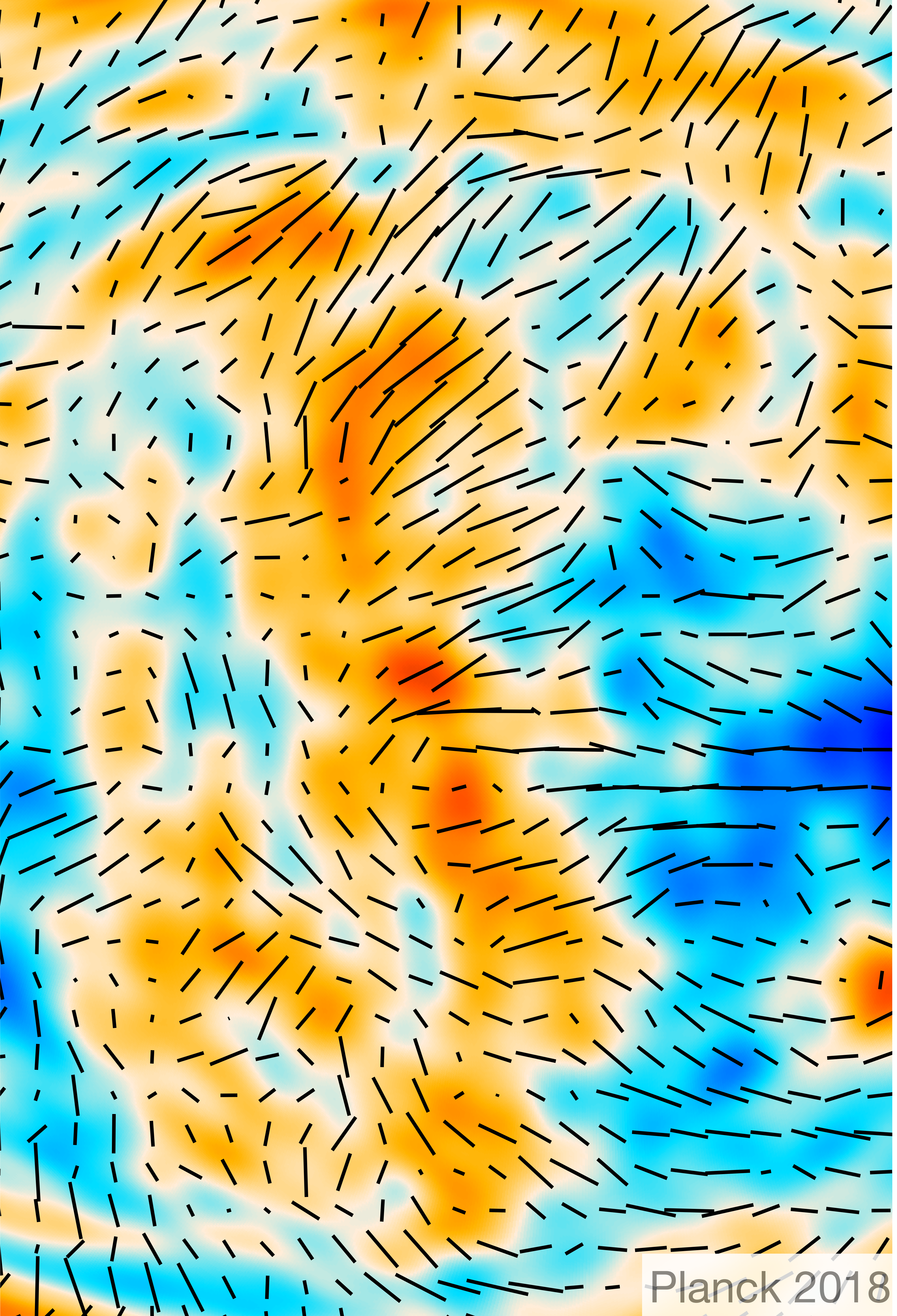
BIASES TO CMB LENSING AND DELENSING

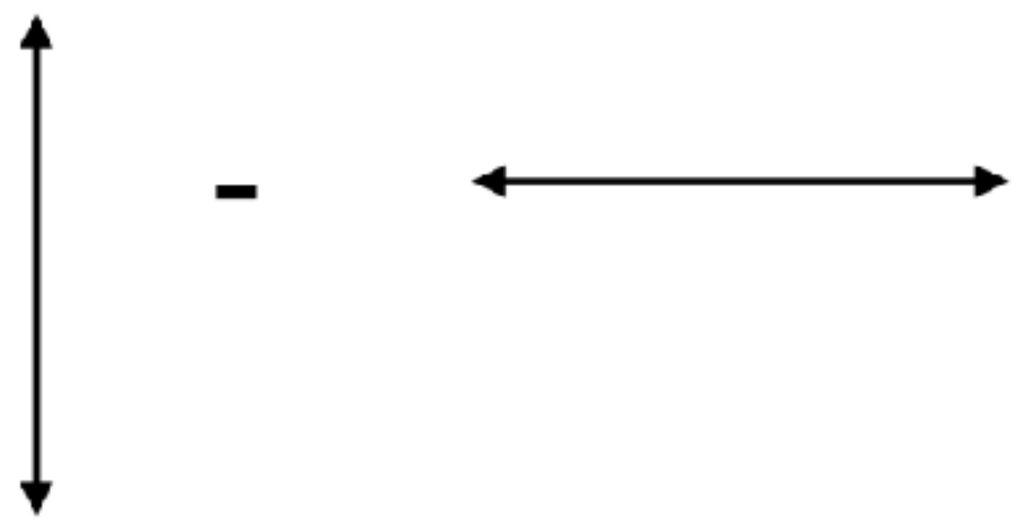
Anton Baleato Lizancos

INPA seminar, Berkeley — 20/10/2020



CMB OBSERVABLES — INTENSITY AND POLARISATION

Observe:



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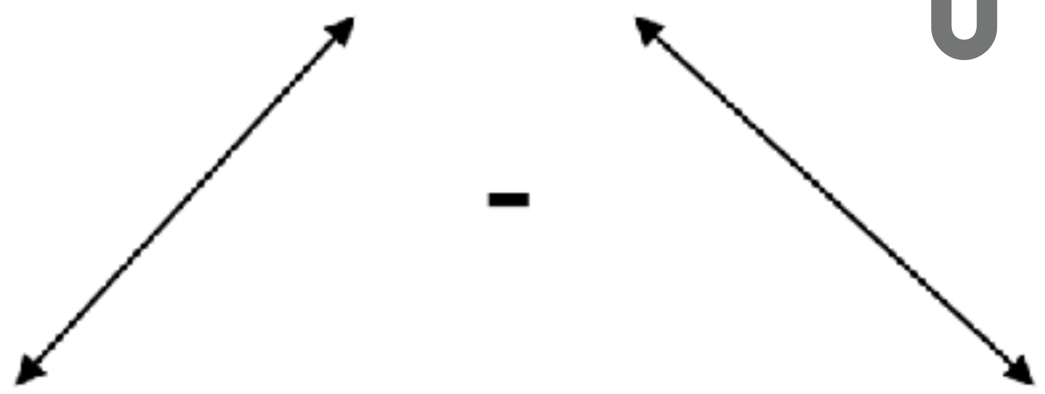
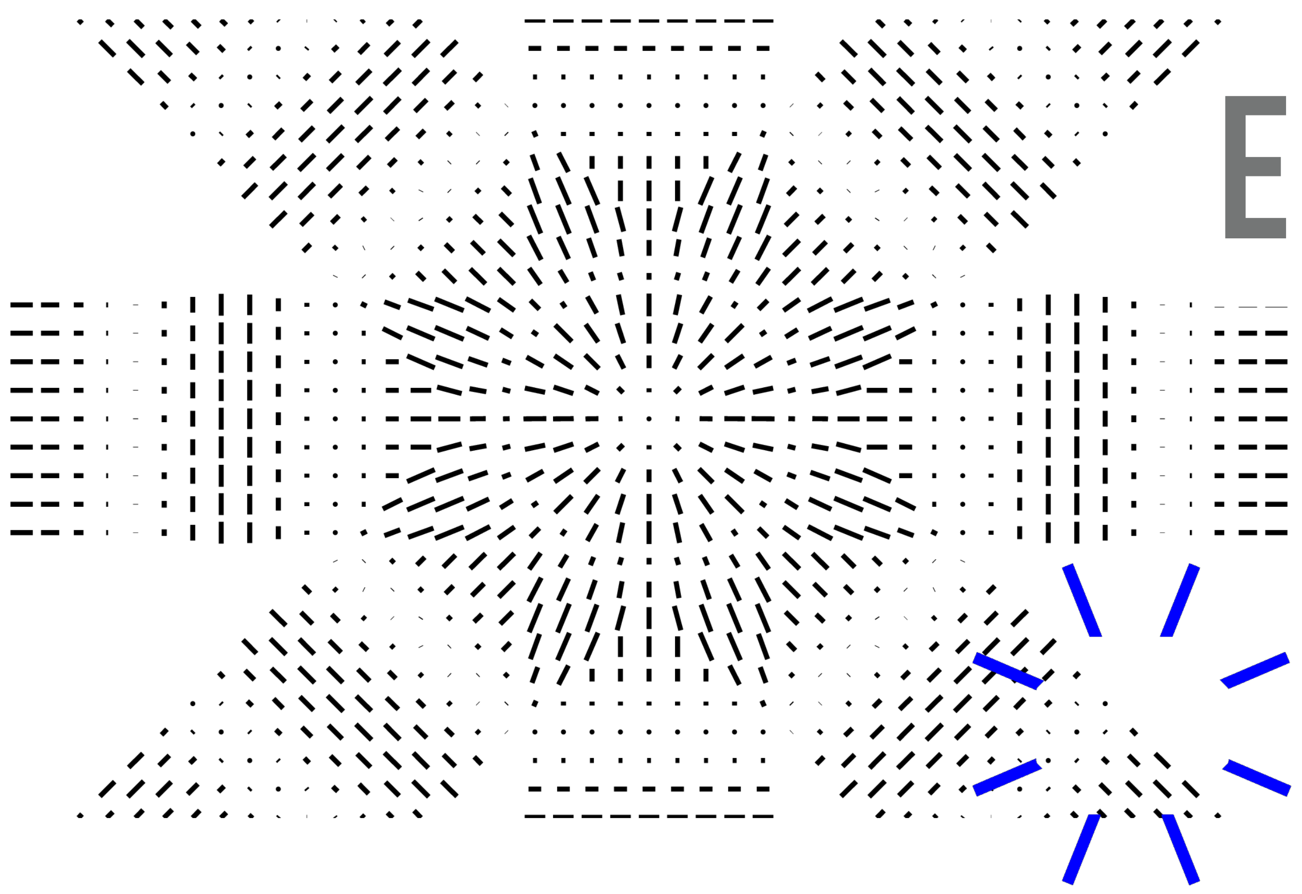
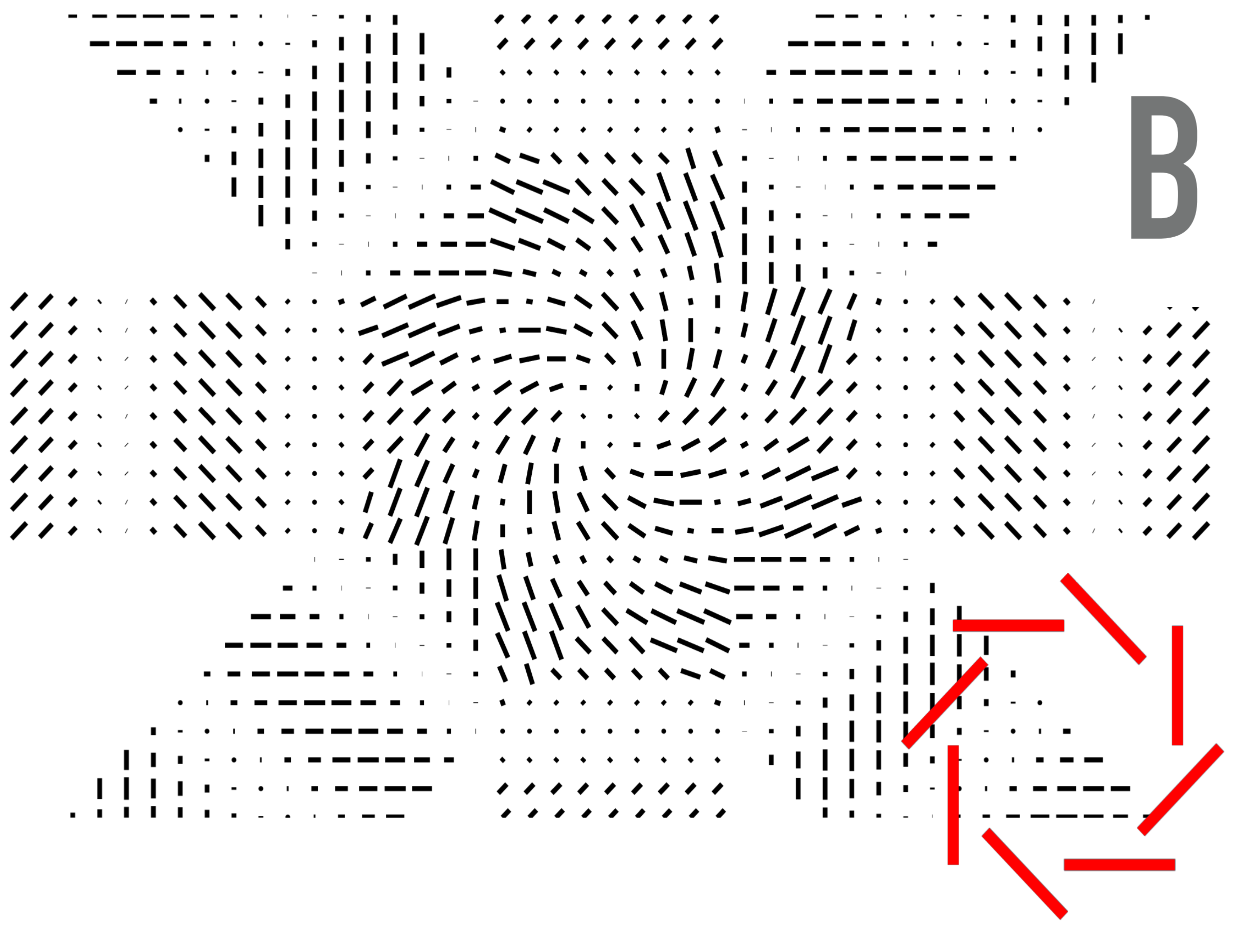


U

Connect with theory:



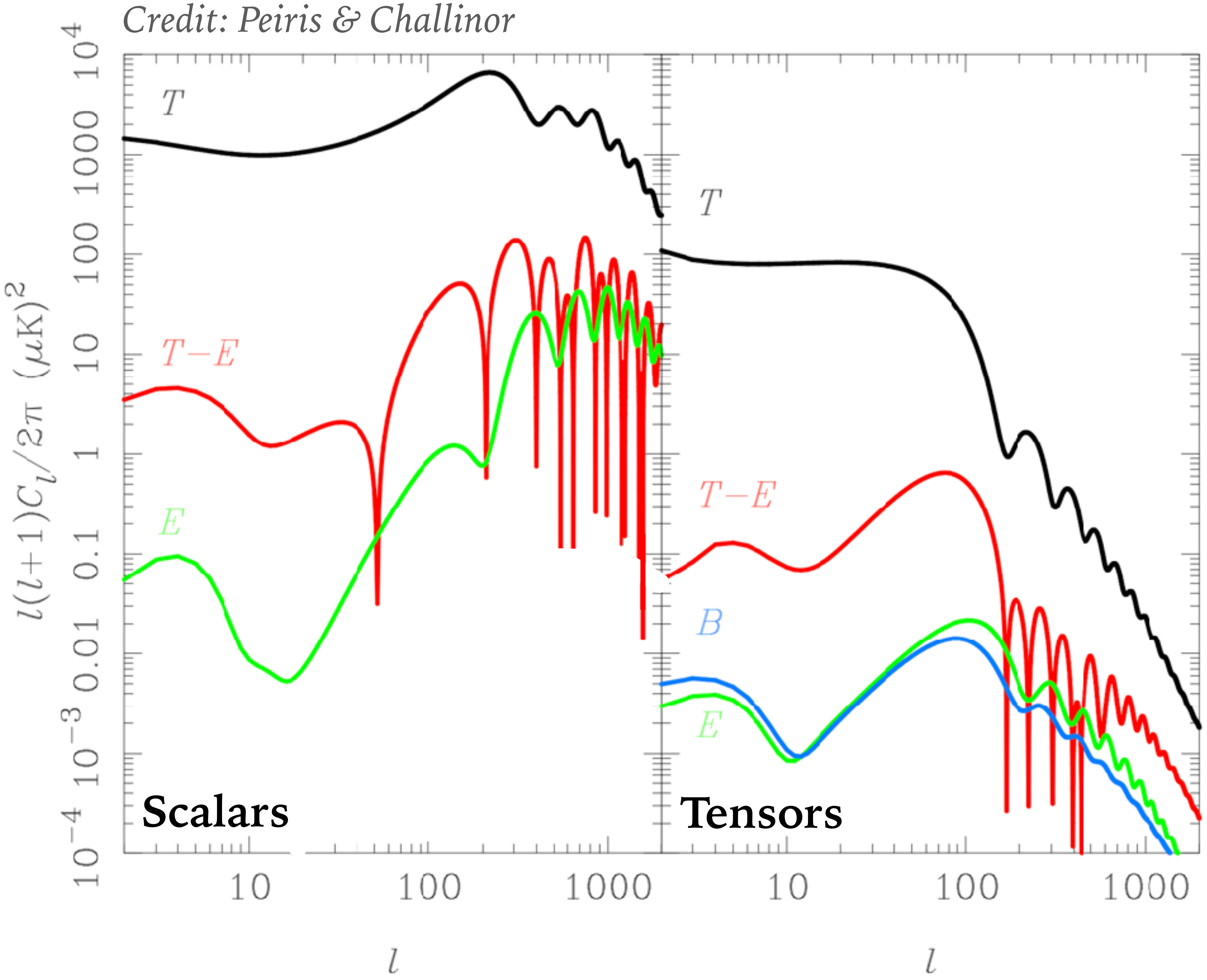
E



B

THE PRIMORDIAL CMB

Credit: Peiris & Challinor



- ➤ Statistically isotropic, Gaussian random field
- ➤ To leading order, B-modes sourced only by primordial gravitational waves
  - ➤ "Smoking gun" of inflation

$r < 0.07$ *BICEP/Keck + Planck*

Many interesting models with $r > 10^{-4}$

CMB LENSING

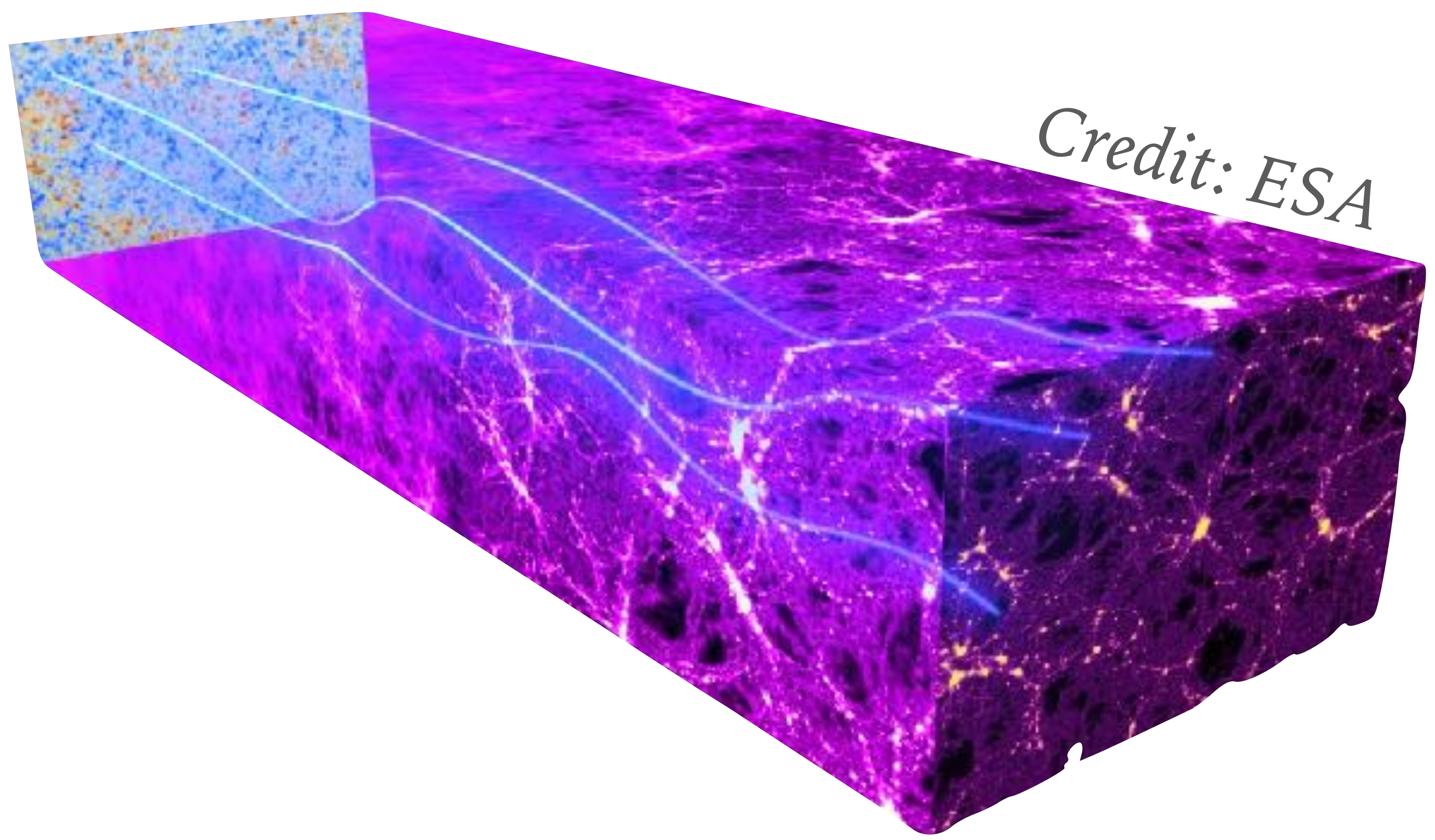
Very accurately described as:

$$\tilde{T}(\mathbf{x}) = T(\mathbf{x} + \alpha(\mathbf{x}))$$
$$\tilde{Q}(\mathbf{x}) = Q(\mathbf{x} + \alpha(\mathbf{x}))$$
$$\tilde{U}(\mathbf{x}) = U(\mathbf{x} + \alpha(\mathbf{x}))$$

Under the Born approximation, $\alpha(\mathbf{x}) = \nabla\phi(\mathbf{x})$, where

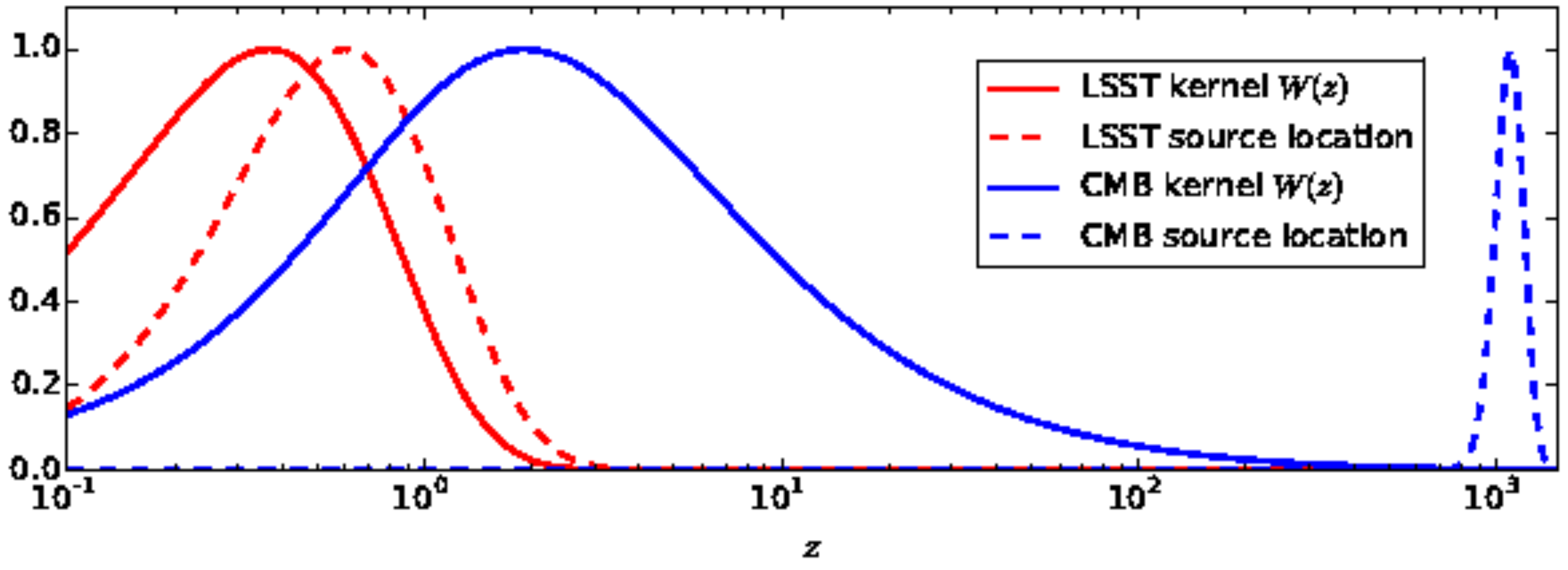
$$\phi(\mathbf{x}) = -2\int_0^{\chi} d\chi\, g(\chi, \chi_*)\Psi(\chi\mathbf{x}, \eta_0 - \chi)$$

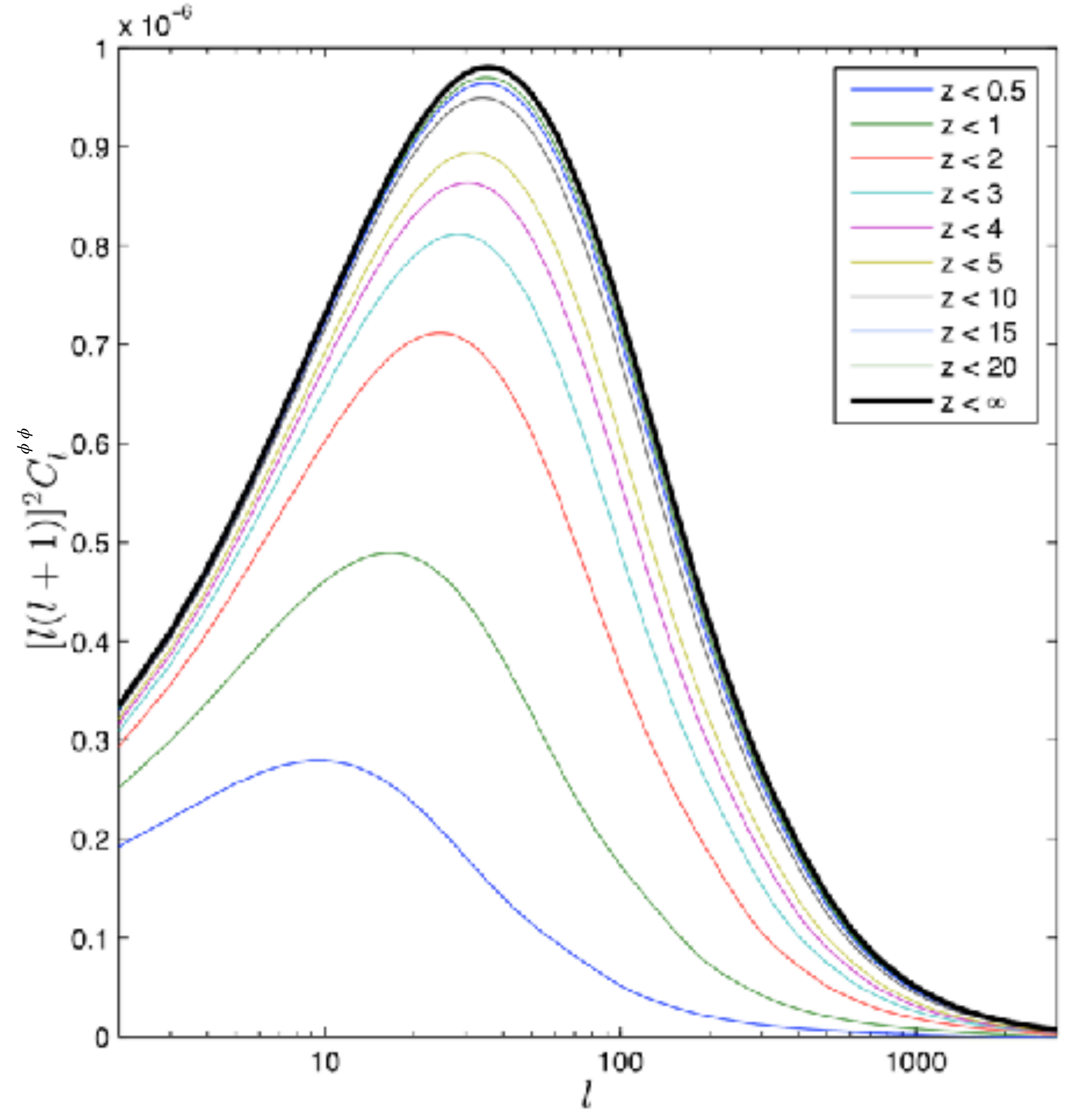
is related to $\kappa = -\frac{1}{2}\nabla^2\phi$.



