

a Λ CDM

Yu-Cheng QIU

Introduction

a Λ CDM

Towards the future

Summary and
Discussion

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July 1, 2025

2503.18924 with Nakagawa, Nakai, Yamada

2503.18120 & 2506.24011 with Luu, Tye

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- Who are we?
- Where do we come from?
- Where are we going?

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I. Introduction

Λ CDM and Cosmic anomalies

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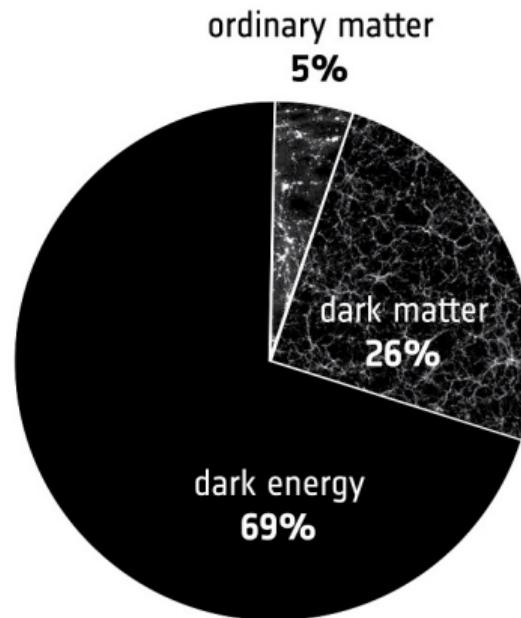
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- Hubble Tension
- S_8/σ_8 Tension
- $w_{\text{DE}} \neq -1$
- Cosmic Birefringence
- ...

Figure: Copyright: ESA.

The universe is expanding

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$$v = HD$$

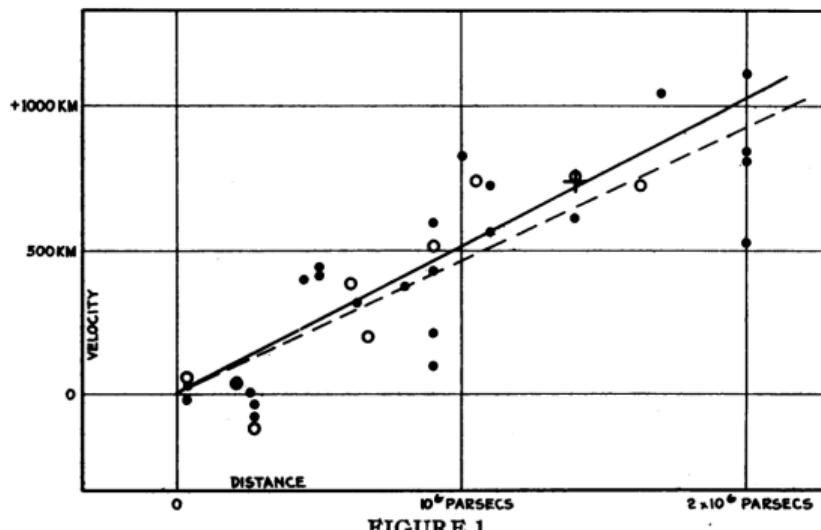


Figure: Hubble (1929)

The universe is acceleratingly expanding

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The Nobel Prize in Physics 2011:
Saul Perlmutter (1/2),
Brian P. Schmidt (1/4)
and Adam G. Riess (1/4)
“for the discovery of the accelerating
expansion of the Universe through
observations of distant supernovae”

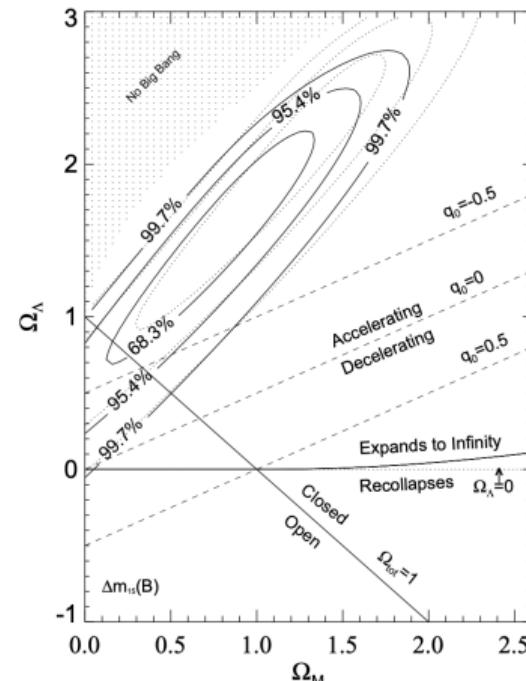


Figure: Riess et al. (1995)

