CMB cosmology

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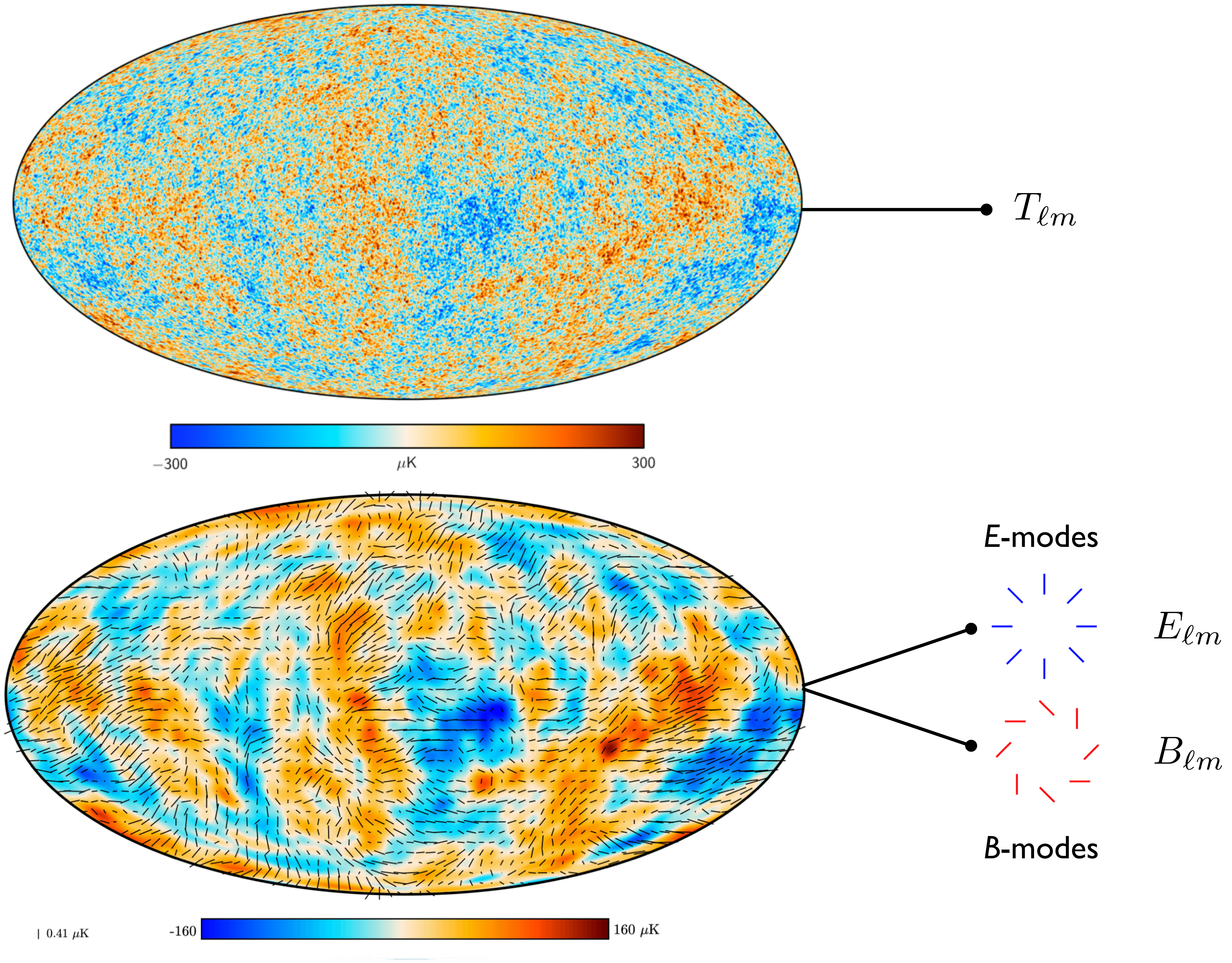
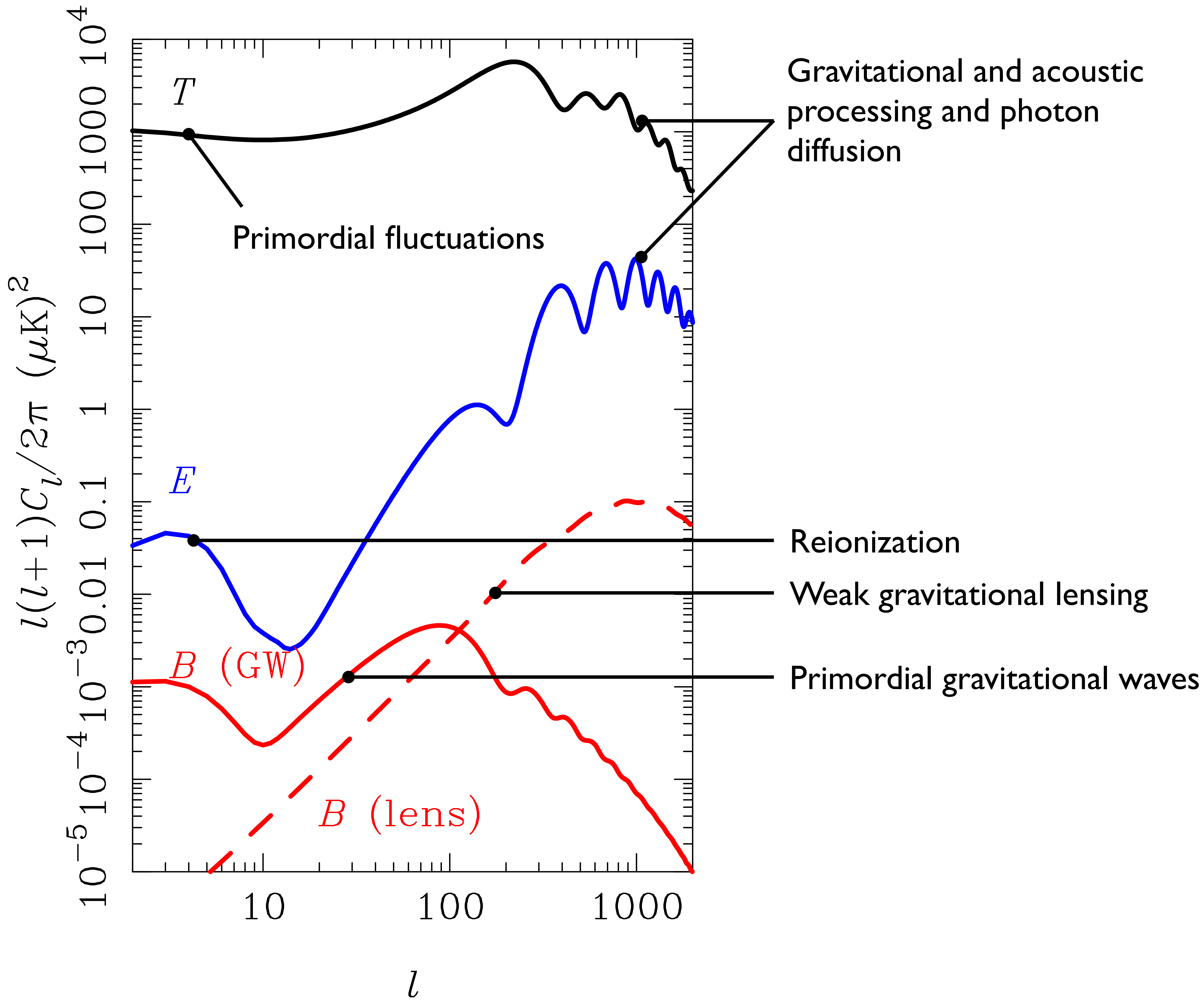
CMB observables

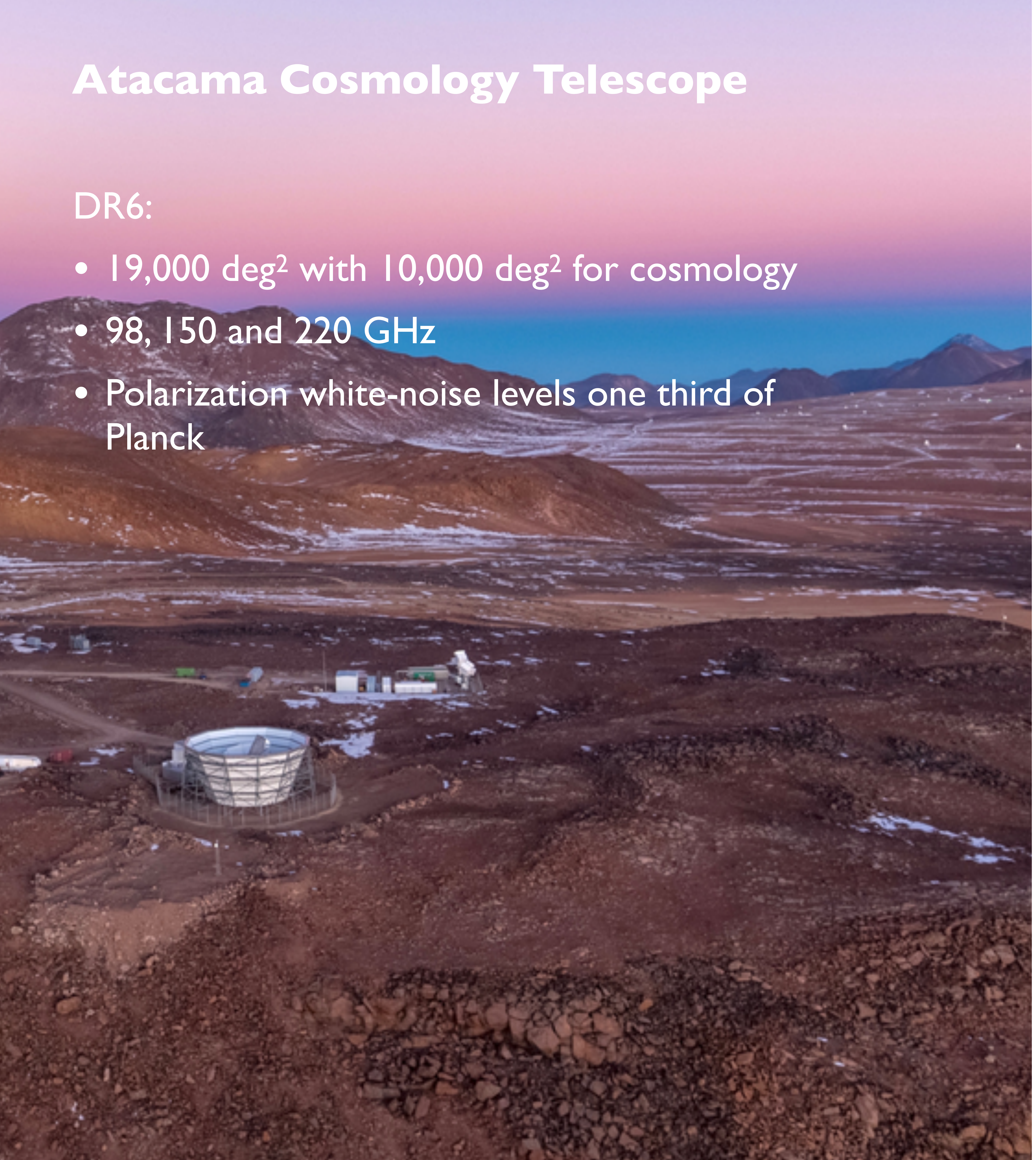


ESA/Planck

CMB physics



T
E
B (GW)
B (lens)
Primordial fluctuations
Gravitational and acoustic processing and photon diffusion
Reionization
Weak gravitational lensing
Primordial gravitational waves
$l(l+1)C_l/2\pi\ (\mu K)^2$
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
10
100
1000
10^4
10
100
1000
l



Atacama Cosmology Telescope

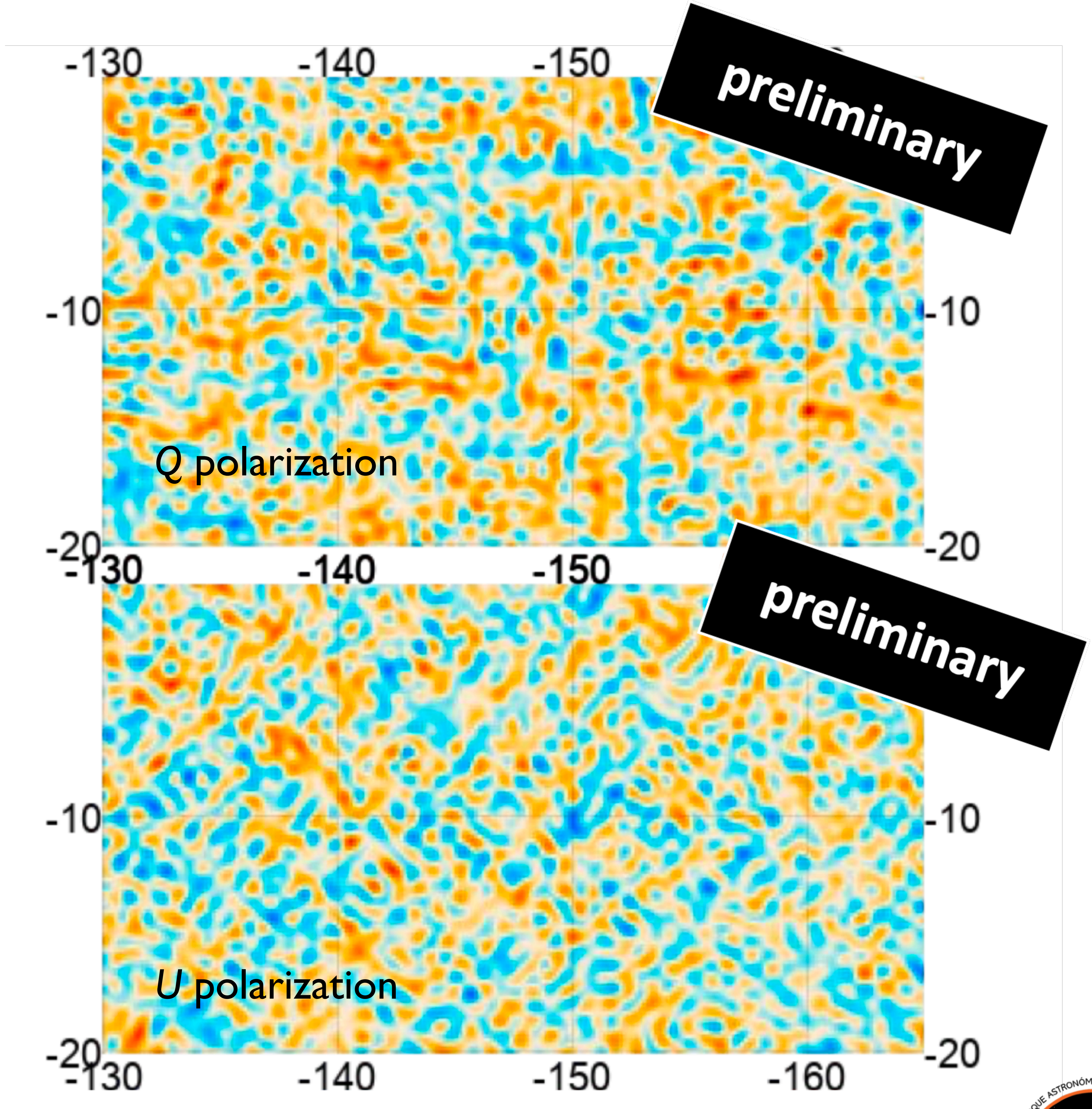
DR6:

- 19,000 deg^2 with 10,000 deg^2 for cosmology
- 98, 150 and 220 GHz
- Polarization white-noise levels one third of Planck