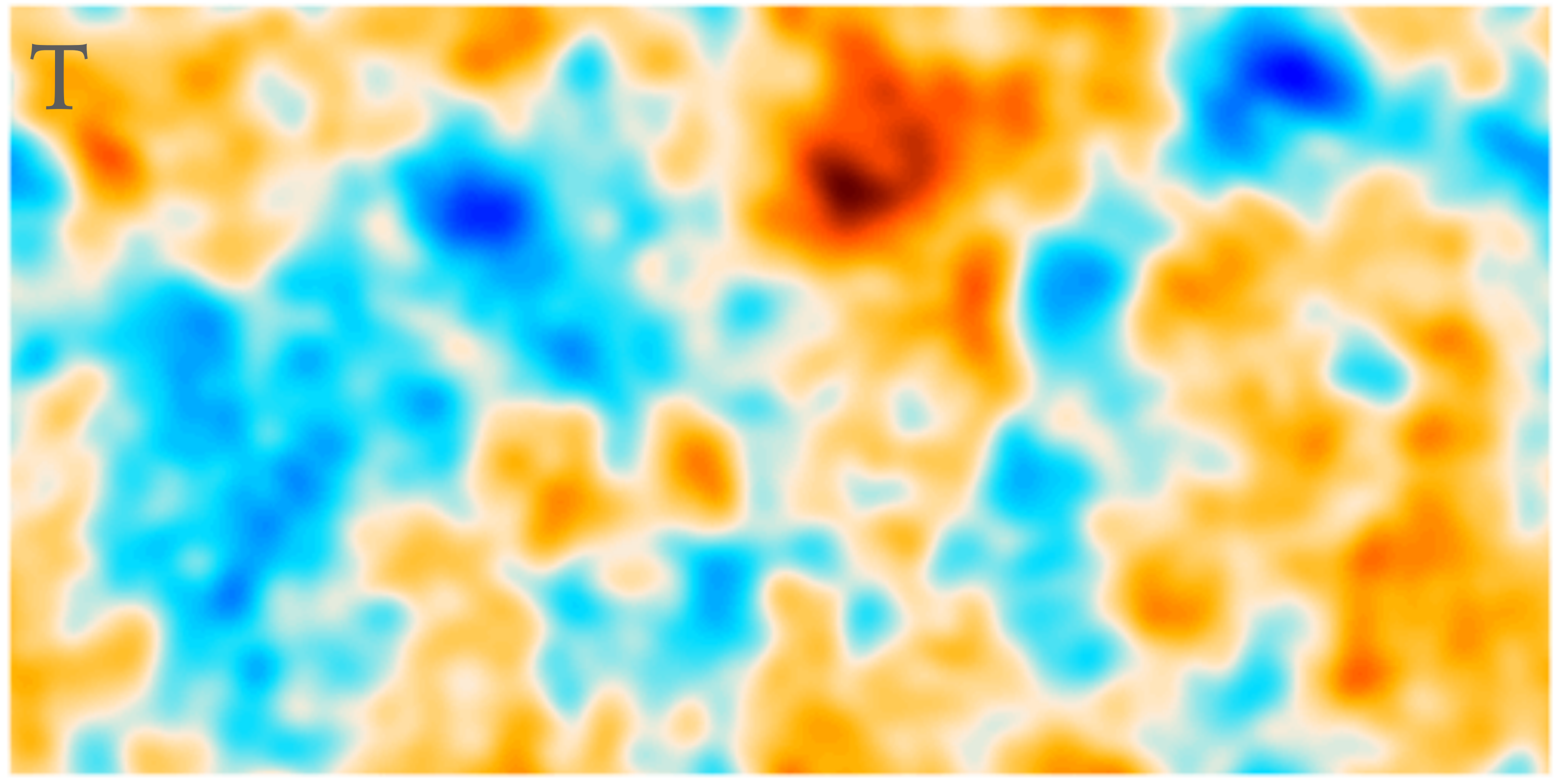
$\alpha \sim$ arcmin, coherent on degree scales (typical lens O(100Mpc))

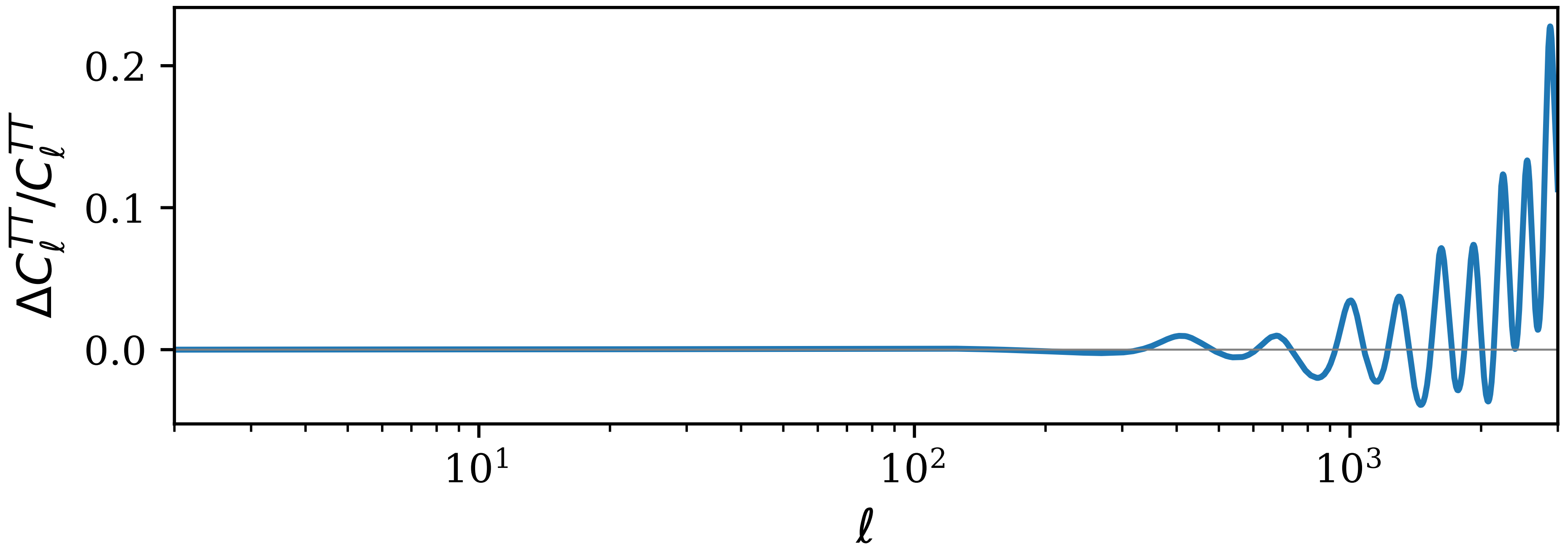
CMB-S4 Science book

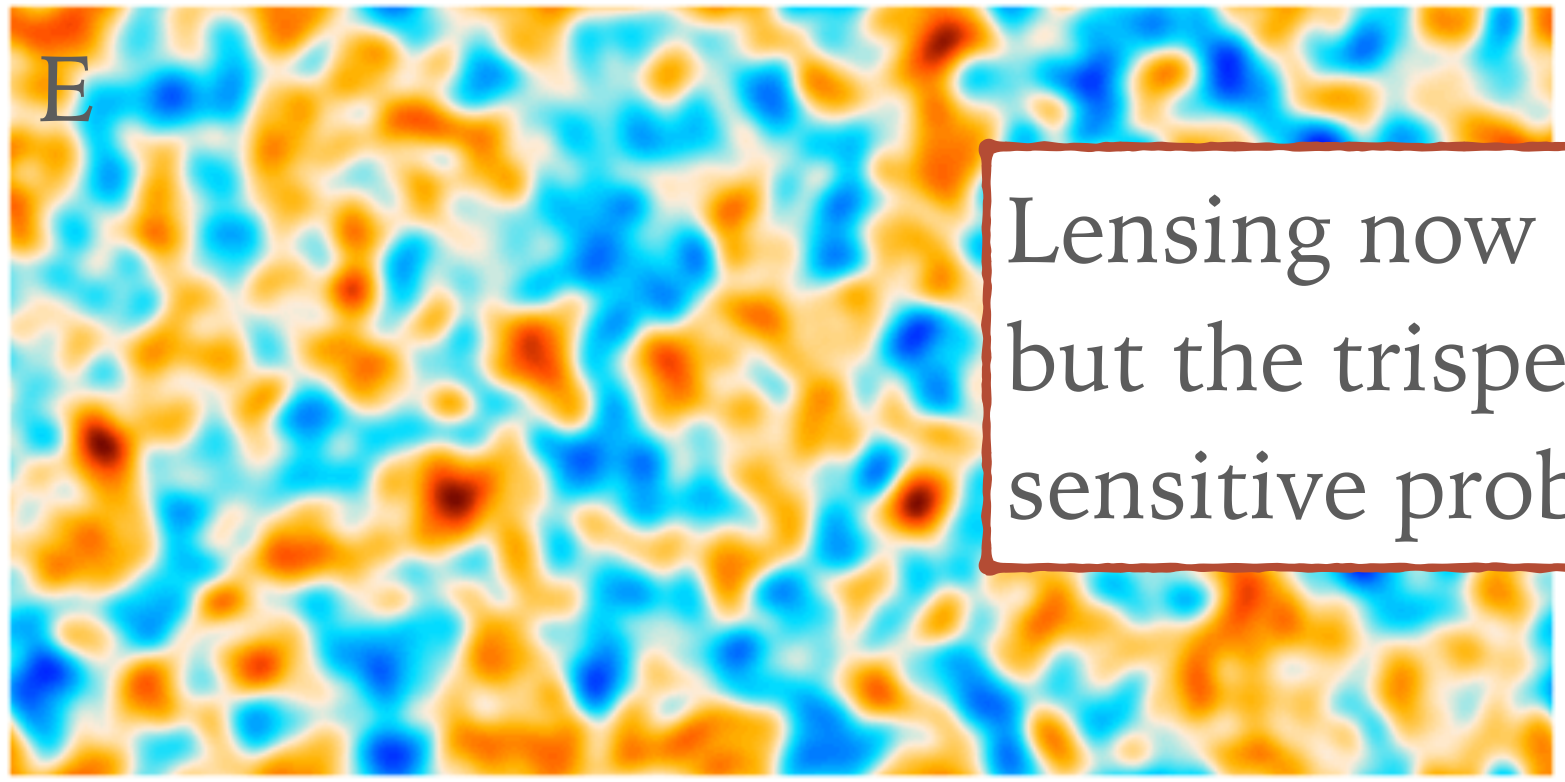


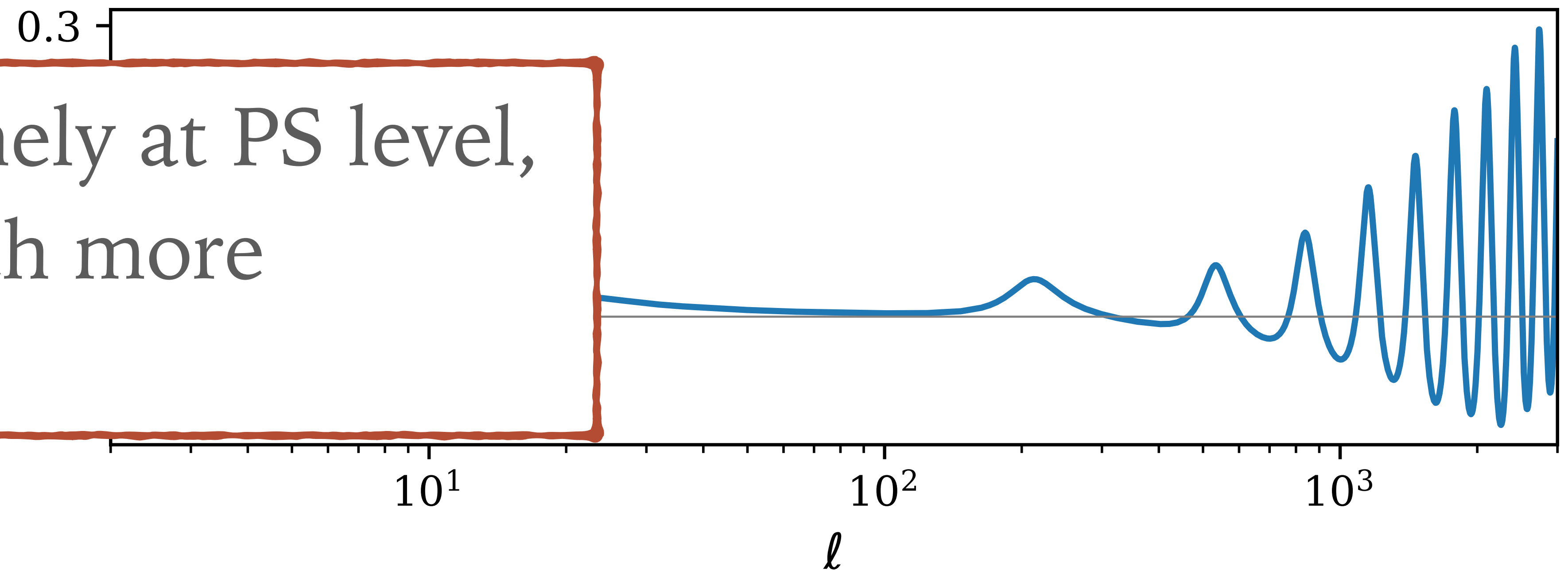


CMB LENSING

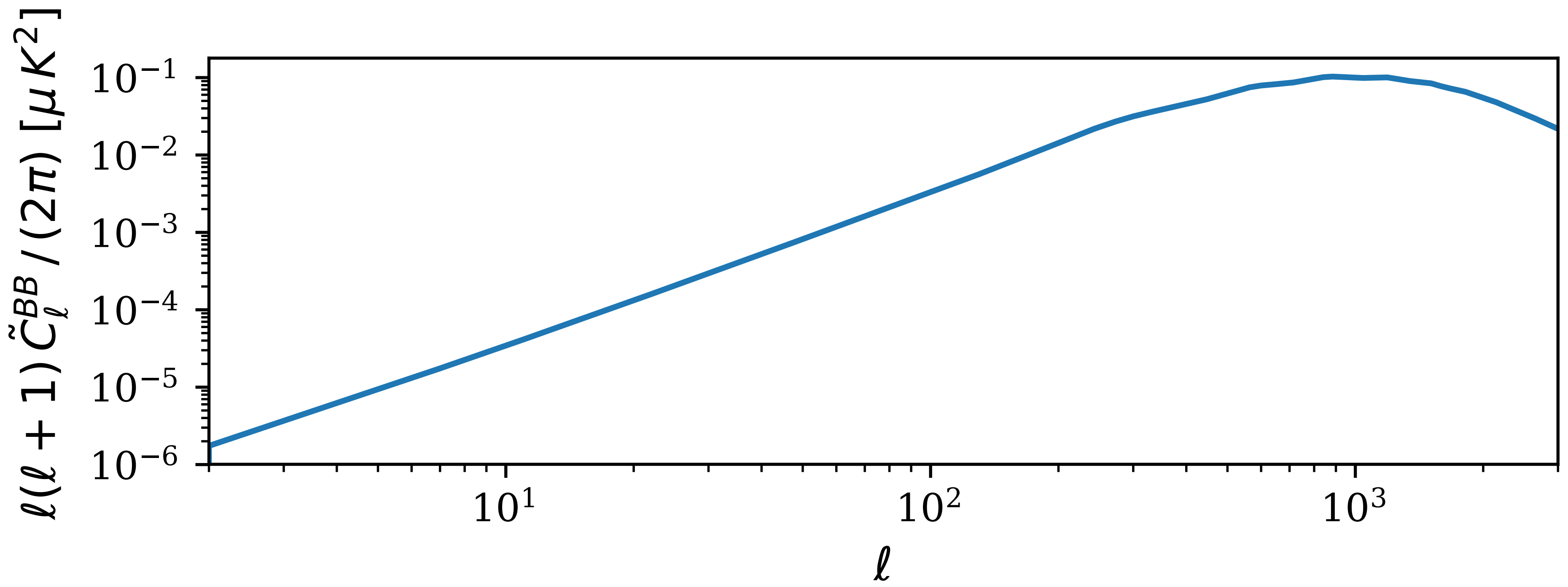








Lensing now detected routinely at PS level, but the trispectrum is a much more sensitive probe *Bernardeau 97*



INTERNAL RECONSTRUCTIONS OF CMB LENSING

Unlensed CMB is statistically isotropic:

$$\langle T(\boldsymbol{l})T(\boldsymbol{l}')\rangle_{CMB} = (2\pi)^2\delta^2(\boldsymbol{l}+\boldsymbol{l}')\,\tilde{C}_l^{TT}$$

Lensing induces statistical anisotropy:

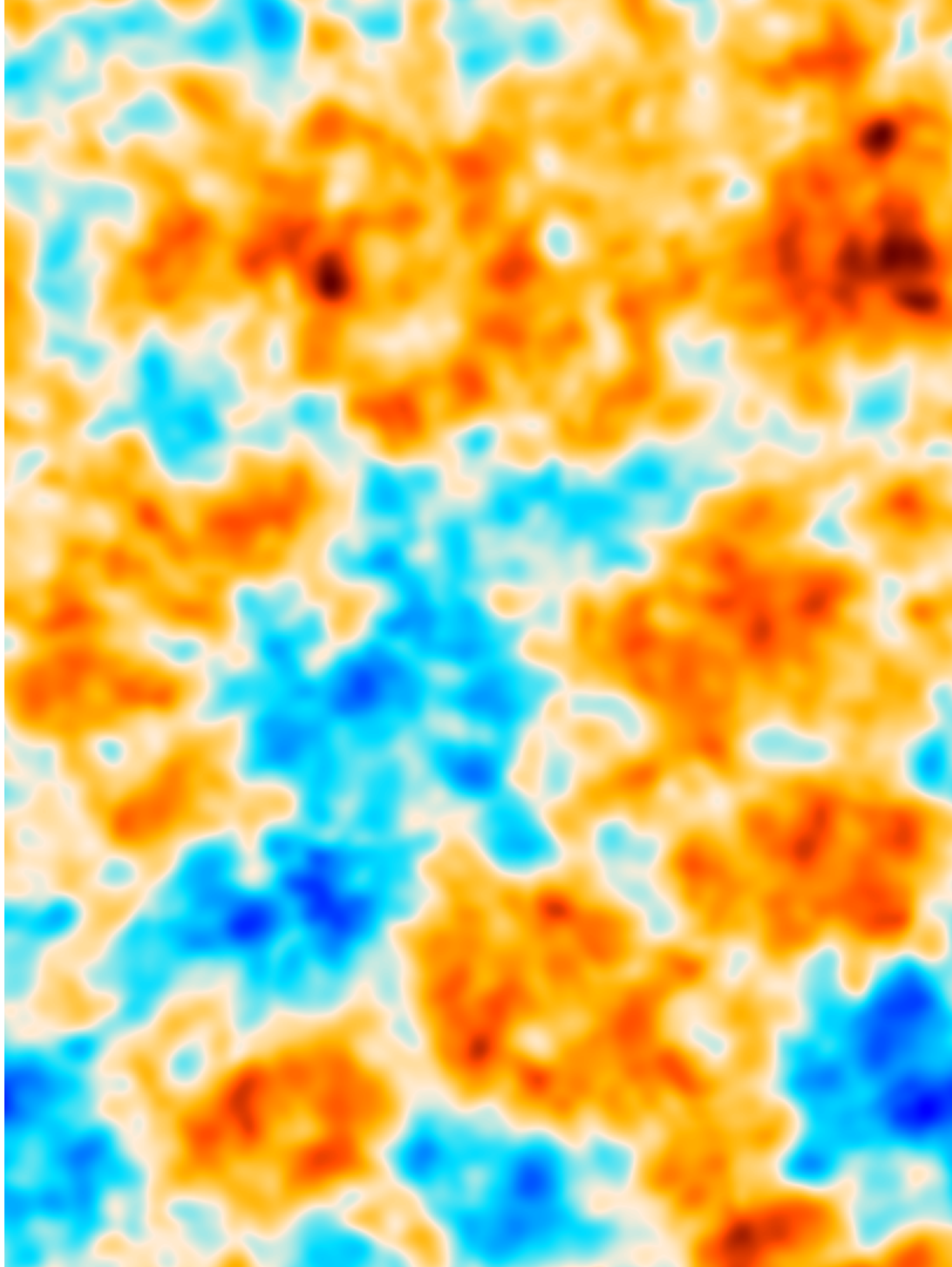
$$\langle \tilde{T}(\boldsymbol{l})\tilde{T}(\boldsymbol{l}')\rangle_{CMB} = f^{TT}(\mathbf{l},\mathbf{l}')\phi(\mathbf{l}+\mathbf{l}')$$

In practice, off-diagonal correlations probe the lensing potential. The **quadratic estimator:**

$$\hat{\phi}^{TT}(\boldsymbol{L}) \equiv N(\boldsymbol{L})\int \frac{d^2\boldsymbol{l}}{2\pi}\,\tilde{T}(\boldsymbol{l})\tilde{T}^*(\boldsymbol{l}-\boldsymbol{L})\,g(\boldsymbol{l},\boldsymbol{L})$$

Hu & Okamoto 01

CMB LENSING SPECTRA



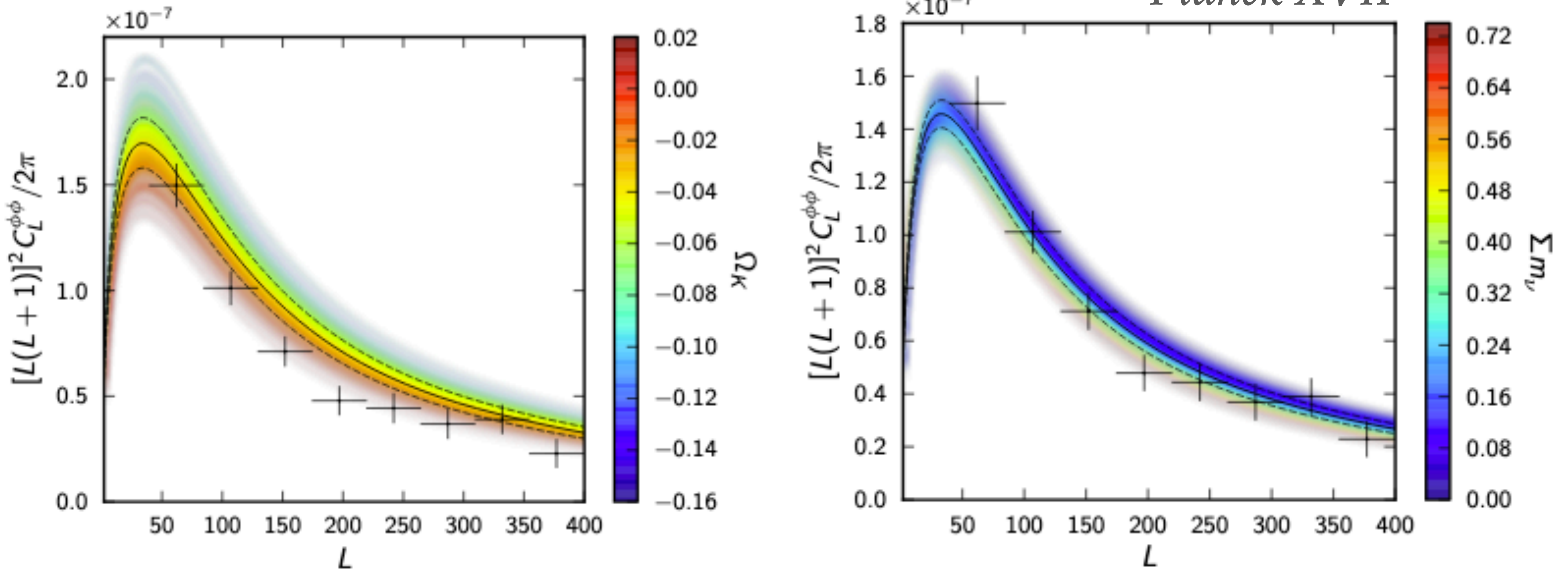
THE POWER SPECTRUM OF LENSING RECONSTRUCTIONS

