Dark Energy after DESI DR2

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In collaboration with K. Lodha, A. Shafieloo, E. Linder, W. Matthewson
& DESI collaboration

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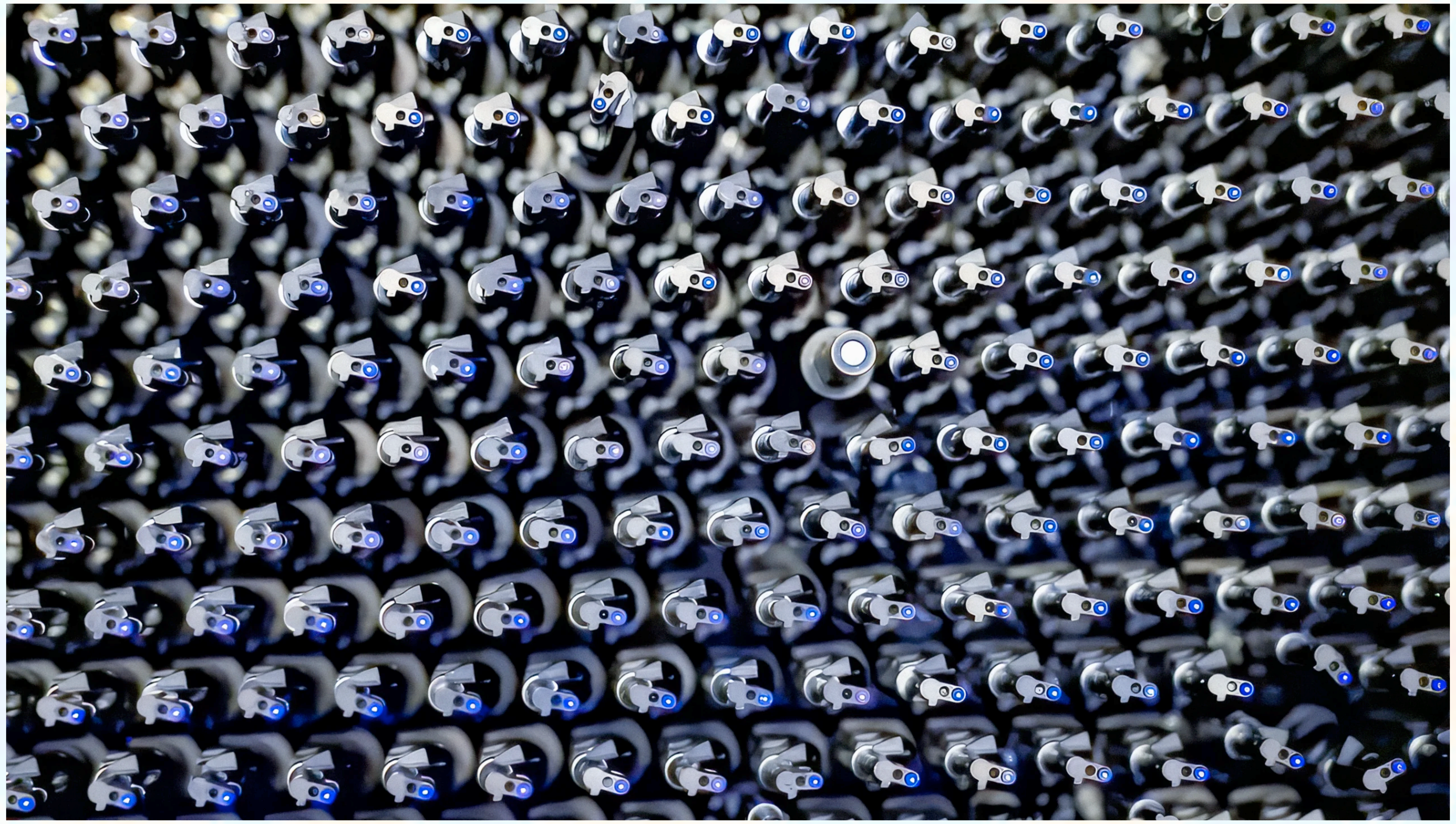
Dark Energy Spectroscopic Instrument

The era of Stage-IV surveys: DESI, Euclid, Rubin



~5,000 (robot) optic fiber positioners

Dark Energy Spectroscopic Instrument

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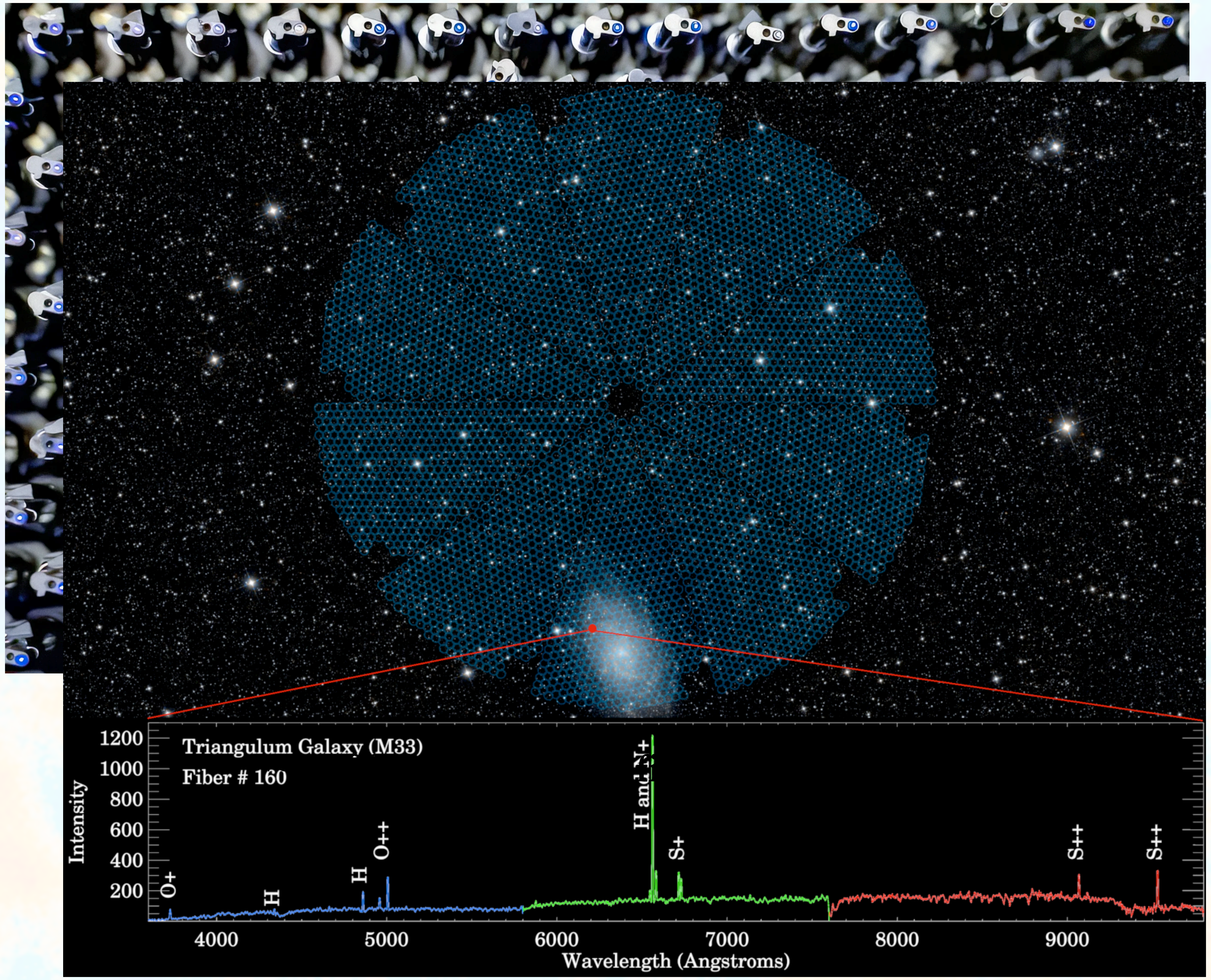

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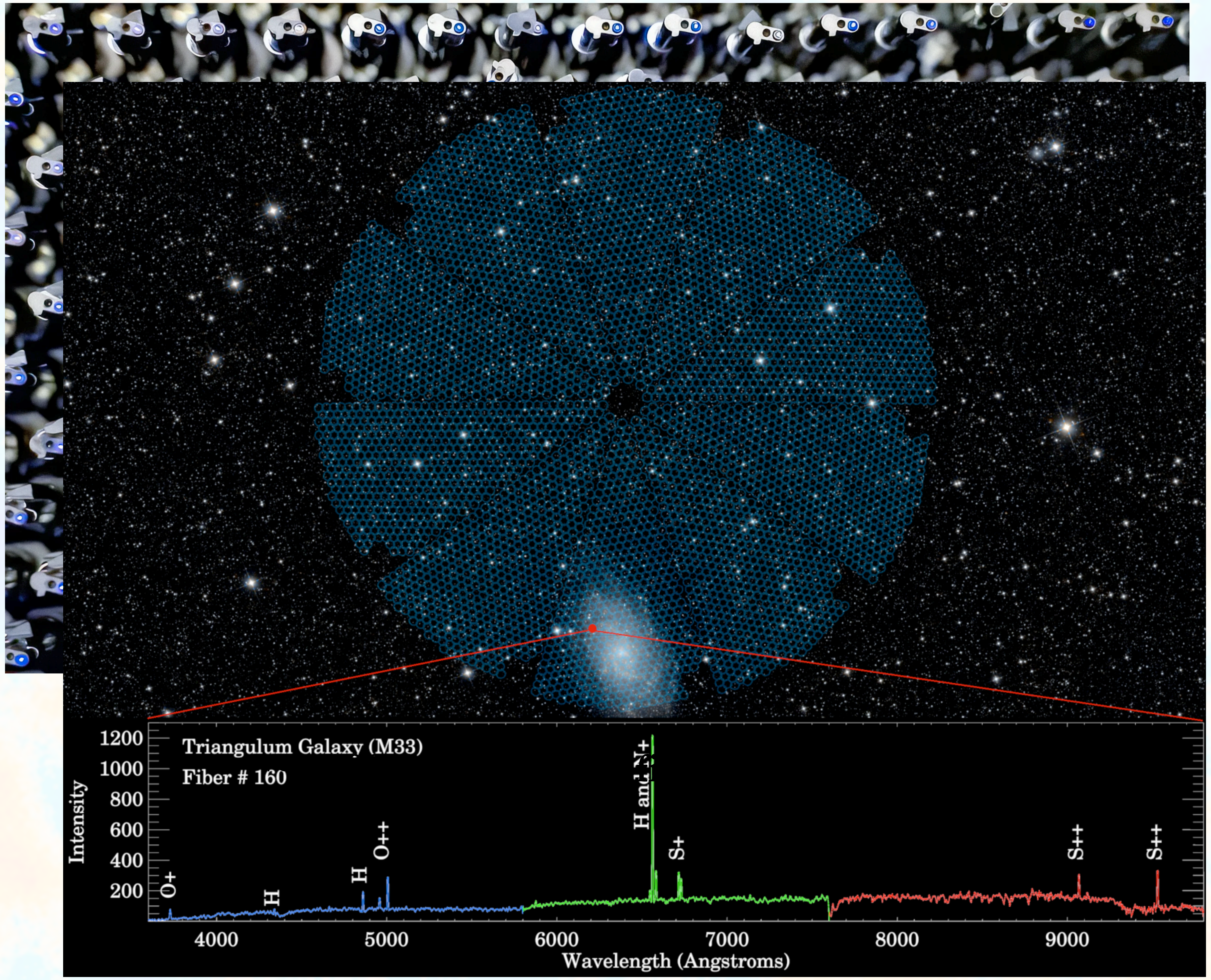
Schematically, LSS probes

$$P_g(z,k,\mu) \sim \underbrace{P_\zeta(k)}_{\text{Inflation}}\ \overbrace{T^2(k)}^{\text{Cosmology}}\ \underbrace{\delta^2(z)}_{\text{Gravity/Expansion}}\ b^2(z\overbrace{,k}^{\text{PNG}})\ \underbrace{\left(1+\beta(z)\mu^2\right)^2}_{\text{Redshift-space}}$$



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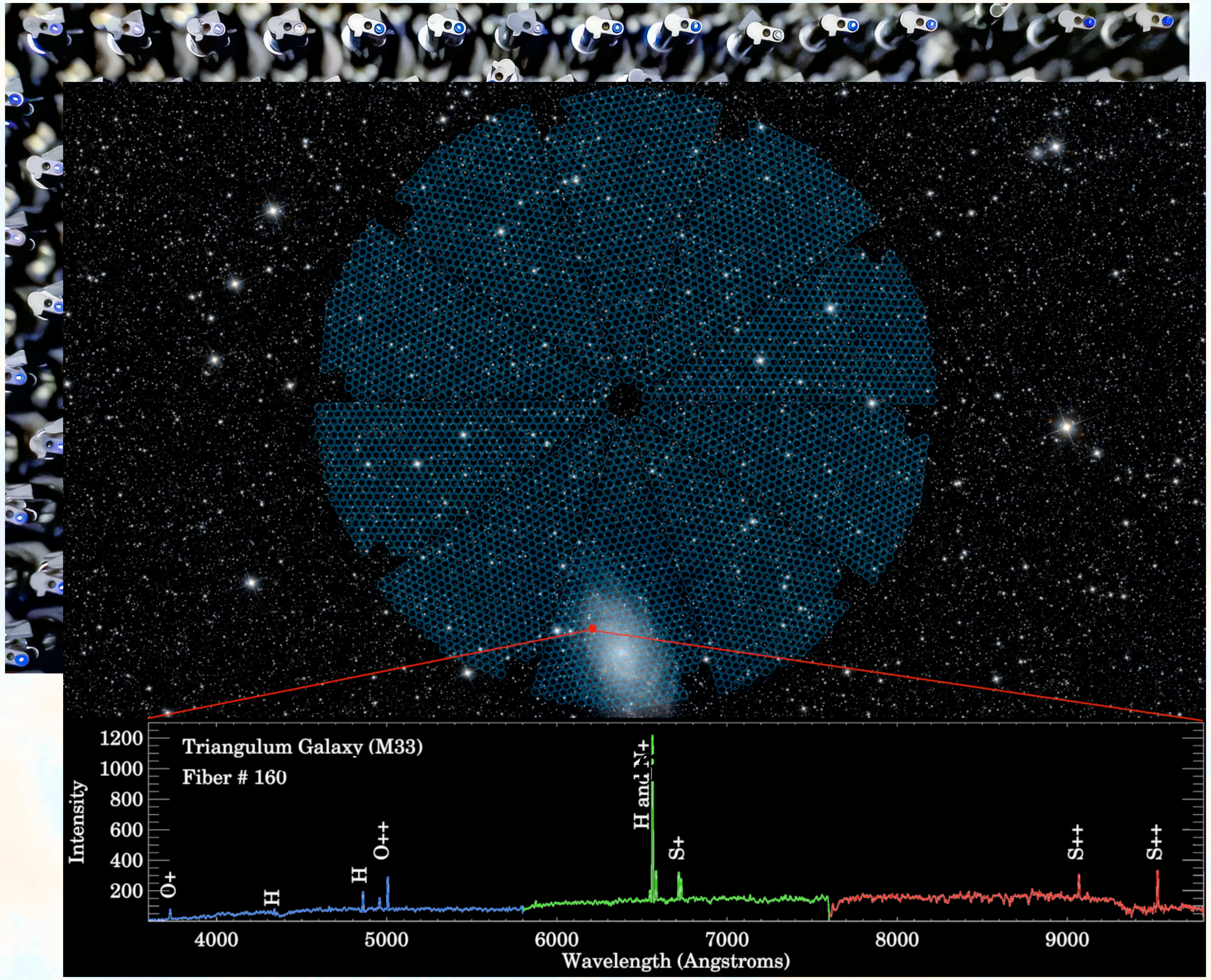
Exquisite measurements of Growth & Expansion Histories!

Modified Expansion $$\frac{H^2(z)}{H_0^2} = \Omega_m a^{-3} + (1-\Omega_m)$$

Modified Growth $$f' + \left(f + 2 + \frac{h'}{h}\right) f = \frac{3}{2}\Omega_m(z)$$



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Modified Expansion
$$\frac{H^2(z)}{H_0^2} = \Omega_m a^{-3} + (1-\Omega_m)\, f_{\rm DE}(z)$$

Modified Growth
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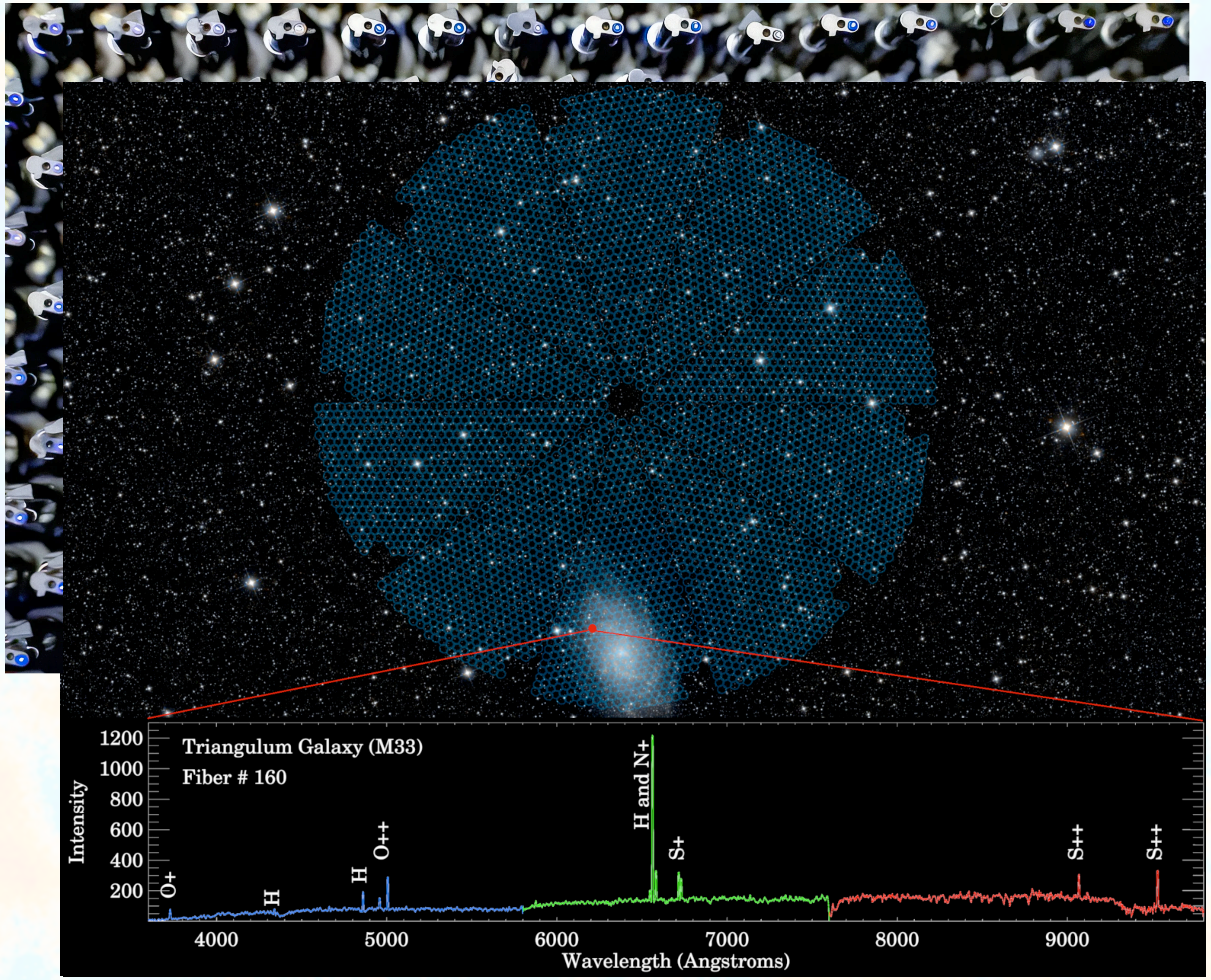


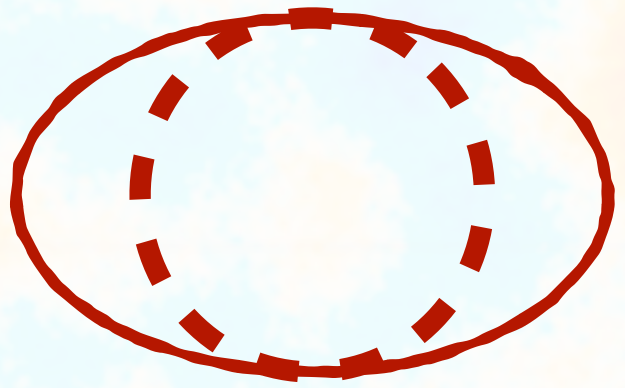

Earth
32 billion light-years

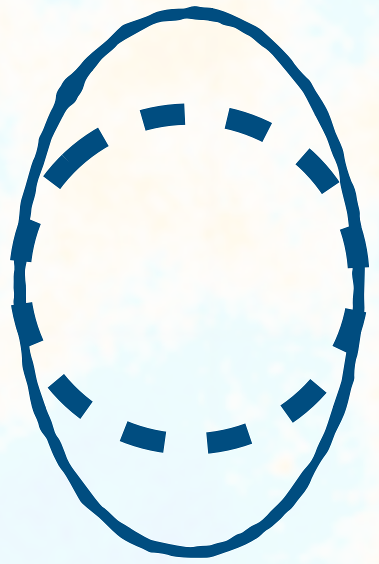
Clustering : 2pt statistics

Raw data in the form :
(z, ϕ, θ)

$$z \xrightarrow{\Theta_{\rm fid} = \Theta^{\rm Planck}_{\Lambda \rm CDM}} r(z)$$

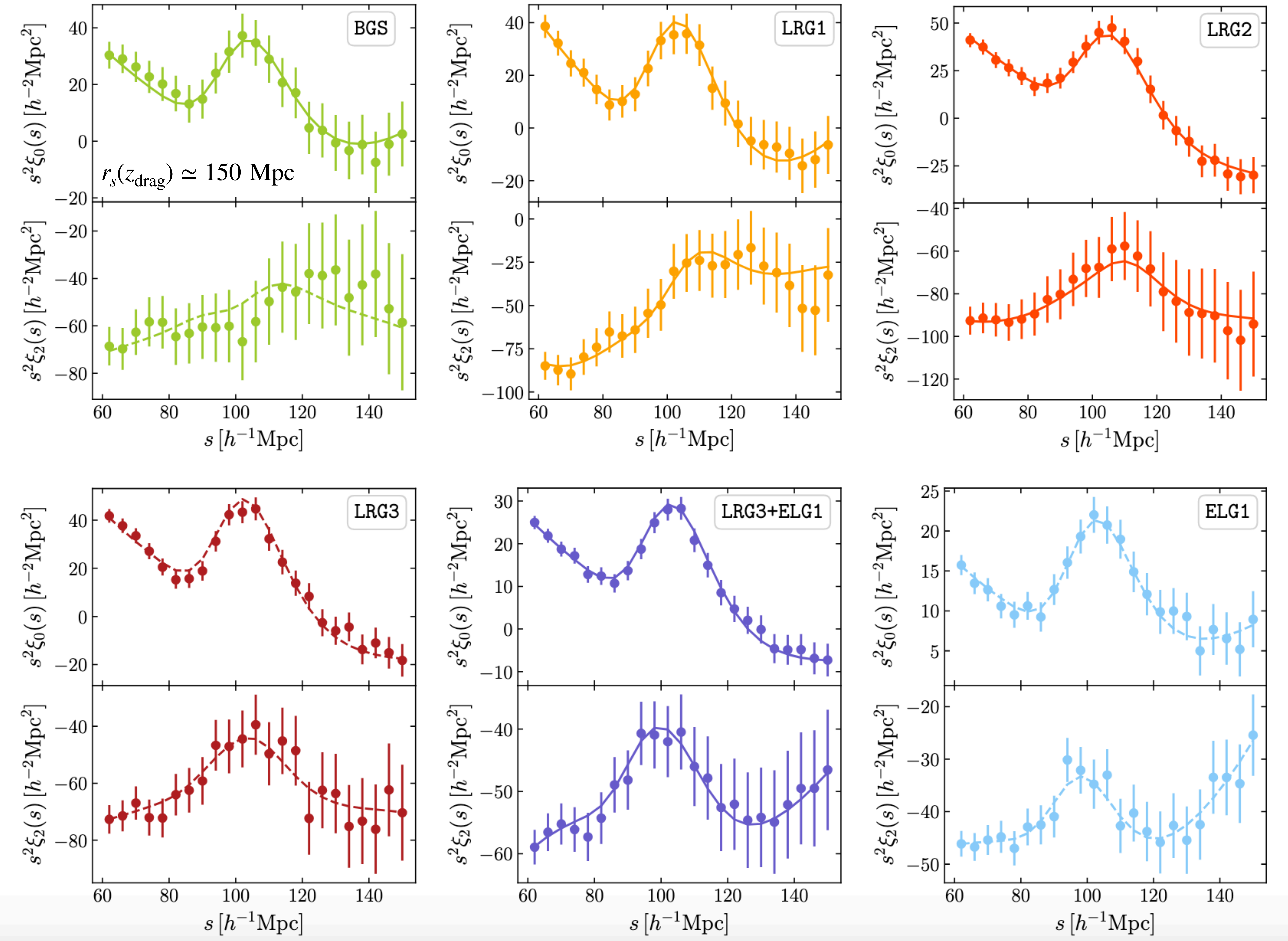
Geometrical "Alcock-Paczyński' (AP) effect





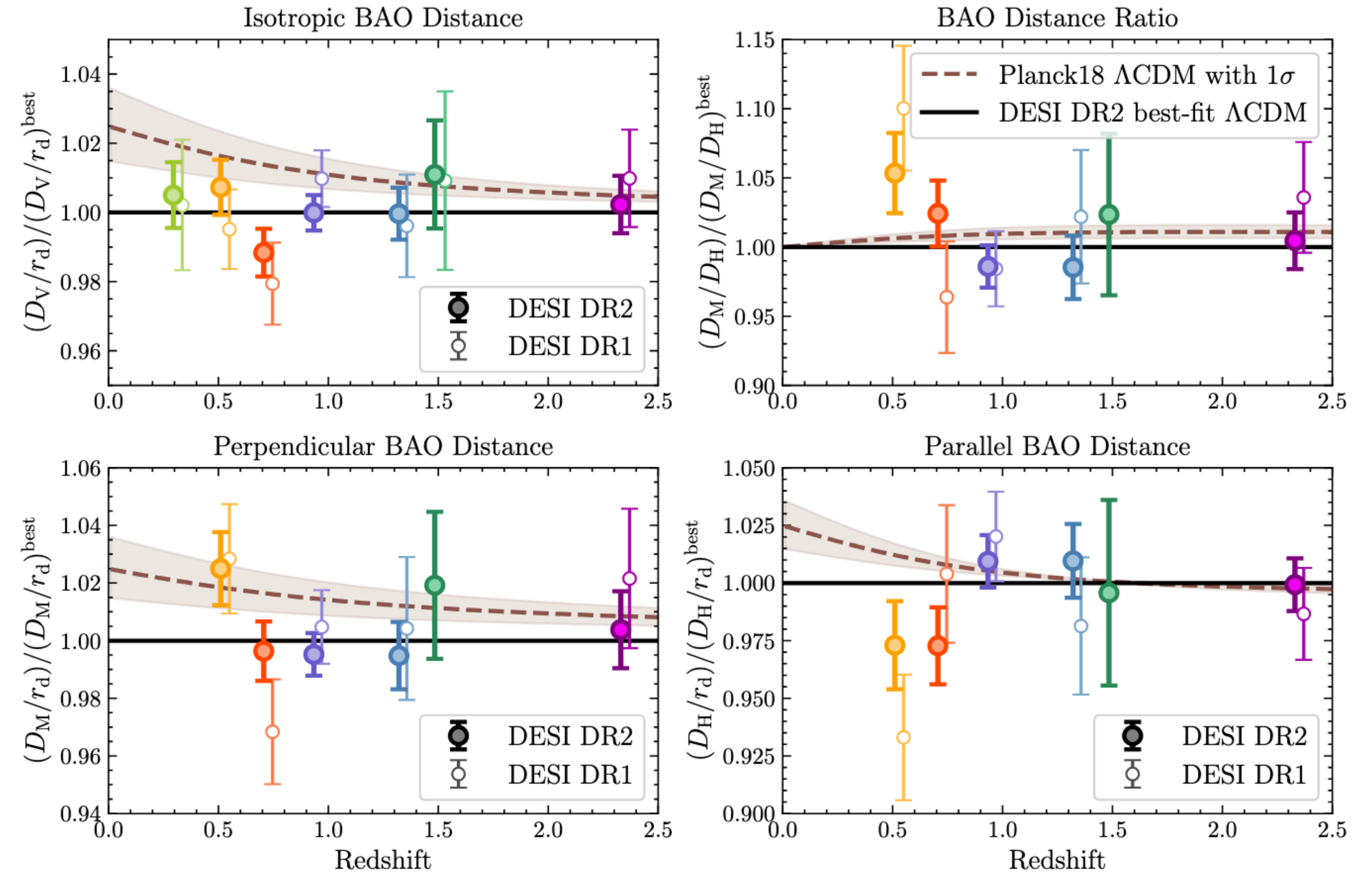
$$\frac{D_M}{r_d} = \alpha_\perp \frac{D_M^{\rm fid}}{r_d^{\rm fid}}$$

$$\frac{D_H}{r_d} = \alpha_{||} \frac{D_H^{\rm fid}}{r_d^{\rm fid}}$$



DESI Collaboration, Abdul-Karim et al - arXiv: 2503.14738

Distance measurements



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$$D_H(z) = H^{-1}(z; \Theta_{cosmo})$$

$$D_M(z) = \int_0^z \frac{dz'}{H(z'; \Theta_{cosmo})}$$

The w_0-w_a plane

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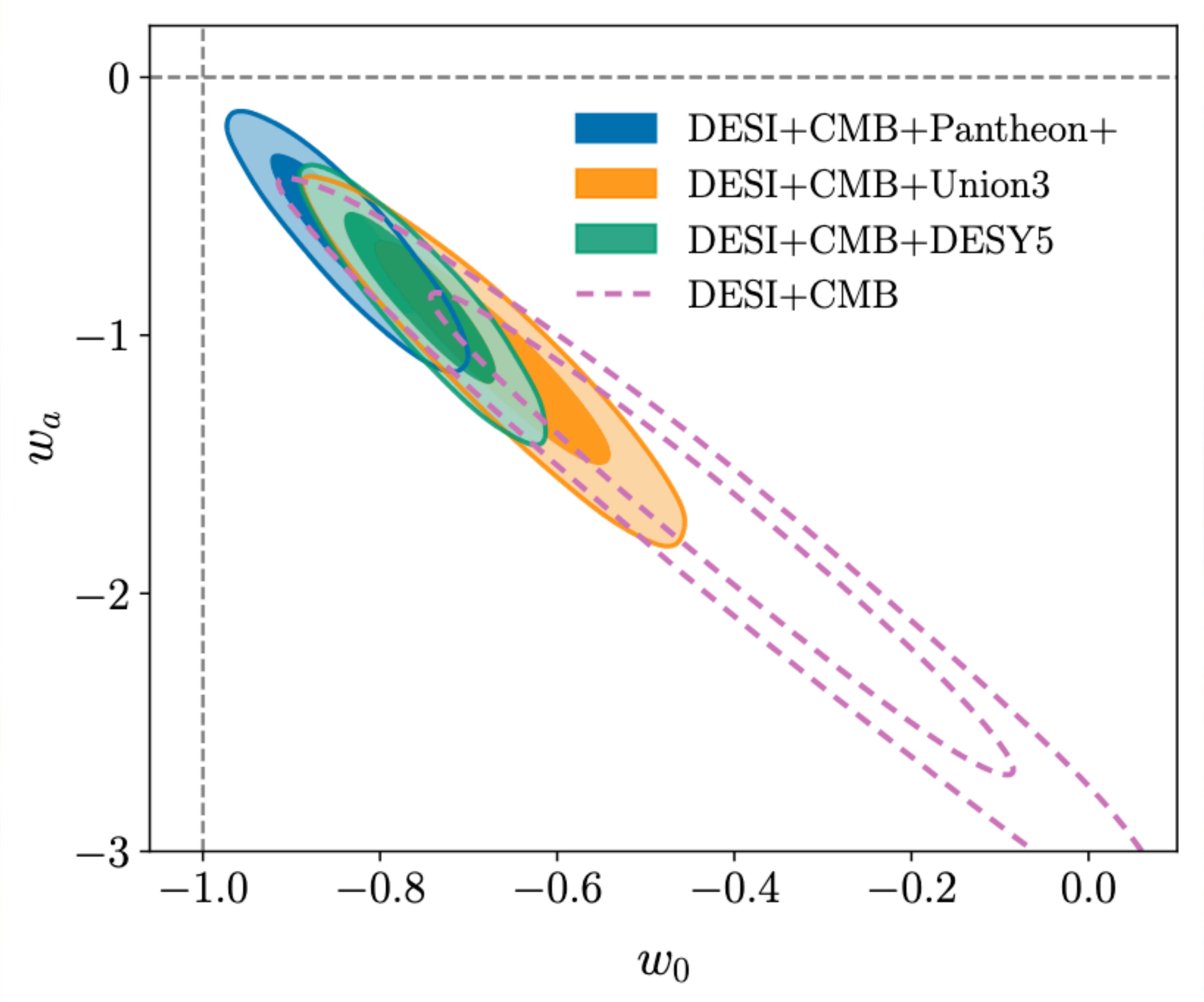

