R^2-inflation vs Higgs-inflation: crucial tests in Particle physics and Cosmology

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Hot topics in Modern Cosmology
Spontaneous Workshop VI

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The essence of the matter on two slides: question

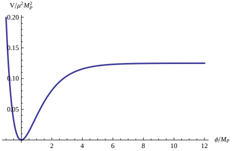
There are two inflationary models
without NEW scalar(s) in PARTICLE PHYSICS SECTOR:

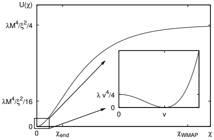
A.Starobinsky (1980) — R^2-inflation

Higgs-inflation — F.Bezrukov, M.Shaposhnikov (2007)

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

with the same inflaton potential at inflation and right after





How one can distinguish one model from another?

The essence of the matter on two slides: answer

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

R^2-inflation: gravity, $\mathscr{L} \propto \phi/M_P$

$$\phi \to hh$$

D.G., A.Panin (2010)

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

Higgs-inflation: finally, at $\phi \lesssim M_P/\xi$ like in SM

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

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

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

with different length of the post inflationary matter domination stage:

F.Bezrukov, D.G. (2011)

- somewhat different predictions for perturbation spectra

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

  break in primordial gravity wave spectra at different frequencies
- in R^2 perturbations 10^{-5} have enough time to enter nonlinear regime: gravity waves from inflaton clumps
- SM Higgs potenial is OK up to the reheating scale:

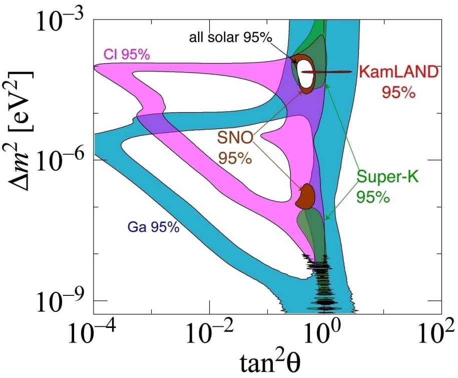
  $m_h \gtrsim 116$ GeV $\qquad$ $m_h \gtrsim 126$ GeV

Outline

Outline

Neutrino oscillations: masses and mixing angles

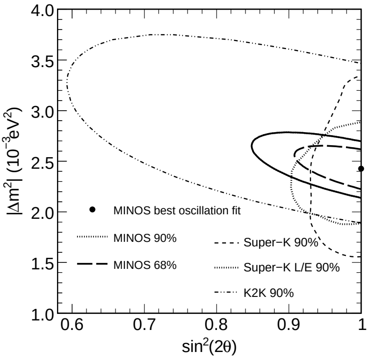
Solar 2×2 "subsector"



http://hitoshi.berkeley.edu/neutrino/

$m_1 > 0.008\,\text{eV}$

Atmospheric 2×2 "subsector"



