Experimental tests of R^2-inflation and its minumal extensions

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Outline

1. Motivation
2. Inflation and reheating with R^2-term
3. Natural dark matter
4. Neutrino oscillations and leptogenesis
5. Scalars as Dark matter
6. Scalar perturbations and gravity waves from (post)inflationary evolution
7. Summary

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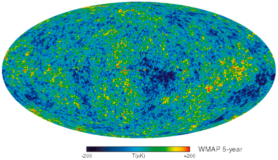
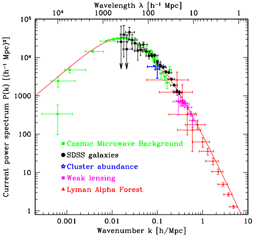
Inflationary solution of Hot Big Bang problems

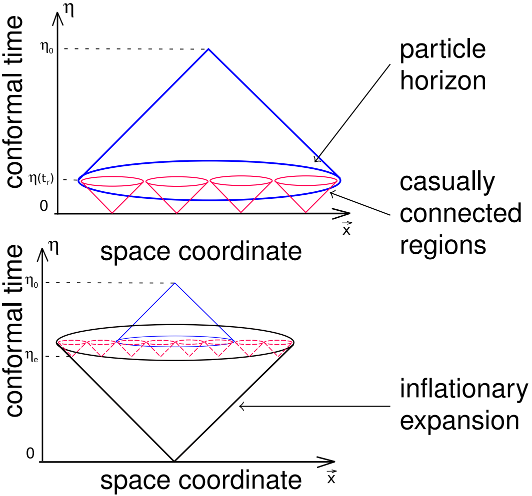
Temperature fluctuations $\delta T/T \sim 10^{-5}$



Universe is uniform!



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



Motivation of minimal extension at UV

inflationary mechanism operating at early times

requires modification of particle physics or gravity

Guiding principle:

use as little “new physics” as possible

Why?

No any hints observed so far!
No FCNC
No WIMPs
No . . .
. . . Nothing new

Extreme case: R^2-inflation

avoid modification of particle physics

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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 → Einstein Frame

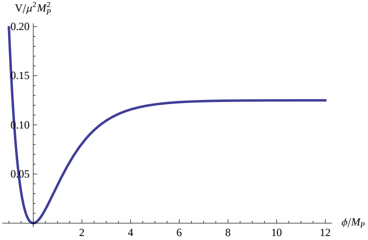
A.Starobinsky (1980)

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

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

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

$\delta\rho/\rho \sim 10^{-5}$ requires
$\mu = m_\phi \approx 1.3 \times 10^{-5}\,M_P \approx 3.1 \times 10^{13}$ GeV



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:

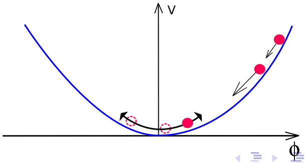
$$S^{EF}_\varphi = \int\sqrt{-\tilde{g}}\,d^4x\left(\frac{1}{2}\,\tilde{g}^{\mu\nu}\partial_\mu\tilde{\varphi}\partial_\nu\tilde{\varphi} - \frac{1}{2\chi}\,m_\varphi^2\tilde{\varphi}^2 + \frac{\tilde{\varphi}^2}{12\,M_P^2}\,\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{\tilde{\varphi}}{\sqrt{6}\,M_P}\,\tilde{g}_{\mu\nu}\partial_\mu\tilde{\varphi}\p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

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

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

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), A.Vilenkin (1985)

$$T_{reh} \approx 3.1\times 10^9\ \text{GeV}$$

D.G., A.Panin (2010)

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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:

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Why?

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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. . . ☹

Possible conclusions: Is it a hint?

- DM particles are fermions!

Nature likes fermions. . . ?

SM has to be extended by introducing new FERMIONS. . . ?

