Status of cosmology and the Higgs boson: Lectures #3-4

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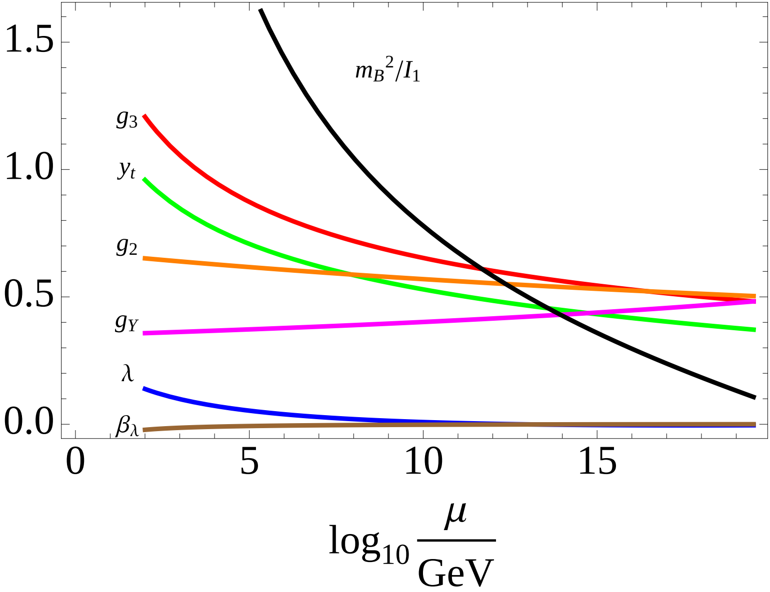
The Helmholtz International School
“Cosmology, Strings, and New Physics”

Running of the SM couplings

1305.7055



Standard Model: Success and Problems

Gauge fields (interactions): γ, $W^{\pm}$, Z, g

Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Baryon asymmetry (Ω_B)
  - Dark matter (Ω_{DM})
  - Inflationary stage
  - Reheating
  - Dark energy (Ω_Λ)
  - Strong CP: ? (boundary terms, new topology, . . .)
  - Gauge hierarchy: ? (No new scales!)
  - Quantum gravity

Try to explain all above

Planck-scale physics saves the day

Outline

1. Higgs and neutrino masses
2. Higgs and baryon asymmetry of the Universe
3. Higgs and dark matter
4. Higgs at (post)inflationary stage
5. Summary

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Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$

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

L_α are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$; in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$ and

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

hence

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

The model has to be UV-completed at the neutrino scale $\Lambda_\nu < \Lambda$

What is beyond the neutrino scale Λ_ν ?

Sterile neutrino lagrangian: fermionic portal

Most general renormalizable with 2(3...) right-handed neutrinos N_I

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

Parameters to be determined from experiments

9(7): active neutrino sector

- 2 Δm_{ij}^2: oscillation experiments
- 3 θ_{ij}: oscillation experiments
- 1 CP-phase: oscillation experiments
- 2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$
- 1(0) m_ν: $^3H \to ^3He + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

- 2: Majorana masses M_{N_I}
- 9: New Yukawa couplings $f_{\alpha I}$ which form
  - 2: Dirac masses $M^D = f\langle H \rangle$
  - 3+1: mixing angles
  - 2+1: CP-violating phases

4 new parameters in total
help with leptogenesis

18: $N = 3$ sterile neutrinos:

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9 new parameters in total
both BAU and DM are possible

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Seesaw mechanism: $M_N \gg 1$ eV

With $m_{active} \lesssim 1$ eV we work in the seesaw (type I) regime:

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

When Higgs gains $\langle H \rangle = v/\sqrt{2}$ we get in neutrino sector

$$\mathscr{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.} = \left(\overline{\nu}_1, \ldots \overline{N}_1^c \ldots\right) \begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^{\mathrm{T}}}{\sqrt{2}} & \hat{M}_N \end{pmatrix} \left(\nu_1, \ldots N_1 \ldots\right)^{\mathrm{T}}$$

Then for $M_N \gg \hat{M}^D = v\,\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues:

$$\simeq \hat{M}_N \quad \text{and} \quad \hat{M}^\nu = -(\hat{M}^D)^{\mathrm{T}}\frac{1}{\hat{M}_N}\hat{M}^D \propto f^2\frac{v^2}{M_N} \lll M_N$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I$

active-active mixing: $U^\dagger \hat{M}^\nu U = diag\,(m_1, m_2, m_3)$

active-sterile mixing: $\theta_{\alpha I} = \dfrac{(M^D)^{\mathrm{T}}_{\alpha I}}{M_I} \propto \hat{f}^{\mathrm{T}}\dfrac{v}{M_N} \ll 1$

