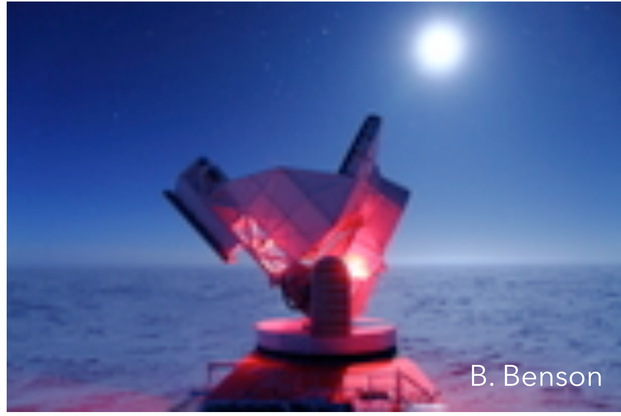
Delensing the CMB with SPT-3G

BICEP/Keck



Outline:

1. De-lensing the CMB for best constraints on primordial gravitational waves from inflation
   quick intro and methods
2. Preliminary work from within the SPT-3G collaboration,
   in order to delens BICEP/Keck for best *r*-constraints
3. Fastest ever spherical harmonic transforms
   S. *Belkner, M.Reinecke, JC 2023*
   JC & M.Reinecke 2025 in prep.

S. Belkner, L. Legrand, O. Darwish

(formerly the Geneva lensing group), for some of the methods.

SPT-3G lensing: *Kimmy Wu, Yuuki Omori, Fei Ge ++, SPT-3G collaboration*

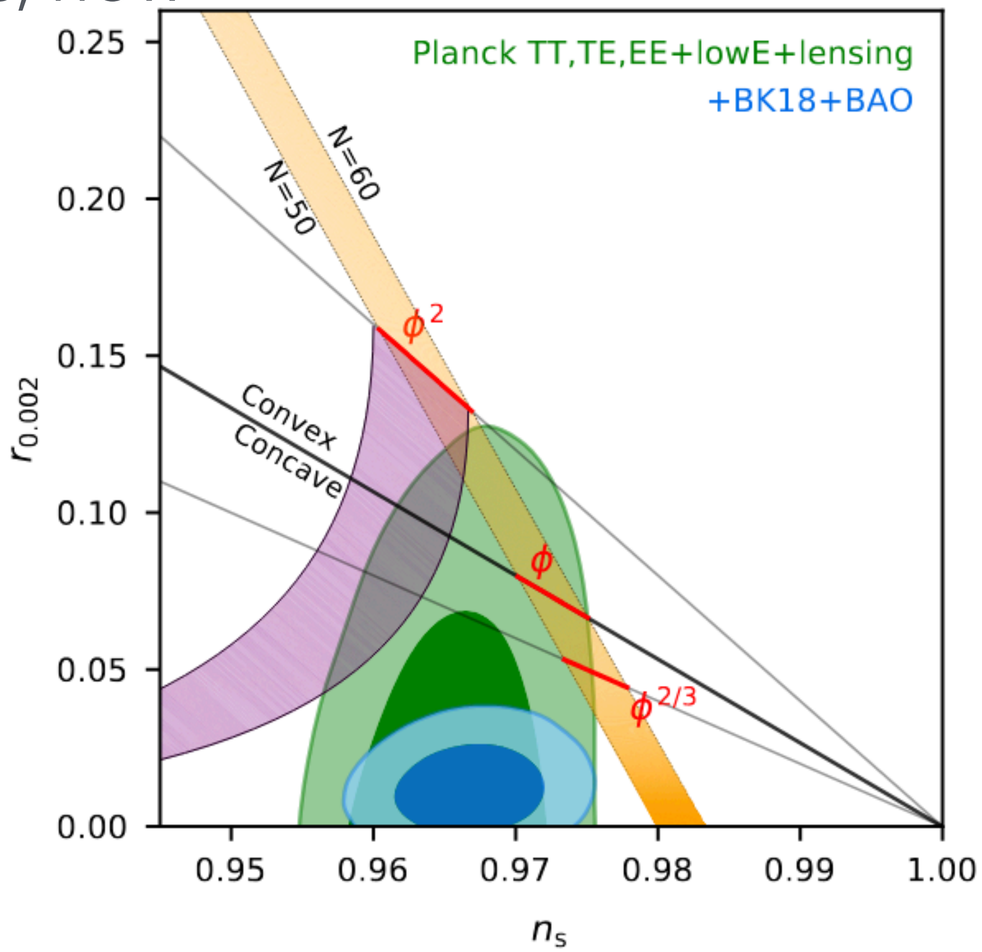
Julien Carron, University of Geneva, 10/06/2025

Swiss National Science Foundation

PGW constraints, now

+ BK18

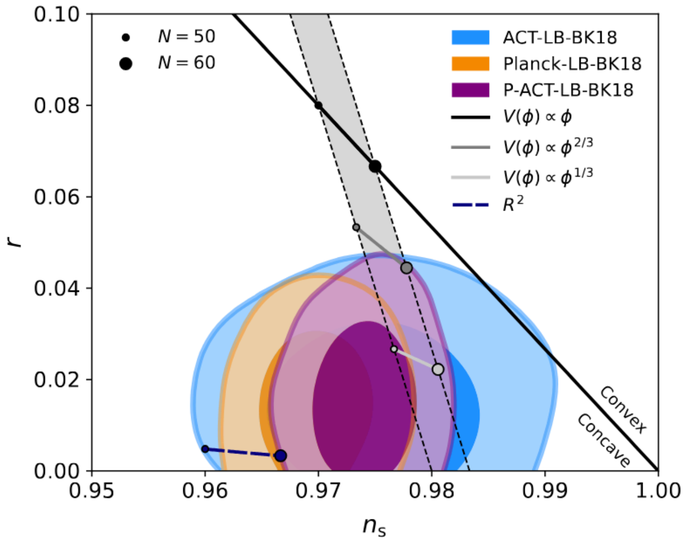
+BAO



BK18 : $\sigma(r_{0.05}) = 0.009, \quad r_{0.05} < 0.036$ (95 % c.l.),

ing. Running the baseline BK18 analysis on simulations which contain no lensing B-modes gives $\sigma(r_{0.05}) = 0.004$,

BK18 2110.00483



Calabrese et al (ACT DR6)

