Backlighting large-scale structure with the CMB

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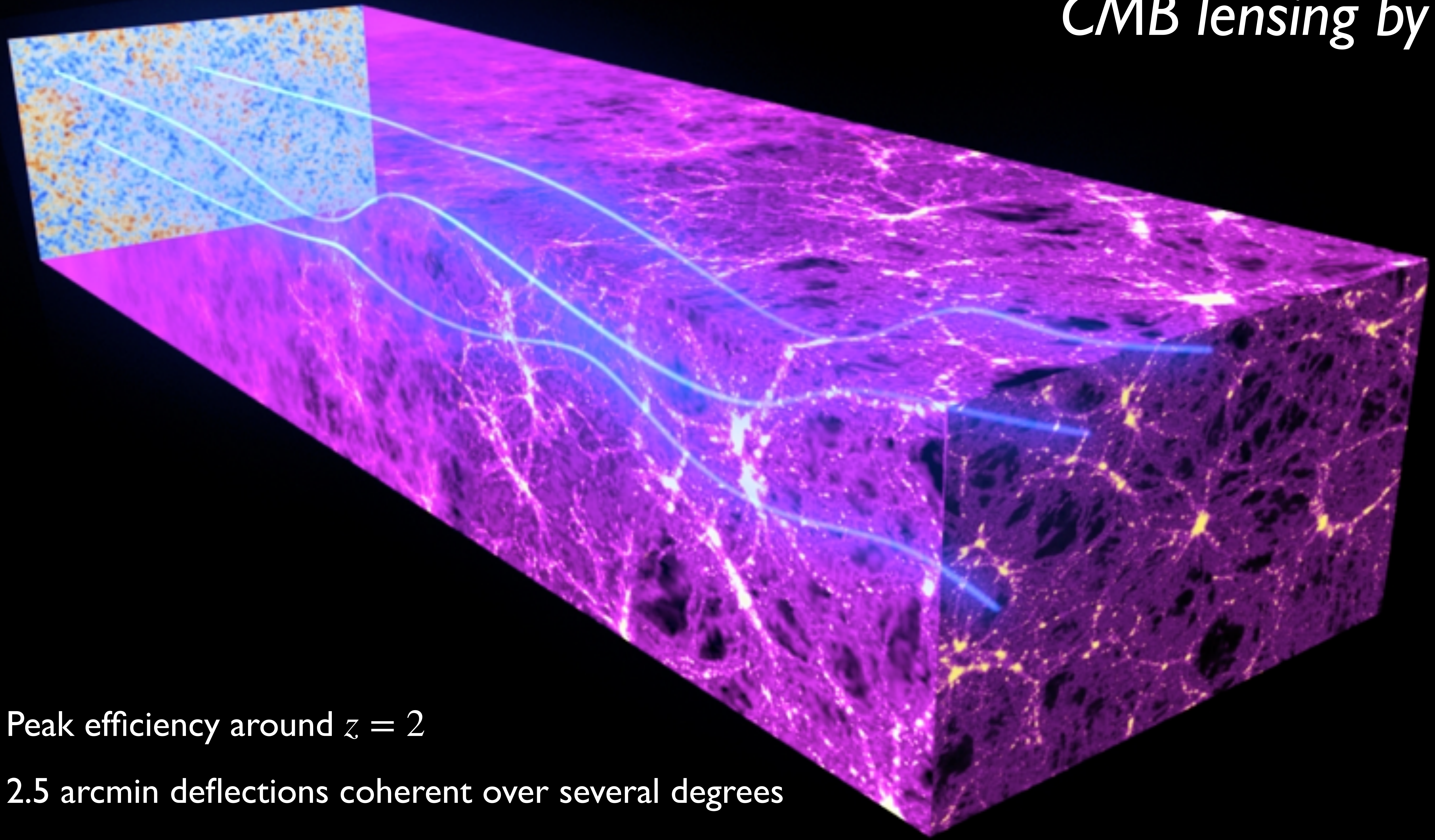
CMB lensing by LSS

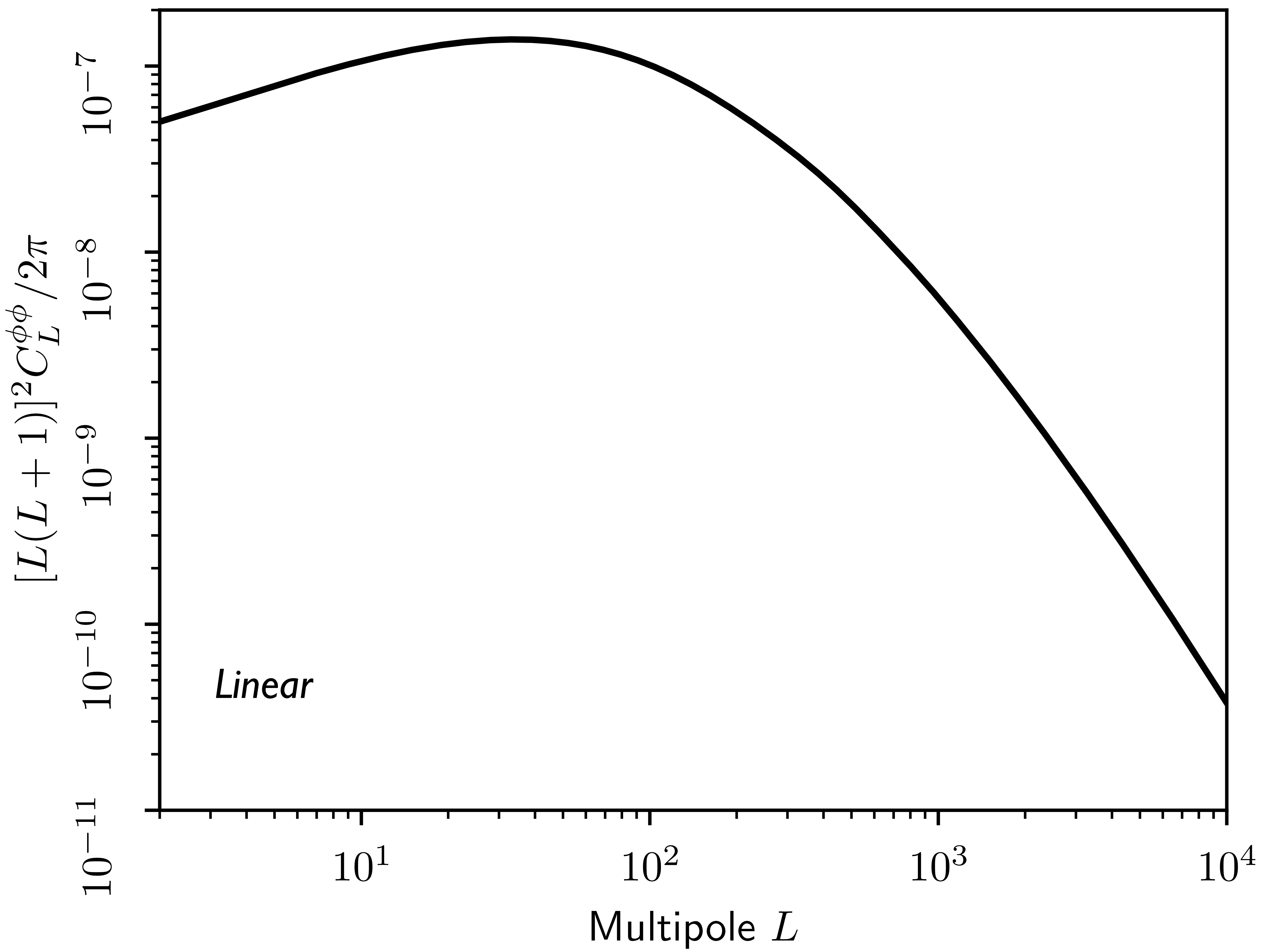


- Peak efficiency around $z = 2$
- 2.5 arcmin deflections coherent over several degrees

CMB lensing: robust probe of mostly linear structure

CMB remapped by $\boldsymbol{d} = \nabla\phi$:

$$\phi(\hat{\boldsymbol{n}}) = -\int_0^{\chi_*} d\chi \, \frac{\chi_* - \chi}{\chi_* \chi} \, (\Phi + \Psi) \, (\chi\hat{\boldsymbol{n}}; \eta_0 - \chi)$$



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

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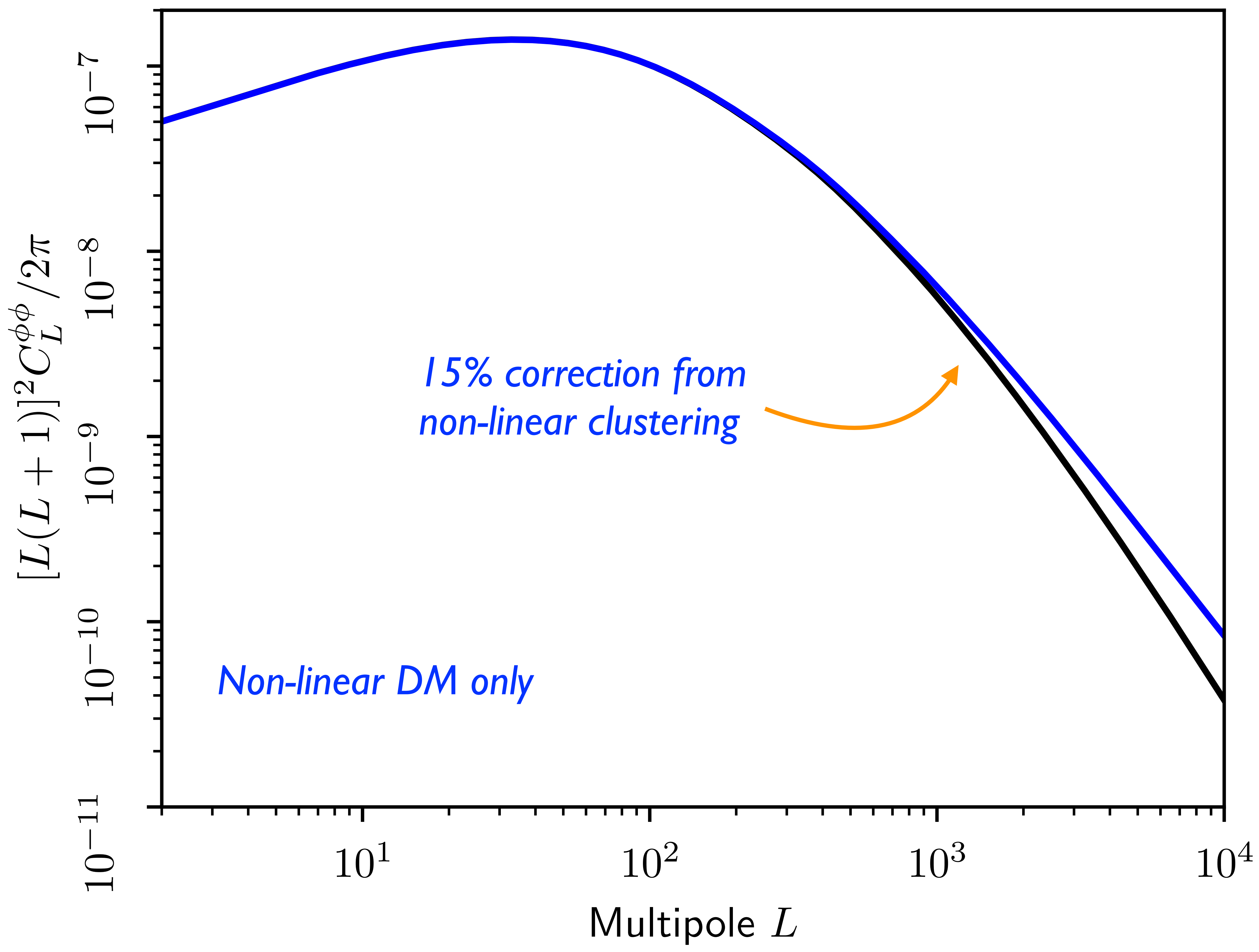

