(Ultra-light) Cold Dark Matter and Dark Energy from $\alpha-$ attractors
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Coherent Oscillations of a Scalar Field

Action for a canonical scalar field minimally coupled to gravity

$$S[\varphi] = -\int d^4x\sqrt{-g}\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + V(\varphi)\right) \tag{1}$$

The equation of state (EOS) parameter is

$$w_\varphi = \frac{p_\varphi}{\rho_\varphi} = \frac{\frac{1}{2}\dot{\varphi}^2 - V(\varphi)}{\frac{1}{2}\dot{\varphi}^2 + V(\varphi)} \tag{2}$$

The equation of motion of the scalar field is given by

$$\ddot{\varphi} + 3\,H\dot{\varphi} + V'(\varphi) = 0. \tag{3}$$

For a scalar field coherently oscillating ($\dot{\varphi}/\varphi \gg H$) around $V(\varphi) \sim \varphi^{2p}$, the time average EOS is [Turner 1983]

$$\langle w_\varphi \rangle = \frac{p-1}{p+1} \tag{4}$$

Hence a scalar field oscillating around the minimum of any $V(\phi)$ having a φ^2 asymptote behaves like **Dark Matter (DM)**.

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- Emphasizing and removing enormous fine-tuning of initial conditions faced by the $m^2\varphi^2$ potential.
- α-attractors, originally proposed by [(Kallosh and Linde, 2013a, 2013b)] in the context of cosmic inflation, can have wider appeal in describing DM [**Mishra, Sahni and Shtanov, JCAP 2017 [arXiv:1703.03295]**] (and even DE **Bag, Mishra and Sahni 2017 [arXiv:1709.09193]** submitted).

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$$V(\varphi) = \frac{1}{2} m^2 \varphi^2 \,,$$

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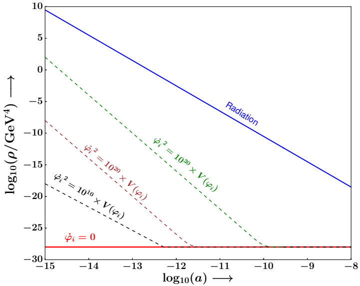
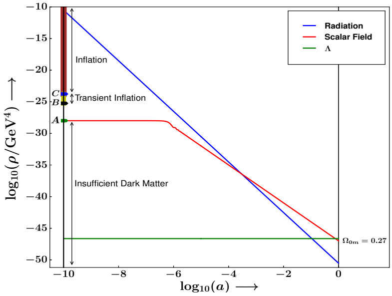
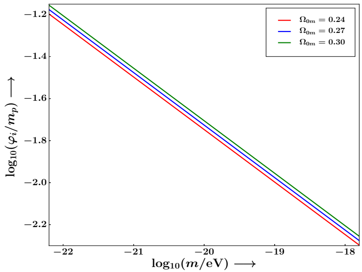
The scalar field equation of motion is $\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0$. During the radiation dominated epoch $\longrightarrow \varphi$ is frozen due to overdamping (like a cosmological constant until the Hubble parameter $H \geq m$)



Fine-tuning problem associated with $V(\varphi) = \frac{1}{2}m^2\varphi^2$





Only a particular given value of φ_i yields $\Omega_{0m} = 0.27$ at the present epoch. These results support the earlier findings of [Zlatev and Steinhardt 1999].

$$\varphi_i = (0.06\ m_p) \times \left(\frac{m}{10^{-22}\ eV}\right)^{-1/4}$$

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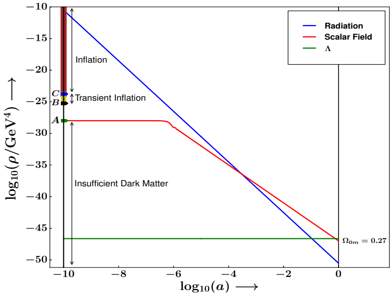

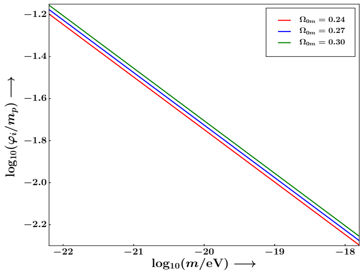

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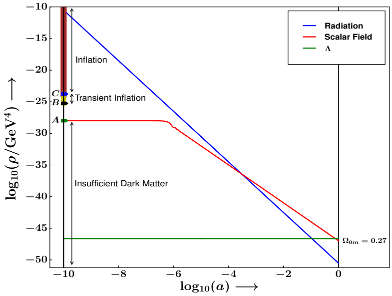