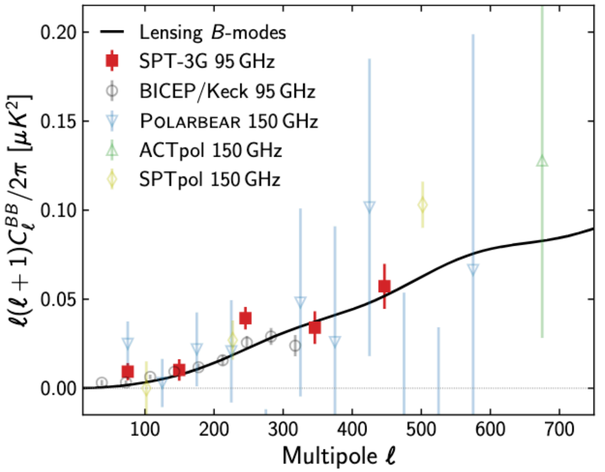
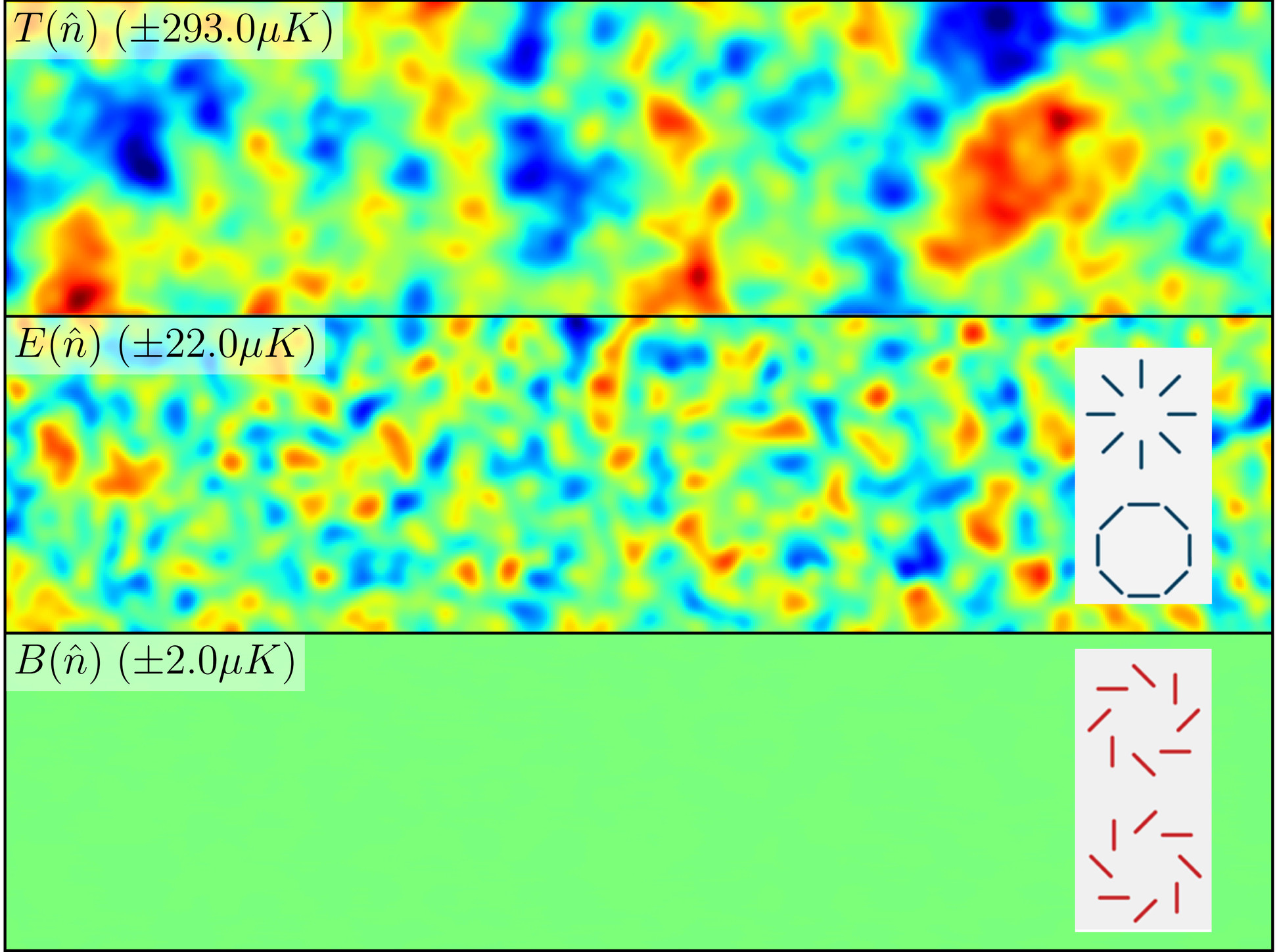
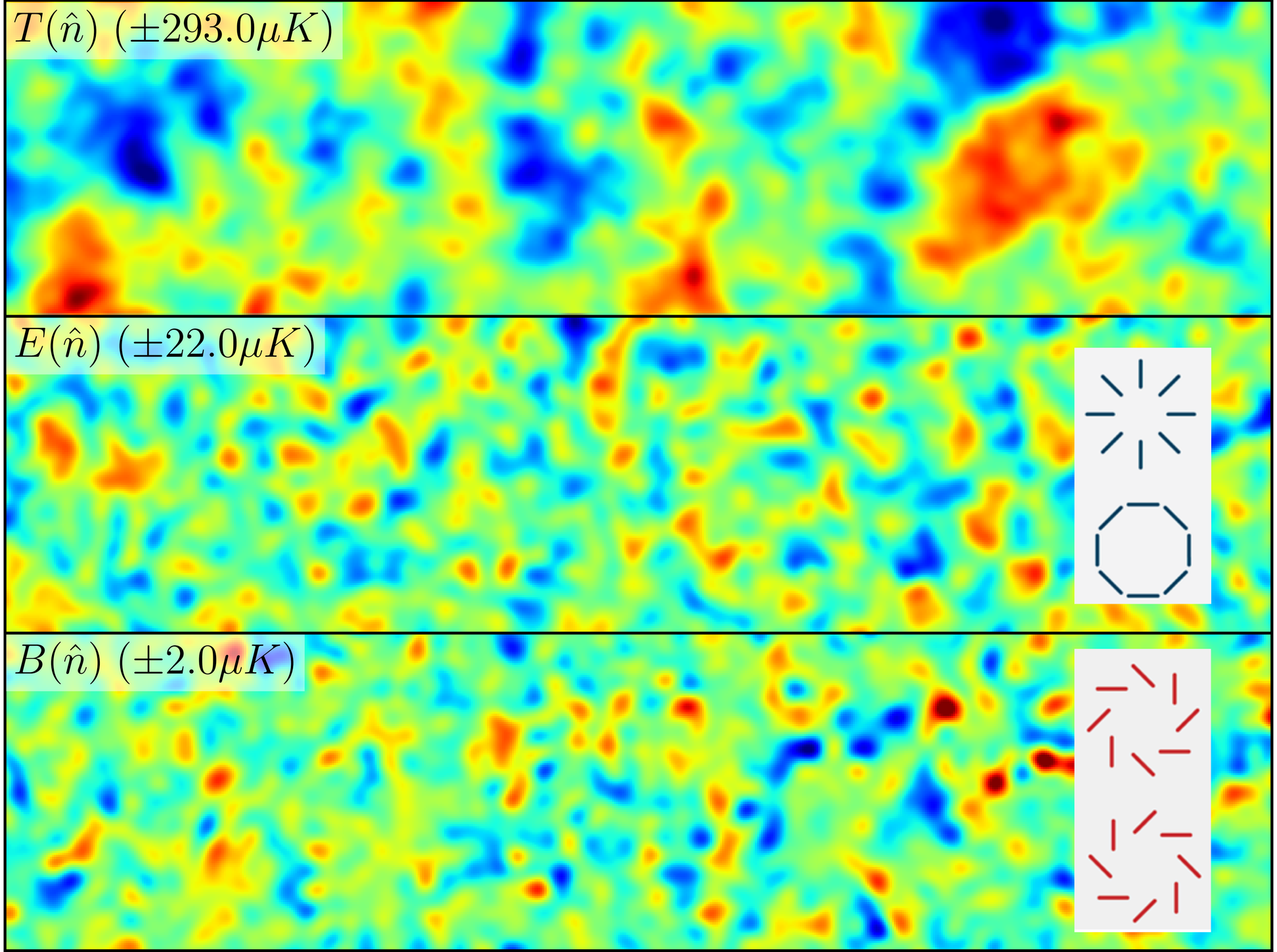


FIG. 7. Ground-based B-mode measurement landscape. Data are from SPTpol [32], ACT [28], POLARBEAR [1], and BICEP/Keck [4].

Zebrowski et al (SPT-3G) 2025

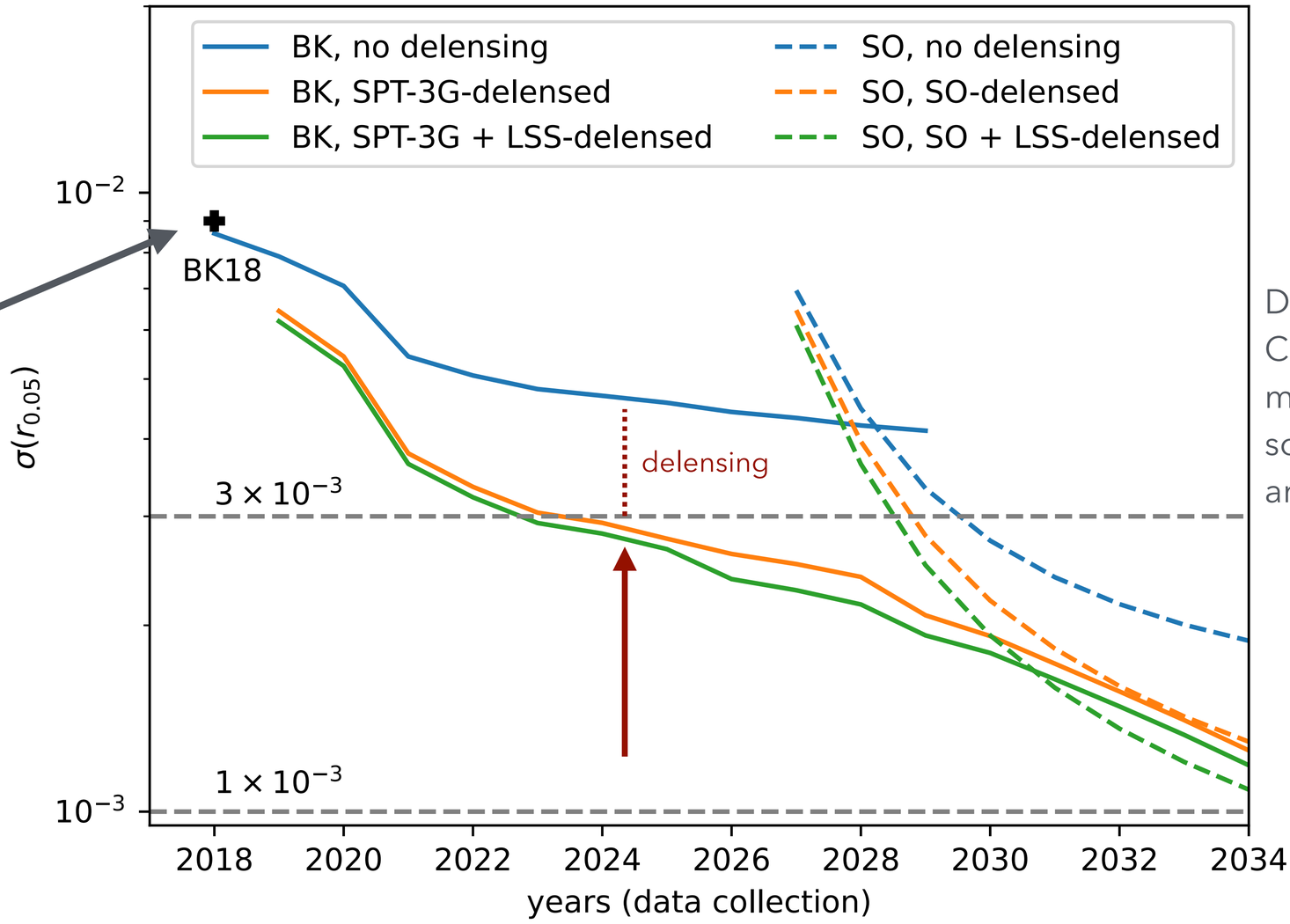

$T(\hat{n})$ $(\pm 293.0 \mu K)$
$E(\hat{n})$ $(\pm 22.0 \mu K)$
$B(\hat{n})$ $(\pm 2.0 \mu K)$


