

Natural DM-DE interaction

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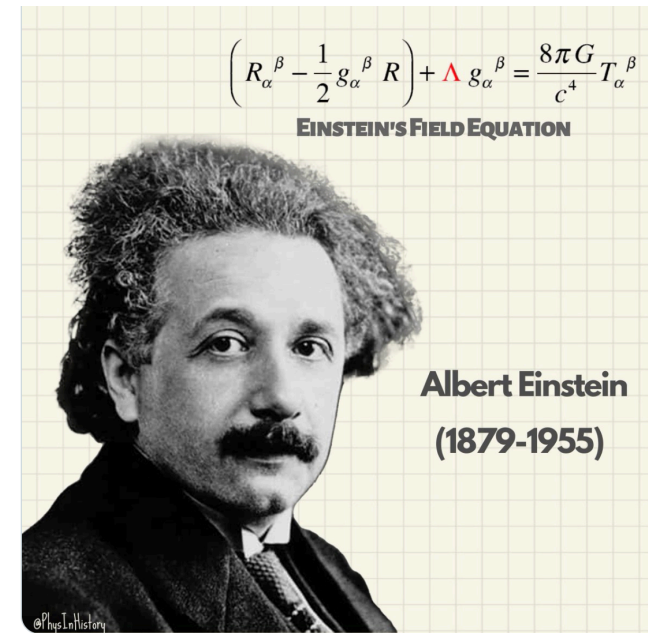
Work in collaboration with
H. Bagherian, M. Reece, Huangyu Xiao, 2609.xxxxx

PPC 2026, UNSW, Sydney, 08/31/2026

Cosmo “standard” model

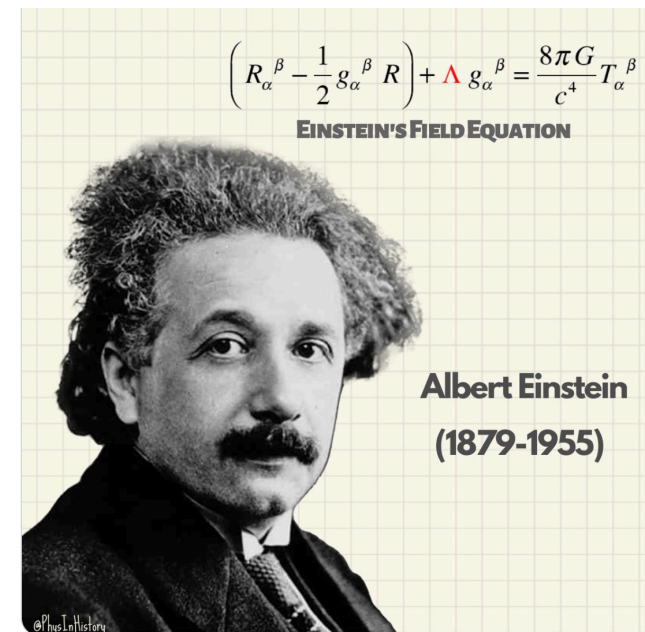
Cosmo “standard” model

One upon a time, cosmological constant is supposed to be zero

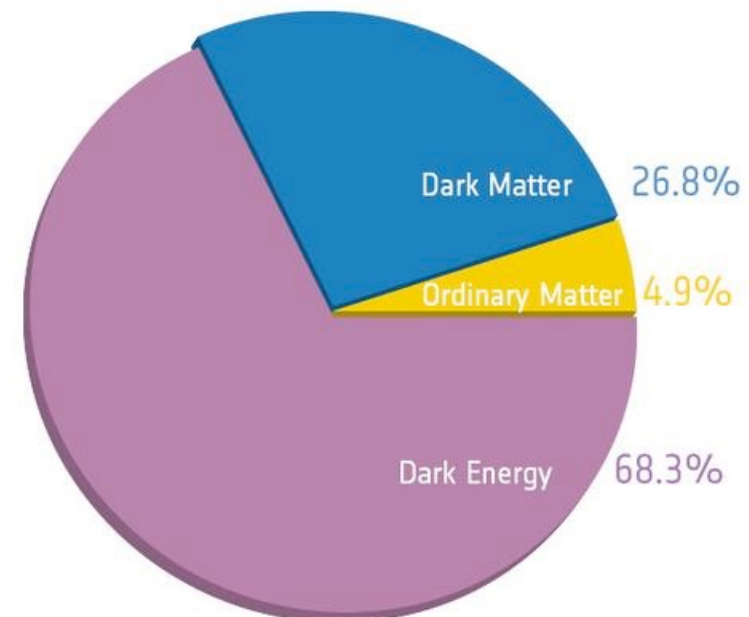


Cosmo “standard” model

One upon a time, cosmological constant is supposed to be zero



About 20 years ago, we accepted that there is dark energy



Dark energy

≈

Cosmological constant

After all, just tune **one** number.

Cosmological constant problem: $(\text{meV})^4 \ll M_{\text{Pl}}^4$

How to explain this tiny **constant**? A landscape of vacua?

The Cosmological Constant Problems*
(Talk given at Dark Matter 2000, Marina del Rey, CA, February 2000)

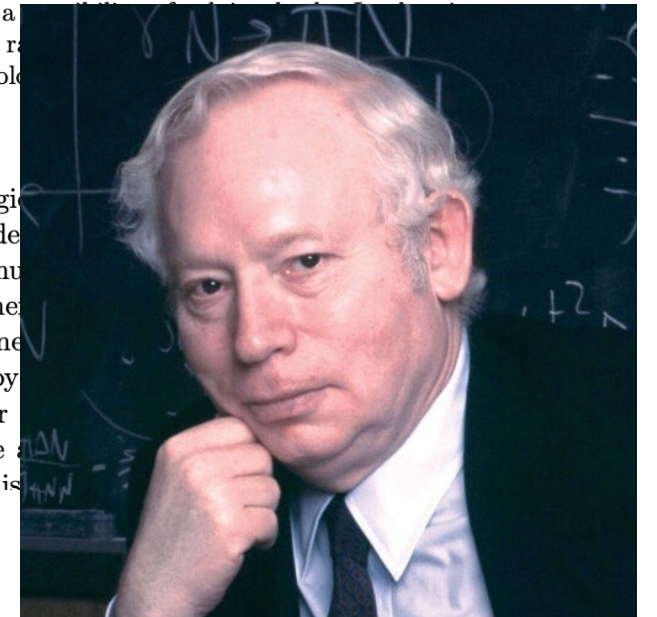
Steven Weinberg
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Abstract

The old cosmological constant problem is to understand why the vacuum energy is so small; the new problem is to understand why it is comparable to the present mass density. Several approaches to these problems are reviewed. Quintessence does not help with either; anthropic considerations offer a way out. A new approach with a scalar field that takes random values in different regions of space may apply to the cosmological constant problem as well.