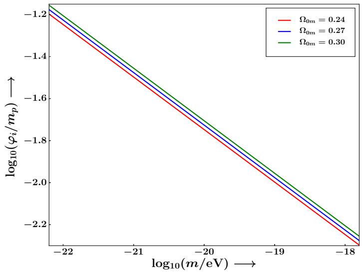

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The general form of α-attractor potentials can be written as [Kallosh and Linde 2013b]

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$$V(\varphi) = V_0\left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\varphi}{m_p}}\right)^2 . \quad (6)$$

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2. The tracker-potential [Sahni and Wang, 2000]

$$V(\varphi) = V_0 \sinh^2 \sqrt{\frac{2}{3\alpha}} \frac{\varphi}{m_p} . \tag{7}$$

Dark Matter from the *E-Model*

E-Model potential is $V(\varphi) = V_0 \left(1 - e^{-\lambda \frac{\varphi}{m_p}}\right)^2$, which closely resembles the Starobinsky model for inflation [Starobinsky, 1980] (For dark matter, the steep wing with $V \sim e^{2\lambda \frac{|\varphi|}{m_p}}$ is more useful).

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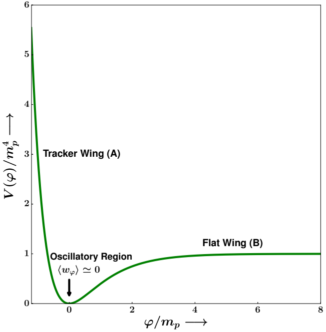

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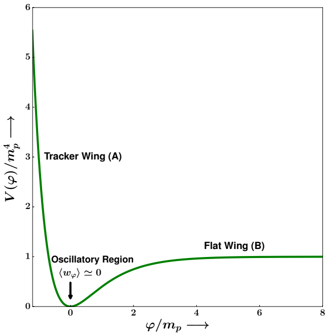

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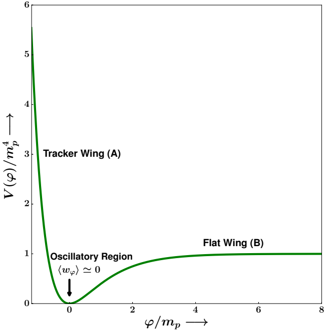

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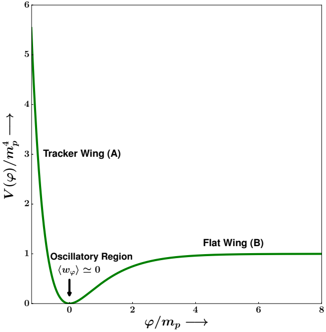

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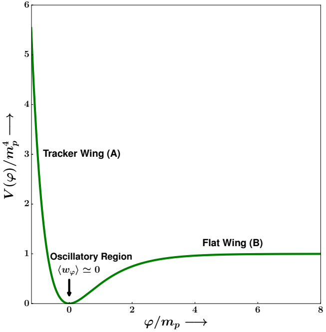
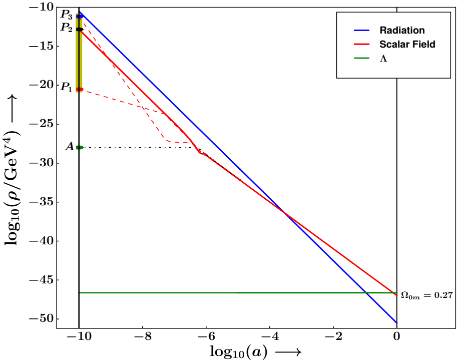


where $m^2 = \frac{2V_0\lambda^2}{m_p^2}$, $\lambda = \sqrt{\frac{2}{3\alpha}}$
and the Scaling solution obeys

$$\Omega_\varphi = \frac{3(1+w_B)}{\lambda^2} = \frac{4}{\lambda^2}, \quad w_\varphi = w_B = \frac{1}{3}$$

Attractor Behaviour the *E-Model*

For $m = 10^{-22}$ eV, $\lambda = 14.5$ ($\alpha = 3.2 \times 10^{-3}$),
$V_0 = 1.37 \times 10^{-28}$ GeV^4, $z_{osc} \simeq 2.8 \times 10^6$
Initial ρ_φ values spanning over more than 85 orders of magnitude converge on to the attractor solution.