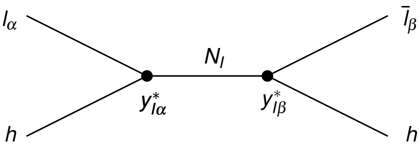
Seesaw mechanism: sterile neutrino scale

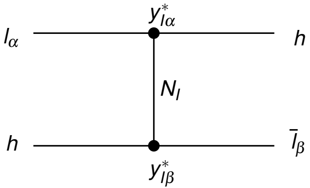
For $M_N \gg \hat{M}^D = v\,\frac{\hat{f}}{\sqrt{2}}$ we found the eigenvalues:

$$\simeq \hat{M}_N \quad \text{and} \quad \hat{M}^\nu = -(\hat{M}^D)^\mathsf{T}\,\frac{1}{\hat{M}_N}\,\hat{M}^D \propto f^2\,\frac{v^2}{M_N} \lll M_N$$

SEESAW says nothing about the sterile neutrino scale M_I !

Unitarity: $f \lesssim 1 \quad \Longrightarrow \quad M_N \lesssim 3\times 10^{14}\ \text{GeV} \times \left(\frac{3{\cdot}10^{-3}\ \text{eV}^2}{\Delta m^2_{atm}}\right)^{1/2} \longrightarrow \Lambda$ in $(LH)^2/\Lambda$





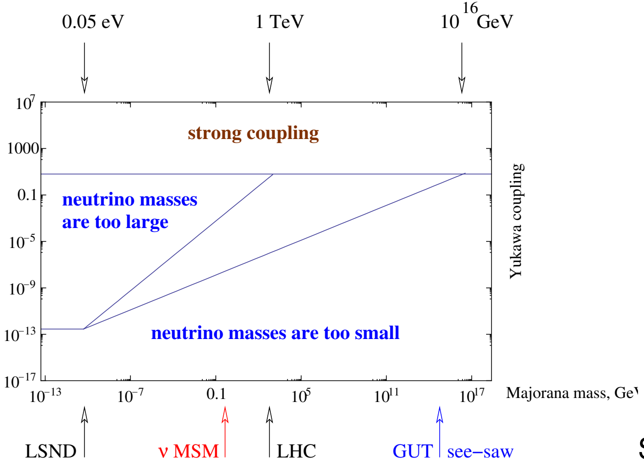
At given M_N without fine tuning the scale of Yukawas $\hat{f}$ and strength of active-sterile mixing $\theta_{\alpha I} = \frac{(M^D)^\mathsf{T}_{\alpha I}}{M_I} \propto \hat{f}\,\frac{v}{M_N} \ll 1$ are fixed

Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

Extended seesaw



Seesaw diagram

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Electroweak sphalerons: $B-L$

$$\partial^\mu j_\mu{}^{B} = 3\frac{g^2}{16\pi^2} V^{a\,\mu\nu}\tilde{V}^a{}_{\mu\nu}\,,$$

$$\partial^\mu j_\mu{}^{Ln} = \frac{g^2}{16\pi^2} V^{a\,\mu\nu}\tilde{V}^a{}_{\mu\nu}\,,\quad n=1,2,3\,,$$

$V^a{}_{\mu\nu} = \partial_\mu V^a_\nu - \partial_\nu V^a_\mu + g\varepsilon^{abc}V^b_\mu V^c_\nu$ refer to $SU(2)_W$, $\tilde{V}^a{}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\lambda\rho}V^{a\,\lambda\rho}$
Anomaly: only left fermions couple to fields V^a_μ.
For nontrivial gauge fields in vacuum or plasma

$$\Delta B = B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3\mathbf{x}\,\partial^\mu j^B_\mu = 3\int_{t_i}^{t_f} d^4x\,\frac{g^2}{16\pi^2} V^{a\,\mu\nu}\tilde{V}^a{}_{\mu\nu}\,,$$

Strong fields are needed: $V^a{}_{\mu\nu} \propto \frac{1}{g}$, (integral is natural number!). Energies of such configurations $\propto \frac{1}{g^2}$.

$$\Delta B = 3\,\Delta L_e = 3\,\Delta L_\mu = 3\,\Delta L_\tau$$

At temperatures 100 GeV $\lesssim T \lesssim 10^{12}$ GeV only 3 linear combinations survive, e.g.

