Dynamical Dark Energy from an Ultralight Axion and The Lifespan of Our Universe

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2503.18120 & 2506.24011
IHEP, Beijing, China   18 July, 2025

What is the fate of our universe ?

Among various speculations, there are two simplest and so most likely scenarios where the fate of the universe is dictated by the value of the cosmological constant Λ :

- The universe continues its present expansion forever if $\Lambda \geq 0$, i.e., with an infinite lifespan.
- It eventually reaches a big crunch if $\Lambda < 0$, when the cosmic scale factor a of the universe collapses to zero, in finite time.

March 2025 observations strongly suggest the second option. We estimate that the lifespan of our universe is 33 billion years.

Basic Cosmology

- The cosmic scale factor a and its variation, the Hubble parameter H: $H = \dot{a}/a$

$$H^2 = \frac{1}{3M_{Pl}^2} \sum \frac{\rho_i}{a^{3(1+w_i)}}$$

where w is the equation of state (pressure/energy density).

$$matter : w = 0, \quad \rho_m/a^3$$

$$radiation : w = 1/3, \quad \rho_r/a^4$$

$$cosmological\ constant : w = -1, \quad \Lambda$$

$$\mathcal{H}^2 = \frac{\Omega_m}{a^3} + \Omega_{DE}$$

Today, $H = H_0$ at $a = 1$,

$$1 = \Omega_m + \Omega_{DE,0}$$

Standard ΛCDM Model

$$\mathcal{H}^2 = \frac{\Omega_m}{a^3} + \Omega_{DE}$$

$$\Omega_m = \Omega_{atom} + \Omega_{dark\ matter}$$

$$\Omega_{DE} = \frac{\Omega_{DE,0}}{a^{3(1+w)}}$$

ΛCDM model:

$$\Omega_{DE} = \Omega_\Lambda, \quad with \quad w = -1$$

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

$$\Omega_m = 0.28, \quad \Omega_\Lambda = 0.72$$

Age of our universe is 13.8 billion years.

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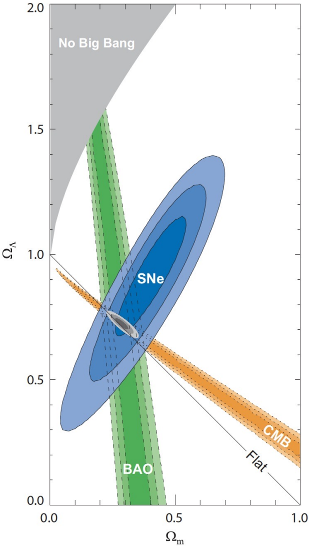
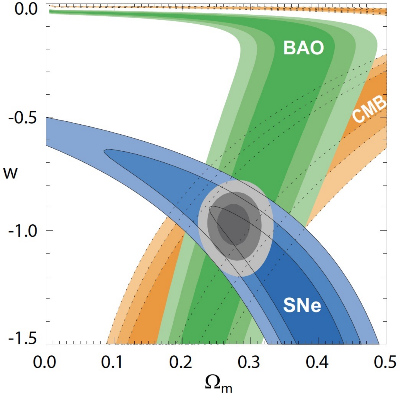


FIG. 15.— 68.3 %, 95.4 % and 99.7% confidence level contours on Ω_Λ and Ω_M obtained from CMB, BAO and the Union SN set, as well as their combination (assuming $w = -1$).

Dark energy $w_{DE} = -1$

Kowolski et al 0804.4142



Astronomers are trying to characterize dark energy by surveying galaxies in different eras of cosmic time.

Dark energy $w_{DE} \neq -1$

In March, 2025, 2 results reported that the w of the dark energy component $w \neq -1$.

• Dark Energy Survey (DES) used the Atacama Cosmology Telescope in Chile to measure the clustering of 16 million galaxies and the luminosity distance/redshift relation of 1,635Type 1A supernovas.
• Dark Energy Spectroscopic Instrument (DESI) at Kitt Peak National Observatory in Arizona has a similar collection of data.

Data implies that the cosmic acceleration driven by dark energy began in earlier time, and is currently weaker than what the standard model predicts (i.e., $w = -1$).

