An address on the state of the Universe [given current data]

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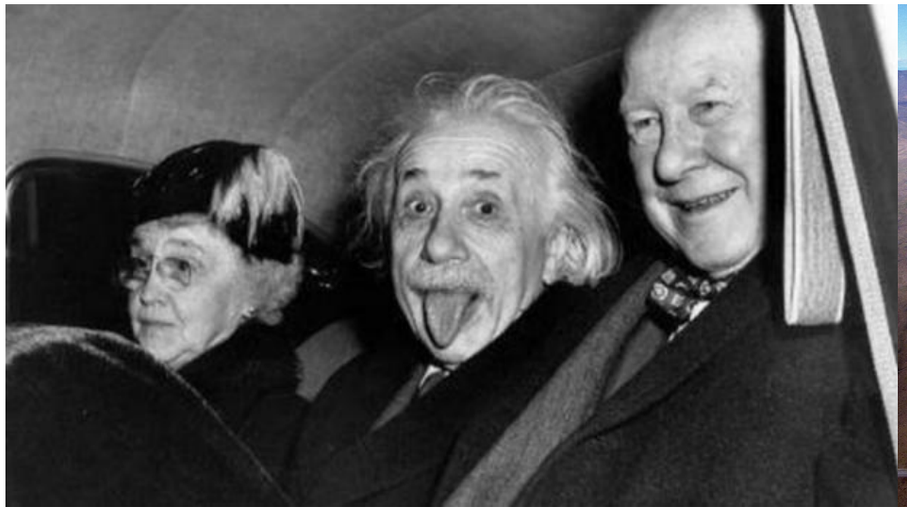
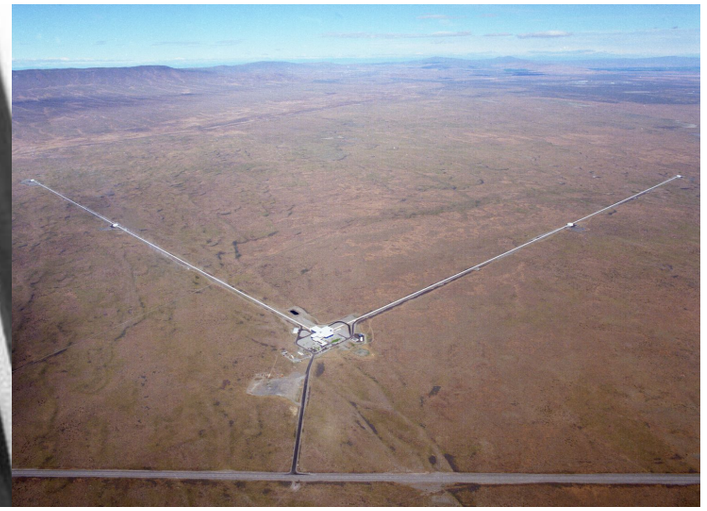
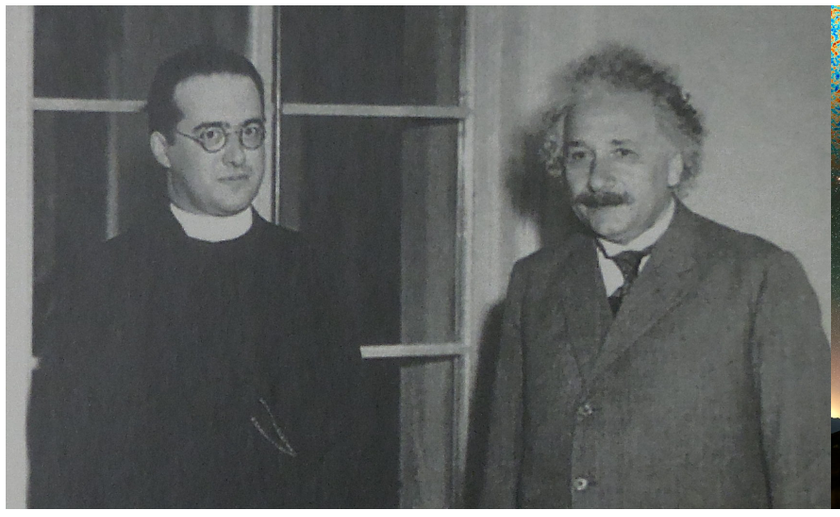
Imperial College London

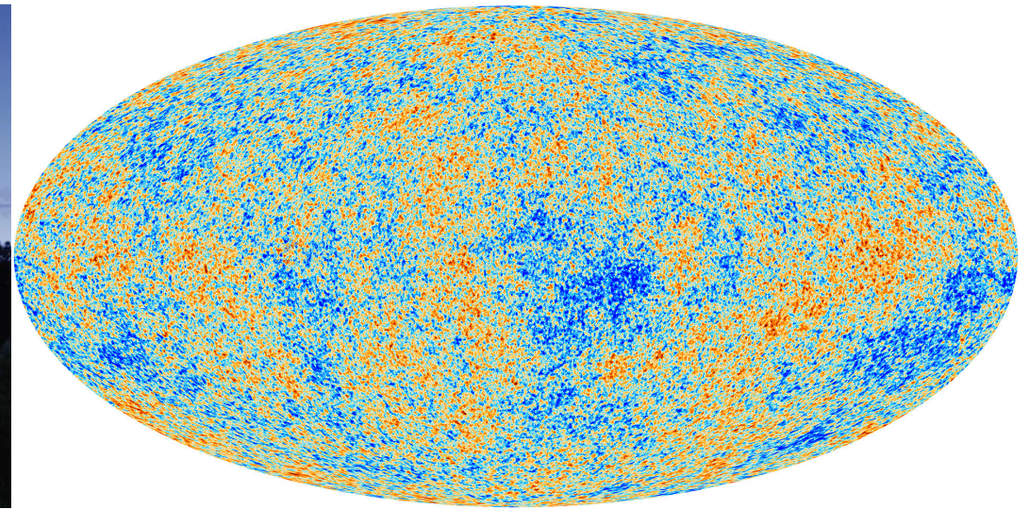




No experimental evidence against Einstein's general theory of relativity (1915)

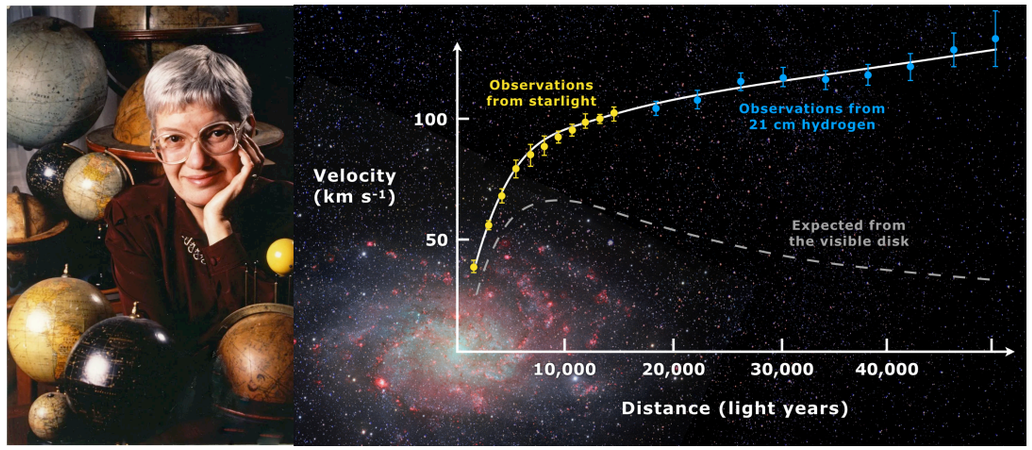


Galaxy redshift surveys support expanding Universe described by FLRW metric (1920s)



Discovery of cosmic microwave background confirms hot Big Bang model (1964)

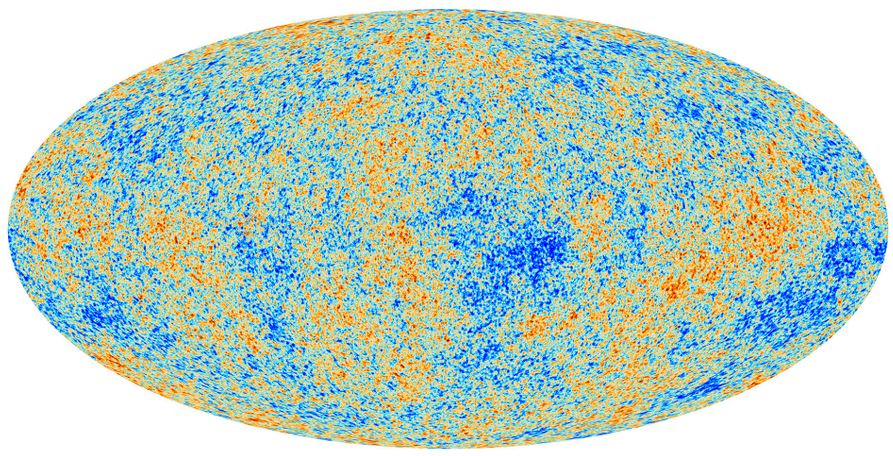
Galaxy clusters



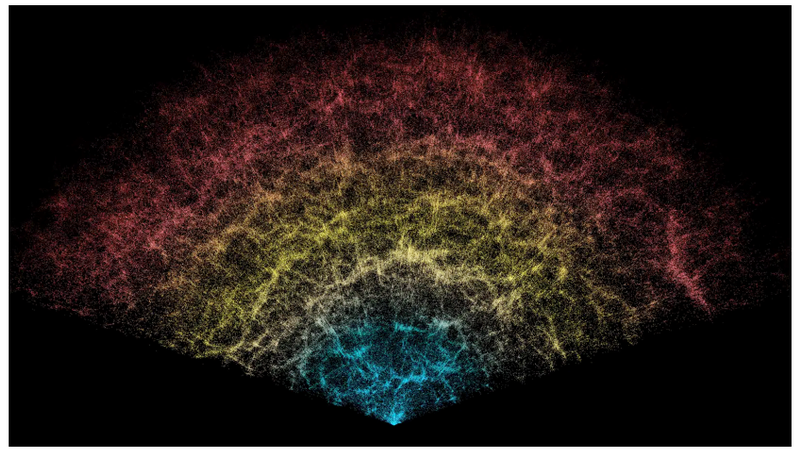
Galaxy rotation curves

Multiple independent observations infer existence of cold dark matter [CDM]

Gravitational lensing

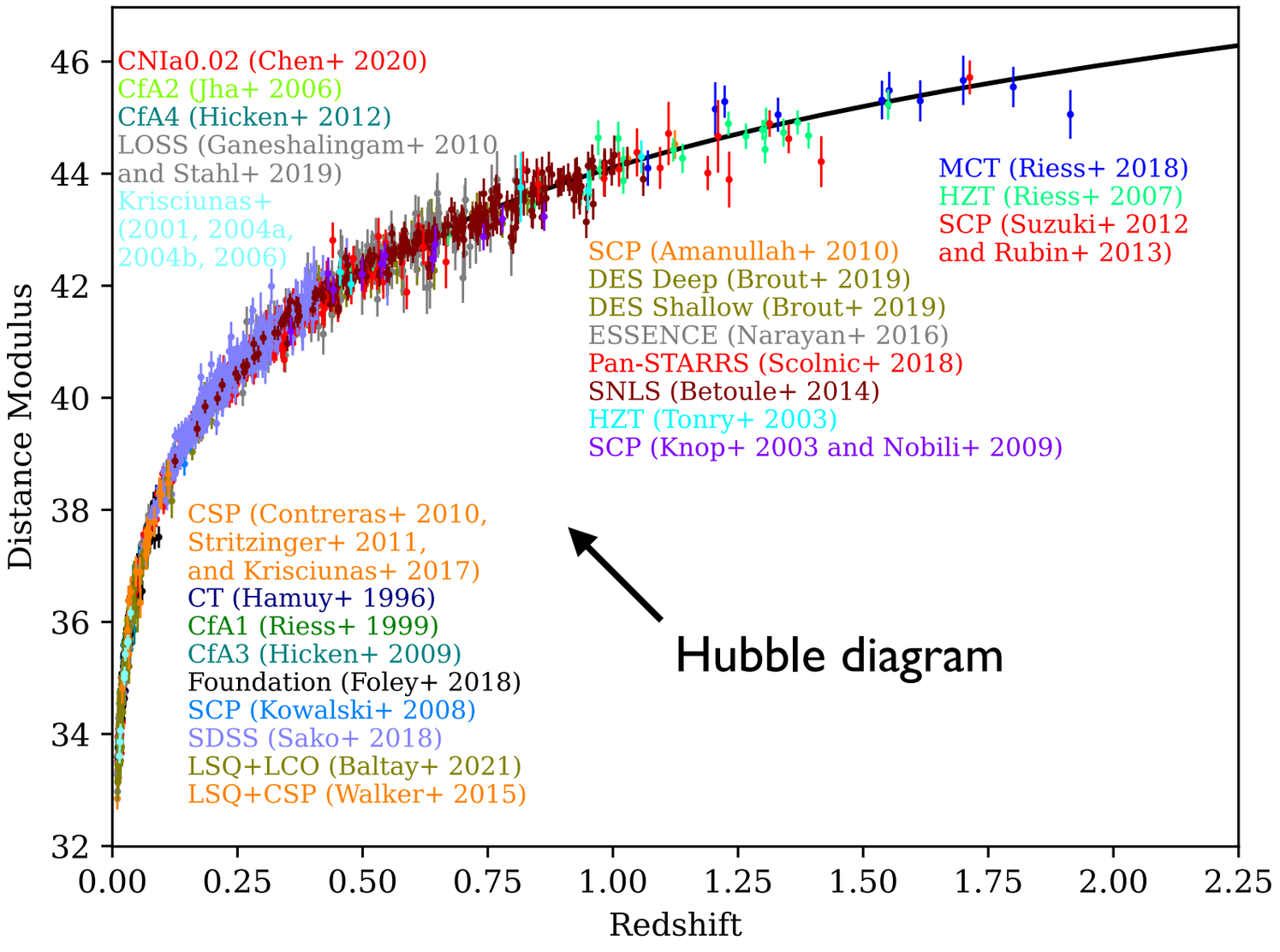


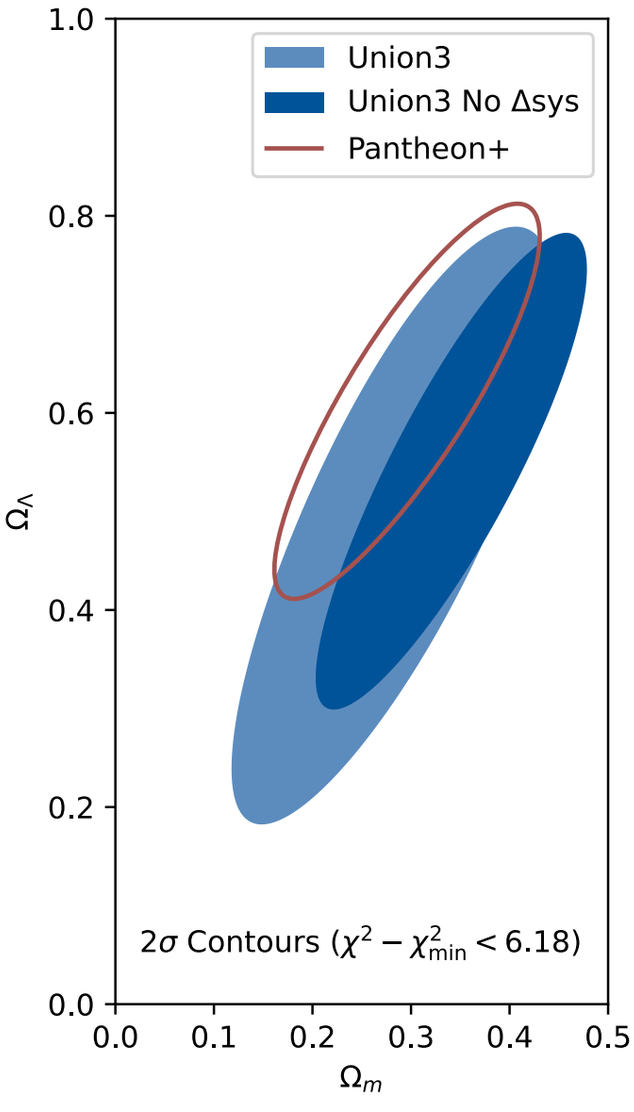
Cosmic microwave background



Large-scale structure

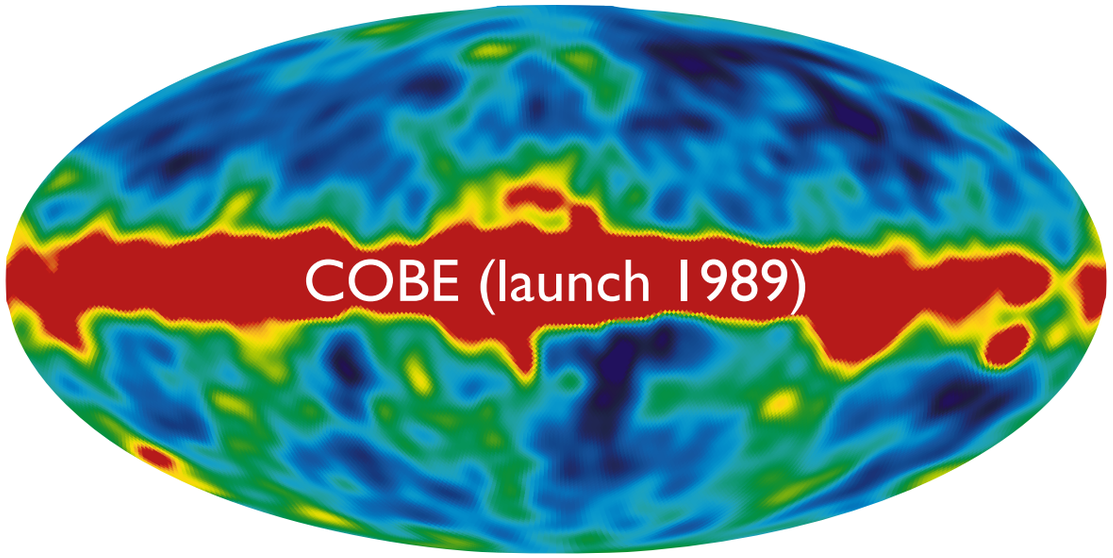
Multiple independent observations infer late-time accelerated expansion [Lambda]