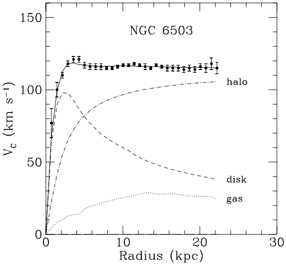
arXiv:0806.2237

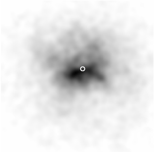
$m_2 > 0.05\,\text{eV}$

DAYA-BAY, RENO: $\sin^2 2\theta_{13} \approx 0.1$

Baryons and Dark Matter in Astrophysics

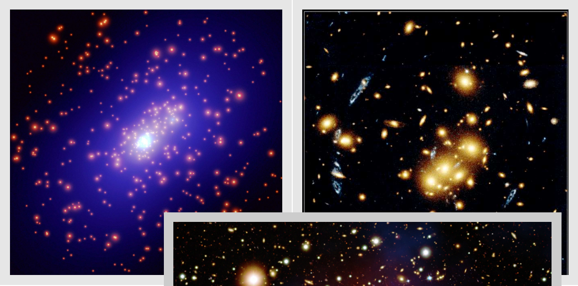
Rotation curves





X-rays from clusters

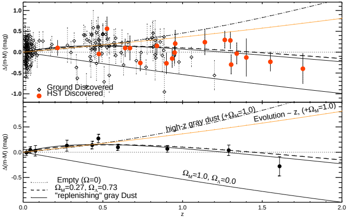
Gravitational lensing



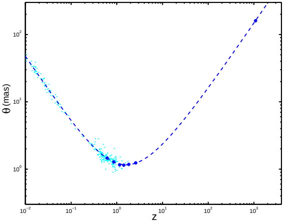
“Bullet” cluster

Baryons and Dark Matter in Cosmology

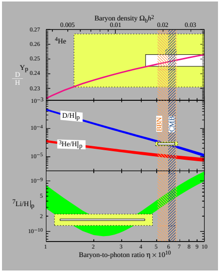
Standard candles

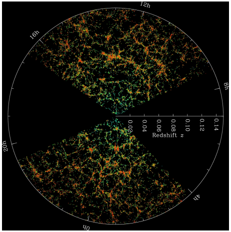


Angular distance

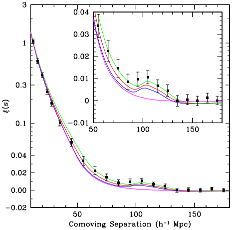


BBN

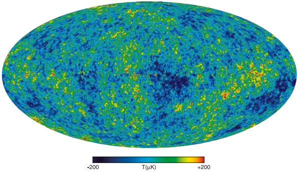




Structures

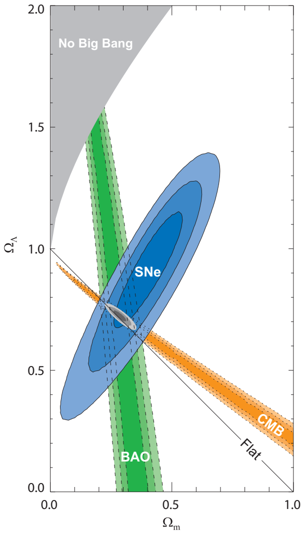


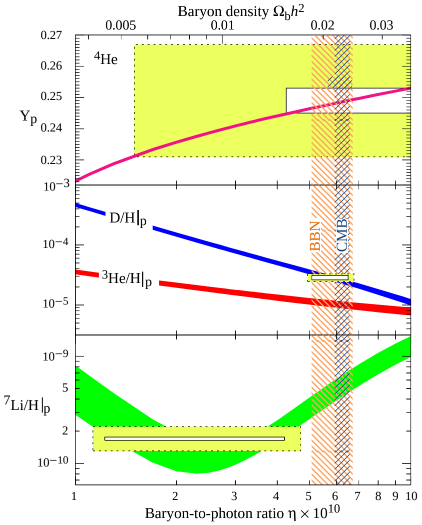
BAO



CMB fluctuations

Cosmological parameters: $\Omega_{DM} = 0.22$, $\Omega_B = 0.046$



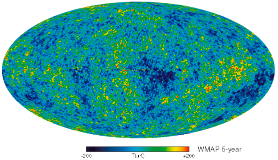


arXiv:0804.4142

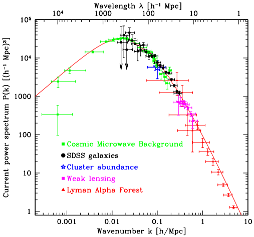
http://pdg.lbl.gov

Inflationary solution of Hot Big Bang problems

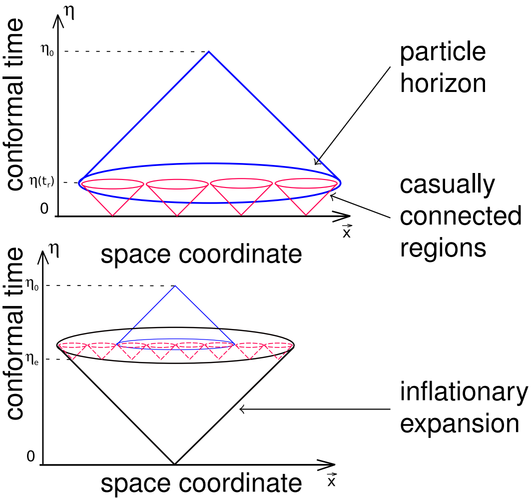
Temperature fluctuations $\delta T/T \sim 10^{-5}$



Universe is uniform!



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



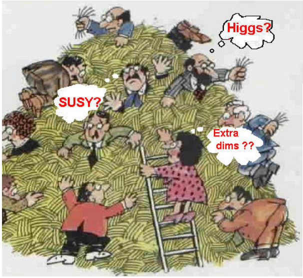
True Extension of the Standard Model should

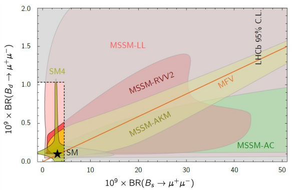
- Reproduce the correct neutrino oscillations
- Contain the viable DM candidate
- Be capable of explaining the baryon asymmetry of the Universe
- Have the inflationary mechanism operating at early times

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

Outline

Inflation: R^2 term

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

Jordan Frame $\rightarrow$ Einstein Frame

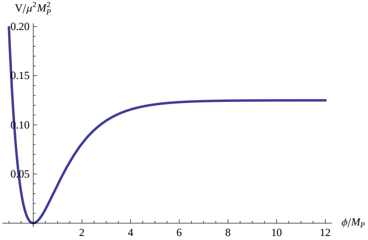
A.Starobinsky (1980)

$$g_{\mu\nu} \rightarrow \tilde{g}_{\mu\nu} = \chi\, g_{\mu\nu}\,, \qquad \chi = \exp\left(\sqrt{2/3}\,\phi/M_P\right)\,.$$

$$S^{EF} = \int\sqrt{-\tilde{g}}\,d^4x\left[-\frac{M_P^2}{2}\tilde{R} + \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{3\mu^2 M_P^2}{4}\left(1 - \frac{1}{\chi(\phi)}\right)^2\right] + S^{EF}_{matter}\,,$$

generation of (almost) scale-invariant scalar perturbations from exponentially stretched quantum fluctuations

$\delta\rho/\rho \sim 10^{-5}$ requires
$\mu = m_\phi \approx 1.3\times 10^{-5}\,M_P$



Post-inflationary Reheating: provided by gravity

$$S^{JF}_{matter} = S(g_{\mu\nu}, \varphi, A_\mu, \dots) \to S^{EF}_{matter} = S(\tilde{g}_{\mu\nu}, \tilde{\varphi}, \tilde{A}_\mu, \dots)$$