Bicep/Keck

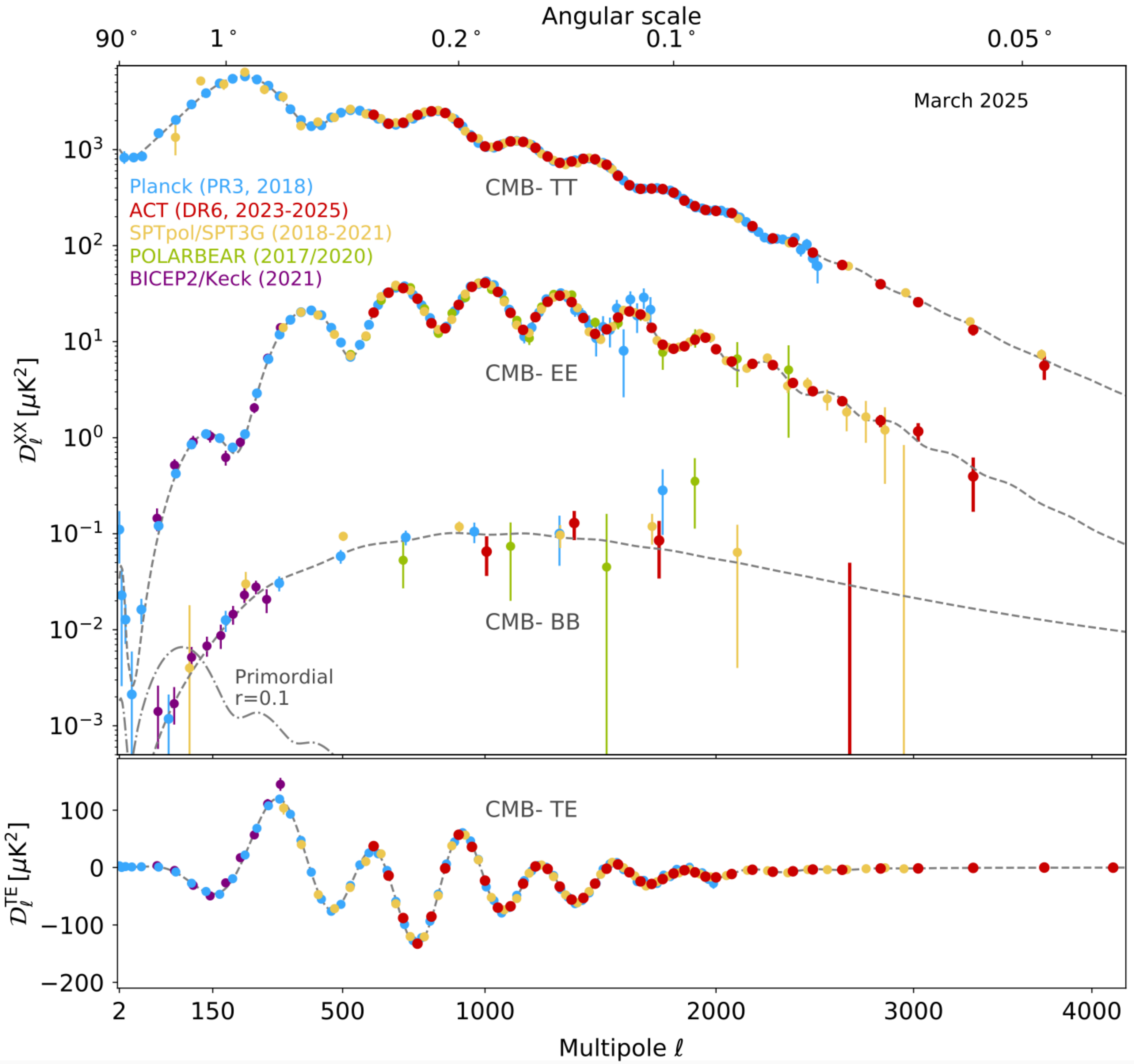
South Pole Telescope

Simons Observatory



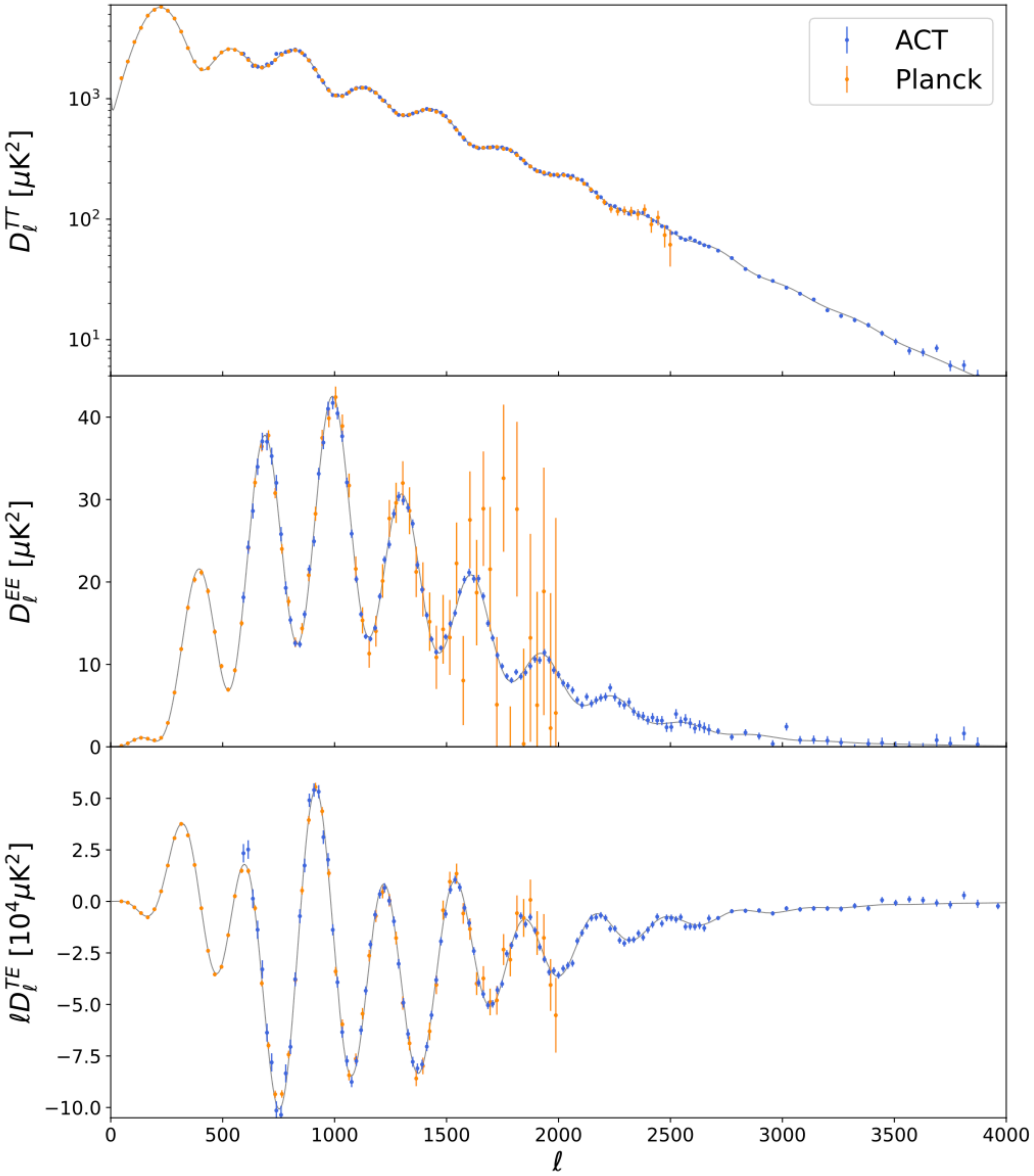
Preliminary maps from SO SAT data

Current CMB power spectrum measurements



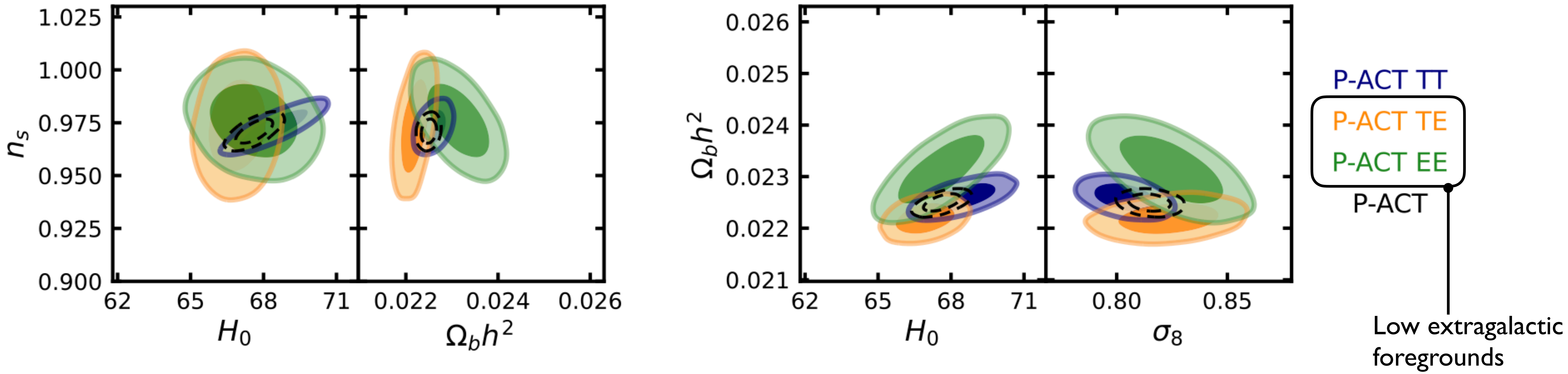
Louis+ 2025

ACT DR6 vs Planck frequency-combined spectra



Louis+ 2025

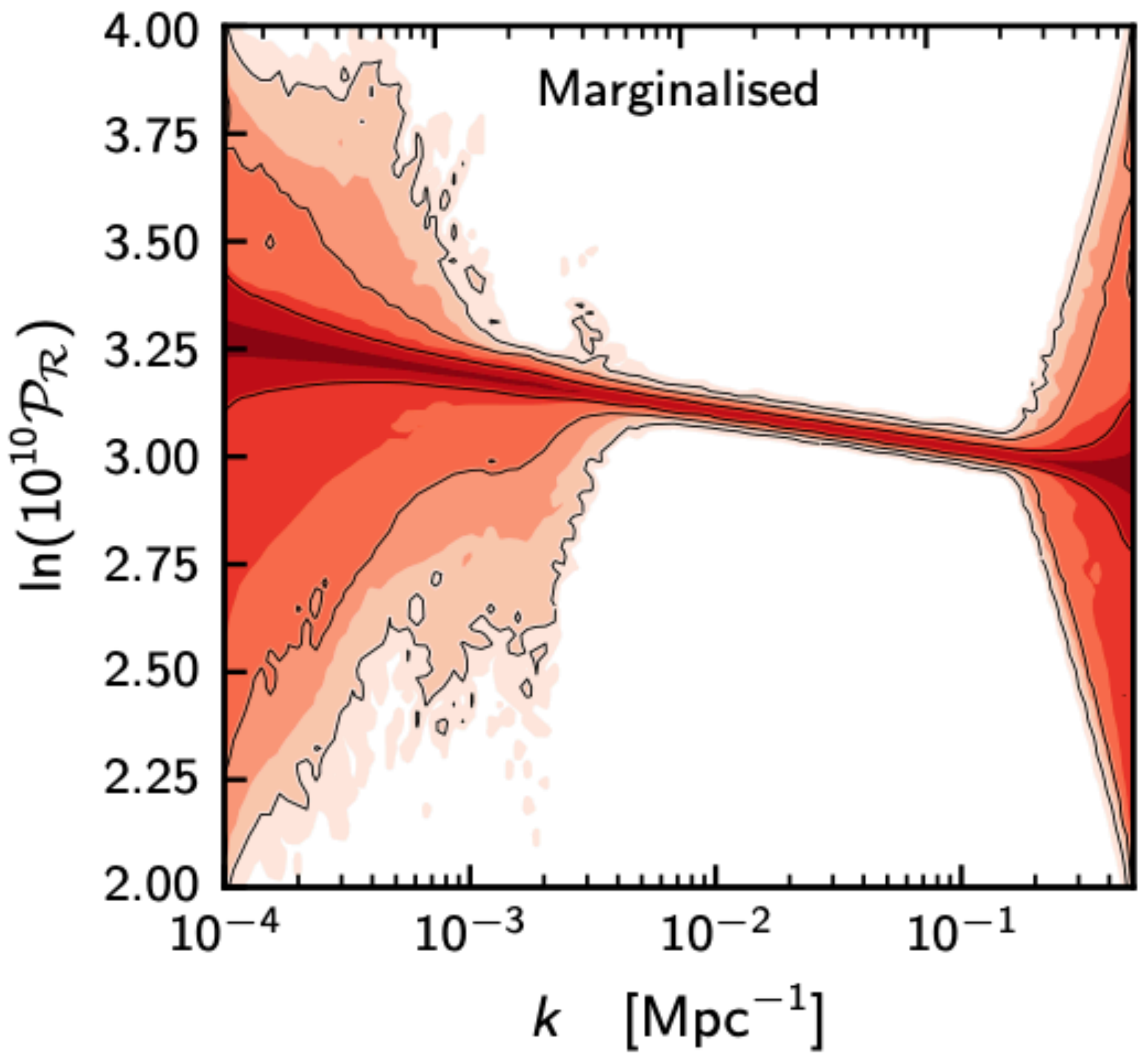
Consistent LCDM cosmology from temperature and polarization

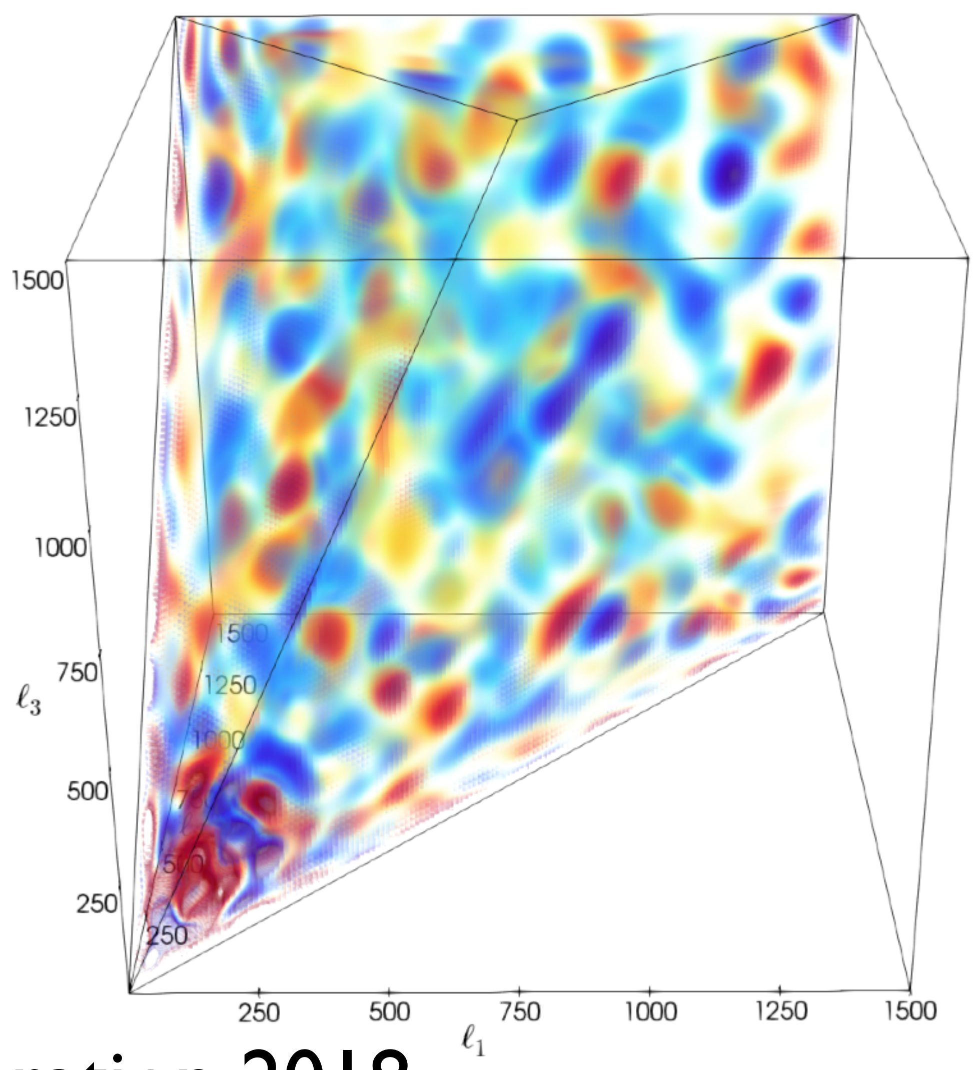


Comparable (and consistent) constraints from temperature and polarization and between experiments, e.g., Planck vs WMAP+ACT

Louis+ 2025

Initial conditions





Planck Collaboration 2018

- Passive evolution of scalar fluctuations from early times
- Super-Hubble fluctuations
- Adiabatic:

$$\text{Fraction } \langle (\Delta T)^2 \rangle_{\ell \leq 2500} < 2\% \quad \text{(Planck)}$$

- Almost scale-invariant scalar fluctuations:

$$n_\mathrm{s} = 0.9649 \pm 0.0044 \quad (68\%\ \text{CL; Planck})$$

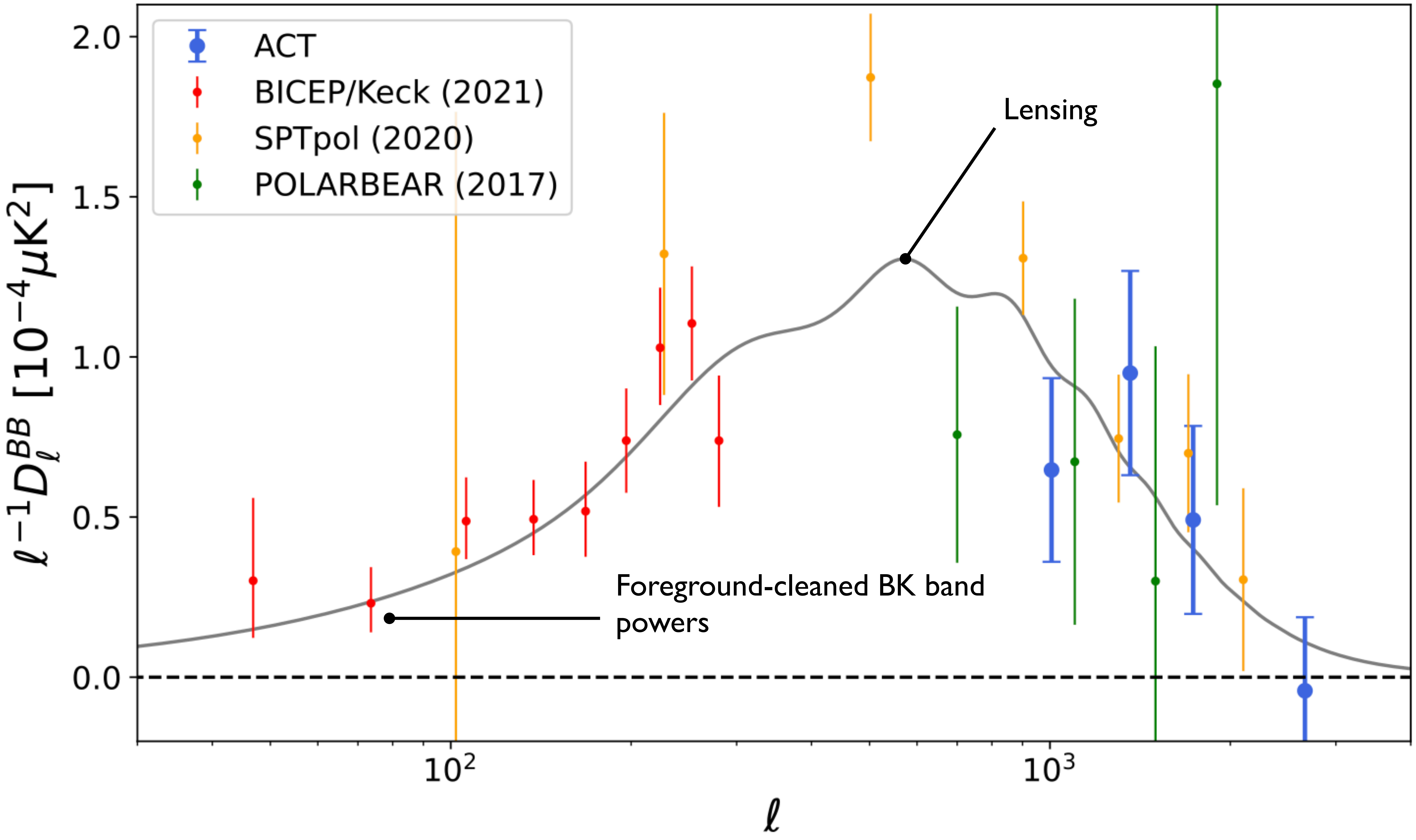
- No evidence for departure from power-law spectrum:

$$dn_\mathrm{s}/d\ln k = -0.006 \pm 0.007 \quad (68\%\ \text{CL; Planck})$$

- Gaussian initial fluctuations:

$$f_\mathrm{NL}^\mathrm{loc} = -0.9 \pm 5.1$$
$$f_\mathrm{NL}^\mathrm{eq} = -18 \pm 47$$
$$f_\mathrm{NL}^\mathrm{orth} = -37 \pm 23$$

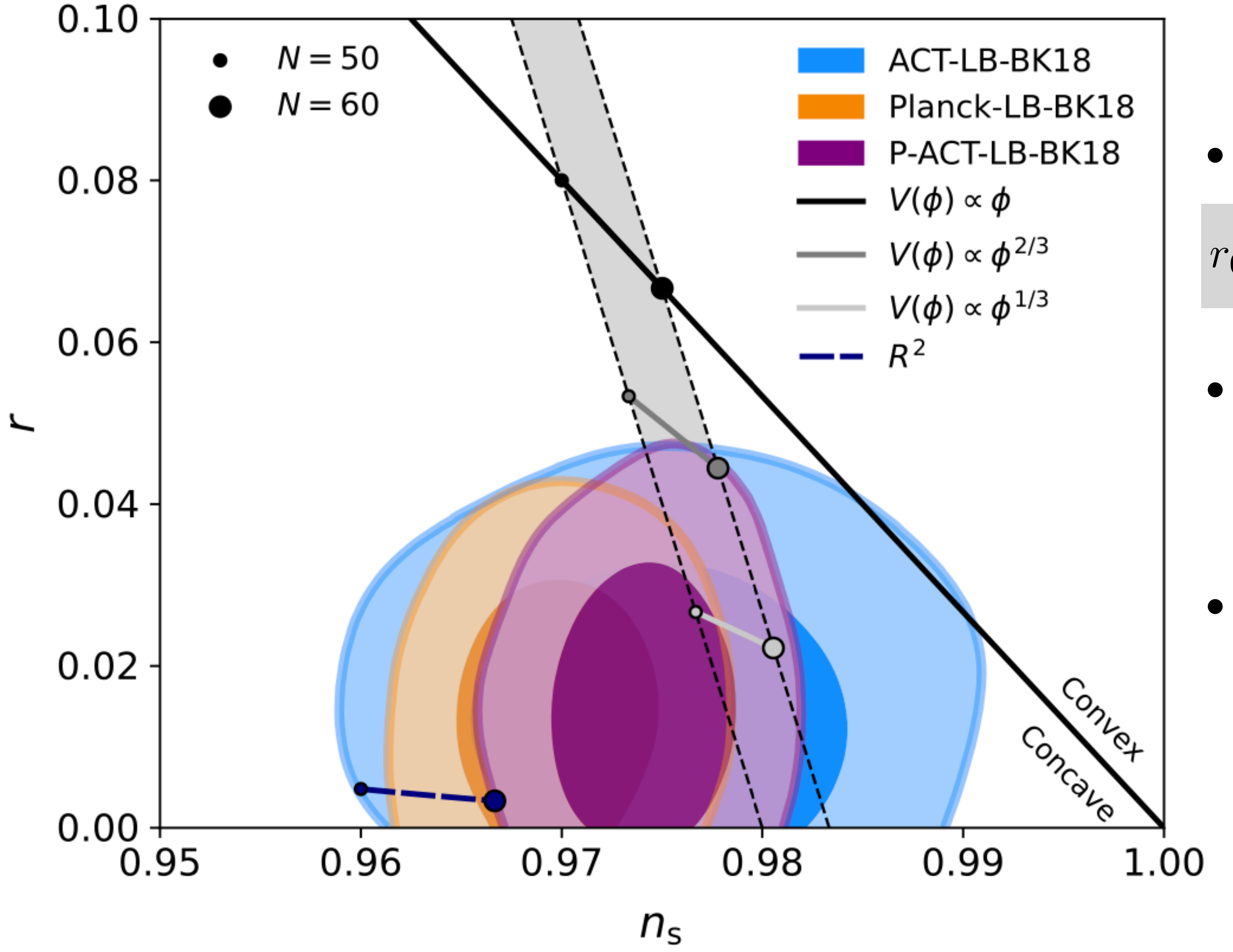
Searching for primordial gravitational waves in B-mode polarization



