Distinguishing between R^2 and Higgs inflation

Fedor Bezrukov

University of Connecticut
&
RIKEN-BNL Research Center
USA

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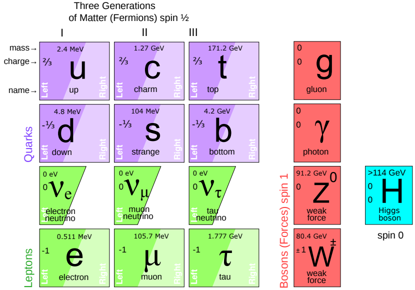
Outline

1. Why whould one want to compare R^2 and Higgs inflation
   - SM is great but definitely not the end of the story
   - νMSM for “late” cosmology
2. Inflation?
   - R^2 inflation
   - Higgs inflation
3. Distinguishing R^2 and Higgs inflation
   - CMB predictions
   - Gravity waves
   - Higgs boson mass
4. Conclusions

Standard Model – describes nearly everything that we know

Gauge theory $SU(3) \times SU(2) \times U(I)$
Describes (together with Einstein gravity)

- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ($T < 1$ MeV, $t > 1$ sec)

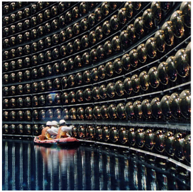


Standard Model has experimental problems

- Laboratory
  - Neutrino oscillations
- Cosmology
  - Baryon asymmetry of the Universe
  - Dark Matter
  - Inflation
    - Horizon problem (and flatness, entropy, ...)
    - Initial density perturbations
  - Dark Energy

Neutrino oscillations

SAGE neutrino observatory (solar oscillations evidence $\nu_e \to \nu_\mu$)

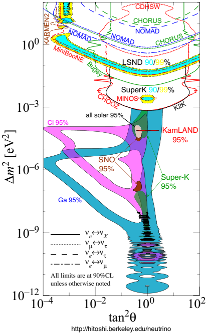


SuperKamiokande (atmosferic oscillations $\nu_\mu \to \nu_\tau$)

Reactor neutrinos, accelerator neutrinos

Oscillation parameters

Δm^2_{21}	$7.59_{\pm 0.20} \times 10^{-5}$ eV^2
$\sin^2 2\theta_{12}$	0.87 ± 0.03
$\lvert\Delta m^2_{32}\rvert$	$2.43_{\pm 0.13} \times 10^{-3}$ eV^2
$\sin^2 2\theta_{23}$	> 0.92
$\sin^2 2\theta_{13}$	< 0.15



Baryon asymmetry of the Universe

- Current universe contains baryons and no antibarions
- Current baryon density

$$\eta_B \equiv \frac{n_B}{n_\gamma} \simeq 6.1 \times 10^{-10}$$

- Does not fit into the SM (too weak CP violation, too smooth phase transition)

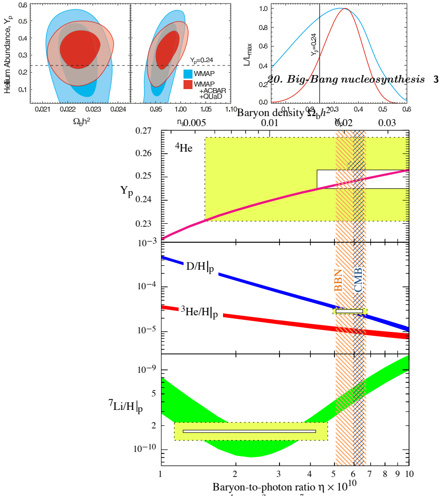
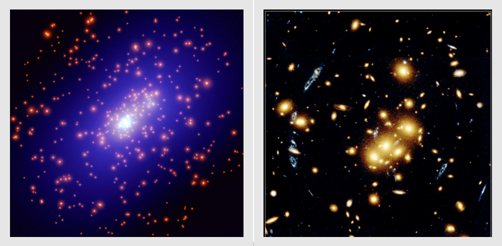
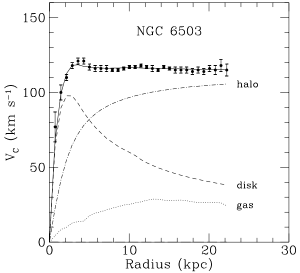


Figure 20.1: The abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard model of Big-Bang nucleosynthesis [11] – the bands show the 95% CL range. Boxes

