Cosmological solutions from multi-measure model

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Contents

Recall the darkon-case

The equations in the darkon case are ([1, 2, 3]):

A cubic equation for $y = \dot{u}$:

$y^3 + 3\mathbf{a}y + 2\mathbf{b} = 0$ with $\mathbf{a} = -\frac{2}{3-24\alpha M_0}$ and $\mathbf{b} = -\frac{2\alpha p_u}{a(t)^3(1-8\alpha M_0)}$.

And **the Friedman equation for** $a(t)$ – after rescaling time by $2|\alpha|/3 = 1$ and absorbing α into Hubble constant ($\bar{\rho} = 4|\alpha|\rho$):

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \bar{\rho} = \left(\frac{1}{2}y^2 + \frac{\mathbf{b}}{\mathbf{a}}y - 1\right) \tag{1}$$

The asymptotics, corresponding to the dark energy term in the late universe, is:

$$\bar{\rho} \xrightarrow[a(t)\to\infty]{} \begin{cases} 1 \ \text{ for } \ \mathbf{a} > 0 \\ -\frac{3}{2}\mathbf{a} - 1 \ \text{ for } \ \mathbf{a} < 0 \end{cases}$$

We use as independent real solutions y_b (our basic solution) and y_s and integrate numerically Eq. (1) to find the evolution of the universe.

Staicova & Stoilov, Mod. Phys. Lett. A, **32**, 1 (2017)

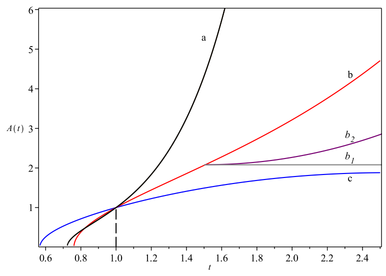
Staicova & Stoilov, arXiv:1801.07133

Universes with or without phase transition

Let $\bar{\bar{\rho}}$ the density corresponding to solution y_s ($\bar{\rho}$ corresponds to y_b).
If for $t_1 = 0$, $\bar{\bar{\rho}}(t_1) < 0$ but for $t_p > t_1$, it changes sign: $\bar{\bar{\rho}}(a(t_p)) = 0$.
Then, for any moment $t > t_p$ we have two "states" of the Universe $\bar{\rho}$ and $\bar{\bar{\rho}}$ such as:

$$0 \leq \bar{\bar{\rho}} < \bar{\rho} \ \text{for} \ \ t \geq t_p. \qquad (2)$$

This opens the possibility the Universe to undergo *"phase transition"*.



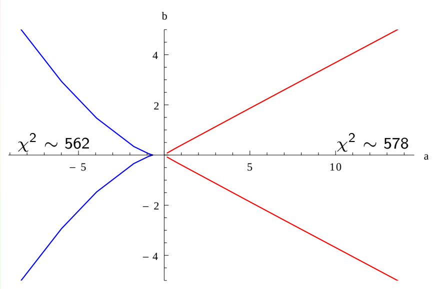


Figure: Left:Graphics of the $a(t)$ evolution for: $\mathbf{a} = -5.987, \mathbf{b} = \frac{-2.932}{a^3}$ (a) $\mathbf{a} = -1, \mathbf{b} = -\frac{2}{a^3}$ (b), $t_p = 1.5074$, $a_s(t_p) = 2.0825$ (b_2), $\mathbf{a} = -.5, \mathbf{b} = -\frac{0.5}{a^3}$ (c),
Right: $b_\pm = \sum_0^4 \pm c_i a^i + O(a^5)$, $c_i = [0.337906, 0.376679, -0.0251697, 0.00148545, 0.11272710^{-3}]$

The multi-measures model Guendelman, Nissimov and Pacheva 2014, 2016

The action of the model $S = S_{darkon} + S_{inflaton}$ is :

$$S_{darkon} = \int d^4x\sqrt{-g}(R(g,\Gamma)) + \int d^4x(\sqrt{-g} + \Phi(C))L(u,Y)$$

$$S_{inflaton} = \int d^4x\Phi_1(A)(R + L^{(1)}) + \int d^4x\Phi_2(B)\left(L^{(2)} + \frac{\Phi(H)}{\sqrt{-g}}\right)$$

where we have auxiliary fields $\Phi_i(X) = \frac{1}{3}\epsilon^{\mu\nu\kappa\lambda}\partial_\mu X_{\nu\kappa\lambda}$ and

$$L(u,X) = -\frac{1}{2}g^{\mu\nu}\partial_\mu u\partial_\nu u - W(u)$$

$$L^{(1)} = -\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi),\ V(\phi) = f_1 e^{-\alpha\phi}$$

$$L^{(2)} = -\frac{b}{2}e^{-\alpha\phi}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + U(\phi),\ U(\phi) = f_2 e^{-2\alpha\phi}$$

