Lensing as a foreground and cosmological probe

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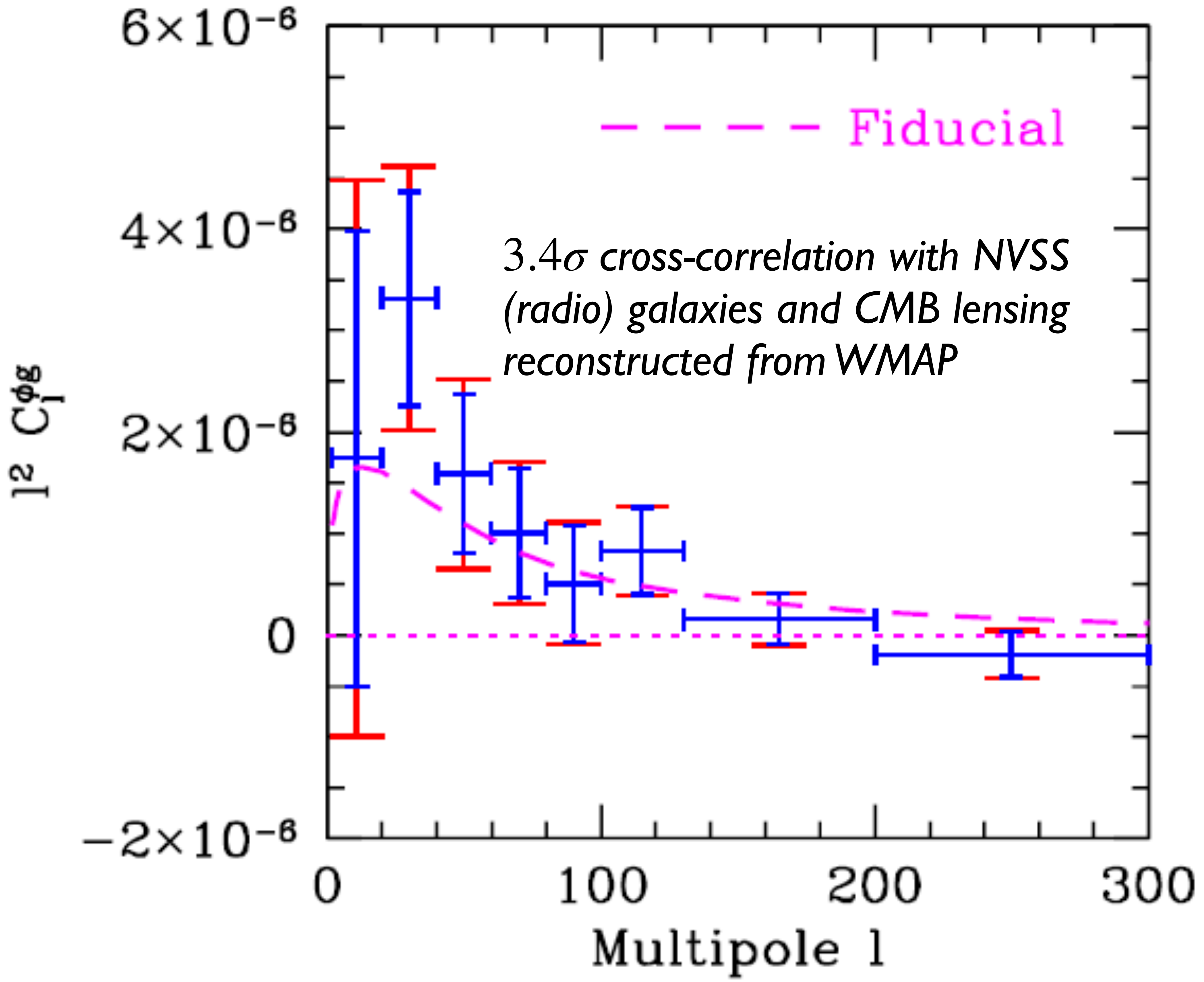
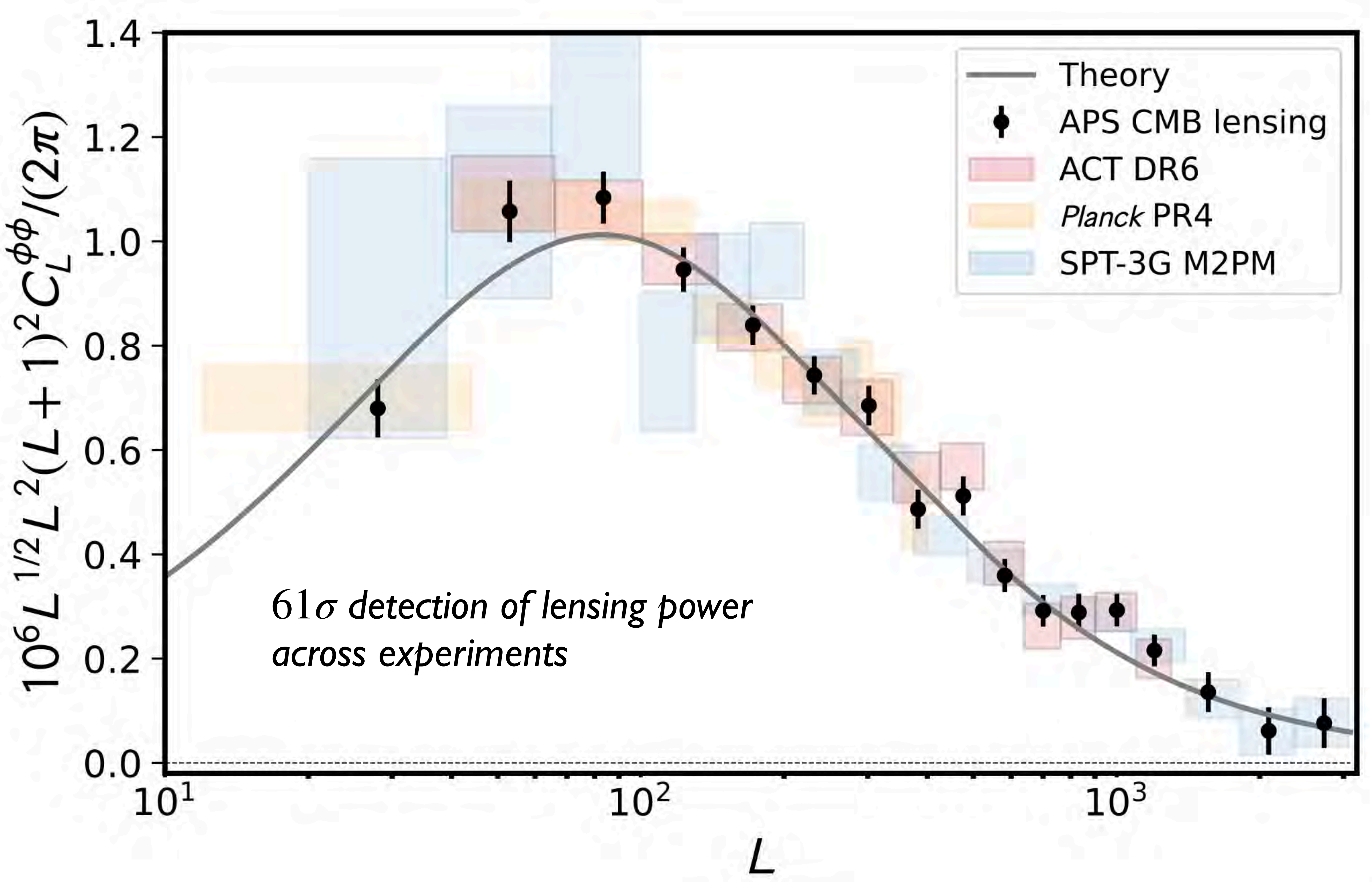
Entering adulthood: CMB lensing@18