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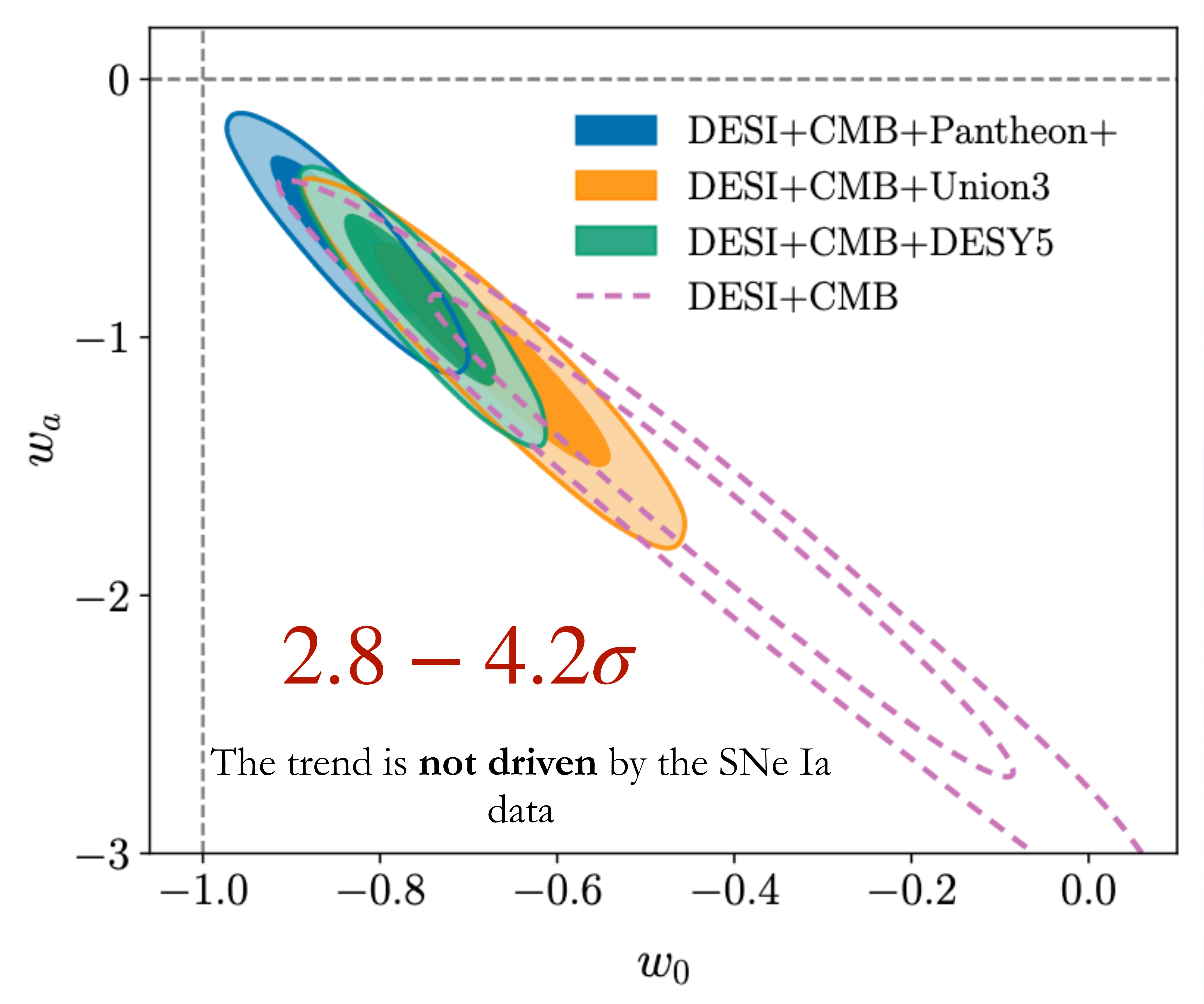

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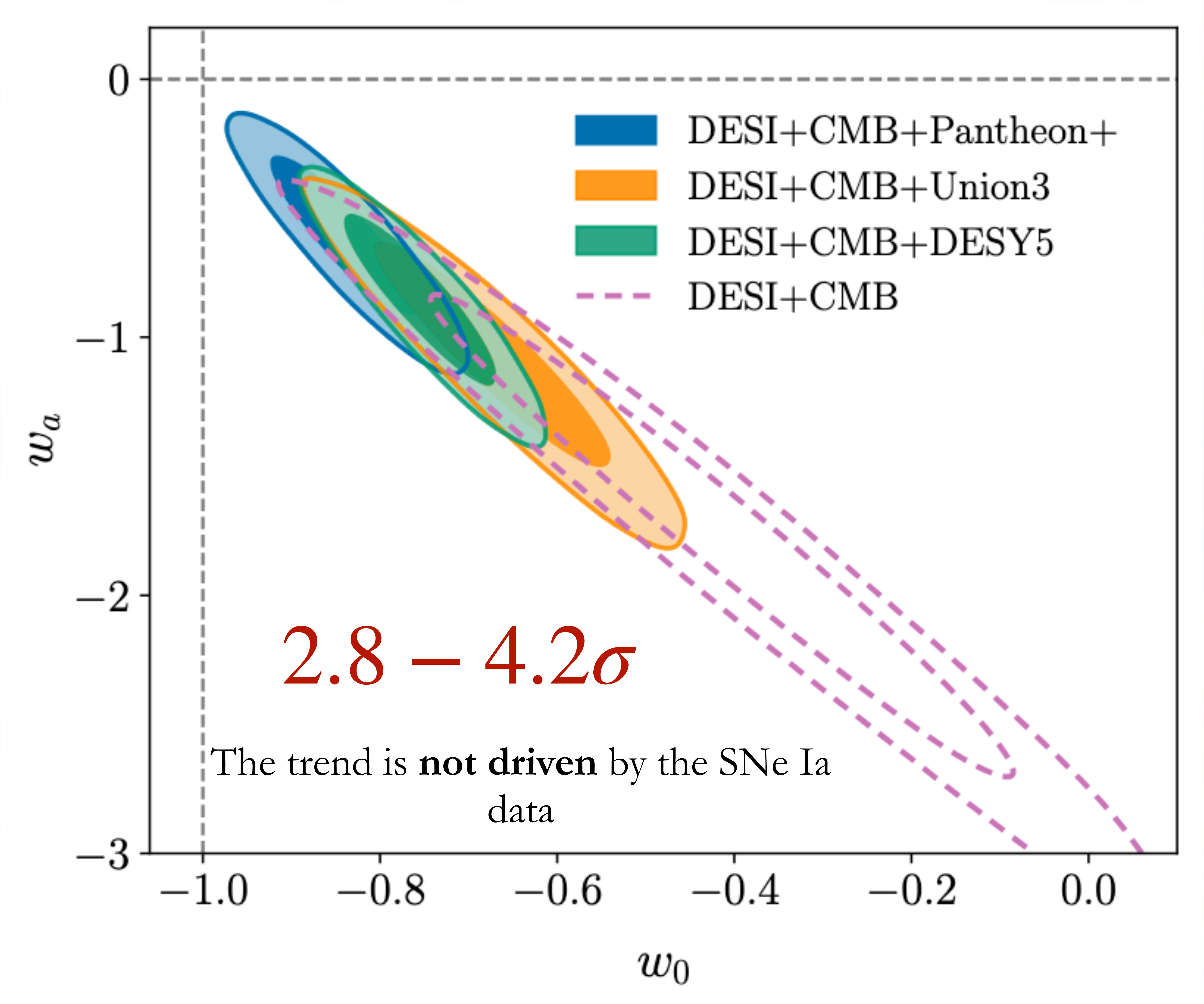

- $w(a) = w_0 + w_a(1 - a)$ is a "phenomenological" parametrisation

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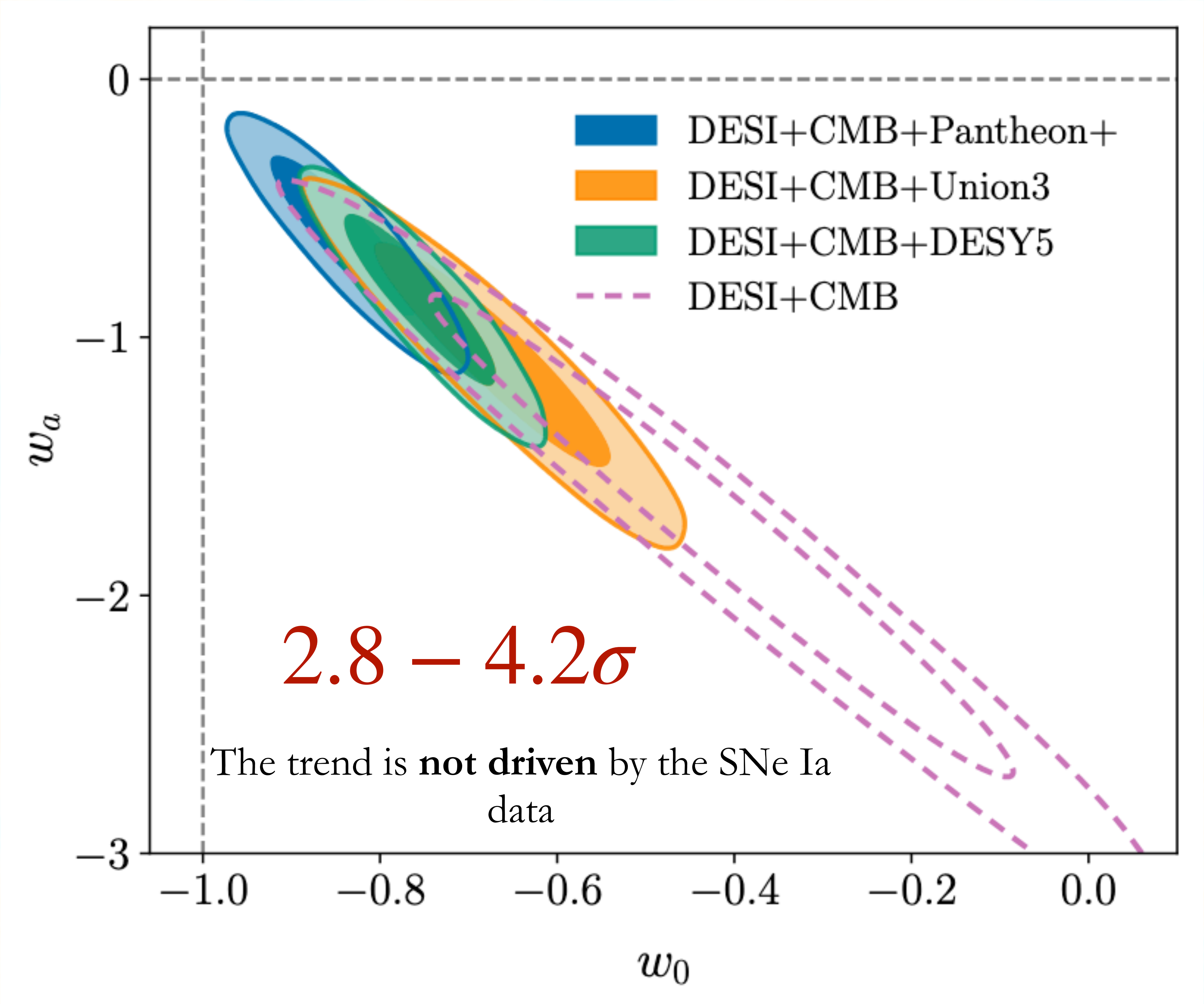

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- Extremely efficient in approximating the observables, i.e. $D_A(z)$ & $H(z)$

  NOT $w(z)$ itself!

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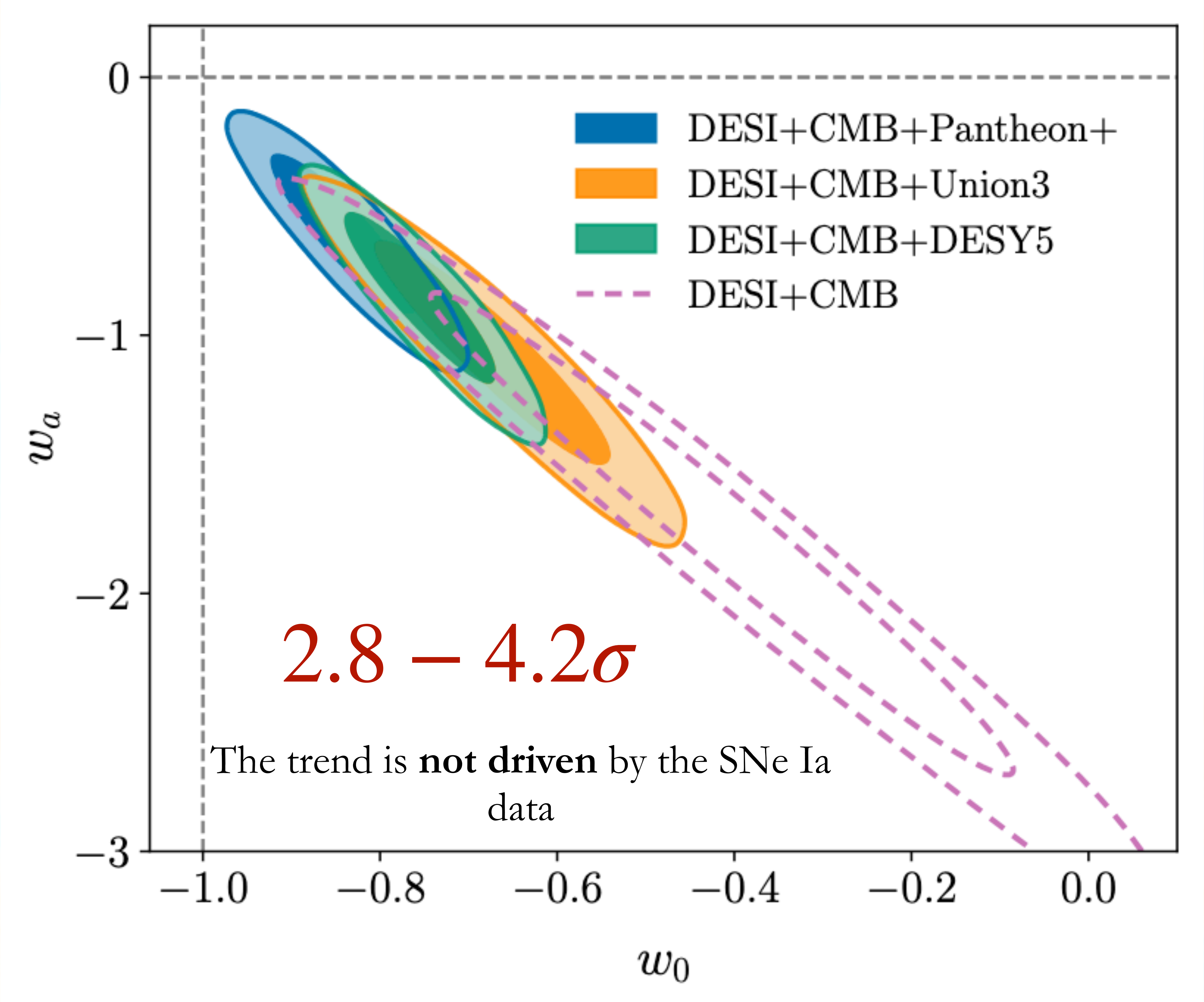

$2.8 - 4.2\sigma$

The trend is **not driven** by the SNe Ia data

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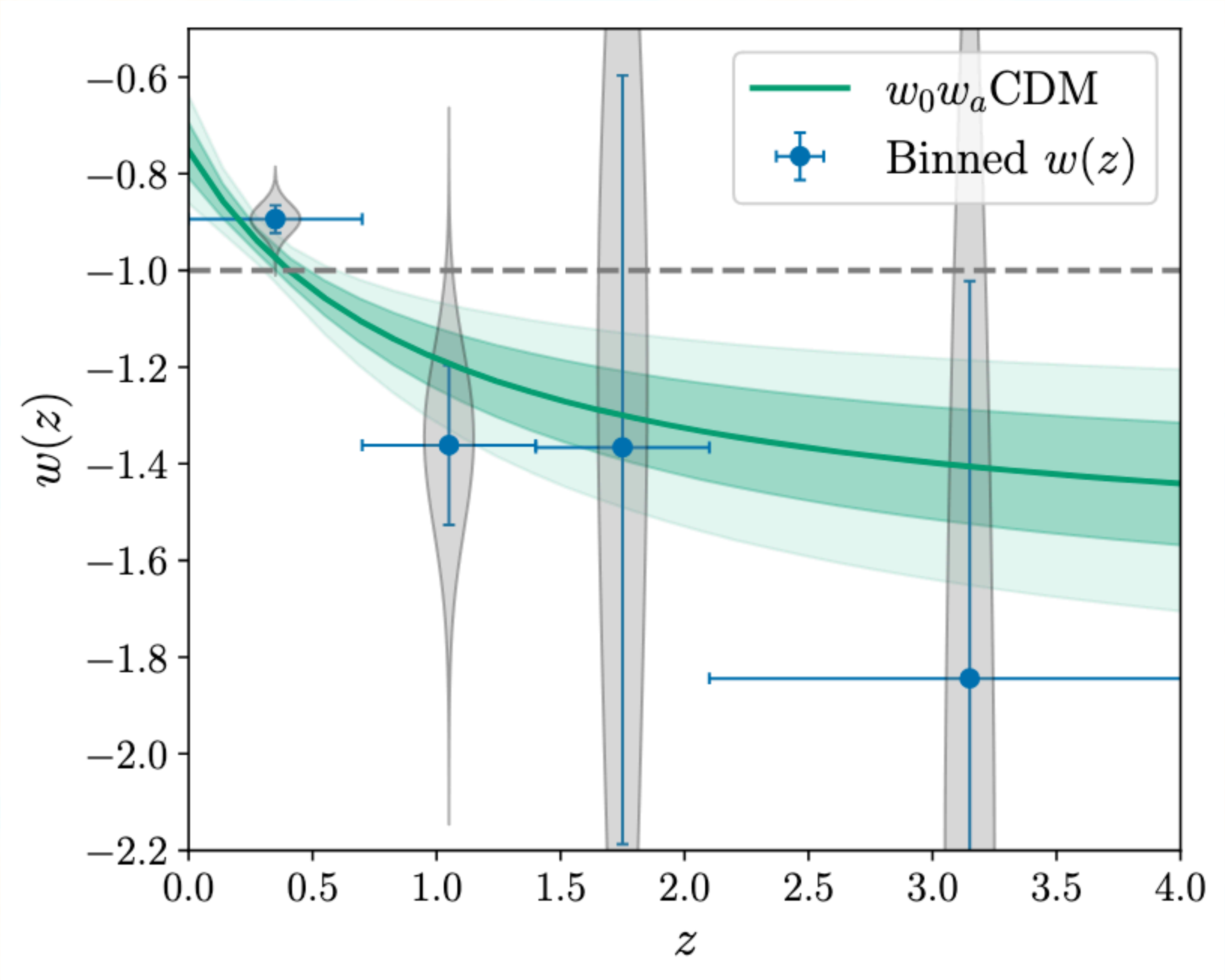

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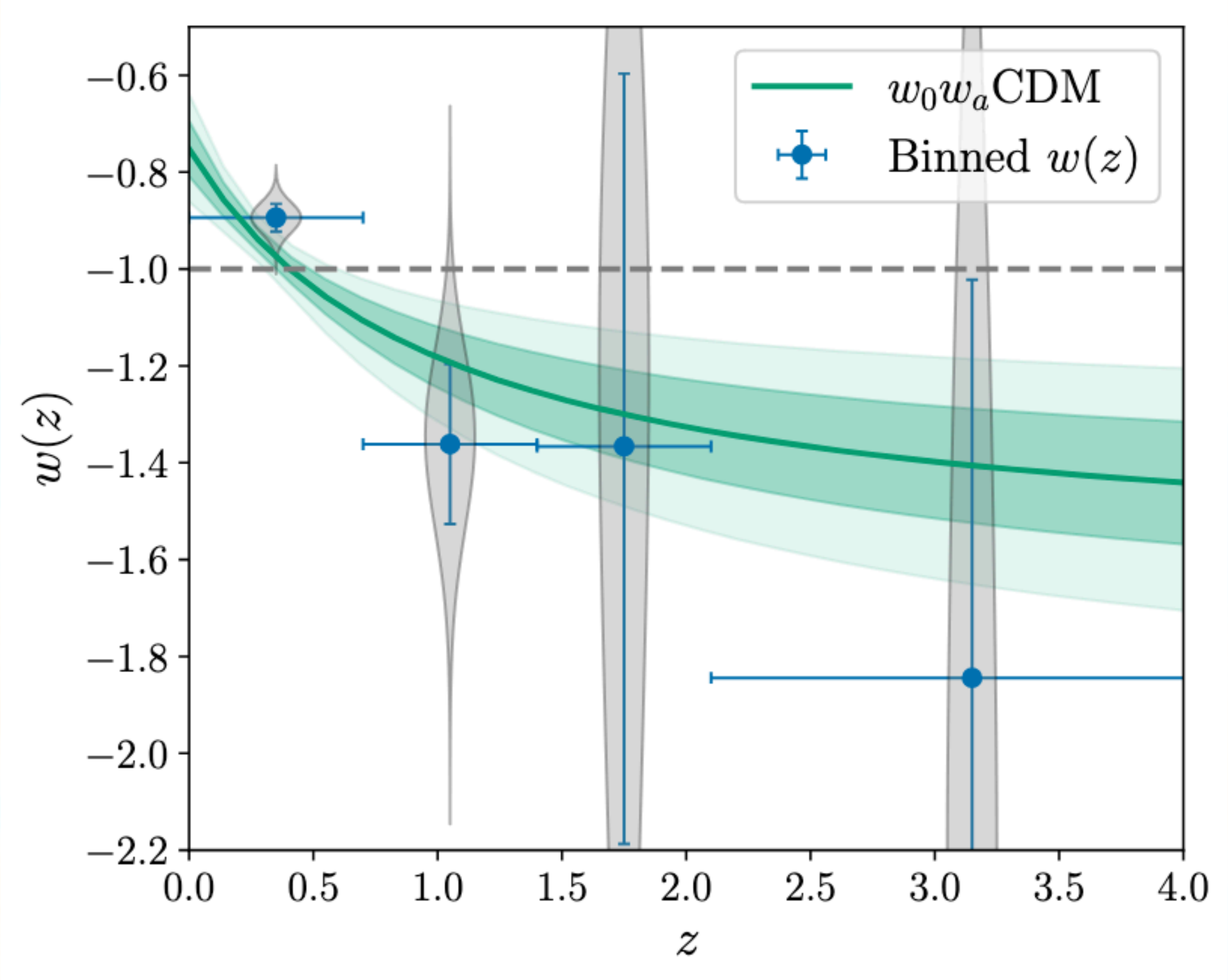

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Minimally-coupled scalar field ϕ

$$w_\phi(z) = \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \longrightarrow \boxed{-1 \leq w_\phi(z) \leq 1}$$

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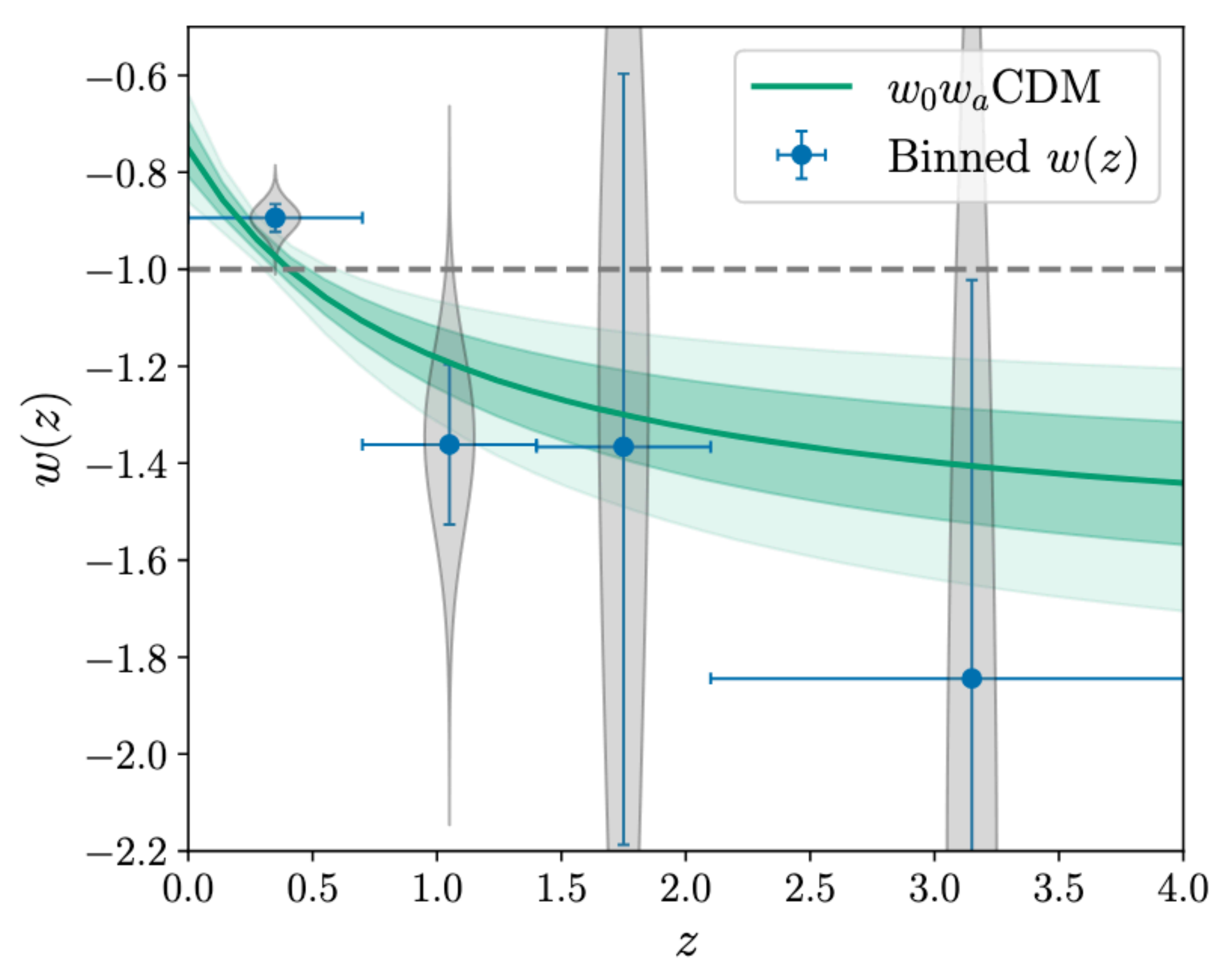

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How robust are these results?

Beyond a linearly evolving $w(a)$

$$3M_{\rm Pl}^2 H^2(z) = \rho_m(z) + \rho_{\rm DE}(z) + \ldots$$

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Chebyshev Polynomial Expansion

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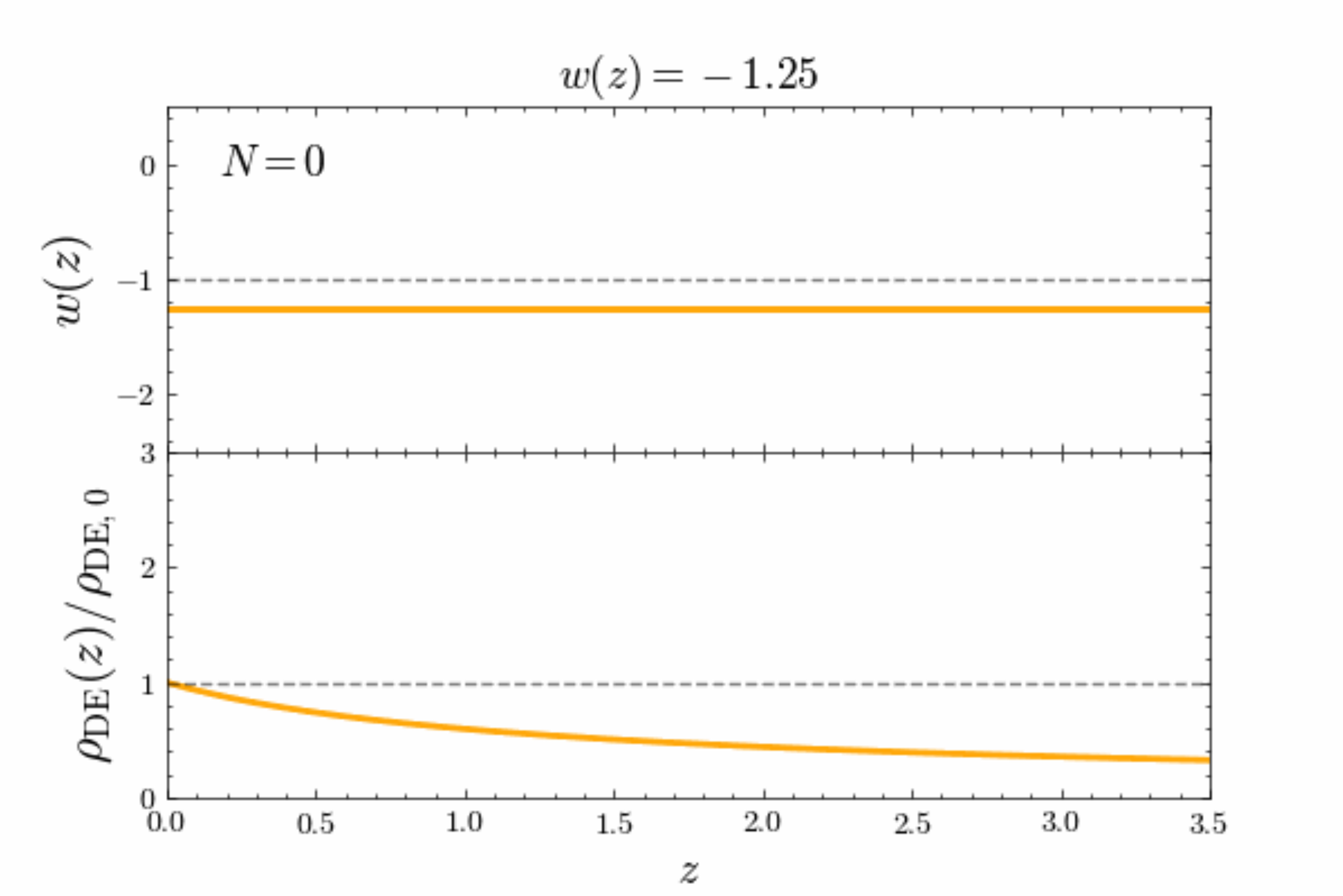

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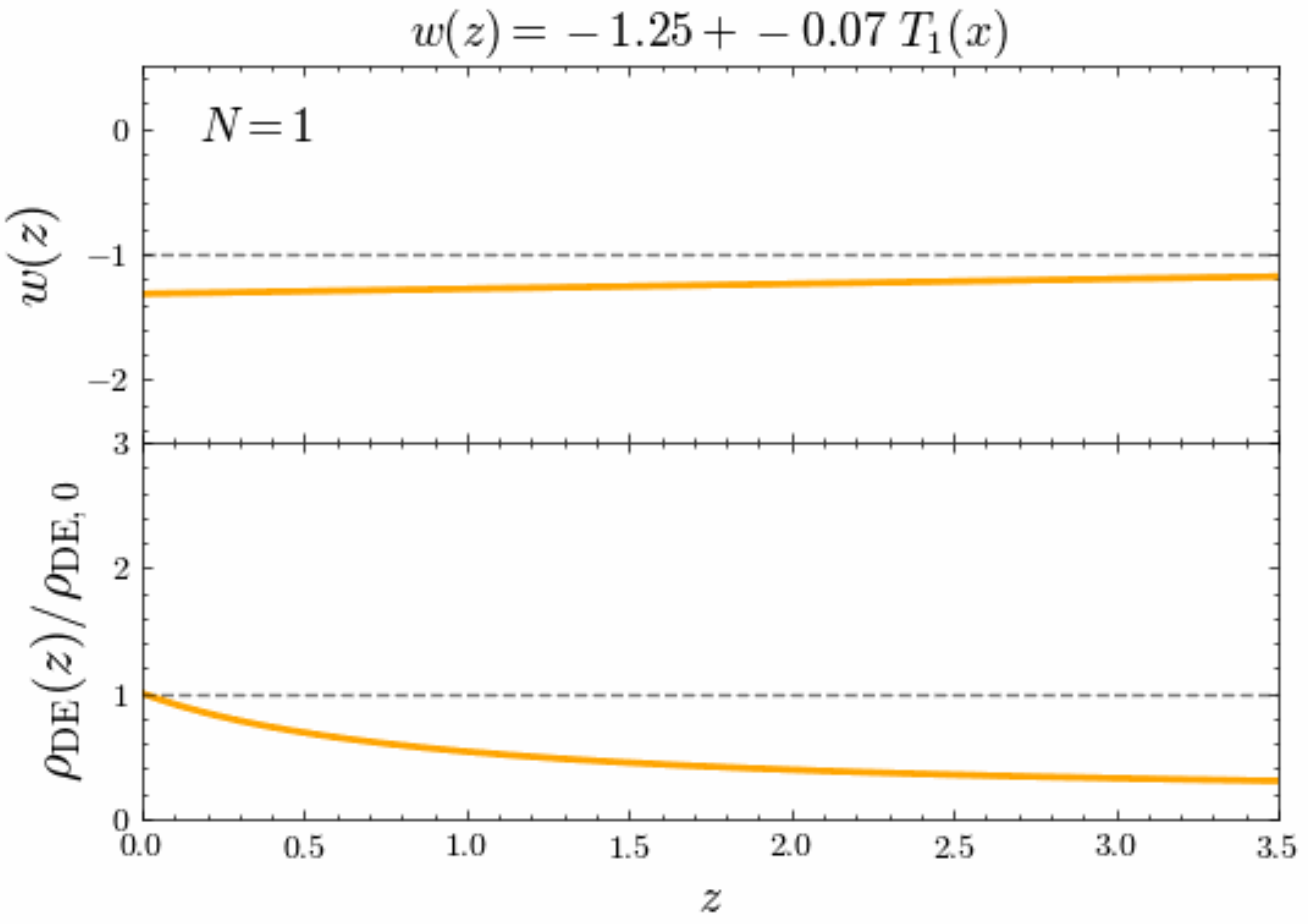

