Delensing:
a worked example from SPT, Herschel, and BICEP/Keck

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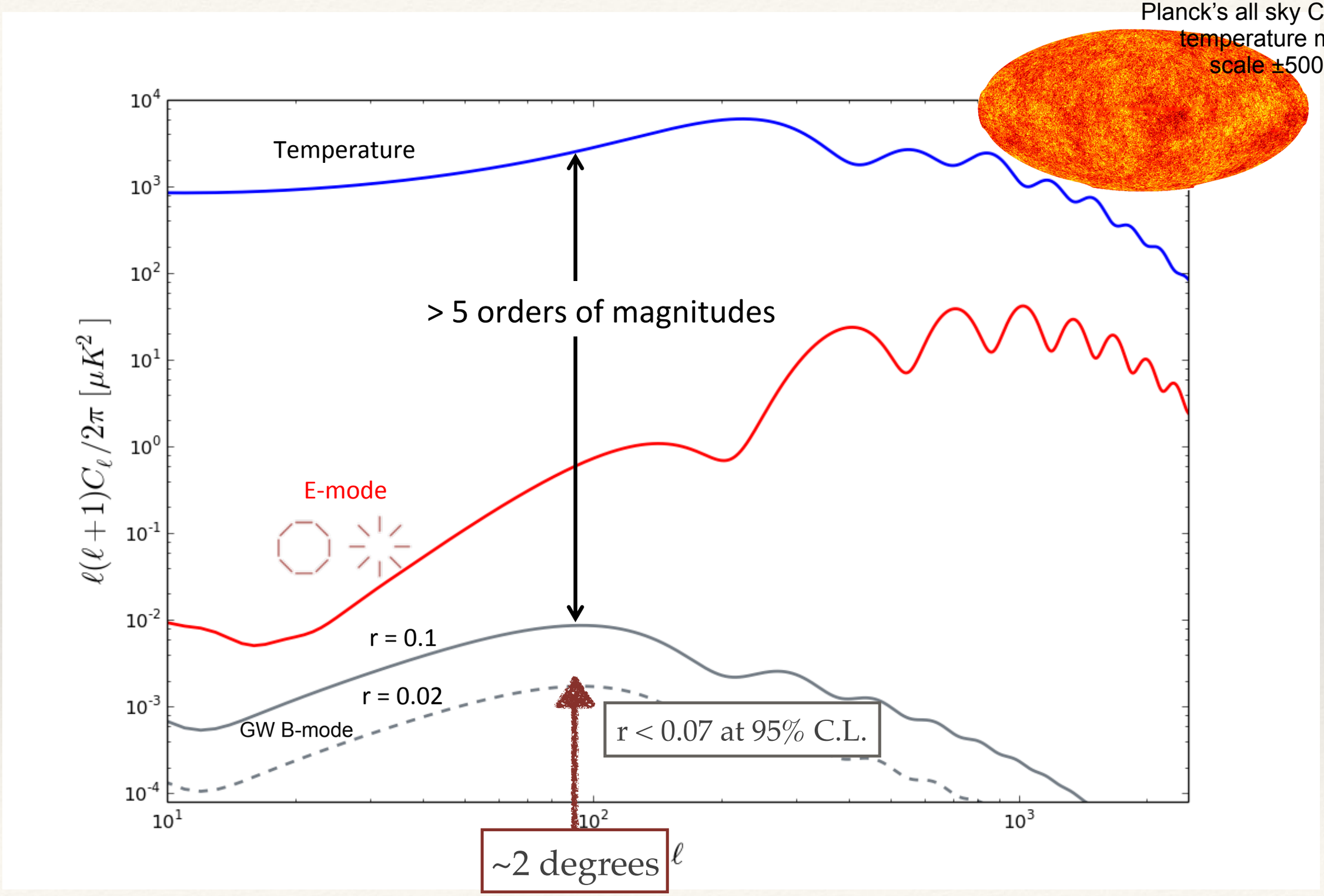
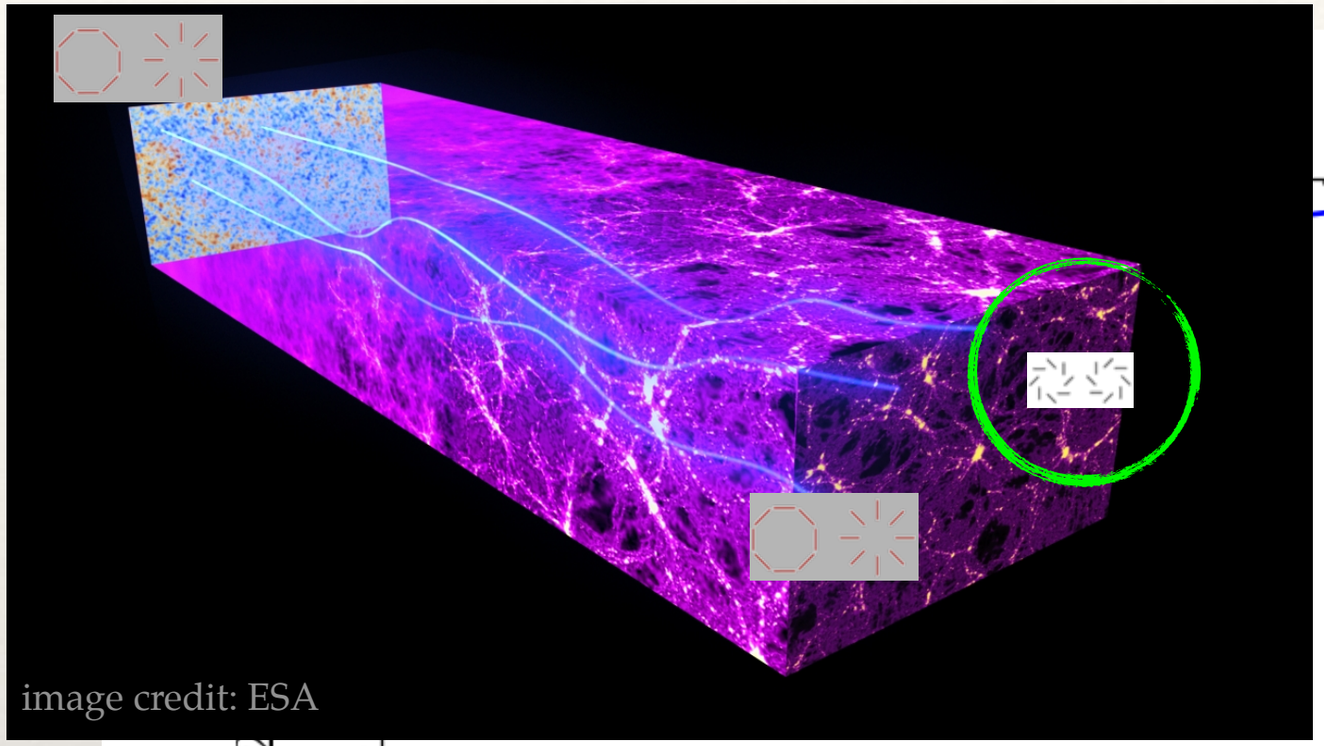
Outline

- Introduction and background for delensing
- Worked example: delensing SPT B modes with Herschel CIB as phi tracer
  - Approach + results
  - Current limitation to delensing
- Work-in-progress: delensing BICEP/Keck B modes with Planck CIB as phi tracer
- Conclusions/Ideas

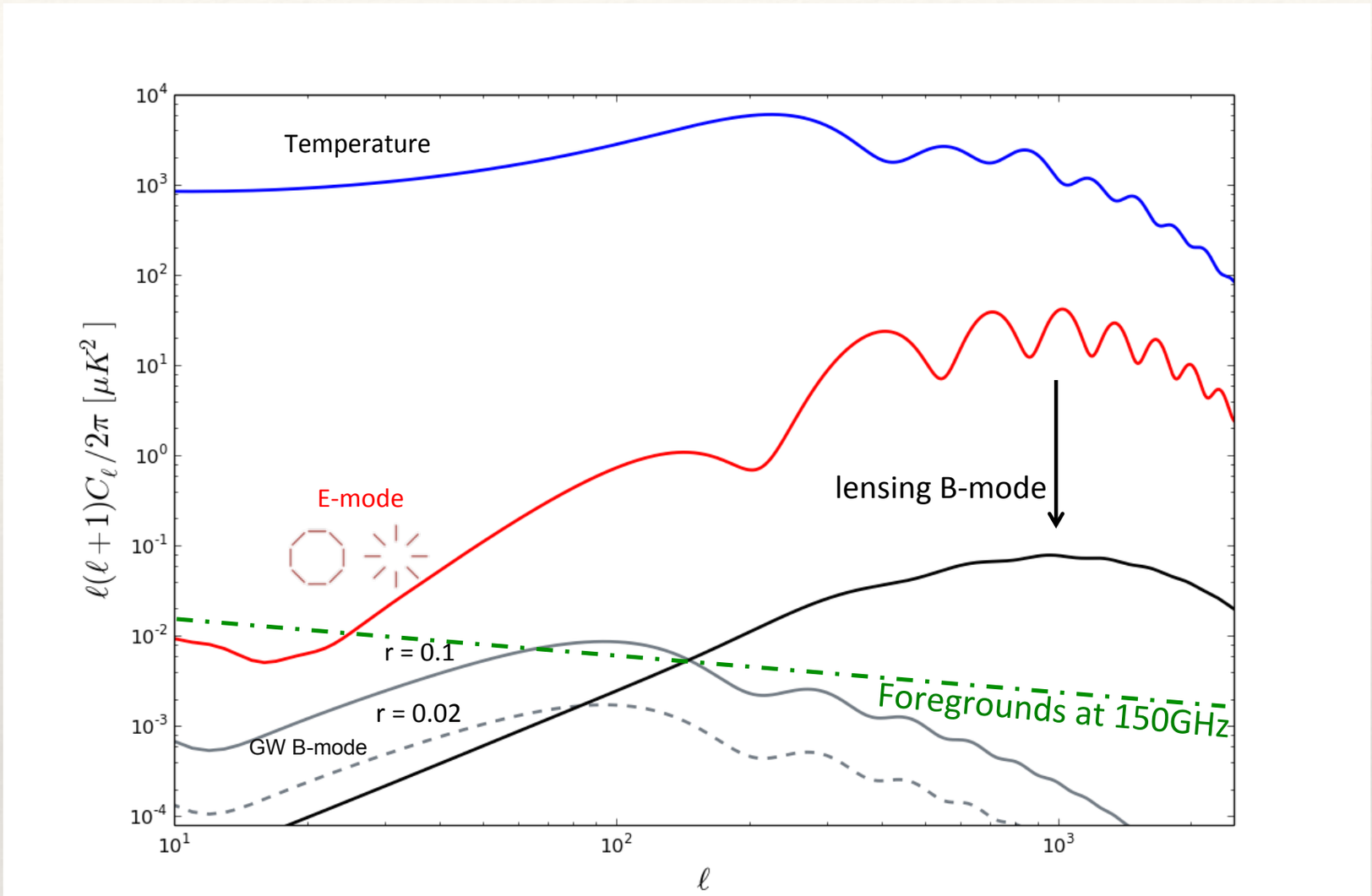
Primordial B-modes are small



CMB spectra + foregrounds



Why delensing?