Dark energy

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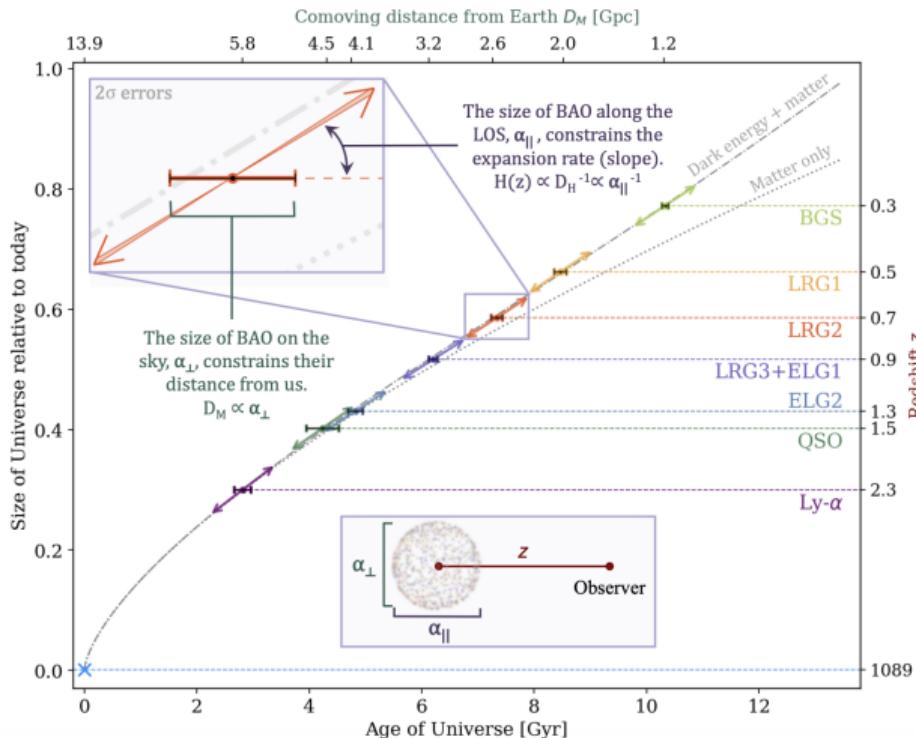


Figure: From DESI DR2.

Dynamical dark energy?

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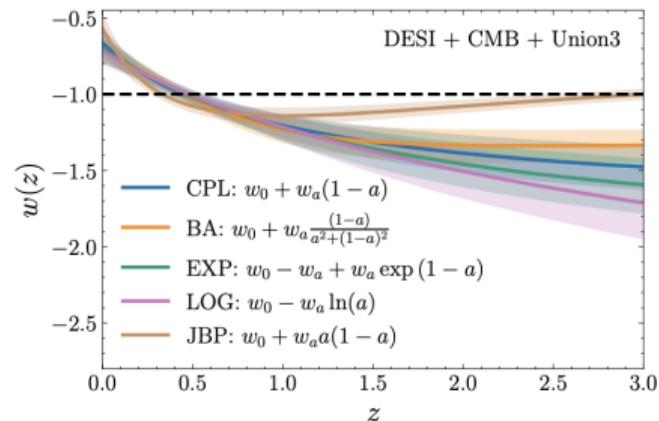
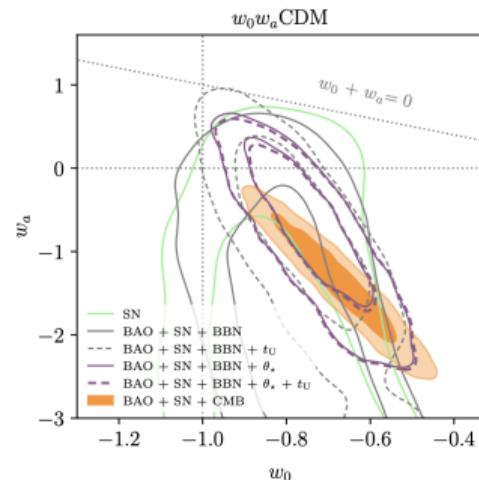
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$$\frac{H^2}{H_0^2} = \begin{cases} \Omega_m a^{-3} + \Omega_\Lambda & \text{for } \Lambda\text{CDM} \\ \Omega_m a^{-3} + \Omega_\Lambda a^{-3(1+w)} & \text{for } w\text{CDM} \\ \Omega_m a^{-3} + \Omega_\Lambda a^{-3(1+w_0+w_a)} e^{-3w_a(1-a)} & \text{for } w_0 w_a \text{CDM} \\ \dots \end{cases}$$



Isotropic Cosmic Birefringence

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$$C_l^{EB,obs} \neq 0 \implies \beta \neq 0$$

- $\beta = 0.35^\circ \pm 0.14^\circ$ (2.4σ)
(Minami and Komatsu 2011.11254)
- $\beta = 0.34^\circ \pm 0.09^\circ$ (3.6σ)
(Eskilt and Komatsu 2205.13962)
- $\beta = 0.20^\circ \pm 0.08^\circ$ (2.5σ)
(ACT 2503.14452)

