CMB LENSING & DELENSING FOR FUNDAMENTAL PHYSICS

THE GOOD, THE BAD & THE SYSTEMATICS

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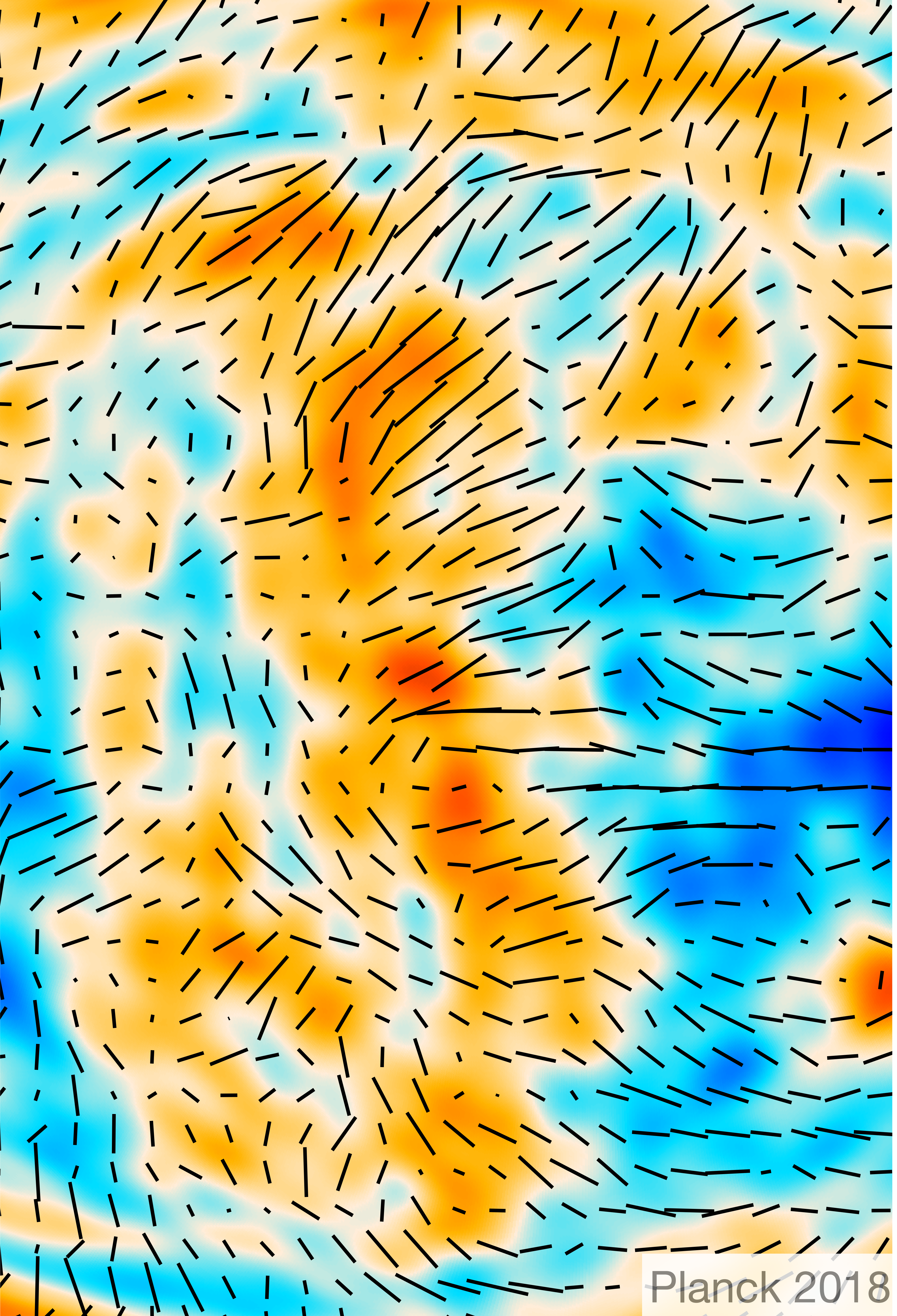
RPM colloquium & BCCP seminar, LBNL — 2/2/2021

OUTLINE

1. THE PRIMORDIAL & THE LENSED CMB →

2. CMB LENSING SPECTRA

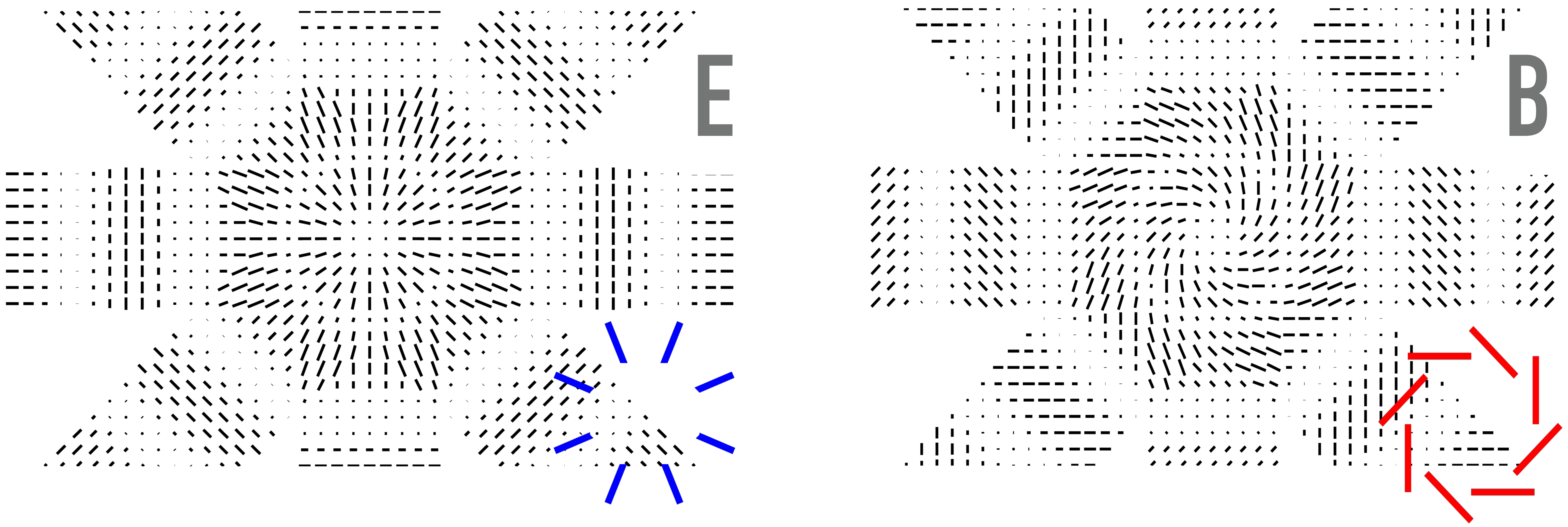
3. DELENSING CMB B-MODES



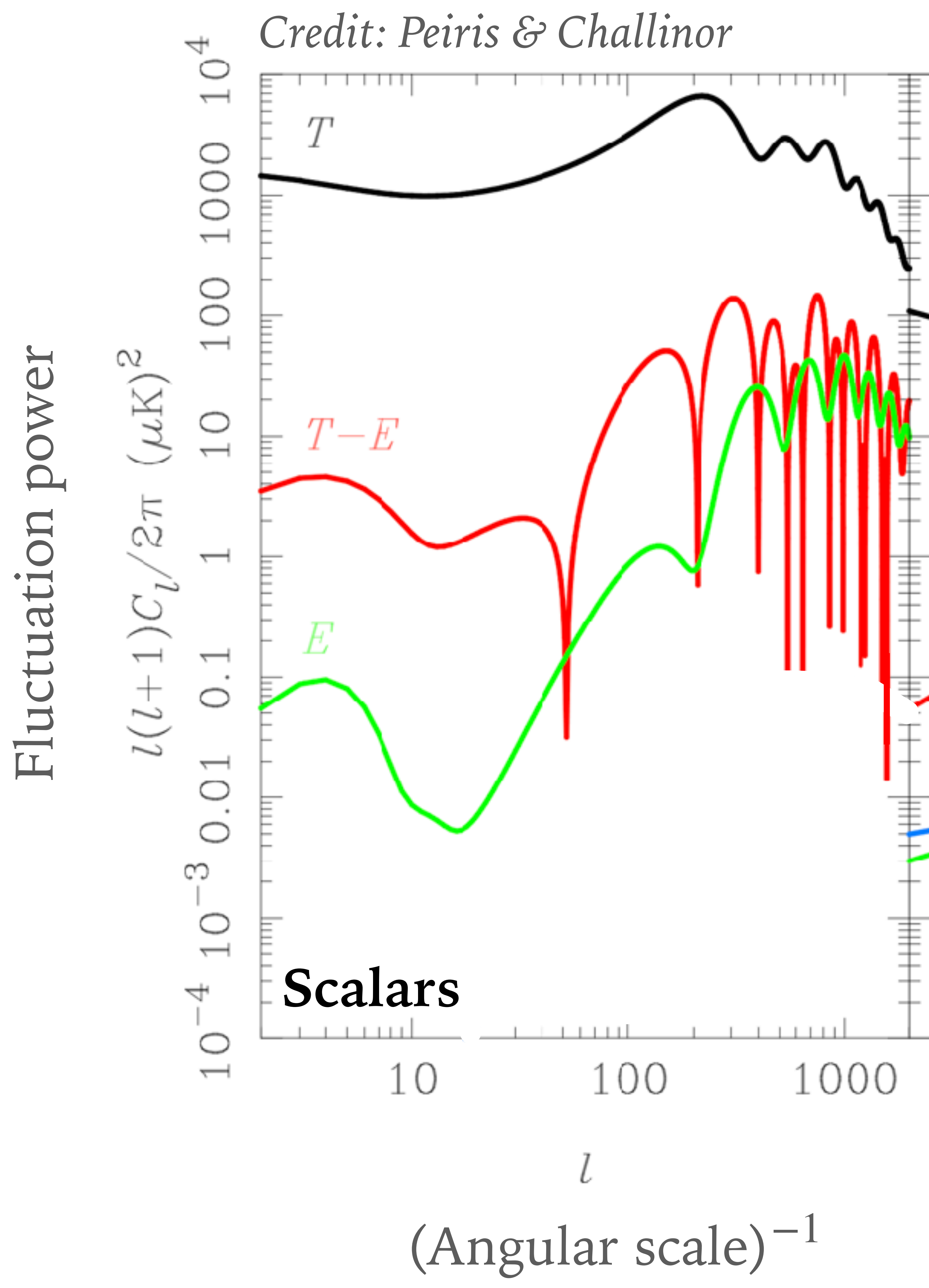
CMB OBSERVABLES — INTENSITY AND POLARISATION

Observe:

Connect with theory:



THE PRIMORDIAL CMB



- To leading order, B-modes sourced only by primordial gravitational waves

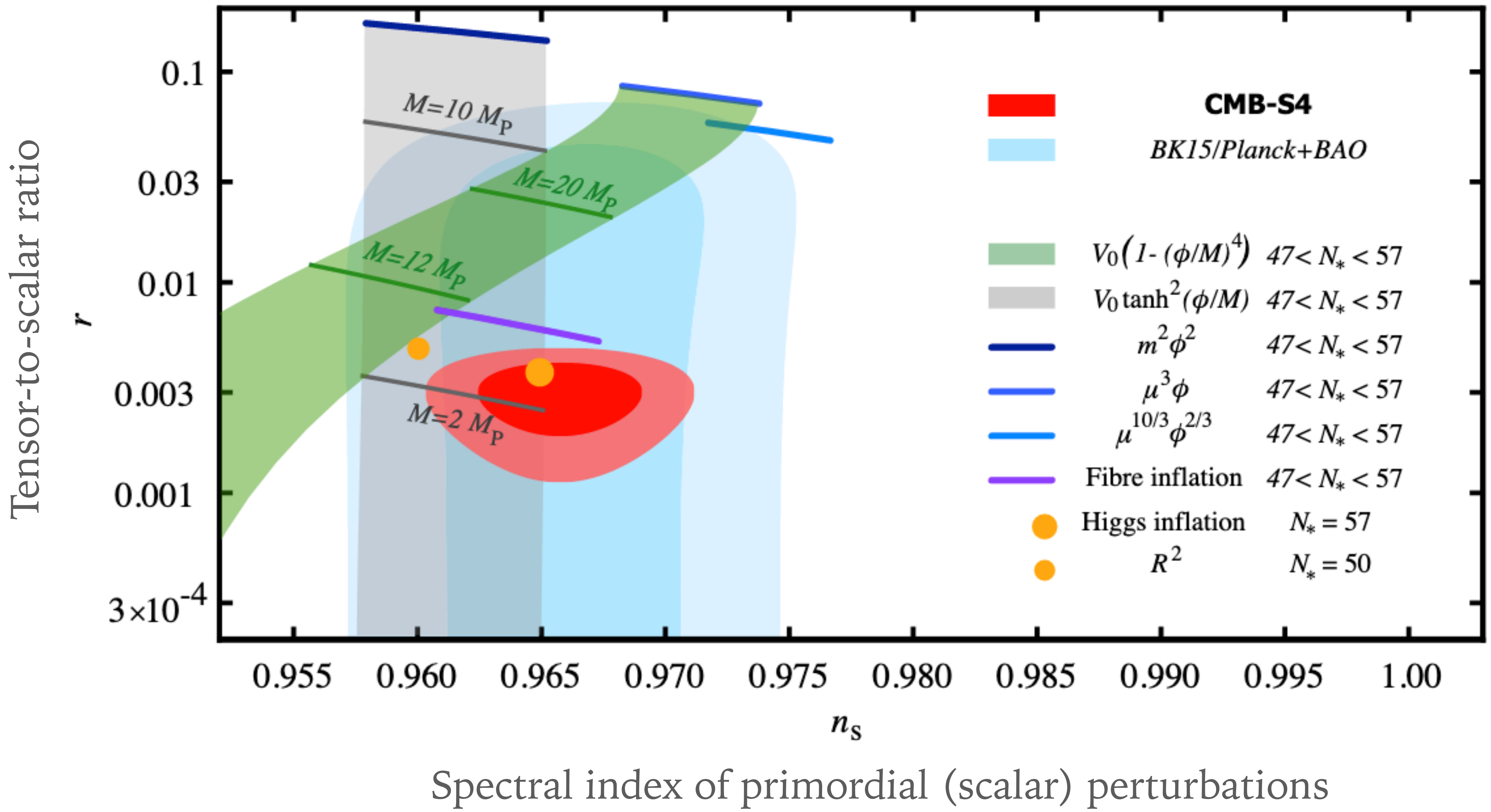
  Kamionkowski+ 97 , Seljak & Zaldarriaga 97

  $r < 0.044$ *Planck + BICEP/Keck*

- Statistically isotropic, Gaussian random field

CONSTRAINING INFLATION THROUGH THE CMB

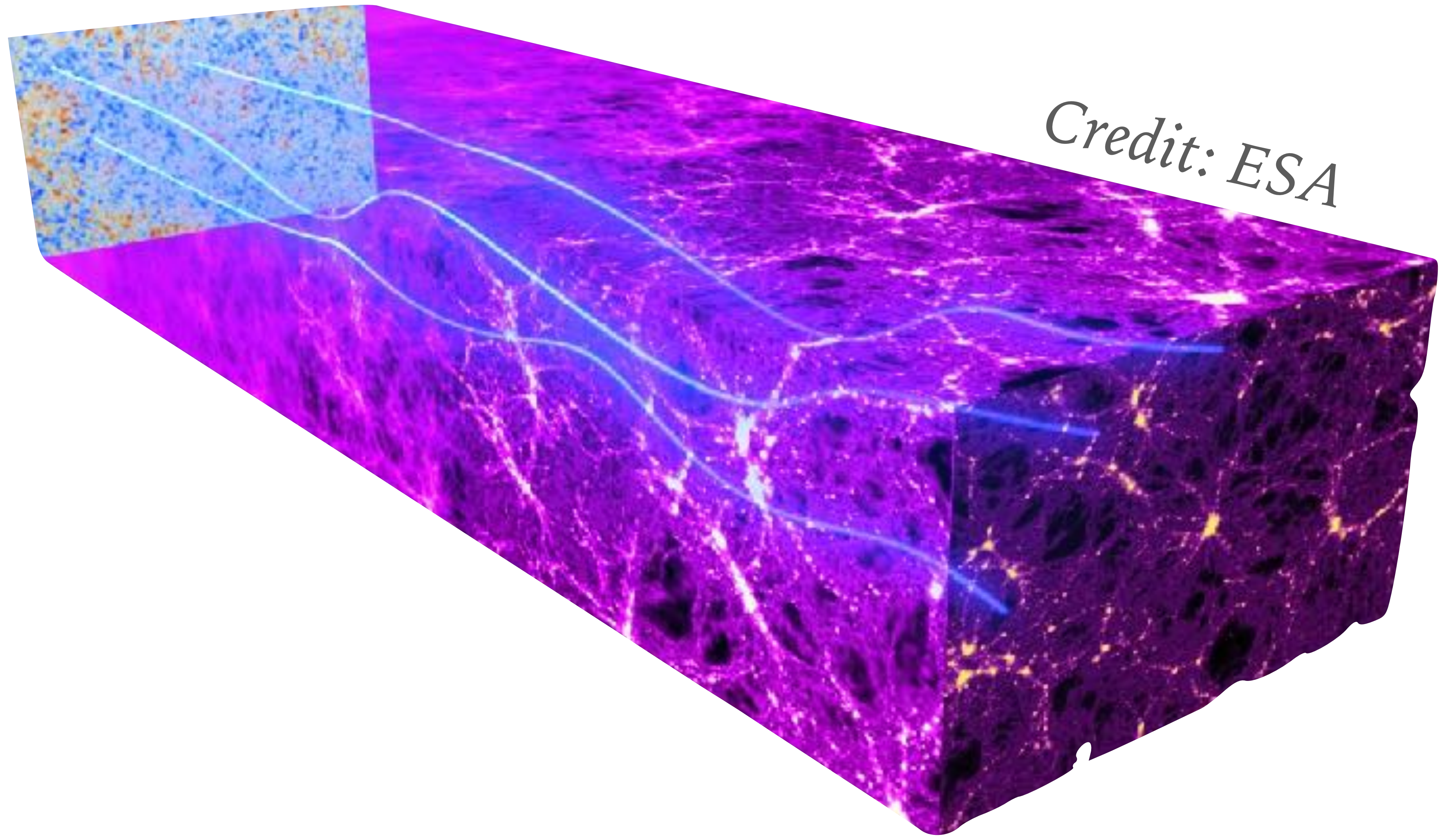
CMB-S4, arXiv:1907.04473



CMB LENSING

Very accurately described as:

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



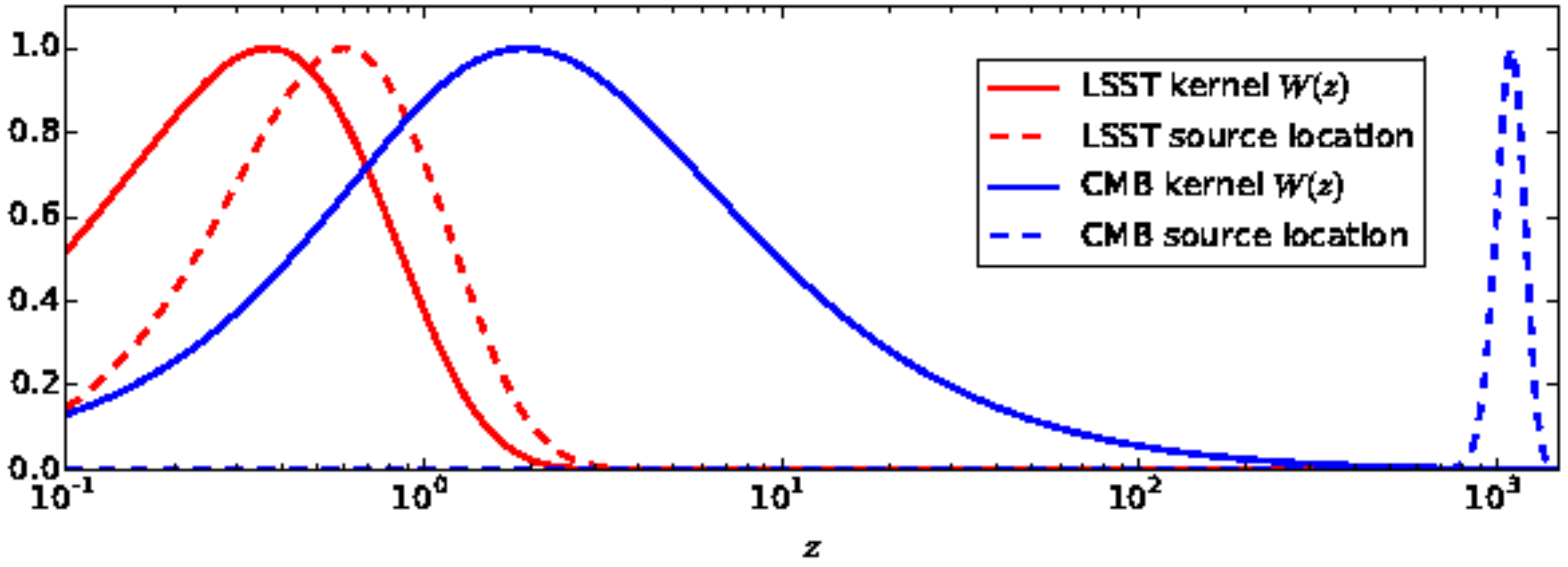
Under the Born approximation, $\alpha(\mathbf{x}) = \nabla\phi(\mathbf{x})$, where

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

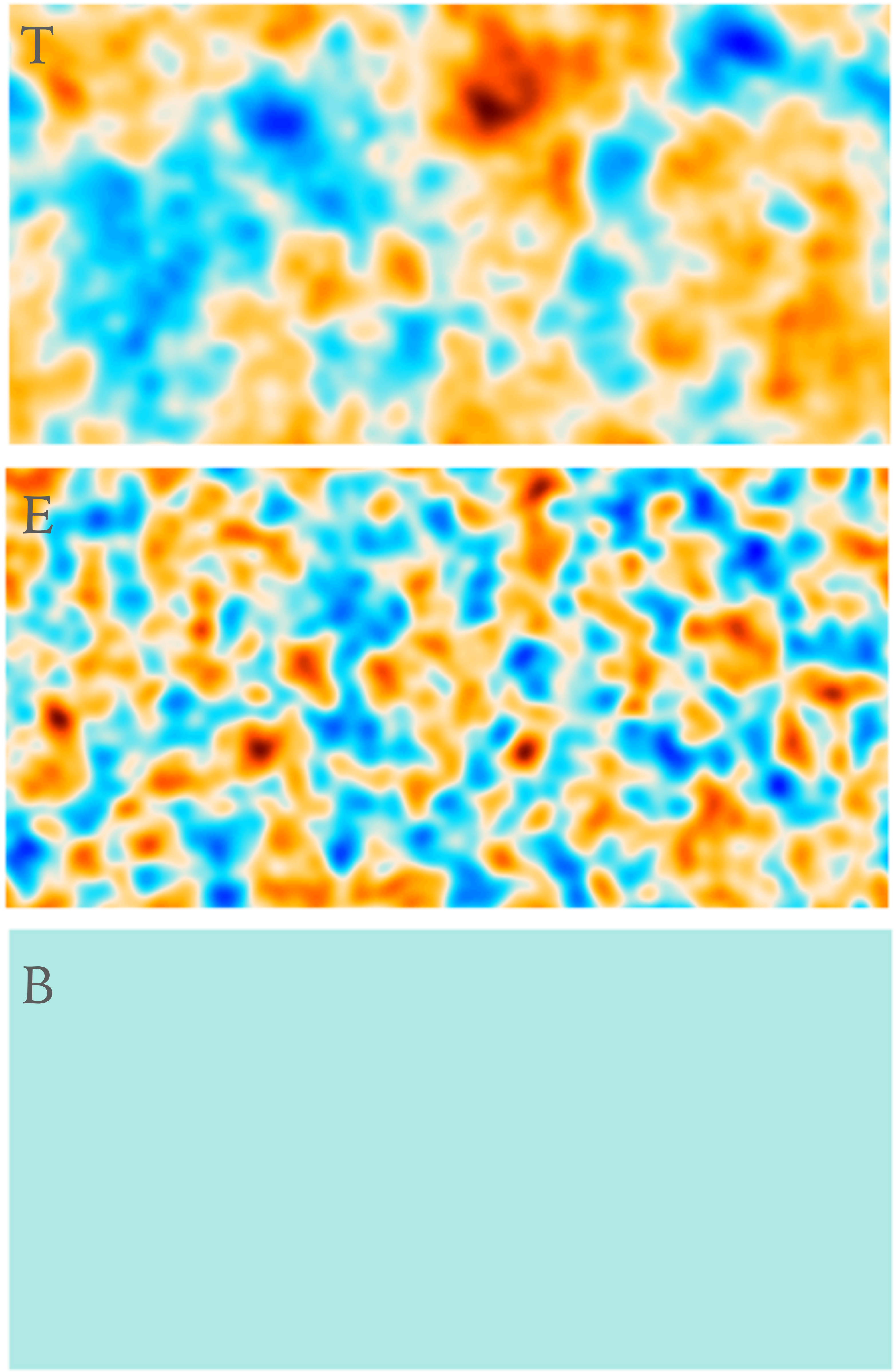
is related to $\kappa = -\frac{1}{2}\nabla^2\phi$.