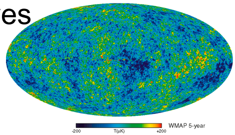
Dark Matter

Gravitational lensing





Rotation curves



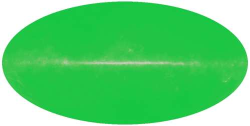
$\Omega_{DM} \simeq 0.21$

CMB fluctuations

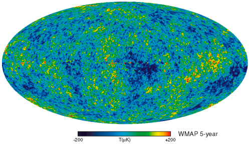
“Bullet” cluster

Inflation evidence – horizon problem

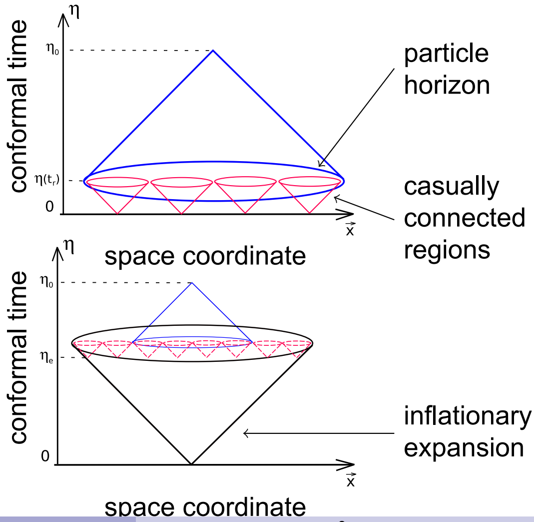
Microwave sky



Temperature fluctuations $\delta T/T \sim 10^{-5}$

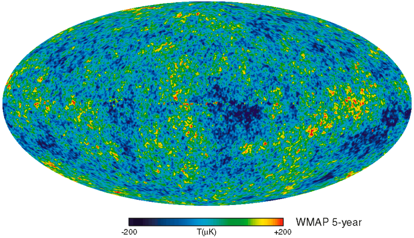


Universe is uniform!

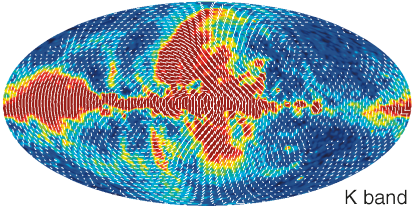


CMB gives measured predictions from inflation

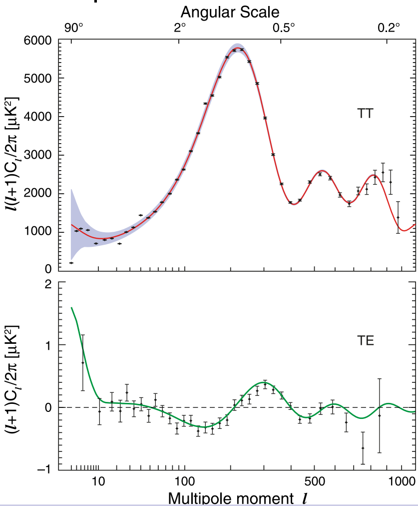
Temperature fluctuations



Polarization

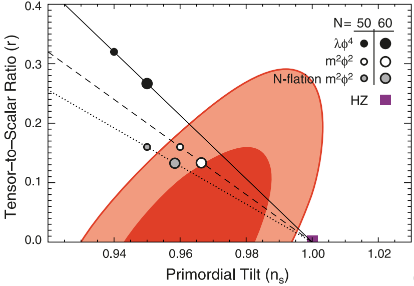


CMB spectrum



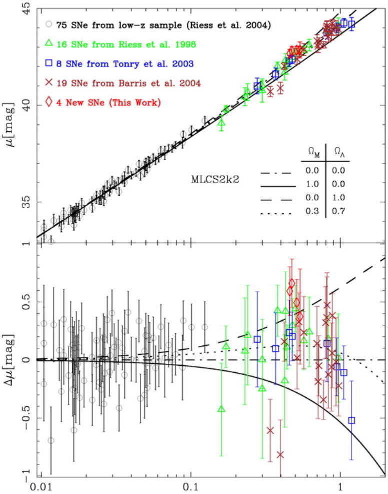
Inflationary parameters from CMB

- Spectrum of primordial scalar density perturbations is just a bit not flat $n_s - 1 \equiv \frac{d\log\mathcal{P}_\mathcal{R}}{d\log k}$
- Tensor perturbations are compatible with zero $r \equiv \frac{\mathcal{P}_{\text{grav}}}{\mathcal{P}_\mathcal{R}}$



(WMAP07 results)

