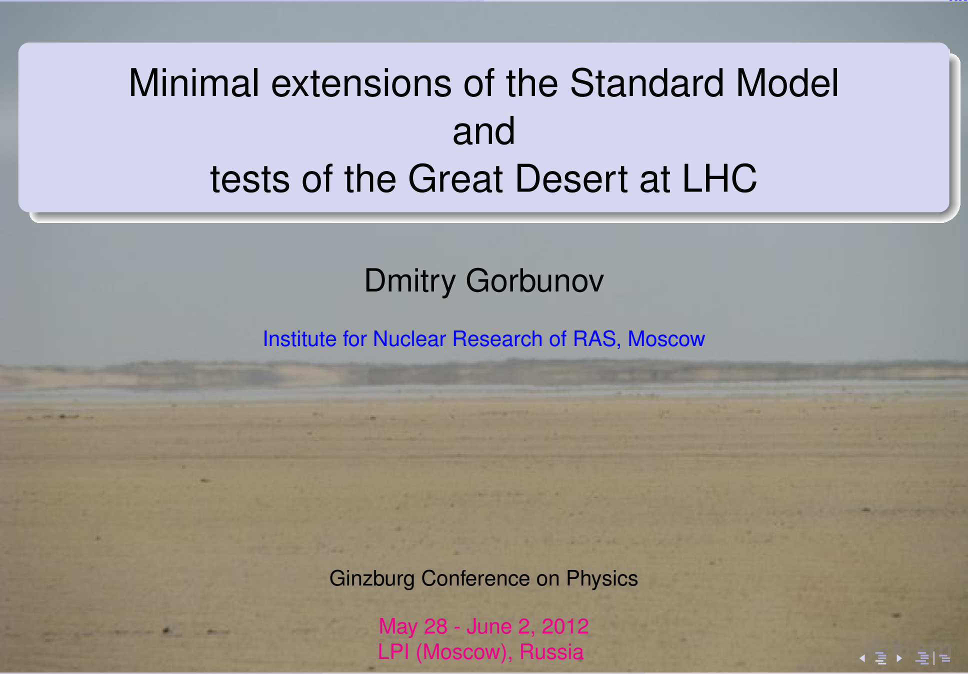


Minimal extensions of the Standard Model and tests of the Great Desert at LHC

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

Ginzburg Conference on Physics

May 28 - June 2, 2012
LPI (Moscow), Russia

Outline

1. Motivation: Why we beleive that SM is incomplete. . .
2. Higgs portal to X^4-inflation: light inflaton at CMS

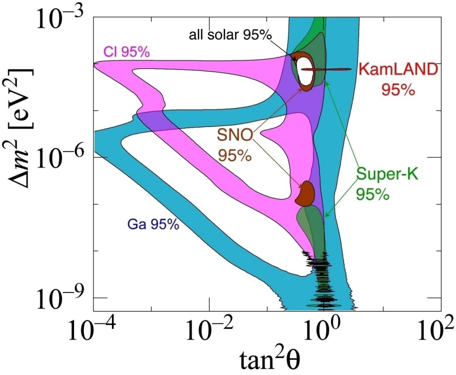
   F.Bezrukov, D.G., JHEP 1005 (2010) 010
3. Starting from R^2-inflation: no new interactions
4. Starting from Higgs-inflation: no new fields
5. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe. . . searches at LHCb?

   D.G., M.Shaposhnikov, JHEP 0710 (2007) 015
6. Summary of the results

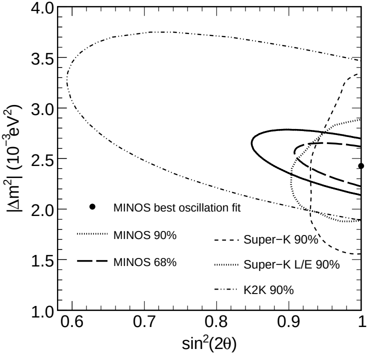
Neutrino oscillations: masses and mixing angles

Solar 2×2 “subsector”

Atmospheric 2×2 “subsector”



