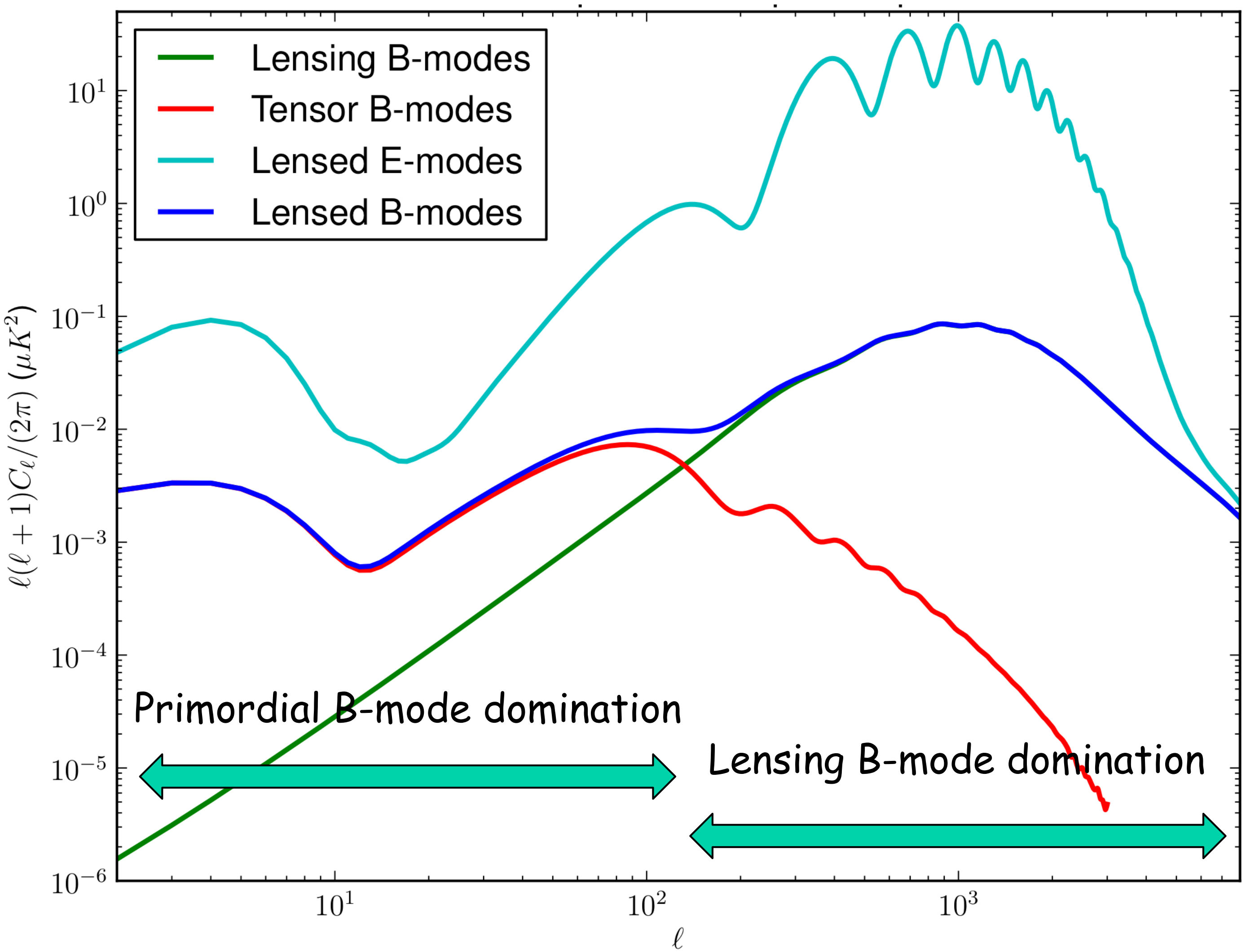
CMB B-mode polarization on small angular scales

Radek Stompor (APC)

CMB polarization

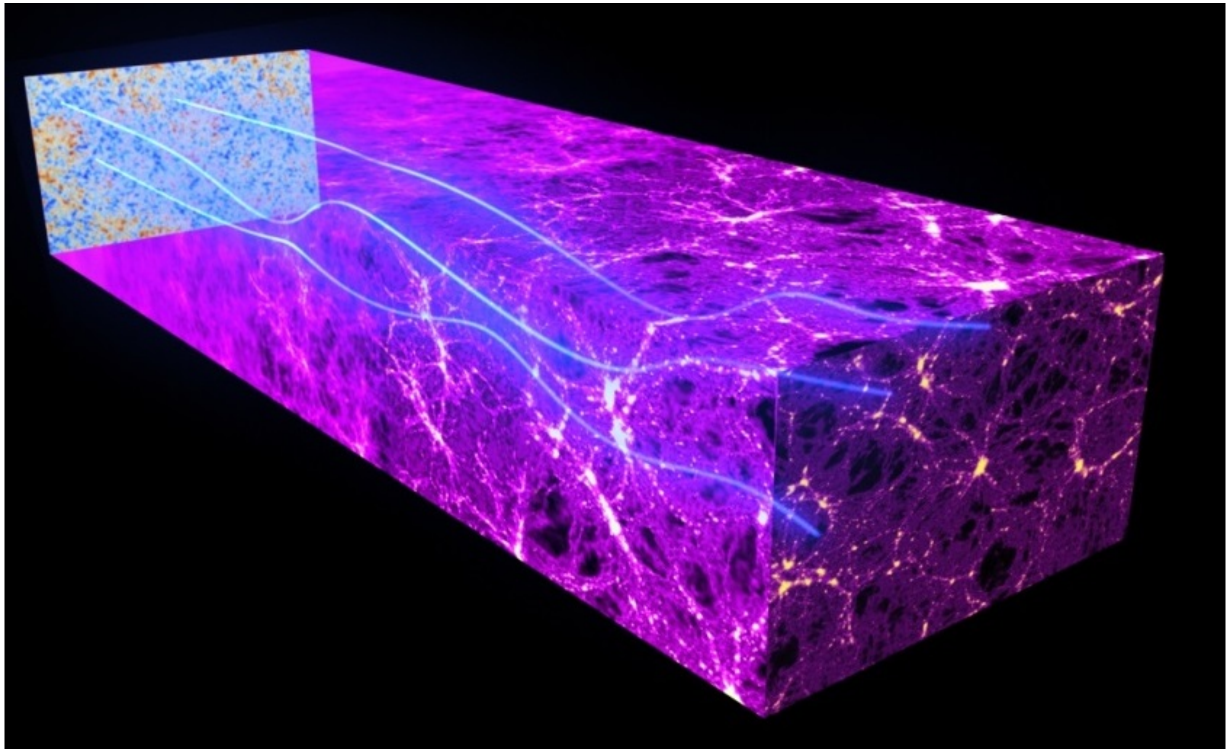


Gravitational lensing of the CMB

Lensing effect (Hu 2000):

$$\tilde{X}(\mathbf{n}) = X(\mathbf{n}+\mathbf{d})$$

$$X = T, Q, U$$



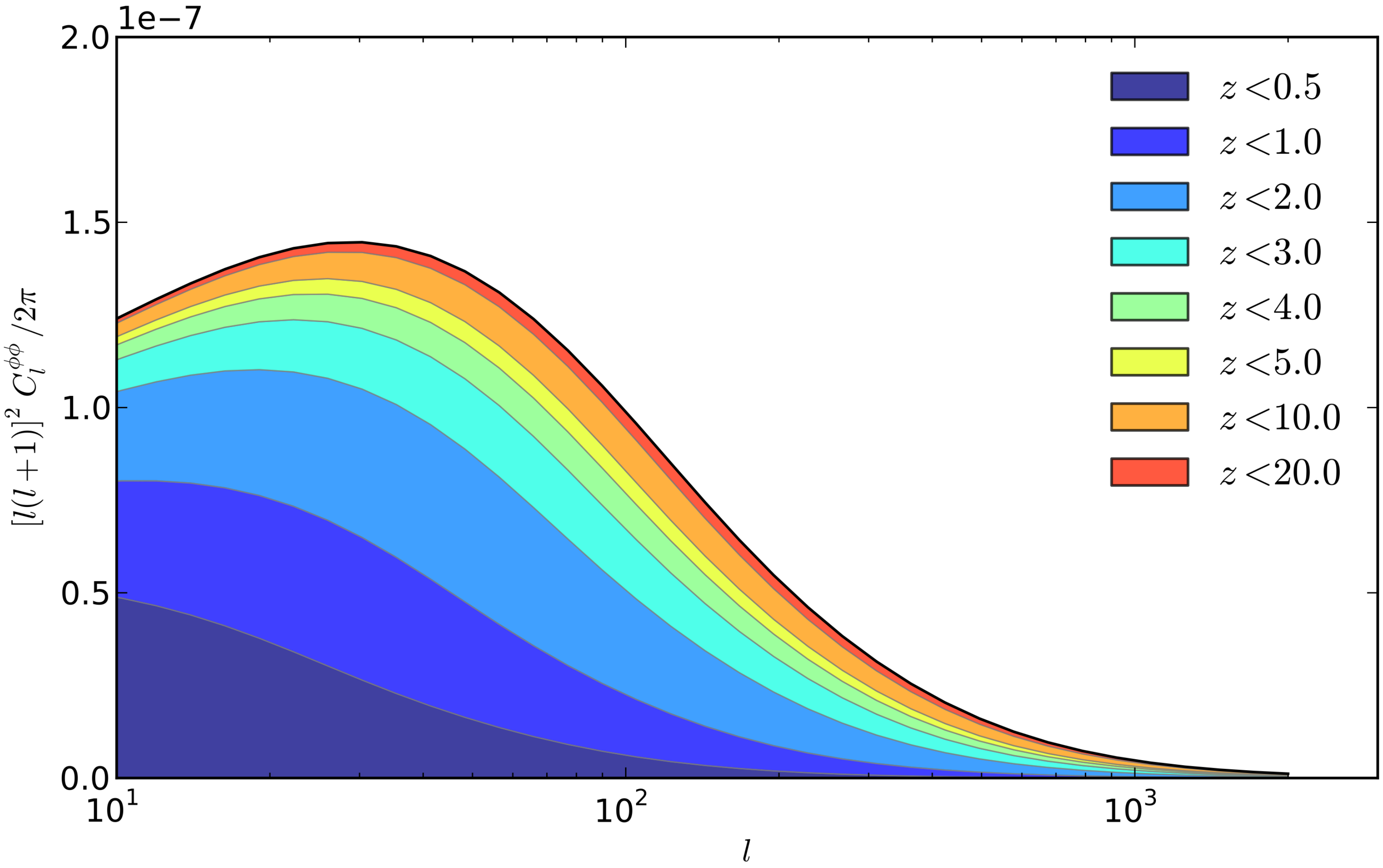
Displacement field:

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

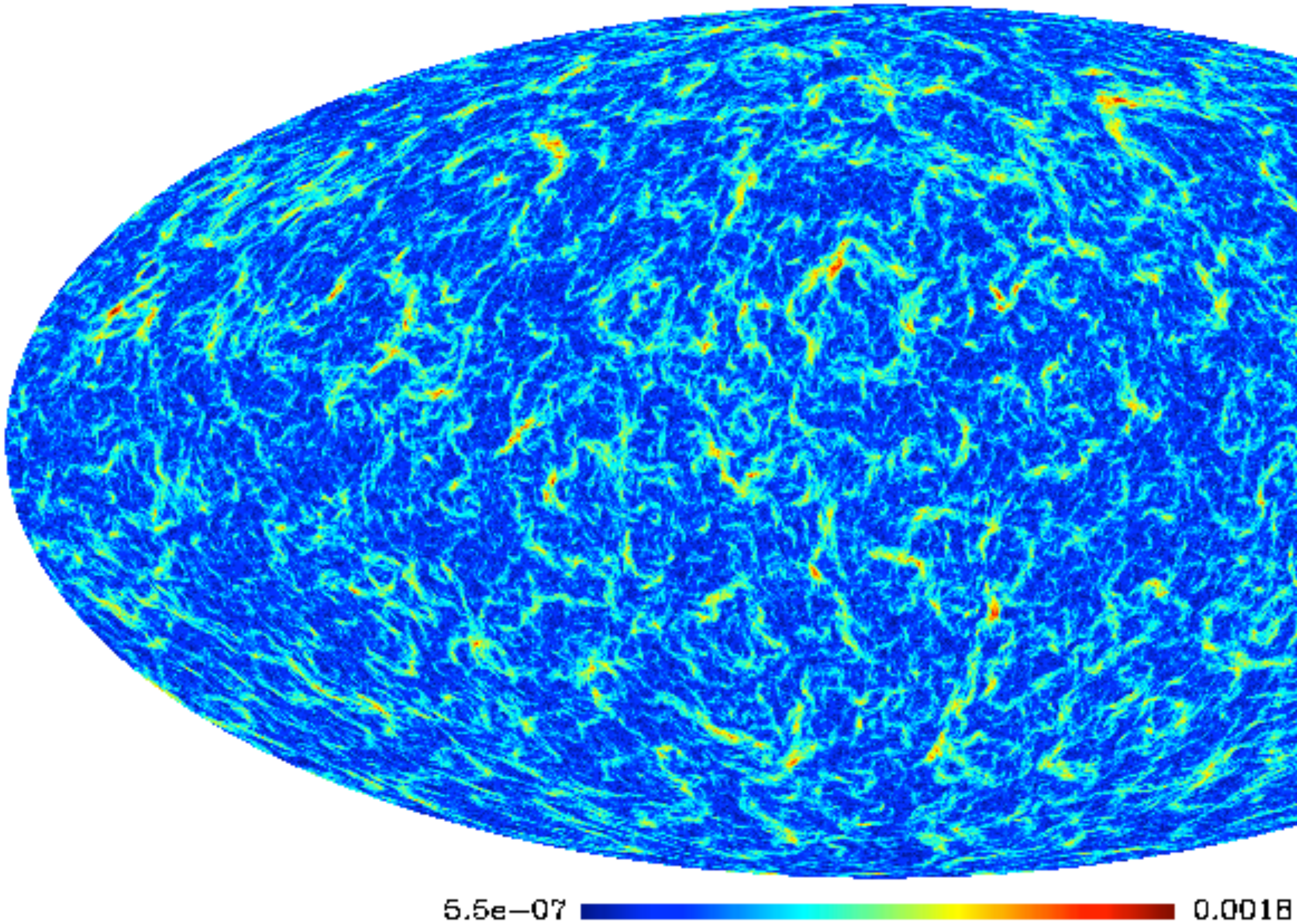
Lensing potential:

$$\Phi(\mathbf{n}) = -2 \int_0^{\eta_{LSS}} d\eta \frac{d_A(\eta - \eta_{LSS})}{d_A(\eta) - d_A(\eta_{LSS})} \Psi(\mathbf{n}, \eta)$$

