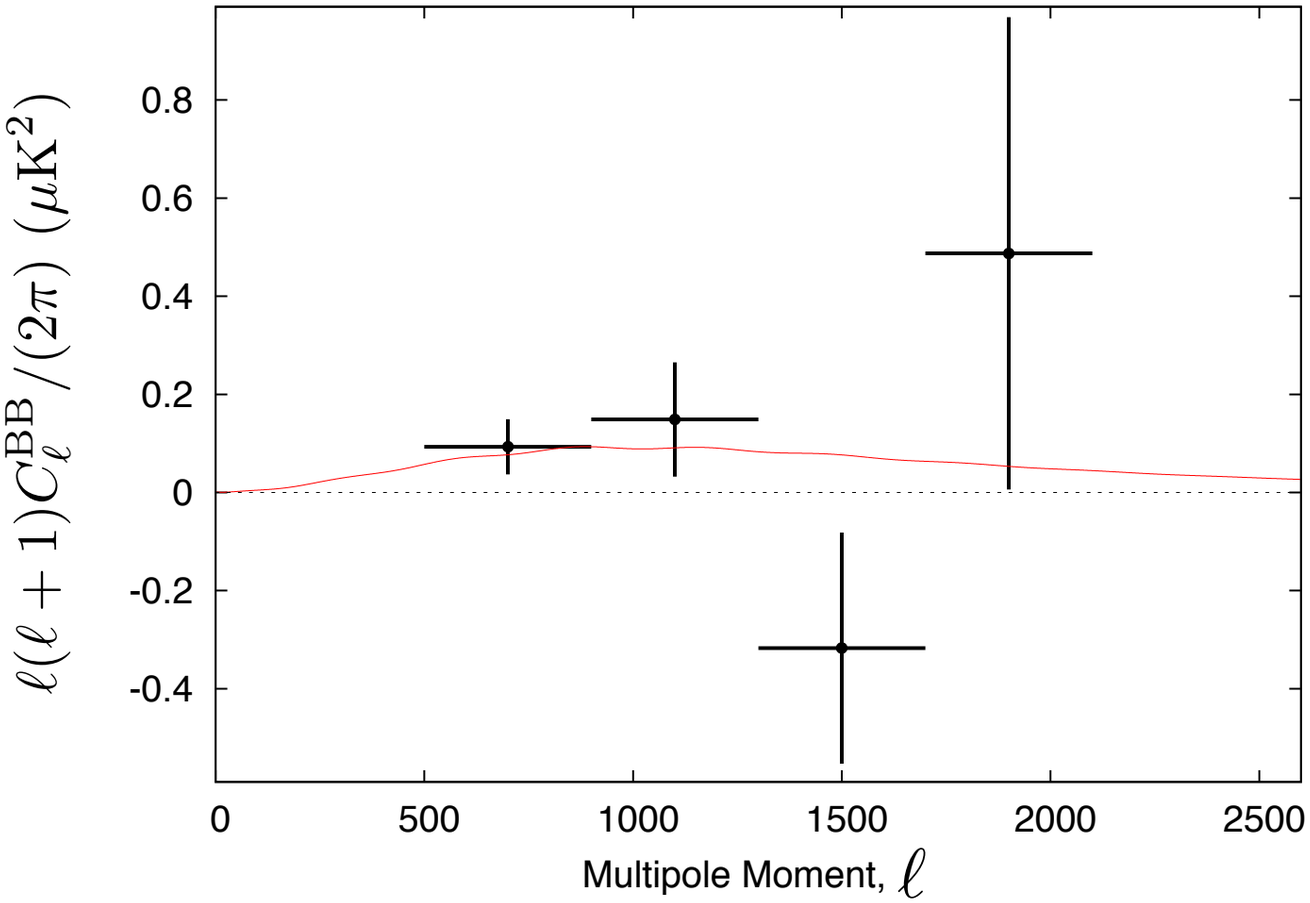
- Amplitude of lensing compared to ΛCDM

$$A_{BB} = 1.12 \pm 0.61(\mathrm{stat})^{+0.04}_{-0.10}(\mathrm{sys}) \pm 0.07(\mathrm{multi})$$

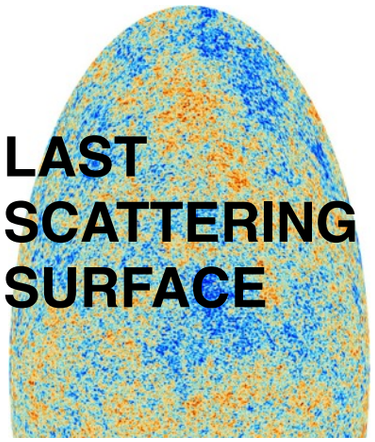
Astrophysical J. 794, 171 (2014)

