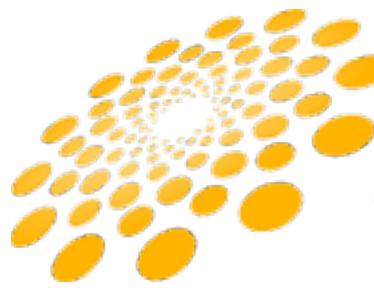


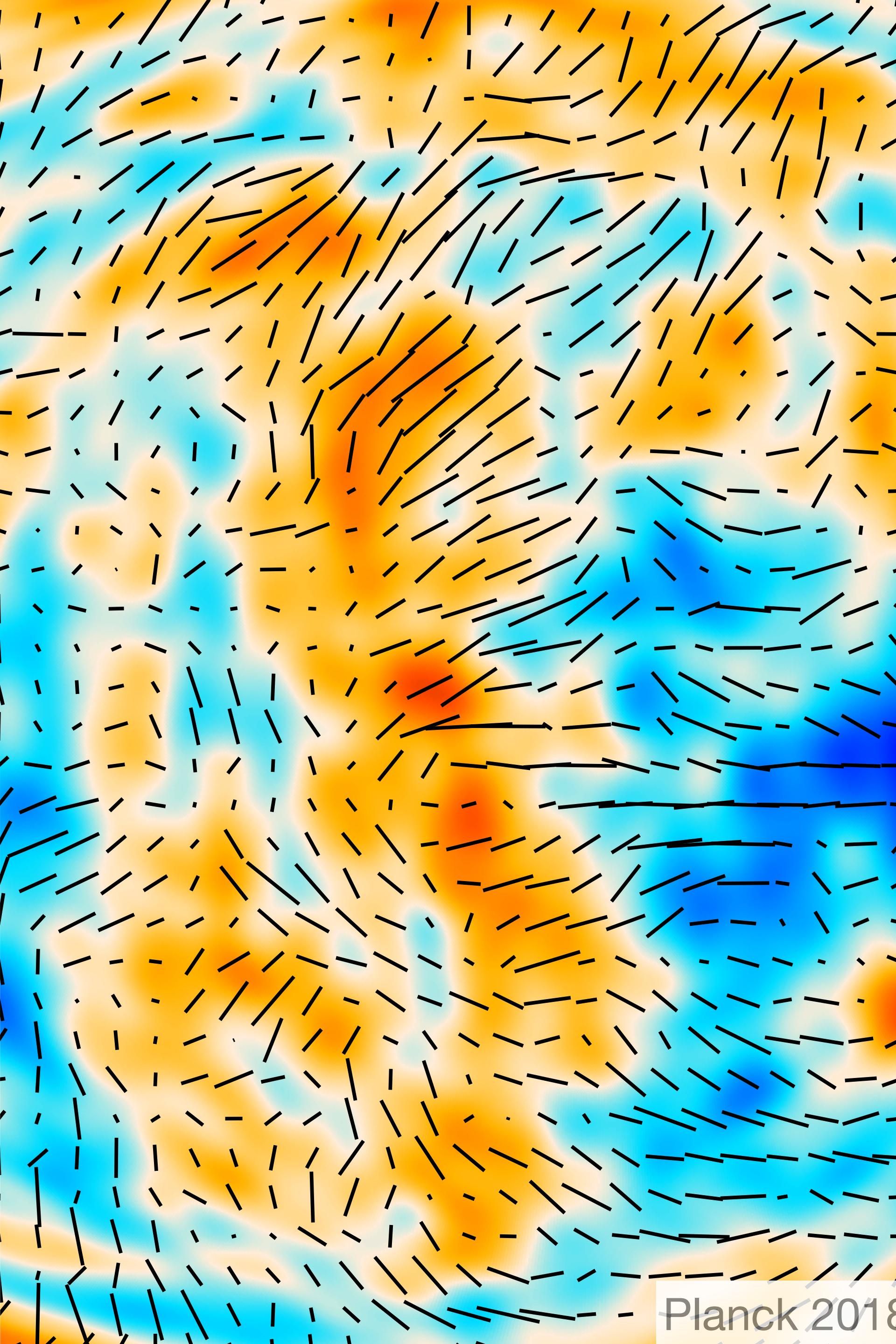
THE IMPACT OF GALAXIES AND CLUSTERS ON DELENSING OF CMB B-MODE POLARIZATION



BERKELEY CENTER *for*
COSMOLOGICAL PHYSICS

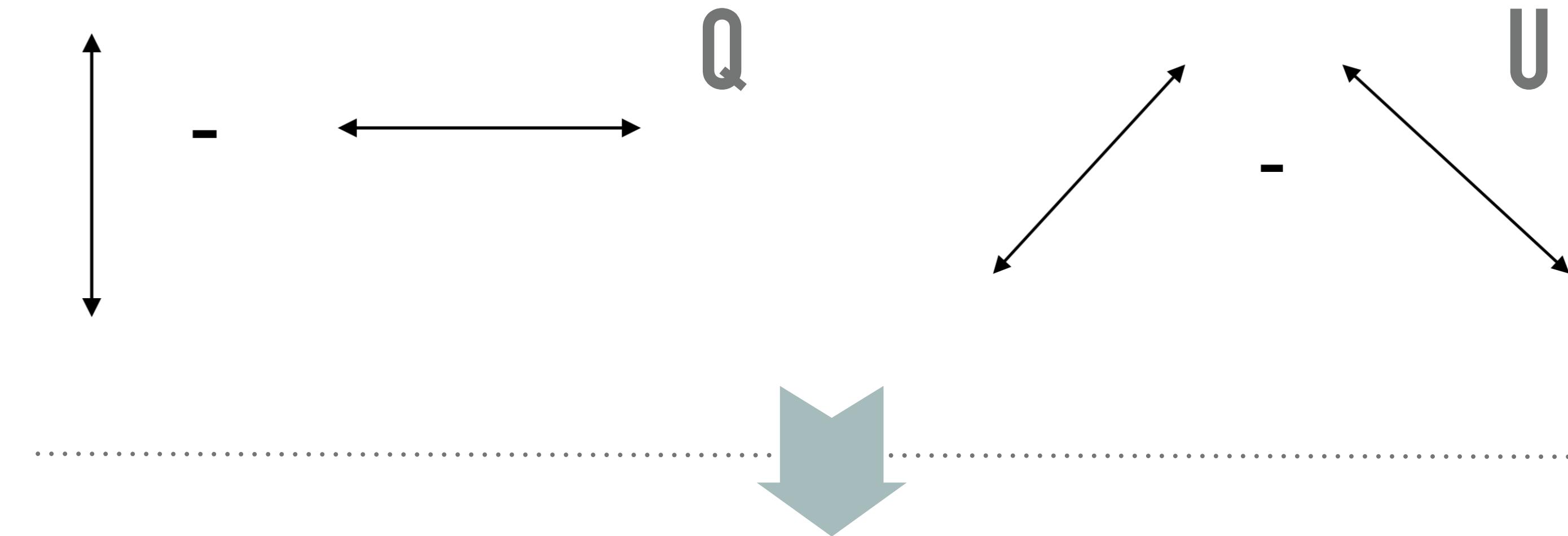


6/6/2022
Cosmology Seminar, KIPAC Stanford

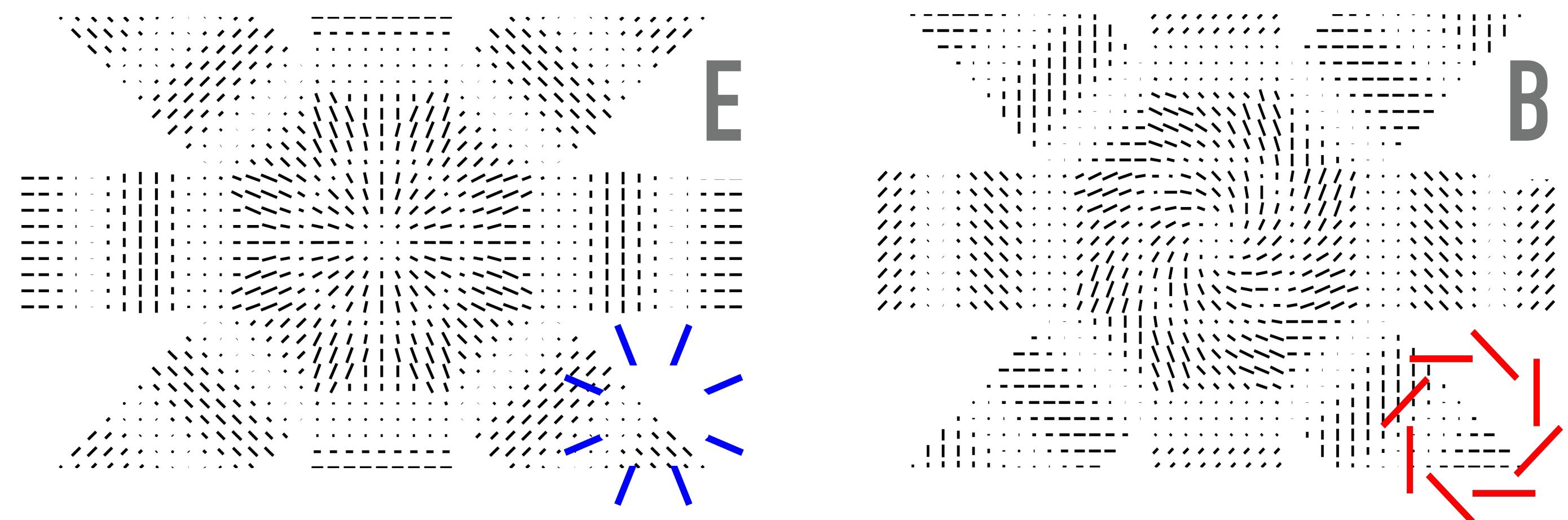


CMB OBSERVABLES — INTENSITY AND POLARISATION

Observe:

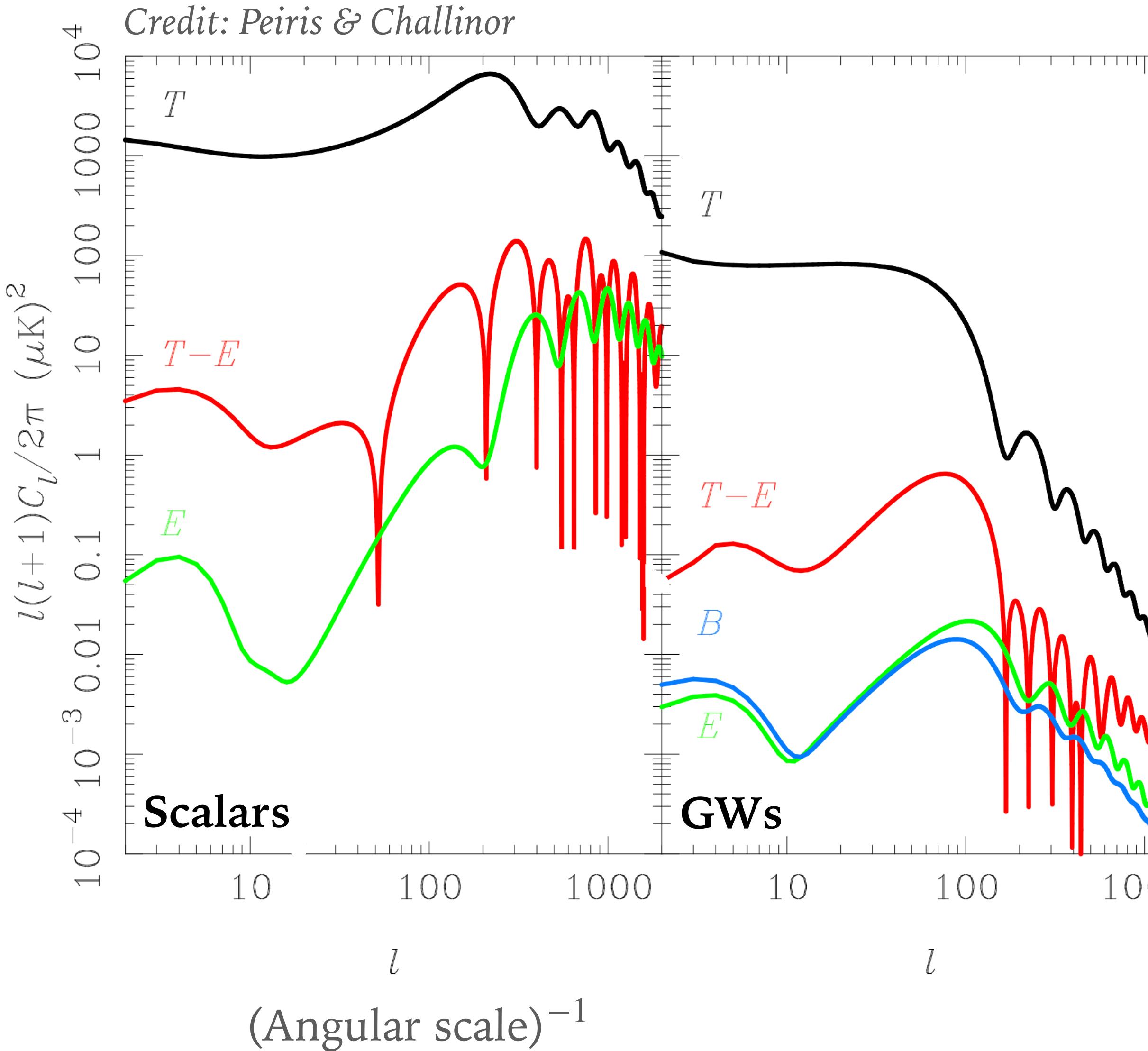


Connect with theory:



THE PRIMORDIAL CMB

Fluctuation power



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

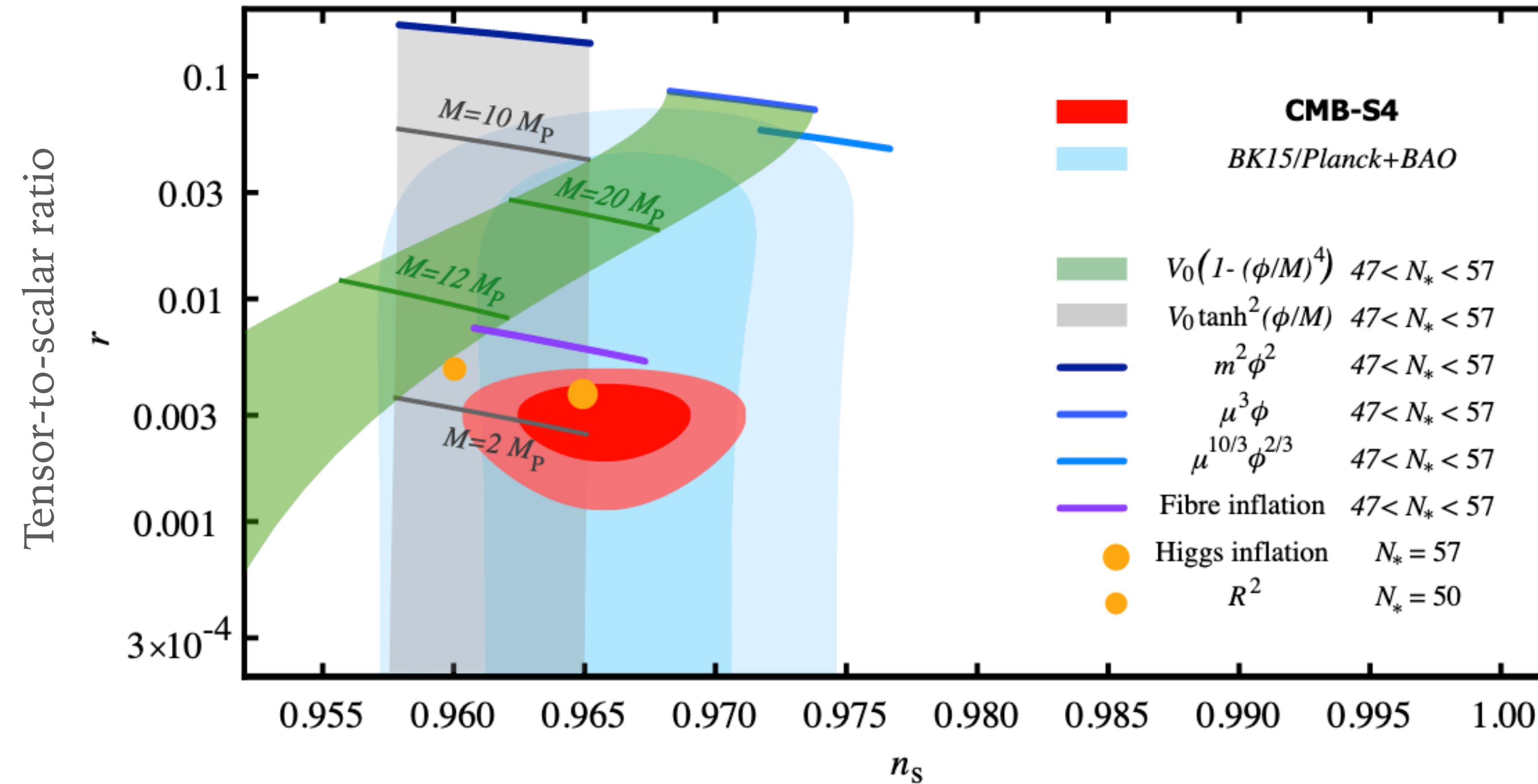
Kamionkowski + 97 , Seljak & Zaldarriaga 97

$r < 0.036$ BICEP/Keck 21

- Statistically isotropic, Gaussian random field

CONSTRAINING INFLATION VIA THE CMB

CMB-S4, arXiv:1907.04473



Spectral index of primordial (scalar) perturbations

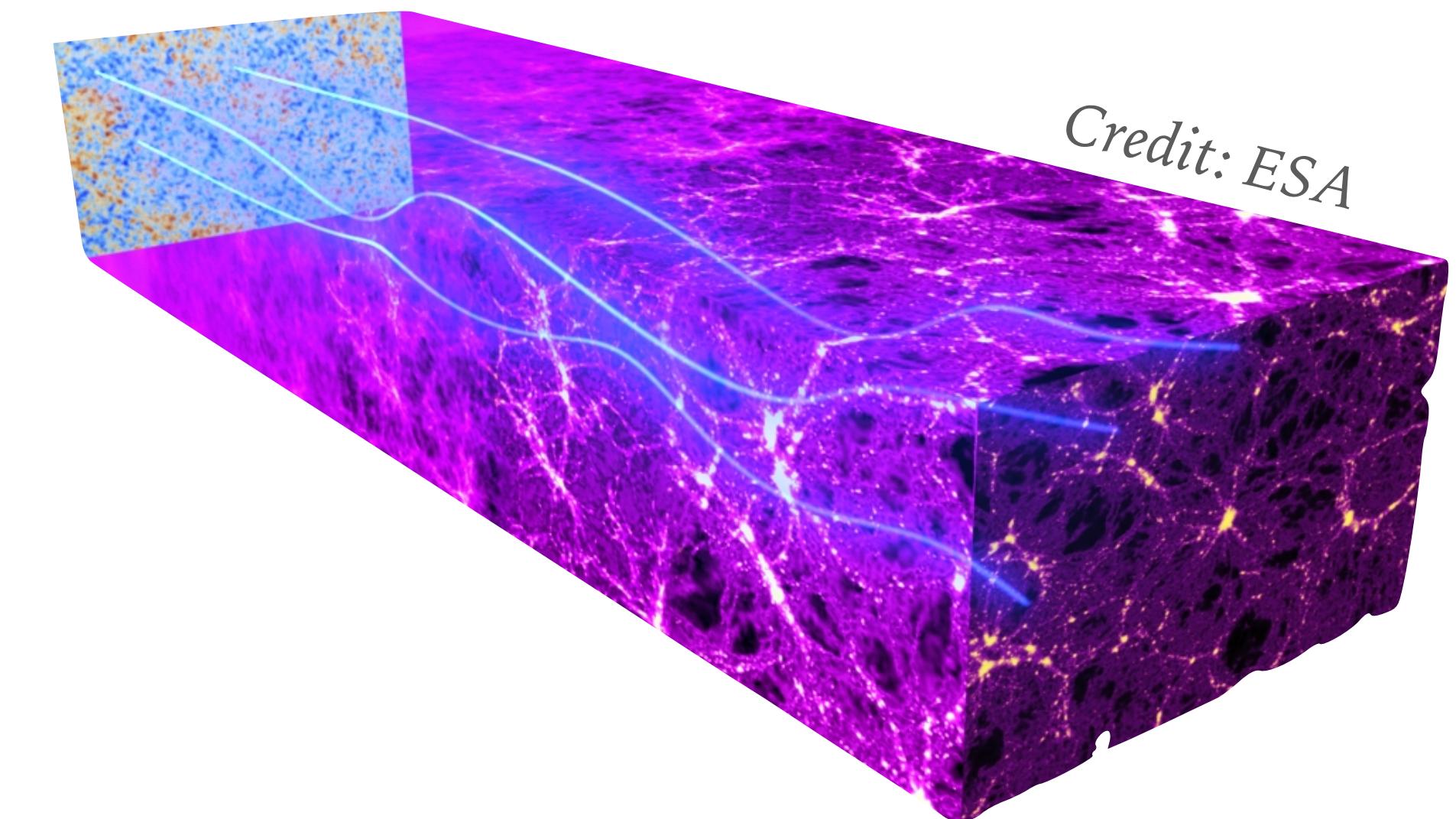
CMB LENSING

Very accurately described as:

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

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

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

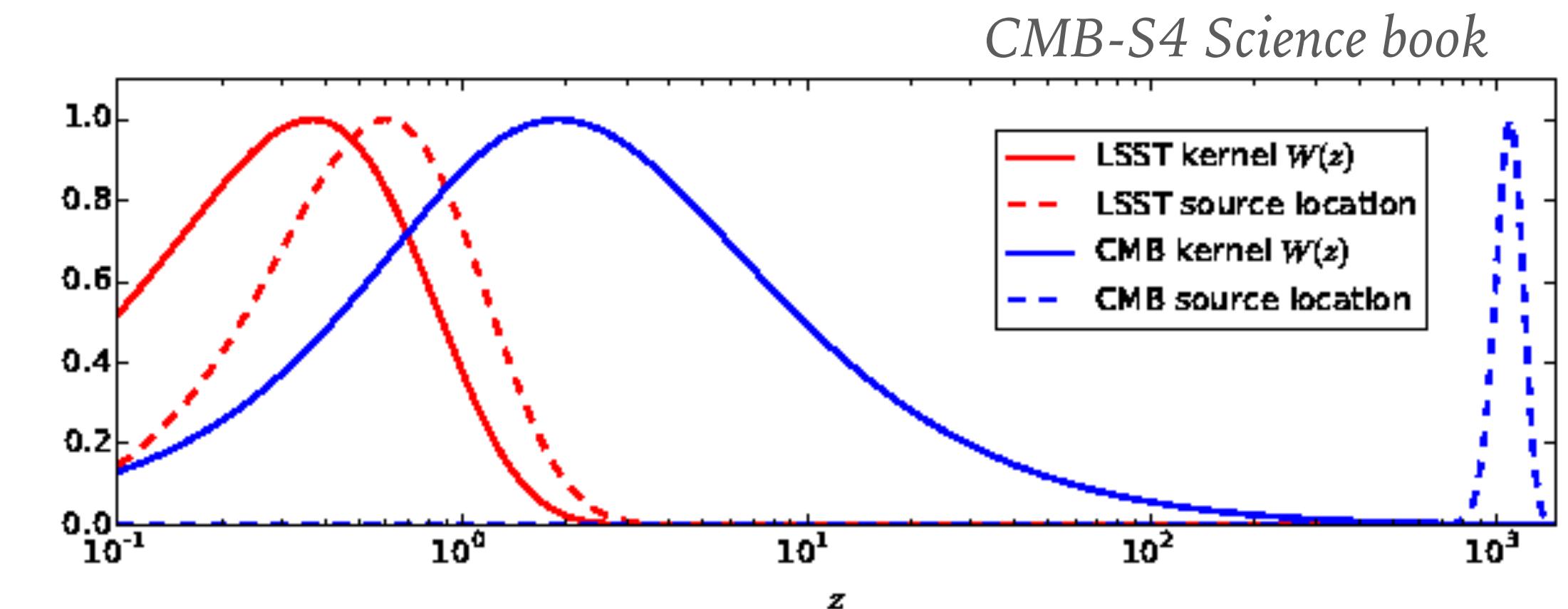


Under the Born approximation, $\alpha(\mathbf{x}) = \nabla \phi(\mathbf{x})$, where

