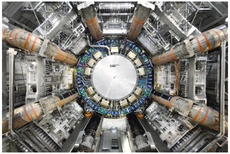
The Standard model Higgs as the inflaton



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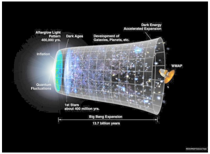

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Outline

1. Inflation—virtues and problems
   - Cosmological requirements
   - “Standard” chaotic inflation
   - Problems with using the SM Higgs for inflation
2. Non-minimally coupled model
   - The model
   - Conformal transformation (Einstein frame)
   - Inflation in the model
   - Radiative corrections—no danger
3. Predictions and expectations
   - CMB parameters—spectrum and tensor modes
   - Higgs mass
4. Conclusions

Outline

Cosmological implications

Problems in cosmology

- Flatness problem (at $T \sim M_P$ density was tuned $|\Omega - 1| \lesssim 10^{-59}$)
- Entropy of the Universe $S \sim 10^{87}$
- Size of the Universe (at $T \sim M_P$ size was $10^{29} M_P$)
- Horizon problem

Solution

Inflation!

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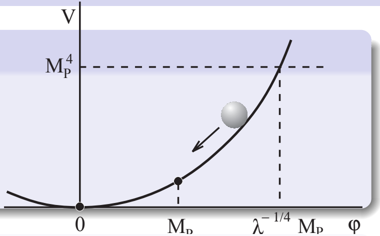
“Standard” chaotic inflation

Usually required for inflation



Scalar field

- quartic coupling constant $\lambda \sim 10^{-13}$
- mass $m \sim 10^{13}\,\text{GeV}$,

Present in the Standard Model

The Higgs boson

- $\lambda \sim 1$
- $m_H \sim 100 GeV$

Even if one writes a potential that flattens at large field values:

- Radiative corrections from t, W generate $\delta V_{rad} \simeq \# h^4 \log h$

Solution: Non-minimal coupling to gravity

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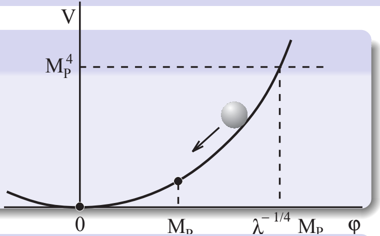

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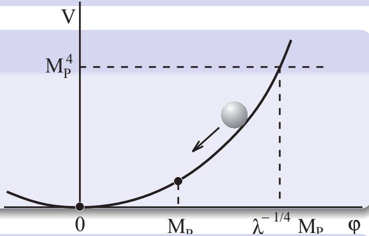

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Non-minimally coupled scalar field

Quite an old idea

Add $\phi^2 R$ term to/instead of the usual $M_P R$ term in the gravitational action

- A.Zee'78, L.Smolin'79, B.Spokoiny'84
- D.Salopek J.Bond J.Bardeen'89

$$S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M^2 + \xi h^2}{2} R + g_{\mu\nu} \frac{\partial^\mu h \partial^\nu h}{2} - \frac{\lambda}{4} \left(h^2 - v^2 \right)^2 \right\}$$

- h is the Higgs field
- $M \gg v\sqrt{\xi}$ so $M \simeq M_P = \frac{1}{\sqrt{8\pi G_N}} = 2.4 \times 10^{18}\,\text{GeV}$

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Conformal transformation

It is possible to get rid of the non-minimal coupling by the conformal transformation (field redefinition)

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \,, \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

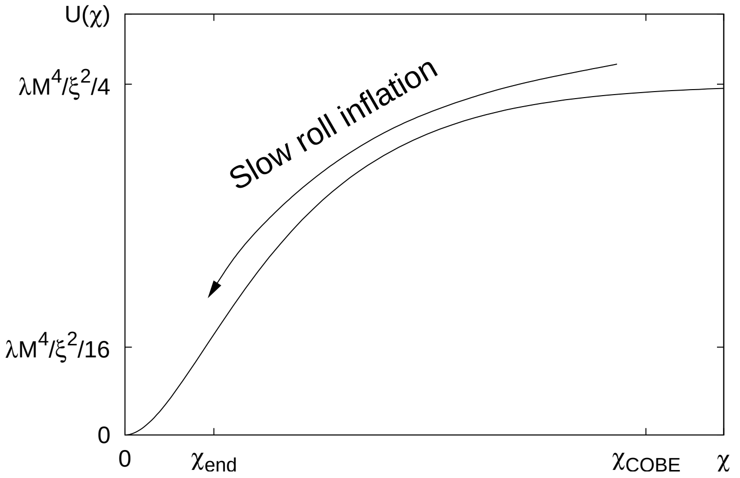
and also redefinition of the Higgs field to make canonical kinetic term

