Image credit: Steffen Richter

CMB polarization B-mode delensing with SPTpol and Herschel

(arXiv:1701.04396)

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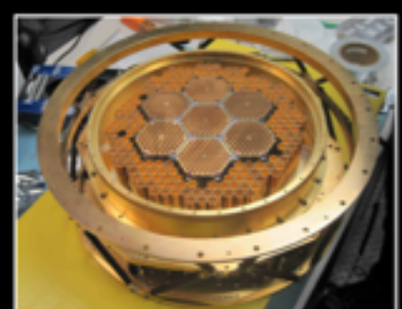
UC Berkeley —> UChicago
Croucher Fellow —> KICP Fellow

Fermilab DPF
August 1st, 2017

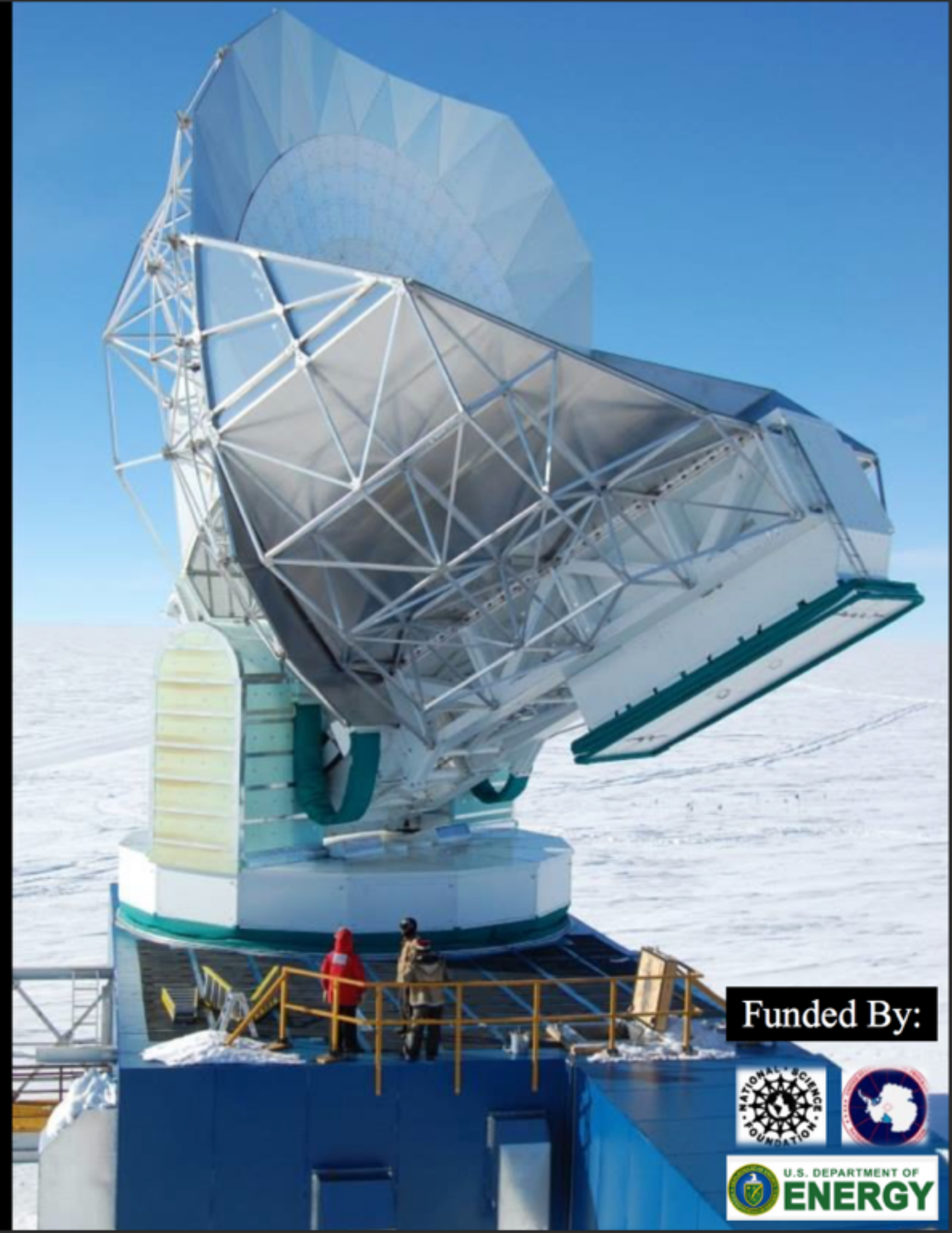
The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

2012: SPTpol
1600 detectors
95,150 GHz
+Polarization

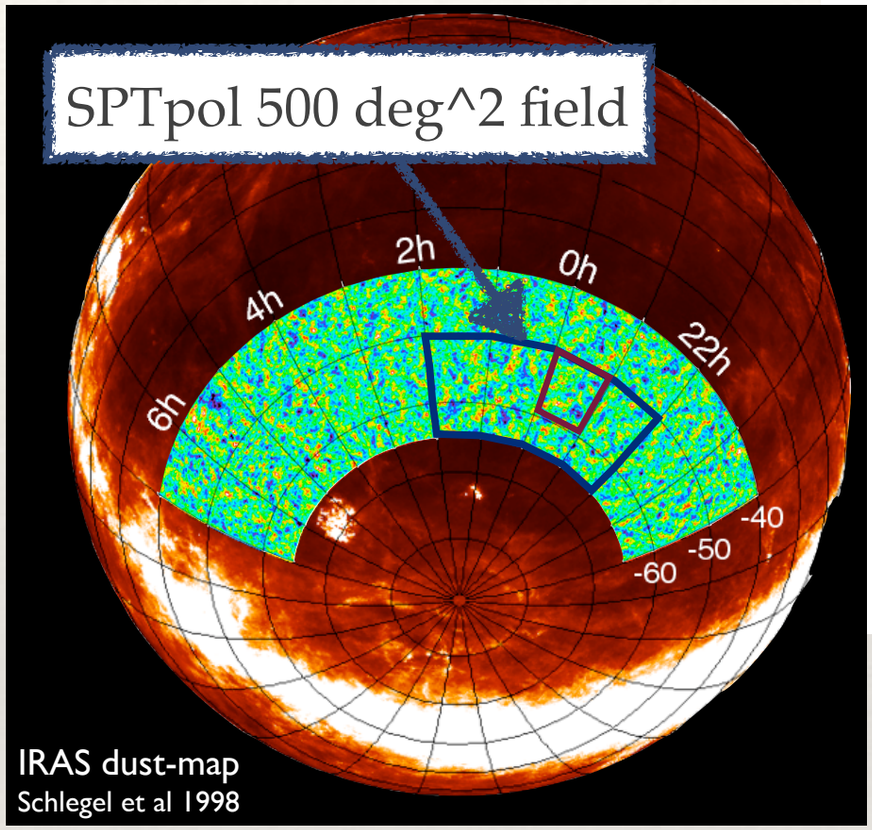


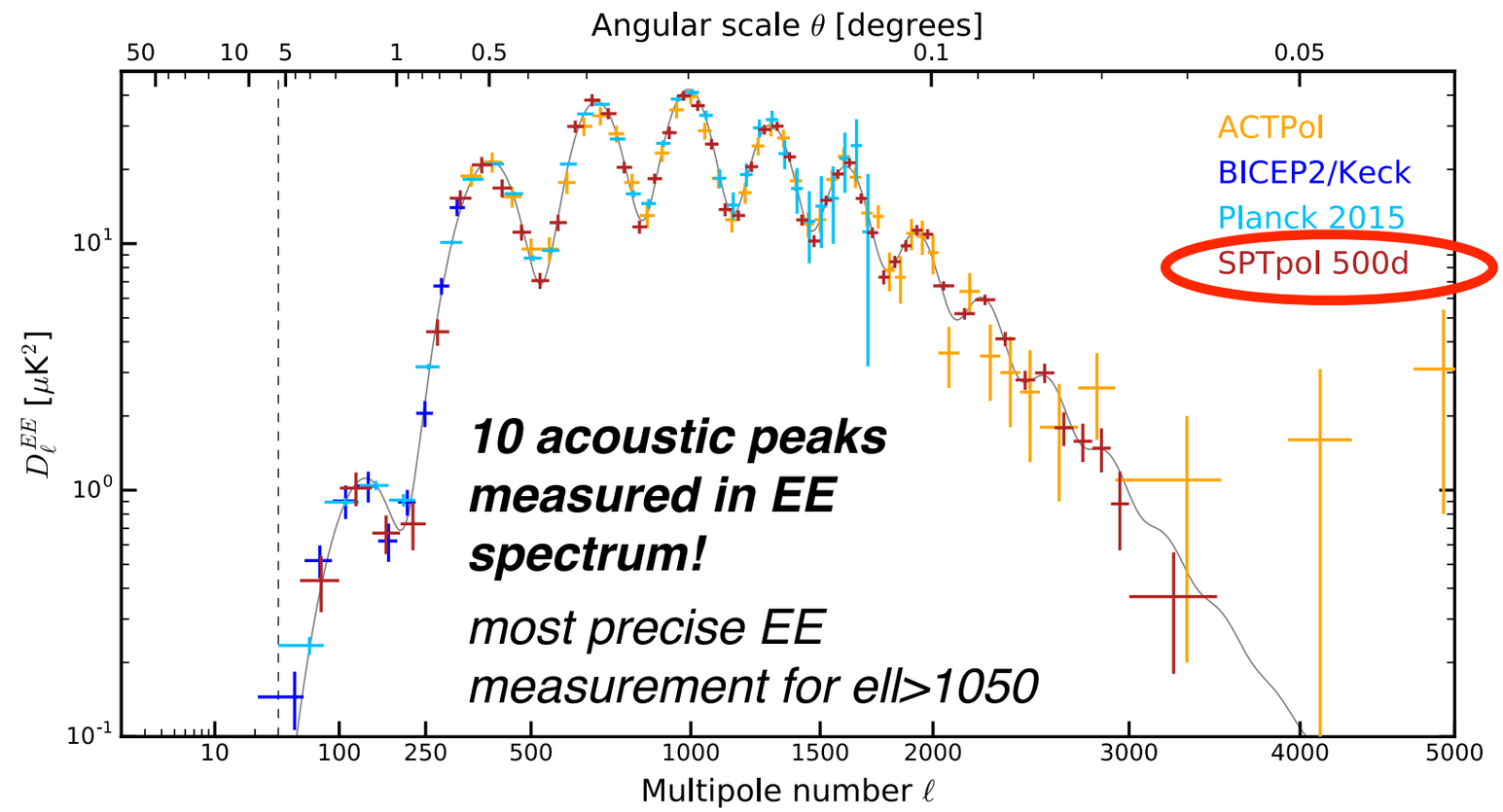
Collaborators:
Alessandro Manzotti, Kyle Story
+ SPTpol collaboration

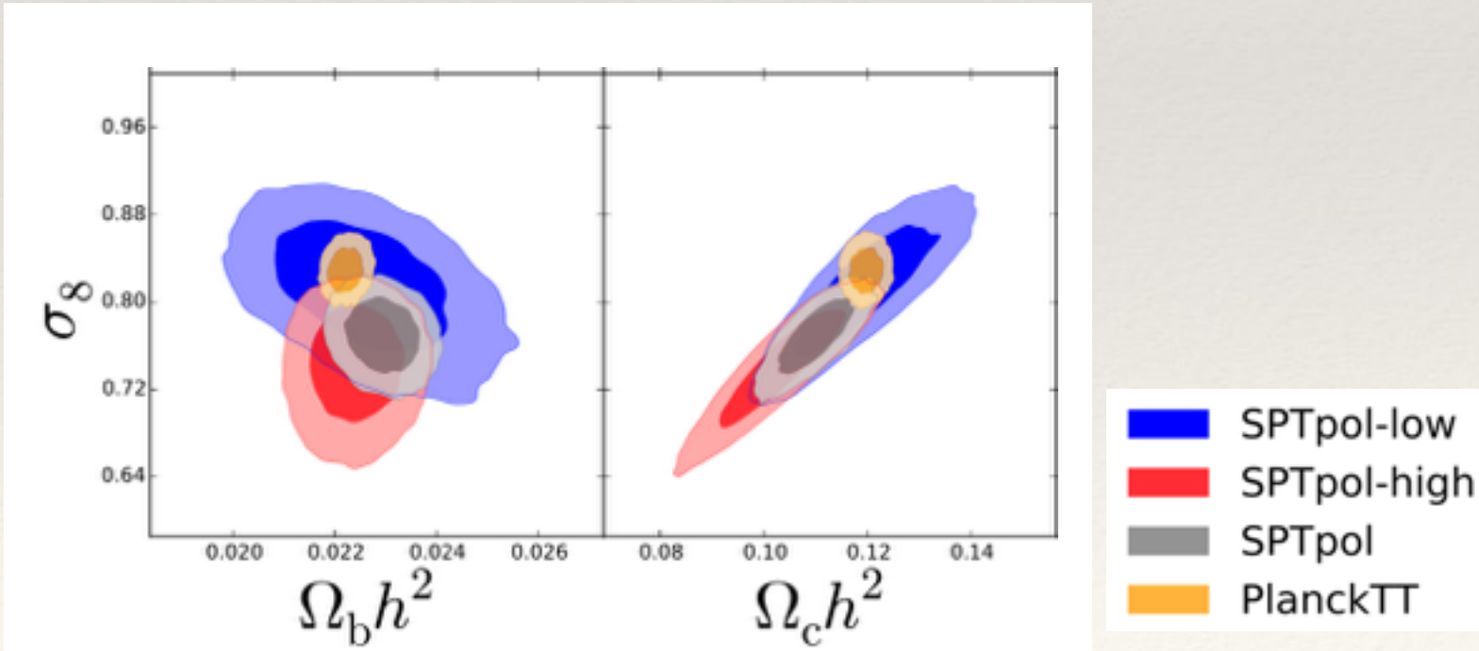


Funded By:

New 500d TE, EE results are out!





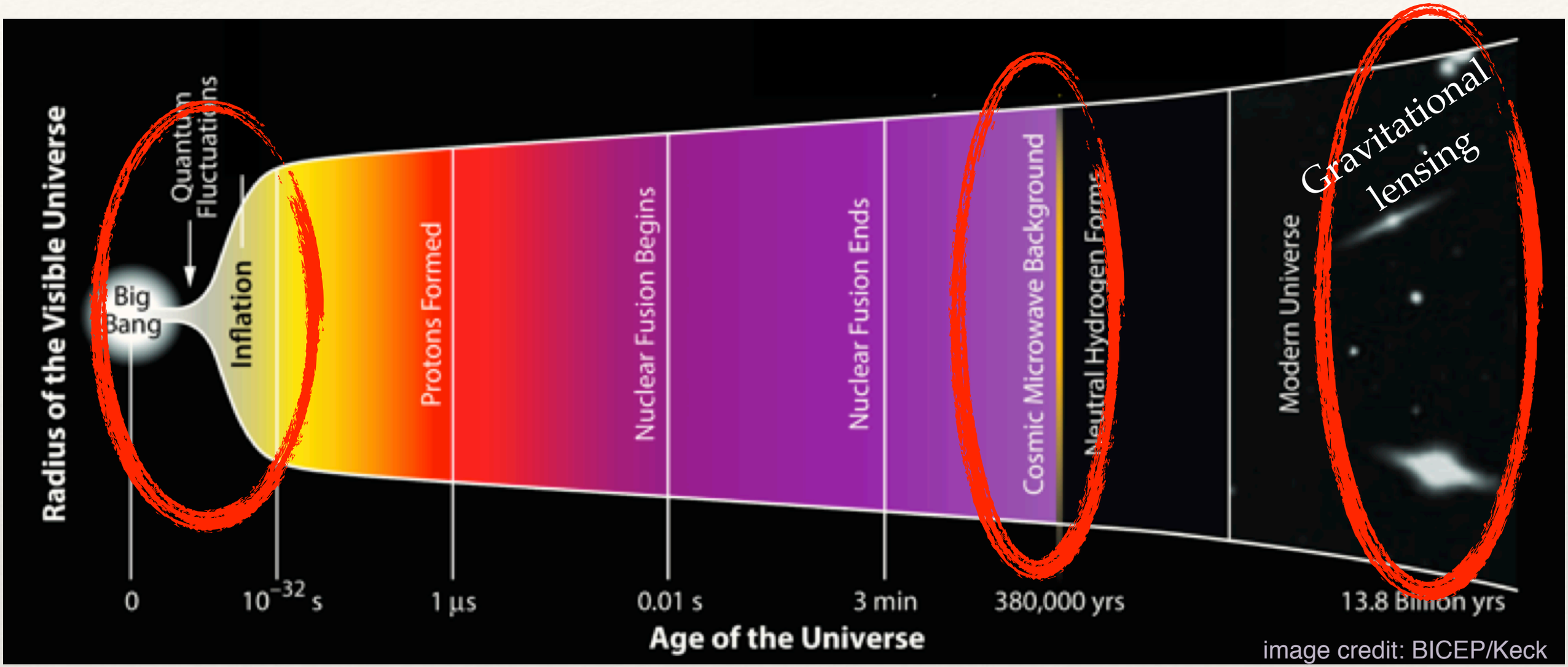


(SPTpol) Henning+ (2017)
arXiv: 1707.09353
on arXiv yesterday!!!