$T(\hat{n})$ $(\pm 293.0 \mu K)$
$E(\hat{n})$ $(\pm 22.0 \mu K)$
$B(\hat{n})$ $(\pm 2.0 \mu K)$

Next decade

Current constraint

$\sigma(r) = 0.009$



Disclaimer:
Crude figure built by myself from public sources, not official in any sort of ways

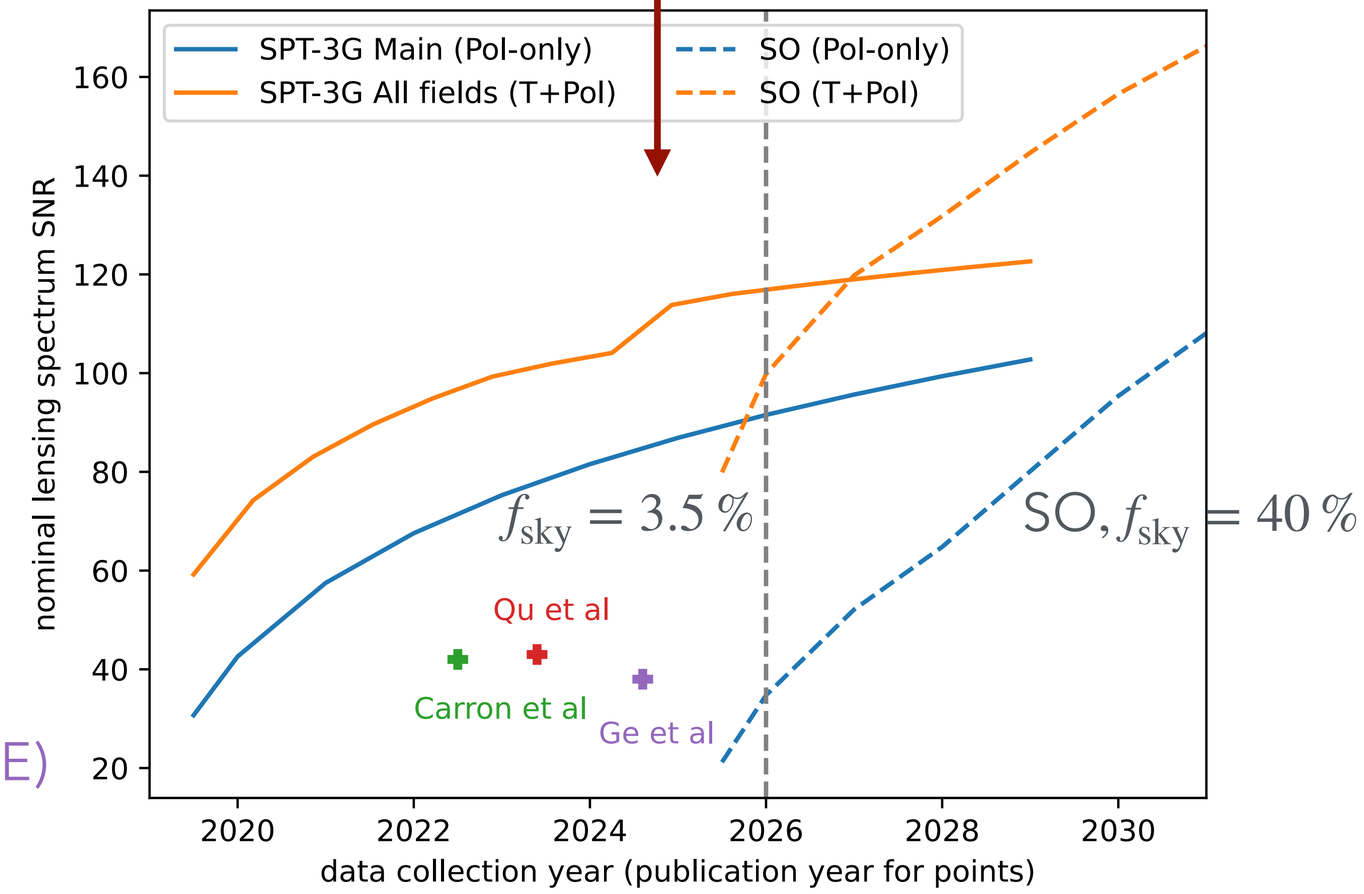
Collected data has now potential for $\sigma(r) \sim 0.003$

(3x improvement over current constraints BK18)

Next decade

Large-scale structure from CMB lensing spectrum

Same collected lensing data

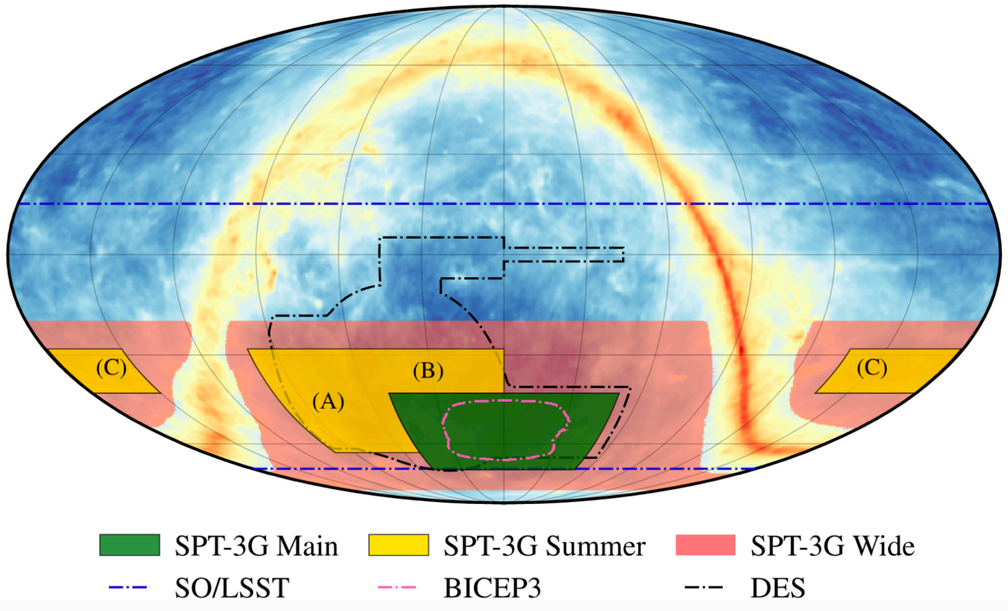


ACT DR6
Planck PR4
SPT-3G (MUSE)

Disclaimer:
Crude figure built by myself from public sources, not official in any sort of ways

All 3 in combination, Qu, Ge et al 2025 2504.20038 (ACT + SPT-3G)