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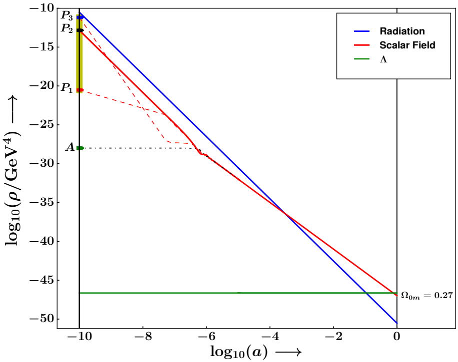

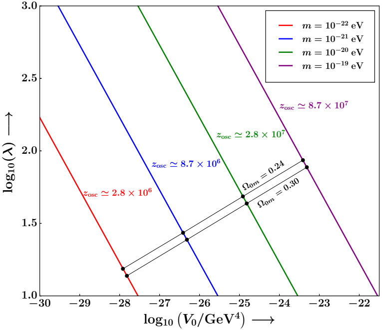

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$$k_J^2 = \sqrt{2\rho}\,\frac{m}{m_p} \ . \tag{11}$$

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2. For the tracker-potential (7), which has the asymptote $V(\varphi) \sim \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4}\varphi^4$, the Jeans scale is given by [Johnson and Kamionkowski 2008]

$$k_J^2 = -\frac{3}{2}\lambda^2\rho + \left[\left(\frac{3}{2}\lambda^2\rho\right)^2 + \rho\frac{m^2}{m_p^2}\right]^{1/2}\ , \tag{12}$$

where $m^2 = \frac{2V_0\lambda^2}{m_p^2}$.

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1. For small oscillations around the minimum of the asymmetric *E-Model* potential which has the asymptote $V(\varphi) \sim \frac{1}{2}m^2\varphi^2 - \frac{1}{3}\mu\varphi^3 + \frac{\lambda}{4}\varphi^4$, the Jeans scale is given by [**Mishra, Sahni and Shtanov JCAP 2017**]

$$k_J^2 = \left(\frac{5}{3}\frac{\mu^2\rho}{m^4} - \frac{9}{4}\frac{\lambda_0\rho}{m^2}\right) + \left[\frac{2m^2}{m_p^2}\rho + \left(\frac{25}{9}\frac{\mu^4}{m^8} + \frac{81}{16}\frac{{\lambda_0}^2}{m^4} - \frac{15}{2}\frac{\lambda_0\mu^2}{m^6}\right)\rho^2\right]^{\frac{1}{2}}$$

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The figure below shows that k_J^2 in all three models converge to that of the $\frac{1}{2}m^2\varphi^2$ model at late enough times (i.e by $z \sim 10^3$).

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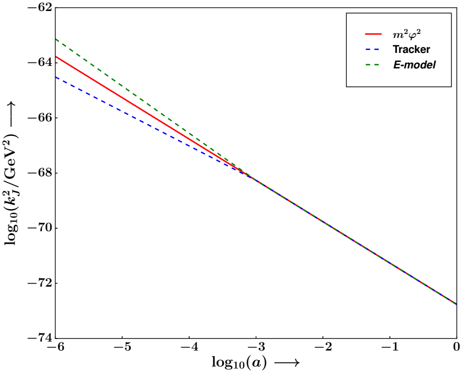
We notice that the differences between the value of k_J^2 in all three models decrease rapidly and they all converge to that of the $\frac{1}{2}m^2\varphi^2$ model at late enough times (i.e by $z \sim 10^3$).



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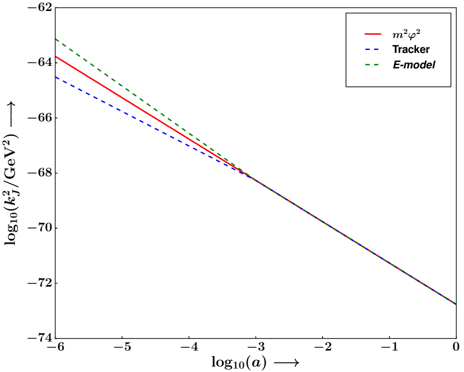

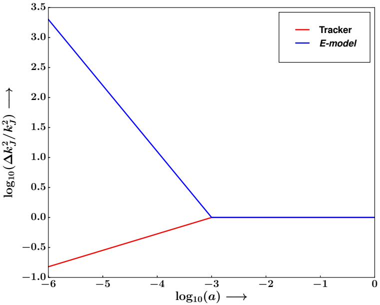

Discussion and further plans

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- Observational Signatures - Matter power spectrum, Pulsar Timing Array, Gravitational Waves (Future Work), CMB and BAO phases.

$$\textbf{Strain} \quad h_c = 2 \times 10^{-16} \left(\frac{10^{-22}\ eV}{m} \right)^2 ,$$

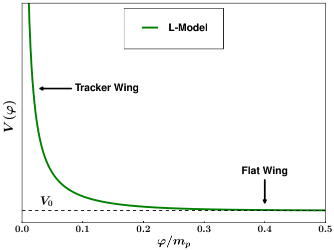
$$\textbf{Frequency} \quad f_c = 50 \times 10^{-9} \left(\frac{m}{10^{-22}\ eV} \right) \ \mathrm{Hz}$$

