Dark Inflation

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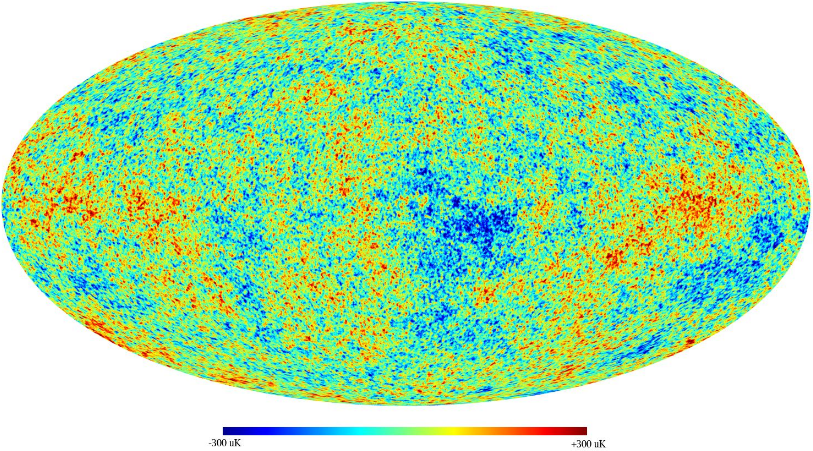
May 25, 2017

Planck 2017

Cosmic microwave background



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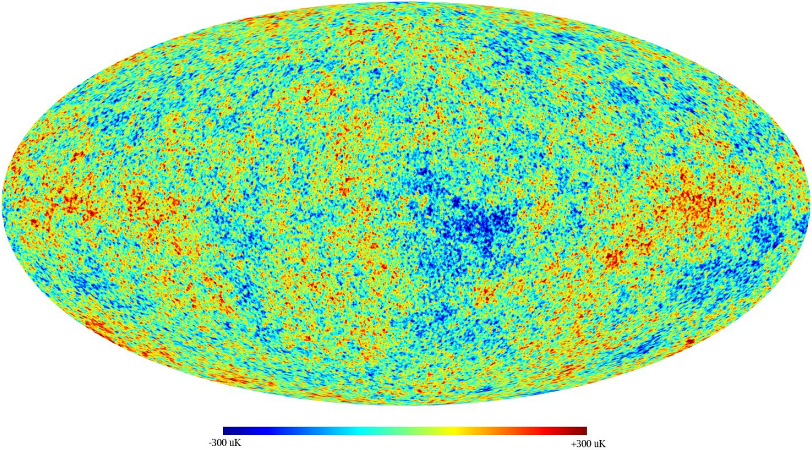
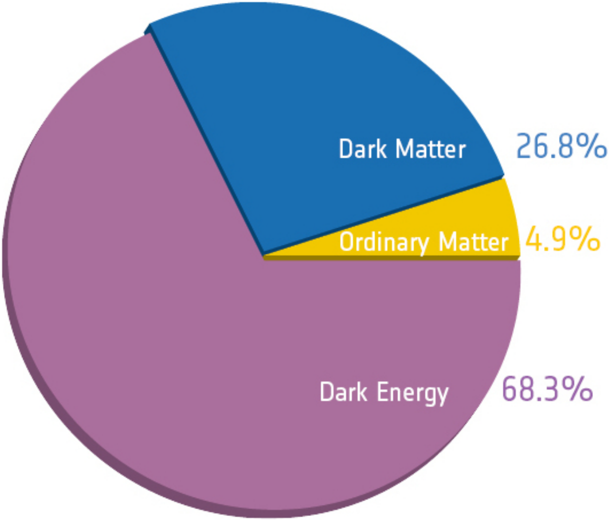


Convention: $8\pi G = 1 = M_p^{-2}$, where $M_p \simeq 2.5 \times 10^{18} GeV$

The cosmic cake



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.

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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.

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- 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

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

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

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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! 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 $n > 2$
- Inflation is driven by a non-canonical form of the inflatons kinetic term (the so-called K-inflation), for instance

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

Possible models of inflation

α-attractors: SUGRA motivated models with natural inflationary plateau. There are basically two options

$$V = f^2 \left(\tanh \frac{\phi}{\sqrt{6\alpha}} \right) \quad \text{or} \quad V = f^2 \left(1 - e^{-\xi\phi} \right) \tag{7}$$

For the first one the gravitational reheating would be completely overwhelmed by self-production of inflaton modes (see Michał Wieczorek talk)

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Scalar-tensor theory: let's consider a Jordan frame action

$$S = \int d^4\sqrt{-g}\left[\frac{1}{2}f(\varphi)R + \frac{1}{2}(\partial\varphi)^2 - M^2(f(\varphi)-1)^2\right] \tag{8}$$

For $f = 1 + \xi\varphi^n$ we get a flat EF plateau and a φ^{2n} minimum

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!

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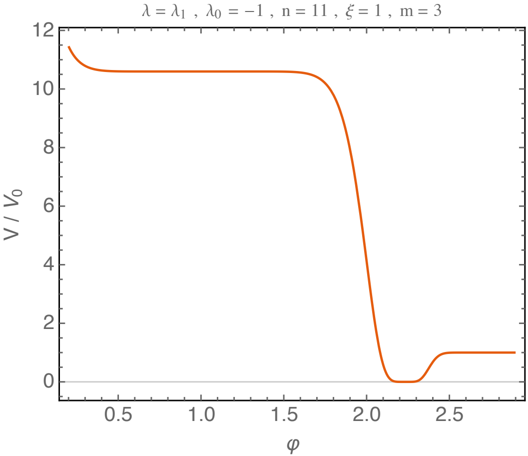
- In the case of inflation with the potential $\lambda\phi^{2n}$ around the minimum one can assume that term with smaller powers also exists, but start to be relevant in smaller scales. For instance the potential may have $m^2\phi^2$ term, which dominates the potential no later than the last scattering 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

EW phase transition and gravitational waves production

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- 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].

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- During the first order phase transition bubbles of true vacuum collide creating gravitational waves. If the EWPT happens in much higher energy densities than in the regular reheating scenario then such a signal would be suppressed. Lack of expected gravitational waves would provide additional motivation for dark inflation!

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- 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

Potential for the dark energy and inflation

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

where

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

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- 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

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