Robust cosmology through combined probes

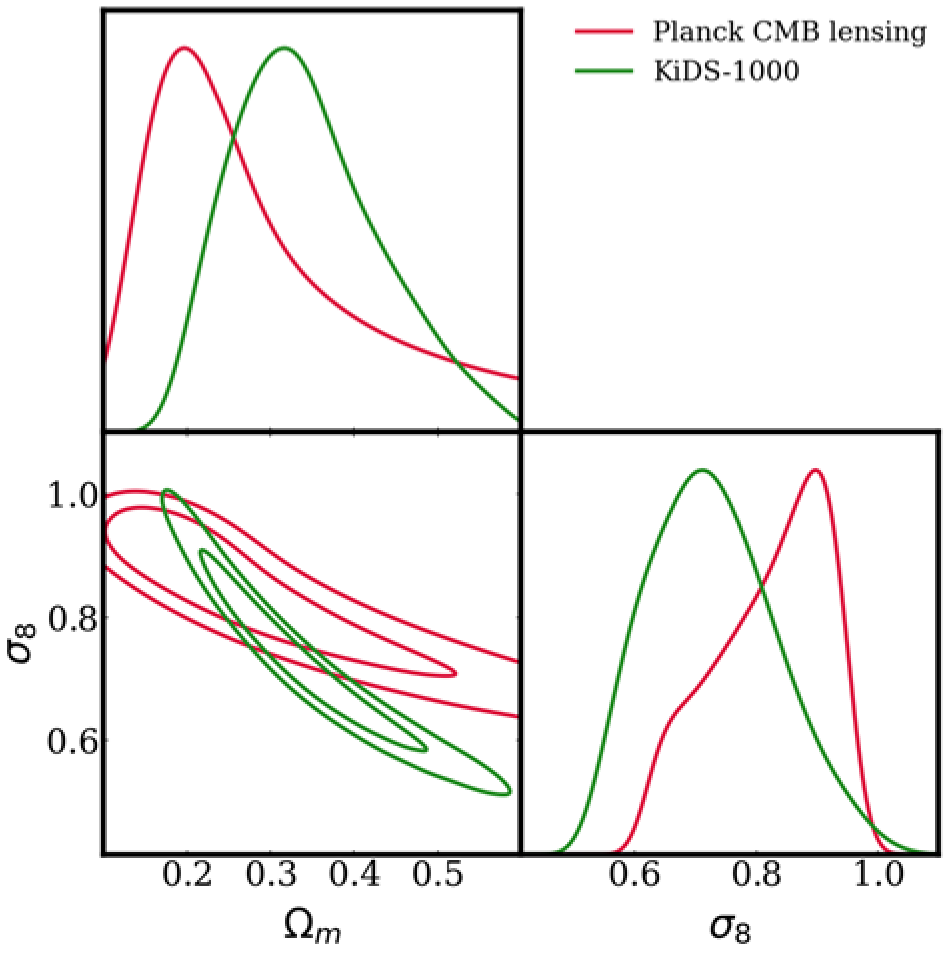
Alexander Reeves

With Andrina Nicola, Alexandre Refregier,
Simone Ferraro, Martin White

Based on 2309.03258, 2502.01772

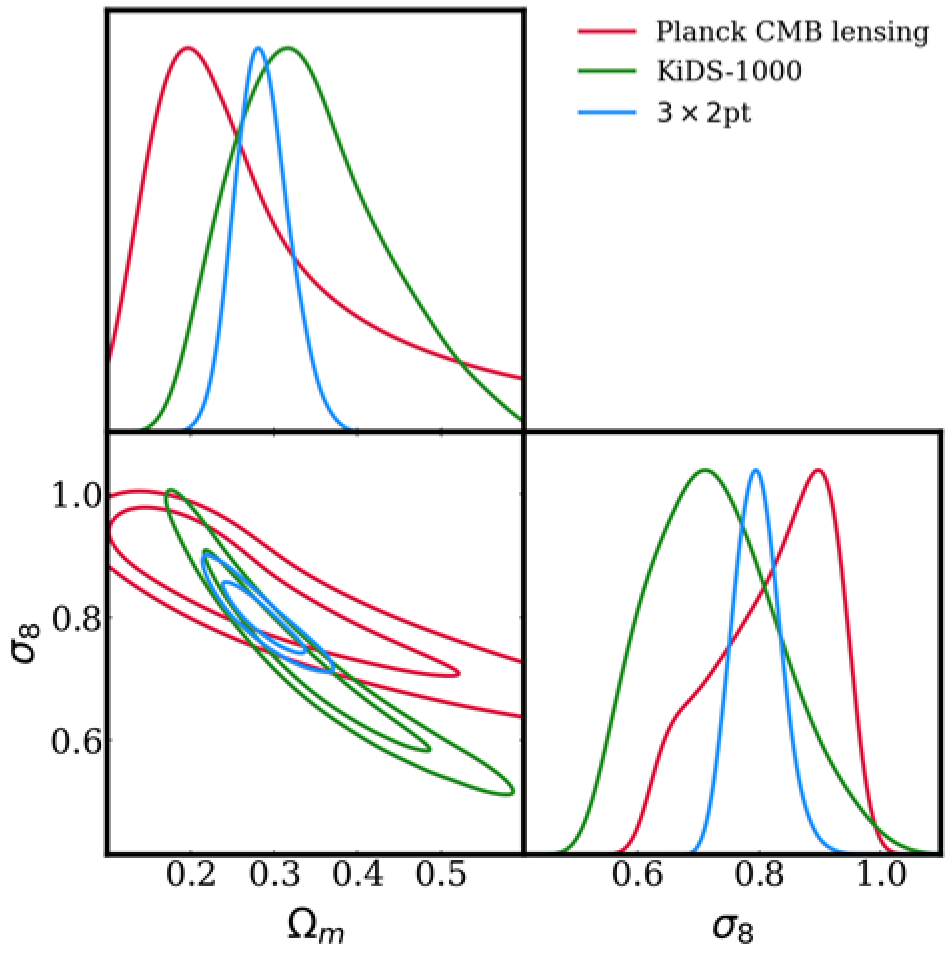
Combined probes: motivations

1. Combining data from independent experiments allows to identify and mitigate systematics
2. Test consistency between probes analysed in a consistent framework
3. Many different scales and redshifts: end-to-end test of cosmological models with strong constraints due to degeneracy breaking

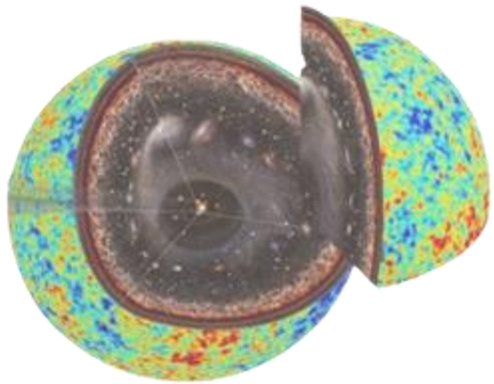


Combined probes: motivations

1. Combining data from independent experiments allows to identify and mitigate systematics
2. Test consistency between probes analysed in a consistent framework
3. Many different scales and redshifts: end-to-end test of cosmological models with strong constraints due to degeneracy breaking



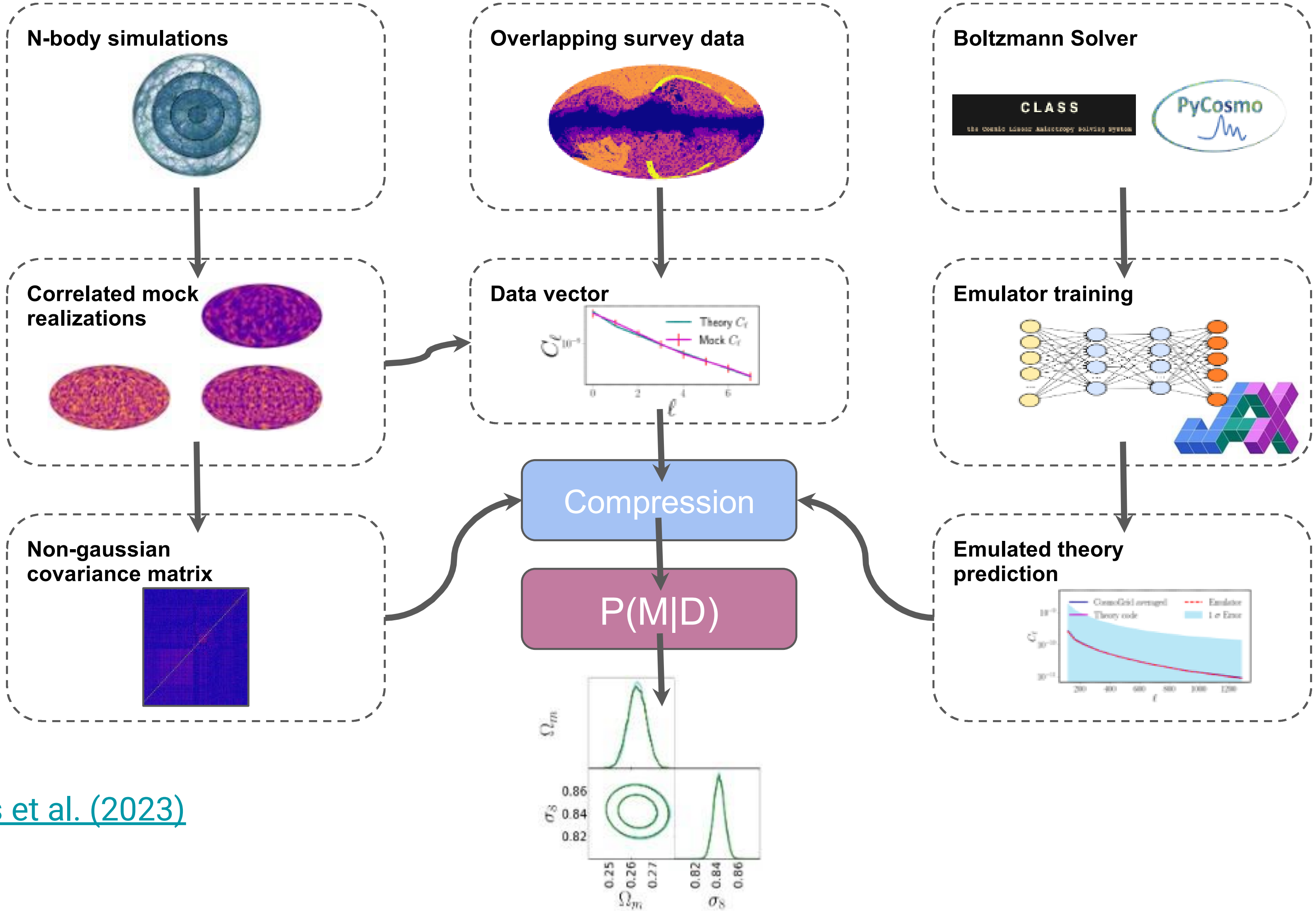
Combined probes: our approach



- Build a consistent pipeline integrating several probes at the 2pt level
- Restrict to scales (and summary statistics!) where simple modelling can be applied
- Carefully quantify tensions between data before combining
- Use emulators for theory predictions and implement all likelihoods in JAX for JIT + GPU acceleration when sampling

The combined probes pipeline

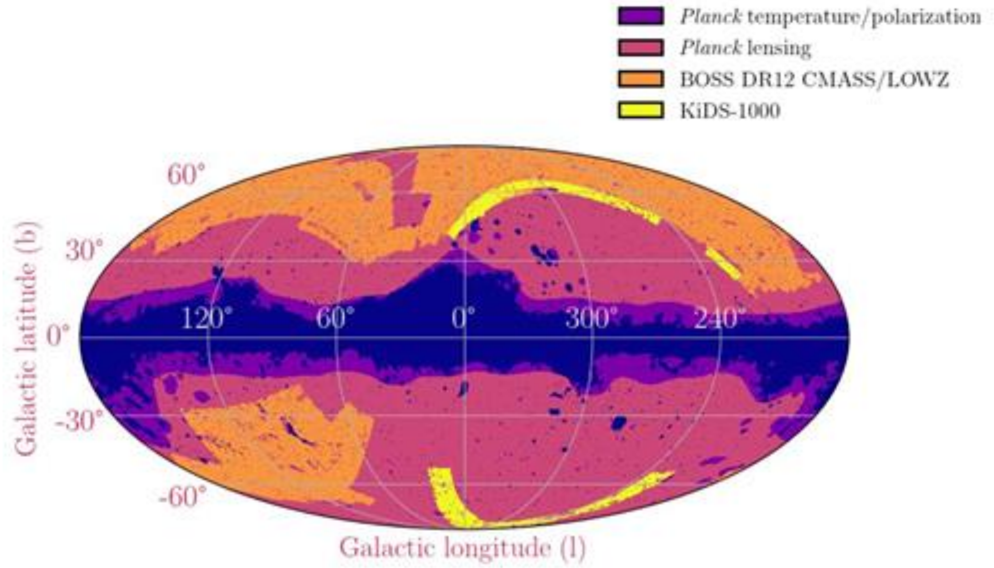
UFALCON2 code [publicly available](#) and can be interfaced with the cosmogrid

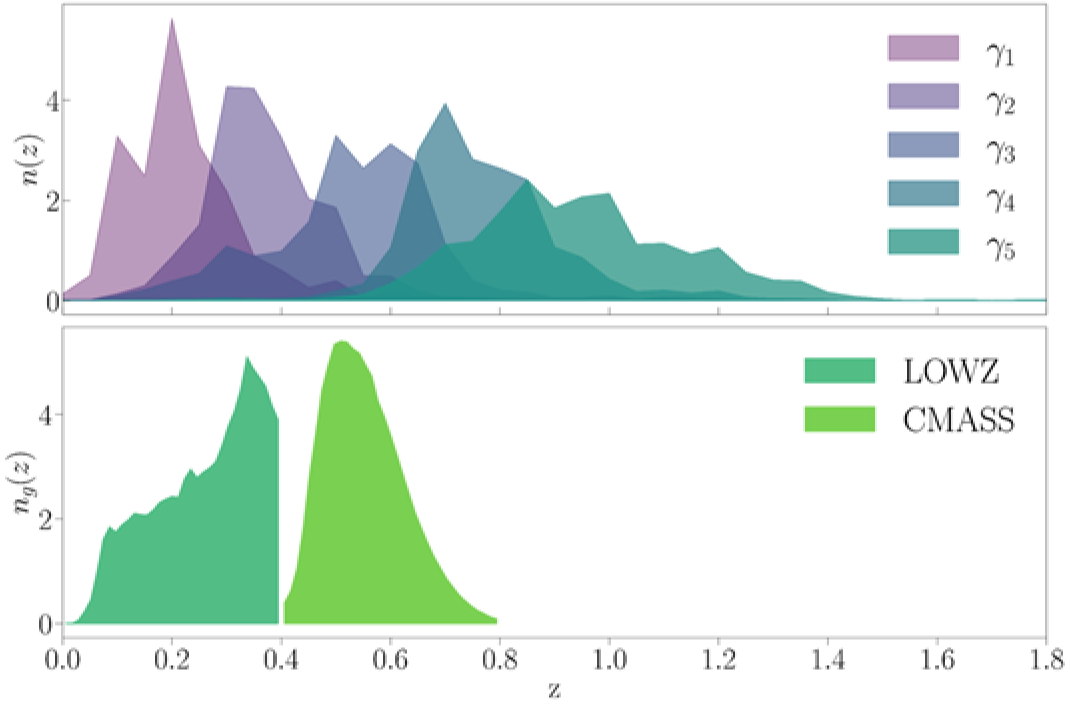


[Reeves et al. (2023)](#)