Lensing breaks angular-diameter-distance degeneracy of unlensed CMB

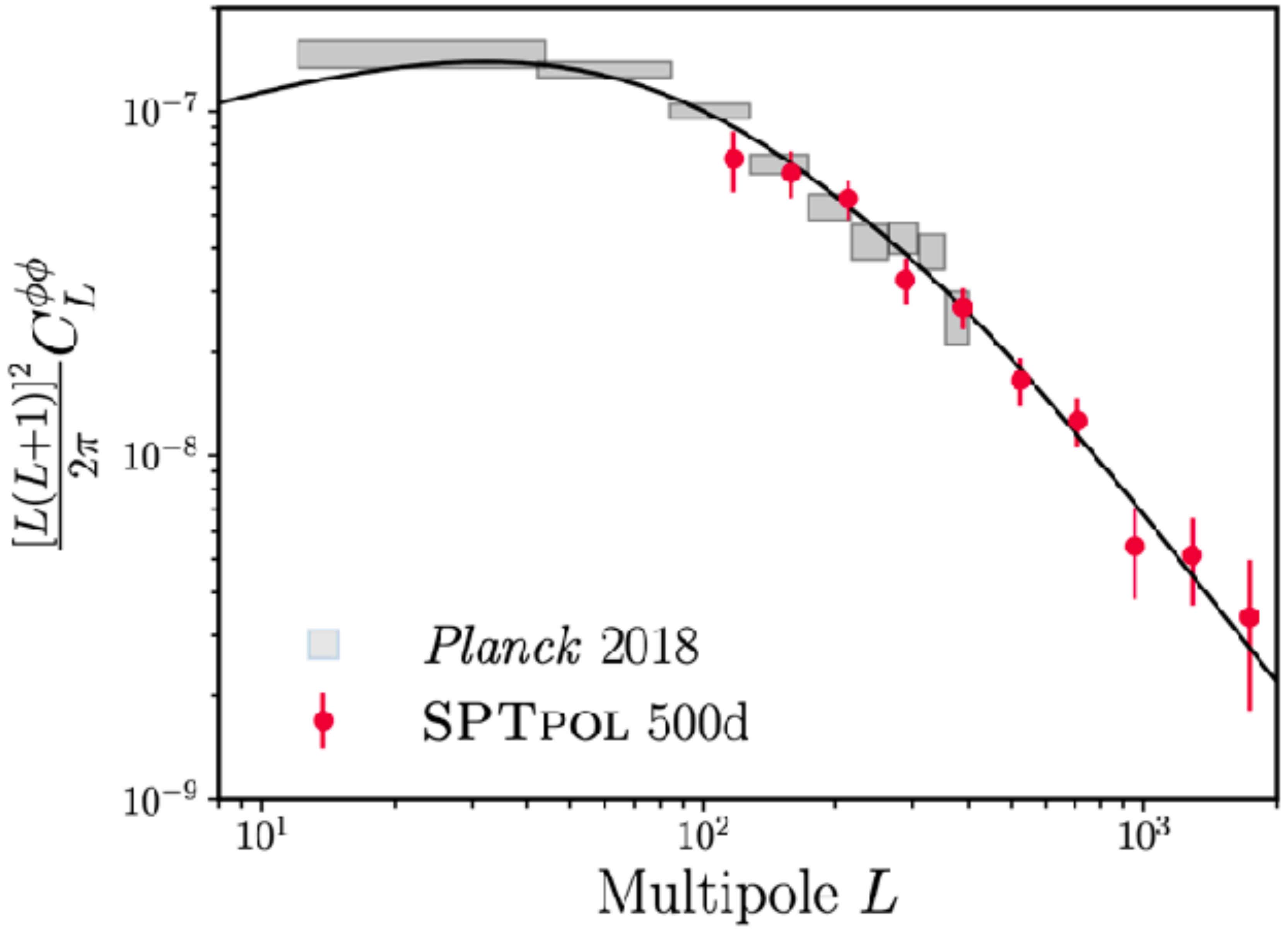
Auto- and cross-correlations probe geometry, neutrino masses, dark energy ++

Cross-correlations can constrain f_{NL} and calibrate photo-z's and shear estimators

Planck XVII



SPT



CMB lensing power spectrum now measured by ACT, SPT, POLARBEAR, BICEP, Planck (40 σ detection)

LENSING POWER SPECTRUM BIASES

A long list:

- $N^{(0)}$ bias (Gaussian contractions)
- $N^{(1)}$ bias (non-primary trispectrum couplings) *Kesden et al. 03, Hanson et al. 11*
- Instrumental systematics (beam-related, gain-related) *Smith et al. 09*
- Non-Gaussianity of galactic foregrounds (dust, synchrotron) *Challinor et al. 18*
- Non-gaussianity of ϕ: non-linear growth & post-Born lensing *Boehm et al. 16, Pratten & Lewis 16, Beck et al. 18*

- **Extragalactic foregrounds** — most challenging at present

BIASES TO LENSING SPECTRA FROM EXTRAGALACTIC FOREGROUNDS

- Temperature reconstruction dominates for SPTPol, AdvACT, SO
- Lensing power spectra and cross-correlations, biased by non-Gaussian extragalactic sources: tSZ, CIB, kSZ

Van Engelen et al. 14, Osborne et al. 14, Ferraro & Hill 18

$$\hat{\phi}[T^{\rm obs}, T^{\rm obs}] = \hat{\phi}[\tilde{T} + s, \tilde{T} + s]$$

Lensing ($\tilde{T}$) — Foreground (correlated with ϕ) (s)

Bias lensing reconstruction power spectrum

$$\langle \hat{\phi}[T^{\rm obs}, T^{\rm obs}]\, \hat{\phi}[T^{\rm obs}, T^{\rm obs}] \rangle = \langle \hat{\phi}[\tilde{T}, \tilde{T}]\, \hat{\phi}[\tilde{T}, \tilde{T}] \rangle + 2\, \langle \hat{\phi}[\tilde{T}, \tilde{T}]\, \hat{\phi}[s, s] \rangle + 4\, \langle \hat{\phi}[\tilde{T}, s]\, \hat{\phi}[\tilde{T}, s] \rangle + \langle \hat{\phi}[s, s]\, \hat{\phi}[s, s] \rangle$$

"Primary bispectrum bias" — "Secondary bispectrum bias" — "Trispectrum bias"

And cross-correlations with low-z matter tracers

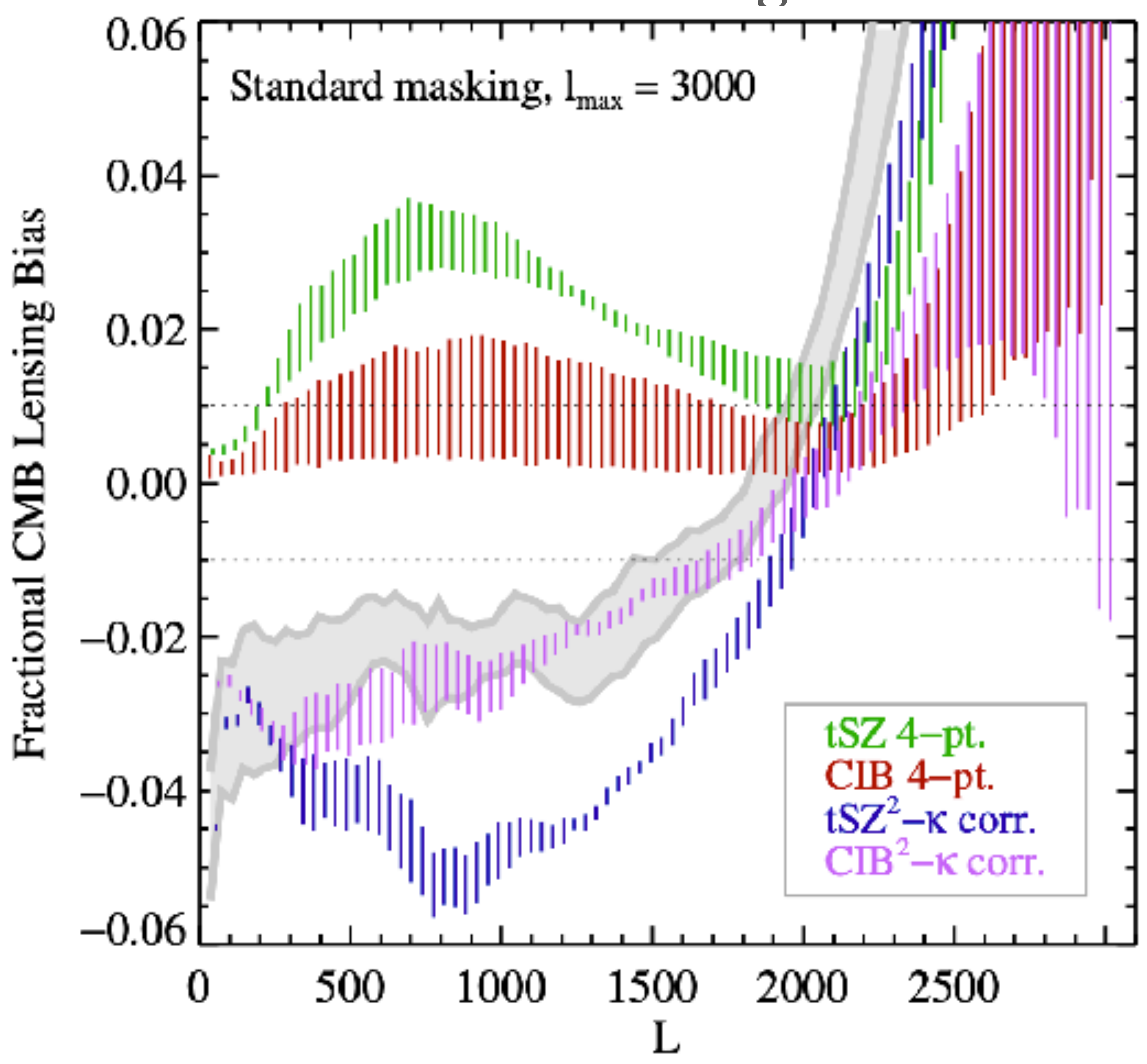
$$\langle g[\phi]\, \hat{\phi}[T^{\rm obs}, T^{\rm obs}] \rangle = \langle g[\phi]\, \hat{\phi}[\tilde{T}, \tilde{T}] \rangle + \langle g[\phi]\, \hat{\phi}[s, s] \rangle$$

"Bispectrum bias"

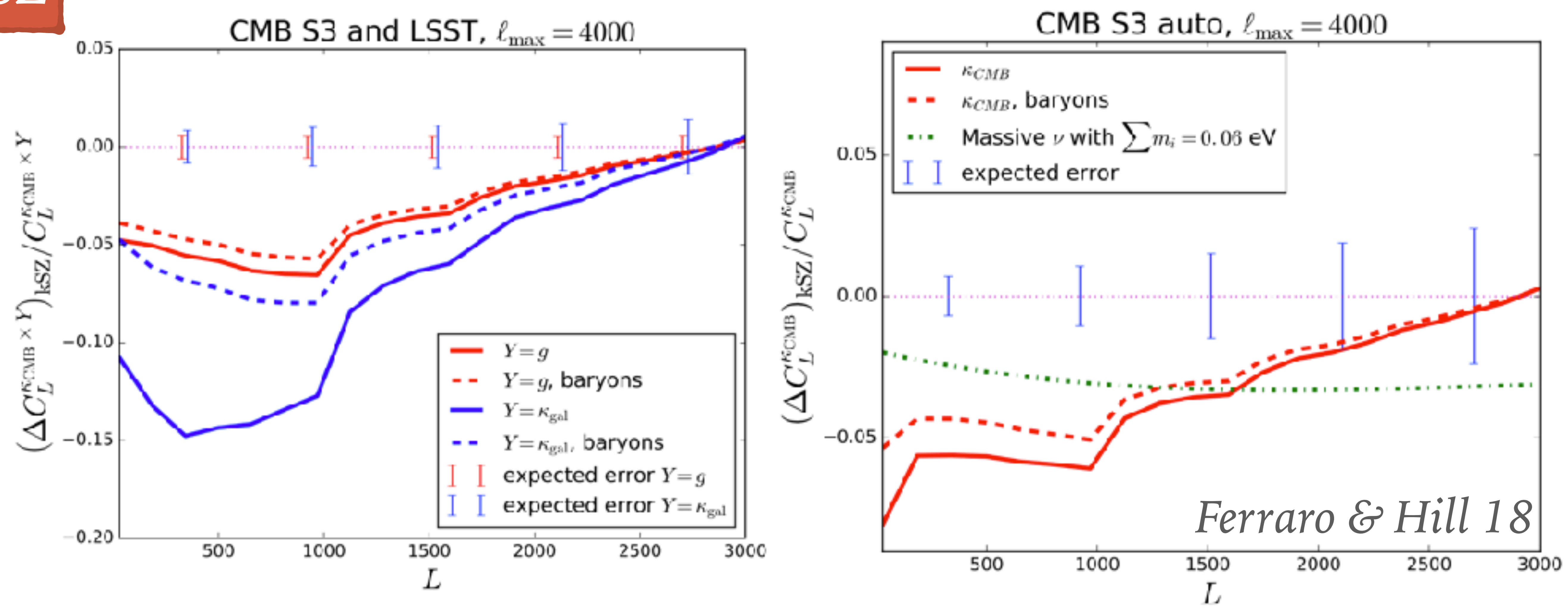
BIASES TO LENSING SPECTRA FROM EXTRAGALACTIC FOREGROUNDS

tSZ & CIB

Van Engelen et al. 14



kSZ

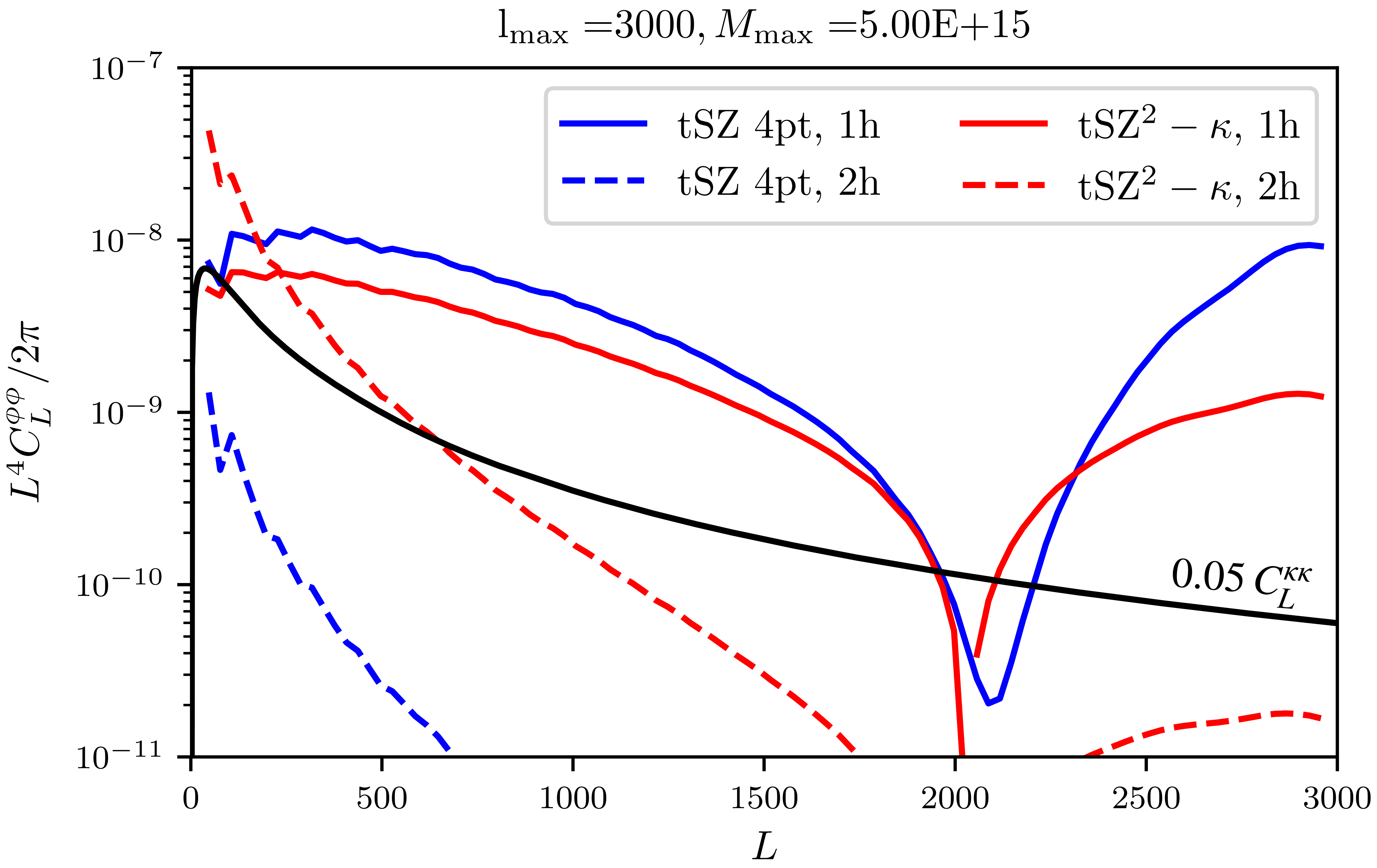


Ferraro & Hill 18

- Frequency cleaning less than ideal for tSZ, CIB. Useless for kSZ
- Mitigation techniques:
  - Simulations *Van Engelen et al. 14*
  - Bias hardening *Namikawa et al. 13, Osborne et al. 14, Sailer et al. 20*
  - Cleaning of gradient leg in QE *Madhavacheril & Hill 18*
  - Shear-only estimators *Schaan & Ferraro 18*

MODELING LENSING BIASES FROM EXTRAGALACTIC SOURCES

We calculate these biases analytically as a function of experimental sensitivity, resolution, point-source masking, etc, using a halo model prescription



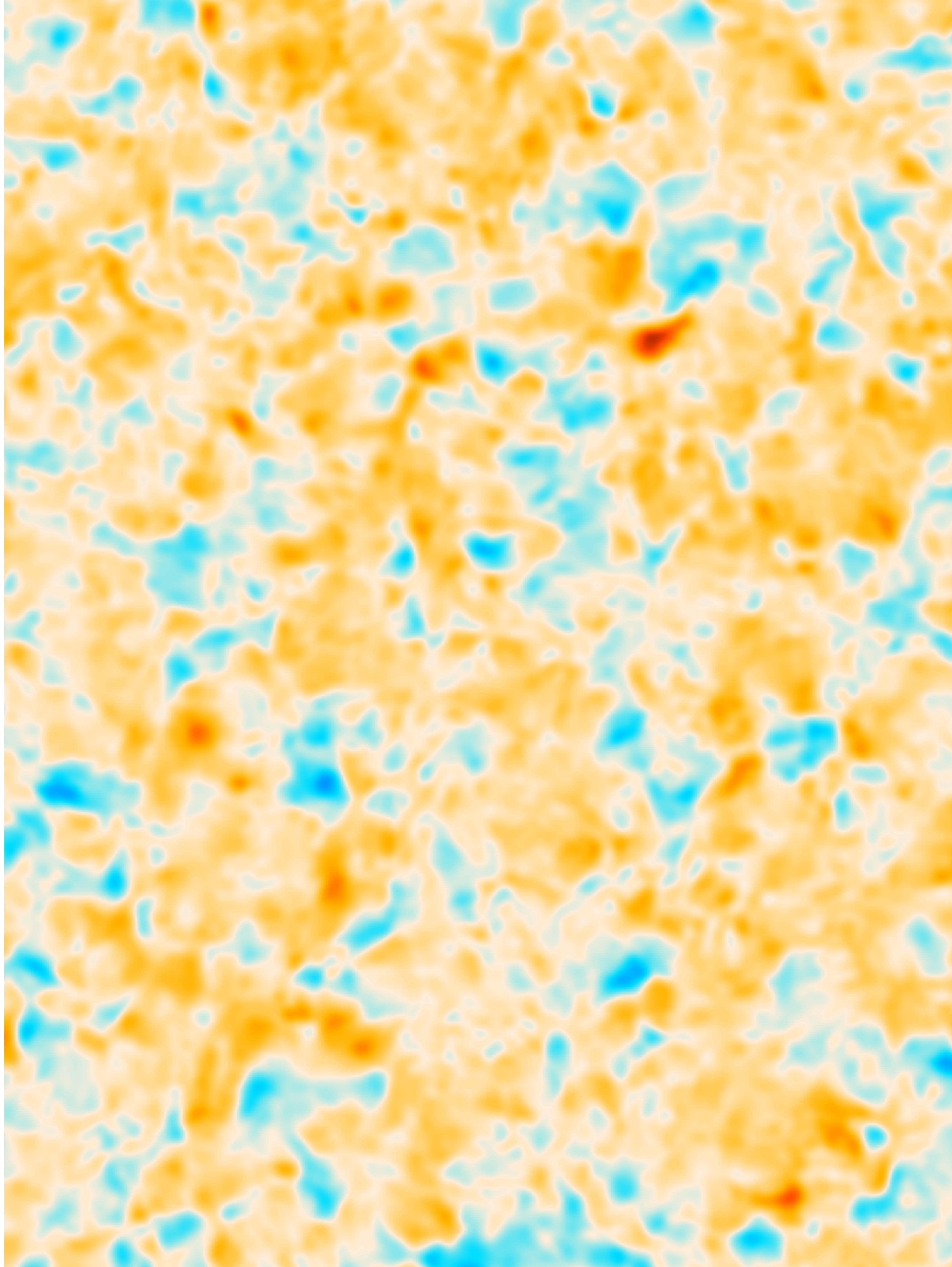
(Example: subset of tSZ biases for an SPT-like experiment)

Preliminary

- **Very fast, 1D method**. Lensing reconstructions done **using FFTlog** (for fast, discrete Hankel transforms), taking O(10ms) per lensing reconstruction on a single laptop core.
- Can calculate biases and associated uncertainties
- Perhaps we could use QE down to small scales and correct bias at PS level?

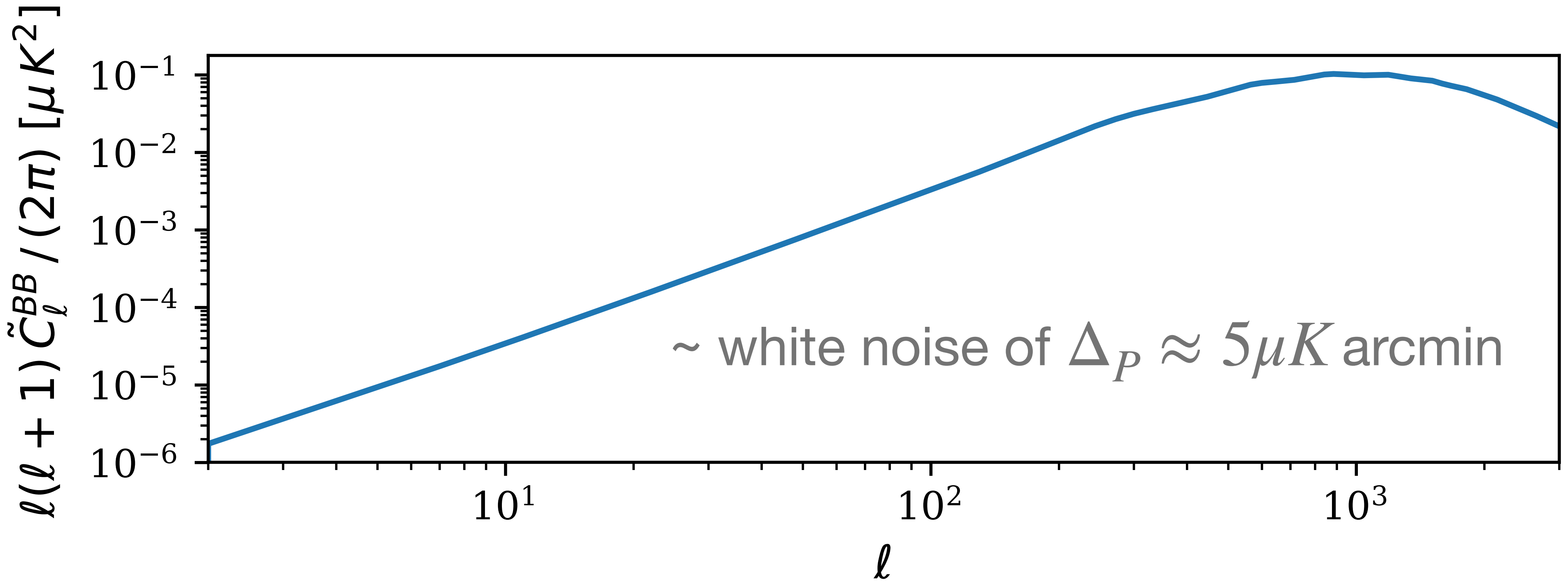
ABL, Coulton, Challinor & Sherwin (in prep.)