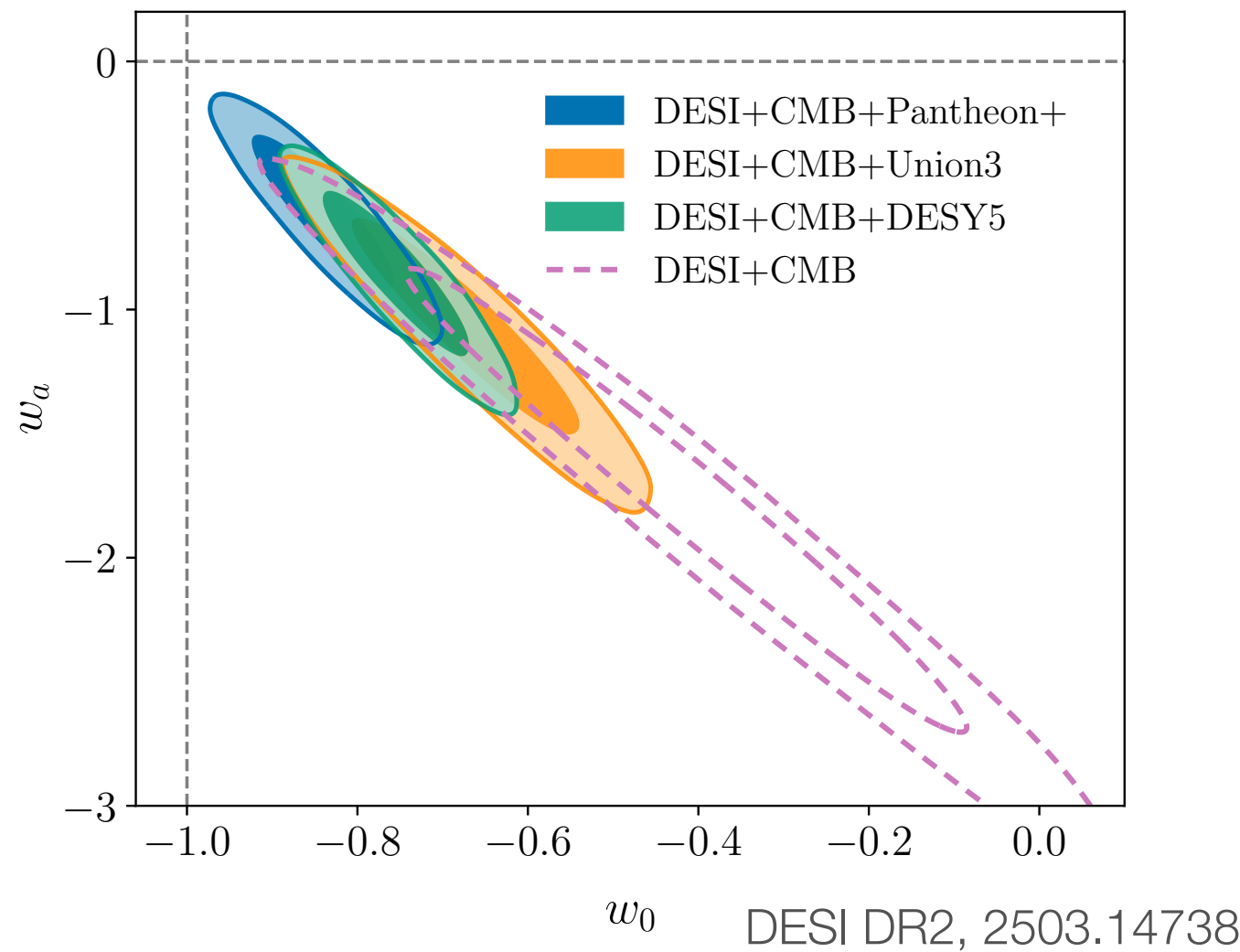
1. Introduction

There are now two cosmological constant problems. The old cosmological constant problem is to understand why the vacuum energy density ρ_V is not very much larger than the present mass density. Contributions to ρ_V , like the energy density of a scalar field at graviton energies near the Planck scale, are much larger than is observationally allowed by the present mass density. The new cosmological constant problem is to understand why the vacuum energy density ρ_V is not very much larger than the present mass density. The cancellation of the vacuum energy density in ρ_V can be cancelled by other contributions, but the cancellation then has to be extremely precise. The cosmological constant problem is to understand why the vacuum energy density is so small.