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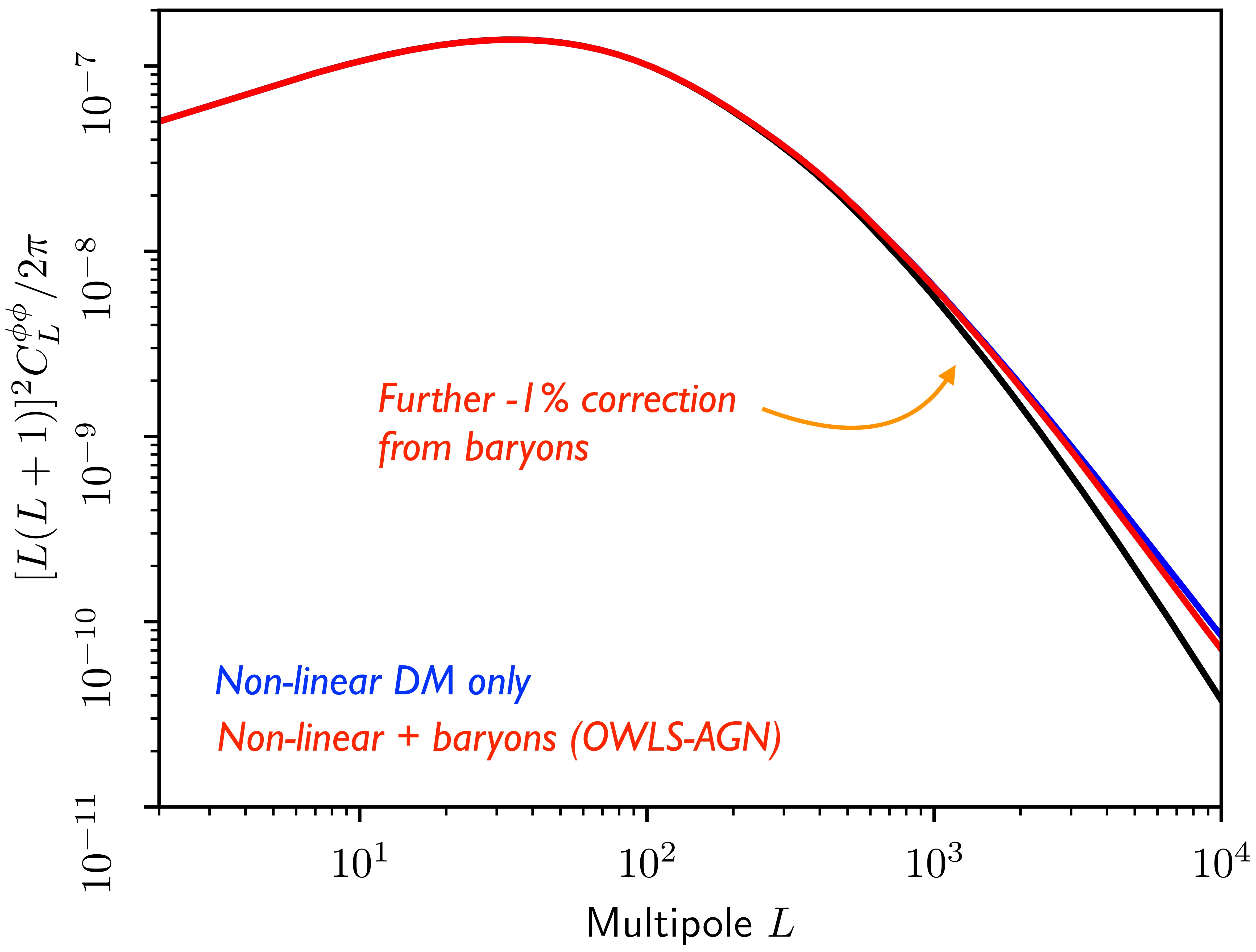


- Redshift of source plane known
- Statistics of fluctuations in source plane well understood
- High-z lenses and relatively large scales
  - Modest non-linear corrections
  - Baryons negligible until CMB-S4 era

CMB lensing reconstruction

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

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

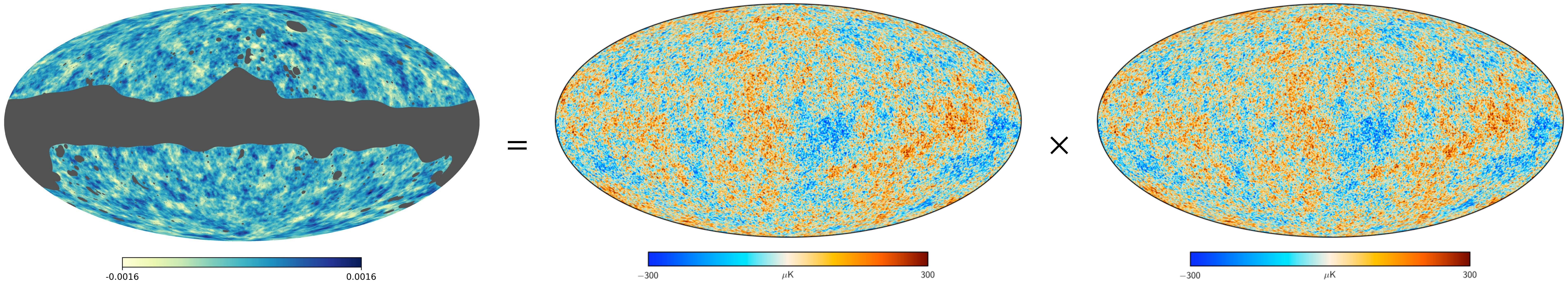
- Statistical (noisy) reconstruction of ϕ from quadratic combinations of CMB fields, e.g.,