Louis+ 2025

Cleaning of Galactic dust emission and **lensing** is critical for degree-scale *B*-mode searches

Inflation constraints



- Constraint on r driven by BICEP/Keck

$$r_{0.05} < 0.038 \quad (95\%; \text{Planck+ACT+BK+lensing+BAO})$$

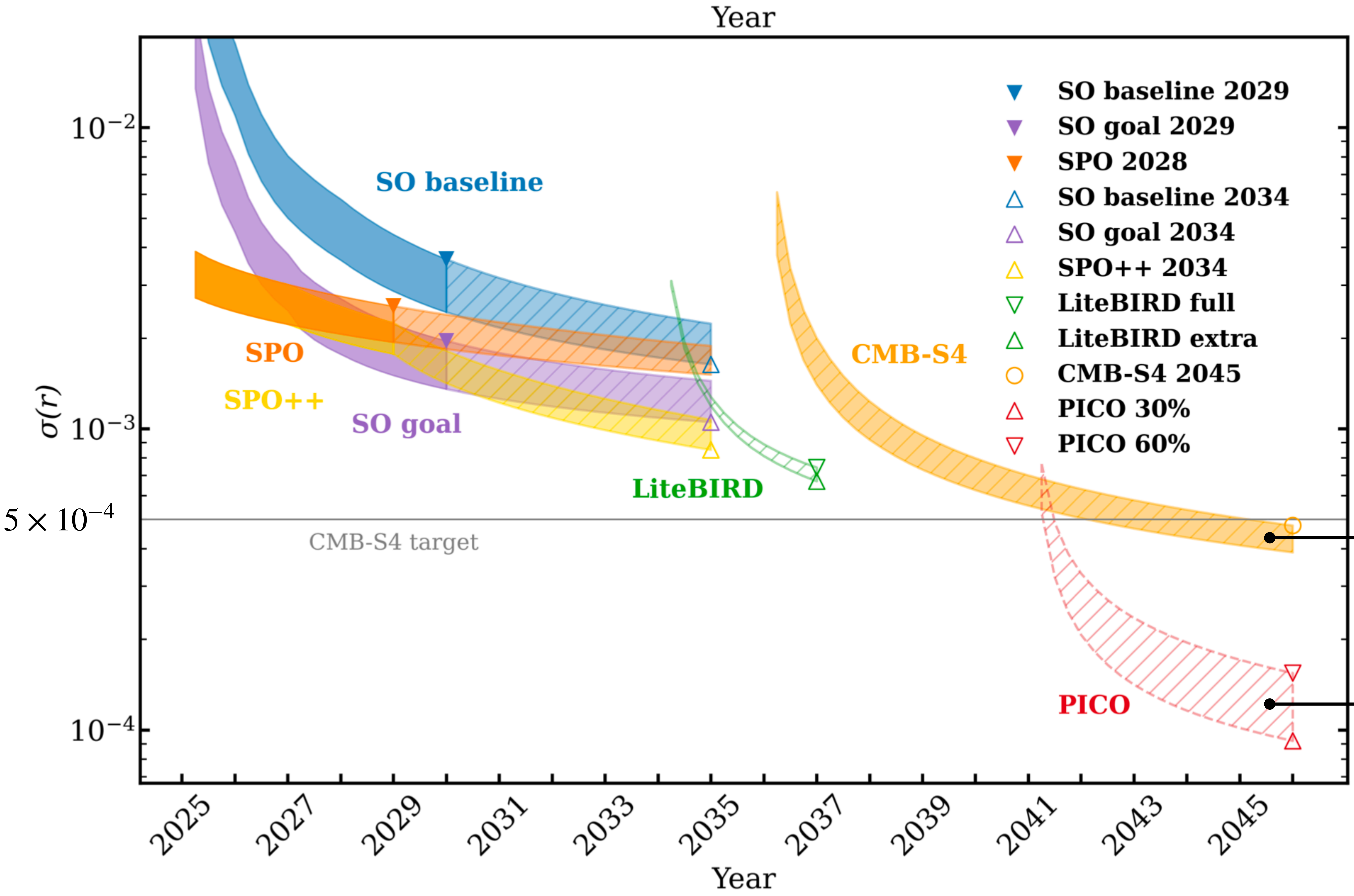
- n_s pushed up 1σ by lower $\Omega_m h^2$ from DESI BAO
  - Implications for natural targets such as R^2 inflation with $r = O(1/N^2)$?
- Goals for future surveys:

SO	$\sigma(r) \leq 0.003$ for $r = 0$
CMB-S4	$\sigma(r) = 5 \times 10^{-4}$ for $r = 0$

Requires aggressive delensing
(see Julien Carron's talk)

Calabrese + 2025

Timeline of improvements in tensor-to-scalar ratio

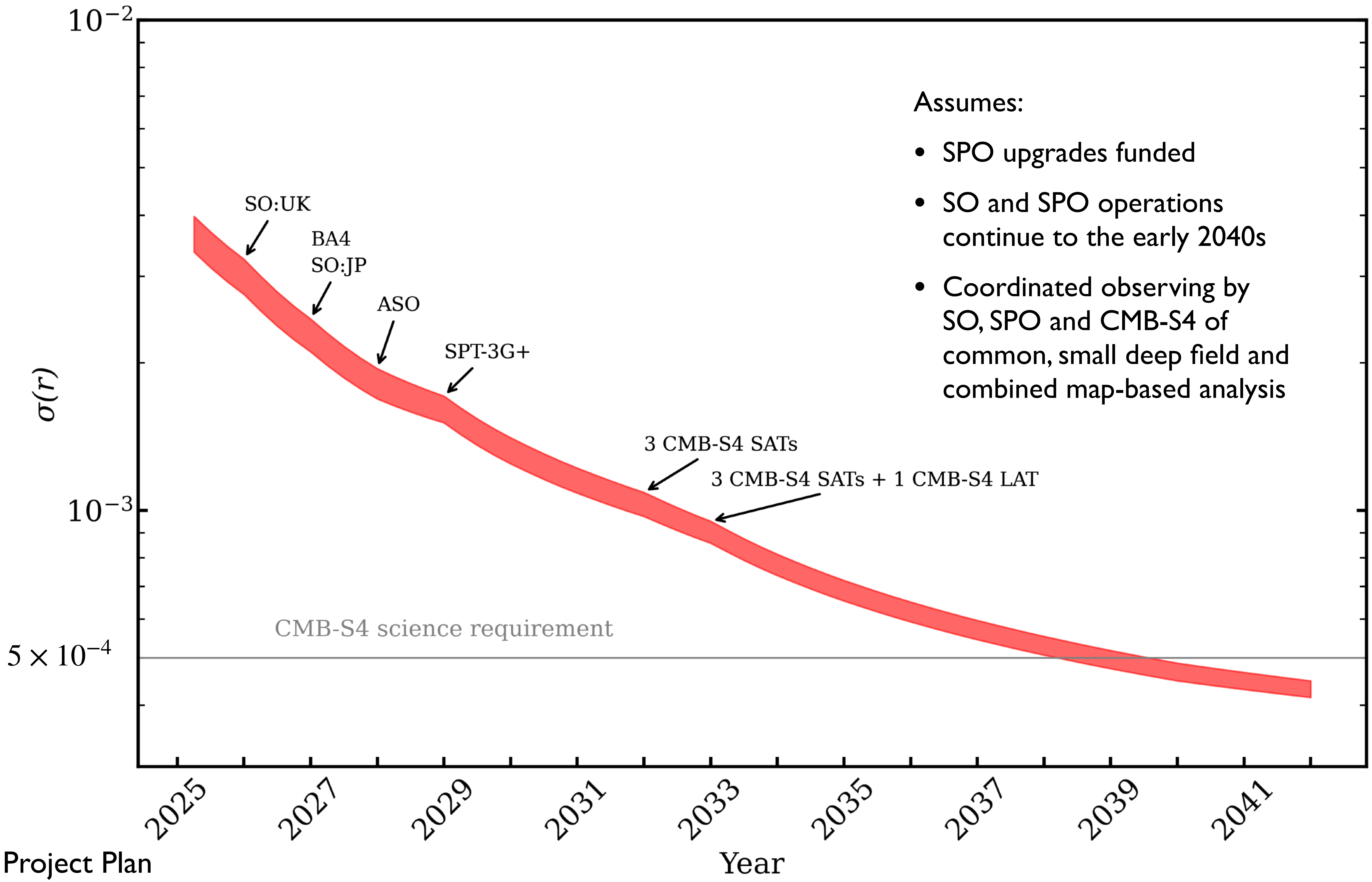


All-Chile stand-alone configuration (not what CMB-S4 is now proposing)

Probe-class mission concept study

CMB-S4 Survey of Current CMB Experiments

Timeline of improvements in tensor-to-scalar ratio from the ground

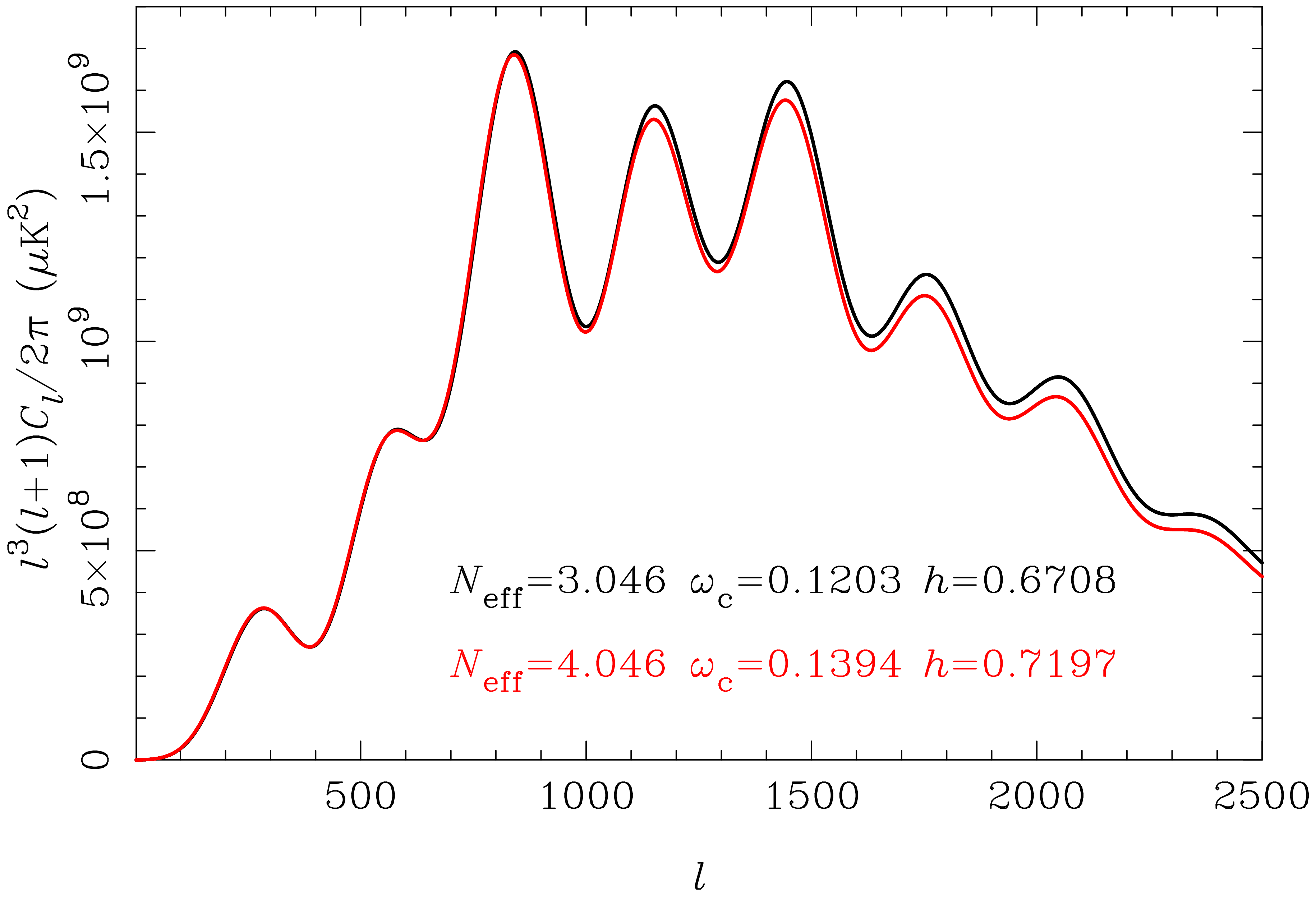


Assumes:

- SPO upgrades funded
- SO and SPO operations continue to the early 2040s
- Coordinated observing by SO, SPO and CMB-S4 of common, small deep field and combined map-based analysis

Revised CMB-S4 Project Plan

Particle content



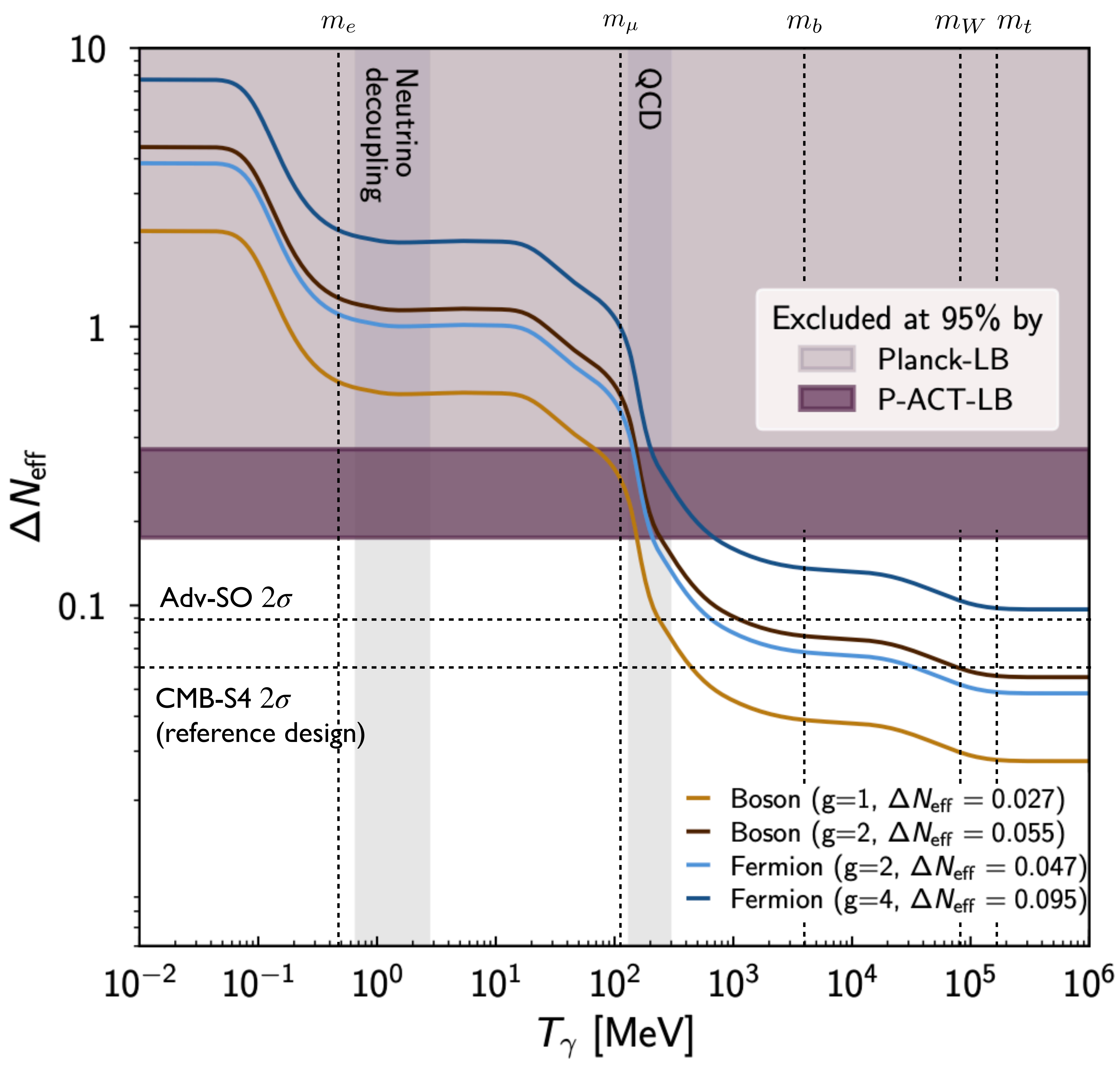
$$\bar{\rho}_\nu = \left(\frac{7}{8}\right)\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\,\bar{\rho}_\gamma$$

- Baryon density consistent with BBN abundances
- Cold dark matter with negligible velocity dispersion or interactions
- No evidence for additional relativistic particles beyond three SM neutrino flavours:

$$N_{\rm eff} = 2.99 \pm 0.17 \quad (68\%\ \text{CL; Planck})$$

  - ACT favours slightly less damping so lower $N_{\rm eff}$
- No evidence for non-minimal neutrino masses
  - Limit depends strongly on external data (e.g., BAO or SN used to break CMB geometric degeneracy)

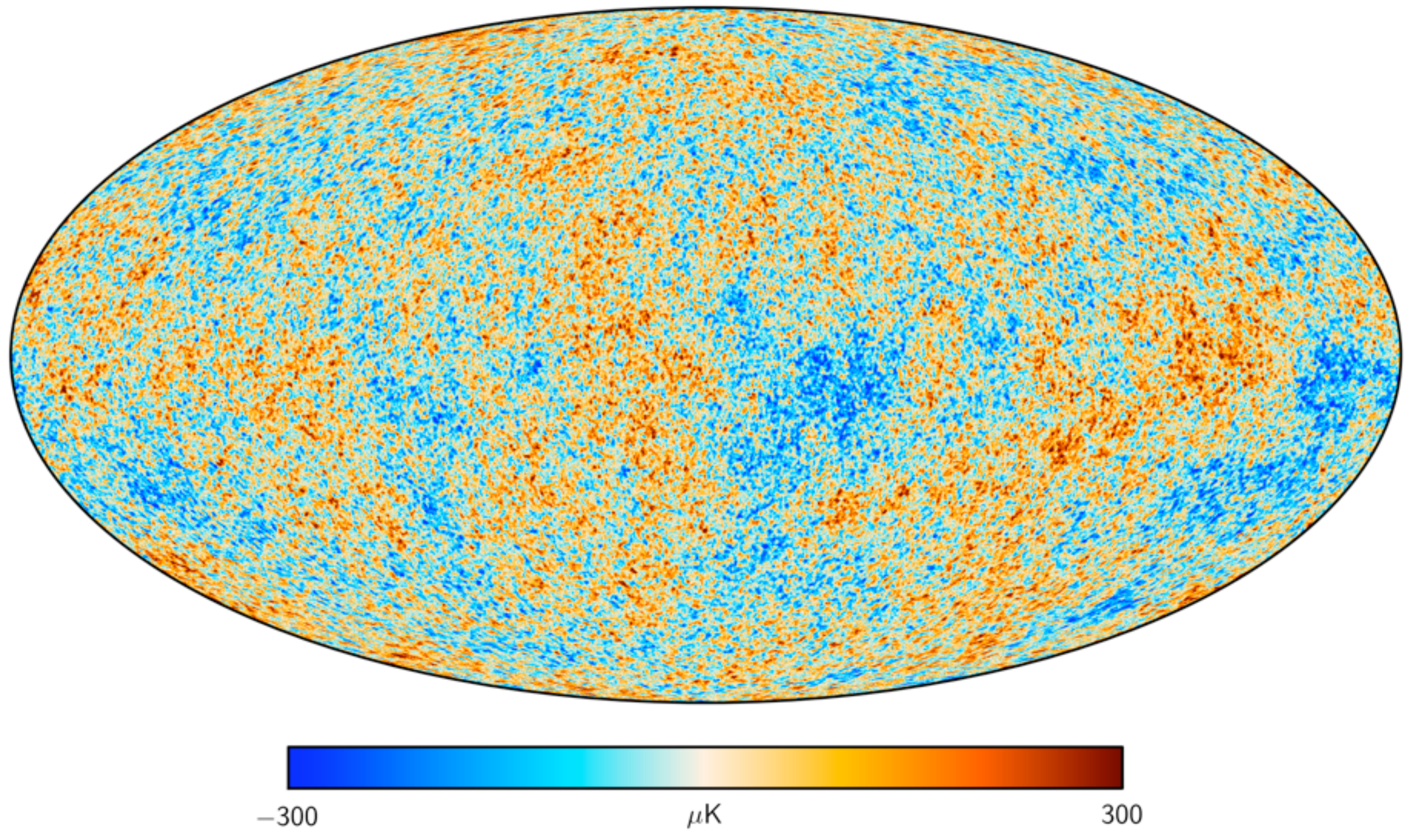
Particle content: effective relativistic degrees of freedom