Lensing potential

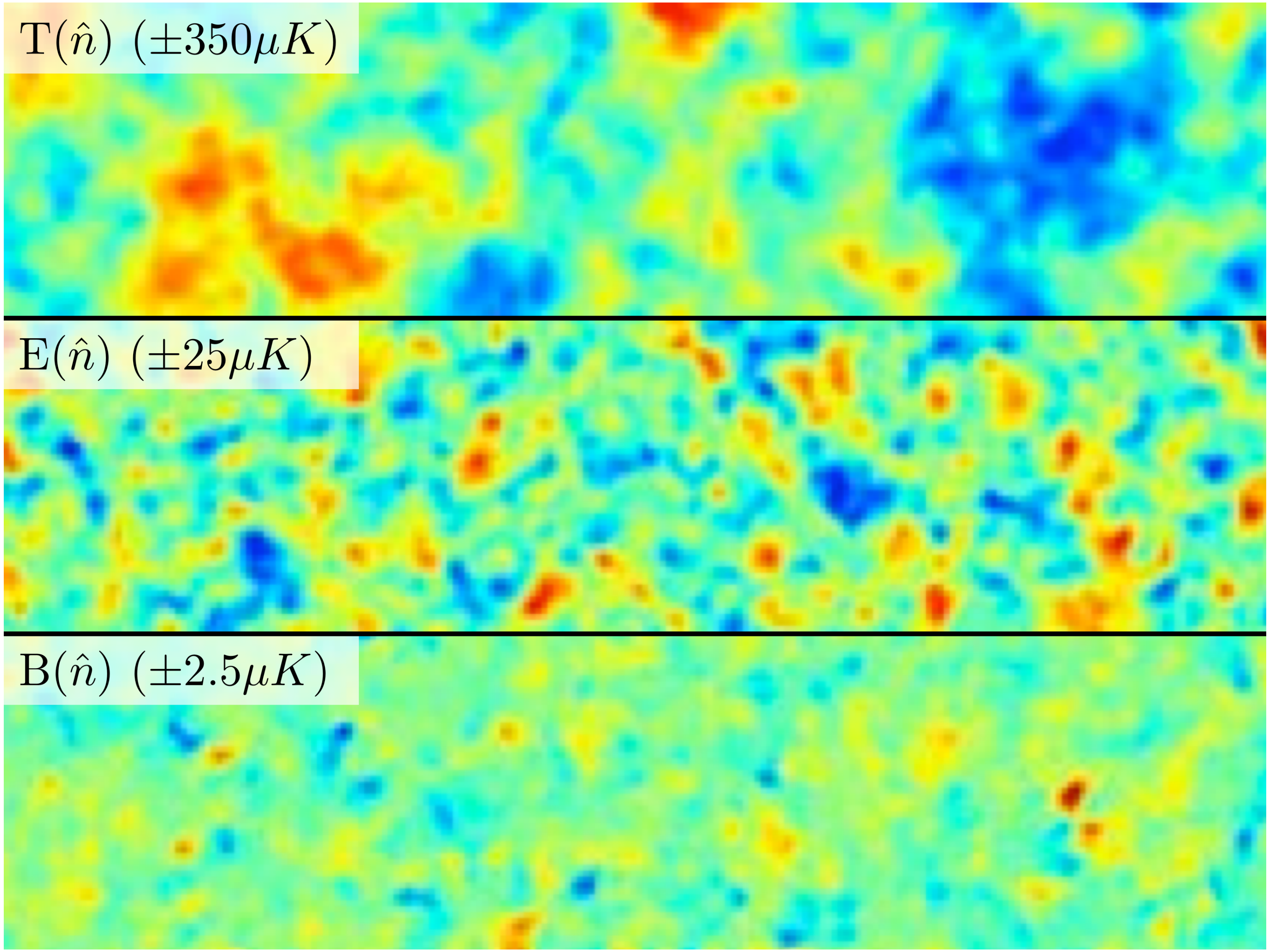


Displacement field



6 arcmin !

Lensing in action



Credit: D. Hanson (McGill)

Gravitational lensing of the CMB – the E-modes

Lensing effect to 1st order (Hu 2000):

$$\tilde{X}(\mathbf{n}) = X(\mathbf{n}+\mathbf{d}) \simeq X(\mathbf{n}) + \nabla X(\mathbf{n}) \nabla \Phi$$

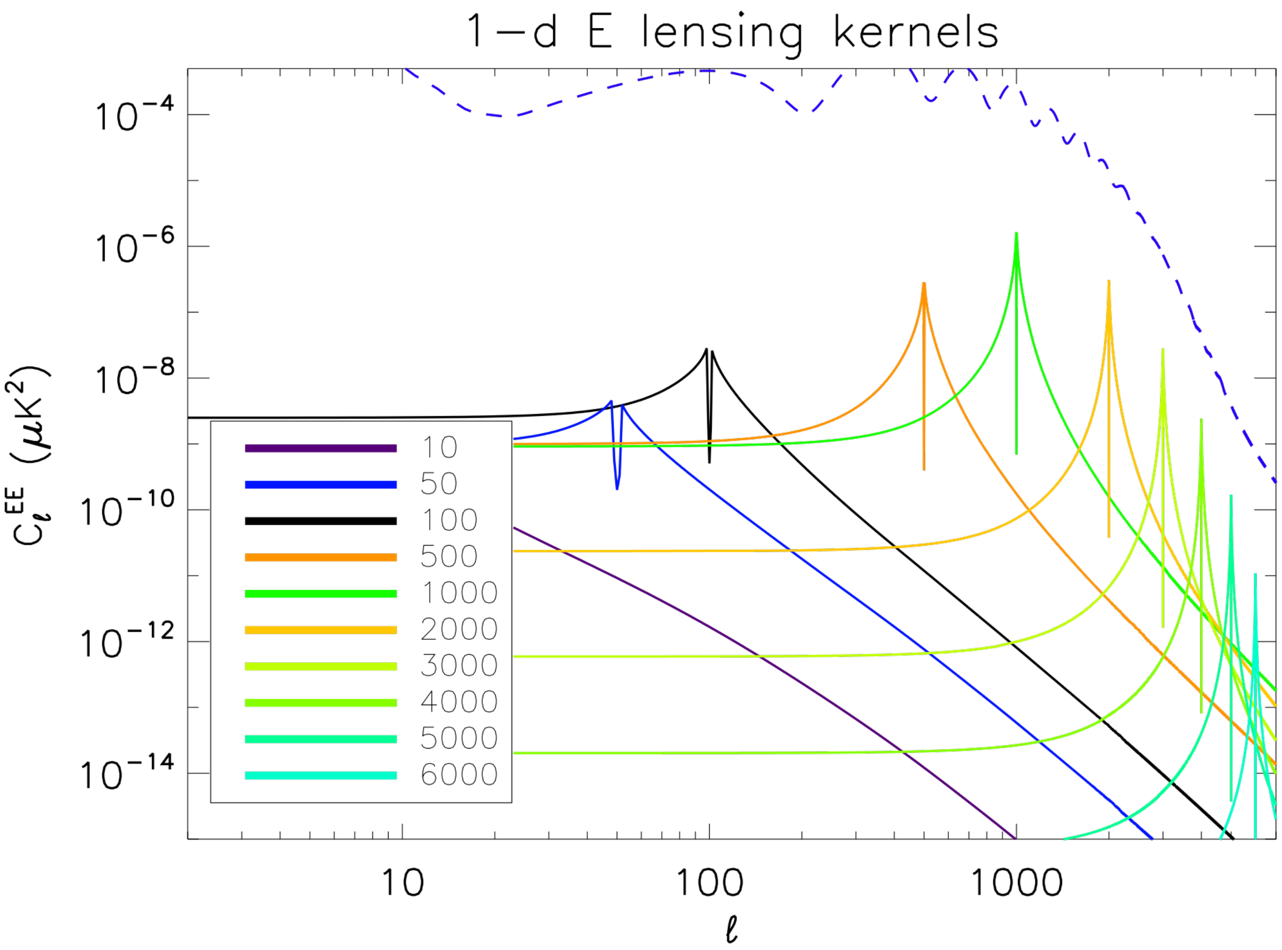
$$X = T, Q, U$$

In harmonic domain:

$$\tilde{C}^{EE}_{\tilde{\ell}_E} = \left[1 - (\tilde{\ell}^2_E + \tilde{\ell}_E - 4)R\right] C^{EE}_{\ell} + $$
$$+ \frac{1}{2} \sum_{\ell_\Phi, \ell_E} \frac{\left|{}_2F_{\tilde{\ell}_E\, \ell_\Phi\, \ell_E}\right|^2}{2\tilde{\ell}_E + 1} \left(1 - (-1)^L\right) C^{\Phi\Phi}_{\ell_\Phi} C^{EE}_{\ell_E}$$

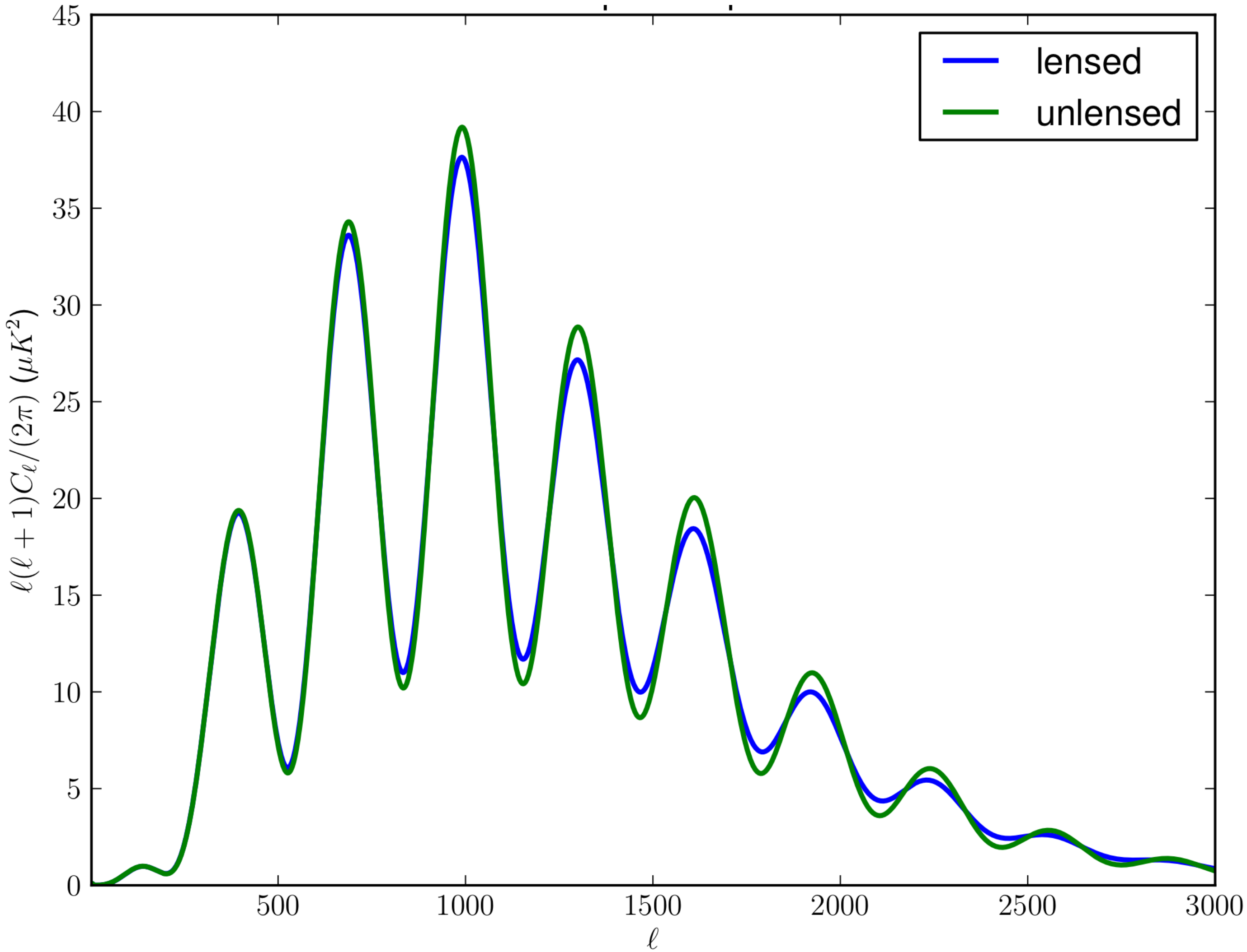
$$L = \tilde{\ell}_E + \ell_\Phi + \ell_E$$

E-mode lensing



Fabbian, Stompor (2013)