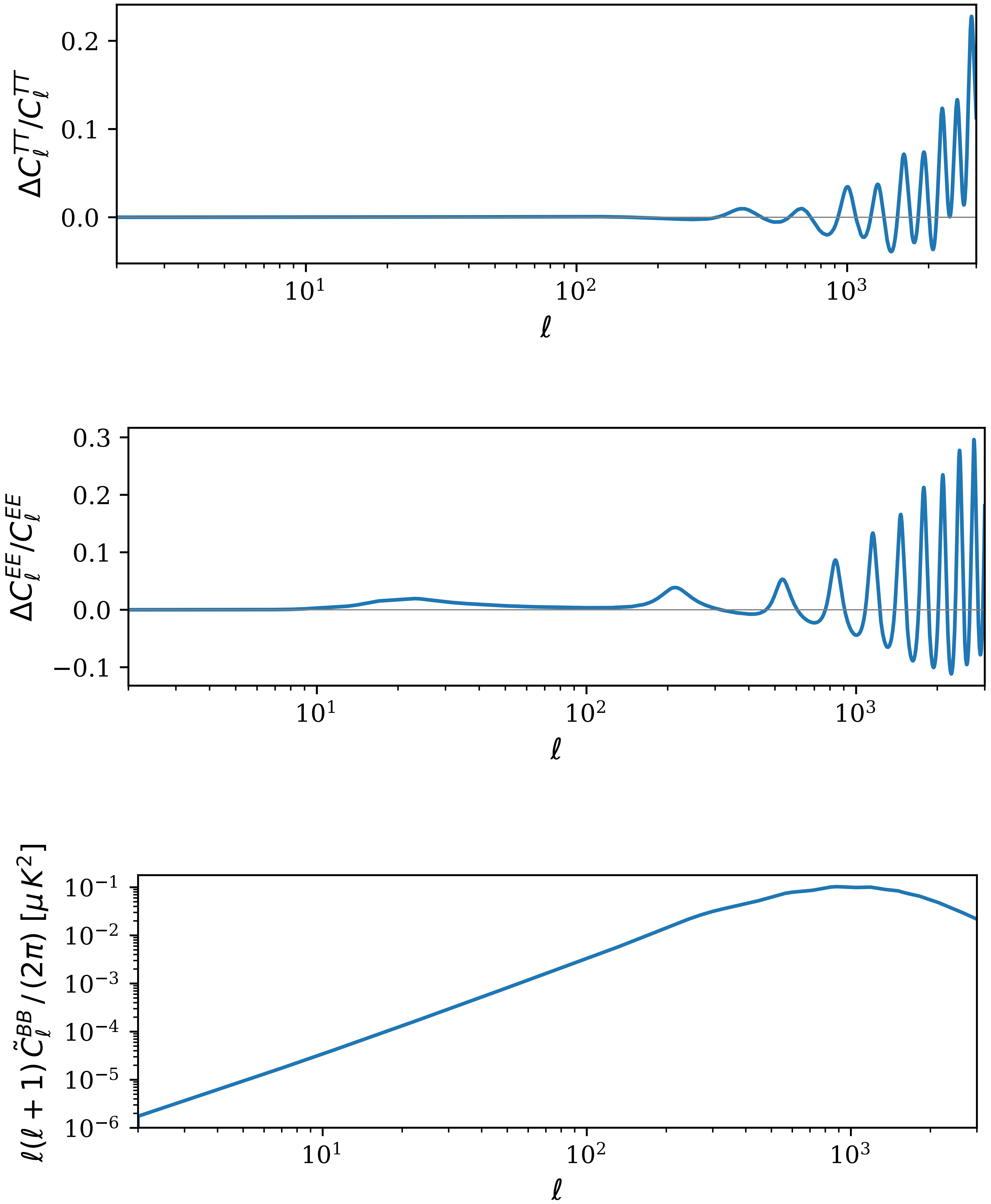
$\alpha \sim$ arcmin, coherent on degree scales (typical lens O(100Mpc))

CMB-S4 Science book



CMB LENSING


T
E
B


$\Delta C_\ell^{TT}/C_\ell^{TT}$
0.2
0.1
0.0
10^1
10^2
10^3
ℓ
$\Delta C_\ell^{EE}/C_\ell^{EE}$
0.3
0.2
0.1
0.0
−0.1
10^1
10^2
10^3
ℓ
$\ell(\ell+1)\,\tilde{C}_\ell^{BB}\,/\,(2\pi)\ [\mu K^2]$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^1
10^2
10^3
ℓ

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:

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

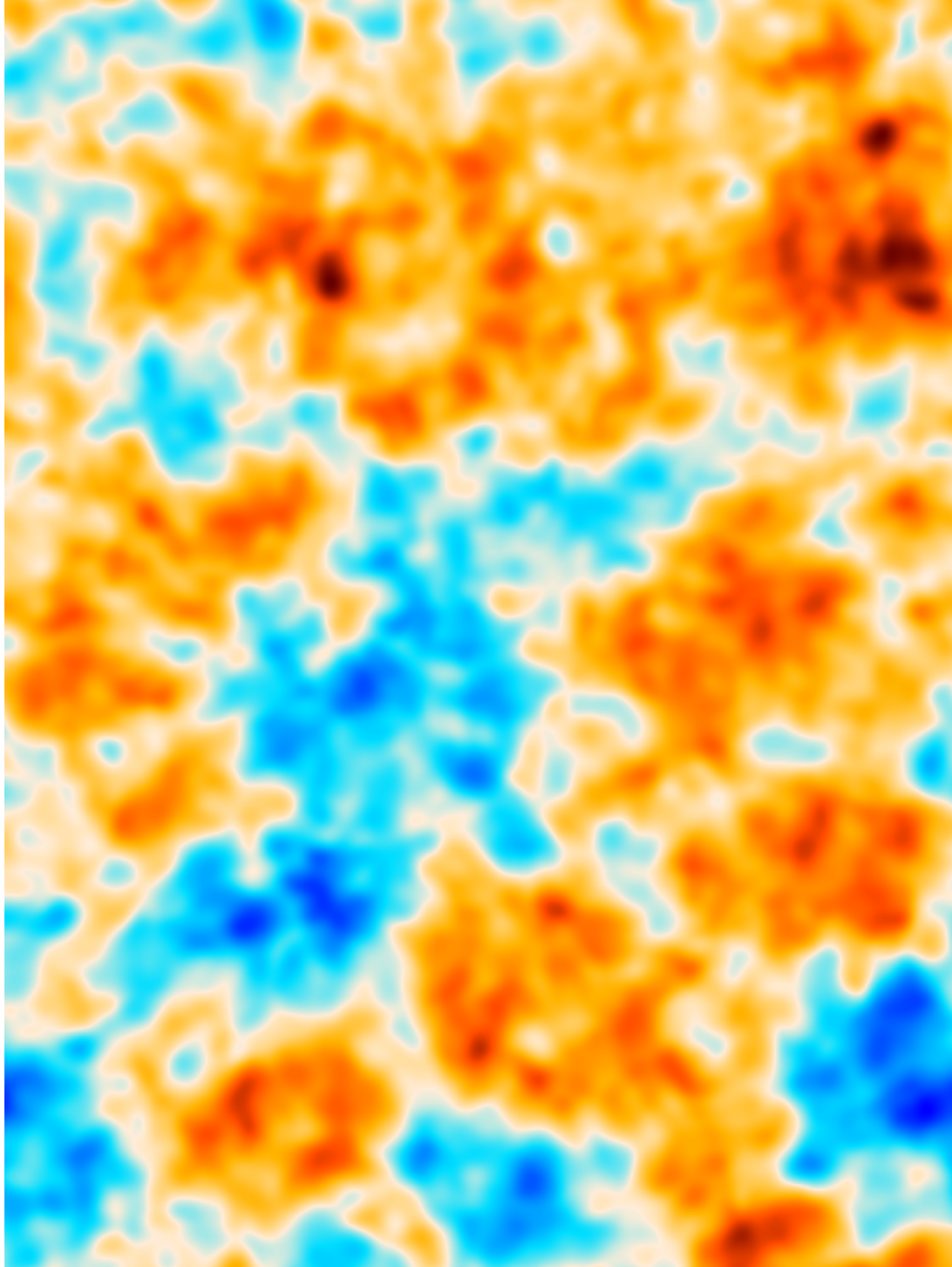
In practice, off-diagonal correlations probe the lensing potential. The **quadratic estimator:**

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

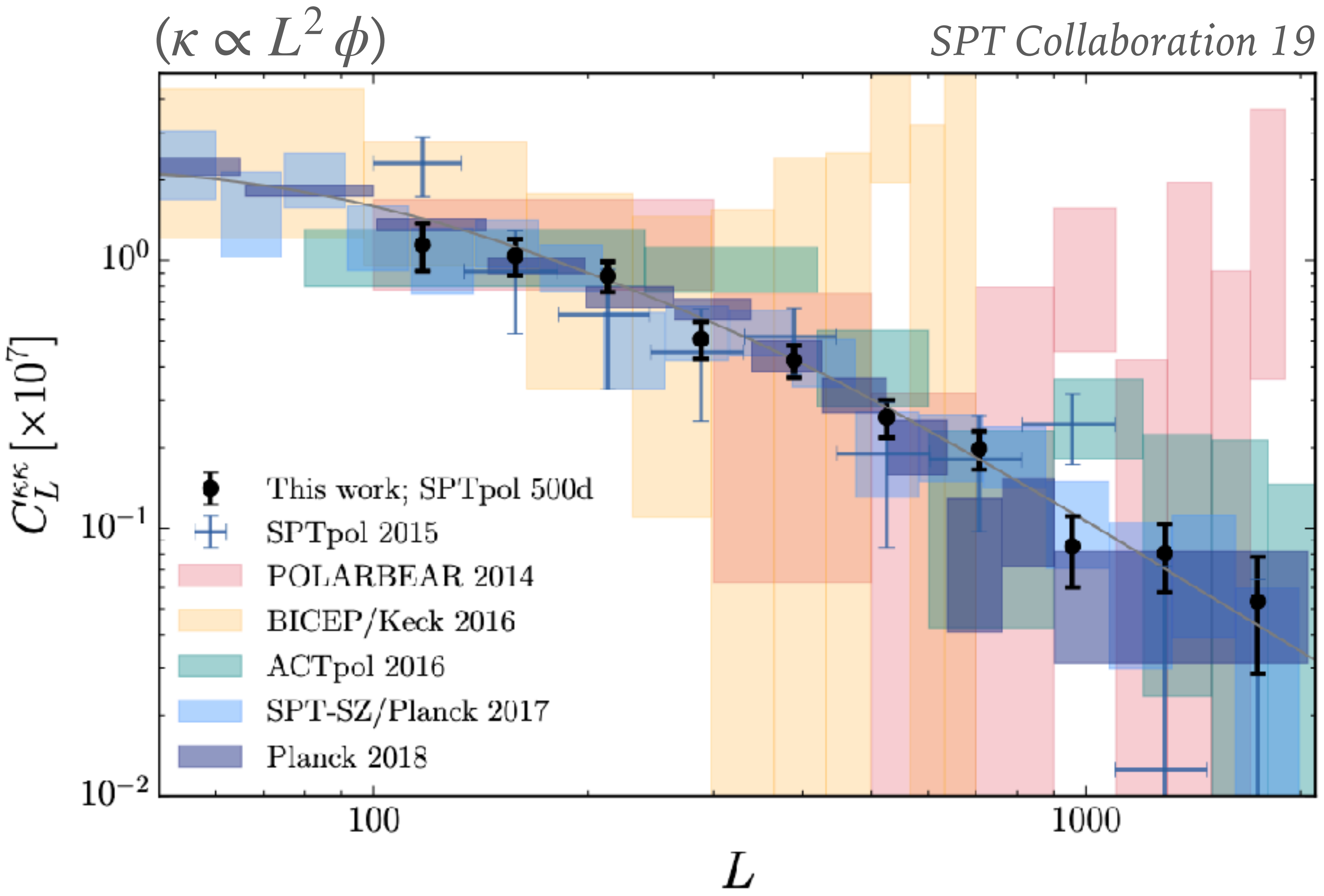
Hu & Okamoto 01

Much more information in the polarization (particularly in small-scale B-modes).

CMB LENSING SPECTRA



CMB LENSING SPECTRA



Breaks degeneracy among late-time Physics in primary CMB

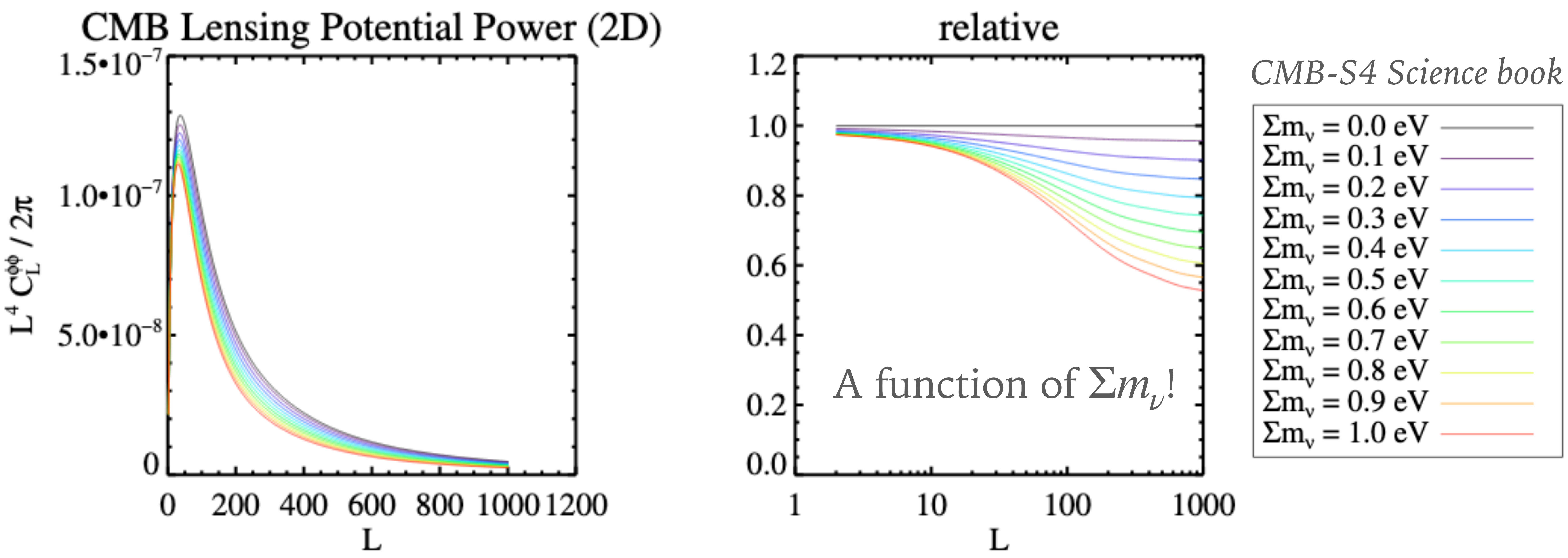
Auto- and cross-correlations probe geometry, neutrino masses, dark energy ++

Cross-correlations useful to calibrate photo-z’s and weak lensing shear estimators

Vallinoto 11, Das+14, Schaan+ 17, …

CMB LENSING CONSTRAINTS OF NEUTRINO MASSES

Massive ν's cause suppression of power on small scales relative to large scales



SO + DESI

SO forecasts 19

$\sigma(\Sigma m_\nu) \approx 31 - 33\,\mathrm{meV}$ (with current τ prior)

$\sigma(\Sigma m_\nu) \approx 17 - 22\,\mathrm{meV}$ (with CLASS/LiteBird τ prior) ⟶ Guaranteed detection! ($\Sigma m_\nu > 60\,\mathrm{meV}$)

Cross-correlations show great promise (also for $\sigma_8, f_{\rm nl}$, +) — can partially get around τ prior

Schmittfull & Seljak 18, Yu+ 18, Wilson & White 19

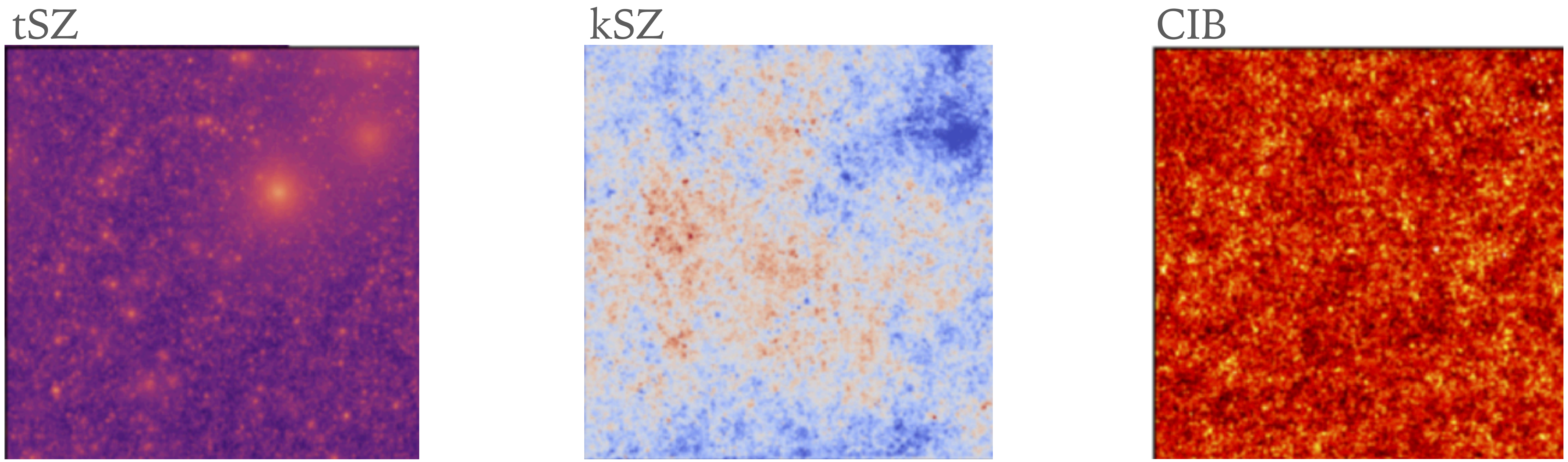
LENSING POWER SPECTRUM MEASUREMENTS

- ✓ Modeling: very easy — little non-linearities, negligible baryonic effects, no galaxy bias
- ✓ Foregrounds: **polarization**-based reconstructions very robust

⚠ **Temperature** reconstructions still important for Stage-2 & 3 CMB (AdvACT, Simons Array, SO…)

In intensity, microwave sky contaminated by non-Gaussian extragalactic sources: tSZ, kSZ, CIB

Van Engelen+14, Osborne+14, Ferraro & Hill 18



Adapted from WebSky

BIASES TO LENSING SPECTRA FROM EXTRAGALACTIC FOREGROUNDS

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

Lensing — Foreground (correlated with ϕ)

Can bias lensing reconstruction power spectrum

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

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

and cross-correlations with low-z matter tracers

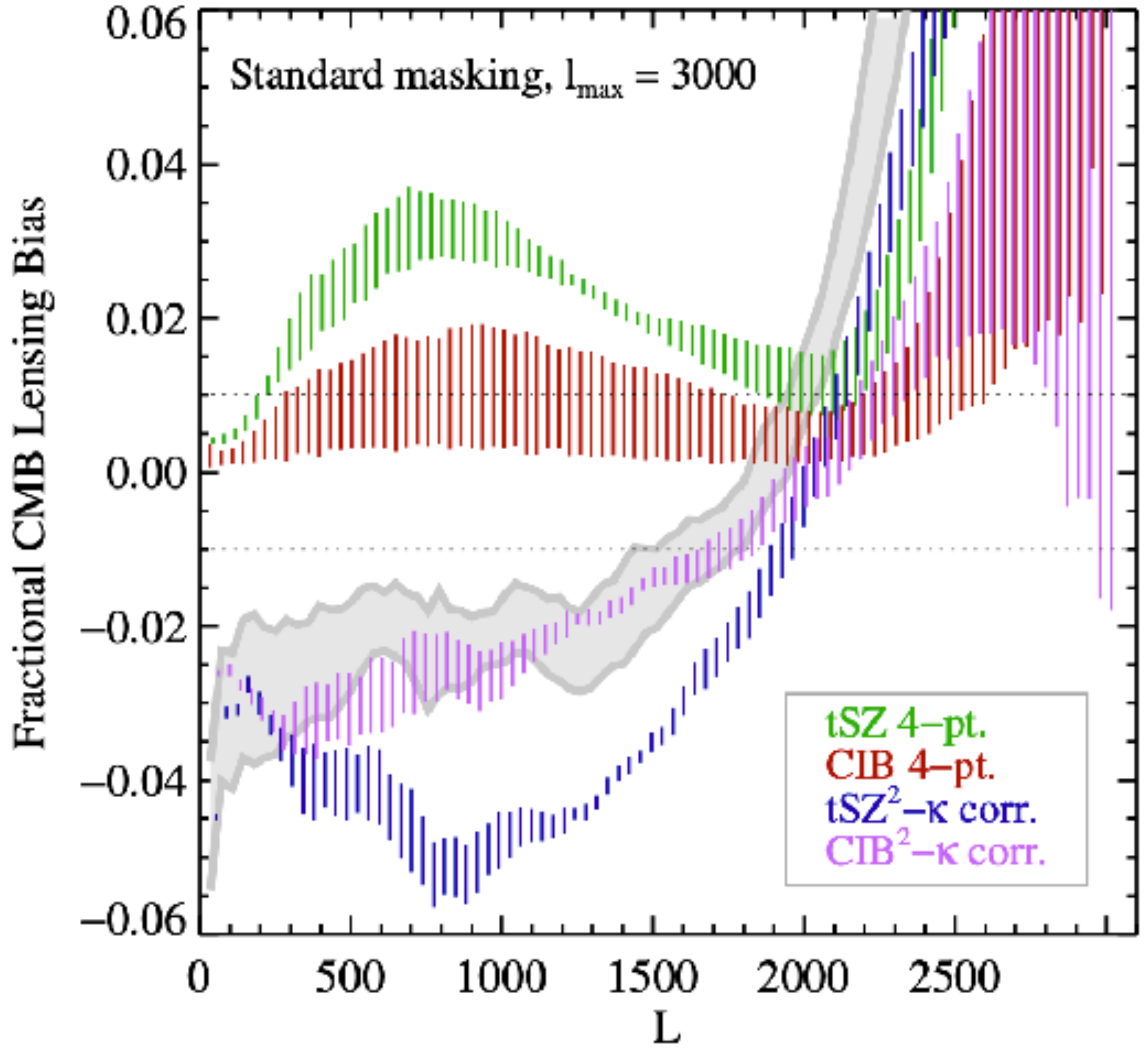
$$\langle g[\phi]\, \hat{\phi} \rangle = \langle g[\phi]\, \hat{\phi}[\tilde{T}, \tilde{T}] \rangle + \langle g[\phi]\, \hat{\phi}[s, s] \rangle$$

"Bispectrum bias"

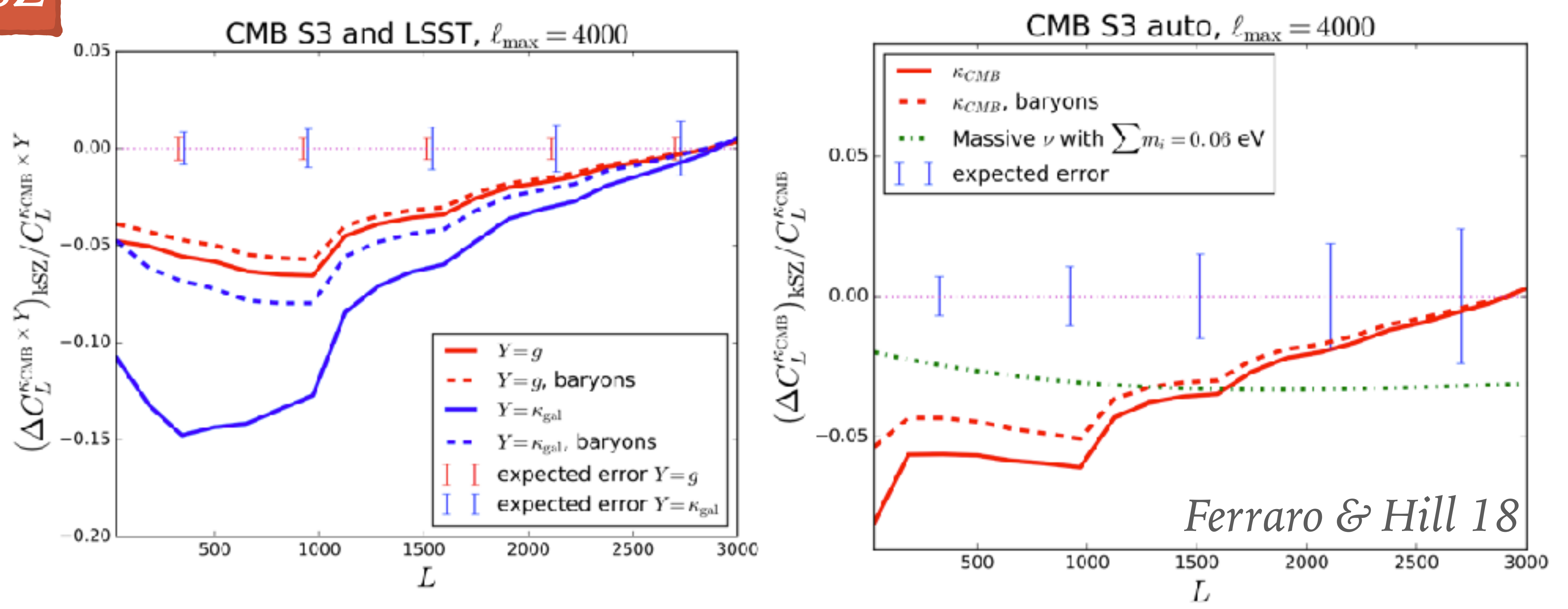
BIASES TO LENSING SPECTRA FROM EXTRAGALACTIC FOREGROUNDS

tSZ & CIB

Van Engelen et al. 14



kSZ



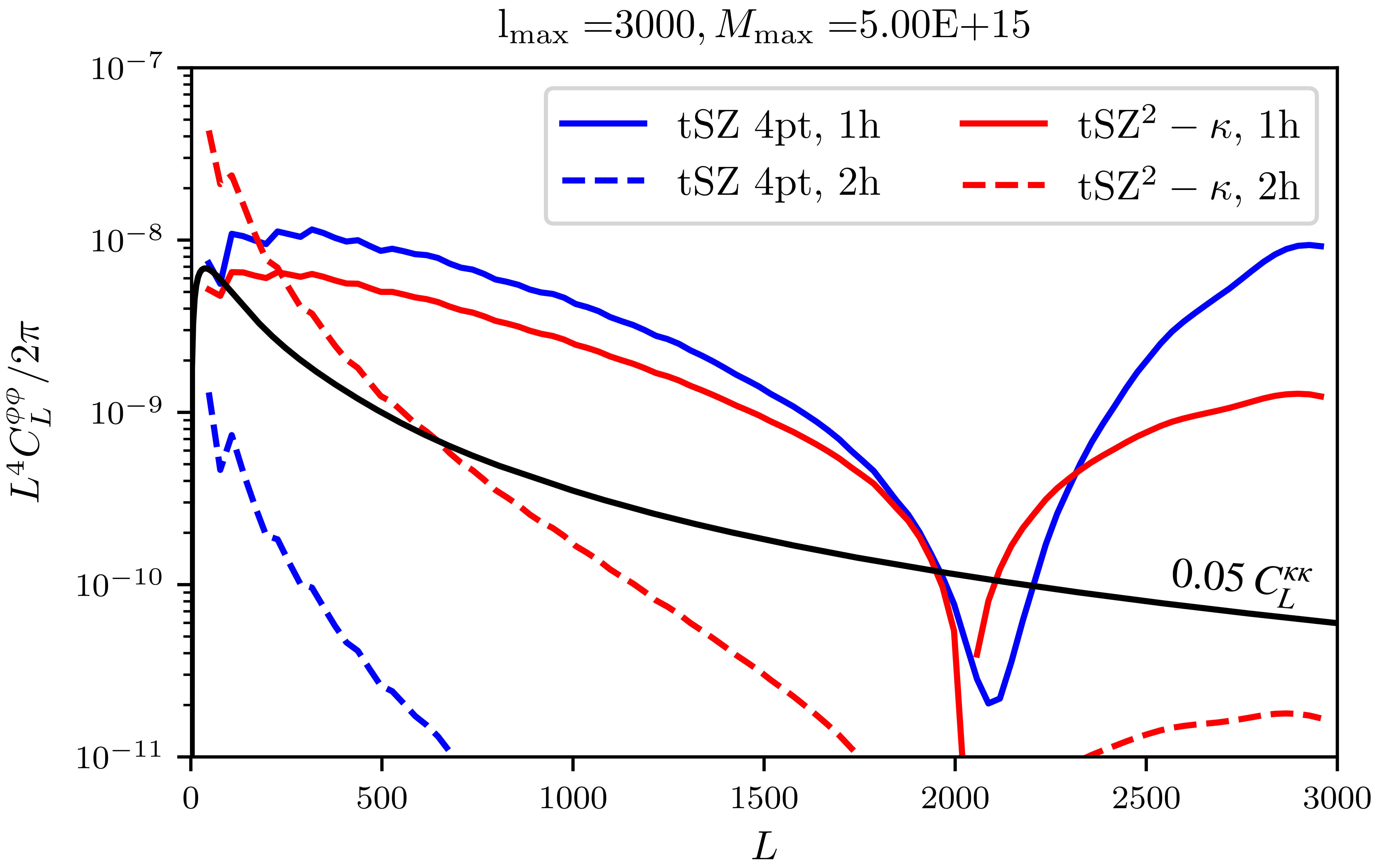
Ferraro & Hill 18

- Impedes reconstruction of lensing from small scales, i.e., sets l_{max}

- Multi-frequency cleaning helps to some extent
- Mitigation techniques:
  - Simulations *Van Engelen+ 14*
  - Bias hardening *Namikawa+13, Osborne+14 Sailer+ 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