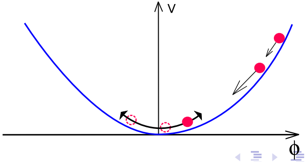
$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \chi\, g_{\mu\nu}\,, \qquad \chi = \exp\left(\sqrt{2/3}\,\phi/M_P\right)\,.$$

for free (in the Jordan frame) scalar φ and fermion ψ fields:

$$S^{EF}_{\varphi} = \int\sqrt{-\tilde{g}}\,d^4x\left(\frac{1}{2}\,\tilde{g}^{\mu\nu}\partial_\mu\tilde{\varphi}\partial_\nu\tilde{\varphi} - \frac{1}{2\chi}\,m^2_\varphi\tilde{\varphi}^2 + \frac{\tilde{\varphi}^2}{12\,M_P^2}\,\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{\tilde{\varphi}}{\sqrt{6}\,M_P}\,\tilde{g}_{\mu\nu}\partial_\mu\tilde{\varphi}\partial_\nu\phi\right)\,,$$

$$S^{EF}_{\psi} = \int\sqrt{-\tilde{g}}\,d^4x\left(i\bar{\tilde{\psi}}\tilde{\hat{\mathscr{D}}}\psi - \frac{m_\psi}{\sqrt{\chi}}\,\bar{\tilde{\psi}}\tilde{\psi}\right)\,.$$

$$\varphi \to \tilde{\varphi} = \chi^{-1/2}\,\varphi\,, \quad \psi \to \tilde{\psi} = \chi^{-3/4}\,\psi\,, \quad \hat{\mathscr{D}} \to \tilde{\hat{\mathscr{D}}} = \chi^{-1/2}\,\hat{\mathscr{D}}$$



New scale $m_\phi \sim \mu$ is screened:

$$\delta\mathscr{L}^{JF} = \frac{M_P^2}{2\mu^2}R^2 \to \mathscr{L}^{EF}_{\phi} \propto 1/M_P$$

Reheating: decay of scalarons

$\rho_\phi = \mu^2\phi^2/2 = \mu n_\phi \to \rho_{rad} \propto T^4$ $\mu \gg m_\varphi, m_\psi$

$$\Gamma_{\phi\to\varphi\varphi} = \frac{\mu^3}{192\pi M_P^2}\,,$$
$$\Gamma_{\phi\to\bar\psi\psi} = \frac{\mu\, m_\psi^2}{48\pi M_P^2}\,.$$

$$T_{reh} \approx 4.5\times 10^{-2}\times g_*^{-1/4}\cdot\left(\frac{N_{scalars}\,\mu^3}{M_P}\right)^{1/2}\,,$$

for the SM with 4 scalar degrees of freedom: A.Starobinsky (1980,1981)

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

D.G., A.Panin (2010)

Outline

Higgs-driven 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 $\lambda\sim 1$

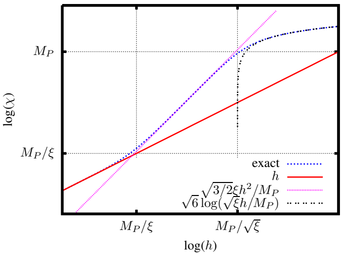
Go to the Einstein frame: $(M_P^2+\xi h^2)\,R\to M_P^2\,\tilde{R}$

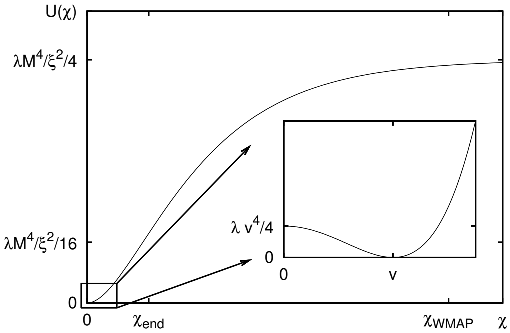
$$g_{\mu\nu}=\Omega^{-2}\tilde{g}_{\mu\nu}\,,\qquad \Omega^2=1+\frac{\xi h^2}{M_P^2}$$

with canonically normalized χ:

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

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

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

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

Advantage: NO NEW interactions to reheat the Universe

inflaton couples to all SM fields!

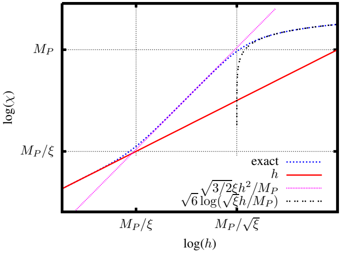
exponentially flat potential! @ $h \gg M_P/\sqrt{\xi}$:

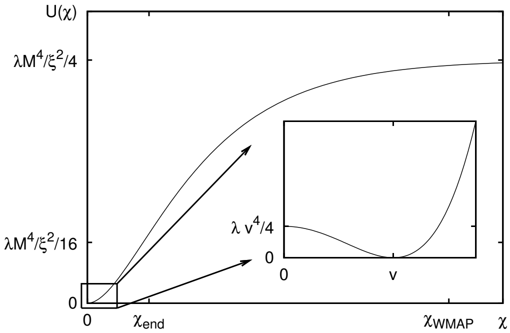
$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

coincides with R^2-model!

But NO NEW d.o.f. 0812.3622, 1111.4397

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





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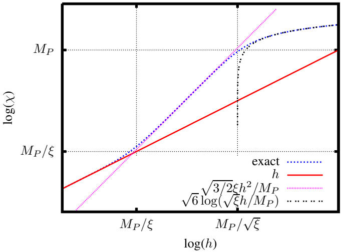
F.Bezrukov, D.G., M.Shaposhnikov, 0812.3622



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

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

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

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

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!

