Inflationary models and scale invariance

Dmitry Gorbunov

Institute for Nuclear Research, Moscow, Russia

Hot topics in Modern Cosmology
Spontaneous Workshop VII

IESC, Cargese, France, 07.05.2013

Why inflation and scale invariance?

Inflation

- solves horizon problem
- solves curvature problem
- provides with matter perturbations
- ...

Phenomenological problems

Scale invariance

- gets rid of (classical) cosmological constant (need instead a quintessence? unimodular gravity?)
- eliminates quadratic divergences

$$\Delta T^{\mu}_{\mu} \propto \left(\Lambda^2 + m_h^2\right) h^2$$

- ...

Theoretical problems

Outline

1. Higgs portal to new physics
2. Higgs portal to X^4-inflation: light inflaton at LHCb
3. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe…
4. Further extension within scale invariance
5. Inflation in presence of dilaton: dilaton production at reheating

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 physics” as possible

Why? No any hints observed so far!

Outline

1. Higgs portal to new physics
2. Higgs portal to X^4-inflation: light inflaton at LHCb
3. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe...
4. Further extension within scale invariance
5. Inflation in presence of dilaton: dilaton production at reheating

New physics from the (still unknown) Higgs sector

- EW baryogenesis:
  not enough CP, not I order phase transition
  could be 2 Higgs doublets!
- Dark Matter candidate: stable due to Z_2-symmetry
  Natural CDM from primordial plasma
  Singlet scalar field: (e.g. Burgess, Pospelov, ter Veldhuis, 2001)

$$\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_0^2}{2}S^2 - \lambda S^2 H^\dagger H + \ldots$$

- one of the SM portals to hidden sectors (SM-gauge singlets: no FCNC!)

$$\beta B^{\mu\nu}_{U(1)_Y} B^{\mu\nu}_{U(1)_{Y'}} \qquad \alpha H^\dagger H \cdot X^\dagger X$$

secluded $U(1)$

$Z - Z'$, $\gamma - \gamma'$

e.g. M.Pospelov
Phys Rev D80 (2009) 095002

renormalizable!
to be tested at
any energy scale!

fascinating example:
$h - \chi$ portal to inflaton!

F.Bezrukov, D.G.
JHEP 1005 (2010) 010

Outline

1. Higgs portal to new physics
2. Higgs portal to X^4-inflation: light inflaton at LHCb
3. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe. . .
4. Further extension within scale invariance
5. Inflation in presence of dilaton: dilaton production at reheating

Inflation & Reheating: simple realization

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

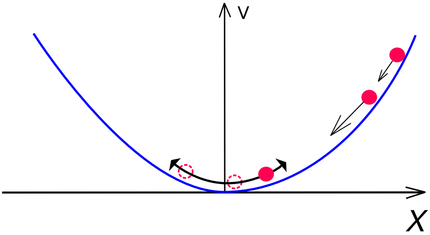
$X_e > M_{Pl}$

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

No scale, no problem

Inflation & Reheating: the model

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

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!

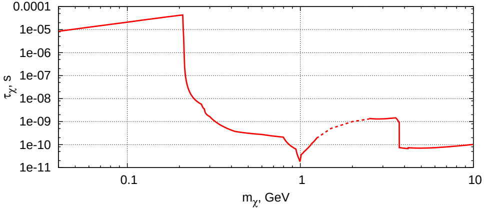
$30\ \text{MeV} \lesssim m_\chi \lesssim 1.8\ \text{GeV}$

