Could known particle physics explain all issues of modern cosmology?

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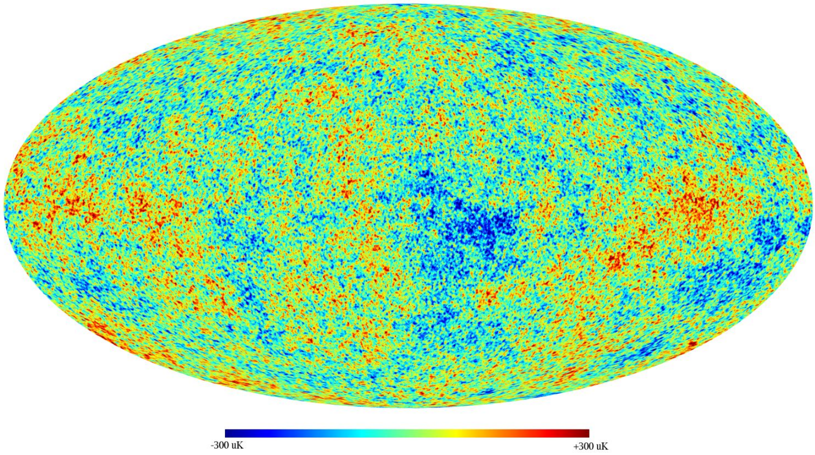
- Dark Matter: Most of the matter in the Universe is not barionic (?).

Cosmic microwave background



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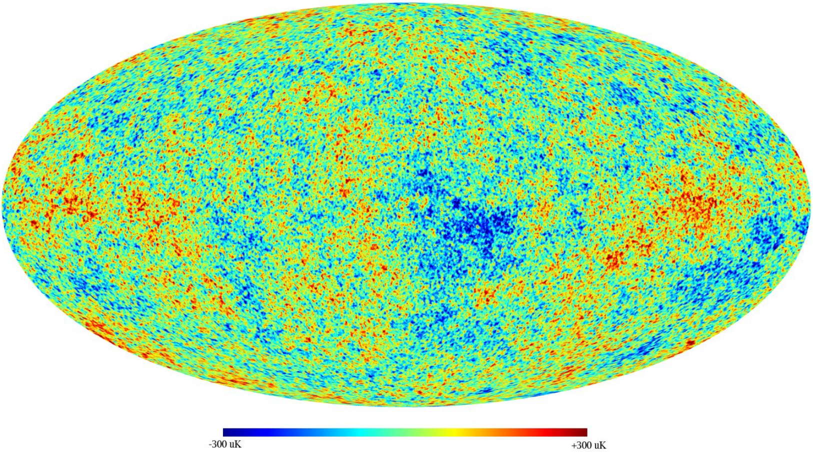

Convention: $8\pi G = 1 = M_p^{-2}$, where $M_p \simeq 2.5 \times 10^{18} GeV$

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

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

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

Primordial inhomogeneities

What we observe are anisotropies of the CMB radiation. We know how to relate them to primordial curvature perturbations $\mathcal{R}$ generated during inflation. We define the power spectrum of $\mathcal{R}$ by

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2}|\mathcal{R}_k|^2 \,. \tag{3}$$

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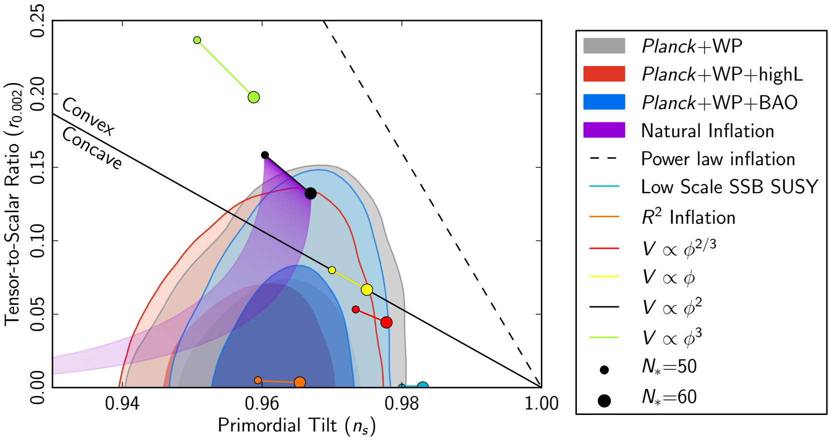
- Tensor-to scalar ratio $r = \mathcal{P}_{\mathcal{R}}/\mathcal{P}_h \simeq 8\left(\frac{V'}{V}\right)^2$

Comparison to the data



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Non-minimal coupling to gravity: Let's assume that in stead of regular GR action we take

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}(1+\xi\varphi^2)R - \frac{1}{2}(\partial\varphi)^2 - \frac{\lambda}{4}\varphi^4\right) + S_m \qquad (4)$$

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In general inflation happens for $\xi\varphi^2 \gg 1$. Normalisation of inhomogeneities gives $\xi \sim 5 \times 10^4\sqrt{\lambda}$. The best thing comparing to other inflationary models? Reheating!

