Dmitry Gorbunov, JGRG 22(2012)111421

"Higgs-inflation and the latest LHC results"

RESCEU SYMPOSIUM ON

GENERAL RELATIVITY AND GRAVITATION

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Higgs-inflation
and the latest LHC results

Dmitry Gorbunov

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RESCEU Symposium on General Relativity and Gravitation

JGRG22, Tokyo

Outline

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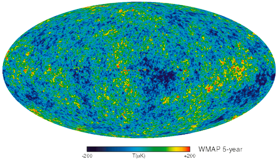
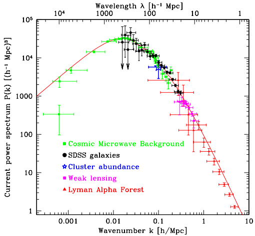
Inflationary solution of Hot Big Bang problems

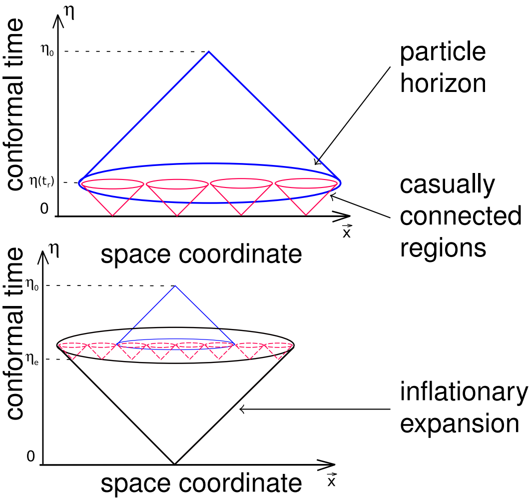
Temperature fluctuations $\delta T/T \sim 10^{-5}$



Universe is uniform!



$\delta\rho/\rho \sim 10^{-5}$



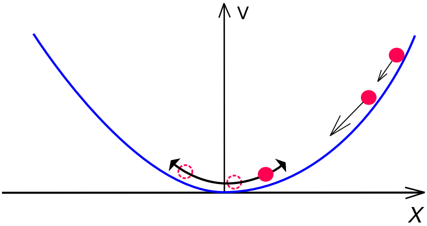
Chaotic inflation: simple realization

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R + \frac{(\partial_\mu X)^2}{2} - \beta X^4\right)$$

$$\ddot{X} + 3H\dot{X} + V'(X) = 0$$

$$\frac{\dot{a}^2}{a^2} = H^2 = \frac{1}{M_P^2}V(X)\;, \qquad a(t) \propto e^{Ht}$$

Chaotic inflation, A.Linde (1983)



slow roll conditions get satisfied at
$X_e > M_{Pl}$ $\qquad M_P^2 = M_{Pl}^2/(8\pi)$

generation of scale-invariant scalar (and tensor) perturbations from exponentially stretched quantum fluctuations of X $\Longrightarrow$

$\delta\rho/\rho \sim 10^{-5}$ requires
$V = \beta X^4 : \beta \sim 10^{-13}$

We have scalar in the SM! The Higgs field!

In a unitary gauge $H^T = \left(0, (h+v)/\sqrt{2}\right)$ (and neglecting $v = 246$ GeV) $\lambda \sim 0.1 - 1$

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

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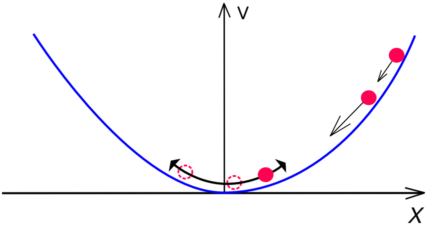

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Outline

Higgs-inflation

F.Bezrukov, M.Shaposhnikov (2007)

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R - \xi H^\dagger HR + \mathscr{L}_{SM}\right)$$

In a unitary gauge $H^T = \left(0\,,(h+v)/\sqrt{2}\right)$ (and neglecting $v = 246\,\text{GeV}$)

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2+\xi\, h^2}{2}R + \frac{(\partial_\mu\, h)^2}{2} - \frac{\lambda\, h^4}{4}\right)$$

slow roll behavior due to modified kinetic term even for $\lambda \sim 1$

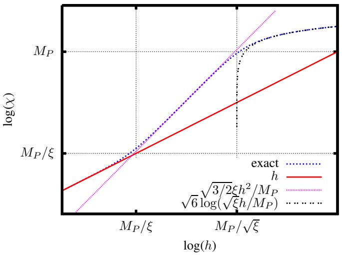
Go to the Einstein frame: $(M_P^2 + \xi\, h^2)\, R \to M_P^2\, \tilde{R}$