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

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

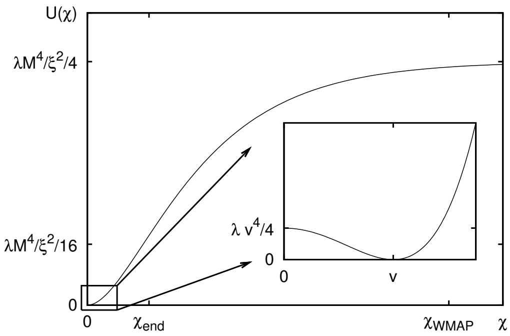
IR: $h \ll M_P/\xi$, $U = \frac{\lambda}{4}h^4$

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 absence of the Landau pole and wrong minimum of the Higgs potential (well) below M_P/ξ

$$125\,\text{GeV} \lesssim m_h \lesssim 195\,\text{GeV}$$



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

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

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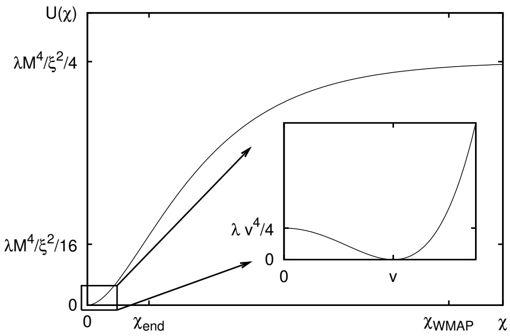

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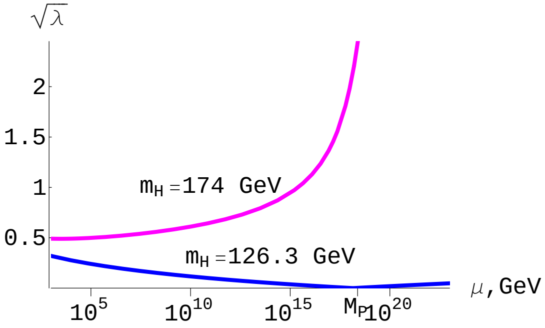
RG-evolution with energy scale μ:

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



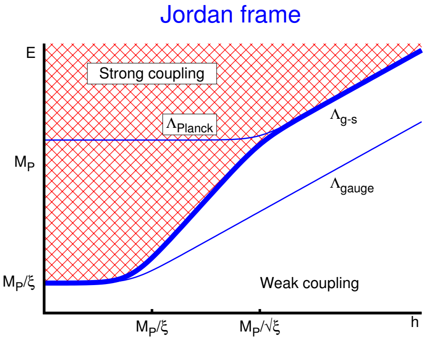
$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

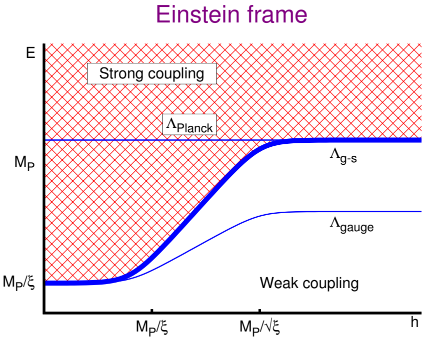
$T_{reh} \simeq 10^{14}$ GeV

0812.3622, 1111.4397

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

Strong coupling in Higgs-inflation: scatterings





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

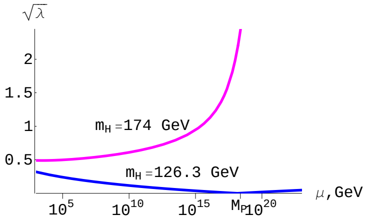
Outline

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)

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

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

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

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

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

Gravity waves from inflation and inflaton clumps

Notice that

$$\text{at MD}: \quad \rho_{GW}/\rho_U \propto 1/a\,, \qquad \text{at RD}: \quad \rho_{GW}/\rho_U \propto \text{const}$$

One expects a break ("knee") in inflationary GW spectrum at $\nu\,(T_{reh})$

$$\text{at MD}: \quad \delta\rho/\rho \propto a$$

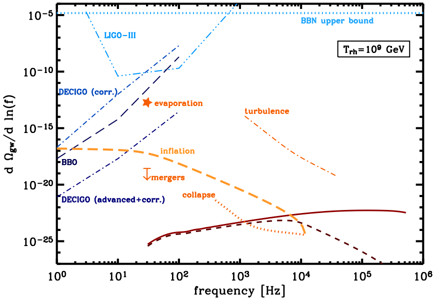
$$R^2-\text{inflation}: \quad \frac{a_{reh}}{a_{inf}} \sim 10^7$$

F.Bezrukov, D.G. (2011)

scalar perturbations enter nonlinear regime
GW from:

- collapses at formation of clumps
- merging of clumps
- evaporation of clumps (scalaron decays)

Since $\rho_{GW}/\rho_U \propto 1/a$, the strongest signal in present GW spectrum is expected at $\nu\,(T_{reh})$



K.Jedamzik, M.Lemoine, J.Martin (2010)

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

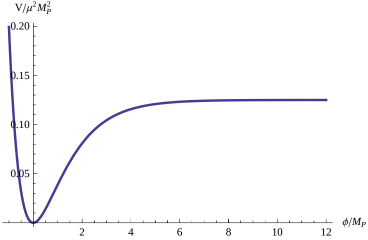
F.Bezrukov, D.G. (2011)

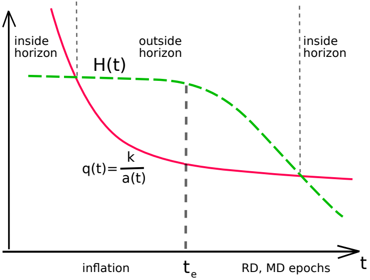
$$N_* \approx 57 - \frac{1}{3}\log\frac{10^{13}\,\text{GeV}}{T_{reh}}\,, \quad N_{R^2} = 54.37, \quad N_H = 57.66.$$