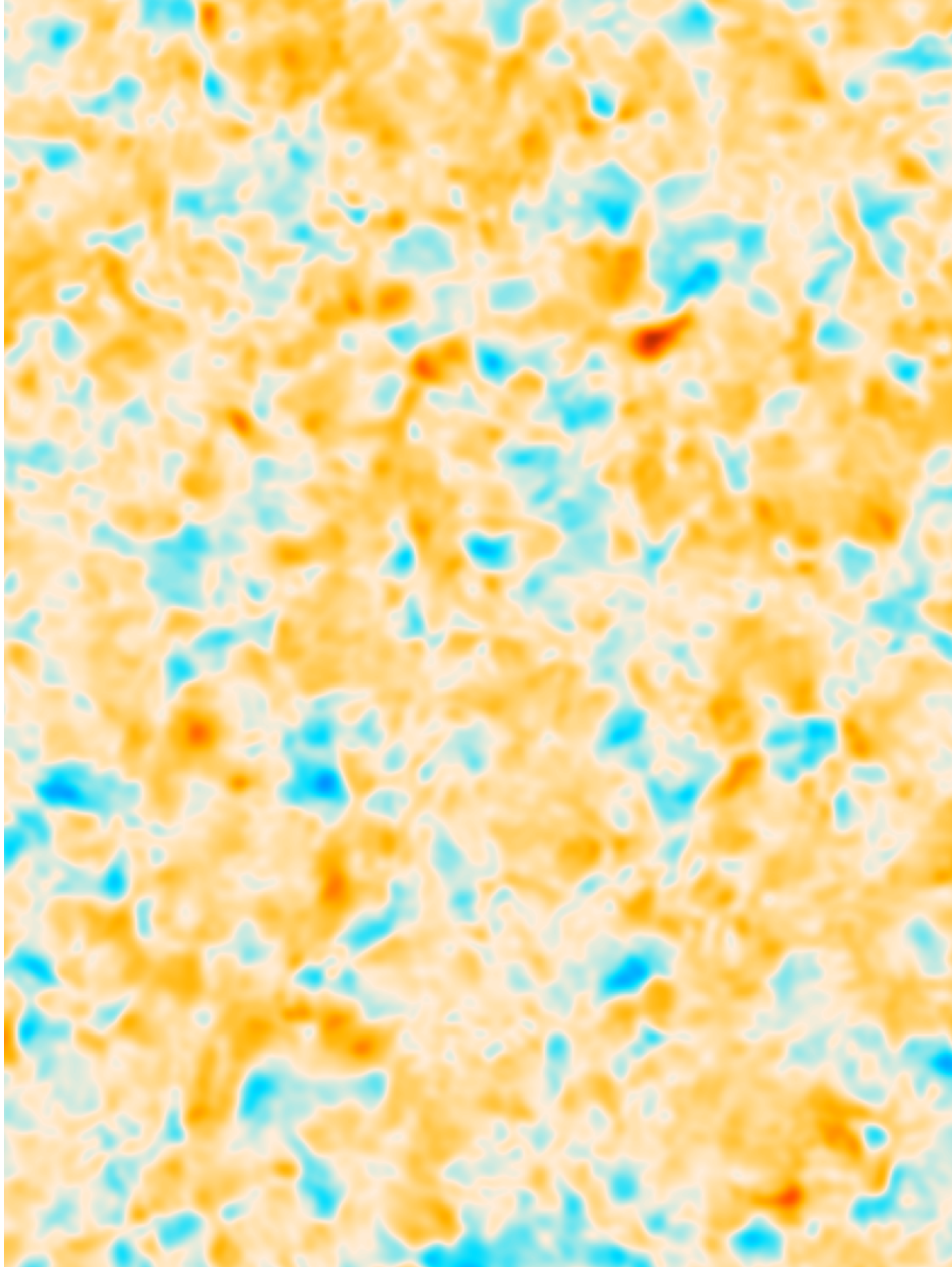
(Example: subset of tSZ biases for an SPT-like experiment)

Preliminary

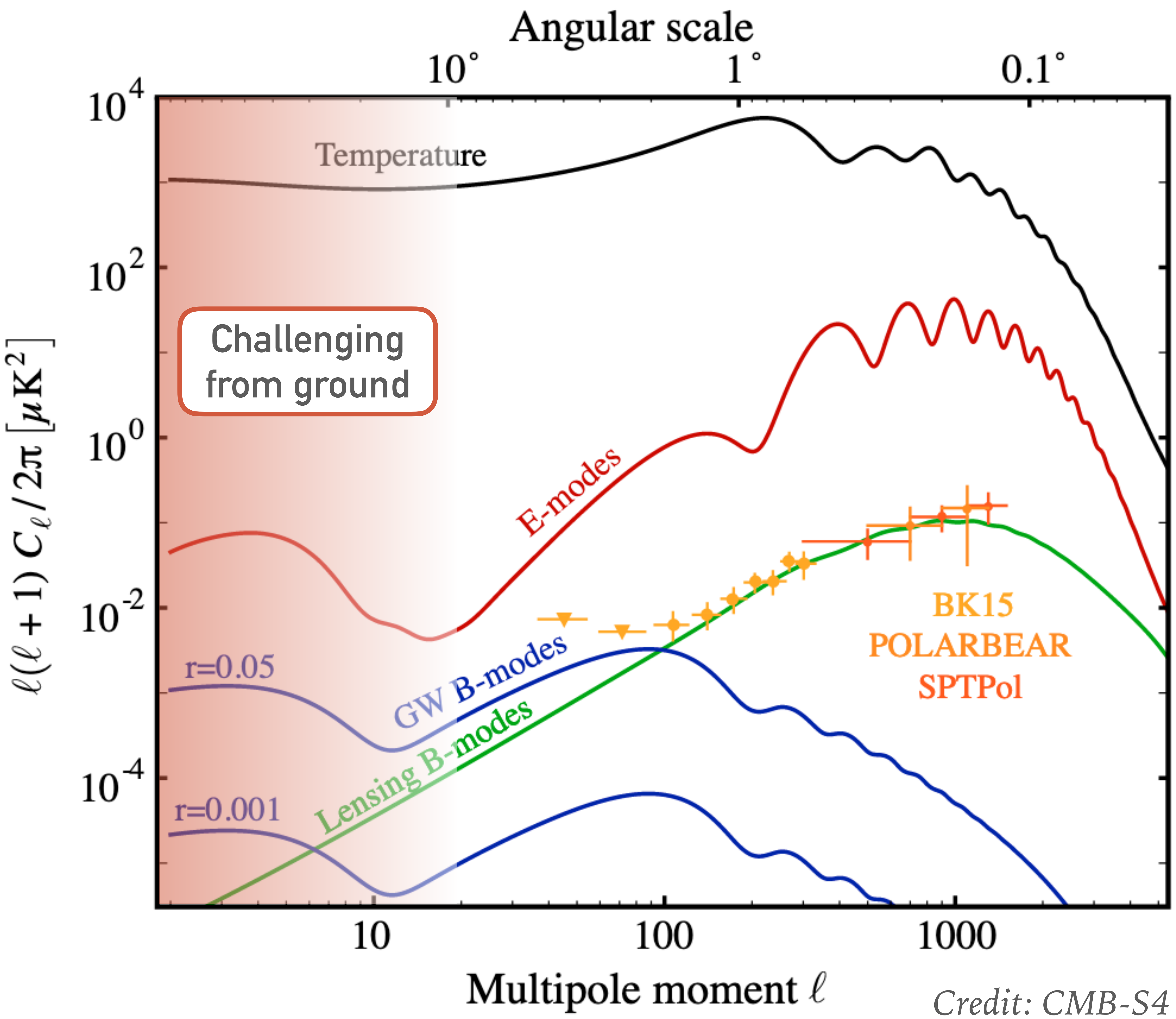
- **Very fast, 1D method**. Lensing reconstructions done **using FFTlog** (for fast, discrete Hankel transforms), taking O(10ms) per lensing reconstruction on a single laptop core.
- Can calculate biases and associated uncertainties
- Perhaps we could use QE down to smaller scales and correct bias at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

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

DELENSING B-MODES



THE LENSING B-MODE

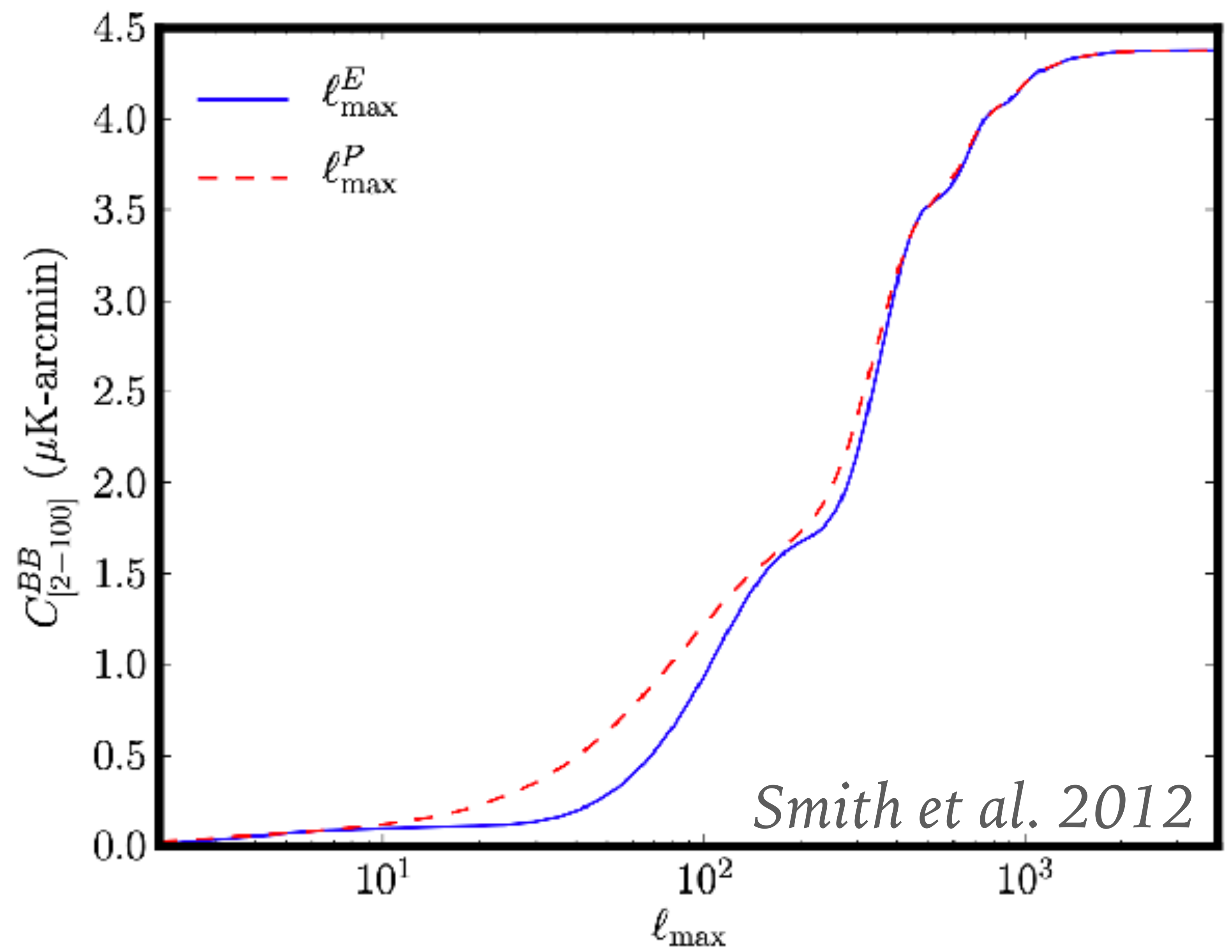


Credit: CMB-S4

Lensing converts E- into B-modes, inducing noise with $\Delta_P \approx 5\mu K$ arcmin

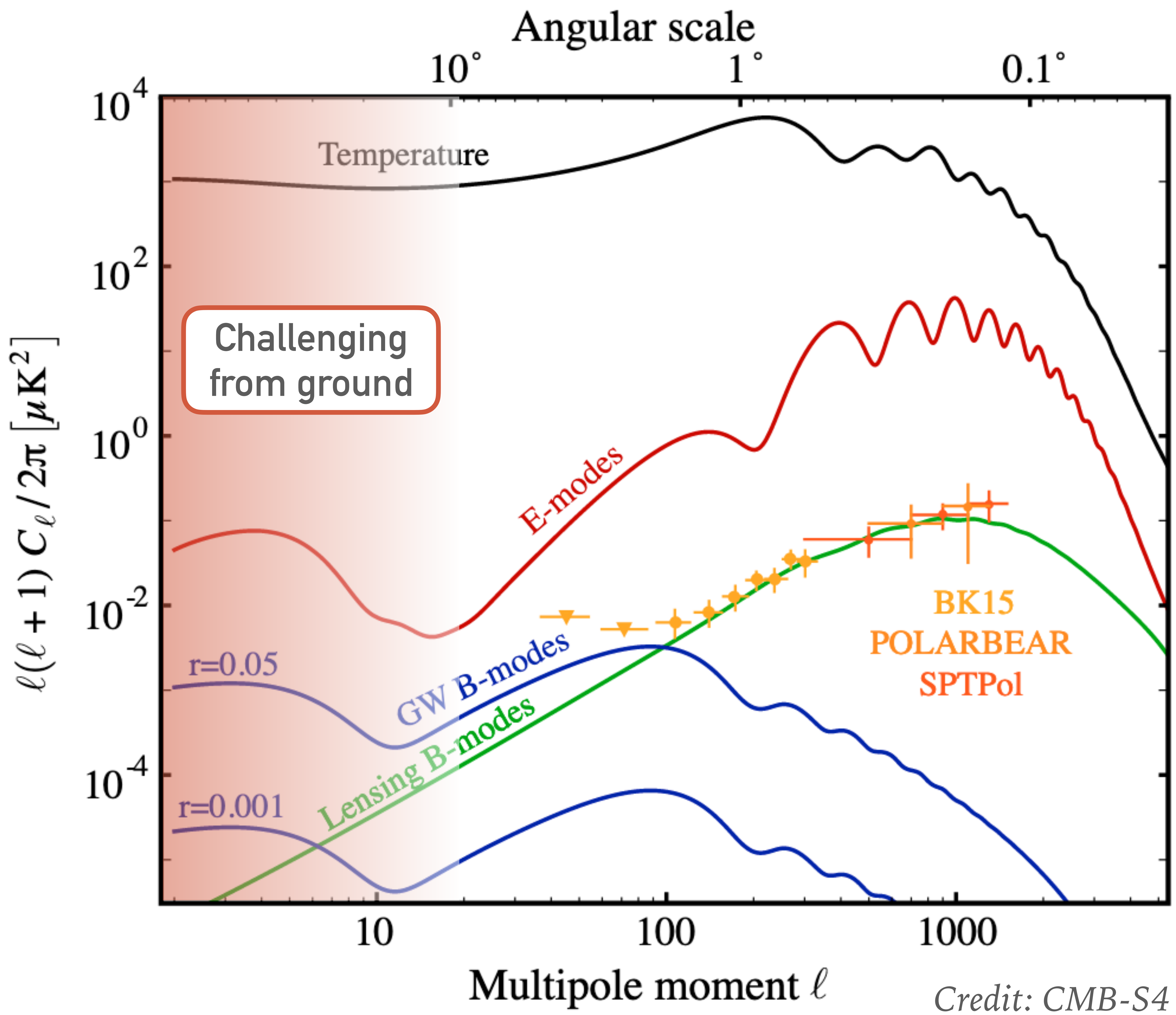
Zaldarriaga & Seljak 98

Why does it look like white noise?



Smith et al. 2012

THE LENSING B-MODE



Credit: CMB-S4

Lensing converts E- into B-modes, inducing noise with $\Delta_P \approx 5\mu K$ arcmin

Zaldarriaga & Seljak 98

$\sigma(r) \propto C_l^{BB} + N_l^{BB}$

- Primordial
- Foregrounds
- **Lensing**

For CMB-S4, delensing improves $\sigma(r)$ by $\times 5$ or more

B-MODE DELENSING

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

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

Challenge: r goals require measuring both

- **large** (degree) angular scale B-modes, where primordial signal peaks
- **intermediate & small** scale lenses and E-modes, to delens those B-modes

Small
Aperture
Telescope

(SAT)

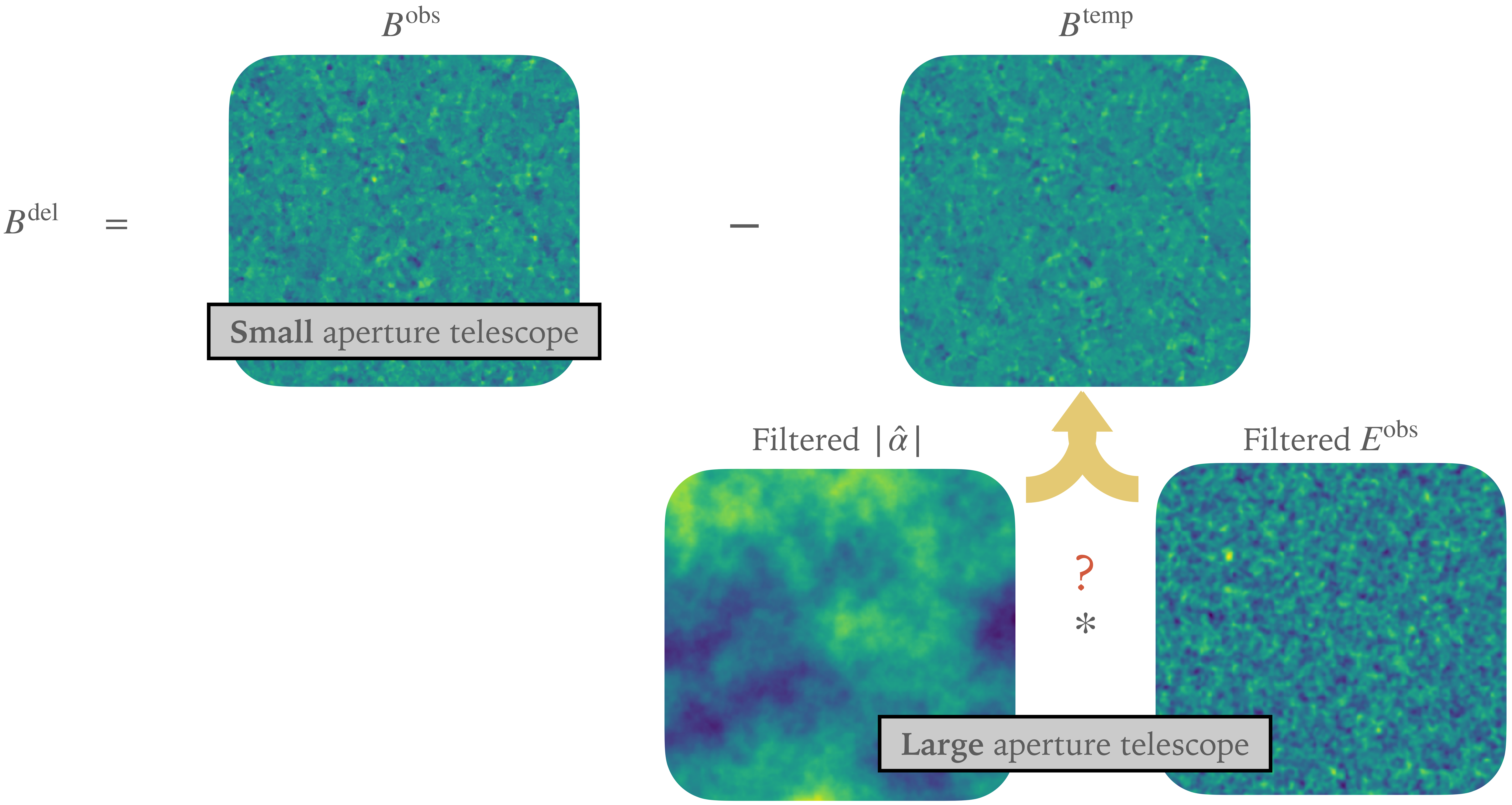
e.g., BICEP/Keck, SO SATs, CLASS, ABS, QUBIC…

Large
Aperture
Telescope

(LAT)

e.g., SPT, ACT, SO LAT, POLARBEAR/SA

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

$$\tilde{B} \quad = \quad E \circledast \phi \quad + \quad O(\phi^2) \quad + \quad \cdots$$

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

$$B^{\rm temp} \quad = \quad \bar{E}^{\rm obs} \circledast \hat{\bar{\phi}} \,. \qquad\qquad \textit{e.g., SPT 17}$$

Why?

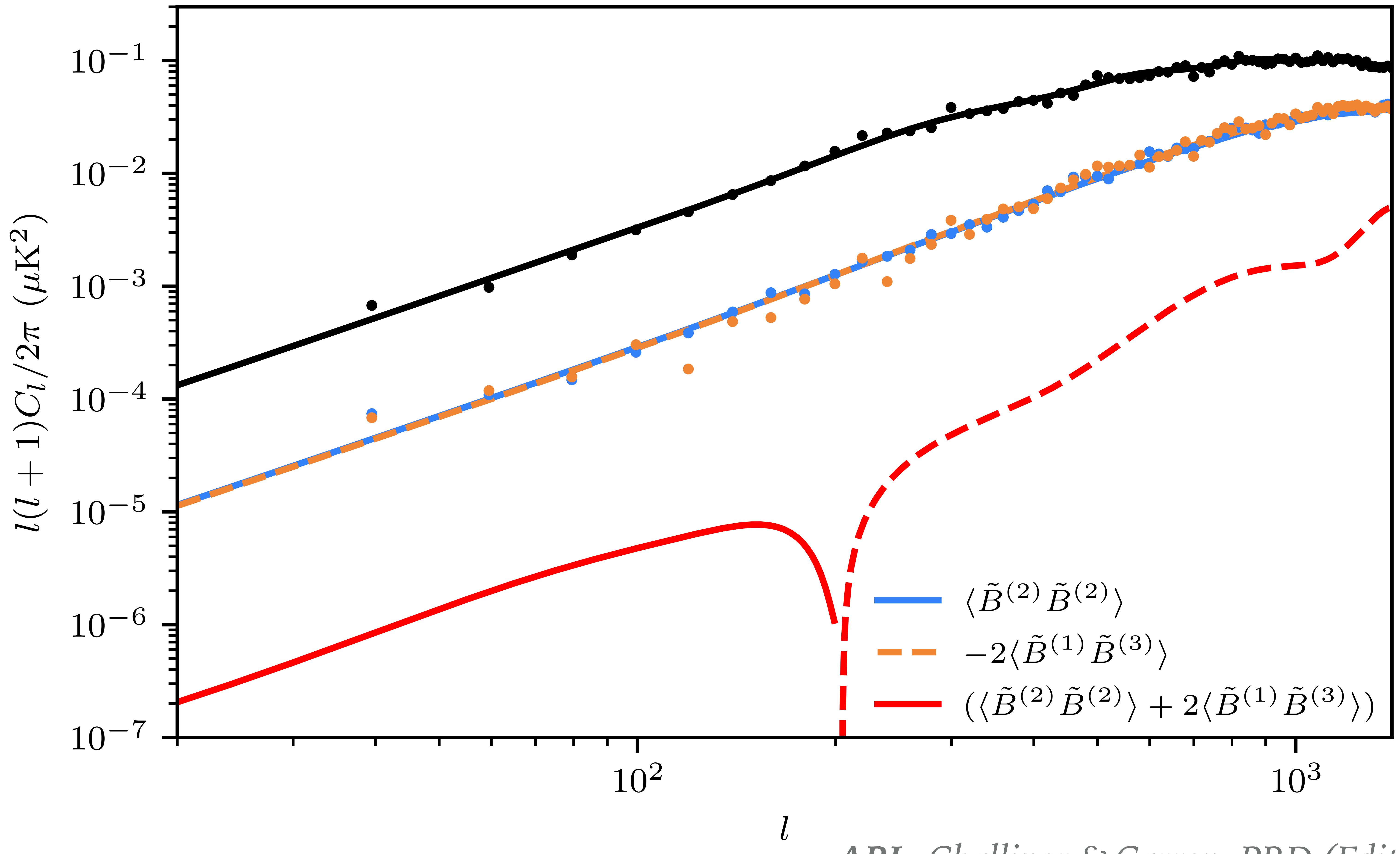
- Optimises strengths of LAT & SAT
- Analytically transparent (clear understanding of systematics)
- Template is **assumed to track true B-modes very accurately**

Non-perturbative template can also be built by deflecting observed E-modes directly:

$$B^{\rm temp}_{\rm non-pert}(\mathbf{l}) = \mathscr{B}_{\mathbf{l}}\left[P^{E^{\rm obs}}(\mathbf{x} + \nabla\hat{\phi})\right] \,. \qquad\qquad \textit{e.g., Planck 18, POLARBEAR 19}$$

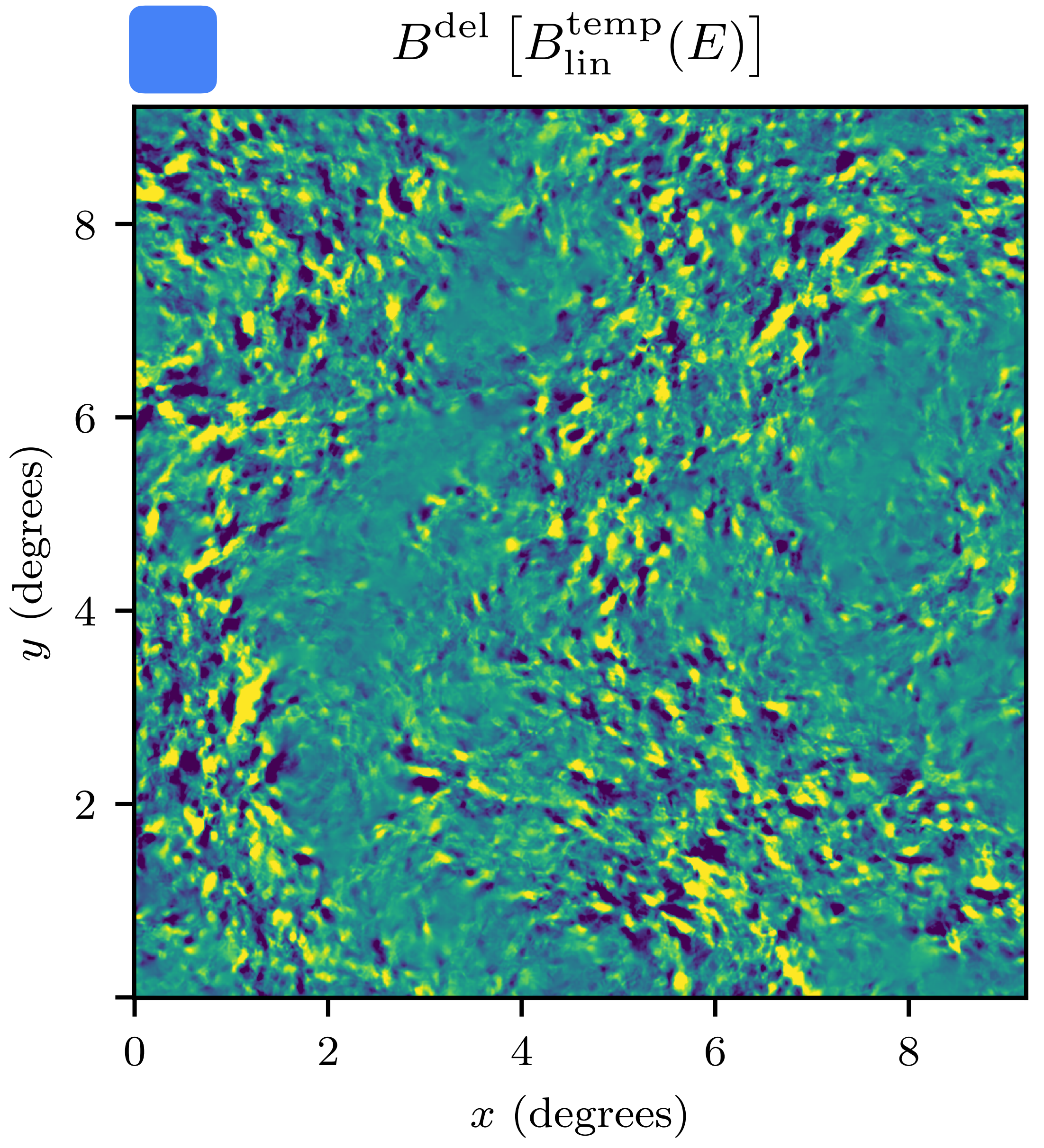
LIMITATIONS OF B-MODE DELENSING USING A TEMPLATE