1. Isotropic
2. Frequency-blind

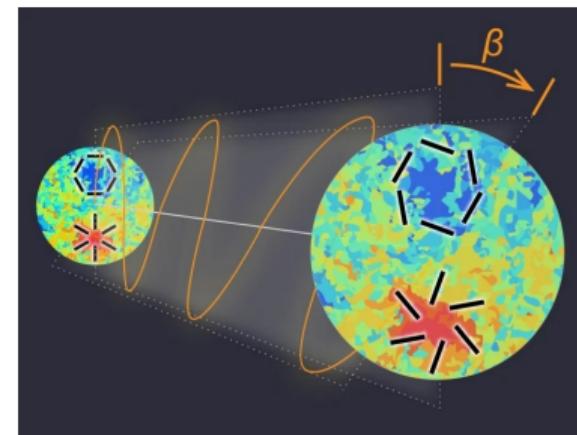


Figure: Credit: Yuto Minami

Misalignment

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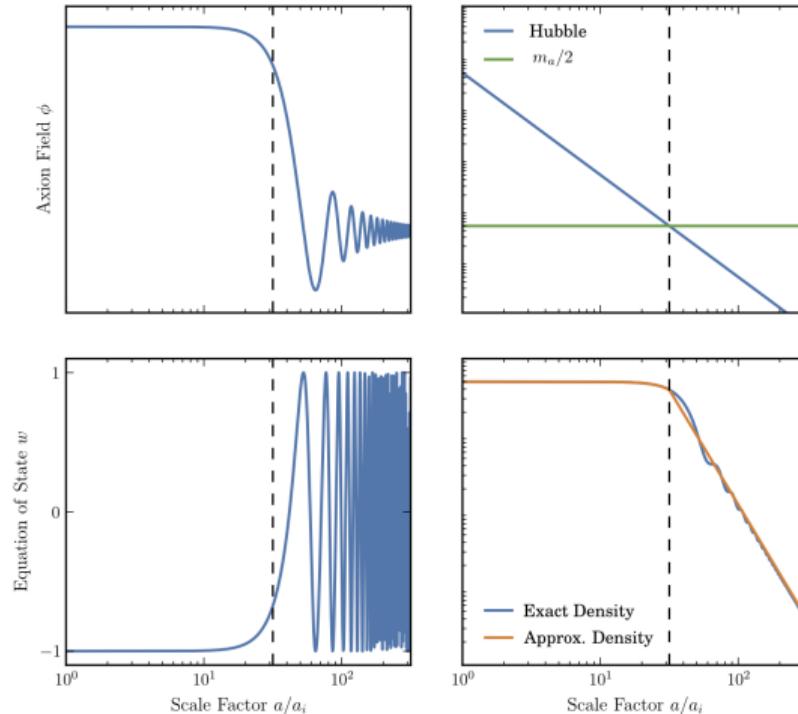


Figure: From Marsh (2016)

For a light (pseudo)scalar ϕ :
 Inflation indicates
 $\phi(\vec{x}, t) \rightarrow \phi(t)$;

- When $H \gg m_\phi$,
 $\phi = \phi_i$, $\rho_\phi = \text{const.}$
- When $H \ll m_\phi$,
 $\phi \simeq e^{-Ht} \cos(m_\phi t)$
 $\langle \rho_\phi \rangle \propto a^{-3}$

$$\Delta\phi = \phi_i - \phi(t_0) \neq 0$$

Axion (ALP) Explanation

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$$\mathcal{L} \supset c_\gamma \frac{\alpha}{4\pi} \frac{\phi}{f_\phi} F_{\mu\nu} \tilde{F}^{\mu\nu} \quad [\text{Carroll, Field (1991)}]$$

$$\implies \beta \simeq 0.067^\circ \times c_\gamma \frac{\Delta\phi}{f_\phi}$$

- Fuzzy dark matter axion, $m \sim 10^{-22}$ eV is too heavy to explain the β .
- axi-Higgs axion ($m \sim 10^{-29}$ eV) is just suitable.
[Fung, Li, Liu, Luu, **Qiu**, Tye (2021)]
- For quintessence axion $m \sim H_0$, $\Delta\phi/f_\phi$ is small. So c_γ should be large.
[Lin, Yanagida (2022)]

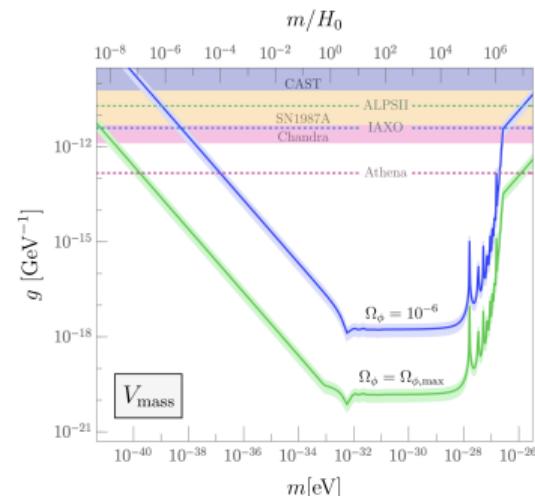


Figure: Fujita et al. 2011.11894

Can SMEFT explain β ?

