aΛCDM

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2503.18924 with Nakagawa, Nakai, Yamada

2503.18120 with Luu, Tye

I. Introduction

ΛCDM and Cosmic anomalies

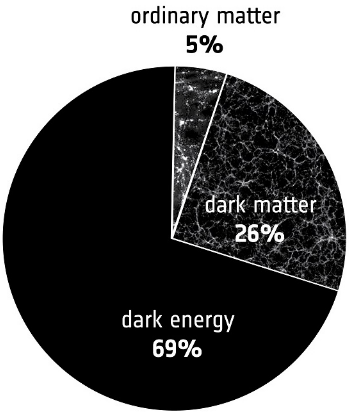


Figure: Copyright: ESA.

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

The universe is expanding

$$v = HD$$

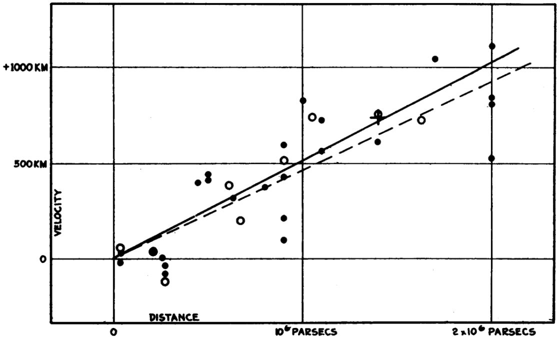


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Figure: Hubble (1929)

The universe is acceleratingly expanding

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"

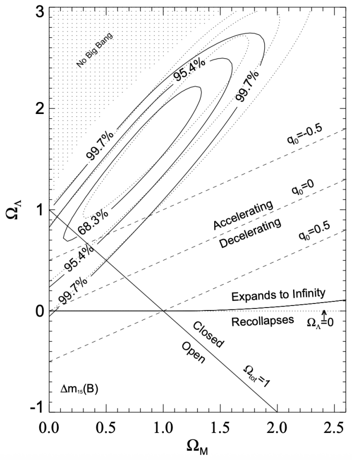


Figure: Riess et al. (1995)

Dark energy

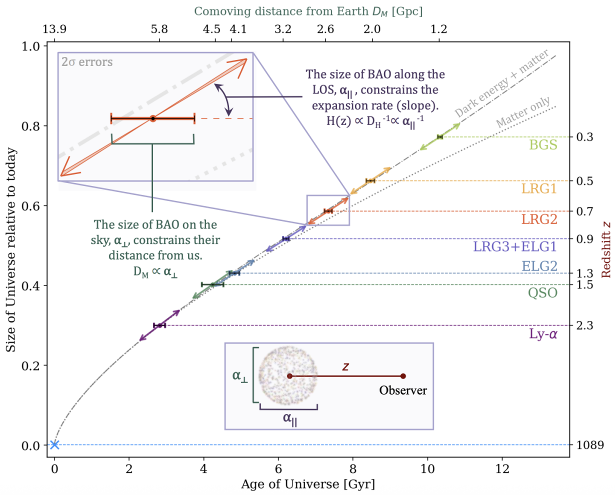
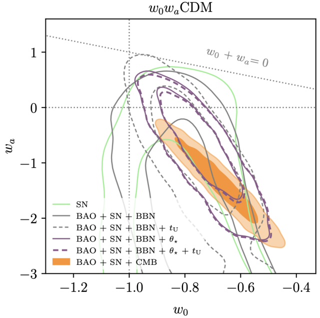
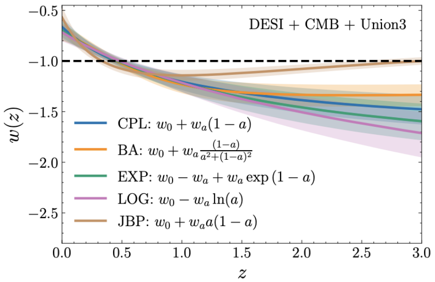


Figure: From DESI DR2.

Dynamical dark energy?

