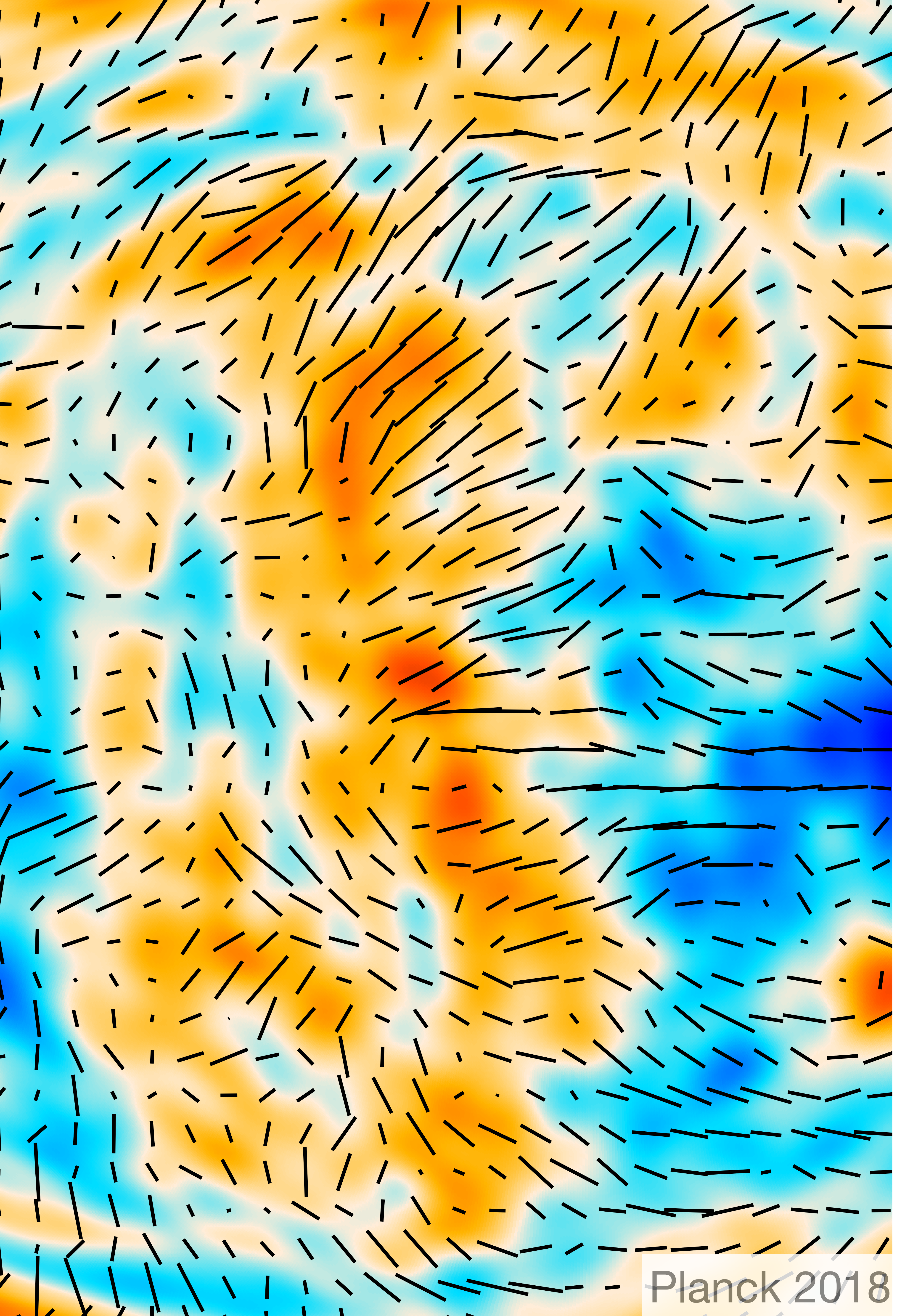
THE IMPACT OF GALAXIES AND CLUSTERS ON DELENSING OF CMB B-MODE POLARIZATION

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

SIMONS OBSERVATORY

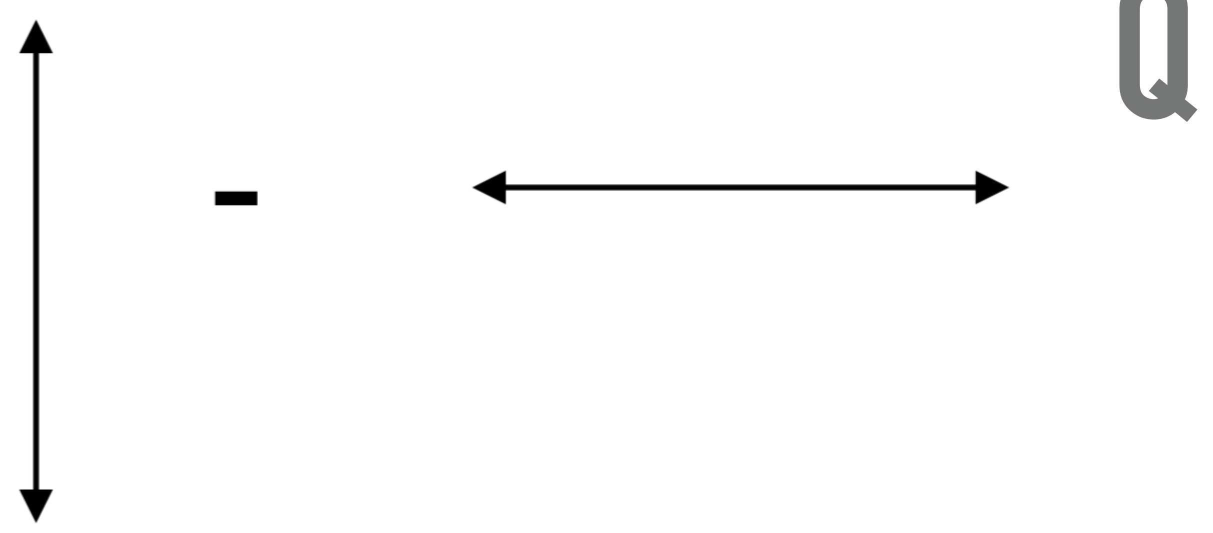
6/6/2022

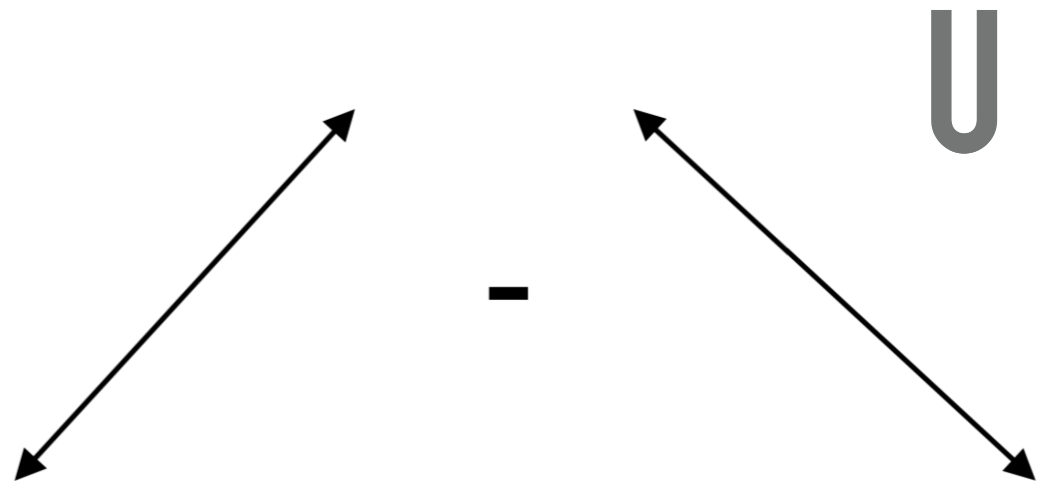
Cosmology Seminar, KIPAC Stanford



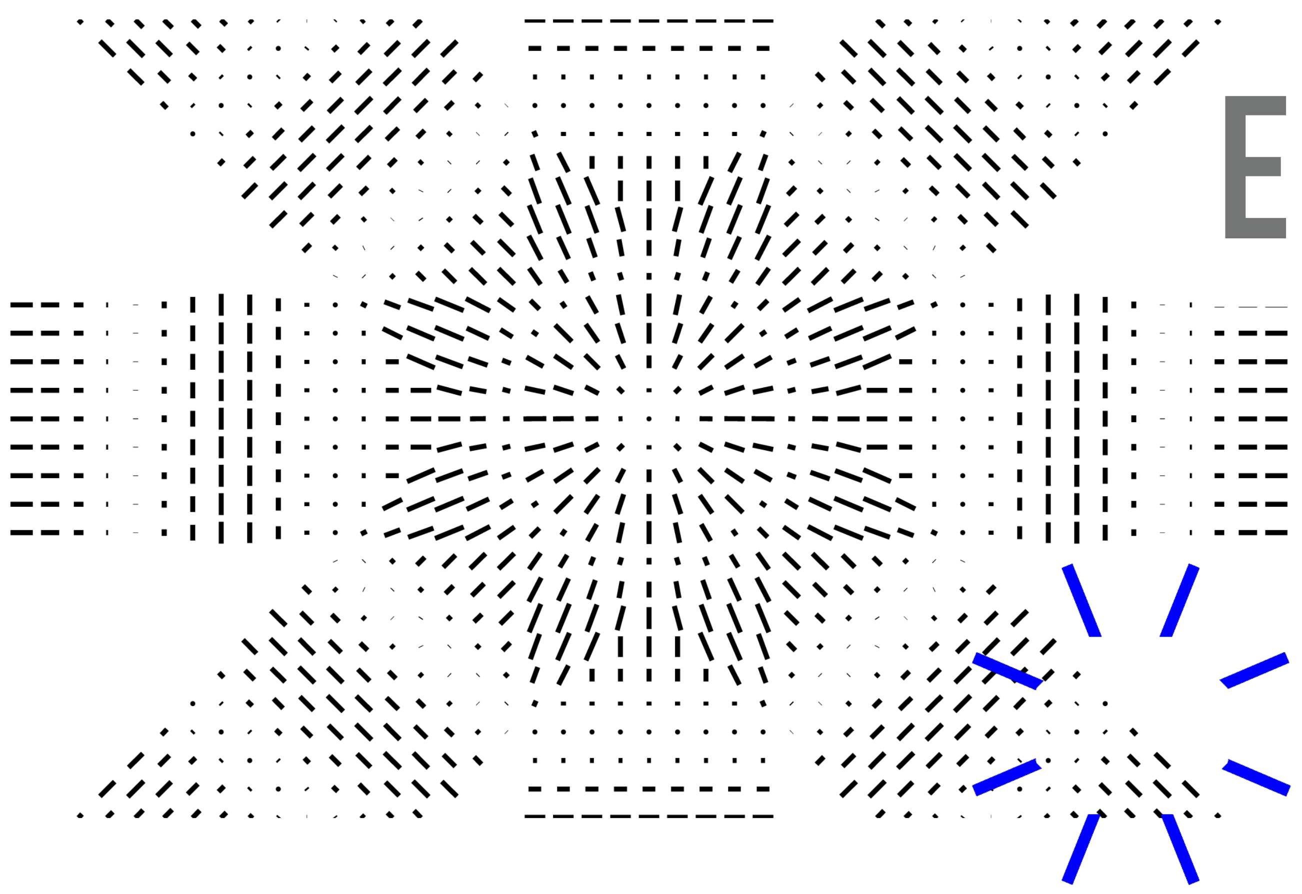
CMB OBSERVABLES — INTENSITY AND POLARISATION

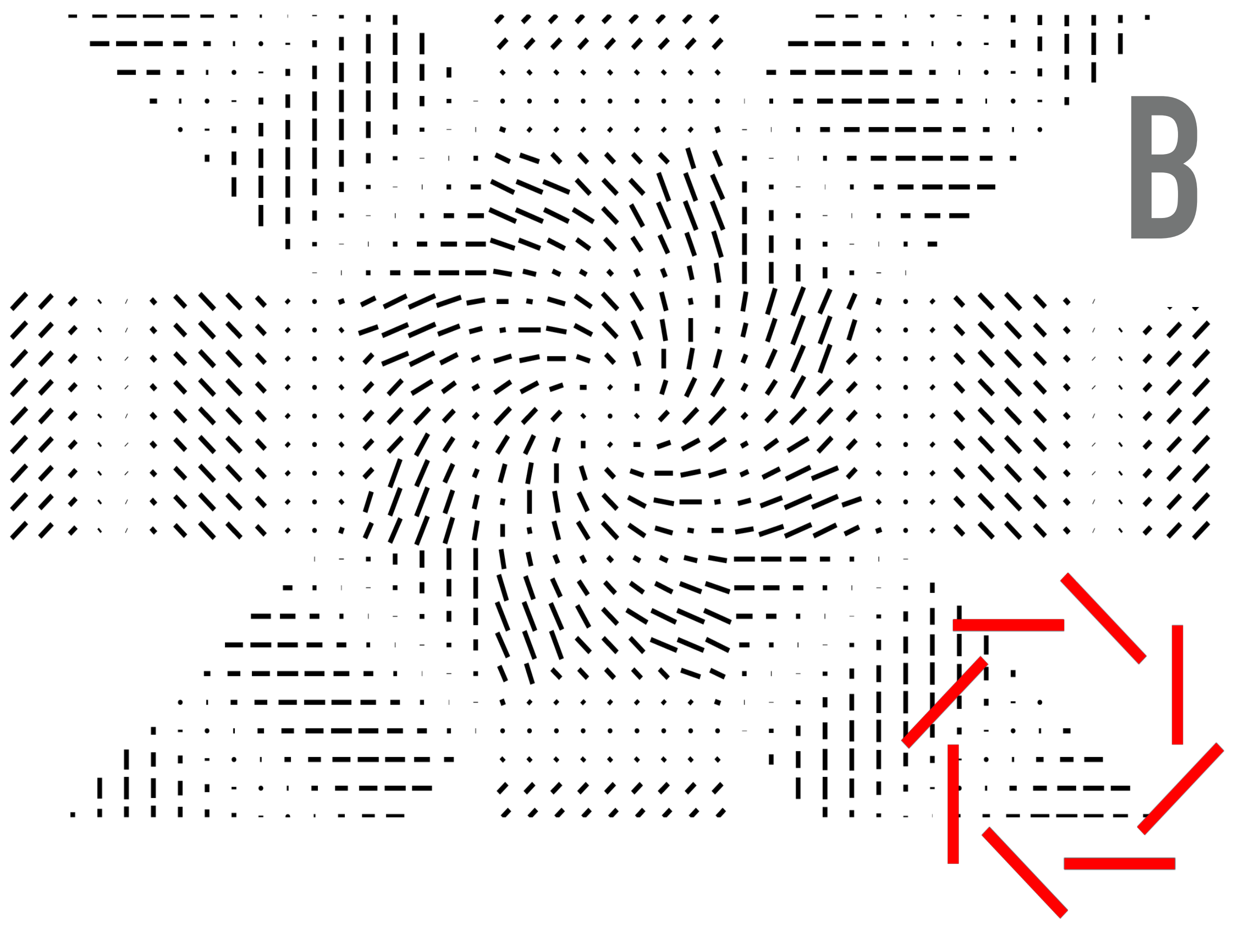
Observe:



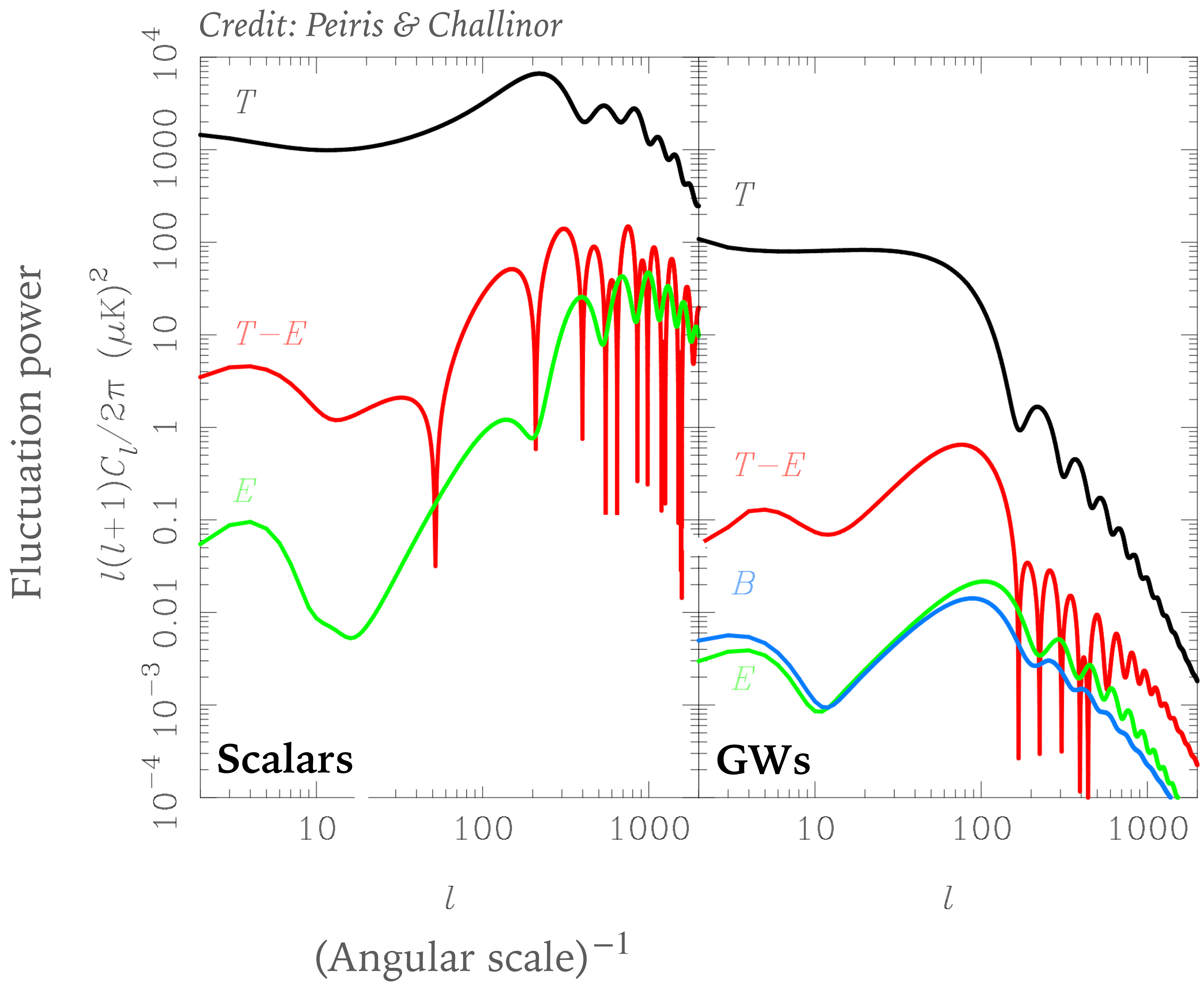


Connect with theory:





THE PRIMORDIAL CMB



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

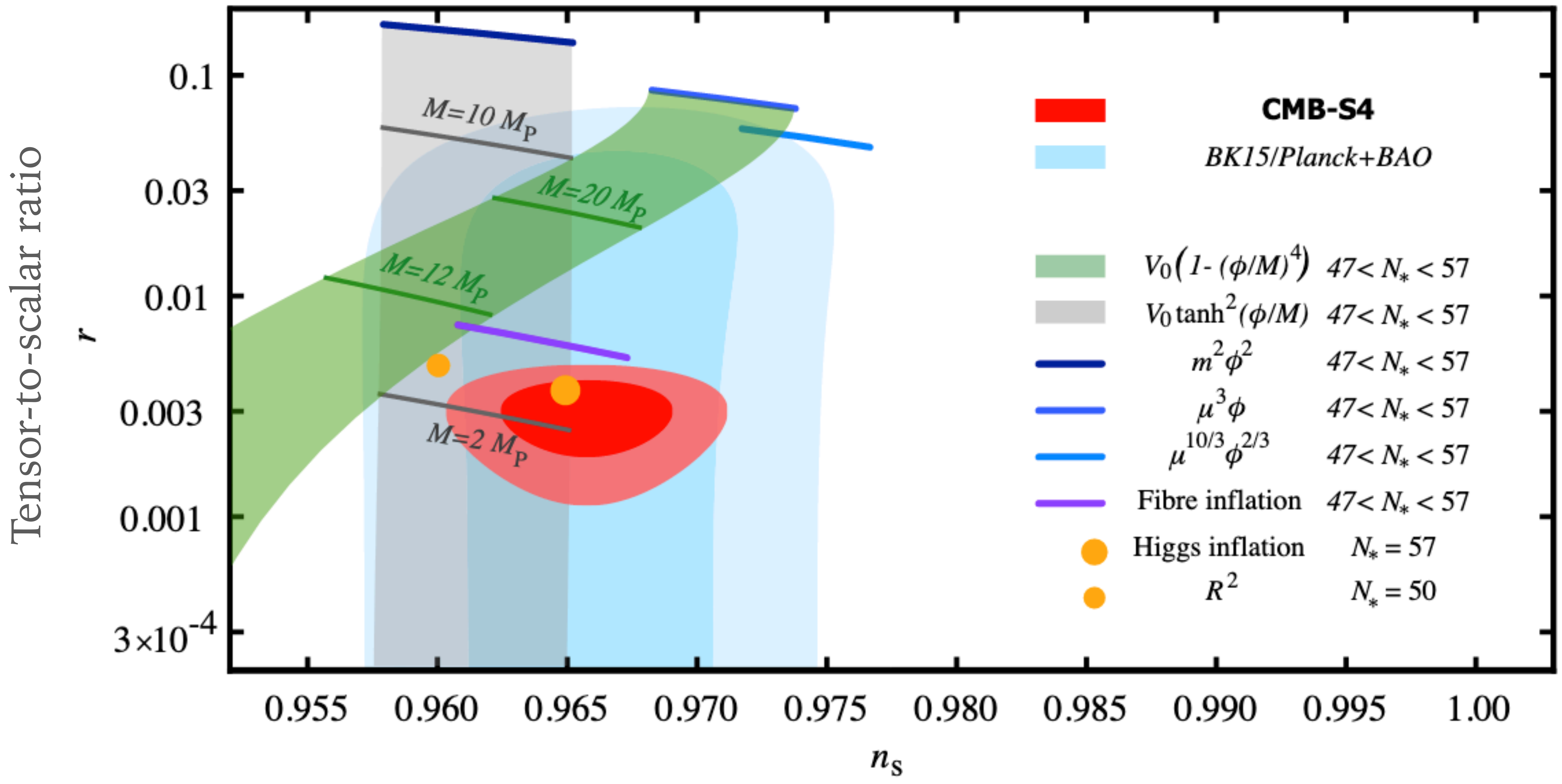
Kamionkowski+ 97 , Seljak & Zaldarriaga 97

$r < 0.036$ *BICEP/Keck 21*

- Statistically isotropic, Gaussian random field

CONSTRAINING INFLATION VIA THE CMB

CMB-S4, arXiv:1907.04473

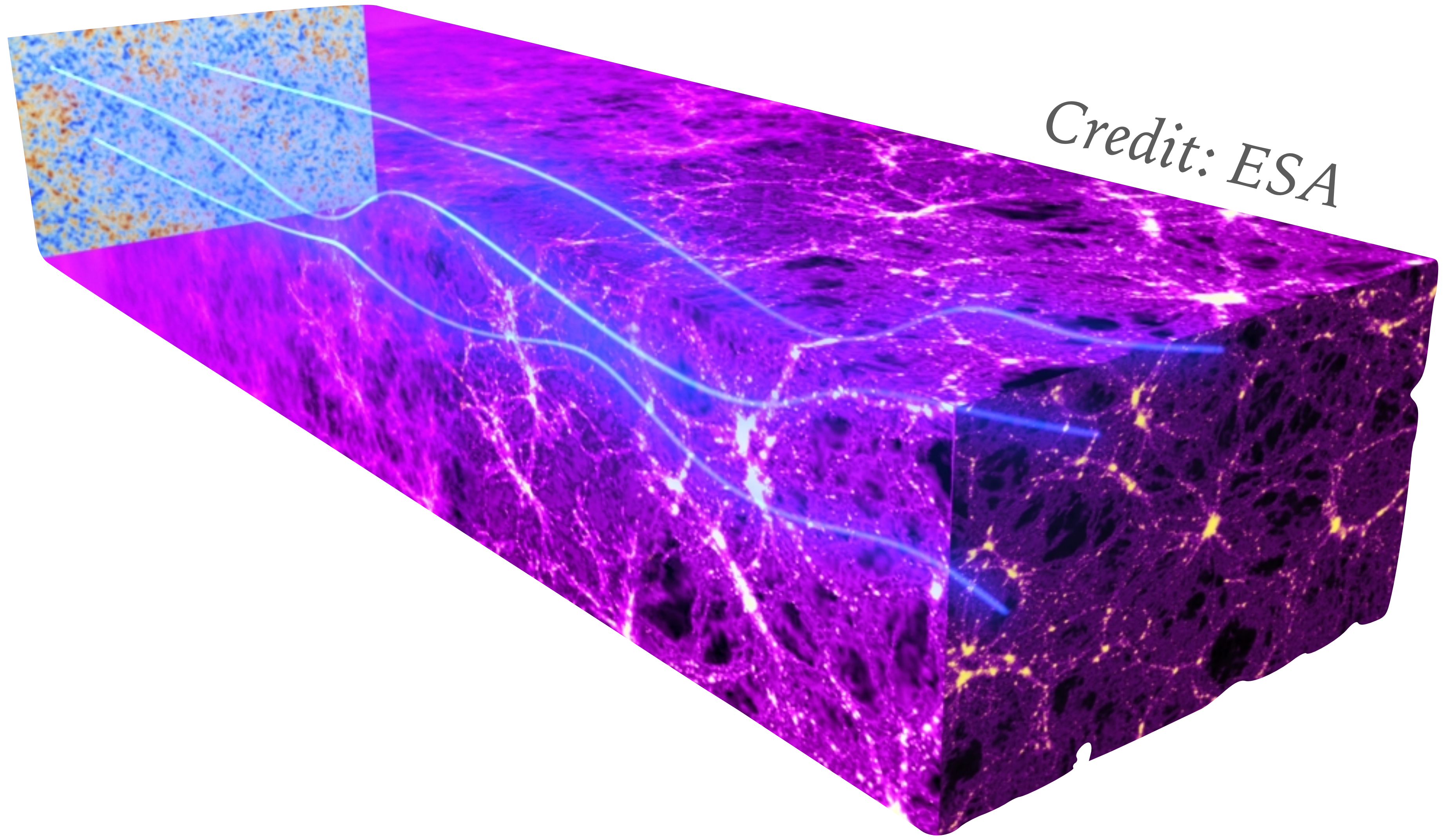


Spectral index of primordial (scalar) perturbations

CMB LENSING

Very accurately described as:

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



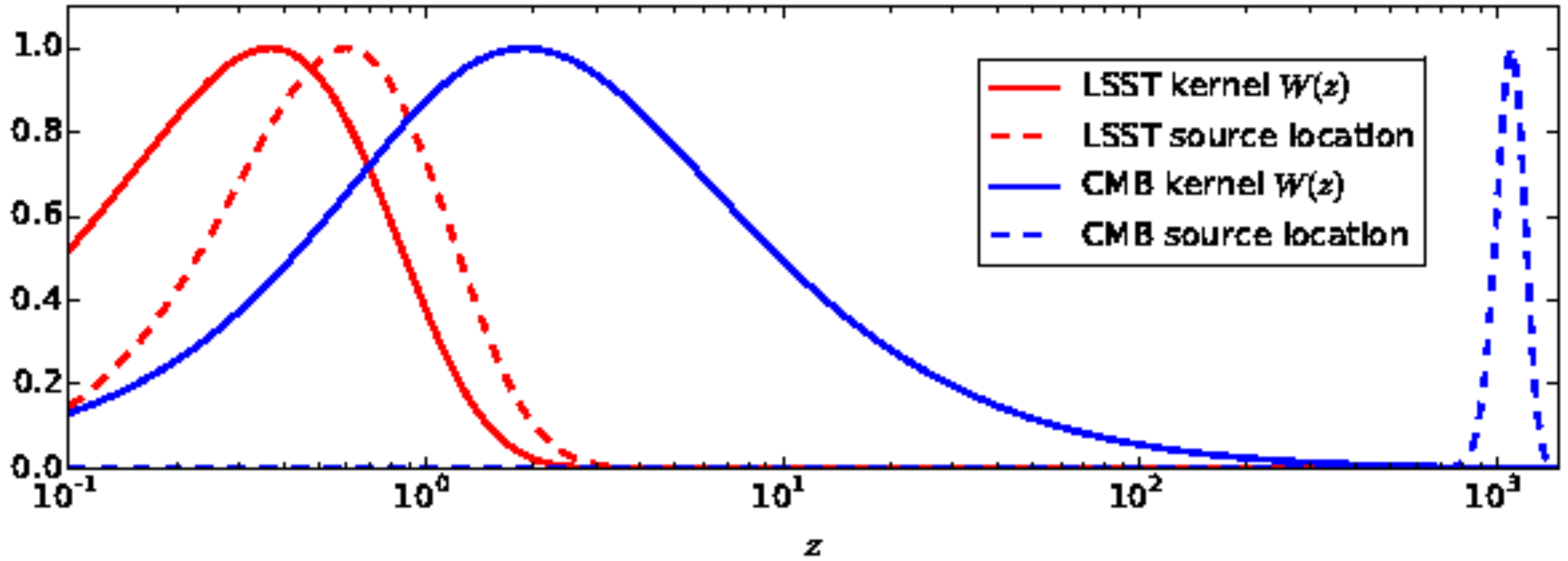
Under the Born approximation, $\alpha(\mathbf{x}) = \nabla\phi(\mathbf{x})$, where

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

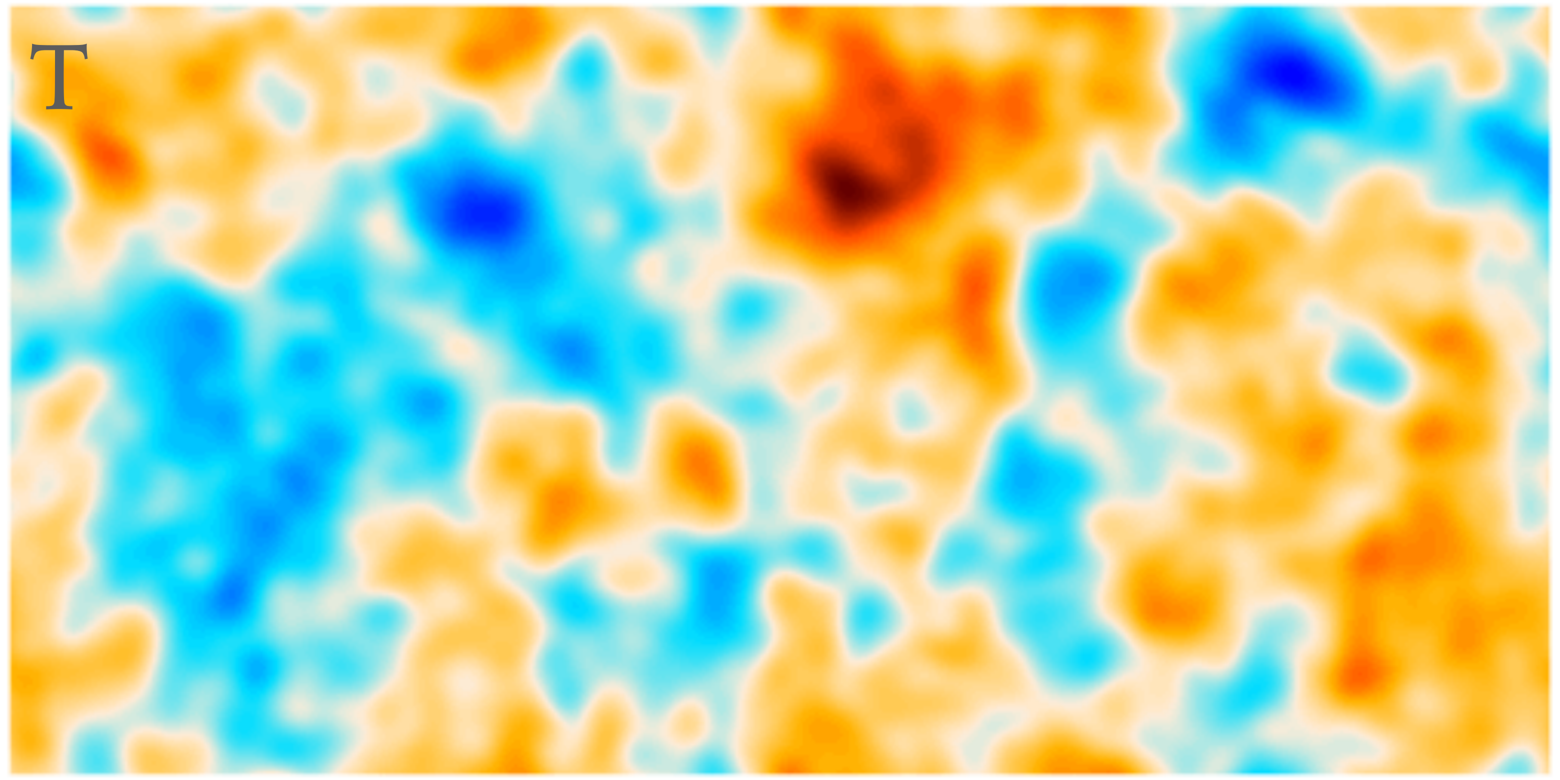
is related to $\kappa = -\frac{1}{2}\nabla^2\phi$.

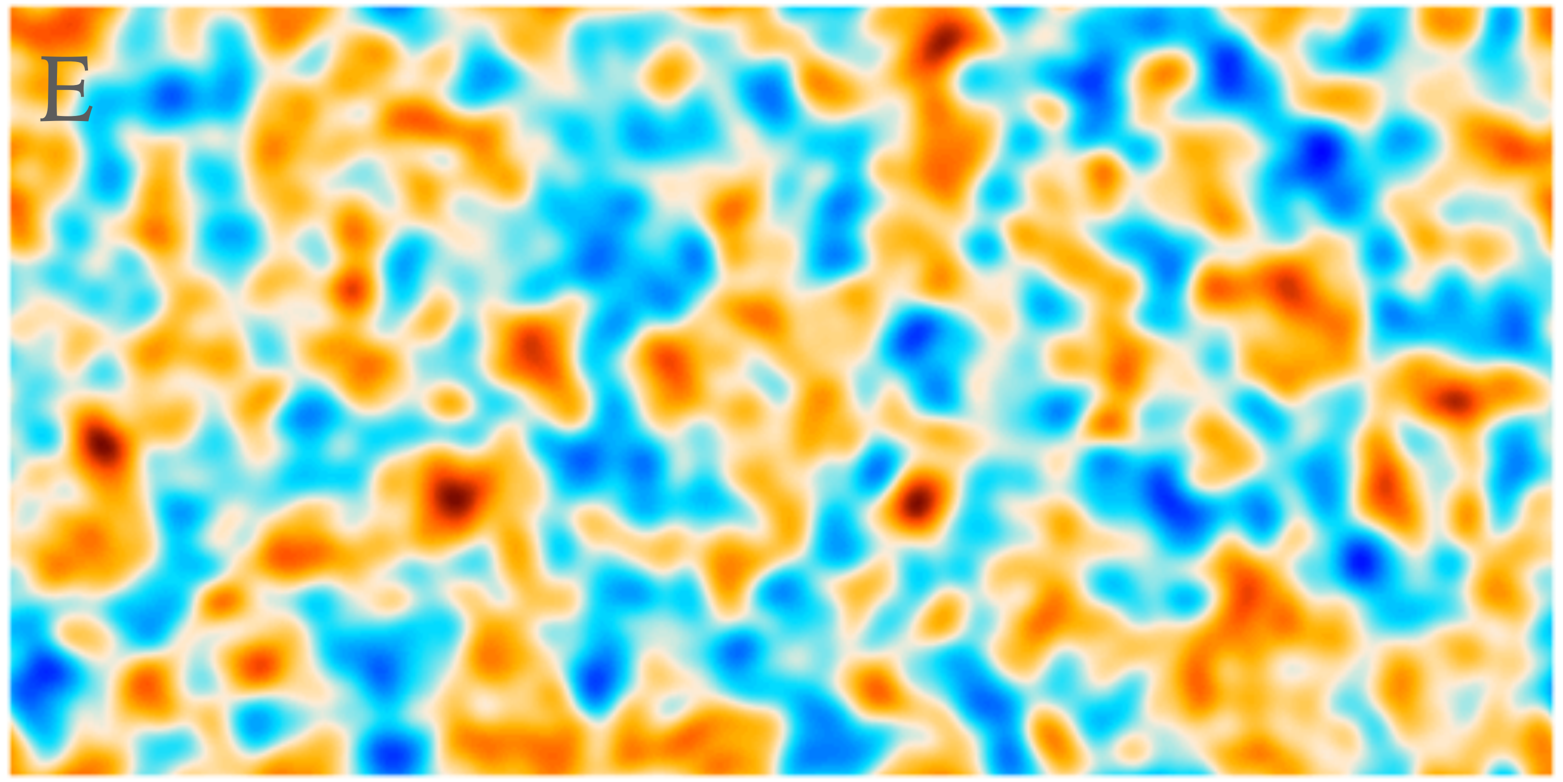
$\alpha \sim$ arcmin, coherent on degree scales (typical lens O(100Mpc))

CMB-S4 Science book

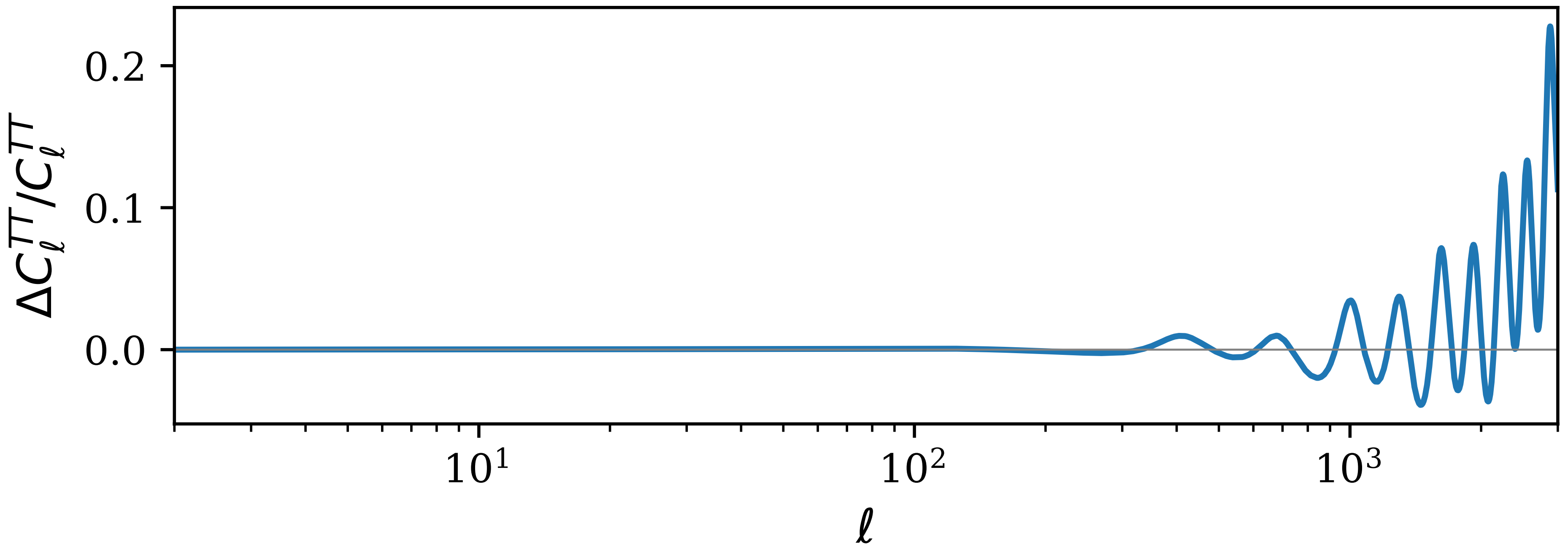


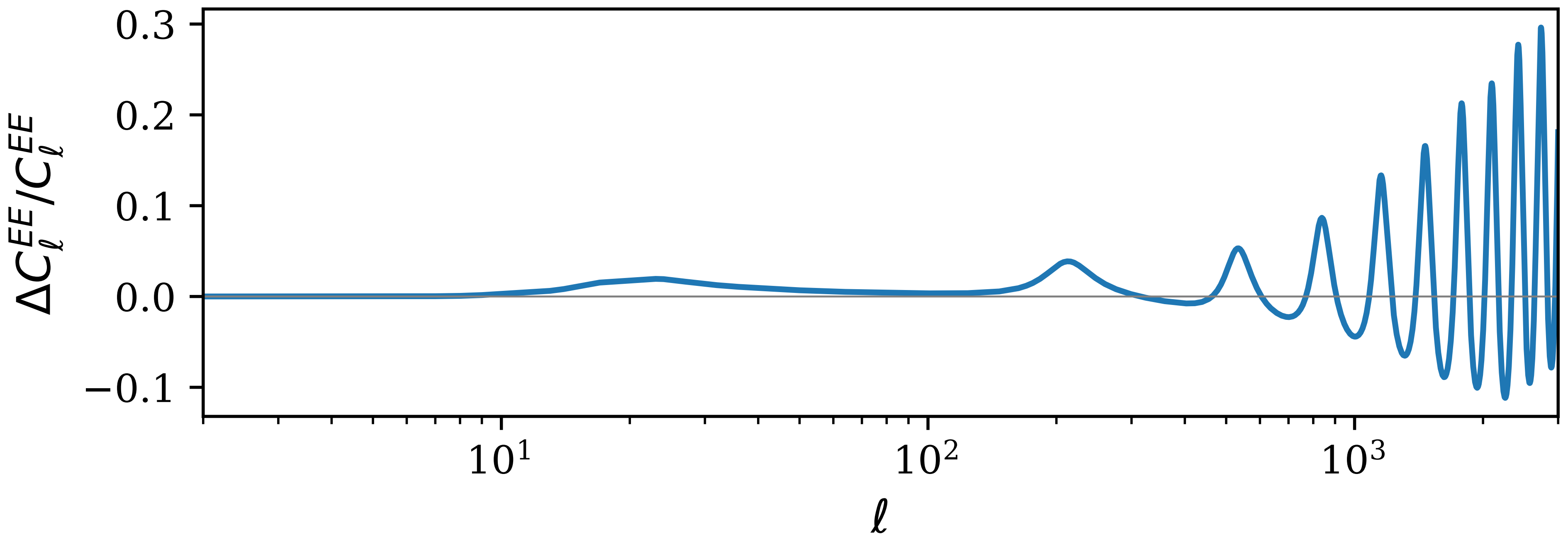
CMB LENSING

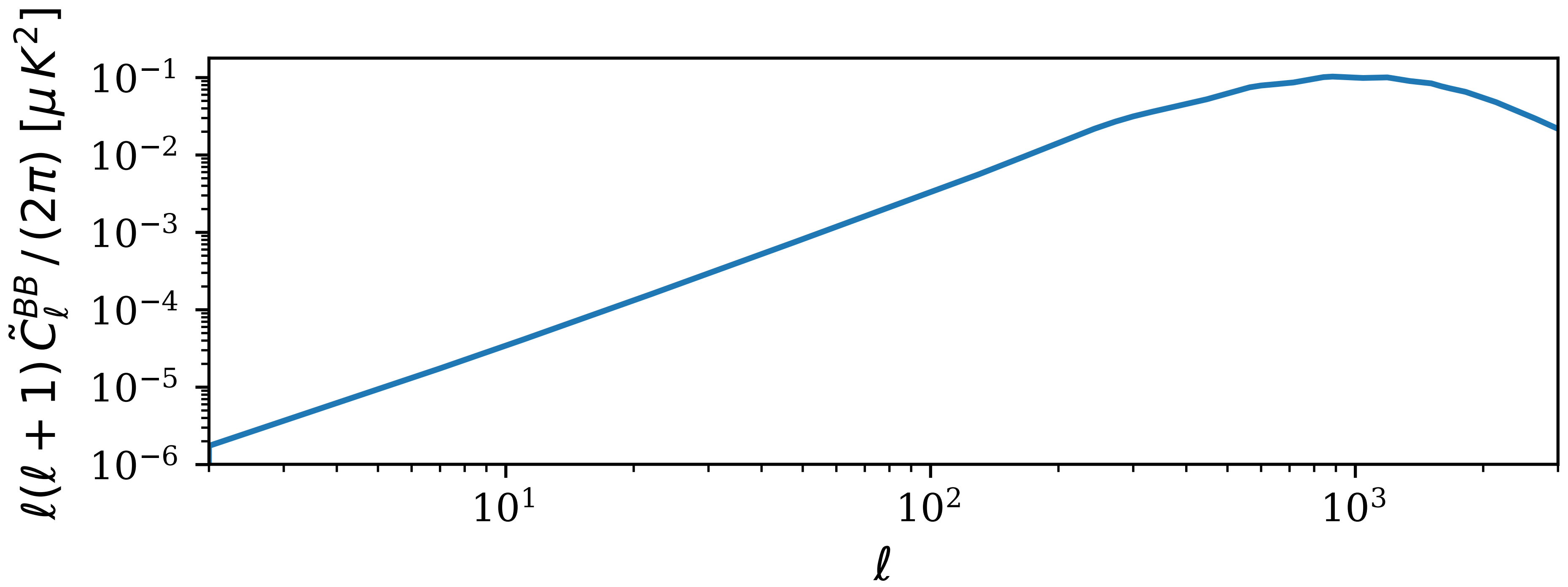

T


E

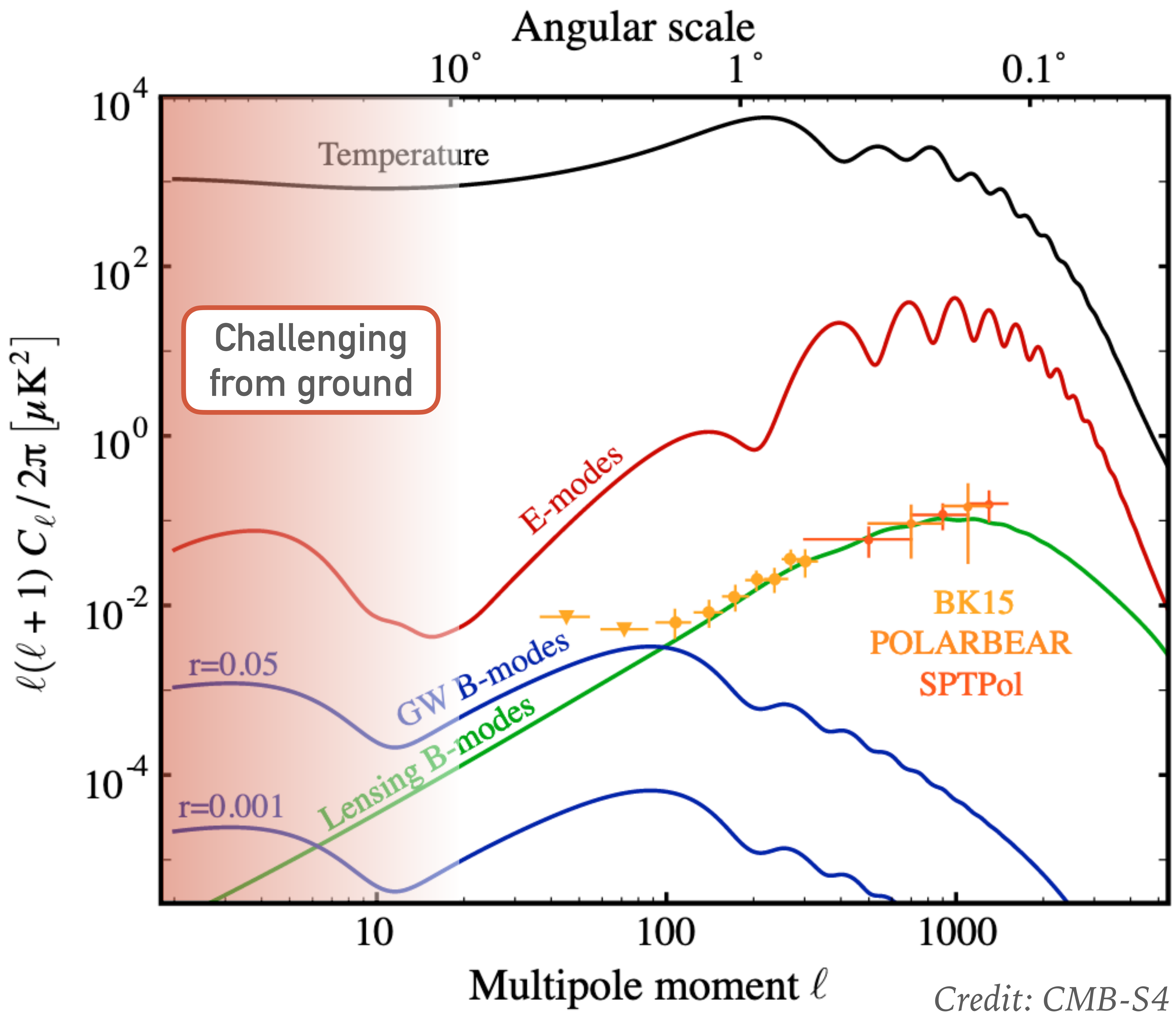

B


$\Delta C_\ell^{TT}/C_\ell^{TT}$
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