$$B-L\,,\quad L_e - L_\mu\,,\quad L_e - L_\tau$$

where $$L \equiv L_e + L_\mu + L_\tau$$

Baryogenesis

Sakharov conditions of successful baryogenesis

- B-violation $(\Delta B \neq 0)\ XY \dots \to X'Y' \dots B$
- C- & CP-violation $(\Delta C \neq 0,\ \Delta CP \neq 0)\ \bar{X}\bar{Y} \dots \to \bar{X}'\bar{Y}' \dots \bar{B}$
- processes above are out of equilibrium $X'Y' \dots B \to XY \dots$

At $100\,\mathrm{GeV} \lesssim T \lesssim 10^{12}\,\mathrm{GeV}$ nonperturbative processes (EW-sphalerons) violate B, L_α, so that only three charges are conserved out of four, e.g.

$$B - L\,, \quad L_e - L_\mu\,, \quad L_e - L_\tau$$

and $B = \alpha \times (B - L)$, $L = (\alpha - 1) \times (B - L)$

Leptogenesis: Baryogenesis from lepton asymmetry of the Universe ... due to sterile neutrinos

Why $\Omega_B \sim \Omega_{DM}$? antropic principle?

Lepton asymmetry from sterile neutrino decays

Most general renormalizable lagrangian with Majorana neutrinos N_I, $I,\alpha = 1,2,3$.

$$\mathscr{L}_{SM} = \overline{N}_I i\partial\!\!\!/ N_I - y_{I\alpha}\bar{L}_\alpha \widetilde{H} N_I - \frac{M_I}{2}\overline{N}_I^c N_I + \text{h.c.}$$

where $\widetilde{H}_i = \varepsilon_{ij}H_j^*$, $i,j = 1,2$; complex Yukawas, Majorana mass: $\Delta L \neq 0$ lepton number violating processes ($N = N^c$!):

$$N_I \to hl_\alpha\ , \quad N_I \to h\bar{l}_\alpha\ ,$$

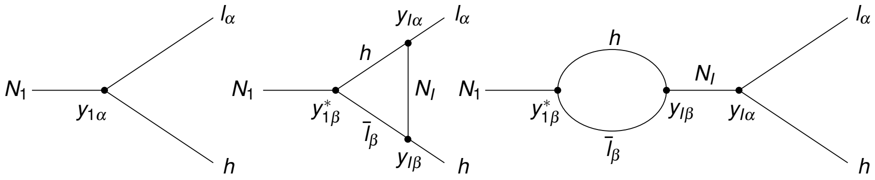
$$hl_\alpha \to h\bar{l}_\beta$$

At tree level one obtains ZERO

$$\Gamma_{N_I}^{tree} = \sum_\beta \frac{|y_{I\beta}|^2}{8\pi} M_I\ .$$

$$\Gamma^{tree}(N_I \to hl_\alpha) = \Gamma^{tree}(N_I \to h\bar{l}_\alpha)\ .$$

Lepton asymmetry δ at 1-loop level $\quad y_{l\alpha}\bar{L}_\alpha N_l \widetilde{H}$



$$\Gamma(N_1 \to lh) = \frac{M_1}{8\pi} \cdot \sum_\alpha \left| y_{1\alpha} + \frac{1}{8\pi} \sum_{\beta,l} f\left(\frac{M_1}{M_l}\right) \cdot y^*_{1\beta} y_{l\alpha} y_{l\beta} \right|^2 , \quad m_\nu \ll M_l$$

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = \frac{1}{8\pi} \sum_{l=2,3} f\left(\frac{M_1}{M_l}\right) \cdot \frac{\mathrm{Im}\left(\sum_\alpha y_{1\alpha} y^*_{l\alpha}\right)^2}{\sum_\gamma |y_{1\gamma}|^2} .$$

$$M_{2,3} \gg M_1 \;, f\left(\frac{M_1}{M_l}\right) = -\frac{3}{2}\frac{M_1}{M_l} \;, \quad \delta = -\frac{3\,M_1}{16\pi} \frac{1}{\sum_\gamma |y_{1\gamma}|^2} \sum_{\alpha\beta l} \mathrm{Im}\left[y_{1\alpha} y_{1\beta} \left(y^*_{l\alpha} \frac{1}{M_l} y^*_{l\beta} \right) \right] .$$

