The POLARBEAR experiment: results from the first observational campaign and beyond

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on behalf of the POLARBEAR collaboration

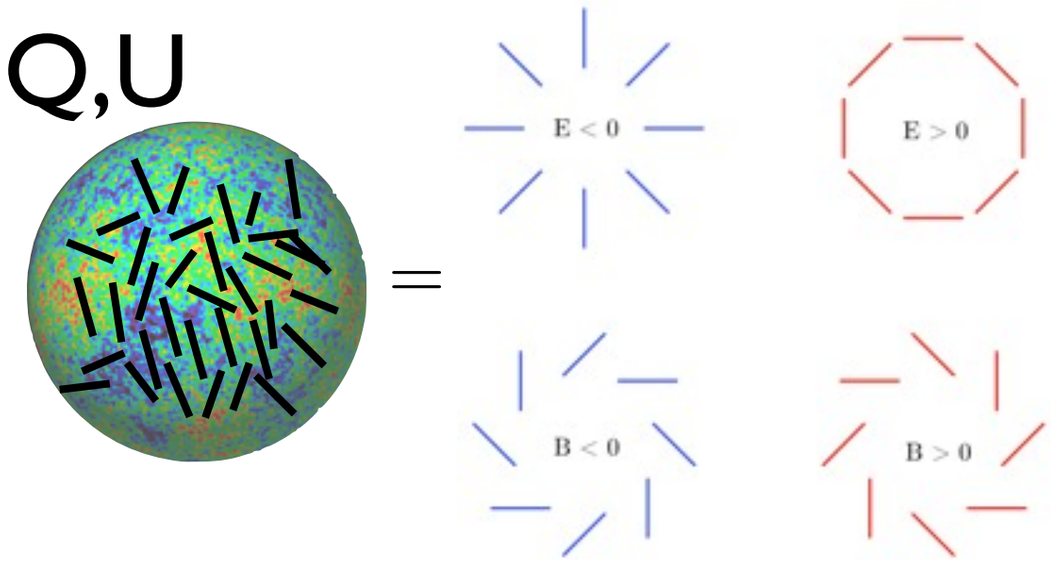
Experimental search for quantum gravity workshop

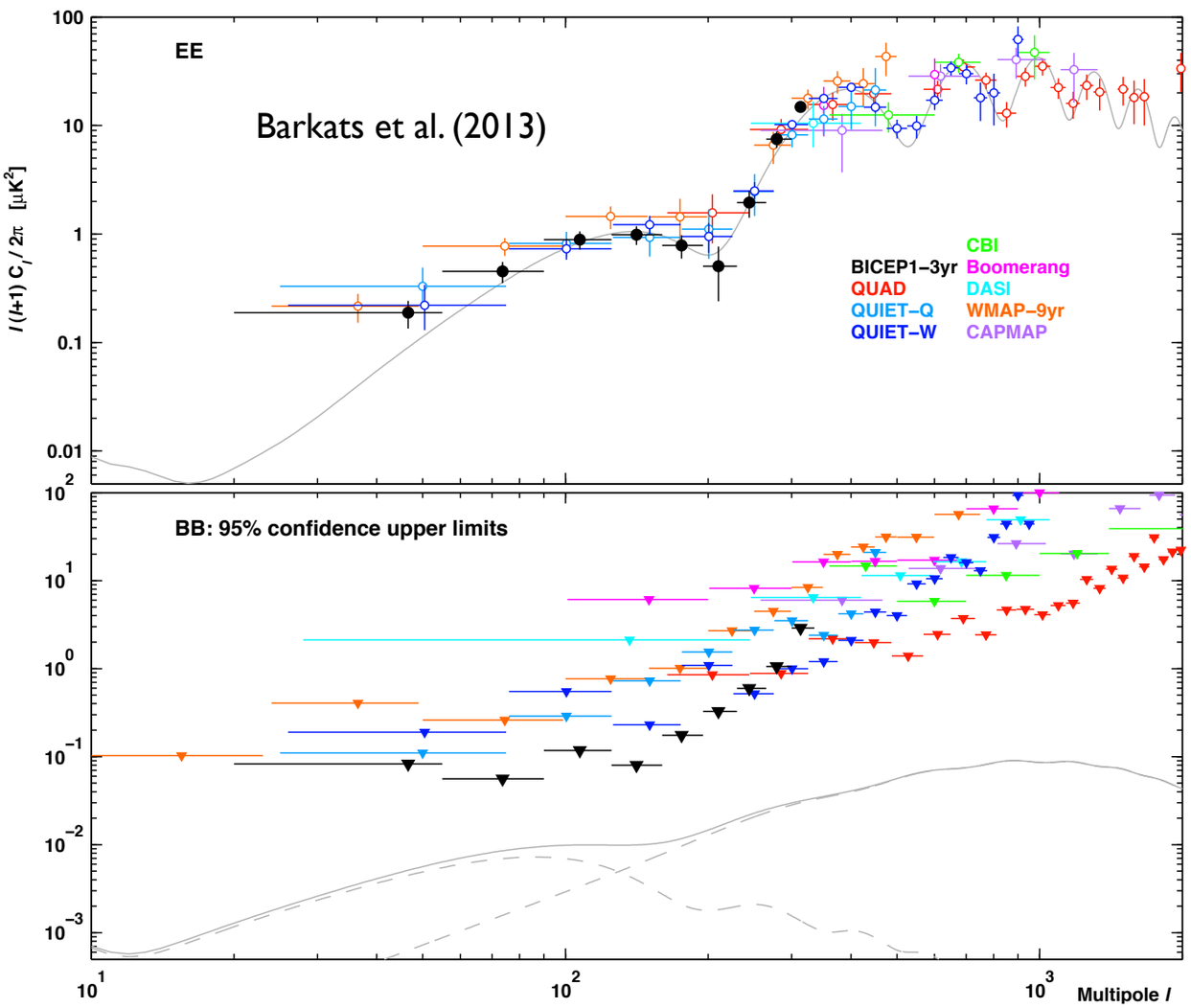
2 September 2014

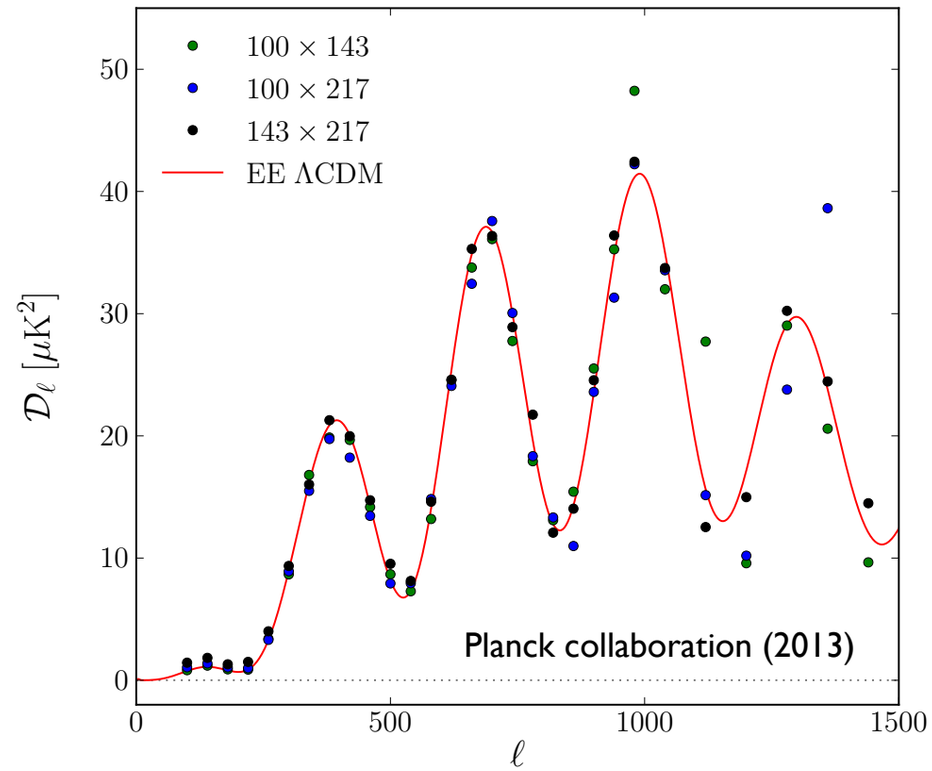
Outline

- Short recap on CMB polarization measurements
- The POLARBEAR experiment
- Results of first observational campaign:
  - Detection of CMB polarization lensing
  - Measurement of B-modes on sub-degree scale
- Upcoming experimental upgrades
- Conclusions

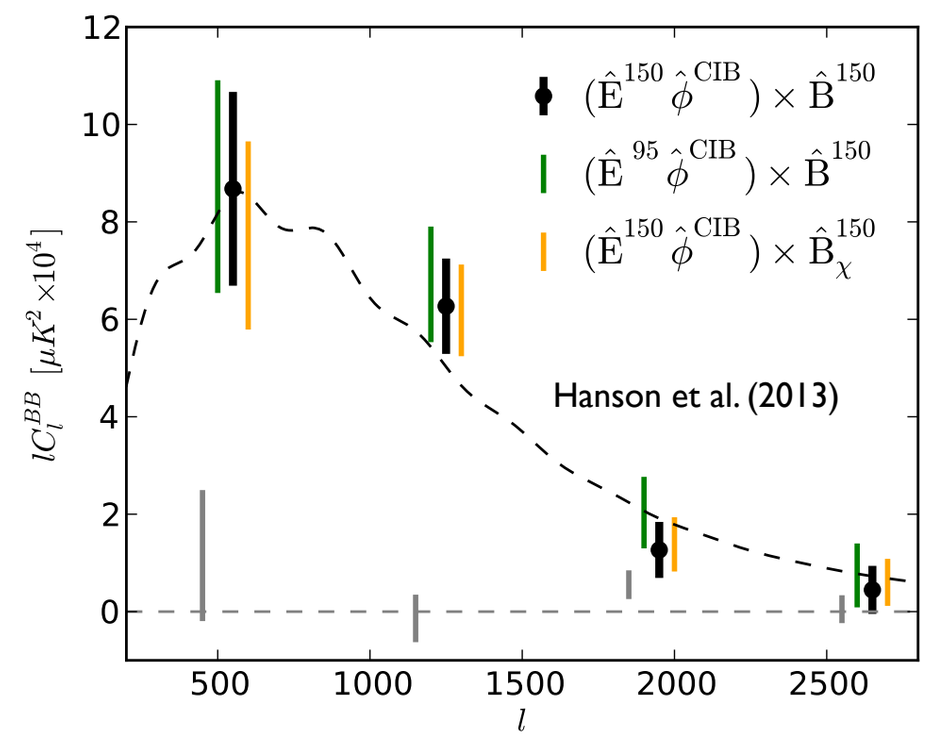
The universe of CMB polarization (till February)





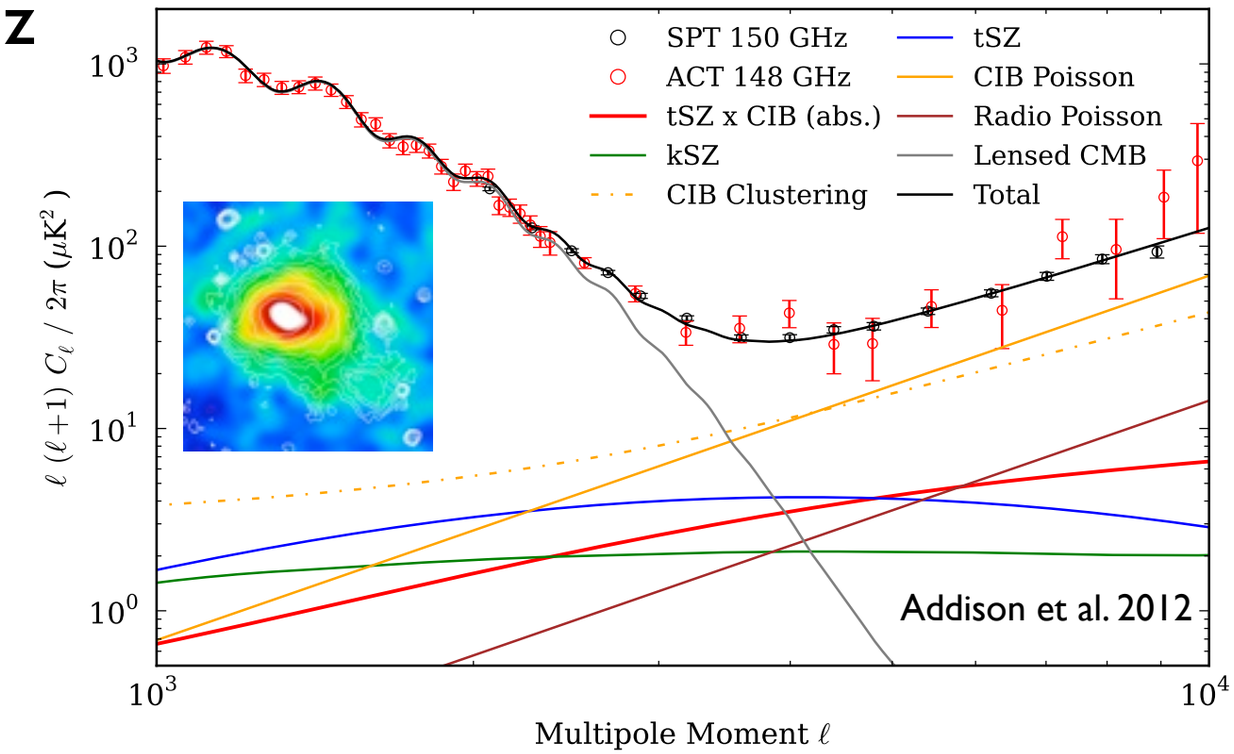


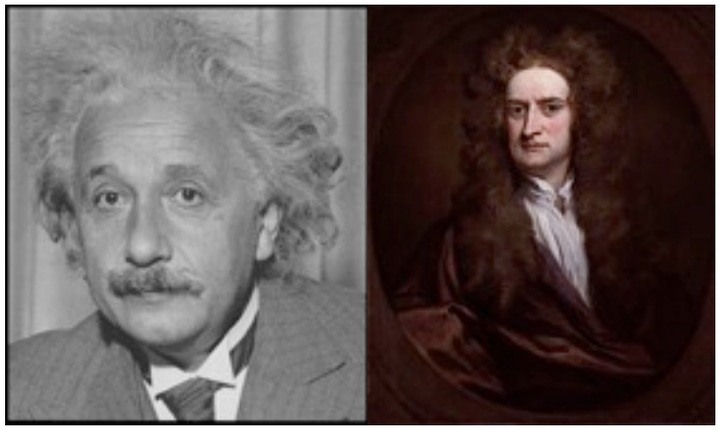
$$B^{\rm lens}(\vec{l}_B) = \int d^2\vec{l}_E \int d^2\vec{l}_\phi W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E)\phi(\vec{l}_\phi)$$

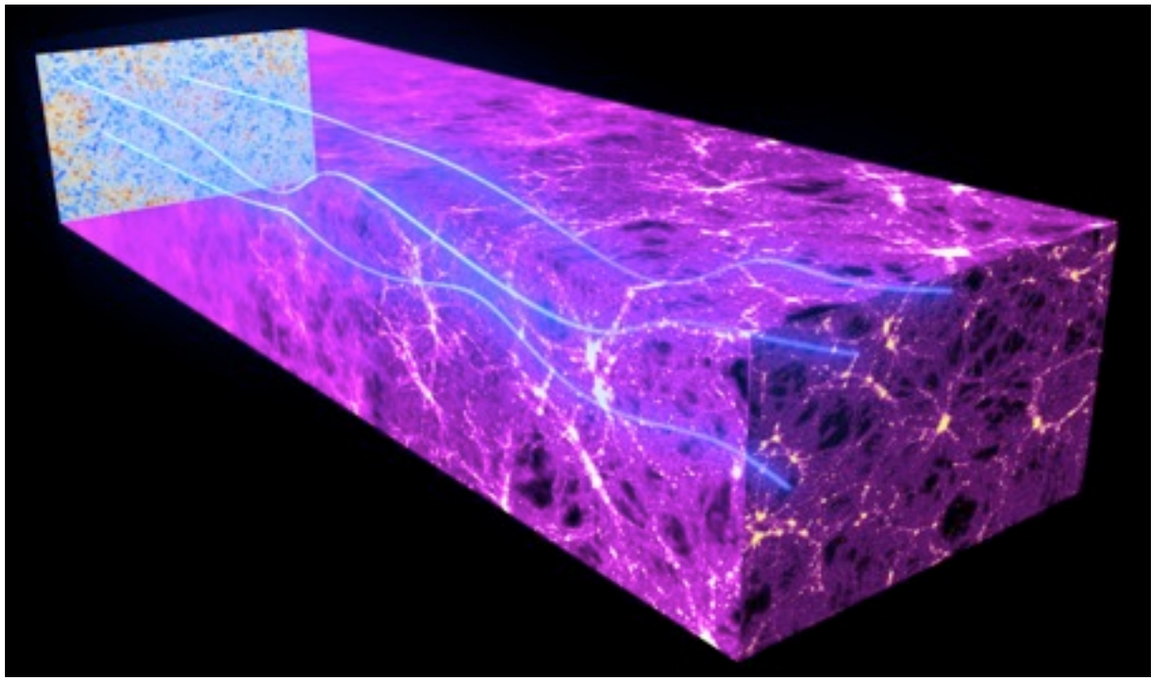


Is CMB "the" CMB?