The Einstein frame picture

The gravitational part of the action may be canonical after transformation to Einstein frame

$$\tilde{g}_{\mu\nu} = f(\varphi) g_{\mu\nu} = (1 + \xi\varphi^2) g_{\mu\nu} \tag{5}$$

which gives the action of the form of

$$S = \int d^4x \sqrt{-\tilde{g}} \left[\frac{1}{2}\tilde{R} - \frac{1}{2}\left(\tilde{\partial}\phi\right)^2 - V(\varphi(\phi)) \right] , \tag{6}$$

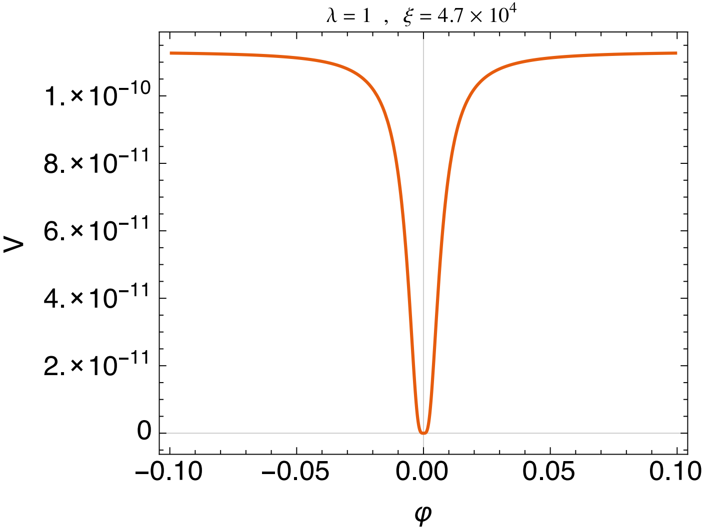
where

$$\frac{d\phi}{d\varphi} = \sqrt{\frac{3}{2}\left(\frac{f_\varphi}{f}\right)^2 + \frac{1}{f}} \tag{7}$$

and

$$V = \frac{\lambda}{4} \frac{\varphi^4}{(1 + \xi\varphi^2)^2} .$$

Einstein frame scalar potential



generalisations of Higgs inflation

So far we have assumed $f(\varphi) = 1 + \xi\varphi^2$. Could we generalise this into any $f(\varphi)$ and still obtain inflation? Sure, as long as Jordan frame scalar potential is

$$U(\varphi) = M^2(f-1)^2\,. \tag{8}$$

For $f = 1 + \xi\varphi^2$ one finds $U = M^2\xi^2\varphi^4$, which means that $\lambda = 4M^2\xi^2$.

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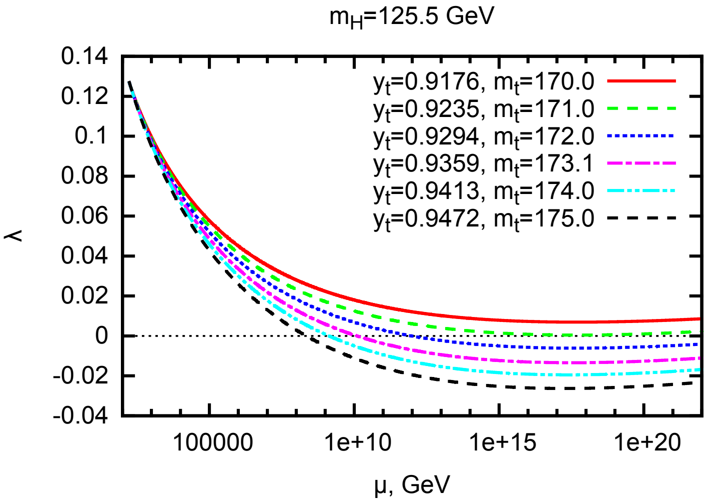
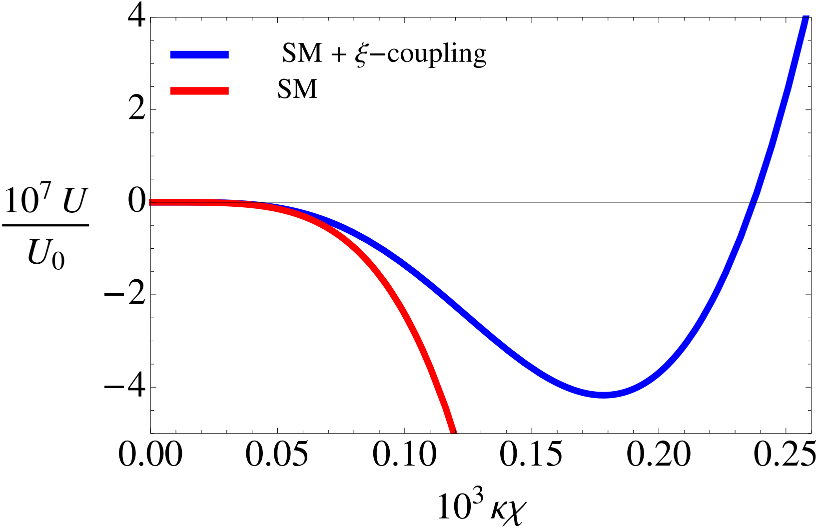
This idea also works for $f = \varphi$ (Brans-Dicke theory), for $f = 1 + \xi\varphi^n$, for $f \propto \sin(\varphi/\mu)$ etc. In the limit $f'^2 \gg f$ one obtains the same result for all f! The so-called conformal attractors (Linde, Kalosh, ...).