DELENSING B-MODES



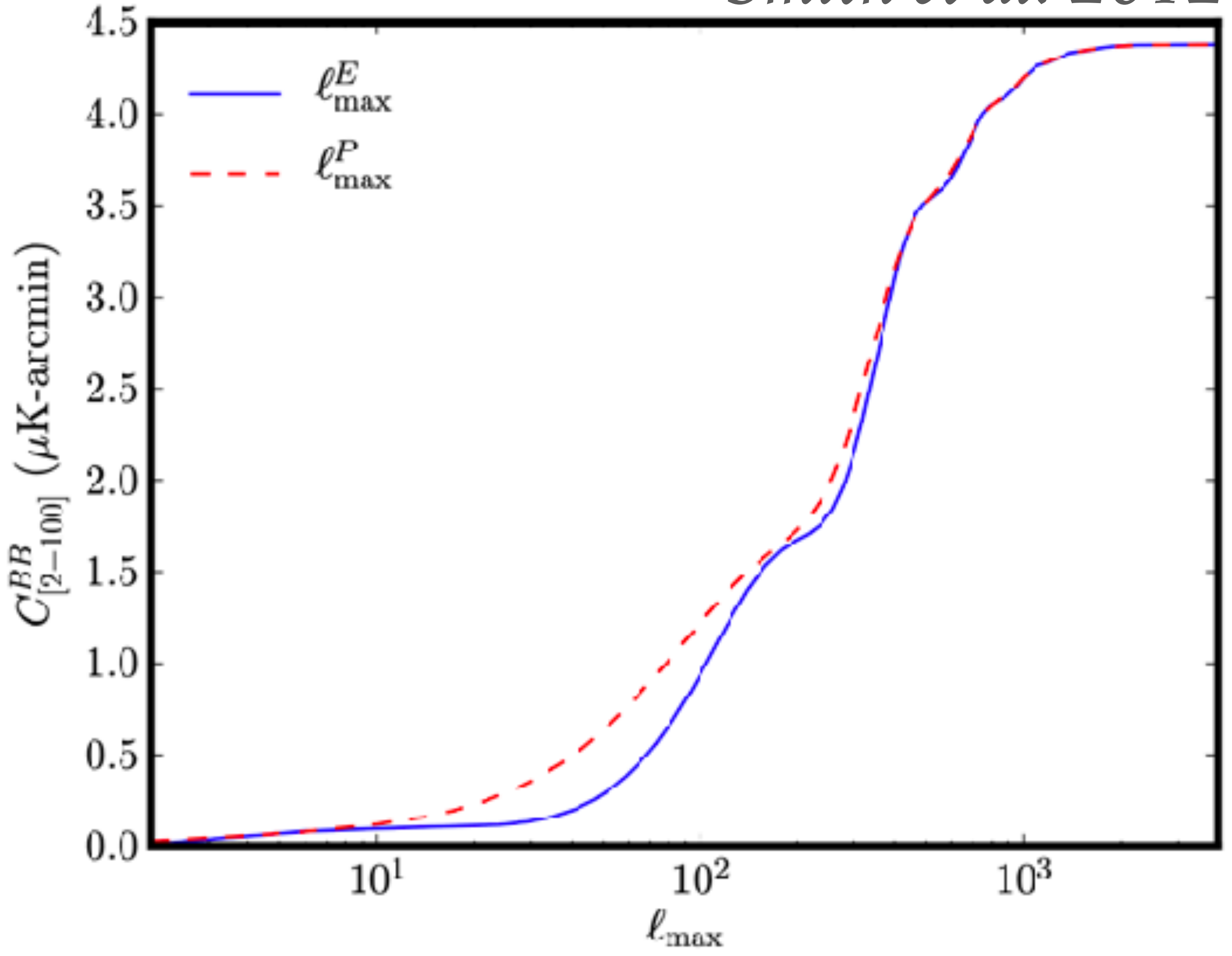
THE LENSING B-MODE

Lensing converts E into B-modes *Zaldarriaga & Seljak 98*

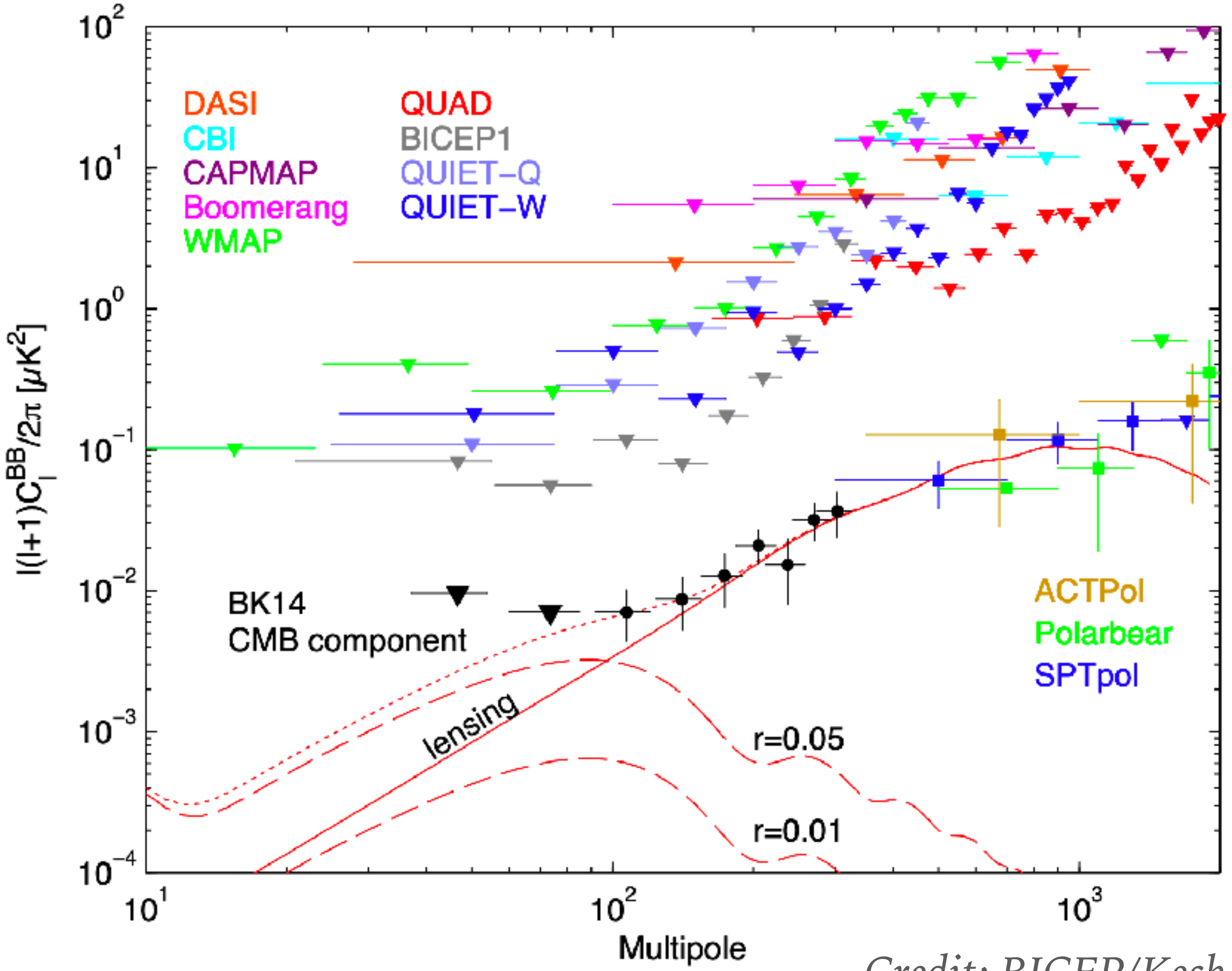


Sourced by intermediate and small-scales lenses & E

Smith et al. 2012



Source of noise for primordial B-mode searches in addition to experimental & foregrounds (not covered in this talk)



Credit: BICEP/Keck

B-MODE DELENSING

$$\text{Lensing:} \quad \tilde{P}(\mathbf{x}) = P(\mathbf{x} + \alpha(\mathbf{x}))$$

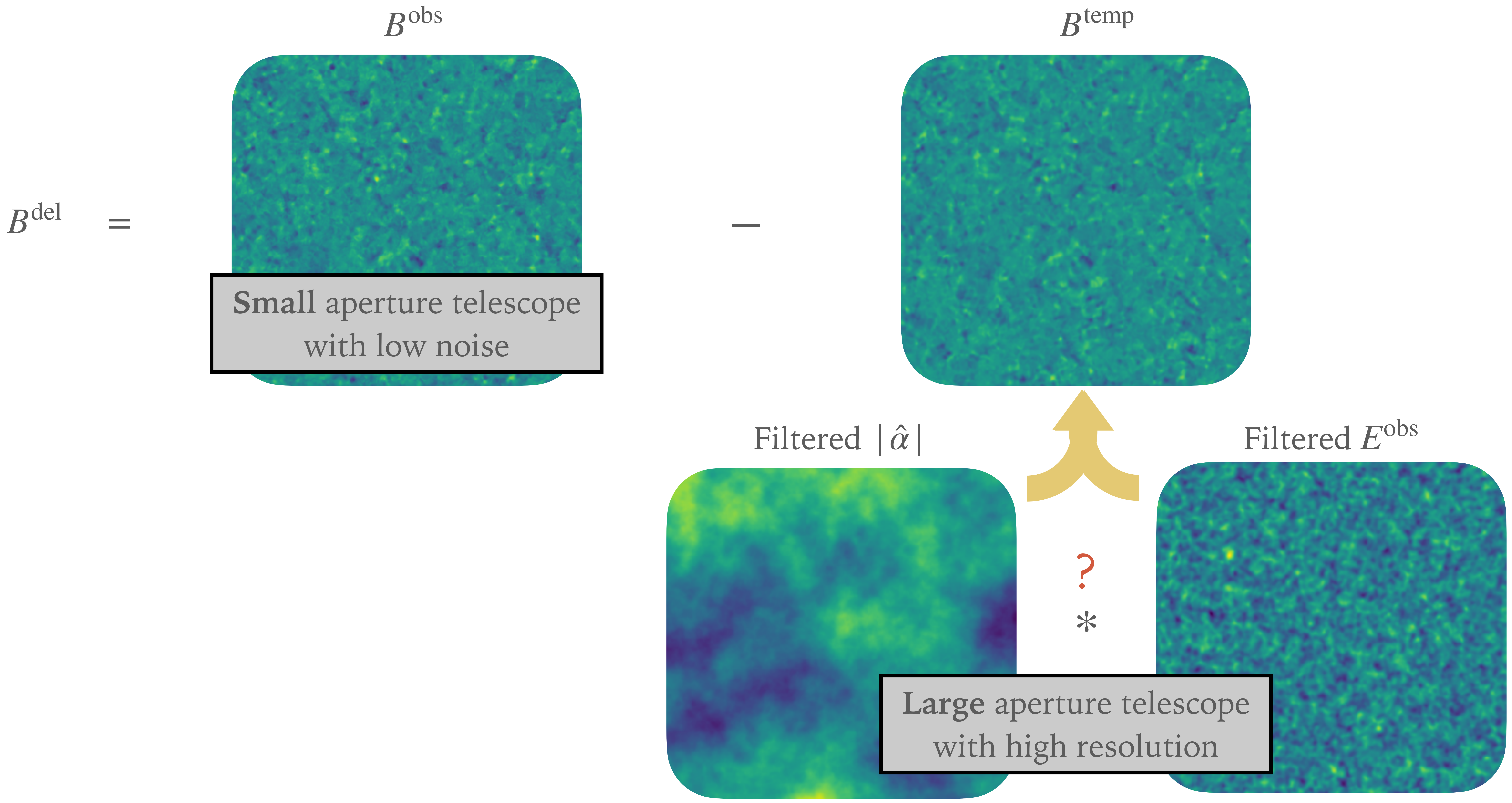
$$\Longrightarrow \quad \text{Delensing:} \quad P^{\text{del}}(\mathbf{x}) = \tilde{P}(\mathbf{x} + \alpha^{-1}(\mathbf{x})) \qquad (\text{often } \alpha^{-1} \approx -\alpha)$$

But recall:

- We're searching for Primordial signal peaks on **large** angular scales
- Lensing component sourced by **intermediate & small** scale lenses and E.

Experimentally, easier to use two separate telescopes, optimised for each purpose.

B-MODE TEMPLATE DELENSING



Patches of 8° on a side. Colour scales differ across panels.

HOW EXACTLY IS THE TEMPLATE BUILT?

The lensing B-mode is

$$\tilde{B}(\mathbf{l}) = \int d^2\mathbf{l}_1\, g(\mathbf{l},\mathbf{l}_1)\, E(\mathbf{l}_1)\phi(\mathbf{l}-\mathbf{l}_1) + O(\phi^2) + \cdots$$

So the template is often built to leading ("gradient") order

$$B^{\mathrm{temp}}(\mathbf{l}) = \int d^2\mathbf{l}_1\, g(\mathbf{l},\mathbf{l}_1)\, \bar{E}^{\mathrm{obs}}(\mathbf{l}_1)\hat{\bar{\phi}}(\mathbf{l}-\mathbf{l}_1)\,.$$

e.g., SPT 17

Why? To optimise strengths of LAT & SAT, for analytic transparency, and because template is **assumed to track true B-modes very accurately**, since $(\tilde{C}_l^{BB} - C_l^{BB,\,\mathrm{temp}})/\tilde{C}_l^{BB} < 0.01$

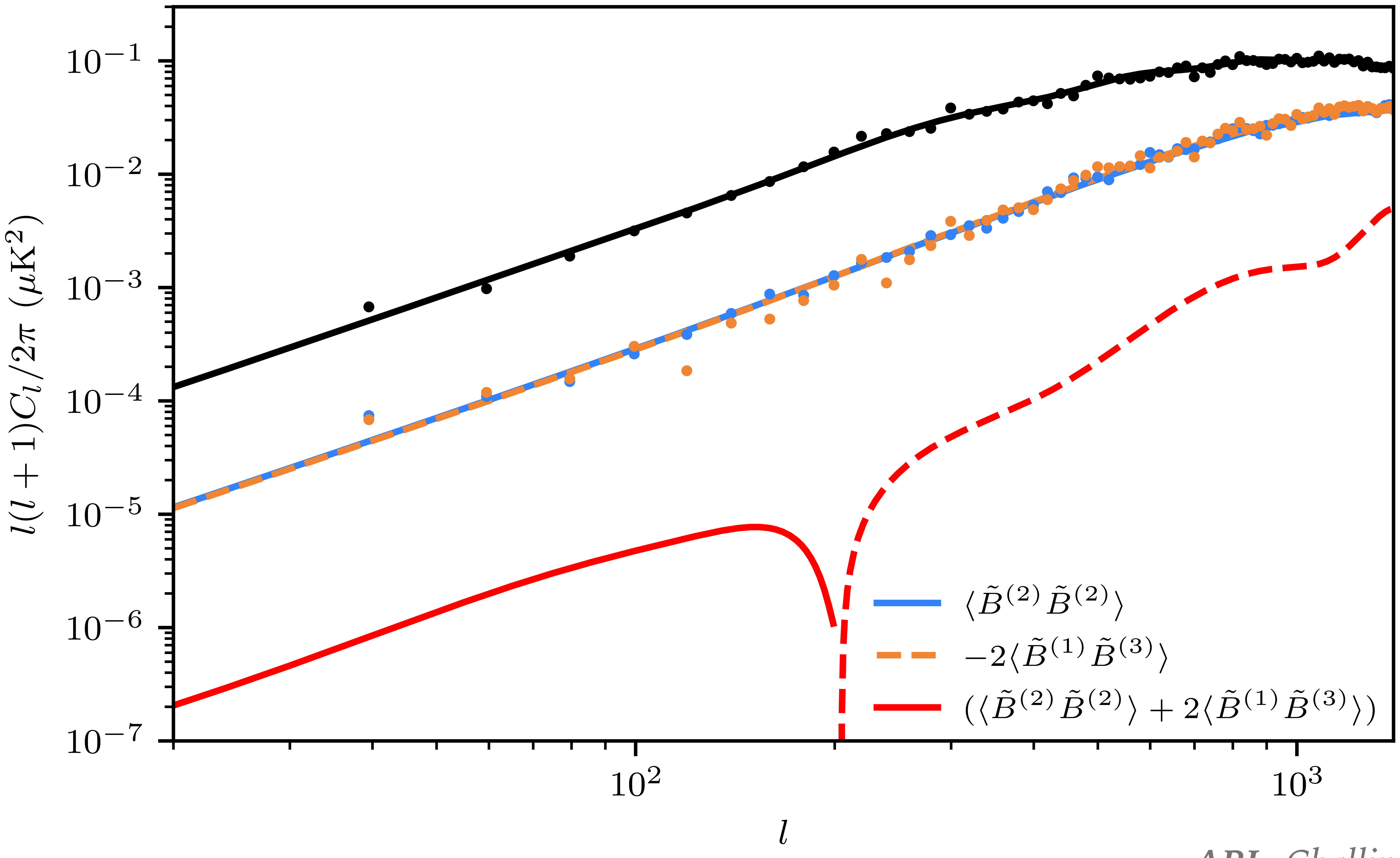
Template can also be built non-perturbatively as

$$B^{\mathrm{temp}}_{\mathrm{non-pert}}(\mathbf{l}) = \mathscr{B}_{\mathbf{l}}\left[P^{E^{\mathrm{obs}}}(\mathbf{x} + \nabla\hat{\phi}))\right]\,.$$

e.g., Planck 18, POLARBEAR 19

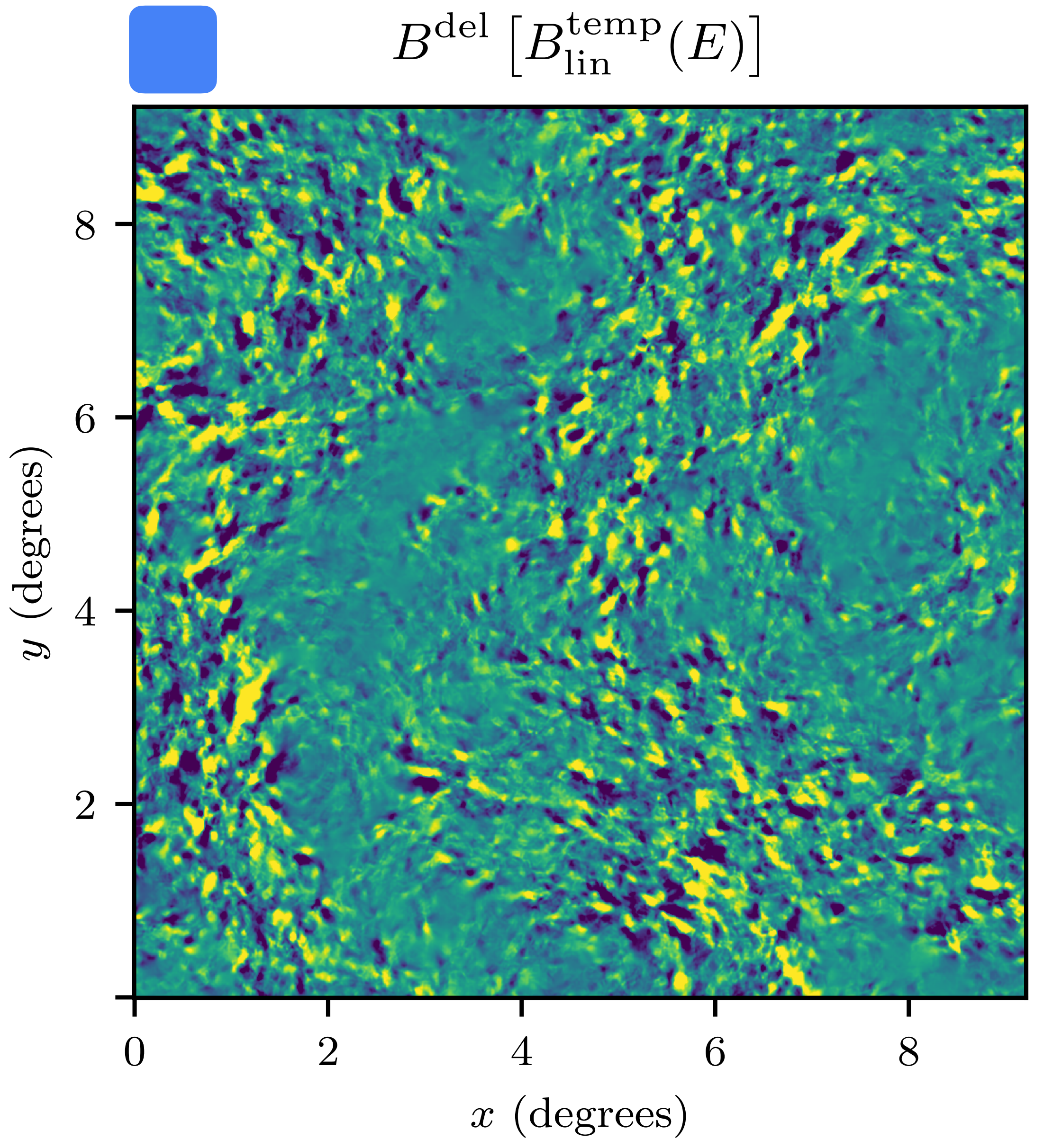
LIMITATIONS OF B-MODE DELENSING USING A TEMPLATE

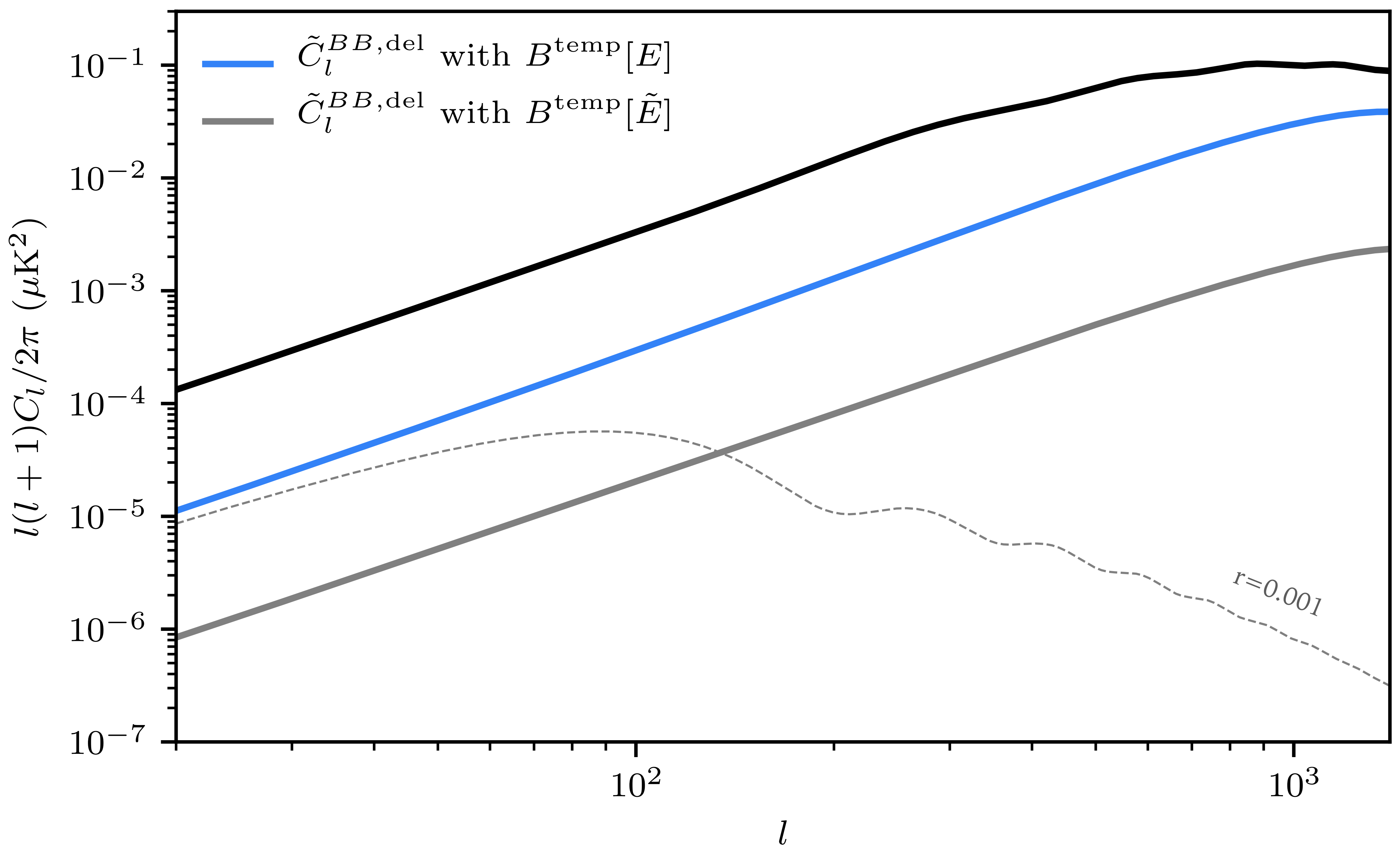
- Corrections to the leading-order calculation of $\tilde{C}_l^{BB}$ smaller than O(1)% because of extensive cancelations between large terms at higher orders.