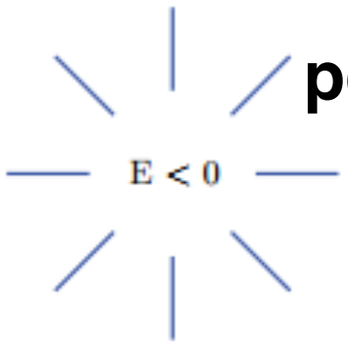
- Negligible contamination from astrophysical foregrounds

- Negligible contamination from systematic effects

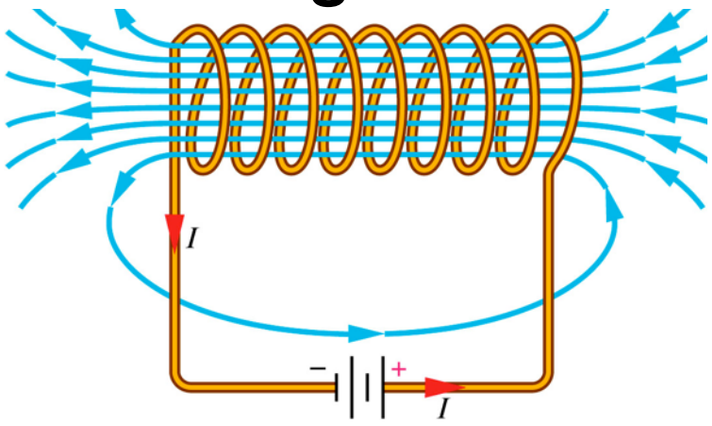


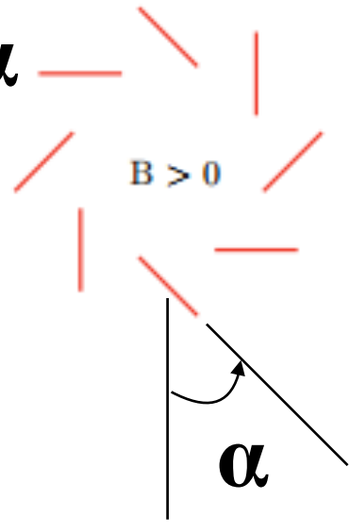
Results: cosmic birefringence / primordial magnetic fields