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

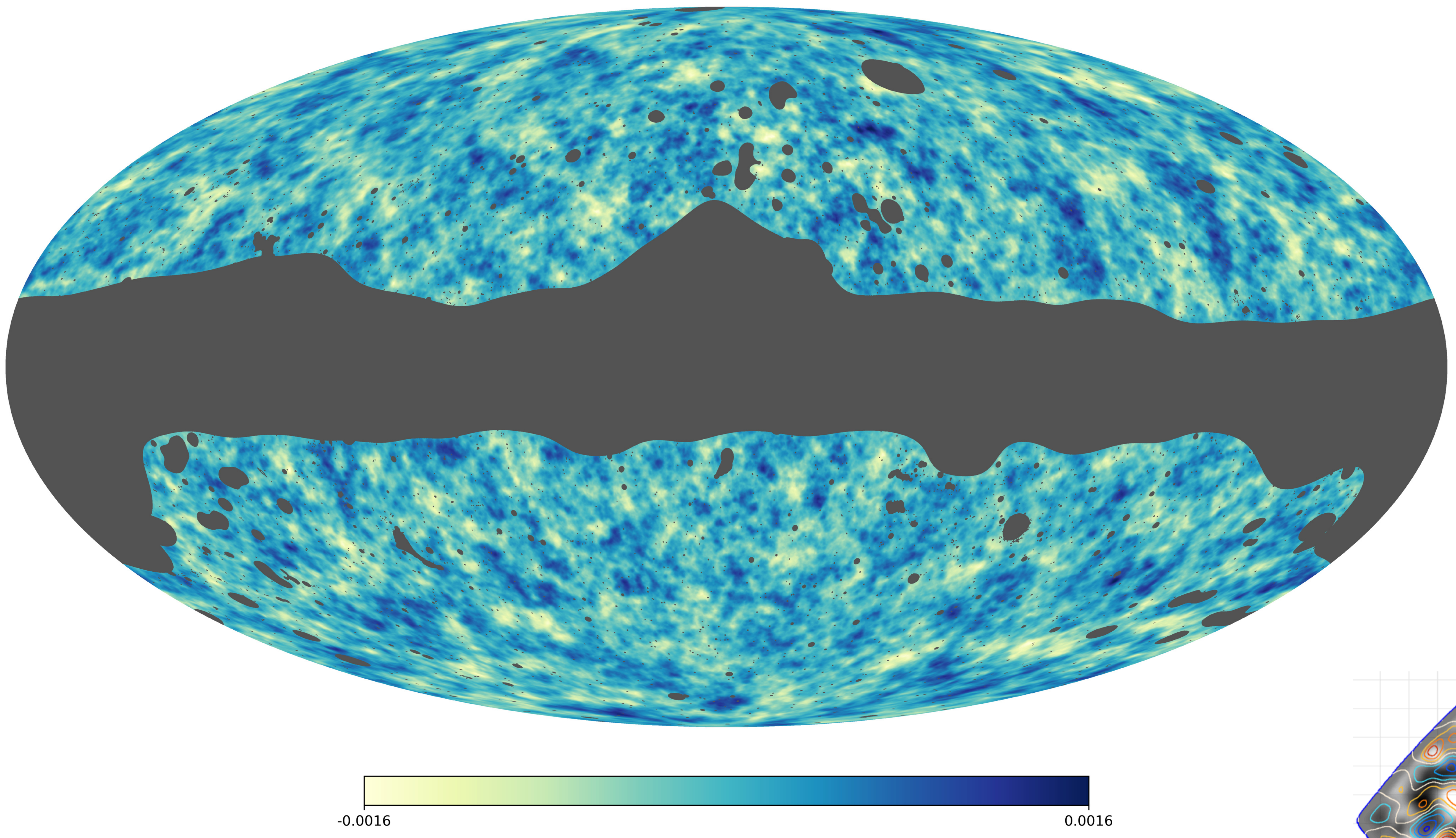
Normalisation

Known response to lensing

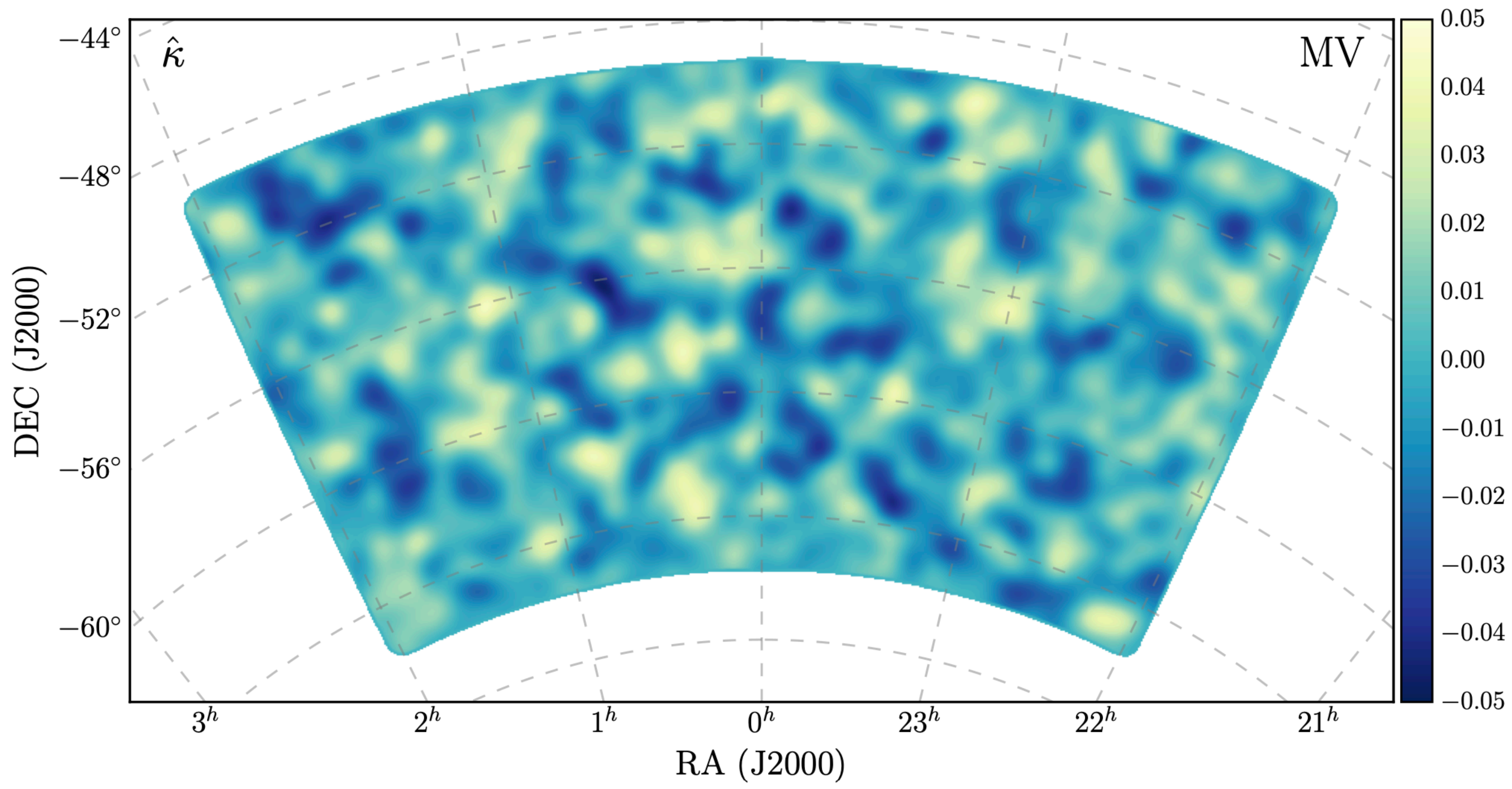
Inverse-variance-filtered CMB fields



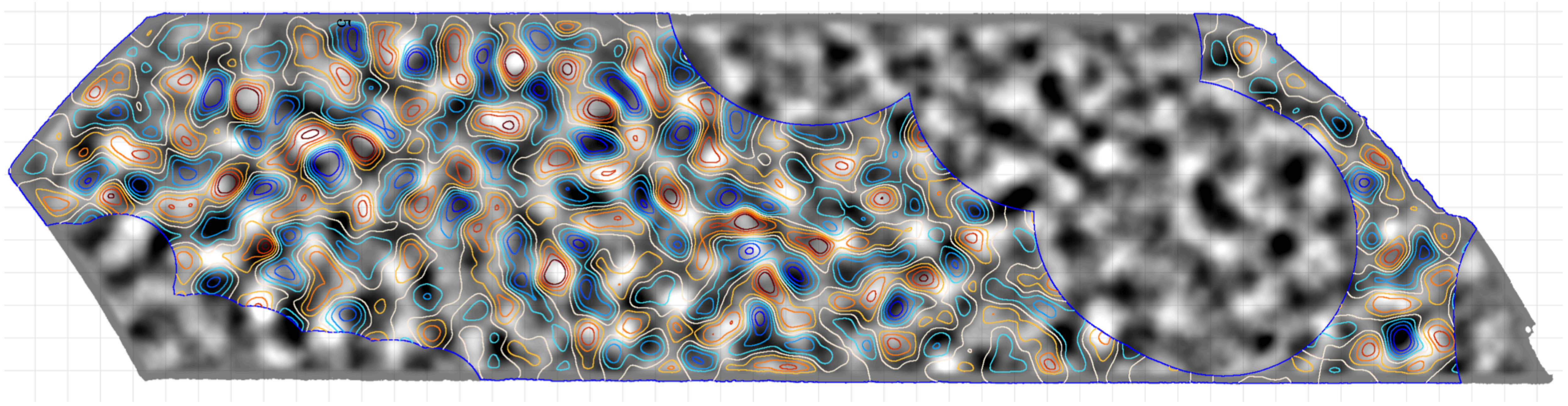
Reconstructed CMB lensing maps



Planck 2018



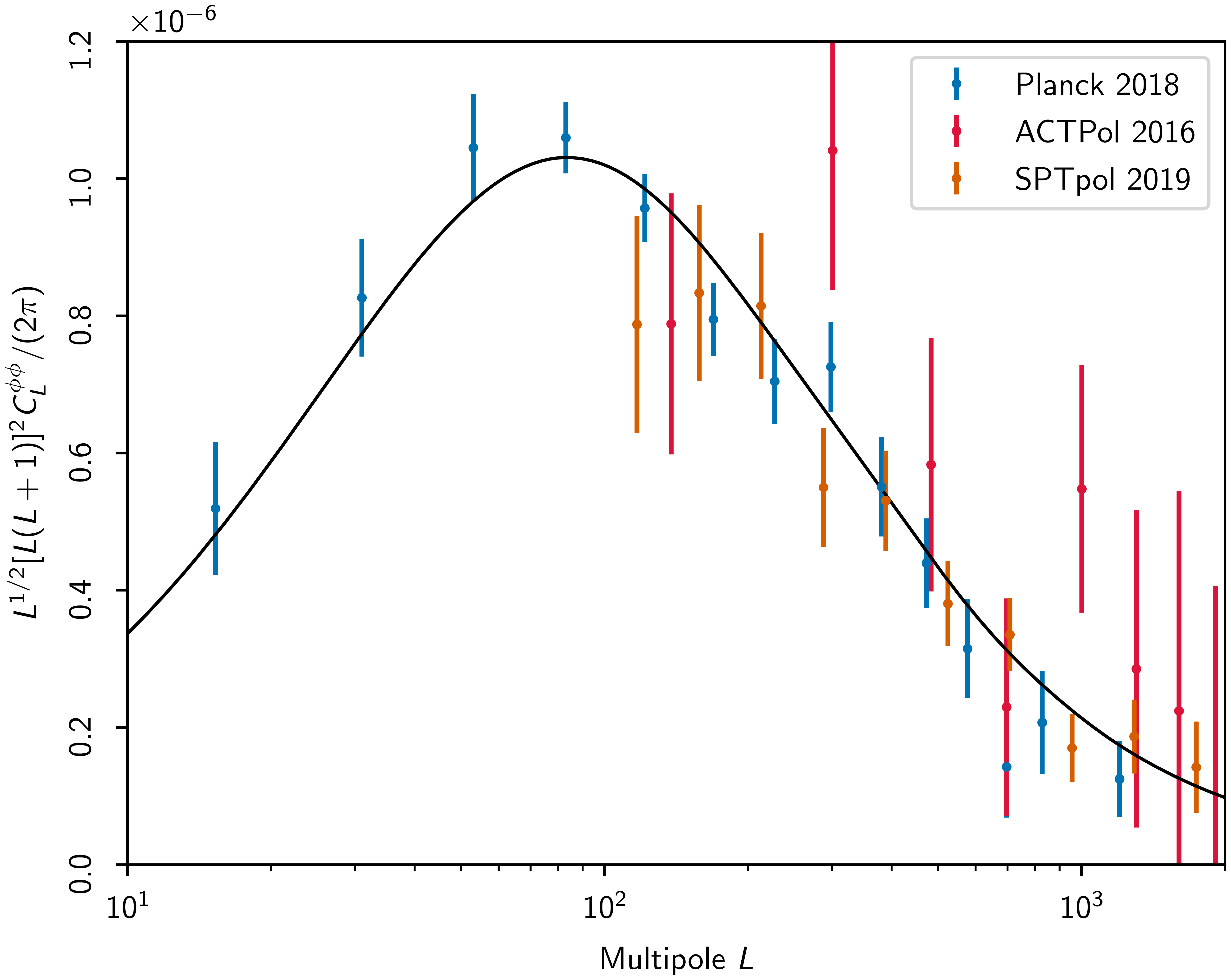
SPT – Wu+ 2019



ACT – Darwish+ 2021

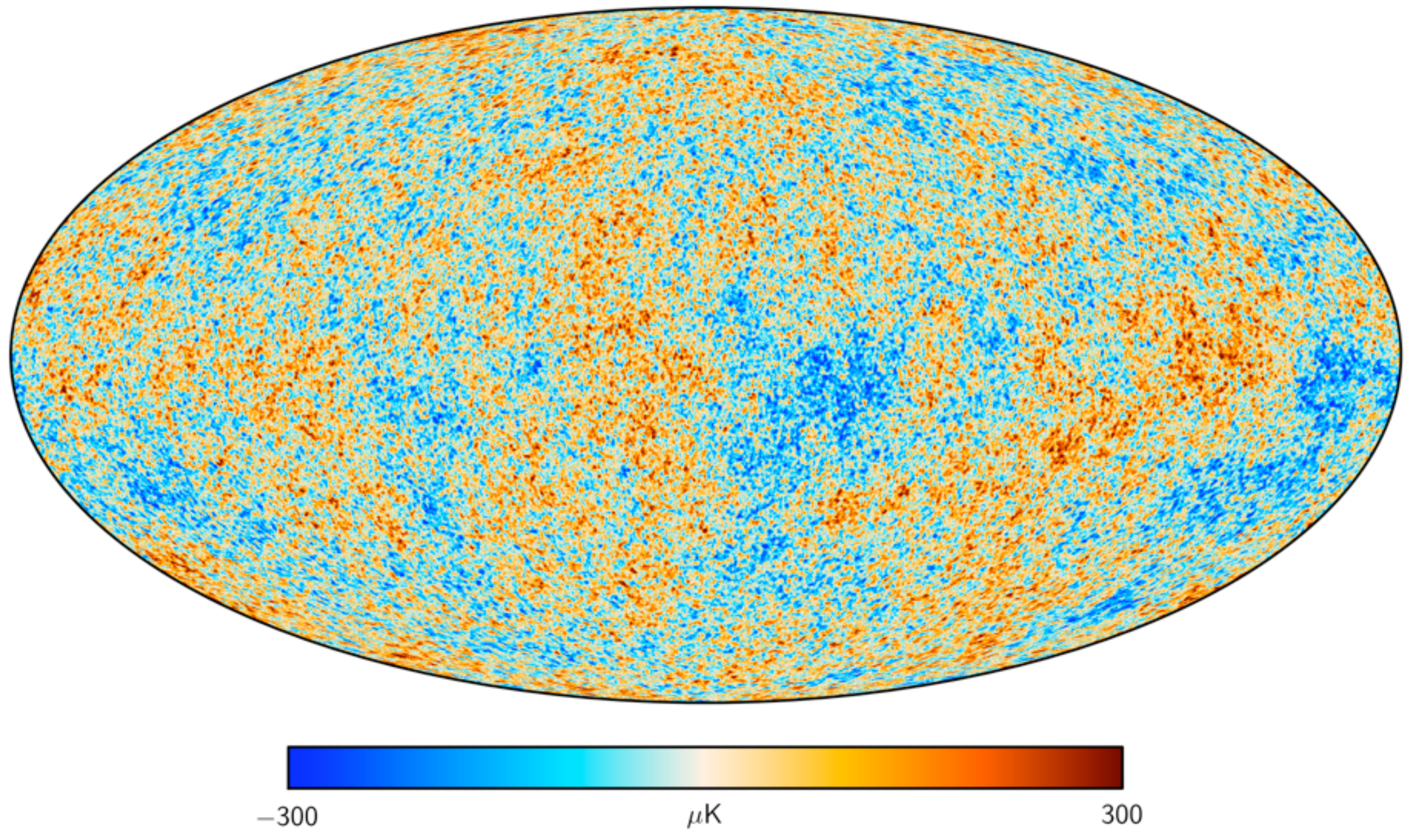
CMB lensing power reconstruction

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

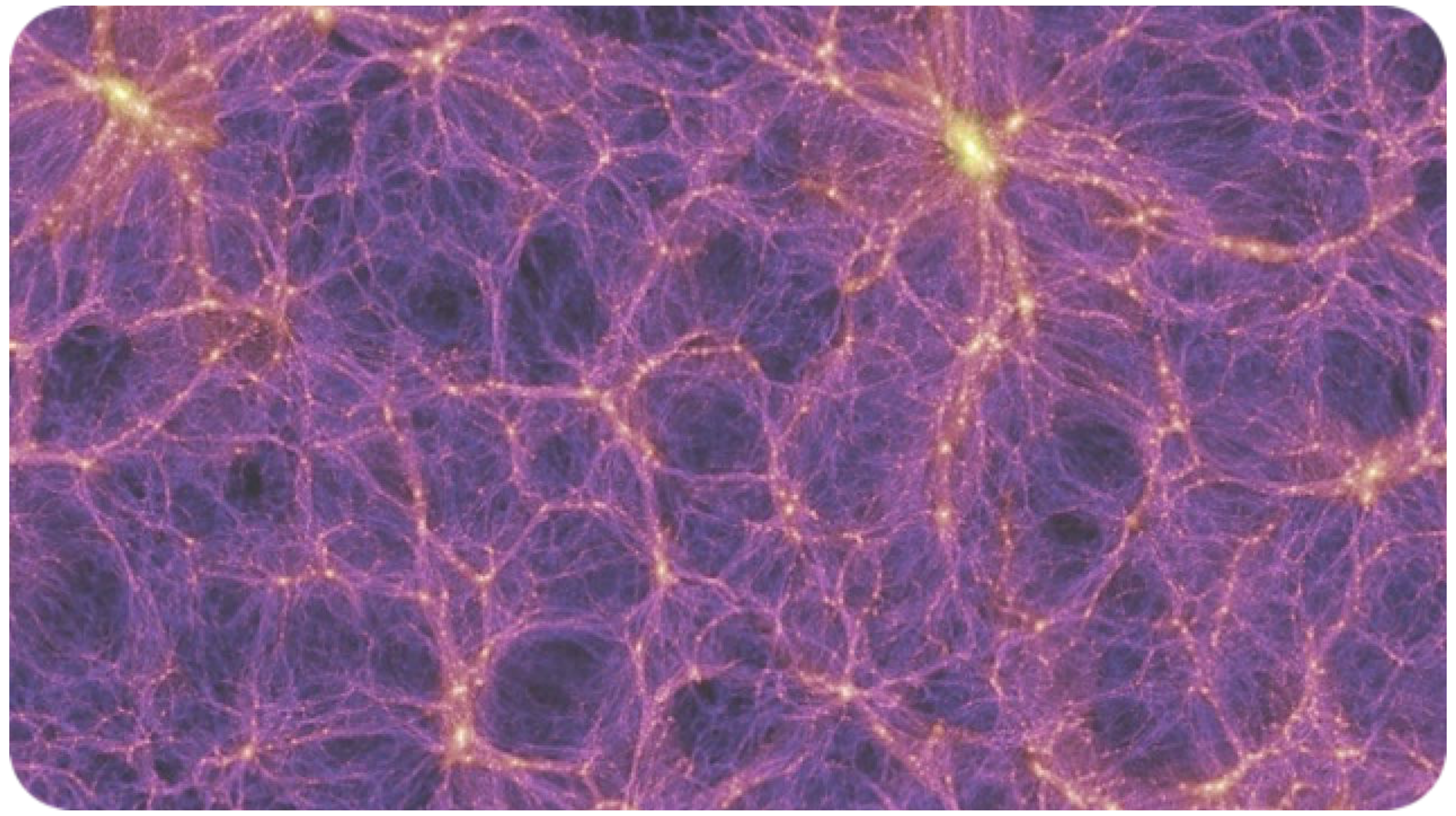


Testing LCDM structure growth

- Do late-time observations of large-scale structure match LCDM predictions, calibrated on high-z CMB?