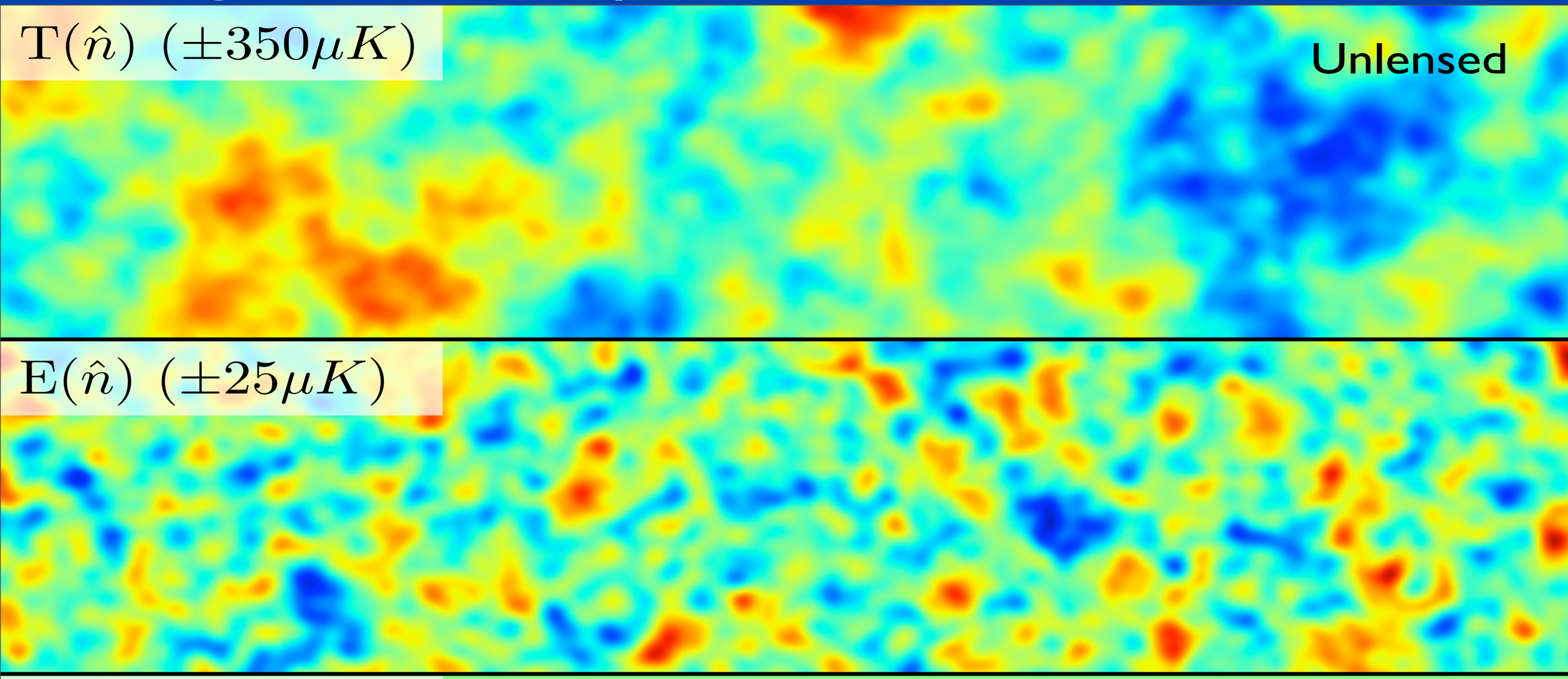
- CMB is a snapshot of the universe at z 1100.... plus something else
- CMB gets contaminated by evolving astrophysical objects and galactic foregrounds
- Imprint of ongoing large scale structures formation
- Photons deviated through the gravitational lensing effect







Lensing on CMB maps

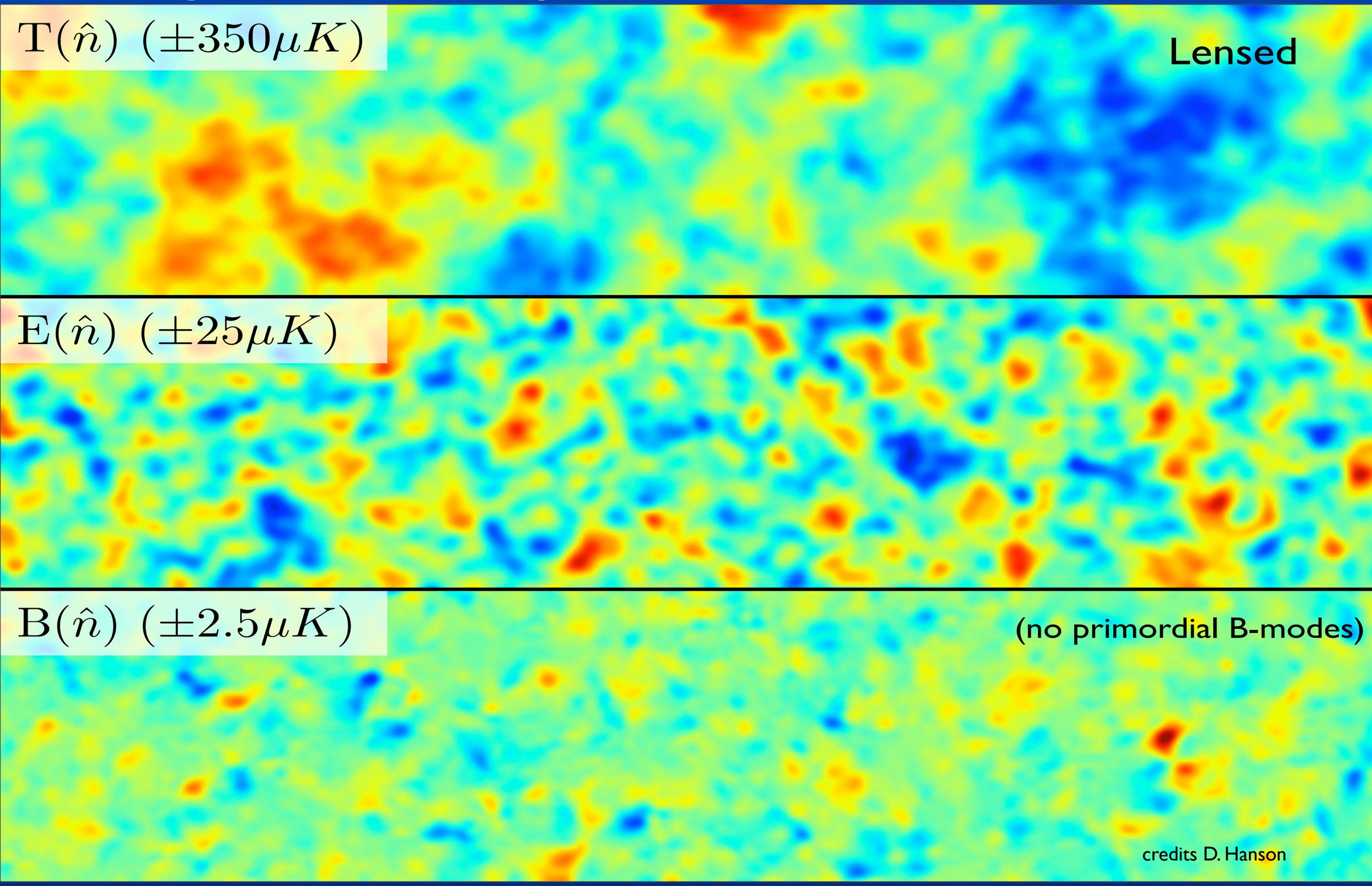


$\mathrm{B}(\hat{n})\ (\pm 2.5\mu K)$

(no primordial B-modes)

credits D. Hanson

Lensing on CMB maps

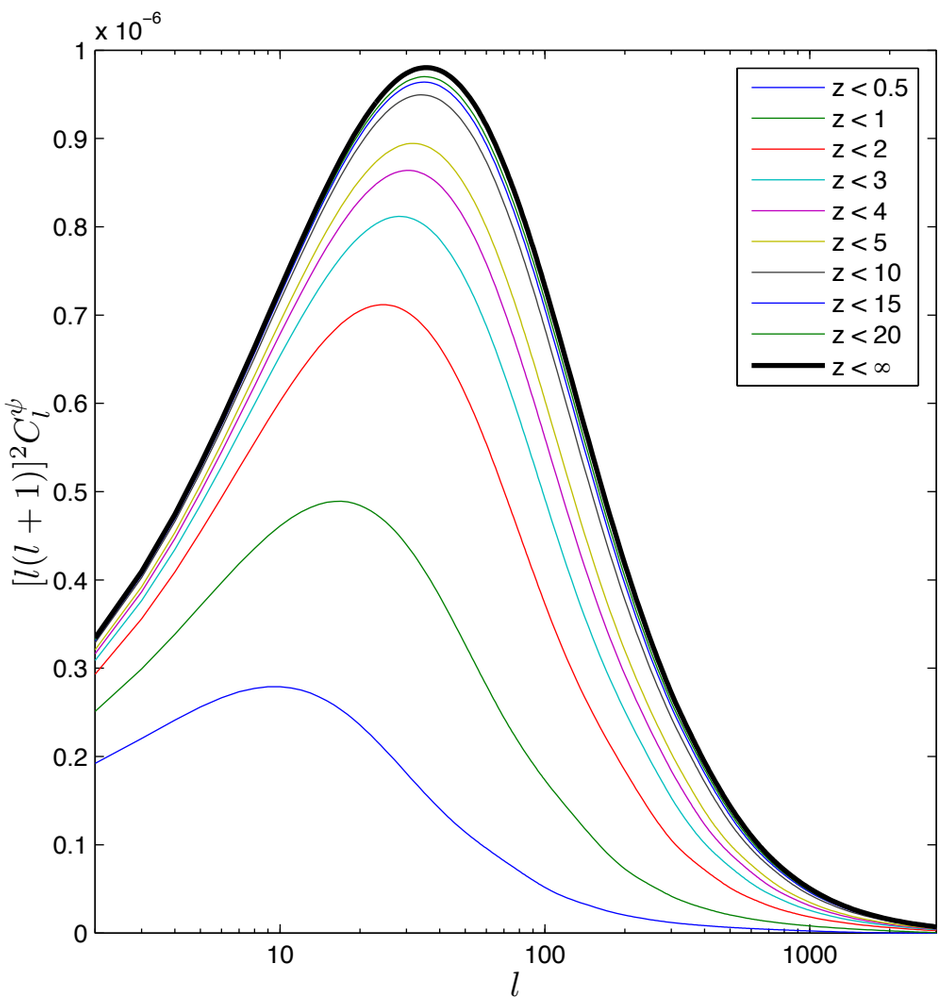


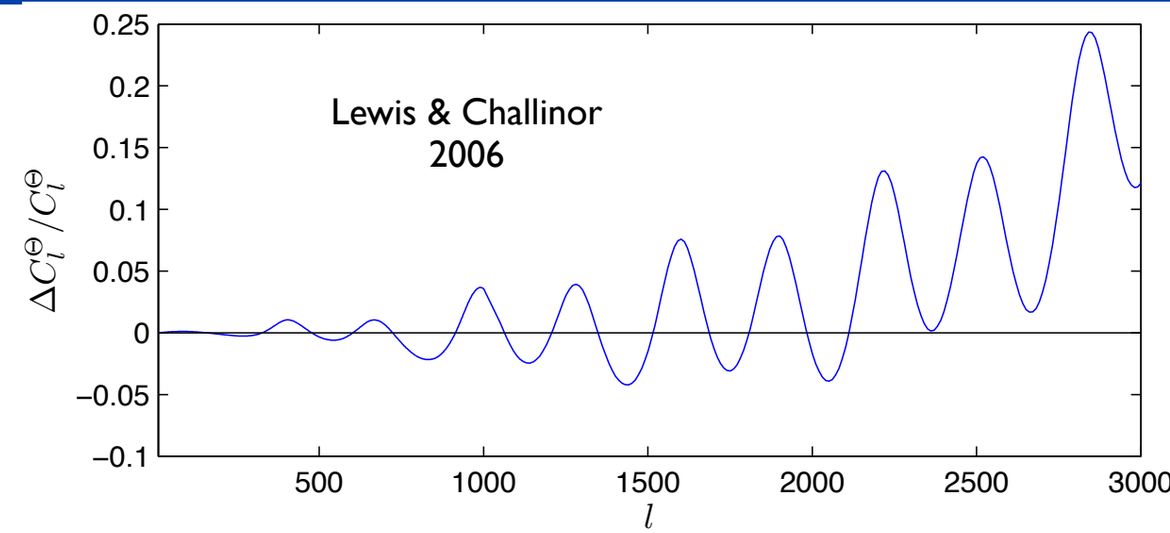
Effects on power spectrum

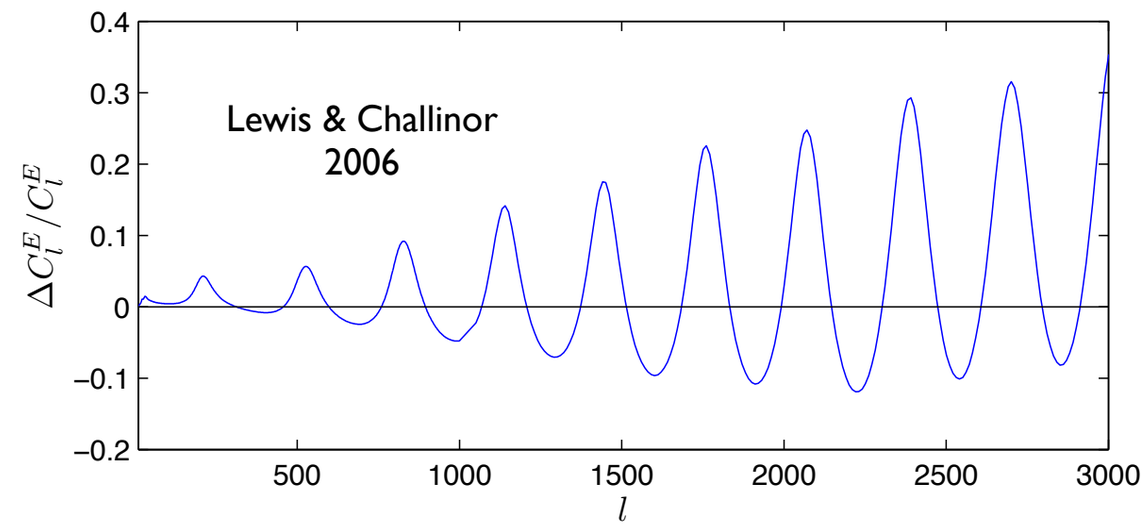
- Small effect on T, more important on E-modes, dramatic on B-modes

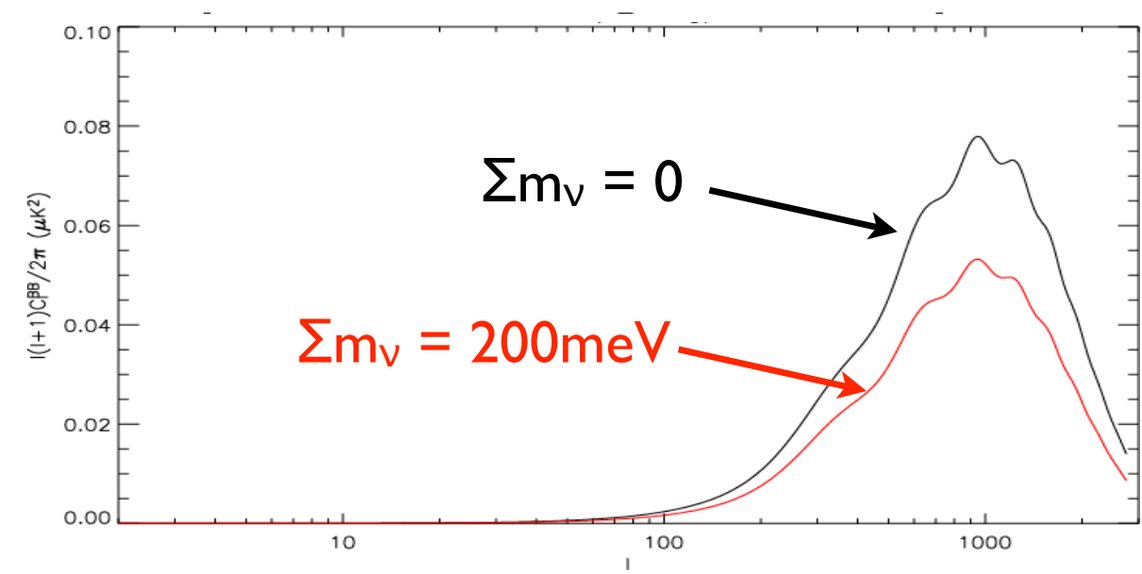
- Effect modeled through the so-called lensing potential

$$\psi(\hat{\mathbf{n}}) \equiv -2\int_0^{\chi_*} \mathrm{d}\chi \, \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{\mathbf{n}}; \eta_0 - \chi)$$