From **the equations of motion** we obtain the following new constants:

$$L(u,Y) = -2M_0 = const, \frac{\Phi_2(B)}{\sqrt{-g}} = \chi_2 = const$$

$$R + L^{(1)} = -M_1 = const, L^{(2)} + \frac{\Phi(H)}{\sqrt{-g}} = -M_2 = const$$

and **the effective potential**:

$$U_{eff}(\phi) = \frac{1}{4}\frac{(f_1 e^{-\alpha\phi} + M_1)^2}{\chi_2(f_2 e^{-2\alpha\phi} + M_2) - 2M_0} \text{ with asymptotics } U_- = \frac{f_1^2}{4\chi_2 f_2}, U_+ = \frac{1}{4}\frac{M_1^2}{\chi_2 M_2 - 2M_0}$$

The equations in FLRW metric

The system of equations we need to solve is:

$$v^3 + 3\mathbf{a}v + 2\mathbf{b} = 0 \text{ for } \mathbf{a} = \frac{-1}{3}\frac{V(\phi) + M_1 - \frac{1}{2}\chi_2 b e^{-\alpha\phi}\dot{\phi}^2}{\chi_2(U(\phi) + M_2) - 2M_0}, \mathbf{b} = \frac{-p_u}{2a(t)^3(\chi_2(U(\phi) + M_2) - 2M_0)} \quad (3)$$

$$\dot{a}(t) = \sqrt{\frac{\rho}{6}}a(t), \quad \rho = \frac{1}{2}\dot{\phi}^2(1 + \frac{3}{4}\chi_2 b e^{-\alpha\phi}v^2) + \frac{v^2}{4}(V + M_1) + \frac{3p_u v}{4a(t)^3} \quad (4)$$

$$\frac{d}{dt}\left(a(t)^3\dot{\phi}(1 + \frac{\chi_2}{2}be^{-\alpha\phi}v^2)\right) + a(t)^3(\alpha\frac{\dot{\phi}^2}{4}\chi_2 b e^{-\alpha\phi}v^2 + \frac{1}{2}V_\phi v^2 - \chi_2 U_\phi\frac{v^4}{4}) = 0 \quad (5)$$

The parameters of this system are 12:

$$\{\alpha, b_0, M_0, M_1, M_2, f_1, f_2, p_u, \chi_2\}$$

Initial and boundary conditions:

$I.\ a(0) = 10^{-12}, \phi(0) = \phi_0, \dot{\phi}(0) = 0$ – initial conditions

$II.\ a(1) = 1$ – normalization

$III.\ a''(t) = 0$ – in 3 points

Constraints on the parameters:

$$\frac{f_1^2}{\chi_2 f_2}, >> \frac{M_1^2}{\chi_2 M_2 - 2M_0} \quad (6)$$

From [1, 2]: $|M_1| \sim M_{EW}^4, M_2 \sim M_{Pl}^4, f_1 \sim f_2 \sim 10^{-8}M_{Pl}^4$

Asymptotics

Limits for the equation of state (EOS) $w = p/\rho$:

$$\begin{aligned} w &\xrightarrow[a(t)=0]{} 1/3 \\ w &\xrightarrow[a(t)\to\infty]{} -1 \end{aligned} \tag{7}$$

Due to a strong friction term, in the far future ($a(t) \to \infty$, $\dot{\phi}(t) \to 0$):

$$\begin{aligned} \rho &\to 0 \ \text{ for } \ \mathbf{a} > 0 \\ \rho &\to \frac{1}{4} \frac{(V(\phi) + M_1)^2}{\chi_2 (U(\phi) + M_2) - 2M_0} \ \text{ for } \ \mathbf{a} < 0 \end{aligned} \tag{8}$$

where $\mathbf{b} \xrightarrow[a(t)\to\infty]{} 0$ and $v \to 0$ for $\mathbf{a} > 0$ and $v \to \sqrt{-3\mathbf{a}}$ for $\mathbf{a} < 0$.