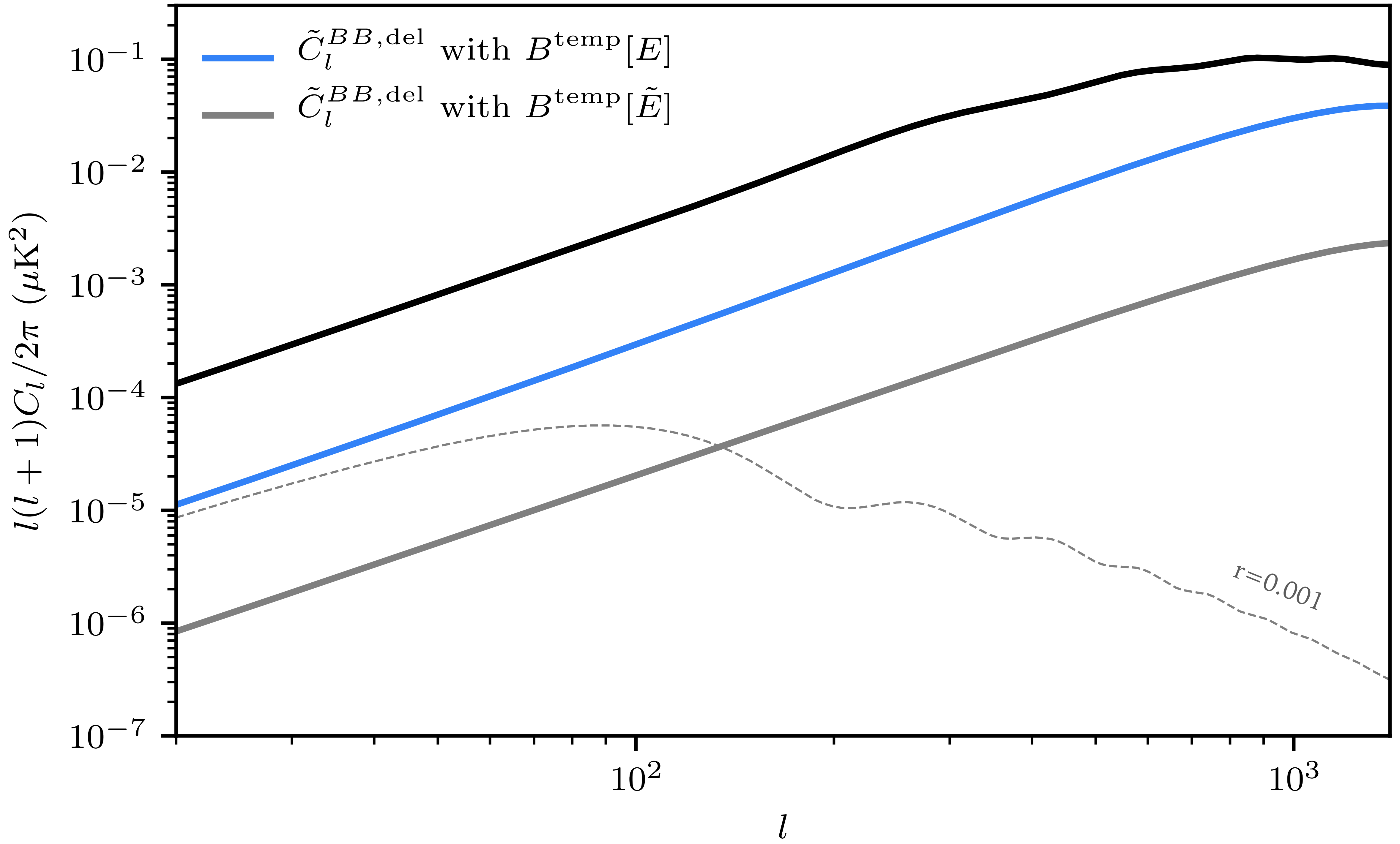
➤ Corrections to the leading-order calculation of lensing B-mode power smaller than O(1)% because of **extensive cancelations between large terms at higher orders.**



__ABL__, Challinor & Carron, PRD (Editor's suggestion), arXiv:2010.14286

LIMITATIONS OF B-MODE TEMPLATE DELENSING: NOISELESS SCENARIO

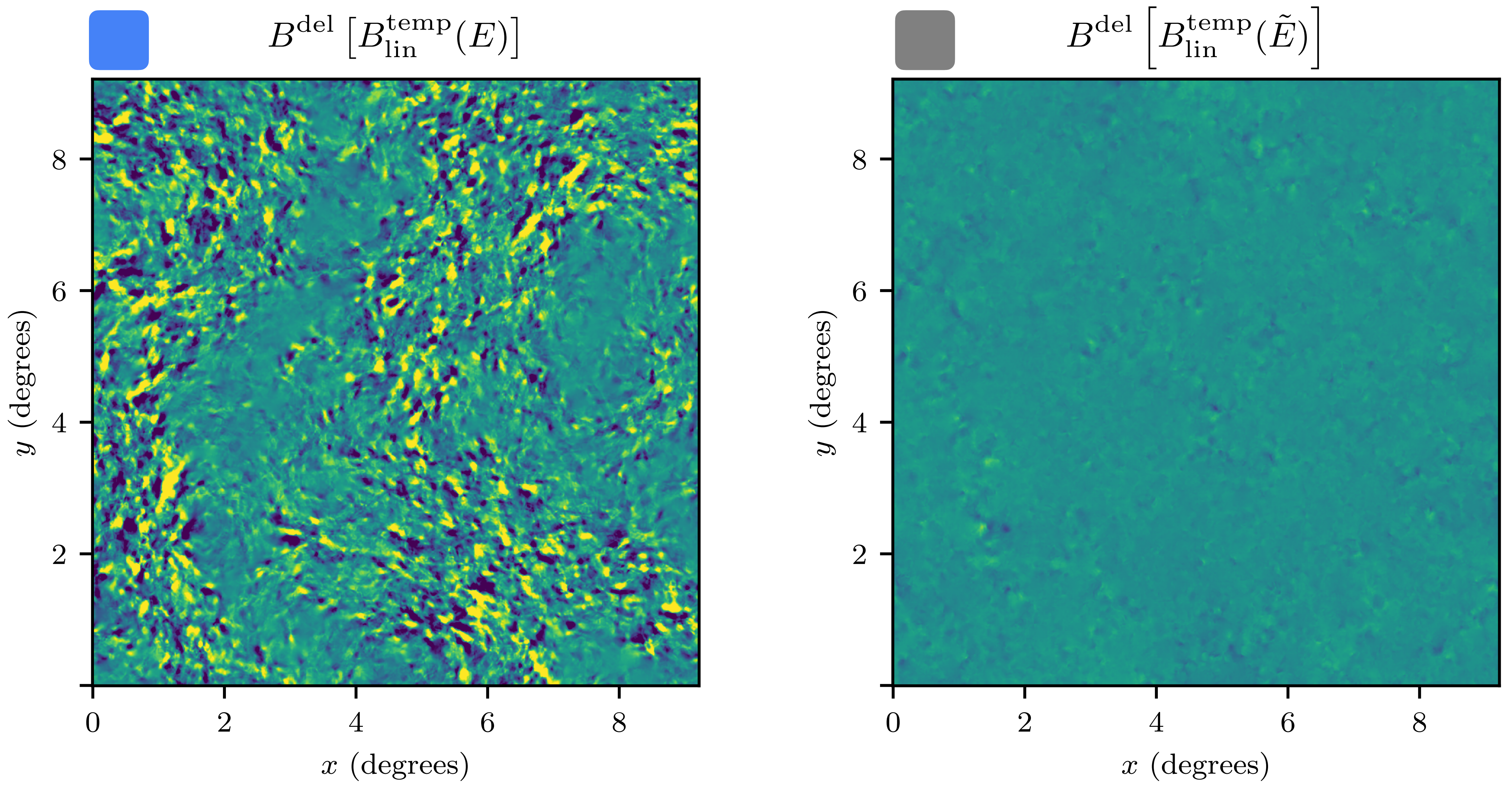


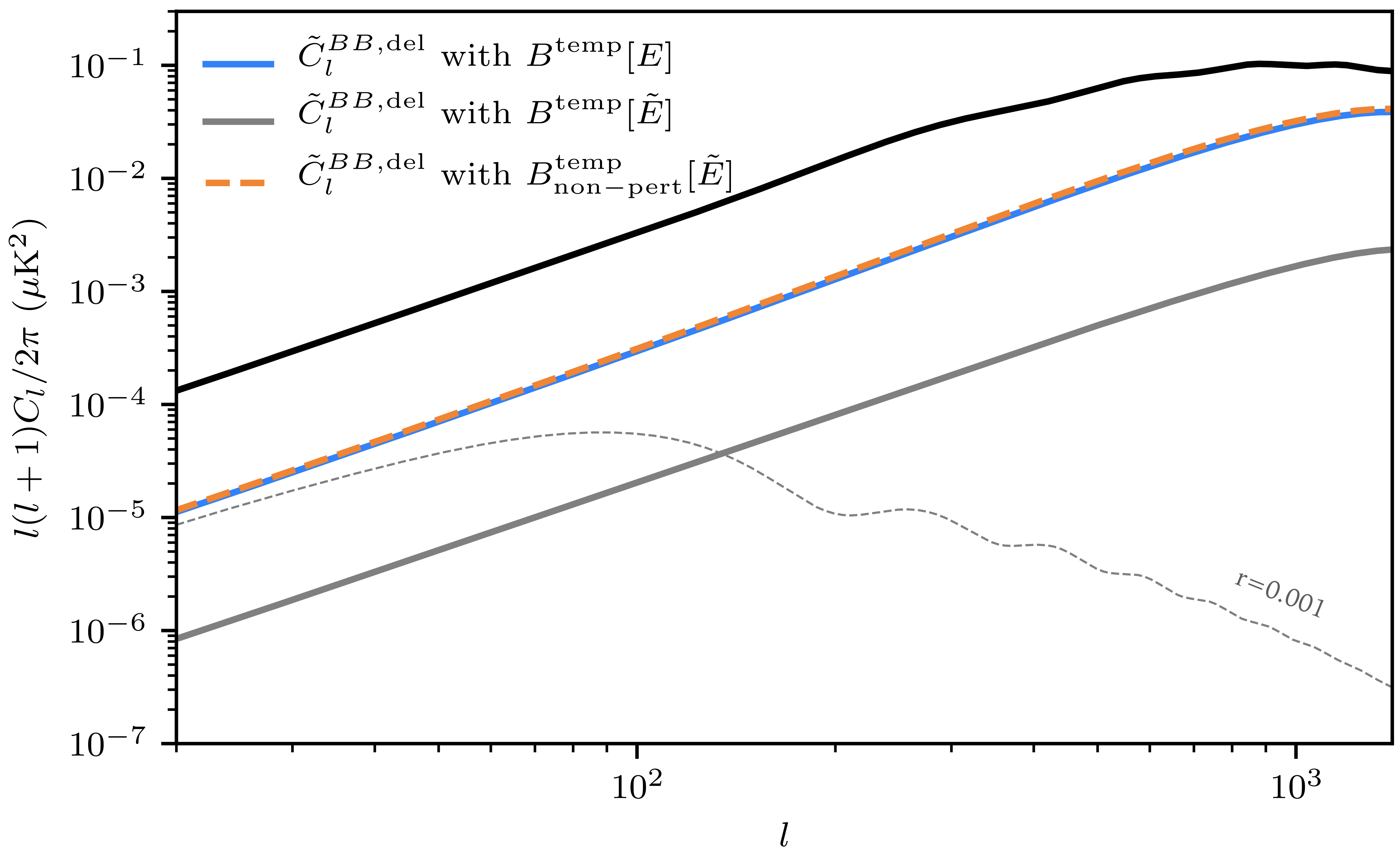


➤ Cancellations disappear if linear template is built from unlensed or delensed E-modes, hit delensing floor of O(10)%

__ABL__, Challinor & Carron, PRD (Editor's suggestion), 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)%

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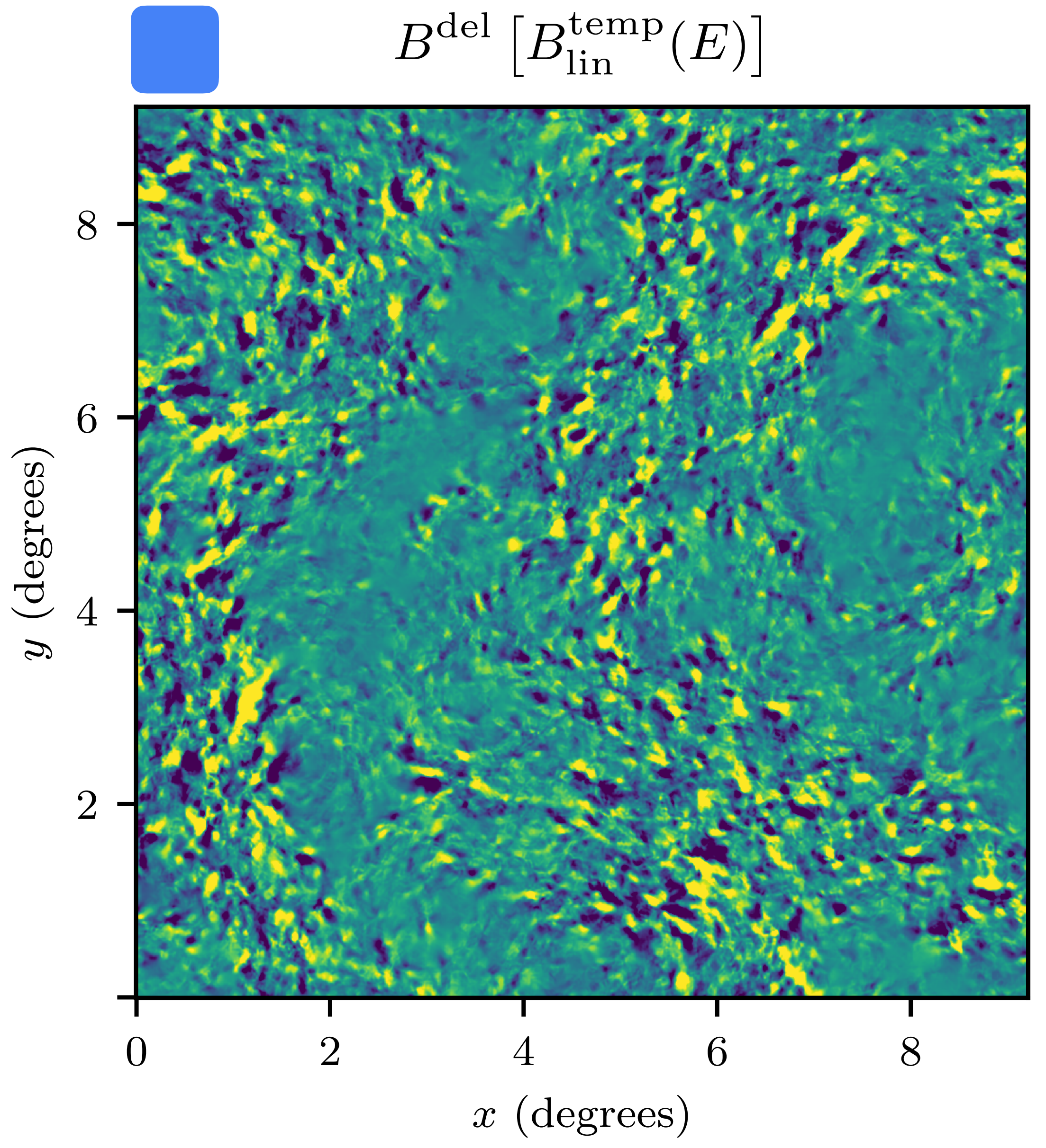
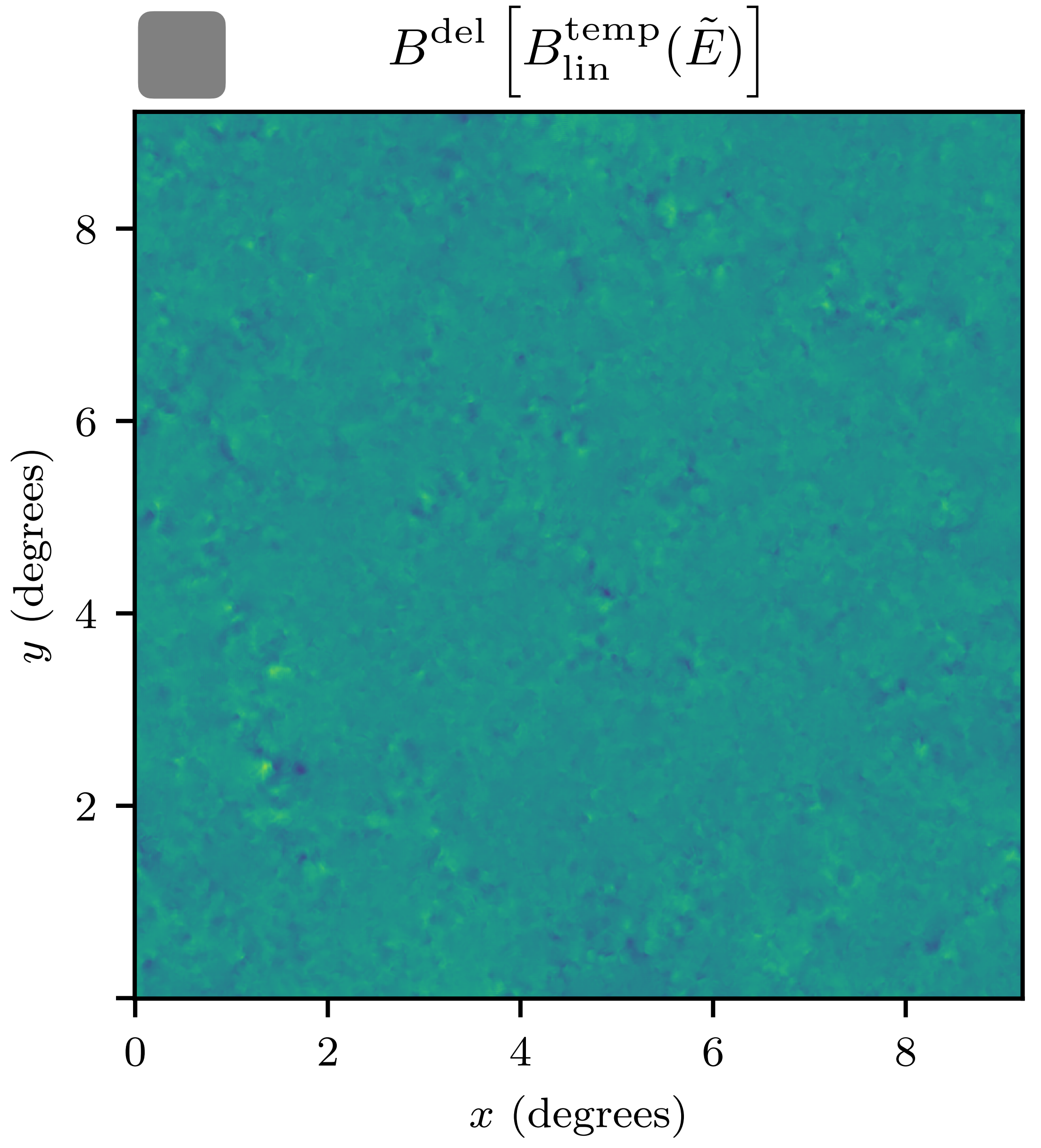
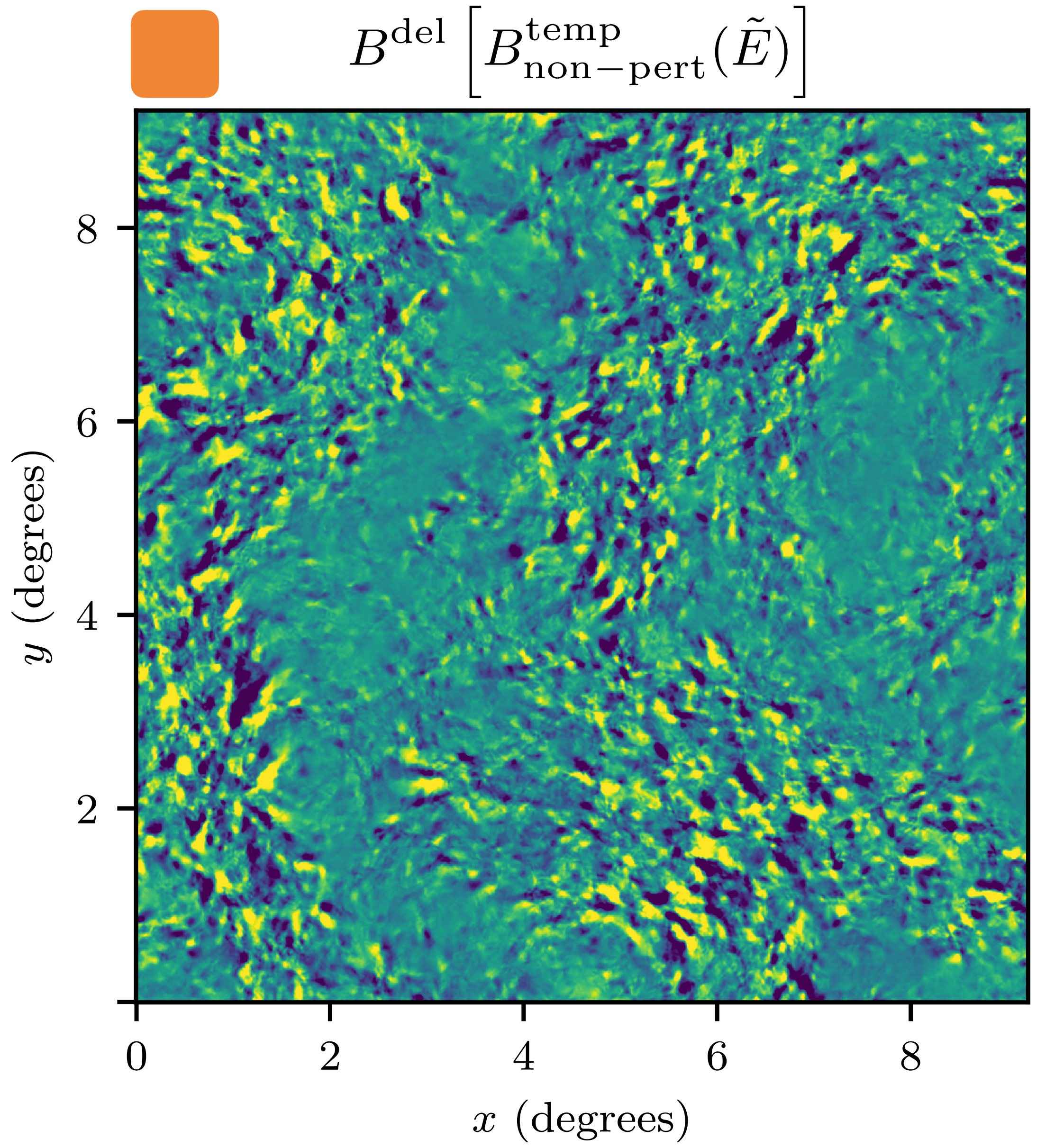
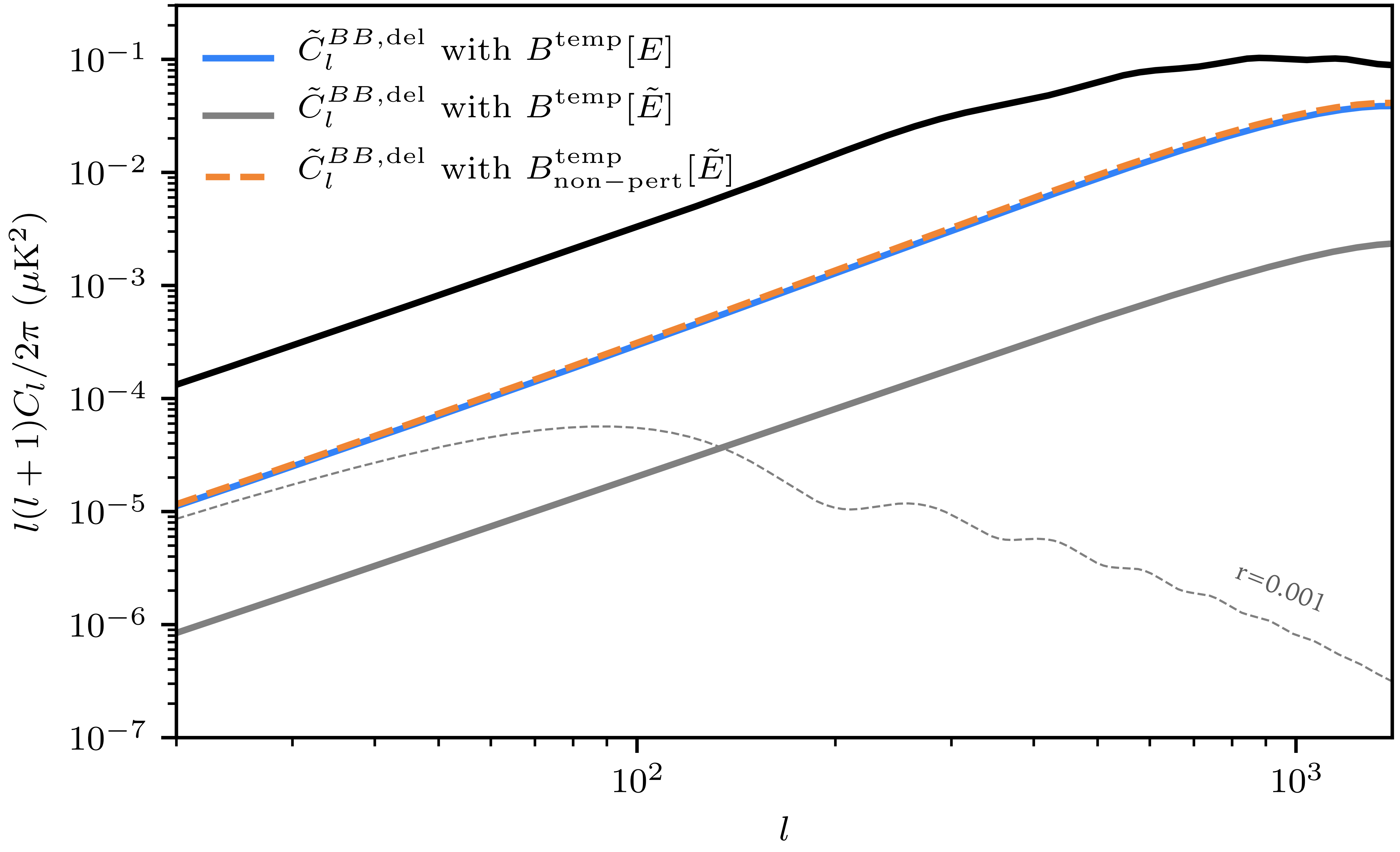
LIMITATIONS OF B-MODE TEMPLATE DELENSING: NOISELESS SCENARIO





