Towards Consistent Dark Energy Constraints from High- and Low-Redshift Probes with the Extended AP Test

Suvedha Suresh Naik

QUC Research Fellow

Korea Institute for Advanced Study (KIAS)

In collaboration with Changbom Park

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Outline

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ΛCDM and Its Tensions

- ΛCDM — cosmological constant + cold dark matter — fits most observations well, yet persistent discrepancies motivate extensions
- **Hubble tension:** $H_0^{\mathrm{SH0ES}} \approx 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ vs $H_0^{\mathrm{Planck}} \approx 67\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$
- **Evolving dark energy:** DESI DR2 + Planck + Pantheon+ prefer $w_0 > -1$, $w_a < 0$ at $\gtrsim 3\sigma$
- S_8 **tension:** weak-lensing surveys favour lower clustering amplitude than CMB-inferred ΛCDM
- These tensions point to **different cosmic epochs**: $H_0 \Rightarrow$ pre-recombination; $(w_0, w_a) \Rightarrow$ late-time expansion history; $S_8 \Rightarrow$ late-time growth
- **This talk:** test the evolving-DE signal against an additional low-z probe and early-universe physics

Evidence for Evolving Dark Energy and Phantom crossing

- DESI DR2 + Planck + Pantheon+: $w_0 = -0.838 \pm 0.055$, $w_a = -0.62^{+0.22}_{-0.19}$
  — ΛCDM at $(w_0, w_a) = (-1, 0)$ excluded at $\sim 3\sigma$ [DESI 2025]
- Best-fit CPL implies $w < -1$ (phantom crossing)
- But how robust is this signal?
  - **Dataset dependence:** significance varies with SN catalogue choice

Evidence for Evolving Dark Energy and Phantom crossing

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- But how robust is this signal?
  - **Dataset dependence:** significance varies with SN catalogue choice
  - **Early-universe dependence:** The CMB fixes the acoustic scale $\theta_* = r_*/D_M(z_*)$; pre-recombination physics that shifts r_* (e.g. EDE) reshapes the inferred low-z $H(z)$ and absorbs part of the w_a signal

- **This work:** extend $w^{\rm CPL}$CDM with axion-like EDE and add an r_d-independent low-z anchor (SDSS eAP) — can high-z and low-z probes be made consistent?

Outline

Dark Energy Models

- **Dynamical Dark Energy (CPL):**

$$w(z) = w_0 + w_a(1 - a)$$

Parameters: w_0, w_a. Affects: $H(z)$ and $D_A(z)$
$\Rightarrow$ shifts distance moduli (SN), BAO ratios, AP distortion

- **Early Dark Energy (EDE) — axion potential:**

$$V(\theta) = m^2 f^2 \left[1 - \cos(\theta)\right]^n$$

Parameters: f_{EDE}, z_c, $\theta \equiv \phi/f$, n.
Active around pre-recombination, temporarily boosts $H(z)$ before last scattering
$\Rightarrow$ **reduces** r_d, **raises** CMB-inferred H_0
$\Rightarrow$ **no direct late-time imprint —** negligible by $z \sim 10$
Implemented with AxiCLASS (Smith et al. 2019)

Outline

Observational Probes

Probe	Redshift	Parameters
High-z probe:		
Planck – CMB TTTEEE + lensing	$z \sim 1100$	$\omega_{\rm cdm},\ \omega_b,\ \tau_{\rm reio},\ \theta_*,\ A_s,\ n_s,\ f_{\rm EDE}$, ($w_0$, w_a weakly)
Low-z probes:		
PantheonPlus – SN Ia	$0.001 < z < 2.26$	$\Omega_m,\ w_0,\ w_a$
SH0ES		H_0
SDSS – extended AP	$0.025 < z < 0.7$	$\Omega_m,\ w_0,\ w_a$ (r_d-independent)
DESI DR2 – BAO	$0.1 < z < 4.2$	$\Omega_m,\ H_0,\ w_0,\ w_a, \omega_b,\ f_{\rm EDE}$

Alcock-Paczynski (AP) test

- An intrinsically isotropic feature appears isotropic **only if** the assumed cosmology is correct
- A wrong cosmology stretches radial and transverse separations by **different factors**:
  - Radial: $s_{\parallel} = c\Delta z / H(z)$ — depends on $H(z)$
  - Transverse: $s_{\perp} = (1+z)\, D_A(z)\, \Delta\theta$ — depends on $D_A(z)$
- Mismatch between the two distortions squashes a circle into an apparent ellipse $\rightarrow$ **the signal**
- The test is r_d-**independent**: the absolute scale cancels in the shape ratio; only the *anisotropy* matters
- Constrained parameters: Ω_m, w_0, w_a

