

De-lensing the CMB to constrain primordial gravitational waves from the South Pole

Julien Carron, 28.10.2025



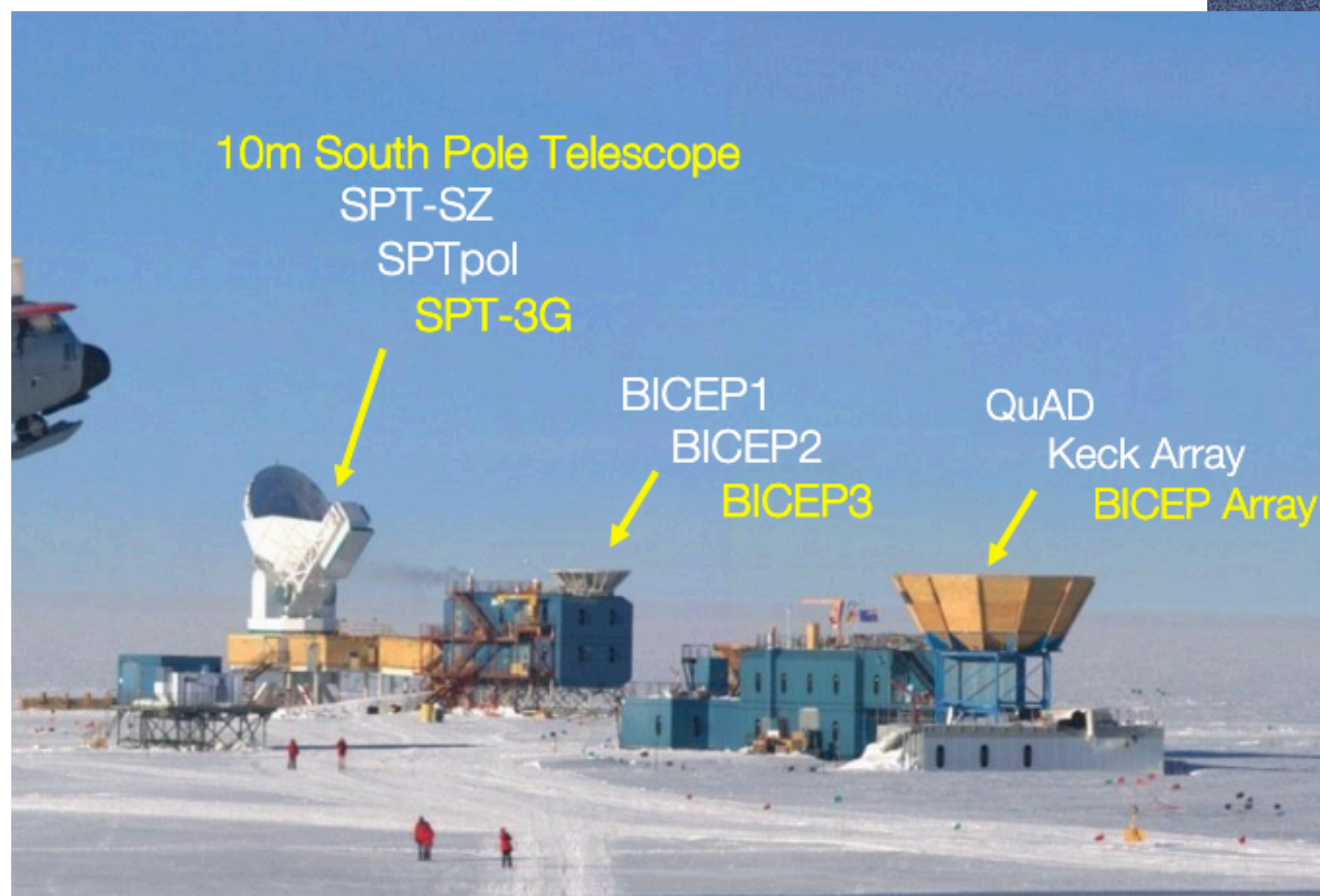
**UNIVERSITÉ
DE GENÈVE**
FACULTÉ DES SCIENCES

US
UNIVERSITY
OF SUSSEX

South Pole Observatory
= SPT-3G + BICEP/Keck



SPO F2F in Chicago, October 2025

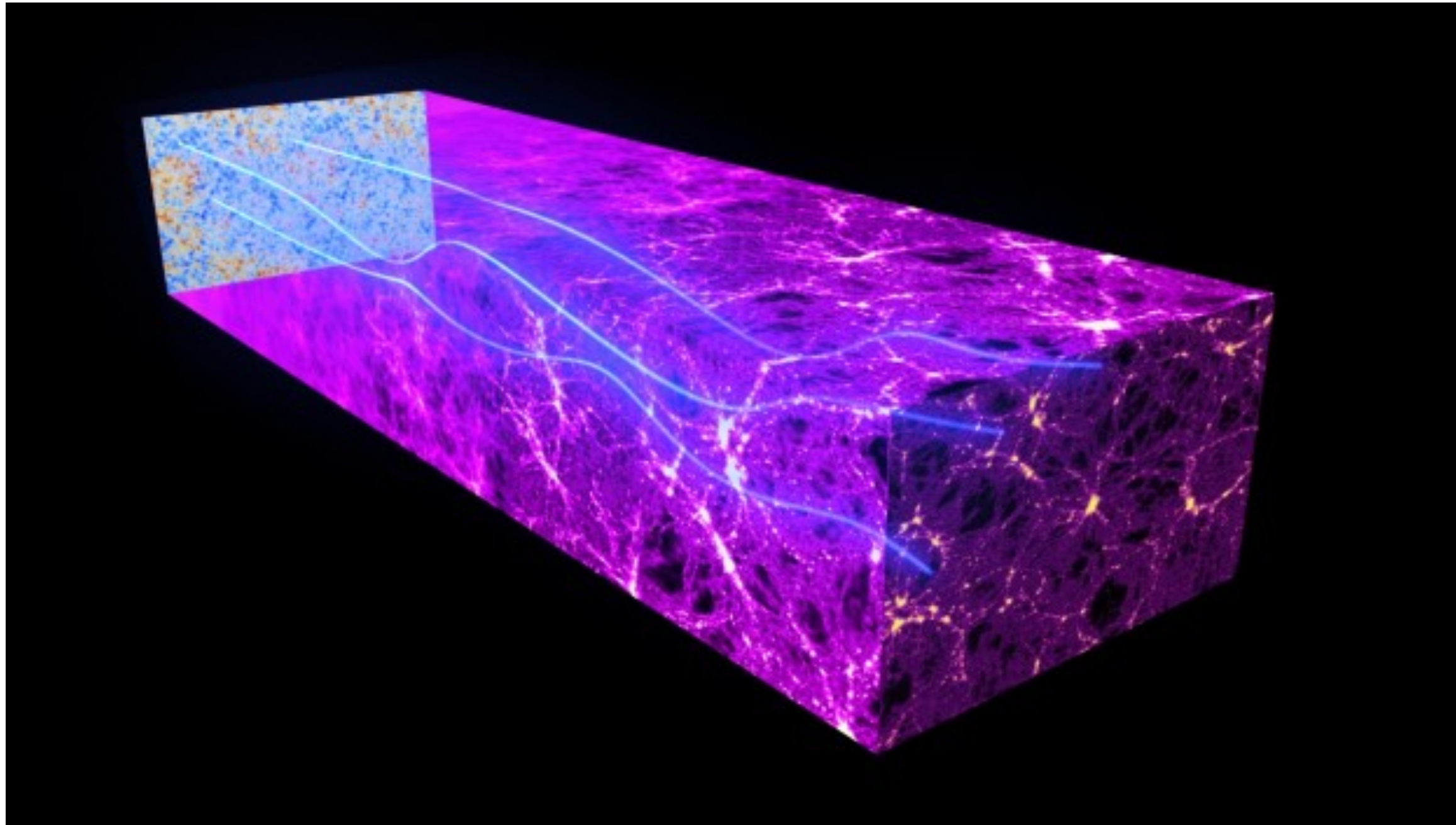


Work from within SPT-3G / the South Pole Observatory (SPO)

Outline

- Quick review of CMB lensing with the help of recent results / prospects
- De-lensing the CMB to constrain primordial gravitational waves from the South Pole.
 1. De-lensing for inflation, context
 2. Faster Spherical Harmonic Transforms on small sky fractions JC & Reinecke in prep.
 3. Porting the Quadratic Estimator (QE) toolbox to « beyond-QE » lensing estimation
JC & 2025

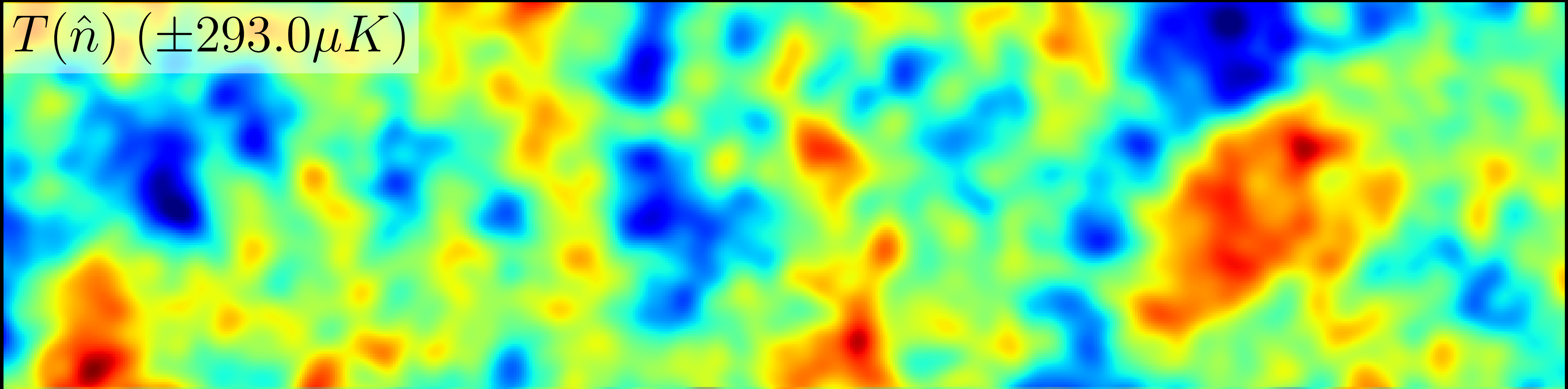
CMB Lensing



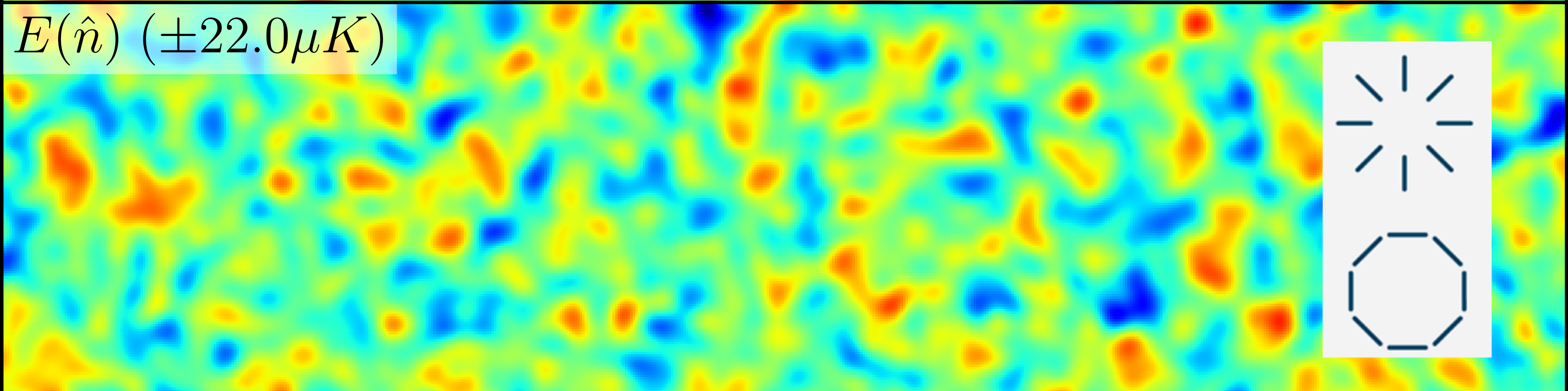
$$\phi(\hat{n}) = -2 \int_0^{\chi_*} d\chi \left(\frac{\chi_* - \chi}{\chi \chi_*} \right) \Psi(\hat{n}, \chi)$$

- Deflections α of a few arcmin by ~ 100 Mpc sized lenses, $\alpha = \nabla \phi$, coherent over a few degrees
- Leading non-Gaussian effect on the CMB (large trispectrum)
- Lensing spectrum a mostly linear probe, well understood source plane, negligible baryonic feedback...

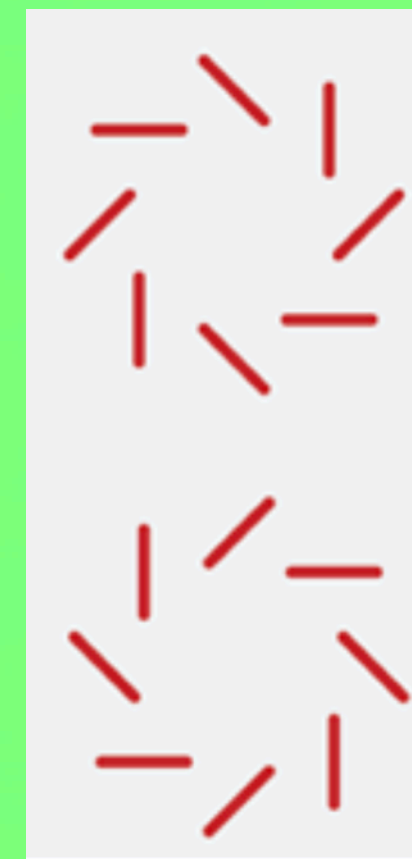
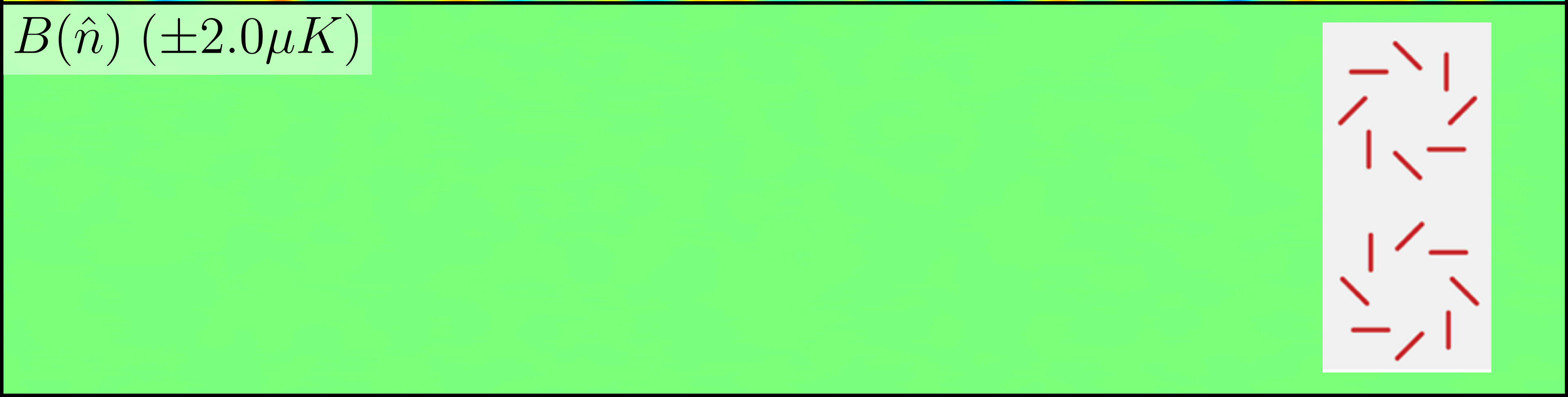
$T(\hat{n})$ ($\pm 293.0\mu K$)



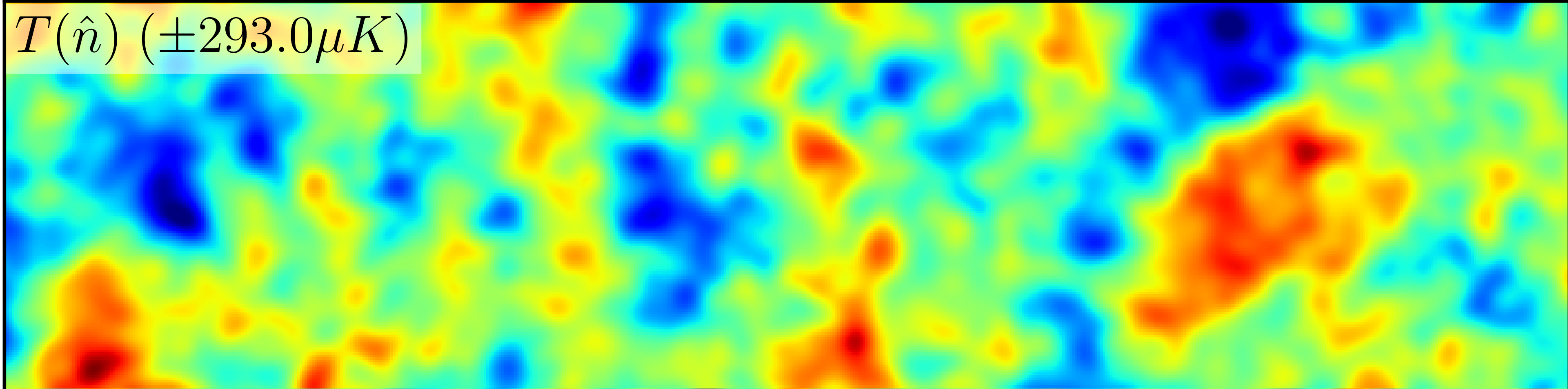
$E(\hat{n})$ ($\pm 22.0\mu K$)



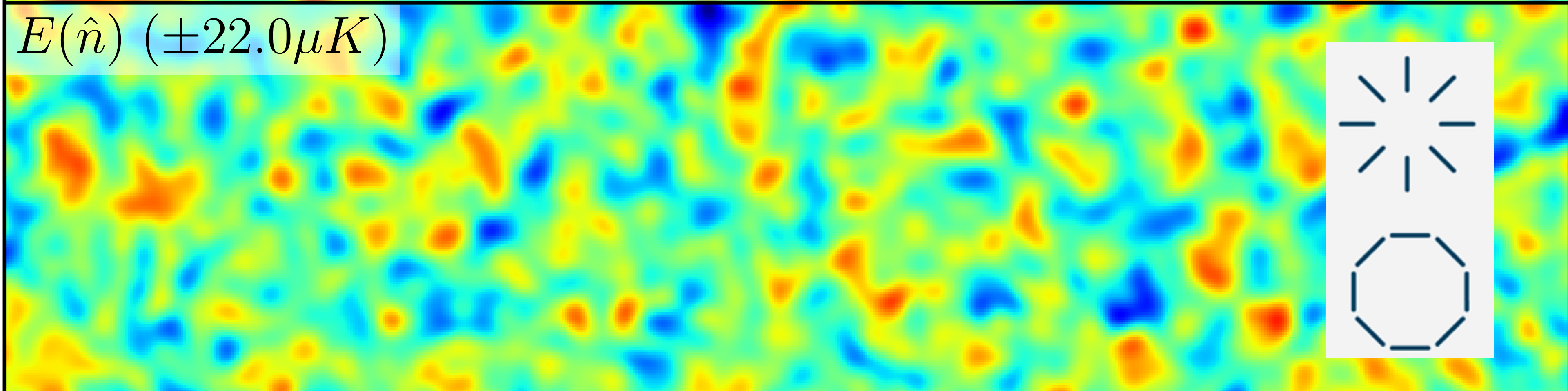
$B(\hat{n})$ ($\pm 2.0\mu K$)



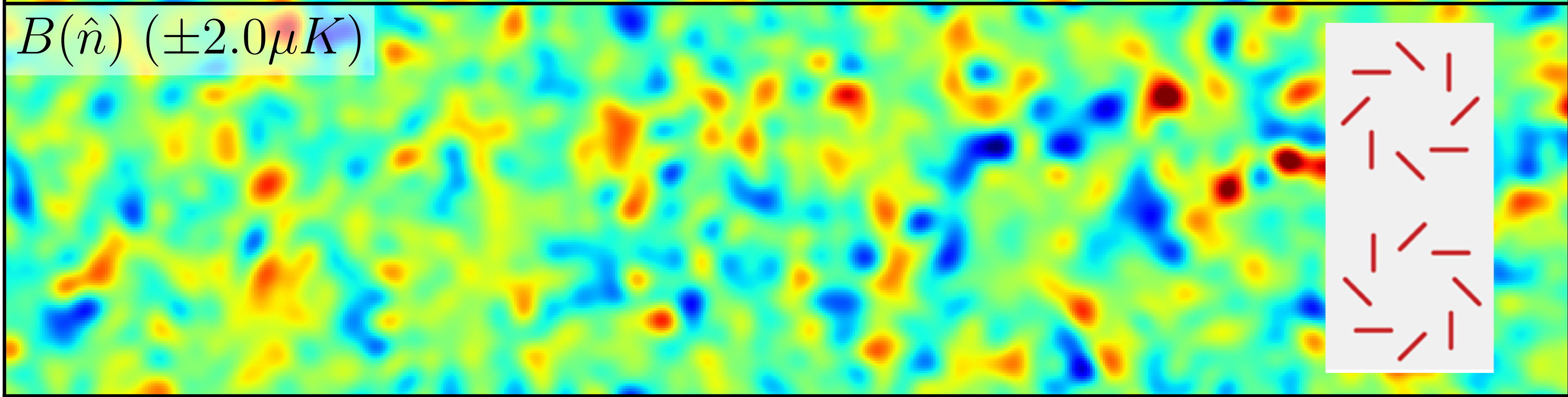
$T(\hat{n})$ ($\pm 293.0\mu K$)



