A New Mechanism for Dynamical Dark Energy to Explain DESI Observations

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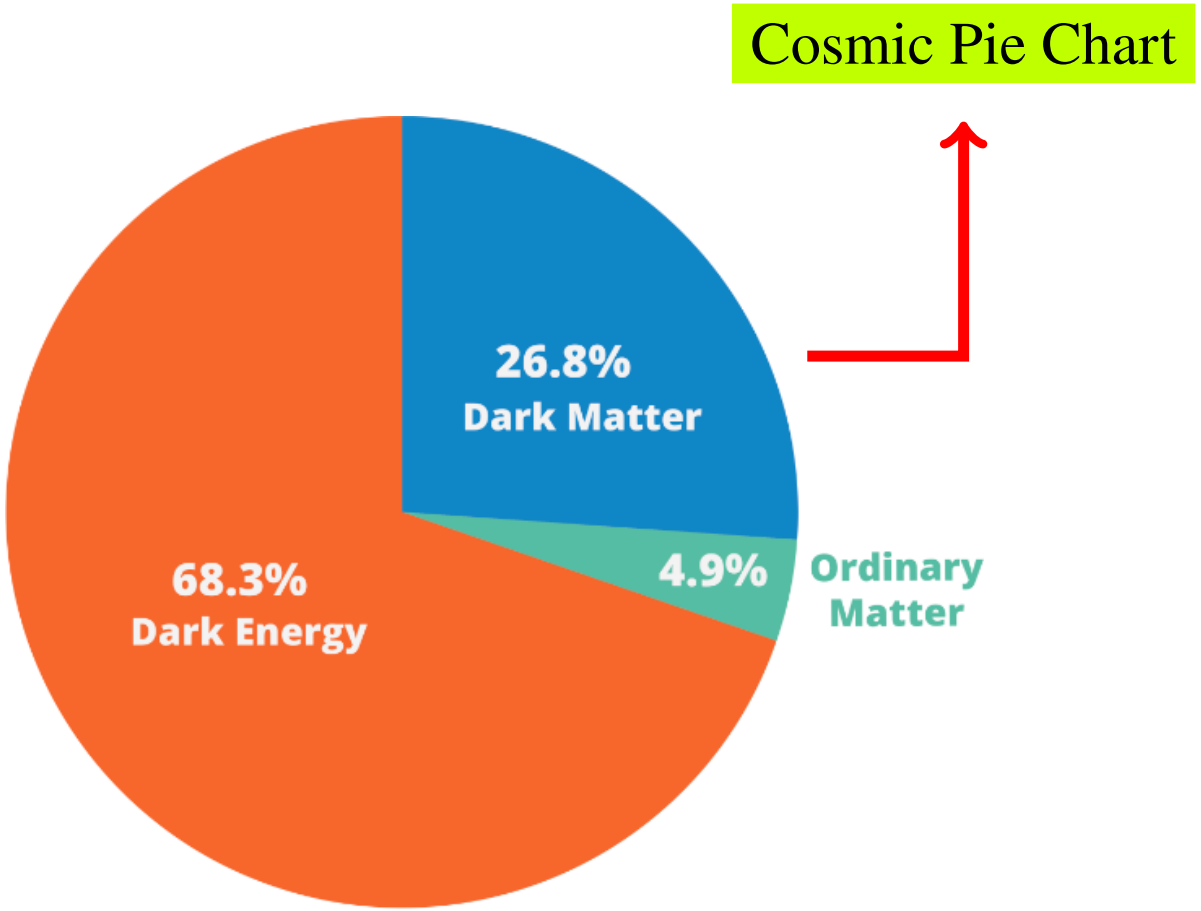
Les Houches Dark Universe 2025

Based on arXiv:2403.14247 & 2503.10806

July 24, 2025

Introduction

- Dark Energy is one of the most abundant objects of our universe, comprising ~ 69% of it.



ΛCDM: The Standard Model of Cosmology

"Most simplistic model of our complex universe" - P.J.Peebles

- Minimalistic yet Powerful: 6 parameters explain a wide range of observations.
- Predictive Successes:
  - CMB anisotropies (Planck)
  - Baryonic Acoustic Oscillations (BAO)
  - Type Ia supernovae (Sne Ia)
  - Large scale structure
- Robust across scales: From recombination epoch to late-time acceleration
- Benchmark for new physics: Any deviation must outperform ΛCDM fit to data.

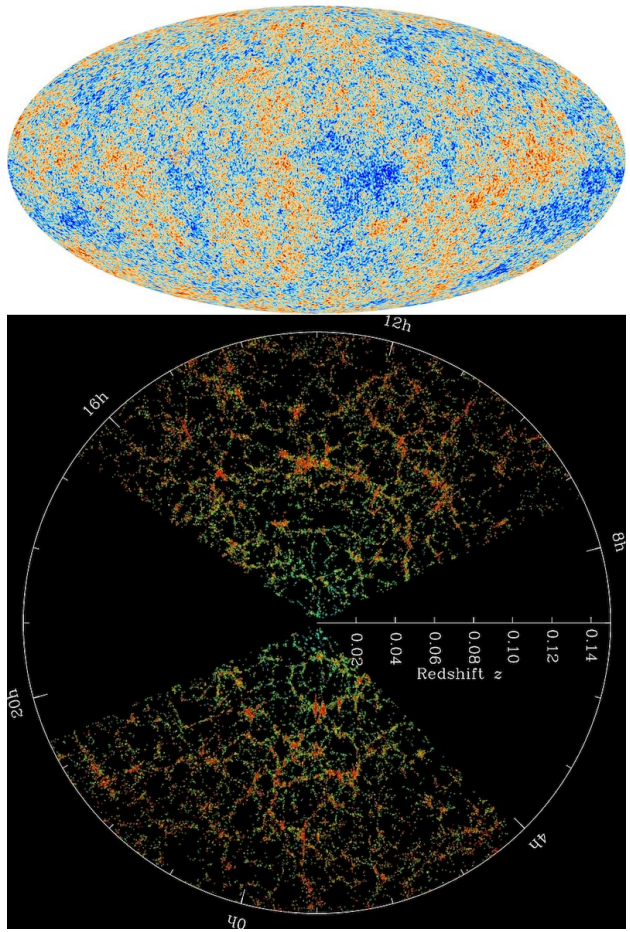
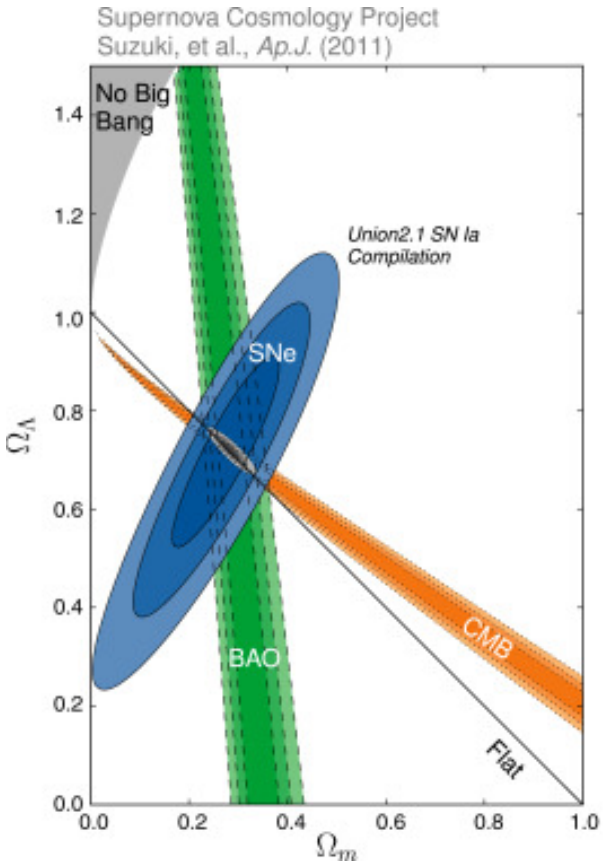


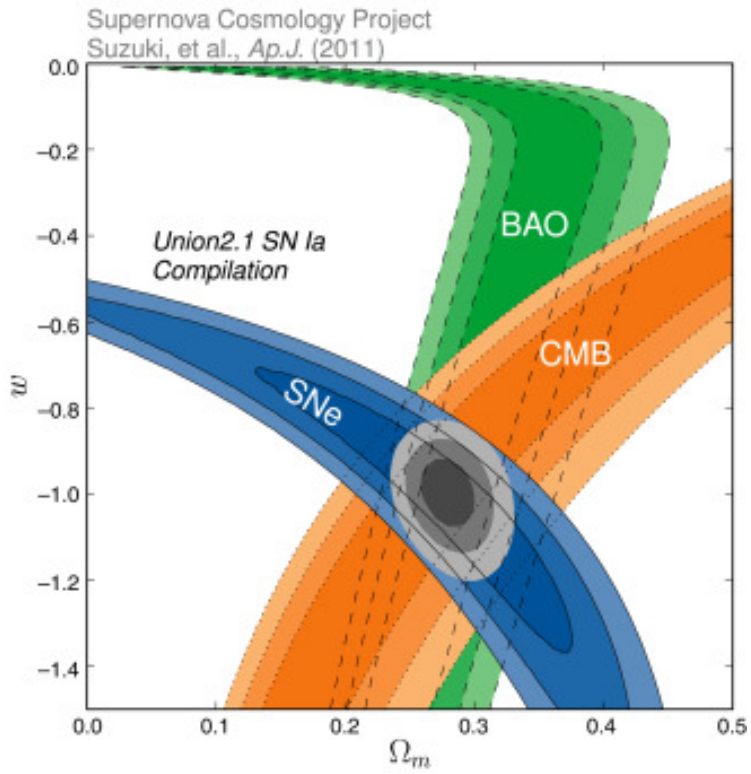
Figure: CMB map from Planck and large scale structure of the universe

Cosmological Constant as Dark Energy

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3} \quad \Longrightarrow \quad P_\Lambda = -\rho_\Lambda$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) \quad \Longrightarrow \quad w < -\frac{1}{3} \text{ for acceleration}$$





$w = -1.03 \pm 0.03$

Limitations of ΛCDM

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- Multiple independent observations suggests ΛCDM is not the full picture!!
- It is time to go beyond Cosmological Constant Λ.