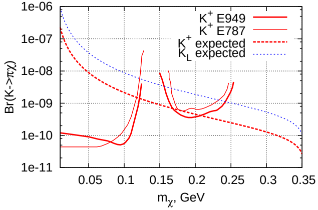
$T_{reh} > 100$ GeV, $m_h < 190$ GeV

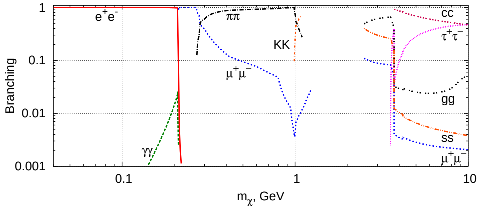
Landau pole above inflation scale

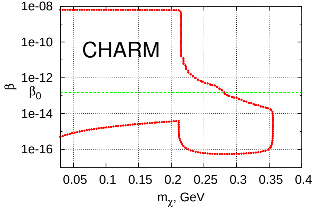
study of reheating:
A.Anisimov, Y.Bartocci, F. Bezrukov (2008)

Phenomenlogy: 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 Phenomenlogy: direct searches

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

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

Recent sensitivity: Belle

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

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. Higgs portal to new physics
2. Higgs portal to X^4-inflation: light inflaton at LHCb
3. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe…
4. Further extension within scale invariance
5. Inflation in presence of dilaton: dilaton production at reheating

True Extension of the Standard Model should

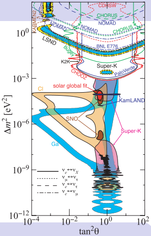
- Reproduce the correct neutrino oscillations
- Contain the viable DM candidate
- Be capable of explaining the baryon asymmetry of the Universe
- Have the inflationary mechanism operating at early times

Guiding principle:

use as little “new physics” as possible

Why? No accidental hints observed so far!

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

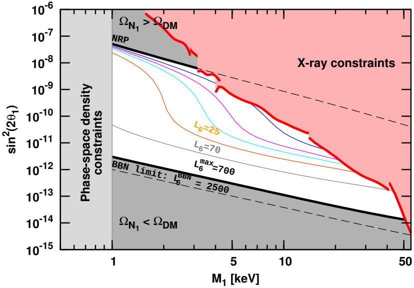
Active-sterile mixings $$\theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \propto f \frac{v}{M_I} \ll 1$$

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



Dark Matter production
from inflaton decays in plasma at $T \sim m_\chi$

M.Shaposhnikov, I.Tkachev (2006)

$$M_{N_I} \bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

Can be "naturally" Warm

F.Bezrukov, D.G. (2009)

$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300 \text{ MeV}} \right) \text{keV}$$

Outline

1. Higgs portal to new physics
2. Higgs portal to X^4-inflation: light inflaton at LHCb
3. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe...
4. Further extension within scale invariance
5. Inflation in presence of dilaton: dilaton production at reheating

Summary

- Renormalizable inflationary model $\beta X^4 + \alpha X^2 H^\dagger H$ with viable reheating can be fully explored by direct searches of $B \to X_s + \chi$ $\quad 250\,\text{MeV} \lesssim m_\chi \lesssim 1.8\,\text{GeV}$

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

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

- combined with νMSM (completed with right handed neutrinos) provides
  - active neutrino masses and mixing angles
  - 10-100 keV neutrino as (warm) Dark Matter
  - mechanism for baryon asymmetry generation
  - seesaw and BAU are testable at fixed target experiments and B-factories: $\text{Br} \simeq 10^{-6} - 10^{-10}$, $c\tau_N \gtrsim 10^5$ cm

D.G., M.Shaposhnikov, JHEP 0710 (2007) 015

LHC: Higgs mass from validity upto $\sqrt{\frac{\alpha}{\lambda}} M_P \simeq \theta \cdot M_P \sim 10^{14} - 10^{15}$ GeV:

$128 \pm 4\,\text{GeV} \lesssim m_h$

Light inflaton: update in 1303.4395

Accepting LHC8, SPT, ACT, WMAP9 and Planck

$$-\frac{1}{2}\,\xi\, R\, X^2$$

Note, it is also scale-invariant…

Light inflaton nonminimally coupled to gravity

$$S_{XSM} = \int \sqrt{-g}\, d^4x \left(\mathscr{L}_{SM} + \mathscr{L}_{XH} + \mathscr{L}_{ext} + \mathscr{L}_{grav}\right),$$

