Hill-climbing inflation and gravitational reheating

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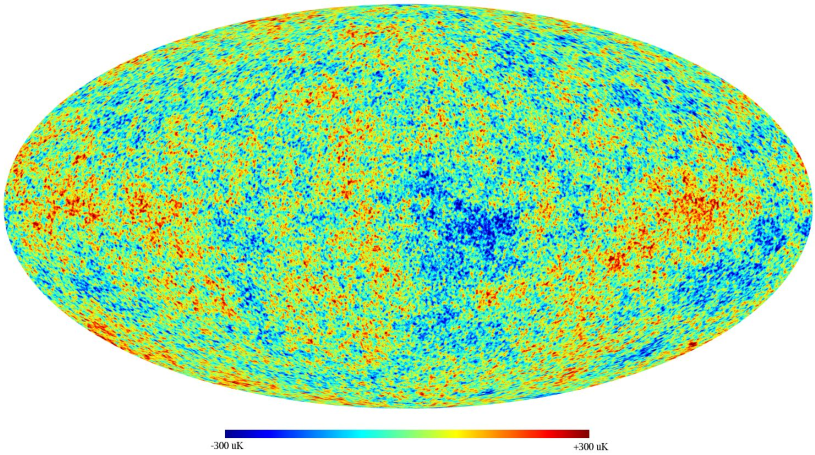
(with Kin-Ya Oda and Z. Lalak)

Cosmic microwave background



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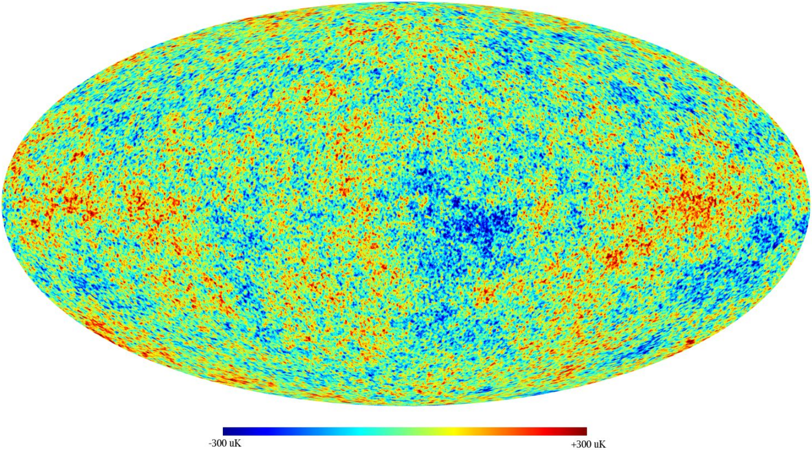
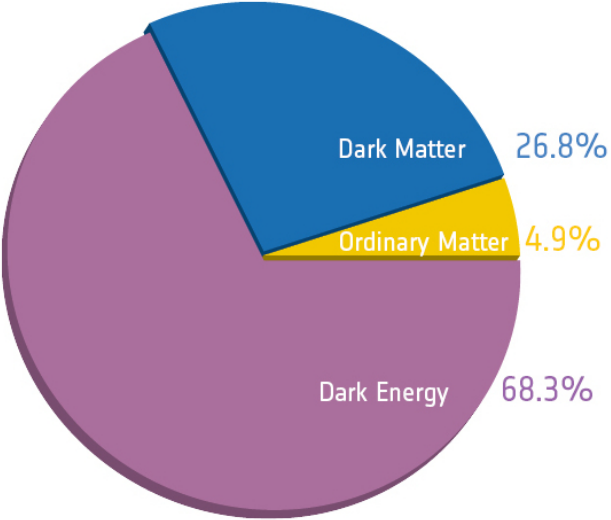