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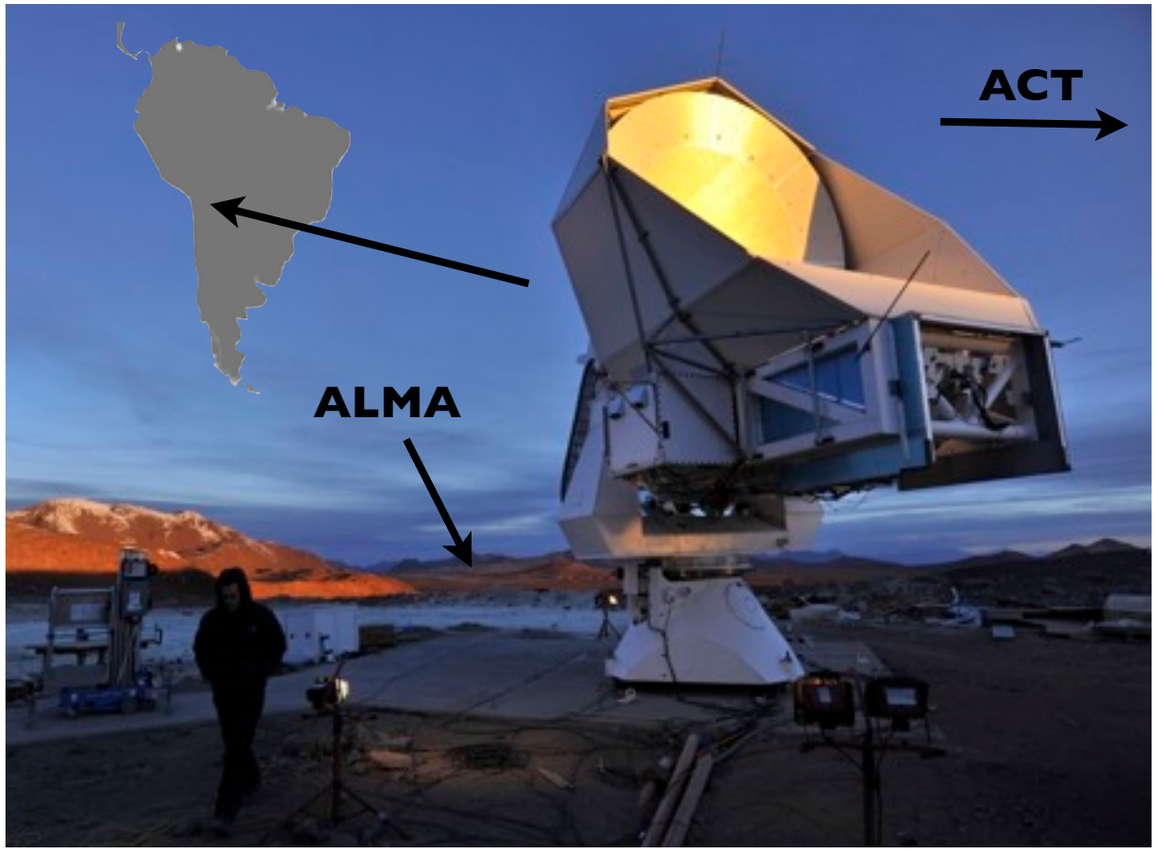
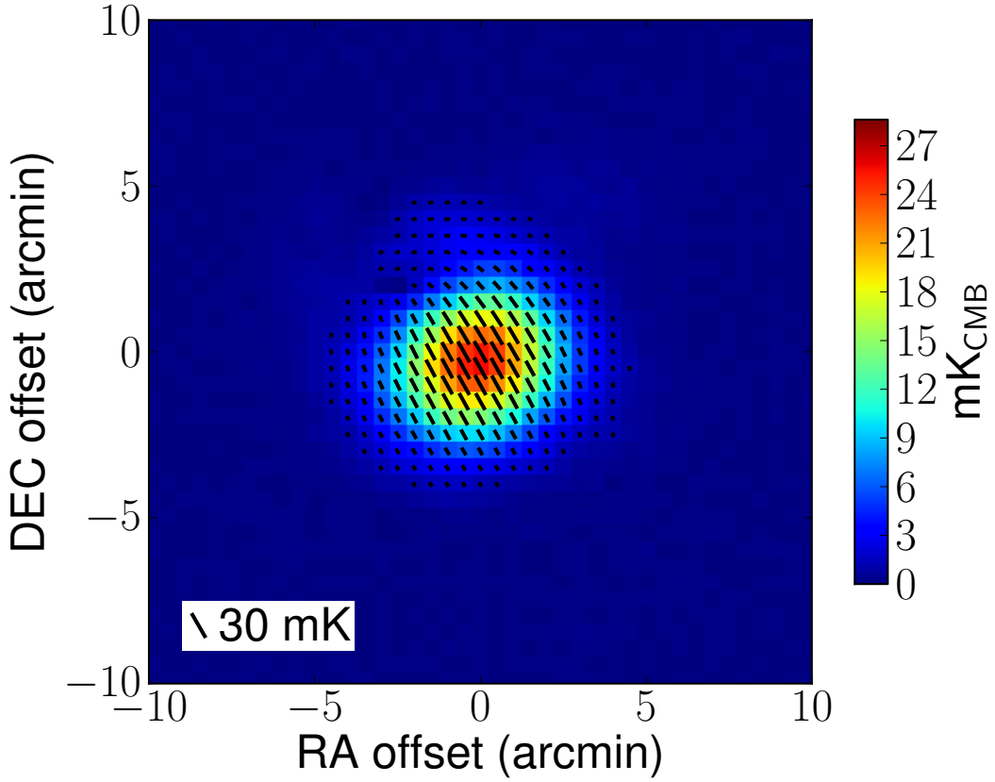
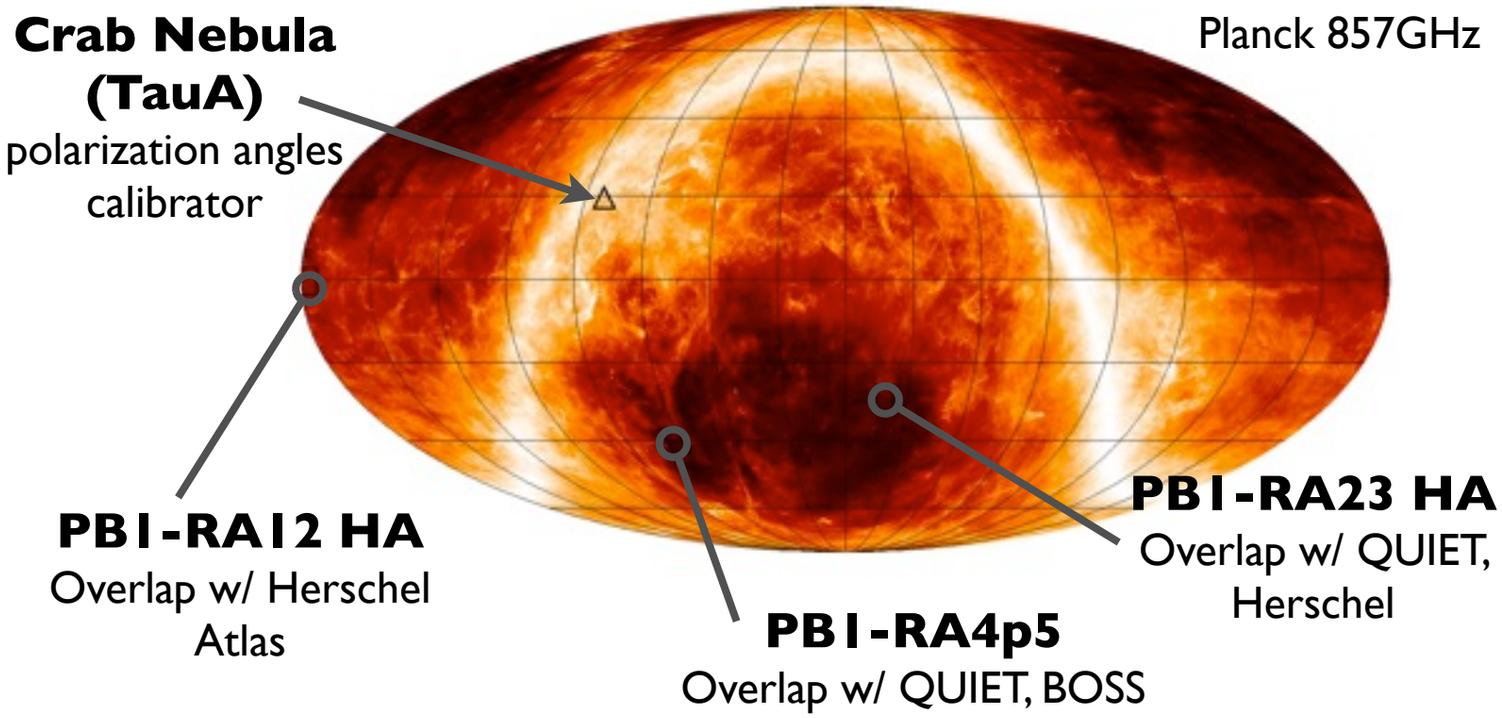
The POLARBEAR experiment

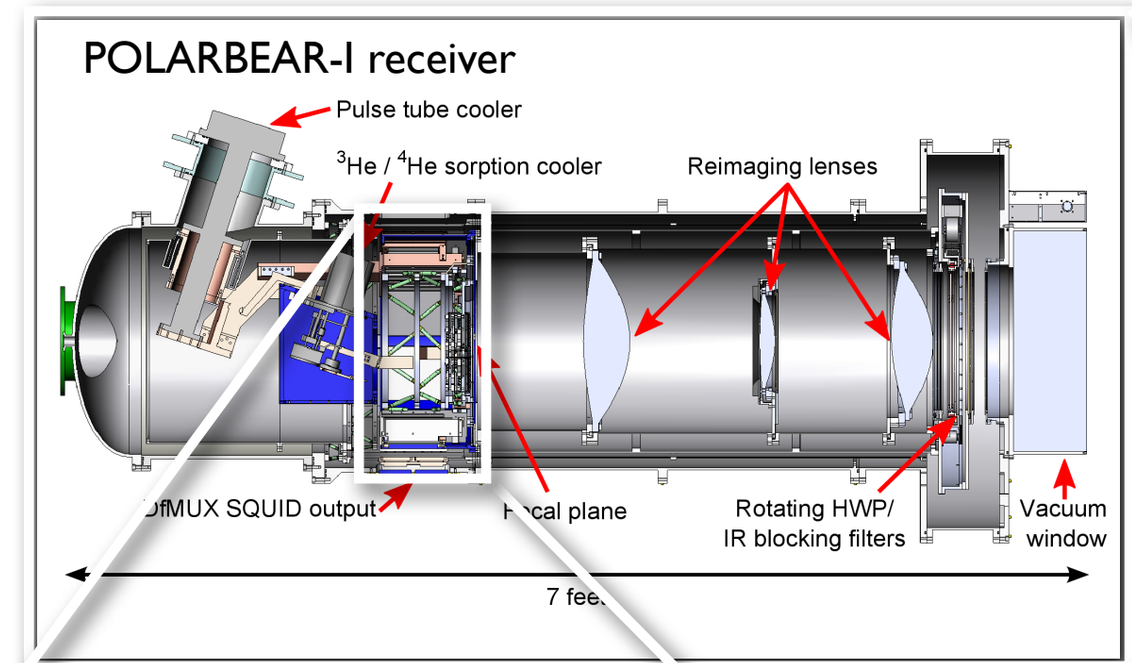
- CMB polarization dedicated experiment in Atacama Desert
- Targeting both large and small scales
- 80% of the sky with *el* > 30 accessible
- First season: deep 5x5 patches integration for sub-degree signal

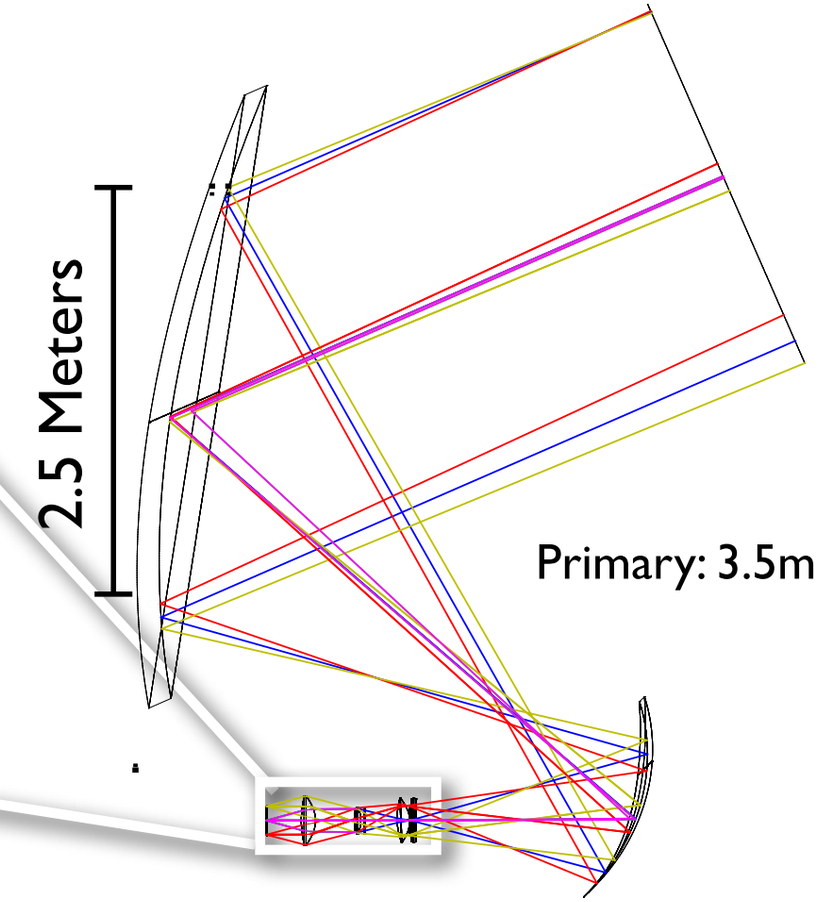






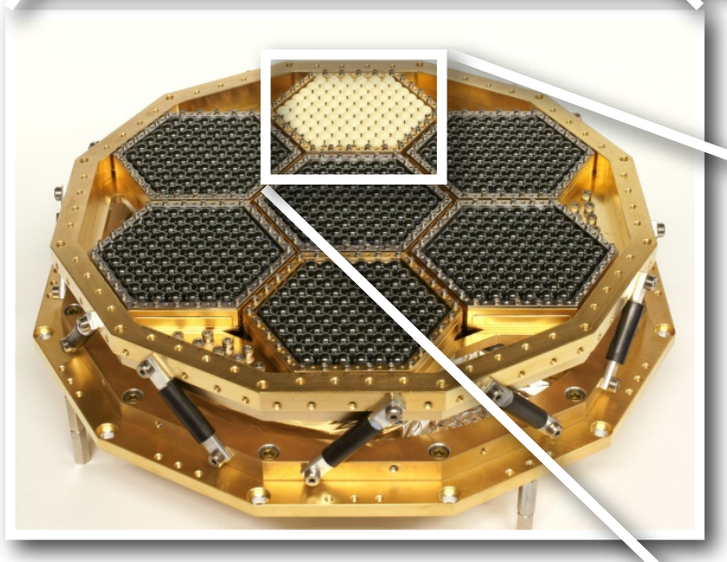
Instrument design





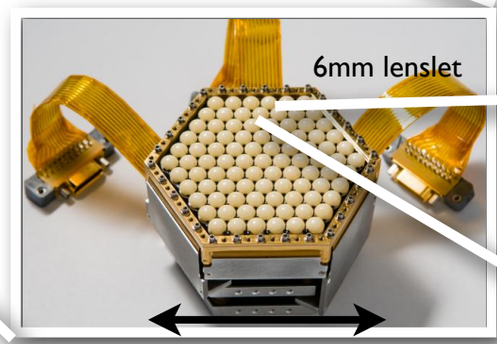
Huan Tran Telescope

Focal plane



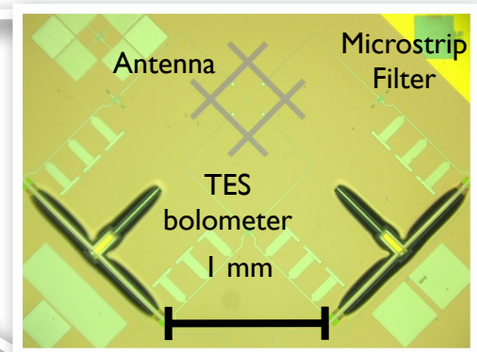
1274 bolometers @ 150 GHz
Cooled to 250 mK

Hex Module



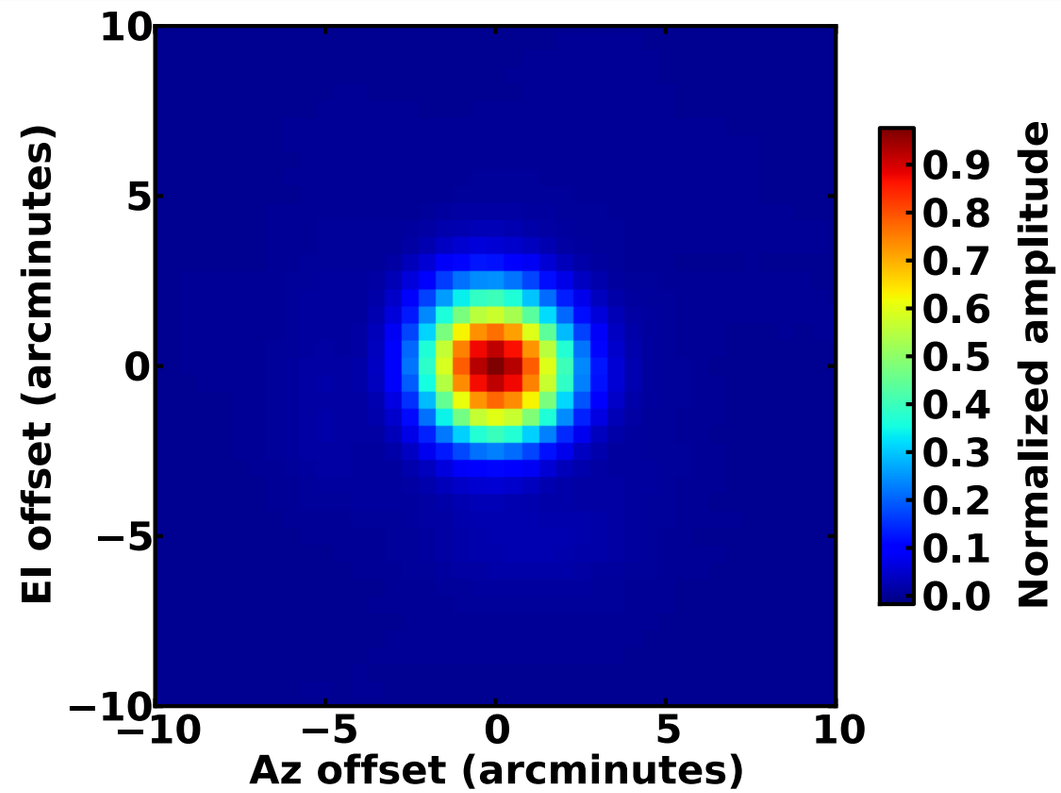
8cm

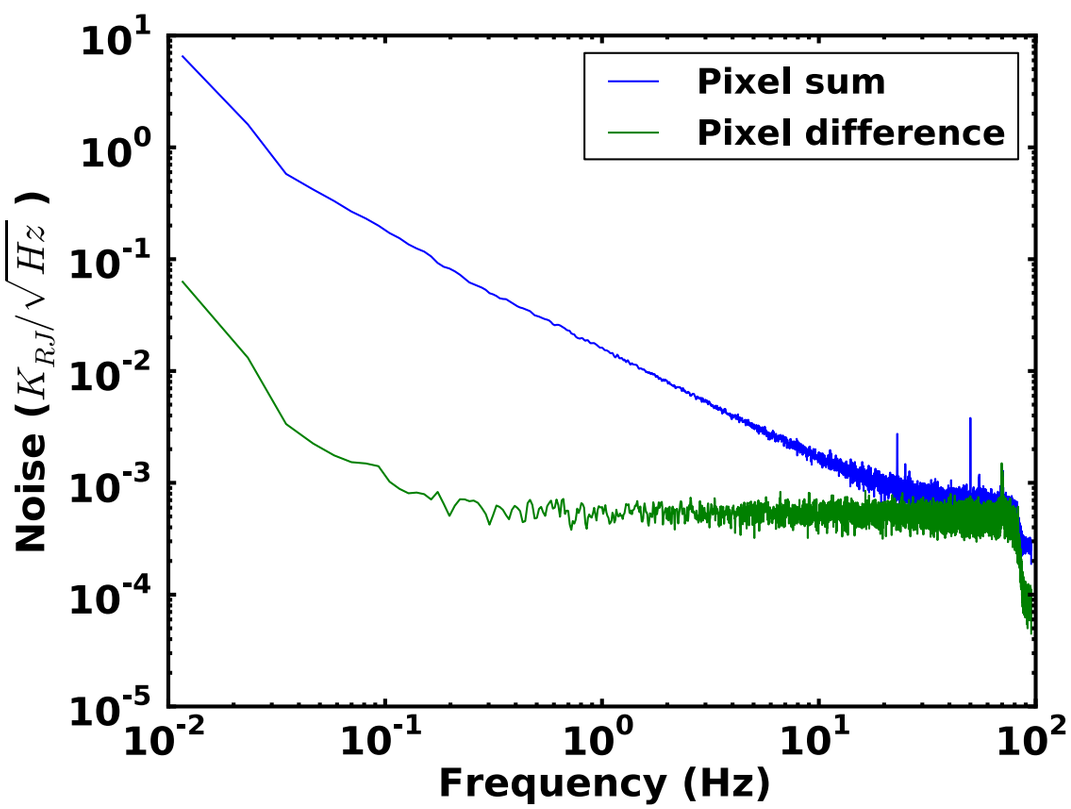
$$d^t(t) = g_{top}\,[I(\hat{\mathbf{n}}(t)) + Q(\hat{\mathbf{n}}(t))\cos(2\psi(t)) + U(\hat{\mathbf{n}}(t))\sin(2\psi(t))]$$
$$d^b(t) = g_{bot}\,[I(\hat{\mathbf{n}}(t)) - Q(\hat{\mathbf{n}}(t))\cos(2\psi(t)) - U(\hat{\mathbf{n}}(t))\sin(2\psi(t))]$$