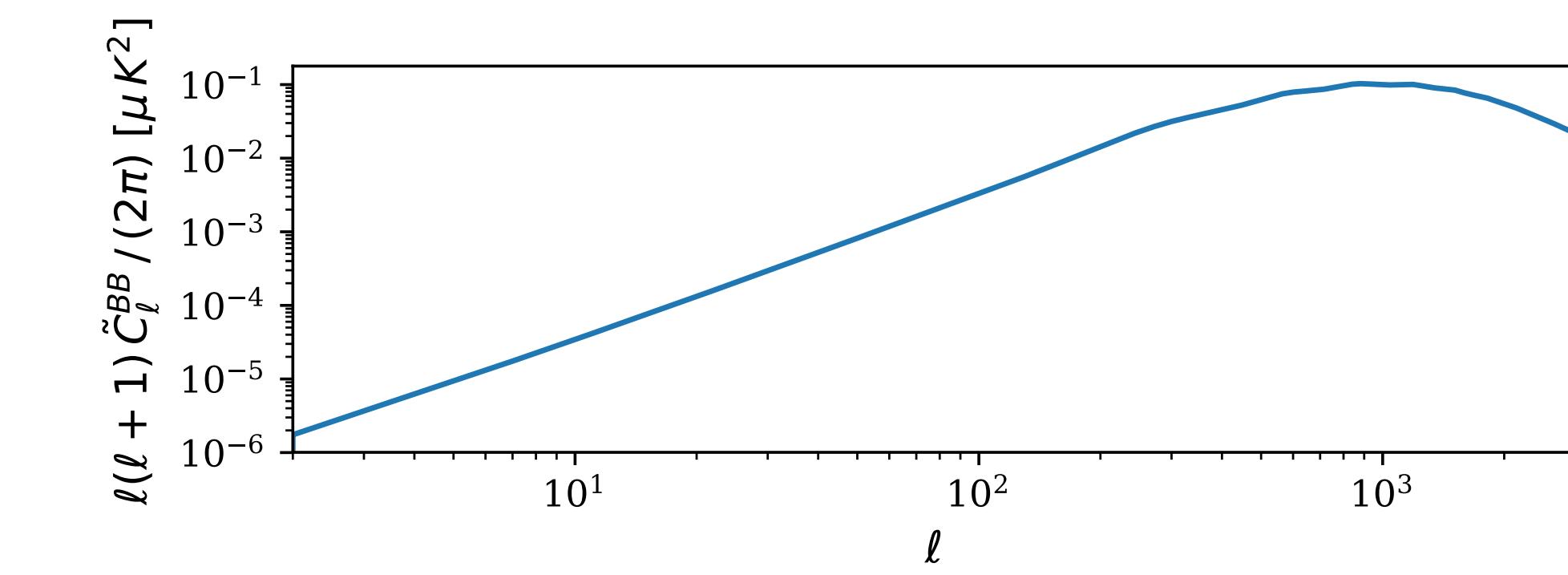
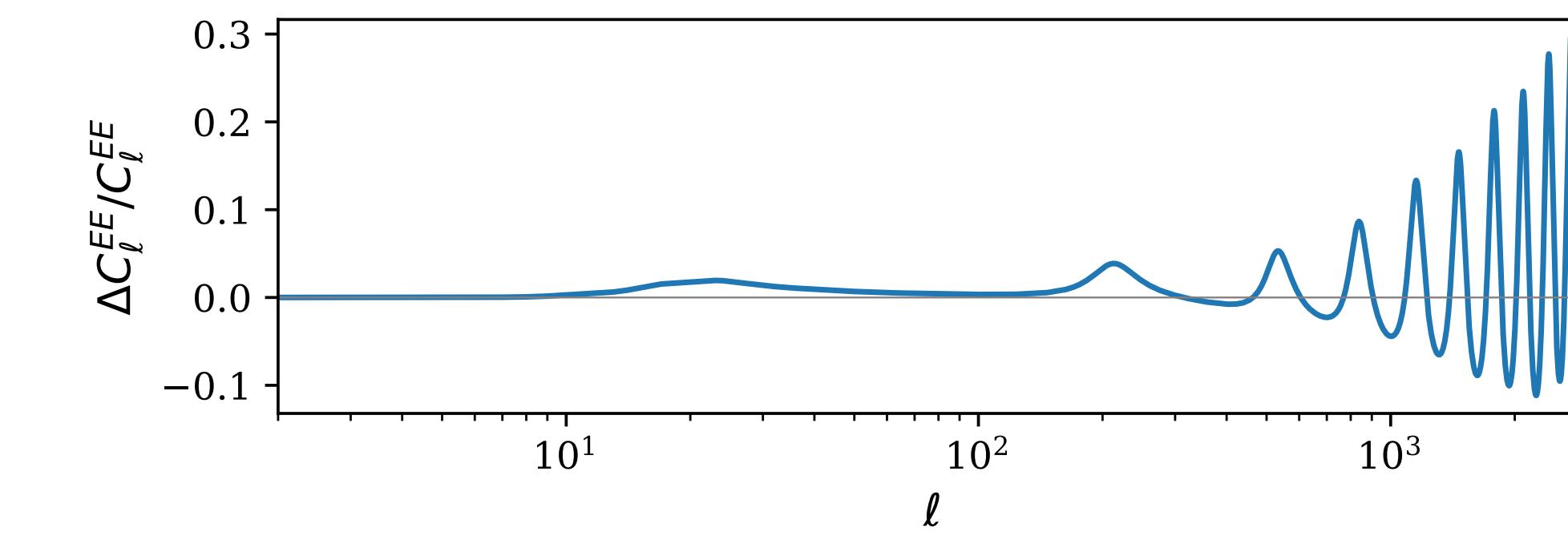
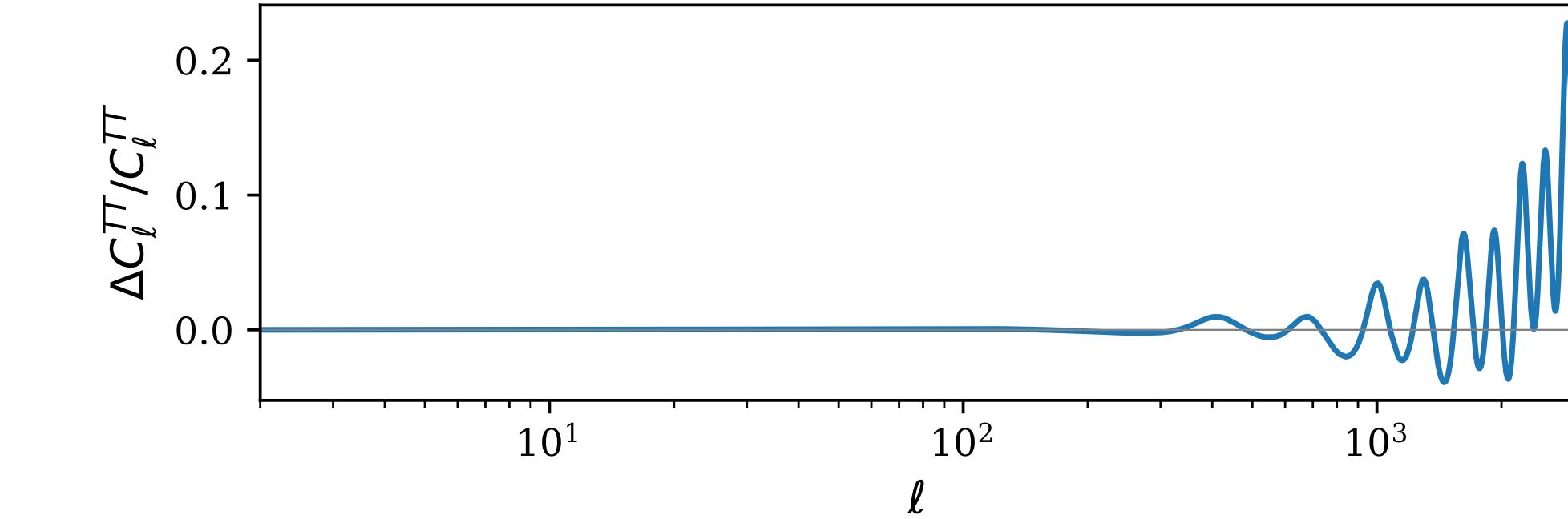
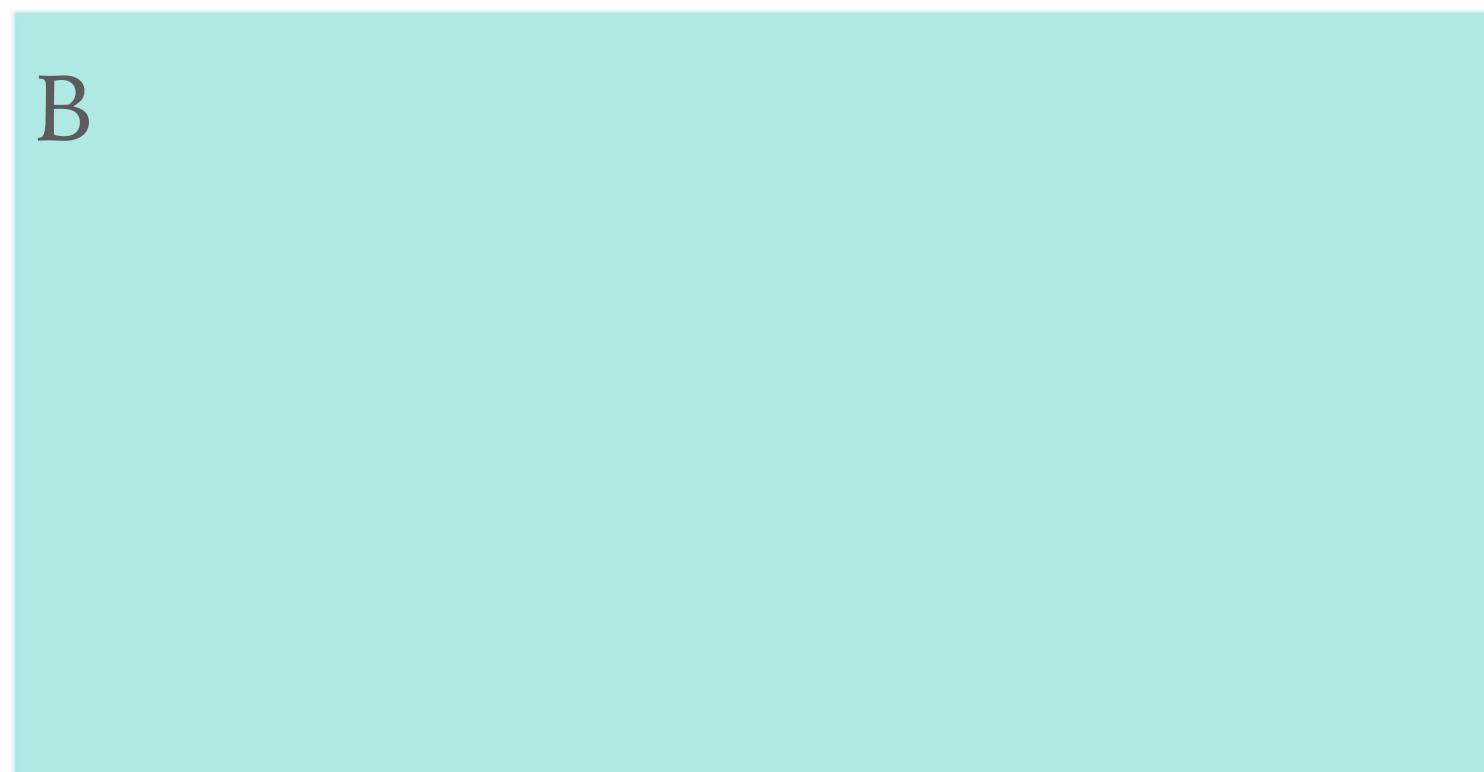
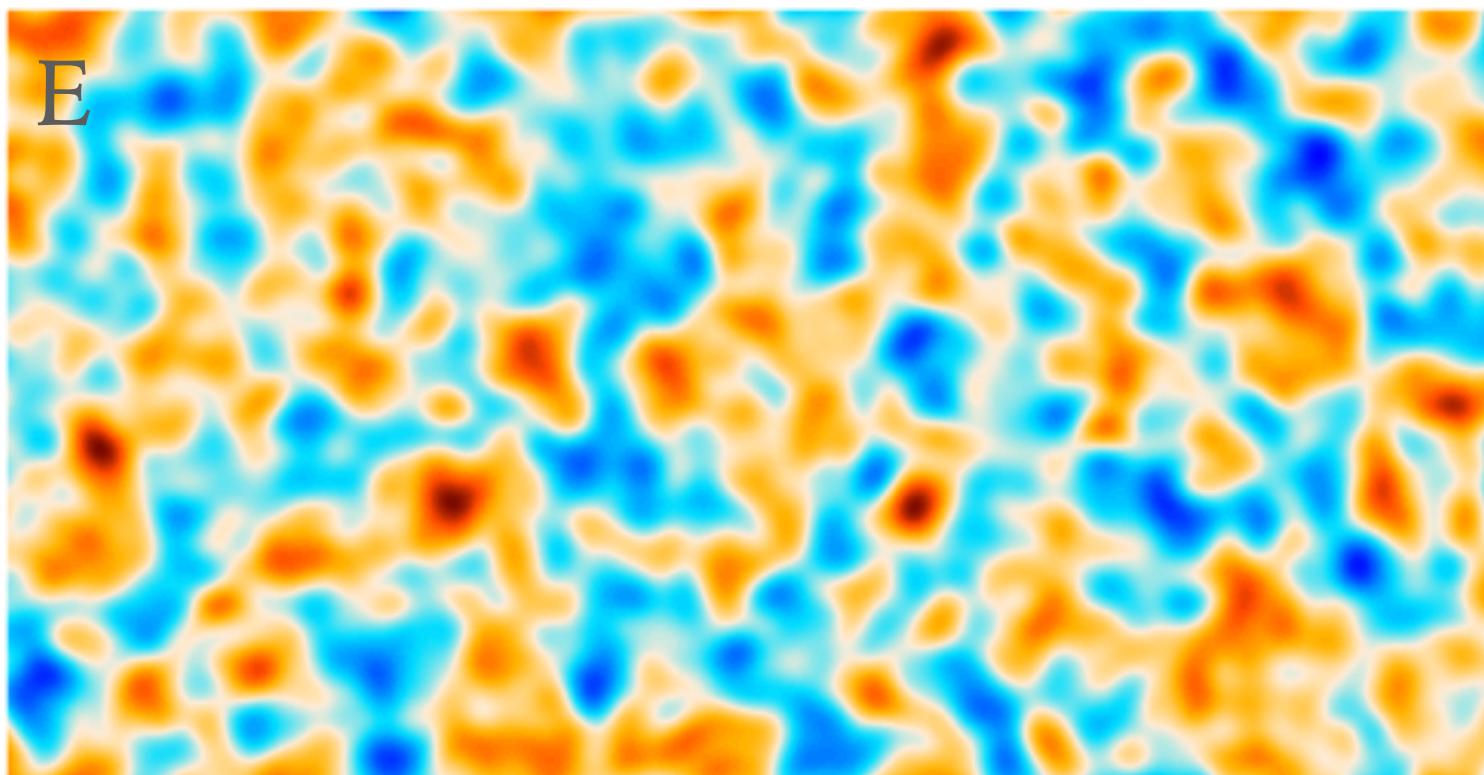
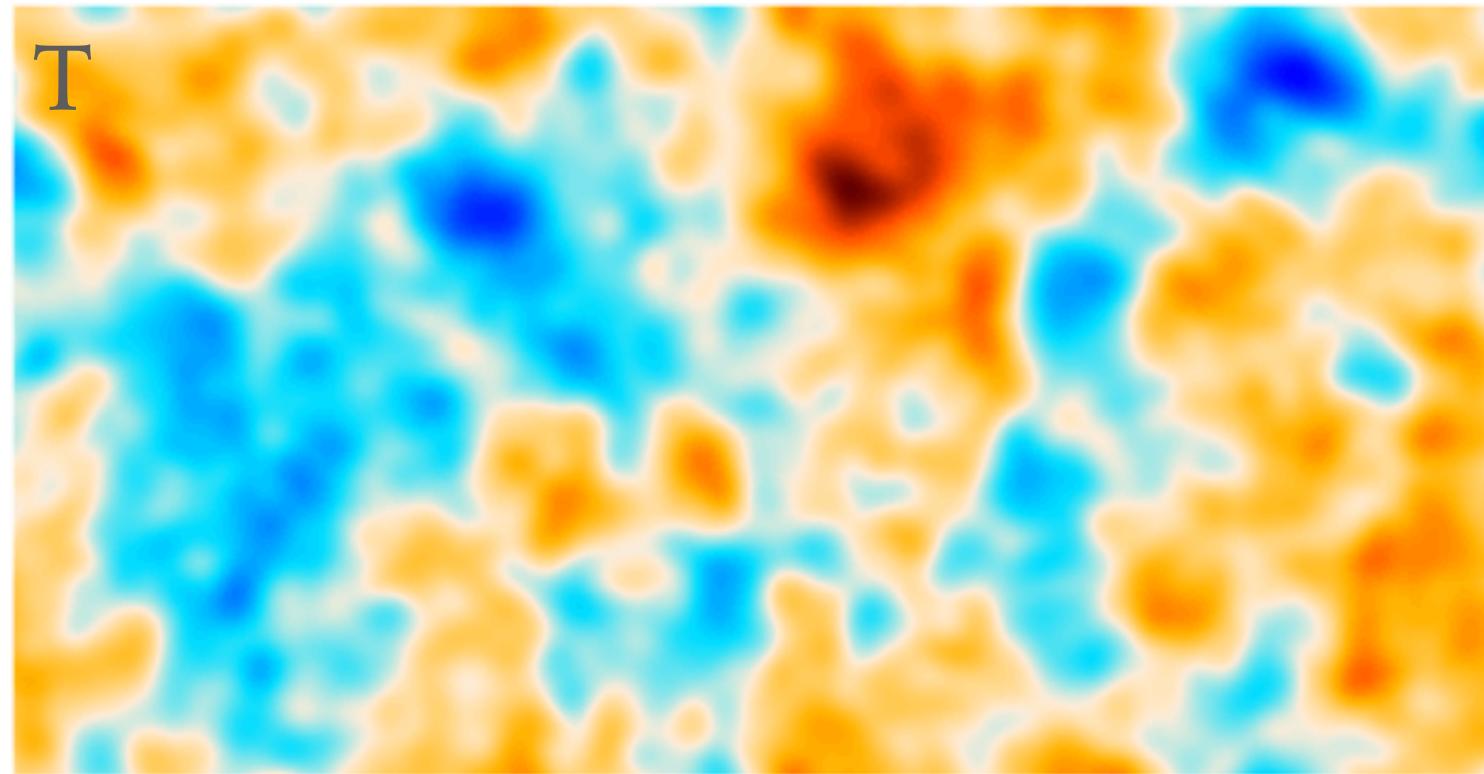
$$\phi(\mathbf{x}) = -2 \int_0^\chi d\chi g(\chi, \chi_*) \Psi(\chi \mathbf{x}, \eta_0 - \chi)$$

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

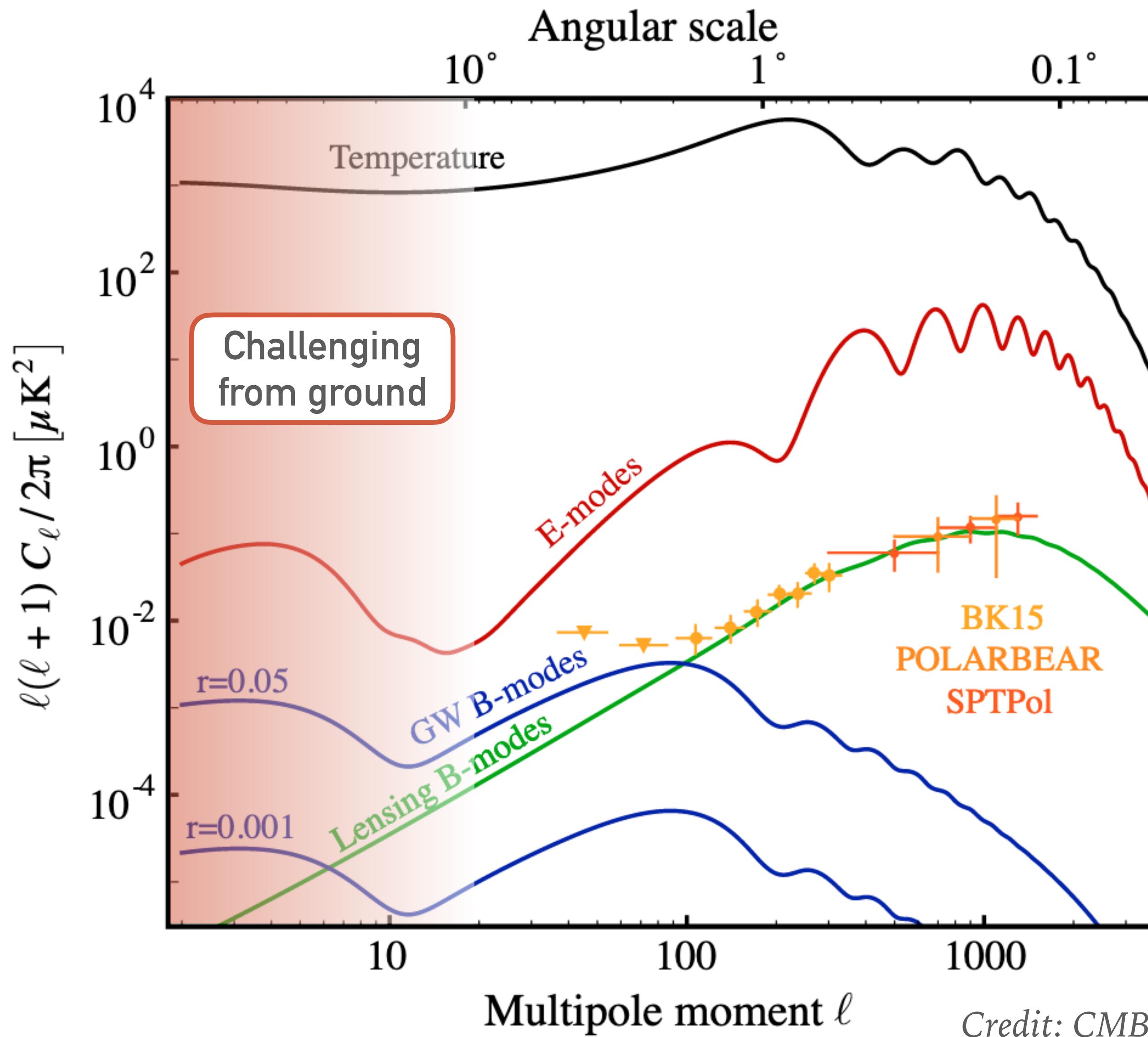
$\alpha \sim \text{arcmin}$, coherent on degree scales (typical lens $O(100\text{Mpc})$)



CMB LENSING



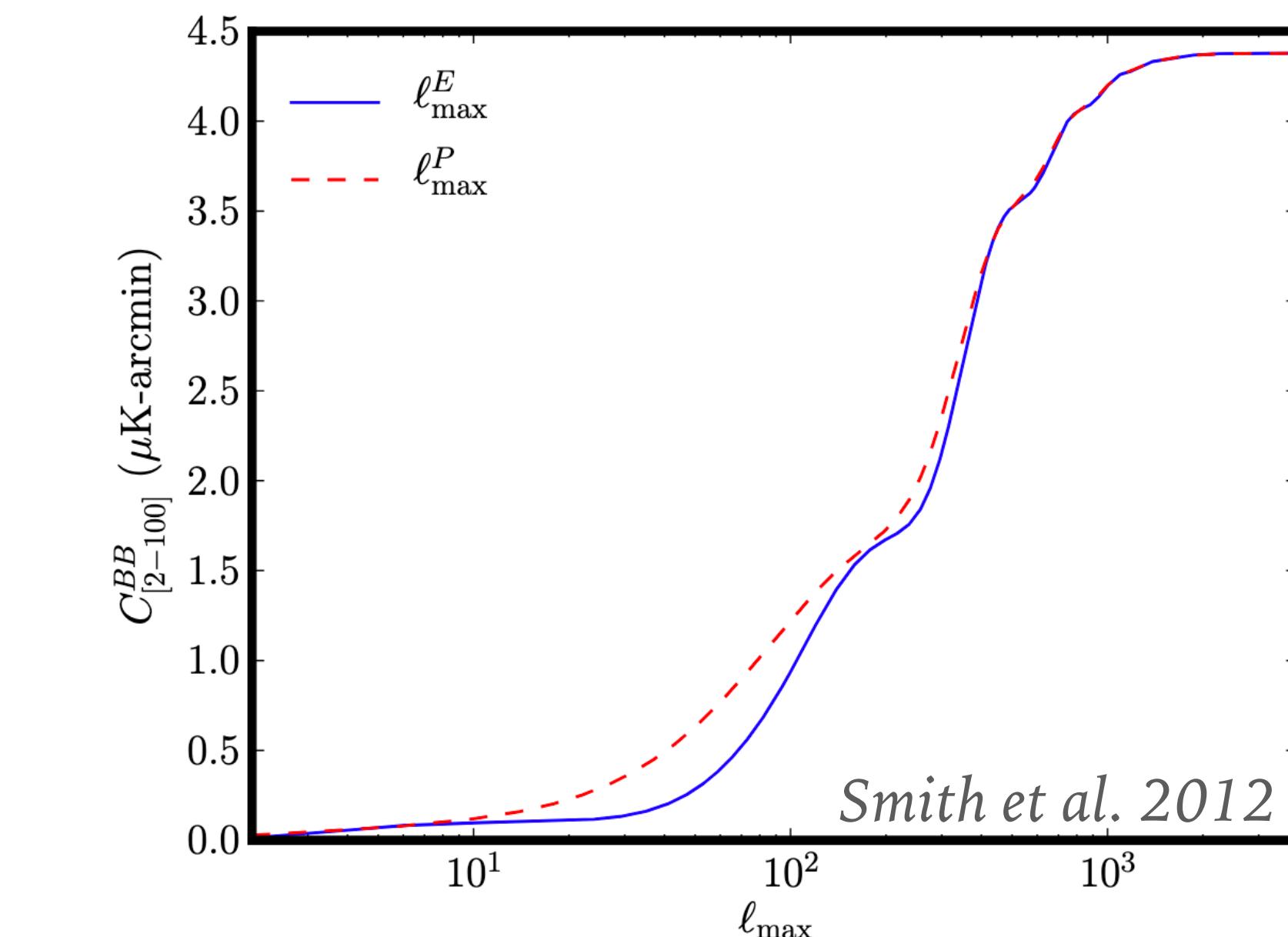
THE LENSING B-MODE



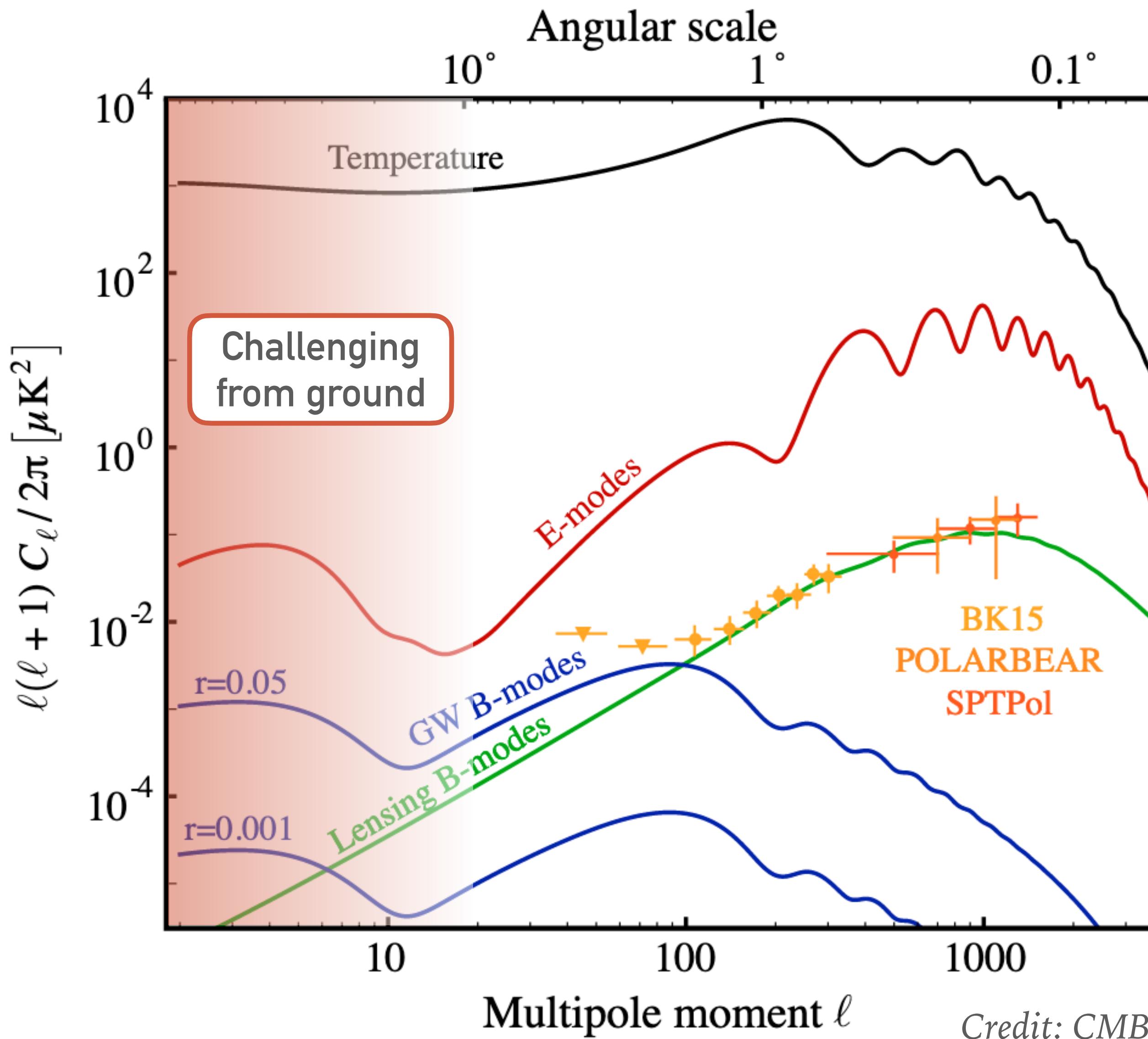
Lensing converts E- into B-modes, inducing noise with $\Delta_P \approx 5\mu\text{K arcmin}$

Zaldarriaga & Seljak 98

Why does it look like white noise?