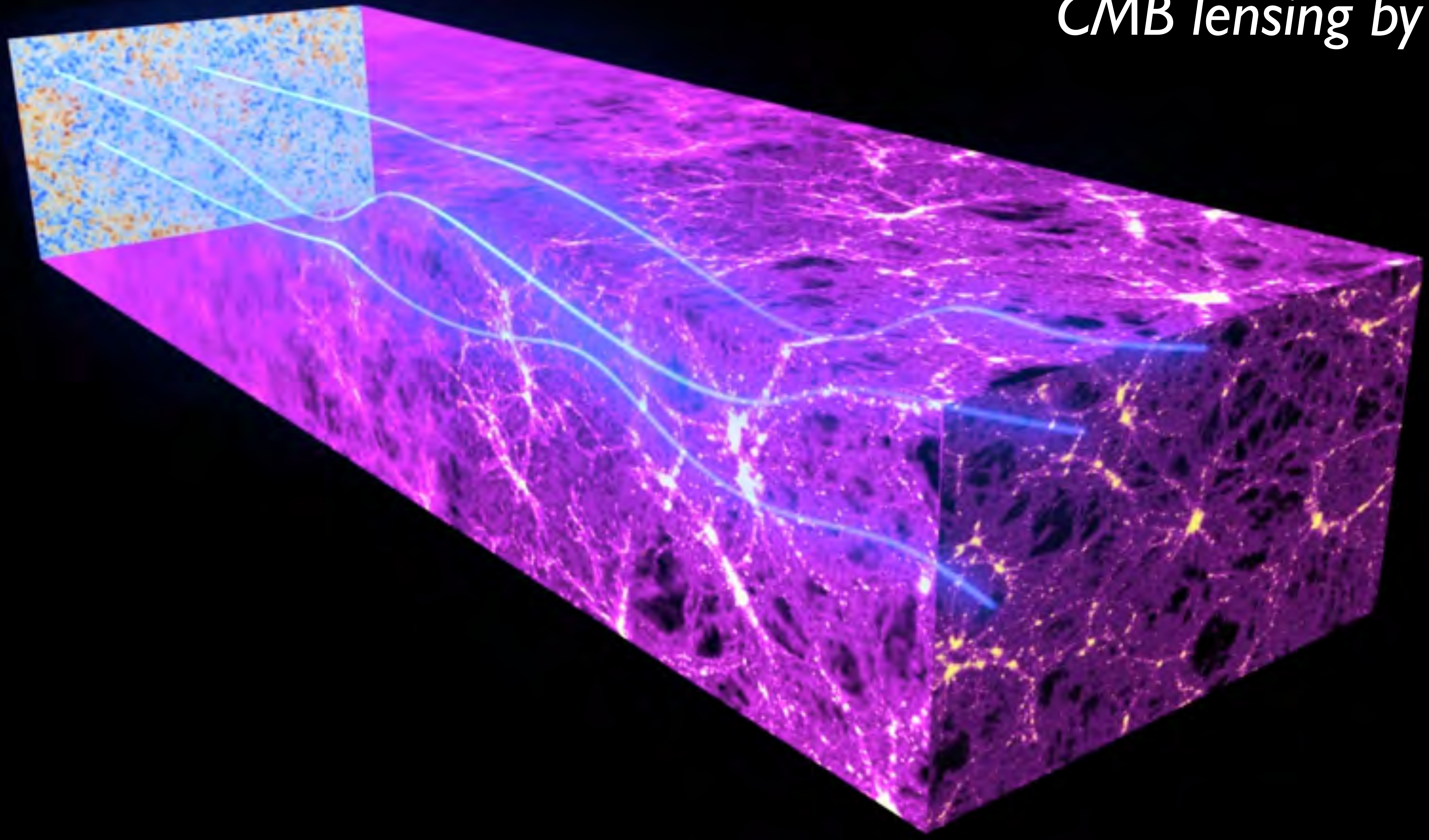




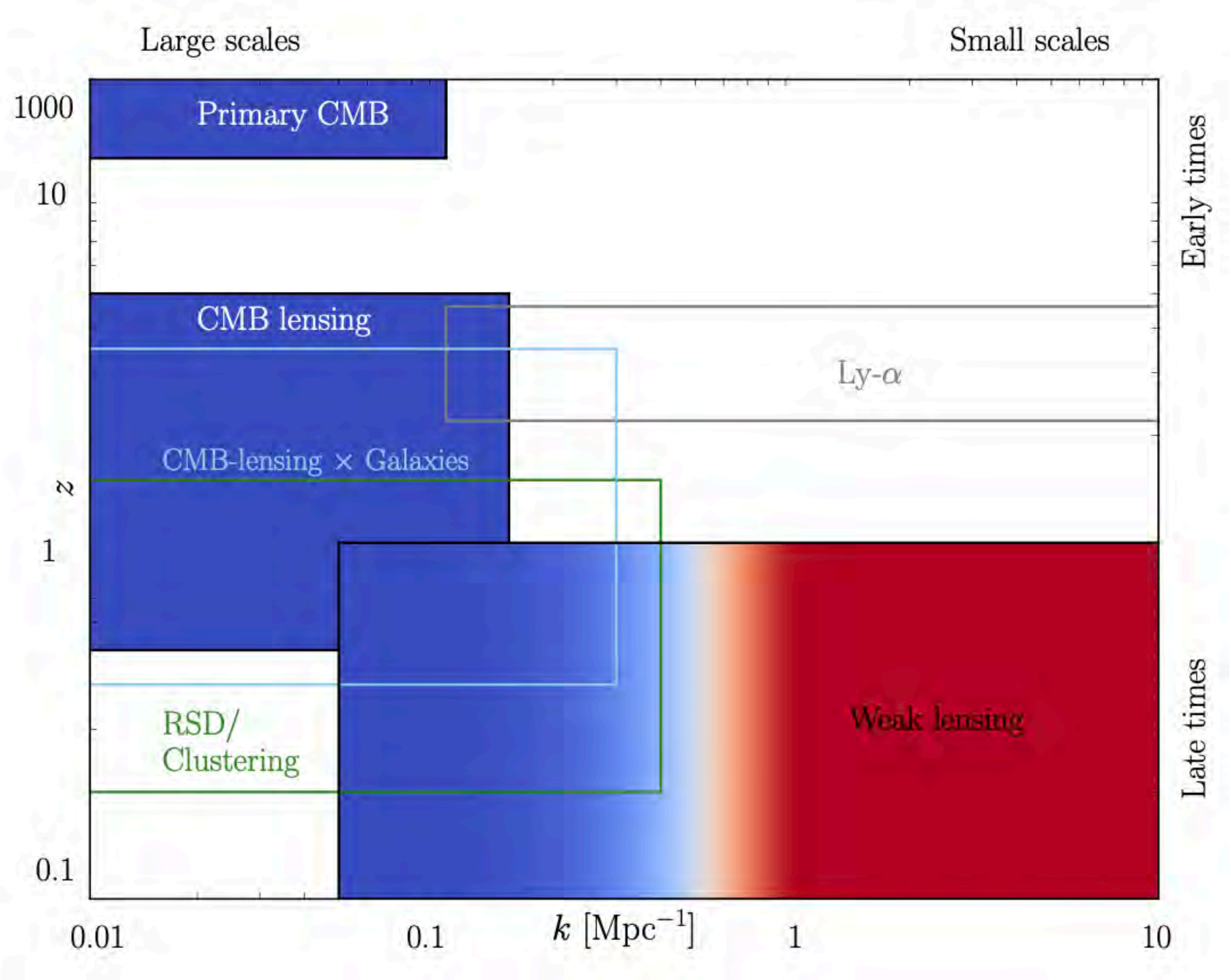
Smith+ 2007

Qu+ 2015

CMB lensing by LSS



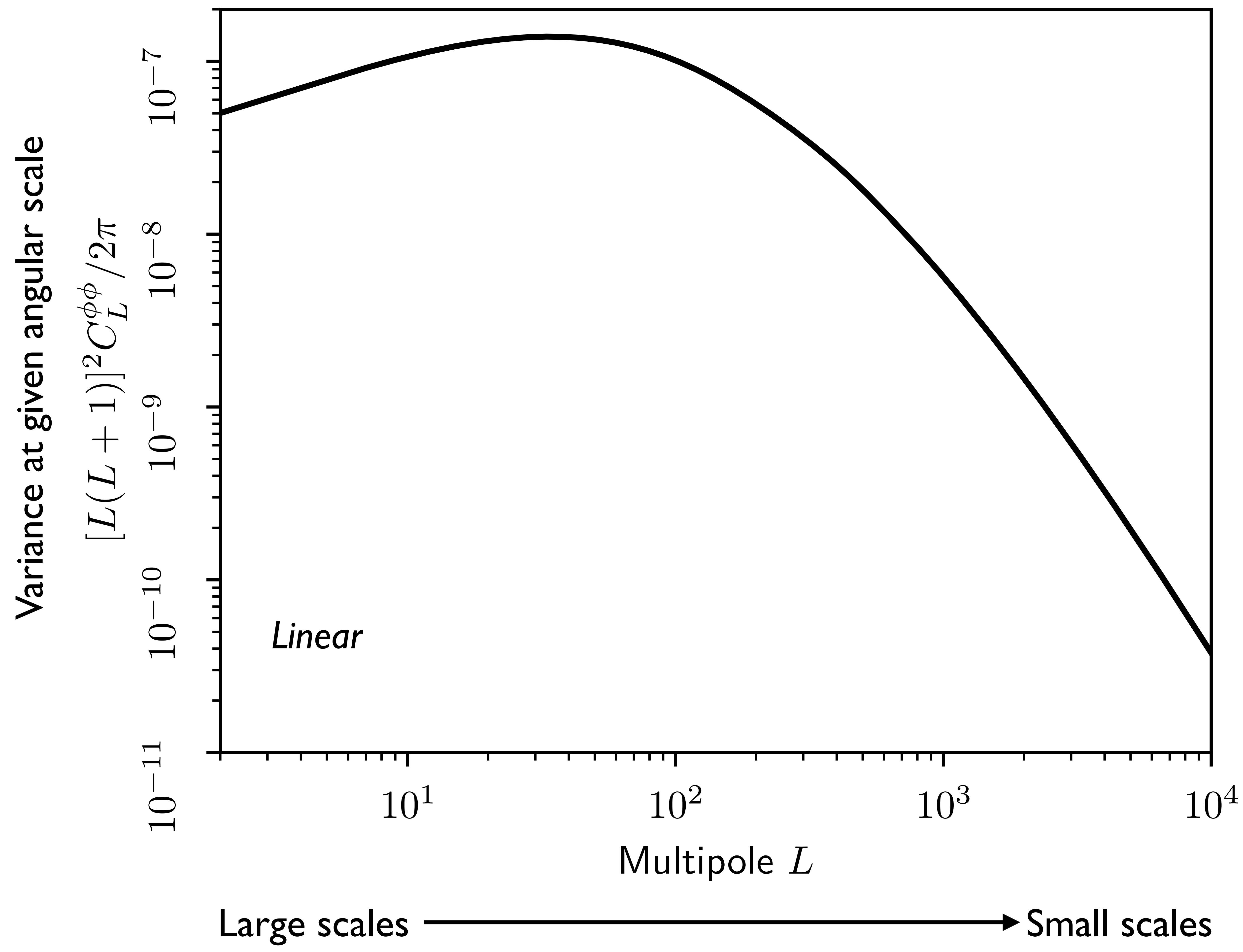
CMB lensing: a large-scale, high-redshift probe of structure



Preston+ 2023

CMB lensing: robust probe of mostly linear structure

$$T^{\text{lens}}(\hat{\boldsymbol{n}}) = T^{\text{unlens}}(\hat{\boldsymbol{n}} + \boldsymbol{\nabla}\phi) \quad \text{where} \quad \phi(\hat{\boldsymbol{n}}) = -\int_0^{\chi_*} d\chi \, \frac{\chi_* - \chi}{\chi_* \chi} (\Phi + \Psi)(\chi \hat{\boldsymbol{n}}; \eta_0 - \chi)$$



- Redshift of source plane known
- Statistics of fluctuations in source plane well understood
- High-z lenses and relatively large scales

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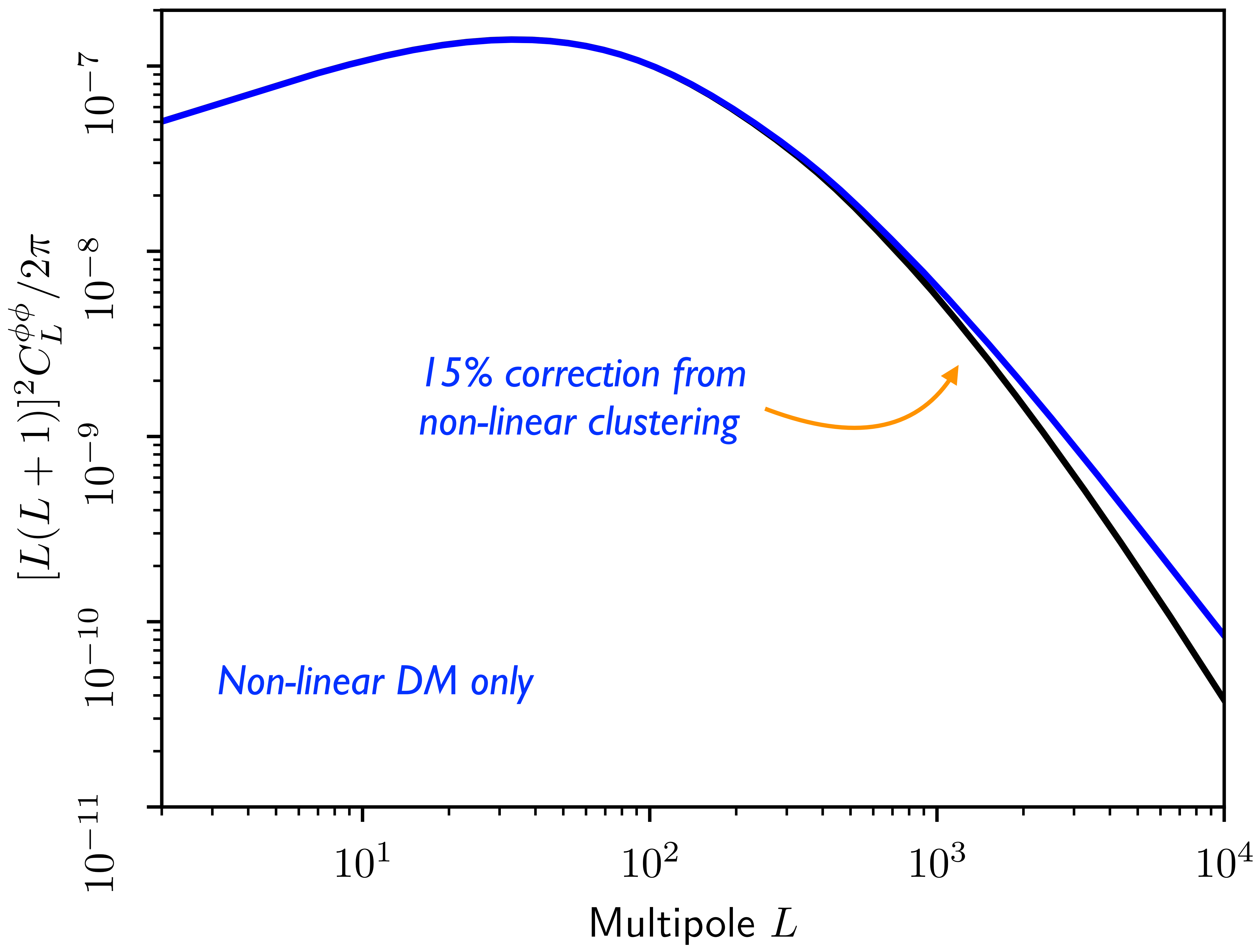

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  - Modest non-linear corrections

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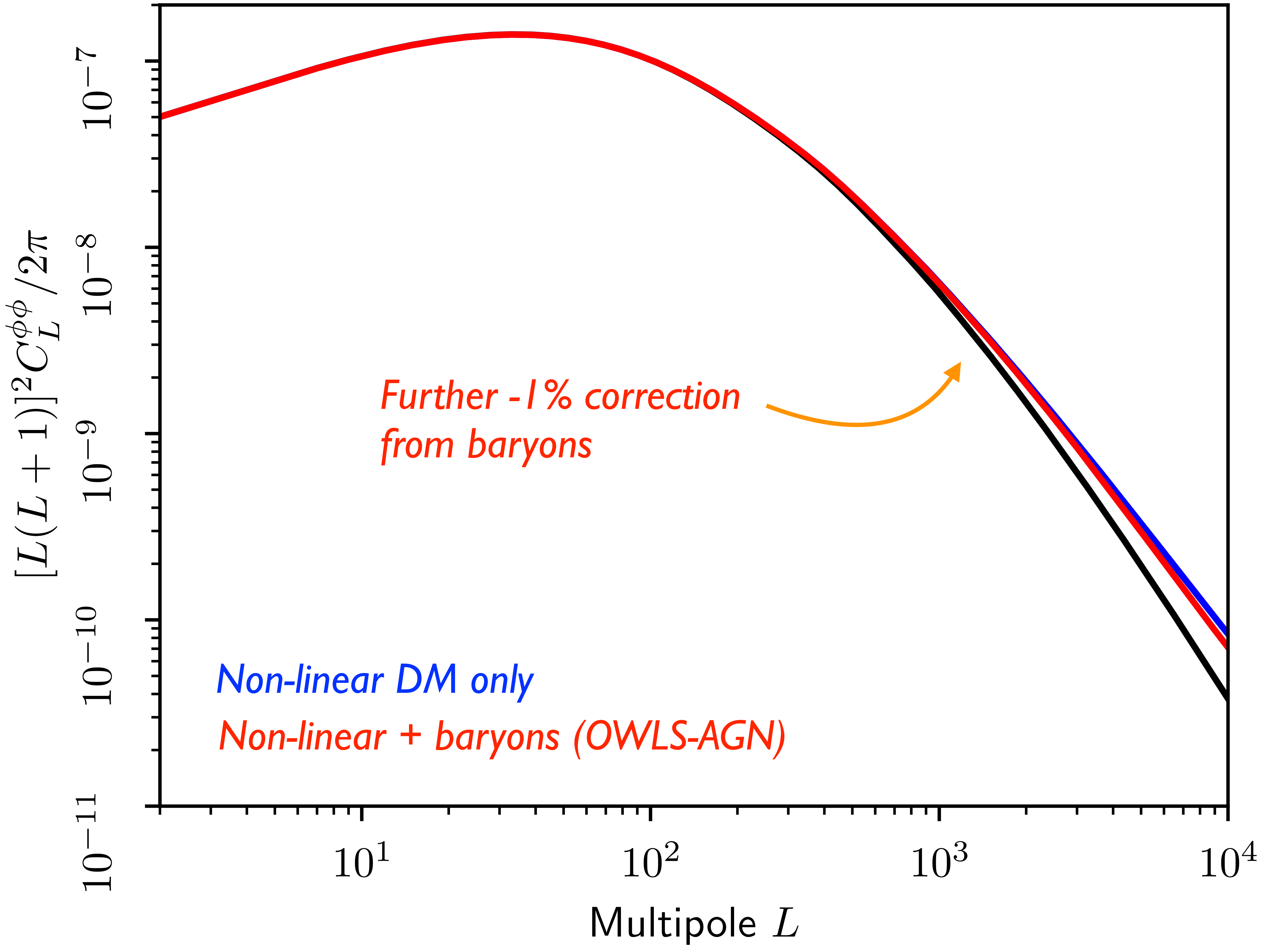


- Redshift of source plane known
- Statistics of fluctuations in source plane well understood
- High-z lenses and relatively large scales
  - Modest non-linear corrections
  - Baryons negligible until CMB-S4 era

CMB lensing reconstruction

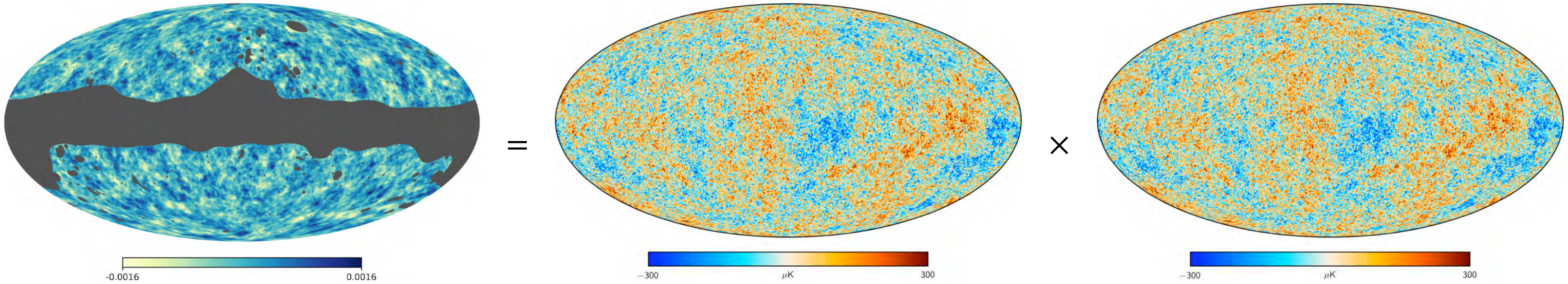
- Fixed lenses ϕ introduce anisotropic correlations in lensed CMB, e.g., for T:

$$\langle T(\boldsymbol{\ell})T(\boldsymbol{L}-\boldsymbol{\ell})\rangle_{\mathrm{CMB}} = \underbrace{\boldsymbol{L}\cdot\left[\boldsymbol{\ell}C_{\ell}^{TT} + (\boldsymbol{L}-\boldsymbol{\ell})C_{|\boldsymbol{L}-\boldsymbol{\ell}|}^{TT}\right]}_{W^{TT}(\boldsymbol{\ell},\boldsymbol{L})}\phi(\boldsymbol{L})$$