The dynamically generated cosmological constant for $\mathbf{a} < 0$

$$\Lambda_{eff} = M_1^2 / (8(\chi_2 M_2 - 2M_0)). \tag{9}$$

Considerations for the parameters

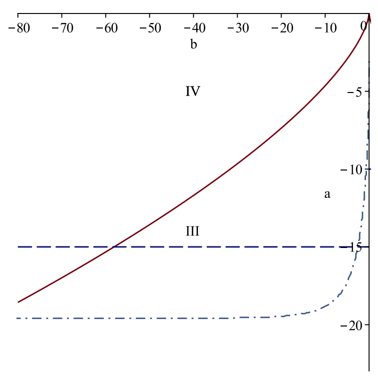
1. $c = 1$, $G = 1/16\pi$ and $t_u = 1$, where t_u is the present day age of Universe. Thus, our mass unit is equal to $1.62 \times 10^{59} M_{Pl}$ where M_{Pl} is Plank mass.
2. The only limit on the parameters is $\frac{f_1^2}{\chi_2 f_2} >> \frac{M_1^2}{\chi_2 M_2 - 2M_0}$
3. $M_0 < 0$, so that $\mathbf{b} < 0$ and y is real
4. $\dot{\phi}(0) = 0$
5. $b_0 > 0$ (problems with ρ otherwise)

Giving us the following cases:

- Case 1: $\chi_2 \sim 1, \;\; M_0 \sim -0.04, \;\; 0 < M_2 << |M_0|$.
  For these parameters, using the value of the cosmological constant (≈ 3.6 in our units) one can easily obtain:
  $$M_1 \sim 1.5. \tag{10}$$
- Case 2: $\chi_2 << 1, \;\; M_0 \sim -0.01, \;\; M_2 = 4 \;\; (\gg |M_0|)$.
  For these parameters the relation between χ_2 and M_1 becomes:
  $$M_1 = 0.24\sqrt{2000\chi_2 + 10} \;\; \sim 0.76 \tag{11}$$

The evolution of the Universe in the $[a, b]$ plane

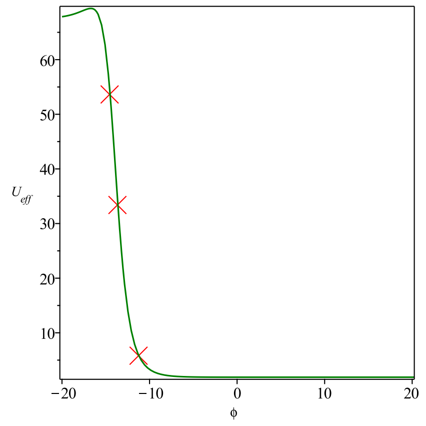
Staicova & Stoilov, Mod. Phys. Lett. A, **32**, 1 (2017)
Staicova & Stoilov, arXiv:1801.07133



Evolution of the parameters $[\mathbf{a}(t), \mathbf{b}(t)]$ for the darkon (dash) and the inflaton (dot-dash).

The evolution of the Universe starts from $b \to -\infty$ and finishes at $b \to 0$
We have chosen the parameters in such a way that: $b = \frac{-p_u}{2a(t)^3(\chi_2(U+M_2)-2M_0)} < 0$. I.e $M_0 < 0$.

Numerical solutions



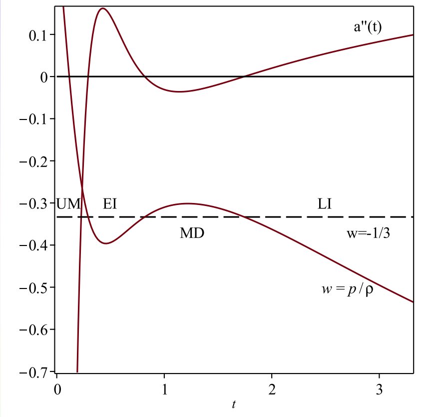
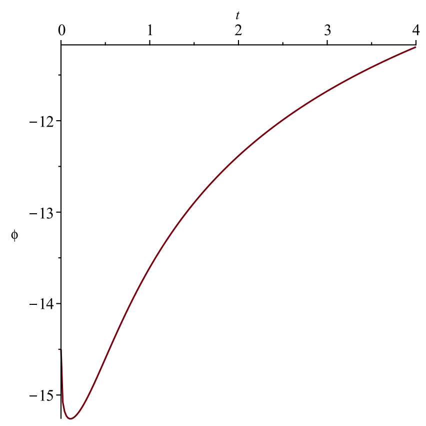
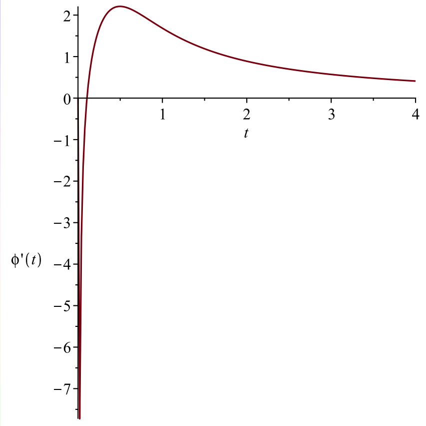


Figure: a) The effective potential.
b) $\ddot{a}(t)$ and $w = p/\rho$, where UM is ultra-relativistic matter domination , EI – the early inflation, MD – the matter domination (MD) and LI – the late inflation.

