Reconstructing dark energy with fewer assumptions

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Dark energy evolution
Recent indications

- Linear equation of state (CPL)

$$w_{\mathrm{de}}(a) = w_0 + w_a(1 - a)$$

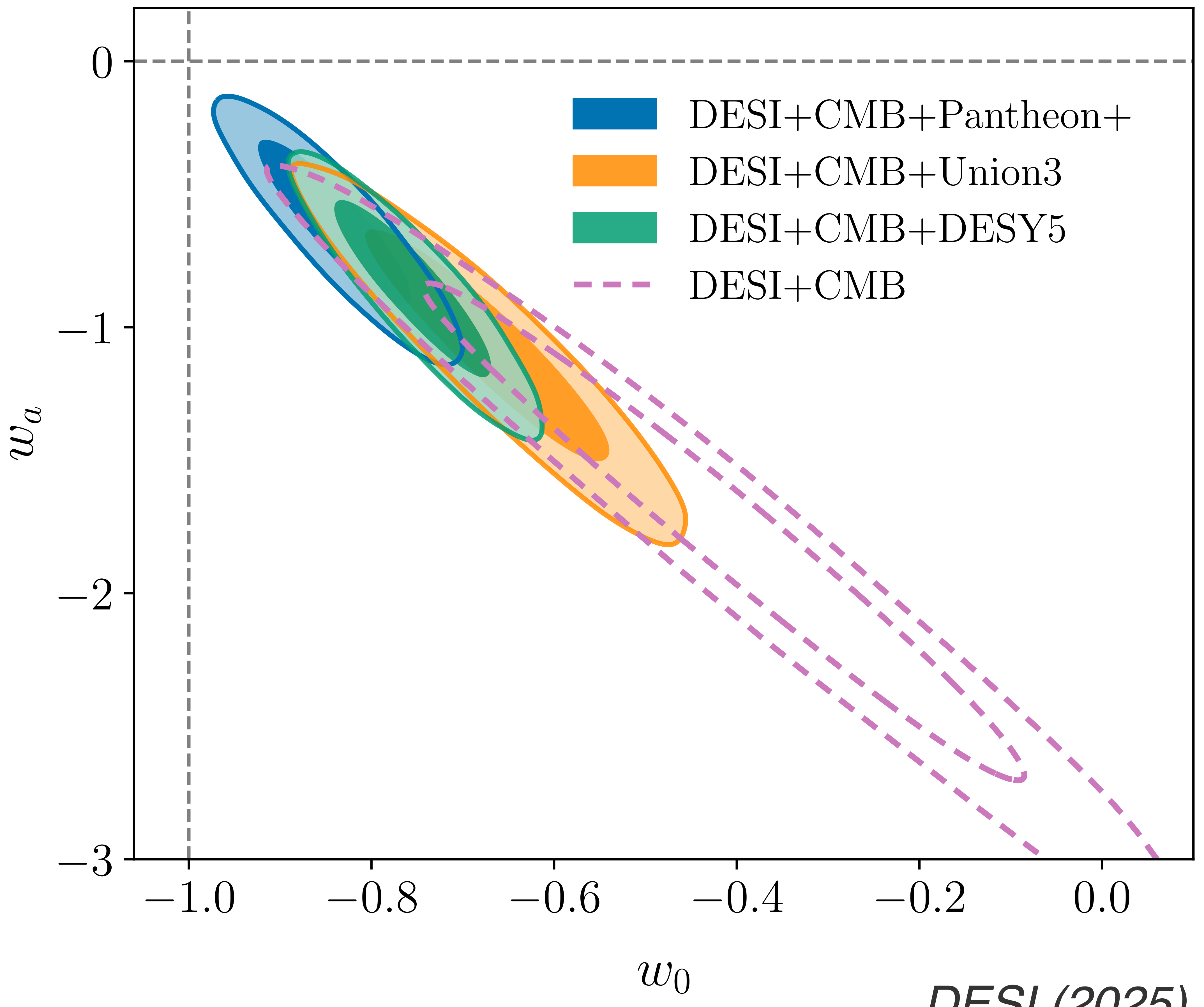
- Constrained by CMB + BAO + SNe
- Deviation from $(w_0, w_a) = (-1,0)$

SDSS BAO ↝ $\sim 2\sigma$

Brout+ (2022), Rubin+ (2023), DES (2024)

DESI BAO ↝ $\sim 3\sigma$

DESI (2025), Popovic+ (2025), Hoyt+ (2026)



DESI (2025)

Dark energy evolution

Questions and criticisms

- Dependence on parametrization?
- Tensions within the datasets?

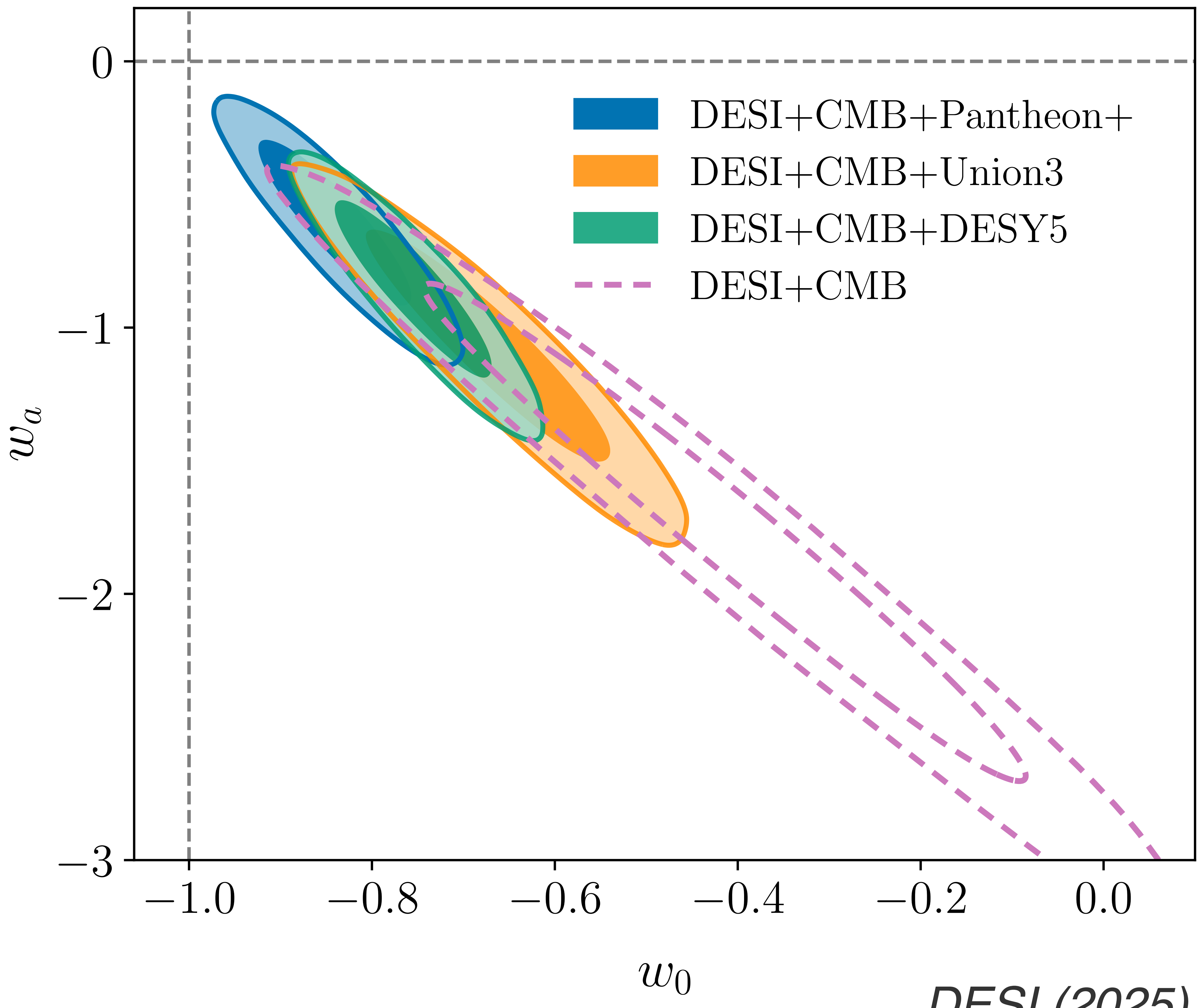
  Ω_m tension between three probes

  τ and *Planck* low-ℓ polarization

  Sailer+ (2025), Jhaveri+ (2025)
- Dependent on individual datasets?