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

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

Planck(?), CMBPol(1-2σ)





Outline

Summary: 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

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; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - 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

Both models can be safely completed

Universaly: e.g., with νMSM (3 sterile neutrinos)

T.Asaka, S.Blanchet, M.Shaposhnikov (2005), T.Asaka, M.Shaposhnikov (2005)

- 2 neurinos at GeV scale are seesaw neutrnos, thus explainig neutrino oscillations and BAU via lepton asymmetry generation due to oscillations in primordial plasma
- 1 neutrino at keV scale serves as dark matter

Specifically

R^2-inflation

- free fermion of $m \simeq 10^7$ GeV as dark matter
- 2 sterile seesaw neutrino of $m \sim 10^{12}$ GeV to explain neutrino oscillations and BAU via leptogenesis

D.G., A.Panin (2010)

Higgs-inflation

At strong coupling scale $\Lambda(h)$ one may expect nonrenormalizable operators

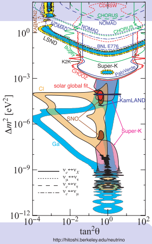
- neutrino oscillations due to $(LH)^2/\Lambda$
- BAU via CP-violating Higgs decays due to $(LH)^2/\Lambda$ and $\bar{L}HE$, $\bar{L}HE \times H^2/\Lambda^2$
- dark matter with additional scalar or fermion

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

Backup slides

Straightforward completion of νMSM

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)

ν Masses and Mixings: "seesaw" from $f_{I\alpha} H \overline{N}_I L_\alpha$

$M_I \gg M^D = f\,v$ says nothing about M_I ! dangerous: $\delta m_h^2 \propto M_I^2$

3 heavy neutrinos with masses M_I similar to quark masses

Light neutrino masses $M^\nu = -(M^D)^T \frac{1}{M_I} M^D \propto f^2 \frac{v^2}{M_I}$

$$U^T M^\nu U = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

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

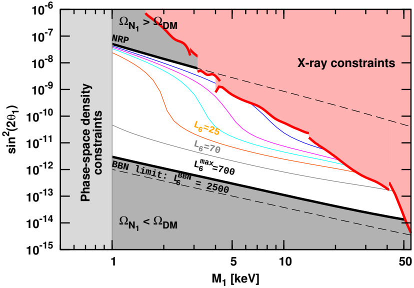
Active-sterile mixings $\theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \propto f \frac{v}{M_I} \ll 1$

Lightest sterile neutrino N_1 as Dark Matter

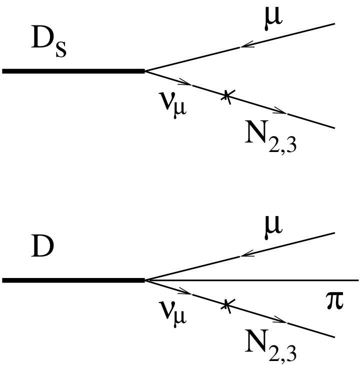
Non-resonant production (active-sterile mixing) is ruled out

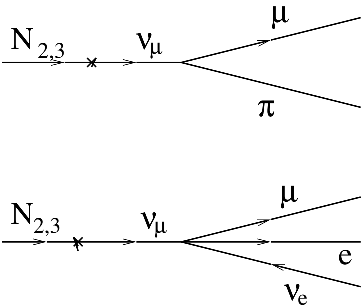
Resonant production (lepton asymmetry) requires $\Delta M_{2,3} \lesssim 10^{-16}$ GeV

arXiv:0804.4542, 0901.0011, 1006.4008

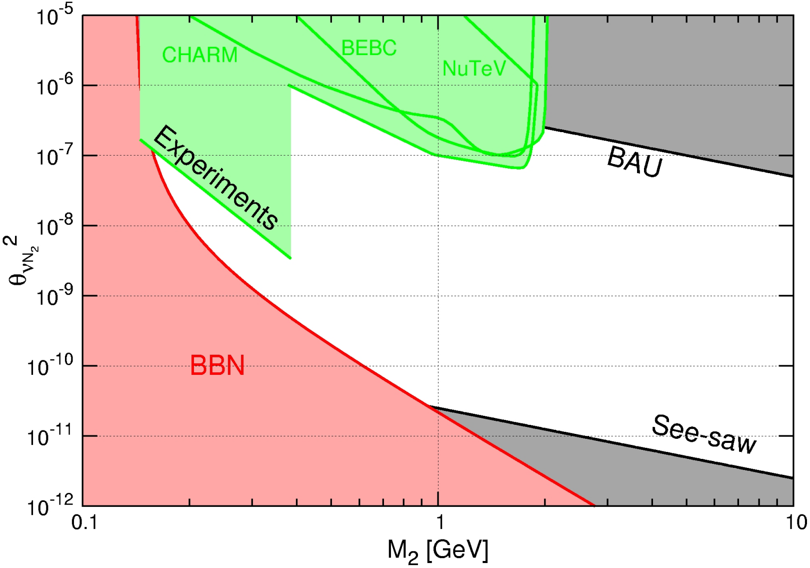


Production and Decays





Searches for sterile seasaw neutrinos $N_{2,3}$



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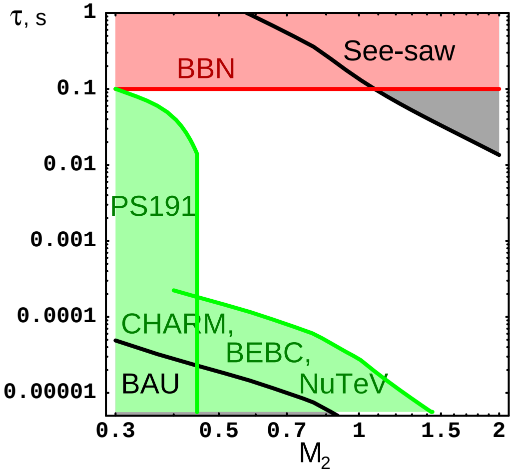