E-modes lensing



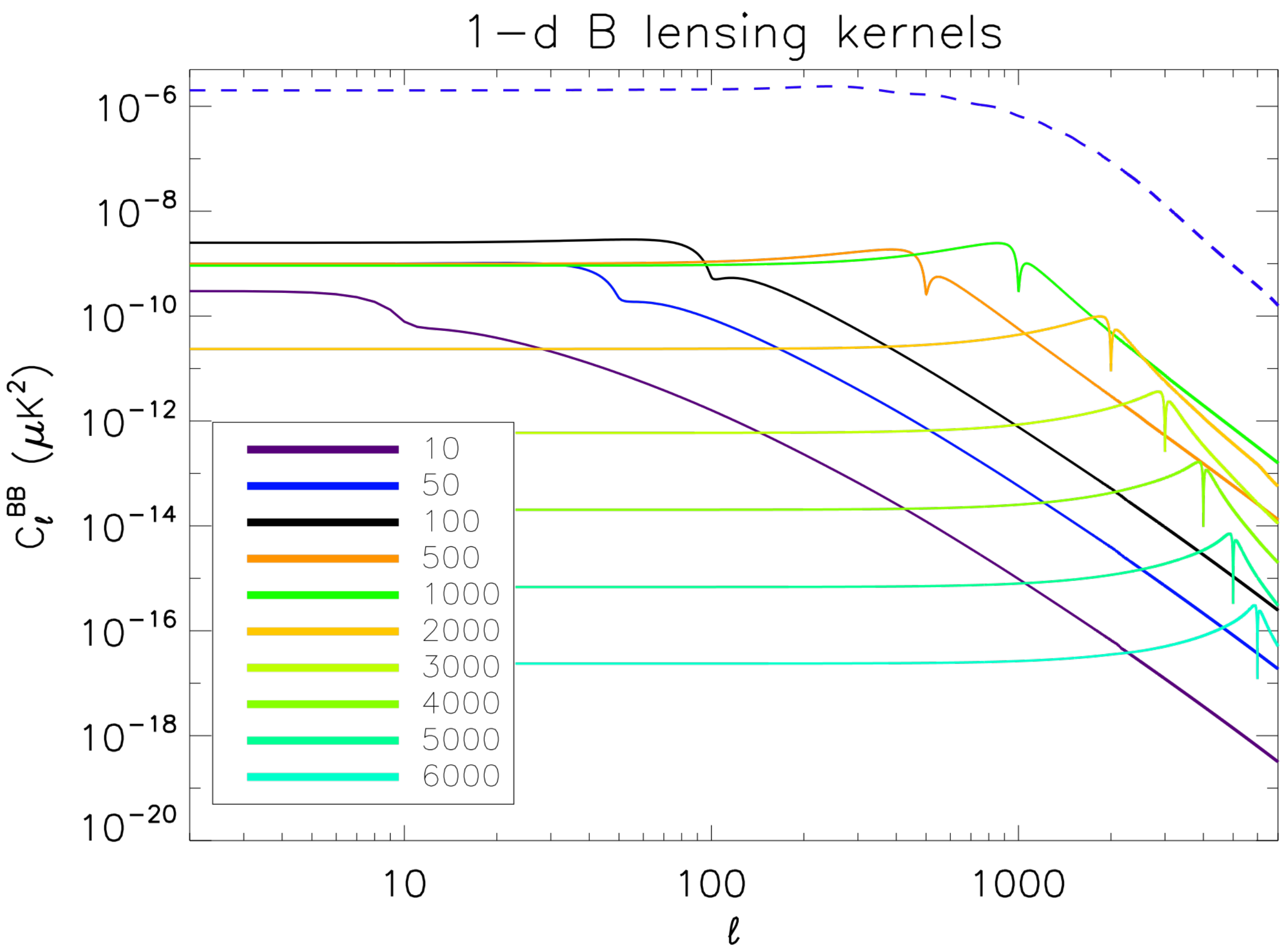
Gravitational lensing of the CMB – the B-modes

In harmonic domain (Zaldarriaga, Seljak 1998, Hu 2000):

$$\tilde{C}^{BB}_{\tilde{\ell}_B} = \frac{1}{2} \sum_{\ell_\Phi, \ell_E} \frac{\left| {}_2F_{\tilde{\ell}_B\, \ell_\Phi\, \ell_E} \right|^2}{2\tilde{\ell}_B + 1} \left(1 - (-1)^L\right) C^{\Phi\Phi}_{\ell_\Phi} C^{EE}_{\ell_E}$$

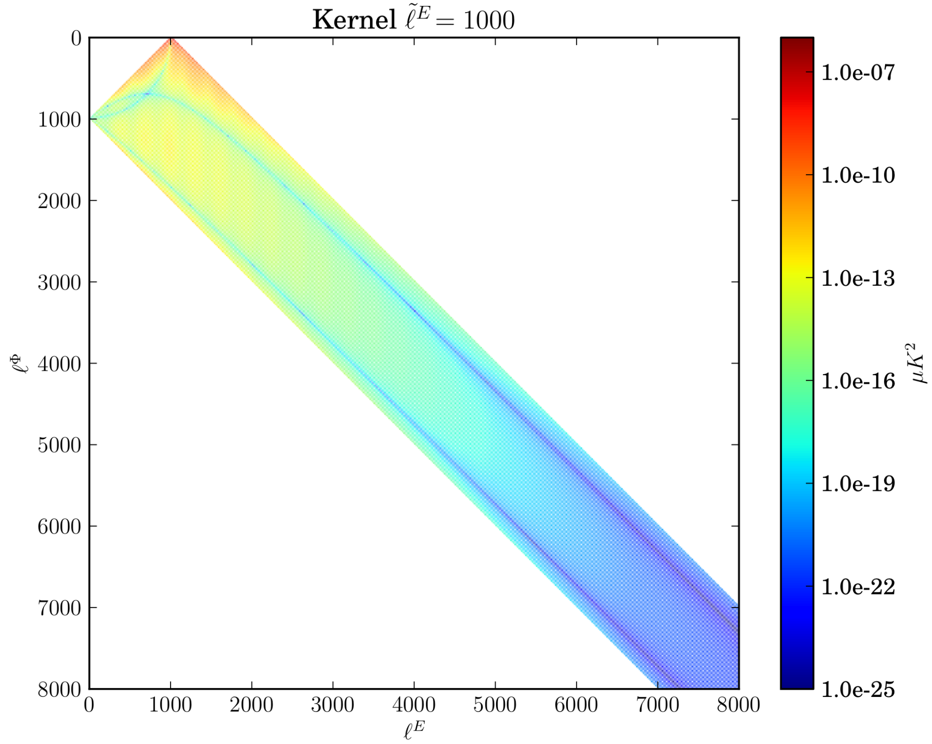
$$L = \tilde{\ell}_B + \ell_\Phi + \ell_E$$

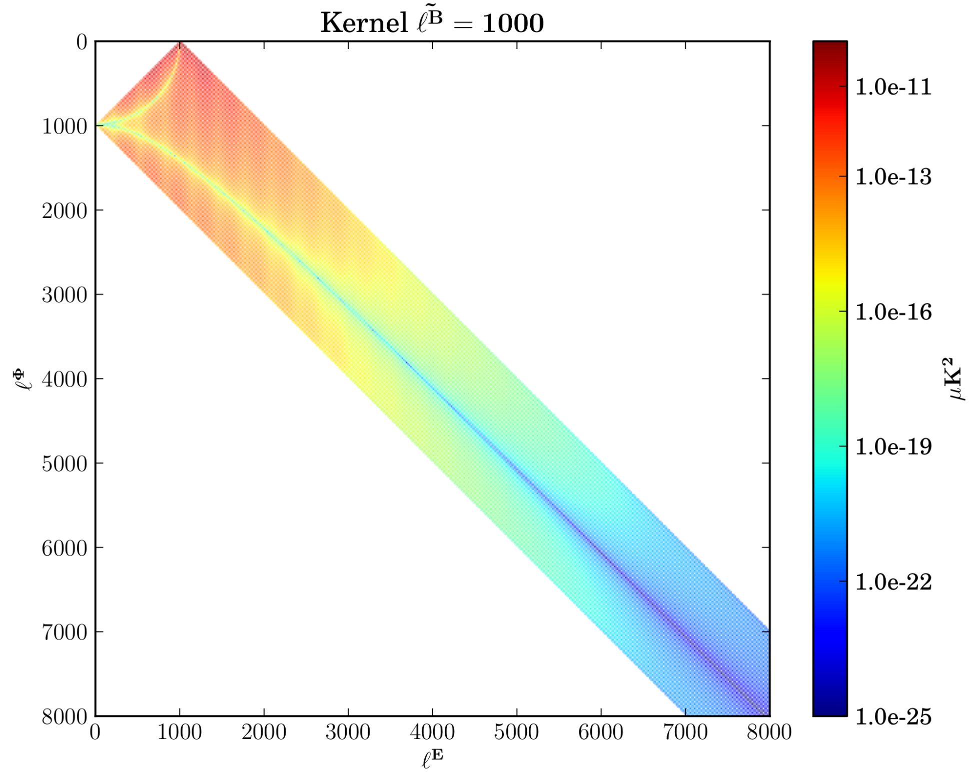
B-mode lensing kernel



Fabbian, Stompor (2013)

E vs B-mode lensing kernels – 2D perspective





Fabbian, Stompor (2013)

Quick recap

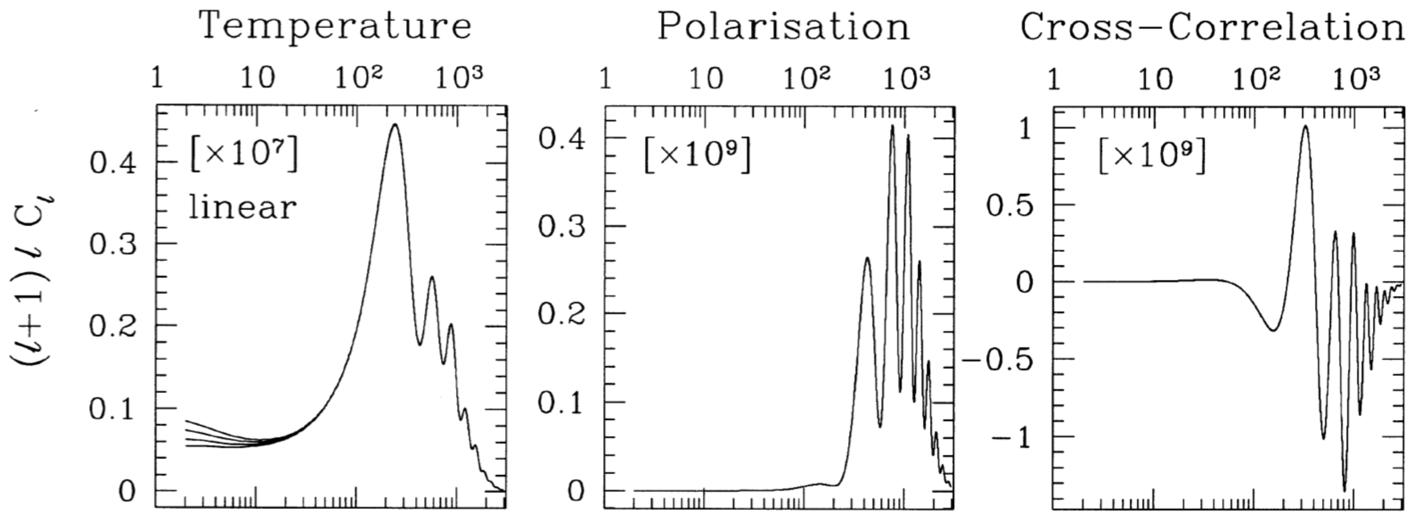
CMB lensing is bound to be there (detected in TT: Planck, SPT, ACT);

Theoretically well understood (within GR) (Hu, Okamoto, Challinor, Lewis, …);

Simulation tools are available (Lewis 2005, Basak et al 2010, Lavaux, Wandelt 2012, Fabbian, Stompor 2013, Louis et al 2013) but need some care in the case of B-modes.

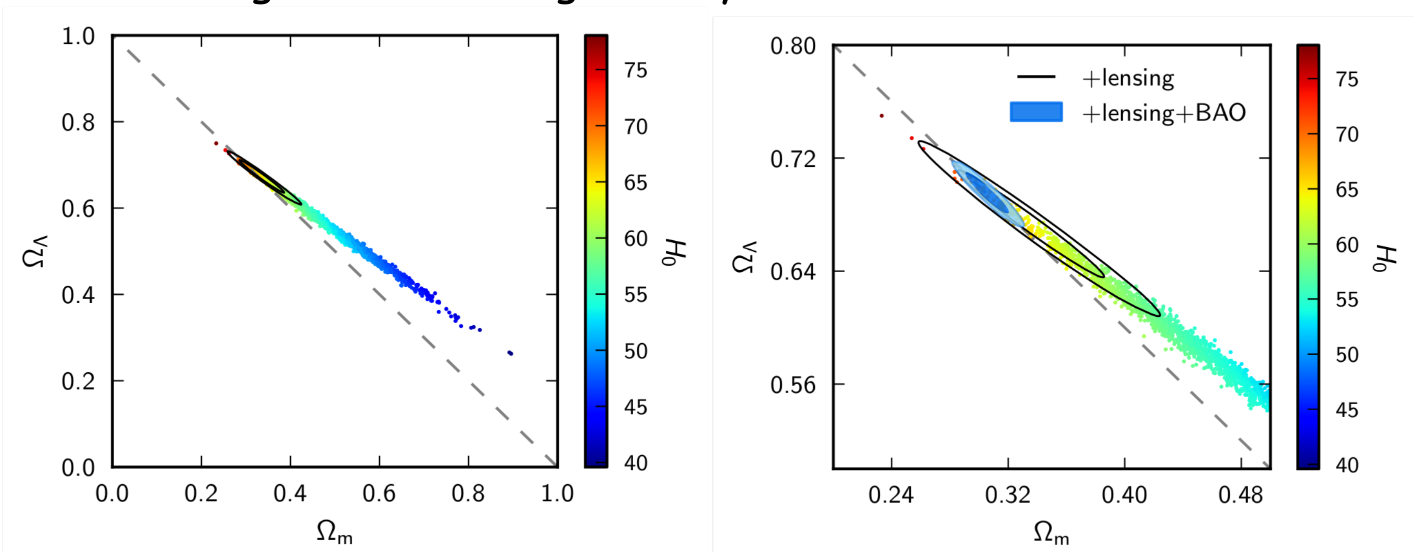
BUT CMB lensing is more than merely a consistency test !