Birefringent universe, polarization angle rotation by α

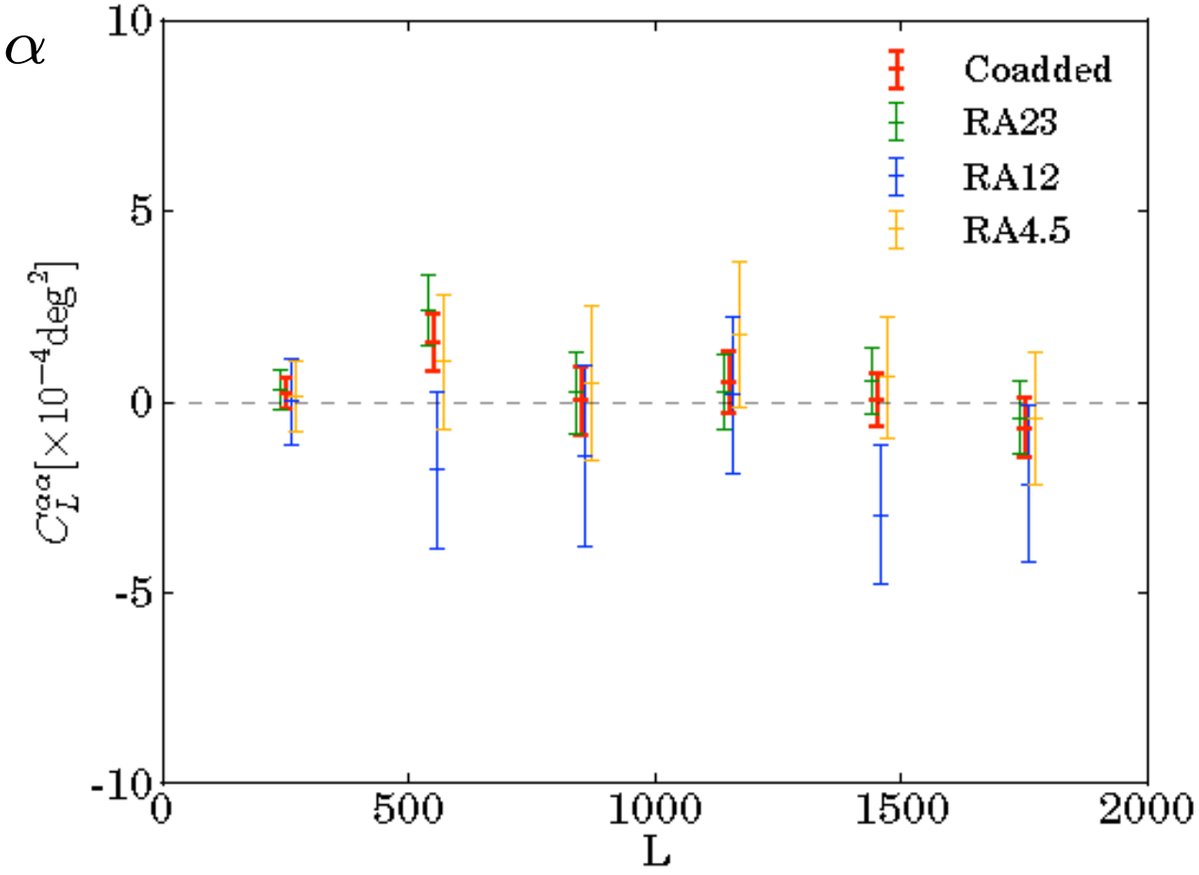




Polarization Measurement → Estimation α field → $C_\ell^{\alpha\alpha}$

Constraint on cosmic birefringence and primordial magnetic fields
< 93 nG (95% c.l.)