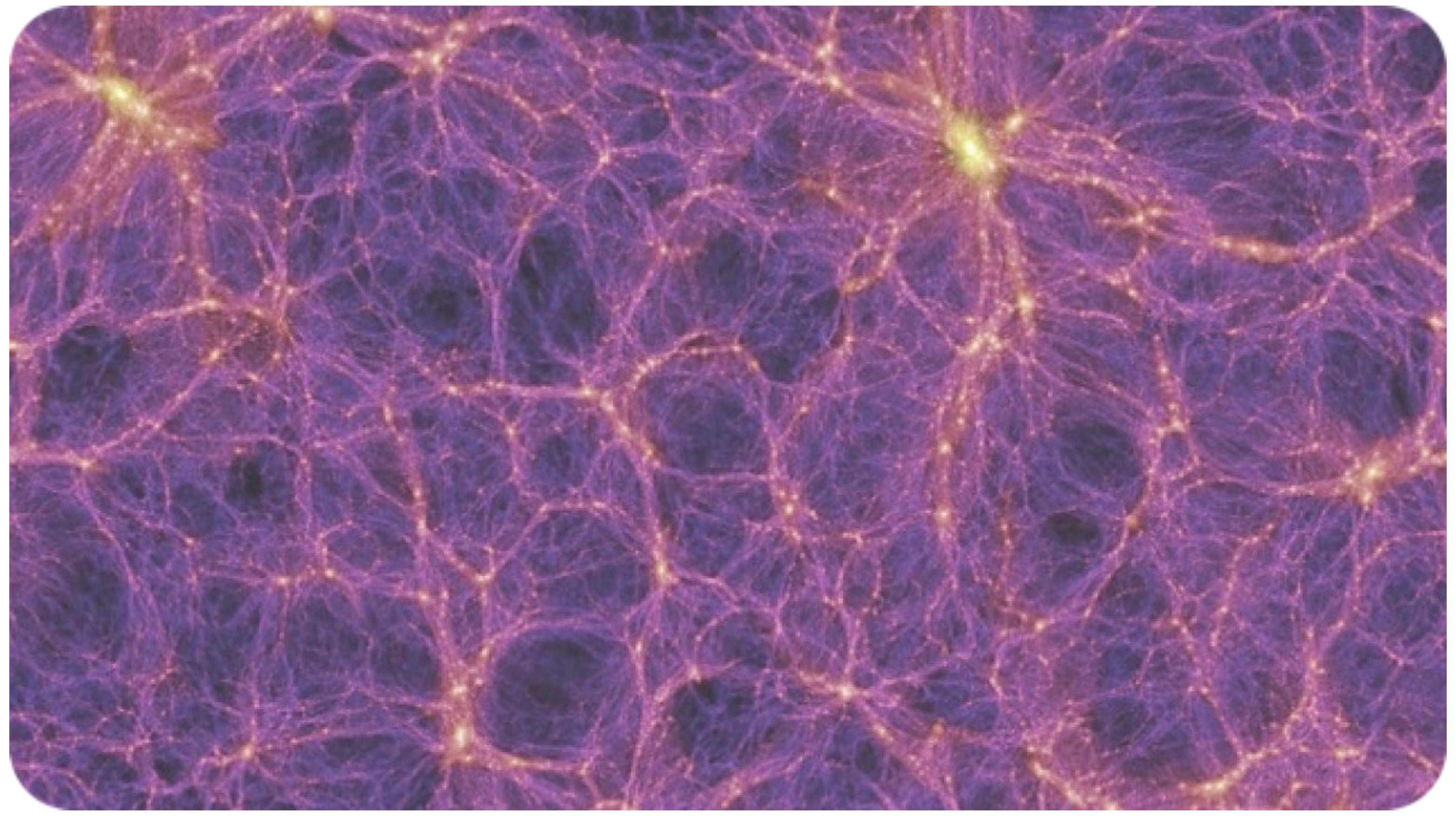
Modified from Calabrese+ 2025

Cosmic concordance? Testing LCDM structure growth

- Do late-time observations match LCDM predictions, calibrated on high-z CMB?
  - Hubble tension
  - Tension with BAO distances from DESI
  - **Late-time clustering**



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

Cosmic concordance? Testing LCDM structure growth

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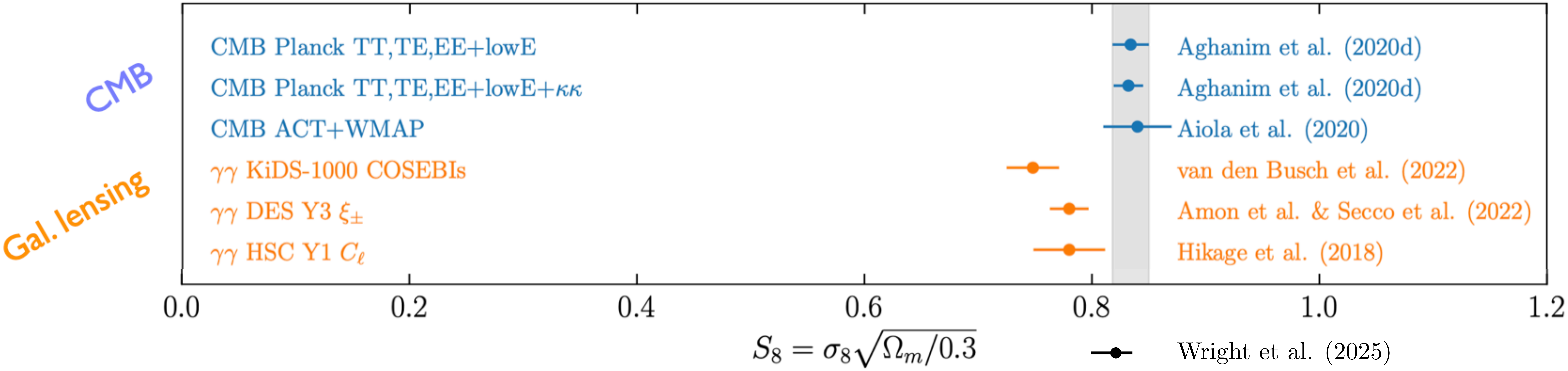
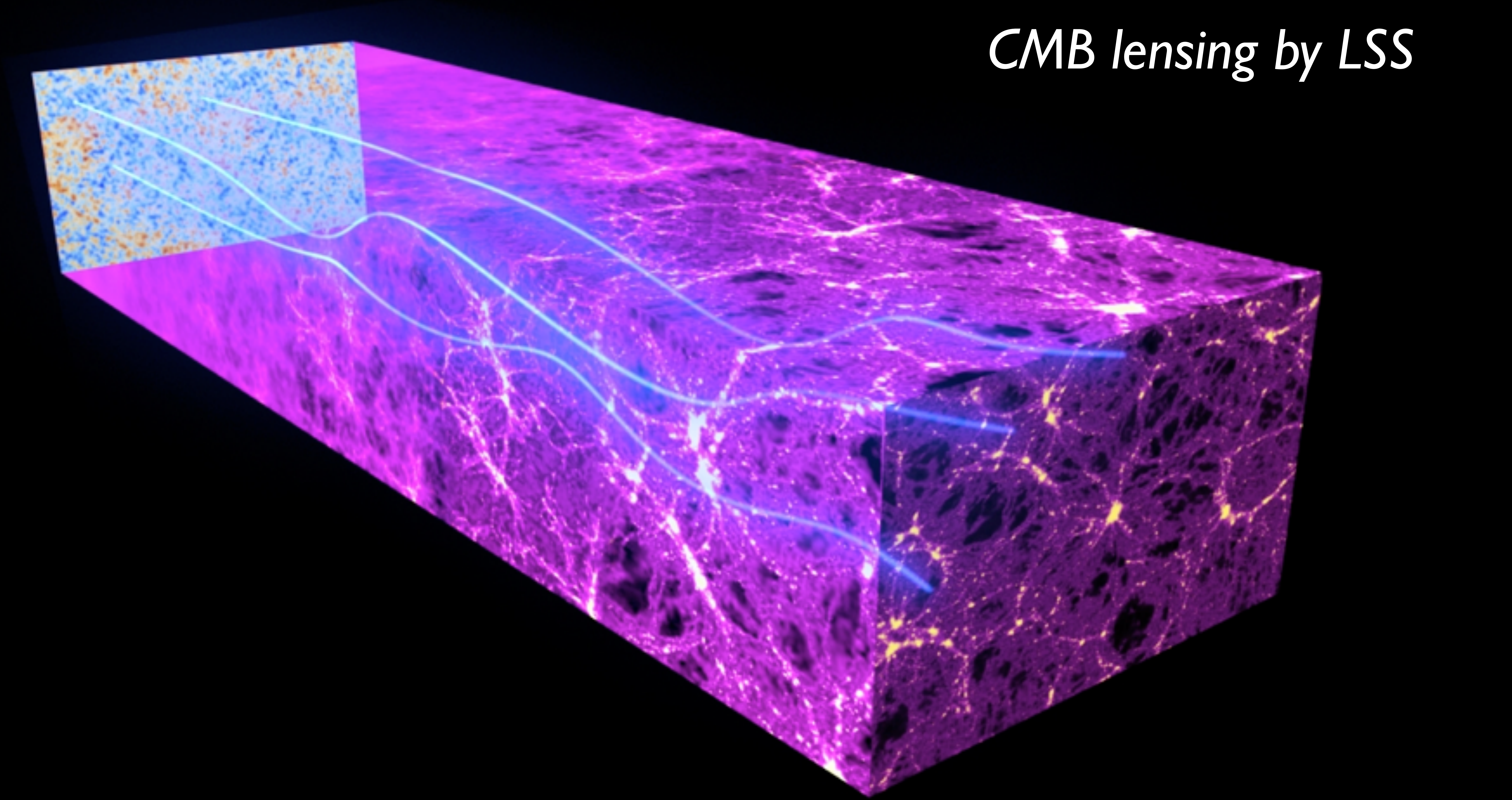


Persistently (until KiDS legacy!) low measurements of clustering amplitude from galaxy lensing

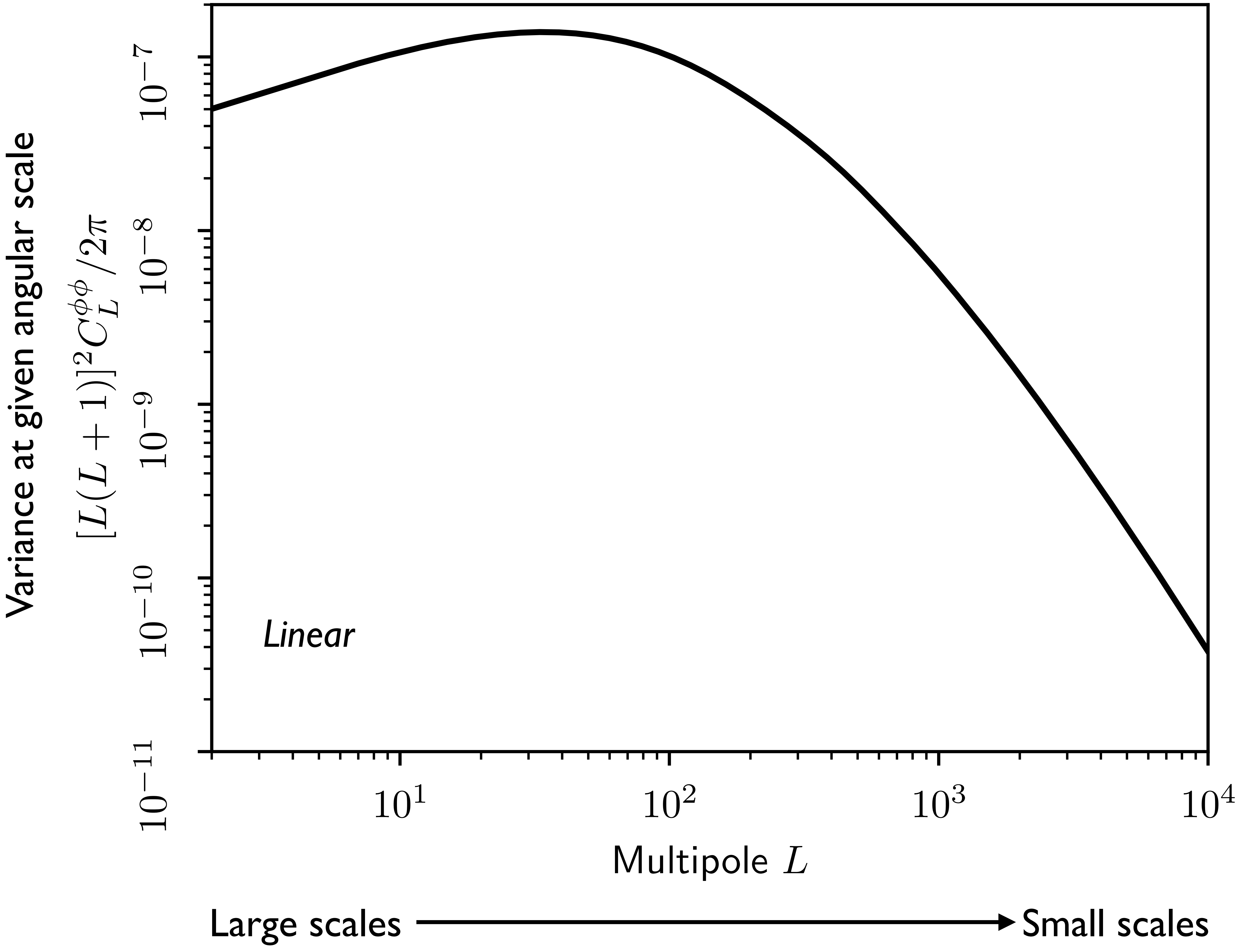
Modified from Chen+ 2022

CMB lensing by LSS



CMB lensing: robust probe of mostly linear structure

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



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

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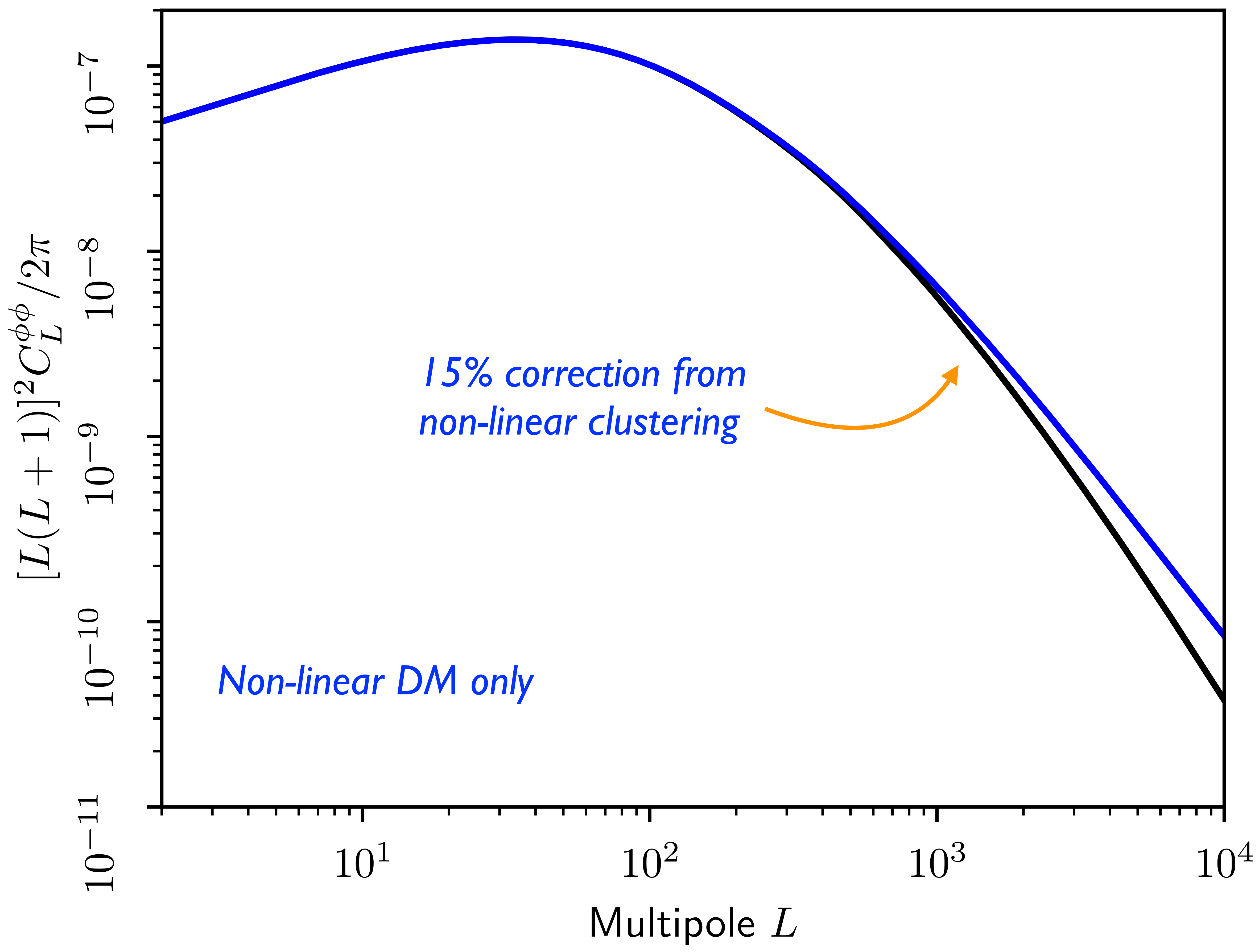

- Redshift of source plane known
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  - Modest non-linear corrections