What lensing T/E-modes are good for …



Stompor, Efstathiou 1999

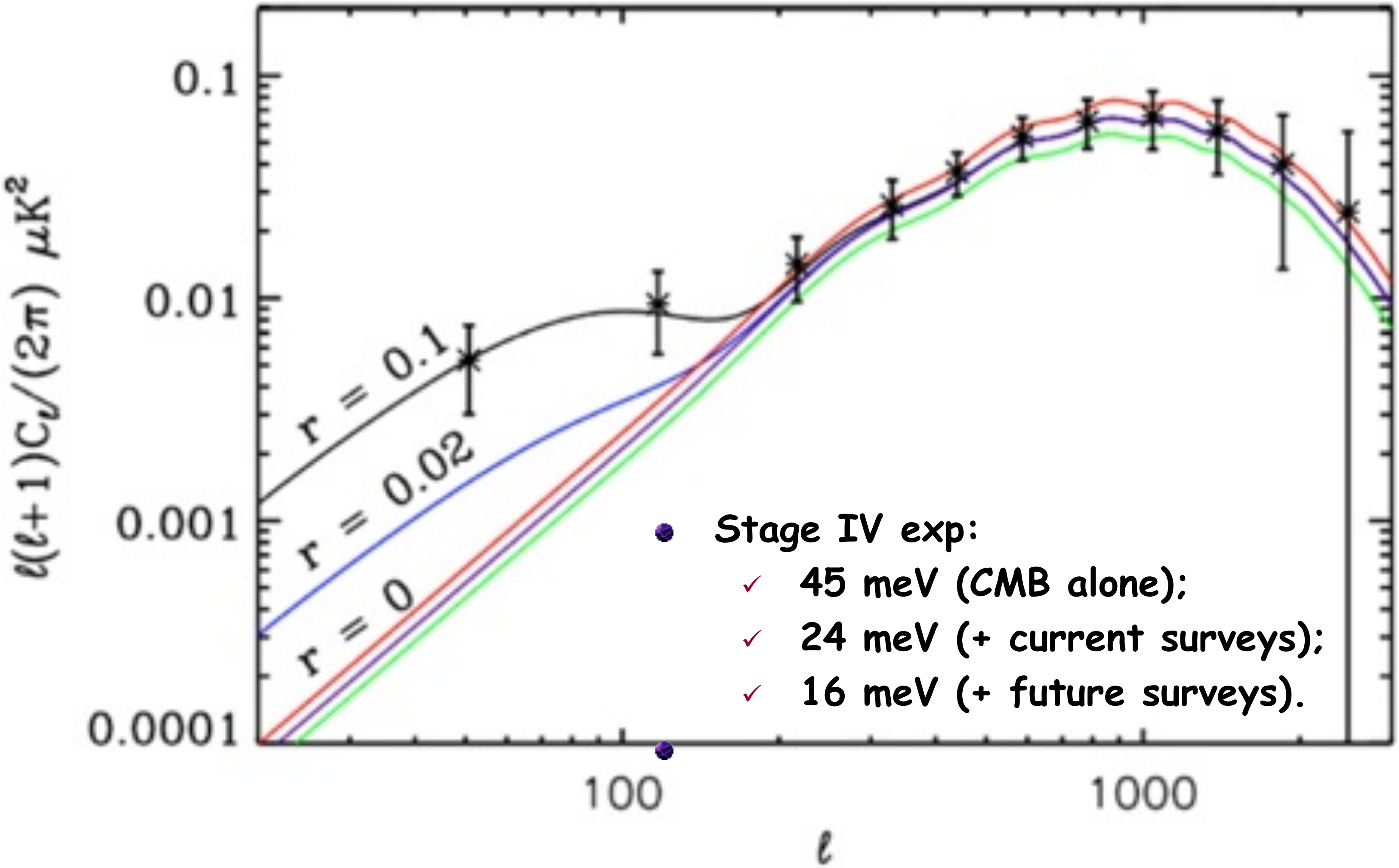
- breaks geometrical degeneracy



The Planck collaboration (2013)
arXiv:1303.7076

What lensing B-modes are good for …

- Neutrinos total mass:

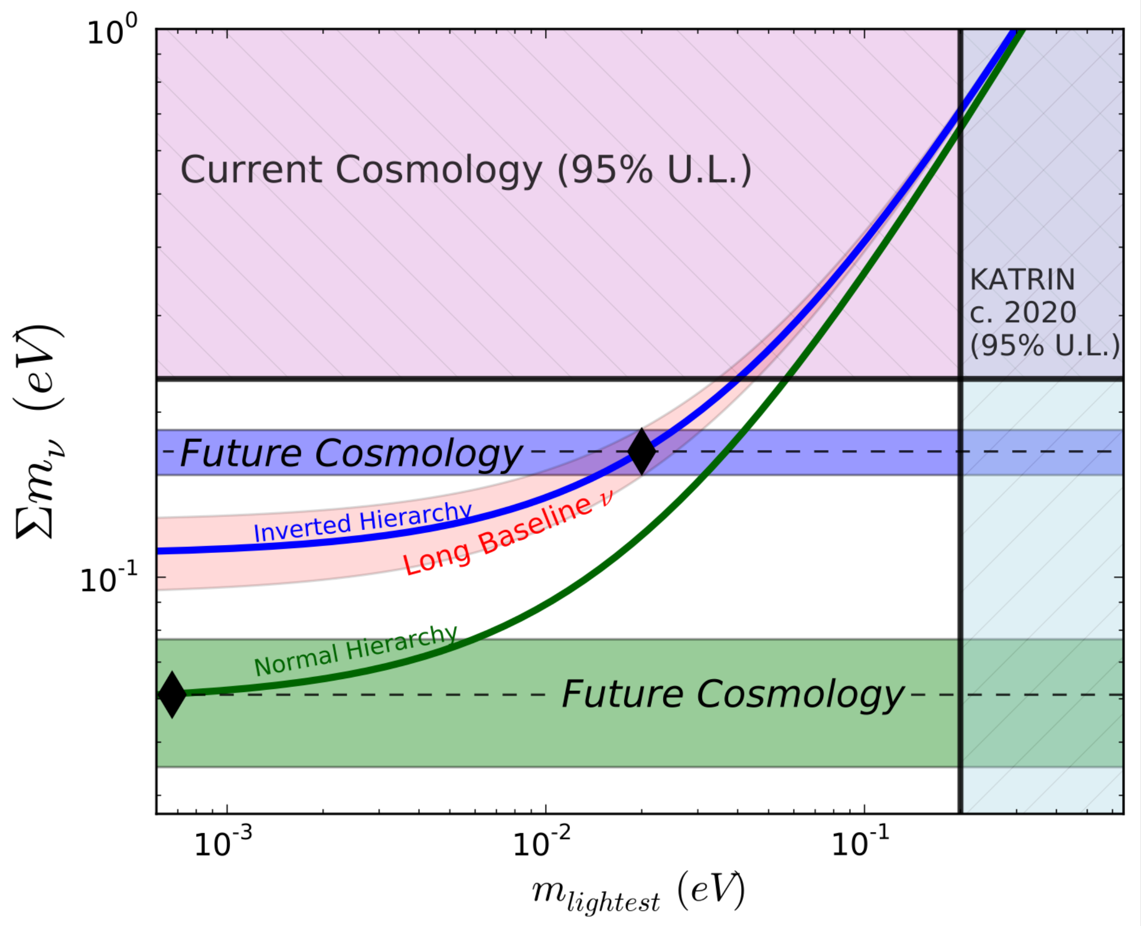


- Stage IV exp:
  - ✓ 45 meV (CMB alone);
  - ✓ 24 meV (+ current surveys);
  - ✓ 16 meV (+ future surveys).

B. Benson (KIPAC/Chicago)

What B-mode lensing is good for …

- **Neutrinos total mass and mass hierarchy:**

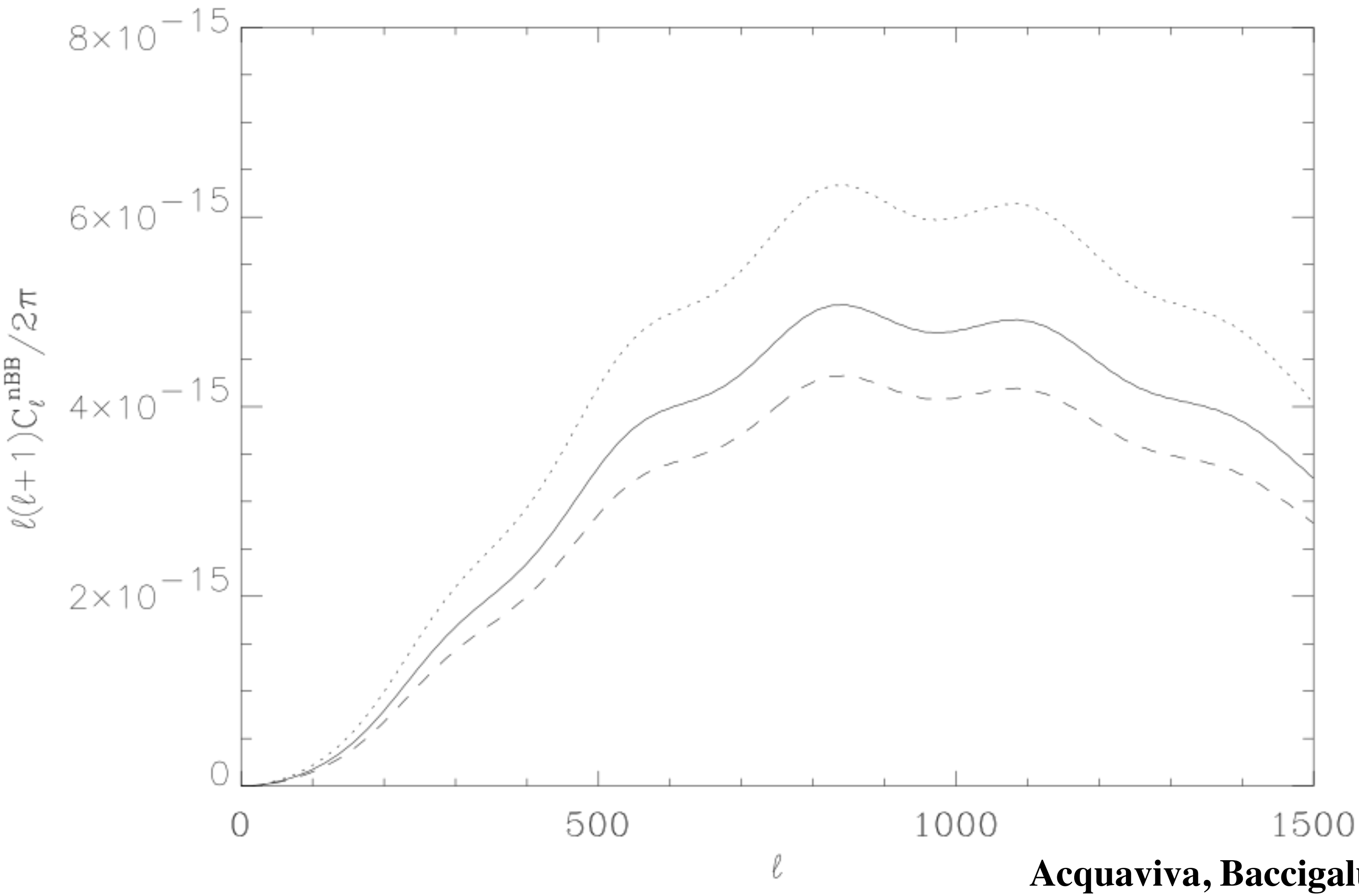


Snowmass report '13/P5 arXiv:1309.5383

- **But also N_{eff} which will be constrained to better than 0.02**

What B-mode lensing is good for …

- **Dark energy at $z \approx 1$:**



Acquaviva, Baccigalupi, 2006

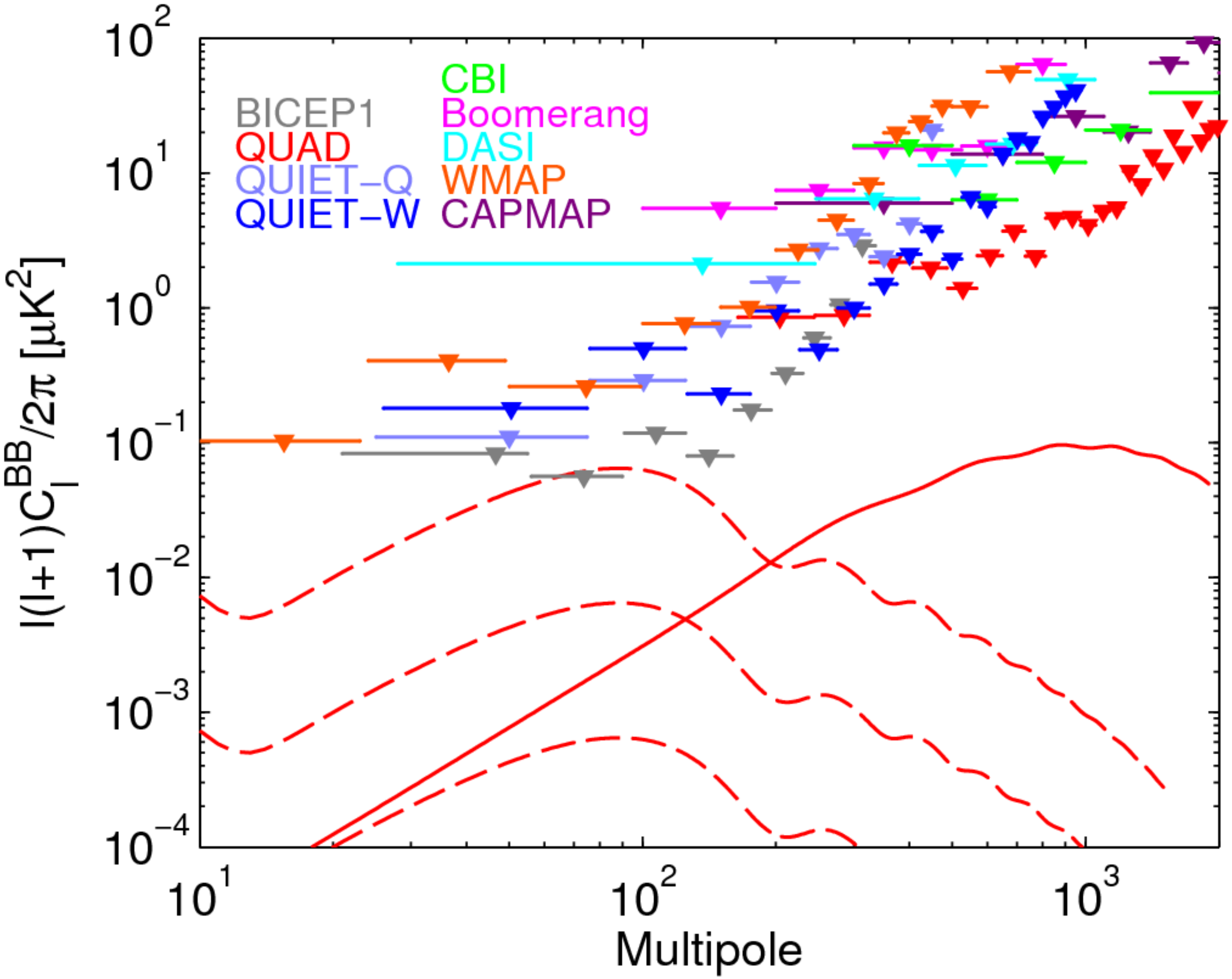
What B-mode lensing is good for …

But also

- modified gravity models …
- models which produce small-scales CMB …
- delensing (if $r = 0.2$ ➔ needed for n_T, otherwise may need to constrain r itself).