Apply framework to data

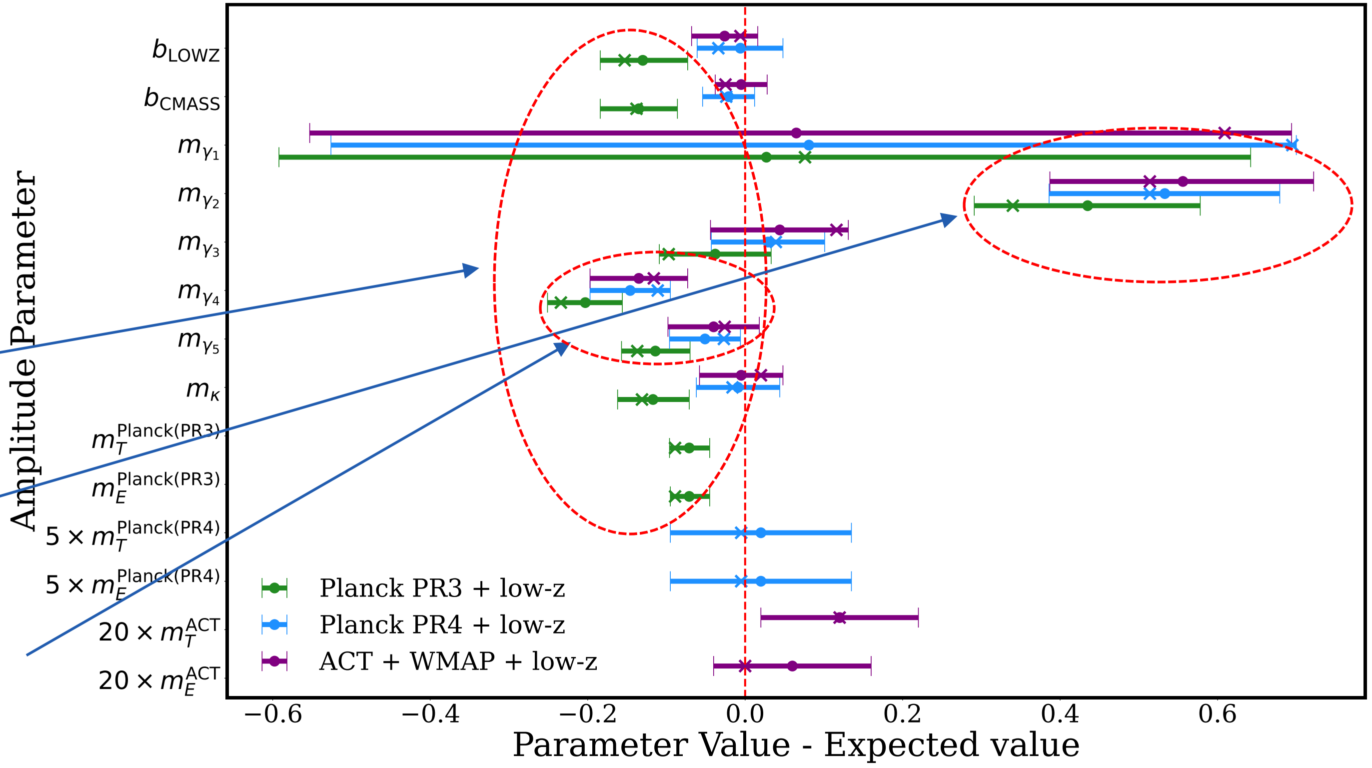
- CMB: Planck PR3, Planck PR4 (Hillipop), ACT DR4+WMAP
- BAO: DESI Y1
- Low-z: CMB lensing + ISW (PR3) X KiDS-1000 X BOSS DR12 (9x2pt)
- Tomographic - measure 43 separate 2-point functions for low-z data vector





Internal consistency

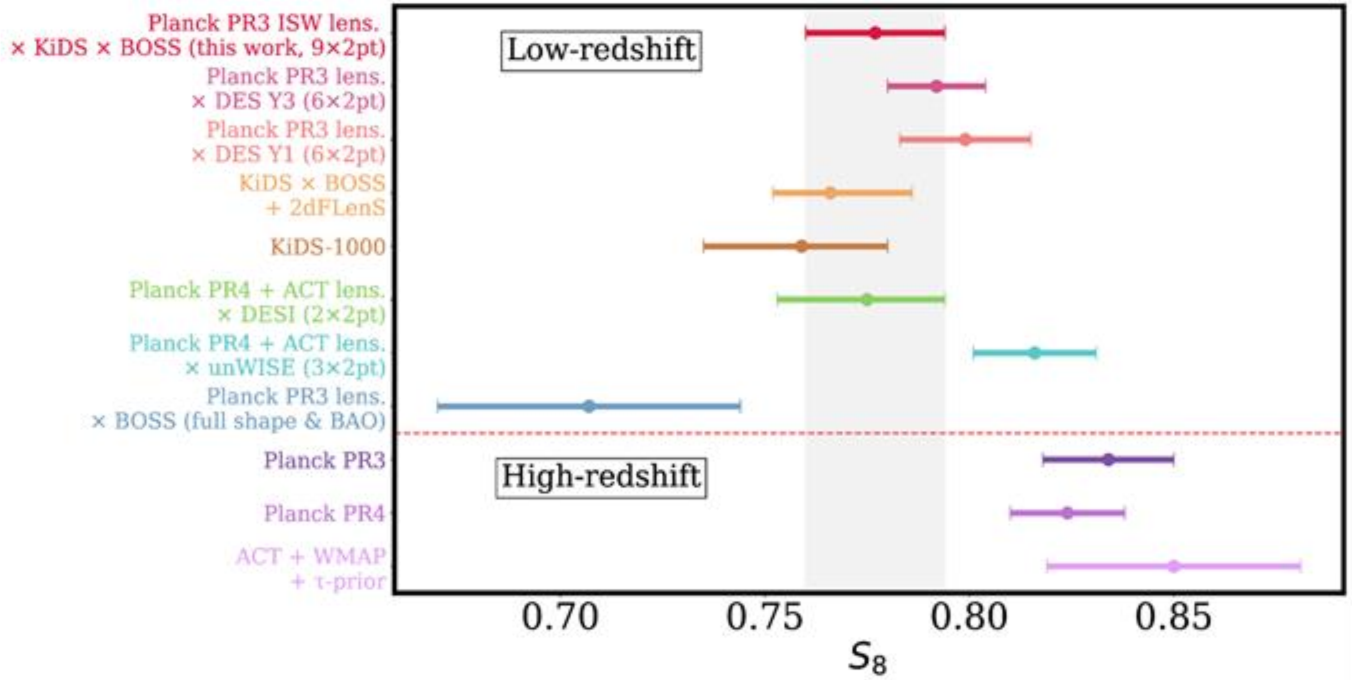
- Amplitude parameter let free for each probe
- Three deviations from expectations:
  - Planck PR3: A-lens systematic detection
  - KiDS z-bin 2: redshift systematic detection
  - KiDS z-bins 4/5: S8 tension



S8 measurement (ΛCDM)

$$S8 = \sigma_8 \sqrt{\Omega_m/0.3}$$

- Novel 9x2pt measurement from this data combination. Consistent with S8 found in other contemporary analyses
- Tension with CMB likelihoods - “S8-tension” which is 2.2σ in for our baseline (Planck PR4)
- In full parameter space reduced to 1.7σ and further still in extended models, and adding BAO (see later)

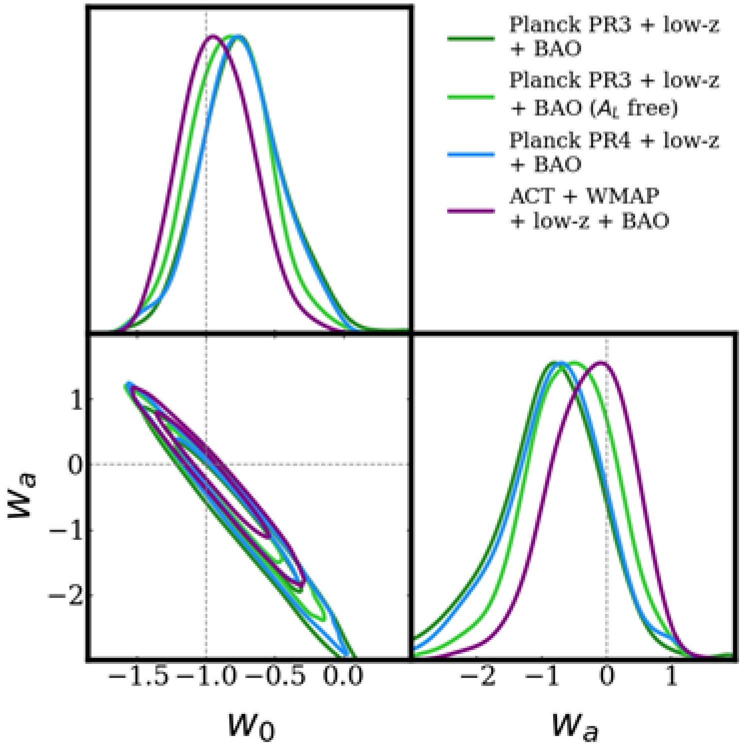


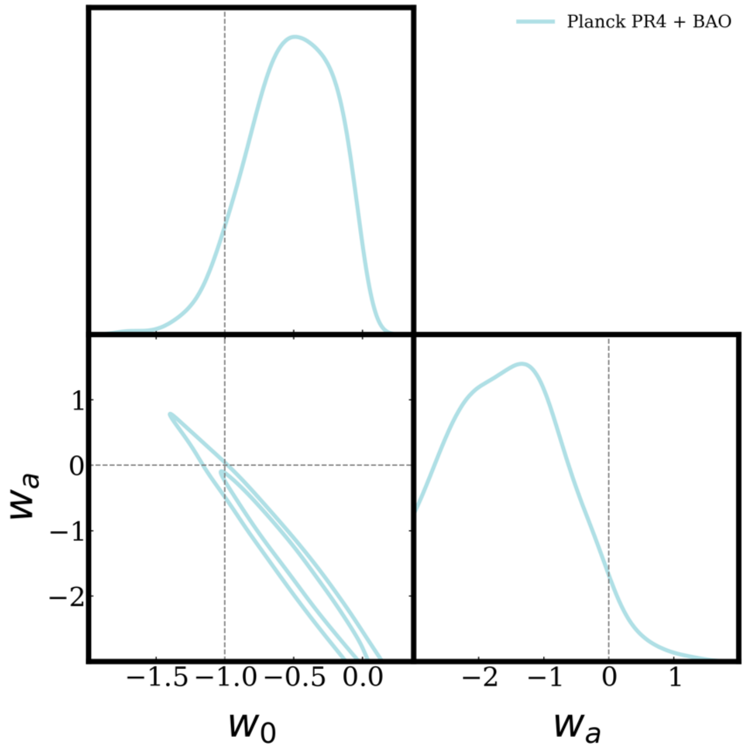
S8 measurements from (in order vertically):
DES collaboration, 2022, Xu et. al 2023, Heymans et. al 2020, Asgari et.al, 2020, Sailer et. al 2024, Farren et. al 2024, Chen et. al 2024.

Reeves et al. (2025)

Dynamical dark energy: multiprobe constraints

- Find models far from a CC worsen the S8 tension between CMB and low-z data (especially KiDS-1000)
- This means that including KiDS-1000 in the analysis pushes constraints towards a CC
- Caveat: based on DESI Y1 BAO and KiDS-1000 (both updated now!)

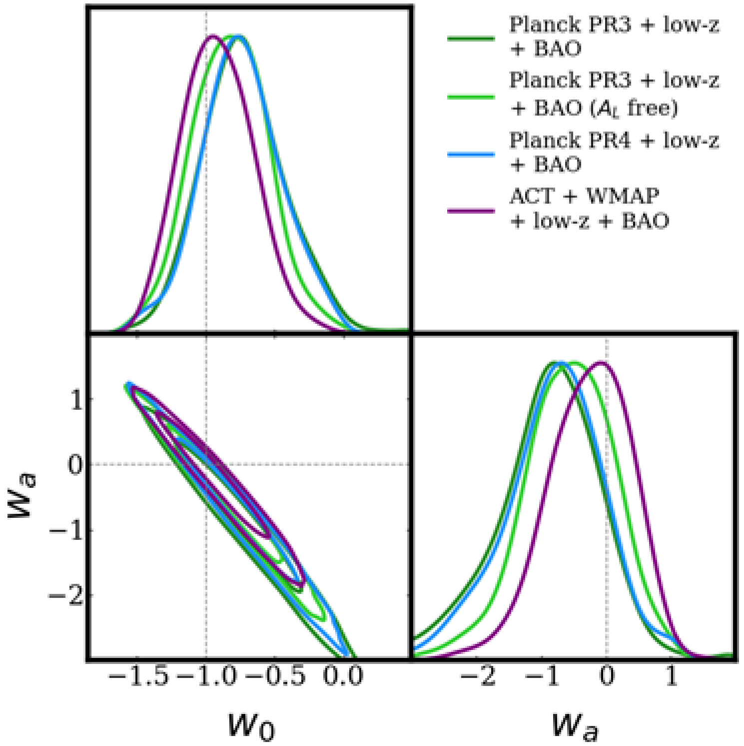


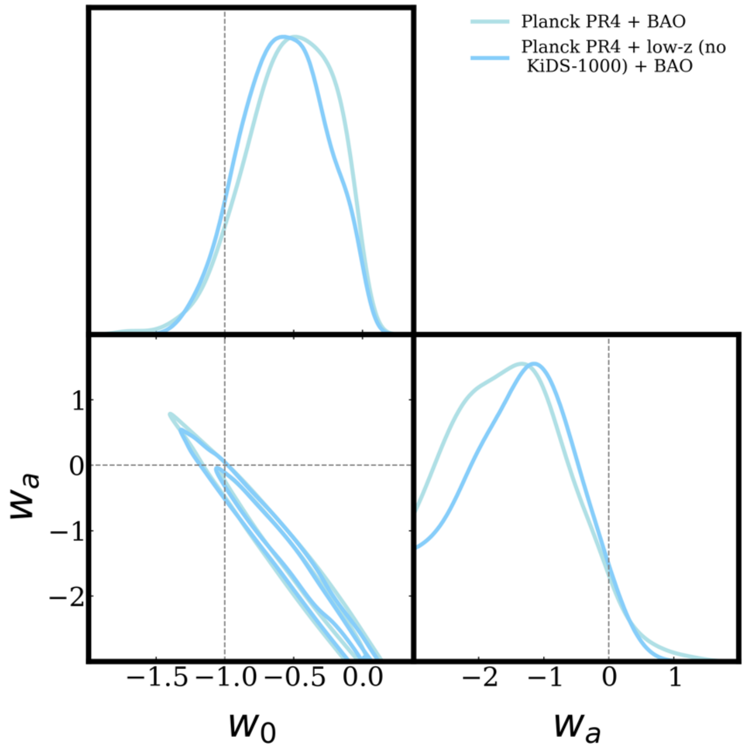


Reeves et al. (2025)

Dynamical dark energy: multiprobe constraints

- Find models far from a CC worsen the S8 tension between CMB and low-z data (especially KiDS-1000)
- This means that including KiDS-1000 in the analysis pushes constraints towards a CC
- Caveat: based on DESI Y1 BAO and KiDS-1000 (both updated now!)