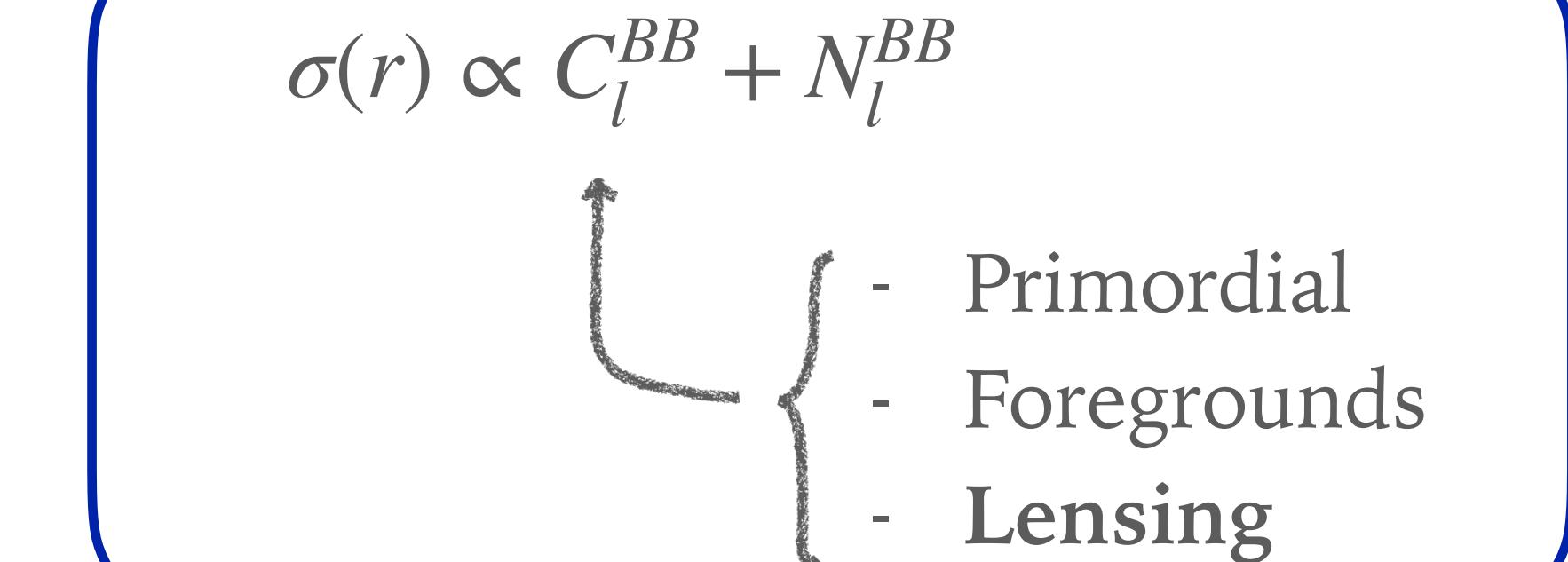


THE LENSING B-MODE



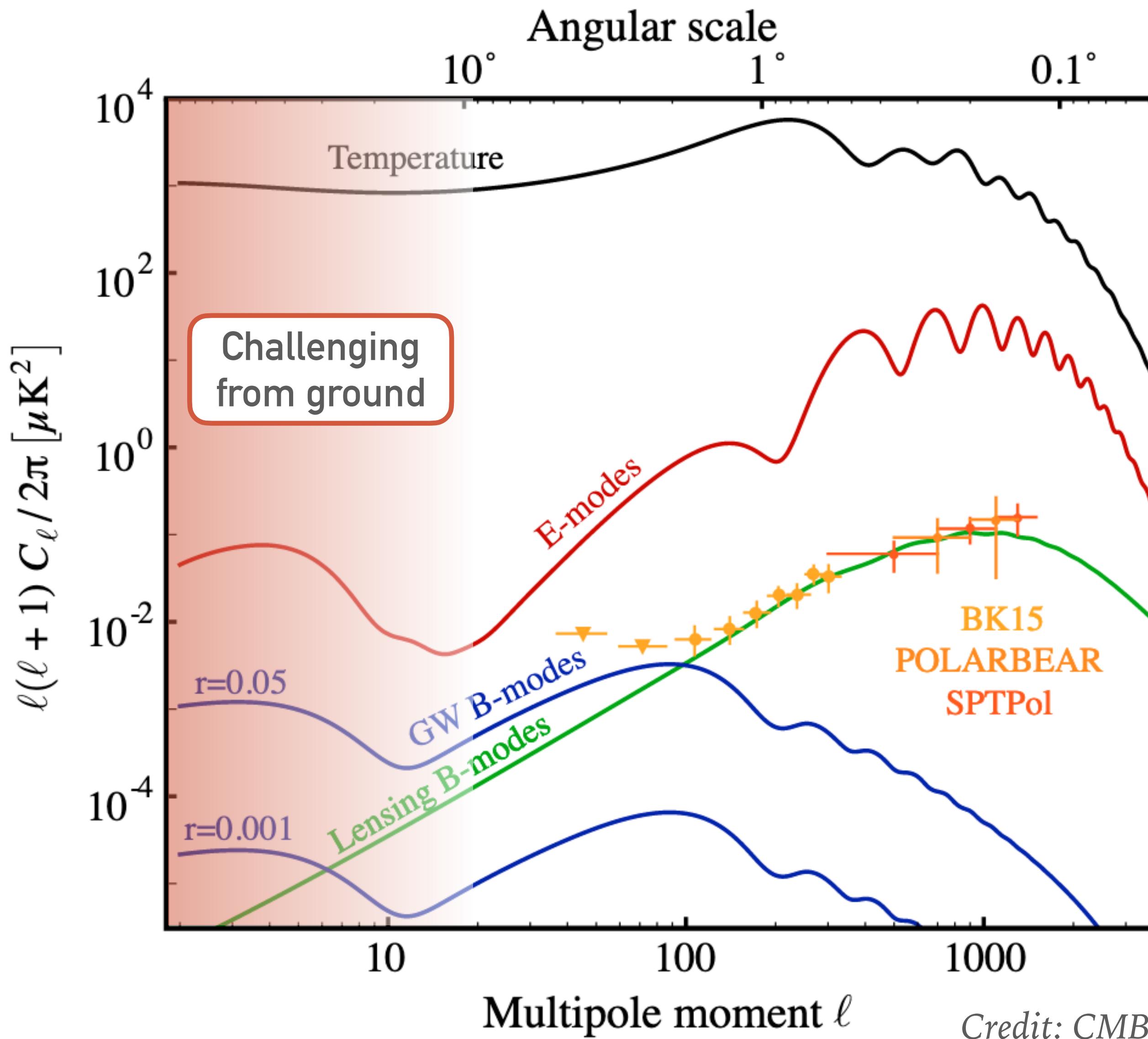
Lensing converts E- into B-modes, inducing noise with $\Delta_P \approx 5\mu\text{K}\text{arcmin}$

Zaldarriaga & Seljak 98



SPO $\sigma(r)$ already limited by lensing

THE LENSING B-MODE



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

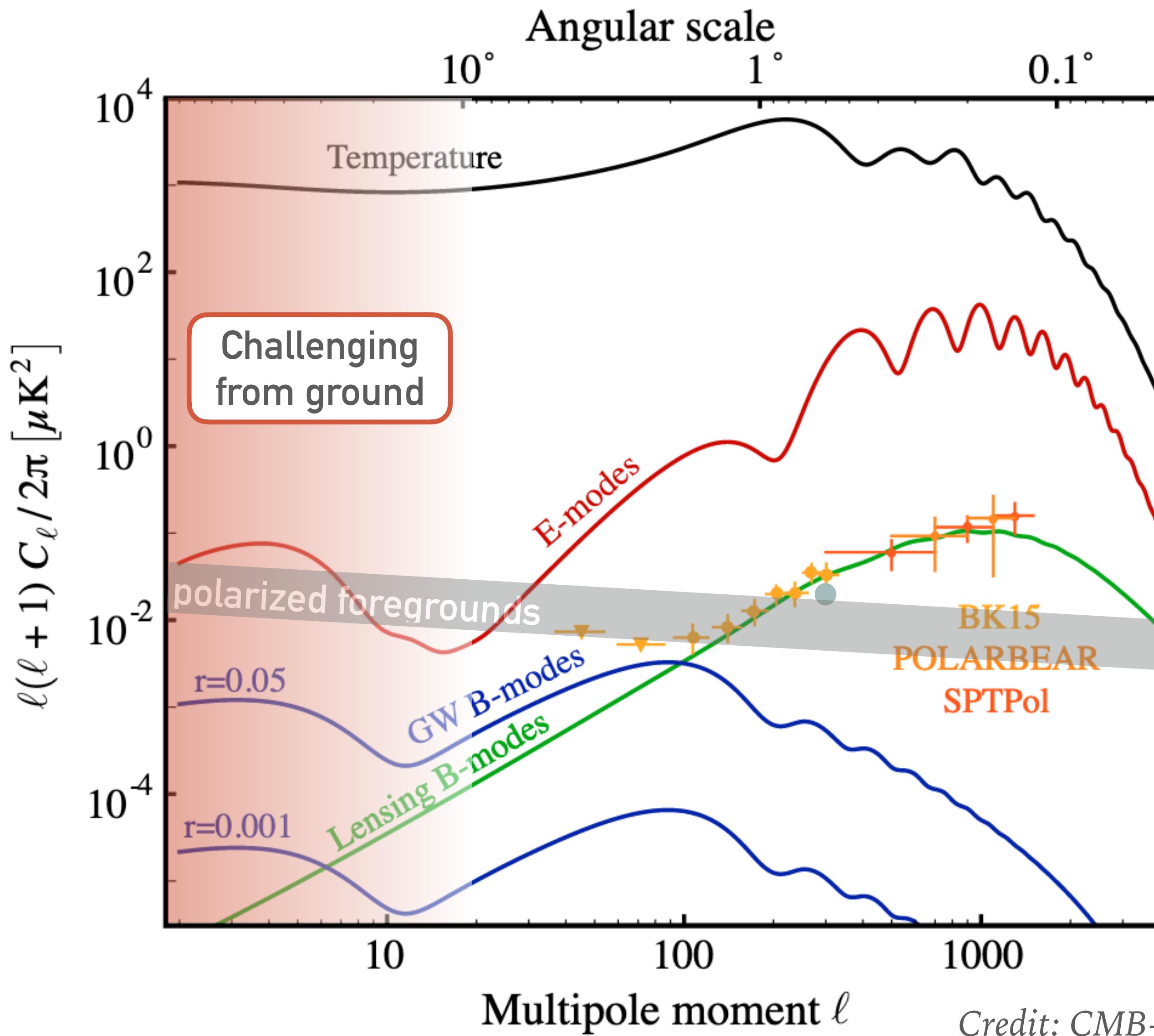
Zaldarriaga & Seljak 98

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

- Primordial
- Foregrounds
- Lensing

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

THE LENSING B-MODE



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

Zaldarriaga & Seljak 98

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

- Primordial
- Foregrounds
- Lensing

Foregrounds can be disentangled using frequency information — lensing cannot

DELENSING THE B-MODES

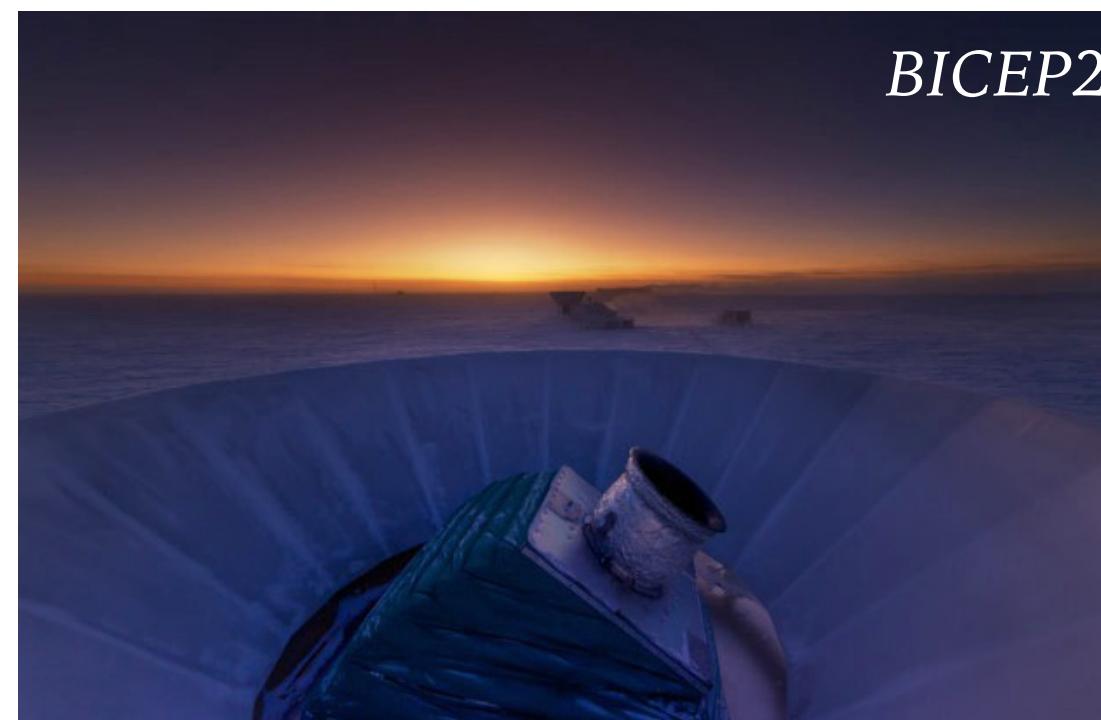
$$\text{Lensing: } \tilde{P}(\mathbf{x}) = P(\mathbf{x} + \alpha(\mathbf{x}))$$

$$\implies \text{Delensing: } P^{\text{del}}(\mathbf{x}) = \tilde{P}(\mathbf{x} + \alpha^{-1}(\mathbf{x}))$$

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)



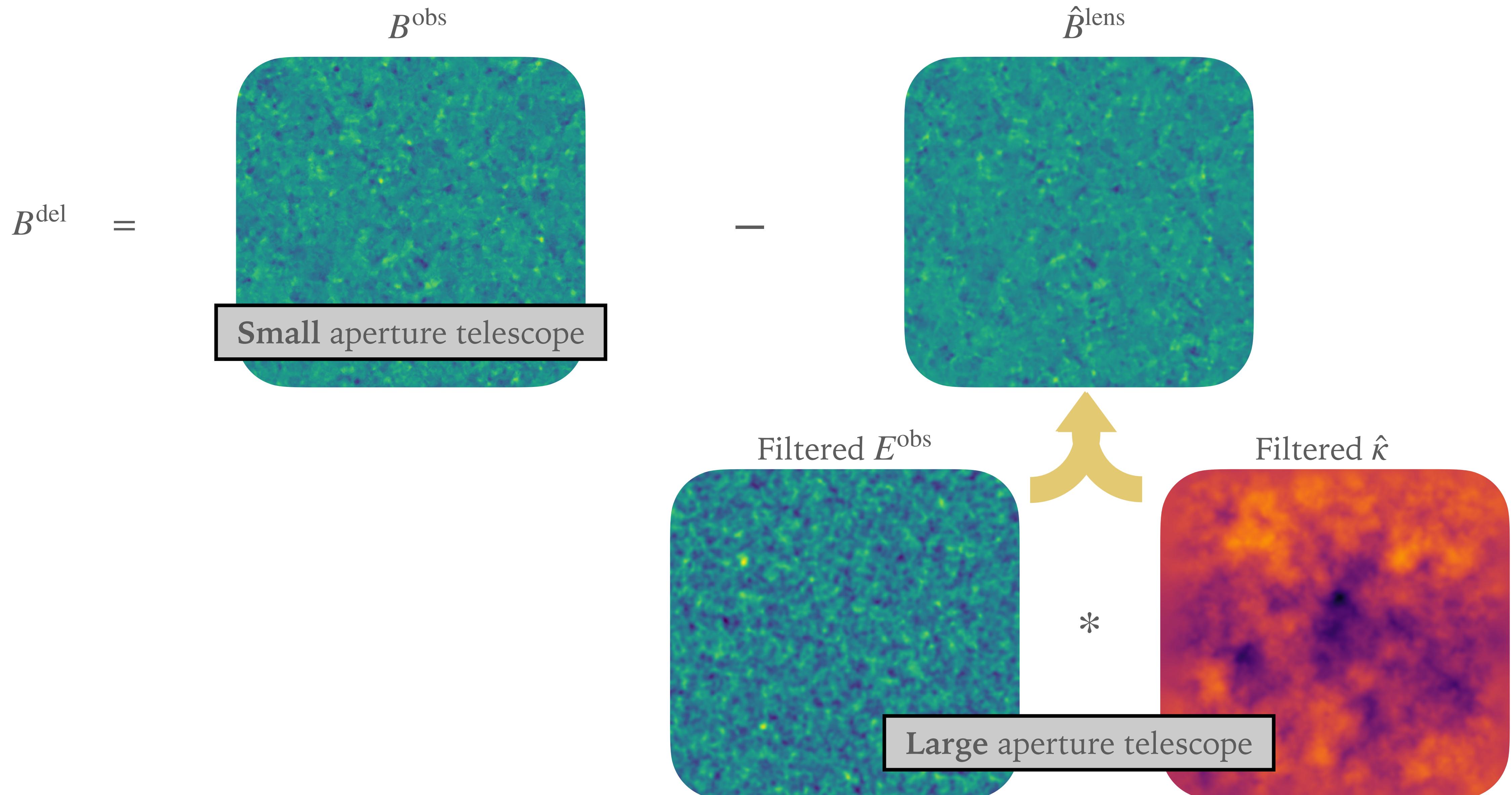
e.g., BICEP/Keck, SO SATs, CLASS, ABS, QUBIC...

Large
Aperture
Telescope
(LAT)



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

DELENSING WITH A B-MODE TEMPLATE



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

HOW EXACTLY IS THE TEMPLATE BUILT?

The lensing B-mode is

$$\tilde{B} = E \circledast \kappa + O(\kappa^2) + \dots$$

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

$$\hat{B}^{\text{lens}} = \bar{E}^{\text{obs}} \circledast \hat{\kappa}. \quad \text{e.g., SPT 17}$$

Why?

- Optimises strengths of LAT & SAT
- Analytically transparent (clear understanding of systematics)
- When built from lensed E-modes, template is effectively optimal until well past the era of CMB-S4

INTERNAL RECONSTRUCTIONS OF CMB LENSING

Unlensed CMB is statistically isotropic:

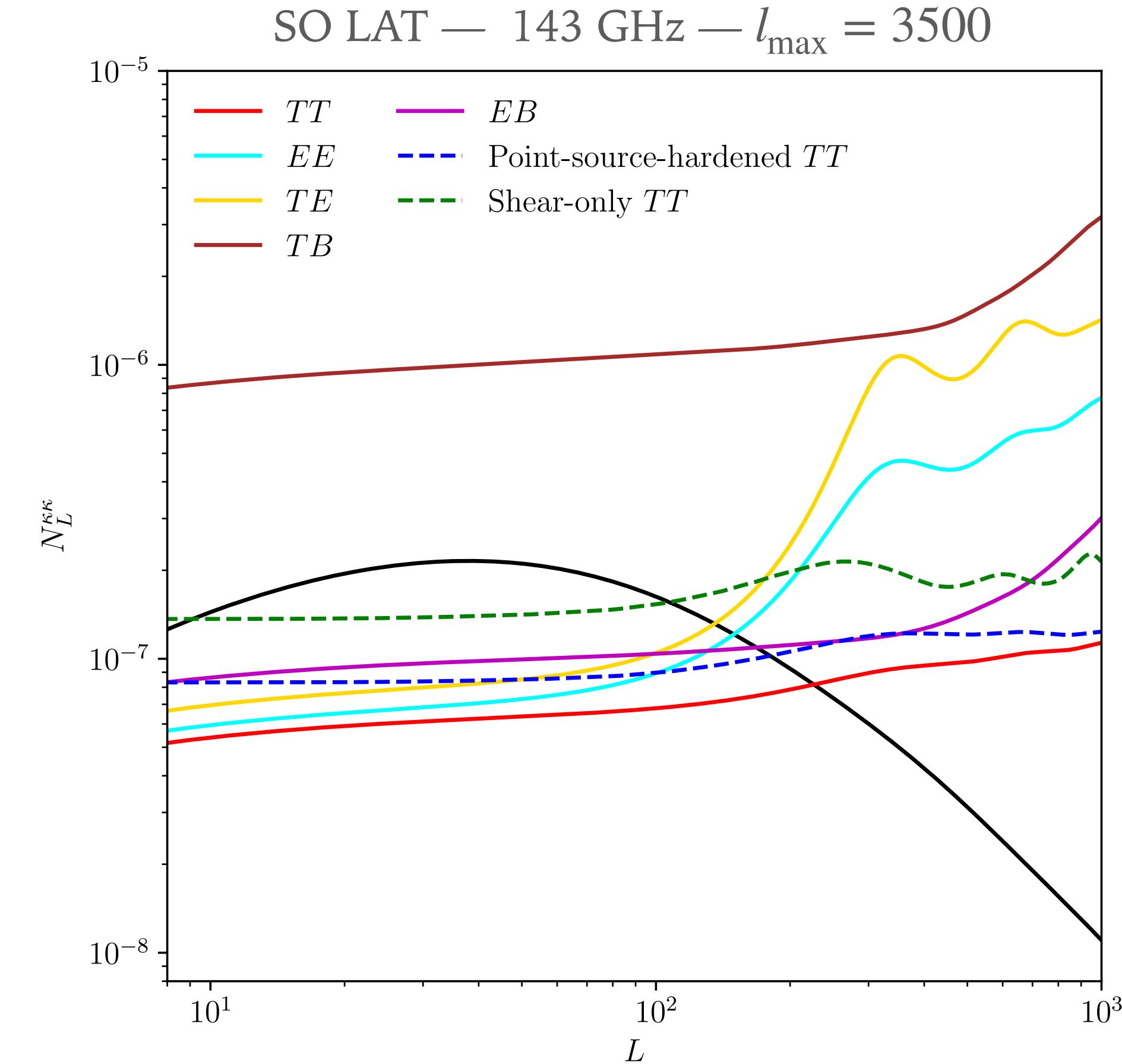
$$\langle T(\mathbf{l})T(\mathbf{l}') \rangle_{CMB} = (2\pi)^2 \delta^2(\mathbf{l} + \mathbf{l}') \tilde{C}_l^{TT}$$

Lensing induces statistical anisotropy:

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

The quadratic estimator (QE):

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



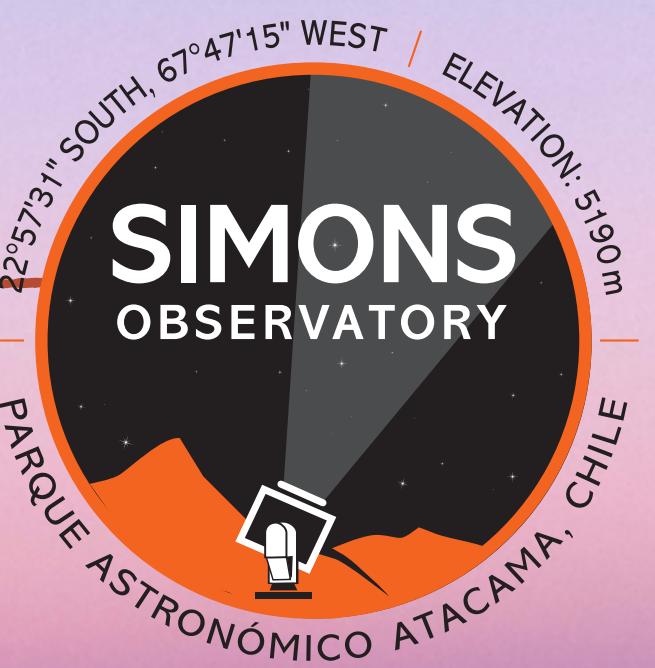
- *Hu & Okamoto 02*: minimum-variance QE for temperature and polarization
- *Osborne+14* : point-source-hardened QE
- *Schaan & Ferraro 18*: shear-only QE

THE SIMONS OBSERVATORY (SO)



Credit: Deborah Kellner

THE SIMONS OBSERVATORY (SO)