Strong friction term on ϕ!



(a) $\phi(t)$



(b) $\dot{\phi}(t)$

From asymptotical analysis: assuming $a(t) = e^{Ht}$, we obtain:

$$\phi(t) = C_1 + C_2 e^{-3Ht}$$

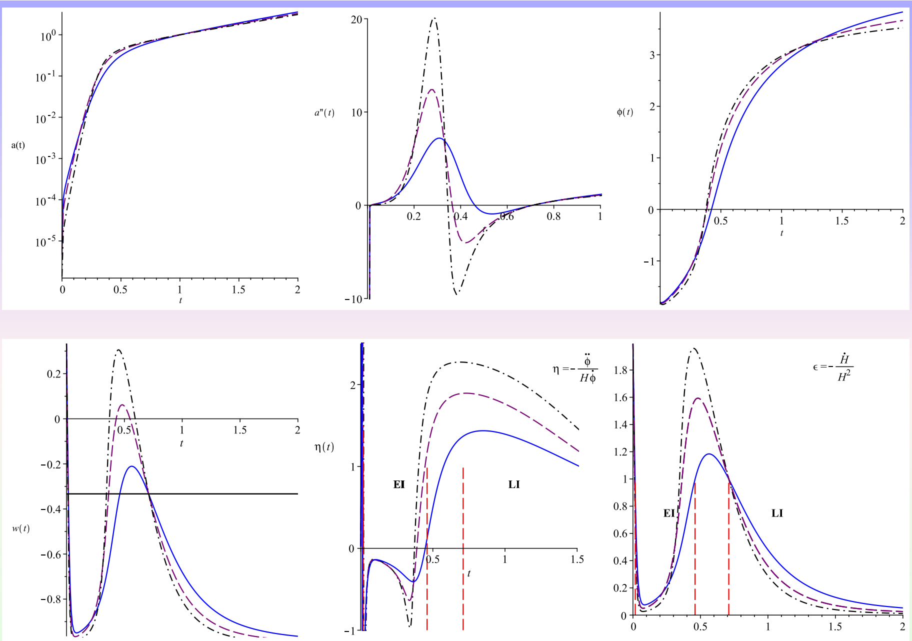


Figure: The Universe evolution in case 1 ($\chi_2 = 1,\ M_0 = -0.04,\ M_1 = 1.5,\ M_2 = 0.001$). The parameters $\{\alpha, b_0, p_u, f_1, f_2\}$ are $\{1, 0.027, 7.7 \times 10^{-9}, 7, 10^{-3}\}$ (solid lines), $\{1.2, 0.021, 1.1 \times 10^{-10}, 6.76, 10^{-3}\}$ (dashed lines) and $\{1.4, 0.016, 3 \times 10^{-12}, 6.35, 10^{-3}\}$ (dot-dashed lines).