- We can fit lensing model + r simultaneously, but limited by sample variance of lensing
- **Delensing** B-modes: using the ***realization-specific*** lensing B-mode sky to reduce lensing sample variance
- Especially important if observing a small sky patch

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Delensing: the idea

1. Use Phi to lens E-mode map to get expected lensing B

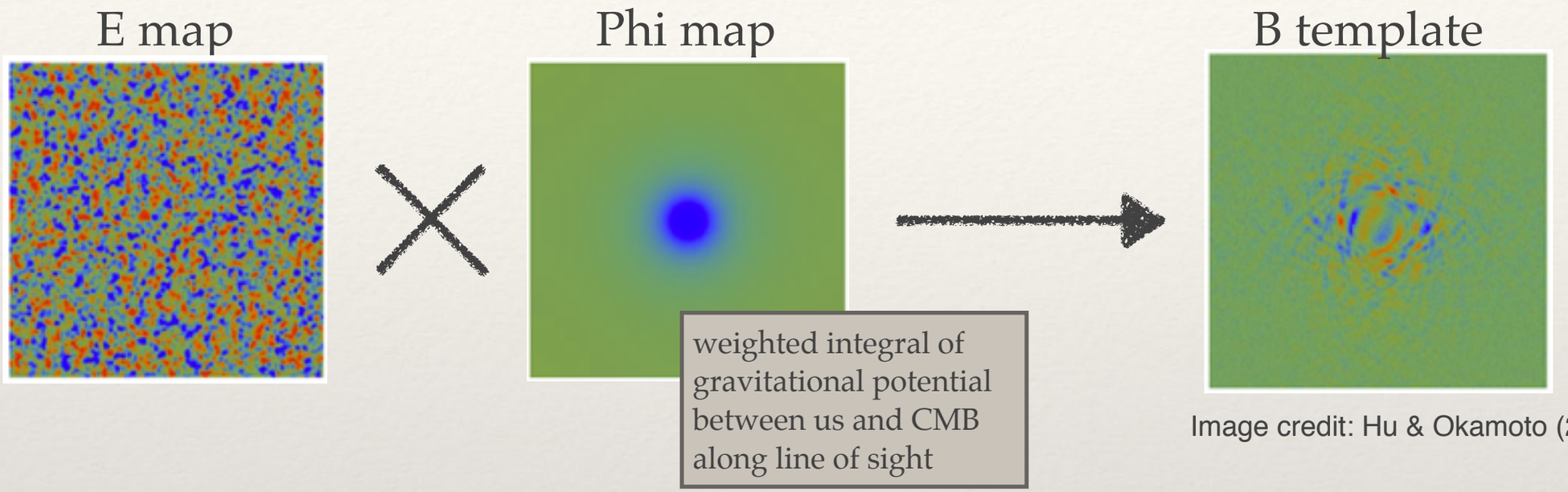
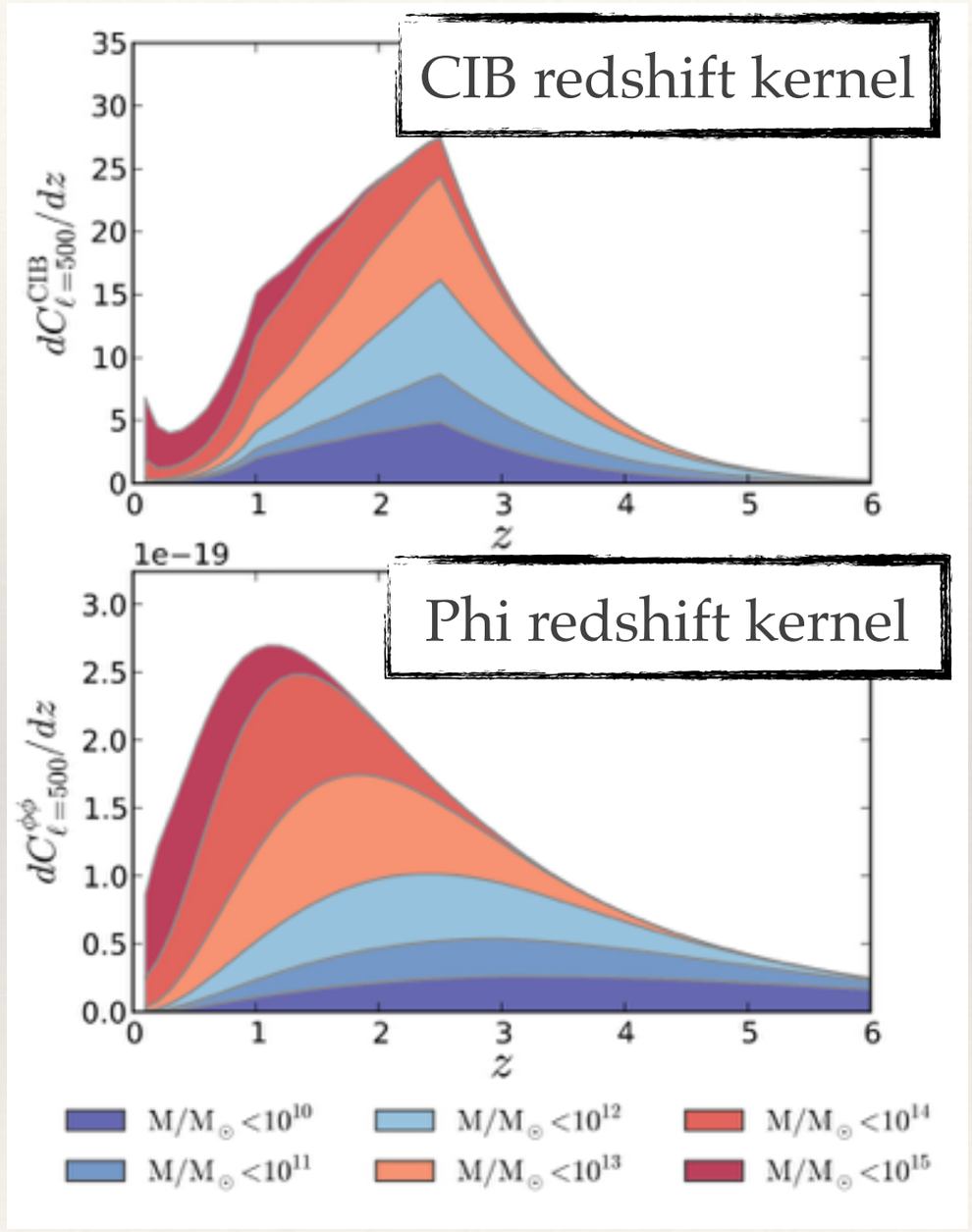


Image credit: Hu & Okamoto (2002)

2. Subtract B template from B map

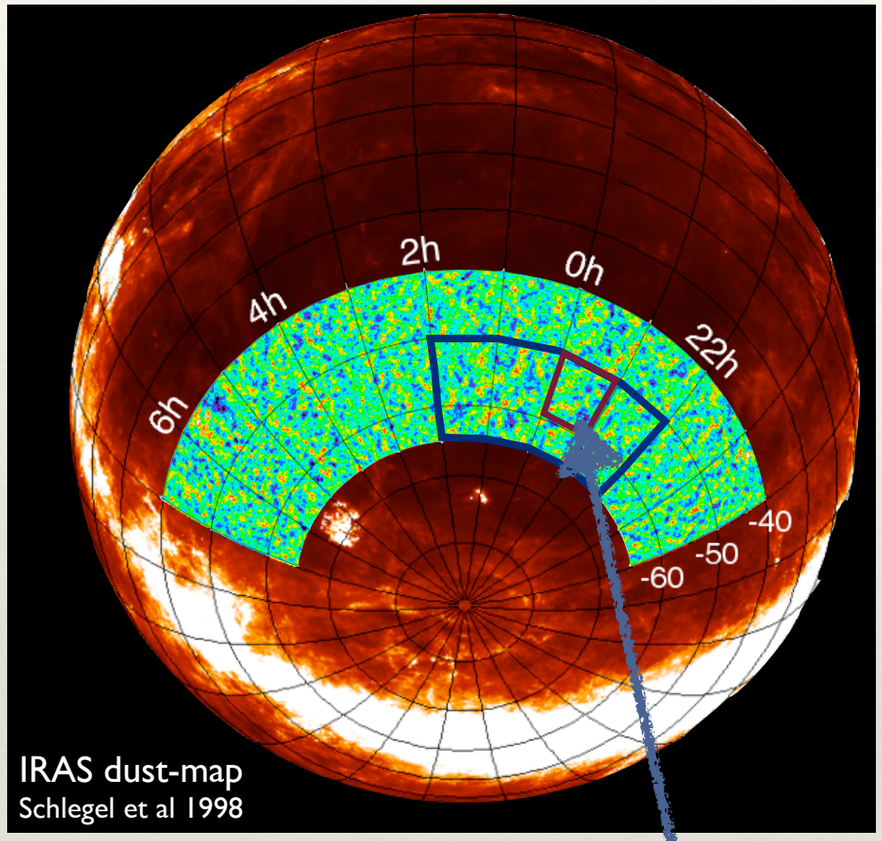
CIB as a Phi tracer

- Phi: can reconstruct from CMB, but S/N rather low currently (Future will be better!)
- Cosmic infrared background (CIB) from dusty star-forming dusty galaxies with redshift distribution peaked between z~1 and 2.
- CMB lensing potential's redshift kernel peaks between $1 < z < 3$
- Cross-correlation can be as high as ~80%
- Used for first detection of lensing B-modes through cross-correlations (Hanson et al. 2013); first delensing of CMB temperature anisotropies (Larson et al. 2016)



Planck 2013 XVIII

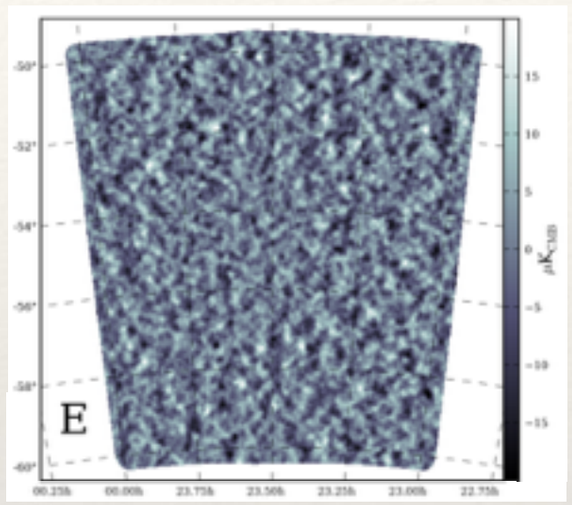
Lensing B template to delens SPTpol B modes



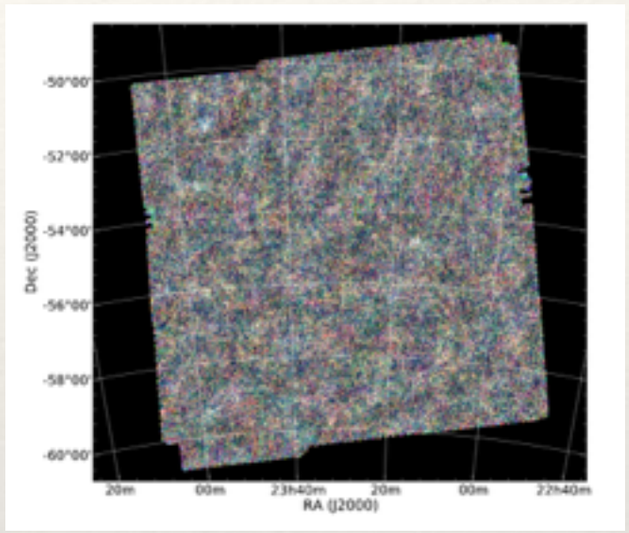
SPTpol 100 deg^2 field

Inputs to form the B template

E-mode measurement
(Crites et al., SPT 2015)