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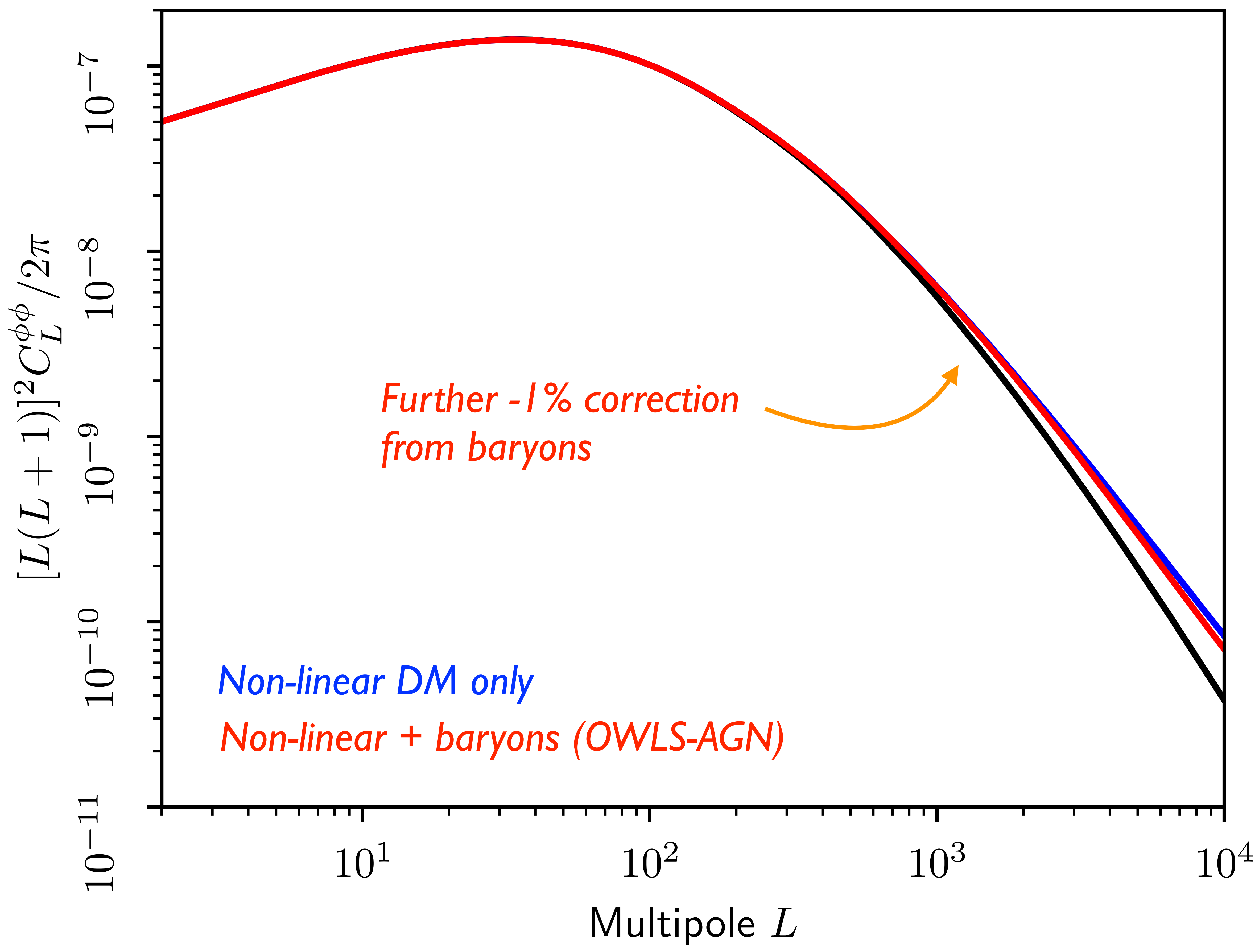
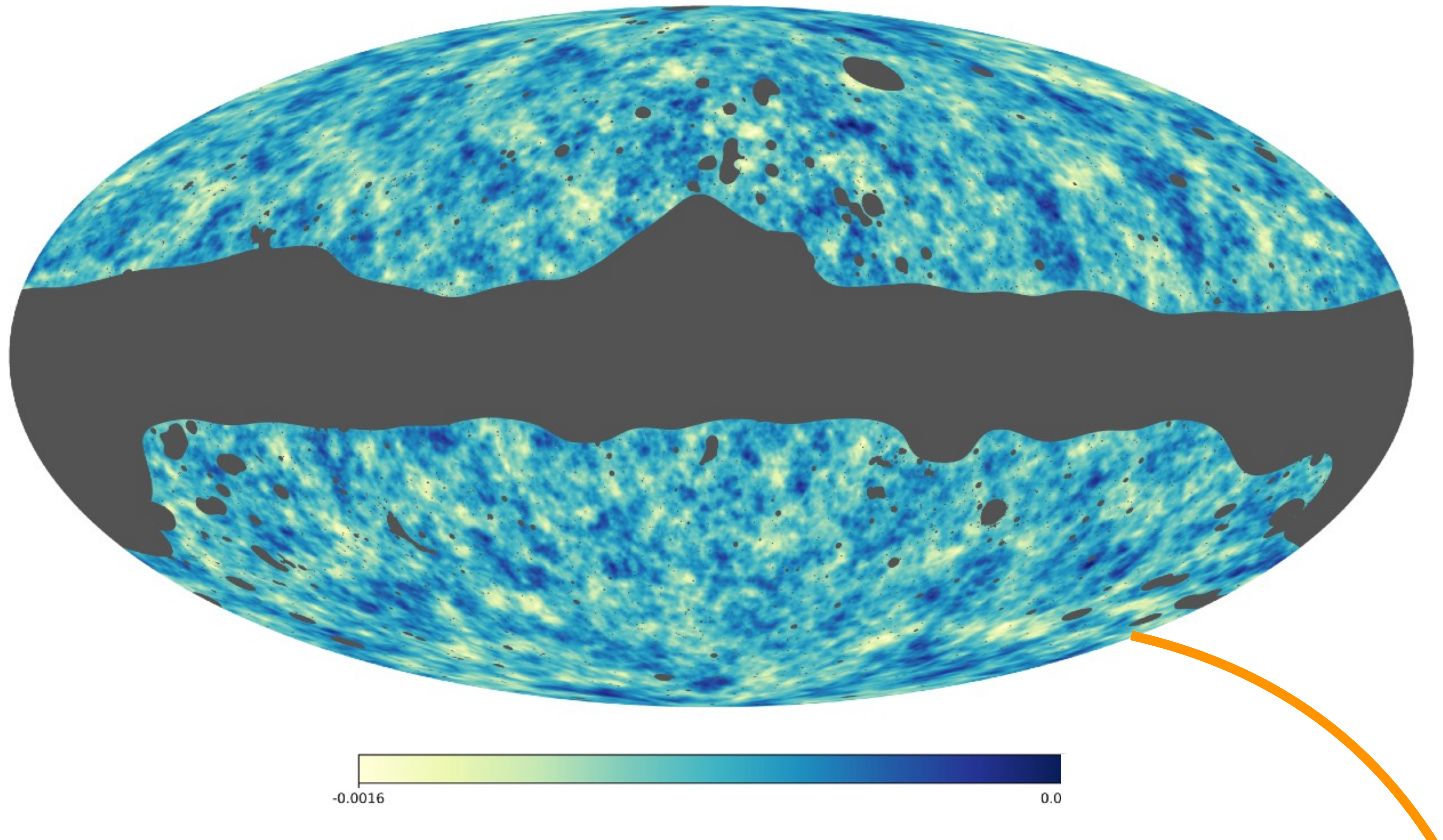
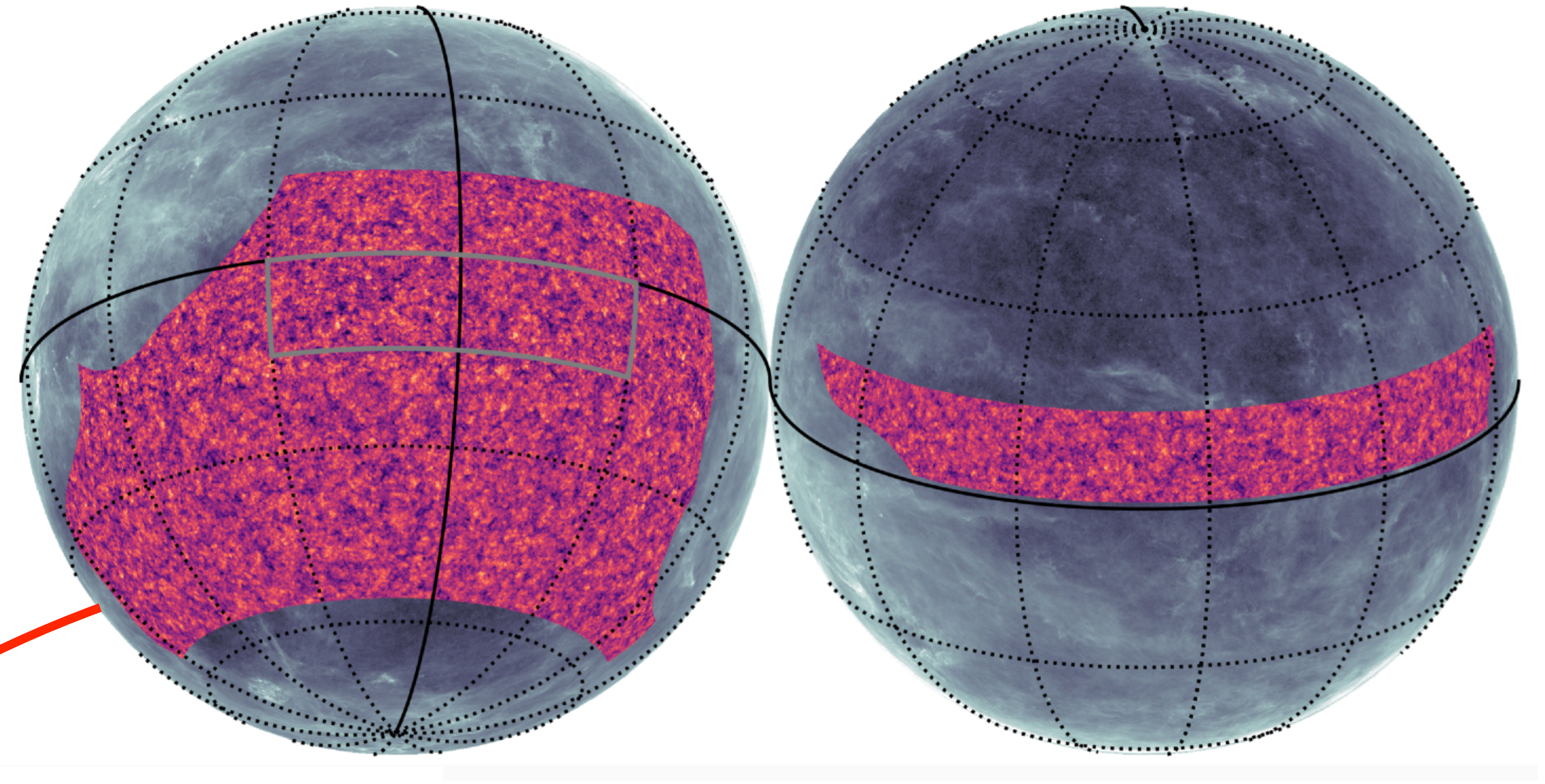


- Redshift of source plane known
- Statistics of fluctuations in source plane well understood
- High-z lenses and relatively large scales
  - Modest non-linear corrections
  - Baryons negligible until CMB-S4 era