THE LENSING B-MODE

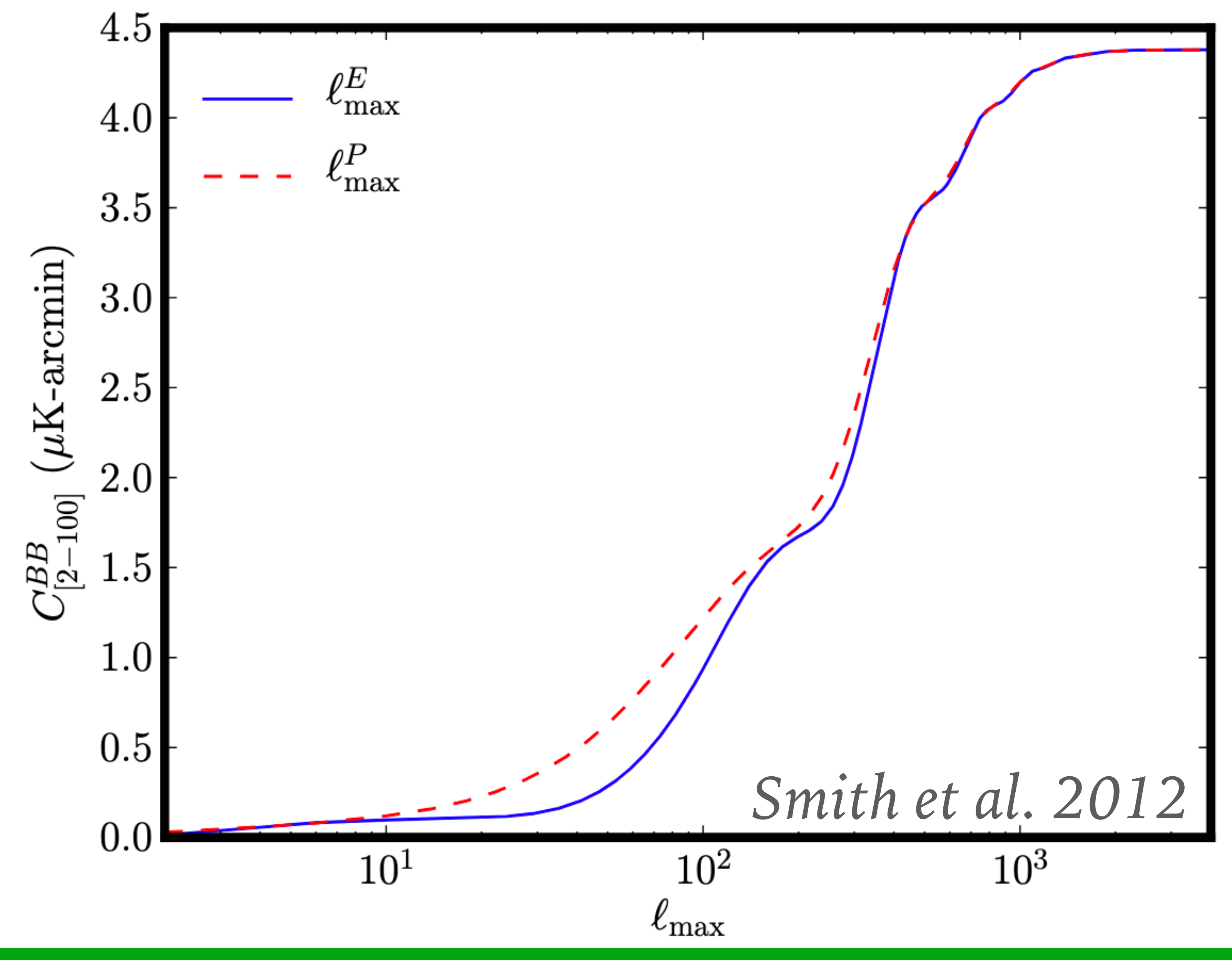


Credit: CMB-S4

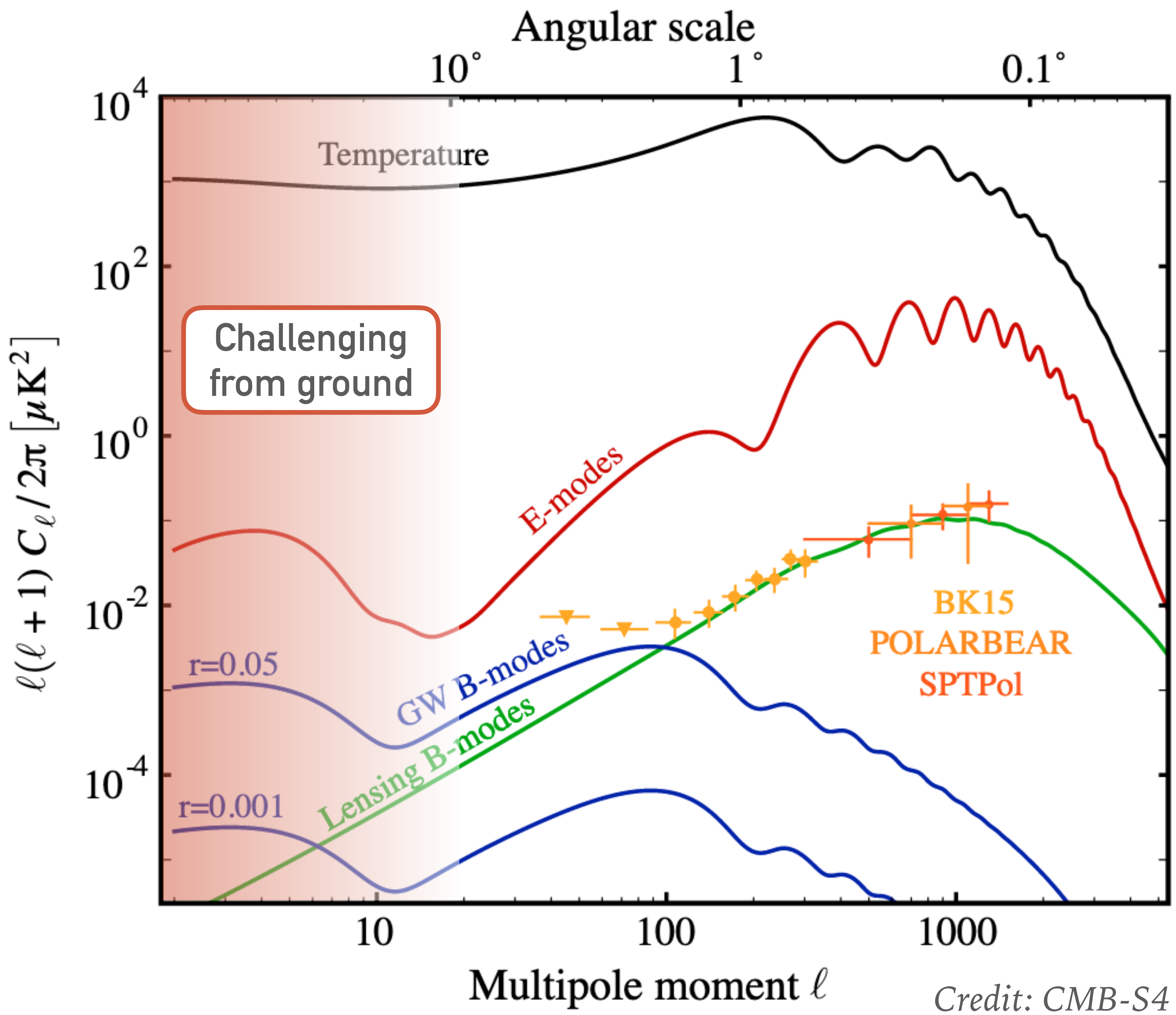
Lensing converts E- into B-modes, inducing noise with $\Delta_P \approx 5\mu K$ arcmin

Zaldarriaga & Seljak 98

Why does it look like white noise?



THE LENSING B-MODE



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

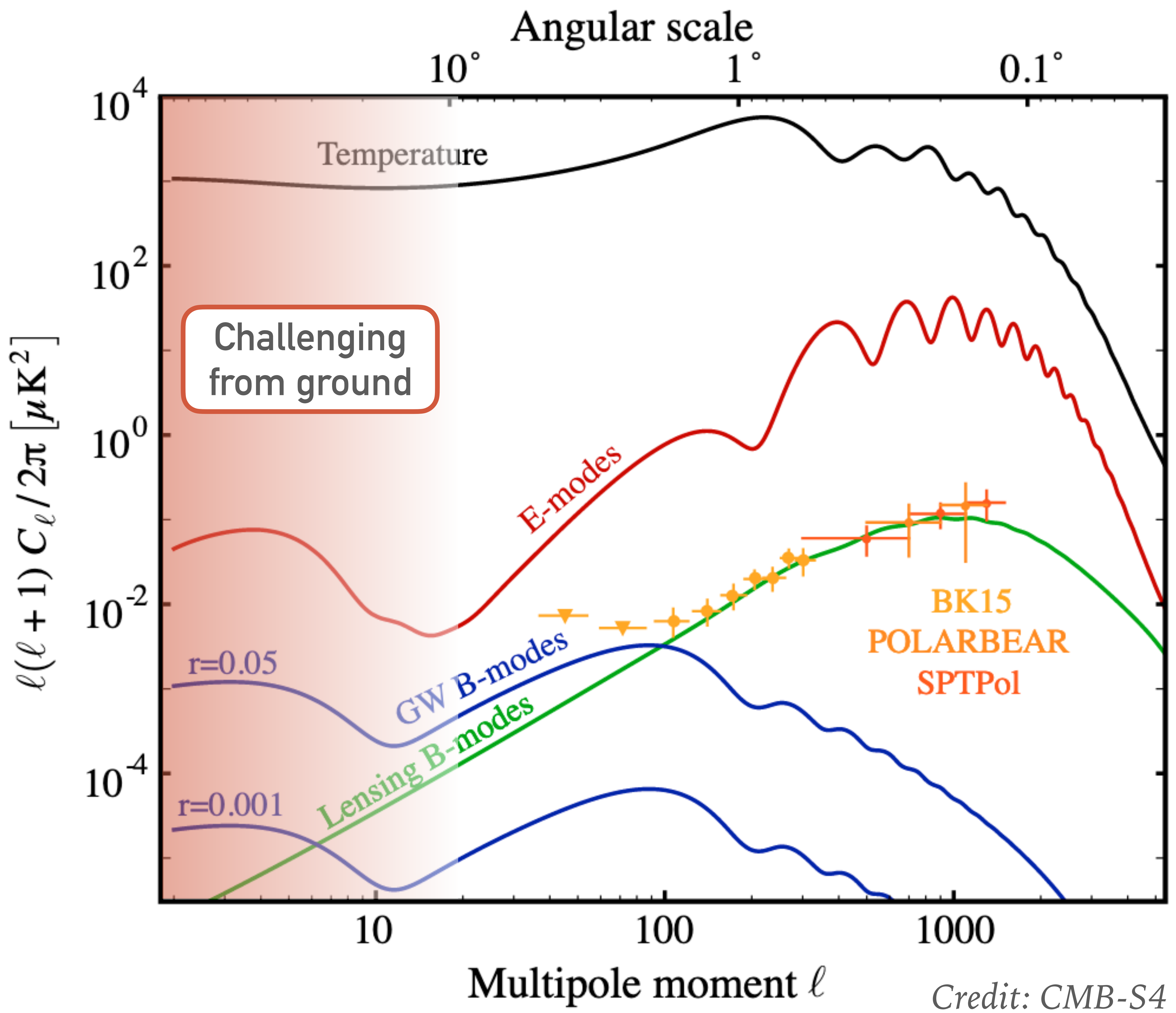
Zaldarriaga & Seljak 98

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

- Primordial
- Foregrounds
- **Lensing**

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

THE LENSING B-MODE



Credit: CMB-S4

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

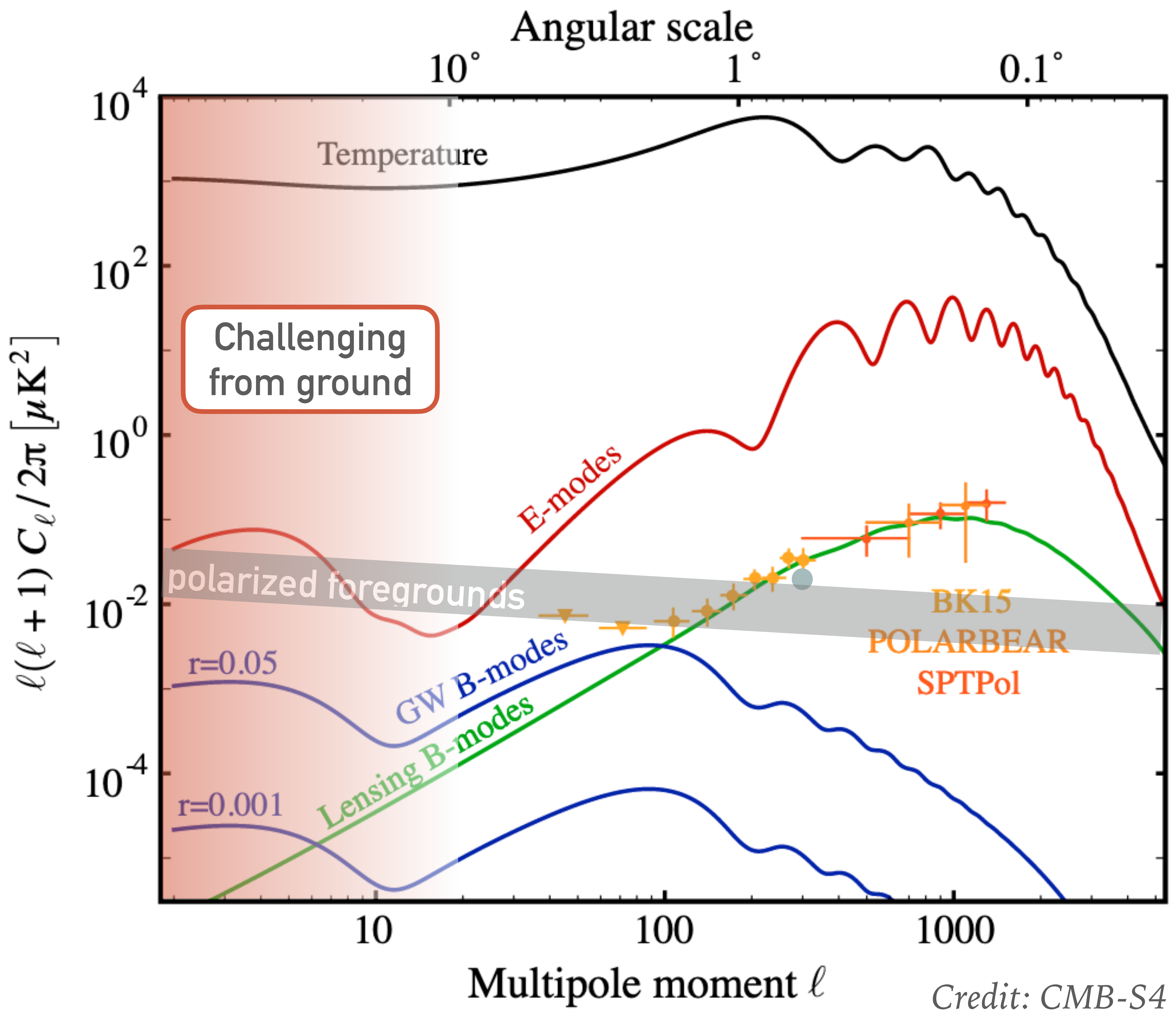
Zaldarriaga & Seljak 98

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

- Primordial
- Foregrounds
- **Lensing**

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

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**

Foregrounds can be disentangled using frequency information — lensing cannot

DELENSING THE B-MODES

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

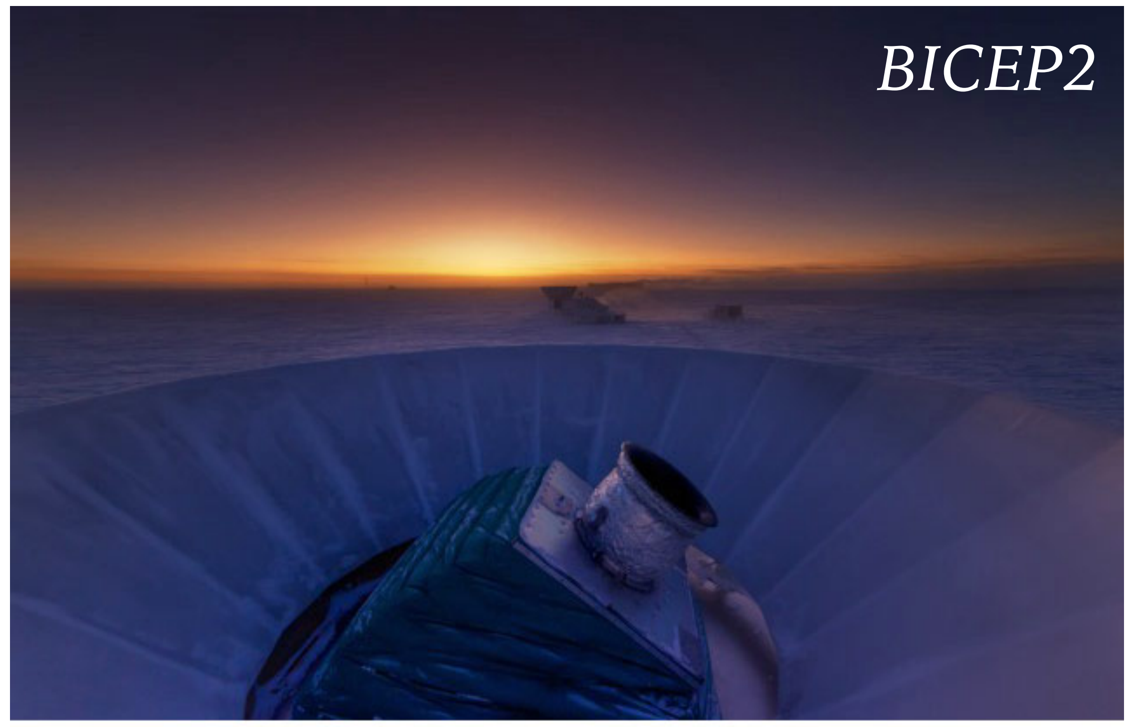
$$\implies \quad \text{Delensing:} \quad P^{\text{del}}(\mathbf{x}) = \tilde{P}(\mathbf{x} + \alpha^{-1}(\mathbf{x}))$$

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

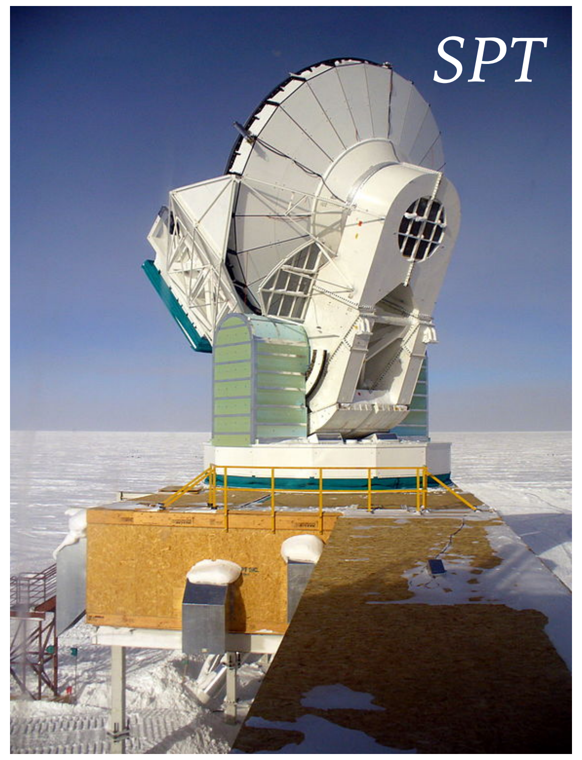
(SAT)



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

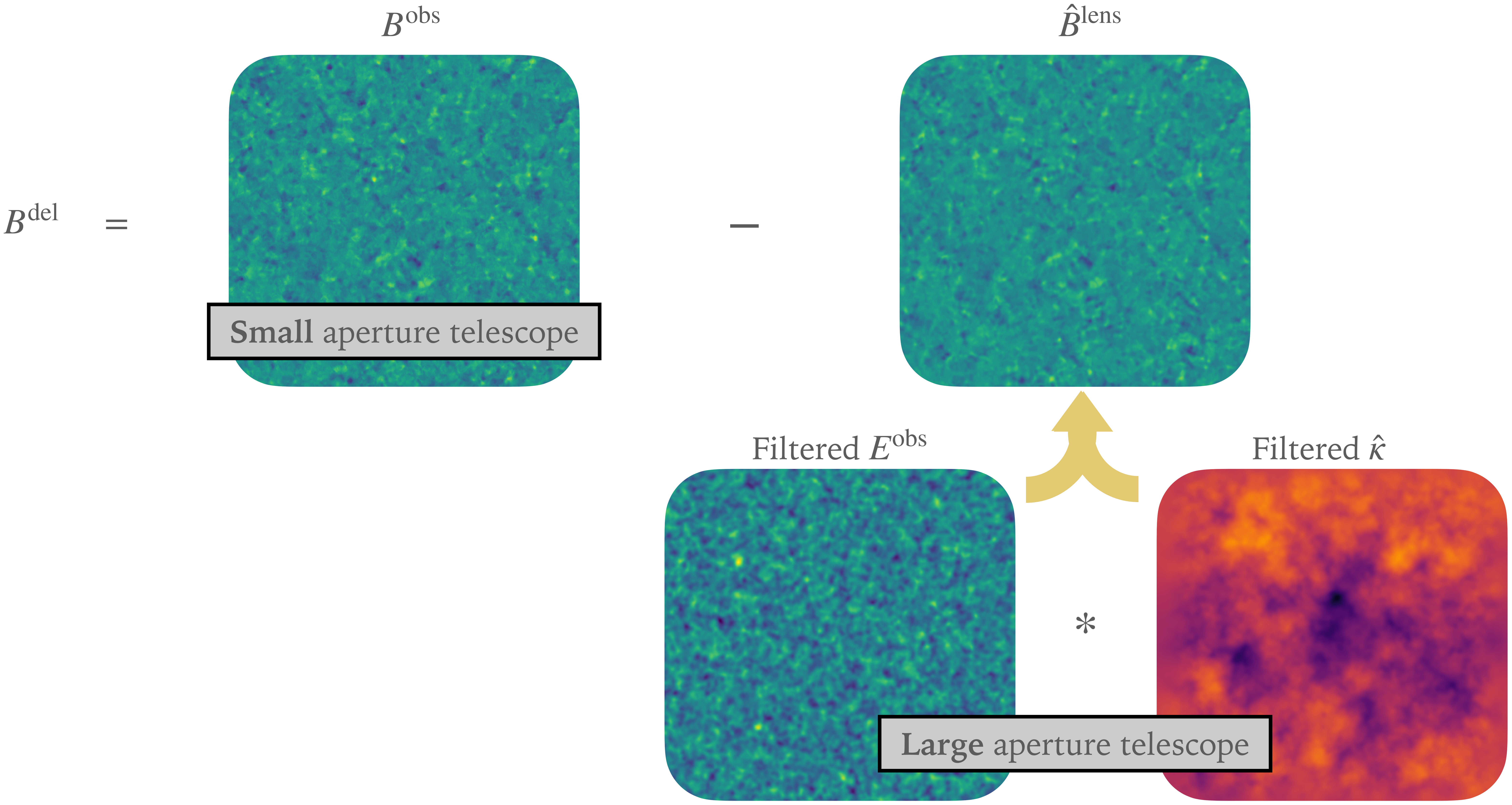
Large Aperture Telescope

(LAT)



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

DELENSING WITH A B-MODE TEMPLATE



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

HOW EXACTLY IS THE TEMPLATE BUILT?