  On individual datapoints?

  DESI LRG, low-z SNe?



DESI (2025)

Dark energy reconstruction

Our methodology and results

- Piecewise constant parametrization
- BAO and SNe distances, CMB-θ_*, BBN-$\Omega_b h^2$

All combinations of BAO and SNe give consistent preferences for dark energy evolution.

Robust to amount of CMB data included and parameter extensions.

Reconstructing dark energy with fewer assumptions

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We perform minimalistic reconstructions of the dark energy density and equation of state using late-time distance measurements. Our methodology avoids assumptions that correlate the values of these functions over time and instead yields their approximate average evolution within seven redshift bins from $z = 0$ to $z = 4.2$. Constraints are obtained using combinations of baryon acoustic oscillation measurements from the Dark Energy Spectroscopic Instrument (DESI) and the completed Sloan Digital Sky Survey (SDSS), alongside Type Ia supernovae measurements from Pantheon+ and the latest recalibrated samples, Union3.1 and DES-Dovekie. Only an acoustic scale prior is included from the Cosmic Microwave Background so that our results are insensitive to the possible matter density tension between early and late-time probes. All combinations yield consistent reconstructed histories: a dark energy density that rises to a local maximum before decreasing at late times and an equation of state with two apparent oscillations around the cosmological constant limit. Both functions tentatively suggest a phantom crossing in the equation of state around $z \sim 0.6$–0.8. These patterns are robust to numerous parameter extensions, such as freely varying spatial curvature and neutrino mass, and they persist in the uncorrelated amplitudes obtained through localized principal component analysis. Deviations from ΛCDM in individual bins reach a maximum significance of ~ 2.6–3σ, while the total chi-square difference between the reconstructions and this model provides up to $\sim 2\sigma$ support for the seven additional parameters in the reconstructions. As these significances remain moderate, our main result is the level of consistency between combinations of the most widely used background-level observations. Our results suggest that the dark energy evolution signal is a persistent feature of the data and that it cannot be explained solely by fluctuations or systematics in individual measurements.

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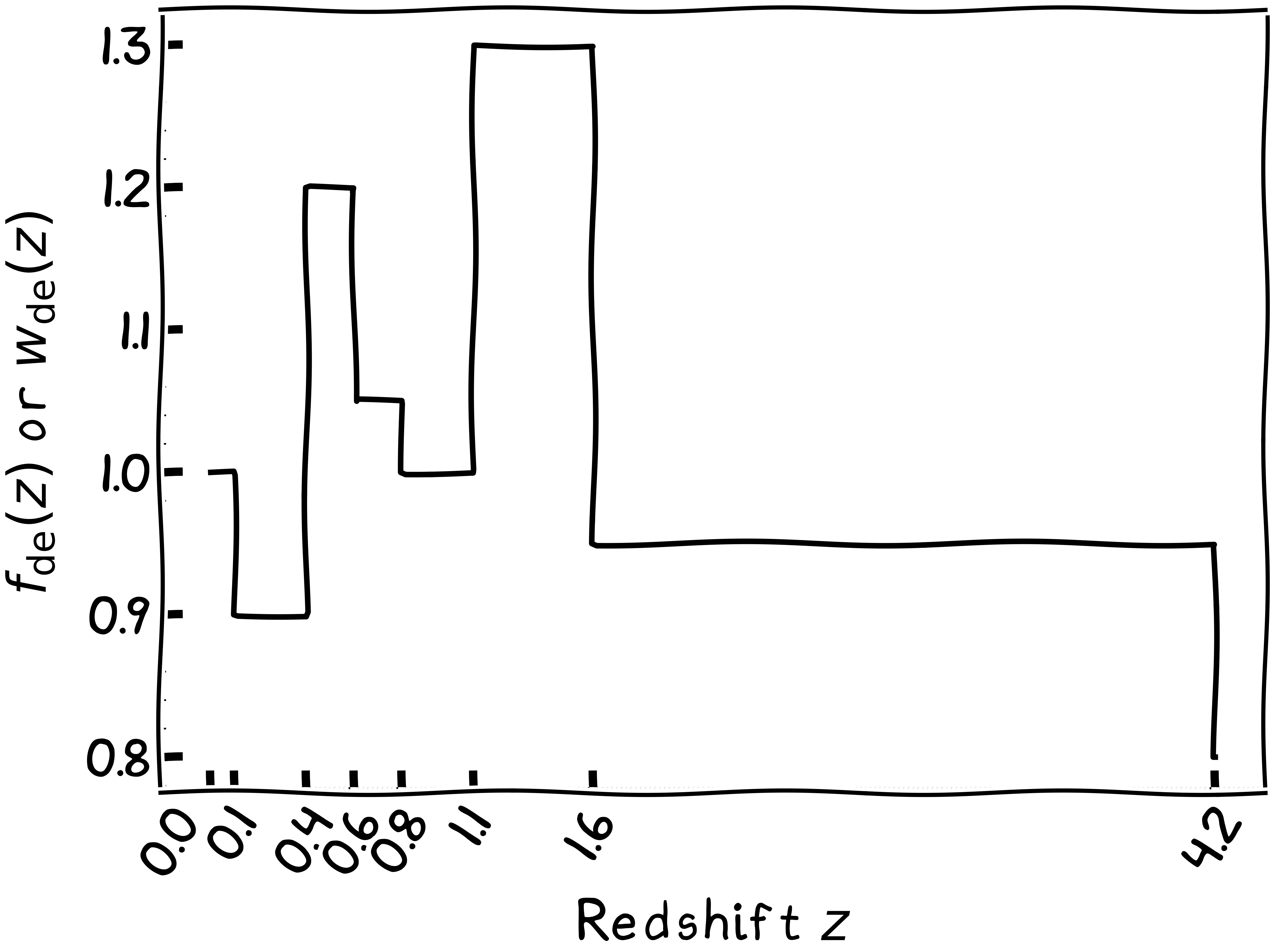
Dark energy reconstruction

Piecewise constant parametrization

- $w_{\rm de}(z) \equiv p_{\rm de}/\rho_{\rm de}$ **or** $f_{\rm de}(z) \equiv \rho_{\rm de}/\rho_{\rm de,0}$

$$\begin{cases} p_1 & z \in [z_1, z_2)\,, \\ p_2 & z \in [z_2, z_3)\,, \\ \vdots & \quad \vdots \\ p_7 & z \in [z_7, z_8) \end{cases}$$