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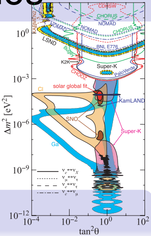
Straightforward completion by 2 sterile neutrinos



http://hitoshi.berkeley.edu/neutrino

- Use as little "new physics" as possible
- Require to get the correct neutrino oscillations
- Explain baryon asymmetry of the Universe

Lagrangian

Most general renormalizable with 2 right-handed neutrinos N_I

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

Extra coupling constants:

2 Majorana masses M_i

9 new Yukawa couplings
(Dirac mass matrix $M^D = f_{I\alpha}\langle H \rangle$ has 2 Dirac masses,
4 mixing angles and 3 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 !

2 heavy neutrinos with masses M_I similar to quark masses

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

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

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

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

Sterile neutrinos: variants

- So far we do not need, but can adopt three sterile neutrinos:
  then all 3 active neutrinos may be massive

- The scale of sterile neutrino masses is not fixed
  - If degenerate ($\Delta M = M_2 - M_1 \ll M_1$),
    lepton asymmetry may be produced in oscillations in primordial plasma, so not very heavy sterile neutrinos (even ~ 1 GeV) are allowed
    A.Pilaftsis (1997)
    Can be directly tested!
    T.Asaka, M.Shaposhnikov (2005)
    then sphalerons transfer it to baryon asymmetry
  - Otherwise, lepton asymmetry may come from decays of heavy sterile neutrinos produced in scalaron decays as all other particles

M.Fukugita, T.Yanagida (1986); G.Lazarides, Q.Shafi (1991)

BAU via leptogenesis

Add sterile neutrinos to explain active neutrino oscillations (OK)

and

use the same universal messenger to produce sterile neutrinos: gravity

$\rho_\phi = m_\phi^2 \phi^2/2 = m_\phi n_\phi \to \rho_N = m_N n_N$ D.G., A.Panin (2010)

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

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

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:

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

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

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

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...!

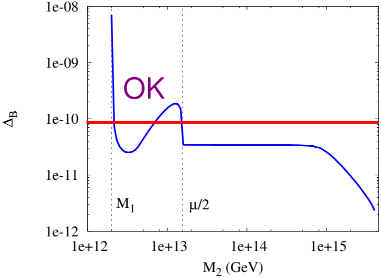
$\mu \sim 10^{13}$ GeV

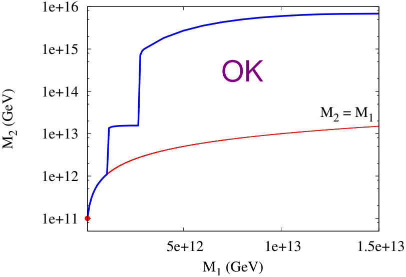
Is it sensitive to CP in active neutrino sector?

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

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Possible conclusions: it is not a hint

- DM particles are fermions!

Nature likes fermions. . . ?

SM has to be extended by introducing new FERMIONS. . . ?

- minimalistic approach: DM particles are scalars!

Scalar Dark Matter: other ways out

Two options within our paradigm of

AVOIDING NEW INTERACTIONS IN PARTICLE PHYSICS:

D.G., A.Panin (2012)

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: $0 < \xi < 1$

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

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 $p = p_* \frac{a(t_*)}{a(t_{reh})}$

Average momentum of produced dark matter particles:

$$\langle p\rangle\,(T_{reh}) = 0.85 \times p_* \gg T_{reh}$$

Ultrarelativistic @ reheating must be conformal “with 20%-accuracy”

To be Warm ($v_{DM} \sim 10^{-3}$ @ equilibrium, $T \approx 0.8\,\text{eV}$) we need:

$$m_\varphi \simeq 1.1\,\text{MeV}\,, \quad \text{then } \xi \approx 1/6 - 0.018\,, \text{ or } \xi \approx 1/6 + 0.018$$

To be Cold ($v_{DM} \ll 10^{-3}$ @ equilibrium, $T \approx 0.8\,\text{eV}$) we need:

$$1/6 - 0.018 < \xi < 1/6 + 0.018\,, \quad m_\varphi = m_\varphi[\text{given } \xi] > 1.1\,\text{MeV}$$

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 $e^{-\phi/M_P}\, m_\varphi^2 \tilde{\varphi}^2$