For the seesaw-neutrino $y_{I\alpha}\bar{L}_\alpha N_I \widetilde{H}$

$$m_{\alpha\beta} = -\frac{v^2}{2}\sum_I y_{I\alpha}\frac{1}{M_I}y_{I\beta}\,, \quad \delta = -\frac{3\,M_1}{16\pi}\frac{1}{\sum_\gamma |y_{1\gamma}|^2}\sum_{\alpha\beta I}\text{Im}\left[y_{1\alpha}y_{1\beta}\left(y^*_{I\alpha}\frac{1}{M_I}y^*_{I\beta}\right)\right]\,.$$

get an estimate for the microscopic asymmetry

$$\delta \lesssim \frac{3\,M_1}{8\,\pi\,v^2}m_{atm} \simeq 10^{-8}\times\frac{M_1}{10^8\text{ GeV}}\,.$$

Production of macroscopic asymmetry

Let sterile neutrinos be in equlibrium at $T > M_1$

$$\Gamma^{tot}_{N_1} = \frac{M_1}{8\pi}\sum_\alpha |y_{1\alpha}|^2 ,$$

$$m_{\alpha\beta} = -\frac{v^2}{2}\sum_I y_{I\alpha}\frac{1}{M_I}y_{I\beta} ,$$

$$\Gamma^{tot}_{N_1} \lesssim H(T \sim M_1) \simeq M_1^2/M^*_{Pl}$$

- Need strong hierarchy in $y_{I\alpha}$
- At $T \gtrsim H(T = M_1)$ other interactions are responsible for sterile neutrino production in plasma
- For the final lepton asymmetry (at $T \ll M_1$)

$$\Delta_L \sim \delta \cdot \frac{n_{N_1}(M_1)}{s(M_1)} \sim \frac{\delta}{g_*(M_1)} \sim 10^{-2} \times \delta$$

- So, $M_1 \gtrsim 10^9$ GeV

$$\Gamma^{tot}_{N_1} \gtrsim H(T \sim M_1) = M_1^2/M^*_{Pl}$$

- Without any hierarchy [inverse decay]

$$K \equiv \frac{\Gamma^{tot}_N}{H(T \sim M_1)} = \frac{m_{atm}M^*_{Pl}}{4\pi v^2} \sim 10^2$$

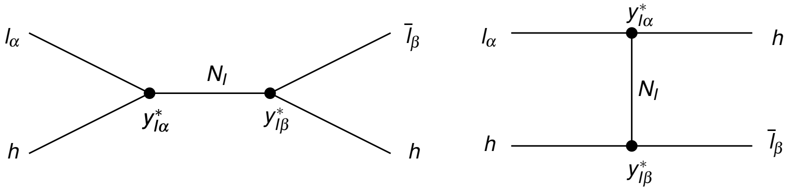
- For the final lepton asymmetry (at $T \ll M_1$)

$$\Delta_L \sim \frac{\delta}{g_*(M_1)\cdot K \cdot \log K} \sim 10^{-5} \times \delta$$

- So, $M_1 \gtrsim 10^{12}$ GeV

Saving macroscopic asymmetry from “washing out”

e.g., due to scatterings $hl_\alpha \to h\bar{l}_\beta$ with exchange of virtual neutrino



at the interesting stage $T \ll M_1$ we estimate cross section for seesaw neutrino

$$\sigma^{tot}_{lh} \propto \sum_{\alpha\beta I} \left| \frac{y_{I\alpha} y_{I\beta}}{M_\gamma} \right|^2 \propto \frac{\mathrm{Tr}\left(mm^\mathrm{T}\right)}{v^4} \propto \frac{1}{v^4} \sum m_\nu^2$$

The asymmetry is safe if:

$\Gamma_{lh} = \mathrm{const} \cdot \sigma^{tot}_{lh} \cdot T^3 \lesssim H(T)$ for $T = M_1$, $M_1 / \log K$ one has $m_\nu < 0.1 - 0.3$ eV coincidence?

Certainly, everything can be obtained by numerical solution of the Boltzmann equation for the plasma components in the expanding Universe

Superheavy sterile neutrinos: $M_N \simeq 10^9$-10^{14} GeV

- Motivation: close to GUT scales, e.g. $SO(10)$
- Bad fact: huge finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \gg m_H^2 (\Rightarrow M_N < 10^7\,\text{GeV})$
  SUSY solution? (New fileds...new problems: e.g. gravitino overproduction with high T_{reh} for leptogenesis)
- Good fact: If $T > M_N$ decays of thermal sterile neutrino yield the lepton asymmetry in the early Universe: M.Fukugita, T.Yanagita (1986)

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = \frac{1}{8\pi} \sum_{l=2,3} f\left(\frac{M_{N_1}}{M_{N_l}}\right) \cdot \frac{\text{Im}\left(\sum_\alpha f_{1\alpha} f_{l\alpha}^*\right)^2}{\sum_\gamma |f_{1\gamma}|^2} .$$

  Needs $M_{N_1} \gtrsim 10^9$ GeV or $M_{N_1} \gtrsim 10^{12}$ GeV without fine tuning in $\hat{f}$
- Exciting fact: to avoid washing out of Δ_L in $hl_\alpha \leftrightarrow h\bar{l}_\beta$ we need ...
  $M^\nu < 0.1 - 0.3\,\text{eV}$!!!
- Cooling down: No way to test further. Can get $\Delta_B \sim 10^{-10}$ even with
  $\theta_{13} = \delta_{\text{CP}} = 0$!