Phys. Rev. D 92, 123509 (2015)
Editors' Suggestion



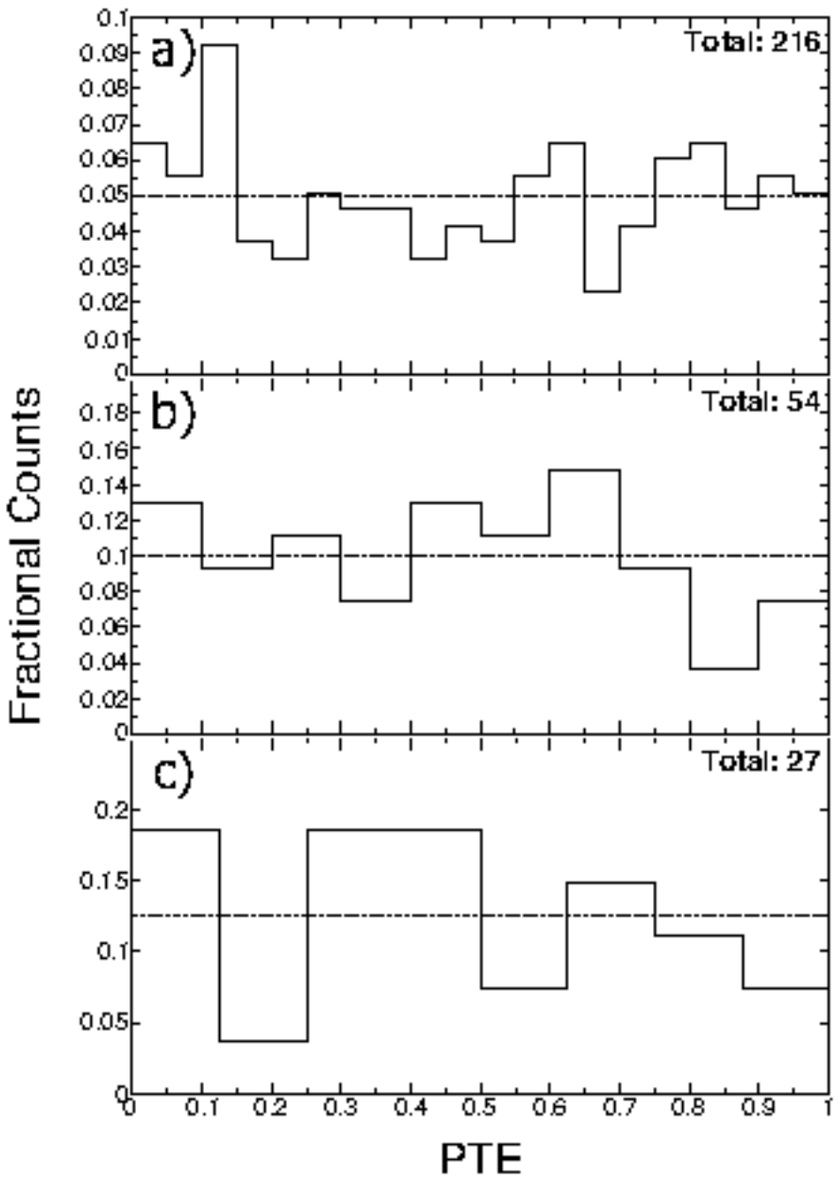
Control of the systematics

- Blind policy: assess data selection and quality without looking at the scientific products

- Null-test (Jackknife test):
  - ✦ temporal
  - ✦ scan properties (azimuthal direction, elevation)
  - ✦ weather
  - ✦ calibration properties
  - ✦ detector selection
  - ✦ bright sources distance.

⇨ Compatible with uniform distribution

⇨ No significant outlier

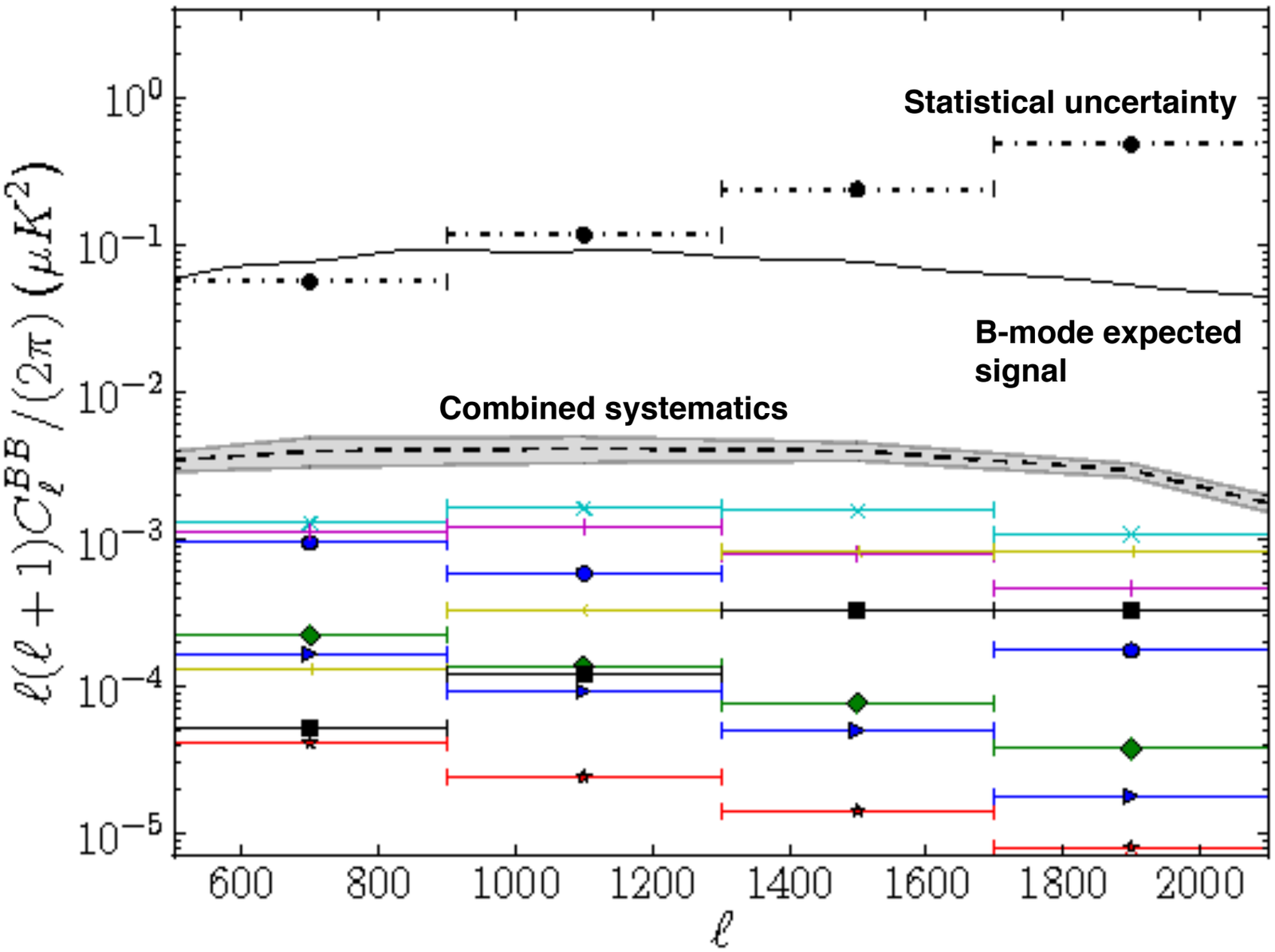


(Probability to exceed)