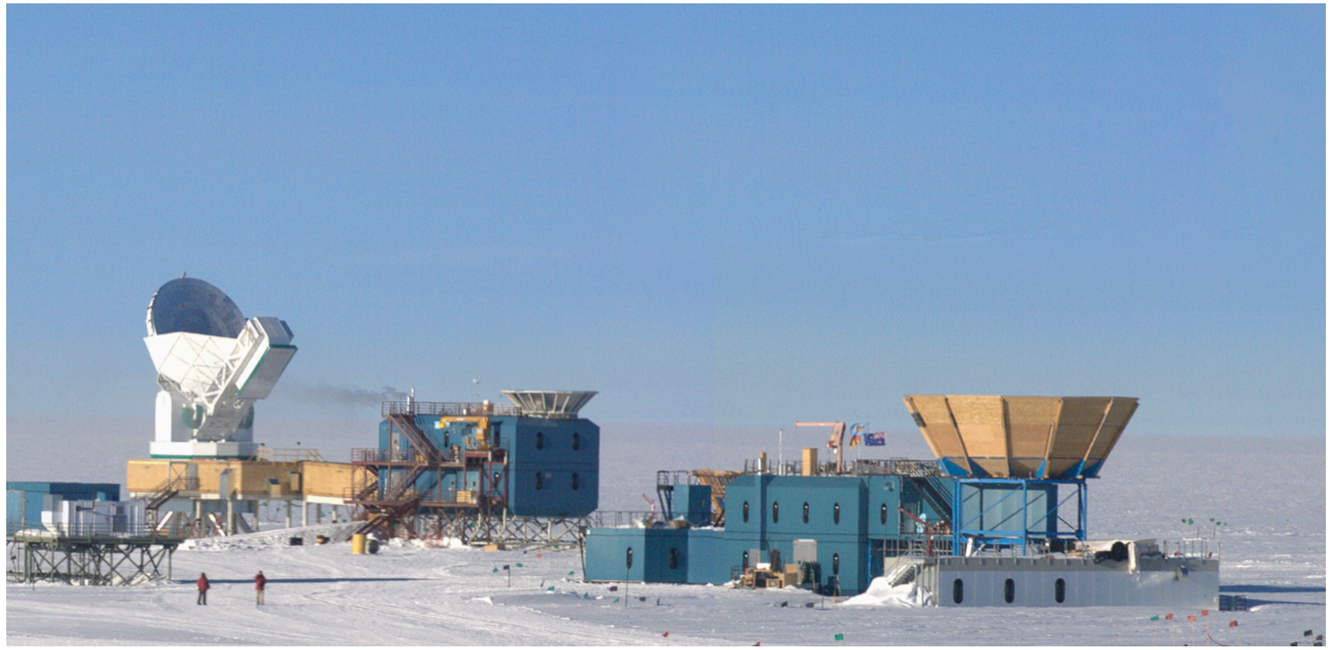
South Pole Observatory



Prabhu et al 2403.17925v3

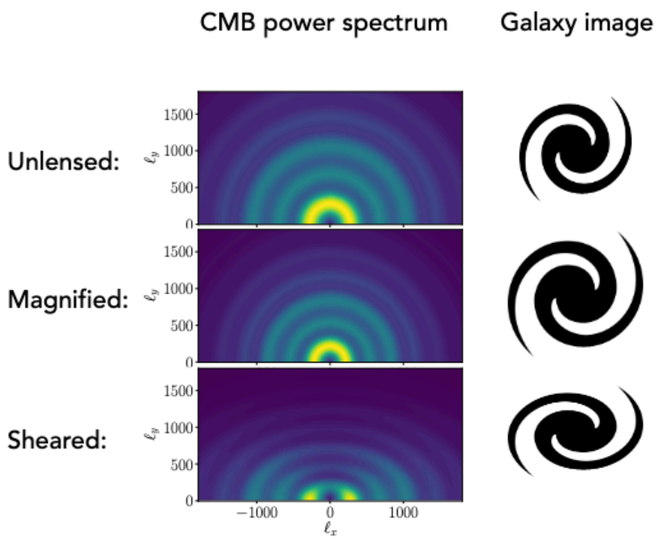
Table 1. Sky fraction and temperature white noise levels in the three bands for different SPT surveys considered in this work. The polarization white noise levels are expected to be $\sim\sqrt{2}$ times higher.

Survey	Area [deg^2]	RA center [deg]	Dec. center [deg]	Years observed	Noise level (Δ_T) [μK-arcmin]			
					95 GHz	150 GHz	220 GHz	Coadded
Completed:								
SPT-3G Main	1500	0	-57.5	2019-2023	3.0	2.5	8.9	1.9



Credit B. Benson

Lensing rec. with quadratic estimators



Schaan et al 2018

- Fixed lenses introduce statistically-anisotropic correlations:

$$\Delta\langle X_{l_1 m_1} Y_{l_2 m_2}\rangle_{\rm CMB} = \sum_{LM} (-1)^M \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \mathcal{W}^{XY}_{l_1 l_2 L} \phi_{LM}$$

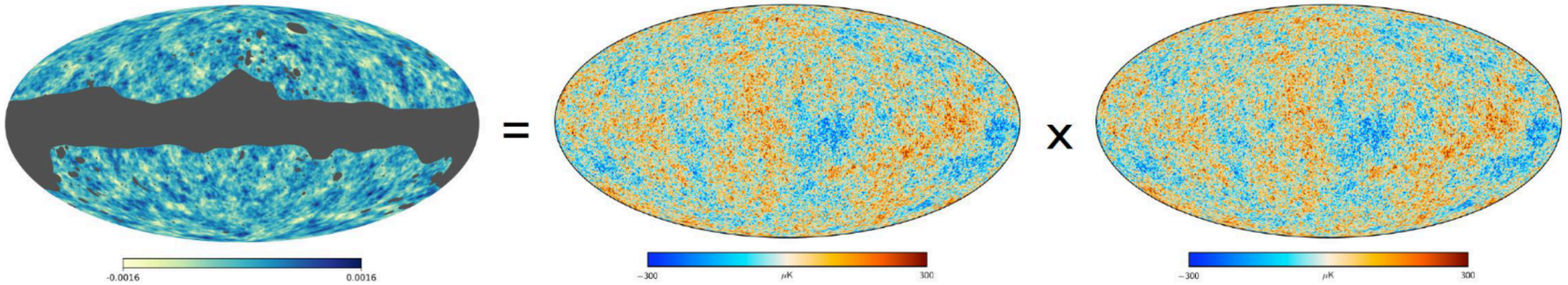
- Noisy lensing estimates from quadratic CMB combinations:

$$\hat{\phi}_{LM} = \frac{(-1)^M}{2} \frac{1}{\mathcal{R}^{XY}_L} \sum_{l_1 m_1, l_2 m_2} \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \left[\mathcal{W}^{XY}_{l_1 l_2 L}\right]^* \bar{X}_{l_1 m_1} \bar{Y}_{l_2 m_2}$$

Normalisation

Known lensing-induced correlations

Inverse-variance-weighted CMB fields



credit A. Challinor

SPT-3G Main field lensing

- Main field $\hat{\kappa}^{EB}$ is in principle the theory-land superstar estimator.

  It is the most powerful for deep data, and often sold as the most robust (since only sensitive to shear, it is immune to magnification-alike systematics). It is also the easiest in practical terms.

- Improves significantly with more Main field data, since reconstruction noise not dominated by primordial fluctuations like TT $\rightarrow EB$ domination

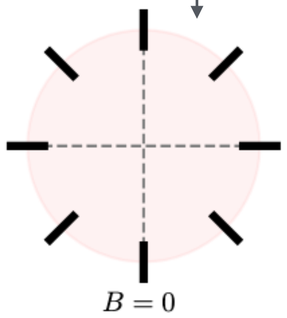
- EB QE eventually gets limited by B lensing power, but this can be de-lensed (Beyond-QE techniques). Significant improvement for the first time in SPT-3G 5 yrs data.

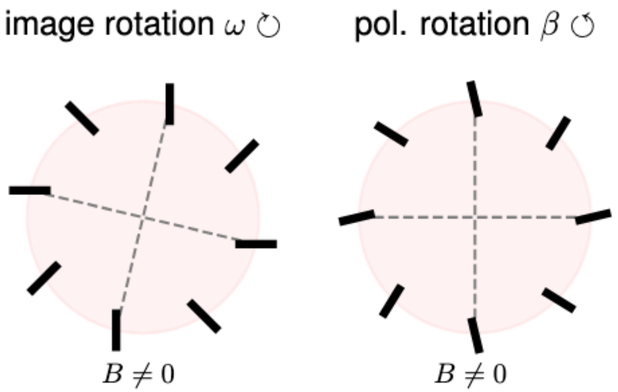
- 5yrs nominal lensing spectrum SNR pred (for beyond-QE, EB-only!) is ~66 ($\geq$ Planck + ACT + SPT-3G just out 2504.20038)

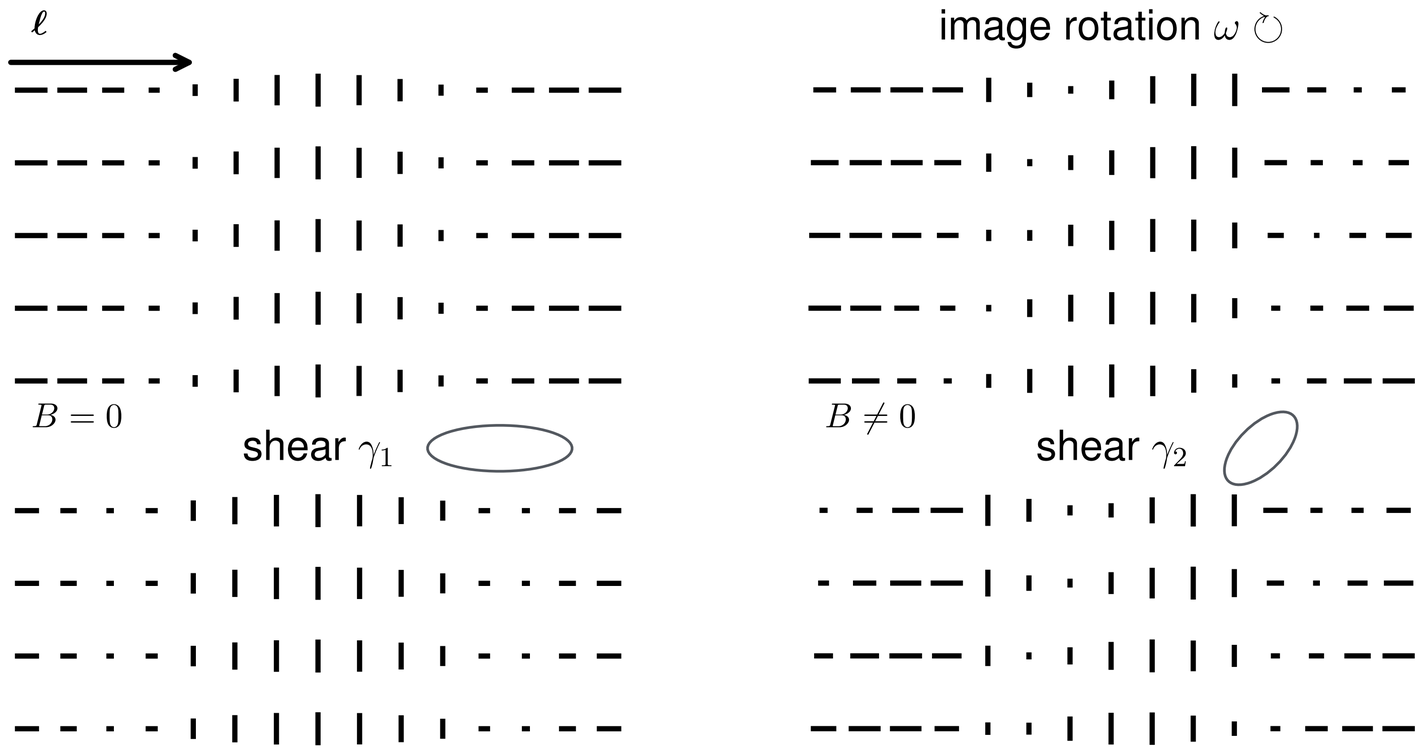
Lensing B-modes and local EB power

Squeezed limit (low lensing L, large CMB ℓ) local C_ℓ^{EB}

Pure E-mode patterns







$$\delta C_\ell^{EB} = C_\ell^{EE}\left(-2\omega - 2\beta + 2\gamma\sin(2(\phi_\gamma - \phi_\ell))\right)$$

Lensing rotation — Pol. rotation — Lensing local shear, anisotropic squashing

No B-modes from convergence κ. EB is « shear-only »

Beyond-QE lensing reconstruction

Idea could not be simpler: extract residual lensing with a new QE on delensed maps, and iterate.