Outline

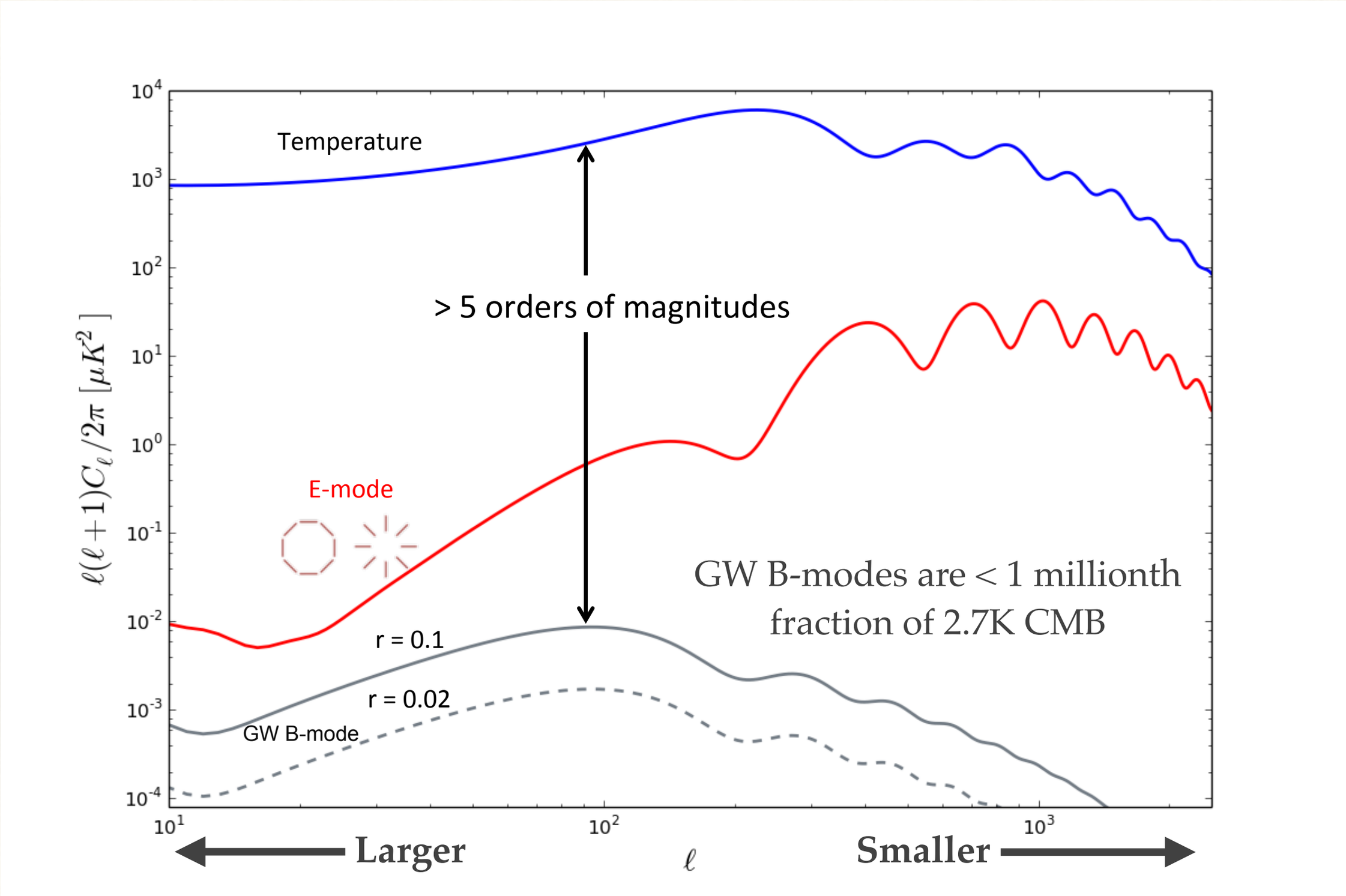
- Background on B-modes and delensing
- Approach to delensing + Results
- Delensing efficiency + Outlook

Inflation and B-mode polarization

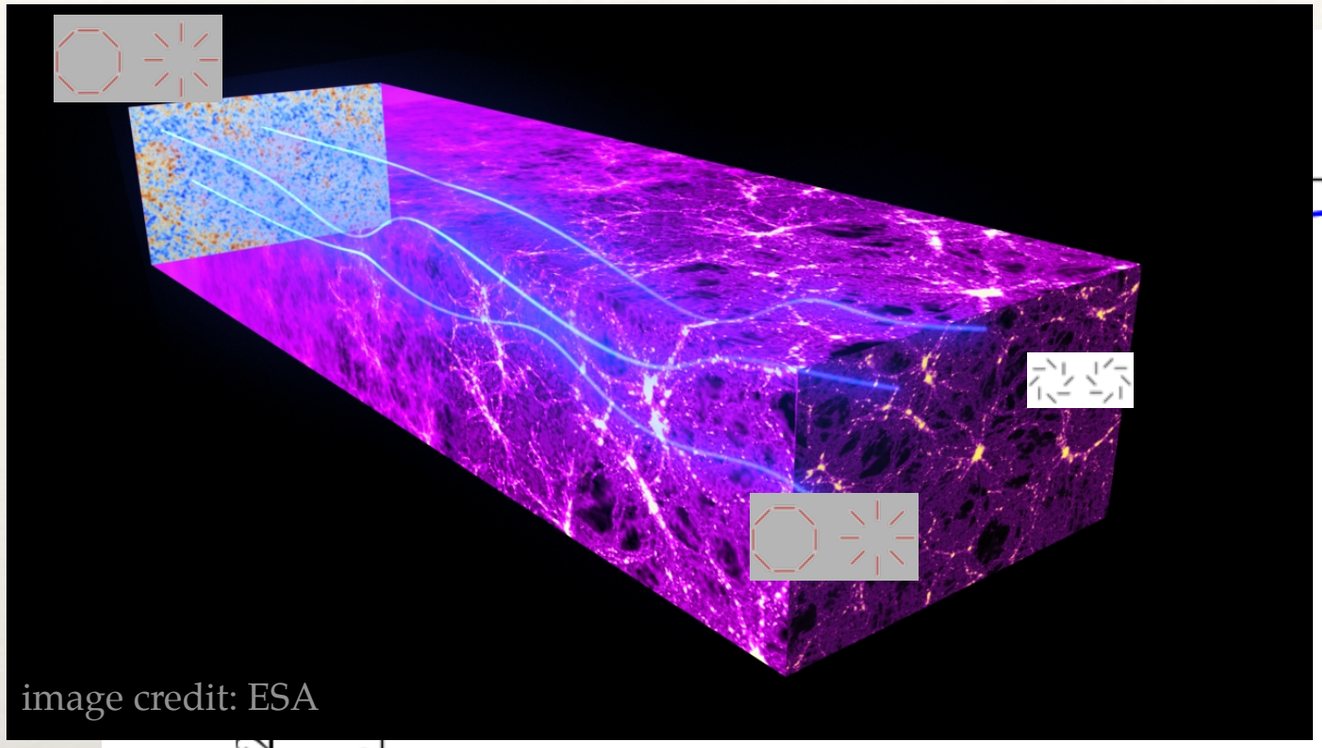


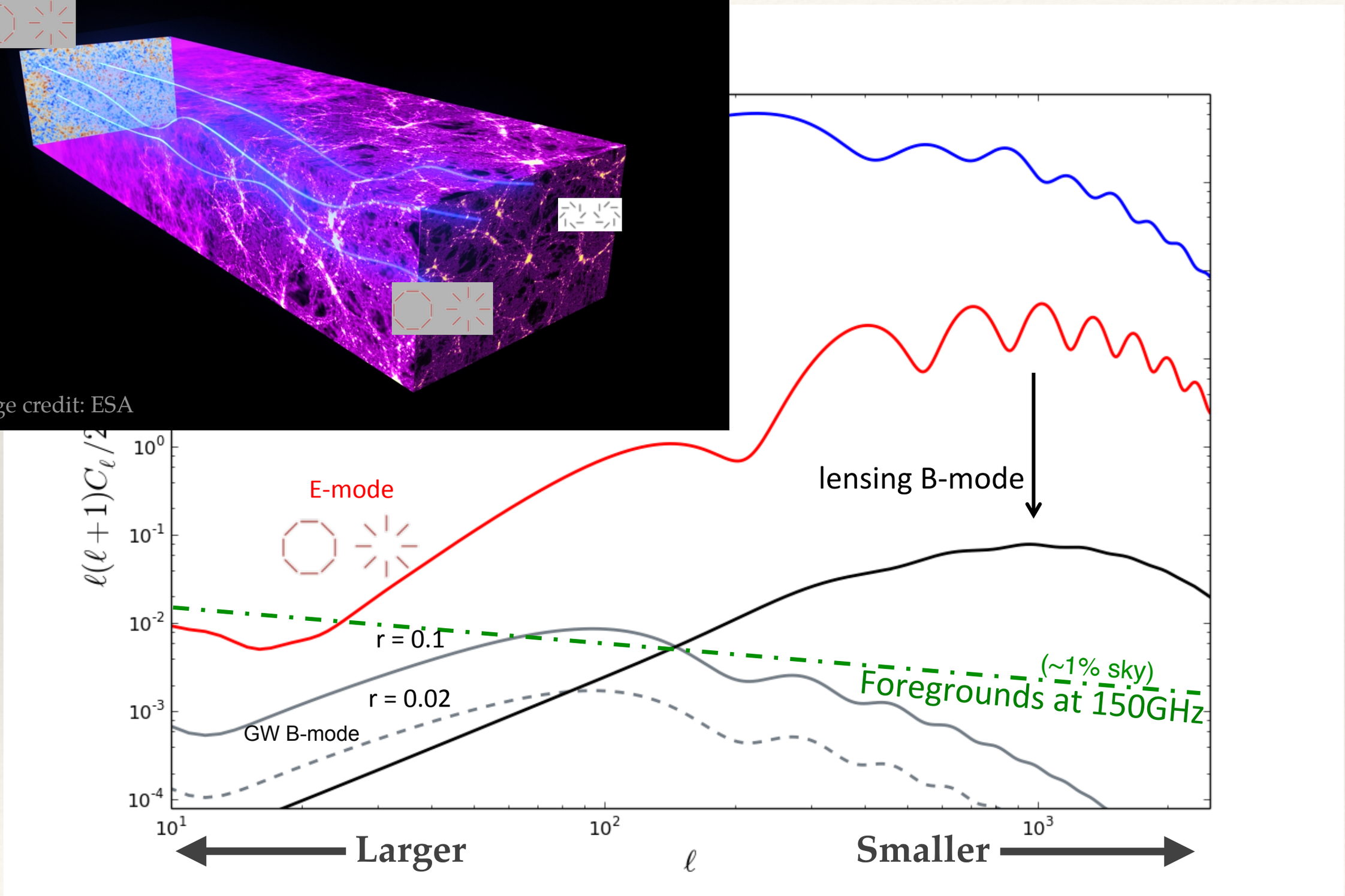
- In LCDM, primordial gravitational waves (tensor-perturbations of the metric) are the only source that imprints B-mode polarization on the CMB at recombination.
- *r* is useful for e.g. determining the energy-scale of inflation, whether inflation is large or small field, and ruling out inflationary models that predicts *r* values.
- CMB primordial B modes provide a unique window to *r*.

Measuring GW B-modes is hard: CMB anisotropy spectra



CMB spectra + foregrounds



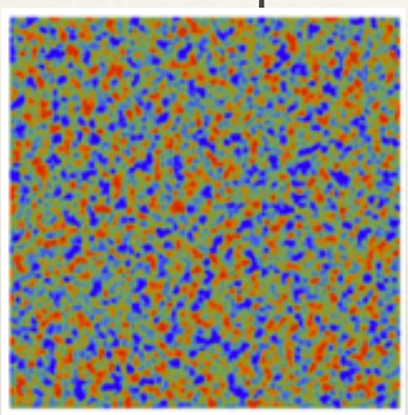


We need delensing

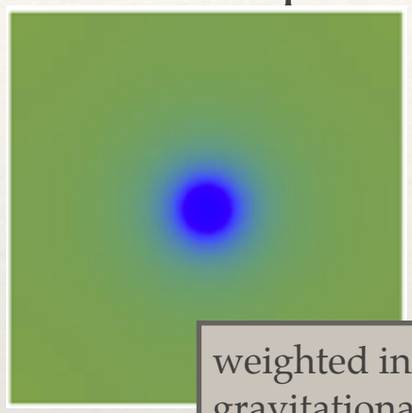
Delensing: the idea

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

E map



Phi map



weighted integral of gravitational potential between us and CMB along line of sight