ABL, Challinor & Carron 20b arXiv:2010.14286

LIMITATIONS OF B-MODE TEMPLATE DELENSING: NOISELESS SCENARIO

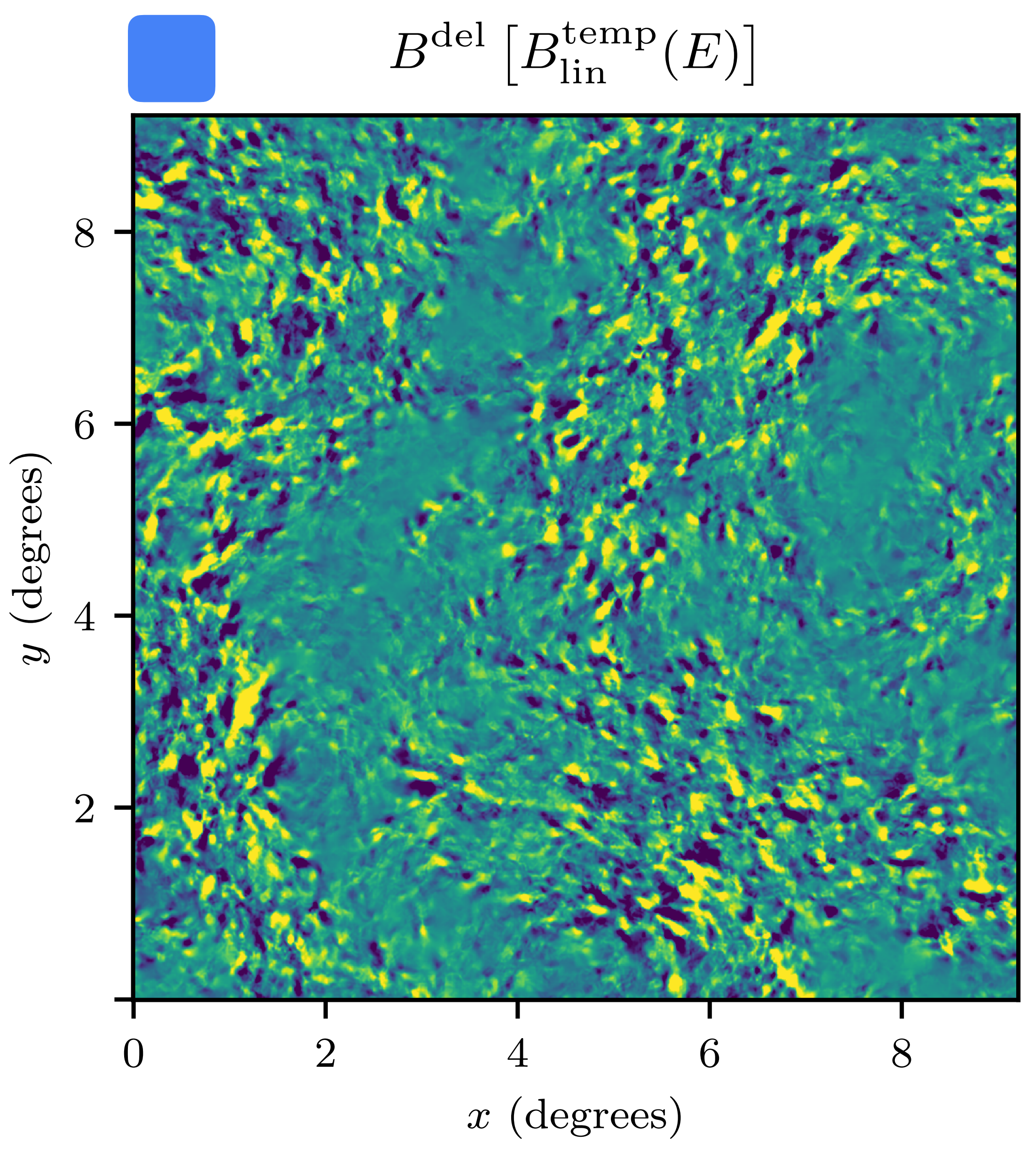


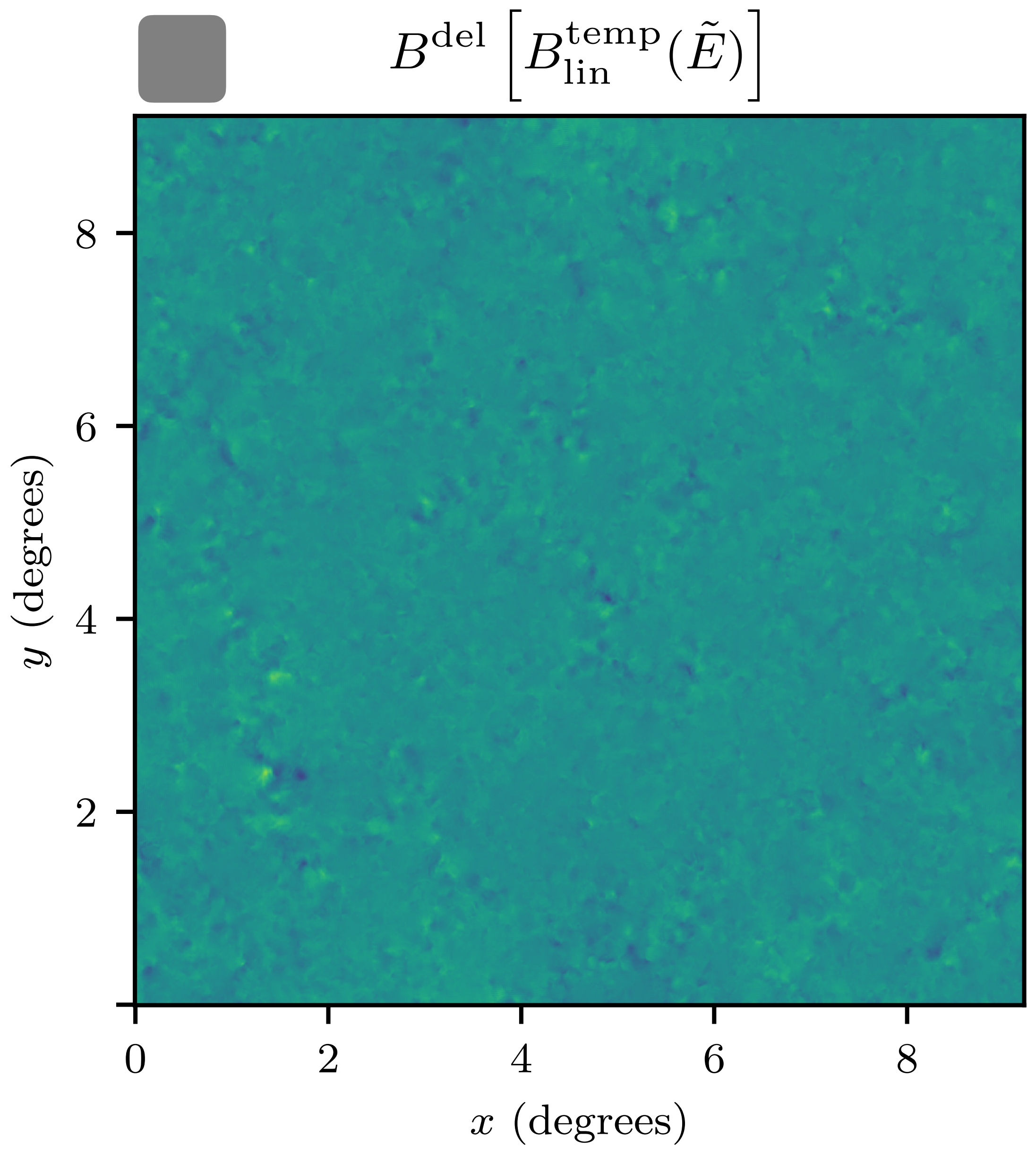


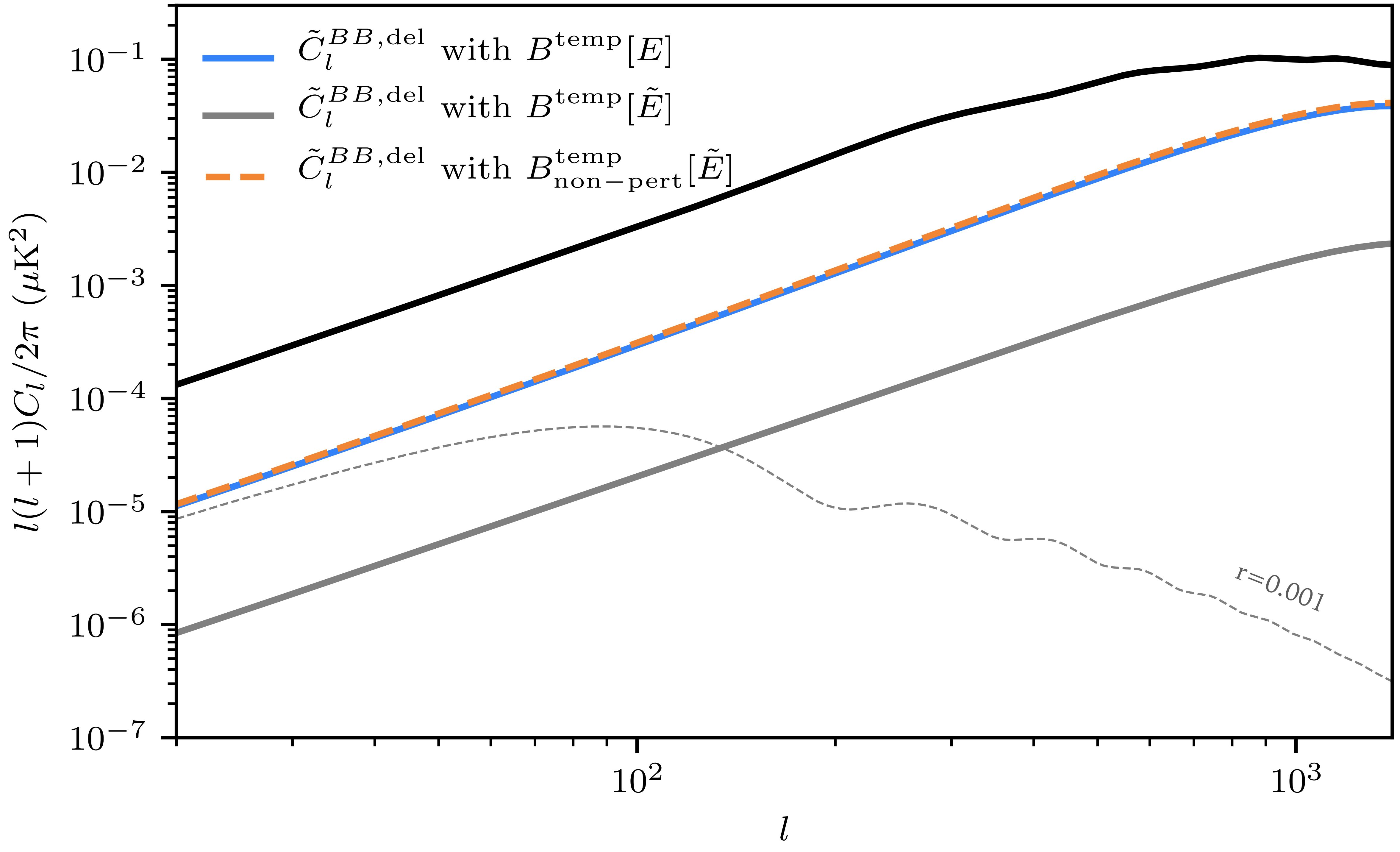
➤ Cancellations disappear if linear template is built from unlensed or delensed E-modes, hit delensing floor of O(10)%

__ABL__, Challinor & Carron 20b arXiv:2010.14286

LIMITATIONS OF B-MODE TEMPLATE DELENSING: NOISELESS SCENARIO



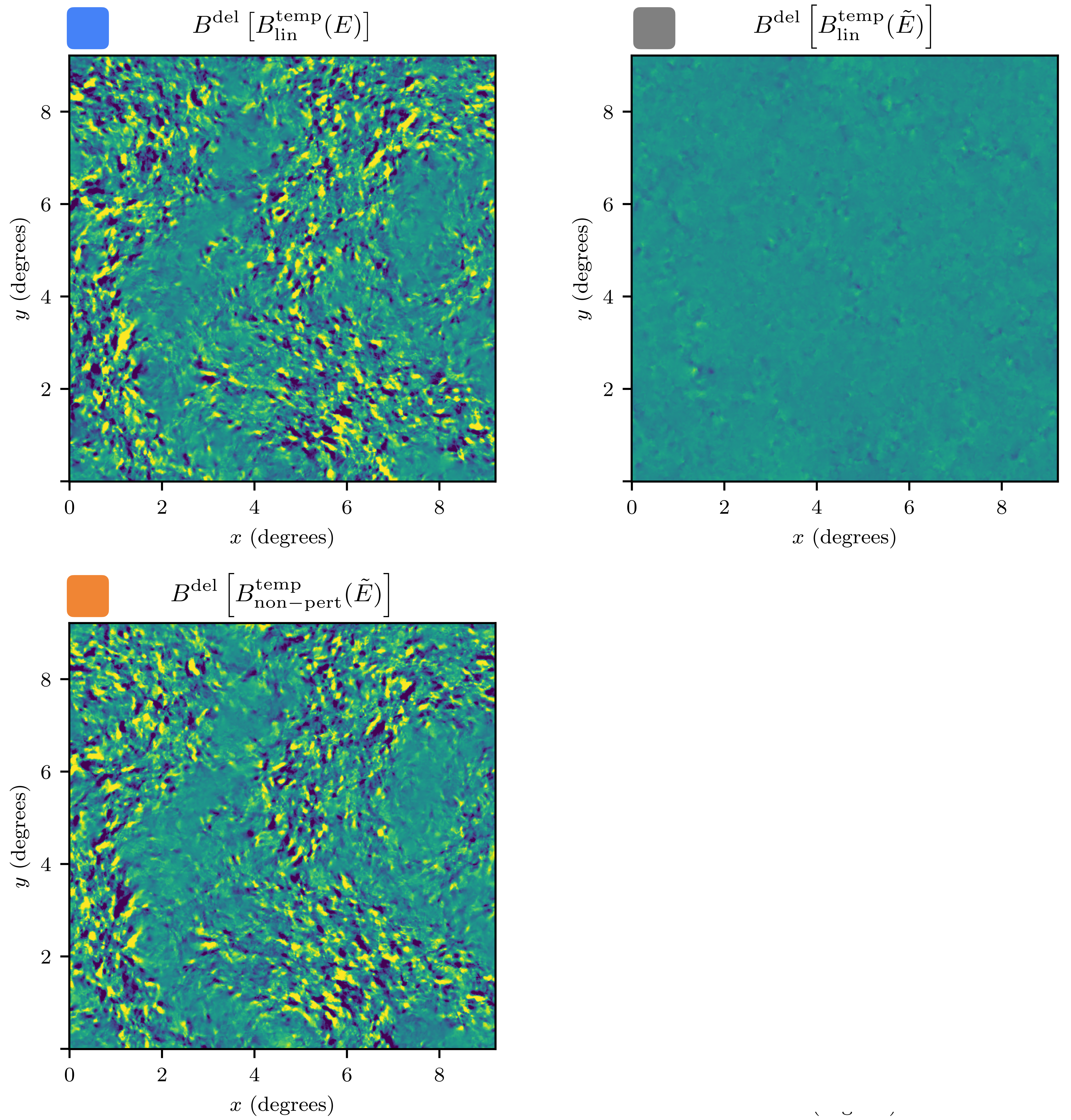


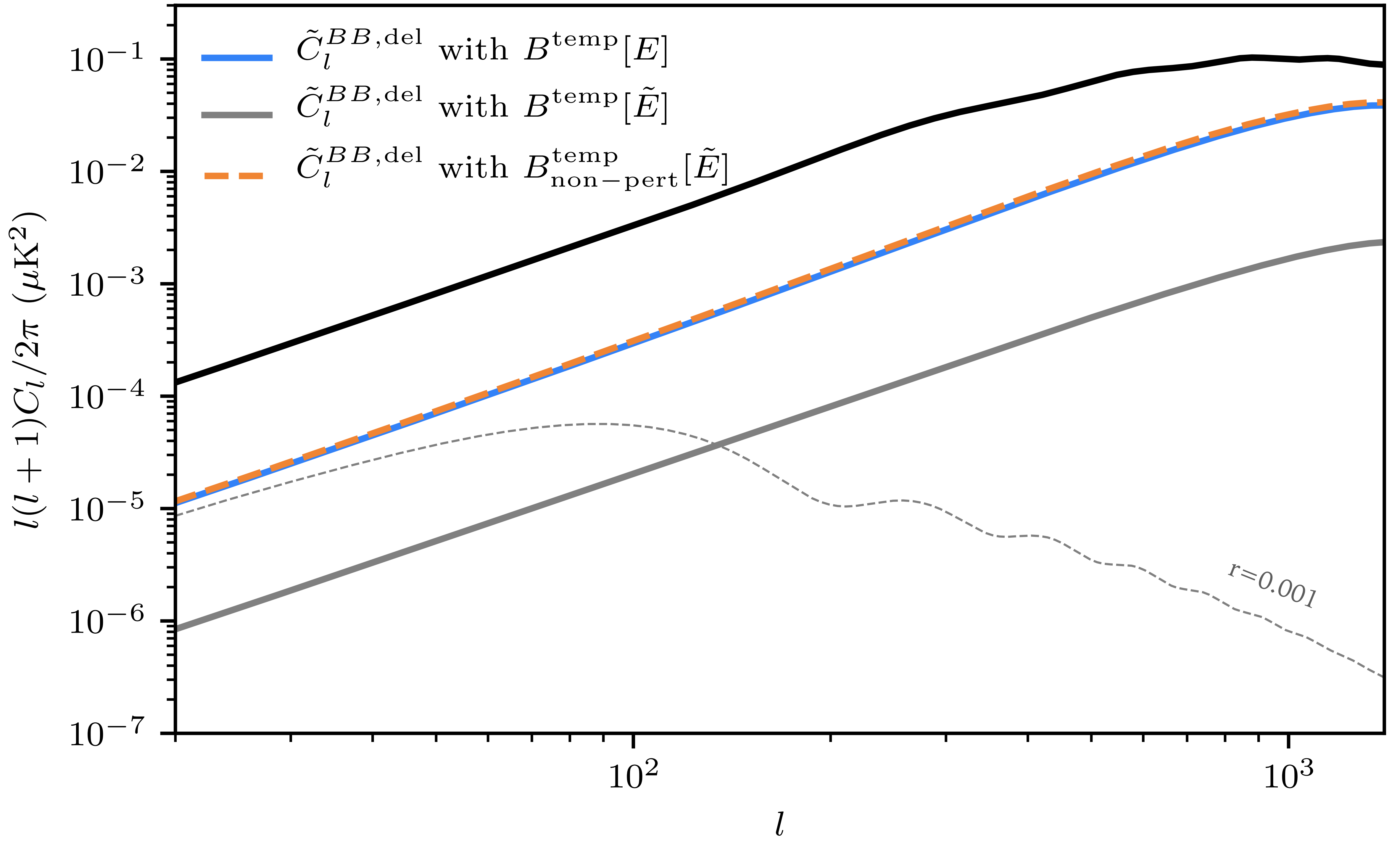


- Cancellations disappear if linear template is built from unlensed or delensed E-modes, hit delensing floor of O(10)%
- New cancellations arise when the lensed E-modes are used in the linear template, so delensing floor is O(1)%

ABL, Challinor & Carron 20b arXiv:2010.14286

LIMITATIONS OF B-MODE TEMPLATE DELENSING: NOISELESS SCENARIO

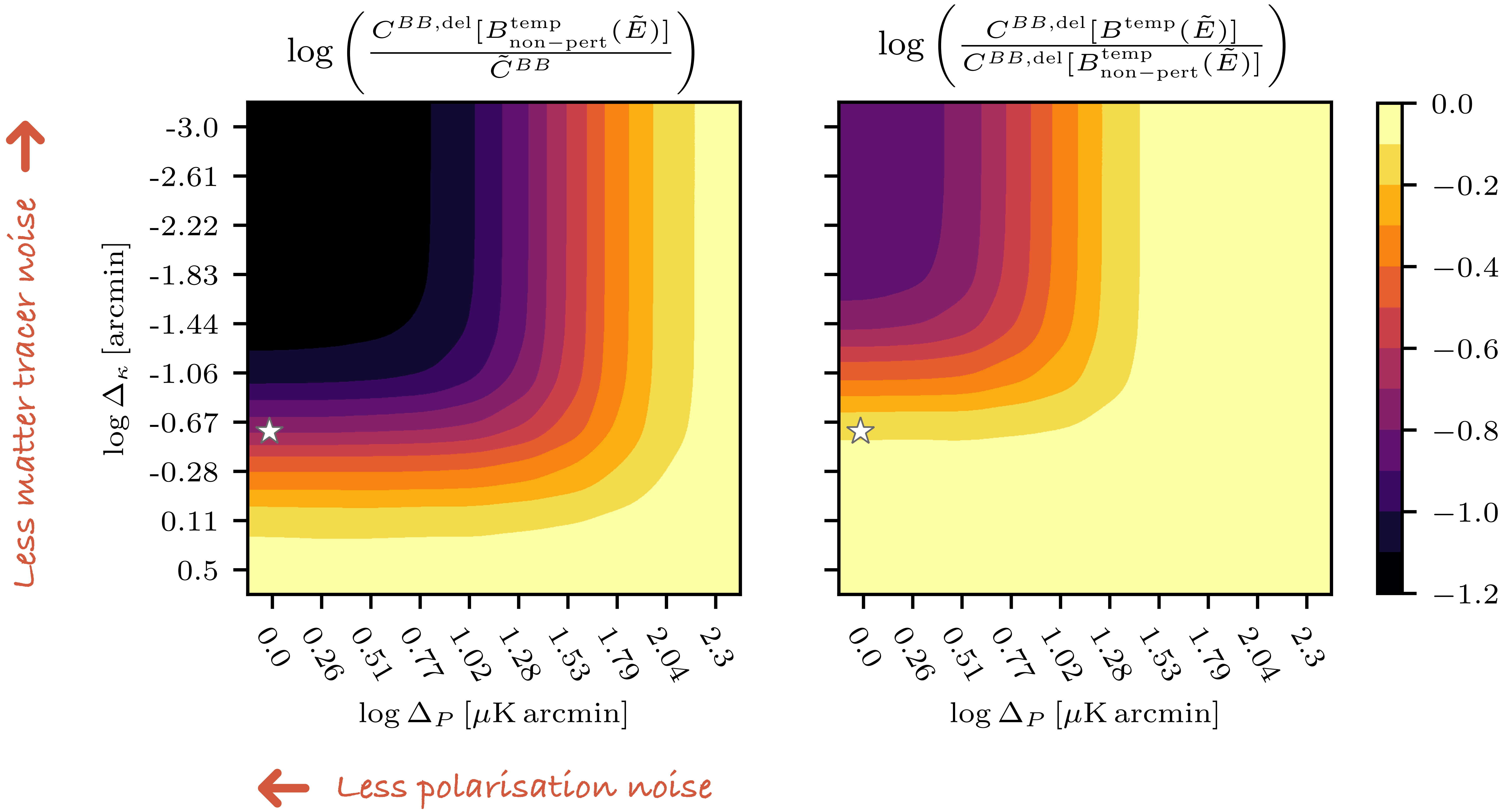




- Cancellations disappear if linear template is built from unlensed or delensed E-modes, hit delensing floor of O(10)%
- New cancellations arise when the lensed E-modes are used in the linear template, so delensing floor is O(1)%
- Advantage is lost when a non-perturbative template is built from lensed E-modes, so the delensing floor is also O(10)%

***ABL**, Challinor & Carron 20b arXiv:2010.14286*

LIMITATIONS OF B-MODE TEMPLATE DELENSING: REALISTIC CASE

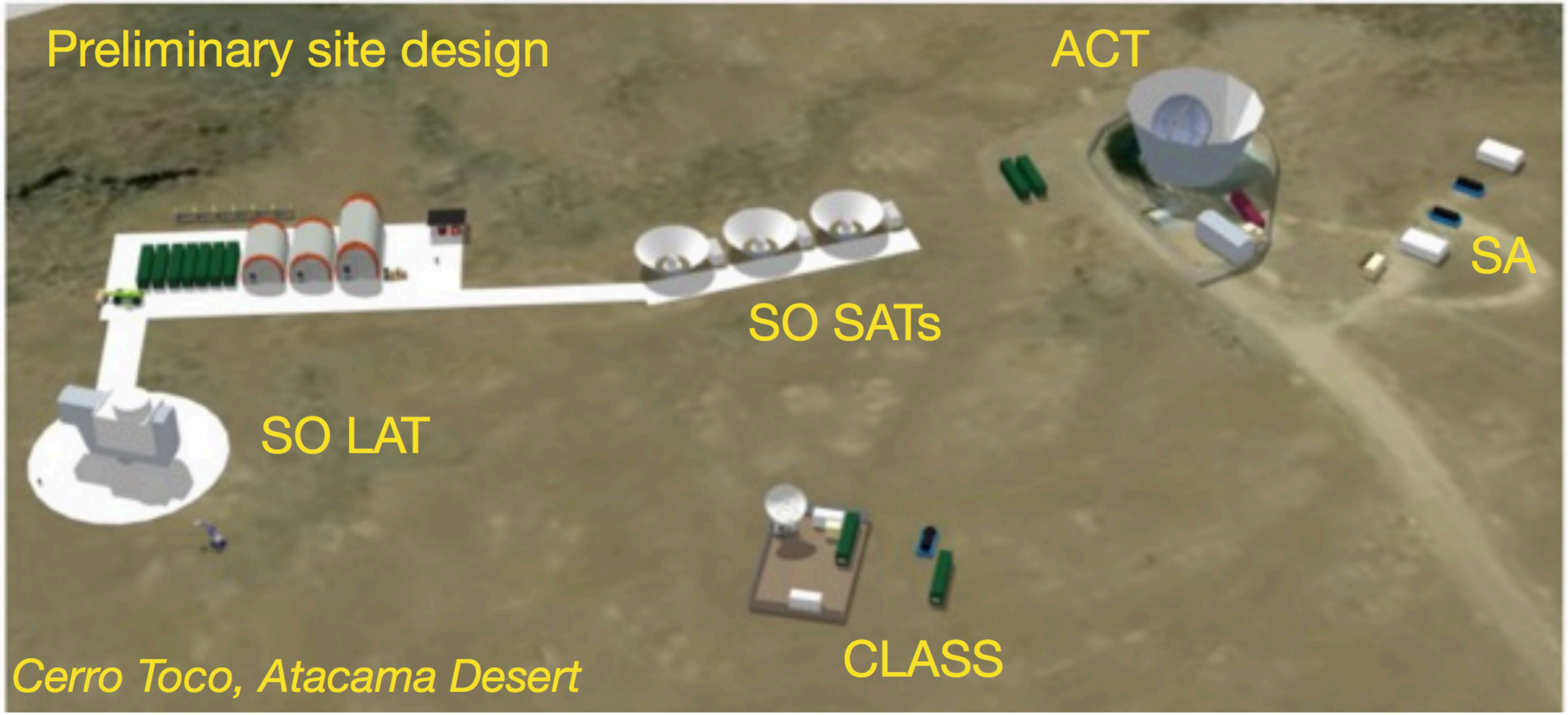


- With lensed E, advantageous to build gradient-order template E even in realistic scenarios
- For CMB-S4, this removes $\sim 5\,\%$ more lensing power

ABL, Challinor & Carron 20b arXiv:2010.14286

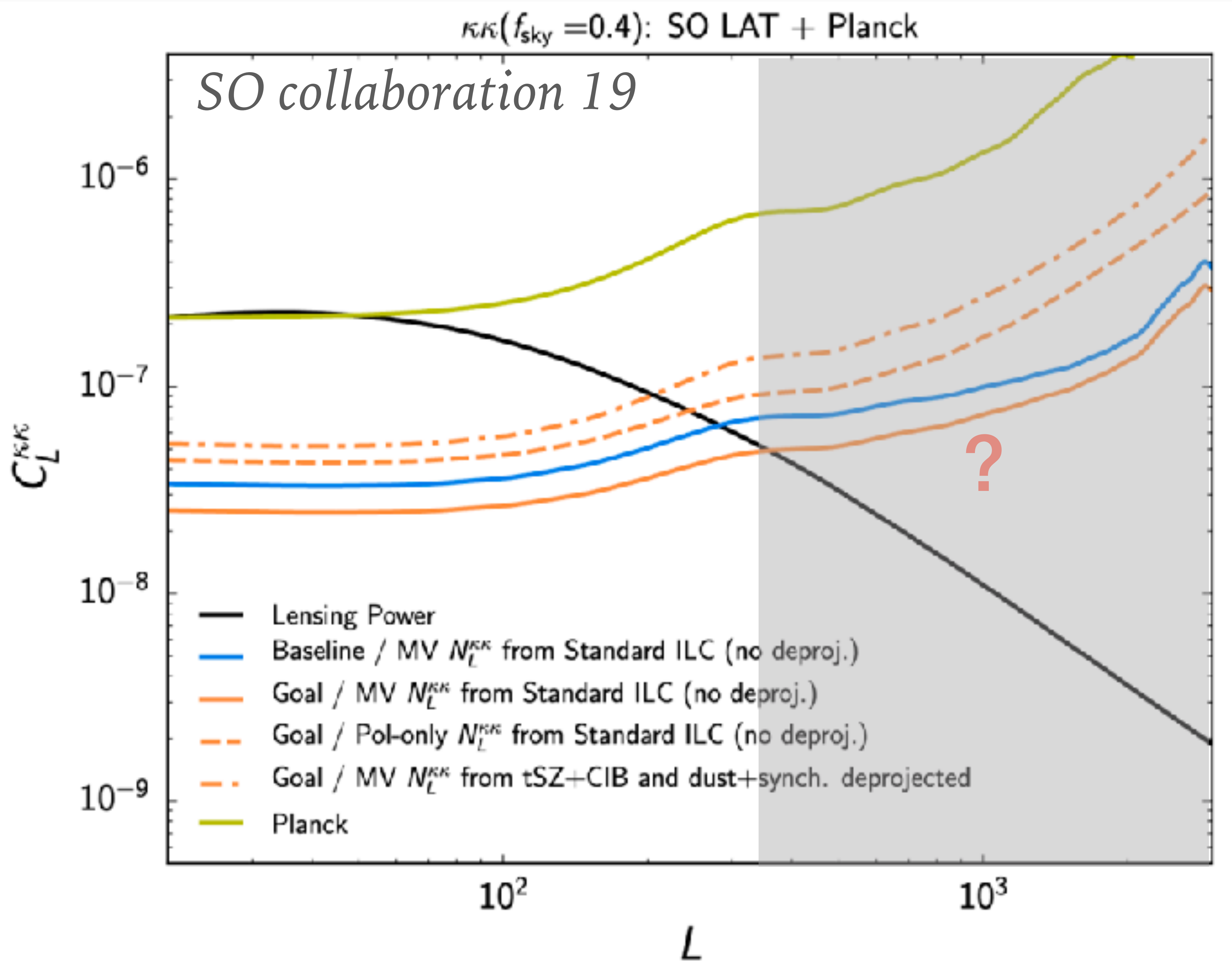
THE SIMONS OBSERVATORY (SO)