NB: can work for nonthermal case as well

production by inflaton decay G.Lazaridies, Q.Shafi (1991) e.g. in R^2-inflation D.G., A.Panin (2010)

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Weakly Interacting Massive Particles

Assumptions:

1. no $X - \bar{X}$ asymmetry $\qquad n_X = n_{\bar{X}}$
2. @ $T < M_X$ in thermal equilibrium with plasma

$$n_X = n_{\bar{X}} = g_X \left(\frac{M_X T}{2\pi}\right)^{3/2} e^{-M_X/T}$$

$$X\bar{X} \longrightarrow \text{light particles}$$

freeze-out temperature T_f $\qquad M_{Pl}^* = M_{Pl}/1.66\sqrt{g_*}$

$$\frac{1}{n_X}\frac{1}{\langle \sigma_{ann} v\rangle} = H^{-1}(T_f) \longrightarrow T_f = \frac{M_X}{\ln\left(\frac{g_X M_X M_{Pl}^* \sigma_0}{(2\pi)^{3/2}}\right)} .$$

Bethe formula: $\qquad$ annihilation in s-wave: $\sigma_{ann} = \frac{\sigma_0}{v}$

Weakly Interacting Massive Particles (WIMPs)

density after freeze-out: $n_X(T_f) = \frac{T_f^2}{M_{Pl}^* \sigma_0}$

present density: $n_X(T_0) = \left(\frac{a(T_f)}{a(T_0)}\right)^3 n_X(T_f) = \left(\frac{s_0}{s(T_f)}\right) n_X(T_f) \propto \frac{1}{T_f} \propto \frac{1}{M_X}$

$X + \bar{X}$ contribution to critical density:

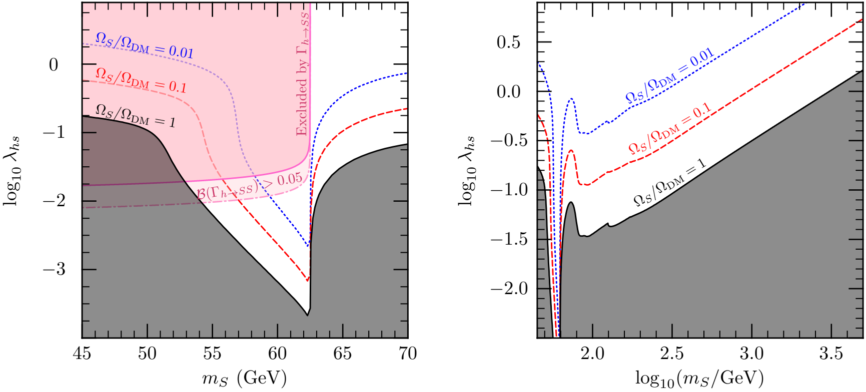
$$\Omega_X = 2\frac{M_X n_X(T_0)}{\rho_c} = 7.6\frac{s_0 \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)}{\rho_c \sigma_0 M_{Pl}\sqrt{g_*(T_f)}}$$

$$= 0.1 \cdot \left(\frac{(10\text{ TeV})^{-2}}{\sigma_0}\right) \frac{0.3}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right) \cdot \frac{1}{2h^2}$$

natural dark matter: $\sigma_0 \sim 0.01 \times \sigma_{weak}$

naturaly "light" $\sigma_0 \lesssim \frac{4\pi}{M_X^2} \longrightarrow M_X \lesssim 100\text{ TeV}$