Quintessence Dark Energy Model

- *Quintessence scalar field always destined to take over matter density by tracking.*

$$\mathcal{L} = \frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - V(\phi)$$

- **Equation of Motion:**

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

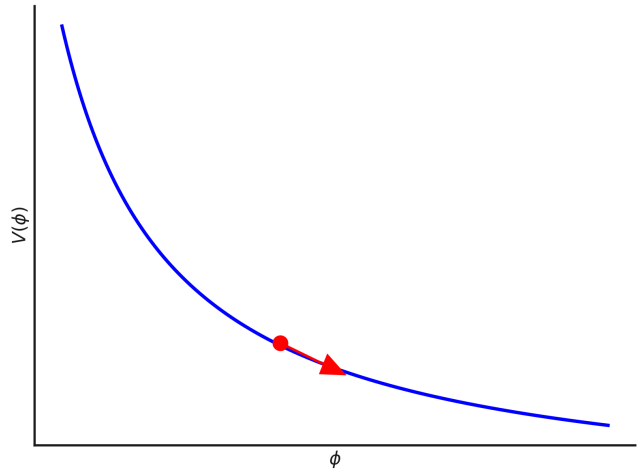
- **Energy Density and Pressure:**

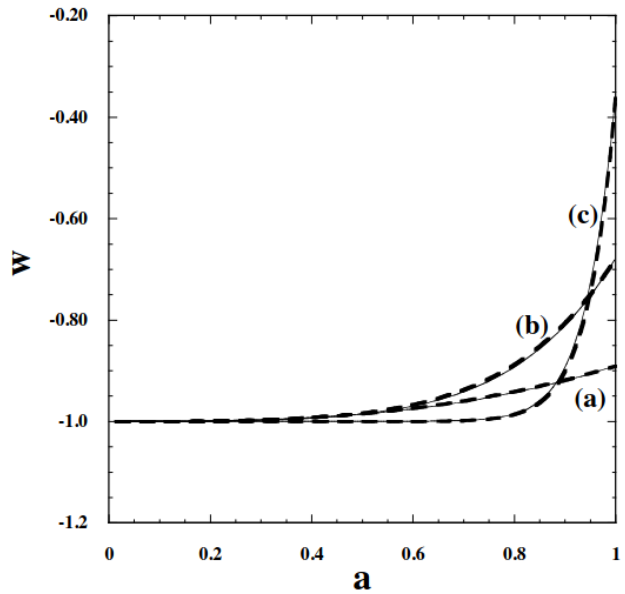
$$\rho_{\phi} = \frac{1}{2}\dot{\phi}^2 + V(\phi), \quad P_{\phi} = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

- **Equation of State Parameter:**

$$w(a) = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \implies w \geq -1$$

R.Caldwell, P.J.Steinhardt(1998)

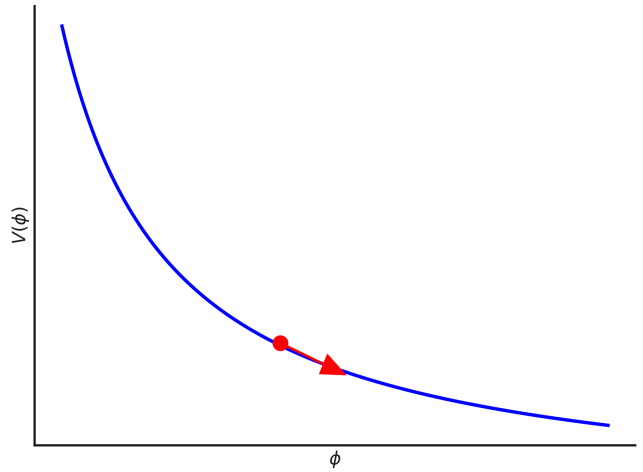


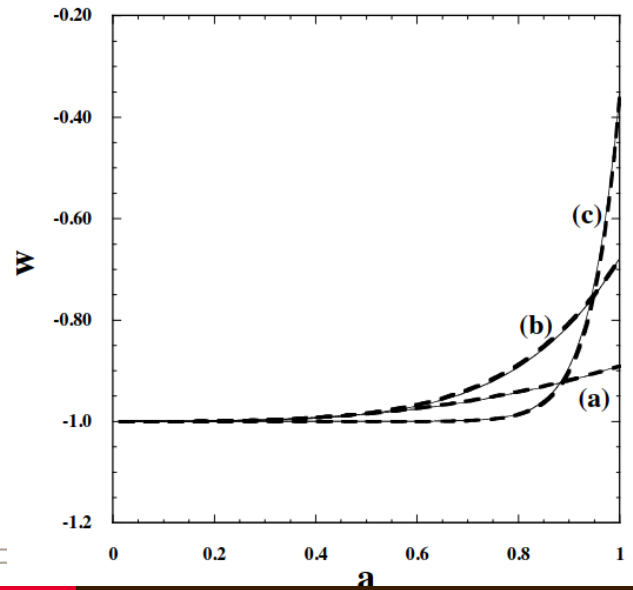


Problems with Quintessence

- For dark energy to dominate close to the present epoch, the model faces a fine-tuning problem.
- The magnitude of the potential has to be finely tuned.
- The initial position and velocity of the scalar field also have to be very finely tuned.

R.Caldwell, P.J.Steinhardt(1998)





An Exciting Possibility: Interacting Dark Sector

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...but what if the majority of the cosmos — dark matter and dark energy — are not silent strangers...
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  - History structure formation (e.g. Ly-α, BAO etc.)
  - Tidal disruption through long-range force ($\sim$ 1Kpc) [Kresden, Kaminkowski (2006)]

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  - History structure formation (e.g. Ly-α, BAO etc.)
  - Tidal disruption through long-range force ($\sim$ 1Kpc) [Kresden, Kaminkowski (2006)]
- Many previous works have been done on this to address different tensions and detection of this interaction. [L.Amendola (2000), A G Valent,VP, LA (2004), AG Valent et.al (2022)...]

Motivation Behind an Interacting Dark Sector

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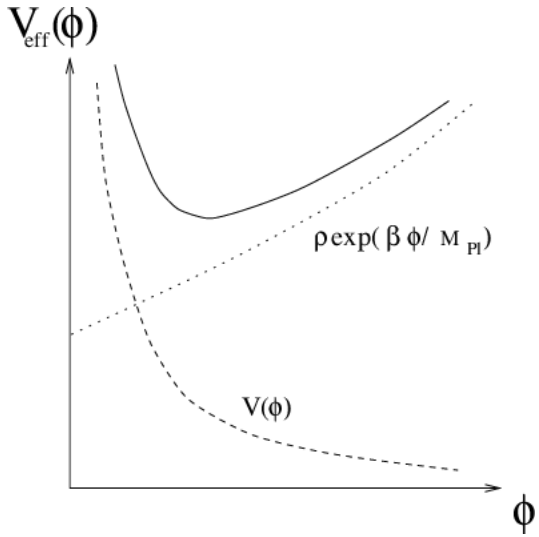
- This work will show a preference for Interaction!!
- It will also show the phantom nature of dark energy without violating the NEC!!