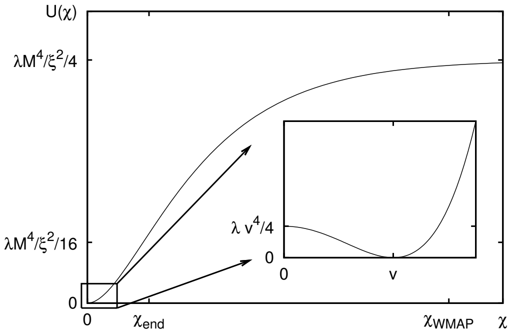
$$g_{\mu\nu} = \Omega^{-2}\tilde{g}_{\mu\nu}\,, \qquad \Omega^2 = 1 + \frac{\xi\, h^2}{M_P^2}$$

with canonically normalized χ:

$$\frac{d\chi}{dh} = \frac{M_P\sqrt{M_P^2 + (6\xi+1)\xi\, h^2}}{M_P^2+\xi\, h^2}\,,\;\; U(\chi) = \frac{\lambda\, M_P^4\, h^4(\chi)}{4(M_P^2+\xi\, h^2(\chi))^2}\,.$$

we have a flat potential at large fields: $U(\chi) \to \text{const}$ @ $h \gg M_P/\sqrt{\xi}$





Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

effective dynamics : $h^2 \to \chi$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

Advantage: NO NEW interactions to reheat the Universe
inflaton couples to all SM fields!

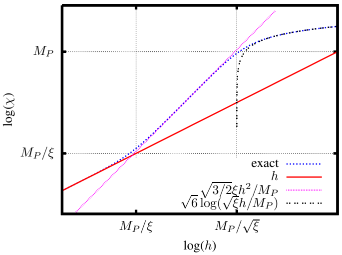
exponentially flat potential! @ $h \gg M_P/\sqrt{\xi}$:

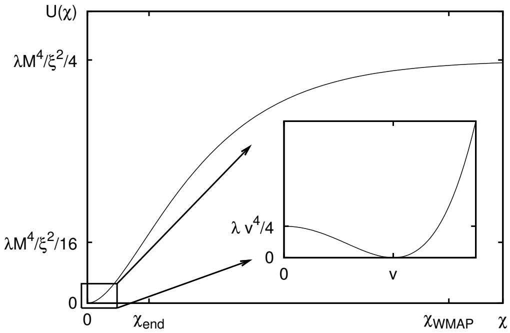
$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

coincides with R^2-model!

But NO NEW d.o.f. 0812.3622, 1111.4397
Different reheating temperature...

from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$





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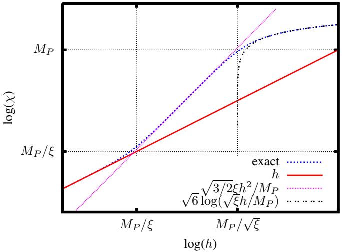
F.Bezrukov, D.G., M.Shaposhnikov, 0812.3622



$$m_W^2(\chi) = \frac{g^2}{2\sqrt{6}}\frac{M_P|\chi(t)|}{\xi}$$

$$m_t(\chi) = y_t\sqrt{\frac{M_P|\chi(t)|}{\sqrt{6}\xi}}\,\text{sign}\,\chi(t)$$

Reheating by Higgs field

after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

reheating via W^+W^-, ZZ production at zero crossings

then nonrelativistic gauge bosons scatter to light fermions

$$\chi \to W^+W^- \to f\bar{f}$$

effective dynamics : $h^2 \to \chi$

$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

Hot stage starts almost from $T = M_P/\xi \sim 10^{14}$ GeV:

$$3.4\times 10^{13}\,\text{GeV} < T_r < 9.2\times 10^{13}\left(\frac{\lambda}{0.125}\right)^{1/4}\text{GeV}$$

Advantage: NO NEW interactions
to reheat the Universe
inflaton couples to all SM fields!

$n_s = 0.967$, $r = 0.0032$

WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$

F.Bezrukov, D.G., 1111.4397

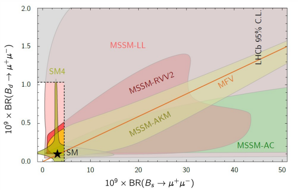
True Extension of the Standard Model should

- Reproduce the correct neutrino oscillations
- Contain the viable DM candidate
- Be capable of explaining the baryon asymmetry of the Universe
- Have the inflationary mechanism operating at early times

Guiding principle:

use as little “new particle physics” as possible

Why?



No any hints observed so far!

No FCNC

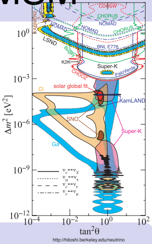
No WIMPs

No . . .

Nothing new at all

(apart of QCD. . .)

