Quintessential Inflation in Palatini $F(\varphi, R)$ Gravity

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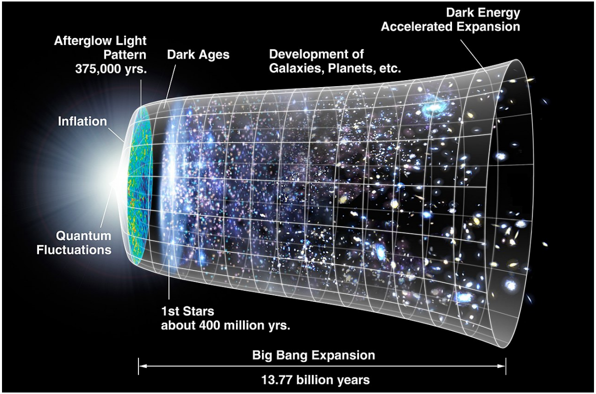
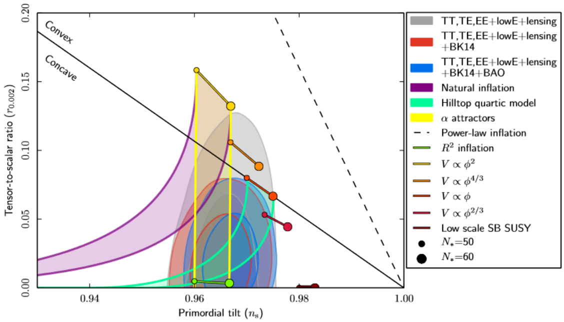
K. Dimopoulos, S.S.L. Phys. Rev. D 103 (2021) 4, 043533 [arXiv:**2012.06831**]
A. Karam, K. Dimopoulos, S.S.L. and E. Tomberg, Galaxies 10 (2022) 2, 57 [arXiv:**2203.05424**]
A. Karam, K. Dimopoulos, S.S.L. and E. Tomberg, JCAP 10 (2022) 076 [arXiv:**2206.14117**]

The History of the Universe



Most of the history of the Universe is well understood. The two big unknowns are the very early universe and the present (cosmic) time.



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

E.o.m.: $\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) - \frac{1}{a^2}\nabla^2\varphi = 0$

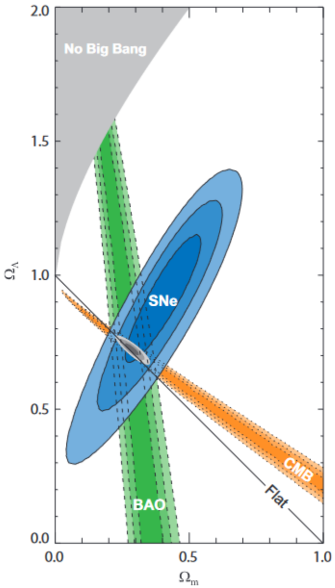
Observables: $n_s = 1 - 6\epsilon + 2\eta \qquad r = 16\epsilon$

$$\epsilon = \frac{m_P^2}{2}\left(\frac{V'}{V}\right)^2 \qquad \eta = m_P^2\frac{V''}{V}$$

- Solves the horizon and flatness problems
- Provides a mechanism for the production of perturbations that source all structure in the universe (*e.g.* LSS or CMB temperature anisotropies)

- $A_s = (2.096 \pm 0.101) \times 10^{-9}$
- $n_s = 0.9661 \pm 0.0040$
- $r < 0.036$

Dark Energy



Observations suggest that around 70% of the energy density of the universe corresponds to *Dark Energy* (DE).

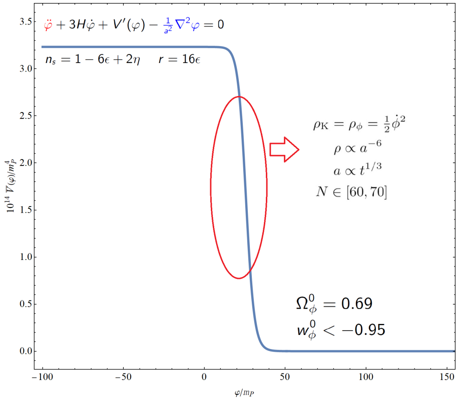
DE has been traditionally explained by introducing a cosmological constant term in the Einstein equations. However, the amount of fine-tuning required is extreme.