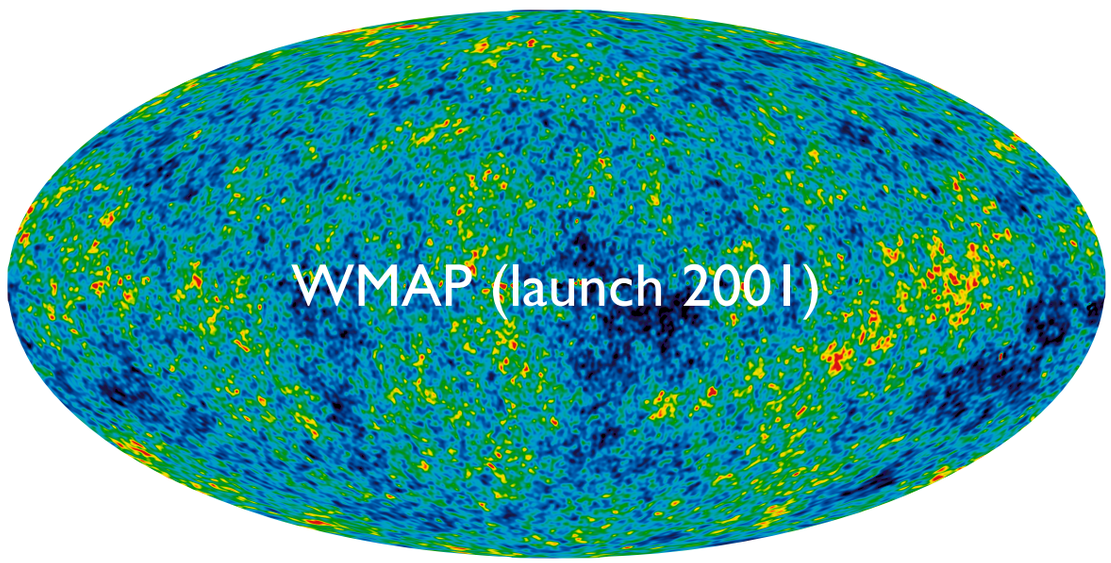


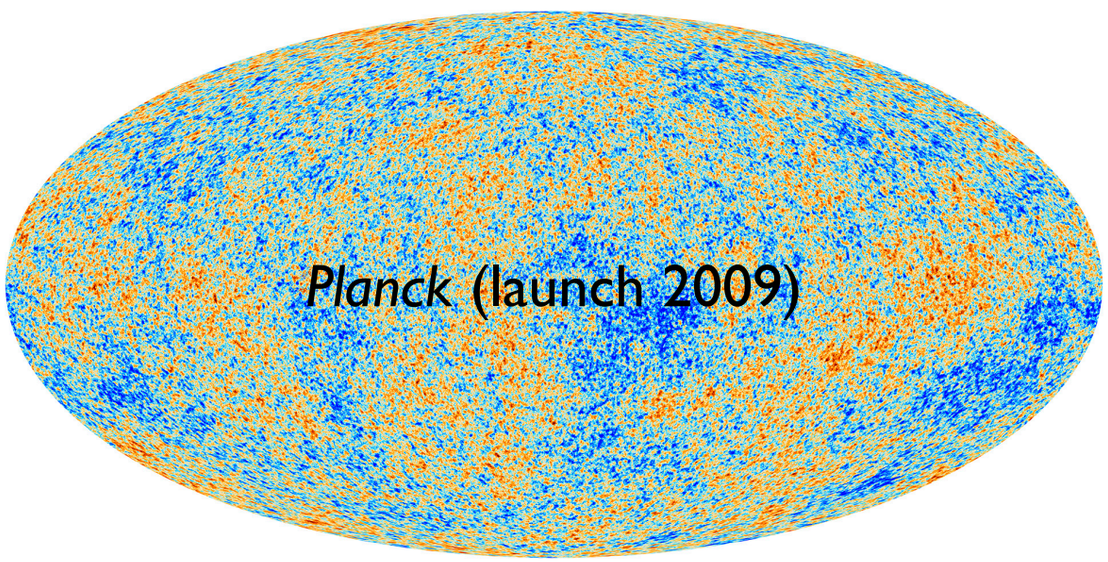


Riess et al. (1998); Perlmutter et al. (1999); Rubin et al. (2025; Union3 supernovae)

Three generations of CMB satellite establish the standard Lambda-CDM model of cosmology



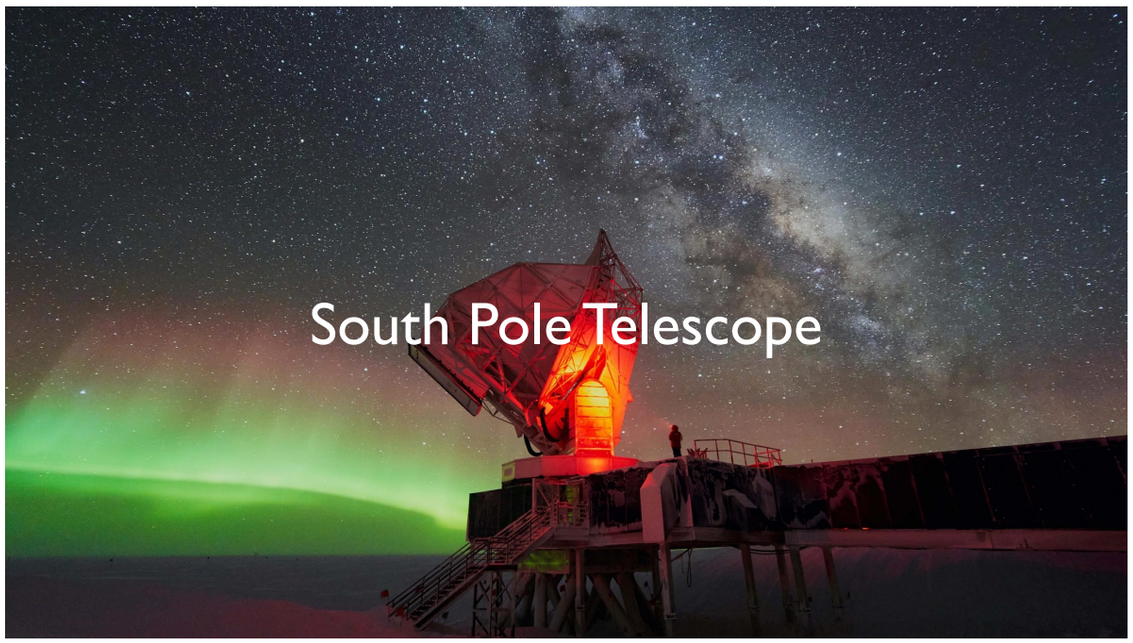


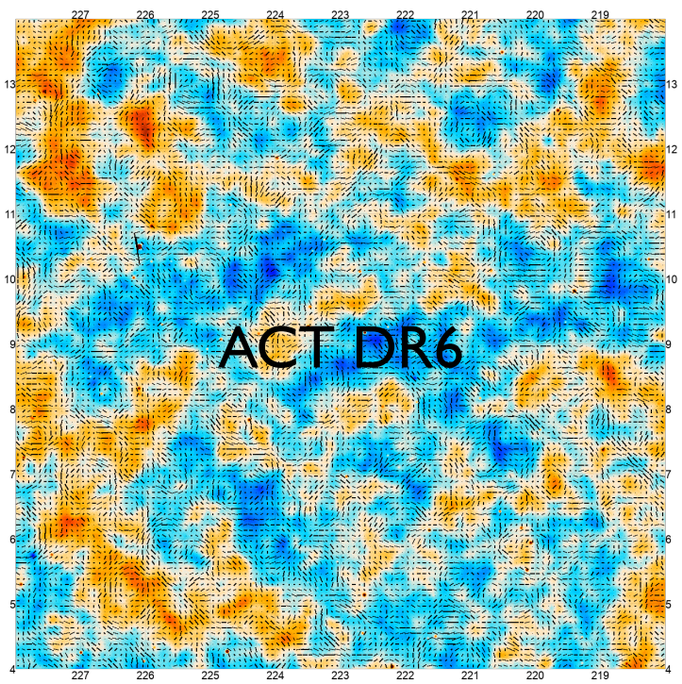


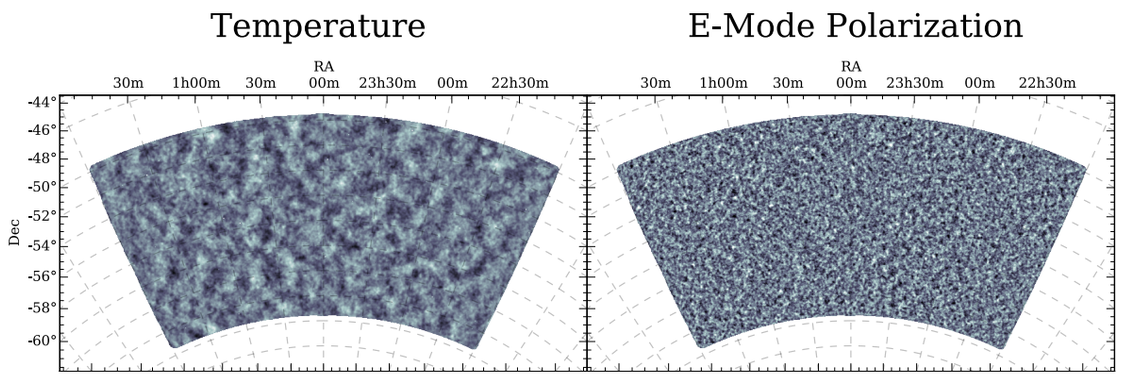
Lambda-CDM: just six numbers

- General relativity + FLRW + Lambda + CDM + baryons + flat: Ω_m, Ω_b, H_0
- Gaussian, adiabatic initial conditions with power-law spectrum: A_s, n_s
- Phase transition from neutral to ionised at epoch of reionisation: τ

Ground-based CMB observatories independently test cosmology through small scales & polarisation



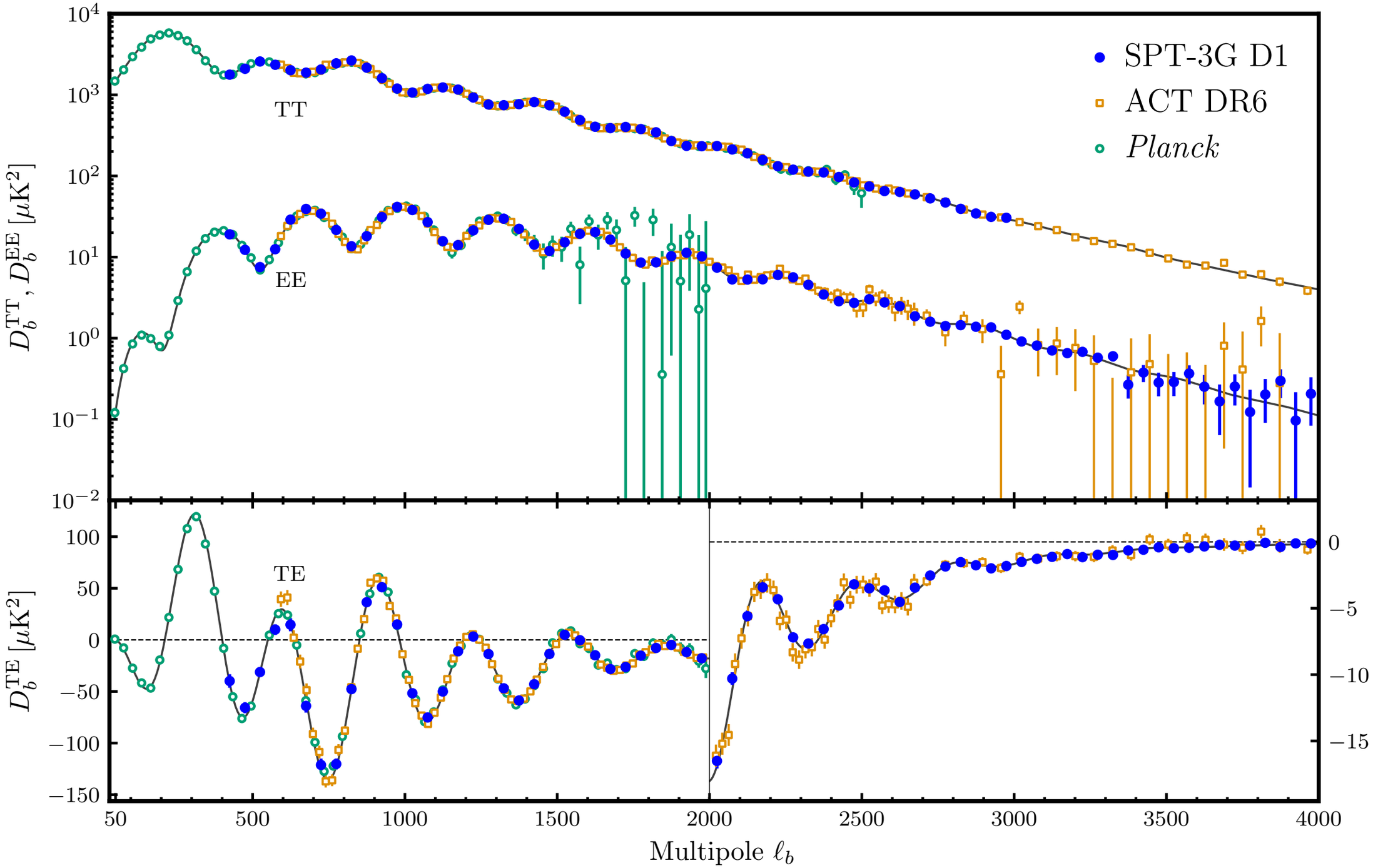




SPT-3G D1

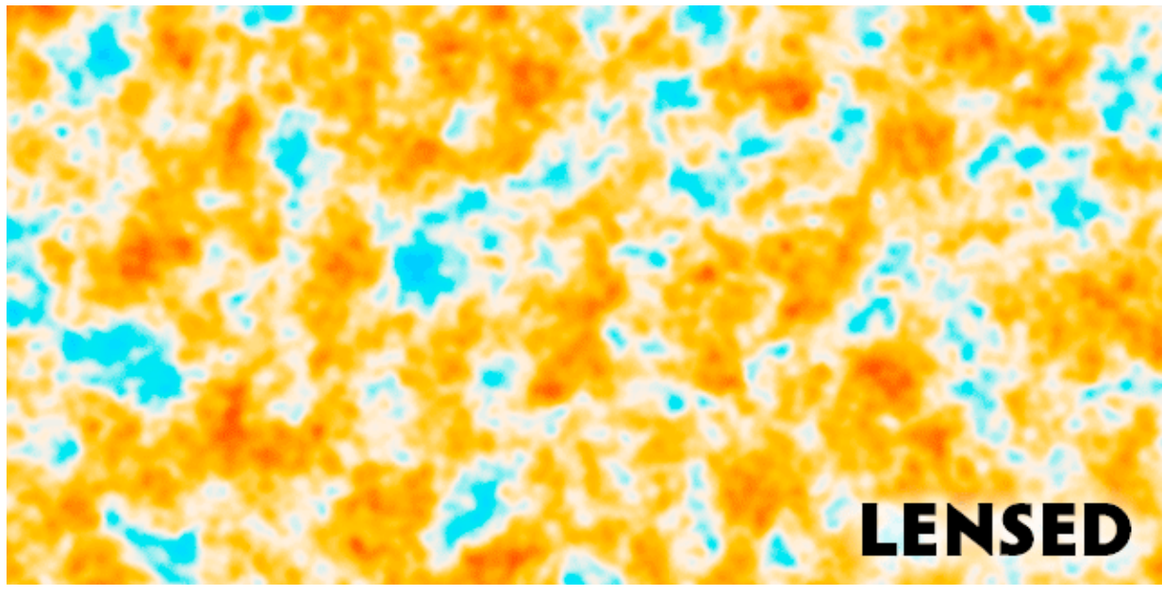
Naess et al. (ACT Collaboration, inc. Rogers, 2025); Chou et al. (SPT Collaboration, 2025)