May 2022



Credit: Deborah Kellner

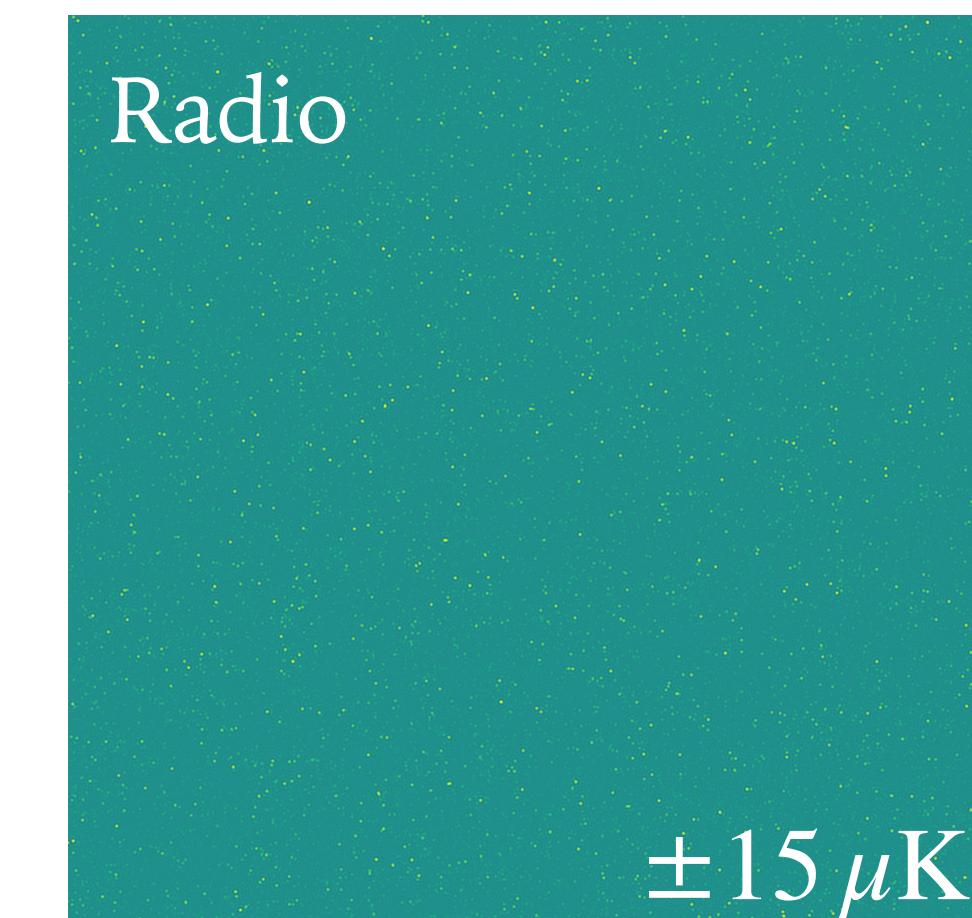
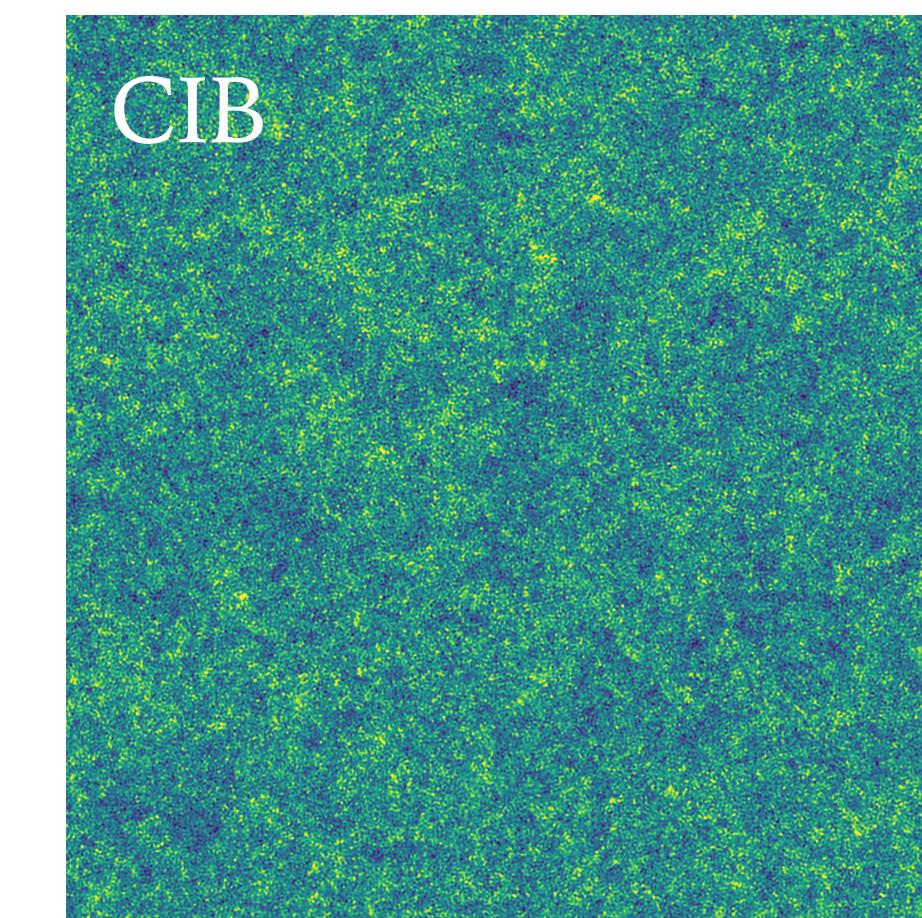
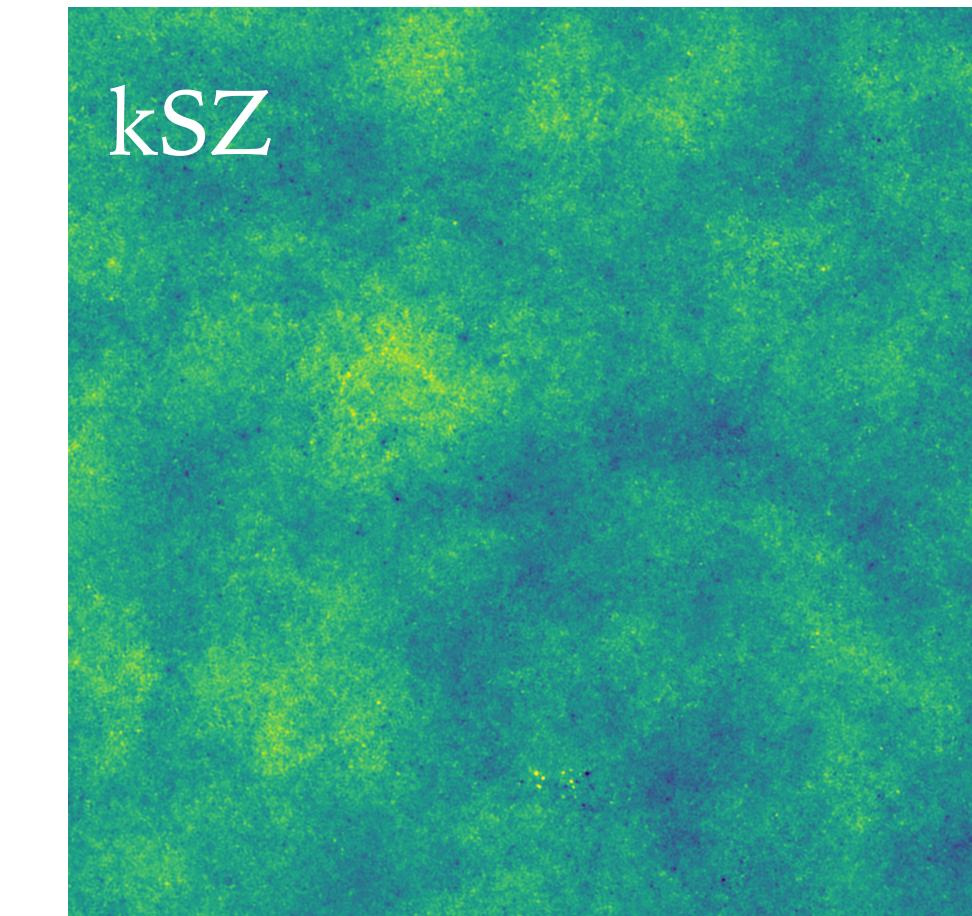
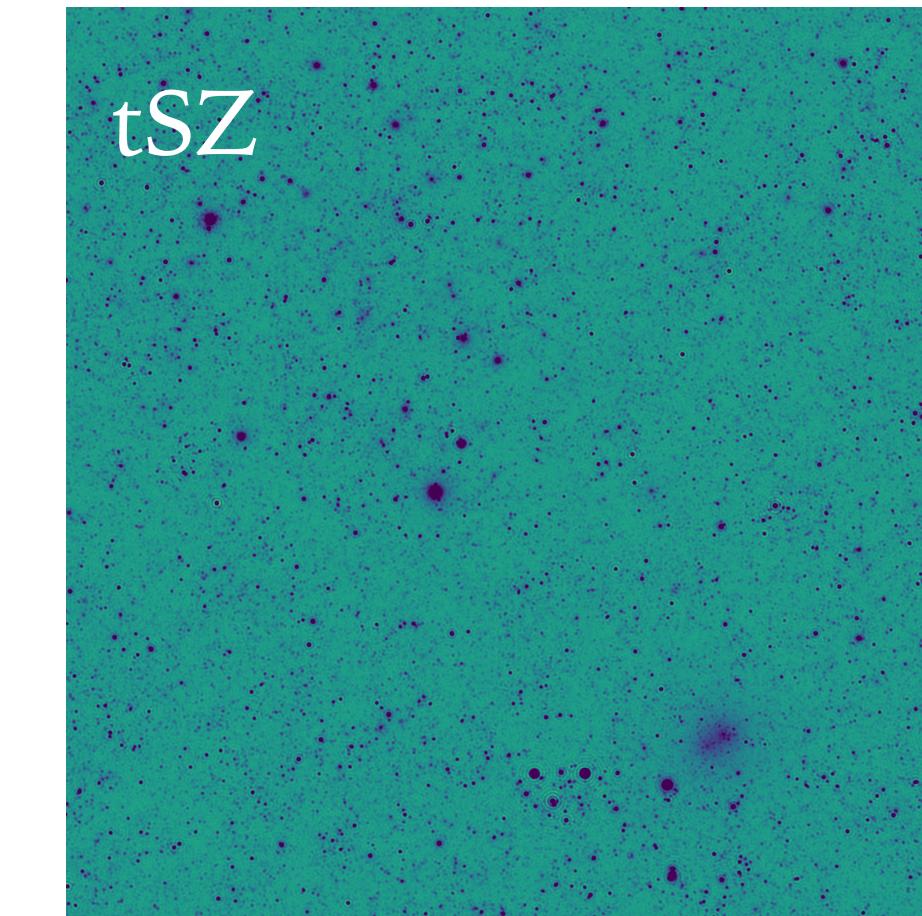
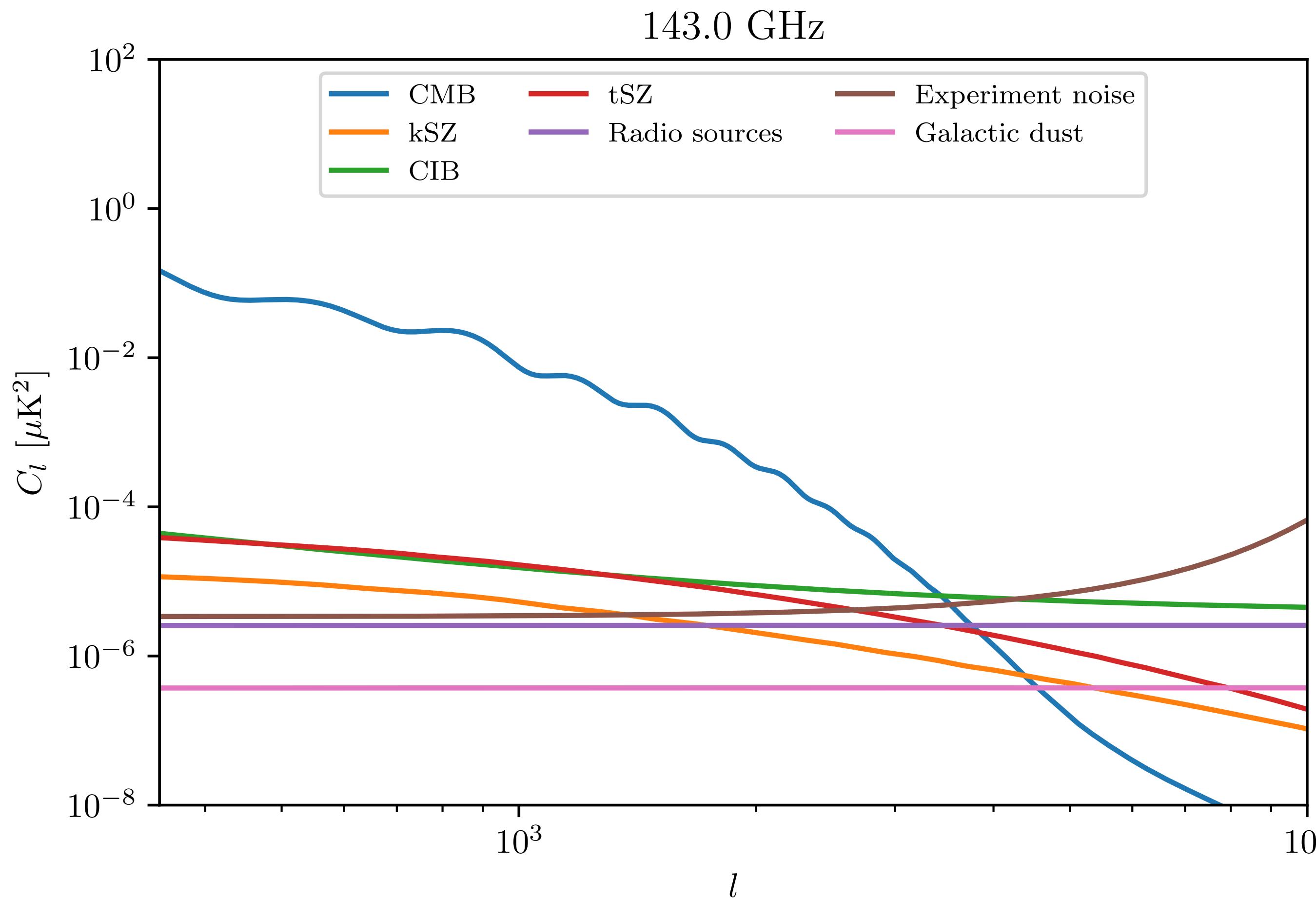
INTERNAL RECONSTRUCTIONS OF CMB LENSING

- CMB lensing reconstructions probe Σm_ν , dark matter, and more... and they **can be used to delens B-modes**
- QE extracts info from leading-order. Ultimately, want all orders *Hirata & Seljak 03, Carron & Lewis 17, Millea+ 20*
- Optimal methods recently demonstrated on data *Millea & SPT 21, POLARBEAR 20*
- The lenses we need for B-mode delensing will ultimately be best reconstructed from polarization
- **For SO**, QE effectively optimal, and dominated by TT

EXTRAGALACTIC FOREGROUNDS



In intensity, microwave sky contaminated by extragalactic emission: tSZ, kSZ, CIB, radio sources.



Websky sims Stein+, Li+

BIASES TO LENSING SPECTRA FROM EXTRAGALACTIC FOREGROUNDS

$$\hat{\kappa} = \hat{\kappa}[\tilde{T} + s^{\text{NG}}, \tilde{T} + s^{\text{NG}}]$$

Lensing Foreground (correlated with κ)

Fgs are non-Gaussian and correlated with lensing. They can bias the power spectrum of lensing reconstructions:

$$\langle \hat{\kappa} \hat{\kappa} \rangle = \langle \hat{\kappa}[\tilde{T}, \tilde{T}] \hat{\kappa}[\tilde{T}, \tilde{T}] \rangle + 2 \langle \hat{\kappa}[\tilde{T}, \tilde{T}] \hat{\kappa}[s^{\text{NG}}, s^{\text{NG}}] \rangle + 4 \langle \hat{\kappa}[\tilde{T}, s^{\text{NG}}] \hat{\kappa}[\tilde{T}, s^{\text{NG}}] \rangle + \langle \hat{\kappa}[s^{\text{NG}}, s^{\text{NG}}] \hat{\kappa}[s^{\text{NG}}, s^{\text{NG}}] \rangle$$

“Primary bispectrum bias”

“Secondary bispectrum bias”

“Trispectrum bias”

as well as cross-correlations with low-z matter tracers

$$\langle g[\kappa] \hat{\kappa} \rangle = \langle g[\kappa] \hat{\kappa}[\tilde{T}, \tilde{T}] \rangle + \langle g[\kappa] \hat{\kappa}[s^{\text{NG}}, s^{\text{NG}}] \rangle$$

↑
“Bispectrum bias”

Amblard + 04

Van Engelen + 14

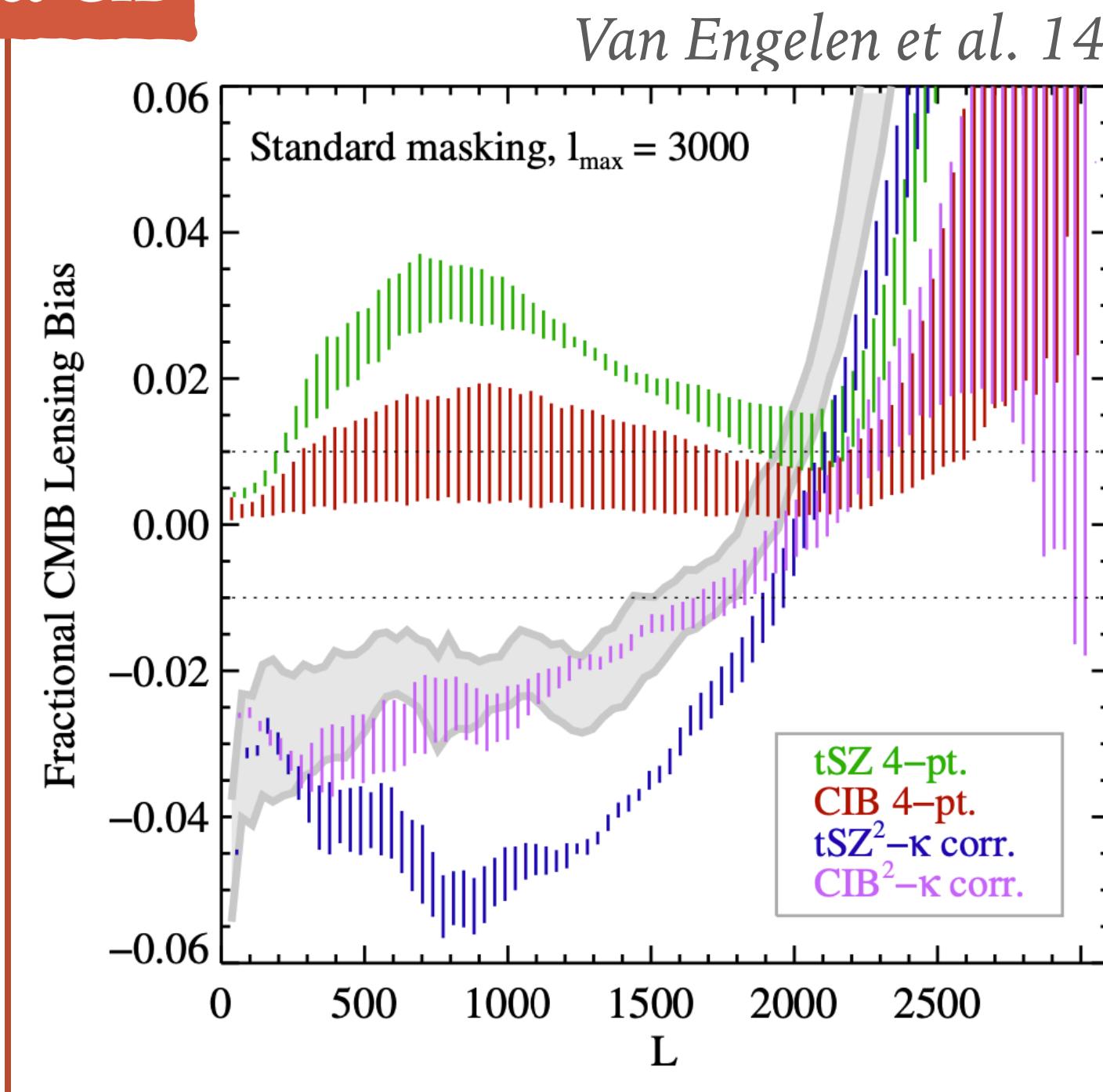
Osborne + 14

Ferraro & Hill 18

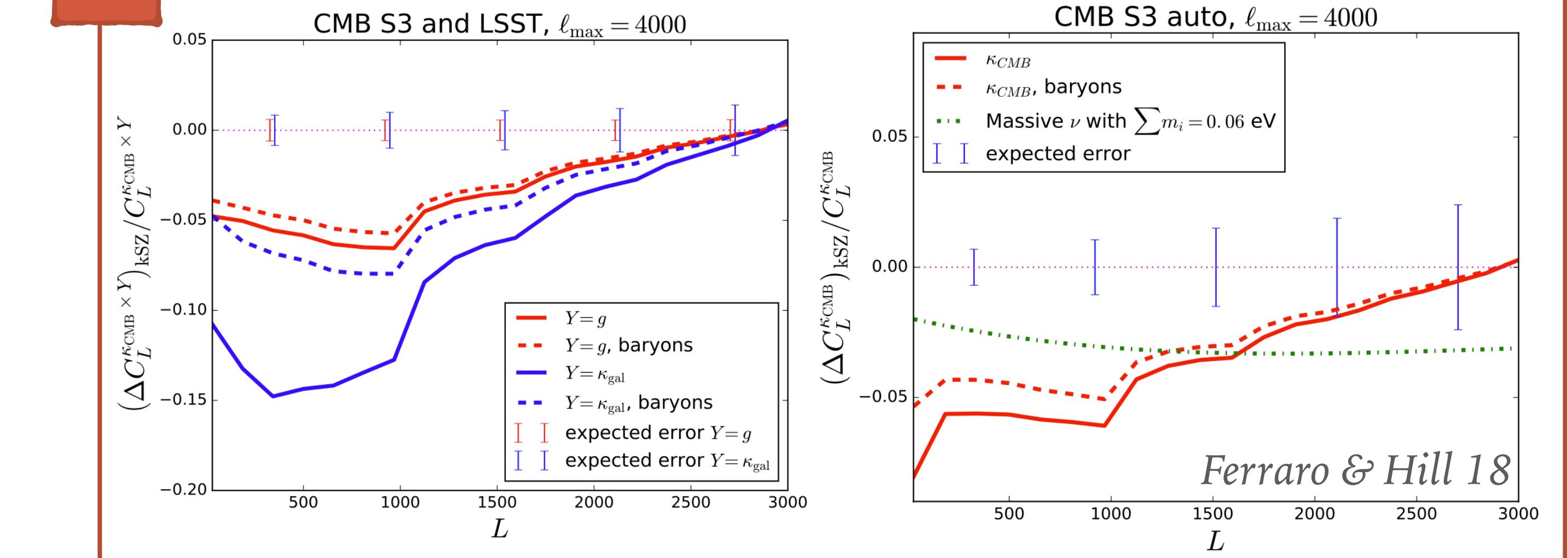
Sailer + 21

BIASES TO LENSING SPECTRA FROM EXTRAGALACTIC FOREGROUNDS

tSZ & CIB



kSZ



- Arguably, the biggest challenge to CMB lensing measurements (at least in temperature)

- Mitigation strategies:

- Simulations

Van Engelen + 14

- Multi-frequency cleaning

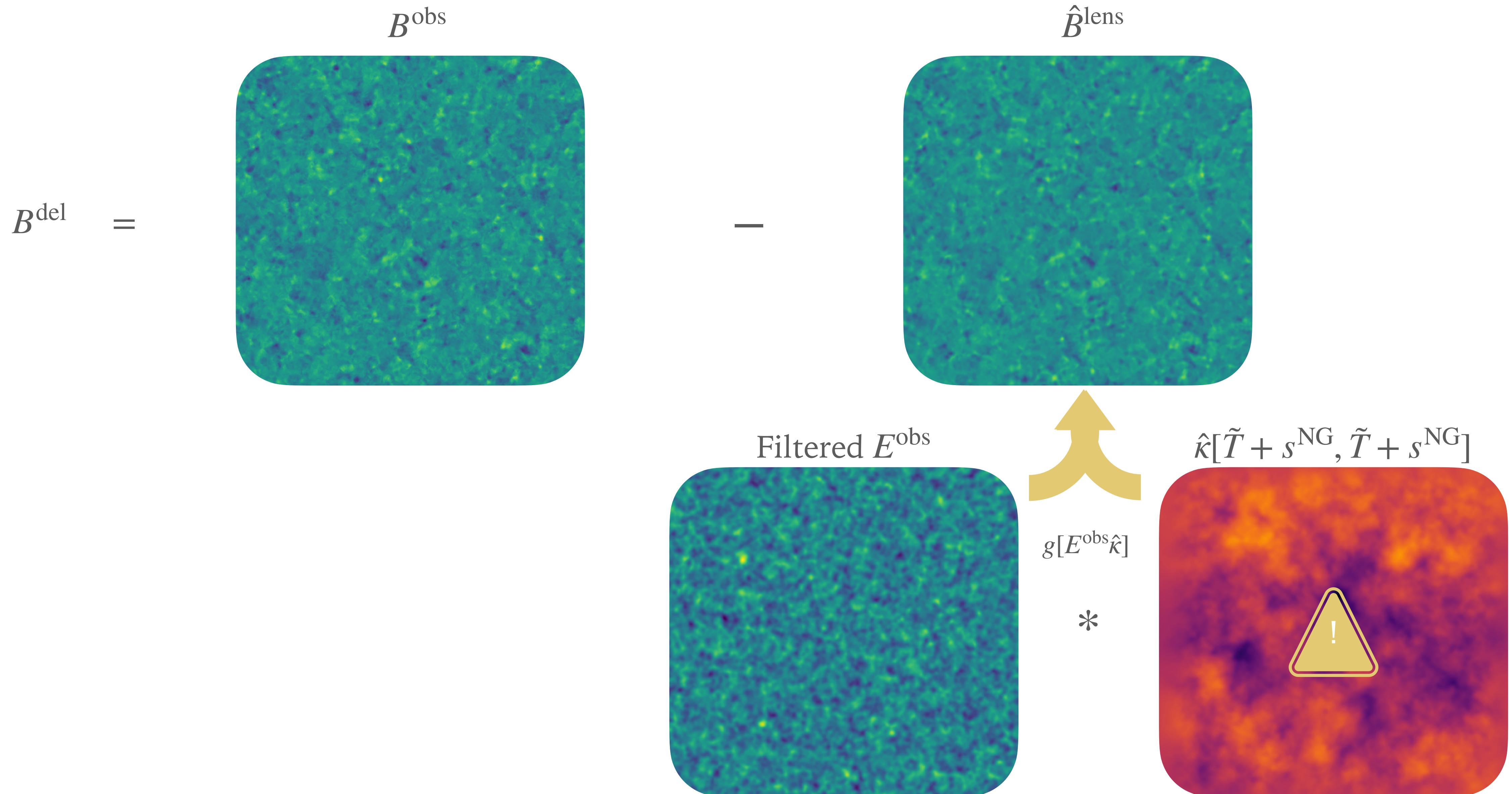
Sailer + 21, Darwisch + 21

- Discard small-scale information (i.e., set ℓ_{max})

- QEs that are robust by design

*Osborne + 14, Schaan & Ferraro 18,
Madhavacheril & Hill 18, Sailer + 20*

COULD THIS ISSUE ALSO AFFECT B-MODE DELENSING?



NEW CONTRIBUTIONS FROM EXTRAGALACTIC FOREGROUNDS

$$\Delta C_l^{BB, \text{del}} = -2 \Delta C_l^{\tilde{B} \times \hat{B}^{\text{lens}}} + \Delta C_l^{\hat{B}^{\text{lens}} \times \hat{B}^{\text{lens}}}$$
$$\Delta C_l^{\tilde{B} \times \hat{B}^{\text{lens}}} \supset g_l \left[\langle \tilde{B} \tilde{E} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}] \rangle_c \right]$$
$$\Delta C_l^{\hat{B}^{\text{lens}} \times \hat{B}^{\text{lens}}} \supset$$
$$\supset 2 h_l \left[\underbrace{\langle E^{\text{obs}} \hat{\kappa}^{TT} [\tilde{T}, \tilde{T}] E^{\text{obs}} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}] \rangle_c} \right]$$
$$+ 4 h_l \left[\underbrace{\langle E^{\text{obs}} \hat{\kappa}^{TT} [\tilde{T}, s^{\text{NG}}] E^{\text{obs}} \hat{\kappa}^{TT} [\tilde{T}, s^{\text{NG}}] \rangle_c} \right]$$
$$+ h_l \left[\underbrace{\langle E^{\text{obs}} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}] E^{\text{obs}} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}] \rangle_c} \right]$$

$C^{EE} \langle \kappa \hat{\kappa} [s^{\text{NG}}, s^{\text{NG}}] \rangle$

primary bispectrum bias

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 $C^{EE, \text{obs}} \langle \kappa \hat{\kappa} [s^{\text{NG}}, s^{\text{NG}}] \rangle$
 primary bispectrum bias

$\Delta C_l^{\hat{B}^{\text{lens}} \times \hat{B}^{\text{lens}}} \supset$

 $\supset 2 h_l \left[\langle E^{\text{obs}} \hat{\kappa}^{TT} [\tilde{T}, \tilde{T}] E^{\text{obs}} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}] \rangle_c \right]$