Important References

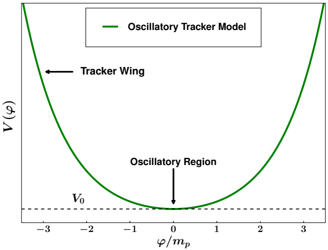
1. "Cold and fuzzy dark matter", W. Hu, R. Barkana and A. Gruzinov, Phys. Rev. Lett. 85 (2000) 1158 [astro-ph/0003365].
2. "Ultralight scalars as cosmological dark matter", L. Hui, Ostriker, S. Tremaine and Ed. Witten, Phys. Rev. D 95 (2017) 043541 [arXiv:1610.08297].
3. "Sourcing DM and DE from α-attractors", S.S Mishra, V. Sahni and Y. Shtanov, JCAP 1706 (2017) no.06, 045 [arXiv:1703.03295]
4. "Axion Cosmology", DJE Marsh, Phys.Rept. 643 (2016) 1-79 [arXiv:1510.07633].

Dark Energy from α-attractors

In addition to the dark matter models alluded to above, we have also discovered 4 new Tracker Models of Dark Energy (**Bag, Mishra and Sahni 2017 [arXiv:1709.09193]** submitted) and explored the possibility that these models give rise to an equation of state close to -1 at the present epoch, as demanded by observations.

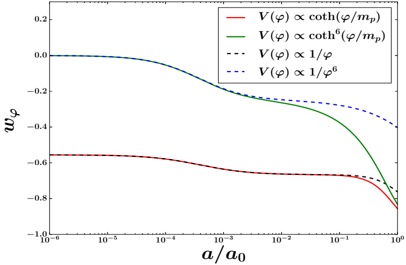


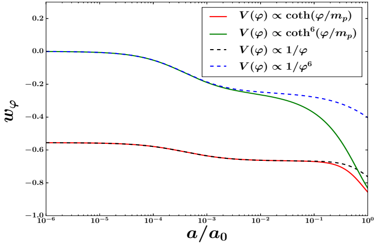
(a)



(b)

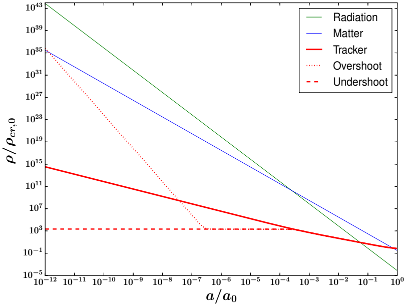
Dark Energy from the L-Model



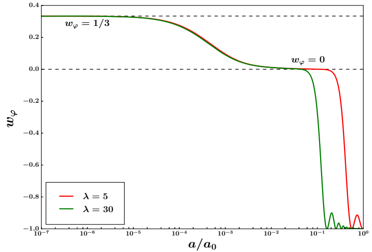


$V(\varphi) = V_0 \coth^p\left(\frac{\varphi}{m_p}\right)$, which for small values of the argument, $0 < \frac{\lambda\varphi}{m_p} \ll 1$, becomes Inverse Power-law (Ratra-Peebles) potential $V \simeq \frac{V_0}{(\lambda\varphi/m_p)^p}$ which has an attractor solution

$$w_\varphi = \frac{pw_B - 2}{p + 2}$$

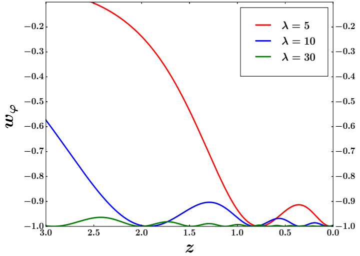


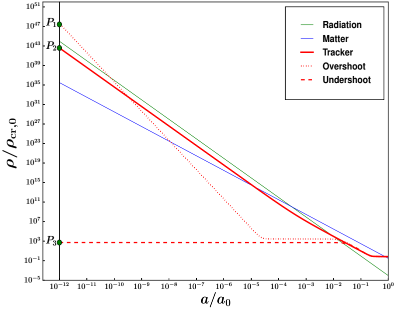
Dark Energy from the OLT-Model



$V(\varphi) = V_0 \cosh\left(\lambda \frac{\varphi}{m_p}\right)$, for large values $\frac{\lambda|\varphi|}{m_p} \gg 1$, has the asymptotic form $V \simeq \frac{V_0}{2} \exp\left(\frac{\lambda\varphi}{m_p}\right)$ which has an attractor scaling solution

$$\Omega_\varphi = \frac{3(1+w_{\rm B})}{\lambda^2}, \quad w_\varphi = w_{\rm B}$$





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Other Project I am involved in $\longrightarrow$ Investigation of initial conditions for inflation for relevant Inflationary Potentials, with particular emphasis on the difference between Power-law Potentials and Asymptotically Flat Potentials.

"Initial Conditions for Inflation in an FRW Universe", S.S Mishra, V. Sahni and A.V. Toporensky, [arXiv:1801.04948].