Interacting Dark Energy: Background Dynamics

"Baryon coupling can be suppressed from string theory"(T.Damor, Polyakov (1994))

[P Brax et. al. (2005)]



Friedmann Equation:

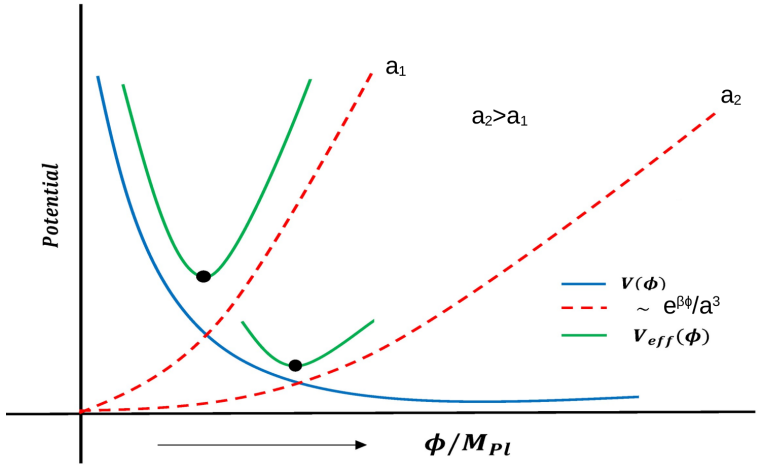
$$3H^2M_{Pl}^2 = \frac{\rho_{DM}^{(0)}}{a^3}\frac{f(\phi/M_{Pl})}{f_0} + \rho_\phi$$

Klein-Gordon Equation:

$$\ddot{\phi} + 3H\dot{\phi} = -V_{,\phi} - \frac{\rho_{DM}^{(0)}}{a^3}\frac{f_{,\phi}}{f_0} = -V_{,\phi}^{eff}$$

- **Coupling:** $f(\phi) = \exp\left(\frac{\beta\phi}{\sqrt{8\pi}M_{\rm Pl}}\right)$
- **Self Interaction Potential:** $V(\phi) \approx \phi^{-\alpha}$

$$\rho_{DM} = \rho_{DM}^{(0)}\frac{f(\phi/M_{Pl})}{a^3};\ \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$



Interacting Dark Energy: Background Dynamics

Subinoy Das et. al. (2005)

Friedmann Equation:

$$3H^2M_{Pl}^2 = \frac{\rho_{DM}^{(0)}}{a^3} + \rho_{DE}^{eff}$$

Non-Interacting

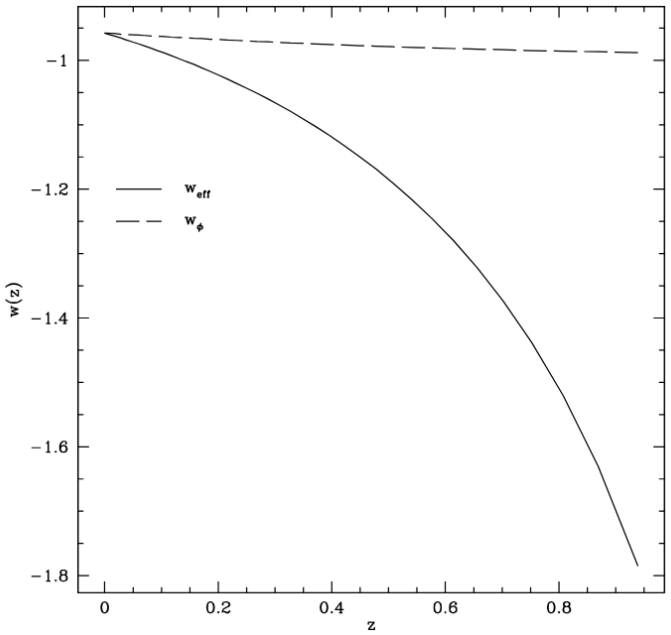
Interacting

$$\rho_{DE}^{eff} = \frac{\rho_{DM}^{(0)}}{a^3}\left[\frac{f(\phi/M_{Pl})}{f(\phi_0/M_{Pl})} - 1\right] + \rho_\phi$$

Equation for w_{eff}:

$$w_{eff} = \frac{w_\phi}{1-x}, \qquad x = -\frac{\rho_{DM}^{(0)}}{a^3\rho_\phi}\left[\frac{f(\phi/M_{Pl})}{f(\phi_0/M_{Pl})} - 1\right]$$

- Increasing $f(\phi/M_{Pl}) \implies x \geq 0$:
- Today: $x = 0; w_{eff}^{(0)} = w_\phi^{(0)} \simeq -1$ (Quint)
- Past: $x > 0, \quad w_{eff} < -1$ (Phantom)



Shooting Algorithm

- Shooting Parameter: $\phi_{\rm ini}$ and Target Parameter: $\Omega^0_{\rm DE}$.
- Present day $\frac{\phi}{\sqrt{8\pi}M_{\rm Pl}} = \frac{\phi_0}{\sqrt{8\pi}M_{\rm Pl}} = \frac{\alpha}{\beta}\frac{\Omega^0_{\rm DE}}{\Omega^0_{\rm DM}}$.
- Normalize the potential:

$$V(\phi) = 3H_0^2 M_{\rm pl}^2 \Omega^0_{\rm de} \left(\frac{\phi_0}{\phi}\right)^{\alpha}$$

- $\dot{\phi}_{\rm ini} = 0$, the shooting does not depend on the initial velocity of the field.

Result From MCMC Analysis

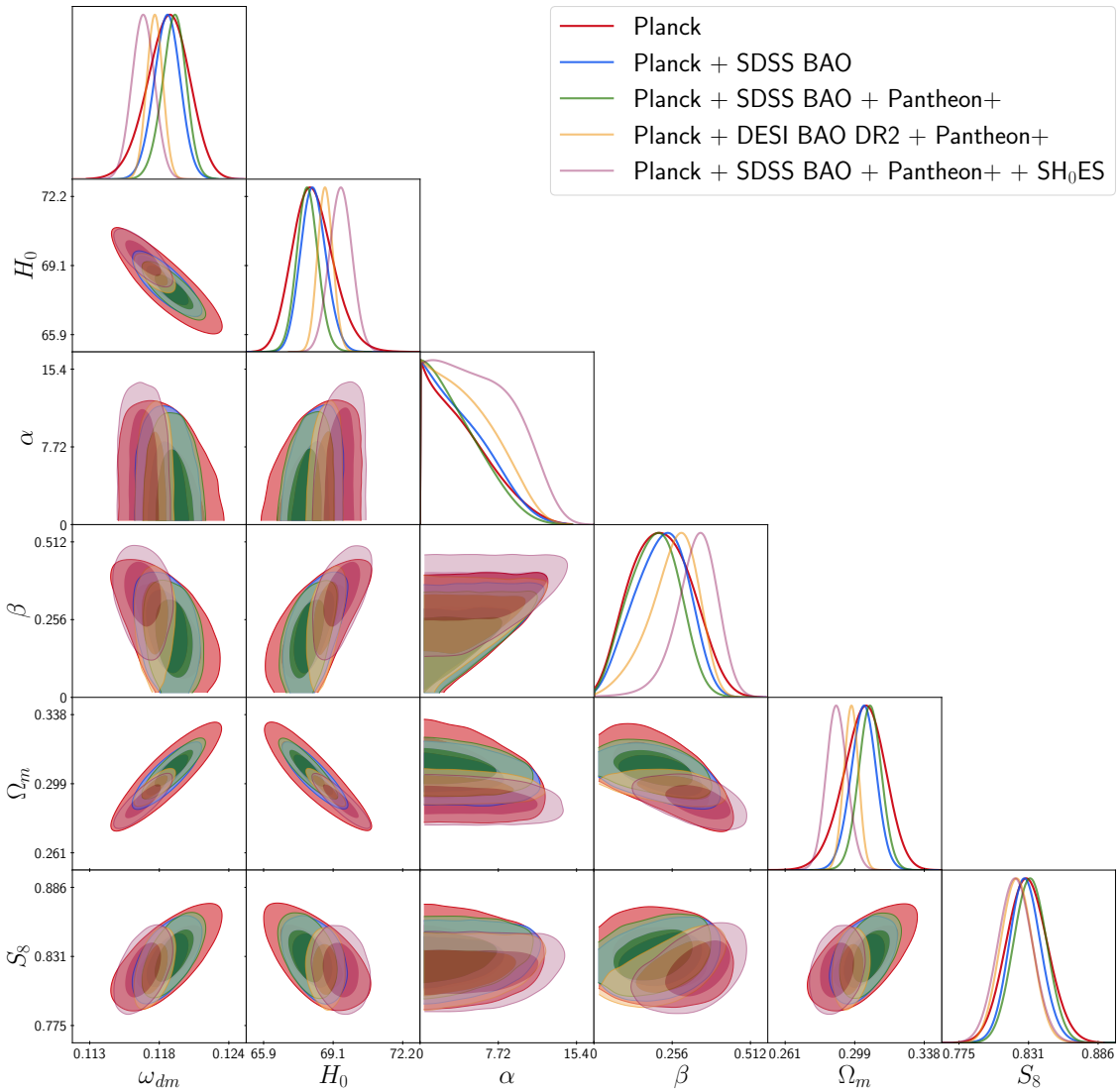
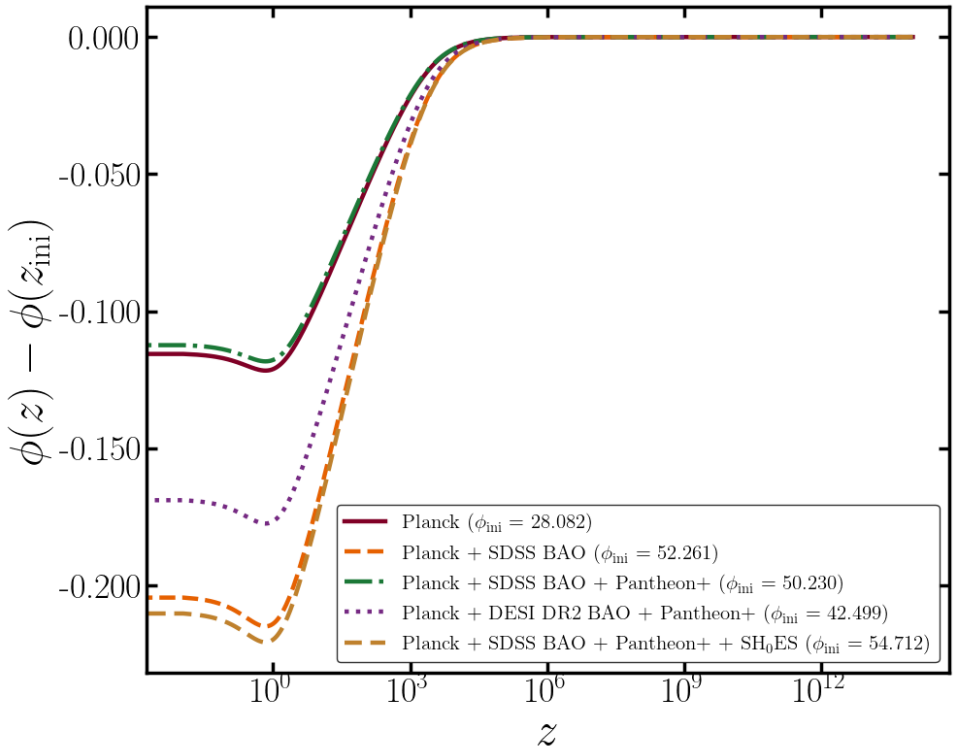
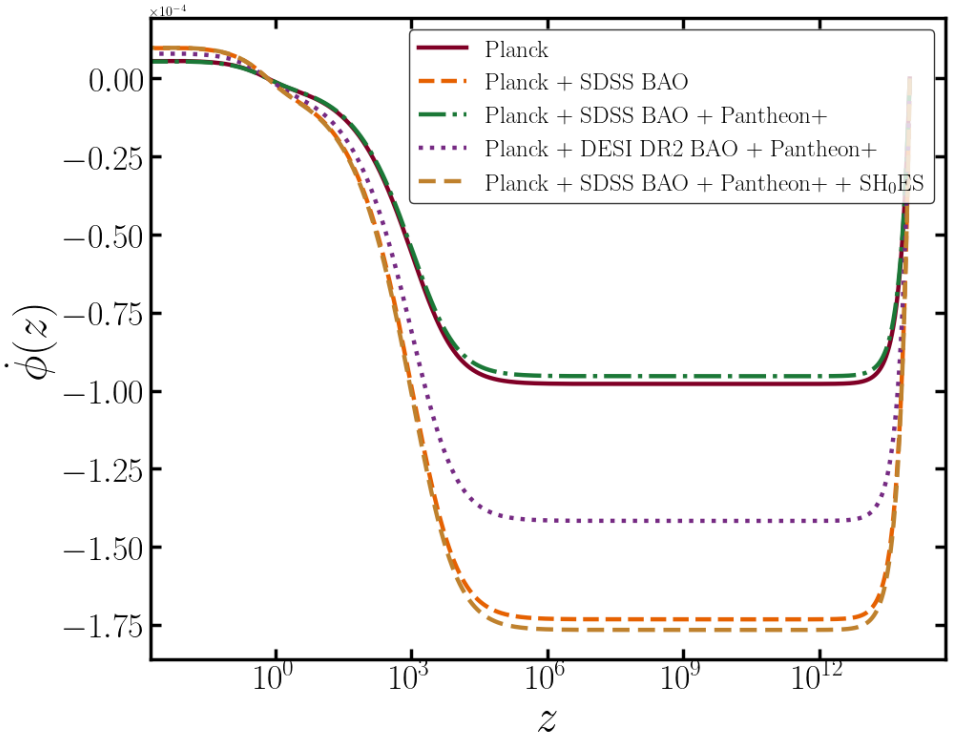