Implementation: tweaked likelihood-based reconstruction:

- « Optimal » estimator of residual lensing (« beyond-ϕ lensing») JC 2025 2502.02399

$$\delta \nabla \hat{\phi} \propto |A(\hat{n})| \left[\bar{B}(\hat{n} + \nabla \phi(\hat{n}))\, \nabla E^{\rm del}(\hat{n} + \nabla \phi(\hat{n}))\right]$$

Magnification (coordinate distortions from delensing)

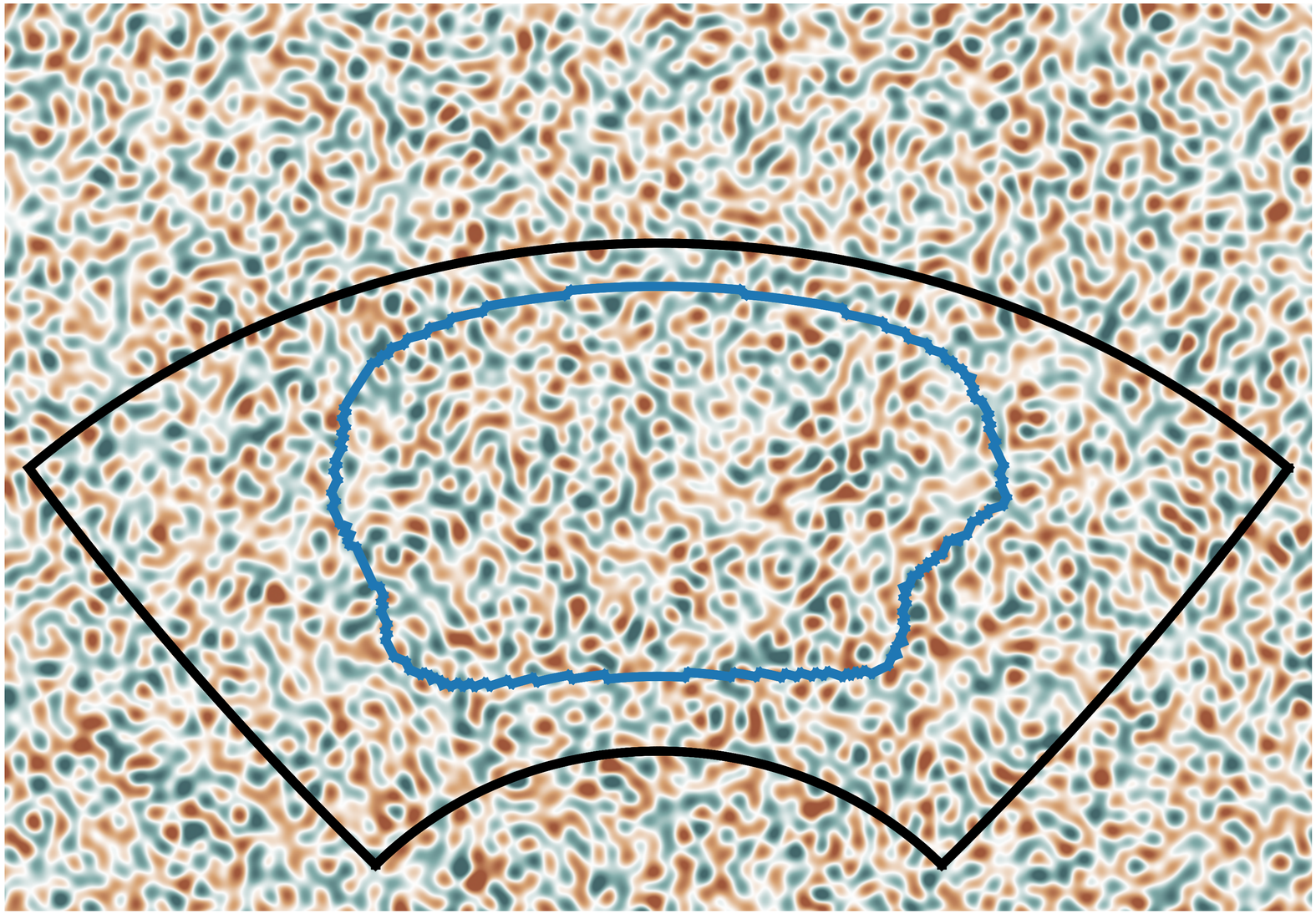
Deflected QE on maps delensed by ϕ

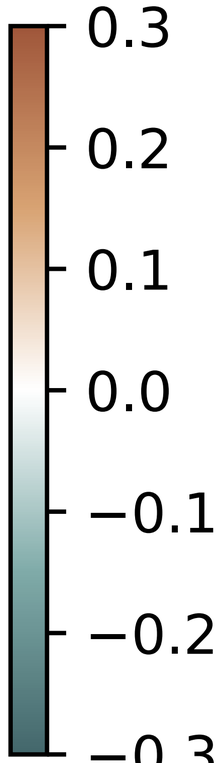
(+ mean-field corrections from non-idealities, including delensed-noise anisotropies) Legrand & JC 2025

B^{input}

SPT-3G

BICEP/Keck

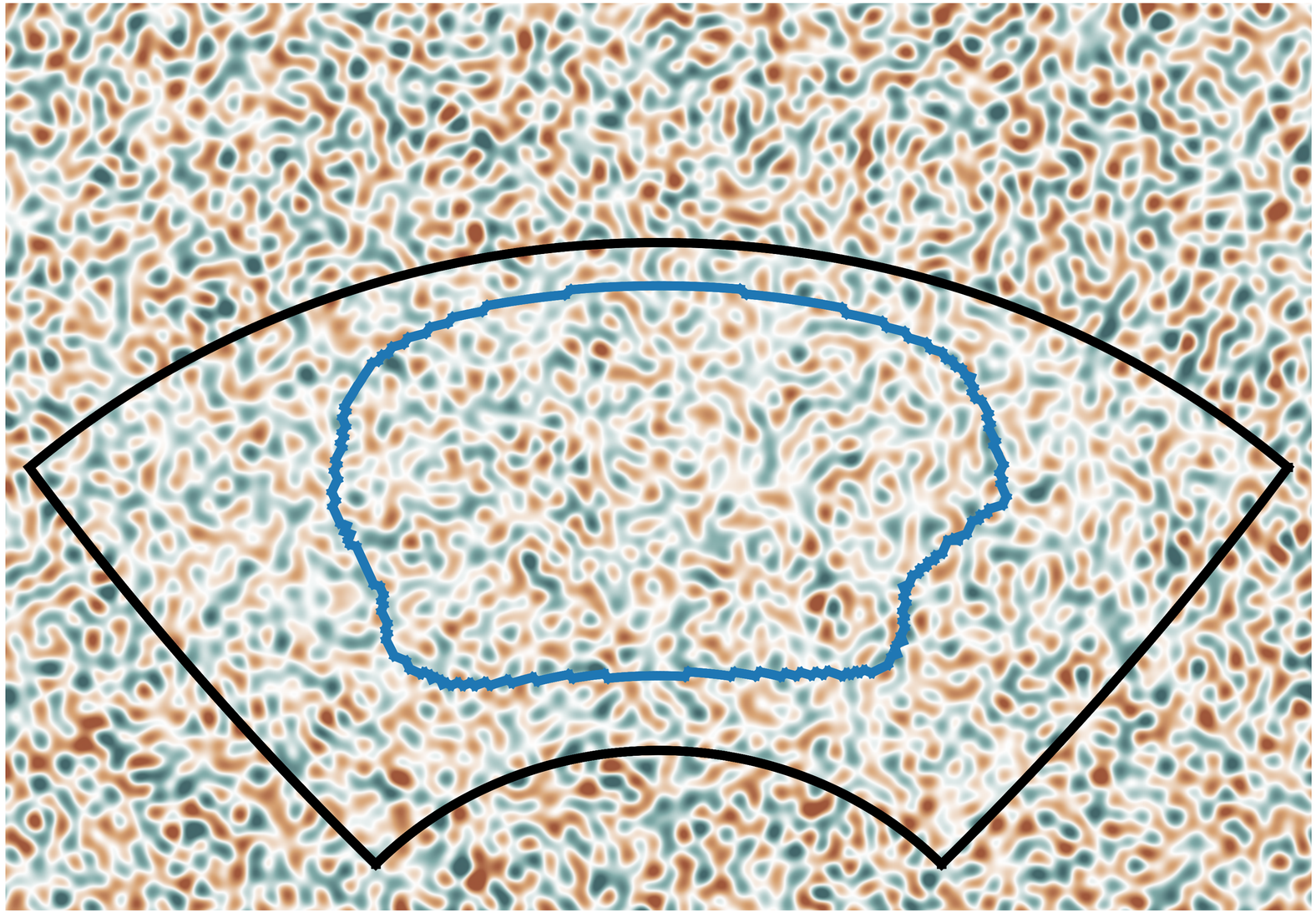


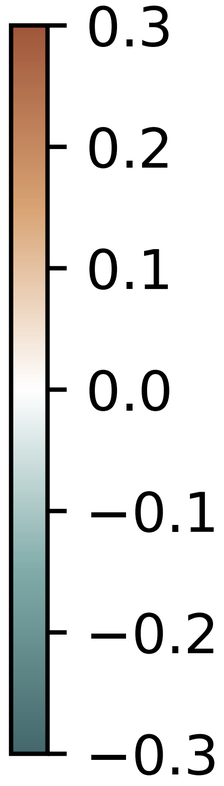


B^{delensed} (iter 0)