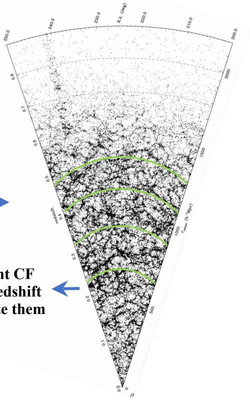
The Extended Alcock-Paczynski Test

using $\xi(s_\perp, s_\parallel)$ as the standard 'shape'

Observed RA, DEC & redshifts of galaxies

Adopt a cosmology, i.e. r(z) relation

Calculated r, θ, ϕ of galaxies



Measure two-point CF $\xi(s_\perp, s_\parallel)$ in each redshift shells & normalize them

Shape differences across redshift shells

$$\Delta\widehat{\xi}(z_i, z_{\rm ref}) = \widehat{\xi}(z_i) - \widehat{\xi}(z_{\rm ref}) - \Delta\widehat{\xi}^{\rm sys}(z_i, z_{\rm ref})$$

Likelihood for many cosmological models

$$\chi^2_{z_{\rm ref}}(\Omega_m, w) = \sum_{\ell=0,2,4} \sum_{\alpha,\beta} P_\ell^{z_{\rm ref}}(s_\alpha) \cdot (C^\ell_{\alpha\beta})^{-1} \cdot P_\ell^{z_{\rm ref}}(s_\beta)$$

Note!

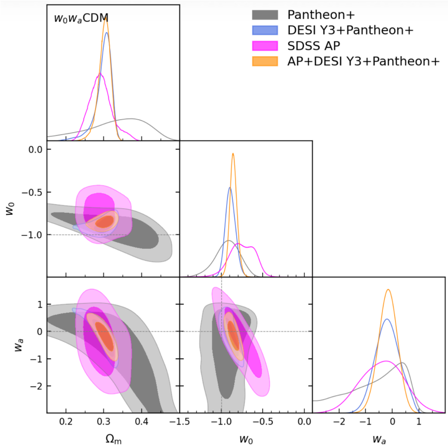
We don't need to know absolute size or shape. Only shape conservation is used across redshifts!

- **Purely geometrical & ~independent of size, mass & clustering evolution!**
- **High statistics!**

see Park et al. (2019), Dong et al. (2023), Dong & Park (2026)

Extended AP test

Low-z constraints from the eAP method paper:

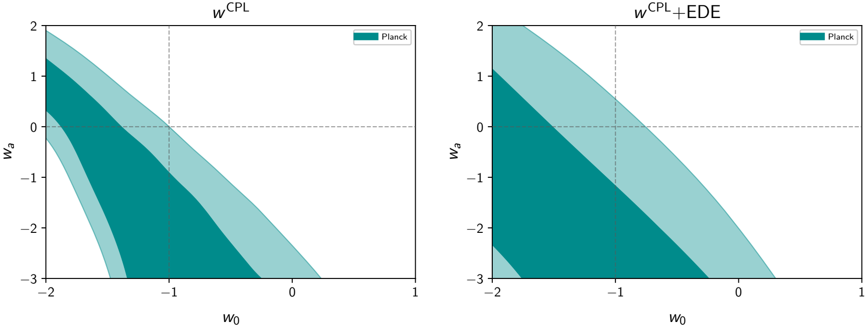


Dong & Park 2026 ApJ 998 66, arXiv: 2510.24089

Outline

Constraints from high-z probe

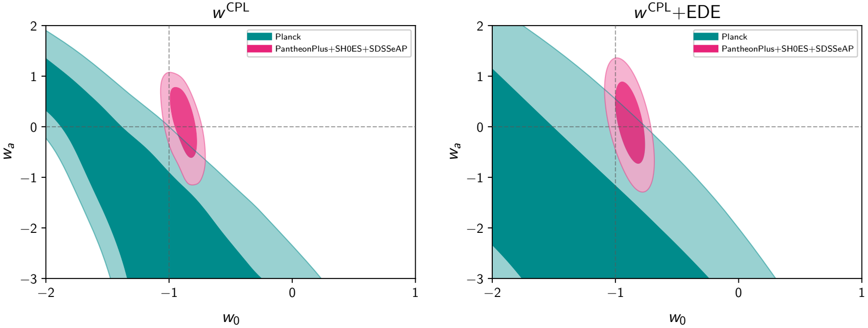
Planck: PR4(TTTEEE+lensing)



