



Image credit: Steffen Richter

CMB polarization B-mode delensing with SPTpol and Herschel

(arXiv:1701.04396)

Wai Ling Kimmy Wu
UC Berkeley → UChicago
Croucher Fellow → KICP Fellow

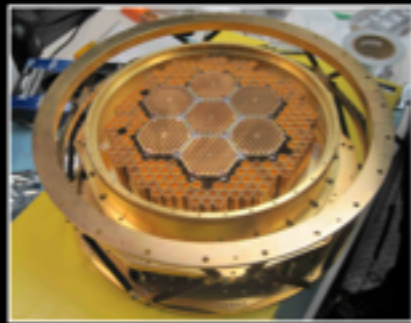
TeVPA 2017
August 7th, 2017

The South Pole Telescope (SPT)

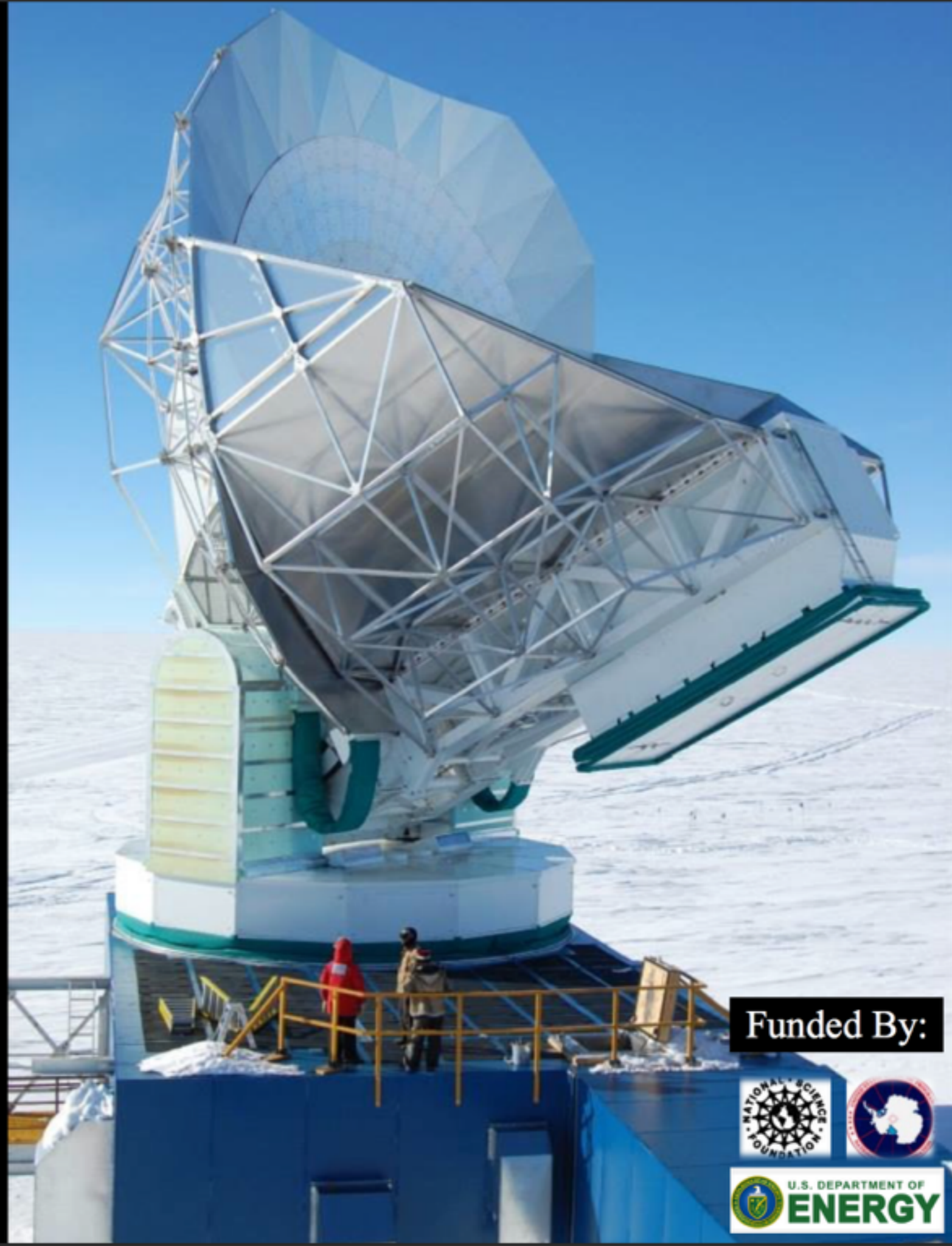
10-meter sub-mm quality wavelength telescope

2012: SPTpol

1600 detectors
95,150 GHz
+Polarization



Collaborators:
Alessandro Manzotti, Kyle Story
+ SPTpol collaboration



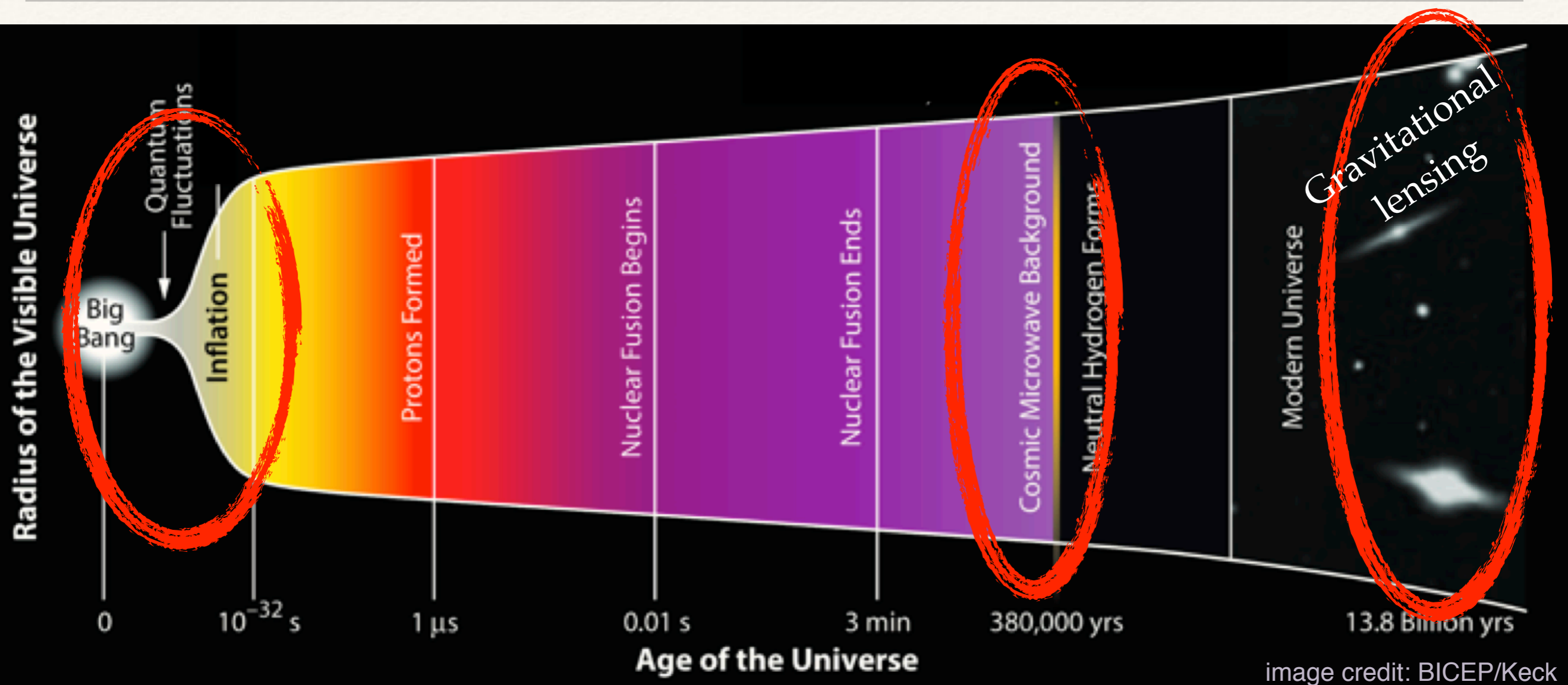
Funded By:



Outline

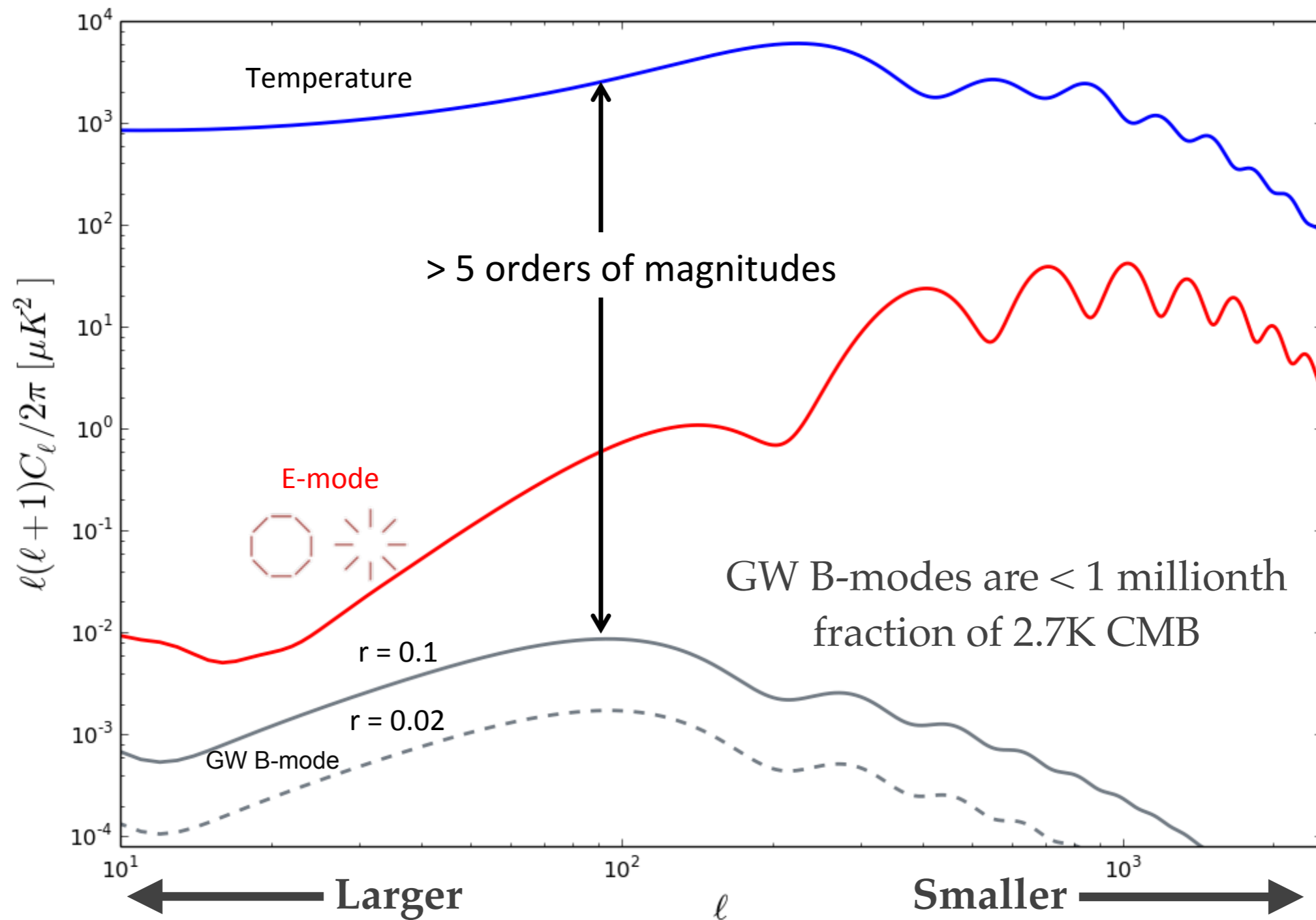
- ❖ Background on B-modes and delensing
- ❖ Approach to delensing + Results
- ❖ Delensing efficiency + Outlook