SPT-3G

BICEP/Keck

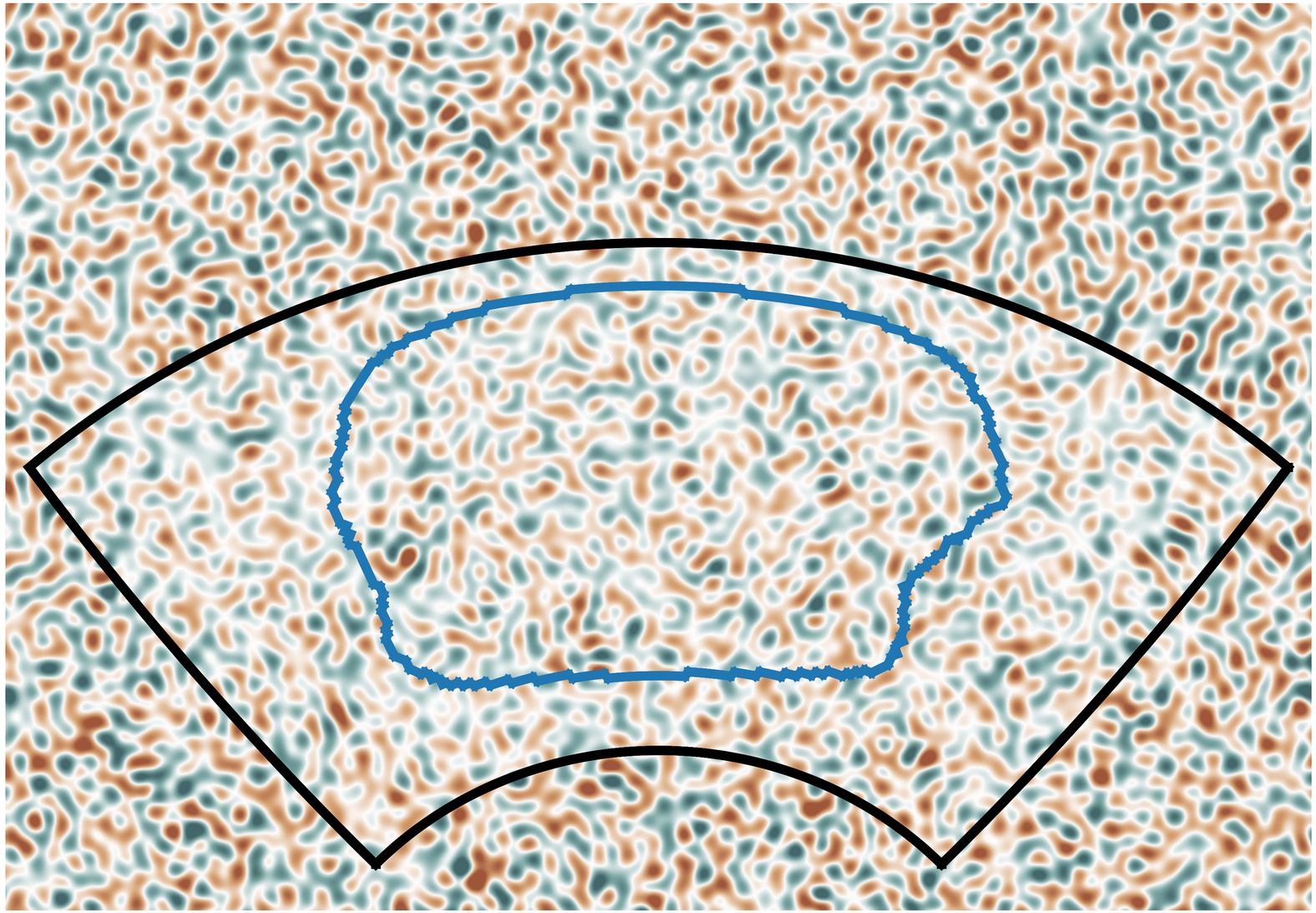


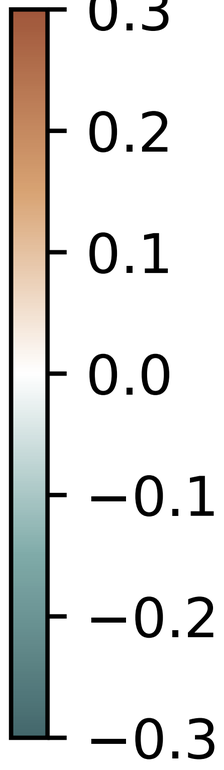


B^{delensed} (iter 1)

SPT-3G

BICEP/Keck

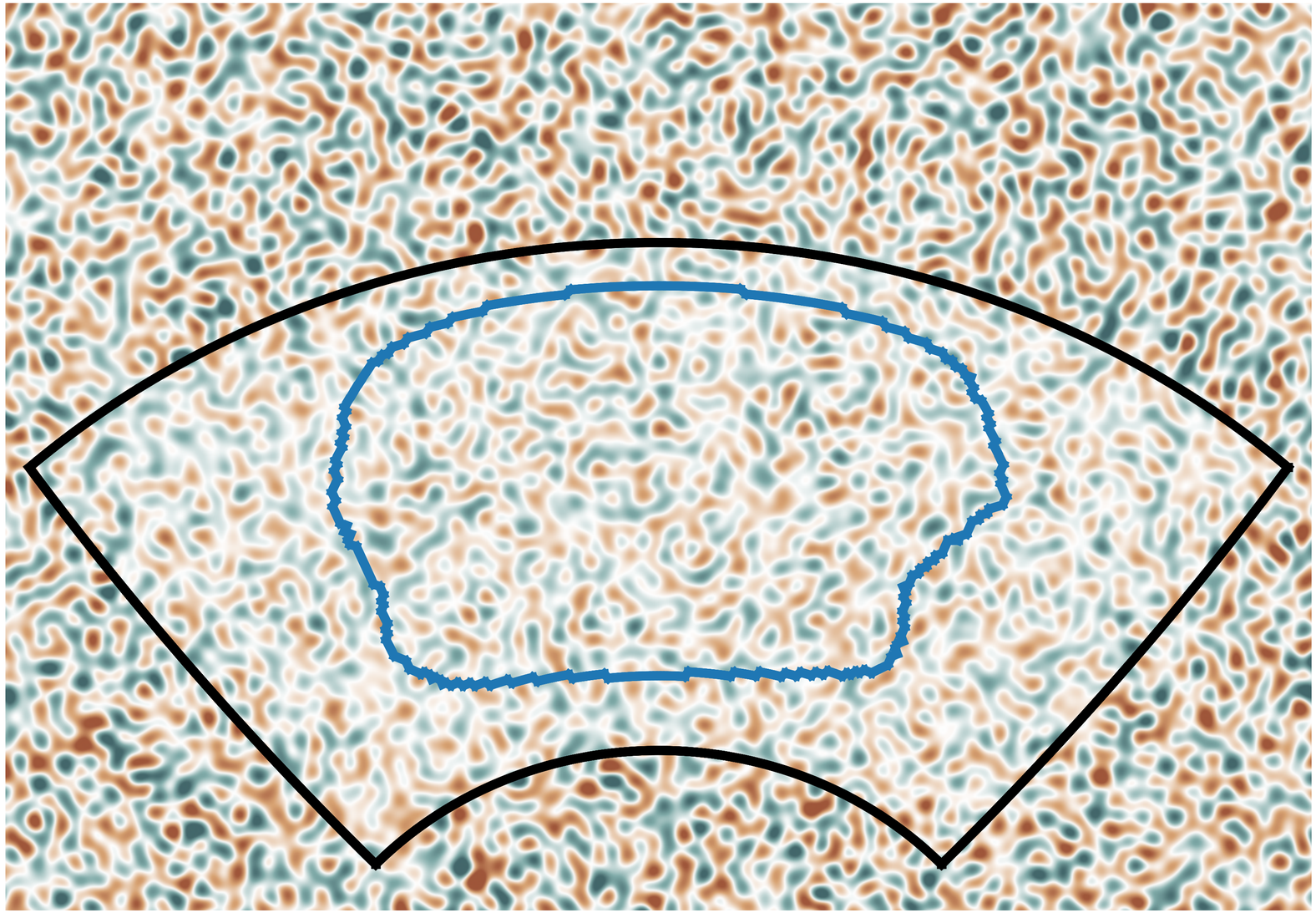


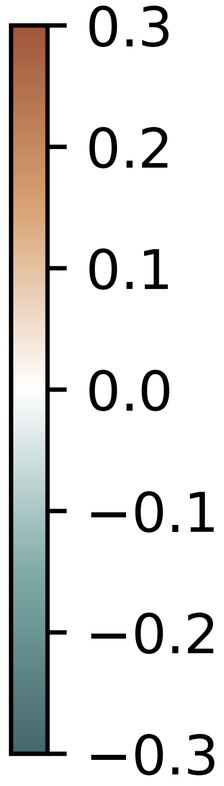


B^{delensed} (iter 2)