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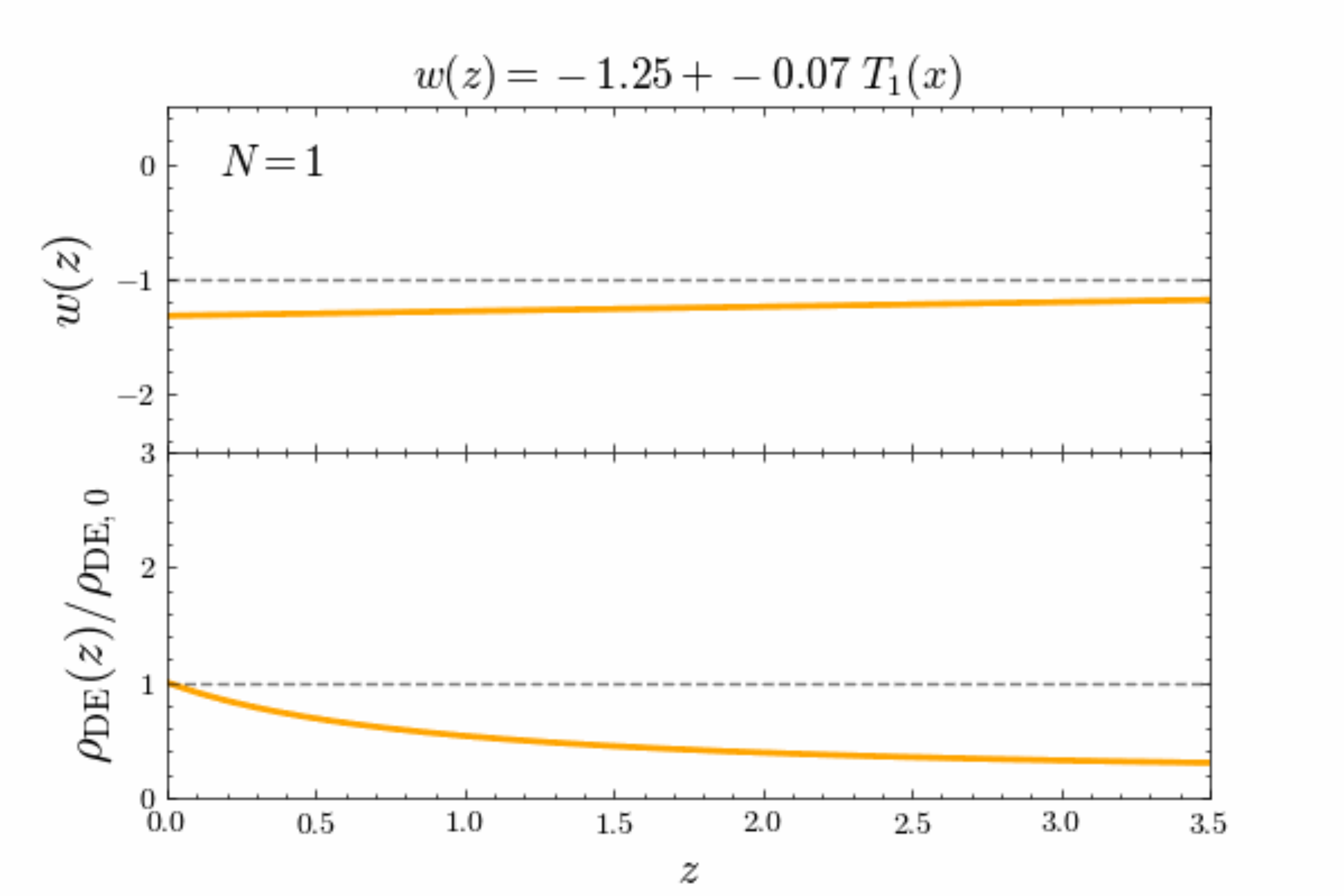

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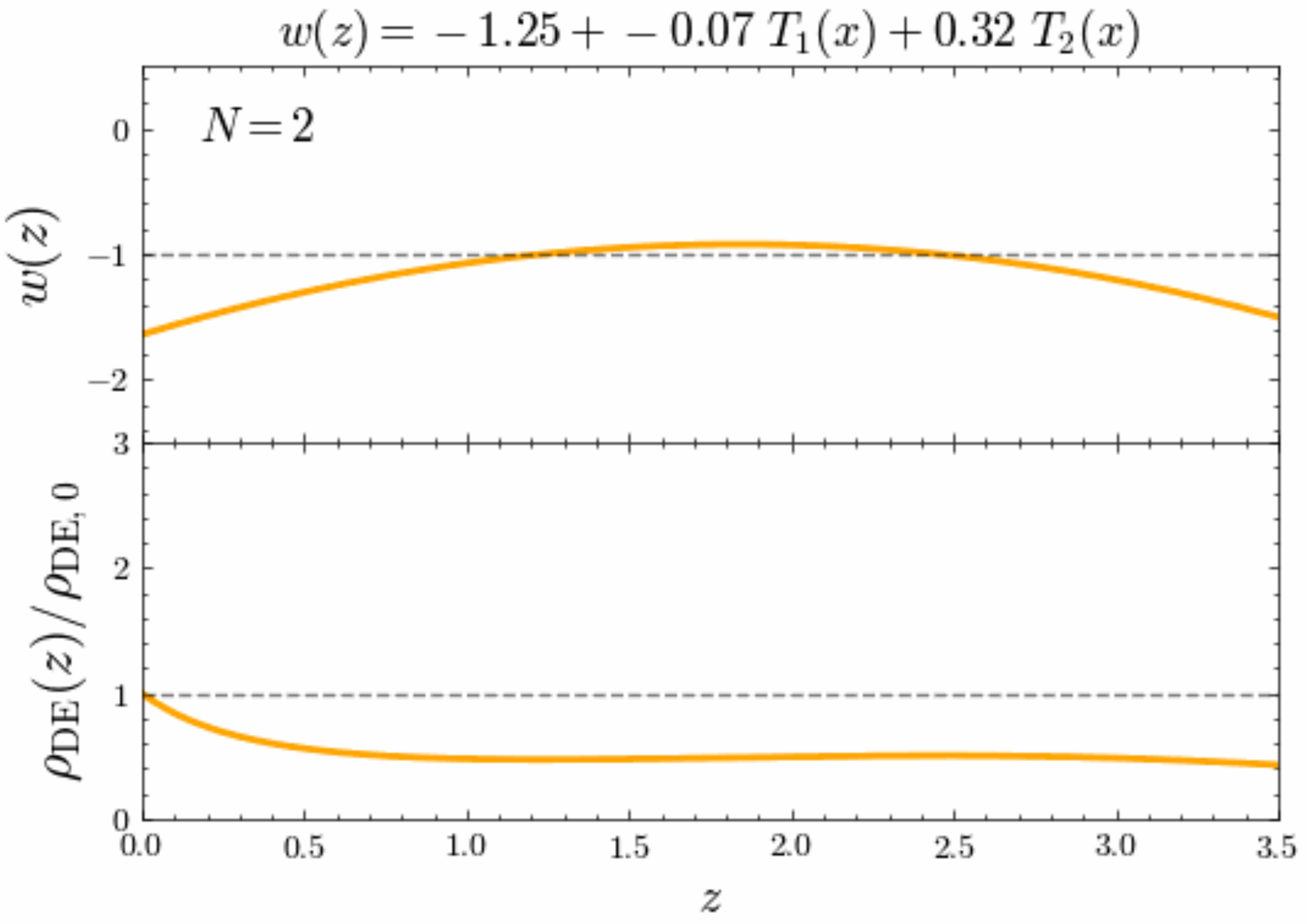

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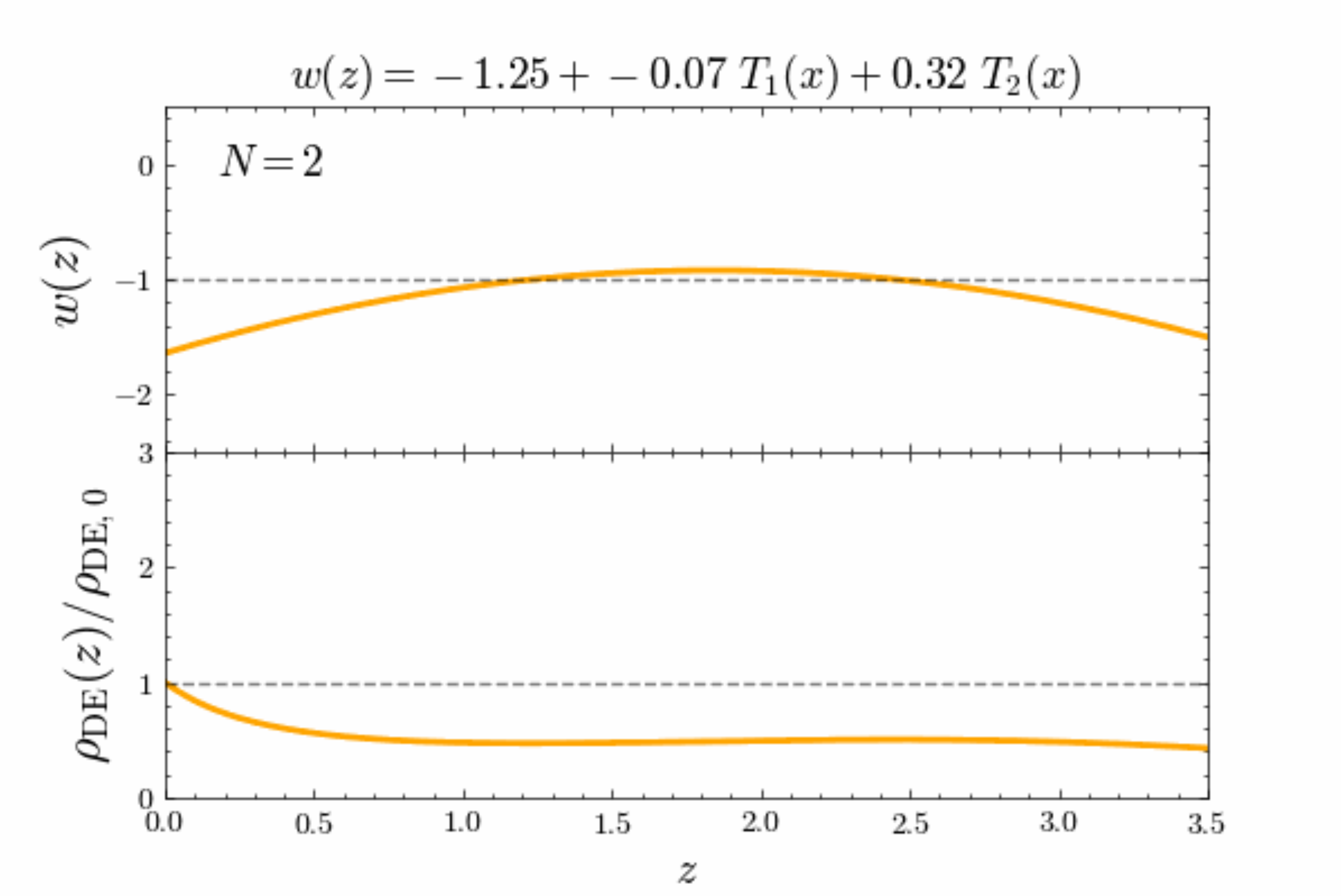

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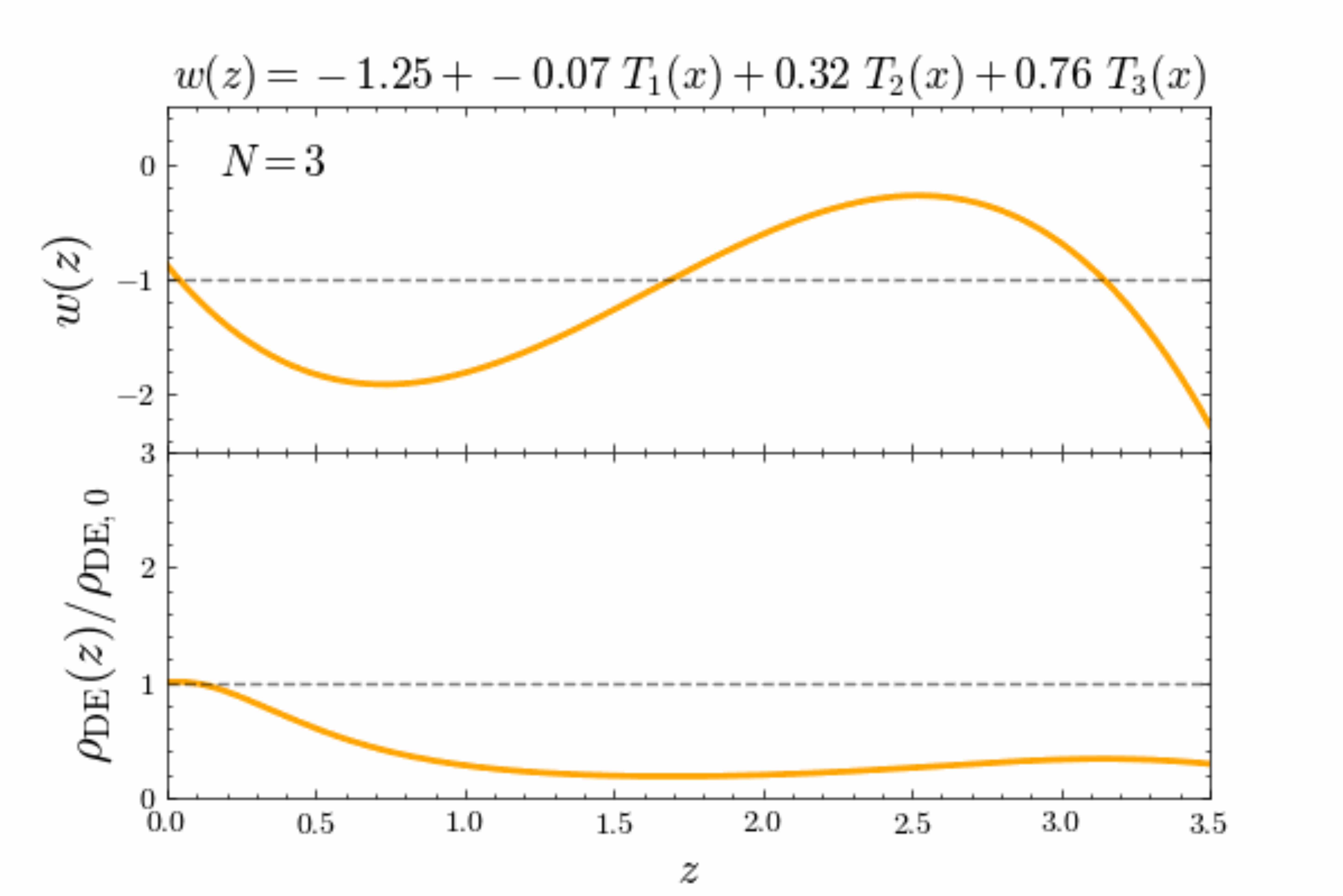

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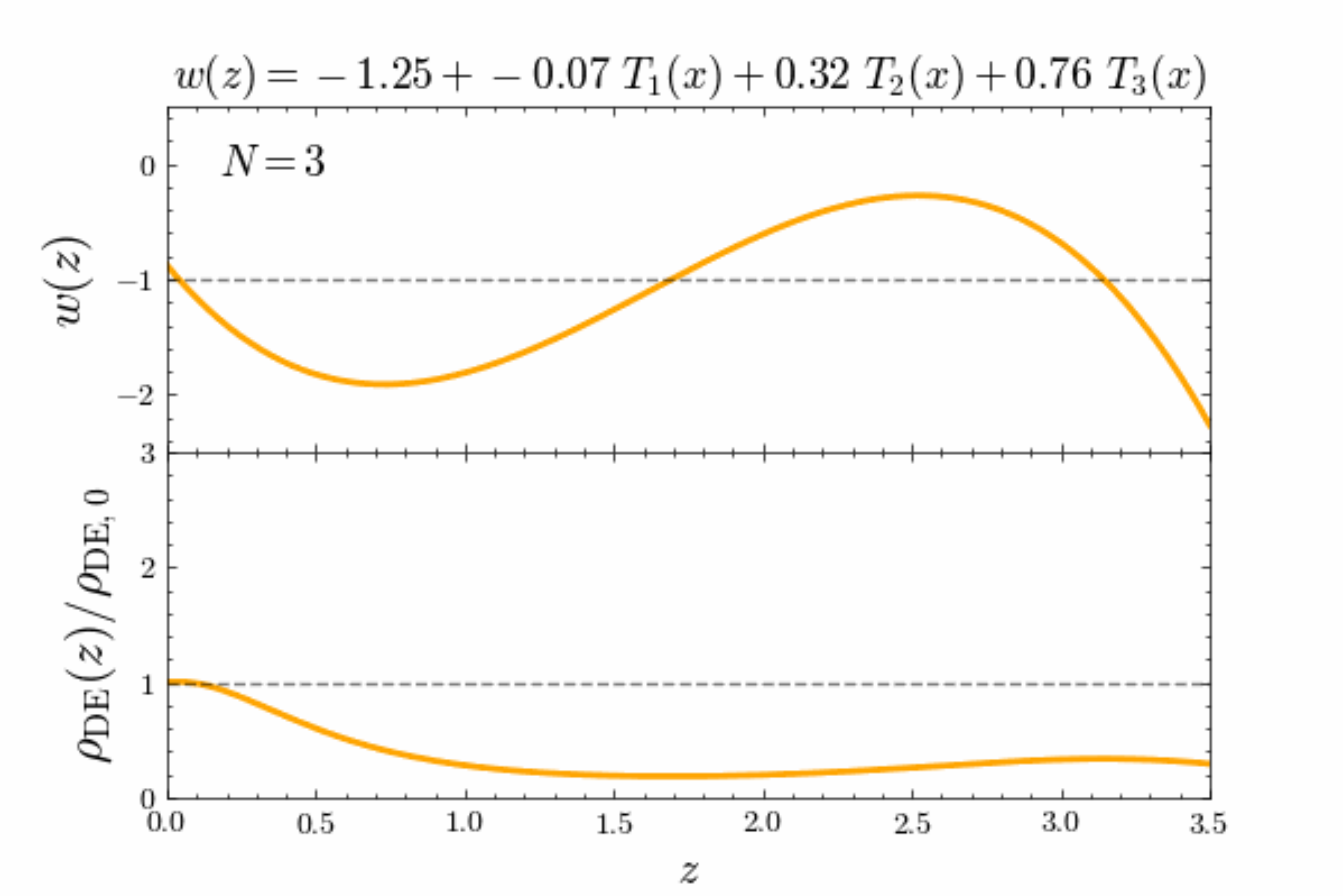

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DESI Collaboration, K. Lodha, **R. Calderon**, W. Matthewson, A. Shafieloo et al.
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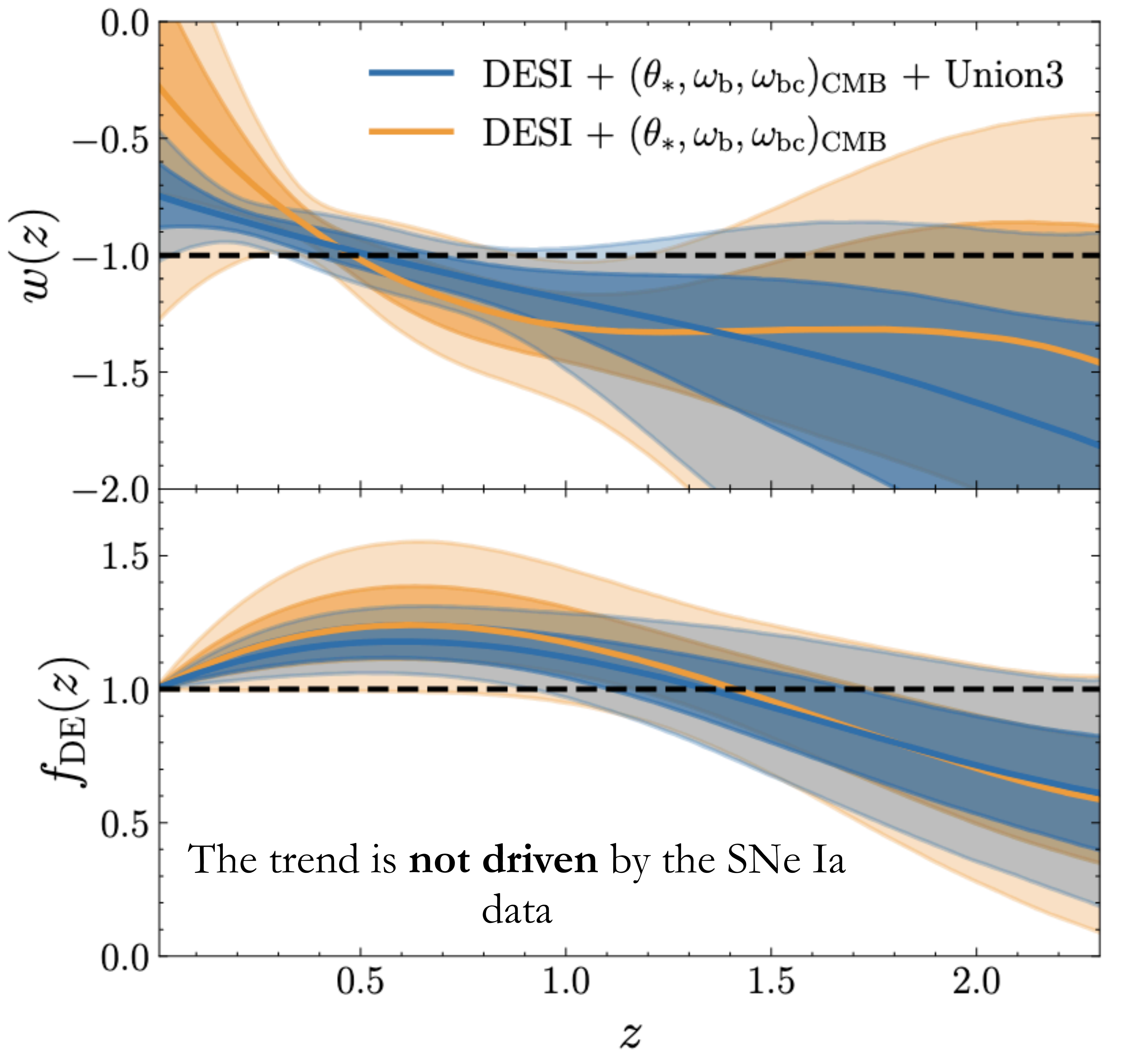

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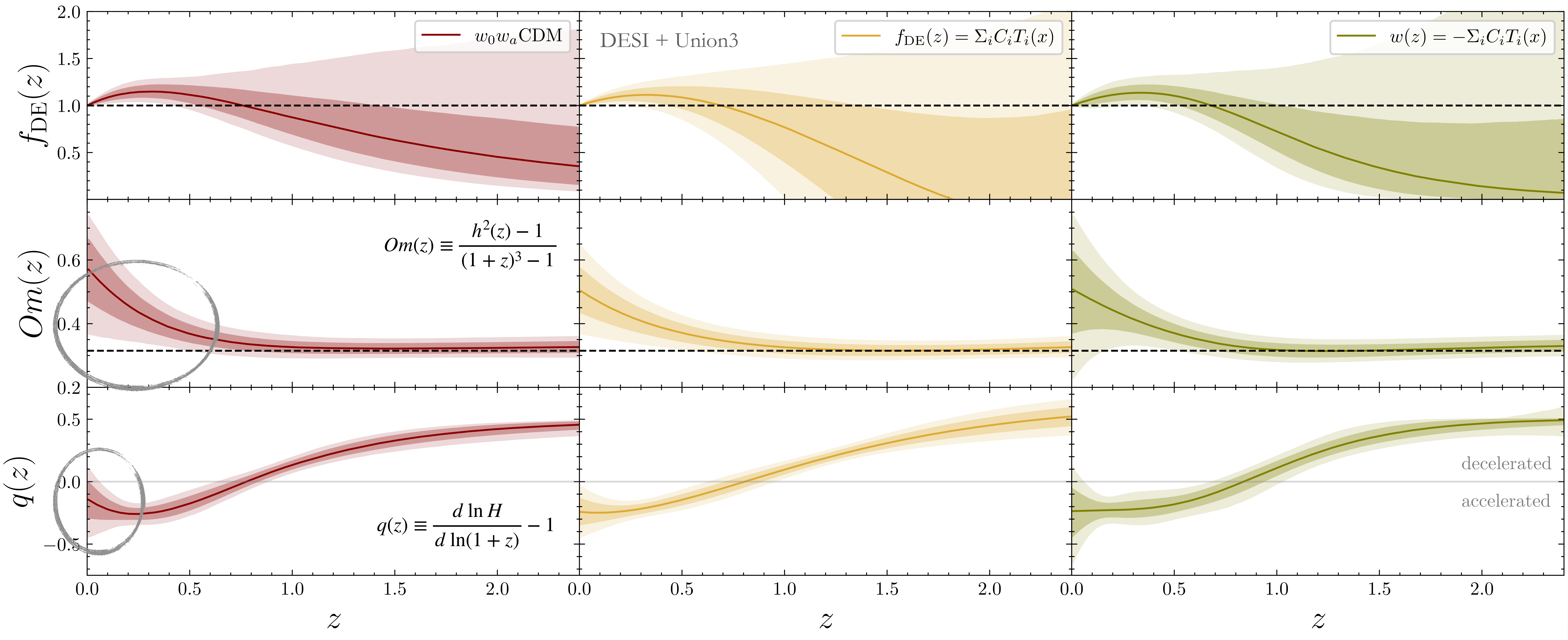
Robustness of the results



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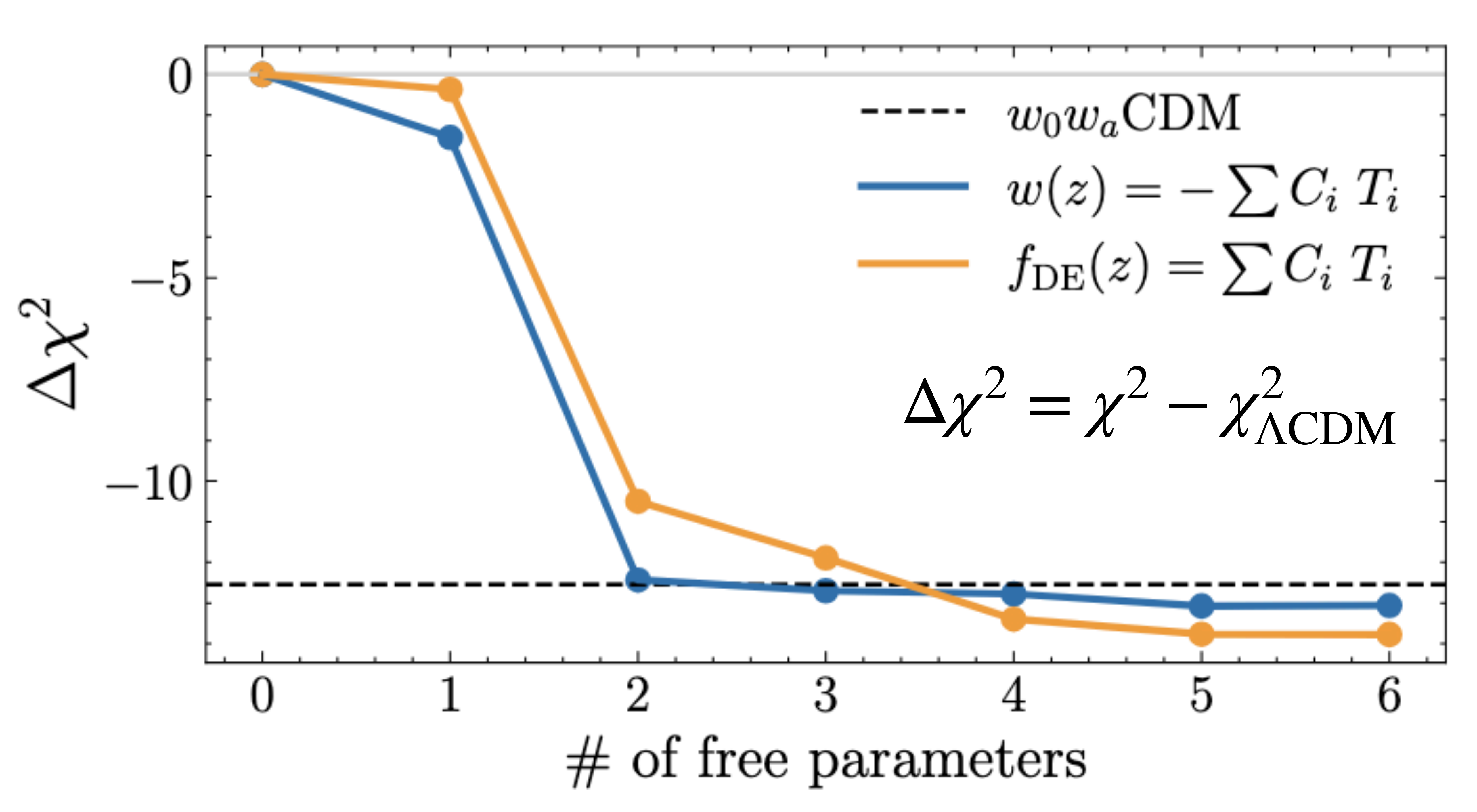

χ^2 'saturates' at ~2 free parameters

Additional degrees of freedom are **NOT** justified/required by the data

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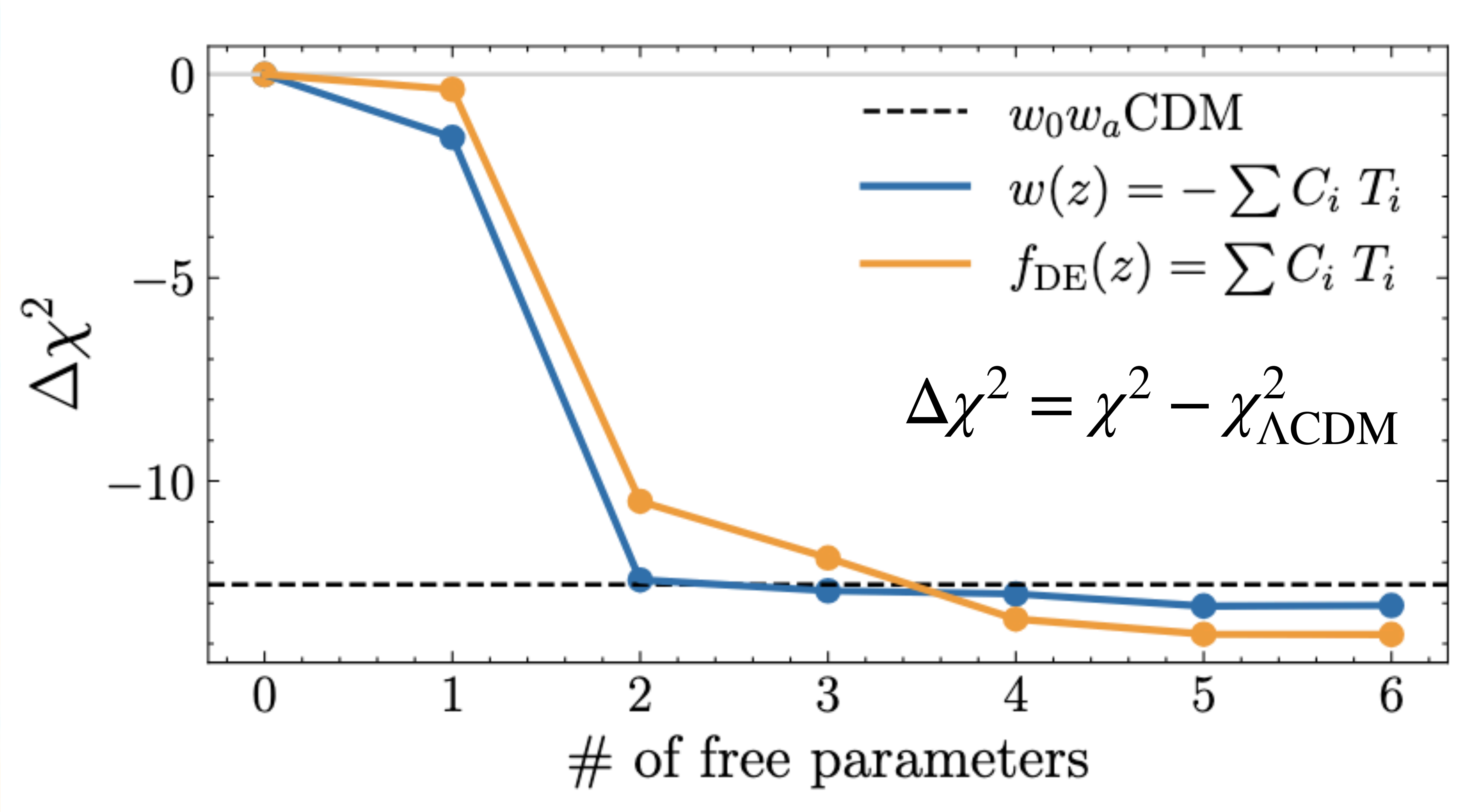