Inflation and B-mode polarization

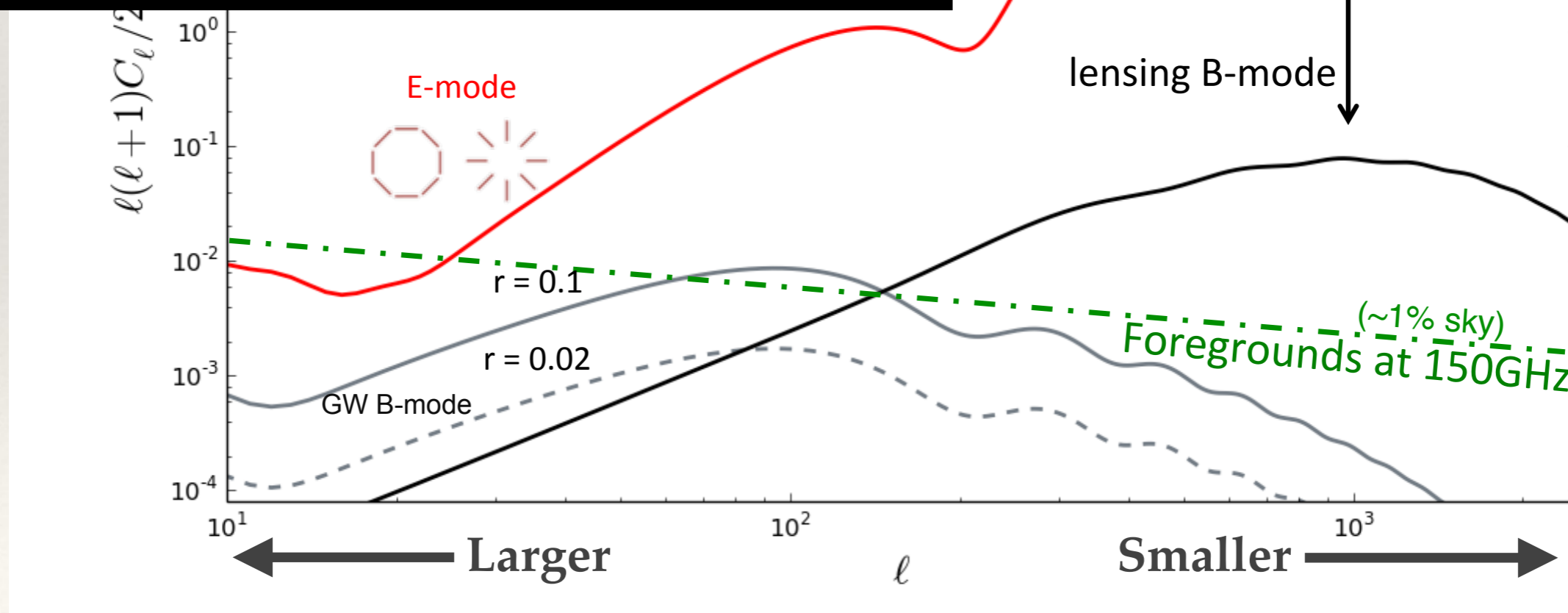
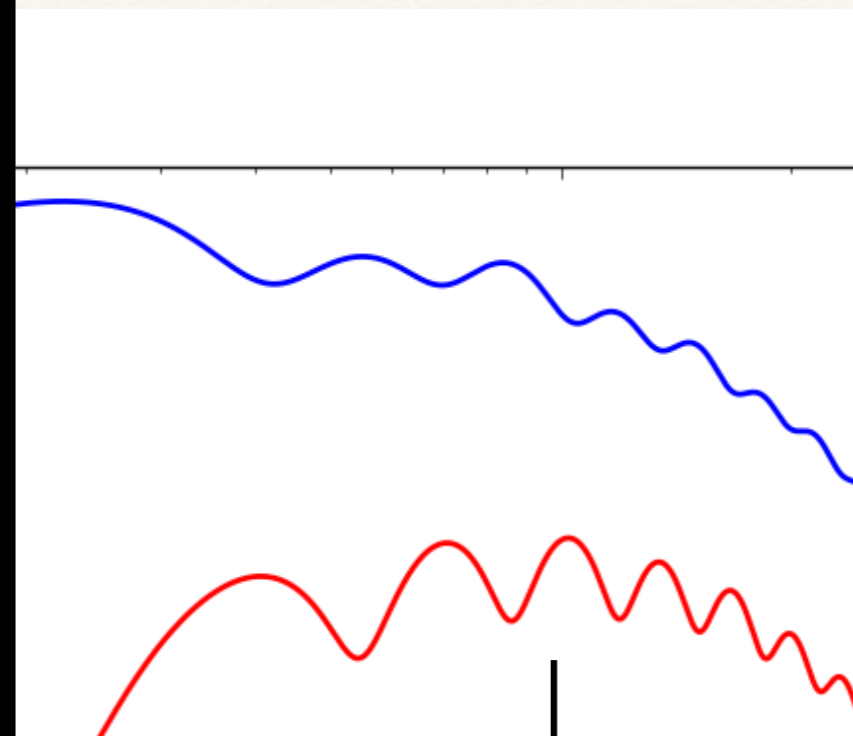
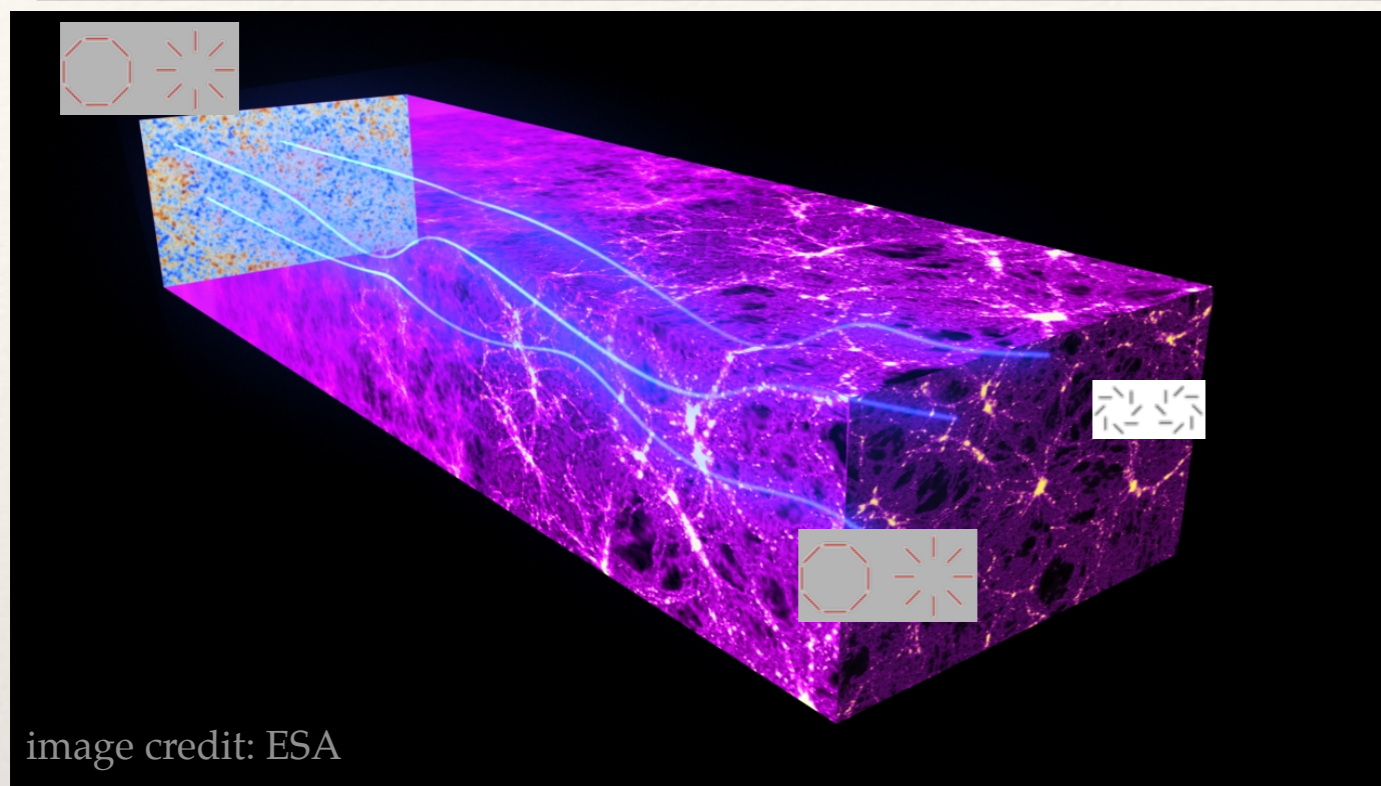


- ❖ In Λ CDM, primordial gravitational waves (tensor-perturbations of the metric) are the only source that imprints B-mode polarization on the CMB at recombination.
- ❖ r is useful for e.g. determining the energy-scale of inflation, whether inflation is large or small field, and ruling out inflationary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

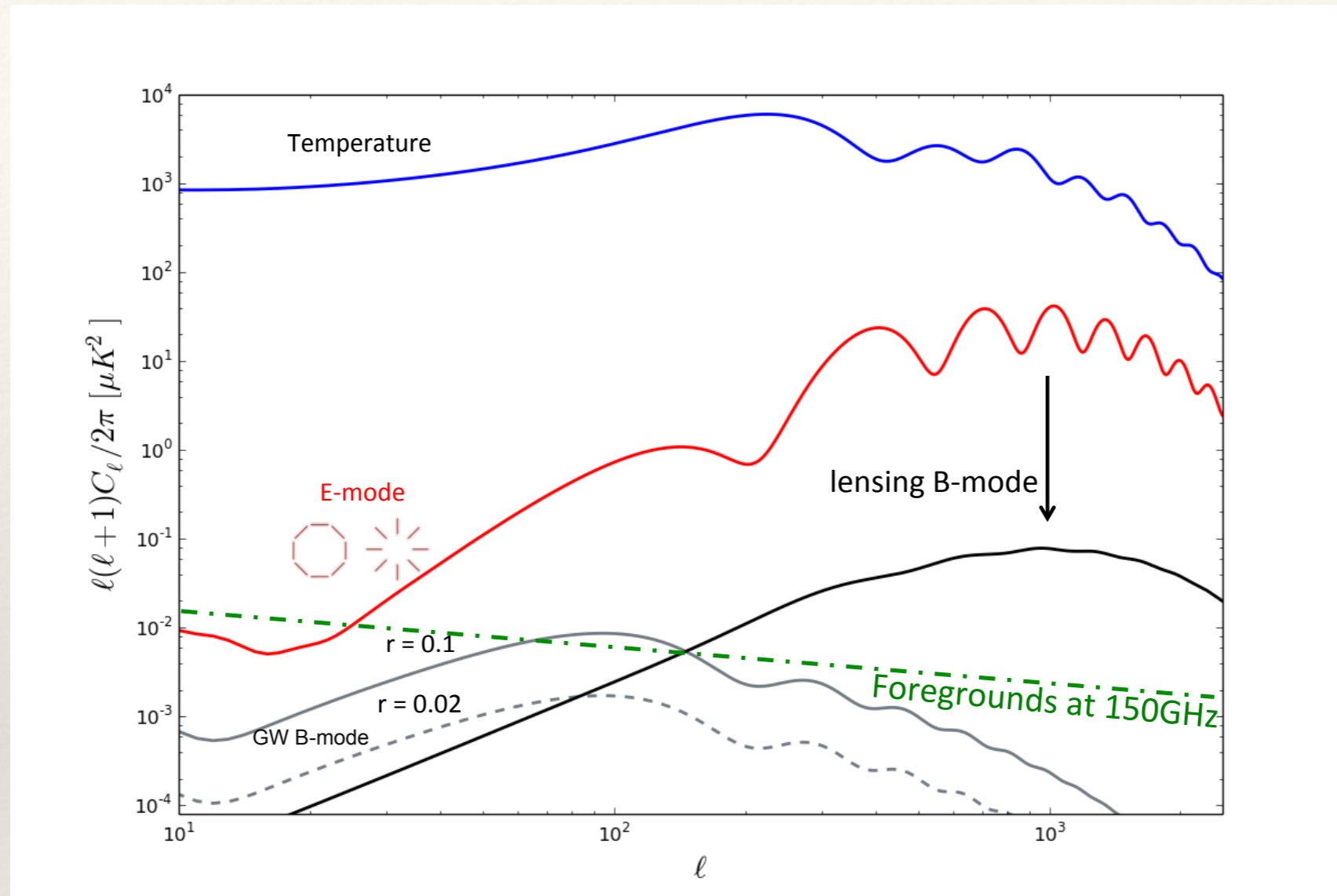
Measuring GW B-modes is hard: CMB anisotropy spectra



CMB spectra + foregrounds



Why delensing?

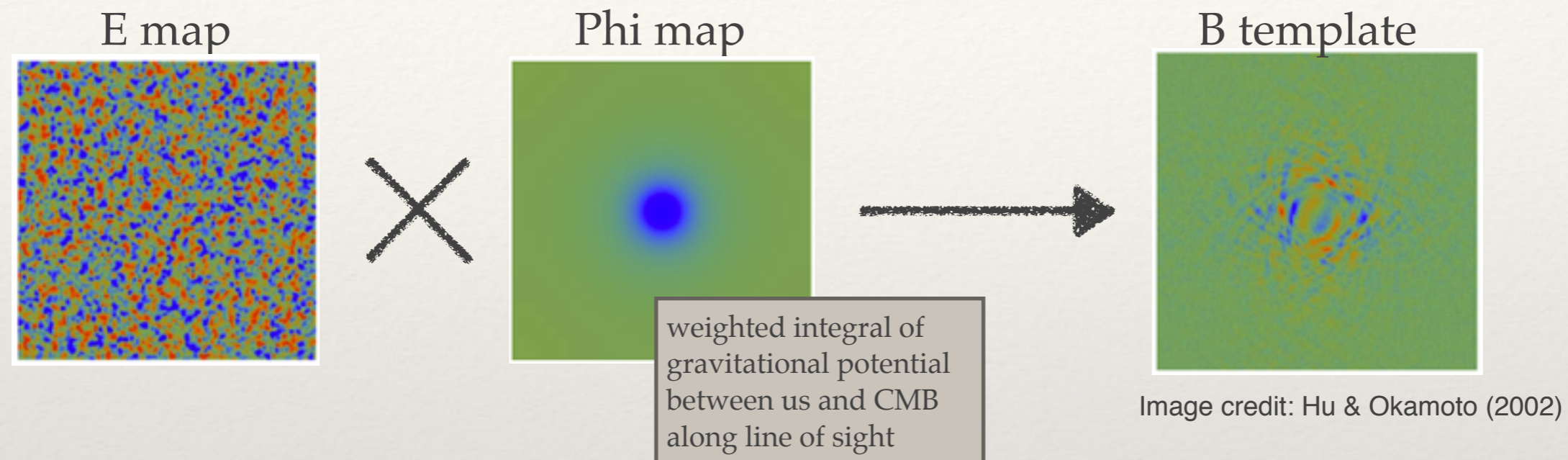


- We can fit lensing model + r simultaneously, but limited by sample variance of lensing
- **Delensing** B-modes: using the *realization-specific* lensing B-mode sky to reduce lensing sample variance
- Especially important if observing a small sky patch