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





Isotropic Cosmic Birefringence

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

- $\beta = 0.35^\circ \pm 0.14^\circ$ (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

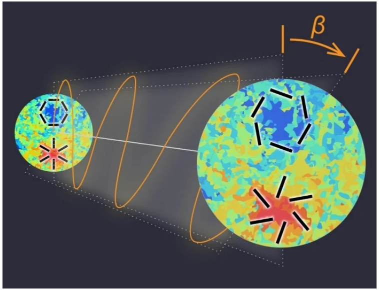


Figure: Credit: Yuto Minami

Misalignment

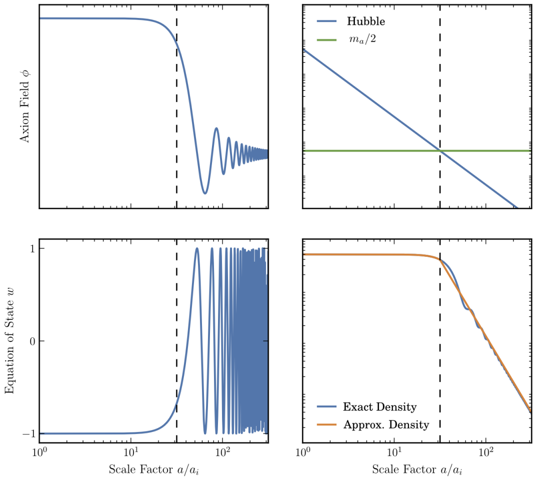


Figure: From Marsh (2016)

For a light (pseudo)scalar ϕ:

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

Axion (ALP) Explanation

$$\mathcal{L} \supset c_\gamma \frac{\alpha}{4\pi} \frac{\phi}{f_\phi} F_{\mu\nu} \tilde{F}^{\mu\nu}$$ [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)]

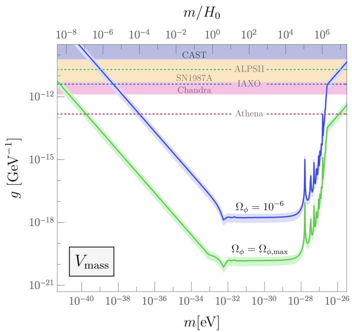


Figure: Fujita et al. 2011.11894

Can SMEFT explain β?

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

Building Blocks:

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

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

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

II. a(xion)ΛCDM

aΛCDM

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

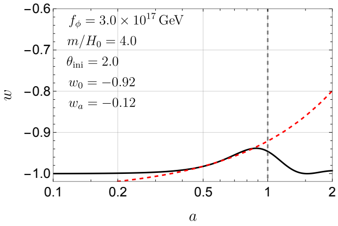
$$\frac{H^2}{H_0^2} = \frac{\Omega_m}{a^3} + \Omega_\Lambda + \frac{\rho_\phi(a)}{\rho_{\text{crit},0}}\ , \quad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

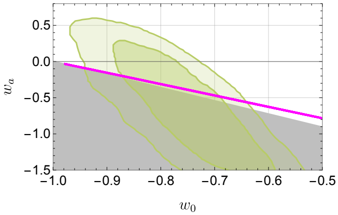
The dark energy is composed of Λ and ρ_ϕ. So the EoS

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

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

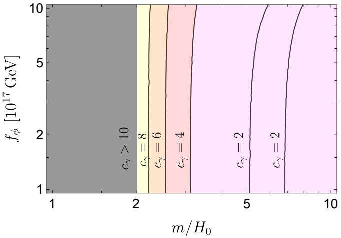
aΛCDM

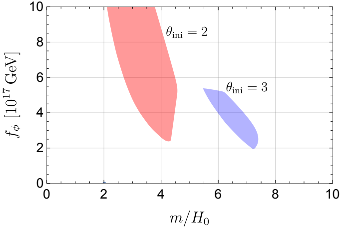




The contour region is best fit values from data set:

BAO + SN + BBN + $\theta_\star$ + $t_{\rm U}$.





We take appropriate $\Omega_\Lambda \in (0.3, 0.7)$ which gives correct relic.