Straightforward renormalizable completion: νMSM



- Use as little “new physics” as possible
- Require to get the correct neutrino oscillations
- Explain DM and baryon asymmetry of the Universe

Lagrangian

Most general renormalizable with 3 right-handed neutrinos N_I

$$\mathscr{L}_{\nu MSM} = \mathscr{L}_{MSM} + \overline{N}_I i\partial\!\!\!/ N_I - f_{I\alpha} H \overline{N}_I L_\alpha - \frac{M_I}{2} \overline{N}_I^c N_I + \text{h.c.}$$

Extra coupling constants:

3 Majorana masses M_i — T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

15 new Yukawa couplings — T.Asaka, M.Shaposhnikov (2005)
(Dirac mass matrix $M^D = f_{I\alpha}\langle H\rangle$ has 3 Dirac masses,
6 mixing angles and 6 CP-violating phases)

The model is remarkably simple:

It explains

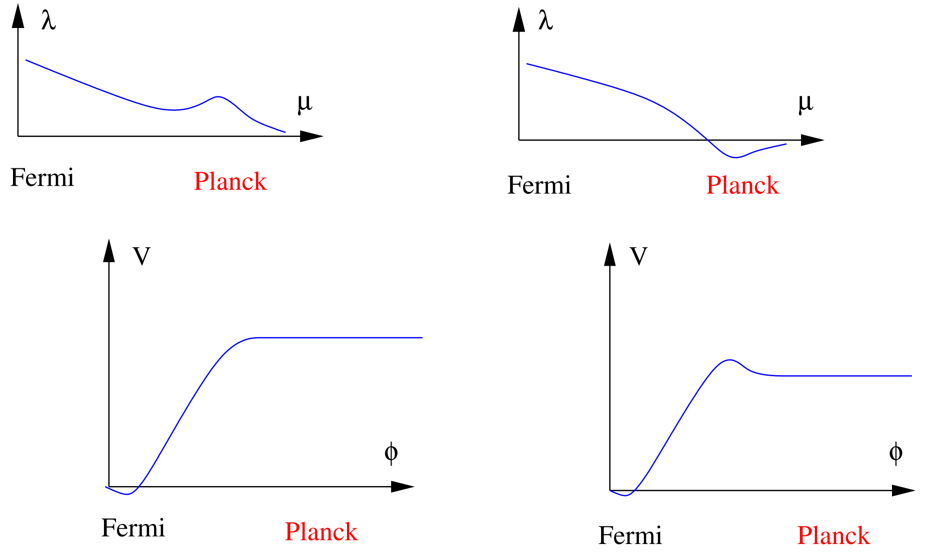
- inflation without introducing a new scalars
- post-inflationary reheating without new interactions with SM fields

It may be further modified (e.g. by νMSM) to resolve other phenomenological problems of the SM:

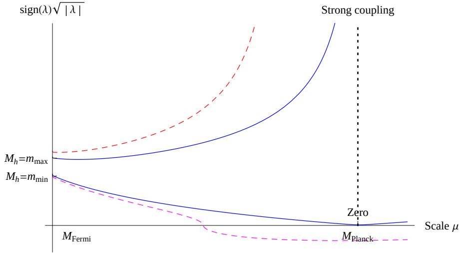
- neutrino oscillations
- dark matter
- baryon asymmetry of the Universe

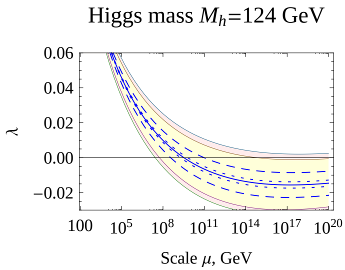
Outline

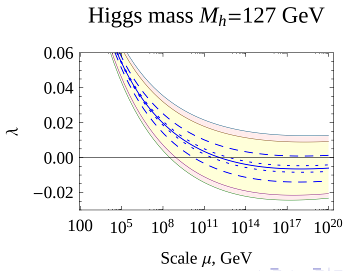
Naively all we need is $V \sim \lambda\, \phi^4 > 0$... (here in the Einstein frame)



Critical point: where EW-vacuum becomes unstable







F.Bezrukov, M.Shaposhnikov (2009)
F.Bezrukov, D.G. (2011)
F.Bezrukov, M.Kalmykov, B.Kniehl, M.Shaposhnikov (2012)
G. Degrassi et al (2012)