We need delensing

Delensing: the idea

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

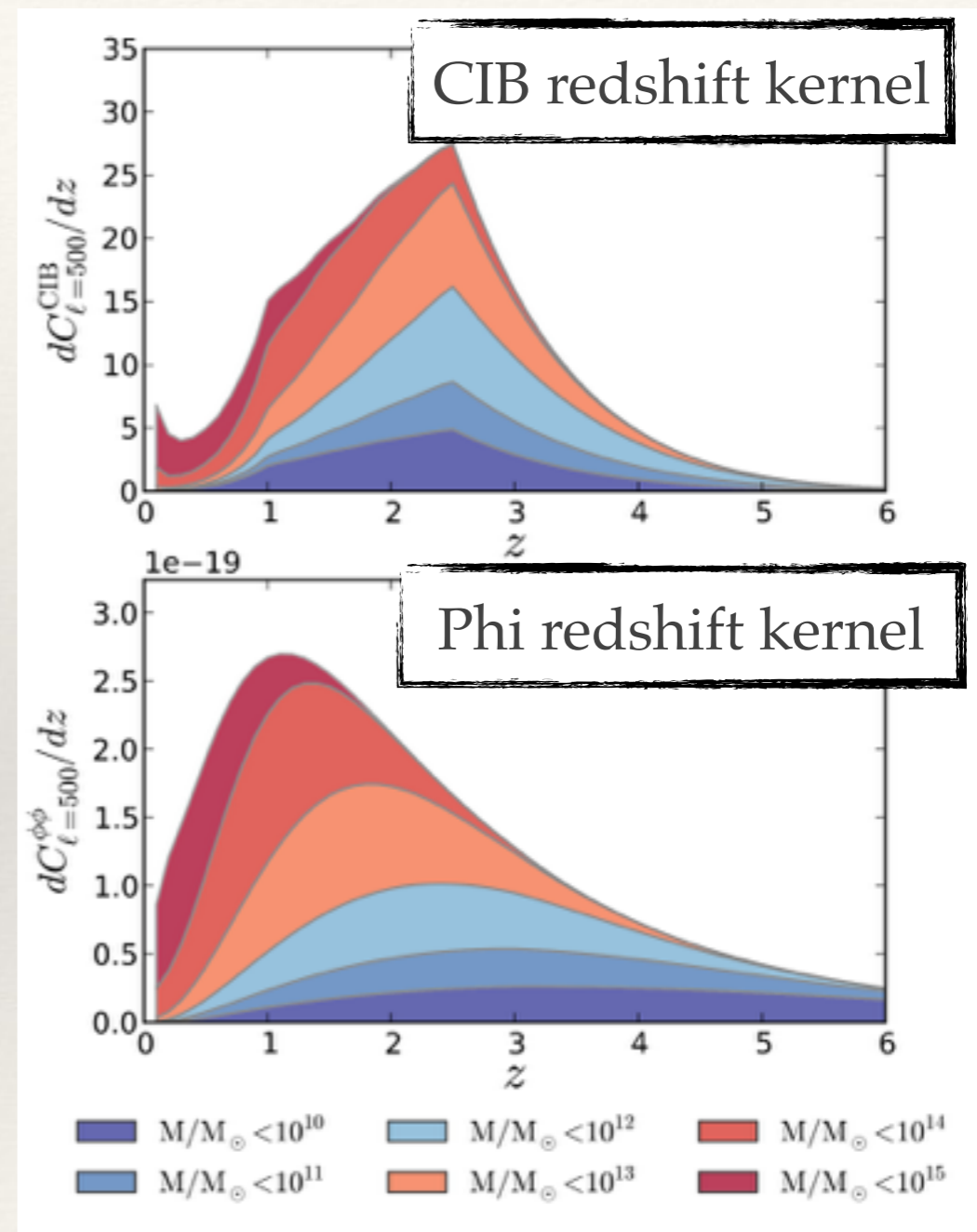


2. Subtract B template from B map



CIB as a Phi tracer

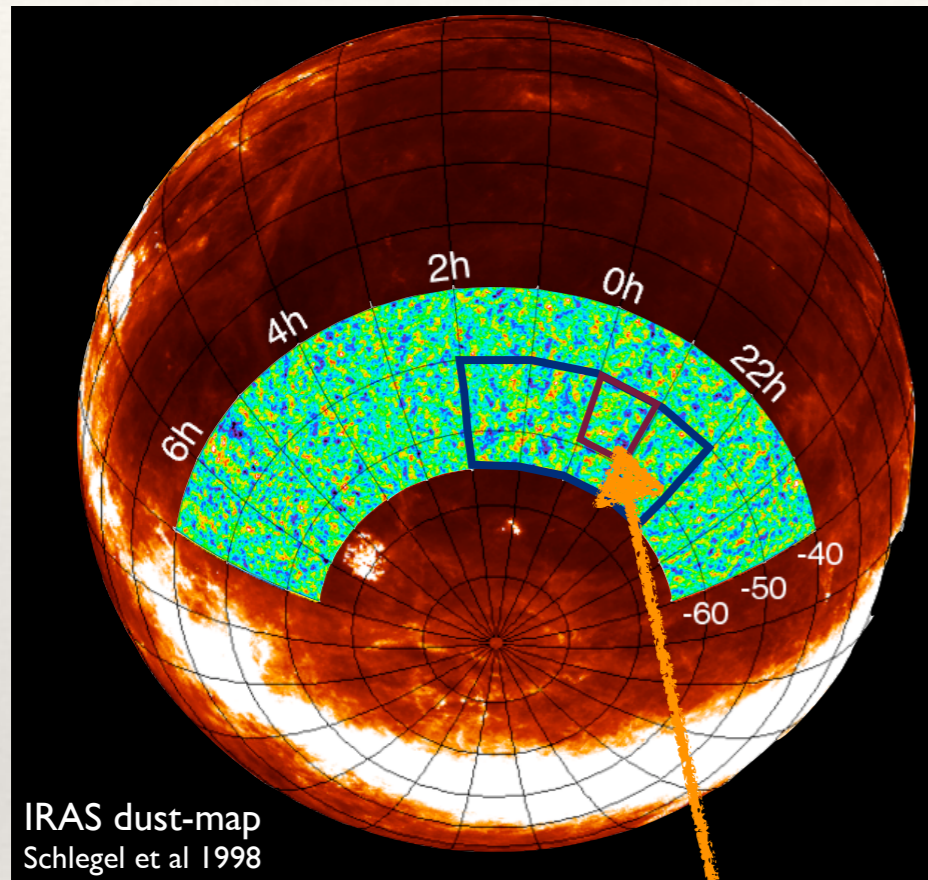
- ❖ Phi: can reconstruct from CMB, but S/N rather low currently (Future will be better!)
- ❖ Cosmic infrared background (CIB) from dusty star-forming galaxies with redshift distribution peaked between $z \sim 1$ and 2.
- ❖ CMB lensing potential's redshift kernel peaks between $1 < z < 3$
- ❖ Cross-correlation can be as high as $\sim 80\%$
- ❖ 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

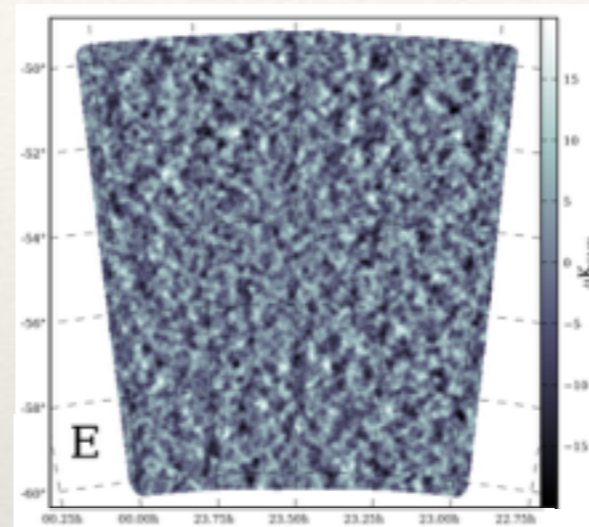
Lensing B template to delens SPTpol B modes

Inputs to form the B template

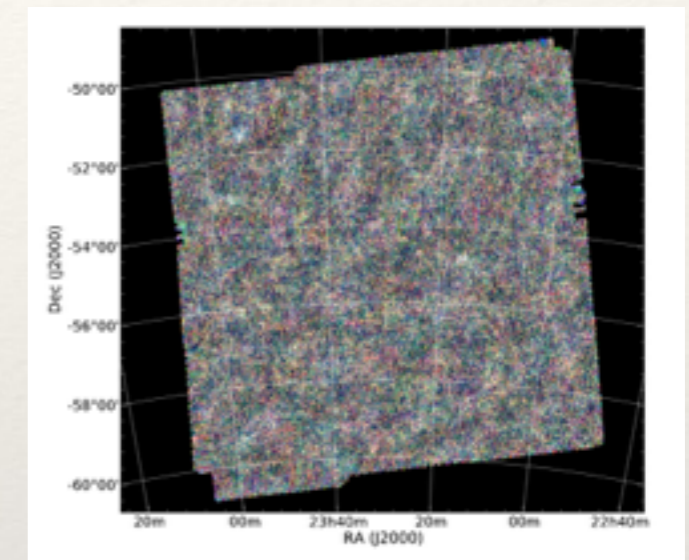


SPTpol 100 deg² field

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

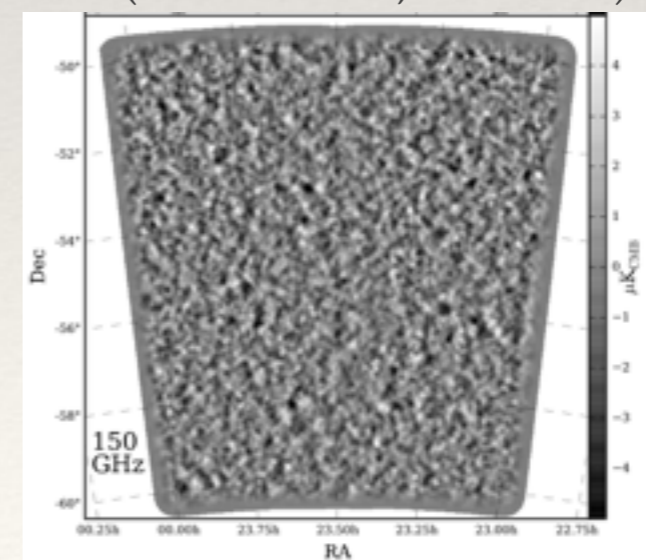


CIB map from Herschel 500 μm map



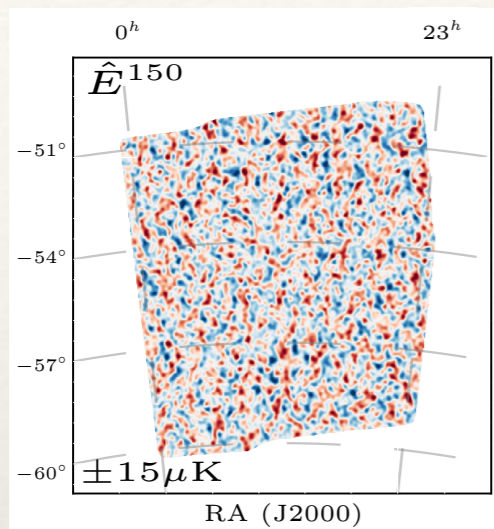
B-mode map to be delensed

(Keisler et al., SPT 2015)

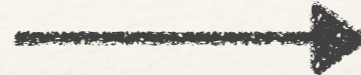
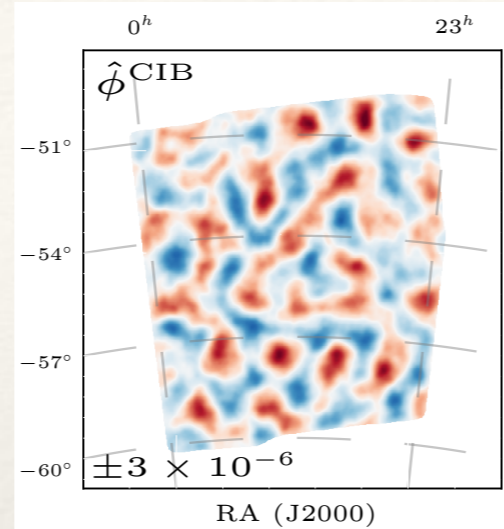


Delens

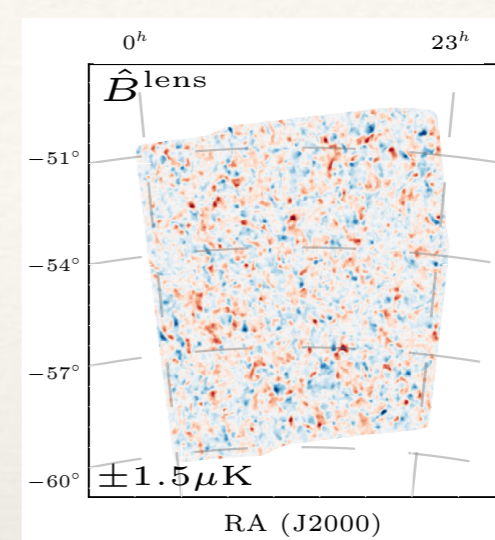
filtered E map



filtered Phi estimate

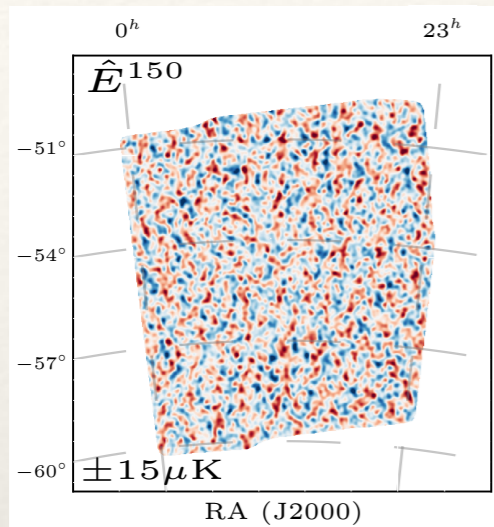


B template

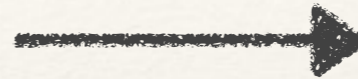
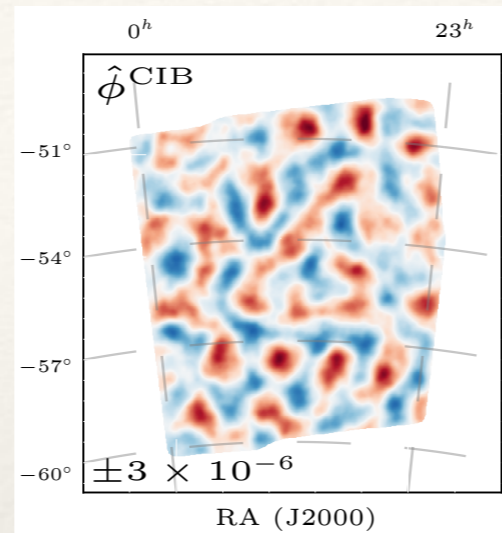


Delens

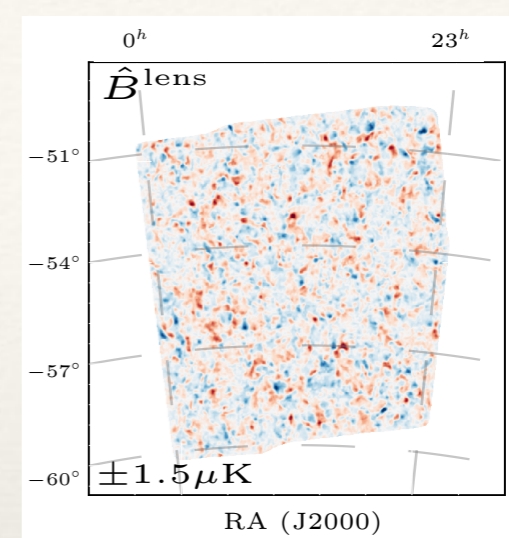
filtered E map



filtered Phi estimate



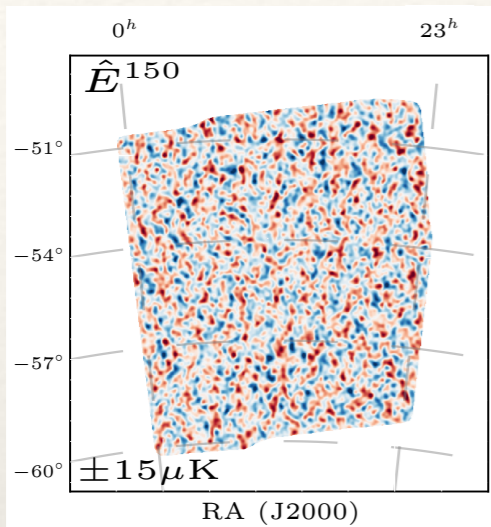
B template



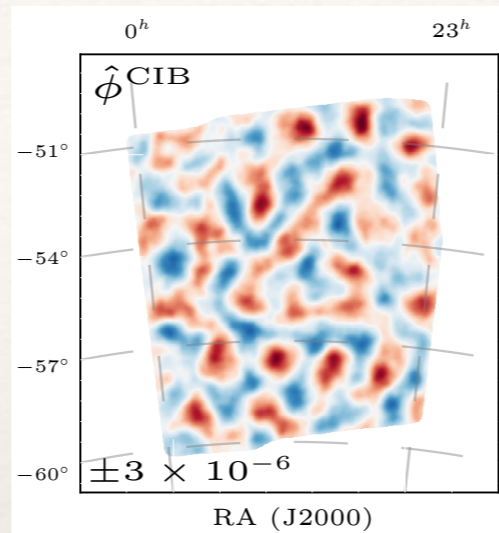
To ensure 'fair subtraction', apply 2D transfer function on the B template before subtracting from B mode map