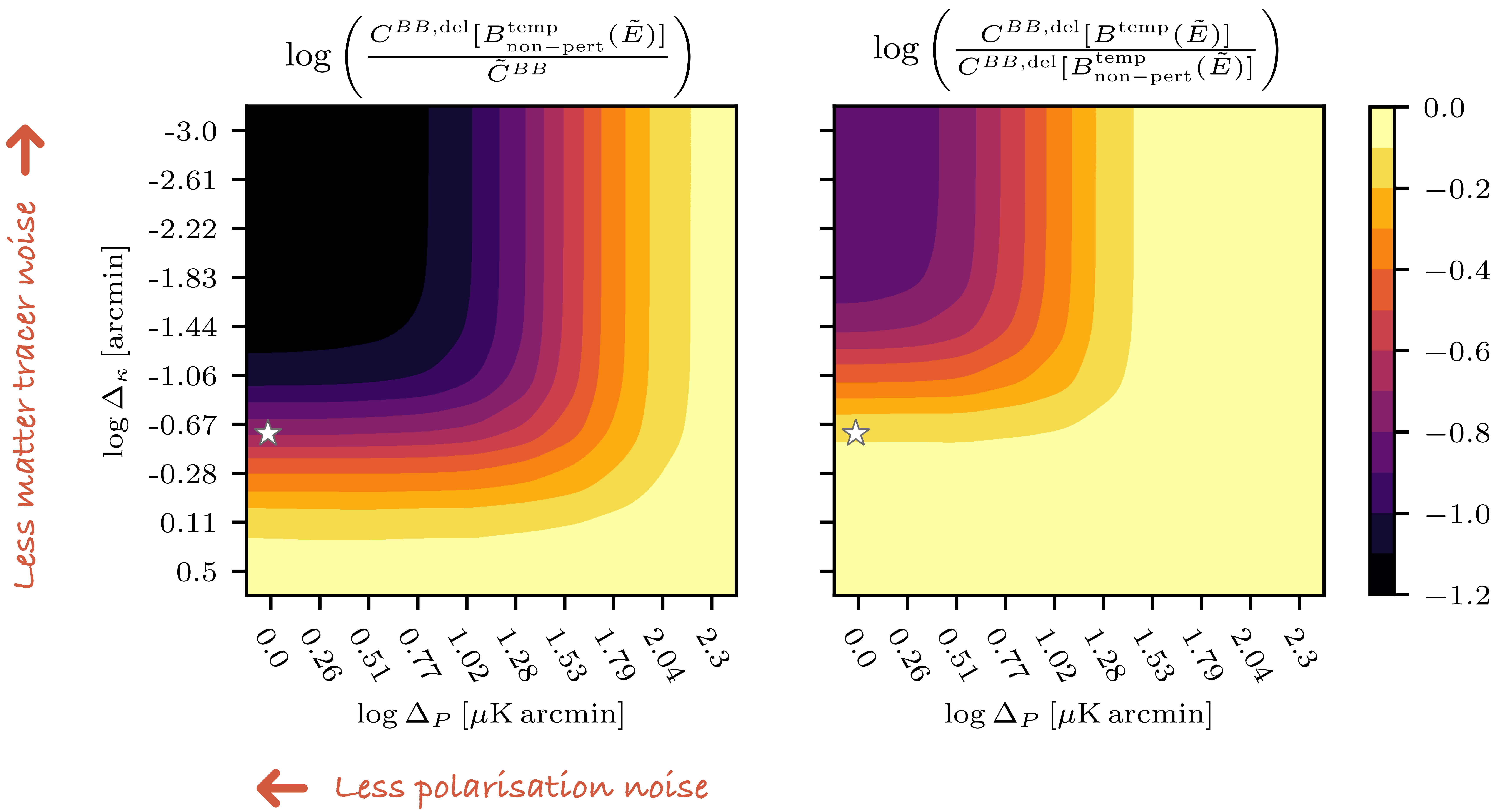




- Cancellations disappear if linear template is built from unlensed or delensed E-modes, hit delensing floor of O(10)%
- New cancellations arise when the lensed E-modes are used in the linear template, so delensing floor is O(1)%
- Advantage is lost when a non-perturbative template is built from lensed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

__ABL__, Challinor & Carron, PRD (Editor's suggestion), arXiv:2010.14286

LIMITATIONS OF B-MODE TEMPLATE DELENSING: REALISTIC CASE



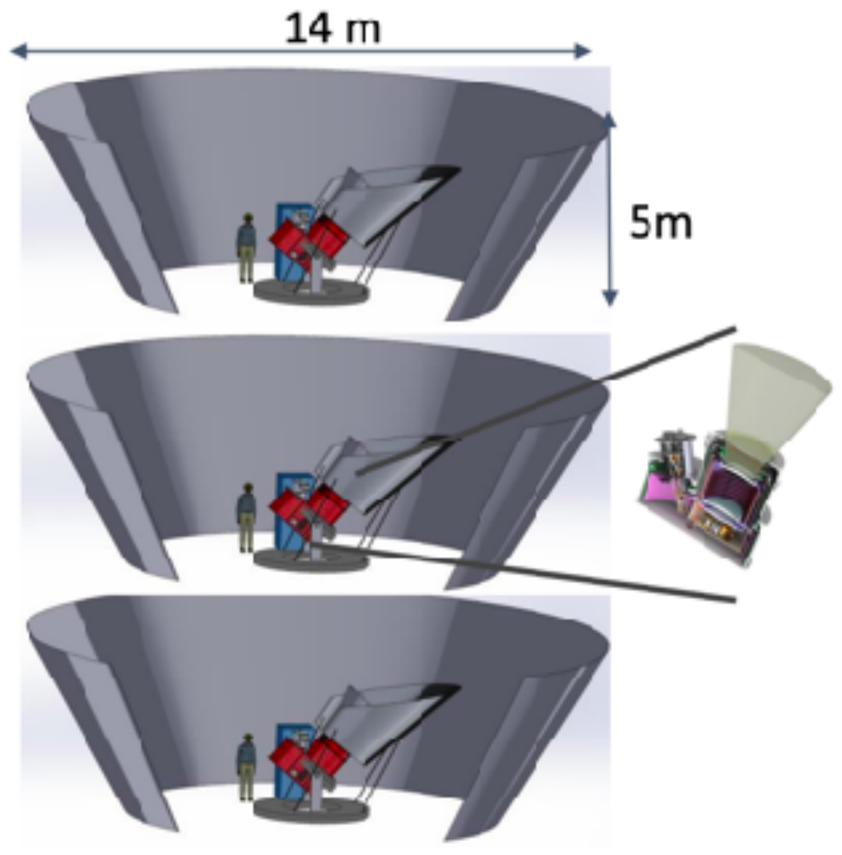
- With lensed E, advantageous to build gradient-order template even in realistic scenarios
- For CMB-S4, this removes $\sim 5\,\%$ more lensing power. Most transparent to systematics.

ABL, Challinor & Carron, PRD (Editor's suggestion), arXiv:2010.14286

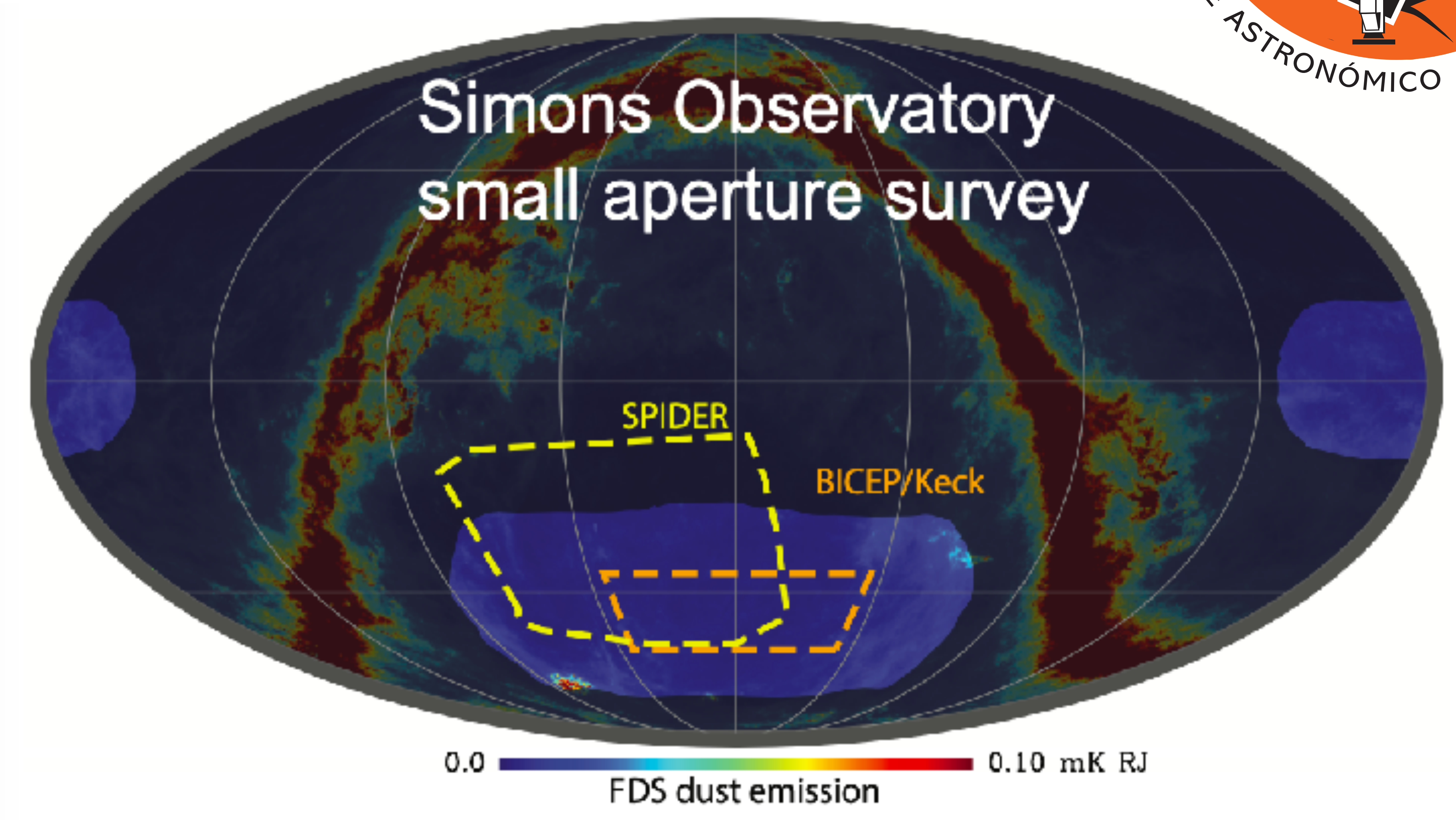
THE SIMONS OBSERVATORY (SO)

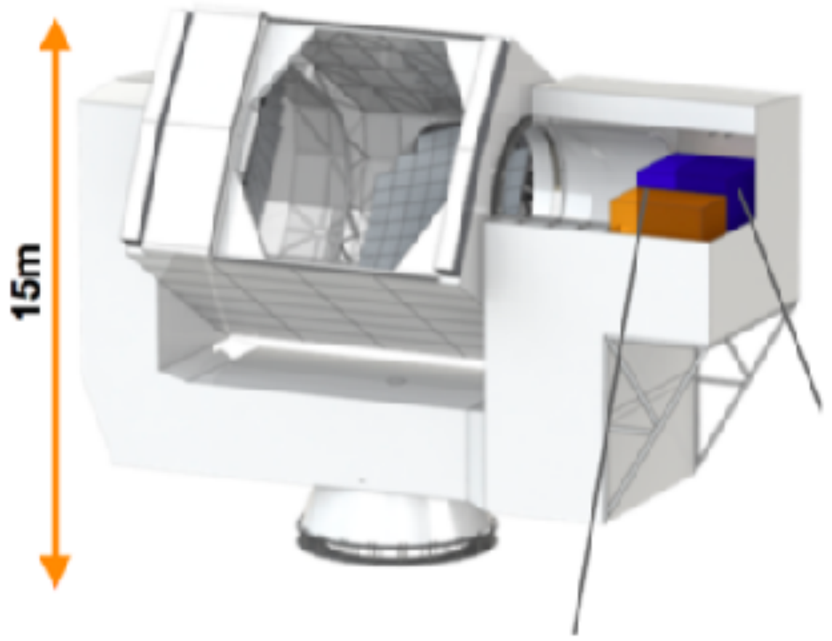
Credit: Deborah Kellner

THE SIMONS OBSERVATORY (SO)

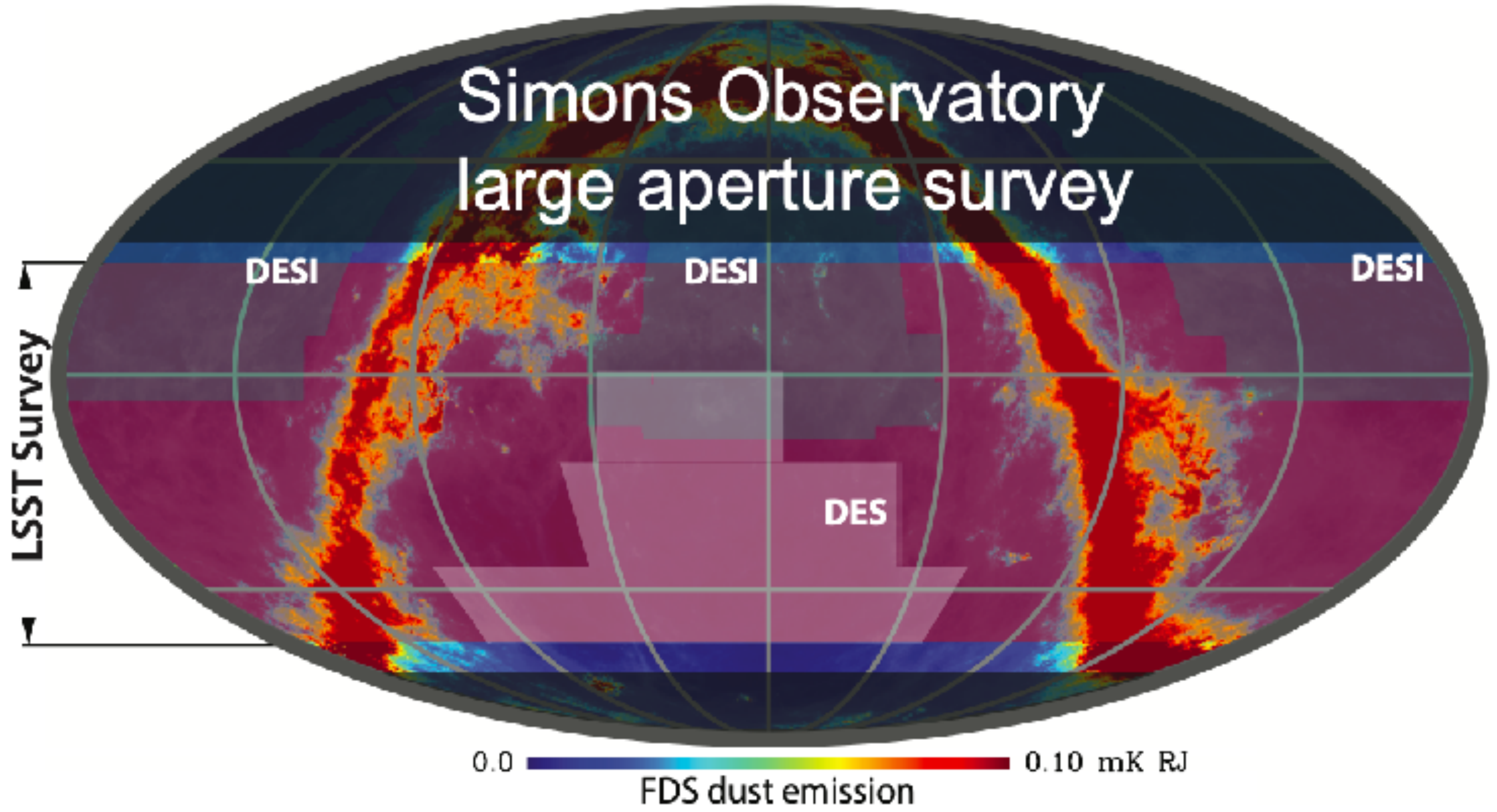


	SATs ($f_{sky} = 0.1$)		
Freq. [GHz]	FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	91	35	25
39	63	21	17
93	30	2.6	1.9
145	17	3.3	2.1
225	11	6.3	4.2
280	9	16	10

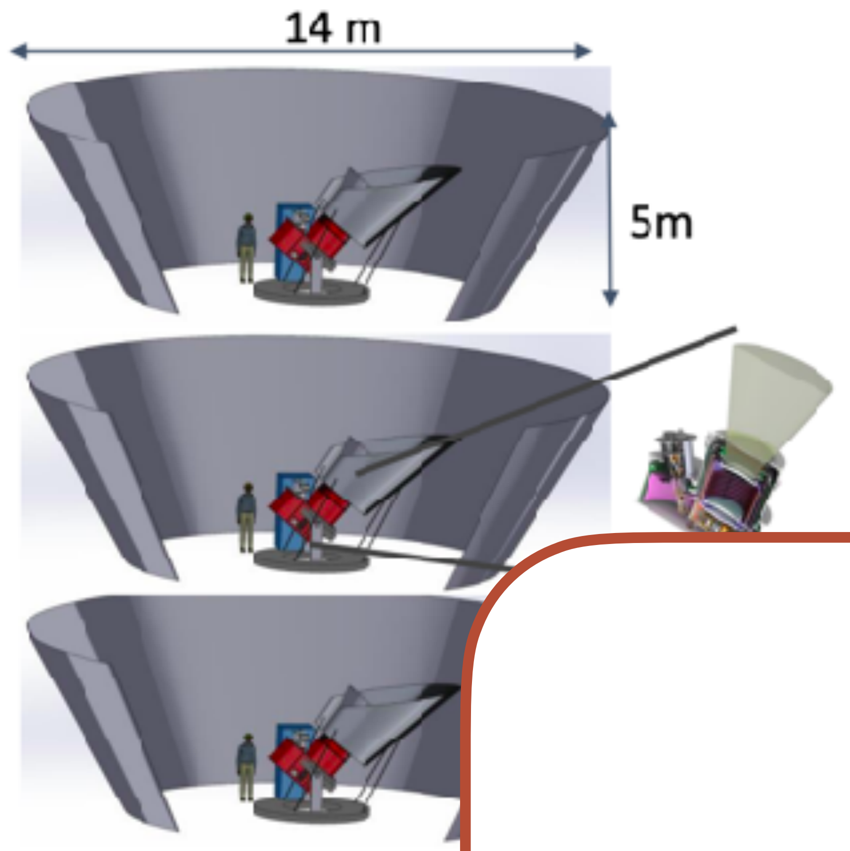




	LAT ($f_{sky} = 0.4$)		
Freq. [GHz]	FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	7.4	71	52
39	5.1	36	27
93	2.2	8.0	5.8
145	1.4	10	6.3
225	1.0	22	15
280	0.9	54	37



THE SIMONS OBSERVATORY (SO)



Freq. [GHz]	SATs ($f_{sky} = 0.1$) FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
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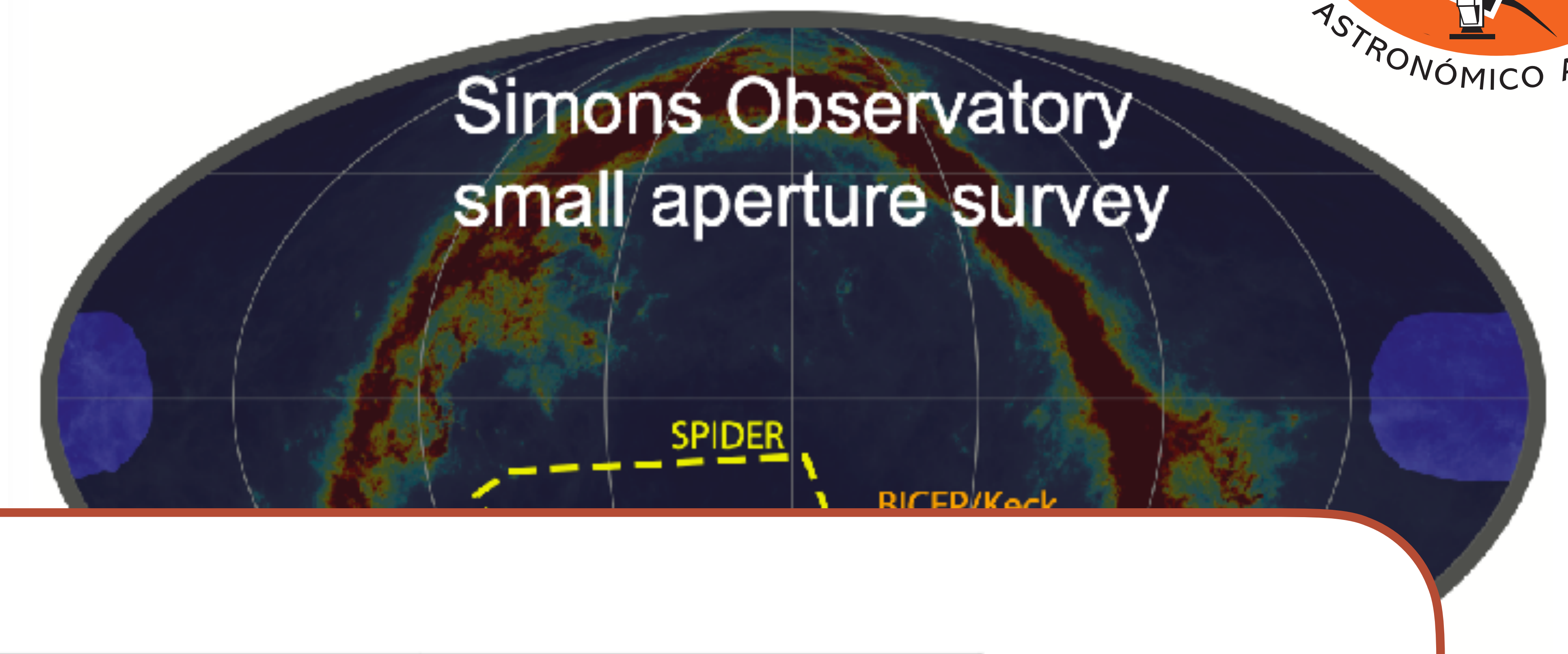
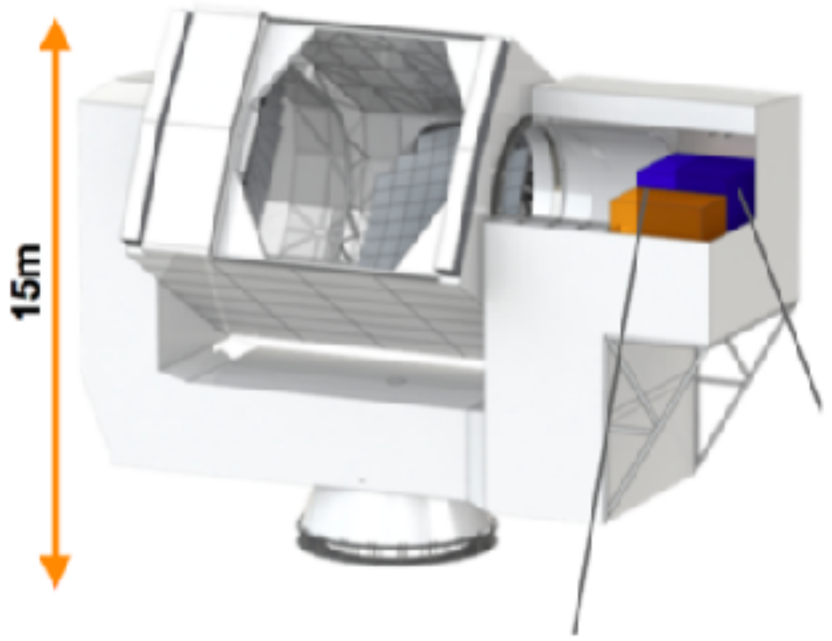


Early '21	Mid '22	Early '23	Mid '24
Testing and integration, optical validation	First light for both SAT + LAT	**First** science observations expected	**Full** science observations expected

… and a stepping stone towards CMB-S4!



Freq. [GHz]	LAT ($f_{sky} = 0.4$) FWHM (′)	Noise (baseline) [μK-arcmin]	Noise (goal) [μK-arcmin]
27	7.4	71	52
39	5.1	36	27
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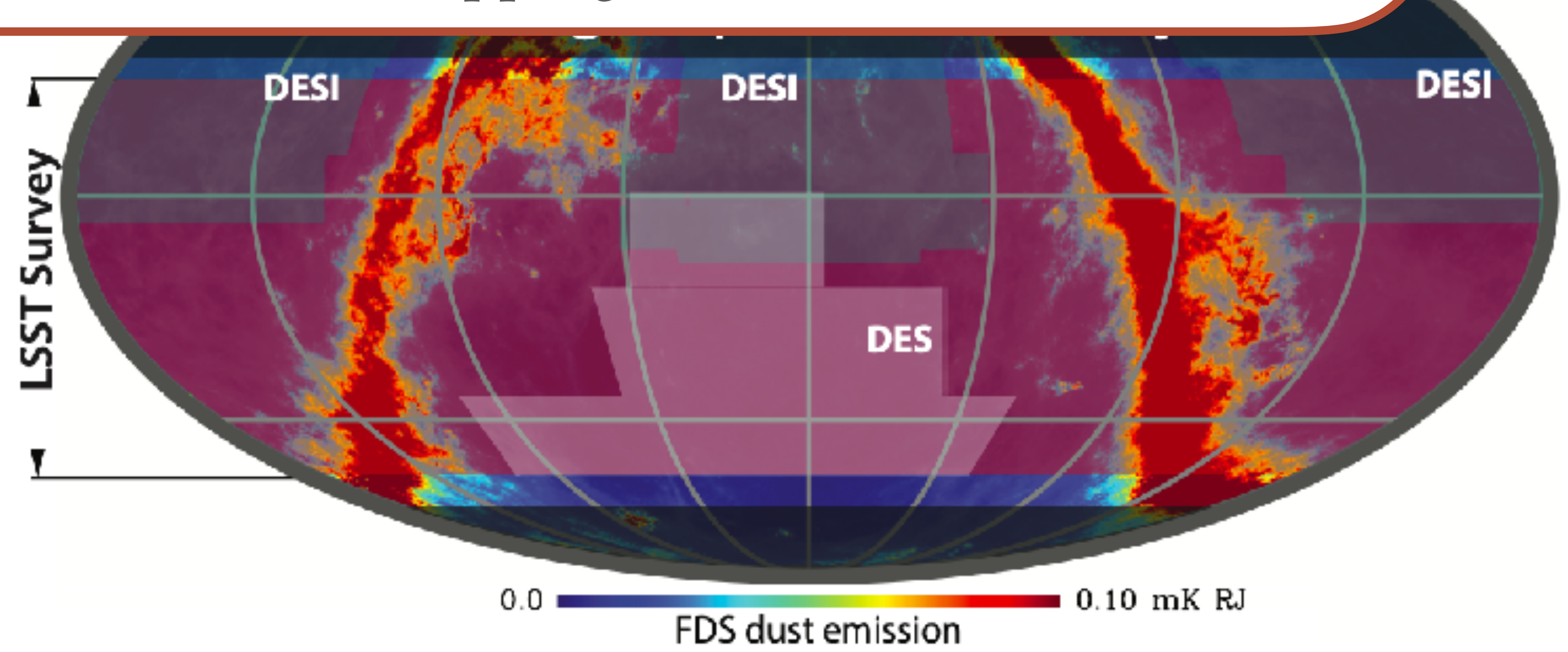
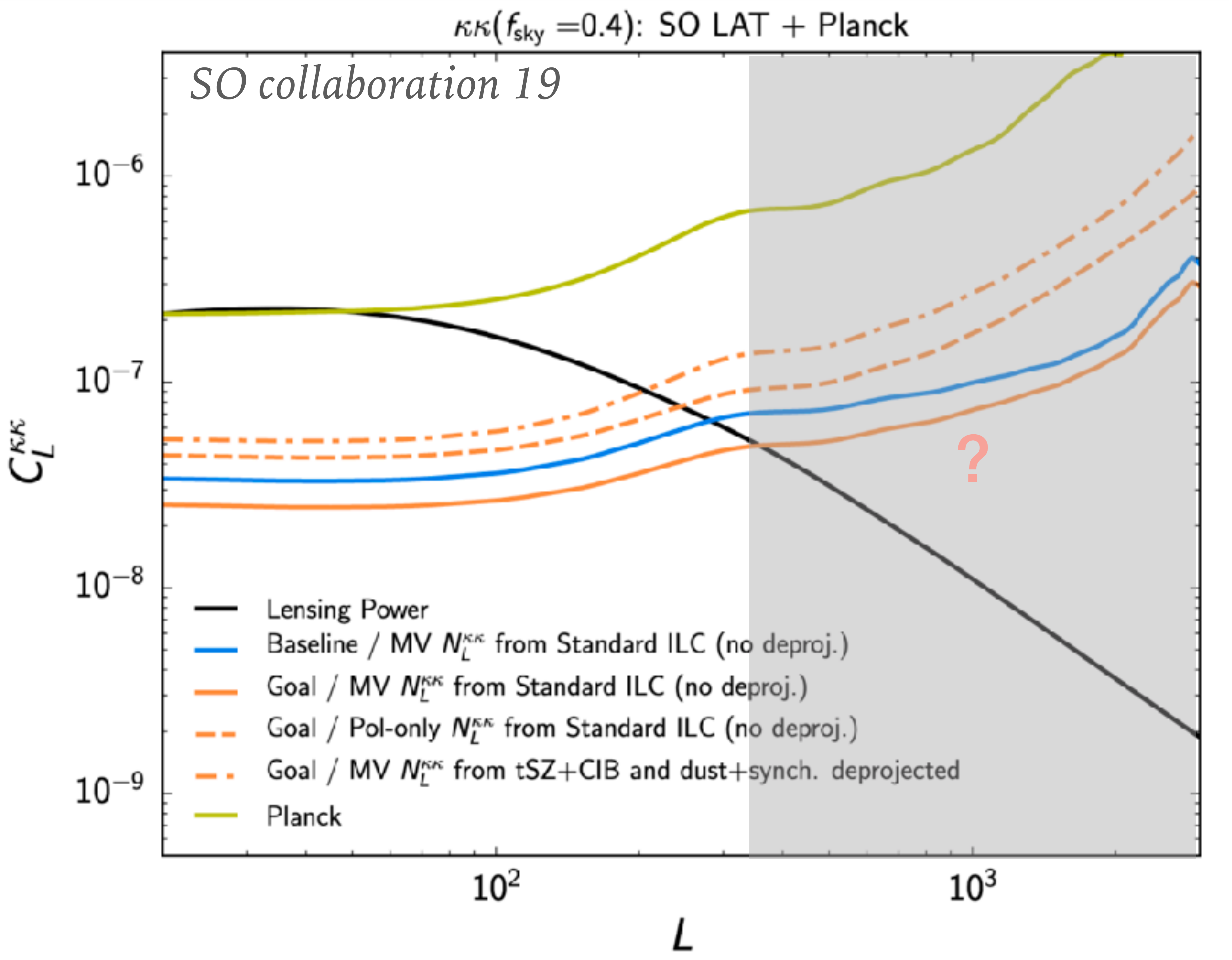
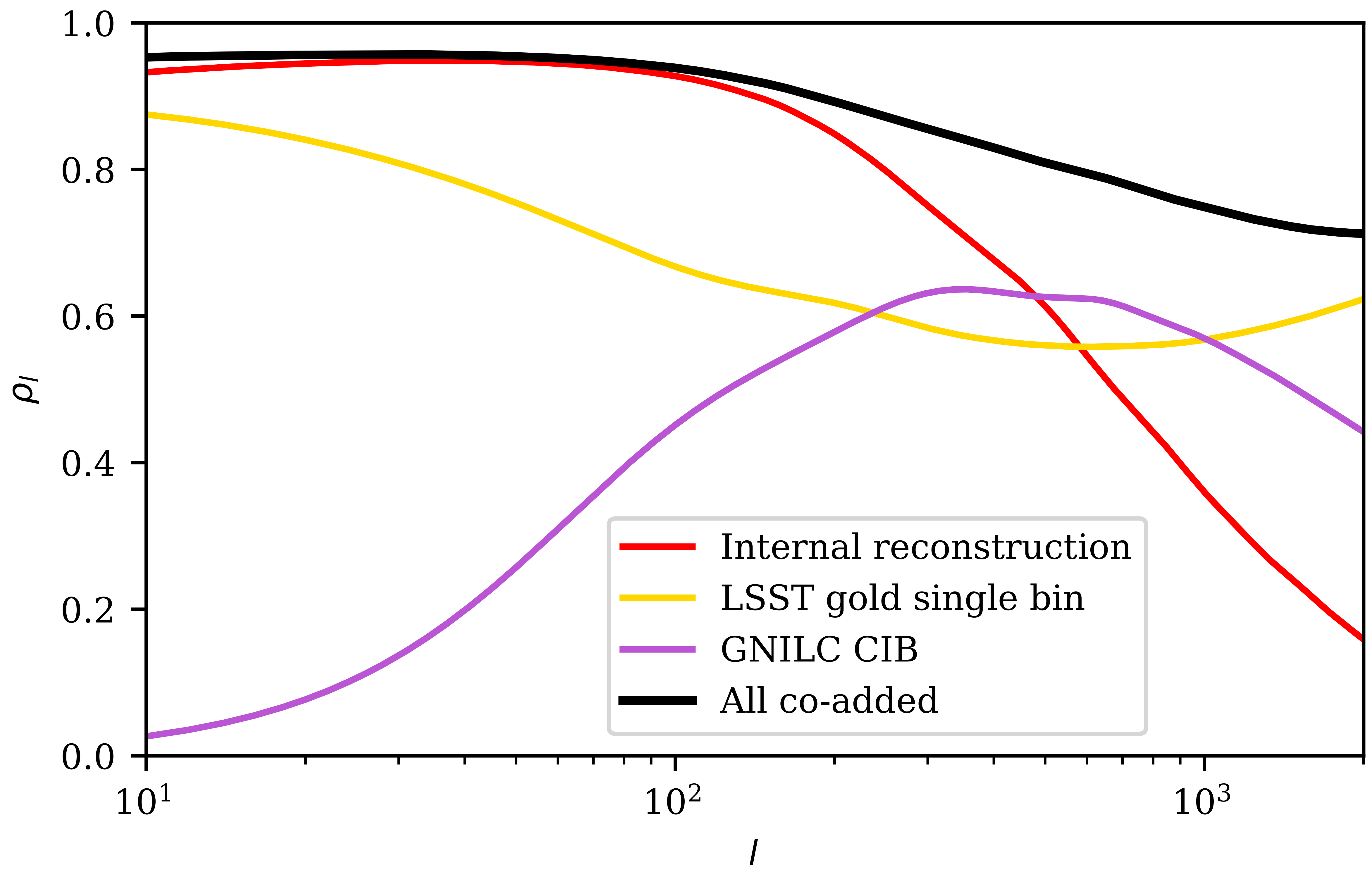