↝ *No correlations imposed*



- Redshift bins from DESI + $[0,0.1)$

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Dark energy reconstruction

Distance measurements and BBN

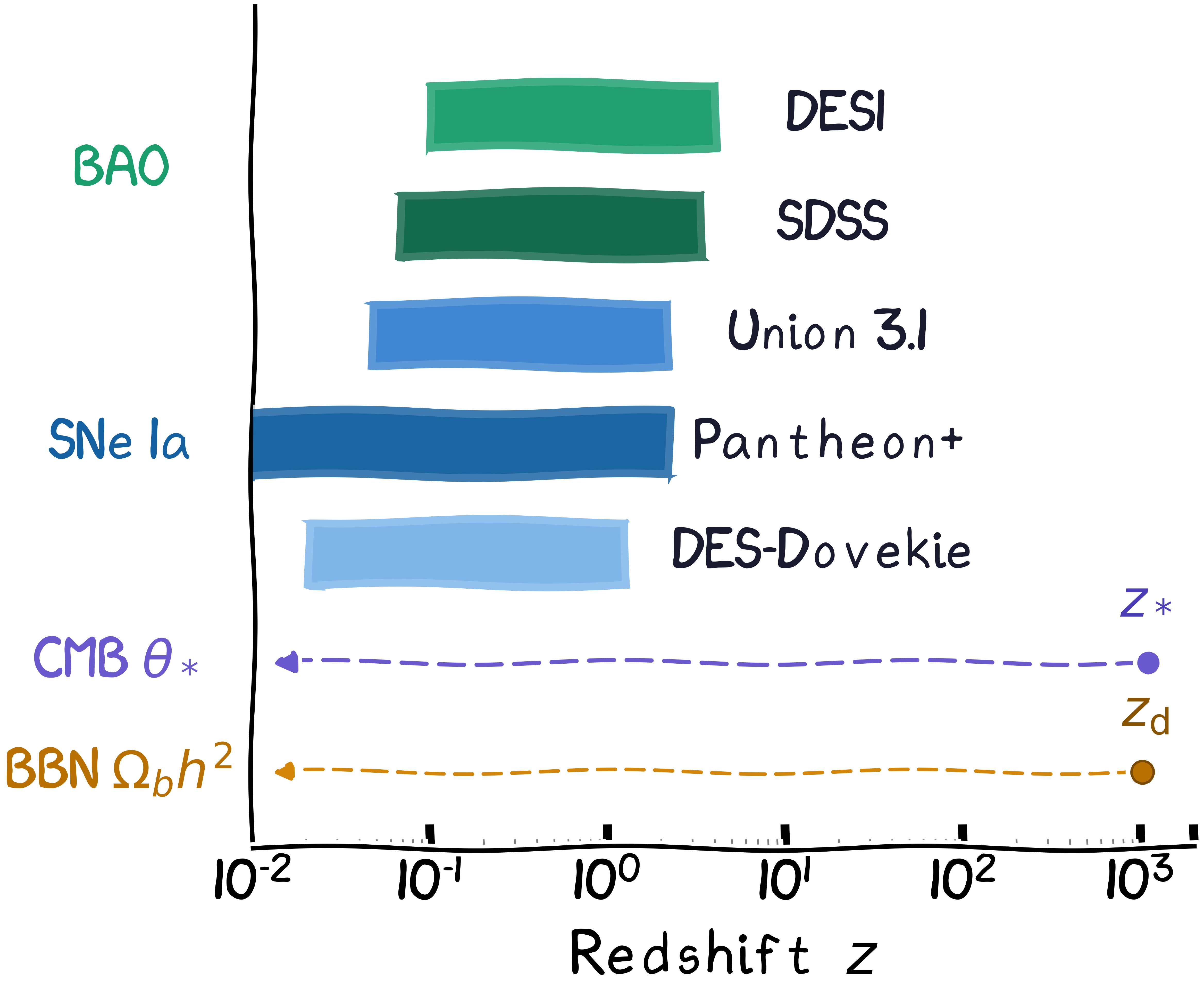
- **BAO**: SDSS or DESI. D/r_d

$$D_\mathrm{H} \equiv 1/H(z)\,, \quad D_\mathrm{M} = \int_0^z \mathrm{d}z'/H(z')$$

- **SNe**: Union3.1, Pantheon+, or DES-Dovekie

$$m - M \sim \log_{10}\left((1+z)\,D_\mathrm{M}(z)\right)$$

- **CMB**: $\theta_* = r_*/D_\mathrm{M}(z_*)$ (*Planck 2018*)
- **BBN**: $\Omega_b h^2$ (*Schöneberg 2024*) ⇝ calibrates r_d



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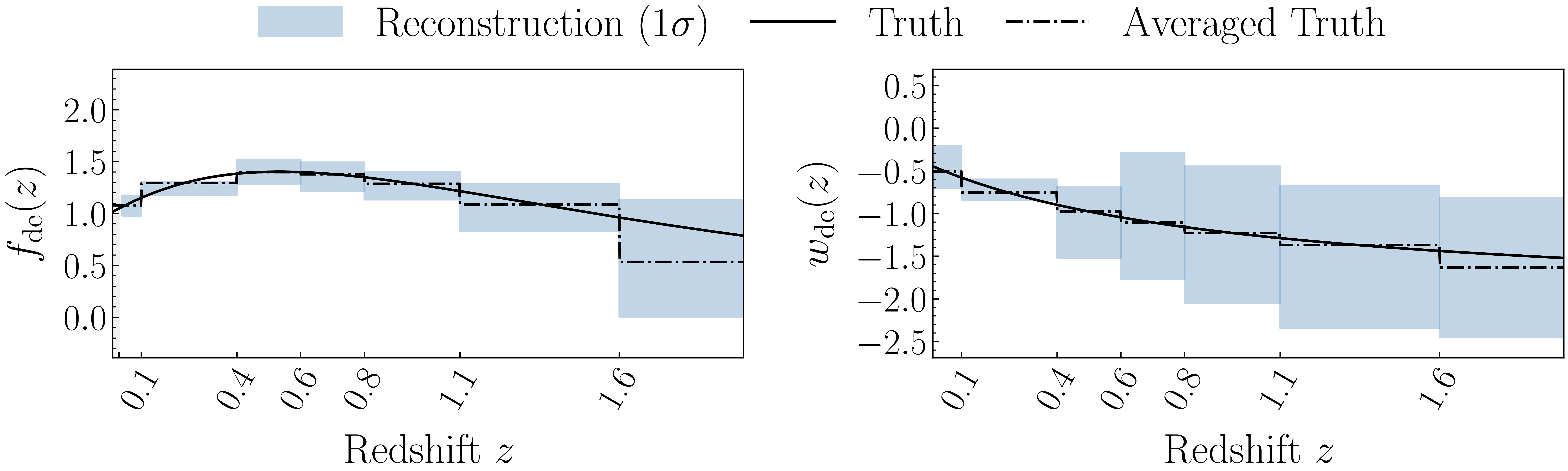
Dark energy reconstruction

What we measure

- Use *mock datasets*: Means $\mu \leftarrow$ Fiducial, Covariance $C \leftarrow$ Real



↝ The reconstructions measure ∼ redshift-averaged truth

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Results: Reconstructed evolution

f_{de} *local maximum ⇒ phantom crossing*: $\mathrm{d}f_{de}/\mathrm{d}z \propto \left(1 + w_{de}(z)\right) = 0$