Unconstrained from CMB alone

Constraints from low-z probes

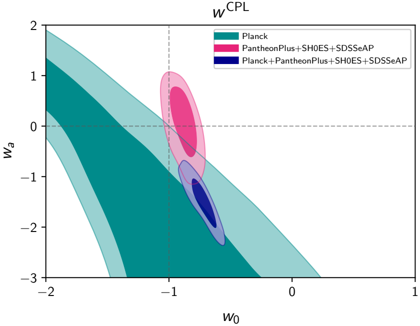
PantheonPlus+SH0ES+SDSS-eAP



- $w^{\rm CPL}$: Constraints from low-z probes are consistent with ΛCDM or weakly dynamical DE; Dong & Park 2026 ApJ 998 66, arXiv: 2510.24089
- $w^{\rm CPL}$+EDE: EDE unconstrained by low-z data (no late-time imprint)

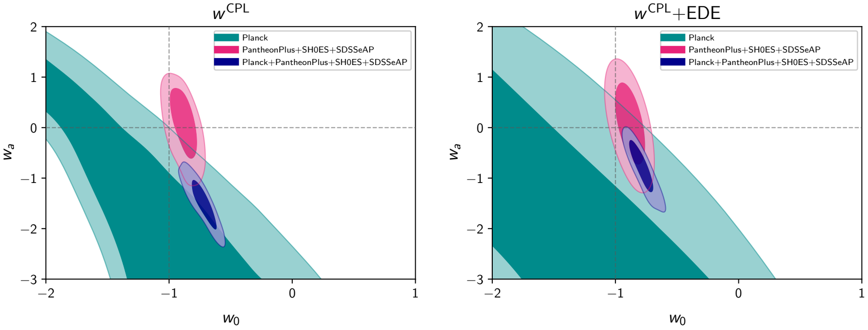
Constraints from high- & low-z probes

Planck+PantheonPlus+SH0ES+SDSS-eAP



Constraints from high- & low-z probes

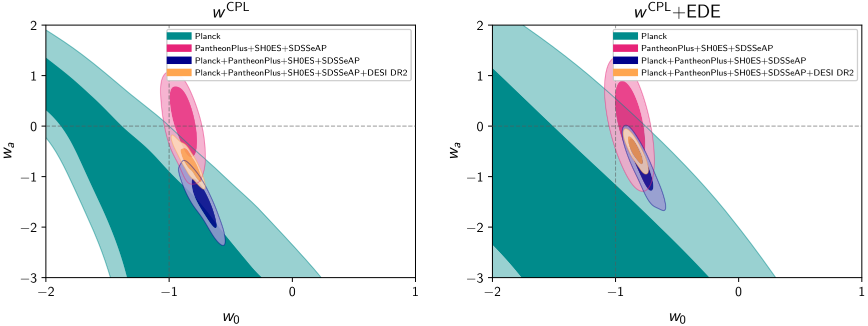
Planck+PantheonPlus+SH0ES+SDSS-eAP



- Hints of dynamical DE become stronger ONLY when CMB is added!
- Addition of EDE reduces the tension with ΛCDM model; EDE raises H_0, lowers r_d