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

Calculation of Bogolubov's transformation coefficients: vacuum initial conditions

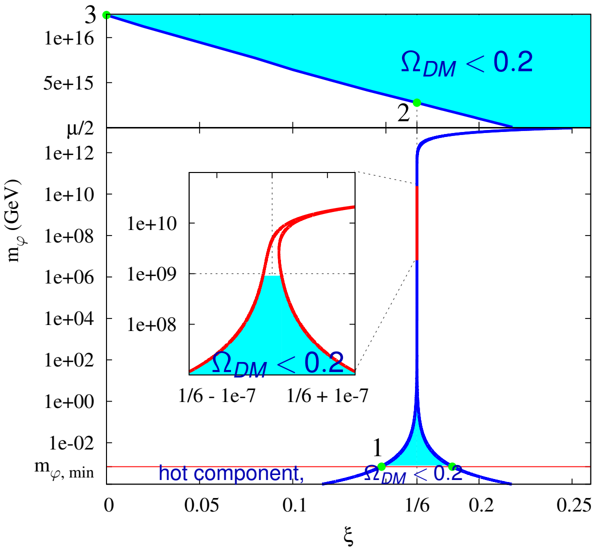
$$s(\eta,\vec{x}) = \frac{1}{(2\pi)^{3/2}}\int d^3p\left(\hat{a}_p s_p(\eta) e^{-i\vec{p}\vec{x}} + \hat{a}_p^\dagger s_p^*(\eta) e^{i\vec{p}\vec{x}}\right)\,, \qquad s_p \to 1/\sqrt{2\omega},\;\; s_p' \to -i\omega s_p\,.$$

DM particle density in post-inflationary Universe $m_\varphi \sim 10^{16}$ 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., A.Panin (2012)



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

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

Warm Dark Matter:

$m_\varphi \gtrsim 1.1$ MeV

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Similarity to λX^4, e.g. Higgs-inflation

F.Bezrukov, M.Shaposhnikov (2007)

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

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

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

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

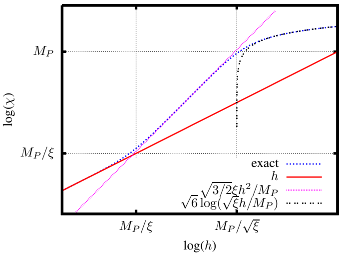
Go to the Einstein frame: $(M_P^2 + \xi h^2) R \to M_P^2 \tilde{R}$

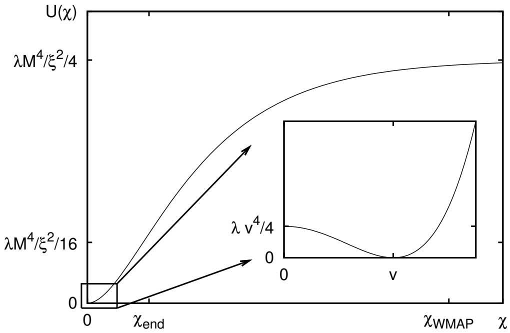
$$g_{\mu\nu} = \Omega^{-2} \tilde{g}_{\mu\nu}\,, \qquad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

with canonically normalized χ: for any value of λ !

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

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

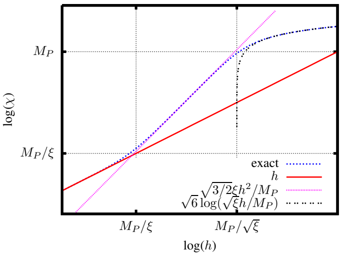
$$U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 - \exp\left(-\frac{\sqrt{2}\chi}{\sqrt{3}M_P}\right)\right)^2$$

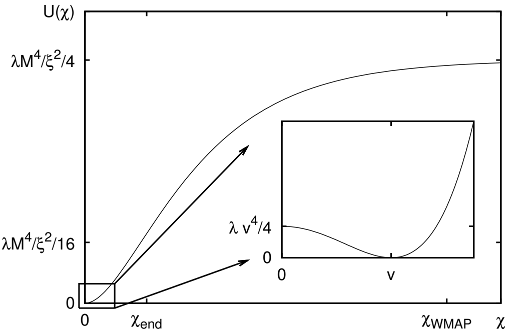
coincides with R^2-model!