B template

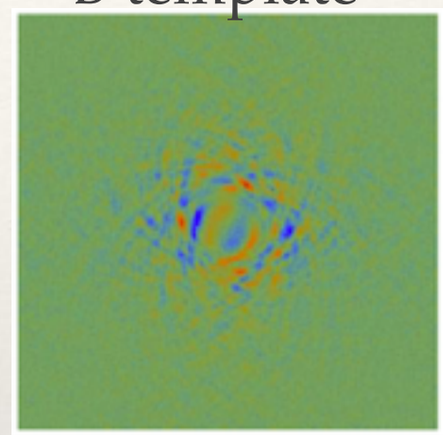


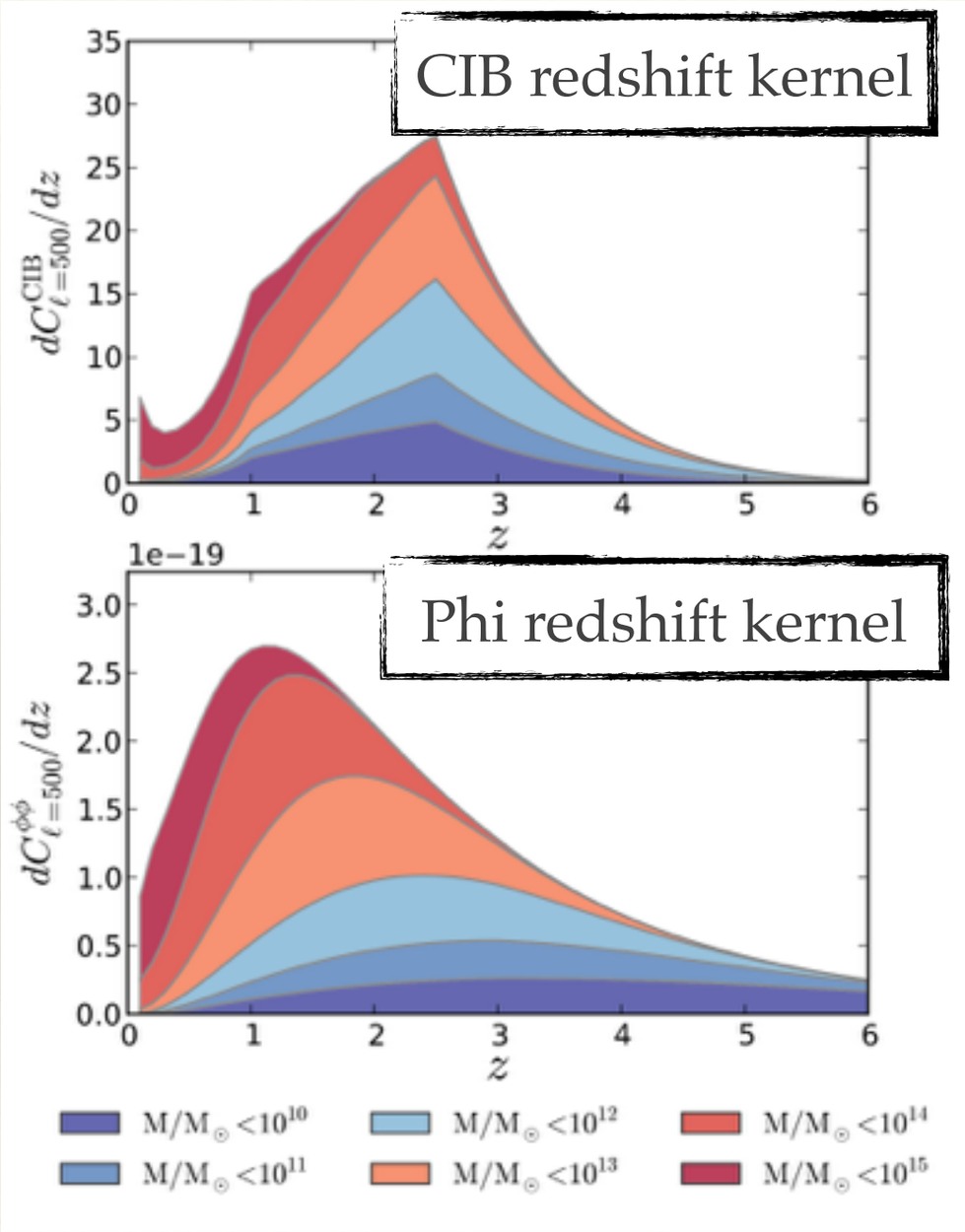
Image credit: Hu & Okamoto (2002)

2. Subtract B template from B map

B map → B template → Delensed B map

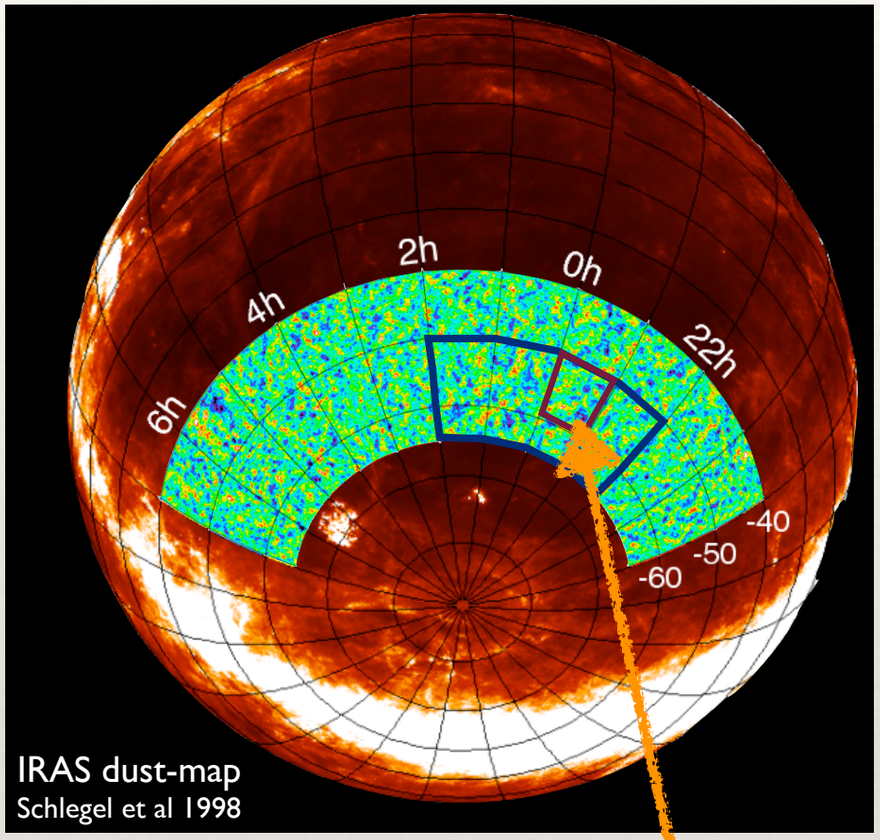
CIB as a Phi tracer

- 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

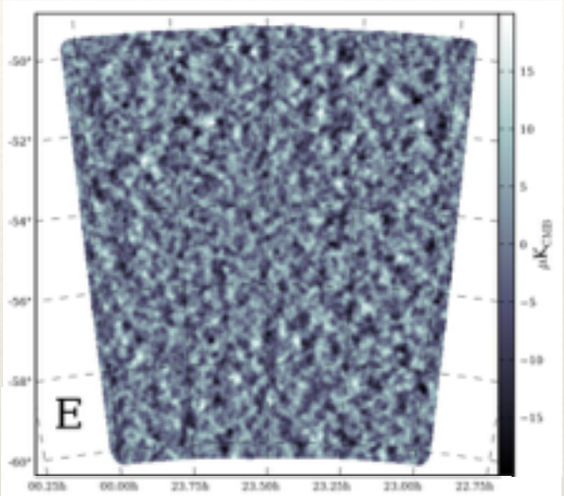
Lensing B template to delens SPTpol B modes



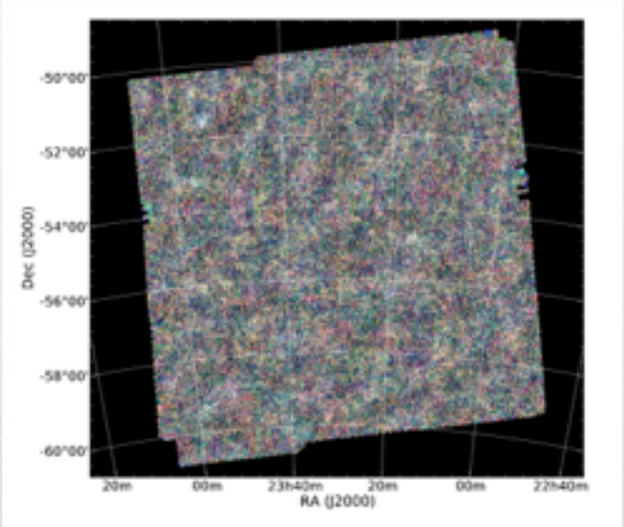
SPTpol 100 deg^2 field

Inputs to form the B template

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

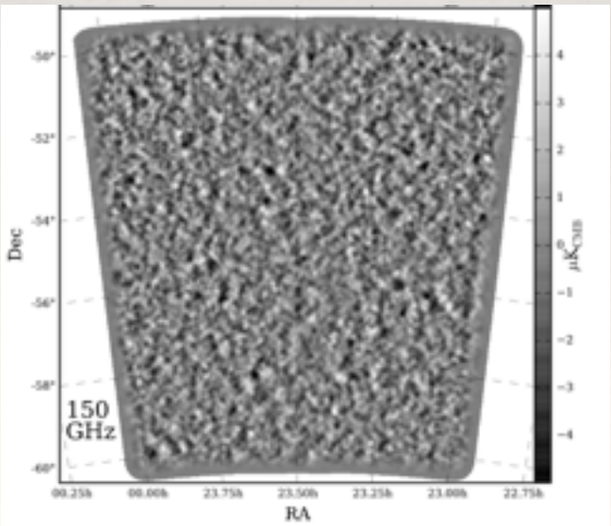


CIB map from Herschel 500μm map



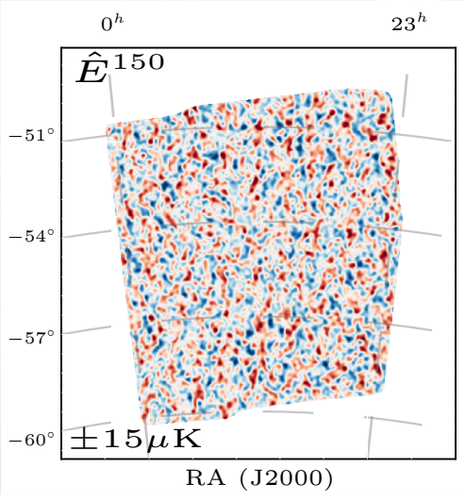
B-mode map to be delensed

(Keisler et al., SPT 2015)



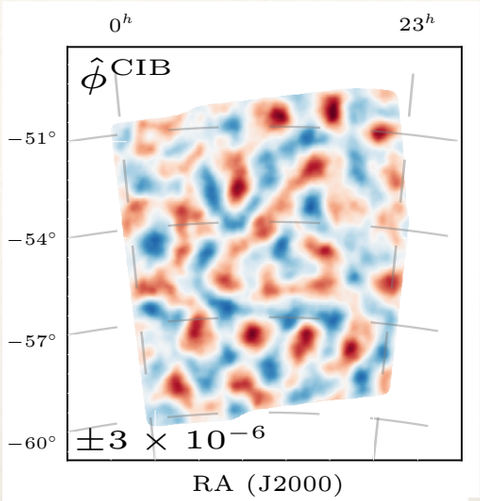
Delens

filtered E map



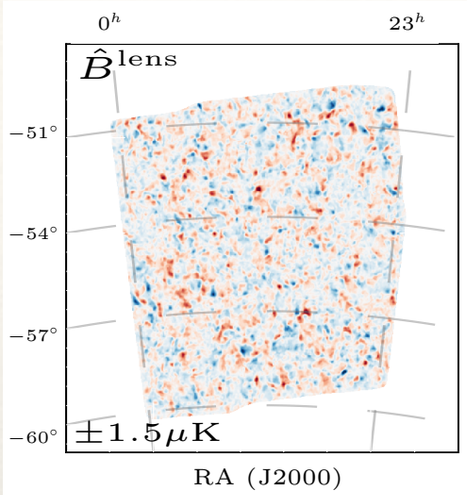
$\otimes$

filtered Phi estimate



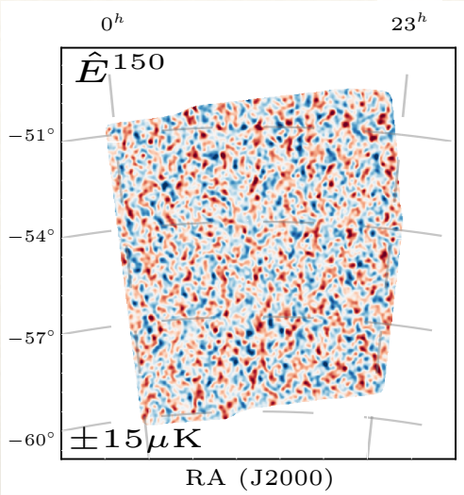
$\longrightarrow$

B template

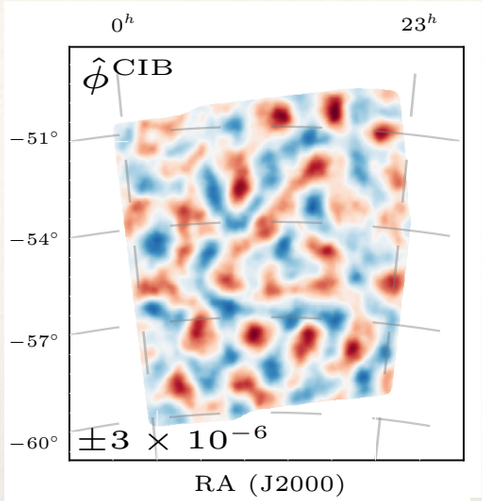


Delens

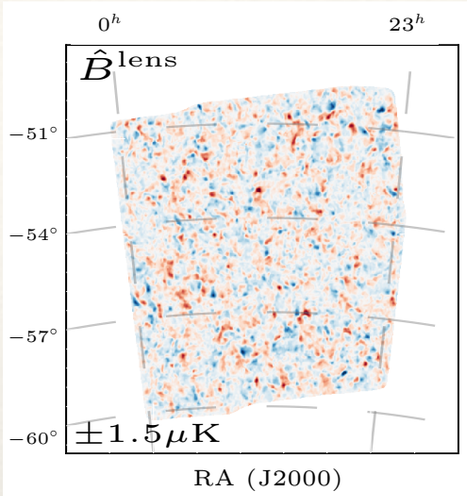
filtered E map



filtered Phi estimate



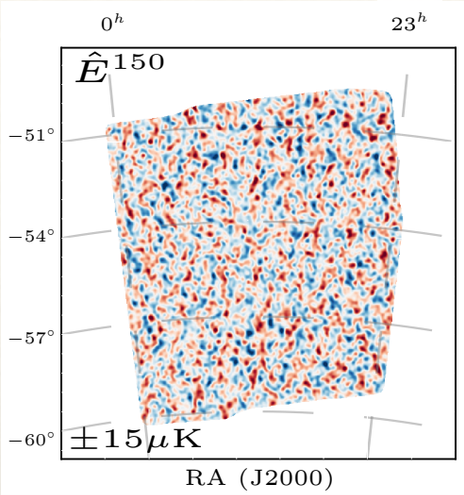
B template



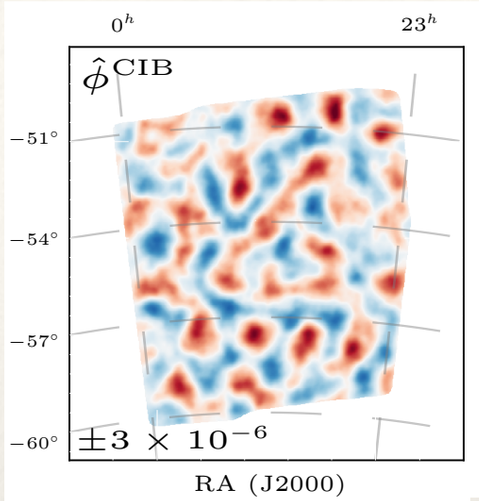
To ensure 'fair subtraction', apply 2D transfer function
on the B template before subtracting from B mode map