Delens

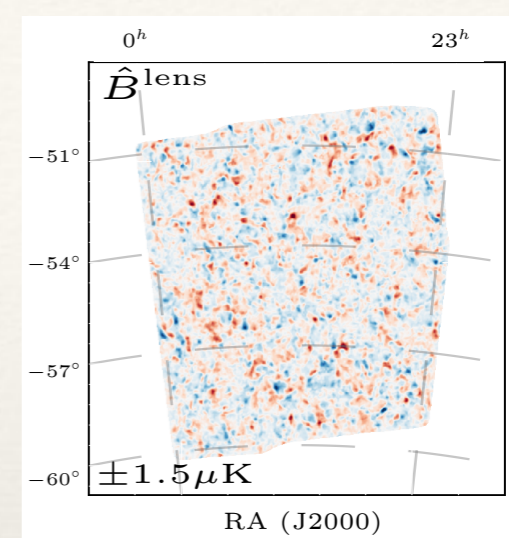
filtered E map



filtered Phi estimate

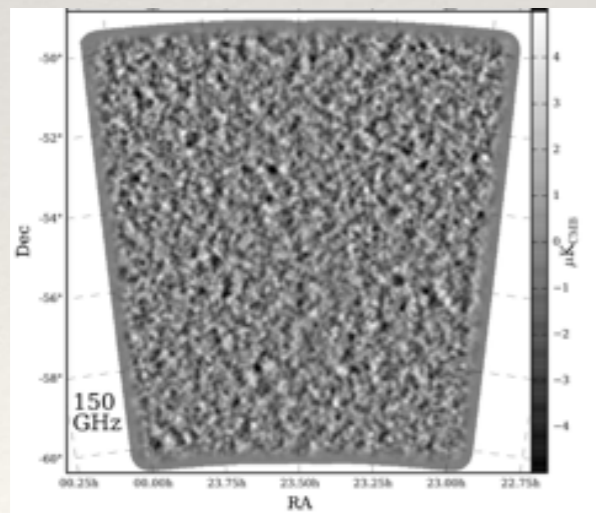


B template

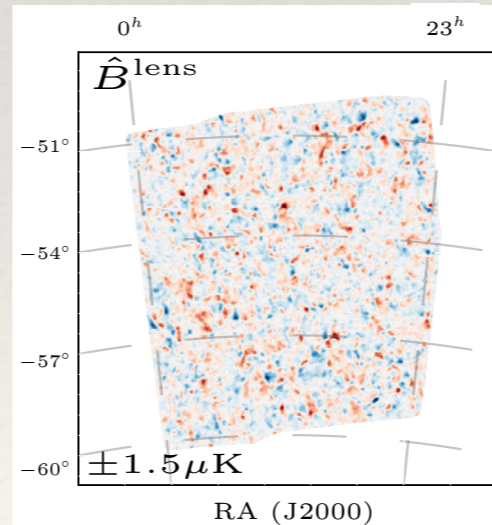


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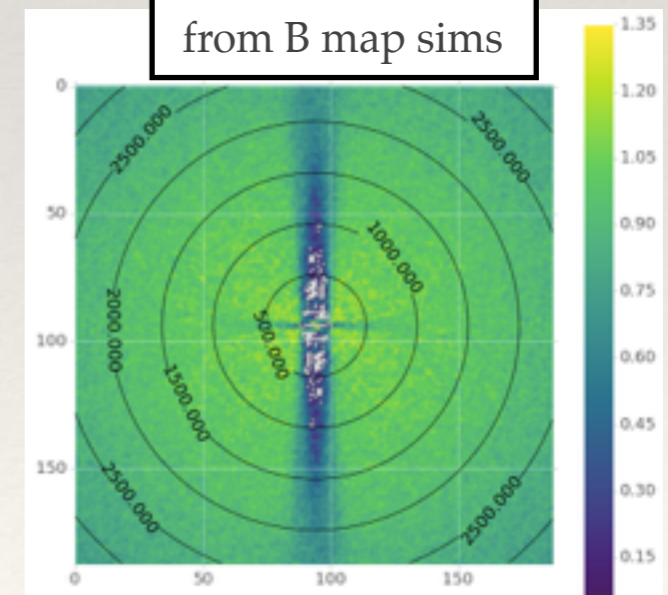
B map



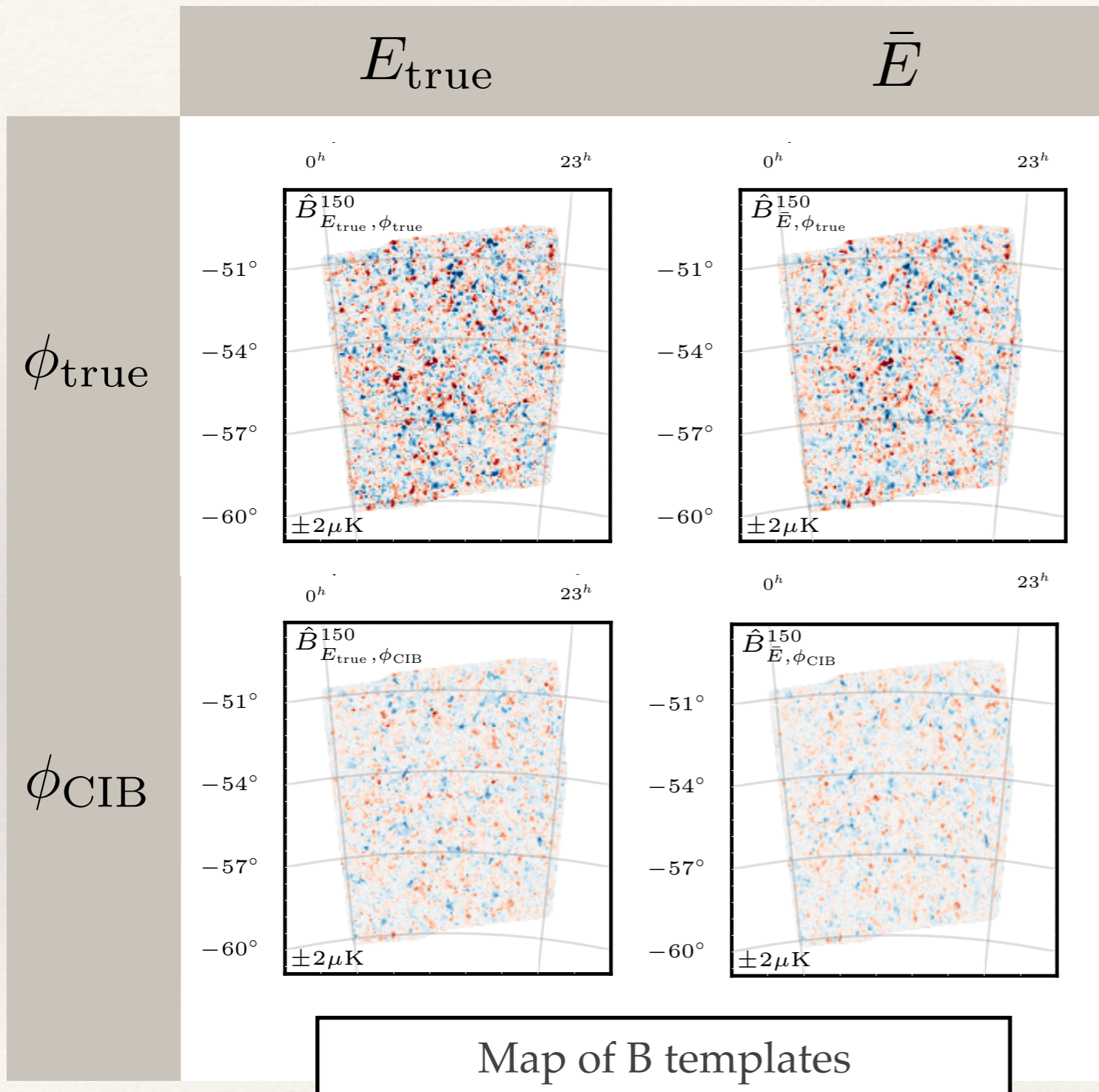
B template



Transfer Function from B map sims



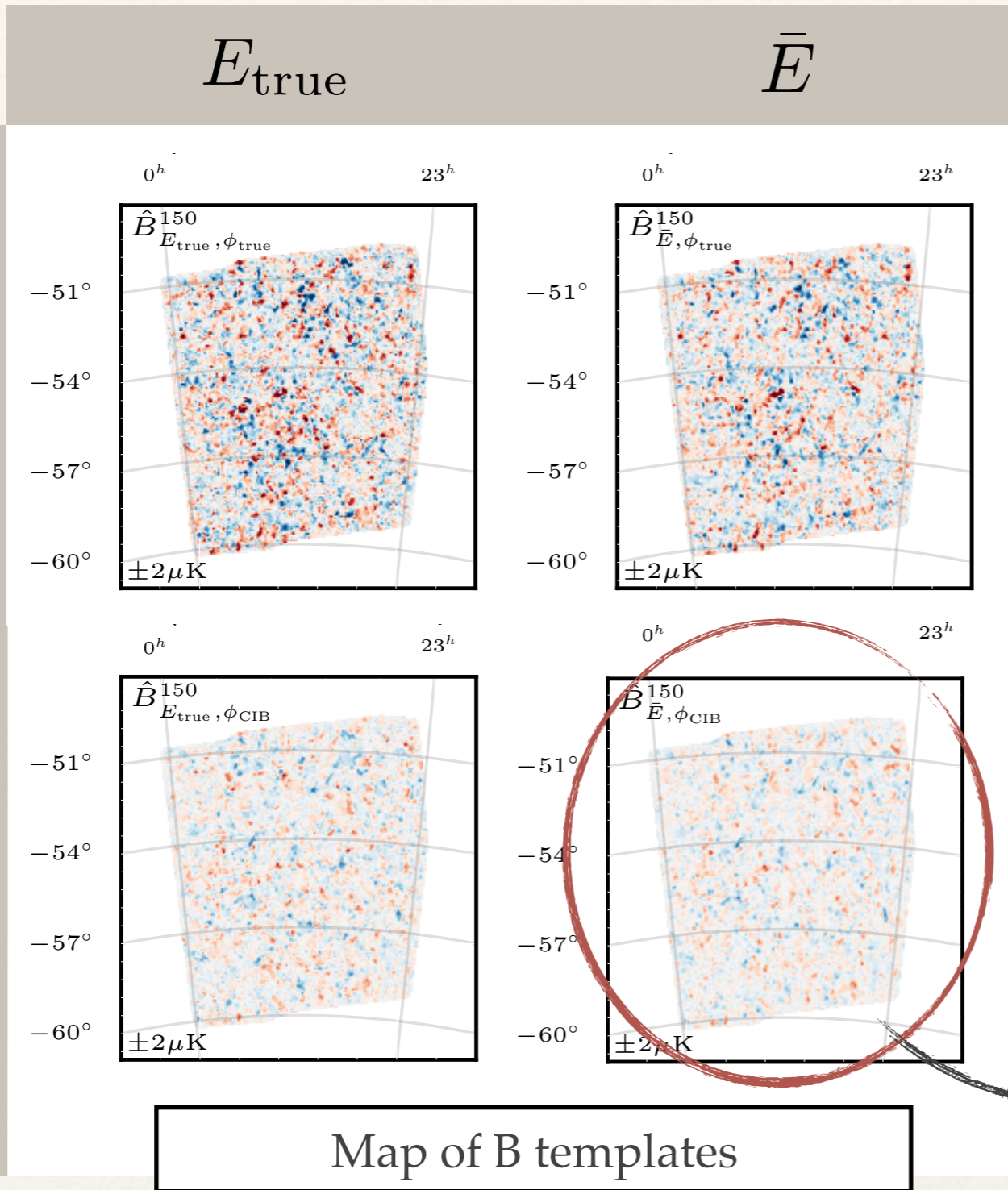
How well we reconstruct lensing B-modes \rightarrow how well we delens



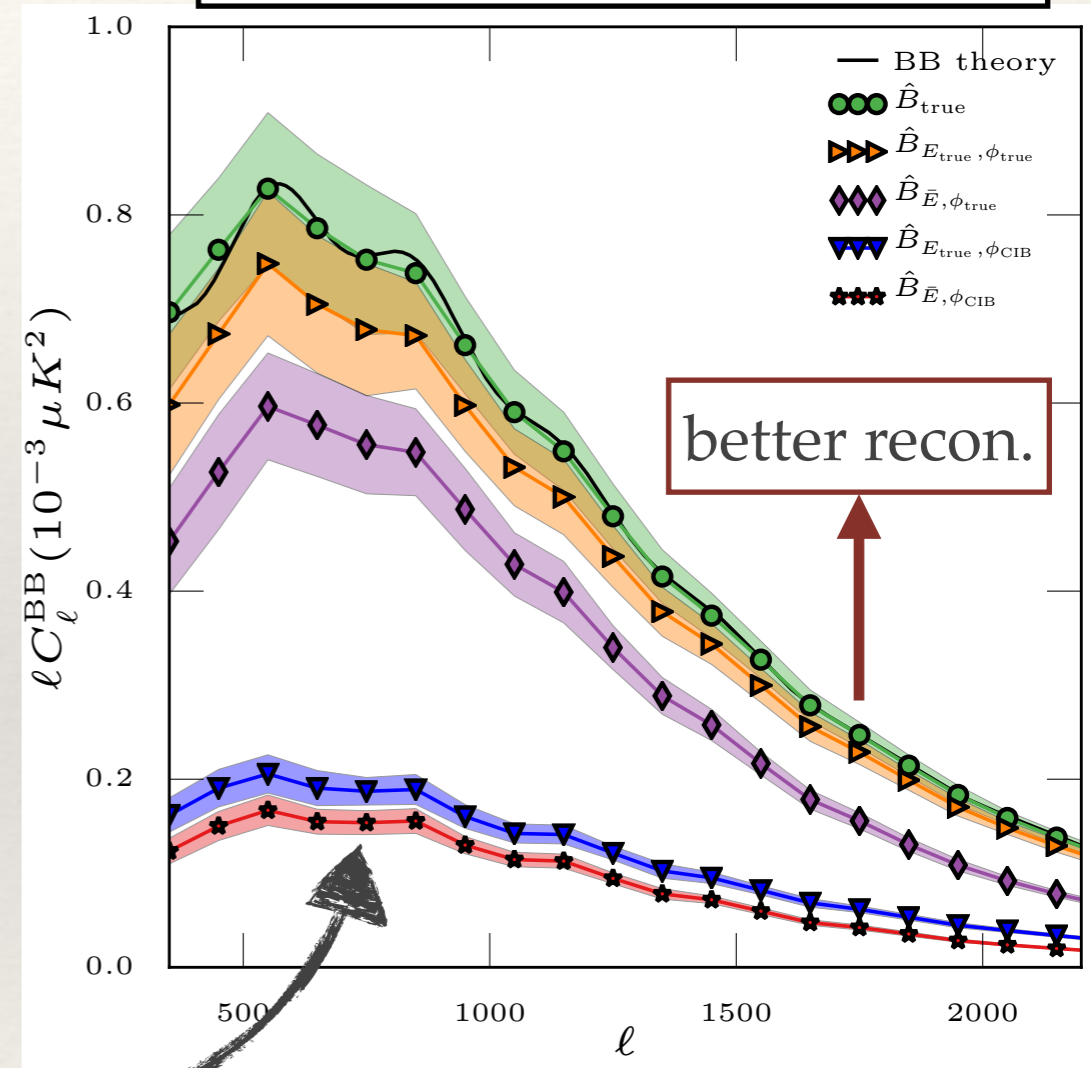
How well we reconstruct lensing B-modes \rightarrow how well we delens