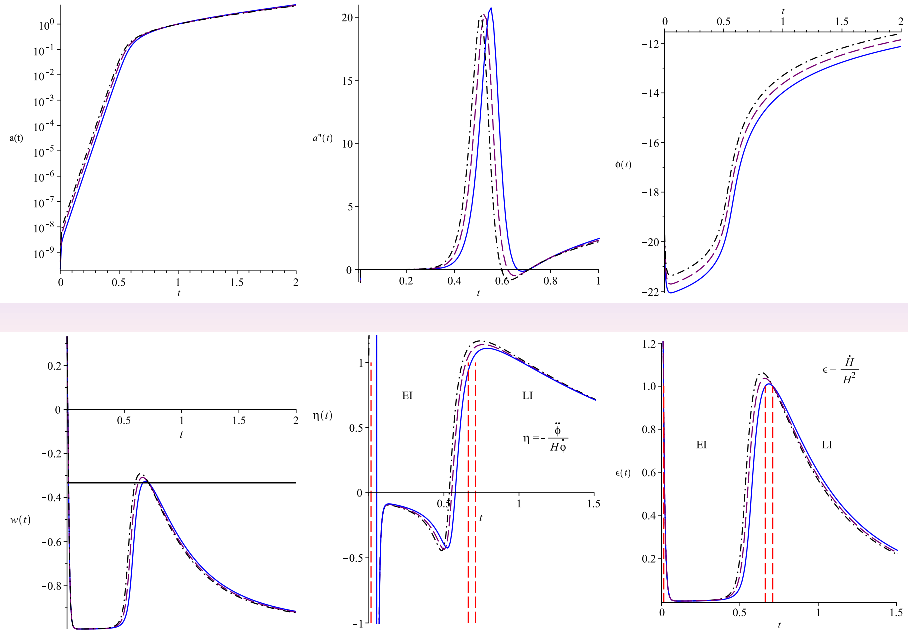


Figure: The Universe evolution in case 2 ($\chi_2 = 4 \times 10^{-5}$, $M_0 = -0.01$, $M_1 = 0.763$, $M_2 = 4$). The parameters $\{\alpha, b_0, p_u, f_1, f_2\}$ are $\{0.64,\ 1.41 \times 10^{-7},\ 6.5 \times 10^{-24}, 10^{-4}, 10^{-8}\}$ (solid lines), $\{0.65, 7.6 \times 10^{-7},\ 5.5 \times 10^{-23}, 10^{-4}, 10^{-8}\}$ (dashed lines), and $\{0.66,\ 2.66 \times 10^{-6},\ 2.4 \times 10^{-22}, 10^{-4}, 10^{-8}\}$ (dot-dashed lines).

Main results (Staicova & Stoilov, arXiv:1806.08199)

A. One can construct a 4-stages Universe

1. At $t_0 = 0$ we observe the EOS of ultra-relativistic matter with $w = 1/3$.
2. Initial inflation with EOS of dark energy $w \to -1$.
3. Matter domination stage where $w > -1/3$ and $w \to 0$.
4. Accelerated expansion with $w < -1/3$.

B. The model can be normalized to $a(1) = 1, t(MD \to LI) = 0.71$ and the effective cosmological constant

C. There is a strong friction term which stops the evolution of ϕ after certain moment.

D. There is an effect of "climbing-up" the potential

E. The slow-roll parameters in the periods of inflation ($[0.017 - 0.460, 0.71 - 1]$ in Case 1 and $[0.015 - 0.662, 0.71 - 1]$) don't seems to satisfy the slow-roll conditions:

$$\epsilon = -\frac{\dot{H}}{H^2} << 1, \quad \eta = -\frac{\ddot{\phi}}{H\dot{\phi}} << 1. \tag{12}$$

Let's return to the effective potential

If one starts with inflaton equations of the type:

$$H^2 = 8\frac{\pi}{3m_{pl}^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right) \tag{13}$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0 \tag{14}$$

Then the slow-roll parameters are defined as:
1) $\ddot{\phi}(t) << 3H\dot{\phi} \rightarrow \eta = -\frac{\ddot{\phi}}{H\dot{\phi}}$
2) $\frac{\ddot{a}(t)}{a(t)} = \dot{H} + H^2 = H^2(1-\epsilon) \rightarrow \epsilon = -\frac{\dot{H}}{H^2}$

If we write the **inflaton equation** in the form:

$$\left(v(t)^2 A(t)+1\right)\ddot{\phi}(t) - \frac{1}{2}v(t)^2\alpha A(t)\dot{\phi}(t)^2 + \left(3v(t)^2 A(t)H + 2v(t)A(t)\dot{v}(t) + 3H\right)\dot{\phi}(t) - \frac{v(t)^2 f_1\alpha}{2e^{\alpha\phi(t)}} + \frac{\chi_2 f_2\alpha v(t)^4}{2e^{2\alpha\phi(t))}} = 0, \tag{15}$$

where $A(t) = \frac{b_0\chi_2}{2e^{\alpha\phi(t)}}$.
If one uses the slow-roll approximation (neglecting the terms $\sim\ \dot{\phi}^2,\ \ \dot{\phi}^3,\ \ \dot{\phi}^4$ and $A(t)$), Eq. (15) simplifies to:

$$\ddot{\phi} + 3H\dot{\phi} + W(\phi) = 0. \tag{16}$$

where $W(\phi) = -\frac{v(t)^2 f_1\alpha}{2e^{\alpha\phi(t)}} + \frac{\chi_2 f_2\alpha v(t)^4}{2e^{2\alpha\phi(t))}}$, i.e. $W(\phi) \neq U'_{eff}$, for $U_{eff}(\phi) = \frac{1}{4}\frac{(f_1 e^{-\alpha\phi}+M_1)^2}{\chi_2(f_2 e^{-2\alpha\phi}+M_2)-2M_0}$.

Then we get the following 2 cases

Case 1: $v(t)^2 A(t) >> 1$:

$$\ddot{\phi} - \frac{1}{2}\alpha\dot{\phi}^2 + \left(3H + 2\frac{\dot{v}}{v}\right)\dot{\phi} - \frac{\alpha e^{-\alpha\phi}}{2A(t)}\left(f_1 - \chi_2 f_2 v^2 e^{-\alpha\phi)}\right) = 0. \qquad (17)$$

Case 2: $v(t)^2 A(t) << 1$:

$$\ddot{\phi} + 3H\dot{\phi} - \frac{v^2\alpha e^{-\alpha\phi}}{2}\left(f_1 - \chi_2 f_2 v^2 e^{-\alpha\phi)}\right) = 0. \qquad (18)$$

Using the asymptotic values of $v(t)$ for $p_u \to 0$:

$$v_p = \sqrt{\frac{f_1 e^{-\alpha\phi} + M_1 - \frac{1}{2}\chi_2 b_0 e^{-\alpha\phi}\dot{\phi}^2}{\chi_2(f_2 e^{-2\alpha\phi} + M_2) - 2M_0}}. \qquad (19)$$

If $v_{pb} = v_p(b_0 \to 0)$, the connection with the effective potential becomes clear: $v_{pb}^2 = \frac{4U_{eff}}{f_1 e^{-\alpha\phi} + M_1}$.