Convention: $8\pi G = 1 = M_p^{-2}$, where $M_p \simeq 2.5 \times 10^{18} GeV$

The cosmic cake



Inflation in scalar-tensor theory

Let's start with the action

$$S = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}F(\phi_J)R - \frac{1}{2}(\partial\phi_J)^2 - V_J(\phi_J)\right], \qquad (1)$$

where ϕ_J and V_J are Jordan frame (JF) field and potential respectively and F is a function, which defines the non-minimal coupling to gravity. For the Einstein frame

$$g_{E\mu\nu} = Fg_{\mu\nu}\,. \qquad (2)$$

Then, one obtains the EF action of the form of

$$S = \int d^4x\sqrt{-g_E}\left[\frac{1}{2}R_E - \frac{1}{2}(\partial\phi_E)^2 - V_E(\phi_E)\right], \qquad (3)$$

where $V_E = V_J/F^2$

Inflation in scalar-tensor theory

Usually one assumes that during inflation $F \gg 1$, which means, that gravity is effectively weaker than in the GR case. This happens for instance for

$$F = 1 + \xi\phi_J^n \tag{4}$$

Then one just needs to assume that for the big values of F one finds $V_J \propto F^2$ in order to obtain a flat plateau in the Einsten frame. This works for e.g.

$$V = \lambda\phi_J^{2n} \tag{5}$$

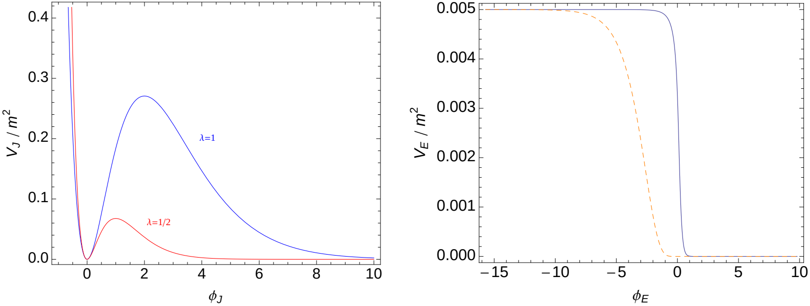
These are the so-called ξ attractors, which also contain the Higgs inflation.

Hill-climbing inflation

What if $F \ll 1$ during inflation? What if gravity gets stronger? Let's consider

$$V_J = \frac{1}{2} m^2 \phi_J^2 e^{-\phi_J/M_V} \qquad F = 1 - e^{-\phi_J/M_F}\,, \tag{6}$$

where M_V, m and M_F have a dimension of mass.



Hill-climbing inflation

In the $\phi_J \ll M_F, M_V$ limit one finds

$$F \simeq \frac{\phi_J}{M_F}\left(1 - \frac{1}{2}\frac{\phi_J}{M_F}\right) , \qquad V_J \simeq \frac{1}{2}m^2\phi_J^2\left(1 - \frac{\phi_J}{M_V}\right) , \tag{7}$$

which gives the following EF potential

$$V_E \simeq \frac{1}{2}m^2 M_F^2\left(1 - \frac{M_F - M_V}{M_F M_V}\phi_J\right) . \tag{8}$$

We obtain a plateau in the EF! The field must increase its value. Otherwise ϕ_J would first of all evolve towards $F = 0$, which is the strong coupling limit of the theory. Thus, we require

$$M_F \geq M_V . \tag{9}$$

Hill-climbing inflation

The EF field is equal to

$$\phi_E = \pm \int d\phi_J \sqrt{\frac{1}{F} + \frac{3}{2} M_p^2 \left(\frac{F_{,\phi_J}}{F} \right)^2} , \qquad (10)$$