ϕ_{true}

ϕ_{CIB}

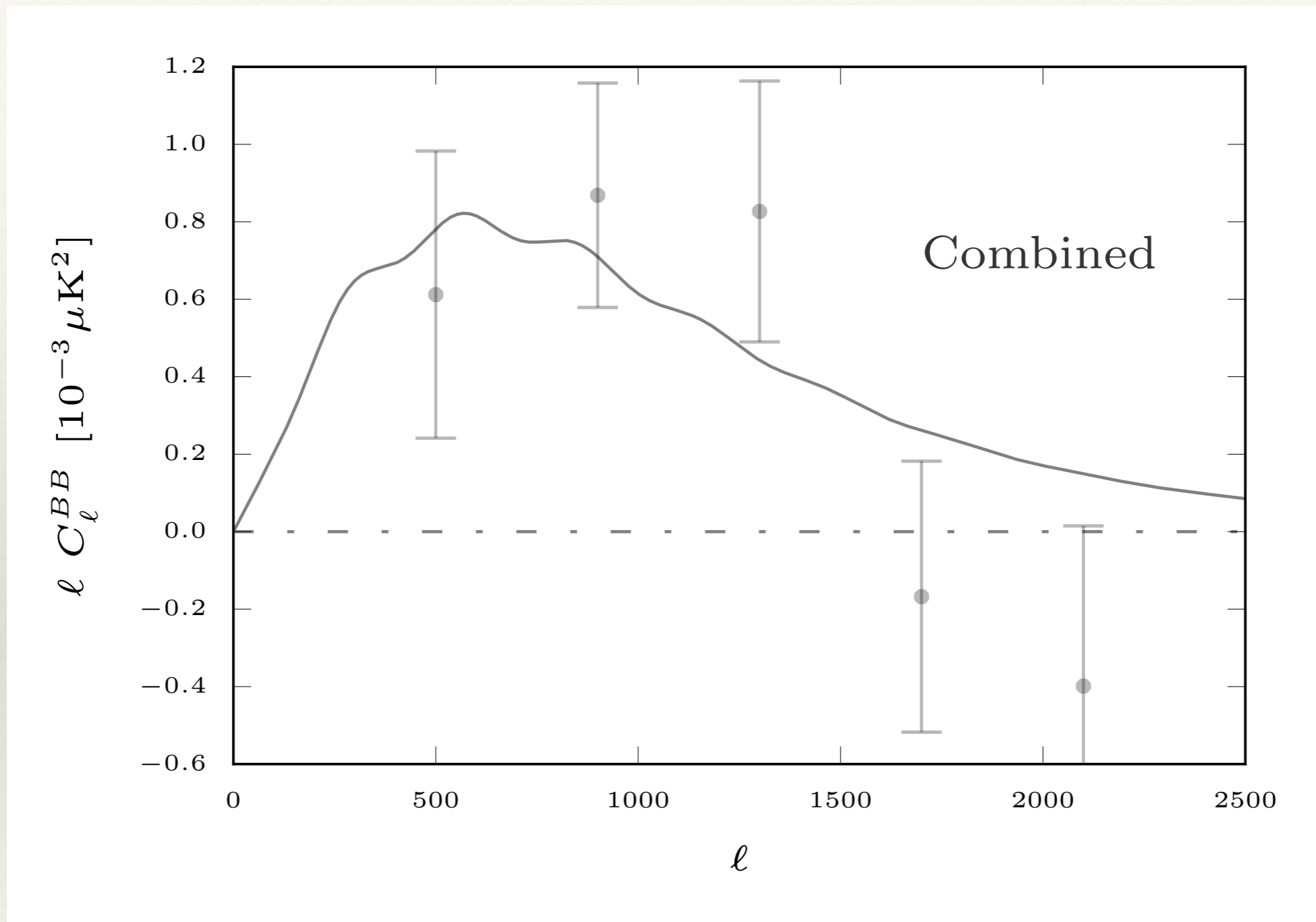


Auto-spectra of B templates

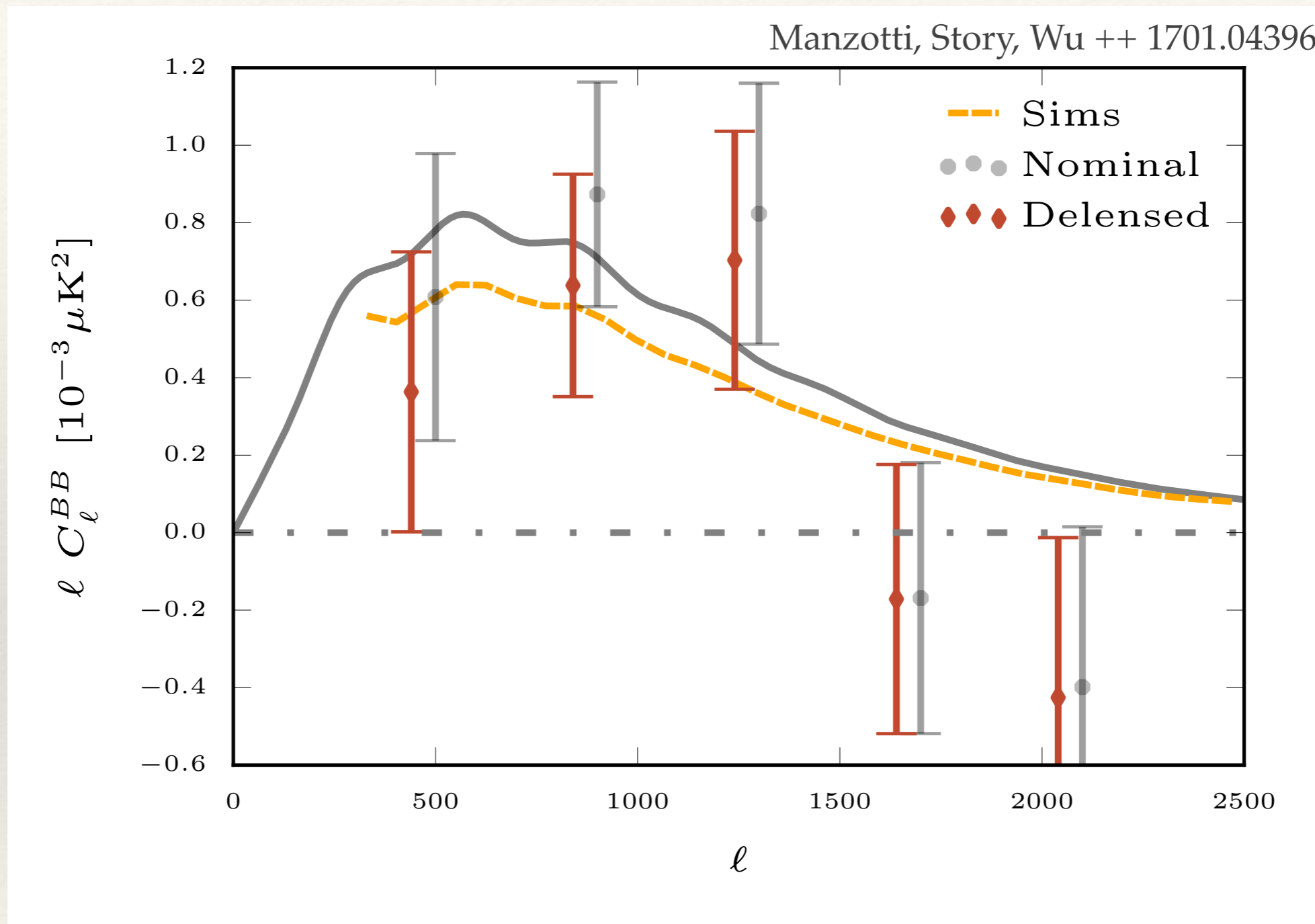


$\sim 20\%$

SPTpol BB spectrum (no delensing)



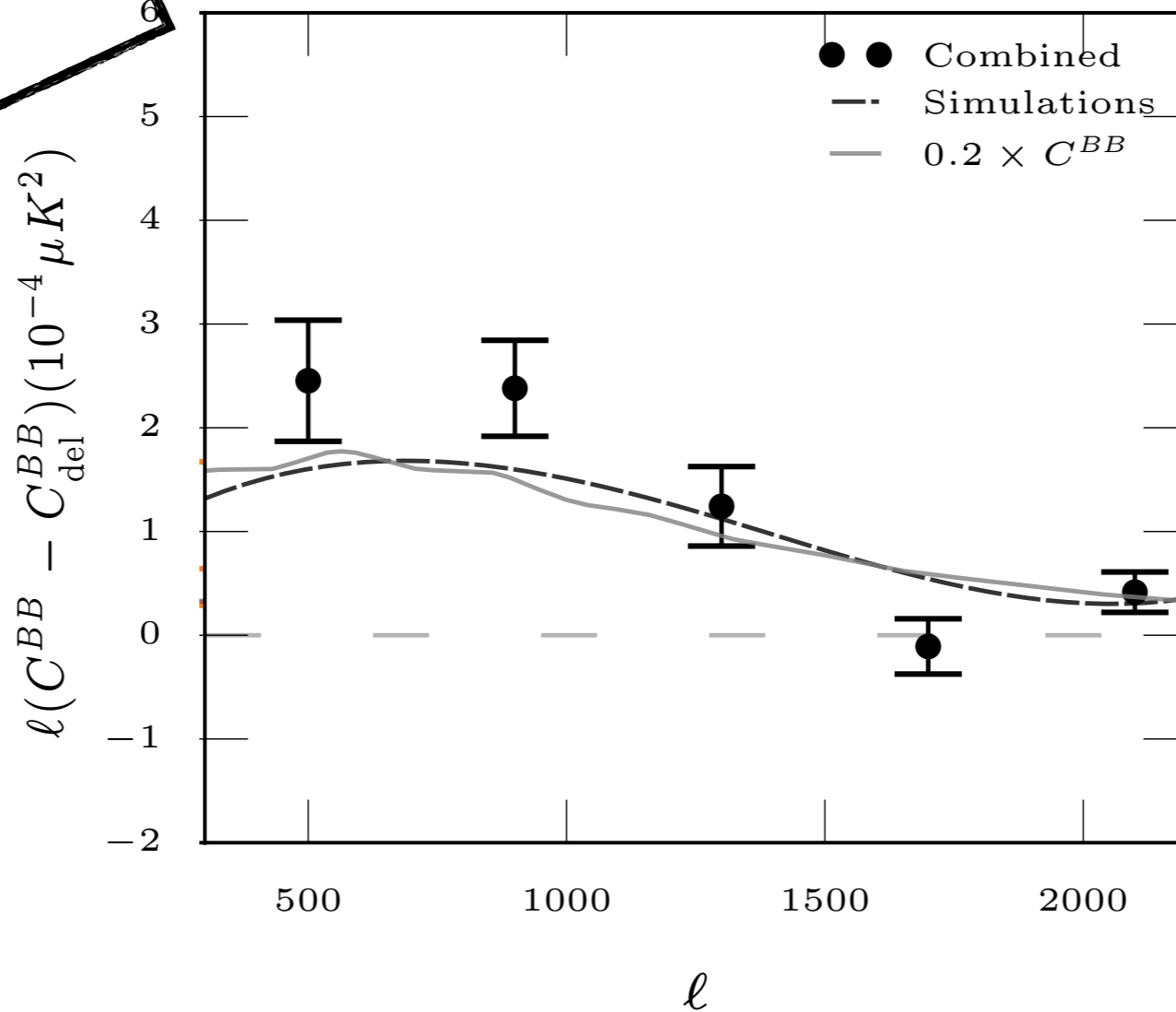
Delensed SPTpol BB spectrum



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!