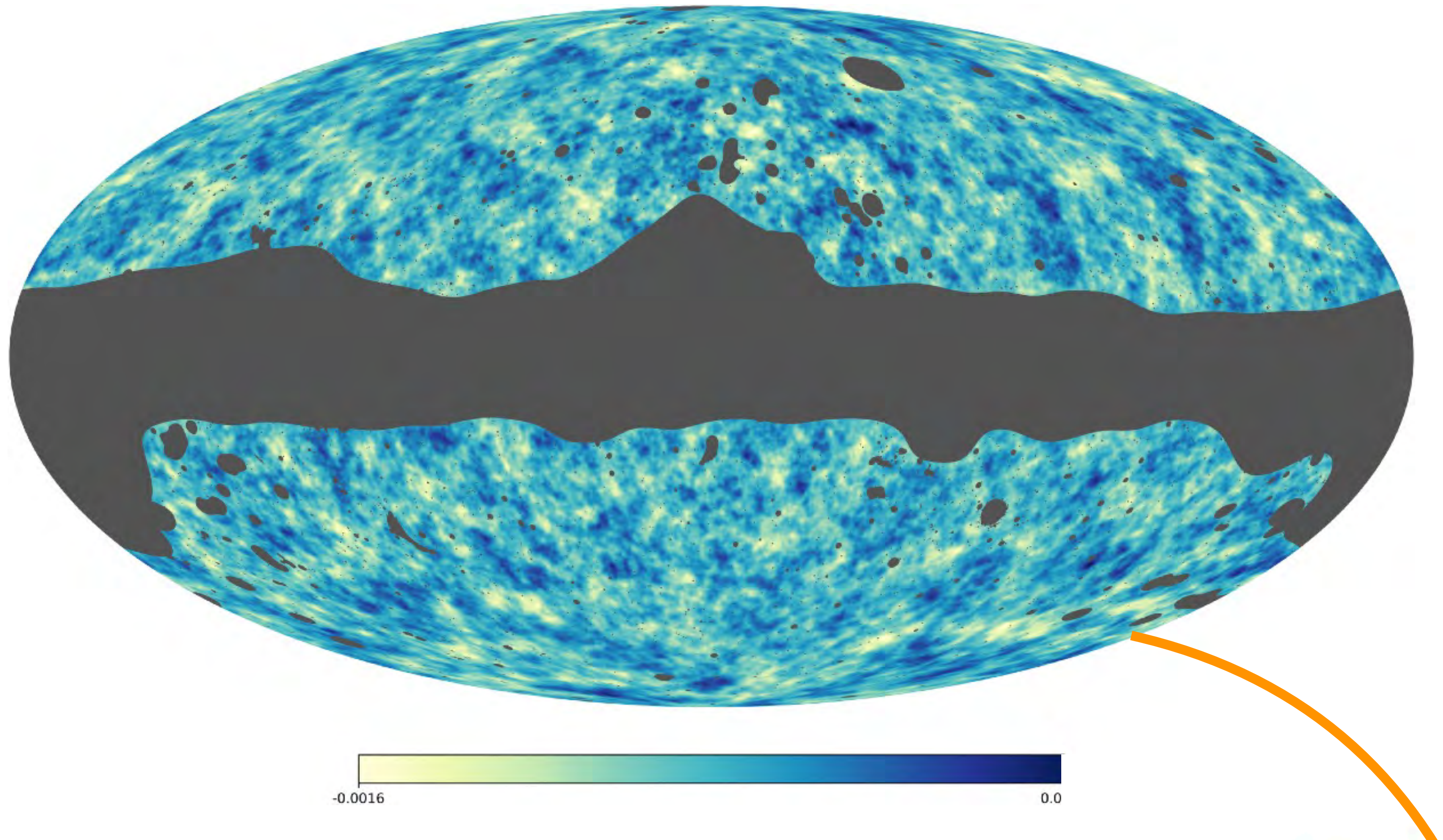
- Statistical (noisy) reconstruction of ϕ from quadratic combinations of CMB fields, e.g.,

$$\hat{\phi}(\boldsymbol{L}) = \frac{1}{\mathcal{R}_L^{TT}}\int\frac{d^2\boldsymbol{\ell}}{(2\pi)^2}\,W^{TT}(\boldsymbol{\ell},\boldsymbol{L})\bar{T}(\boldsymbol{\ell})\bar{T}(\boldsymbol{L}-\boldsymbol{\ell})$$

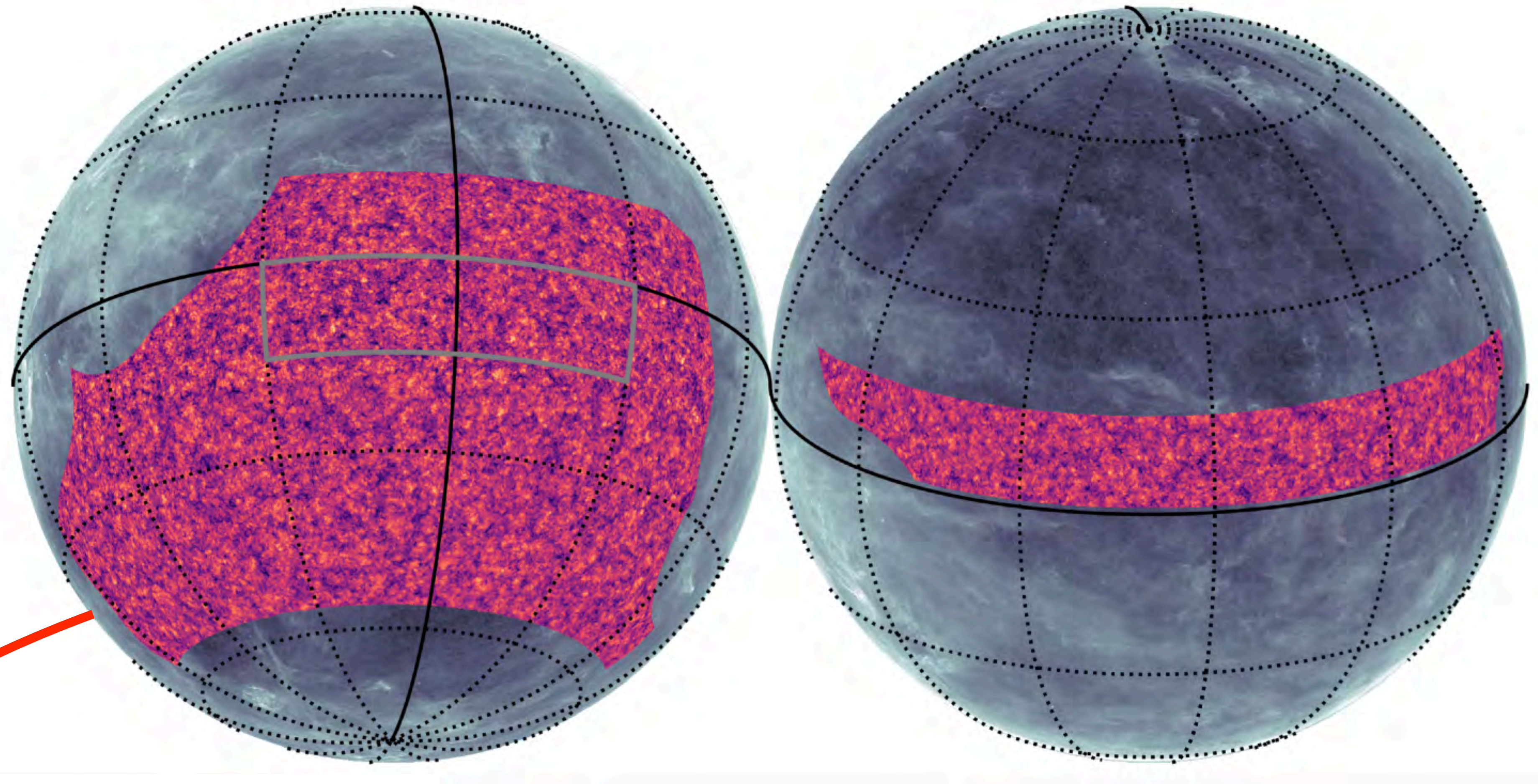
Normalisation *Known response to lensing* *Inverse-variance-filtered CMB fields*