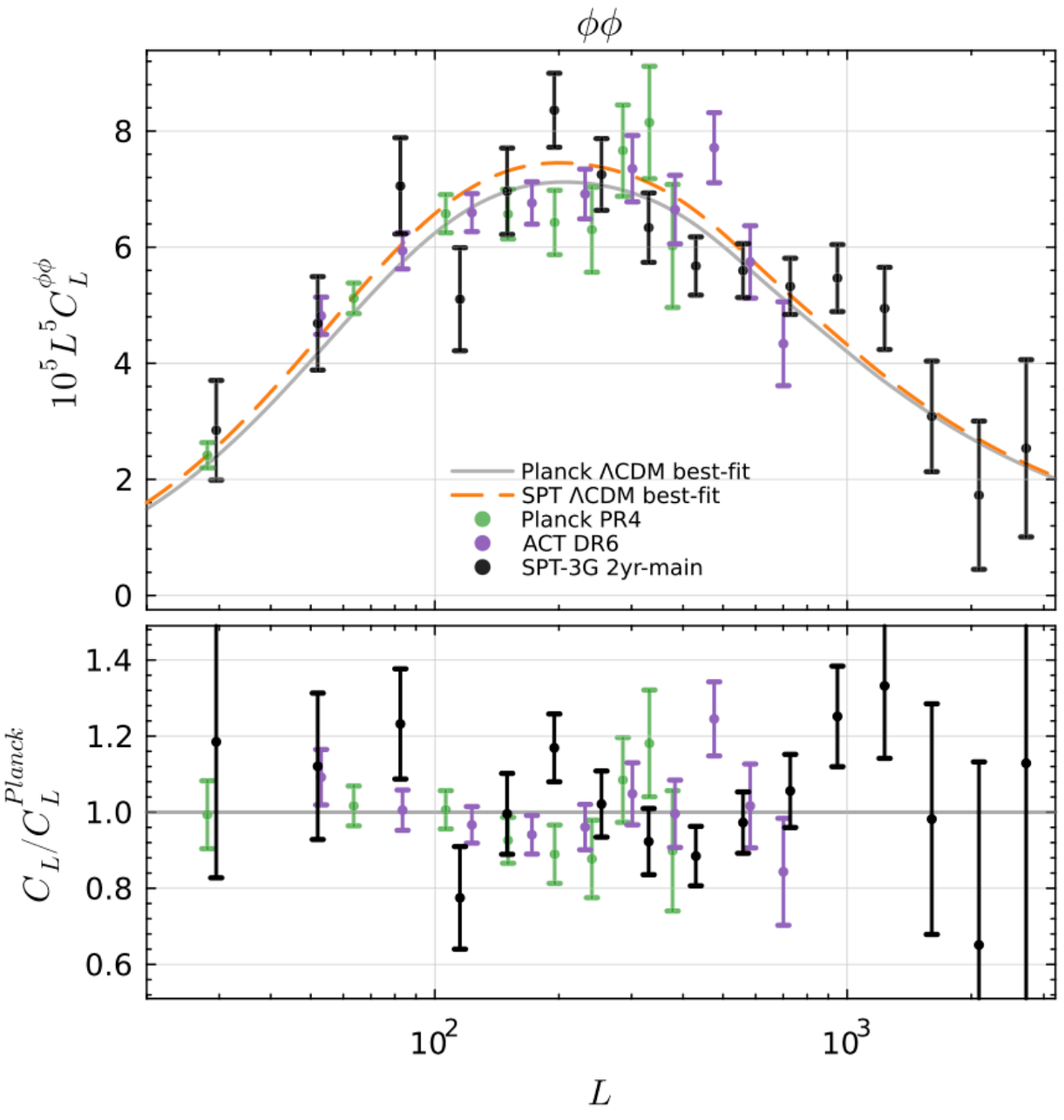
CMB temperature *T* & polarisation *E* angular power spectra



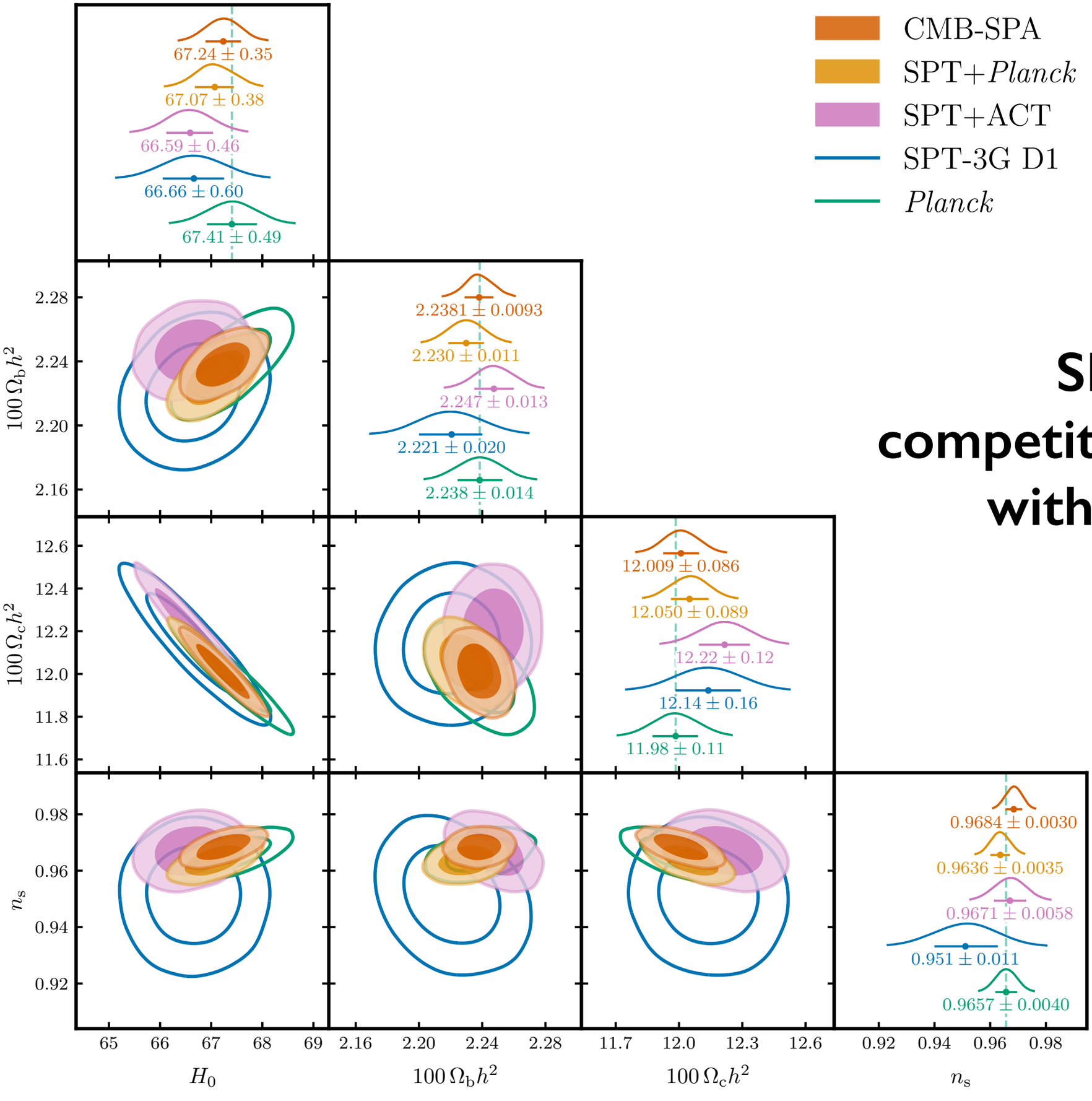
Camphuis+ (SPT Collaboration, 2025); Louis+ (ACT Collaboration, inc. Rogers, 2025)

CMB lensing potential ϕ angular power spectrum





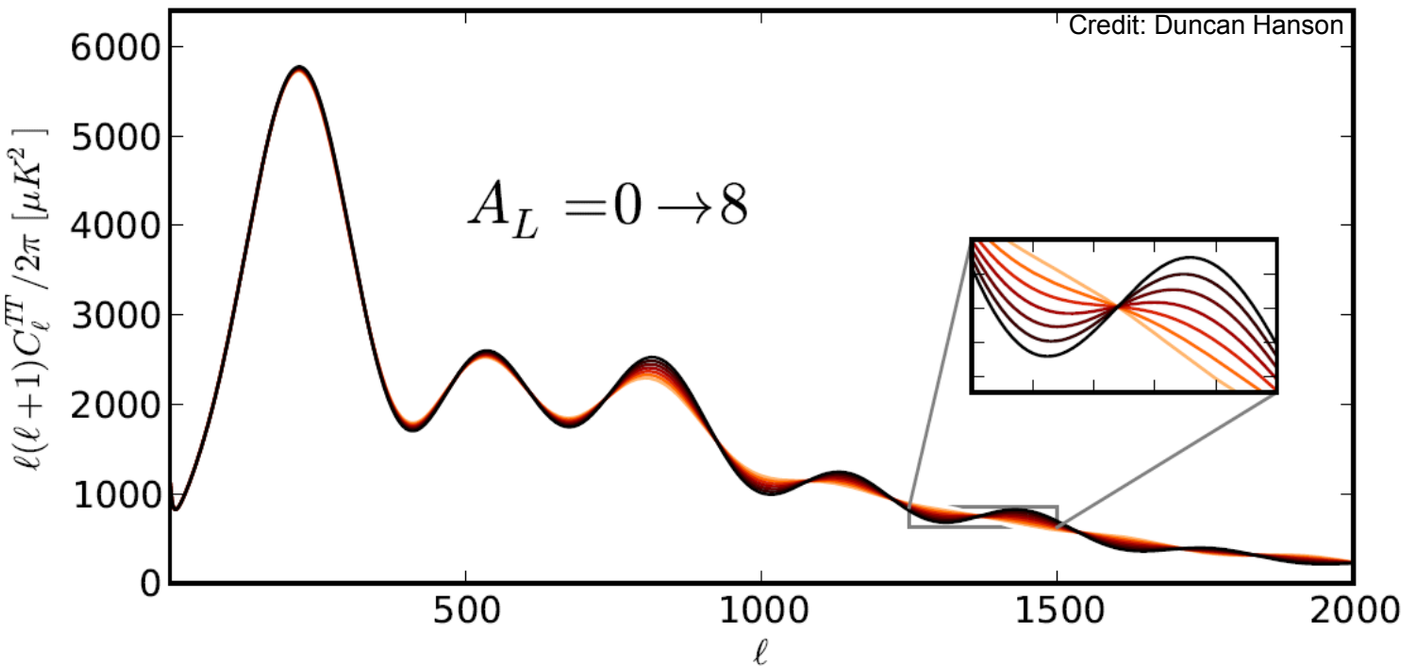
Ge et al. (SPT Collaboration, 2025)

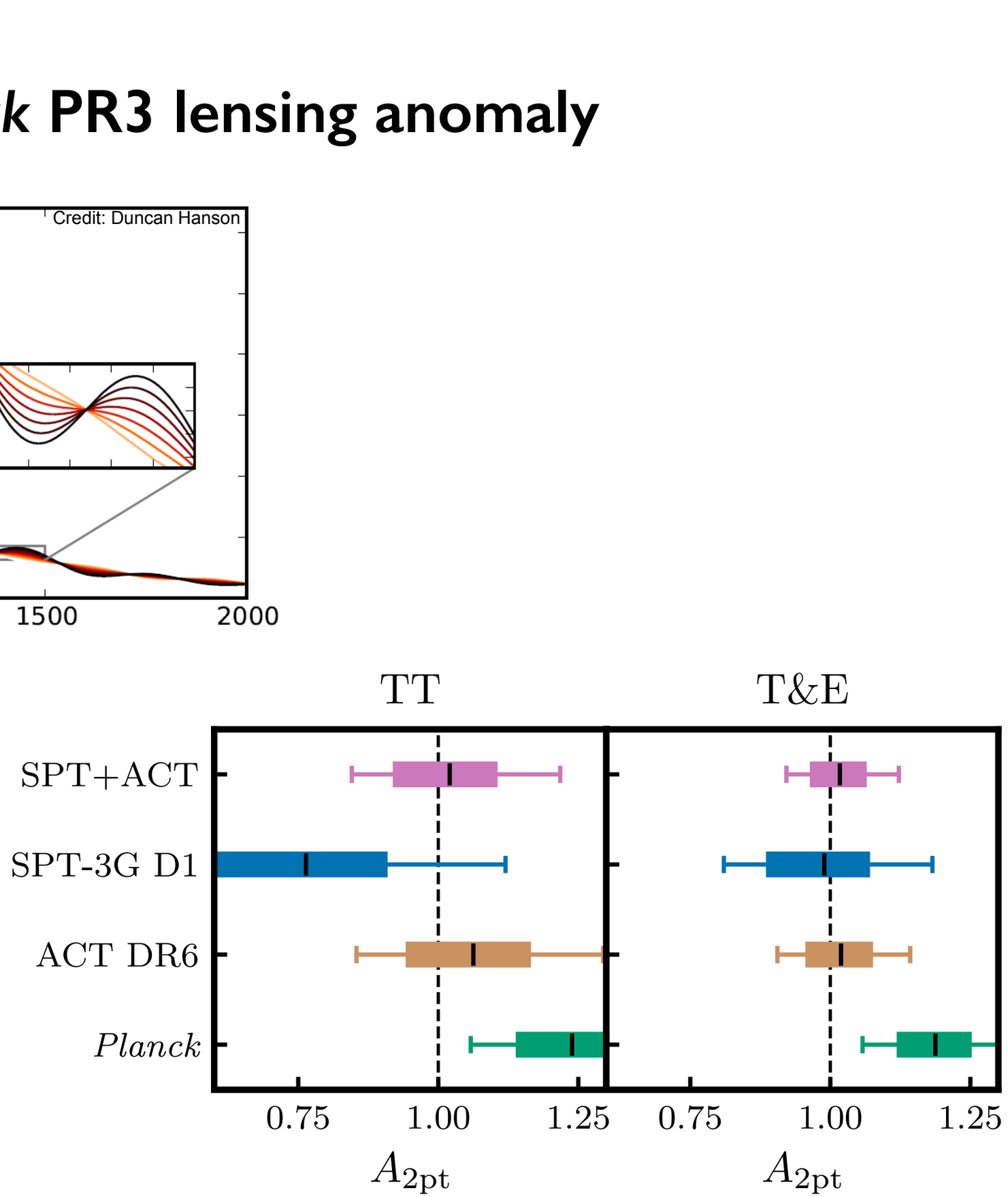


SPT+ACT competitive & consistent with *Planck* PR3

Camphuis+ (SPT Collaboration, 2025); Louis+ (ACT Collaboration, inc. Rogers, 2025)