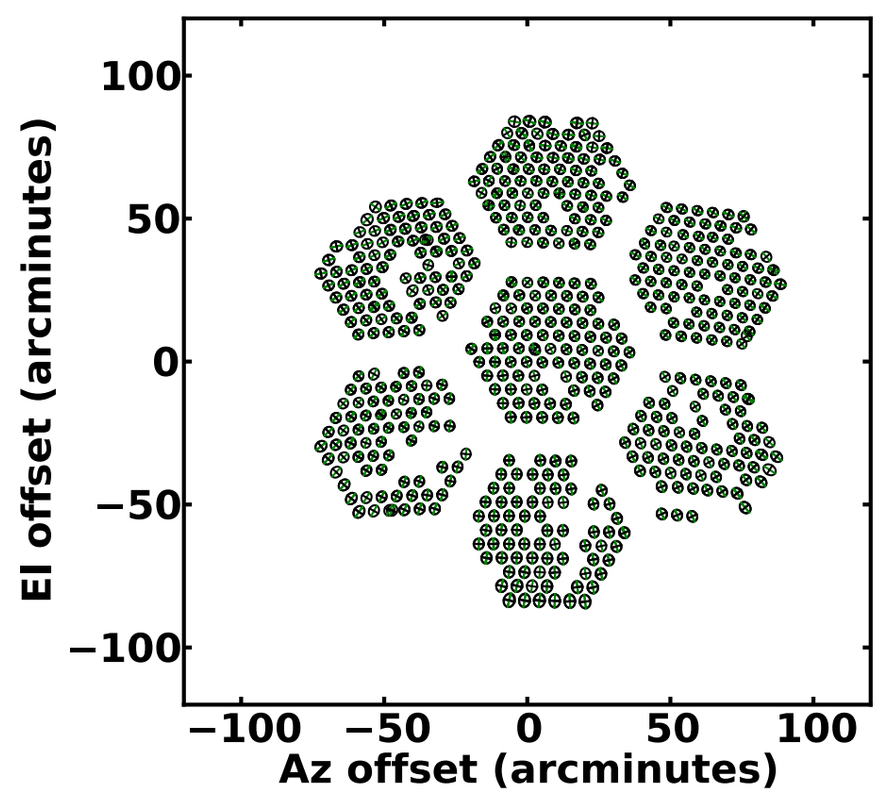


Instrument characterization

- Good availability of on-sky calibrators
- 3.5 arcmin beam FWHM
- Ellipticity < 5%, differential ellipticity 1%
- Pointing errors 20 ~ 40 arcsec
- Array NET $23\mu K \cdot \sqrt{s}$

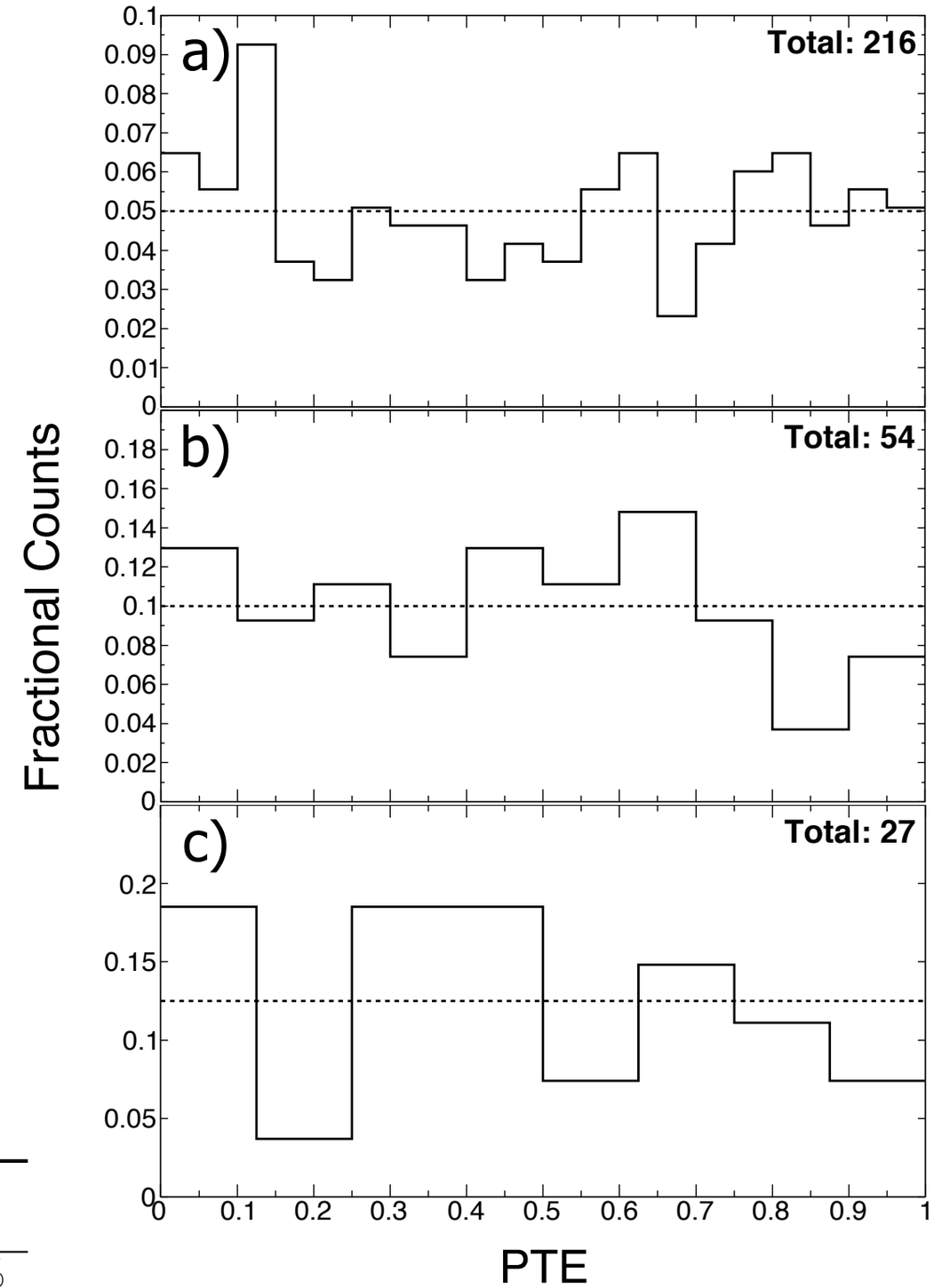






Instrumental systematics and data selection

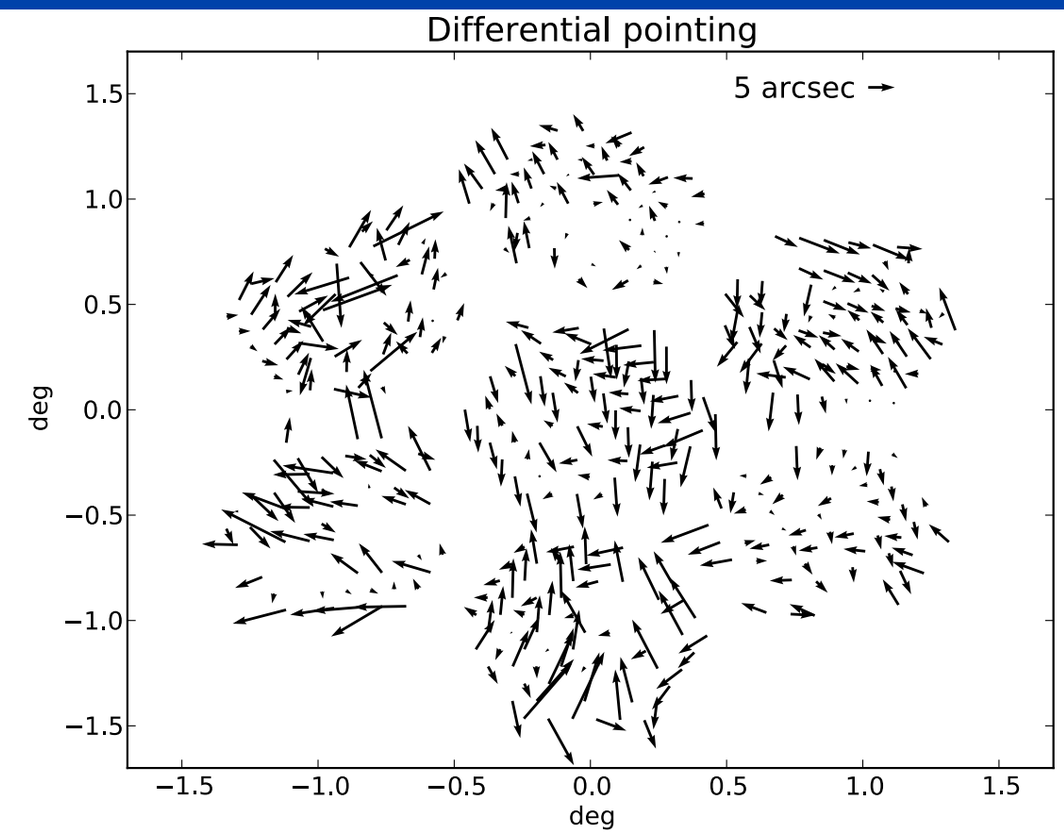
- Blind-analysis policy: careful tests for systematic errors required
- Null-tests suite for systematics contamination estimation:
  - temporal, scan direction, weather, calibration, elevation, detector selection, bright sources contamination....
- Kolmogorov-Smirnov test consistent with uniform probability PTEs distribution
- No significant outliers found



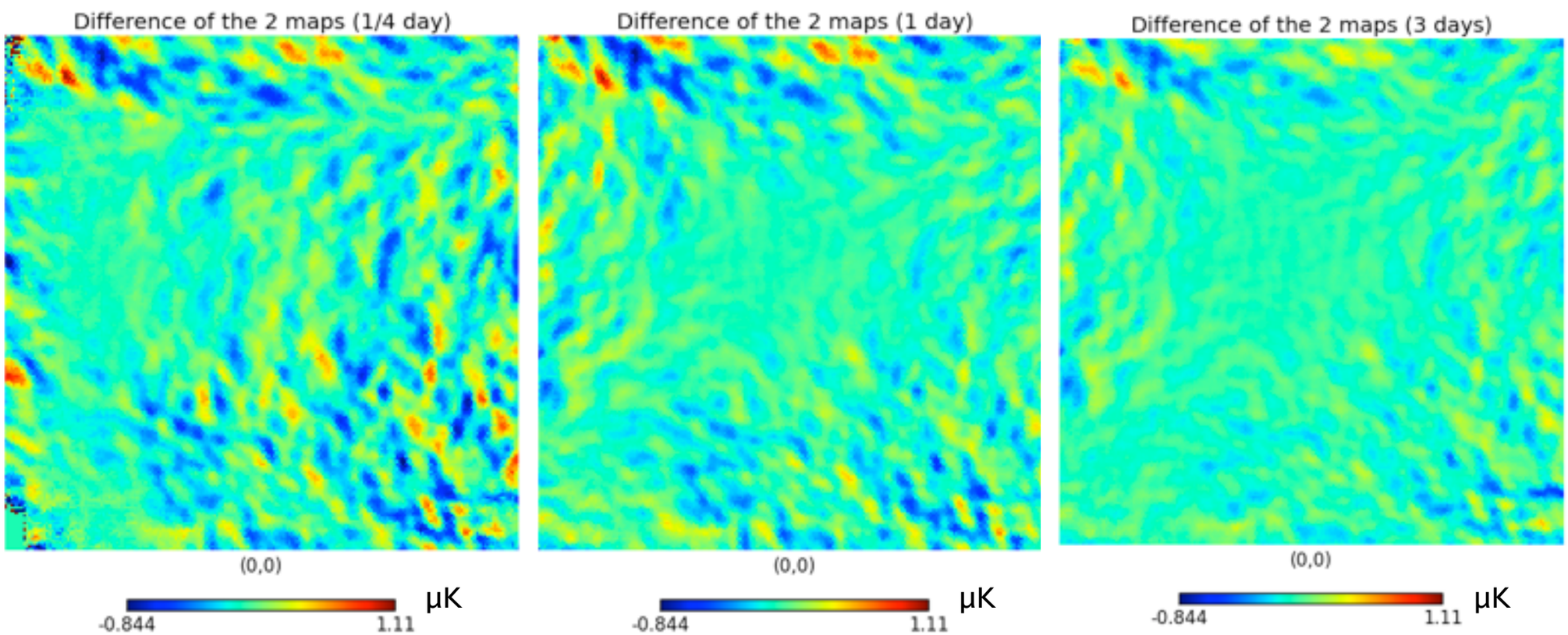
Patch	average of $\chi_{\rm null}(b)$	extreme of $\chi^2_{\rm null}(b)$	extreme of $\chi^2_{\rm null}$ by EB/BB	extreme of $\chi^2_{\rm null}$ by test	total $\chi^2_{\rm null}$
RA4.5	11.6%	16.6%	20.6%	21.8%	14.0%
RA12	92.4%	84.2%	60.8%	23.8%	52.6%
RA23	75.2%	61.6%	6.0%	7.0%	18.6%

Systematics errors propagation

- *Ab initio* high-resolution instrumental systematics simulation pipeline
- 12 different effects analyzed
- Propagation of systematics error through science pipeline
- Sky-rotation helps mitigating systematics!



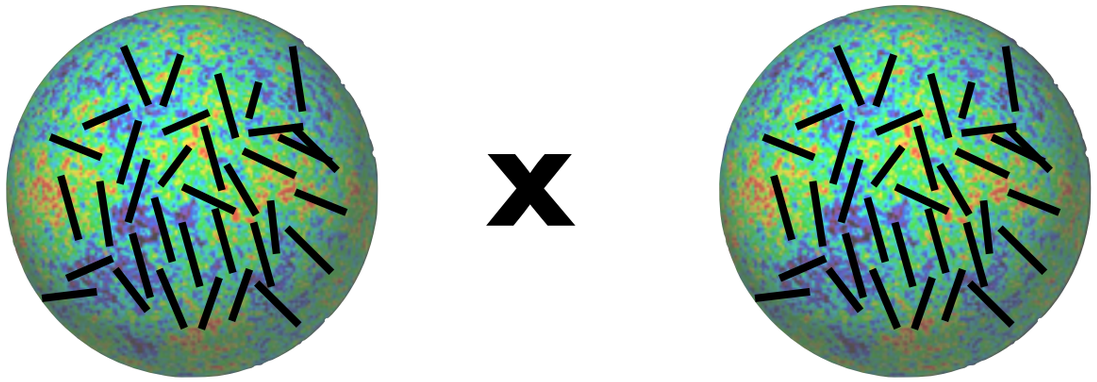
Q



Which evidence for B-modes?

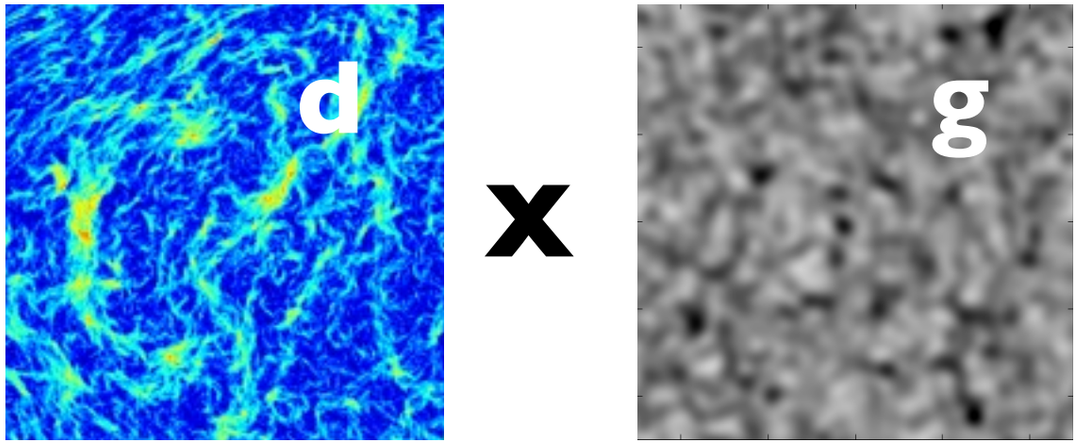
- 2-point correlation:
  CMB power spectrum

  arXiv:1403.2369 ApJ accepted



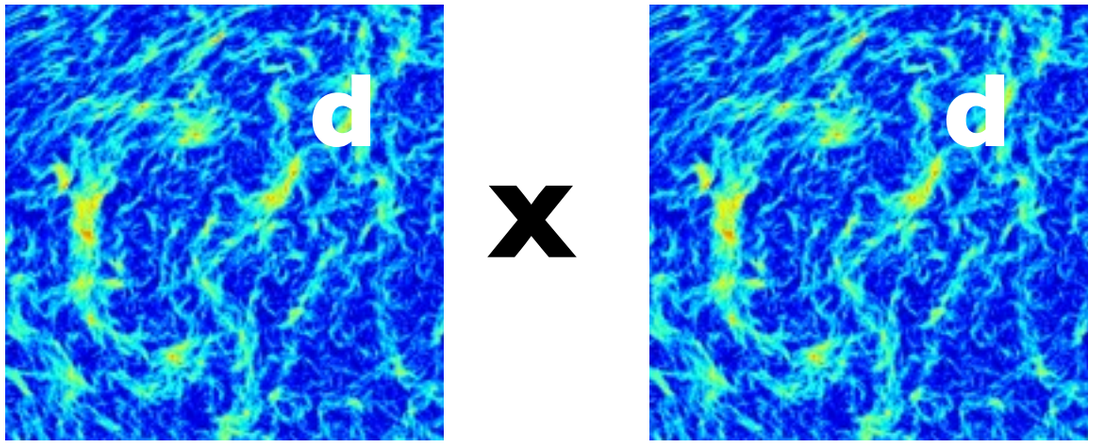
- 3-point correlation:
  CMB cross correlation with biased tracers of dark matter halos

  arXiv:1312.6646 PRL.112.131302



- 4-point correlation: lensing reconstruction with polarization

  arXiv:1312.6645 PRL.13.021301



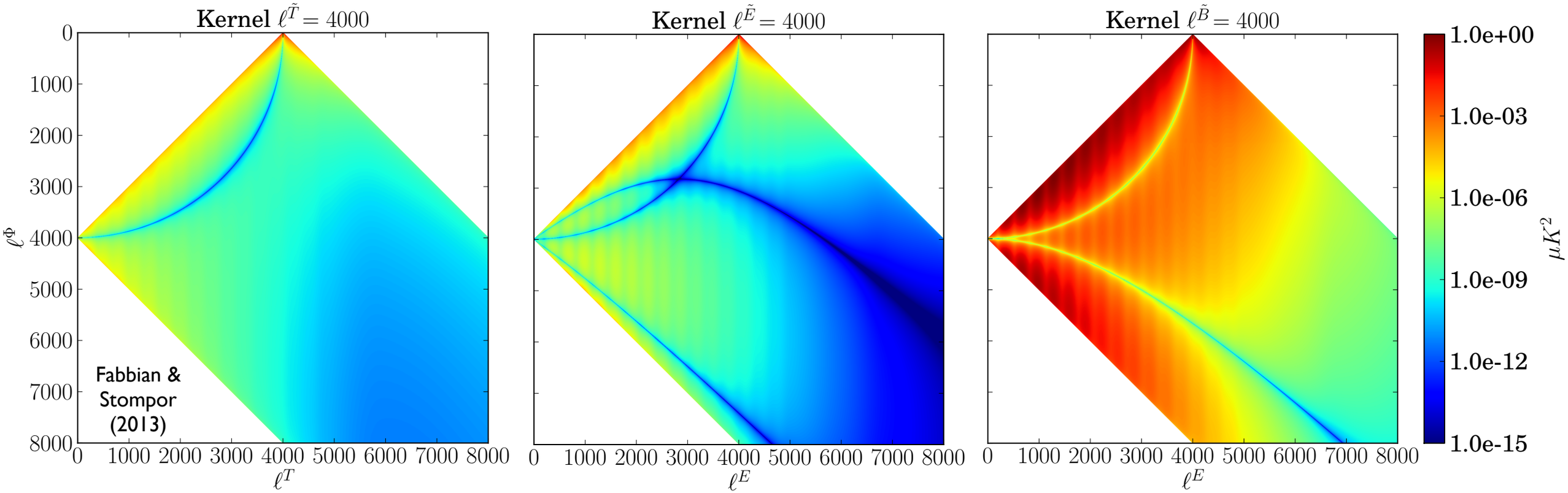
Gravitational lensing in harmonic domain

- Lensing correlates Fourier modes on a wide range of angular scales

$$\tilde{C}^{BB}_{\tilde{\ell}^B} = \frac{1}{2}\sum_{\ell^\Phi \ell^E} \frac{|{}_2F_{\tilde{\ell}^B \ell^\Phi \ell^E}|^2}{2\tilde{\ell}^B + 1} C^{\Phi\Phi}_{\ell^\Phi} C^{EE}_{\ell^E} (1 - (-1)^L)$$

- B-modes are ideal for lensing reconstruction: mode coupling is stronger!