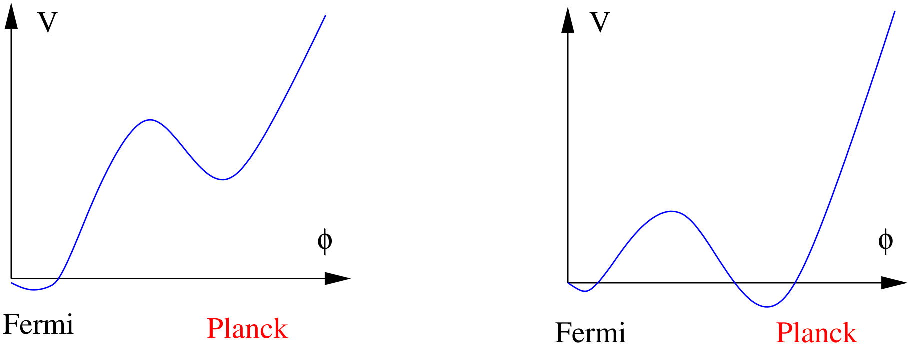
$$m_h^{\rm H} > \left[129.0 + \frac{m_t - 172.9\,{\rm GeV}}{1.1\,{\rm GeV}} \times 2.2 - \frac{\alpha_s(M_Z) - 0.1181}{0.0007} \times 0.56\right] {\rm GeV}$$

present measurements at CMS and ATLAS:

$$m_h \simeq 125.5 \pm 1\ {\rm GeV}$$

Update at HCP2012, Nov.12-16

Multiple point principle: D.Bennett, H.Nielsen (1993), C.Froggatt, H.Nielsen (1995)



$\Lambda \simeq 0 \Rightarrow V(\phi_{EW}) = V(\phi_{Planck}) = 0 \Rightarrow \lambda(\mu_{Planck}) = 0$

Planck scale enters $\Rightarrow V'(\phi_{EW}) = V'(\phi_{Planck}) = 0 \Rightarrow \frac{d\lambda(\mu)}{d\log\mu}(\mu_{Planck}) = 0$

It gives $m_t \simeq 173$ GeV and $m_h \simeq 129$ GeV

Upper limit on the Higgs boson mass

Higgs-inflation: selfconsistency, $h \sim M_{Pl}$

F.Bezrukov, M.Shaposhnikov (2009)
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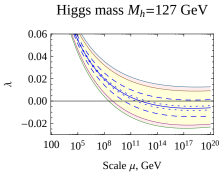
critical value refers to $\lambda(h \to M_P) \to 0$

WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda} \cdots \to 0$?

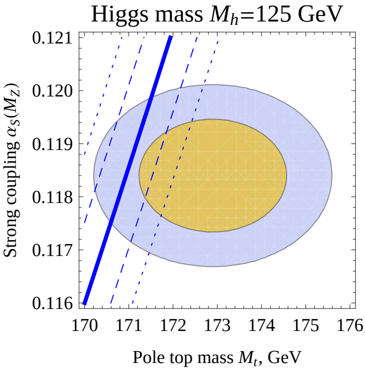
$\xi \sim 1$ would imply $\lambda \sim 10^{-13}$ at finit interval $\Delta h \sim M_{Pl}$

$$\frac{d\lambda}{d\log\mu} = +\#\lambda^2 - Y_t^4 + \alpha_W + \ldots$$

Can not be arranged. . .



errors in M_W give uncertainties < 0.2 GeV



Experimental uncertainties: 2-3 GeV
Theoretical uncertainties: 1-2 GeV

Important for further improvement:

- 3-loop matching and QCD for t
- measurement of α_s, m_t and m_h at LHC(?)

The SM Higgs boson (?) found @ 125 GeV

- When the digit matters. . . !!
- Smooth incorporation of gravity @ M_{Pl}?

  – Great desert up to Gravity scale (asymptotic safety?)

  (no gauge hierarchy problem: all NP we need is either @ EW-scale or in gravity sector)

  – viable (ν, DM, BAU) SM extensions: R^2-inflation with νMSM, Higgs-inflation (can $S^2 H^\dagger H$ help?), . . .
- It's another scale: e.g. PQ-scale, or Leptogenesis, etc
- Just a coincidence, e.g. as GUT

  – gauge coupling unification $\to$ (gauge hierarchy problem, then not at a single point) $\to$ SUSY

  – there are other "hints":

  $m_h^2 \approx m_Z m_t, \qquad m_h \approx v/2 \approx 3m_Z/2, \qquad \lambda\,(m_h = 125\text{ GeV}) \approx 0.125$

  Is Nature aware of GeV and decimal system?