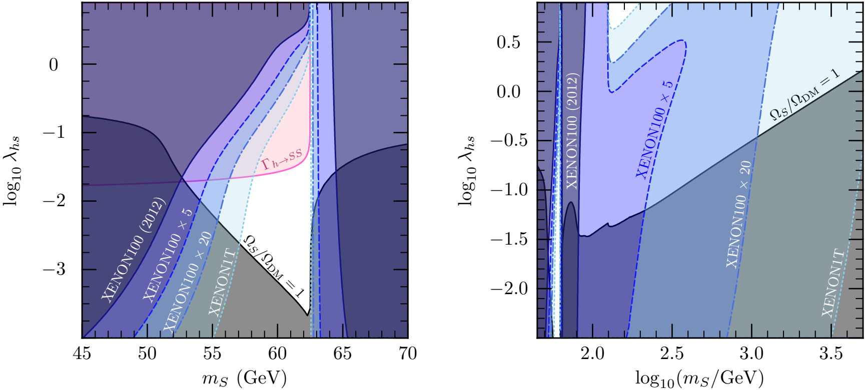
dark matter production with $V = \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{2} S^2 H^\dagger H$



$m_S^2 = \mu^2 + \frac{\lambda_S}{2} v^2$

1306.4710

dark matter searches with $V = \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{2} S^2 H^\dagger H$



$$m_S^2 = \mu^2 + \frac{\lambda_S}{2} v^2$$

1306.4710

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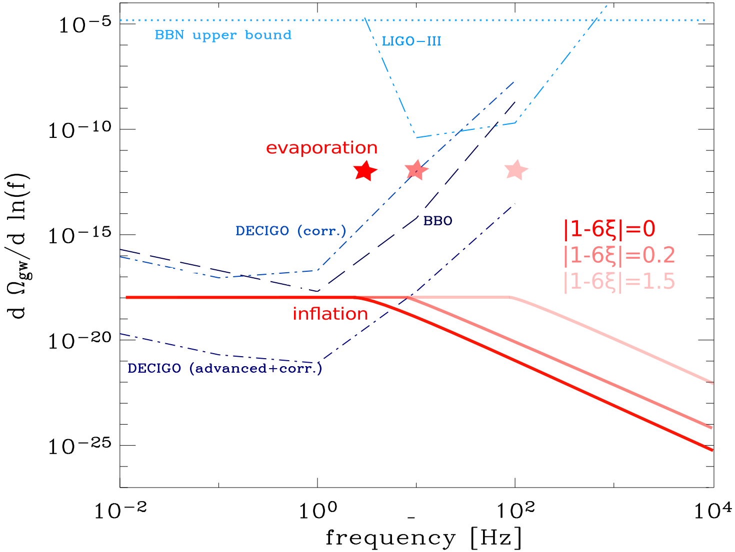
Possible roles at pre Big Bang epoch

- Reaching the EW vacuum after inflation
  at inflation all fields gain fluctuations $h \sim H_{inf}$
  hence one requires $\lambda(H_{inf}) > 0$ and no tunneling before reheating!
  Danger for chaotic inflation: if initially all scalar fields $\sim M_{Pl}$
  has been already tested!
- Reheating via Higgs boson production
  scalar portal: $H^\dagger H S^2$ for any inflaton S
  specific models: say, in R^2-inflation
  can be tested
- Higgs as inflaton

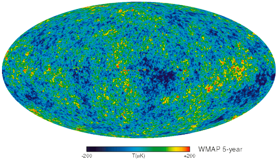
Check of reheating: usually impossible



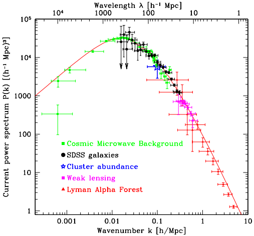
D.G., A.Tokareva (2012)

Inflationary solution of Hot Big Bang problems

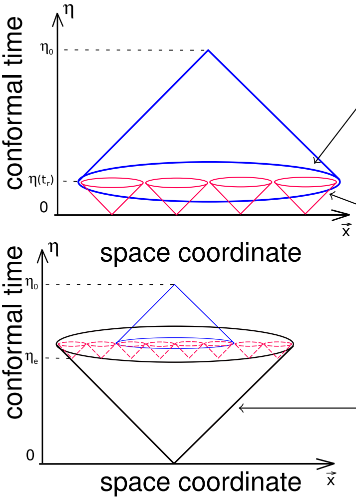
Temperature fluctuations
$\delta T/T \sim 10^{-5}$



Universe is uniform!