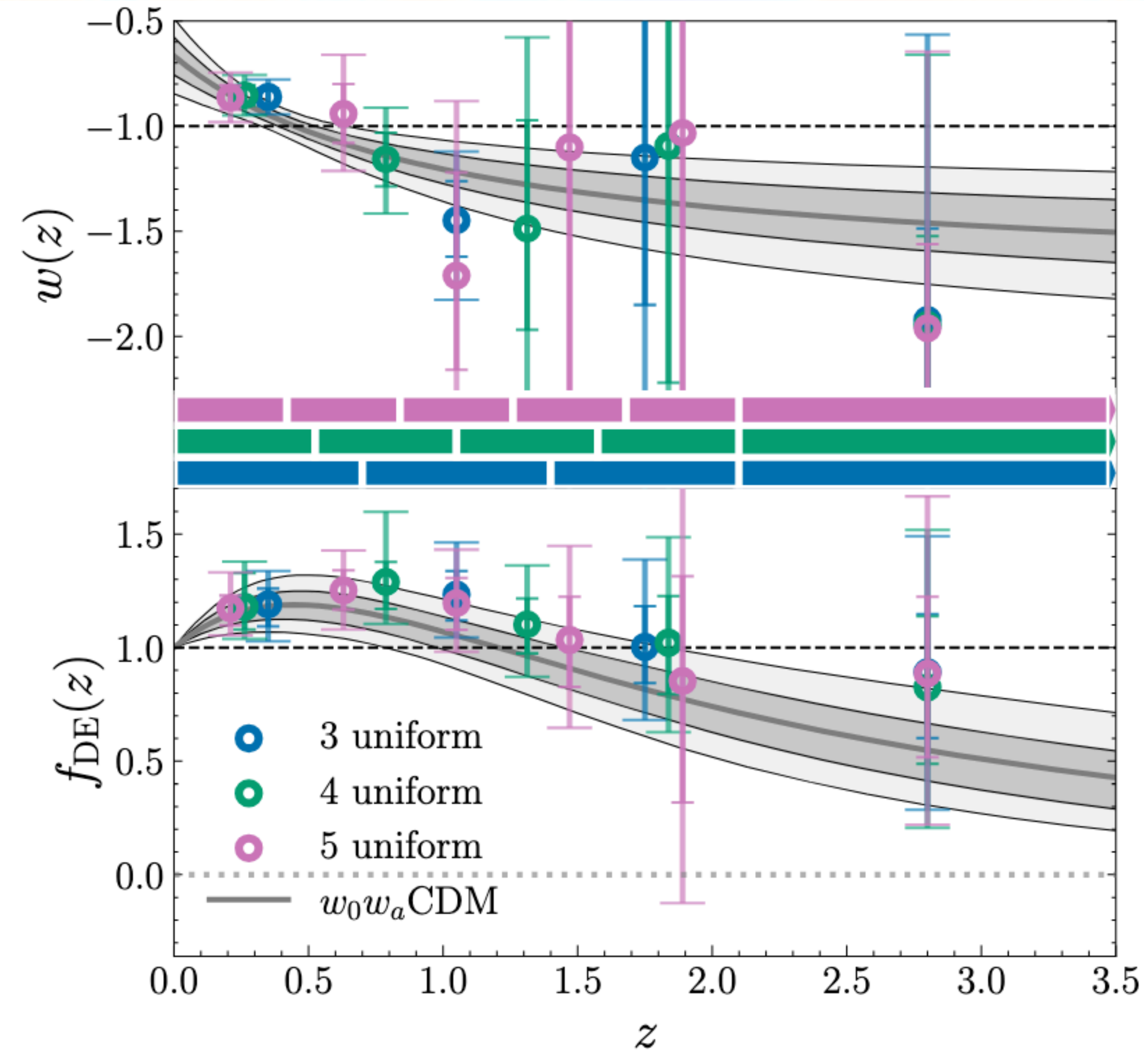

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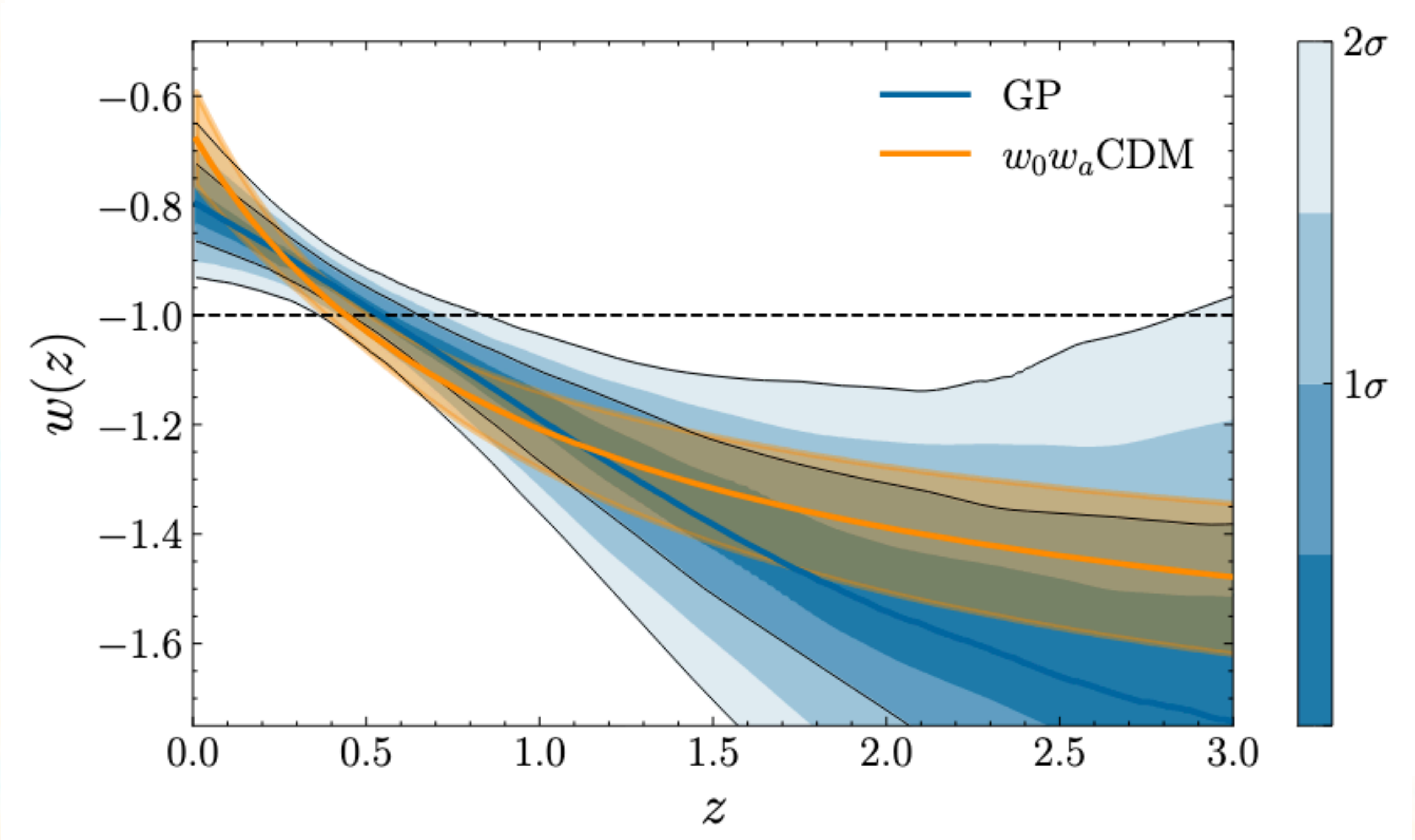

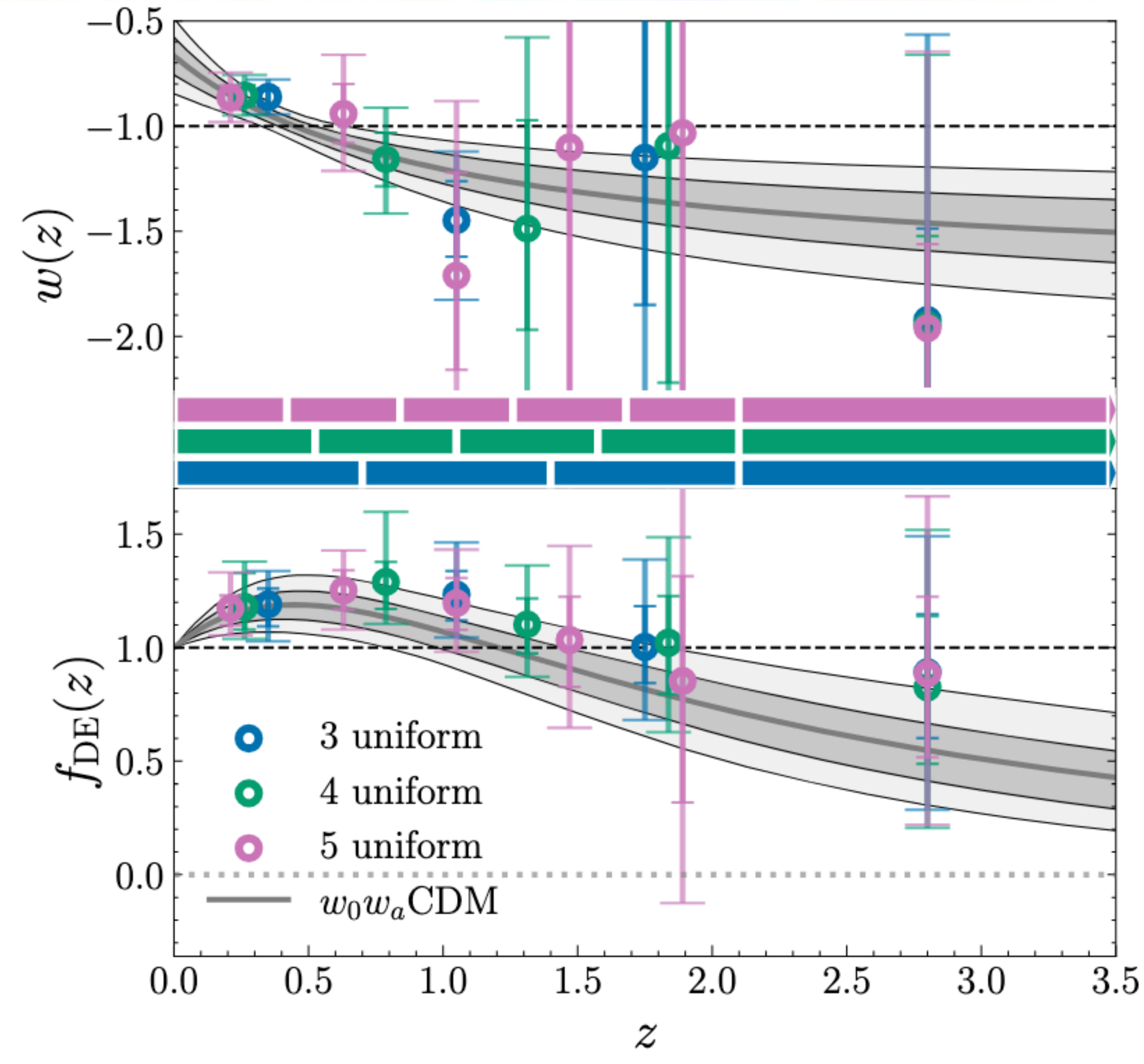

All parametric and non-parametric methods suggest **the same DE behaviour**, in agreement with w_0w_aCDM.

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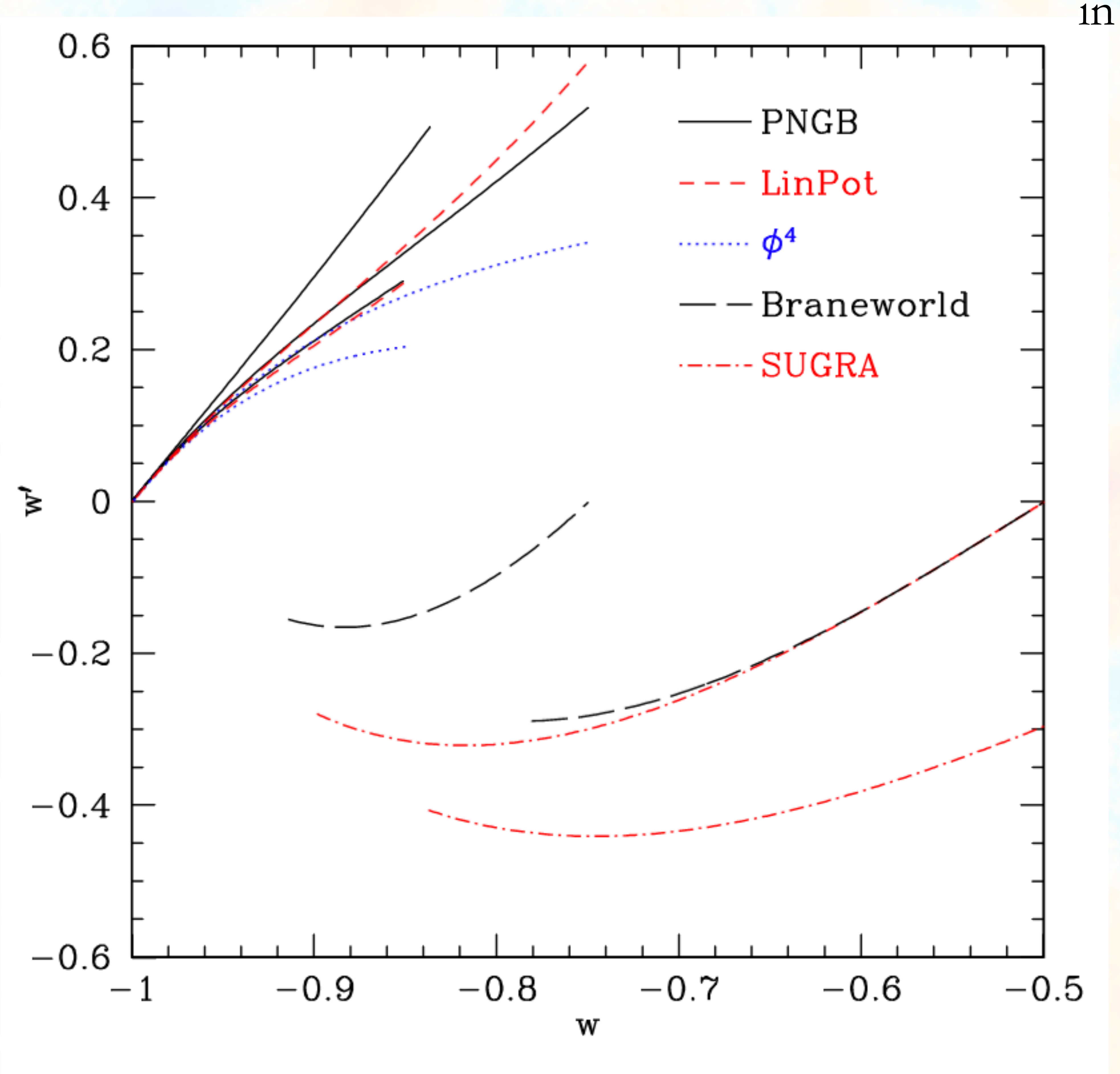
Dynamics of various DE models

$$(\phi, \dot{\phi}) \longrightarrow (w, w')$$

2 “distinct” regions in phase-space



R. de Putter & E. Linder - JCAP 10 (2008) 042

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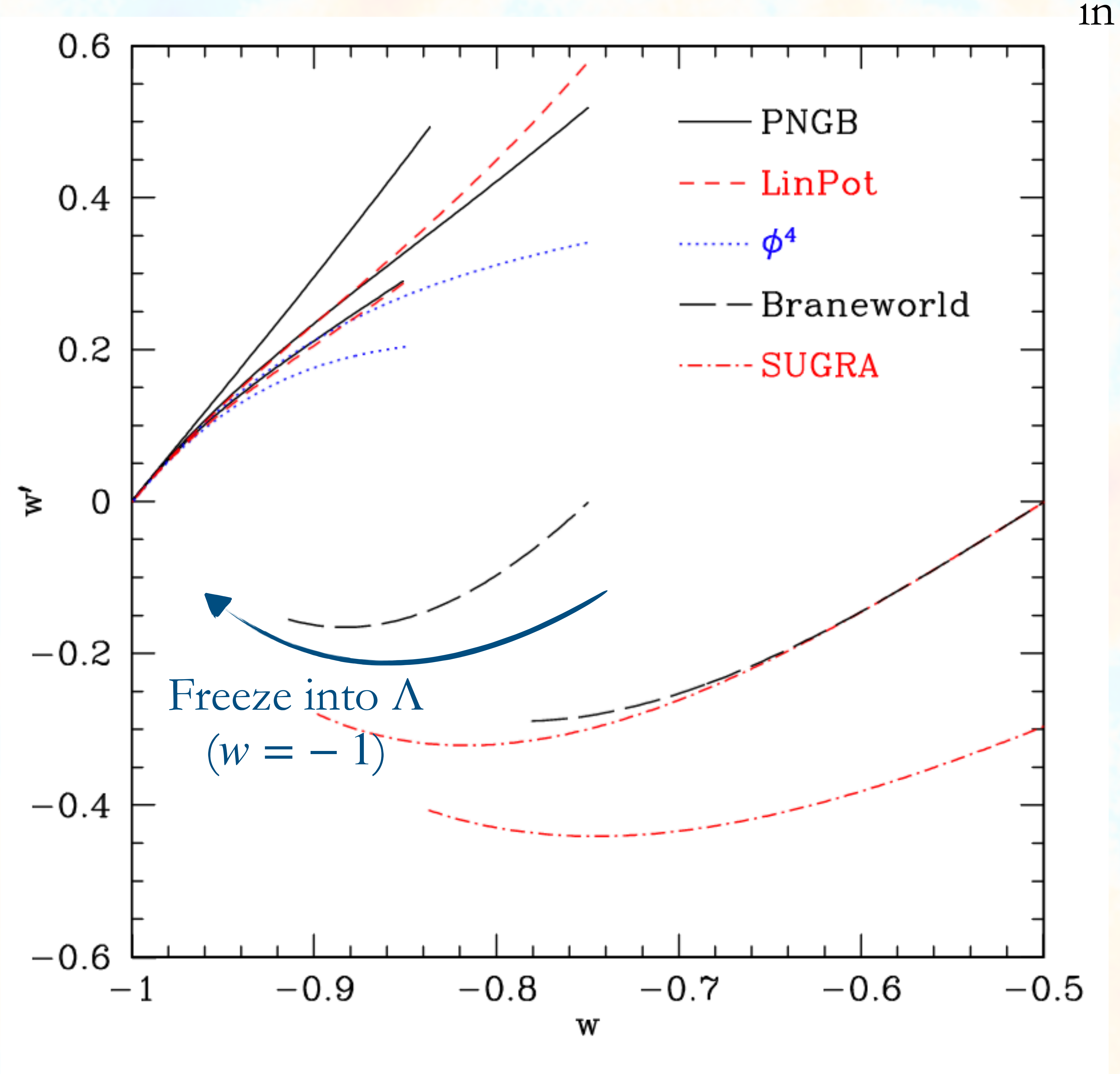

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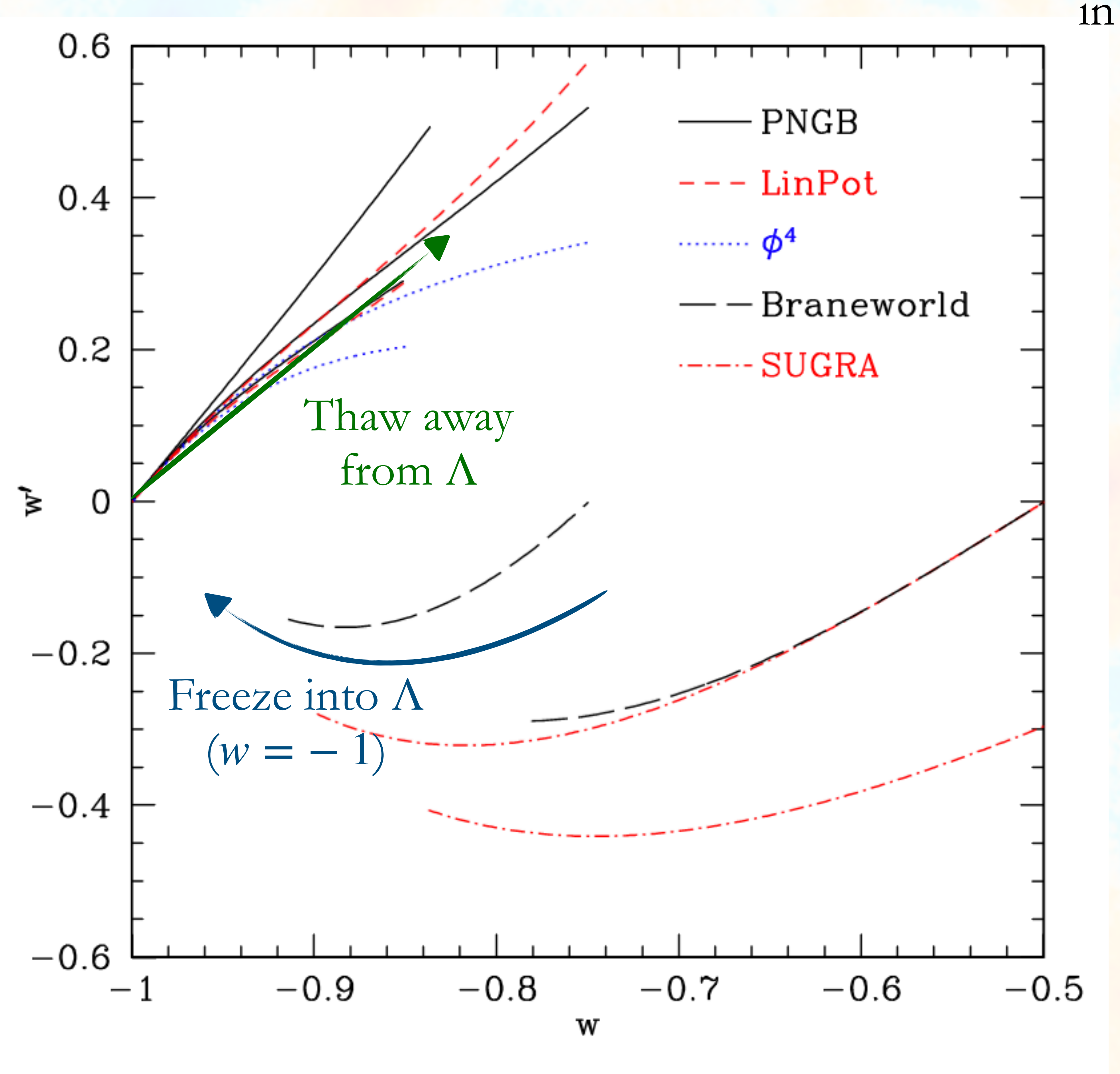

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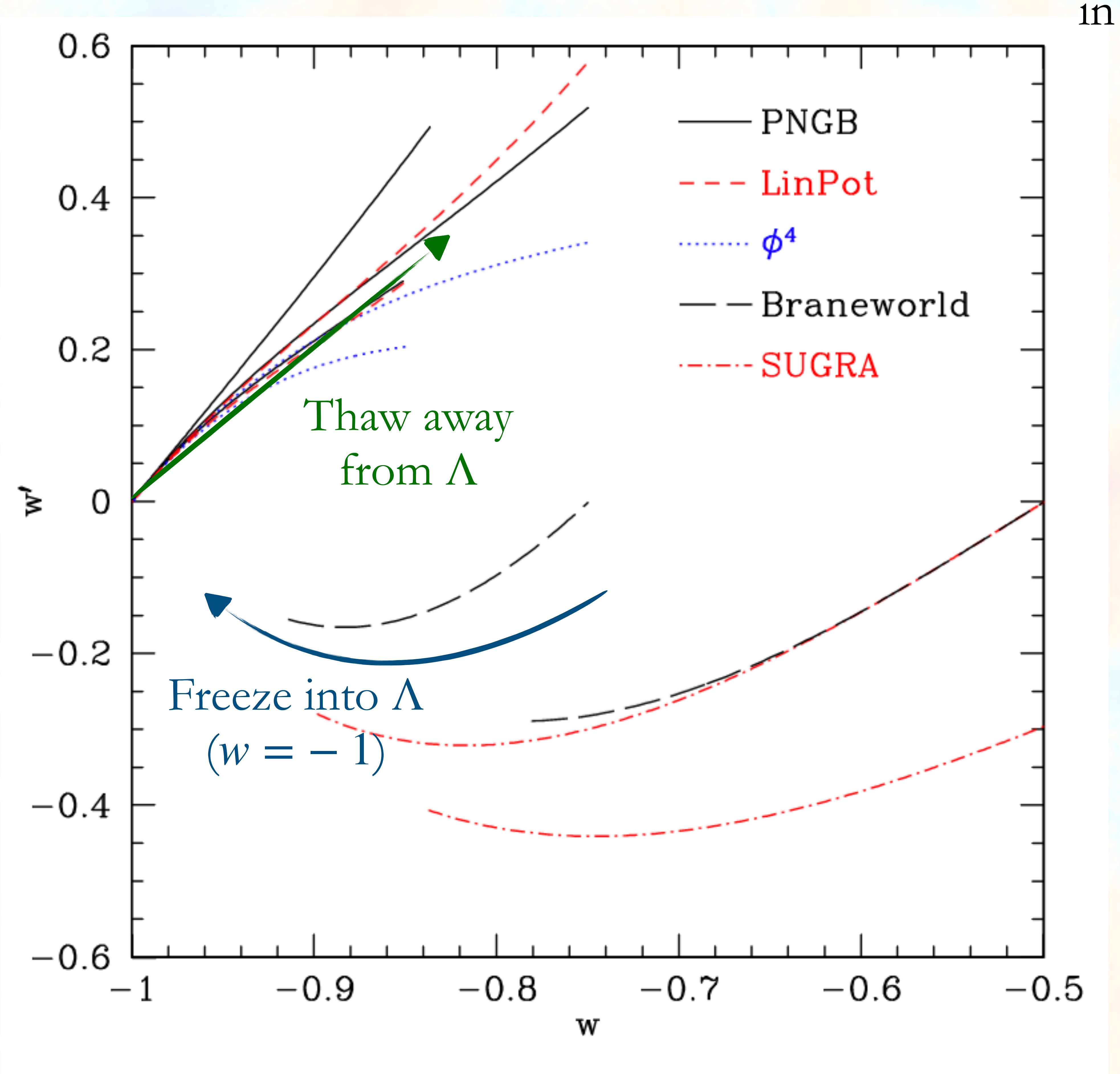

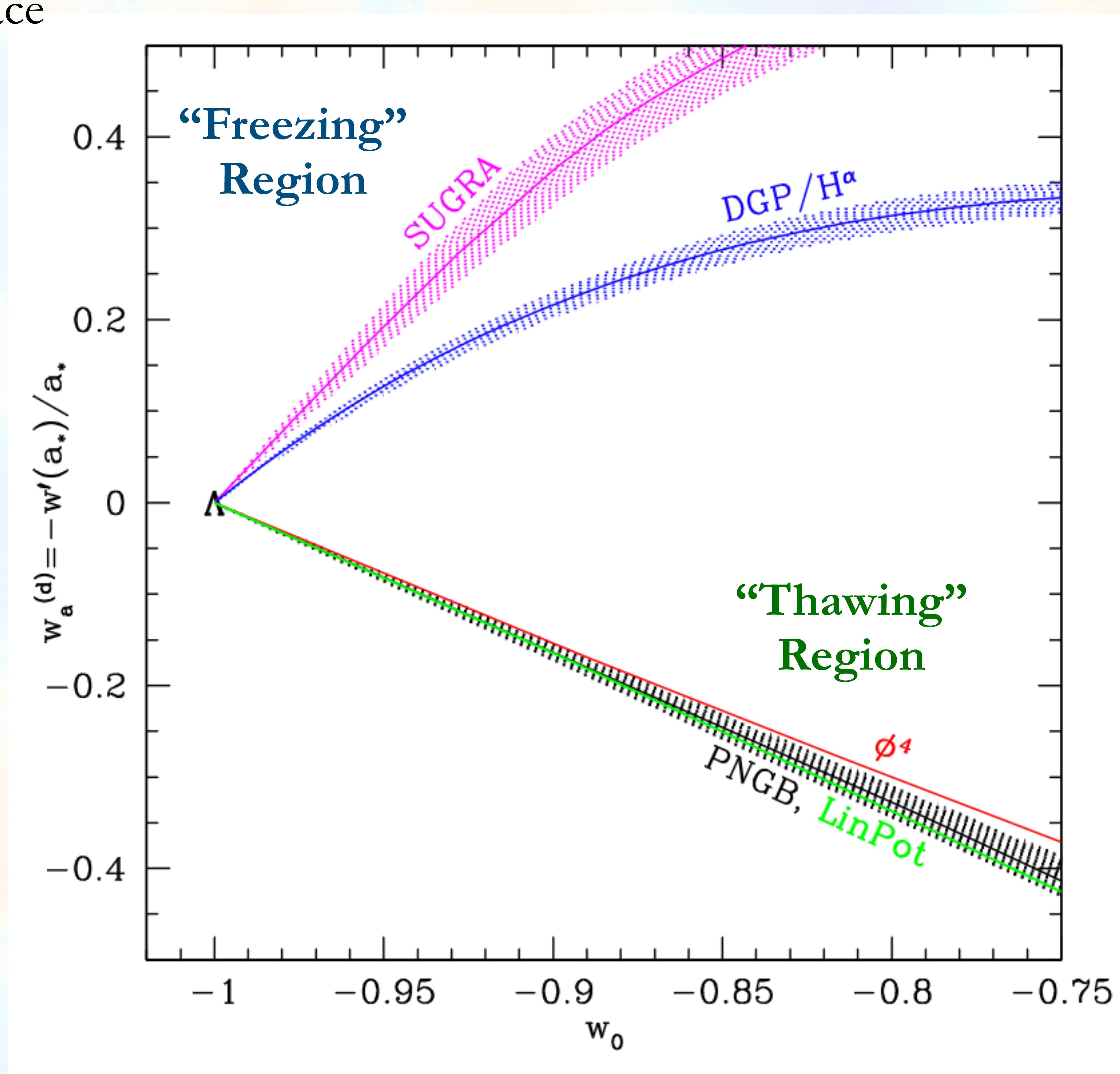

R. de Putter & E. Linder - JCAP 10 (2008) 042

Dynamics of various DE models

$$(\phi, \dot{\phi}) \longrightarrow (w, w')$$

2 "distinct" regions
in phase-space

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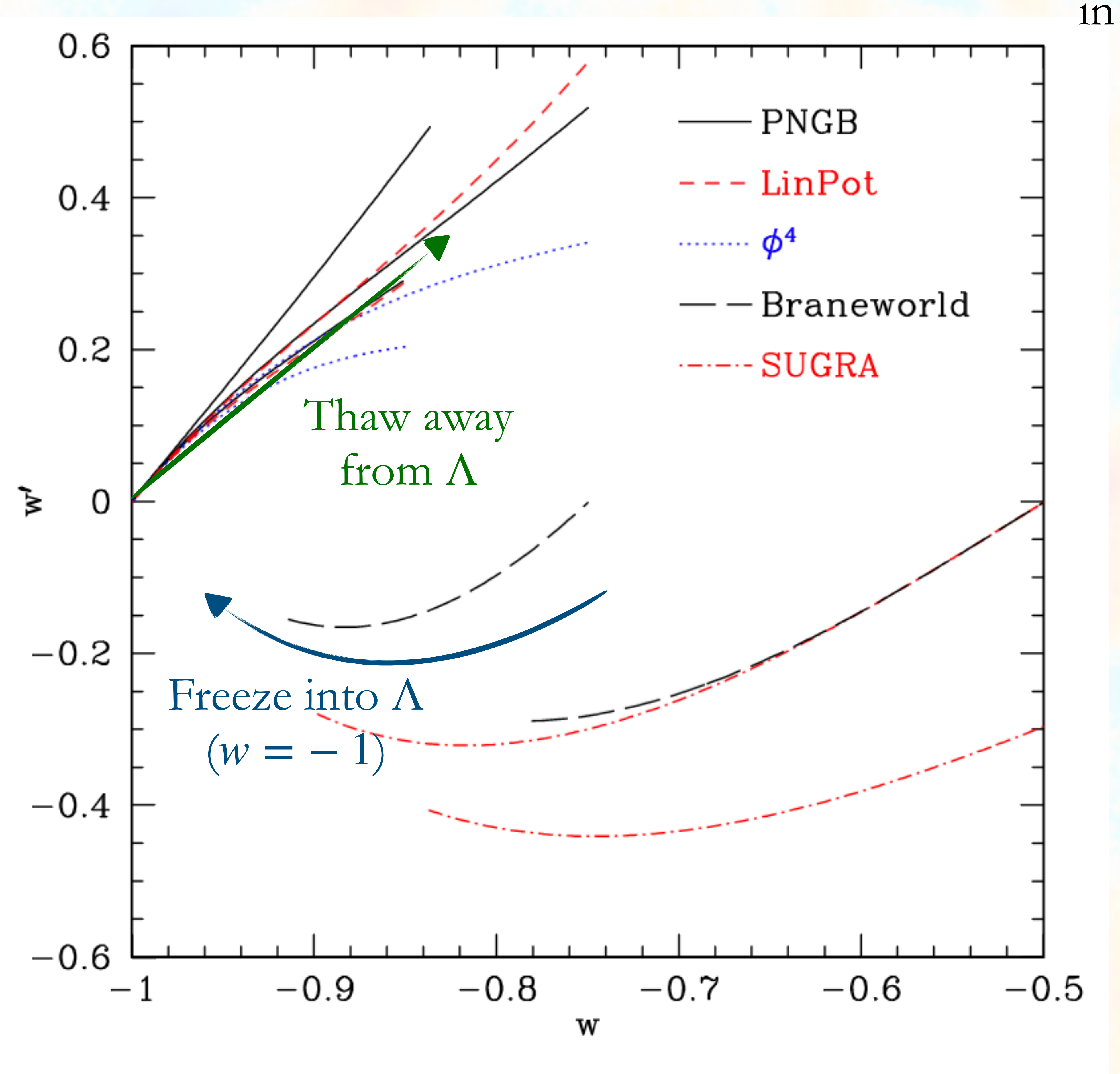