In quintessence, DE is a scalar field, though the fine-tuning problem is only mildly alleviated since one still needs to explain the initial conditions of the field.

- $-1 \leq w_\phi^0 \leq -0.95$
- $w_a \in [-0.55, 0.03]$
- $H_0 = 67.66 \pm 0.42 \frac{\text{km}}{s\ Mpc}$

where $w_a = -\left.\frac{\mathrm{d}w_\phi}{\mathrm{d}a}\right|_{a=a_0}$

Quintessential Inflation

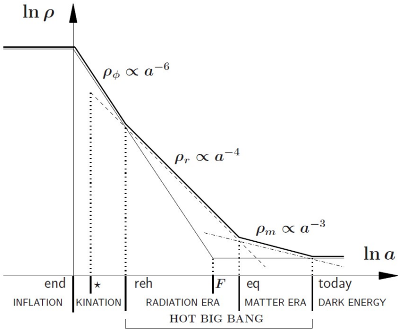


A typical quintessential inflation potential.

Quintessential inflation identifies the inflaton and quintessence fields.

- Economical approach (one single scalar field explains both the inflationary and dark energy epochs!).
- Heavily constrained (easily falsifiable).
- The initial conditions of quintessence are fixed by the inflationary attractor.

Quintessential Inflation



Log-log plot of the density of the Universe and its individual components with respect to the scale factor (adapted from *Introduction to Cosmic Inflation and Dark Energy*, K. Dimopoulos).

This approach does not come without its shortcomings.

- No minimum in the potential as the field has to survive until the present.
- Fifth force problems (for super-Planckian distances in field space).
- Radiative corrections might lift the flatness of the potential (for super-Planckian distances in field space).

The Model

We consider a simple exponential potential $V(\varphi) = M^4 e^{-\kappa\varphi}$ in Palatini $F(\varphi, R)$ gravity [arXiv:**2206.14117**]. Our choice for $F(\varphi, R)$ is motivated by renormalization considerations in QFT in curved spacetime.

$$S_\mathrm{J} = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}\left(1+\xi\varphi^2\right)R + \frac{1}{4}\alpha R^2 - \frac{1}{2}g^{\mu\nu}\nabla_\mu\varphi\nabla_\nu\varphi - V(\varphi)\right] + S_m[g_{\mu\nu}, \psi],$$

An appropriate conformal transformation $g_{\mu\nu} \to \bar{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$ gives

$$S_\mathrm{E} = \int \mathrm{d}^4x\sqrt{-\bar{g}}\left[\frac{1}{2}\bar{R} - \frac{1}{2}(\bar{\nabla}\varphi)^2\frac{1+\xi\varphi^2}{(1+\xi\varphi^2)^2+4\alpha V} - \frac{V}{(1+\xi\varphi^2)^2+4\alpha V} + \mathcal{O}(\bar{\nabla}\varphi)^4\right] + S_m\left[\Omega^{-2}\bar{g}_{\mu\nu}, \psi\right],$$

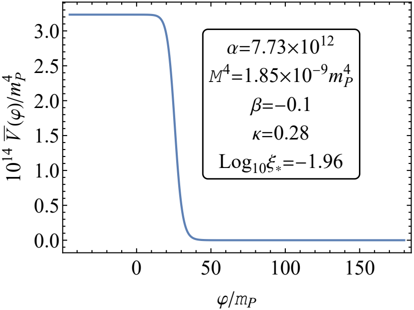
As $V(\varphi)$ monotonically increases with decreasing φ, for large negative values of the field the potential density is approximately constant

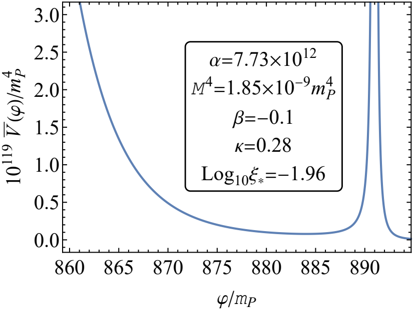
$$\bar{V}(\varphi) \simeq \frac{1}{4\alpha}.$$