Figure: A. Chakraborty, T. Ray, S. Das, A. Banerjee, V. Ganeshan (2024) arXiv:2403.14247

Scalar Field Dynamics





Effective Dark Energy Equation of State

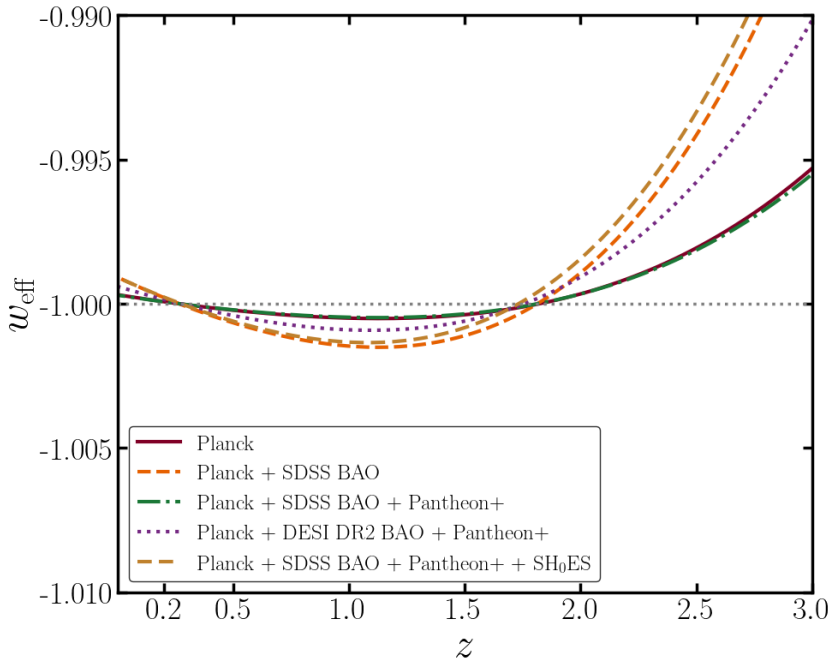
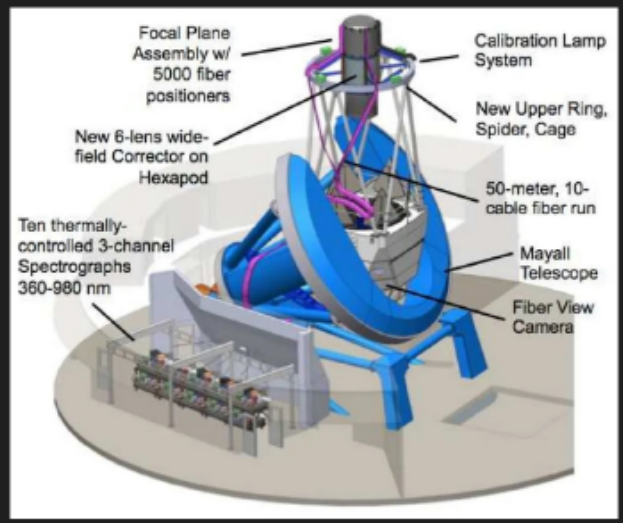


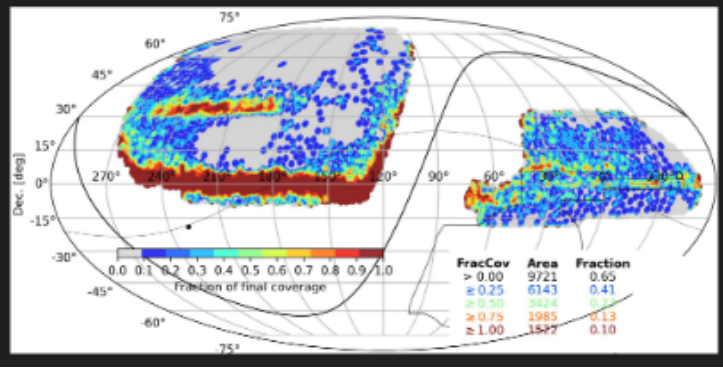
Table IV. Comparison of $\Delta\chi^2_{\rm min}$ and ΔAIC per experiment for Chameleon and ΛCDM models.