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



particle horizon

casually connected regions

inflationary expansion

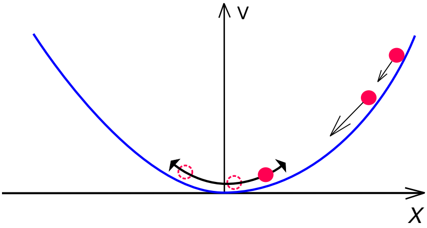
Chaotic inflation: simple realization

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

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

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

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 $v = 246\,\text{GeV}$) $\lambda \sim 0.1 - 1$

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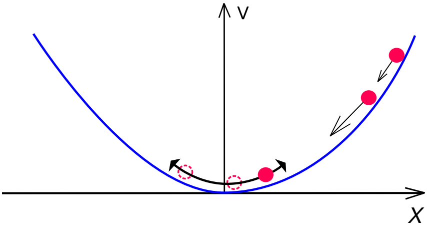

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Higgs-inflation

F.Bezrukov, M.Shaposhnikov (2007)

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

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 $\lambda \sim 1$

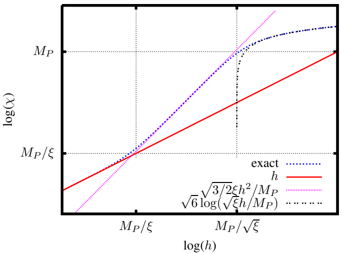
Go to the Einstein frame: $(M_P^2 + \xi h^2) R \to M_P^2 \tilde{R}$

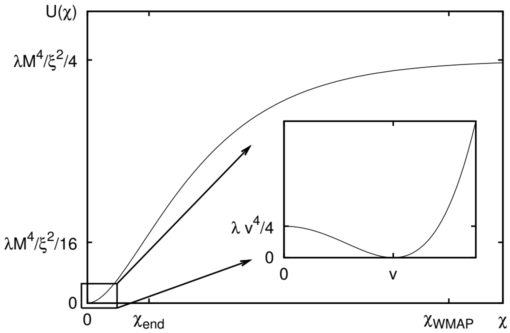
$$g_{\mu\nu} = \Omega^{-2} \tilde{g}_{\mu\nu}\,, \qquad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

with canonically normalized χ:

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

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

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

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

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

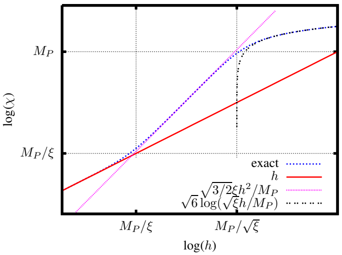
$$\mathscr{L} = \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{\lambda}{6}\frac{M_P^2}{\xi^2}\chi^2$$

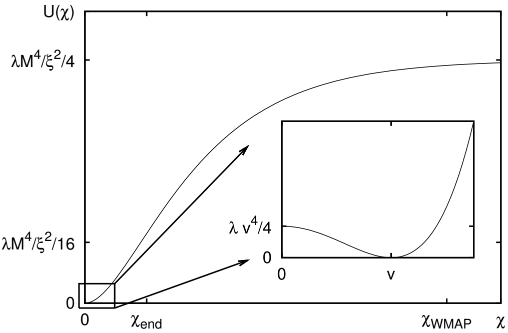
coincides with R^2-model!

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

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

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





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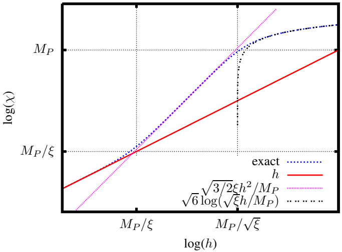


$$m_W^2(\chi) = \frac{g^2}{2\sqrt{6}}\frac{M_P|\chi(t)|}{\xi}$$

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

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:

$$3.4\times10^{13}\,\text{GeV} < T_r < 9.2\times10^{13}\left(\frac{\lambda}{0.125}\right)^{1/4}\text{GeV}$$

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

$n_s = 0.967$, $r = 0.0032$ F.Bezrukov, D.G., 1111.4397

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

Fine theoretical descriptions both in

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

and in

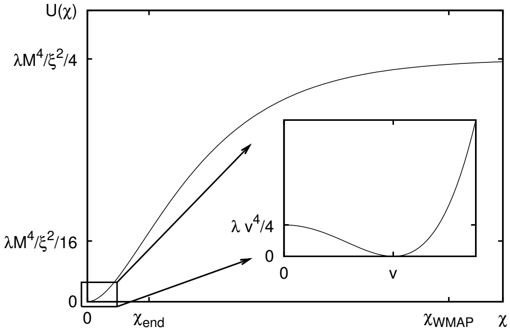
$$\text{IR:}\quad h \ll M_P/\xi\,,\quad U = \frac{\lambda}{4}h^4$$

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!
But NO NEW d.o.f. 0812.3622