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



arXiv:0806.2237

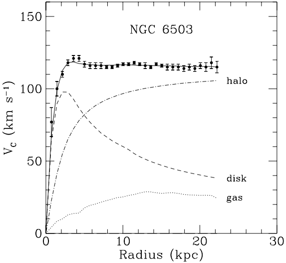
$m_1 > 0.008\,\text{eV}$

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

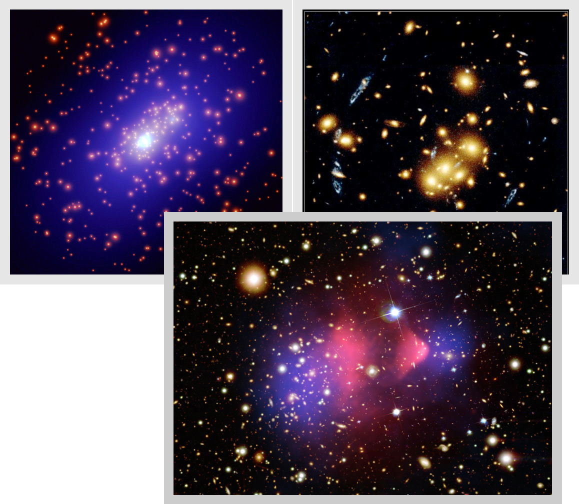
DAYA-BAY, RENO: $\sin^2 2\theta_{13} \approx 0.1$

