Constraining B-modes with the POLARBEAR experiment

Davide Poletti

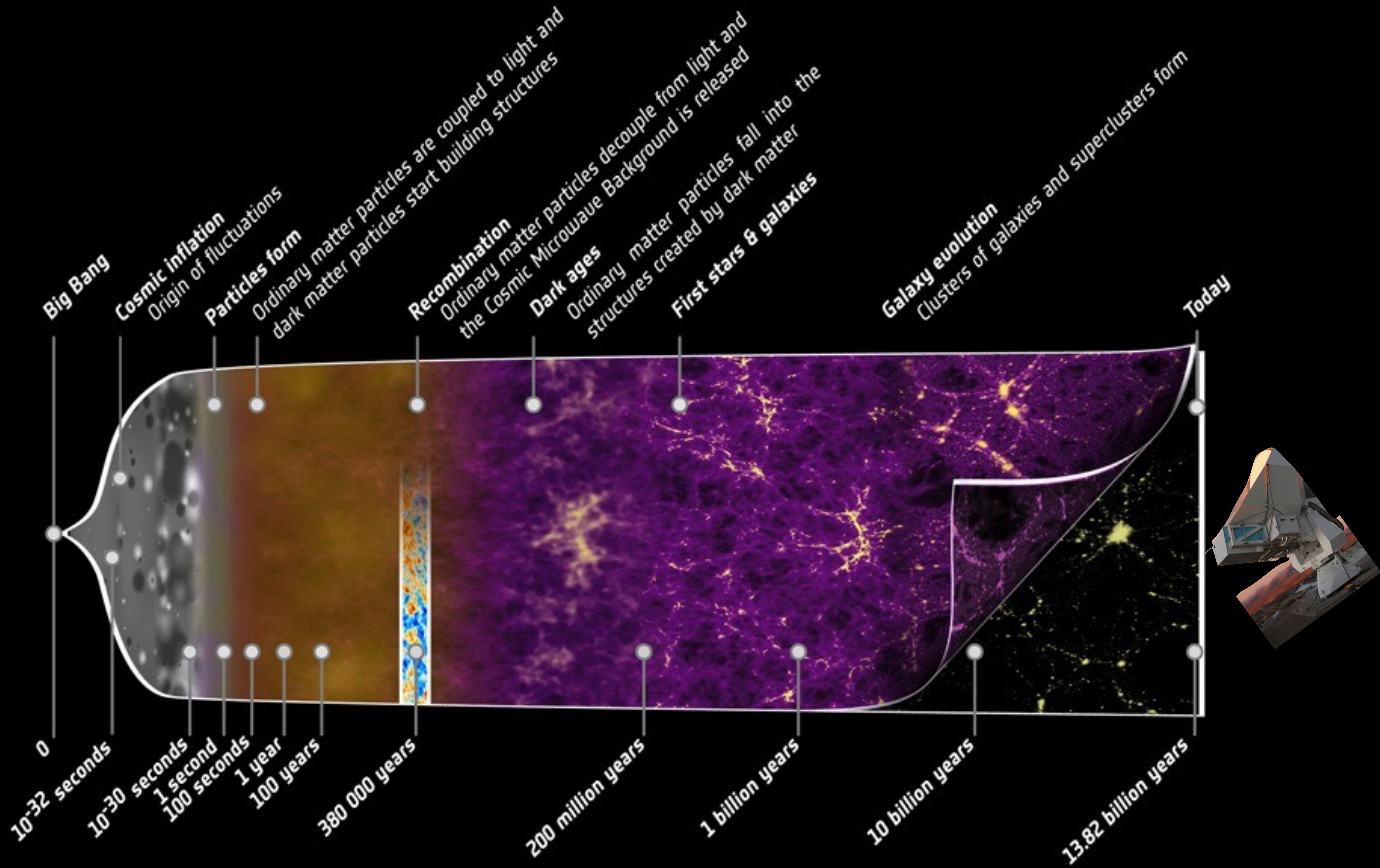
26 September 2017

AstroTS

- The Cosmic Microwave Background: still a goldmine

- Technical study and cosmological results from POLARBEAR first and second season

Poletti et al, A&A, 600 (2017) A60
POLARBEAR Collaboration, 2017, arXiv:1705.02907

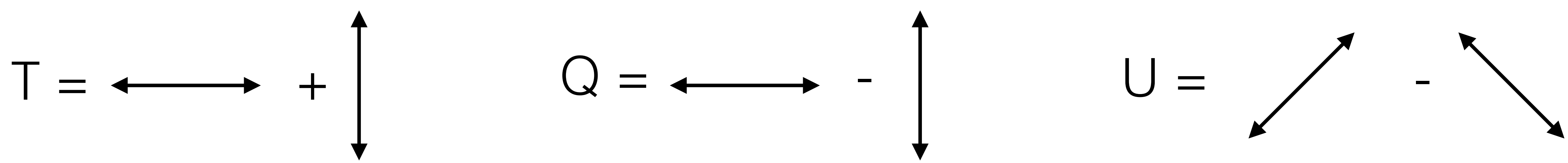


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the
structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

ESA/Planck

CMB anisotropies

For every direction on the sky:
intensity and linear polarisation
⇨ T, Q, U Stokes parameters



$$T(\hat{\boldsymbol{n}}) = \sum_{lm} a_{T,lm} Y_{lm}(\hat{\boldsymbol{n}}),$$

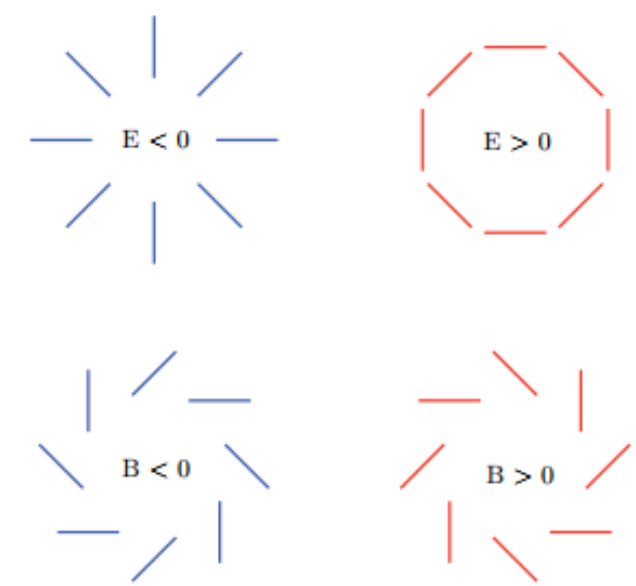
$$(Q+iU)(\hat{\boldsymbol{n}}) = \sum_{lm} a_{2,lm\,2} Y_{lm}(\hat{\boldsymbol{n}}),$$

$$(Q-iU)(\hat{\boldsymbol{n}}) = \sum_{lm} a_{-2,lm\,-2} Y_{lm}(\hat{\boldsymbol{n}}).$$

$$a_{E,lm} = -(a_{2,lm} + a_{-2,lm})/2,$$

$$a_{B,lm} = i(a_{2,lm} - a_{-2,lm})/2.$$

Kamionkowski et al. (1997),
Zaldarriaga and Seljak (1997)



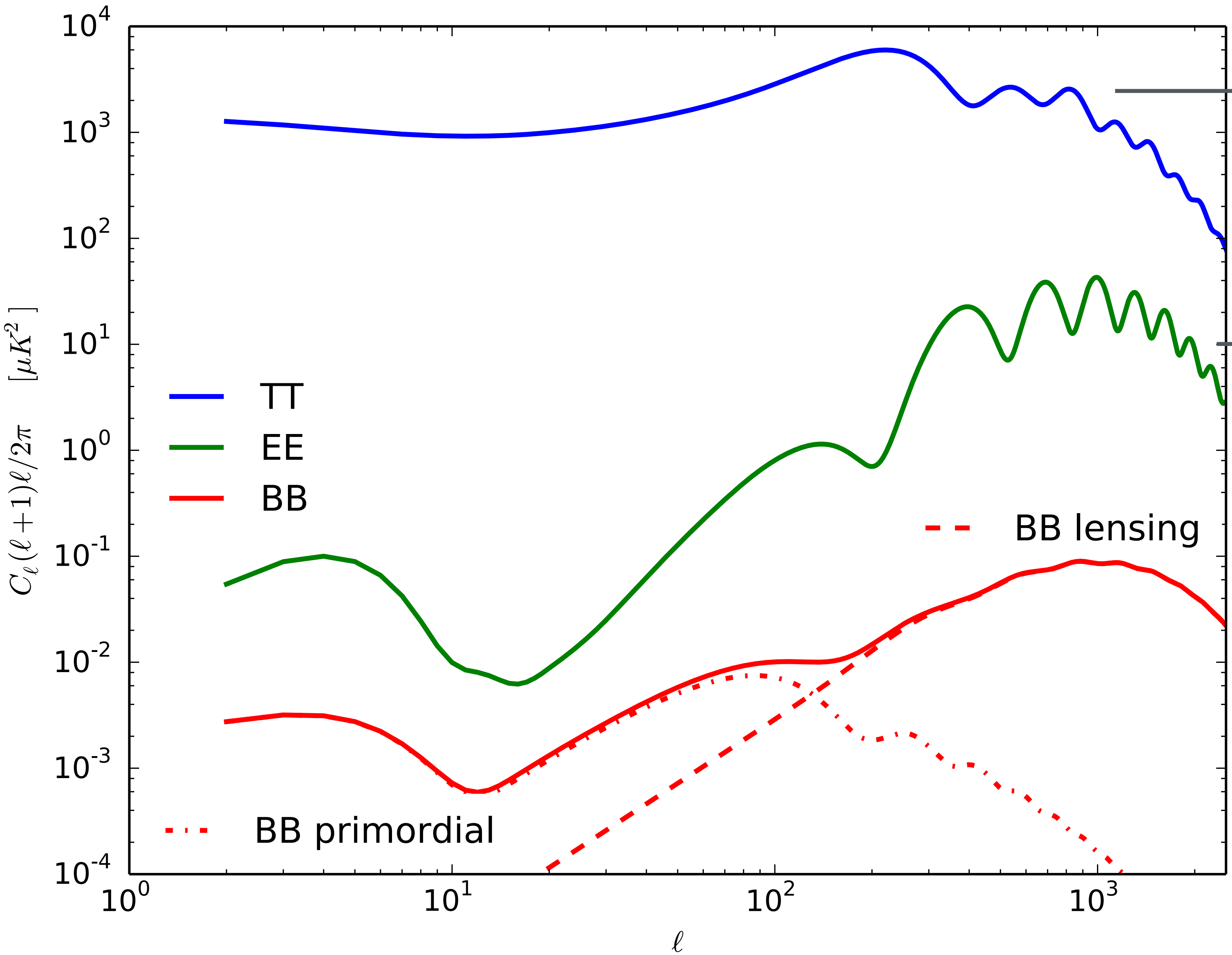
Assuming statistical isotropy

$$\langle a^*_{\ell m} a_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C_\ell$$ Angular power spectrum

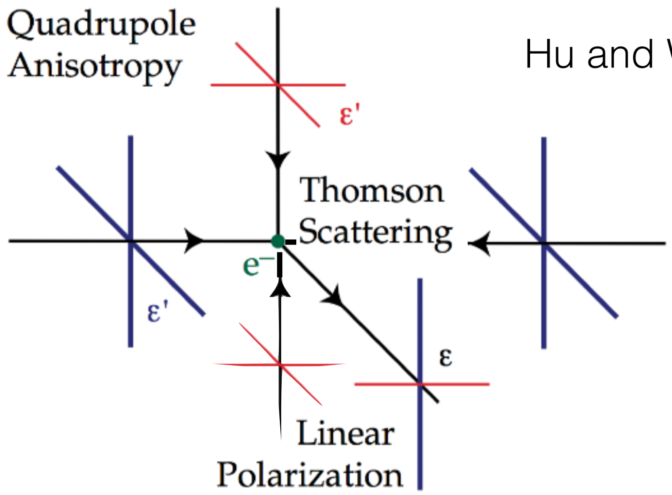
$$\hat{C}_\ell = \sum_{m=-\ell}^{\ell} \frac{a^*_{\ell m} a_{\ell m}}{2\ell + 1}$$

$\ell \sim 1/\text{angular size}$

The CMB power spectrum



Induced by primordial scalar perturbations.
Goldmine of cosmological information



Hu and White (1997)

Scalar perturbations also produce polarization, only E modes (to linear order)

Primordial B-modes

Prediction from inflationary models:
both scalar and tensor perturbations

In simplest slow-roll scalar-field inflation

$$\Delta_s^2(k) = \frac{1}{8\pi^2}\frac{H_\star^2}{m_{\rm Pl}^2}\frac{1}{\varepsilon_\star}$$

$$\Delta_t^2(k) = \frac{2}{\pi^2}\frac{H_\star^2}{m_{\rm Pl}^2}$$

$\varepsilon_\star$ Slow roll parameter

$H_\star^2$ Hubble parameter
Energy density of the universe

Tensor power spectrum $\propto$(Energy scale of inflation)$^{1/4}$

(~10^{16} GeV for r = 0.1)

$$r \equiv \frac{\Delta_t^2}{\Delta_s^2} = -8n_t$$

➡ Consistency relation

Lensing B-Modes

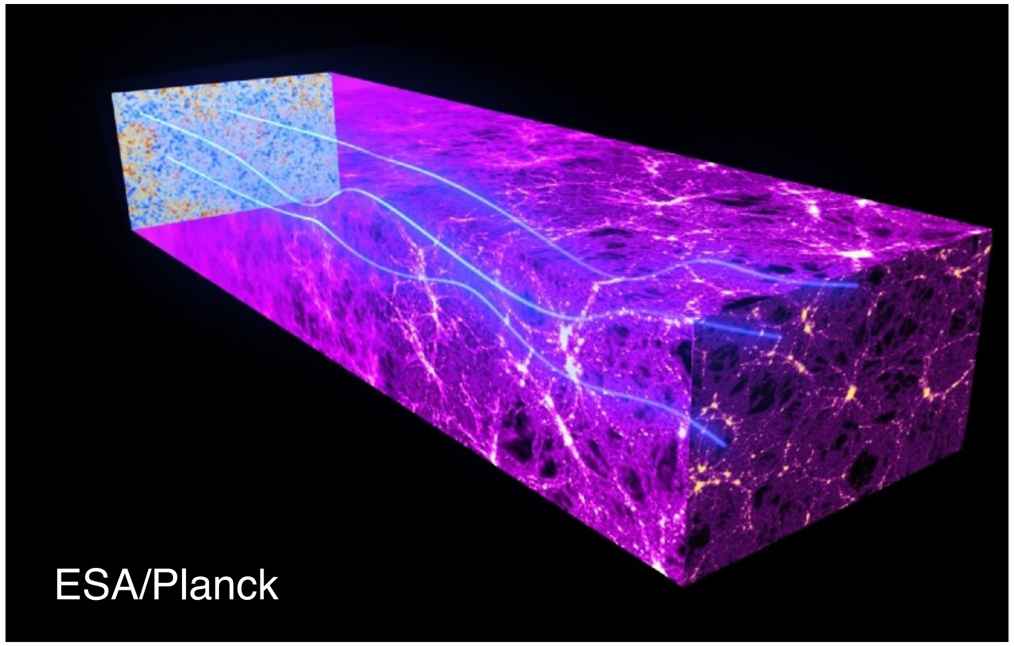
$$\delta E(\mathbf{l};\mathbf{l}') = -[E(\mathbf{l}')\cos 2\varphi_{\mathbf{l}'\mathbf{l}} - B(\mathbf{l}')\sin 2\varphi_{\mathbf{l}'\mathbf{l}}][\mathbf{l}\cdot(\mathbf{l}-\mathbf{l}')]\phi(\mathbf{l}-\mathbf{l}')$$

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

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

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

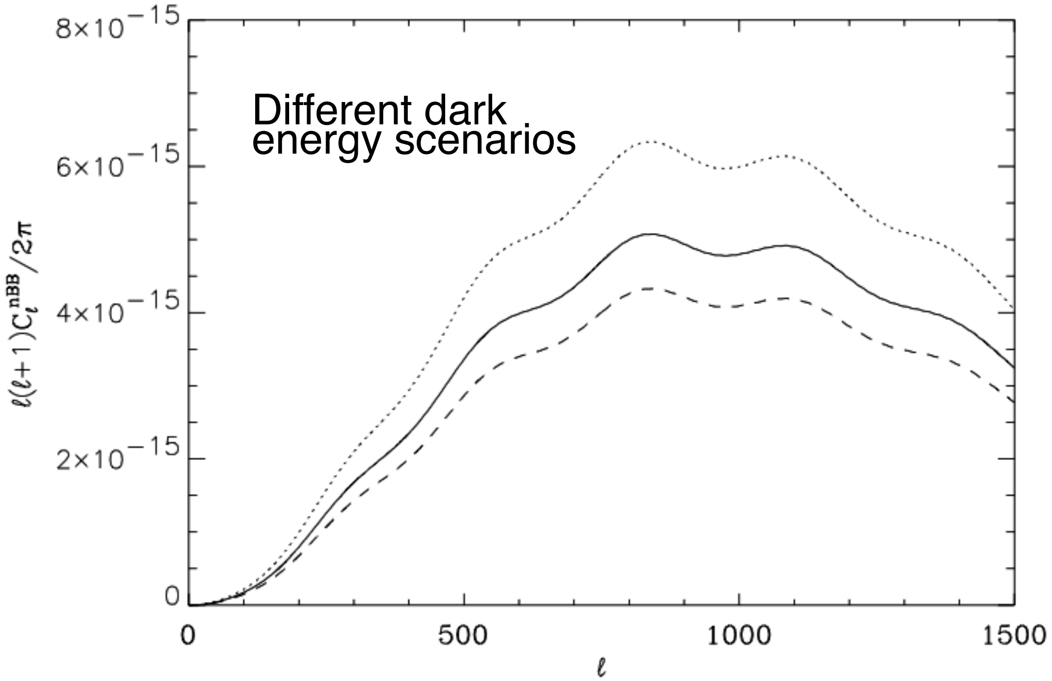
Hu and Okamoto (2002)



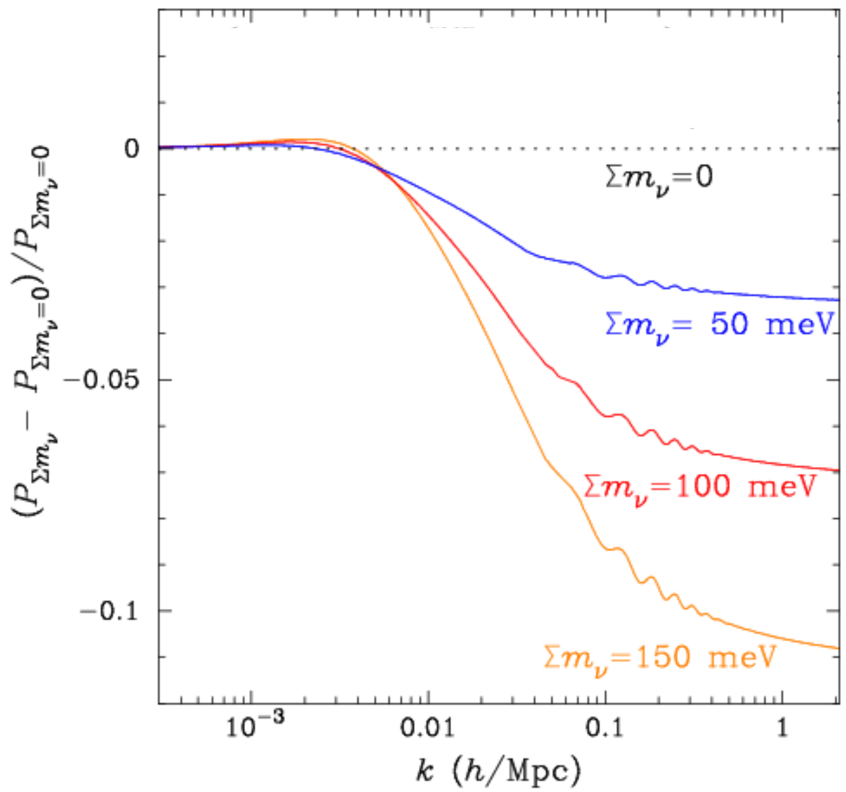
Constrain on structure formation

- total mass of the neutrinos
- dark energy
- and more

Acquaviva and Baccigalupi (2006)

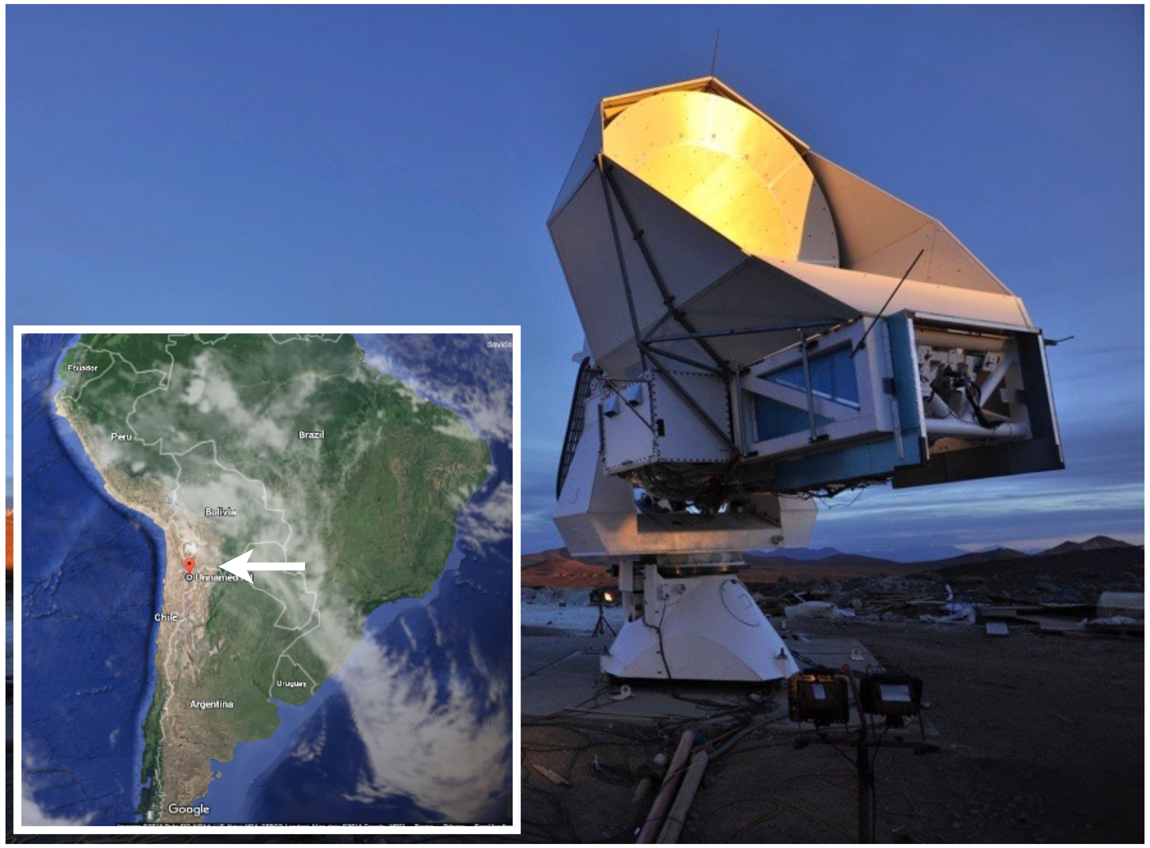


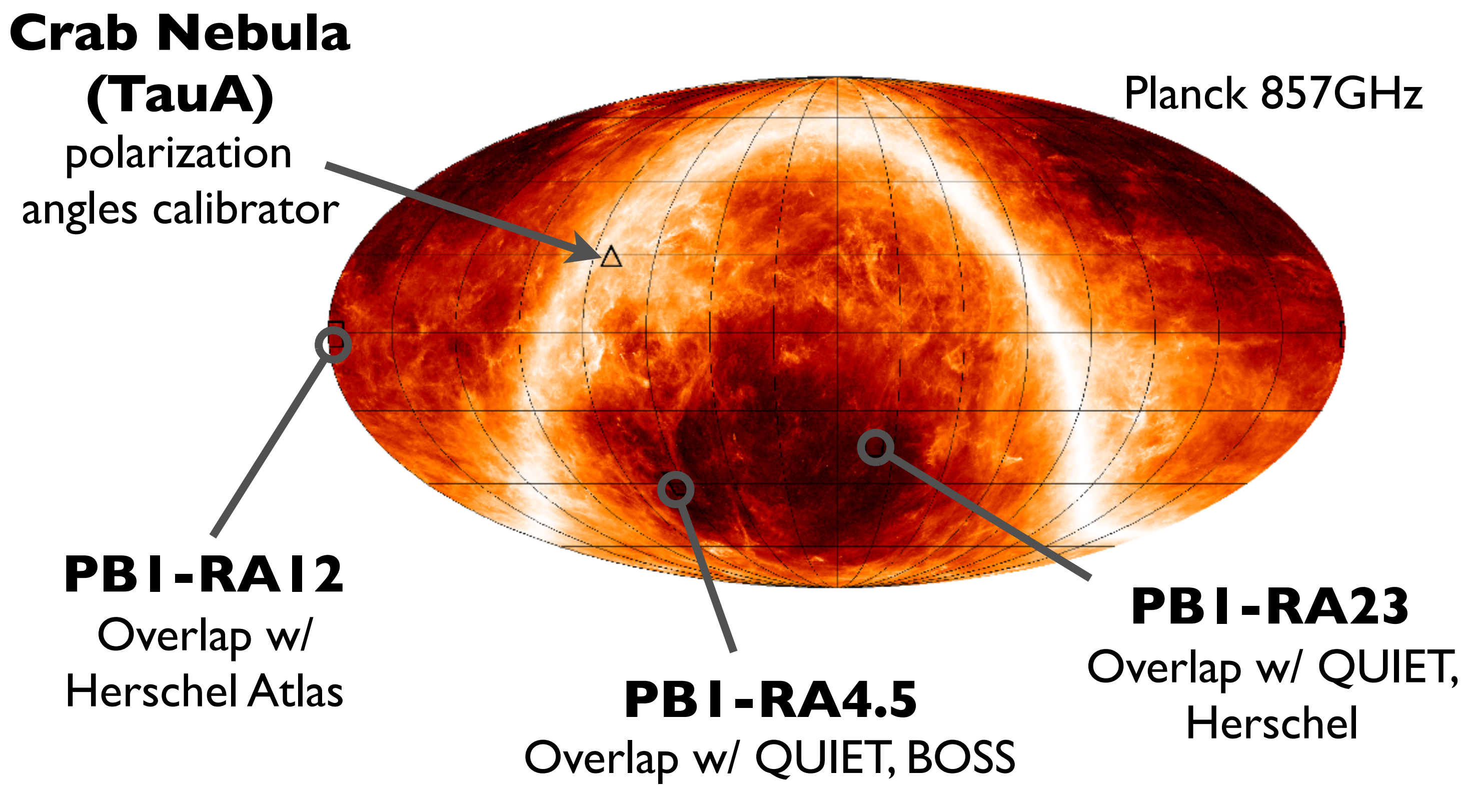
Abazajian et al. 2013



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:
  May 2012 to June 2013
- Second season:
  June 2013 to June 2014
- Target:
  deep integration of
  3 patches 5 deg x 5 deg