Recently

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

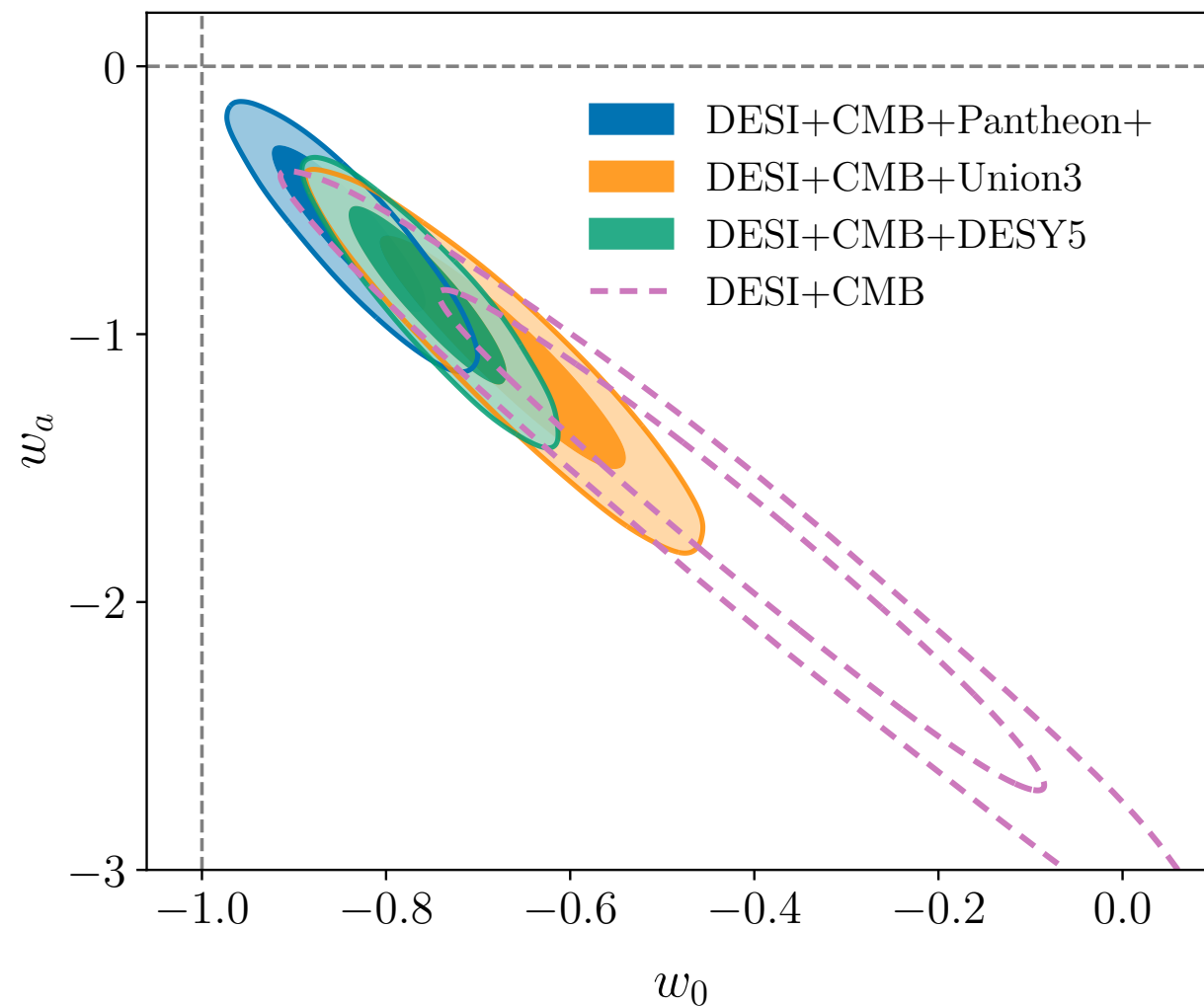


$$w(z) = \frac{P(z)}{\rho(z)}$$

$$w_\phi = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

constant DE: $w = -1$

Significant evolution of w ?



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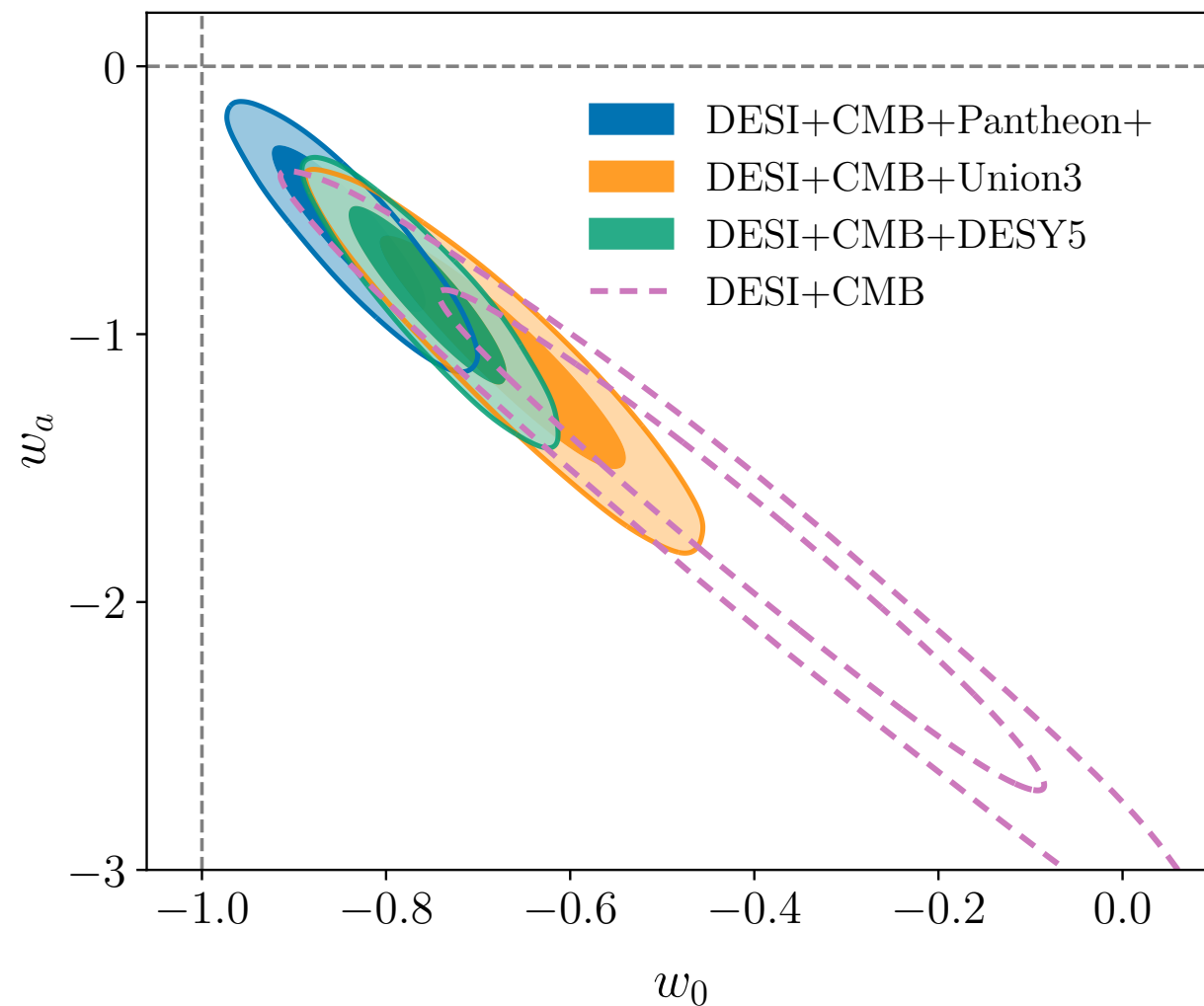
Matter: $w = 0$