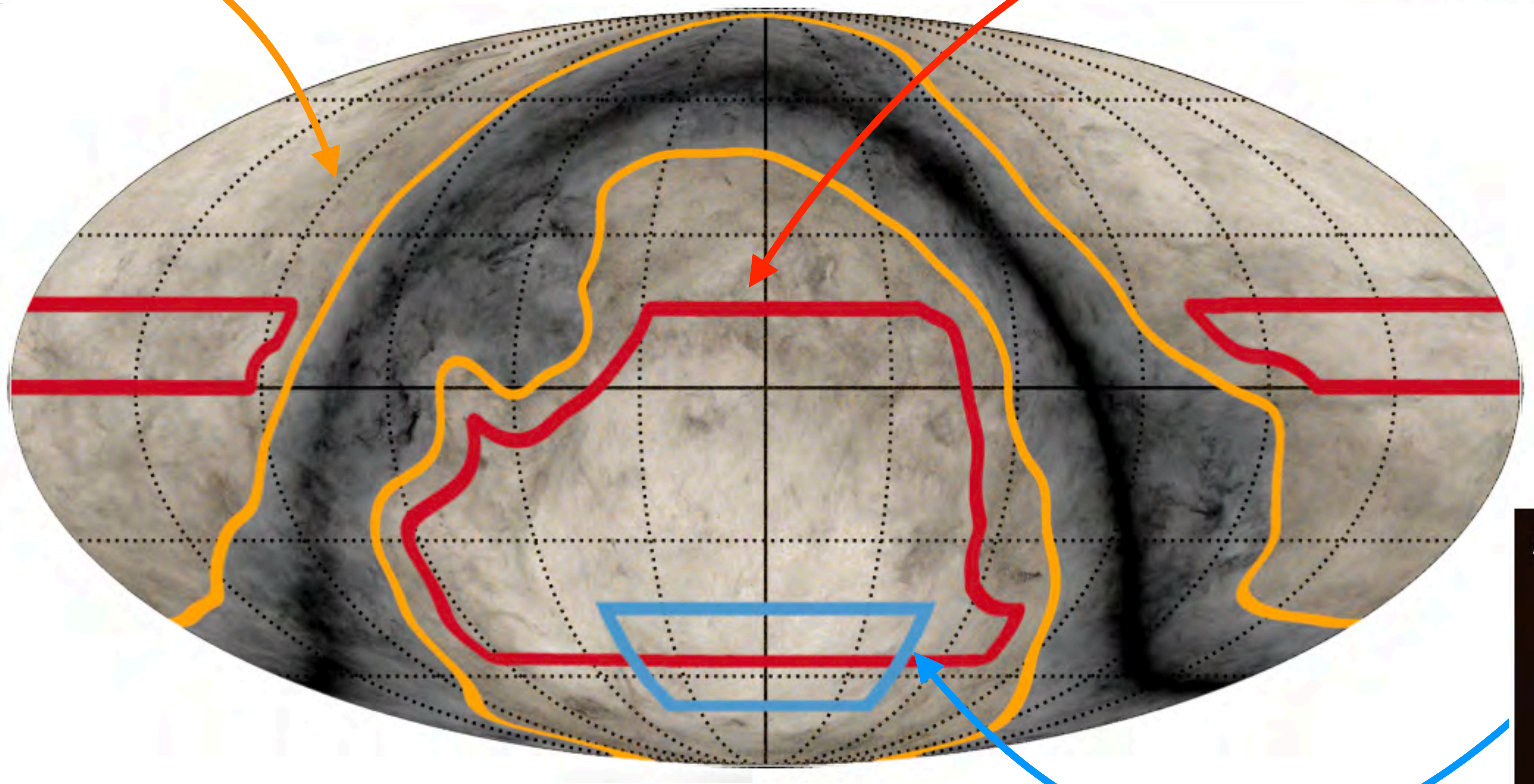
Reconstructed CMB lensing maps

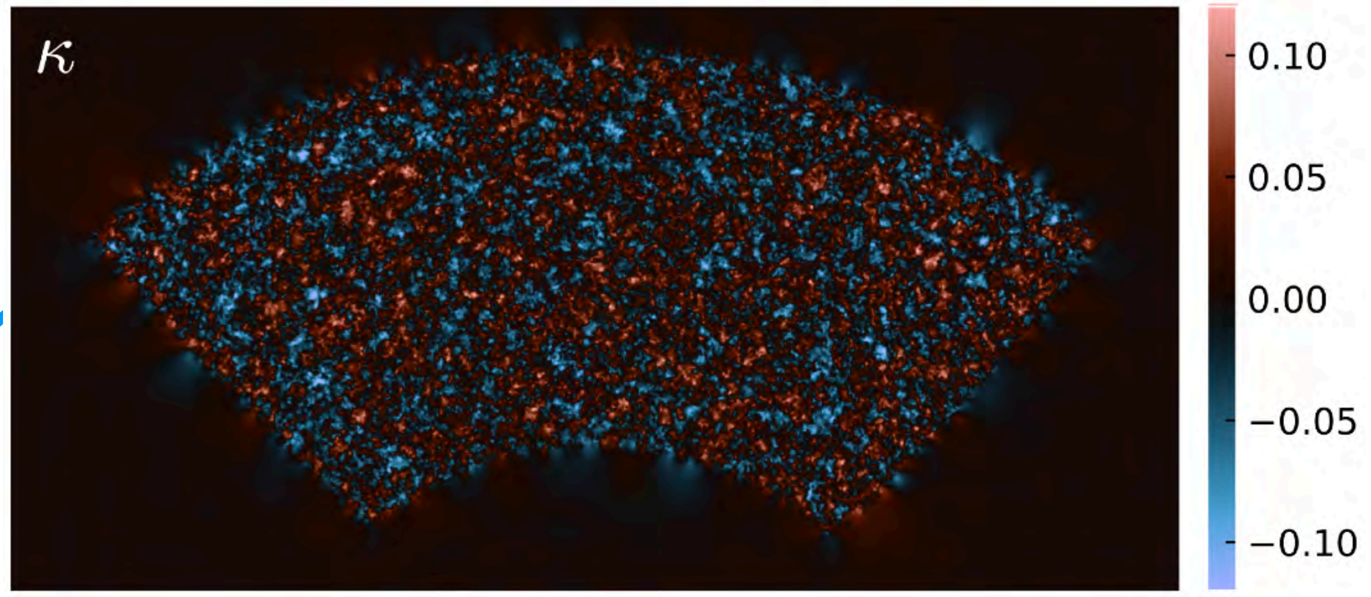


Planck 2018



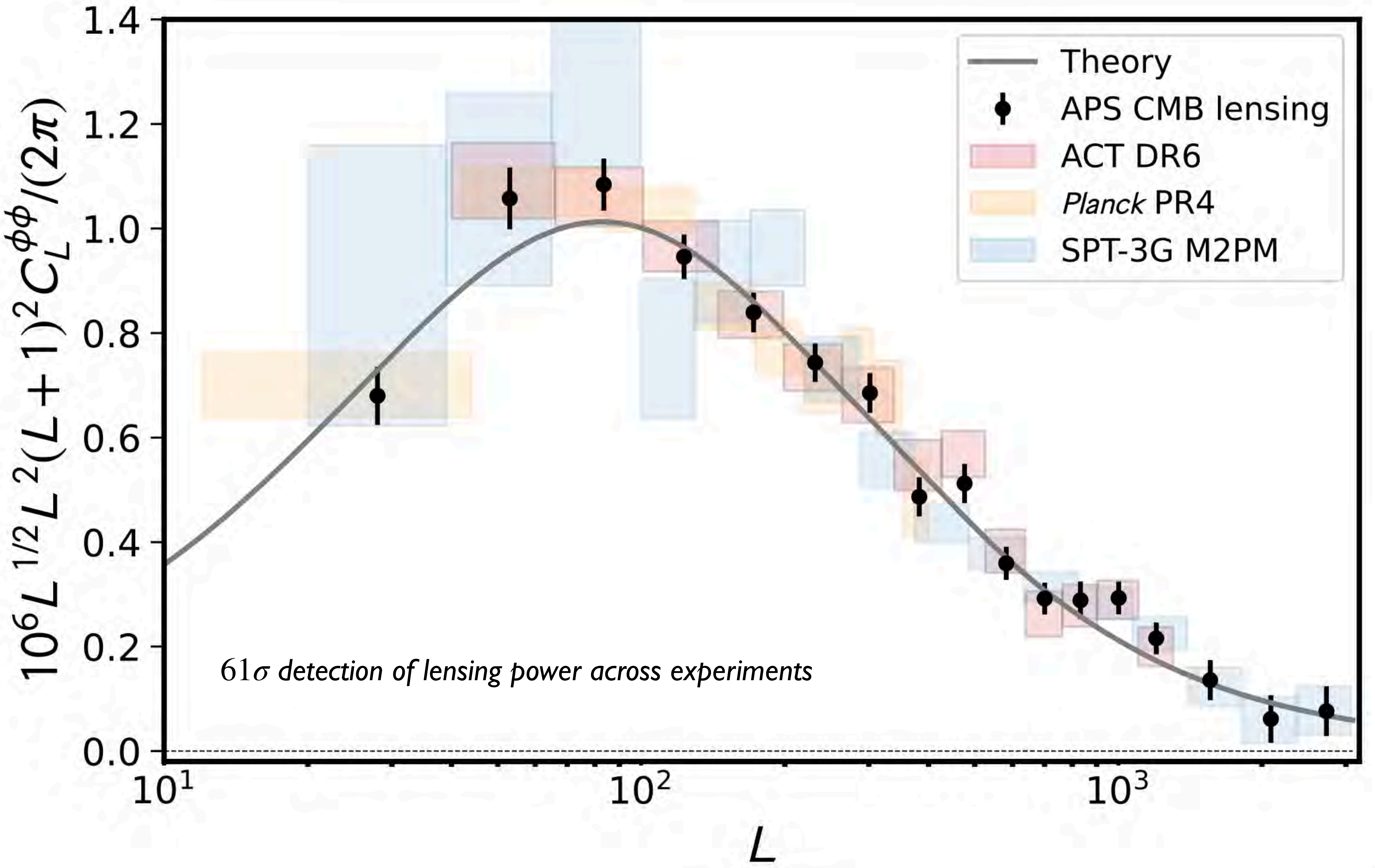
ACT – Madhavacheril+ 2024

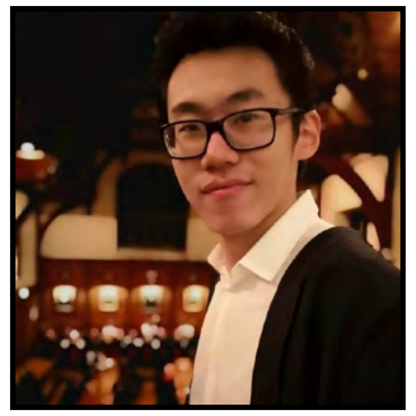




SPT-3G – Ge+ 2024

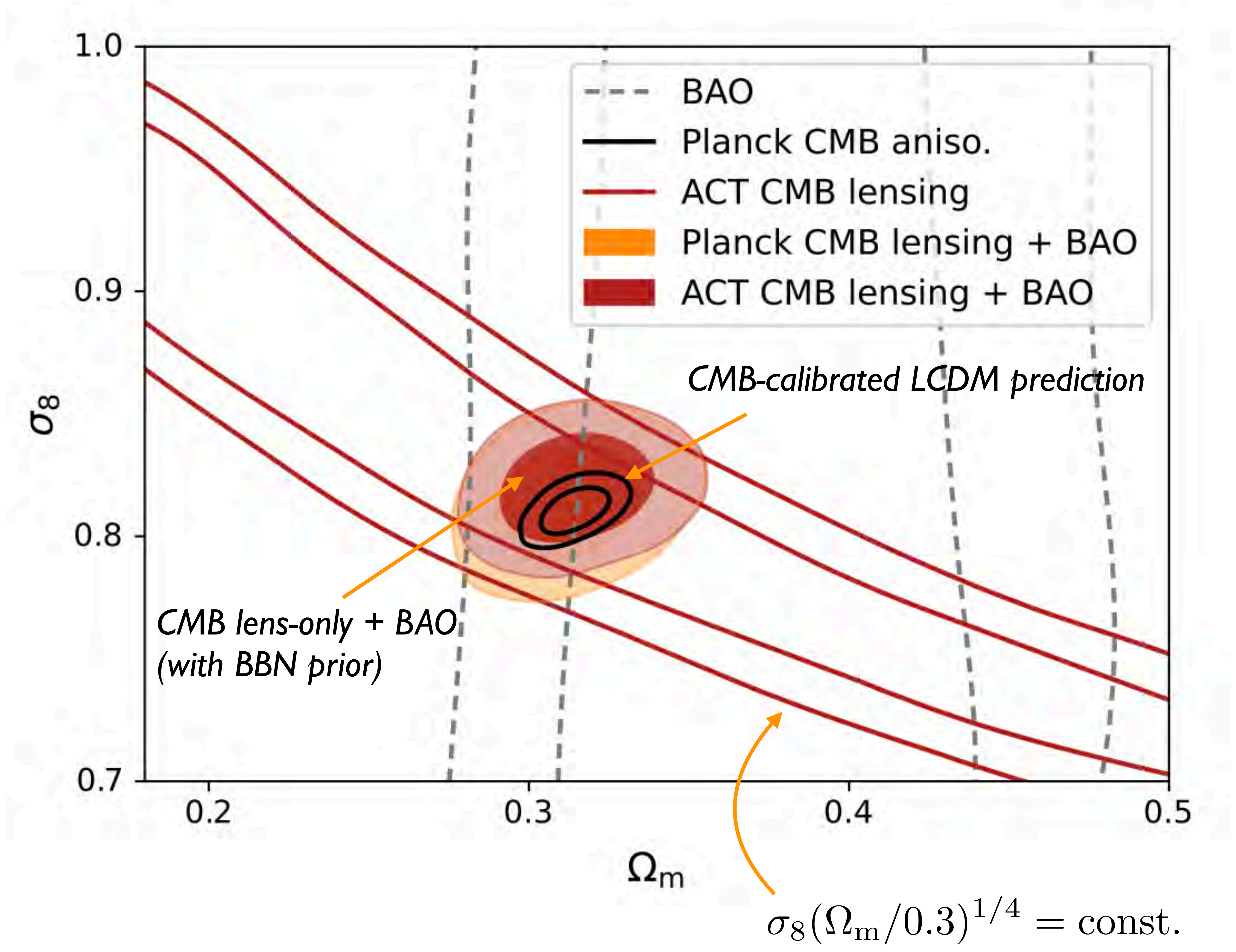
Reconstructed lensing power spectra





Qu+ 2025

CMB-lensing-only LCDM constraints



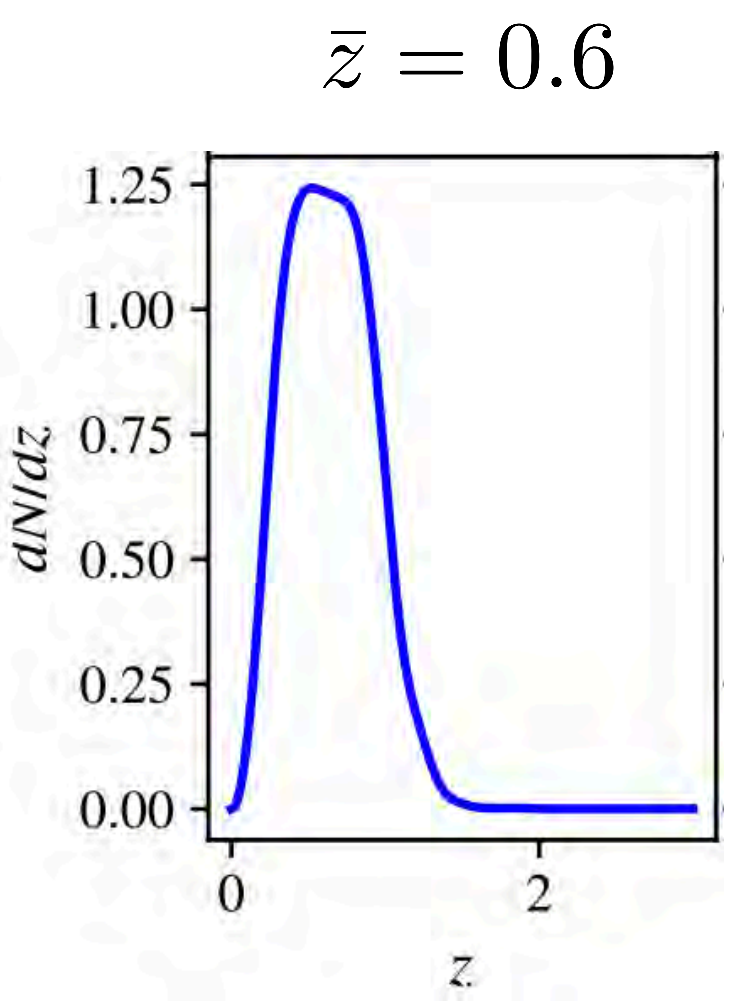
Priors for lens-only:

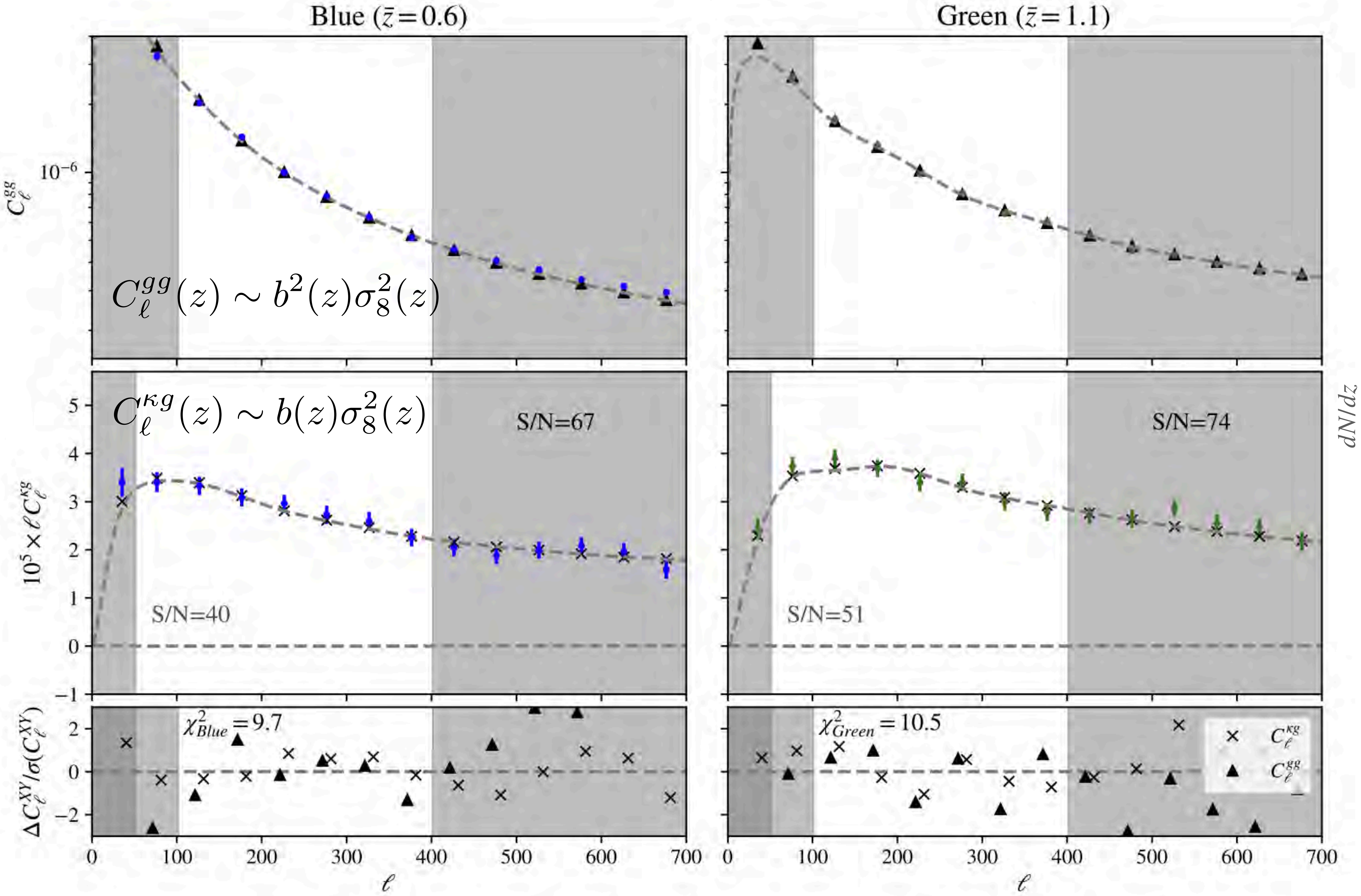
$$n_\mathrm{s} = 0.96 \pm 0.02$$
$$0.4 < h < 1.0$$
$$\Omega_\mathrm{b} h^2 = 0.0223 \pm 0.0005 \quad \mathrm{(BBN)}$$