In a small field limit one finds

$$\phi_E \simeq -\sqrt{\frac{3}{2}} \log F \qquad \Rightarrow \qquad \phi_J \simeq M_F e^{-\sqrt{2/3}\,\phi_E} , \qquad (11)$$

which gives

$$V_E(\phi_E) \simeq \frac{1}{2} m^2 M_F^2 \left(1 - \frac{M_F - M_V}{M_V} e^{-\sqrt{2/3}\,\phi_E} \right) , \qquad (12)$$

which is a Starobinsky-like model. Note that the case of $M_V = M_F$ also gives inflationary solution. Then the Eq. (8) takes form of

$$V_E \simeq \frac{1}{2} m^2 M_F^2 \left(1 - \frac{1}{12} \left(\frac{\phi_J}{M_F} \right)^2 \right) = \frac{1}{2} m^2 M_F^2 \left(1 - \frac{1}{12} e^{-2\sqrt{2/3}\,\phi_E} \right) . \qquad (13)$$

Primordial inhomogeneities

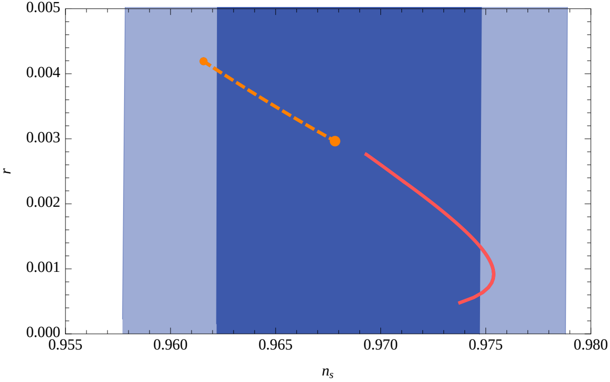


Figure: *Results for* $M_V = 10^{-3}$ *and* $M_F \in [M_V, 100M_V]$.

Post-inflationary evolution

After inflation one enters the big field limit, where $\phi_J \gg M_F, M_V$. Then one finds

$$\epsilon \to \frac{M_p^2}{2M_V^2}, \qquad \eta \to \frac{M_p^2}{M_V^2}, \tag{14}$$

where ϵ and η are slow-roll parameters. This means that for $M_V, M_F \ll M_p$ one finds

$$\epsilon, \eta \gg 1 \tag{15}$$

After inflation the field rolls very quickly at the steep slope of the potential, its kinetic energy dominates the potential one and the field enters the kinaton regime, for which

$$\frac{1}{2}\dot{\phi}_E^2 \gg V_E \quad \Rightarrow \quad p \simeq \rho \quad \Rightarrow \quad w \simeq 1 \tag{16}$$

Reheating of the Universe

$\rho_r \propto a^{-4} \propto e^{-4Ht}$, so the radiation is exponentially suppressed during inflation. Therefore, besides the warm inflationary models the Universe at the end of inflation is extremely cold and empty.

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The inflaton field couples to scalars, fermions and vectors and produces lots of relativistic degrees of freedom - this is the reheating of the Universe! Problems?

$$N_\star \simeq 67 - \log\left(\frac{k_\star}{a_0 H_0}\right) + \frac{1}{4}\log\left(\frac{V_{hor}^2}{M_p^4 \rho_{end}}\right) + \frac{1-3w}{12(1+w)}\log\left(\frac{\rho_{th}}{\rho_{end}}\right) \tag{17}$$

- What is the reheating temperature? (Affects predictions of inflation)
- How couplings to other fields influence the flatness of the potential?

Gravitational particle production

Nearby the end of inflation we can divide the evolution of space into 3 periods

$$a(\eta)^2 \propto \begin{cases} \frac{1}{\eta^2} & \text{de Sitter} \\ a_0 + a_1\eta + a_2\eta^2 + a_3\eta^3 & \text{transition} \\ b_0(b_1+\eta)^{\frac{4}{3w+1}} & \text{general } w \neq -1/3 \end{cases} \tag{18}$$

where $w = p/\rho$. From continuity equations we find a_i and b_i coefficients.