$\mathrm{Br}(D \to lN) \lesssim 2 \cdot 10^{-8}$

$\mathrm{Br}(D_s \to lN) \lesssim 3 \cdot 10^{-7}$

$\mathrm{Br}(D \to KlN) \lesssim 2 \cdot 10^{-7}$

$\mathrm{Br}(D_s \to \eta lN) \lesssim 5 \cdot 10^{-8}$

$\mathrm{Br}(D \to K^* lN) \lesssim 7 \cdot 10^{-8}$

$\mathrm{Br}(B \to DlN) \lesssim 7 \cdot 10^{-8}$

$\mathrm{Br}(B \to D^* lN) \lesssim 4 \cdot 10^{-7}$

$\mathrm{Br}(B_s \to D_s^* lN) \lesssim 3 \cdot 10^{-7}$

$c\tau_N \gtrsim 10^5$ cm

D.G., M.Shaposhnikov (2007)

R^2-inflation with dark matter, neutrino oscillations and BAU

Dark Matter production in scalaron decays

The same universal messenger: gravity

D.G., A.Panin (2010)

$\rho_\phi = \mu^2 \phi^2/2 = \mu n_\phi \to \rho_{DM} = m_{DM} n_{DM}$

$$\Gamma_{\phi\to\varphi\varphi} = \frac{\mu^3}{192\pi M_P^2}\,, \qquad \Gamma_{\phi\to\bar\psi\psi} = \frac{\mu\, m_\psi^2}{48\pi M_P^2}\,.$$

not Dark Matter

$$m_\varphi \approx 7\text{ keV} \times \left(\frac{N_{scalars}}{4}\right)^{1/2} \left(\frac{g_*}{106.75}\right)^{1/4},$$

Cold Dark Matter

$$m_\psi \approx 10^7\text{ GeV} \times \left(\frac{N_{scalars}}{4}\right)^{1/6} \left(\frac{106.75}{g_*}\right)^{1/12}.$$

Heavier stable particles are excluded!

Scalars are overheated: $p_\varphi \sim 10^{13}$ GeV at $T_{reh} \approx 3 \times 10^9$ GeV

Still too fast for proper structure formation at 1 eV epoch… ☹

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Still too fast for proper structure formation at 1 eV epoch. . . ☹

Scalar Dark Matter: other ways out

Two options within our paradigm of
AVOIDING NEW INTERACTIONS IN PARTICLE PHYSICS:

1. switch on nonminimal (conformal) coupling to GRAVITY: $\frac{\xi}{2}R\varphi^2$
2. consider a SUPERHEAVY dark matter candidate: $m_\varphi > \mu/2$

1: Light scalar with nonminimal coupling to gravity

$$S_\varphi^{JF} = \int \sqrt{-g}\, d^4x \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi - \frac{1}{2} m_\varphi^2 \varphi^2 + \frac{\xi}{2} R \varphi^2 \right) ,$$

introducing no new scales, not interfering with inflation: $0 < \xi < 1$

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \chi\, g_{\mu\nu} \,, \qquad \chi = \exp\left(\sqrt{2/3}\, \phi / M_P \right) , \qquad \varphi \to \tilde{\varphi} = \chi^{-1/2} \varphi \,.$$

for free (in the Jordan frame) scalar field φ:

$$S_\varphi^{EF} = \int \sqrt{-\tilde{g}}\, d^4x \left[\frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\varphi} \partial_\nu \tilde{\varphi} + \frac{\xi}{2} \tilde{R} \tilde{\varphi}^2 - \frac{1}{2\chi} m_\varphi^2 \tilde{\varphi}^2 \right.$$
$$\left. + \frac{1}{2} \left(\frac{1}{6} - \xi \right) \frac{\tilde{\varphi}^2}{M_P^2} \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \sqrt{6} \left(\frac{1}{6} - \xi \right) \frac{\tilde{\varphi}}{M_P} \tilde{g}^{\mu\nu} \partial_\mu \tilde{\varphi} \partial_\nu \phi \right] .$$

$$\Gamma_{\phi \to \varphi\varphi} = \left(1 - 6\xi + 2 \frac{m_\varphi^2}{\mu^2} \right)^2 \frac{\mu^3}{192 \pi M_P^2} \,.$$

1: Warm or Cold scalar dark matter

$$\Gamma_{\phi\to\varphi\varphi} = \left(1 - 6\xi + 2\frac{m_\varphi^2}{\mu^2}\right)^2 \frac{\mu^3}{192\pi M_P^2}\,.$$

scalar 3-momentum @ production: $p_* = \sqrt{\mu^2/4 - m_\varphi^2}$, then redshifting $p = p_* \frac{a(t_*)}{a(t_{reh})}$

Spectrum of produced dark matter particles:

$$f(p) \propto \frac{1}{p^{3/2}}\,, \qquad \langle p\rangle (T_{reh}) = \frac{3}{5} p_* \gg T_{reh}$$

Ultrarelativistic @ reheating

must be conformal "with 20%-accuracy"