Temperature E-modes B-modes



Lensing reconstruction with polarization data

- Clean reconstruction of the deflection field from CMB polarization

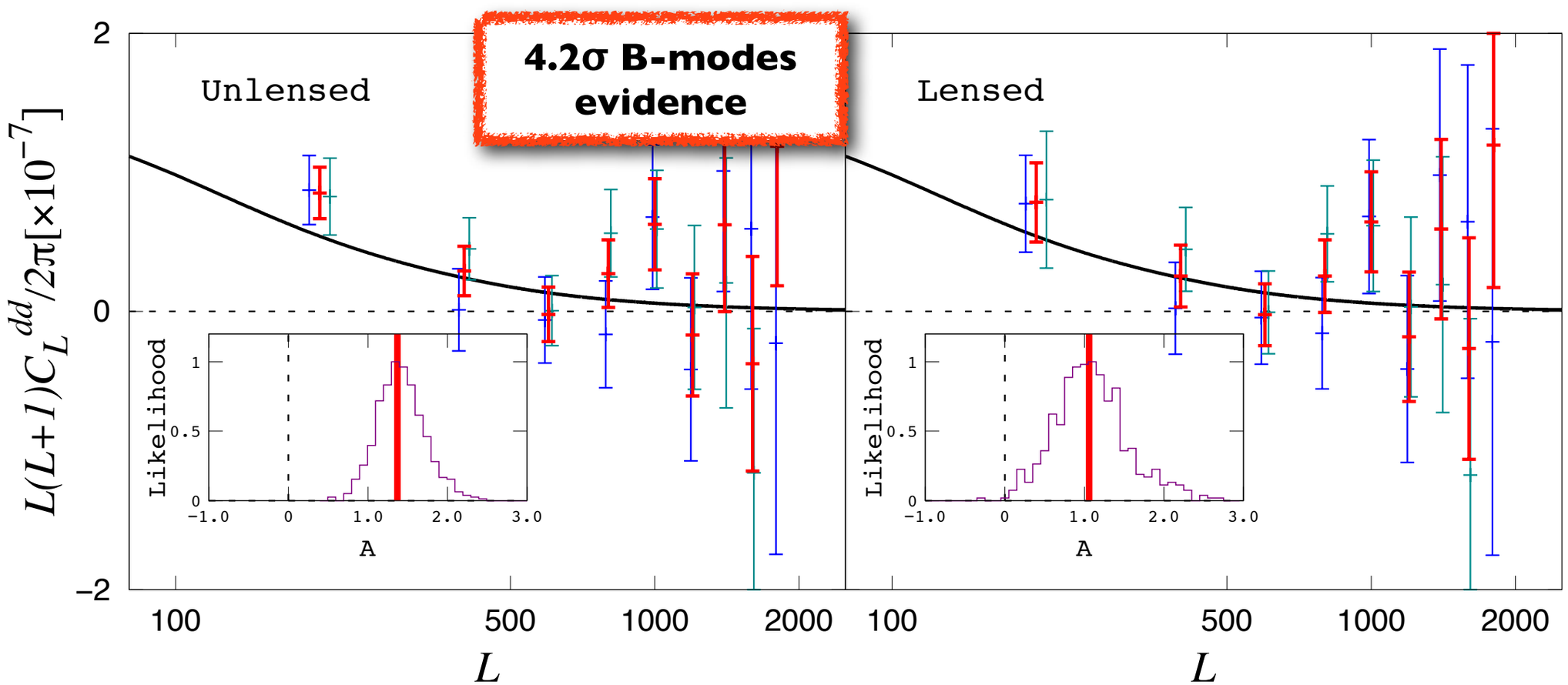
$$\boldsymbol{d} = \nabla\phi$$

$$d_{EB}(\mathbf{L}) = \frac{A_{EB}(L)}{L}\int \frac{d^2\mathbf{l}}{(2\pi)^2} E(\mathbf{l})B(\mathbf{l}')\frac{\tilde{C}_l^{EE}\mathbf{L}\cdot\mathbf{l}}{C_l^{EE}C_{l'}^{BB}}\sin 2\phi_{\mathbf{ll}'}$$

$$d_{EE}(\mathbf{L}) = \frac{A_{EE}(L)}{L}\int \frac{d^2\mathbf{l}}{(2\pi)^2} E(\mathbf{l})E(\mathbf{l}')\frac{\tilde{C}_l^{EE}\mathbf{L}\cdot\mathbf{l}}{C_l^{EE}C_{l'}^{EE}}\cos 2\phi_{\mathbf{ll}'}$$

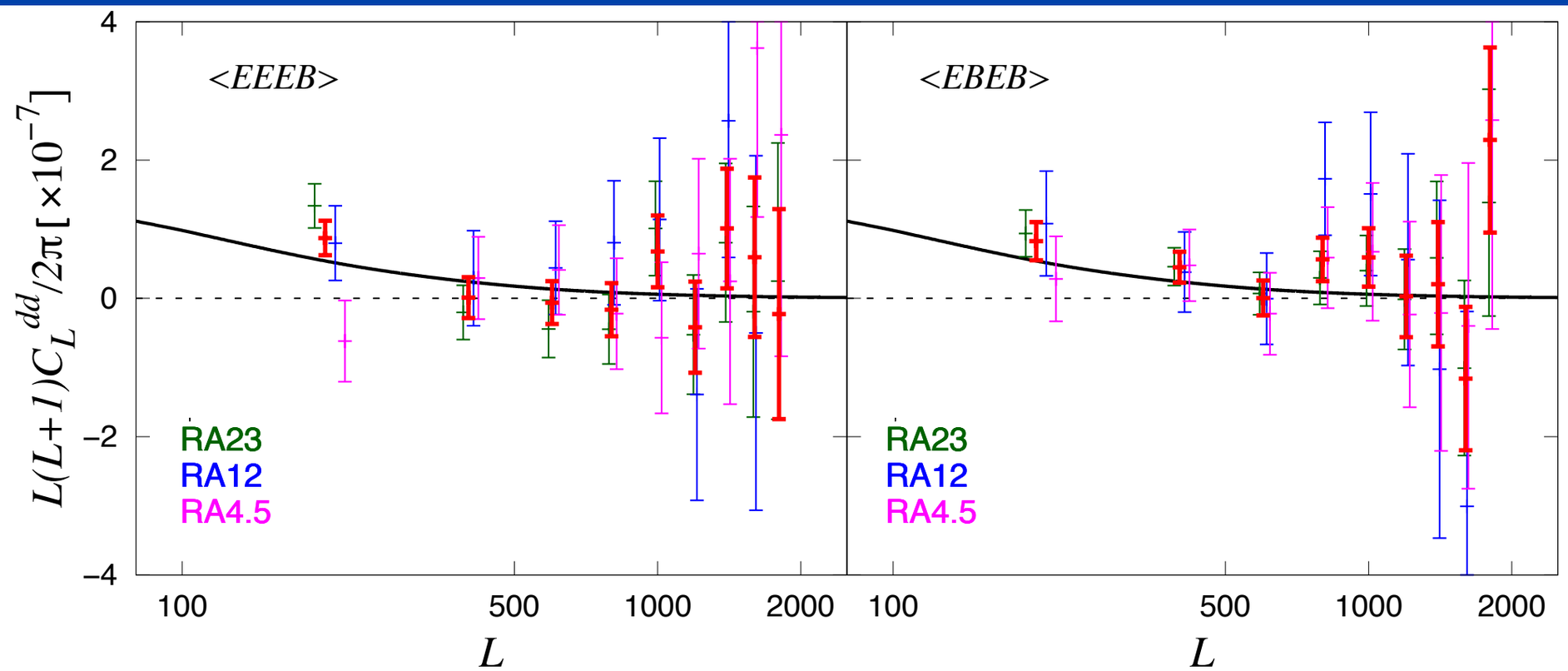
$$\longrightarrow \mathcal{A}/\Delta\mathcal{A}$$

- Detection of lensing of CMB polarization from CMB alone

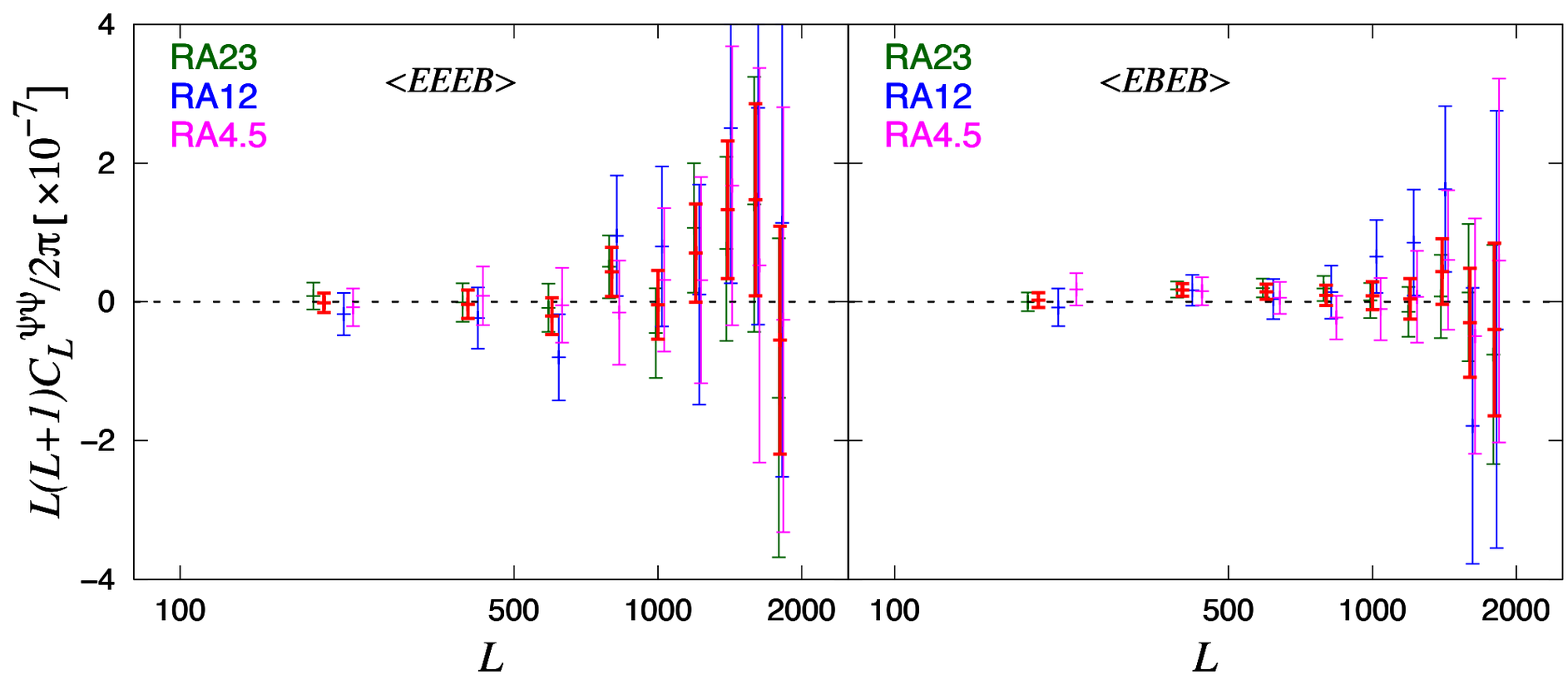


Lensing reconstruction robustness and systematics

- Single channel and patch combined



- Swap-patch, channel, curl-mode null-tests passed



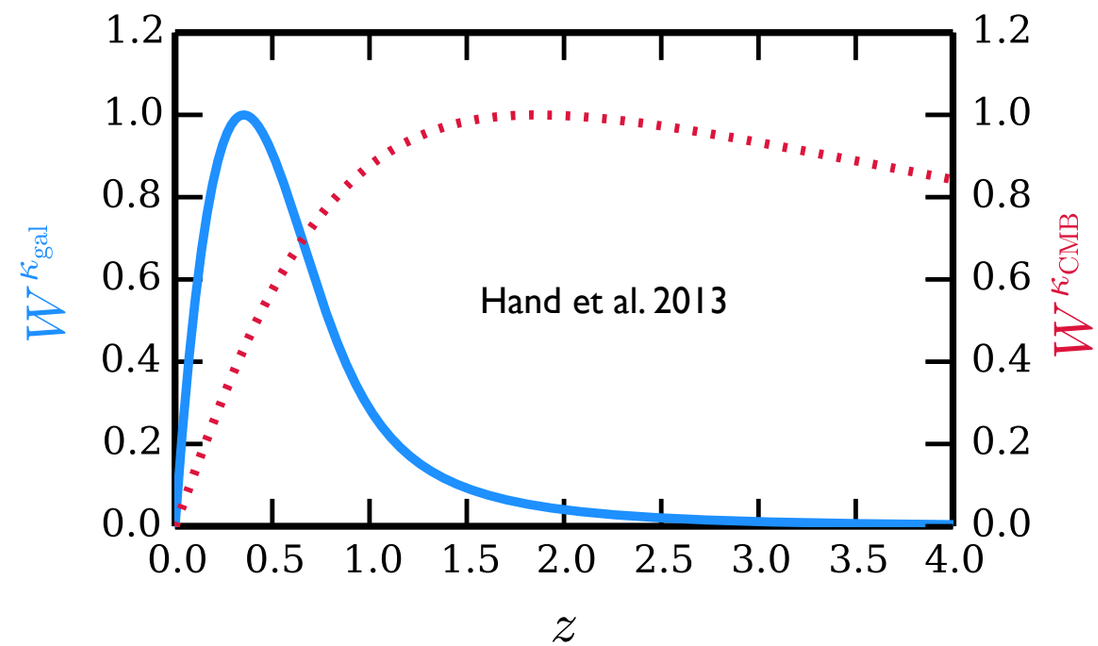
POLARBEAR/HERSCHEL cross-correlation

- CMB lensing convergence $\kappa = -\frac{1}{2}\nabla \cdot \mathbf{d}$ and large scale structures trace the same DM distribution

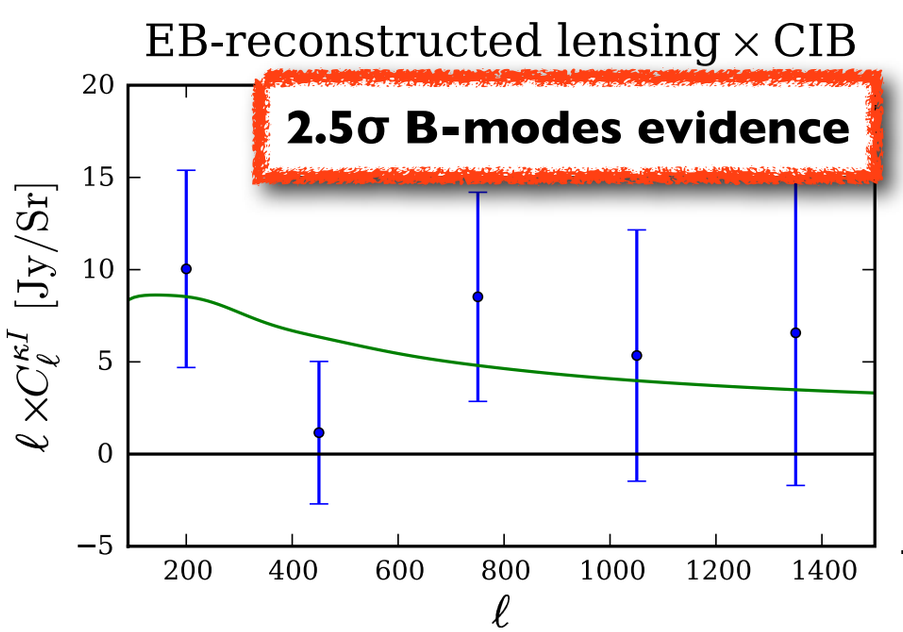
$$W^{\kappa}(z) = \frac{3}{2H(z)}\Omega_0 H_0^2 (1+z)\eta(z)\frac{(\eta^* - \eta(z))}{\eta^*}$$

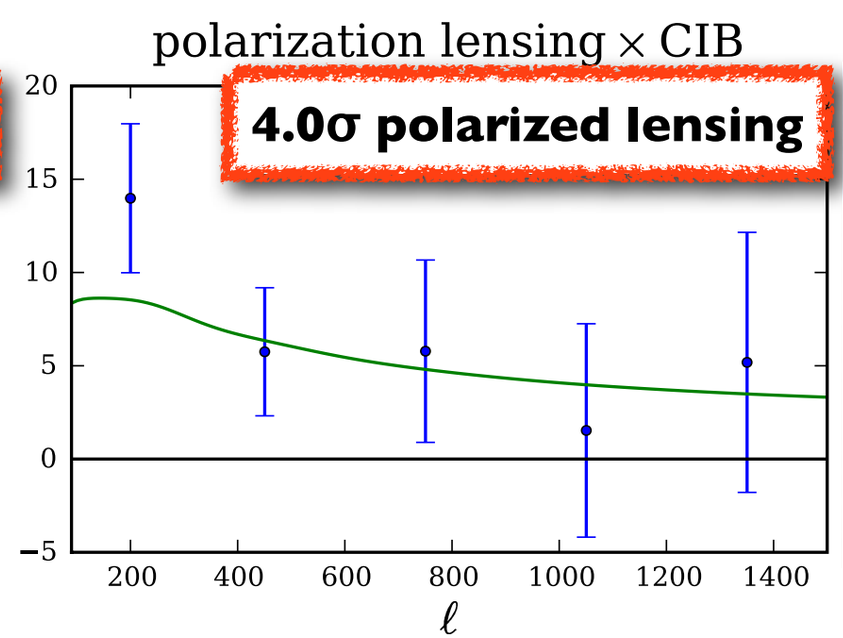
$$W^{I}(z) = \frac{3}{2}\Omega_m H_0^2 \frac{(1+z)}{H(z)}\frac{\eta(z)}{c}\int_z^{\infty} dz' \frac{dN^I}{dz'}\frac{\eta(z') - \eta(z)}{\eta(z')}$$