The lensing B-mode is

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

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

$$\hat{B}^{\rm lens} \quad = \quad \bar{E}^{\rm obs} \circledast \hat{\bar{\kappa}}\,.$$

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

***ABL**, Challinor & Carron 21*

INTERNAL RECONSTRUCTIONS OF CMB LENSING

Unlensed CMB is statistically isotropic:

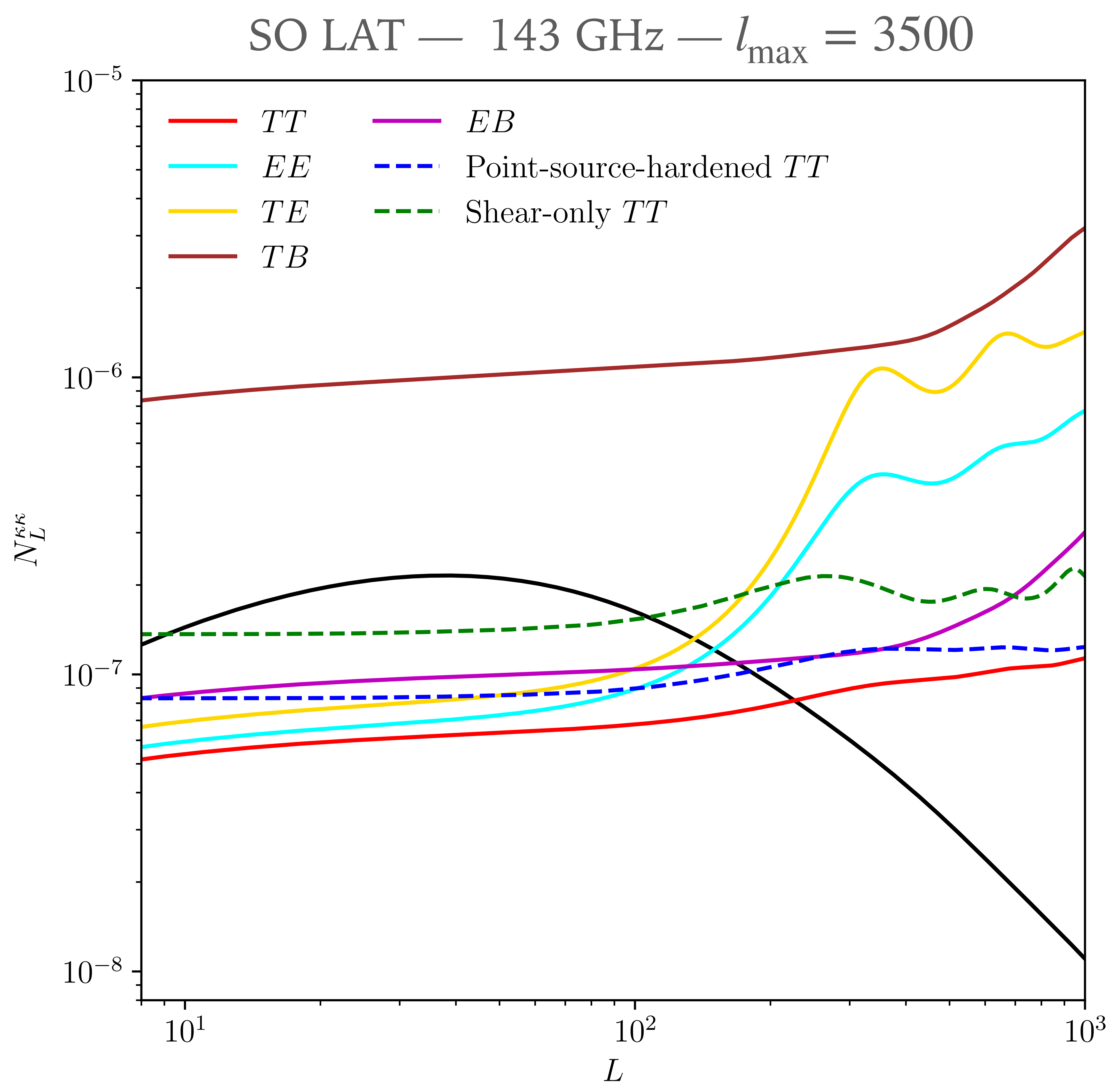
$$\langle T(\boldsymbol{l})T(\boldsymbol{l}')\rangle_{CMB} = (2\pi)^2\delta^2(\boldsymbol{l}+\boldsymbol{l}')\,\tilde{C}_l^{TT}$$

Lensing induces statistical anisotropy:

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

The **quadratic estimator** (QE):

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



- *Hu & Okamoto 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)

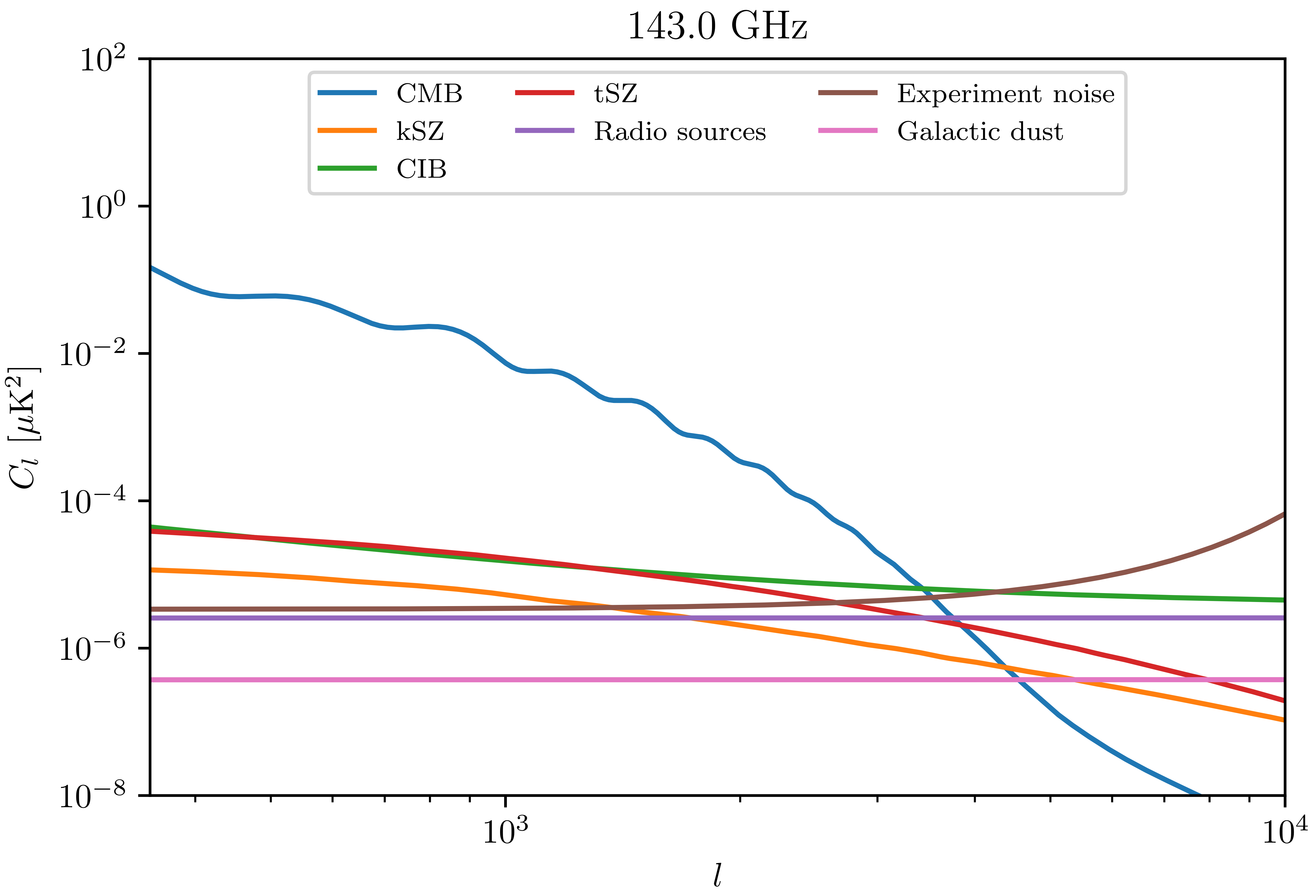
Credit: Deborah Kellner

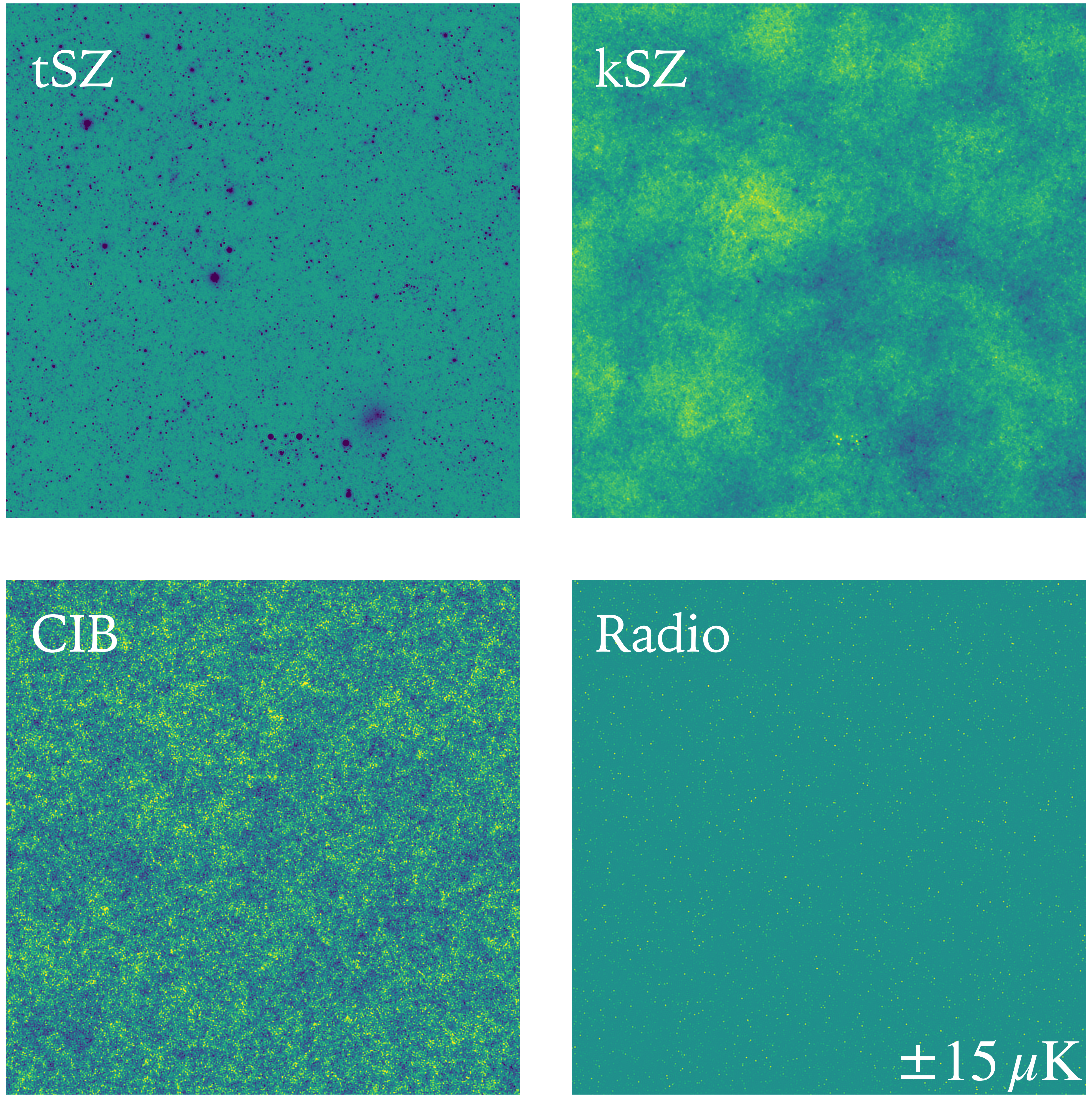
INTERNAL RECONSTRUCTIONS OF CMB LENSING

- 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

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

Lensing   Foreground (correlated with κ)

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

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

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

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

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

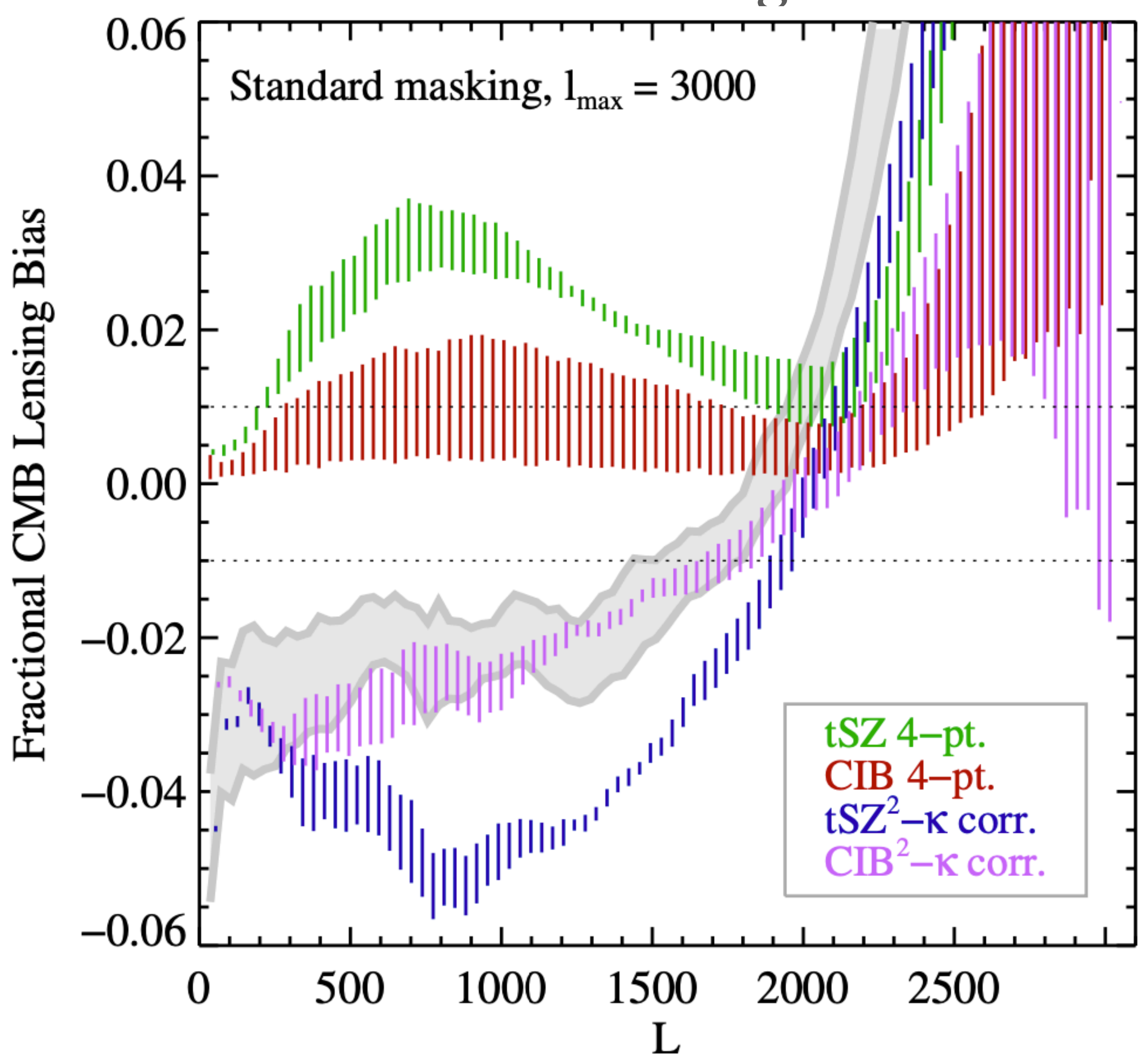
"Bispectrum bias"

Amblard+ 04
Van Engelen+14
Osborne+14
Ferraro & Hill 18
Sailer+21

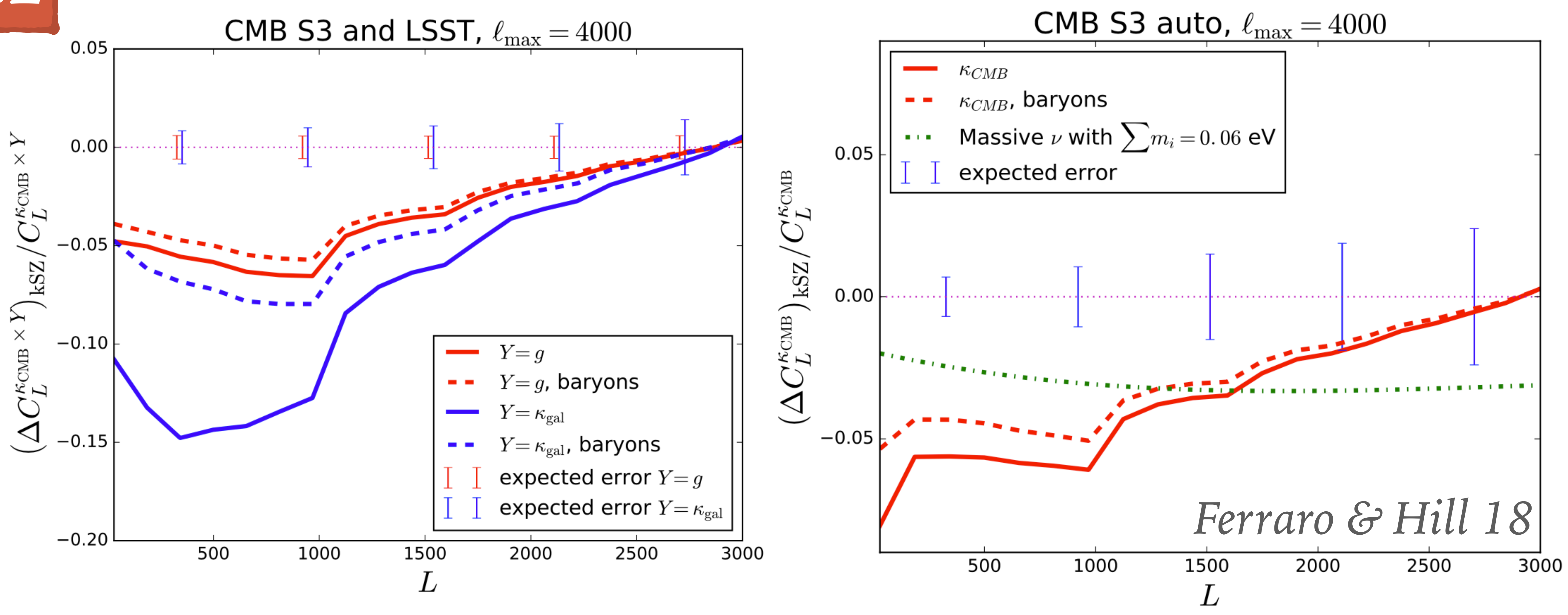
BIASES TO LENSING SPECTRA FROM EXTRAGALACTIC FOREGROUNDS

tSZ & CIB

Van Engelen et al. 14



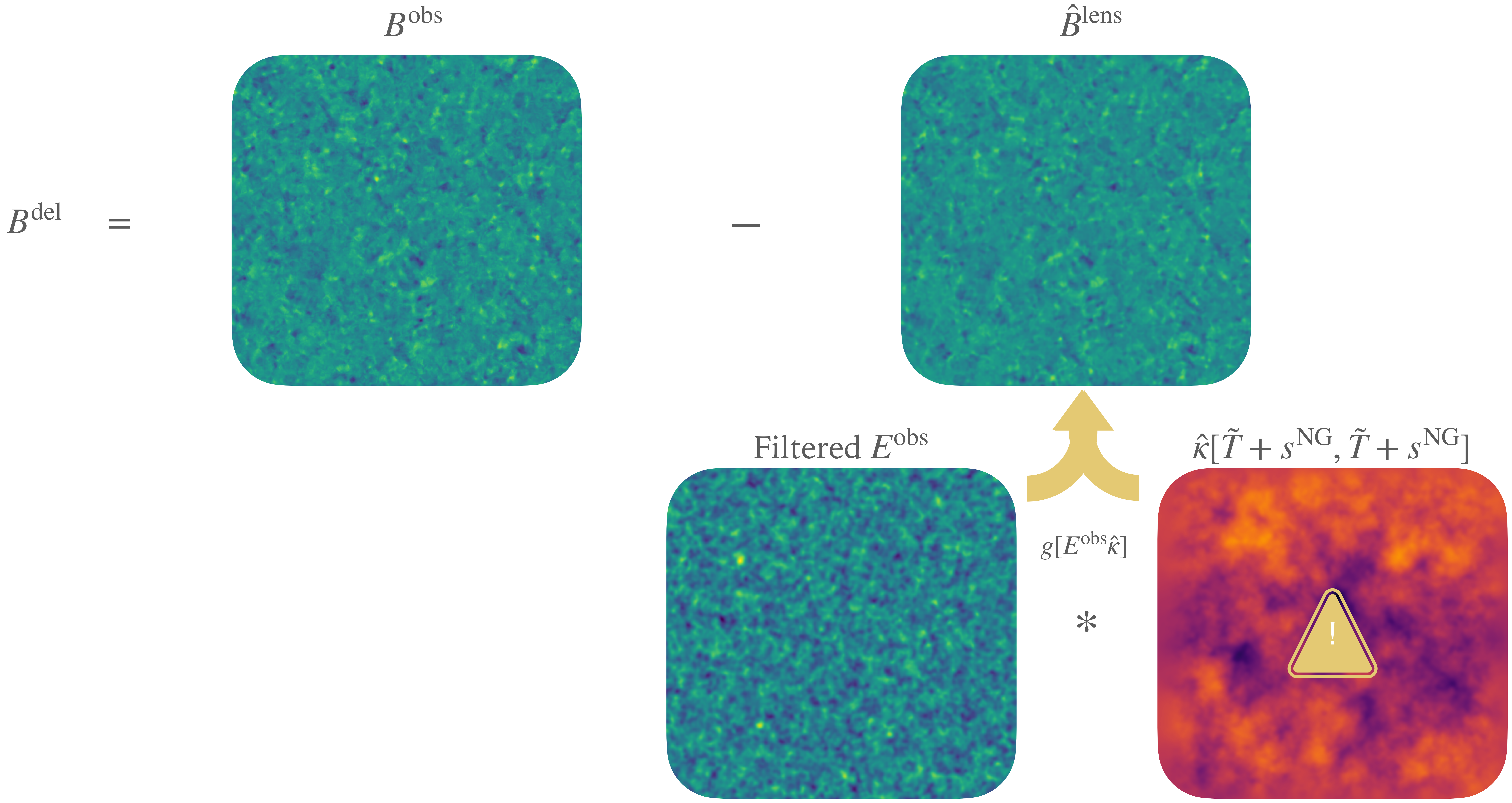
kSZ



Ferraro & Hill 18

- Arguably, the biggest challenge to CMB lensing measurements (at least in temperature)
- Mitigation strategies:
  - Simulations *Van Engelen+ 14*
  - Multi-frequency cleaning *Sailer+ 21, Darwish+ 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

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

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

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

primary bispectrum bias

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

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

$$+ 4\,h_l \left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T}, s^{\mathrm{NG}}\right] E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}} \right]$$

$$+ h_l \left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right] E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}} \right]$$

ABL & Ferraro 22

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

primary bispectrum bias

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

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

$$+\,4\,h_l \left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T}, s^{\mathrm{NG}}\right] E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}}\right]$$

$$+\,h_l \left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right] E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}}\right]$$

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

$C^{EE,\,\mathrm{obs}}\,\langle\hat{\kappa}[\tilde{T}, s^{\mathrm{NG}}]\,\hat{\kappa}[\tilde{T}, s^{\mathrm{NG}}]\rangle$

secondary bispectrum bias

$$\begin{aligned}\Delta C_l^{\hat{B}^{\mathrm{lens}}\times\hat{B}^{\mathrm{lens}}} &\supset \\ &\supset 2\,h_l\left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T},\tilde{T}\right]E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}}\right] \\ &+ 4\,h_l\left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T}, s^{\mathrm{NG}}\right]E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}}\right] \\ &+ h_l\left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right]E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}}\right]\end{aligned}$$

ABL & Ferraro 22

NEW CONTRIBUTIONS FROM EXTRAGALACTIC FOREGROUNDS

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

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

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

trispectrum bias

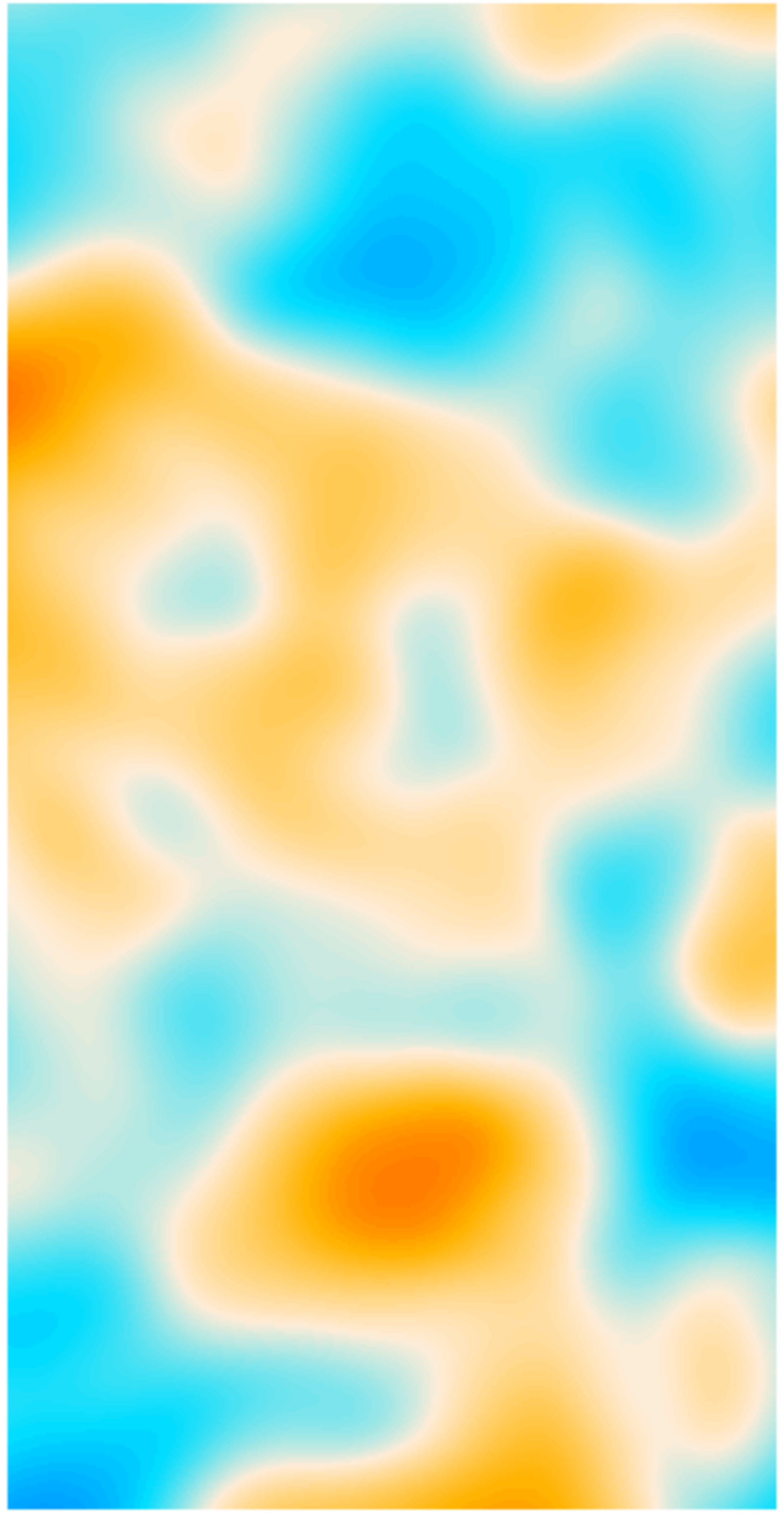
$$\Delta C_l^{\hat{B}^{\mathrm{lens}}\times\hat{B}^{\mathrm{lens}}} \supset$$