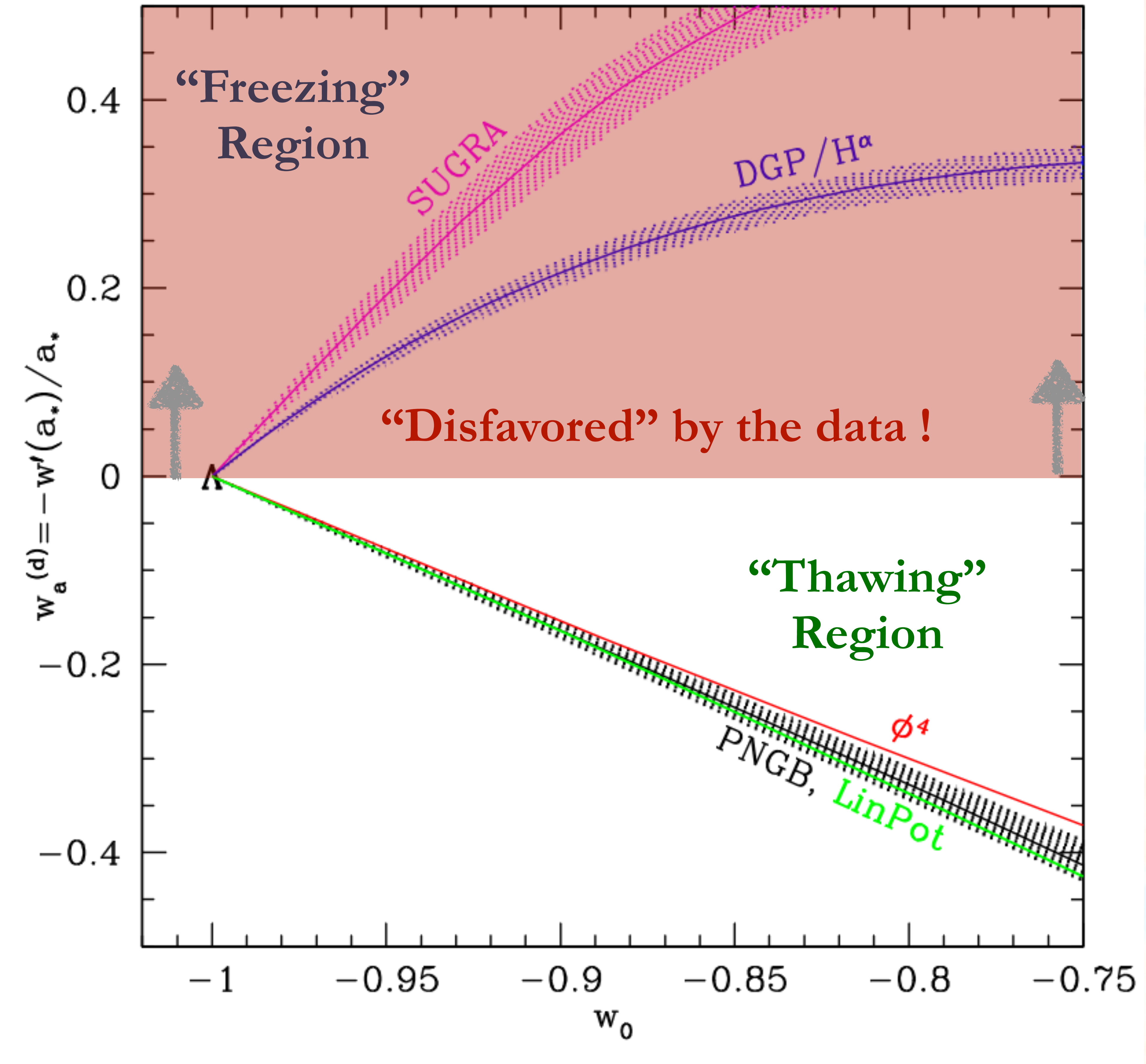

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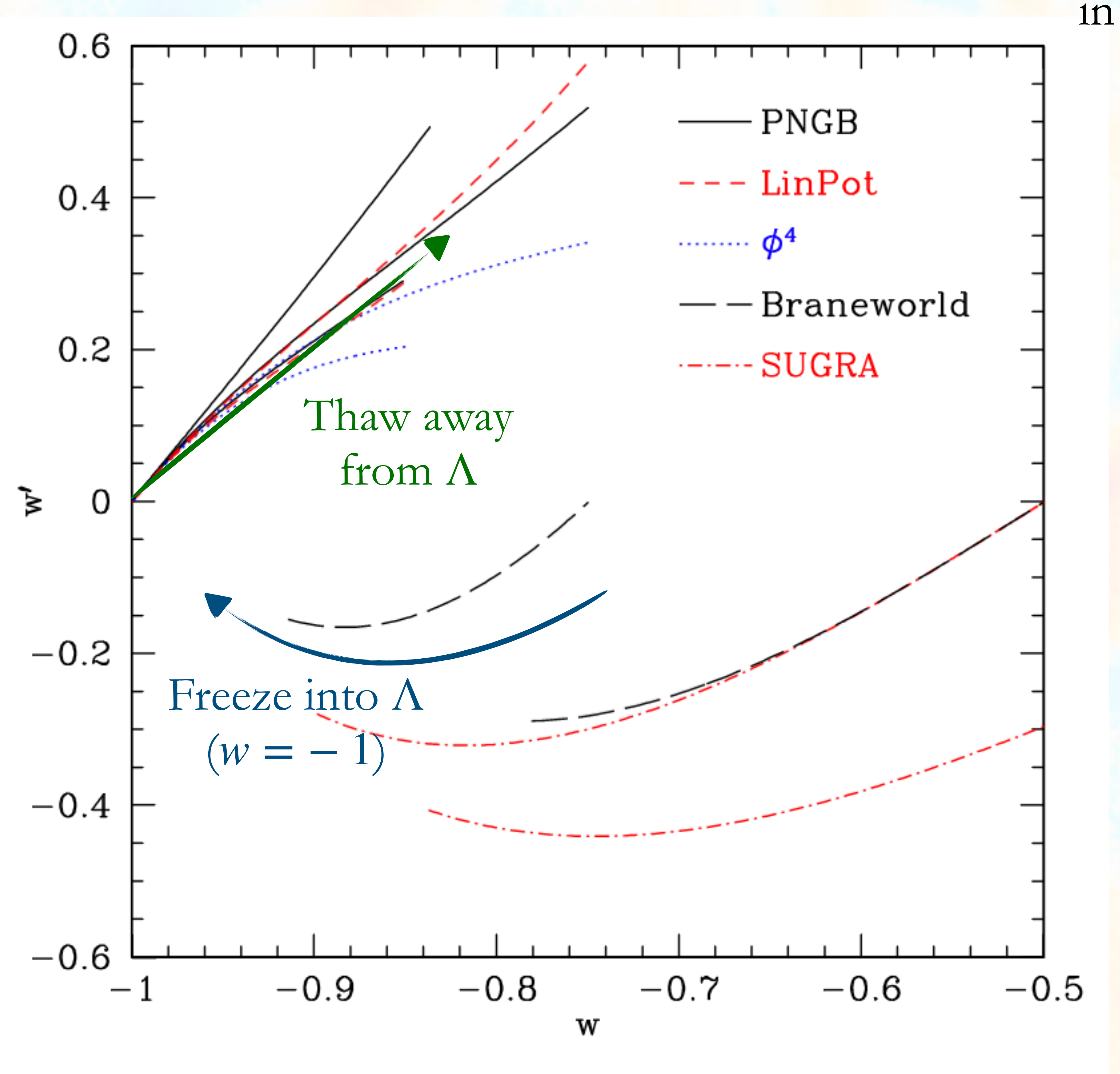
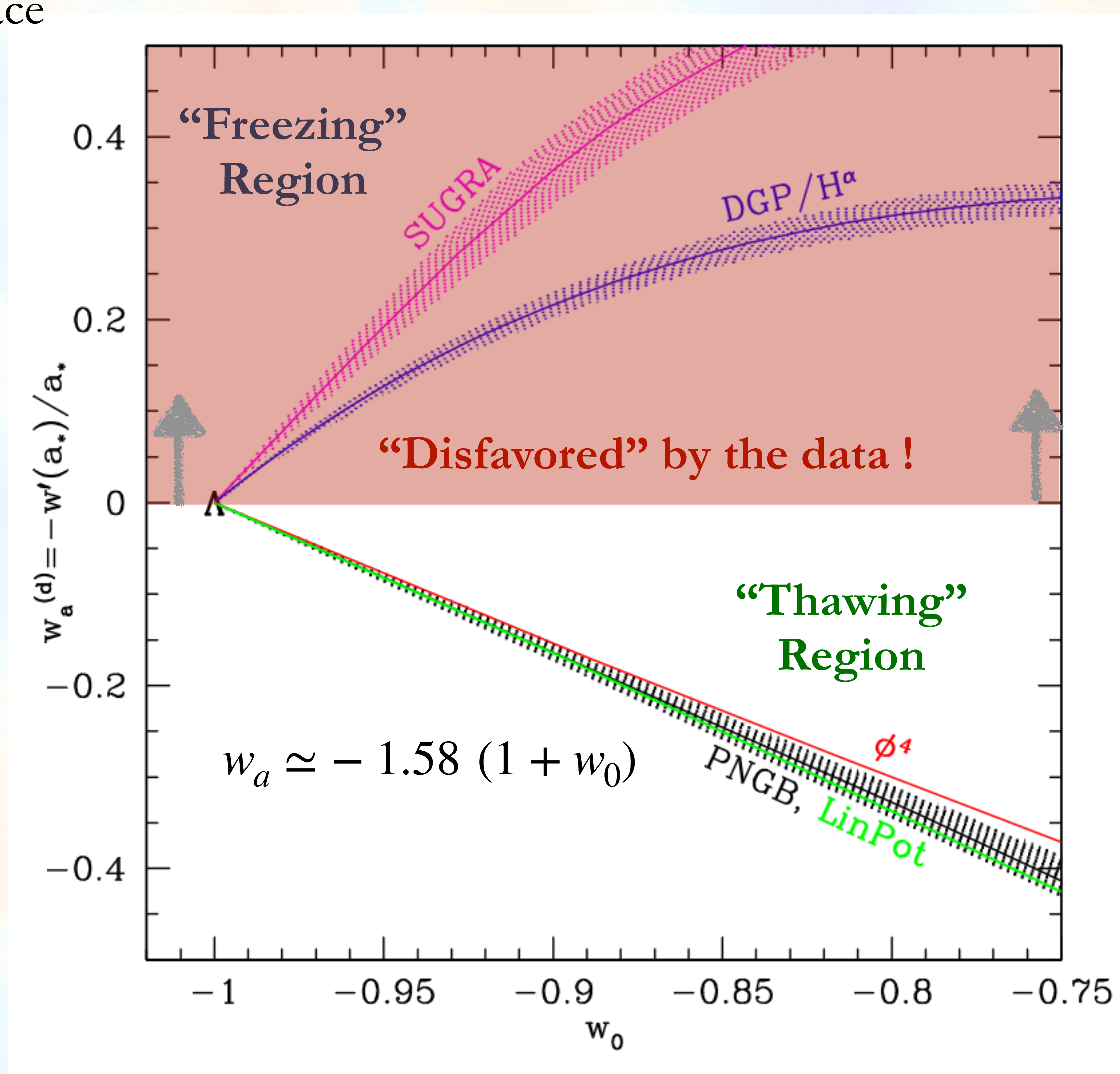
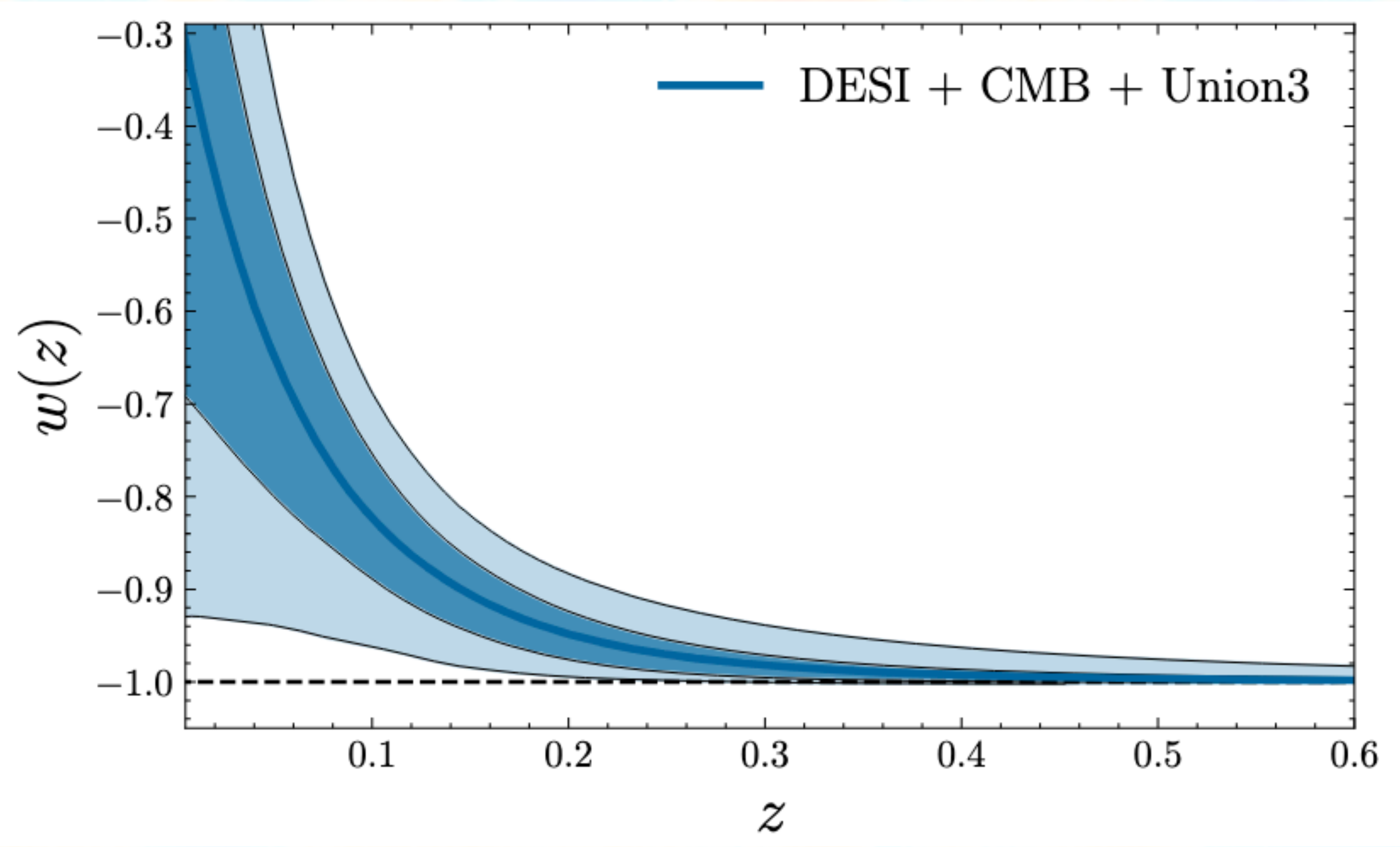




R. de Putter & E. Linder - JCAP 10 (2008) 042

Quintessence-like models

DESI Collaboration, K. Lodha, **R. Calderon**, W. Matthewson, A. Shafieloo et al.
arXiv: 2503.14743



$$w \geq -1$$

E. Linder - *Gen.Rel.Grav.* 40 (2008) 329-356

$$1 + w(a) = (1 + w_0)a^p \left(\frac{1 + b}{1 + ba^{-3}} \right)^{1-p/3}$$

"Thawing"
Dynamics

Frozen by
Hubble friction
$w \simeq -1$

- **PNGB/Axion-like**
- $V \propto \phi^2$
- $V \propto \phi^4$

A concrete axion-like $V(\varphi)$

DESI Collaboration, K. Lodha, **R. Calderon**, W. Matthewson, A. Shafieloo et al.
arXiv: 2503.14743

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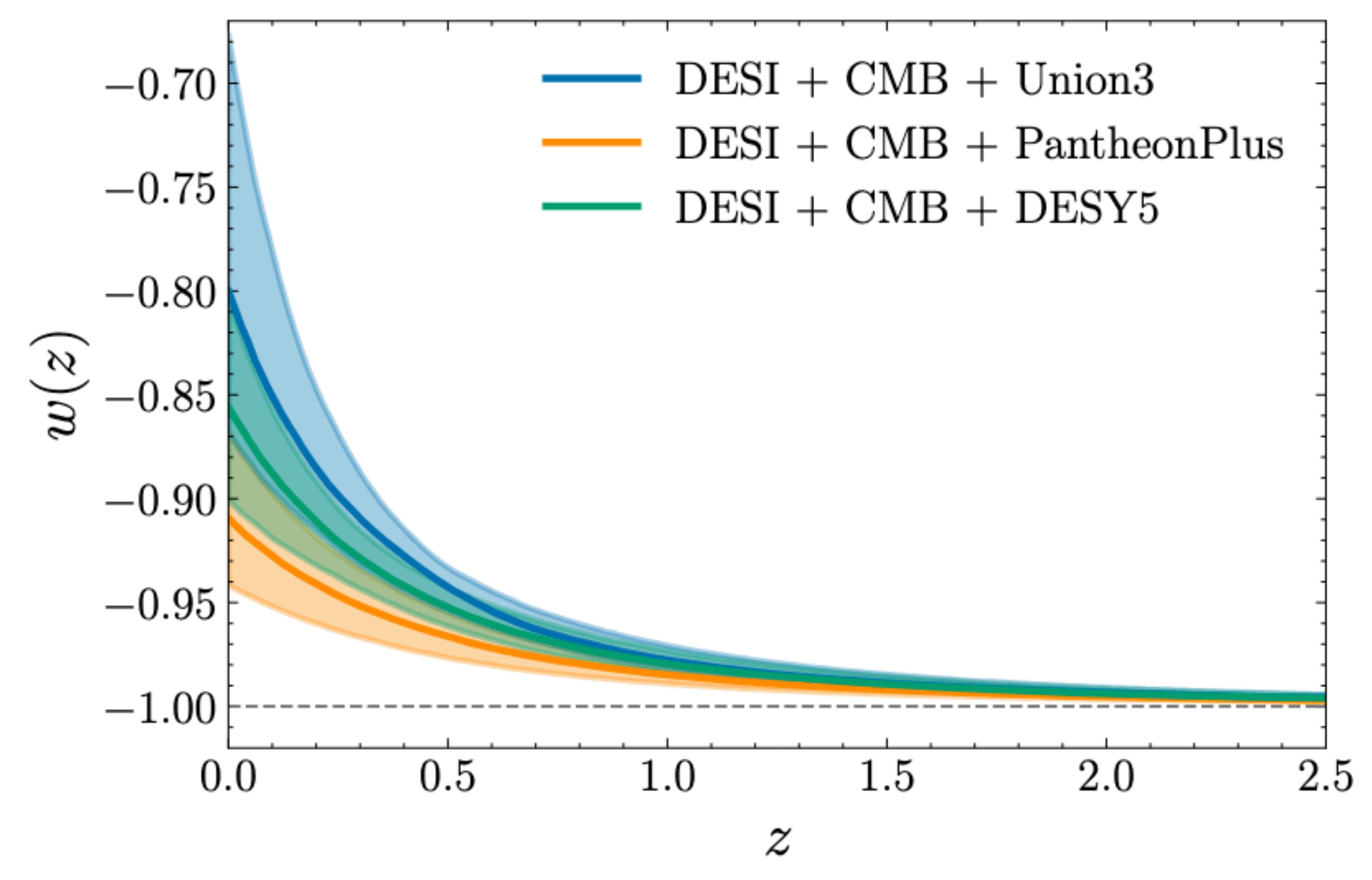


$$V(\varphi) = m_a^2 f_a^2 \, [1 + \cos(\varphi/f_a)]$$

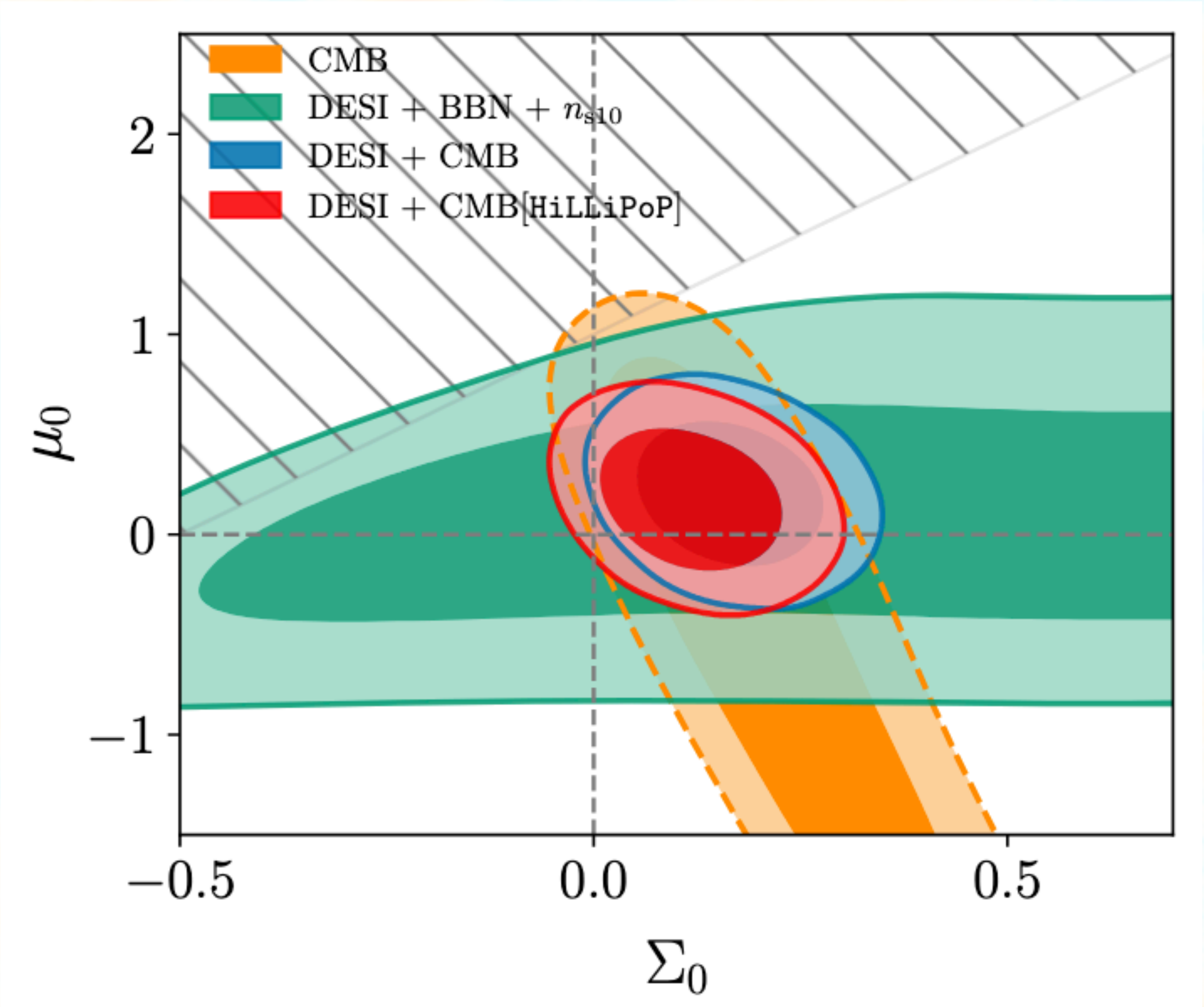
$$\Delta\chi^2_\varphi = -6.9$$

vs.

$$\Delta\chi^2_{w_0 w_a} = -17.4$$

Phantom crossing seems to be **needed to significantly improve** the fit over ΛCDM

Testing gravity at cosmological scales



DESI Collaboration, A.G. Adame et al - arXiv: 2411.12022

Massive Particles (Growth)

$$-\frac{k^2}{a^2}\Psi = 4\pi G\mu(a,k)\rho\delta$$

$$\mu(a) = 1 + \mu_0 \frac{\Omega_{\mathrm{DE}}(a)}{\Omega_{\mathrm{DE},0}}$$

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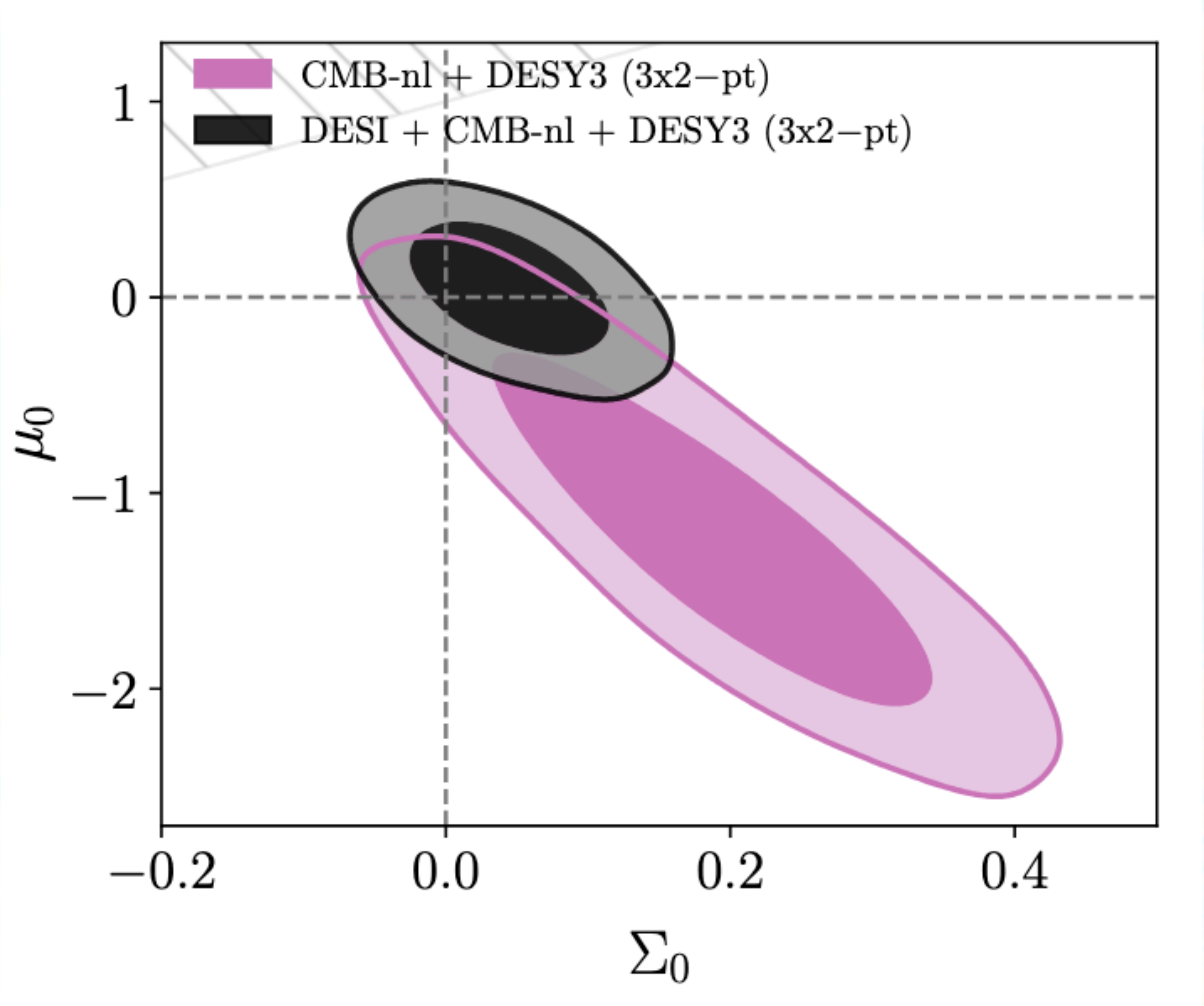

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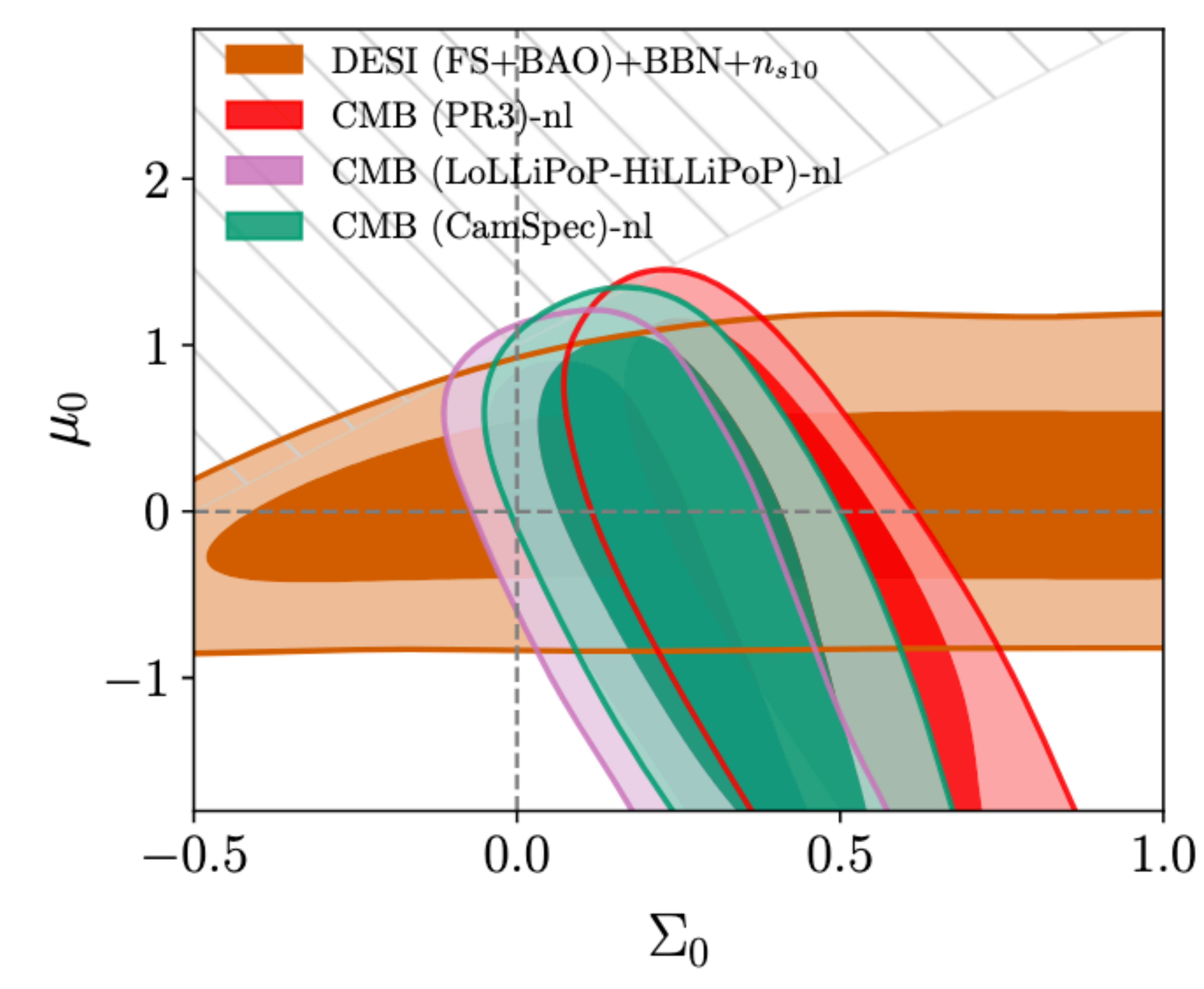
Hints of modified gravity ?