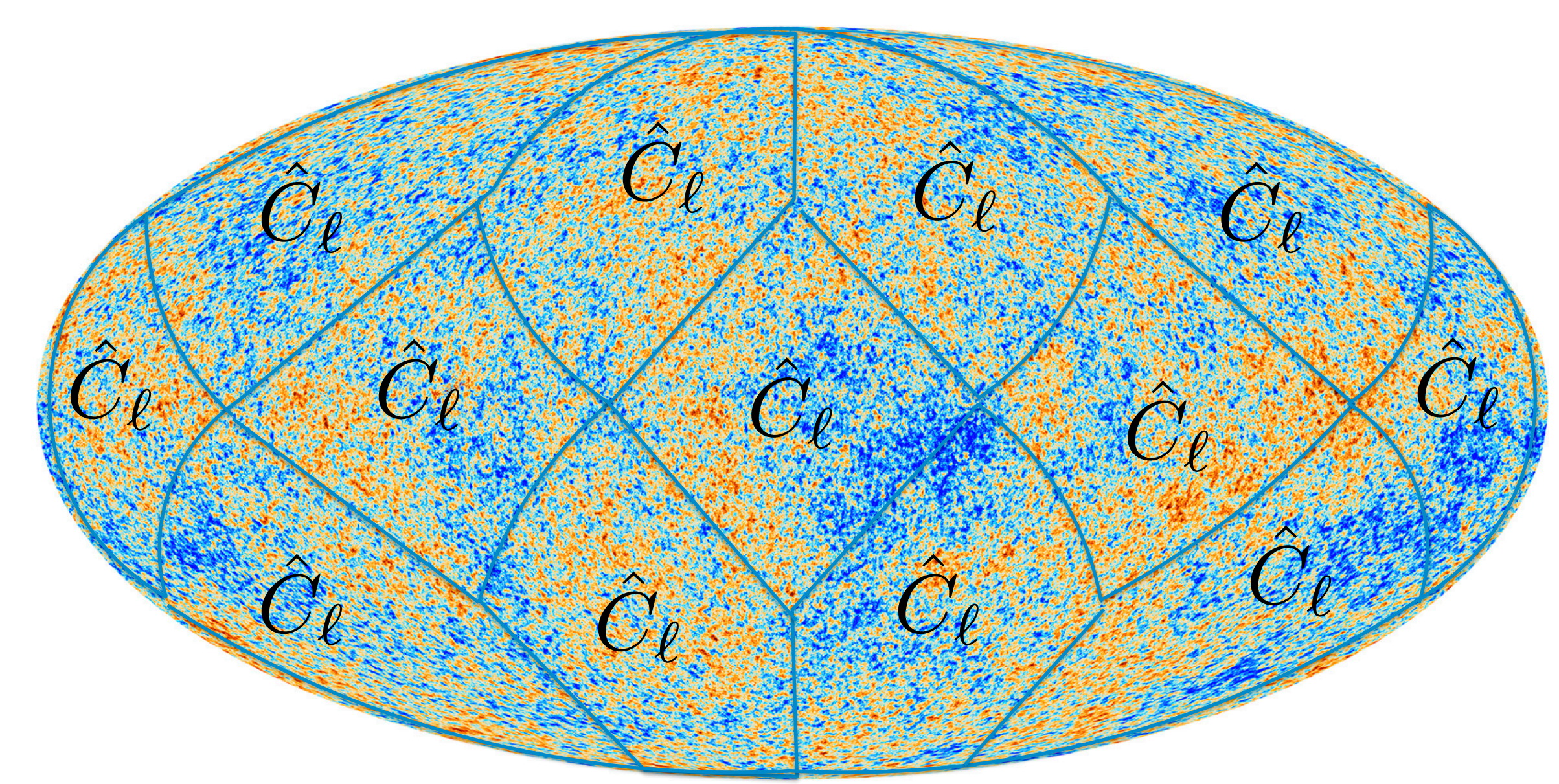
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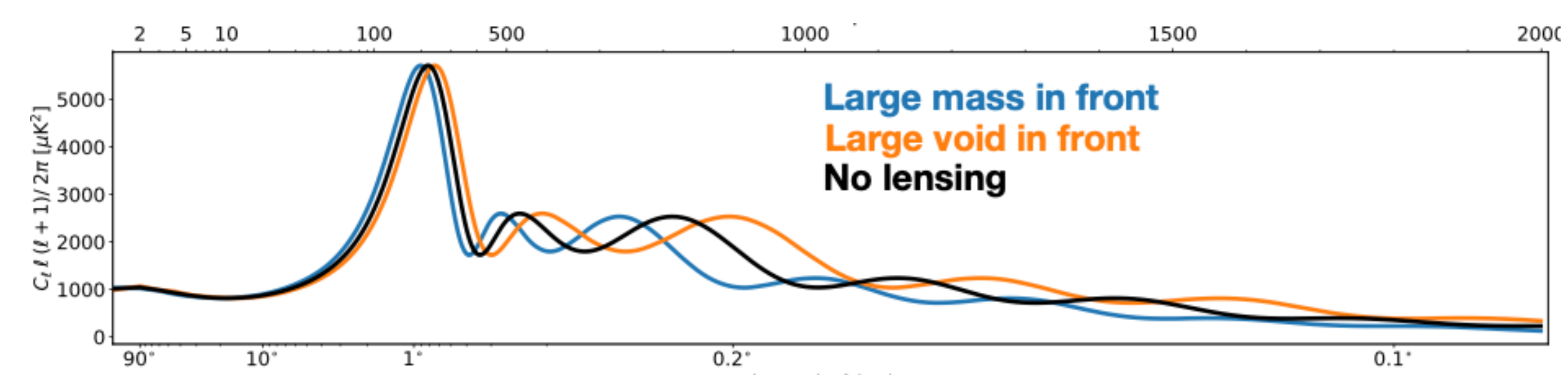
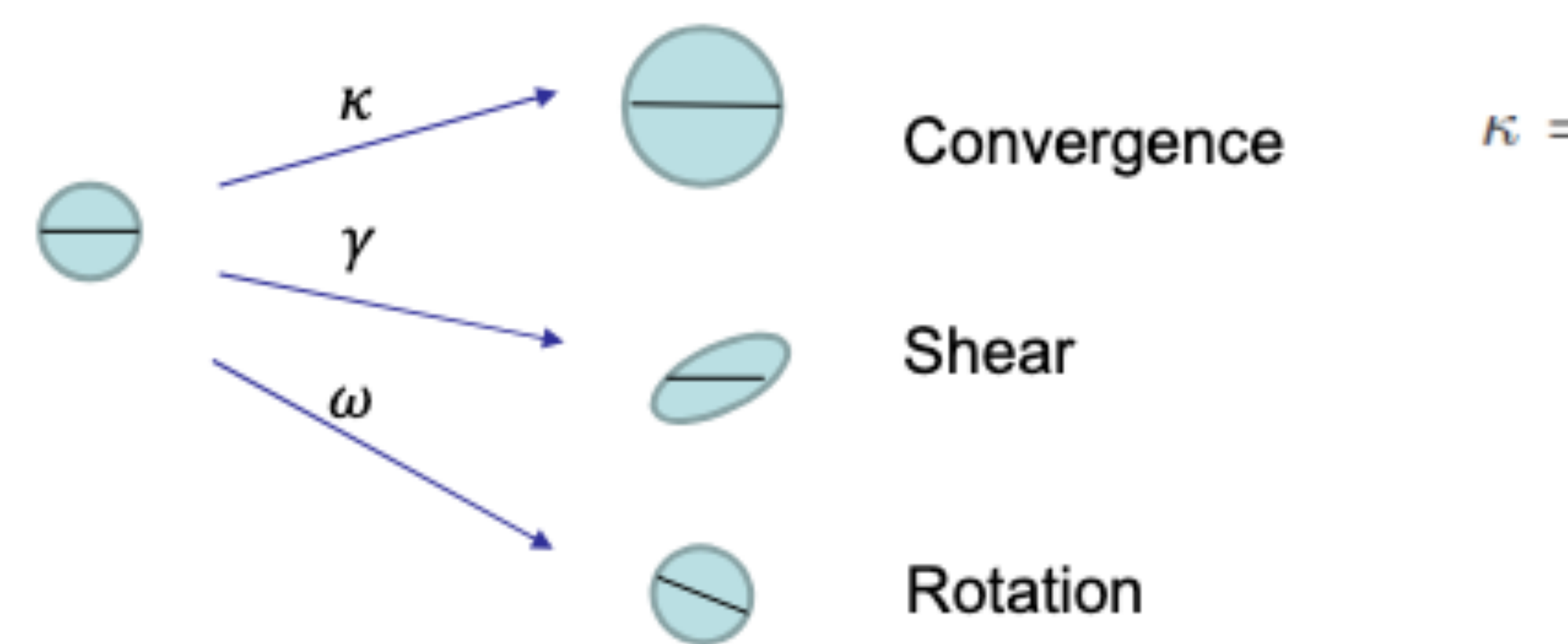
$B(\hat{n})$ ($\pm 2.0\mu K$)



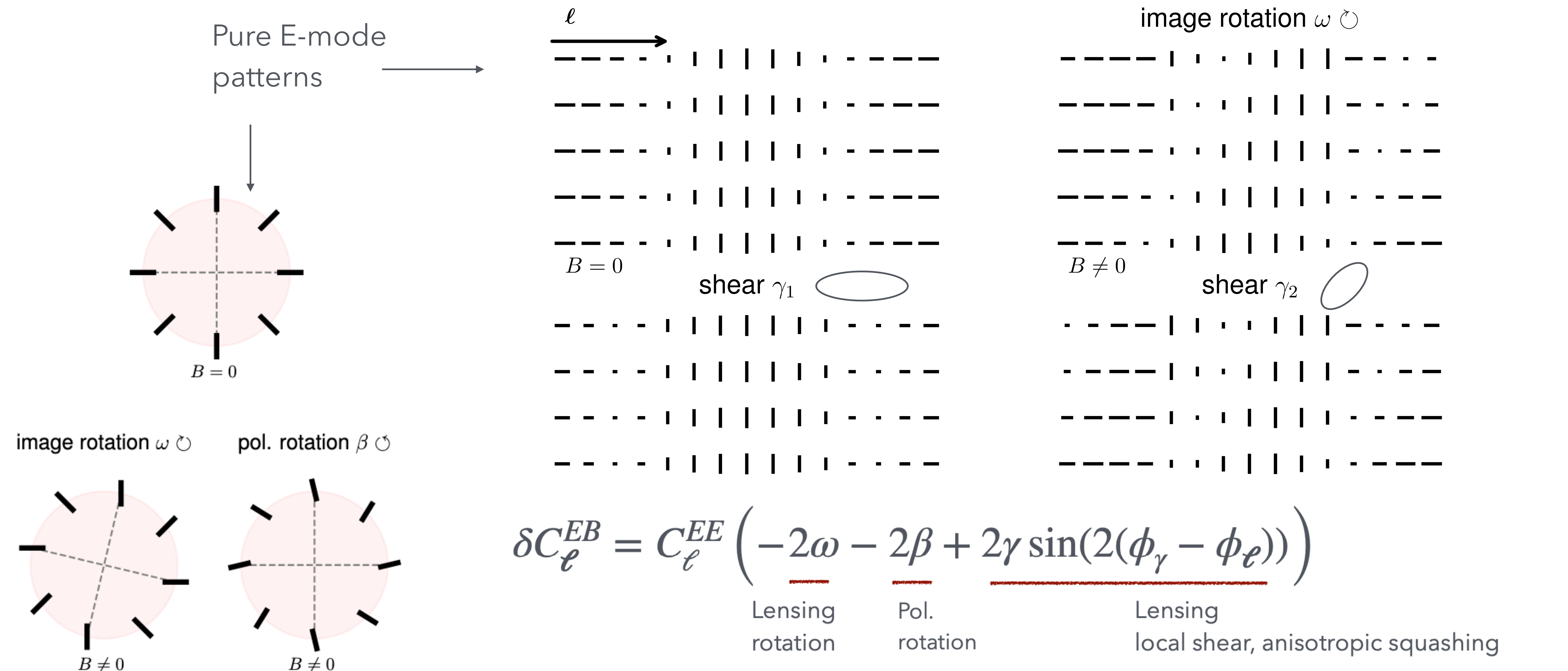
Local changes to CMB power



$$A_{ij} \equiv \delta_{ij} + \frac{\partial}{\partial \theta_i} \alpha_j = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 + \omega \\ -\gamma_2 - \omega & 1 - \kappa + \gamma_1 \end{pmatrix}$$



Local CMB EB power, lensing B-modes



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

Quadratic lensing estimation

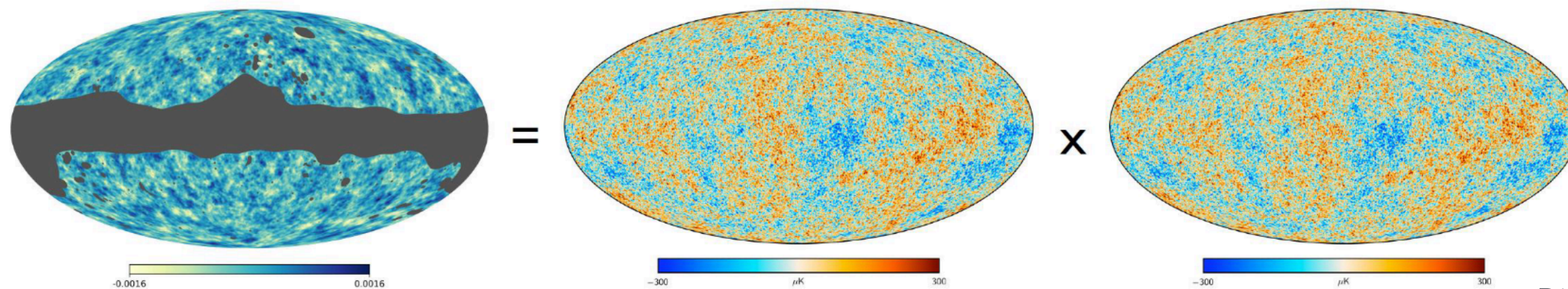
- Fixed lenses introduce statistically-anisotropic correlations:

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

- Noisy lensing estimates from quadratic CMB combinations:

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

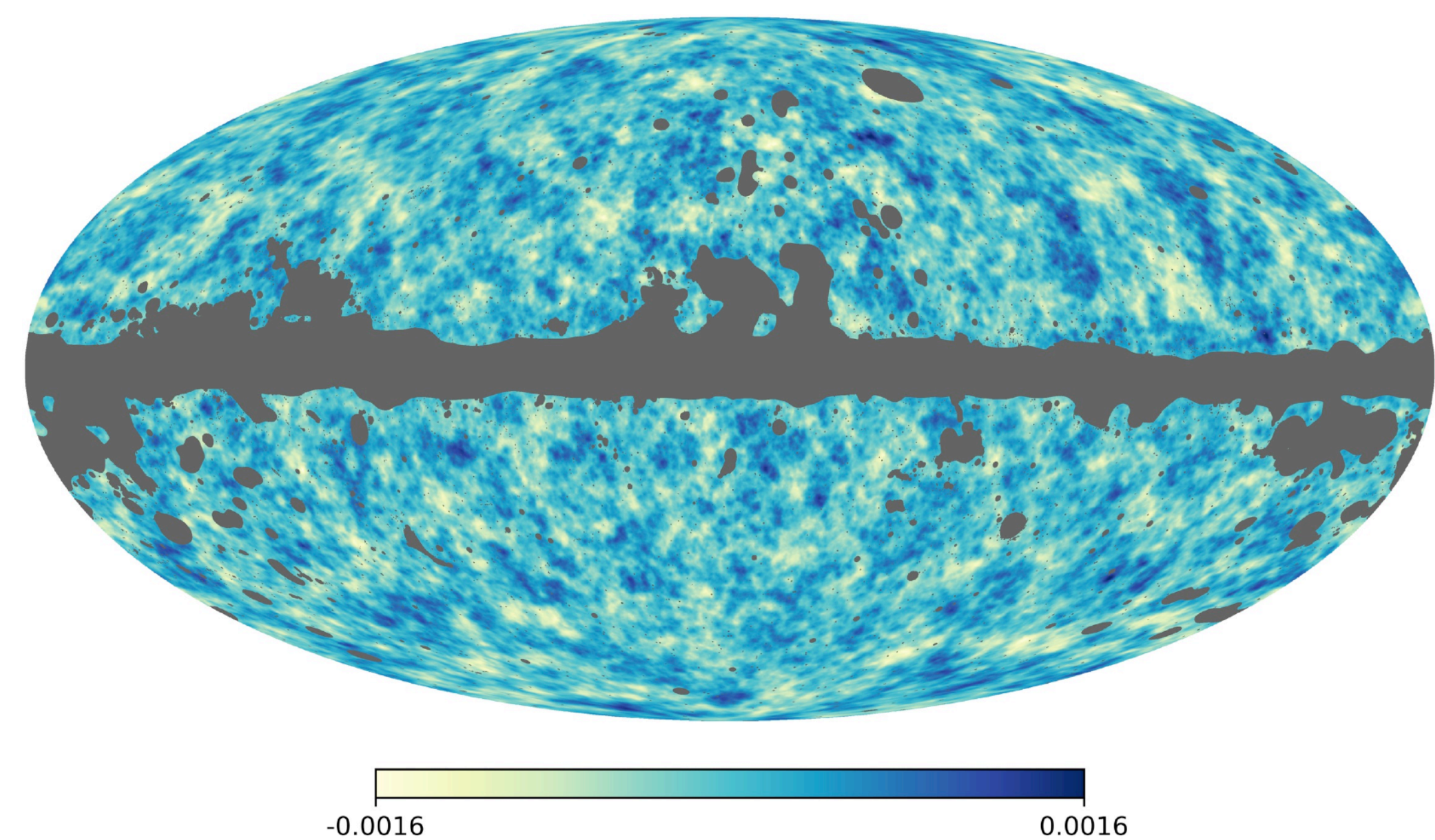
Normalisation
Known lensing-induced correlations
Inverse-variance-weighted CMB fields



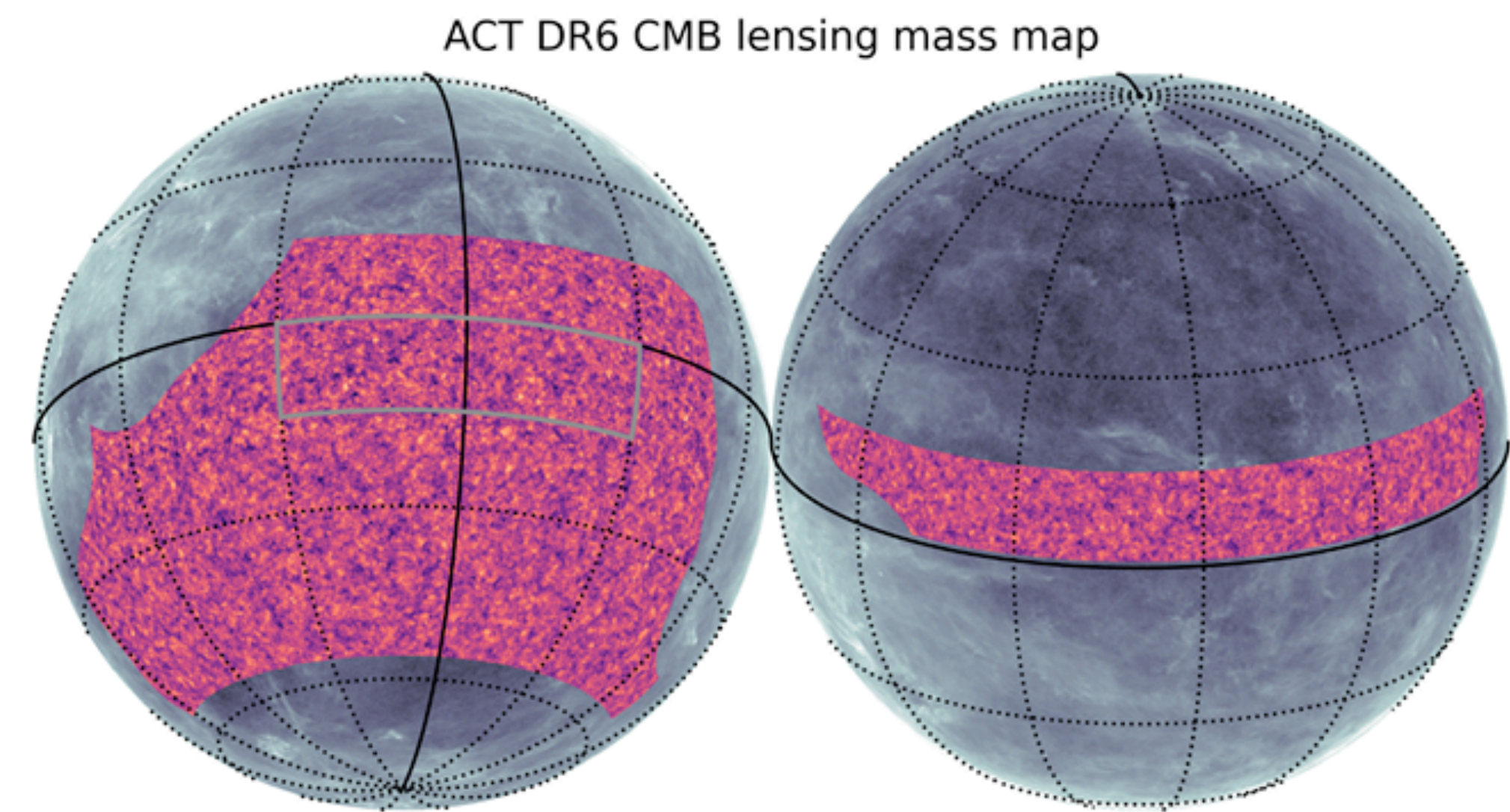
Bispectrum expansions
 Schaan & Ferraro 2018 (flat-sky)
 JC & Lewis 2024 (curved-sky)

credit A. Challinor

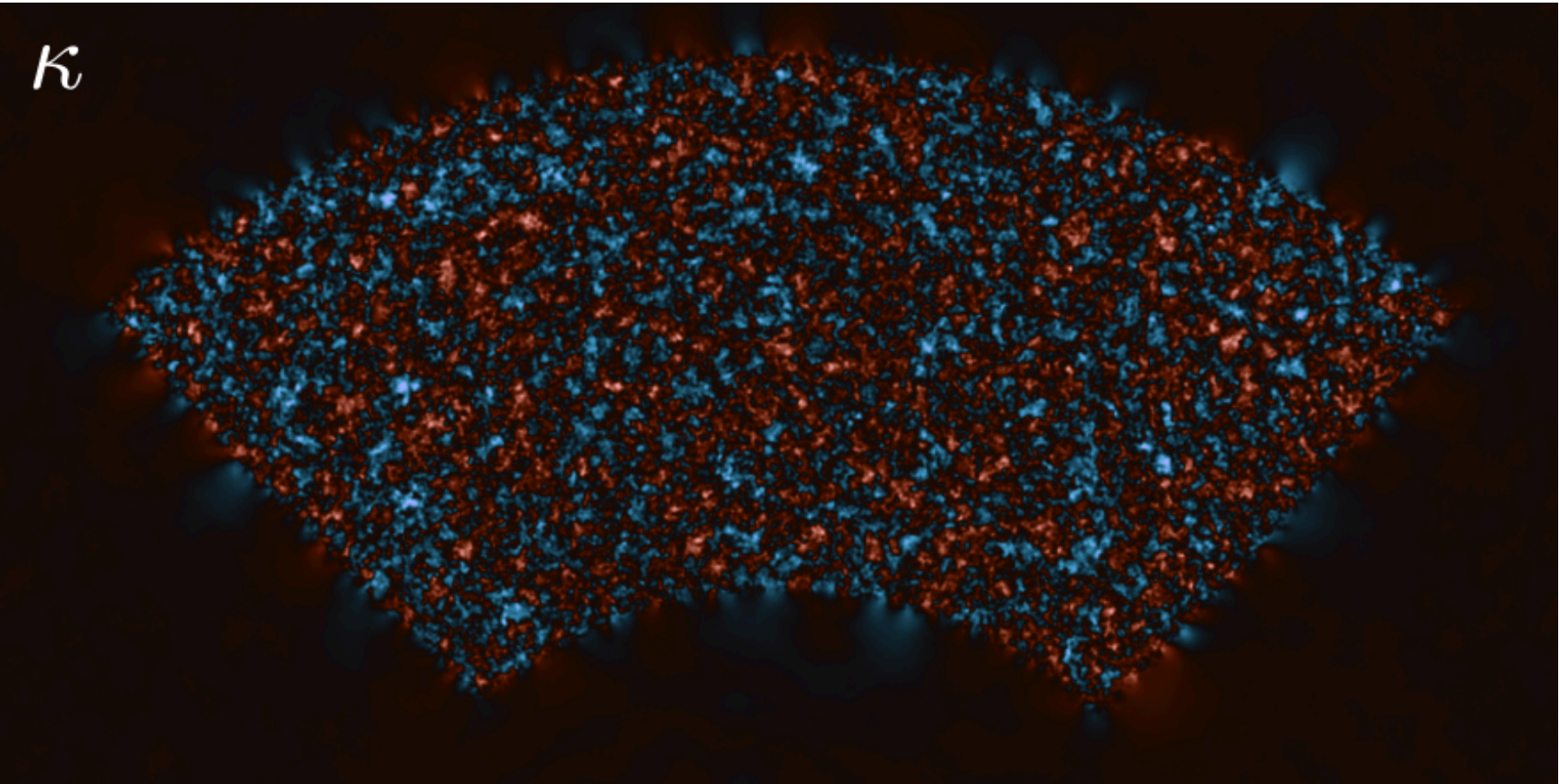
Reconstructed CMB lensing maps



Planck PR4: TT-dominated, space, $f_{\text{sky}} = 67 \%$
Carron et al 2022
(also ISW-lensing bispectrum likelihood)