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

Situation after season I

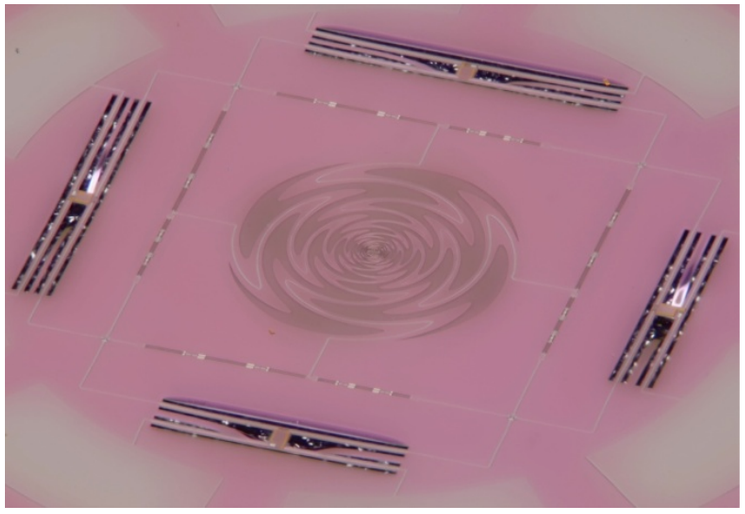
- Season I successfully probed small scales
- Systematics: under control
- Sensitivity: close to lensing B-modes level
  - Analysis of the season II ongoing
- BICEP2 and Planck: foregrounds dominate large scales

- B-modes science and measurements
- The POLARBEAR experiment
- First season's results
- **POLARBEAR 2 and Simons Array**

The future: POLARBEAR 2 and Simons array

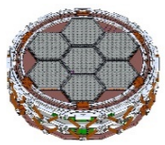
2016: POLARBEAR 2
new telescope and receiver

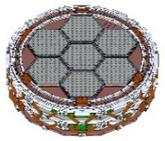
- 7,588 detectors
- Multichroic pixels (95/150 GHz)