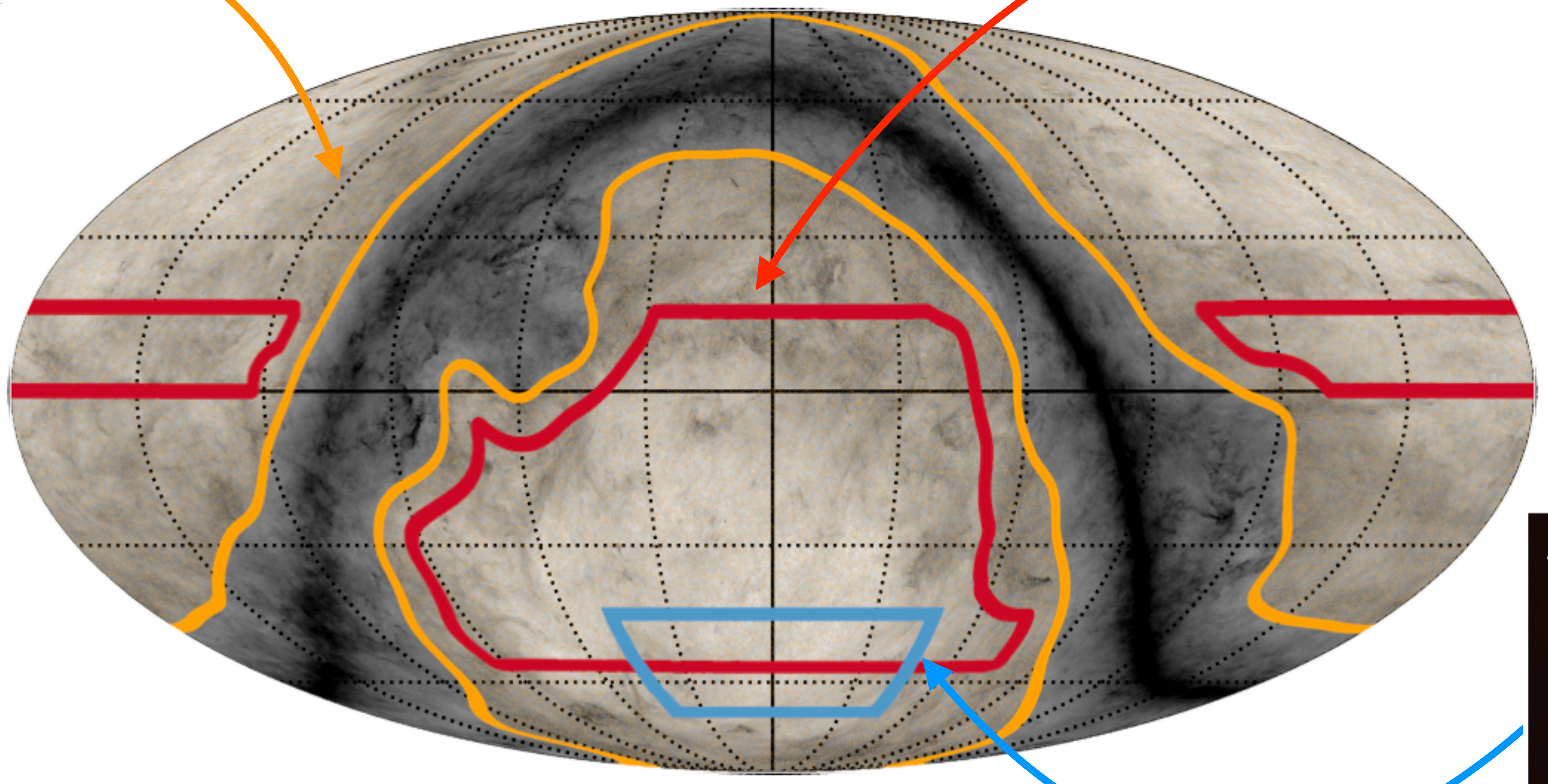
Reconstructed CMB lensing maps

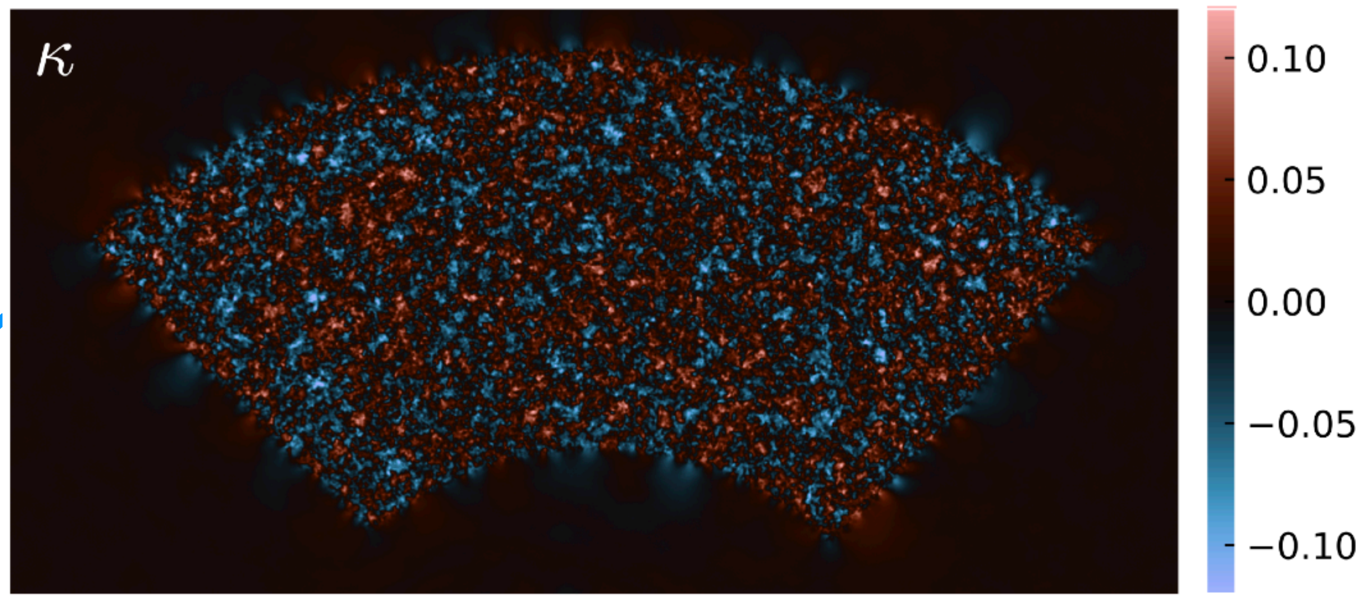


Planck 2018



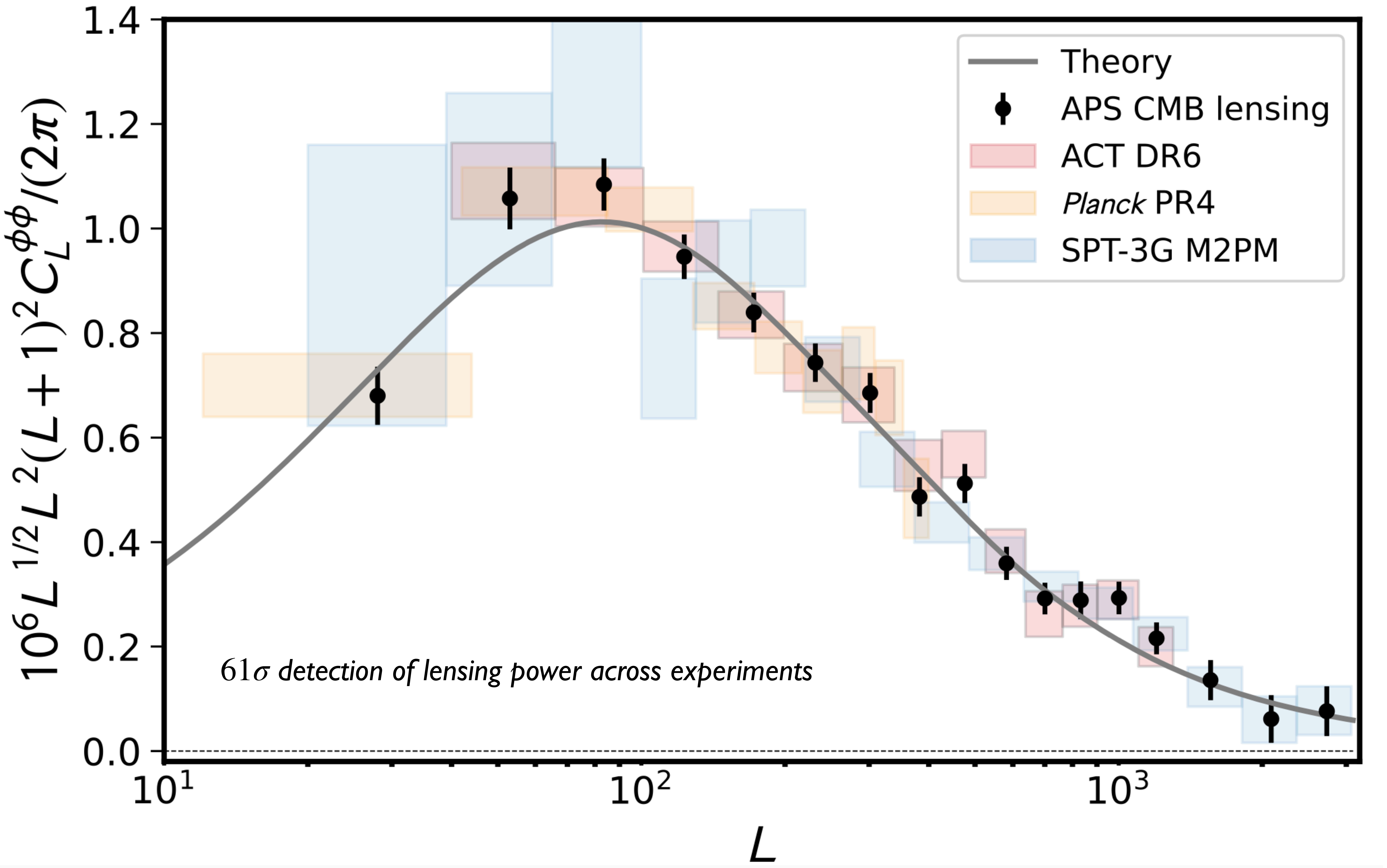
ACT – Madhavacheril+ 2024





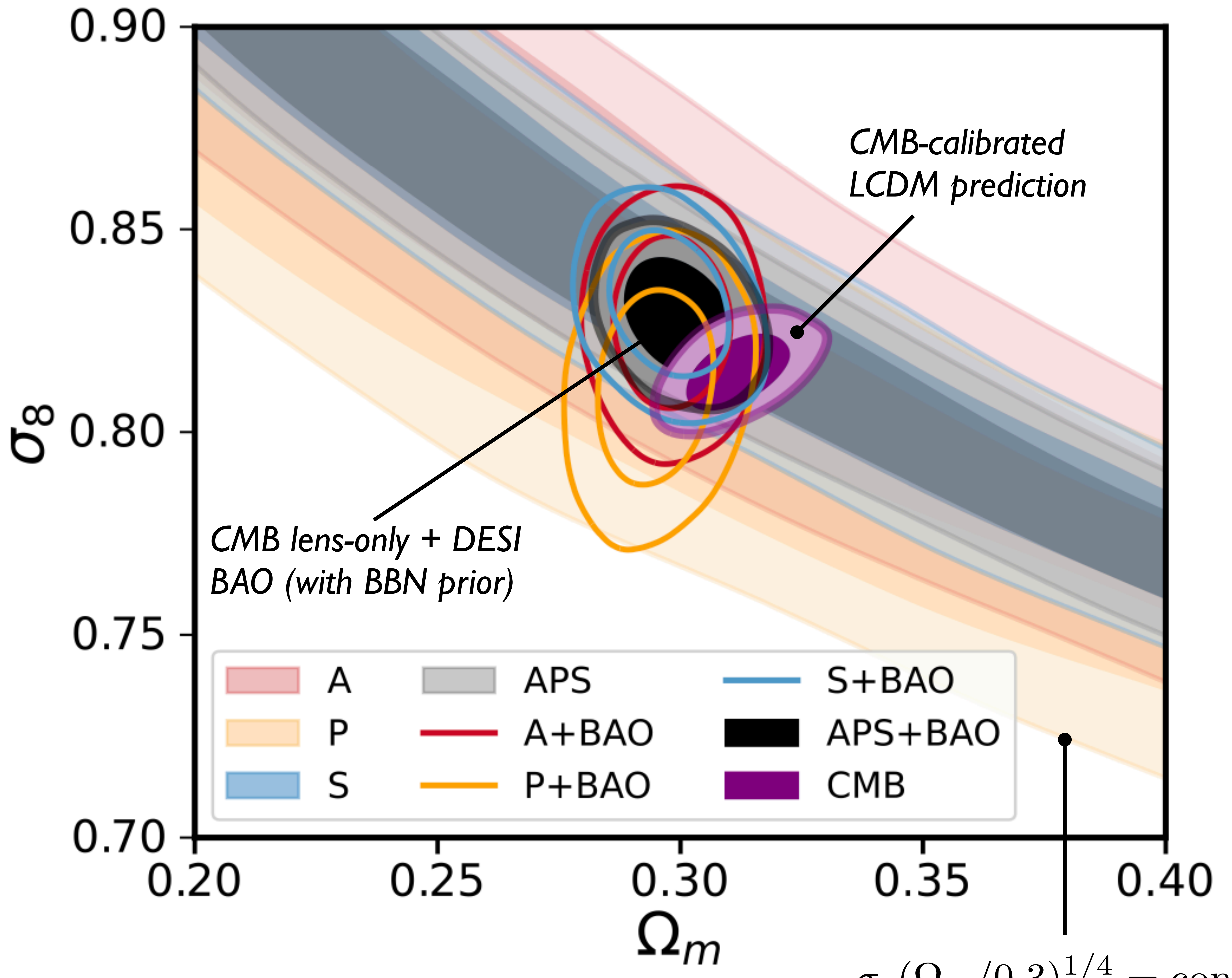
SPT-3G – Ge+ 2024

Reconstructed lensing power spectra



Qu+ 2025

CMB-lensing-only LCDM constraints



$\sigma_8(\Omega_\mathrm{m}/0.3)^{1/4} = \mathrm{const.}$

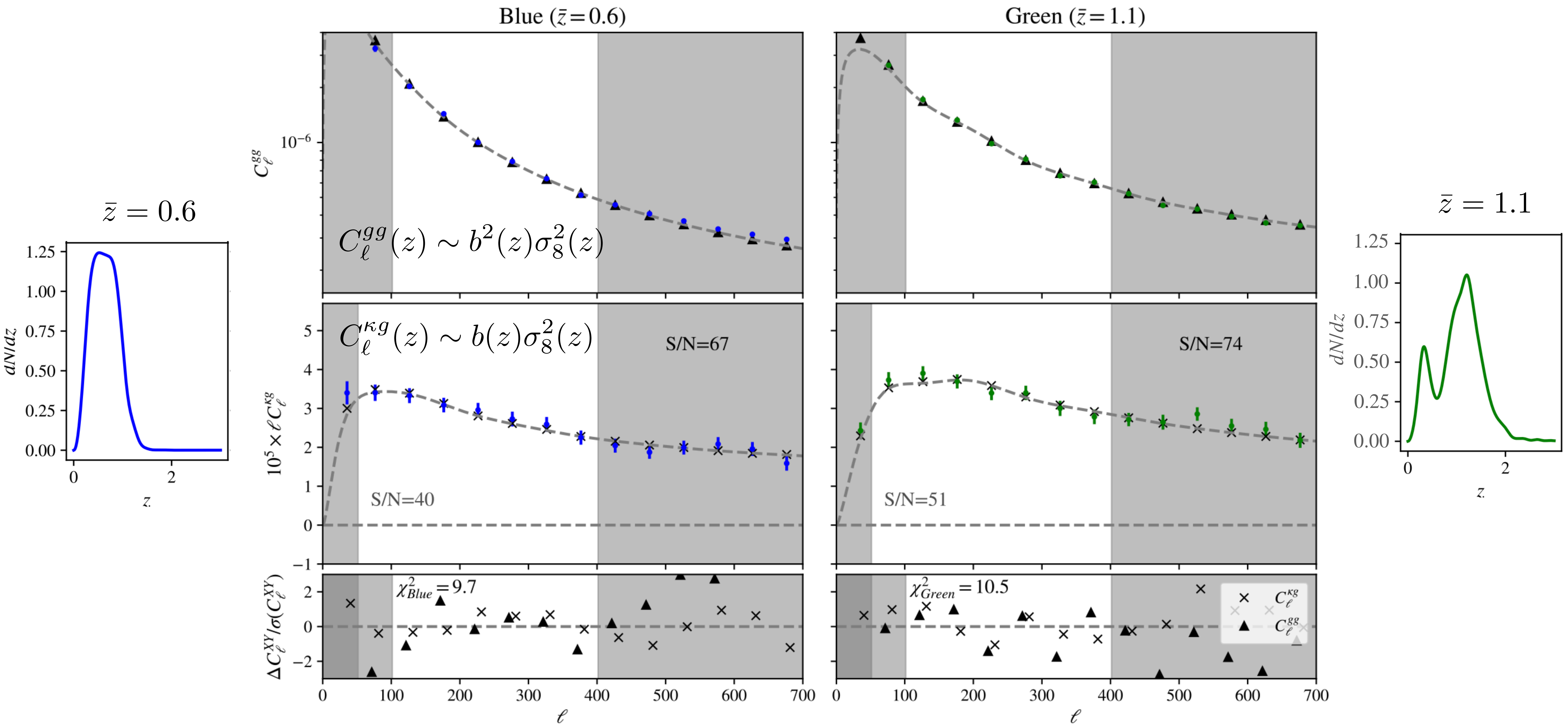
Priors for lens-only:

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

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

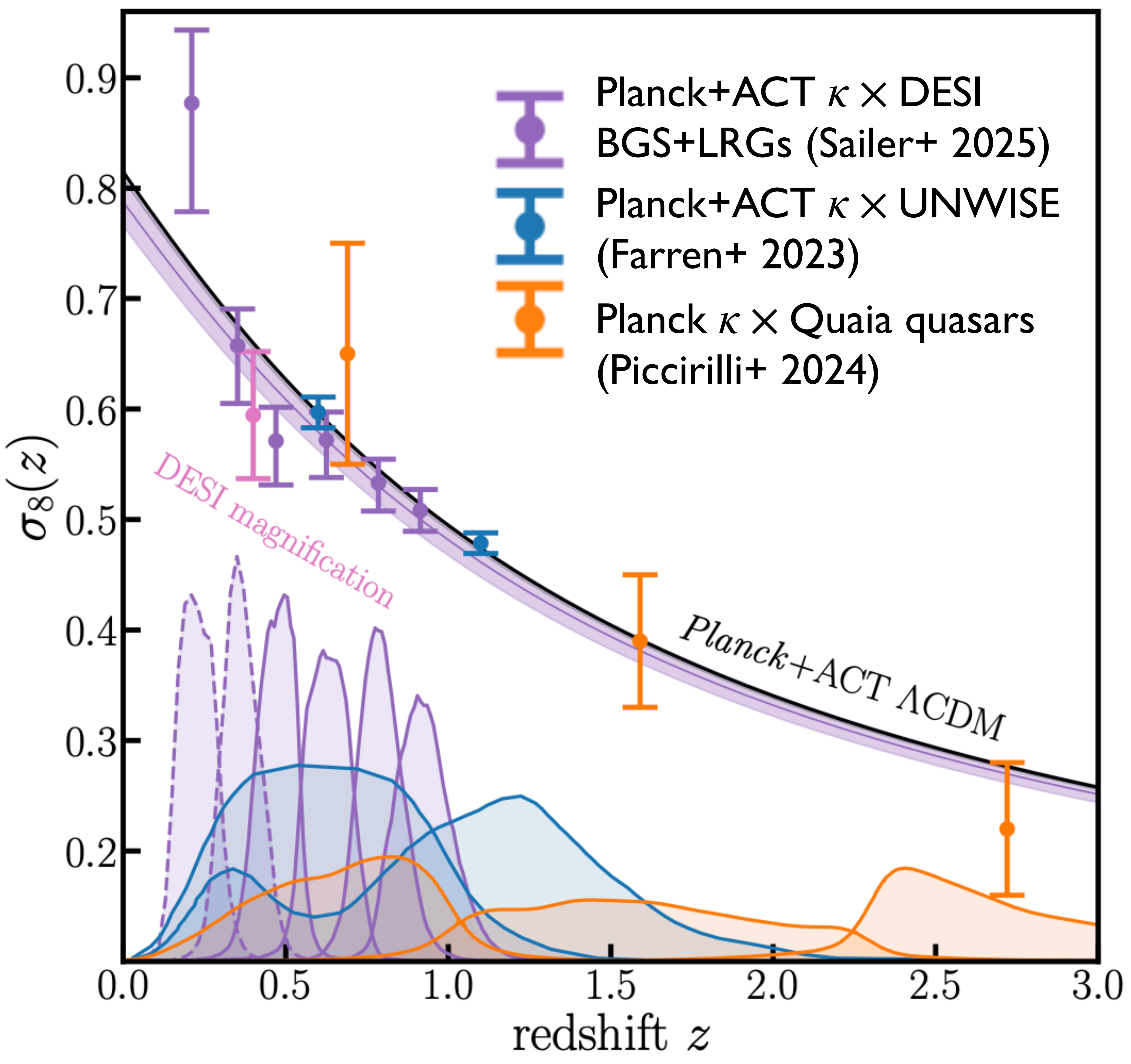
Qu+ 2025

Cross-correlation measurements with unWISE galaxies



Farren+ 2024

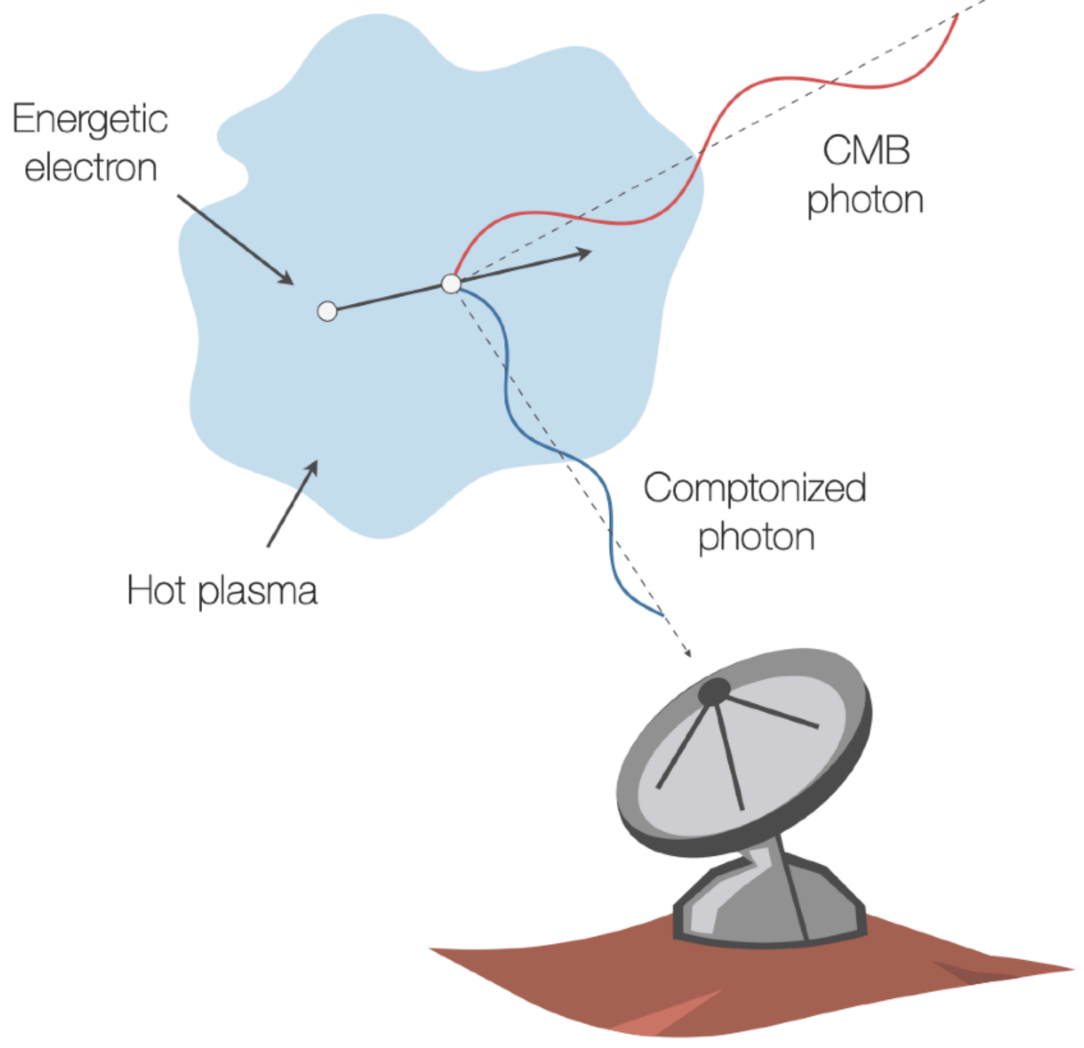
Recent CMB lensing x galaxies measurements

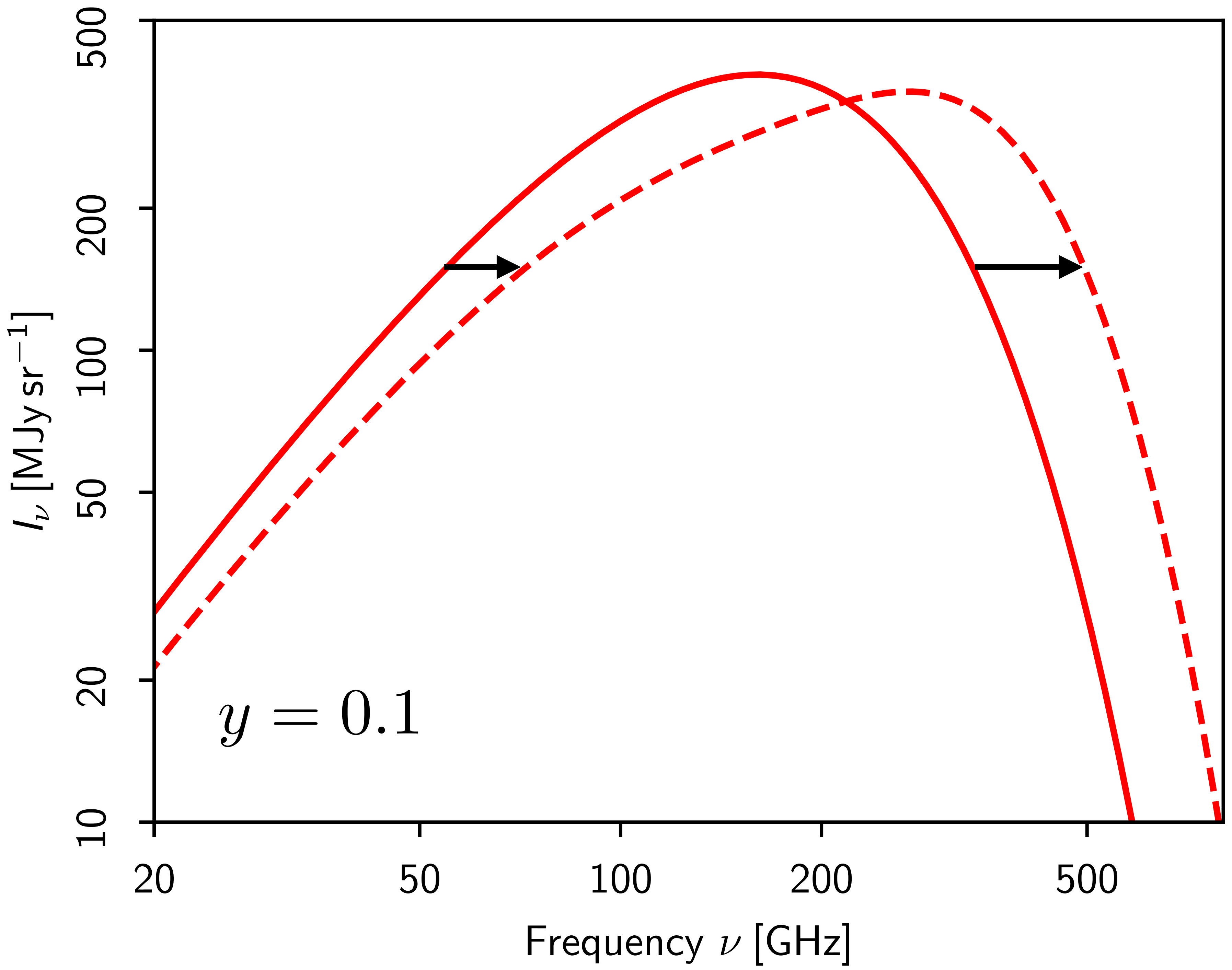


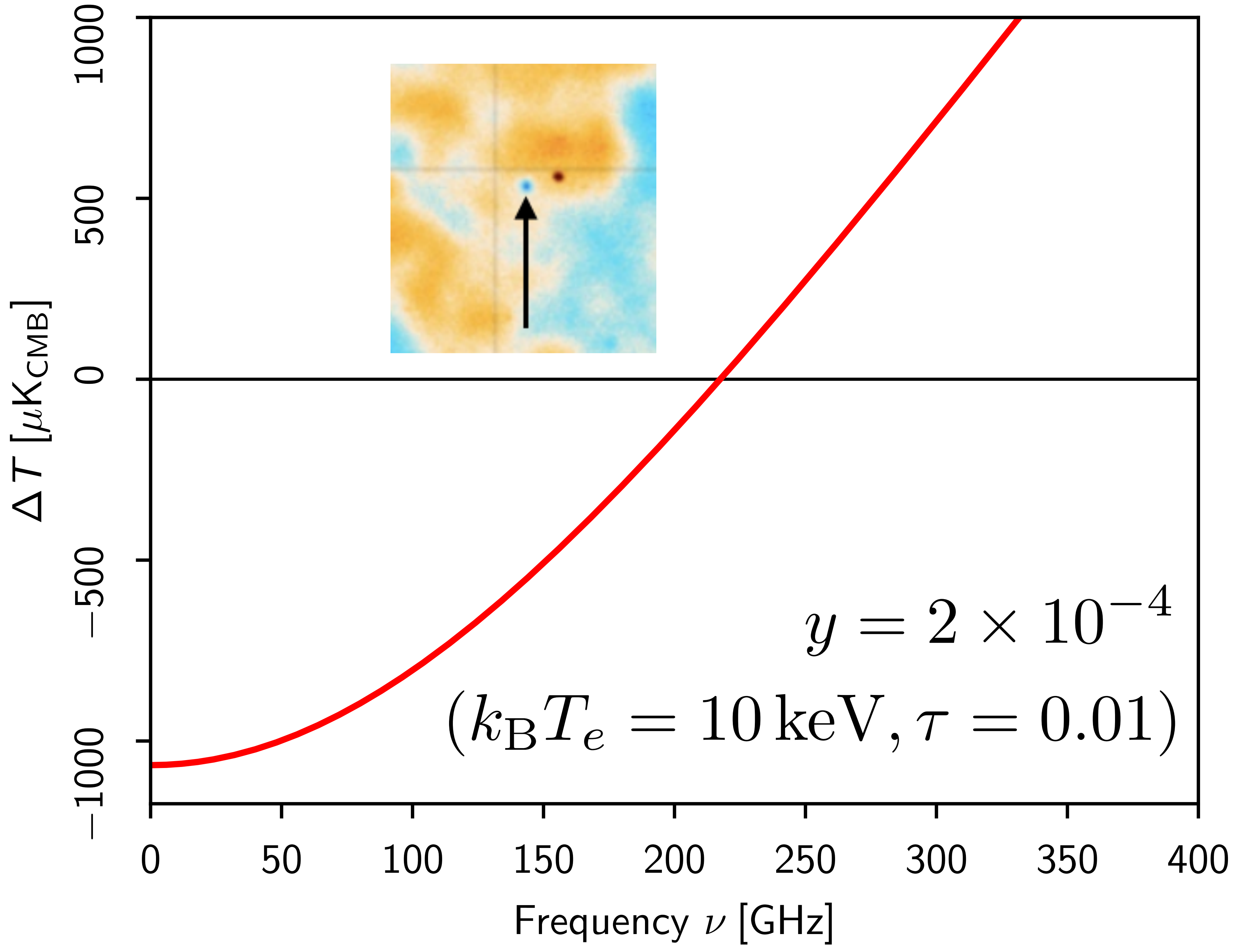
LCDM structure growth down to $z \sim 0.2 - 1.6$ for $k < 0.2\,\mathrm{Mpc}^{-1}$ consistent with primary CMB