Dark Energy



← Supernova type Ia redshifts

accelerated expansion of the Universe today

$$\Omega_\Lambda \simeq 0.74$$

Different from inflation

- Much lower scale
- No need to stop it

Can be explained "just" by a cosmological constant

Let us expand the model in a minimal way

I will follow a "Minimal" approach

Explain the experimental facts with

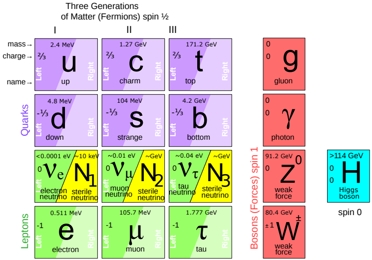
- minimal number of new particles
- no new physical scales

- Higgs boson inflation
- R^2 inflation
- …

} + νMSM

Dark matter, BAU – just add sterile neutrinos (νMSM)

gravity + inflation +



[Asaka, Blanchet, Shaposhnikov’05]

- DM sterile neutrinos are produced by oscillations from active neutrinos
- Two heavier sterile neutrinos provide for the baryon asymmetry (via low scale leptogenesis)

R^2 inflation

Modifying the gravity action gives inflation

The first working inflationary model

[Starobinsky'80]

The gravity action gets higher derivative terms

$$S_J = \int d^4x\sqrt{-g}\left\{-\frac{M_P^2}{2}R + \frac{\zeta^2}{4}R^2\right\} + S_{SM}$$

Conformal transformation

conformal transformation (change of variables)

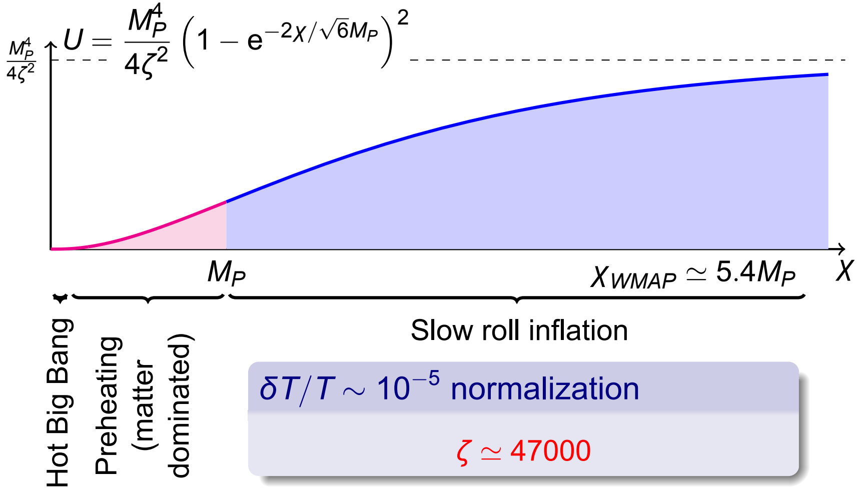
$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \; , \qquad \Omega^2 \equiv \exp\left(\frac{\chi(x)}{\sqrt{6}M_P}\right)$$

$\chi(x)$ — new field (d.o.f.) “scalaron”

Resulting action (Einstein frame action)

$$S_E = \int d^4x\sqrt{-\hat{g}}\left\{-\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu\chi\partial^\mu\chi}{2} - \frac{M_P^4}{4\zeta^2}\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)^2\right\}$$

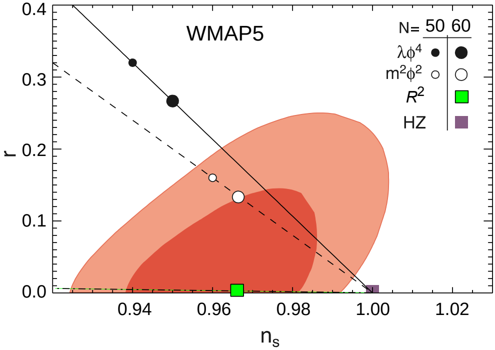
Inflationary potential



$\delta T/T \sim 10^{-5}$ normalization

$\zeta \simeq 47000$

CMB parameters are predicted



spectral index $n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97$

tensor/scalar ratio $r \simeq \frac{192}{(4N+3)^2} \simeq 0.0033$

Reheating is due to the Planck suppressed terms

Jordan frame action – matter

$$S_J^{\text{scalar}} = \int d^4x \left\{ \frac{1}{2}\partial\varphi\partial\varphi - \frac{m_\varphi^2}{2}\varphi^2 \right\}$$