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$$\mathcal{L}_{\text{CS}} = \frac{\alpha}{8\pi} \sum_a \frac{\tilde{\mathcal{O}}_a}{\Lambda_a^n} F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad n = \dim[\tilde{\mathcal{O}}_a]$$

Building Blocks:

$$H(\text{dim 1}), \quad D_\mu(\text{dim 1}), \quad \psi(\text{dim 3/2}), \quad X_{\mu\nu}(\text{dim 2})$$

- $n = 2$: $H^\dagger H$
- $n = 3$: (LEFT) $\mathcal{C}^{ij} \bar{e}^i P_L e^j + \text{h.c.}$, ($e \rightarrow \nu, d, u$).
- $n = 4$: $\sum_{X=F,Z,W,G} X_{\alpha\beta} X^{\alpha\beta} + X_{\alpha\beta} \tilde{X}^{\alpha\beta}$

No. All SM particles does not explain the observed β
[Nakai, Namba, obata, **Qiu**, Saito (2023)]

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II. a(xion) Λ CDM

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$$\ddot{\phi} + 3H(t)\dot{\phi} + V'(\phi) = 0, \quad V(\phi) = m^2 f_\phi^2 (1 - \cos \phi/f_\phi)$$

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \Omega_\Lambda + \frac{\rho_\phi(a)}{\rho_{\text{crit},0}}, \quad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

The dark energy is composed of Λ and ρ_ϕ . So the EoS

$$w_{\text{DE}} = \frac{\dot{\phi}^2/2 - V(\phi) - \Lambda}{\dot{\phi}^2/2 + V(\phi) + \Lambda} = -1 + \frac{\dot{\phi}^2}{\dot{\phi}^2/2 + V(\phi) + \Lambda}$$

We propose the rolling of ϕ explains the β and $w_{\text{DE}} \neq -1$.

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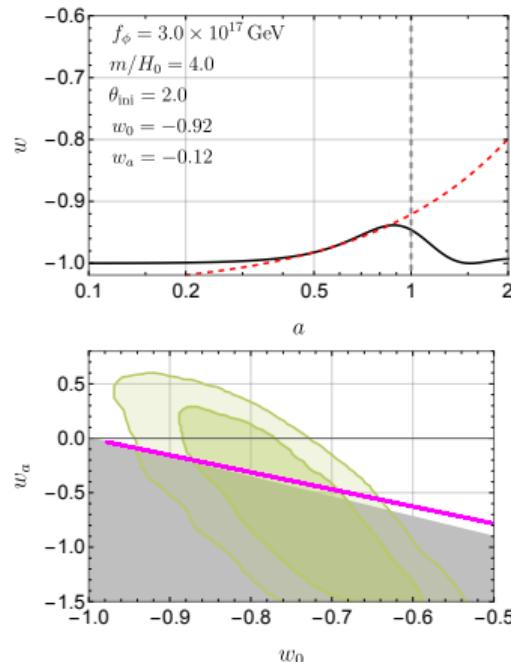
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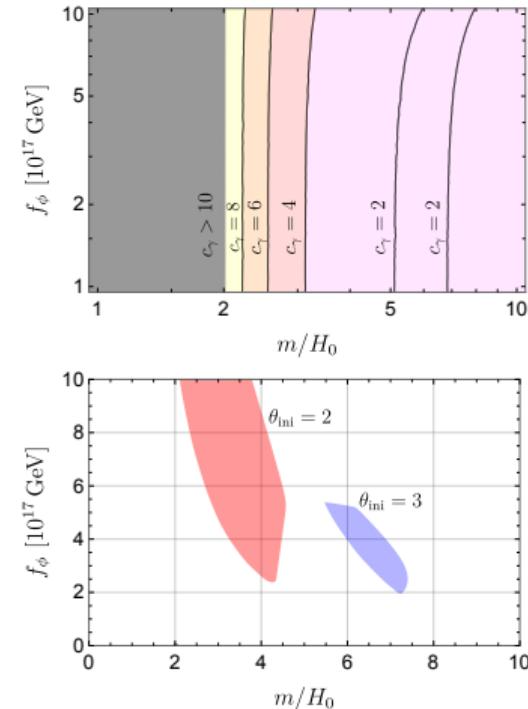
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The contour region is best fit values from data set:
 BAO + SN + BBN + θ_\star + t_U .



We take appropriate $\Omega_\Lambda \in (0.3, 0.7)$ which gives correct relic. $\theta = \phi/f_\phi$

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To explain the $\beta \sim 0.3^\circ$ and $w_{\text{DE}} \neq -1$, we have

- axion mass:

$$2H_0 \lesssim m \lesssim 7H_0 ,$$

- consistent with string motivated axion $f_\phi \sim \mathcal{O}(10^{17}) \text{ GeV}$,
- small $c_\gamma \sim \mathcal{O}(1)$,
- and dS vacuum $\Lambda > 0$.