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

$$\mathscr{L}_{grav} = -\frac{M_P^2 + \xi X^2}{2} R,$$

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \qquad \Omega^2 = 1 + \xi X^2 / M_P^2,$$

$$U(X) = \frac{\beta X^4}{4\Omega^4} \to \text{const} = \frac{\beta}{\xi^2} M_P^4 \quad \text{at} \quad X \to \infty.$$

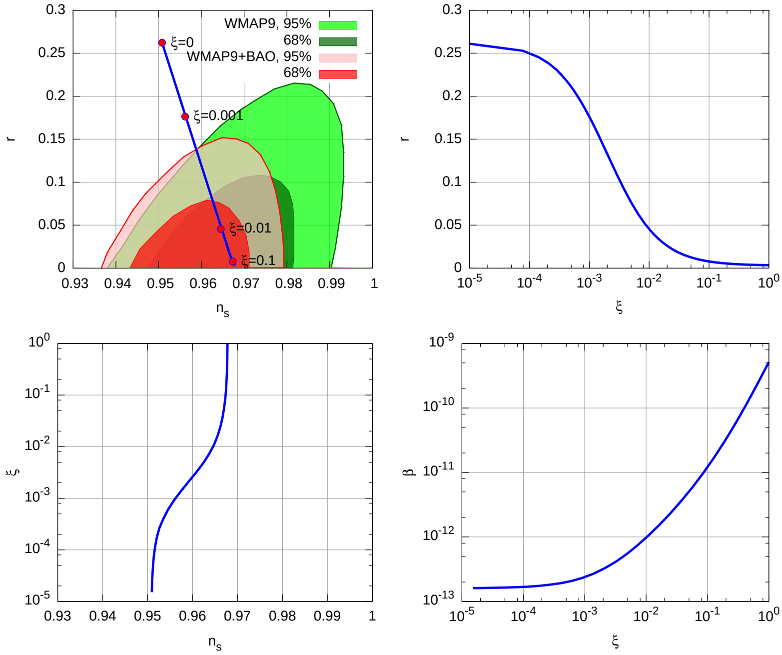
$$X \to \mathscr{X}: \quad \frac{d\mathscr{X}}{dX} = \sqrt{\frac{\Omega^2 + 6\xi^2 X^2/M_P^2}{\Omega^4}}$$

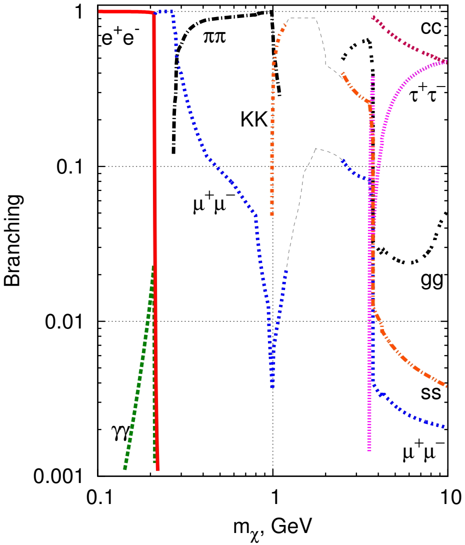
$$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}} = \sqrt{\frac{\beta}{\lambda\theta^2}}.$$