Dataset	Chameleon	
	$\Delta\chi^2_{\rm min}$	ΔAIC
Planck	-0.31	+3.69
Planck+ SDSS BAO	-0.556	+3.444
Planck + SDSS BAO + Pantheon+	-1.96	+2.04
Planck + DESI DR2 BAO + Pantheon+	-4.75	-0.75
Planck + SDSS BAO + Pantheon+ + SH$_0$ES	-6.41	-2.41

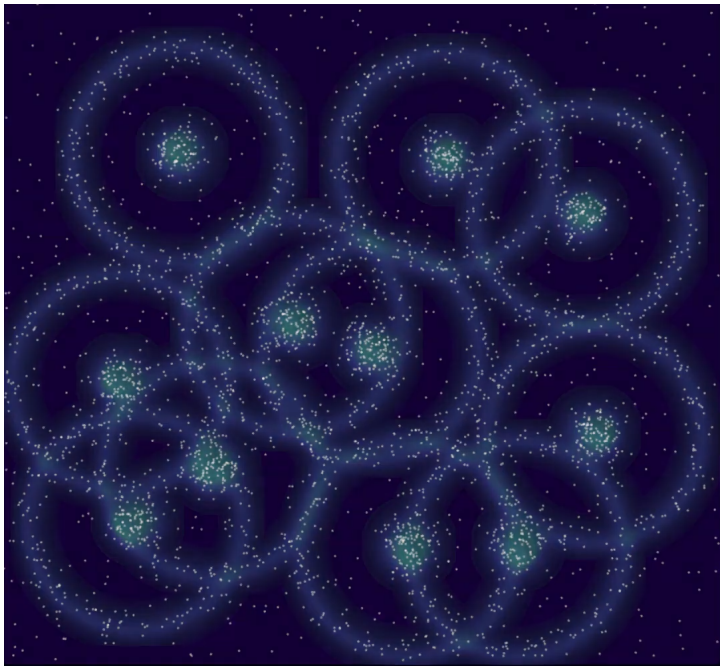
Dark Energy Spectroscopic Instrument

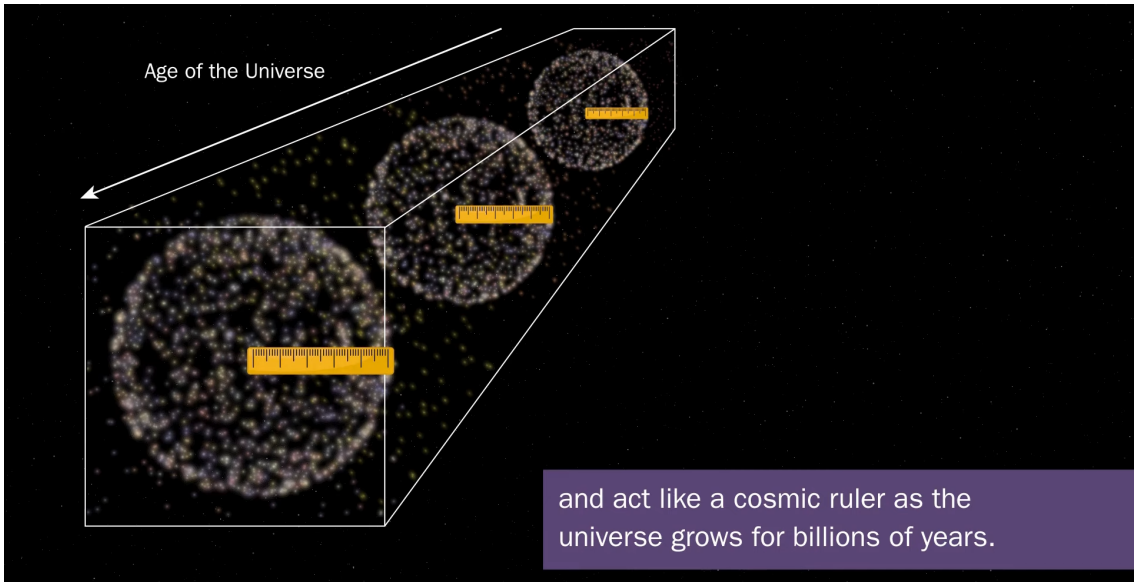
- Situated at the top of Kitt Peak, Arizona. 5000 fibres can be positioned to accuracy of $<5\ \mu$m.
- 40 million redshifts in 5 years!
- Catalogue-level blind analysis to mitigate observer/confirmation biases.
- Theory developments in BAO fitting procedure. Wide-ranging tests of systematic errors, done before unblinding
- Year 1 data! – already biggest ever BAO dataset (both in N_{eff} and volume).

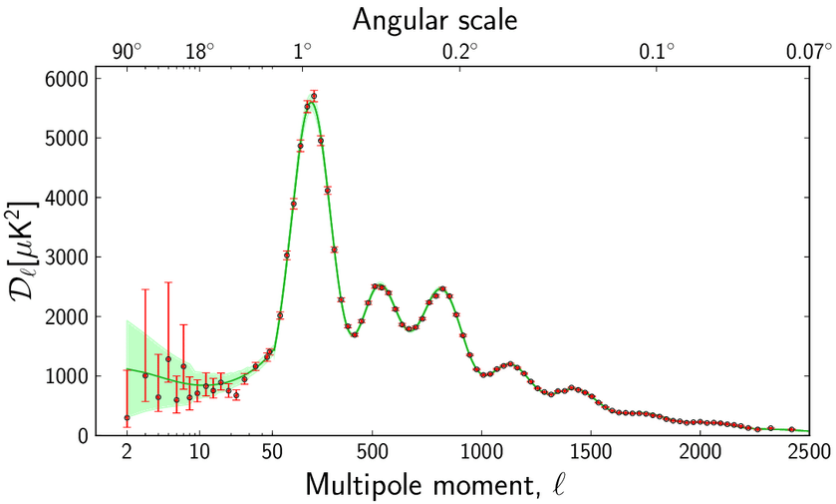


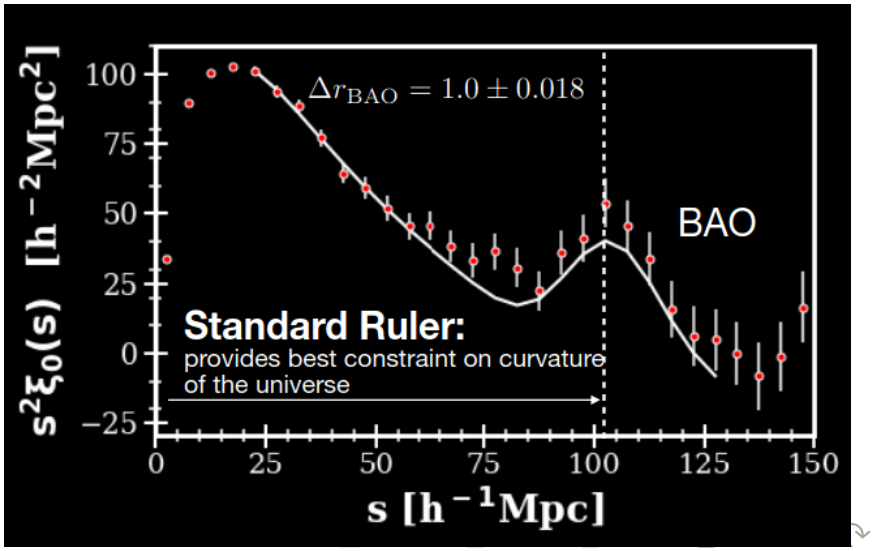


DESI Baryonic Acoustic Oscillations



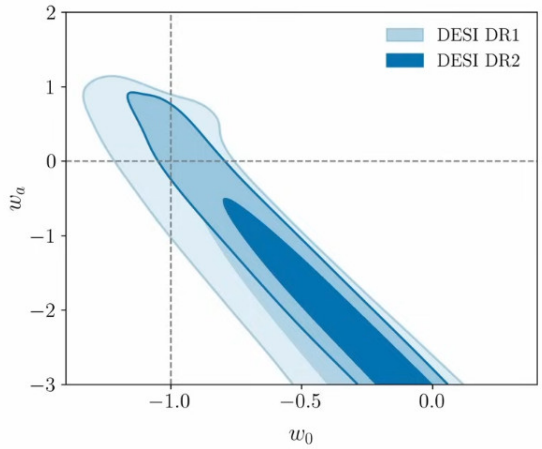


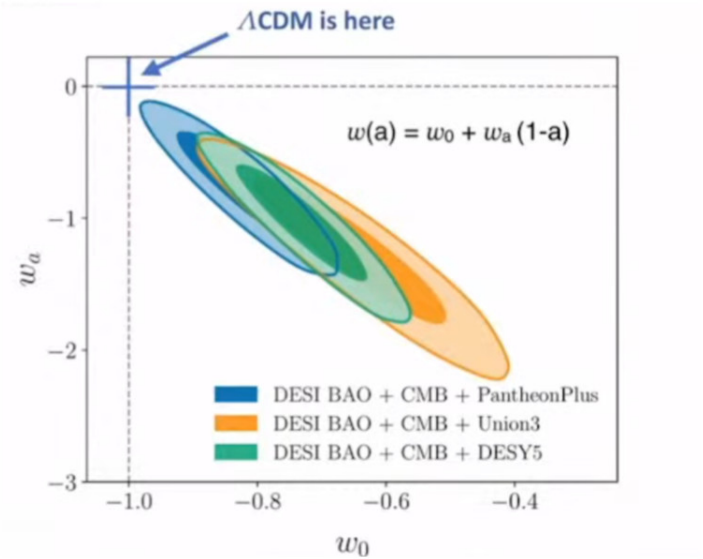




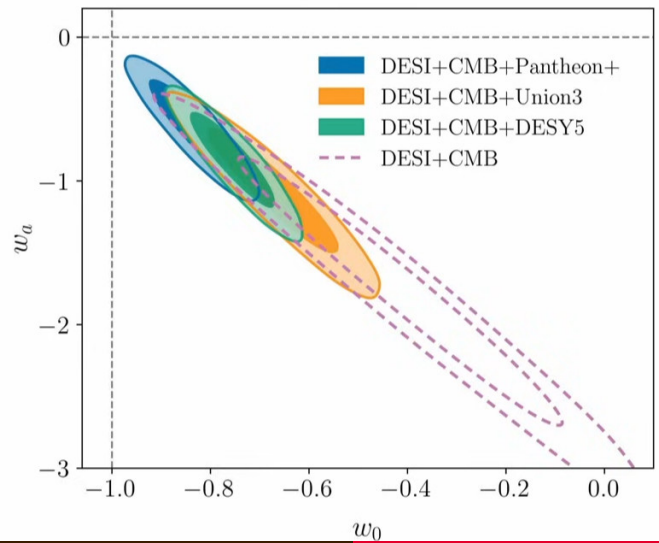
DESI DR2: Stronger Evidence on Evolving Dark Energy

We model evolving dark energy through: $w(a) = w_0 + w_a(1-a)$





However... **DESI+CMB** by itself is now showing a 3.1σ tension with ΛCDM.