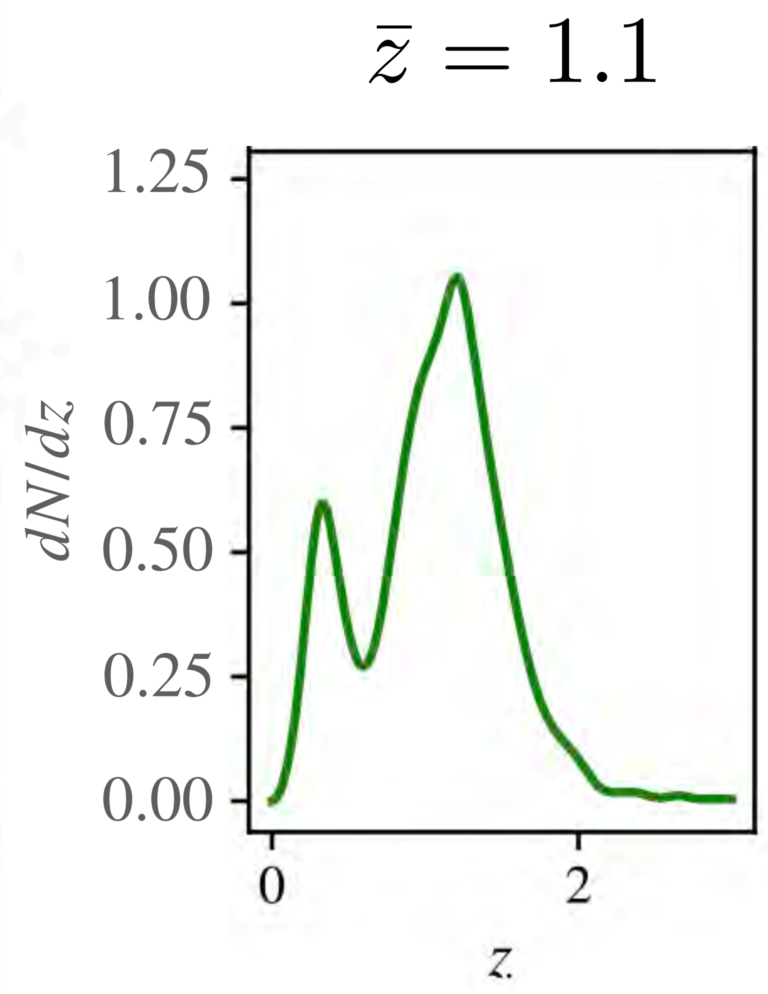
LCDM structure growth down to $z = 0.5\text{--}5$ for $k < 0.2\,\mathrm{Mpc}^{-1}$ consistent with primary CMB

Madhavacheril+ 2024

Cross-correlation measurements with unWISE galaxies

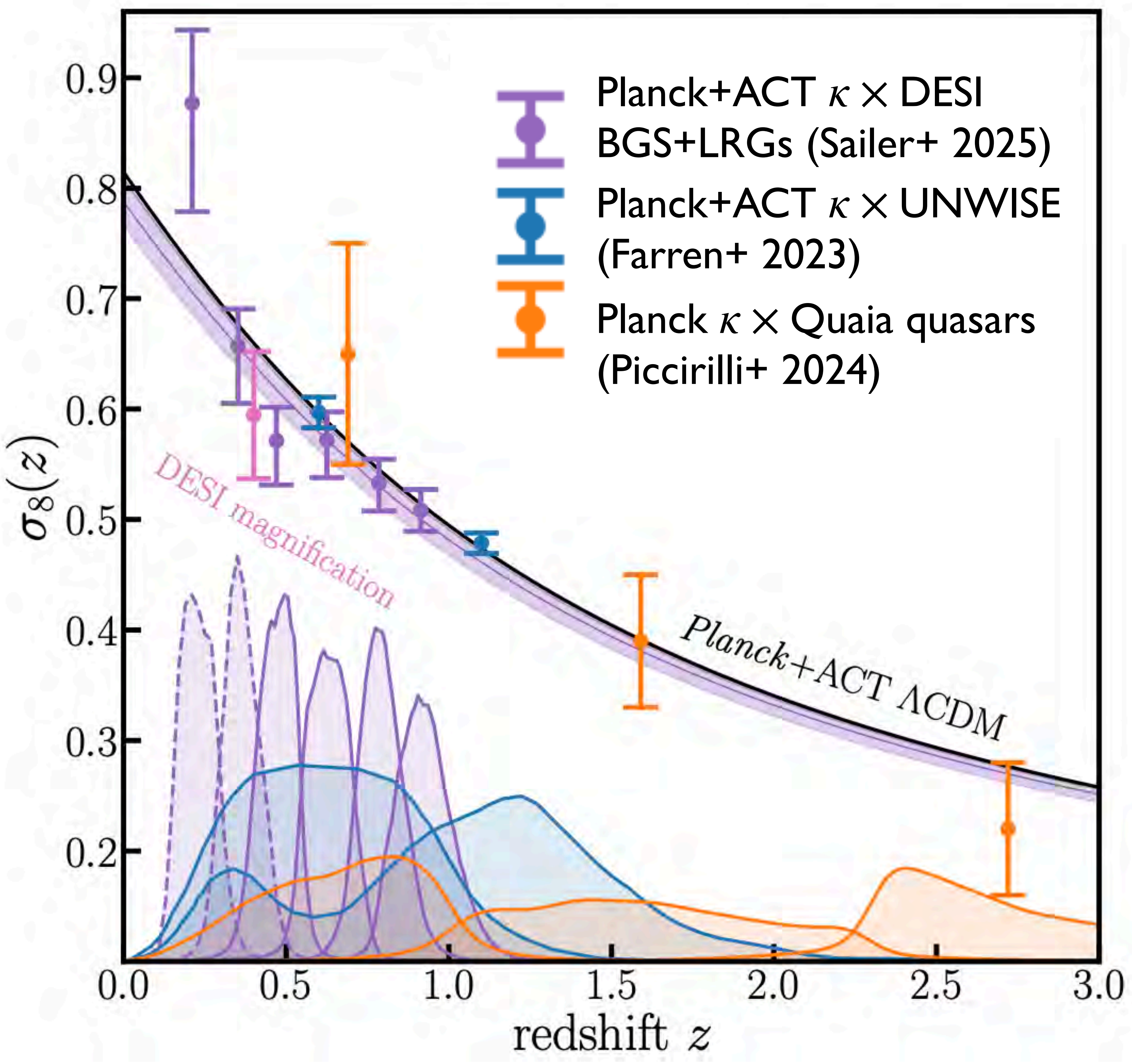






Farren+ 2024

Recent CMB lensing x galaxies measurements

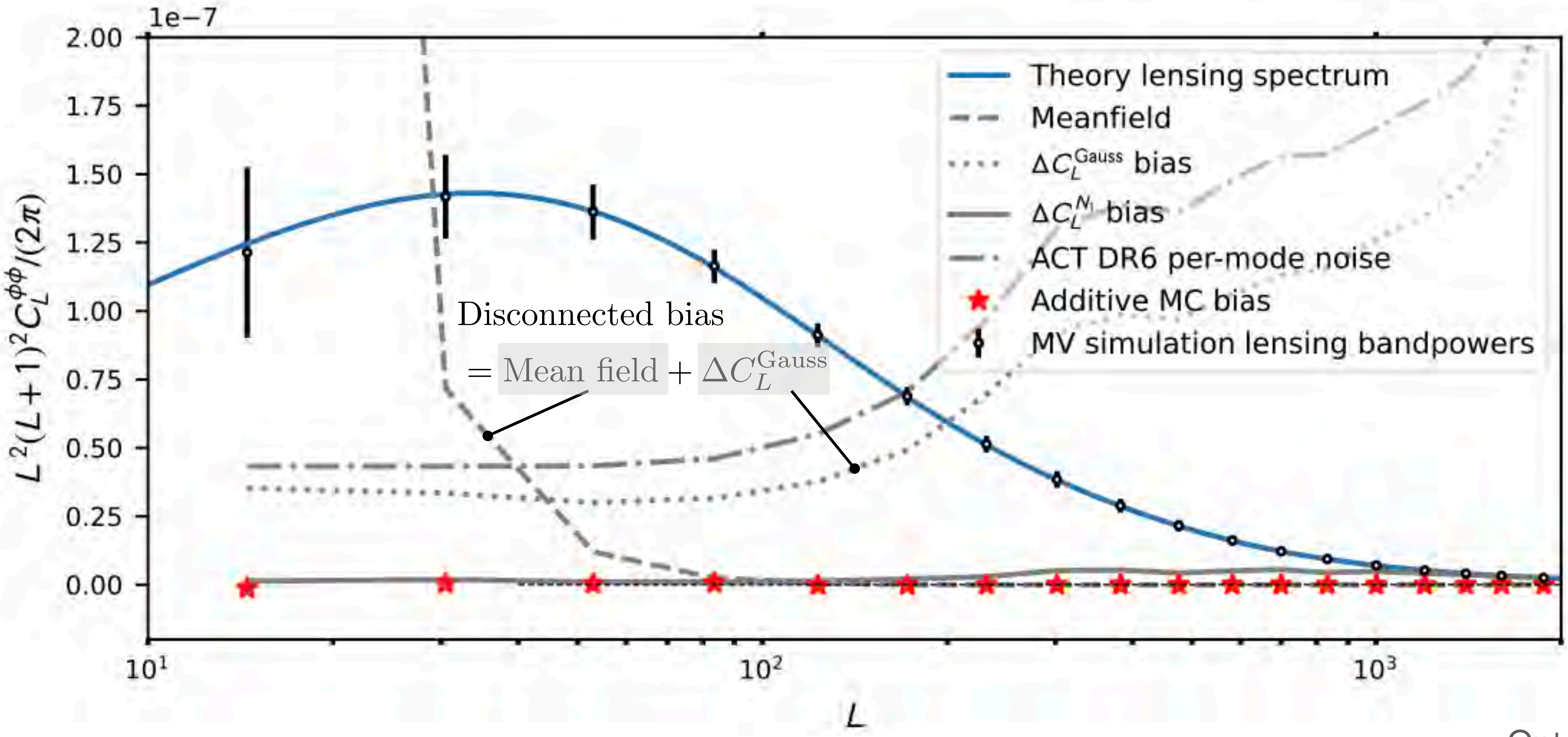


LCDM structure growth down to $z \sim 0.2-1.6$ for $k < 0.2\,\mathrm{Mpc}^{-1}$ consistent with primary CMB

Sailer+ 2025

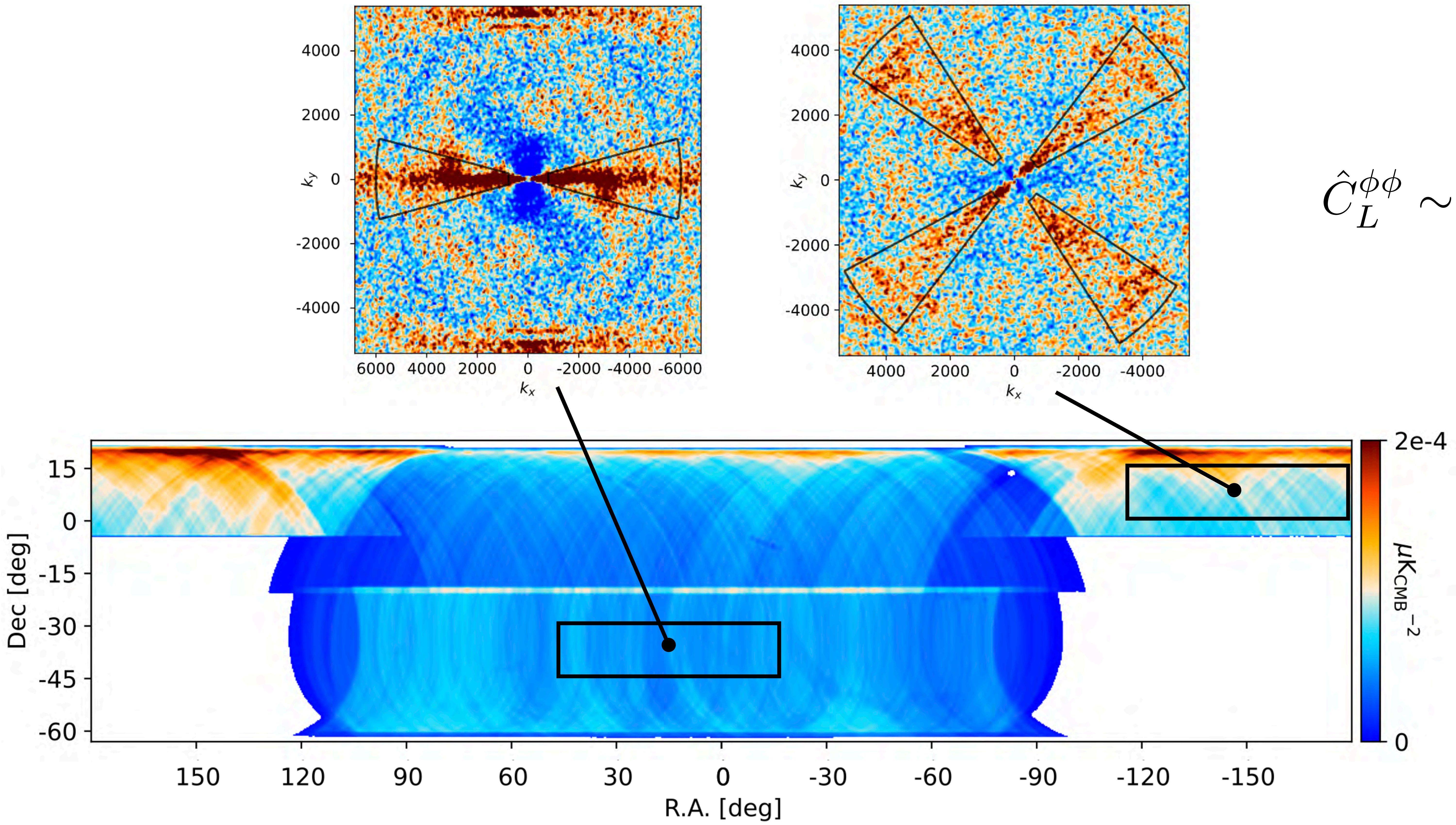
CMB lensing power reconstruction – bias subtraction

$$\hat{C}_L^{\phi\phi} \sim \hat{\phi}(T,T)\hat{\phi}(T,T) - \text{Disconnected bias} - N_L^{(1)}$$



Qu+ 2024

Mitigation for noise mis-modelling: cross-split estimator



Ground-based (ACT) noise is complicated: inhomogeneous and with anisotropic correlations

Split-based estimator:

$$\hat{C}_L^{\phi\phi} \sim \hat{\phi}(T_1, T_2)\hat{\phi}(T_3, T_4) - \text{Disconnected bias} - N_L^{(1)}$$

Splits with independent noise

Noise sims not required to subtract bias

Can also extend to more optimal (likelihood-based) estimators [Legrand+ in prep.]