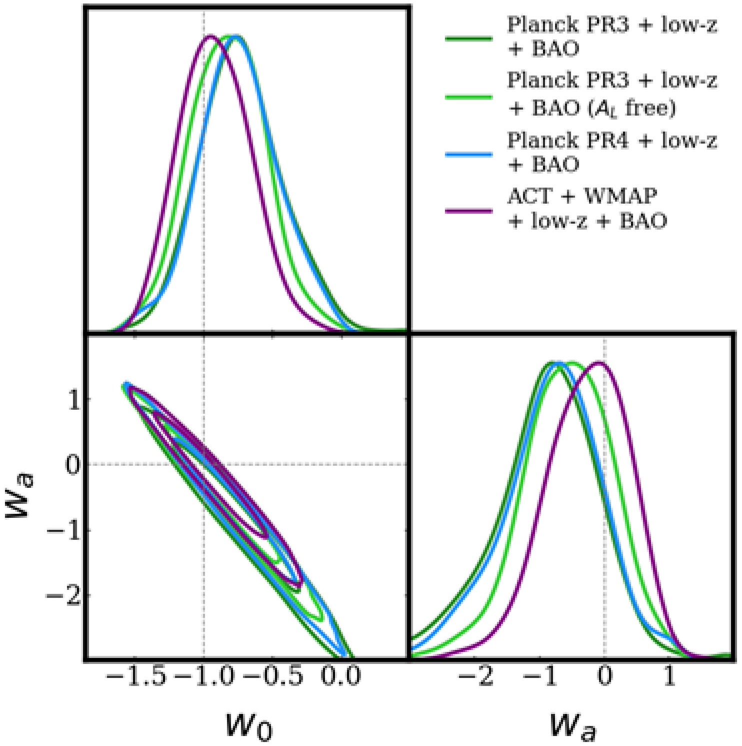


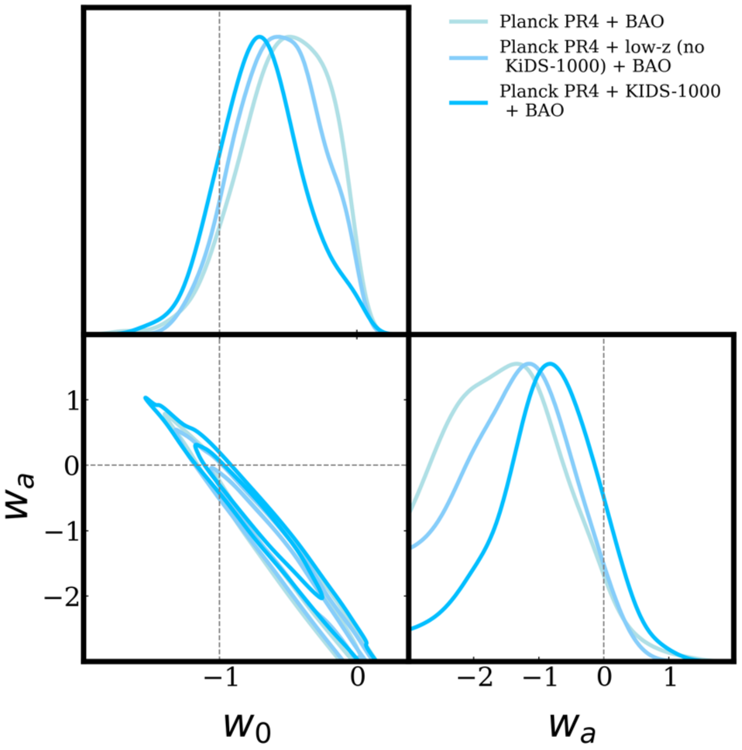


[Reeves et al. (2025)](#)

Dynamical dark energy: multiprobe constraints

- Find models far from a CC worsen the S8 tension between CMB and low-z data (especially KiDS-1000)
- This means that including KiDS-1000 in the analysis pushes constraints towards a CC
- Caveat: based on DESI Y1 BAO and KiDS-1000 (both updated now!)

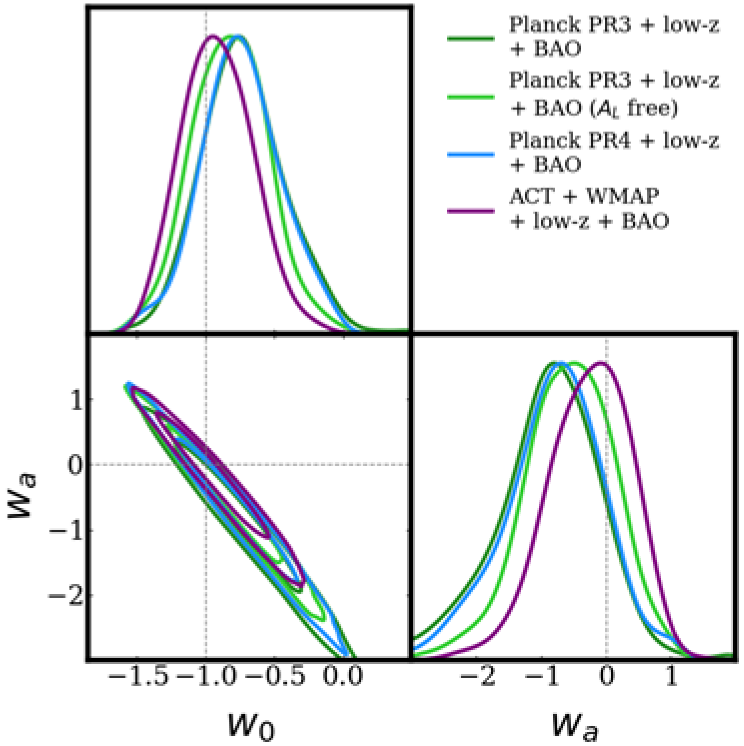


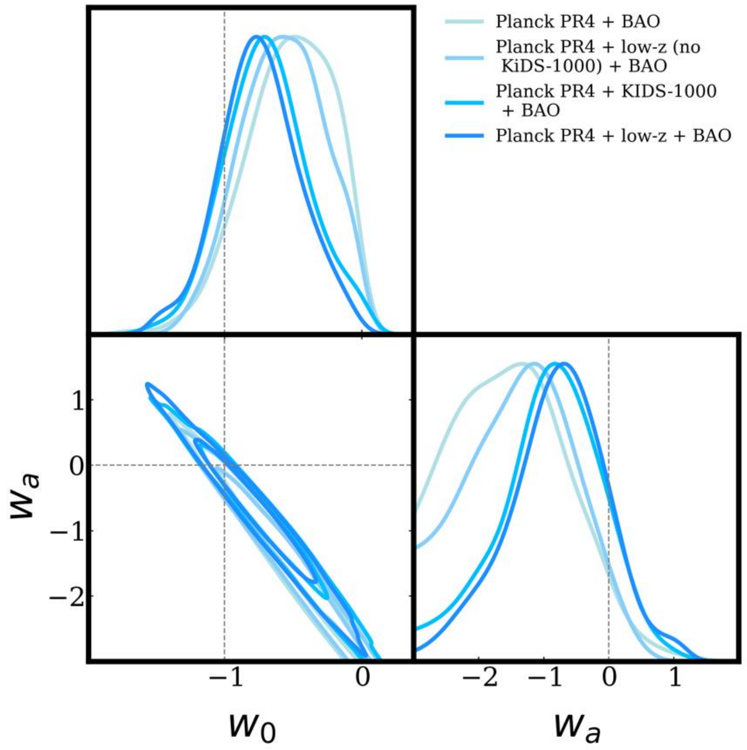


[Reeves et al. (2025)]

Dynamical dark energy: multiprobe constraints

- Find models far from a CC worsen the S8 tension between CMB and low-z data (especially KiDS-1000)
- This means that including KiDS-1000 in the analysis pushes constraints towards a CC
- Caveat: based on DESI Y1 BAO and KiDS-1000 (both updated now!)

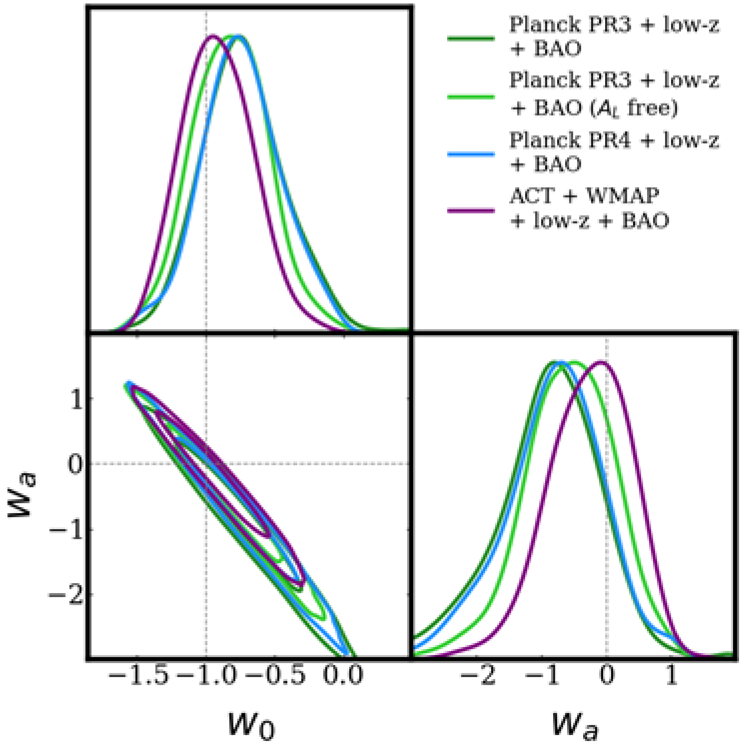


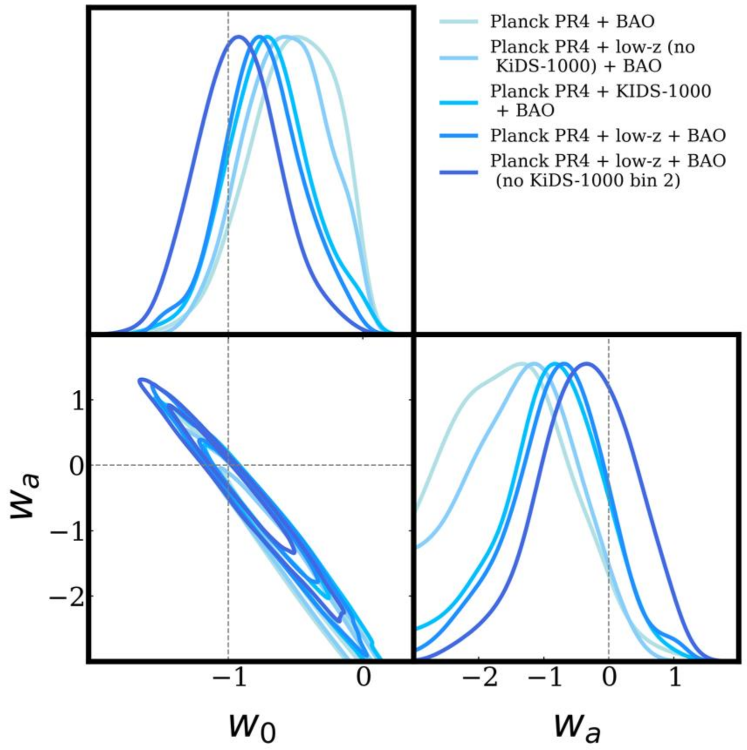


Reeves et al. (2025)

Dynamical dark energy: multiprobe constraints

- Find models far from a CC worsen the S8 tension between CMB and low-z data (especially KiDS-1000)
- This means that including KiDS-1000 in the analysis pushes constraints towards a CC
- Caveat: based on DESI Y1 BAO and KiDS-1000 (both updated now!)