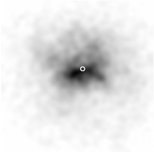
Baryons and Dark Matter in Astrophysics

Rotation curves



Gravitational lensing



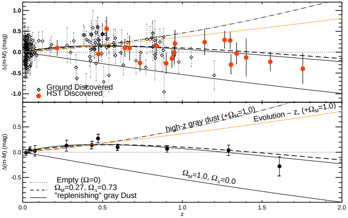


X-rays from clusters

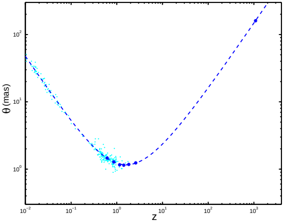
“Bullet” cluster

Baryons and Dark Matter in Cosmology

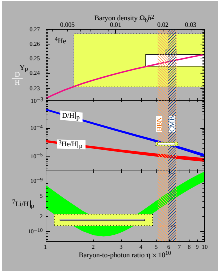
Standard candles

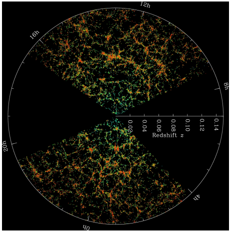


Angular distance

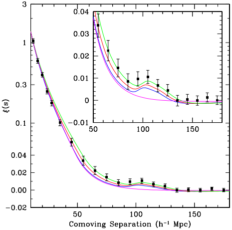


BBN

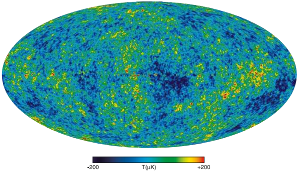




Structures

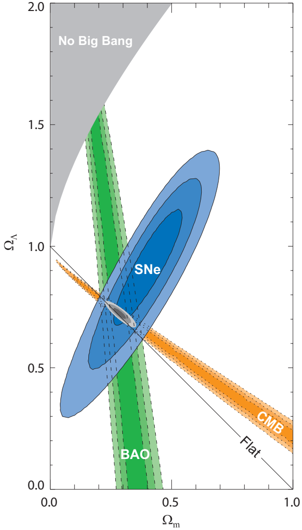


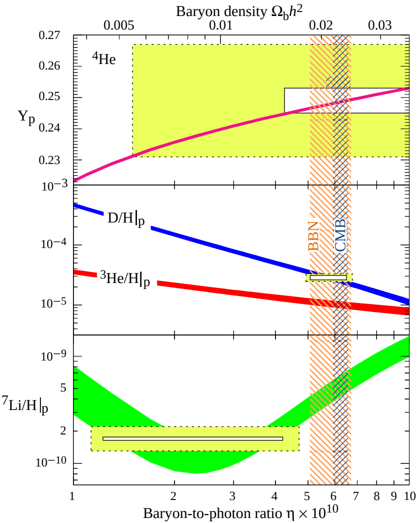
BAO



CMB fluctuations

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



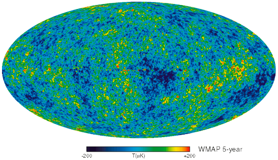


arXiv:0804.4142

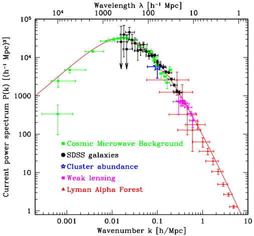
http://pdg.lbl.gov

Inflationary solution of Hot Big Bang problems

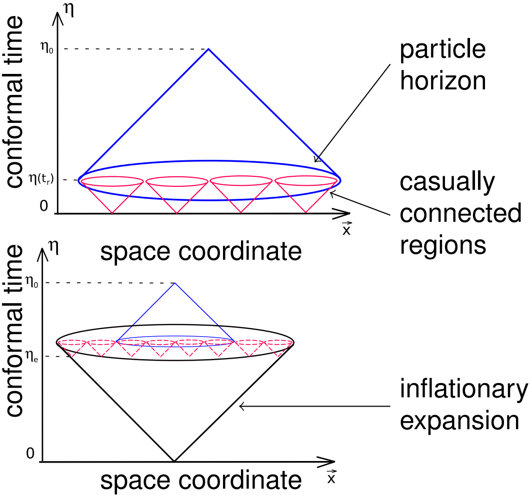
Temperature fluctuations $\delta T/T \sim 10^{-5}$



Universe is uniform!



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



particle horizon

casually connected regions

inflationary expansion

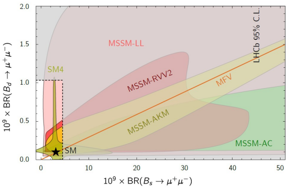
True Extension of the Standard Model should

- 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

(news from B-physics)

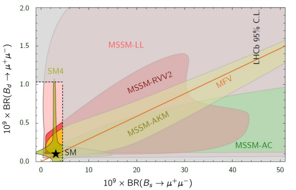
Phenomenological motivation for NP at EW scale

- 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

(news from B-physics)

Weakly Interacting Massive Particles

Assumptions:

1. X and $\bar{X}$ are stable (at cosmological time scale)
2. no $X - \bar{X}$ asymmetry $\qquad n_X = n_{\bar{X}}$
3. @ $T < M_X$ in thermal equilibrium with plasma

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

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

Bethe formulae: s-wave: $\sigma_{ann} = \frac{\sigma_0}{v}$

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

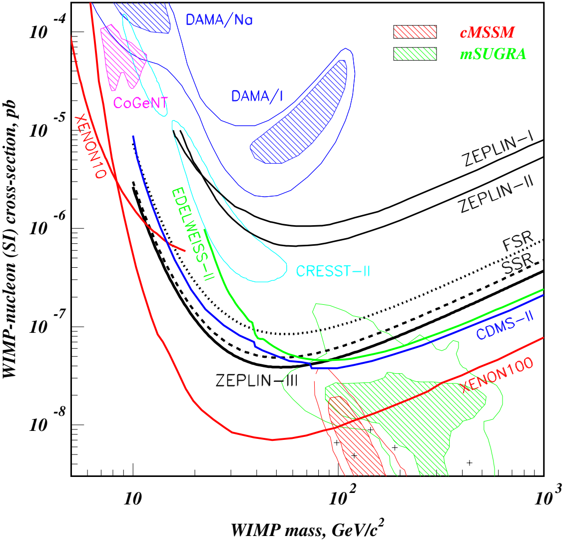
$$\Omega_X = 0.1 \times \frac{(1\ \text{TeV})^{-2}}{100 \times \sigma_0} \frac{0.3}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right) \cdot \frac{1}{2h^2}$$

natural dark matter

naturaly “light” $\qquad \sigma_0 \lesssim \frac{4\pi}{M_X^2} \longrightarrow M_X \lesssim 30\ \text{TeV}$

WIMPs: No clear direct evidence so far. . .

1110.4769



Dark Matter: Other well-motivated candidates

Unrelated to the EW scale!

sterile neutrinos	sharp line: $\nu_s \to \nu_a + \gamma$, (XMM, INTEGRAL, ...)
light scalar field	caustics in Bose condensate
axion	oscillations $a + \mathbf{B} \to \gamma$
gravitino	missing energy at LHC, ...
Heavy relics	if unstable: decay into Cosmic rays
(Topological) defects	lensing of CMB
Massive Astrophysical Compact Heavy Objects	microlensing
Primordial black hole remnants	Cosmic rays

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

- Without direct hints at “motivated” new physics at 1 TeV ...
- Do we need LHC further?

- YES, since there are minimal models which can explain all above
- LHC can check some predictions of these models

Outline

1. Motivation: Why we beleive that SM is incomplete. . .
2. Higgs portal to X^4-inflation: light inflaton at CMS

   F.Bezrukov, D.G., JHEP 1005 (2010) 010
3. Starting from R^2-inflation: no new interactions
4. Starting from Higgs-inflation: no new fields
5. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe. . . searches at LHCb?