DESI Collaboration - M. Ishak, J. Pan, **R. Calderon** et al - arXiv: 2411.12022

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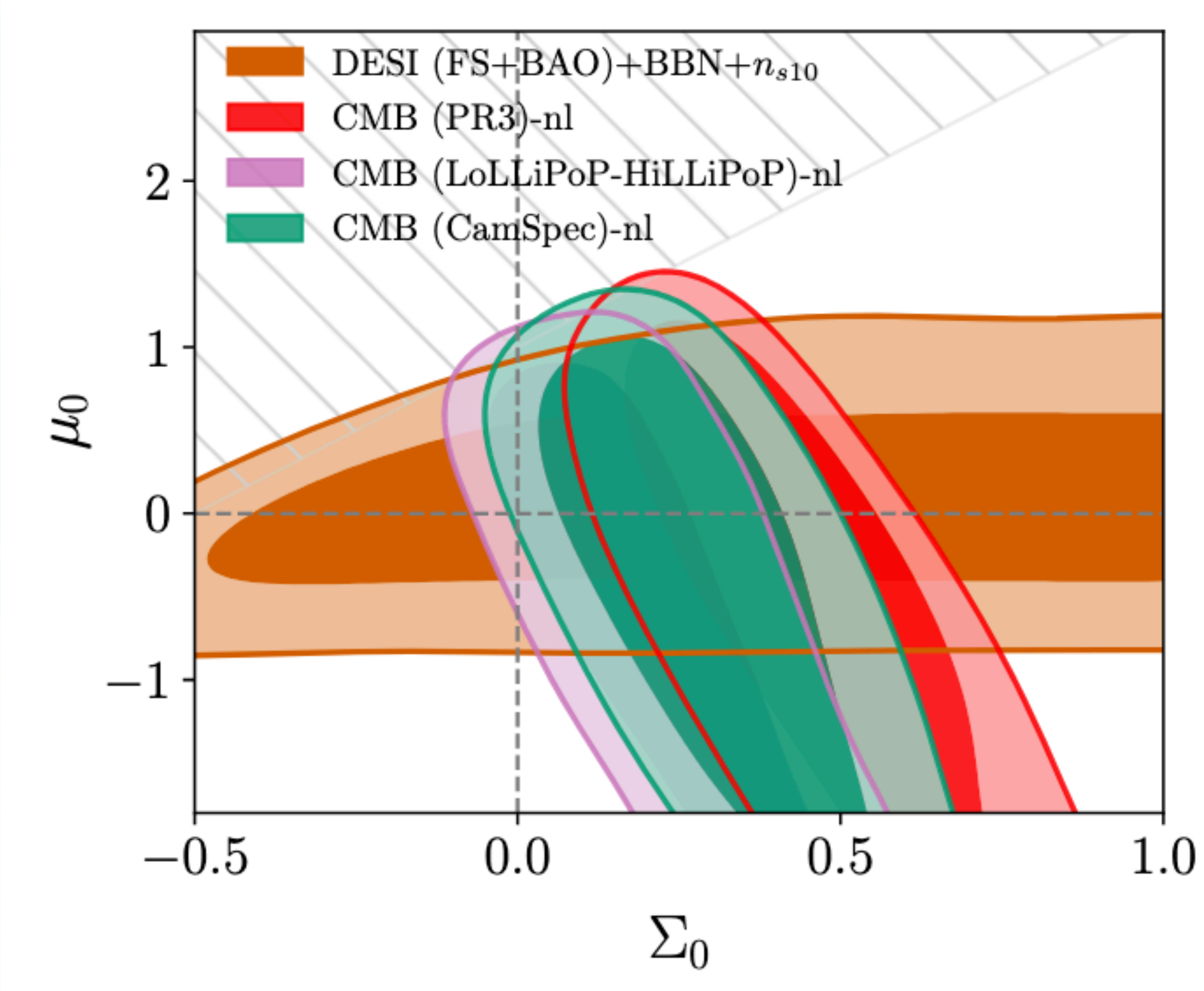

- **DESI (on its own) can only constrain the growth of structures $\mu(z)$**

DESI Collaboration - M. Ishak, J. Pan, **R. Calderon** et al - arXiv: 2411.12022

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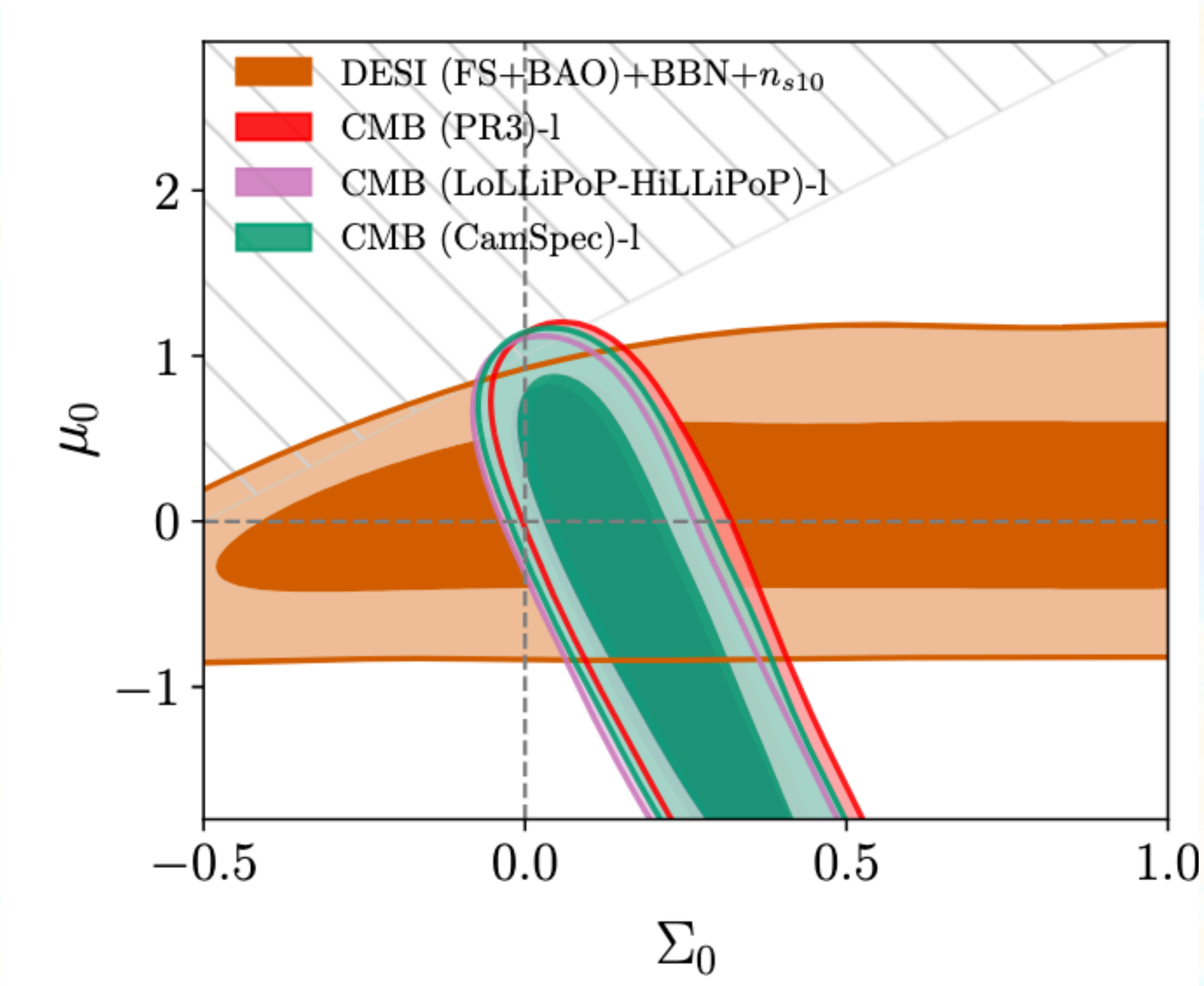

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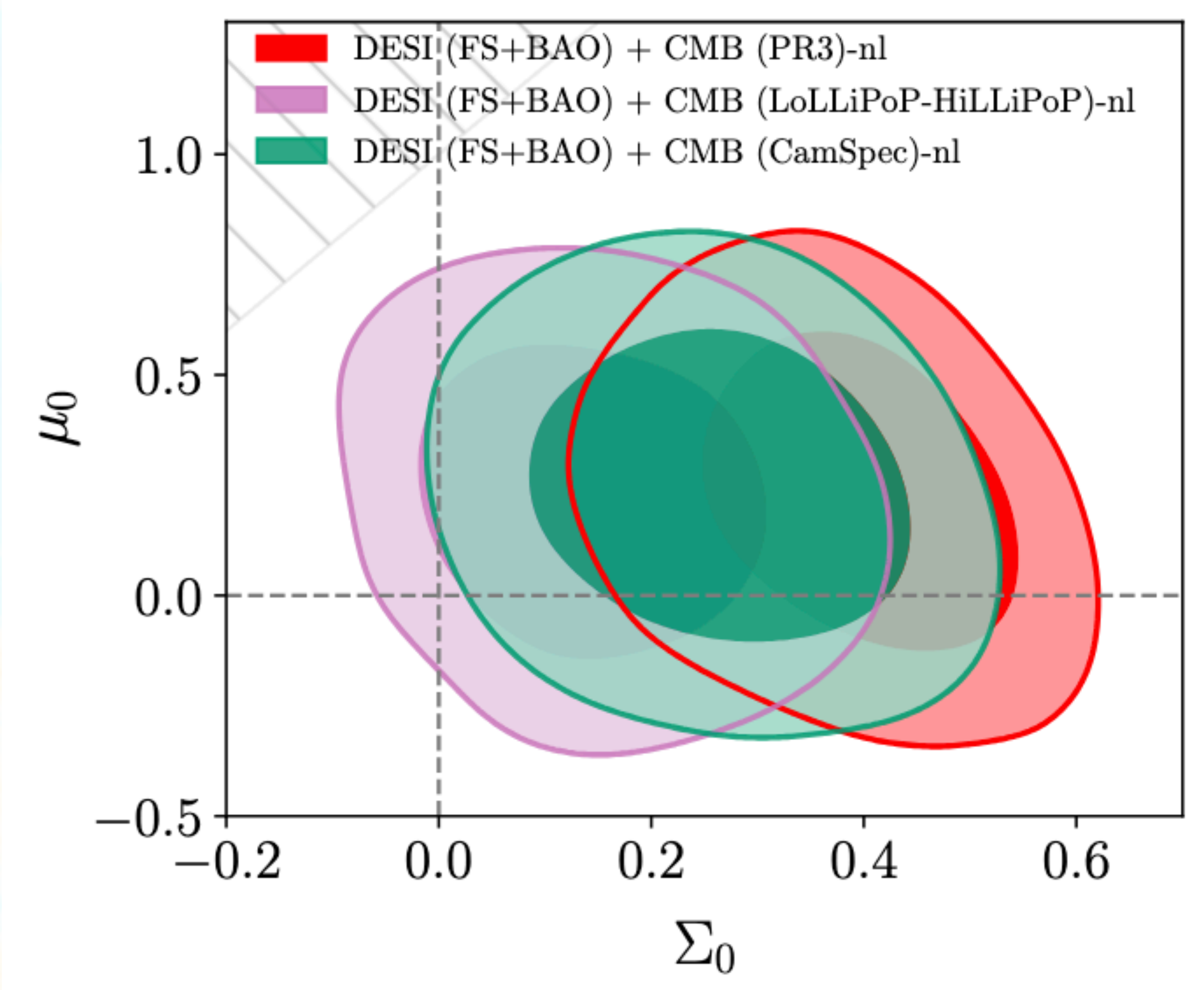

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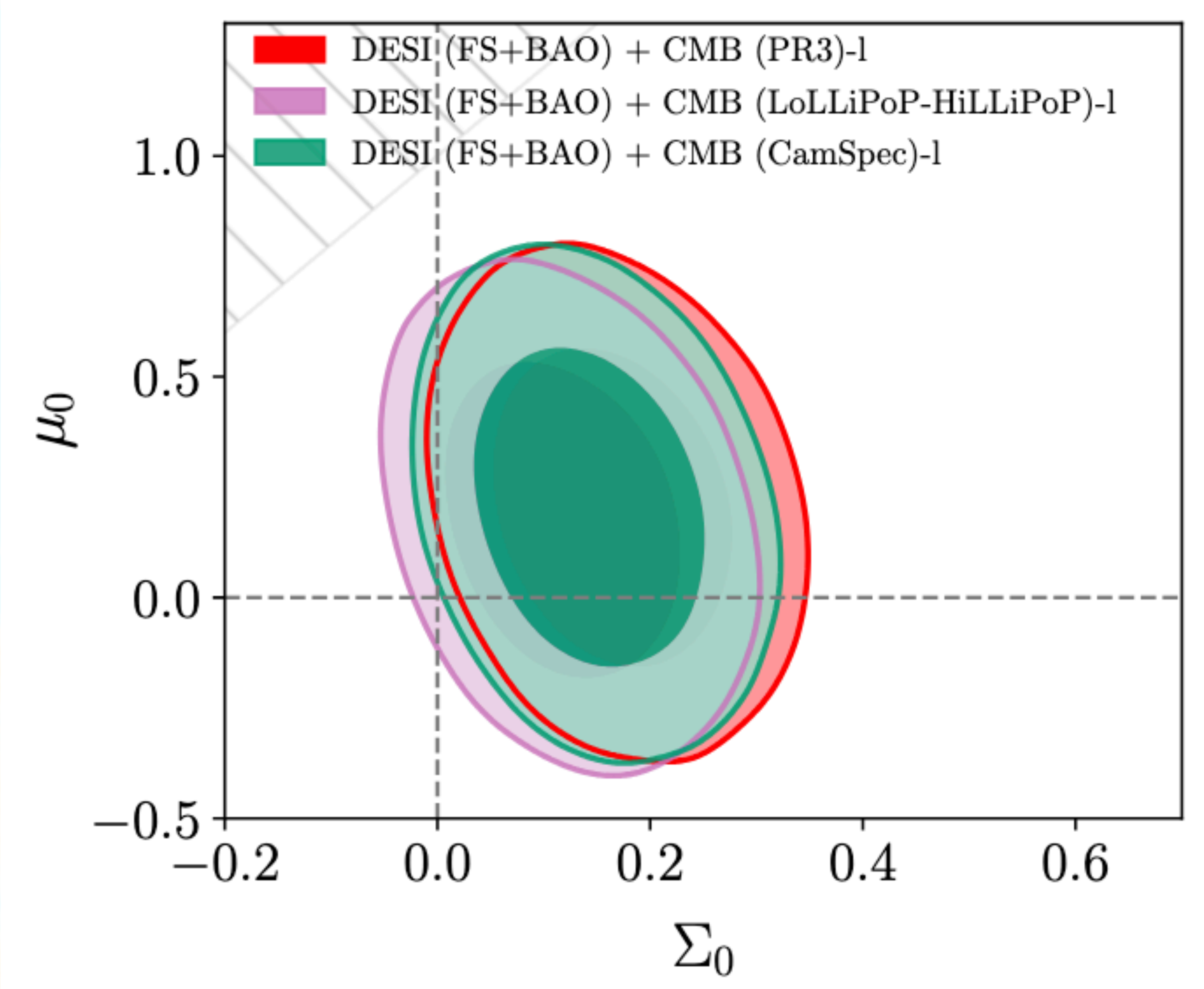

- **DESI (on its own) can only constrain the growth of structures $\mu(z)$**
- **Without CMB lensing, constraints on $\Sigma(z)$ are highly sensitive to the choice of CMB likelihood**
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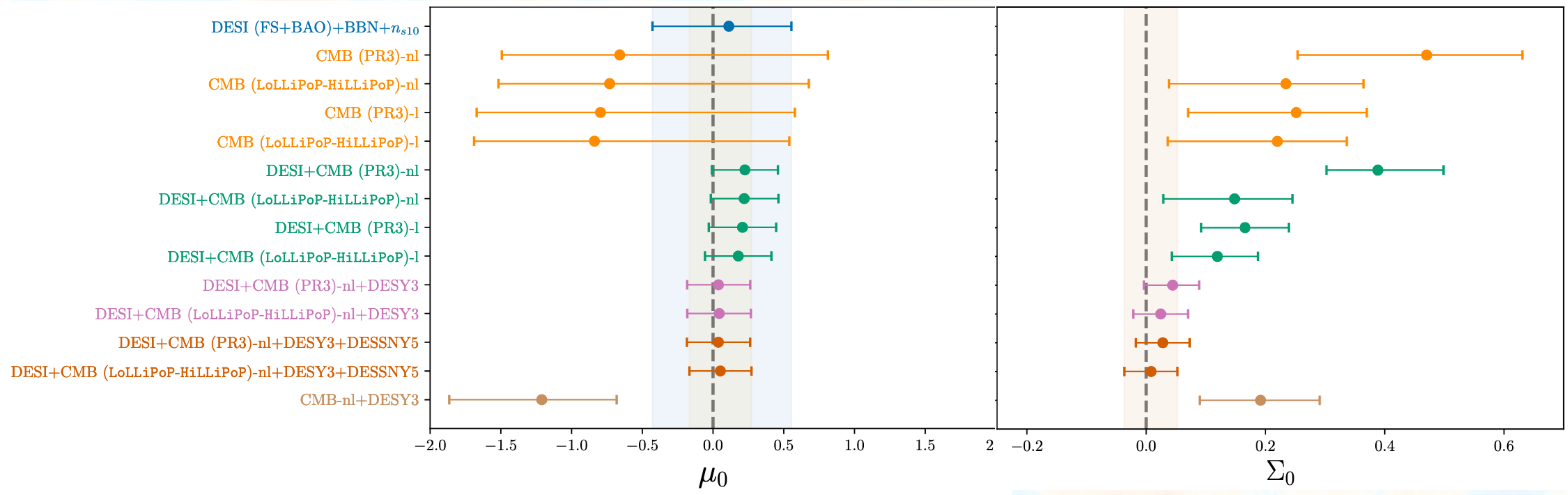
DESI Collaboration - M. Ishak, J. Pan, **R. Calderon** et al - arXiv: 2411.12022

Hints of modified gravity ?



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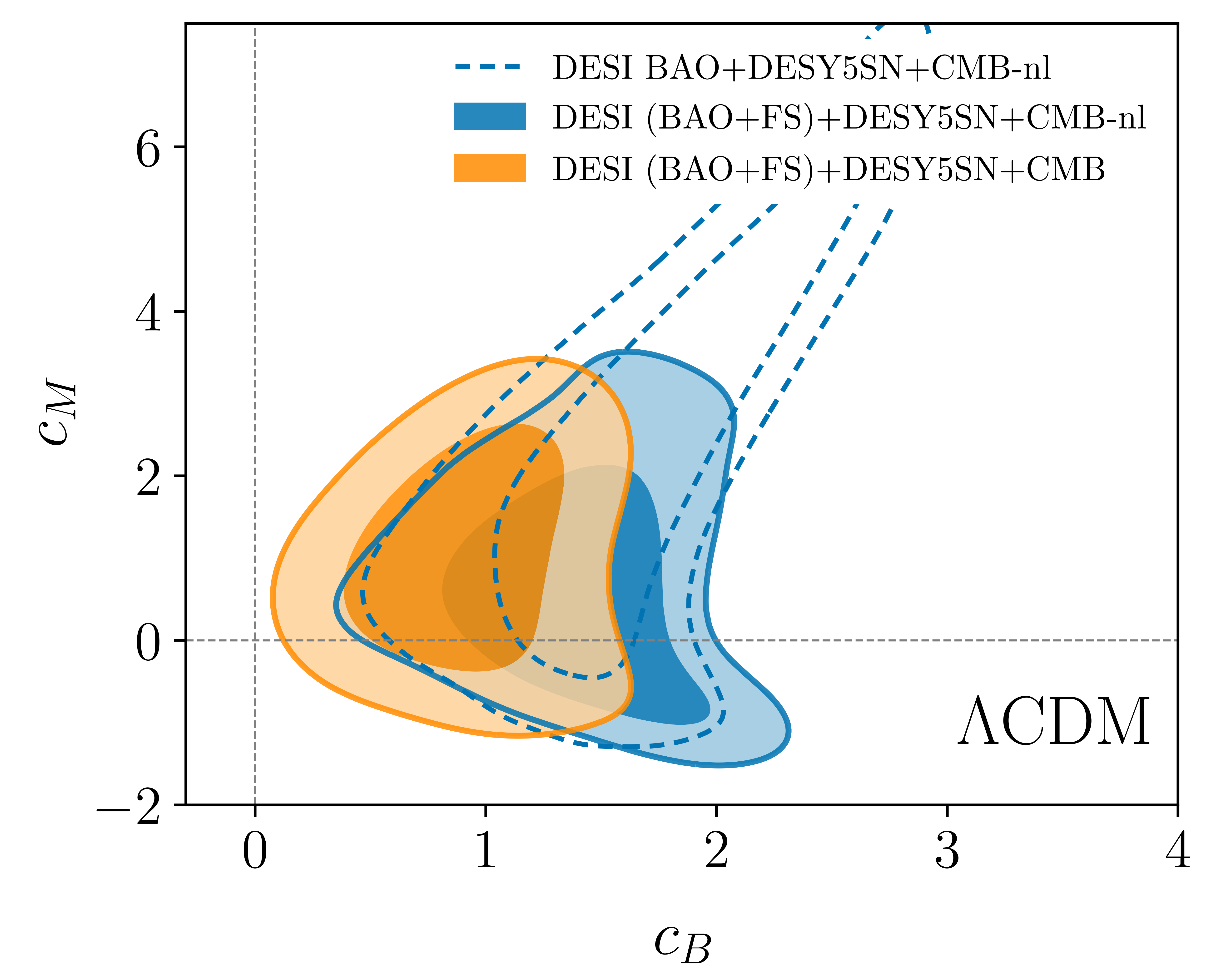
Implications of $w(z) < -1$



DESI Collaboration - M. Ishak, J. Pan, **R. Calderon** et al - arXiv: 2411.12022

In the EFT of DE, linear perturbations **entirely characterised** by 4 functions of time

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- "Braiding": $\alpha_B(t)$
- "Kineticity": $\alpha_K(t)$
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At least one of the $\alpha_i(t) \neq 0$!

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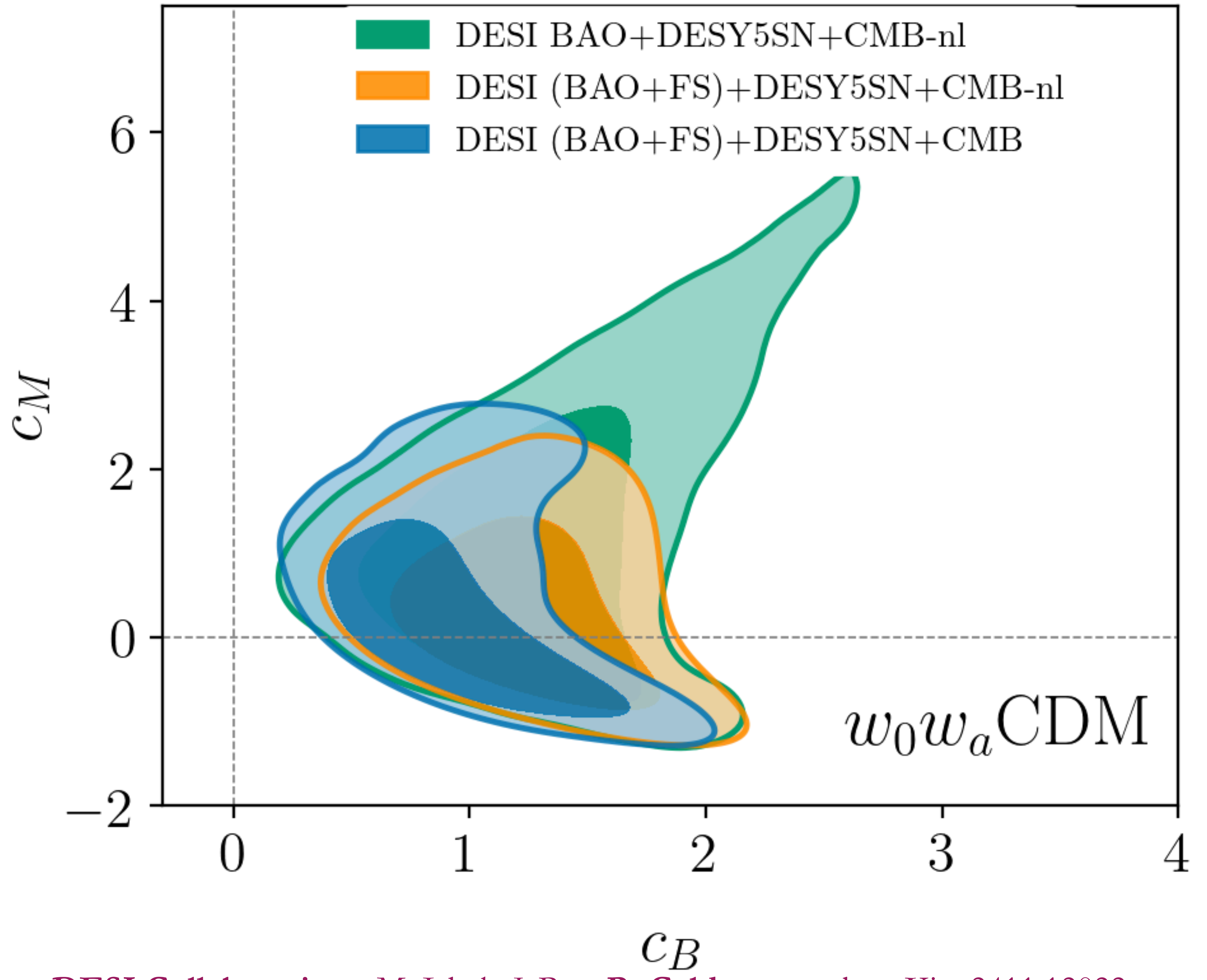

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Summary

- Tantalising hints of an **evolving dark energy** component:
  $\sim 3-4\sigma$ deviation from Λ ($w_0 = -1$, $w_a = 0$)
  Results are **stable** under different **data combinations**
  & **NOT** driven by the parametrisation of $w(a)$

- Models that cross $w = -1$ consistently fit the data better than those that do not
  (GP suggests $w(z) < -1$ at $\sim 3\sigma$)

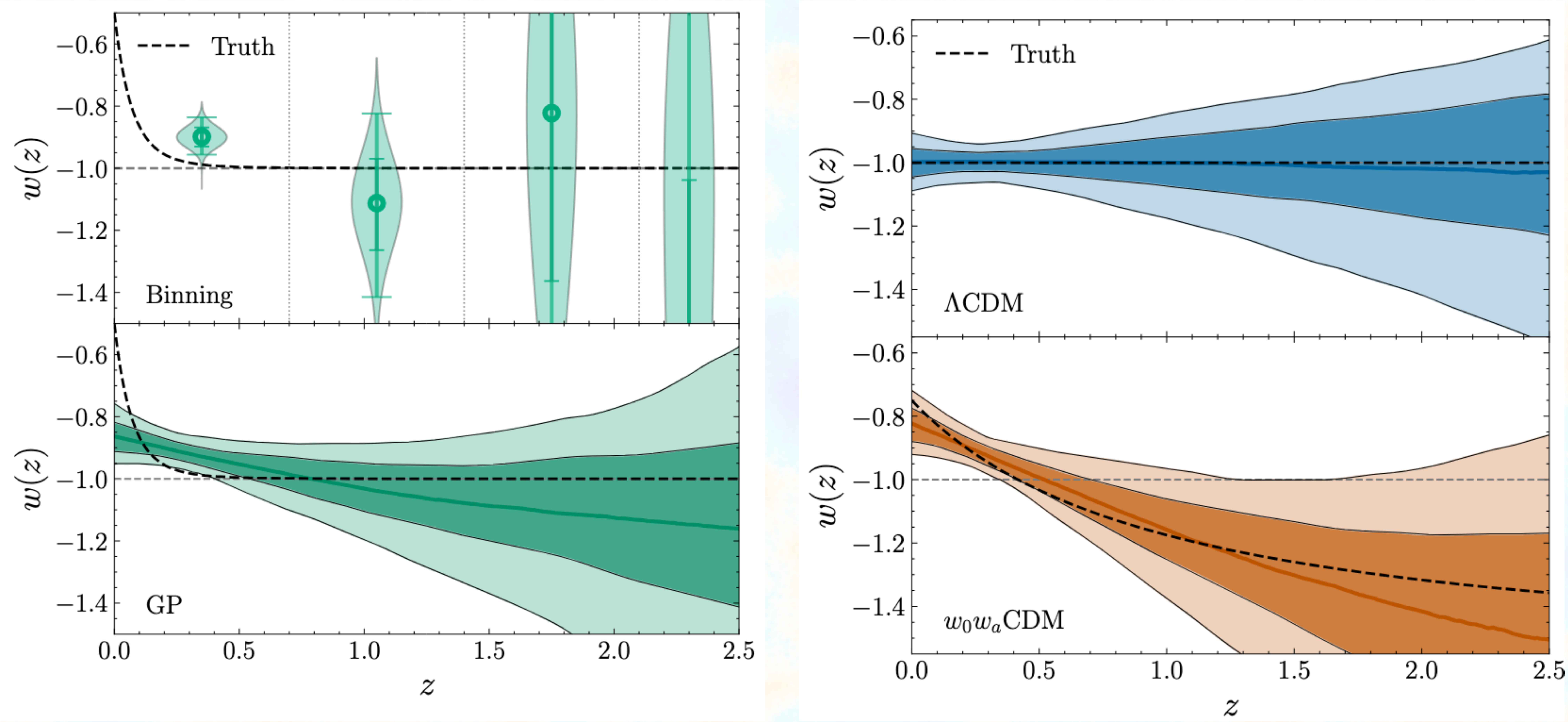
- If confirmed, these results could have profound theoretical implications for DE
  DE/DM interactions, Non-minimal couplings/Modified gravity

- Careful investigation of the CMB lensing excess ($A_{\rm lens}>1$)
  $\rightarrow \Sigma(z) > 1$
- $\rightarrow \Sigma m_\nu < 0$

- DESI (DR2) constraints from 2-pt & 3-pt functions are on the way (+Euclid results!)
  Extremely exciting times for Cosmology

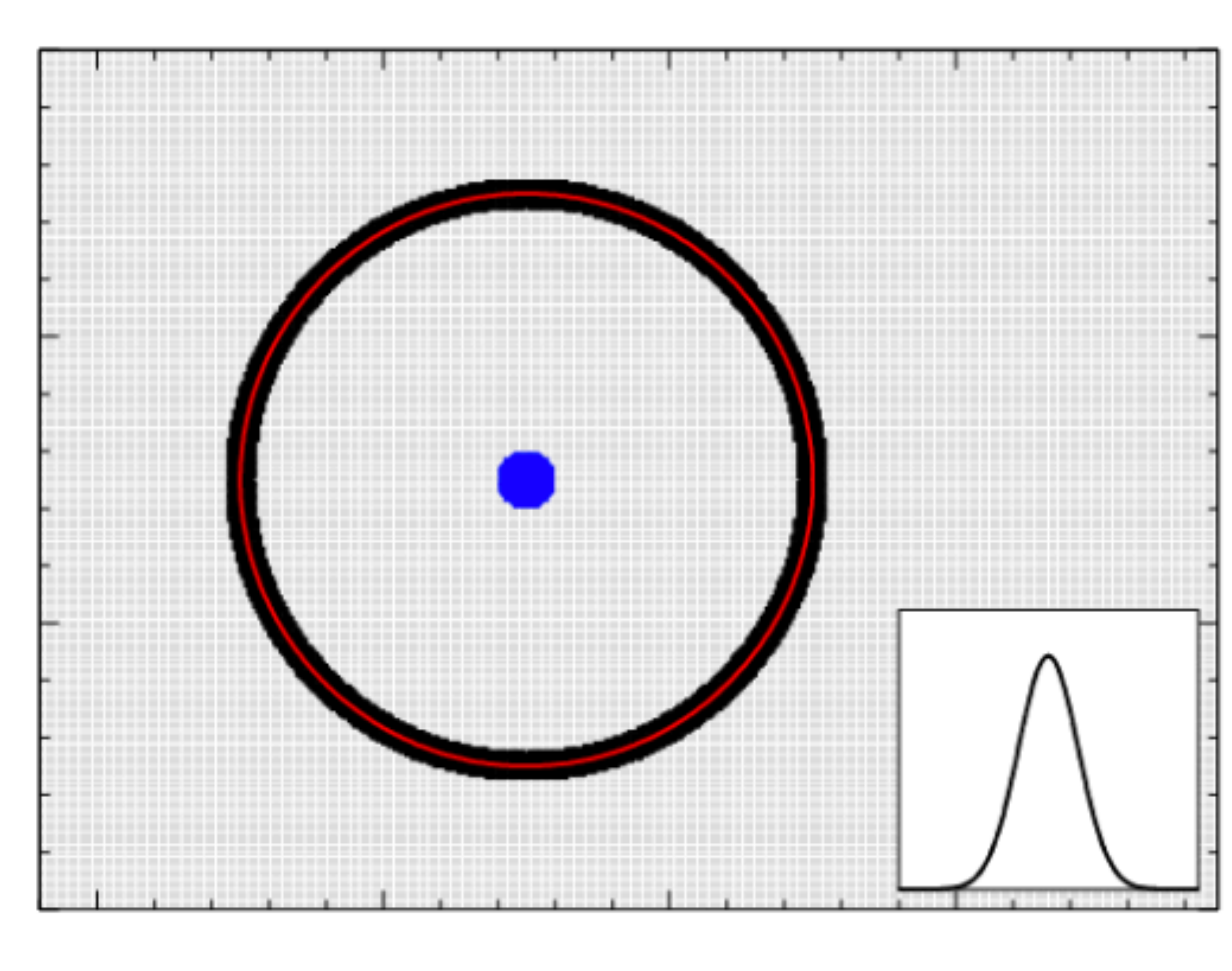
calderon@fzu.cz

Validation with Mocks



DESI Collaboration, K. Lodha, **R. Calderon**, W. Matthewson, A. Shafieloo et al.
arXiv: [2503.14743]

Baryon Acoustic Oscillations



Padmanabhan et al. (2012) MNRAS

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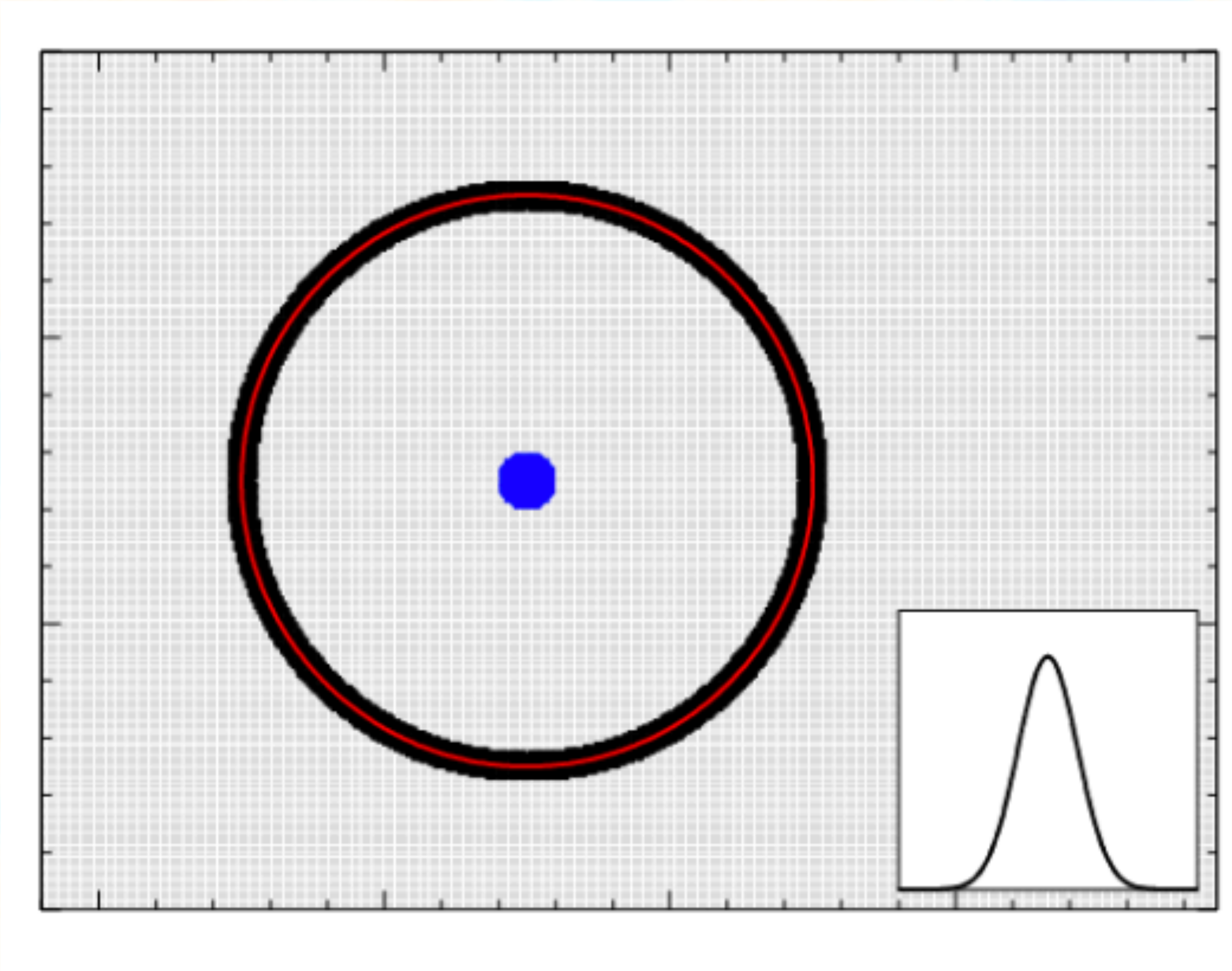