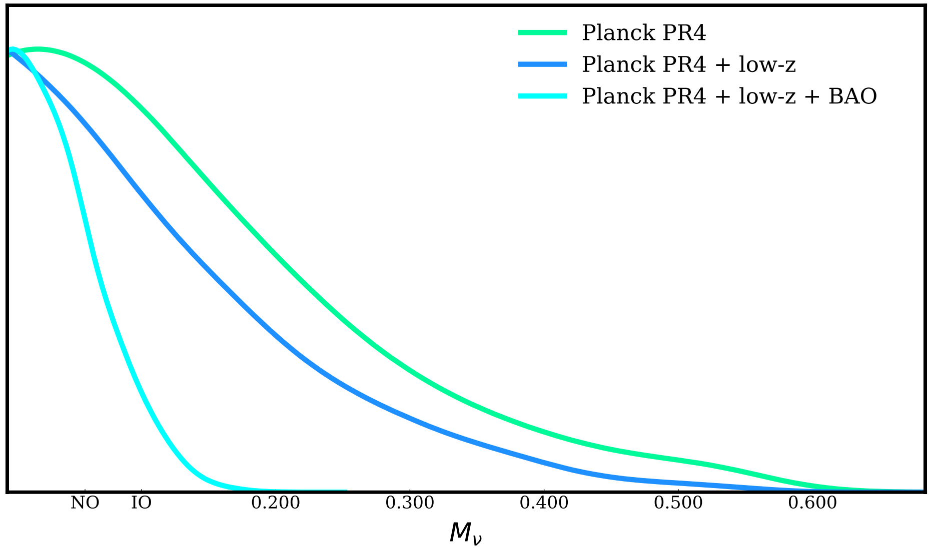
[Reeves et al. (2025)](#)

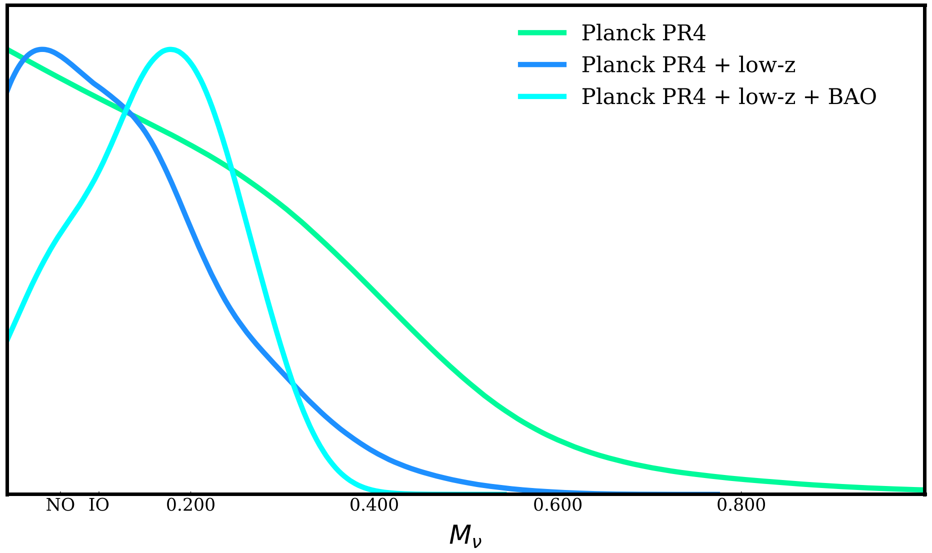
Neutrino masses

- Fiducial neutrino mass measurement from combination:

$$M_\nu < 0.12\text{eV}$$

- Explored effect of “A-lens” parameter finding the combined probes approach makes upper limits robust to this systematic
- Upper limit loosened when considering DDE background

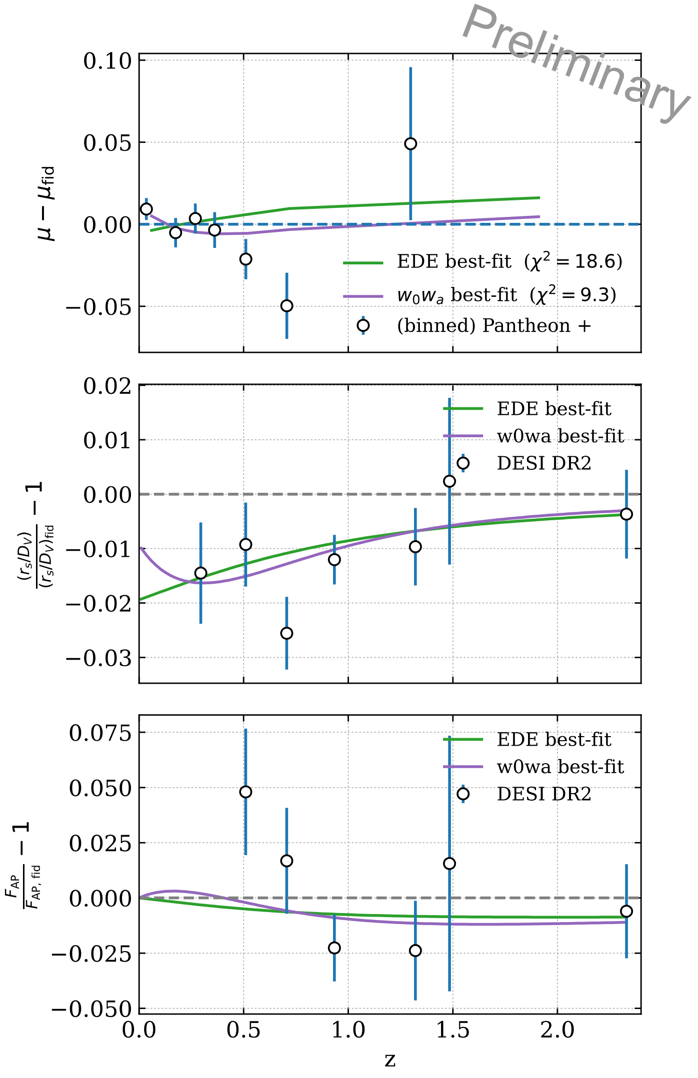




Reeves et al. (2025)

Outlook and conclusions

- Multiprobe analyses are powerful for:
  a. Identifying and mitigating systematics that do not correlate between datasets
  b. Exploring and understanding tensions between datasets
  c. Providing strong constraints on cosmological parameters via degeneracy breaking
- Including KiDS-1000 data in a joint analysis pushes DDE constraints towards a CC
- DDE models can loosen neutrino mass bounds, relieving tension with neutrino oscillation data
- Several recent data releases- ACT DR6, DESI DR2 BAO, KiDS legacy. Currently working analysis with updated BAO, LSS and now SNe data, exploring early and late extensions – say tuned!

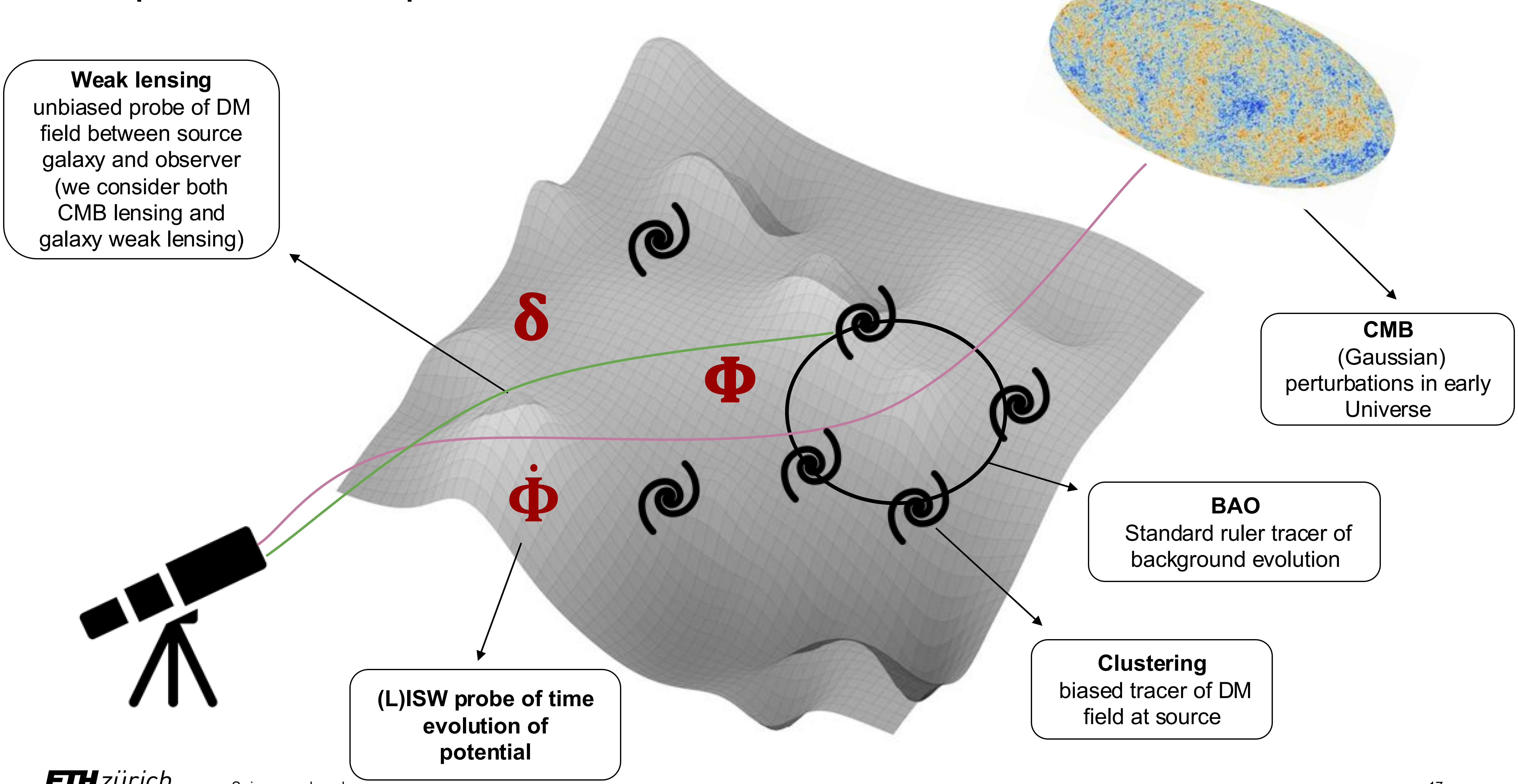


Plot inspired by Chaussidon et al. 2025

BACKUP

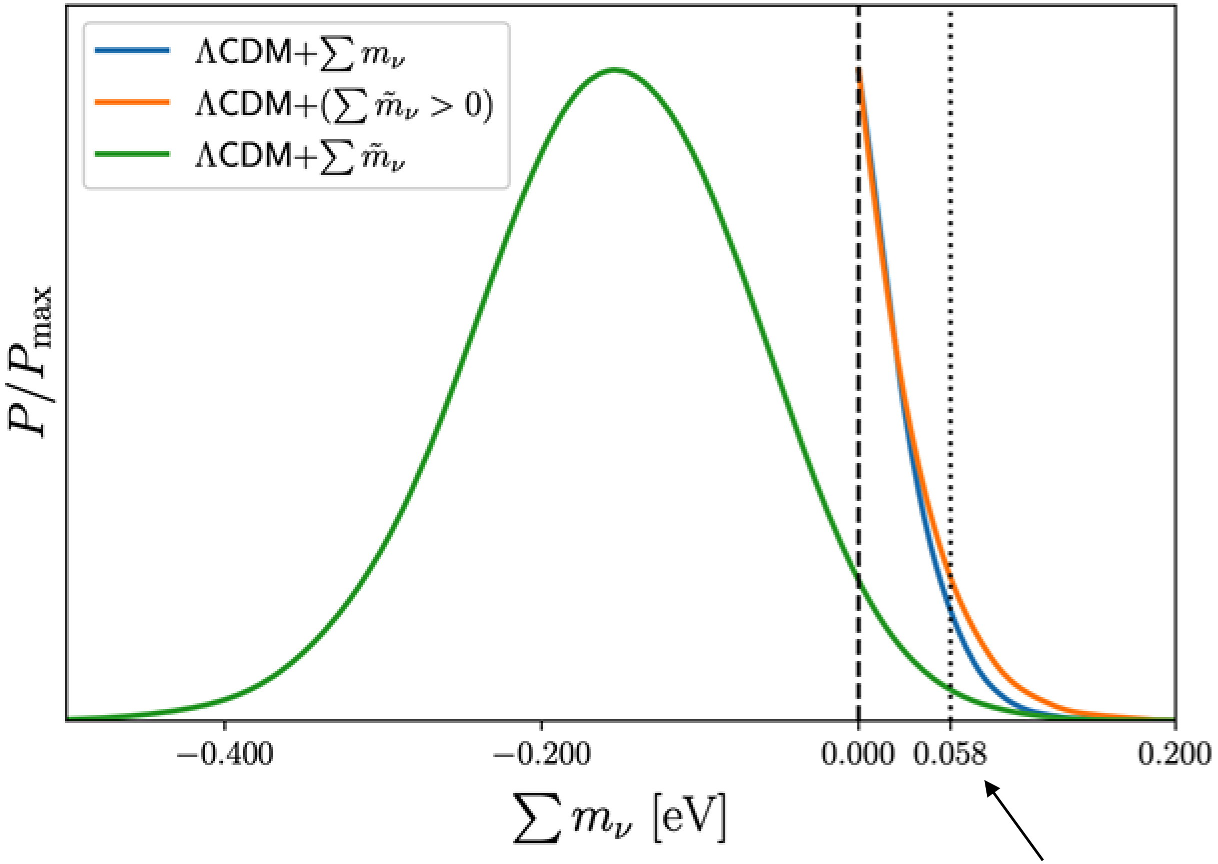
Multiprobe landscape

Image credits:
Planck collaboration



Preference for negative neutrino mass?