The derivative of the effective potential with respect to ϕ written in terms of the effective potential and the velocity v_{pb} becomes:

$$U'_{eff} = -\frac{2U_{eff}\alpha e^{-\alpha\phi}}{f_1 e^{-\alpha\phi}+M_1}\left(f_1 - \frac{4U_{eff}\chi_2 f_2 e^{-\alpha\phi}}{f_1 e^{-\alpha\phi}+M_1})\right) \approx$$
$$\approx -\frac{v_{pb}^2}{2}\alpha e^{-\alpha\phi}\left(f_1 - v_{pb}^2 f_2 \chi_2 e^{-\alpha\phi}\right). \quad (20)$$

Then, in the limit $v \to v_{pb}$, the equations reduce to:
Case 1:

$$\ddot{\phi} + \frac{1}{2}\left(\frac{U'_{eff}}{U_{eff}} + \frac{\alpha e^{-2\alpha\phi}\chi_2 f_2 v_{pb}^4}{2U_{eff}} - \alpha\right)\dot{\phi}^2 + 3H\dot{\phi} + \frac{1}{v_{pb}^2 A(t)}U'_{eff} = 0. \quad (21)$$

Case 2:

$$\ddot{\phi} + 3H\dot{\phi} + U'_{eff} = 0. \quad (22)$$

One can see that in Case 2, we are able to approximate with the standard equation, in Case 1 – no.

Numerical analysis

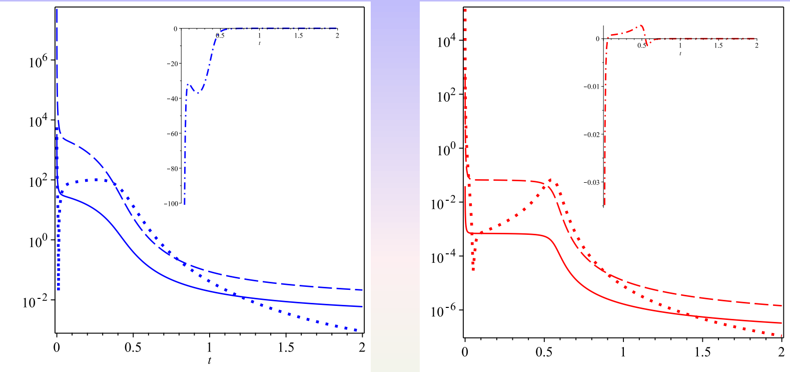


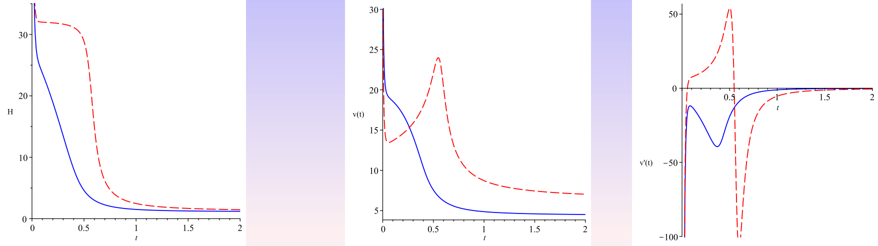
Figure: Left – Case 1 ($\chi_2 = 1,\ M_0 = -0.04,\ M_1 = 1.5,\ M_2 = 0.001$) for parameters $\{\alpha, b_0, p_u, f_1, f_2\} = \{1, 0.027, 7.7 \times 10^{-9}, 7, 10^{-3}\}$. Right – Case 2 in case 2 ($\chi_2 = 4 \times 10^{-5},\ M_0 = -0.01,\ M_1 = 0.763,\ M_2 = 4$). for parameters $\{\alpha, b_0, p_u, f_1, f_2\} = \{0.64,\ 1.41 \times 10^{-7},\ 6.5 \times 10^{-24}, 10^{-4}, 10^{-8}\}$. On the plots, one can see T_1 (solid lines), T_2 (dotted lines), T_3 (dash lines), T_4 (dash-dot lines).