Sailer+ 2025

Galaxy cluster counts from Sunyaev–Zel'dovich effect







$$\Delta I_\nu = y I_\nu \frac{x e^x}{(e^x - 1)} \left[x \coth(x/2) - 4 \right]$$

$$\Delta T_\mathrm{CMB} = y T_\mathrm{CMB} \left[x \coth(x/2) - 4 \right]$$

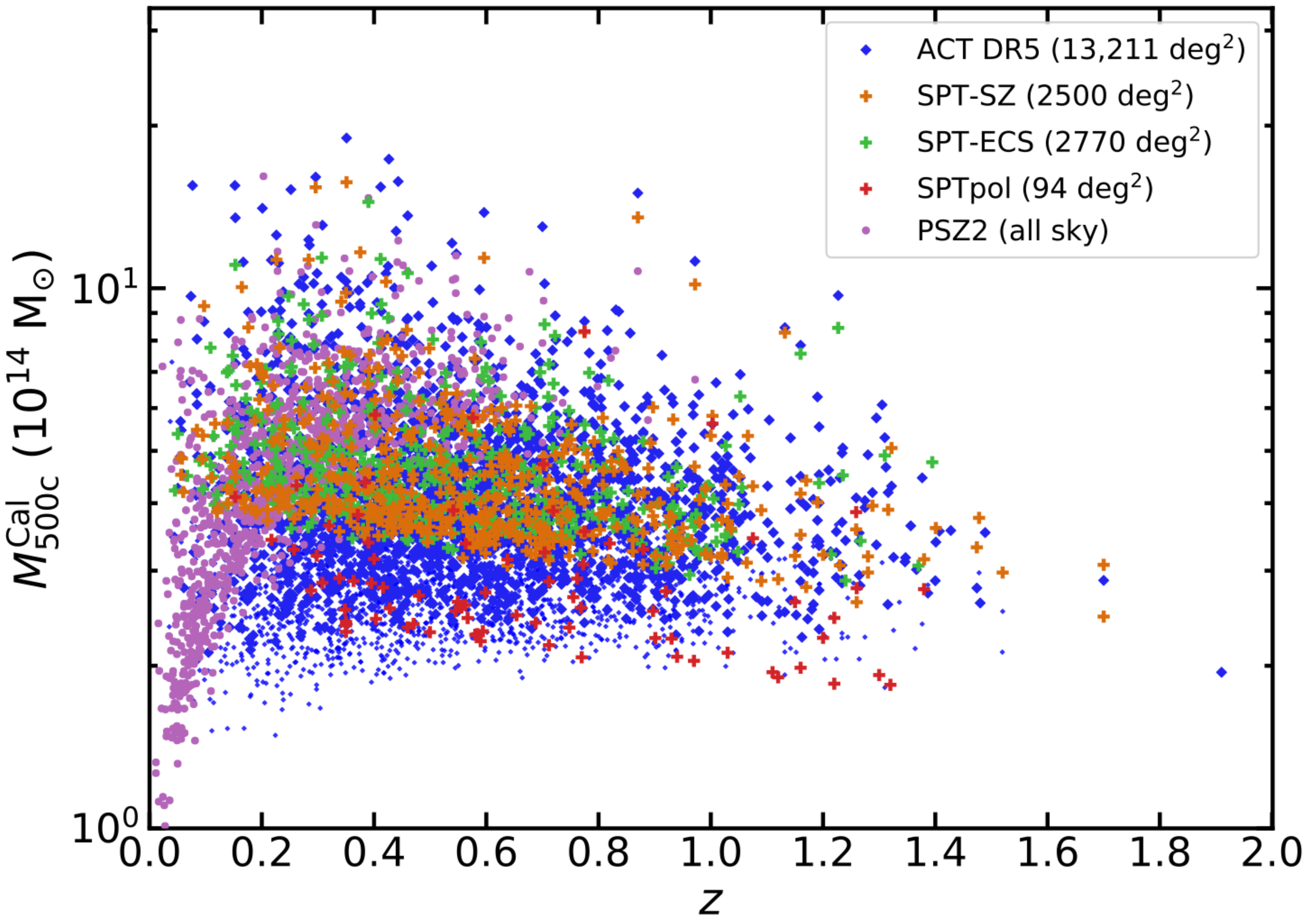
$$y = \int \frac{k_\mathrm{B} T_e}{m_e c^2} n_e \sigma_\mathrm{T} \, dl$$

$$x = \frac{h\nu}{k_\mathrm{B} T_\mathrm{CMB}}$$

Scattering → independent of redshift

Mroczkowski+ 2019

SZ-selected cluster samples

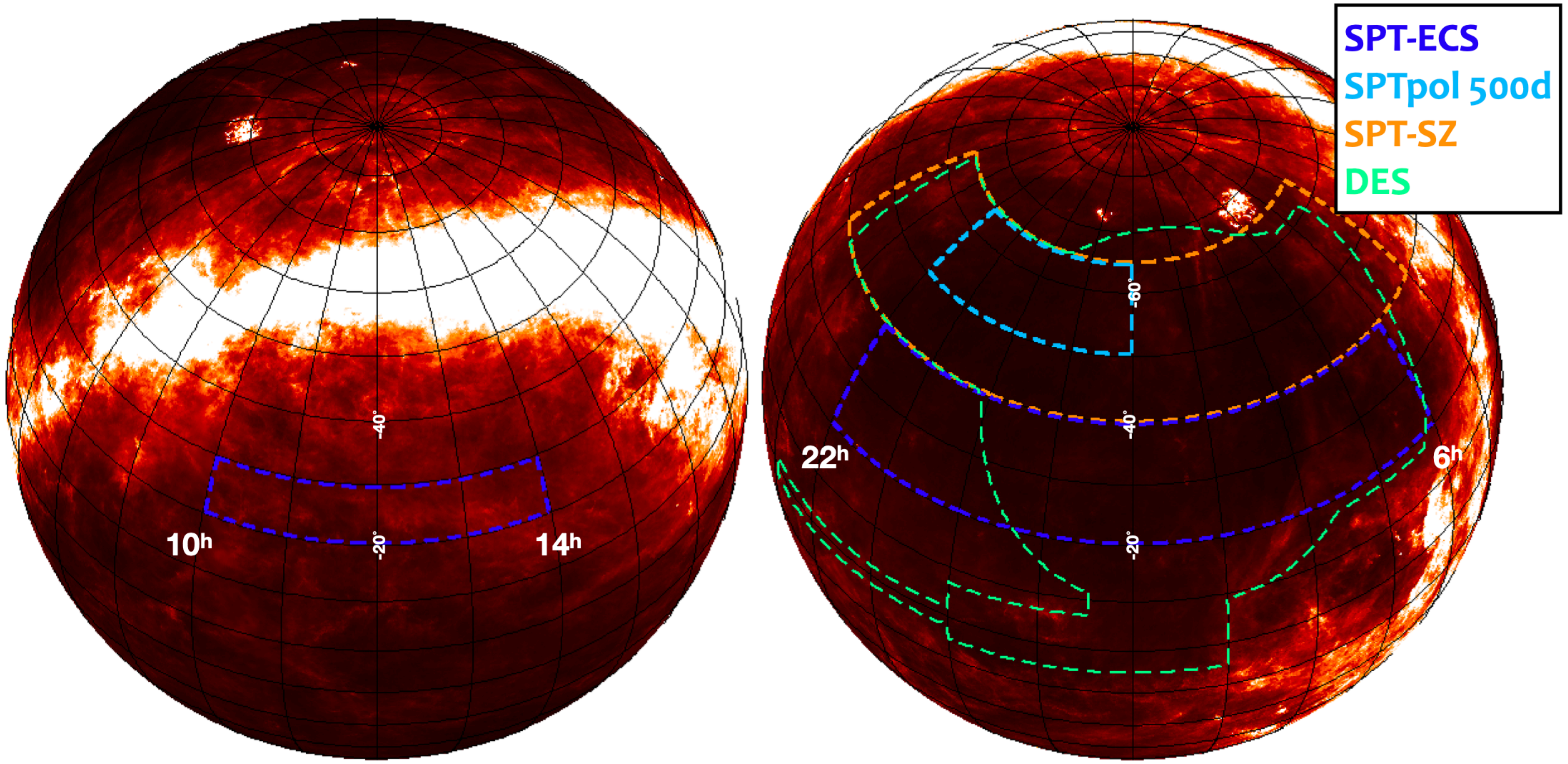


- Well-understood selection (SZ S/N q) almost mass-limited to high z
- Limiting issue: relating SZ observable to mass → lensing mass calibration, ideally for full cluster sample

Hilton 2021

Latest results from SPT SZ-selected clusters + DES lensing calibration

- 5200 deg^2 of Southern sky
- 1005 clusters with $z > 0.25$ and S/N $q > 5$
- 3600 deg^2 overlap with DES
- DES weak lensing for 688 clusters at $z < 0.95$
- HST weak lensing for 39 clusters with $0.6 < z < 1.7$



Bocquet+ 2024

Bleem+ 2020

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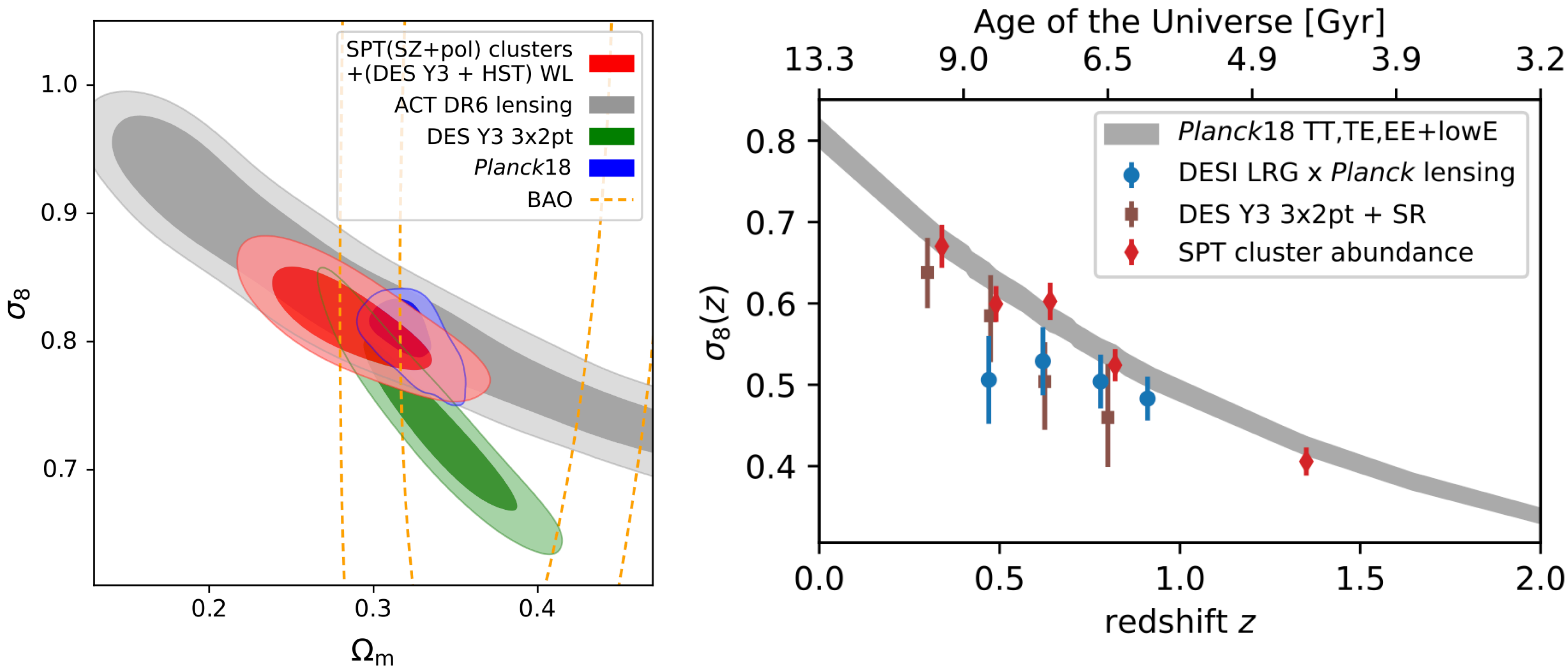
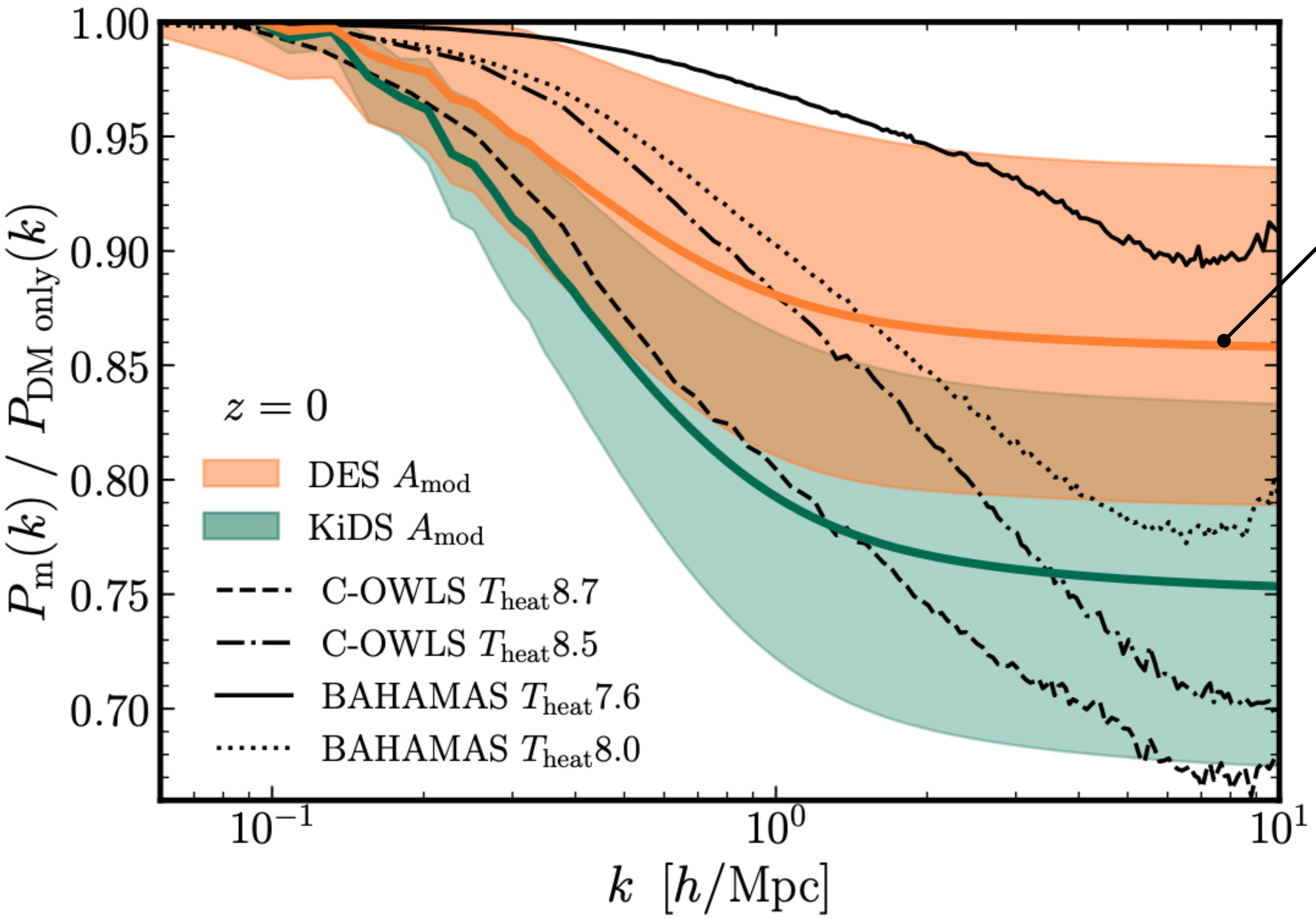


LCDM structure growth down to $z \sim 0.3$ consistent with primary CMB

Bocquet+ 2024

Reconciling with cosmic shear?