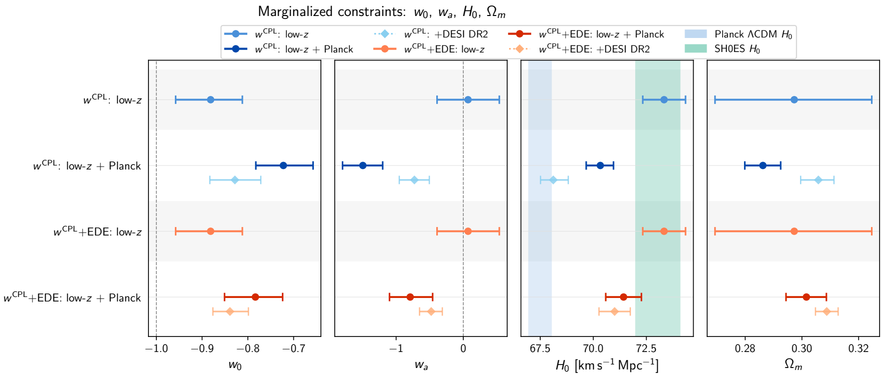
Constraints from high- & low-z probes

Planck+PantheonPlus+SH0ES+SDSS-eAP+DESI BAO



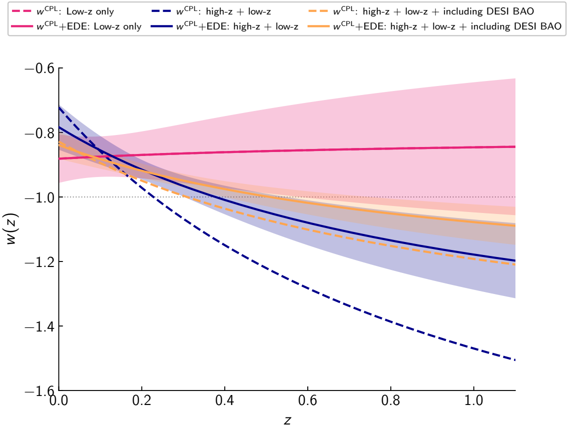
Effects of DESI BAO - contour shifts only mildly for EDE case $\Rightarrow$ low-z + CMB result is stable

Results



Marginalized constraints: w_0, w_a, H_0, Ω_m
w^{CPL}: low-z
w^{CPL}: low-z + Planck
w^{CPL}: +DESI DR2
w^{CPL}+EDE: low-z
w^{CPL}+EDE: low-z + Planck
w^{CPL}+EDE: +DESI DR2
Planck ΛCDM H_0
SH0ES H_0
w^{CPL}: low-z
w^{CPL}: low-z + Planck
w^{CPL}+EDE: low-z
w^{CPL}+EDE: low-z + Planck
−1.0 −0.9 −0.8 −0.7
w_0
−1 0
w_a
67.5 70.0 72.5
H_0 [km s^{-1} Mpc^{-1}]
0.28 0.30 0.32
Ω_m

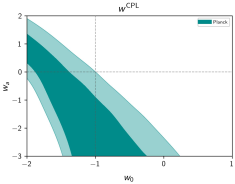
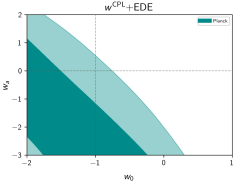
Evolution w(z)

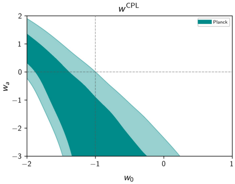
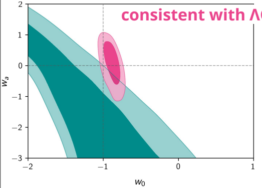
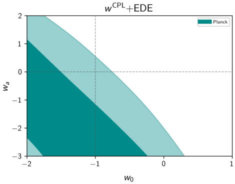
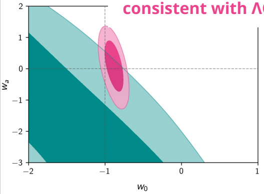


- Low-z only: no crossing of $w = -1$ at $z < 0.7$ (thawing-like); crossing appears only once CMB is added

Contents

	High-z probes	Low-z probes	Low-z + high-z probes
w^{CPL} models			
w^{CPL} + EDE models			

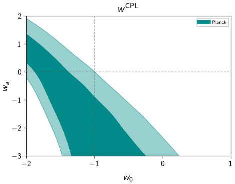
	High-z probes	Low-z probes	Low-z + high-z probes
w^{CPL} **models**			
w^{CPL} **+ EDE models**	**EDE unconstrained by CMB alone** 		

	High-z probes	Low-z probes	Low-z + high-z probes
w^{CPL} models		$(w_0, w_a) = (-0.881^{+0.073}_{-0.073}, 0.07^{+0.53}_{-0.38})$ consistent with ΛCDM 	
w^{CPL}+ EDE models	EDE unconstrained by CMB alone 	$(w_0, w_a) = (-0.881^{+0.073}_{-0.073}, 0.07^{+0.53}_{-0.38})$ consistent with ΛCDM 	

	High-z probes	Low-z probes	Low-z + high-z probes

w^{CPL} models

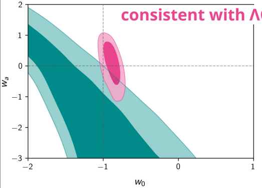
High-z probes



Low-z probes

$$(w_0, w_a) = (-0.881^{+0.073}_{-0.073}, 0.07^{+0.53}_{-0.38})$$

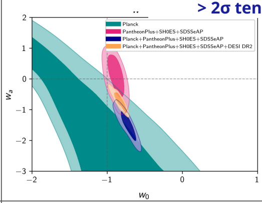
consistent with ΛCDM



Low-z + high-z probes

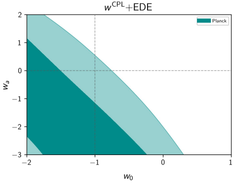
$$(w_0, w_a) = (-0.722^{+0.075}_{-0.054}, -1.49^{+0.33}_{-0.27})$$