Atkins+ 2023

Madhavacheril+ 2020

Extragalactic foreground mitigation

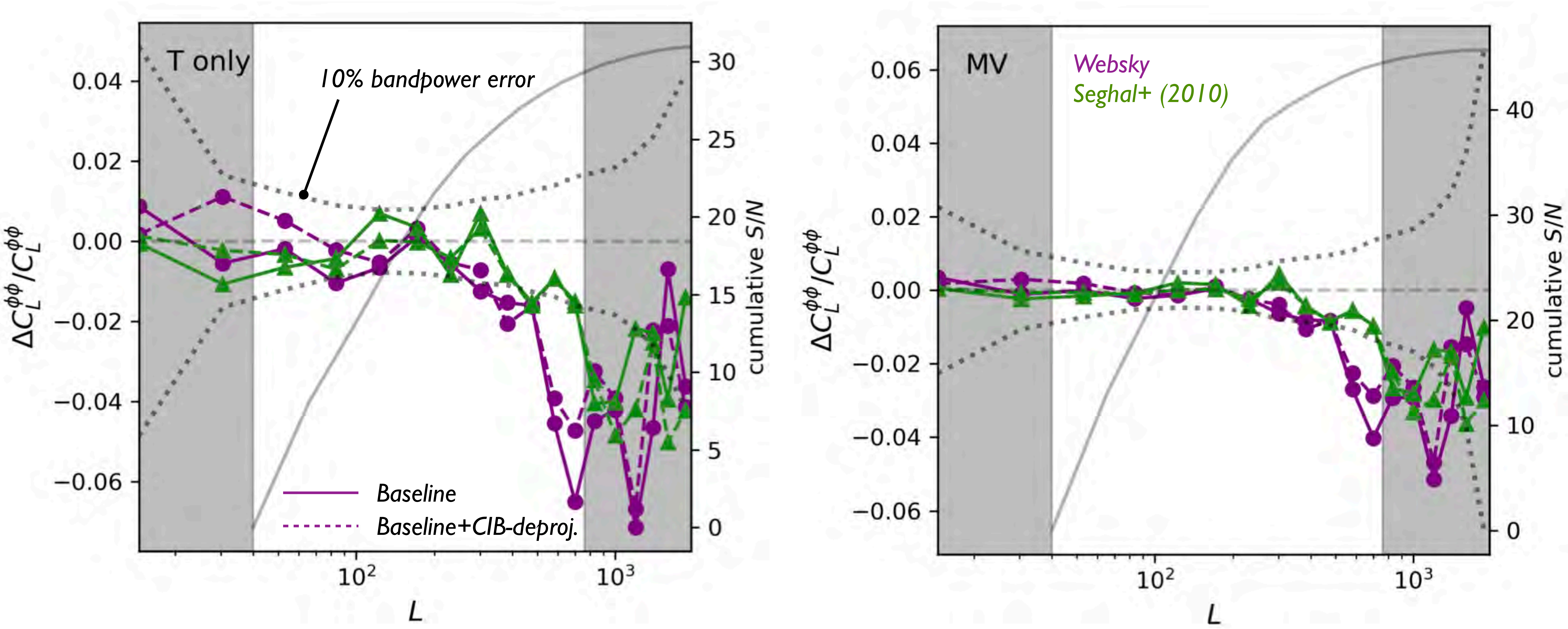
$$
\begin{aligned}
\langle|\hat{\phi}(c+f,c+f)|^2\rangle_c &= \langle|\hat{\phi}(c,c)|^2\rangle_c + 2\langle\hat{\phi}(c,c)\times\hat{\phi}(f,f)\rangle + \langle|\hat{\phi}(f,f)|^2\rangle_c + \cdots \\
&= \langle|\phi|^2\rangle + 2\langle\phi\times\hat{\phi}(f,f)\rangle + \langle|\hat{\phi}(f,f)|^2\rangle_c + \cdots
\end{aligned}
$$

Lensing power *Primary bispectrum* *Foreground trispectrum* *Secondary bispectrum*

Limited frequency coverage and option of higher $\ell_{\max}$ for ground-based measurements makes extragalactic foreground contamination more of a concern

- Multi-frequency cleaning in one or both "legs" of QE
- Point-source and tSZ cluster subtraction and/or masking
- Bias harden to null response from Poisson-distributed objects (point-source or profile)
- Shear-only estimators removing response to isotropic foreground power
- Inter-frequency null tests

ACT DR6 estimated foreground contamination

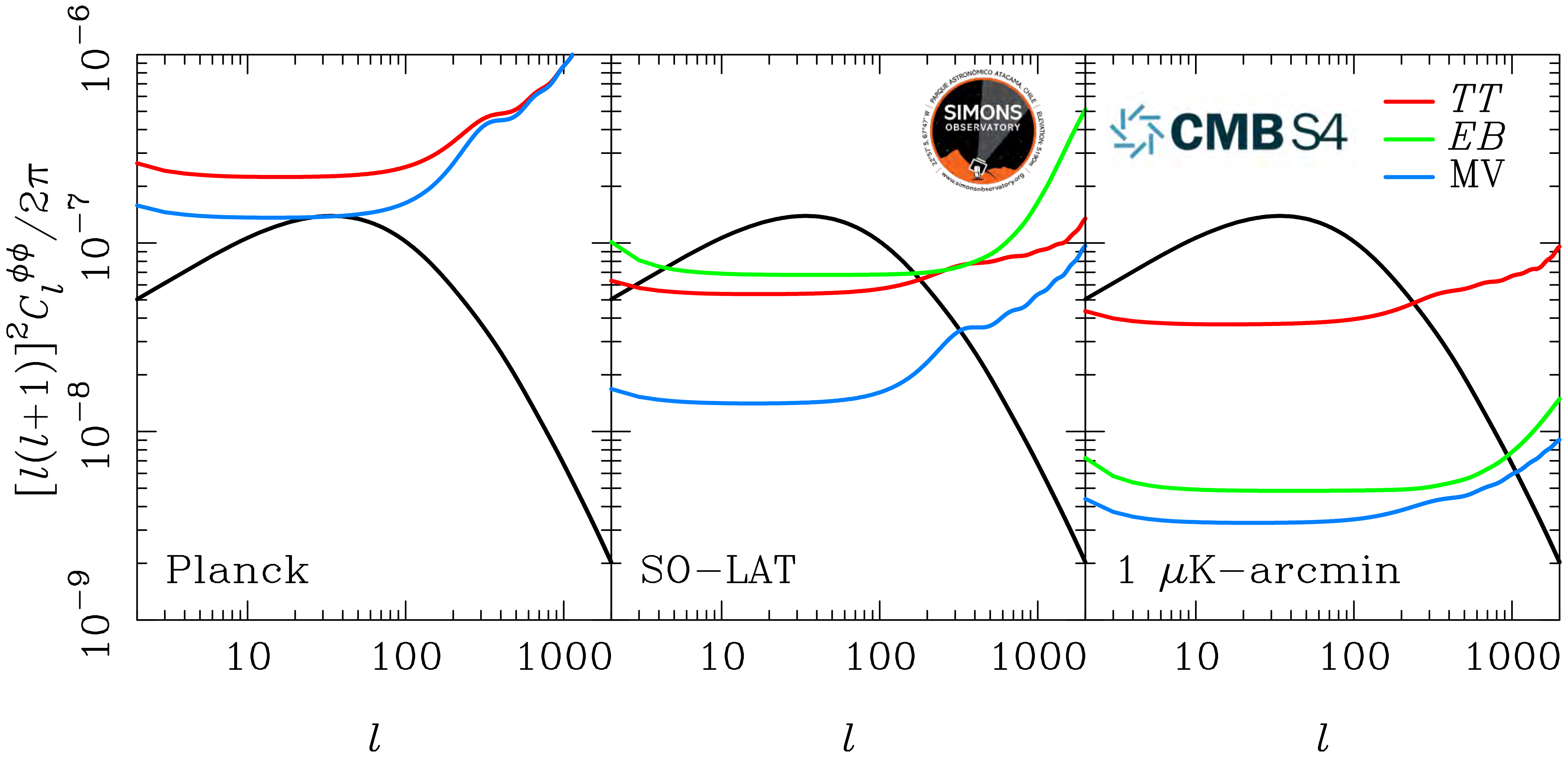


ACT DR6 baseline: 90+150 GHz co-add + point-source and cluster subtraction + profile hardening

$$\Delta A_{\mathrm{lens}} = -0.31\sigma\ (TT); \qquad \Delta A_{\mathrm{lens}} = -0.18\sigma\ (\mathrm{MV})$$

MacCrann+ 2024

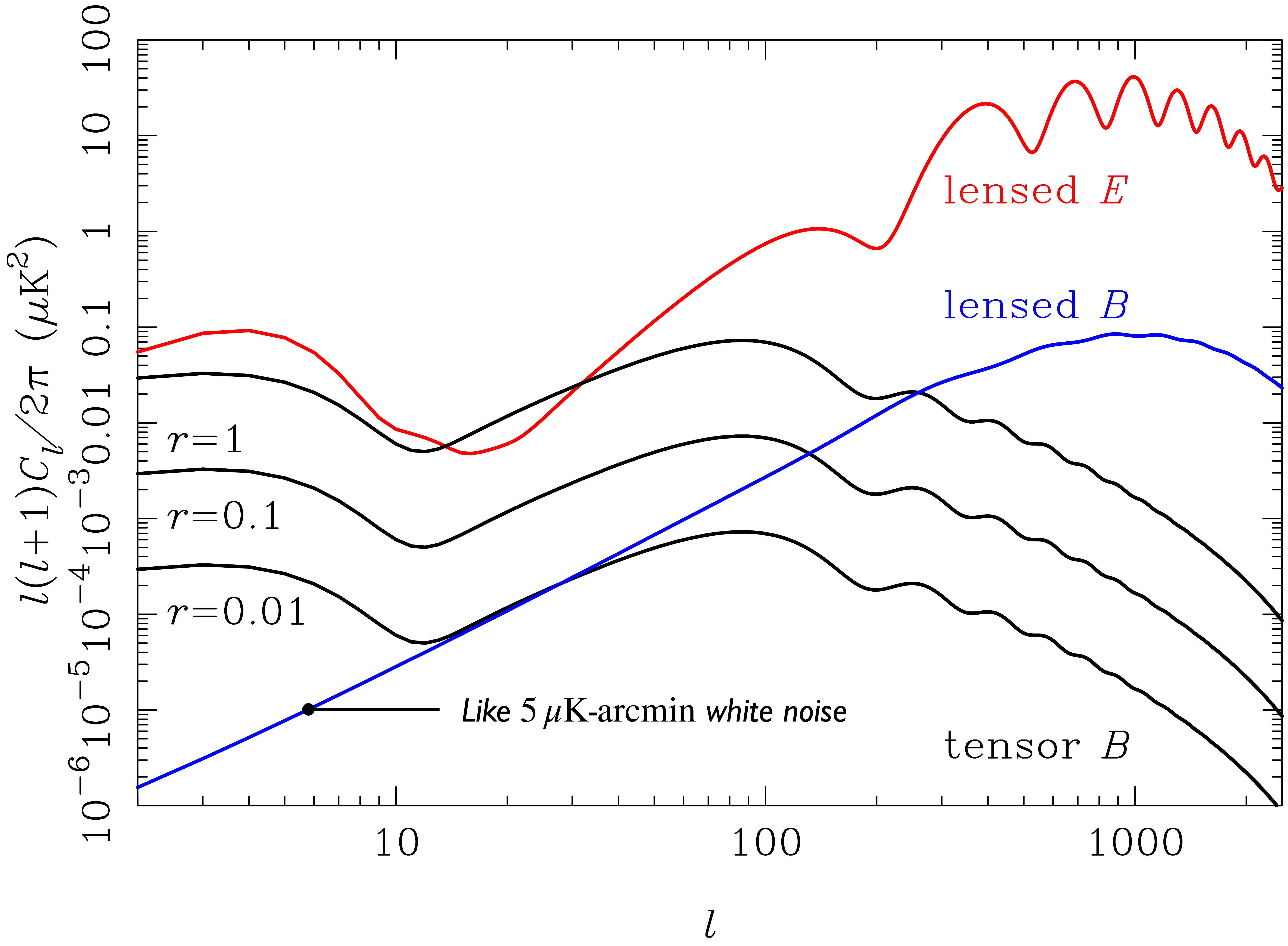
Simons Observatory and beyond



- Lensing S/N > 100 (2x improvement over current)
- Percent-level constraints on $\sigma_8(z)$ in several redshift bins from lensing+LSST
- Moving towards *EB* dominance
- More optimal (beyond-QE) estimators