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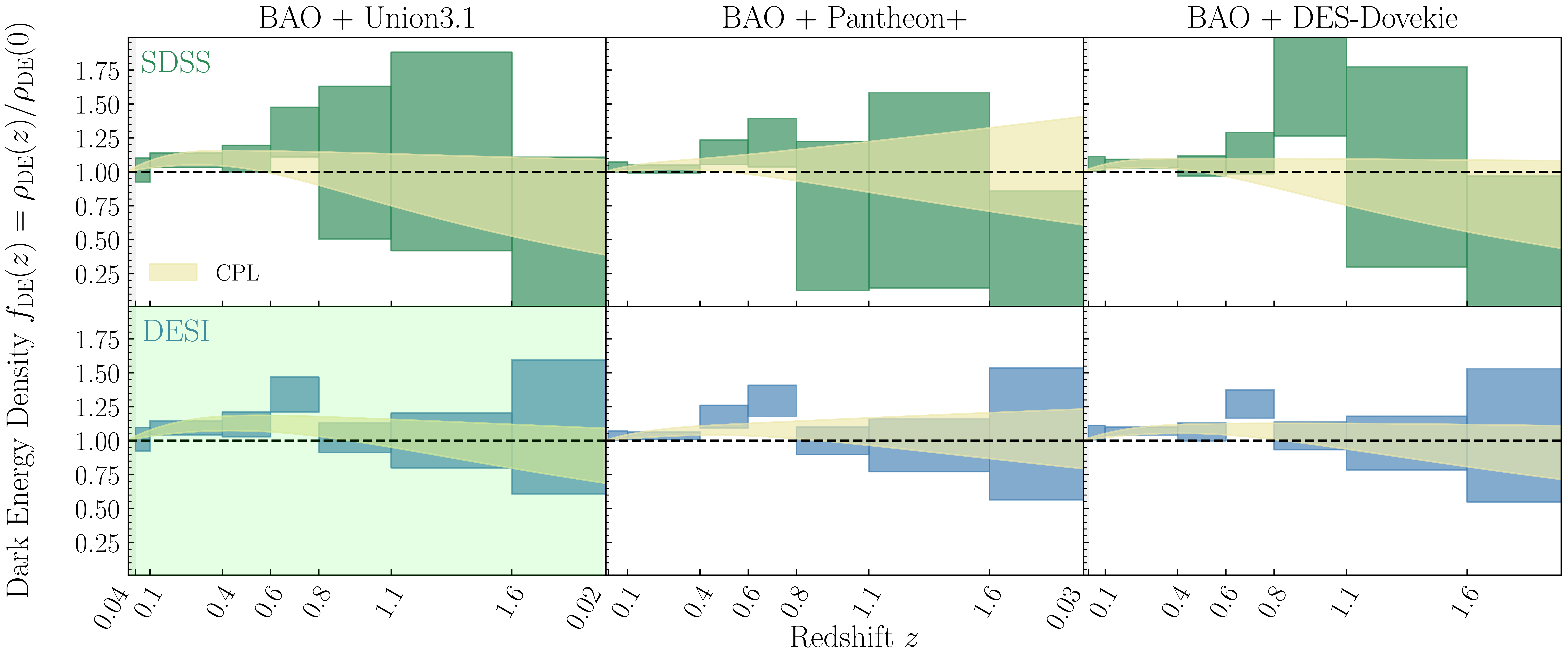
Results: Dark energy density



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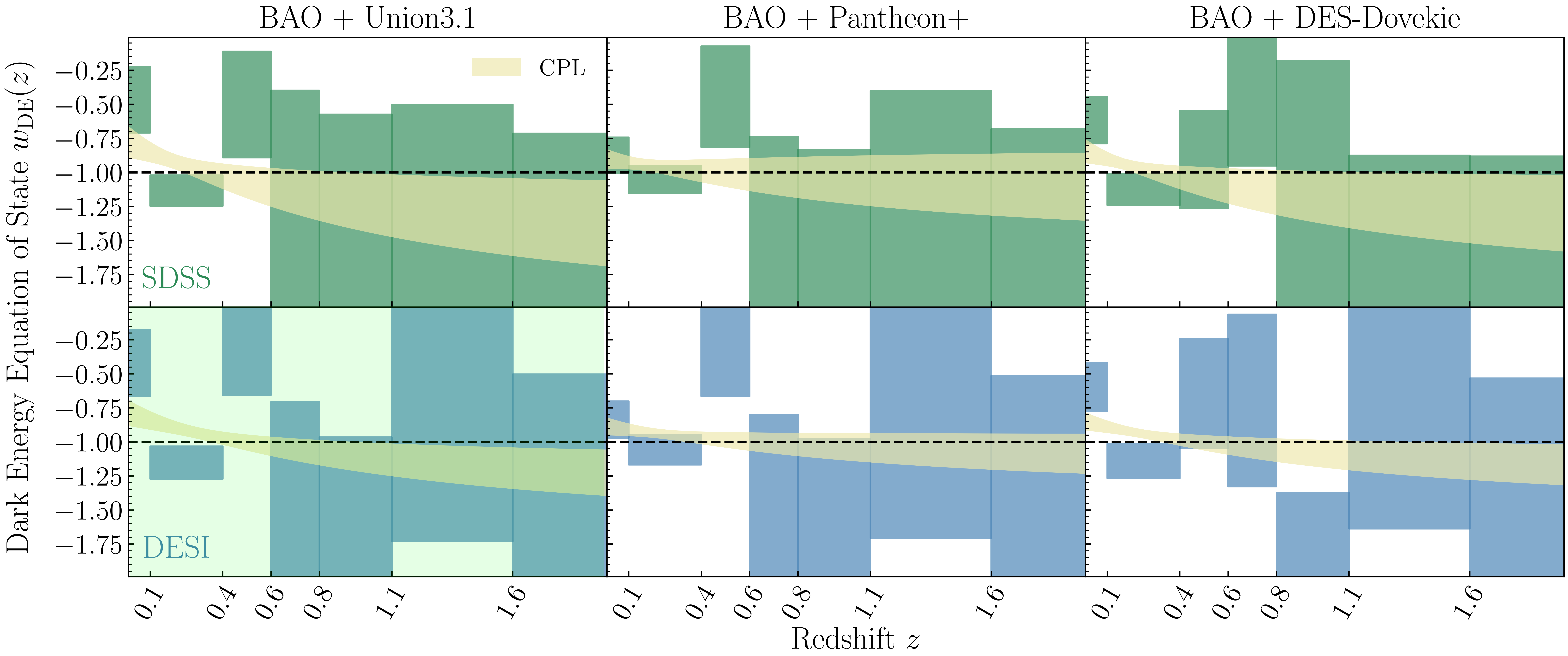
Results: Dark energy equation of state



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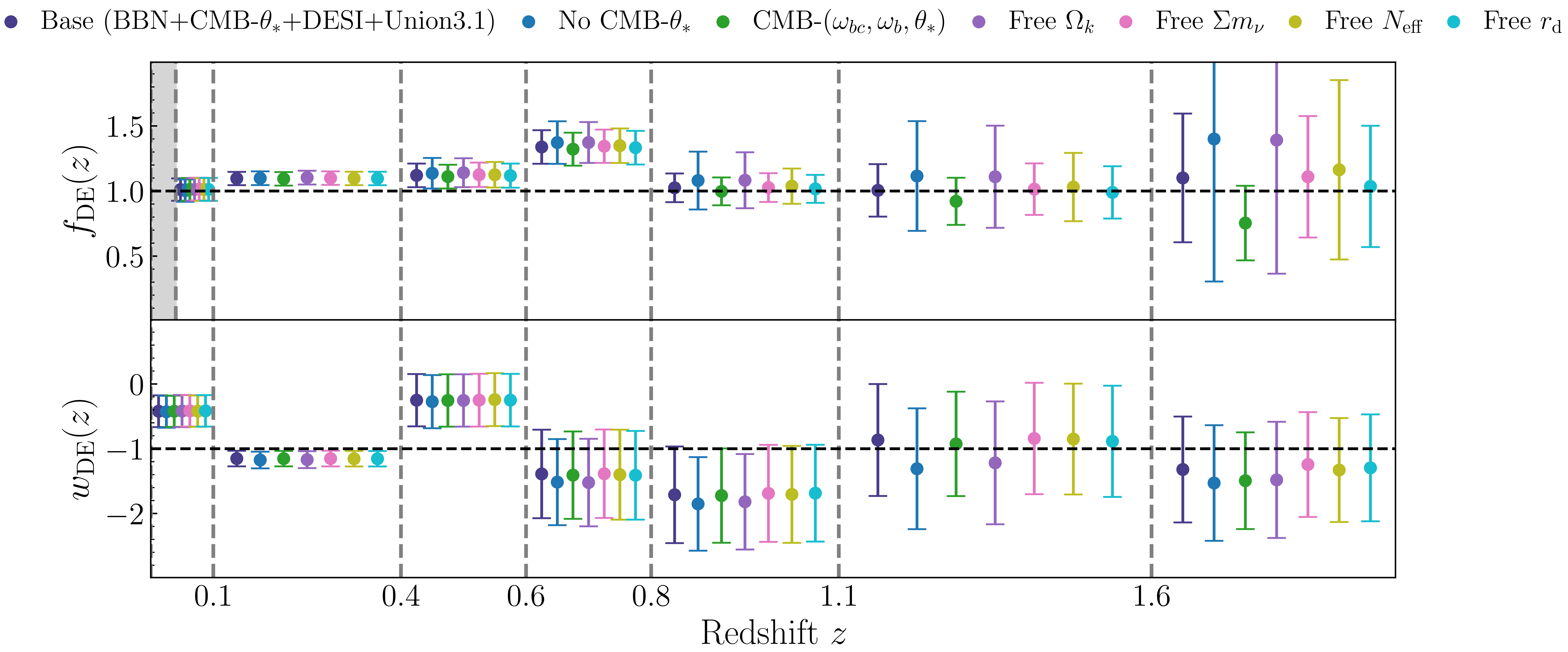
Results: Robustness to assumptions