SPT-3G

BICEP/Keck

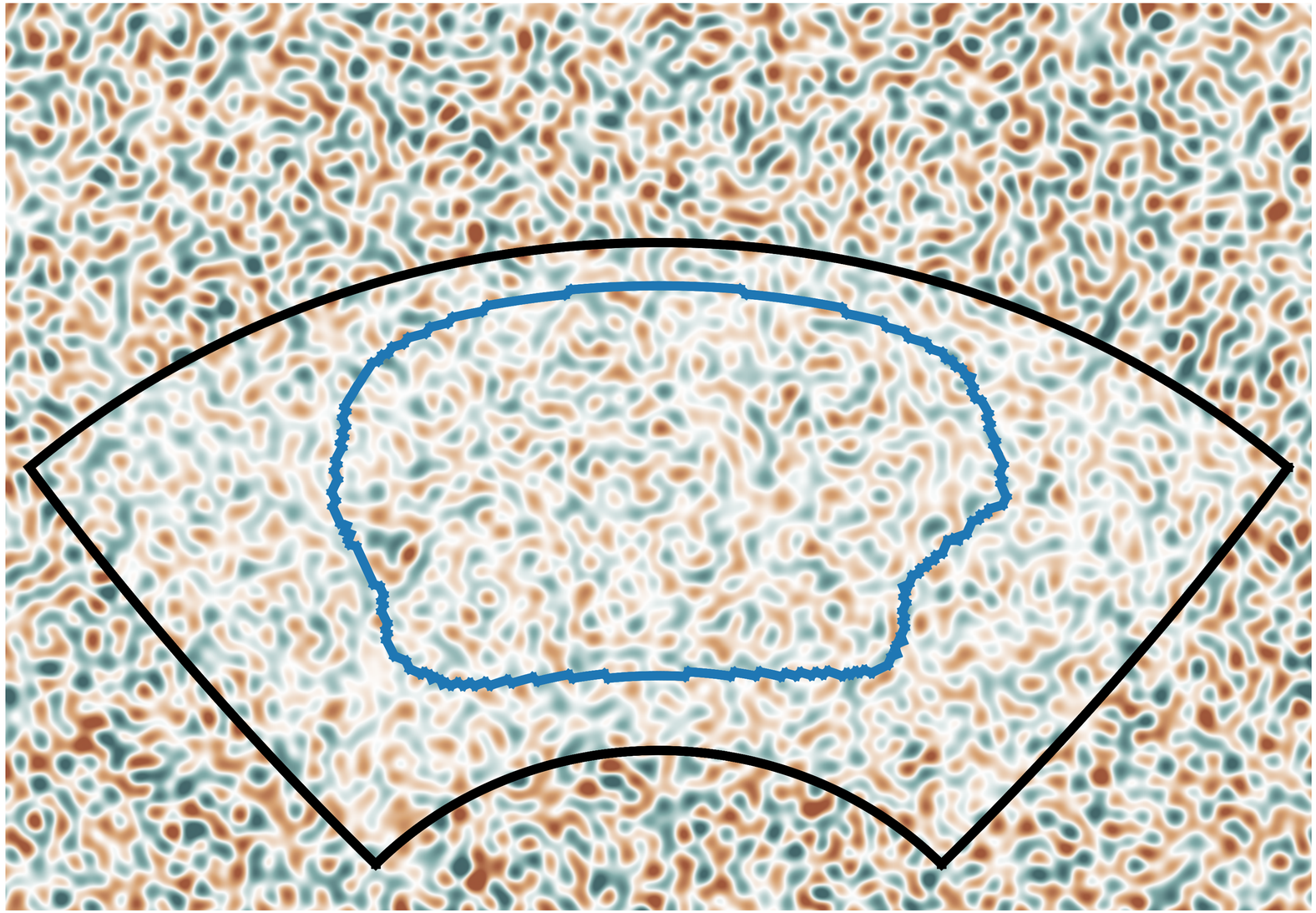


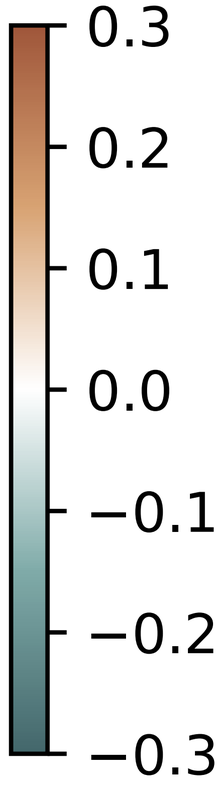


B^{delensed} (iter 3)

SPT-3G

BICEP/Keck

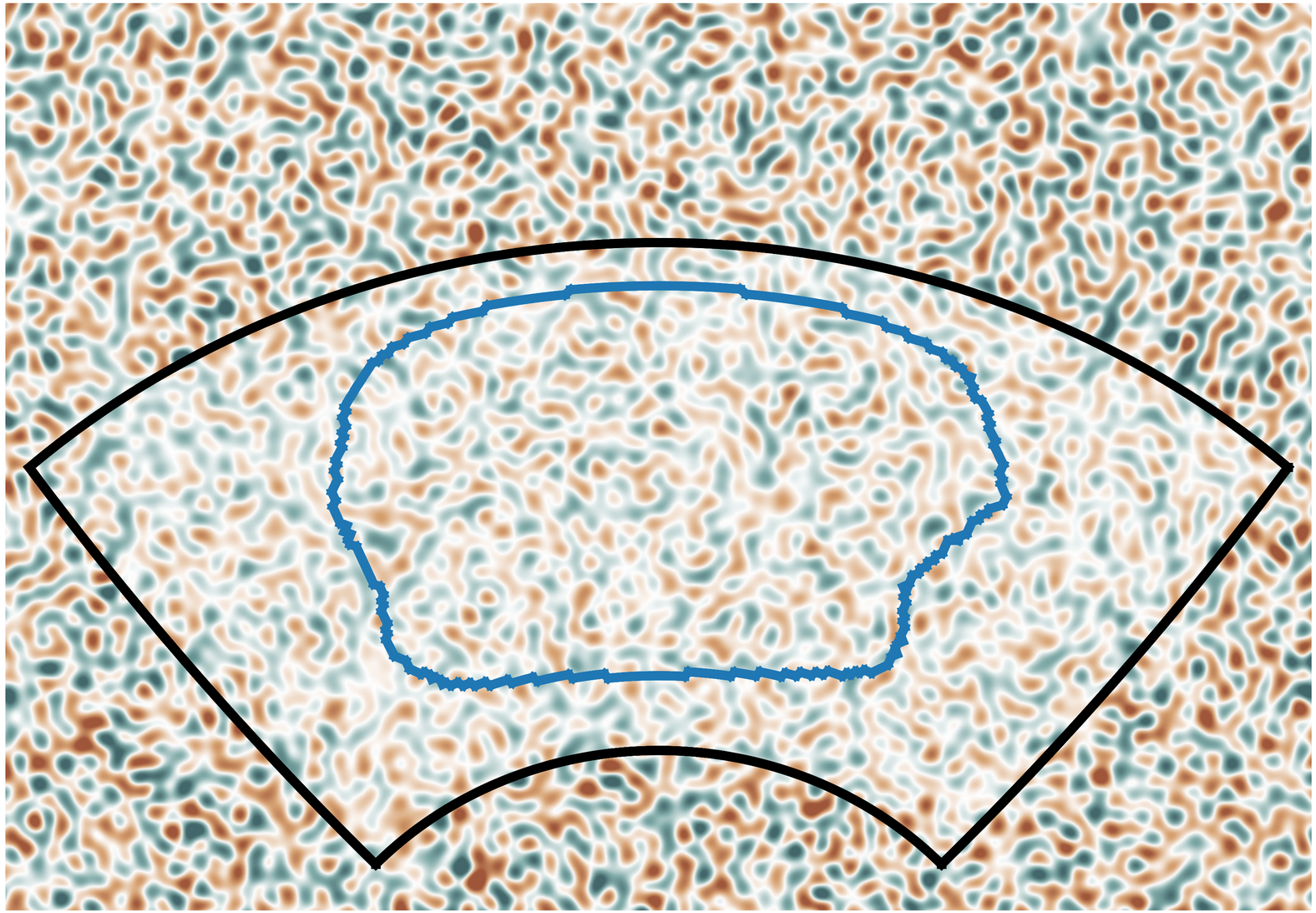


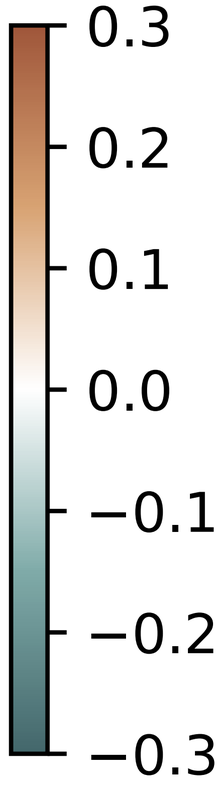


B^{delensed} (iter 4)