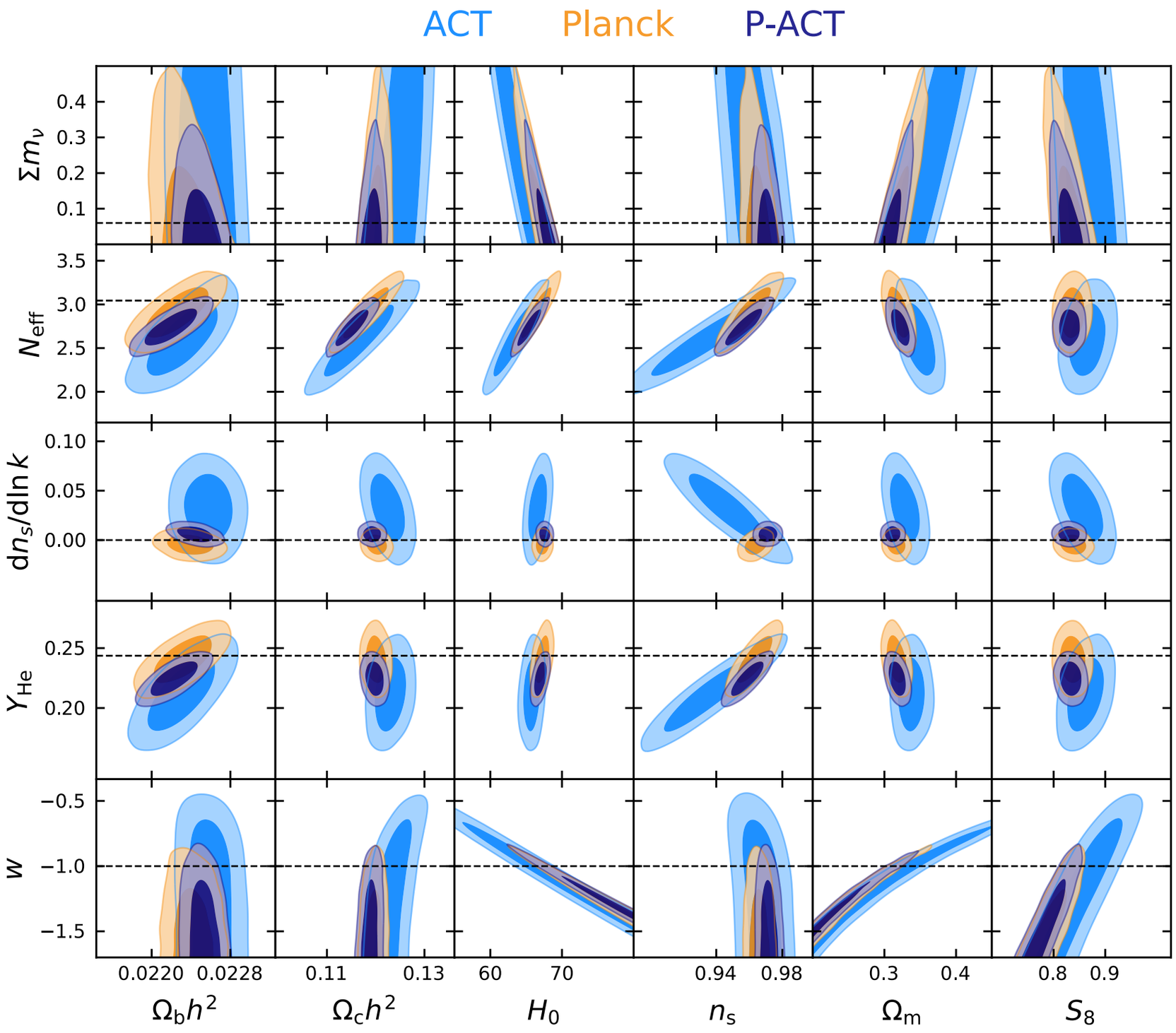
The *Planck* PR3 lensing anomaly





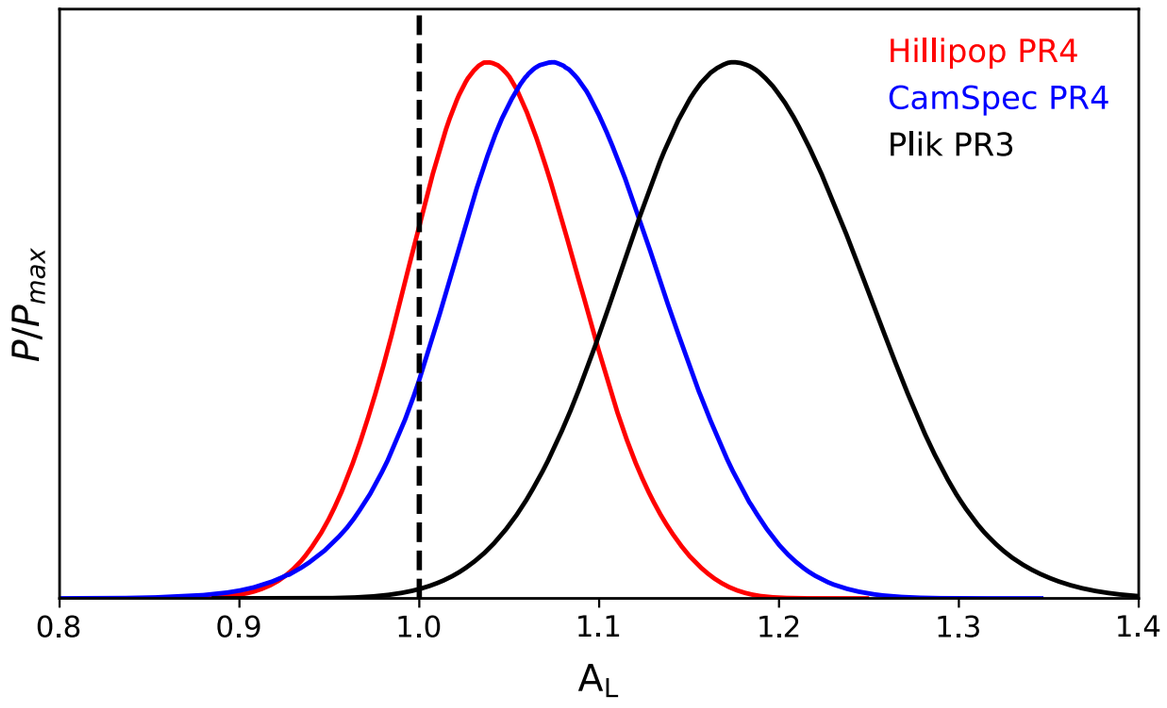
Camphuis+ (SPT Collaboration, 2025); Louis+ (ACT Collaboration, inc. Rogers, 2025)

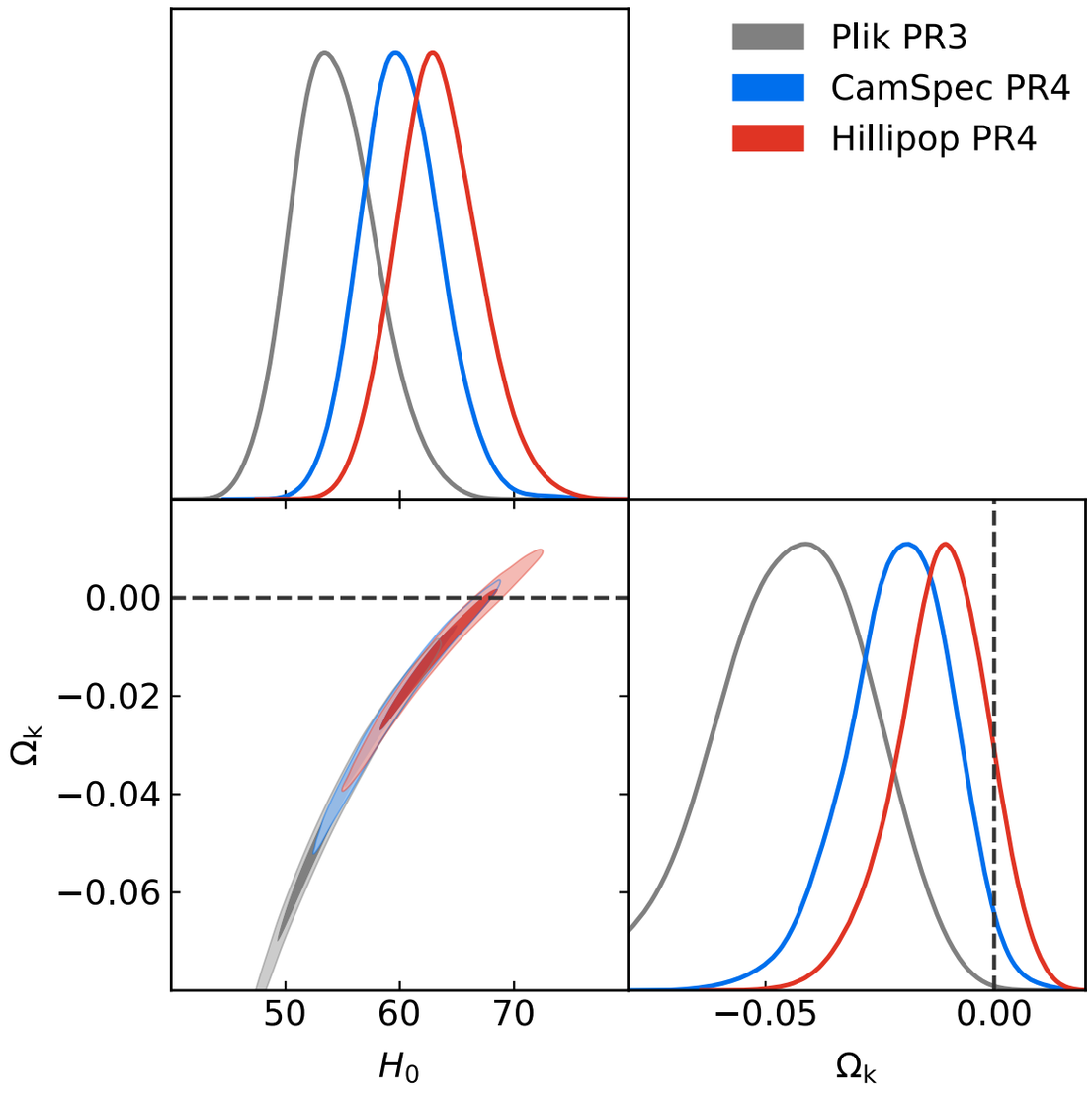
No new physics in the CMB



Calabrese et al. (ACT Collaboration, inc. Rogers, 2025)

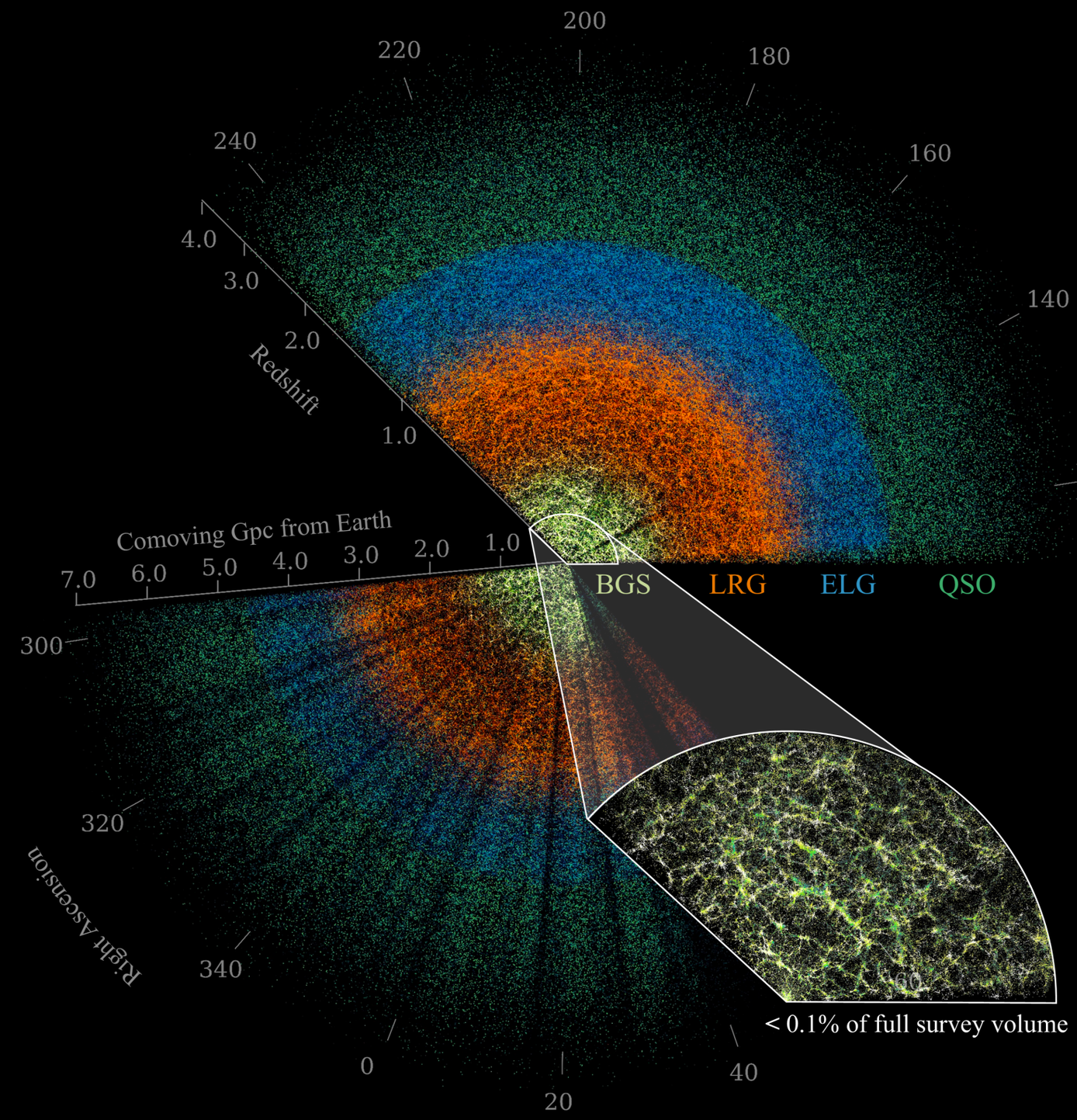
Using more raw *Planck* data suppresses lensing anomaly & drives cosmology to flatness