MULTI-TRACER DELENSING WITH SO





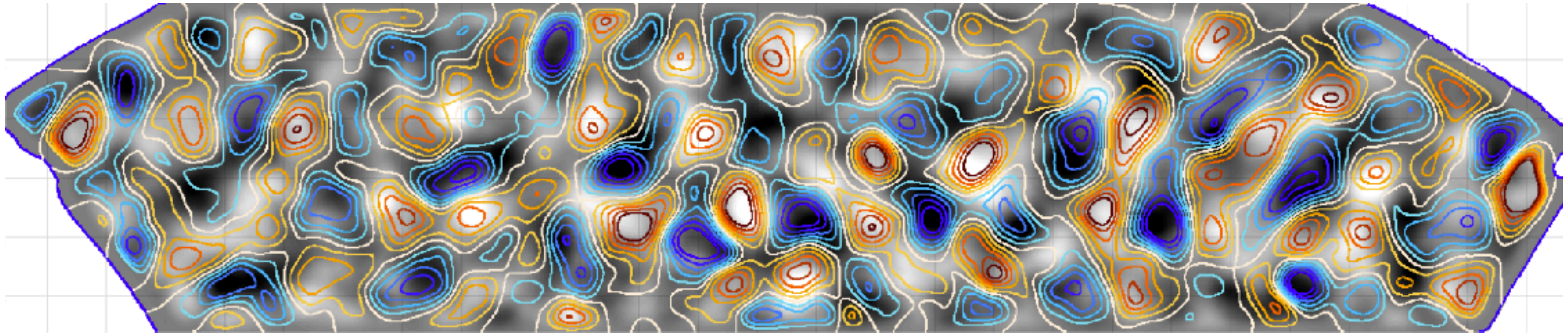
Combine internal reconstructions with external tracers of the LSS to get small-scale lenses at high z

Sherwin & Schmittfull 15, Manzotti 18 …

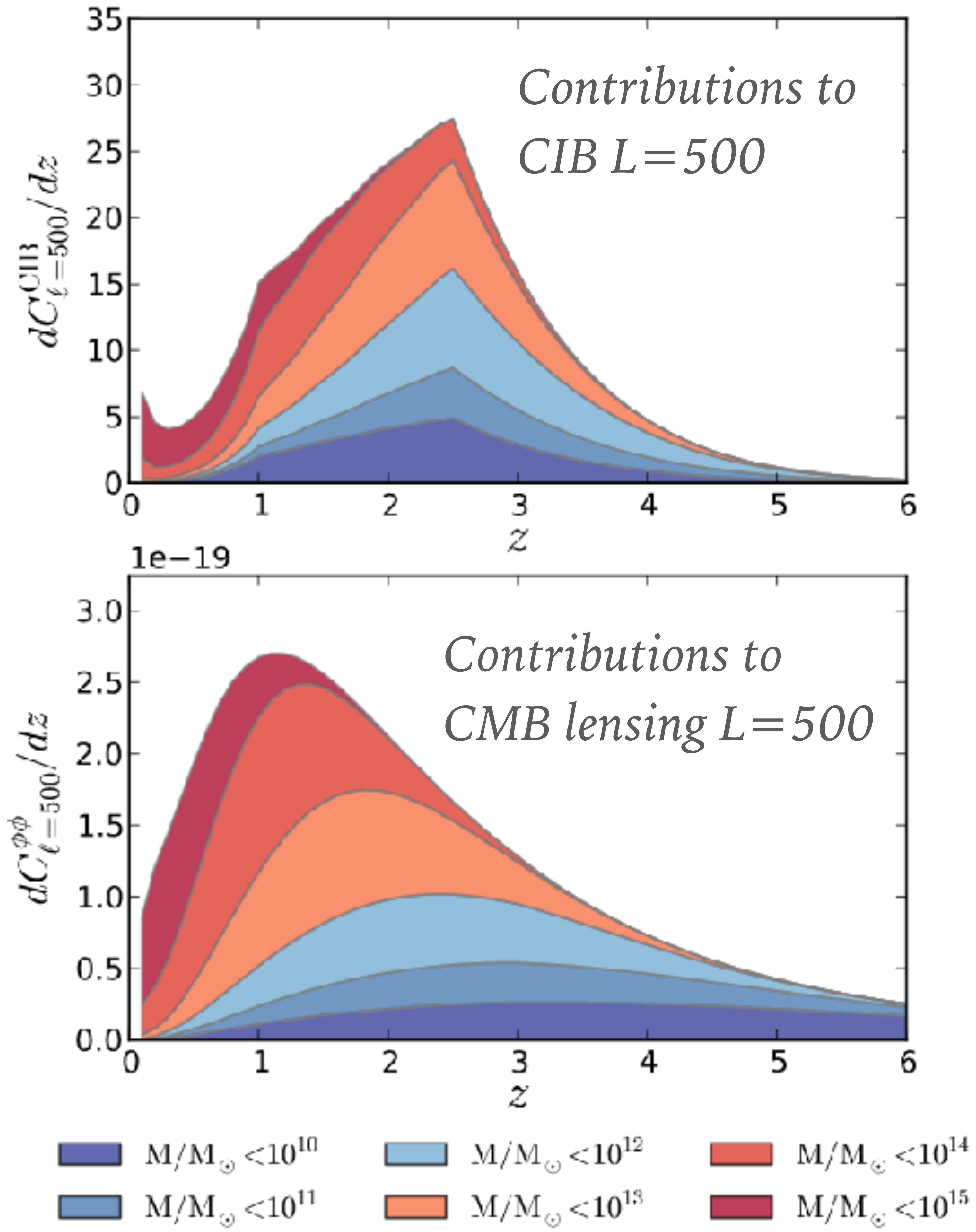
ASIDE – THE COSMIC INFRARED BACKGROUND (CIB)

The CIB: emission from UV-heated dust in star-forming galaxies

Highly correlated with CMB lensing on the (arcminute) scales we need
Sherwin & Schmittfull 15



ACT lensing vs. CIB *Darwish+. 20*

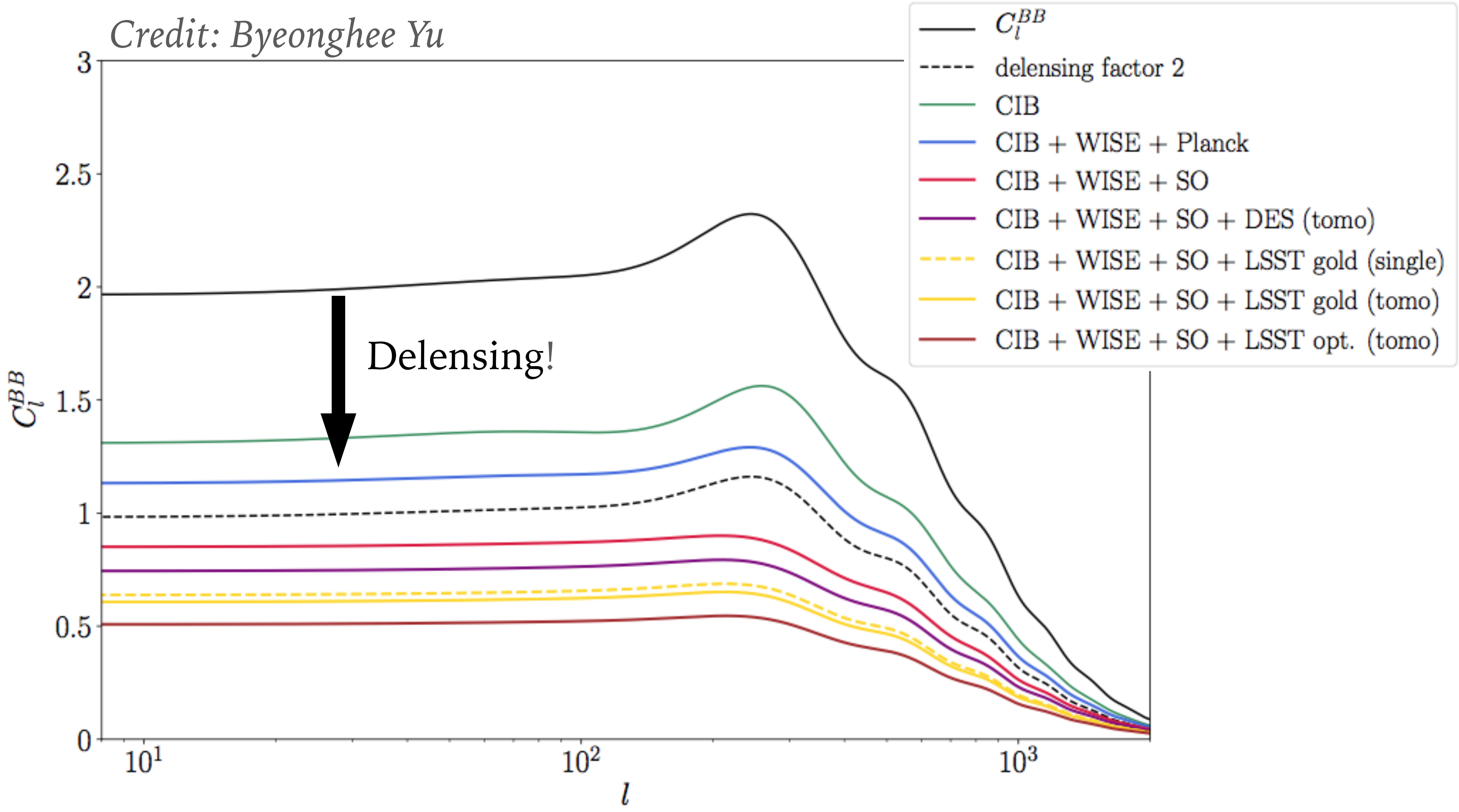


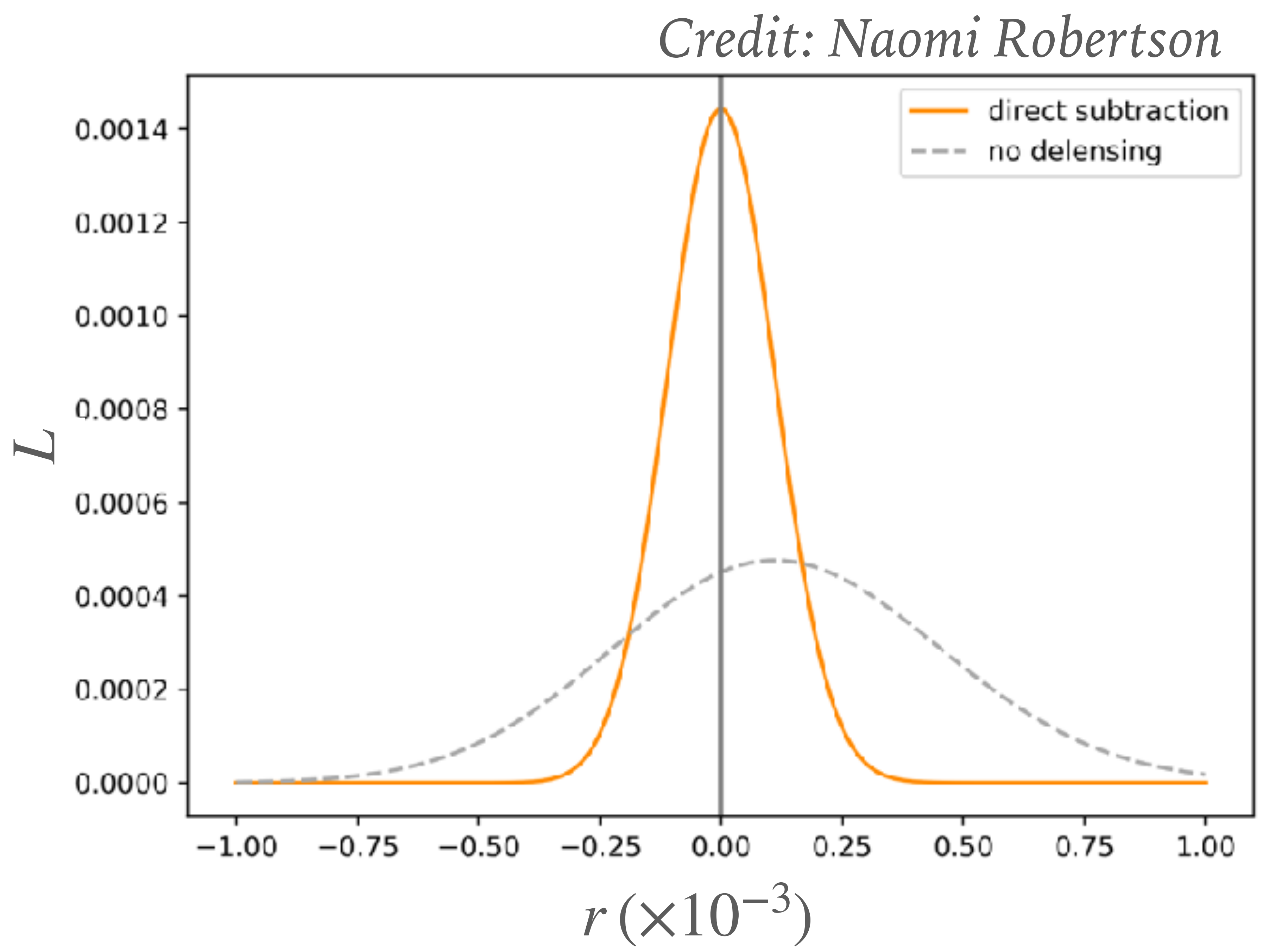
Planck 13 XVIII

Used in:

- First demonstration of delensing in general *Larsen+ 16*
- First demonstration of B-mode delensing *SPT 17*
- First improvement on $\sigma(r)$ from delensing *SPT + BICEP/Keck 20*

DELENSING WITH SO



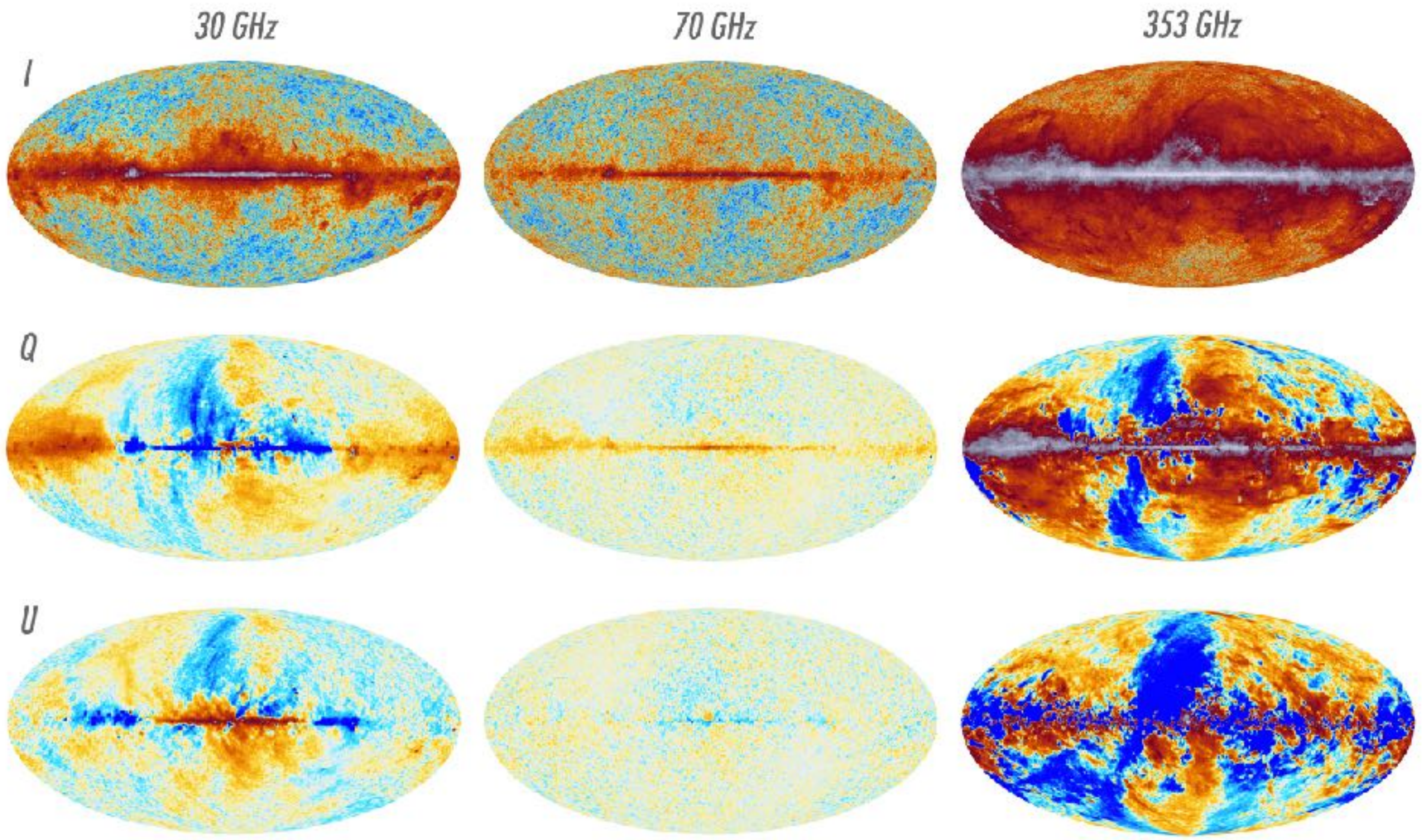


Close to idealised performance on realistic simulations including inhomogeneous noise and masking

Currently $\sigma(r) = 0.044$ (Planck + BICEP/Keck), SO forecast after delensing $\sigma(r) = 0.003$

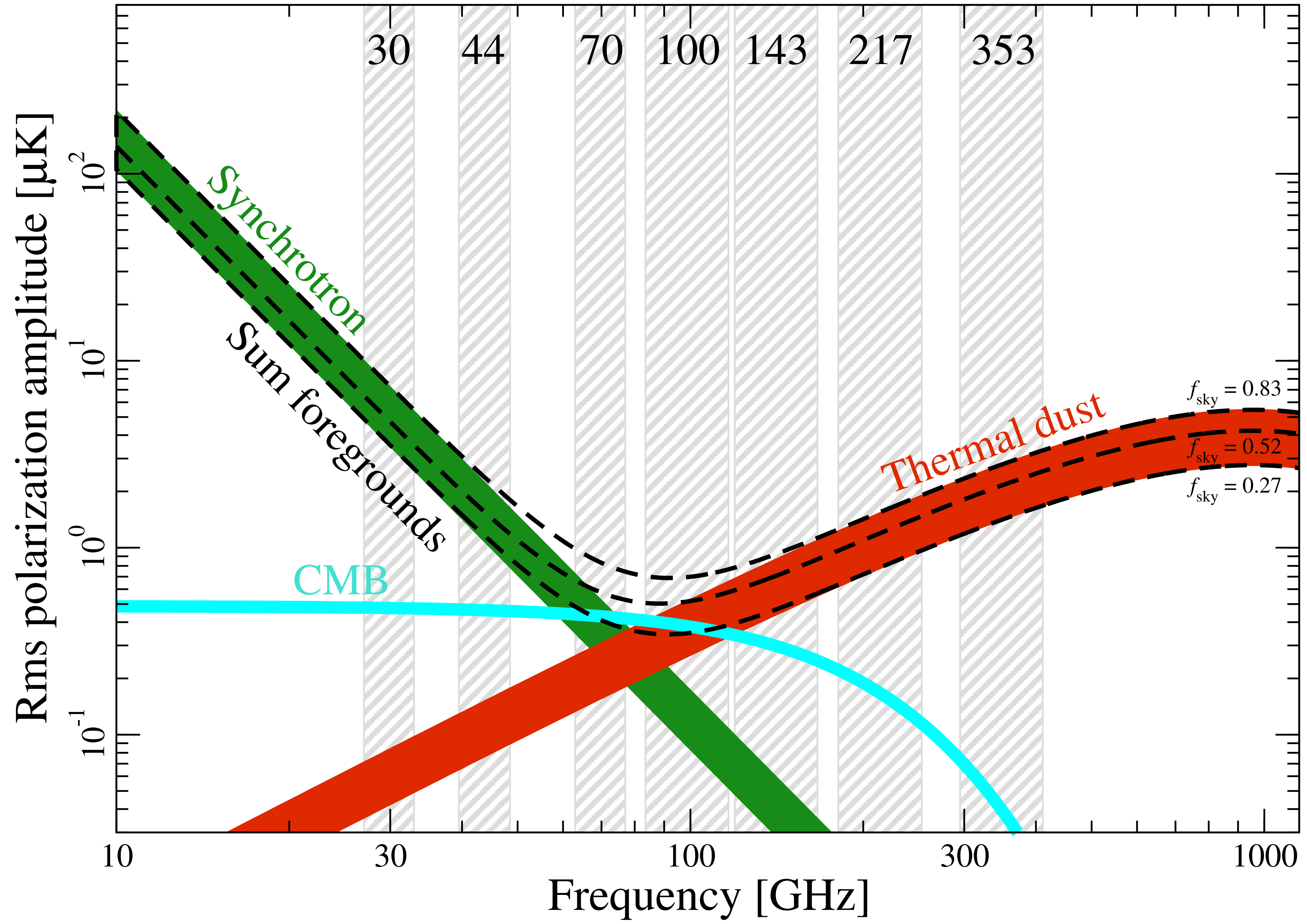
*Namikawa, **ABL**, Robertson, Challinor, Sherwin, Yu + 21 (to be submitted)*

BIASES TO DELENSING FROM FOREGROUNDS



Credit: Planck

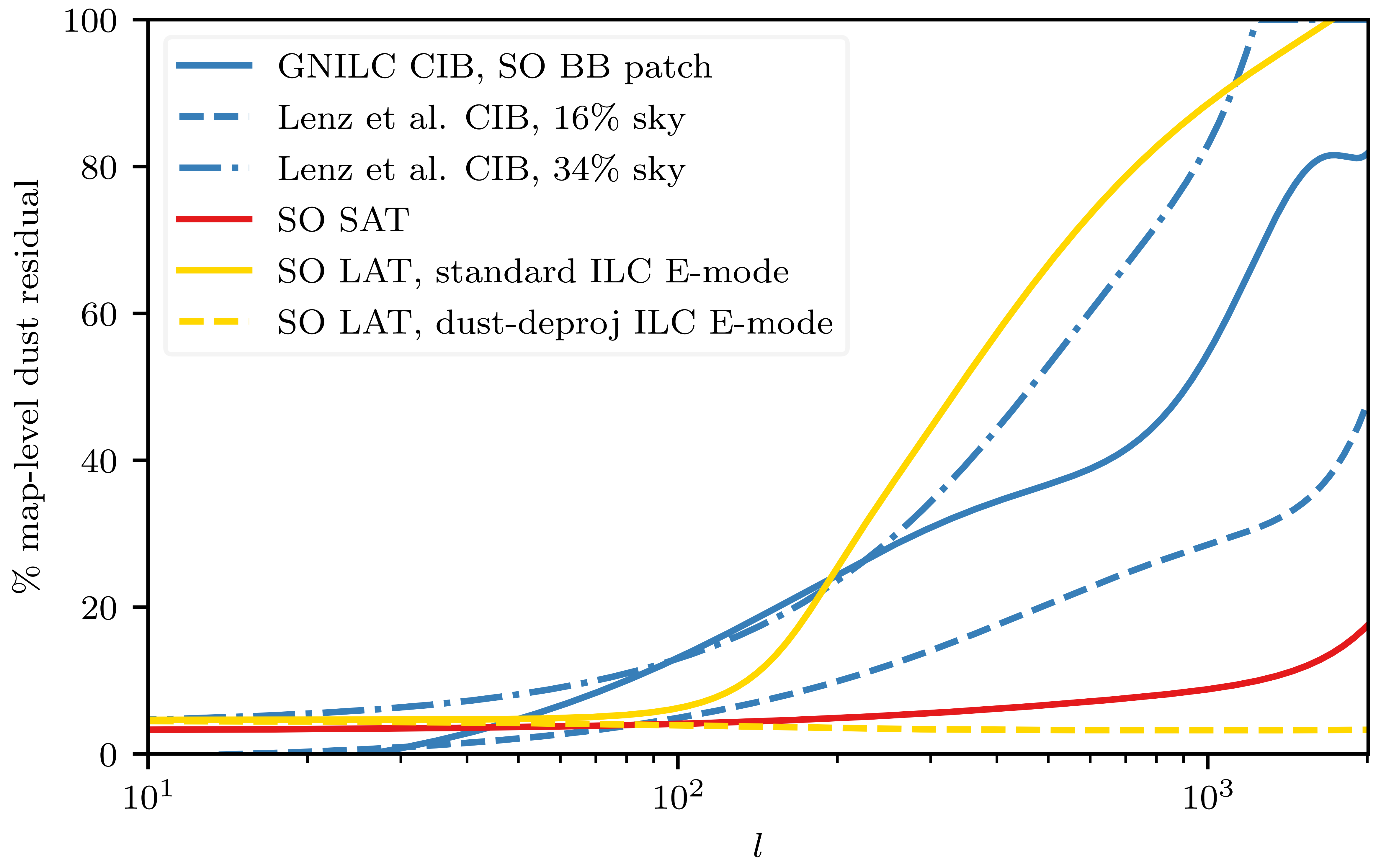
Credit: C. Dickinson



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

… but what about CIB-delensing?