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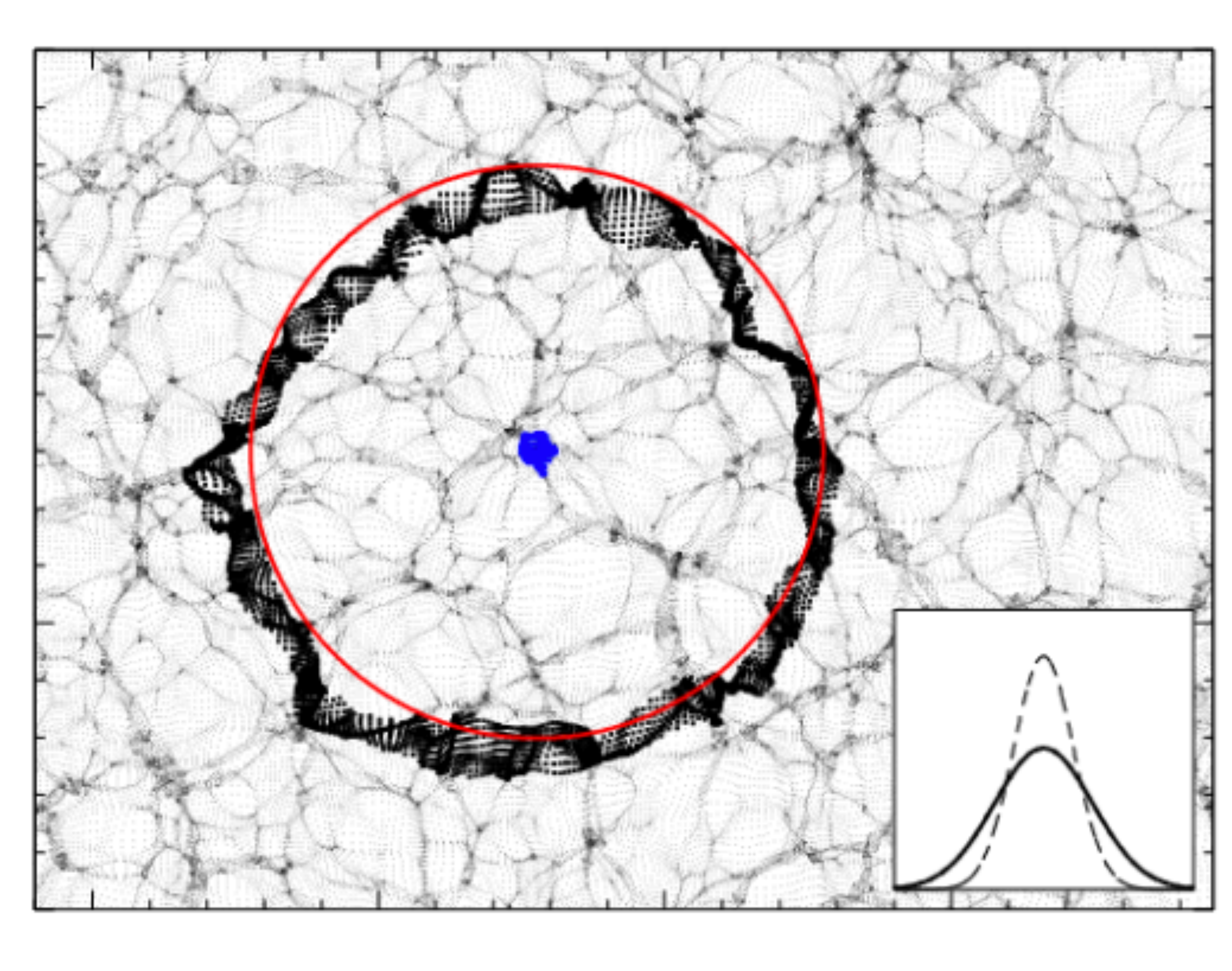

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  → Broadening of the BAO peak in 2pt correlation function

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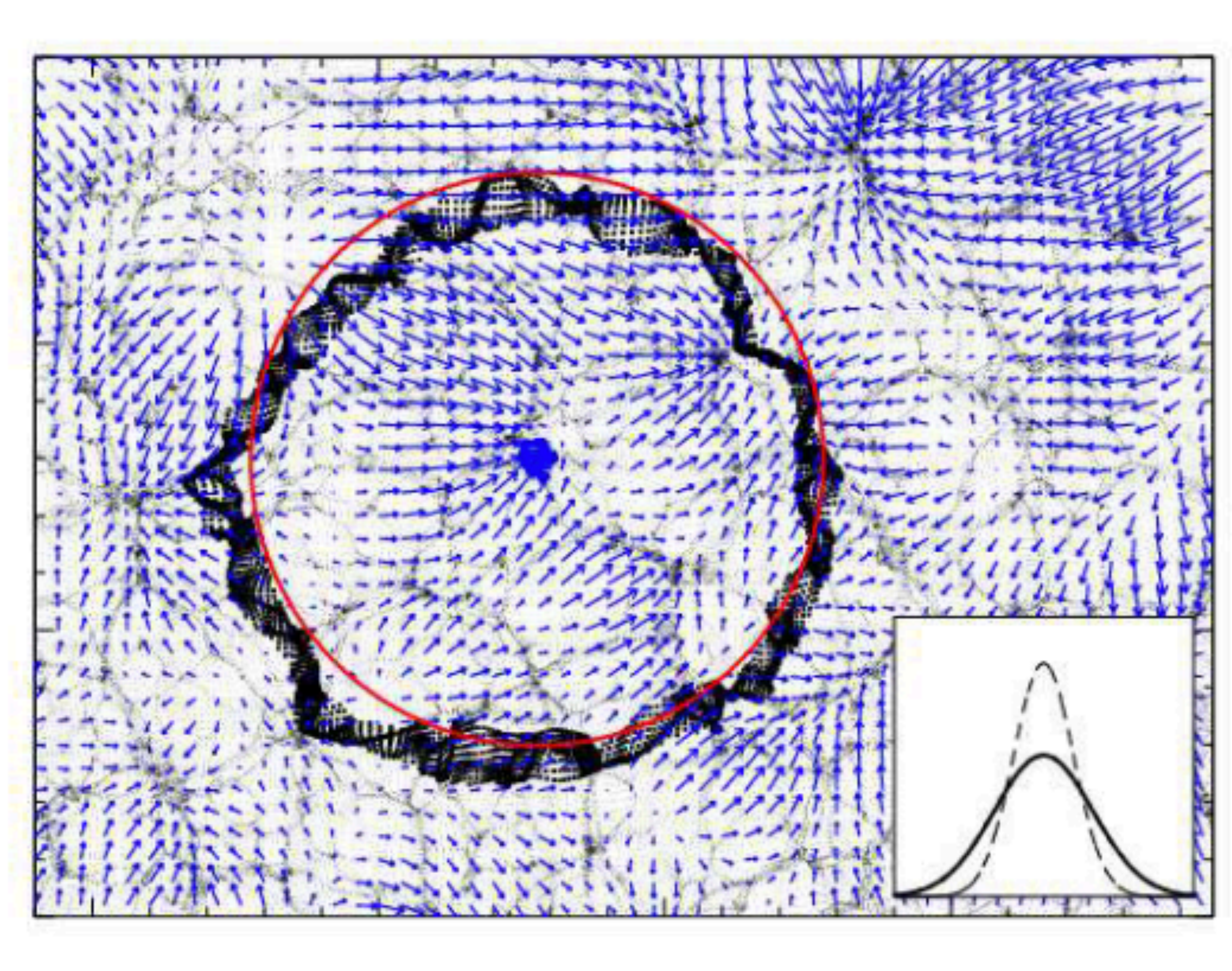

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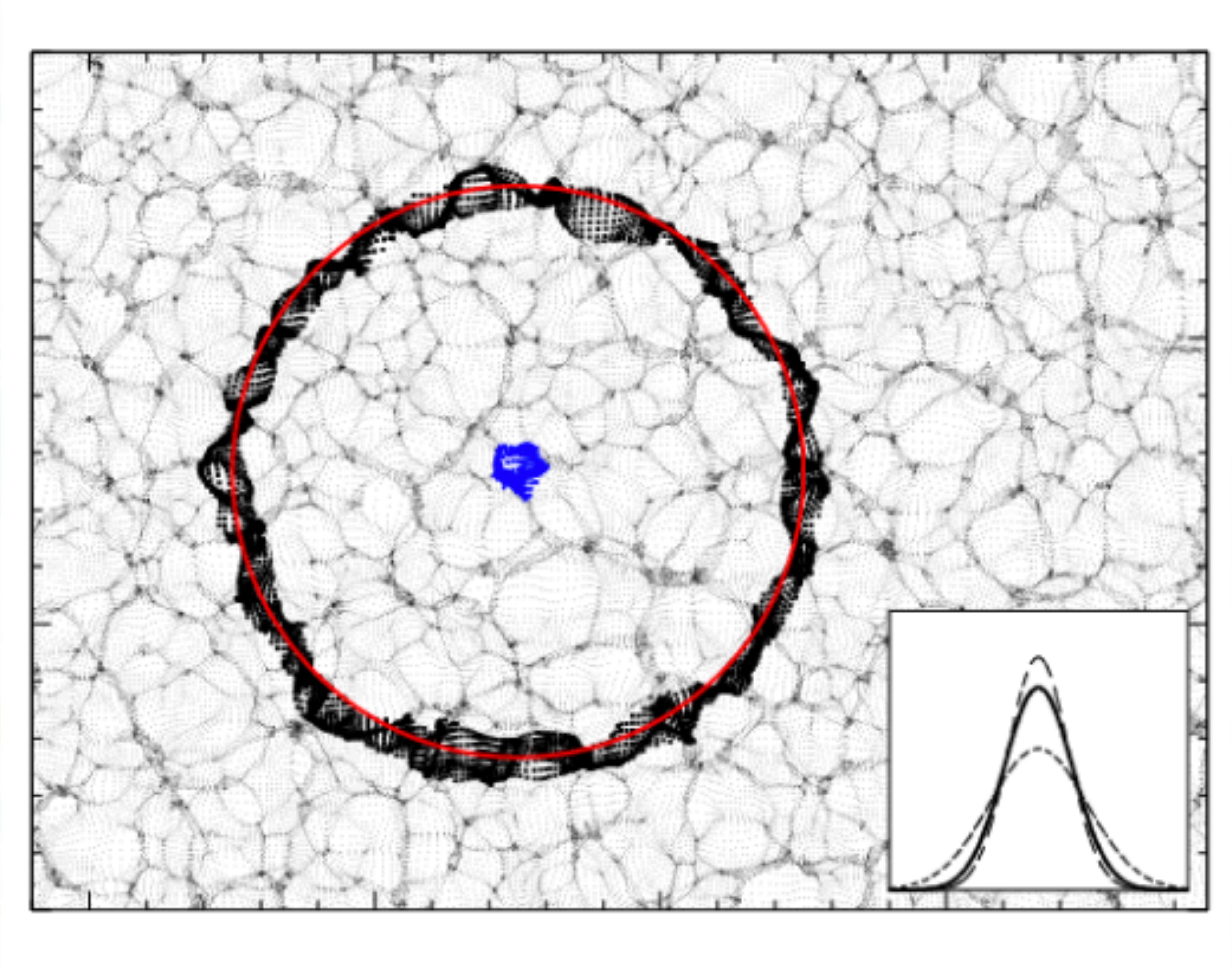

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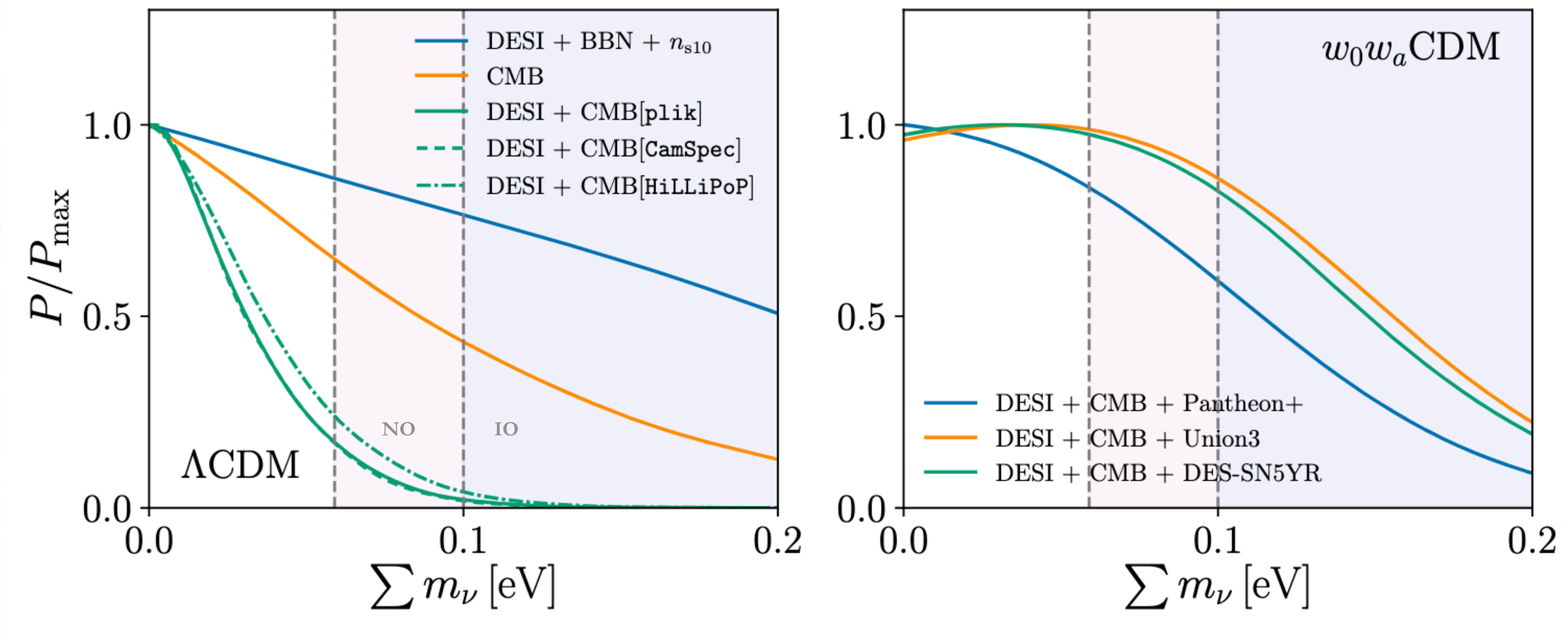
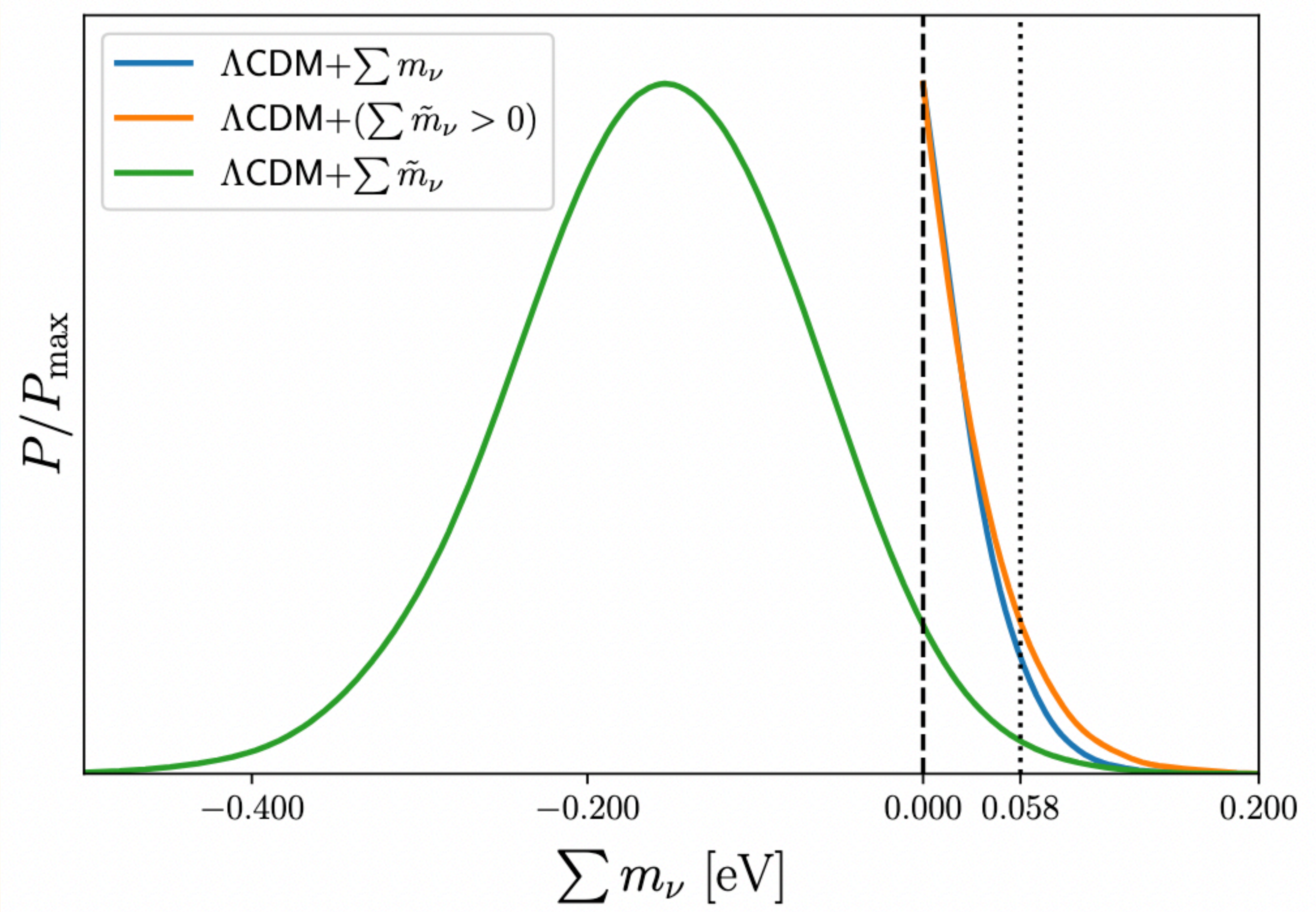
Ruling out inverted ordering for ν's?



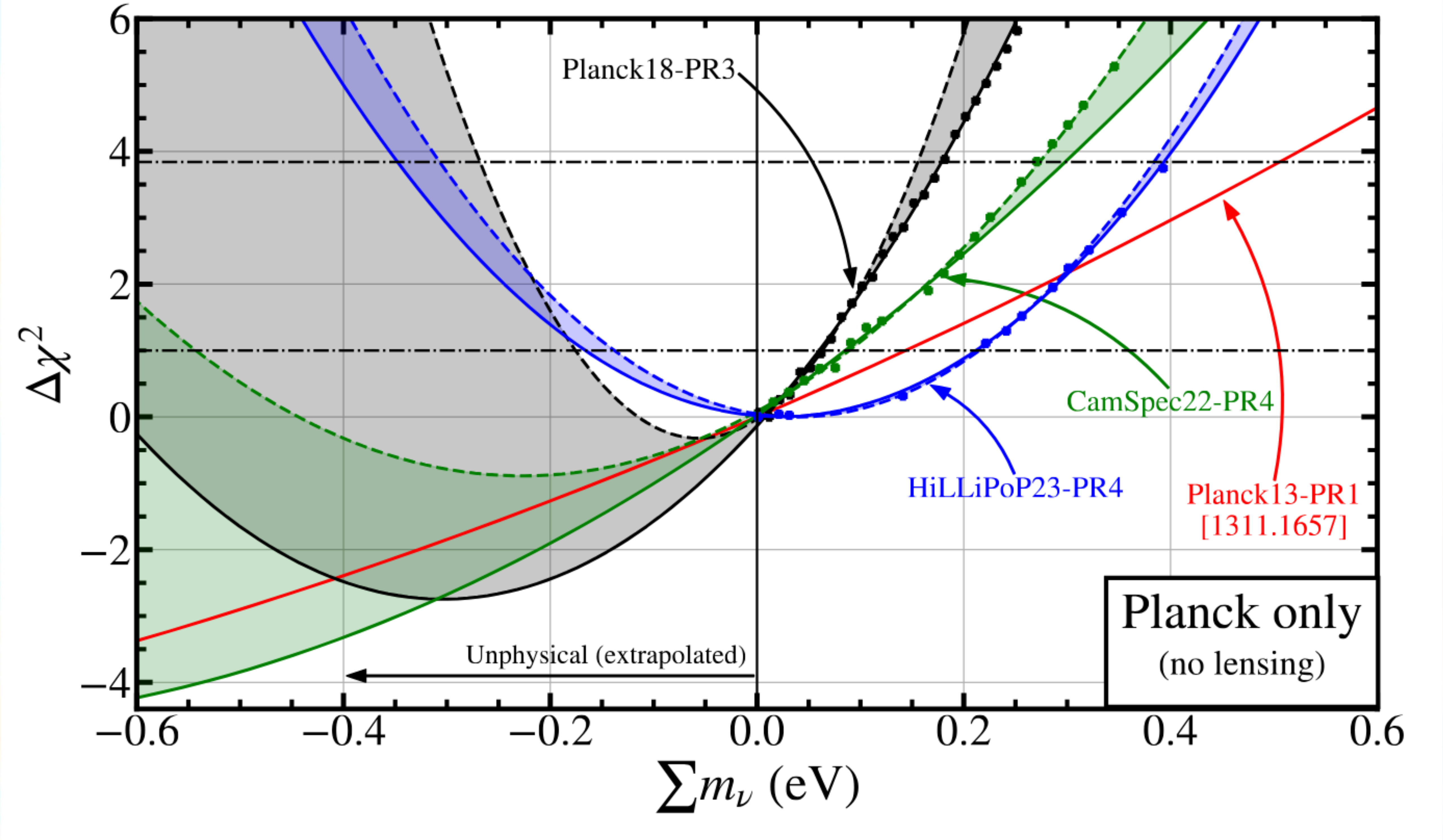
DESI Collaboration, A.G. Adame et al - arXiv: 2411.12022

$$\Delta P(k)/P(k) \propto -\Omega_\nu/\Omega_m$$

Negative neutrino masses ?



Craig et al. [2405.00836]

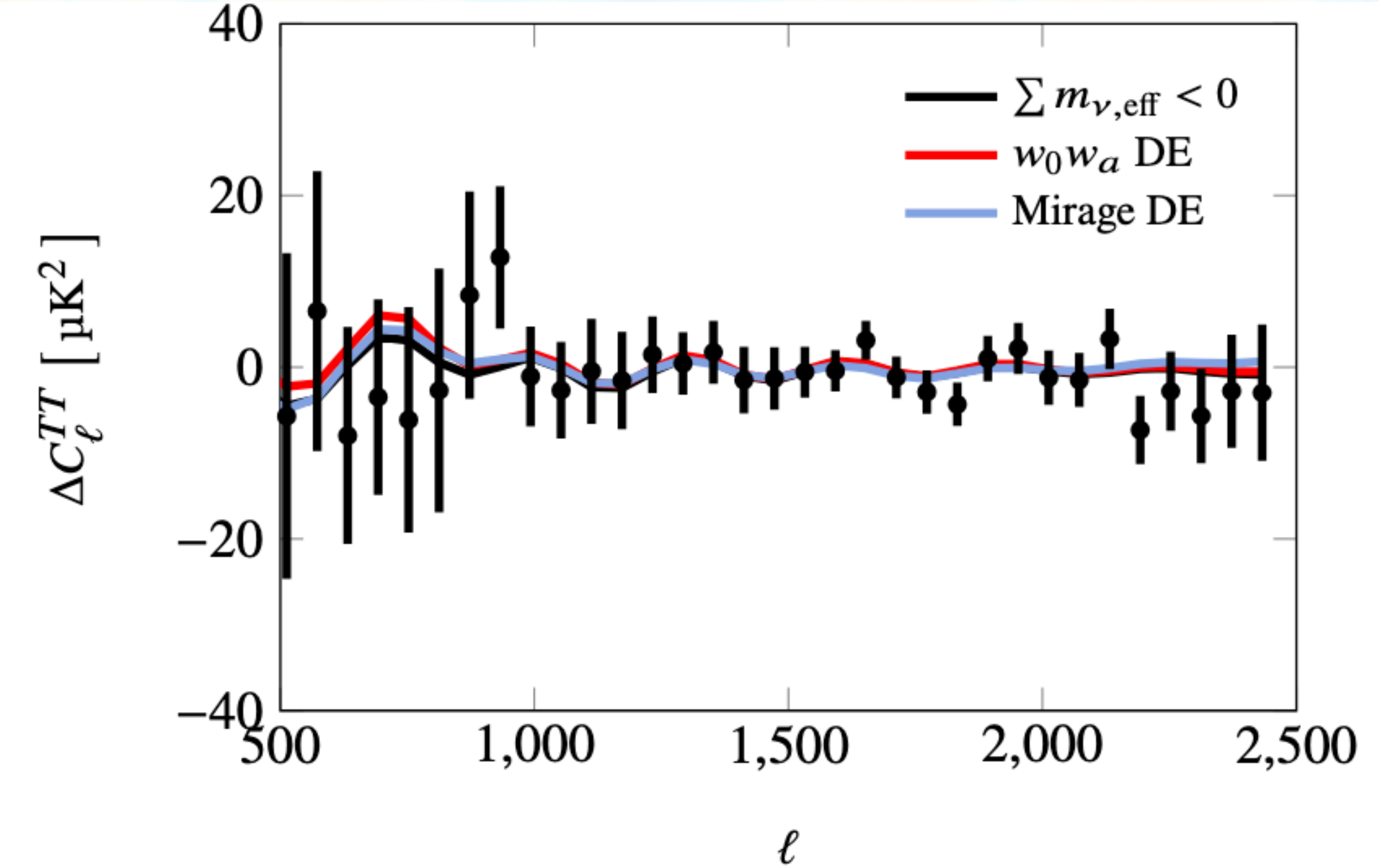


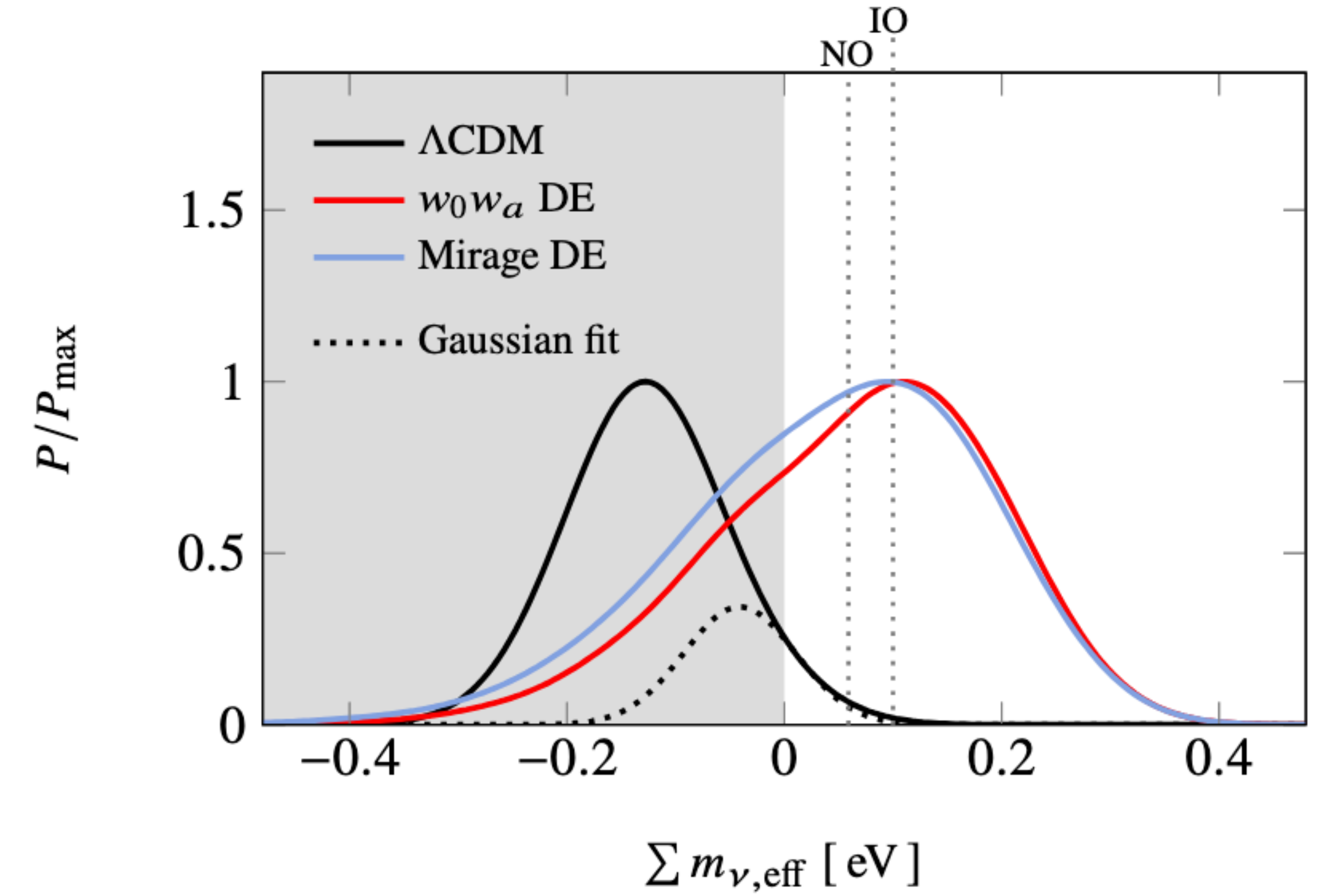
D. Naredo-Tuero et al. [2407.13831]

Tightly connected to the CMB lensing excess/anomaly (A_{lens}>1)

Negative neutrino masses ?

$$X_\theta^{\sum m_{\nu,\rm eff}} \equiv X_\theta^{\sum m_\nu = 0} + \mathrm{sgn}\left(\sum \mathrm{m}_{\nu,\rm eff}\right)\left[\mathrm{X}_\theta^{|\sum \mathrm{m}_{\nu,\rm eff}|} - \mathrm{X}_\theta^{\sum \mathrm{m}_\nu = 0}\right]$$





W. Elbers et al. [2407.10965]

2.8 – 3.3σ with tension neutrino oscillations

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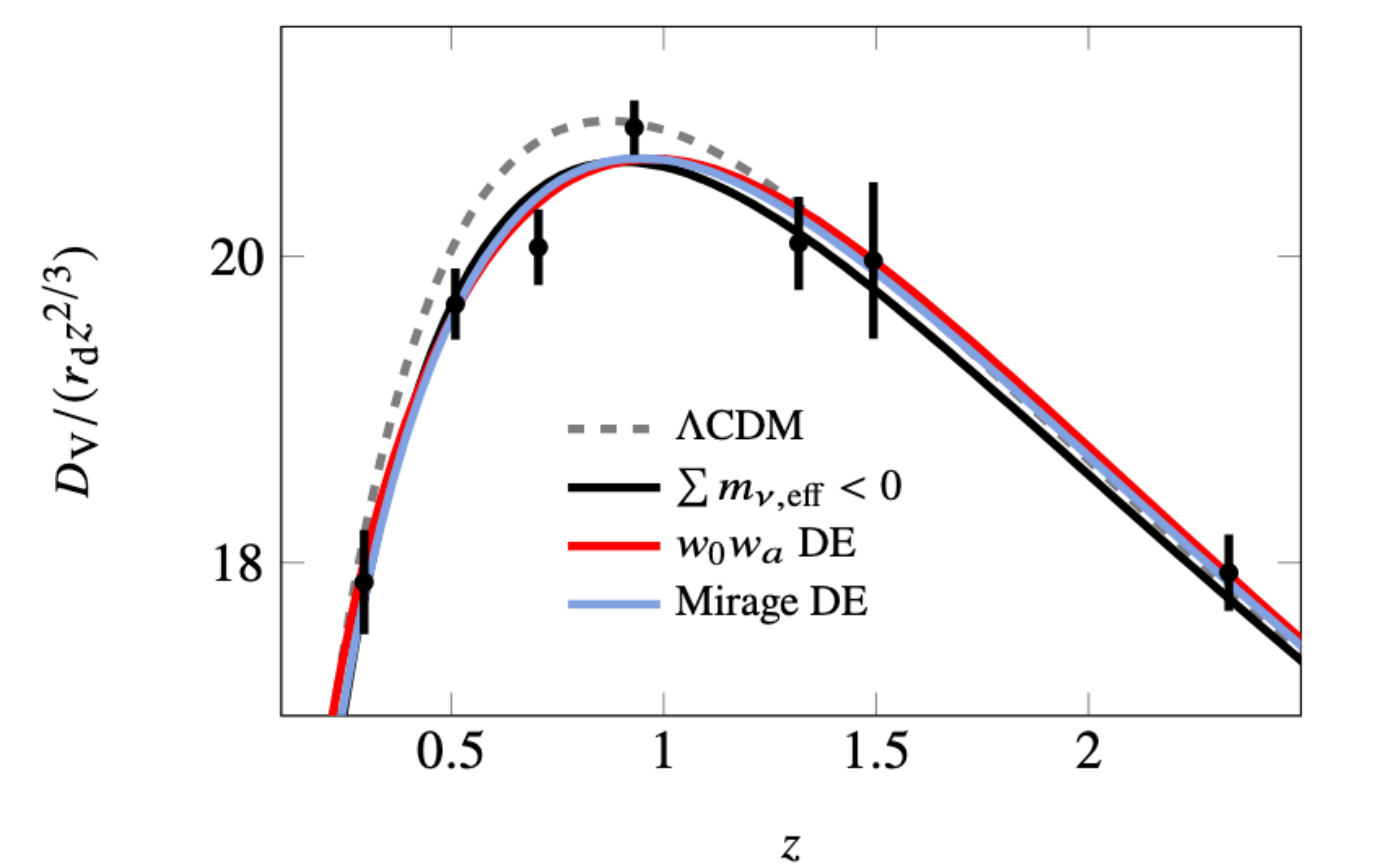