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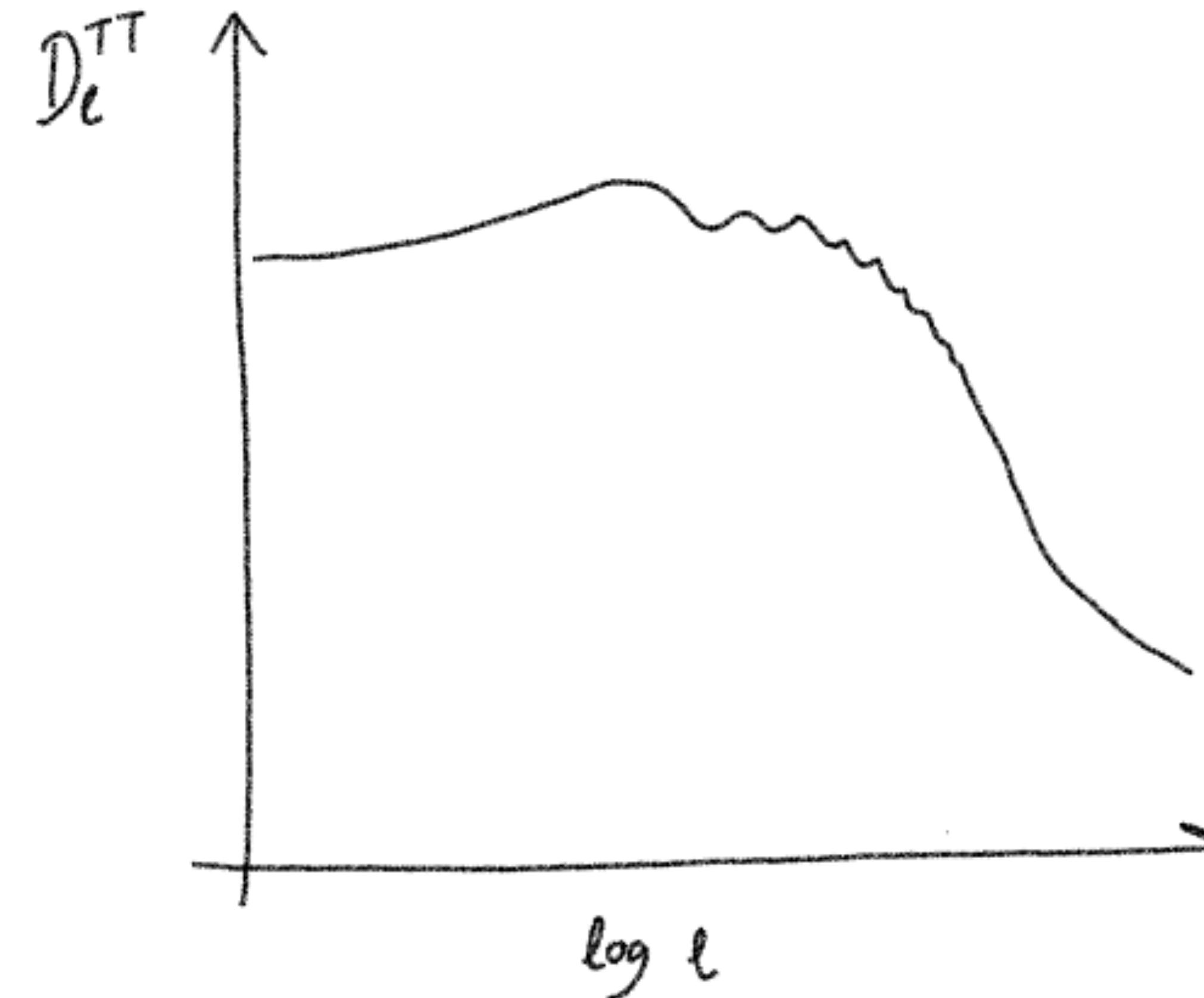
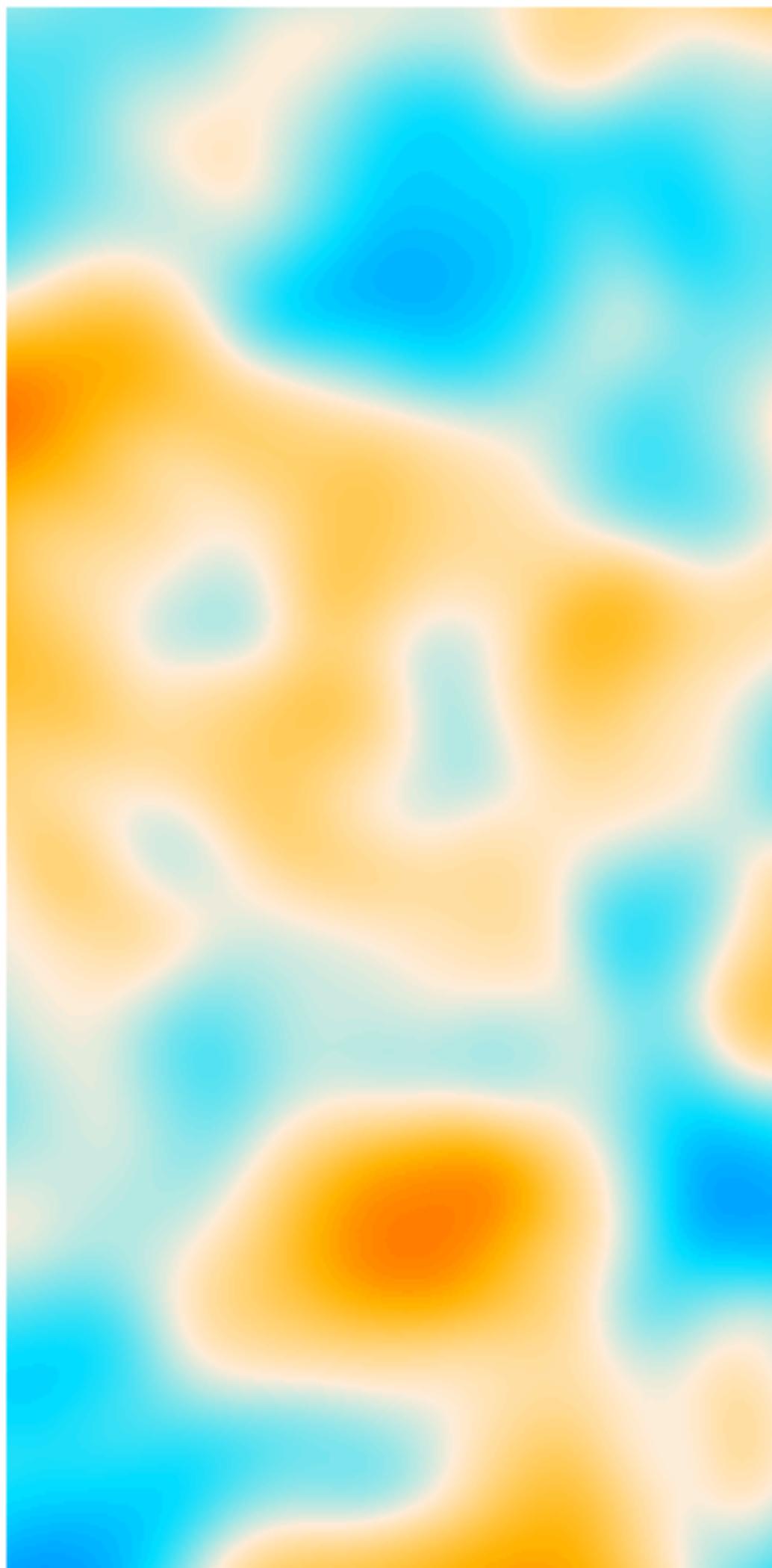
$C^{EE, \text{obs}} \langle \hat{\kappa}[\tilde{T}, s^{\text{NG}}] \hat{\kappa}[\tilde{T}, s^{\text{NG}}] \rangle$
 secondary bispectrum bias

NEW CONTRIBUTIONS FROM EXTRAGALACTIC FOREGROUNDS

$$\Delta C_l^{BB, \text{del}} = -2 \Delta C_l^{\tilde{B} \times \hat{B}^{\text{lens}}} + \Delta C_l^{\hat{B}^{\text{lens}} \times \hat{B}^{\text{lens}}}$$
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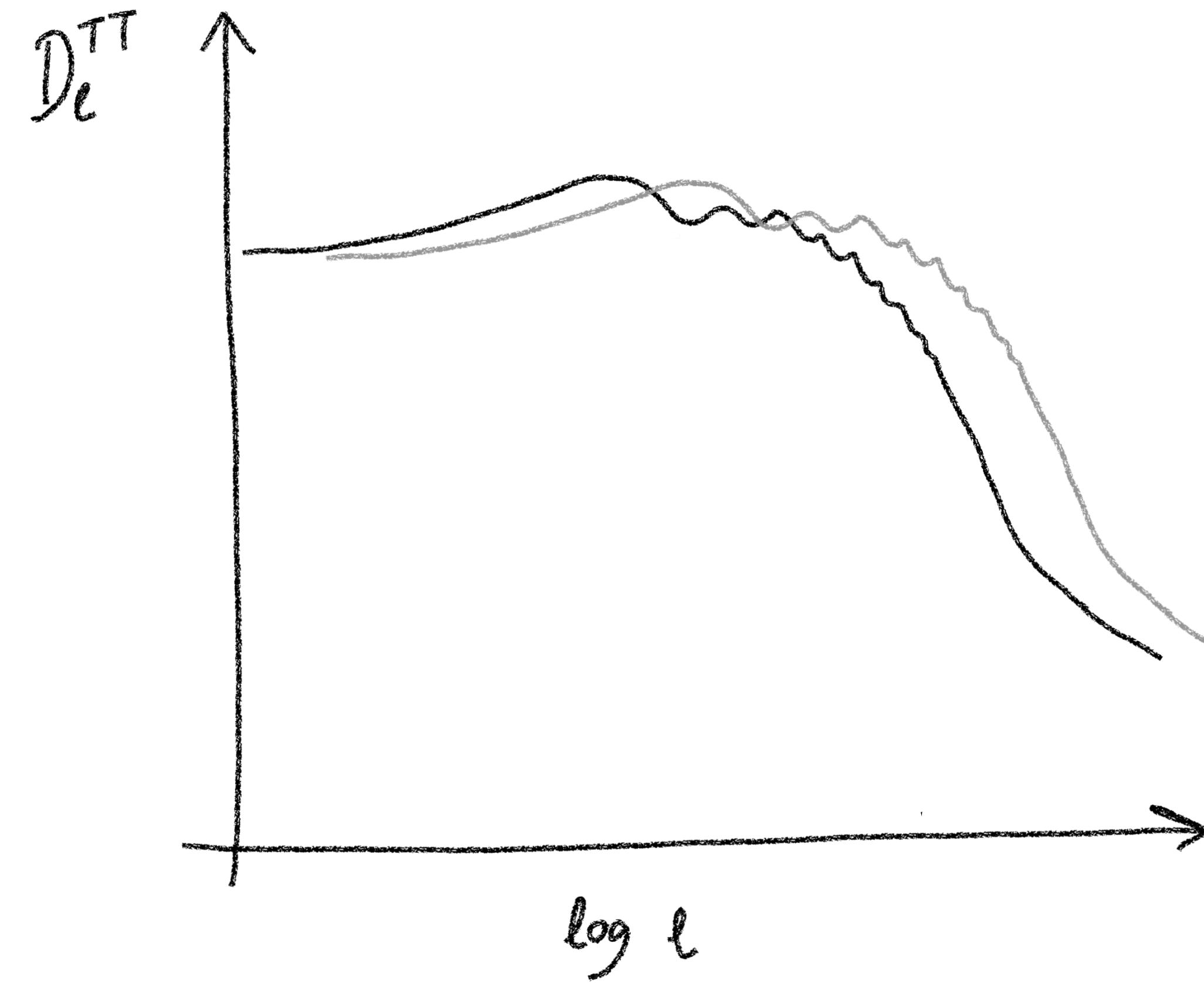
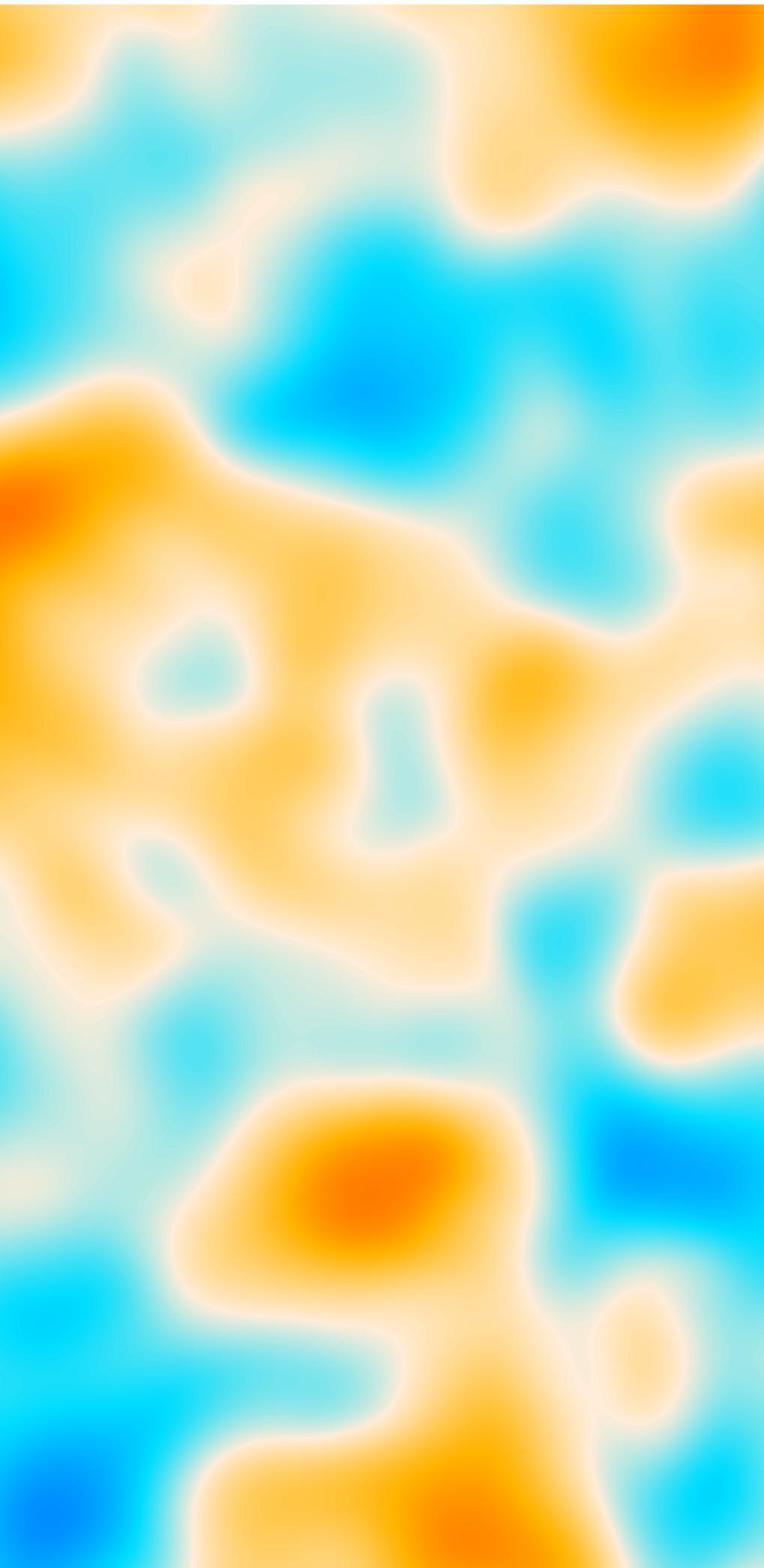
$C^{EE, \text{obs}} \langle \hat{\kappa}[s^{\text{NG}}, s^{\text{NG}}] \hat{\kappa}[s^{\text{NG}}, s^{\text{NG}}] \rangle$
trispectrum bias

NOTE: WE EXPECT BISPECTRUM BIASES TO BE NEGATIVE



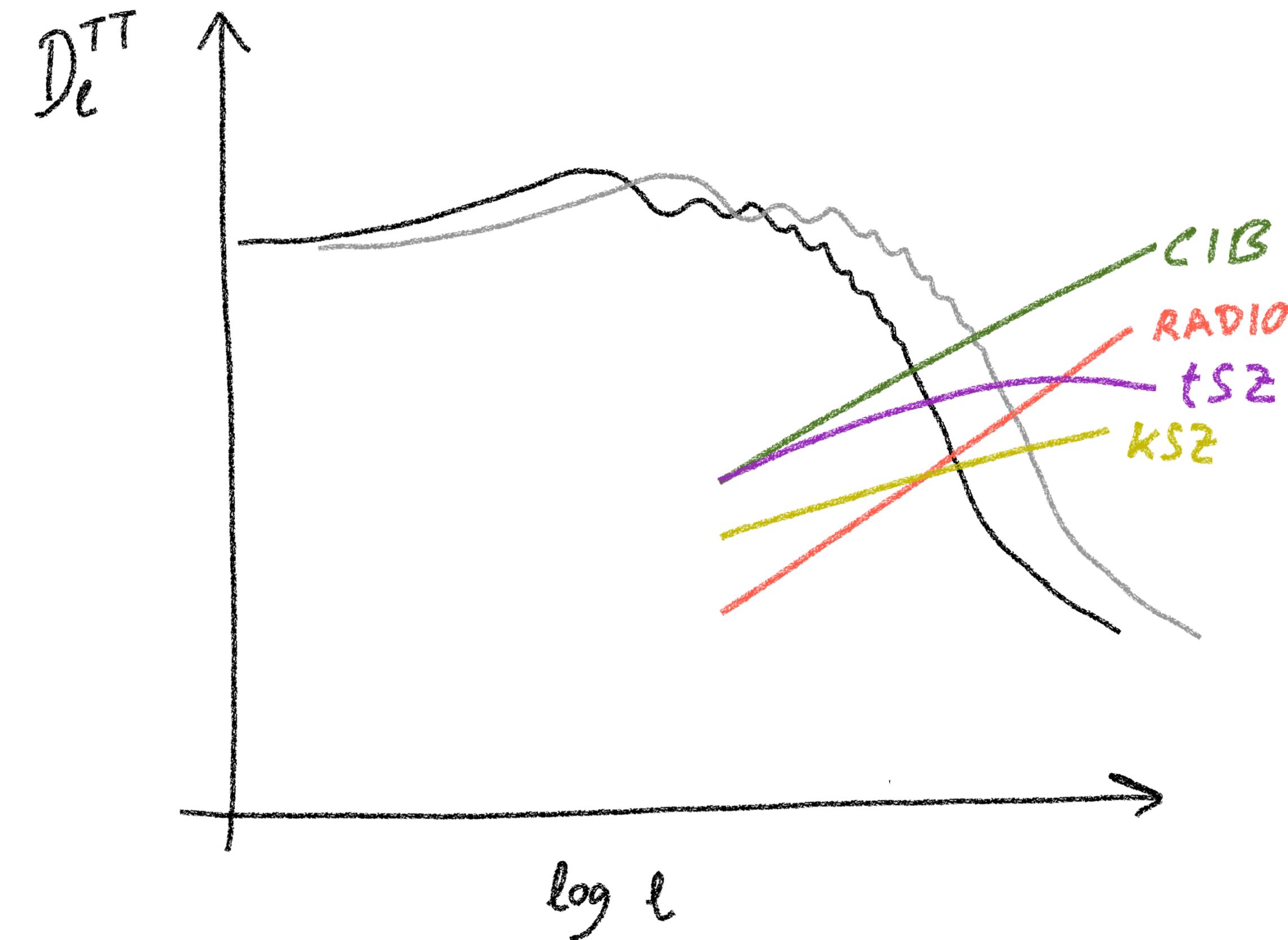
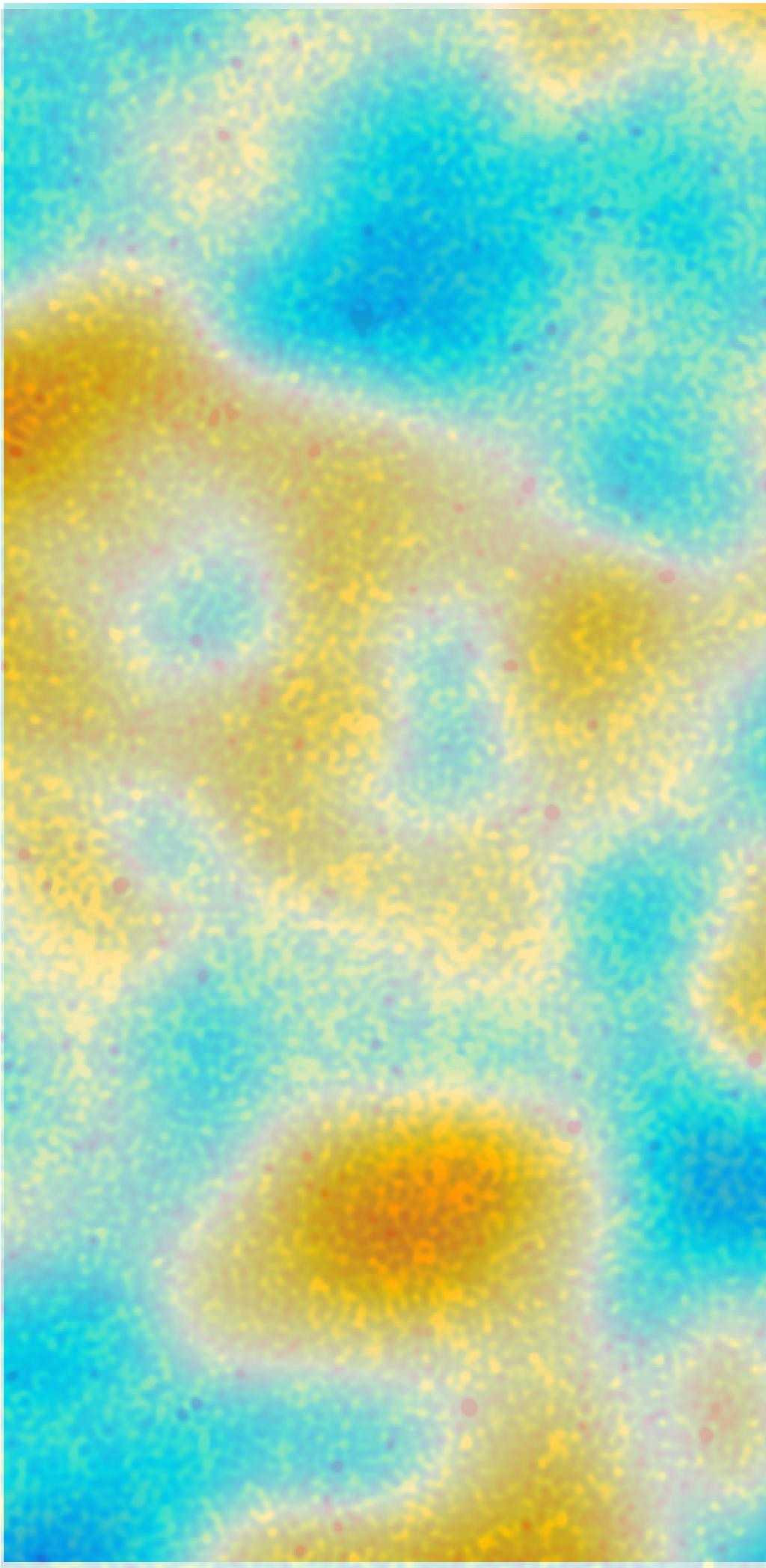
Where $\kappa < 0$, the CMB spectrum is shifted to smaller scales

NOTE: WE EXPECT BISPECTRUM BIASES TO BE NEGATIVE



Where $\kappa < 0$, there is excess power on small scales \Rightarrow the QE interprets excess small-scale power as being due to $\kappa < 0$

NOTE: WE EXPECT BISPECTRUM BIASES TO BE NEGATIVE



When the excess small-scale power is due to fgs, the QE still attributes it to $\kappa < 0 \implies$ anti-correlation between fg power and κ (i.e., a bispectrum)

EXPECTATIONS

$$\Delta C_l^{BB, \text{del}} = -2 \Delta C_l^{\tilde{B} \times \hat{B}^{\text{lens}}} + \Delta C_l^{\hat{B}^{\text{lens}} \times \hat{B}^{\text{lens}}}$$

$\Delta C_l^{\tilde{B} \times \hat{B}^{\text{lens}}} \supset g_l \left[\langle \tilde{B} \tilde{E} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}] \rangle_c \right]$
 $\Delta C_l^{\hat{B}^{\text{lens}} \times \hat{B}^{\text{lens}}} \supset$

- $v \epsilon$ ↑ ↑
+ 4 h_l \left[\langle E^{\text{obs}} \hat{\kappa}^{TT} [\tilde{T}, s^{\text{NG}}] E^{\text{obs}} \hat{\kappa}^{TT} [\tilde{T}, s^{\text{NG}}] \rangle_c \right]
+ h_l \left[\langle E^{\text{obs}} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}] E^{\text{obs}} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}] \rangle_c \right]

+ v \epsilon →

MEASURING THE NEW CONTRIBUTIONS

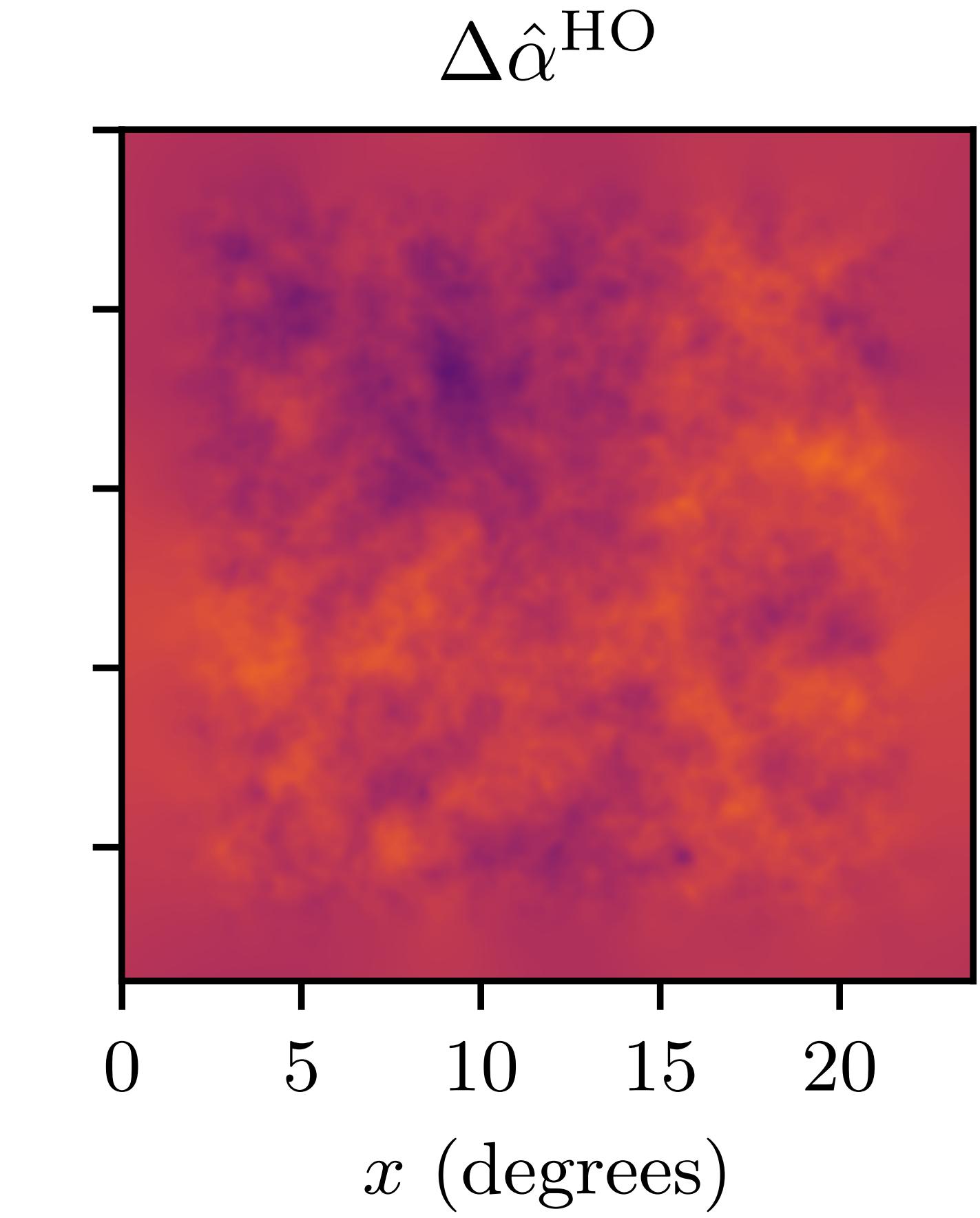
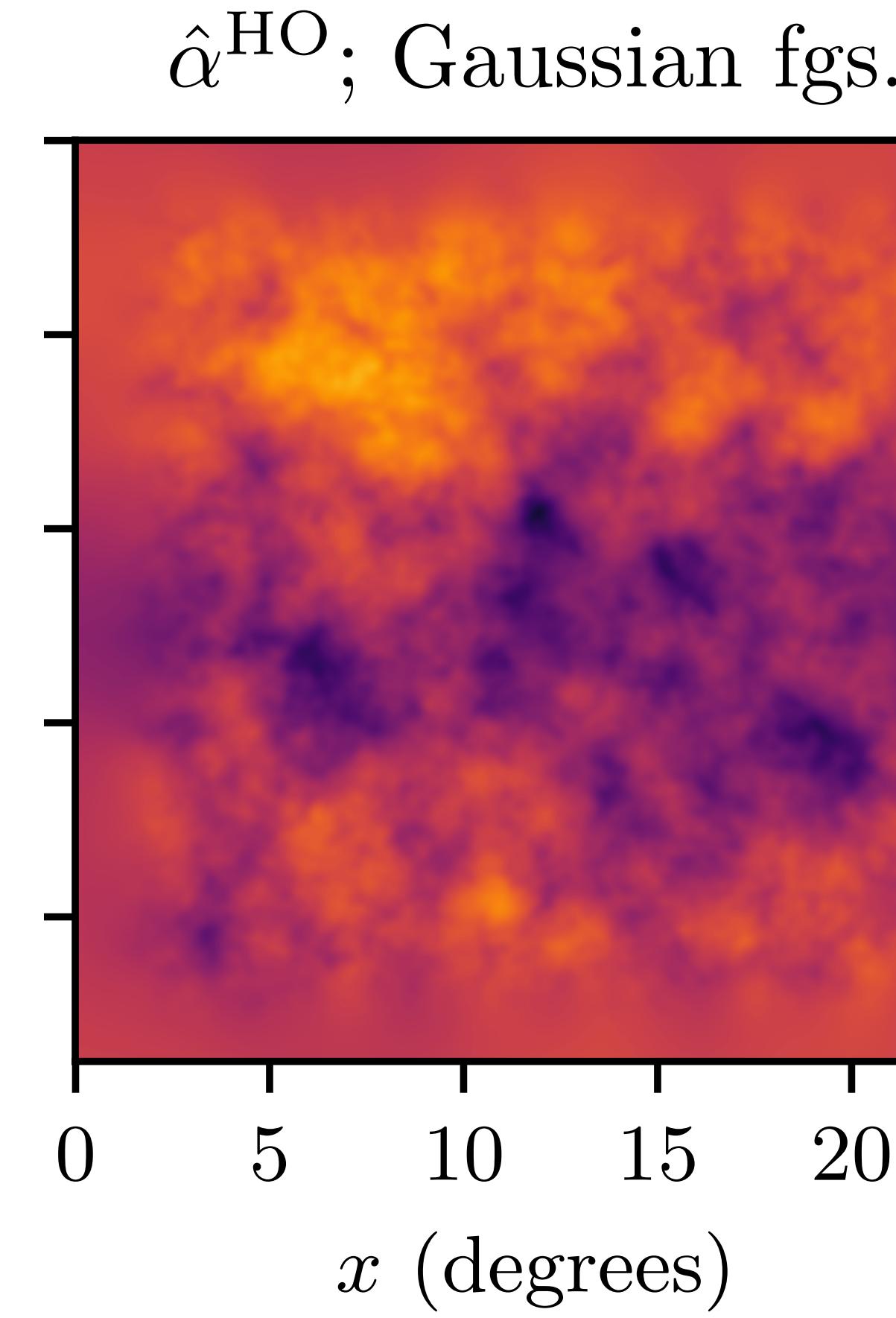
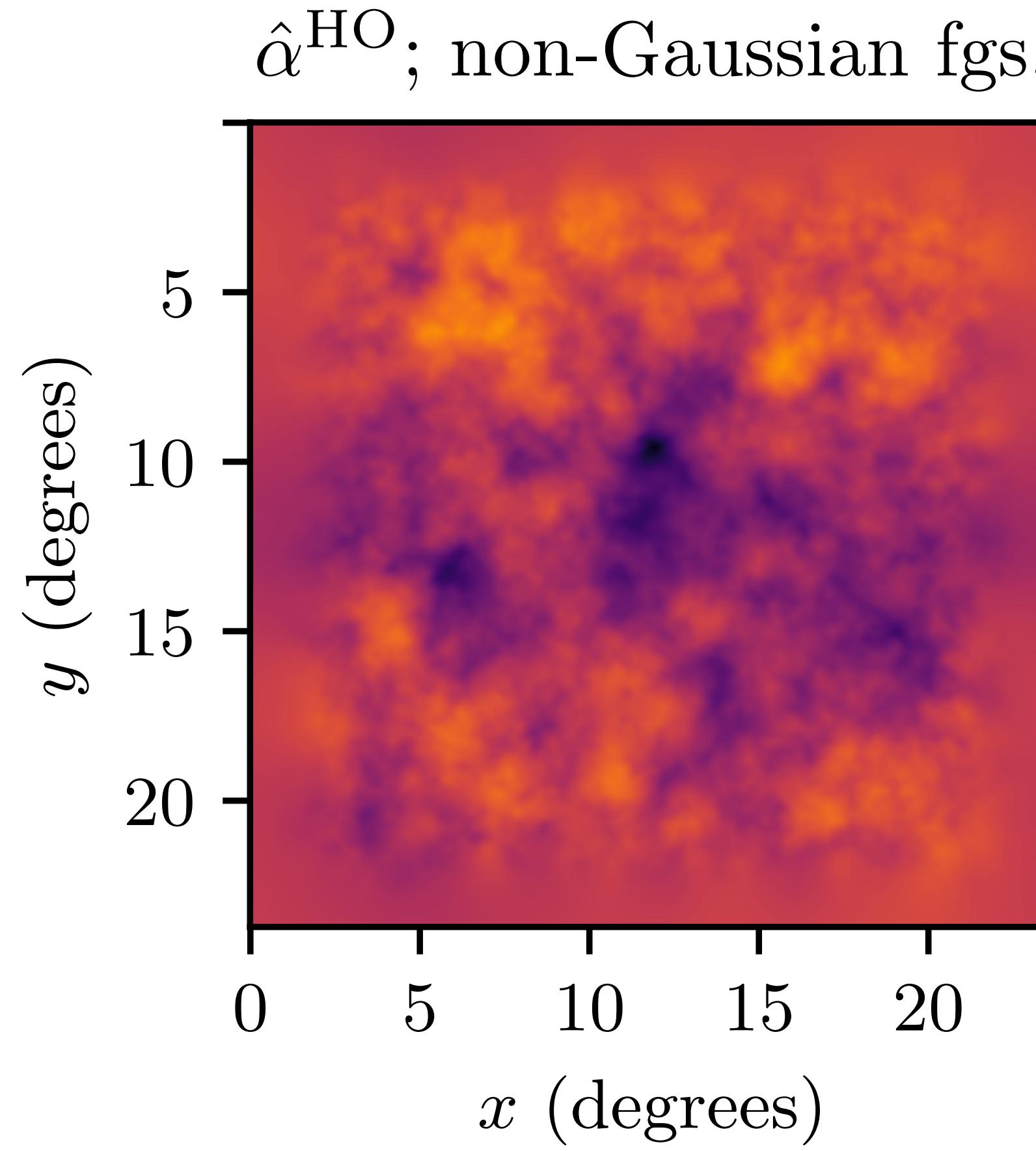
Using the Websky simulations, we measure