DELENSING WITH THE CIB — POSSIBLE BIASES



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

$$B^{\mathrm{del}} = B^{\mathrm{obs}} - E^{\mathrm{obs}} \circledast I$$

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

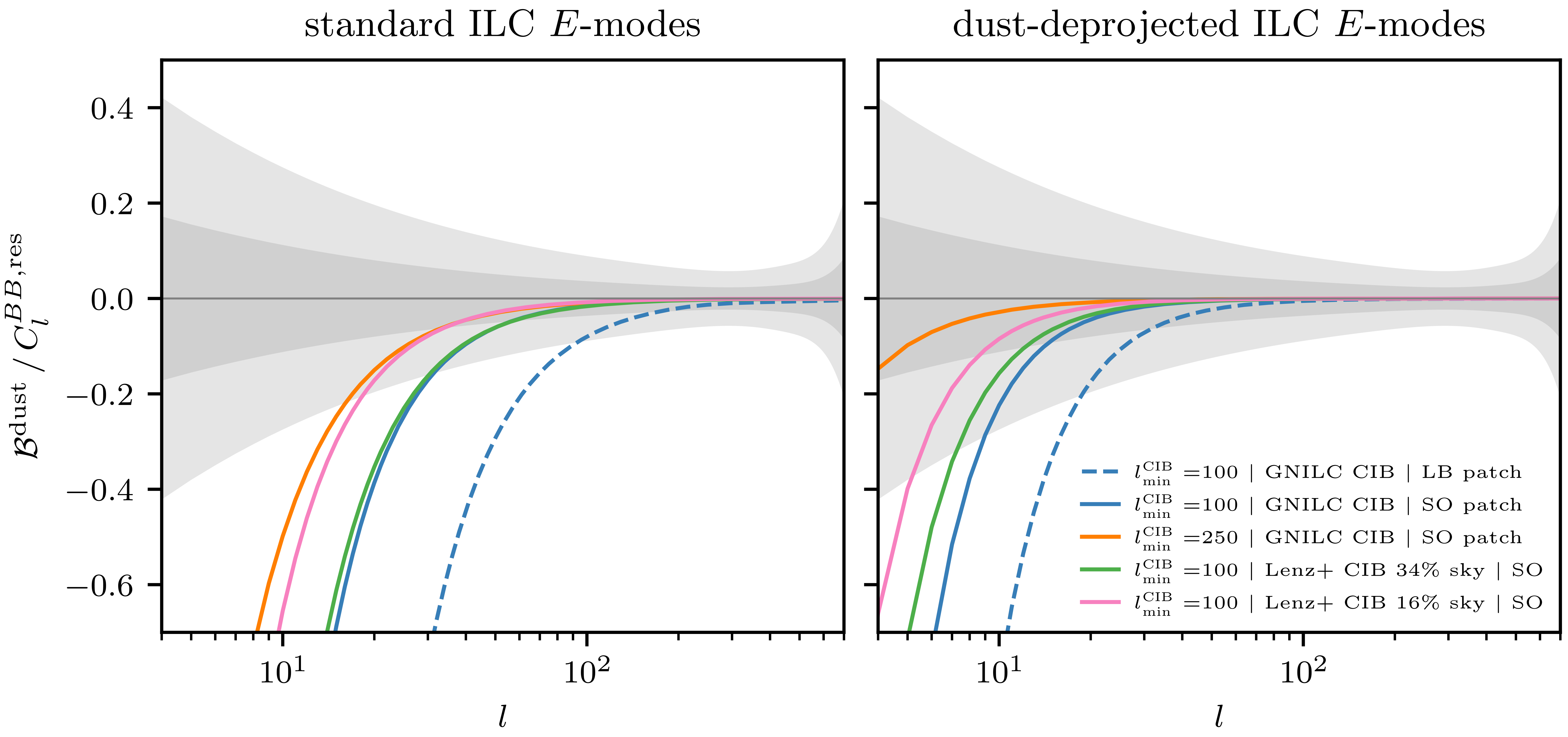
Difficult to disentangle!

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 21, arXiv:2102.01045

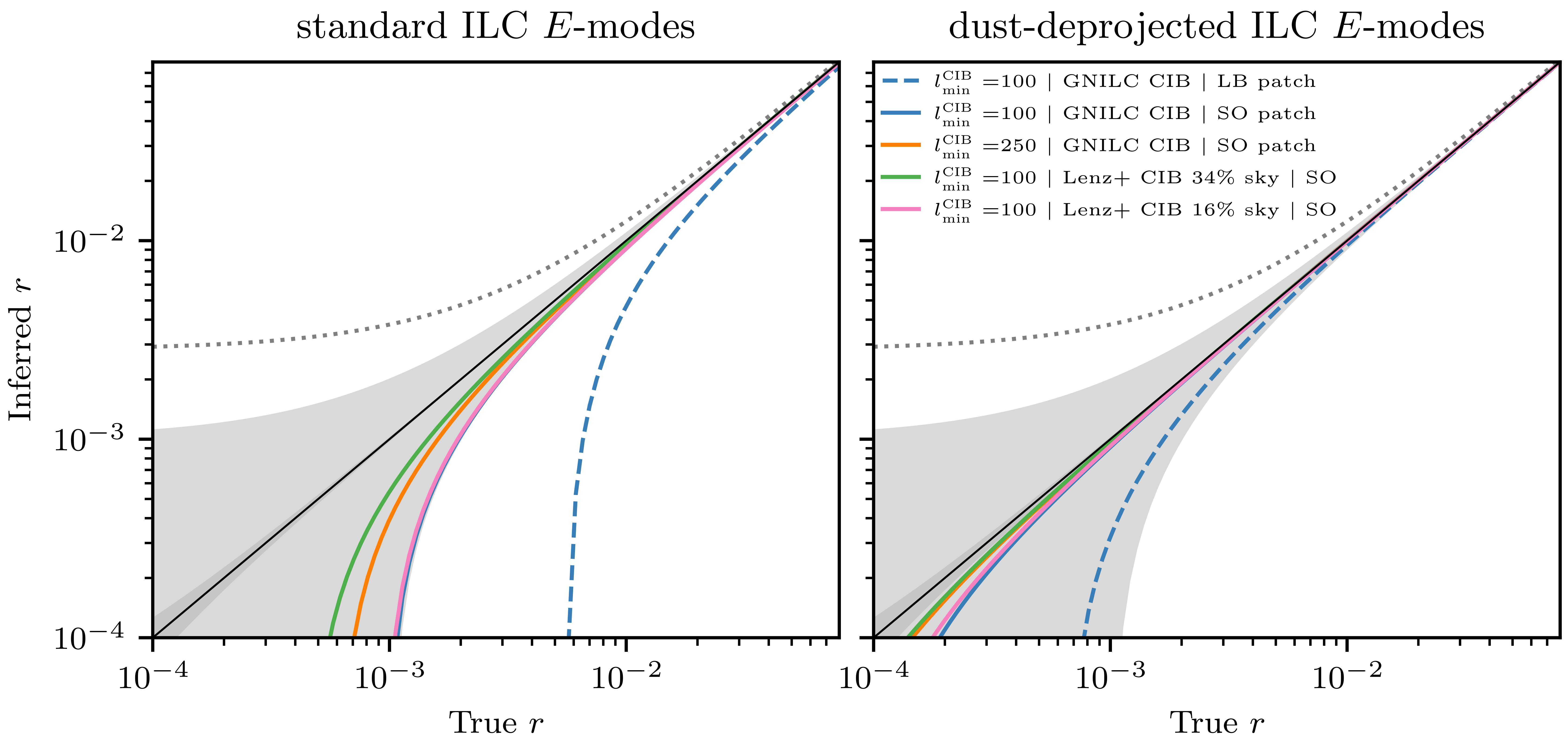
DELENSING SO WITH THE CIB — BIAS FROM RESIDUAL GALACTIC DUST



- Negative bias dominated 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 21, arXiv:2102.01045

DELENSING SO WITH THE CIB — BIAS FROM RESIDUAL GALACTIC DUST



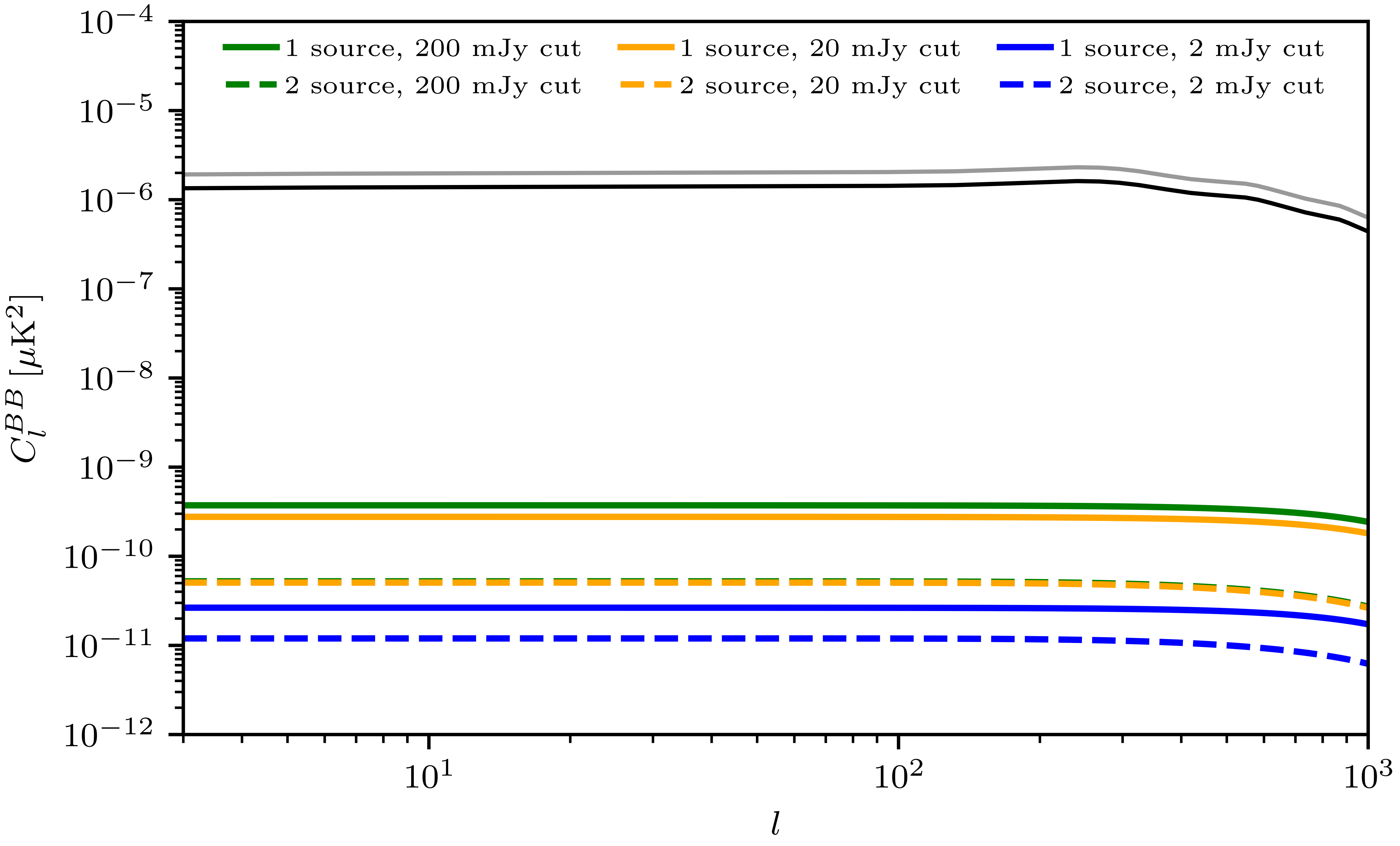
- Bias leads to underestimation of r
- Can be mitigated by nulling dust contribution to E-modes, with only small penalty in delensing efficiency
- Small on scales probed from the ground

__ABL__, Challinor, Sherwin & Namikawa 21, arXiv:2102.01045

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

In a minimal analytic model with uncorrelated source polarisation angles,

$$\mathcal{B}_l^{BEI} = 2p^2 G_{353\,\mathrm{GHz}} G^2_{145\,\mathrm{GHz}} \int \frac{d^2\boldsymbol{l}'}{(2\pi)^2} \frac{\boldsymbol{l}' \cdot (\boldsymbol{l} - \boldsymbol{l}')}{|\boldsymbol{l} - \boldsymbol{l}'|^2} \mathcal{W}^E(\boldsymbol{l}')\mathcal{W}^I(|\boldsymbol{l} - \boldsymbol{l}'|) \sin^2 2(\psi_{\boldsymbol{l}'} - \psi_{\boldsymbol{l}})$$
$$\times \int dz \left(\frac{I^{\mathrm{CIB}}[145(1+z)\,\mathrm{GHz}]}{I^{\mathrm{CIB}}[353(1+z)\,\mathrm{GHz}]} \right)^2 \left[S^{(3)}_{353\,\mathrm{GHz}}(z) + \frac{H(z)}{cr^2(z)} S^{(2)}_{353\,\mathrm{GHz}}(z) S^{(1)}_{353\,\mathrm{GHz}}(z) P_g\left(|\boldsymbol{l} - \boldsymbol{l}'|/r(z); z\right) \right]$$



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

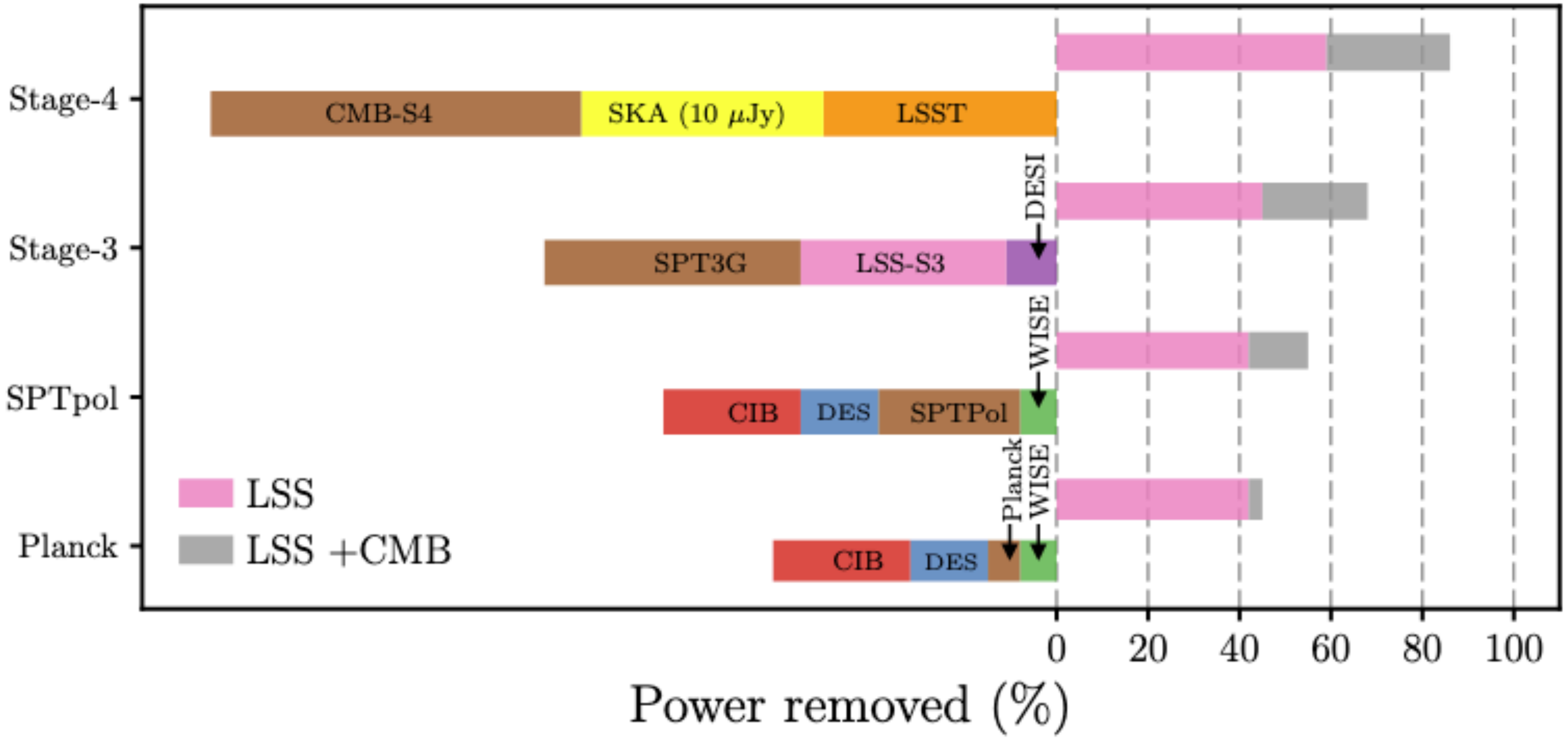
and $\langle B^{CIB}E^{CIB}T^{CIB}\rangle \gg \langle E^{CIB}T^{CIB}E^{CIB}T^{CIB}\rangle$ for expected flux cuts.

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

ABL, Challinor, Sherwin & Namikawa 21, arXiv:2102.01045

INTERNAL DELENSING

Manzotti 17



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

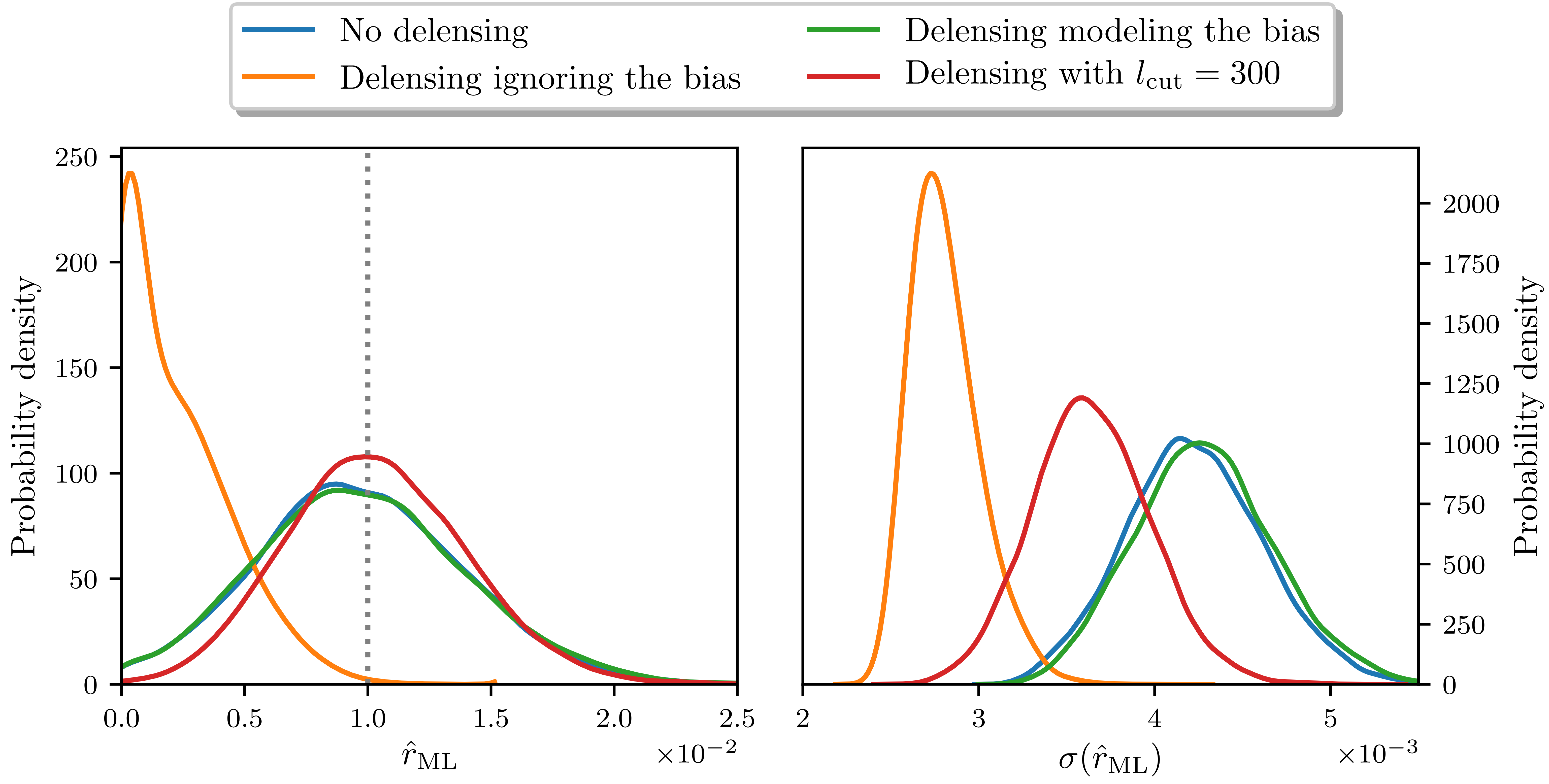
Maximum-a-posteriori (MAP) $\hat{\phi}$ reconstruction will supersede QEs *Hirata & Seljak 03, Carron & Lewis 17*

Delensing with MAP $\hat{\phi}$ and Bayesian lensing reconstruction both recently demonstrated on data!

Millea+20, POLARBEAR 20

INTERNAL DELENSING BIAS

- Overlap in modes between B in EB estimator and B-modes to be delensed causes spurious suppression of delensed power spectrum and its **variance** *Teng et al. 11, Namikawa & Nagata 14*
- Could this lower variance translate to improved constraints on r ? NO



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

__ABL__, Challinor & Carron, JCAP, arXiv:2007.01622

CONCLUSIONS

- **CMB lensing spectra** probes anything affecting growth of structure (including Σm_ν). Great synergy with Stage-4 LSS surveys
- Polarization-based reconstructions very clean. Temperature can be biased by extragalactic foregrounds, but can be mitigated
  - We calculate these biases analytically — good for understanding, informing masking & marginalising over modeling uncertainties.
    - Upcoming data (CCATp & SO) will improve models. Next: extend to polarisation & iterative reconstructions.