Calibrate LCDM parameters on primary CMB fluctuations at $z \approx 1100$



Predict statistics (e.g., power spectrum) of clustering at low z and compare with observations

LCDM parameter dependencies

- In Limber approximation

$$L^4 C_L^{\phi\phi} = 4\int_0^{\chi_*} d\chi \, (k \times \underbrace{k^3 P_\Psi})(k = L/\chi; \eta_0 - \chi)\,(1 - \chi/\chi_*)^2$$

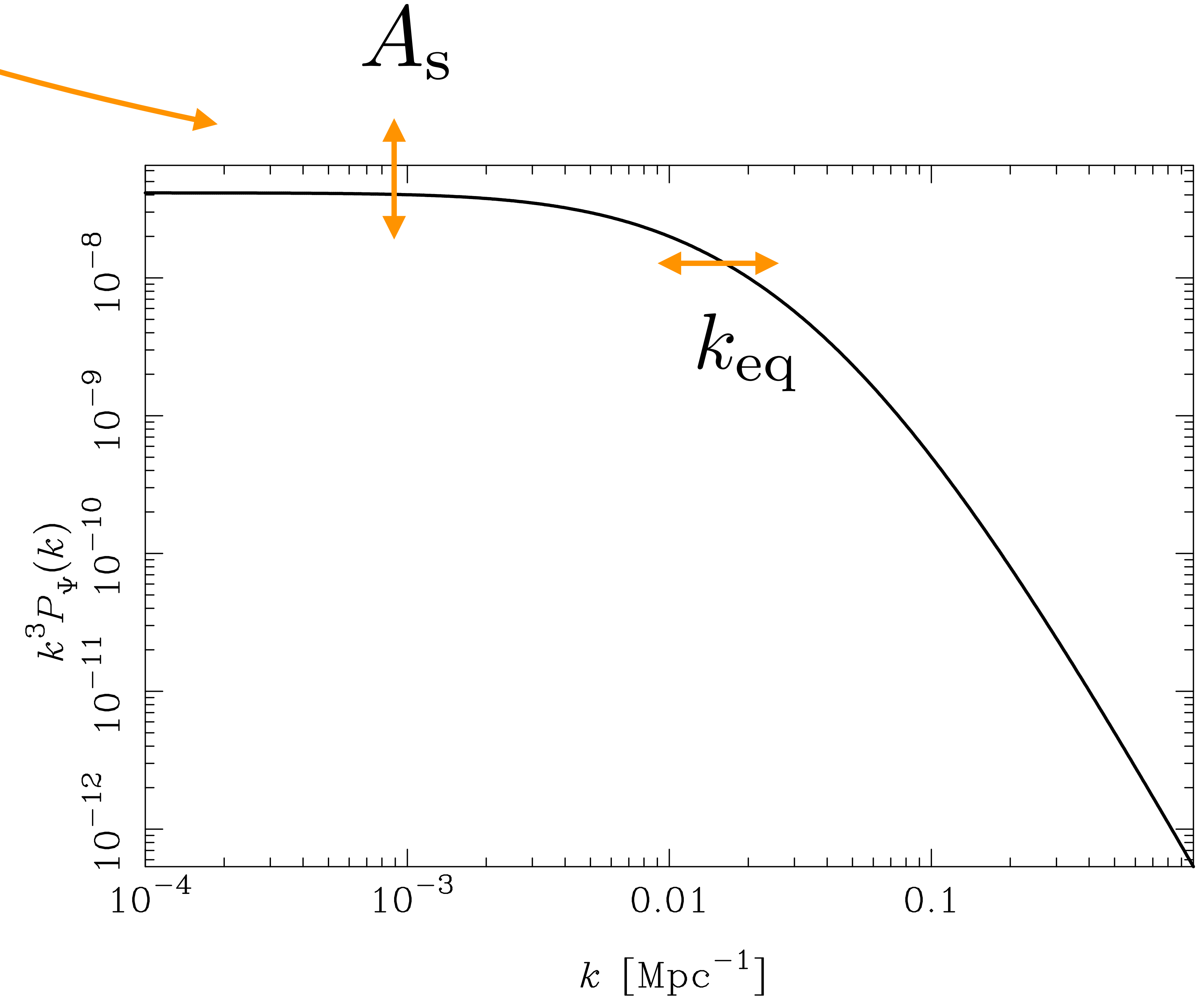
Can ignore time dependence for $L > 100$

- For $L > 100$

$$C_L^{\phi\phi} \sim (A_s \ell_{eq})\, f(L/\ell_{eq}) \qquad (\ell_{eq} \equiv k_{eq}\chi_*)$$

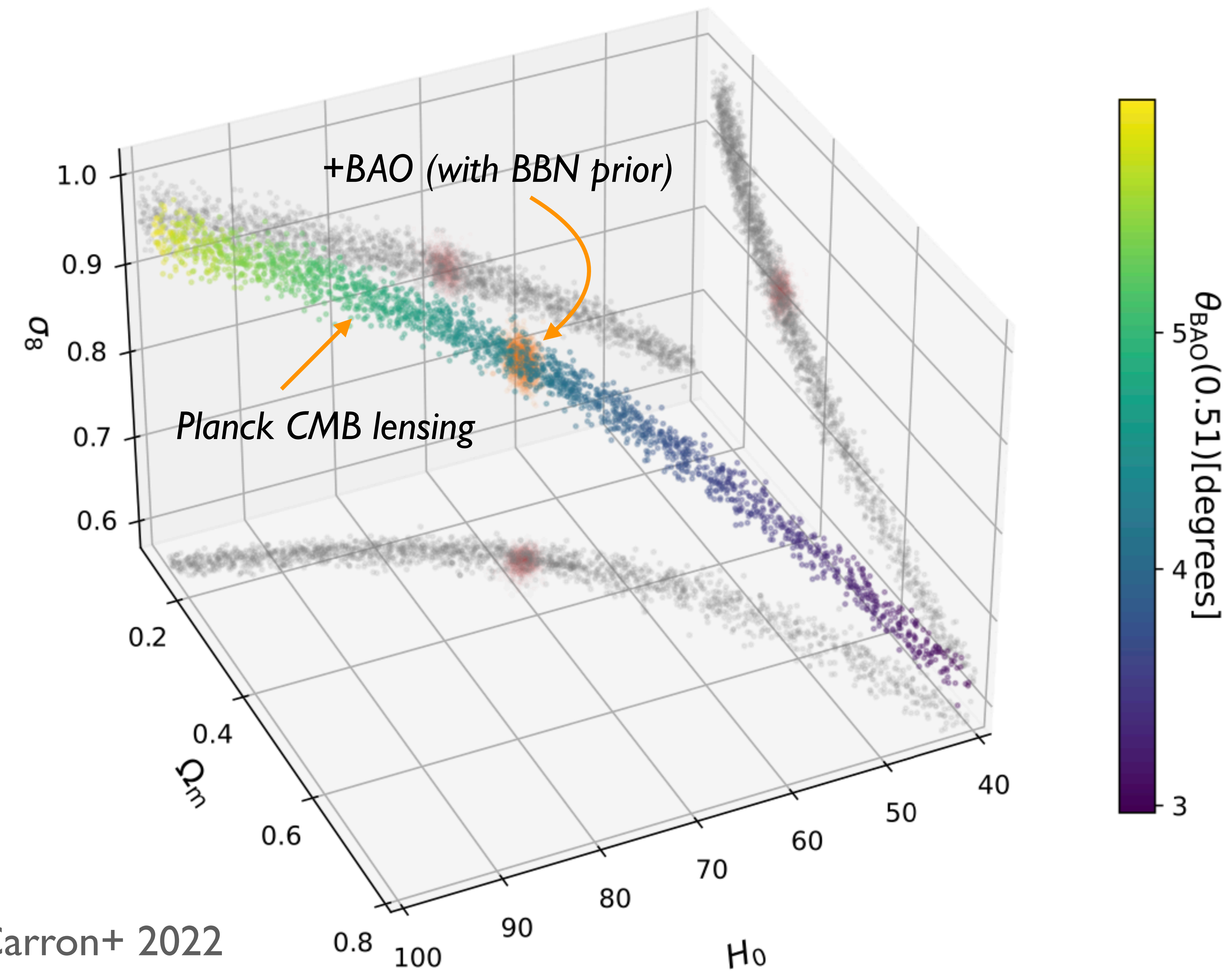
(Mean-squared deflection) x (no. of k_{eq}^{-1} scale lenses in χ_*)