To be Warm ($v_{DM} \sim 10^{-3}$ @ equilibrium, $T \sim 1$ eV) we need:

$$m_\phi \simeq 0.7\,\text{MeV}\,, \quad \text{then } \xi \approx 1/6 - 0.019\,, \text{ or } \xi \approx 1/6 + 0.019\,.$$

To be Cold ($v_{DM} \ll 10^{-3}$ @ equilibrium, $T \sim 1$ eV) we need:

$$1/6 - 0.019 < \xi < 1/6 + 0.019\,, \quad m_\phi = m_\phi(\xi) > 0.7\,\text{MeV}$$

2: Superheavy dark matter candidate, $m_\varphi > \mu/2$

Particle production in the expanding Universe

$$ds^2 = a^2(\eta)\left(d\eta^2 - d\vec{x}^2\right), \qquad \tilde{\varphi} = s/a(\eta),$$

Main effect: production at the end of inflation $\quad e^{-\phi/M_P} m_\varphi^2 \tilde{\varphi}^2$

$$\left\{ \frac{\partial^2}{\partial\eta^2} - \frac{\partial^2}{\partial\vec{x}^2} + \frac{1}{\chi} a^2 m_\varphi^2 - \left(\frac{1}{6} - \xi\right)\left(6\frac{a''}{a} + \frac{\phi'^2}{M_P^2} + \frac{\sqrt{6}\,a^2}{M_P}\frac{\partial V(\phi)}{\partial\phi}\right)\right\} s(\eta,\vec{x}) = 0,$$

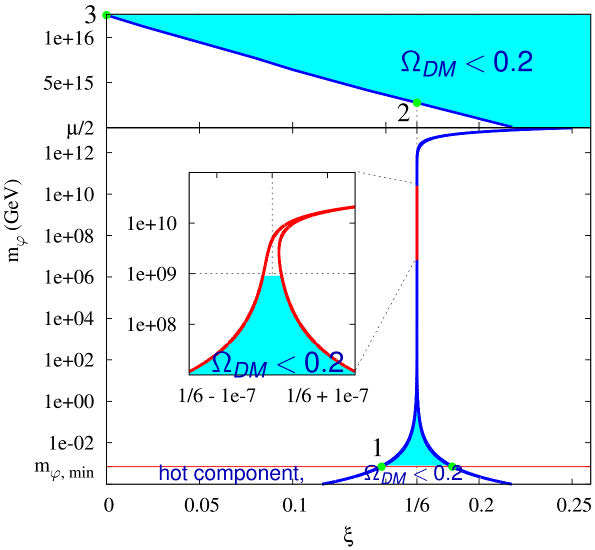
Calculation of Bogolubov's transformation coefficients: $\quad$ vacuum initial conditions

$$s(\eta,\vec{x}) = \frac{1}{(2\pi)^{3/2}}\int d^3p\left(\hat{a}_p s_p(\eta) e^{-i\vec{p}\vec{x}} + \hat{a}_p^\dagger s_p^*(\eta) e^{i\vec{p}\vec{x}}\right), \qquad s_p \to 1/\sqrt{2\omega},\;\; s_p' \to -i\omega s_p.$$

DM particle density in post-inflationary Universe $\quad m_\varphi \sim 10^{16}$ GeV to explain DM

$$n_\varphi = \frac{1}{(2\pi a)^3}\int d^3p\,|\beta_p|^2, \qquad |\beta_p|^2 = \frac{|s_p'|^2 + \omega^2|s_p|^2}{2\omega} - \frac{1}{2}.$$

Summary on scalar Dark Matter:



D.G., Panin, 1110.xxxx

Minimal coupling to gravity, $\xi = 0$:
Superheavy DM:
$m_\phi = 1.3 \times 10^{16}$ GeV

Conformal coupling to gravity, $\xi = 1/6$:
Superheavy DM:
$m_\phi = 2.8 \times 10^{15}$ GeV
Heavy DM: $m_\phi > 10^9$ GeV is forbidden
due to production @ $H \sim m_\phi$

Warm Dark Matter:

$m_\phi \gtrsim 0.7$ MeV

BAU via leptogenesis

Add sterile neutrinos to explain active neutrino oscillations (OK)

either νMSM (BAU via oscillations in primordial plasma) or

use the same universal messenger to produce sterile neutrinos: gravity

$\rho_\phi = m_\phi^2 \phi^2/2 = m_\phi n_\phi \to \rho_N = m_N n_N$

$$\mathscr{L}^{JF} = i\bar{N}_I \gamma^\mu \partial_\mu N_I - y_{\alpha I} \bar{L}_\alpha N_I \tilde{\Phi} - \frac{M_I}{2} \bar{N}_I^c N_I + h.c.$$

$$\frac{n_{N_I}}{s}(T_{reh}) = 3 \times 10^{-6} \times \left(\frac{M_I}{5 \times 10^{12}\ \text{GeV}} \right)^2 .$$

seesaw mechanism:

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

neutrino of $M_N > 10^{10}$ GeV decays before reheating:

$$\Gamma_{N_I} = \frac{M_I}{8\pi} \sum_\alpha |y_{\alpha I}|^2 \sim \frac{\sqrt{\Delta m^2_{atm}}}{4\pi} \frac{M_I^2}{v^2} .$$

Lepton asymmetry from seesaw neutrino decays

Only the lightest sterile neutrino contribution ($I = 1,2$, $M_1 \ll M_2$) is enough

$$\delta_L = \frac{\Gamma(N_1 \to hl) - \Gamma(N_1 \to h\bar{l})}{\Gamma^{tot}_{N_1}} \lesssim \frac{3\,M_1\,\sqrt{\Delta m^2_{atm}}}{8\pi v^2}$$

an order of magnitude estimate for the asymmetry right before the reheating

$$\Delta_L = \frac{n_L}{s} = \delta_L \cdot \frac{n_{N_1}}{s} \lesssim 1.5 \times 10^{-9} \times \left(\frac{M_1}{5 \times 10^{12}\ \text{GeV}}\right)^3 .$$

we got
$\Delta_{B,0} = \Delta_L/3 \sim 0.5 \times 10^{-9}$

we need
$\Delta_{B,0} \approx 0.88 \times 10^{-10}$

Cannot obtain much larger...!