$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_P^2}{\Omega^4}} \quad \Longrightarrow \begin{cases} h \simeq \chi & \text{for } h < M_P/\xi \\ h \simeq \frac{M_P}{\sqrt{\chi}} \exp\left(\frac{\chi}{\sqrt{6}M_P}\right) & \text{for } h > M_P/\sqrt{\xi} \end{cases}$$

Resulting action (Einstein frame action)

$$S_E = \int d^4x \sqrt{-\hat{g}} \left\{ -\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu\chi\partial^\mu\chi}{2} - \frac{1}{\Omega(\chi)^4}\frac{\lambda}{4}\left(h(\chi)^2 - v^2\right)^2 \right\}$$

Inflationary potential



For $\chi \gtrsim M_P$: $$U(\chi) \simeq \frac{\lambda M_P^4}{4\xi^2}\left(1+\exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$$

Slow roll stage

$$\epsilon = \frac{M_P^2}{2}\left(\frac{dU/d\chi}{U}\right)^2 \simeq \frac{4}{3}\exp\left(-\frac{4\chi}{\sqrt{6}M_P}\right)$$
$$\eta = M_P^2\frac{d^2U/d\chi^2}{U} \simeq -\frac{4}{3}\exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)$$

Slow roll ends at $\chi_{\text{end}} \simeq M_P$

Number of e-folds of inflation at the moment h_N is $N \simeq \frac{6}{8}\frac{h_N^2 - h_{\text{end}}^2}{M_P^2/\xi}$

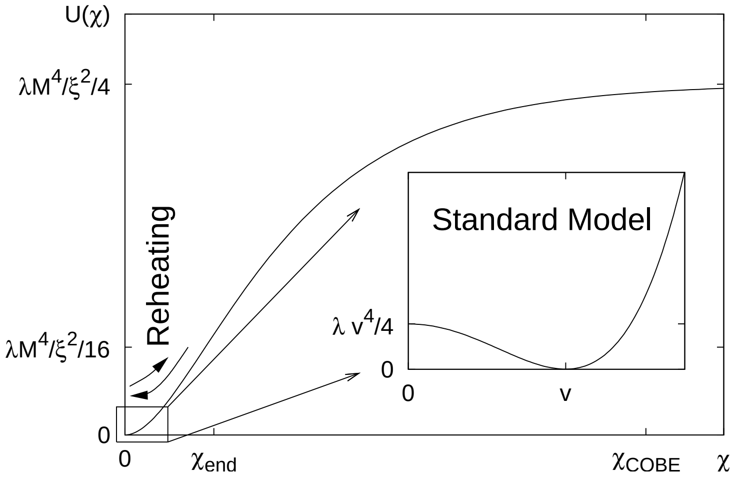
$$\chi_{60} \simeq 5M_P$$

COBE normalization $U/\epsilon = (0.027M_P)^4$ gives

$$\xi \simeq \sqrt{\frac{\lambda}{3}}\frac{N_{\text{COBE}}}{0.027^2} \simeq 49000\sqrt{\lambda} = 49000\frac{m_H}{\sqrt{2}v}$$

Connection of ξ and the Higgs mass!

After inflation—reheating and back to the SM



For $\chi \lesssim M_P/\xi$: the Standard Model.

Instant reheating: $T_{reh} \sim 10^{13}\,\text{GeV}$ (careful analysis gives even larger)

Radiative corrections

Could be a problem

In the ordinary situation effective potential is generated

$$\Delta U(h) \sim \frac{m^4(h)}{64\pi^2} \log \frac{m^2(h)}{\mu^2}$$

standard Yukawa interaction $m = y \cdot h$

$$\Delta U \propto -y^4 h^4 \log \frac{h^2}{\mu^2}$$

Spoils flatness of the potential (for top quark $y \sim 1$!)

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Radiative corrections

This is also cured by non-minimal coupling!

Effective potential is still generated

$$\Delta U(\chi) \sim \frac{m^4(\chi)}{64\pi^2} \log \frac{m^2(\chi)}{\mu^2}$$

But the interactions are suppressed now!