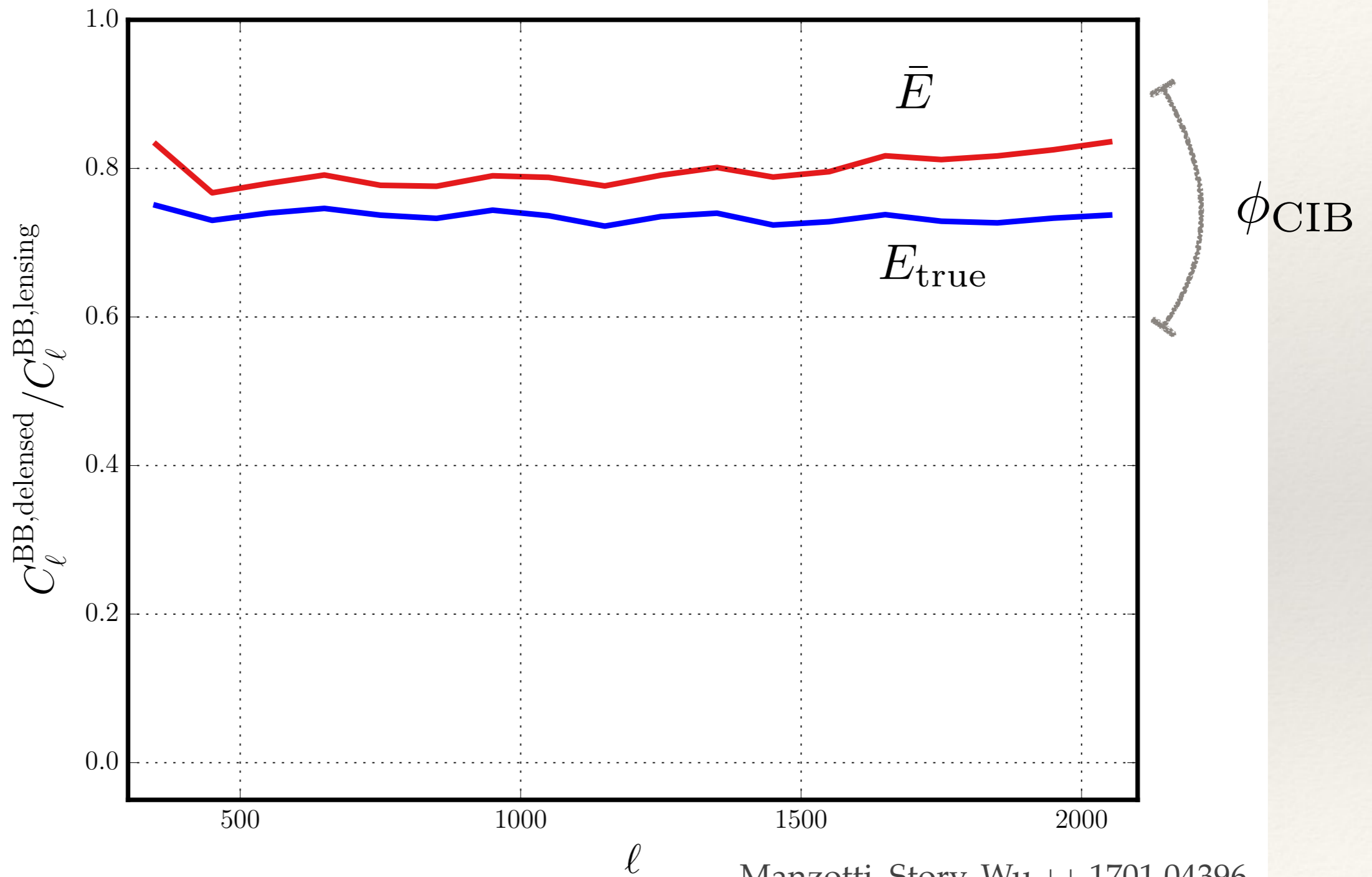
Case study: limitation to delensing

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

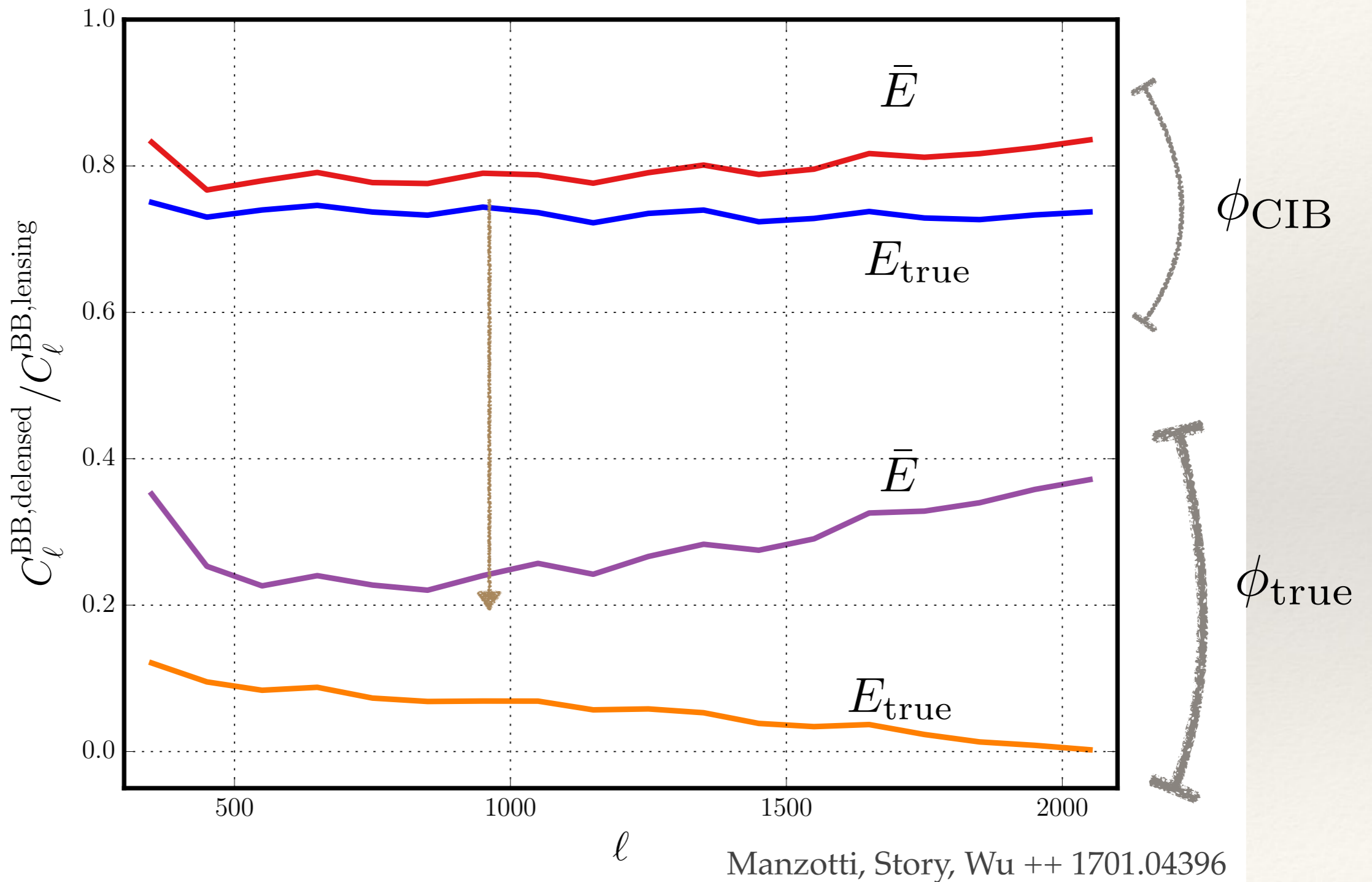
Less delensing ↑



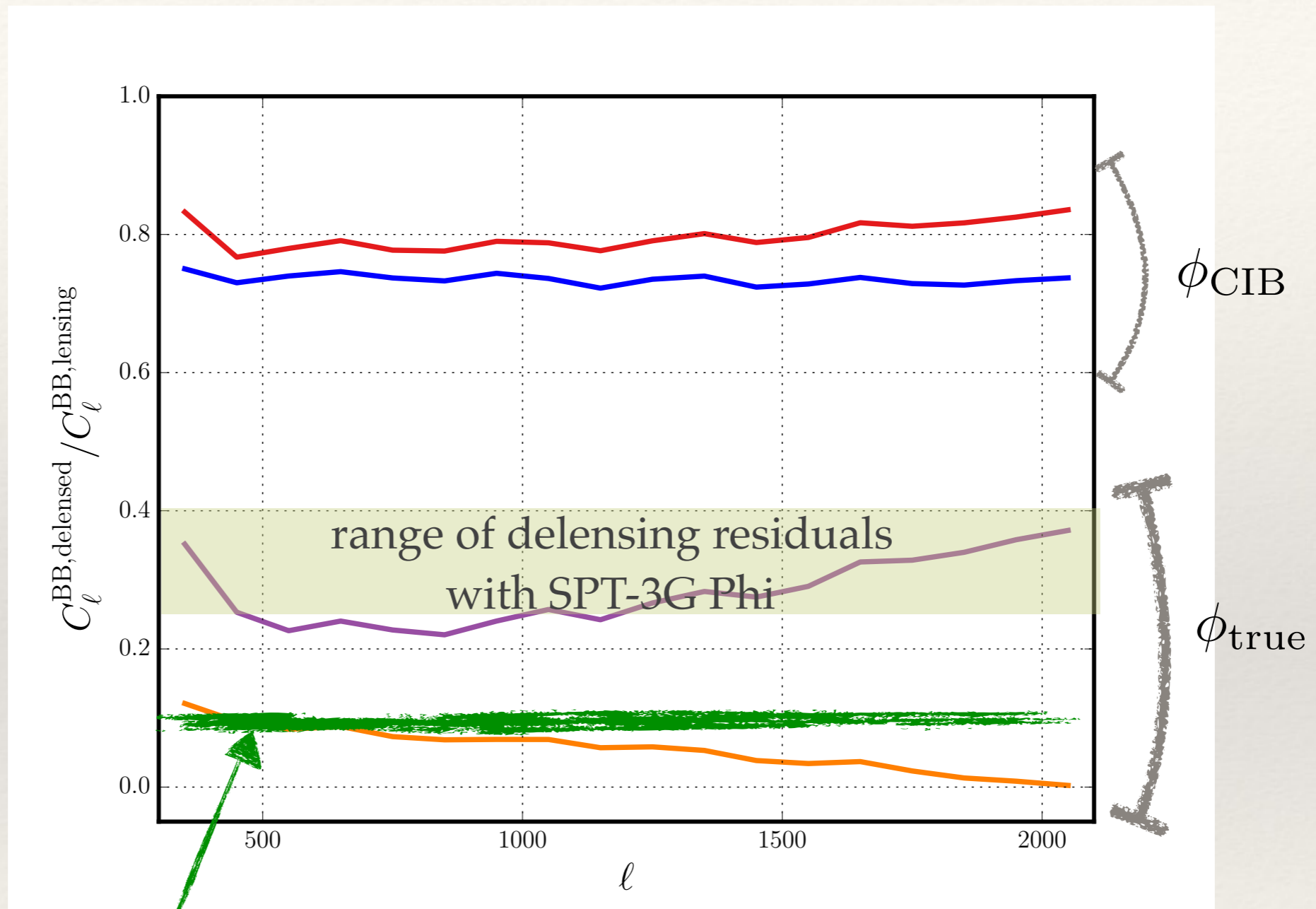
Manzotti, Story, Wu ++ 1701.04396

Delensing currently limited by Phi

Less delensing ↑

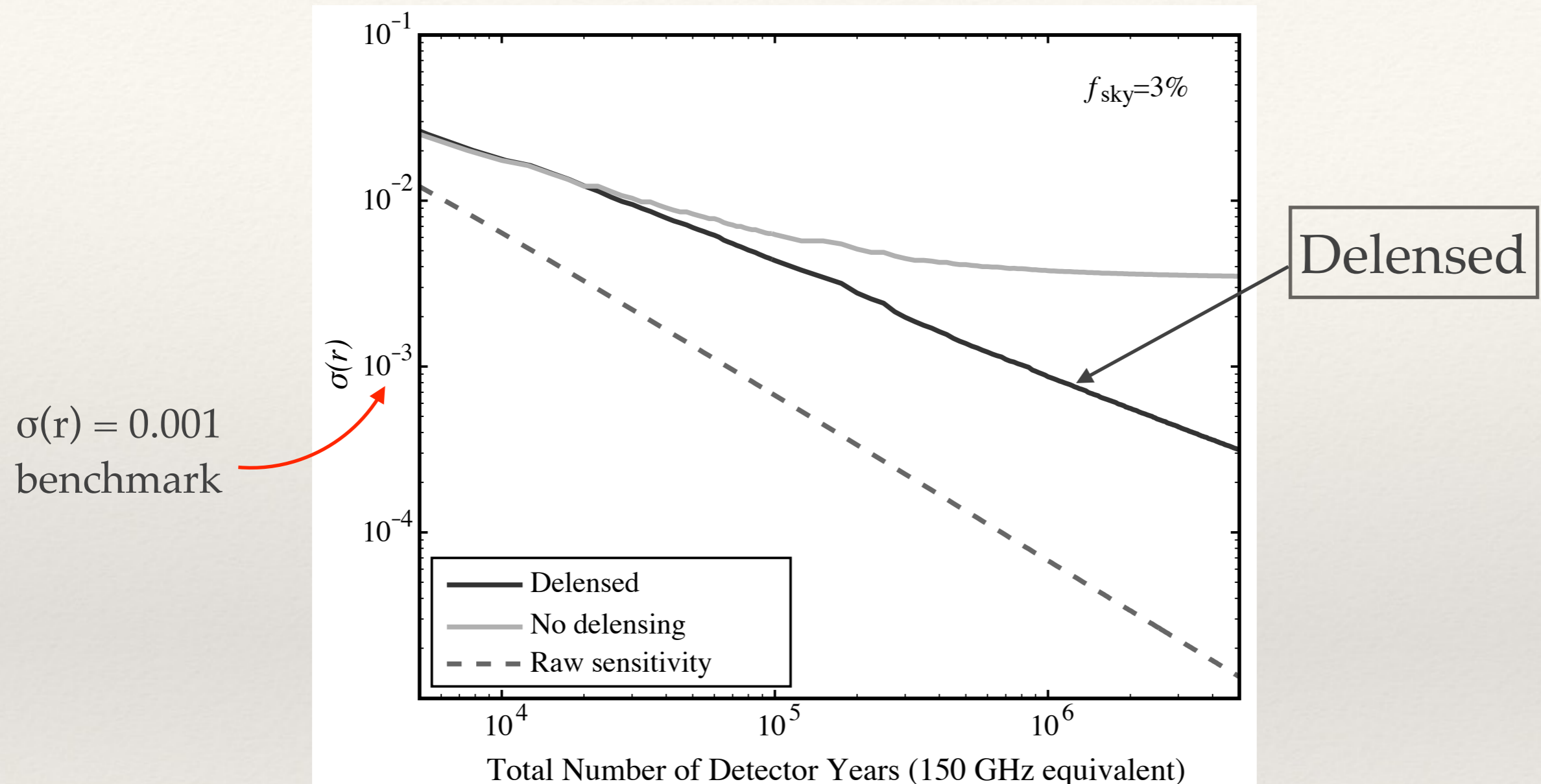


Future CMB-phi



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

r forecast with CMB-S4



CMB-S4 Science Book

- With Φ reconstructed with Stage-4 level noise, we expect $\sim 10\%$ lensing Cl^{BB} residuals