Back-up slides

B-modes from lensing

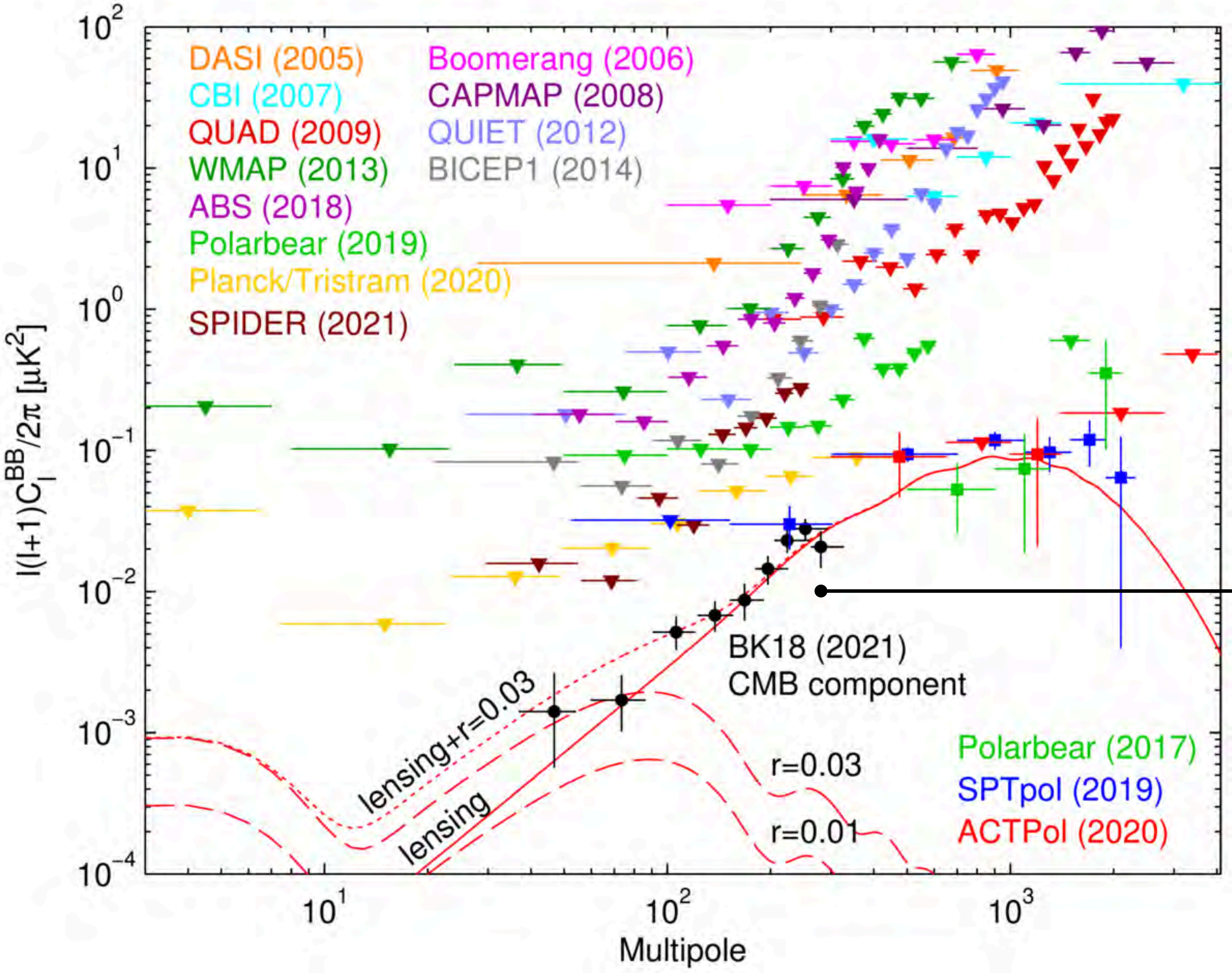


- Lensing *B*-mode can be accurately modelled and subtracted
- Main obstacle is **cosmic variance** from lensed *B*-modes
- Lensing limits

$$\sigma(r) > 5 \times 10^{-4}$$

from $\ell > 30$ over 70% of sky

Current B-mode power measurements

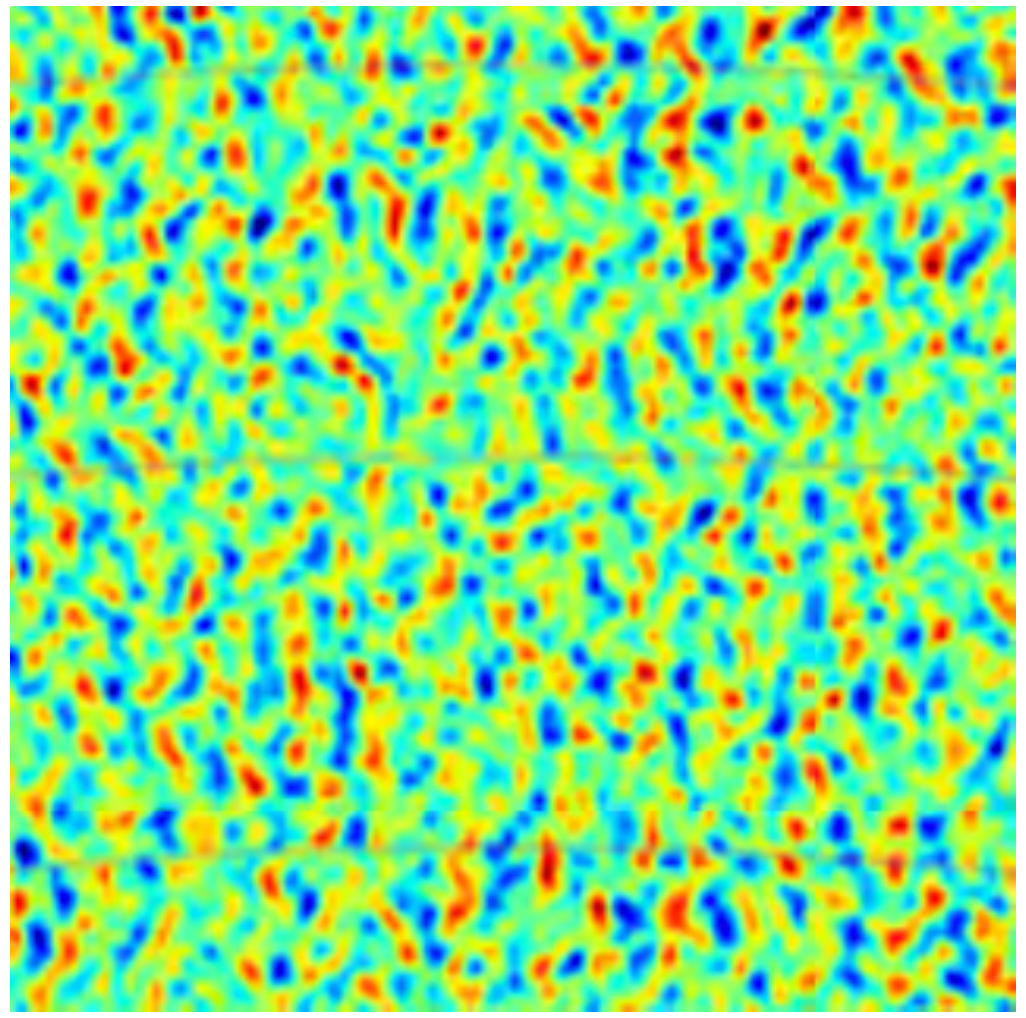


2.8 μK-arcmin white noise at 95 GHz and 150 GHz over 600 deg^2/400 deg^2

BK 2021

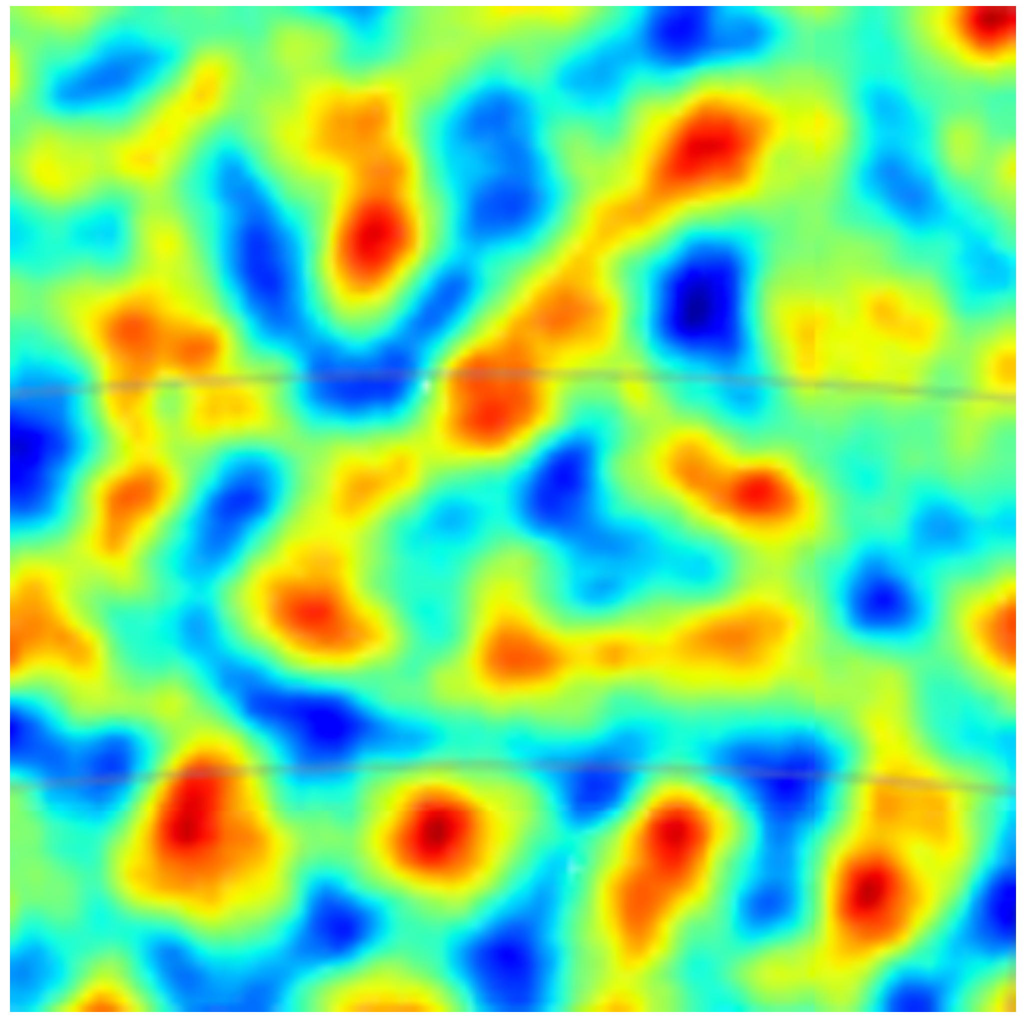
B-mode delensing

$$B^{\mathrm{delens}} = B^{\mathrm{obs}} - E^{\mathrm{WF}} * \hat{\phi}^{\mathrm{WF}}$$