$$\begin{aligned}\Delta C_l^{BB, \text{del}} = & \langle |\tilde{B} - g_l [\tilde{E} \hat{\kappa} [f + s^{\text{NG}}, f + s^{\text{NG}}]]|^2 \rangle \\ & - \langle |\tilde{B} - g_l [\tilde{E} \hat{\kappa} [f + s^{\text{G}}, f + s^{\text{G}}]]|^2 \rangle.\end{aligned}$$

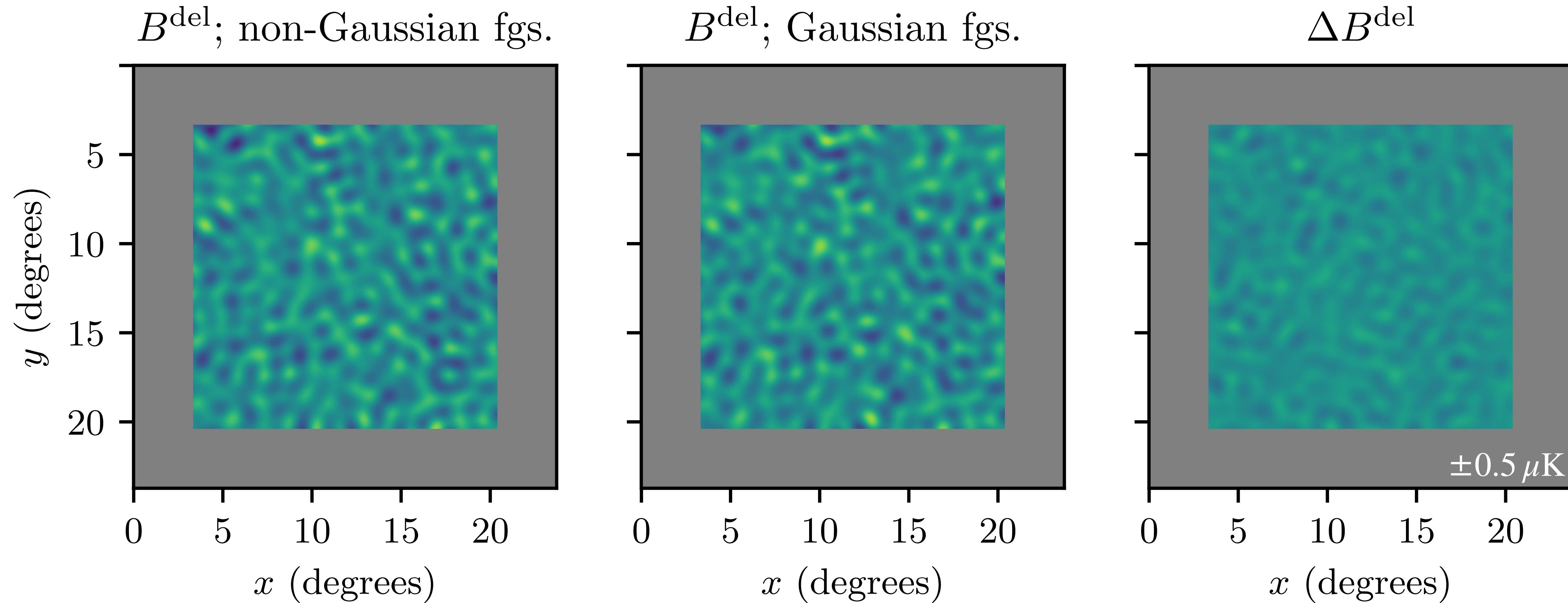
We take the foregrounds to be unpolarized.

MAP-LEVEL EFFECT

$$\alpha \equiv 2\kappa/l$$



MAP-LEVEL EFFECT

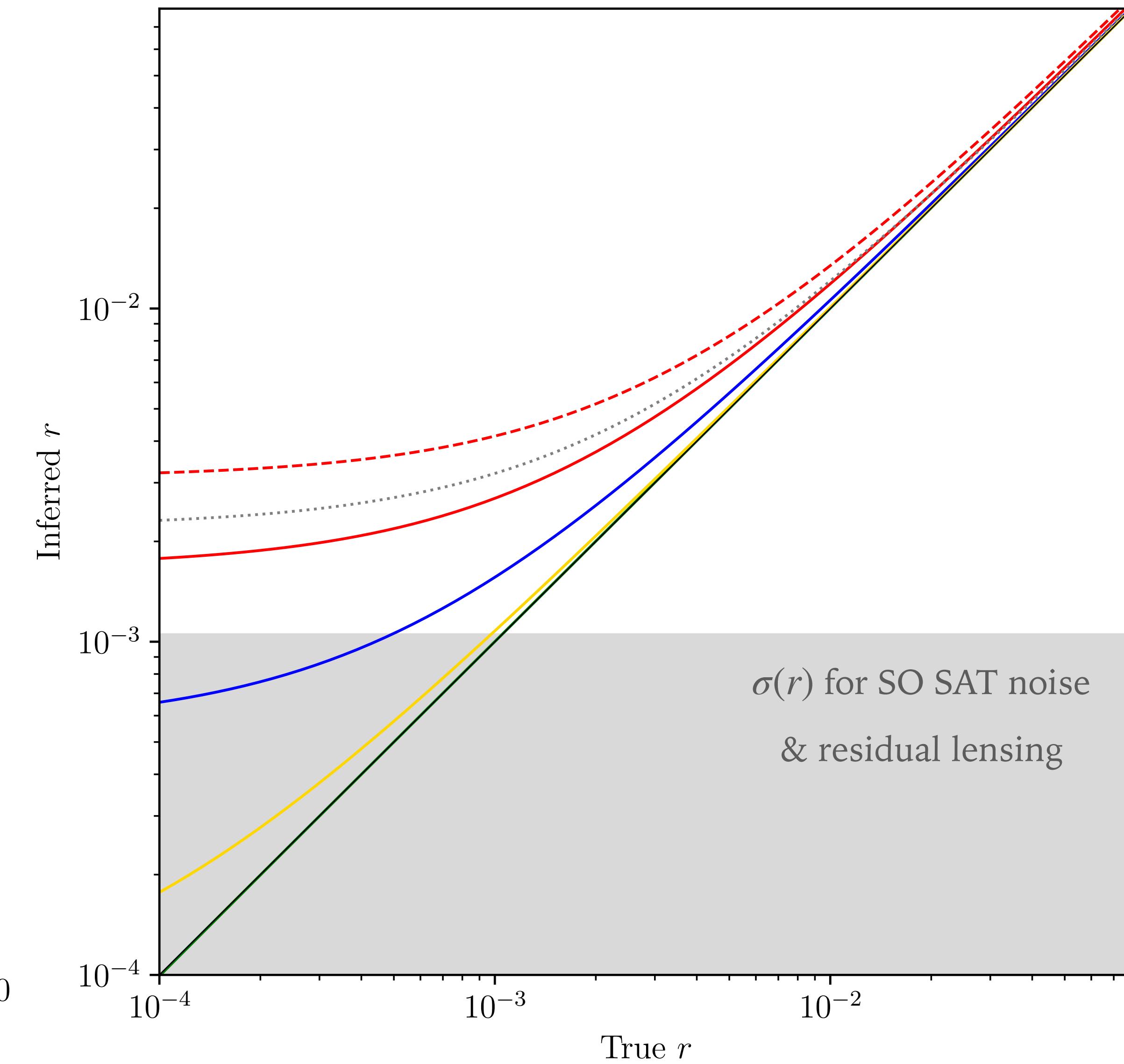
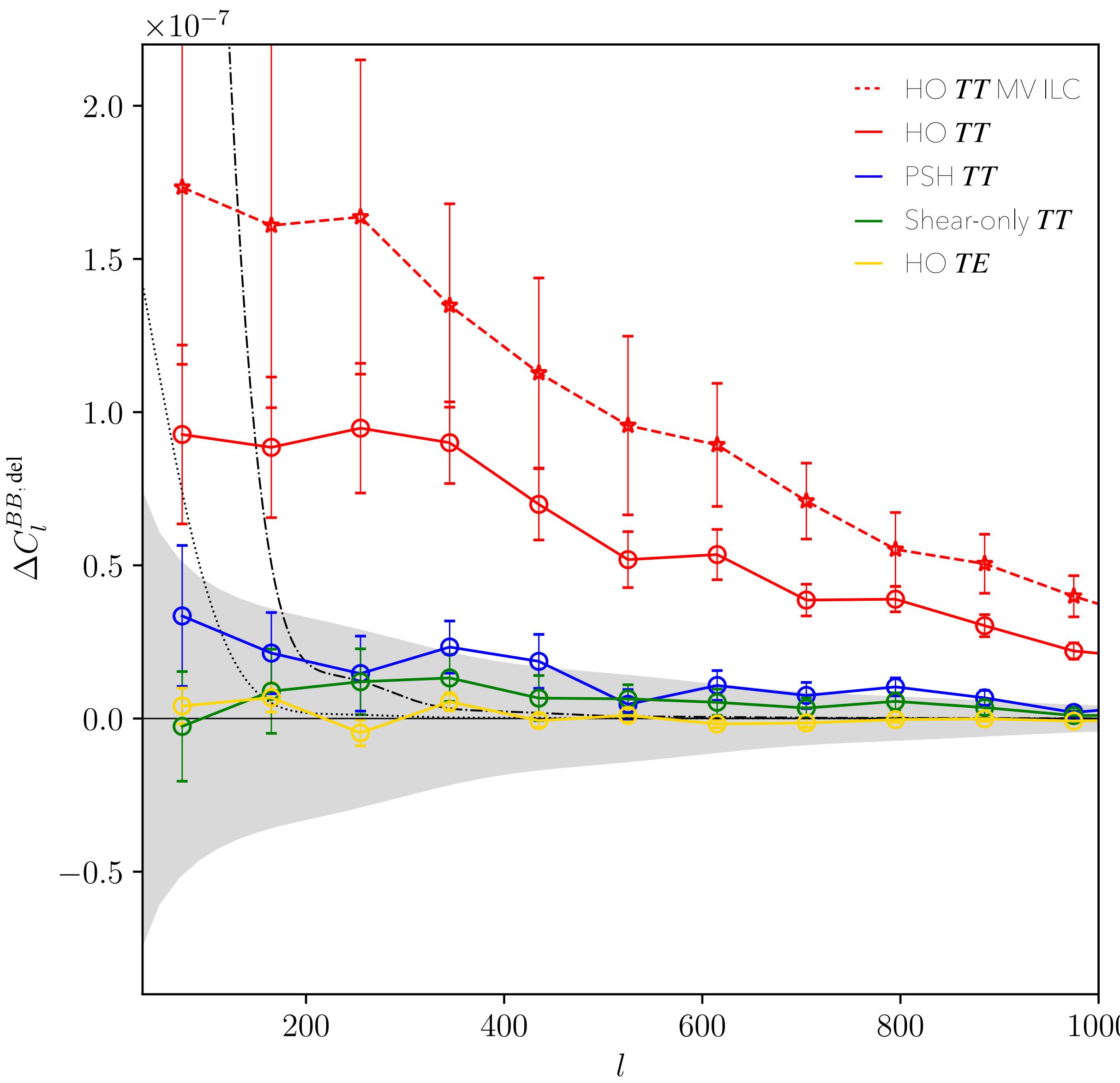


Noiseless B -modes, but SO-like template with $l_{\max,T} = 3500$ in reconstructions

Filtered out $l > 300$ modes to highlight degree-scale signal

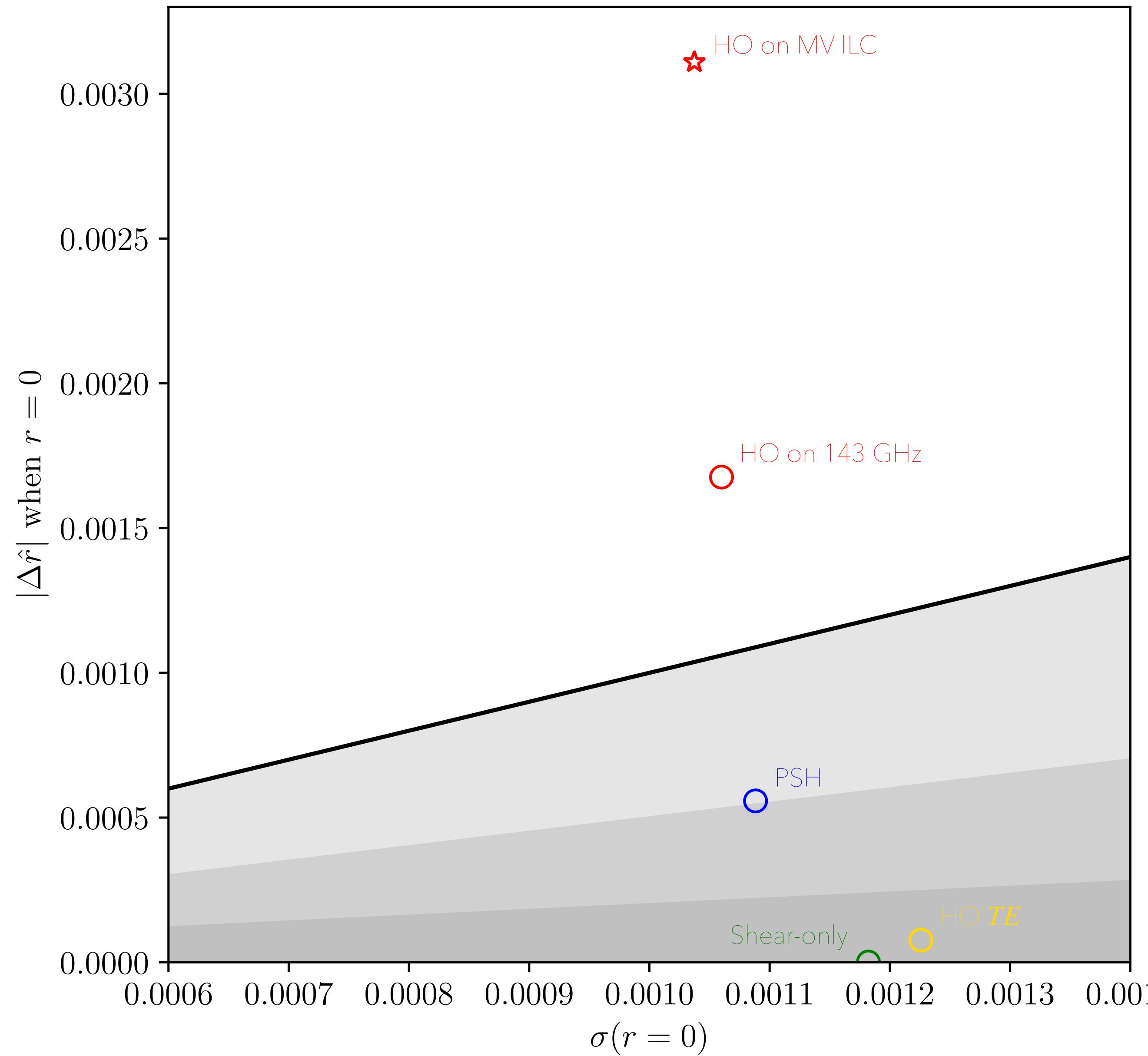
PATHWAYS TO MITIGATION

$\text{HO} \equiv$ Hu-Okamoto
 $\text{PSH} \equiv$ Point-source-hardened



BIAS VS NOISE

For all estimators, $l_{\max} = 3500$



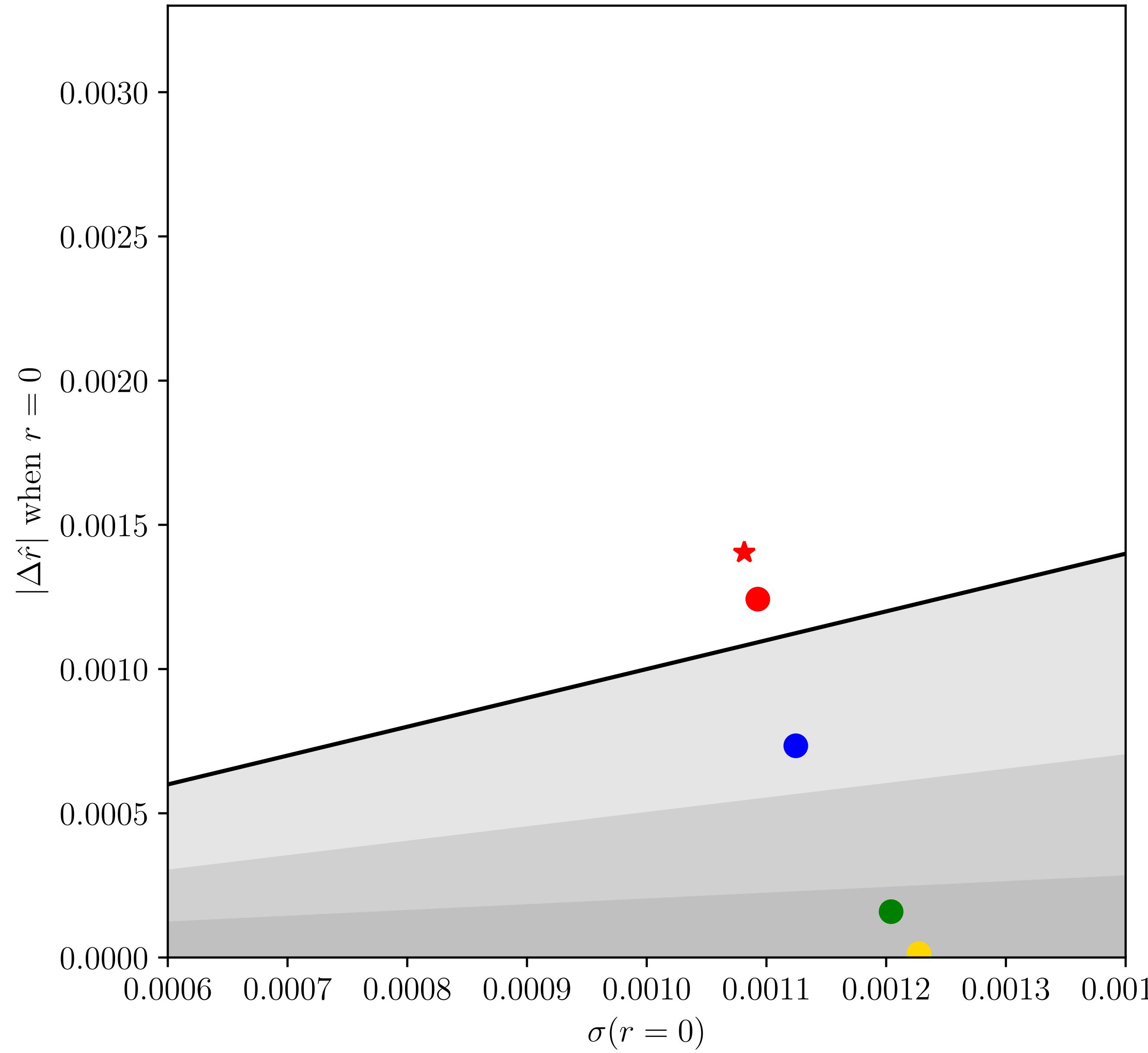
$$|\Delta \hat{r}|/\sigma(r) = 1$$

$$|\Delta \hat{r}|/\sigma(r) = 1/2$$

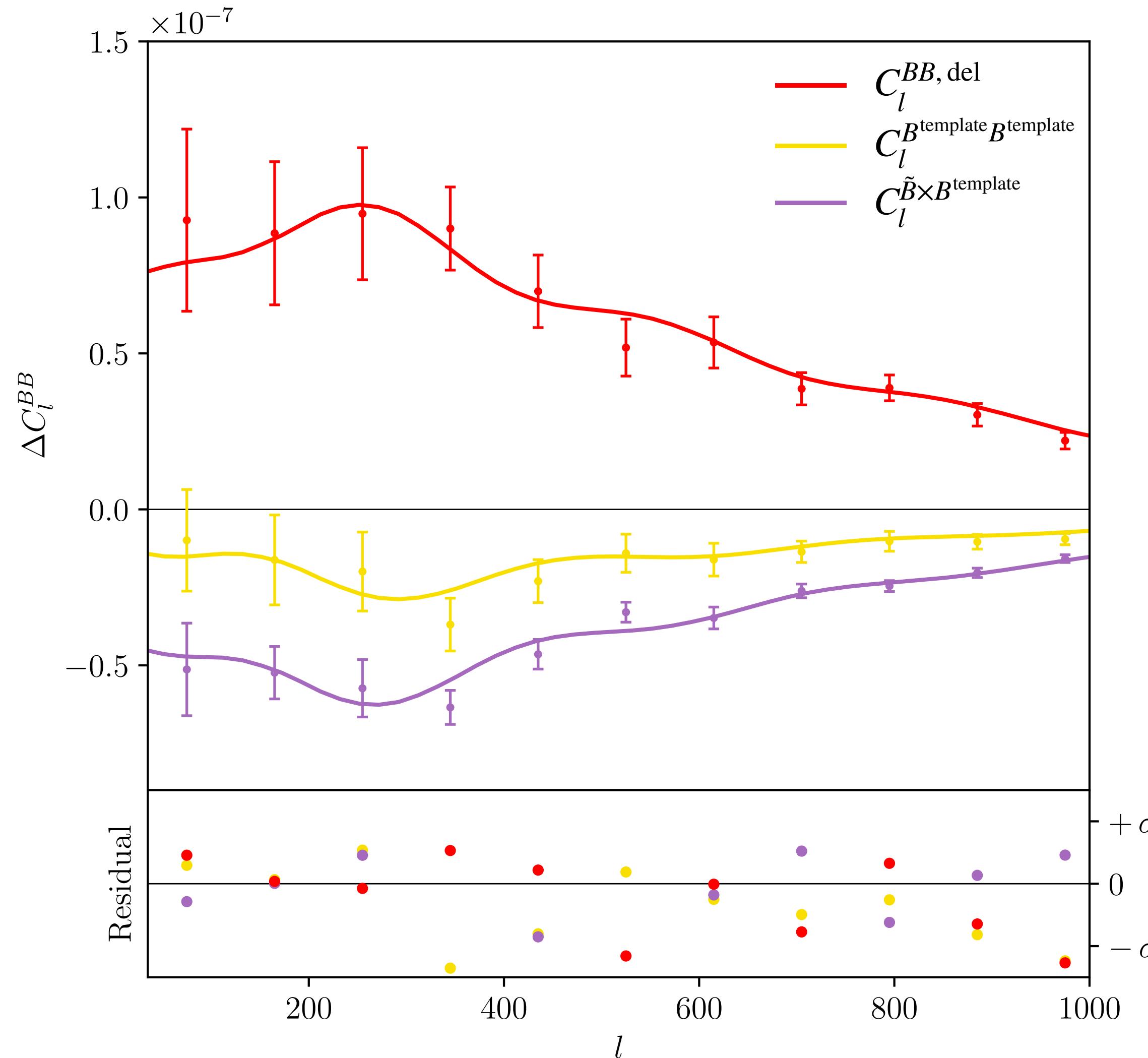
$$|\Delta \hat{r}|/\sigma(r) = 1/5$$

BIAS VS NOISE

For all estimators, $l_{\max} = 3000$



MODELING THE BIAS



The dominant terms can be modelled as

$$\Delta C_l^{\hat{B}^{\text{lens}} \times \hat{B}^{\text{lens}}} = \int \frac{d^2 \mathbf{l}'}{(2\pi)^2} W^2(\mathbf{l}, \mathbf{l}') \left(\mathcal{W}_{l'}^E \mathcal{W}_{|\mathbf{l}-\mathbf{l}'|}^\kappa \right)^2 \times C_{l'}^{EE, \text{tot}} \Delta C_{\mathbf{l}-\mathbf{l}'}^{\hat{\kappa}\hat{\kappa}},$$