   D.G., M.Shaposhnikov, JHEP 0710 (2007) 015
6. Summary of the results

Inflation: simple realization with new particles at LHC

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

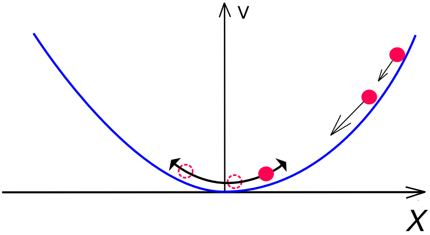
$X_e > M_{Pl}$

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

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

reheating ? renormalizable?

the only choice: $\alpha H^\dagger H X^2$



Chaotic inflation, A.Linde (1983)

larger α larger T_{reh}

quantum corrections $\propto \alpha^2 \lesssim \beta$

Gravity solves all problems — No scale, no problem

Inflation & Reheating: the model

M.Shaposhnikov, I.Tkachev (2006)

$$\mathscr{L}_{XN} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2} m_X^2 X^2 - \frac{\beta}{4} X^4 - \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2$$

The SM-like vacuum of the scalar potential

$$v = \sqrt{\frac{2\alpha}{\beta\lambda}}\, m_X = 246\ \text{GeV}\,, \quad m_h = \sqrt{2\lambda}\, v\,, \quad m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}}$$

Higgs-inflaton $(h - \chi)$ mixing angle

$$\theta = \sqrt{\frac{2\alpha}{\lambda}} = \frac{\sqrt{2\beta}\, v}{m_\chi} \sim 10^{-3} \times \left(\frac{100\ \text{MeV}}{m_\chi} \right)$$

Amplitude of primordial perturbations: $\beta \approx 1.5 \cdot 10^{-13}$

F.Bezrukov, D.G. (2009)

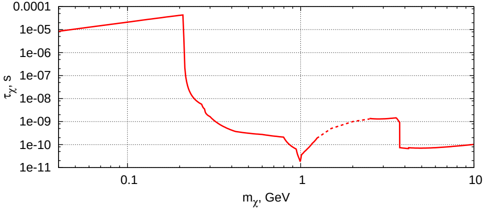
Only one free parameter!

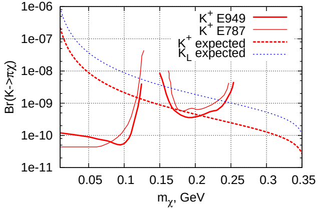
$30\ \text{MeV} \lesssim m_\chi \lesssim 1.8\ \text{GeV}$

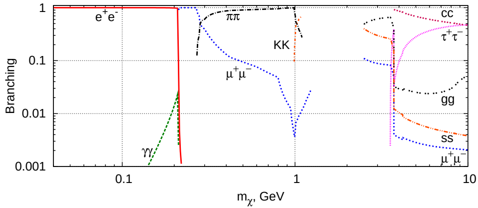
$T_{reh} > 100\ \text{GeV}$, $m_h < 190\ \text{GeV}$

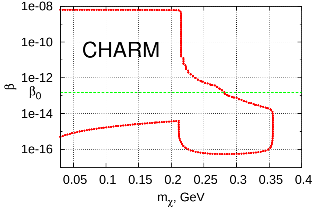
reheating:
A.Anisimov, Y.Bartocci, F. Bezrukov (2008)

Phenomenology: Higgs-inflaton mixing!









$m_\chi \lesssim$ 250 MeV is already excluded ! from $K \to \pi\chi$ and $pN \to \ldots\chi(\chi \to \mu^+\mu^-)$

Inflaton Phenomenology: direct searches

$$\mathrm{Br}\left(B \to \chi X_s\right) \simeq 0.3 \frac{\left|V_{ts} V_{tb}^*\right|^2}{\left|V_{cb}\right|^2} \left(\frac{m_t}{M_W}\right)^4 \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \theta^2$$

$$\simeq 10^{-6} \cdot \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \left(\frac{300\ \mathrm{MeV}}{m_\chi}\right)^2 ,$$

Recent sensitivity: Belle, LHCb

$\mathrm{Br}(B \to K^{(*)} l^+ l^-) \gtrsim 10^{-7}$ $250\ \mathrm{MeV} \lesssim m_\chi \lesssim 1.8\ \mathrm{GeV}$

Expectation for the Inflaton:

scalar channel $B \to K\chi$

displaced decay vertex $c\tau_\chi \sim 3 - 30\ \mathrm{cm}$

peaks at a given energy for $\mu^+\mu^-$, $\pi^+\pi^-$, K^+K^-

This INFLATIONARY model can be directly and fully explored thanks to B-physics!