$\Lambda < 0?$

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In supergravity, the supersymmetric vacuum is AdS.
AdS vacua are ubiquitous in String landscape.

If we forget about Cosmic Birefringence, $\Lambda < 0$ is allowed.

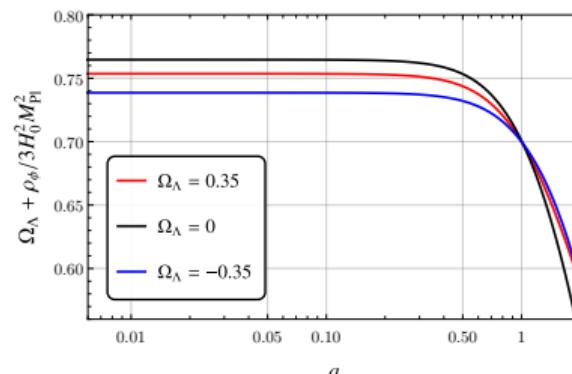


Figure: For $m = 2 \times 10^{-33}$ eV

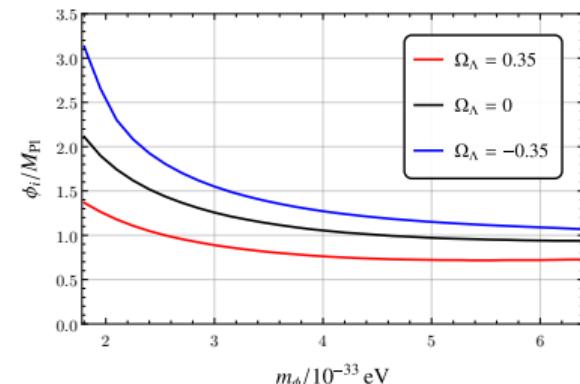


Figure: Parameter space that recreating the correct relic.

$\Lambda < 0?$

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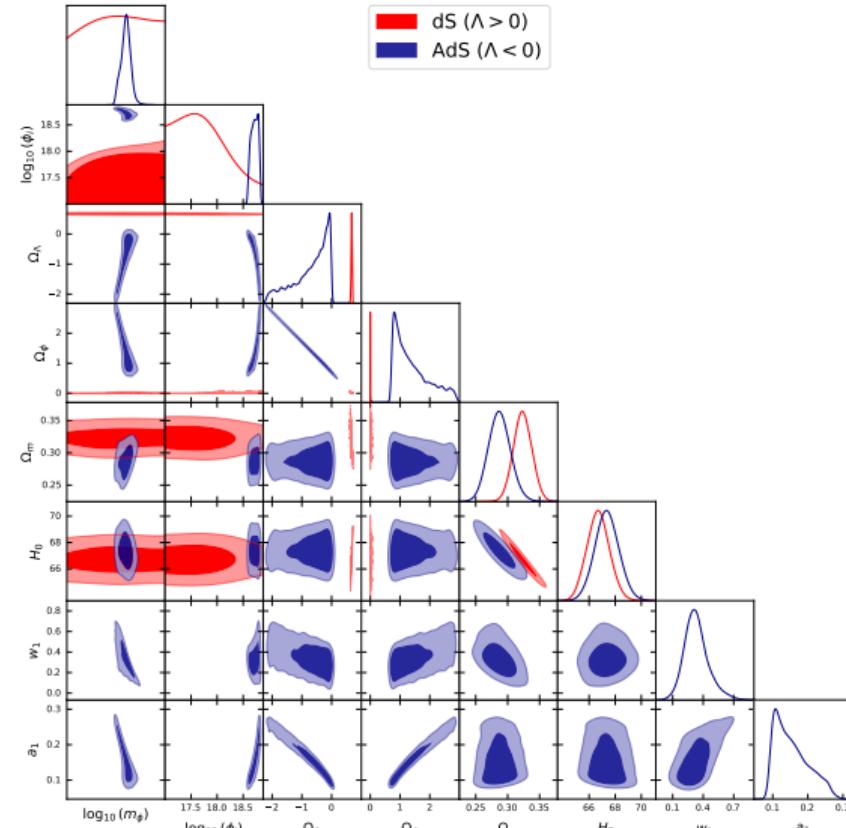
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The units of m_ϕ , ϕ_i and H_0 are implicitly assumed as eV, GeV and km/s/Mpc.