Radiation: $w = \frac{1}{3}$

Vacuum energy: $w = -1$

No ghost, $w > -1$

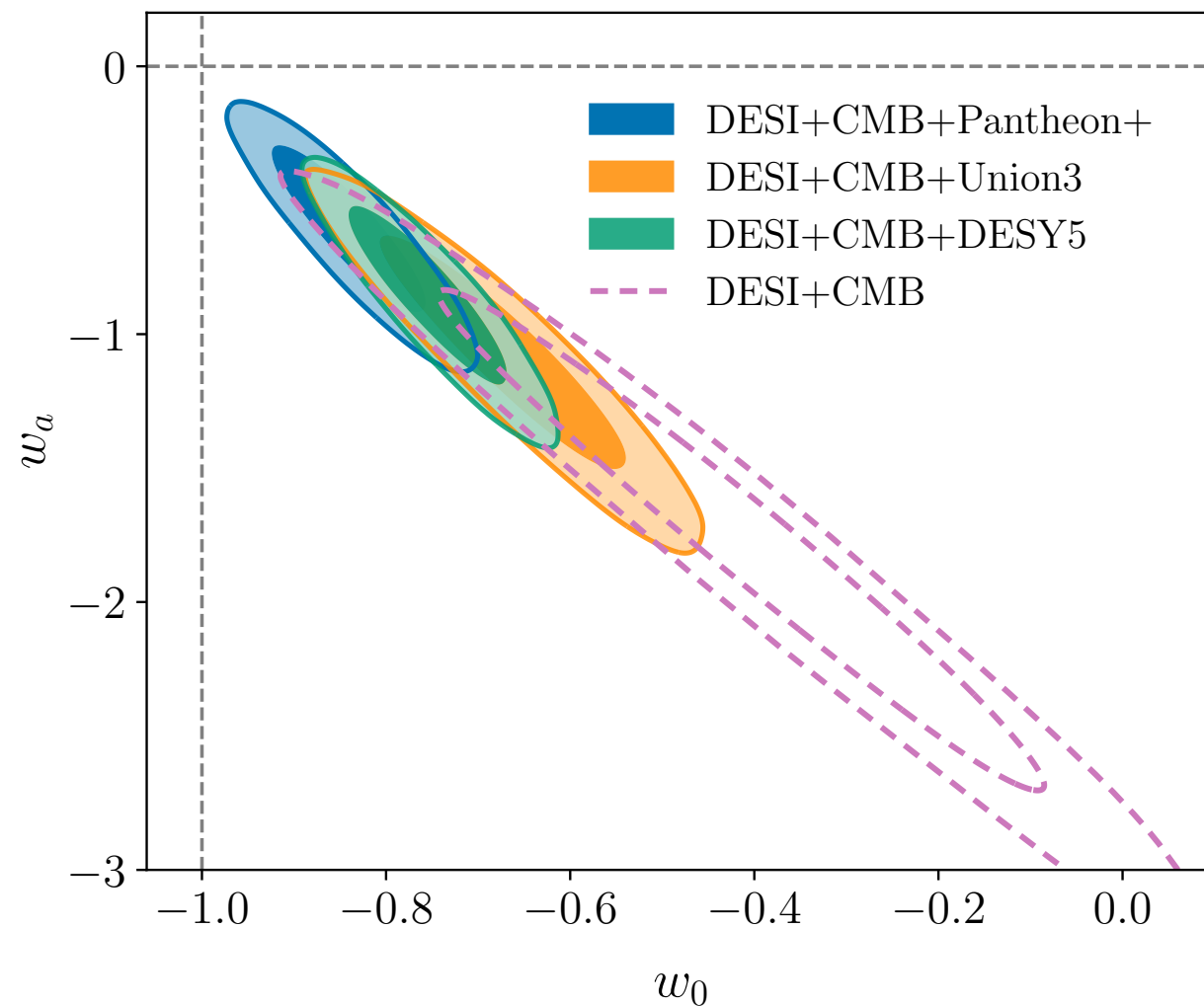
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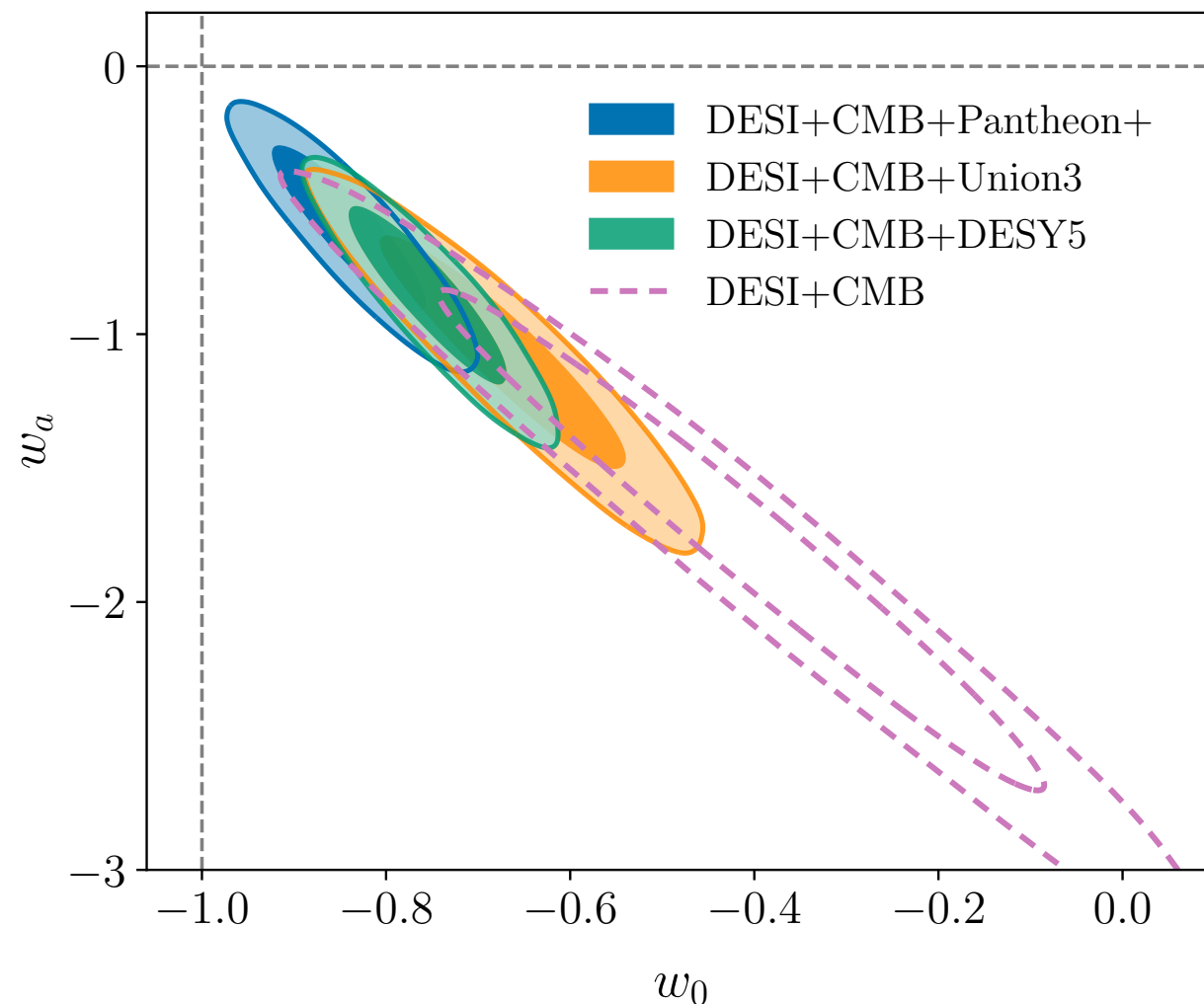


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First of all, evidence
overwhelming yet.

Significant evolution of w ?