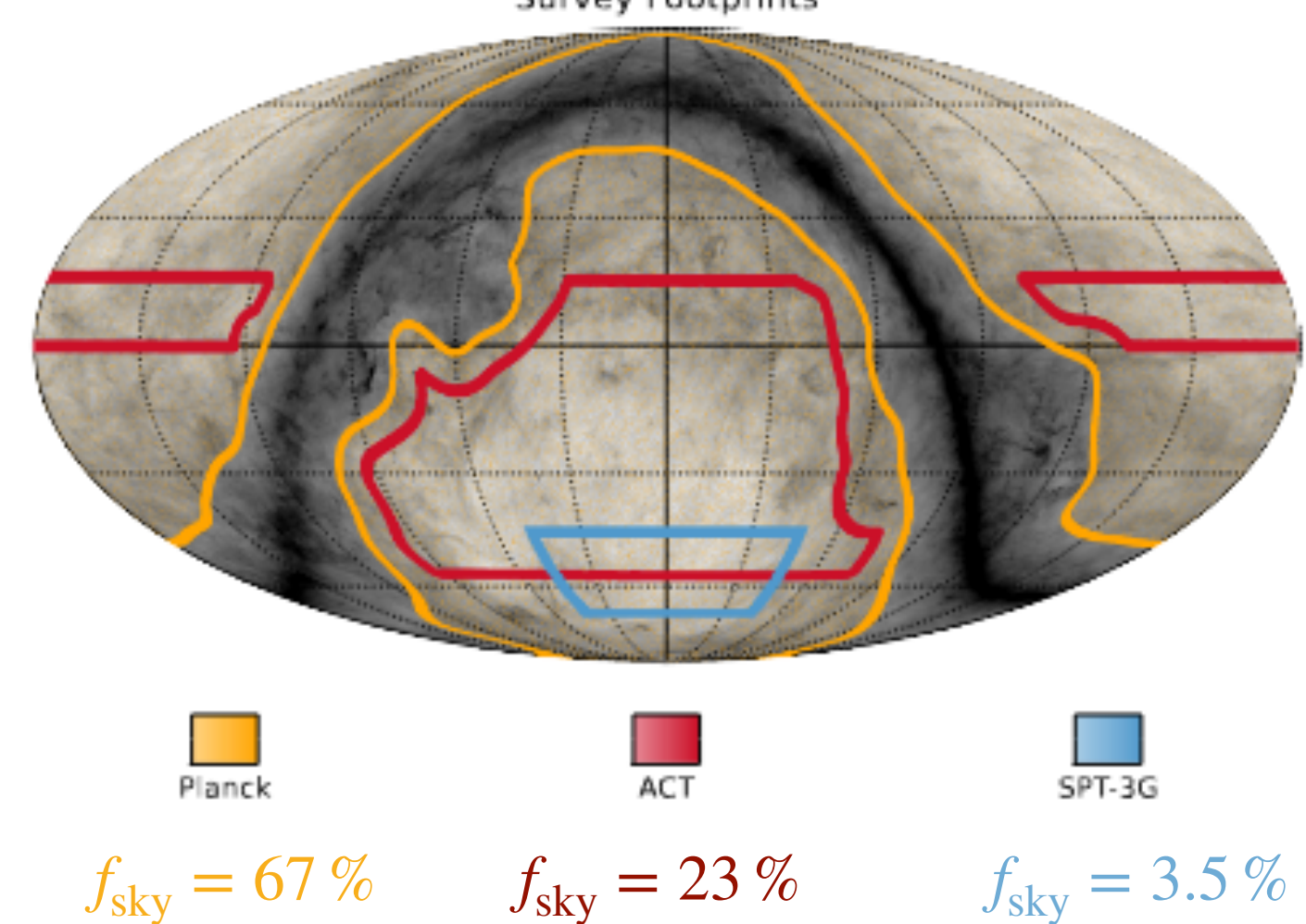
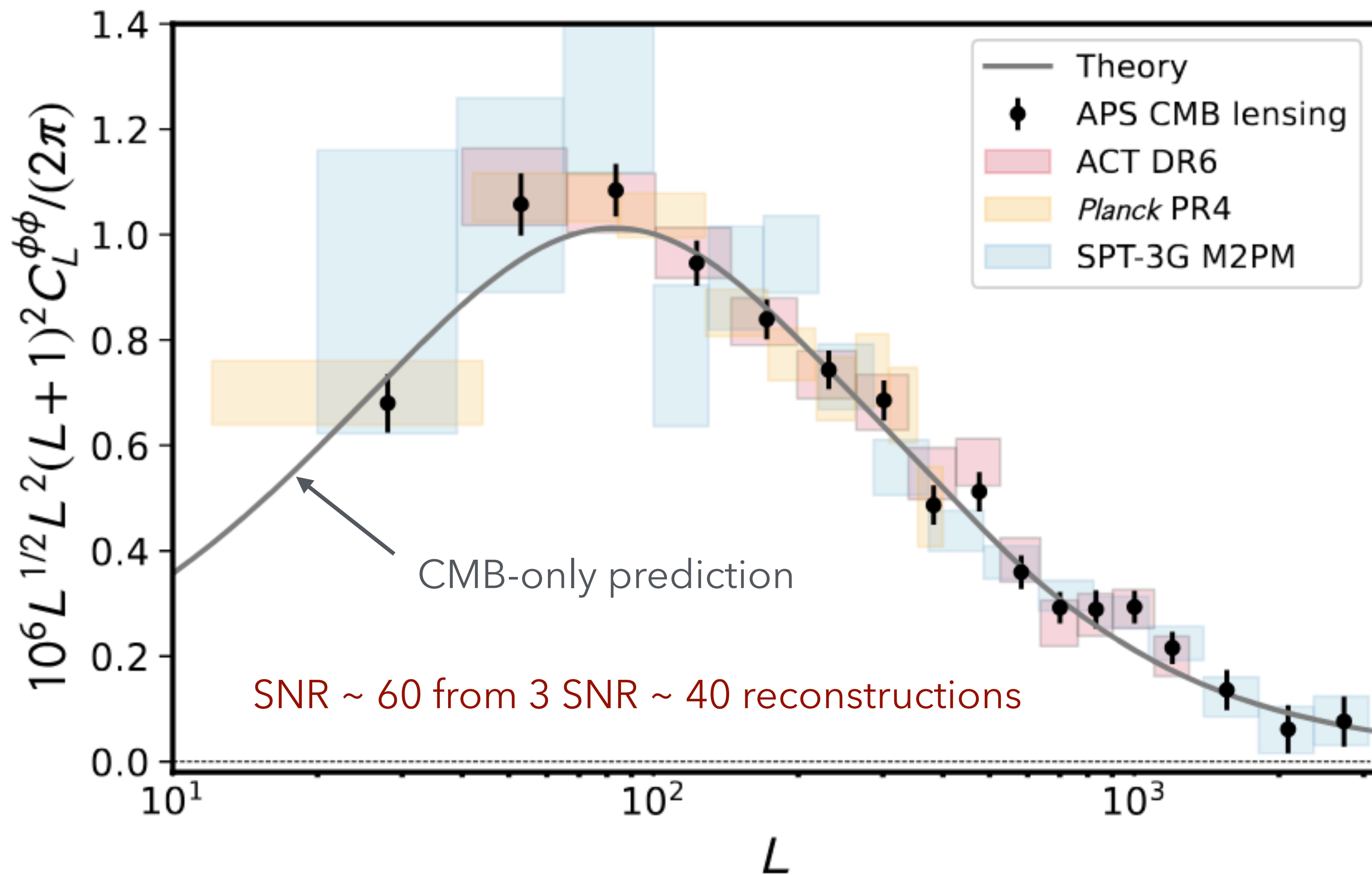
ACT DR6 CMB lensing mass map
ACT DR6, from Chile, $f_{\text{sky}} = 23 \%$
Madhavacheril et al 2023



SPT-3G (MUSE), Polarization-only, from the South Pole, $f_{\text{sky}} = 3.5 \%$

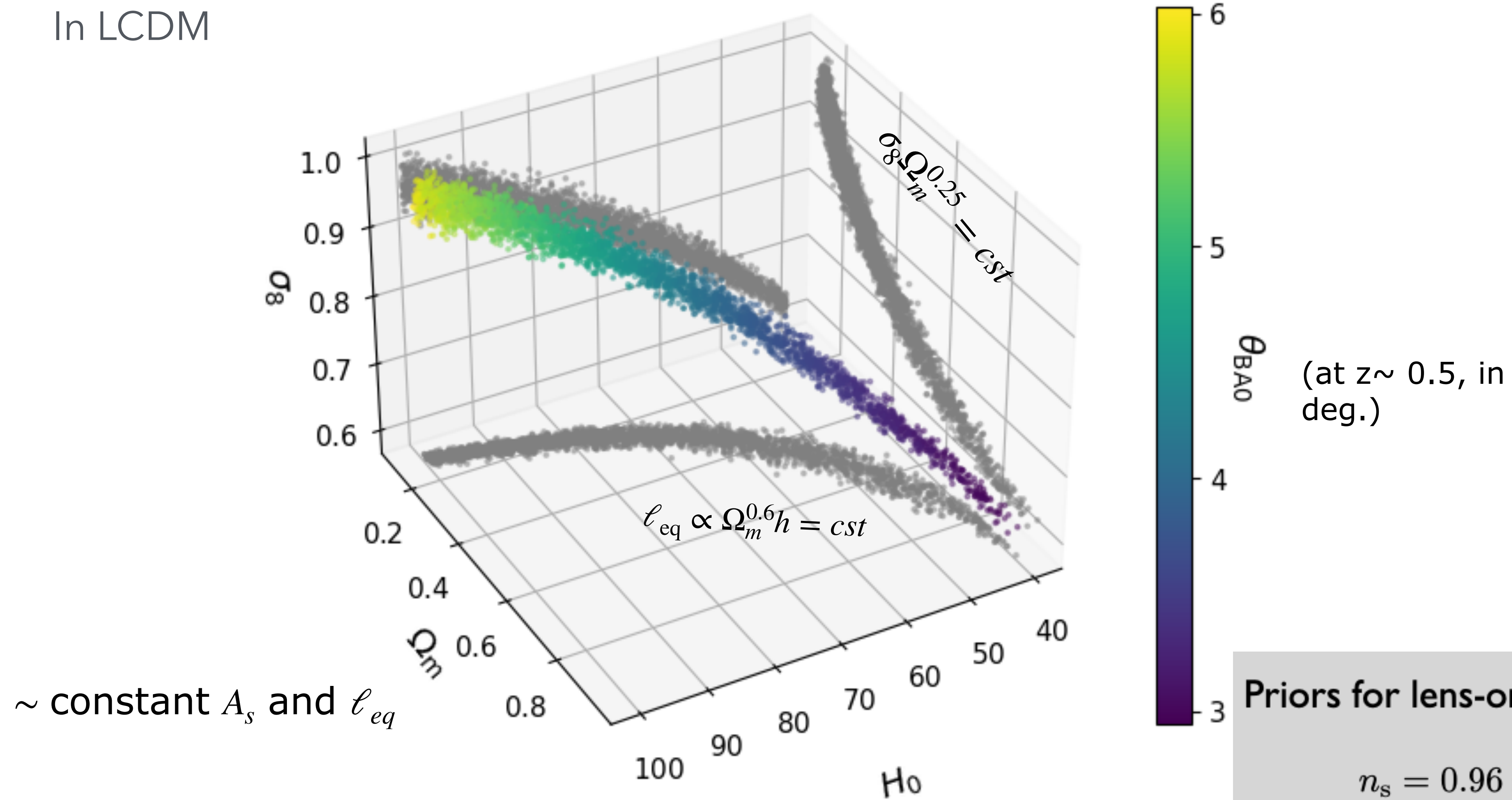
Ge et al 2024

Qu, Ge et al 2025 (ACT + SPT collaborations)



What does CMB lensing measure ?

In LCDM



Priors for lens-only:

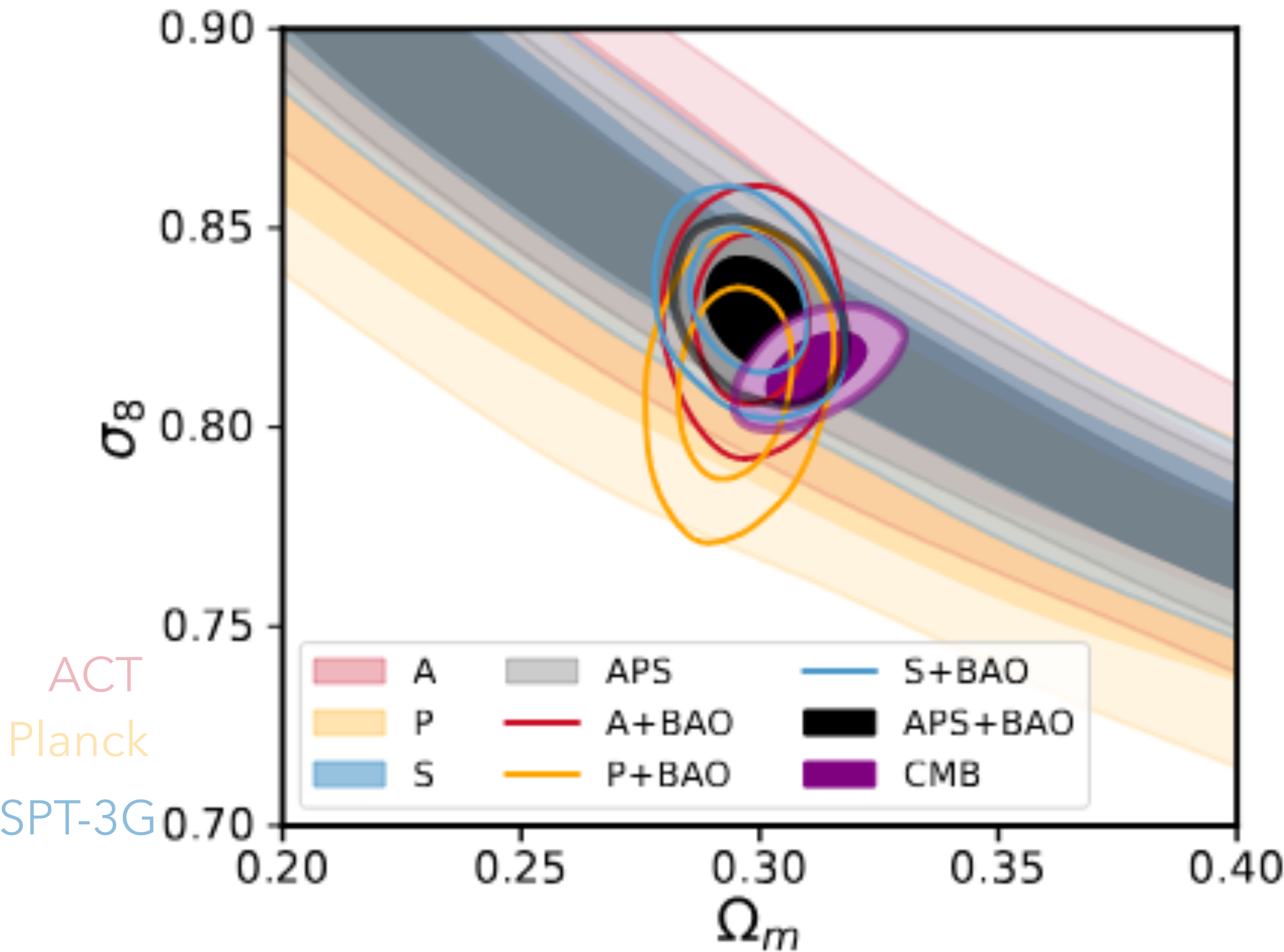
$$n_s = 0.96 \pm 0.02$$

$$0.4 < h < 1.0$$

$$\Omega_b h^2 = 0.0223 \pm 0.0005 \quad (\text{BBN})$$

Lensing-only (+BBN), and + DESI BAO

Qu, Ge et al 2025 (ACT + SPT collaborations)

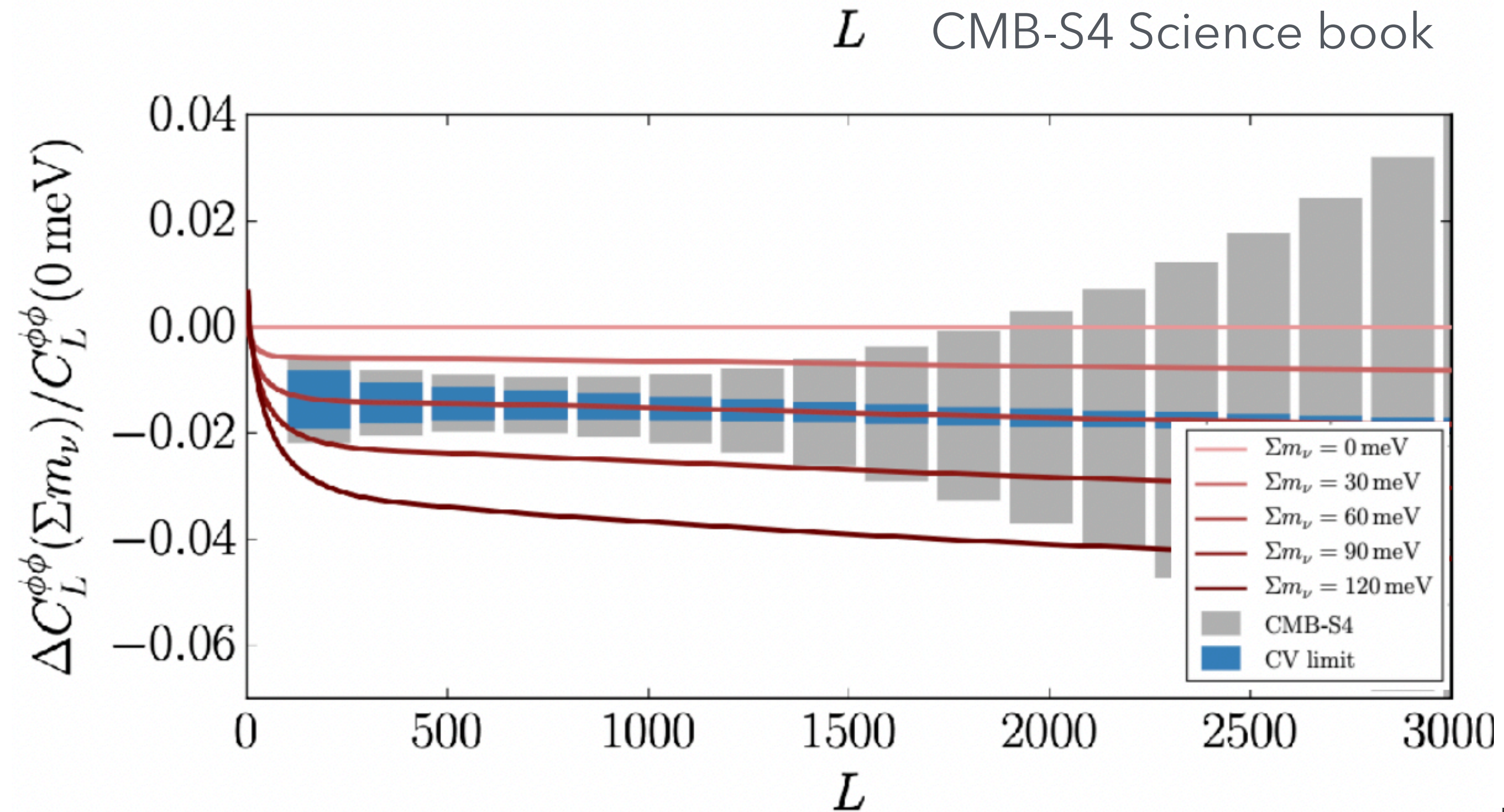


$\sigma_8 = 0.829 \pm 0.009$ (68% C.L., APS + BAO)

$H_0 = 68.77 \pm 0.53 \text{ km s}^{-1} \text{ Mpc}^{-1}$
(68% C.L., APS + BAO).

What can CMB lensing measure ?

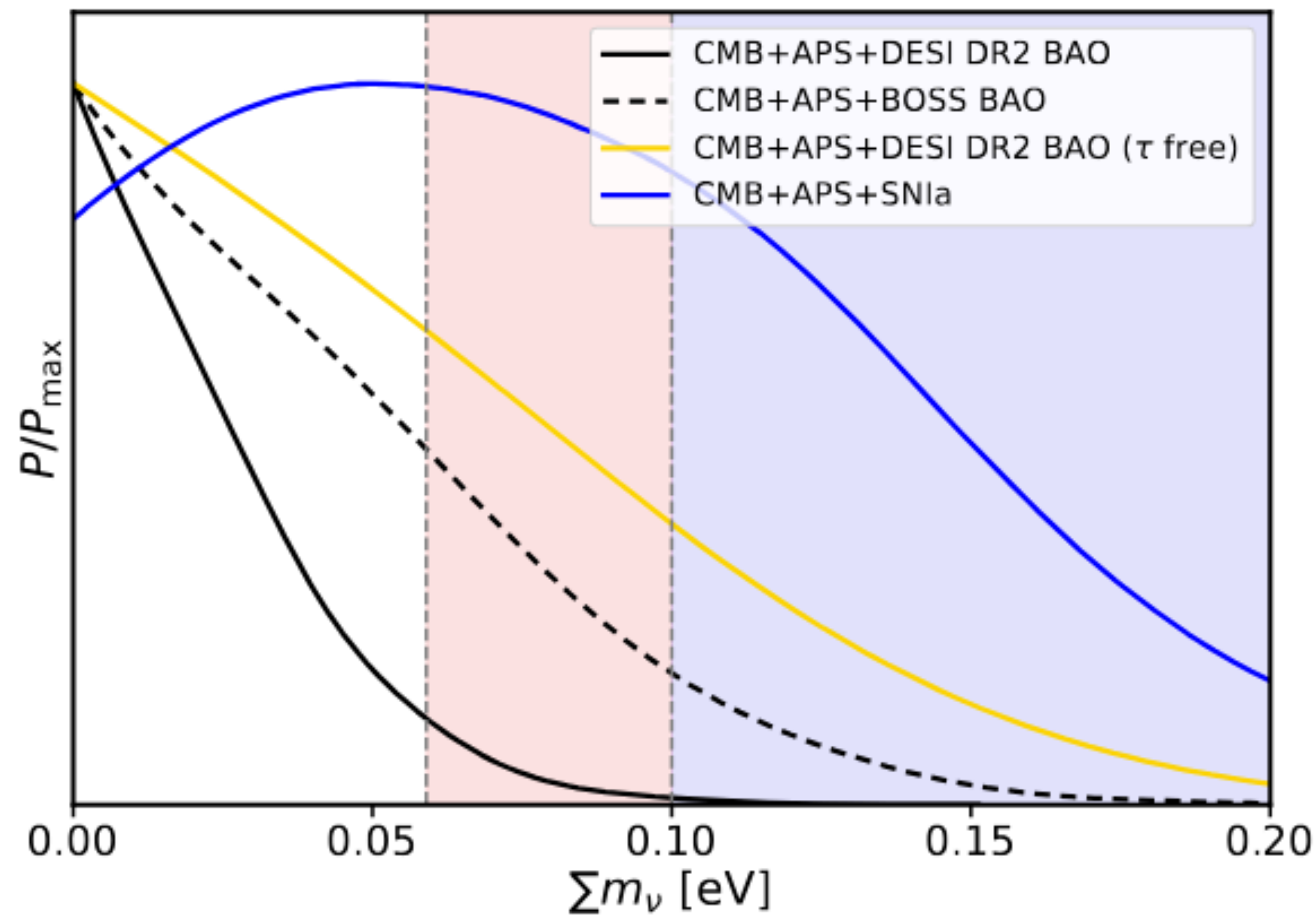
- *neutrino mass*



- *Argument used to be: with combination with good anchor of primordial amplitude (optical depth τ), and low redshift BAO to break degeneracies, and in combination with oscillation data, one can actually measure the neutrino mass scale in a most robust manner.*

