Non-oscillating Early Dark Energy and Quintessence from α-Attractors

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Outline

Motivation - The Hubble Tension

In observational cosmology there are two types of measurements:

Early-time measurements

- Measure observables that depend on the history of the Universe at early times (for example around decoupling or matter-radiation equality)
- Examples: CMB, BAO (baryon acoustic oscillations)

Planck data [1] gives a Hubble constant of
$H_0 = 67.44 \pm 0.58$ km s^{-1} Mpc^{-1}

Late-time measurements

- Measure observables that depend on the history of the Universe to the present day
- Examples: Type-1a Supernovae, Cepheid variables (basically anything in the cosmic distance ladder)

The SH_0ES collaboration [2] gives a Hubble constant of
$H_0 = 73.04 \pm 1.04$ km s^{-1} Mpc^{-1}

These two measurements are in 5σ tension!
There is no indication that this arises from systematic error.

Early Dark Energy

- Early Dark Energy (EDE) is a possible way to resolve the Hubble tension
- EDE is an injection of dark energy around matter-radiation equality, always remaining subdominant, that decays away before it can be detected in the CMB
- Lowers the value of the sound horizon at last scattering, such that the Hubble constant today is higher. The comoving sound horizon is given by

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz, \tag{1}$$

where $c_s(z)$ is the sound speed of baryon acoustic oscillations (BAO) and $H(z)$ is the Hubble parameter, both as a function of redshift.

Quintessence

Quintessence: Late-time dark energy (dark energy that makes up 70% of the Universe today) that is caused by a scalar field. So named because it is the fifth substance in the Universe content, after baryonic matter, radiation, dark matter and neutrinos.

In this project we aim to use a scalar field with an α-attractor potential to cause both early dark energy and late-time dark energy, thus resolving the Hubble tension and finding a cause for dark energy today.

α-attractors

- α-attractors [3] are a class of inflationary models
- In supergravity, introducing curvature to the internal field-space manifold can result in kinetic poles for some of the scalar fields of the theory. The free parameter α is inversely proportional to said curvature.
- These are called attractors because:
  1. multiple initial field trajectories will evolve to a unique one
  2. the inflationary predictions each model results in are broadly generic for the class.

This results in a non-standard Lagrangian for the field

$$\mathcal{L} = \frac{-\frac{1}{2}(\partial\varphi)^2}{(1 - \frac{\varphi^2}{6\alpha\, m_P^2})^2} - V(\varphi)\,, \quad (2)$$

where φ is the non-canonical scalar field and we use the short-hand notation $(\partial\varphi)^2 \equiv g^{\mu\nu}\partial_\mu\varphi\,\partial_\nu\varphi$.

Lagrangian and Field Equations

We then redefine the non-canonical field in terms of the canonical scalar field ϕ as

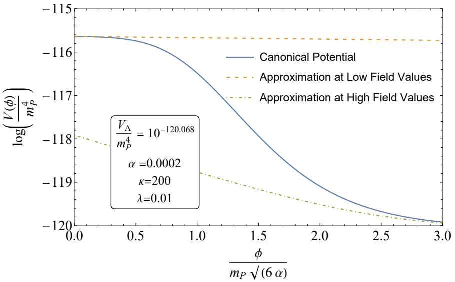
$$\mathrm{d}\phi = \frac{\mathrm{d}\varphi}{1 - \frac{\varphi^2}{6\alpha m_{\mathrm{P}}^2}} \quad \Rightarrow \quad \varphi = m_{\mathrm{P}}\sqrt{6\alpha}\,\tanh\left(\frac{\phi}{\sqrt{6\alpha}\,m_{\mathrm{P}}}\right). \tag{3}$$

The poles $\varphi = \pm\sqrt{6\alpha}$ are transposed to infinity, giving the Lagrangian of the canonical field the more typical form

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi). \tag{4}$$

It is necessary to specify the potential such that it produces the desired combination of behaviours...