POLARBEAR Collaboration

MEXT
SIMONS FOUNDATION
Advancing Research in Basic Science and Mathematics

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

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

UC Irvine
Chang Feng

Cardiff University
Peter Ade

NASA Goddard
Nathan Miller

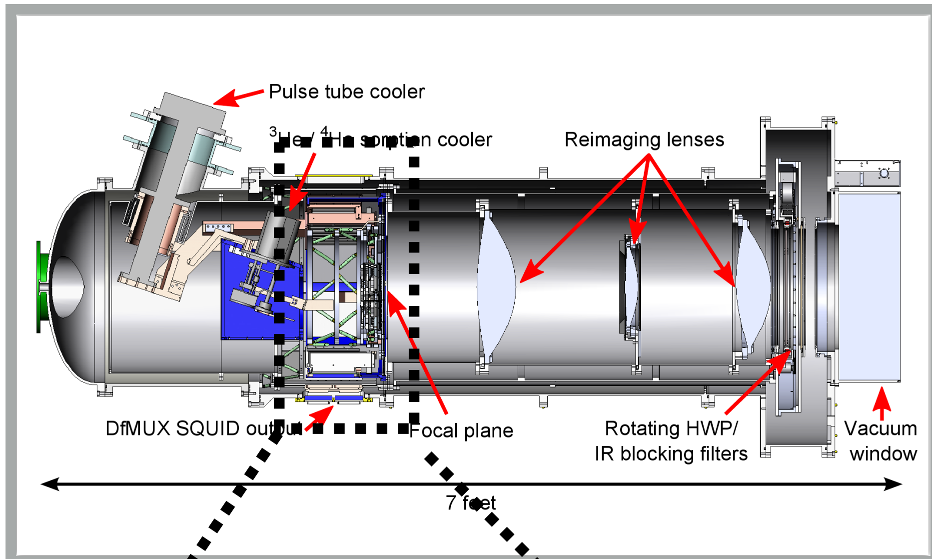
Argonne NL
Amy Bender

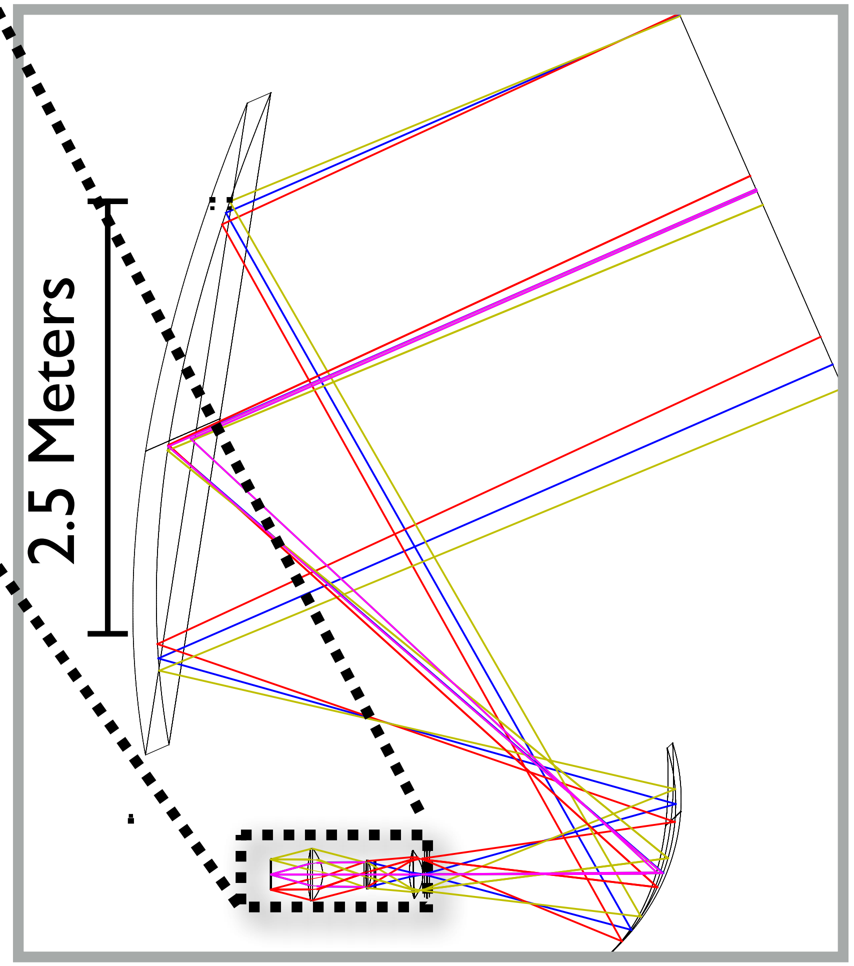
Católica (PUC)
David Boettger
Rolando Dunner

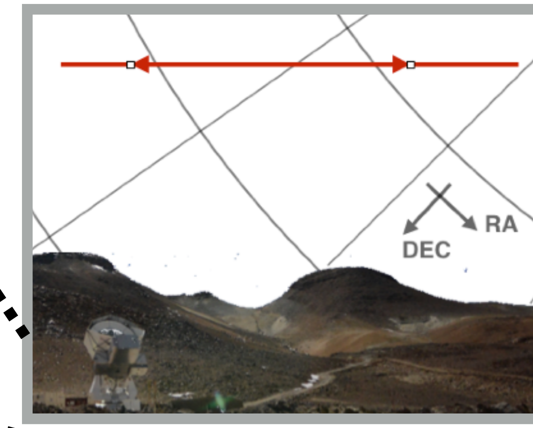
U of Sussex
Julien Peloton

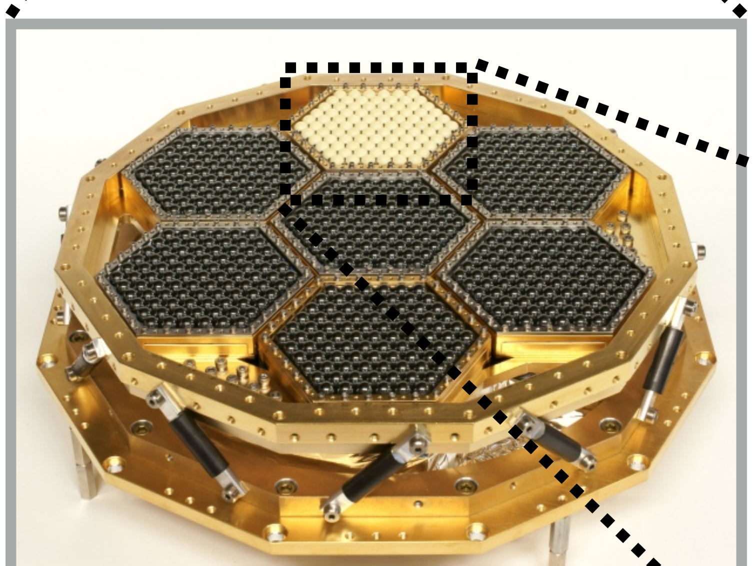
And many more in years past…

Instrumental design of POLARBEAR



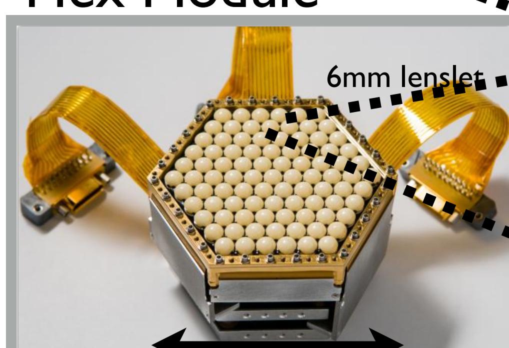




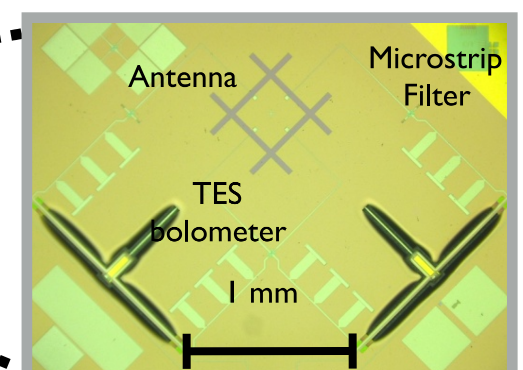


1274 bolometers @ 150 GHz
Cooled to 250 mK

Hex Module



8cm



see e.g. Kermish et al. (2012)
and Arnold et al. (2012)

CMB data analysis

Data volume (Nº "samples", order of)	Data analysis step
	• Data acquisition
10^{10} - 10^{12}	- - - - - - - - - - - - - - - - - - - -
	• Low level data processing (Calibration, pointing reconstruction…)
	• Map-making
10^{5} - 10^{7}	- - - - - - - - - - - - - - - - - - - -
	• Component separation
	• Power spectrum estimation
10 - 10^{2}	- - - - - - - - - - - - - - - - - - - -
	• Cosmological parameter estimation
1 - 10	

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Our involvement

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1 - 10	

Poletti et al. (2017)

Our involvement

The POLARBEAR Collaboration (2017)

The map-making problem

A single sample

$$d_t = I_{p_t} + \cos(2\varphi_t)Q_{p_t} + \sin(2\varphi_t)U_{p_t} + n_t$$

The complete time stream

$$\mathbf{d} = \mathbf{A}\mathbf{s} + \mathbf{n}$$

$\mathbf{A} = \text{Pointing matrix}$

$\mathbf{s} = \text{sky signal}$

$\mathbf{n} = \text{noise with covariance } \mathbf{N}$

Generalised
Least
Squared
estimator

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

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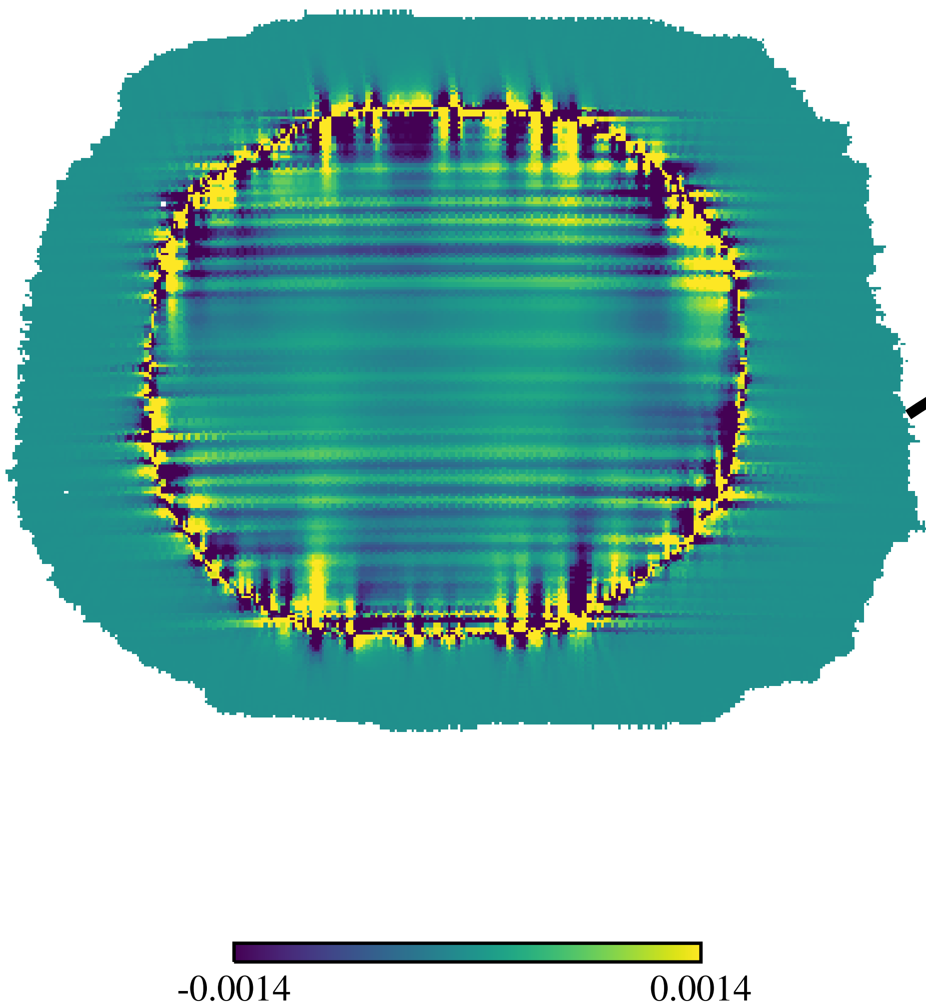
Generalised
Least
Squared
estimator

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

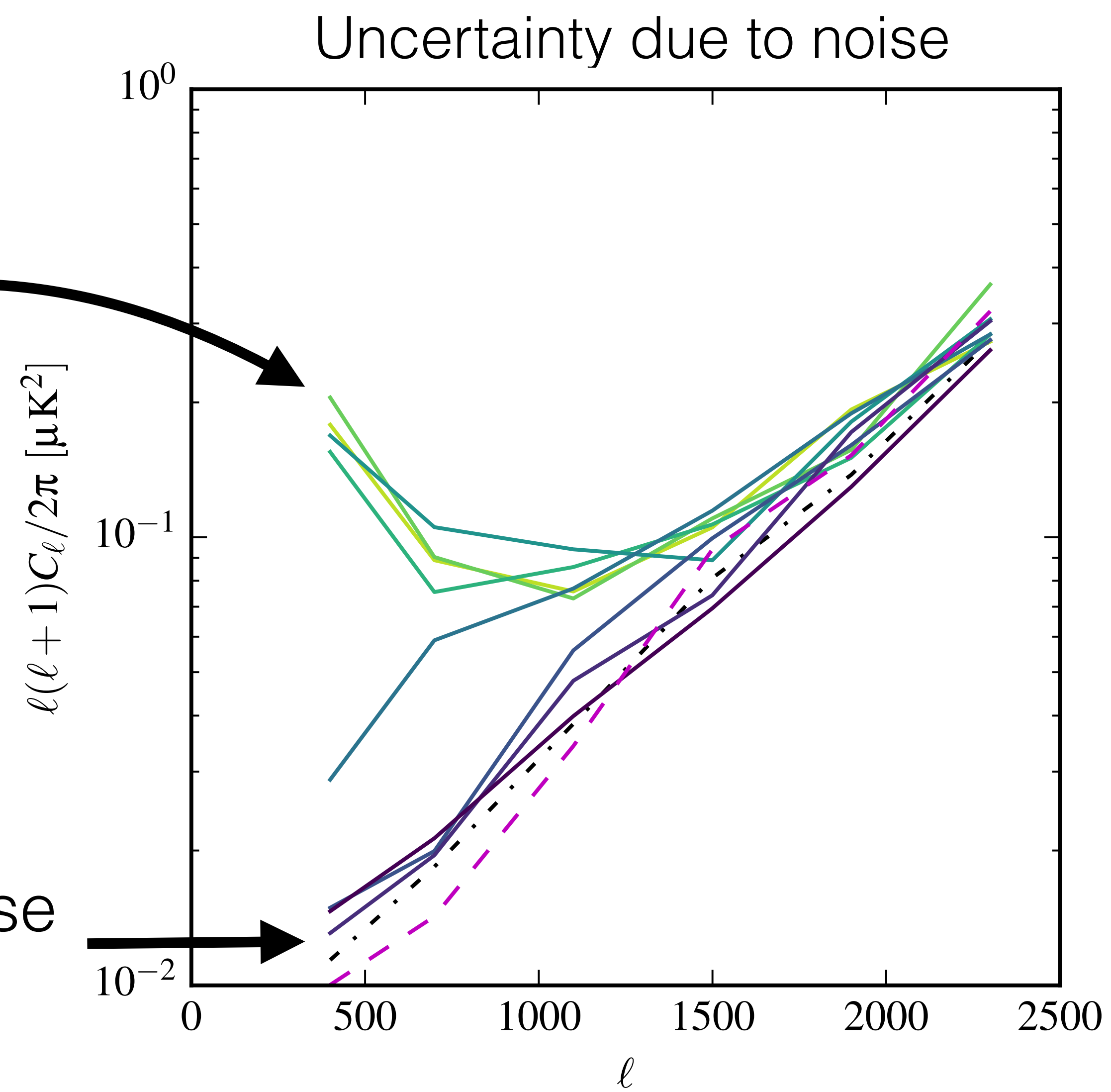
$\mathbf{F_T}$ TOD signal processing

Example of the effect on final products

TOD-processing produced map-domain correlations…



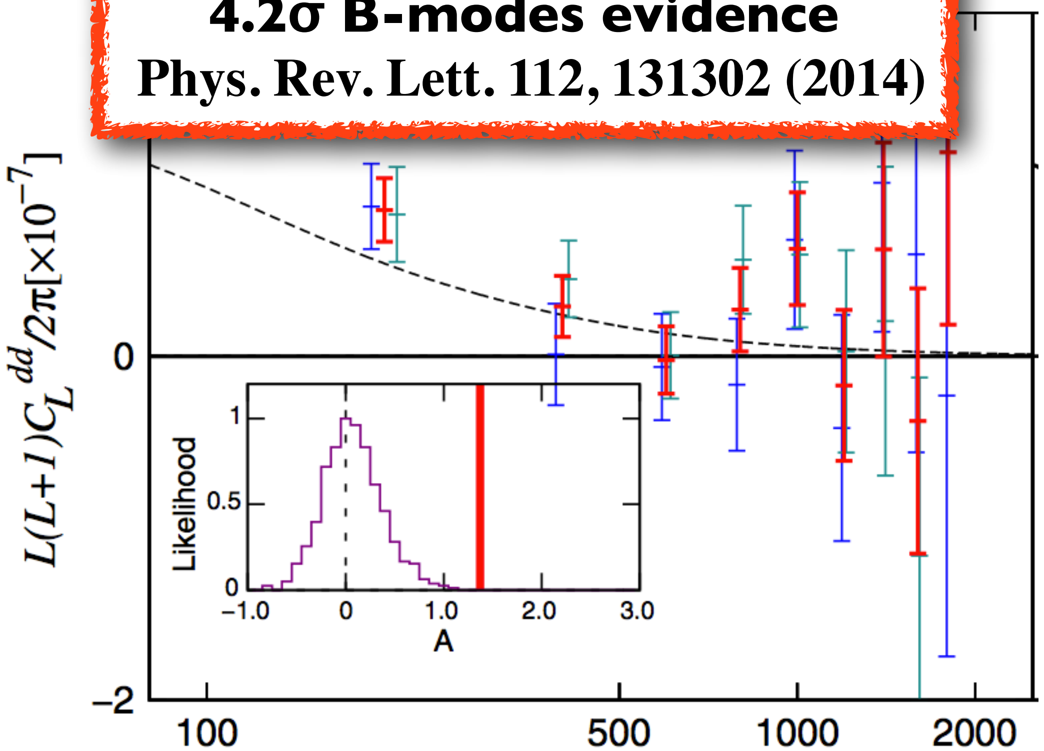
…that made the power spectrum estimation sub-optimal



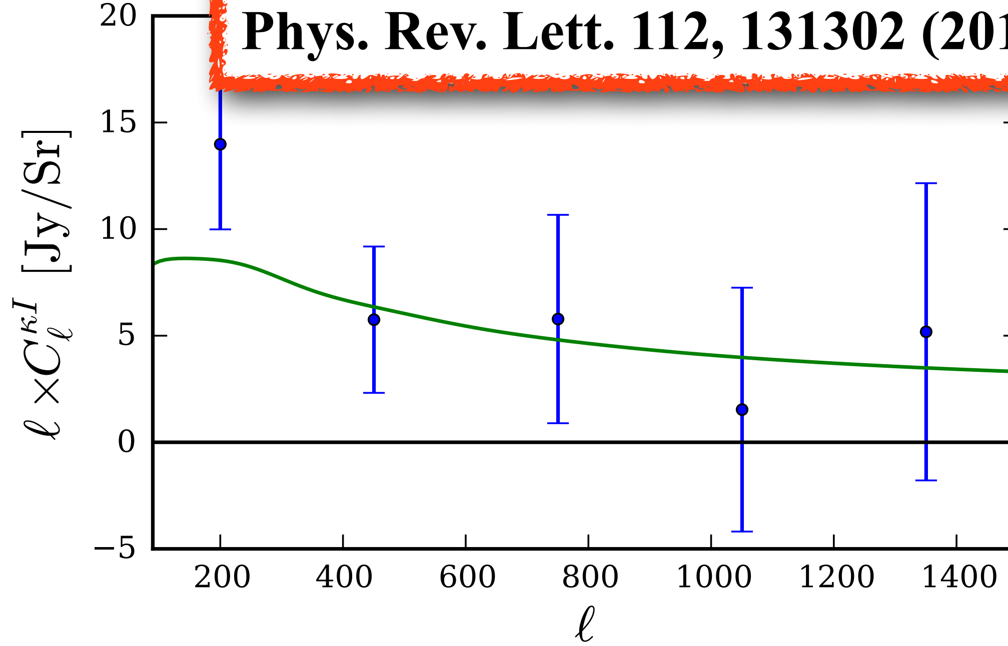
White noise case

Cosmological results from the first season

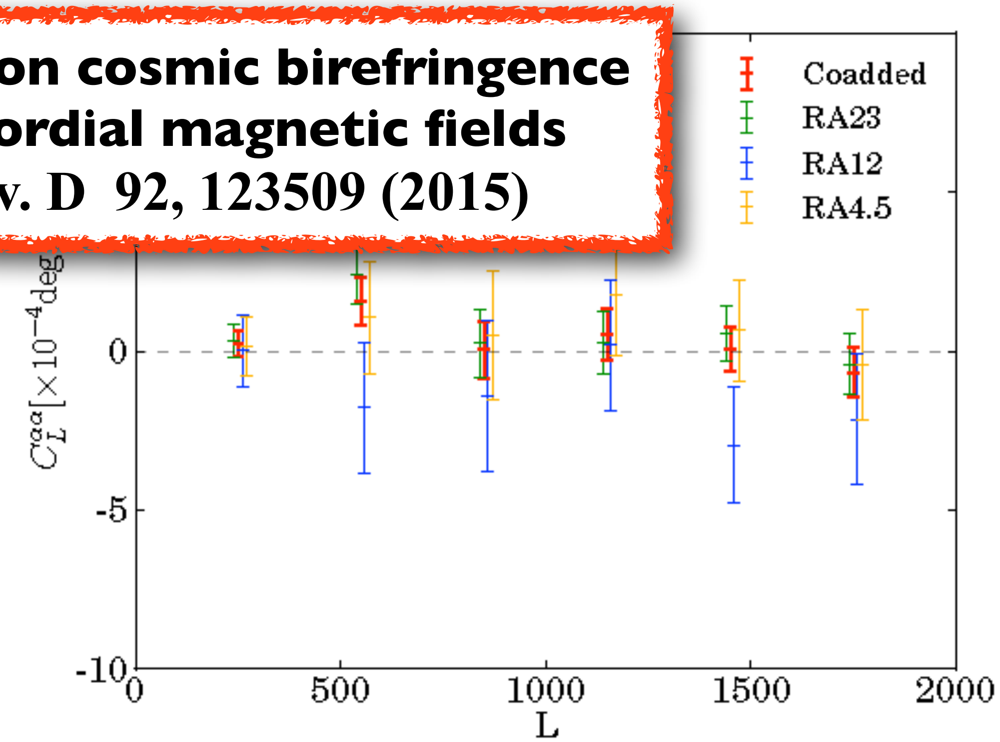
Lensing reconstruction from polarisation alone
4.2σ B-modes evidence
Phys. Rev. Lett. 112, 131302 (2014)



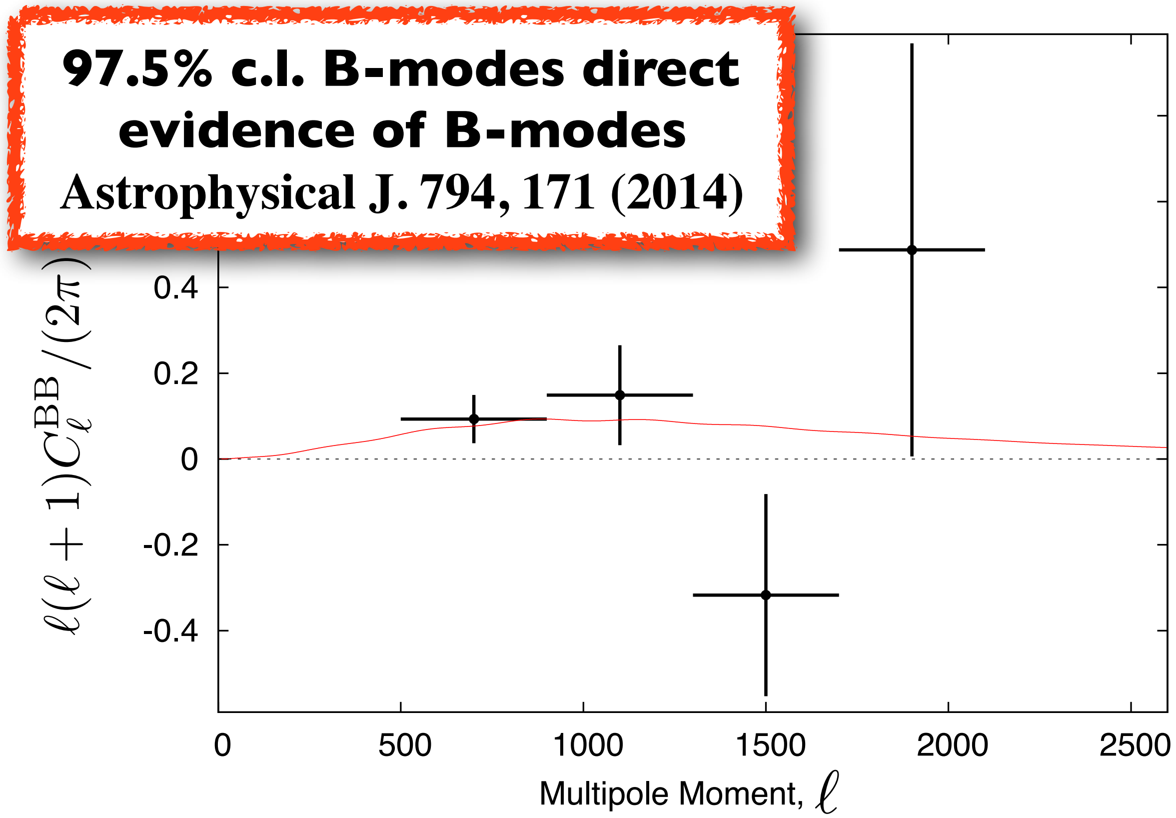
4.0σ polarized lensing
Phys. Rev. Lett. 112, 131302 (2014)