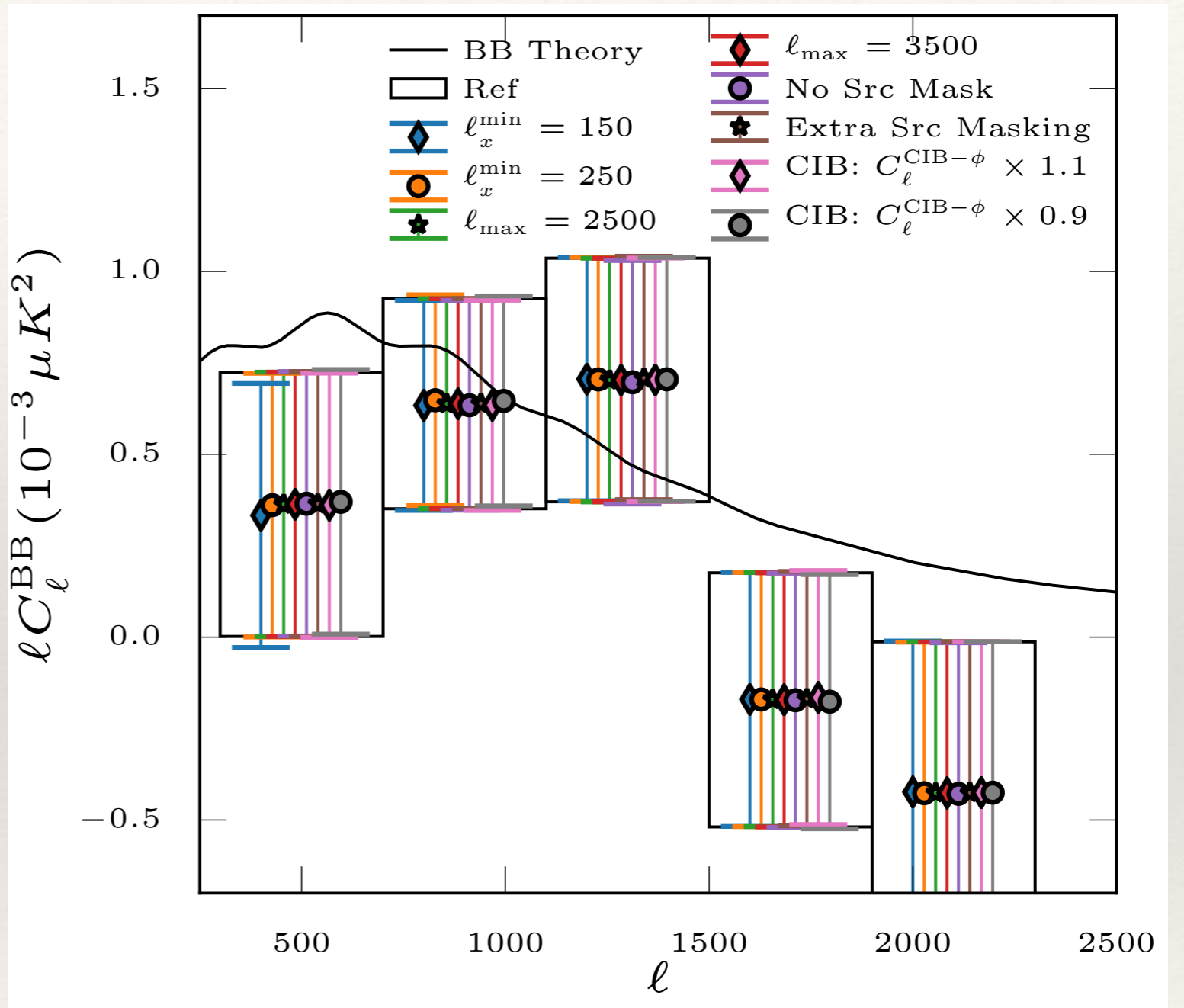
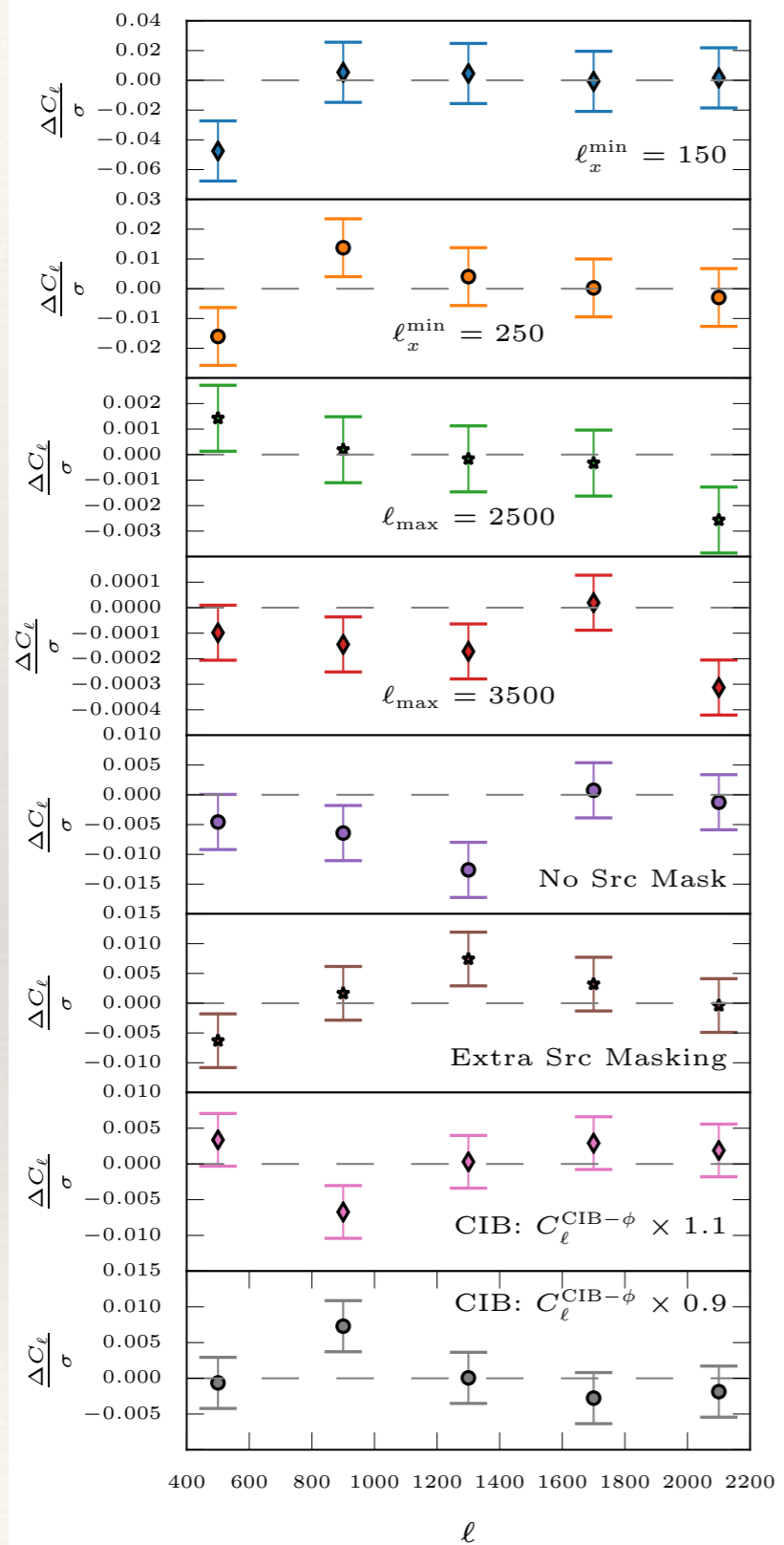
Summary

- ❖ 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 $\sigma(r)$.

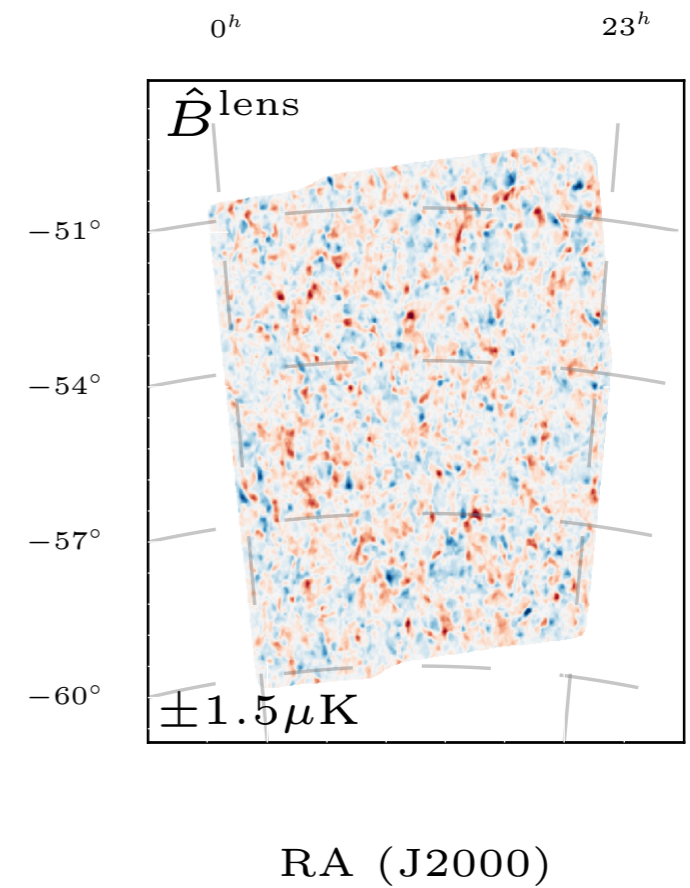
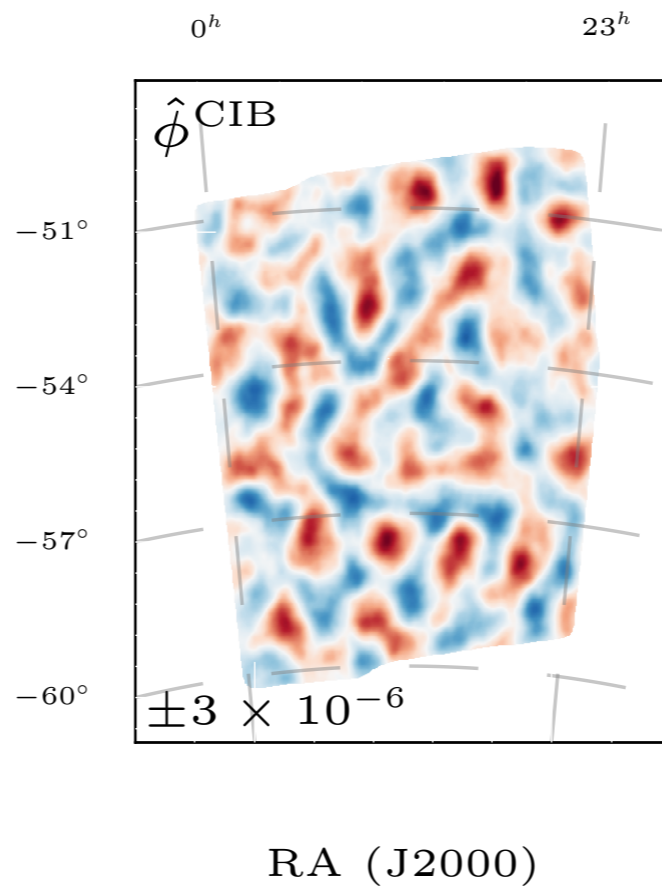
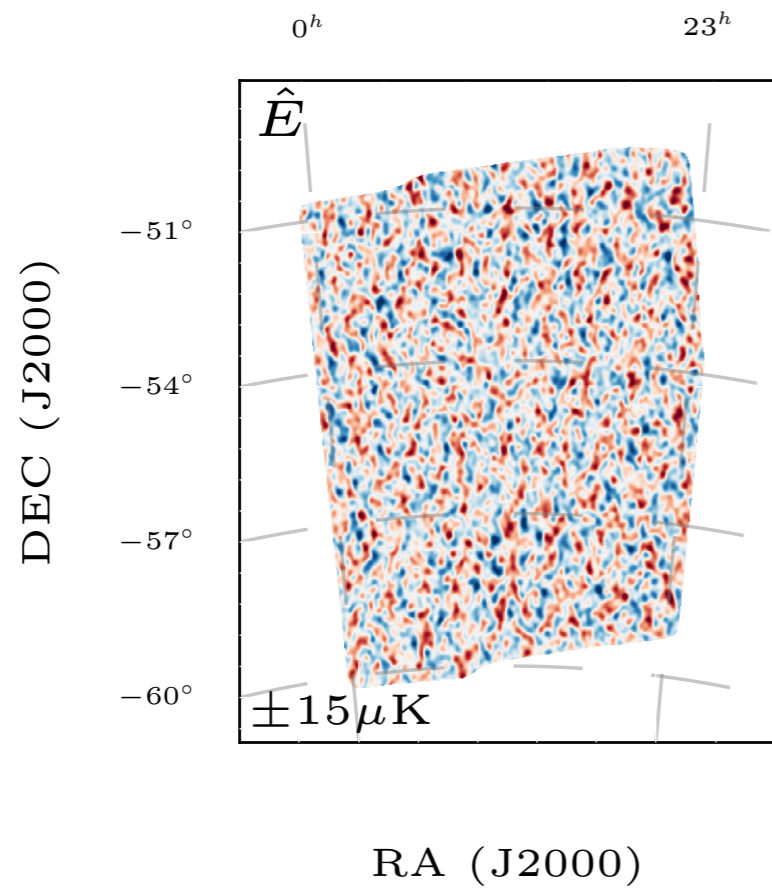
Thank you for your attention