$\theta = \phi/f_\phi$

aΛCDM

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

- axion mass:

$$2H_0 \lesssim m \lesssim 6H_0 \ ,$$

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

$\Lambda < 0$?

In supergravity, the supersymmetric vacuum is AdS.
AdS vacua are ubiquitious in String landscape.
If we forget about Cosmic Birefringence, $\Lambda < 0$ is allowed.

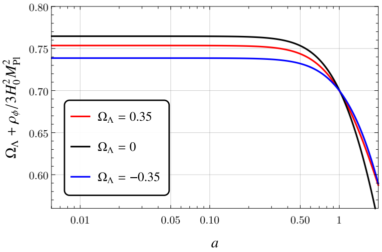


Figure: For $m = 2 \times 10^{-33}$ eV

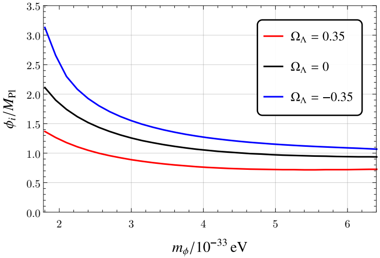


Figure: Parameter space that recreating the correct relic.

$\Lambda < 0$?

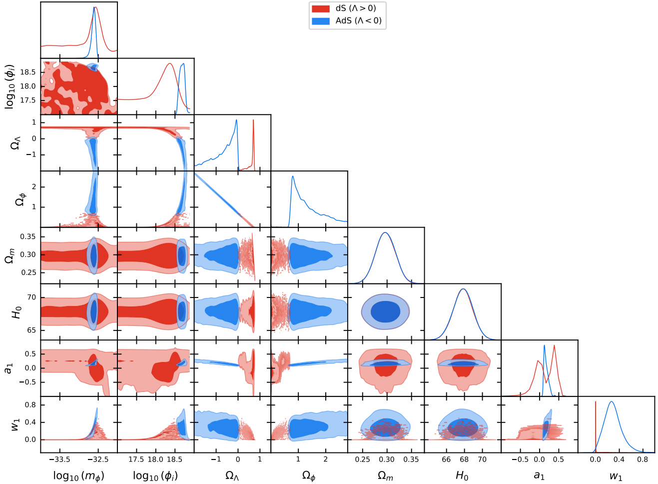


Figure: The units of m_ϕ, ϕ_i and H_0 are implicitly assumed as eV, GeV and $\mathrm{km}/s/\mathrm{Mpc}$.

New fitting formula

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

Taking

$m \simeq 2.8 \times 10^{-33}$ eV

$\phi_i \simeq 5.8 \times 10^{18}$ GeV

$\Omega_\Lambda \simeq -2.2$

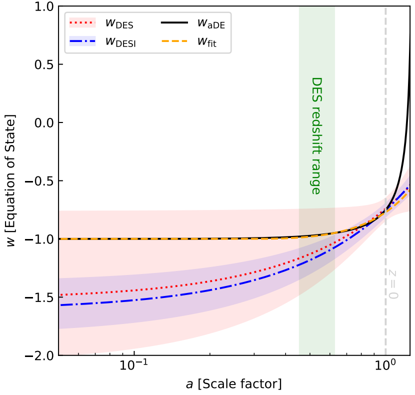
$\Omega_m \simeq 0.3$

$H_0 \simeq 67.9$ km/s/Mpc.

Best fit:

$w_1 \simeq 0.458$

$a_1 \simeq 0.292$



Summary

1. We propose a simple extension to ΛCDM to explain cosmic birefringence and dynamical dark energy.
2. The axion mass is pinned down to $2H_0 \lesssim m \lesssim 6H_0$, 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.

Thank you

Equation of motion

The equation of motion expressed in scale factor a is

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

Two Friedmann equations are

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

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

Combining the above two gives

$$\frac{H'}{H} = -\frac{3}{2}\frac{\Omega_m}{a^4}\frac{H_0^2}{H^2} - \frac{1}{4}a\frac{f_\phi^2}{M_{\rm Pl}^2}\theta'^2 \tag{4}$$

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