Adding a logarithmic running for the coupling constant allows us to have two different values for ξ during inflation and during the dark energy era

$$\xi(\varphi) = \xi_*\left(1 + \beta\log\frac{\varphi^2}{\mu^2}\right)$$

The Potential

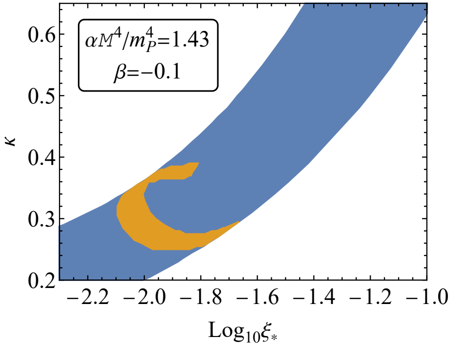




The Einstein frame potential reads

$$\bar{V} \equiv \frac{M^4 e^{-\kappa\varphi(\phi)/m_{\rm P}}}{\left(1+\frac{\xi\varphi(\phi)^2}{m_{\rm P}^2}\right)^2 + \frac{4\alpha M^4}{m_{\rm P}^4} e^{-\kappa\varphi(\phi)/m_{\rm P}}}.$$

The Model Put to Test



Parameter space $\kappa(\xi_*)$ for a correct n_s (blue) and for correct r and α_s plus a correct range for $\bar{N}_*$ (orange). The orange band corresponds to $\bar{N}_* \in [60, 75]$.

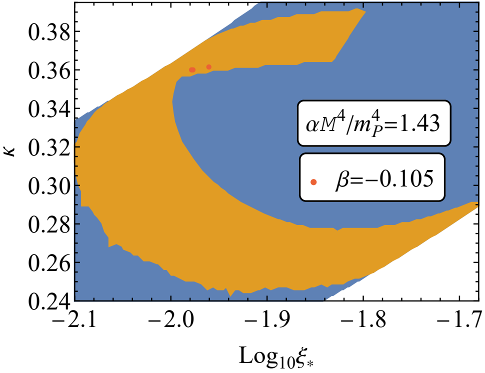
Planck data:

- $A_s = (2.096 \pm 0.101) \times 10^{-9}$
- $n_s = 0.9661 \pm 0.0040$
- $r < 0.036$
- $-0.0179 < \alpha_s < 0.0089$

One example point in parameter space with correct observational predictions is

- $\kappa = 0.3$ and $\xi_* = 0.01$
- $\beta = -0.1$ and $\mu = -6 m_{\mathrm{P}}$
- $\alpha = 10^{11}$ and $M^4 = 10^{-9} m_{\mathrm{P}}^4$

The Parameter Space



Same slice of the parameter space as in the last slide, now with the successful dark energy points in red.

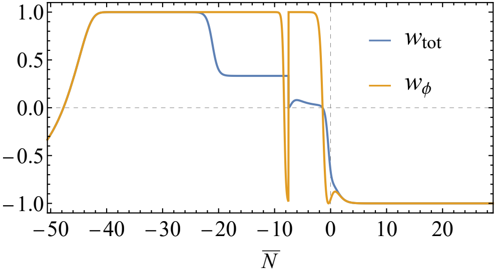
Planck data:

- $-1 \leq w_\phi^0 \leq -0.95$
- $w_a \in [-0.55, 0.03]$
- $H_0 = 67.66 \pm 0.42 \frac{\text{km}}{s\ Mpc}$

The three points in the figure have roughly

- $\kappa = 0.36$
- $\log_{10} \xi_* = -1.96$
- $\beta = -0.105$
- $\mu = -6 m_{\text{P}}$

The Barotropic Parameter of Quintessence

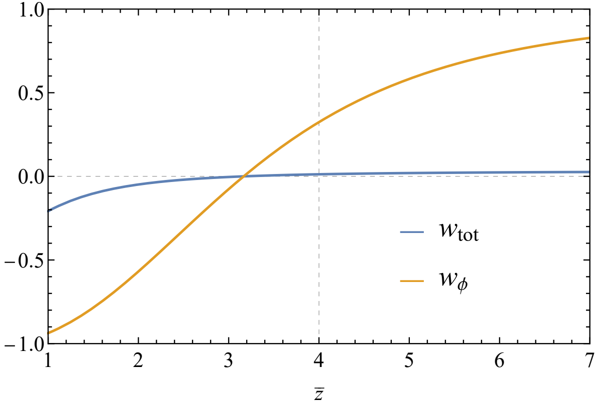


Barotropic parameter of the universe (blue) and of the field (orange) as a function of the number of *e*folds, where $\log a = 0$ corresponds to the present time.