Shape of Potential



The potential has the form

$$V(\varphi) = V_X \exp(-\lambda e^{\kappa\varphi/m_\mathrm{P}}),$$

with $$V_\Lambda \equiv \exp(-\lambda e^{\kappa\sqrt{6\alpha}}) V_X. \quad (5)$$

In terms of the canonical scalar field, the Lagrangian density is then given by Eq. (4), where the scalar potential is

$$V(\phi) = \exp(\lambda e^{\kappa\sqrt{6\alpha}}) \\ V_\Lambda \exp[-\lambda e^{\kappa\sqrt{6\alpha}\tanh(\phi/\sqrt{6\alpha}\, m_\mathrm{P})}]\,. \quad (6)$$

The potential is approximated at early times by

$$V_\mathrm{eq} \simeq \exp[\lambda(e^{\kappa\sqrt{6\alpha}} - 1)]\, V_\Lambda \exp(-\kappa\lambda\,\phi_\mathrm{eq}/m_\mathrm{P})\,, \quad (7)$$

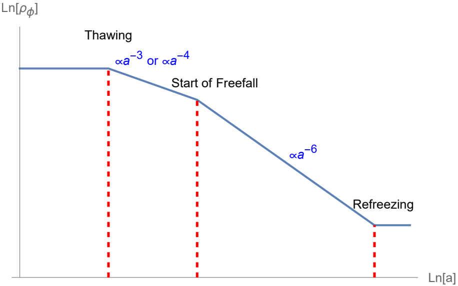
and at late times by

$$V_0 \simeq V_\Lambda \left[1 + 2\kappa\lambda e^{\kappa\sqrt{6\alpha}}\sqrt{6\alpha}\,\exp\left(-\frac{2\phi_0}{\sqrt{6\alpha}\,m_\mathrm{P}}\right)\right] \quad (8)$$

Expected Field Behaviour

Klein-Gordon equation of motion:

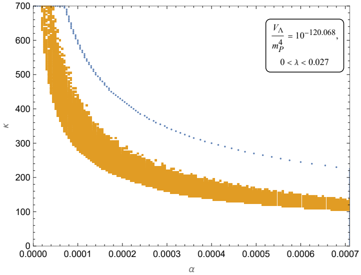
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0\,, \qquad (9)$$

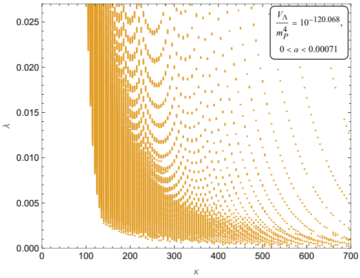


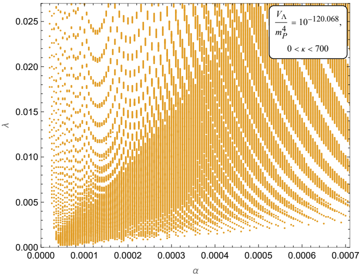
We solved the equations of motion with a matter+radiation background in Mathematica to find the subsequent field evolution numerically...

- The field should begin frozen and thaw around matter-radiation equality, peaking at roughly 10% of the overall energy density.
- It will then enter a period of kinetic domination (freefall) and redshift away as a^{-6}. (It can follow a scaling attractor for a short time before this)
- After this, it will refreeze at an energy density comparable to that of today, mimicking ΛCDM.
- The field will either grow to dominate while frozen or begin to thaw around the present day.

Parameter Space

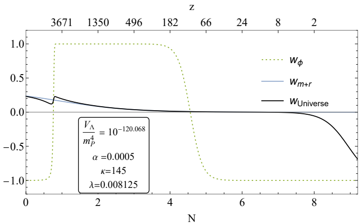


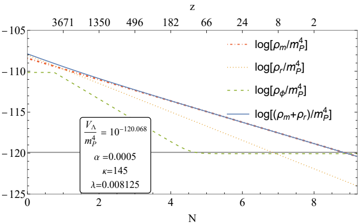


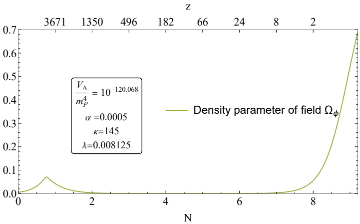


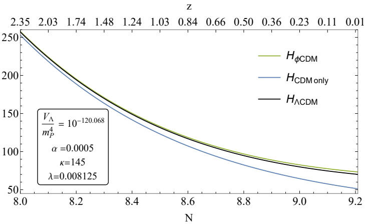
- $\kappa \sim 10^2$ and $\lambda \sim 10^{-3}$, which are rather reasonable values
- The redshift of matter-radiation equality occurs earlier than usual at $z_{\text{eq}} \simeq 4000$
- In contrast, the redshift of last scattering is where we would expect it at $z_{\text{ls}} \simeq 1087$.