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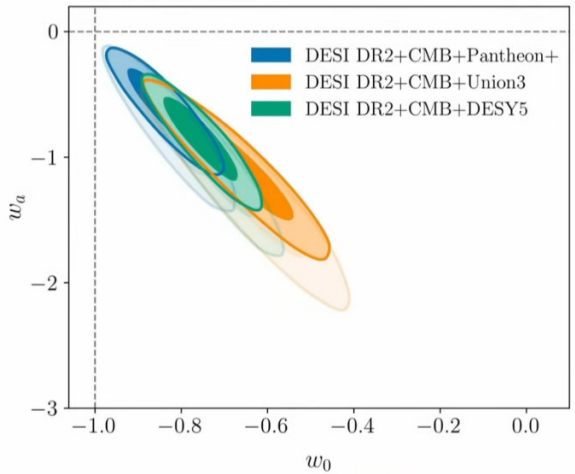
Tensions have marginally increased by 0.3σ with respect to DESI DR1 results.

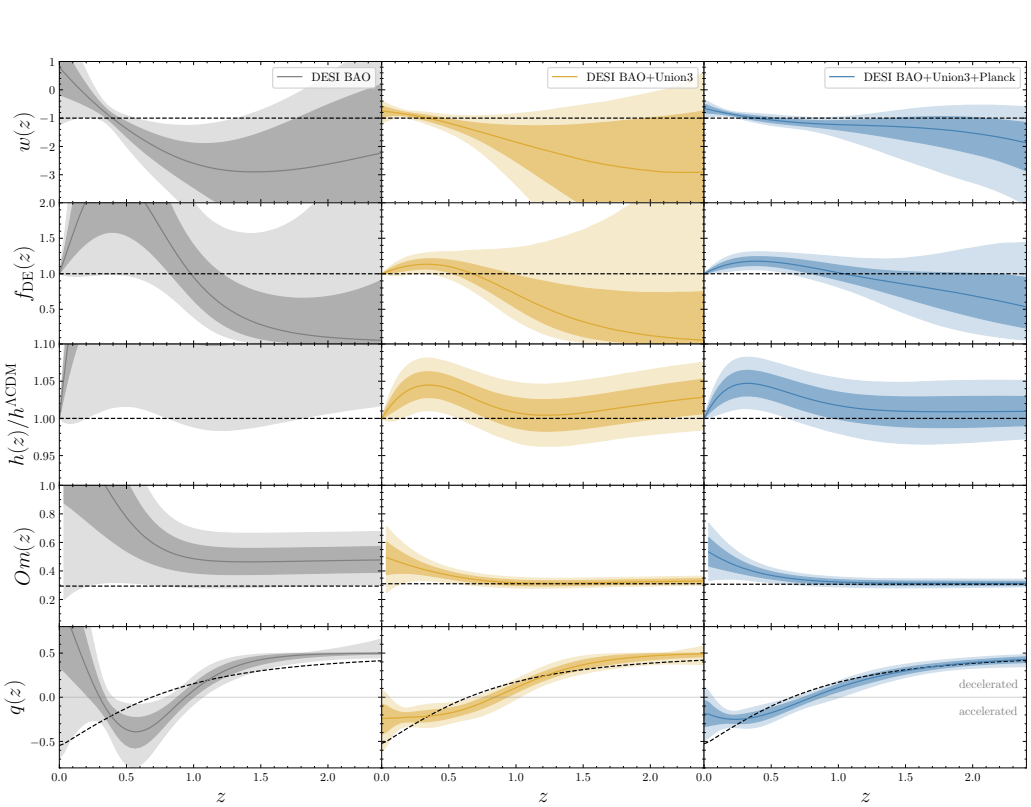


Tension with a cosmological constant is now at: **DESI+CMB+**

Pantheon+ SNe Ia: 2.8σ **Union3 SNe Ia: 3.8σ** **DES-SN5YR SNe Ia: 4.2σ**

Reconstructing Dark Energy Equation of State $w(z)$

$$w(z) = w_\Lambda \sum_{i=0}^{N=3} C_i T_i(x)$$



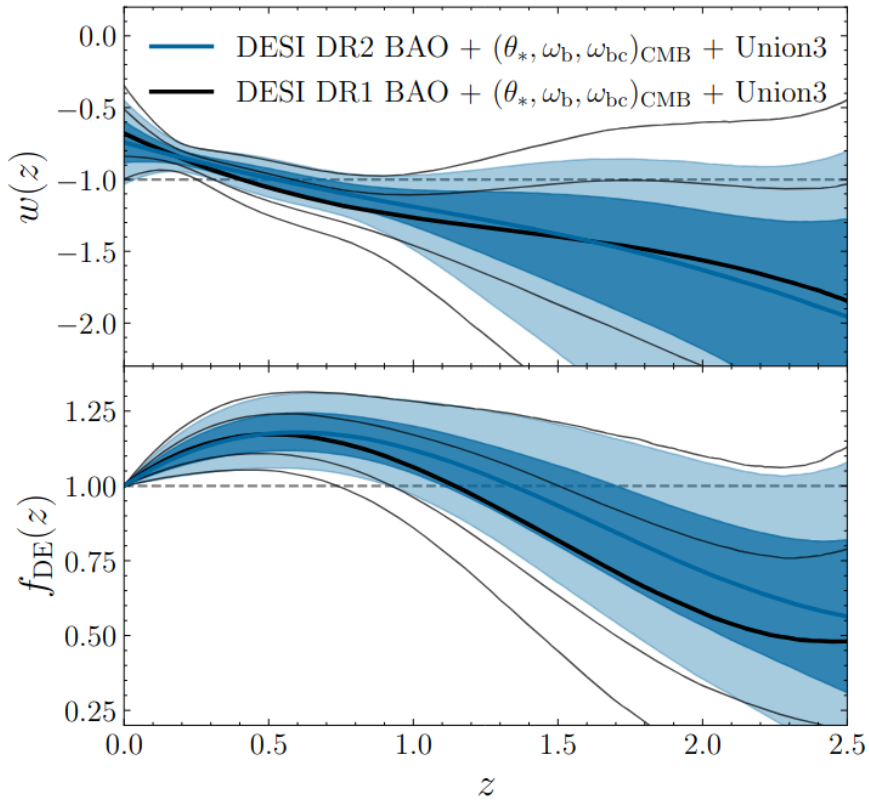


Figure: R. Calderon et al. (2024) & K.Lodha et.al (2025)

Interacting Dark Energy Model

[Philippe Brax et. al. (2005)]

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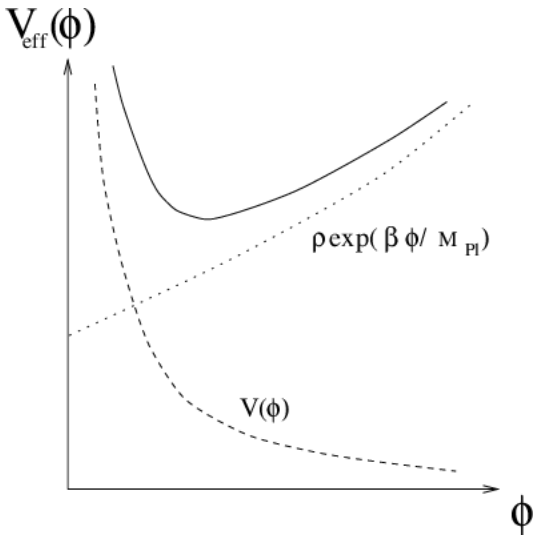