Outline

1. Motivation: Why we beleive that SM is incomplete…
2. Higgs portal to X^4-inflation: light inflaton at CMS

   F.Bezrukov, D.G., JHEP 1005 (2010) 010
3. Starting from R^2-inflation: no new interactions
4. Starting from Higgs-inflation: no new fields
5. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe… searches at LHCb?

   D.G., M.Shaposhnikov, JHEP 0710 (2007) 015
6. Summary of the results

The first inflationary model: nothing new at LHC

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

Jordan Frame → Einstein Frame

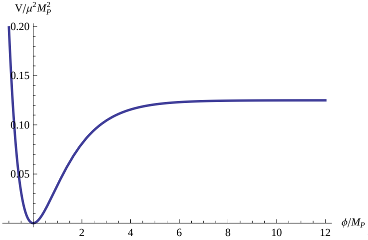
A.Starobinsky (1980)

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

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

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

$\delta\rho/\rho \sim 10^{-5}$ requires
$\mu = m_\phi \approx 1.3\times10^{-5}\,M_P$



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:

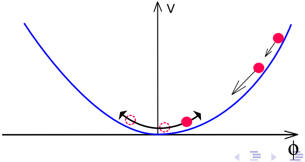
$$S^{EF}_{\varphi} = \int \sqrt{-\tilde{g}}\, d^4x \left(\frac{1}{2}\, \tilde{g}^{\mu\nu} \partial_\mu \tilde{\varphi} \partial_\nu \tilde{\varphi} - \frac{1}{2\chi}\, m^2_\varphi \tilde{\varphi}^2 + \frac{\tilde{\varphi}^2}{12\, M_P^2}\, \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{\tilde{\varphi}}{\sqrt{6}\,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

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

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

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 into the Higgs bosons

$\rho_\phi = \mu^2\phi^2/2 = \mu n_\phi \to \rho_{rad} \propto T^4$

$\mu \gg m_\varphi, m_\psi$

A.Starobinsky (1980,1981)

$$\Gamma_{\phi\to\varphi\varphi} = \frac{\mu^3}{192\pi M_P^2}\,,$$

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

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

for the SM with 4 scalar degrees of freedom:

D.G., A.Panin (2010)

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

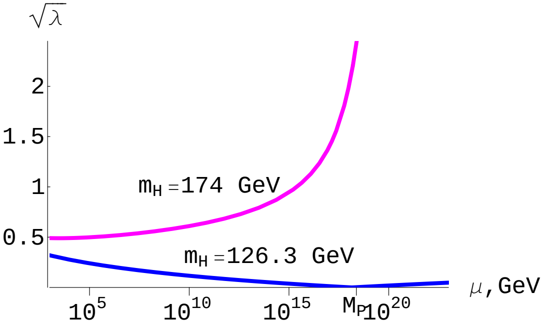
RG-evolution with energy scale μ:

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

Absence of the Landau pole upto inflationary scale $\sim 10^{13}$ GeV and stability of the Higgs potential at the hot stage from T_{reh}

$$116\,\text{GeV} \lesssim m_h \lesssim 195\,\text{GeV}$$

F.Bezrukov, D.G. (2010)



LHC HAS ALREADY CHECKED

THIS MODEL !!!

$\phi \to hh$

if the SM Higgs boson exists...

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

D.G. A.Panin (2010)

Outline

1. Motivation: Why we beleive that SM is incomplete. . .
2. Higgs portal to X^4-inflation: light inflaton at CMS

   F.Bezrukov, D.G., JHEP 1005 (2010) 010
3. Starting from R^2-inflation: no new interactions
4. Starting from Higgs-inflation: no new fields
5. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe. . . searches at LHCb?