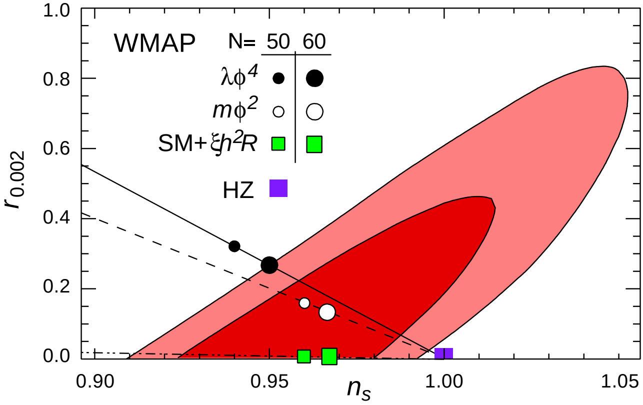
$$m_{\psi,A}(\chi) = \frac{m(v)}{v}\frac{h(\chi)}{\Omega(\chi)} \xrightarrow{\chi\to\infty} \text{const}$$

(where $\Omega(\chi) \propto h(\chi)$ for large χ)

$$\Longrightarrow \qquad \Delta U(\chi) \sim \text{const}$$

Outline

CMB parameters—spectrum and tensor modes



$$n = 1 - 6\varepsilon + 2\eta \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97$$

$$r = 16\varepsilon \simeq \frac{192}{(4N+3)^2} \simeq 0.0033$$

Expected window for the Higgs mass

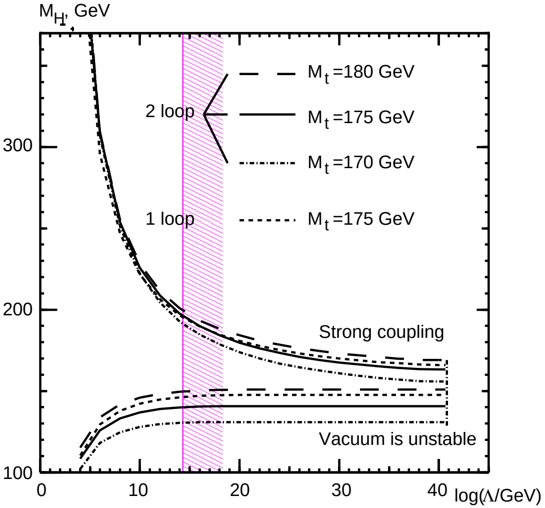
Standard Model should remain applicable up to

$$M_P/\xi \simeq 10^{14}\,\text{GeV}$$

We expect the Higgs mass

$$130\,\text{GeV} < M_H < 190\,\text{GeV}$$

Discovery of the Higgs with different mass will close the model!



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Outline

Conclusions

- Adding non-minimal coupling $\xi H^\dagger H R$ of the Higgs field to the gravity makes inflation possible without introduction of new fields
  - The new parameter of the model, non-minimal coupling ξ, relates the normalization of CMB fluctuations and the Higgs mass $\xi \simeq 49000 \, m_H/\sqrt{2}v$
- Predicted for CMB
  - $n_s \simeq 0.97$
  - $r \simeq 0.0033$
- Expected for LHC
  - Higgs mass $130\,\text{GeV} < M_H < 190\,\text{GeV}$
  - No new physics up to at least $M_P/\xi \sim 10^{14}\,\text{GeV}$

Appendix Outline

Field redefinition

$h \ll M_P/\xi$

$h \simeq \chi \qquad \Omega \simeq 1 \qquad V = \frac{\lambda}{4}\left(h^2 - v^2\right)^2$

$M_P/\xi \ll h \ll M_P/\sqrt{\xi}$

$\chi \simeq \sqrt{3/2}\,\xi h^2/M_P \qquad \Omega \simeq 1 \qquad U(\chi) \simeq \frac{\lambda M_P^2}{6\xi^2}\chi^2$

$h \gg M_P/\sqrt{\xi}$

$h \simeq \frac{M_P}{\sqrt{\xi}}\exp\left(\frac{\chi}{\sqrt{6}M_P}\right) \qquad \Omega \simeq h\sqrt{\xi}/M_P \qquad U(\chi) \simeq \frac{\lambda M_P^4}{4\xi^2}\left(1+\exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$