Outline

Fine theoretical descriptions both in

UV: $\chi \gg M_P\,,\ U = \text{const} + \mathcal{O}\left(\exp\left(-\sqrt{2}\chi/\sqrt{3}M_P\right)\right)$

and in

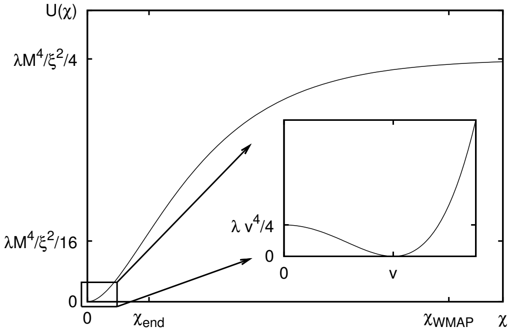
IR: $h \ll M_P/\xi\,,\ U = \frac{\lambda}{4}h^4$

no gravity corrections at inflation!
(Unlike βX^4) All inflationary predictions are robust

Obvious problem with QFT-description of IR/UV matching at intermediate $\chi < \chi_{\text{end}}$ and $h < M_P/\sqrt{\xi}$

Hence no reliable prediction for the SM Higgs boson mass $m_h = \sqrt{2\lambda}\,v$ except the absence of Landau pole and wrong minimum of Higgs potential (well) below M_P/ξ

$$130\,\text{GeV} \lesssim m_h \lesssim 190\,\text{GeV}$$



exponentially flat potential! @ $\quad h \gg M_P/\sqrt{\xi}$:

$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

coincides (apart of $T_{reh} \simeq 10^{14}$ GeV) with R^2-model!
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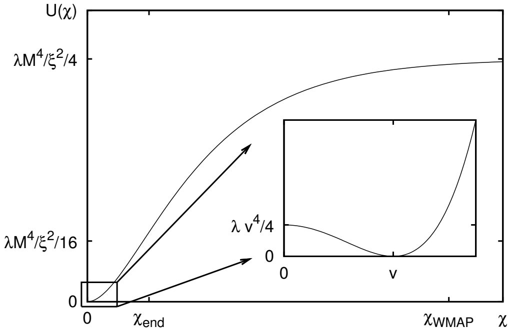

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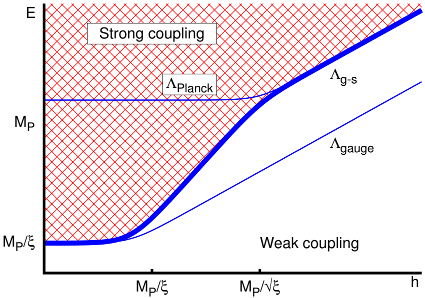
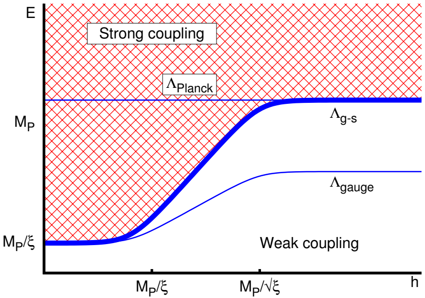
Strong coupling in Higgs-inflation: scatterings

Jordan frame



Einstein frame



gravity-scalar sector:

$$\Lambda_{g-s}(h) \simeq \begin{cases} \frac{M_P}{\xi}, & \text{for } h \lesssim \frac{M_P}{\xi}, \\ \frac{\xi h^2}{M_P}, & \text{for } \frac{M_P}{\xi} \lesssim h \lesssim \frac{M_P}{\sqrt{\xi}}, \\ \sqrt{\xi} h, & \text{for } h \gtrsim \frac{M_P}{\sqrt{\xi}}. \end{cases}$$

gravitons: $\Lambda^2_{\text{Planck}} \simeq M_P^2 + \xi h^2$

gauge interactions:

$$\Lambda_{\text{gauge}}(h) \simeq \begin{cases} \frac{M_P}{\xi}, & \text{for } h \lesssim \frac{M_P}{\xi}, \\ h, & \text{for } \frac{M_P}{\xi} \lesssim h, \end{cases}$$

1008.5157

Strong coupling at M_P/ξ ...

Introducing new fields to push the scale up: out of the logic

Can it change the initial conditions of the Hot Big Bang?

1. reheating temperature
2. baryon (lepton) asymmetry of the Universe
3. dark matter abundance

Let's test these options adding all possible nonrenormalizable operators to the model

What can nonrenormalizable operators do?

F.Bezrukov, D.G., Shaposhnikov (2011)

$$
\begin{aligned}
\delta\mathscr{L}_{\mathrm{NR}} = & -\frac{a_6}{\Lambda^2}(H^\dagger H)^3 + \cdots \\
& + \frac{\beta_L}{4\Lambda} F_{\alpha\beta} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \frac{\beta_B}{\Lambda^2} O_{\text{baryon violating}} + \cdots + \text{h.c.} \\
& + \frac{\beta_N}{2\Lambda} H^\dagger H \bar{N}^c N + \frac{b_{L_\alpha}}{\Lambda} \bar{L}_\alpha (\not{D} N)^c \tilde{H} + \cdots ,
\end{aligned}
$$