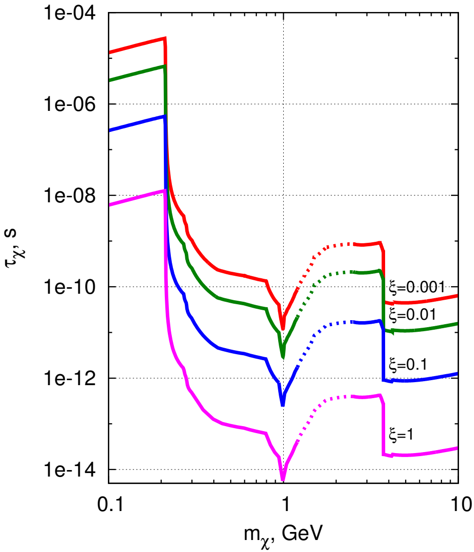
$$\theta^2 = \frac{2\beta v^2}{m_\chi^2} = \frac{2\alpha}{\lambda}.$$

Outcome: easier to test!

$$\beta \nearrow \implies \tau_\chi \searrow, \ \text{Br}(B \to \chi) \nearrow$$


WMAP9, 95%
68%
WMAP9+BAO, 95%
68%
ξ=0
ξ=0.001
ξ=0.01
ξ=0.1
r
n_s
ξ
β

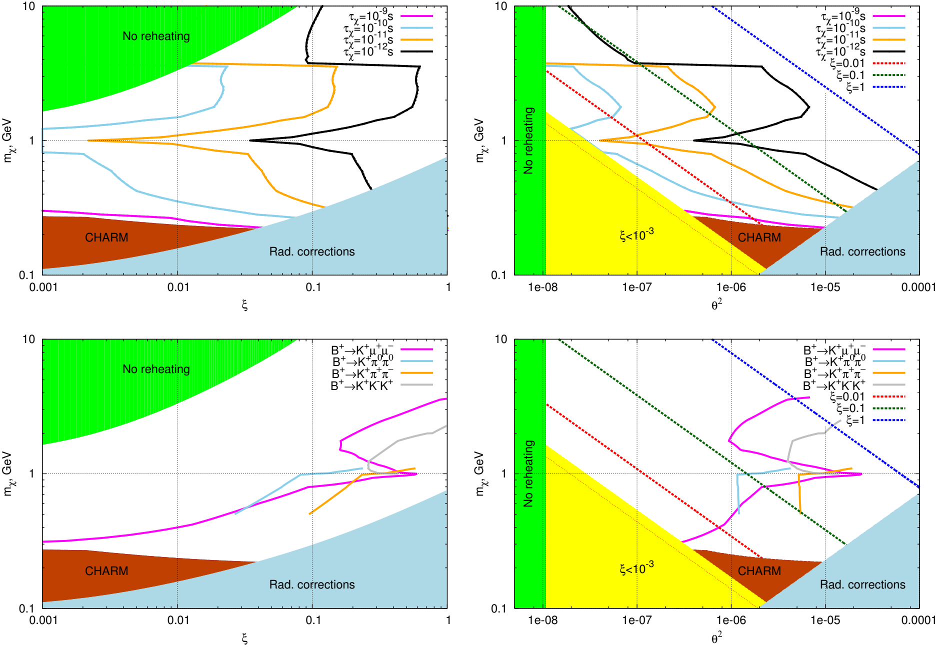




$$\mathrm{Br}(B \to \chi X_s) \simeq$$
$$10^{-6} \times \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \left(\frac{\beta(\xi)}{1.5 \times 10^{-13}}\right) \left(\frac{300\ \mathrm{MeV}}{m_\chi}\right)^2$$

with $\xi > 10^{-2}$ inflaton decays earlier, at production point

and B-meson branching grows $\propto \beta$


No reheating
CHARM
Rad. corrections
ξ<10^-3
τχ=10^-9 s
τχ=10^-10 s
τχ=10^-11 s
τχ=10^-12 s
ξ=0.01
ξ=0.1
ξ=1
B+→K+μ+μ−
B+→K+π0π0
B+→K+π+π−
B+→K+K-K+
mχ, GeV
ξ
θ2
0.001
0.01
0.1
1
1e-08
1e-07
1e-06
1e-05
0.0001
10

The model of light inflaton

- simple
- renormalizable
- weakly coupled
- SM sector is scale-invariant
- directly testable !!!