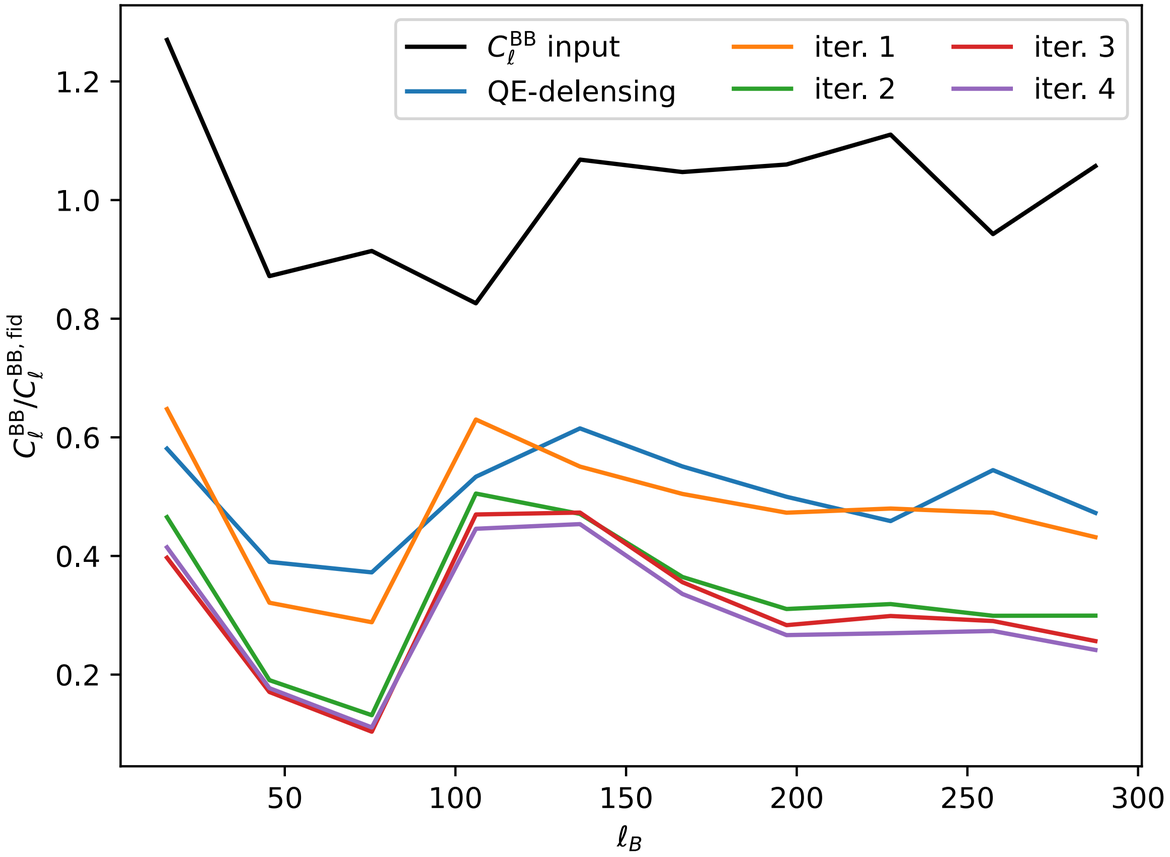
SPT-3G

BICEP/Keck

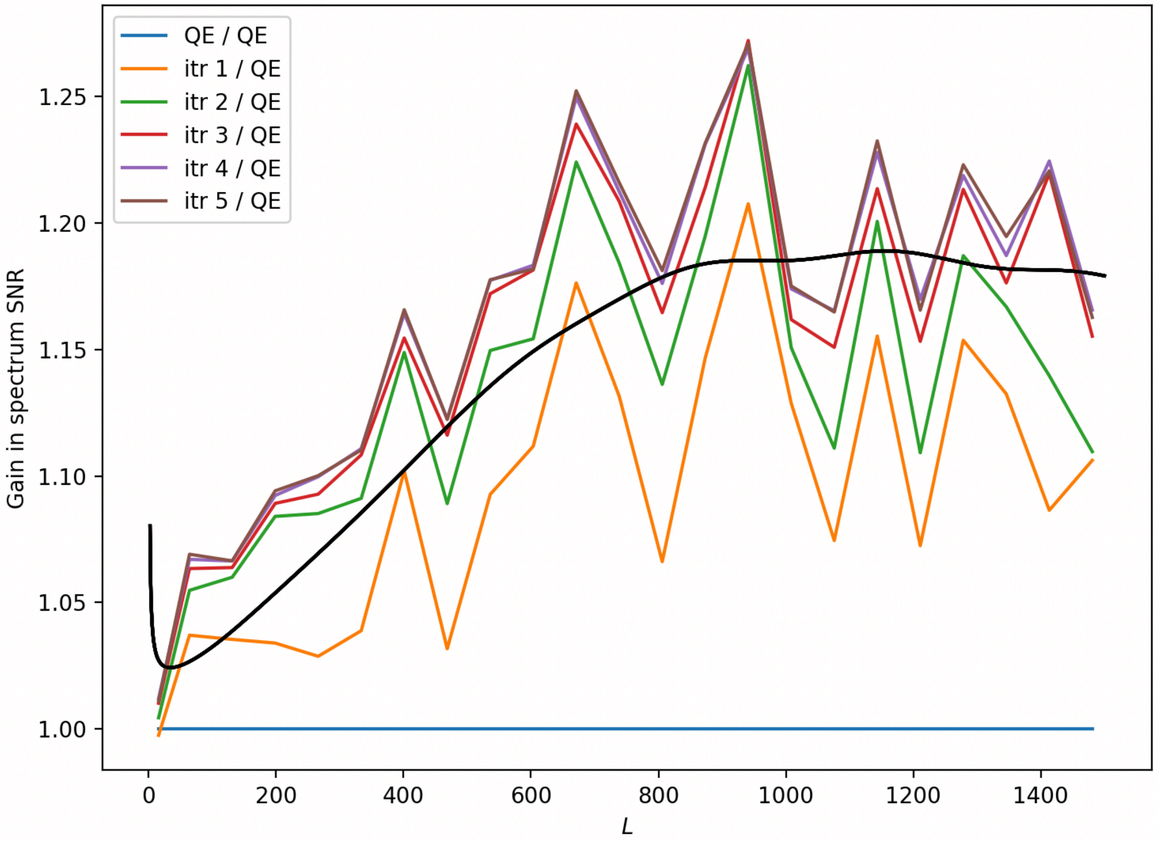




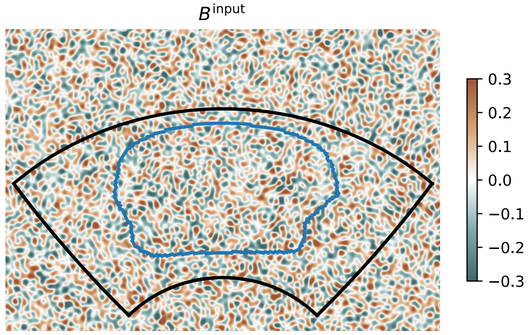
Residual lensing power



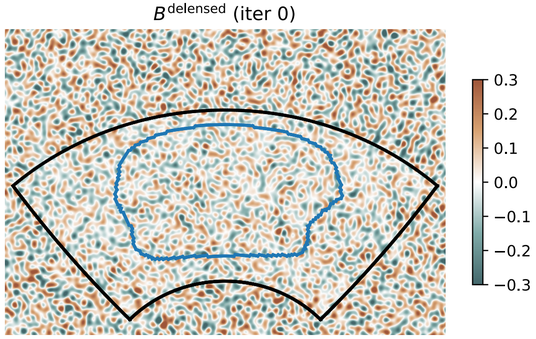
Improvement in lensing spectrum SNR



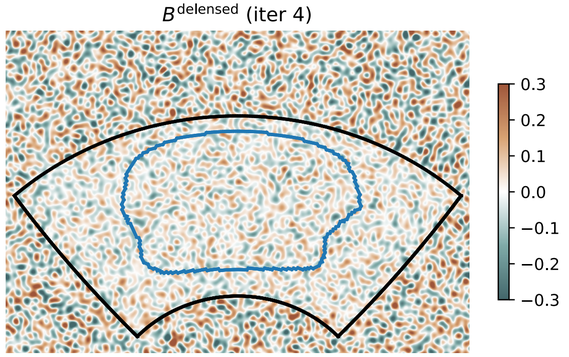
Input



QE



bQE



Conclusions

- CMB B-modes provide a unique probe of a background of primordial gravitational wave from inflation, focussing very large efforts from the CMB community

- The top constraints are now limited by gravitational lensing effects on the CMB.

- BICEP/Keck + SPT-3G now available data has potential for $\sigma(r) \sim 0.003$ (3x better than BK18), and delensing is essential to achieve this.

- *« … everybody said that curved sky iterated lensing reconstruction was too hard or impossible »*
  (Well-known top figure in r-constraints business, pers. comm.)
  → this has been done (see Belkner et al 2024 +) and works now for SPT-3G better than ever

- These (and other upcoming) lensing maps will also have much larger statistical power on the growth of structure, and be most useful in cross-correlation to large-scale structure surveys.