- With sufficient range of L can decouple A_s and ℓ_{eq}

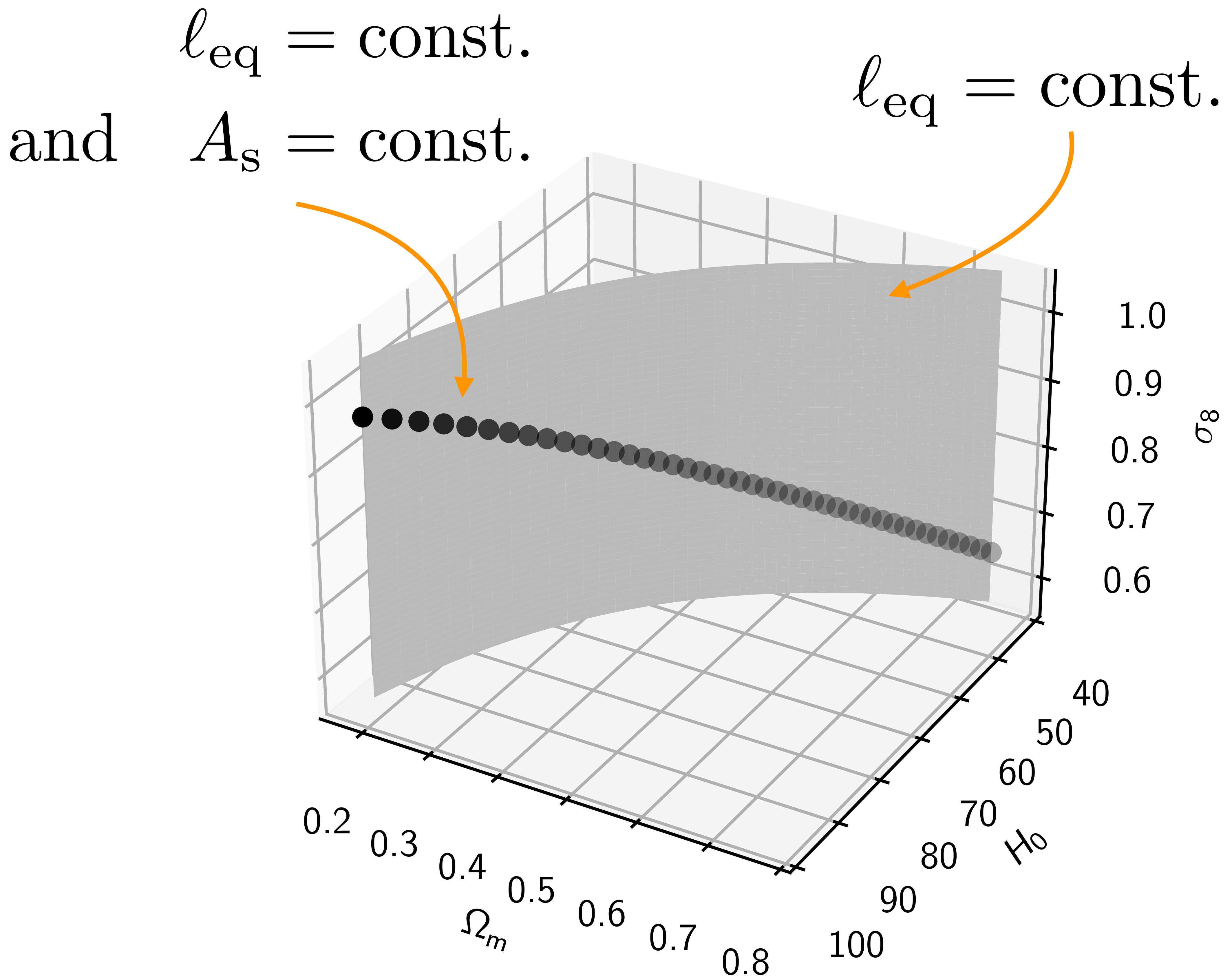


Pan+ 2014; Planck 2016

LCDM parameter dependencies



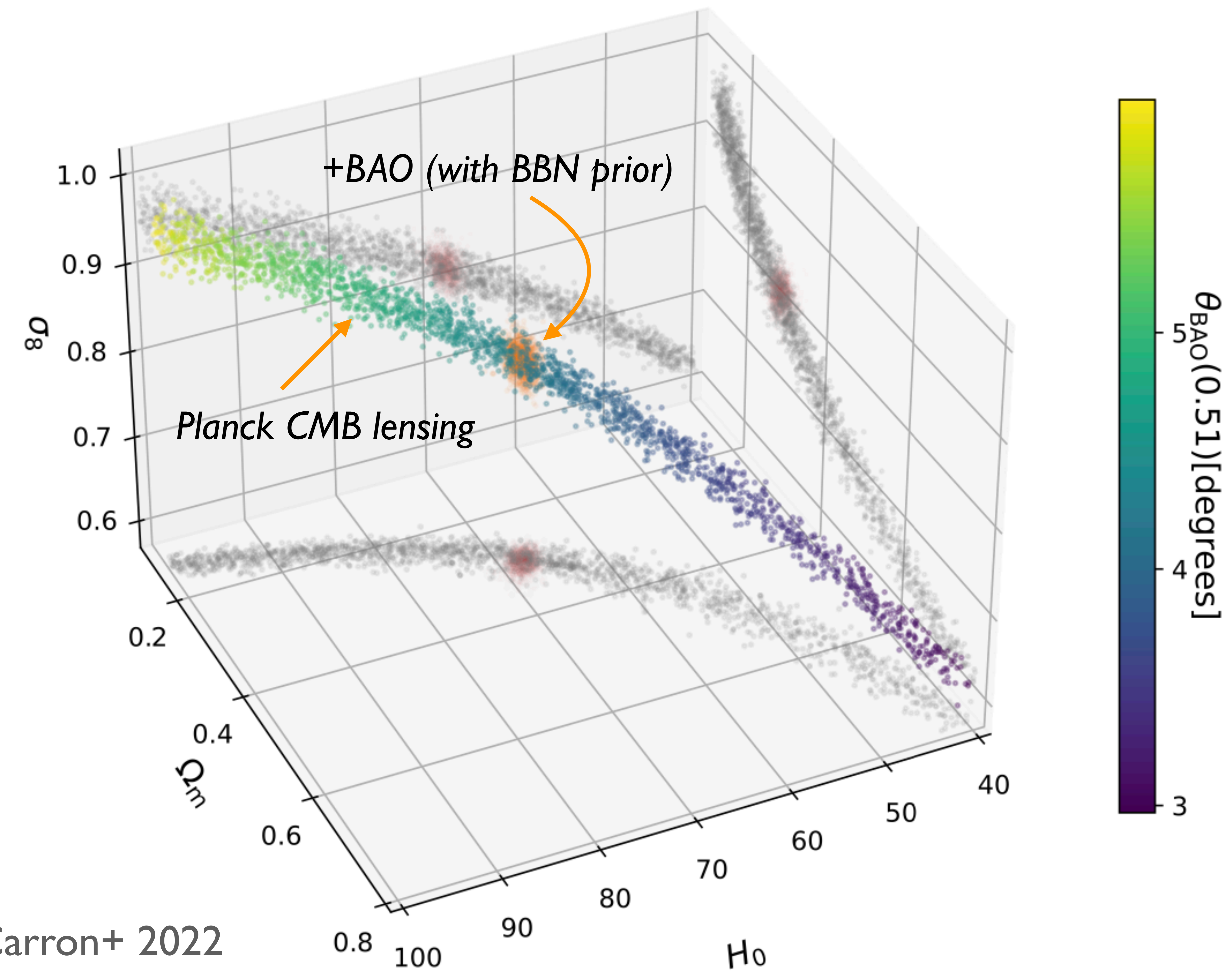
Carron+ 2022



$$\ell_{\rm eq} \propto \Omega_{\rm m}^{0.6} H_0$$

$$A_{\rm s} \propto \sigma_8^2 \Omega_{\rm m}^{-1.5} H_0^{-3.5}$$

LCDM parameter dependencies



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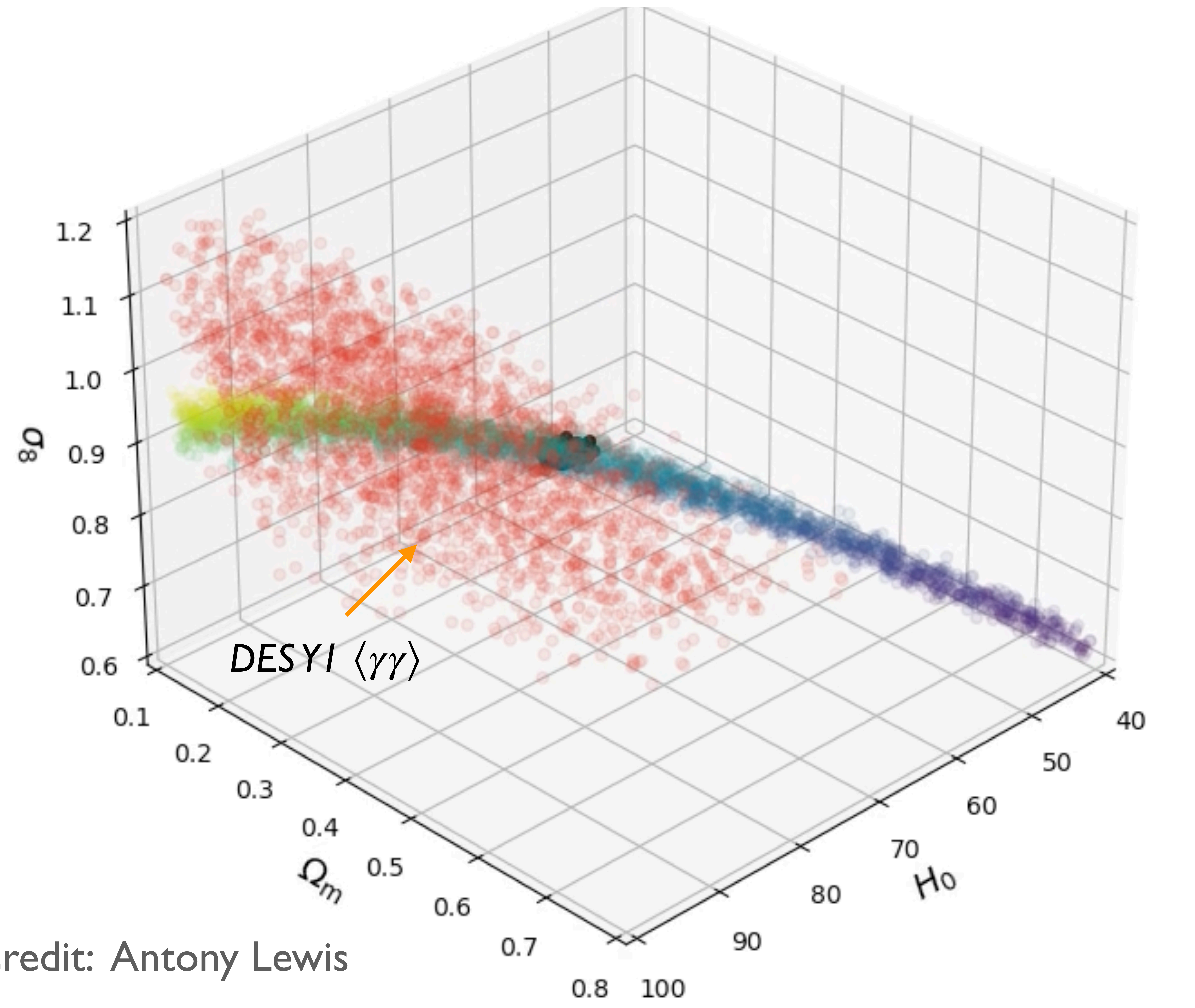
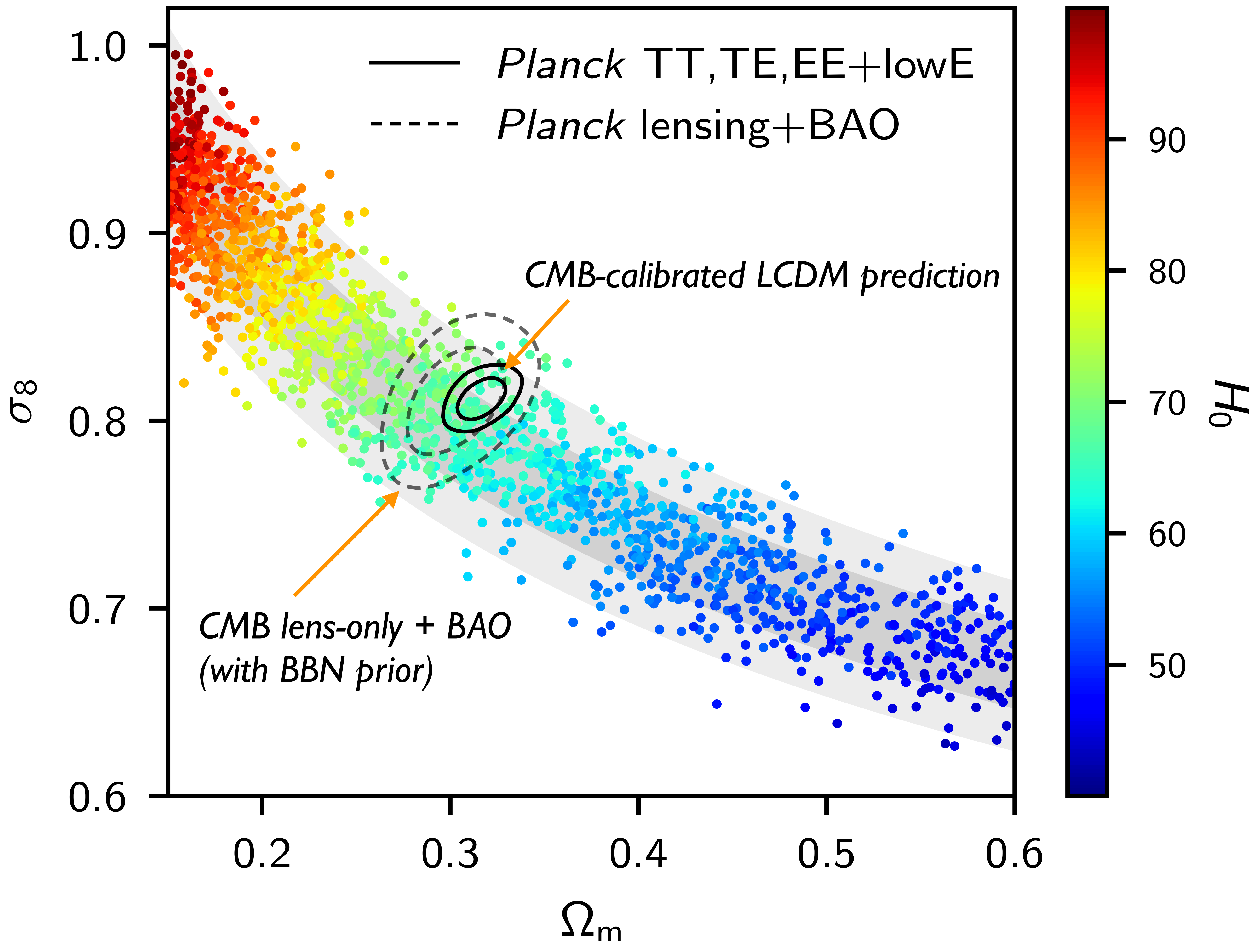


Credit: Antony Lewis

CMB-lensing-only LCDM constraints



Model-independent marginalisation based on observed spectra

$$\langle \hat{C}_L^{\phi\phi} \rangle \sim \left(\frac{C^{TT} C^{TT}}{C^{TT}_{\rm fid} C^{TT}_{\rm fid}} \right) C_L^{\phi\phi}$$

Priors for lens-only:

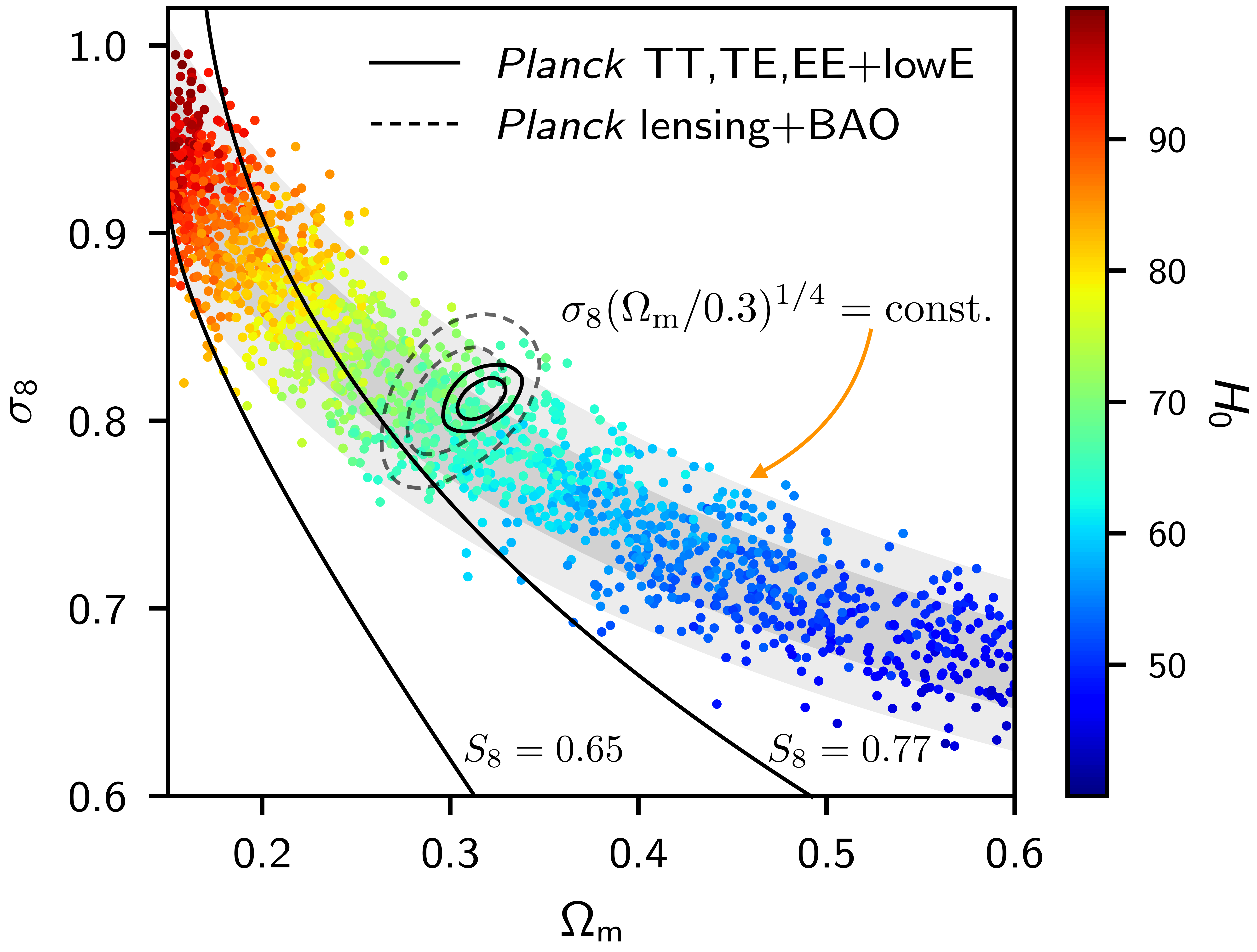
$$n_{\rm s} = 0.96 \pm 0.02$$

$$0.4 < h < 1.0$$

$$\Omega_{\rm b} h^2 = 0.0222 \pm 0.0005 \quad ({\rm BBN})$$

Excellent agreement with LCDM expectation calibrated by primary CMB!

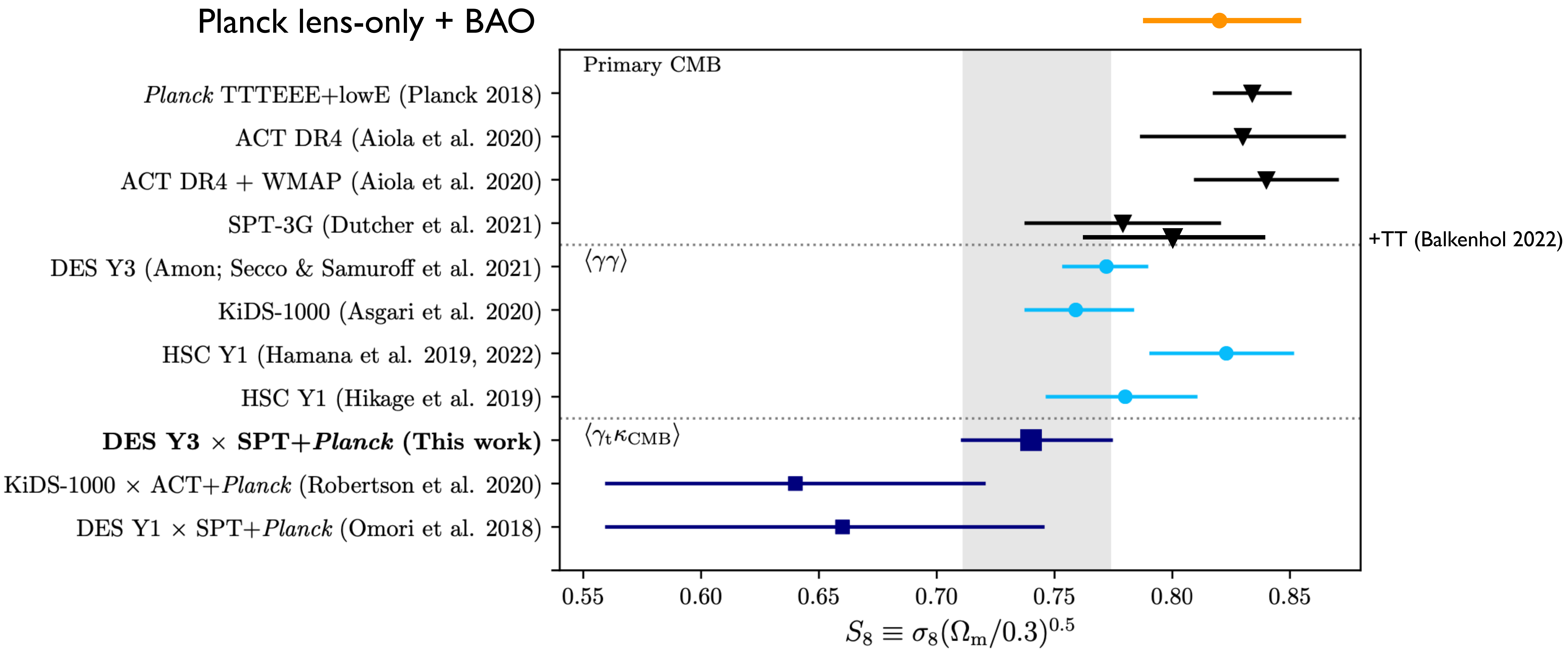
CMB-lensing-only LCDM constraints



Lensing of galaxies ($z < 1$) best constrain

$$S_8 \equiv \sigma_8(\Omega_m/0.3)^{1/2}$$

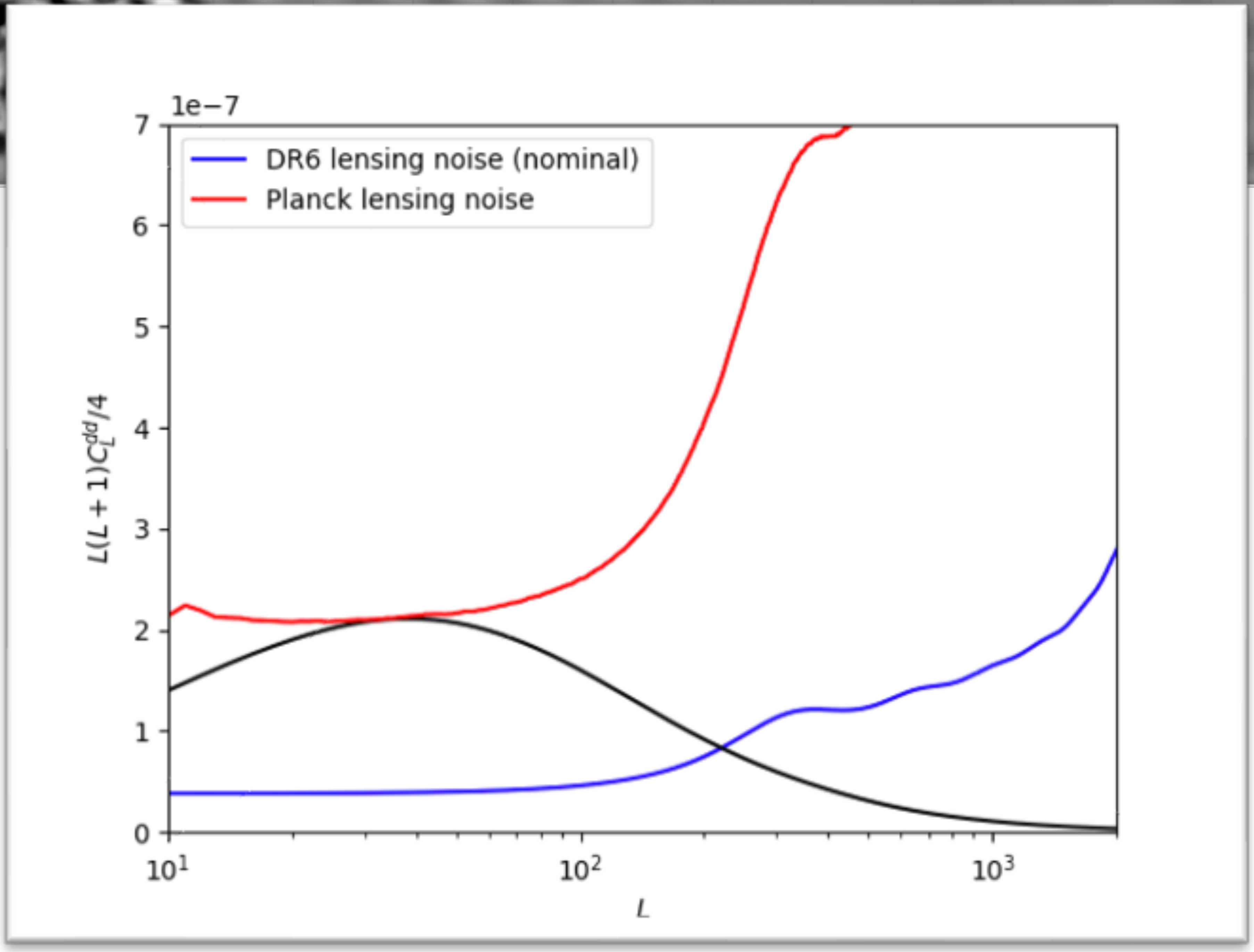
Recent structure measurements from lensing



Similarly low S_8 including galaxy clustering

Chang+ 2023

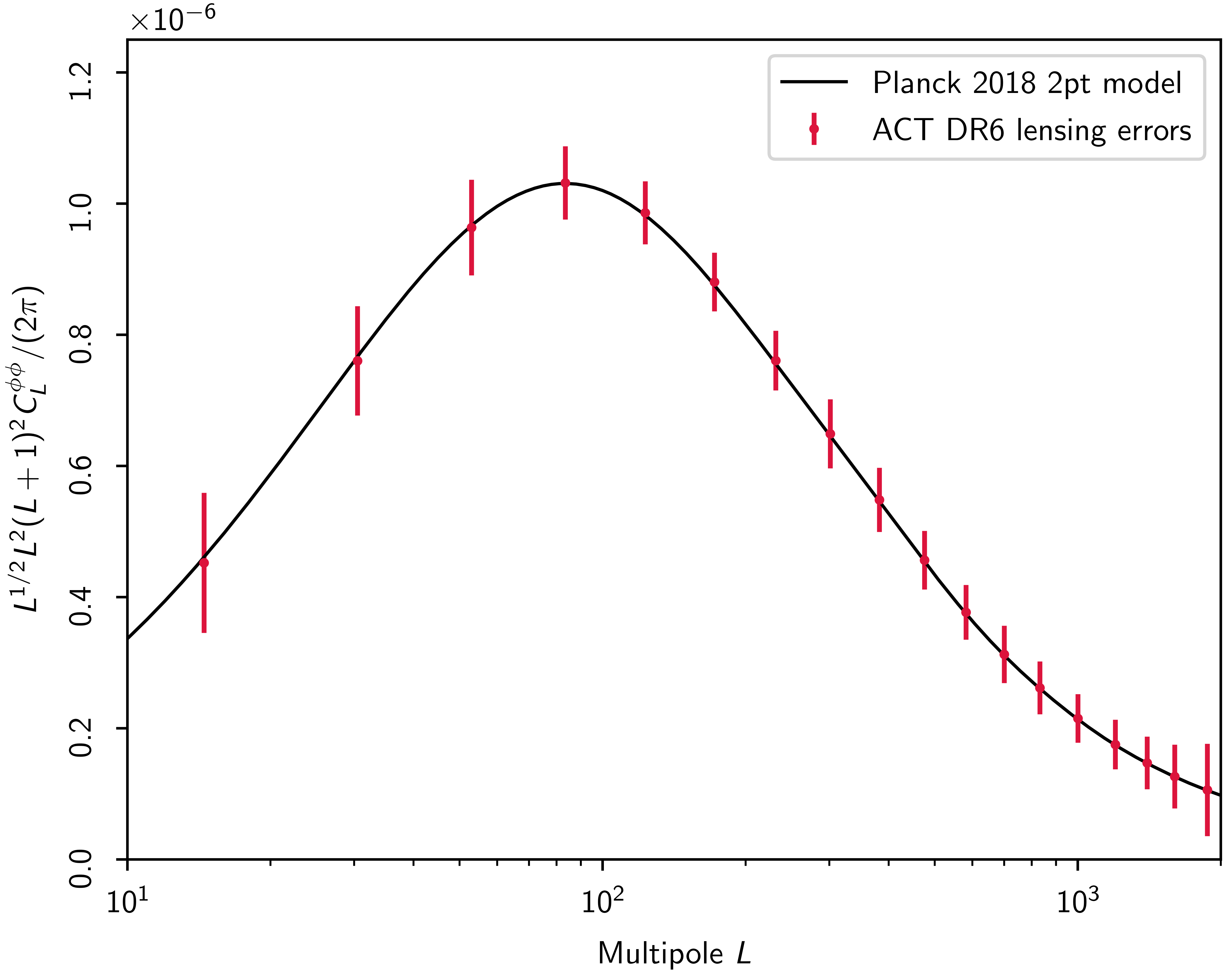
CMB lensing maps from ACT DR6



- 2x lower reconstruction noise than Planck
  - New cross-split estimator to mitigate noise complications
  - Profile-hardened against extragalactic foregrounds
- 10,000 deg^2