$$S_J^{\text{fermion}} = \int d^4x \left\{ i\bar{\psi}\not{D}\psi - m_\psi\bar{\psi}\psi \right\}$$

$$\hat{\varphi} = \Omega^{-1}\varphi$$

$$\hat{\psi} = \Omega^{-3/2}\psi$$

$$\Omega^2 \equiv \exp\left(\frac{\chi(x)}{\sqrt{6}M_P}\right)$$

Einstein frame action – χ interactions are M_P suppressed

$$S_E^{\text{scalar}} = \int d^4x \left\{ \frac{1}{2}\Omega^{-2}\partial(\Omega\hat{\varphi})\partial(\Omega\hat{\varphi}) - \frac{m_\varphi^2}{2}\Omega^{-2}\hat{\varphi}^2 \right\}$$

$$S_E^{\text{fermion}} = \int d^4x \left\{ i\bar{\hat{\psi}}\not{D}\hat{\psi} - m_\psi\Omega^{-1}\bar{\hat{\psi}}\hat{\psi} \right\}$$

Reheating happens at relatively low temperature

- Scalaron decay ($\mu = M_P/(\sqrt{3}\zeta)$ is the scalaron mass)
$$\Gamma_{\chi\to\varphi\varphi} = \frac{\mu^3}{192\pi M_P^2} \qquad \Gamma_{\chi\to\bar\psi\psi} = \frac{\mu m_\psi^2}{48\pi M_P^2}$$
- Main decay contribution is from the non-conformal kinetic term of the scalar
- No resonant enhancement (near immediate rescattering of the decay products)

Reheating temperature from the scalaron decay

$$T_r \approx 3.5 \times 10^{-2} g_*^{-1/4} \sqrt{\frac{N_s}{\zeta}} \approx 3.1 \times 10^9\,\text{GeV}$$

[Gorbunov, Panin'11]

Higgs inflation

Non-minimal coupling to gravity solves the problem

Quite an old idea

Add h^2R term (required by renormalization) to of the usual M_PR term in the gravitational action

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

Scalar part of the (Jordan frame) action

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

- h is the Higgs field; $M_P \equiv \frac{1}{\sqrt{8\pi G_N}} = 2.4 \times 10^{18}$ GeV
- SM higgs vev $v \ll M_P/\sqrt{\xi}$

Conformal transformation – way to calculate

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

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

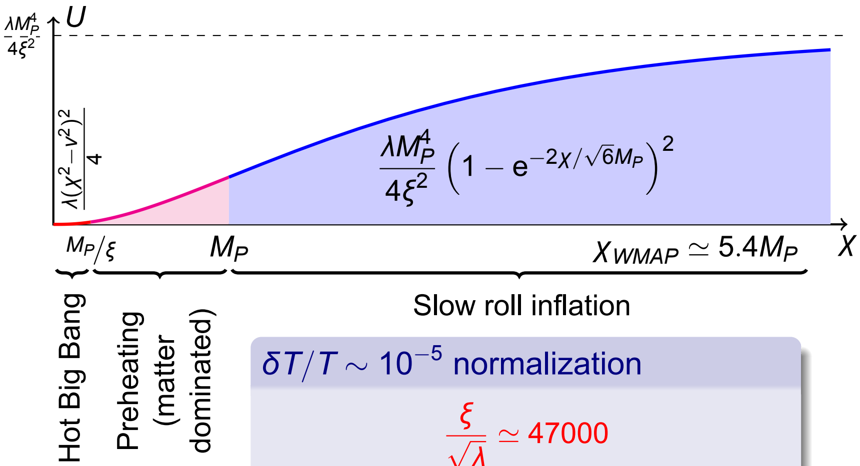
Redefinition of the Higgs field to get canonical kinetic term

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

Resulting action (Einstein frame action)

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

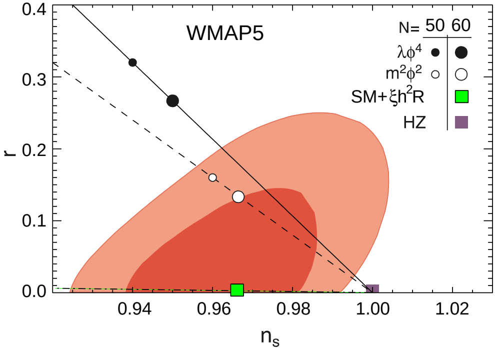
Potential – different stages of the Universe