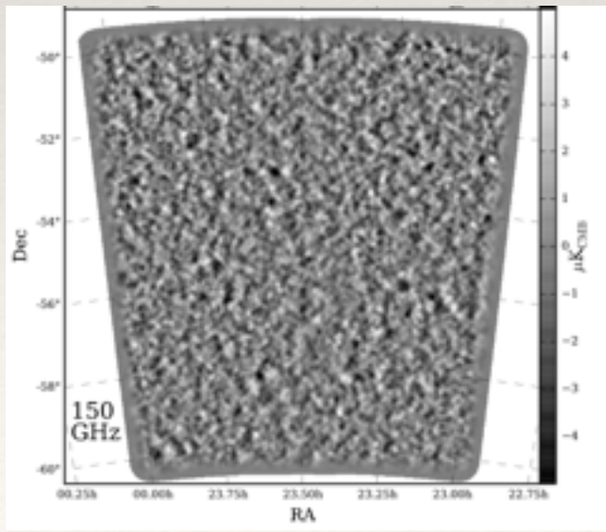


CIB map from Herschel 500μm map

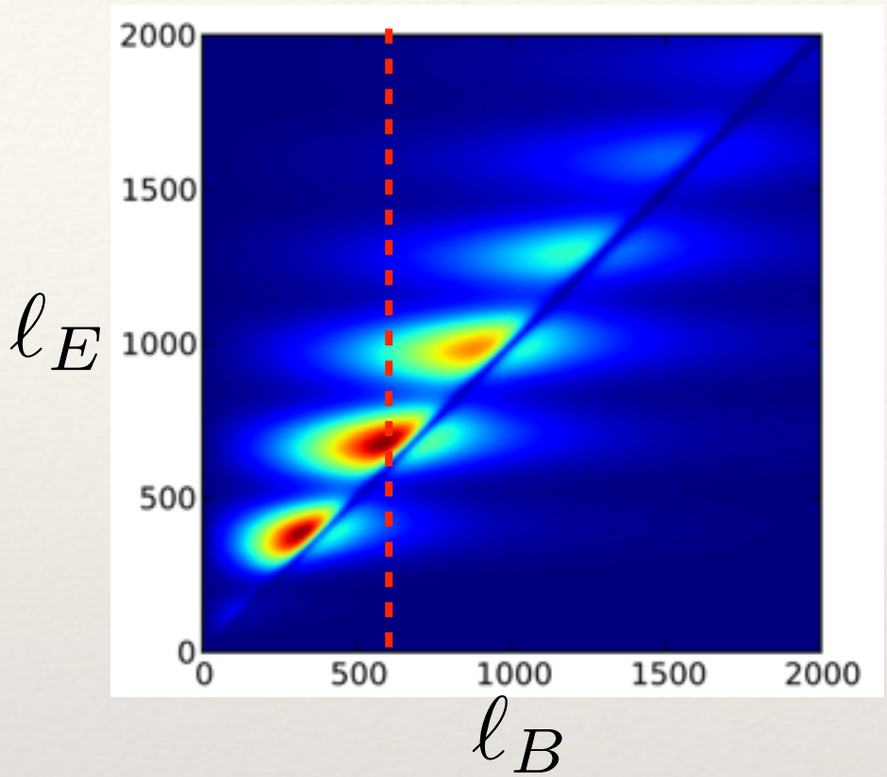


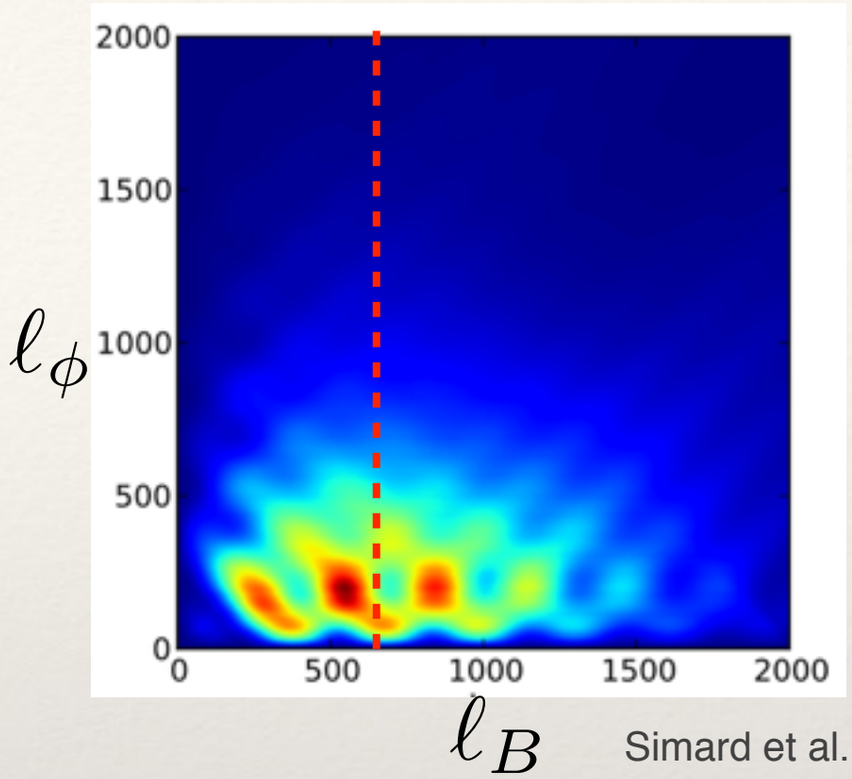
B-mode map to be delensed

(Keisler et al., SPT 2015)



Forming the B template: I



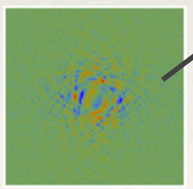


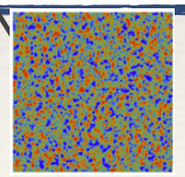
Simard et al. 2014 (1401.0691)

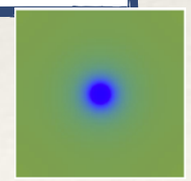
Lensing B modes to first order in Phi has the form*

$$B^{\rm lens}(\boldsymbol{\ell}) = \int \frac{d^2\boldsymbol{\ell}'}{(2\pi)^2} W(\boldsymbol{\ell},\boldsymbol{\ell}') E(\boldsymbol{\ell}') \phi(\boldsymbol{\ell}-\boldsymbol{\ell}')$$

theoretical unlensed E, phi







where weight function

$$W(\boldsymbol{\ell},\boldsymbol{\ell}') = \boldsymbol{\ell}' \cdot (\boldsymbol{\ell}-\boldsymbol{\ell}') \sin(2\varphi_{\boldsymbol{\ell},\boldsymbol{\ell}'}).$$

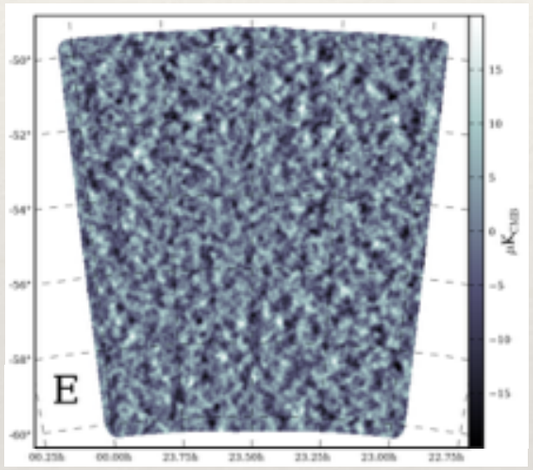
* flat-sky approx.: $\boldsymbol{\ell} = 2\pi|\boldsymbol{u}|$, u is Fourier mode.

Forming the B template: II

So we can build a B template by replacing theory E/Phi with measured+filtered E/Phi

$$\hat{B}^{\rm lens}(\boldsymbol{\ell}) = \int \frac{d^2\boldsymbol{\ell}'}{(2\pi)^2} W(\boldsymbol{\ell},\boldsymbol{\ell}')\bar{E}(\boldsymbol{\ell}')\hat{\phi}(\boldsymbol{\ell}-\boldsymbol{\ell}')$$

Input maps



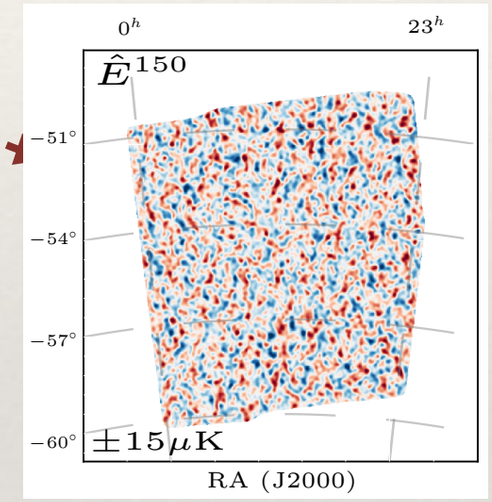
Filtering

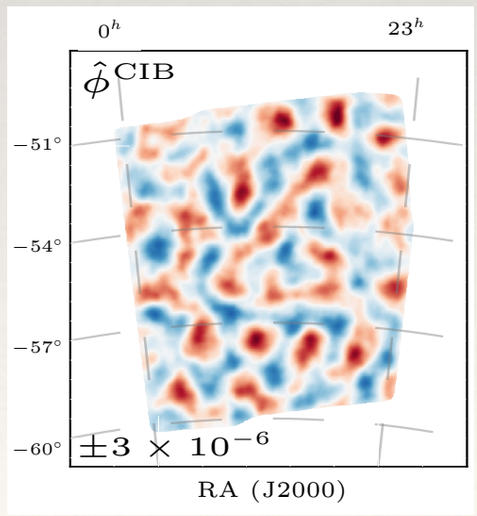
$$\bar{E}(\boldsymbol{\ell}) \approx \left(\frac{C_\ell^{EE}}{C_\ell^{EE}+N_\ell^{EE}}\right) E^N(\boldsymbol{\ell})$$

$$\hat{\phi}^{\rm CIB}_{\boldsymbol{\ell}} = \left(\frac{C_l^{\rm CIB\text{-}\phi}}{C_l^{\rm CIB\text{-}CIB}}\right) I^{\rm CIB}(\boldsymbol{\ell})$$

filters chosen to minimize residual variance

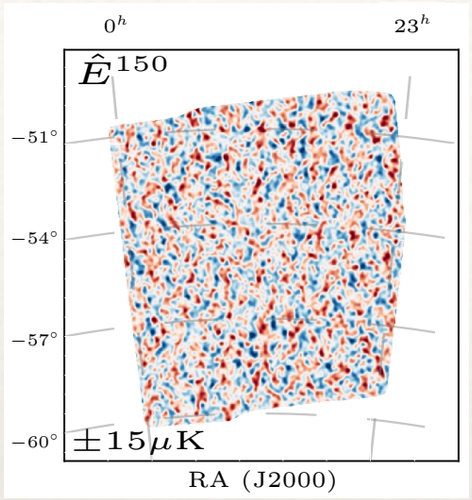
Filtered maps



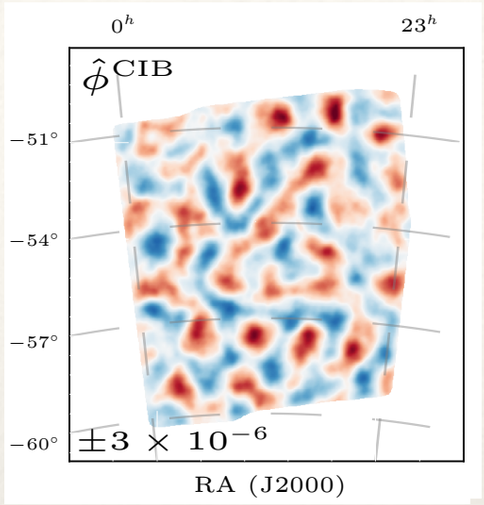


Delens

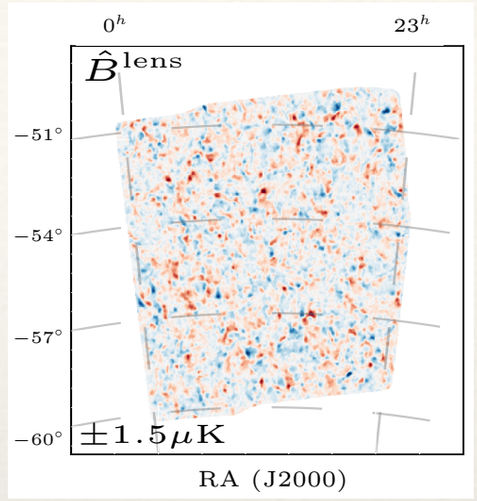
filtered E map



filtered Phi estimate

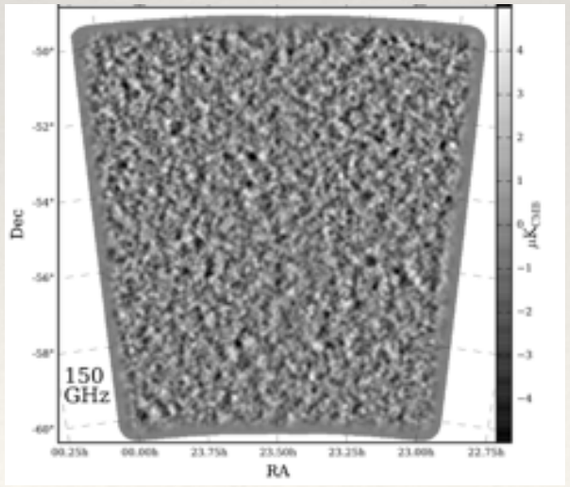


B template

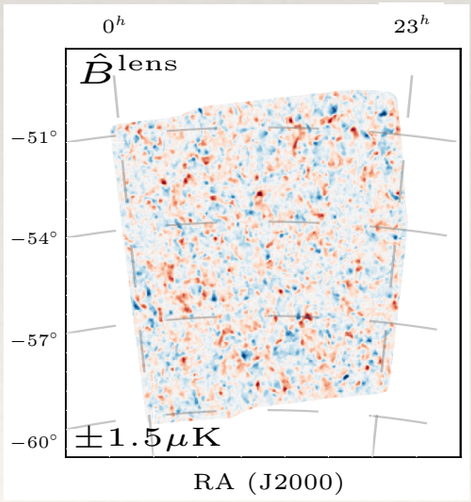


To ensure 'fair subtraction', apply 2D transfer function on the B template before subtracting from B mode map