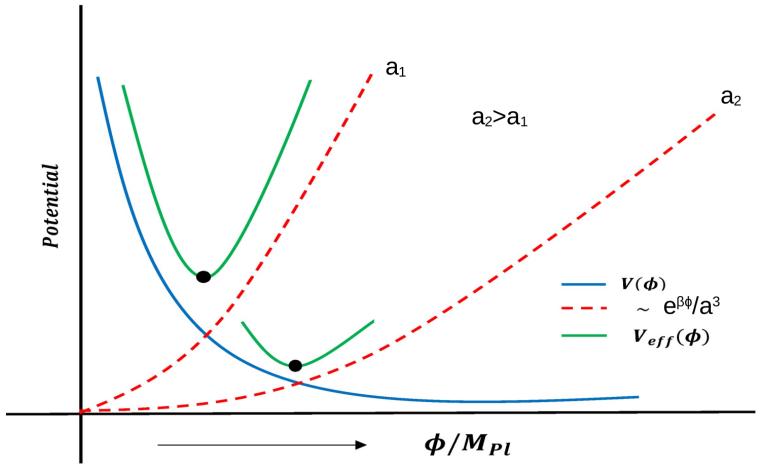

Relaxing Previous Assumption

$$w_{eff} = \frac{w_\phi}{1-x}, \quad x = -\frac{\rho_{DM}^{(0)}}{a^3\rho_\phi}\left[\frac{f(\phi/M_{Pl})}{f(\phi_0/M_{Pl})} - 1\right], \quad w_\phi = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

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Previously:

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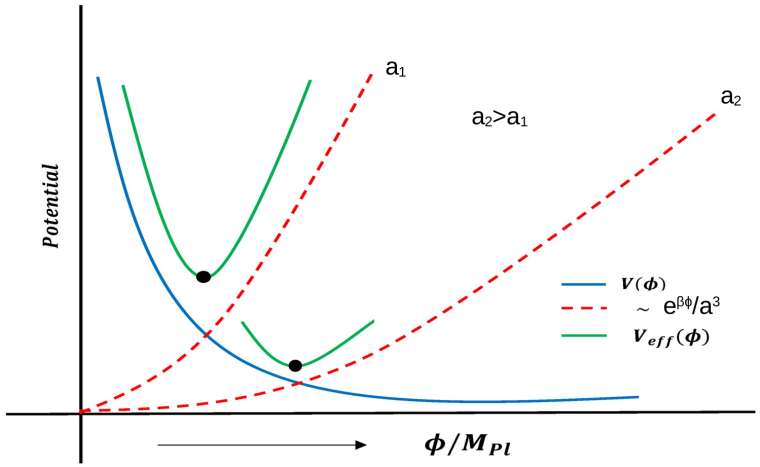
Now:

- What if ϕ doesn't stop at the minima ϕ_0 at present-day?
- $\dot{\phi}^2_{\text{present}} > 0 \& V(\phi_{\text{present}}) < V(\phi_0) \implies \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) = \rho_{\text{DE}}$
- Today: $\phi_{\text{present}} \gtrsim \phi_0 \implies x \simeq 0;\ w_{eff}^{(0)} = w_\phi^{(0)} \geq -1$ (Phantom-Crossing!!)

Scalar Field Dynamics for Polynomial Potential

For $V(\phi) \sim \phi^{-\alpha}$



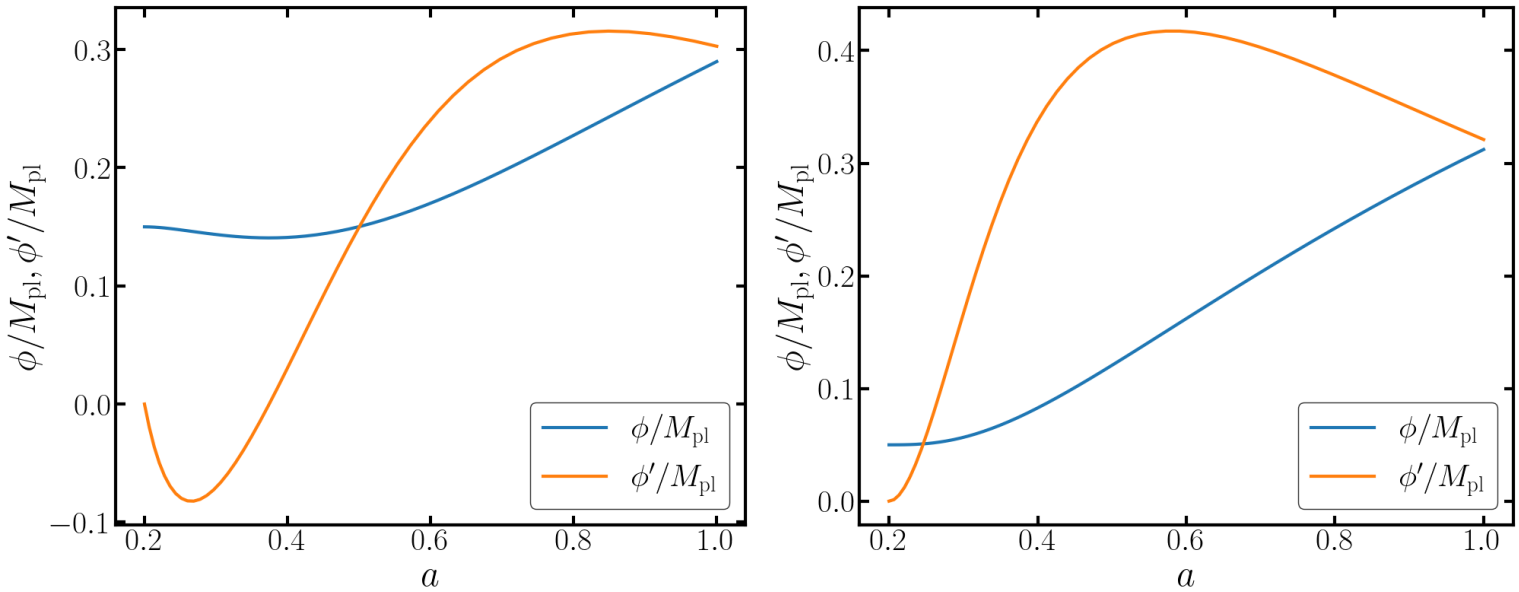


Figure: A.Chakraborty et.al. (2025) [arXiv:2503.10806]

Result- Polynomial Potential

For $V(\phi) \sim \phi^{-\alpha}$

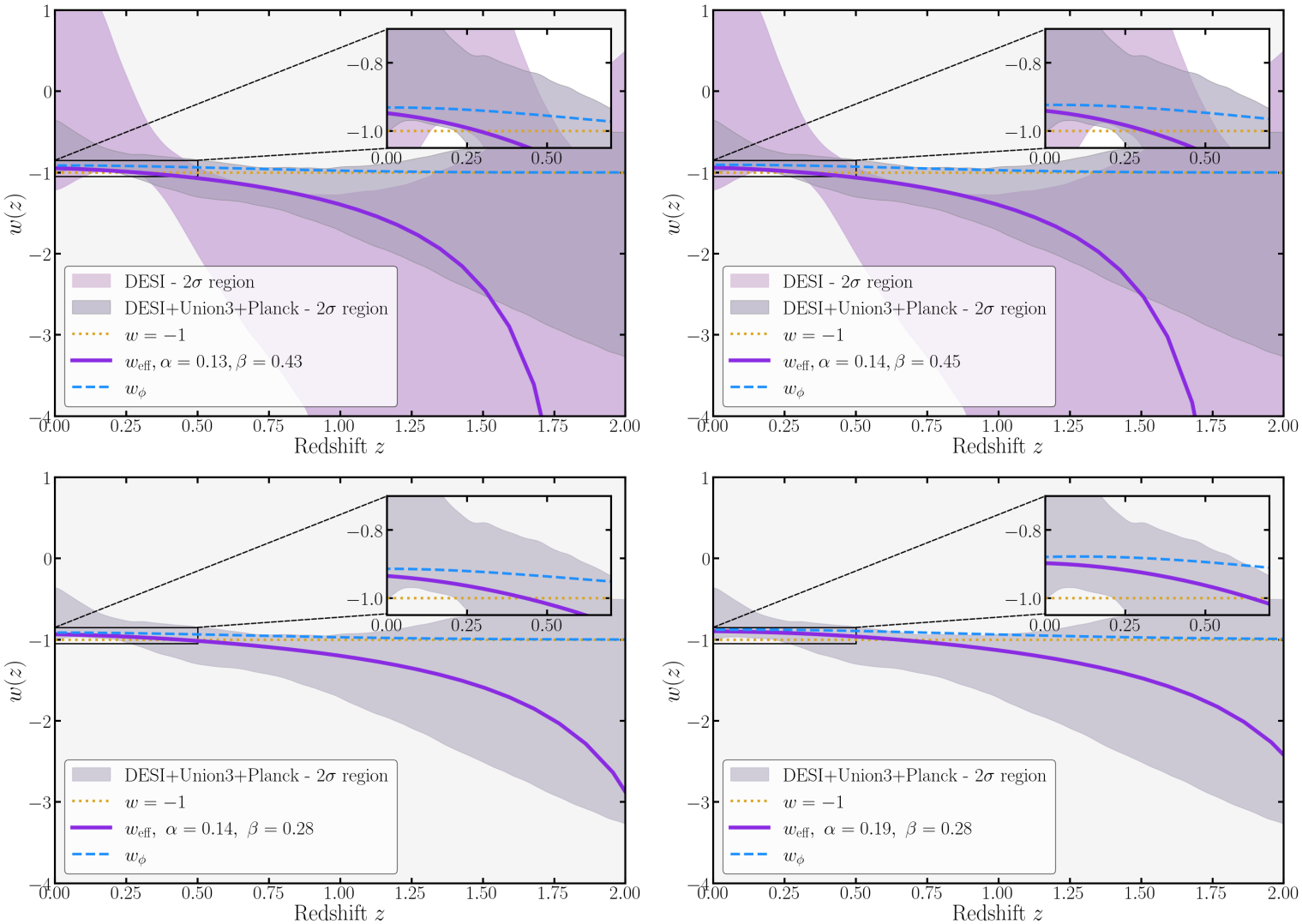


Figure: A.Chakraborty et.al. (2025) [arXiv:2503.10806]