But NO NEW d.o.f.

0812.3622, 1111.4397

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





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

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

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

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

coincides with R^2-model!

But NO NEW d.o.f.

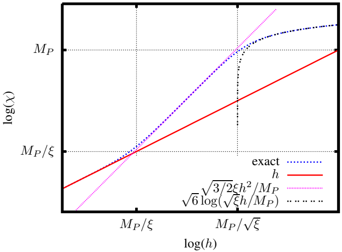
0812.3622, 1111.4397

Advantage: NO NEW interactions to reheat the Universe

inflaton couples to all SM fields!

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

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



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

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

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!

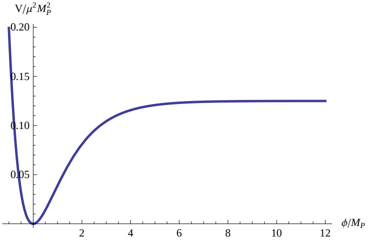
from WMAP-normalization: $\xi \approx 47000\times\sqrt{\lambda}$

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

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

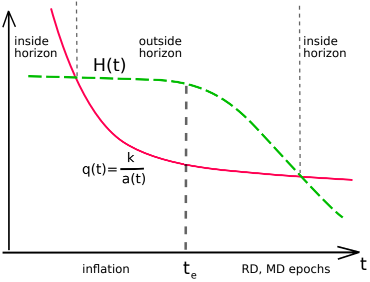
The difference is

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

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



Planck(?), CMBPol(1-2σ)

Upper limit on the Higgs boson mass

R^2-inflation: stability while the Universe evolves

from $Q = T_{reh} \approx 3 \times 10^9$ GeV

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

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

Higgs-inflation: stability while the Universe evolves

from $Q = T_{reh} \approx 6 \times 10^{13}$ GeV

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

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

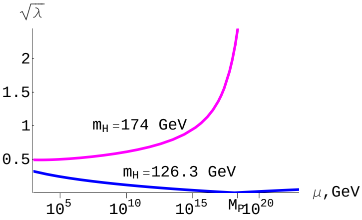
stability while the Universe evolves

right after inflation $h \approx 10^{13}$ GeV

F.Bezrukov et al (2012), G.Degrassi et al (2012)

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

at present (LHC): $m_h \approx 125.5$ GeV



Theoretical uncertainties:

about $1 - 2$ GeV

due to unknown QCD-corrections

Important for further improvement:

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

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 $\nu(T_{reh})$

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

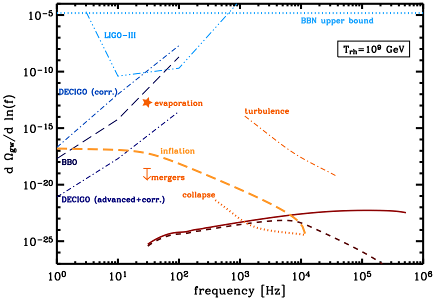
$$R^2\text{-inflation}: \quad \frac{a_{reh}}{a_{inf}} \sim 10^7$$

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 $\nu(T_{reh})$

F.Bezrukov, D.G. (2011)



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

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

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

  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 | $m_h \gtrsim 124 - 134$ GeV

Outline

1. Motivation
2. Inflation and reheating with R^2-term
3. Natural dark matter
4. Neutrino oscillations and leptogenesis
5. Scalars as Dark matter
6. Scalar perturbations and gravity waves from (post)inflationary evolution
7. Summary

Summary

Simple inflationary model R^2
extended by three sterile fermions (neutrinos) OR by two sterile neutirnos and superheavy or almost-conformal scalar explains

- active neutrino masses and mixing angles
- DM as 10^7 GeV free fermions or superheavy or almost-conformal scalar
- baryon asymmetry via leptogenesis due to heavy sterile neutrinos of 10^{12}-10^{13} GeV produced by scalaron decay

  is in the right ballpark !