Delens

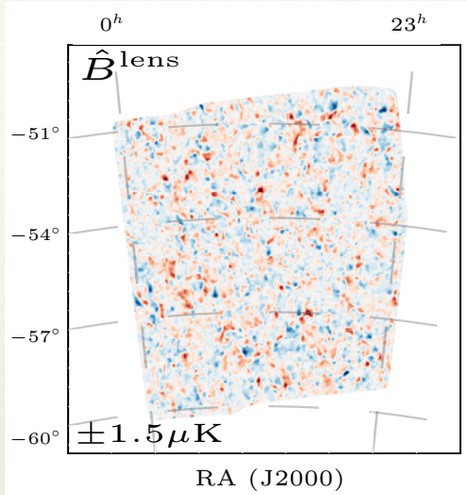
filtered E map



filtered Phi estimate



B template



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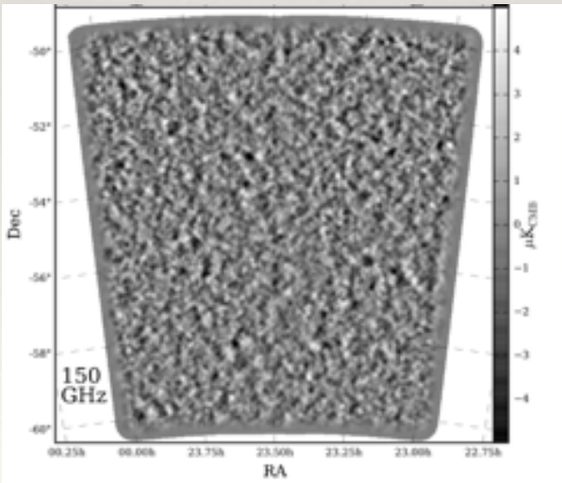
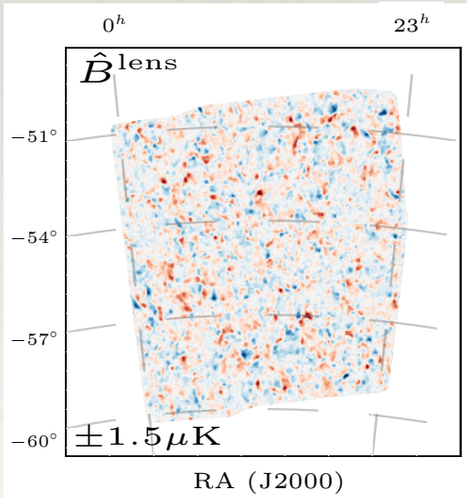
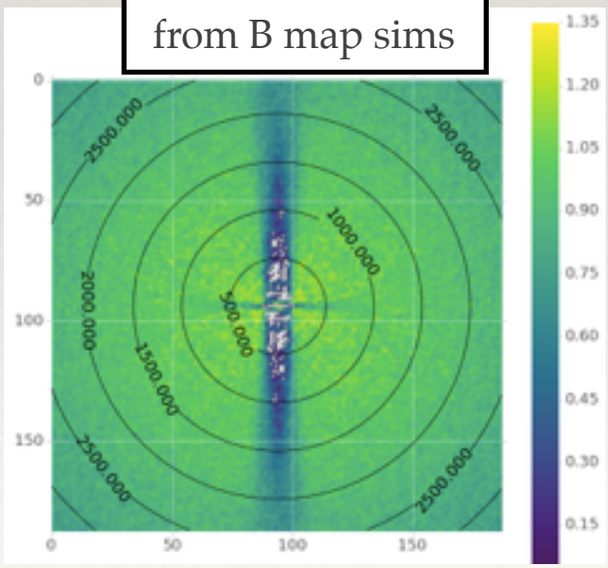
B map



