Dark Inflation

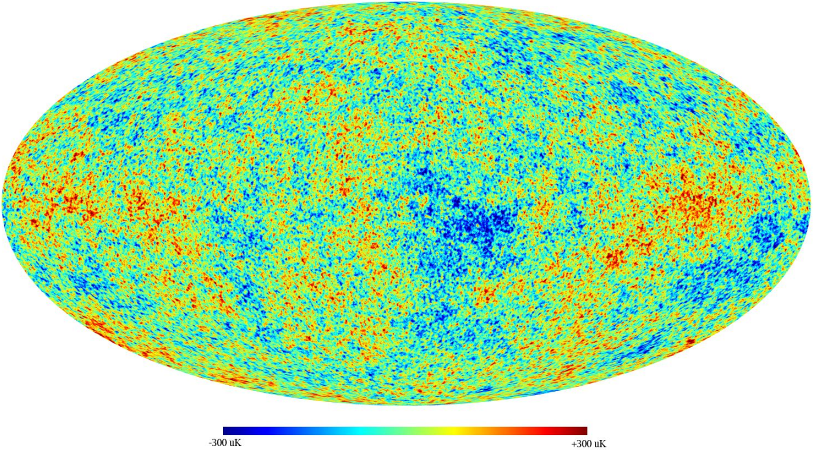
Michał Artymowski

Jagiellonian University

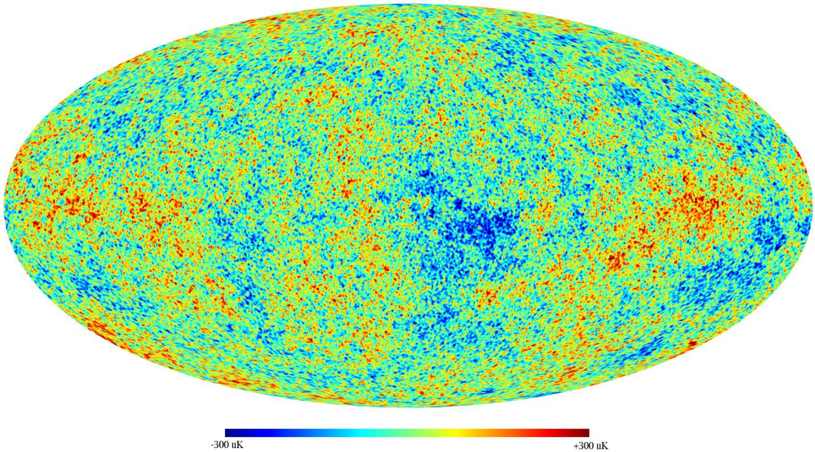
July 13, 2017

DSU 2017

Cosmic microwave background

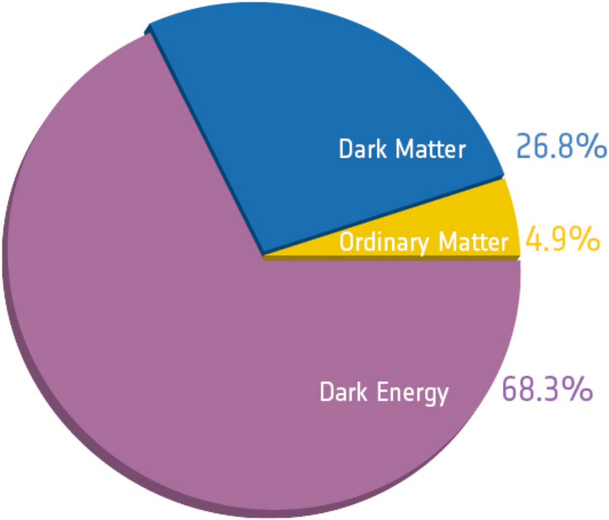


Cosmic microwave background



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

The cosmic cake



Introduction to cosmic inflation

Let us assume, that the flat FRW Universe with the metric tensor

$$ds^2 = -dt^2 + a(t)^2(dx^2 + dy^2 + dz^2) \ ,$$

is filled with a homogeneous scalar field $\phi(t)$ with potential $V(\phi)$. The $a(t)$ is the scale factor. Then Einstein equations are following

$$3H^2 = \rho = \frac{1}{2}\dot{\phi}^2 + V \ , \qquad 2\dot{H} = -(\rho + P) = -\dot{\phi}^2 \ , \qquad (1)$$

where $H = \frac{\dot{a}}{a}$ is a Hubble parameter.