However

- both inflaton and gravity sectors contain dimensionful parameters (mass term m_X^2 and Planck mass M_P^2)
- hence they are scale non-invariant
- as 10^2 GeV$\sim m_X \ll M_P \sim 10^{18}$ GeV we get the hierarchy problem imaging gravity as QFT

Outline

1. Higgs portal to new physics
2. Higgs portal to X^4-inflation: light inflaton at LHCb
3. Natural completion of νMSM: neutrino mass and mixing, dark matter, baryon asymmetry of the Universe...
4. Further extension within scale invariance
5. Inflation in presence of dilaton: dilaton production at reheating

Dilaton X gives to

SM Higgs

$$\frac{\lambda}{4}\left(h^2-\alpha^2 X^2\right)^2 \longrightarrow \frac{\lambda}{4}\left(h^2-v^2\right)^2$$

General Relativity

$$\frac{\xi_X}{2} X^2 R \longrightarrow \frac{M_P^2}{2} R$$

For inflation one can resort to minimalistic setups provided all scale-invariant terms are introduced

Higgs-inflation

$$\xi_h H^\dagger H R$$

Starobinsky model

$$\beta\, R^2$$

The same inflaton potential at inflation !

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

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

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

Two models with dilaton

slightly shifted n_s, r, $\Delta_{\mathscr{R}}$

Major event: dilaton production by inflaton

$\xi_h H^\dagger HR$

J.Garcia-Bellido, J.Rubio, M.Shaposhnikov (2012)

Nonperturbative production (gravity driven by oscillating Higgs)

$$\delta\ddot{\rho}_\chi + \left(3H + 2\dot{b}(h)\right)\delta\dot{\rho}_\chi + \frac{k^2}{a^2}\delta\rho_\chi = 0$$

$$\Delta N_{eff} = \left(\frac{\rho_\chi}{\rho_\nu}\right)_{\text{BBN}} \sim 10^{-7}$$

Untestable

βR^2

D.G., A.Tokareva (in preparation)

scalaron perturbative decays into dilatons

$$\Gamma_{\to hh} = \left(\frac{1}{6\beta}\right)^{3/2} \frac{4M_P}{192\pi}(1+6\xi_h)^2$$

$$\Gamma_{\to\chi\chi} = \left(\frac{1}{6\beta}\right)^{3/2} \frac{M_P}{192\pi}$$

$$\Delta N_{eff} \approx 2.85\frac{\rho_\chi}{\rho_h} = \frac{0.71}{(1+6\xi_h)^2}$$

Is already being tested !!!

and for conformal Higgs $H^\dagger HR/6$ it is forbidden

Border line between Higgs and R^2

If both terms are introduced (and hence all scale-invariant terms play)

$$S_0 = \int d^4x\sqrt{-g}\left\{\frac{1}{2}[\beta R^2 + (\partial_\mu X)^2 - \xi_X X^2 R - \xi_h h^2 R + (\partial_\mu h)^2] - \frac{\lambda}{4}(h^2 - \alpha^2 X^2)^2\right\}.$$

Which of nonminimal couplings ξ_X, ξ_h is larger?

$\xi_h H^\dagger H R$	βR^2
$\xi_X^2 < \xi_h^2\,,\quad \beta\lambda < \xi_h^2$	$\xi_h < \xi_X \lesssim 0.008$
$T_r \to 10^{13}\,\text{GeV}$	$T_r \to 3\times 10^9\,\text{GeV}$