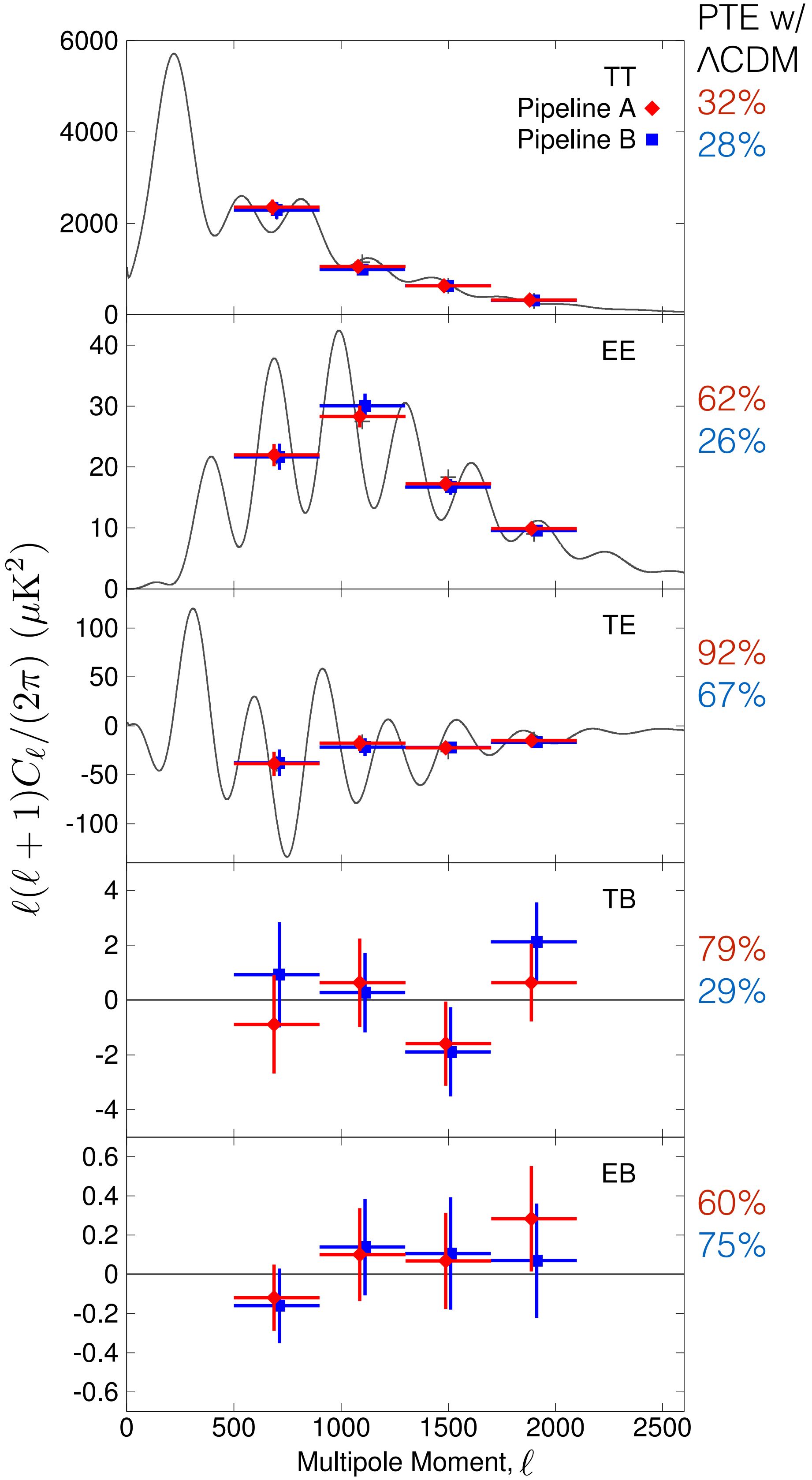
Constraint on cosmic birefringence and primordial magnetic fields
Phys. Rev. D 92, 123509 (2015)

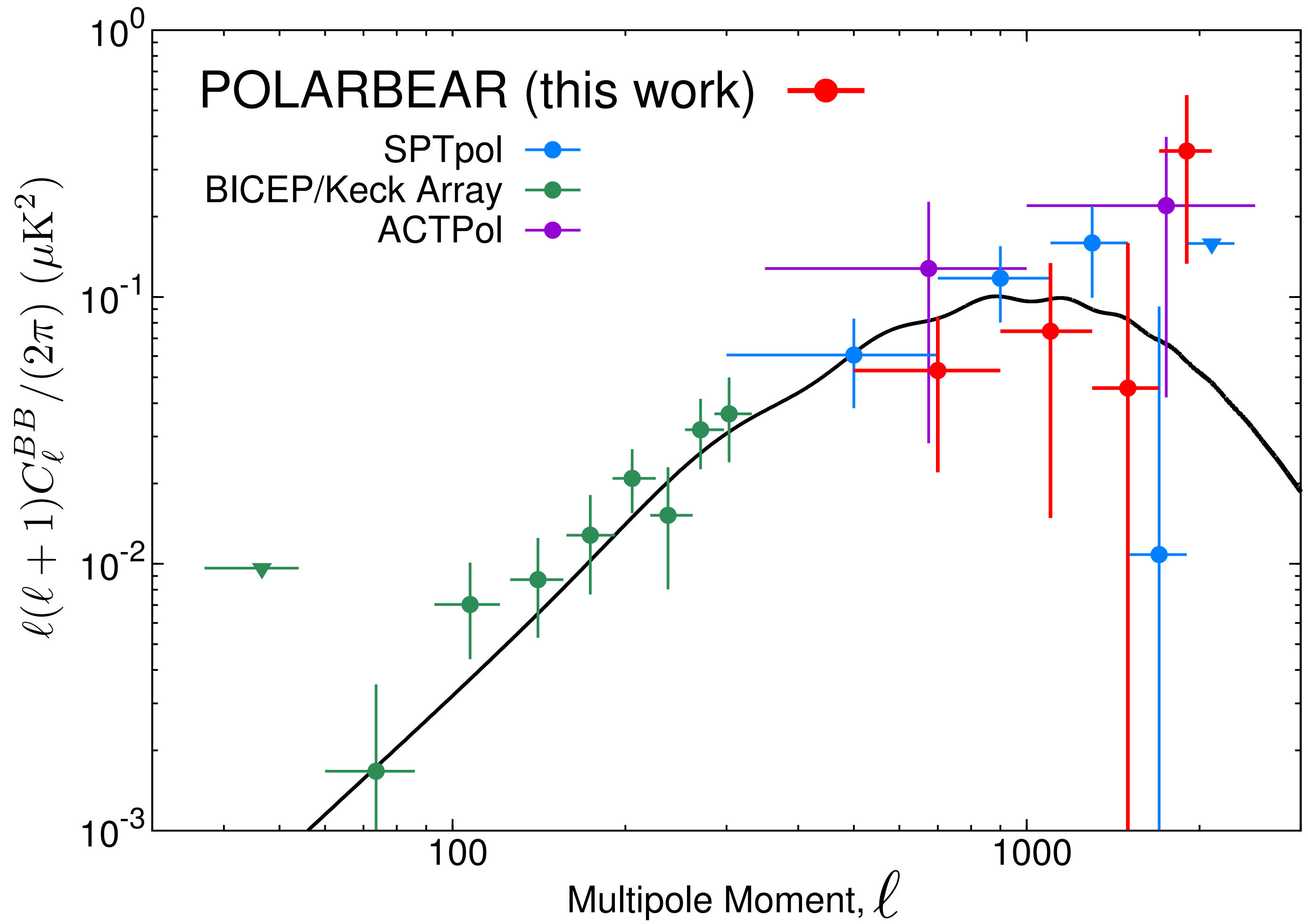


97.5% c.l. B-modes direct evidence of B-modes
Astrophysical J. 794, 171 (2014)



First and second season power spectra





Sensitivity doubled compared to the first season

- 61% more data
- improved calibration
- improved uncertainty estimate

Significance: 3.1 σ rejection of the null hypothesis of no B modes

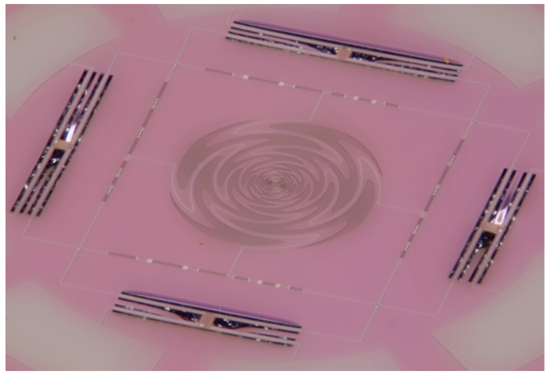
The future

Since May 2014, **large patch** observation

- ~700 deg^2 patch
- Access to primordial B-modes

End of 2017: **POLARBEAR 2**
New telescope and receiver

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



2018: **Simons Array**
New telescopes, 2 new PB2-like receivers

- 22,764 detectors
- 95/150/220/270 GHz channel

$\sigma(r = 0.1) = 6 \cdot 10^{-3}$ $\sigma(\Sigma m_\nu = 0) = 40\mathrm{meV}$

Simons Observatory

- Merge POLARBEAR and ACT Collaboration
- 5 year $45M+ program for key CMB science

Summary

CMB B-modes are a window on

- inflation
- structure formation
- and much more

Challenging measure:

- Sensitivity
- Systematics control
- Data analysis
- Foregrounds

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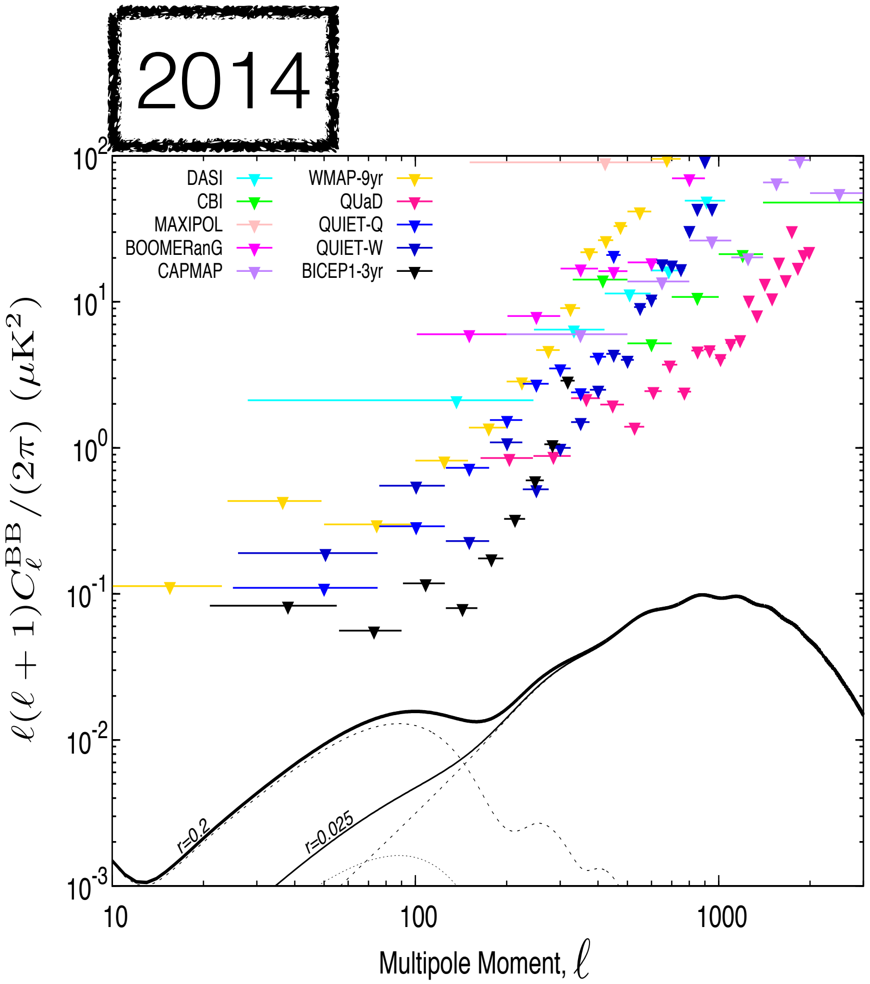

Summary

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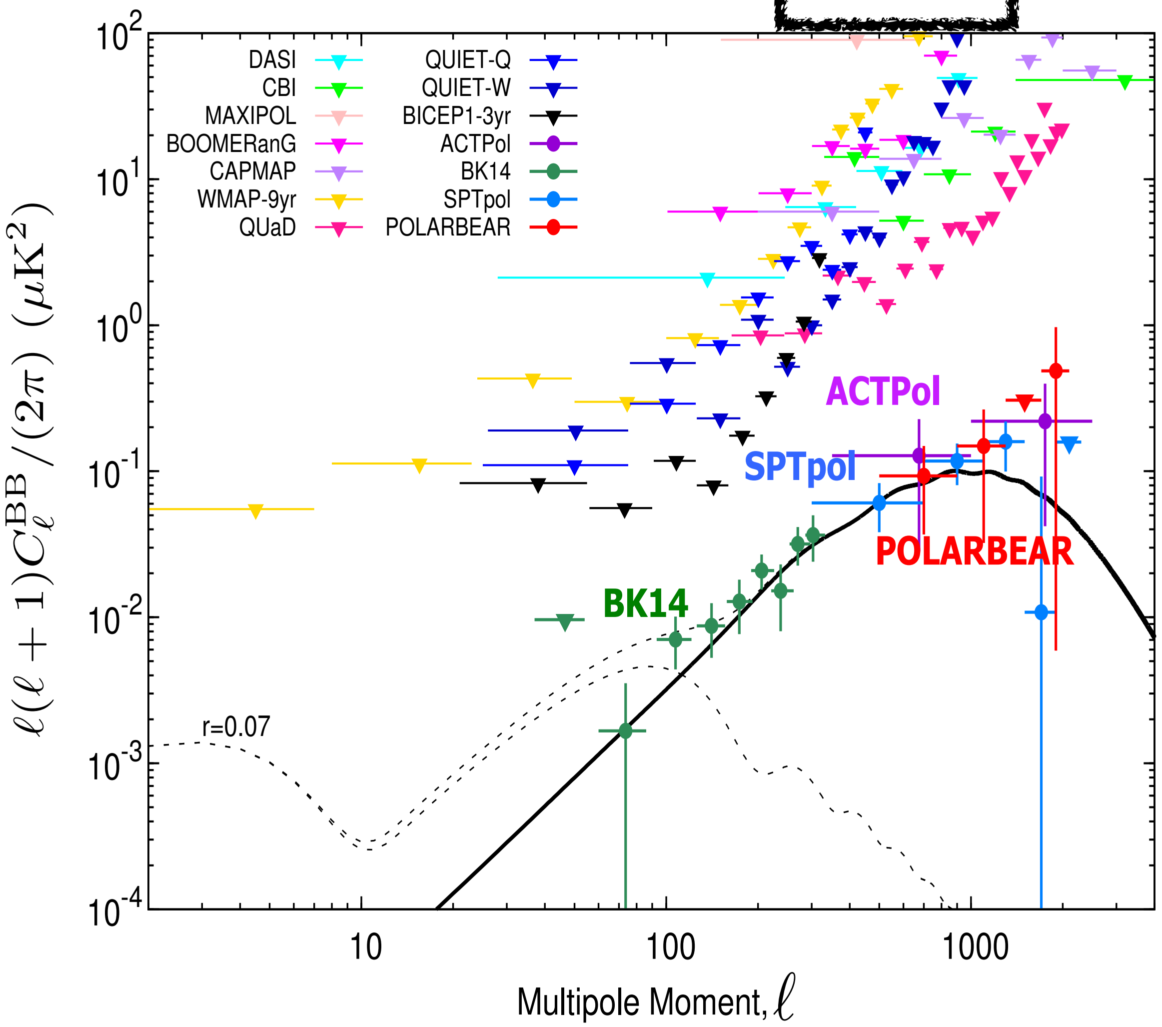
From B-mode detection to cosmological constraints in few years

2017

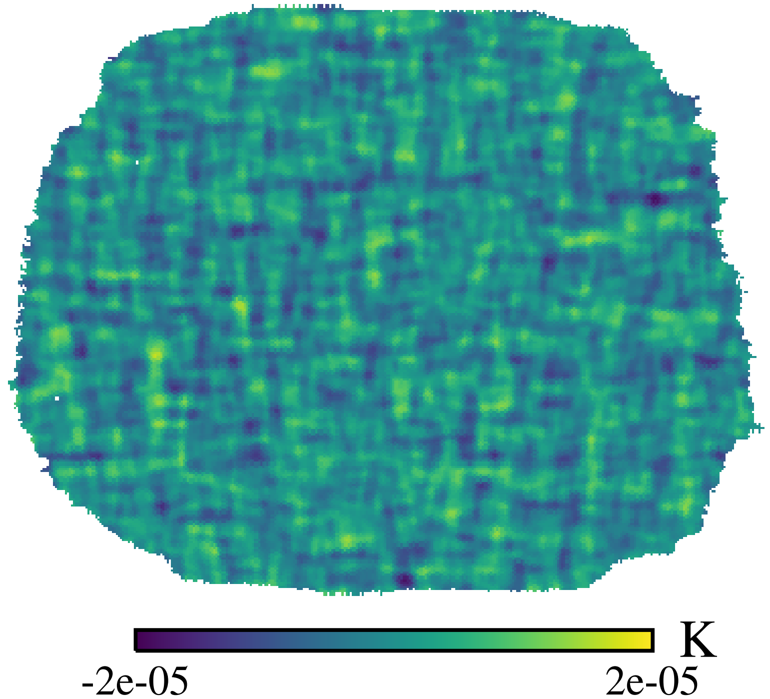


Plus measurements through cross-correlation!
- SPTPol
- POLARBEAR
- ACTPol
- Planck

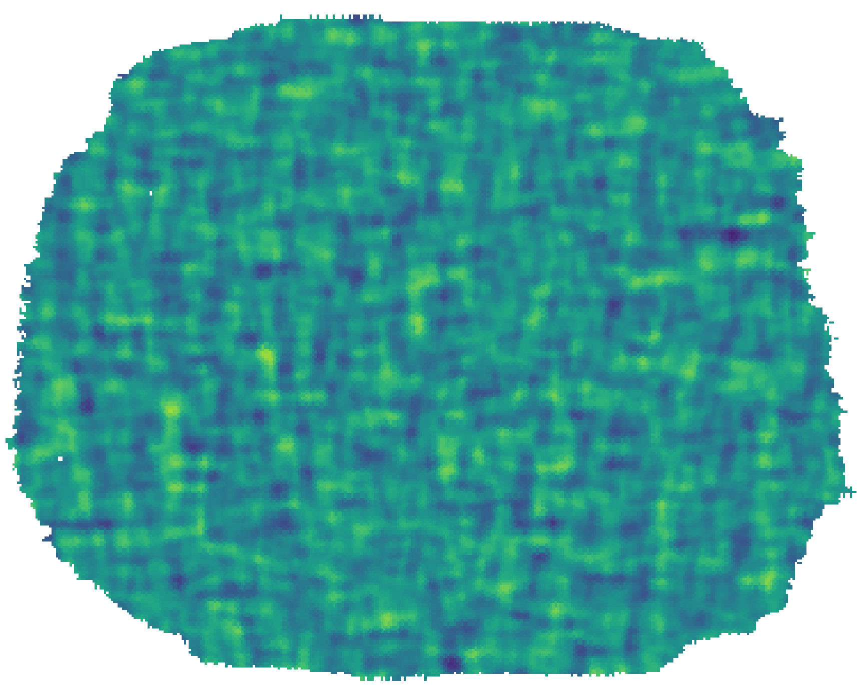
Thanks for your attention

Quality of the reconstruction

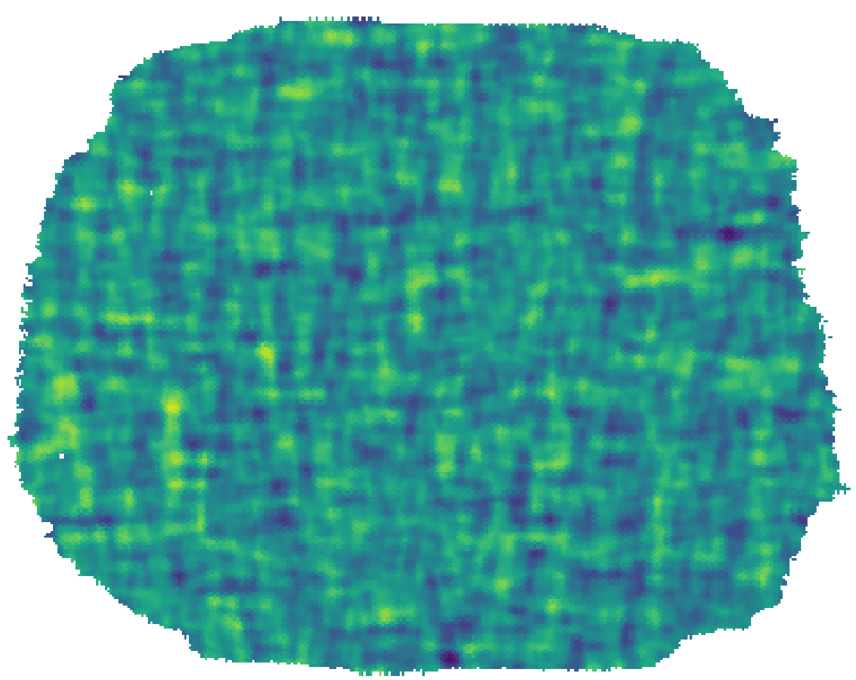
Signal-only input map
(Only Q displayed)



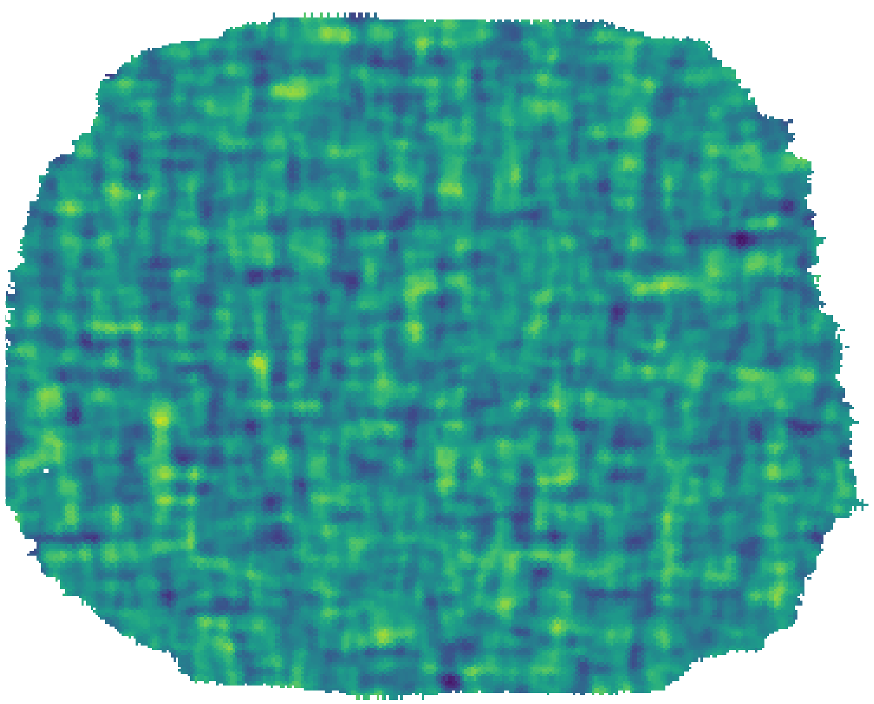
Biased estimator



Unbiased, PCG implementation



Unbiased explicit implementation
(singular modes removed)



Quality of the reconstruction

Signal-only input map
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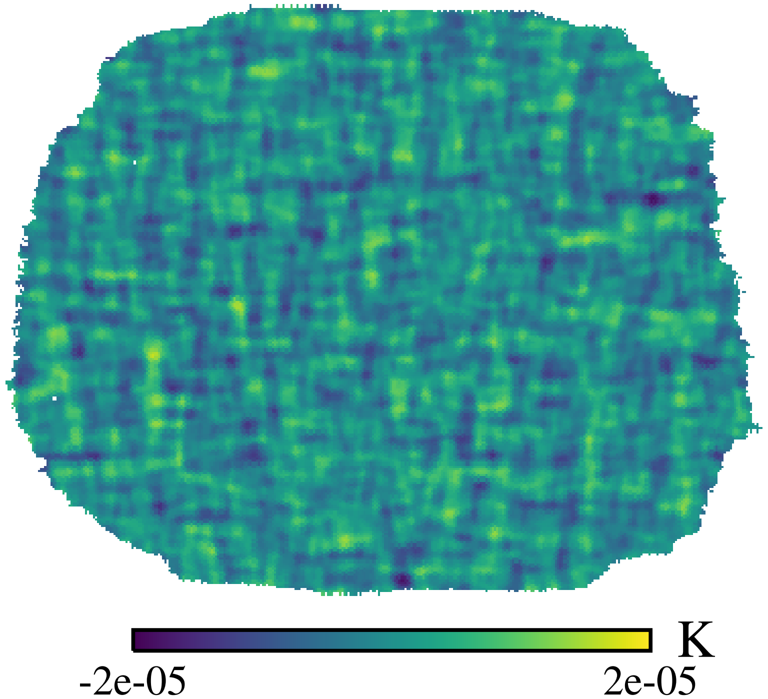