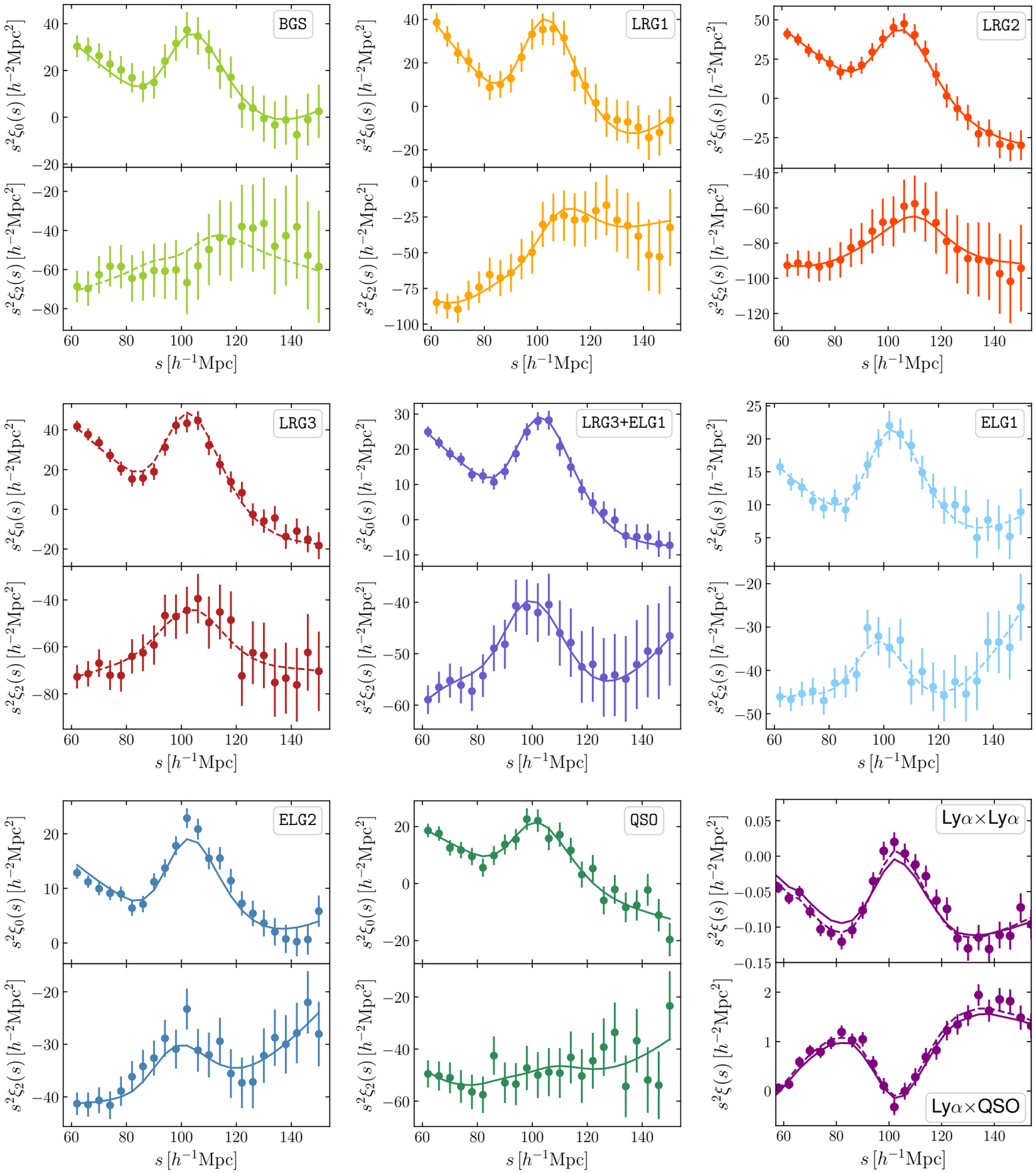


Planck Collaboration et al. (2020); Rosenberg et al. (2022); Tristram et al. (2024)

The Dark Energy Spectroscopic Instrument galaxy redshift survey

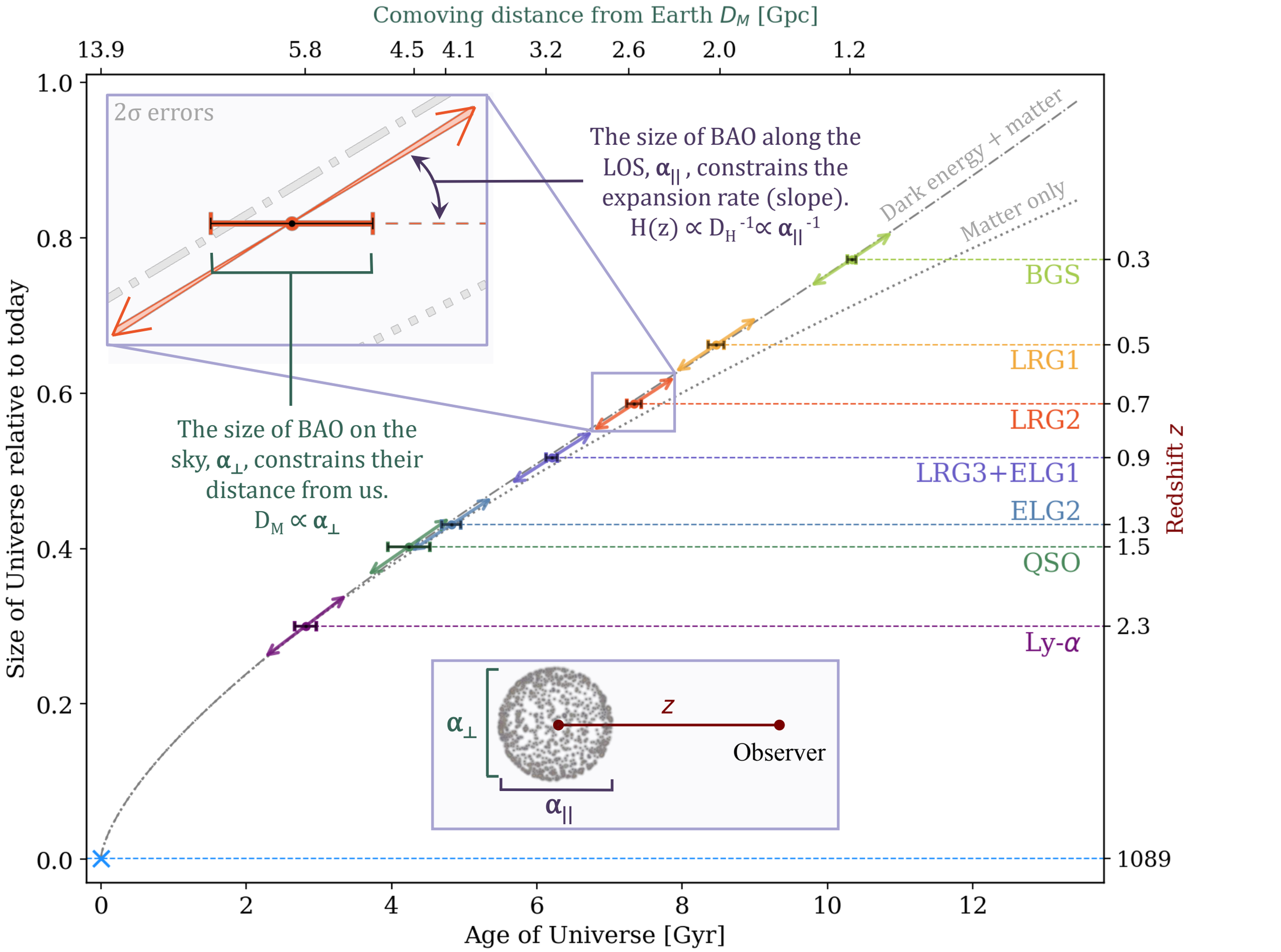


DESI Collaboration et al. (2025)



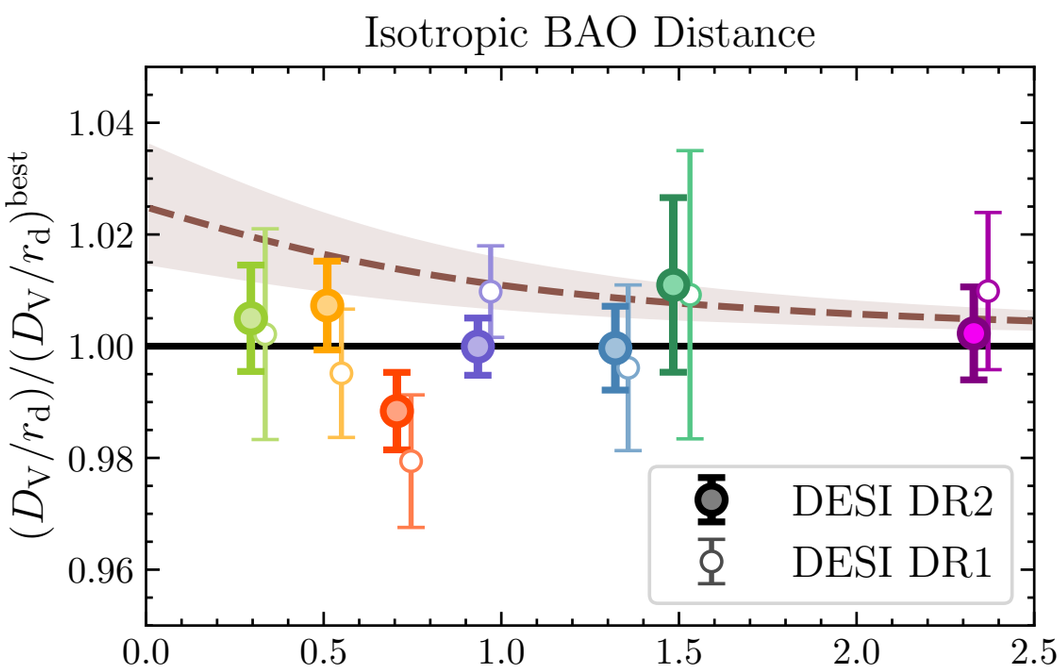
Baryon acoustic oscillation detected in nine redshift bins

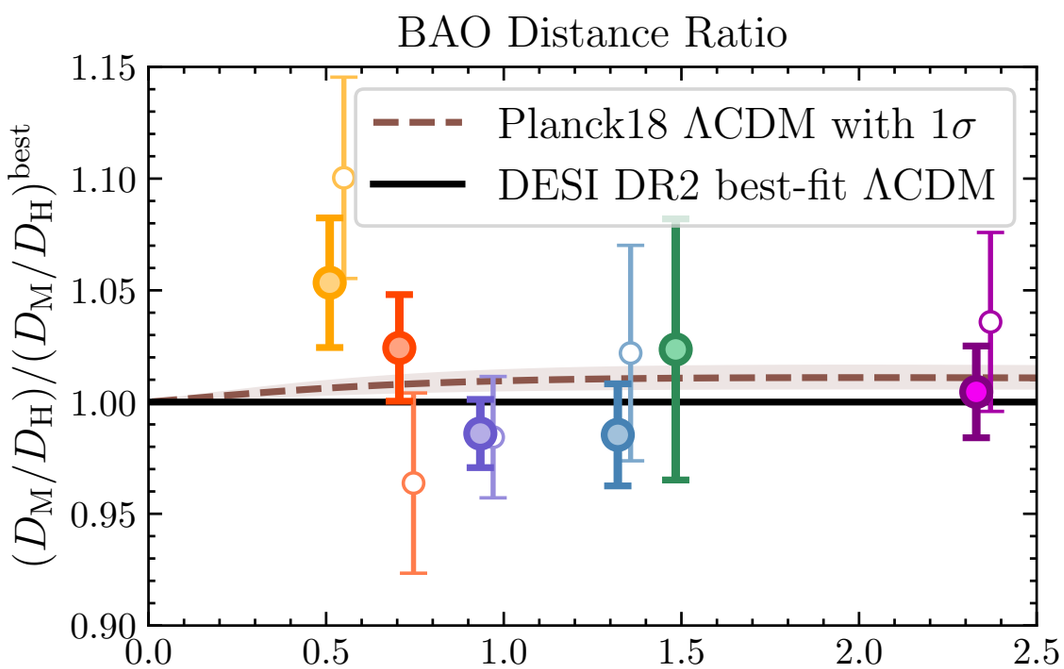
DESI Collaboration et al. (2025)

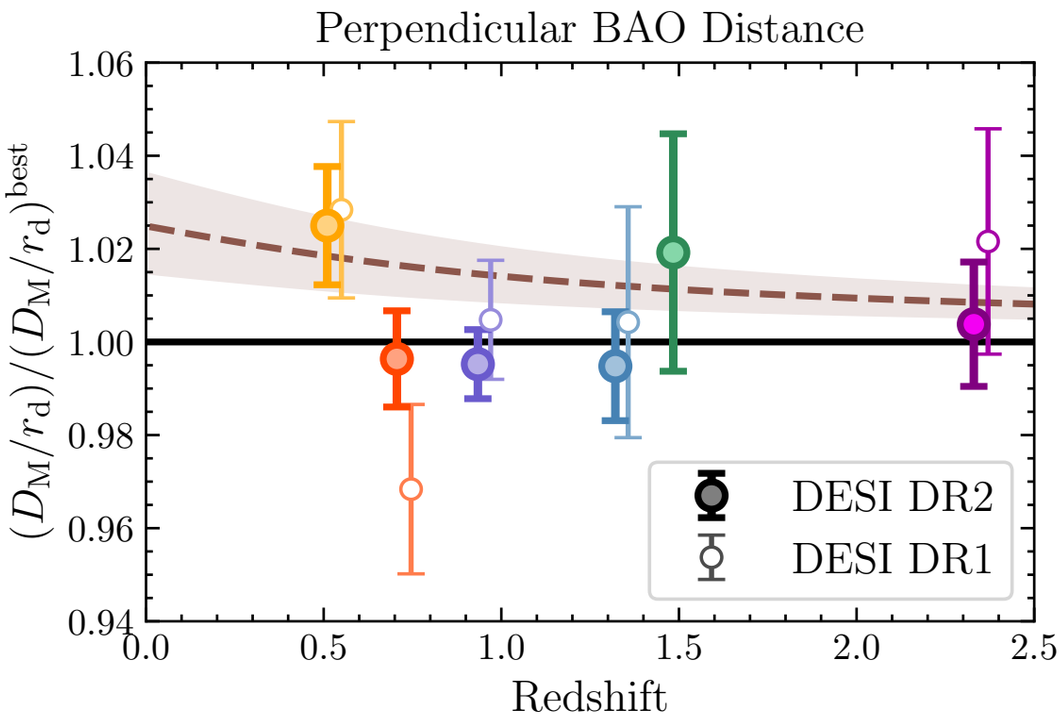


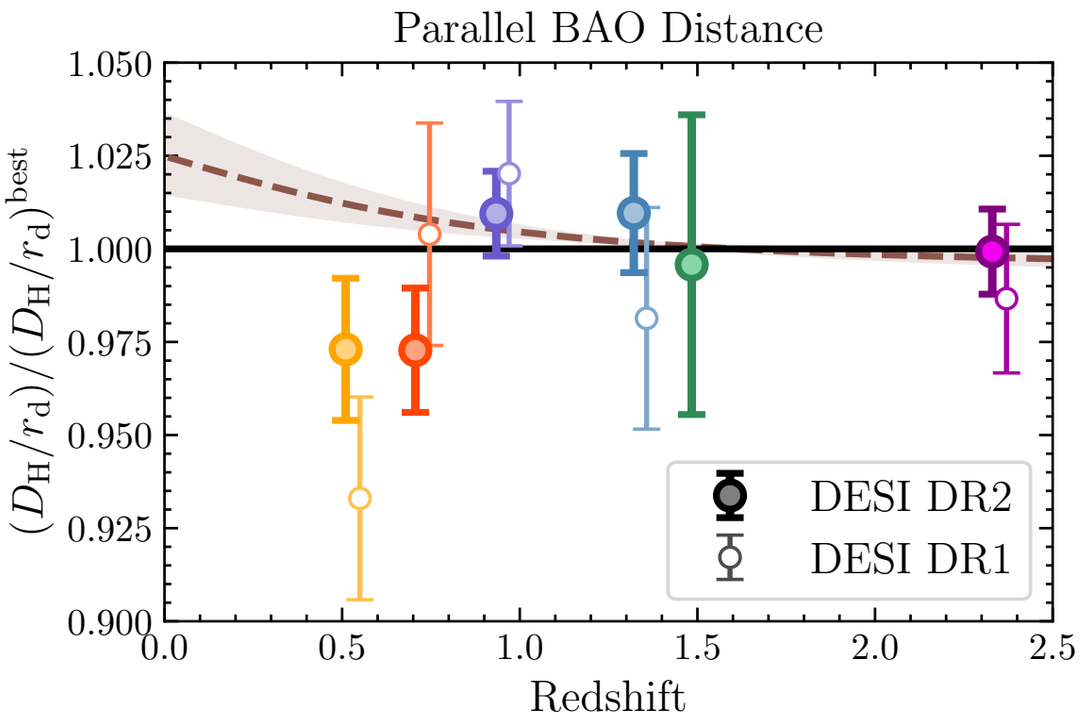
DESI Collaboration et al. (2025)

