# Dark inflation

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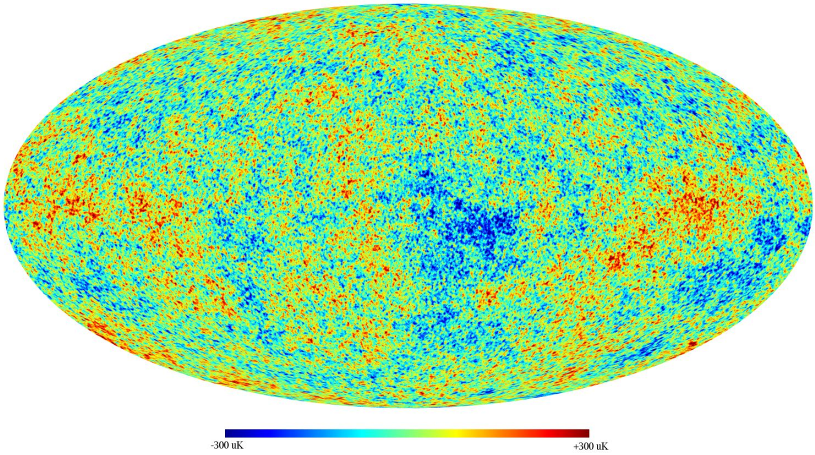
(with Olga Czerwińska, M. Lewicki and Z. Lalak)

# Cosmic microwave background



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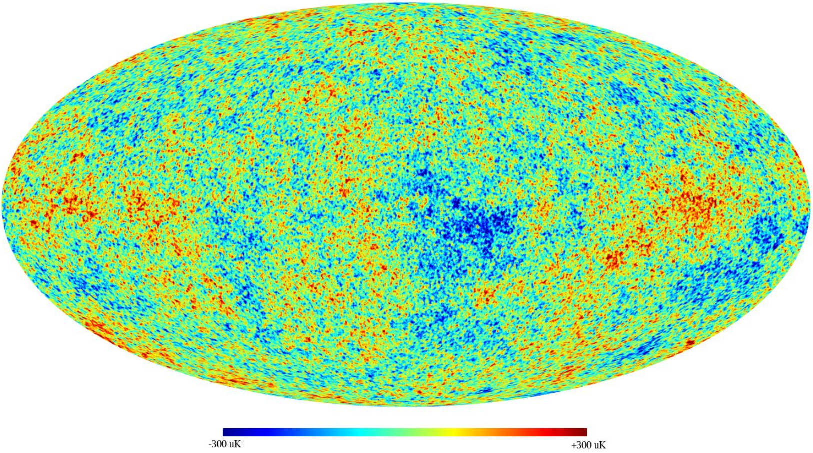
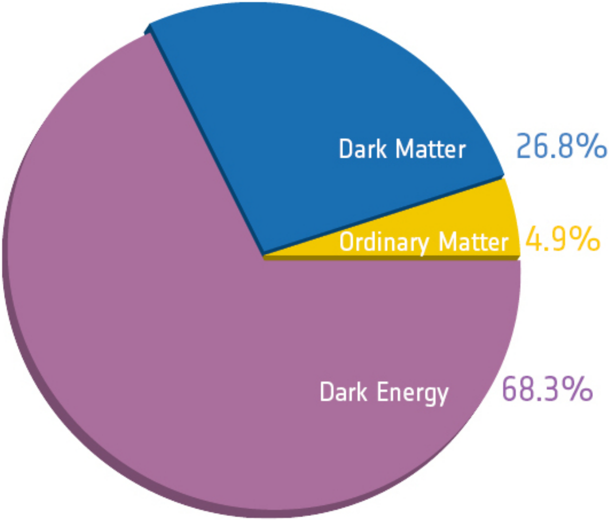



Convention: $8\pi G = 1 = M_p^{-2}$, where $M_p \simeq 2.5 \times 10^{18} GeV$

# The cosmic cake



# Introduction to 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

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

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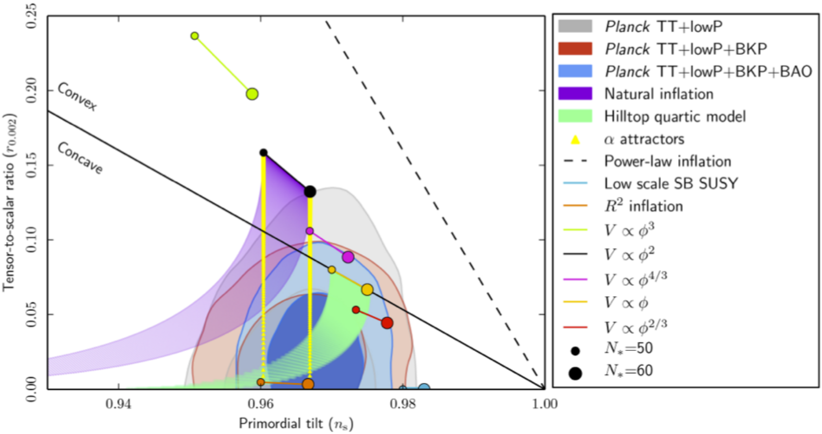
where $H = \frac{\dot{a}}{a}$ is a Hubble parameter. Let us note that