And then there is also EB cross-correlation ➔ parity violating physics

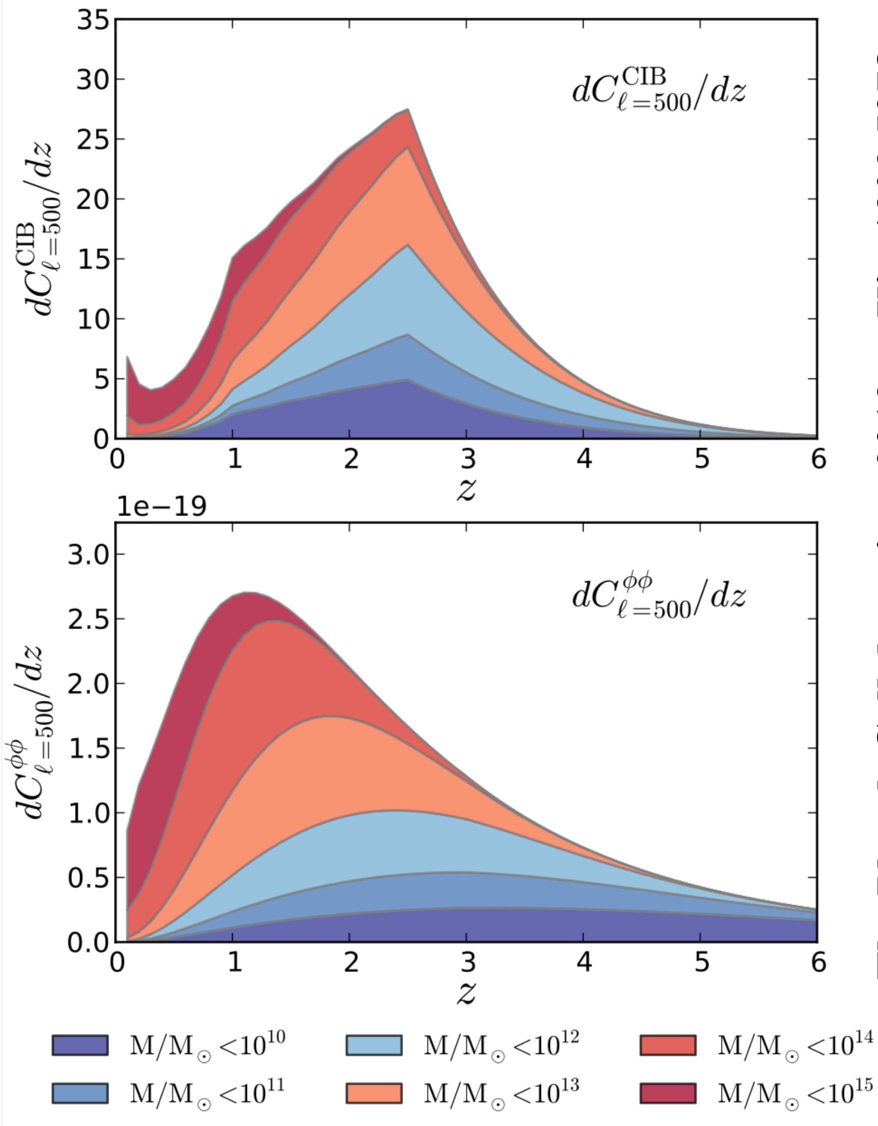
CMB B-modes as of summer '13



C. Pryke

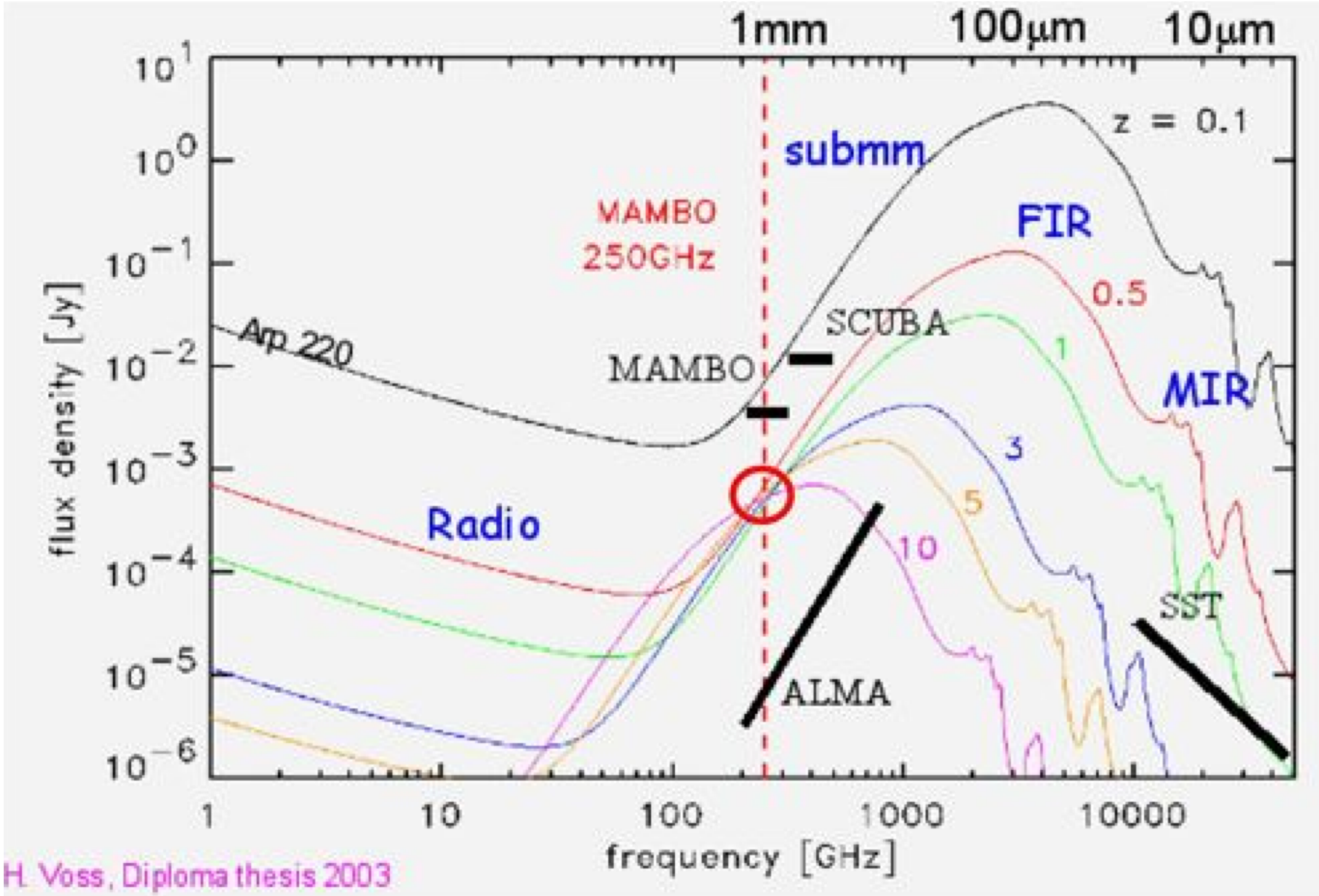
CMB lensing from cross-correlations

- Easy way to increase s/n if the high and reliable s/n template is available
- CIB seems to provide an excellent template to cross-correlate CMB with.
- CMB lensing was detected through cross-correlation of the CMB T map from WMAP and galaxy surveys (Smith et al 2007, Hirata et al 2008).
- A caveat: it can measure <u>only</u> the lensing B-modes.

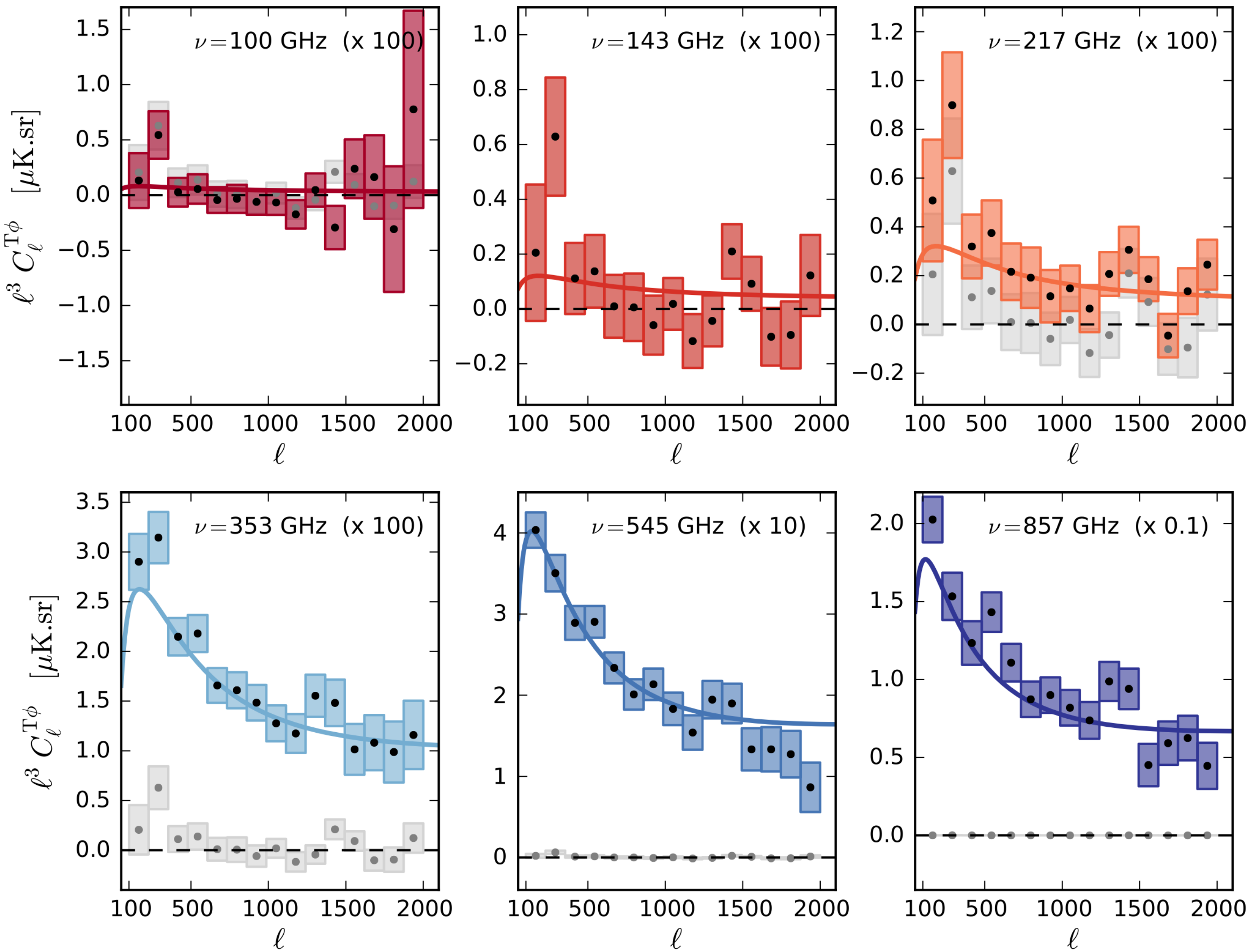


The Planck Collaboration, 2013, arXiv:1303.5078

Flux density for sub-mm galaxies



Planck internal: CMB x CIB cross-correlation

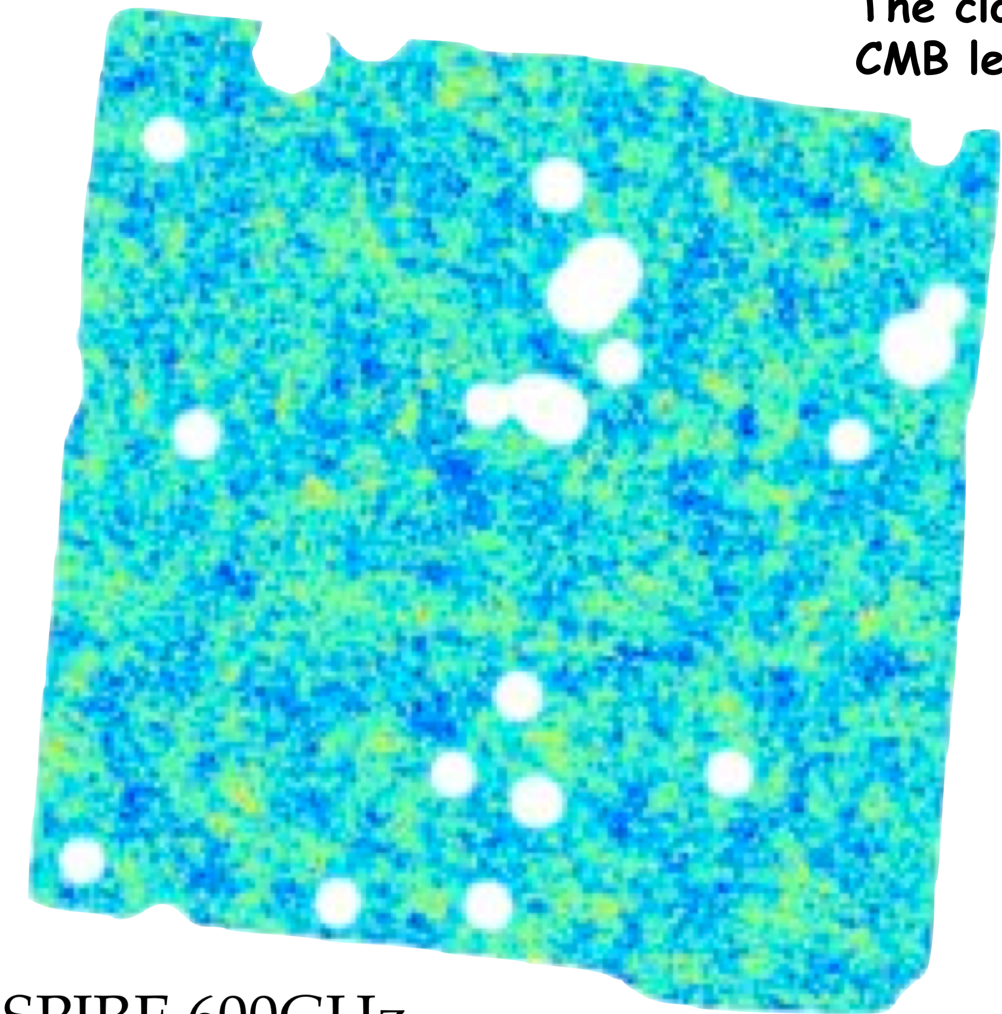


The Planck Collaboration, 2013, arXiv:1303.5078

Correlation up to 80%

Herschel/SPIRES

The closest kernel to that of the CMB lensing (Holder et al, 2013)