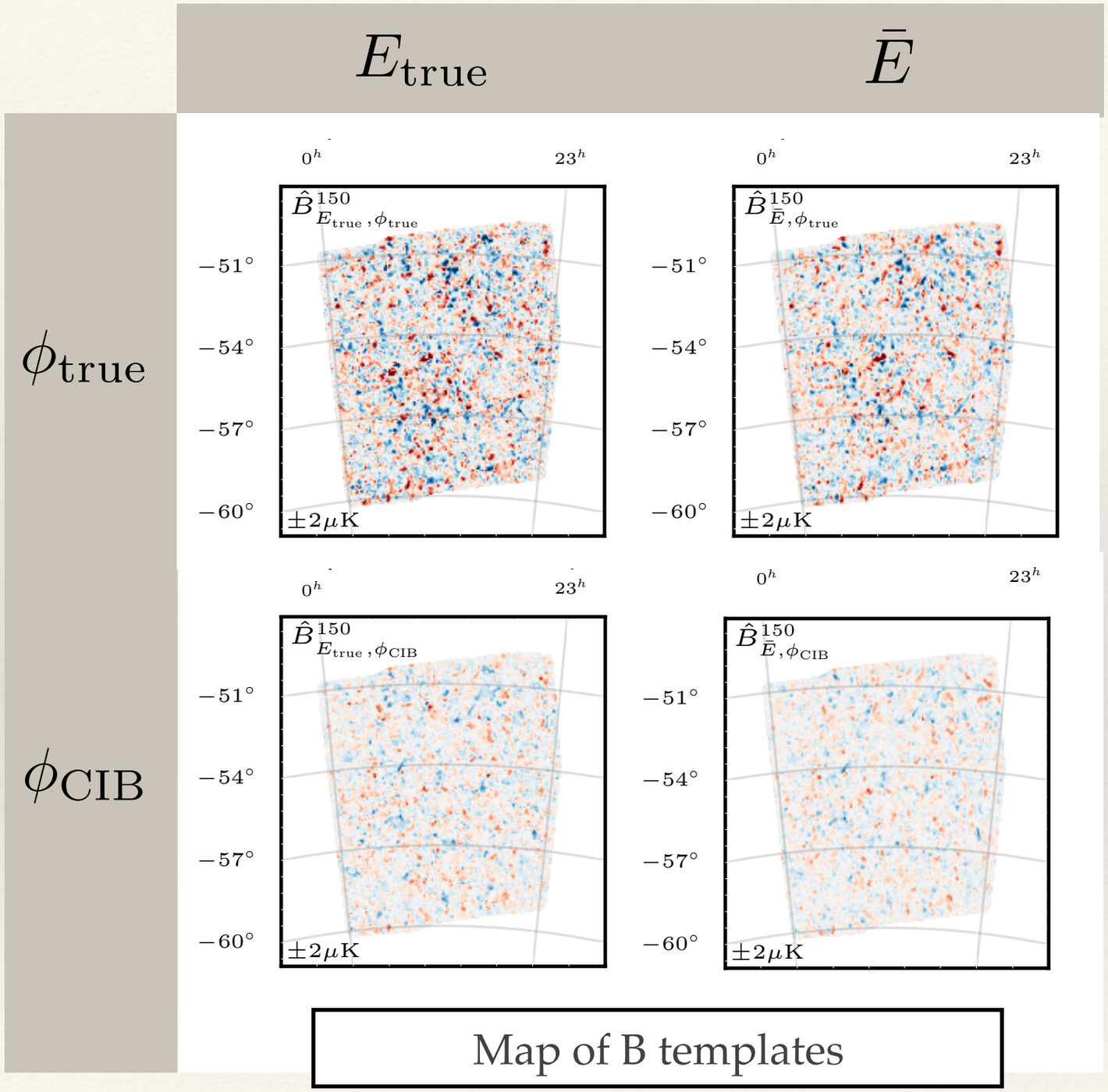
B template



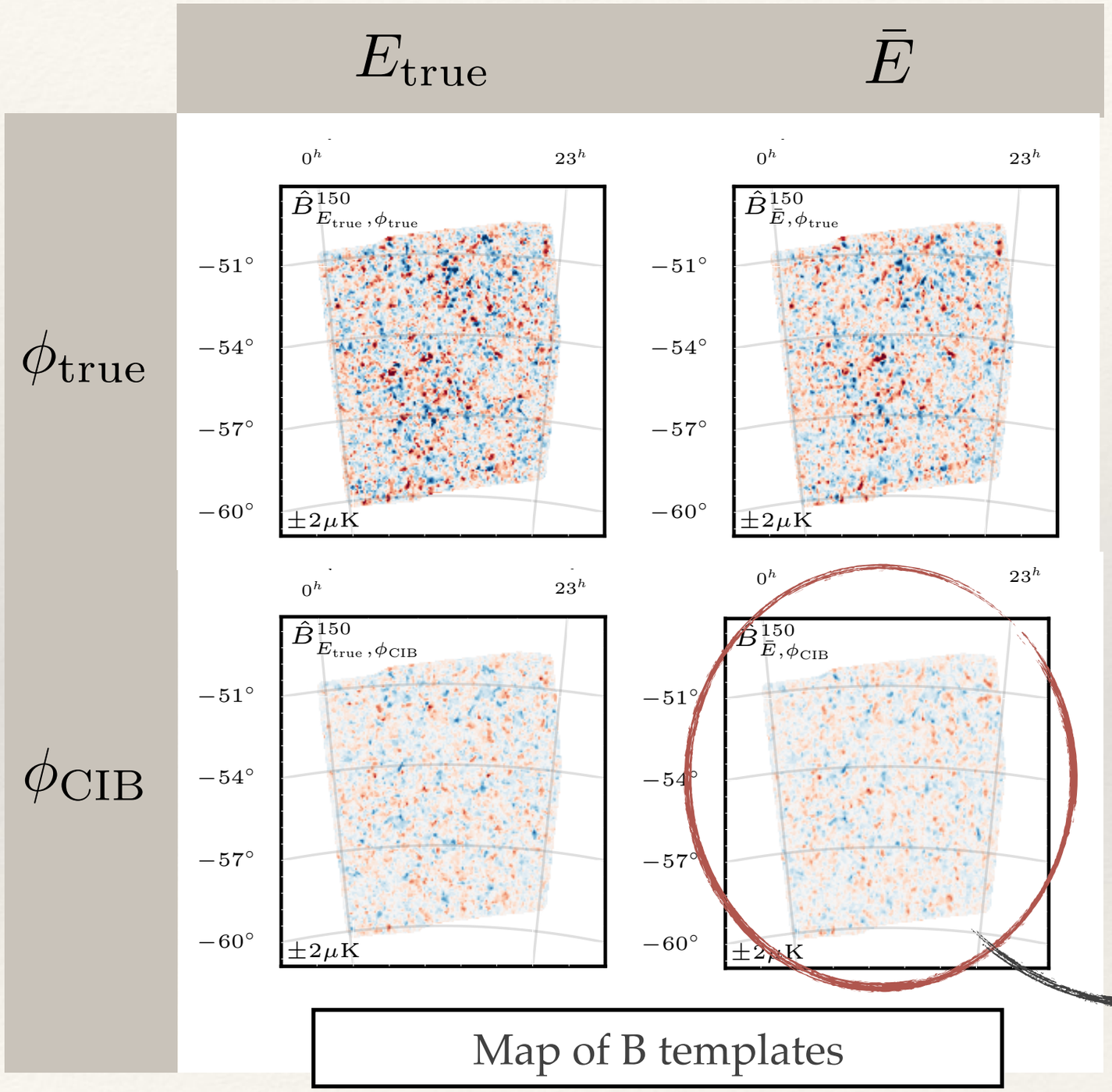
Transfer Function from B map sims

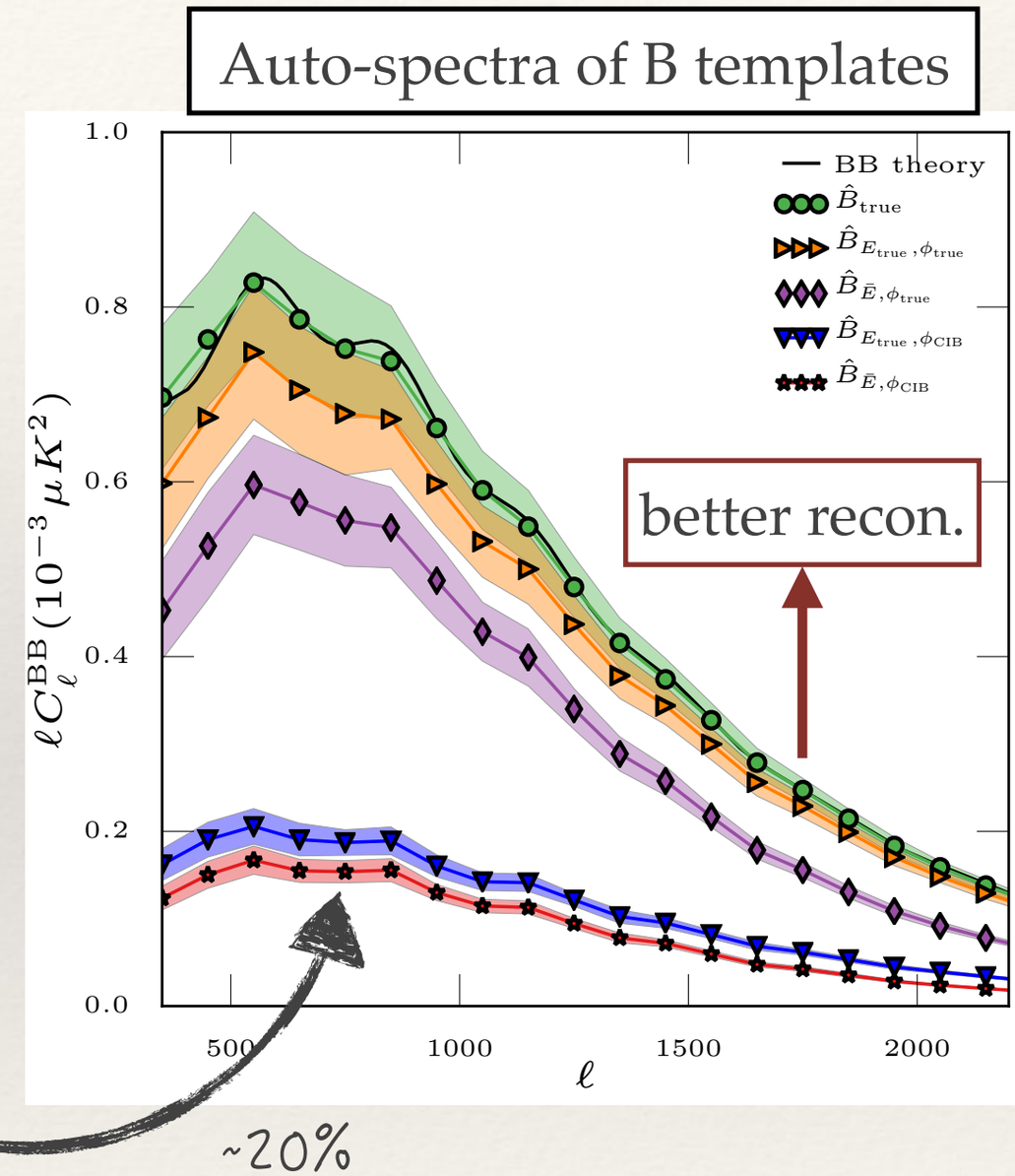


How well we reconstruct lensing B-modes → how well we delens

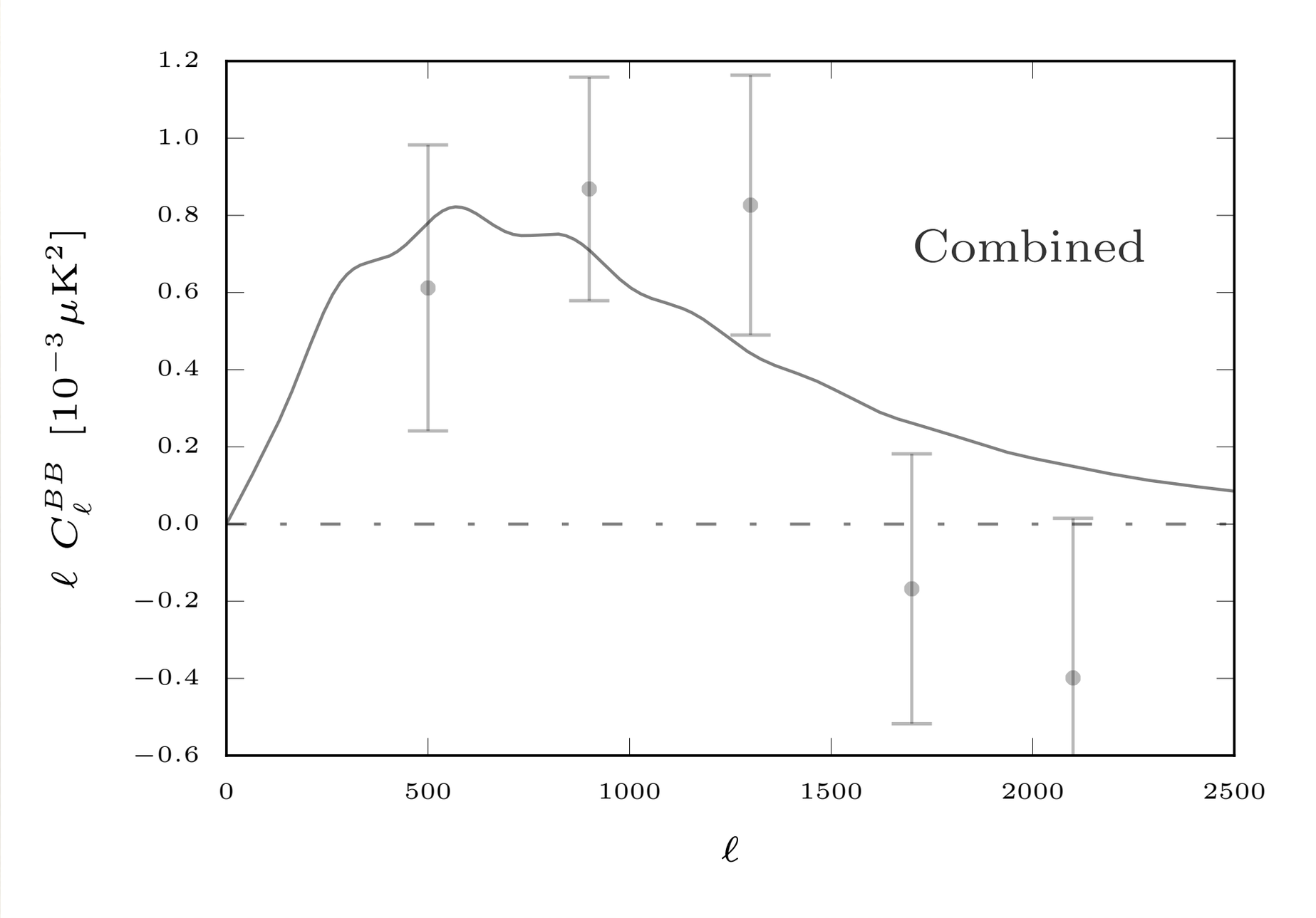


How well we reconstruct lensing B-modes → how well we delens

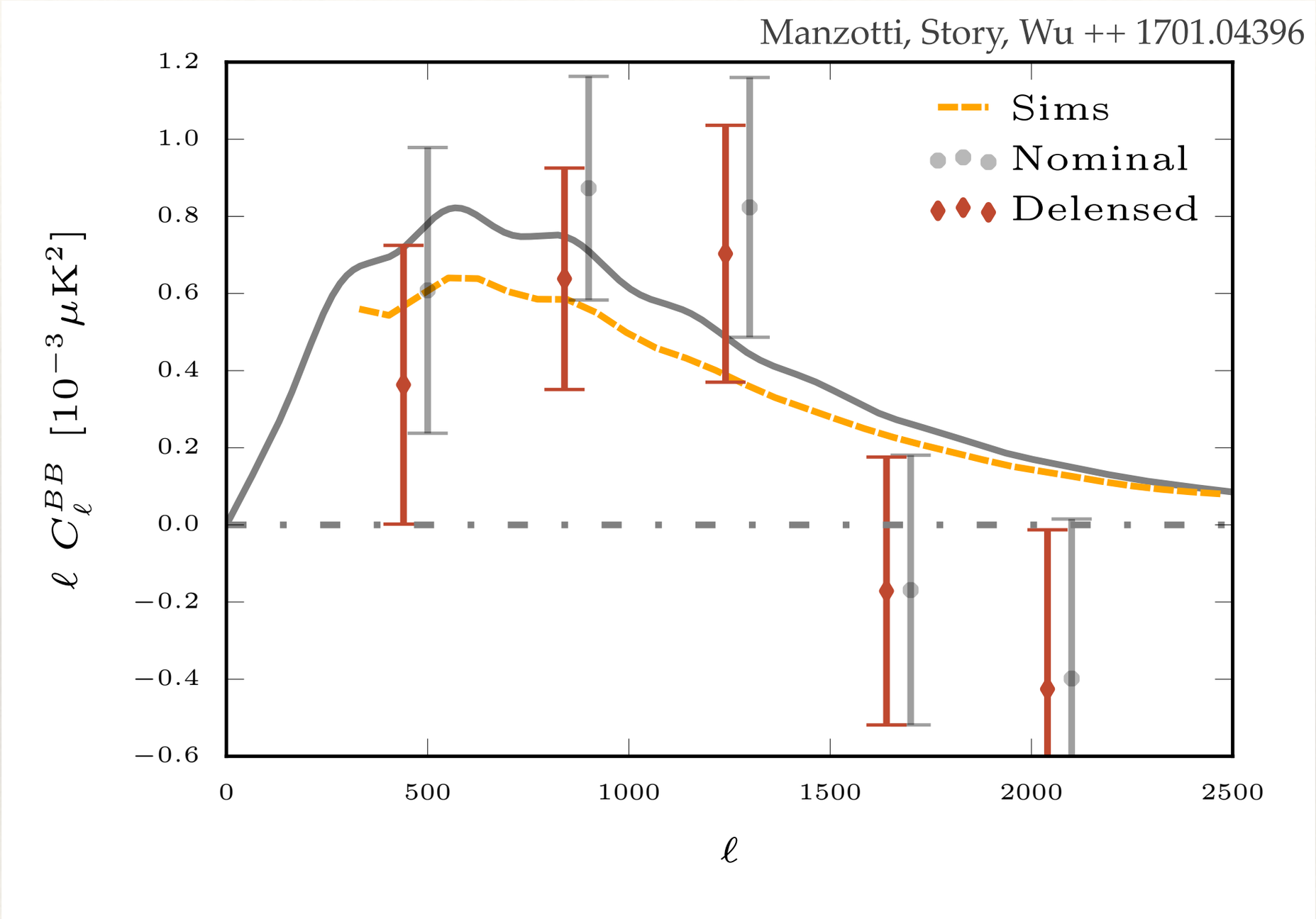




SPTpol BB spectrum (no delensing)



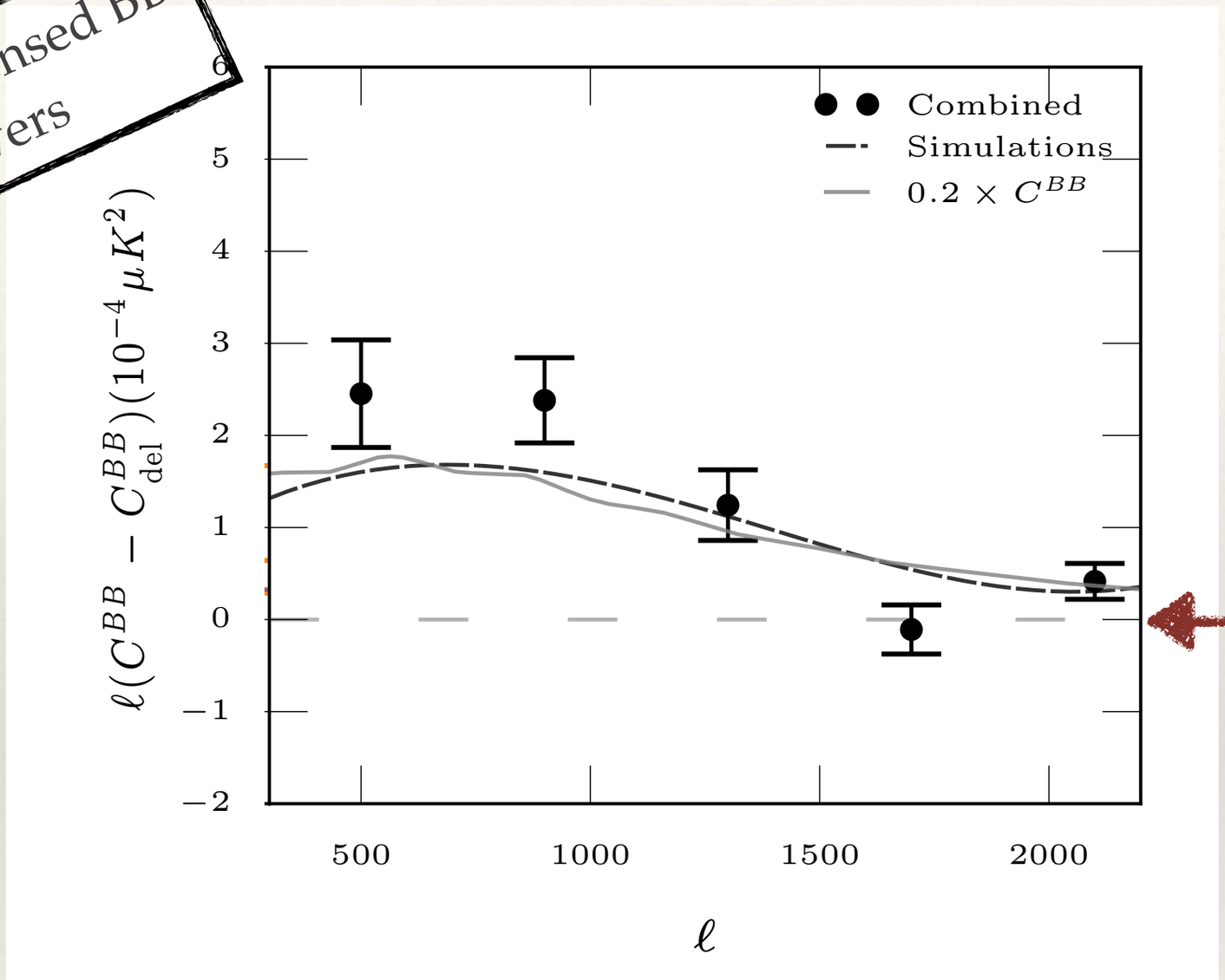
Delensed SPTpol BB spectrum



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

Successful demonstration of delensing B-modes!

Case study: limitation to delensing

Notations

More ideal

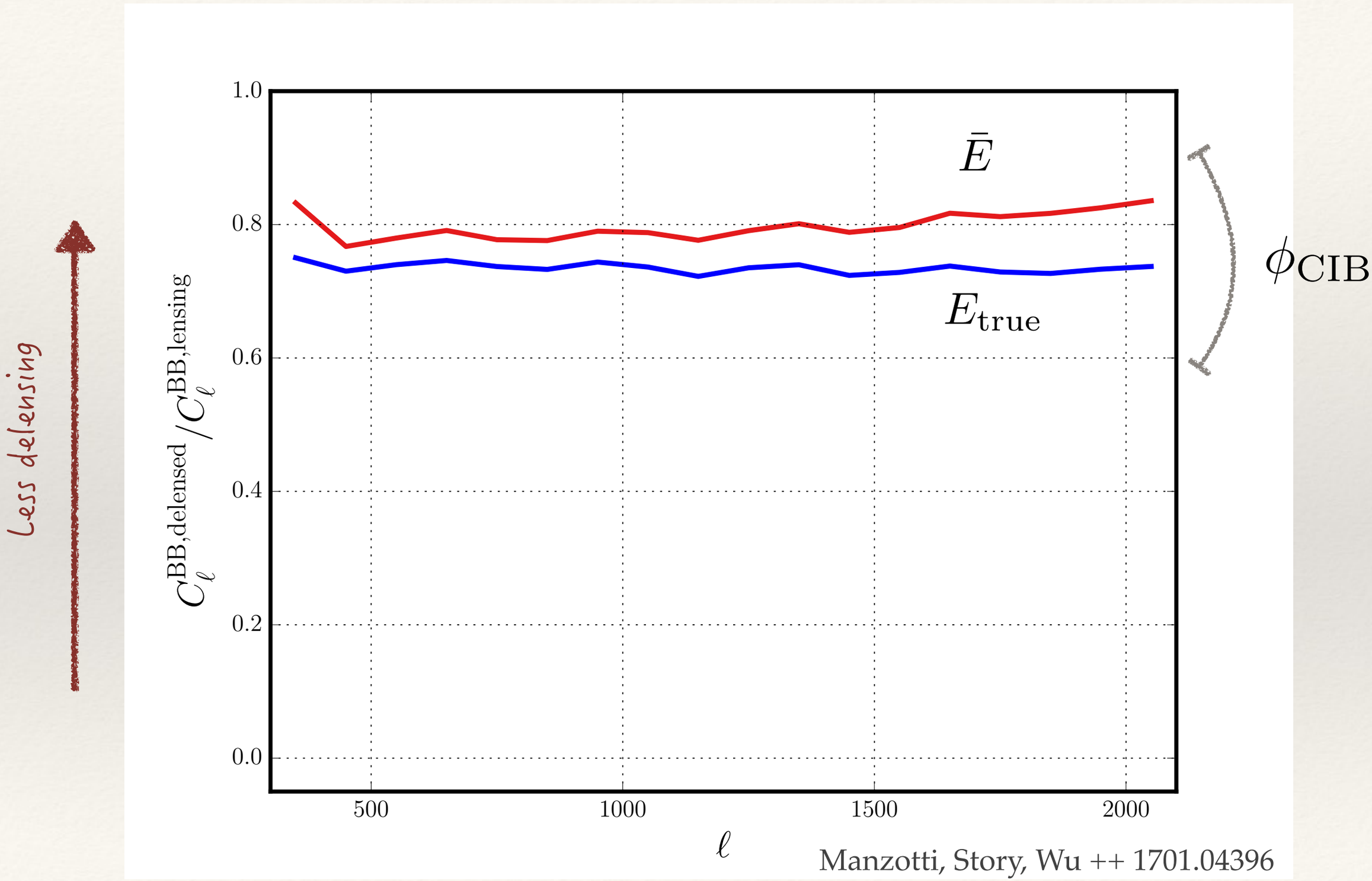
E_{true} noiseless, unfiltered E map; (LCDM realizations projected)

$\bar{E}$ noisy, filtered E map; (missing modes)