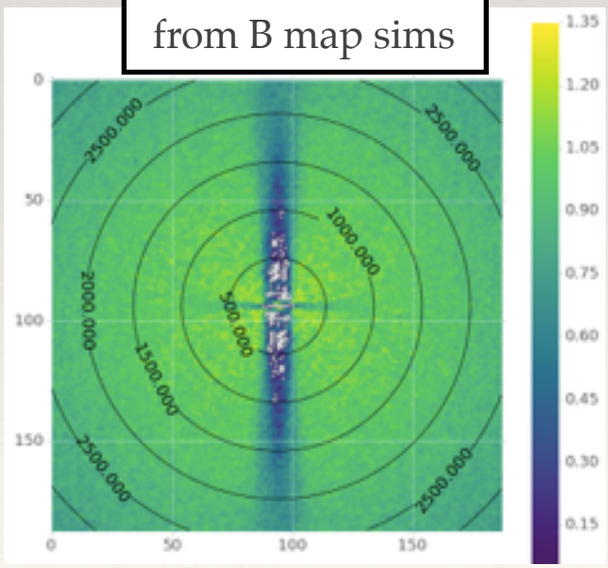
B map



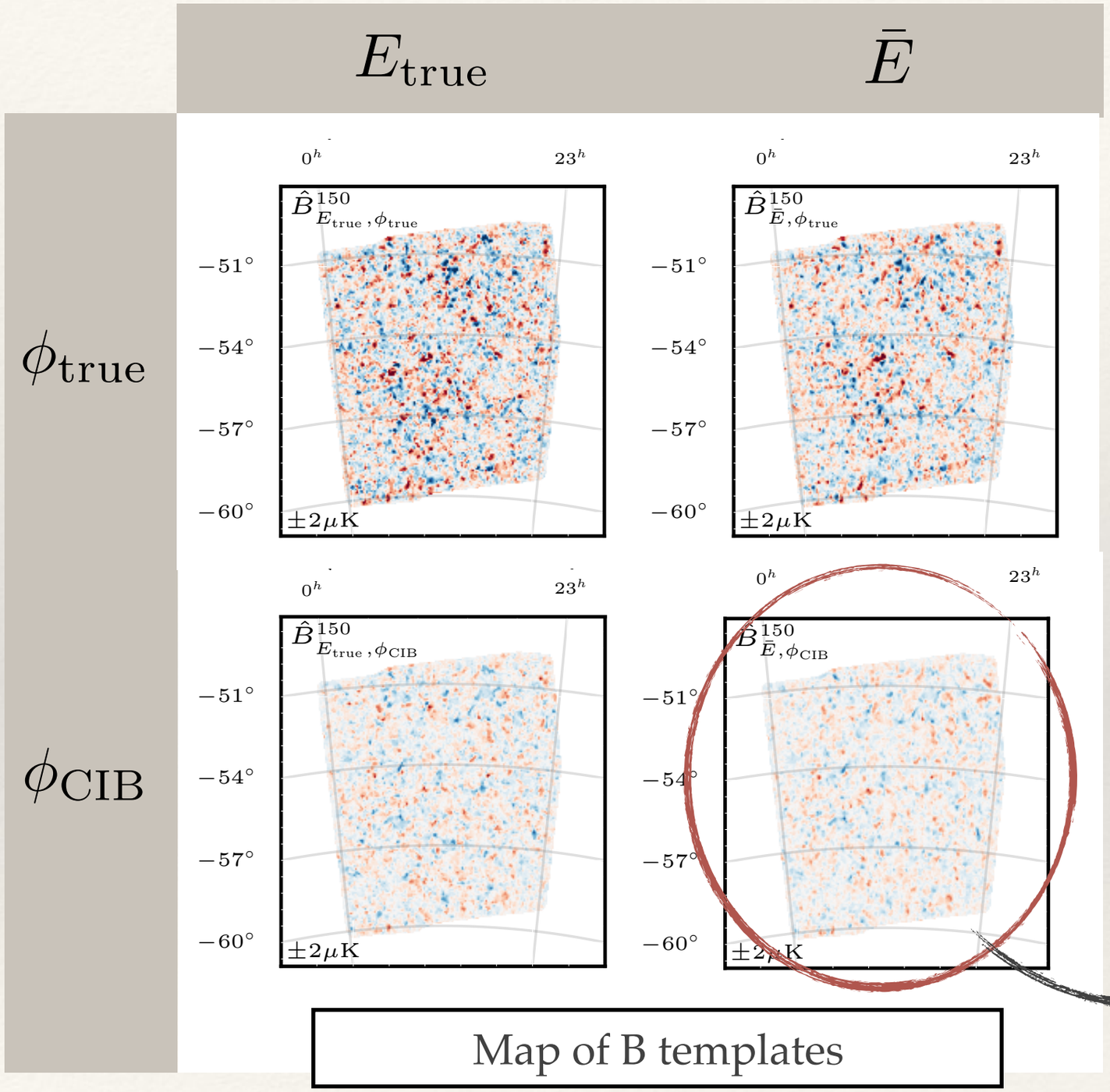
B template

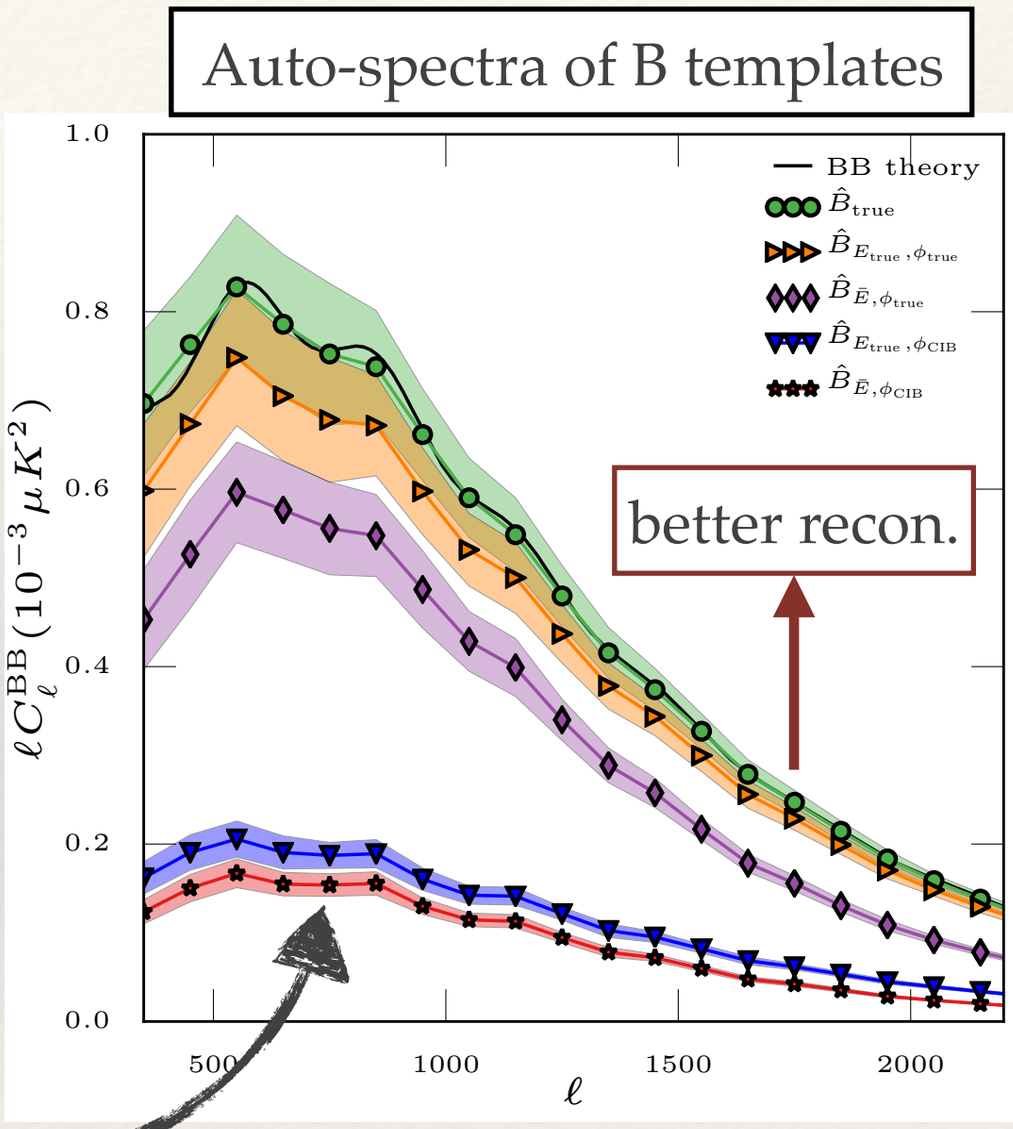


Transfer Function from B map sims

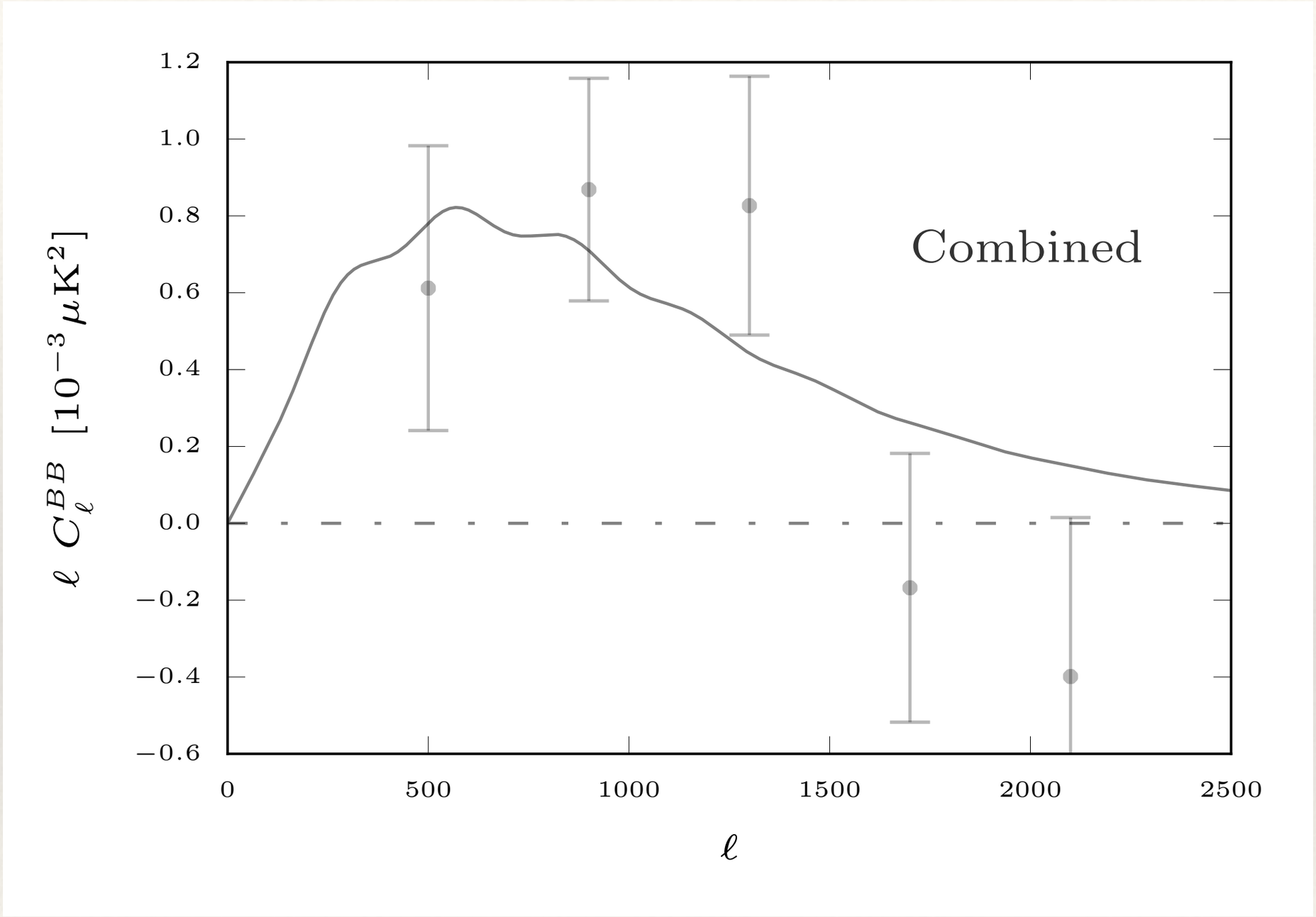


How well we reconstruct lensing B-modes → how well we delens