L_α are SM leptonic doublets, $\alpha = 1,2,3$, N stands for right handed sterile neutrinos potentially present in the model, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$;

and

$$
\Lambda = \Lambda(h) = \left\{ \Lambda_{g-s}(h)\,,\, \Lambda_{\text{gauge}}(h)\,,\, \Lambda_{\text{Planck}}(h) \right\}
$$

couplings can differ significantly in different regions of h:
today $h < M_P/\xi$, at preheating $M_P/\xi < h < M_P/\sqrt{\xi}$

LFV, BV nonrenormalizable operators today

Neutrino masses: easily

$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{\beta_L v^2}{4\Lambda}\frac{F_{\alpha\beta}}{2}\bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

hence

$$\Lambda \sim 3\times 10^{14}\,\text{GeV}\times\beta_L\times\left(\frac{3\times10^{-3}\,\text{eV}^2}{\Delta m^2_{\text{atm}}}\right)^{1/2}$$

when

$$\Lambda = \frac{M_P}{\xi} \sim 0.6\times 10^{14}\,\text{GeV}$$

can explain with

$$\beta_L \sim 0.2$$

Proton decay: probably

$$\mathscr{L}^{(6)} \propto \frac{\beta_B}{\Lambda^2}QQQL$$

then from experiments

$$\Lambda \gtrsim \sqrt{\beta_B}\times 10^{16}\,\text{GeV}\times\left(\frac{\tau_{p\to\pi^0 e^+}}{1.6\times10^{33}\,\text{years}}\right)^{1/4}$$

with the same

$$\Lambda = \frac{M_P}{\xi} \sim 0.6\times 10^{14}\,\text{GeV}$$

one needs

$$\beta_B < 0.4\times 10^{-4}$$

Either B and L_α are significantly different
or we will observe proton decay in the next generation experiment

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$$\mathcal{L}^{(6)} \propto \frac{\beta_B}{\Lambda^2}\,QQQL$$

then from experiments

$$\Lambda \gtrsim \sqrt{\beta_B}\times 10^{16}\,\text{GeV}\times\left(\frac{\tau_{p\to\pi^0 e^+}}{1.6\times10^{33}\,\text{years}}\right)^{1/4}$$

with the same

$$\Lambda = \frac{M_P}{\xi} \sim 0.6\times 10^{14}\,\text{GeV}$$

one needs

$$\beta_B < 0.4\times 10^{-4}$$

Either B and L_α are significantly different
or we will observe proton decay in the next generation experiment

LFV, BV nonrenormalizable operators today

Neutrino masses: easily

$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{\beta_L v^2}{4\Lambda}\frac{F_{\alpha\beta}}{2}\bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

hence

$$\Lambda \sim 3\times 10^{14}\,\text{GeV}\times \beta_L \times \left(\frac{3\times 10^{-3}\,\text{eV}^2}{\Delta m^2_{\text{atm}}}\right)^{1/2}$$

when

$$\Lambda = \frac{M_P}{\xi} \sim 0.6\times 10^{14}\,\text{GeV}$$

can explain with

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Leptogenesis, $\Delta_B \approx \Delta_L/3$: can be successful

$$i\frac{d}{dt}\hat{Q}_L = \left[\hat{H}_{\rm int}, \hat{Q}_L\right]\,, \quad \Delta n_L \equiv n_L - n_{\bar{L}} = \langle Q_L \rangle$$

$$\mathscr{L}_Y = -Y_\alpha \bar{L}_\alpha H E_\alpha + \text{h.c.}\,, \qquad \mathscr{L}^{(5)}_{\nu\nu} = \frac{\beta_L}{4\Lambda} F_{\alpha\beta} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.}$$

$$d\Delta n_L/dt \propto \text{Im}\left(\beta_L^4\, \text{Tr}\left(FF^\dagger FYYF^\dagger YY\right)\right) \propto \beta_L^4 y_\tau^4 \cdot \text{Im}\left(F_{3\beta}F^*_{\alpha\beta}F_{\alpha 3}F^*_{33}\right)$$

for the gauge cutoff $\Lambda = h$ one has

$$\beta_L^4 \left(\frac{y_\tau}{0.01}\right)^4 \left(\frac{0.25}{\lambda}\right)^{5/4} \times 10^{-10} < \Delta_L < \beta_L^4 \left(\frac{y_\tau}{0.01}\right)^4 \left(\frac{0.25}{\lambda}\right) \times 10^{-9}\,,$$

for gravity-scalar cutoff $\Lambda = \xi\, h^2/M_P$

$$\beta_L^4 \left(\frac{y_\tau}{0.01}\right)^4 \left(\frac{0.25}{\lambda}\right)^{13/4} \times 6.3 \times 10^{-13} < \Delta_L < \beta_L^4 \left(\frac{y_\tau}{0.01}\right)^4 \left(\frac{0.25}{\lambda}\right)^2 \times 2.4 \times 10^{-10}$$

In both cases the asymmetry can be (significantly) increased with operator

$$\delta\mathscr{L}^\tau = y_\tau L_\tau H E_\tau + \beta_y L_\tau H E_\tau \frac{H^\dagger H}{\Lambda^2} + \cdots$$

one can fancy the hierarchy

$$1 \sim \beta_y \gg y_\tau \sim 10^{-2}\,.$$

gives a factor up to 10^8 !