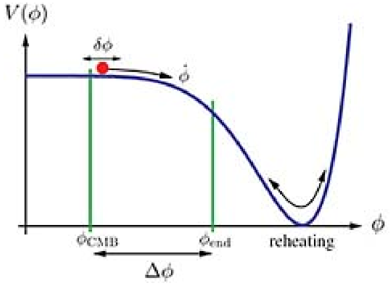
$$\frac{\dot{H}}{H^2} = -\frac{3\dot{\phi}^2}{\dot{\phi}^2 + 2V} \quad \Rightarrow \quad \dot{H} \ll H^2 \ \text{ for } \ \dot{\phi}^2 \ll V \ . \qquad (2)$$

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

# Comparison to the data



# Which models are OK?




Long story short: the Planck+BICEP data suggests, that we need very flat potentials. Inflationary plateaus preferred over chaotic inflation.

# Reheating of the Universe

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

- 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

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

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$$\rho_r \sim N(1-6\xi)^2(1+w)^2 \times 10^{-2} H_{inf}^4 a^{-4} \tag{5}$$

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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

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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

$$w = \frac{n-1}{n+1} \tag{6}$$

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- 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

$$\mathcal{L} = K_1(\phi)X + K_2(\phi)X^2 \ , \quad \text{where} \quad X = \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi \quad (7)$$

# 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?

$$\left.\frac{H}{H_R}\right|_{BBN} = \sqrt{1 + \frac{7}{43}\Delta N_{\nu_{eff}}}\,, \tag{8}$$

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

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!

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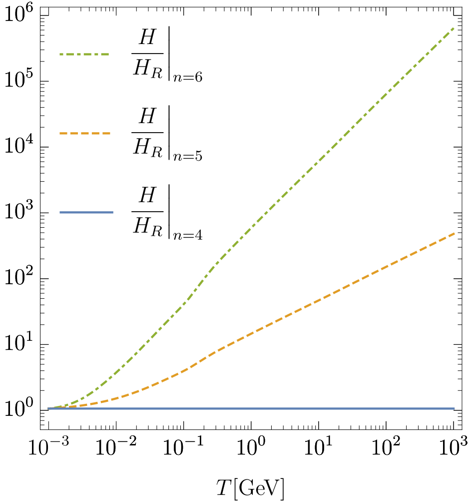


# Constraints from nucleosynthesis

The radiation's energy density at the moment of reheating (which is $\rho_{\rm inf} = \rho_R$) is

$$\rho_{reh} = 3H_{\rm inf}^2 M_p^2 \left( \frac{3N_{\rm eff}(1+w)^2 H_{\rm inf}^2}{128\pi^2 M_p^2} \right)^{\frac{3(w+1)}{3w-1}} \tag{9}$$

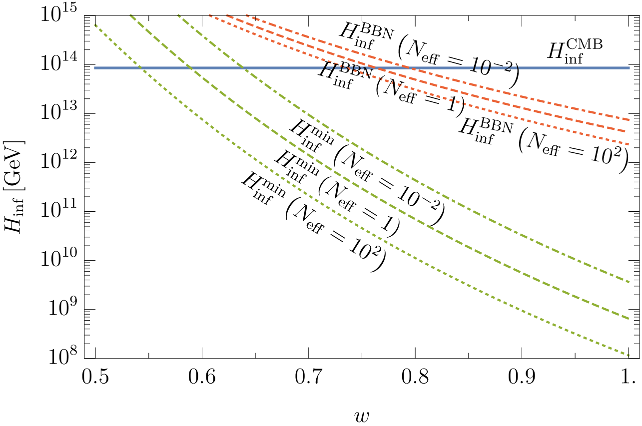
From the constrain on $H$ at the BBN one finds

$$\frac{H_{\rm inf}}{M_p} \geq \left[ (\alpha - 1)^{-\frac{1}{3w-1}} \frac{\left(\frac{1}{3}\rho_{\rm BBN}\right)^{1/4}}{M_p} \left( \frac{3N_{\rm eff}(1+w)^2}{128\pi^2} \right)^{-\frac{3}{4}\frac{1+w}{3w-1}} \right]^{\frac{3w-1}{3w+1}} . \tag{10}$$

So the scale of inflation cannot be too small. Otherwise the inflaton's contribution at the BBN will be too big!