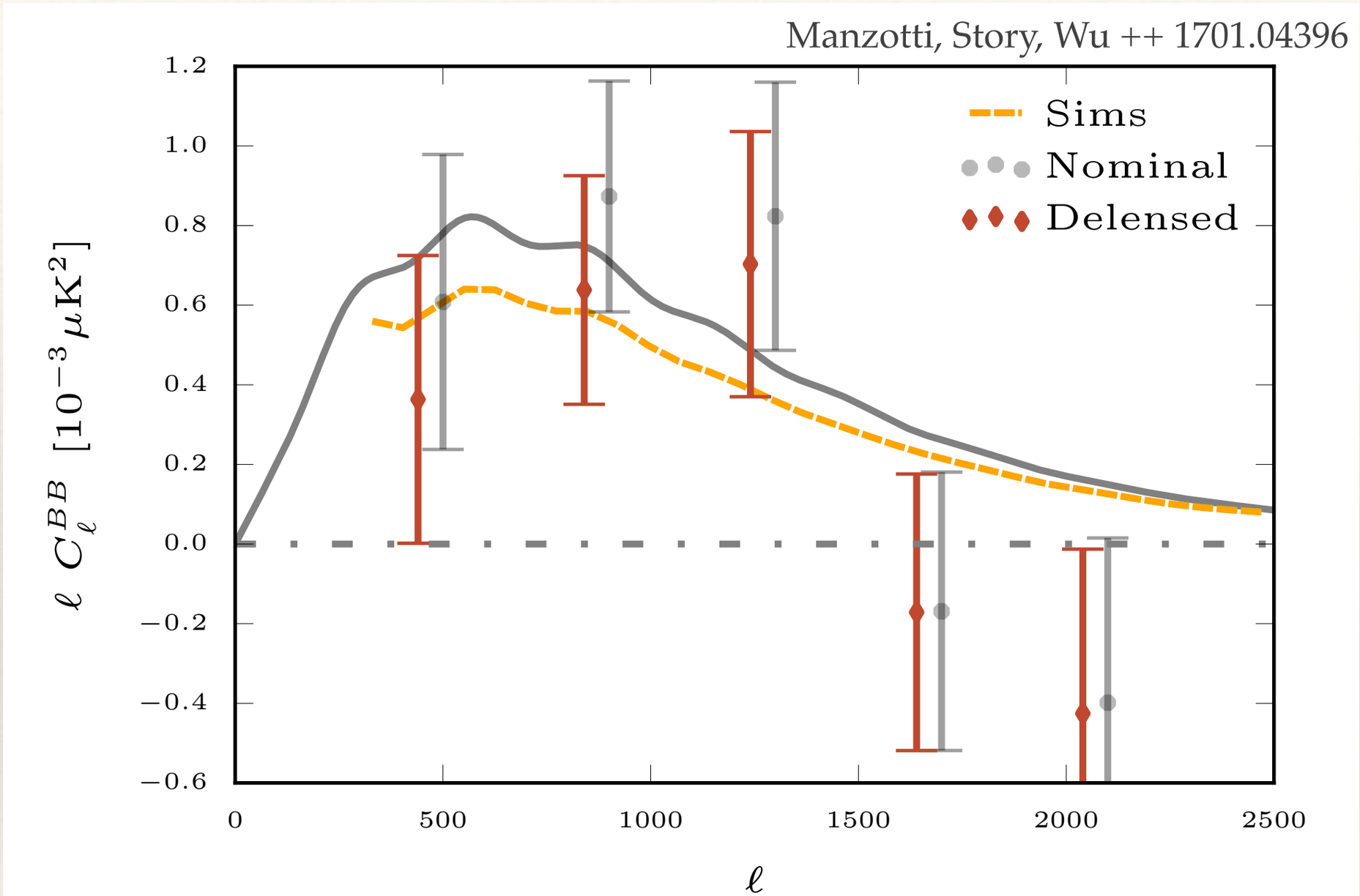




SPTpol BB spectrum (no delensing)



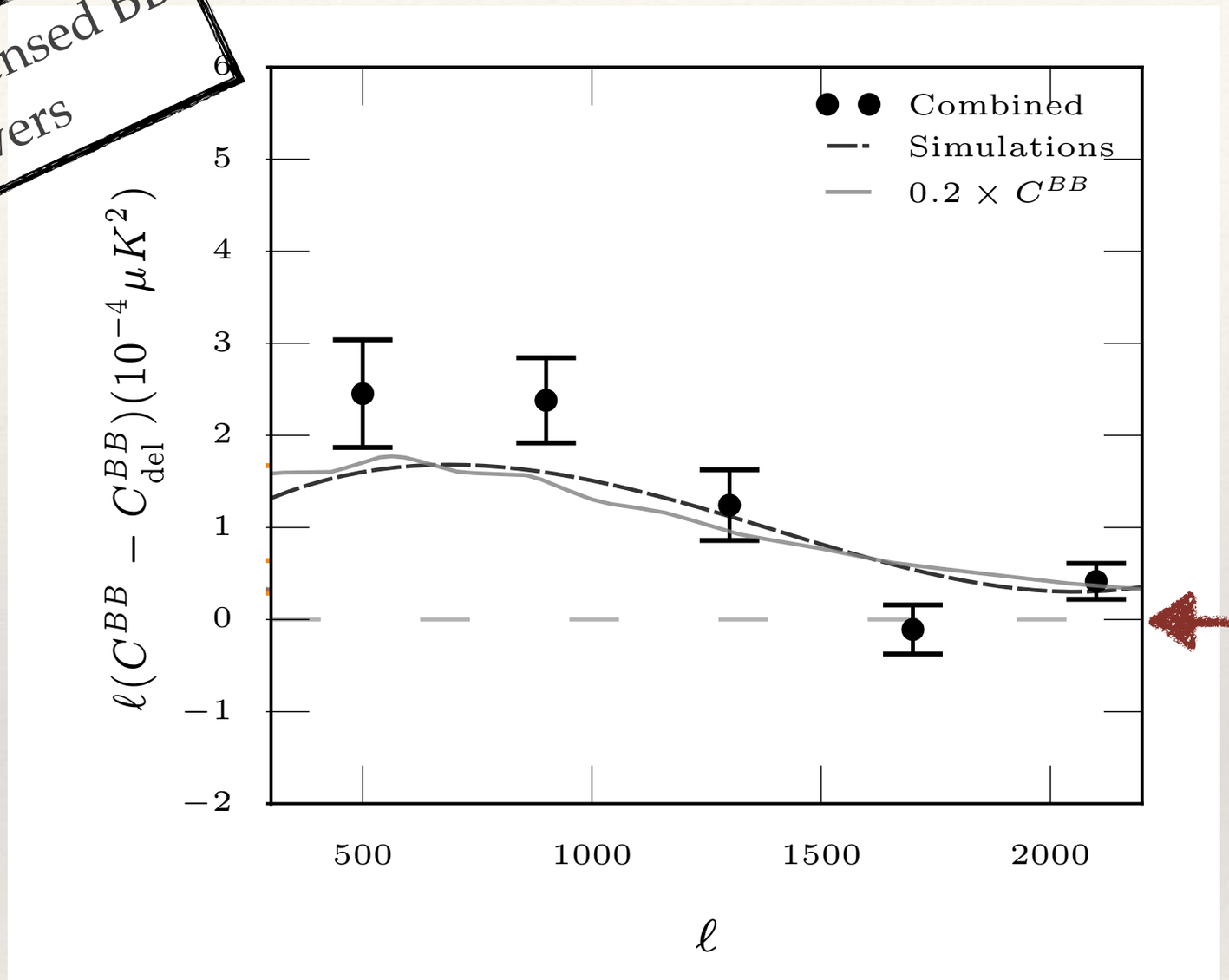
Delensed SPTpol BB spectrum



28% reduction in best-fit A_L
(consistent with expectations from simulations)