↝ The *reconstructions* are *driven by late-time distances*

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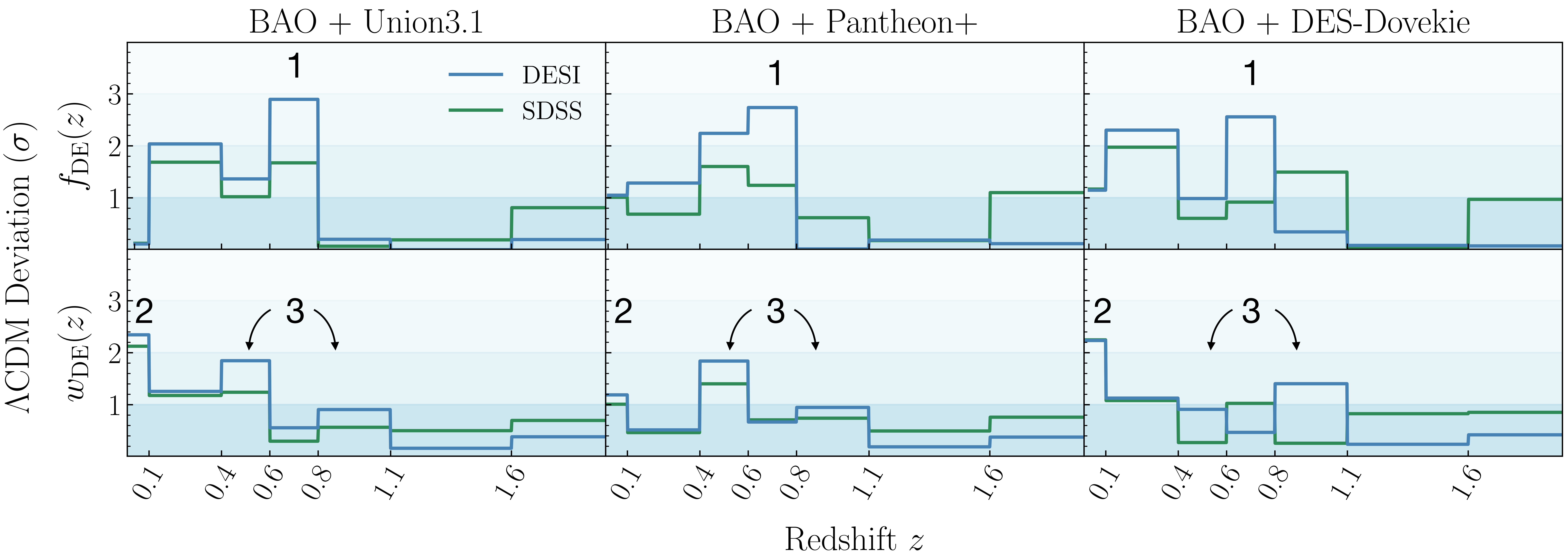
Results: Deviations from ΛCDM



1 f_{de} local maximum ($2.5 - 3\sigma$) **2** $w_{de} > -1$ ($1 - 2\sigma$) **3** w_{de} crossing -1 ($1 - 2\sigma$)

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Conclusions

- Consistency between distance measurements on dark energy evolution

- Insensitive to confounding effects and robust to CMB data, parameter extensions

- Preferences for ΛCDM deviations:

  $f_{\rm de}$ deviations $\lesssim 3\sigma$

  $w_{\rm de}$ deviations $\lesssim 2\sigma$

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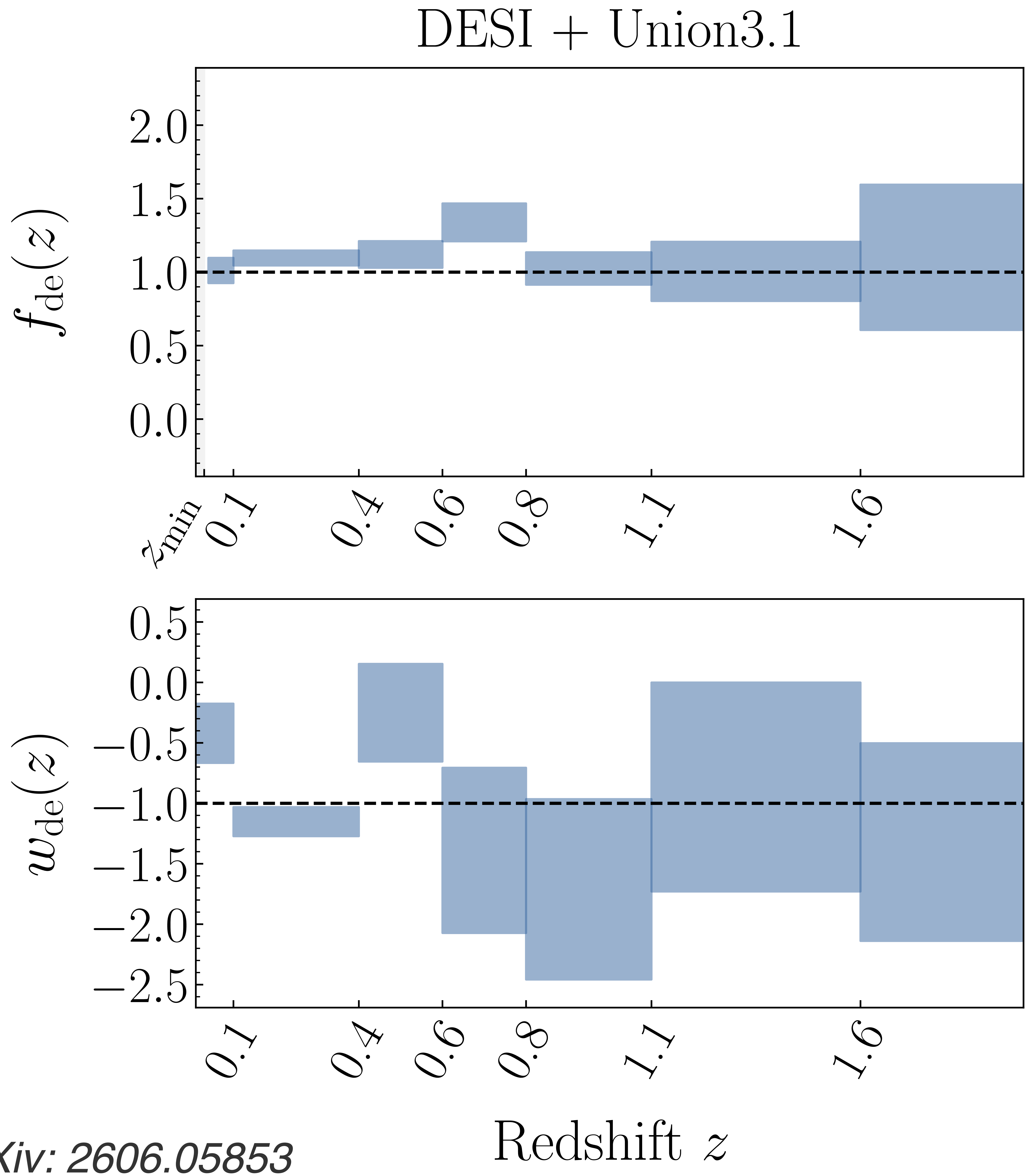
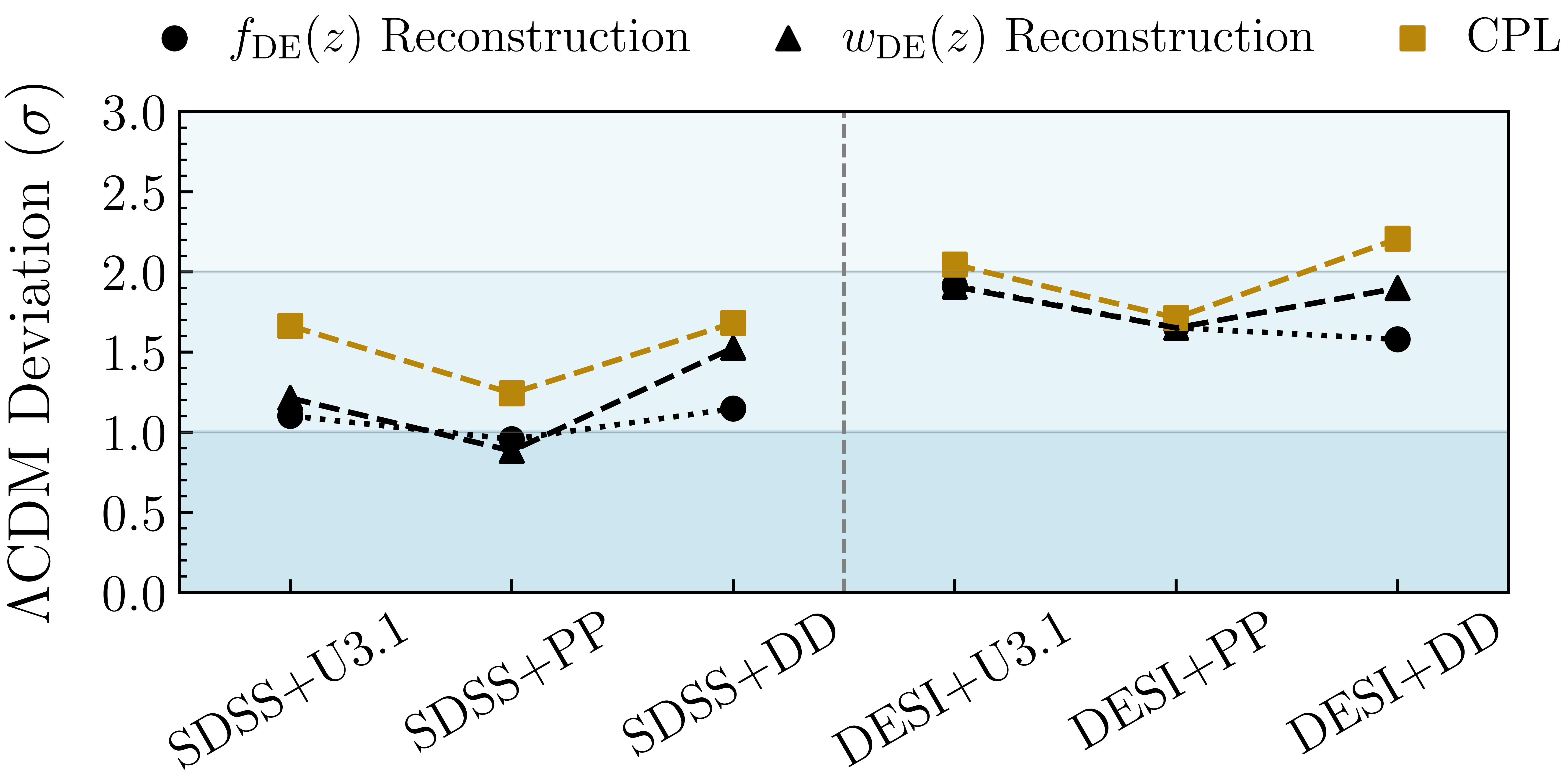


THANK YOU

BACKUP

Results: Global deviations from ΛCDM

- Wilks' theorem: $(\Delta\chi^2, \Delta\mathrm{DOF}) \mapsto \mathrm{Gaussian}\ \sigma$



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Results:

Connecting to observations

- $f_{\rm de}(z)$ maximum from

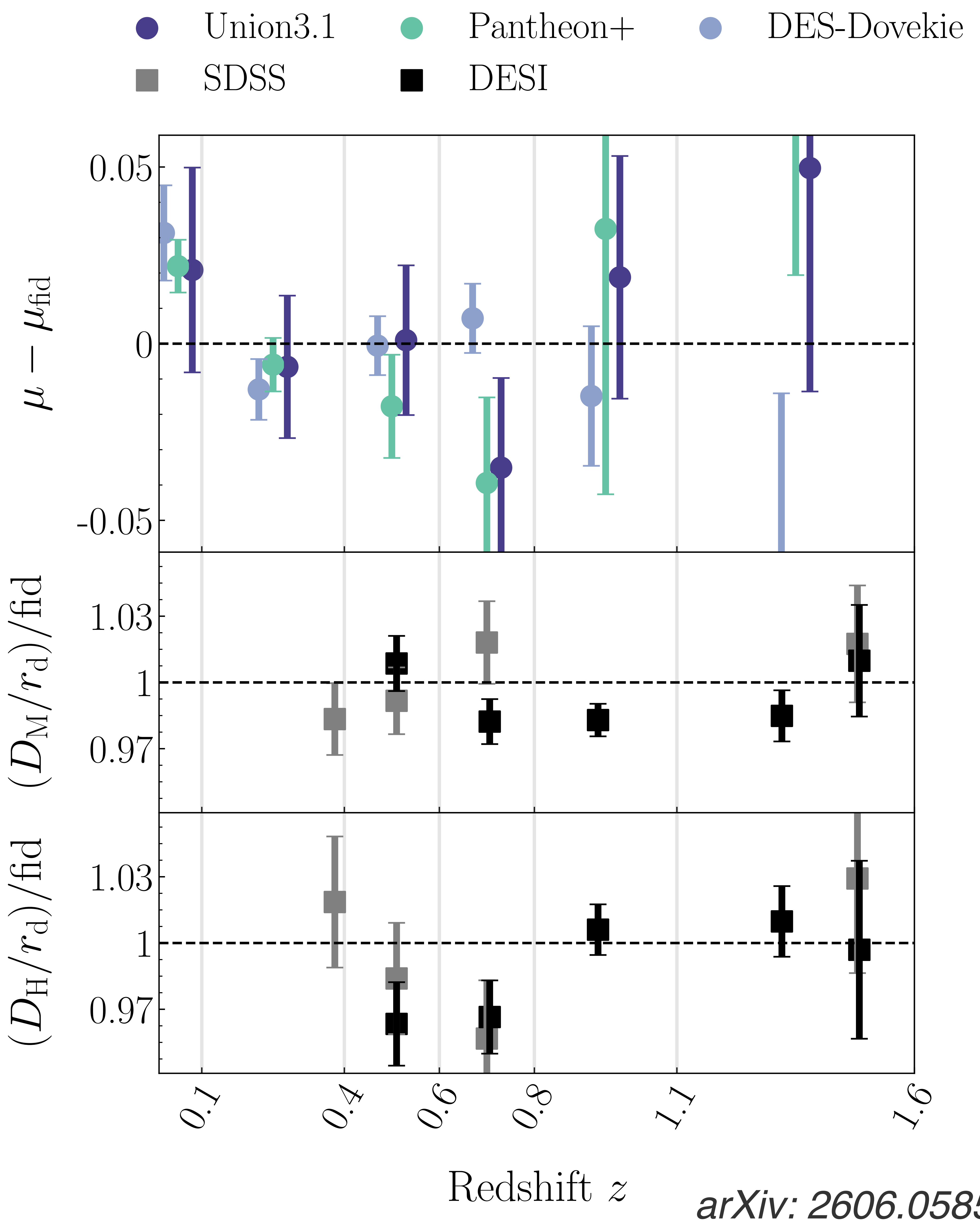
  $D_{\rm H}/r_{\rm d}$ minimum at $z \sim 0.4$ - 0.8