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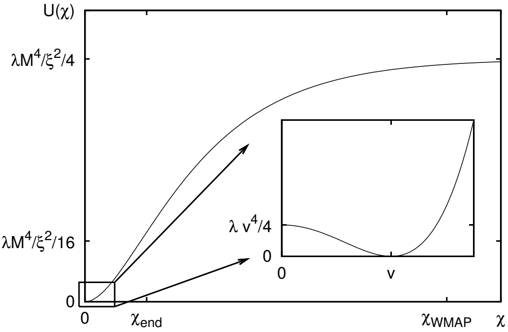

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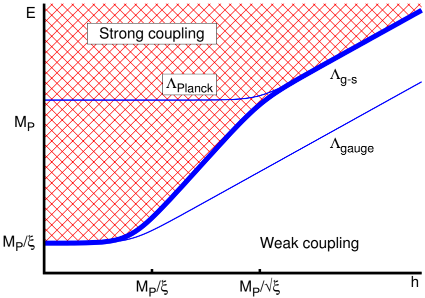
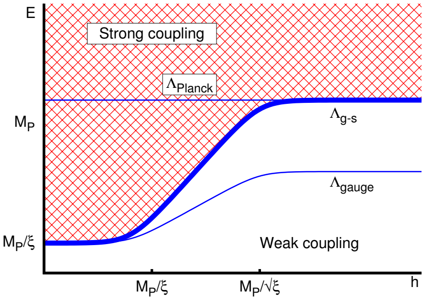
Strong coupling in Higgs-inflation: scatterings

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)

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

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

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

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

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

when

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

can explain with

$$\beta_L \sim 0.2$$

Proton decay: probably

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

then from experiments

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

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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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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Outline

1. Higgs and neutrino masses
2. Higgs and baryon asymmetry of the Universe
3. Higgs and dark matter
4. Higgs at (post)inflationary stage
5. Summary

Summary

LHC hints at 125 GeV may point at:

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

  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 $m_h \sim 125\,\mathrm{GeV}$ (e.g. hill-top potential in simple tensor-scalar gravity I.Masina, A.Notari (2012))
- Higgs is welcome in SM economic extensions capable of explaining
  - neutrino oscillations
  - dark matter
  - baryon asymmetry of the Universe
  - inflation and reheating

Backup slides

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:

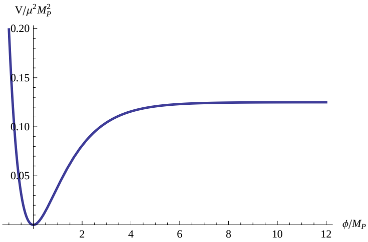
  $m_h \gtrsim 116$ GeV | $m_h \gtrsim 120 - 129$ GeV

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

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

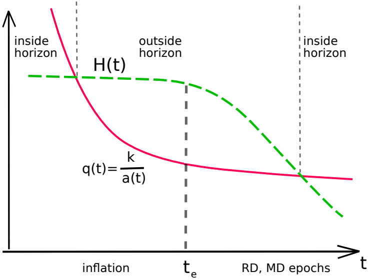
The difference is

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: $n_s = 0.965$, $r = 0.0036$,

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



Planck(?), CMBPol(1-2σ)

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  the only direct evidence, but the NP-scale is hidden: $m_\nu \sim M_D^2/M_N$
- baryon asymmetry of the Universe: baryogenesis
  requires NP, but the scale is hidden 100 GeV $< E < M_{Pl}$
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  a lack of gravity is observed: WIMPs @ EW? modified gravity?
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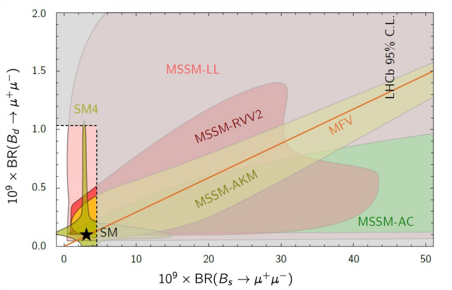
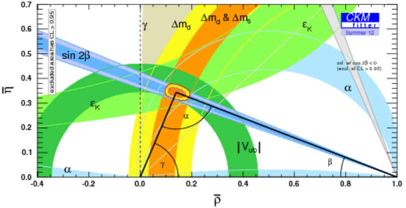
Physics beyond the SM: no any signs in

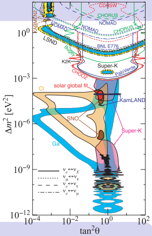
- direct production of new particles: superpartners, KK-excitations, techno-resonances, etc
- rare processes: quantum correction from new (heavy) particles





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)