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Dark matter: an example of sterile fermion

$$\mathscr{L}_{\rm int} = \beta_N \frac{H^\dagger H}{2\Lambda} \bar{N}^c N = \frac{\beta_N}{4} \frac{h^2}{\Lambda(h)} \bar{N}^c N$$

can be produced at preheating or at the hot stage

DM fermion has to be light! (WDM?)

Indeed, today

$$\frac{b_{L_\alpha}}{\Lambda} \bar{L}_\alpha (\not{D} N)^c \tilde{H}$$

$$f_\alpha \sim b_{L_\alpha} \frac{M_N}{\Lambda} \,.$$

So, N is unstable with the $\gamma\nu$ partial width of the order

$$\Gamma_{N\to\gamma\nu} \sim \frac{9\, b_{L_\alpha}^2 \alpha G_F^2}{512\pi^4} \frac{v^2 M_N^5}{\Lambda^2} \,.$$

EGRET gives $\tau_{\gamma\nu} \gtrsim 10^{27}$ s, hence 0709.2299

$$\text{for } \Lambda = M_P : \quad M_N \lesssim 200\,\text{MeV}\,, \qquad \text{for } \Lambda = M_P/\xi : \quad M_N \lesssim 4\,\text{MeV}$$

Outline

Summary

LHC hints at 125 GeV may point at:

- Multiple point principle ...?
- No new particle physics upto gravity scale
- Higgs-inflation: 129 GeV $\lesssim m_h \lesssim$ 195 GeV

  needs better precision in measurement of m_h, m_t, y_t, α_s

  may ask for UV-completion... asymptotic safety?

  Some other inflationary models also point at $m_h \sim 125\,\text{GeV}$ (e.g. hill-top potential in simple tensor-scalar gravity I.Masina, A.Notari (2012))
- Higgs-inflation may be easily completed to account for
  - neutrino oscillations
  - dark matter
  - baryon asymmetry of the Universe

  Examples: νMSM, nonrenormalizable operators at strong coupling UV-scale

Backup slides

Absence of the Landau pole upto inflationary scale $\sim 10^{13}$ GeV and stability of the Higgs potential at large post-inflationary values of the Higgs boson field $h \sim M_{Pl}$

$$129\,\text{GeV} \lesssim m_h \lesssim 195\,\text{GeV}$$

F.Bezrukov, D.G. (2010)

Lower bound refer to the case of $\lambda\,(M_{Pl}) = 0$

Message: Zero Planck-scale corrections from gravity?

PAST: gauge coupling unification…

Message: $\lambda(125\text{ GeV}) = 0.125$

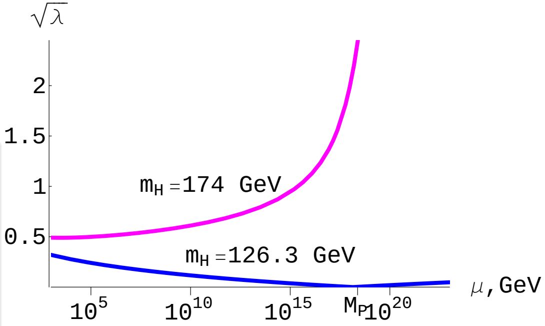
Nature knows

GeV and decimal system !! ☺

THIS MODEL HAS ALREADY BEEN CORNERED BY LHC !!

RG-evolution with energy scale μ:

$$\frac{d\lambda}{d\log\mu^2} \propto +\#\cdot\lambda^2 - \#\cdot Y_t^4$$



$h \to W^+W^-,\ ZZ$

$T_{reh} \simeq 3 \times 10^{13}$ GeV

F.Bezrukov, D.G., M.Shaposhnikov (2009)

Models without NEW scalar(s) in PARTICLE PHYSICS SECTOR

A.Starobinsky (1980) R^2-inflation Higgs-inflation F.Bezrukov, M.Shaposhnikov (2007)

$$S^{JF} = -\frac{M_P^2}{2}\int\sqrt{-g}\,d^4x\left(R - \frac{R^2}{6\mu^2}\right) + S^{JF}_{matter}\,, \quad S^{JF} = \int\sqrt{-g}\,d^4x\left(-\frac{M_P^2}{2}R - \xi H^\dagger H R\right) + S^{JF}_{matter}$$

In this two models “inflatons” couple to the SM fields in different ways

R^2-inflation: gravity, $\mathscr{L} \propto \phi/M_P$ Higgs-inflation: finally, at $\phi \lesssim M_P/\xi$ like in SM