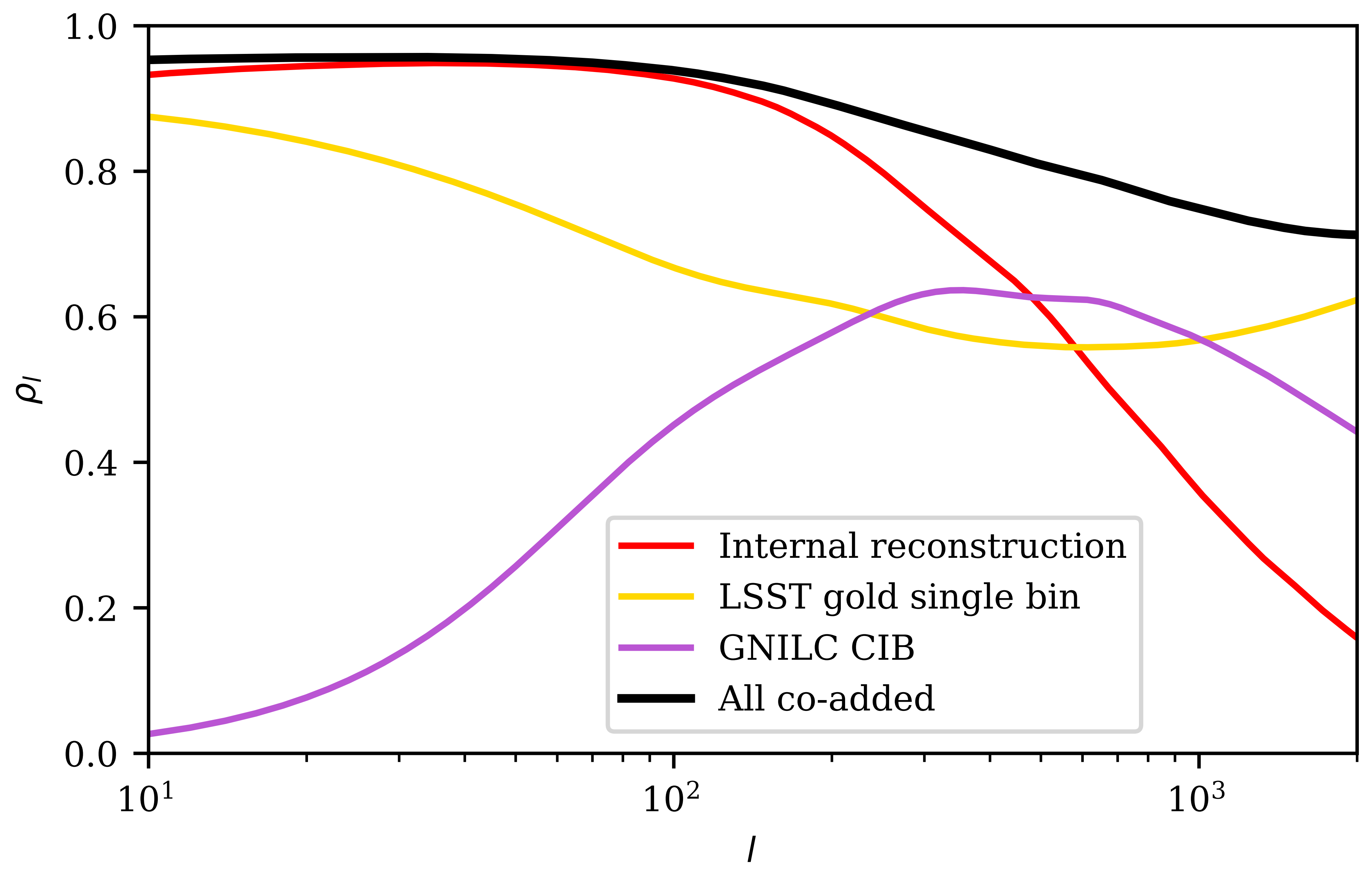
One 6m Large Aperture Telescope
Three 0.5m Small Aperture Telescopes
Five-year survey planned 2021-26, six frequencies 30-280 GHz



Large telescope: resolution needed for all science goals except tensor-to-scalar ratio
Small telescopes: lower noise at the few-degree-scale B-mode signal, for tensor-to-scalar ratio

MULTI-TRACER DELENSING WITH SO

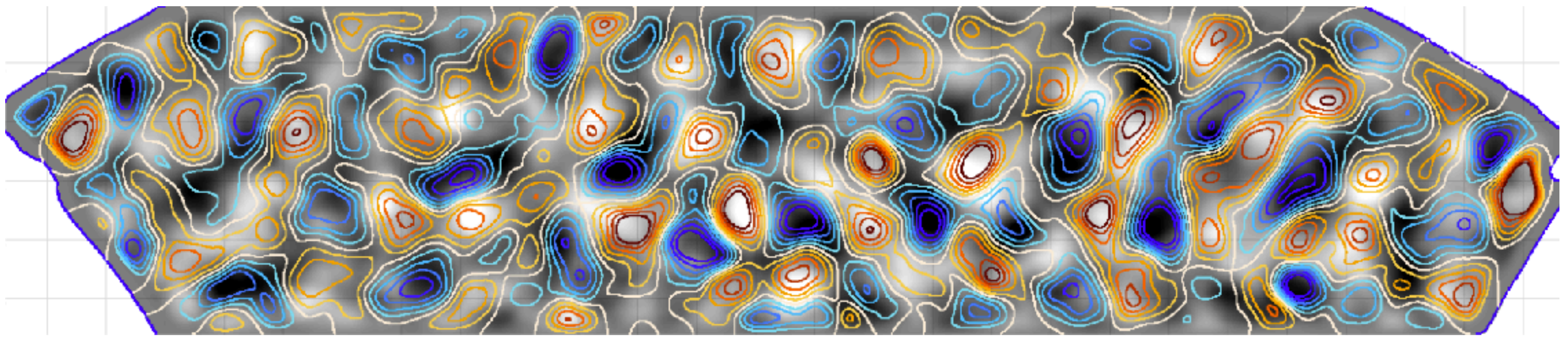




Combine internal reconstructions with external tracers of the LSS

Smith et al. 2012, Sherwin & Schmittfull 2015, …

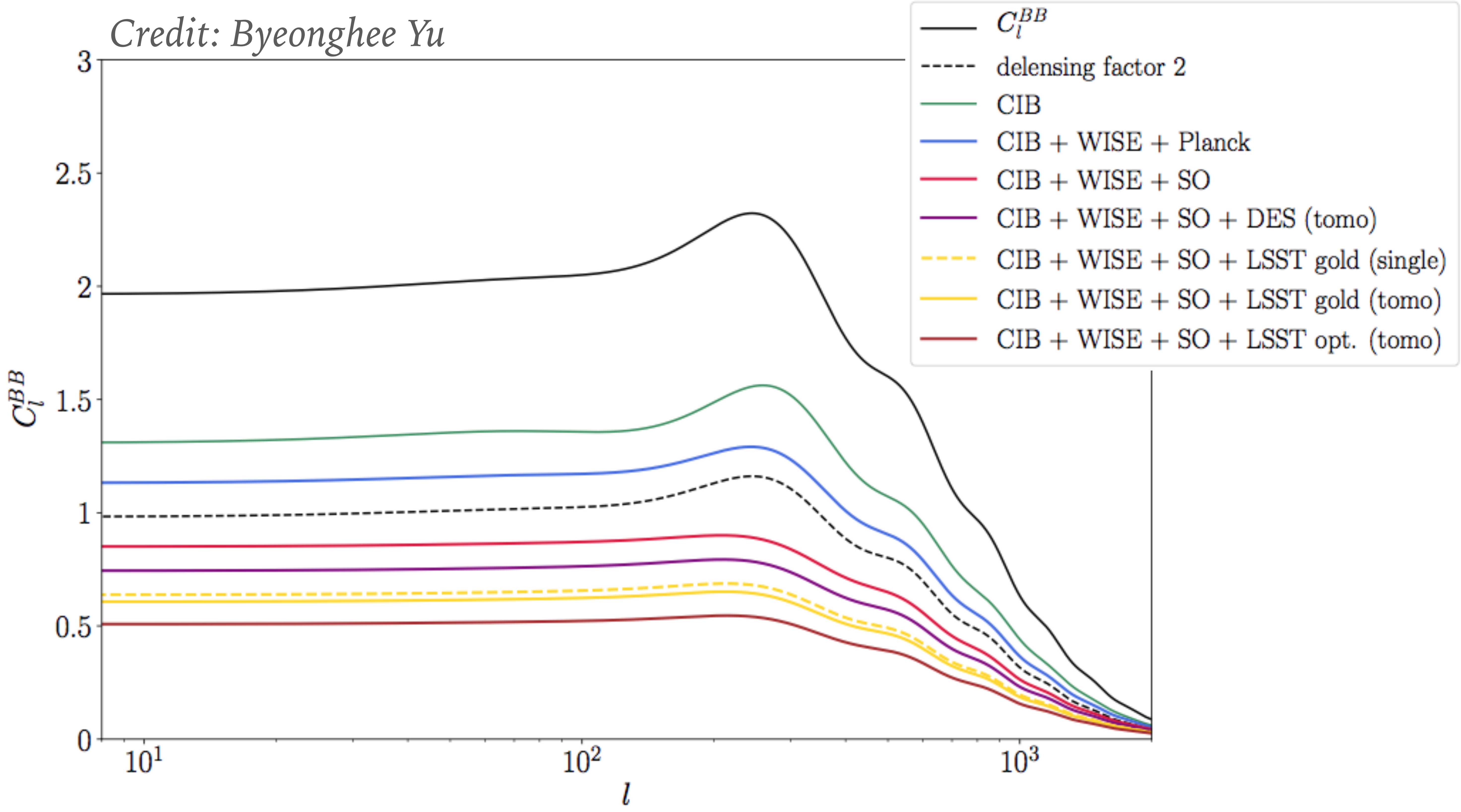
Demonstrated by Larsen et al. 16, SPT 17, Planck 18, BICEP/Keck +SPT 20



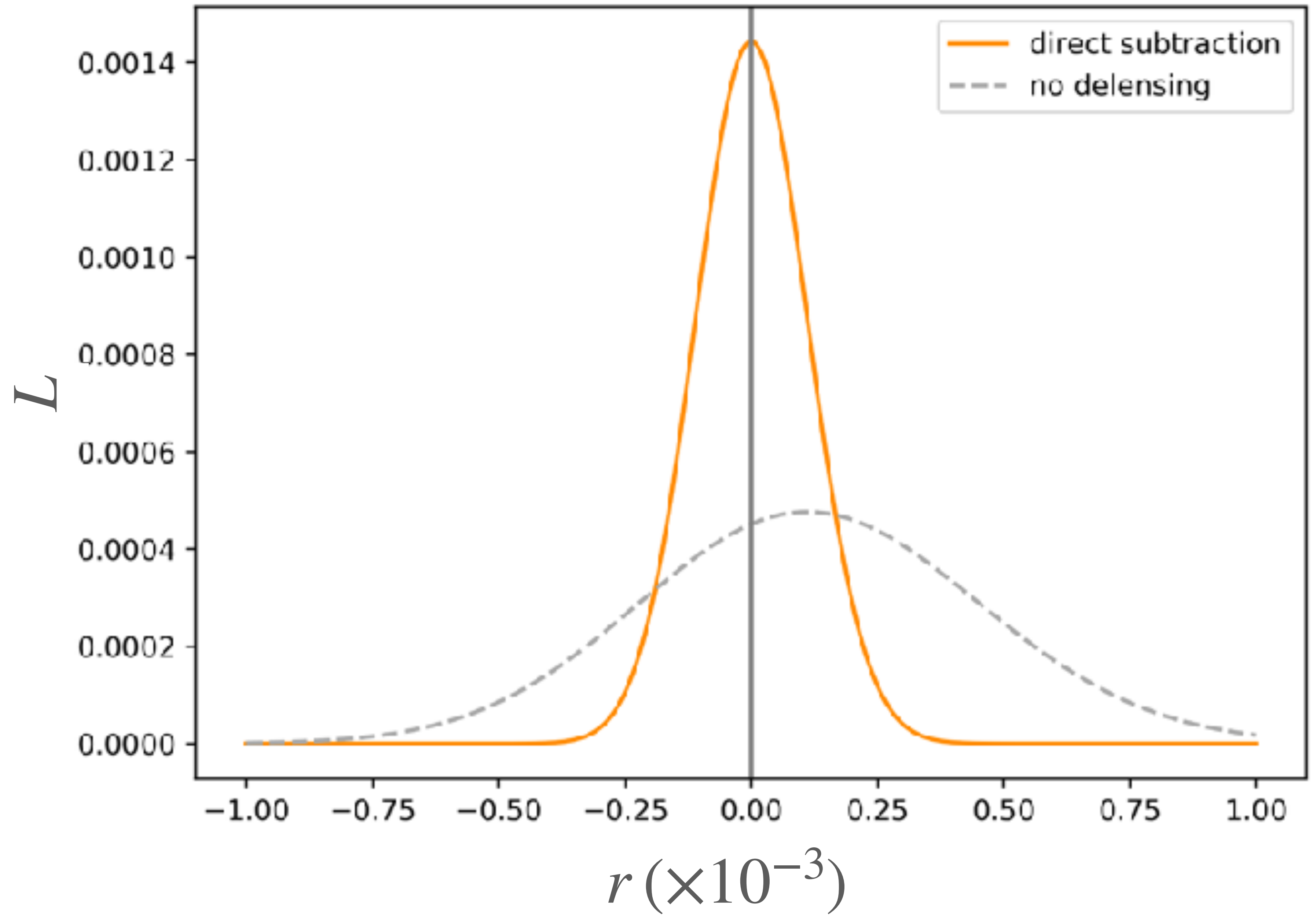
ACT $\hat{\kappa}$ vs. CIB *Darwish et al. 20*

DELENSING WITH SO

Credit: Byeonghee Yu



Credit: Naomi Robertson

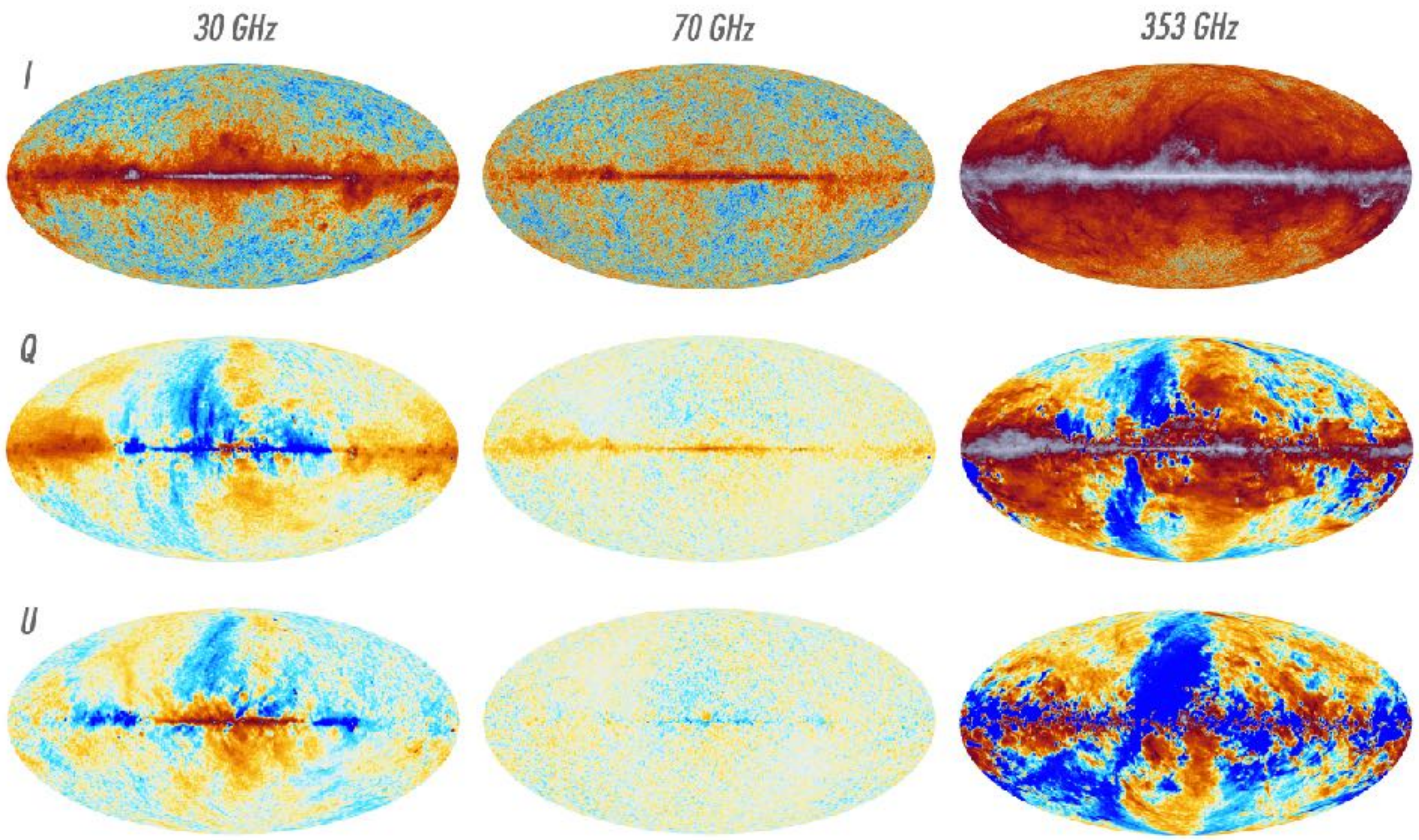


Close to idealised performance on realistic simulations including inhomogeneous noise and masking

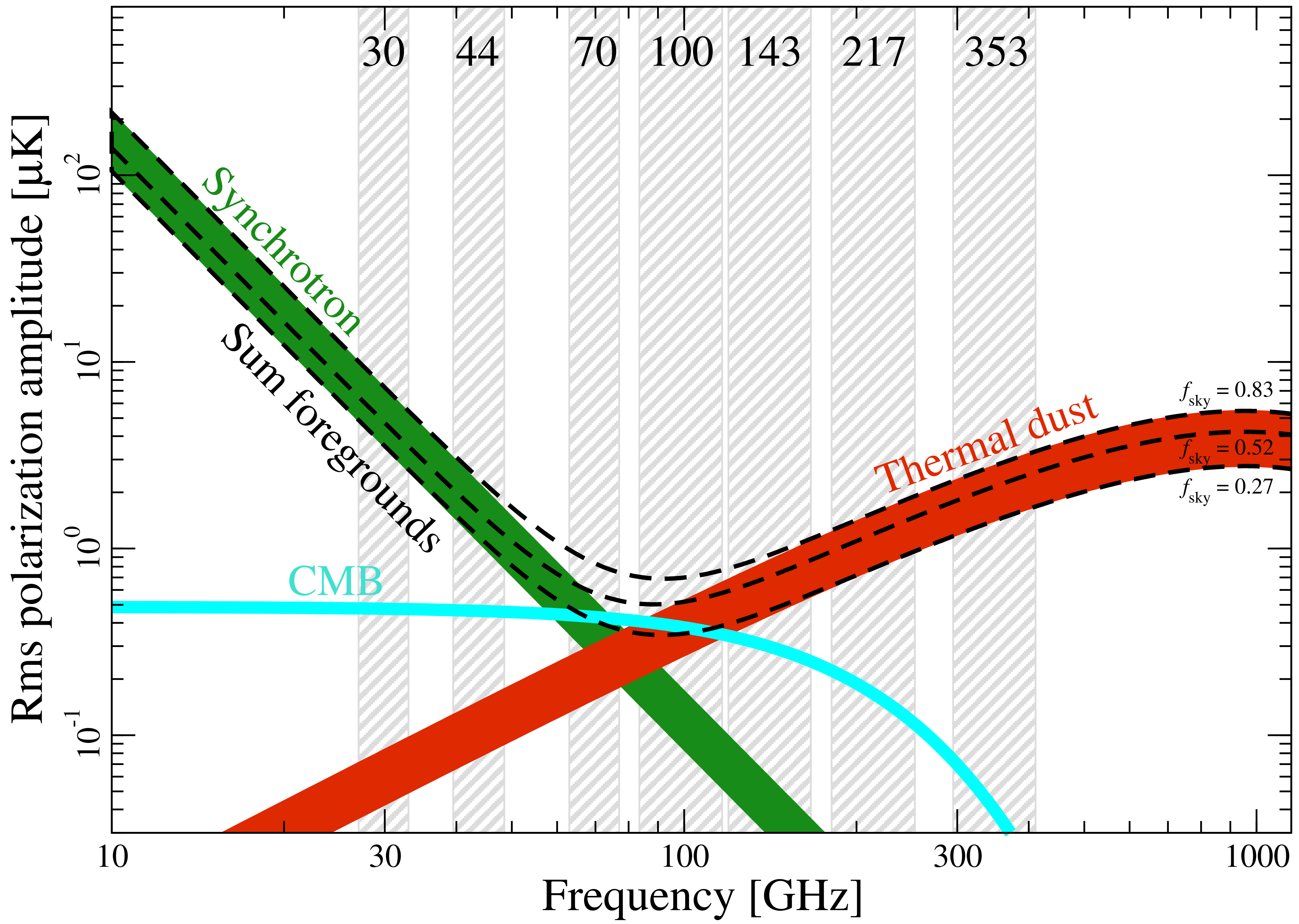
Currently $\sigma(r) = 0.07$ (BICEP2/Keck), SO forecast after delensing $\sigma(r) = 0.003$

*Namikawa, **ABL**, Robertson, Challinor, Sherwin & Yu 20 (to be submitted)*

BIASES TO DELENSING FROM FOREGROUNDS



Our galaxy produces linearly polarised emission

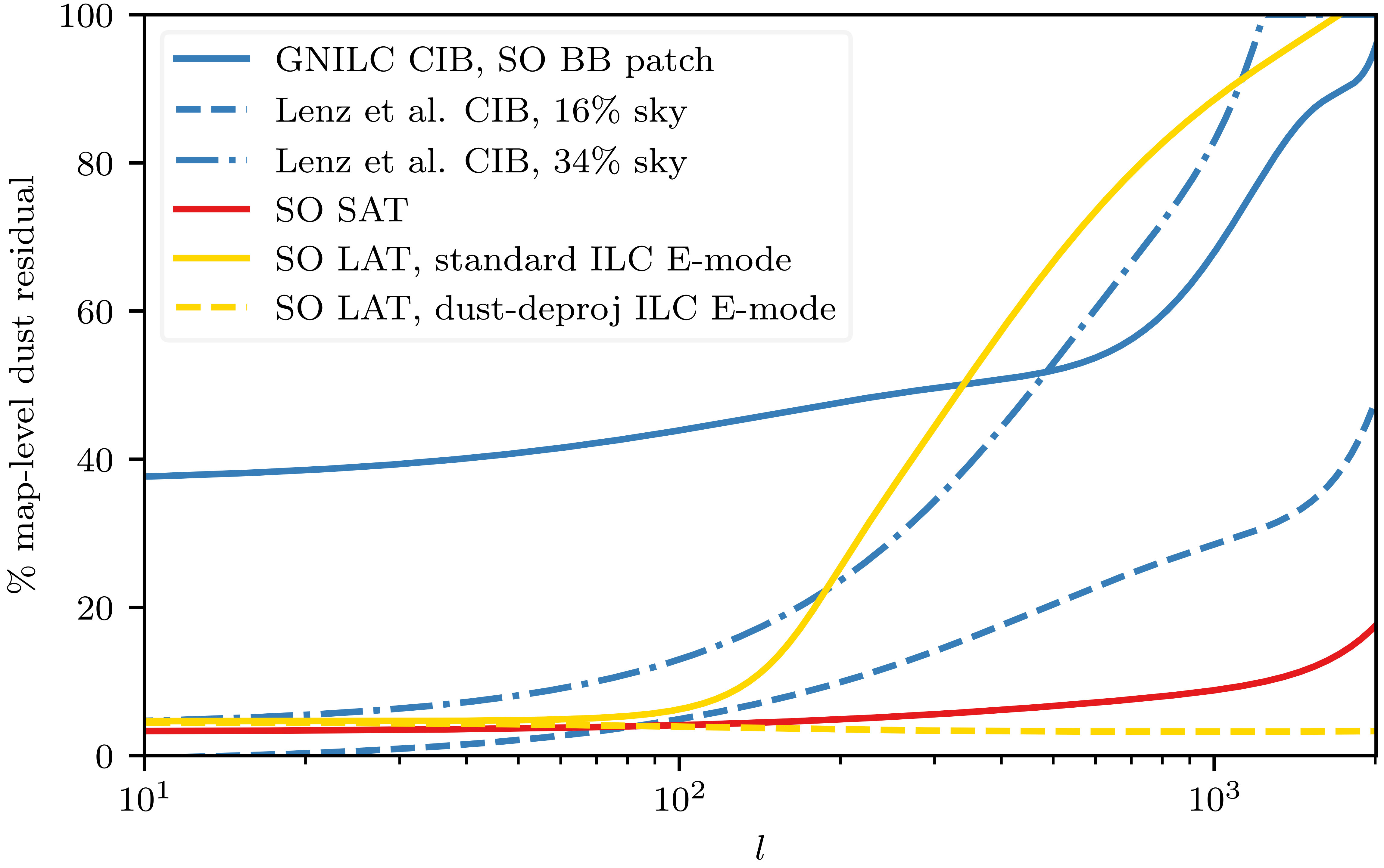


Difference in foreground and CMB SEDs can be used to separate them, but residuals will remain

Negligible bias from internal delensing of CMB-S4 after foreground cleaning *D. Beck et al. 20*

… but what about CIB-delensing?