$$T_1 = v(t)^2 b_0 \chi_2 e^{-\alpha\phi(t)}/2 = v(t)^2 A(t),\ T_2 = v(t)^2 b_0 \dot{\phi}(t)^2 \alpha \chi_2 e^{-\alpha\phi(t)}/4, \quad (23)$$

$$T_3 = 3v(t)^2 b_0 \chi_2 H e^{-\alpha\phi(t)},\ T_4 = v(t) b_0 \chi_2 \dot{v}(t) e^{-\alpha\phi(t)}, \quad (24)$$

$$T_5 = -v(t)^2 f_1 \alpha e^{-\alpha\phi(t)}/2 + \chi_2 f_2 \alpha v(t)^4 e^{-2\alpha\phi(t)}/2, \quad (25)$$

Evolution of some physical parameters in the two cases



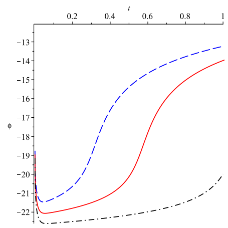
(a) (b) (c)

Figure: With solid lines (Case 1) and dashed (Case 2), we display the Hubble parameter H, the darkon field $v(t)$ and its first derivative $\dot{v}(t)$.

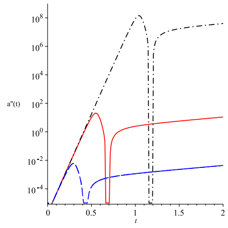
The H-term dominates Case 2 but does not dominate Case 1 until late times.

As expected $\dot{v} \to 0$ during late-time inflation, however, in the early times, terms depending on v and $\dot{v}$ cannot be ignored.

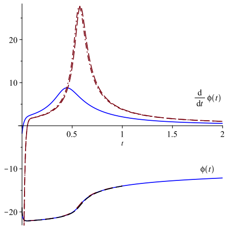
Stability of the solution with respect to ϕ_0



(a)



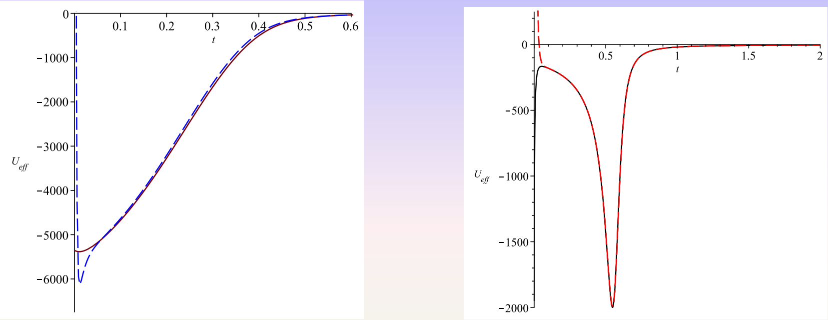
(b)



(c)

Figure: Using the parameters for Case 2, we plot a) the inflaton ϕ and b) the second derivative of the scale factor $\ddot{a}(t)$ for $\phi(0) = -17.9$ (dashed line), $\phi(0) = -18$ (solid line), $\phi(0) = -18.1$ (dot-dashed line). c) the dependence$\phi(t)$ and $\dot{\phi}(t)$ for $\dot{\phi}(0) = 0, \pm 10^4$ where the solid line corresponds to zero initial velocity.

Comparison of U'_{eff} and T_5



(a) (b)

Figure: Comparison of the term T_5 (dash) with the derivative of the effective potential U'_{eff} (solid) in the two cases. Note, here the x-axis for Case 1 stops before $t = 2$ in order to zoom on the interval in t where the difference is the most significant

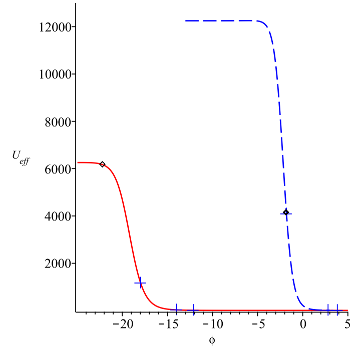
Numerical integration

In summary we observe that:

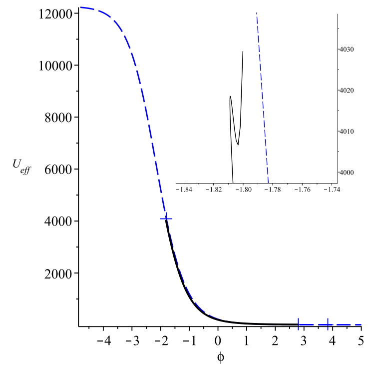
1. Independent of the value of $\phi(0)$, there is a period for which ϕ increases in absolute value – i.e. it climbs up the slope of the effective potential
2. This effect becomes more pronounced the more we increase in absolute value $\phi(0)$
3. The effect does not depend on $\dot{\phi}(0)$. That is to say that this effect is not connected with the inflaton gaining kinetic energy so that it can climb the slope.
4. The time during which this happens puts it in the interval when the effective potential is not a good approximation of the potential term.