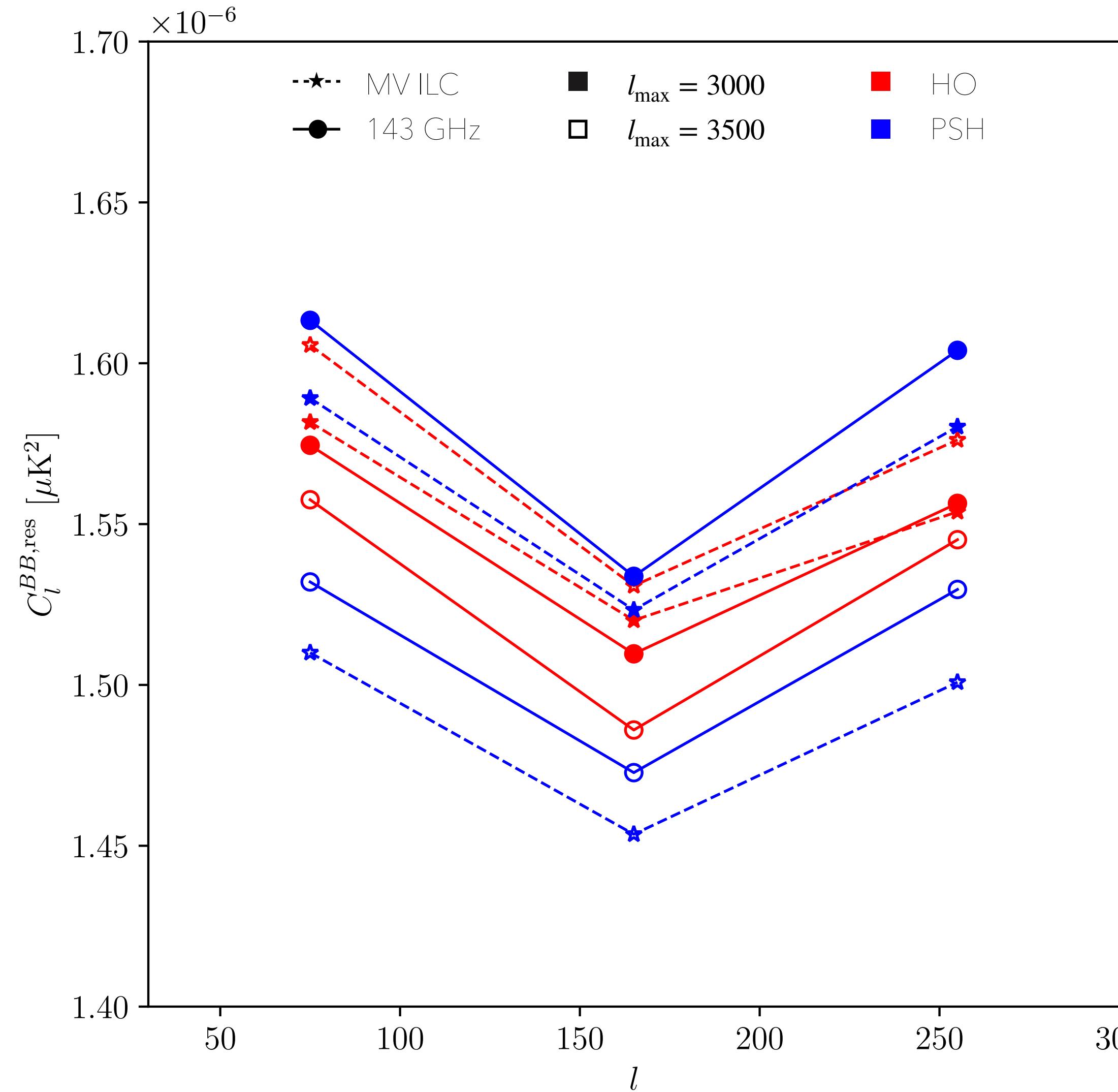
Smooth fit to auto-spectrum of a (biased) TT reconstruction

and

$$\Delta C_l^{\tilde{B} \times \hat{B}^{\text{lens}}} = \int \frac{d^2 \mathbf{l}'}{(2\pi)^2} W^2(\mathbf{l}, \mathbf{l}') \mathcal{W}_{l'}^E \mathcal{W}_{|\mathbf{l}-\mathbf{l}'|}^\kappa \times C_{l'}^{EE} \Delta C_{\mathbf{l}-\mathbf{l}'}^{\kappa\hat{\kappa}}.$$

Ditto to cross-correlation between TT and pol-only reconstructions

WHAT ESTIMATOR IS BEST?



If the modeling approach works, we'll avoid bias

... BUT ...

we still face a **tradeoff** between removing actual lensing B-modes and adding spurious power due to fg non-Gaussianity.

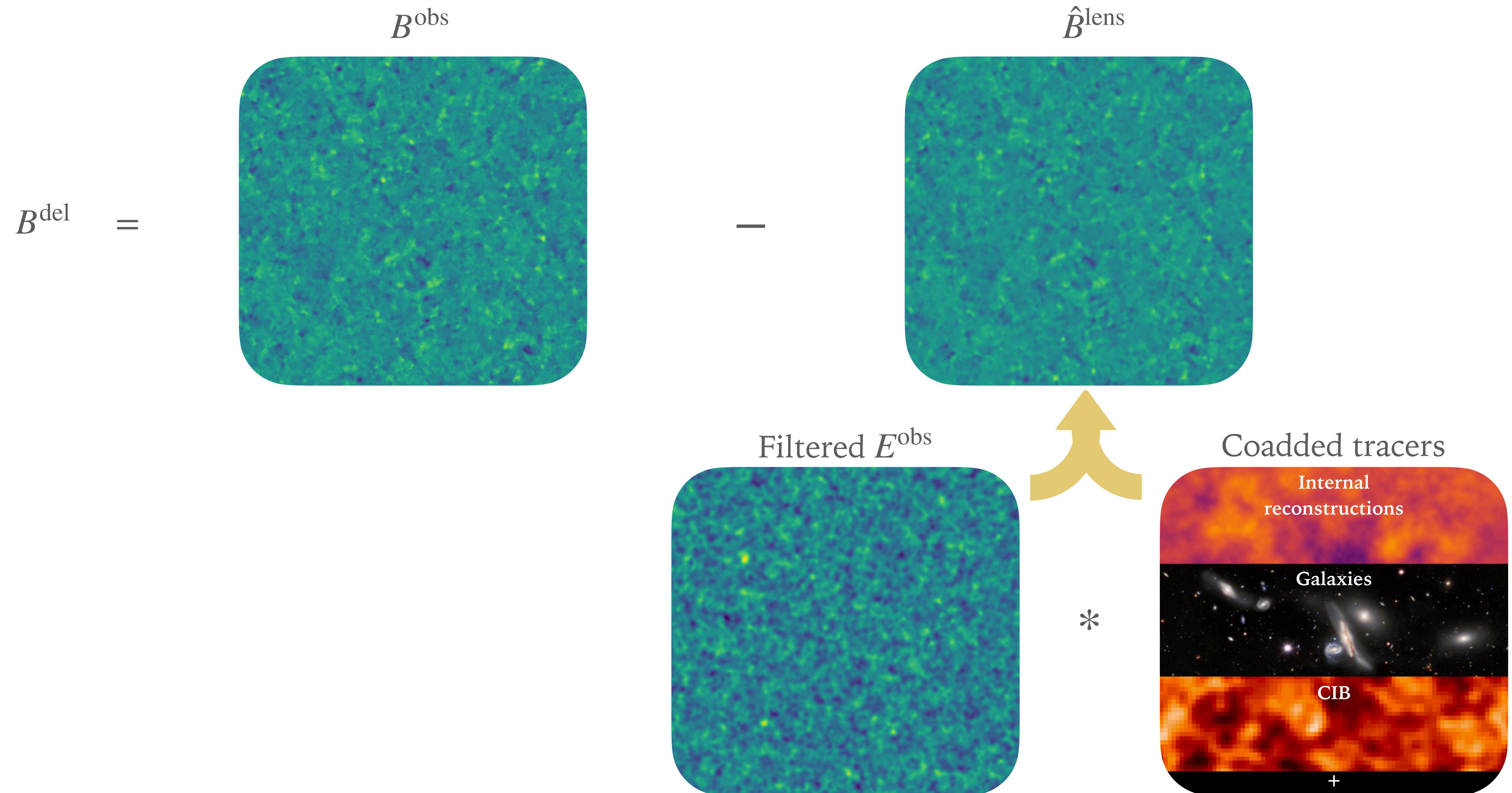
We must determine what choice of

- Lensing estimator
- l_{max}
- Foreground cleaning scheme
- Point-source masking protocol

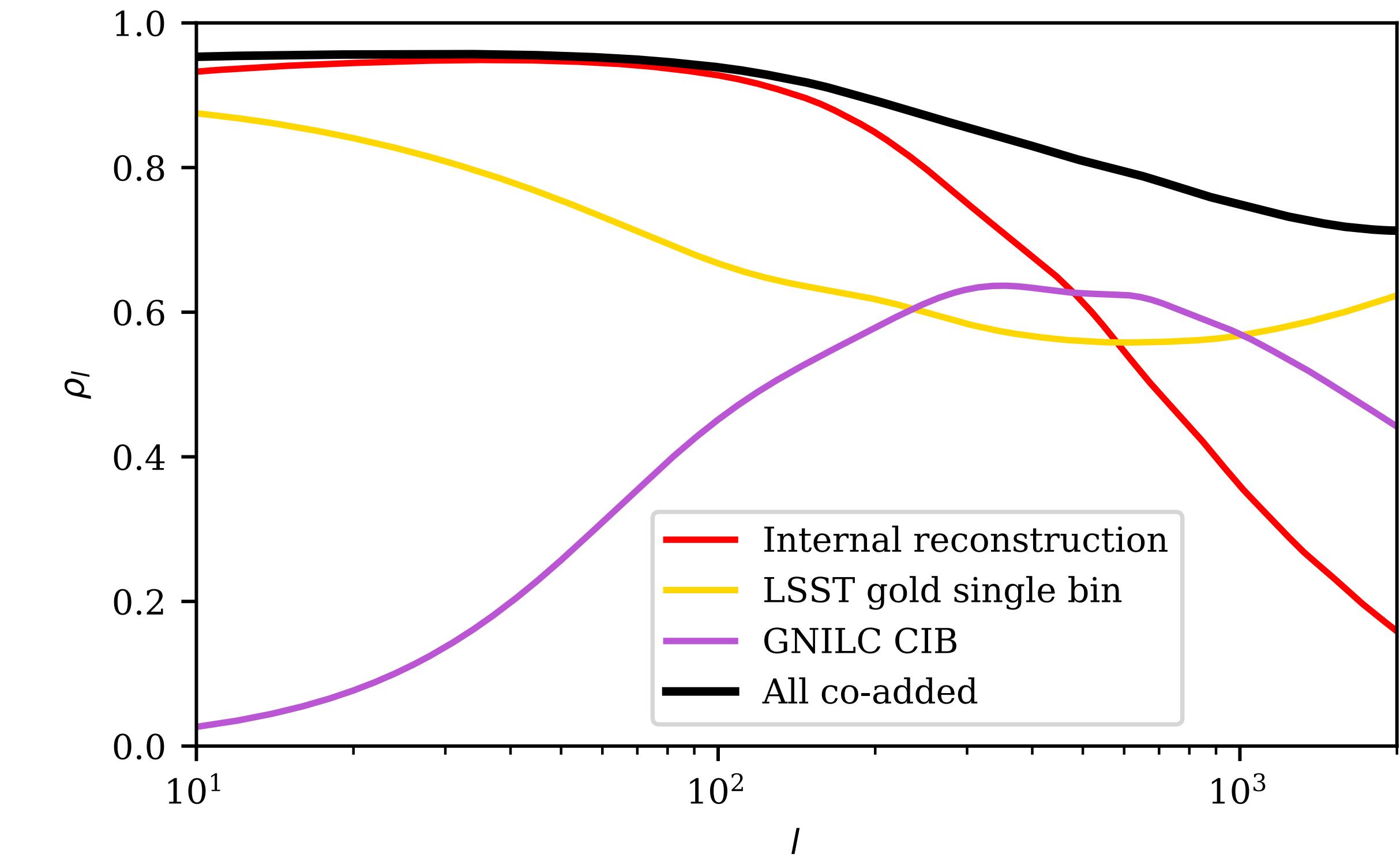
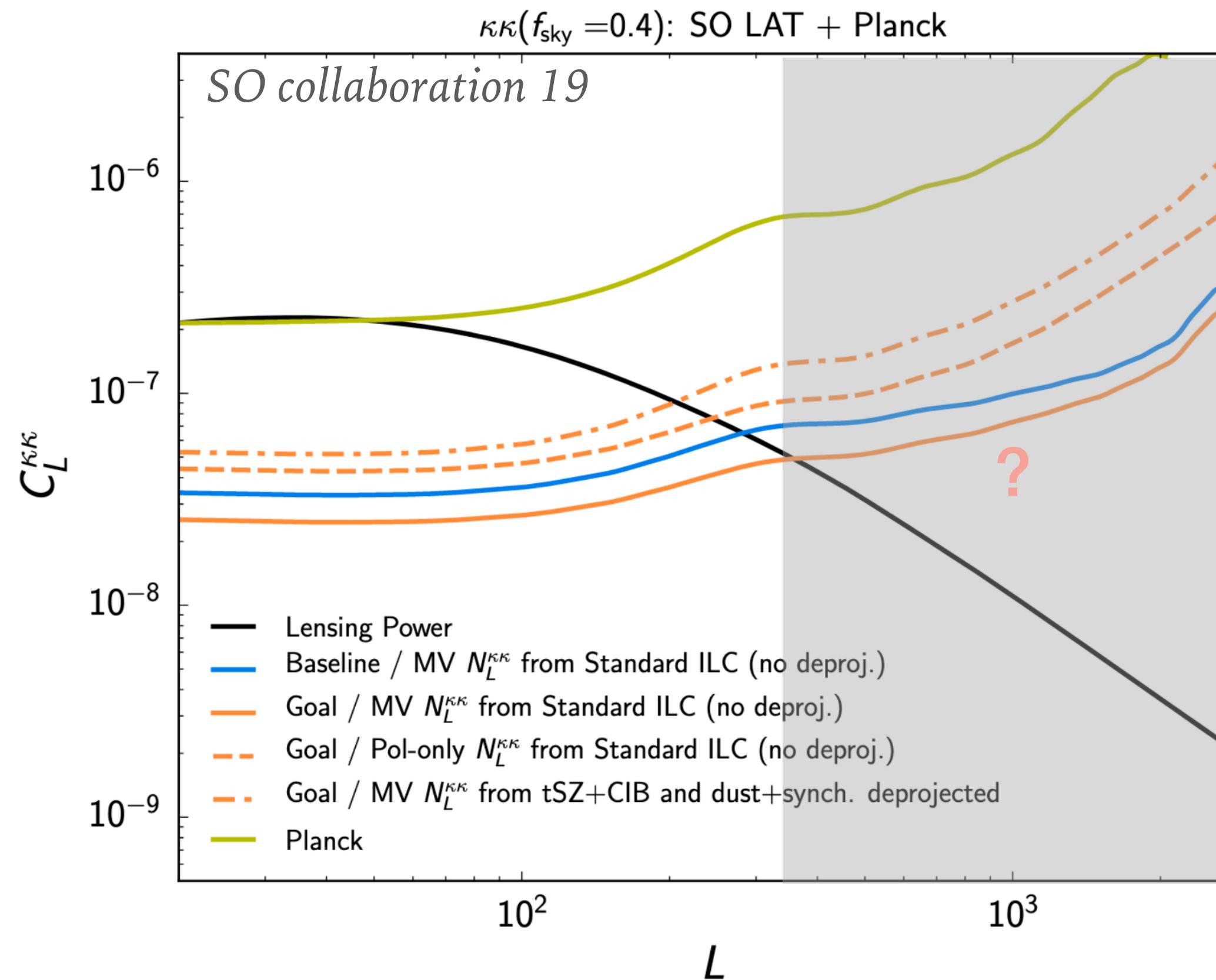
results in the least amount of B-mode power after delensing.

Working on an analytic code to do this!

MULTITRACER DELENSING



MULTI-TRACER DELENSING WITH SO



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

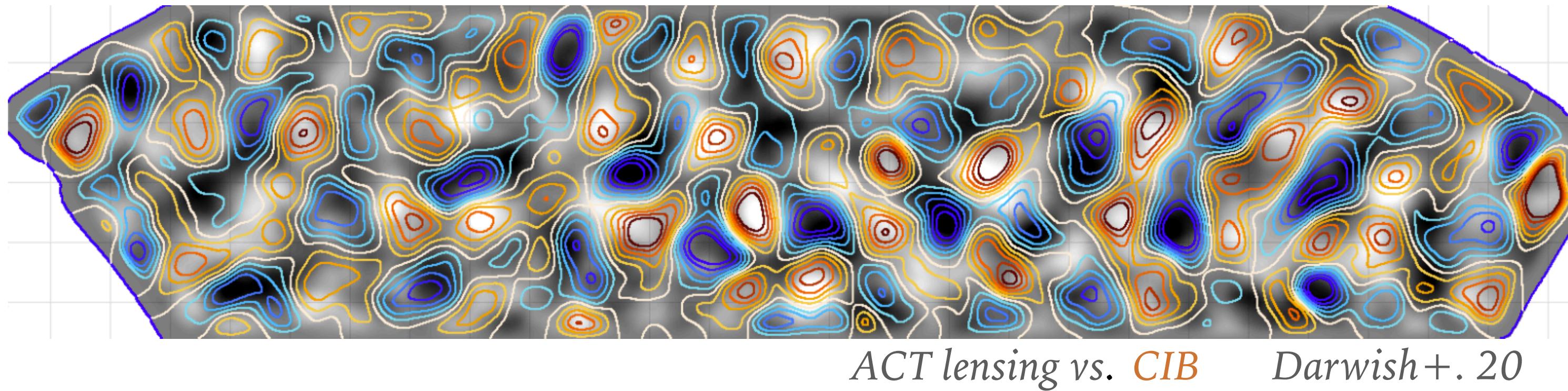
Sherwin & Schmittfull 15, Manzotti 18 ...

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

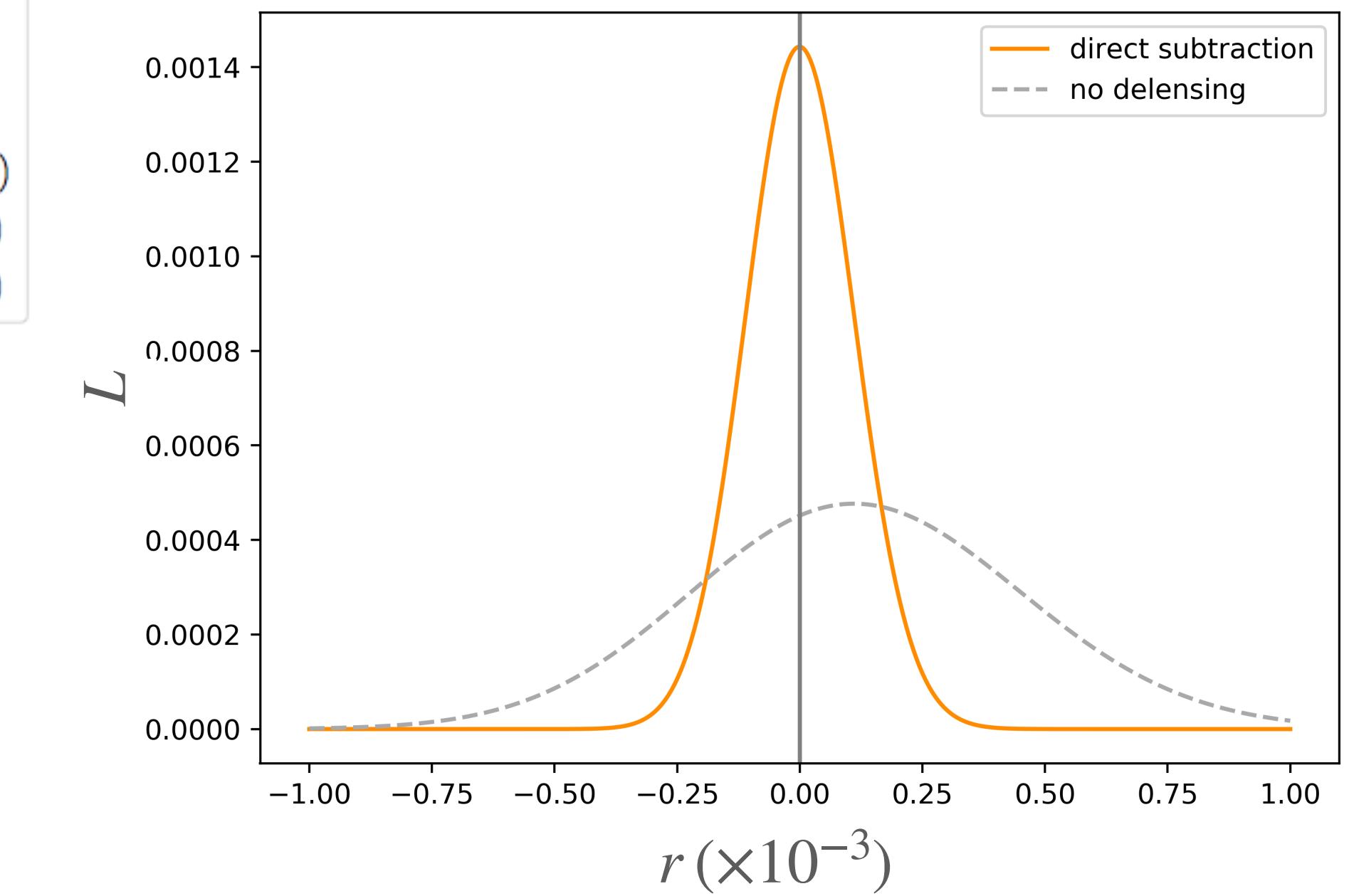
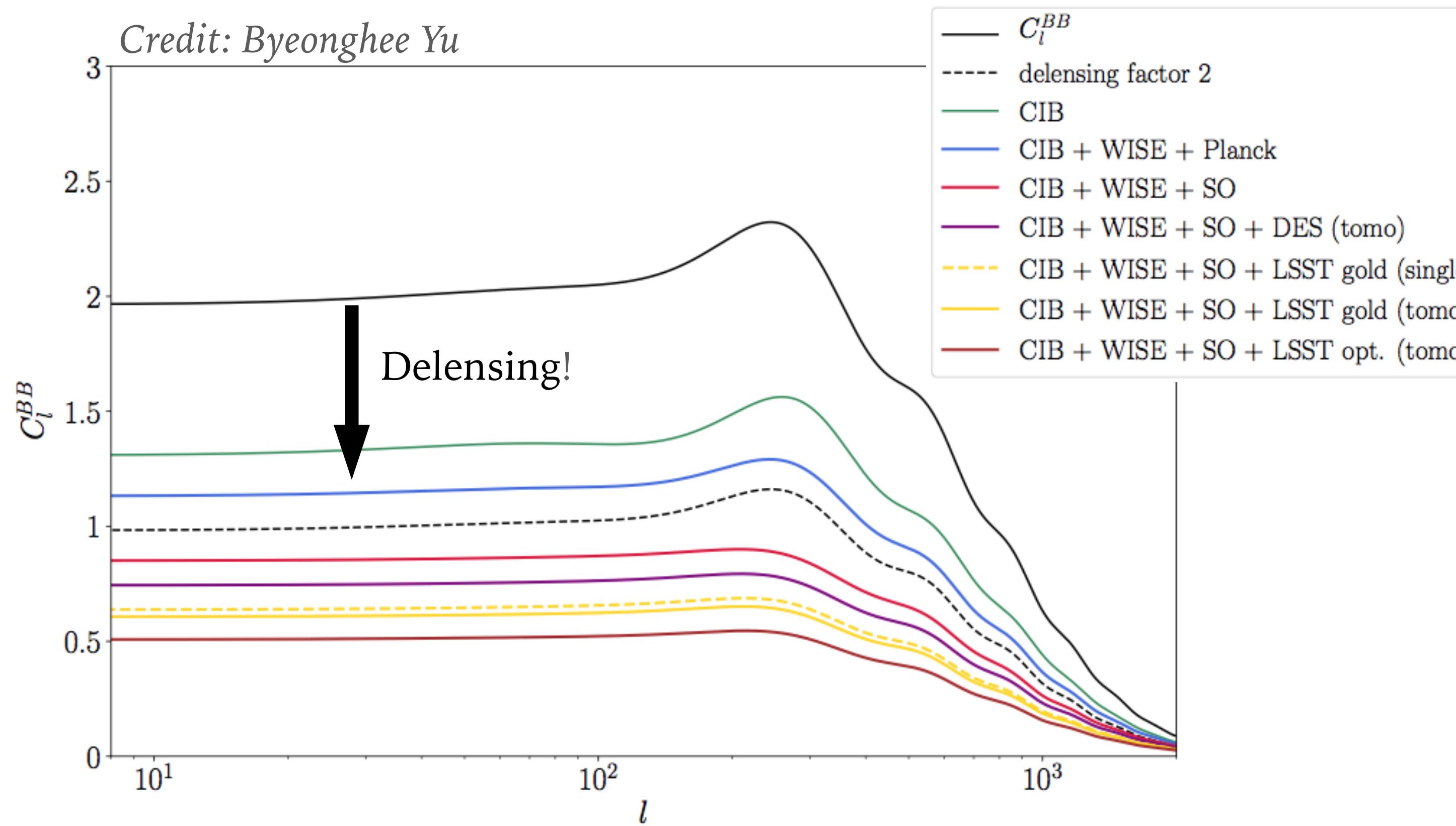
Sherwin & Schmittfull 15



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



Currently $\sigma(r) = 0.036$ (BICEP/Keck), SO forecast after delensing $\sigma(r) = 0.003$

MULTI-TRACER DELENSING BIAS

$$\begin{aligned}\Delta C_l^{BB, \text{del}} = & -2g_l \left[c^{TT} \langle \tilde{B} \tilde{E} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] \rangle \right] + h_l \left[(c^{TT})^2 \langle |E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}]|^2 \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\ & - 2g_l \left[c^{TE} \langle \tilde{B} \tilde{E} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E] \rangle \right] + h_l \left[(c^{TE})^2 \langle |E^{\text{obs}} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E]|^2 \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\ & + 2h_l \left[c^{TT} c^{TE} \langle E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] E^{\text{obs}} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E] \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\ & + 2h_l \left[c^{TT} \langle E^{\text{obs}} \sum_{i \neq TT, TE} c^i \hat{\kappa}^i E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] \rangle \right] - (s^{\text{NG}} \rightarrow s^G).\end{aligned}$$

Dilution of TT bias

MULTI-TRACER DELENSING BIAS

$$\begin{aligned}\Delta C_l^{BB, \text{del}} = & -2g_l \left[c^{TT} \langle \tilde{B} \tilde{E} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] \rangle \right] + h_l \left[(c^{TT})^2 \langle |E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}]|^2 \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\ & - 2g_l \left[c^{TE} \langle \tilde{B} \tilde{E} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E] \rangle \right] + h_l \left[(c^{TE})^2 \langle |E^{\text{obs}} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E]|^2 \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\ & + 2h_l \left[c^{TT} c^{TE} \langle E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] E^{\text{obs}} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E] \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\ & + 2h_l \left[c^{TT} \langle E^{\text{obs}} \sum_{i \neq TT, TE} c^i \hat{\kappa}^i E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] \rangle \right] - (s^{\text{NG}} \rightarrow s^G).\end{aligned}$$

Dilution of TE bias

MULTI-TRACER DELENSING BIAS

$$\begin{aligned}
\Delta C_l^{BB, \text{del}} = & -2g_l \left[c^{TT} \langle \tilde{B} \tilde{E} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] \rangle \right] + h_l \left[(c^{TT})^2 \langle |E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}]|^2 \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\
& - 2g_l \left[c^{TE} \langle \tilde{B} \tilde{E} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E] \rangle \right] + h_l \left[(c^{TE})^2 \langle |E^{\text{obs}} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E]|^2 \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\
& + 2h_l \left[c^{TT} c^{TE} \langle E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] E^{\text{obs}} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E] \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\
& + 2h_l \left[c^{TT} \langle E^{\text{obs}} \sum_{i \neq TT, TE} c^i \hat{\kappa}^i E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] \rangle \right] - (s^{\text{NG}} \rightarrow s^G).
\end{aligned}$$