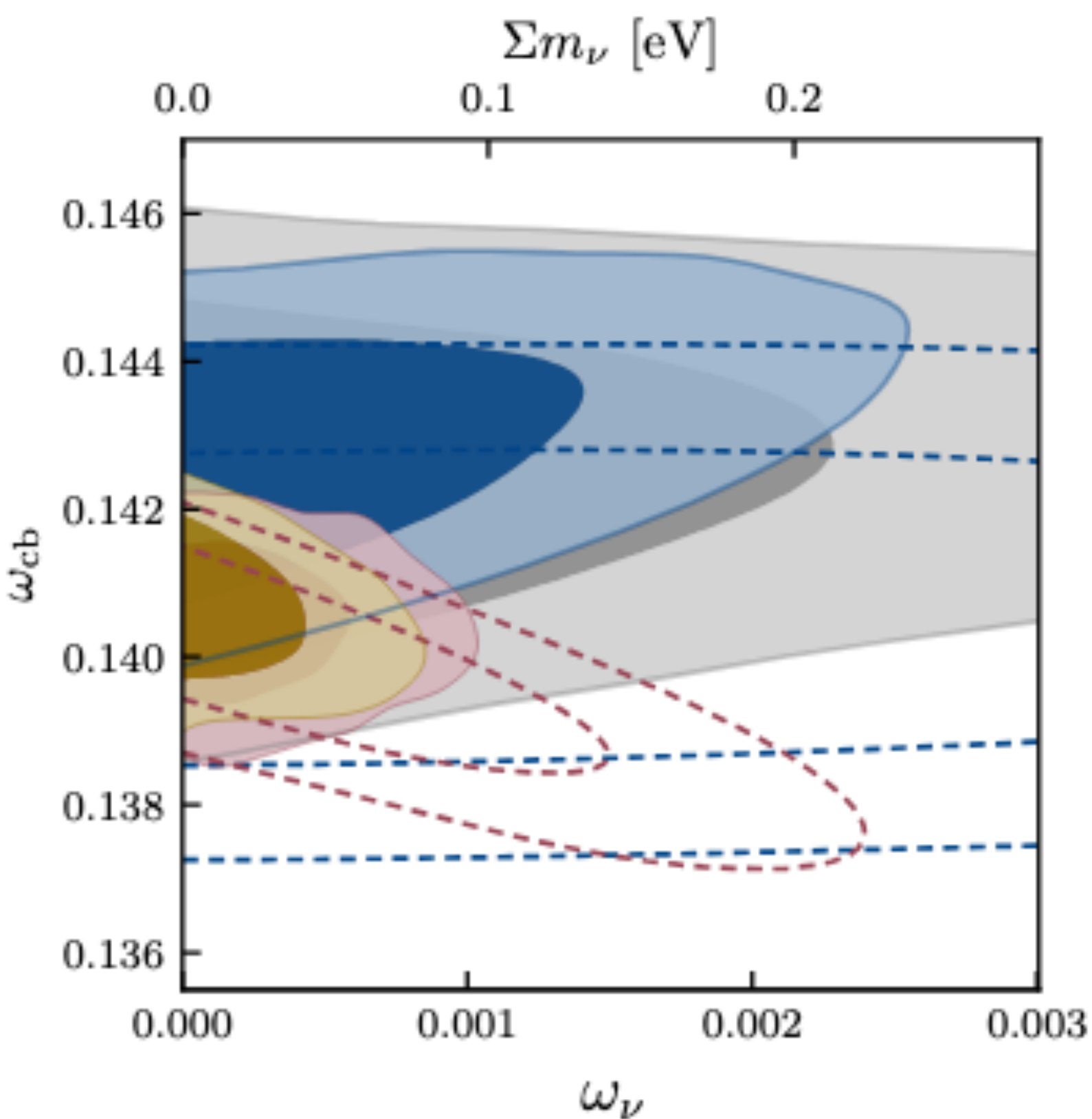
Neutrino mass

Qu, Ge et al 2025 (ACT + SPT collaborations):



- ‘Lensing excess’, or ‘matter-density deficit’ or τ is too low, or ...

Lynch & Knox 2025



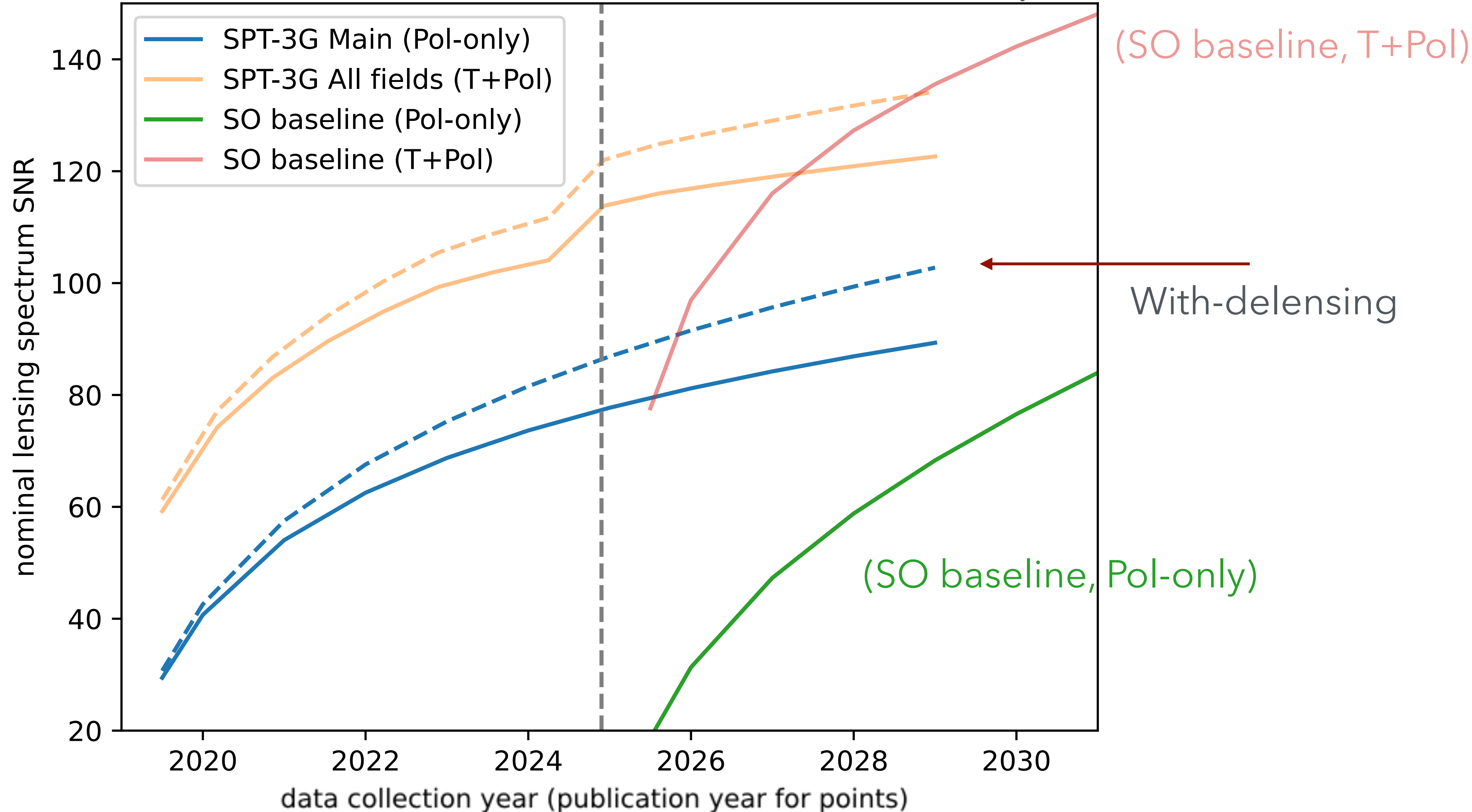
- CMB lensing and BAO complementary but somewhat discrepant ($< 3\sigma$)

Sailer et al 2025

Consistent with?	$\tau = 0.06$	$\tau = 0.09$
<i>Planck</i> low- ℓ polarization	✓	✗✗ ^a
WMAP low- ℓ polarization	✓	✓
BAO within Λ CDM	✗	✓
$\Sigma m_\nu \geq 0.06$ eV	✗	✓
Cosmological constant Λ	✗	✓

Lensing spectrum SNR in the near future
(Not official in any sort of ways)

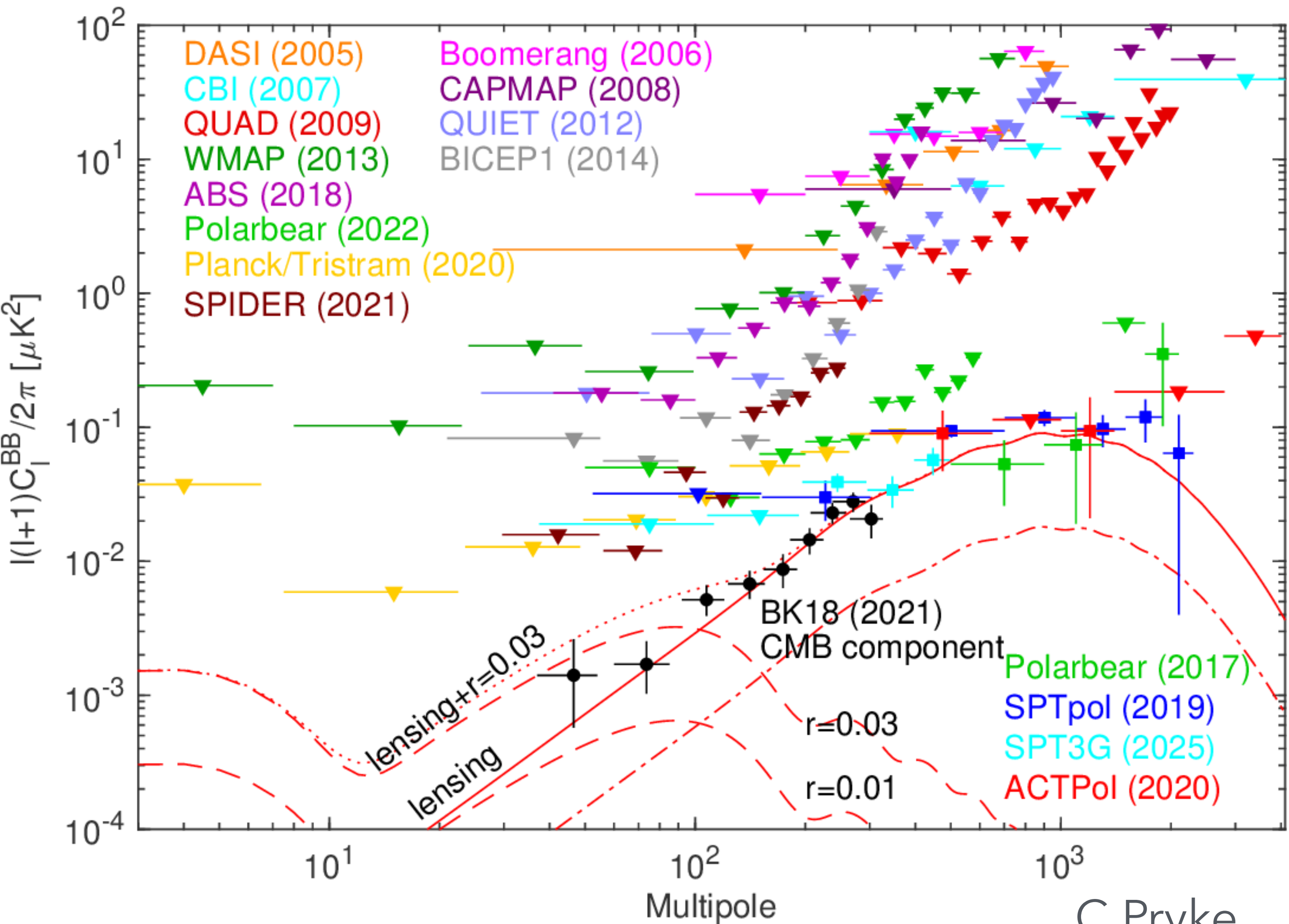
SO: Simons Observatory f_{sky} SO = 40 %
 f_{sky} SPT-3G Main = 3.6 %



This Fall: ACT DR6+ and SPT-3G main field QE

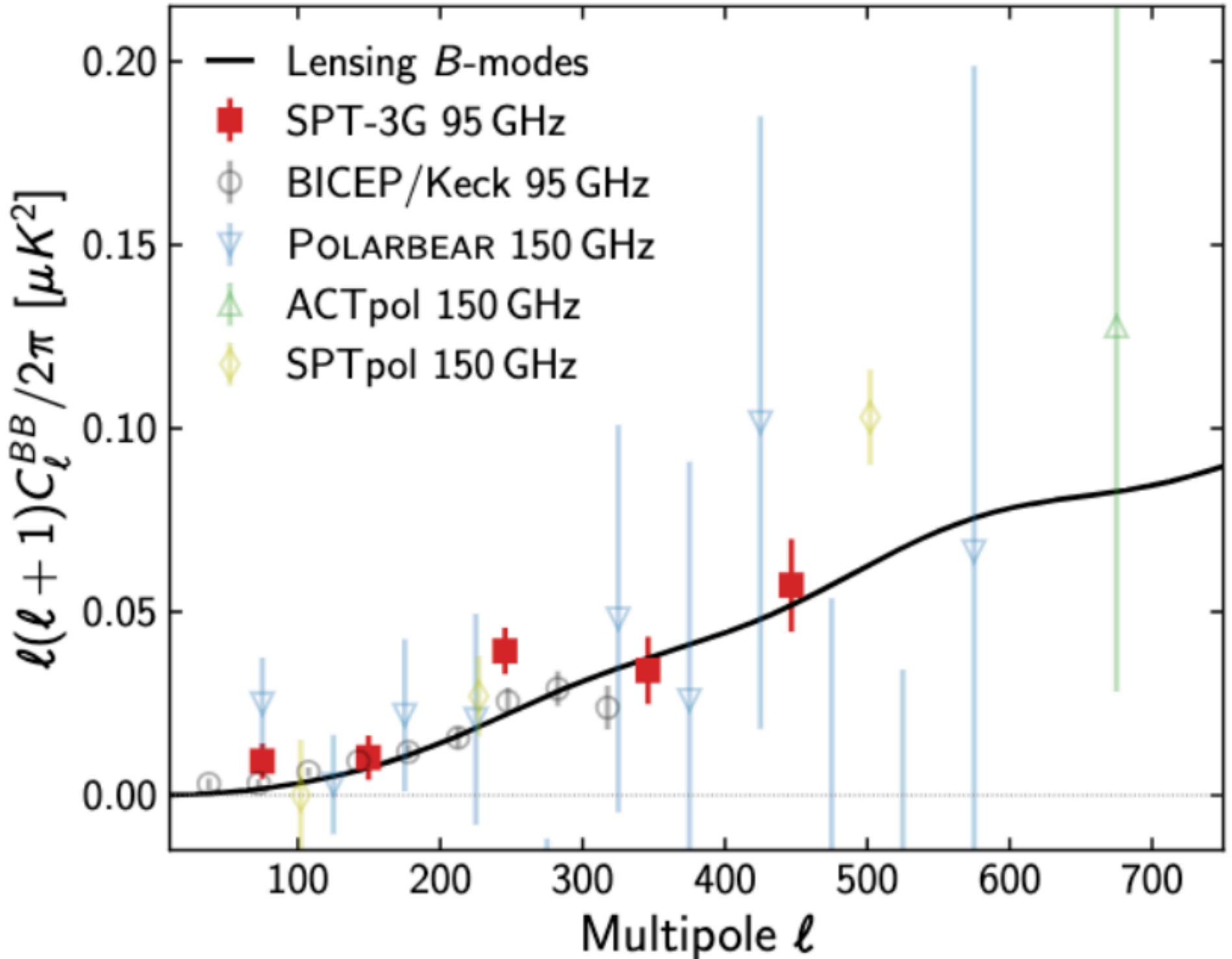
De-lensing for inflation

CMB B-mode power



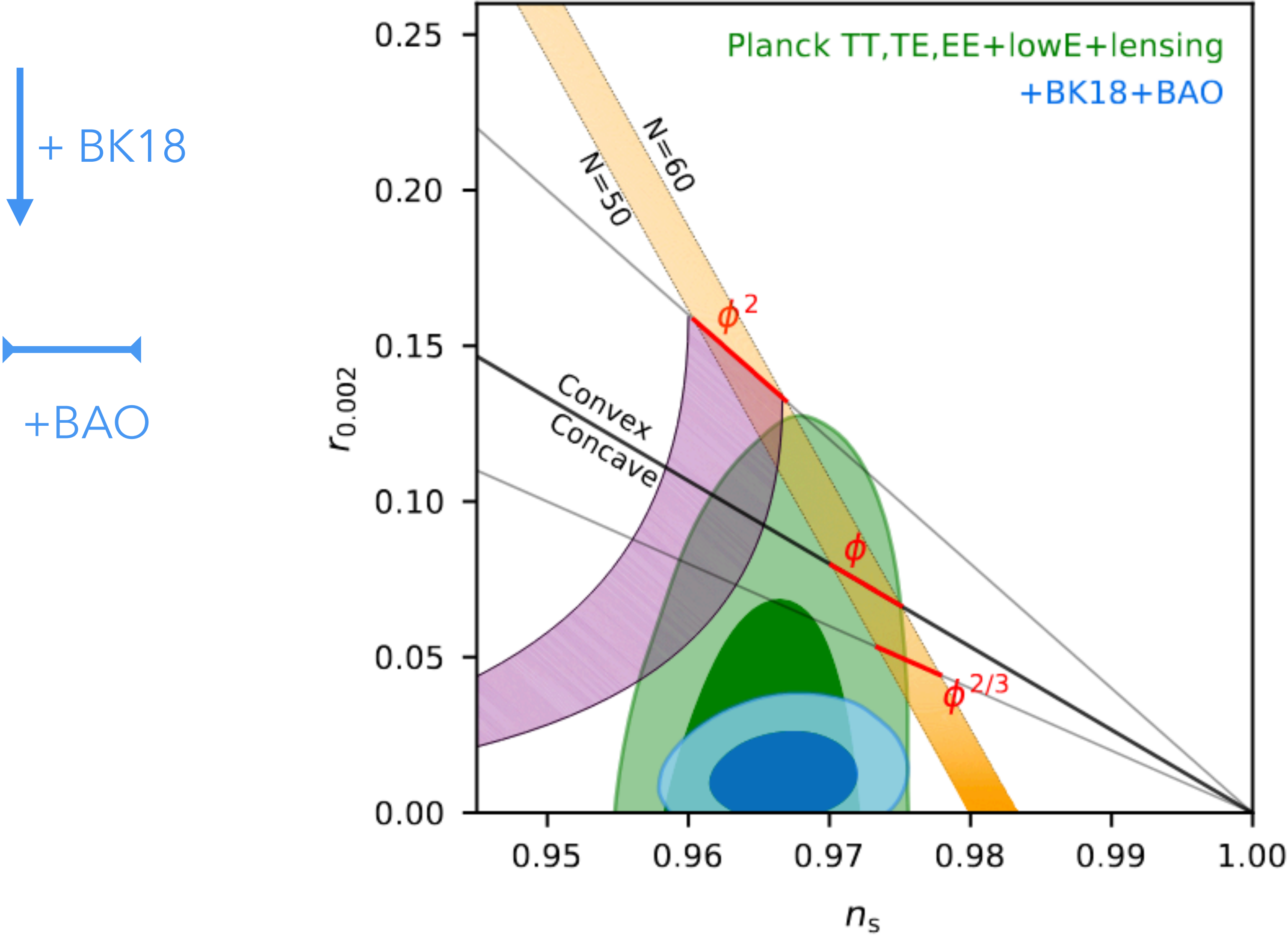
C.Pryke

Zebrowski et al 2025



Characterising inflation: BICEP/Keck

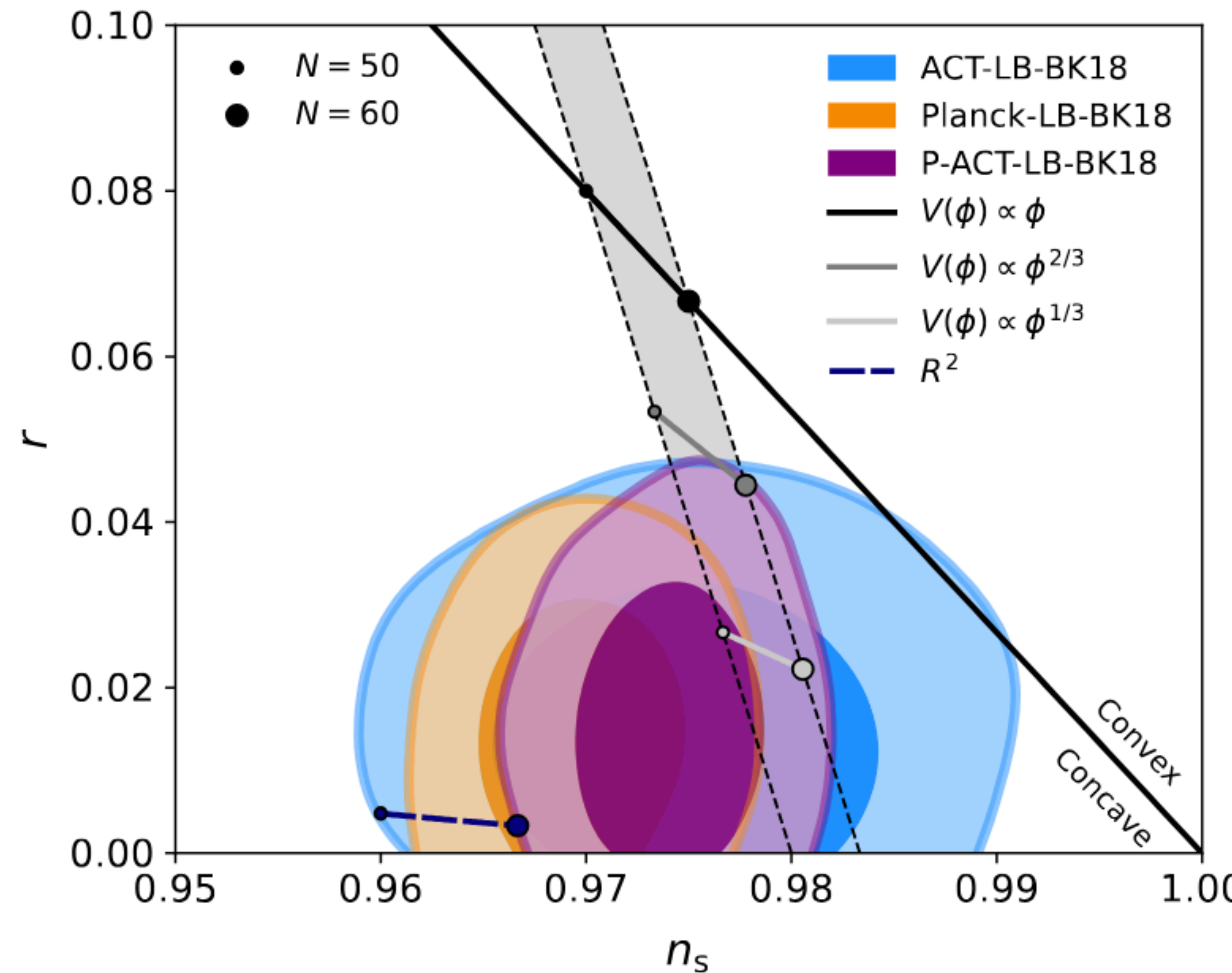
BK18 2110.00483



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

r - n_s plot:

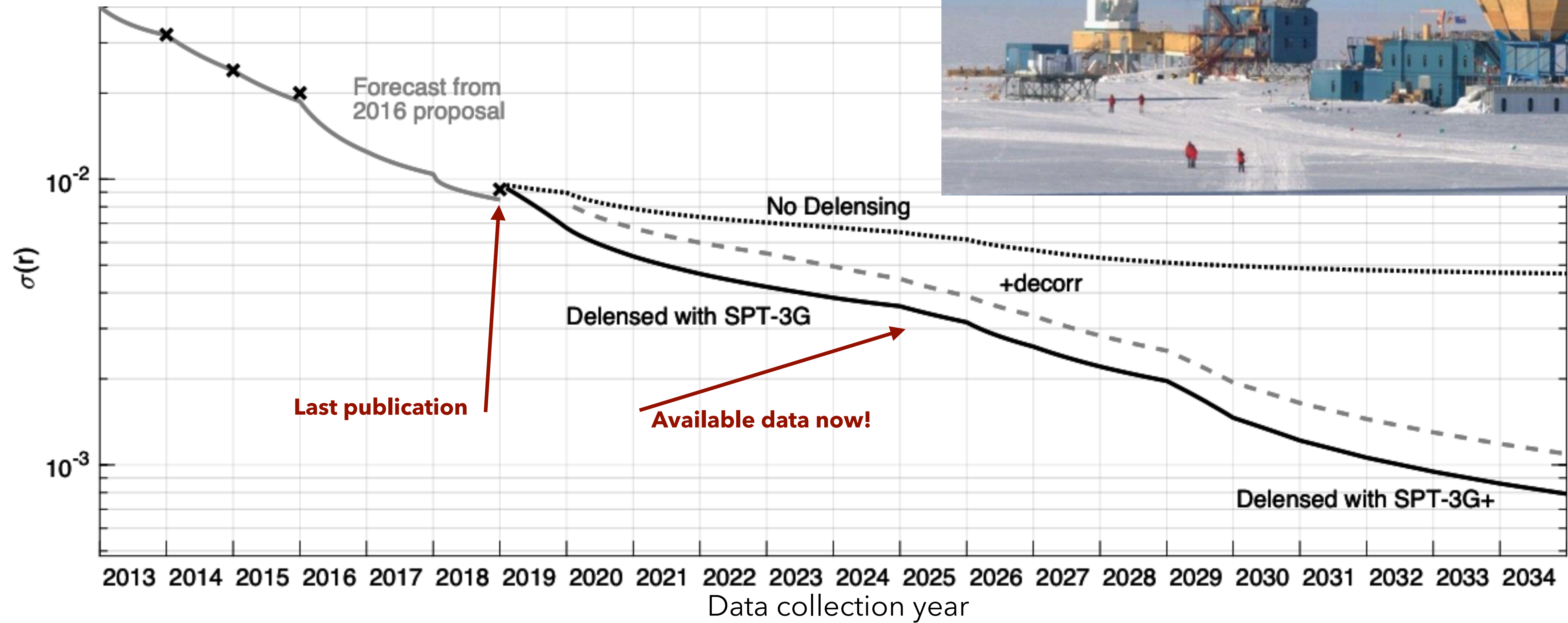
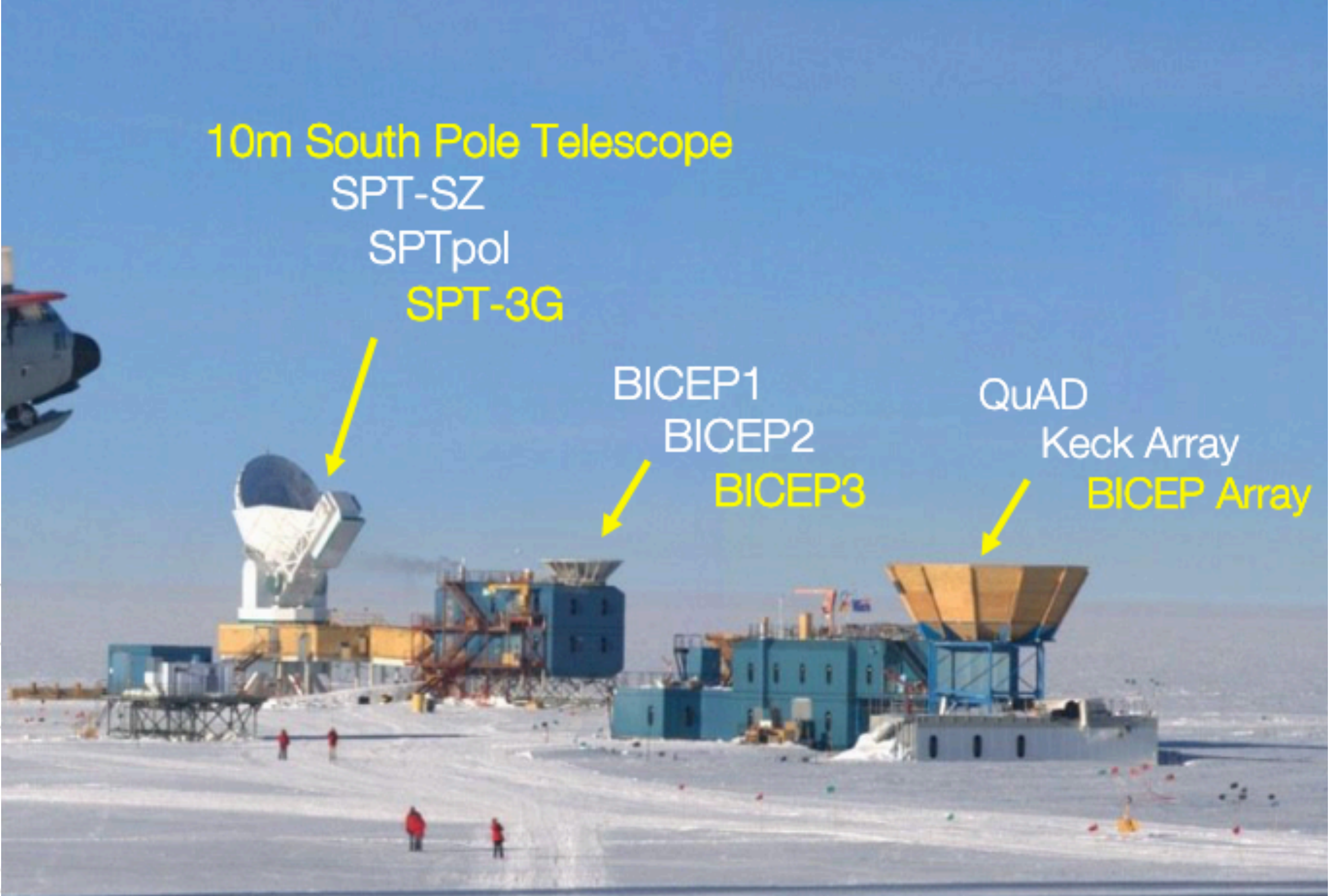
- CMB observations will tighten n_s significantly from wide-area CMB spectra (SPT-3G Ext-10k, and then Simons Observatory with $\sigma(n_s)$ 0.002, twice better than Planck)
- But now, $\sigma(r)$ is dominated by lensing B-mode variance.
(no-lensing $\sigma(r)$ from BK18 would be a factor of 2 tighter)
- BK can only progress by removing the lensing signal in some way



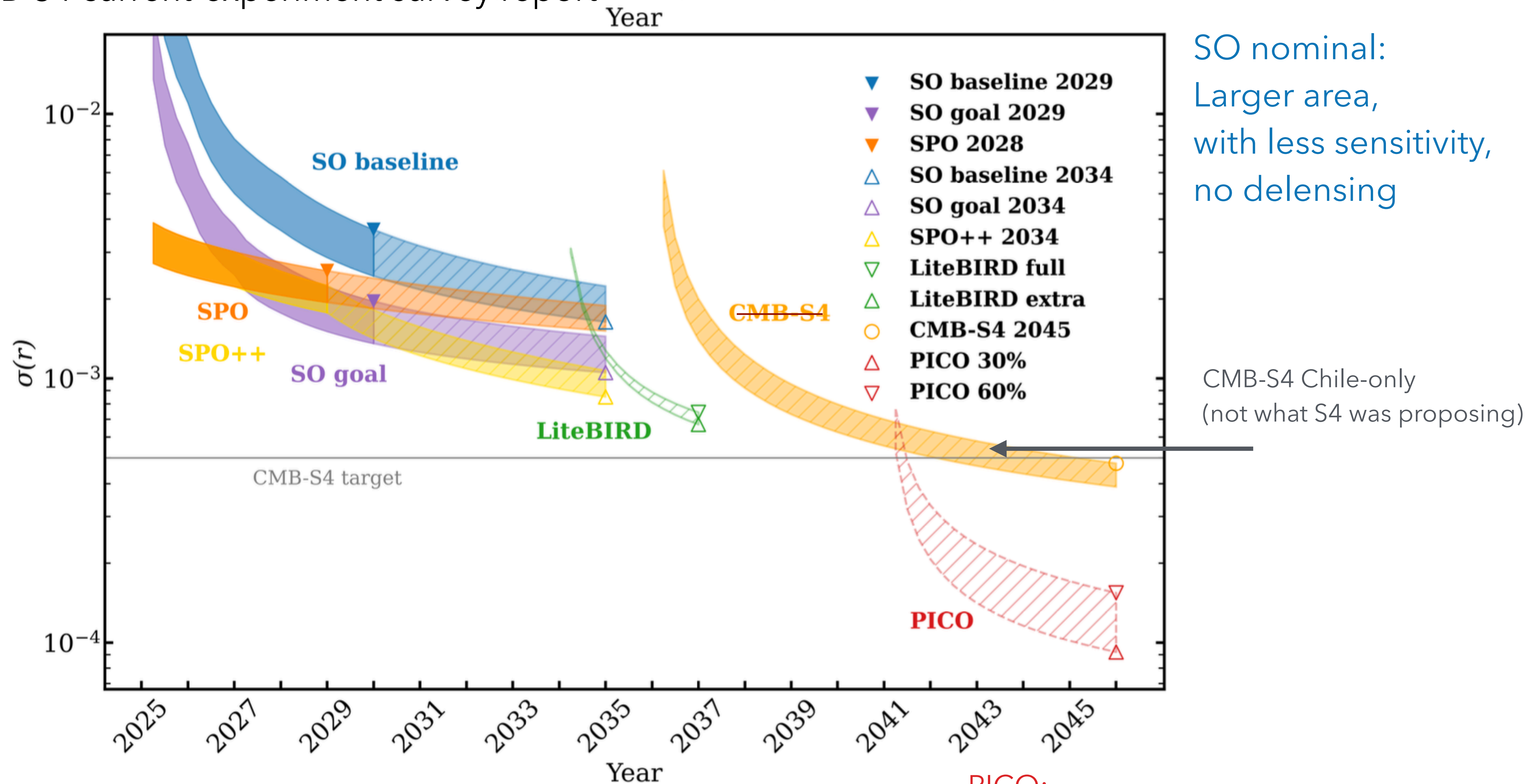
Calabrese et al (ACT DR6)

The South Pole Observatory (SPO)

$\sigma(r) \sim 0.009$ published (BK only)
 $\sigma(r) \sim 0.003$ achievable with current data with SPT-3G
 $\sigma(r) \sim 0.001$ by 2034



CMB-S4 current-experiment survey report



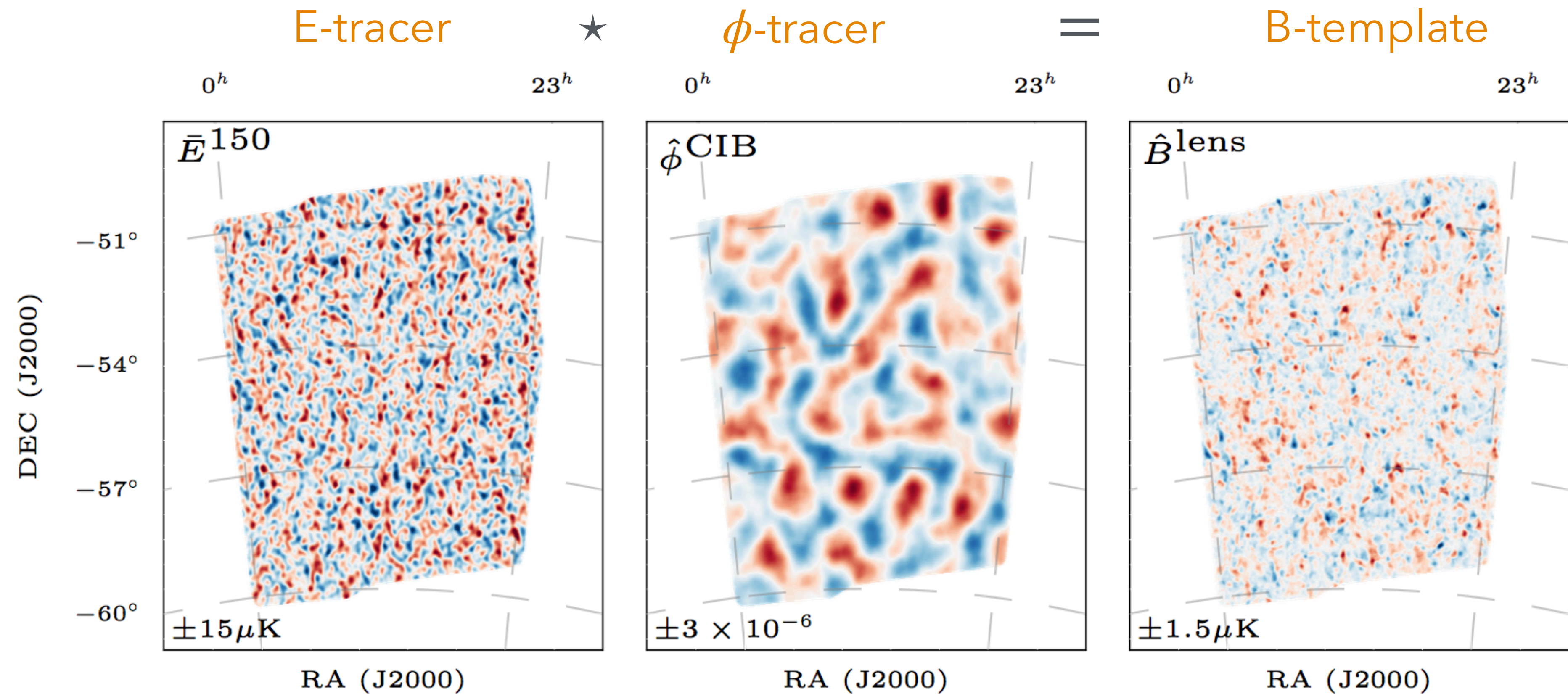
SO nominal:
Larger area,
with less sensitivity,
no delensing

PICO:
Nasa Probe-class mission concept study
Higher resolution so can delens.

LiteBIRD: JAXA-lead space mission targeting low- ℓ ,

How to delens ?

-Template method :

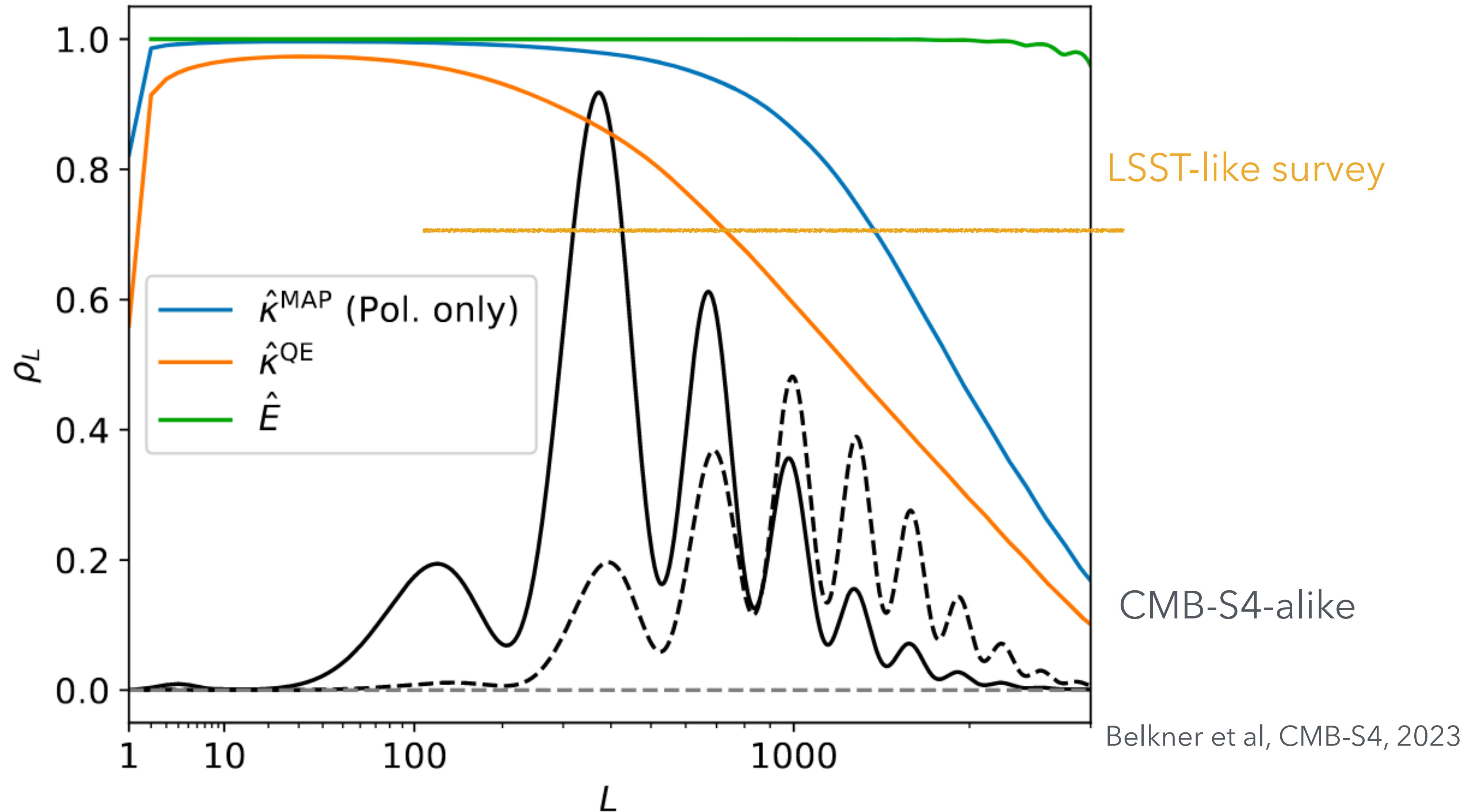


Manzotti et al 1701.04396 (SPT B-mode delensing with CIB)

Also BK-SPTpol 2011.08163

(Here tracer is Cosmic Infrared Background from Herschel)

The lensing tracer must be eventually be obtained from the CMB itself, and with methods that go beyond quadratic estimators

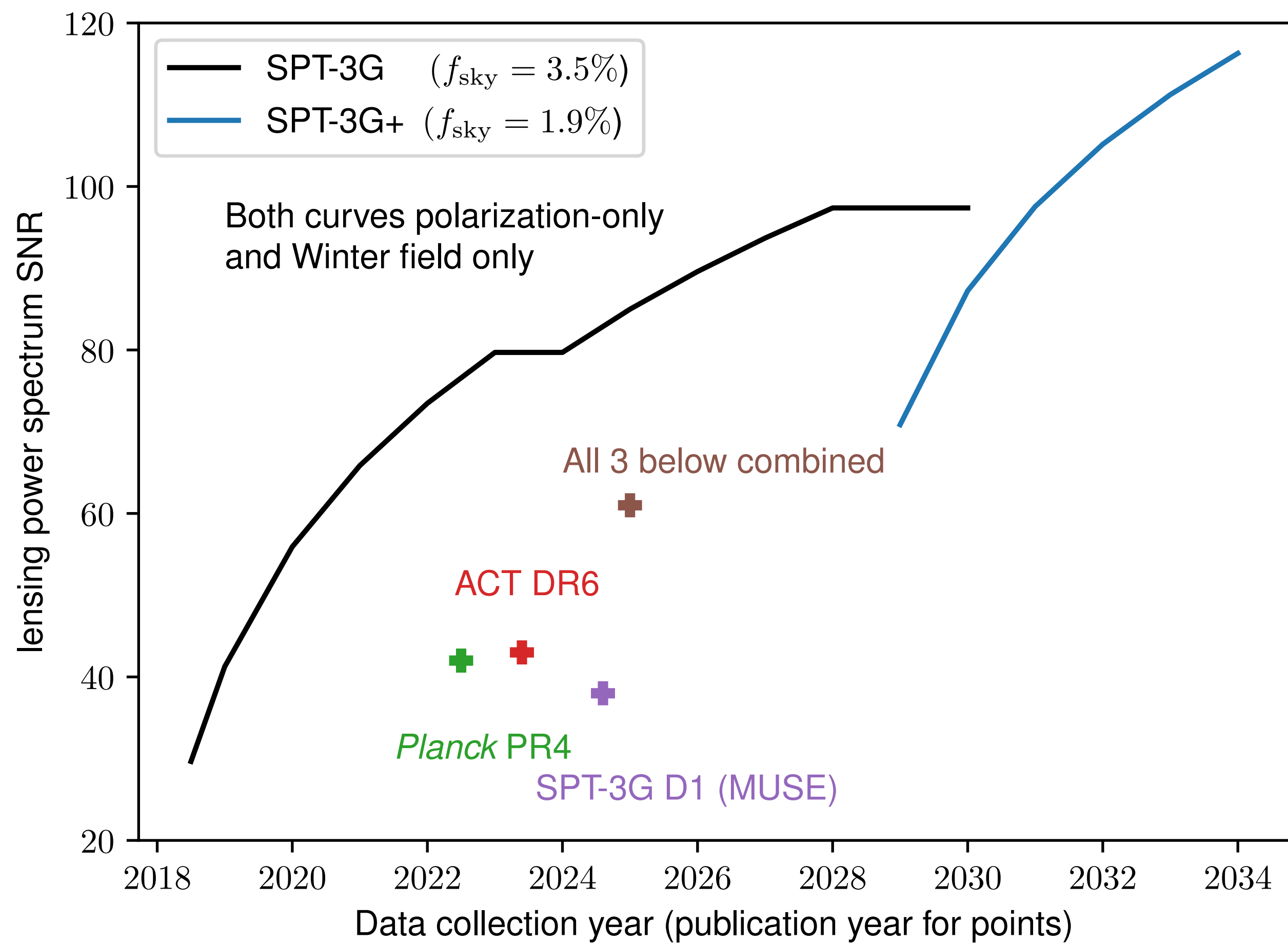


SPT-3G 5yrs Main field lensing

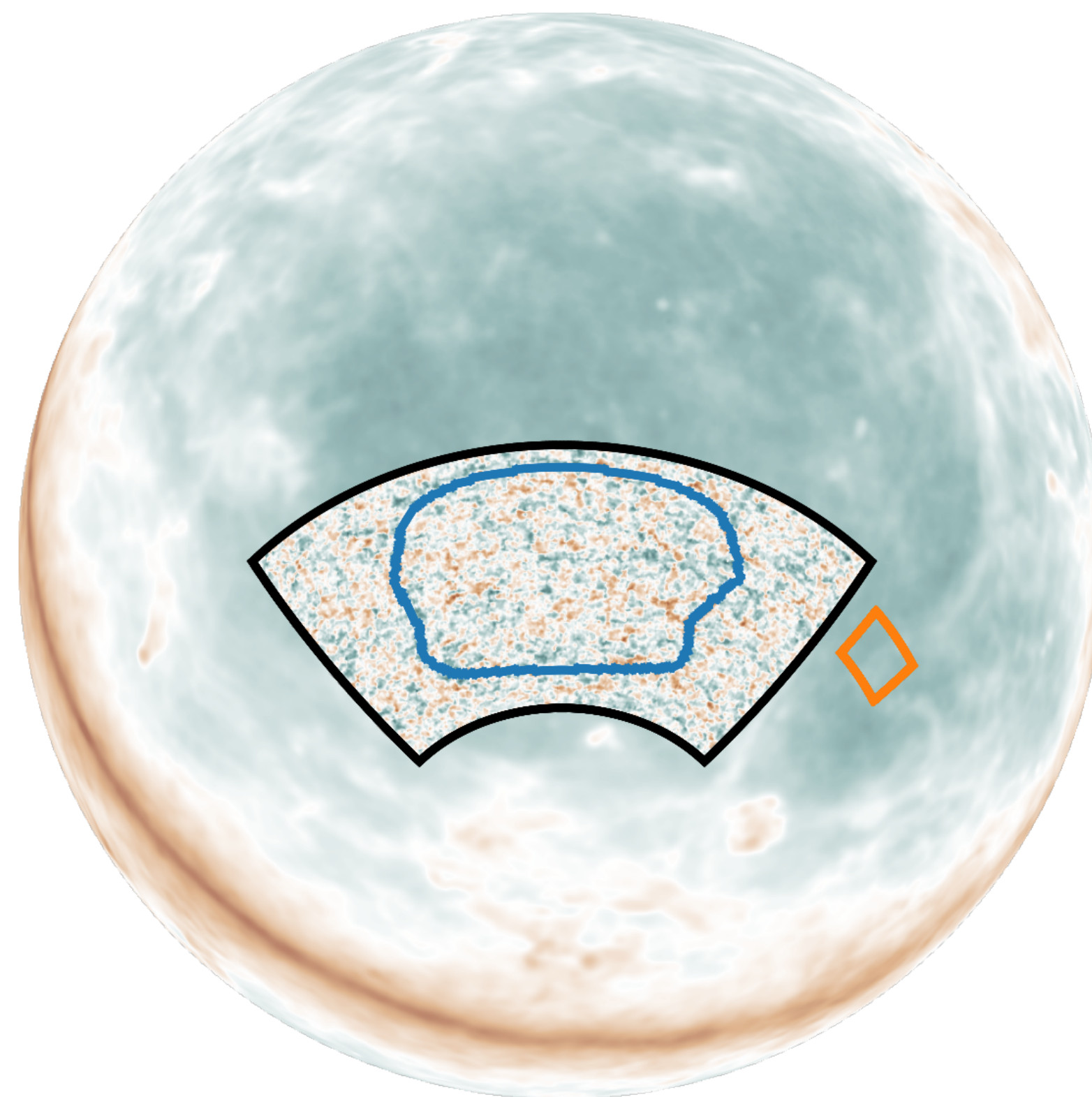
- Main field $\hat{\kappa}^{EB}$ is in principle the **theory-land superstar** estimator.