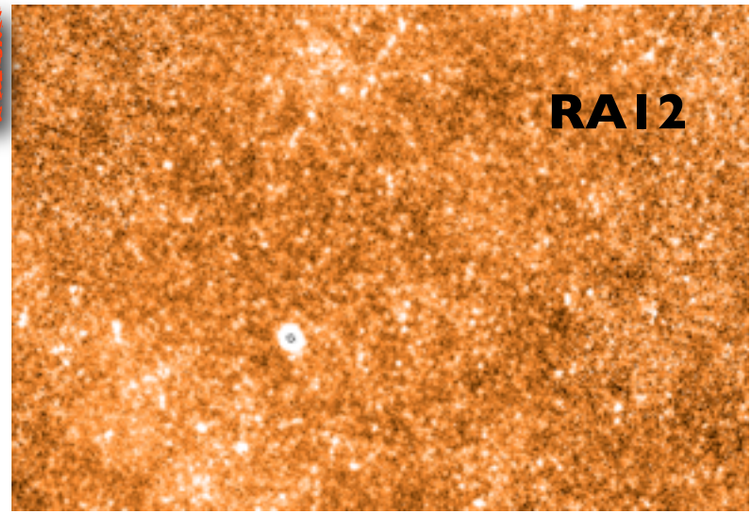
$$C_\ell^{\kappa I} = \int \frac{dz H(z)}{\eta^2(z)} W^{\kappa}(z) W^{I}(z) P(k = \ell/\eta(z), z)$$



- HERSCHEL/SPIRE H-ATLAS data and POLARBEAR convergence





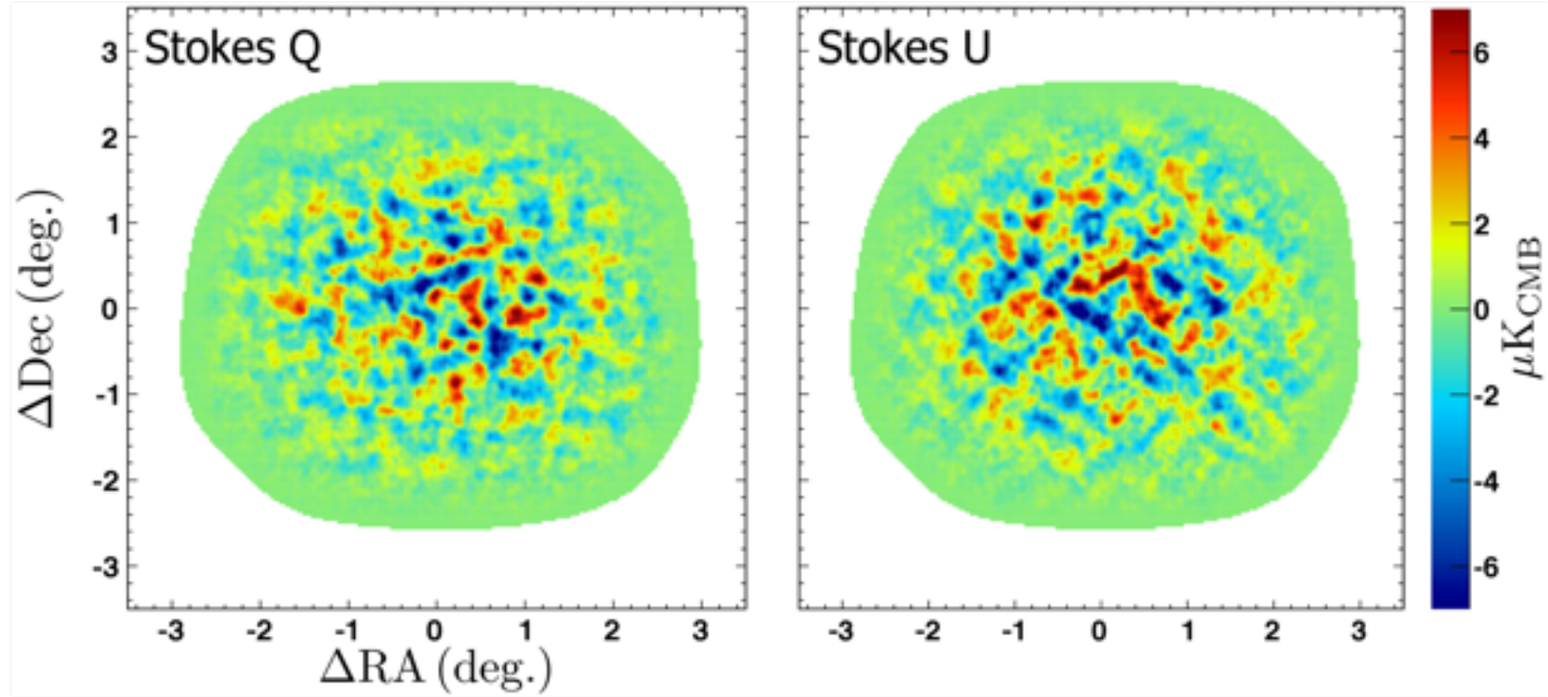


Data analysis framework

- Filtered mapmaking

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

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

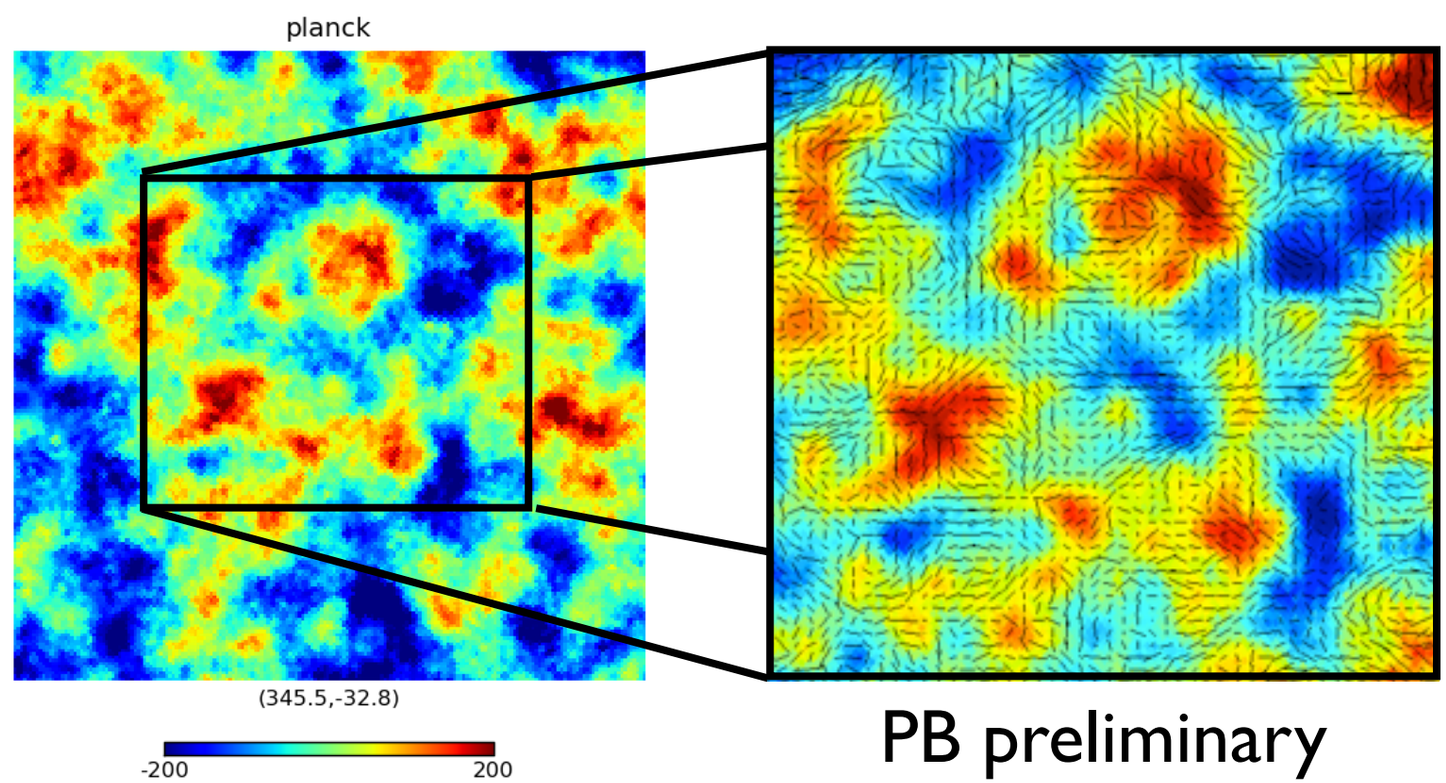


Cross check and validation

- Unbiased mapmaking

$$(A^T F^{-1} A)\hat{s}_{ith} = A^T F d$$

- Curved sky pure-pseudo power spectrum estimation with monthly cross-spectra

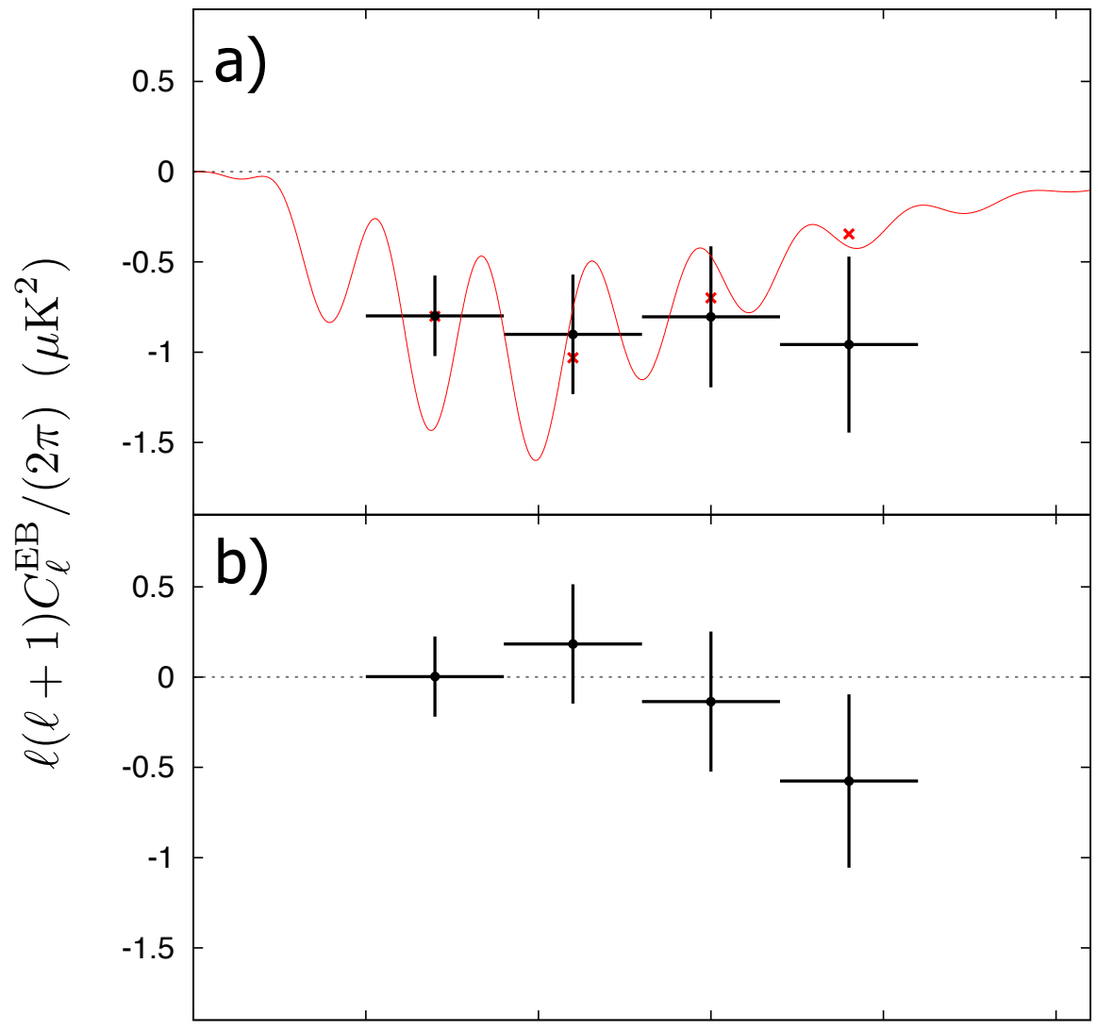


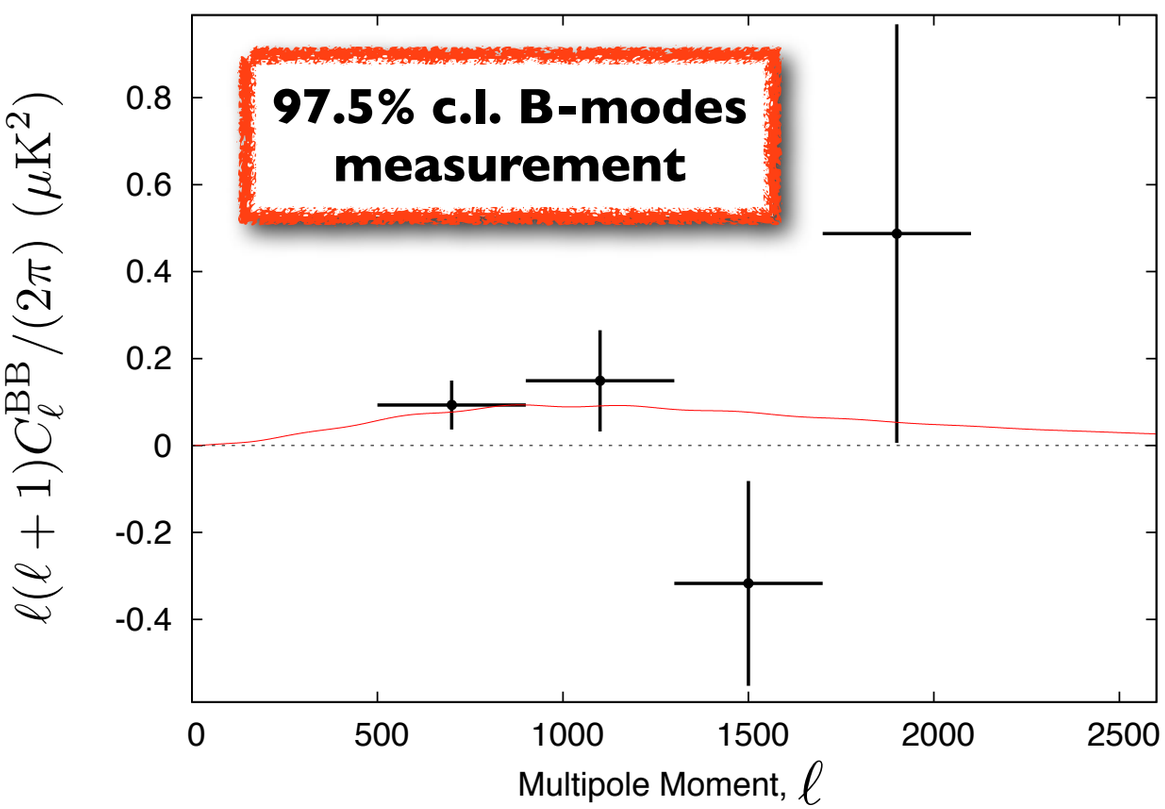
PB preliminary

Direct B-modes measurement

- Polarization angle self-calibration from detected EB power (~1deg)
- Negligible contamination from astrophysical foregrounds
- First evidence for B-modes power spectrum (ApJ, in press)

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





Foreground	Predicted power in $\ell\,(\ell+1)\,C_\ell^{BB}/2\pi$ $(10^{-4}\ \mu\mathrm{K}^2)$			
	500-900	900-1300	1300-1700	1700-2100
Galactic dust	15	9.2	6.7	5.3
Galactic synchrotron	0.7	0.5	0.5	0.4
Radio galaxies	4.9	12	22	36
Dusty galaxies	2.8	4.5	6.5	8.7
Total bias	23	26	36	50

Robustness to instrumental systematics

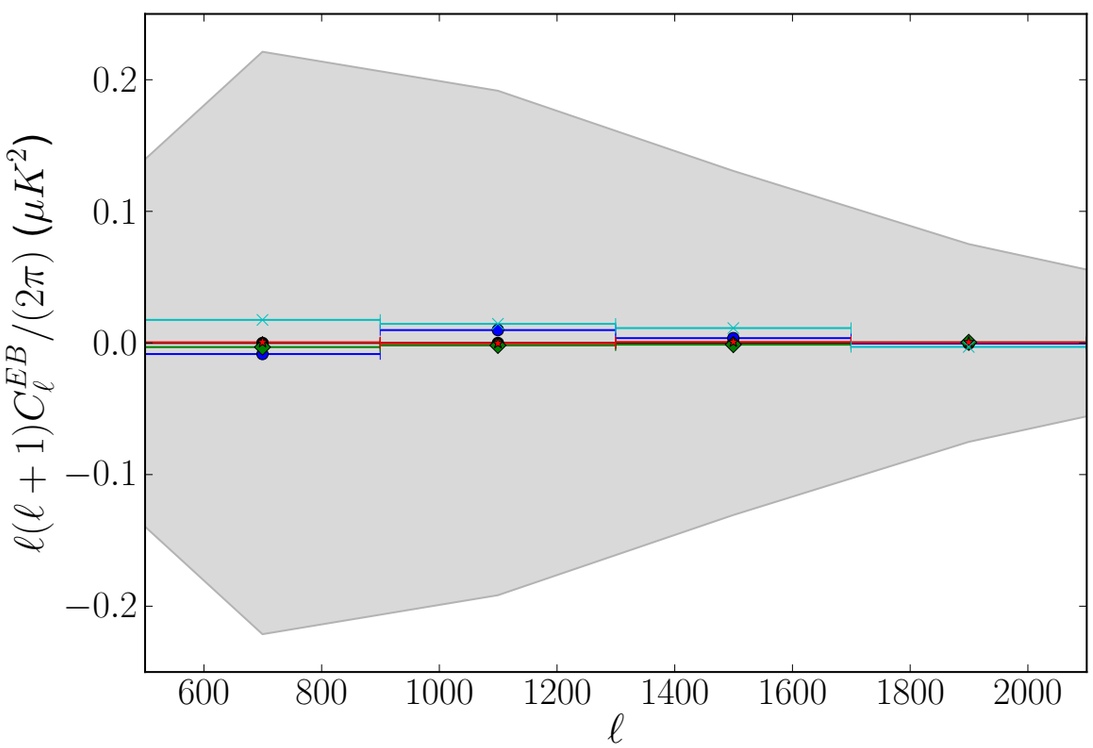
- No temperature/polarization correlation detected on map level