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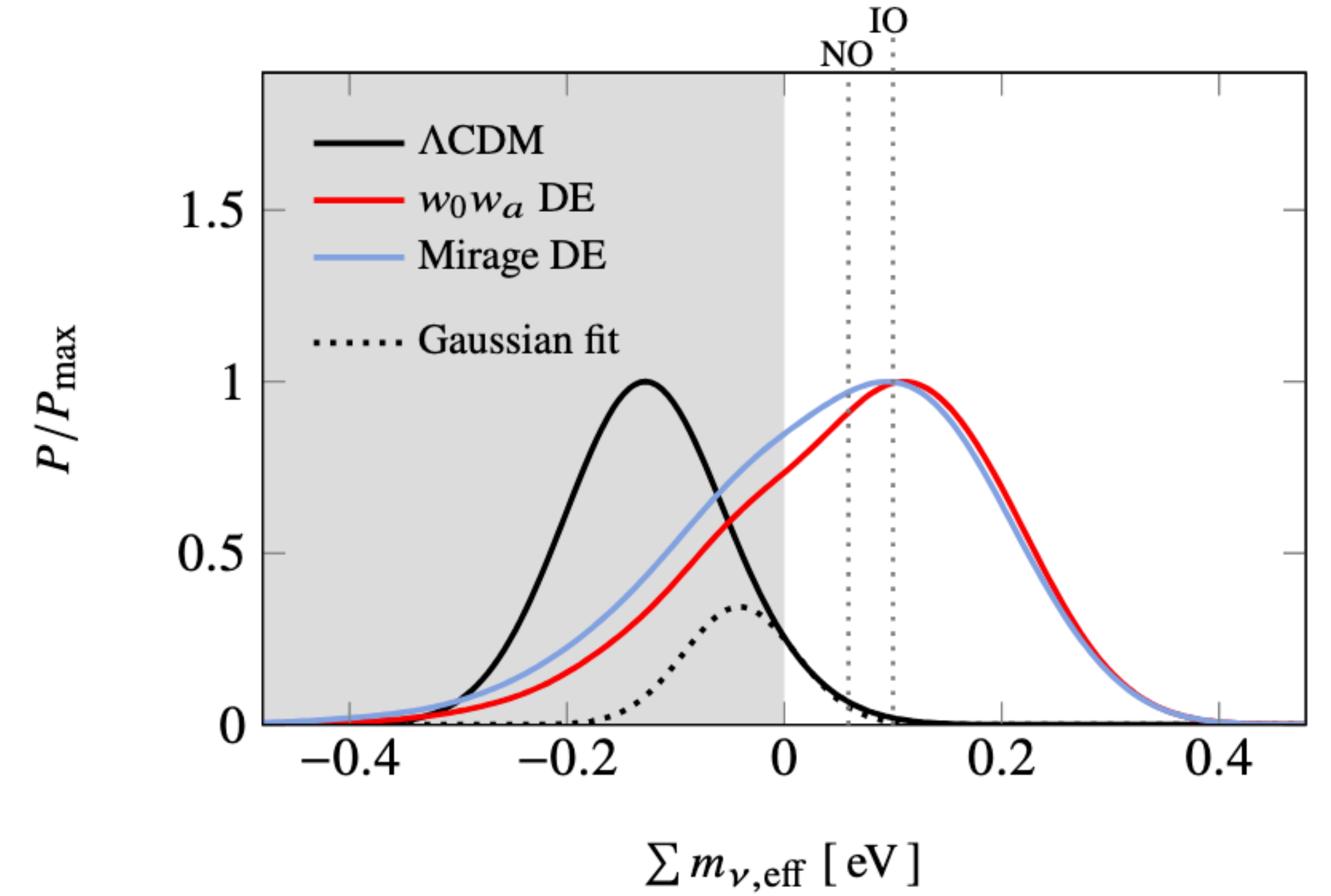

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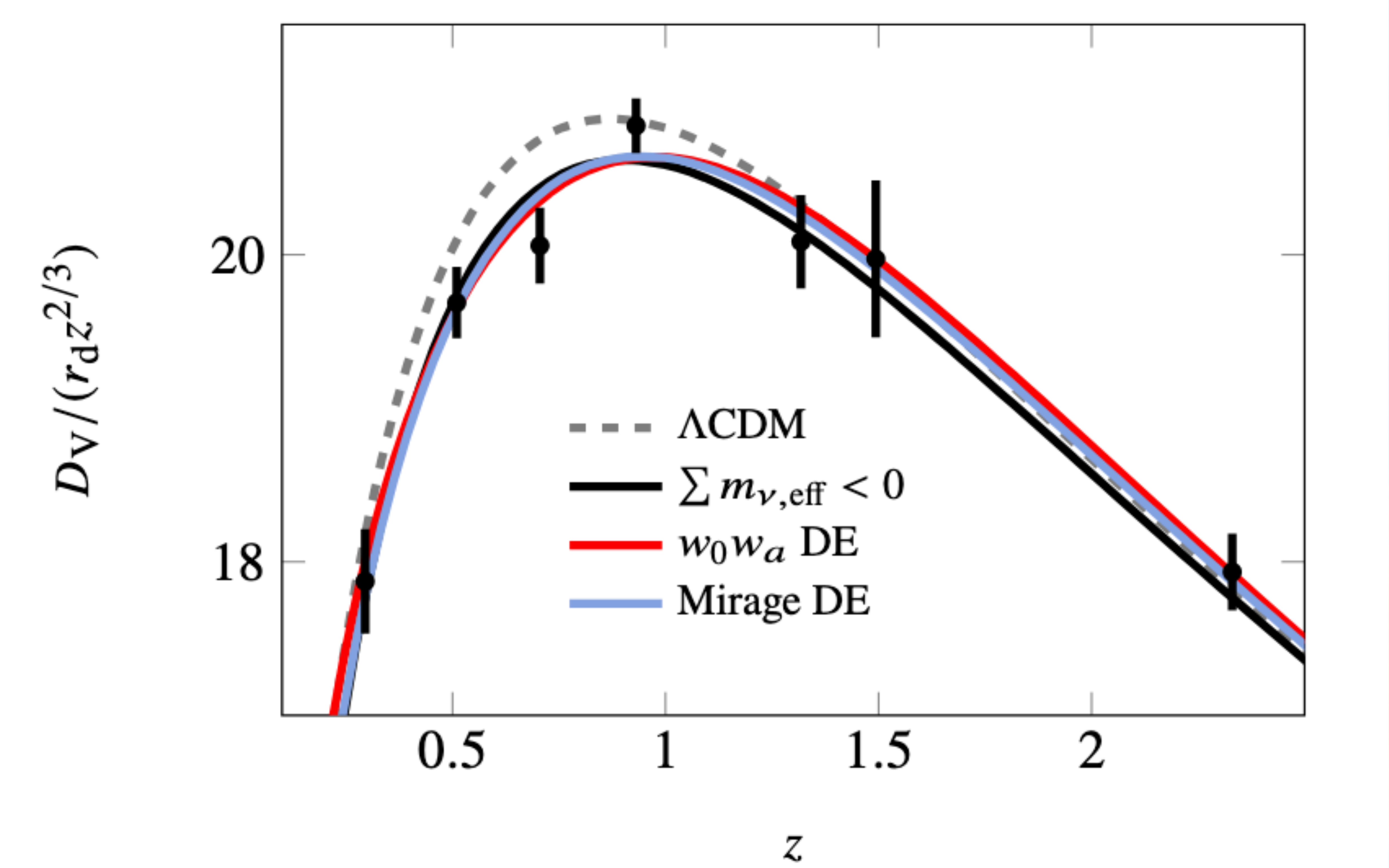

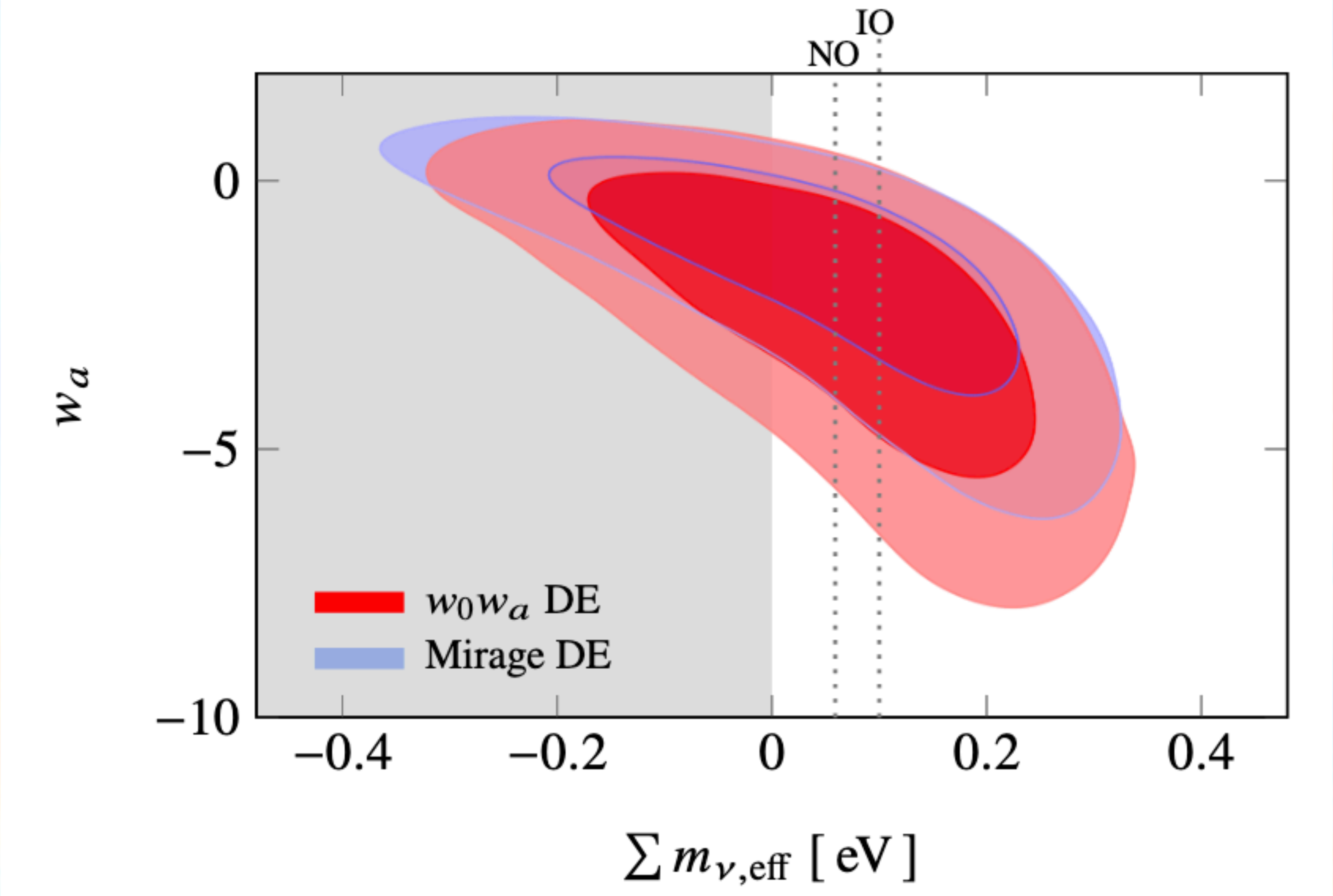

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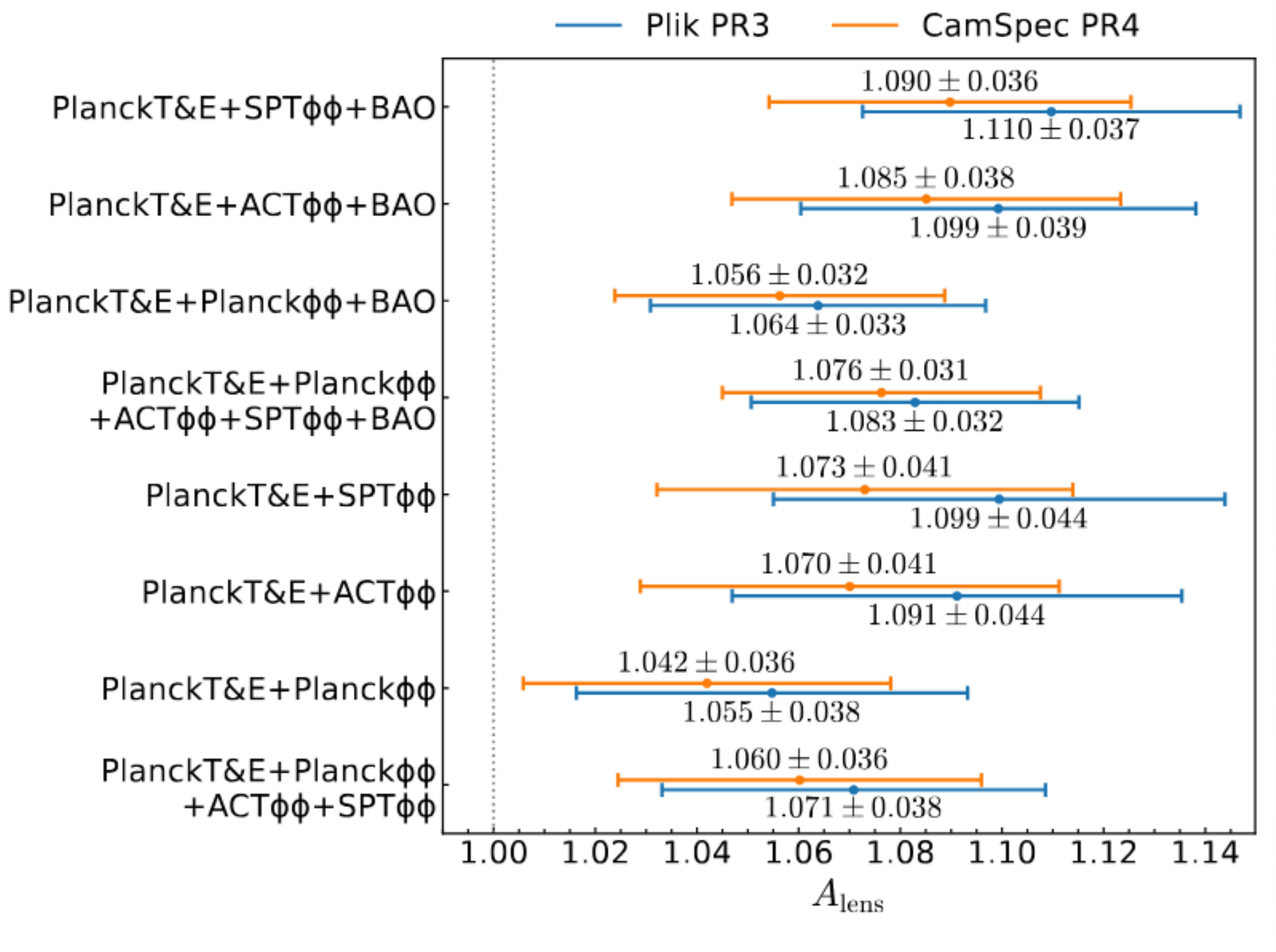
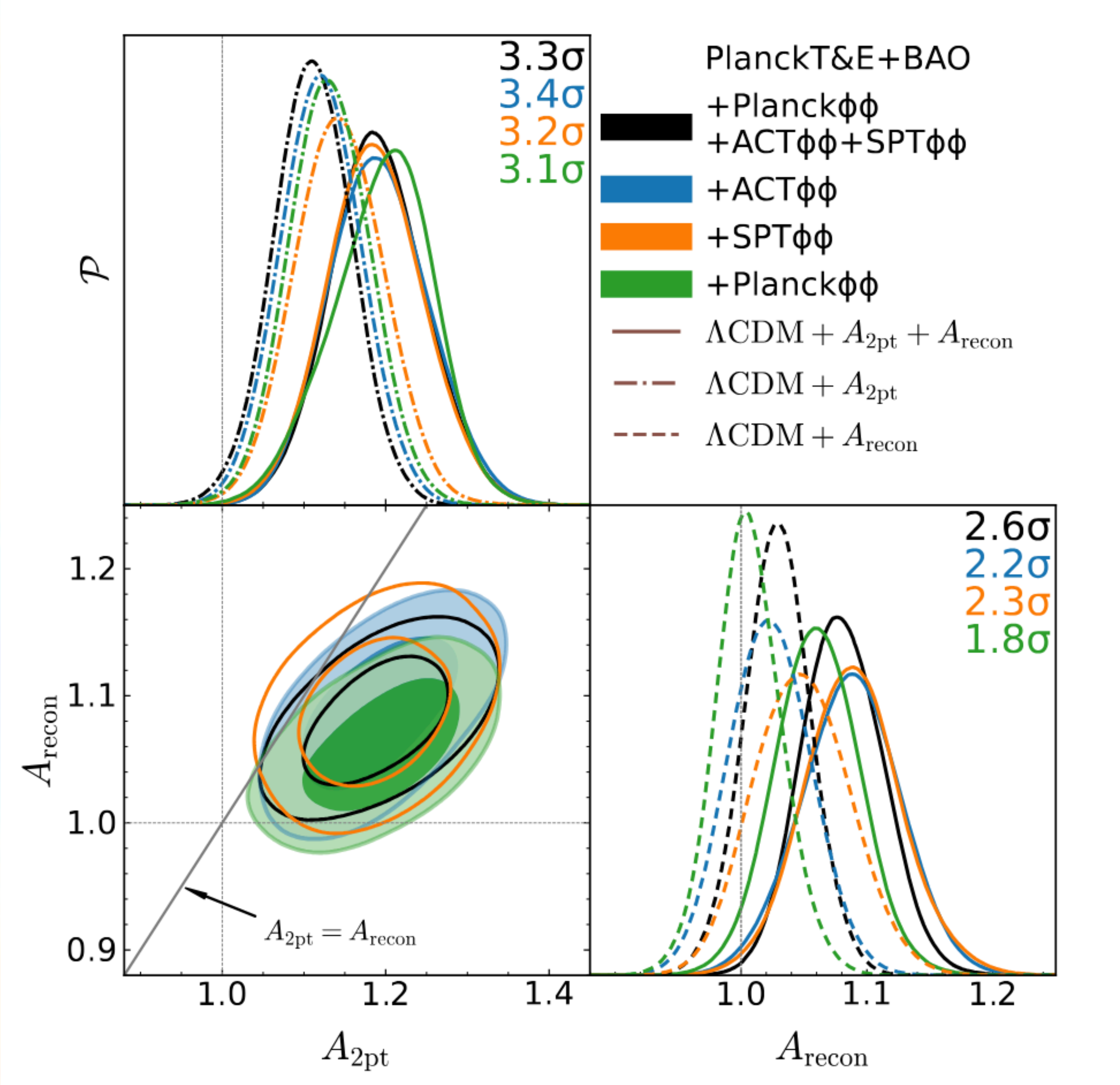
Is there an excess of lensing ?

Cosmology from CMB lensing and delensed EE power spectra using SPT-3G polarization data



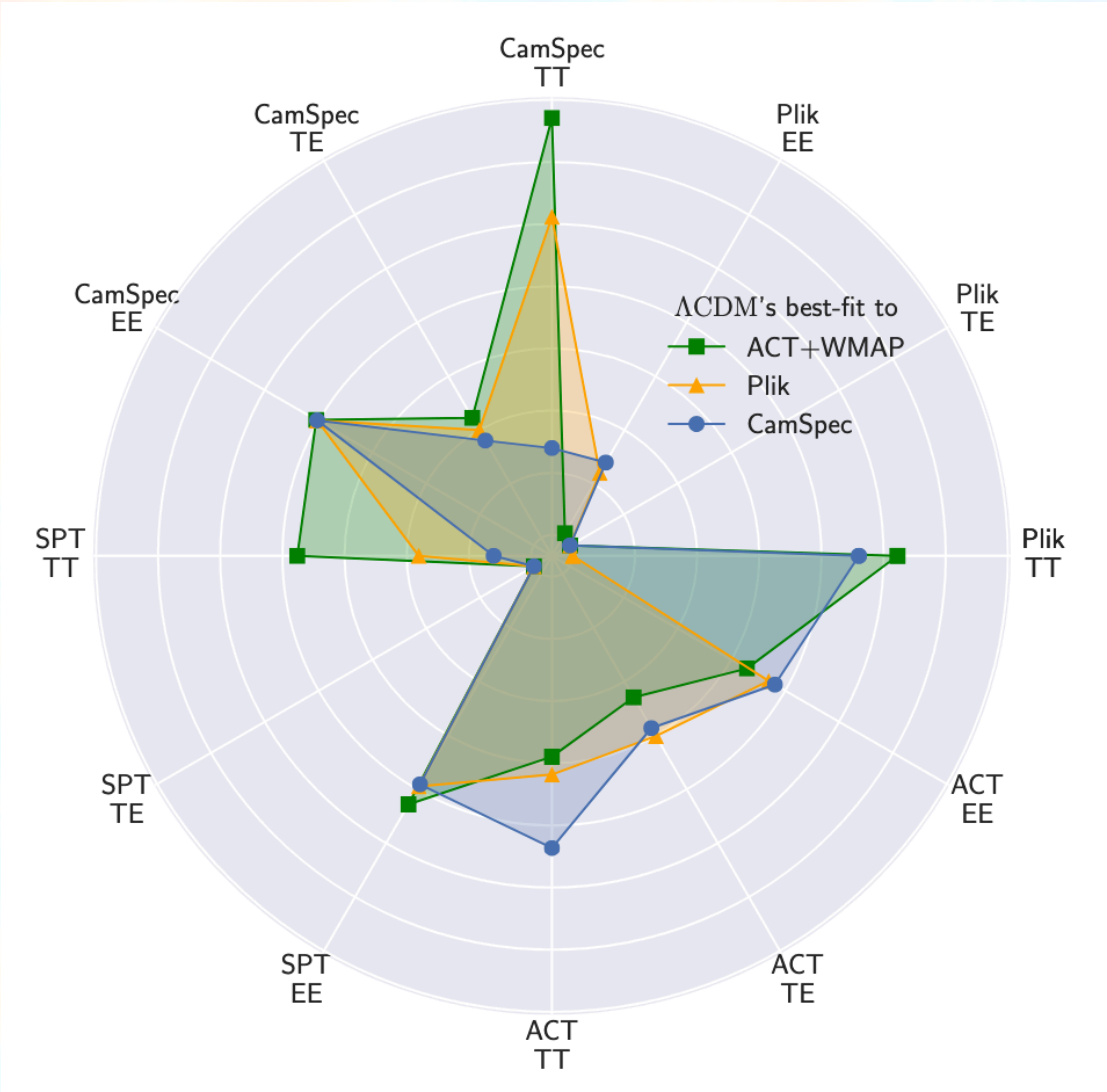


SPT Collaboration - Ge et al. [2411.06000]

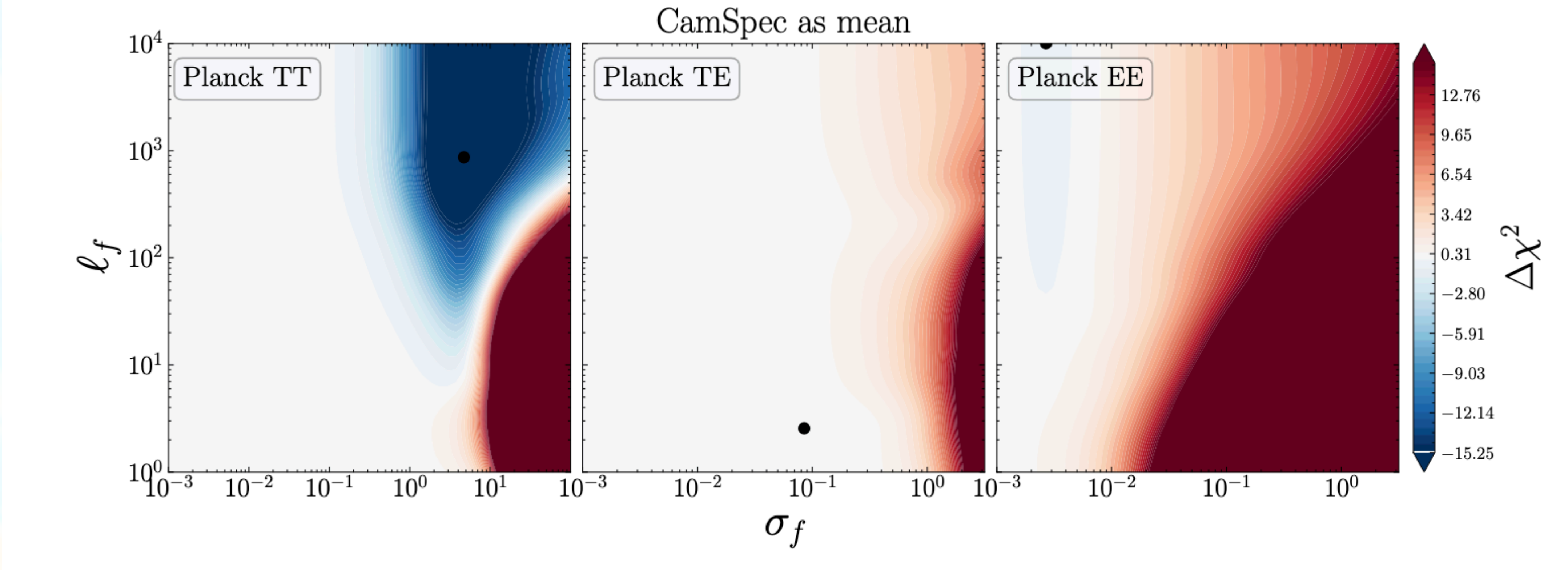
$$\Sigma\tilde{m}_\nu = -0.122 \pm 0.072\,\mathrm{eV}$$

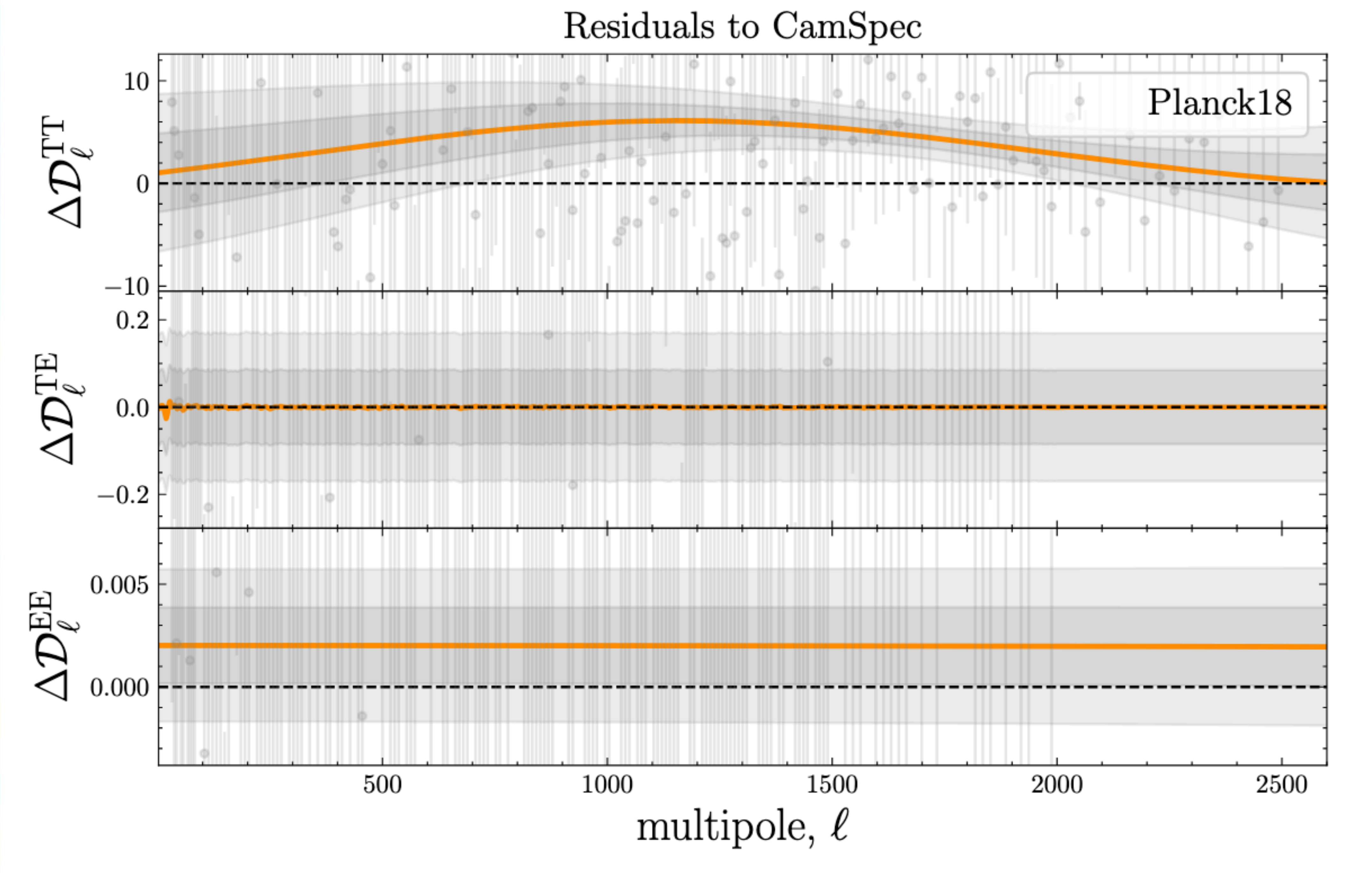
Neutrino-like lensing template

Systematics in the data ?



R. Calderon, A. Shafieloo, D. Hazra, W. Sohn - *JCAP* 08 (2023) 059





The "cosmic calibration" tension

Standard "Candle"

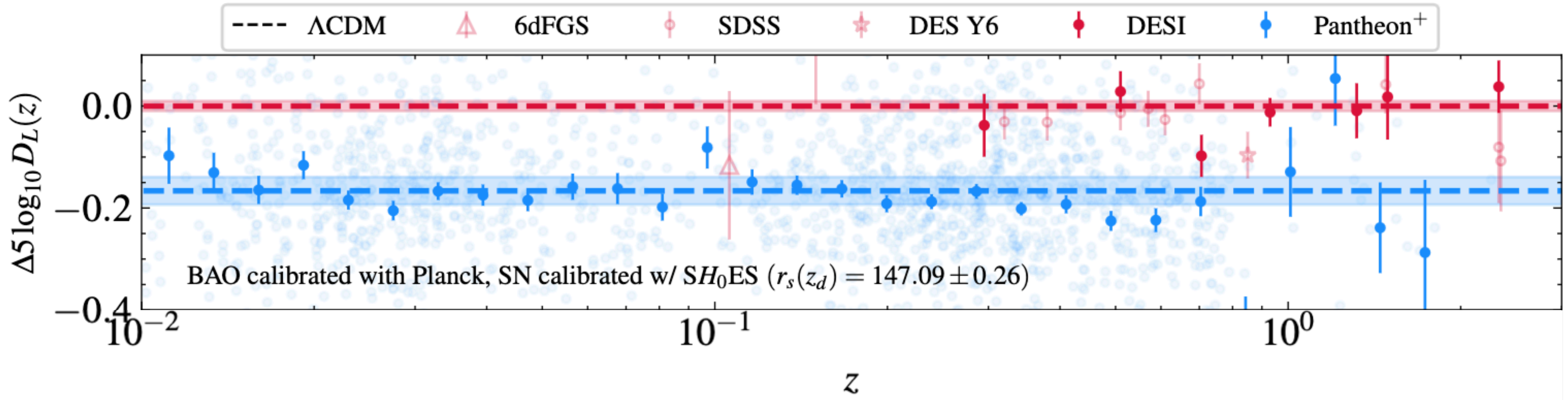
$$m_B(z) = 5\log_{10} D_L(z) + 25 + M_B$$

Distance-Duality Relation (DDR)

$$D_L(z) = (1+z)^2 D_A(z)$$

Standard "Ruler"

$$\alpha_\perp(z_{\rm eff}) \propto \frac{D_M(z_{\rm eff})}{r_d} = \frac{D_A(z_{\rm eff})}{r_d\,(1+z_{\rm eff})}$$



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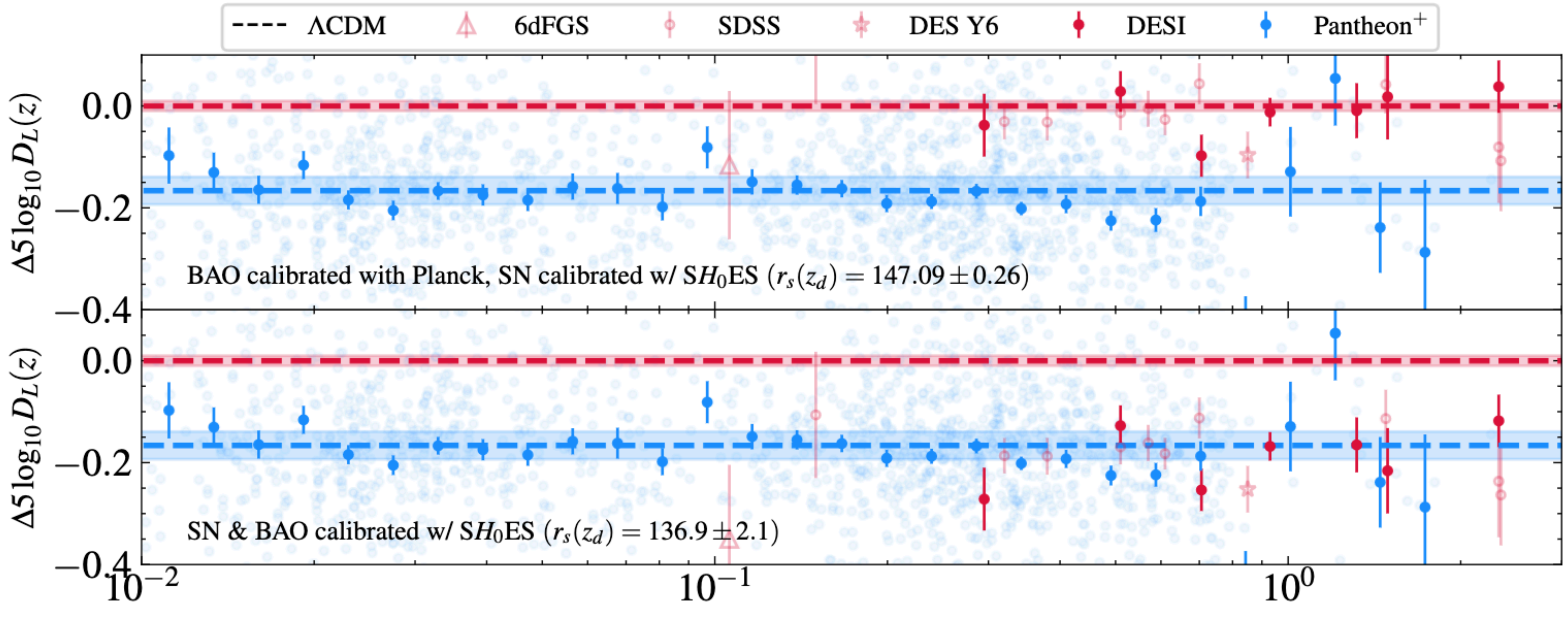

V. Poulin, T. L. Smith, **R. Calderon**, T. Simon - arXiv: 2407.18292