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
- EB QE eventually gets limited by B lensing power, but this can be de-lensed (Beyond-QE techniques). **30% to 20% improvements in reconstruction noise** for SPT-3G 5 yrs data.
- 5yrs nominal lensing spectrum SNR pred (for beyond-QE, EB-only!) is **~ 66** (**$\geq$ Planck + ACT + SPT-3G lensing just out 2504.20038**)

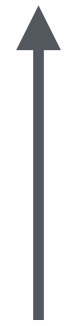


BICEP
SPT-3G



2. Fast general Spherical Harmonic Transforms on small sky fractions

JC & Reinecke, in prep.



(Meaning to or from arbitrary points)

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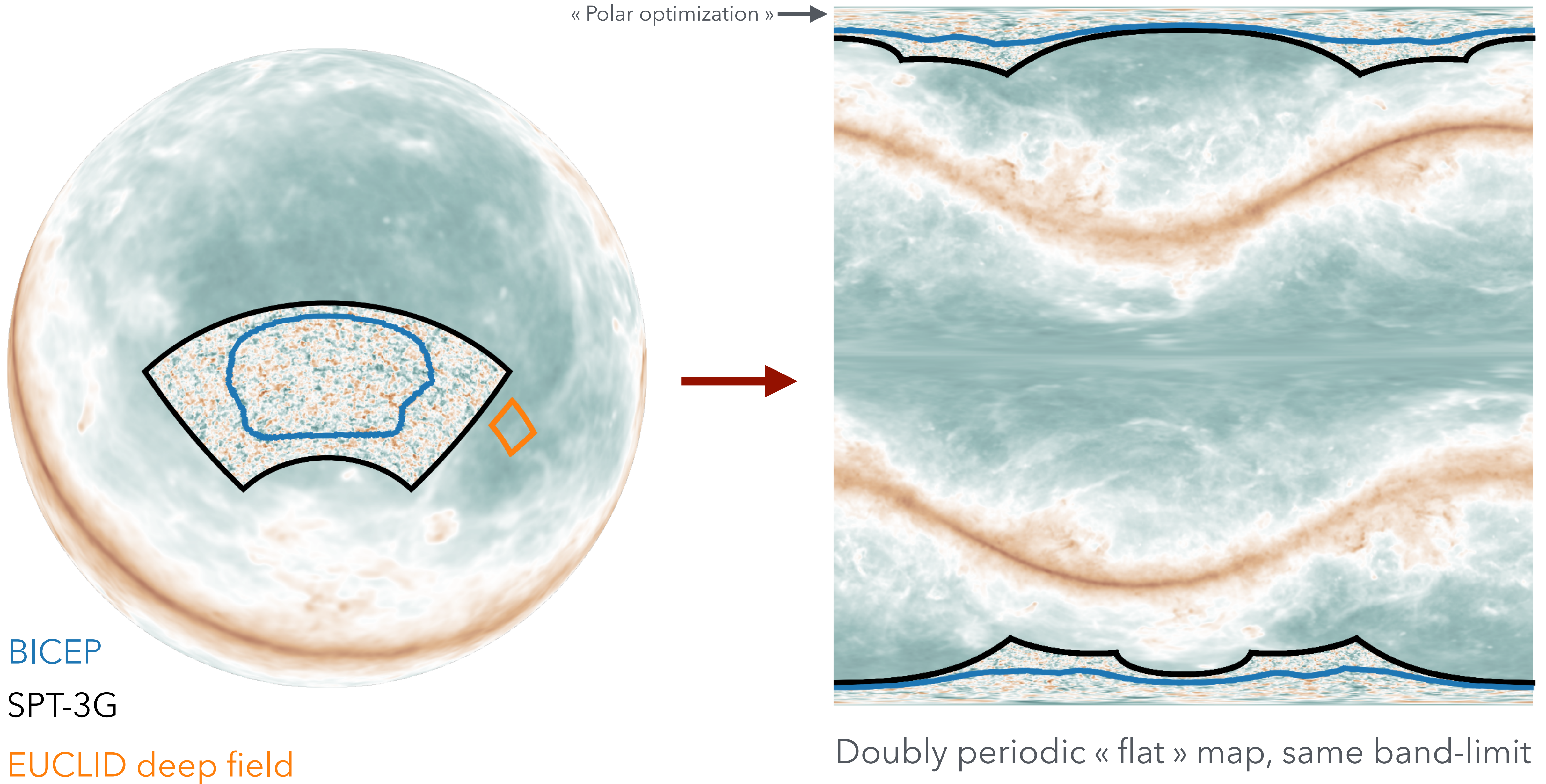


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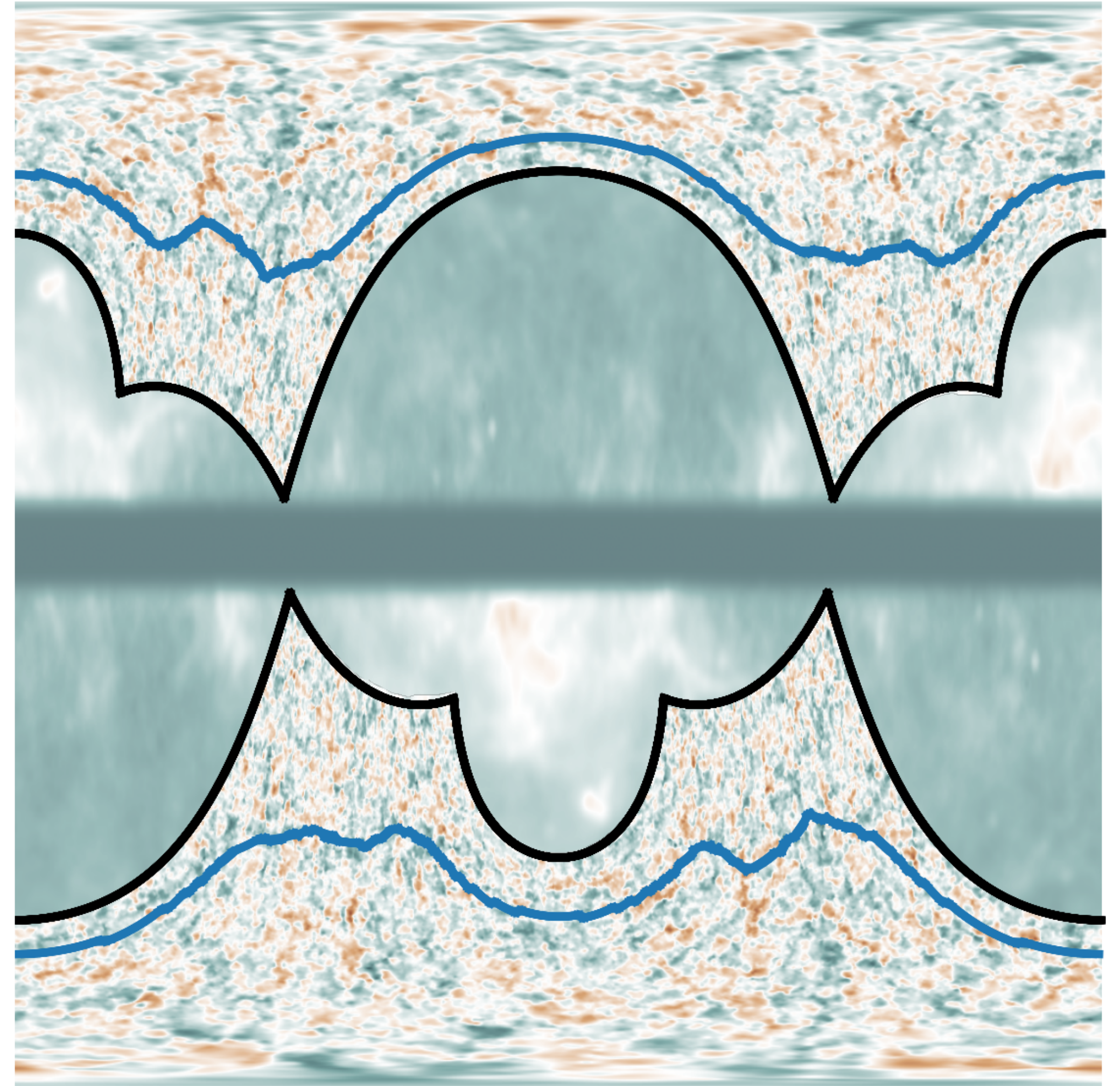
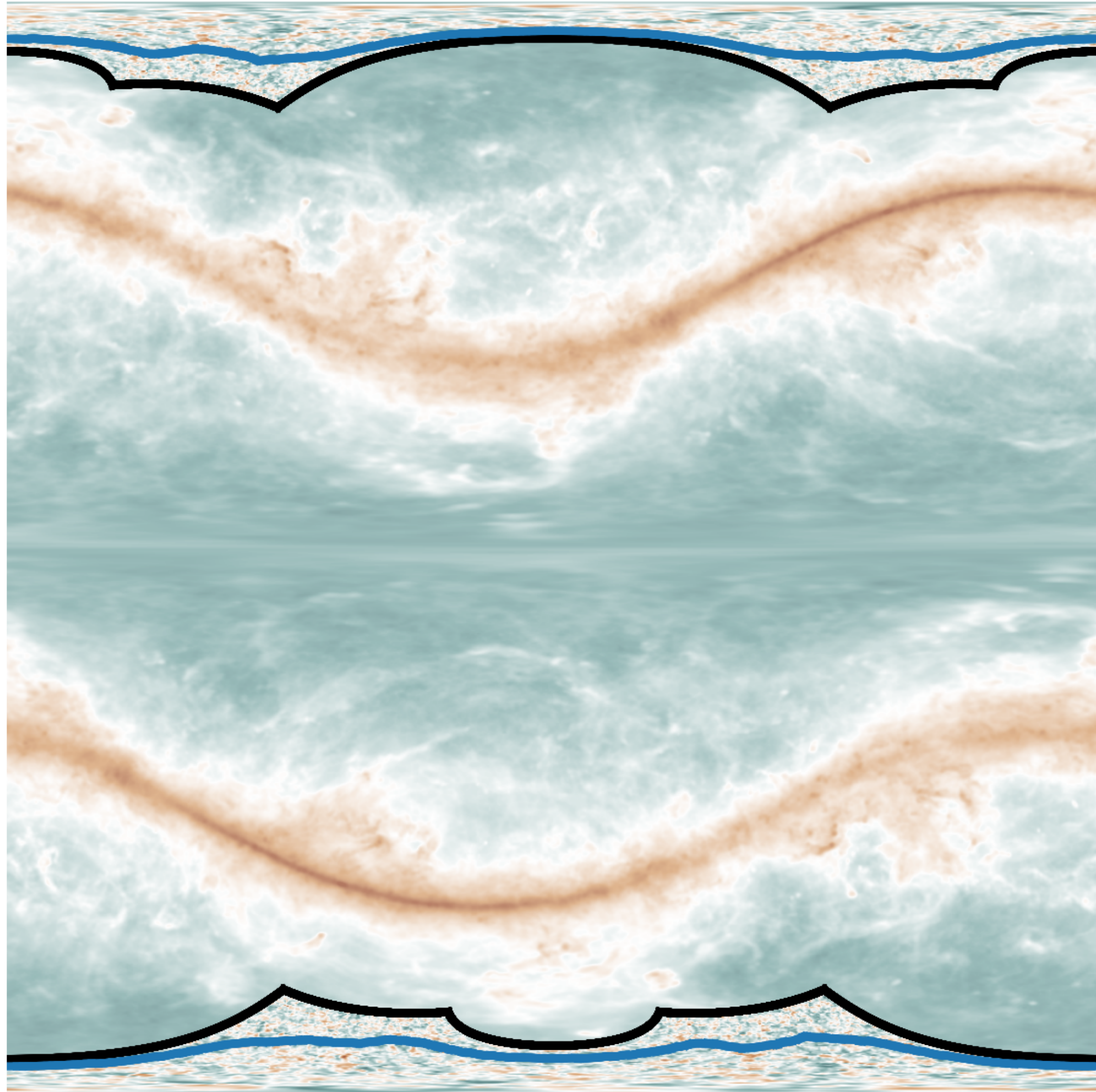
Motivations

- CMB-(de-)lensing work has loads of high-resolution SHTs to perform.
- In the coming years, CMB r -constraints will come from small sky fractions.
- So.... let's speed-up the SHTs. Generic purpose code.

Step 1: Doubled Fourier Sphere (Reinecke, Belkner et Carron 2023, Basak et al 2009) + « Polar optimization »

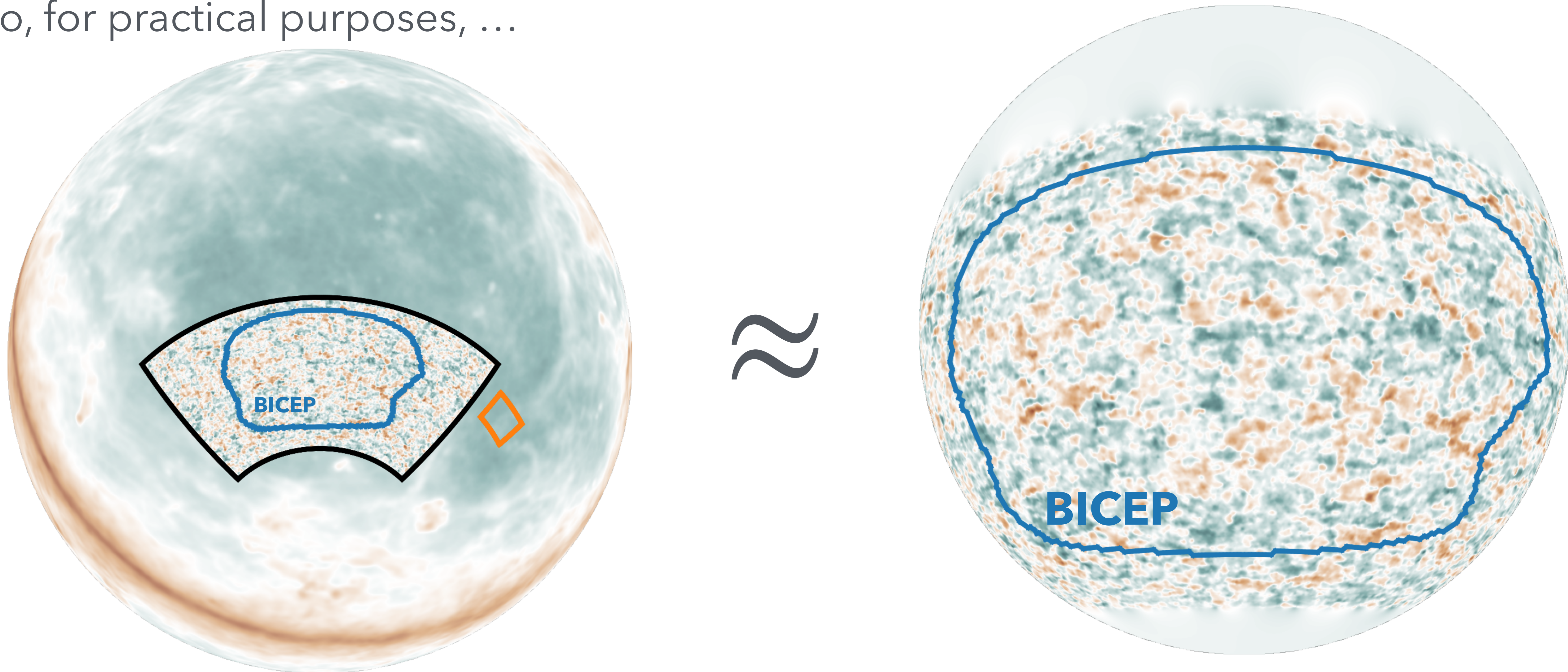


Step 2: Magnifying and cross-fading/weighting



BICEP
SPT-3G

So, for practical purposes, ...



SHT numerical cost typically dominated by the « effective number of required Legendre transforms » (rings).

For a band-limit ℓ_{max} , this number is $\simeq \ell_{\text{max}}$, and this is brought down now to $\ell_{\text{max}} \left(\frac{\theta^*}{\pi} \right) (1 + \epsilon)^2$

speed-up factor comes from this, and polar optimization

3. Extending the QE toolbox to beyond-QE

JC 2025

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JC 2025

Motivations

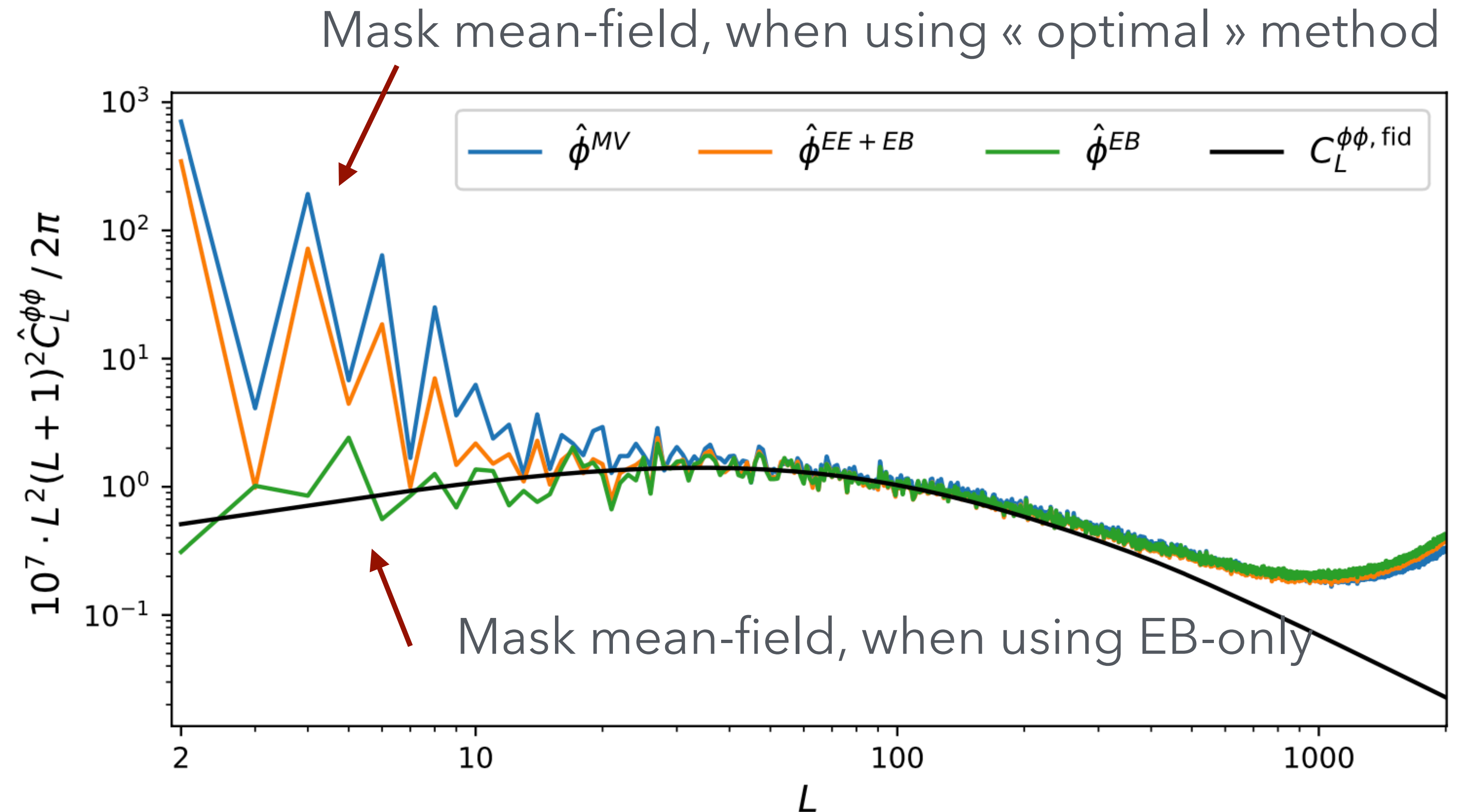
- « Optimal » beyond-QE
CMB lensing estimation is
important for best r
-constraints
- Quadratic estimation is
however much better
understood and has lots of
redundancy / robustness
variations
- So.... let's transpose all
these variations to beyond-
QE In a simple way

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JC 2025

Motivations

- « Optimal » beyond-QE CMB lensing estimation is important for best r -constraints
- Quadratic estimation is however much better understood and has lots of redundancy / robustness variations
- So.... let's transpose all these variations to beyond-QE In a simple way



CMB lensing likelihood gradients

$$-\ln p(X^{\text{dat}} | \phi) = \frac{1}{2} X^{\text{dat}} \mathbf{Cov}_{\phi}^{-1} X^{\text{dat}} + \frac{1}{2} \ln \det \mathbf{Cov}_{\phi}$$

Anisotropic CMB spectra

(Hirata & Seljak 2003, JC & Lewis 2017)



Likelihood gradients w.r.t. to ϕ_{LM} :

$$g_{\phi} - \langle g_{\phi} \rangle$$

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Anisotropic CMB spectra

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Likelihood gradients w.r.t. to ϕ_{LM} :

$$g_{\phi} - \langle g_{\phi} \rangle$$

Massage these equations a bit, to find:

$$g_{\phi}(\hat{n}) = |A(\hat{n})| \text{ (Optimal QE on } \phi\text{-delensed CMB)} (\hat{n} + \nabla \phi(\hat{n}))$$

Magnification
(coordinate distortions
from delensing)

Deflected QE on maps delensed by ϕ

Beyond-QE EB lensing reconstruction

- « Optimal » EB-estimator of residual lensing

Weighted B-residuals

(~ data - prediction from delensed E,
« template delensing »)

Stokes gradient maps from rec. E


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

Magnification
(coordinate distortions
from delensing)