Qu+ 2023 (in internal review)

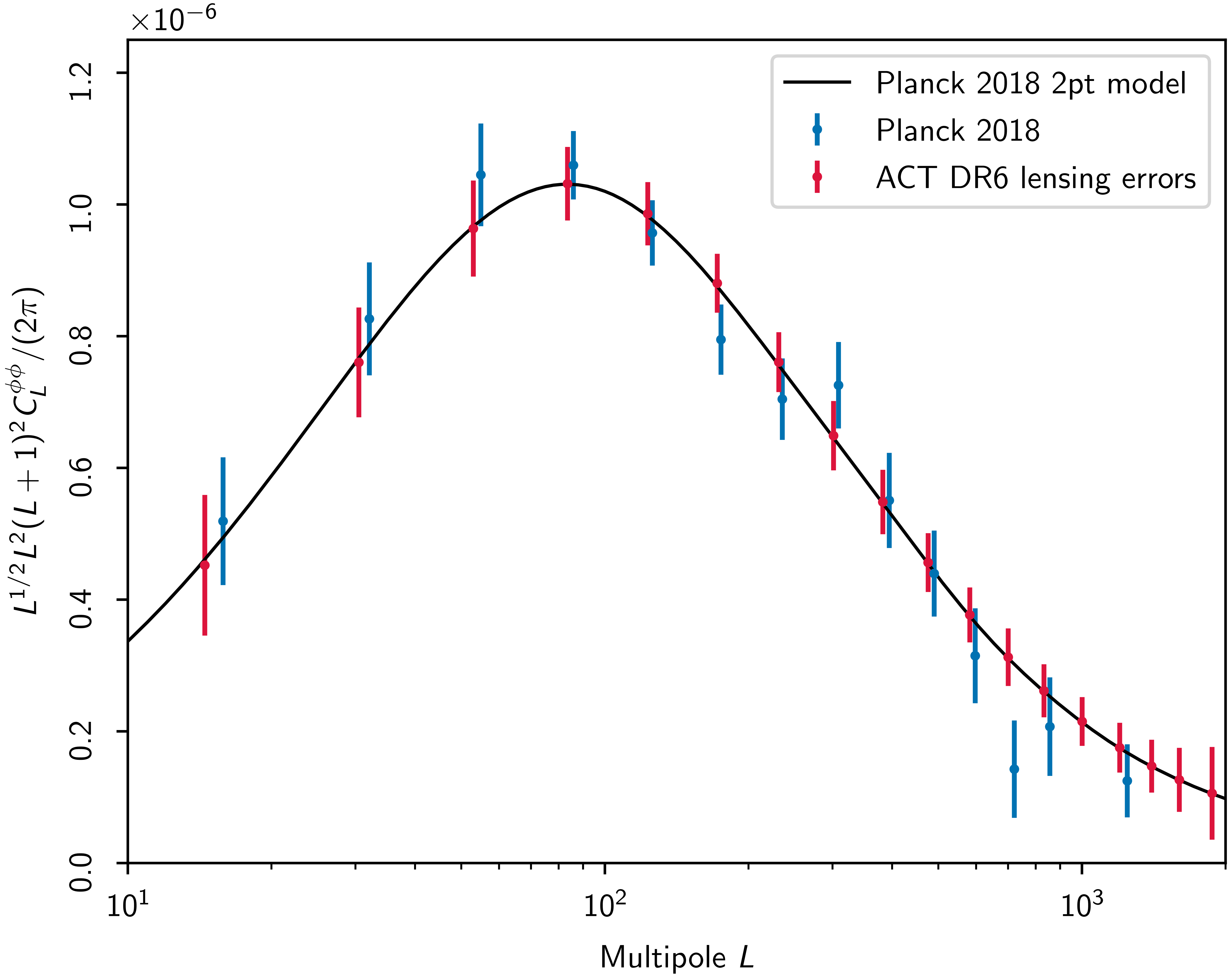
ACT DR6 lensing power spectrum errors



Real ACT DR6 error bars but centred on theory

Qu+ 2023 (in internal review)

ACT DR6 lensing power spectrum errors



- Comparable constraining power to Planck and weakly correlated
  - State-of-the-art S_8 and $\sum m_\nu$ constraints from combination (+BAO)

Qu+ 2023 (in internal review)

Thank you!

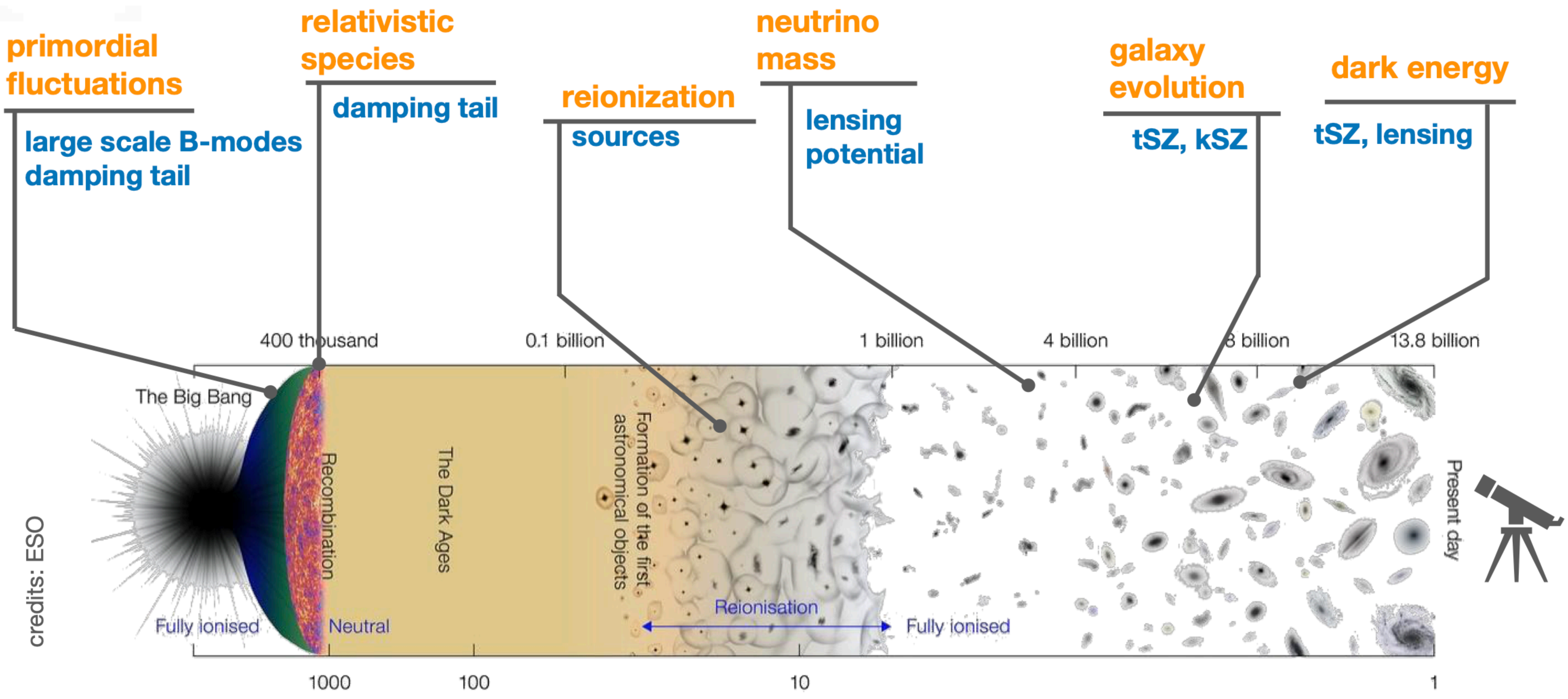
Simons Observatory

- 3 US SATs + 2 UK SATs + 1 JPN SAT for *B*-mode science
- 40 % of sky with arcmin-resolution LAT survey overlapping DES, DESI, Rubin and LSST
- Six frequencies: 27–280 GHz
- First data in 2023!

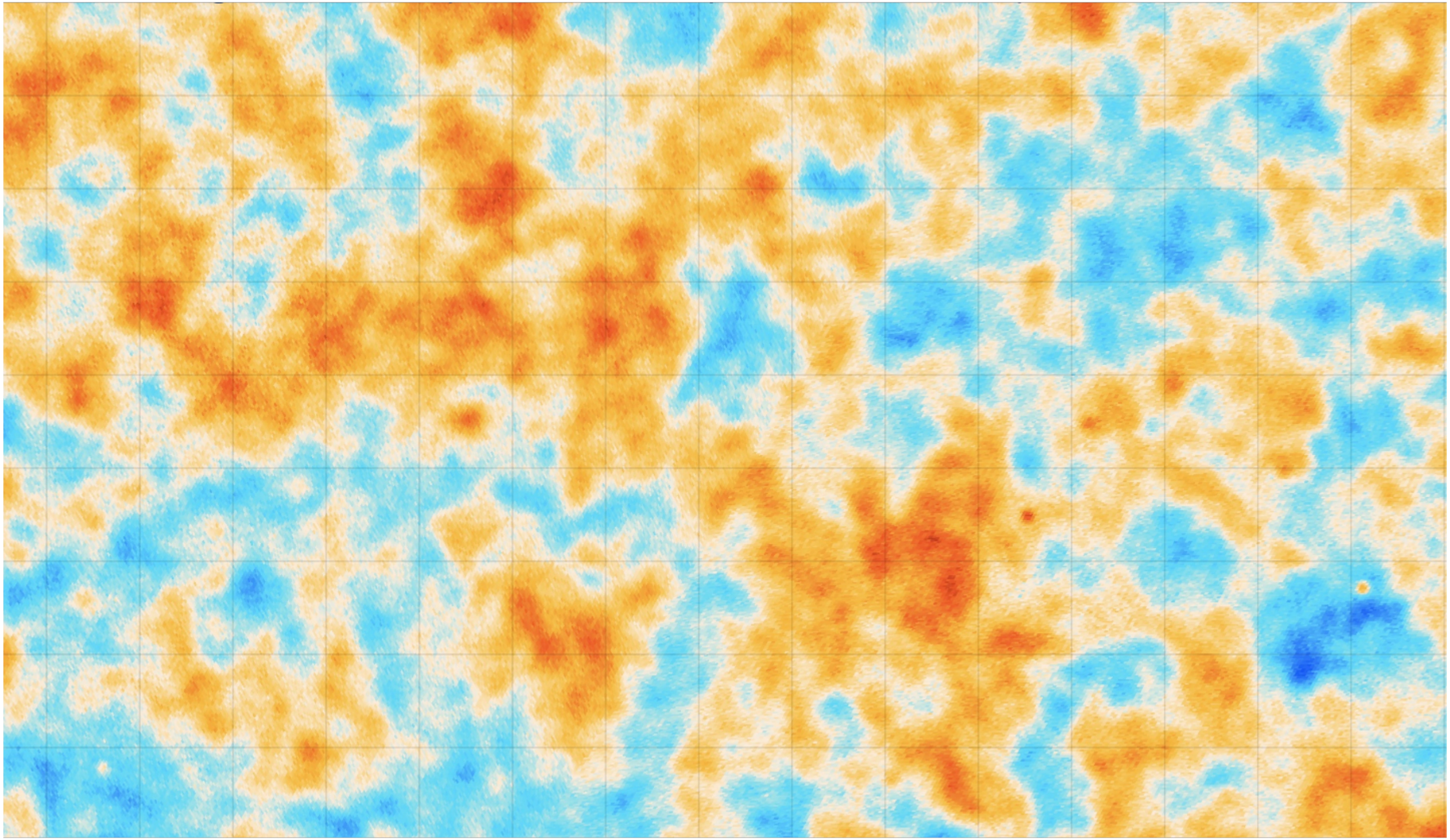
SO:UK (£18M UKRI infrastructure fund + STFC)