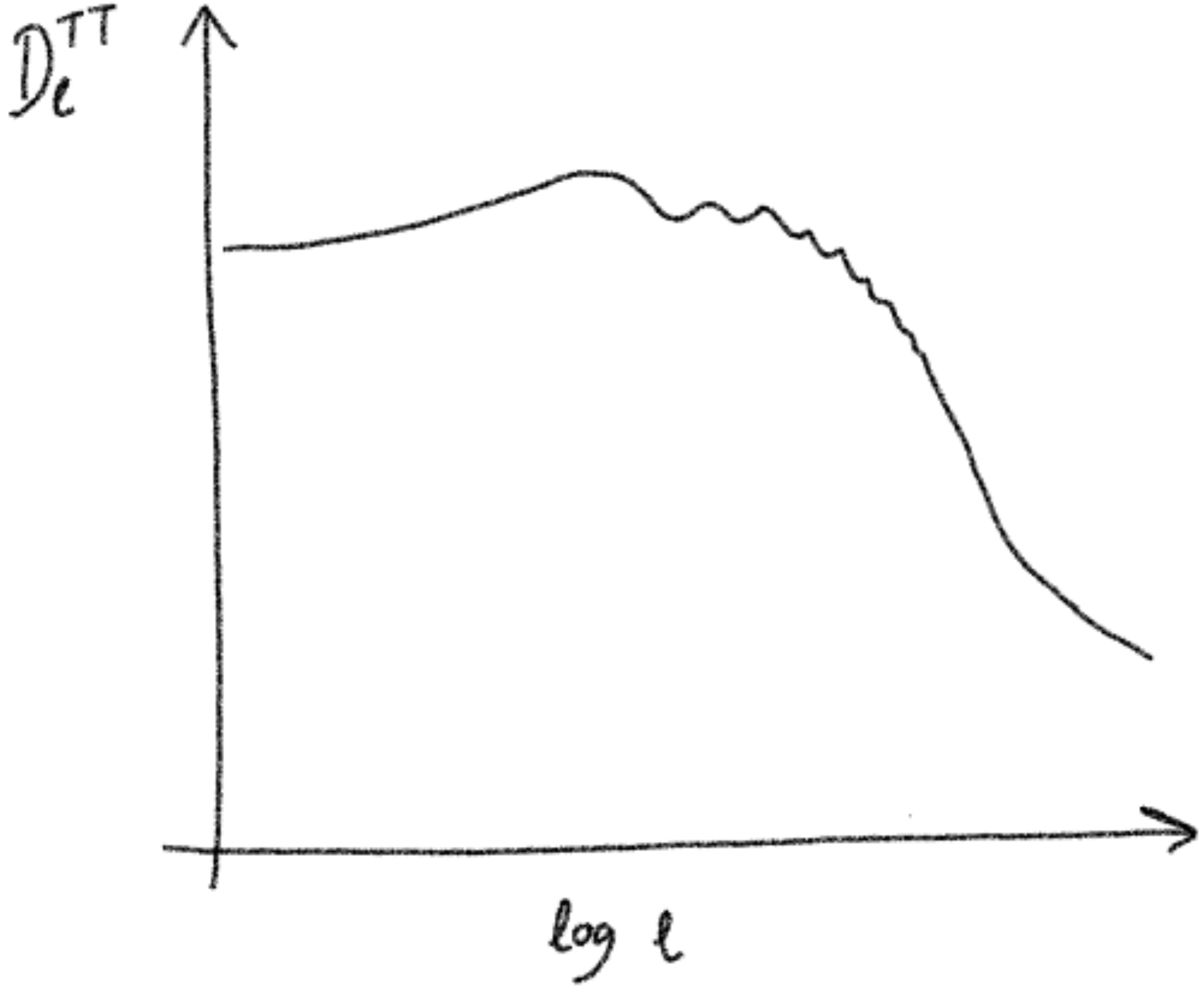
$$\supset 2\,h_l\left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T},\tilde{T}\right] E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}}\right]$$

$$+\,4\,h_l\left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T}, s^{\mathrm{NG}}\right] E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[\tilde{T}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}}\right]$$

$$+\,h_l\left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right] E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right]\rangle_{\mathrm{c}}\right]$$

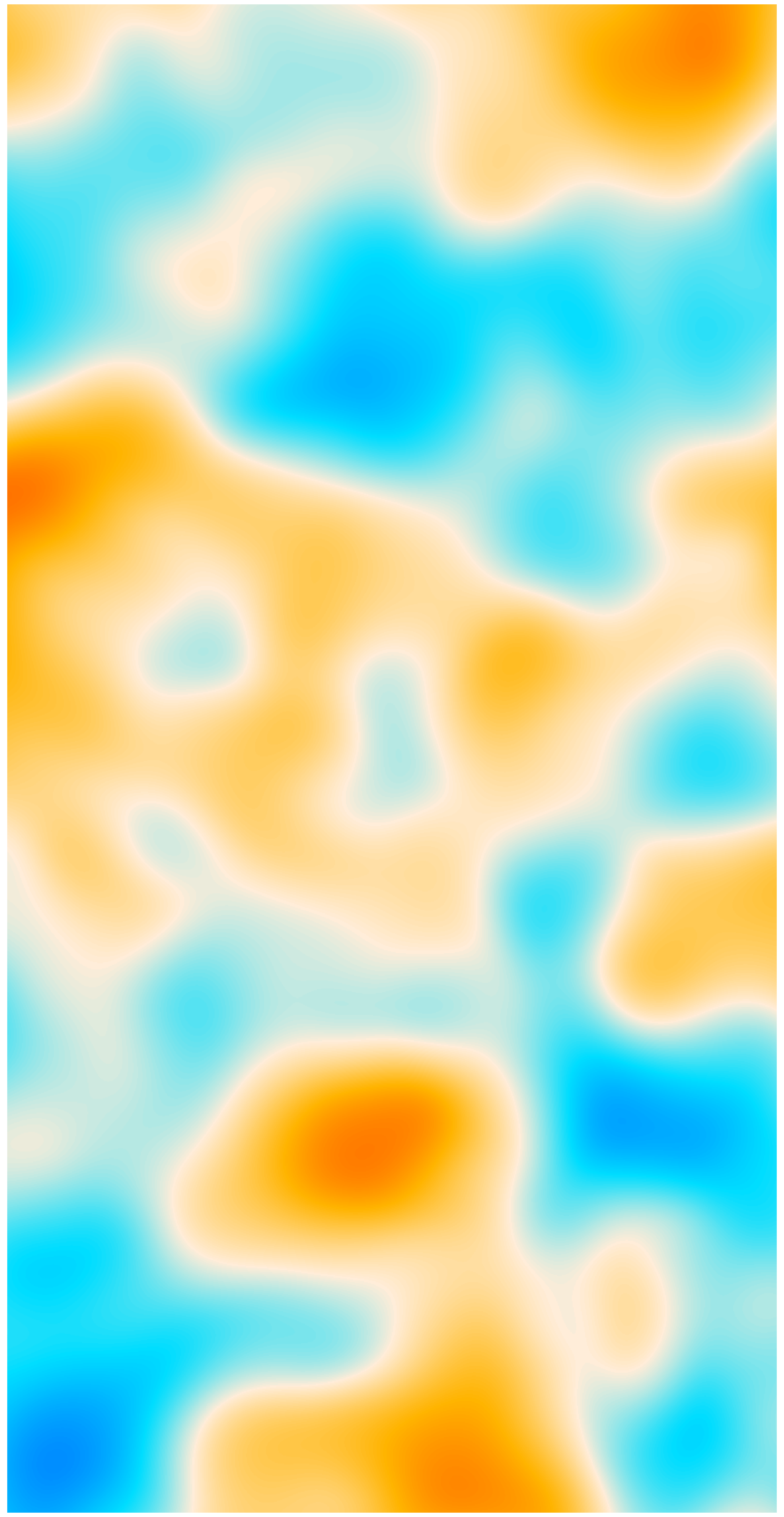
NOTE: WE EXPECT BISPECTRUM BIASES TO BE NEGATIVE

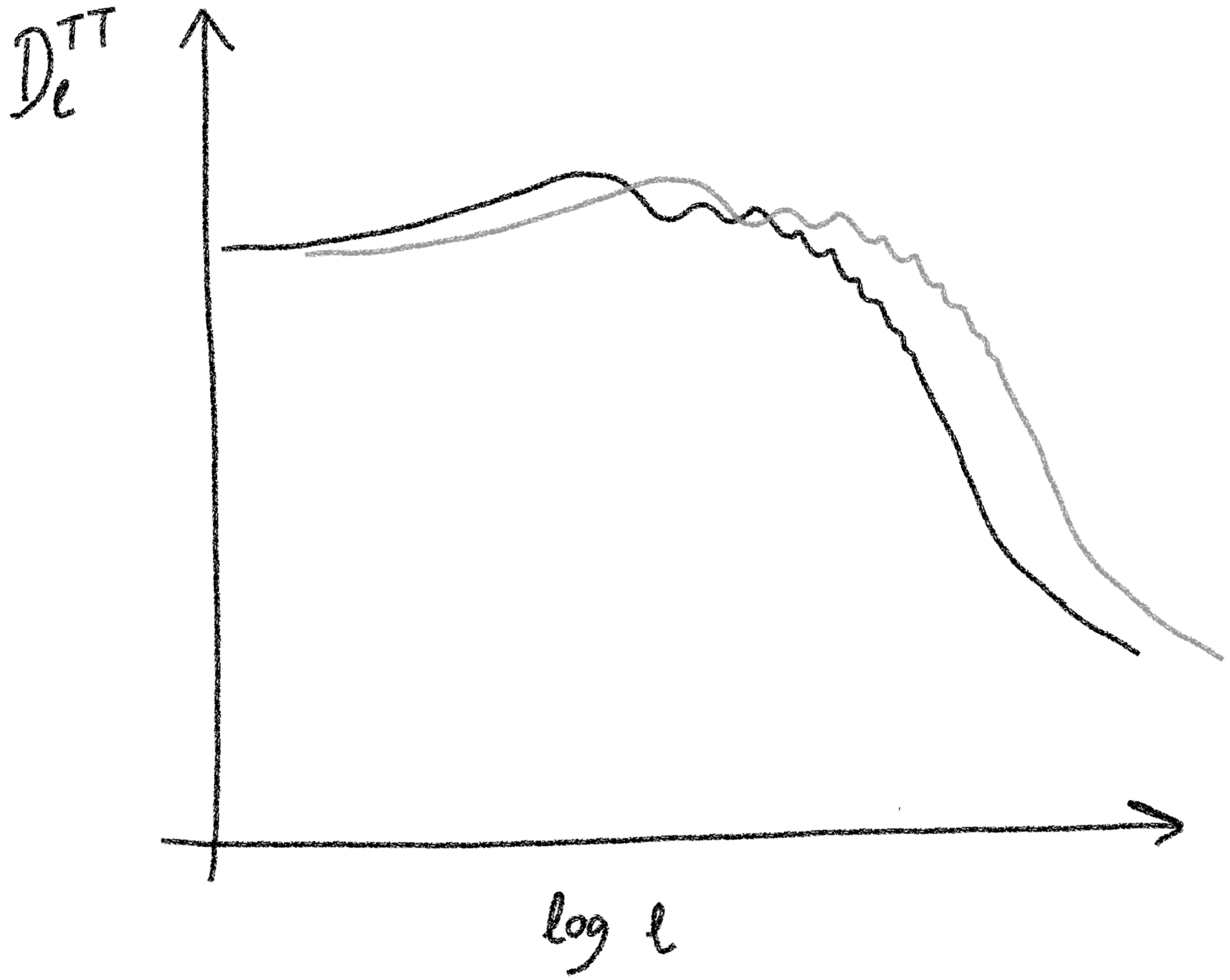




Where $\kappa < 0$, the CMB spectrum is shifted to smaller scales

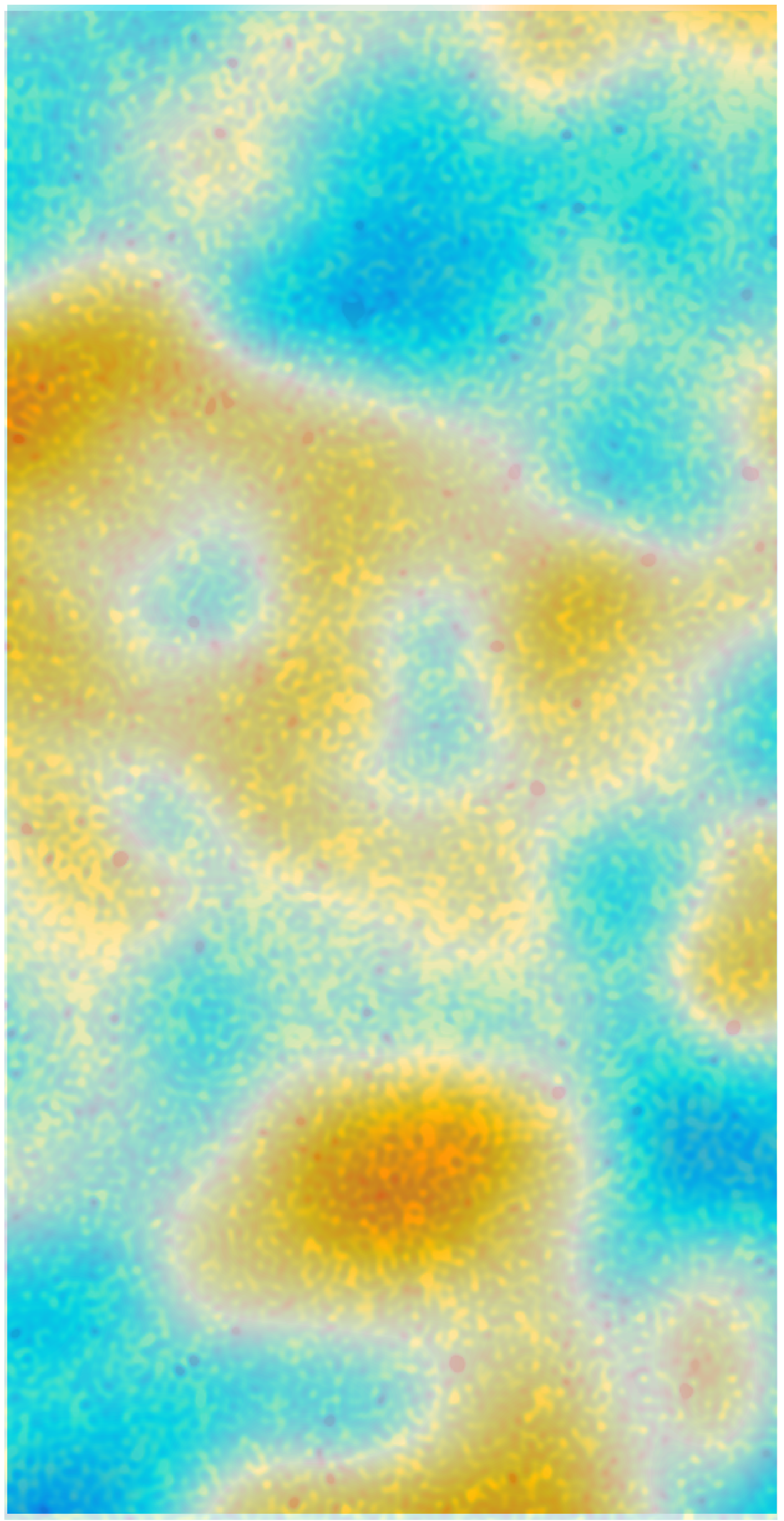
NOTE: WE EXPECT BISPECTRUM BIASES TO BE NEGATIVE

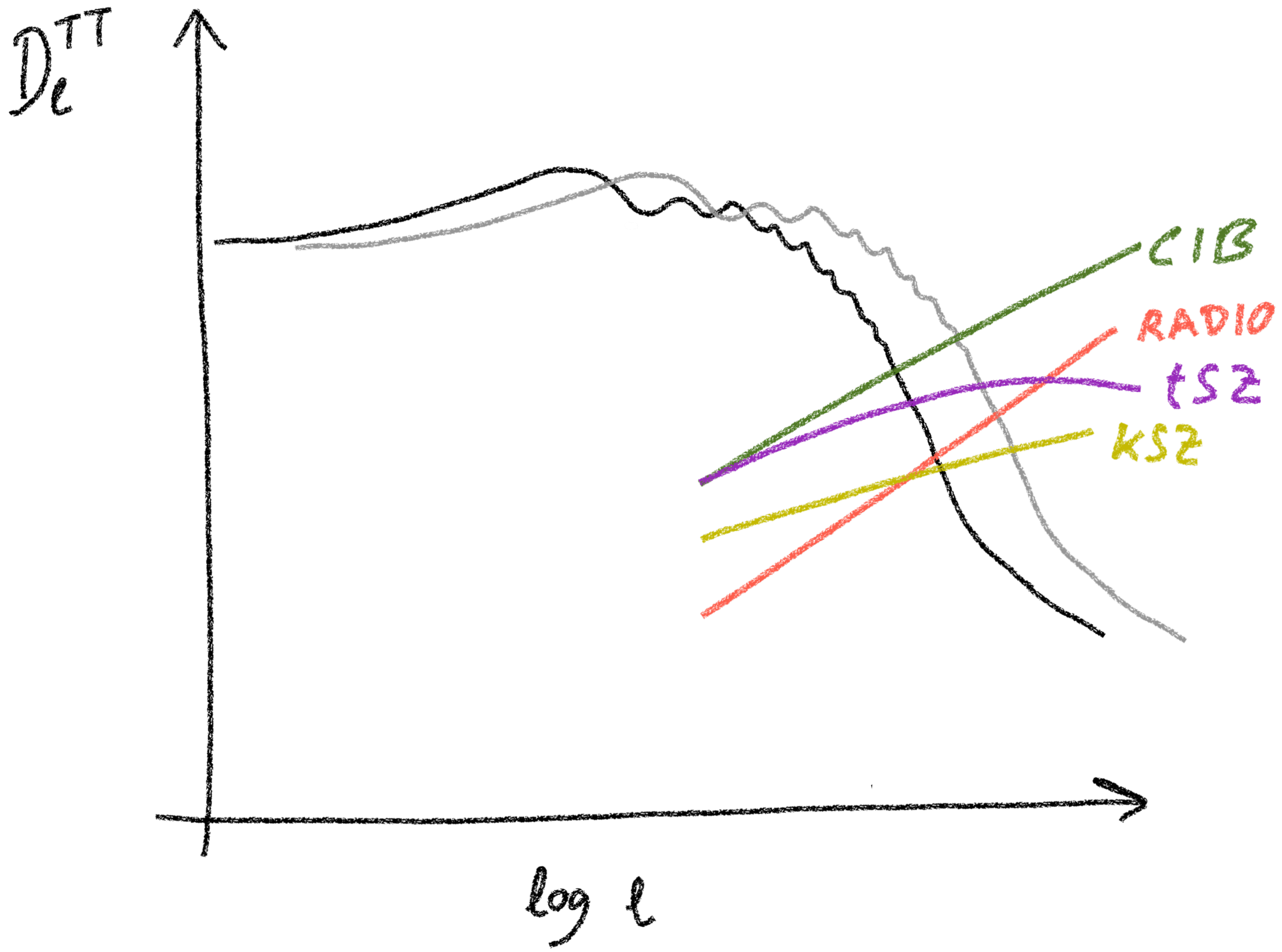




Where $\kappa < 0$, there is excess power on small scales $\Longrightarrow$ the QE interprets excess small-scale power as being due to $\kappa < 0$

NOTE: WE EXPECT BISPECTRUM BIASES TO BE NEGATIVE





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

EXPECTATIONS

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

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

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

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

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

$$+\,h_l \left[\langle E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right] E^{\mathrm{obs}}\hat{\kappa}^{\mathrm{TT}}\left[s^{\mathrm{NG}}, s^{\mathrm{NG}}\right]\rangle_c \right]$$

-ve

+ve

MEASURING THE NEW CONTRIBUTIONS

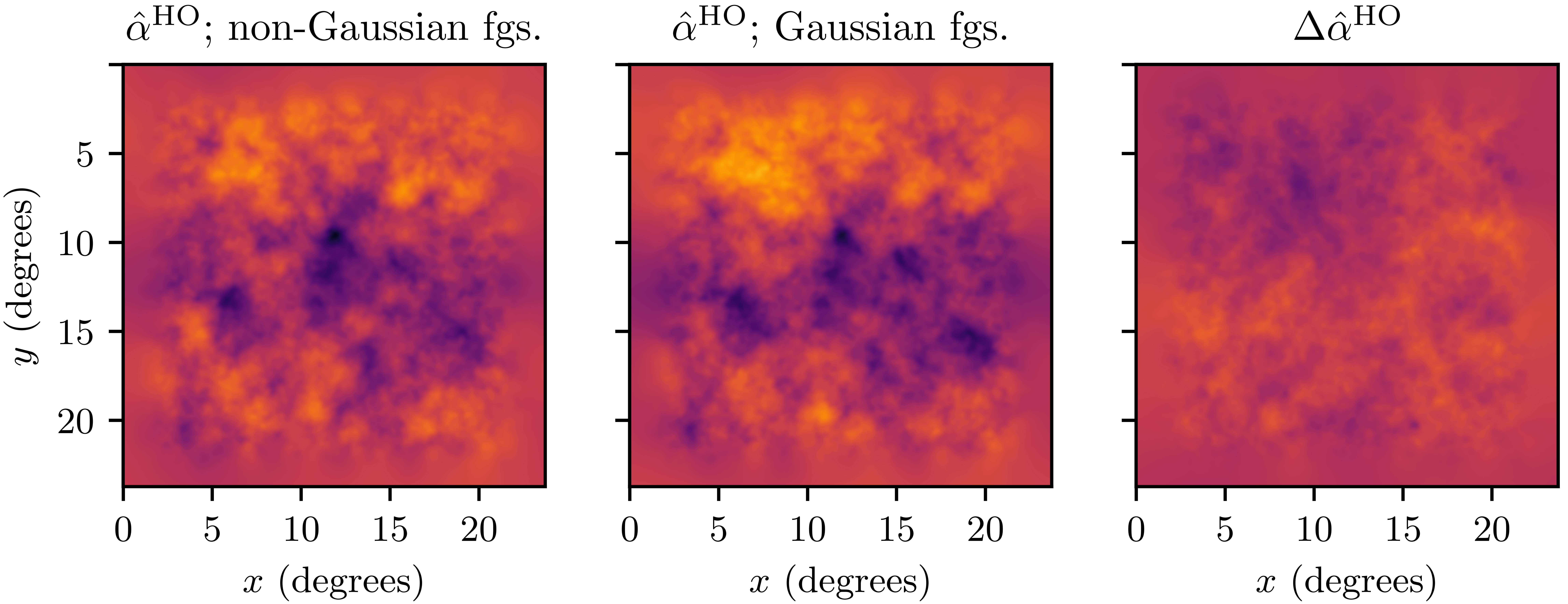
Using the Websky simulations, we measure

$$\Delta C_l^{BB,\mathrm{del}} = \langle|\tilde{B} - g_l\left[\tilde{E}\hat{\kappa}\left[f + s^{\mathrm{NG}}, f + s^{\mathrm{NG}}\right]\right]|^2\rangle$$
$$-\langle|\tilde{B} - g_l\left[\tilde{E}\hat{\kappa}\left[f + s^{\mathrm{G}}, f + s^{\mathrm{G}}\right]\right]|^2\rangle\,.$$

We take the foregrounds to be unpolarized.