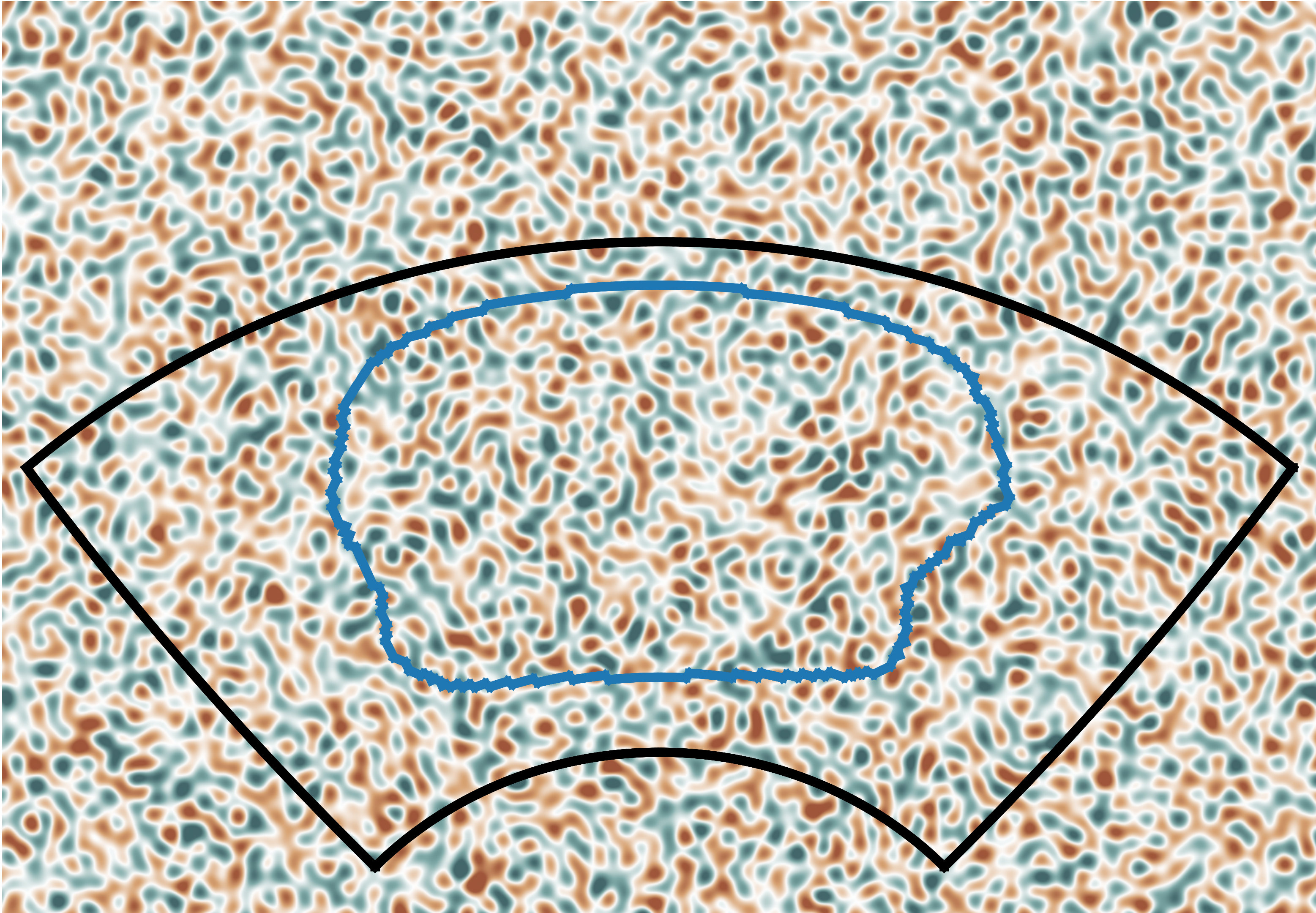
Deflected QE on maps delensed by ϕ

Simulated BK24 EB-delensing

B input

SPT-3G

BICEP/Keck

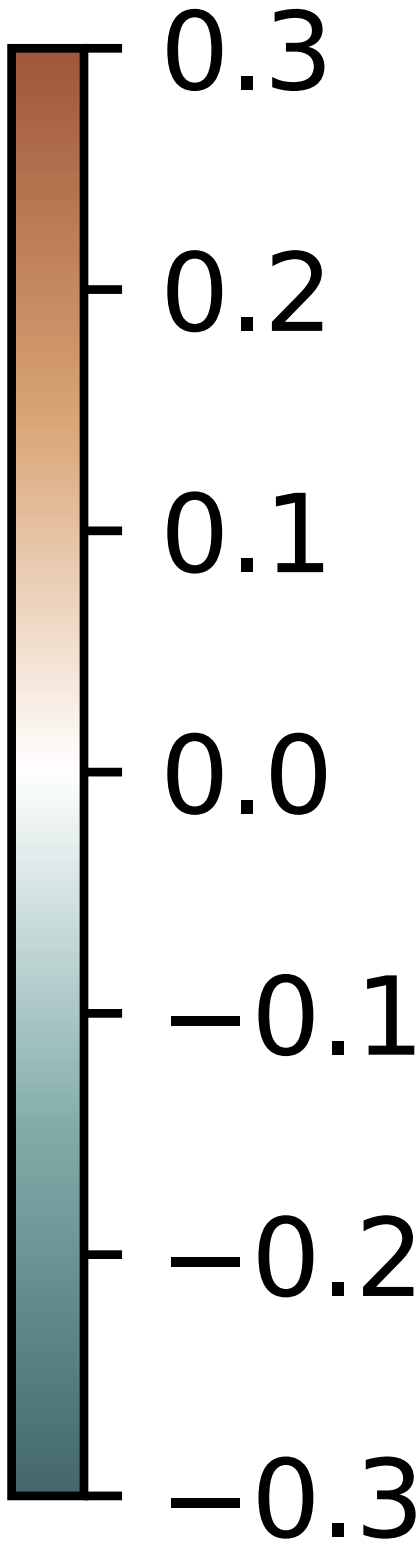
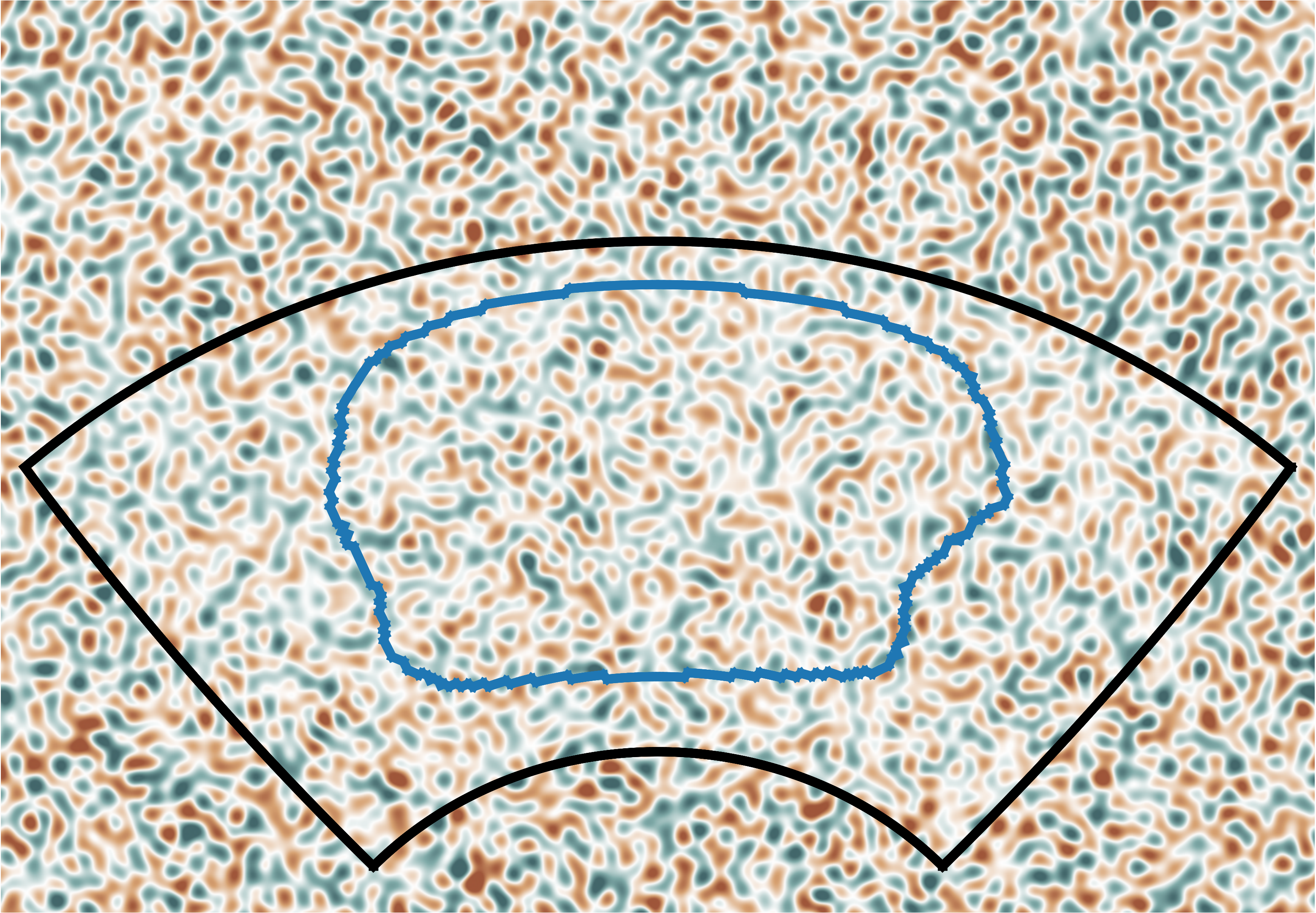


Simulated BK24 EB-delensing

B^{delensed} (iter 0)

SPT-3G

BICEP/Keck

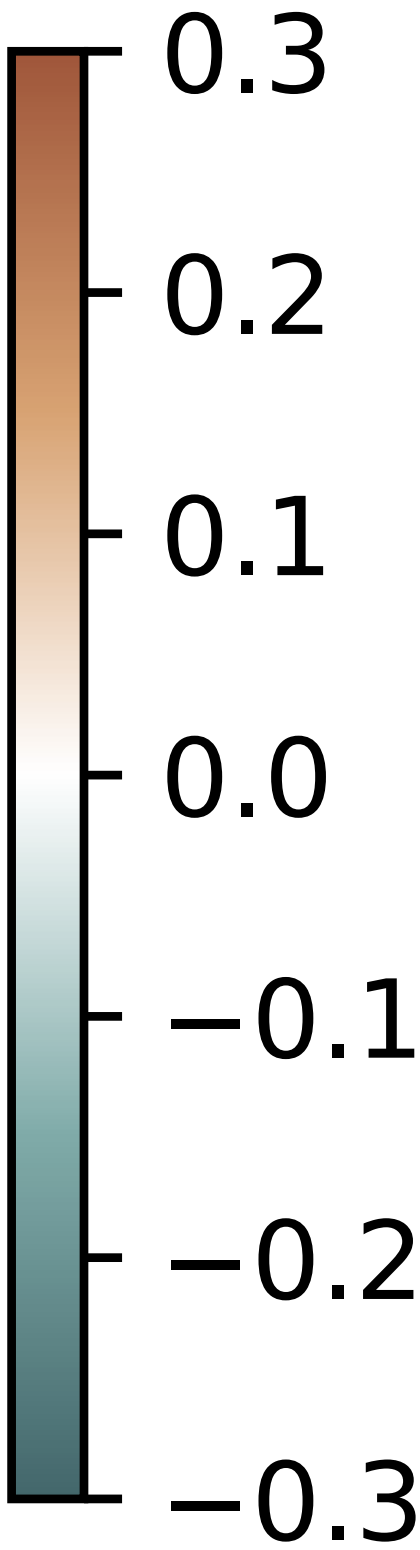
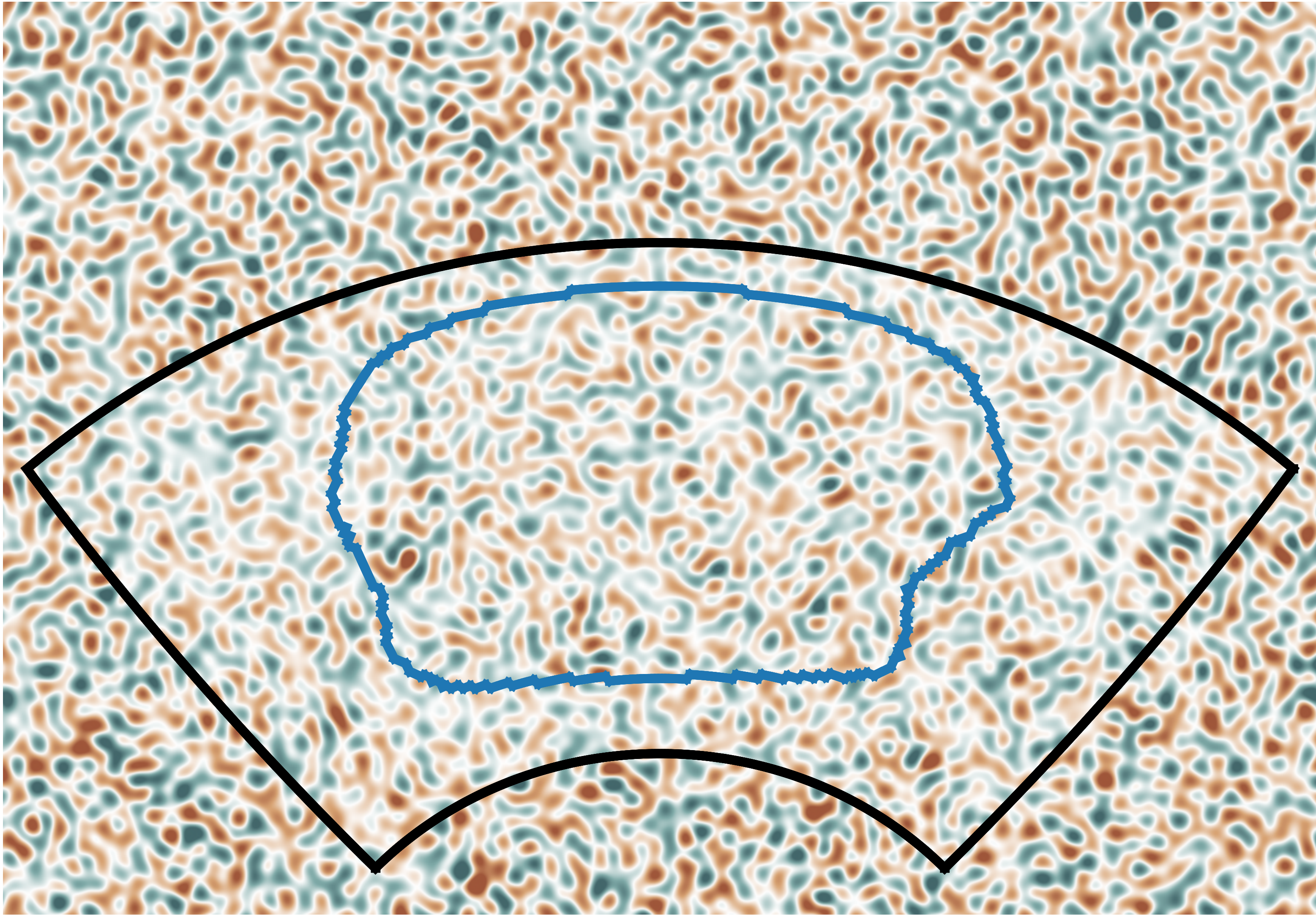


Simulated BK24 EB-delensing

B^{delensed} (iter 1)

SPT-3G

BICEP/Keck

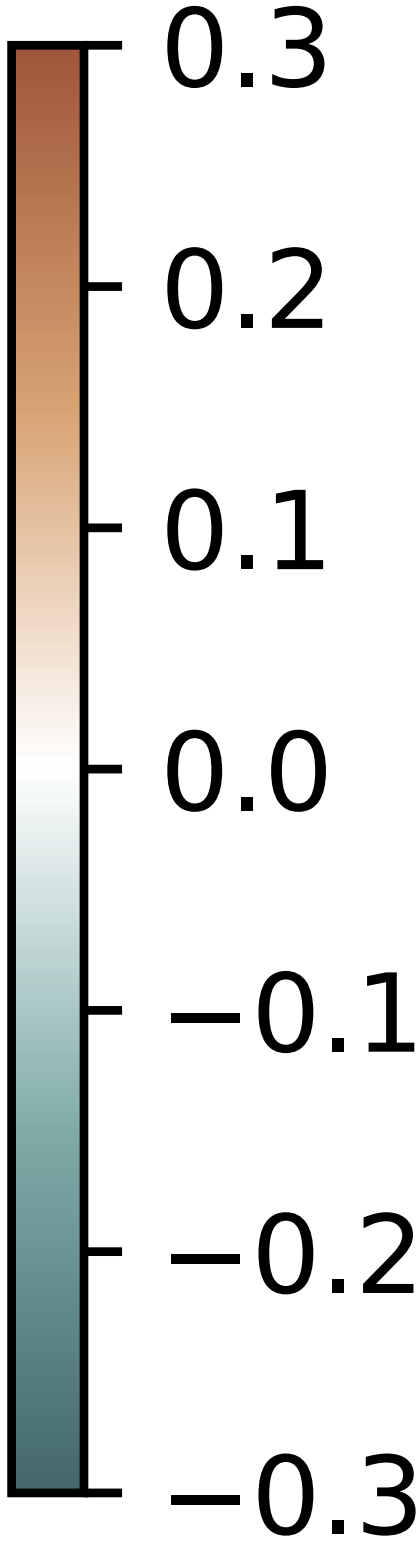
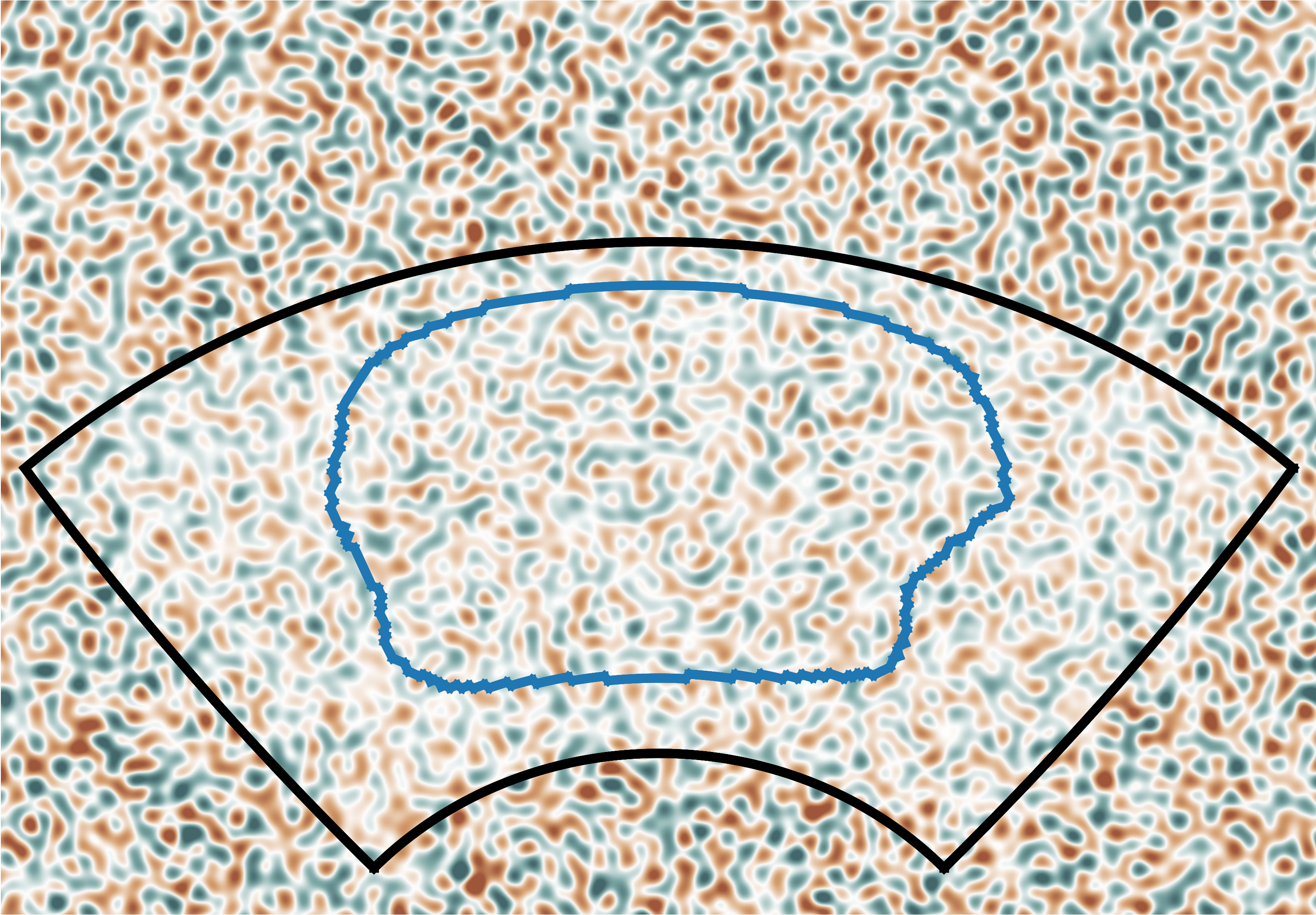


Simulated BK24 EB-delensing

B^{delensed} (iter 2)

SPT-3G

BICEP/Keck

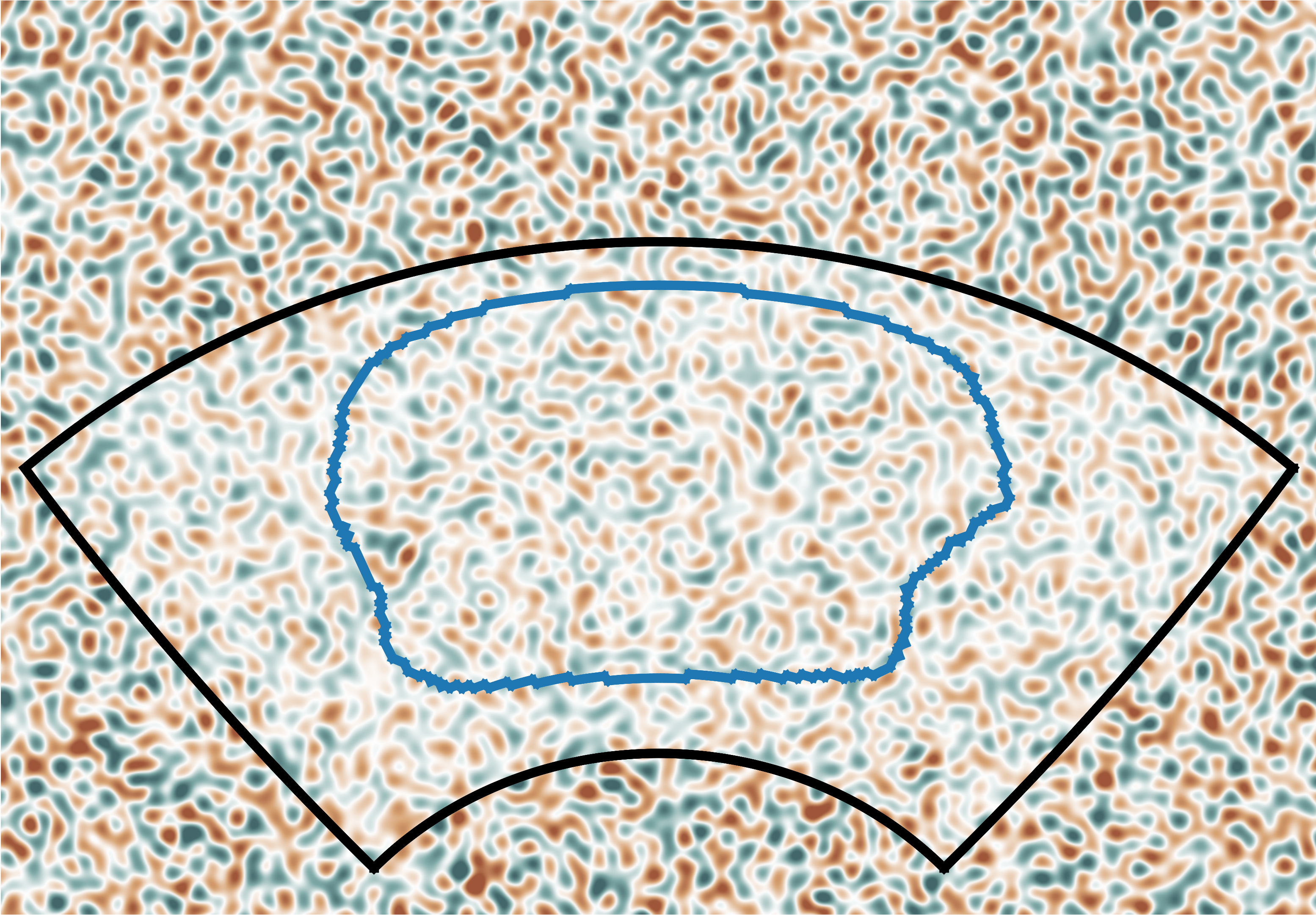


Simulated BK24 EB-delensing

B^{delensed} (iter 3)