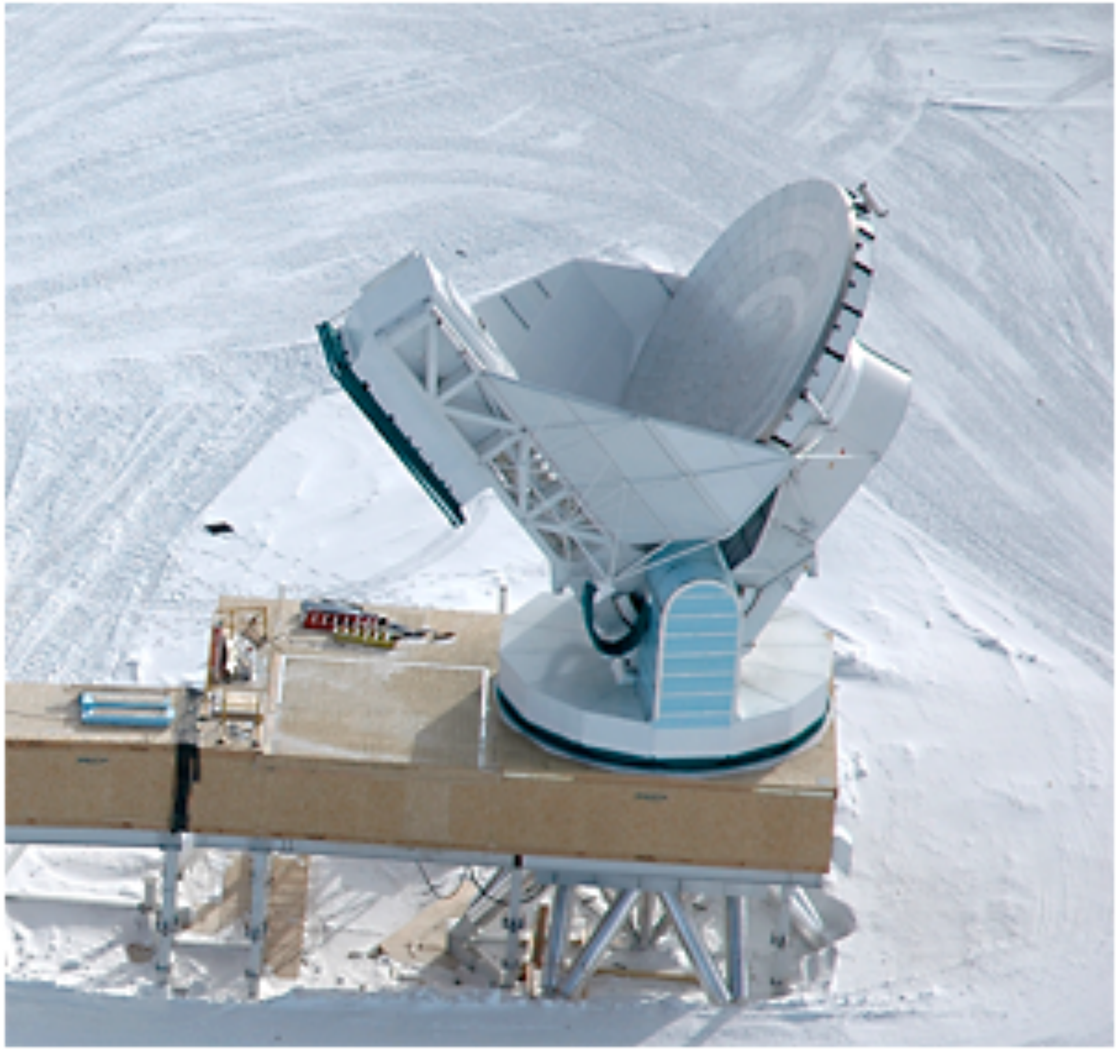


Herschel/SPIRE 600GHz

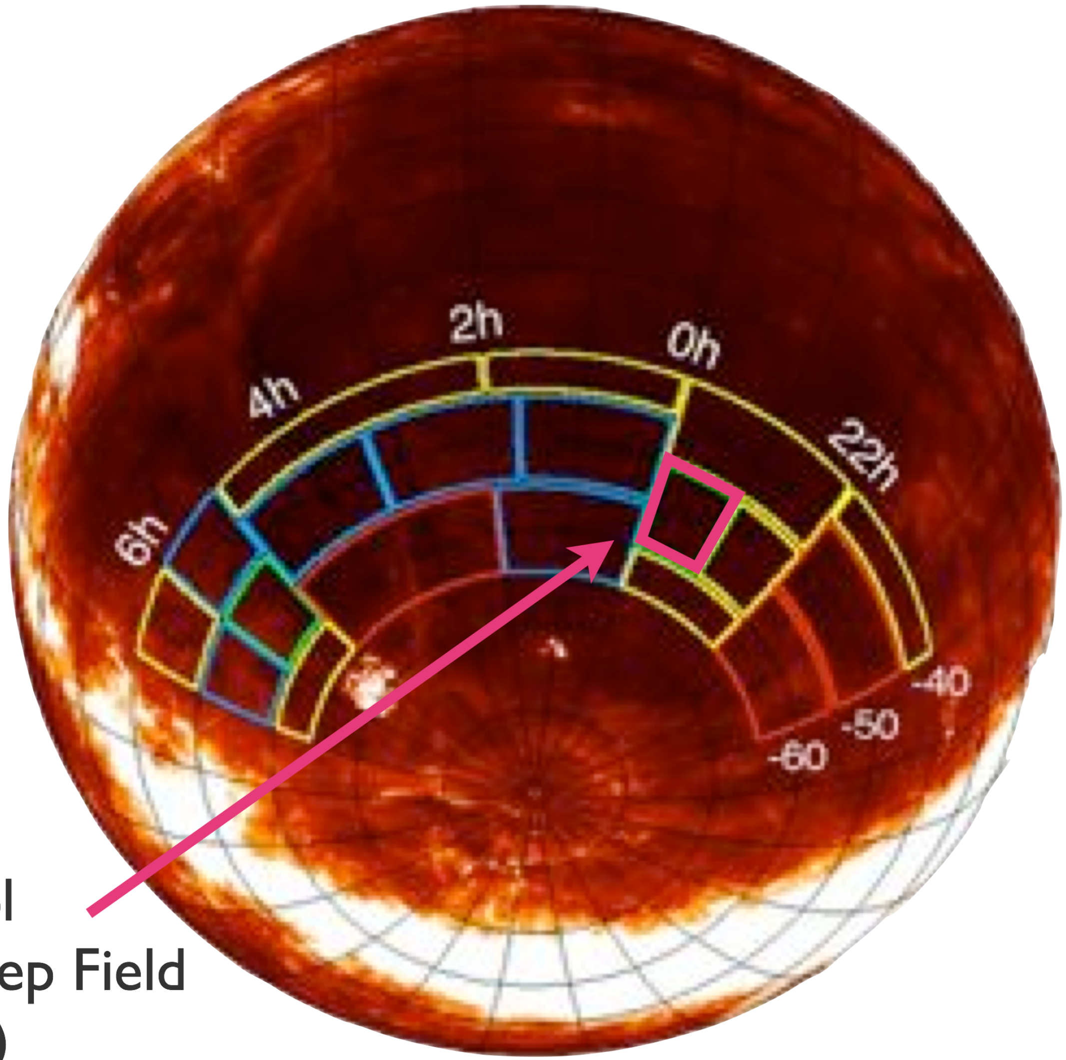
Credit: D. Hanson

SPTpol in a nutshell

- Evolution of SPT;
- Since 2012 1,600 polarization-sensitive detectors;
- 2 frequency bands: 95 and 150 GHz;
- 1 arcmin resolution at 150 GHz (1.6' @ 95GHz);
- Deep patch 100 sq. degrees;
- 9 uK arcmin in polarization.



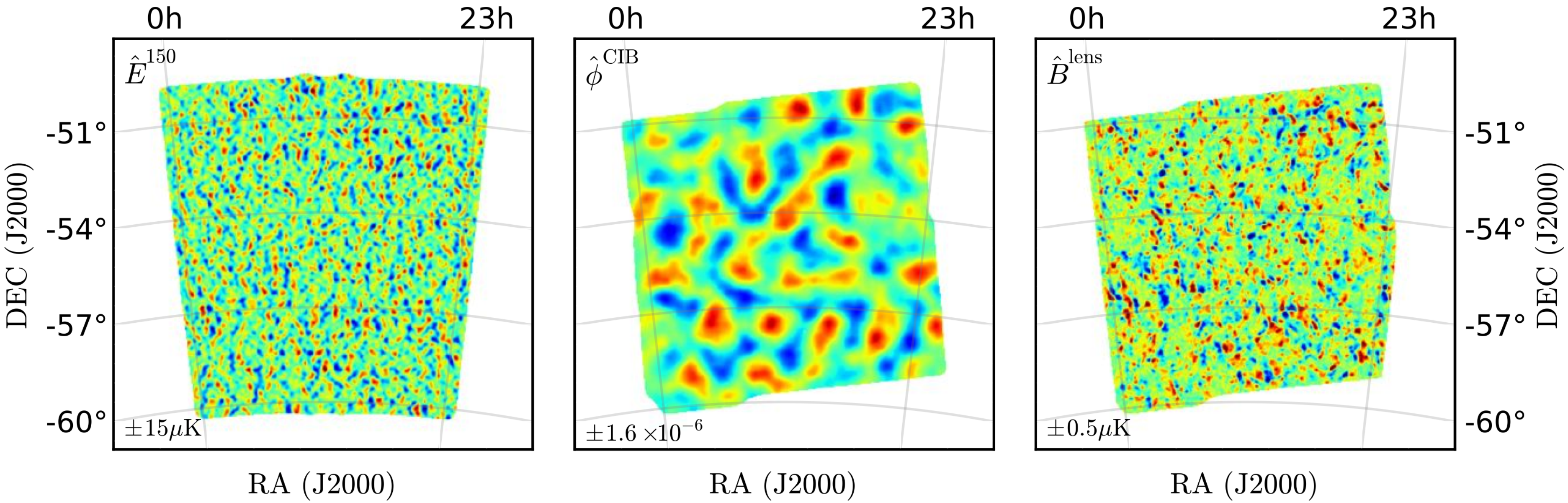
South Pole Telescope



SPTpol
~100deg^2 Deep Field
(2012)

et. al. 2012

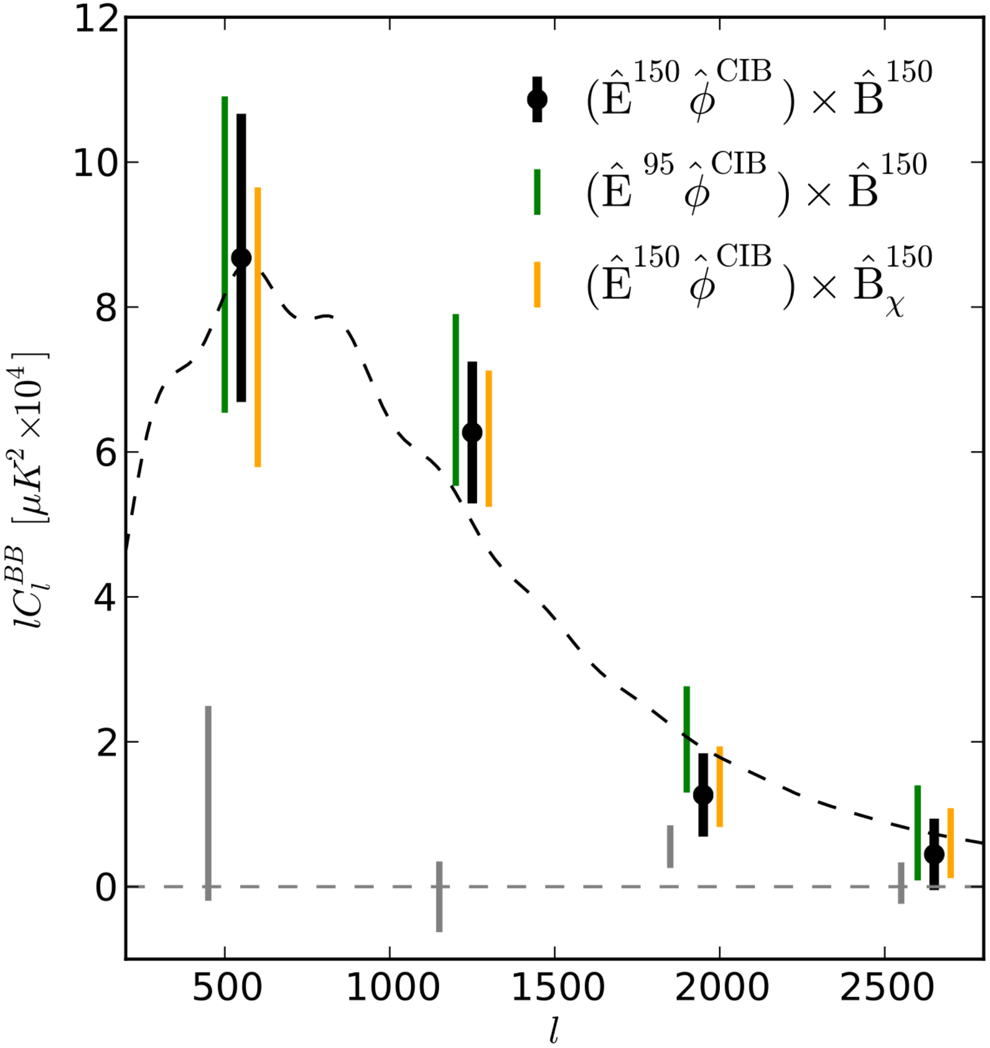
SPTpol approach to cross-correlation:



[Wiener filtered map of E (from SPTpol data)] × [Wiener filtered map of Φ (from Herschel 600 GHz data)] ≈ [Synthesized map of B ≈ E Φ]

Hanson et al 2013, arXiv:1307.5830

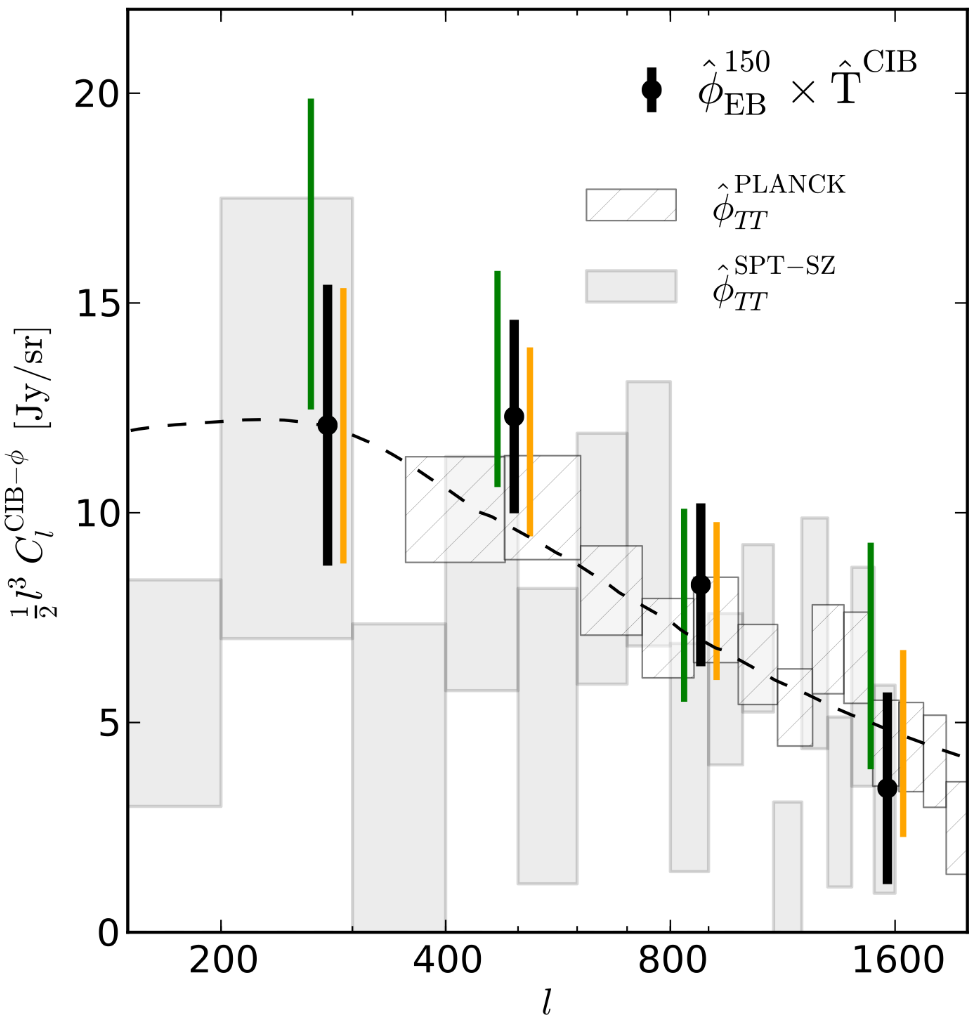
SPTpol: B-mode perspective



7.7 σ detection of the cross-correlation (lensing B-mode signal) wrt the fiducial model

Hanson et al, (2013), Phys. Rev. Lett., 111, id. 141301,

SPTpol: Lensing perspective



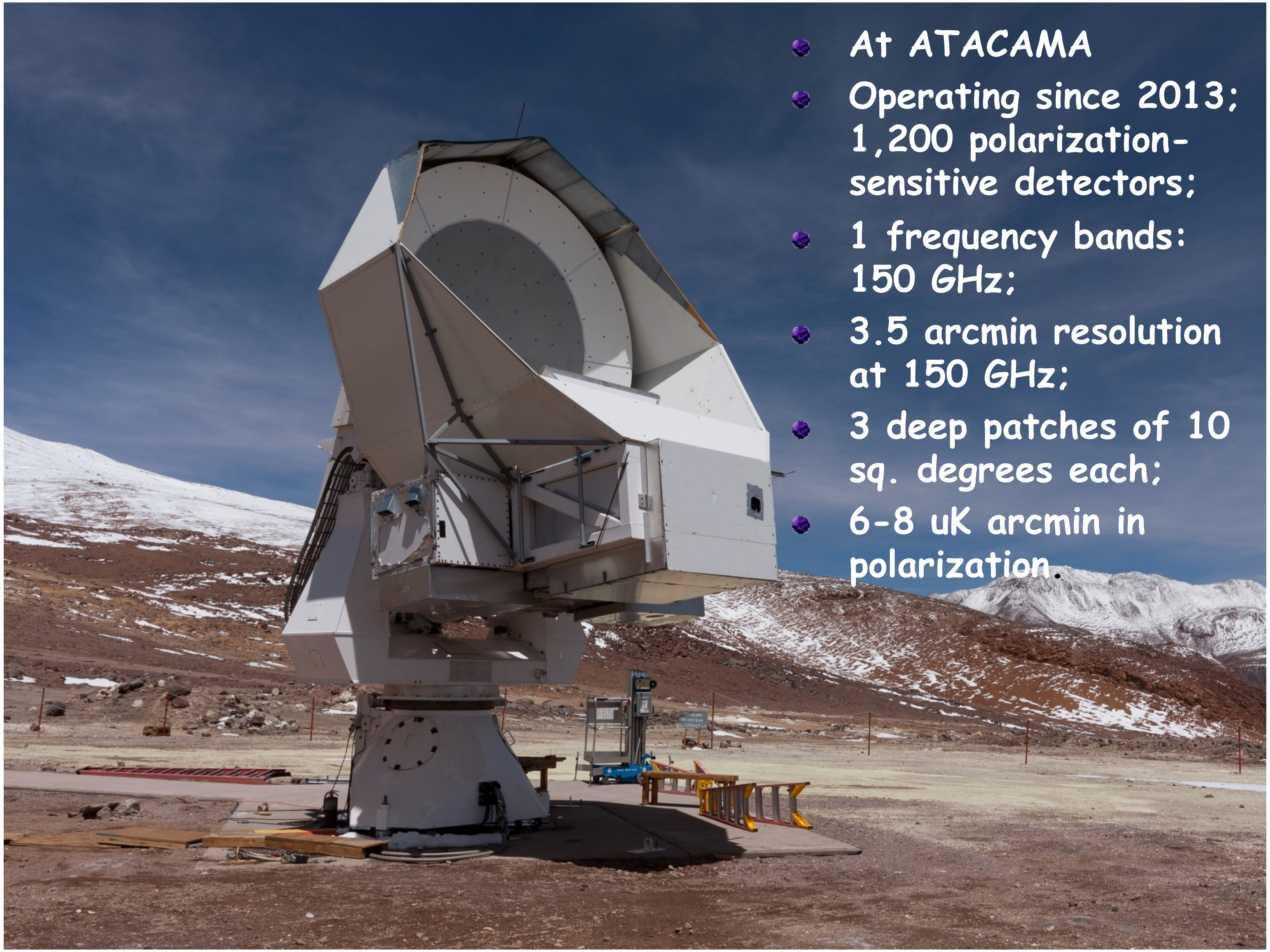
7.7 σ detection of the cross-correlation lensing potential wrt the fiducial model

EBxEB correlation gives rise to 2.5σ wrt the fiducial model;

EExEB – 3σ.

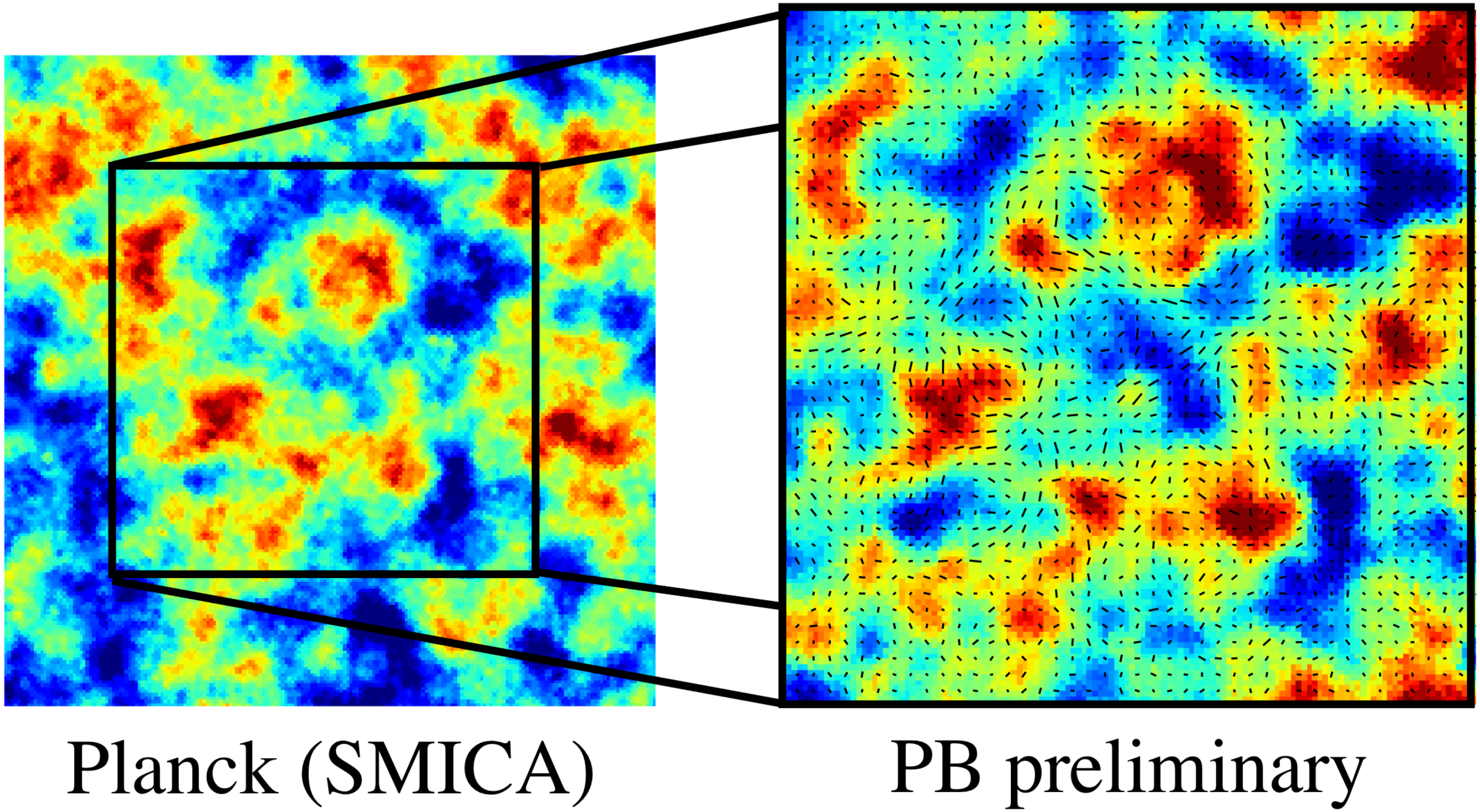
Hanson et al, Phys. Rev. Lett., 111, id. 141301, 2013

POLARBEAR



- At ATACAMA
- Operating since 2013; 1,200 polarization-sensitive detectors;
- 1 frequency bands: 150 GHz;
- 3.5 arcmin resolution at 150 GHz;
- 3 deep patches of 10 sq. degrees each;
- 6-8 uK arcmin in polarization.

POLARBEAR 2013 campaign



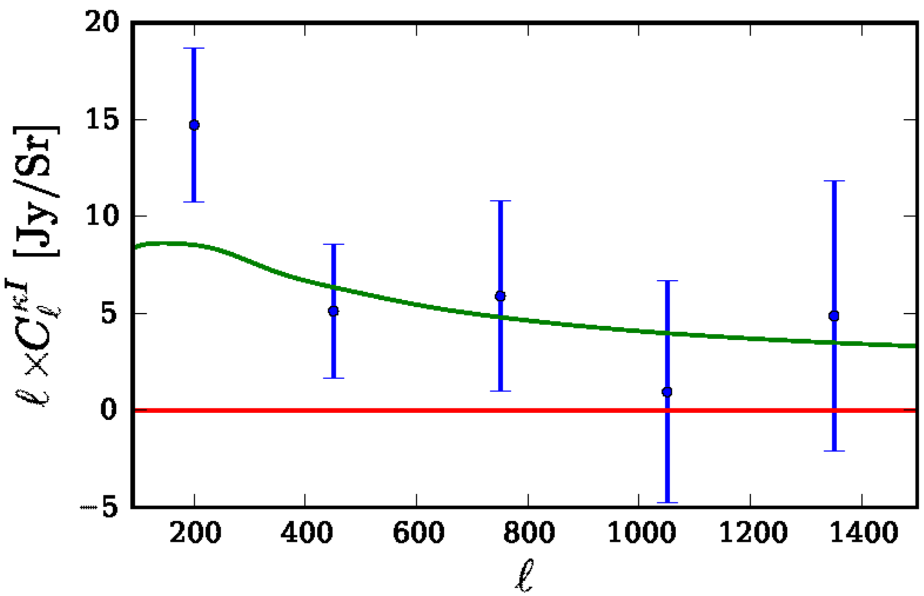
Observed 3 patches like this: ≈ 30 sq degrees.