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$$\rho_r \sim N(1-6\xi)^2(1+w)^2 \times 10^{-2} H_{inf}^4 a^{-4} \quad (19)$$

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$H_{inf}^4 \ll H_{inf}^2$ in Planck units, so it's a very inefficient process, the radiation is still subdominant after the particle production

Gravitational reheating as the only one needed

At the end of inflation the inflaton still dominates the Universe. Let's assume that the inflaton is dark (i.e. it is not coupled to any SM fields) and let's see how to obtain radiation domination era.

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We need an inflaton, which redshifts faster than radiation! A good example is the massless scalar field, for which $w = 1$ and $\rho \propto a^{-6}$. Two options

- Fast-rolling inflaton with a steep potential. For a sufficiently steep post-inflationary potential the inflaton's kinetic energy dominates over the potential one, which effectively leads to $w = 1$ (our case!)

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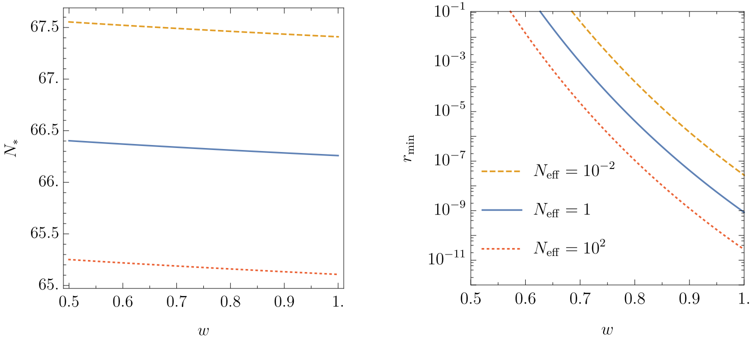
- Fast-rolling inflaton with a steep potential. For a sufficiently steep post-inflationary potential the inflaton's kinetic energy dominates over the potential one, which effectively leads to $w = 1$ (our case!)
- Inflation is driven by a non-canonical form of the inflatons kinetic term (the so-called K-inflation or G -inflation), for instance

$$\mathcal{L} = K_1(\phi)X + K_2(\phi)X^2 \ , \quad \text{where} \quad X = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi \quad (20)$$

Fixing the pivot scale freeze-out

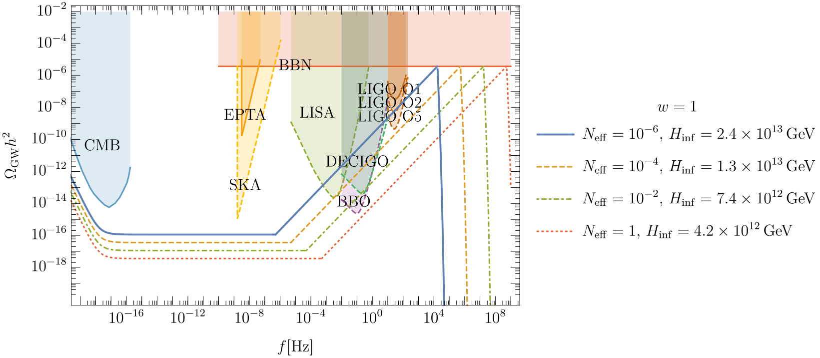
It appears that $N_\star$ is $H_{\rm inf}$ independent! The uncertainty on $N_\star$ is so small!

$$N_\star \simeq 64.82 + \frac{1}{4}\ln\left(\frac{128\pi^2}{N_{\rm eff}(1+w)^2}\right) . \tag{21}$$



Gravitational Waves signal

For $N_{eff} \ll 1$ you can get a powerful signal from dark inflation!
This can happen, if $\xi \simeq 1/6$



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- Reheating via the gravitational particle production - not very efficient, but possible
- Dark inflation sets $N_\star$ very precisely comparing to normal one
- Gravitational waves signal to observe in the future for non minimal coupling to gravity with $\xi \sim 1/6$