$\delta T/T \sim 10^{-5}$ normalization

$$\frac{\xi}{\sqrt{\lambda}} \simeq 47000$$

CMB parameters are predicted

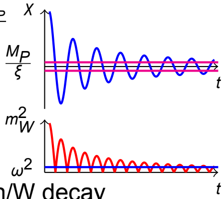


spectral index $n \simeq 1 - \frac{8(4N+9)}{(4N+3)^2} \simeq 0.97$

tensor/scalar ratio $r \simeq \frac{192}{(4N+3)^2} \simeq 0.0033$

Preheating

- Background evolution after inflation $\chi < M_P$ ($h < M_P/\sqrt{\xi}$)
  - Quadratic potential $U \simeq \frac{\mu^2}{2}\chi^2$ with $\mu = \sqrt{\frac{\lambda}{3}}\frac{M_P}{\xi}$
  - Matter dominated stage $a \propto t^{2/3}$



- Stohastic resonance
  - Particle masses $m_W^2(\chi) \sim g^2 \frac{M_P|\chi|}{\xi}$
  - W bosons are created (non-relativistic)
    - $\sqrt{\langle\chi^2\rangle} \gtrsim 23\left(\frac{\lambda}{0.25}\right)\frac{M_P}{\xi}$: non-resonant creation/W decay
    - $\sqrt{\langle\chi^2\rangle} \lesssim 23\left(\frac{\lambda}{0.25}\right)\frac{M_P}{\xi}$: resonant creation/W annihilation
  - Higgs creation – relativistic, less efficient
    $\sqrt{\langle\chi^2\rangle} \sim 2.6\left(\frac{\lambda}{0.25}\right)^{1/2}\frac{M_P}{\xi}$

Reheating at

$$T_r \gtrsim 3.4 \times 10^{13}\ \text{GeV}$$

[FB, Gorbunov, Shaposhnikov'08]. [Garcia-Bellido, Figueroa, Rubio'09]

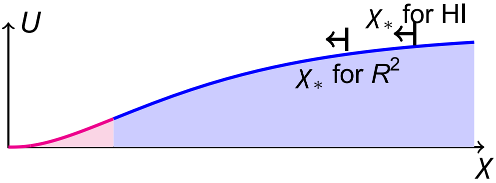
Different T_r means different field at horizon exit

- Hubble at the Horizon exit $H_* = \frac{k}{a_0}\frac{a_0}{a_r}\frac{a_r}{a_e}e^{N_*}$

$$\frac{a_r}{a_0} = \left(\frac{g_0}{g_r}\right)^{1/3}\frac{T_0}{T_r}, \qquad \frac{a_r}{a_e} = \left(\frac{V_e}{g_r\frac{\pi^2}{30}T_r^4}\right)^{1/3}$$

- E-folding number of the hirizon exit

$$N_* \simeq 57 - \frac{1}{3}\log\frac{10^{13}\,\text{GeV}}{T_r} \quad \Rightarrow \quad N_{HI} = 57.7, \qquad N_{R^2} = 54.4$$

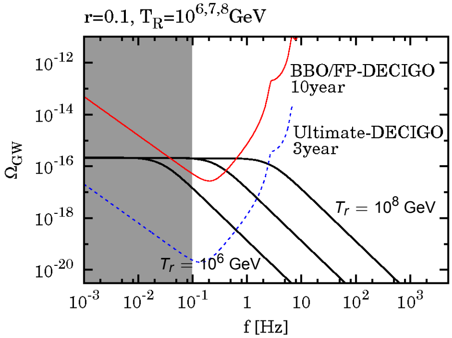


Different predictions for CMB observables

Higgs inflation:	$n_s = 0.967$,	$r = 0.0032$
R^2 inflation:	$n_s = 0.965$,	$r = 0.0036$

- Planck $\Delta n_s \sim 0.0045$ — not there, but not too far away
- CMBPol $\Delta n_s \sim 0.0016$, $\delta r \sim 10^-3$

Features in tensor perturbations for gravity wave detectors

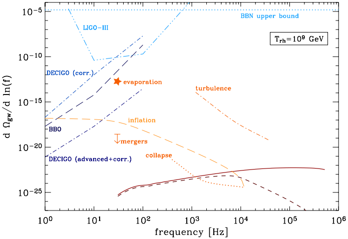


[Kuroyanagi et.al.'11]