   D.G., M.Shaposhnikov, JHEP 0710 (2007) 015
6. Summary of the results

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 $\lambda\sim 1$

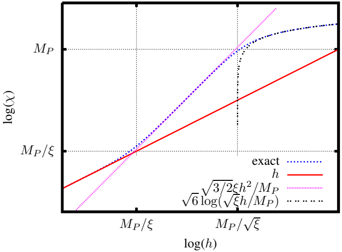
Go to the Einstein frame: $(M_P^2+\xi\,h^2)\,R\to M_P^2\,\tilde{R}$

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

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

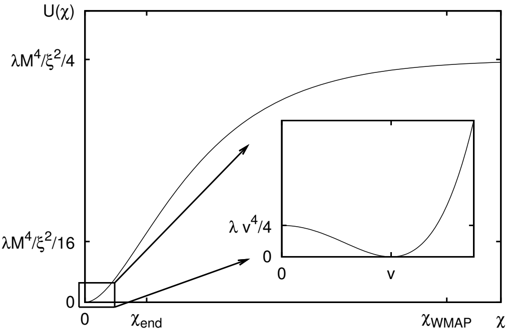
after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

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

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

Advantage: NO NEW interactions to reheat the Universe

inflaton couples to all SM fields!



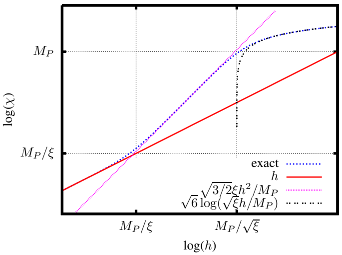
exponentially flat potential! @ $h \gg M_P/\sqrt{\xi}$:

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

coincides with R^2-model!

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

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



Reheating by Higgs field

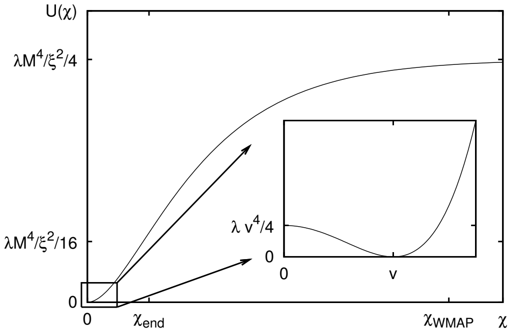
after inflation: $M_P/\xi < h < M_P/\sqrt{\xi}$

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

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

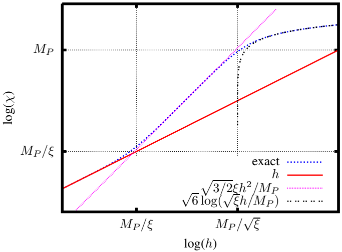
coincides with R^2-model!

But NO NEW d.o.f.

0812.3622, 1111.4397

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

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



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!

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

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

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

then nonrelativistic gauge bosons scatter to light fermions

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

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

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

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

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 $\lambda\left(M_{Pl}\right) = 0$

Message: Zero Planck-scale corrections from gravity?

PAST: gauge coupling unification. . .

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

Nature knows

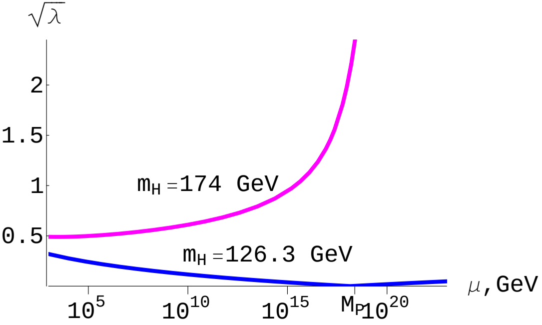
GeV and decimal system !!

☺

THIS MODEL HAS ALREADY BEEN CORNERED BY LHC !!

RG-evolution with energy scale μ:

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



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

$T_{reh} \simeq 3\times10^{13}$ GeV

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

Upper limit on the Higgs boson mass

F.Bezrukov, M.Kalmykov, B.Kniehl, M.Shaposhnikov (2012)

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

F.Bezrukov, D.G. (2011)

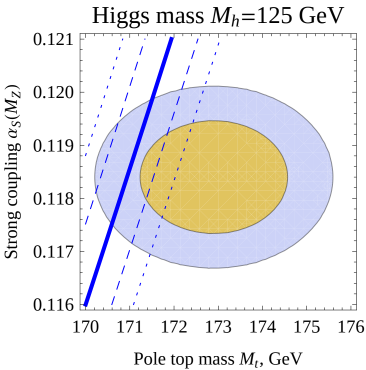
$$m_h^{R^2} > \left[116.5 + \frac{m_t - 172.9\,\text{GeV}}{1.1\,\text{GeV}} \times 2.6 - \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \times 0.6\right] \text{GeV}$$