- 2x SATs
- 1x UHF optics tube for LAT
- UK data centre serving science-ready data products
- @CAM: LAT simulations and product readiness for lensing science

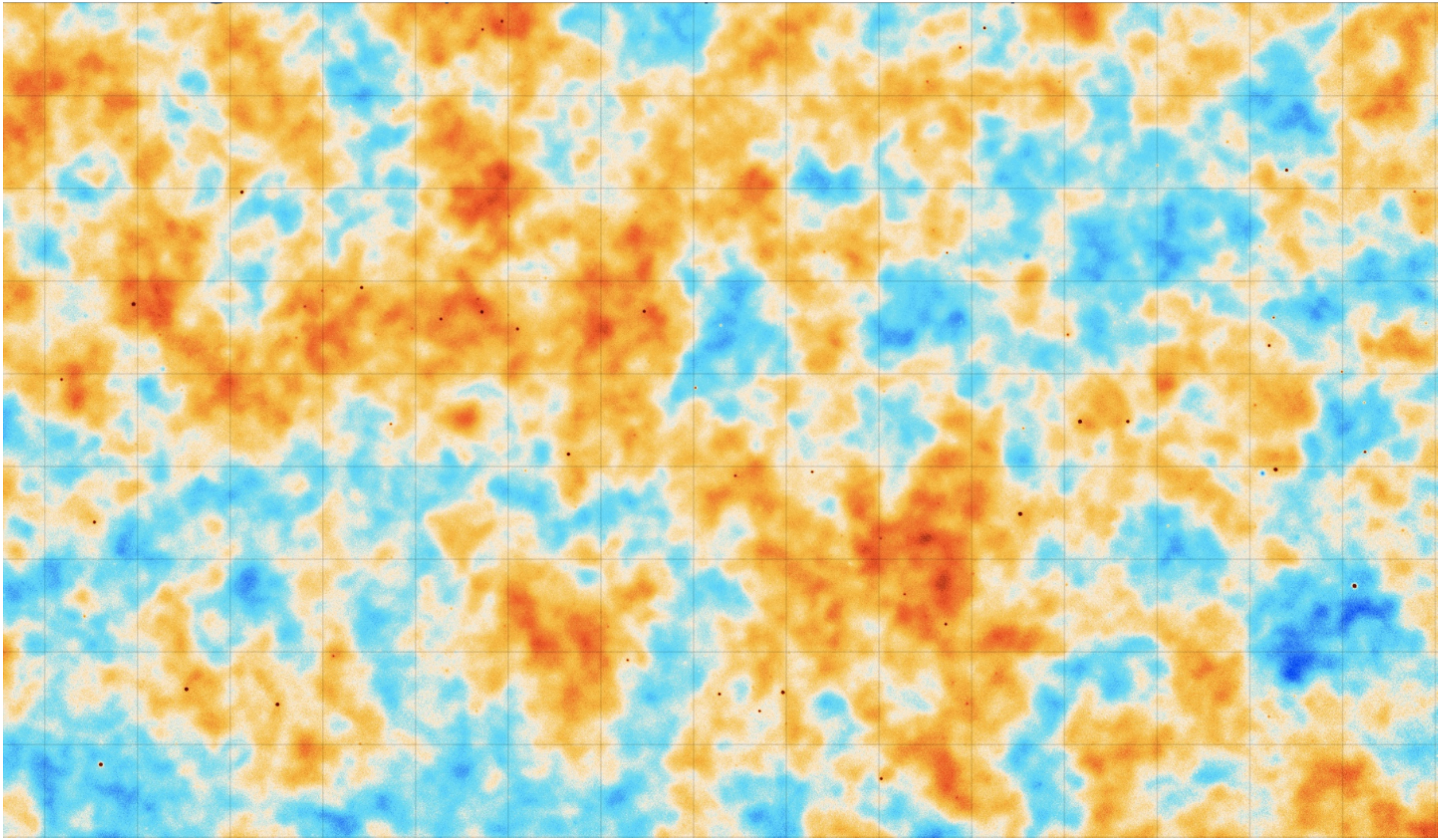
CMB science: from the early universe to galaxy evolution



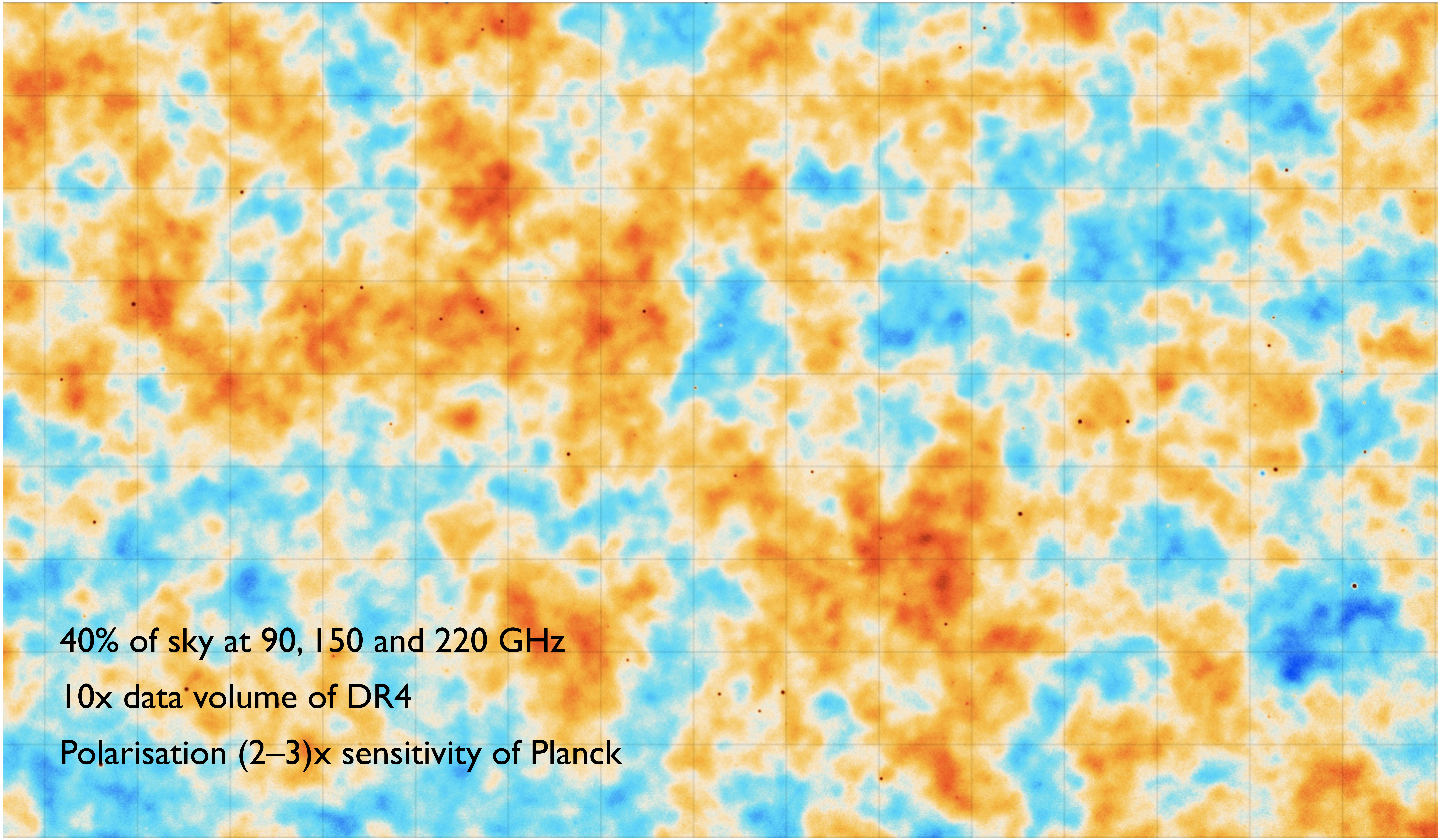
Planck temperature



Forthcoming ACT DR6 temperature



Forthcoming ACT DR6 maps

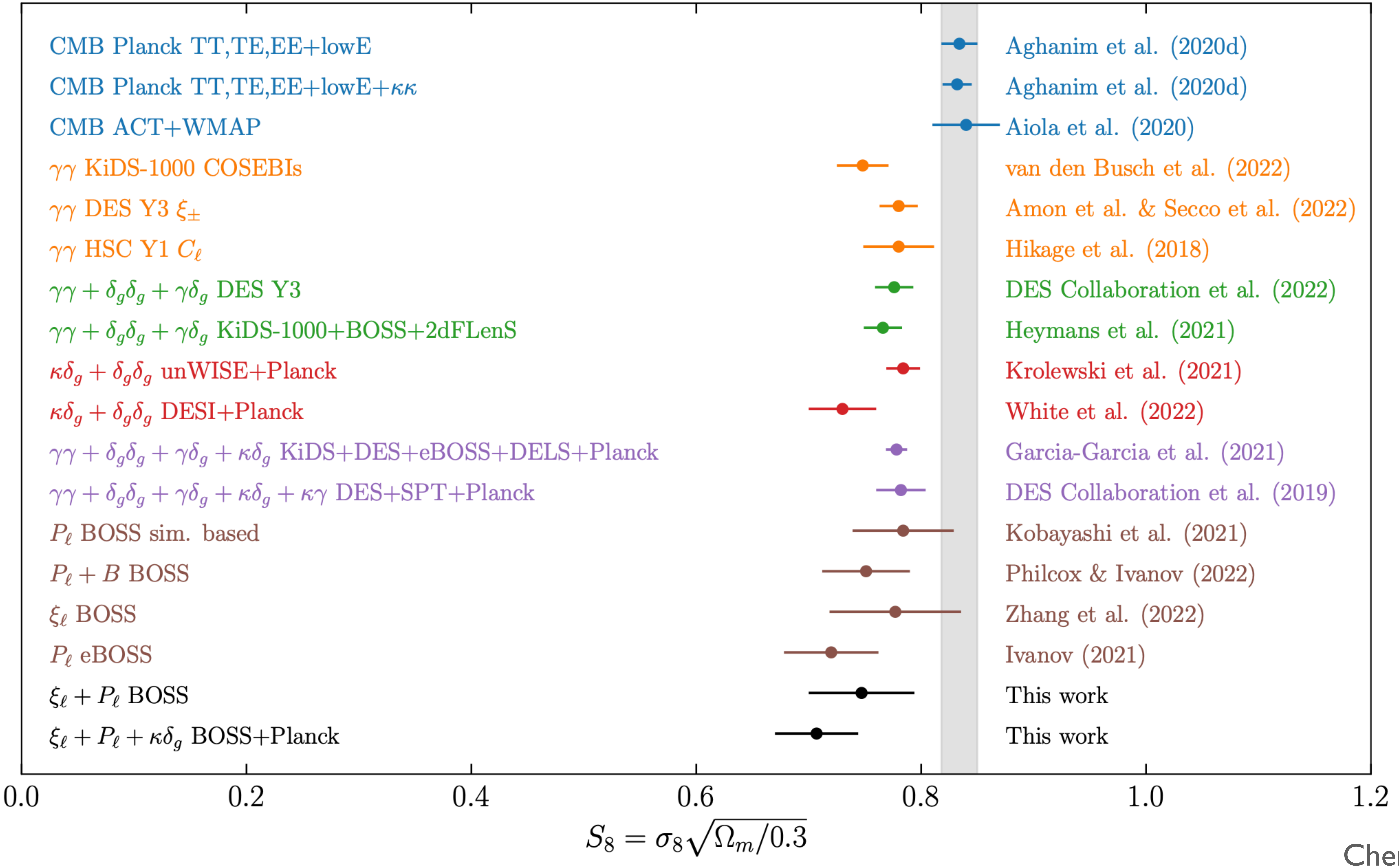


40% of sky at 90, 150 and 220 GHz

10x data volume of DR4

Polarisation (2–3)x sensitivity of Planck

Recent structure measurements ADD PLANK kk POINT



Chen+ 2022