> 2σ tension



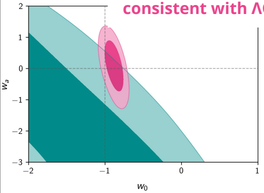
w^{CPL} + EDE models

EDE unconstrained by CMB alone



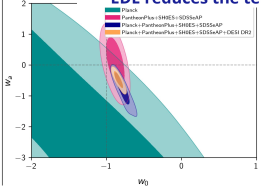
$$(w_0, w_a) = (-0.881^{+0.073}_{-0.073}, 0.07^{+0.53}_{-0.38})$$

consistent with ΛCDM



$$(w_0, w_a) = (-0.784^{+0.065}_{-0.074}, -0.79^{+0.41}_{-0.30})$$

EDE reduces the tension



Take-away points

- The evolving-DE signal is **driven by the inclusion of high-z CMB**:
  - Low-z alone (eAP + Pantheon+, no CMB): consistent with ΛCDM
  - Adding Planck pulls the fit away from ΛCDM, $\approx 2\sigma$
- The r_d-independent eAP anchor stays consistent with ΛCDM
- **Early dark energy partially absorbs the pull:** with improved eAP consistency, but a substantial $w_a < 0$ deviation remains
- Extended AP will be applied directly to DESI DR2.
- Unified early + late scalar-field models will be explored.

Thank You

wCPL — Marginalized Constraints

Parameter	Planck	Low-z	Planck+Low-z	Planck+Low-z+DESI
H_0 $[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	82^{+20}_{-7}	73.3 ± 1.0	$70.33^{+0.52}_{-0.76}$	$68.11^{+0.45}_{-0.78}$
w_0	$-1.17^{+0.35}_{-0.64}$	-0.881 ± 0.073	$-0.722^{+0.075}_{-0.054}$	$-0.828^{+0.065}_{-0.052}$
w_a	< -0.646	$0.07^{+0.53}_{-0.38}$	$-1.49^{+0.33}_{-0.27}$	-0.73 ± 0.22
Ω_m	$0.225^{+0.020}_{-0.083}$	$0.297^{+0.025}_{-0.030}$	$0.2862^{+0.0070}_{-0.0057}$	$0.3058^{+0.0068}_{-0.0046}$
σ_8	$0.926^{+0.12}_{-0.055}$	—	$0.8334^{+0.0090}_{-0.010}$	$0.8140^{+0.0084}_{-0.0097}$
S_8	$0.783^{+0.025}_{-0.047}$	—	0.814 ± 0.011	0.8218 ± 0.0089
χ^2_{total}	10970.5	1454.8	12450.9	12471.6

Low-z = Pantheon++ + SH0ES + SDSS eAP.   Intervals 68 % C.L. marginalized.

wCPL+EDE — Marginalized Constraints

Parameter	Planck	Low-z	Planck+Low-z	Planck+Low-z+DESI
H_0 $[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	87^{+20}_{-10}	73.3 ± 1.0	71.43 ± 0.85	71.00 ± 0.75
w_0	< -1.01	-0.881 ± 0.073	$-0.784^{+0.065}_{-0.074}$	-0.839 ± 0.041
w_a	< -0.809	$0.07^{+0.53}_{-0.38}$	$-0.79^{+0.41}_{-0.30}$	$-0.48^{+0.20}_{-0.13}$
Ω_m	$0.215^{+0.021}_{-0.094}$	$0.297^{+0.025}_{-0.030}$	$0.3016^{+0.0080}_{-0.0061}$	$0.3088^{+0.0037}_{-0.0042}$
σ_8	$0.963^{+0.13}_{-0.084}$	—	0.835 ± 0.010	0.8318 ± 0.0092
S_8	$0.783^{+0.030}_{-0.056}$	—	0.837 ± 0.012	0.844 ± 0.010
f_{EDE}	$0.055^{+0.025}_{-0.040}$	—	$0.119^{+0.028}_{-0.024}$	0.131 ± 0.023
χ^2_{total}	10967.9	1454.8	12437.0	12447.8

Low-z = Pantheon+ + SH0ES + SDSS eAP. Intervals 68 % C.L. marginalized.
f_{EDE} unconstrained without CMB; Low-z column reduces to wCPL.
Planck-only f_{EDE} (no SH0ES) is consistent with zero