Field Behaviour









Field Behaviour

Constraint	Field Value
$0.015 \leq \Omega_\phi^{\mathrm{eq}} < 0.107$	0.05178
$\Omega_\phi^{\mathrm{ls}} < 0.015$	0.001722
$\Omega_\phi^{\mathrm{eq}} > \Omega_\phi^{\mathrm{ls}}$	YES
$0.6833 \leq \Omega_\phi^0 \leq 0.6945$	0.6889
$-1 \leq w_\phi^0 \leq -0.95$	-1.000
$-0.55 \leq w_\phi^a \equiv -\left.\frac{\mathrm{d}w_\phi}{\mathrm{d}a}\right\rvert_0 \leq 0.03$	-4.850×10^{-11}
$72.00 \leq \frac{H_0}{\mathrm{km\ s^{-1}\ Mpc^{-1}}} \leq 74.08$	**73.27**
$\kappa\lambda$	1.178
$(\phi_0 - \phi_{\mathrm{eq}})/m_{\mathrm{P}} < 1$	0.4274

Table: Table giving the constraints and their corresponding values for an example point, $\alpha = 0.0005$, $\kappa = 145$, $\lambda = 0.008125$, and V_Λ tuned to the $\mathrm{SH_0ES}$ cosmological constant, in the viable parameter space. The Hubble constant obtained in this example is $H_0 = 73.27$ km/s Mpc.

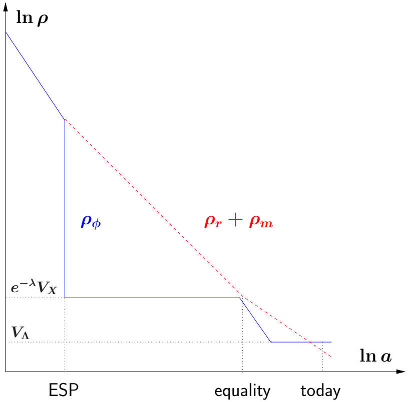
- Field fits the expected behaviour, generating a higher H_0 with the maximum allowed value of the EDE density parameter always below 0.1
- It is possible that this is too restrictive a constraint, because the constraint was developed for oscillating EDE [4] - in non-oscillating EDE, the field has a true free-fall period, redshifting away exactly as a^{-6} rather than just below this rate.

Summary and Conclusions

- This non-oscillatory model of unified early and late dark energy resolves the Hubble tension and explains dark energy today with the assumption of relatively natural values in the model parameters.
- The scalar field lies originally frozen at the origin, until it thaws near the time of equal matter-radiation densities, when it becomes EDE. Afterwards it free-falls until it refreezes at a lower potential energy density value, which provides the vacuum density of ΛCDM.
- The potential is engineered to be steep enough to induce free-fall.
- However, the model is a proof of concept. It demonstrates that any suitably steep runaway potential can produce a model unifying EDE with ΛCDM.

Extension - Quintessential Inflation with EDE

- The α-attractors construction leads to two flat regions in the scalar potential of the canonical fields.



- This has been used for quintessential inflation models, with the low-energy plateau responsible for quintessence and the high-energy plateau for inflation.
- Analytical estimates suggests that a shift in field space, along with a modification of the scalar potential such that it reduces to our potential near the earlier pole, can produce quintessential inflation.

$$V(\tilde{\varphi}) = V_X \exp\{-2\lambda \sinh[\kappa(\tilde{\varphi} - \Phi)/m_\mathrm{P}]\}\,, \tag{10}$$

- A mechanism is needed to ensure the field freezes. In the paper we suggest an interaction with a second field such that the inflaton becomes trapped at an ESP (enhanced symmetry point).

Thank you for listening

Any questions?

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