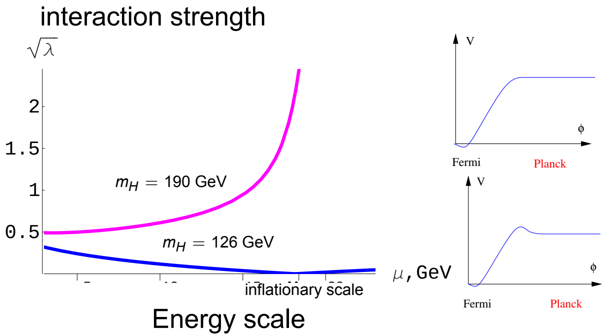
Gravity waves at matter dominated stage

- Primordial density of scalar perturbations $\delta\rho/\rho \sim 10^{-5}$
- Grow $\propto$ scalefactor at matter domination
- Can reach $\delta\rho/\rho \sim 1$ for long matter domination and small scales, generating scalaron (inflaton) "clumps"
- Gravity waves can be generated
  - collapse of scalaron perturbations
  - merging of clumps
  - evaporation of clumps at reheating

For R^2 inflation can be in DECIGO reach [Jedamzik et.al.'10]



Higgs mass bound in the Higgs inflation



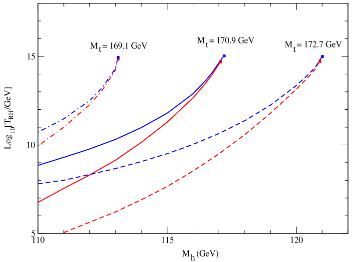
Higgs mass bound

$$m_H > 128.9\,\text{GeV} + \frac{m_t - 172.9}{1.1} \times 2.2 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.56$$

[FB, Magnin, Shapshnikov'08, FB, Shaposhnikov'09]

No (weak) Higgs mass bounds in the R^2 inflation

The electroweak vacuum may decay at high temperature



Higgs mass bounds in R^2

$$m_H > 116.5\,\text{GeV} + \frac{m_t - 172.9}{1.1} \times 2.2 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.56$$

[Espinosa, Giudice, Riotto'08]

- If SM (νMSM) is valid up to the inflationary scale —
  - still can explain all observable experimental facts
  - while nothing (except Higgs boson) is seen on LHC
- Inflation can be provided in several ways, with seemingly equivalent potentials
  - Higgs inflation (non-minimally coupled to gravity)
  - R^2 inflation
- Models can be distinguished, due to different evolution after inflation
  - slightly different CMB predictions
  - gravity wave signatures
  - Higgs inflation may be excluded by discovery of a light Higgs boson

Radiative corrections modify the inflationary potential

If we assume

- the full UV theory respects the scale invariance at high fields (or shift invariance in the Einstein frame)
- the quadratic divergences are subtracted to zero (e.g. work in dimensional regularisation)

then we can compute the radiative corrections to the inflationary potential *and* relate them to the parameters of the low energy physics (Higgs boson mass).

[FB, Sibiryakov, Shaposhnikov'10]

Prescription to calculate potential with radiative corrections

1. Run all constants with SM two-loop RG equations from the EW scale up to $M_P/\sqrt{\xi}$
2. Run all constants $\lambda_i(\mu)$ with chiral EW theory RG equations up to scale μ equal to a typical particle mass for the given field background χ
$$\mu^2 = \kappa^2 m_t^2(\chi) = \kappa^2 \frac{y_t(\mu)^2}{2} \frac{M_P^2}{\xi(\mu)} \left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right) .$$
3. Calculate the effective potential $U(\chi) = U_{\text{tree}}(\lambda_i(\mu), \chi) + U_{1-\text{loop}}(\lambda_i(\mu), \chi) + U_{2-\text{loop}}(\lambda_i(\mu), \chi)$
4. Calculate the inflationary properties for the resulting potential

[FB, Magnin, Shapshnikov'08, FB, Shaposhnikov'09]

Light inflaton model adds one scalar particle to the SM

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \alpha H^\dagger H X^2 + \frac{\beta}{4} X^4$$

Standard Model — Interaction — Inflationary sector

(where $\beta \simeq \beta_0 = 1.5 \times 10^{-13}$ – inflationary requirement)

$$m_X = m_h \sqrt{\frac{\beta}{2\alpha}}$$ – the inflaton mass is defined by α

The Higgs-inflaton scalar potential is

$$V(H, X) = \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2 + \frac{\beta}{4} X^4 - \frac{1}{2}\mu^2 X^2 + V_0$$

[Anisimov, Bartocci, FB'08, FB, Gorbunov'09]

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