Result- Exponential Potential

For $V(\phi) \sim e^{-\alpha\phi}$

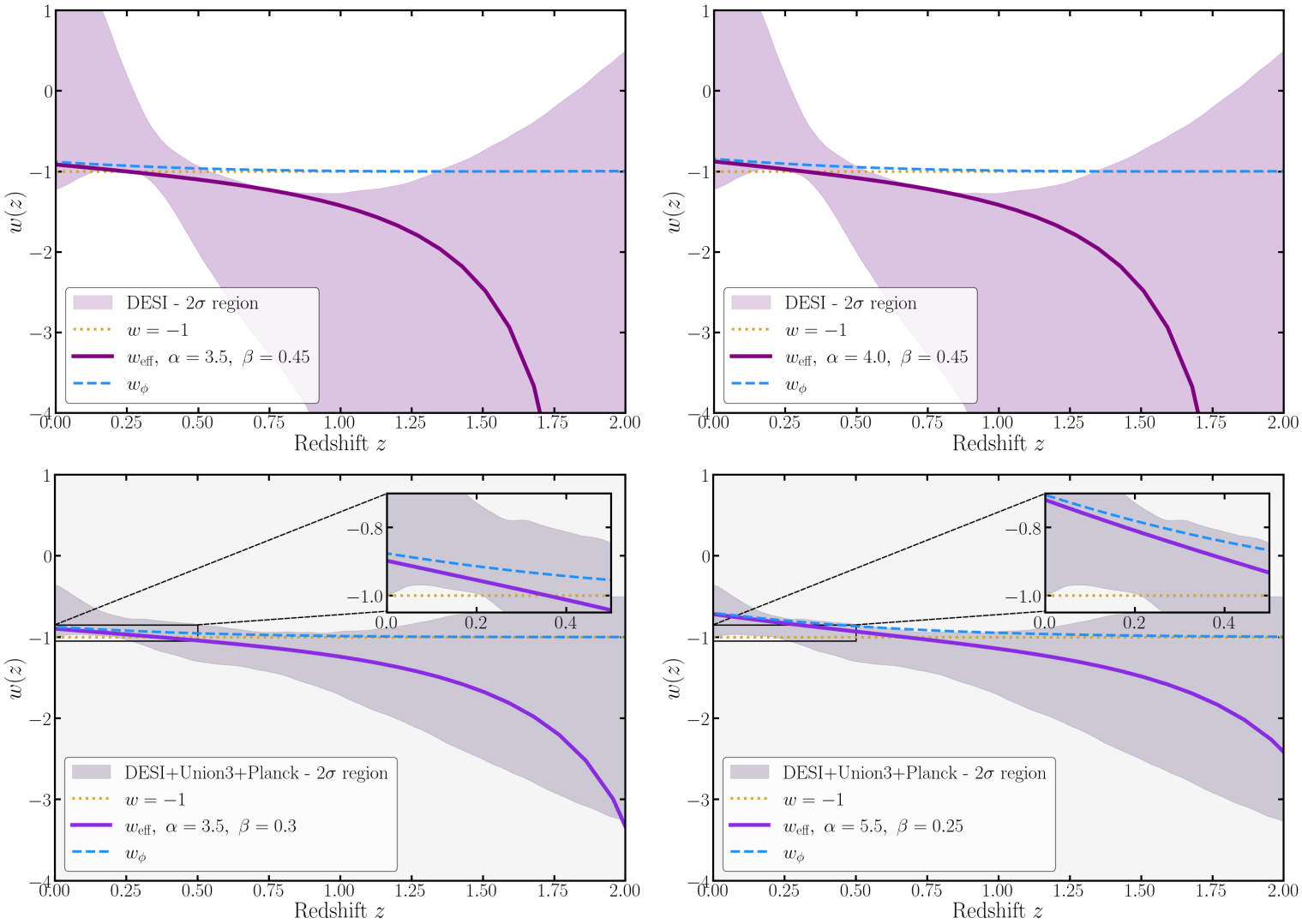


Figure: A.Chakraborty et.al. (2025) [arXiv:2503.10806]

Result- Fitting in $w_0 - w_a$ Plane with CPL Parameterization

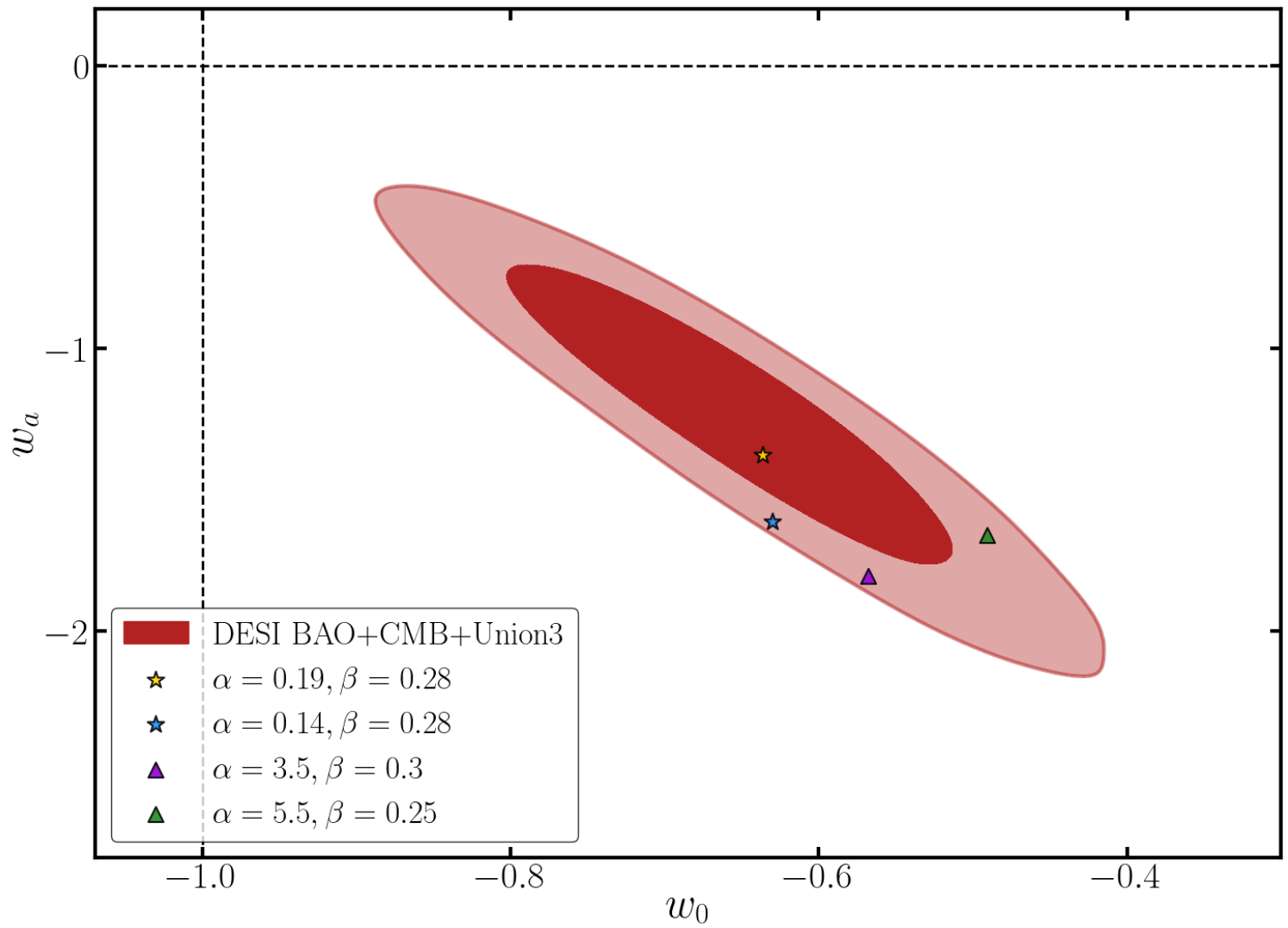


Figure: A.Chakraborty et.al. (2025) [arXiv:2503.10806]

Conclusion

- An observer agnostic about the coupling in the dark sector can only measure the effective equation of state.
- This model, for the first time, data prefers an interacting dark sector.
- Our model provides an economical solution to DESI observations.
- The model has a distinctive capability to transcend the phantom divide, explaining the DESI results.

Thank You