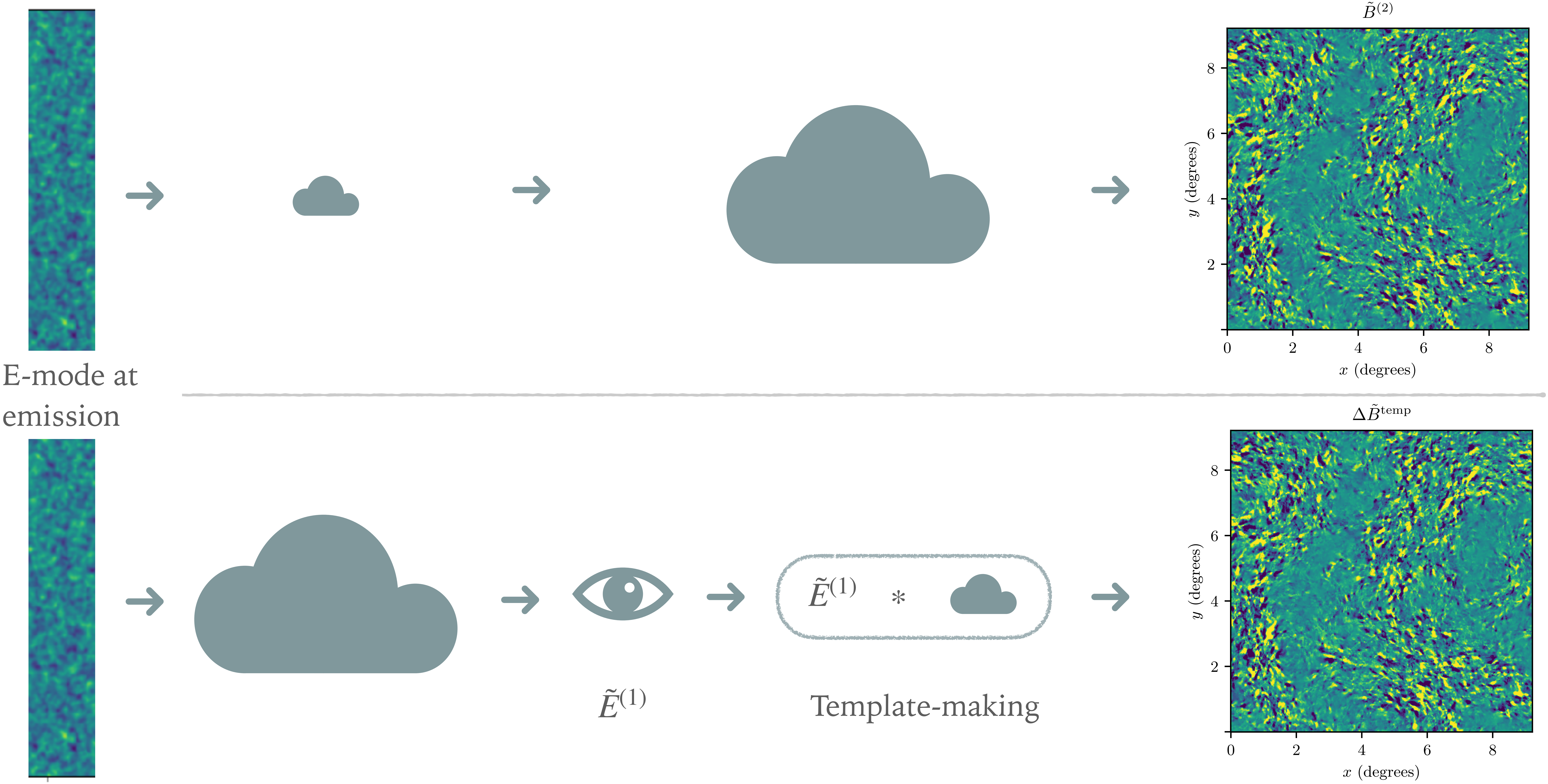
- Primordial B-modes probe inflation/alternatives via the tensor-to-scalar ratio, r
- **Delensing B-modes** is **essential** for CMB-S3 & CMB-S4 r targets
  - First-order lensing B-mode template built from lensed E is effectively optimal beyond CMB-S4 & transparent to systematics
  - For SO, multi-tracer delensing removes $\sim 70\,\%$ of power, halves $\sigma(r)$
  - LSS tracers great for delensing (even CMB-S3). CIB particularly useful, but deproject galactic dust to avoid bias
  - Internal delensing biases, with us for the foreseeable future — better to mask overlapping modes than to model

Thank you very much for having me!

a.baleatolizancos@ast.cam.ac.uk

BACK-UP SLIDES

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



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

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

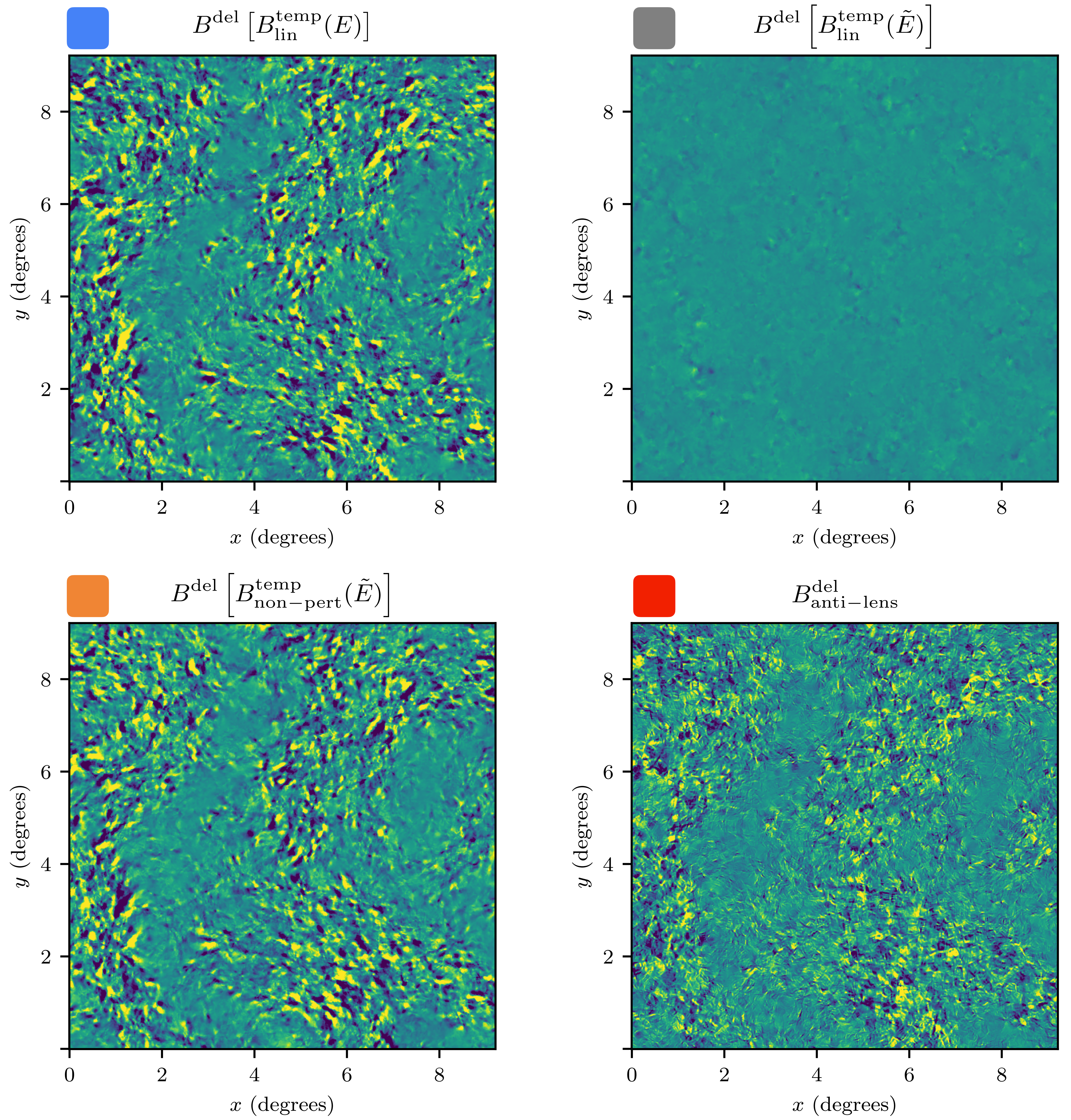
When subtracting this off of observations,

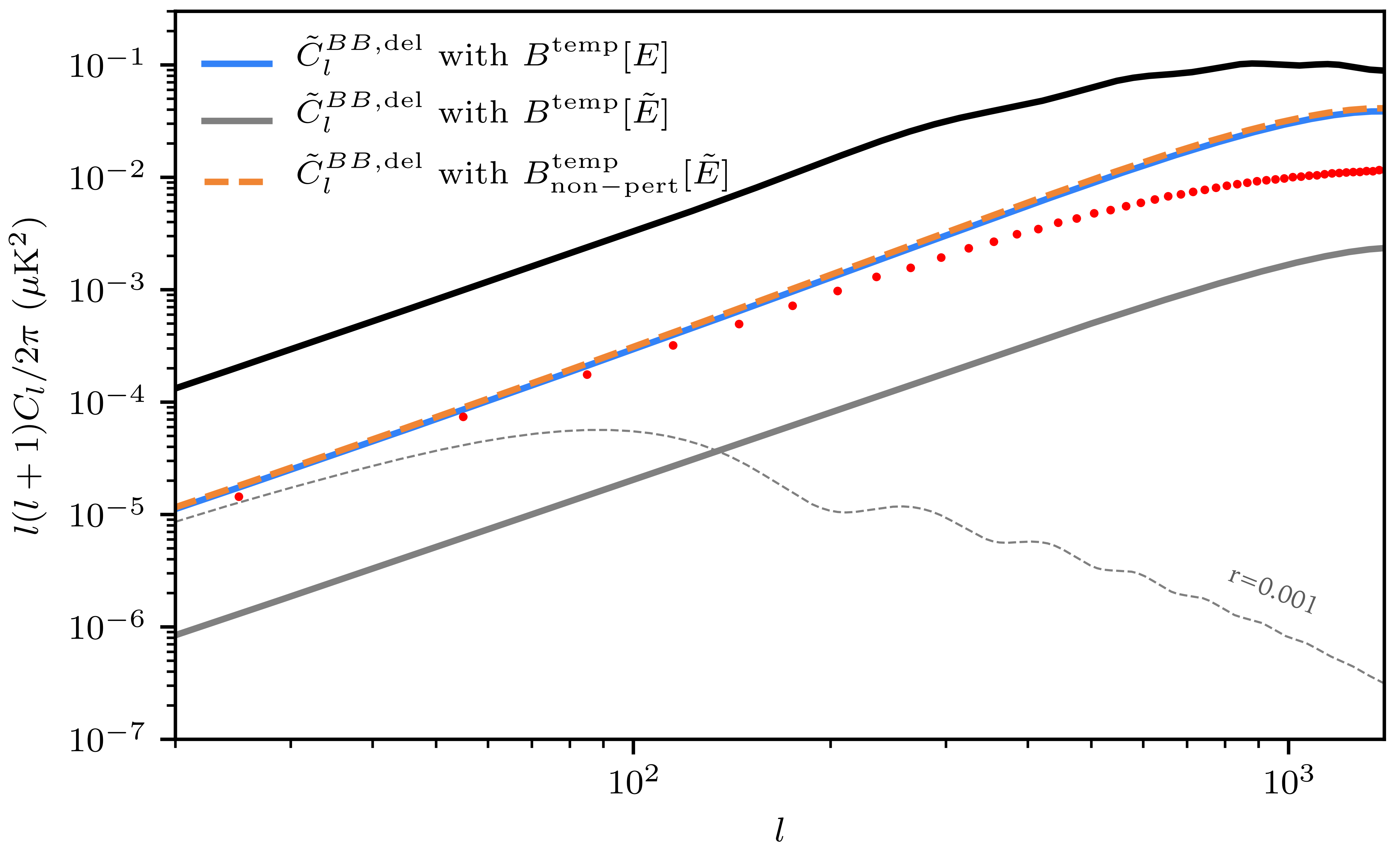
$$B^{\rm del} = B^{\rm obs} - \tilde{B}^{\rm temp}_{\rm non-pert} = \left(\cancel{\tilde{B}^{(1)}}(\mathbf{l}) + \cancel{\tilde{B}^{(2)}}(\mathbf{l}) + O(\phi^3)\right) - \left(\cancel{\tilde{B}^{(1)}}(\mathbf{l}) + \underline{\Delta\tilde{B}^{\rm temp}(\mathbf{l})} + \cancel{\tilde{B}^{(2)}}(\mathbf{l})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

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

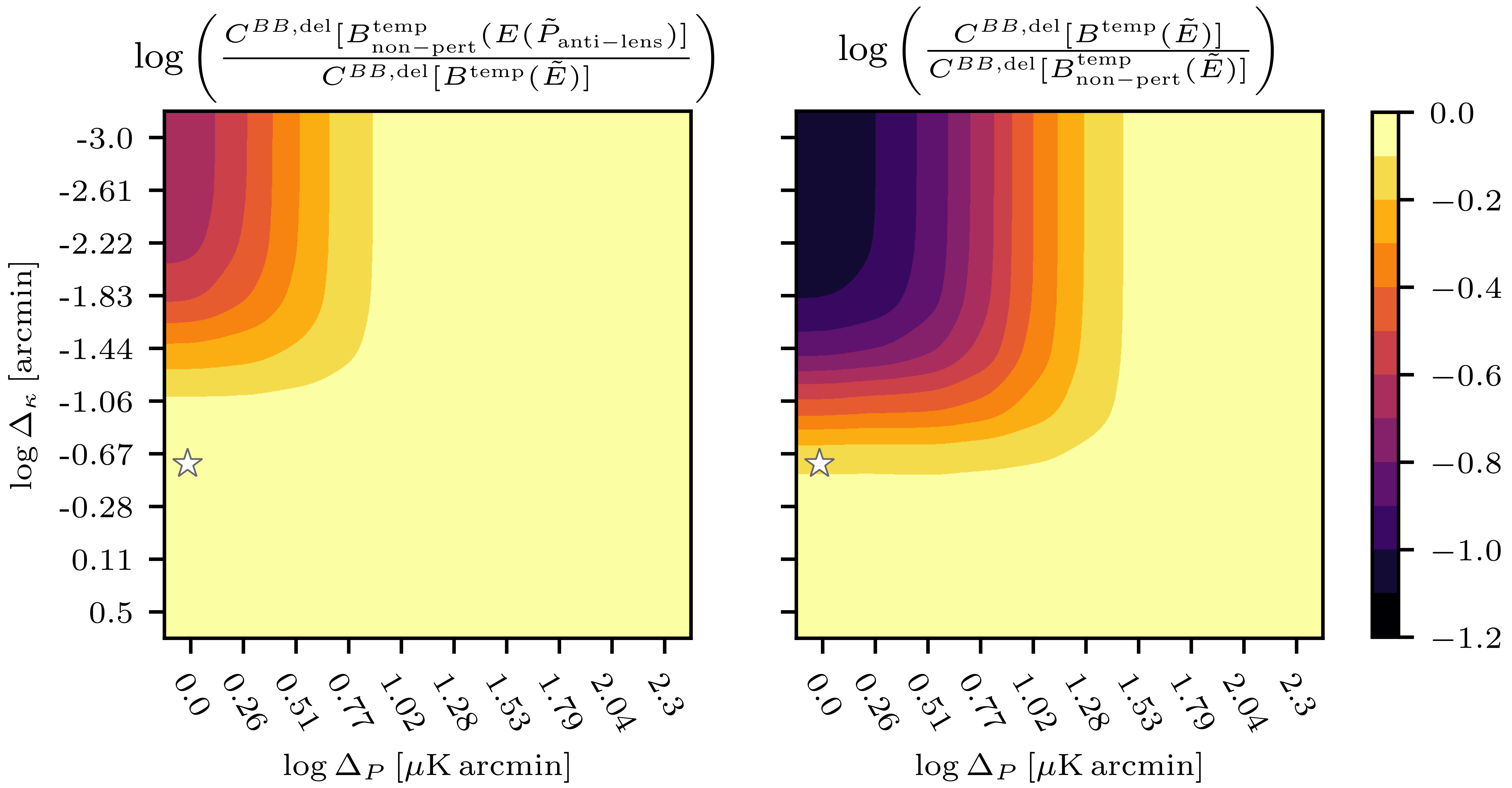




- Cancellations disappear if linear template is built from unlensed or delensed E-modes, hit delensing floor of O(10)%
- New cancellations arise when the lensed E-modes are used in the linear template, so delensing floor is O(1)%
- Advantage is lost when a non-perturbative template is built from lensed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

__ABL__, Challinor & Carron, PRD (Editor's suggestion), arXiv:2010.14286

ADDITIONAL SLIDES



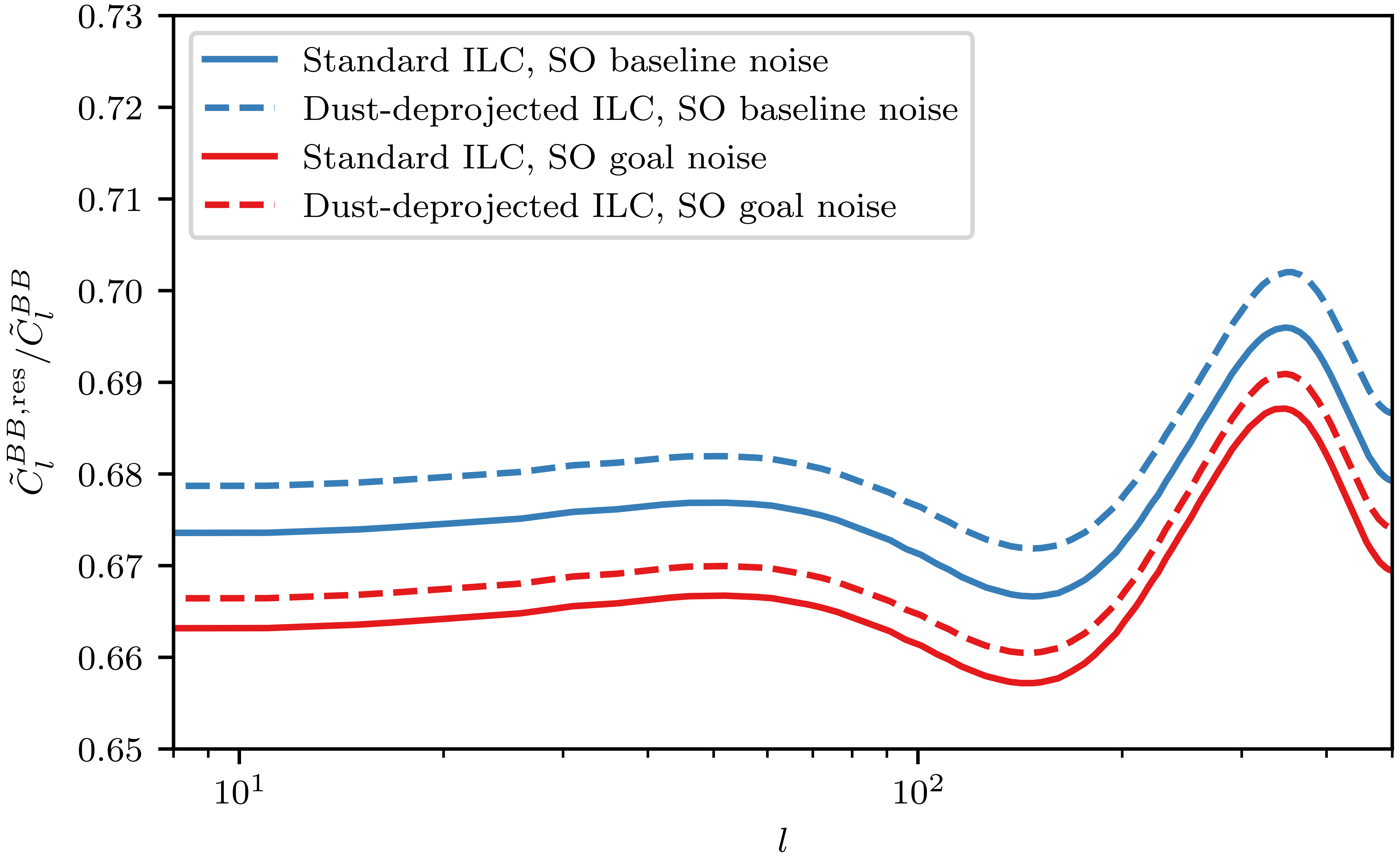
Left panel numerator:

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.

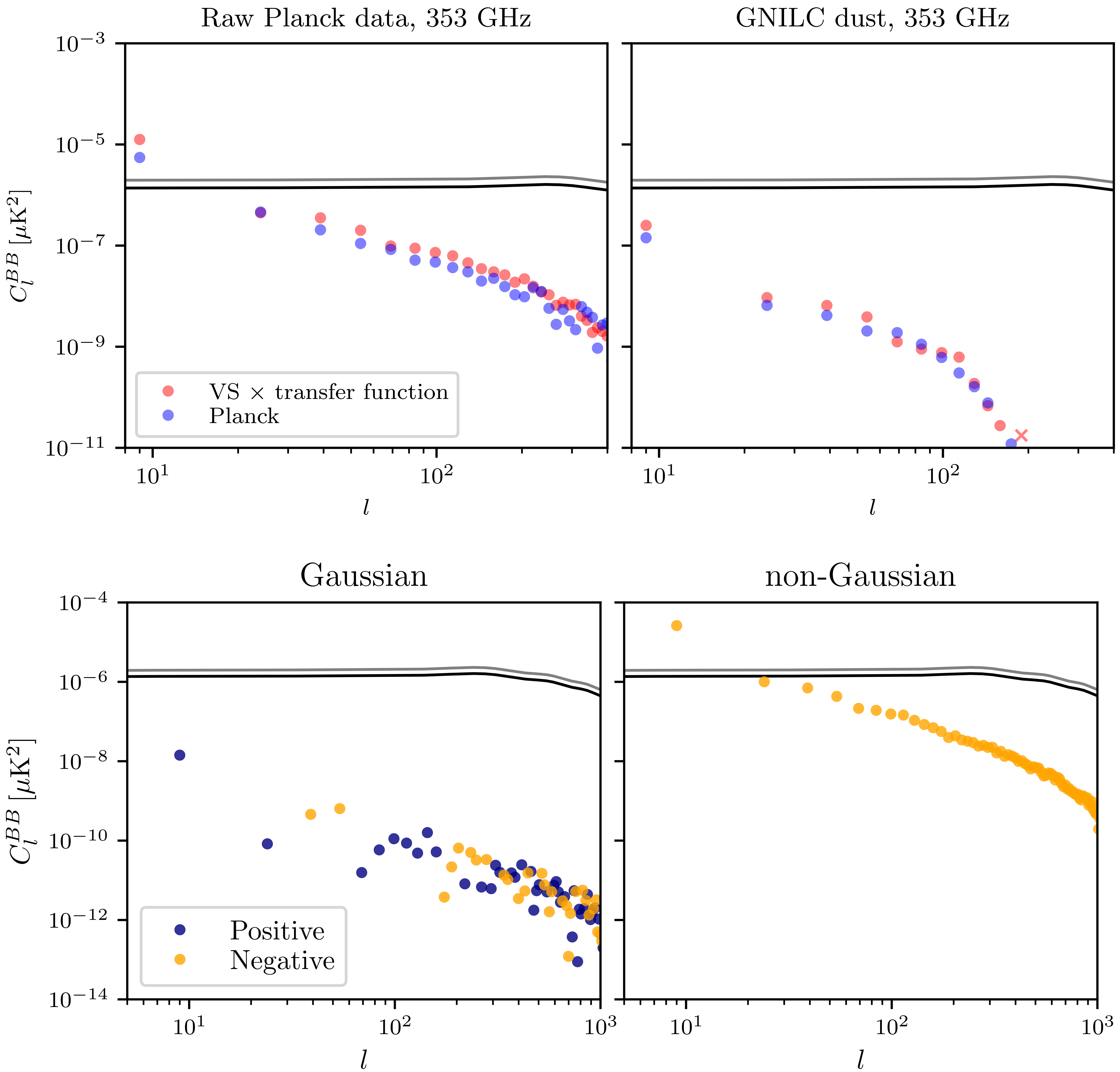
ADDITIONAL SLIDES

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



***ABL**, Challinor, Sherwin & Namikawa 21, arXiv:2102.01045*

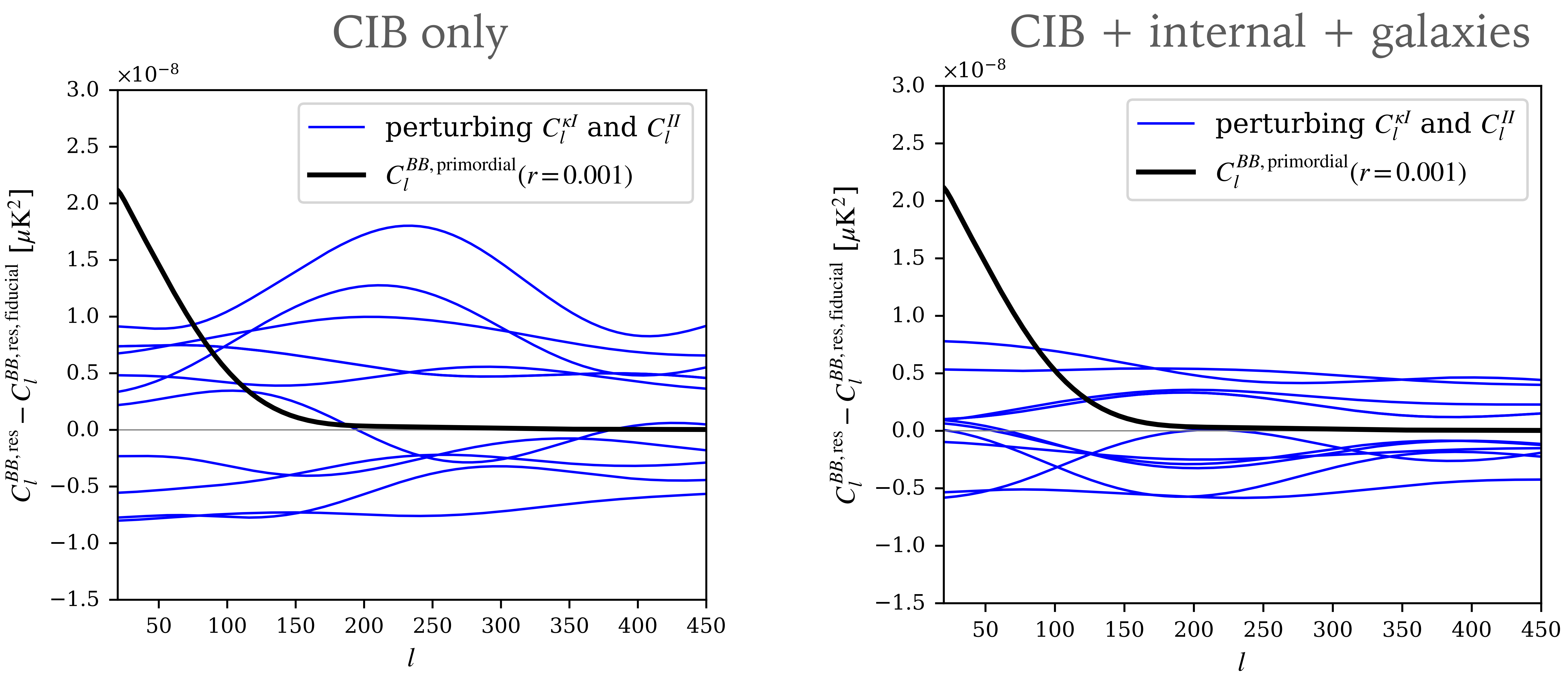
ADDITIONAL SLIDES



__ABL__, A. Challinor, B. Sherwin & T. Namikawa 21 (out today!)

CHALLENGES TO MULTI-TRACER DELENSING

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



Flat enough to marginalise over amplitude parameter!

*T. Namikawa, **ABL**, N. Robertson, A Challinor, B. Sherwin & B. Yu 21 (to be submitted)*

- The impact of foregrounds

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:

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

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

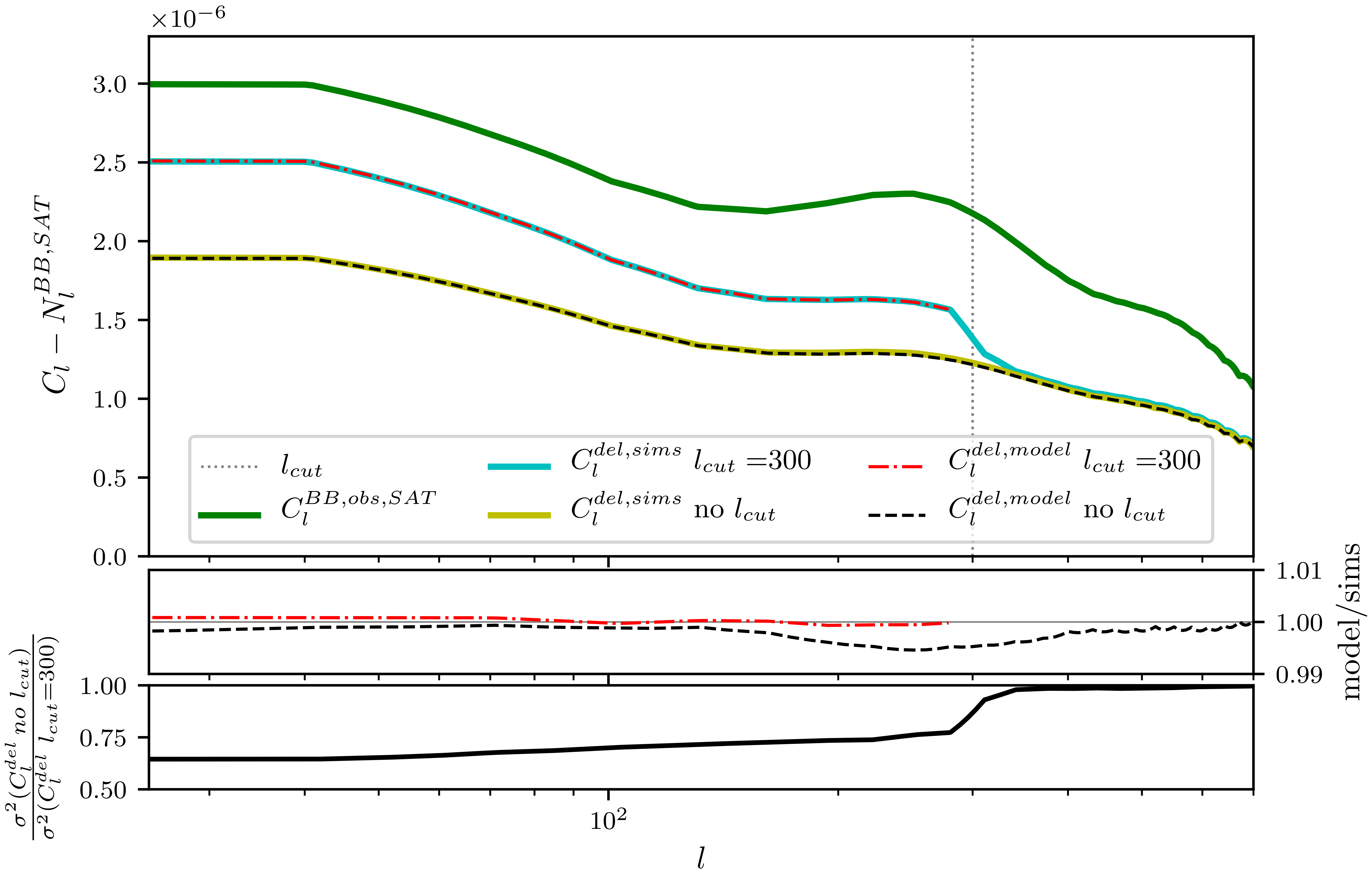
$$\langle B^{obs}E^{obs}E^{obs}B^{obs}\rangle$$

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

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

Teng+11, Namikawa & Nagata 14

INTERNAL DELENSING BIAS



Variance of delensed spectrum is reduced!

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

ABL, Challinor & Carron, JCAP, arXiv:2007.01622