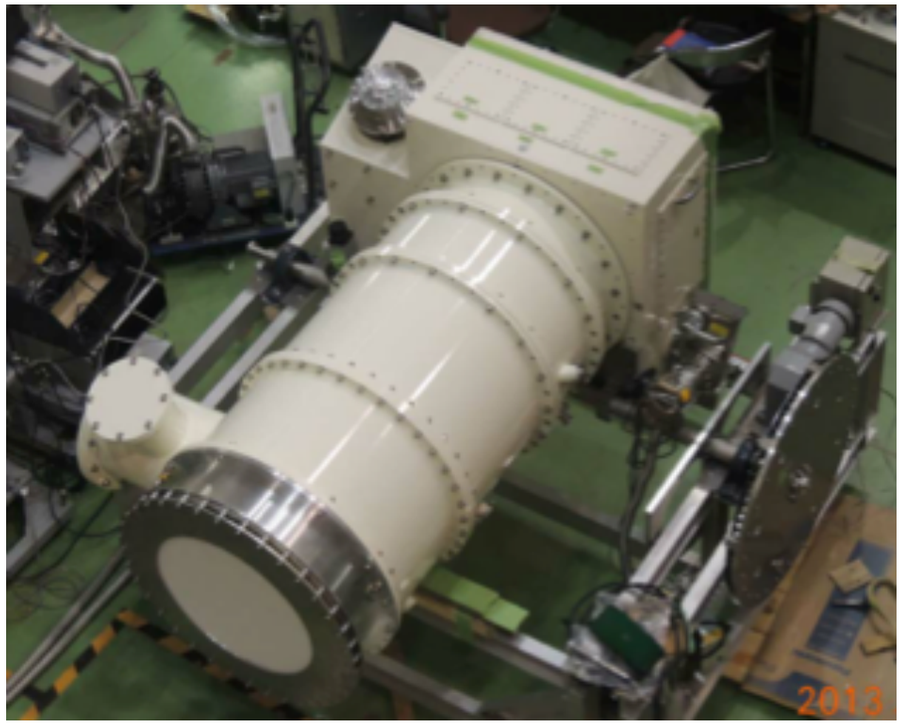


2017: Simons Array
new telescopes, 2 new PB2-like receivers

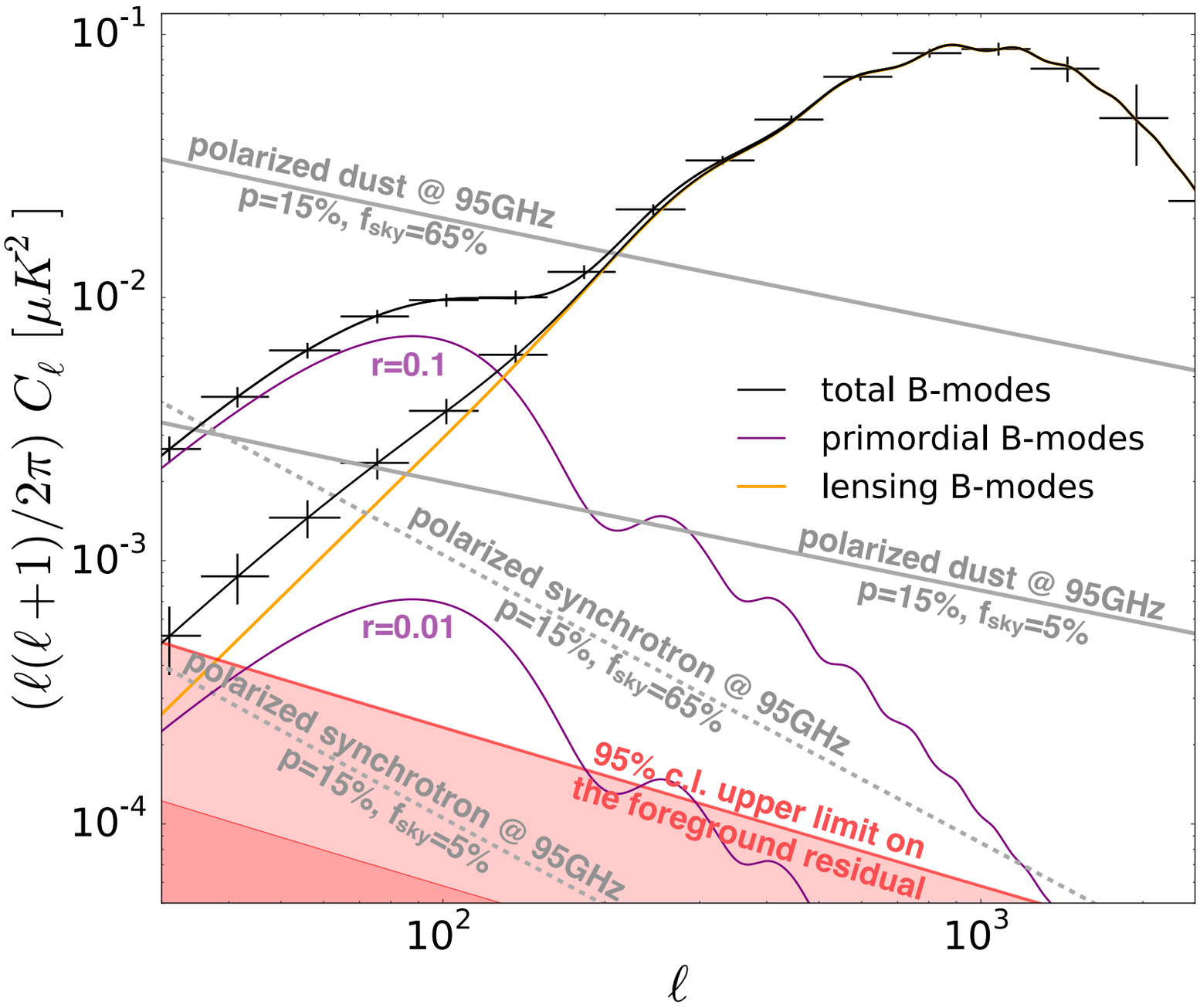
- 22,764 detectors
- 95/150/220 GHz channel

2 
95/150

1x 
150/220



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

$r < 0.07$ BK VI (2015)
$\Sigma m_\nu < 0.15$ 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 11: 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.

Thank you