Higgs-inflation: stability while the Universe evolves right after inflation $h \sim M_{Pl}$

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

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

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



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

Important for further improvement:

- 3-loop matching and QCD for top
- measurement of m_t, y_t and m_h at LHC

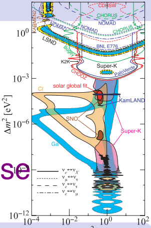
Outline

1. Motivation: Why we beleive that SM is incomplete. . .
2. Higgs portal to X^4-inflation: light inflaton at CMS

   F.Bezrukov, D.G., JHEP 1005 (2010) 010
3. Starting from R^2-inflation: no new interactions
4. Starting from Higgs-inflation: no new fields
5. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe. . . searches at LHCb?

   D.G., M.Shaposhnikov, JHEP 0710 (2007) 015
6. Summary of the results

Straightforward completion by νMSM



http://hitoshi.berkeley.edu/neutrino

- Use 3 sterile neutrinos
- TO get active neutrino oscillations
- AND 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)

Outline

1. Motivation: Why we beleive that SM is incomplete. . .
2. Higgs portal to X^4-inflation: light inflaton at CMS

   F.Bezrukov, D.G., JHEP 1005 (2010) 010
3. Starting from R^2-inflation: no new interactions
4. Starting from Higgs-inflation: no new fields
5. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe. . . searches at LHCb?

   D.G., M.Shaposhnikov, JHEP 0710 (2007) 015
6. **Summary of the results**

Summary

We considered the simplest one-field inflationary models:

- Chaotic inflation: $\beta X^4 + \alpha X^2 H^\dagger H$ with viable reheating can be fully explored by direct searches of $B \to X_s + \chi$ 250 MeV$\lesssim m_\chi \lesssim$1.8 GeV

F.Bezrukov, D.G. JHEP 1005 (2010) 010 $$\mathrm{Br}\,(B \to \chi X_s) \simeq 10^{-6} \cdot \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \left(\frac{300\ \mathrm{MeV}}{m_\chi}\right)^2$$

$$\chi \to \mu^+\mu^-\,, \pi^+\pi^-\,, K^+K^- \qquad c\tau_\chi \simeq 3-30\,\mathrm{cm}$$

- R^2-inflation: 116 GeV $\lesssim m_h \lesssim$ 195 GeV already proved by LHC. . . ?
- Higgs-inflation: 129 GeV $\lesssim m_h \lesssim$ 195 GeV
  needs better precision in measurement of m_h, m_t, y_t, α_s
- Some other inflationary models also point at $m_h \sim 125$ GeV (e.g. hill-top potential in simple tensor-scalar gravity I.Masina, A.Notari (2012))
- Can be easily completed to account for
  - neutrino oscillations
  - dark matter
  - baryon asymmetry of the Universe

  Example: νMSM, responsible for BAU 1 GeV sterile neutrinos to be searched for at LHCb (CMS ?) D.G., M.Shaposhnikov, JHEP 0710 (2007) 015, LOI LHCb (2011)

Backup slides

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

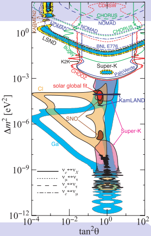
At strong coupling scale $\Lambda(h)$ one may expect nonrenormalizable operators

- 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)

Straightforward completion of νMSM

νMSM



http://hitoshi.berkeley.edu/neutrino

- 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 $\nu_\alpha = U_{\alpha i}\nu_i + \theta_{\alpha I} N_I^c$

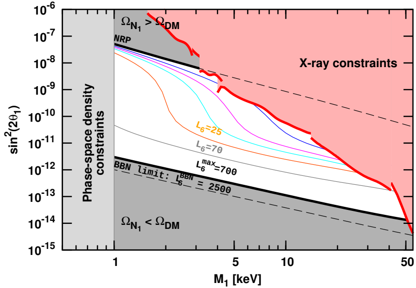
Active-sterile mixings $\theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \propto f \frac{v}{M_I} \ll 1$