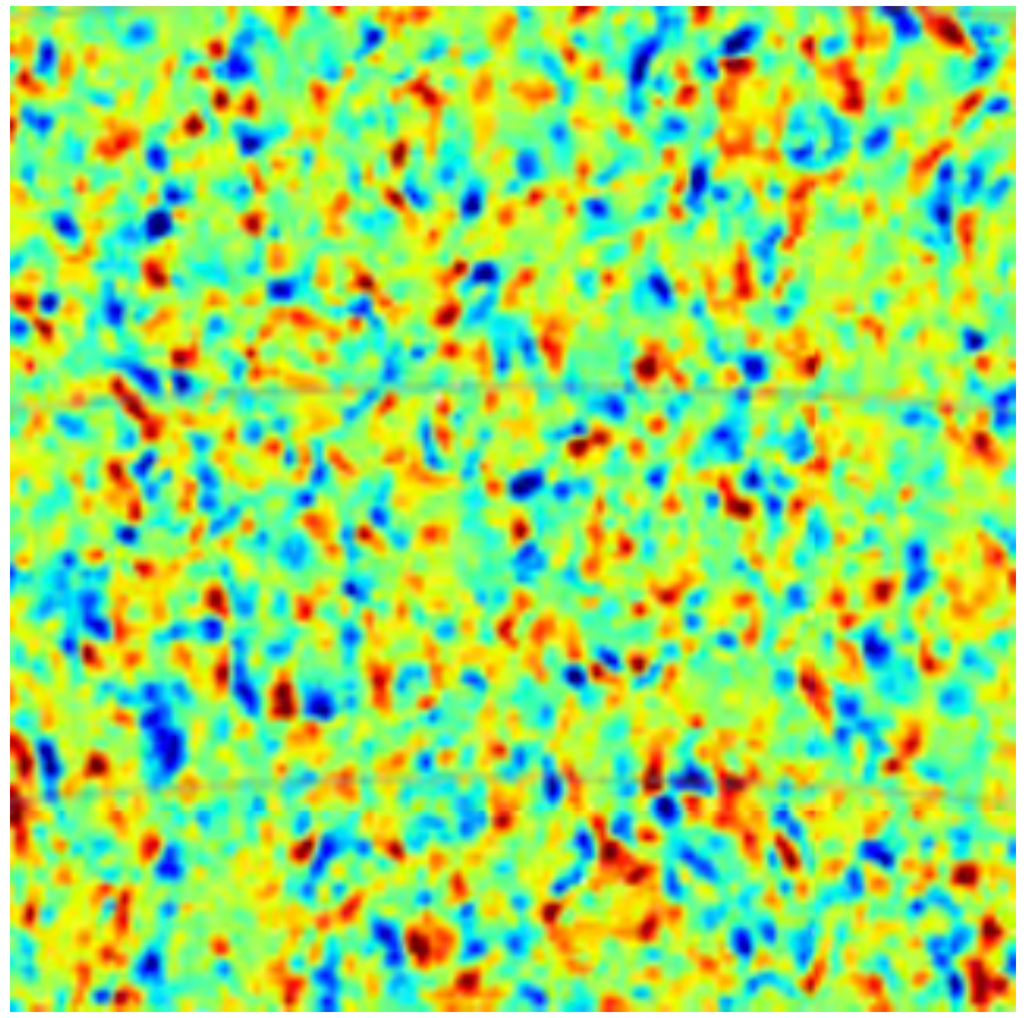
Filtered E modes

$*$



$\hat{\phi}$

$=$

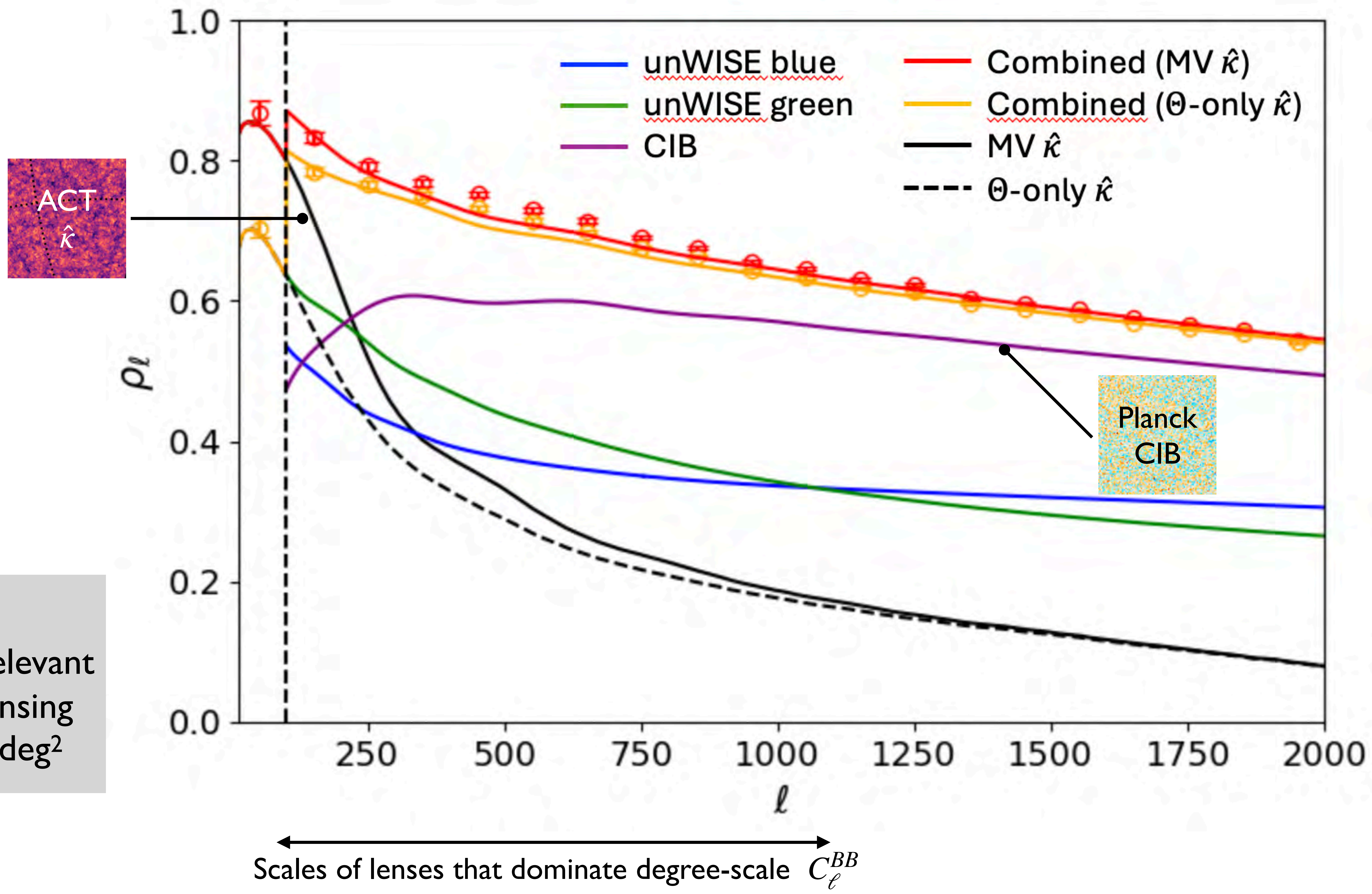


$\hat{B}^{\mathrm{lens}}$

Want high-S/N *E*-modes and highly correlated tracer of lensing

Hanson+ 2014

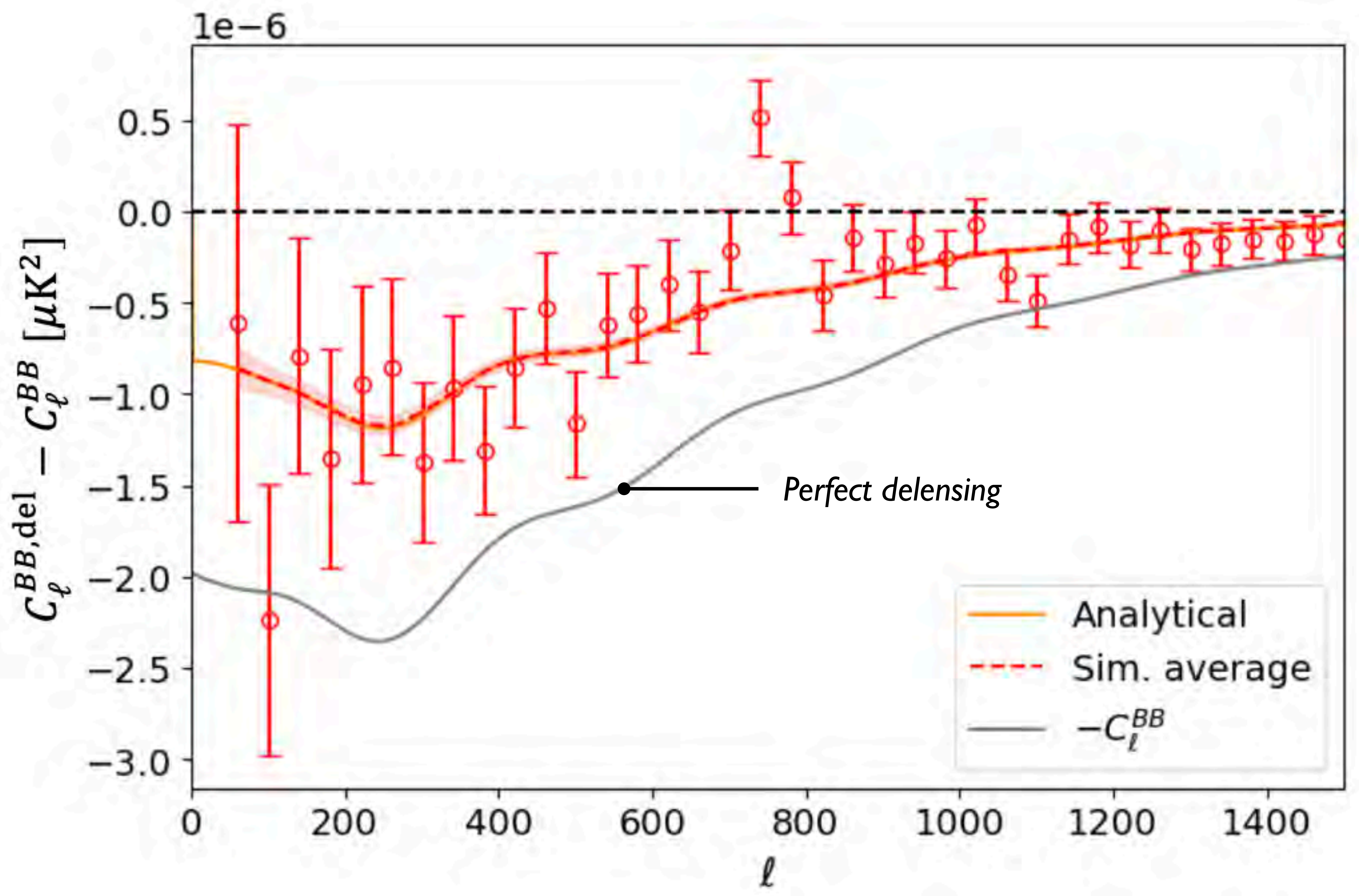
Multi-tracer delensing



Greater than 70% correlation over relevant scales ⇒ 50% delensing **now** over 10,000 deg²

Hertig+ in prep.

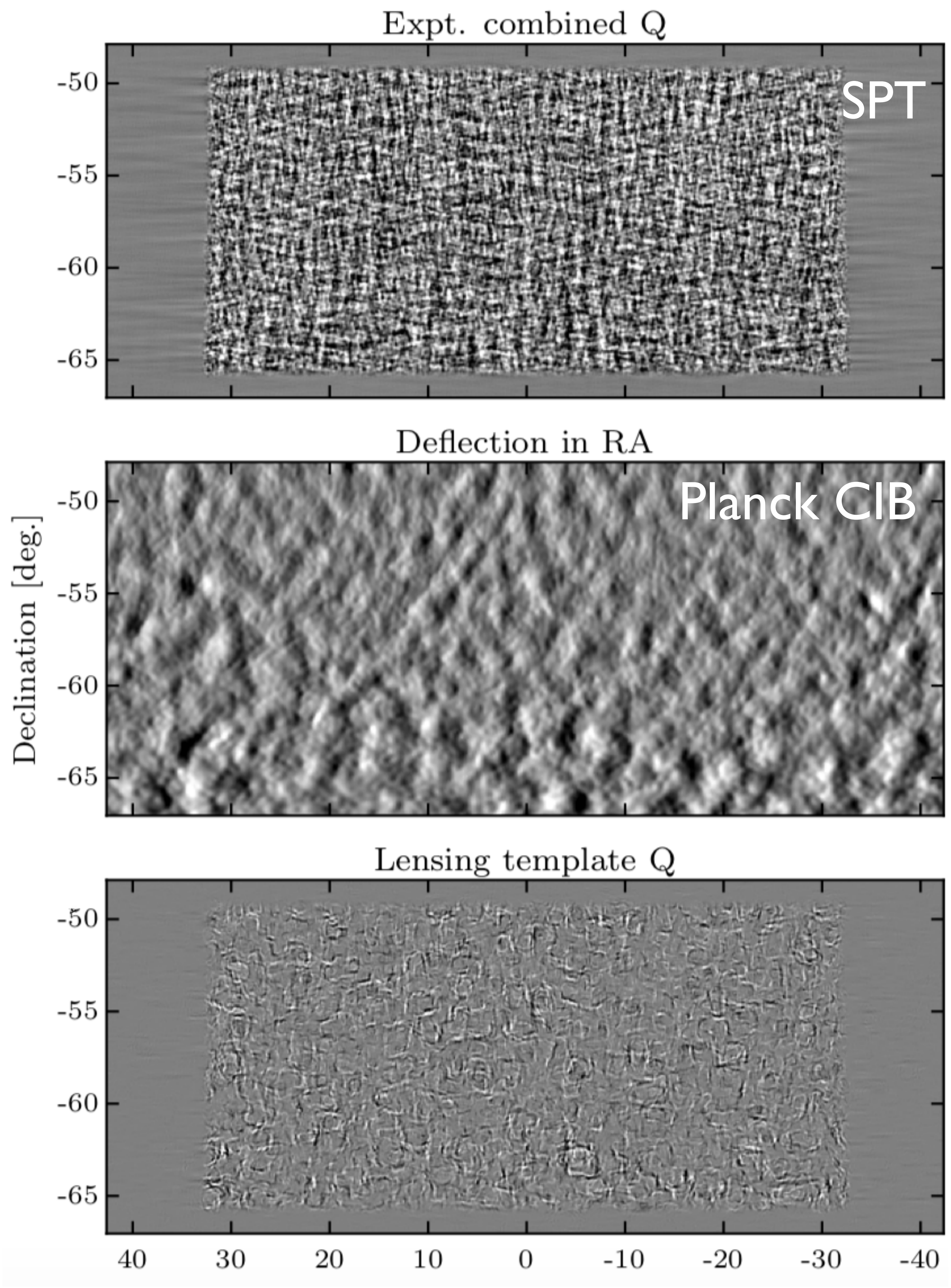
Correlations with observed Planck B-modes

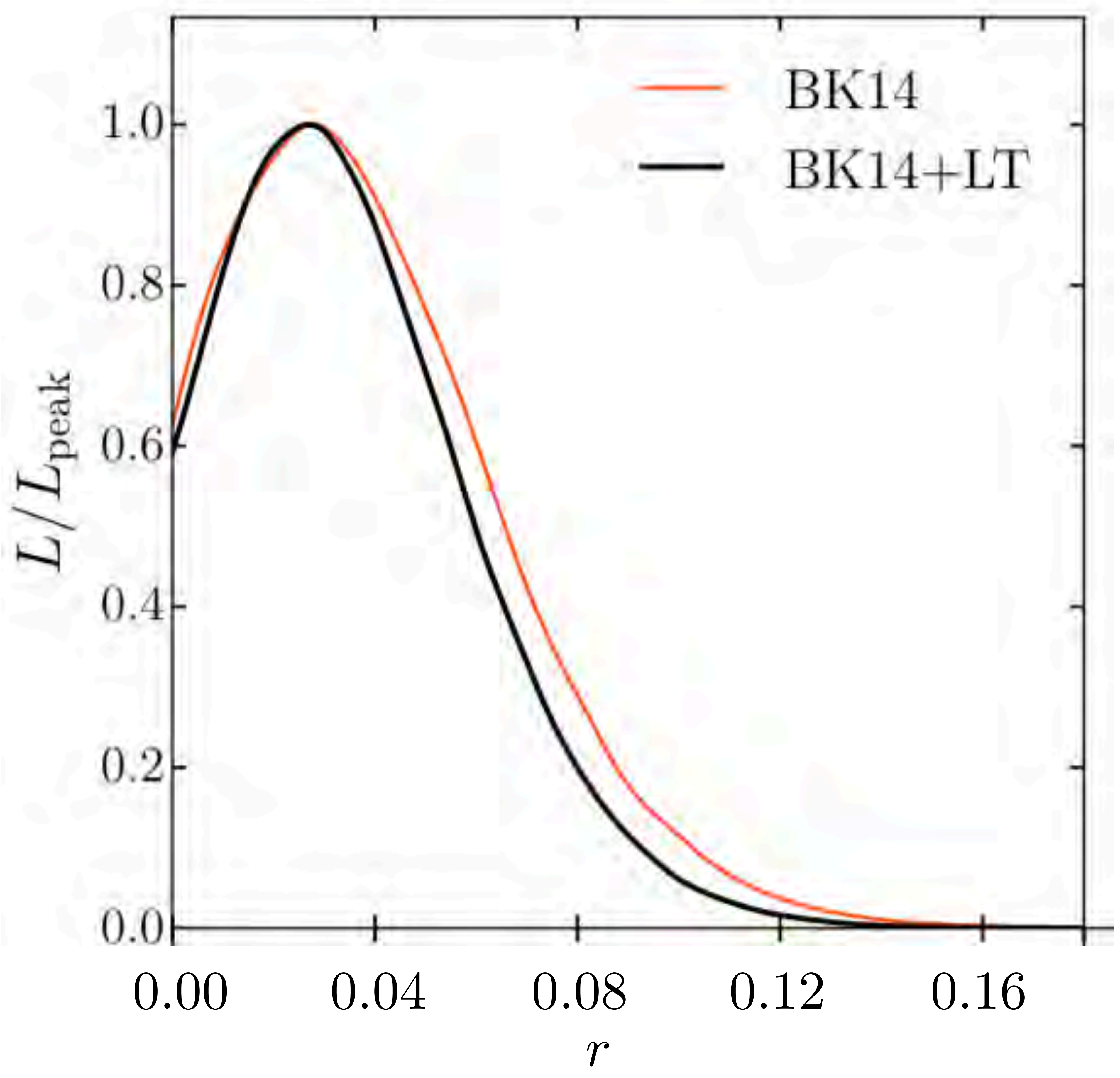


Around 50% reduction in lensing power with current template from ACT, unWISE, CIB template

Hertig+ in prep.

Delensing now improving $\sigma(r)$





$$\sigma(r) = 0.024 \rightarrow \sigma(r) = 0.022$$

BK+SPT 2021

Expected future improvements from delensing

- Targeting $\sigma(r) \leq 0.003$ for $r = 0$
- 65% efficiency delensing for template from SO-LAT QE (goal noise levels, nominal survey) + CIB + LSST gold galaxy sample
- Spectral-based forecasts with goal SO-SAT noise:
    - Up to 37% reduction in $\sigma(r)$ for $r = 0$, depending on foreground complexity
- Greater improvements for extended SO

Hertig+ 2024

- Targeting $\sigma(r) = 5 \times 10^{-4}$ for $r = 0$
- Requires aggressive delensing
- Map-based simulations achieve more than 90% efficiency delensing with template from internal, **iterative** lens reconstruction
    - Significant improvement over 75% efficiency for QE reconstruction

Belkner+ 2024