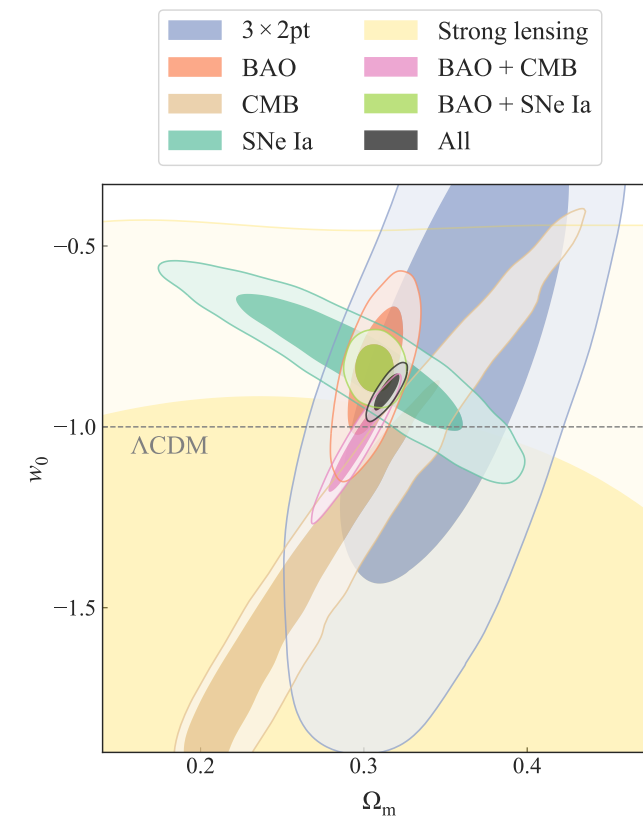
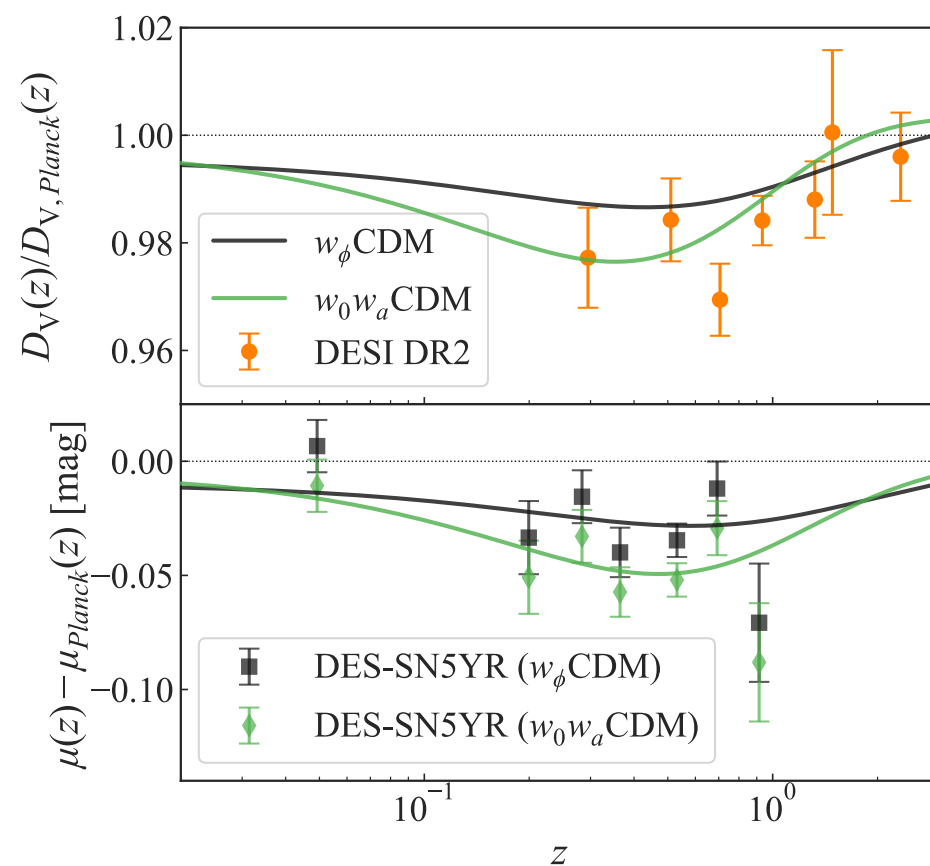
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And, it a result of parameterization $w(a) = w_0 + w_a(1 - a)$

Model dependence



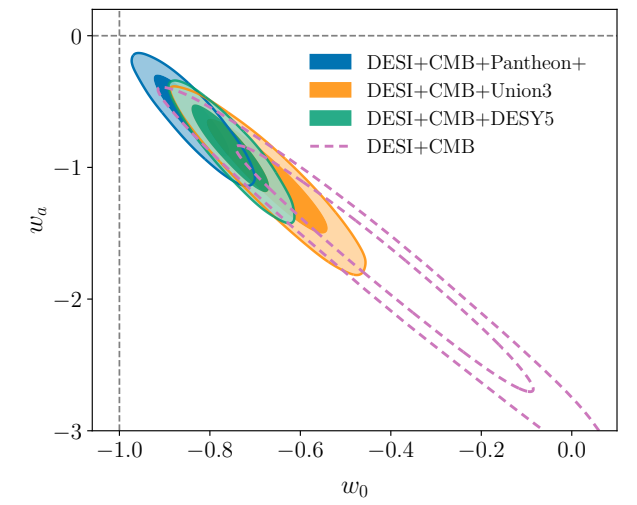
A. Shajib, J. Frieman, 2502.06929

A different fitting function

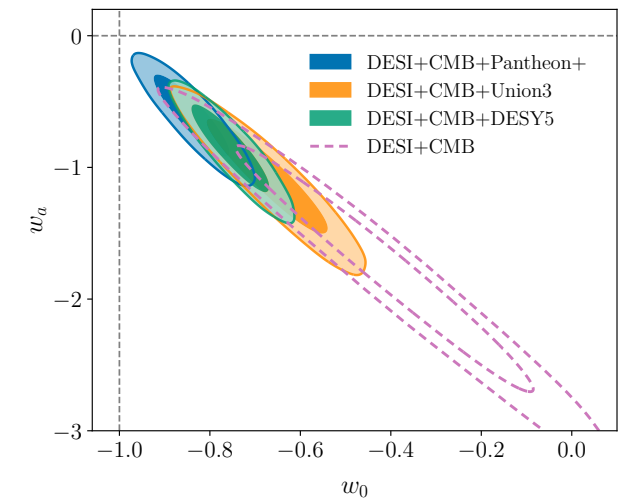
$$w_\phi^{\text{fit}}(z) = -1 + (1 + w_0)e^{-\alpha z}$$

From more “reasonable” DE models, power law, axion-like

Our work



Our work

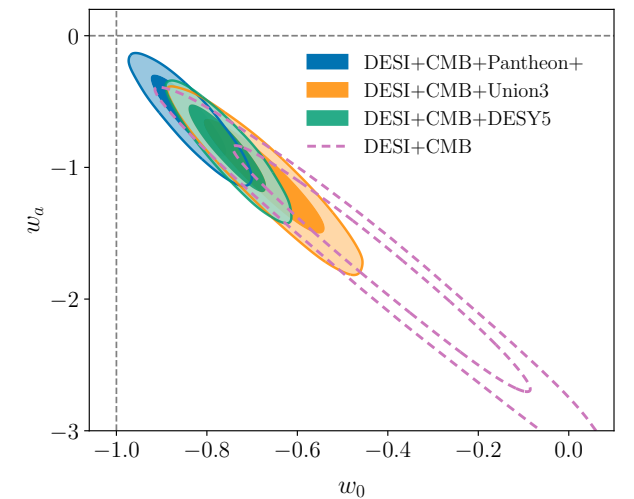


We will take DESI as a motivation to explore models which

Can have significant late time variations in $w(z)$

May even possible to have $w(z) < -1$

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May even possible to have $w(z) < -1$

We will find

It is not easy.