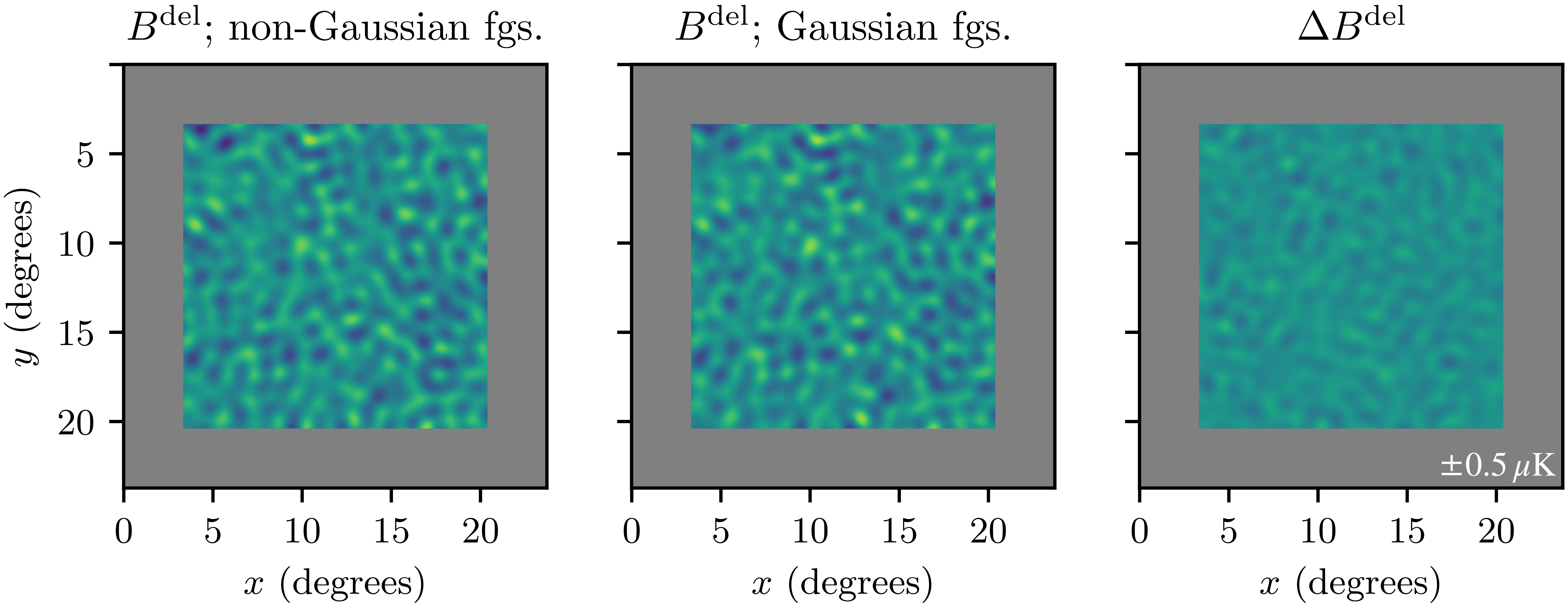
MAP-LEVEL EFFECT

$\alpha \equiv 2\kappa/l$



ABL & Ferraro 22

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

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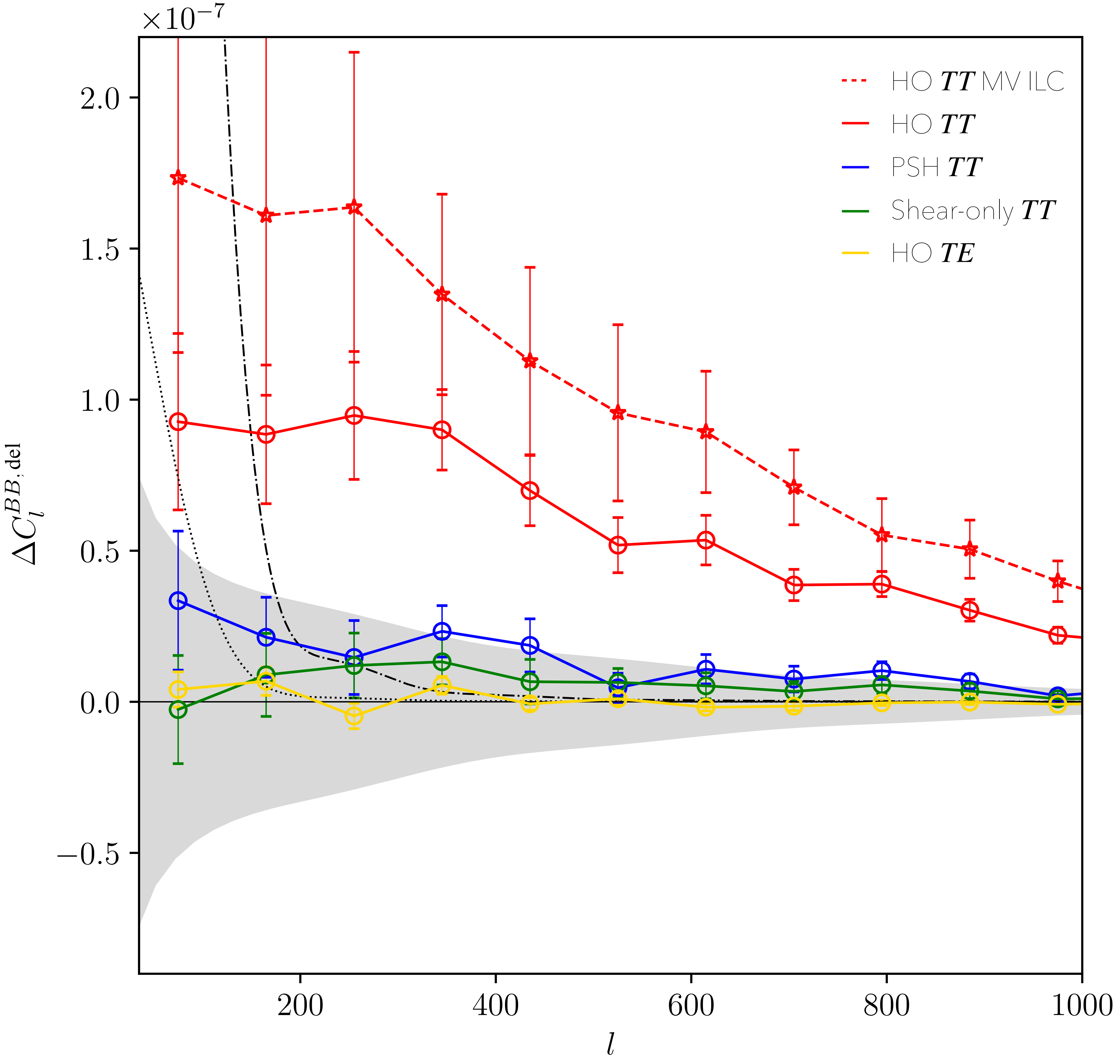
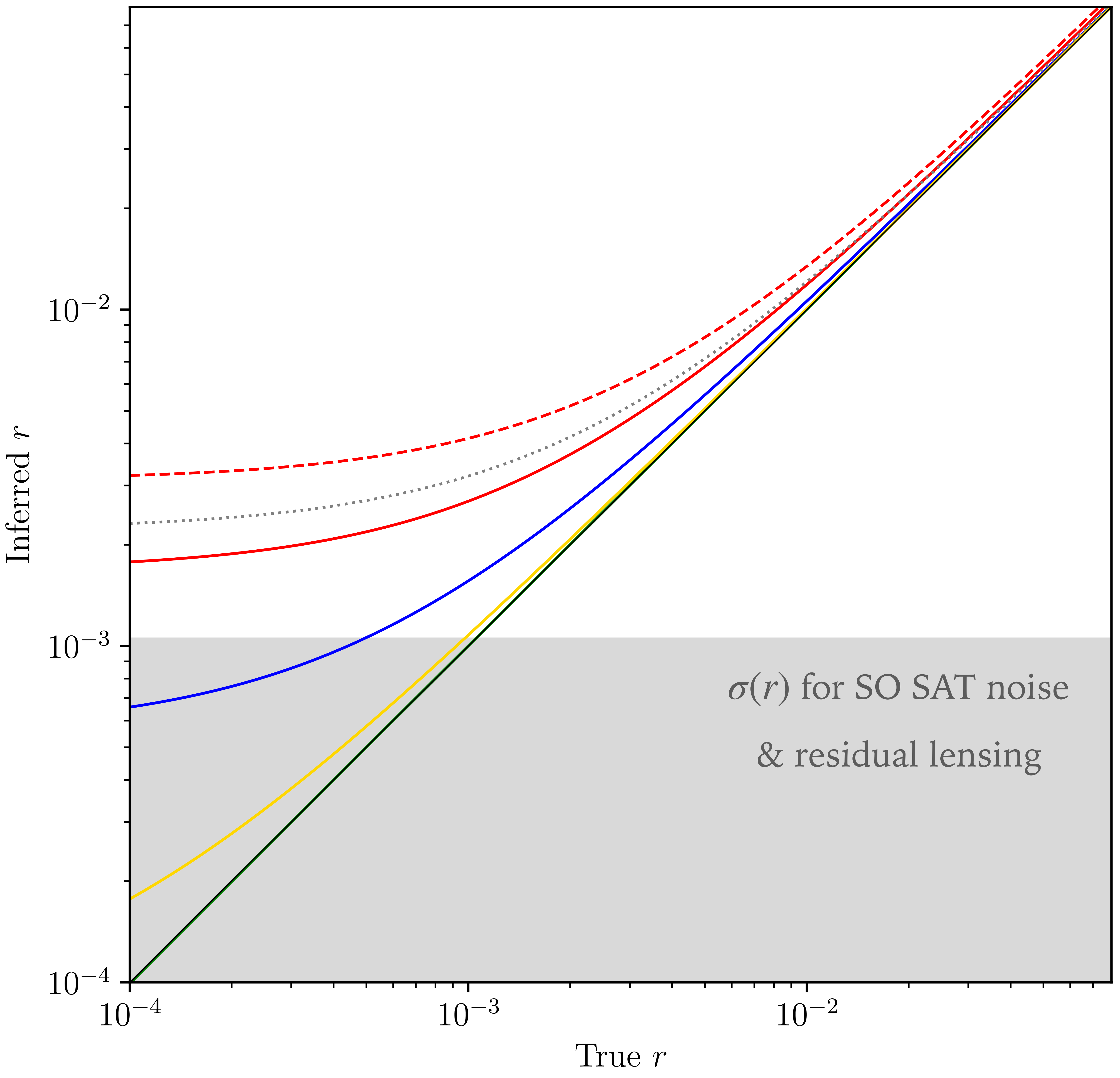
PATHWAYS TO MITIGATION

HO ≡ Hu-Okamoto
PSH ≡ Point-source-hardened





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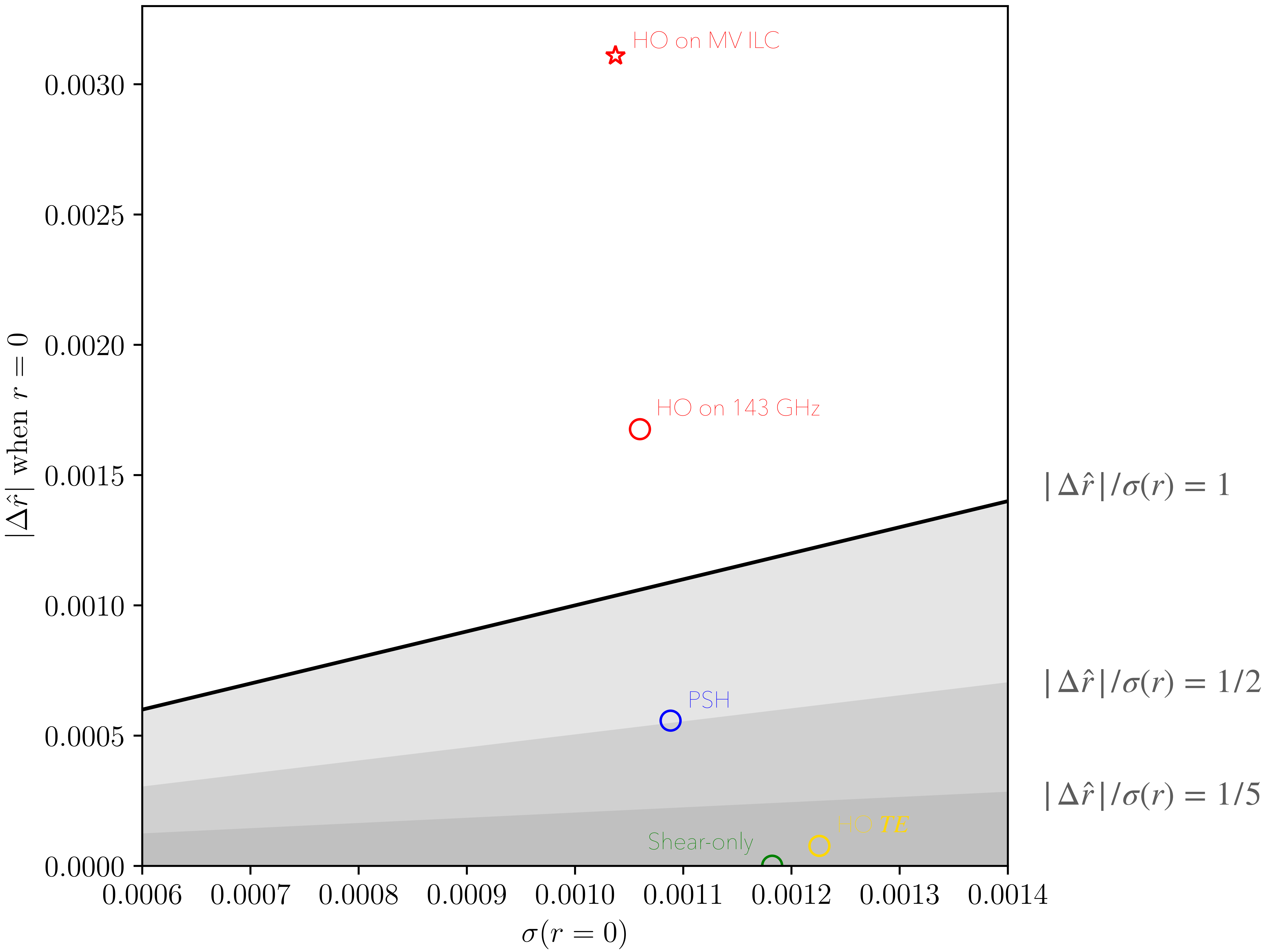
BIAS VS NOISE

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



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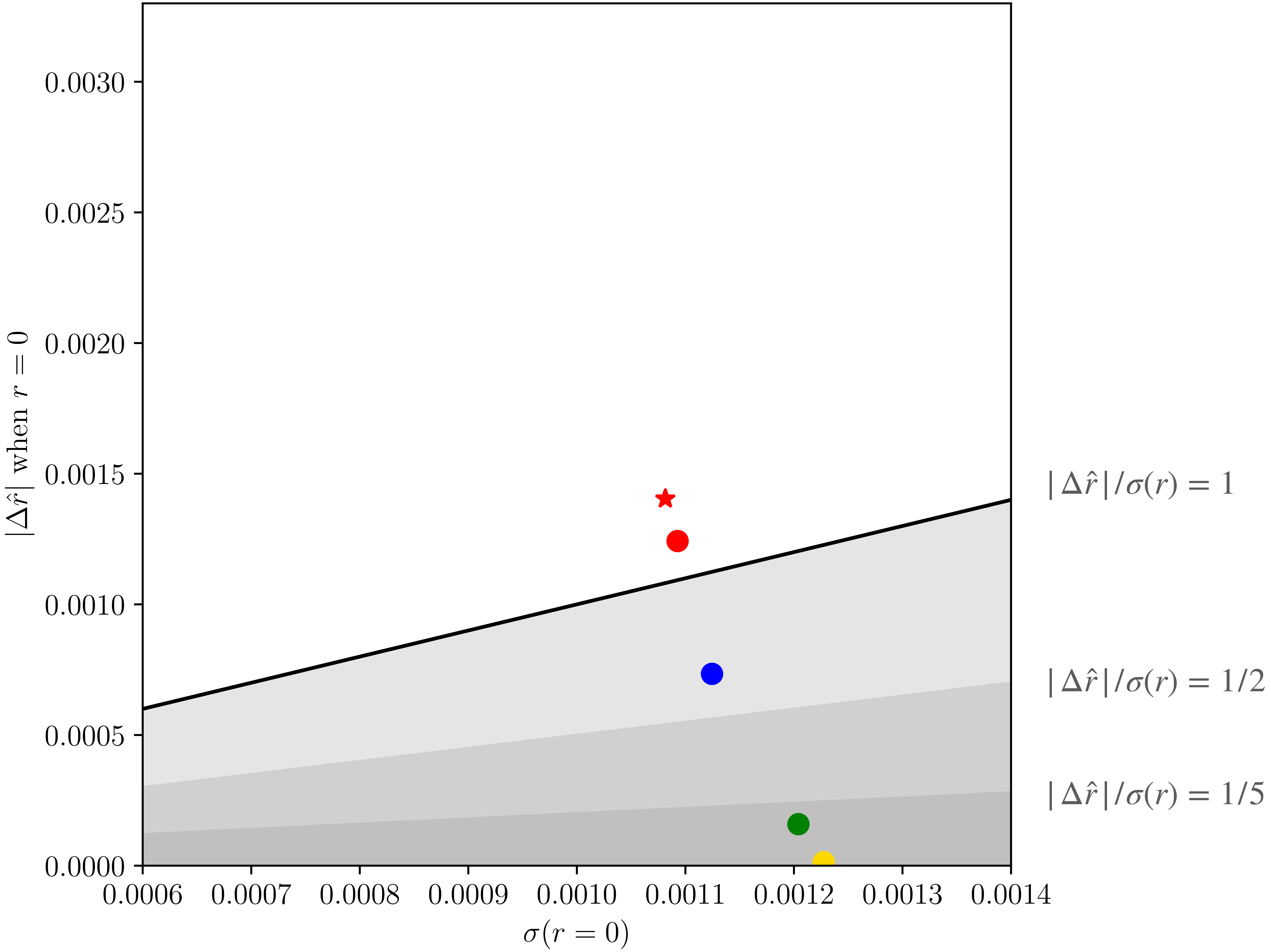
BIAS VS NOISE

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



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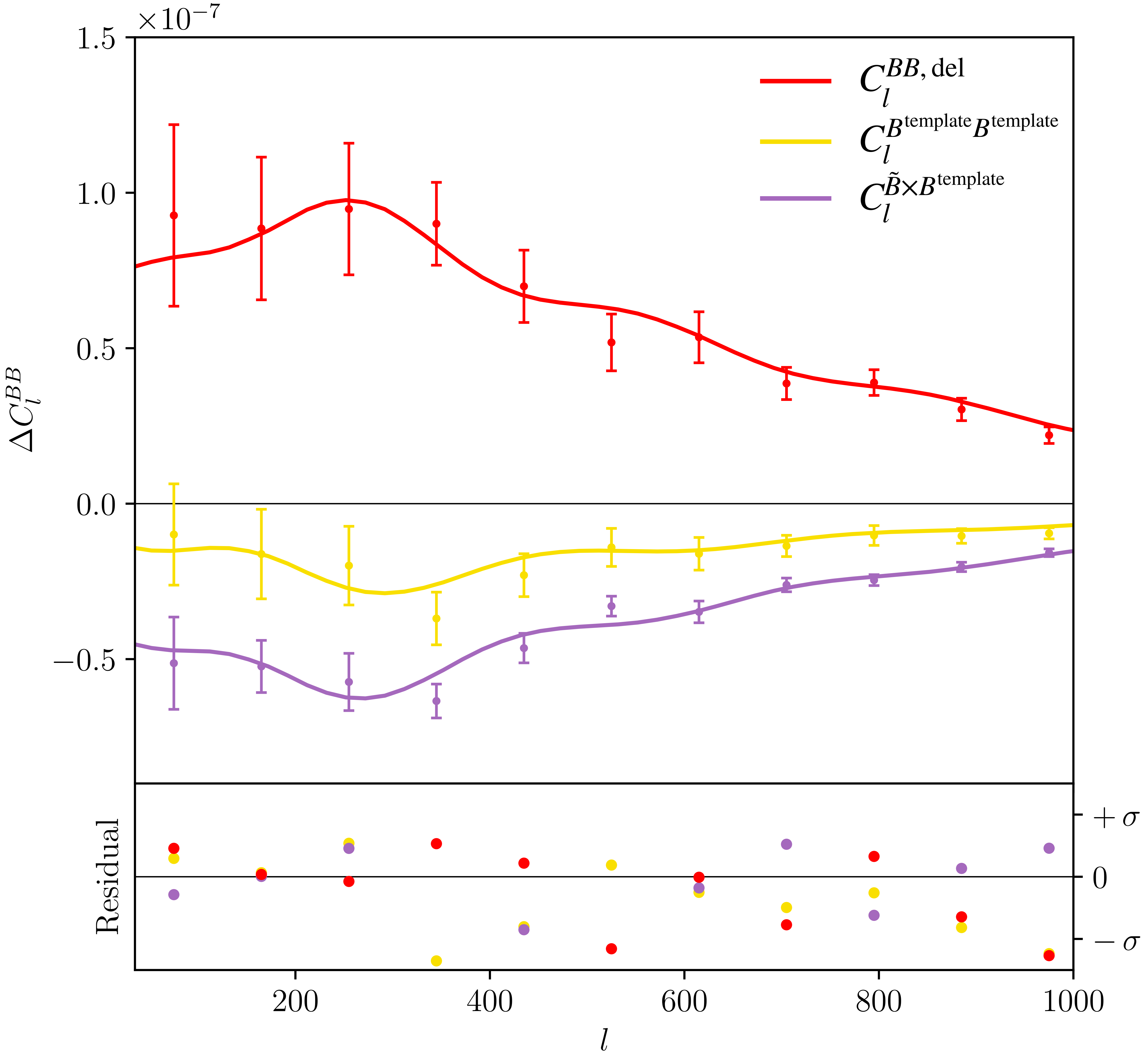
MODELING THE BIAS



The dominant terms can be modelled as

$$\Delta C_l^{\hat{B}^{\mathrm{lens}}\times\hat{B}^{\mathrm{lens}}} = \int \frac{d^2\boldsymbol{l}'}{(2\pi)^2} W^2(\boldsymbol{l},\boldsymbol{l}') \left(\mathcal{W}^E_{l'}\mathcal{W}^\kappa_{|\boldsymbol{l}-\boldsymbol{l}'|}\right)^2 \times C_{l'}^{EE,\mathrm{tot}} \underline{\Delta C^{\hat{\kappa}\hat{\kappa}}_{\boldsymbol{l}-\boldsymbol{l}'}}\,,$$

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

and

$$\Delta C_l^{\tilde{B}\times\hat{B}^{\mathrm{lens}}} = \int \frac{d^2\boldsymbol{l}'}{(2\pi)^2} W^2(\boldsymbol{l},\boldsymbol{l}') \mathcal{W}^E_{l'}\mathcal{W}^\kappa_{|\boldsymbol{l}-\boldsymbol{l}'|} \times C_{l'}^{EE} \underline{\Delta C^{\kappa\hat{\kappa}}_{\boldsymbol{l}-\boldsymbol{l}'}}.$$

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

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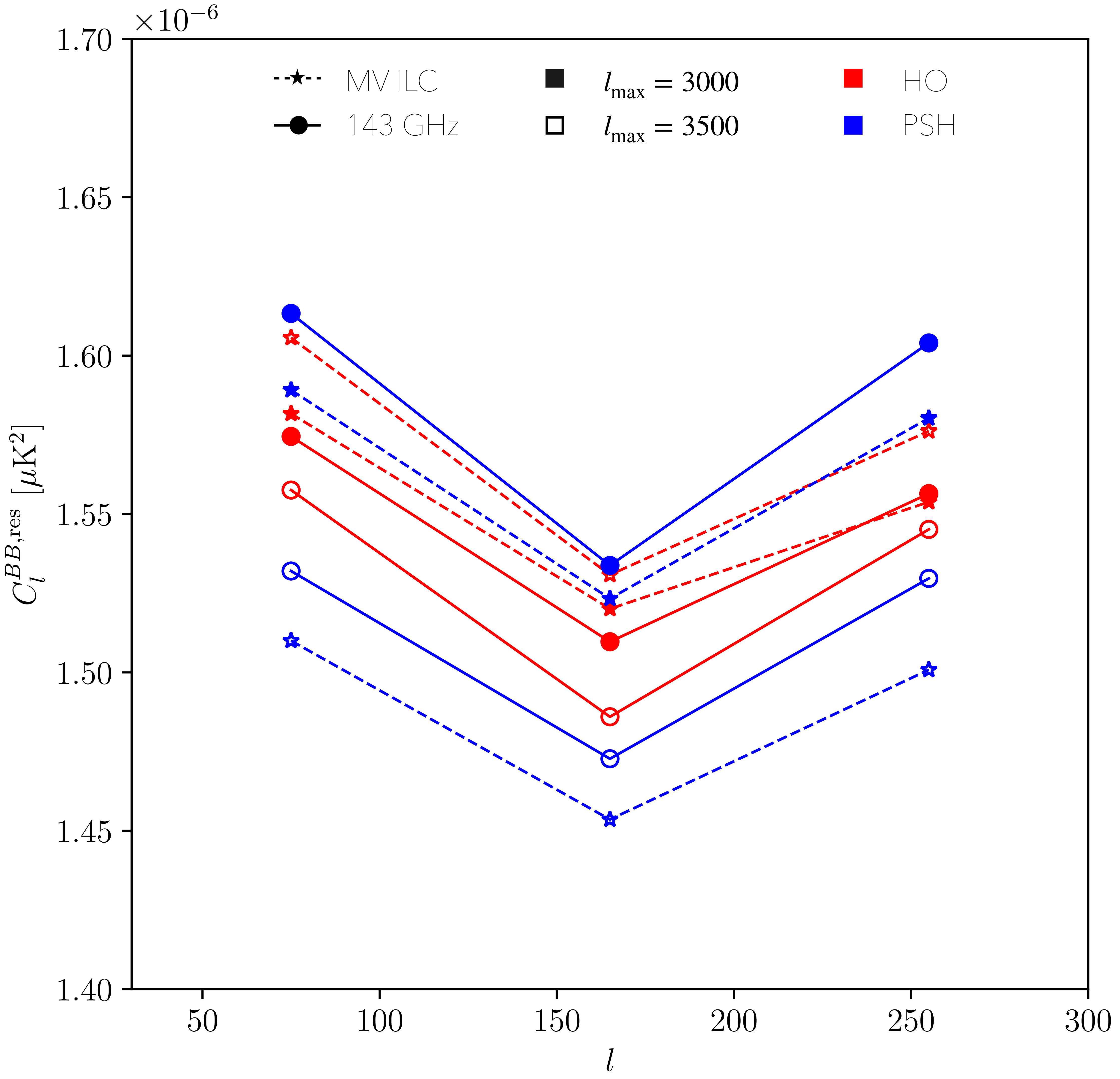
WHAT ESTIMATOR IS BEST?