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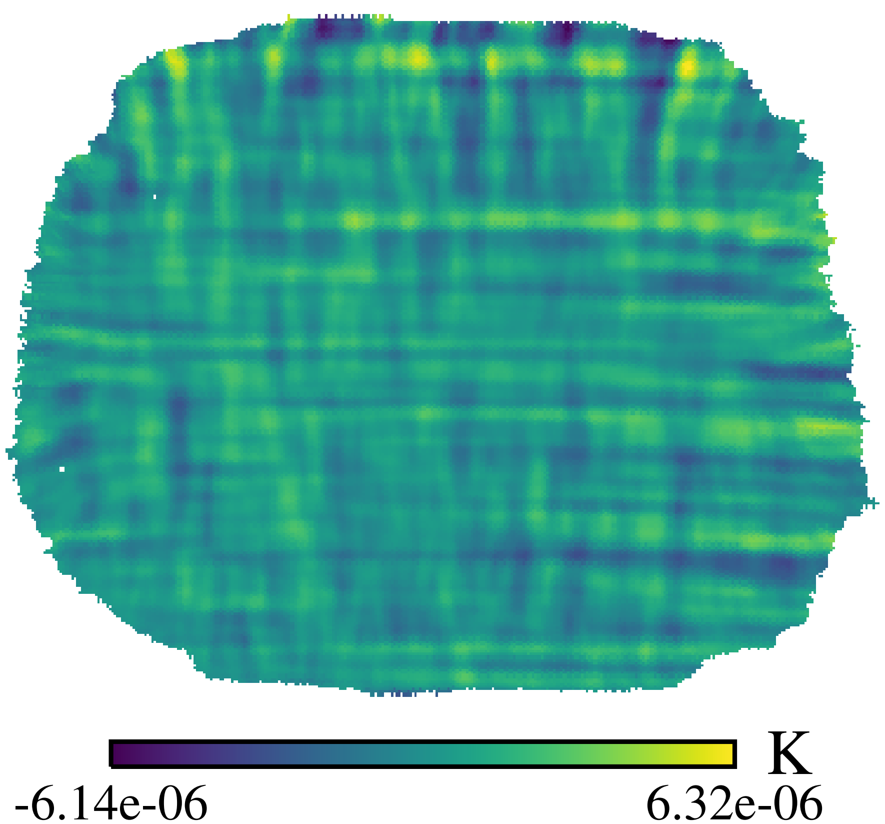
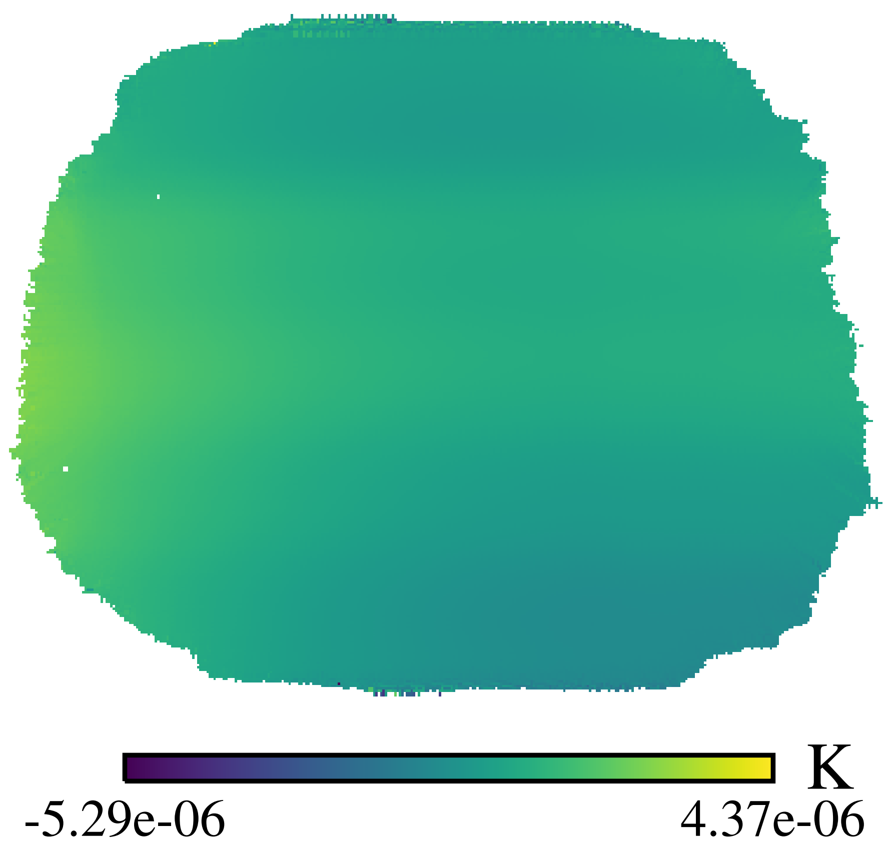


Unbiased, PCG implementation



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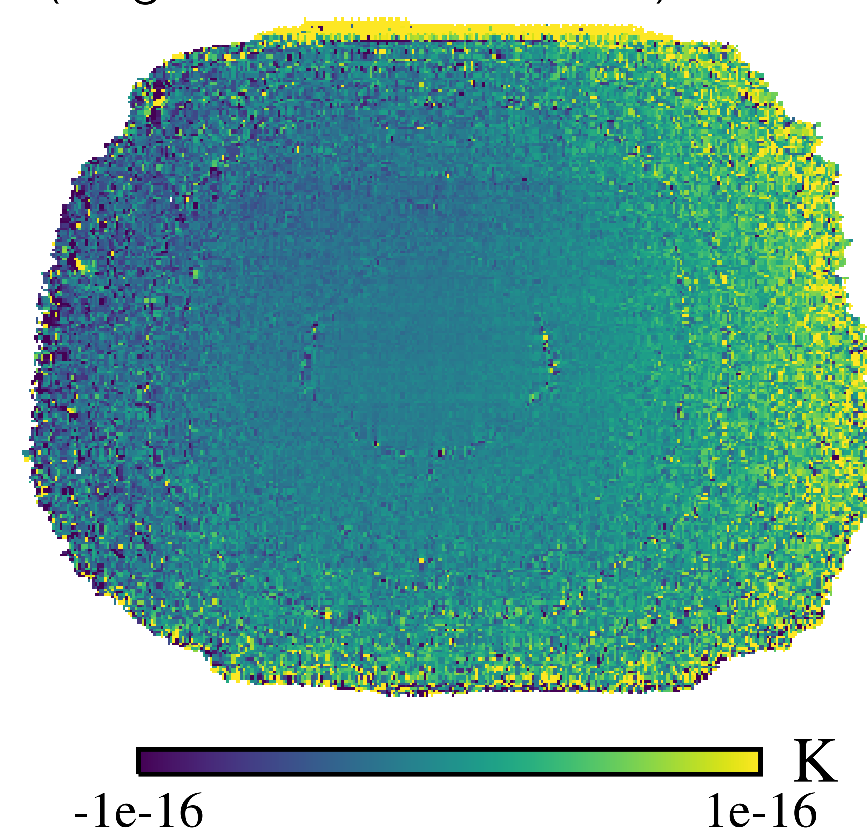
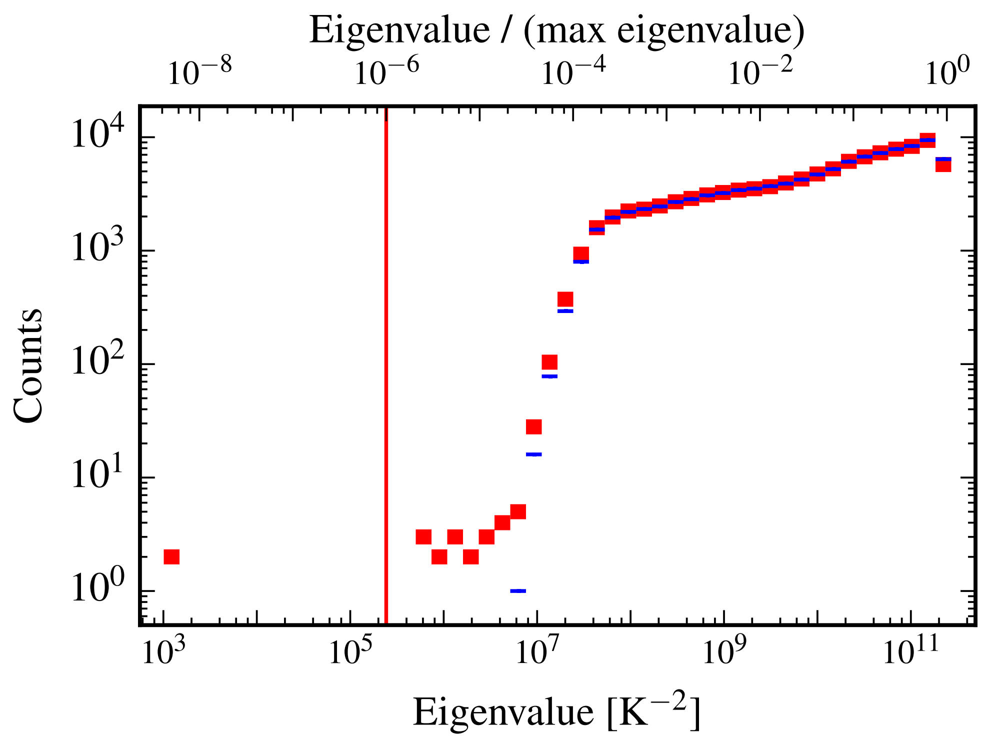


The eigenstructure of $\mathbf{A}^\top \mathbf{F}_\mathbf{T} \mathbf{A}$



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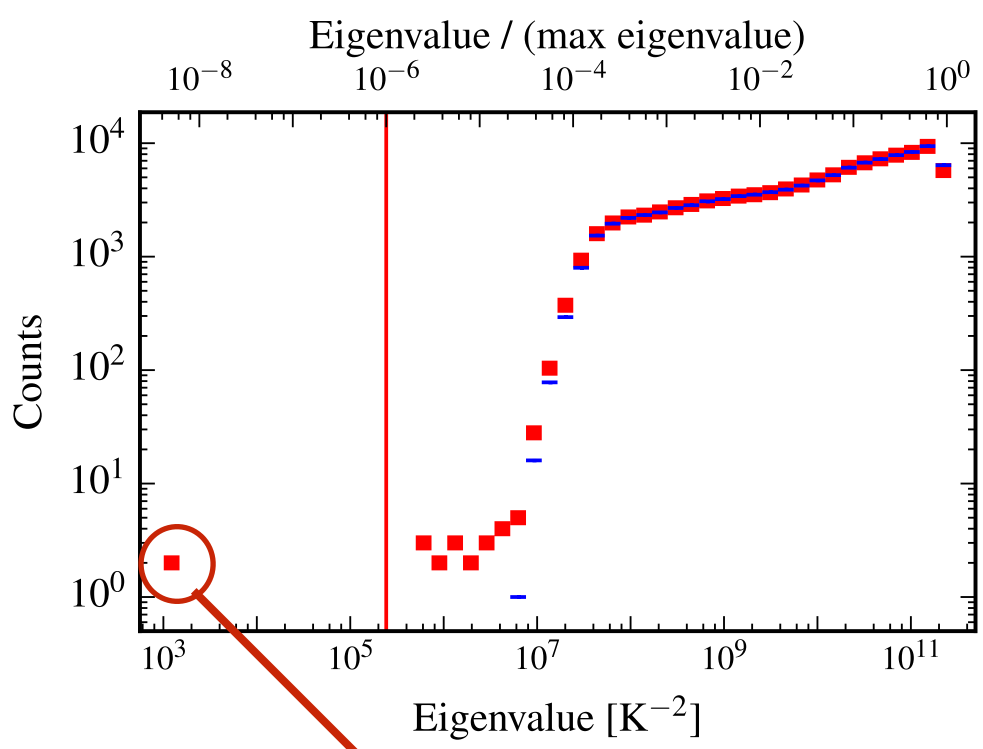

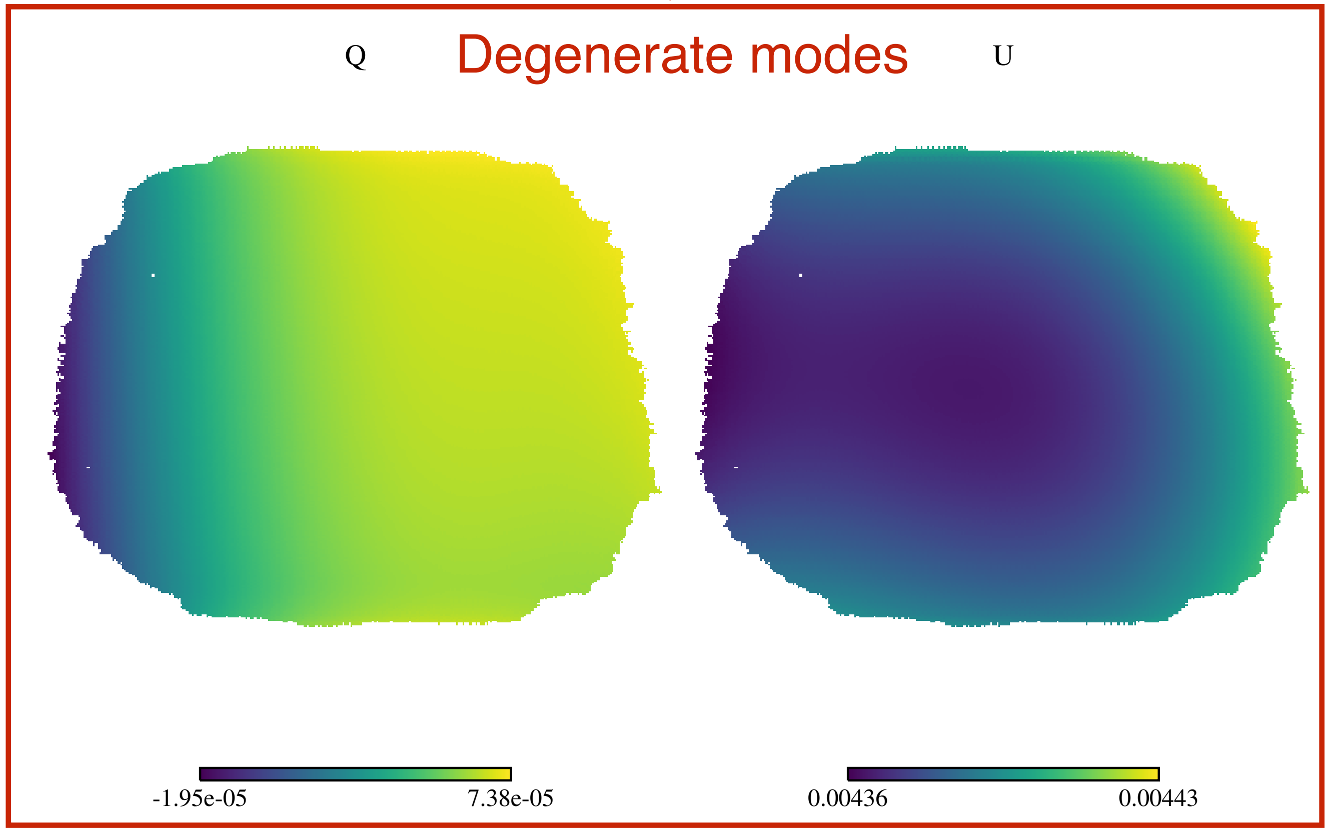

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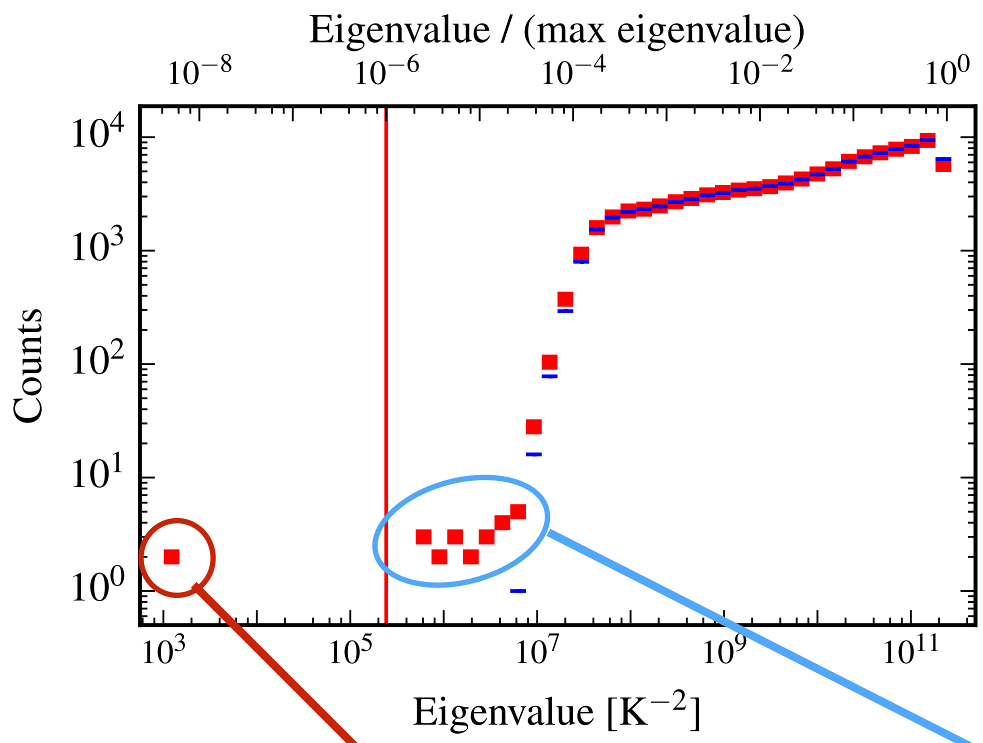