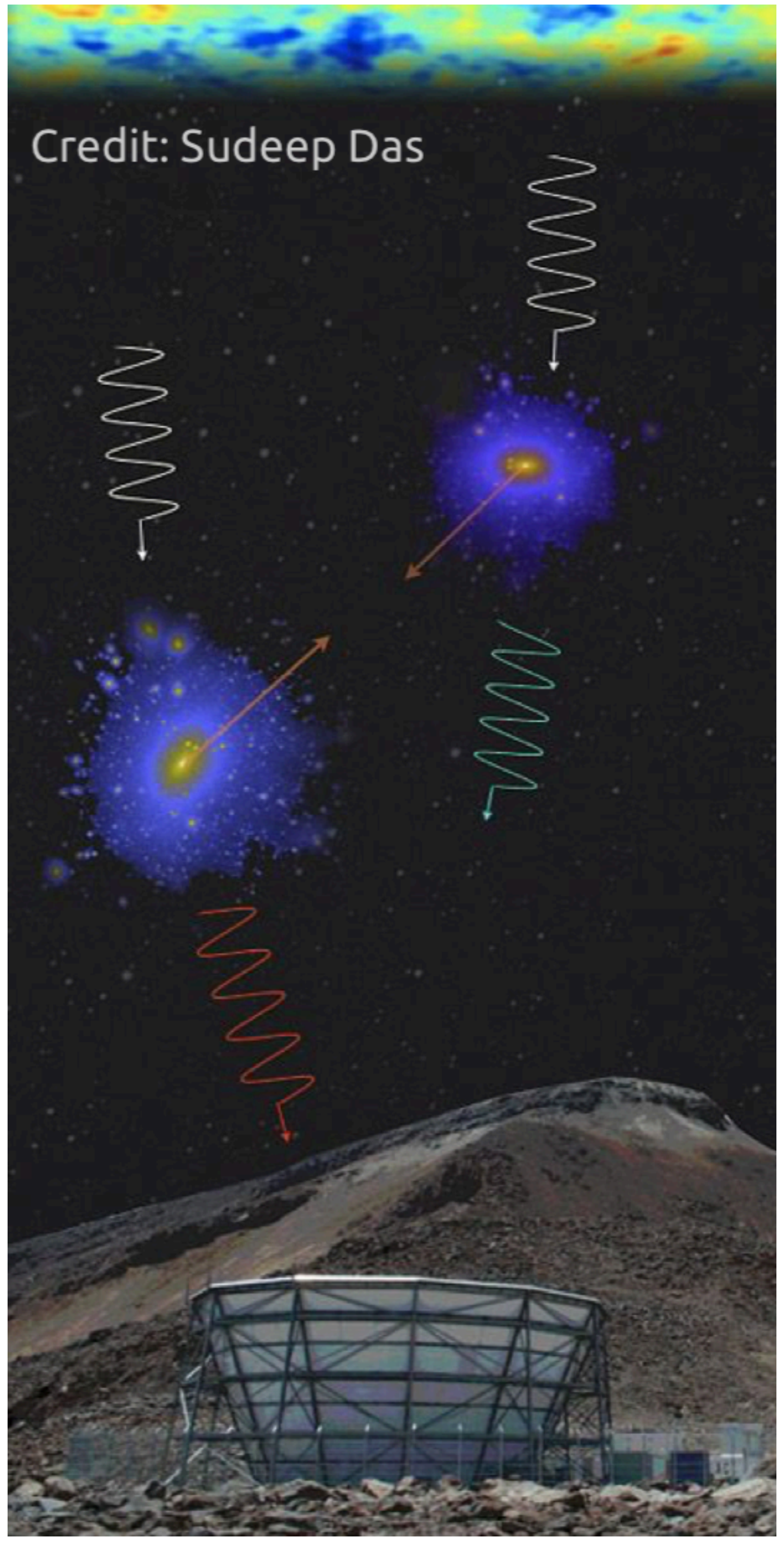


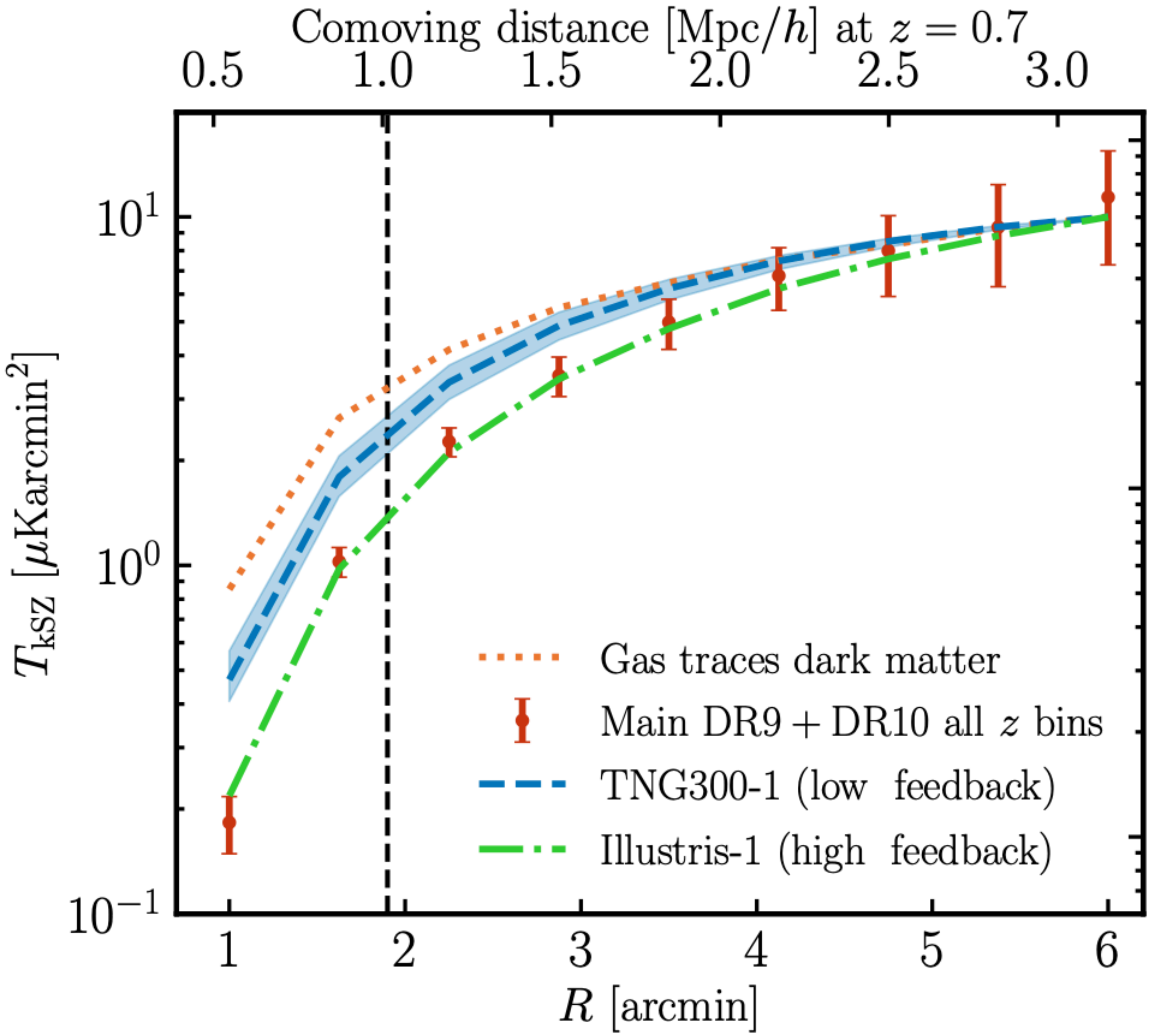
Suppression required to fit DES+Planck jointly

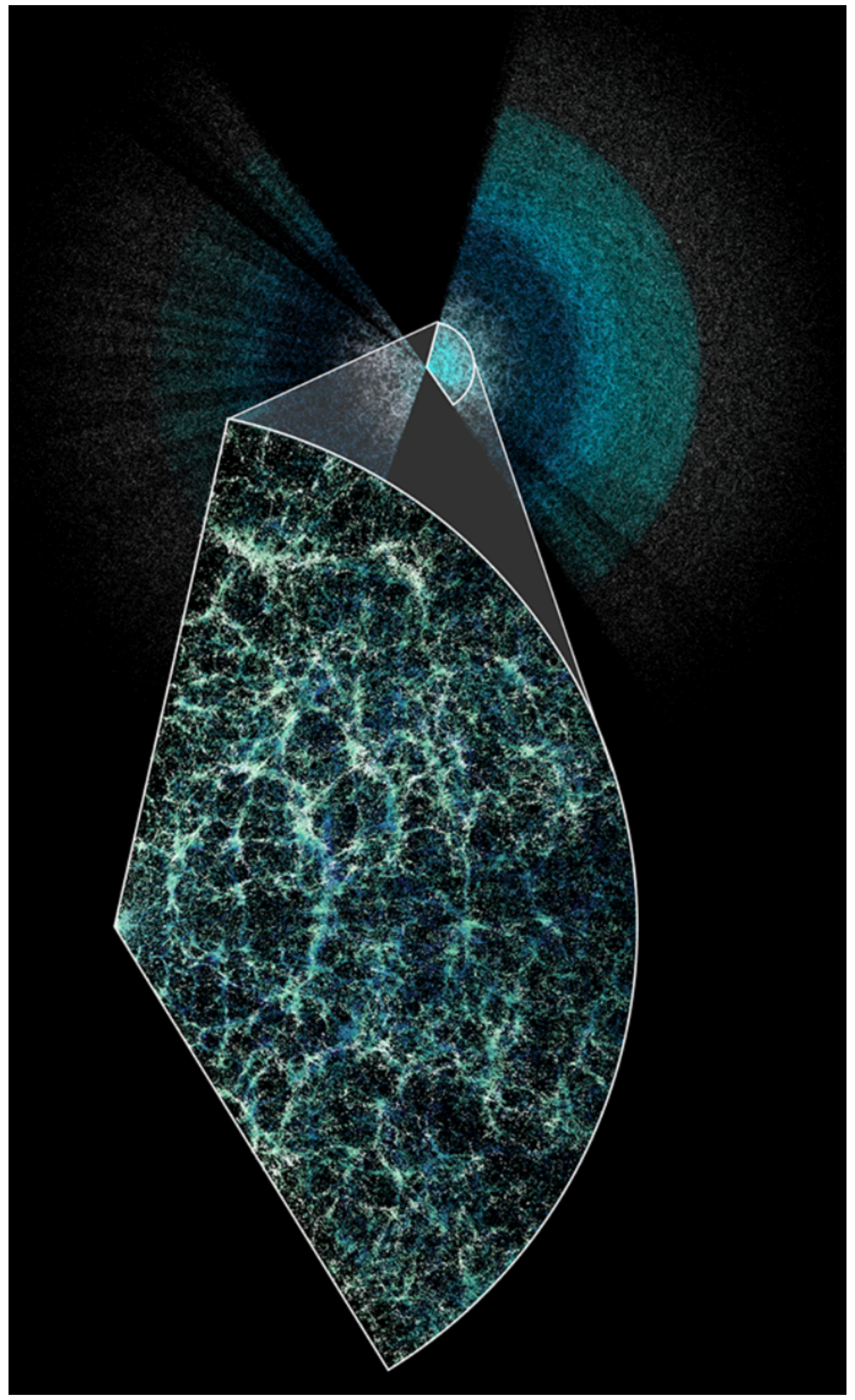
- Small-scale power suppression (more-extreme baryon feedback?)
- Systematics in modelling of intrinsic alignments (e.g., McCullough+ 2024)

Preston+ 2023

Extended gas profiles from kSZ







$T_{\rm kSZ}/\bar{T}_{\rm CMB} = \tau v_r/c$

Velocity-weighted stacks of ACT CMB temperature on DESI LRGs

Hadzhiyska+ 2024; see also Guachalla+ 2025

So much still to learn from the CMB

Key primary-CMB targets:

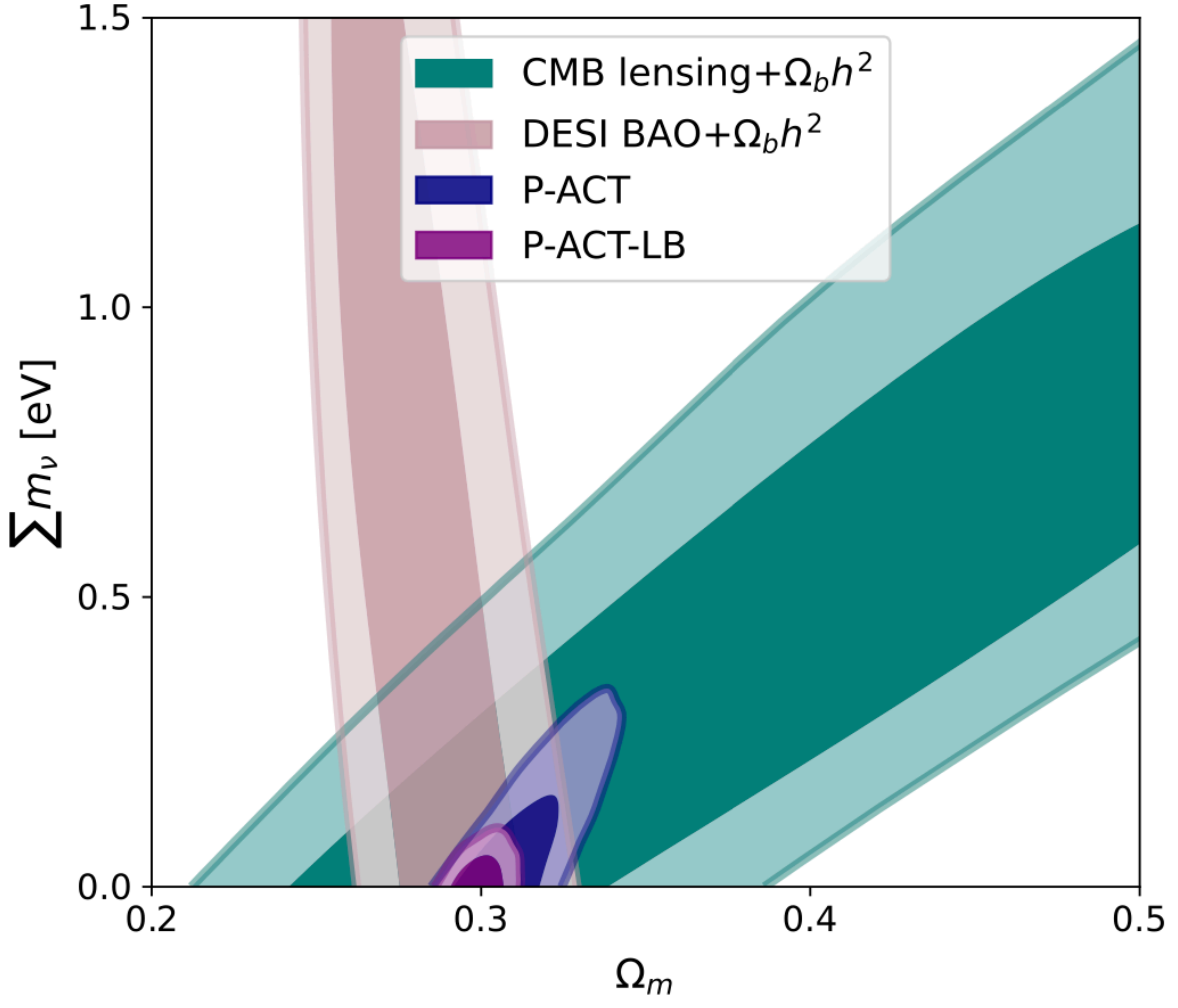
- Primordial gravitational waves from degree-scale *B*-modes
- Particle content, e.g., $N_{\rm eff}$, from wide and deep *E*-mode observations

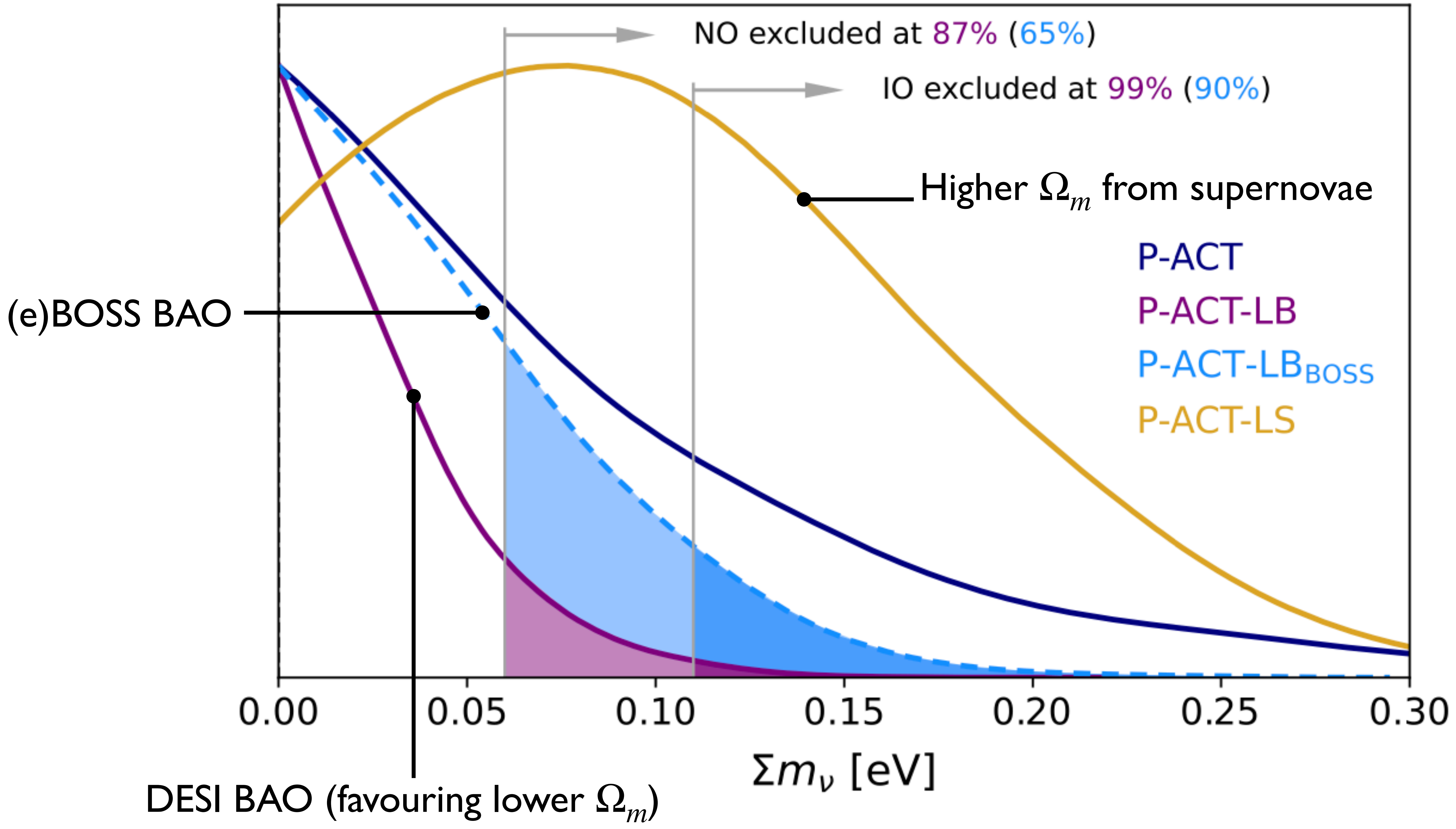
Secondary-anisotropy targets:

- Neutrino mass from CMB lensing and/or tSZ-selected galaxy clusters
- Structure growth from lensing and/or tSZ
- Reionization from large-angle *E*-mode polarization (optical depth) and from kSZ (morphology and duration)
- Constraints on galaxy evolution and baryon feedback from SZ

Back-up slides

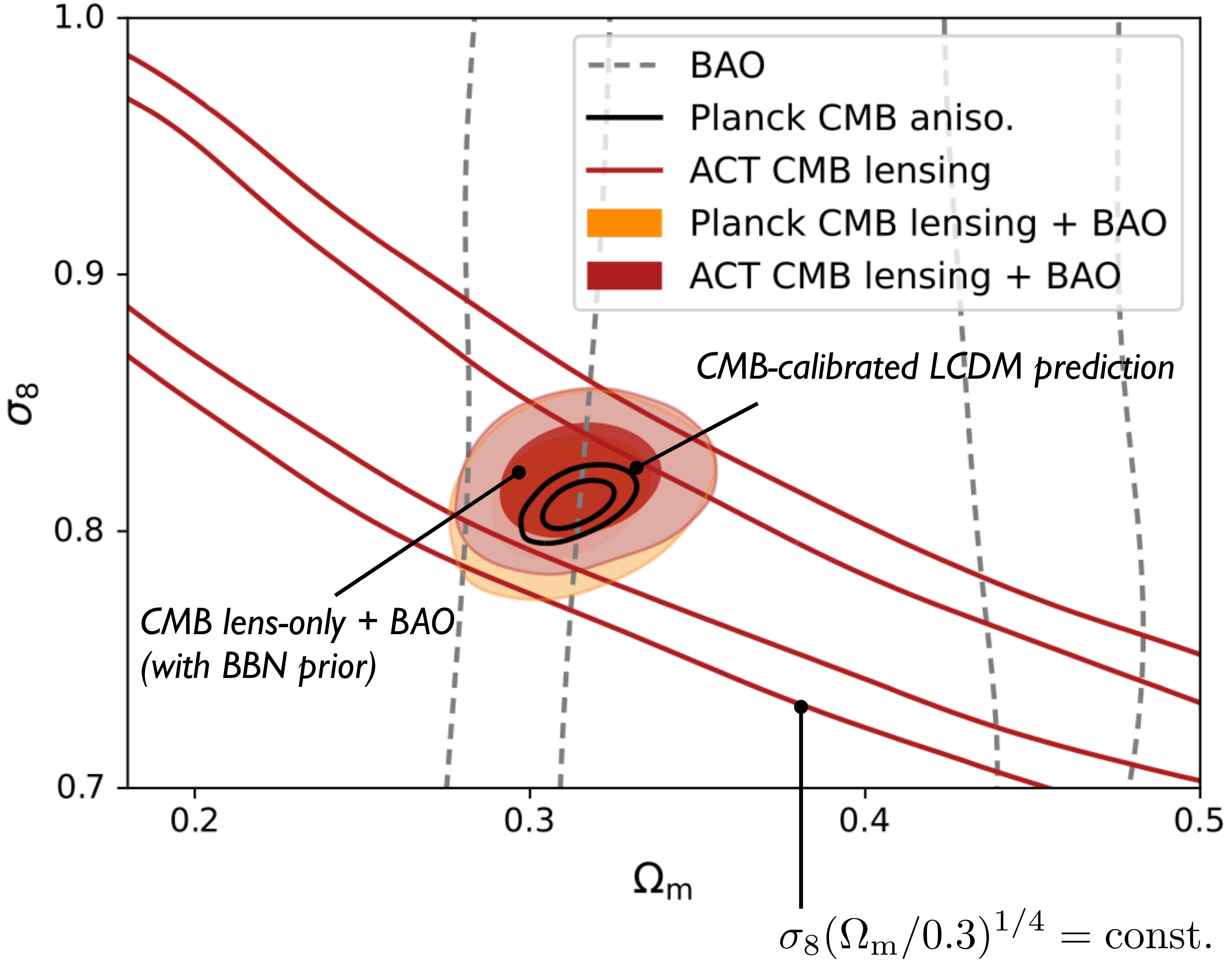
Neutrino masses





Calabrese+ 2025

CMB-lensing-only LCDM constraints



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Madhavacheril+ 2024