The axion Dark Energy (aDE) Model

Natural explanation:

An ultralight axion-like-particle with potential

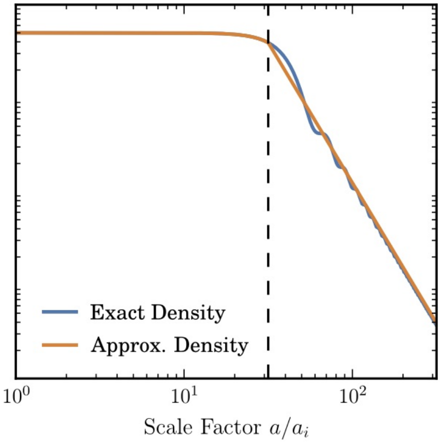
$$V(\phi) = m^2 f^2 (1 - cos(\phi/f))$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

aDE model : $V(\phi) + \Lambda$

$$V(\phi) = m^2\phi^2/2$$

Start at $\phi = \phi_i$ when $H > m$.



$$V(\phi) = m^2 M_{Pl}^2 \left(1 - cos(\frac{\phi}{M_{Pl}})\right)$$

Here, we include a cosmological constant Λ in addition to the axion field,

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

Today, $H = H_0$ at $a = 1$,

$$\mathcal{H}_0^2 = 1 = \Omega_m + \Omega_\Lambda + \Omega_{\phi,0}$$

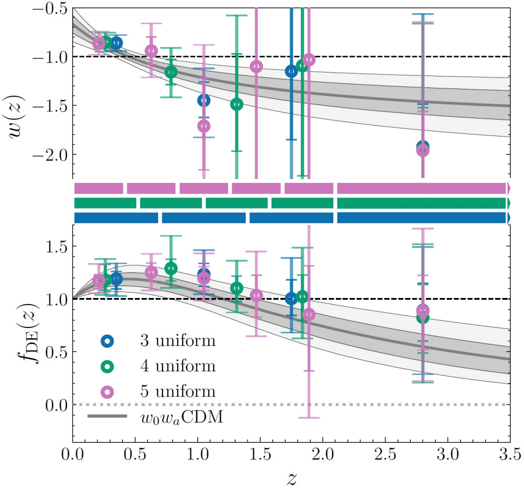
From cosmological data collected in the past decades, we find that today

$$1 = \Omega_m + \Omega_{DE} \simeq 0.3 + 0.7$$

where Ω_m includes both ordinary matter (0.04) and dark matter (0.26), while the dark energy Ω_{DE} has $w \sim -1$.

DES/DESI Observation

DESI data



$z \sim 0.4$
$t \sim 10^{10}$ years old

If constant:
$w = -0.948^{+0.028}_{-0.027}$

A varying w yields a better fit.

Combining DES/DESI data, DES claims the discrepancy between data and $w = -1$ reaches 4.2σ level.

Comparing the 2 models

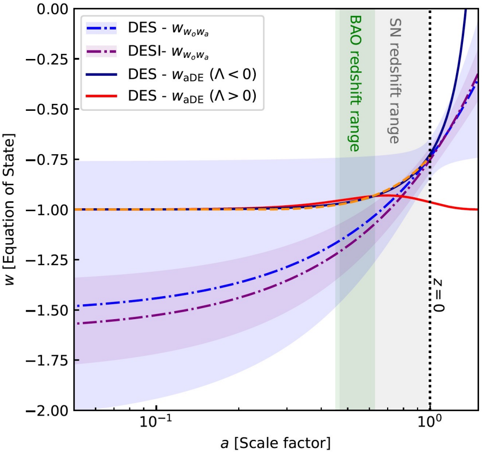
$$a = 1/(1+z)$$

The CPL or $w_0 w_a$ model

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

The aDE or $w_1 a_1$ model

$$w = -1 + w_1(a - a_1)^2$$



Best-fit values of the aDE model

The best-fit values for the aDE model we obtain,

$$
\begin{aligned}
m_\phi &= 2.93 \times 10^{-33}\ \mathrm{eV}\ , \\
\phi_i &= 6.28 \times 10^{18}\ \mathrm{GeV}\ , \quad \mathrm{or} \quad \theta_i = 0.82\pi\ , \\
\Omega_{\phi,0} &= 2.33\ , \quad \Omega_\Lambda = -1.61 \quad \rightarrow \quad \Omega_{DE,0} = 0.72\ , \\
\Omega_{\mathrm{m}} &= 0.28\ , \\
H_0 &= 67.46\ \mathrm{km}/s/\mathrm{Mpc} = (14.5\ \mathrm{Gyr})^{-1}\ , \\
w_0 &= -0.738
\end{aligned}
$$

$$w = -1 + w_1(a - a_1)^2 \simeq -1 + 0.44(a - 0.23)^2$$

w starts to increase from $w = -1$ around $z \sim 3$

$\Omega_\Lambda < 0$ means that we live in an AdS space.