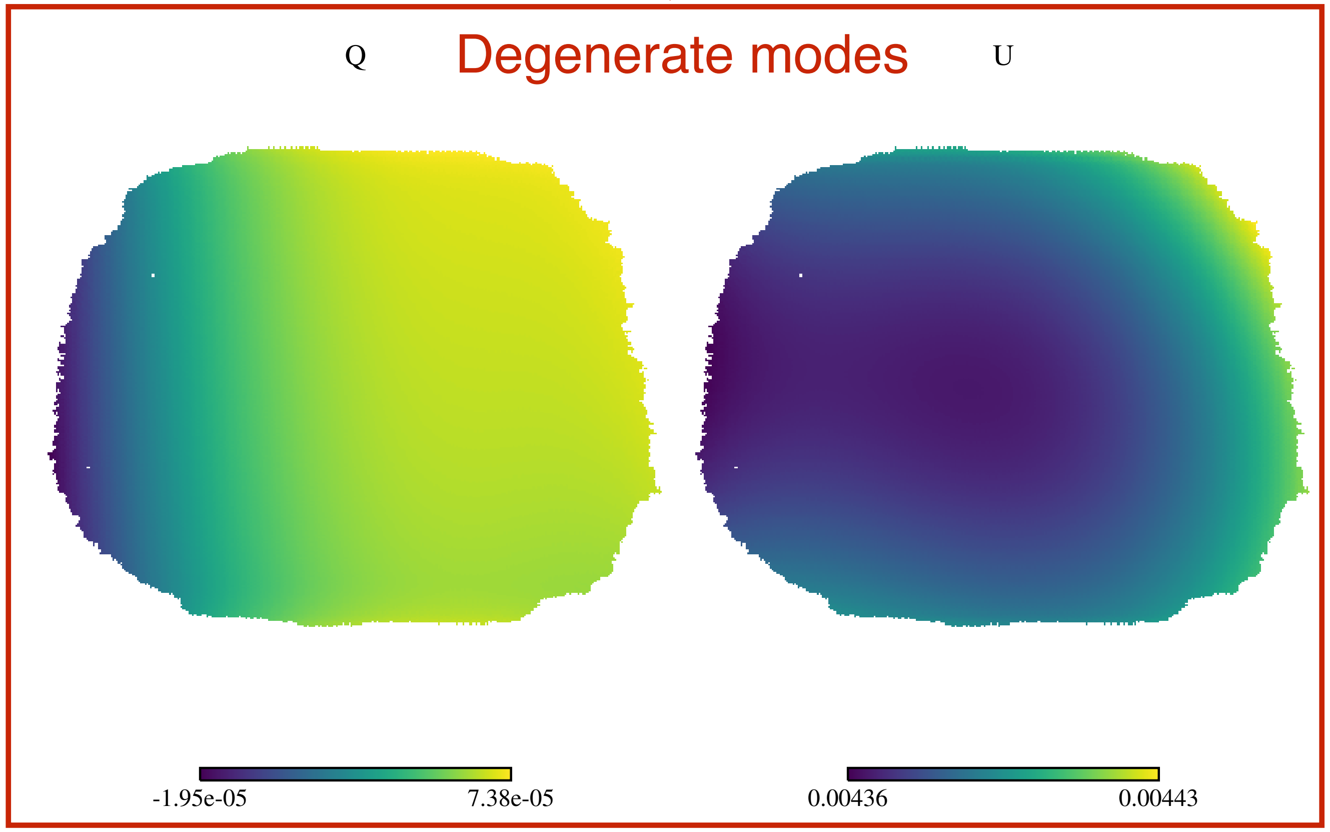

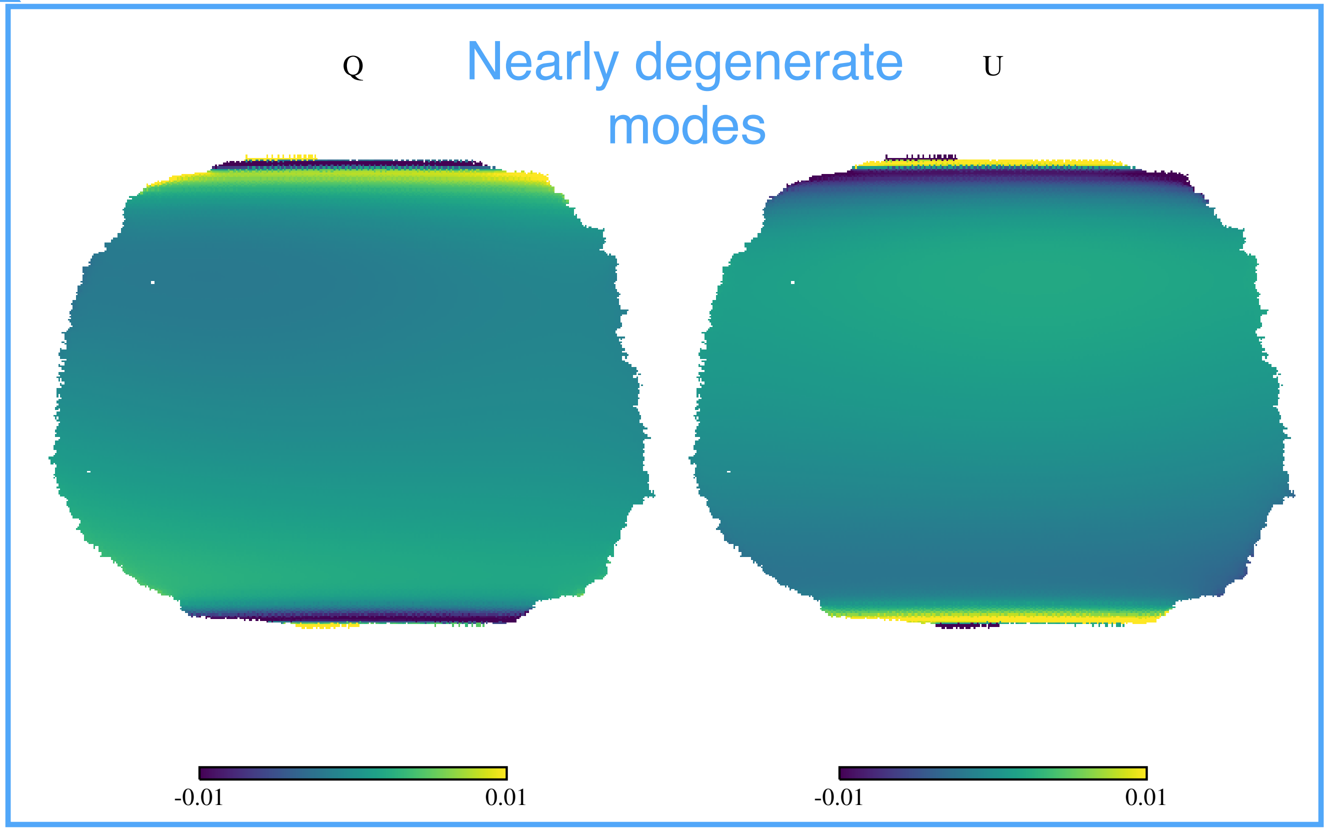

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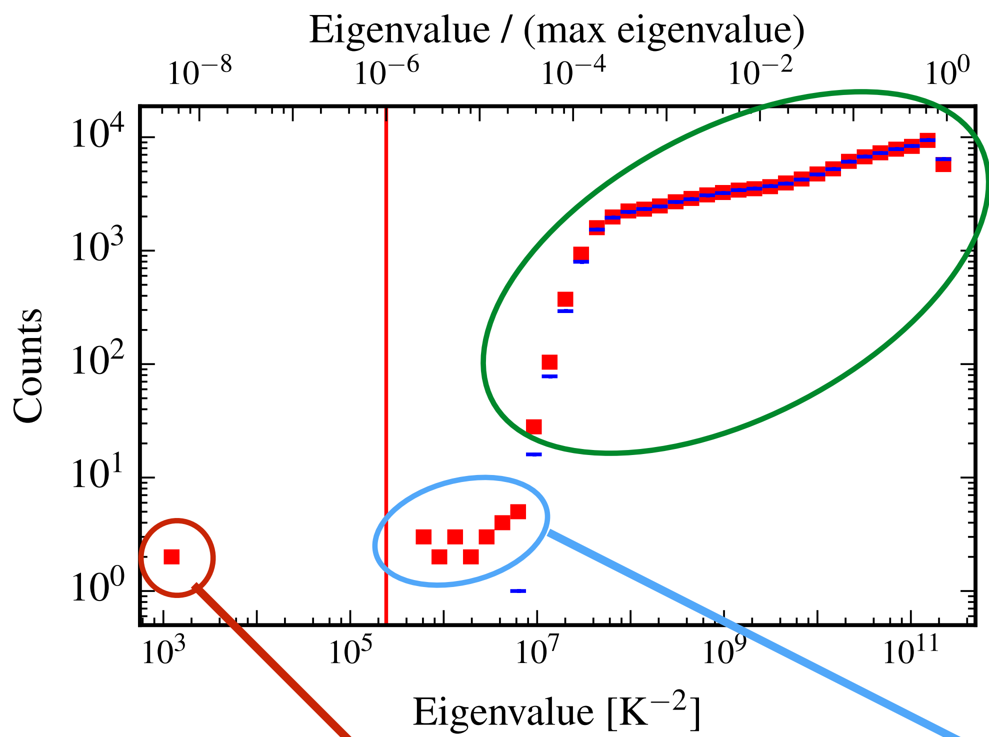
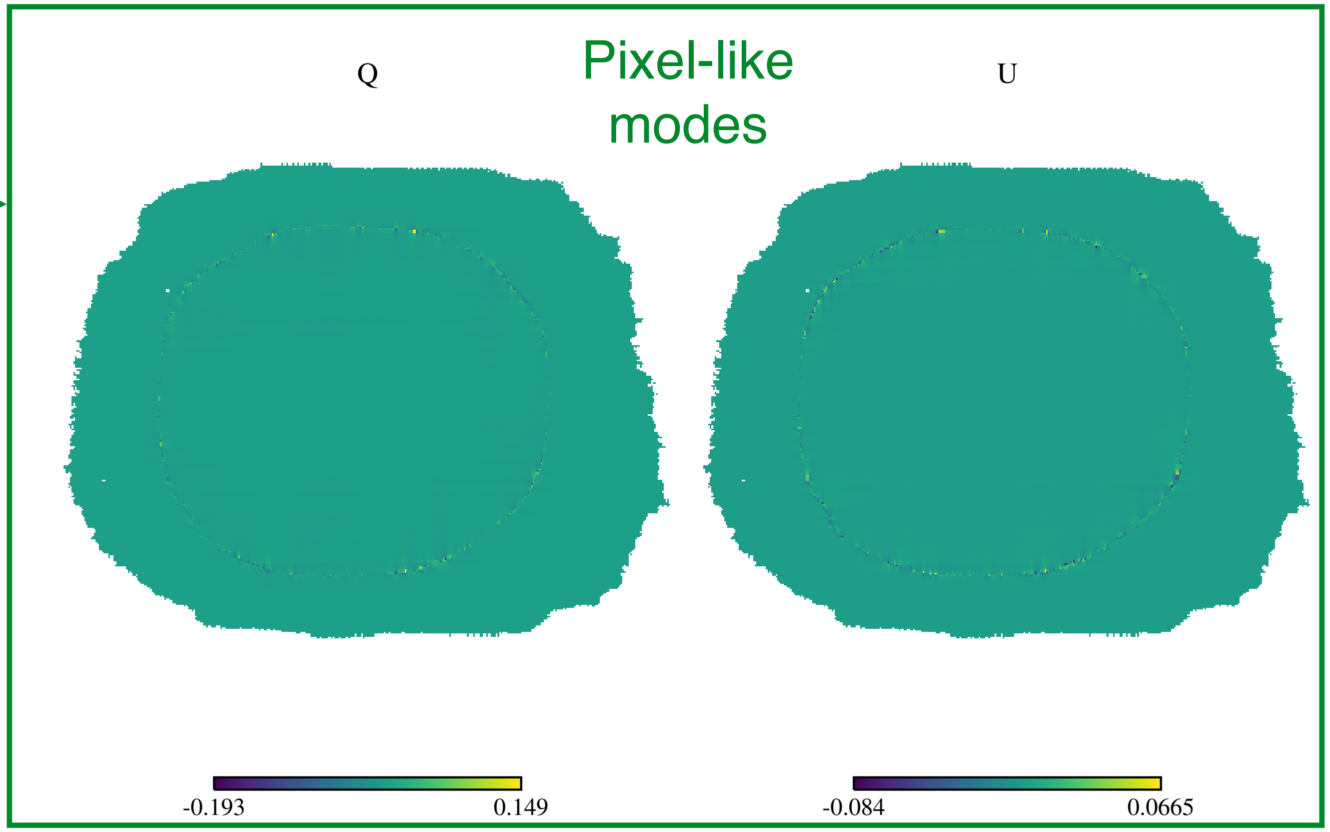
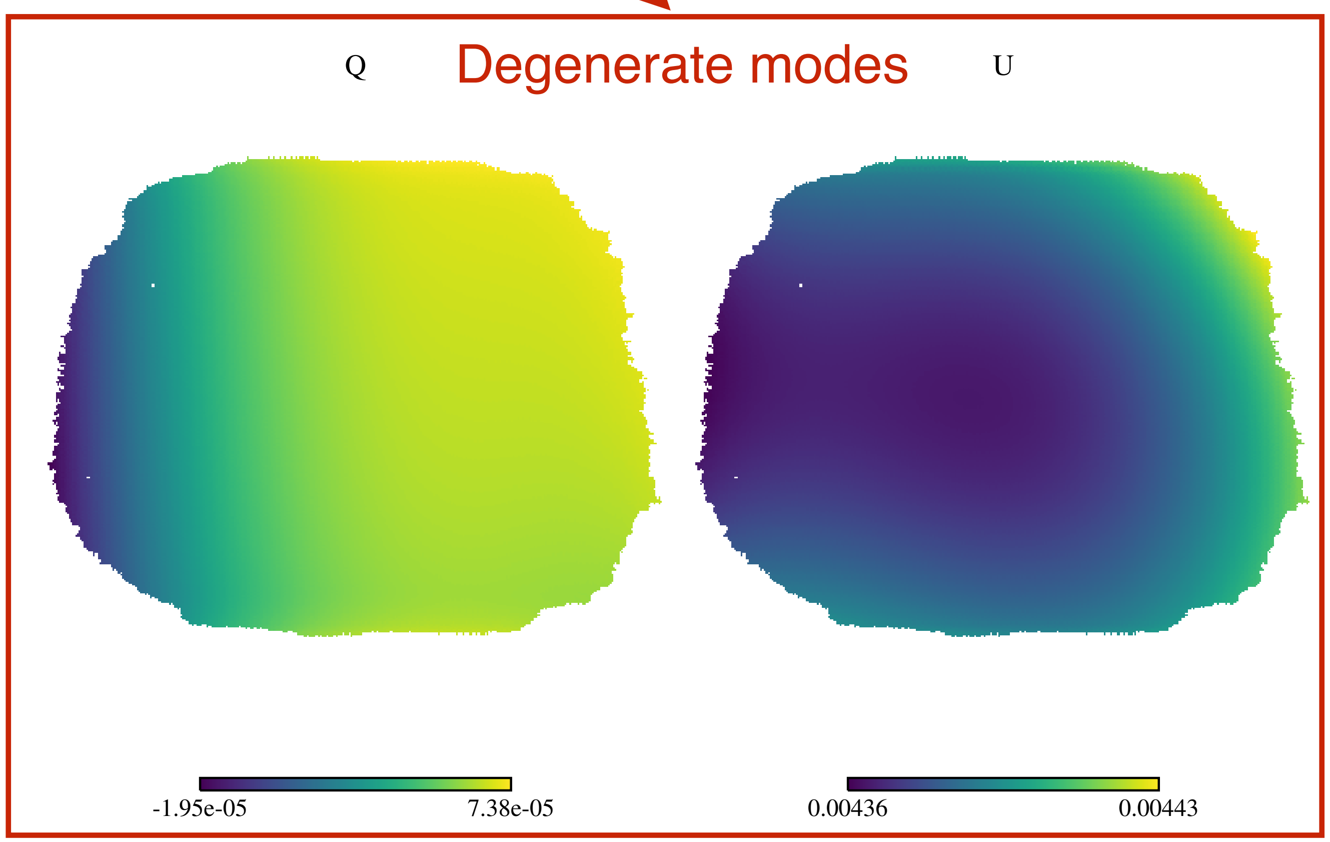
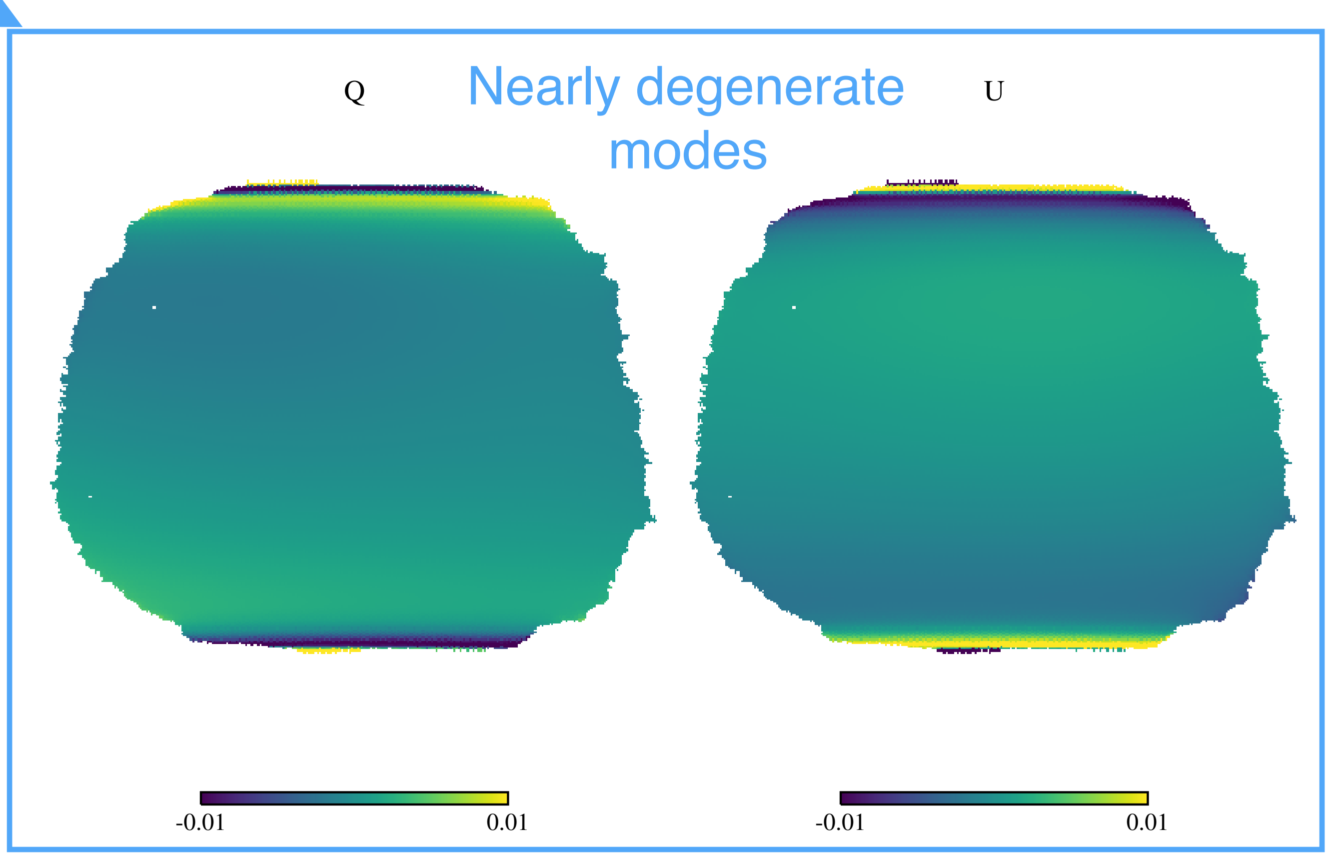








Calibration

POINTING
Parametric model fitted with observations of known point-like sources

27'' (30'') measured pointing accuracy for season 1 (season 2)

BEAM
Dedicated observations of Jupiter

Gaussian core w/ 3'.5 ± 0'.1 FWHM

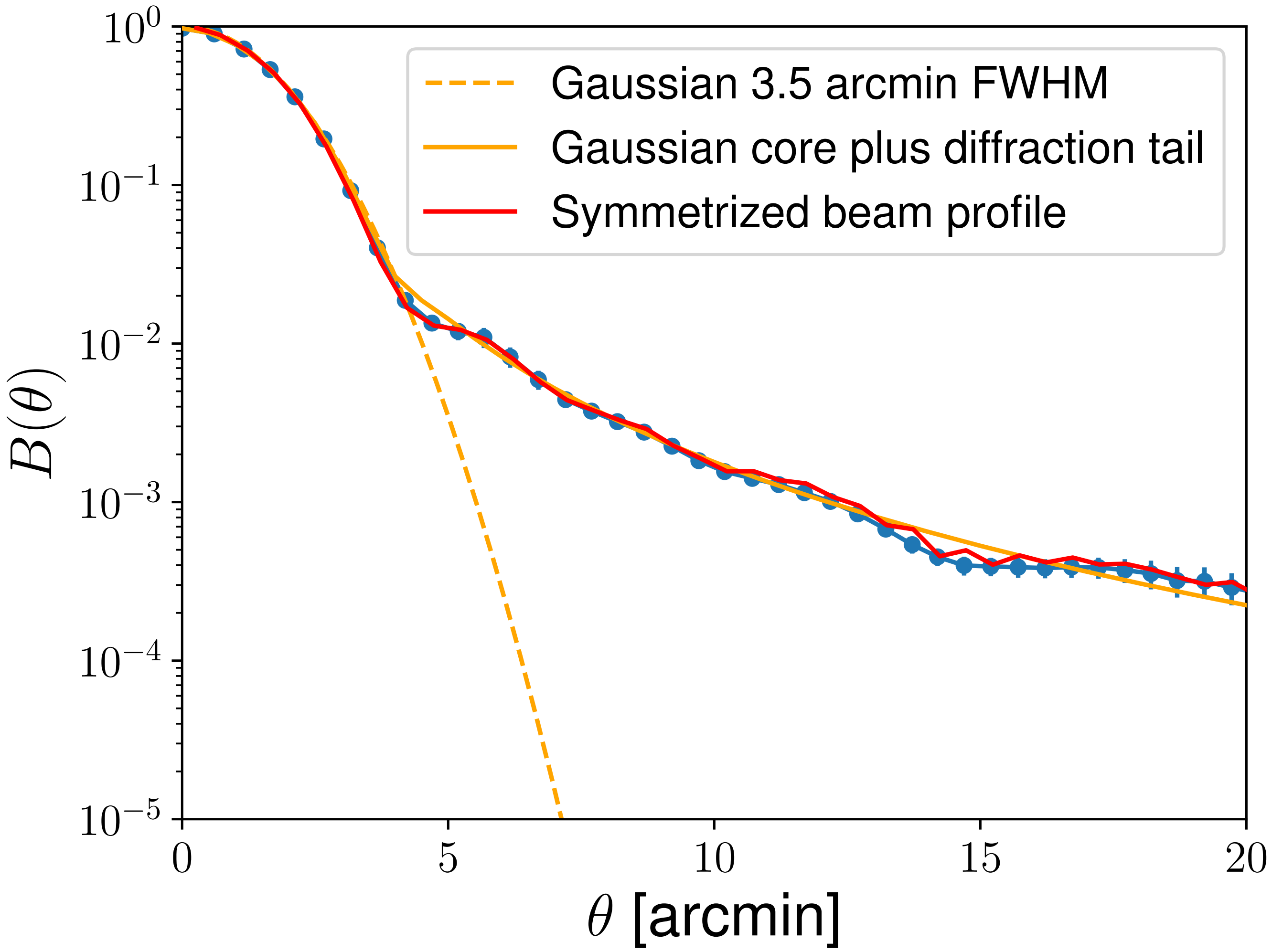
5% median ellipticity
(1.6% for same focal plane pixels)

POLARIZATION ANGLE
Fit POLARBEAR Tau A reconstruction to IRAM Tau A polarization map.

Polarization angle further constrained assuming zero EB power spectrum

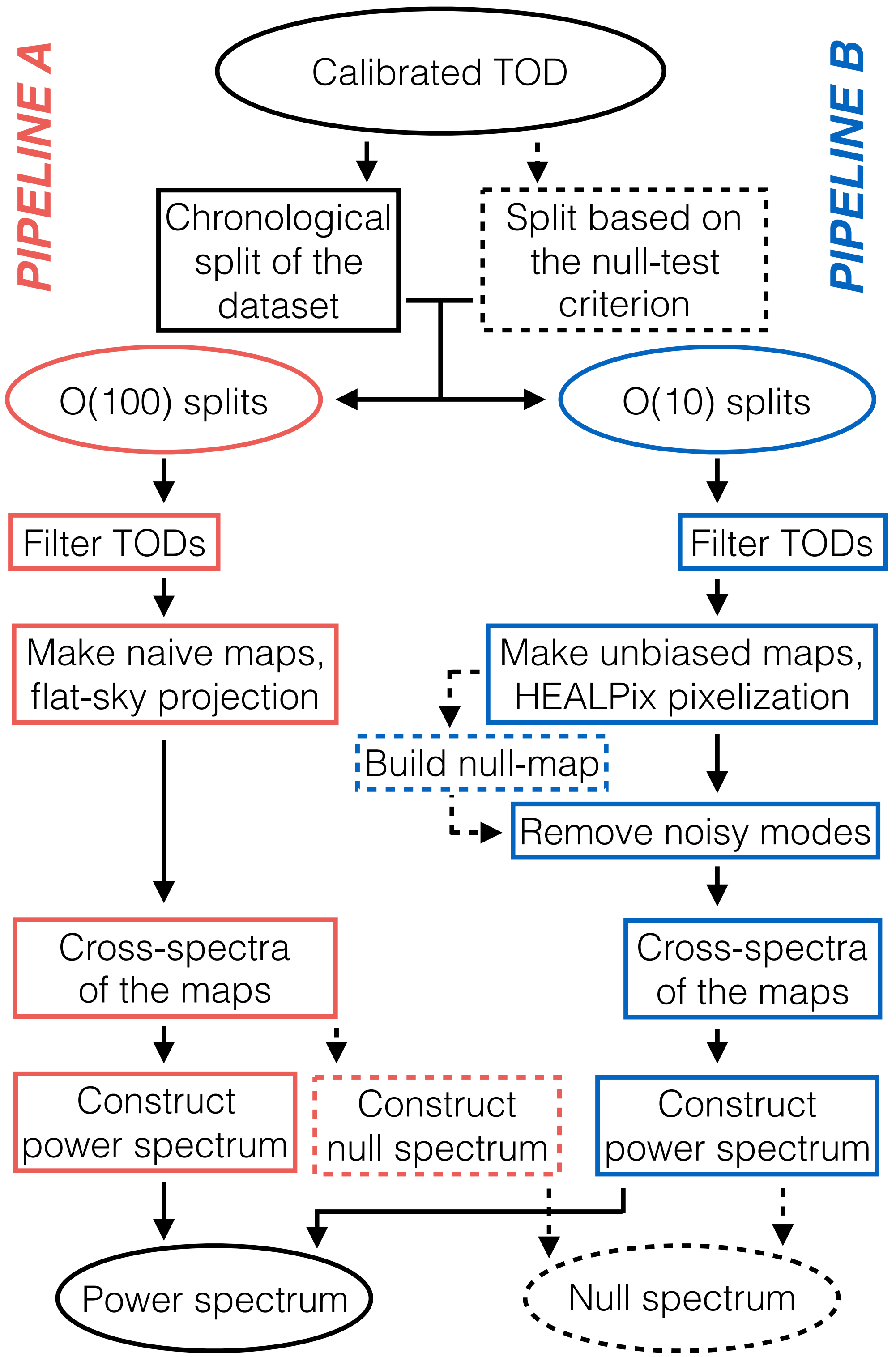
GAIN
Internal thermal source and Saturn observation: relative calibration

Fit CMB temperature anisotropies to those measured by Planck



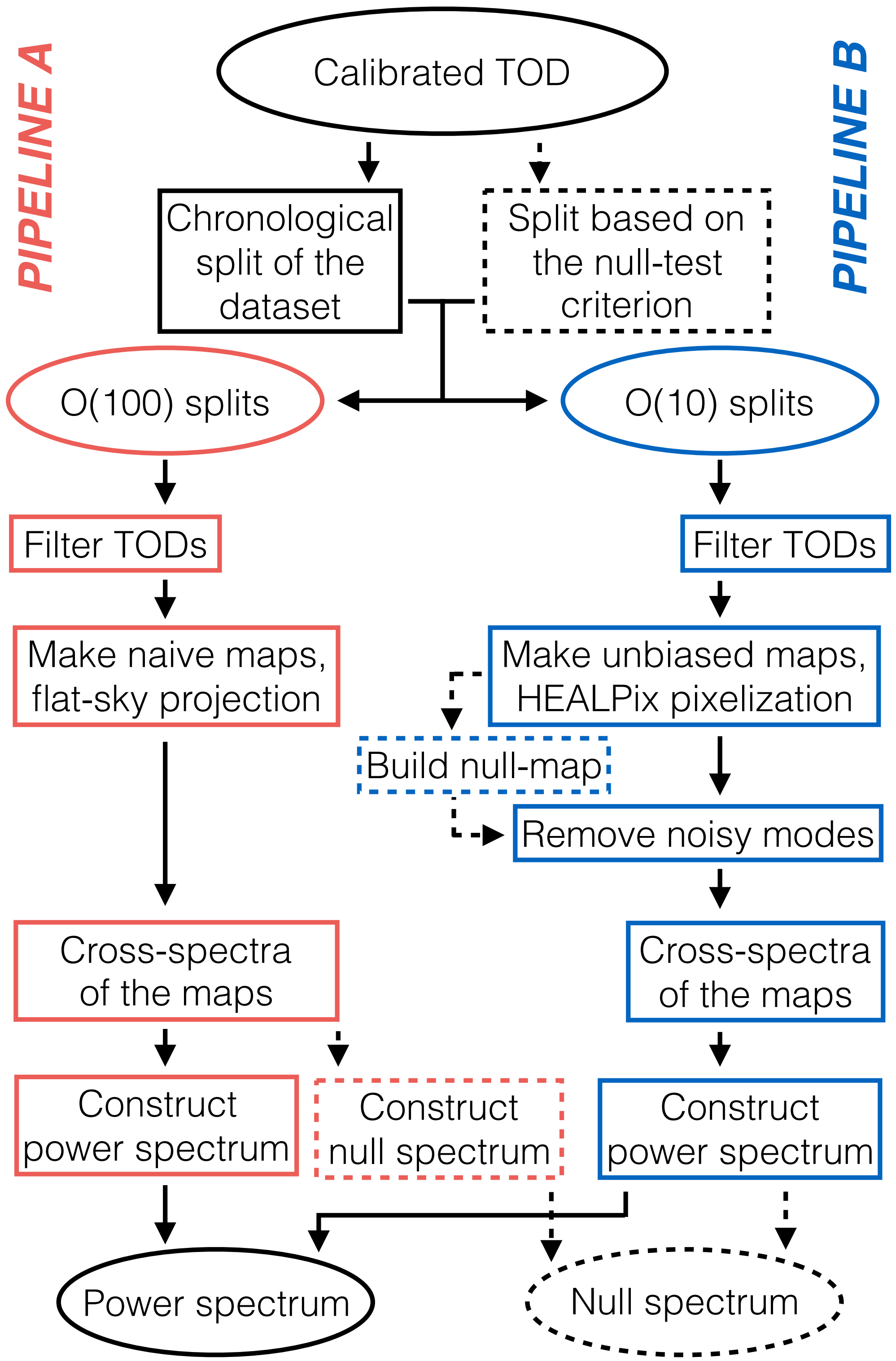
Data analysis

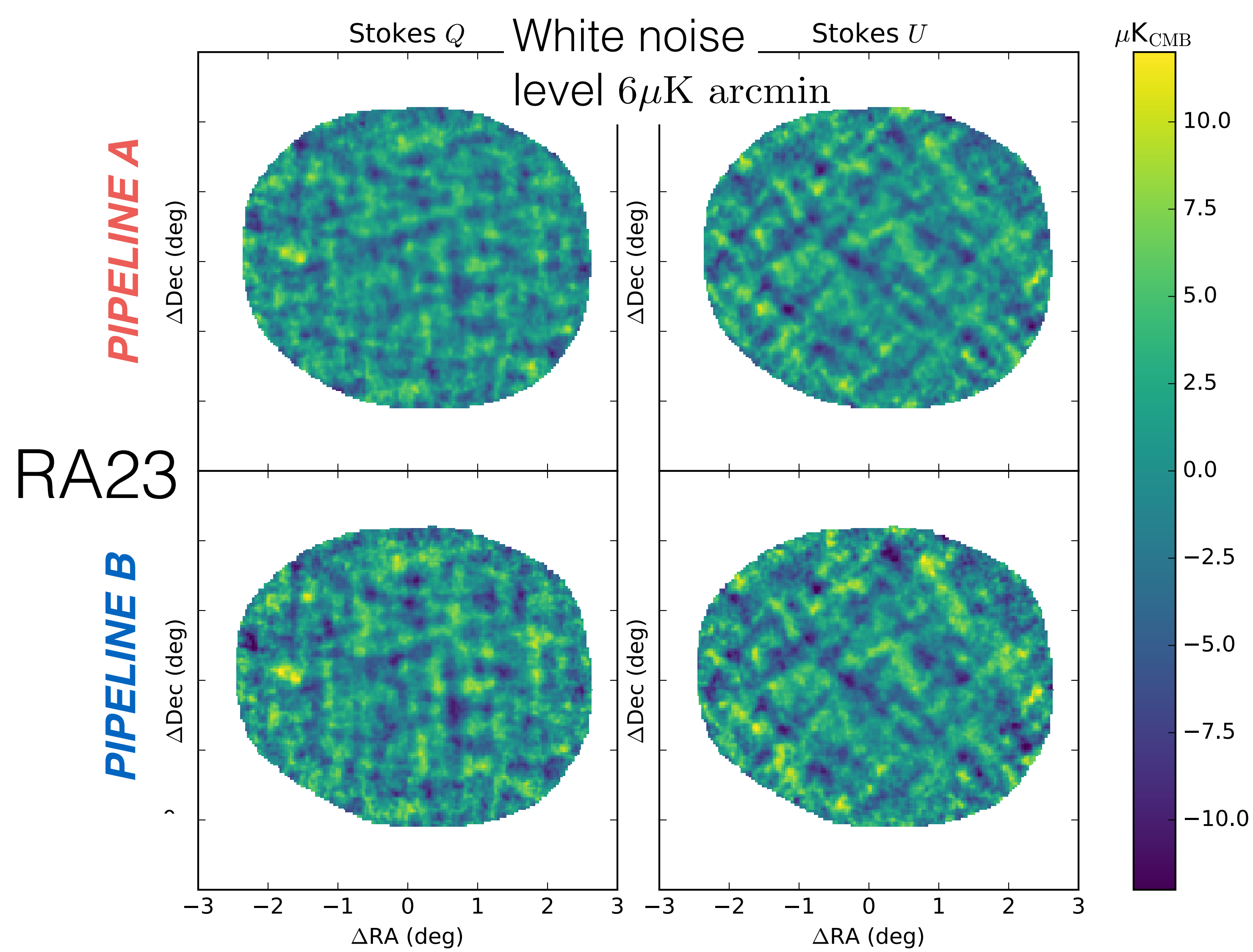
Two independent pipelines compress TOD into maps and power spectra



Data analysis

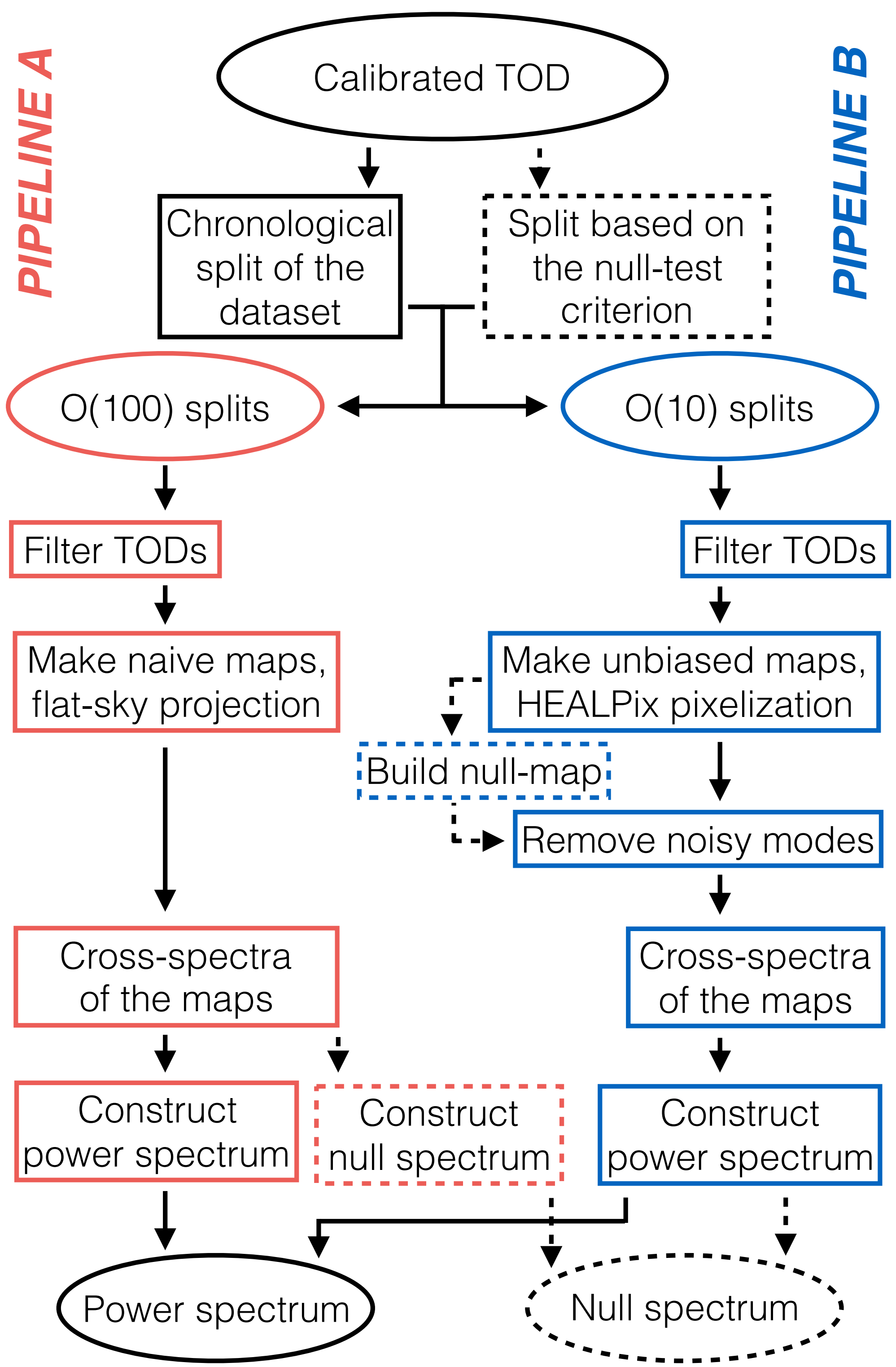
Two independent pipelines compress TOD into maps and power spectra