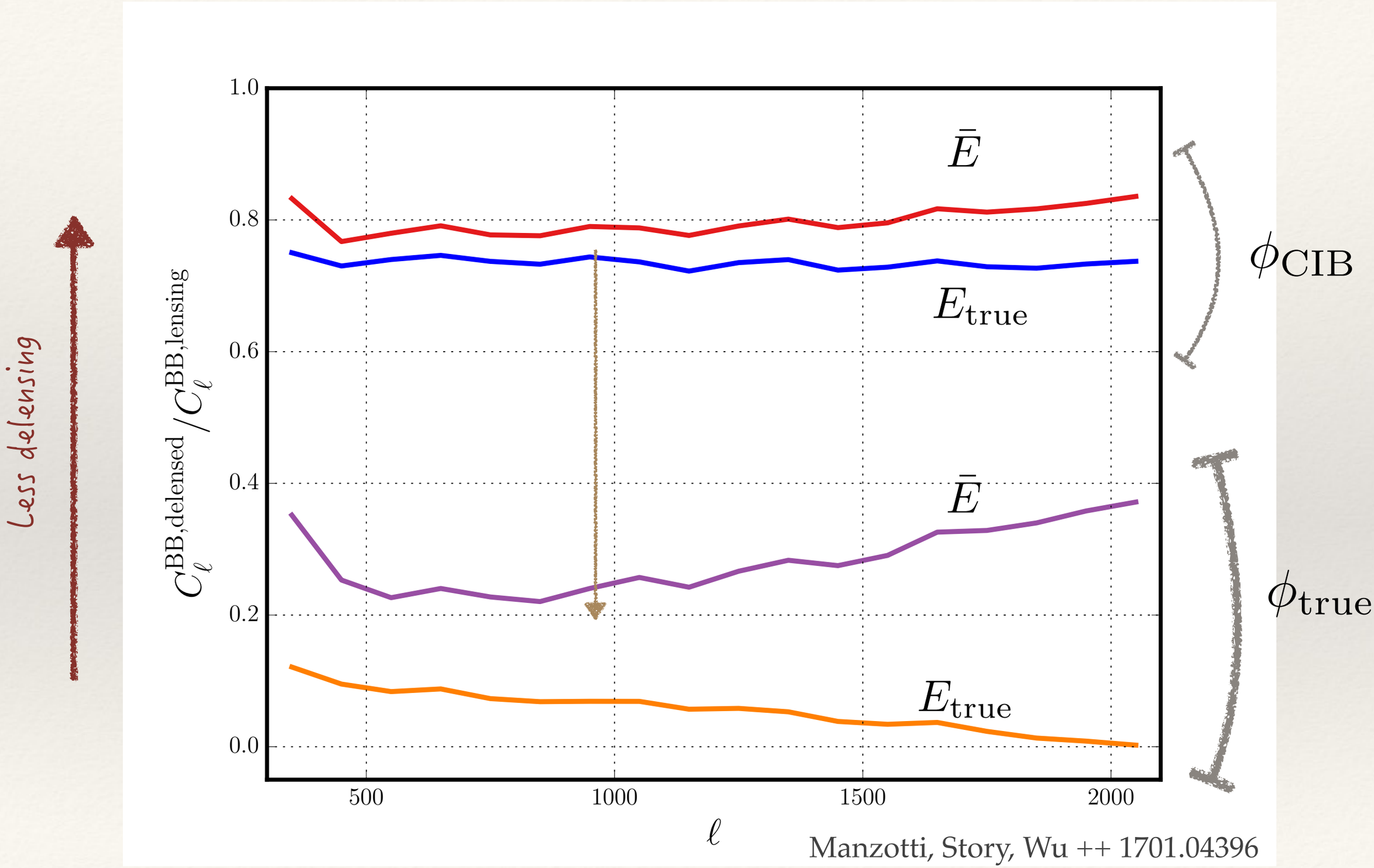
ϕ_{true} noiseless phi

ϕ_{CIB} CIB estimated phi

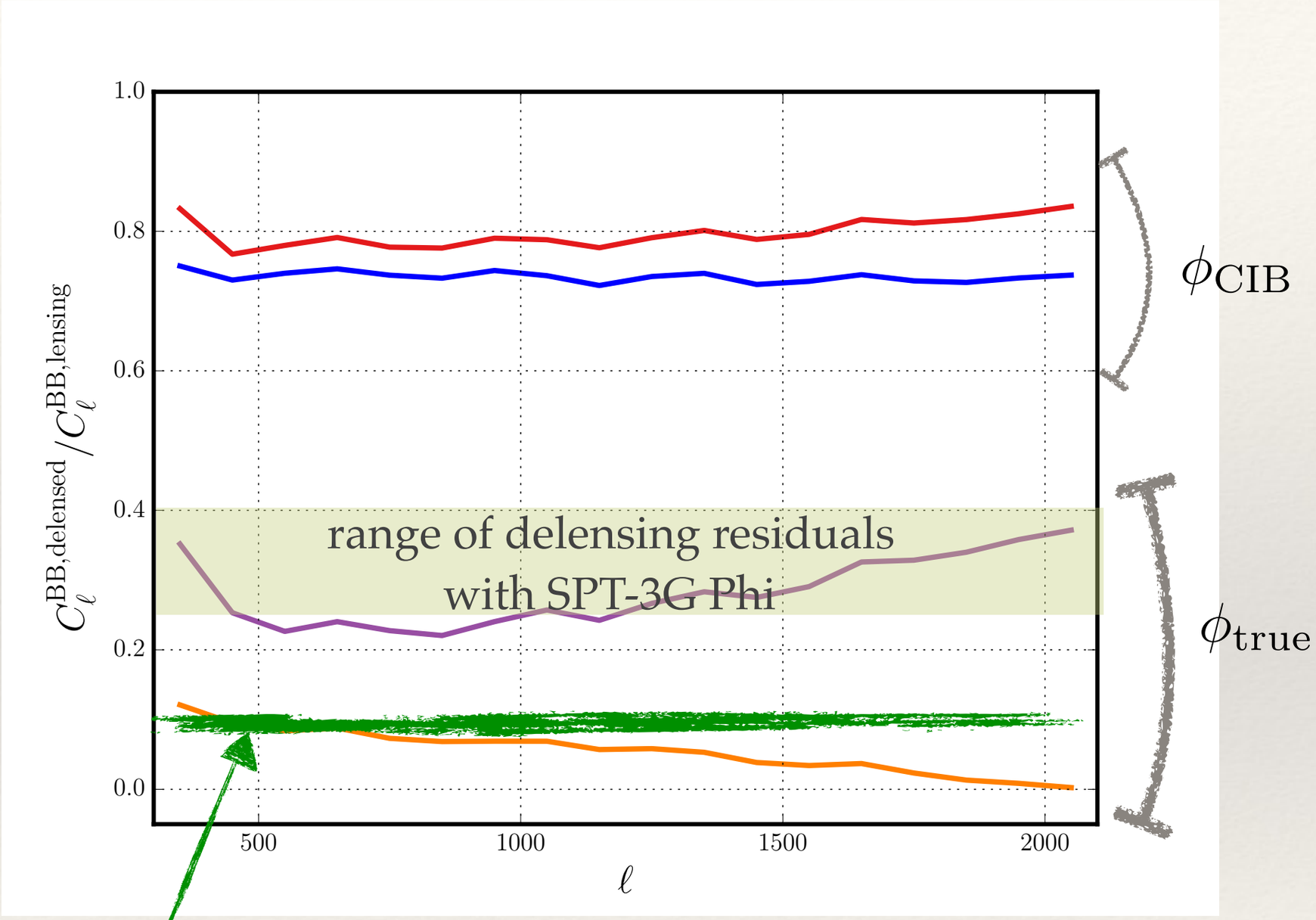
Delensing currently limited by Phi



Delensing currently limited by Phi

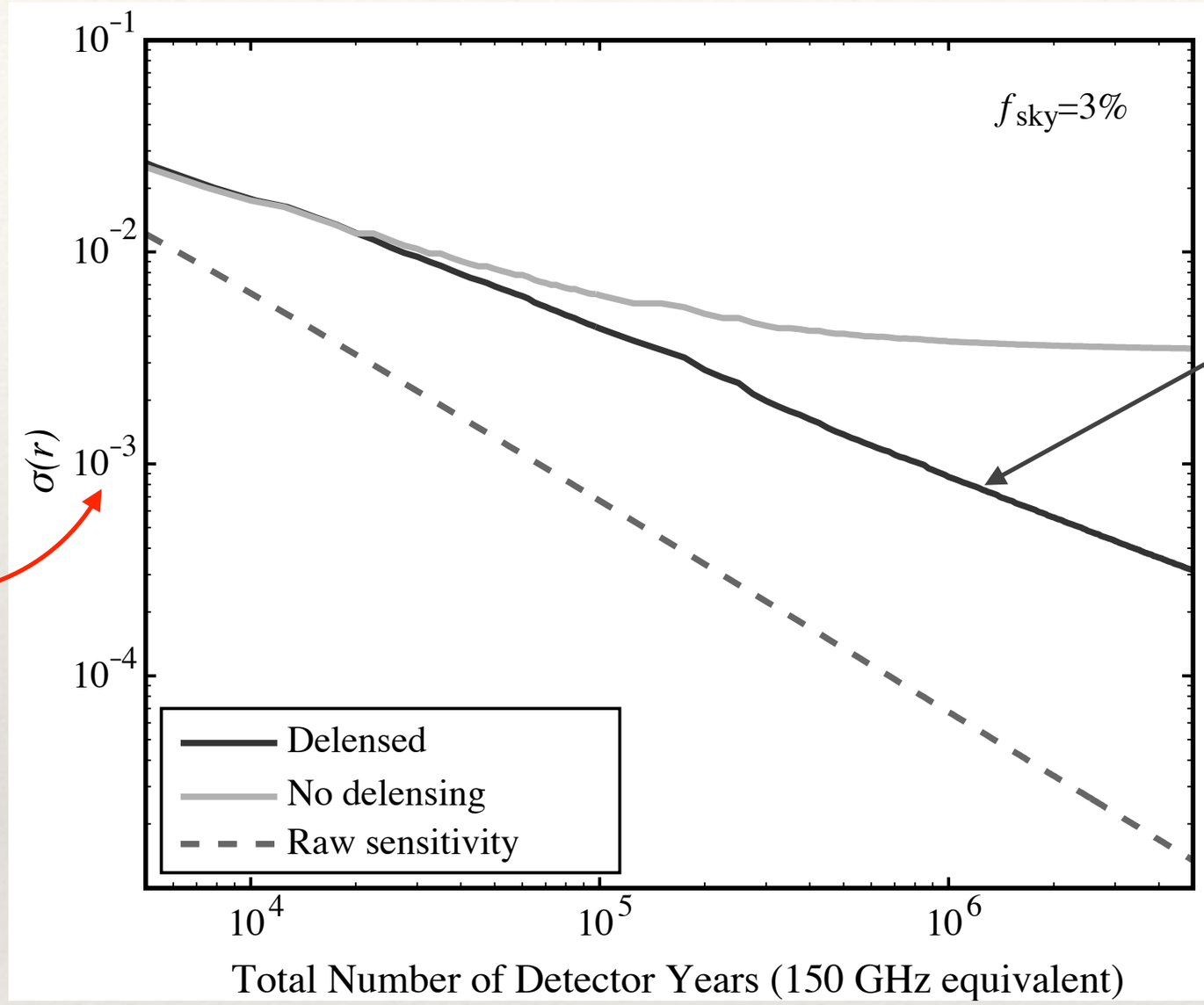


Future CMB-phi



~ CMB-S4 analytic forecast level (3% sky for r)

r forecast with CMB-S4



Delensed

σ(r) = 0.001 benchmark

CMB-S4 Science Book

- With Phi reconstructed with Stage-4 level noise, we expect ~10% lensing Cl^BB residuals