Spectrum difference: test no delensing

lensing BB - delensed BB bandpowers

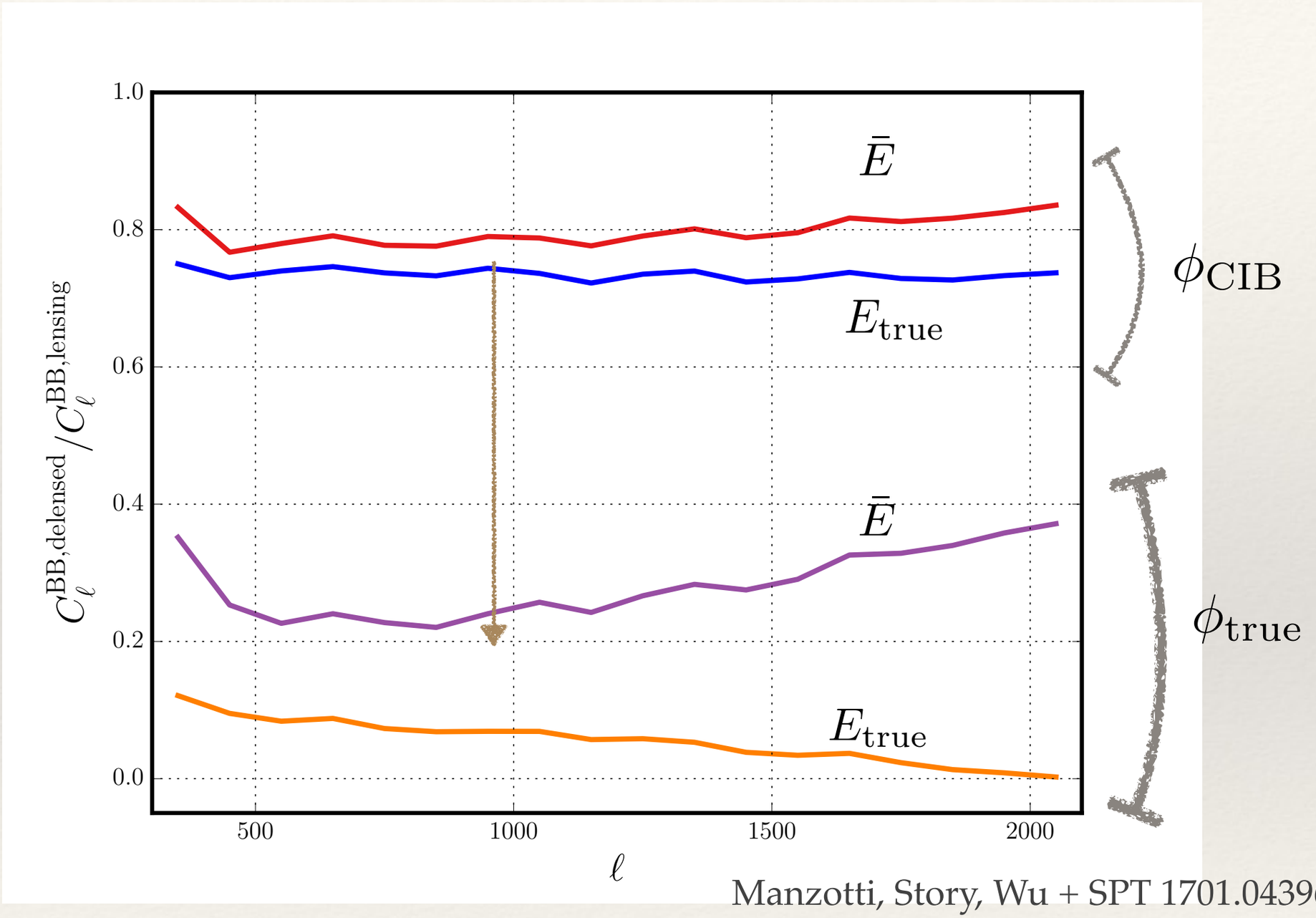


zero,
if no delensing

Reject no delensing at 6.9 sigma

Current limitations to delensing

Less delensing



Manzotti, Story, Wu + SPT 1701.04396

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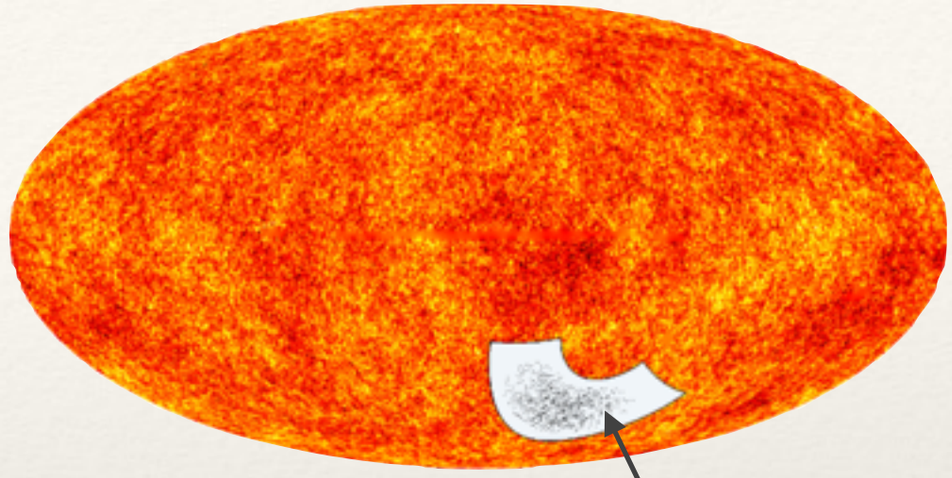
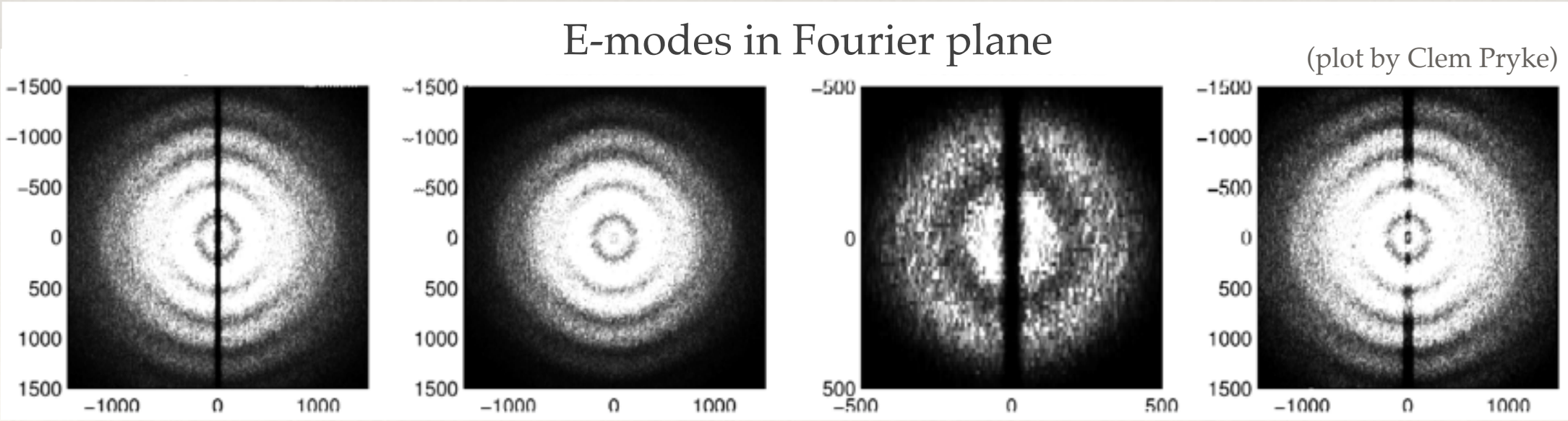
Inputs to BK delensing analysis

- Phi tracer: Planck's CIB map
- Q/U maps: combination of BICEP/Keck, SPTpol, and Planck maps



E-modes in Fourier plane

(plot by Clem Pryke)



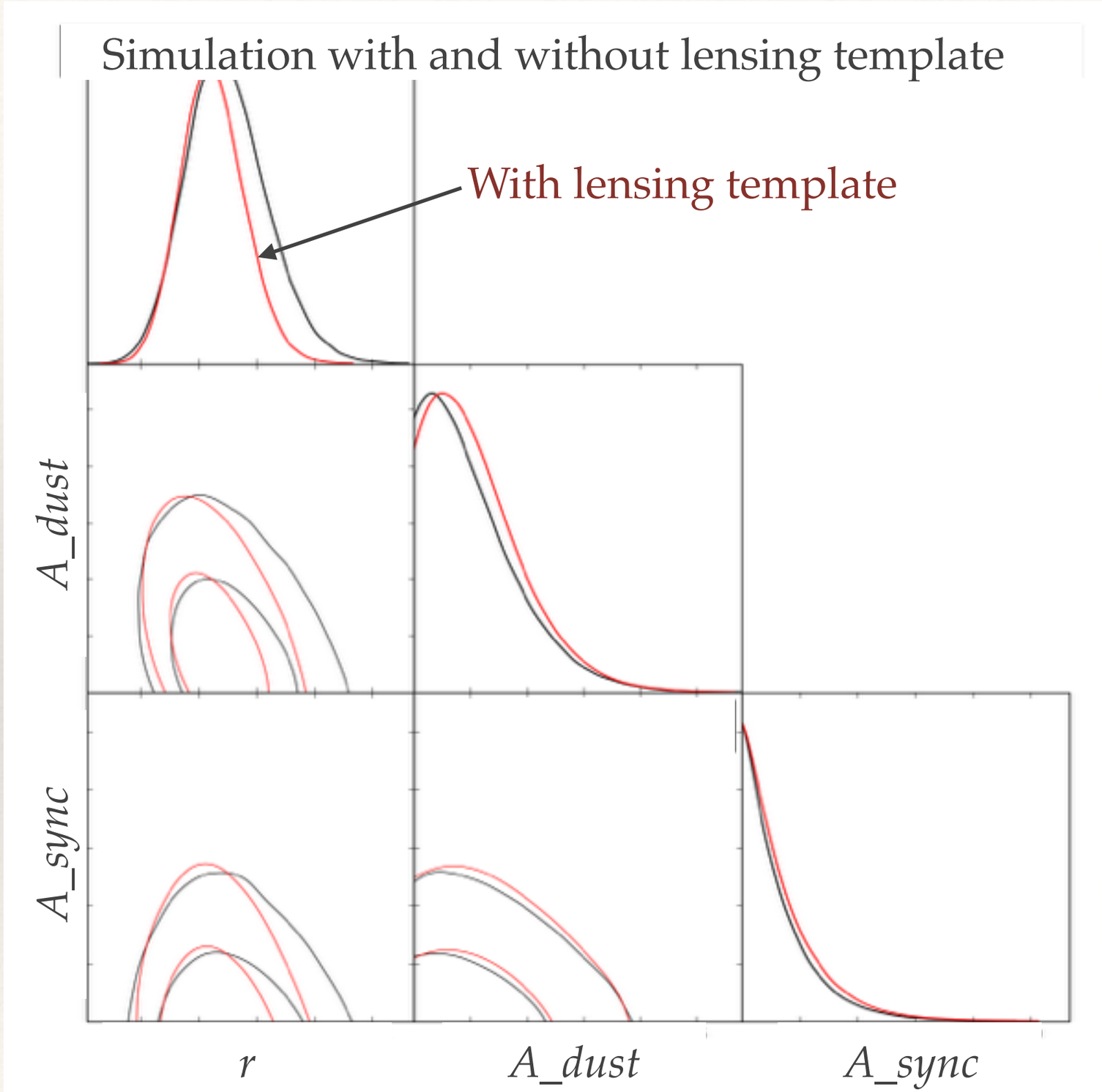
SPTpol | Planck | BICEP/Keck (note different ell-range) | Combined

Lensing template as input in multicomponent analysis

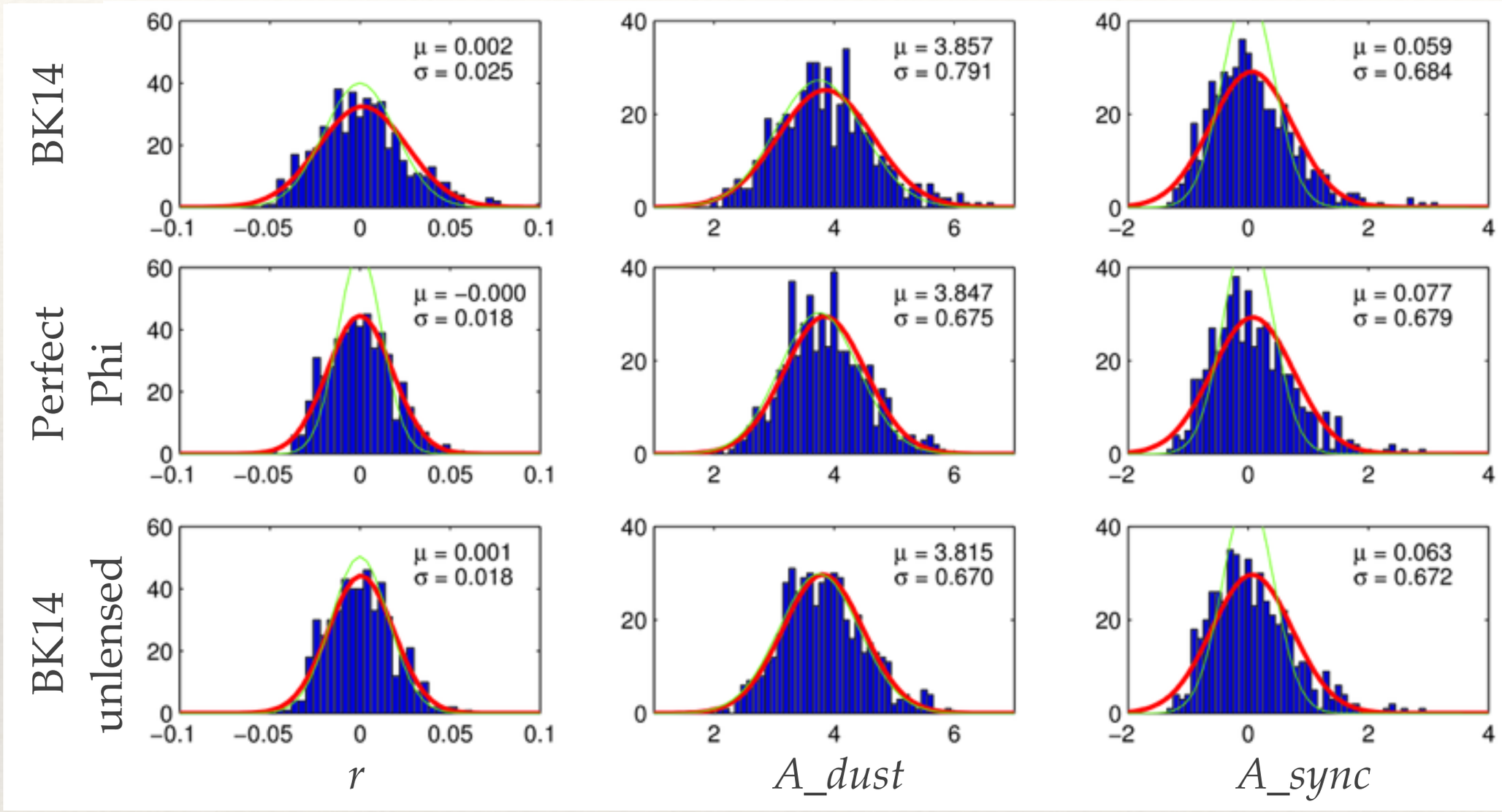
- Instead of subtracting the lensing modes from the maps, use them as input to constrain the lensing component in the multi-component analysis.