New term involving:

$$\begin{aligned}
\Delta C_l^{BB, \text{res}} \supset & \\
\supset & 2h_l \left[c^{TT} c^{TE} \langle \overbrace{E^{\text{obs}} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}]} E^{\text{obs}} \hat{\kappa}^{TE} [\tilde{T}, \tilde{E}] \rangle_c \right] \\
& + 4h_l \left[c^{TT} c^{TE} \langle \overbrace{E^{\text{obs}} \hat{\kappa}^{TT} [\tilde{T}, s^{\text{NG}}]} E^{\text{obs}} \hat{\kappa}^{TE} [s^{\text{NG}}, \tilde{E}] \rangle_c \right]
\end{aligned}$$

\sim primary bispectrum bias

\sim secondary bispectrum bias

MULTI-TRACER DELENSING BIAS

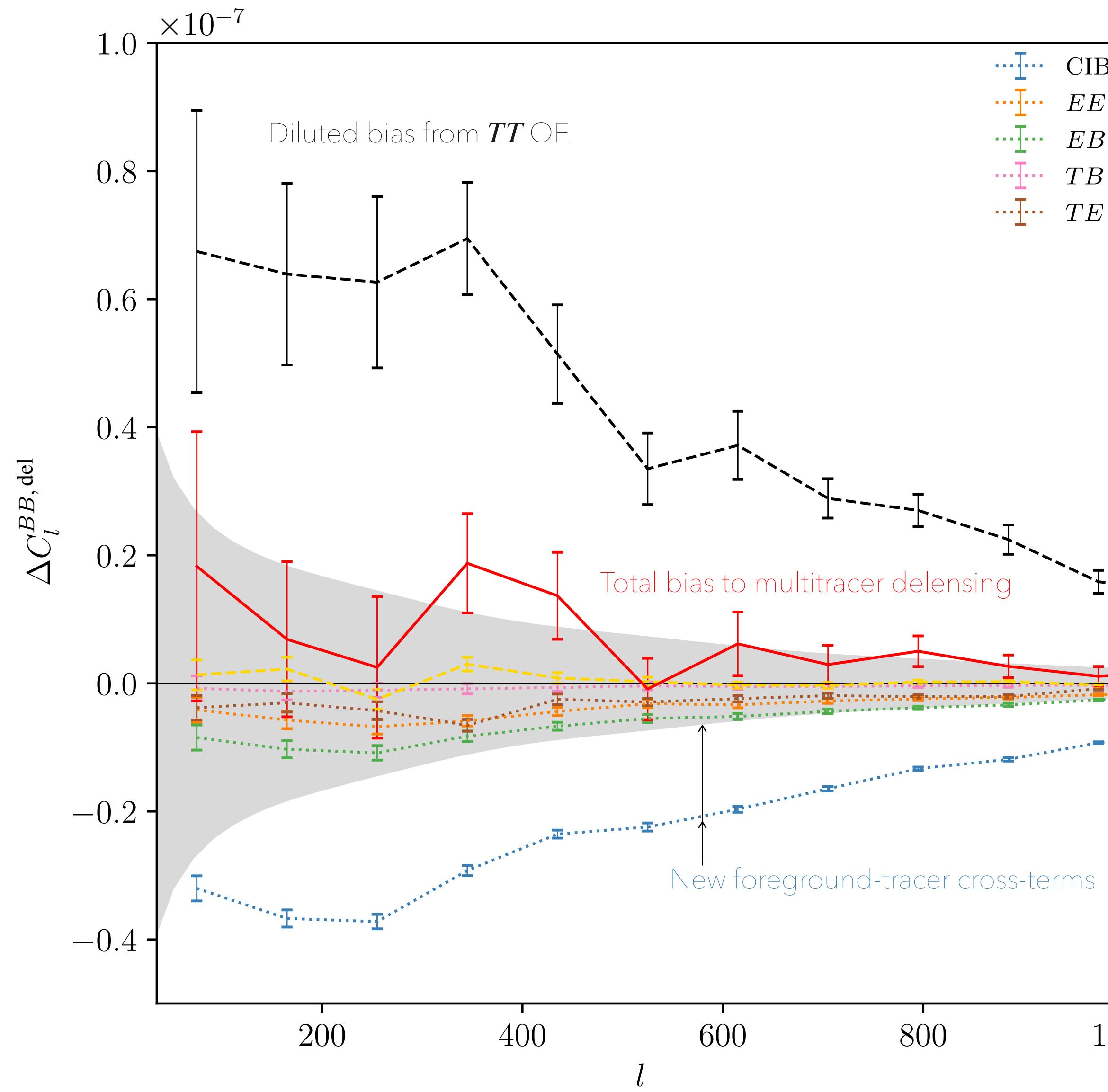
$$\begin{aligned}
\Delta C_l^{BB, \text{del}} = & -2g_l \left[c^{TT} \langle \tilde{B} \tilde{E} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] \rangle \right] + h_l \left[(c^{TT})^2 \langle |E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}]|^2 \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\
& - 2g_l \left[c^{TE} \langle \tilde{B} \tilde{E} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E] \rangle \right] + h_l \left[(c^{TE})^2 \langle |E^{\text{obs}} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E]|^2 \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\
& + 2h_l \left[c^{TT} c^{TE} \langle E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] E^{\text{obs}} \hat{\kappa}^{TE} [f_T + s^{\text{NG}}, f_E] \rangle \right] - (s^{\text{NG}} \rightarrow s^G) \\
& + 2h_l \left[c^{TT} \langle E^{\text{obs}} \sum_{i \neq TT, TE} c^i \hat{\kappa}^i E^{\text{obs}} \hat{\kappa}^{TT} [f_T + s^{\text{NG}}, f_T + s^{\text{NG}}] \rangle \right] - (s^{\text{NG}} \rightarrow s^G).
\end{aligned}$$

New term involving:

$$\Delta C_l^{BB, \text{res}} \supset 2h_l \left[c^{TT} c^i \langle \overbrace{E^{\text{obs}} \hat{\kappa}^i}^{} E^{\text{obs}} \hat{\kappa}^{TT} [s^{\text{NG}}, s^{\text{NG}}] \rangle_c \right]$$

A function of $\langle sss \rangle$ or $\langle \kappa ss \rangle$

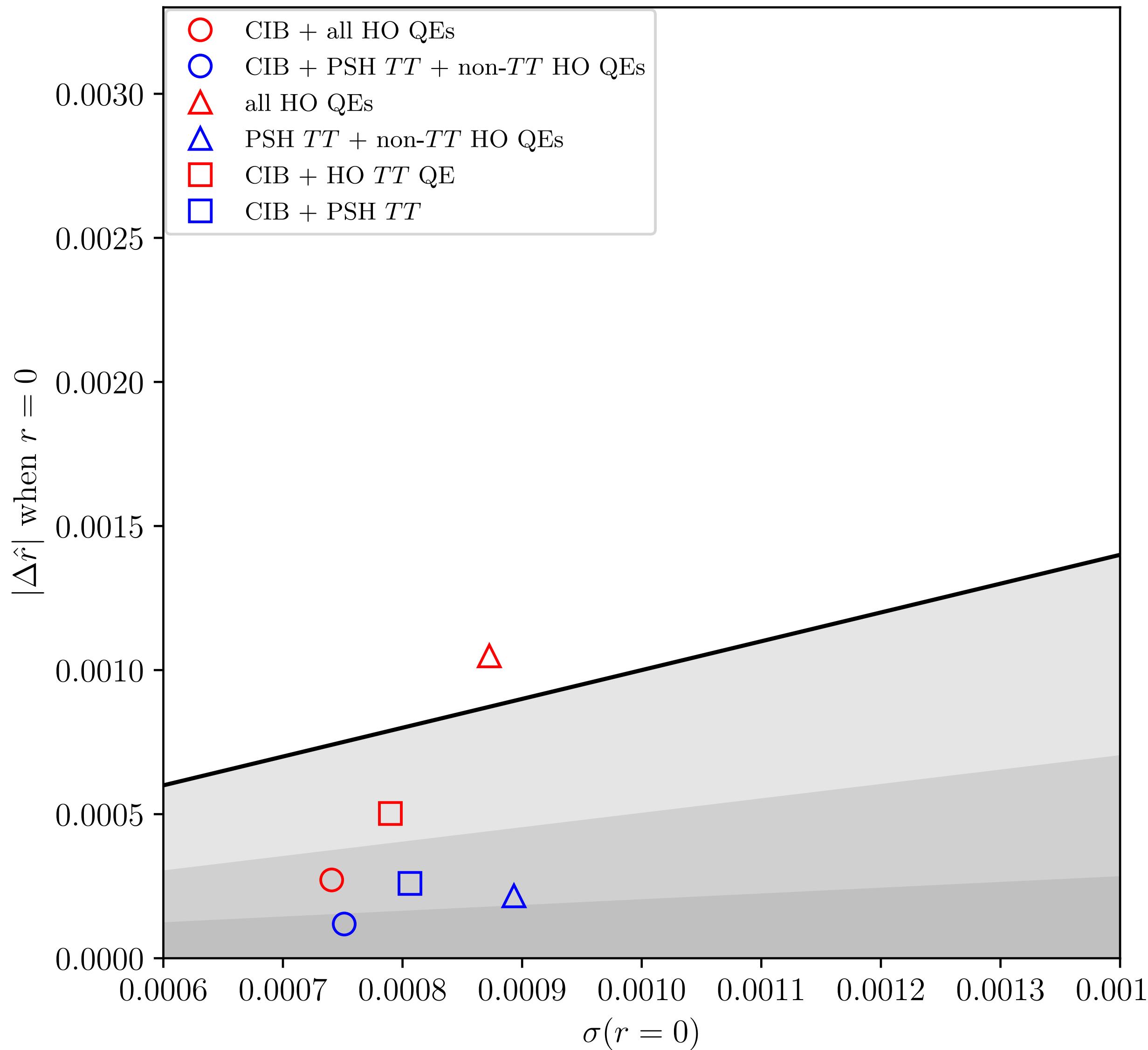
BIAS TO MULTI-TRACER DELENSING



The diluted bias from TT cancels extensively with new cross-terms involving internal and external tracers — especially when the CIB is used as a matter tracer

Here too, empirically-calibrated models can capture the residual effects of foreground non-Gaussianity

BIAS VS NOISE



$$|\Delta \hat{r}|/\sigma(r) = 1$$

$$|\Delta \hat{r}|/\sigma(r) = 1/2$$

$$|\Delta \hat{r}|/\sigma(r) = 1/5$$

CONCLUSIONS

Key points:

- Delensing now essential to improve constraints on primordial gravitational waves
- Non-Gaussianity of extragalactic fgs must be taken into account when delensing with TT — otherwise risk $\sim 1.5\sigma$ bias on r (for SO, $l_{\max} = 3500$)
- Naive fg cleaning could be detrimental — reconstructing from MV ILC leads to $\sim 3\sigma$ bias on r
- Bias can be modelled away using analytic expressions relying on empirically-calibrated $C^{\hat{\kappa}\hat{\kappa}}$ and $C^{\kappa\hat{\kappa}}$
- Non-trivial couplings appear when coadding TT with pol-only QEs or external tracers — they actually help us by cancelling diluted bias from TT
- Point-source-hardened QEs is rather immune to bias while retaining much of delensing efficiency — can lead to lower B-mode power after delensing than Hu-Okamoto QE

Check out arXiv:2205.0900

Next, we must investigate:

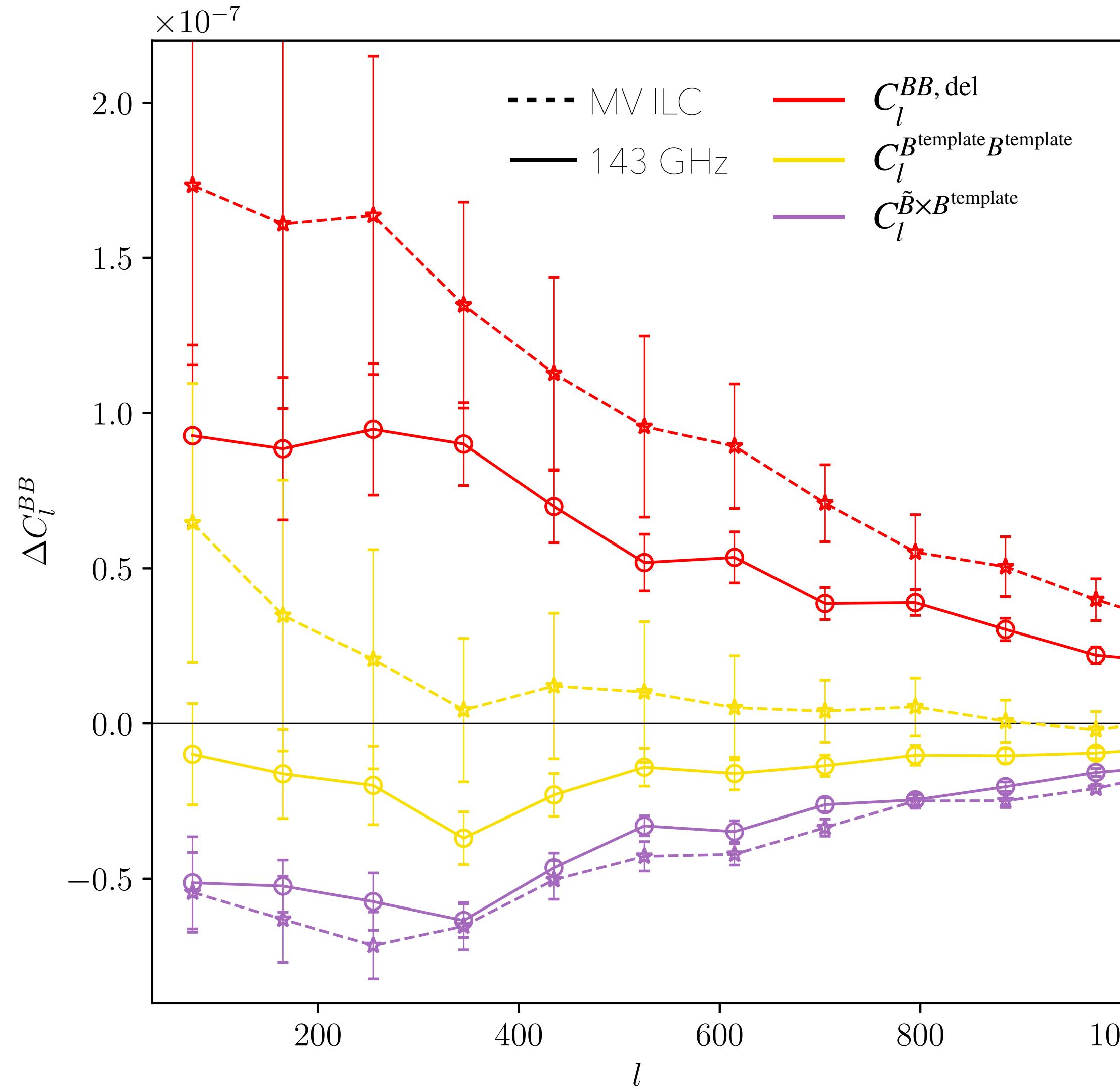
- Impact of polarized (point) sources?
- Impact on delensing of acoustic peaks?

Thank you for having me!

a.baleatolizancos@berkeley.edu

ADDITIONAL SLIDES

MV ILC LEADS TO HIGHER BIAS



When both $\Delta C^{B \text{ template } B \text{ template}}$ and $\Delta C^{\tilde{B} \text{ template}}$ are dominated by bispectrum bias, they cancel each other out, and scatter also \downarrow

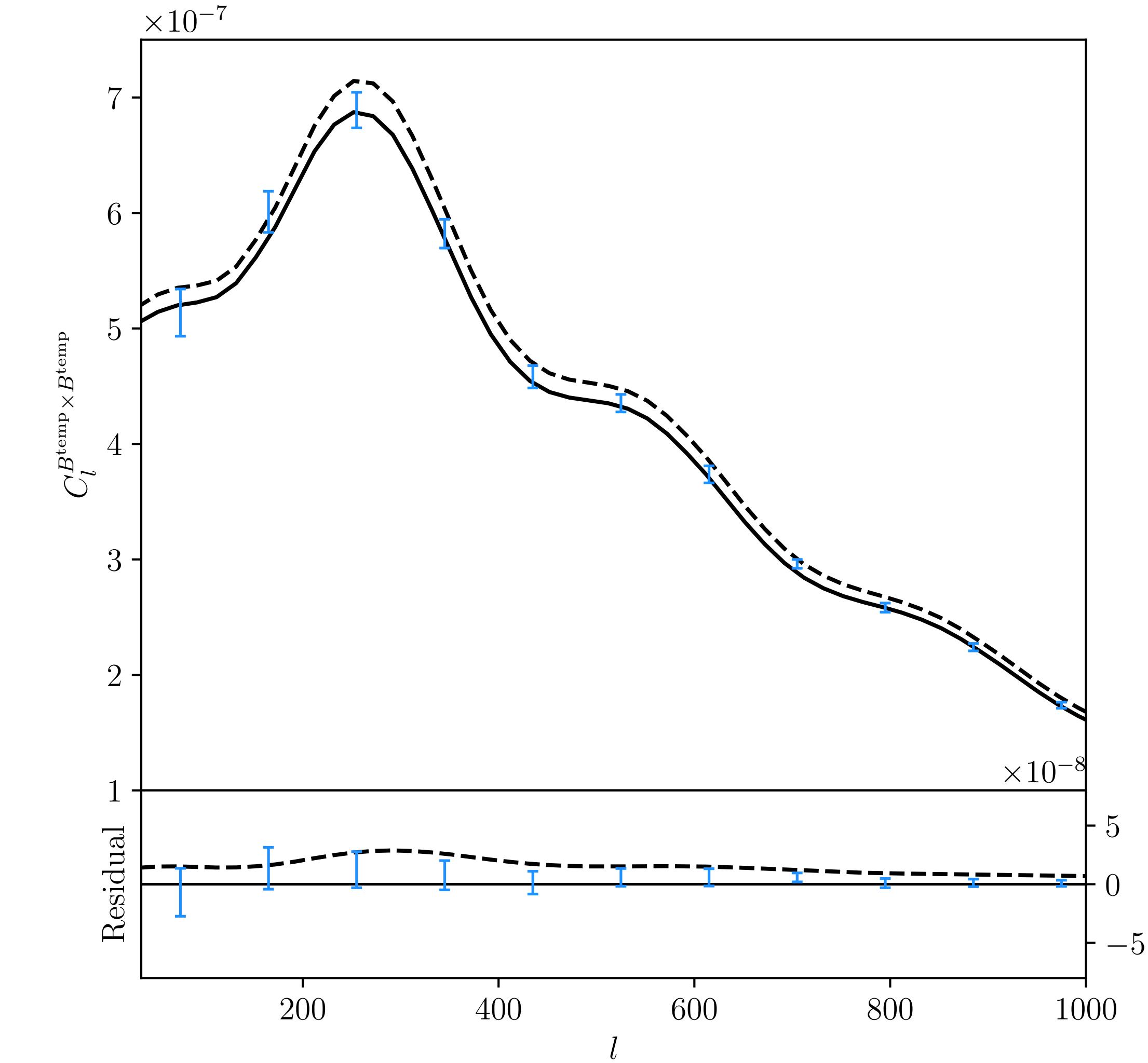
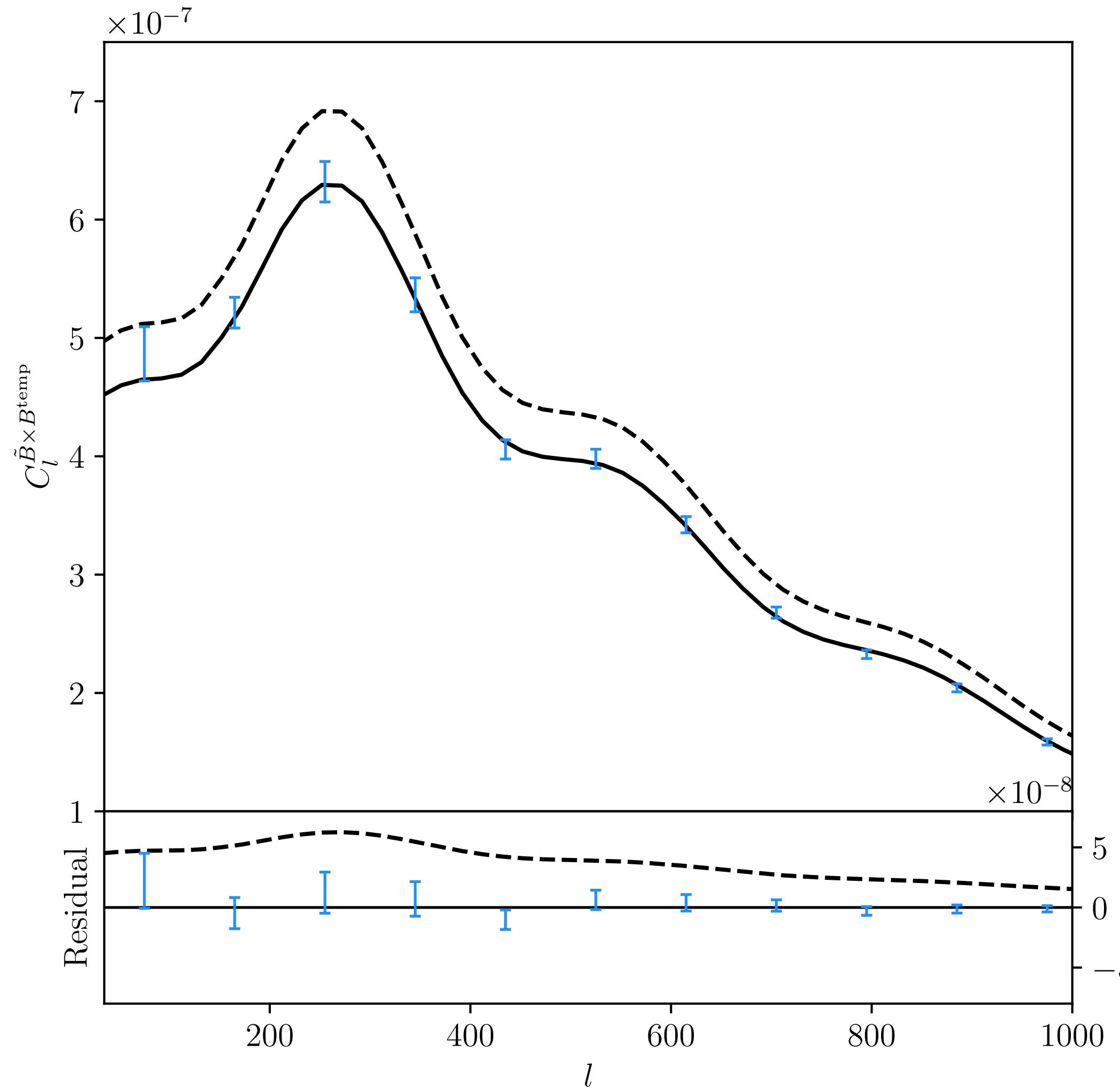
MV ILC boosts tSZ by a factor of $\sim 2^{1/2}$

\Rightarrow trispectrum grows by $(2^{1/2})^4$, bispectrum less responsive

\Rightarrow template auto- moves “up”

\Rightarrow $\Delta C^{BB, \text{del}}$ can \uparrow while $|\Delta C^{B \text{ template } B \text{ template}}|$ and $|\Delta C^{\tilde{B} \text{ template}}| \downarrow$ or stay =

EMPIRICALLY-CALIBRATED MODELS OF BIASED B-MODE SPECTRA

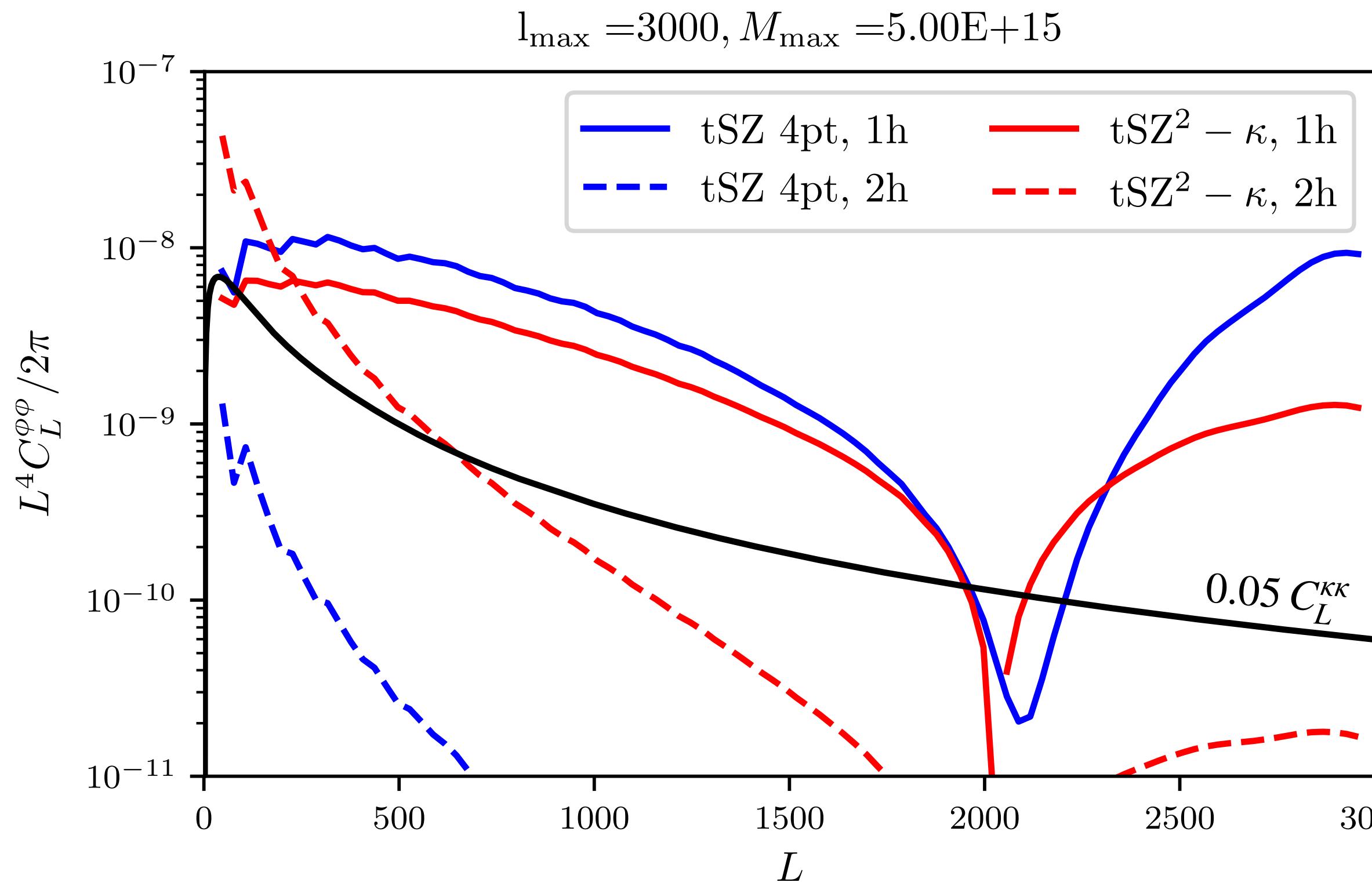


Models were computed using $\langle C^{\hat{k}\hat{k}} \rangle$ and $\langle C^{\kappa\hat{k}} \rangle$ featuring {

Gaussian fgs
 non-Gaussian fgs

A FLEXIBLE TOOL TO OPTIMIZE OUR ANALYSIS CHOICES

A code to calculate these effects analytically as a function of experimental sensitivity, resolution, point-source masking, etc, using the halo model



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

Preliminary

- Very fast implementation, calculates lensing reconstructions using FFTlog (for fast, discrete Hankel transforms), taking $O(10\text{ms})$ per lensing reconstruction on a single laptop core.
- Can calculate biases and associated uncertainties