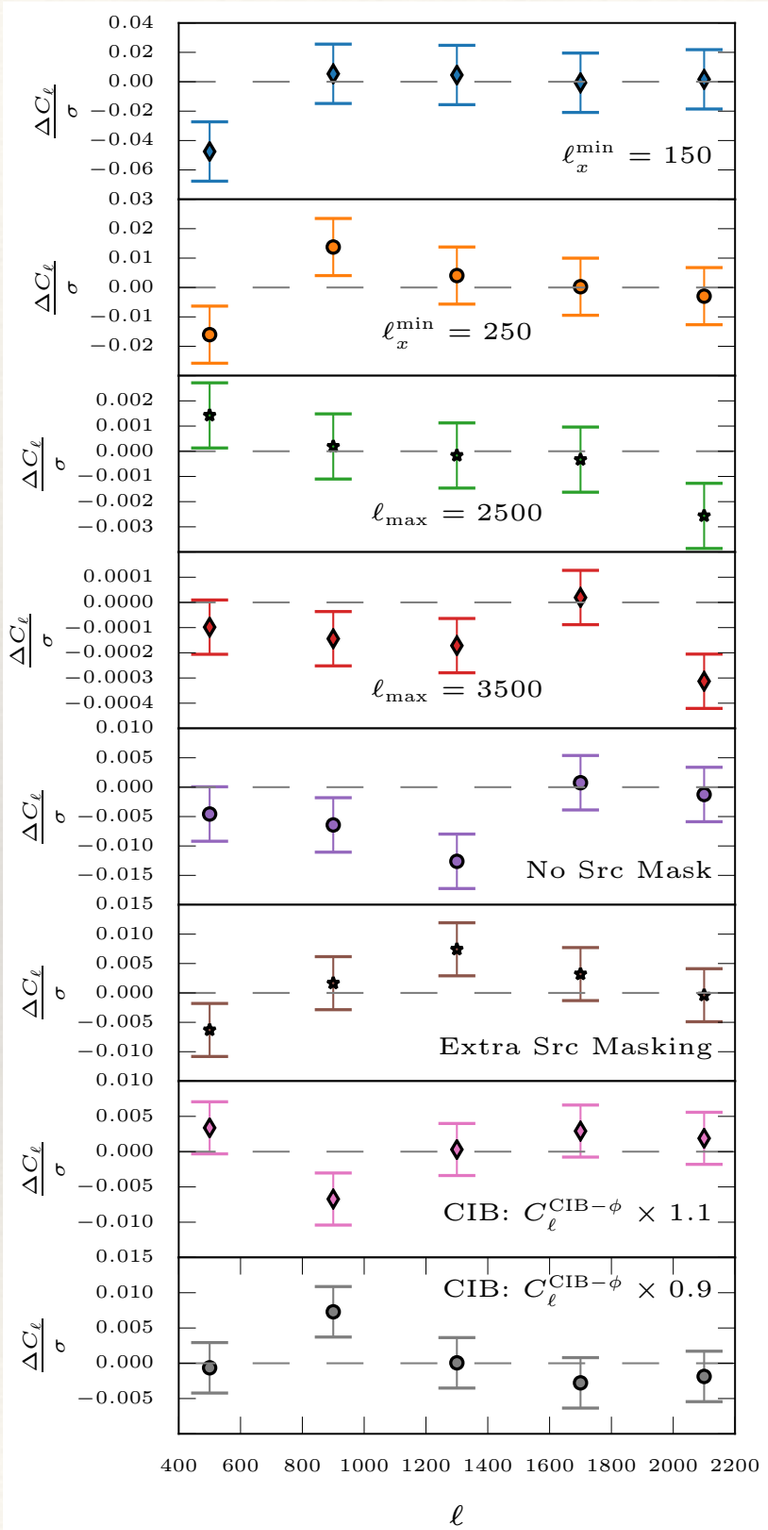
Summary

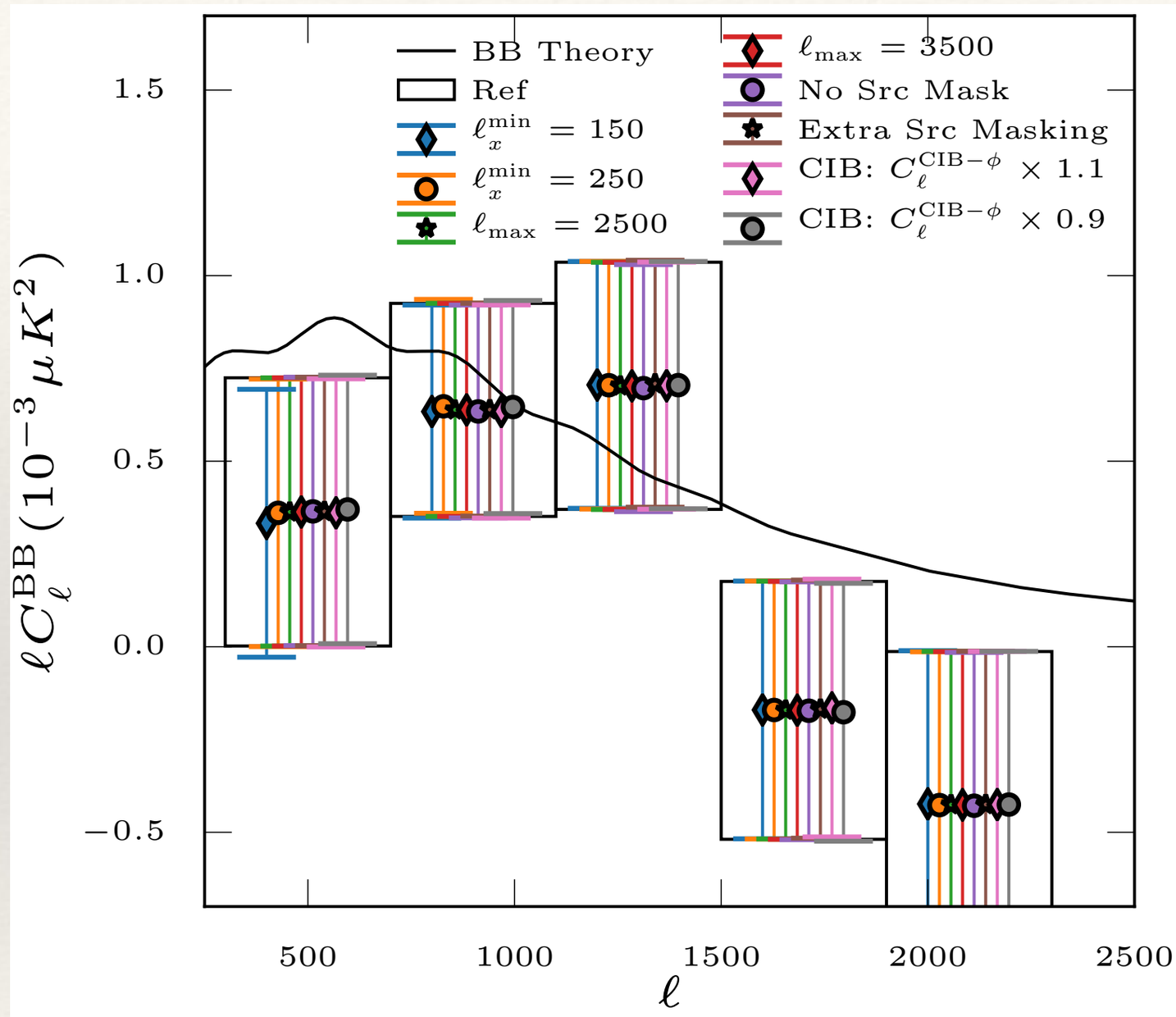
- Using SPTpol and Herschel data, we have demonstrated delensing of B modes. We reduced the best-fit lensing amplitude by 28% and ruled out the no delensing hypothesis at 6.9 sigma.
- Delensing is currently limited by the fidelity of the Phi maps.
- With upcoming CMB experiments' deeper maps, better Phi maps will be available and we can improve delensing significantly.
- For CMB-S4, delensing is essential for reaching benchmark sigma(r).

Thank you for your attention

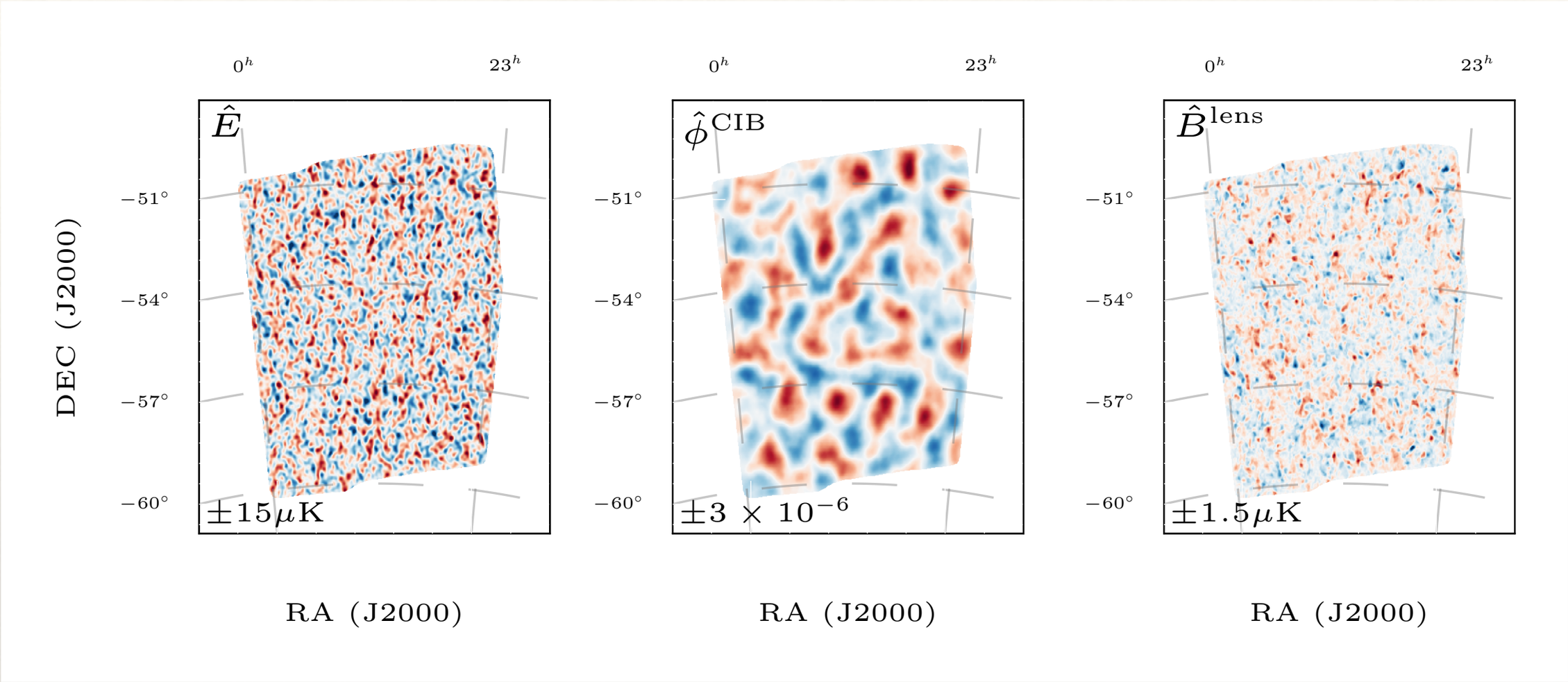
extras

Systematics tests

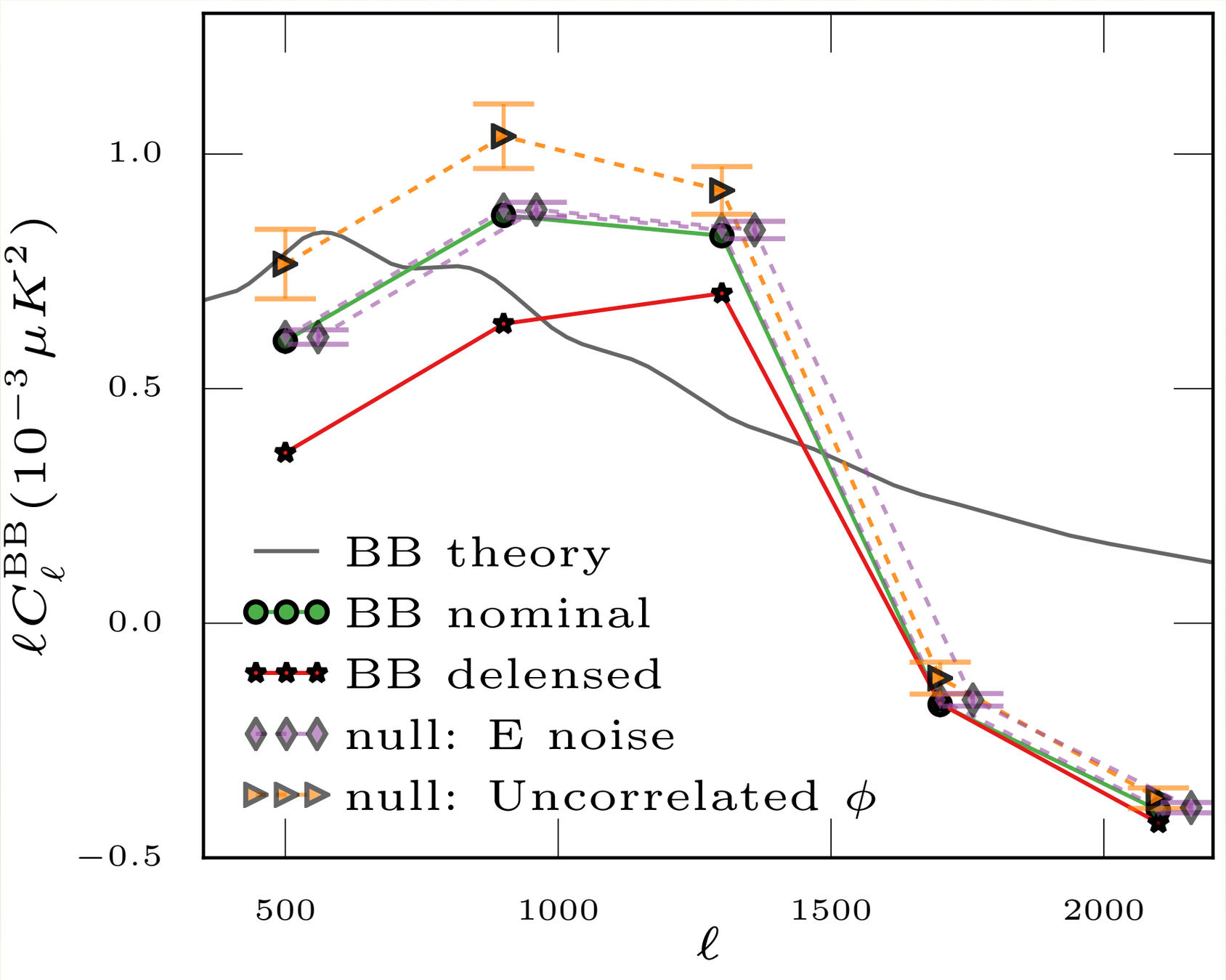




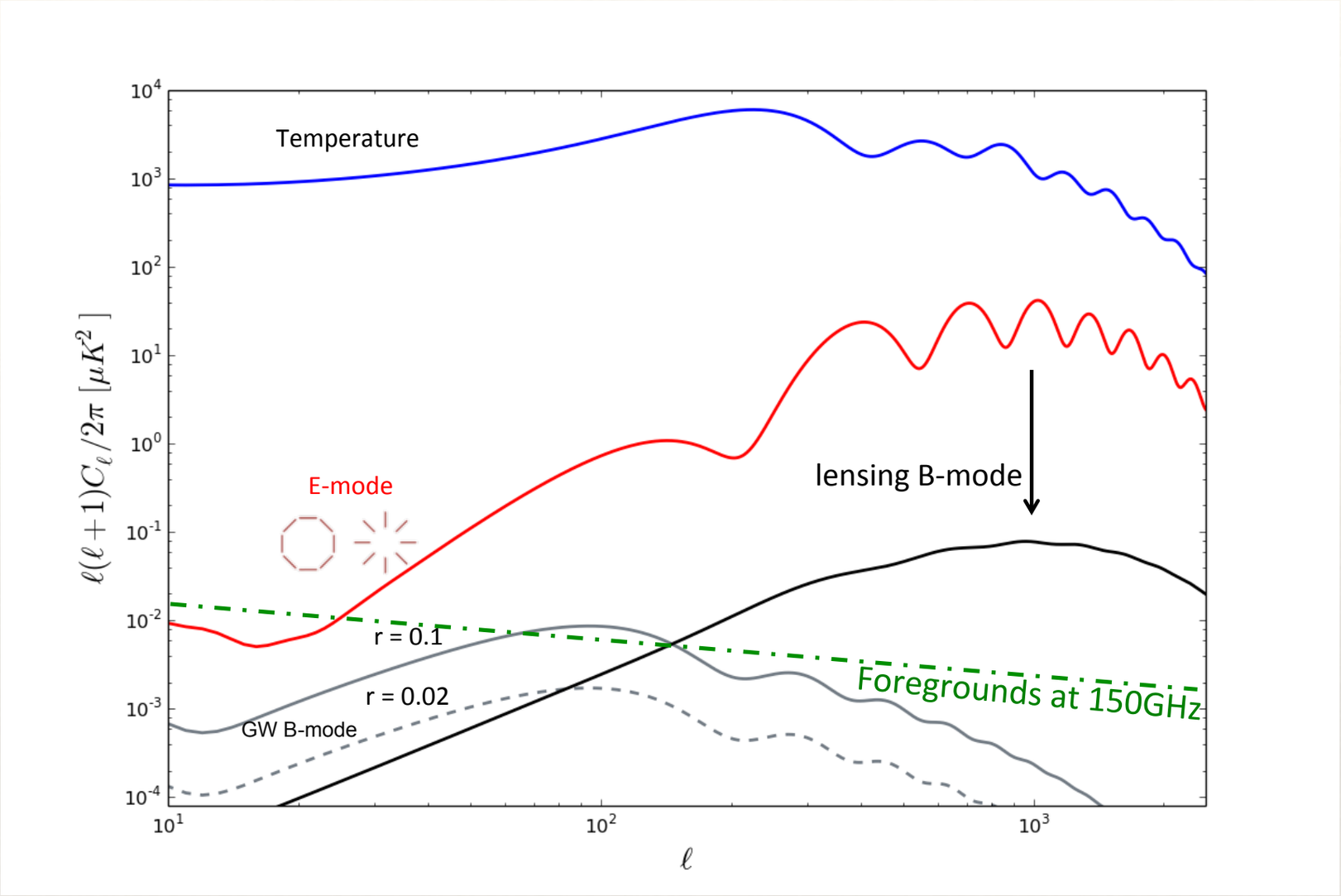
Data maps


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

null tests

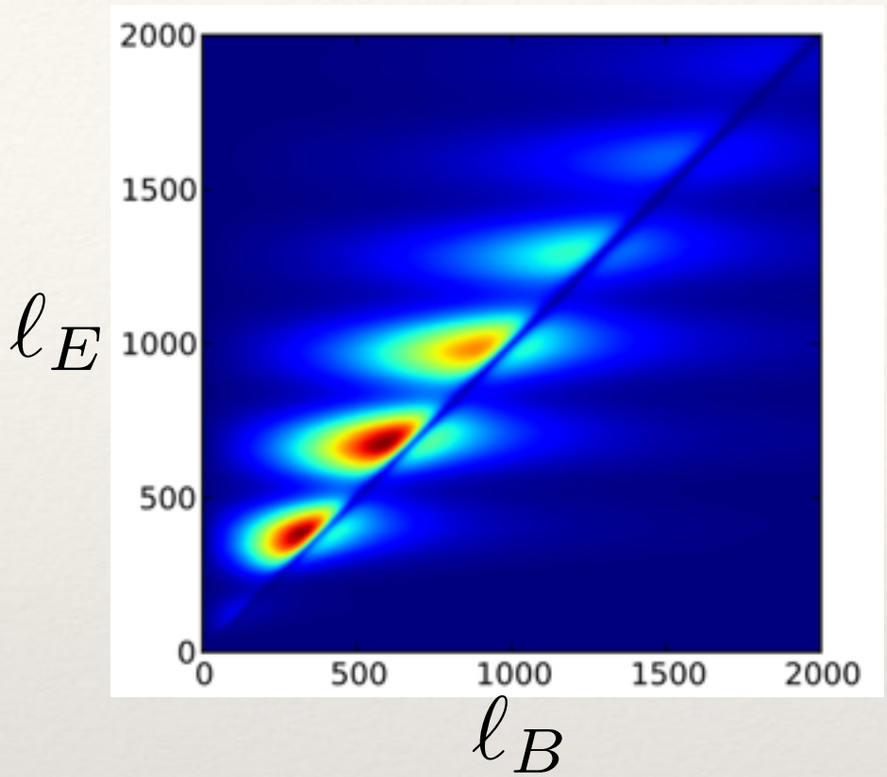

1.0
0.5
0.0
−0.5
500
1000
1500
2000
ℓ
$\ell C_\ell^{BB}\,(10^{-3}\,\mu K^2)$
BB theory
BB nominal
BB delensed
null: E noise
null: Uncorrelated ϕ