Introduction to cosmic inflation

Let us assume, that the flat FRW Universe with the metric tensor

$$ds^2 = -dt^2 + a(t)^2(dx^2 + dy^2 + dz^2) \ ,$$

is filled with a homogeneous scalar field $\phi(t)$ with potential $V(\phi)$. The $a(t)$ is the scale factor. Then Einstein equations are following

$$3H^2 = \rho = \frac{1}{2}\dot{\phi}^2 + V \ , \qquad 2\dot{H} = -(\rho + P) = -\dot{\phi}^2 \ , \qquad (1)$$

where $H = \frac{\dot{a}}{a}$ is a Hubble parameter. Let us note that

$$\frac{\dot{H}}{H^2} = -\frac{3\dot{\phi}^2}{\dot{\phi}^2 + 2V} \quad \Rightarrow \quad \dot{H} \ll H^2 \ \text{ for } \ \dot{\phi}^2 \ll V \ . \qquad (2)$$

When $H \sim const$ one obtains $a \sim e^{Ht}$ $\rightarrow$ exponential expansion of the Universe! This is an example of the cosmic inflation.

Reheating of the Universe

Pre-inflationary Universe could be in principle very hot. Note however, that since $\rho_r \propto a^{-4}$ 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.

Reheating of the Universe

Pre-inflationary Universe could be in principle very hot. Note however, that since $\rho_r \propto a^{-4}$ 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. We need to fill it with Standard Model particles and Dark Matter!

The inflaton field couples to scalars, fermions and vectors and produces lots of relativistic degrees of freedom - this is the reheating (or preheating) of the Universe!

Reheating of the Universe

Pre-inflationary Universe could be in principle very hot. Note however, that since $\rho_r \propto a^{-4}$ 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. We need to fill it with Standard Model particles and Dark Matter!

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

- 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 (Yokoyama's talk)

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

From continuity equations we find conditions for a_i and b_i coefficients.

Gravitational particle production

Nearby the end of inflation we can divide the evolution of space into 3 periods (Yokoyama's talk)

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

From continuity equations we find conditions for a_i and b_i coefficients. You change the background → you move the vacuum → you produce particles [Ford 1986, Kunumitsu, Yokoyama 2014]. This can be calculated via Bogoljubov transformation.

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

where H_{infl} is a Hubble parameter during inflation

Gravitational particle production

Nearby the end of inflation we can divide the evolution of space into 3 periods (Yokoyama's talk)

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

From continuity equations we find conditions for a_i and b_i coefficients. You change the background → you move the vacuum → you produce particles [Ford 1986, Kunumitsu, Yokoyama 2014]. This can be calculated via Bogoljubov transformation.

$$\rho_r \sim (1+w)^2 \times 10^{-2} H_{inf}^4 a^{-4} \tag{4}$$

where H_{infl} is a Hubble parameter during inflation

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.

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.

We need an inflaton, which redshifts faster than radiation! Two options

- $V(\phi) \propto \phi^{2n}$ around the minimum. Then the barotropic parameter is

$$w = \frac{n-1}{n+1} \tag{5}$$

From $w > 1/3$ one finds $n > 2$.

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.

We need an inflaton, which redshifts faster than radiation! Two options

- $V(\phi) \propto \phi^{2n}$ around the minimum. Then the barotropic parameter is

$$w = \frac{n-1}{n+1} \tag{5}$$

From $w > 1/3$ one finds $n > 2$. problems

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.

We need an inflaton, which redshifts faster than radiation! Two options

- $V(\phi) \propto \phi^{2n}$ around the minimum. Then the barotropic parameter is
$$w = \frac{n-1}{n+1} \tag{5}$$
From $w > 1/3$ one finds $n > 2$. problems
- Inflation is driven by a non-canonical form of the inflatons kinetic term (the so-called K-inflation or G -inflation - Yokoyama's talk), for instance

$$\mathcal{L} = K_1(\phi)X + K_2(\phi)X^2 \ , \quad \text{where} \quad X = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi \tag{6}$$