One class of model might work

DM-DE interaction

S. Das, P. S. Corasaniti, J. Khoury, 2006

J. Khoury, M.-X. Lin, M. Trodden, 2025

ϕ (evolving) drives the dark energy

Dark matter mass depends on ϕ

$$m(\phi) \equiv m_0 A(\phi) \quad \rho_{\text{DM}}(\phi) = \frac{A(\phi)}{A(\phi_0)} \frac{\rho_{\text{DM}}^0}{a^3}$$

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If we analyze the cosmology of this model, assuming (wrongly) constant dark matter mass

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

$$w_{\text{eff}} = \frac{w_\phi}{1 + \left[\frac{A(\phi)}{A(\phi_0)} - 1 \right] \frac{\rho_{\text{DM}}^0}{a^3 \rho_\phi}},$$

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$$\rho_{\text{DE}}^{\text{eff}} = \rho_\phi + \left[\frac{A(\phi)}{A(\phi_0)} - 1 \right] \frac{\rho_{\text{DM}}^0}{a^3} \quad w_{\text{eff}} = \frac{w_\phi}{1 + \left[\frac{A(\phi)}{A(\phi_0)} - 1 \right] \frac{\rho_{\text{DM}}^0}{a^3 \rho_\phi}},$$

Additional time dependence for w_{eff} , can even be < -1

Why is this hard?

For example: fermionic dark matter χ

$$\mathcal{L}_f = -\frac{1}{2}(\partial\varphi)^2 + i\bar{\chi}\not{\partial}\chi - V(\varphi) - m_\chi(\varphi)\bar{\chi}\chi$$

Dark energy field φ

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Dark energy field φ

Integrate out dark matter will correct $V(\varphi)$

$$V_\varphi^{(1)}(\varphi) = \frac{c_\chi}{2} \int_0^\Lambda \frac{d^3\vec{k}}{(2\pi)^3} \sqrt{\vec{k}^2 + m_\chi(\varphi)^2} \quad c_\chi = -4$$

Simplest case

Yukawa coupling: $m_\chi(\varphi) = y\varphi$

At 1-loop: $V^{(1)} \simeq \frac{y^2}{16\pi^2} \Lambda^2 \varphi^2$

To avoid fine-tuning: $V(\varphi) > V^{(1)}$

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$$V_{\text{ind}}(\varphi) = \rho_\chi(\varphi) = m_\chi(\varphi)n_\chi$$

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$$V_{\text{ind}}(\varphi) = \rho_\chi(\varphi) = m_\chi(\varphi)n_\chi$$

For this to work, V_{ind} needs to dominate at some point

$$V_{\text{ind}} > V(\varphi) + V^{(1)} > V^{(1)}$$

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Putting these together:

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$$E_F = \frac{1}{2m_\chi} (3\pi^2 n_\chi)^{2/3} \gg 0.66 \left(\frac{\Lambda}{m_\chi} \right)^{4/3} m_\chi \gtrsim m_\chi$$

Can't be non-relativistic, χ can't be DM

More generally,

$$V_{\varphi}^{(1)}(\varphi) = \frac{c_{\chi}}{2} \int_0^{\Lambda} \frac{d^3 \vec{k}}{(2\pi)^3} \sqrt{\vec{k}^2 + m_{\chi}(\varphi)^2}$$

$$\begin{aligned} \frac{d}{d\varphi} V_{\varphi}^{(1)}(\varphi) &= \frac{c_{\chi}}{2} m_{\chi}(\varphi) m'_{\chi}(\varphi) \int_0^{\Lambda} \frac{d^3 \vec{k}}{(2\pi)^3} \frac{1}{\sqrt{\vec{k}^2 + m_{\chi}(\varphi)^2}} \\ &= \frac{c_{\chi}}{16\pi^2} m_{\chi}(\varphi) m'_{\chi}(\varphi) \left(2\Lambda^2 - m_{\chi}(\varphi)^2 \log \frac{\Lambda^2}{m_{\chi}(\varphi)^2} + \dots \right) \end{aligned}$$

Naturalness: $|V'(\varphi)| \gg \left| \frac{d}{d\varphi} V_{\varphi}^{(1)}(\varphi) \right| \approx \left| \frac{c_{\chi} m_{\chi}(\varphi) m'_{\chi}(\varphi) \Lambda^2}{8\pi^2} \right|$

DM-DE

Following the similar logic

$$V_{\text{ind}}(\varphi) = \rho_{\chi}(\varphi) = m_{\chi}(\varphi)n_{\chi}$$

$$|V'_{\text{ind}}(\varphi)| = |m'_{\chi}(\varphi)n_{\chi}| \gg |V'(\varphi)|$$

$$n_{\chi} \gg \frac{|c_{\chi}|}{8\pi^2} m_{\chi} \Lambda^2 \quad \text{with} \quad \Lambda \gg m_{\chi}(\varphi)$$

For sermonic dark matter, same conclusion.

$$E_F = \frac{1}{2m_{\chi}} (3\pi^2 n_{\chi})^{2/3} \gg 0.66 \left(\frac{\Lambda}{m_{\chi}} \right)^{4/3} m_{\chi} \gtrsim m_{\chi}$$

Scalar DM

$$m_\chi n_\chi = \frac{\pi^2}{30} g_* T_{\text{eq}}^4 \approx (0.8 \text{ eV})^4 \quad \text{and} \quad n_\chi \gg \frac{|c_\chi|}{8\pi^2} m_\chi \Lambda^2$$

We have: $m_\chi \ll 1.7 \text{ eV}$ wave-like DM

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Consider a simple DM-DE example

$$\Lambda_\varphi^4 \cos\left(\frac{\varphi}{f_\varphi}\right) + \Lambda_\chi^4 \cos\left(\frac{\chi}{f_\chi}\right) + \Lambda_{\varphi\chi}^4 \cos\left(\frac{\varphi}{f_\varphi} + \frac{\chi}{f_\chi}\right) \quad \Lambda_\varphi \sim \Lambda_{\varphi\chi}$$

Λ_χ controls dark matter mass, typically $\Lambda_\chi \gg \Lambda_\varphi, \Lambda_{\varphi\chi}$

dark matter DE interaction suppressed by $\Lambda_{\varphi\chi}/\Lambda_\chi$

Not as sharp as the fermion case, still hard

Way out?