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
- $l_{\rm max}$
- 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!

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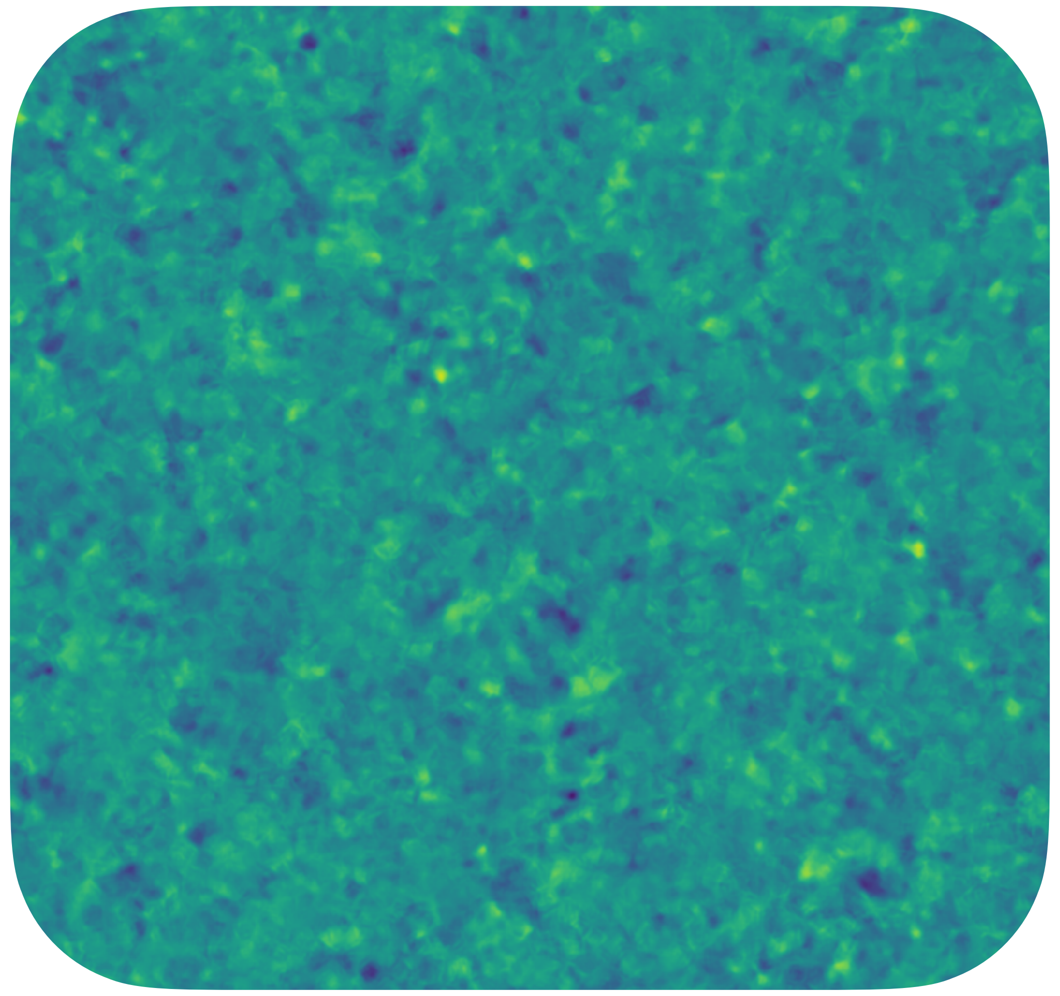
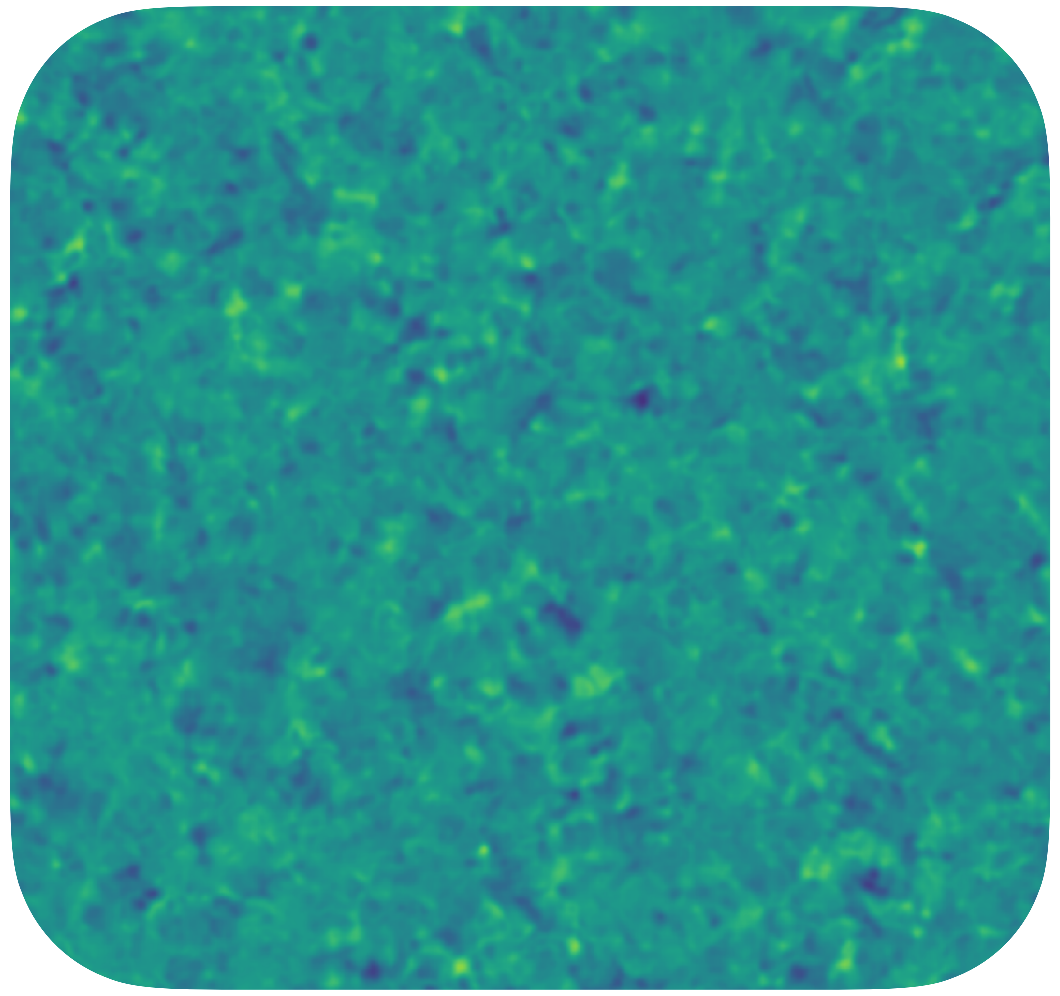
MULTITRACER DELENSING

B^{obs}

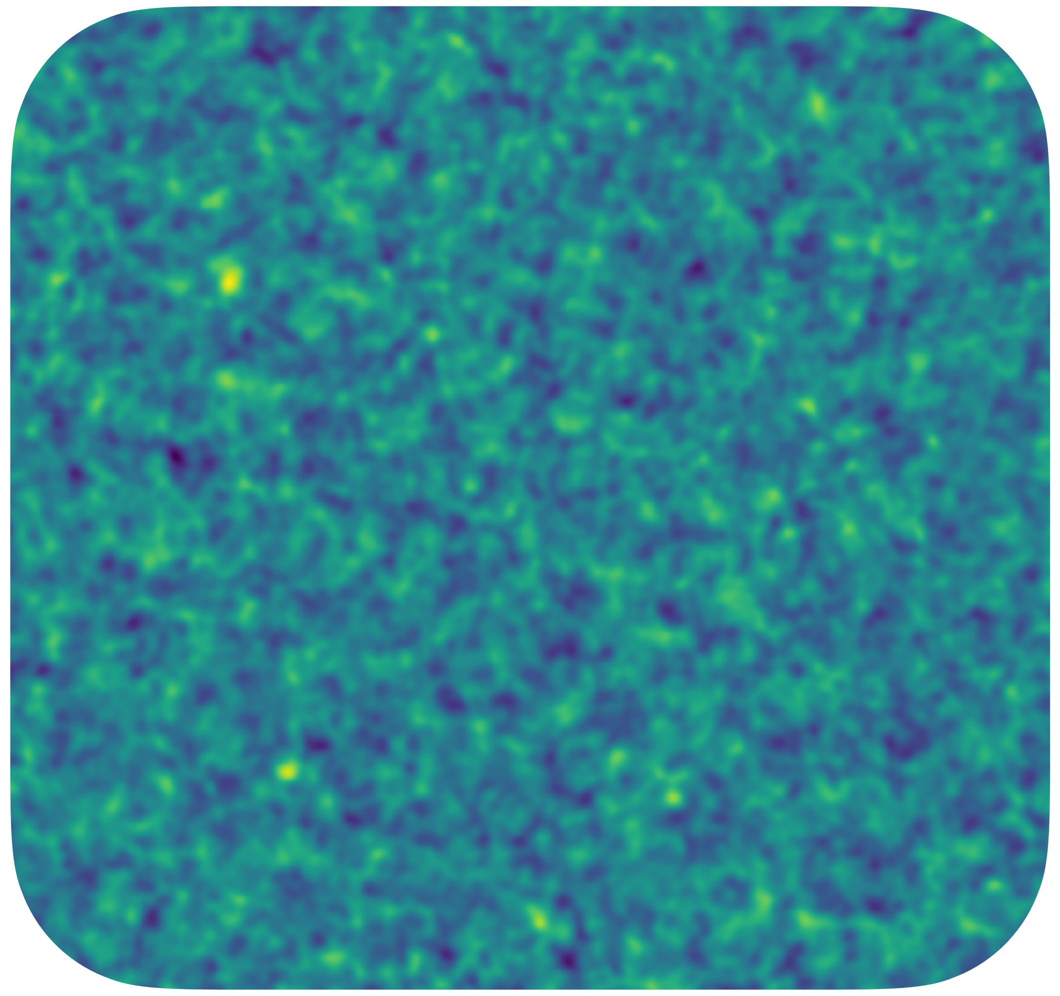


$\hat{B}^{\mathrm{lens}}$



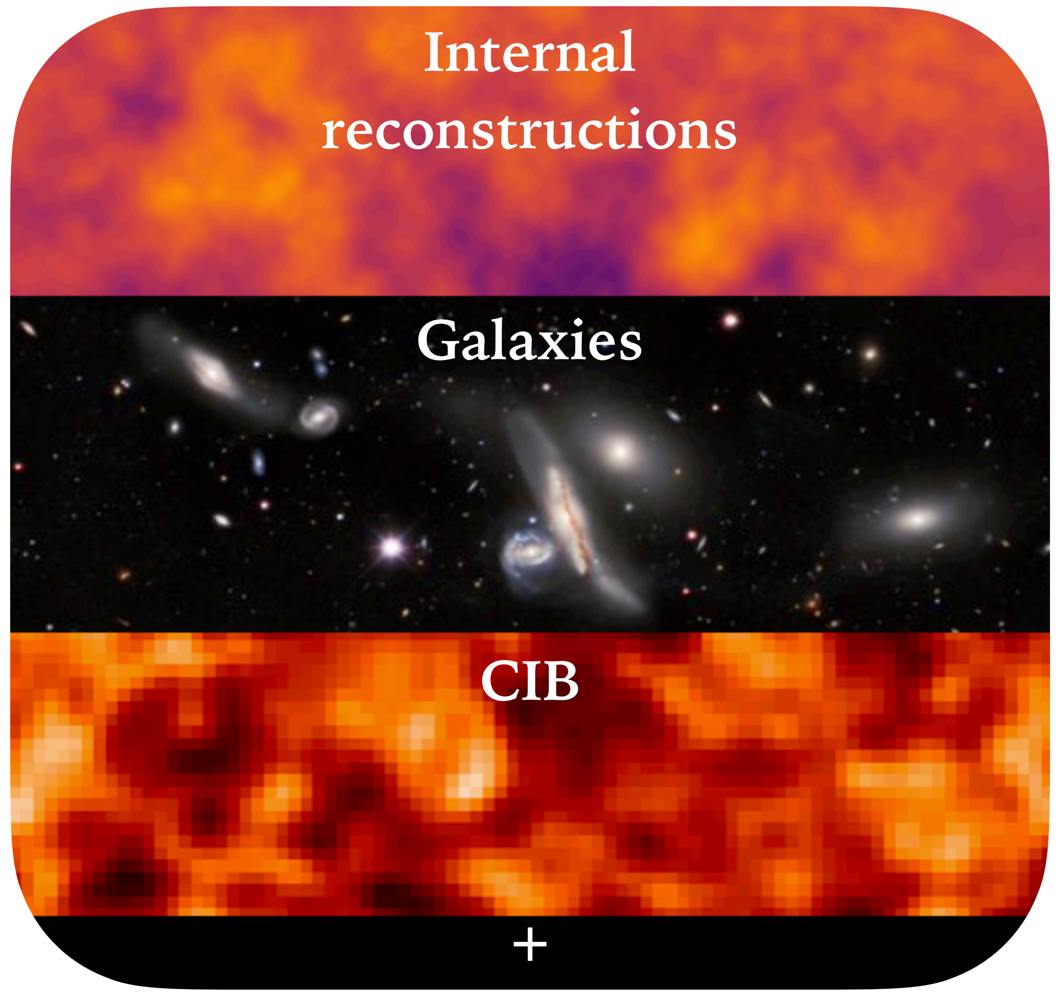
$B^{\mathrm{del}} \quad = \quad B^{\mathrm{obs}} \quad - \quad \hat{B}^{\mathrm{lens}}$