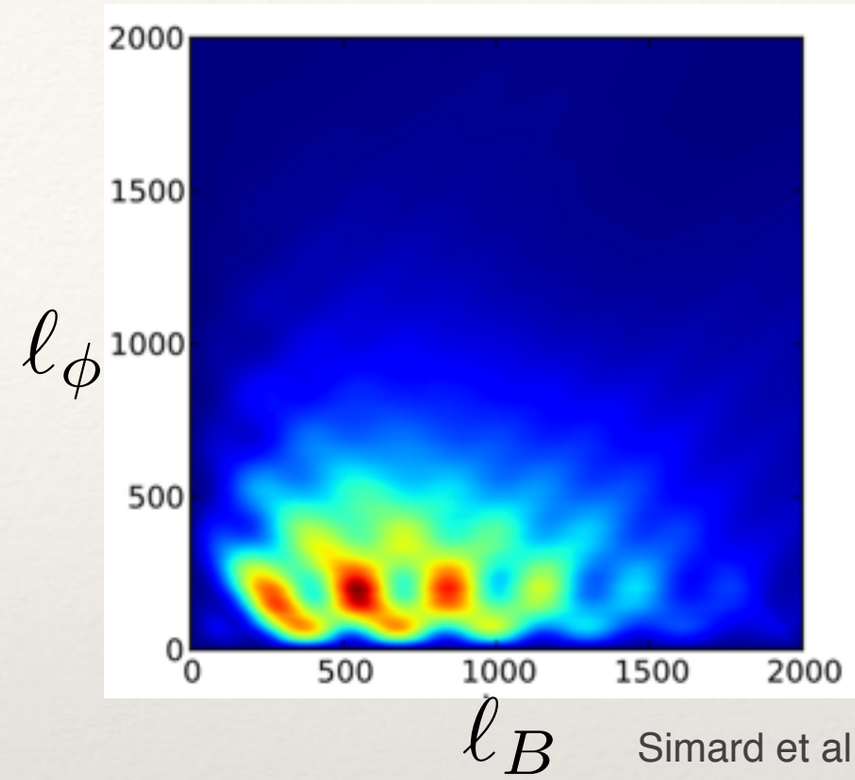
Why delensing?



- 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

Forming the B template: I



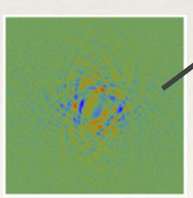


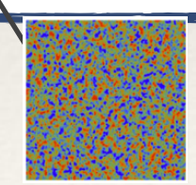
Simard et al. 2014 (1401.0691)

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



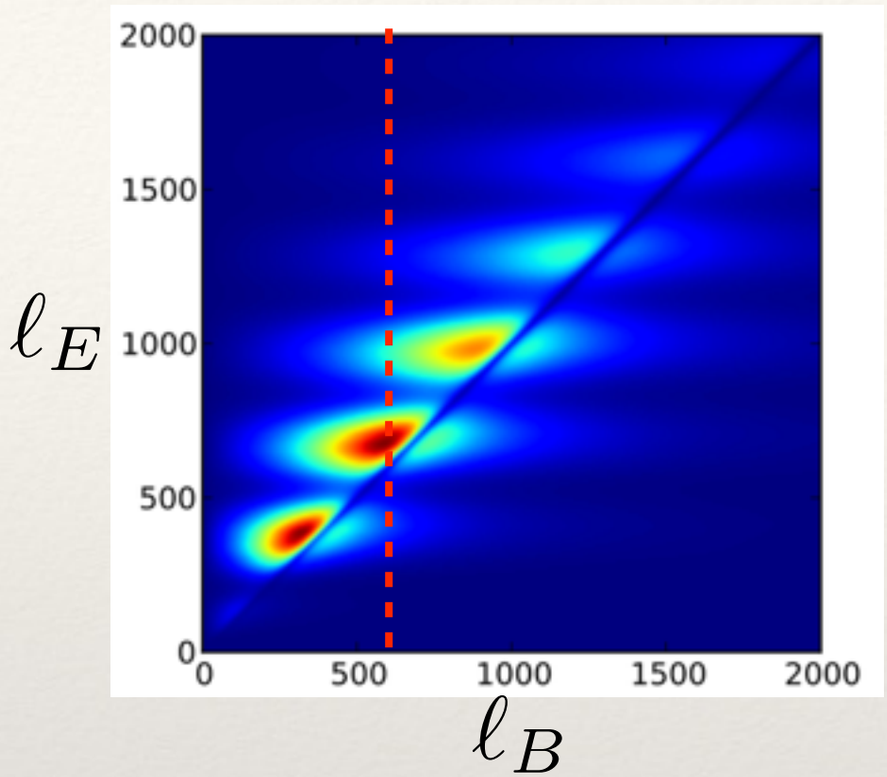


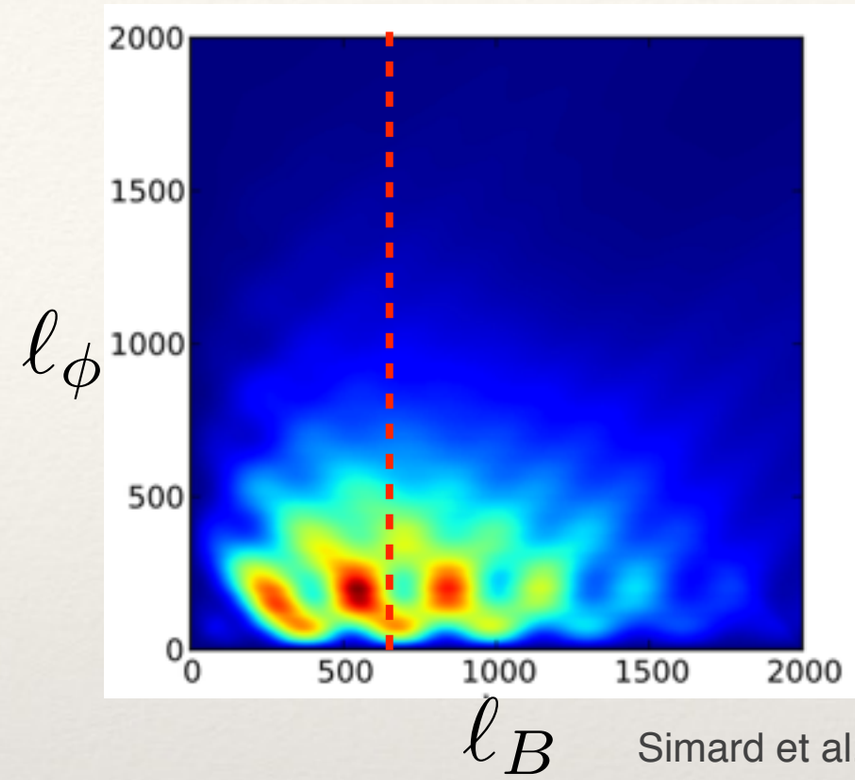
where weight function

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

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

Forming the B template: I



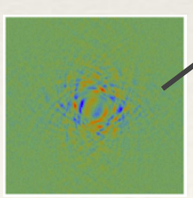


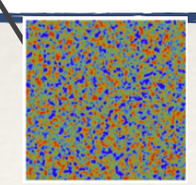
Simard et al. 2014 (1401.0691)

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

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

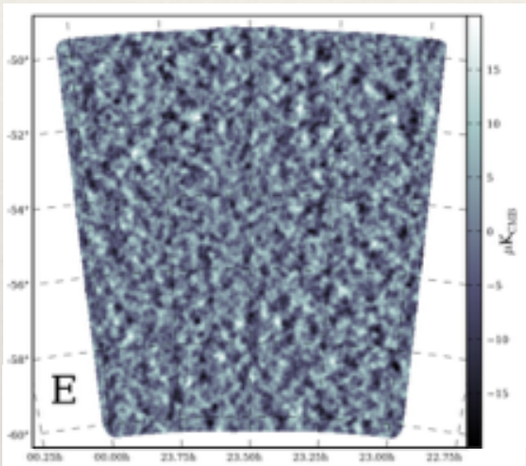
* flat-sky approx.: $\boldsymbol{\ell} = 2\pi|\boldsymbol{u}|$, u is Fourier mode.

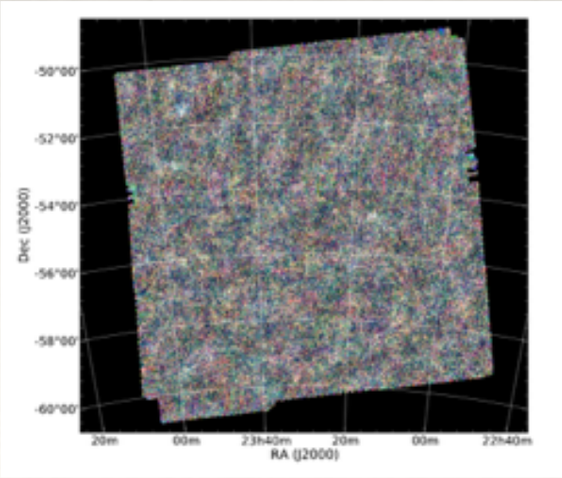
Forming the B template: II

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





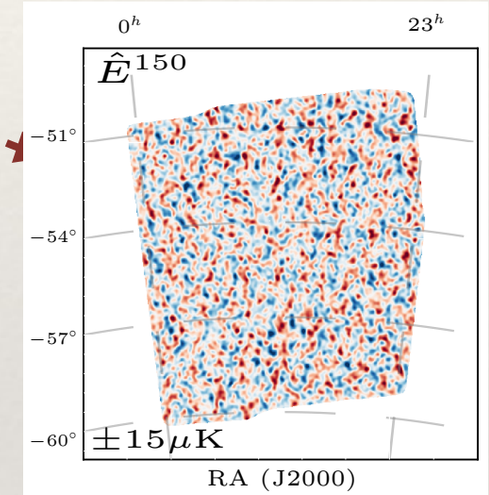
Filtering

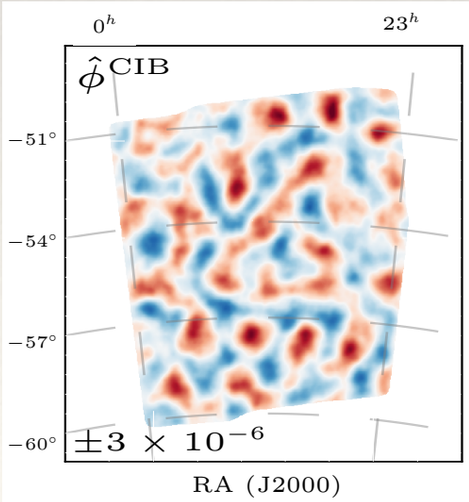
$$\bar{E}(\boldsymbol{\ell}) \approx \left(\frac{C_\ell^{EE}}{C_\ell^{EE}+N_\ell^{EE}}\right) E^N(\boldsymbol{\ell})$$

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

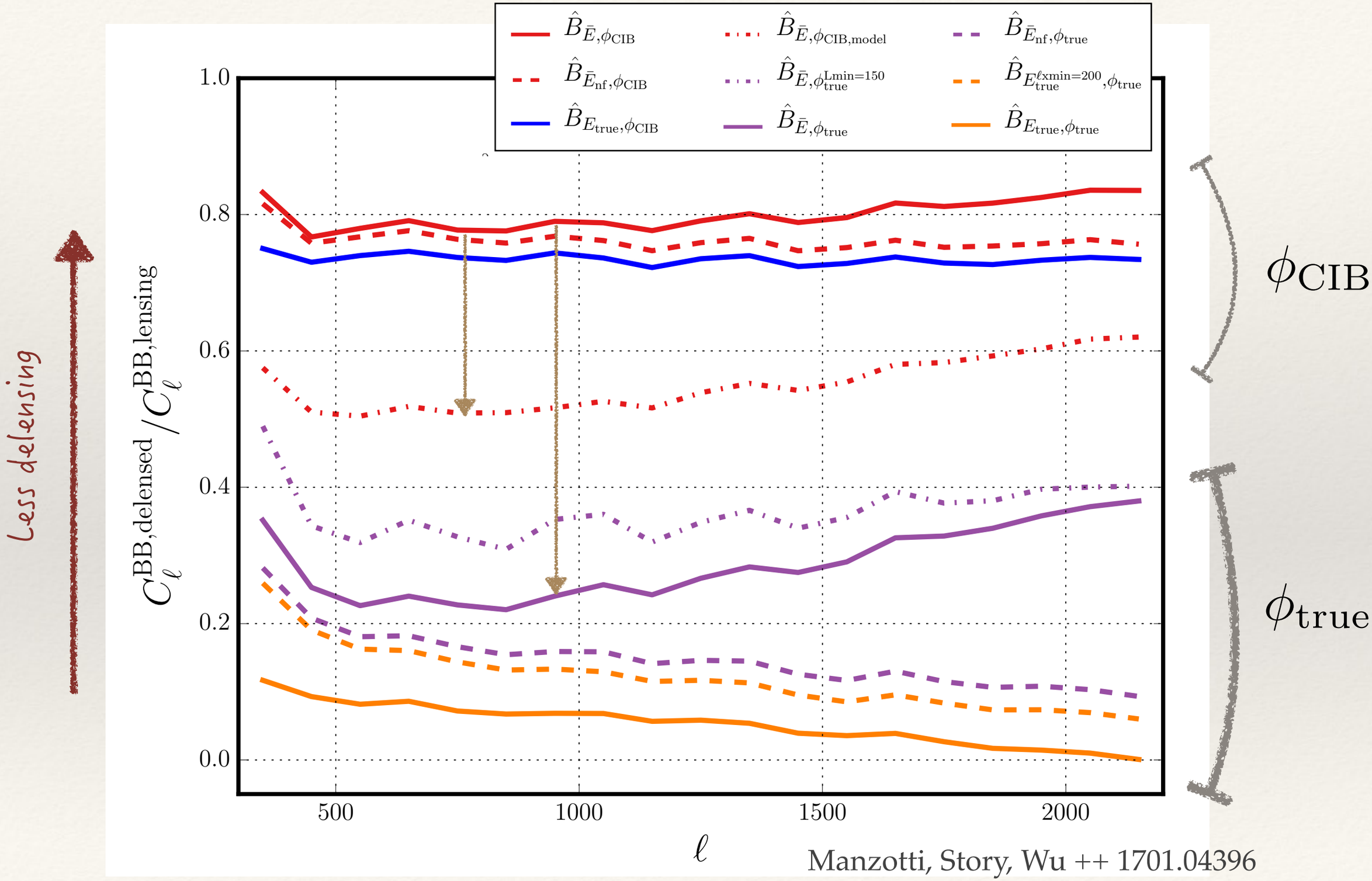
filters chosen to minimize residual variance

Filtered maps





Delensing currently limited by Phi



Manzotti, Story, Wu ++ 1701.04396