Lightest sterile neutrino N_1 as Dark Matter

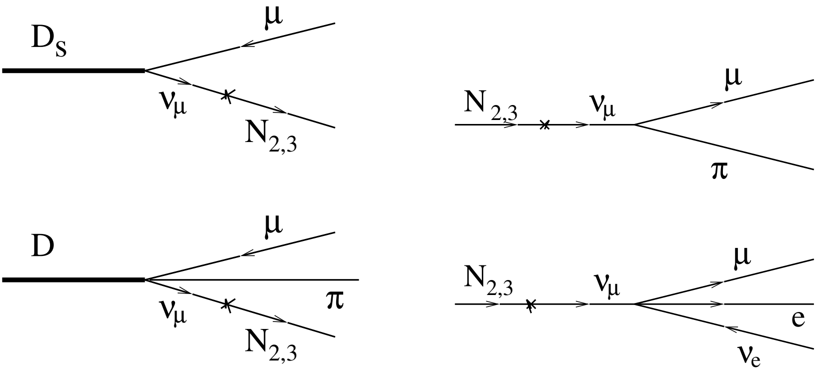
Non-resonant production (active-sterile mixing) is ruled out

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

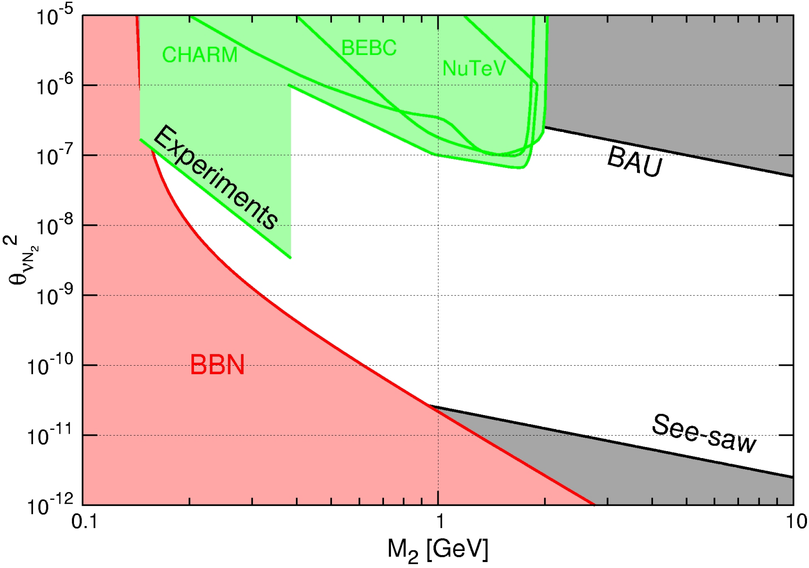
arXiv:0804.4542, 0901.0011, 1006.4008



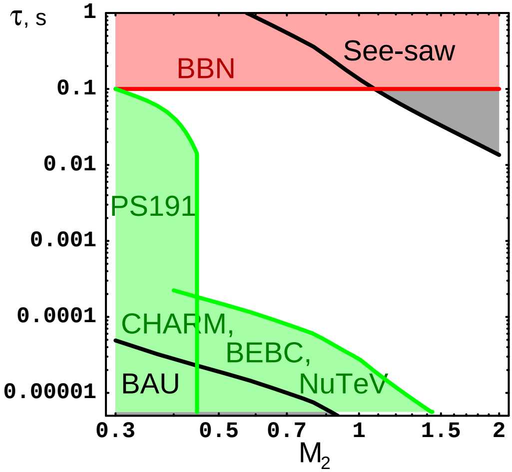
Production and Decays



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



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



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

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

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

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

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

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

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

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

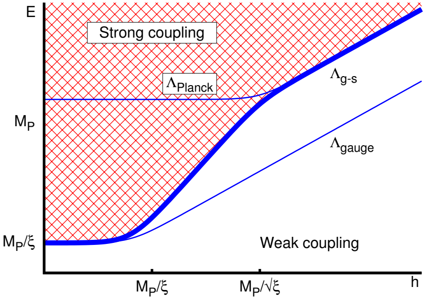
$c\,\tau_N \gtrsim 10^5$ cm

D.G., M.Shaposhnikov (2007)

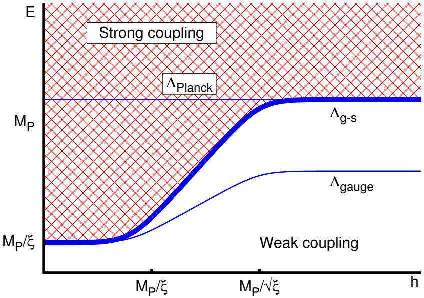
R^2-inflation with dark matter, neutrino oscillations and BAU

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)

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

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