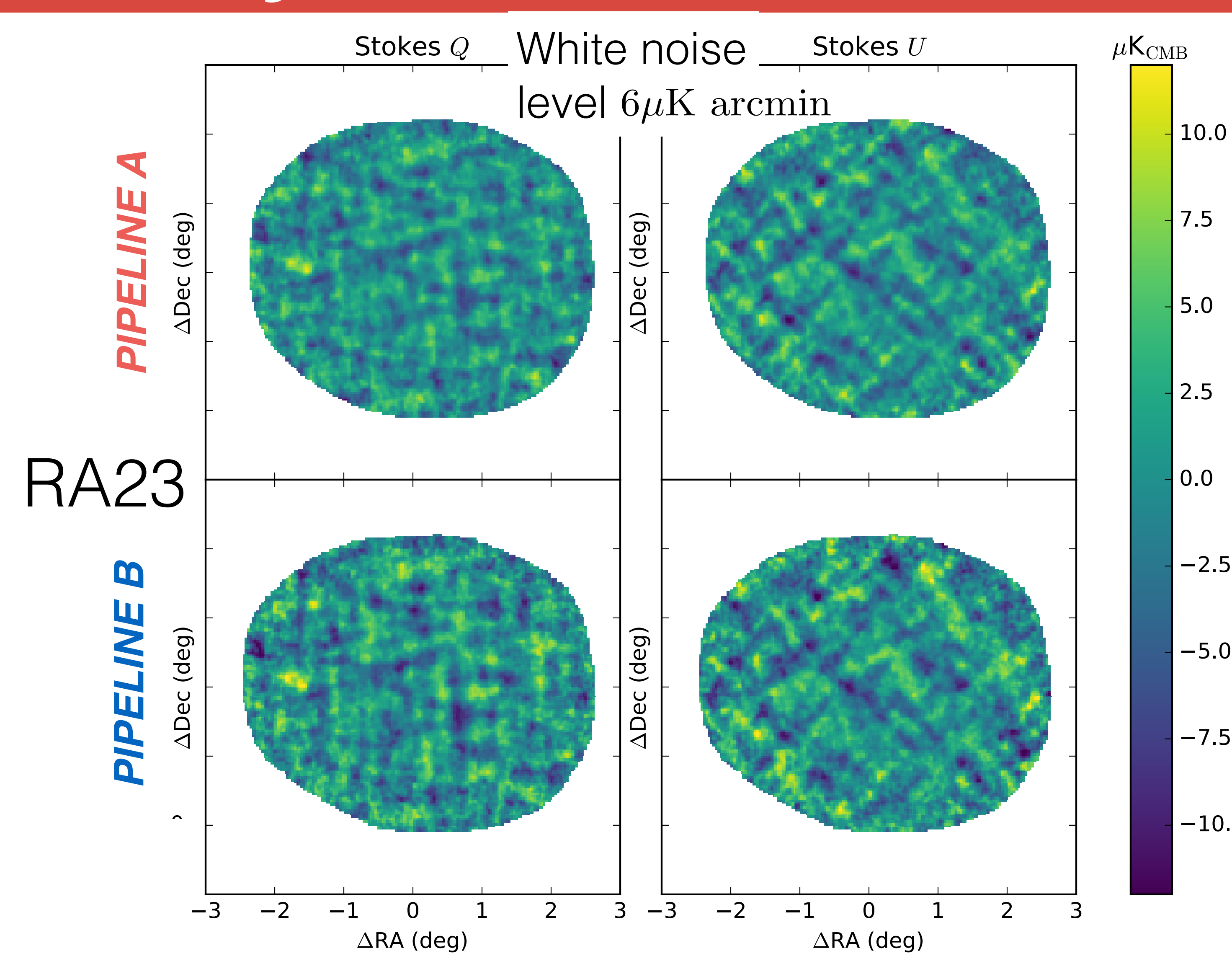




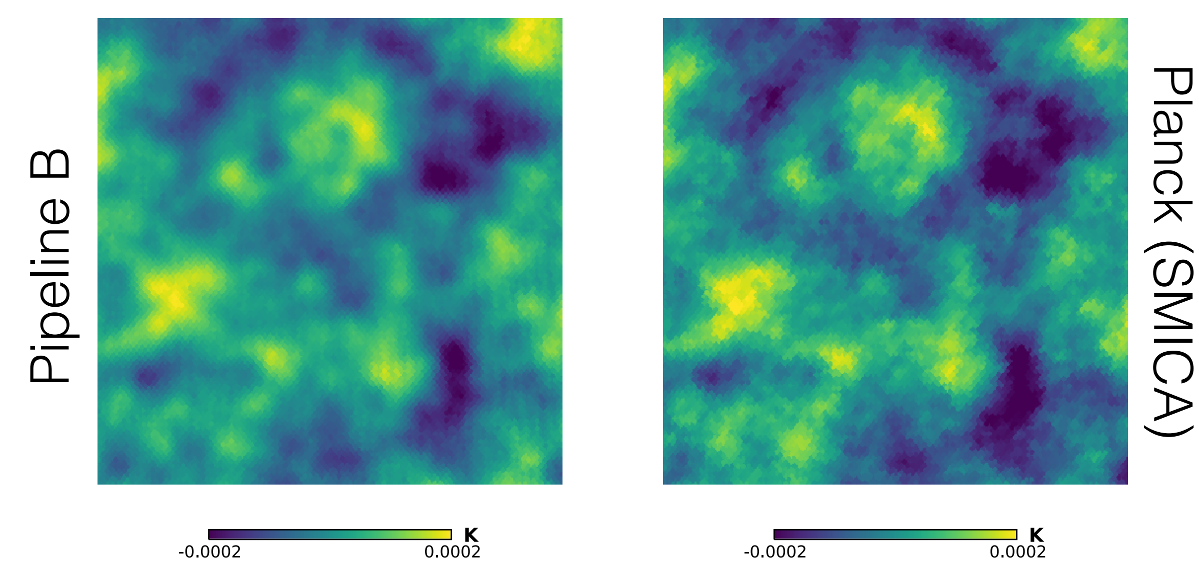
Data analysis

Two independent pipelines compress TOD into maps and power spectra





RA23
Stokes T
3°x3°
center



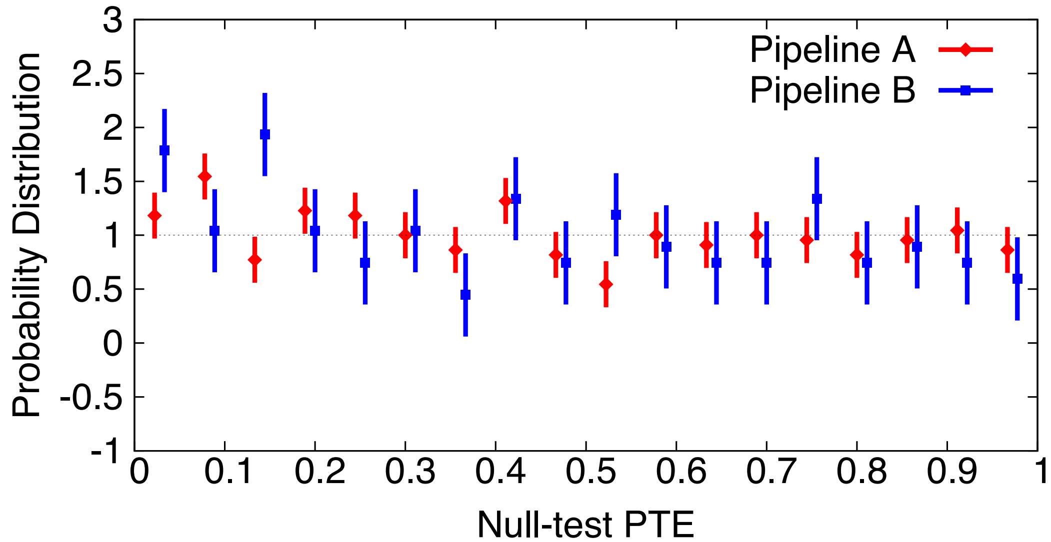
Validation

Blind policy

Data selection and quality assessment before inspecting the BB power spectrum

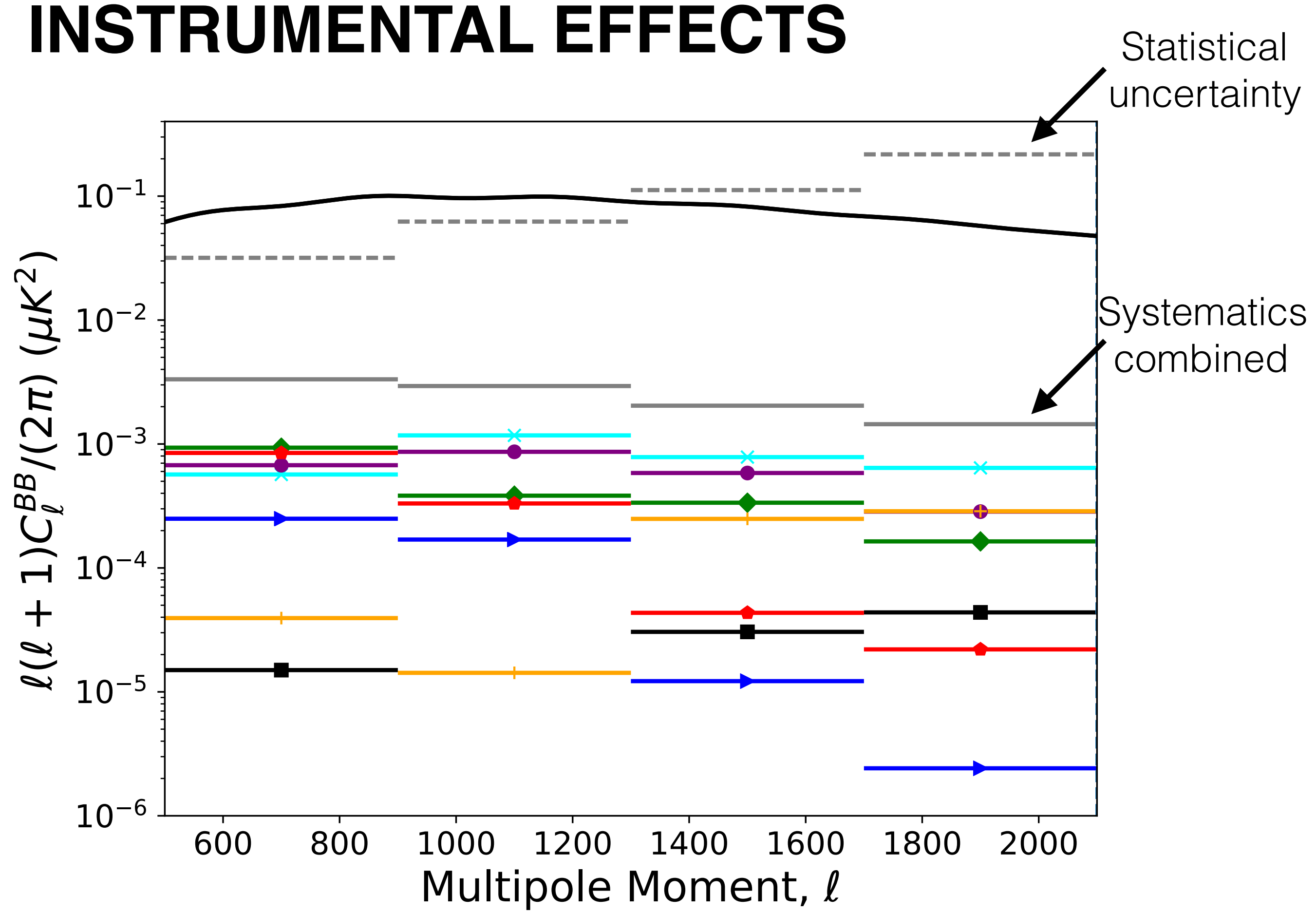
NULL TESTS

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.
Pixel polarization angle
Differential pointing
Gain drifts
Crosstalk
Differential beam ellipticity and shape.

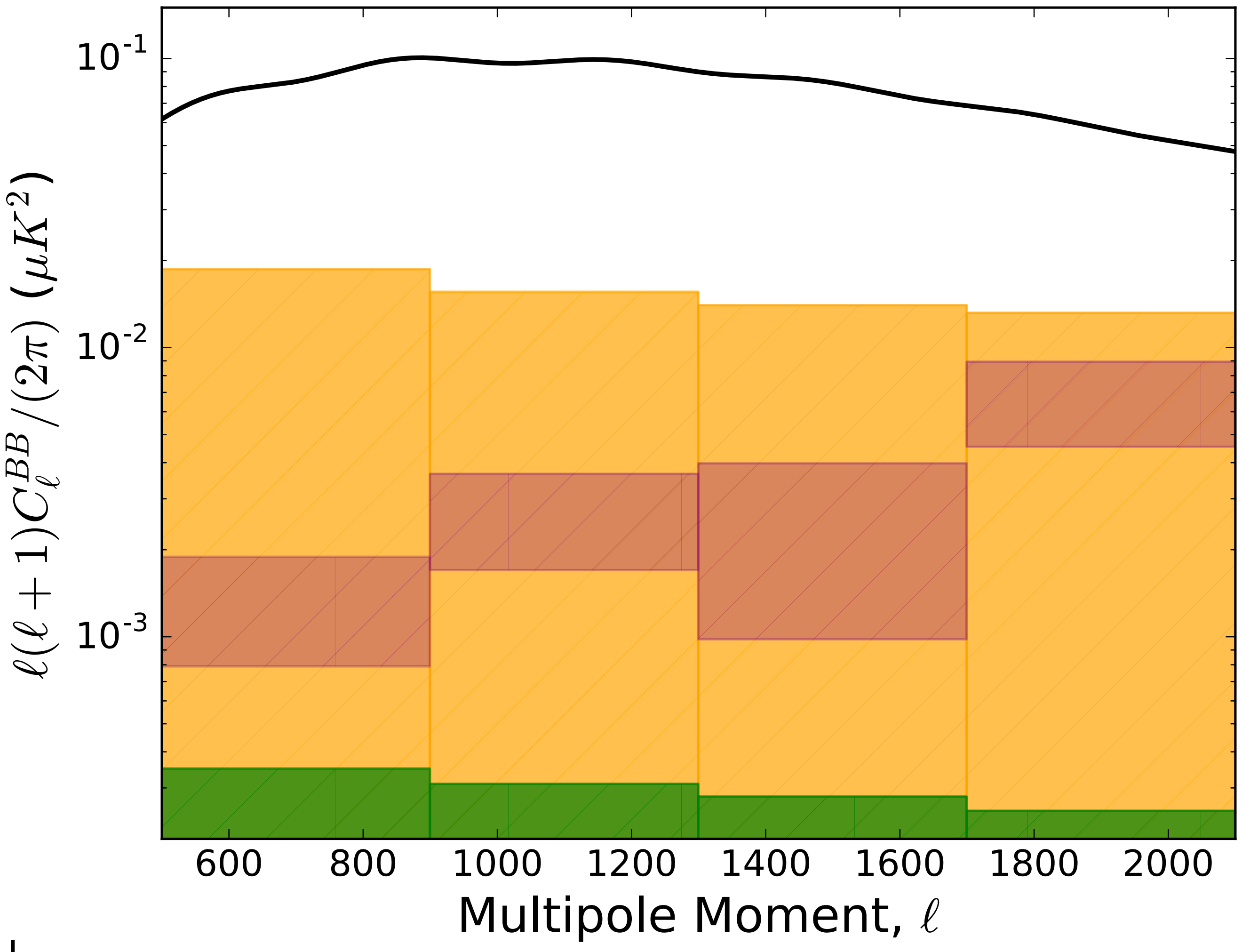
Foregrounds

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

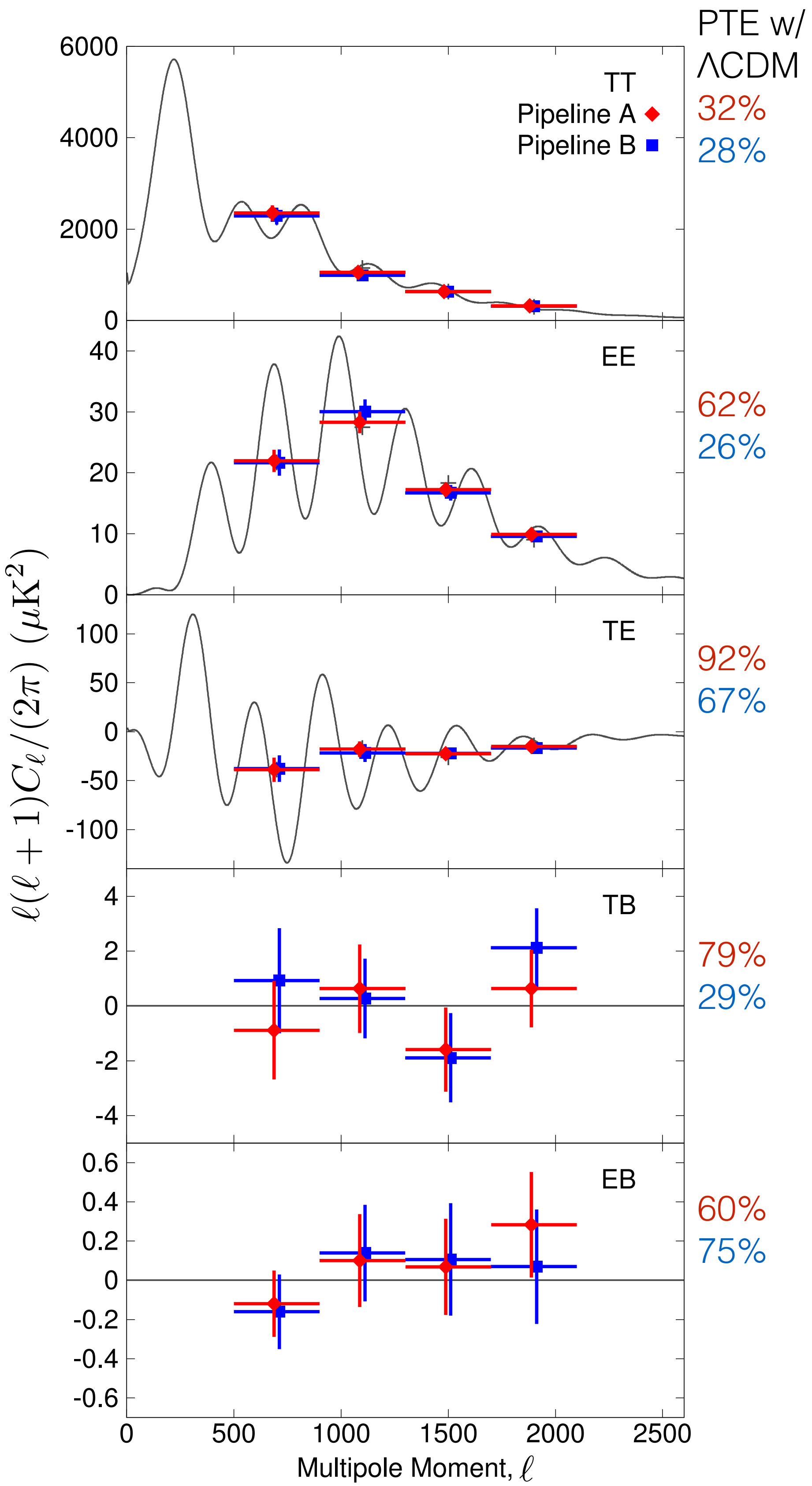
➡ Contamination compatible with zero

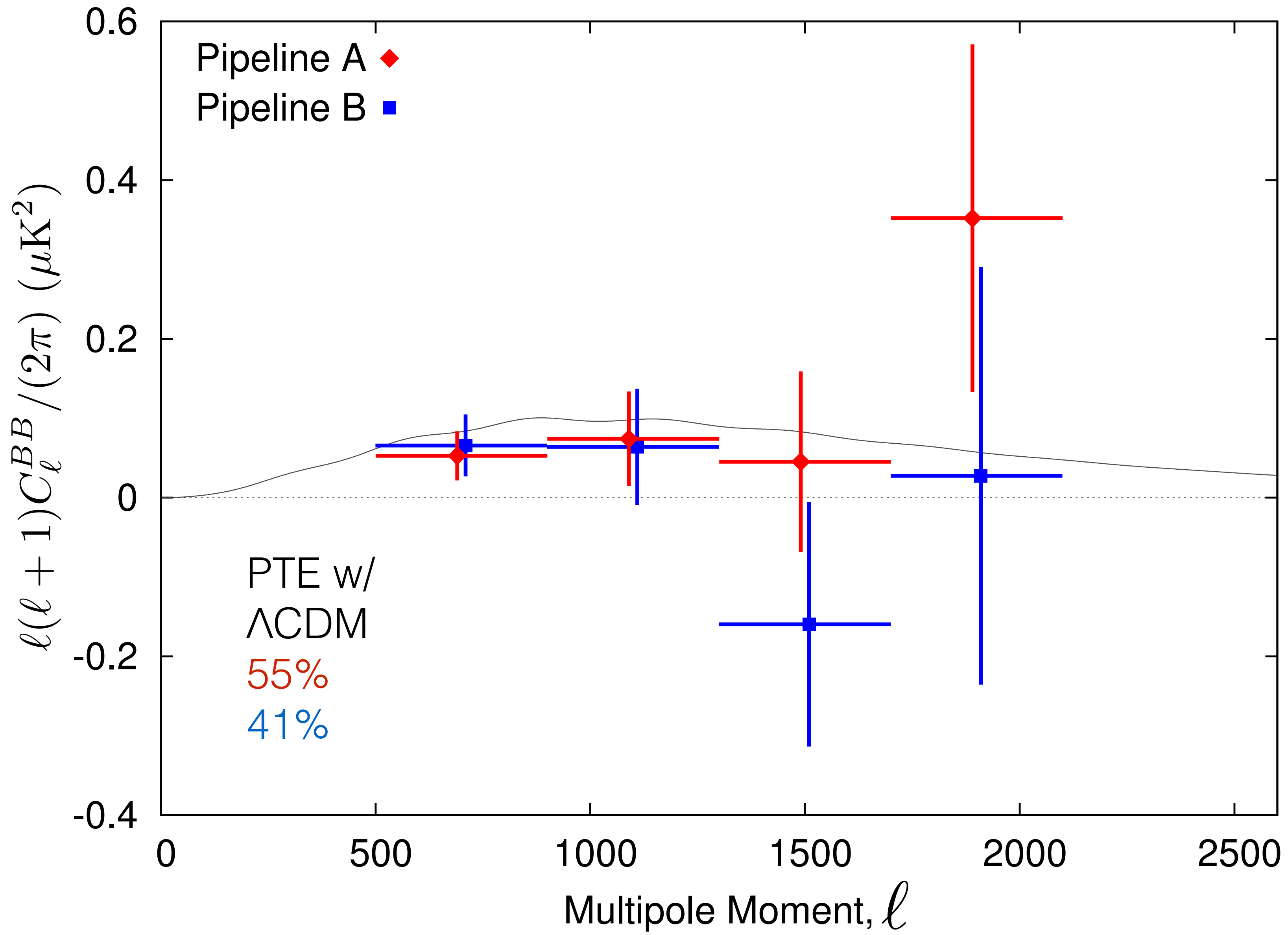


Dusty and radio galaxies

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)

Power spectra



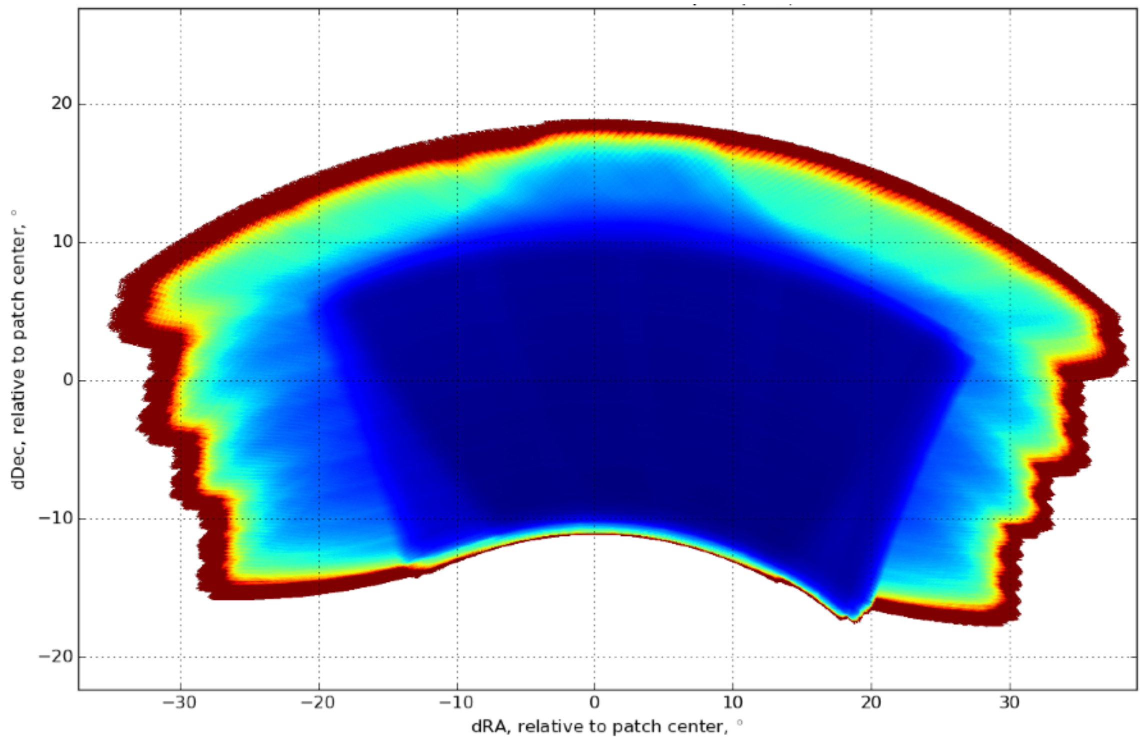


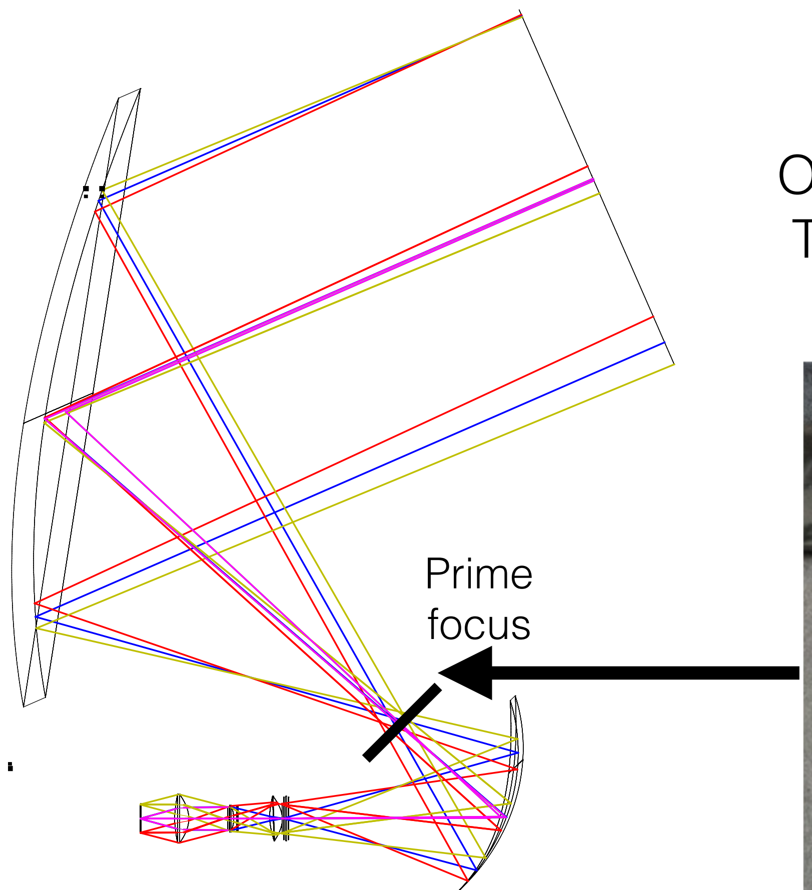
- All spectra are compatible with ΛCDM and between the pipelines (28% pte)