Why this is so important? Because there may be higher order non-renormalisable terms in the scalar potential. In principle we don't know the scale that suppressed them. With this mechanism we don't have to worry about them.

"Problems" with running of λ

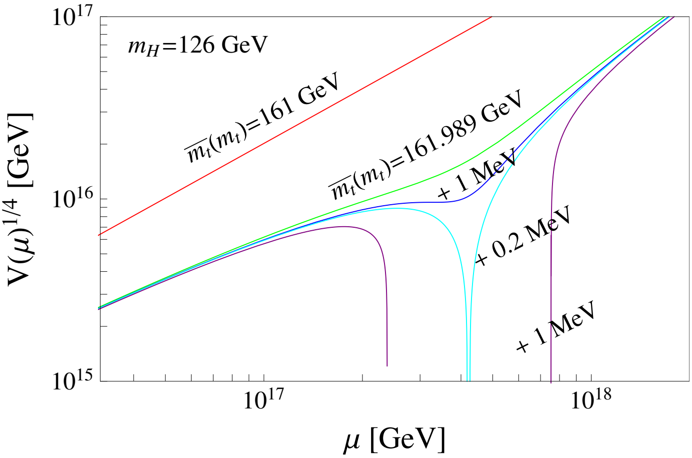


Sort of solution?



Non-minimal coupling suppose stabilise the vacuum

Fine-tuned inflation without non-minimal coupling



The idea of Isabella Masina - fine tuning required!

Higgs inflation as a maximally flat theory

Let's start from a general scalar theory with minimal coupling to gravity

$$S = \int d^4\sqrt{-g}\left[\frac{1}{2}R + \frac{1}{2}(\partial\phi)^2 - V(b(\phi))\right] , \tag{9}$$

where

$$b(\phi) = \xi \sum_{k=1}^{n} \lambda_k\, \phi^k , \tag{10}$$

In general such a potential does not need to be flat anywhere and therefore it is not suitable for inflation. We want to assume that V (and therefore $b(\phi)$) is at least locally flat $\Rightarrow$ has a stationary point at some ϕ_s. The maximal order of ϕ_s is $n-1$, which gives

$$b(\phi) = \frac{\xi}{n}\,(n\,\lambda_n)^{\frac{-1}{n-1}}\left(1 - \left(1 - (n\,\lambda_n)^{\frac{1}{n-1}}\,\phi\right)^n\right) . \tag{11}$$

Higgs inflation as a maximally flat theory

What would happen if we require $n \to \infty$, i.e. infinitely flat potential around the stationary point? For general form of λ the $b(\phi)$ does not converge. But for

$$\lambda_n = \frac{1}{\xi}\left(\frac{\xi}{n}\right)^n \tag{12}$$

one finds in the $n \to \infty$ limit

$$b(\phi) = 1 - e^{-\xi\phi} \tag{13}$$

so for $V \propto f^2$ one obtains

$$V \propto (1 - e^{-\xi\phi})^2\,, \tag{14}$$

which is exactly the Einstein frame potential of Higgs inflation in the $\xi^2\varphi^2 \gg 1 + \xi\varphi^2$ limit.

Dark matter from primordial black holes?

Just a brief idea from paper of Clesse and Garcia-Bellido from ArXiv:1501.07565 - inflation has two phases between which there is a break $\Rightarrow$ few fields running inflation or one field with few flat regions. This causes growth of primordial inhomogeneities at some scales and in consequence a creation of primordial black holes.

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Some generalisations of Higgs inflation could be responsible for such an inflationary break!

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- Final answer is NO - we still have puzzles to answer (CP violation, missing satellite problem etc.), but but perhaps we don't need to go that far from the SM.