- This is similar to using the WMAP/Planck frequencies to constraint galactic dust/ synchrotron components.

- In the BICEP/Keck analysis to constraint *r*, foreground model include galactic dust, synchrotron, and lensing.



How much do we improve sigma(r)?



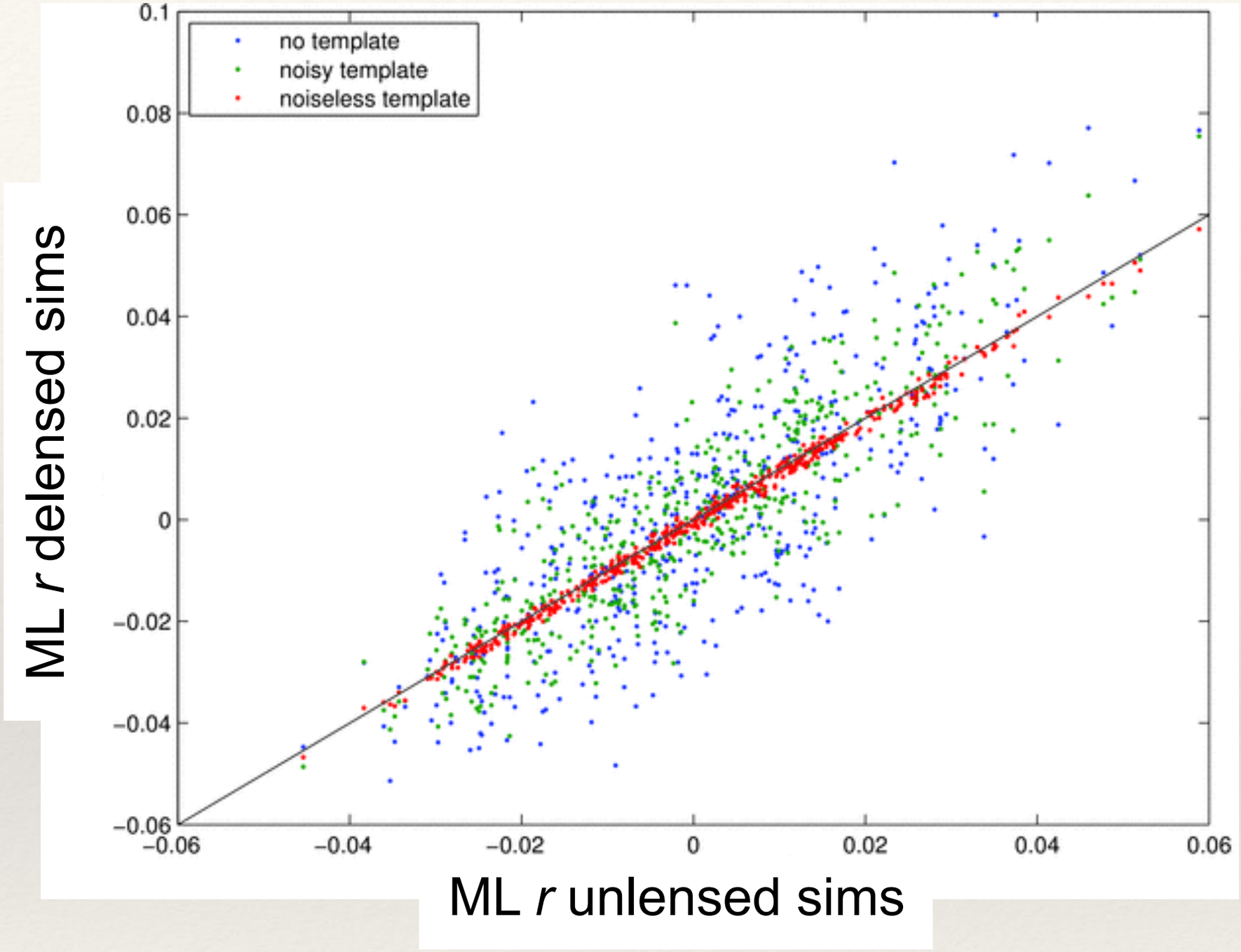
(plot by Colin Bischoff)

- With perfect Phi map (no decorrelation, no noise), adding a lensing template to the BK14 data set improves sigma(r) from 0.025 to 0.018
- Using CIB phi tracer to form the lensing template, sigma(r) improves by ~10% from BK14

Conclusions/Ideas

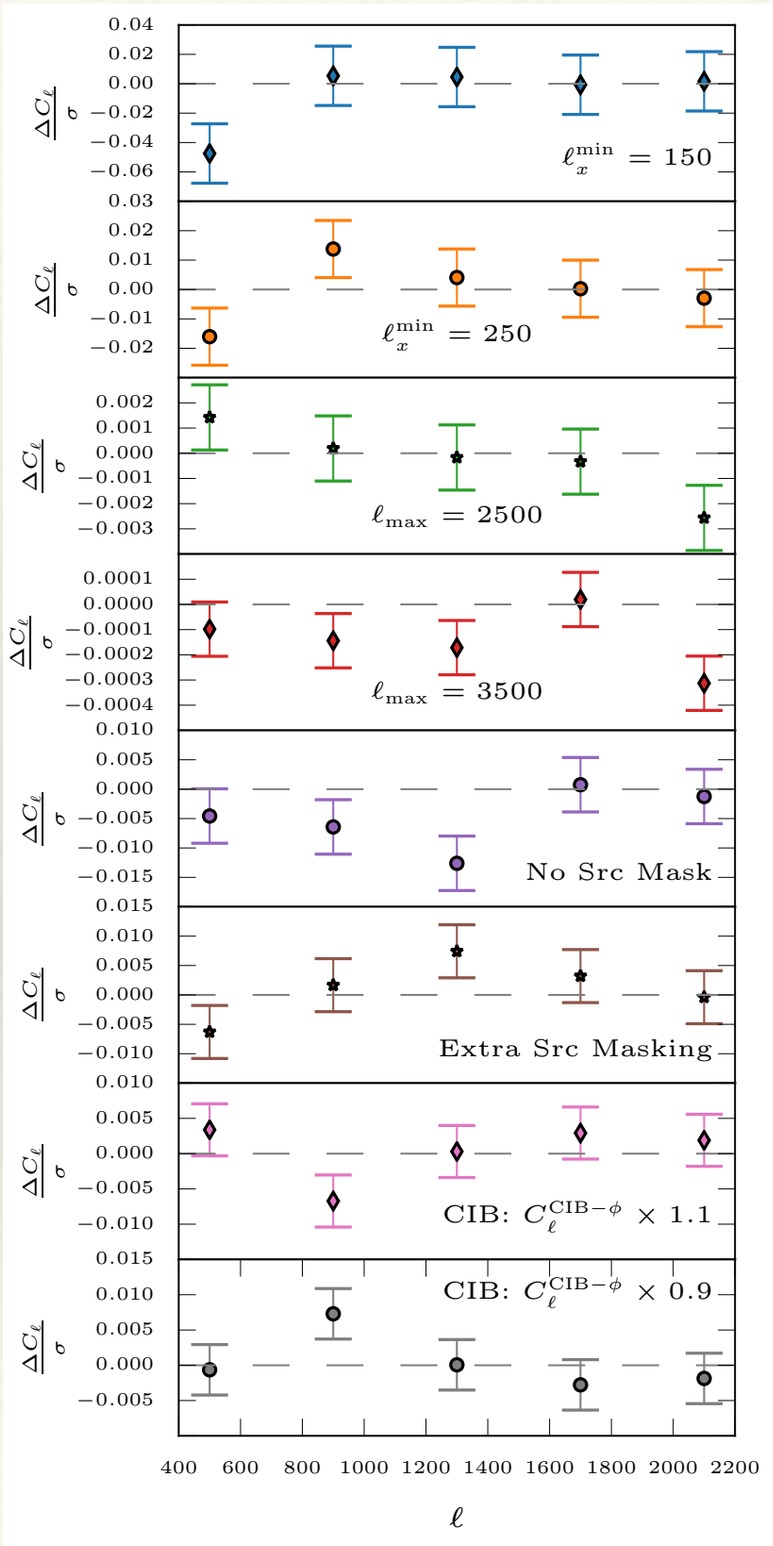
- Using SPTpol and Herschel data, we have demonstrated delensing of B modes. We reduced the best-fit lensing amplitude by 28% and ruled out the no delensing hypothesis at 6.9 sigma.
- Delensing is currently limited by the noise/decorrelation of the Phi tracers.
- Work in progress that demonstrate reduction of sigma(r) through delensing in BICEP/Keck data.
- For satellite experiment like Litebird with low resolution and full-sky coverage, while constraining *r* through the reionization bump does not need delensing, one can get additional check using the recombination bump. To get a good Phi tracer,
  - Can internally reconstruct phi using CMB maps (e.g. BICEP/Keck's phi reconstruction 1606.01968)
  - Can also get CIB internally
  - External tracers available from LSST, Euclid, SKA, and competitive for delensing (e.g. Manzotti 1710.11038)