Supersymmetry:

Very low scale breaking, not viable

Goldstone, shift symmetry, e.g. from some strong dynamics/compositeness

Shift symmetry broken by coupling to DM

Monodromy mass

A tower of particles, the n th with mass

$$m_n(\varphi)^2 \approx m_\chi^2 + m_{\chi\phi}^2 \left(n - \frac{\varphi}{2\pi f} \right)^2 + \dots$$

Full spectrum invariant under gauge transformation: $\varphi \mapsto \varphi + 2\pi f$

Summing over the full tower, the correction to $V(\varphi)$ suppressed by

$$\exp(-S) \text{ with } S = \frac{2\pi m_\chi}{m_{\chi\phi}}$$

Example, KK-tower

Extra-dimension $M_4 \times S^1$, KK tower of charged particle.

$$\text{Axion} = \int A_5 = 2\pi R\theta$$

$$m_n^2 = m_{5d}^2 + \frac{1}{R^2} \left(n + \frac{q\theta}{2\pi} \right)^2 \quad R = \text{size of 5th dim}$$

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Integrating out the tower of KK particles.

The induced potential suppressed by, for $m_{5d} \gg R^{-1}$

$$e^{-m_{5d}R}$$

Why e^{-S} suppression?

Locality

$$\text{Axion} = \int A_5 = 2\pi R\theta \quad \text{“Spread over” full 5th dim}$$

Heavy particle localized in a region $\sim m_{5d}^{-1} \ll R$

Hence, the effect is $\propto e^{-m_{5d}R}$

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Symmetry:

Axion descends from A_5 is protected by a 1-form symmetry (electric).
The breaking effect of such symmetry is often exponentially suppressed

We consider: Monopole + dyon tower

Dark sector 't Hooft - Polyakov monopole.

Charged under a dark $U(1)_D$, $\alpha_D = e_D^2/4\pi$

$$\mathcal{L} \supset \frac{\alpha_D}{8\pi} \frac{\varphi}{f_a} F' \tilde{F}' + \Lambda^4 \left(1 - \cos \left[\frac{\varphi}{f_a} \right] \right)$$

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Monopole induce axion potential with the scale

$$\Lambda^4 = m_a^2 f_a^2 \sim v_D^4 e^{-2\pi/\alpha_D}$$

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Monopole has a tower of dyonic excitations, labelled by integer n .

Witten effect: Monopole picks up an electric charge for $\theta \neq 0$

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Mass of n -th dyon $m_D(n, \theta) = m_M + \gamma m_M \frac{\alpha_D^2}{2} \left(n - \frac{\theta}{2\pi} \right)^2 + \dots$

Of the monodromy form! Hence, exponential suppression for $V(\theta)$ similar to the KK tower case.

We consider: Monopole + dyon tower

This exponential suppression can also be viewed in two ways

1. Small instanton effect from $G \rightarrow U(1)$ that generates monopole.
2. Axion shift symmetry, though anomalous, can be generalized to a non-invertible symmetry which still protects axion potential. This can only be broken by heavy defect, hence exponential suppression.

C. Cordova, K. Ohmori, 2023

Monopole + dyon tower

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Monopole induce axion potential with the scale

$$\Lambda^4 = m_a^2 f_a^2 \sim v_D^4 e^{-2\pi/\alpha_D}$$

For example, $v_D \simeq 10 \text{ TeV}$, $\alpha_D \simeq 0.044$

$$\Lambda^4 \simeq \rho_{\text{DE}}$$

DE potential $V(\theta)$, $\theta = \varphi/f$

$$m_D(n, \theta) = m_M + \gamma m_M \frac{\alpha_D^2}{2} \left(n - \frac{\theta}{2\pi} \right)^2 + \dots$$

$$V_{\text{eff}}(\theta) = V_{\text{inst}} + V_{\text{ind}} \equiv \Lambda^4(1 - \cos \theta) + \gamma m_M n_M \frac{\alpha_D^2}{2} \left(n - \frac{\theta}{2\pi} \right)^2$$

$$= m_D n_M$$

This has the needed for to implementing DM-DE scenario.

DM-DE interaction

$$\begin{aligned} V_{\text{ind}}(\varphi) &= \sum_{n \in \mathbb{Z}} (\rho_n(\varphi) - \rho_n(0)) \\ &= \sum_{n \in \mathbb{Z}} \gamma \alpha_D^2 f_n n_M m_M \left(-n \left(\frac{\varphi}{2\pi f} \right) + \frac{1}{2} \left(\frac{\varphi}{2\pi f} \right)^2 \right) \\ &= n_M m_M \frac{\gamma \alpha_D^2}{2} \left(\frac{\varphi}{2\pi f} \right)^2. \end{aligned}$$

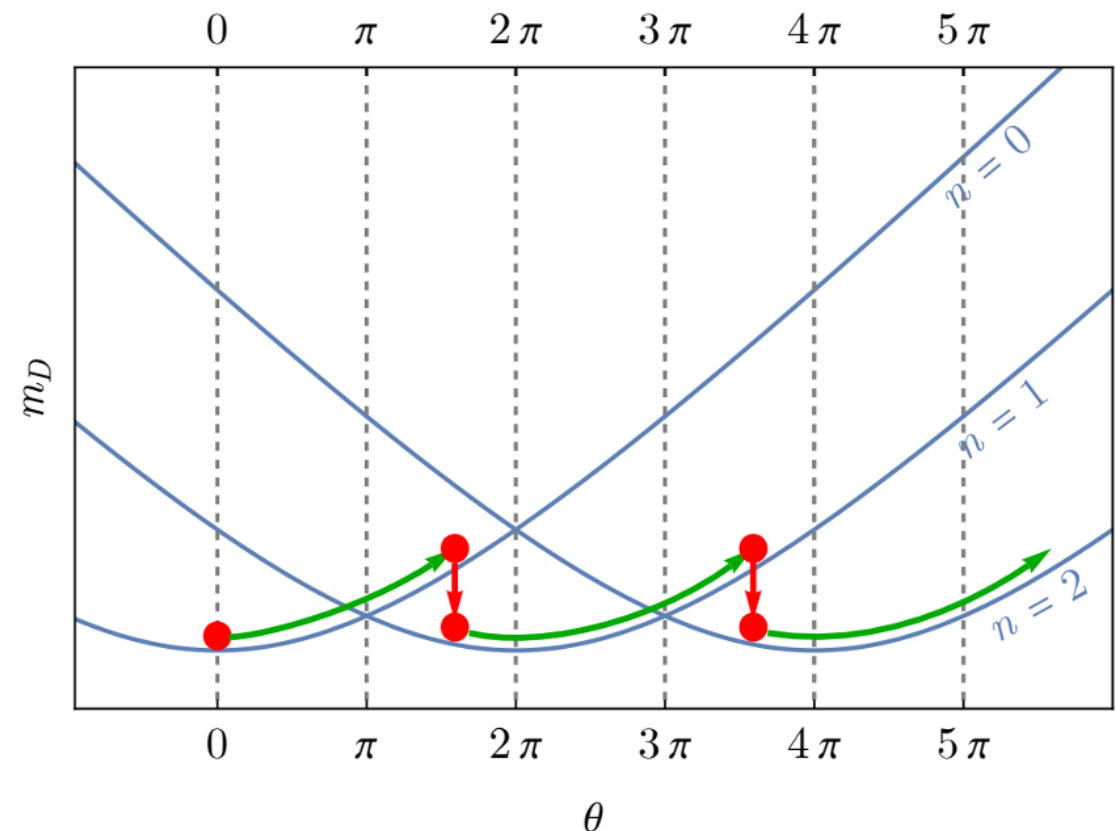
Assuming fractions $f_n = f_{-n}$. Interaction small since suppressed by α_D^2