DELENSING WITH THE CIB — POSSIBLE BIASES



$$\tilde{E} + E^{CIB} + \delta E^{dust}$$

$$B^{\mathrm{del}} = B^{\mathrm{obs}} - E^{\mathrm{obs}} * \mathscr{W} I$$

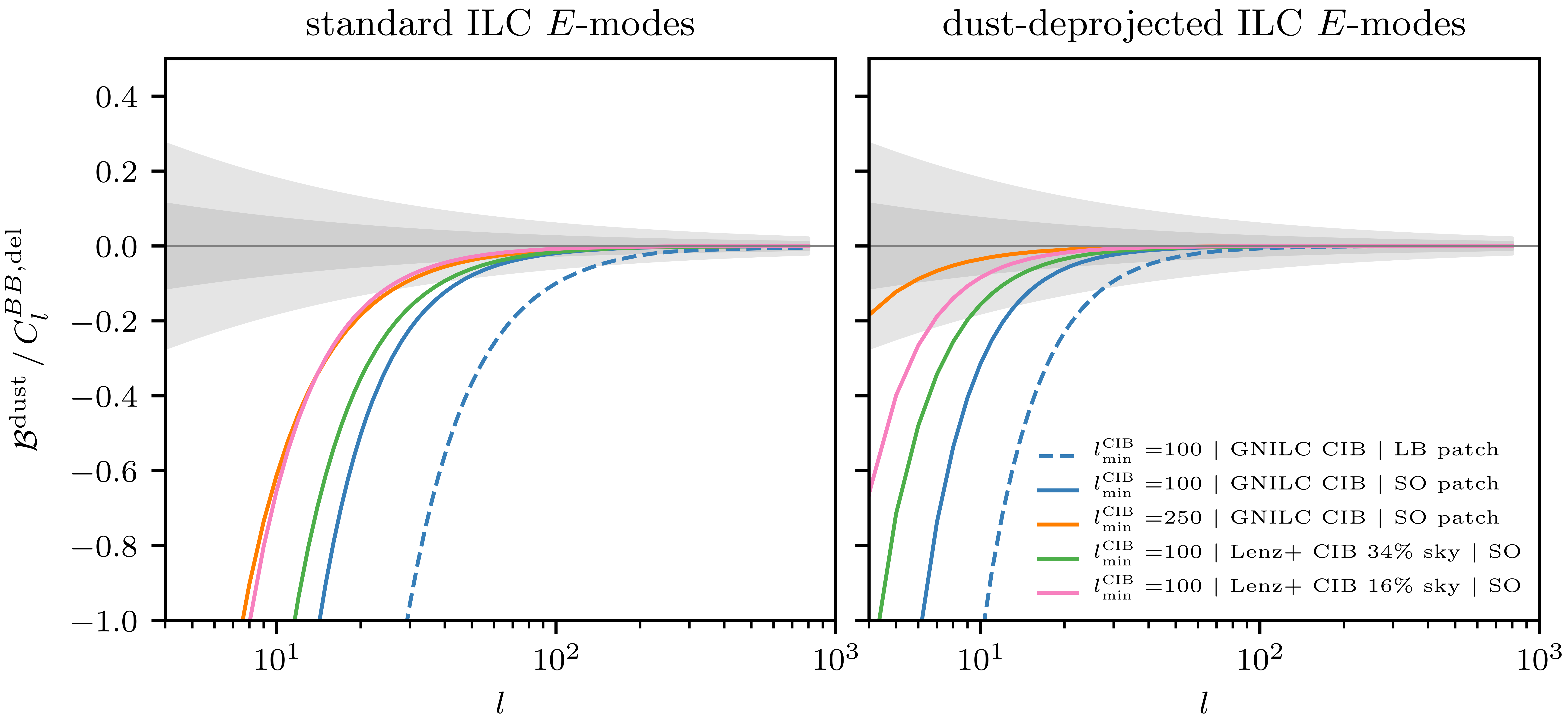
$$\tilde{B} + B^{CIB} + \delta B^{dust} \qquad I^{CIB} + \delta I^{dust}$$

The power spectrum of delensed B-modes is then biased:

$$C_\ell^{BB,del} \supset \langle B^{dust}_{100GHz} E^{dust}_{100GHz} I^{dust}_{353GHz} \rangle, \langle B^{CIB}_{100GHz} E^{CIB}_{100GHz} I^{CIB}_{353GHz} \rangle \ldots$$

__ABL__, Challinor, Sherwin & Namikawa 20 (to be submitted)

DELENSING WITH THE CIB — BIAS FROM RESIDUAL GALACTIC DUST



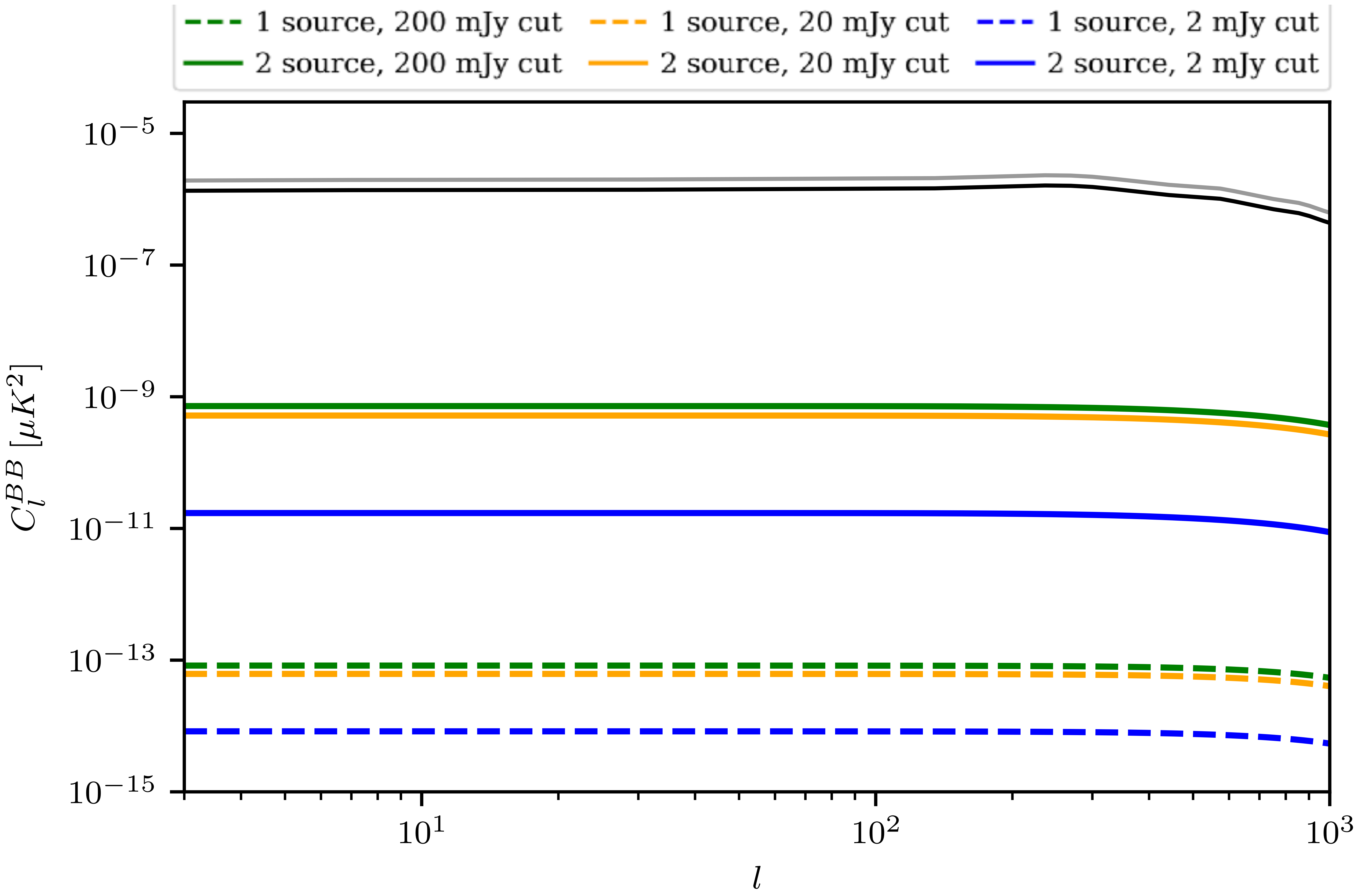
- Negative bias nominated by $\langle B^{dust} E^{dust} I^{dust} \rangle$
- Can be mitigated by nulling dust contribution to E-modes, with only small penalty in delensing efficiency
- Small on scales probed from the ground

__ABL__, Challinor, Sherwin & Namikawa 20 (to be submitted)

DELENSING WITH THE CIB — BIAS FROM CIB BI- & TRISPECTRUM

In a minimal analytic model with uncorrelated source polarisation angles,

$$\mathcal{B}^{BET}(\boldsymbol{l}) = \frac{8p^2}{\pi}\int \frac{d^2\boldsymbol{l}'}{(2\pi)^2}\frac{\boldsymbol{l}'\cdot(\boldsymbol{l}-\boldsymbol{l}')}{|\boldsymbol{l}-\boldsymbol{l}'|^2}\mathcal{W}^E(\boldsymbol{l}')\mathcal{W}^I(|\boldsymbol{l}-\boldsymbol{l}'|)\sin^2 2(\phi_{\boldsymbol{l}'}-\phi_{\boldsymbol{l}})\int dz\left[(2\pi)^{-3}S^{(3)}(z)+\frac{H(z)}{c}S^{(2)}(z)S^{(1)}(z)P_g\left((l-l')/r(z),z\right)\right], \quad (20)$$



where

$$S_\nu^{(n)}(z) \equiv \int_{s_{\min}}^{s_{\max}} dS\,S^n \frac{d^2N}{dSdzd\Omega}(z,\nu)$$

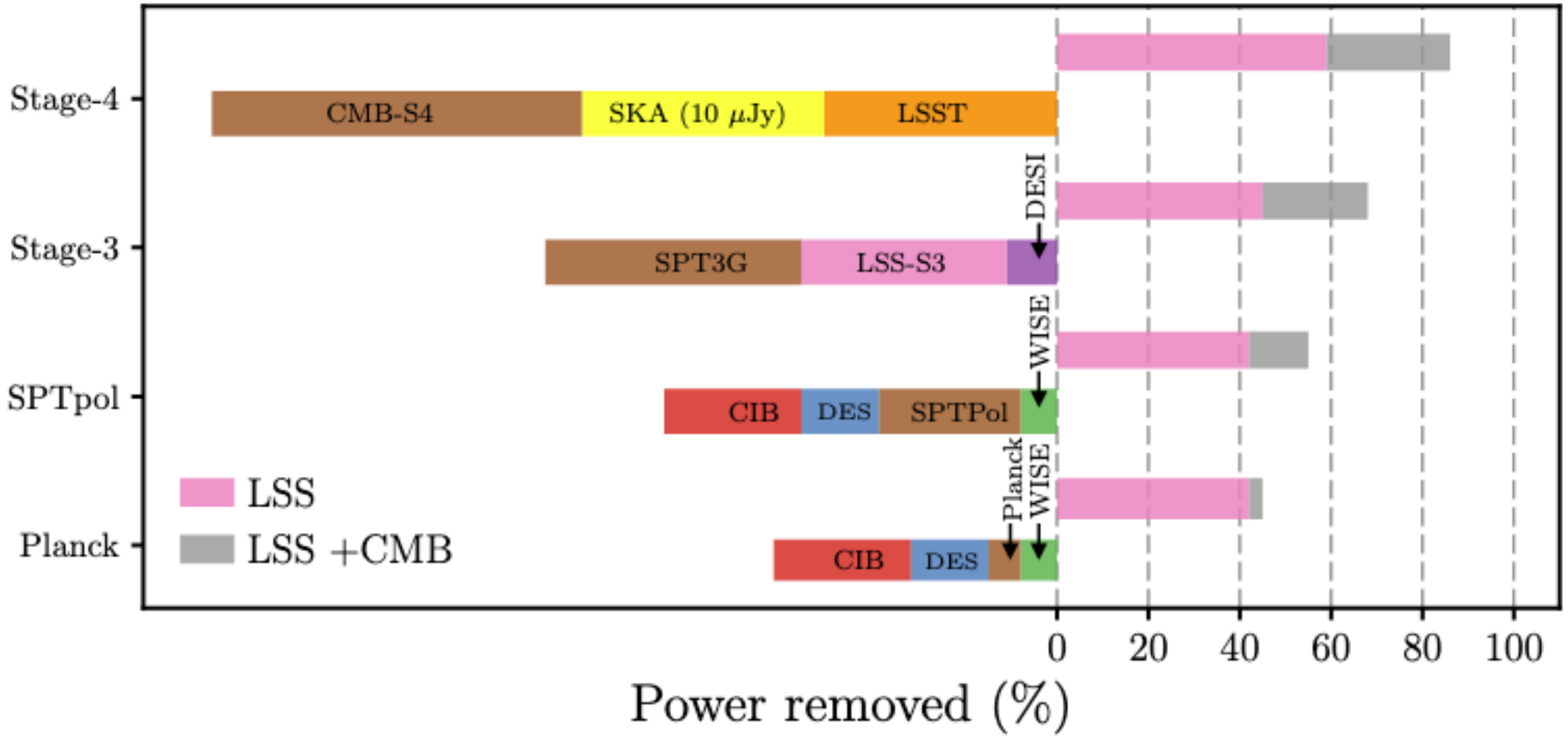
and $\langle B^{CIB}E^{CIB}T^{CIB}\rangle \gg \langle E^{CIB}T^{CIB}E^{CIB}T^{CIB}\rangle$ for expected flux cuts.

Hence, **negligible** for any implementation of CIB-delensing

__ABL__, Challinor, Sherwin & Namikawa 20 (to be submitted)

INTERNAL DELENSING

Manzotti 17



Soon dominated by internal lensing reconstructions based on CMB polarisation (mainly EB)

Maximum-a-posteriori $\hat{\phi}$ equivalent to iterative application of QEs *Hirata & Seljak 03, Carron & Lewis 17*

Sampling from $P(\phi, X^{\text{unl}} \,|\, \text{data})$ or $P(r \,|\, X^{\text{obs}}, \phi)$ optimal (but indistinguishable from iterative for r)

Millea et al. 20, Carron 19

RECAP OF B-MODE DELENSING

Schematically:

$$\langle |B^{obs} - E^{obs}\hat{\phi}|^2 \rangle = \langle |B^{obs}|^2 \rangle - 2\,\langle B^{obs} E^{obs} \hat{\phi} \rangle + \langle E^{obs}\hat{\phi} E^{obs}\hat{\phi} \rangle :$$

delensing: $\langle \tilde{B}(E,\phi)\tilde{E}\phi \rangle_c$

= residual lensing + experimental noise

INTERNAL DELENSING BIAS

Schematically:

$$\langle | B^{obs} - E^{obs}\hat{\phi} |^2 \rangle = \langle | B^{obs} |^2 \rangle - 2 \langle B^{obs} E^{obs} \hat{\phi} \rangle + \langle E^{obs} \hat{\phi} E^{obs} \hat{\phi} \rangle :$$

$$\hat{\phi} = \hat{\phi}^{EB}(E, B)$$

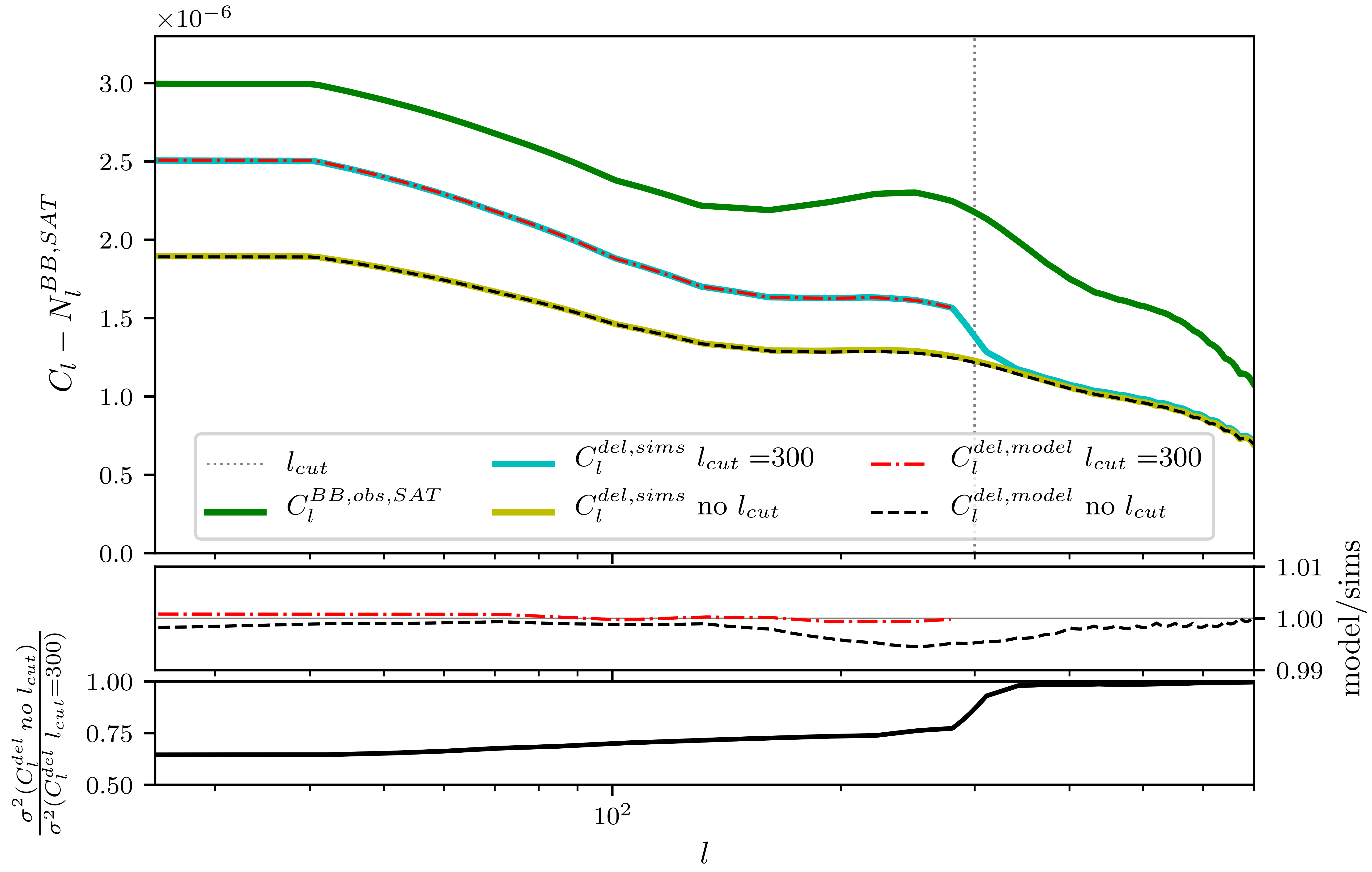
$$\langle B^{obs} E^{obs} E^{obs} B^{obs} \rangle$$

$$\langle E^{obs} E^{obs} B^{obs} E^{obs} E^{obs} B^{obs} \rangle$$

- Suppression of power beyond a simple removal of lensing
- Bias is *local* — avoid by removing overlapping modes

Teng et al. 11, Namikawa & Nagata 14

INTERNAL DELENSING BIAS

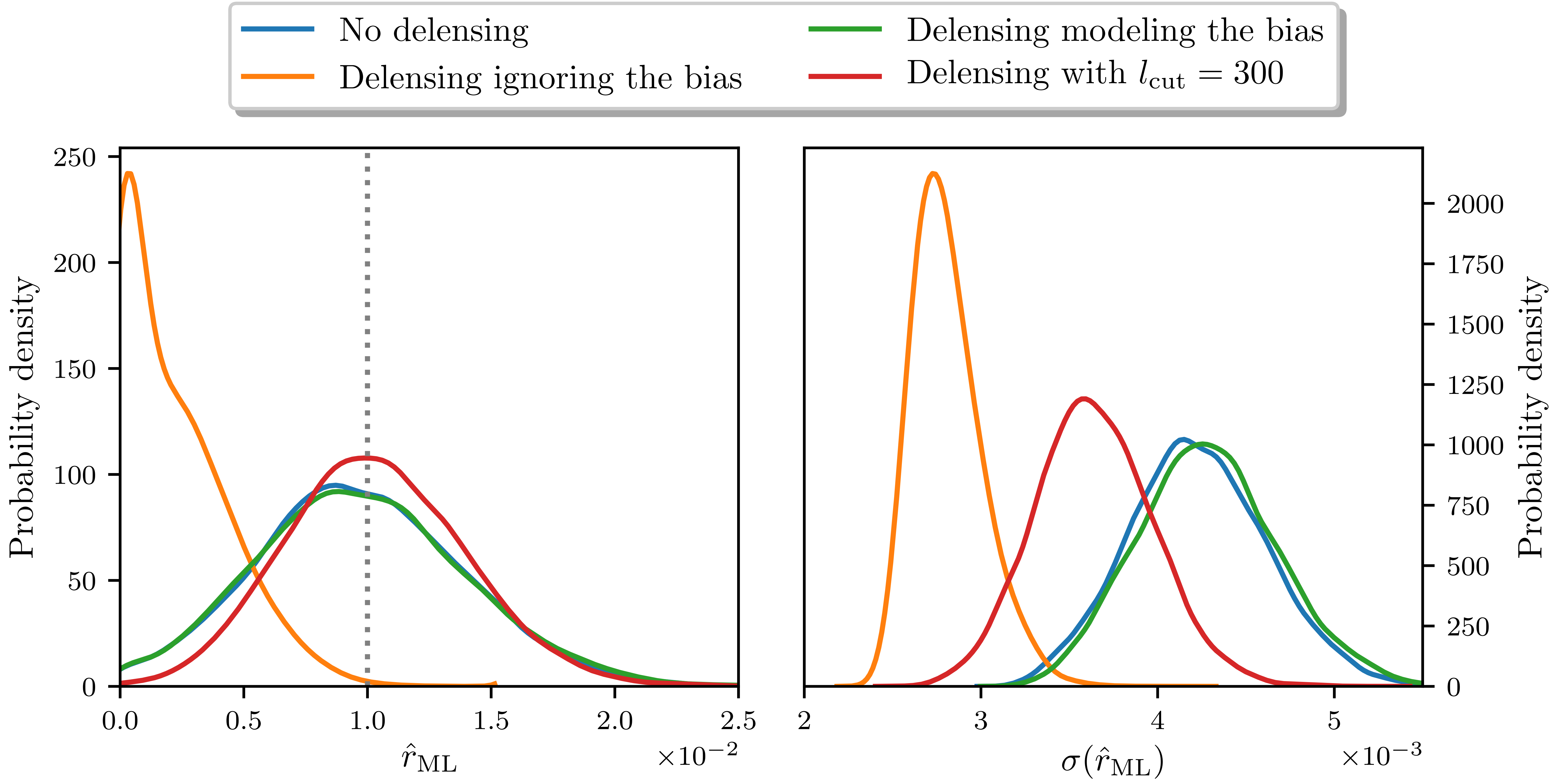


Variance of delensed spectrum is reduced!

$$\text{Model:} \quad \frac{C_l^{BB,\text{del,biased}}}{(D_l-1)^2} = C_l^{BB,\text{del,unbiased}} + \left(\frac{D_l}{D_l-1}\right)^2 \left[C_l^W + N_l^{BB,\text{LAT}} + N_l^{BB,\text{SAT}}\left(\frac{2}{D_l}-1\right) - \frac{2}{D_l}N_l^X\right], \qquad 0 < D_l < 1$$

***ABL**, Challinor & Carron 20a (arXiv:2007.01622)*

INTERNAL DELENSING BIAS



- Primordial signal is suppressed by a larger fraction than the “noise”
- Relevant for iterative delensing
- Preferable to avoid by masking overlapping modes (small impact on S/N) than renormalising/modeling

__ABL__, Challinor & Carron 20a (arXiv:2007.01622)

CONCLUSIONS

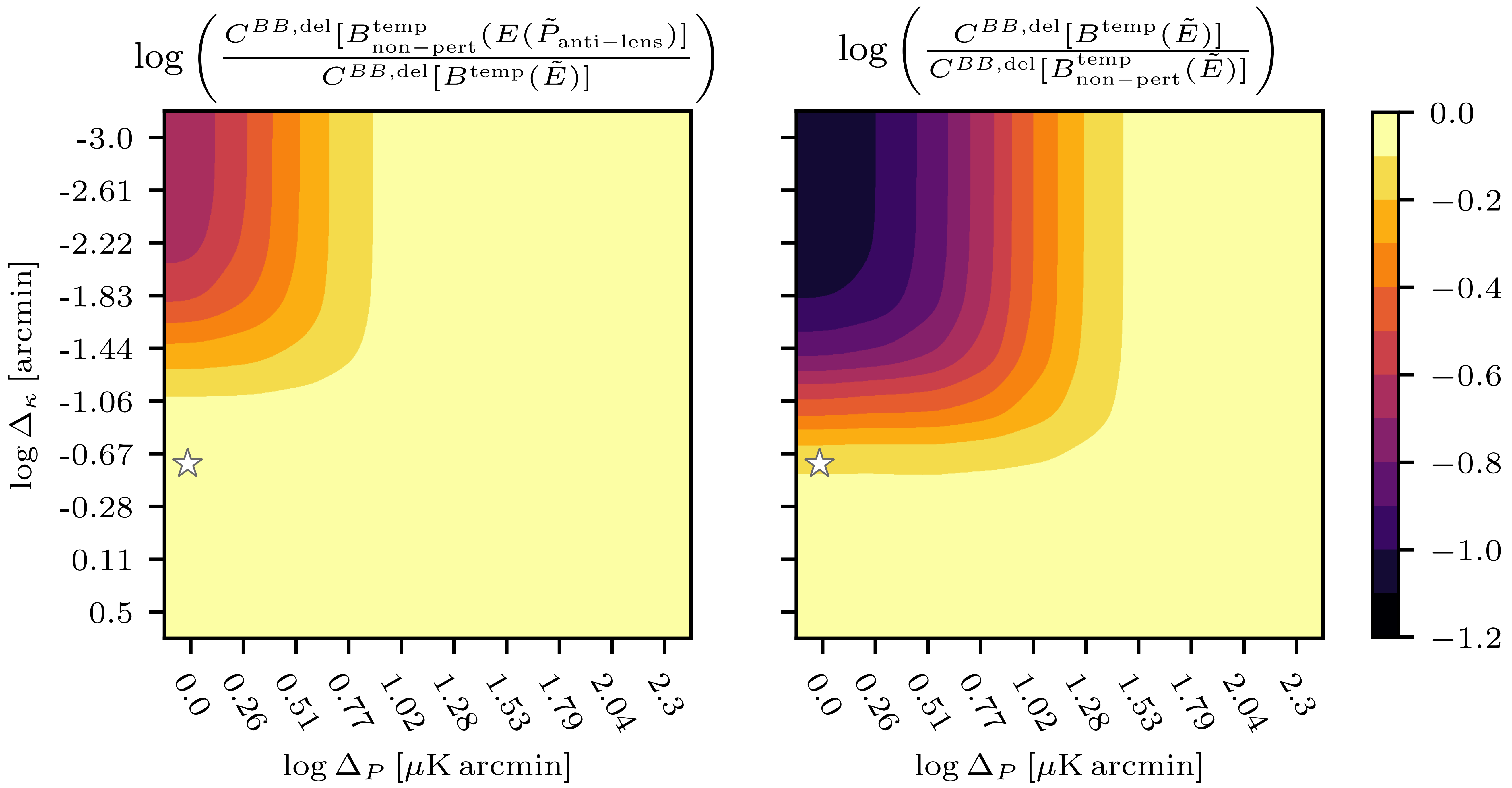
- CMB lensing biases from extragalactic foregrounds, a major challenge but can be mitigated
  - We calculate these biases analytically — good for understanding, informing masking & marginalising over modeling uncertainties.
    - Upcoming data (CCATp & CMB-S3) will improve models
    - Next: extend to polarisation & iterative reconstructions. Apply to SO for improved statistical power (?)

- Delensing B-modes with a leading-order template built from lensed E: a transparent & effective for present & future (beyond CMB-S4)
- For SO, multi-tracer delensing removes $\sim 70\,\%$ of power, halves $\sigma(r)$
- LSS tracers great for delensing. CIB particularly useful, but need to null dust emission to avoid bias
- Internal delensing biases, with us for the foreseeable future — better to mask than to model

Thank you very much for having me!