POLARBEAR large patch

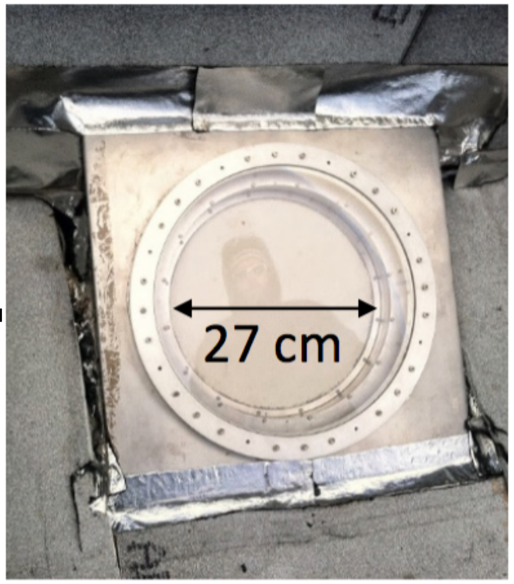
Since May 2014
- Observation of a ~700 deg^2 patch
  - ➡ Access to large scales
- Continuously rotating half-wave plate
  - ➡ 1/f mitigation

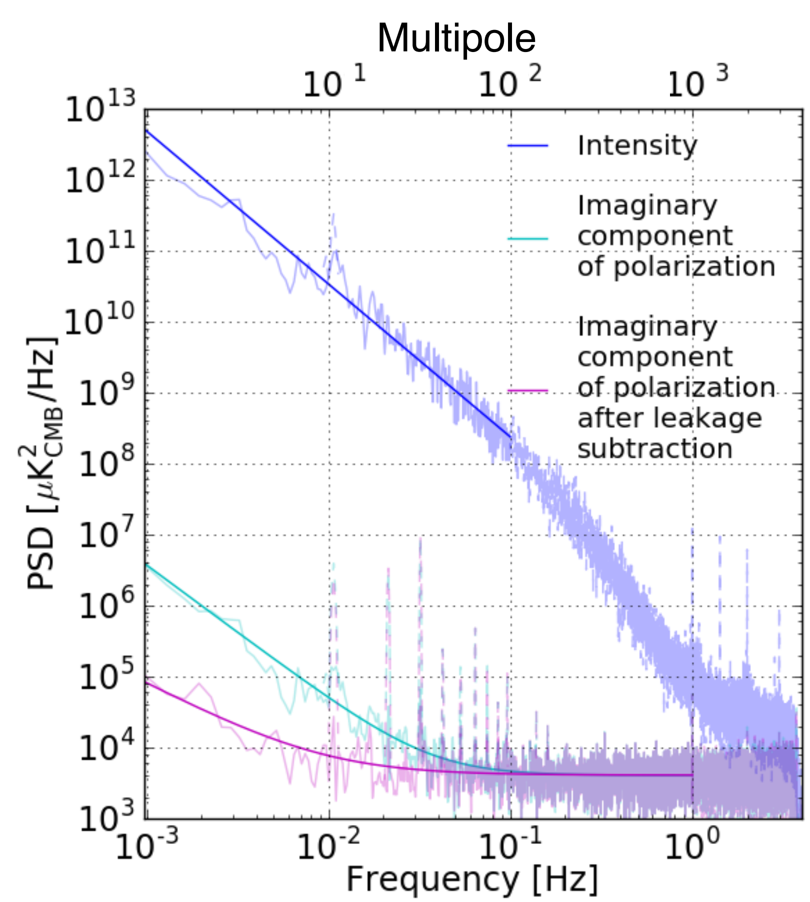
Targeting primordial B-modes





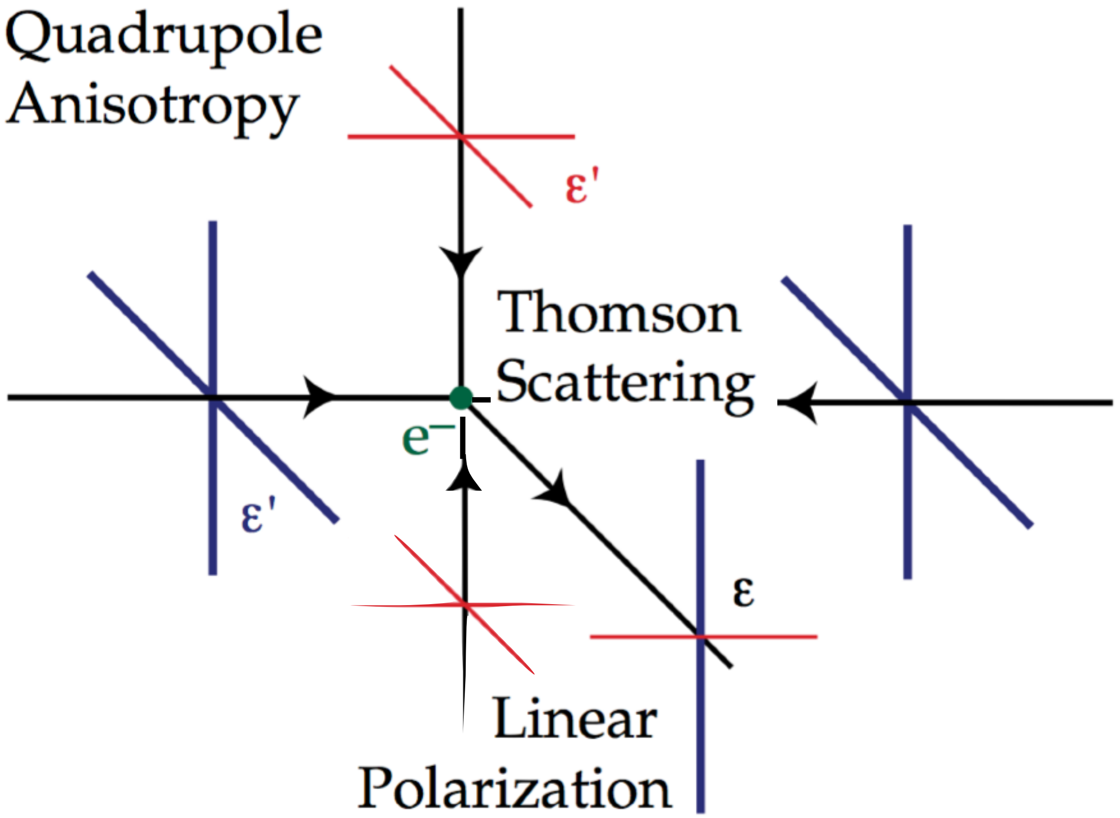
On sky performance:
Takakura et al JCAP 05 (2017) 008



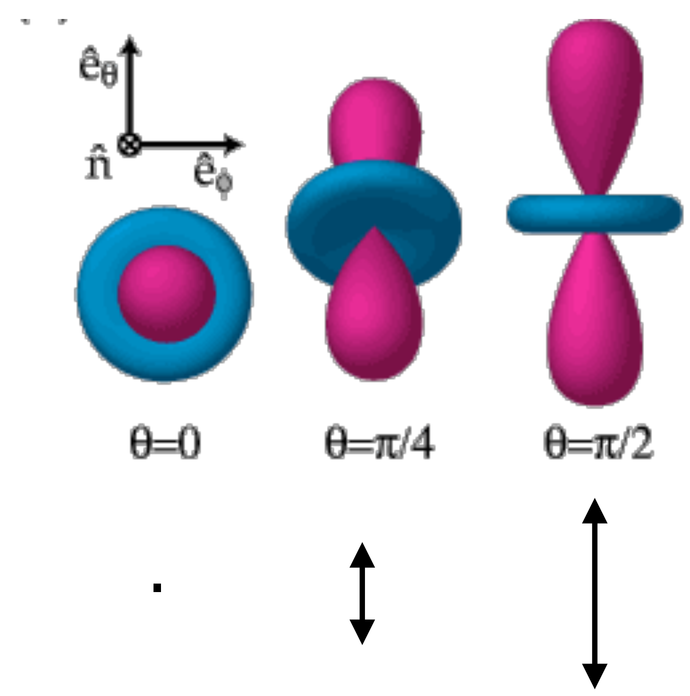


Polarising the CMB

- Dominant process: Thomson scattering $\frac{d\sigma_T}{d\Omega} \propto |\hat{\epsilon} \cdot \hat{\epsilon}'|^2$
- Last scattering surface is not homogeneous
- Unpolarised light -> polarised light

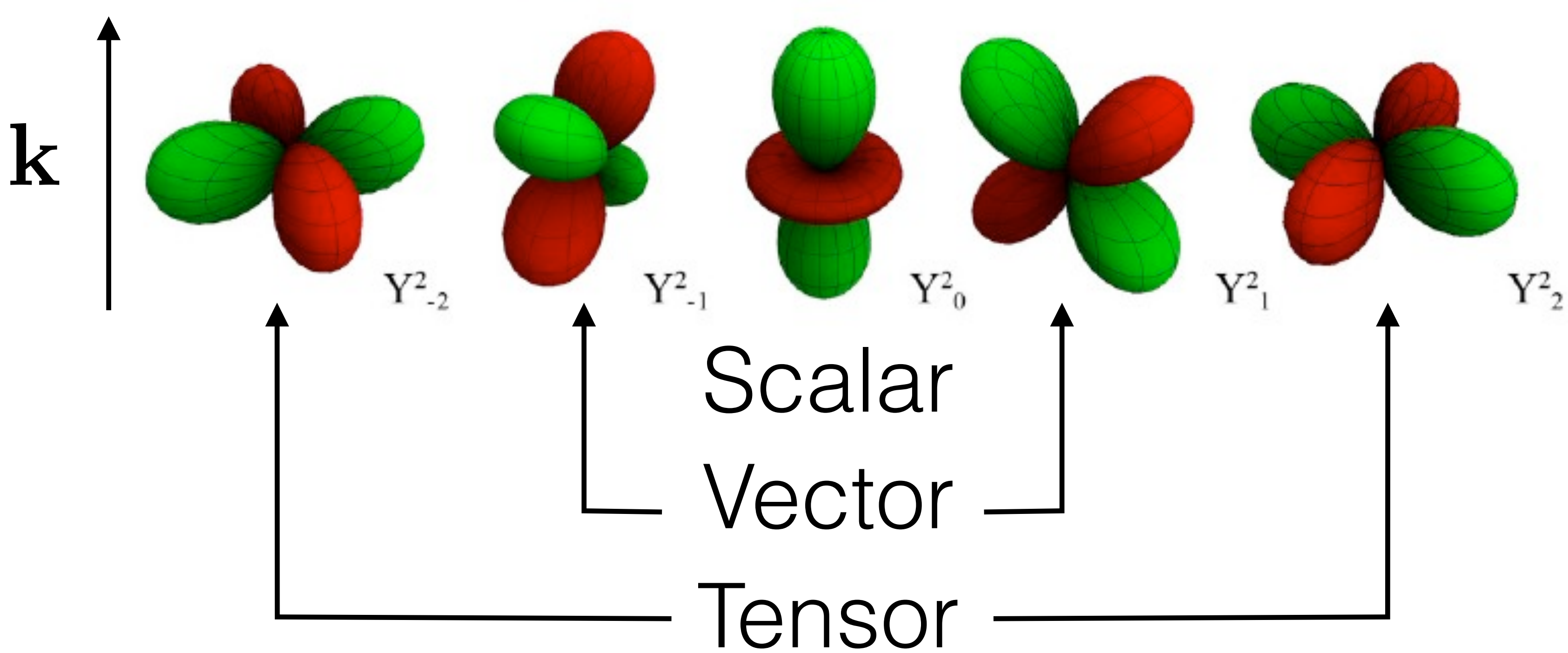


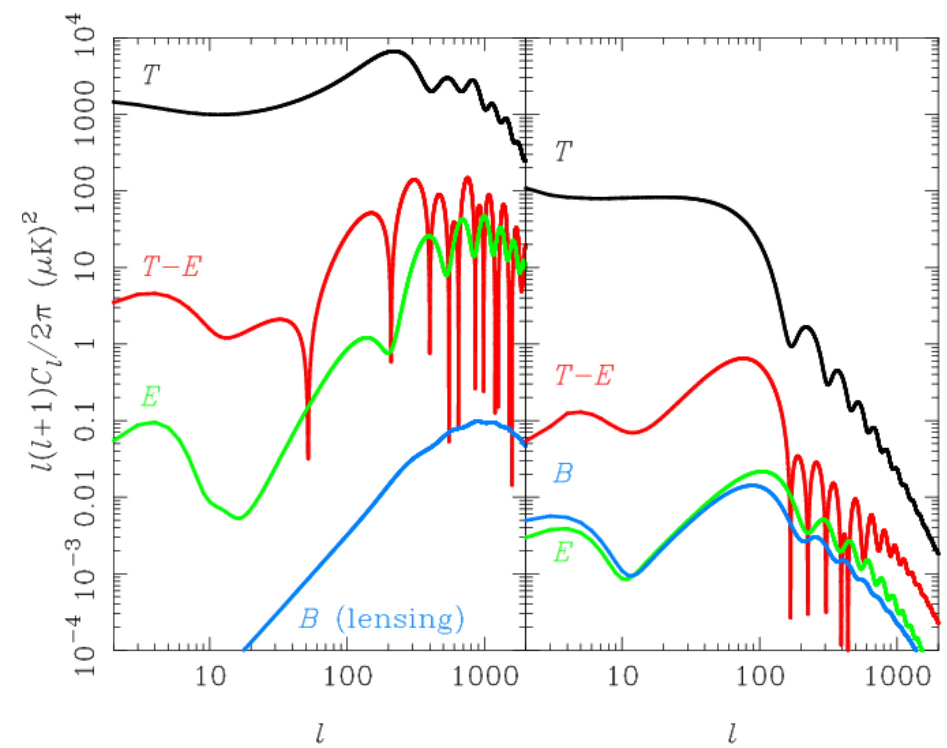
What matters is the quadrupole moment:
l = 2



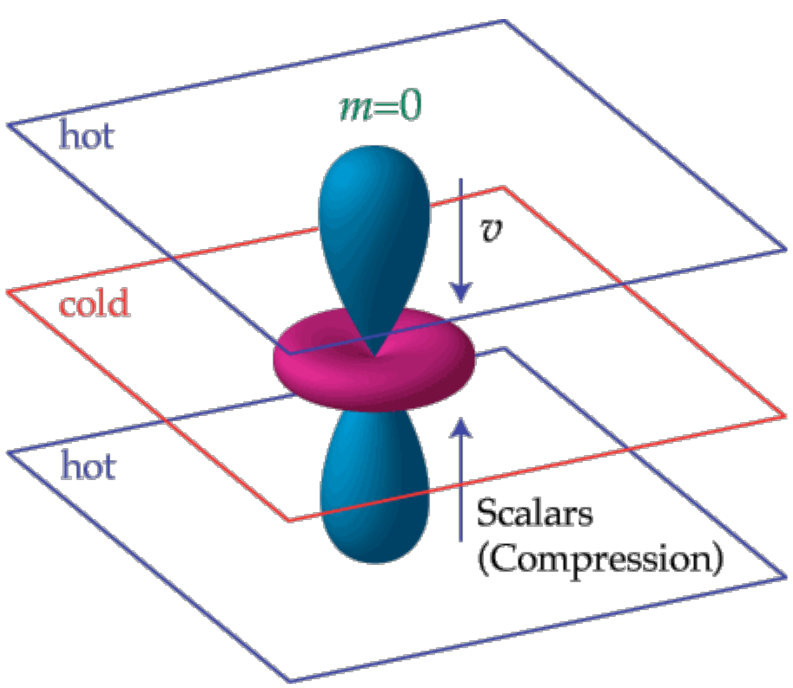
e.g. Hu and White (1997)

Quadrupole moments

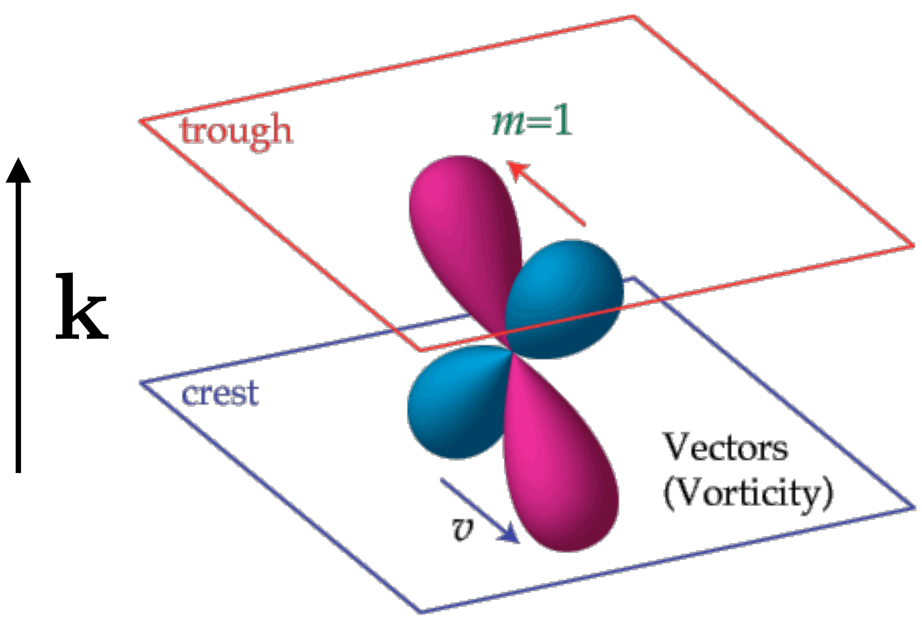




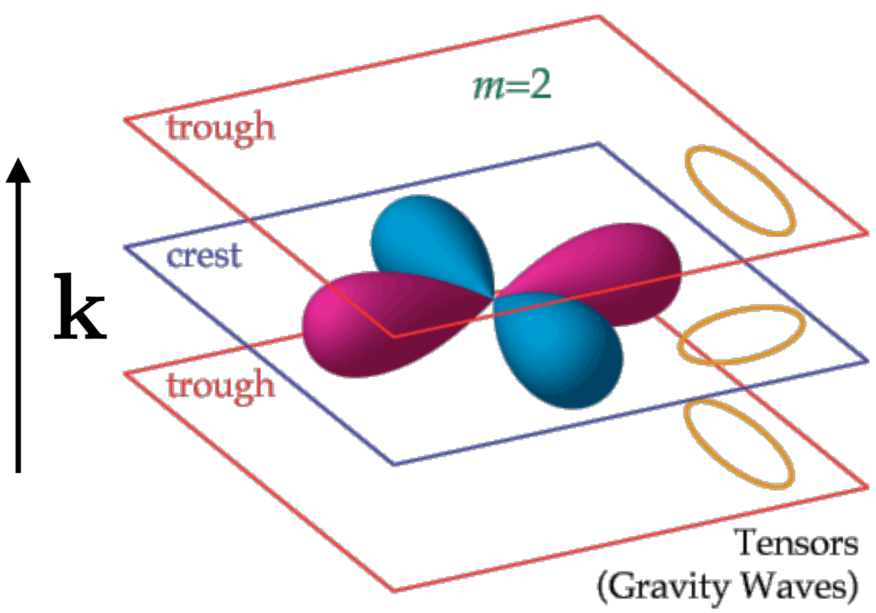
e.g. Hu and White (1997)



E only

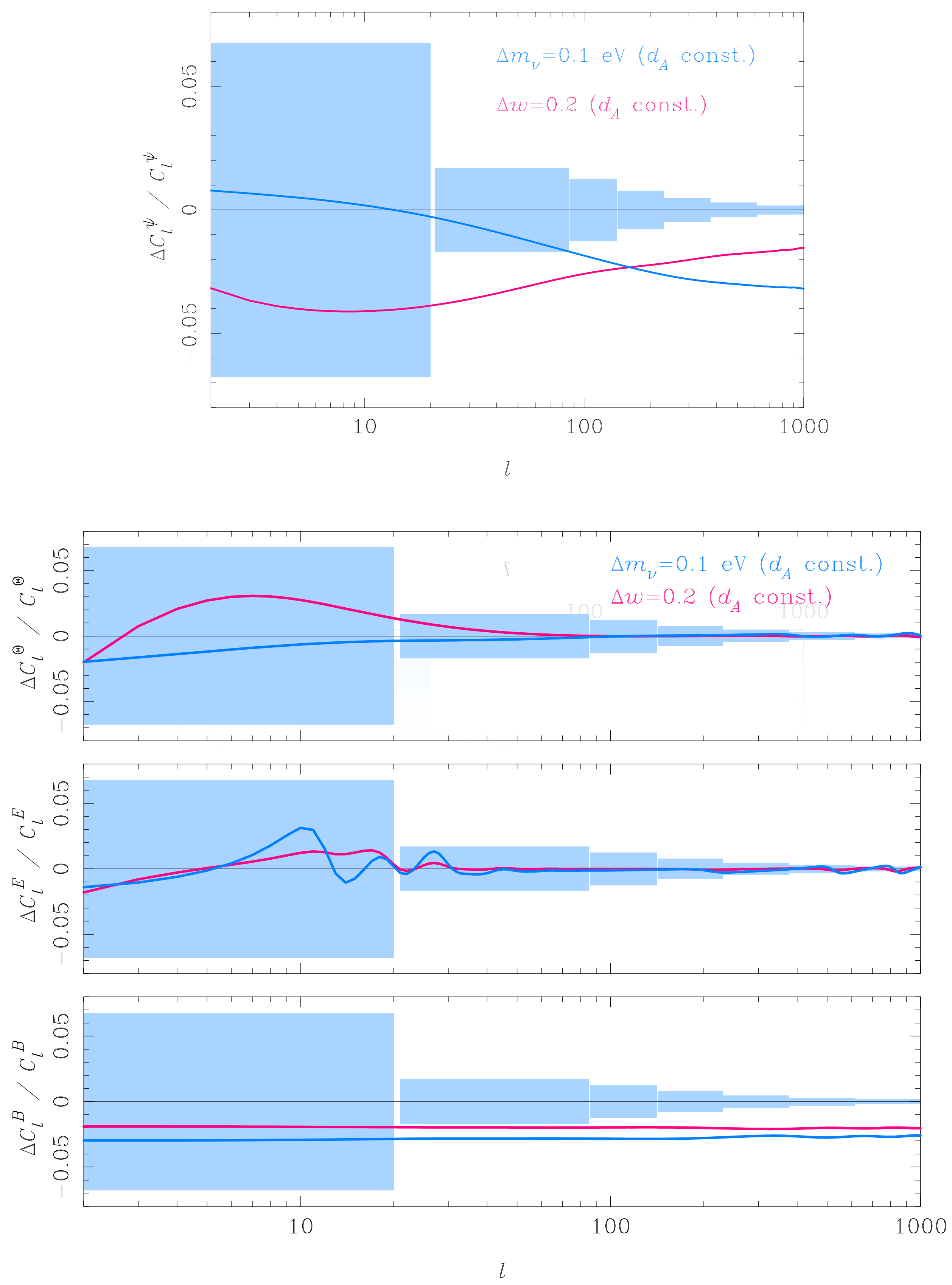


E and B

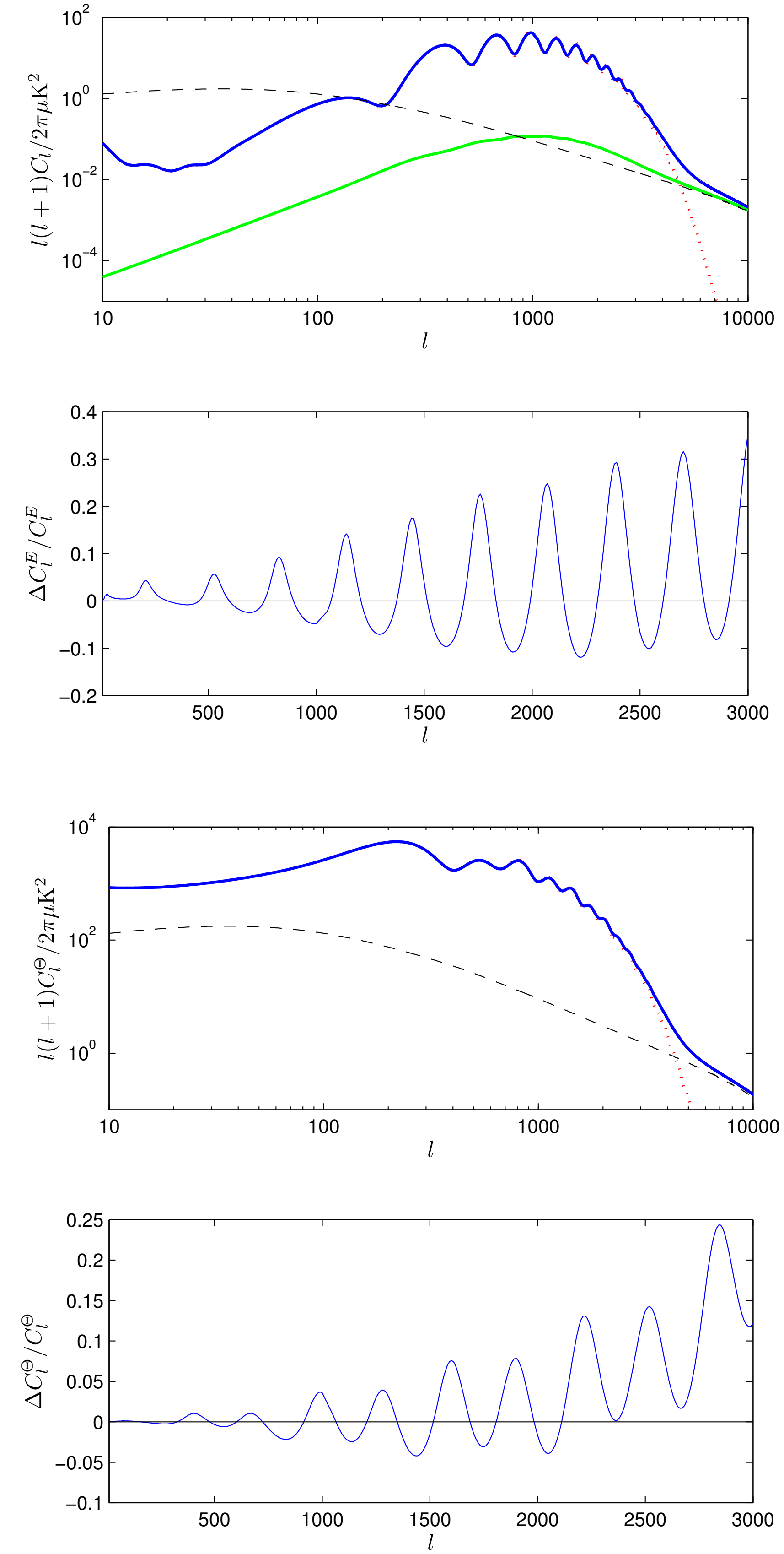


E and B

Lensing



Δm_ν=0.1 eV (d_A const.)
Δw=0.2 (d_A const.)
$\Delta C_l^\psi / C_l^\psi$
$\Delta C_l^\Theta / C_l^\Theta$
$\Delta C_l^E / C_l^E$
$\Delta C_l^B / C_l^B$
l