Filtered E^{obs}

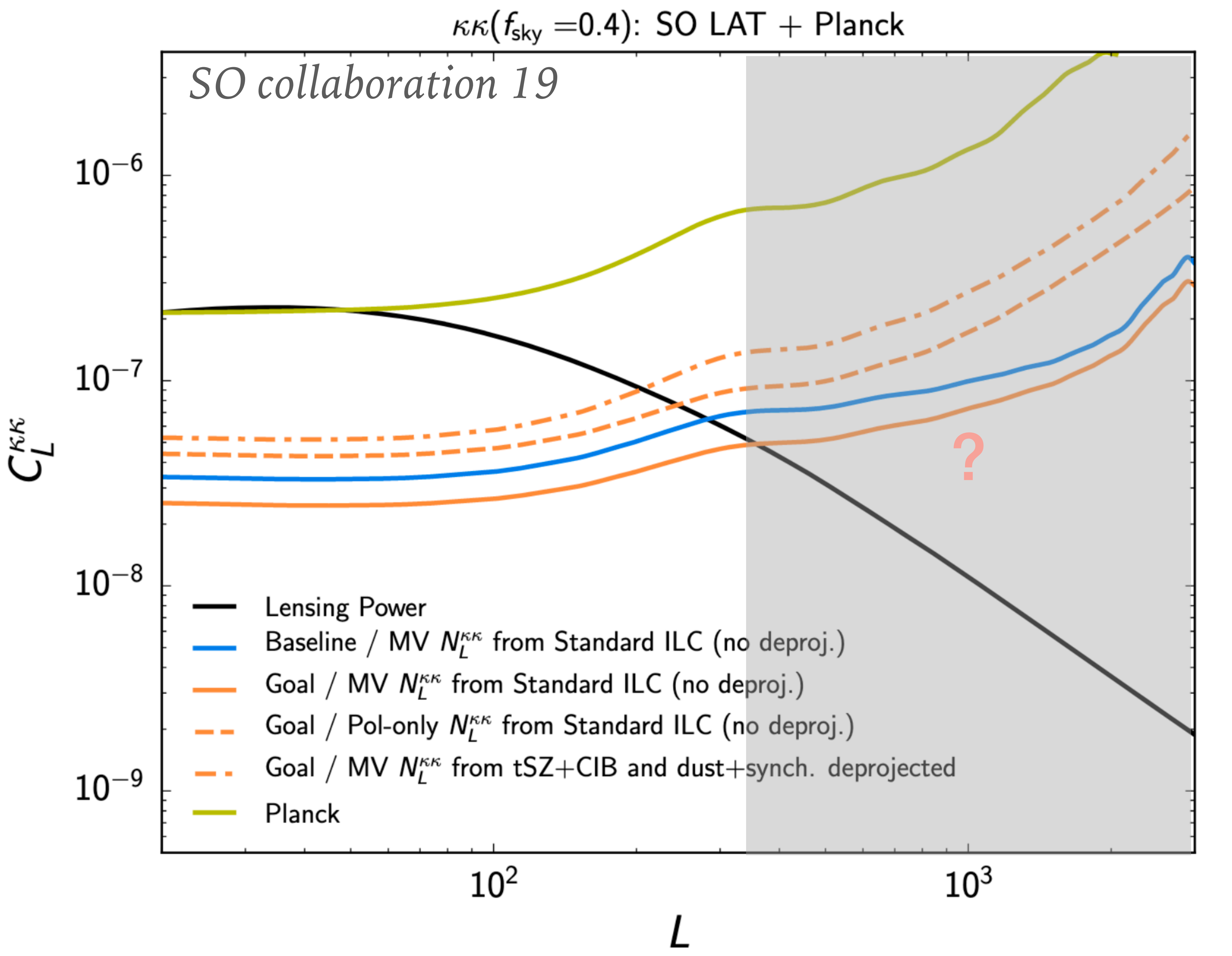


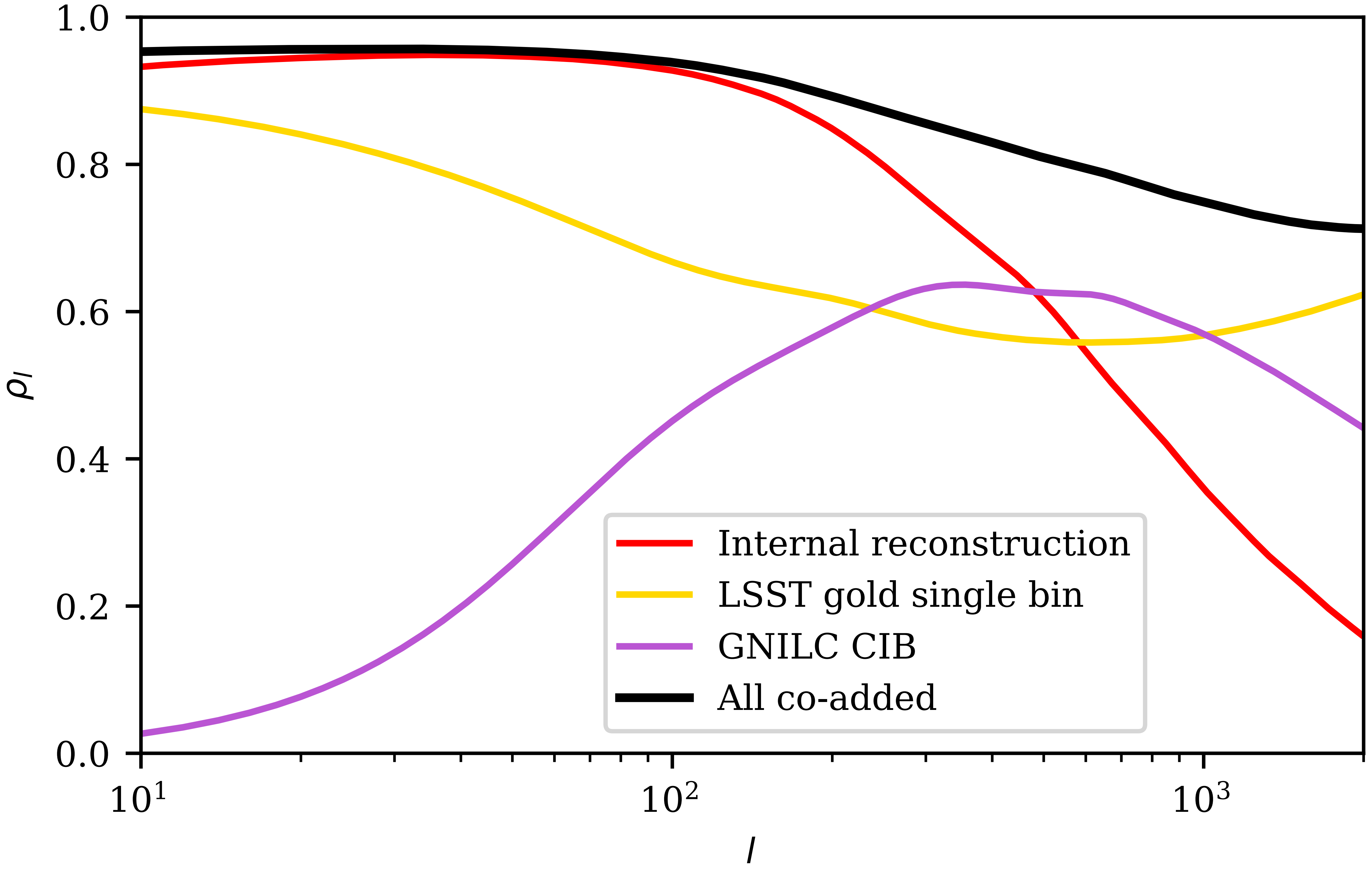
$*$

Coadded tracers



MULTI-TRACER DELENSING WITH SO





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

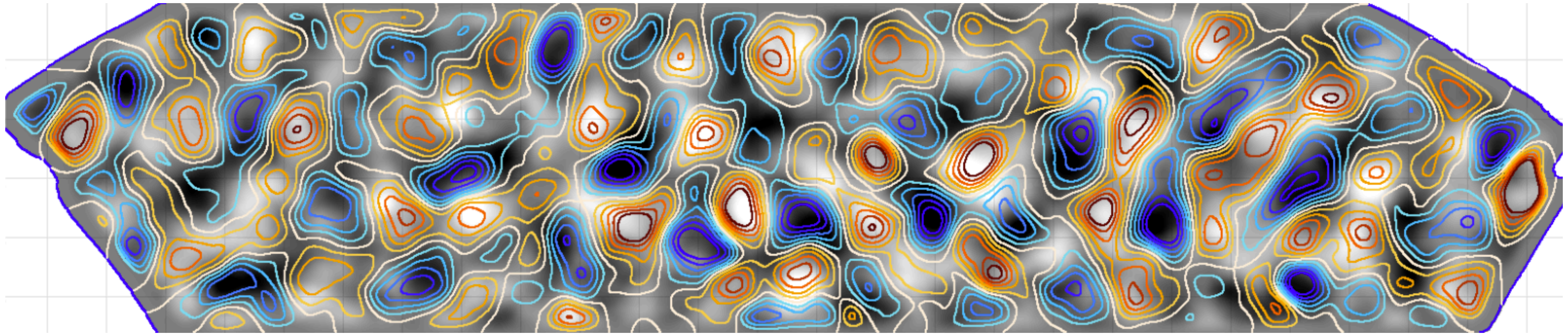
Sherwin & Schmittfull 15, Manzotti 18 …

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

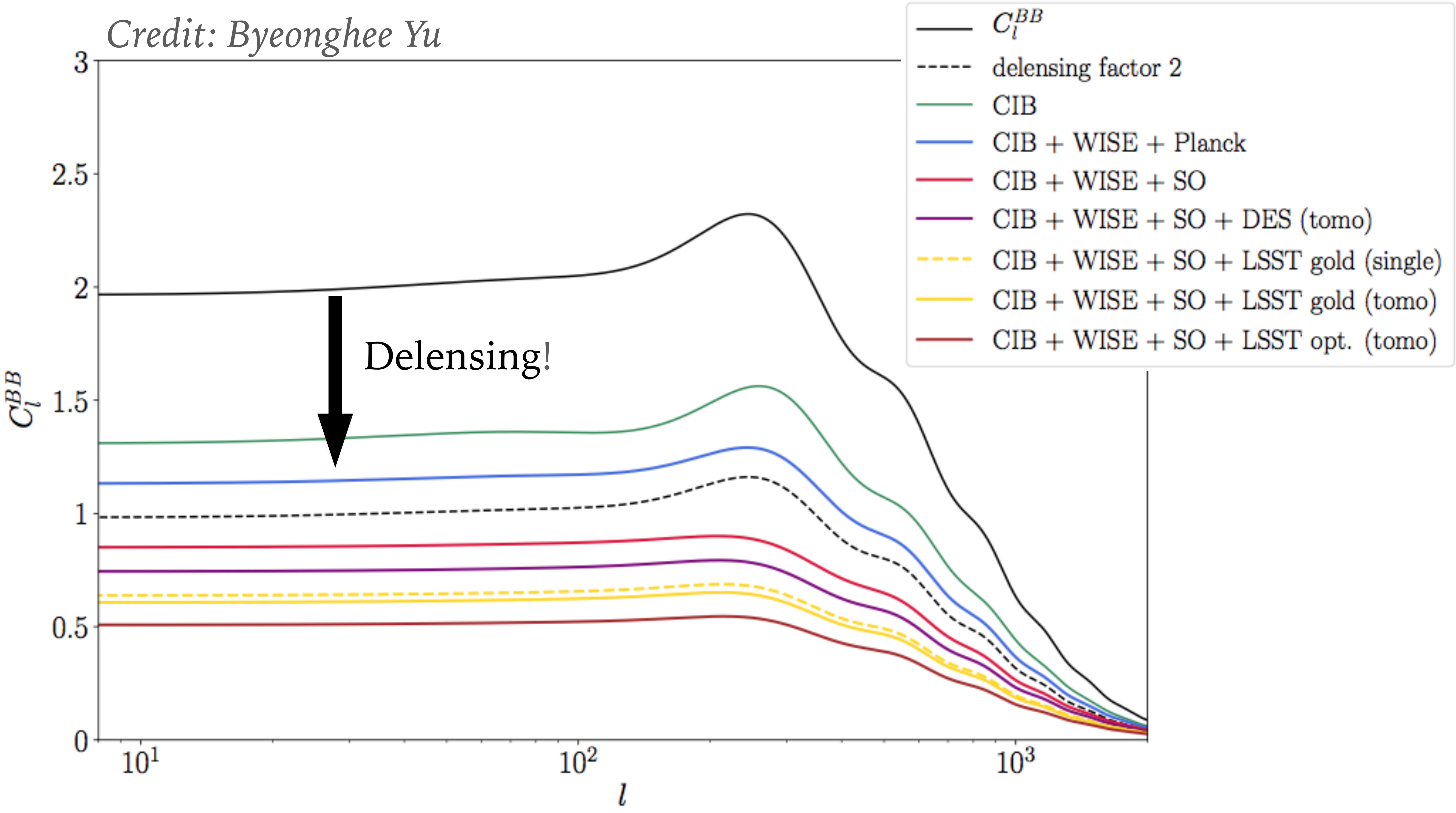


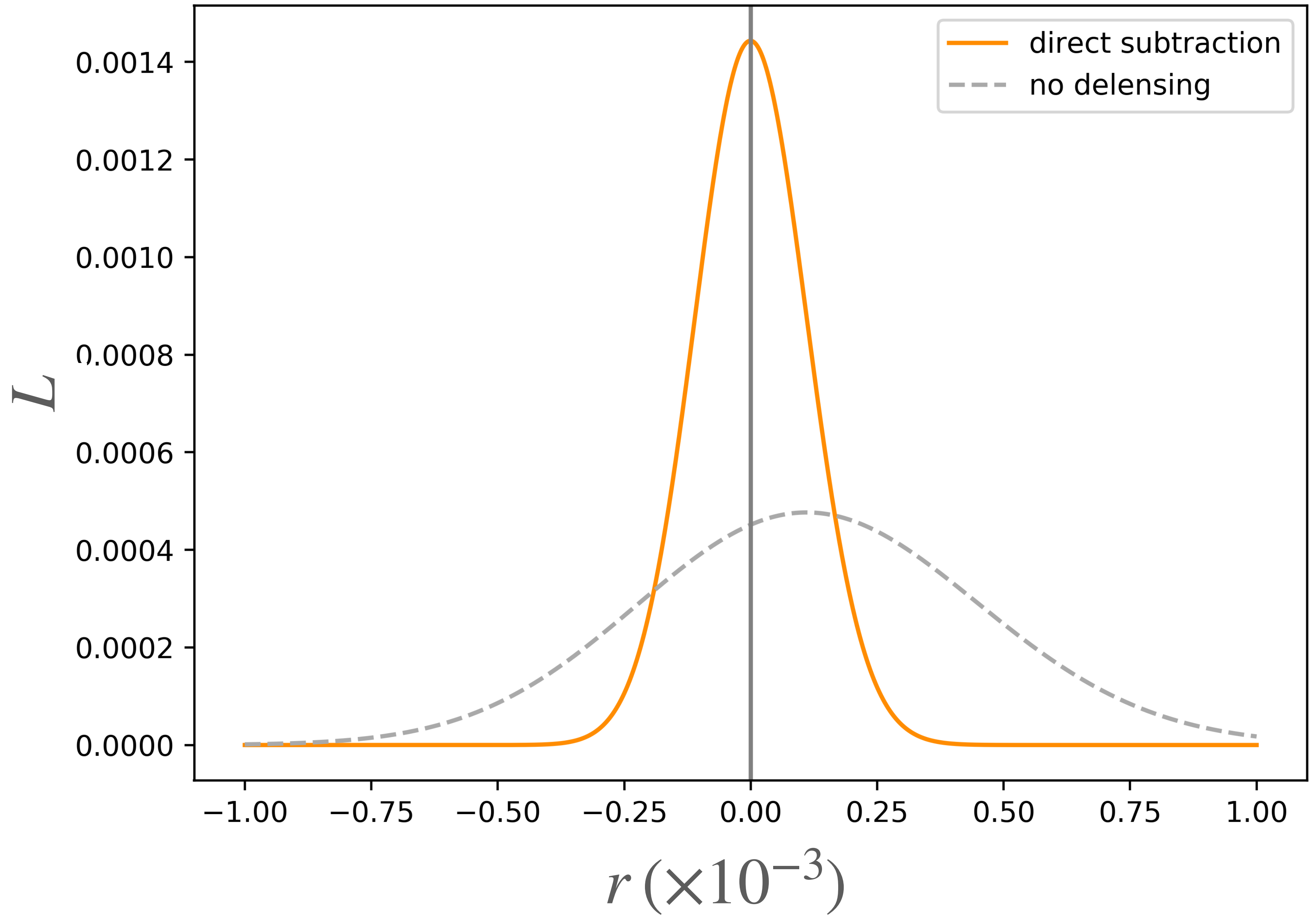
ACT lensing vs. CIB *Darwish+. 20*

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 $\sigma(r) = 0.003$

*Namikawa, **ABL** & SO Collaboration 21*

MULTI-TRACER DELENSING BIAS

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

Dilution of TT bias

MULTI-TRACER DELENSING BIAS

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

Dilution of *TE* bias

MULTI-TRACER DELENSING BIAS

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

New term involving:

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

~ primary bispectrum bias

~ secondary bispectrum bias

MULTI-TRACER DELENSING BIAS

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

New term involving:

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

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

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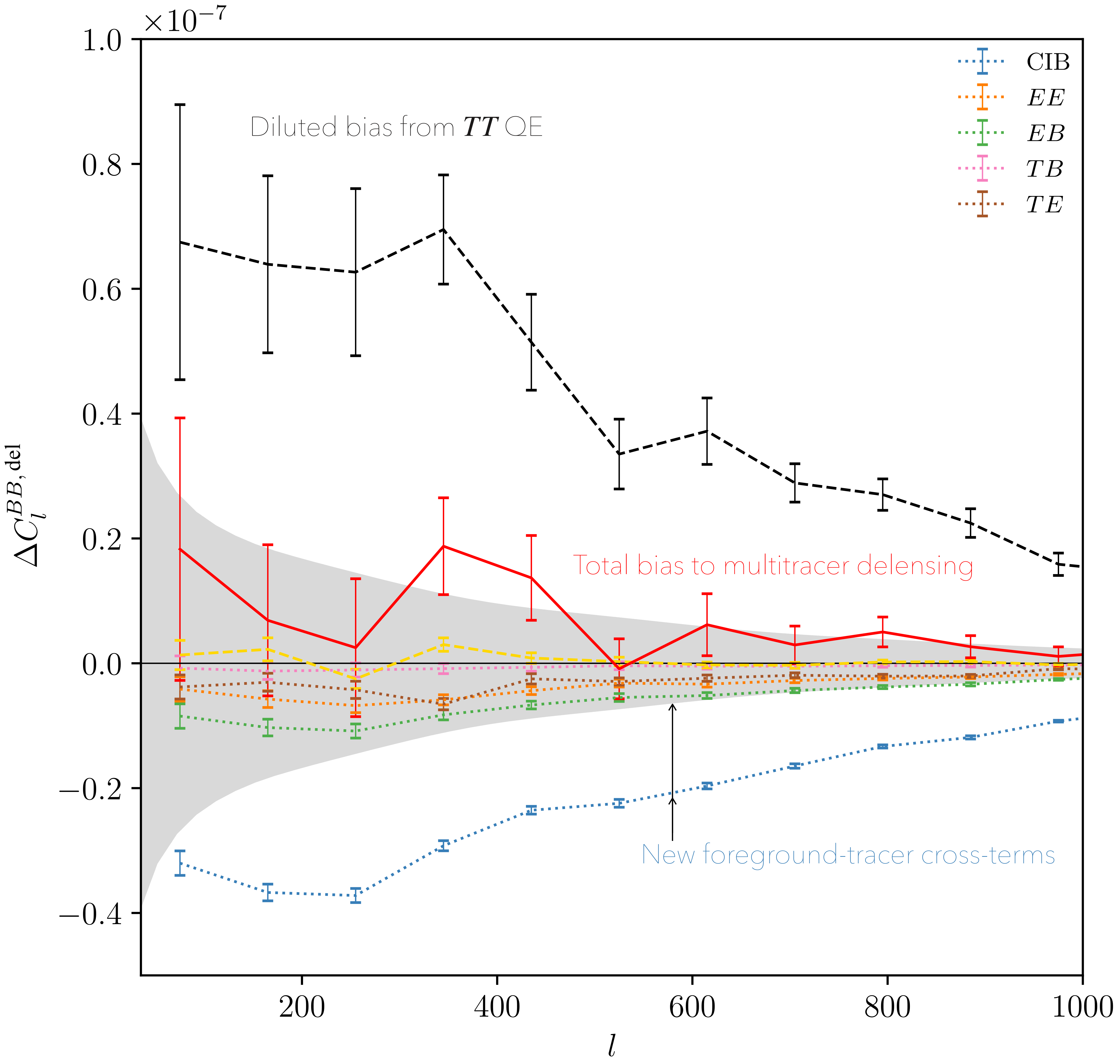
BIAS TO MULTI-TRACER DELENSING



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

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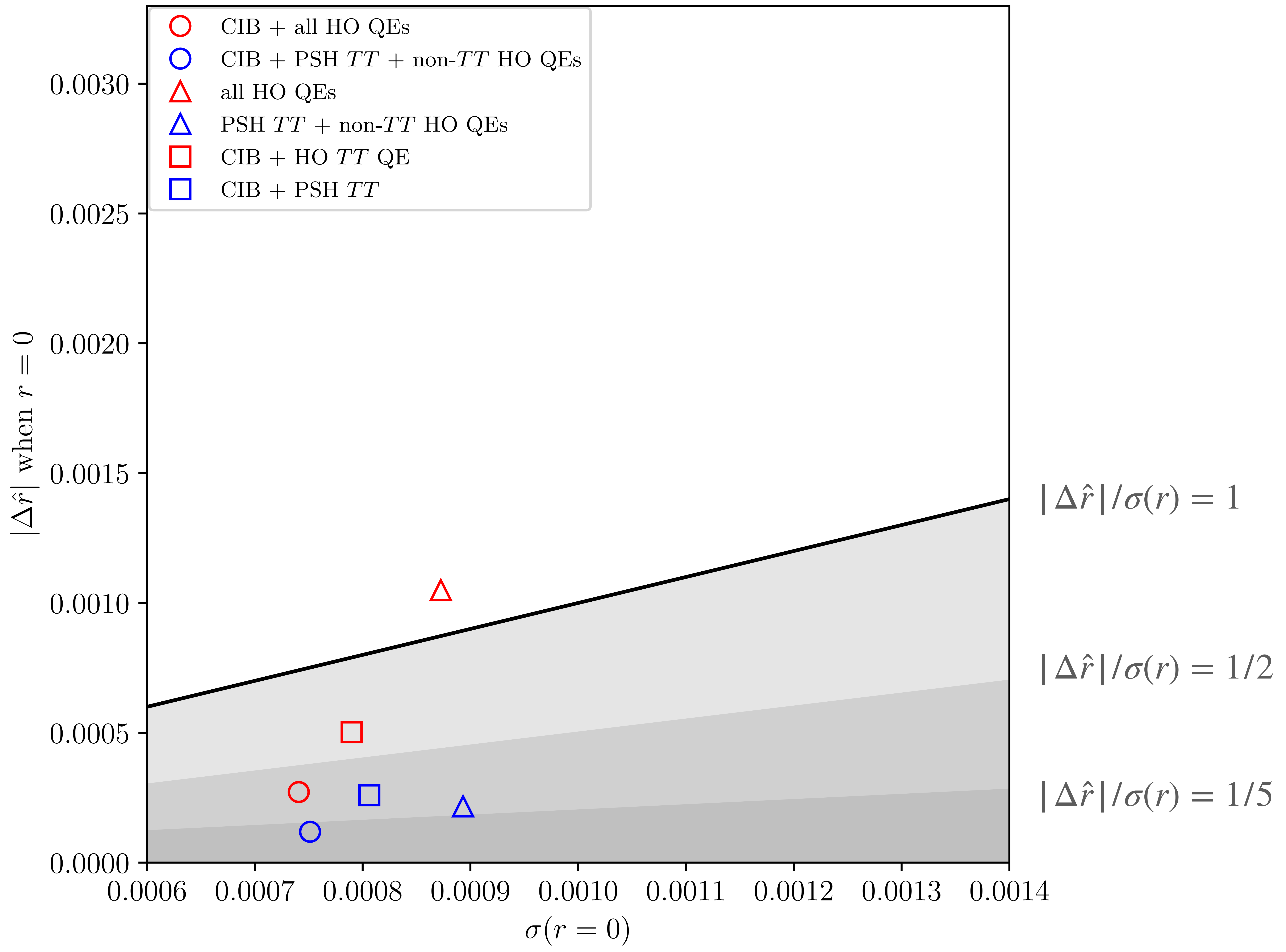
BIAS VS NOISE



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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:

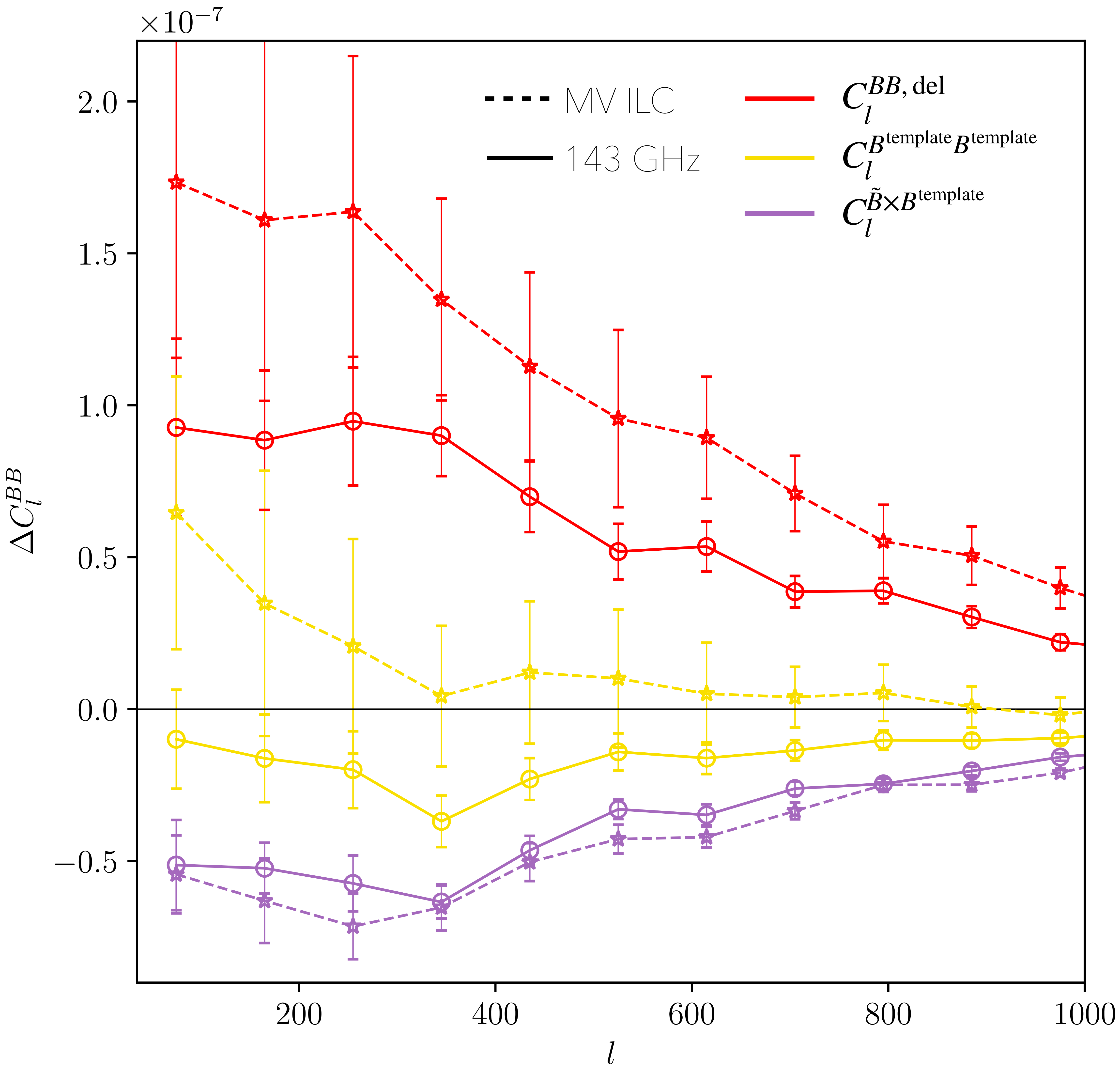
- Impact of polarized (point) sources?
- Impact on delensing of acoustic peaks?

Thank you for having me!

a.baleatolizancos@berkeley.edu

ADDITIONAL SLIDES

MV ILC LEADS TO HIGHER BIAS



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

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

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

$\Longrightarrow$ template auto- moves "up"

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

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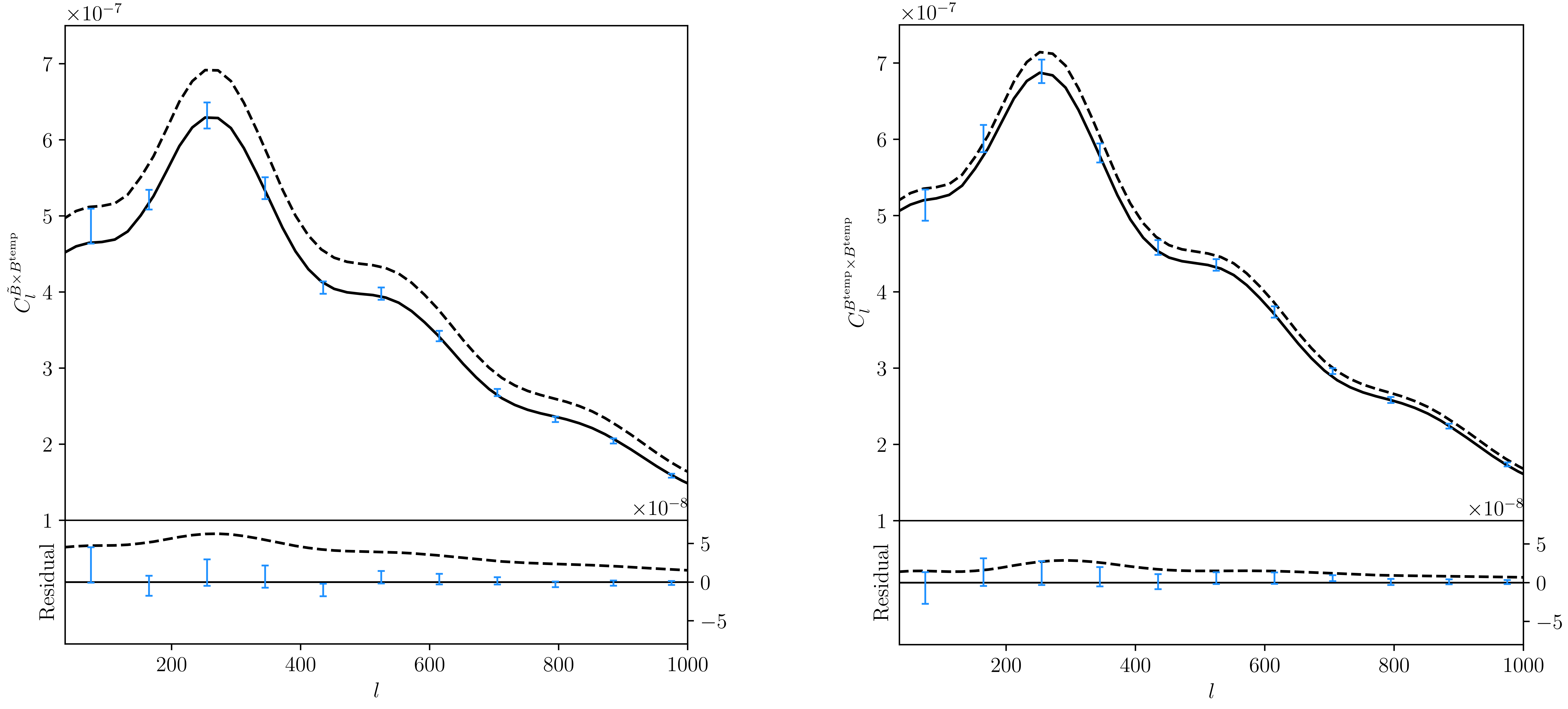
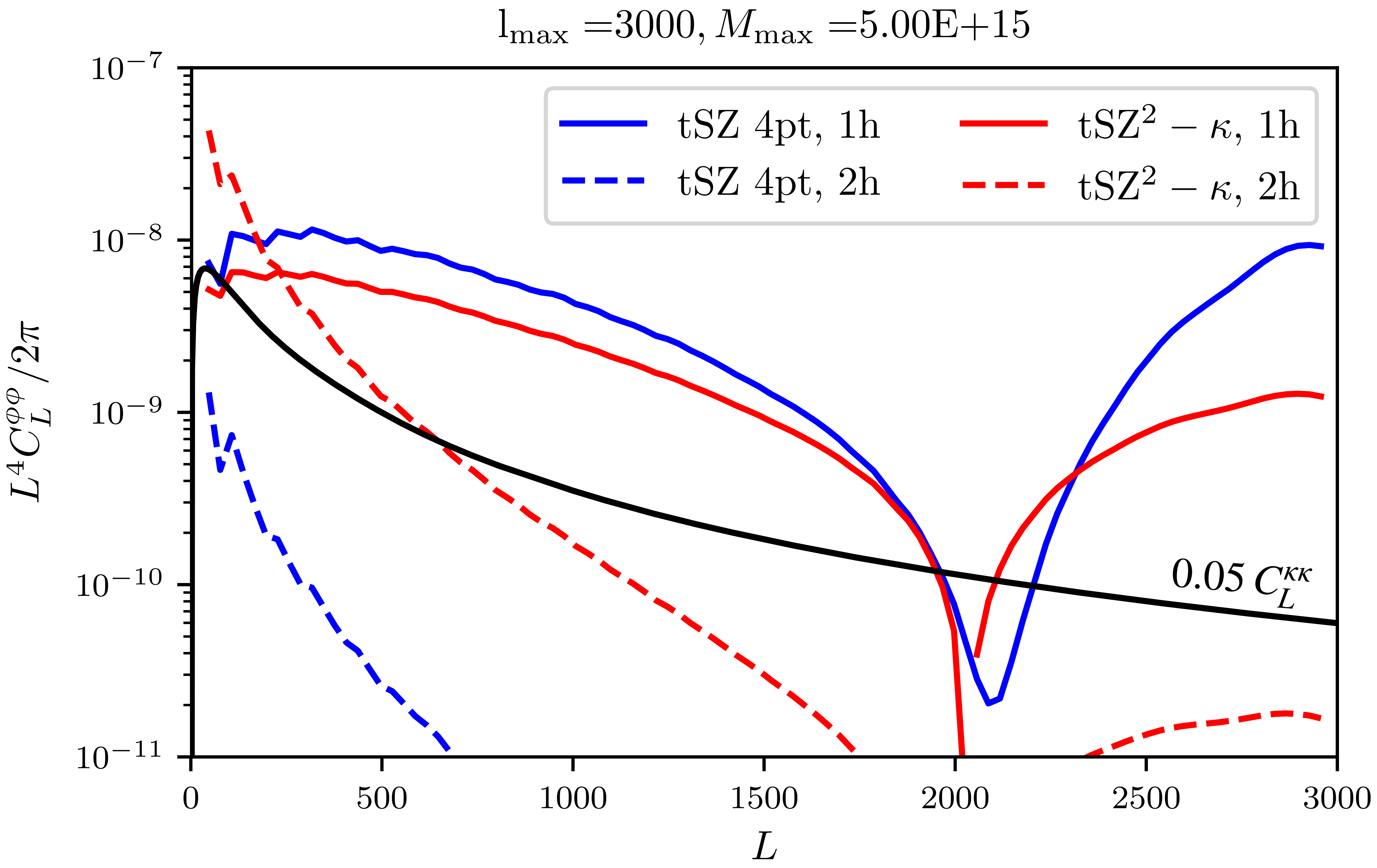
EMPIRICALLY-CALIBRATED MODELS OF BIASED B-MODE SPECTRA



Models were computed using $\langle C^{\hat{\kappa}\hat{\kappa}}\rangle$ and $\langle C^{\kappa\hat{\kappa}}\rangle$ featuring $\left\{ \begin{array}{l} \text{Gaussian fgs} \\ \text{non-Gaussian fgs} \end{array} \right.$

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(10ms) per lensing reconstruction on a single laptop core.
- Can calculate biases and associated uncertainties

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