In the CPL parametrization $w_\phi = w_\phi^0 + w_a \left(1 - \frac{a}{a_0}\right)$, where $w_a = -\frac{\mathrm{d}w_\phi}{\mathrm{d}a}\Big|_{a=a_0}$ is to be probed by future experiments (as EUCLID). Our w_ϕ at $\bar{N} = 0$ has

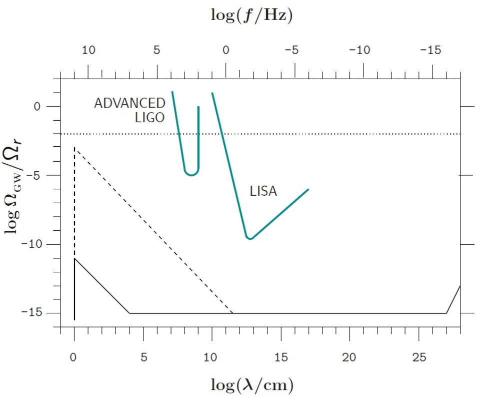
- $w_\phi^0 = -0.956$
- $w_a = -0.1596$

The Barotropic Parameter of the Universe at $z \sim 4 - 6$



The barotropic parameter of the universe at $\bar{z} \sim 4 - 6$, *i.e.*, at redshifts corresponding to galaxy formation, is very close to zero.

Outlook: Observable GWs in Palatini modified gravity



Log-log plot of the spectral GW density parameter $\Omega_{\rm GW}(\lambda)$ as a function of the comoving wavelength λ (adapted from *Introduction to Cosmic Inflation and Dark Energy*, K. Dimopoulos).

In the regime where the quartic kinetic term dominates the energy density of the universe, the equation of motion of the inflaton and its barotropic parameter, in terms of the number of e-folds in the Einstein frame, read

$$\begin{aligned} \phi'' &= \frac{\phi'(\phi'^2-6)(\phi'^2+12)}{6(\phi'^2-12)} \\ w_\phi &= \frac{1}{9}(3+\phi'^2), \end{aligned}$$

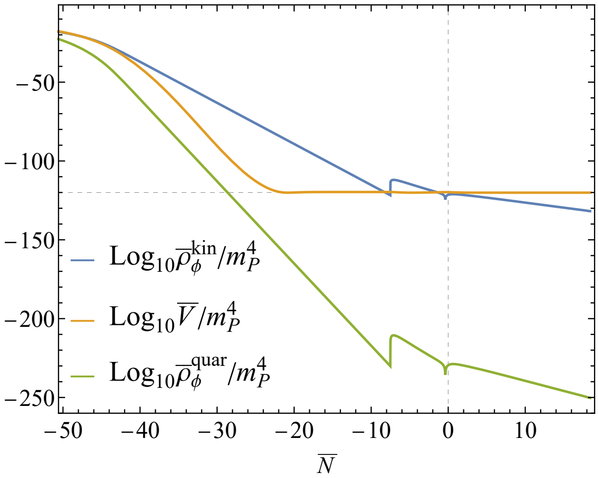
where

$$\dot{\phi} = \phi' \sqrt{\frac{2(6-\phi'^2)}{3\alpha\phi'^4}}\,.$$

Conclusions

- Quintessential inflation is an economical way of modelling the history of the universe. The initial conditions of quintessence are fixed by the inflationary attractor.
- Adding a (non-minimal coupling term and) an R^2 term (in the Palatini formalism) is an effective way of rescuing otherwise discarded models by observational data.
- Solving numerically the full equations in the Jordan frame and performing a parameter scan of the theory allows us to obtain specific predictions for the running of w_ϕ, to be tested in the near future.

The Contributions to the Energy Density of the Field



The contribution of the quartic kinetic term to the total energy density of the field is negligible throughout the history of the universe.