  $D_{\rm M}/r_{\rm d}$ decrease after $z \sim 0.6$

  μ preferences unclear

- $w_{\rm de}(0) > -1$ from

  μ increase before $z \sim 0.1$



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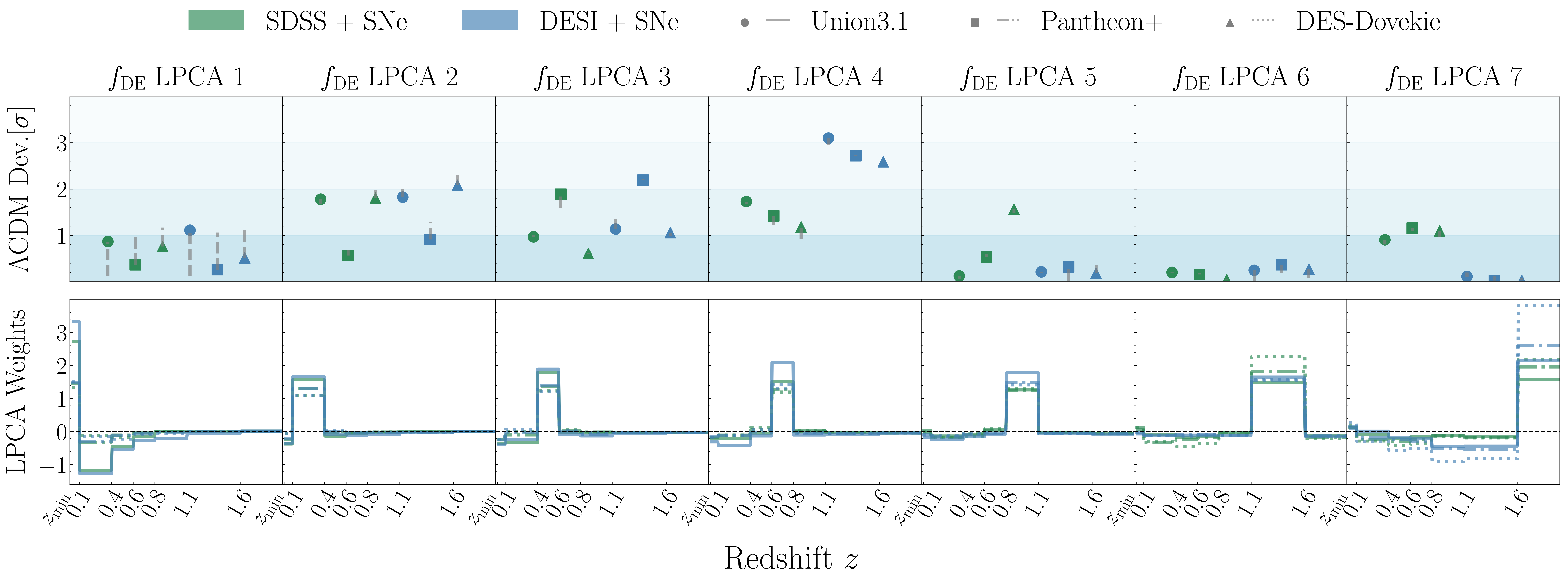
Results: Localized principal components

- Uncorrelated amplitudes prefer the same ΛCDM deviations



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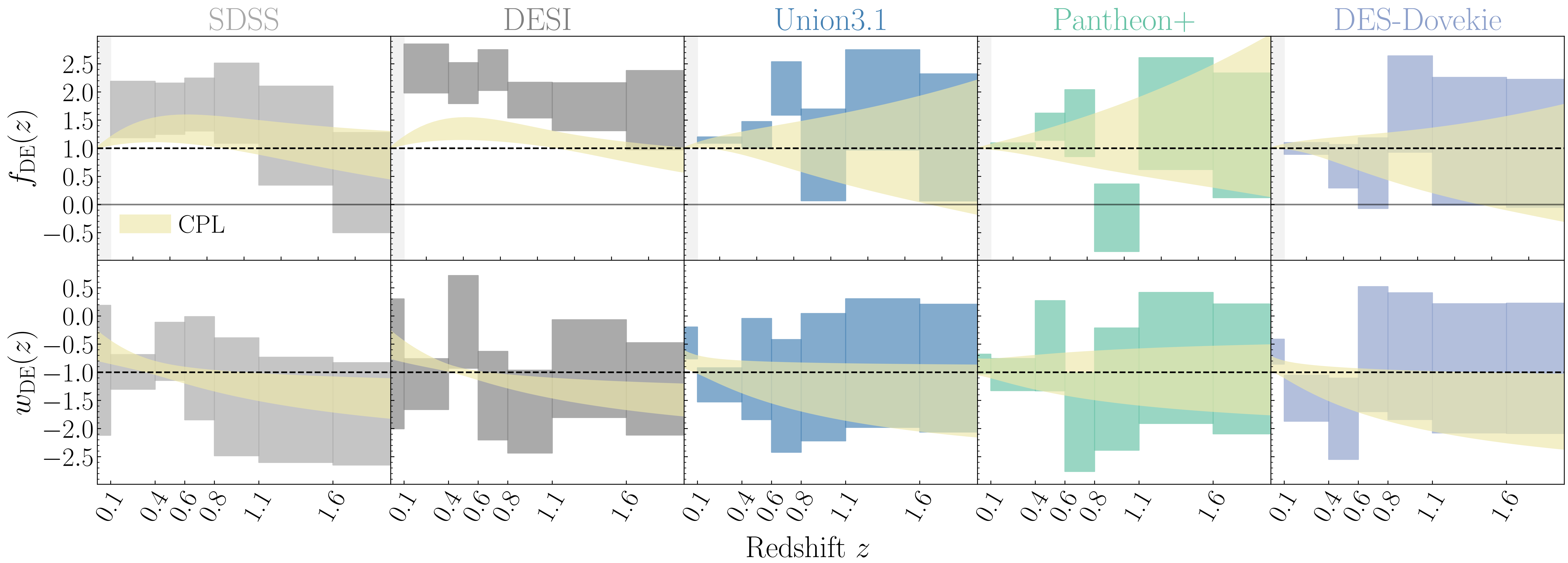
Results: Individual datasets