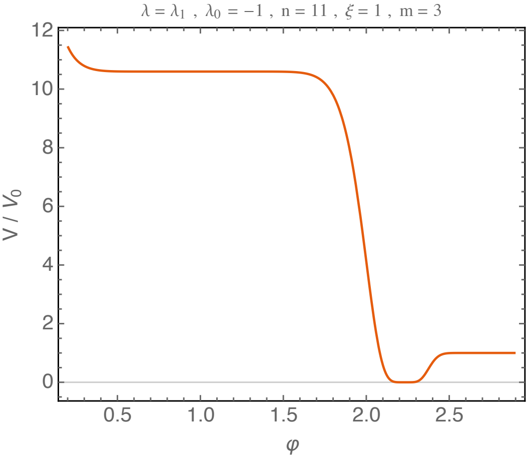
Applications # 1 and 2 - No reheating uncertainty + Dark Matter

- If inflation ends up with oscillation phase and then regular reheating we can't say much about the thermal history of the Universe. This increases uncertainty on the freeze-out of the pivot scale and weakens the predictability of inflationary models. For dark inflation all of the details of reheating are fully dependent on the inflationary potential. We exactly know when a given scale have left the horizon!

Applications # 1 and 2 - No reheating uncertainty + Dark Matter

- If inflation ends up with oscillation phase and then regular reheating we can't say much about the thermal history of the Universe. This increases uncertainty on the freeze-out of the pivot scale and weakens the predictability of inflationary models. For dark inflation all of the details of reheating are fully dependent on the inflationary potential. We exactly know when a given scale have left the horizon!
- In the case of inflation with the potential $\lambda\phi^{2n}$ around the minimum one can assume that term with smaller powers also exists, but start to be relevant in smaller scales. For instance the potential may have $m^2\phi^2$ term, which dominates the potential no later than the last scattering era. Such an oscillating scalar field is a perfect candidate for dark matter!

Application # 3 - Dark energy



$$V = V_0(1 - \exp(-f(\varphi)))^2$$

where $f(\varphi)$ has a stationary point or comes from α-attractors

Thermal history of the Universe

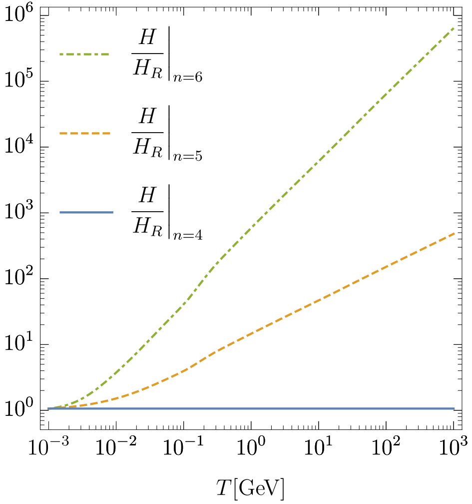
What is the strongest constraint on the thermal history of the Universe? BBN! Let's assume that there was something more than radiation at the BBN era. How much more matter we can get in order to fit to the data? How much bigger the Hubble parameter could be?

$$\left.\frac{H}{H_R}\right|_{BBN} = \sqrt{1 + \frac{7}{43}\Delta N_{\nu_{eff}}}\,, \tag{7}$$

where $\Delta N_{\nu_{\mathrm{eff}}}$ is the difference between the SM radiation $N = 3.046$ and the observed central value $N_{\nu_{\mathrm{eff}}} = 3.28 \pm 0.28$

The initial difference is tiny, but if your additional dark component redshifts faster than radiation it should lead to dark field domination in higher energies [1601.01681, 1609.07143]. This is exactly the case of dark inflation!

Thermal history of the Universe



EW phase transition and gravitational waves production

The electro-weak phase transition happens around $T = 100 GeV$ and provides us the CP violation needed for bariogenesis. How dark inflation can influence that process?

EW phase transition and gravitational waves production

The electro-weak phase transition happens around $T = 100GeV$ and provides us the CP violation needed for bariogenesis. How dark inflation can influence that process?

- The energy density of the Universe at the EWPT can be in principle much higher than the one, which comes only from radiation. This can help to relax constraints on parameters of different EWPT models [1601.01681, 1609.07143].

EW phase transition and gravitational waves production

The electro-weak phase transition happens around $T = 100\,GeV$ and provides us the CP violation needed for bariogenesis. How dark inflation can influence that process?

- The energy density of the Universe at the EWPT can be in principle much higher than the one, which comes only from radiation. This can help to relax constraints on parameters of different EWPT models [1601.01681, 1609.07143].