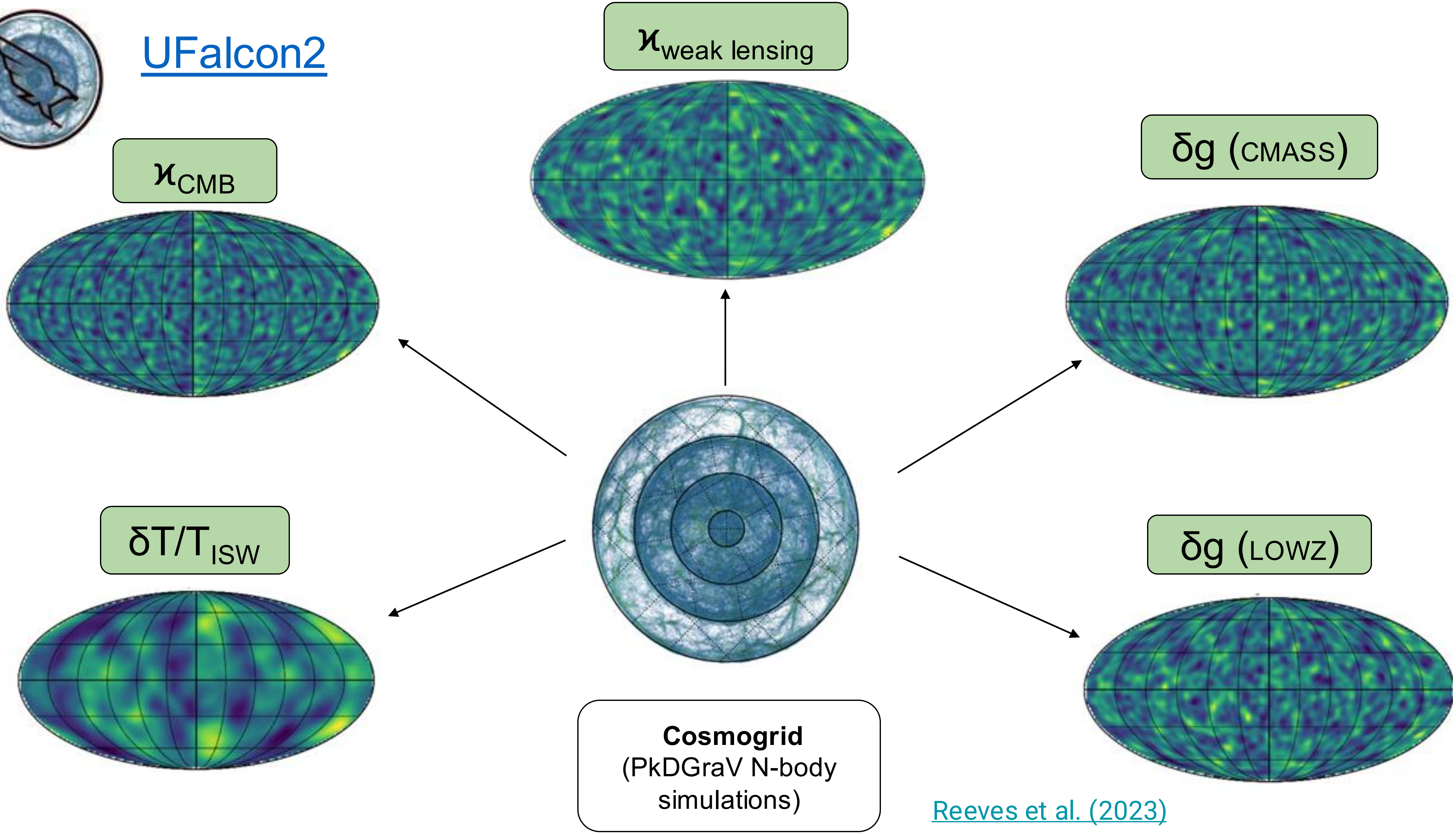
- We know from neutrino oscillations that we must have the total neutrino mass greater than 0.058eV. Find a 2-3σ tension with this data
- How do we interpret this?
  - An issue with the assumed cosmological model?
  - A hint of systematics in our data?
  - Expected statistical fluctuation within the uncertainties of current data?



Craig et al. 2024

minimum neutrino mass in NO

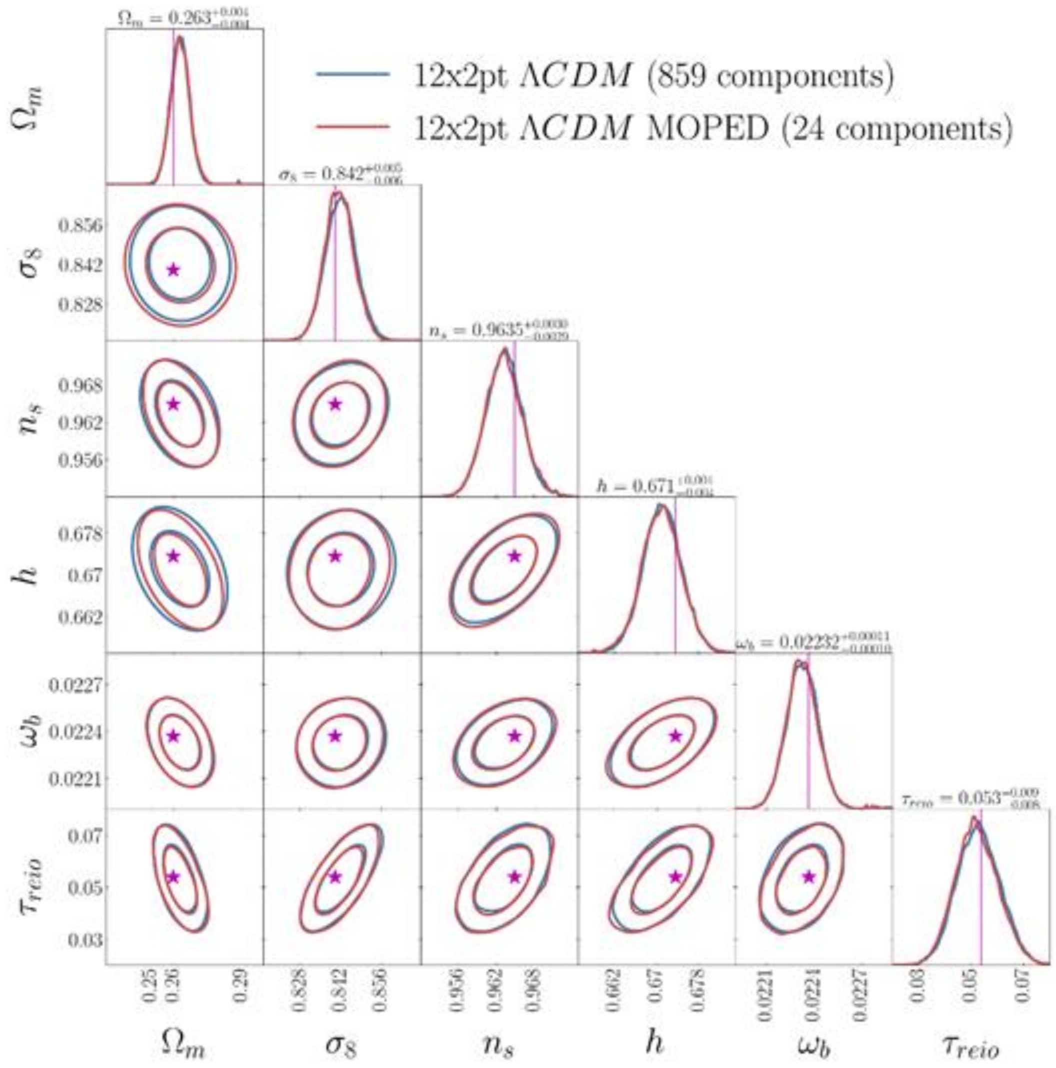
UFalcon2



Reeves et al. (2023)

Validate pipeline with mock data

- Mock analysis of CMB, LSS (galaxy clustering, weak lensing and CMB lensing/ISW)
- Validate covariance matrix and inference side of pipeline
- Checked the pipeline reproduces literature results with real data for individual likelihoods

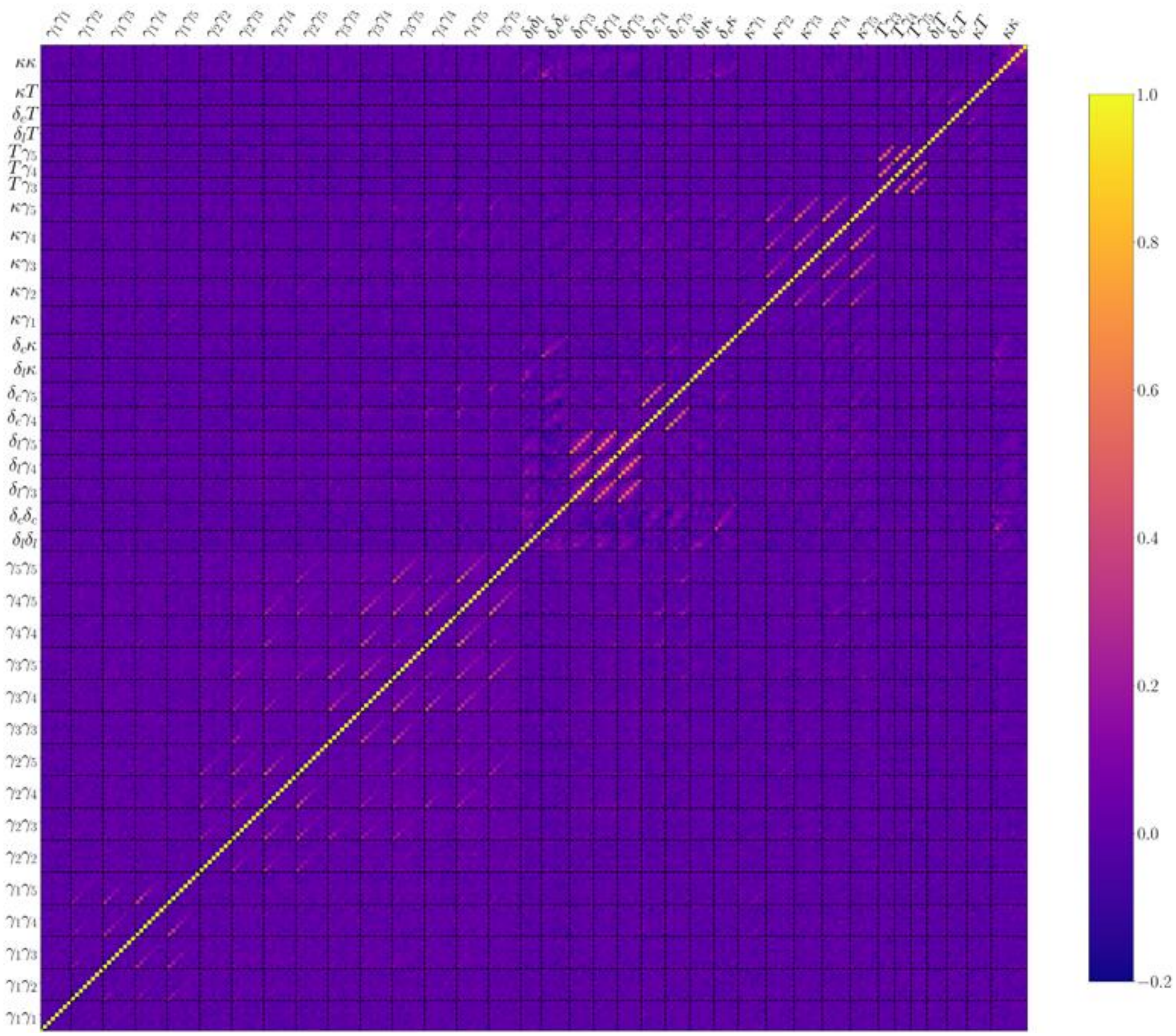


Reeves et al. (2023)

The multi-probe covariance matrix

- Survey noise modelled on the map level
- Using 2000 random **cosmogrid** fiducial simulations
- Checked convergence
- CMB primary and BAO treated separately

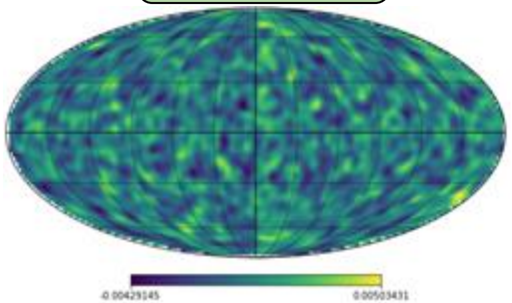
Reeves et al. (2023)

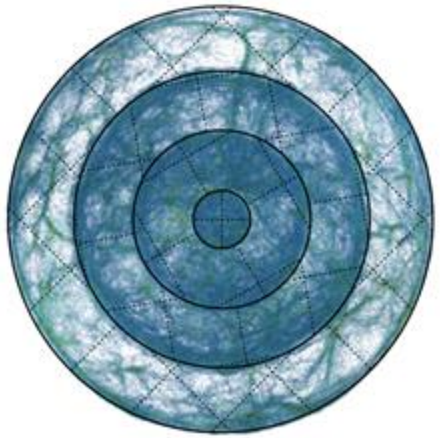


UFalcon2

- Use Born approximation weak lensing kernel
- Approximate integral over matter density as sum over lighcone shells
- Input source n(z) distribution

$\varkappa_{\text{weak lensing}}$





Cosmogrid
(PkDGraV N-body simulations)

$$\kappa(\theta_{\rm pix}) \approx \frac{3}{2}\Omega_m \sum_b W_b \left(\frac{H_0}{c}\right)^3 \frac{N_{\rm pix}}{4\pi} \frac{V_{\rm sim}}{N_{\rm p}} \frac{n_p(\theta_{\rm pix}, \Delta\chi_b)}{\mathcal{D}^2(z_b)}$$

Sum over lightcone shells

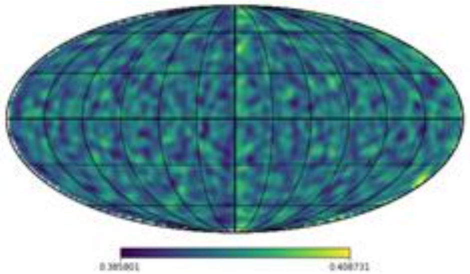
Number of DM simulation particles at angle theta in given shell

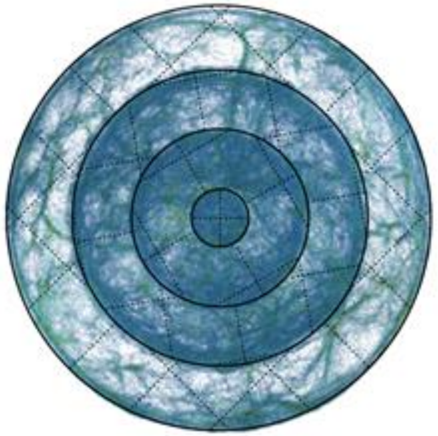
$$W_b^{n(z)} = \left(\int_{\Delta z_b} \frac{dz}{E(z)} \int_z^{z_s} dz' n(z') \frac{\mathcal{D}(z)\mathcal{D}(z,z')}{\mathcal{D}(z')} \frac{1}{a(z)}\right) / \left(\int_{\Delta z_b} \frac{dz}{E(z)} \int_{z_0}^{z_s} dz' n(z')\right)$$

Source redshift distribution

UFalcon2

$\varkappa_{\text{CMB}}$





Cosmogrid
(PkDGraV N-body simulations)

- Identical to weak lensing shear case but with Dirac-function source at z_cmb

$$\kappa(\theta_{\text{pix}}) \approx \frac{3}{2}\Omega_m \sum_b W_b \left(\frac{H_0}{c}\right)^3 \frac{N_{\text{pix}}}{4\pi} \frac{V_{\text{sim}}}{N_{\text{p}}} \frac{n_p(\theta_{\text{pix}}, \Delta\chi_b)}{\mathcal{D}^2(z_b)}$$

$$W_b^{z_s} = \left(\int_{\Delta z_b} \frac{\mathrm{d}z}{E(z)} \frac{\mathcal{D}(z)\mathcal{D}(z,z_s)}{\mathcal{D}(z_s)} \frac{1}{a(z)}\right) / \left(\int_{\Delta z_b} \frac{\mathrm{d}z}{E(z)}\right)$$