Lambda-CDM is a good fit to DESI BAO but not for *Planck* CMB parameter values

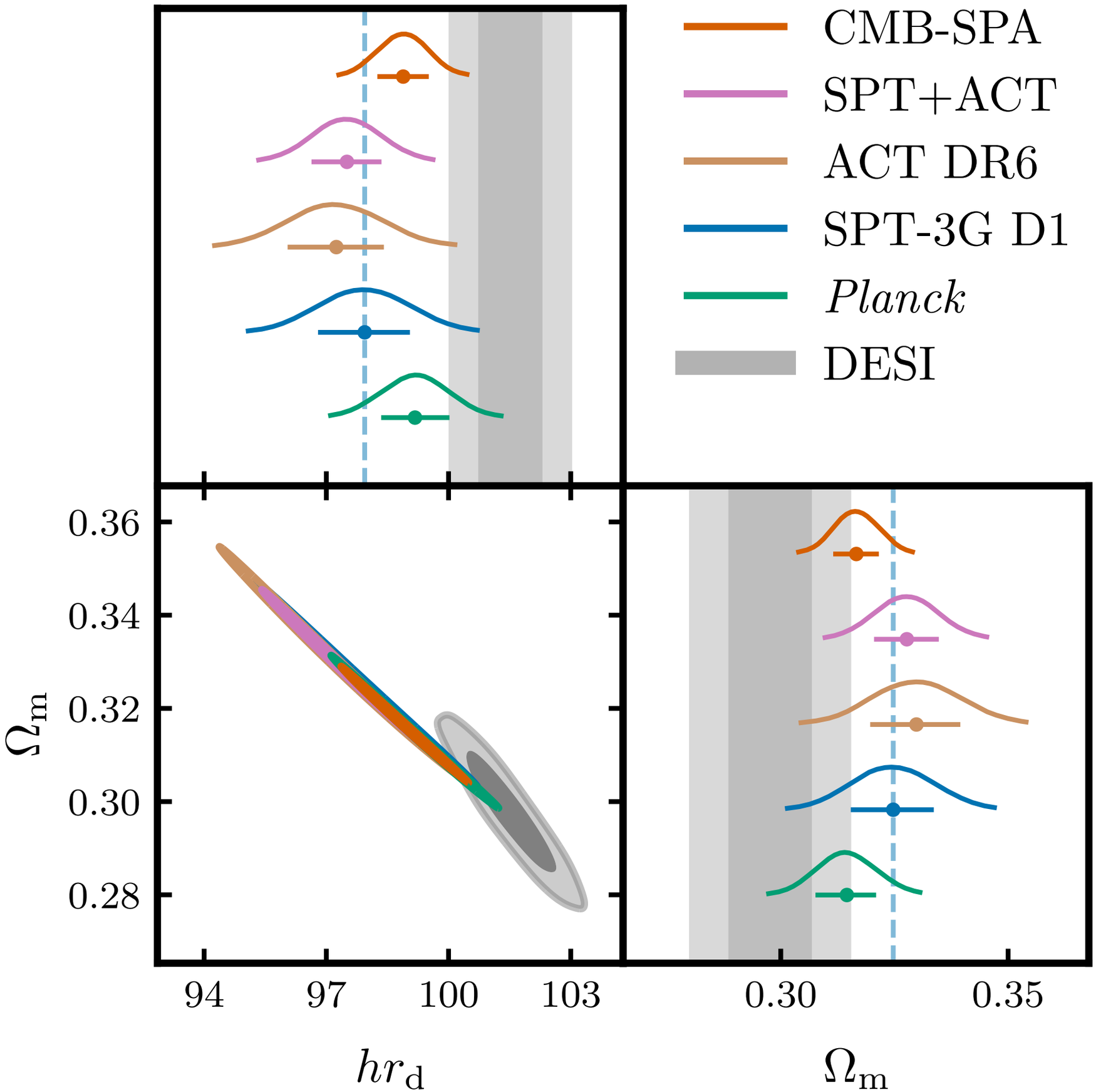








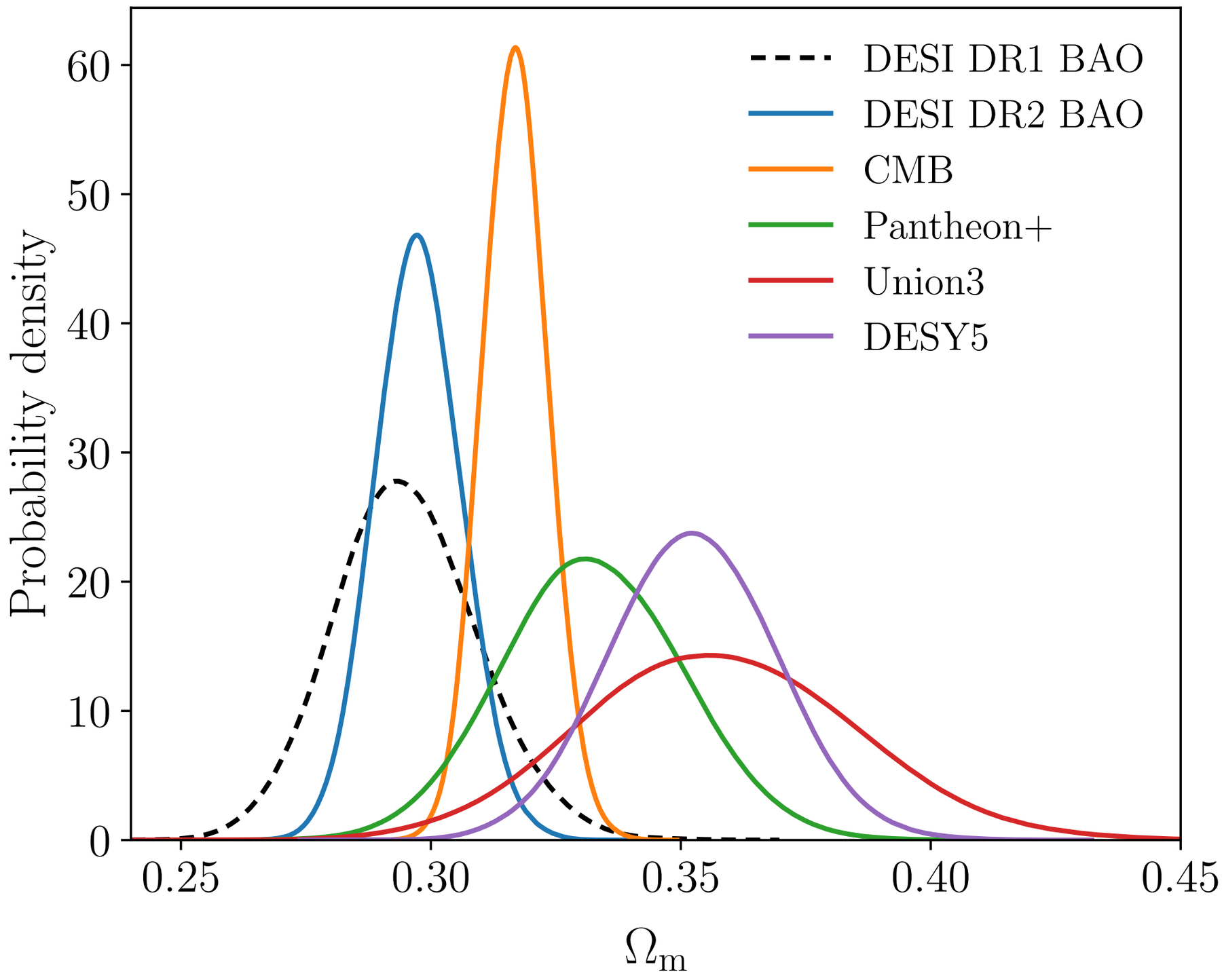
DESI Collaboration et al. (2025)



2.8σ CMB-BAO discrepancy

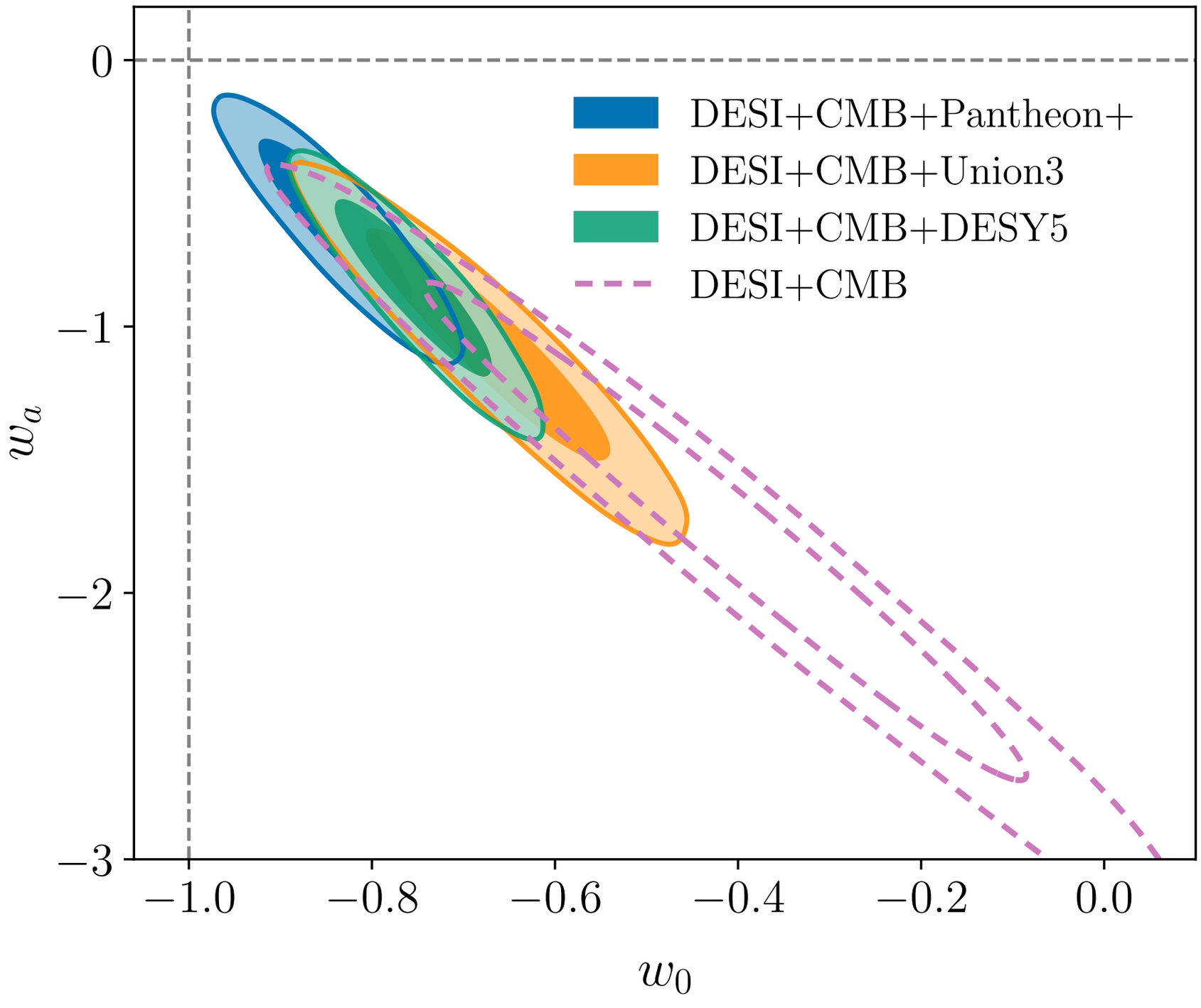
Camphuis+ (SPT Collaboration, 2025); DESI Collaboration et al. (2025)

And then the supernovae tend to prefer *higher* Ω_m…

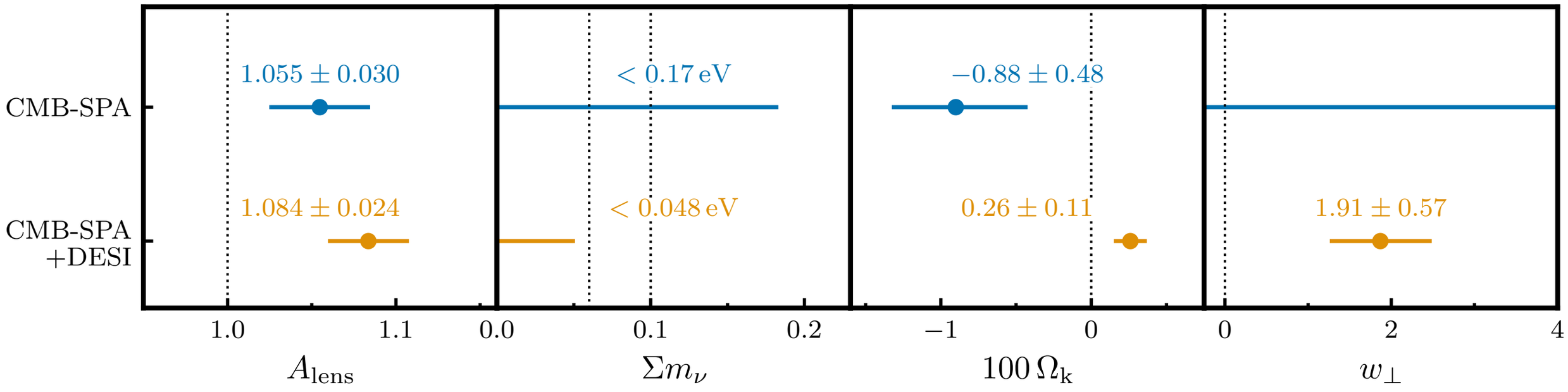


DESI Collaboration et al. (2025)

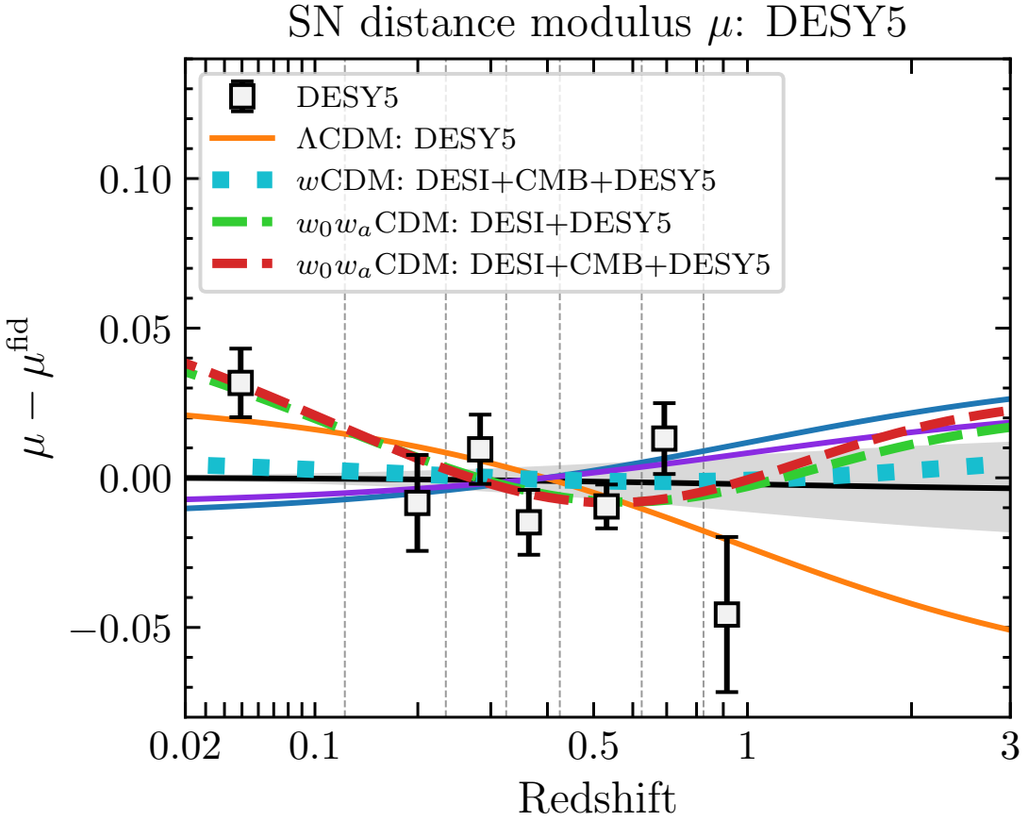
Two-parameter dark energy equation of state shifts away from Lambda-CDM



DESI Collaboration et al. (2025)