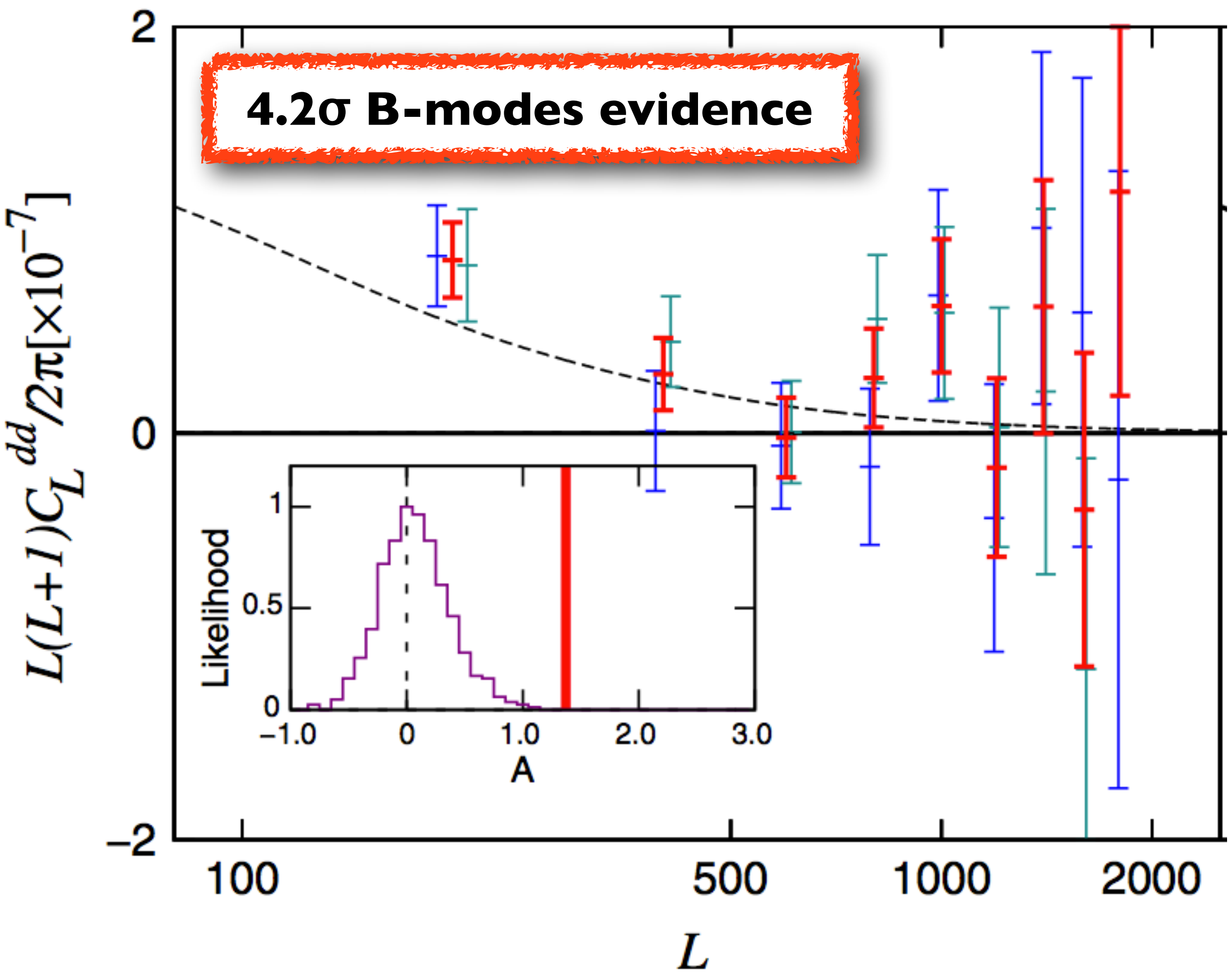


$l(l+1)C_l/2\pi\mu K^2$
$\Delta C_l^E / C_l^E$
$l(l+1)C_l^\Theta/2\pi\mu K^2$
$\Delta C_l^\Theta / C_l^\Theta$
l

Results: lensing from polarization alone

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

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



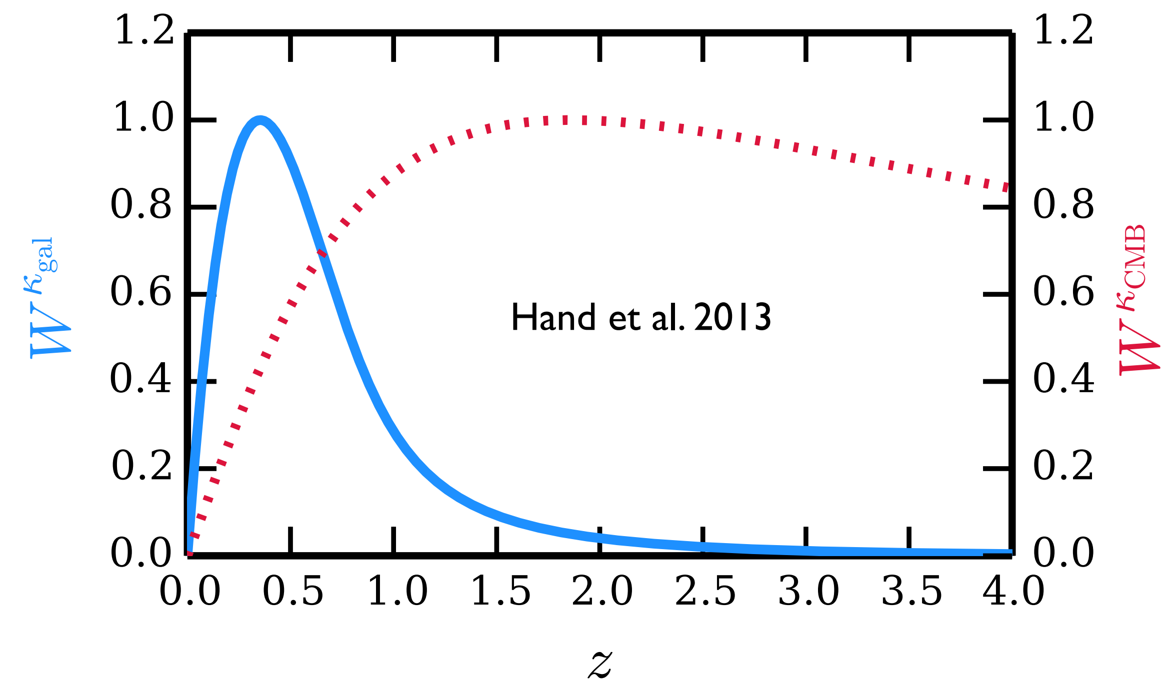
Results: cross-correlation with CIB

Polarization Measurement

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

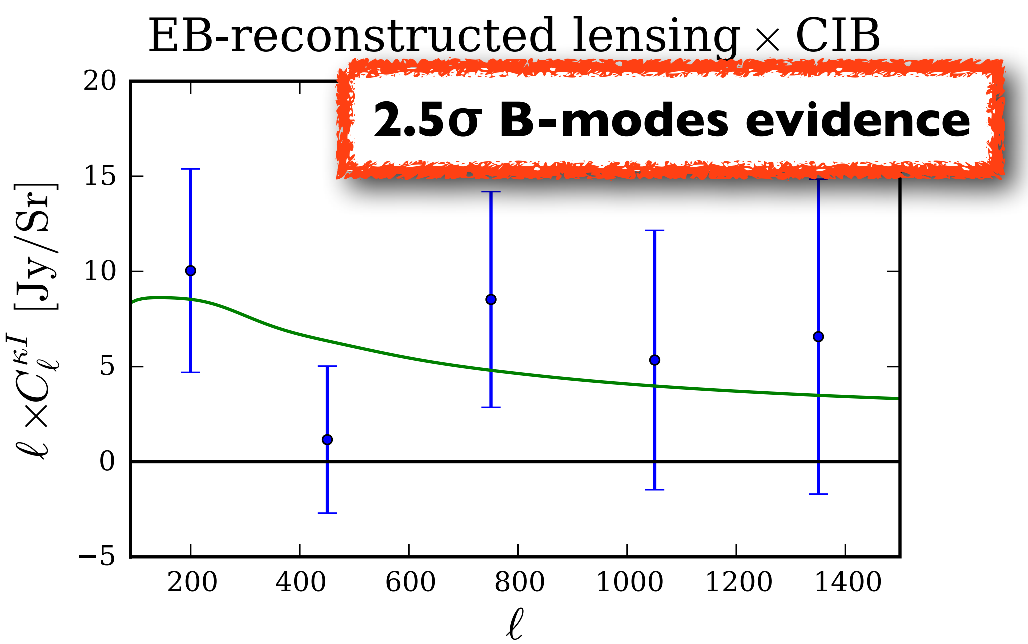
Cosmic Infrared Background

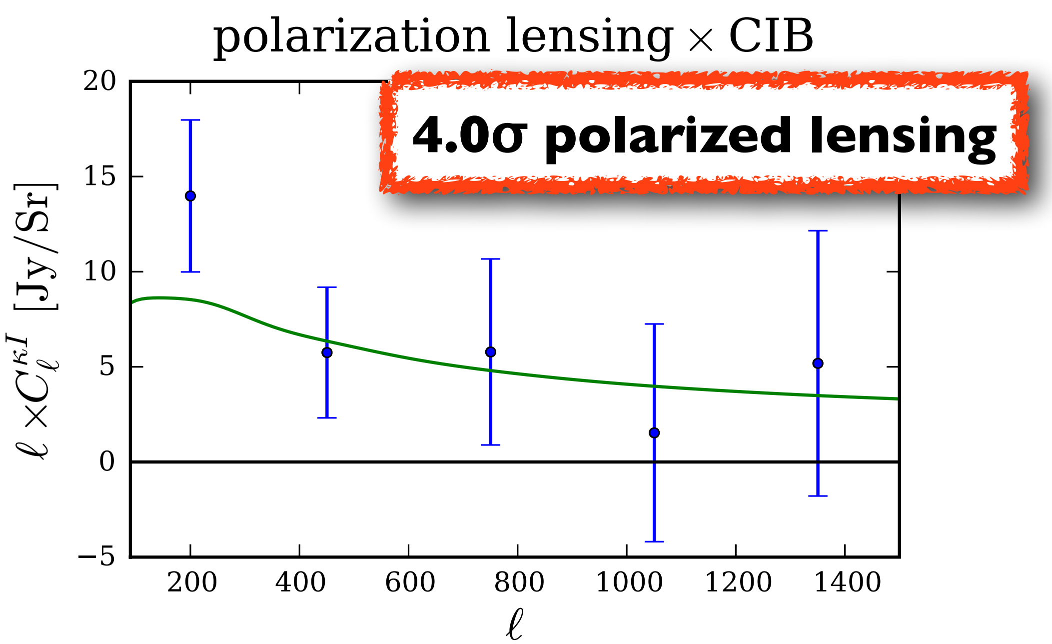
Tracer of density field



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

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





Results: BB spectrum measurement

- First direct evidence of lensing B-modes

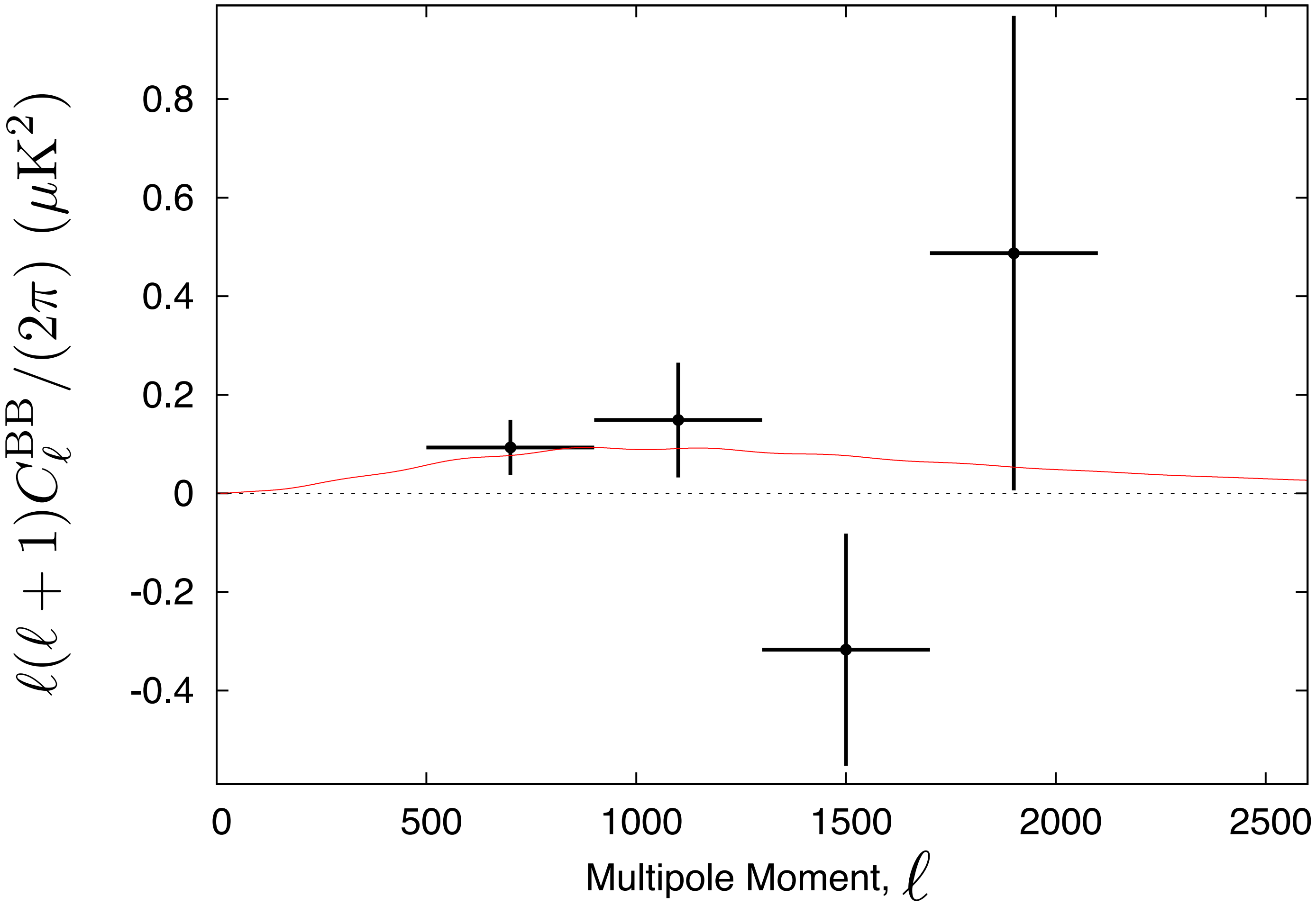
97.5% c.l. B-modes evidence

- Amplitude of lensing compared to ΛCDM

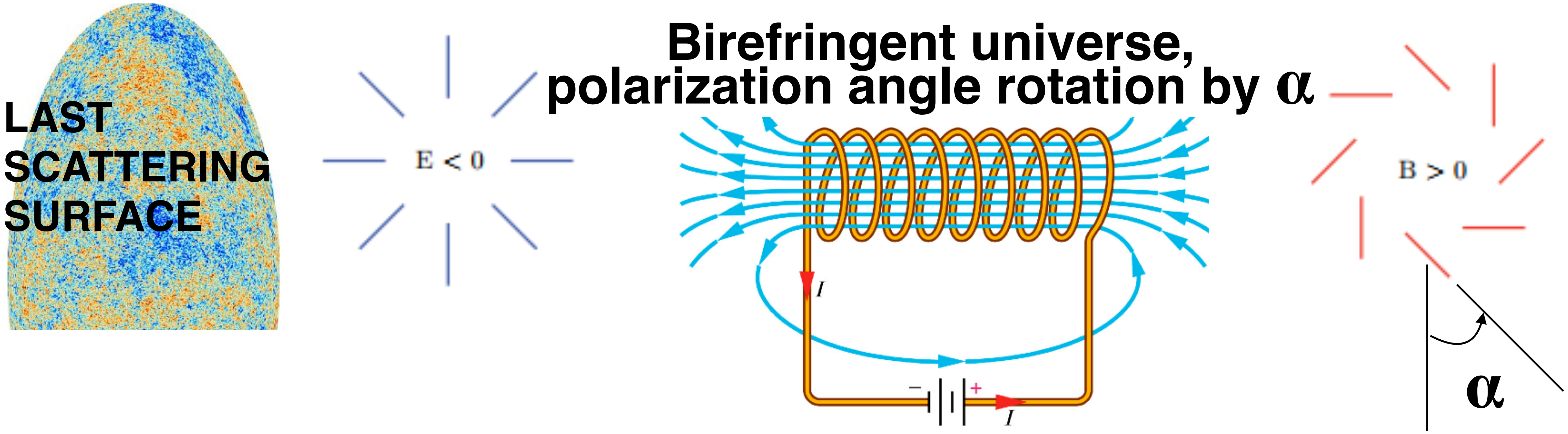
Astrophysical J. 794, 171 (2014)

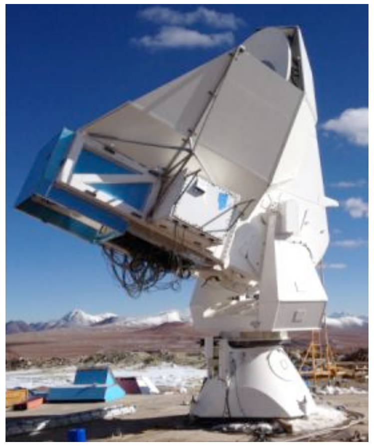
$$A_{BB} = 1.12 \pm 0.61(\mathrm{stat})^{+0.04}_{-0.10}(\mathrm{sys}) \pm 0.07(\mathrm{multi})$$

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

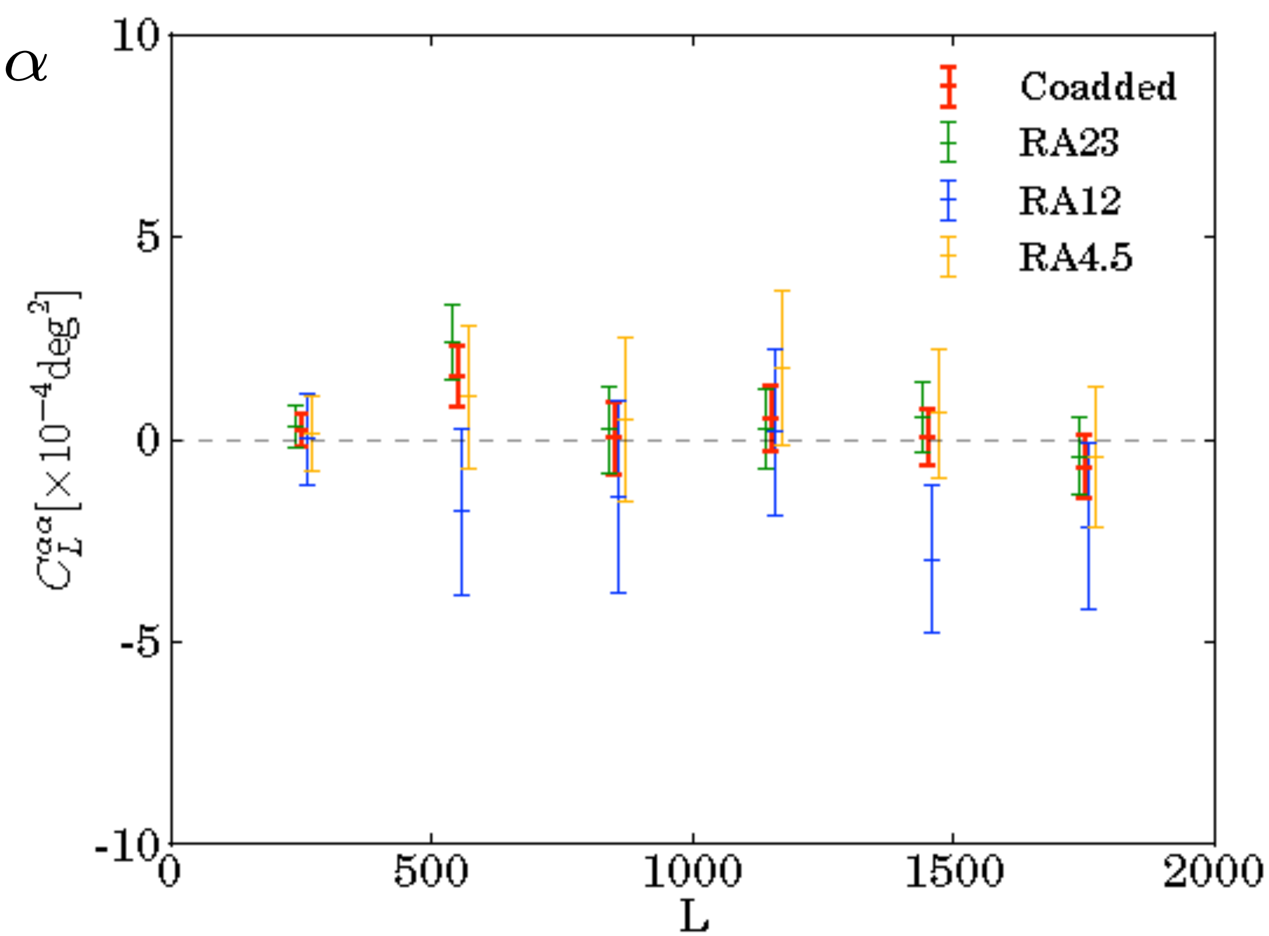


Results: cosmic birefringence / primordial magnetic fields





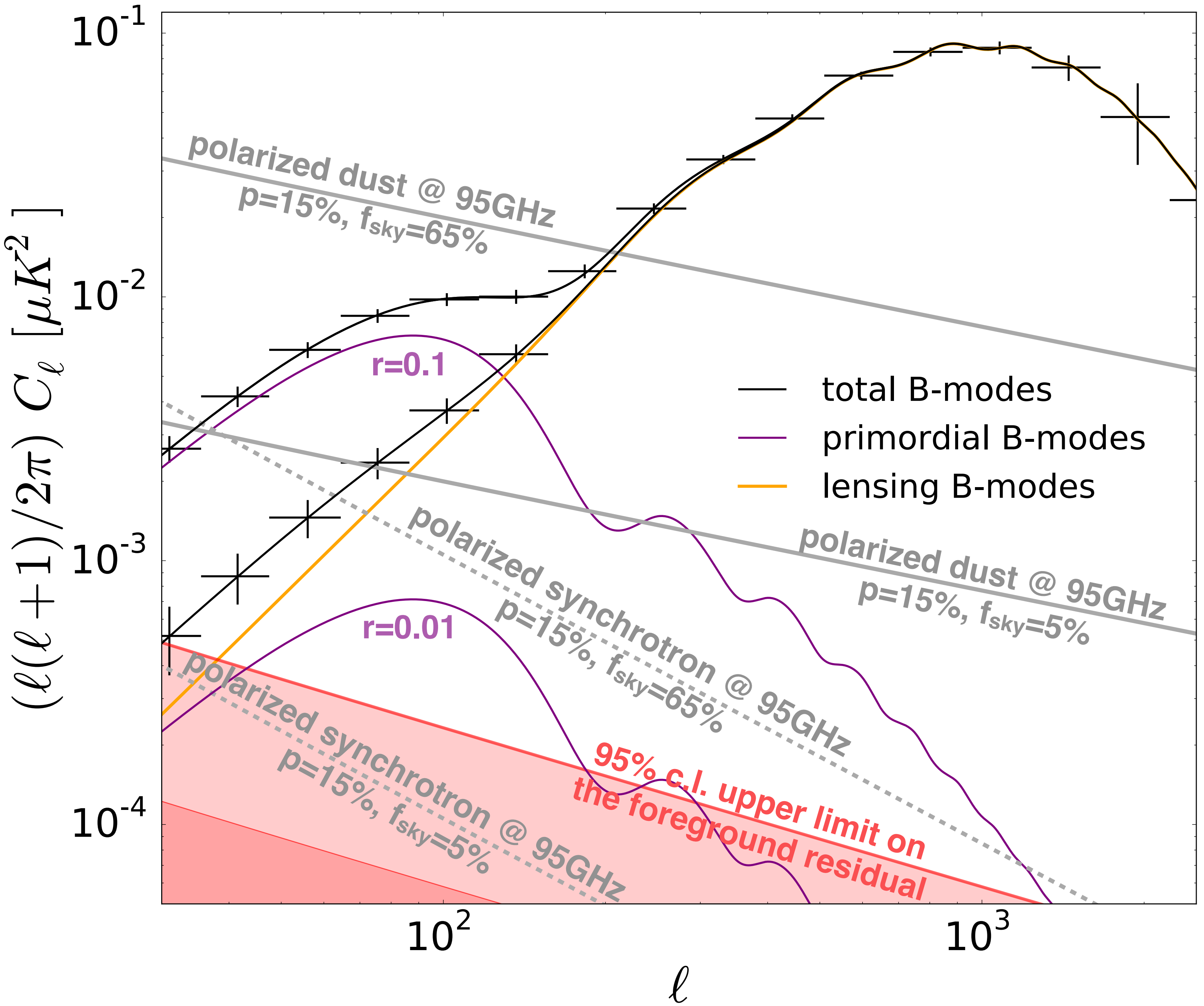
Polarization Measurement → Estimation α field → $C_\ell^{\alpha\alpha}$



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

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

Simons Array: sensitivity and foreground rejection



Simons Array
95/150/220 GHz
combined with
Planck and C-Bass

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

$$\sigma(\Sigma m_\nu = 0) = 40\mathrm{meV}$$

Combined with DESI BAO

r < 0.07 BK VI (2015)
Σm_ν < 0.15 eV
Palanque-Delabrouille et al (2015)

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