extras

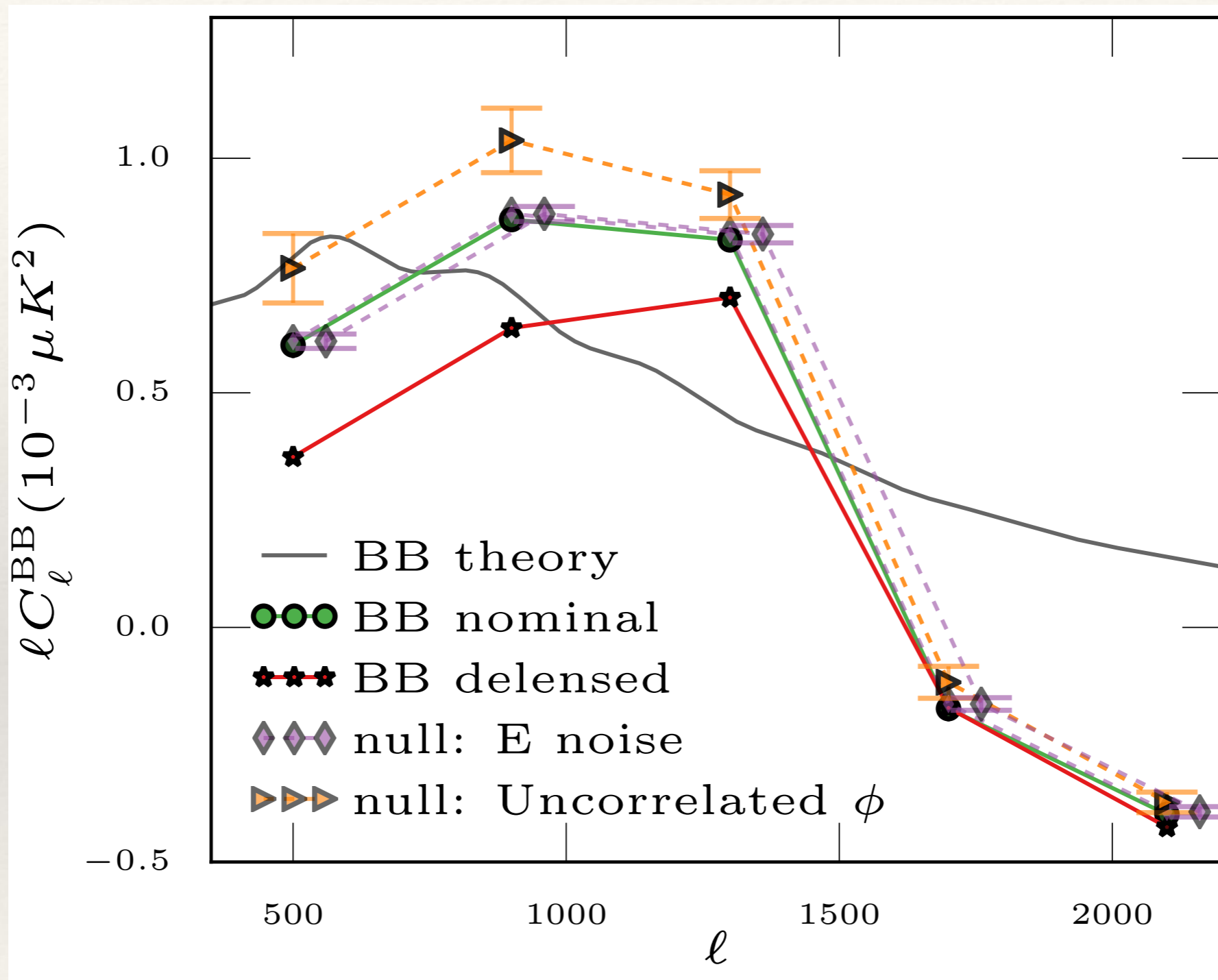
Systematics tests



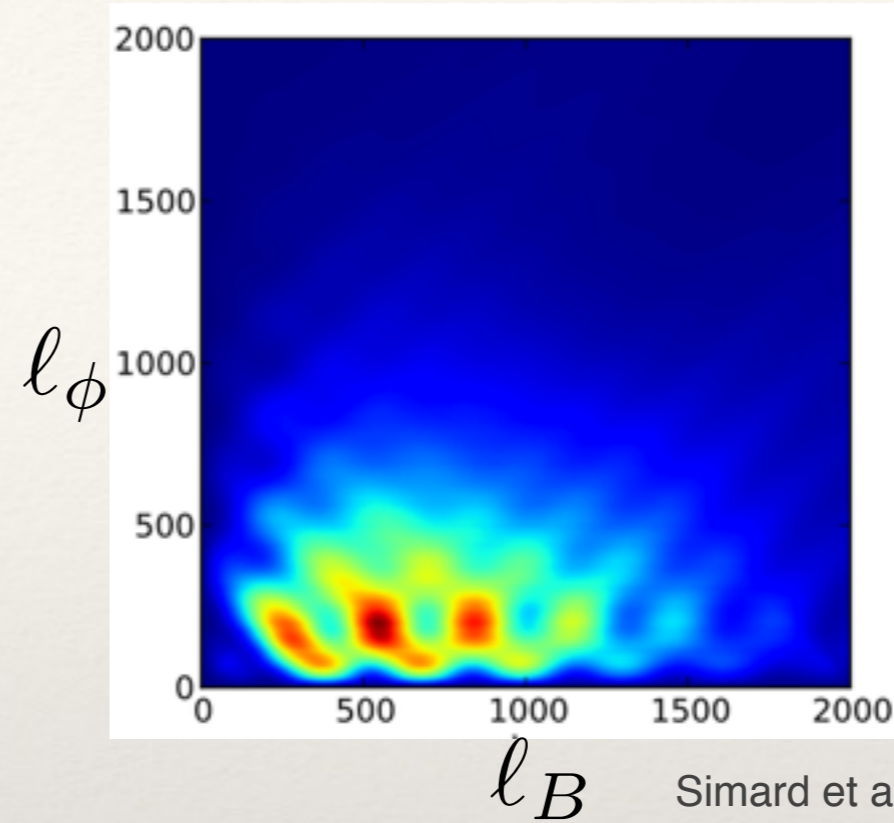
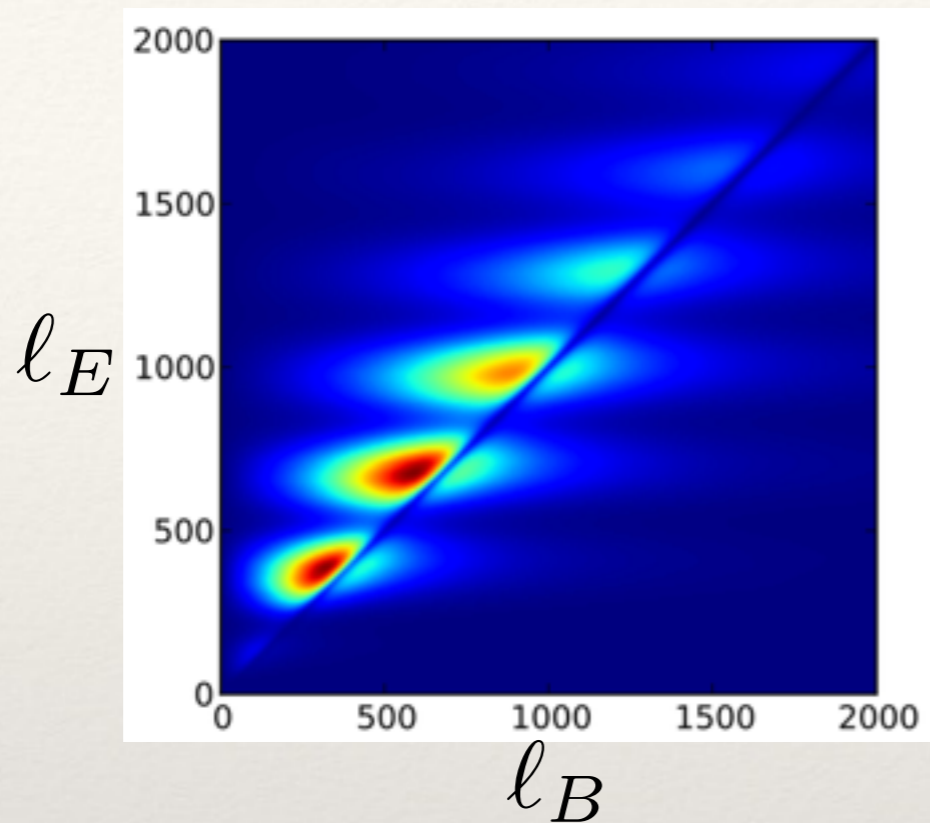
Data maps



null tests



Forming the B template: I

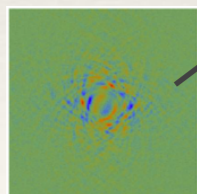


Simard et al. 2014 (1401.0691)

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

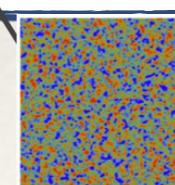
$$B^{\text{lens}}(\ell) = \int \frac{d^2\ell'}{(2\pi)^2} W(\ell, \ell') E(\ell') \phi(\ell - \ell')$$

theoretical unlensed E, phi



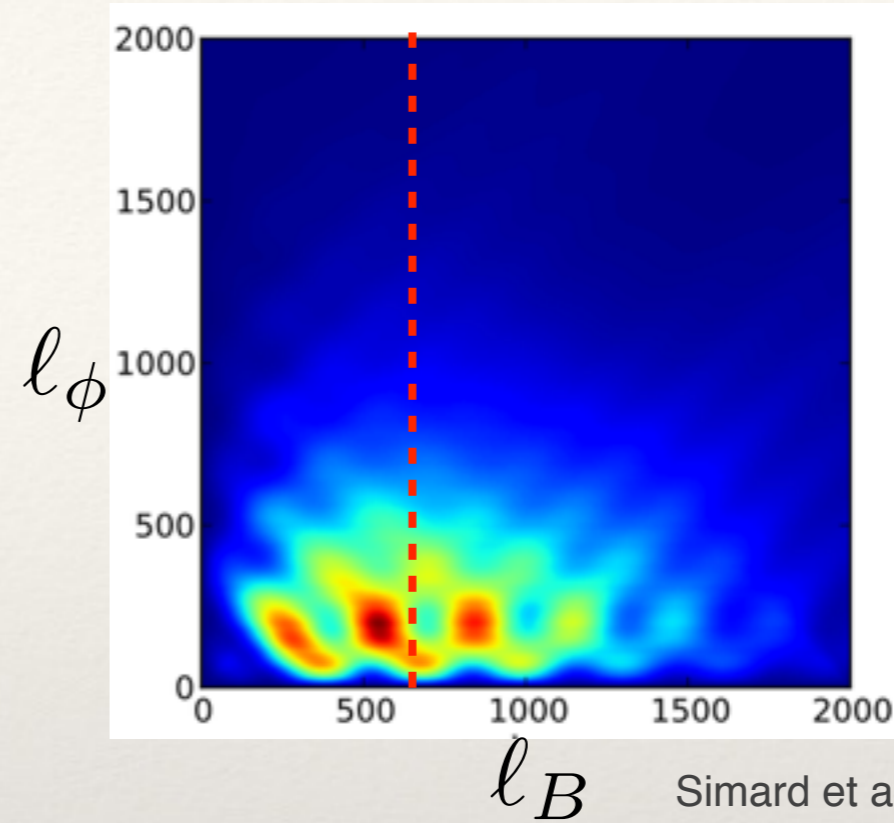
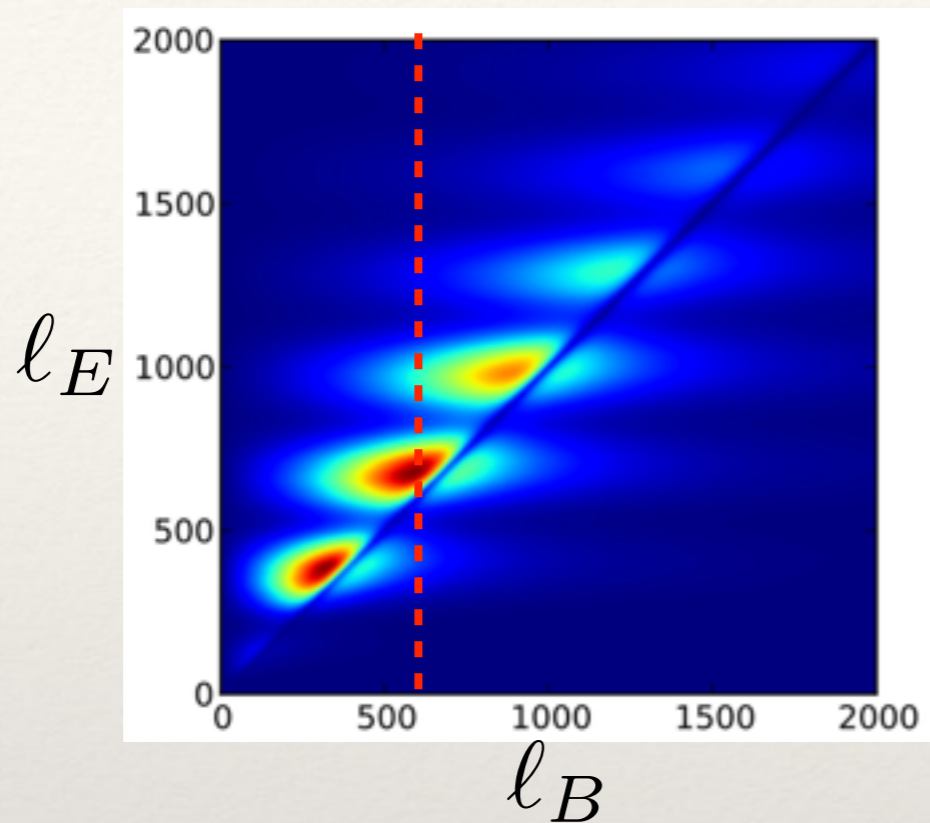
where weight function

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



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

Forming the B template: I

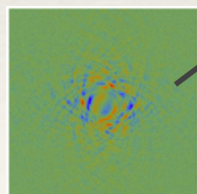


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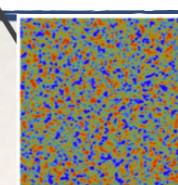
$$B^{\text{lens}}(\boldsymbol{\ell}) = \int \frac{d^2\boldsymbol{\ell}'}{(2\pi)^2} W(\boldsymbol{\ell}, \boldsymbol{\ell}') E(\boldsymbol{\ell}') \phi(\boldsymbol{\ell} - \boldsymbol{\ell}')$$

theoretical unlensed E, phi



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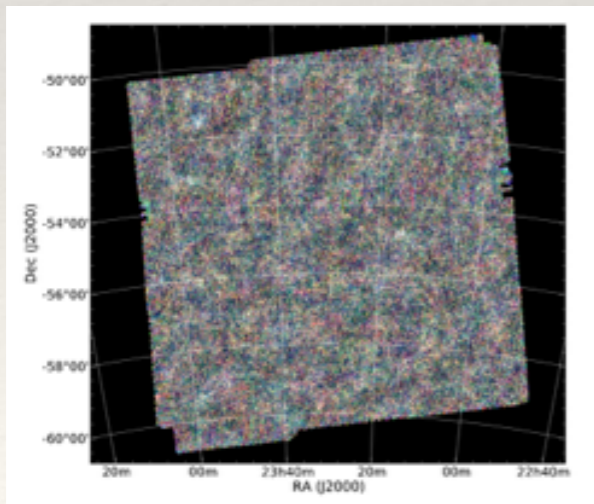
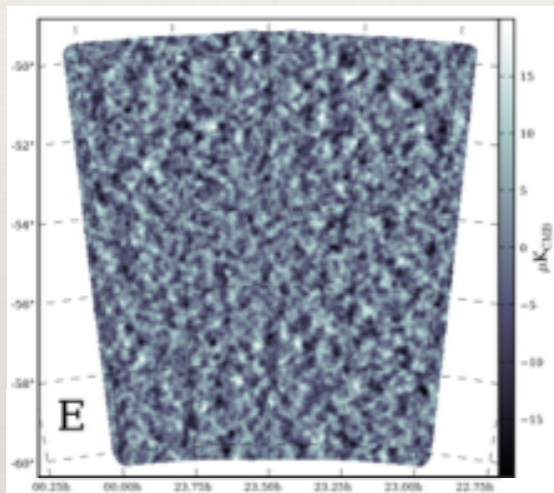
* flat-sky approx.: $\boldsymbol{\ell} = 2\pi|\mathbf{u}|$, \mathbf{u} is Fourier mode.

Forming the B template: II

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

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

Input maps



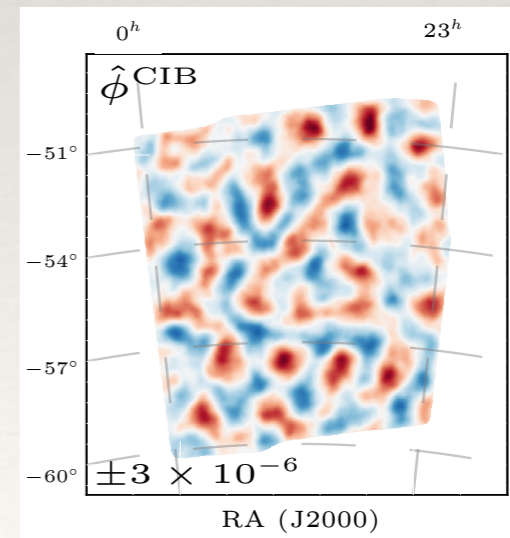
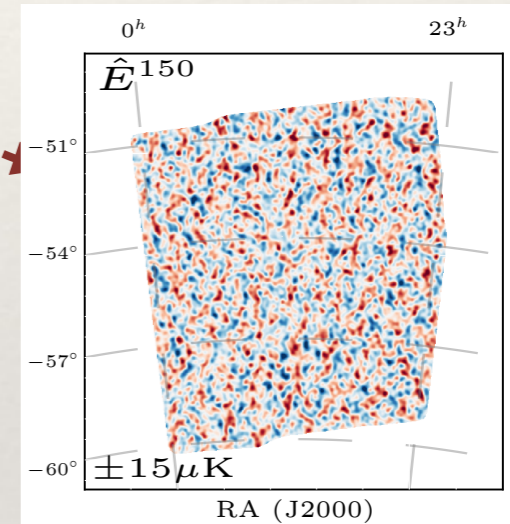
Filtering

$$\bar{E}(\ell) \approx \left(\frac{C_l^{EE}}{C_l^{EE} + N_l^{EE}} \right) E^N(\ell)$$

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

filters chosen to minimize residual variance

Filtered maps



Delensing currently limited by Phi