Different Scenarios

$$\Omega_{\phi,0} + \Omega_{\Lambda} = 0.72$$

$$\Omega_{\phi,0} = 0, \quad \Omega_{\Lambda} = 0.72$$

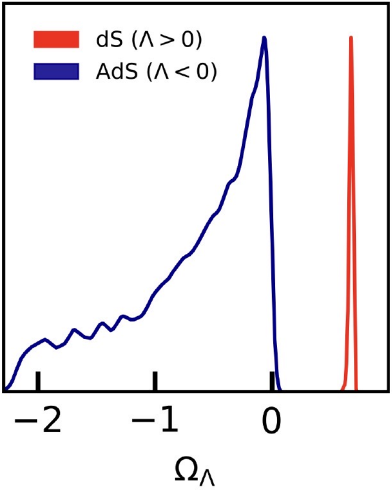
$$\Omega_{\phi,0} > 0, \quad 0 < \Omega_{\Lambda} < 0.72$$

$$\Omega_{\phi,0} = 0.72, \quad \Omega_{\Lambda} = 0$$

$$\Omega_{\phi,0} = 1.41, \quad \Omega_{\Lambda} = -0.69$$

$$\Omega_{\phi,0} = 2.33, \quad \Omega_{\Lambda} = -1.61$$

Posterior distribution of Ω_Λ



Clearly this shows that $\Omega_\Lambda < 0$ is preferred.

If we treat this distribution as a probability distribution, then $\Omega_\Lambda < 0$ is highly preferred.

Recently, arXiv:2506.21542 claims that DESI data shows that the probability of $\Omega_\Lambda < 0$ is 93.8%

The future

Consider $\Omega_\phi \to 0$. In the unit of H_0,

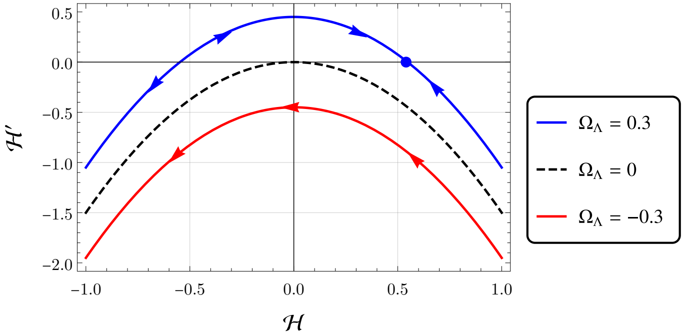
$$\mathcal{H}^2 = \frac{\Omega_{\rm m}}{a^3} + \Omega_\Lambda \ ,$$
$$\mathcal{H}' = -\frac{3}{2}\frac{\Omega_{\rm m}}{a^3} \ ,$$

one has

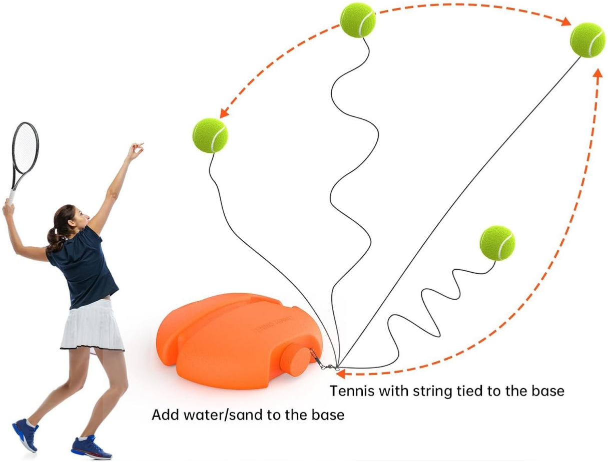
$$\mathcal{H}' = -\frac{3}{2}\left(\mathcal{H}^2 - \Omega_\Lambda\right) \ .$$

Dependence on the sign of Ω_Λ

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



Crunching picture



The approximate aDE version

Axion can be approximated as

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

So it is an effective ΛCDM, with $\Omega_{\rm m} + \Omega_{\phi,0} \to \bar{\Omega}_{\rm m}$.

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

$T \simeq \frac{2\pi}{3H_0\sqrt{|\Omega_\Lambda|}} + 13.8\,\text{Gyr} = 30.9$ billion years

The evolution of the aDE model

$\theta = \phi/f$

Numerical evolution from $H_0 t_0 = 0.952$:

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

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

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

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

$$\overline{V}(\theta_0) = \frac{1}{2}(1-\Omega_\mathrm{m})(1-w_0) - \Omega_\Lambda ,$$

$$\theta'_0 = \pm\sqrt{3(1-\Omega_\mathrm{m})(1+w_0)}$$

The lifespan of our universe

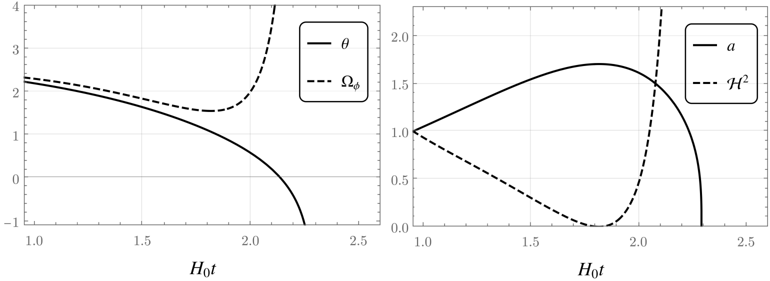


Figure: The cosmic evolution of best-fit parameters: $m_\phi = 2.93 \times 10^{-33}$ eV, $\Omega_\Lambda = -1.61$, $\theta_i = 0.82\pi$, $\Omega_m = 0.284$, $f = M_{Pl}$.

The lifespan is $T = 33.3$ Gyr!

11 Gyr from now (at $H_0t = 1.71$), $a_{max} = 1.69$.

The overall picture

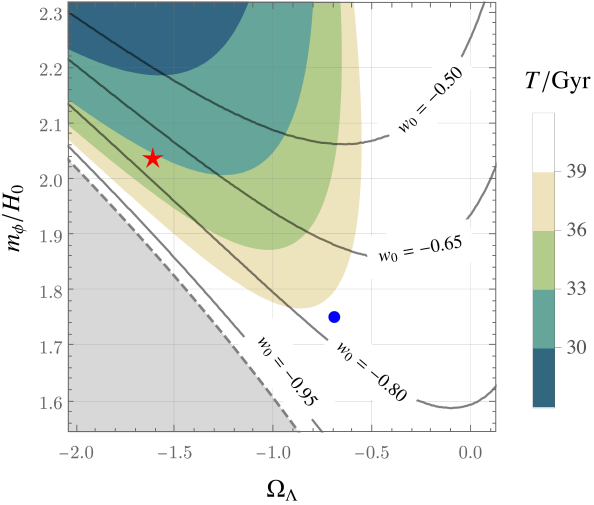


Figure: The red star is the best-fit. The blue dot is the average.

Future Observations

DESI will continue collecting data for at least another year. Other telescopes, on the ground and in space, are charting their own views of the cosmos; among them are

• the Zwicky Transient Facility in San Diego,

• the European Euclid space telescope and

• NASA's recently launched SPHEREx mission.

• The Vera C. Rubin Observatory in Chile is already operating.

• NASA's Nancy Grace Roman Space Telescope is set to launch in 2027.

Remark on SUSY

String theory suggests that constructing a metastable vacuum with a positive cosmological constant can be challenging, while constructing vacua with a negative cosmological constant is generic. Presumably, non-supersymmetric vacua are unstable or meta-stable, so they will eventually evolve towards supersymmetric vacua, which have negative Λ.

It is clear that SUSY is broken today. A generic mass splitting term of TeV scale will shift the standard model particle masses, but cosmological observations such as the BBN and CMB measurements show that the masses of the electron and nucleons should not have been shifted by more than a few percent since big bang nucleosynthesis time.

Cycle and Reincarnation

Can the universe transition to the next cycle ?
The singularity at the end of the universe manifests in the collapse of the cosmic scale factor a ending in a crunch, a purely classical phenomenon. Does quantum effects come into play here, especially during the collapsing phase ? Maybe quantum effects allow the universe to transition to the next cycle.

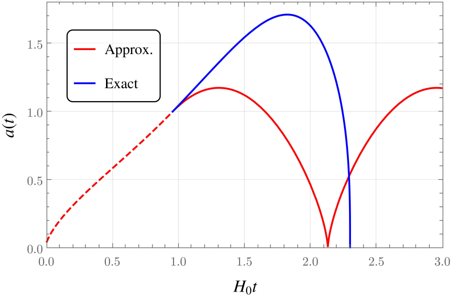


Figure: $\Omega_\Lambda = -1.61$.

Remark on Singularities

There are 3 types of singularities we encounter in the study of gravity :

- black holes
- the origin of the universe
- the crunch at the end of the universe.

Imagine the following scenario:

As the universe is collapsing, matters are push together to form a giant black hole, which in turns shields/hides the crunch singularity.

Summary

The determination of the lifespan of our universe depends on the recent observation that $w > -1$ and the validity of the aDE model.

It is crucial that the DES/DESI observation is confirmed and the aDE model with a negative Λ is rigorously tested.

Fortunately, a number of projects measuring different aspects of the dark energy are forthcoming in the near future.

We look forward to a more precise determination of the universe's lifespan.

THANKS

The aDE model on DES/DESI observation