BACK-UP SLIDES

ADDITIONAL SLIDES

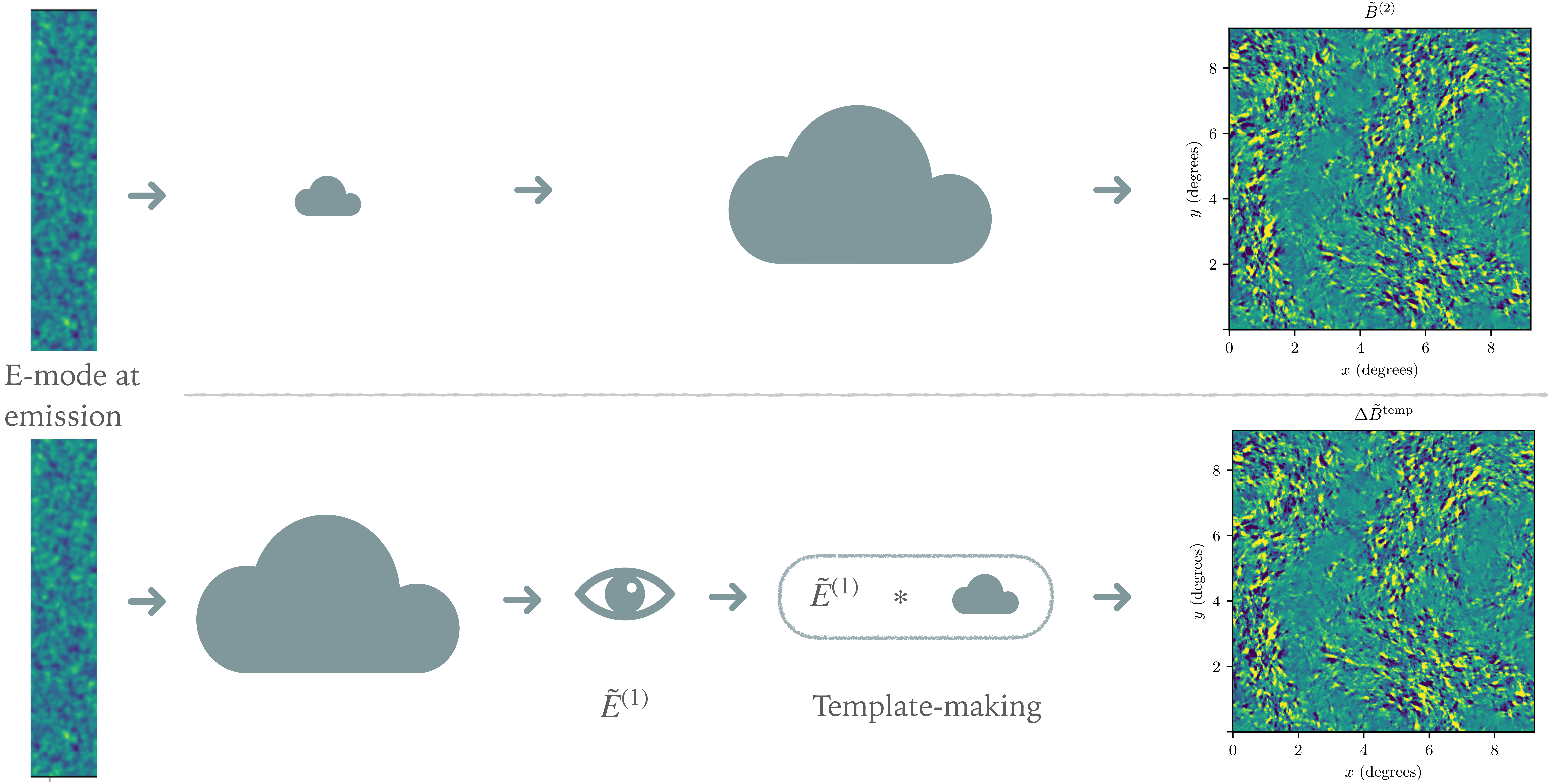


Left panel numerator:

1. *Observe QU, extract E*
2. *Anti-lens these observations*
3. *Extract E-modes*
4. *Form non-perturbative template*
5. *Delens*

… but less clear what's happening to primordial B-modes.

WHY THE CANCELLATIONS IN $B^{\mathrm{del}}[B^{\mathrm{temp}}_{\mathrm{lin}}(\tilde{E})]$?



WHY THE LARGE FLOOR IN $B^{\rm del}[B^{\rm temp}_{\rm non-pert}(\tilde{E})]$?

$$\tilde{B}^{\rm temp}_{\rm non-pert}(\mathbf{l}) = \tilde{B}^{(1)}(\mathbf{l}) + \Delta\tilde{B}^{\rm temp}(\mathbf{l}) + \tilde{B}^{(2)}(\mathbf{l}) + O(\phi^3)\,.$$

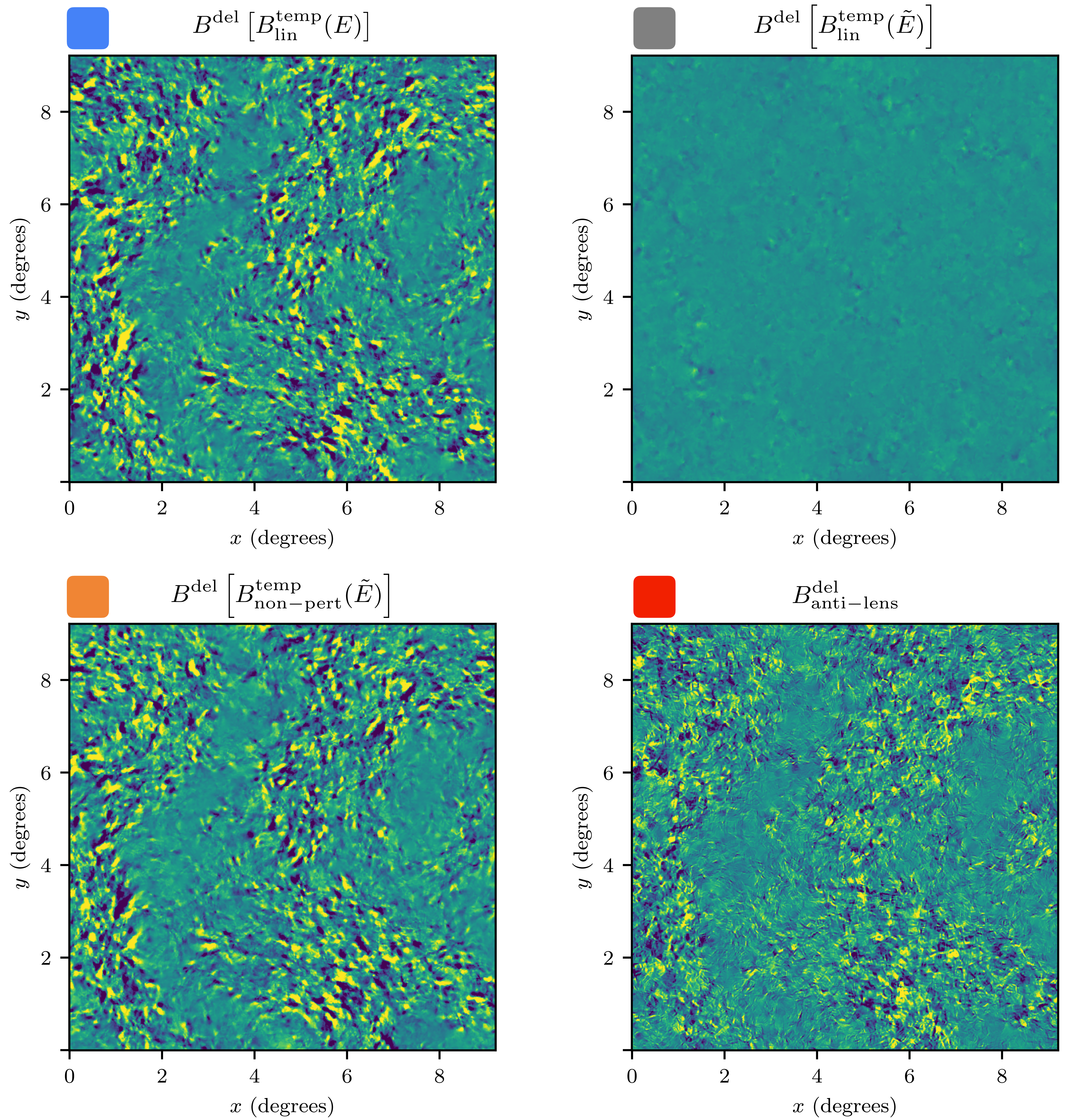
When subtracting this off of observations,

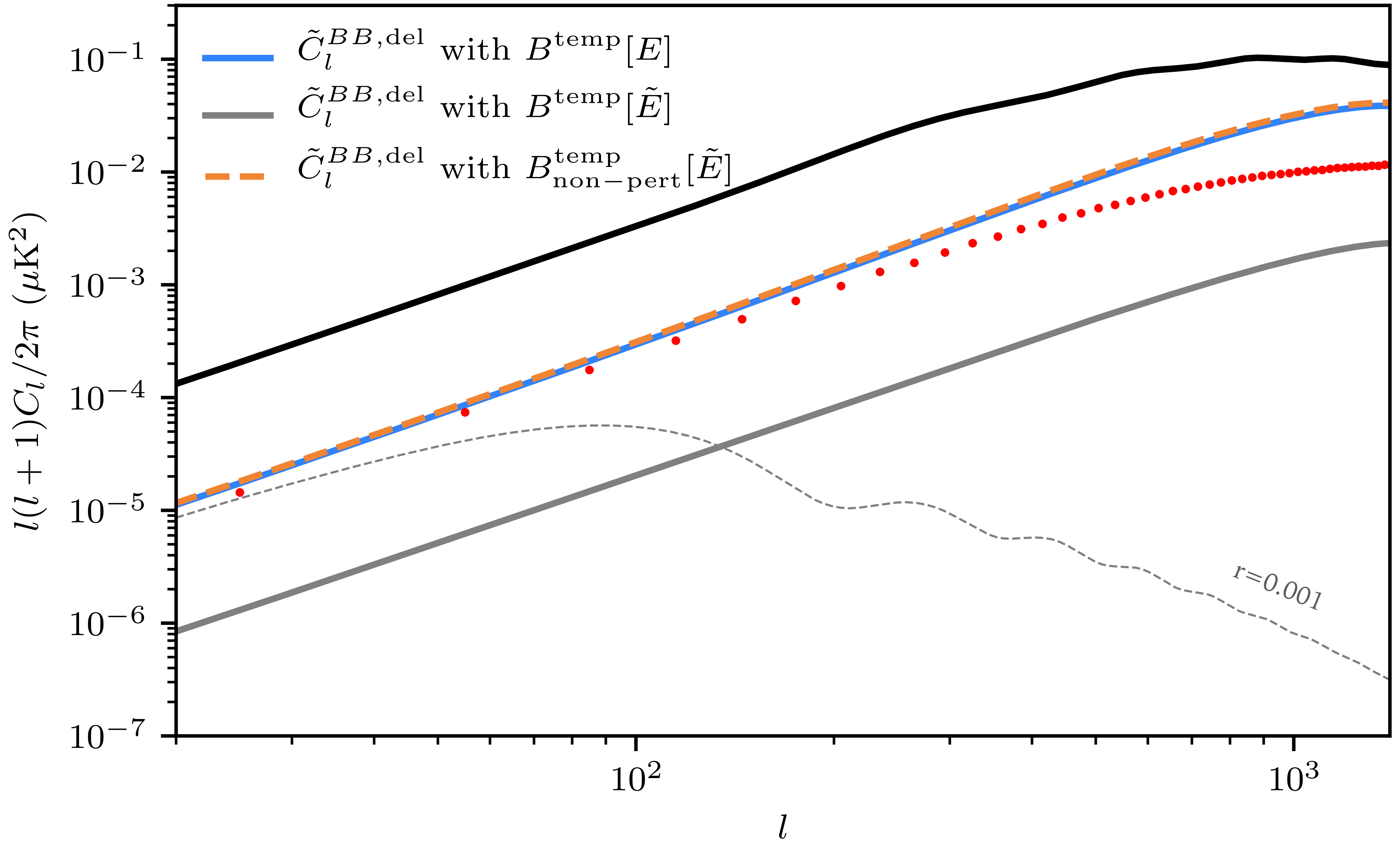
$$B^{\rm del} = B^{\rm obs} - \tilde{B}^{\rm temp}_{\rm non-pert} = \left(\tilde{B}^{(1)}(\mathbf{l}) + \tilde{B}^{(2)}(\mathbf{l}) + O(\phi^3)\right) - \left(\tilde{B}^{(1)}(\mathbf{l}) + \underline{\Delta\tilde{B}^{\rm temp}(\mathbf{l})} + \tilde{B}^{(2)}(\mathbf{l}) + O(\phi^3)\right)\,.$$

So the power spectrum of delensed B-modes is has a large floor:

$$\langle\,|B^{\rm del}|^2\rangle \approx \langle\,|\Delta\tilde{B}^{\rm temp}|^2\rangle \sim O(0.1\,\tilde{C}^{BB})\,.$$

LIMITATIONS OF B-MODE TEMPLATE DELENSING: NOISELESS SCENARIO





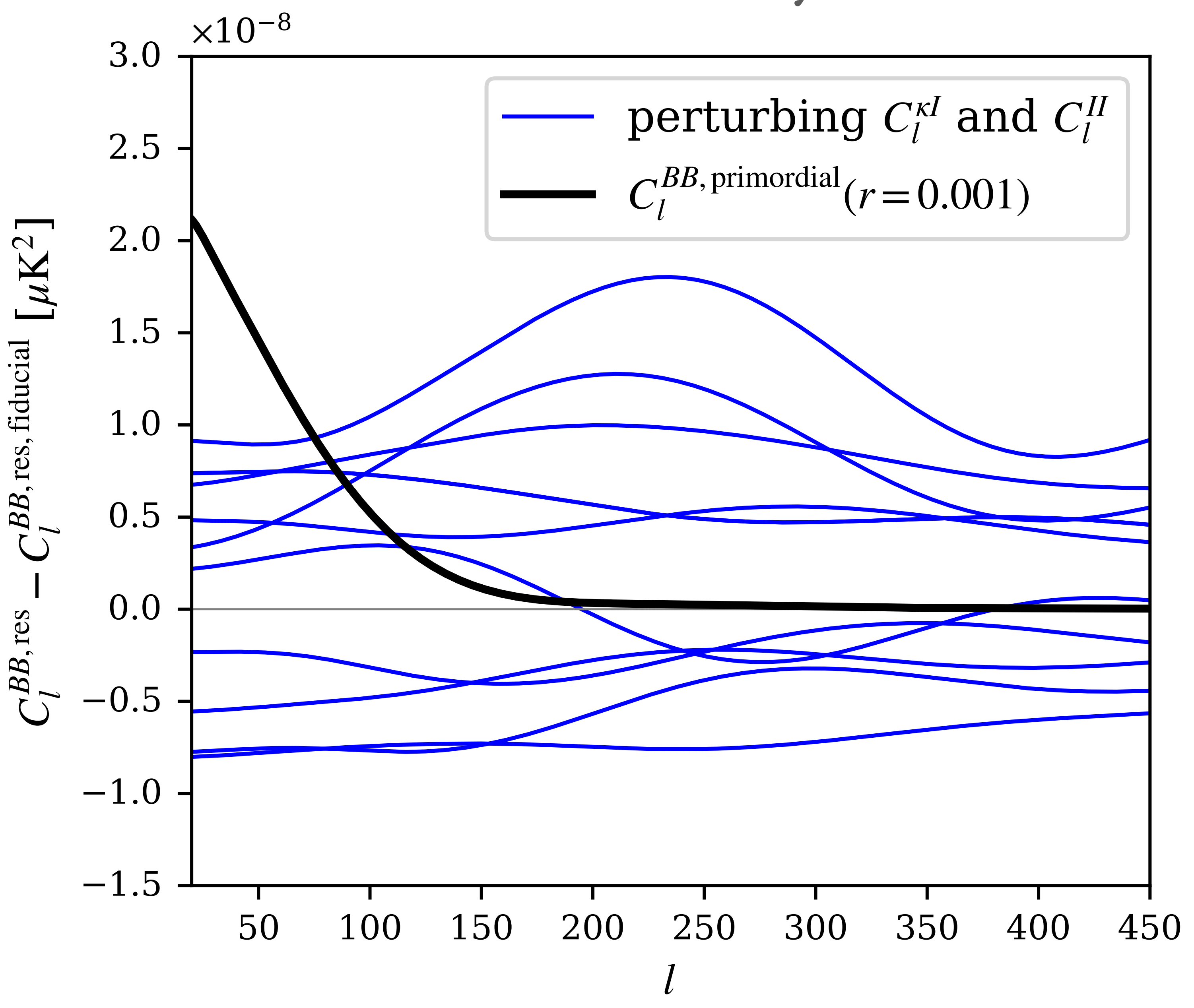
- Cancellations disappear if linear template is built from unlensed or delensed E-modes, hit delensing floor of O(10)%
- New cancellations arise when the lensed E-modes are used in the linear template, so delensing floor is O(1)%
- Advantage is lost when a non-perturbative template is built from lensed E-modes, so the delensing floor is also O(10)%

__ABL__, A. Challinor & J. Carron 20b arXiv:2010.14286

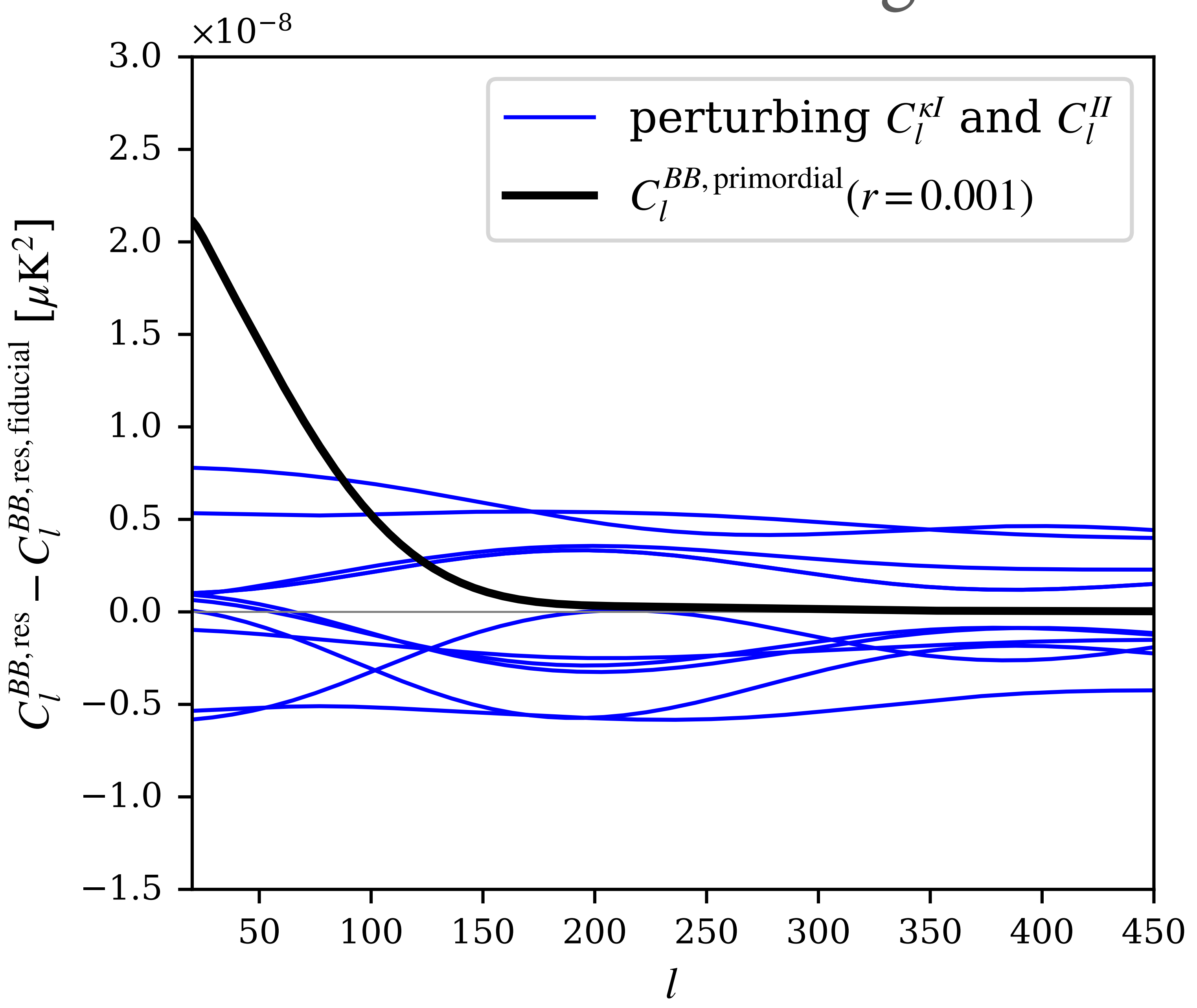
CHALLENGES TO MULTI-TRACER DELENSING

- Uncertainties in measurements of tracer auto- and cross- spectra:

CIB only



CIB + internal + galaxies



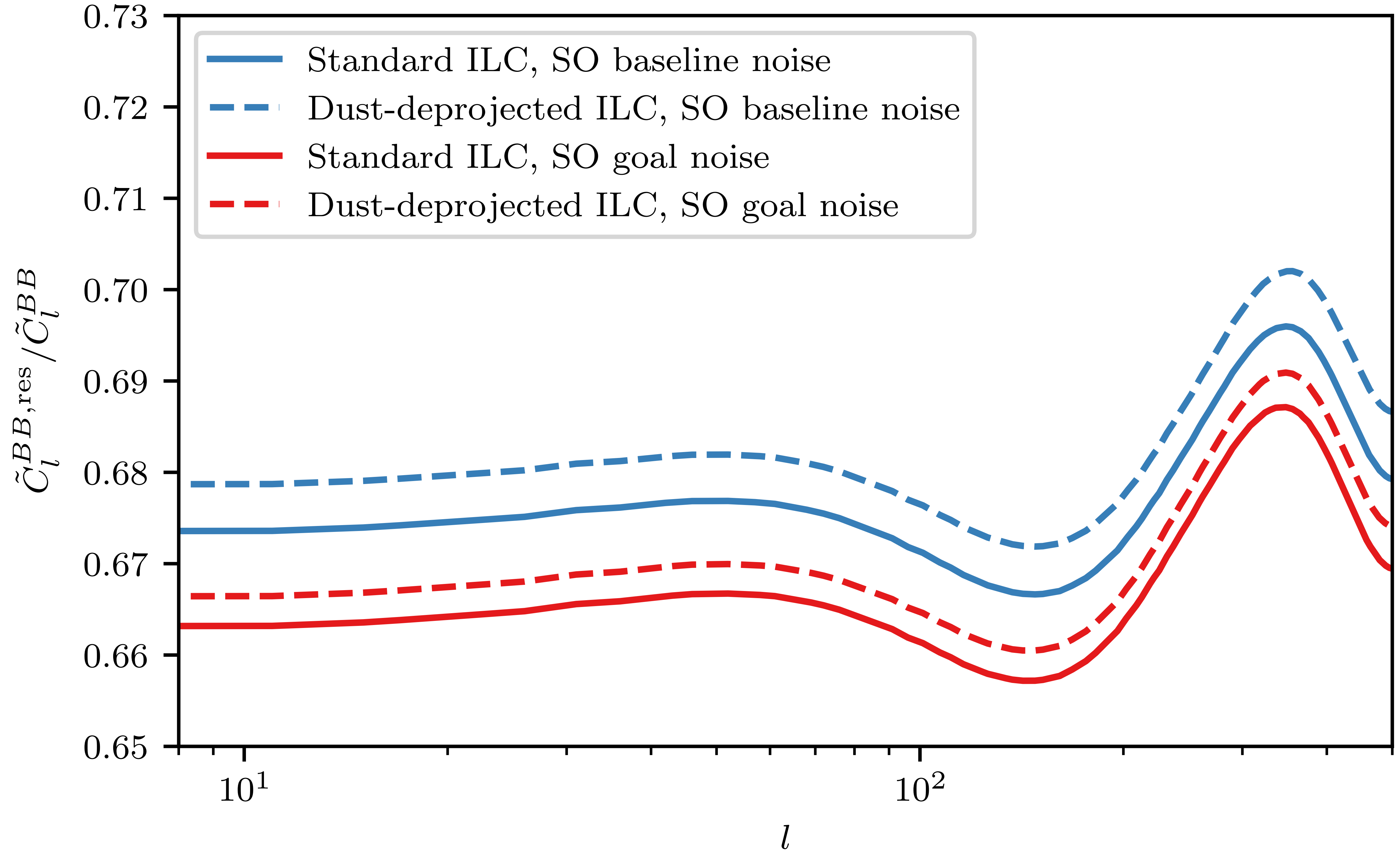
Flat enough to marginalise over amplitude parameter!

*T. Namikawa, **ABL**, N. Robertson, A Challinor, B. Sherwin & B. Yu 20 (to be submitted)*

- The impact of foregrounds

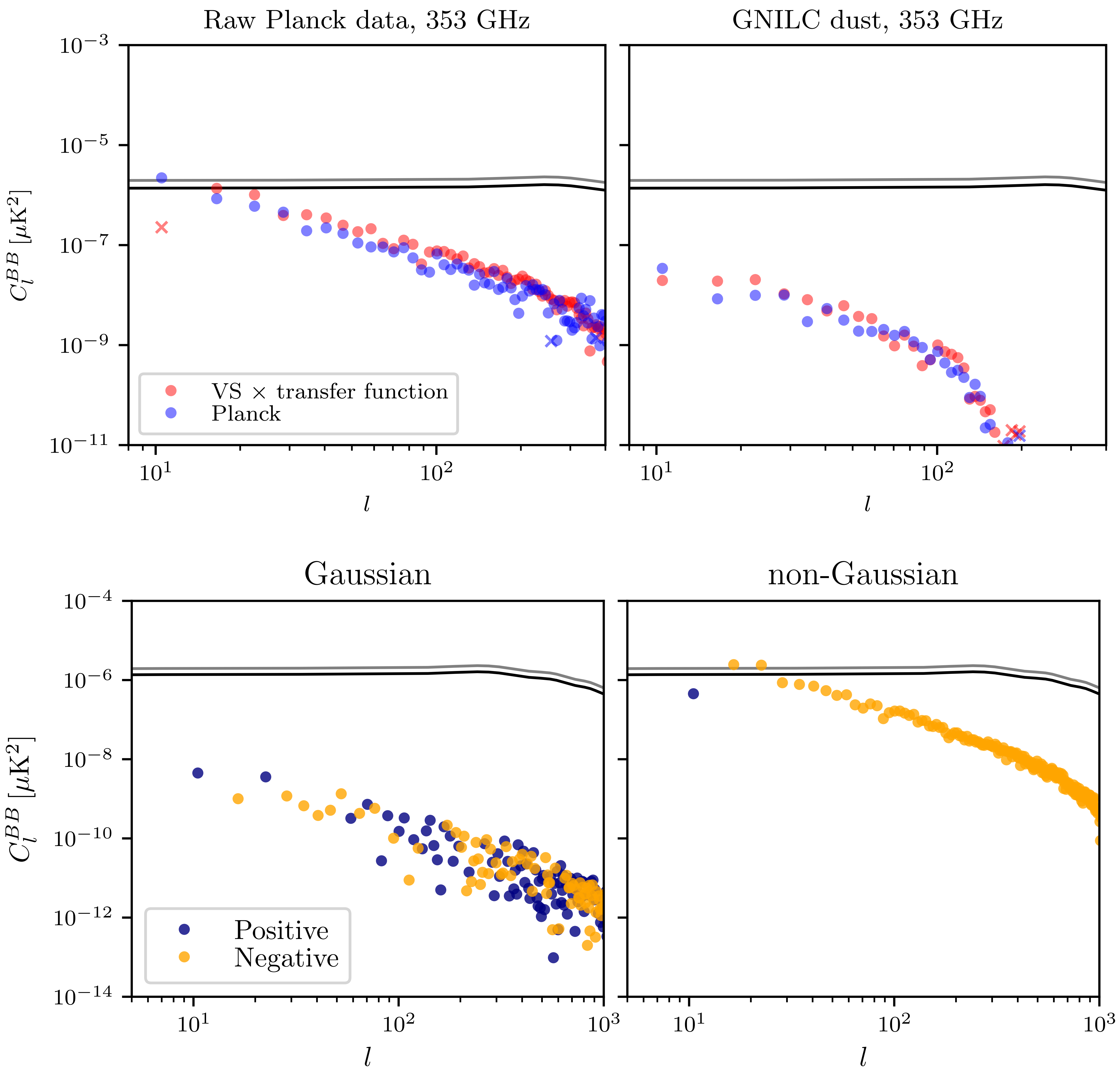
ADDITIONAL SLIDES

Small degradation in delensing efficiency from deprojecting dust from LAT E-modes



***ABL**, A. Challinor, B. Sherwin & T. Namikawa 20 (to be submitted)*

ADDITIONAL SLIDES



***ABL**, A. Challinor, B. Sherwin & T. Namikawa 20 (to be submitted)*