UFalcon2

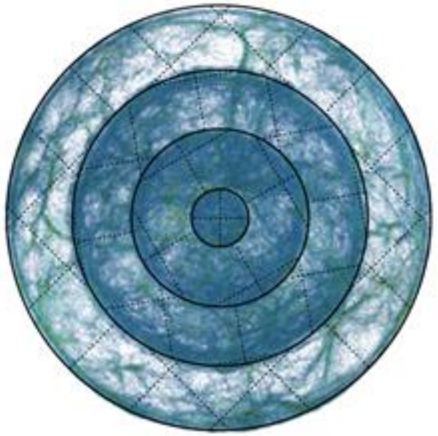
- Linear bias model currently implemented
- Ongoing work to introduce EFTofLSS forward model

$$\delta_g(\theta_{\rm pix}) \approx \sum_b W_b^{\delta_g} \left(\frac{H_0}{c}\right)^2 \frac{N_{\rm pix}}{4\pi} \frac{V_{\rm sim}}{N_p} \frac{n_p(\theta_{\rm pix}, \Delta\chi_b)}{\mathcal{D}^2(z_b)}$$

$$W_b^{\delta_g} = \left(\int_{\Delta z_b} \frac{{\rm d}z}{E(z)} H(z) b(z) n(z)\right) / \left(\int_{\Delta z_b} \frac{{\rm d}z}{E(z)}\right)$$

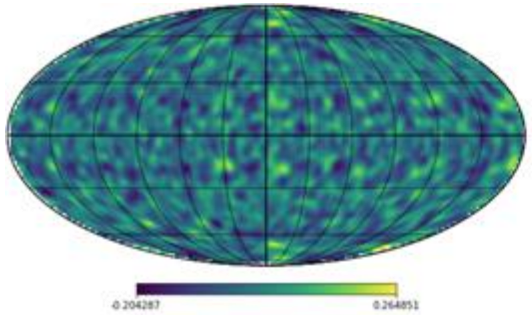
Linear bias model

Source redshift distribution

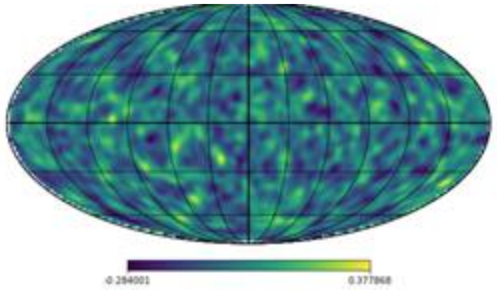


Cosmogrid
(PkDGraV N-body simulations)

δg CMASS



δg LOWZ



UFalcon2

- New routine utilising the Spherical Bessel transform
- Significant improvement over previous implementation requiring interpolation over snapshot to estimate potential

$$\delta^i_{\ell m} = \int_0^{\pi} \int_0^{2\pi} \frac{\delta^i(\theta, \phi)}{D(z_{\mathrm{eff}})} Y^*_{\ell m}(\theta, \phi) \sin(\theta)\, d\phi\, d\theta.$$

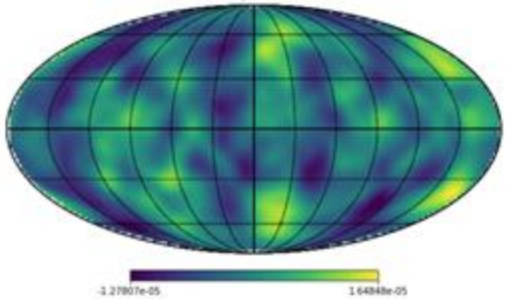
SBT transform of DM field

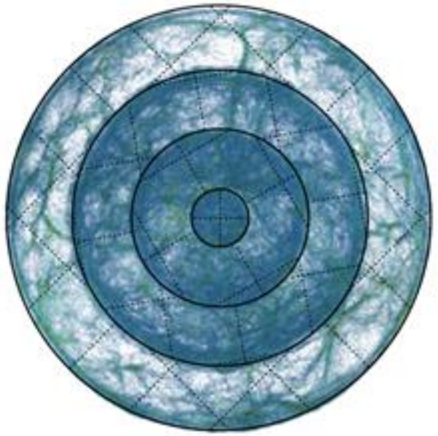
$$\delta_{\ell mn} = \sum_i \delta^i_{\ell m} \int_{r^i_{\mathrm{min}}}^{r^i_{\mathrm{max}}} R_{\ell n}(r)\, r^2\, dr.$$

$$\Delta T^{ISW}_{\ell m} = \frac{3H_0^2\Omega_{m,0}}{c^3} \sum_{n=1}^{n_{max}} \frac{\delta_{\ell mn}}{k^2_{\ell n}} \int_0^{r(z_{max})} D(a(r))H(a(r))[1 - f(a(r))]R_{\ell n}(r)dr$$

Linear growth factor (from Astropy instance)

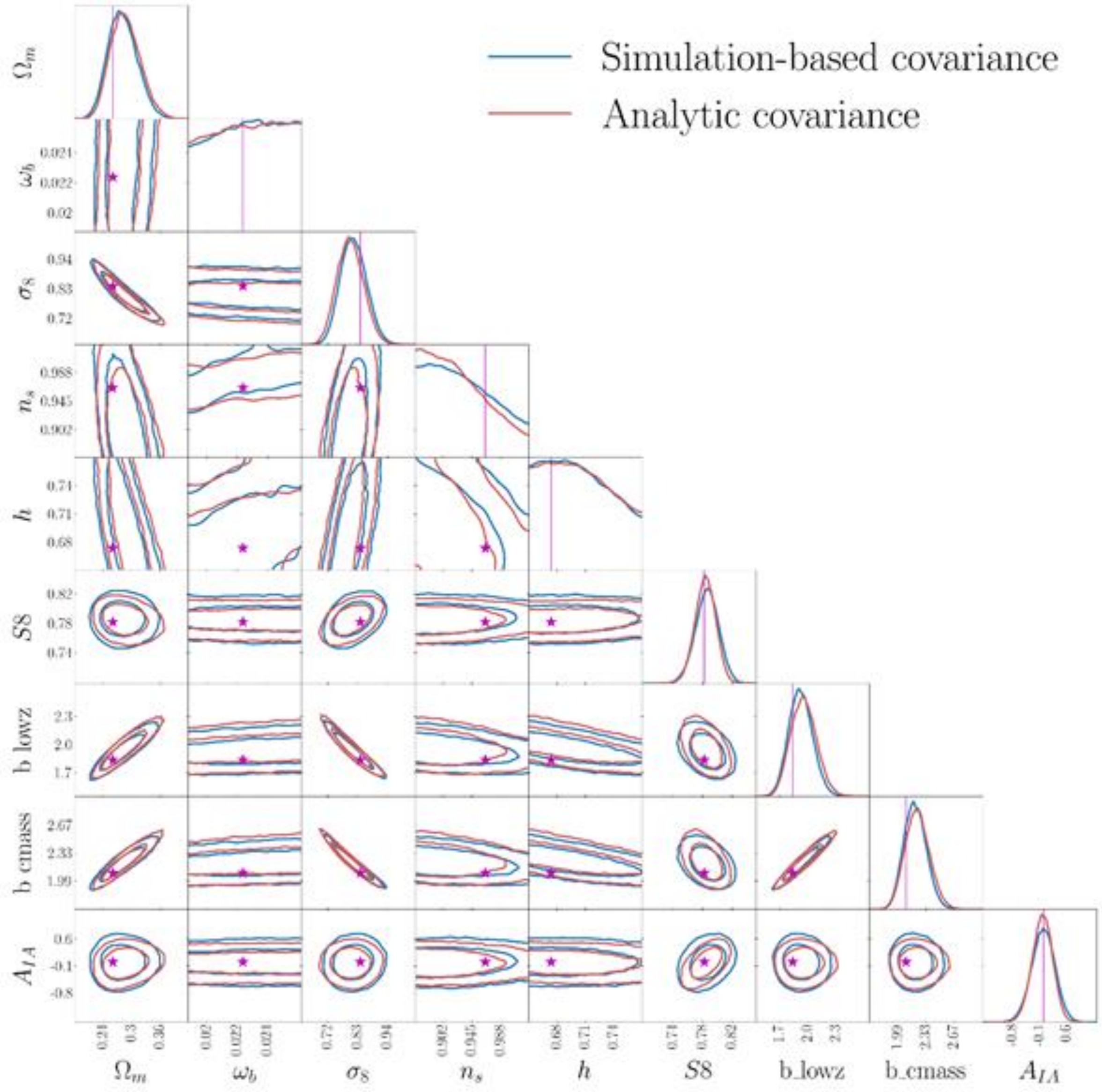
$\delta T/T_{ISW}$





Cosmogrid
(PkDGraV N-body simulations)

Covariance matrix validation



A cosmologists neutrino mass review

- From oscillation experiments (e.g. Super-Kamiokande, SNO, KamLAND) there are two possible mass orderings: normal ordering (NO) and Inverted ordering (IO)
- Lab based measurements: KATRIN upper limit of electron anti-neutrino mass of 0.8eV (doi: 10.1038/s41567-021-01463-1)
- Cosmology sensitive to sum of neutrino mass eigenstates* (   )- current precision at least 10X stronger** than lab based measurements

M_ν

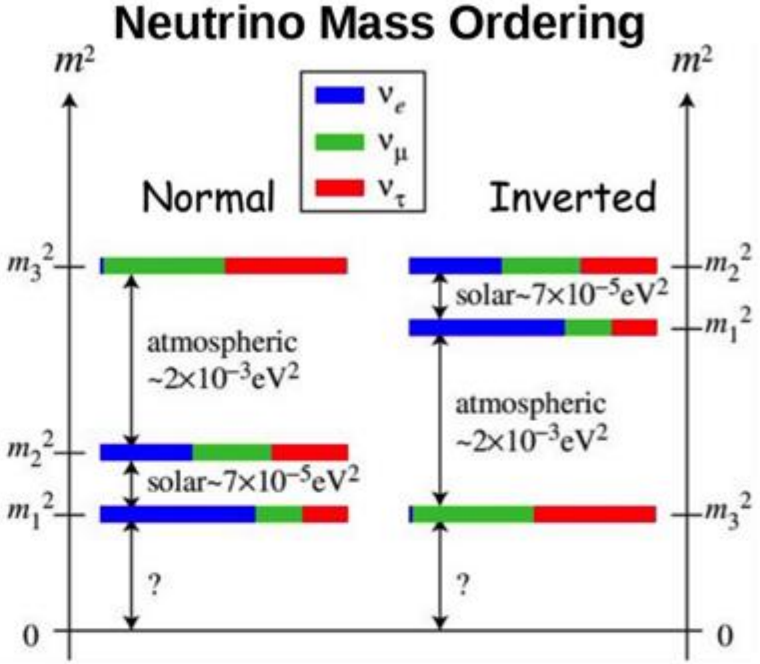


Image credit: Pablo Fernandez

$$M_\nu < 0.072\text{eV}$$

Planck + DESI Y1 BAO in $\nu\Lambda$CDM

DESI collaboration, 2024

* Based on sensitivity of current data
** Model dependent

Internal consistency: measuring tensions

Model	Experiment	$\sigma S8$ (Gaussian)	n_σ (All Params)
ΛCDM	*Planck* PR3	2.45	1.964 ± 0.006
	Planck PR4	2.15	1.703 ± 0.005
	ACT (DR4) + WMAP	2.04	1.595 ± 0.004
	Planck PR3 + DESI Y1	1.76	1.271 ± 0.004
	Planck PR4 + DESI Y1	1.68	1.301 ± 0.004
	ACT (DR4) + WMAP + DESI Y1	1.60	1.252 ± 0.004
$\nu\Lambda$CDM	*Planck* PR3	2.54	1.655 ± 0.005
	Planck PR4	2.12	1.469 ± 0.004
	ACT (DR4) + WMAP	1.62	1.699 ± 0.005
	Planck PR3 + DESI Y1	1.66	1.320 ± 0.004
	Planck PR4 + DESI Y1	1.62	1.263 ± 0.004
	ACT (DR4) + WMAP + DESI Y1	1.41	1.172 ± 0.005
w_0w_aCDM	*Planck* PR3	0.00	1.042 ± 0.005
	Planck PR4	0.28	0.725 ± 0.004
	ACT (DR4) + WMAP	0.46	0.970 ± 0.005
	Planck PR3 + DESI Y1	0.80	1.734 ± 0.006
	Planck PR4 + DESI Y1	1.05	1.282 ± 0.004
	ACT (DR4) + WMAP + DESI Y1	0.87	0.923 ± 0.001

Parameter differences full parameter space tension

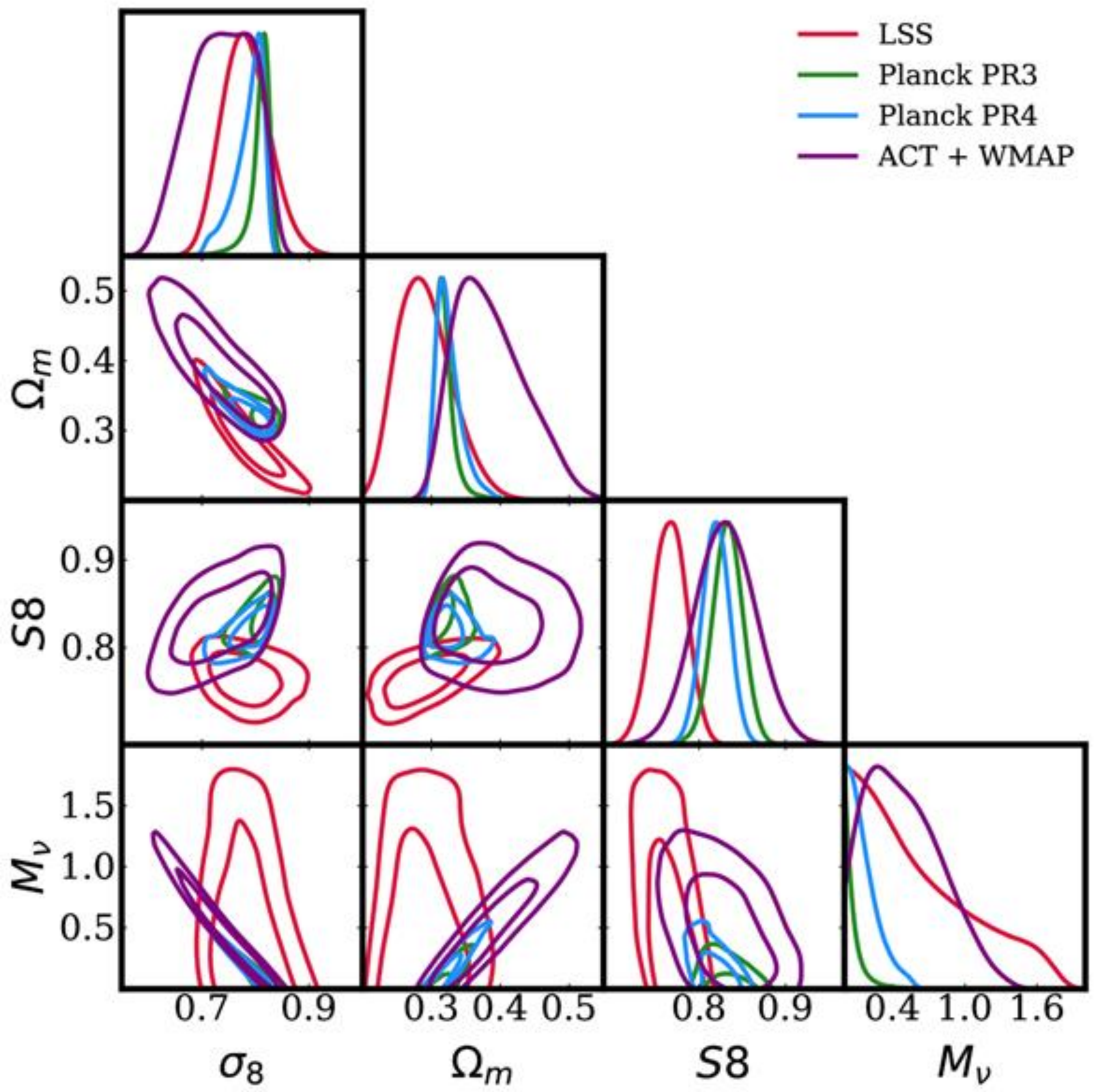
Internal consistency: measuring tensions