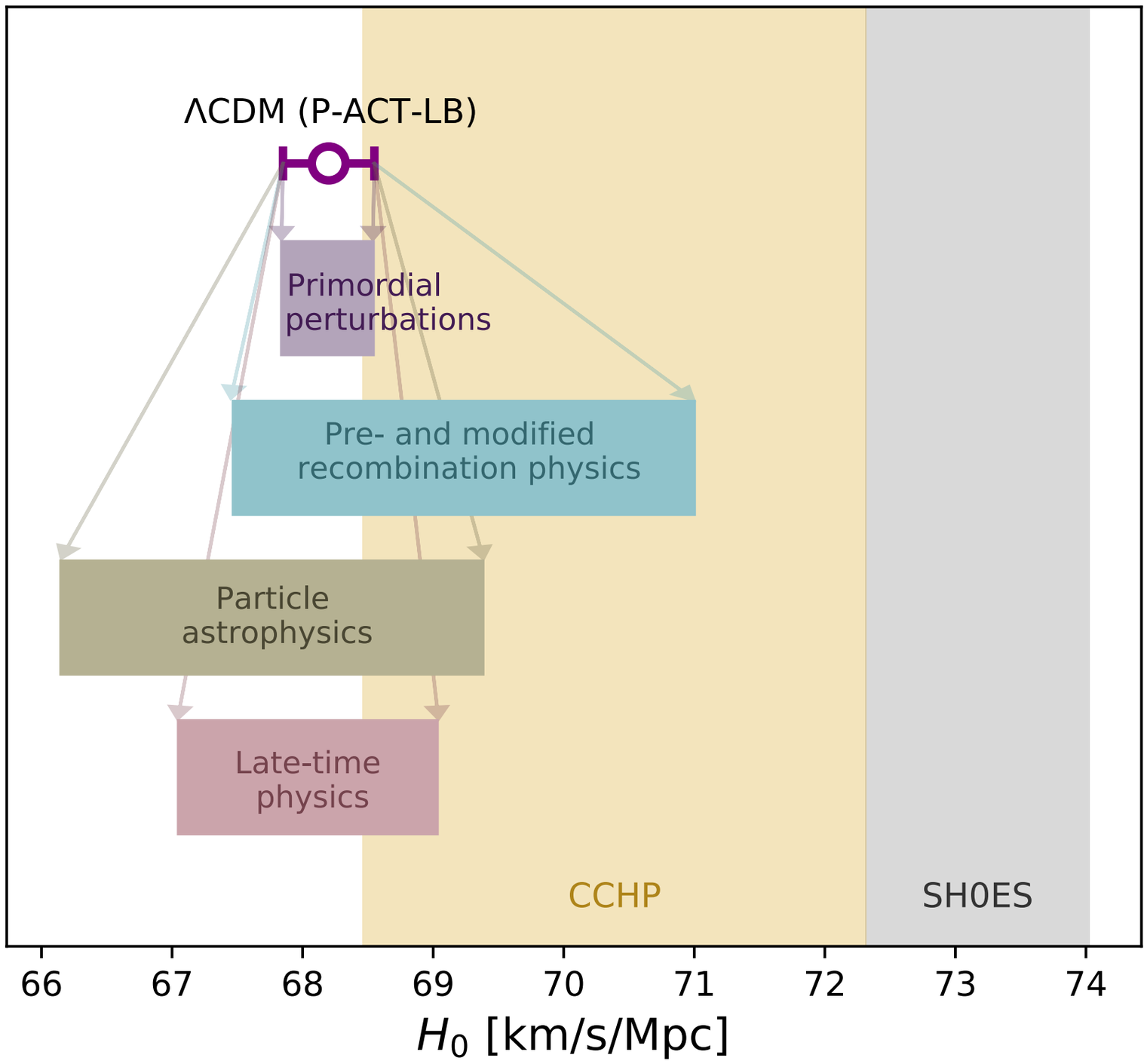
Dark energy not the only implication from the CMB-BAO discrepancy



Significance of w_0-w_a preference reduced without low-redshift ($z < 0.1$) supernovae

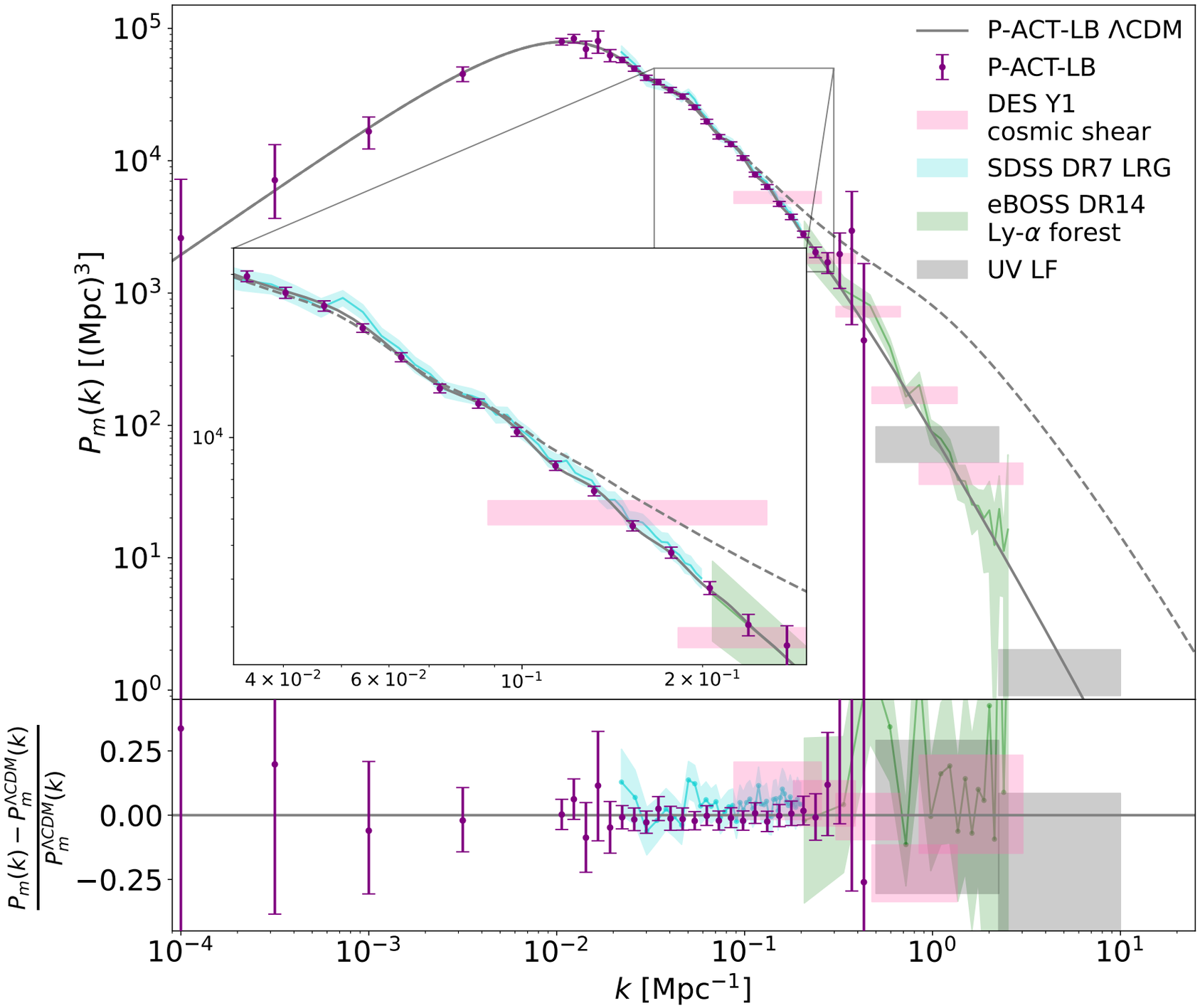
Camphuis+ (SPT Collaboration, 2025); DESI Collaboration et al. (2025)

6.4σ CMB-SH0ES Hubble tension not *fully* resolved by any cosmological model



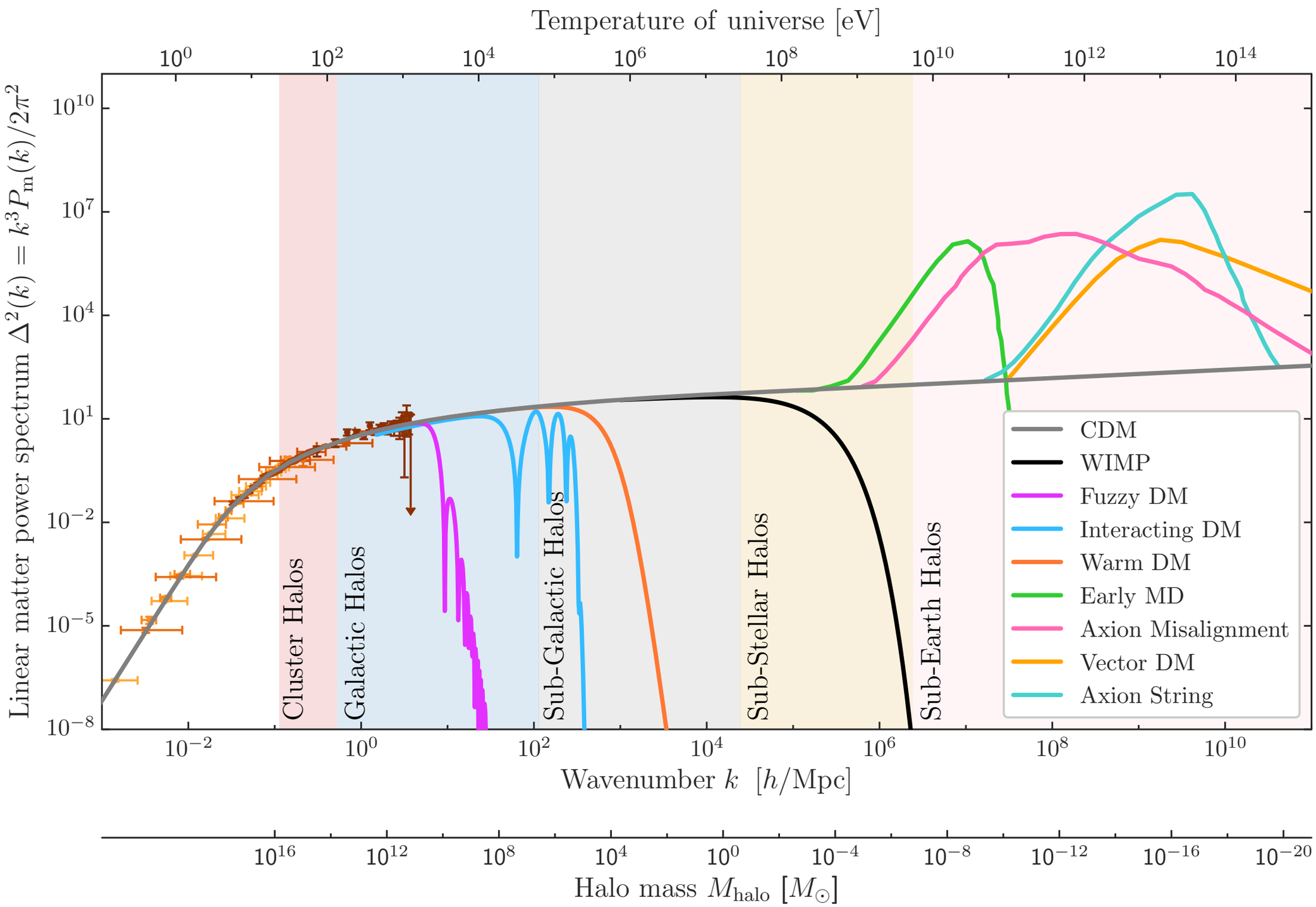
Calabrese et al. (ACT Collaboration, inc. Rogers, 2025)

The cold dark matter paradigm is robustly tested on "large scales" in the linear matter power spectrum

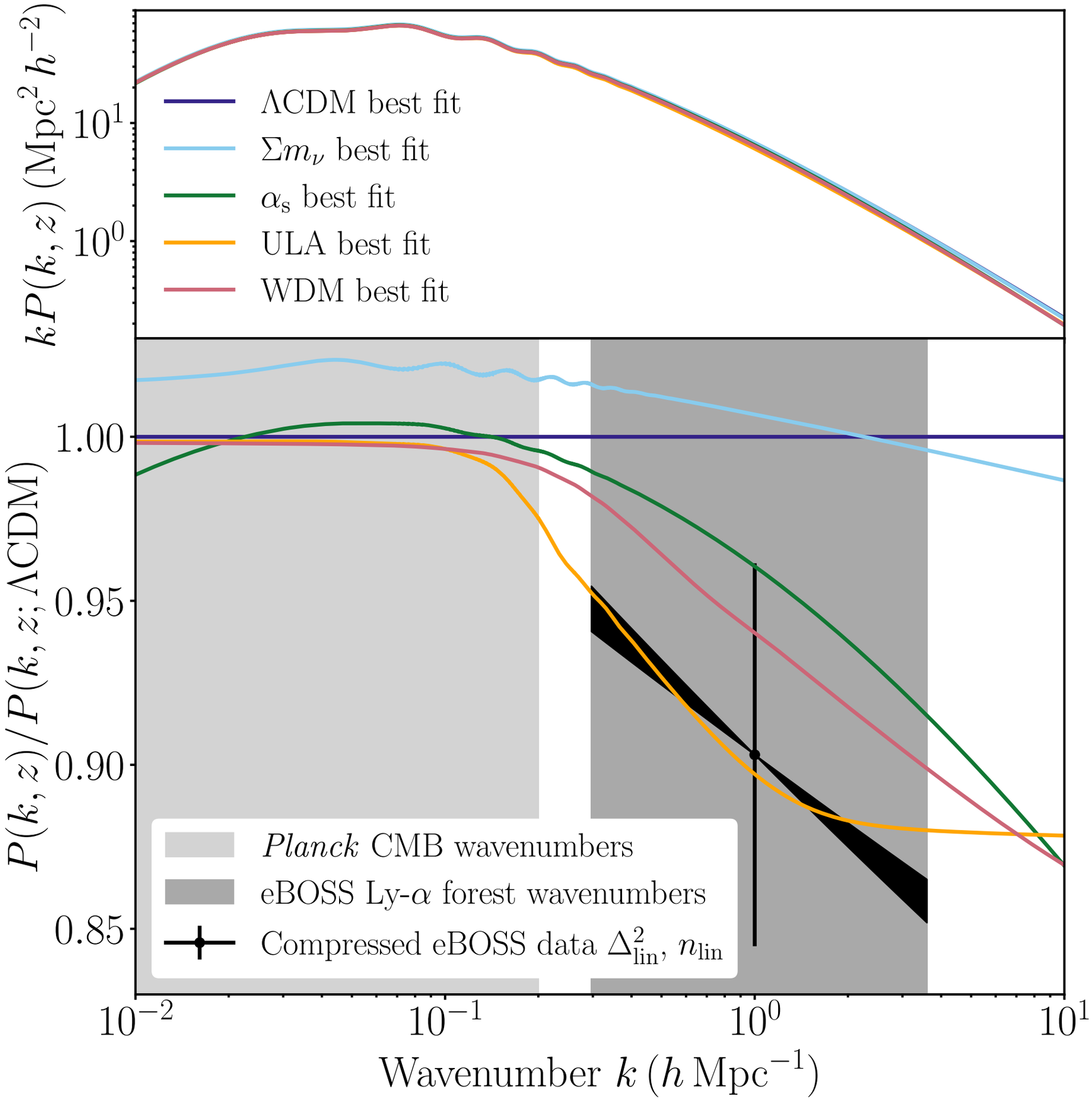


Calabrese et al. (ACT Collaboration, inc. Rogers, 2025)

But it hasn't been tested on "small scales"…



Drlica-Wagner et al. (Snowmass, 2022)