CMB-CIB cross-correlations a la POLARBEAR

[Raw map of E (from the POLARBEAR data)] × [Raw map of B (from the POLARBEAR data)] ≈ [Map of convergence: $\varkappa = \frac{1}{2} \nabla d$]

$\varkappa \times I_{CIB}$: (« lensing view »)

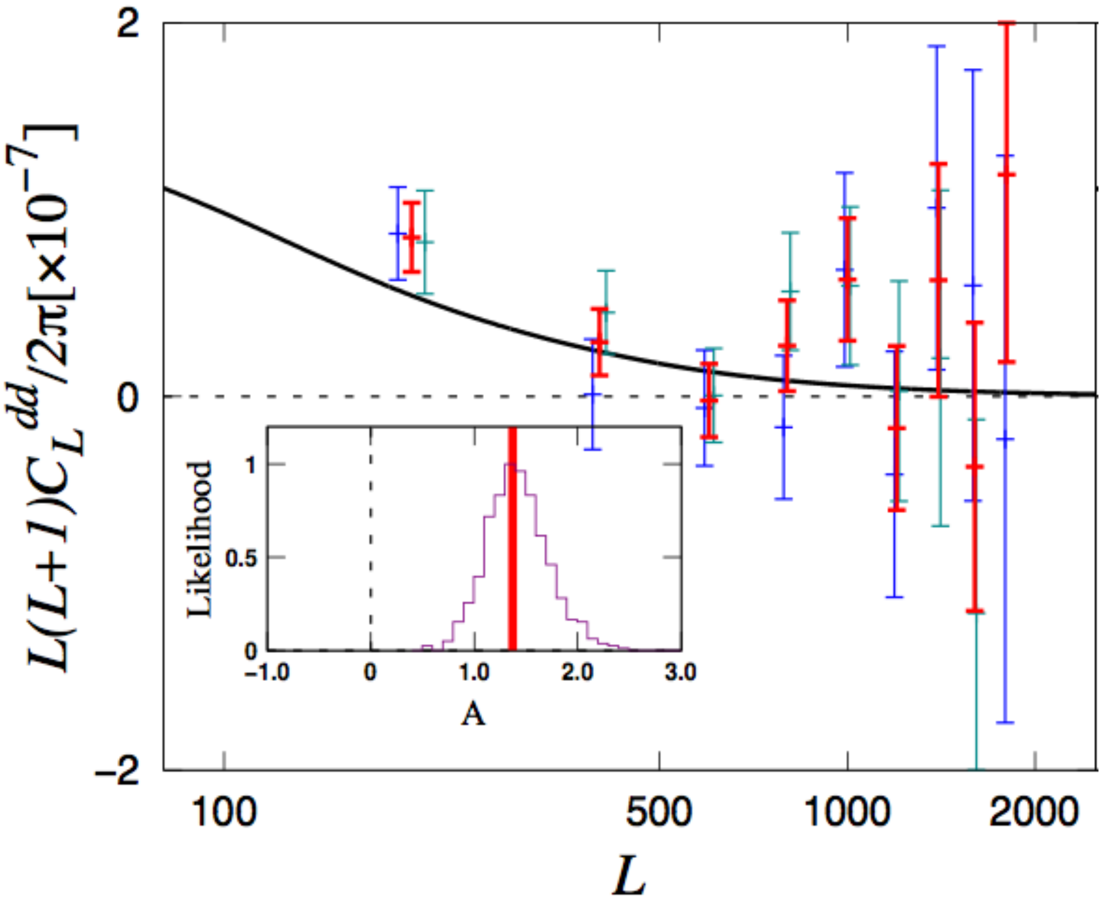
- 2.3σ evidence for the B-mode lensing;
- 4.0σ evidence for the polarization lensing



Internal cross-correlations

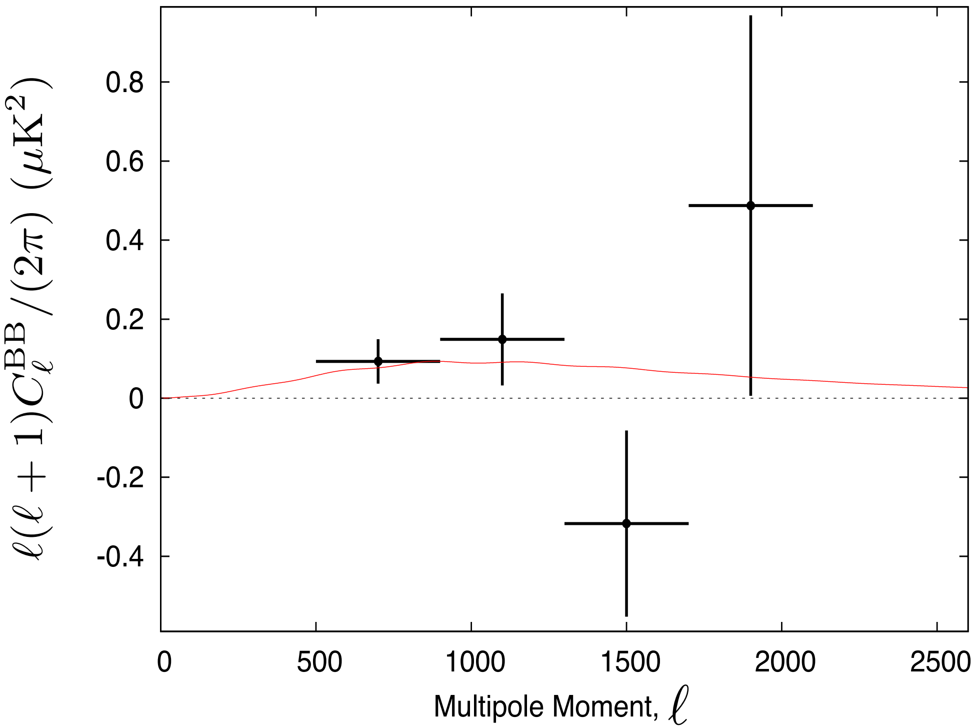
EExEB + EBxEB:

- 4.2σ rejection of the null hypothesis;
- 2.3σ detection of the lensing amplitude



The POLARBEAR collaboration, 2013, arXiv:1312.6646

Direct BB power measurement

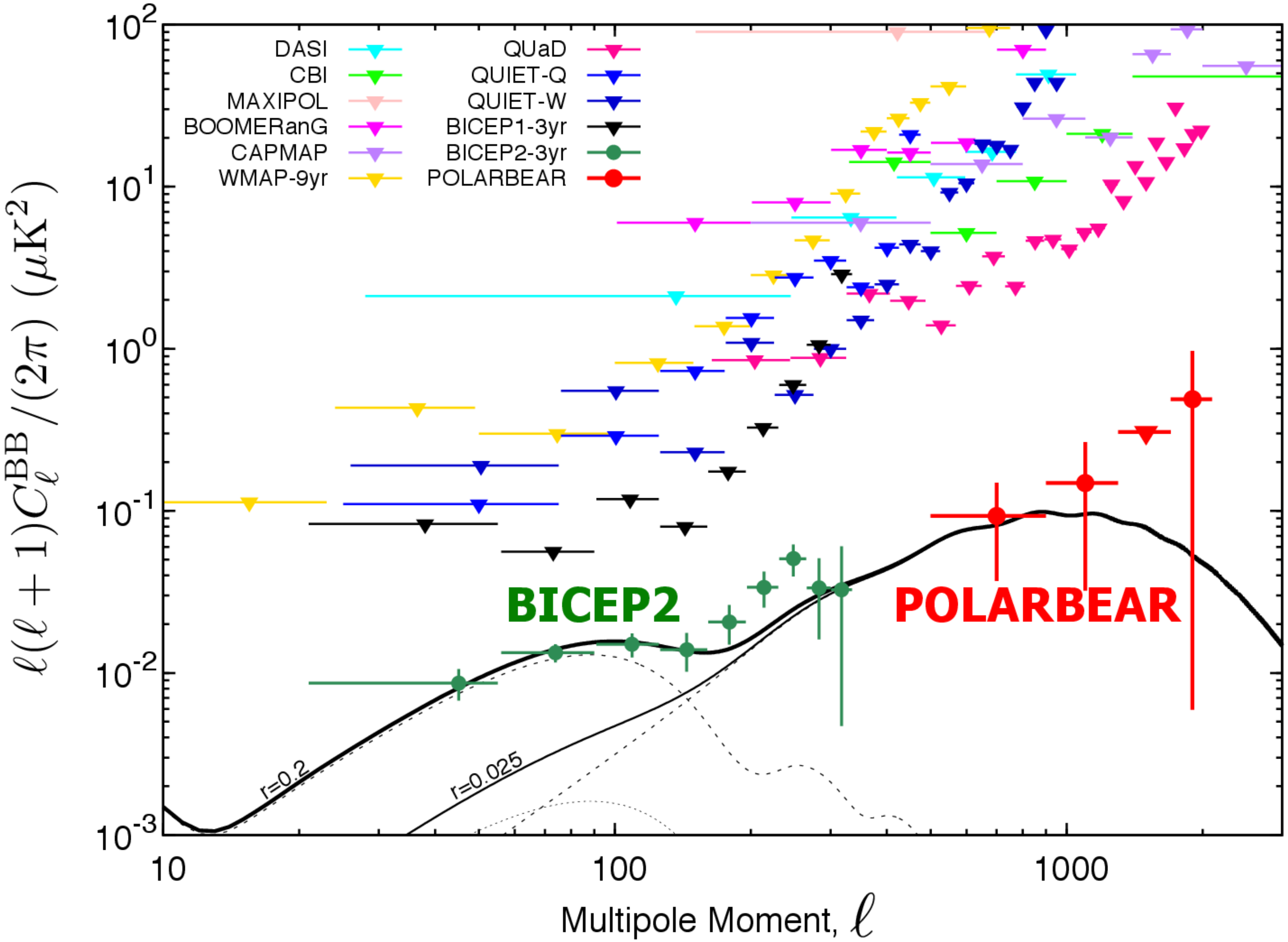


Model-independent rejection of no B-power at 2σ

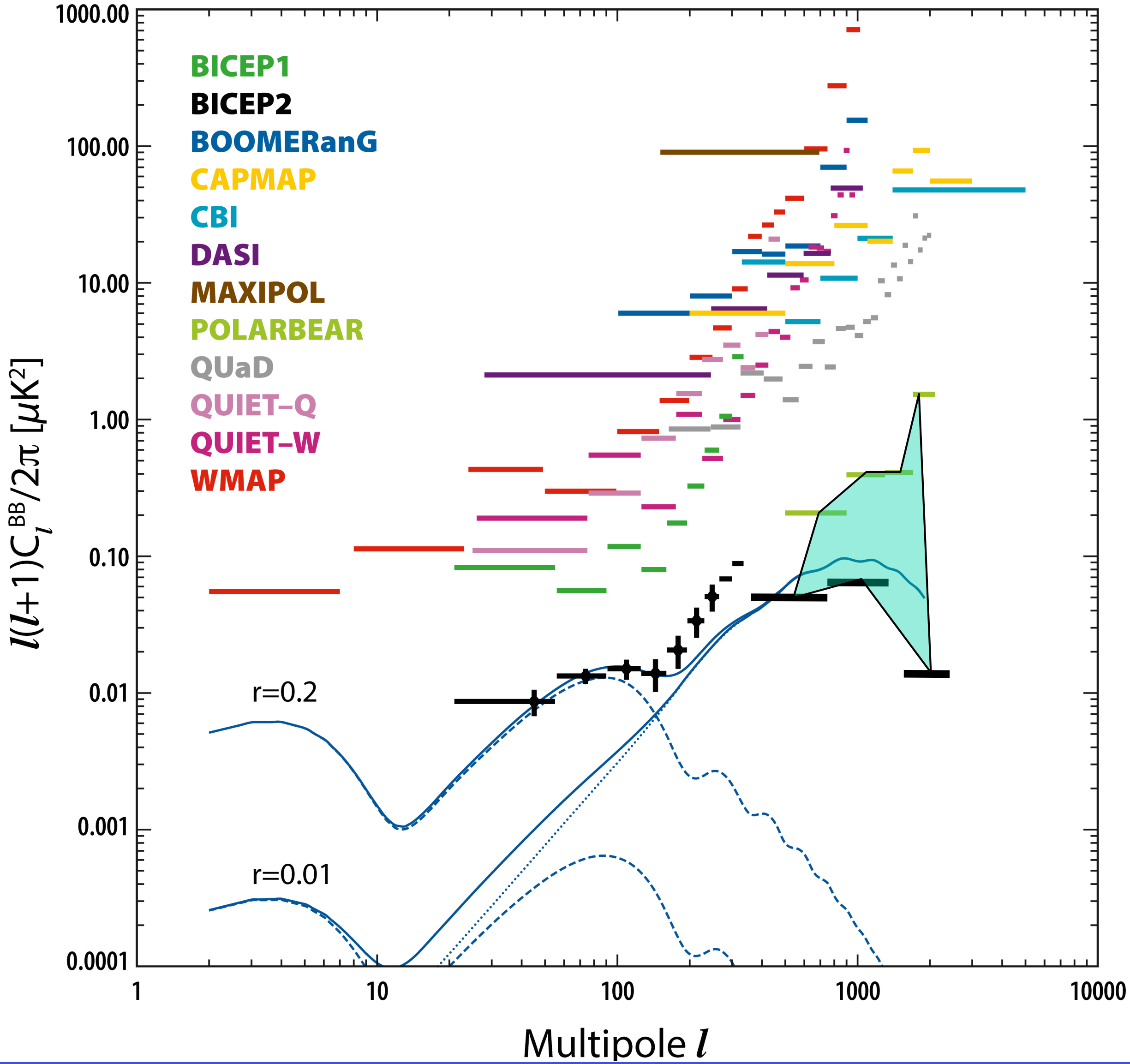
2σ confirmation of the lensing amplitude wrt the fiducial model.

The POLARBEAR Collaboration 2014, arXiv:1403.2369

« Global view »


DASI
CBI
MAXIPOL
BOOMERanG
CAPMAP
WMAP-9yr
QUaD
QUIET-Q
QUIET-W
BICEP1-3yr
BICEP2-3yr
POLARBEAR
BICEP2
POLARBEAR
r=0.2
r=0.025
$\ell(\ell+1)C_\ell^{BB}/(2\pi)\ (\mu K^2)$
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10
100
1000
Multipole Moment, ℓ

« Global view » - a LAMBDA alternative



Upper limit: POLARBEAR

Lower limit: SPTpol

Credit: Lambda website

Summary

- There is a lot to learn from the CMB B-modes on small-angular and CMB B-mode lensing in particular.
- The sensitivity is finally (and nearly) there !
- Indirect, high significance detections are there but use lots of modeling and assumptions : consistency tests , lower limit on CMB BB ?!
- First measurement of the CMB BB spectrum with uncertainties on order of the expected signal have become recently available …
- More work needed and prospects as exciting as ever (CMB-S3/S4, satellite missions, …)