Model	Experiment	$\sigma S8$ (Gaussian)	n_σ (All Params)
	Planck PR3	2.45	1.964 ± 0.006
ΛCDM	*Planck* PR4	2.15	1.703 ± 0.005
	ACT (DR4) + WMAP	2.04	1.595 ± 0.004
	Planck PR3 + DESI Y1	1.76	1.271 ± 0.004
	Planck PR4 + DESI Y1	1.68	1.301 ± 0.004
	ACT (DR4) + WMAP + DESI Y1	1.60	1.252 ± 0.004
	Planck PR3	2.54	1.655 ± 0.005
$\nu\Lambda$CDM	*Planck* PR4	2.12	1.469 ± 0.004
	ACT (DR4) + WMAP	1.62	1.699 ± 0.005
	Planck PR3 + DESI Y1	1.66	1.320 ± 0.004
	Planck PR4 + DESI Y1	1.62	1.263 ± 0.004
	ACT (DR4) + WMAP + DESI Y1	1.41	1.172 ± 0.005
	Planck PR3	0.00	1.042 ± 0.005
w_0w_aCDM	*Planck* PR4	0.28	0.725 ± 0.004
	ACT (DR4) + WMAP	0.46	0.970 ± 0.005
	Planck PR3 + DESI Y1	0.80	1.734 ± 0.006
	Planck PR4 + DESI Y1	1.05	1.282 ± 0.004
	ACT (DR4) + WMAP + DESI Y1	0.87	0.923 ± 0.001

Largest value in Table

General decrease when adding BAO and in extended models

Single probe neutrino mass constraints (why does this not help S8?)

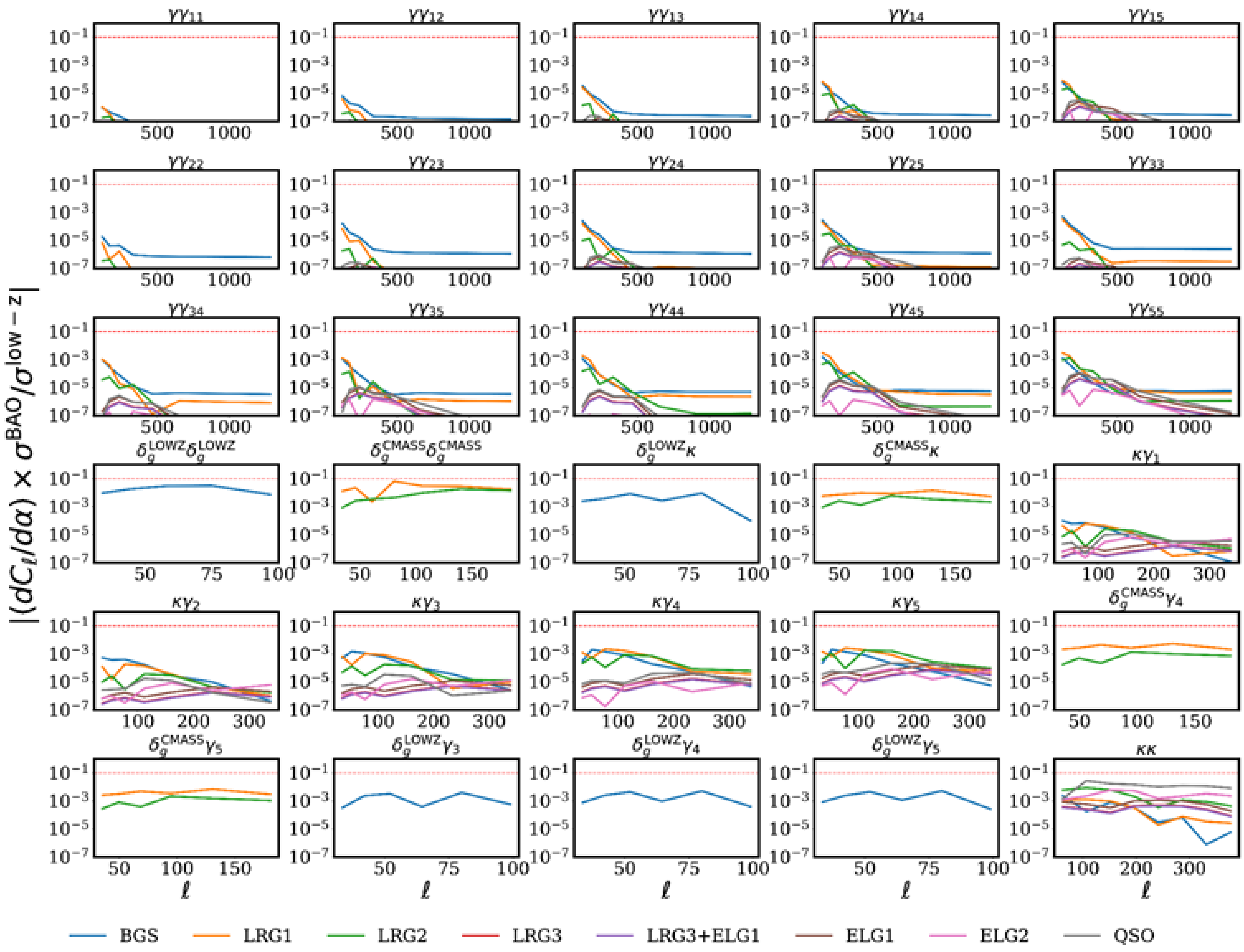


Baseline neutrino mass constraints tension with orderings

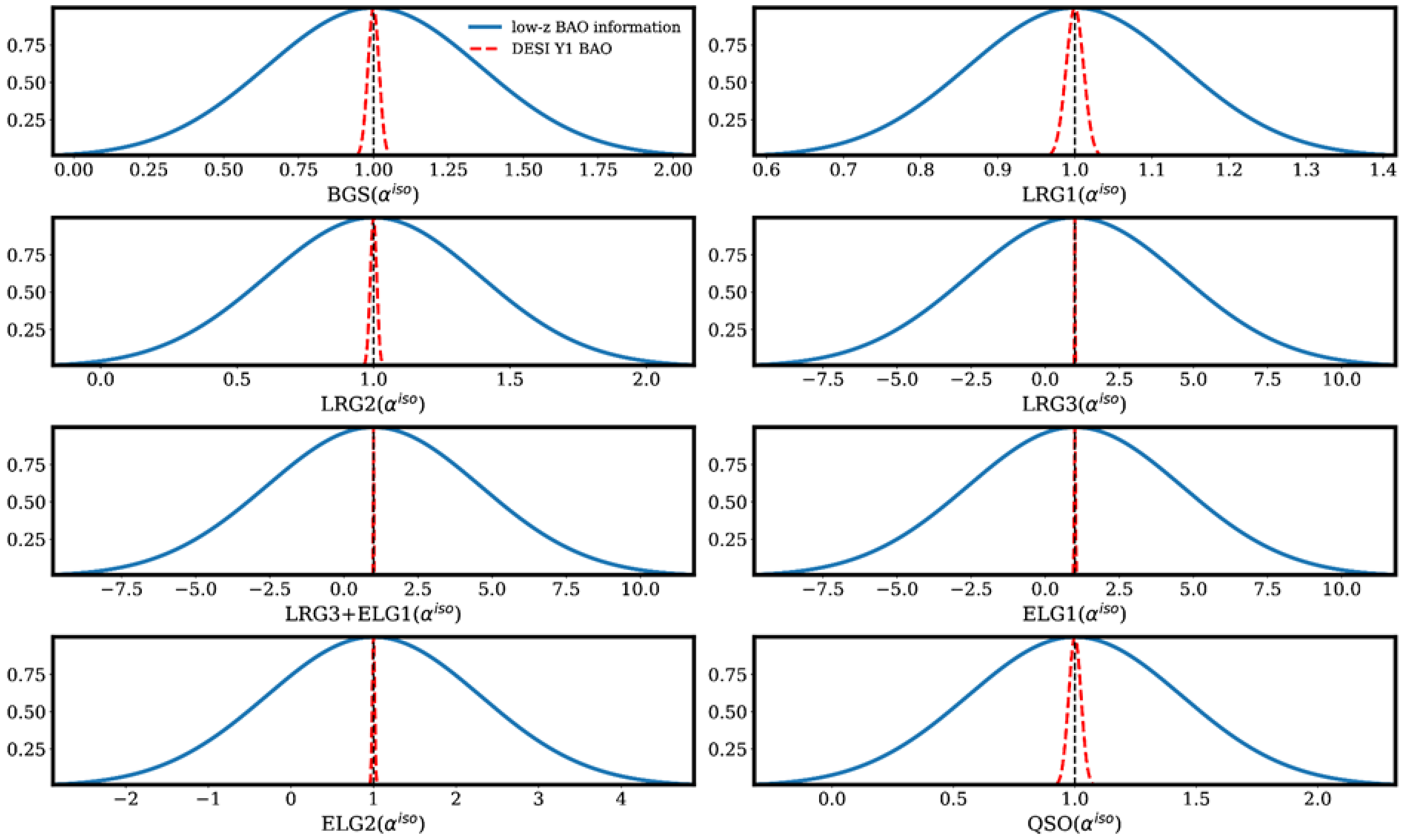
- P(M_nu<0.06)=0.29 ~ 0.5sigma tension with NO minimal mass
- P(M_nu<0.10)=0.078 ~ 1.7sigma tension with IO minimal mass

Note this is with a hard prior at M_nu=0 and so these tensions are lower than if we modelled the impact of an effective negative neutrino mass

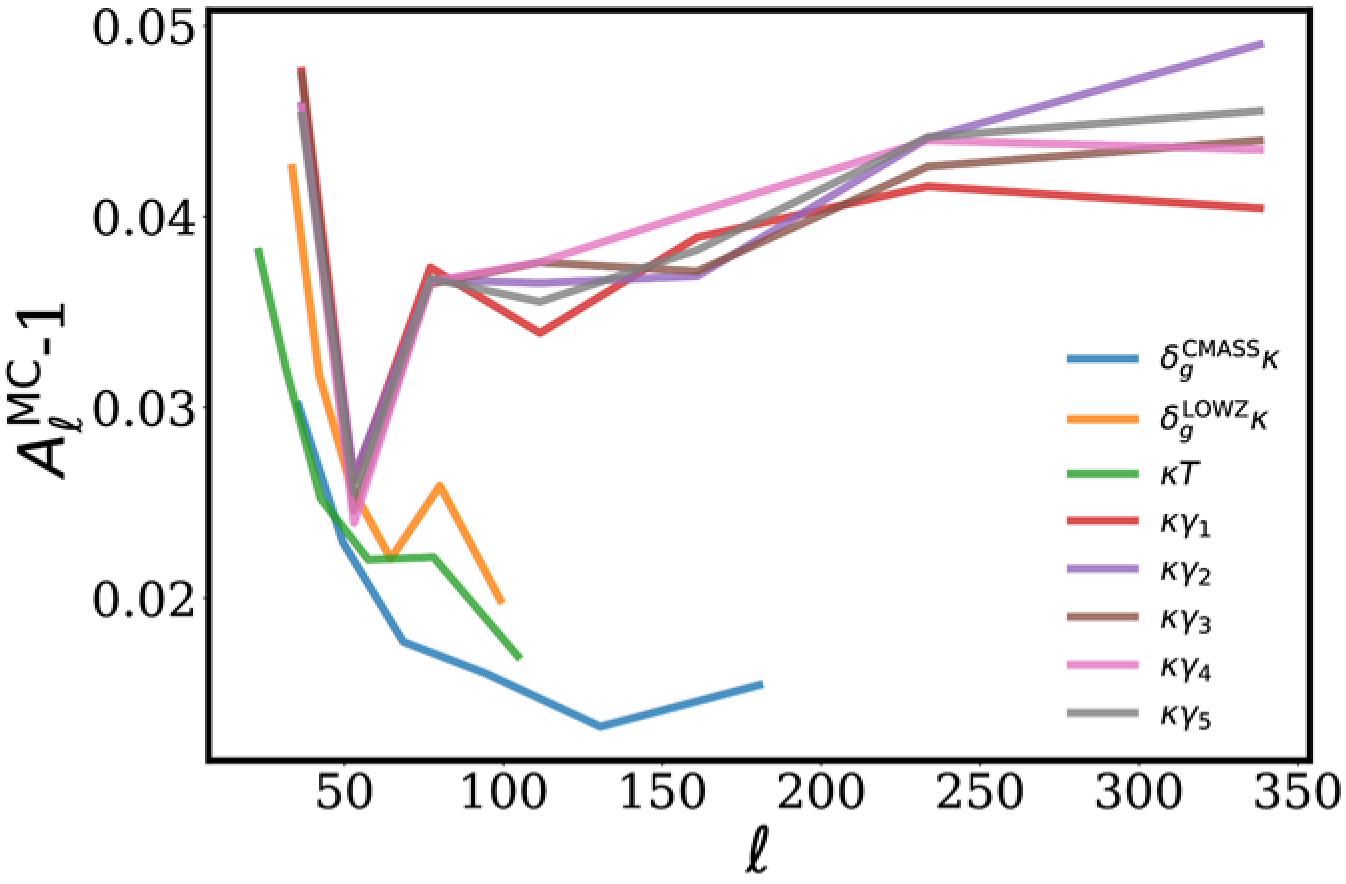
Constraining power from low-z data on DESI BAO bins