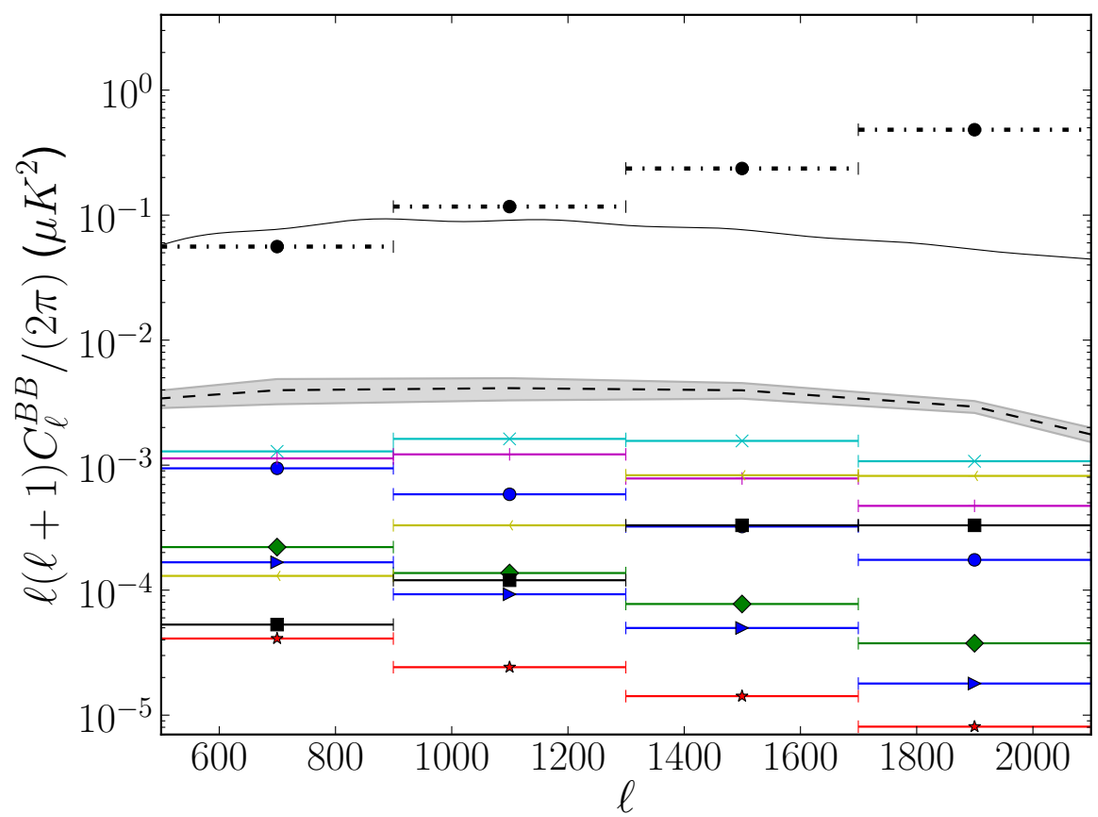
- Result robust to systematics marginalization for different type of leakages

$$d^- \approx G + \mathrm{Q}\cos(2\psi) + \mathrm{U}\cos(2\psi)$$

$$d^- \approx [\nabla_{\hat{\mathbf{n}}}\mathrm{I} \cdot \delta\hat{\mathbf{n}}] + \mathrm{Q}\cos(2\psi) + \mathrm{U}\cos(2\psi)$$

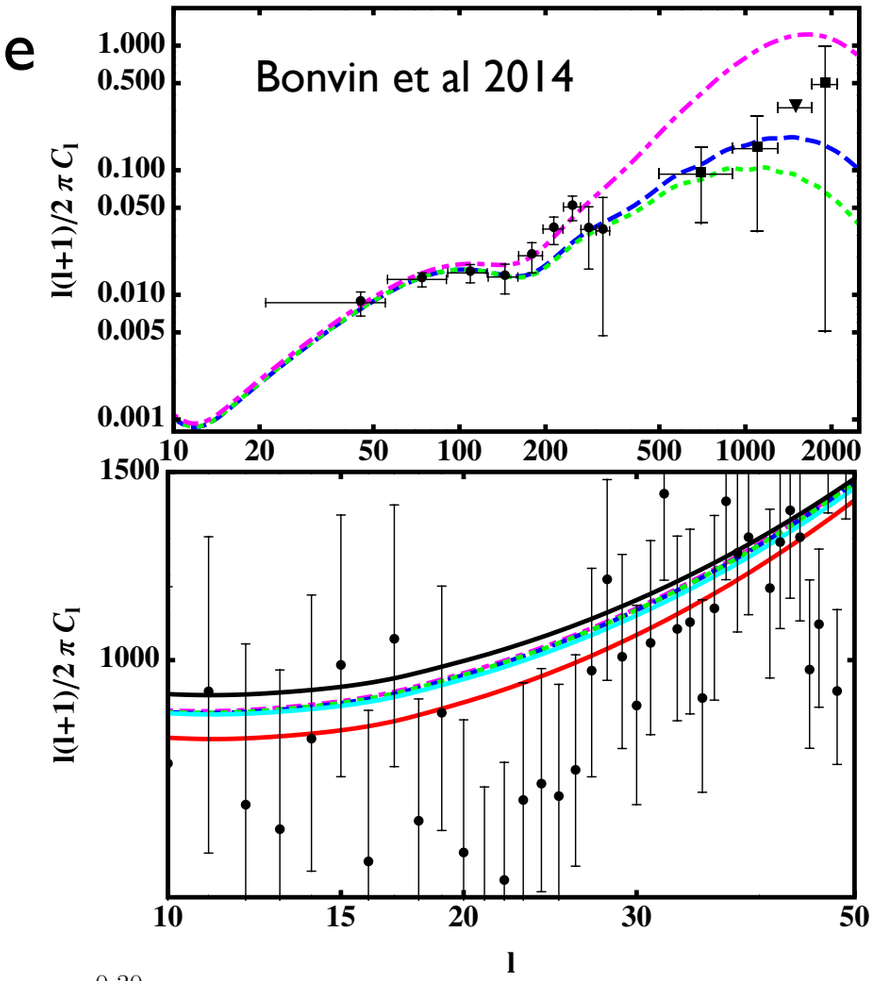
- Careful instrumental systematics uncertainties propagation: negligible!

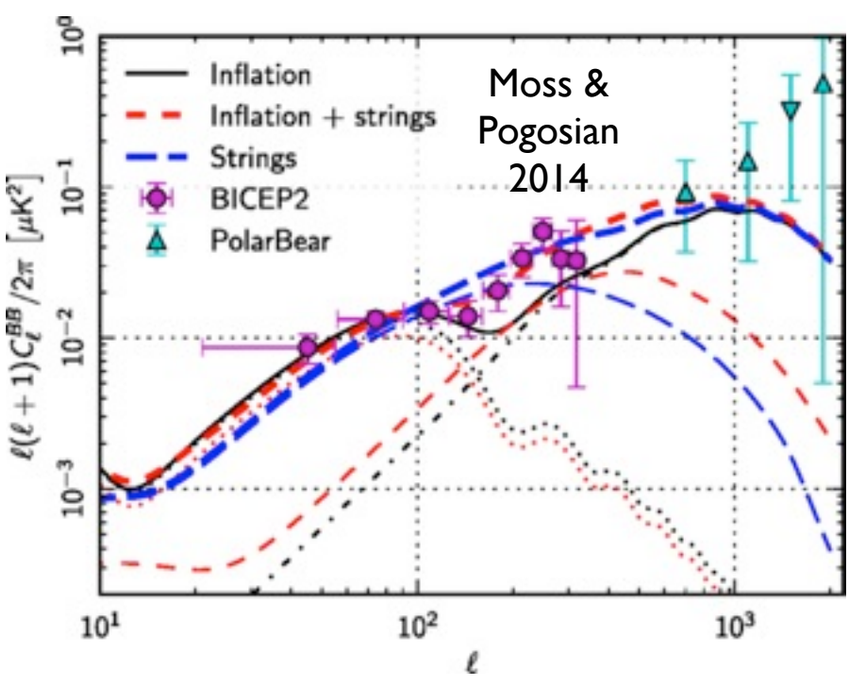


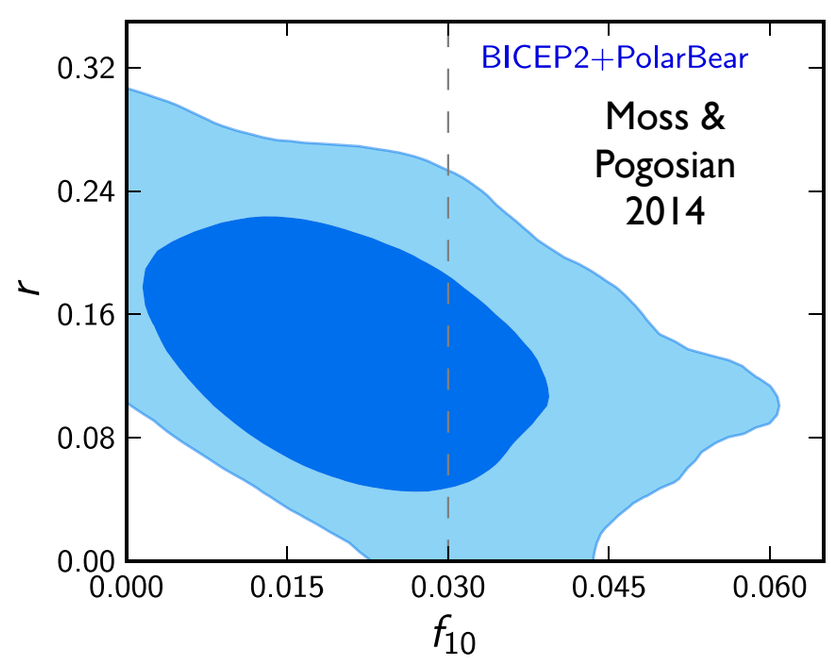


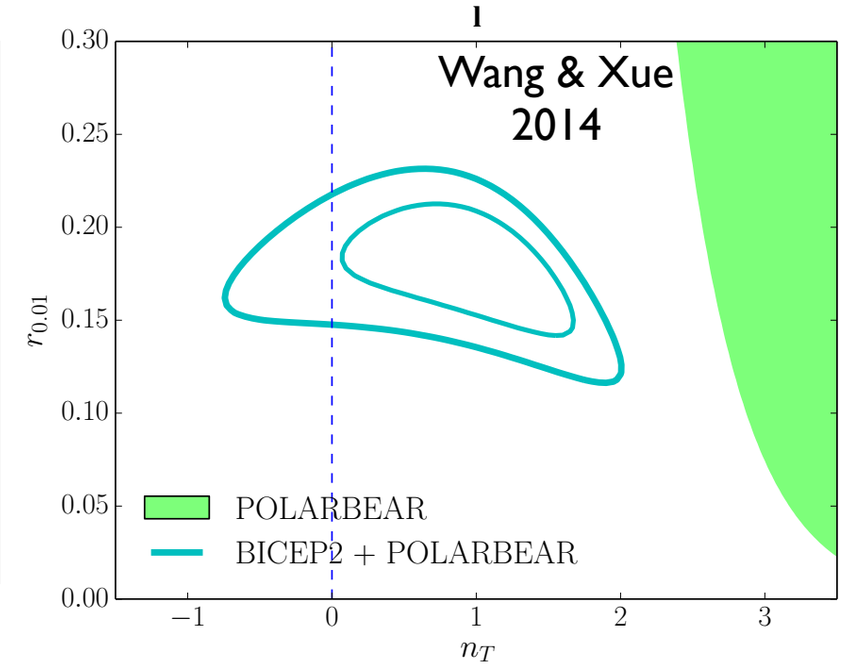
Cosmological constraints with POLARBEAR

- Constraints on inflationary magnetogensis: compatible with lower r and blue tensor spectra
- Cosmic defects / vector plus tensor modes can explain data but rule out local strings
- Alternatives to inflation can be tightly constrained:
  - string gas cosmology with blue tensor spectrum
  - slow roll or null energy condition violation etc....



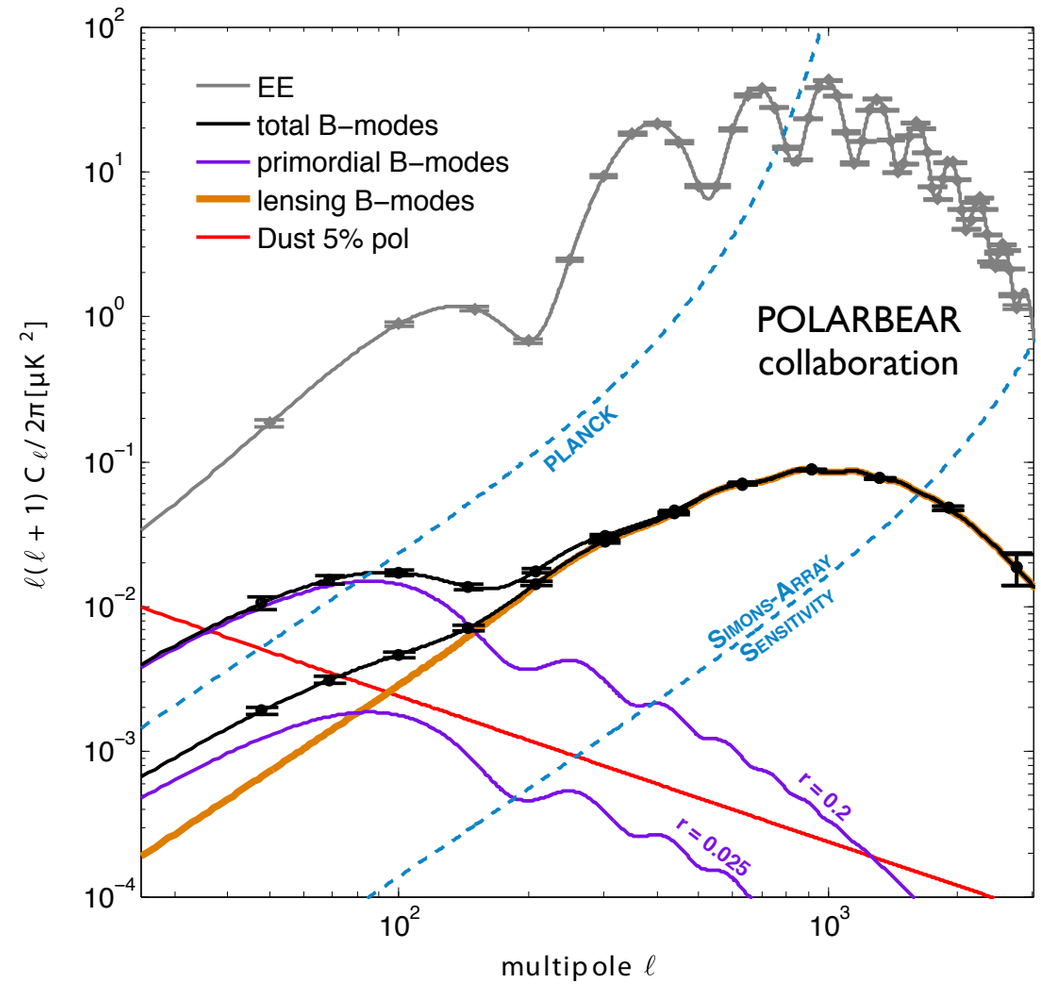






The future of the POLARBEAR experiment

- Multichroic pixels receiver in 2014: 7,588 detectors, 95/150 GHz
- Simons Array by 2018: 3 telescopes, 22,764 detectors, 95/150/220 GHz
- High sensitivity for B-modes characterization on all angular scales
- Robust foregrounds monitoring and subtraction



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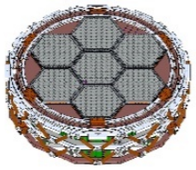

95/150

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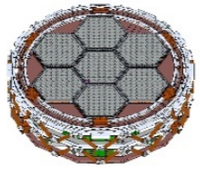
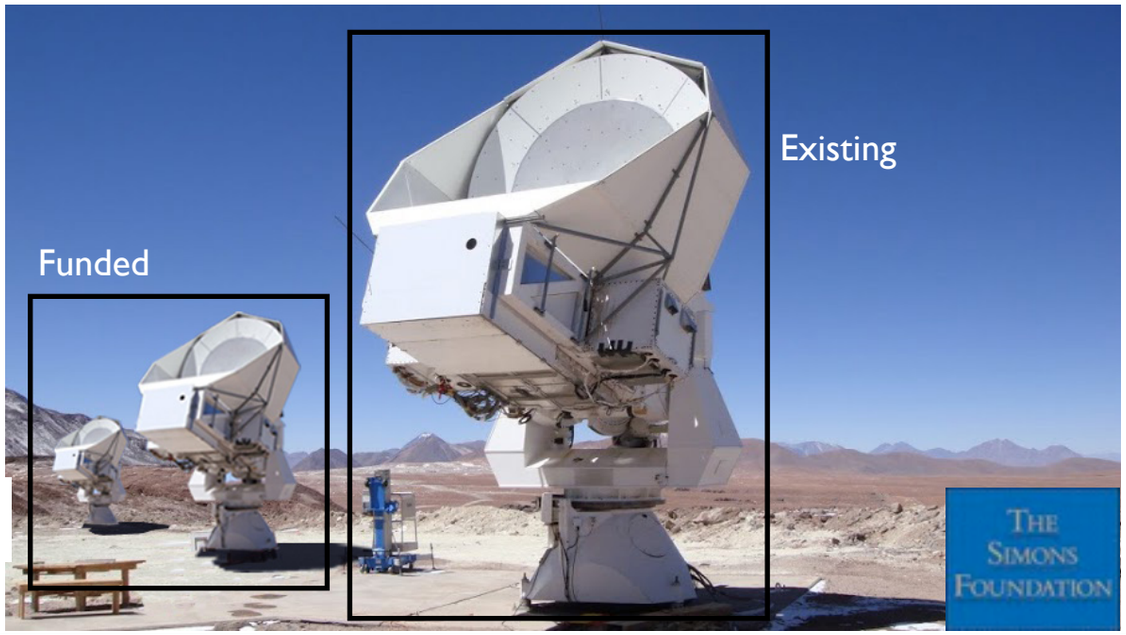
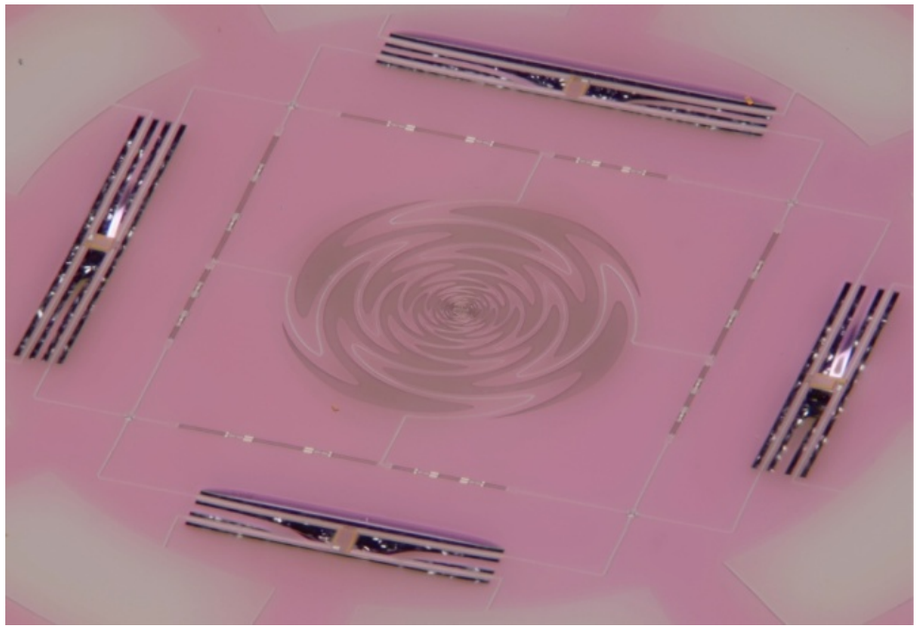