- During the first order phase transition bubbles of true vacuum collide creating gravitational waves (Ryusuke Jinno's talk). If the EWPT happens in much higher energy densities than in the regular reheating scenario then such a signal would be suppressed $\Rightarrow \Omega_{GW} \propto (H_r/H)^2 \ll 1$. Lack of expected gravitational waves would provide additional motivation for dark inflation! Peak frequency changes like $f \propto (H/H_R) \gg 1$

Freeze-out of the dark matter

Since the Hubble parameter before the BBN can be in principle much higher than in the radiation-domination scenario, it can also influence the dark matter freeze-out. For instance the moment of decoupling of WIMPS is

$$\Gamma = H \tag{8}$$

and since H can be many orders of magnitude bigger, the free-out scale goes up as well! This enable us to massively relax conditions for couplings in DM models. For details see Lewicki, Wells et.all [1702.06124]

Summary

Summary

- Inflation leaves the Universe empty and cold - reheating needed

Summary

- Inflation leaves the Universe empty and cold - reheating needed
- Reheating via the gravitational particle production - not very efficient, but possible

Summary

- Inflation leaves the Universe empty and cold - reheating needed
- Reheating via the gravitational particle production - not very efficient, but possible
- We need an oscillating scalar field with a steep potential or a kinetic inflation in order to enable the radiation to dominate

Summary

- Inflation leaves the Universe empty and cold - reheating needed
- Reheating via the gravitational particle production - not very efficient, but possible
- We need an oscillating scalar field with a steep potential or a kinetic inflation in order to enable the radiation to dominate
- Possible applications: Dark energy, dark matter

Summary

- Inflation leaves the Universe empty and cold - reheating needed
- Reheating via the gravitational particle production - not very efficient, but possible
- We need an oscillating scalar field with a steep potential or a kinetic inflation in order to enable the radiation to dominate
- Possible applications: Dark energy, dark matter
- Different thermal history of the Universe $\rightarrow$ different EW phase transition and gravitational waves production

Summary

- Inflation leaves the Universe empty and cold - reheating needed
- Reheating via the gravitational particle production - not very efficient, but possible
- We need an oscillating scalar field with a steep potential or a kinetic inflation in order to enable the radiation to dominate
- Possible applications: Dark energy, dark matter
- Different thermal history of the Universe $\rightarrow$ different EW phase transition and gravitational waves production
- This mechanism of particle production can hopefully be used in cases of gravitationally mediated interactions, e.g. in case of inflation in extra dimensions (see Sang Hui Im's talk)

Potential for the dark energy and inflation

$$V = V_0 \left(1 - e^{-f(\varphi)}\right)^{2m} \, ,$$

where

$$f(\varphi) = \lambda_0 + \frac{\xi}{n}\left(1 + (\varphi - 1)^n\right)$$

This form of $f(\varphi)$ may come from

Potential for the dark energy and inflation

$$V = V_0 \left(1 - e^{-f(\varphi)}\right)^{2m} \,,$$

where

$$f(\varphi) = \lambda_0 + \frac{\xi}{n}\left(1 + (\varphi - 1)^n\right)$$

This form of $f(\varphi)$ may come from

- Non canonical kinetic term and field re-definition. The kinetic term needs to have a pole - something like α-attractors

Potential for the dark energy and inflation

$$V = V_0 \left(1 - e^{-f(\varphi)}\right)^{2m} \, ,$$

where

$$f(\varphi) = \lambda_0 + \frac{\xi}{n}\left(1 + (\varphi - 1)^n\right)$$

This form of $f(\varphi)$ may come from

- Non canonical kinetic term and field re-definition. The kinetic term needs to have a pole - something like α-attractors
- The existence of a stationary point of a scalar potential, which indicates a local flatness.

The reheating happens on the steep slope between plateaus.. The same can be done within the ST theory

Scale of dark energy?

The problem with the dark energy is that its scale is so low comparing to the Planck scale. In order to obtain a very low scale of a plateau around φ_s we need $f_s \simeq 0$. Thus, for $\lambda = \lambda_1$ and $\lambda_0 = 0$ one obtains

$$V_s = V(\phi_s) = V_0 \left(1 - e^{-\frac{\xi}{n}}\right)^{2m} , \tag{9}$$

which for $n \gg \xi$ gives

$$V_s \simeq V_0 \left(\frac{\xi}{n}\right)^{2m} . \tag{10}$$

In order to fit the data one needs

$$\log_{10} \frac{n}{\xi} \simeq \frac{55}{m} \tag{11}$$