New fitting formula

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$$w(a) = \begin{cases} -1 + w_1(a - a_1)^2 & 1 > a \geq a_1 \\ -1 & a < a_1 \end{cases}$$

Taking

$$m \simeq 2.93 \times 10^{-33} \text{ eV}$$

$$\phi_i \simeq 6.28 \times 10^{18} \text{ GeV}$$

$$\Omega_\Lambda \simeq -1.61$$

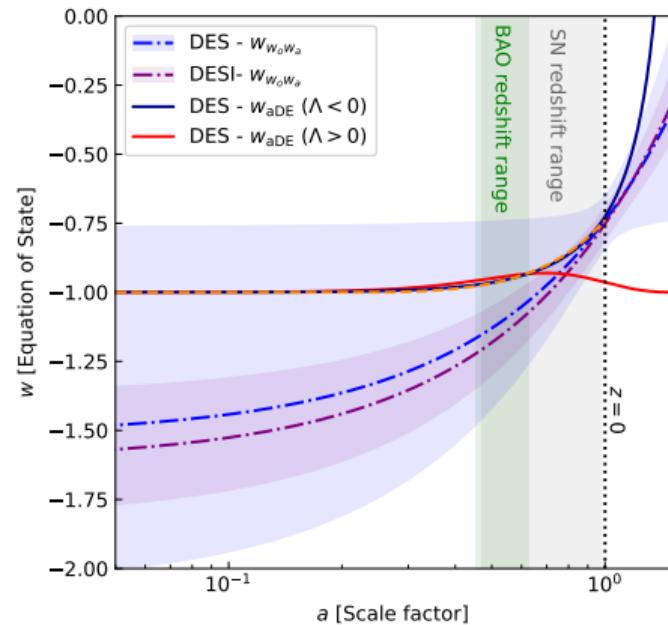
$$\Omega_m \simeq 0.284$$

$$H_0 \simeq 67.46 \text{ km/s/Mpc.}$$

Best fit:

$$w_1 \simeq 0.44$$

$$a_1 \simeq 0.23$$



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III. Towards the future

The future

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In the unit of H_0 ,

$$\mathcal{H}^2 = \frac{\Omega_m}{a^3} + \Omega_\Lambda + \Omega_\phi ,$$

$$\mathcal{H}' = -\frac{3}{2} \frac{\Omega_m}{a^3} - \frac{3}{2} (\Omega_\Lambda + \Omega_\phi) (w_{DE} + 1)$$

For $\Omega_\phi \rightarrow 0$, one has

$$\mathcal{H}' = -\frac{3}{2} (\mathcal{H}^2 - \Omega_\Lambda)$$

A phase space relation!

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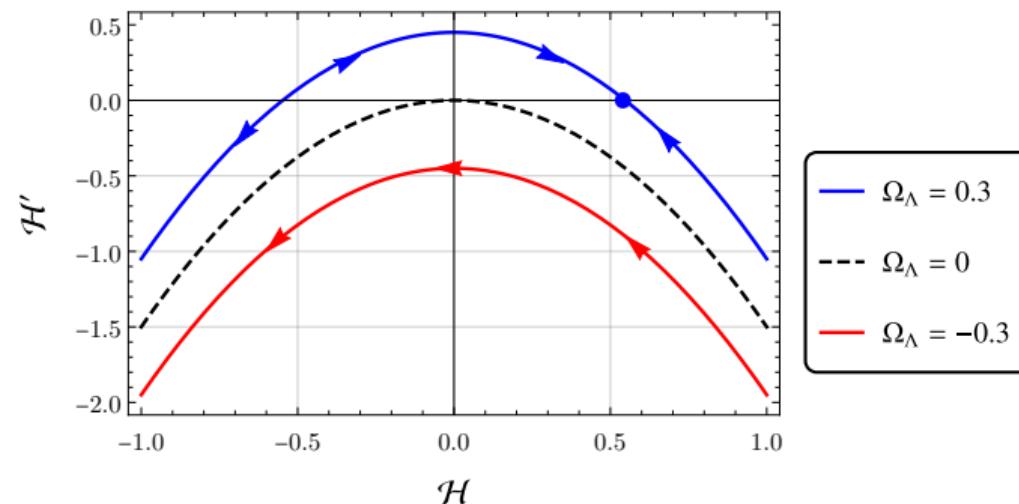
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$$\mathcal{H}' = -\frac{3}{2} (\mathcal{H}^2 - \Omega_\Lambda)$$



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$$\Omega_\phi(a) \simeq \begin{cases} \Omega_{\phi,0} & a \leq 1 \\ \Omega_{\phi,0}a^{-3} & a > 1 \end{cases},$$

So it is an effective Λ CDM, with $\Omega_m + \Omega_{\phi,0} \rightarrow \Omega_m$.

$$\frac{a'}{a} = \sqrt{\mathcal{H}^2} = \sqrt{\frac{1 - \Omega_\Lambda}{a^3} + \Omega_\Lambda}$$

$$a(t)^3 = \frac{\Omega_\Lambda - 1}{\Omega_\Lambda} \sin^2 \left[\frac{3}{2} \sqrt{-\Omega_\Lambda} H_0 (t - t_0) + \arctan(\sqrt{-\Omega_\Lambda}) \right],$$