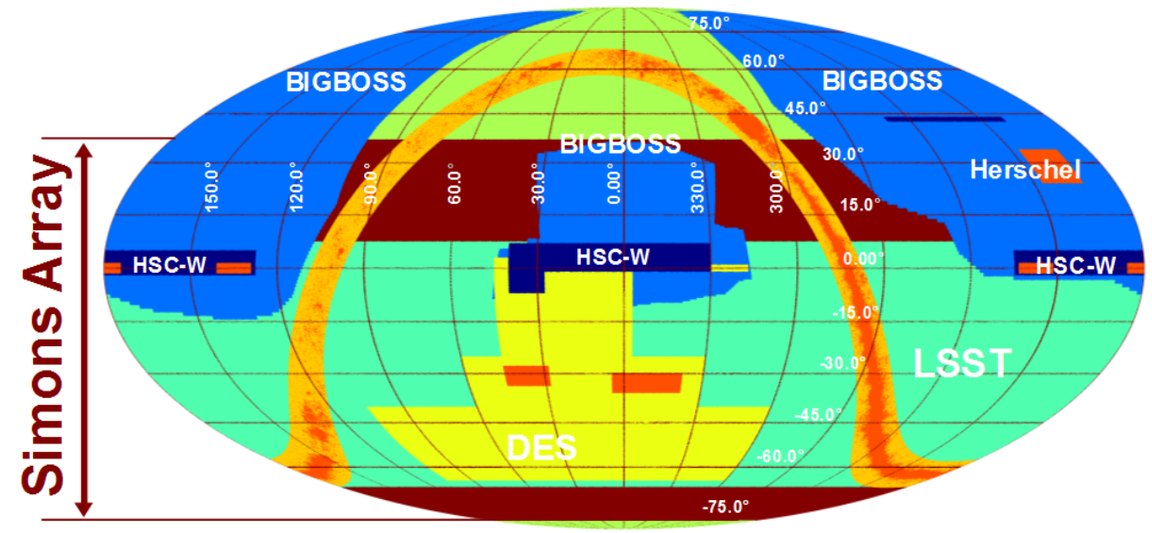
150/220



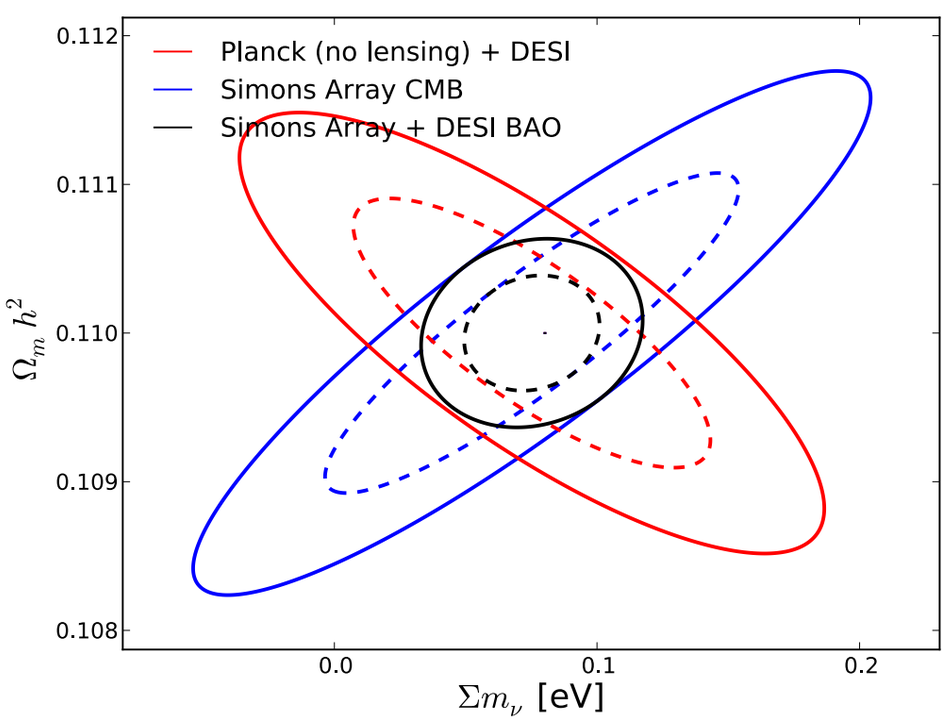


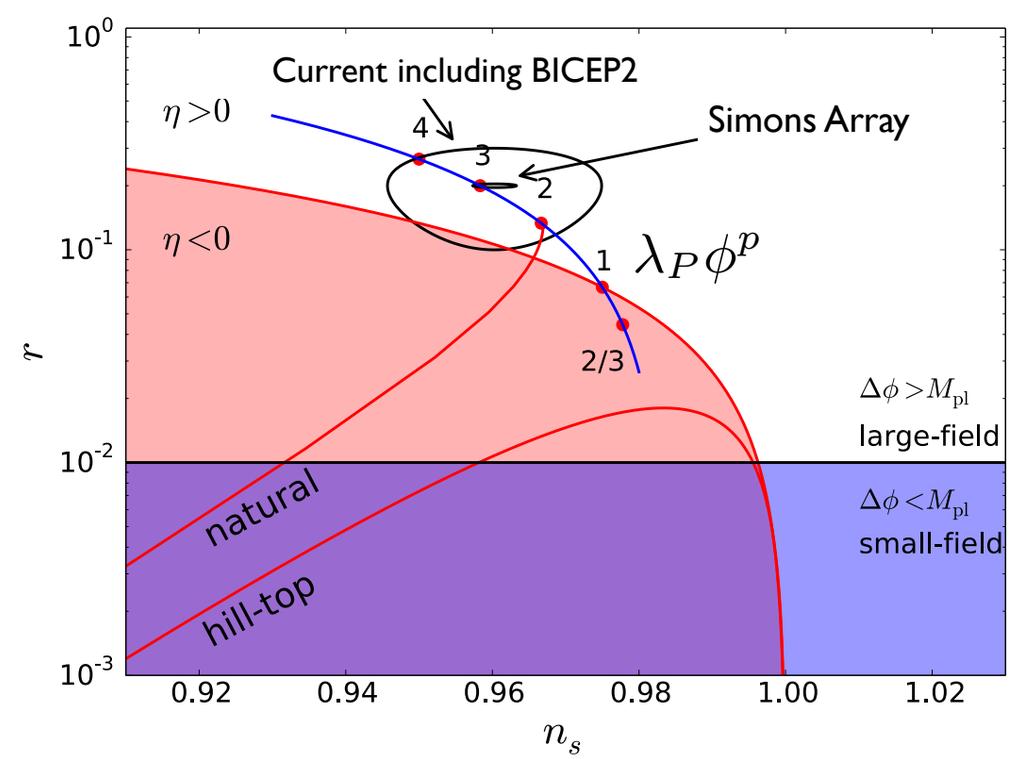
Simons array capabilities

- Large sky coverage
- Constrain neutrino mass hierarchy, mass bias properties
- Percent accuracy constraints on r and de-lensing capabilities
- Cosmic birefringence, primordial magnetic fields, dark radiation...
- Your favorite theory here!



Parameter	Planck+hi-ℓ+BAO	Simons Array+BAO
r	0.055	0.002
m_ν	0.12	0.019
N_{eff}	0.27	0.049
n_s	0.0054	0.0015





Conclusions

- POLARBEAR: first direct detection of lensing on CMB polarization validated with CIB cross-correlation (both PRL Editor's suggestions)
- Exciting March 2014: measurements of B-modes by POLARBEAR and BICEP2
- New frontier to test fundamental physics with cosmology is open!
- POLARBEAR2 and Simons Array will provide nearly cosmic-variance limited B-modes measurements
- 2nd season data analysis ongoing, more exciting results to come so....

EDITORS' SUGGESTION

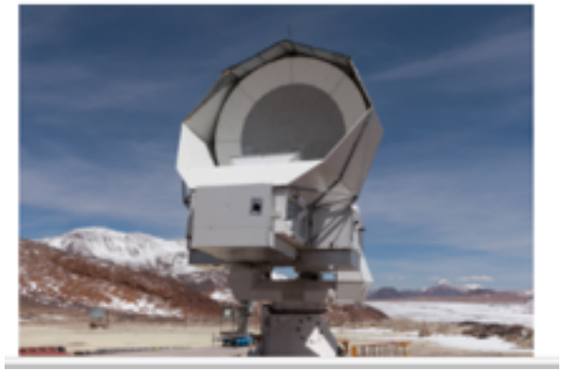
Measurement of the Cosmic Microwave Background Polarization Lensing Power Spectrum with the POLARBEAR Experiment

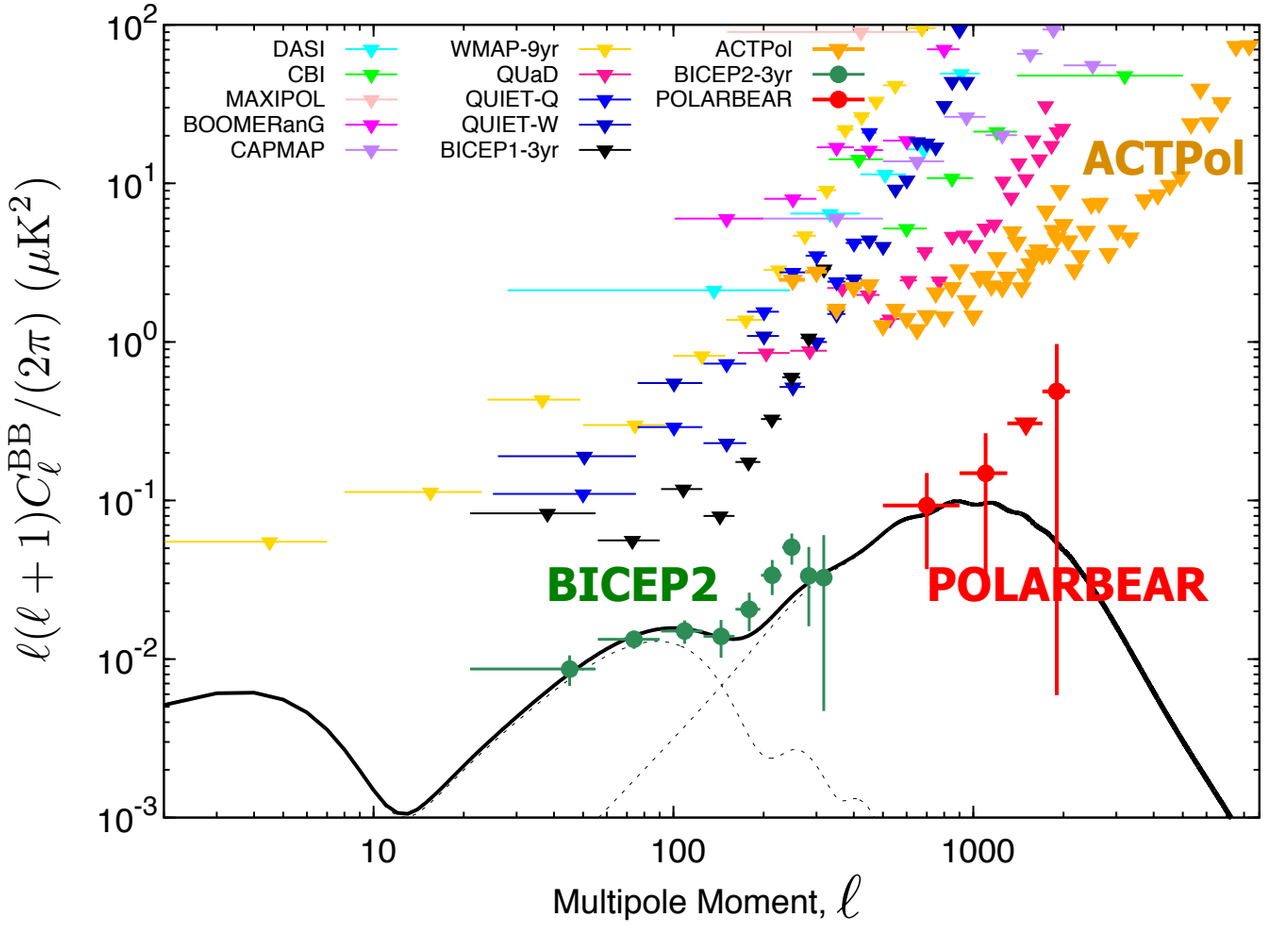
P. A. R. Ade et al. (POLARBEAR Collaboration)

EDITORS' SUGGESTION

Evidence for Gravitational Lensing of the Cosmic Microwave Background Polarization from Cross-Correlation with the Cosmic Infrared Background

P. A. R. Ade et al. (POLARBEAR Collaboration)





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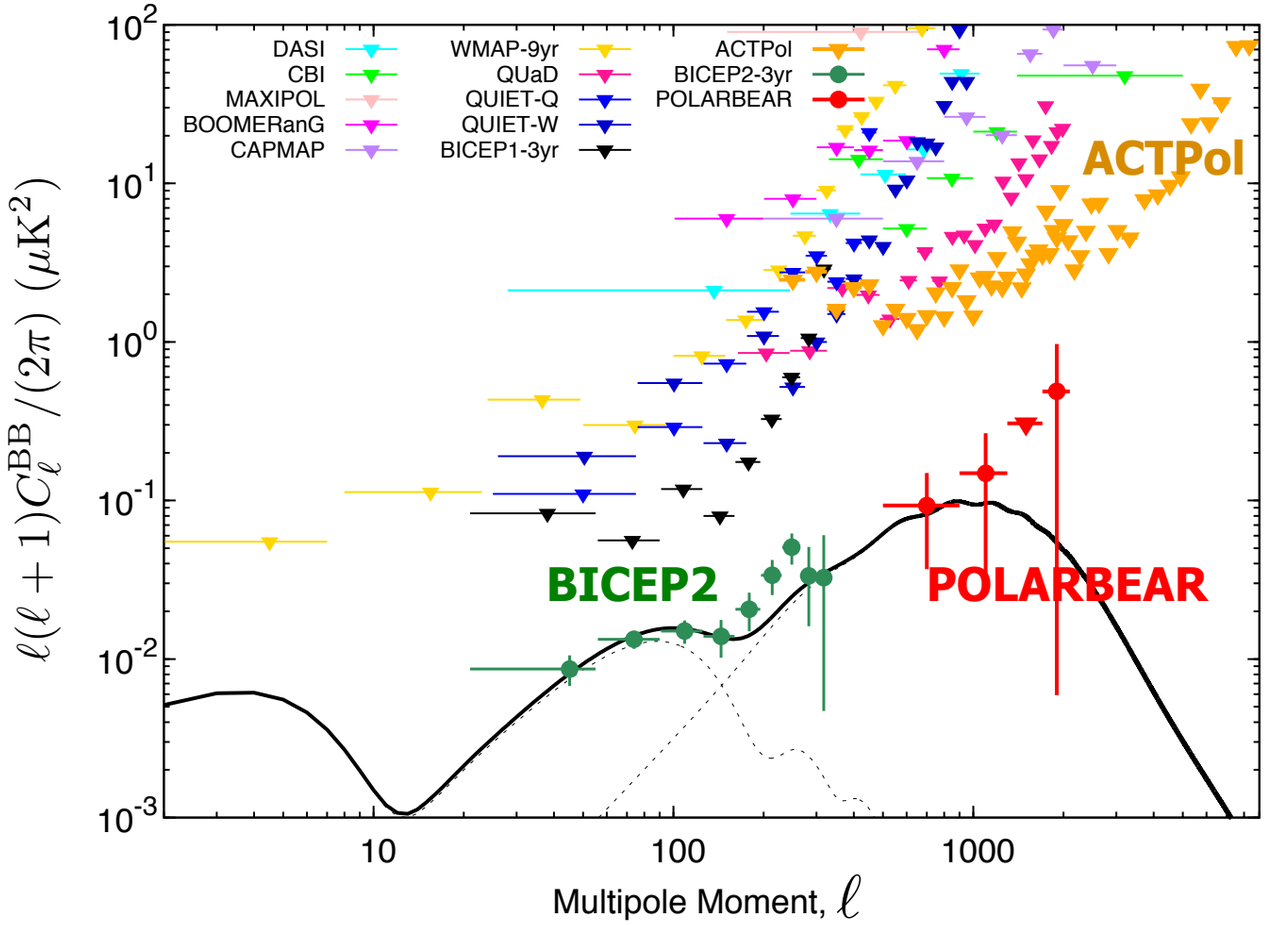


THANK
YOU
GRACIAS
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TINGKI
YAQHANYELAY
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MEHRBANI
MAAKE
KOMAPSUMNIDA
GOZAIMASHITA
EFCHARISTO
JUSPAXAR
PALDIES

Lensing and cross-correlation systematics estimate

- Lensing systematics:

Systematics	$\Delta\mathcal{A}$
Pol. point sources	±0.08 (±0.14)
0.5% T→{Q,U}	±0.10 (±0.13)
Beam uncert.	$^{+0.19}_{-0.16}$
Calibration	$^{+0.22}_{-0.18}$
Total	±0.13 ($^{+0.32}_{-0.27}$)

- Cross-correlation is insensitive to systematics

- Robust to polarized PS masking of ATCA catalogue (0.2σ difference)

- 1% T leakage, 10% QU leakage do not bias the estimate at 1% level

- Beams and pol. angle systematics change significance of 0.2σ level

- Curl and swap-field null tests with excellent PTEs (>50%)