SPT-3G

BICEP/Keck

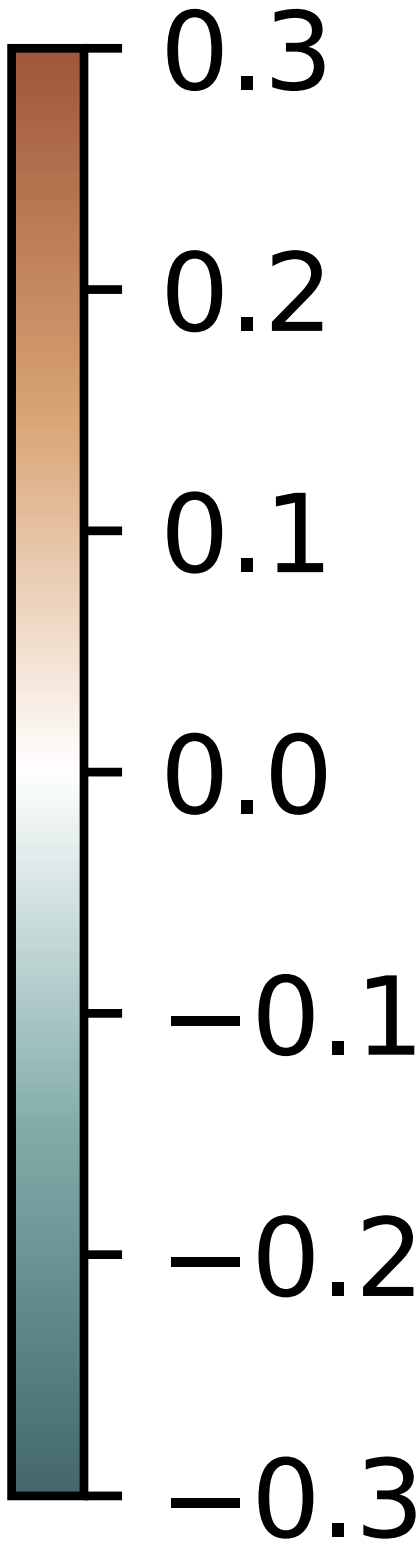
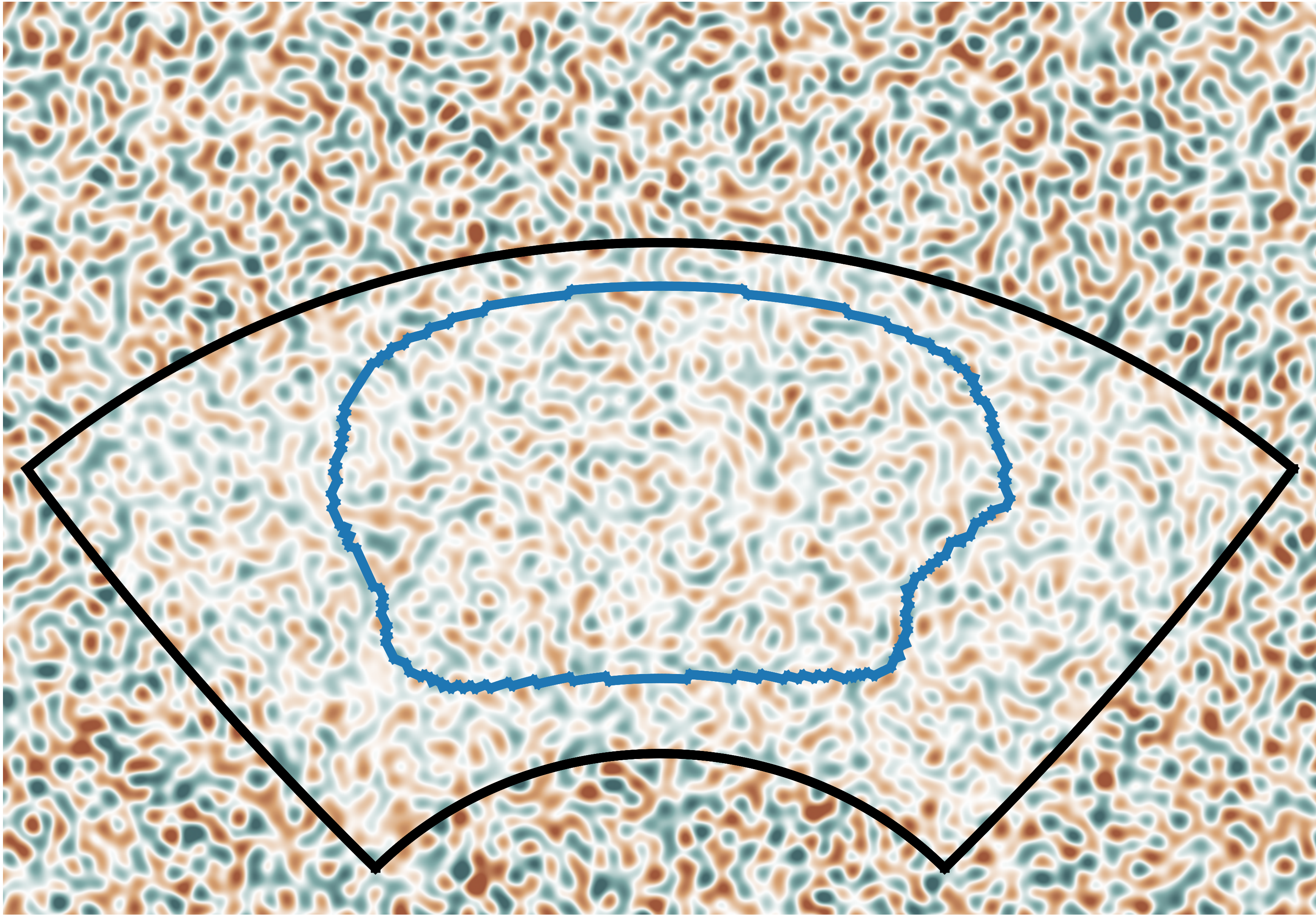


Simulated BK24 EB-delensing

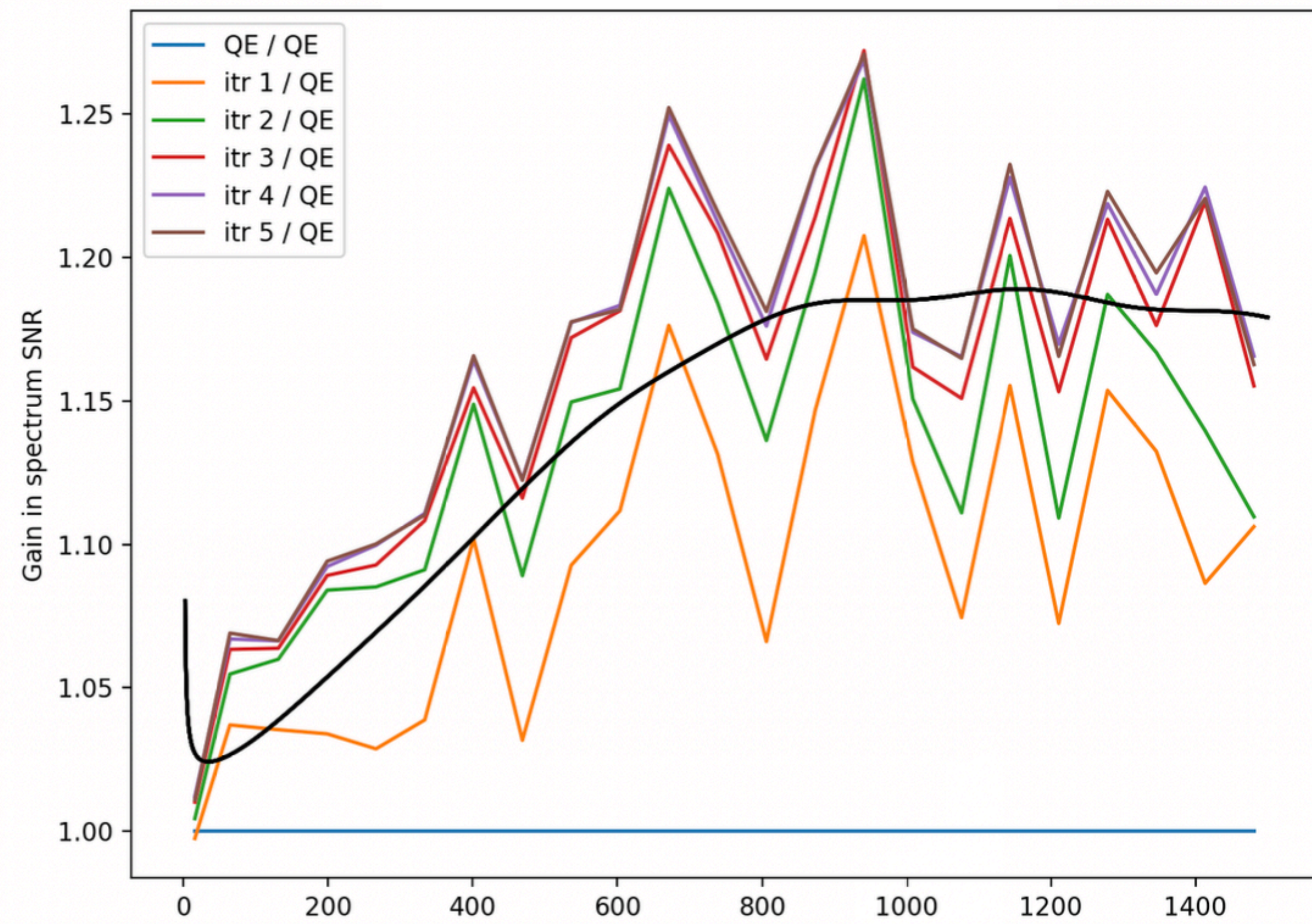
B^{delensed} (iter 4)

SPT-3G

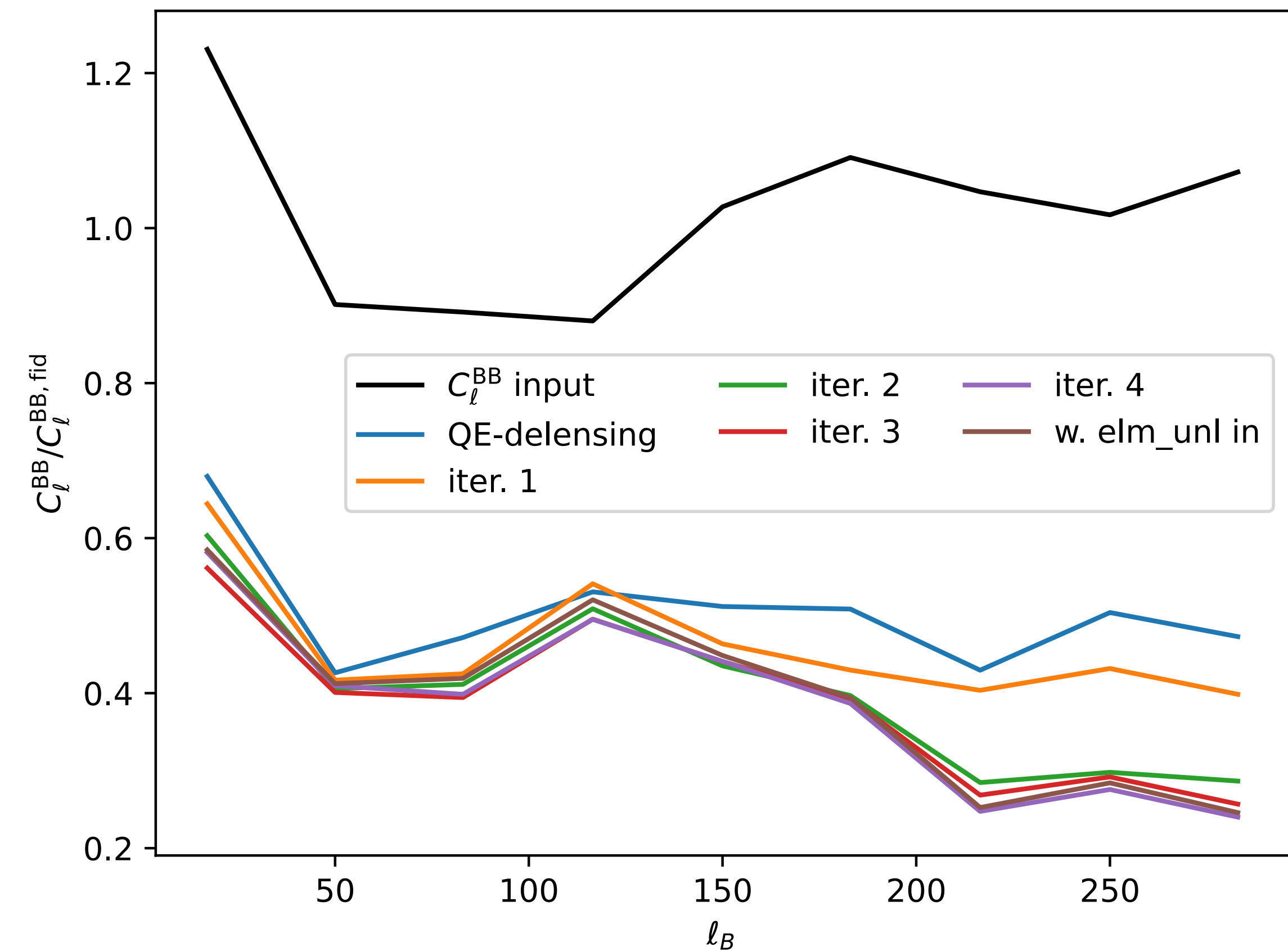
BICEP/Keck



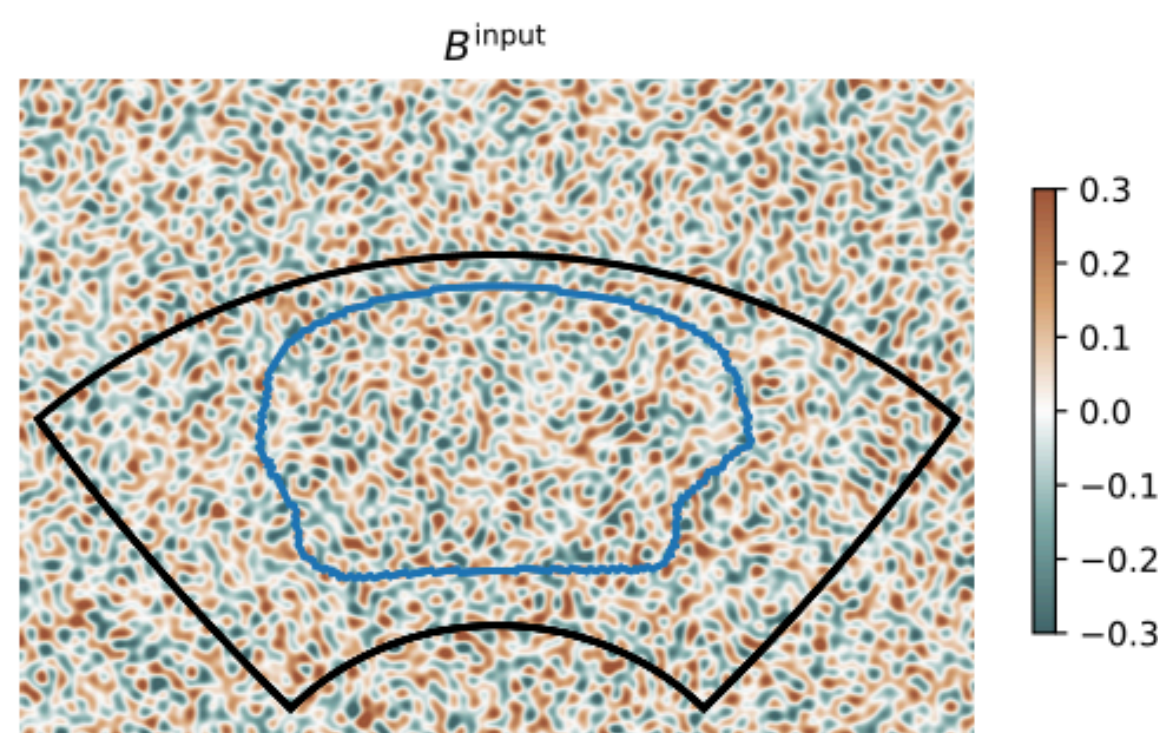
Improvement in lensing spectrum SNR



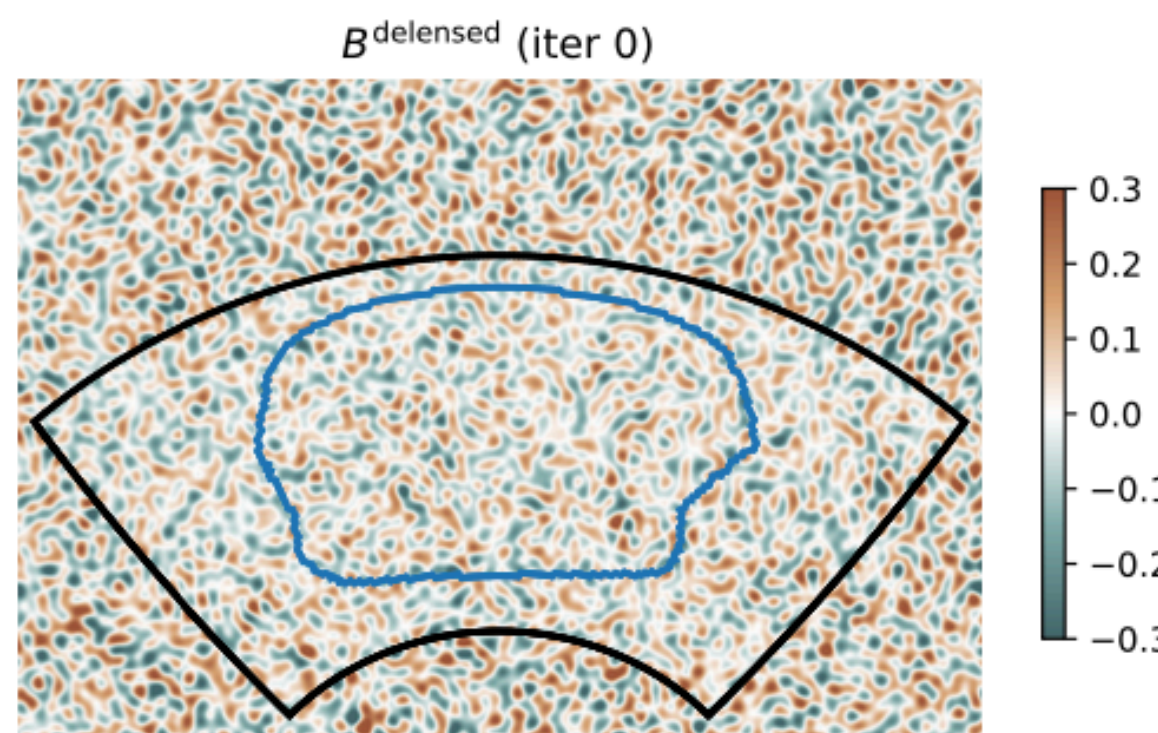
Reduction in degree-scale B-power



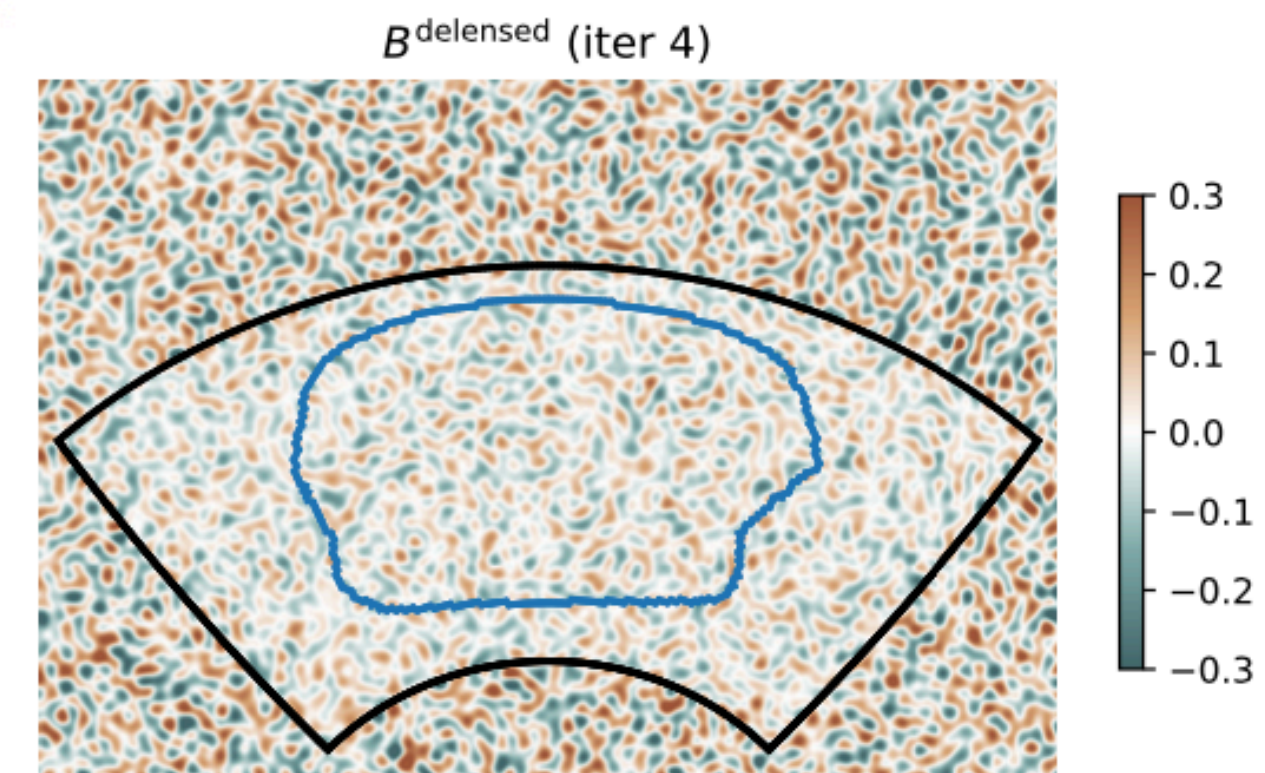
Input



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. Progress requires now a « Synergy of CMB experiments »
- BICEP/Keck + SPT-3G now available data has potential for $\sigma(r) \sim 0.003$, depending on assumptions (3x better than BK18), and delensing is essential to achieve this. We are working on it.
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Thanks!