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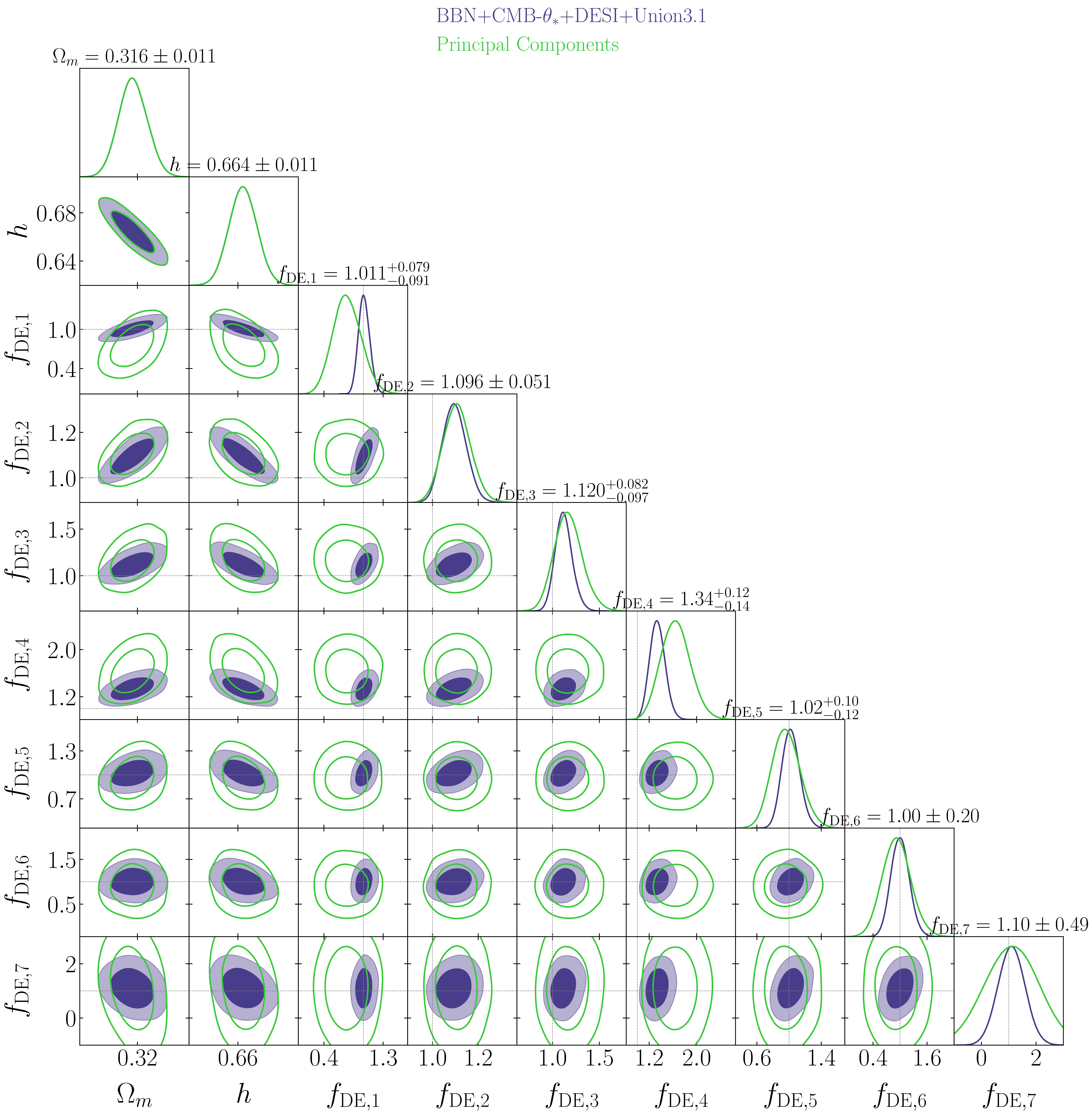
Results: $f_{\rm de}$ posteriors



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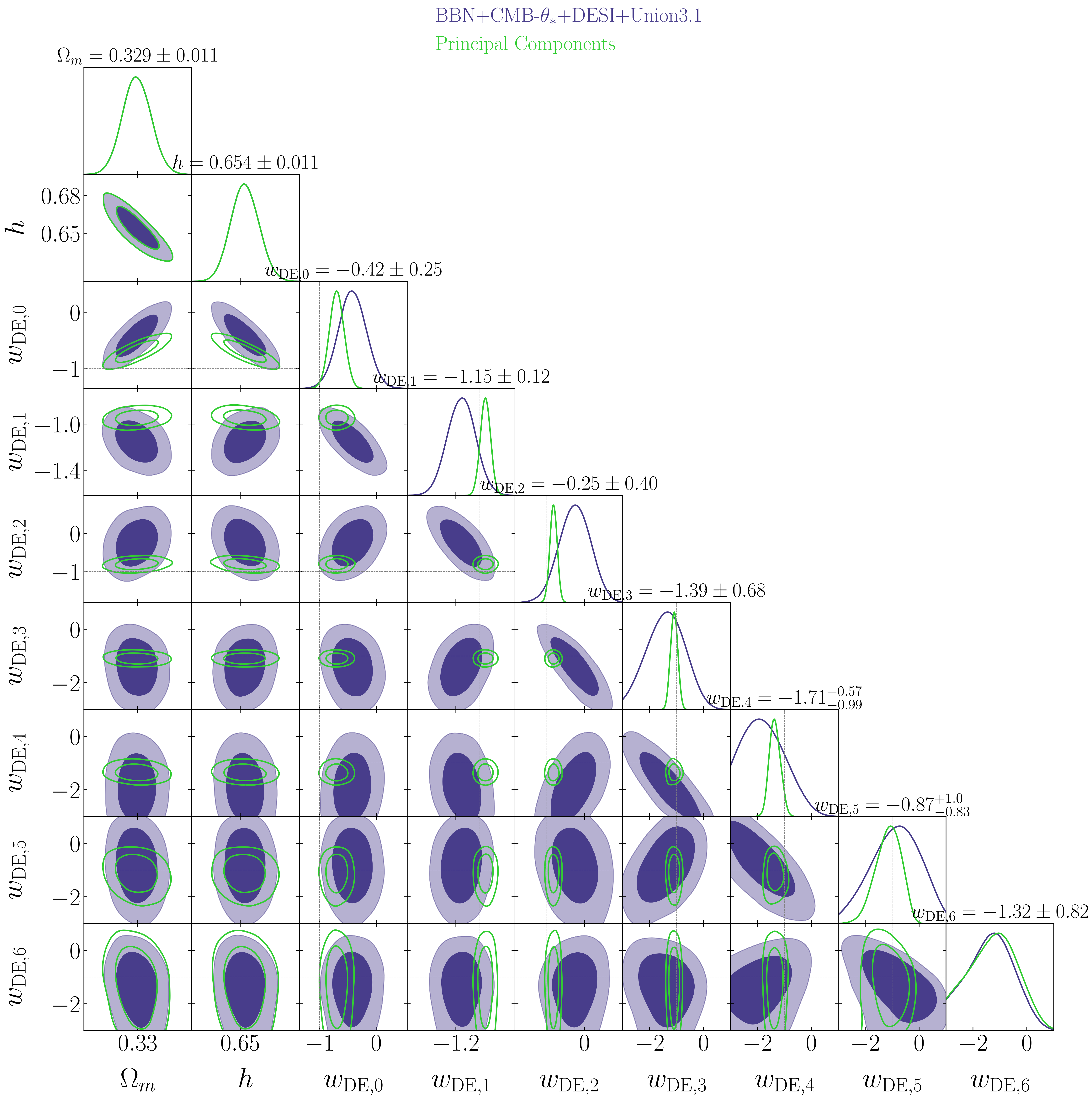
Results: $w_{\rm de}$ posteriors



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