# Constraints from nucleosynthesis

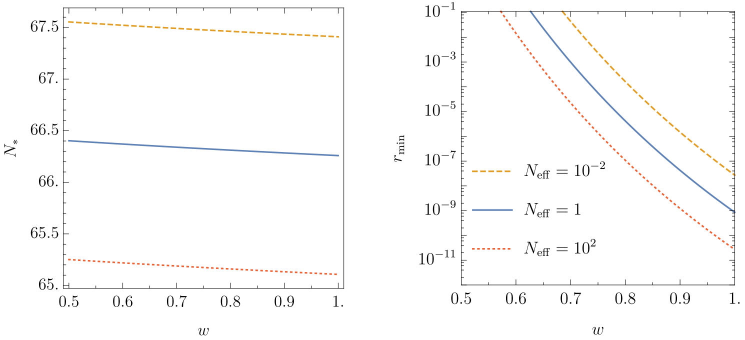
You need to be sure that during the big bang nucleosynthesis radiation dominates, which puts lower and higher bounds on the scale of inflation



# Fixing the pivot scale freeze-out

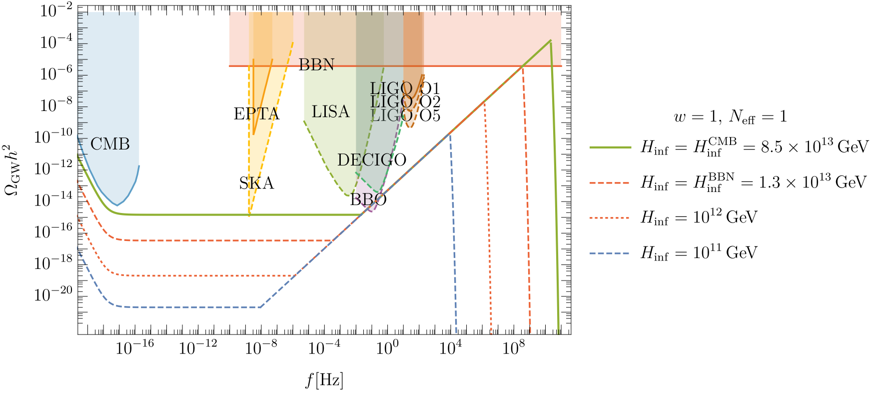
It appears that $N_\star$ is $H_{\rm inf}$ independent! The uncertainty on $N_\star$ is so small!

$$N_\star \simeq 64.82 + \frac{1}{4}\ln\left(\frac{128\pi^2}{N_{\rm eff}(1+w)^2}\right) . \tag{11}$$



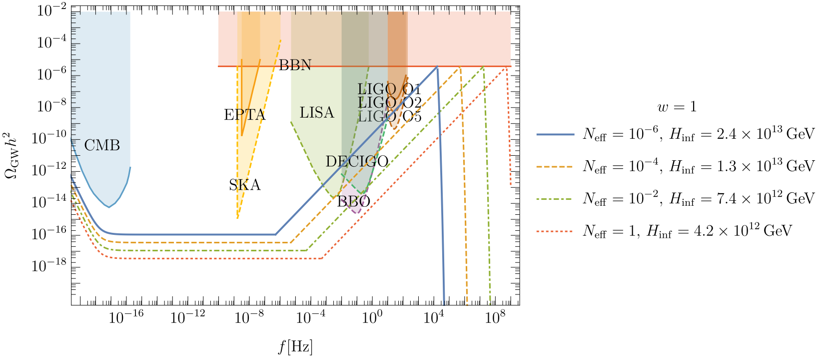
# Constraints from Cosmic Microwave Background

We define $\Omega_{GW} = \rho_{GW}/\rho$. During the dark inflaton domination this guy should grow, because the total energy density redshiftes faster than radiation!

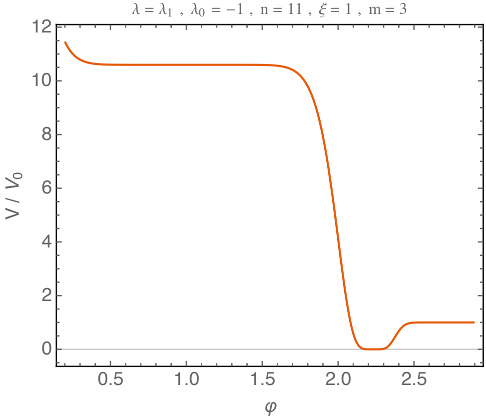


# Gravitational Waves signal

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



# A possible application - Dark energy




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

where $f(\varphi)$ has a stationary point or comes from $\alpha$-attractors. There's a great paper of Dimopoulos and Owen on this kind of potential.

# EW phase transition and gravitational waves production

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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 the bubble production would be suppressed $\Rightarrow \Omega_{GW} \propto (H_r/H)^2 \ll 1$. Later on $\Omega_{GW}$ grows due to the smaller redshift $\Rightarrow$ the final spectrum may be enhanced! A way to test physics beyond the SM and thermal history of the Universe!

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- Possible applications: Dark energy, dark matter