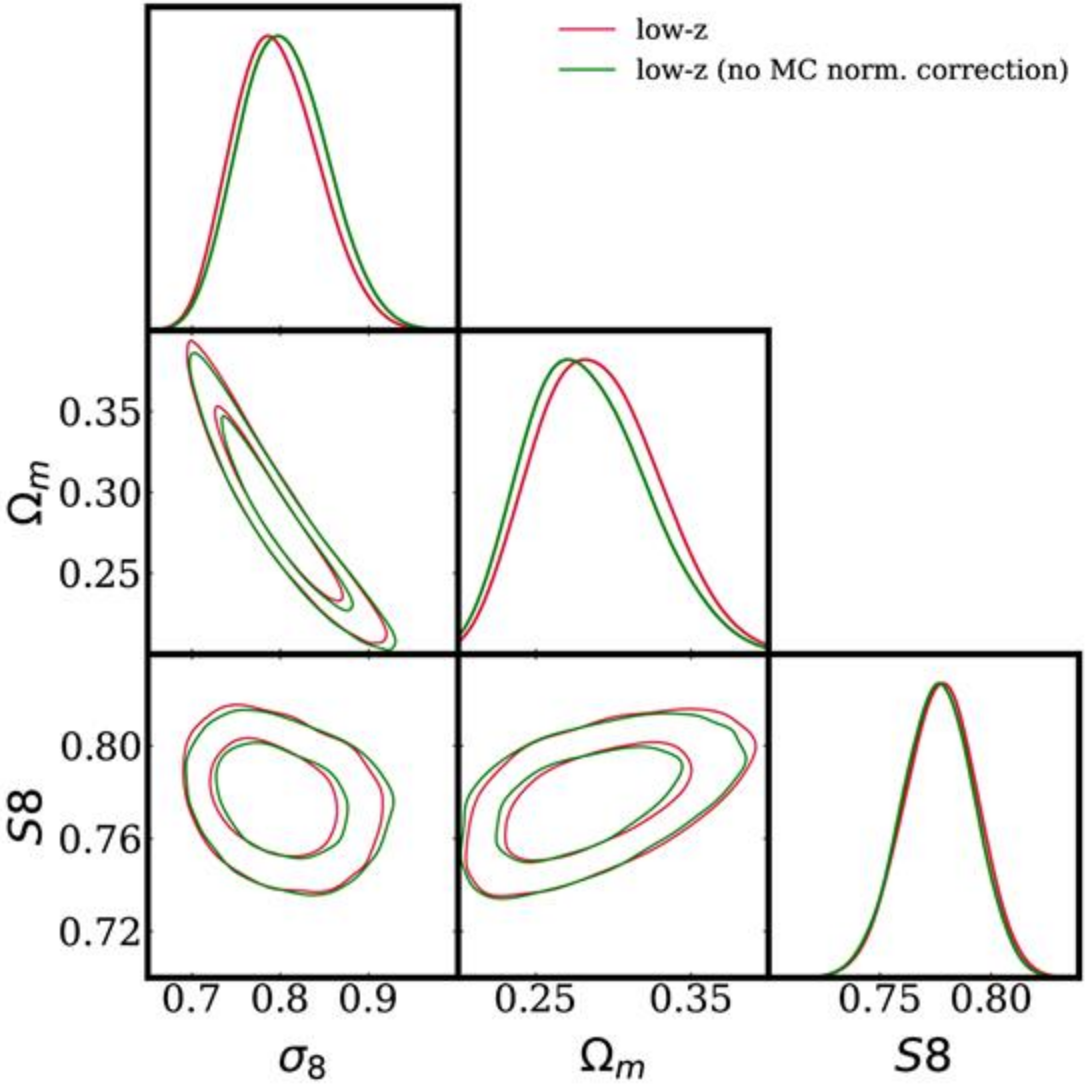


Fisher information for BAOs low-z vs DESI Y1



MC norm correction





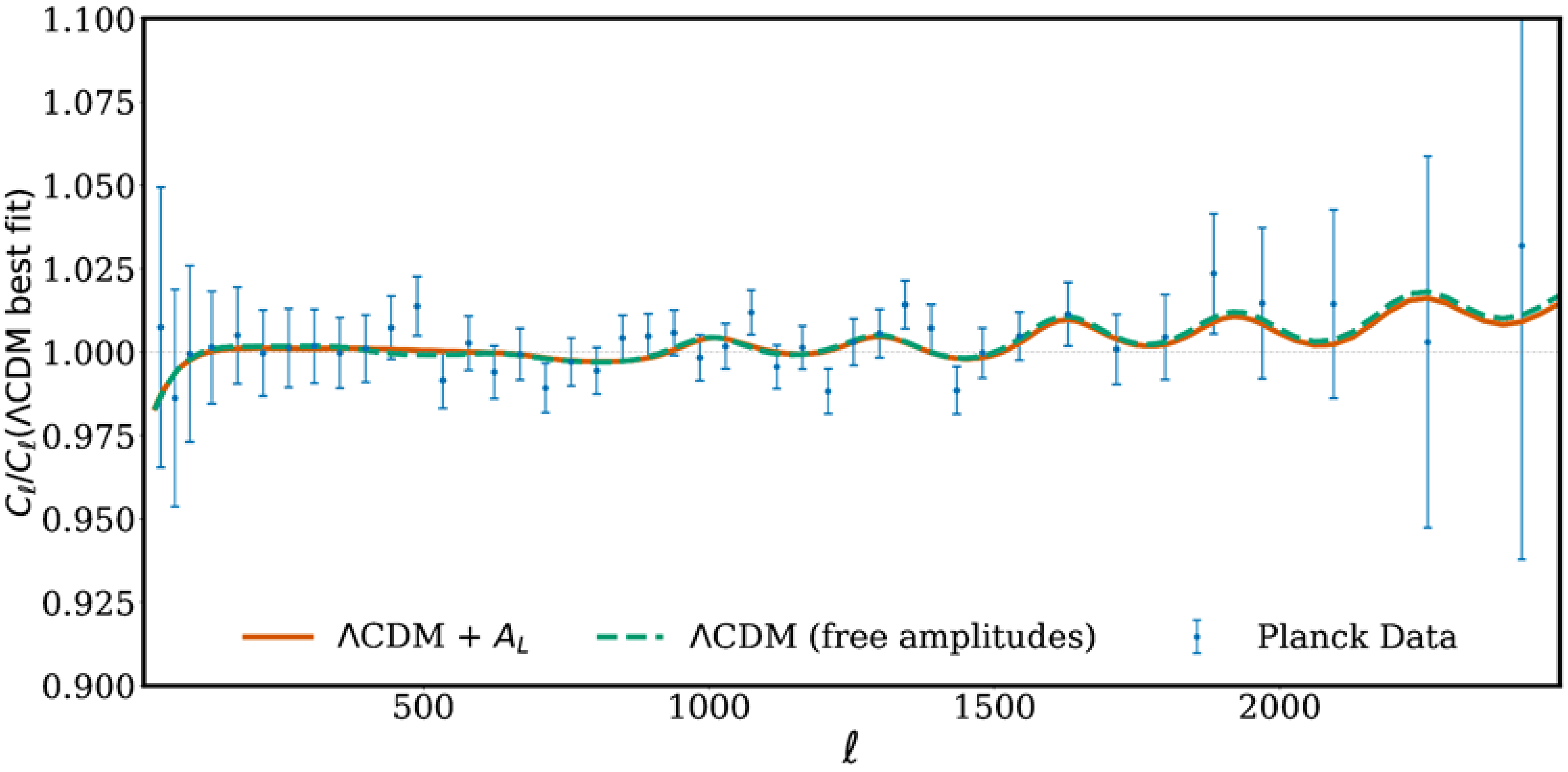
Model selection

Table 10: Comparison of ΔAIC compared to the baseline ΛCDM model for different cosmological models under various datasets. The first block shows results *without* BAO, and the second block shows results *with* BAO.

No BAO			
	Planck PR3 + low-z	*Planck* PR4 + low-z	ACT + WMAP + low-z
$\nu\Lambda$CDM	+2.22	+3.12	+1.95
w_0w_aCDM	-0.95	+2.48	+3.40
νw_0w_aCDM	+1.50	+4.95	+4.90
With BAO			
	Planck PR3 + low-z + BAO	*Planck* PR4 + low-z + BAO	ACT + WMAP + low-z + BAO
$\nu\Lambda$CDM	-1.14	+0.24	2.33
w_0w_aCDM	-1.39	+1.13	5.73
νw_0w_aCDM	+0.06	+2.99	4.87

A-lens parameter

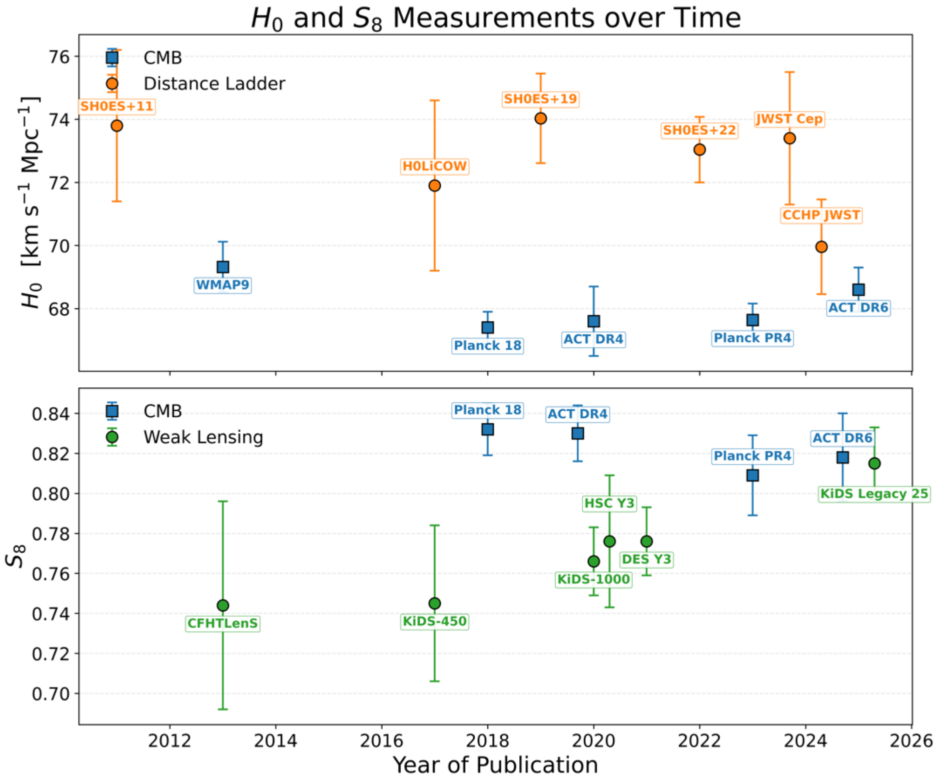
- Having m_i<0 allows for a higher amplitude of clustering which fits the same “excess lensing” residual in PR3
- Choose PR4 + low-z as baseline data combination



[Reeves et al. (2025)](#)

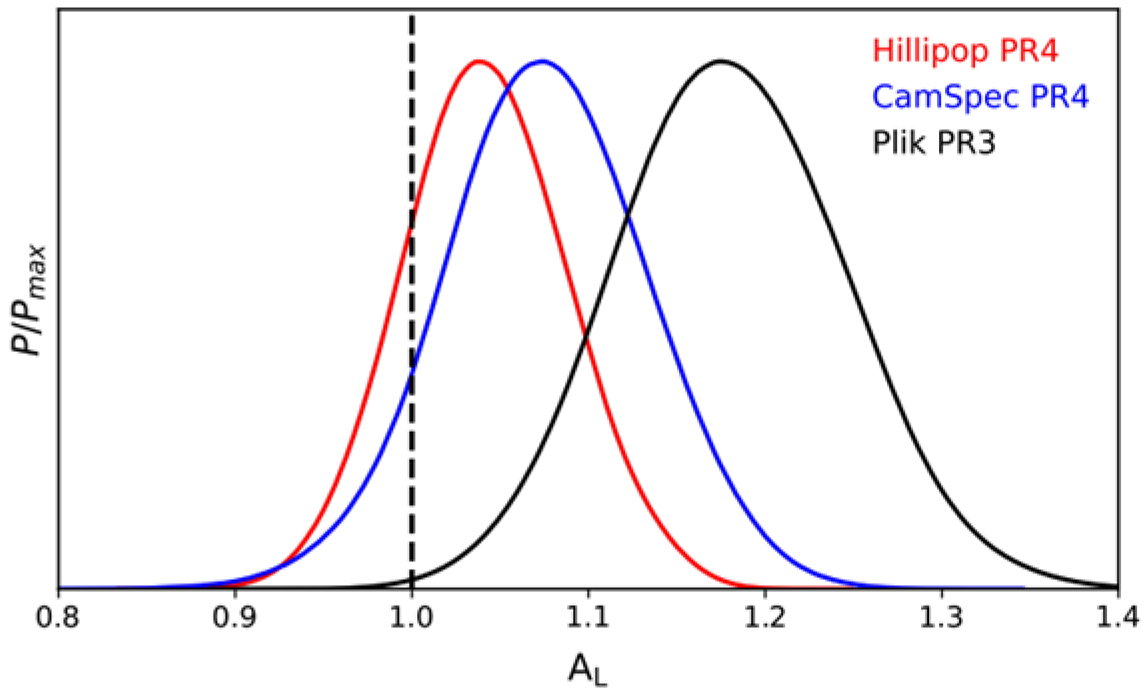
Combined probes: key challenges

1. Large data vectors/covariance matrix
2. Different systematics and noise modelling for each probe with many associated parameters
3. Tensions between datasets: how justified are we in combining data?



A-lens parameter

- A_L is a phenomenological re-scaling parameter whereby (Calabrese et al. 2008):
$$C_\ell^{\phi\phi} \to A_L C_\ell^{\phi\phi}$$
(only for the impact of lensing on CMB primary!)
- Measures consistency between CMB lensing information in the CMB primary and amplitude of CMB primary: expect A_L=1 in ΛCDM
- CMB likelihoods:
  - Planck PR3 gives A_L>1 at 3σ
  - PR4 favours A_L>1 at 0.75σ
  - ACT+WMAP has no preference for A_L>1



Tristram et al. 2023