D.G., A.Panin (2010) F.Bezrukov, D.G., M.Shaposhnikov (2008)

$T_{reh} \approx 3 \times 10^9$ GeV $T_{reh} \approx 6 \times 10^{13}$ GeV

with different length of the post inflationary matter domination stage: F.Bezrukov, D.G. (2011)

- somewhat different perturbation spectra

  $n_s = 0.965\,,\ r = 0.0032$ $n_s = 0.967\,,\ r = 0.0036$

  break in primordial gravity wave spectra at different frequencies
- in R^2 perturbations 10^{-5} enter nonlinear regime:

  gravity waves from inflaton clumps
- SM Higgs potenial is OK up to the reheating scale:

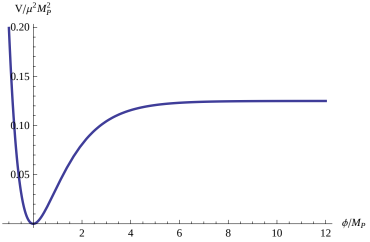
  $m_h \gtrsim 116$ GeV $m_h \gtrsim 120 - 129$ GeV

The power spectra of primordial perturbations

The same potential, the same ϕ at the end of inflation

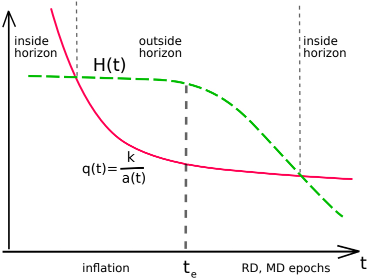
e.g. F.Bezrukov, D.G., M.Shaposhnikov (2008)

$$n_s \simeq 1 - \frac{8(4N+9)}{(4N+3)^2}\,, \qquad r \simeq \frac{192}{(4N+3)^2}$$



But WMAP observes different N in the two models:
$k/a_0 = 0.002/\text{Mpc}$ exits horizon at different moments

$$N = \frac{1}{3}\log\left(\frac{\pi^2}{30\sqrt{27}}\right) - \log\frac{(k/a_0)}{T_0 g_0^{1/3}} + \log\frac{V_*^{1/2}}{V_e^{1/4}\,M_P} - \frac{1}{3}\log\frac{V_e^{1/4}}{10^{13}\,\text{GeV}} - \frac{1}{3}\log\frac{10^{13}\,\text{GeV}}{T_{reh}}$$



The difference is

F.Bezrukov, D.G. (2011)

$$N_* \approx 57 - \frac{1}{3}\log\frac{10^{13}\,\text{GeV}}{T_{reh}}\,,\; N_{R^2} = 54.37,\;\; N_H = 57.66.$$

R^2-inflation: $n_s = 0.965$, $\quad r = 0.0036$,

Higgs-inflation: $n_s = 0.967$, $\quad r = 0.0032$.

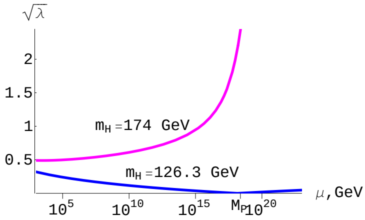
Planck(?), CMBPol(1-2σ)

Upper limit on the Higgs boson mass

R^2-inflation: stability while the Universe evolves
from $Q = T_{reh} \approx 3 \times 10^9$ GeV

J.Espinosa, G.Giudice, A.Riotto (2007) F.Bezrukov, D.G. (2011)

$$m_h^{R^2} > \left[116.5 + \frac{m_t - 172.9\,\text{GeV}}{1.1\,\text{GeV}} \times 2.6 - \frac{\alpha_s(M_Z) - 0.1181}{0.0007} \times 0.5\right] \text{GeV}$$



Higgs-inflation: stability while the Universe evolves
from $Q = T_{reh} \approx 6 \times 10^{13}$ GeV

F.Bezrukov, M.Shaposhnikov (2009) F.Bezrukov, D.G. (2011)

$$m_h^{\text{H}} > \left[120.0 + \frac{m_t - 172.9\,\text{GeV}}{1.1\,\text{GeV}} \times 2.1 - \frac{\alpha_s(M_Z) - 0.1181}{0.0007} \times 0.5\right] \text{GeV}$$

Uncertainties: about $2 - 3$ GeV
due to unknown QCD-corrections

stability while the Universe evolves
right after inflation $h \approx 10^{13}$ GeV

$$m_h^{\text{H}} > [129.0 + \ldots]\ \text{GeV}$$

Important for further improvement:

- (N)NLO corrections in QCD coupling
- measurement of m_t and m_h at LHC

present limit from CMS: $m_h < 127$ GeV @ 95%CL