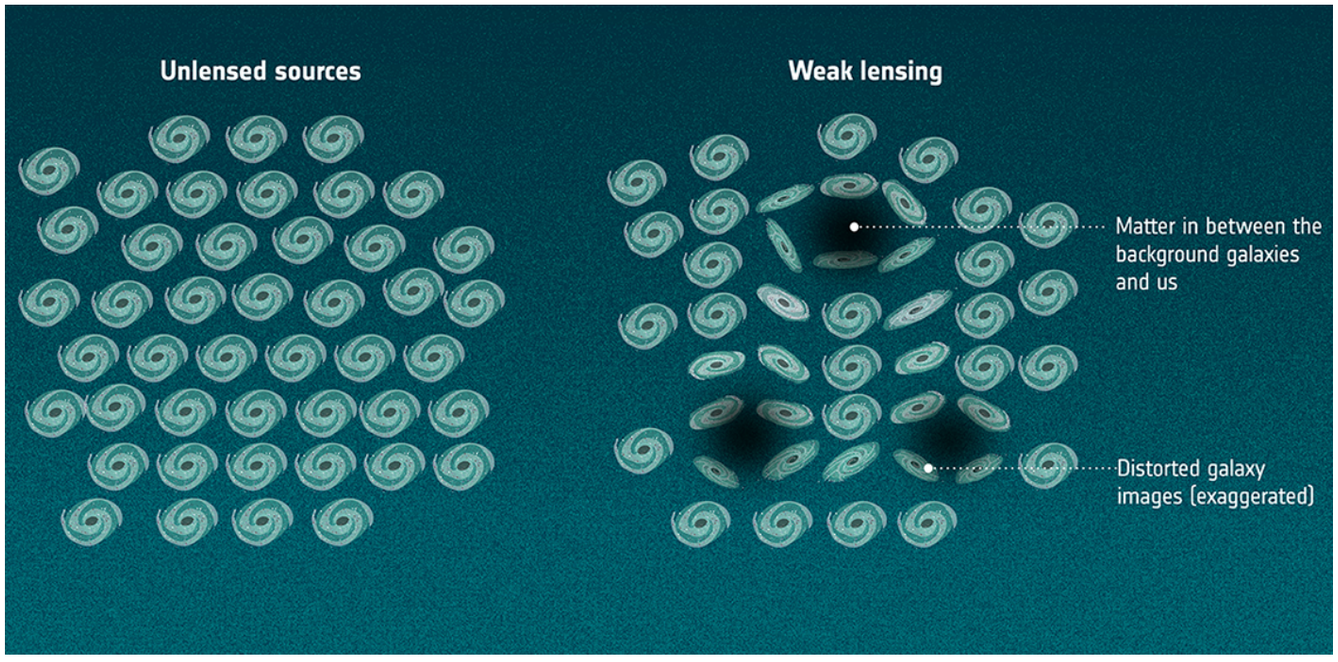


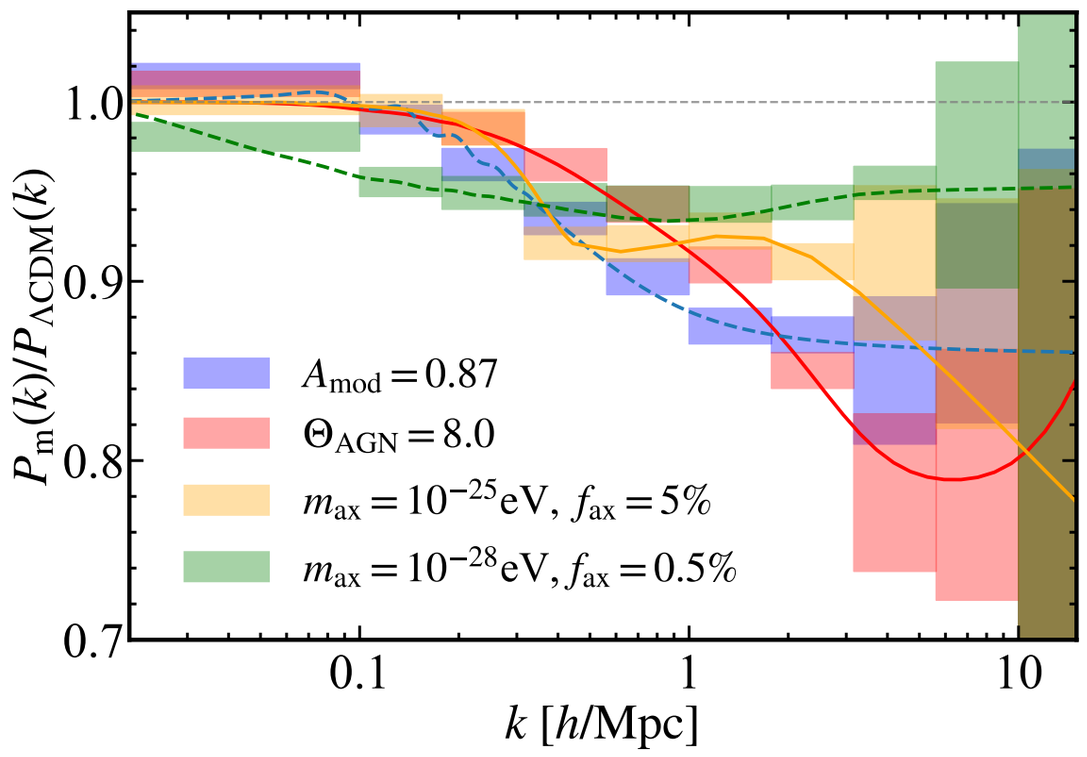
4.9σ tension between eBOSS Ly-af & *Planck* CMB

Chabanier et al. (2019); Goldstein et al. (2023); Rogers & Poulin (Phys. Rev. Res., 2025)

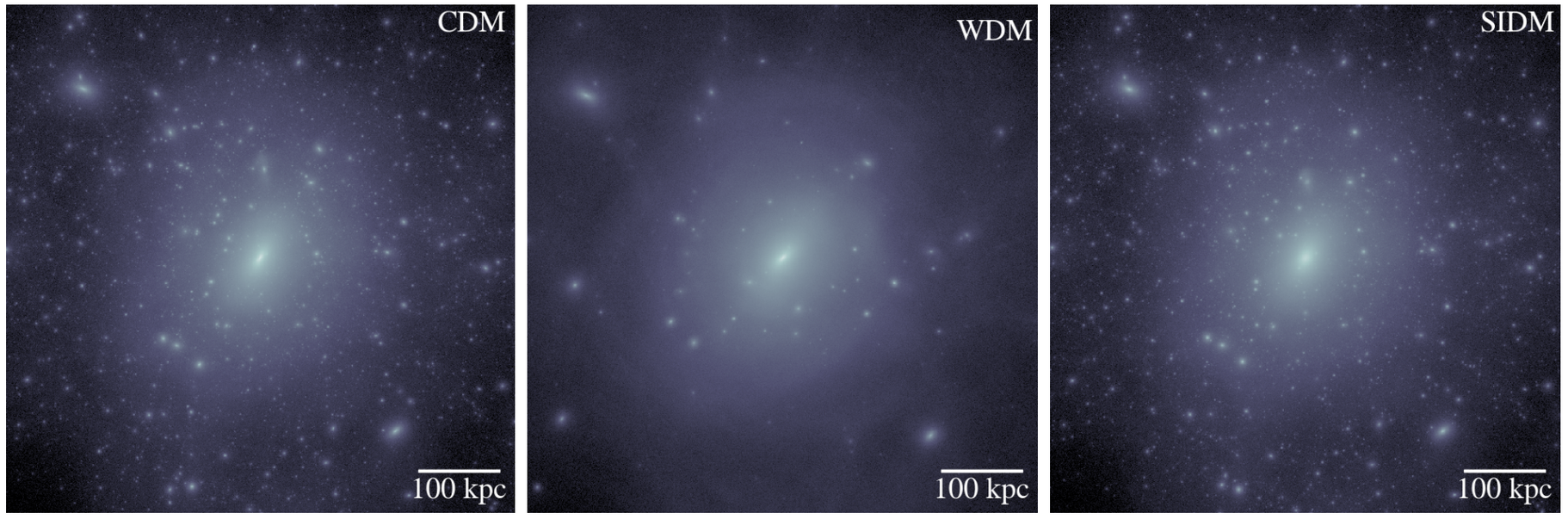
Rubin Observatory's *Legacy Survey of Space and Time* will see 4 million SNe/20 billion galaxies/17 billion stars

VERA C. RUBIN
OBSERVATORY



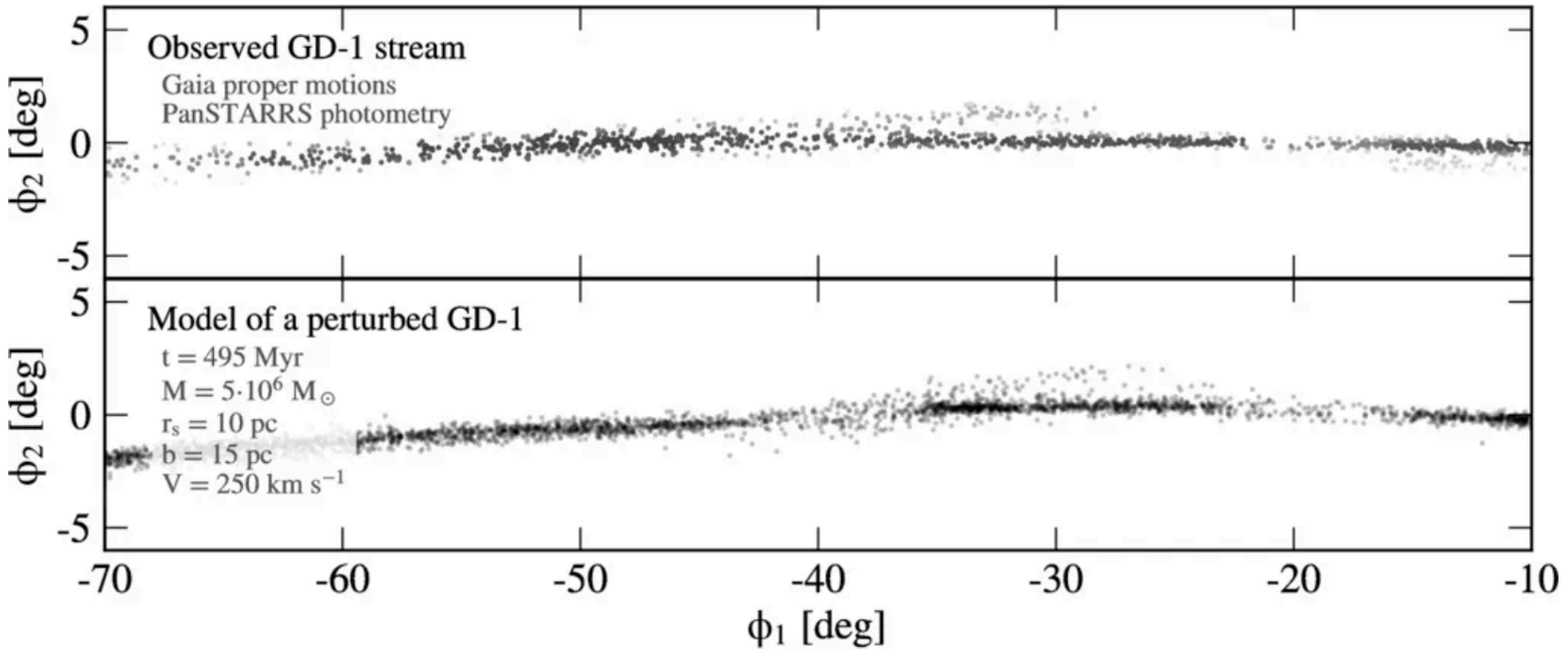


Weak gravitational lensing of galaxies can distinguish axion dark matter from feedback



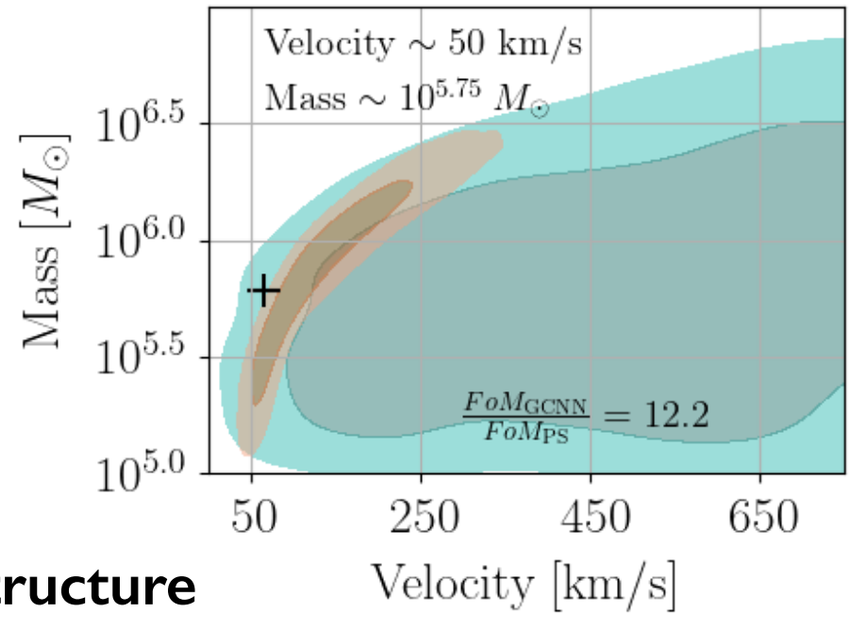
Milky Way satellite galaxies trace dark matter sub-halo mass function

Drlica-Wagner et al. (Snowmass, 2022); Preston, Rogers, et al. (MNRAS, 2025)

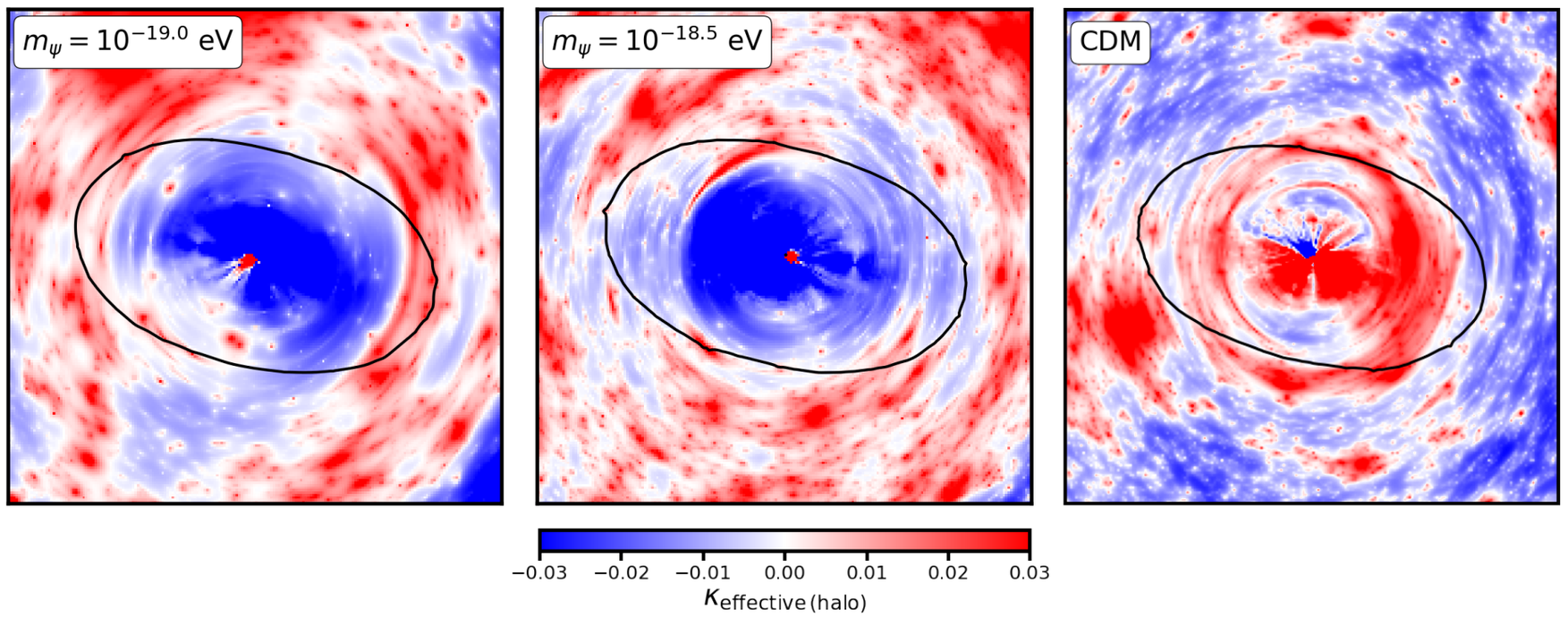


With AI data compression

Without AI data compression



Stellar streams gravitationally perturbed by dark matter sub-structure



Strong gravitational lenses sensitive to sub-structure in lensing halo

Ma, Rogers, et al. (ApJ, 2025); Laroche et al. (2022)

Summary

- **No evidence for new physics** beyond Lambda-CDM in any individual dataset

- **2.8σ CMB-BAO discrepancy** alleviated by two-parameter dark energy model

- **Rubin Observatory** will test dark energy/dark matter in new regime