The effective potential might not be a good approximation!

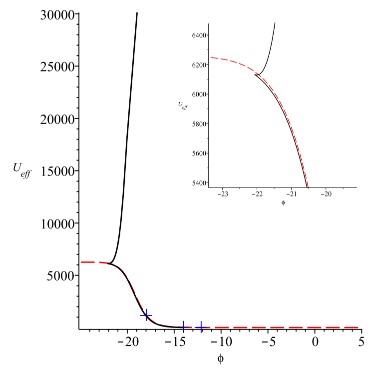
- We reconstruct the effective potential U_{eff}^{num} from T_5 trough the means of numerical integration. I.e. we assume that $U_{eff}^{num} \sim \int T_5(\phi) d\phi$.
- We use numerical integration of the data points $[\phi(t_i), T_5(t_i)]$ with a modified Simpson's rule adapted to work in Maple with 1000 datapoints.
- The constant of integration has been determined by comparing the numerical potential and the effective one at late times.



12000
10000
8000
6000
4000
2000
U_{eff}
−20 −15 −10 −5 0 5
ϕ



12000
10000
8000
6000
4000
2000
U_{eff}
−4 −3 −2 −1 0 1 2 3 4 5
ϕ
4030
4020
4010
4000
−1.84 −1.82 −1.80 −1.78 −1.76 −1.74



30000
25000
20000
15000
10000
5000
U_{eff}
−20 −15 −10 −5 0 5
ϕ
6400
6200
6000
5800
5600
5400
U_{eff}
−23 −22 −21 −20
ϕ

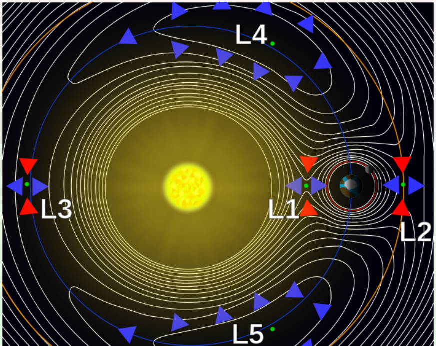
The results, Staicova, arXiv:1808.08890

- The effect of "climbing up the slope" does not appear in the numerically integrated potential term.
- The integrated potential coincides with the effective potential after some moment in time, i.e. the effective potential indeed a very good approximation of the potential term.
- The deviation between the two is seen during the early times of the integration.

Analogue with the Lagrange points:

$$\ddot{r} + 2(\Omega x \dot{r}) = -\nabla(V_g(r) - 1/2\Omega^2 r^2)$$

$$V_g(r) = -\frac{GM_1}{\sqrt{(x + r1)^2 + y^2}} - \frac{GM_2}{\sqrt{(x + r2)^2 + y^2}}$$



Conclusions:

1. We have numerically confirmed that the multi-measure model can be applied to the inflaton+darkon case.
2. We have shown that it is not possible to start from the left plateau and to obtain physically realistic solutions
3. There is friction term which stops the evolution of the inflaton
4. The theory can produce "realistic" Universe if evolution starts from the slope.
5. The effective potential is a good approximation to the actual potential term only after certain moment.

Summary of the viable (left) and nonviable (right) Scalar-Tensor theories after GW170817 [Ezquiaga and Zumalacárregui (2017)]

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [47] Brans-Dicke/$f(R)$ [48, 49] Kinetic Gravity Braiding [51]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [50] $G_{\mu\nu}\phi^\mu\phi^\nu$ [5], $f(\phi)\cdot$Gauss-Bonnet [53]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

$$\mathcal{L} = G_2 - G_3\nabla^2\phi$$
$$+ G_4 R + G_{4,X}[\nabla\nabla\phi]^2 + G_5 G_{\mu\nu}\nabla^\mu\nabla^\nu\phi - \frac{G_{5,X}}{6}[\nabla\nabla\phi]^3$$

arXiv: 1710.05901, arXiv: 1712.06556

Thank you for you attention!

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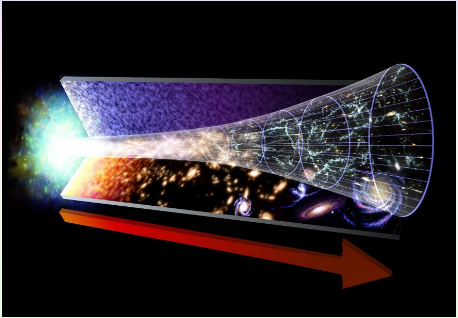

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