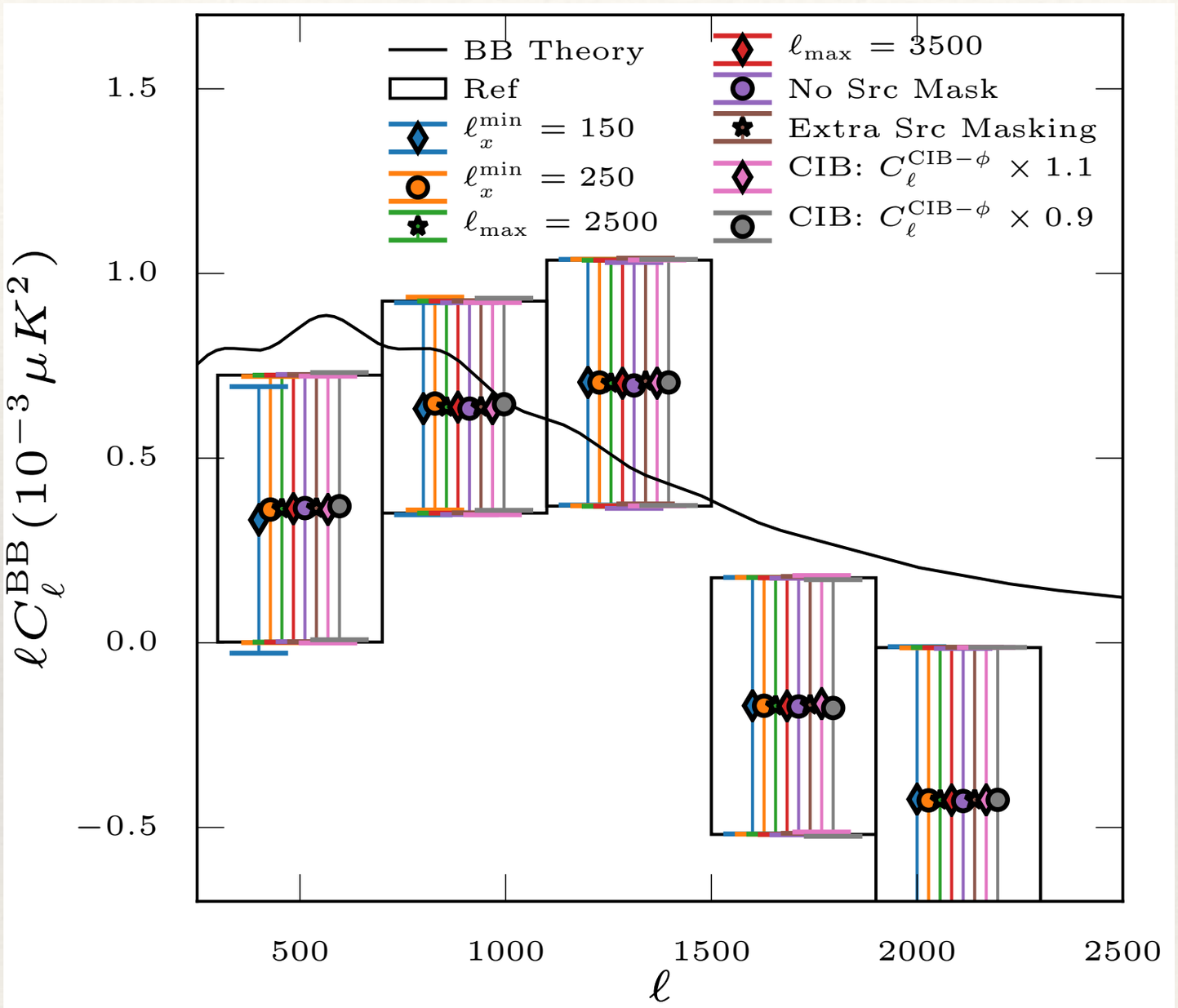
extras



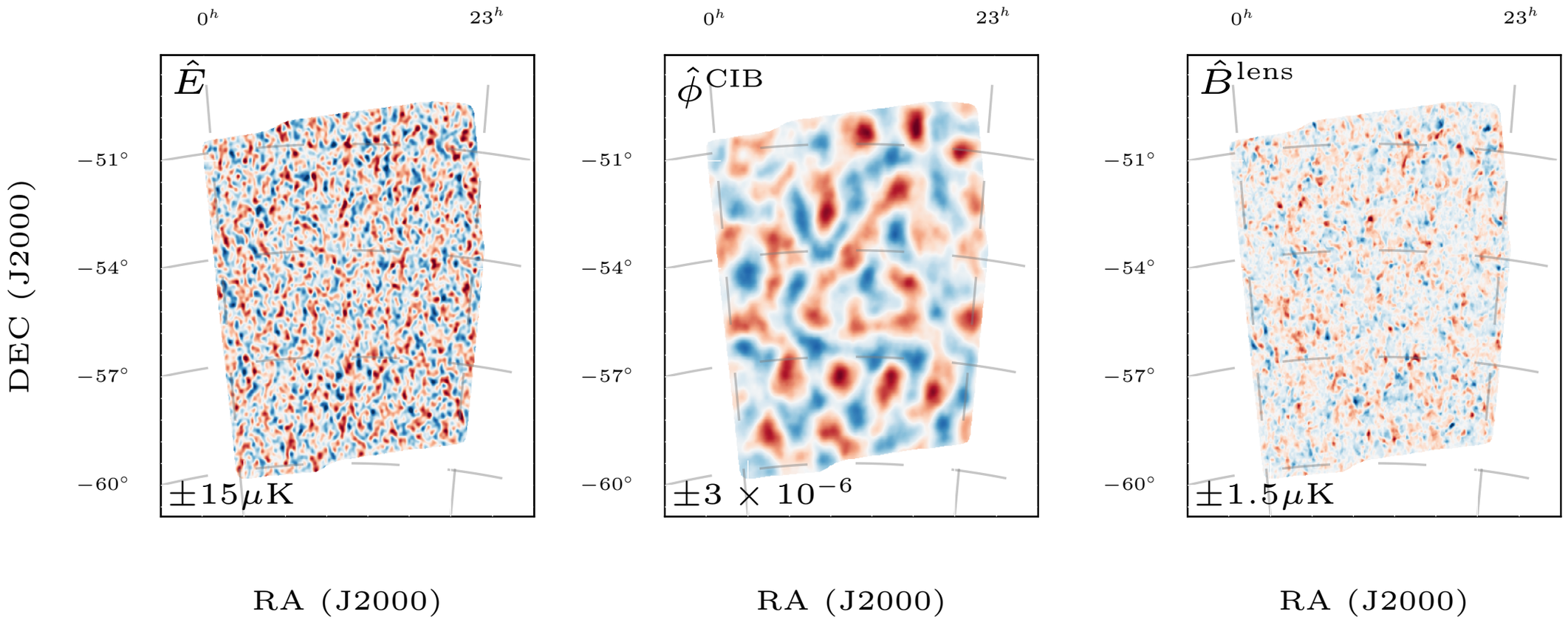
If we have a perfect lensing template then “delensing” works perfectly - the ML *r* values are identical between unlensed and delensed sims on a *realization-by-realization* basis. (red points)

Systematics tests

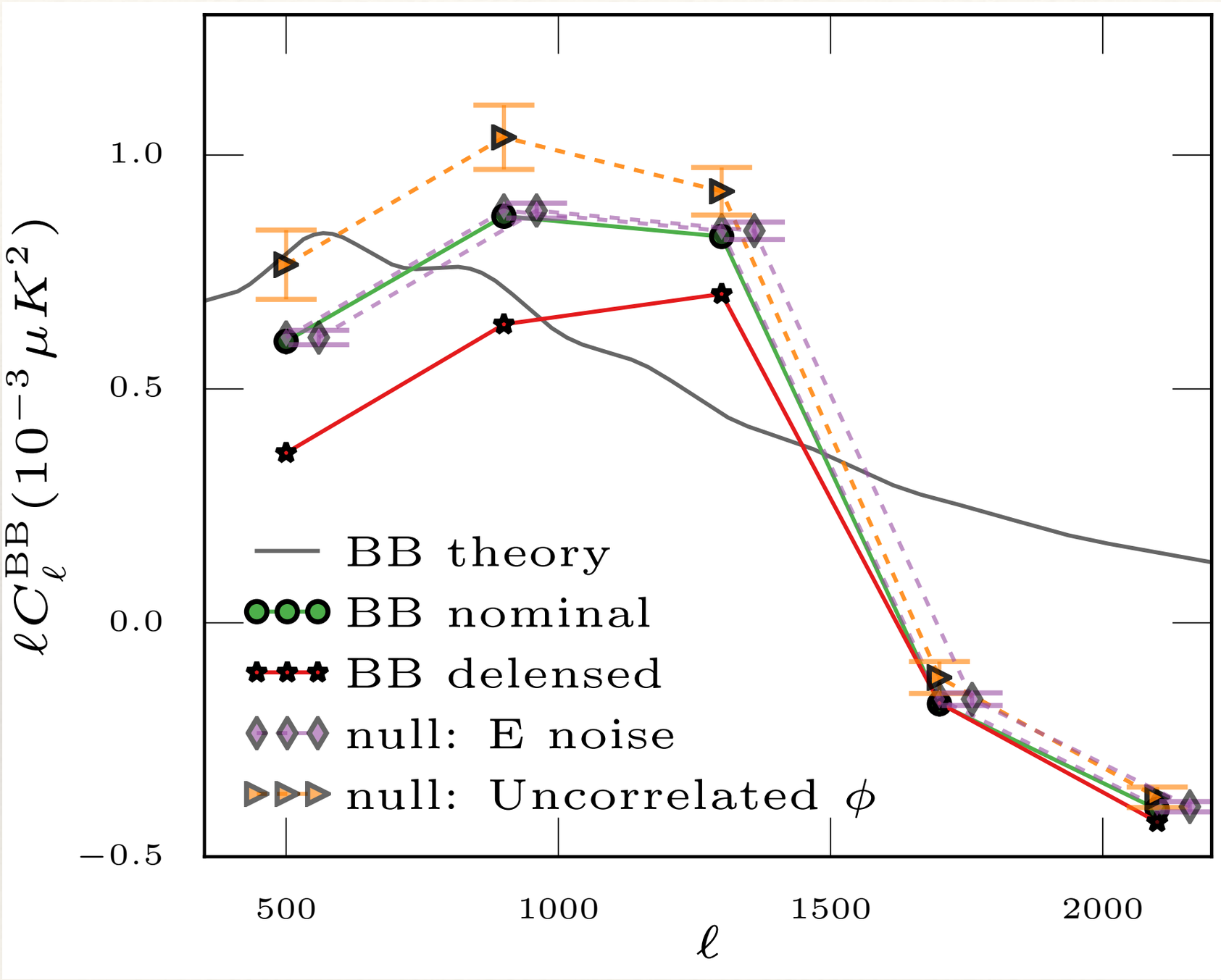




Data maps


$\hat{E}$
$\hat{\phi}^{\rm CIB}$
$\hat{B}^{\rm lens}$
0^h
23^h
$-51°$
$-54°$
$-57°$
$-60°$
$\pm 15\mu$K
$\pm 3 \times 10^{-6}$
$\pm 1.5\mu$K
DEC (J2000)
RA (J2000)
RA (J2000)
RA (J2000)

null tests


1.0
0.5
0.0
−0.5
500
1000
1500
2000
ℓ
$\ell C_\ell^{\rm BB}\,(10^{-3}\,\mu K^2)$
BB theory
BB nominal
BB delensed
null: E noise
null: Uncorrelated ϕ

Understanding delensing efficiency

Delensed BB spectrum:

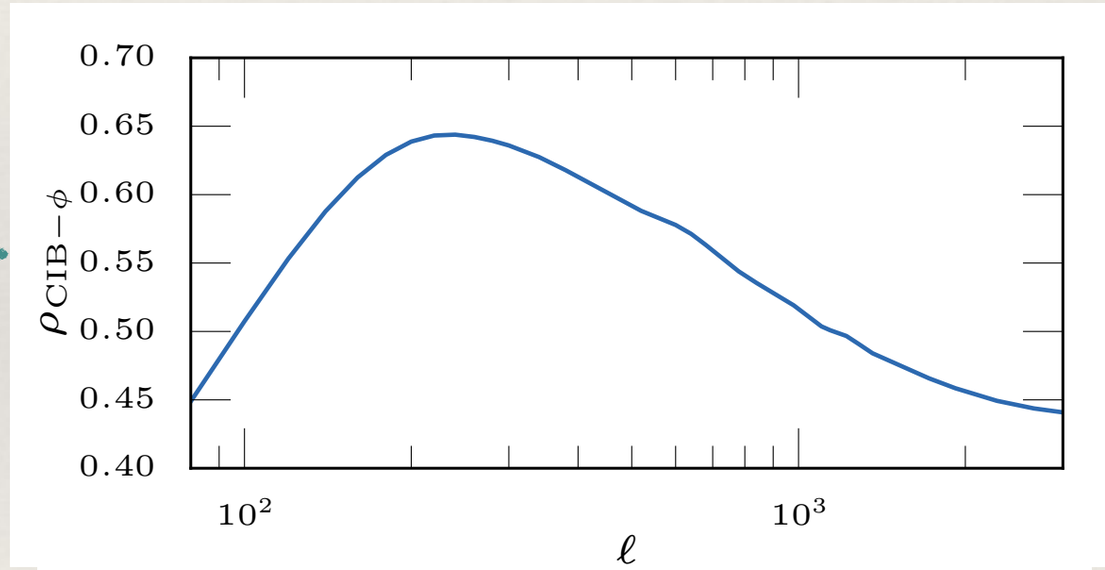
Nominal lensing B

B template part

$$C_\ell^{BB,\mathrm{res}} = \int \frac{d^2\boldsymbol{\ell'}}{(2\pi)^2} W^2(\boldsymbol{\ell},\boldsymbol{\ell'}) C_{\ell'}^{EE} C_{|\boldsymbol{\ell}-\boldsymbol{\ell'}|}^{\phi\phi} \left[1 - \left(\frac{C_{\ell'}^{EE}}{C_{\ell'}^{EE} + N_{\ell'}^{EE}}\right) \rho^2_{|\boldsymbol{\ell}-\boldsymbol{\ell'}|}\right]$$

CIB-phi cross-correlation

$$\rho_\ell = \frac{C_\ell^{\text{CIB-}\phi}}{\sqrt{C_\ell^{\text{CIB-CIB}} C_\ell^{\phi\phi}}}$$



Factors affecting delensing efficiency:

- E noise
- phi 'noise' (decorrelation)
- Non-idealities in E/phi signal