$$n_s - 1 \approx -8\xi_X \coth(4\xi_X N)\,,\implies \xi_X < 0.01$$

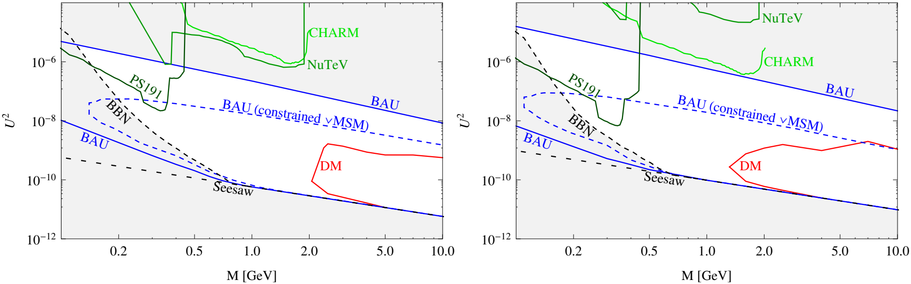
Conclusion

On the way towards scale-invariant theory of everything there are simple inflationary models which are

- cosmologically and phenomenologically viable
- can be extended further to be phenomenologically complete
- cosmologically and phenomenologically testable

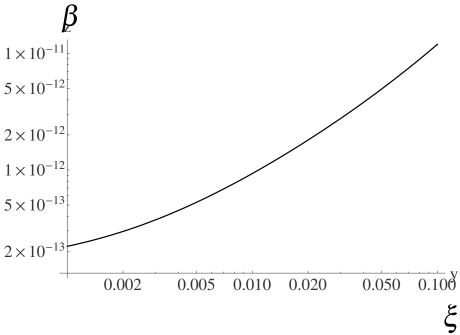
Backup slides

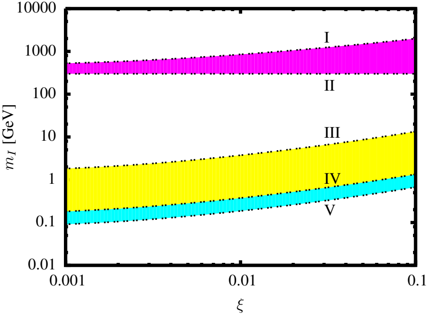
νMSM parameter space with resonant DM



L.Canetti, M.Drewes, M.Shaposhnikov 1204.3902

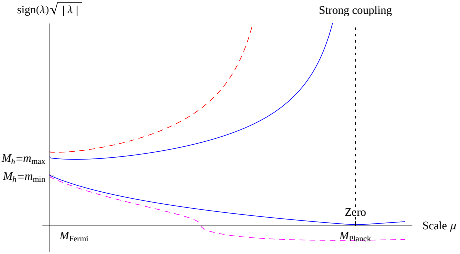
Inflaton mass as a function of ξ





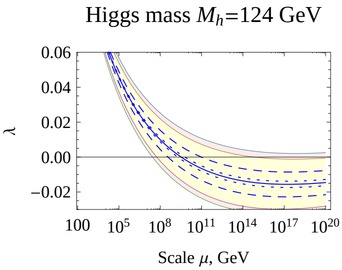
0809.1097

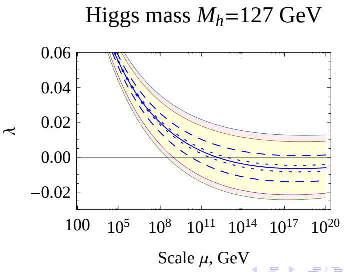
Critical point: where EW-vacuum becomes unstable



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

G. Degrassi et al (2012)





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

theoretical uncertainties 1-2 GeV

present measurements at CMS and ATLAS:

$$m_h \simeq 125.8 \pm 0.9\,\mathrm{GeV}$$

Important for inflation, when usually $h \sim H$

Spectra

$$\Delta^2_{\mathscr{R}} = \frac{\lambda \sinh^2(4\xi_X N)}{1152\pi^2 \xi_X^2 \xi_h^2}\,, \;\; n_s - 1 = -8\xi_X \coth(4\xi_X N)\,, \; U = \lambda M_P^4 \frac{(1+6\xi_X)^2}{(\xi_h - \xi_X)^2}$$

F.Bezrukov et al (2012)