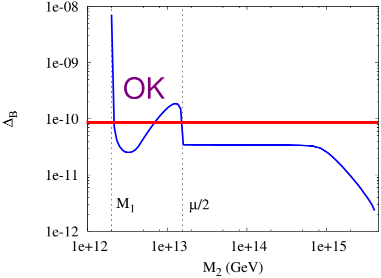
$\mu \sim 10^{13}$ GeV

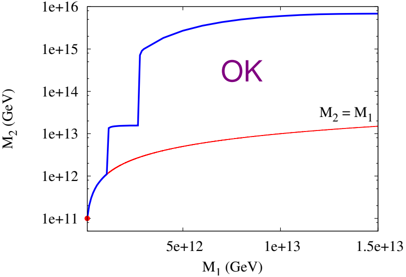
Is it sensitive to CP in active neutrino sector?

One active neutrino is massless
and we
switch off all phases in PMNS

$m_1 = 0,\ m_2 = m_{sol} = 8.75 \times 10^{-3}$ eV,
(normal hierarchy) $m_3 = m_{atm} = 5 \times 10^{-2}$ eV
$\theta_{12} = 33.8^\circ,\ \theta_{23} = 45.5^\circ,\ \alpha = 0,\ \theta_{13} = 0$

Scan over parameters of sterile neutrino sector





$M_1 = 2 \times 10^{12}$ GeV
Maximum Δ_B we can obtain at a given M_2

$\Delta_{B,0} = 0.88 \times 10^{-10}$
Limit from above on M_2 at a given M_1

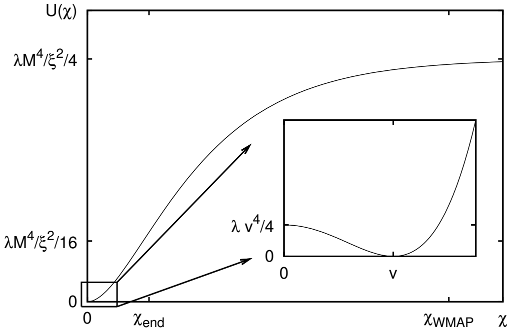
Higgs-inflation with nonrenormalizable operators

Fine theoretical descriptions both in

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

and in

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



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 (apart of $T_{reh} \simeq 10^{14}$ GeV) with R^2-model!
But NO NEW d.o.f. 0812.3622

$$n_s = 0.97\,, \quad r = 0.0034\,, \quad N = 59$$

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 $m_h = \sqrt{2\lambda}\, v$

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

Fine theoretical descriptions both in

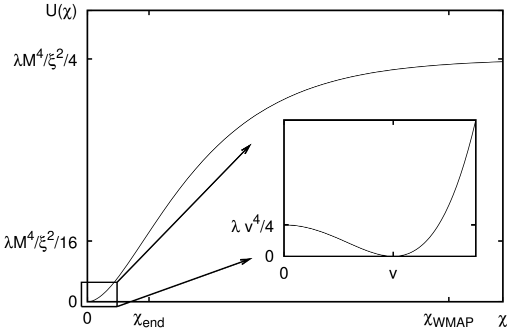
UV: $\chi \gg M_P\,,\ \ U = \text{const} + \mathcal{O}\left(\exp\left(-\sqrt{2}\,\chi/\sqrt{3}M_P\right)\right)$

and in

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

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

Hence no reliable prediction for the SM Higgs boson mass $m_h = \sqrt{2\lambda}\,v$



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

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

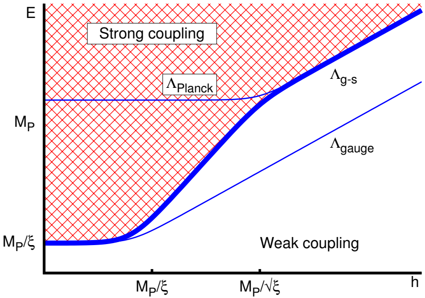
coincides (apart of $T_{reh} \simeq 10^{14}$ GeV) with R^2-model!
But NO NEW d.o.f. 0812.3622

$$n_s = 0.97\,,\ \ r = 0.0034\,,\ \ N = 59$$

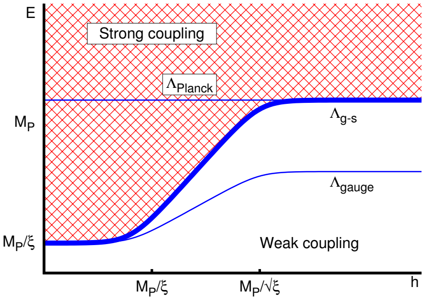
from WMAP-normalization: $\xi \approx 47000 \times \sqrt{\lambda}$

Strong coupling in Higgs-inflation

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

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

Nonrenormalizable operators today

Neutrino masses: easily

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

hence

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

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

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

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

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

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 gives a factor up to 10^8 !

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

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Dark matter: an example of sterile fermion

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

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

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