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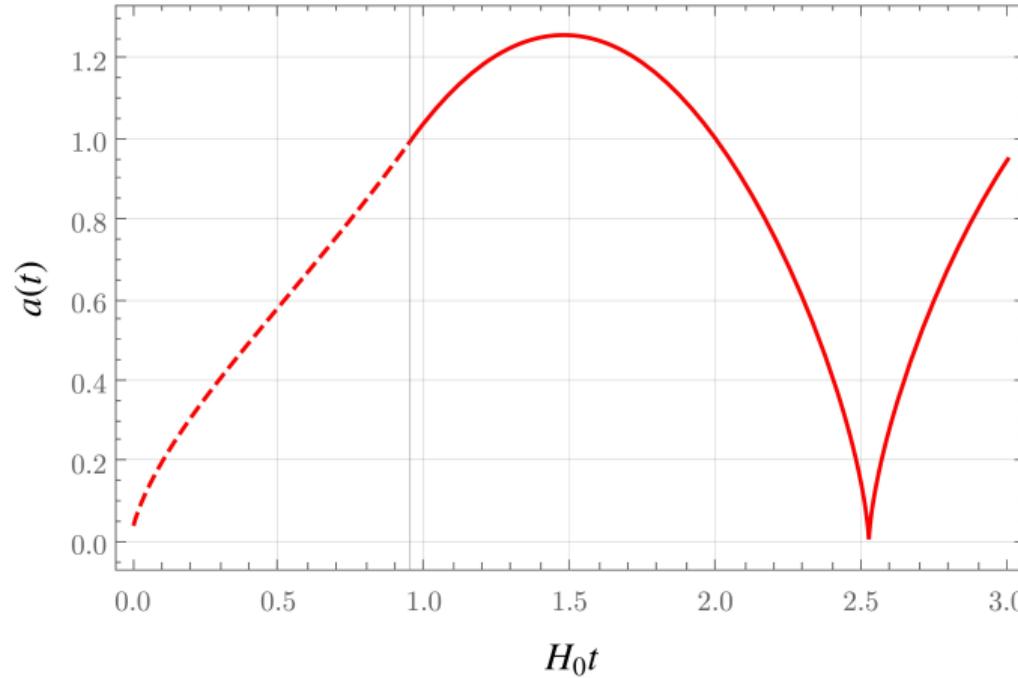


Figure: Effective Λ CDM with $\Omega_\Lambda = -1$ for $t > t_0$ and $\Omega_\Lambda = 0.7$ for $t < t_0$. The age of universe is $t_0 = 13.8$ Gyr, and $H_0 t_0 = 0.952$.

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Numerical evolution from $H_0 t_0 = 0.952$:

$$\theta'' + 3\mathcal{H}\theta' + \frac{m_\phi^2}{H_0^2} \sin \theta = 0$$

$$a' = \mathcal{H}a$$

$$\mathcal{H}' = -\frac{3}{2} \frac{\Omega_m}{a^3} - \frac{1}{2} \theta'^2$$

Initial conditions can be obtained from observation on EoS today w_0 :

$$\bar{V}(\theta_0) = \frac{1}{2}(1 - \Omega_m)(1 - w_0) - \Omega_\Lambda ,$$

$$\theta'_0 = \pm \sqrt{\frac{3}{\beta^2}(1 - \Omega_m)(1 + w_0)}$$

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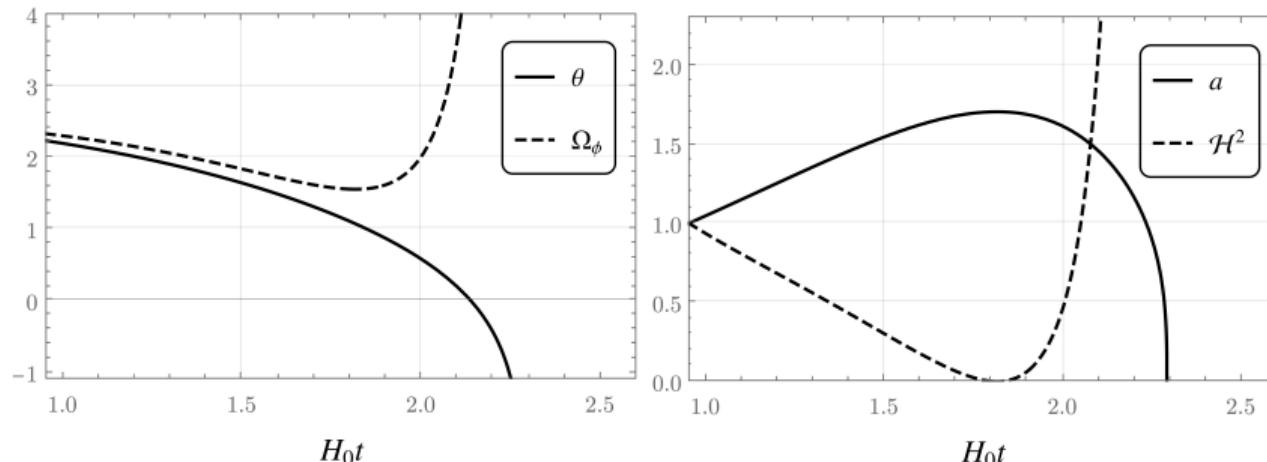


Figure: The cosmic evolution of best-fit parameters: $m_\phi = 2.93 \times 10^{-33}$ eV,
 $\Omega_\Lambda = -1.61$, $\theta_i = 0.82\pi$, $\Omega_m = 0.284$, $f = M_{\text{Pl}}$.