Asymmetric dyon production

However, it can't be the axion that controls DE.

$$\frac{\rho_\theta}{\rho_{\text{crit}}} \sim \frac{\dot{\theta}^2 f_a^2}{H^2 M_{\text{pl}}^2} < 1$$

Can't have $\dot{\theta} \gg H$



We can introduce a second axion also couples to monopole.
Has significant rolling, and subdominant in abundance.

A second axion

Second axion abundance less than the DM

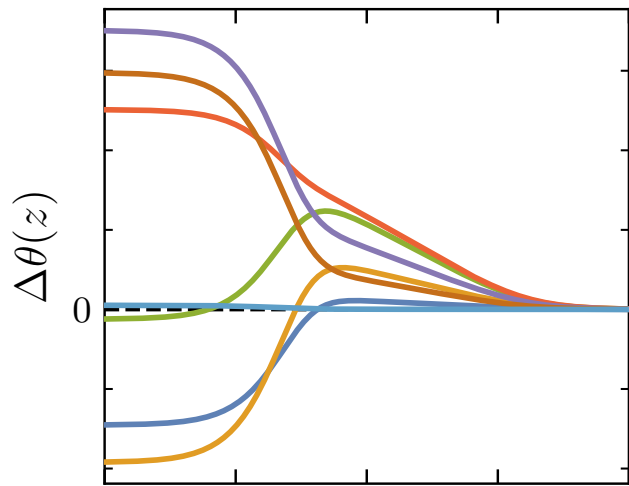
$$f'_a \lesssim \left(\frac{g_*(T_c) T_0 T_c M_{\text{pl}}}{\mathcal{N} m'_a} \right)^{1/2} \approx 8.7 \times 10^{14} \text{ GeV} \left(\frac{10^{-6} \text{ eV}}{m'_a} \right)^{1/2}$$

Coupling to monopole does not prevent it from rolling

$$f_{a'} \gtrsim \left(\frac{\alpha_D^2 T_0}{2\pi^2 T_c} \right)^{1/2} M_{\text{pl}} \approx 10^{10} \text{ GeV}.$$

Cosmological history

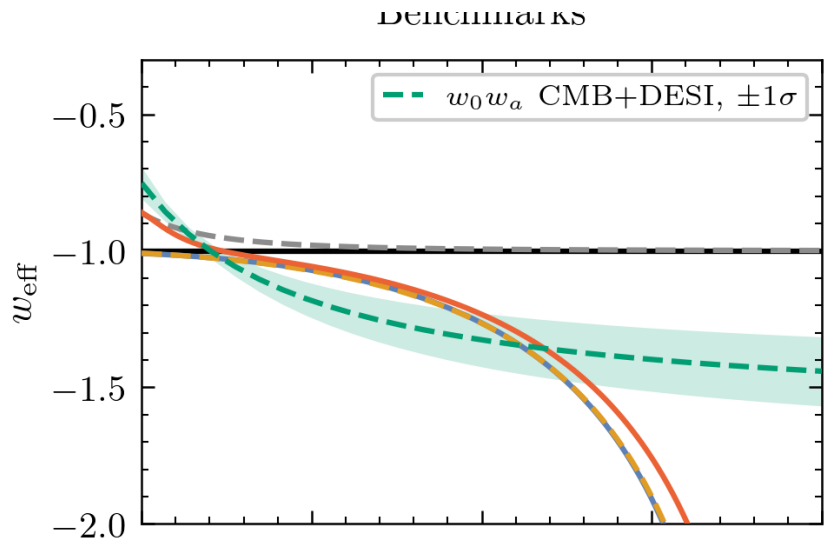
Rolling of axion:



	θ_i/π	f/M_{Pl}	H_0	Ω_{Mon}
	0.25	1.437	63.9	0.158
	0.50	0.682	65.7	0.150
	0.75	0.461	68.3	0.139
	0.99	0.442	68.7	0.138
	1.25	0.543	66.9	0.146
	1.50	0.789	65.1	0.155
	1.99	10.000	43.3	0.354

varying $\Omega_\Lambda \mid \theta_i/\pi = 3/4, \alpha_D = 0.044$

$w_{\text{eff}}(z)$



	Model	μ	θ_i/π	Ω_Λ	f/M_{Pl}	H_0
	Λ CDM	0	0.75	0.682	—	67.15
	Quint.	2	0.75	0.000	0.582	65.21
	Mon.	0	0.75	0.708	0.095	69.26
	Ax.-Mon.	2	0.75	0.686	0.096	69.25
	Ax.-Mon.	5	1.25	0.599	0.099	67.32

μ sweep, $\Omega_\Lambda = 0.65, \theta_i = 0.75\pi, n_e = 30$

Results preliminary. Shows significant evolution possible.

After thoughts: Implications of $\rho_{\text{DE}} \neq \text{constant}$

Some fun with rolling scalar models.
More fine-tuned than cosmological constant.
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More exciting: this could be telling us there is some **dynamical** mechanism to adjusting the dark energy towards zero.

No workable model yet.

Conclusions

- * If DE evolves, such as discovery would be extremely exciting.
- * DM-DE interaction (quick generic) can lead to interesting evolution.
 - * However, a natural model is difficult.
- * DM with monodromy coupling to DE is promising.
 - * We show that it is possible to implement this with monopole-axion system.
- * Hoping to hear the good news in the near future!

Monopole abundance

No controlled calculation, can only estimate

$$\text{Attraction: } F_d \sim q_M^2/r^2 \qquad \text{drag: } F \sim -\beta_c T^2 v$$

The balance of these two sets the typical time scale for annihilation.

$$\frac{\rho_M}{s} \approx \frac{\alpha_D \beta_c}{2\pi g_*^{1/2}(T_c)} \frac{m_M^2}{M_{\text{pl}}} \approx 0.44 \text{ eV} \left(\frac{\alpha_D}{0.04} \right) \left(\frac{\beta_c^2}{g_*(T_c)} \right)^{1/2} \left(\frac{m_M}{8.8 \times 10^2 \text{ TeV}} \right)^2$$