The lifespan is $T = 33.3$ Gyr!

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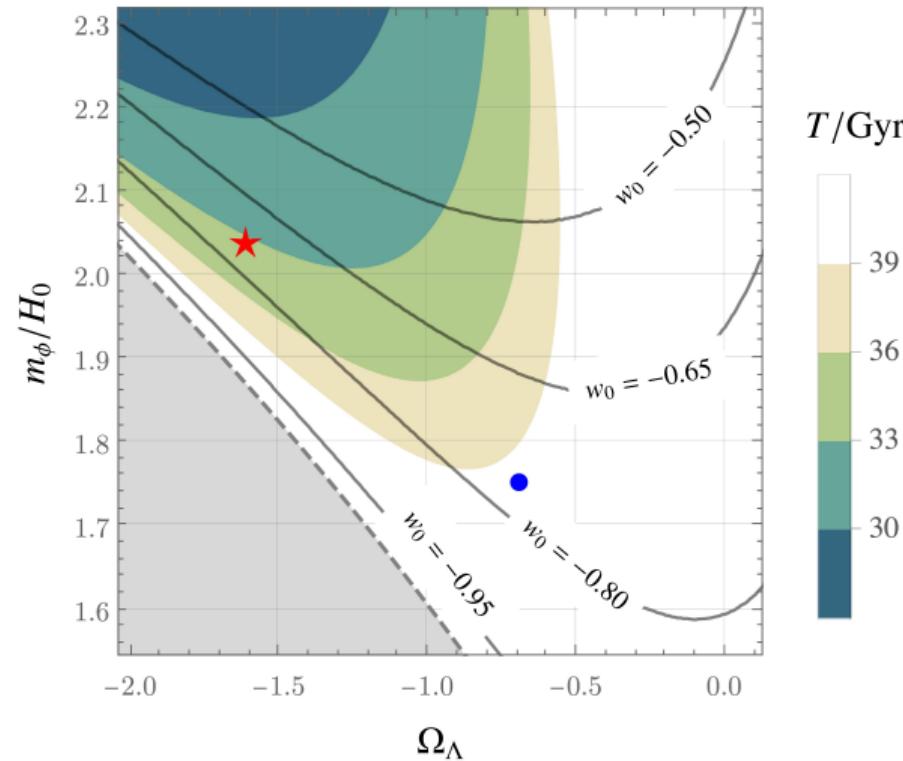


Figure: The red star is the best-fit. The blue dot is the average.

Summary

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1. We propose a simple extension to Λ CDM to explain cosmic birefringence and dynamical dark energy.
2. The axion mass is pinned down to $2H_0 \lesssim m \lesssim 7H_0$, with $f_\phi \sim \mathcal{O}(10^{17})$ GeV and small c_γ .
3. Neglecting the cosmic birefringence, the data allow AdS vacuum.
4. New fitting formula for the dynamical dark energy is proposed, pending for future analysis.
5. Best-fit lifespan is 33 billion years.

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Thank you

Equation of motion

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The equation of motion expressed in scale factor a is

$$\theta'' + \left(\frac{4}{a} + \frac{H'}{H} \right) \theta' + \frac{m^2}{a^2 H^2} \sin \theta = 0. \quad (1)$$

Two Friedmann equations are

$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \Omega_\Lambda + \frac{1}{6} \frac{H^2}{H_0^2} \frac{f_\phi^2}{M_{\text{Pl}}^2} \theta'^2 + \frac{V(\theta)}{3H_0^2 M_{\text{Pl}}^2} \quad (2)$$

$$a \frac{HH'}{H_0^2} = -\frac{3}{2} \frac{\Omega_m}{a^3} - \frac{1}{4} \frac{f_\phi^2}{M_{\text{Pl}}^2} \frac{a^2 H^2 \theta'^2}{H_0^2}. \quad (3)$$

Combining the above two gives

$$\frac{H'}{H} = -\frac{3}{2} \frac{\Omega_m}{a^4} \frac{H_0^2}{H^2} - \frac{1}{4} a \frac{f_\phi^2}{M_{\text{Pl}}^2} \theta'^2 \quad (4)$$

$$\frac{H^2}{H_0^2} = \left(\frac{\Omega_m}{a^3} + \Omega_\Lambda + \frac{V(\theta)}{3H_0^2 M_{\text{Pl}}^2} \right) \left(1 - \frac{1}{6} \frac{f_\phi^2}{M_{\text{Pl}}^2} \theta'^2 \right)^{-1} \quad (5)$$