All above is due to universal coupling of scalaron to matter provided by gravity (and neutrino)

Predictions: $n_s = 0.965$ and $r = 0.0036$
SM up to Planck scale: $125.5\,\text{GeV}\,(?) \approx (?) m_h \gtrsim 116\,\text{GeV}$

active neutrino sector...? $m_1 = 0$? $\delta_{CP} = 0$? (any pattern seems OK)

Spec: scale invariance at the Planck scale

For critical $m_h \sim 124 - 134$ GeV self-coupling λ evolves very slowly and approaches zero in the Planck region. . .

Hint? Scale invariance at UV?

. . . May be. . .

then add $\Delta\mathscr{L} = \frac{1}{6} R H^\dagger H$

What happens then?

D.G., A.Tokareva (to be 2012)

Reheating via conformal anomaly

$\phi \to gg$

$T_{reh} \simeq 1.4 \times 10^8$ GeV

- slightly (log !) different

  $n_s = 0.962, \quad r = 0.0040$

- GW from scalaron clumps at

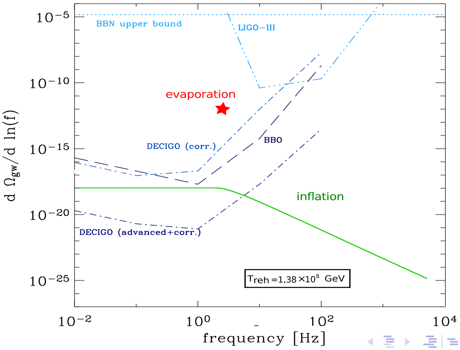
  lower frequency $\nu \gtrsim 2$ Hz

- thermal history is OK from

  $m_h > 110$ GeV

  with higgs fluctuations accounted for within stochastic approach:

  $m_h > 126$ GeV

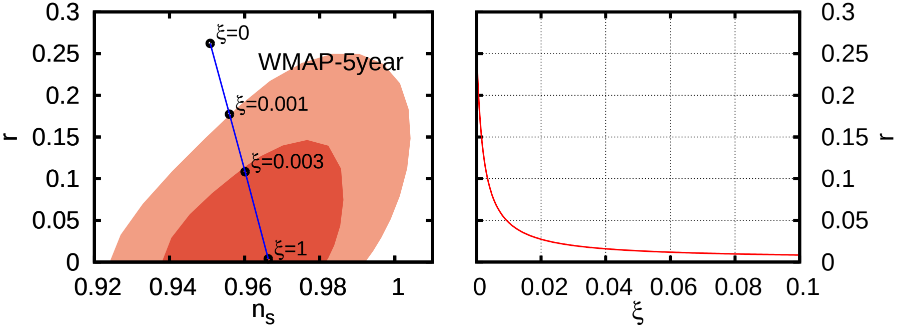


Backup slides

Cosmological test of λX^4-inflation ?

With non-minimal coupling to gravity

$$\xi R X^2$$



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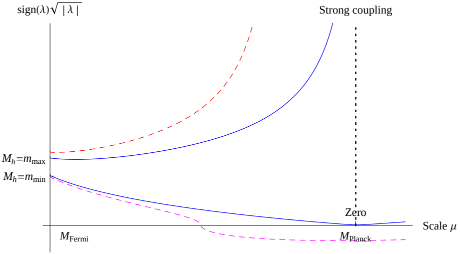
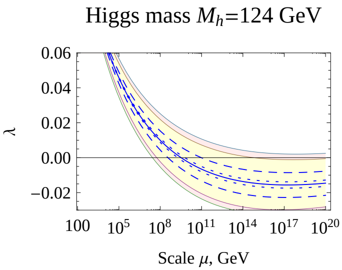
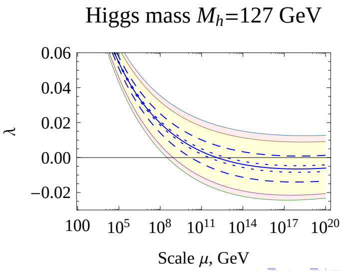
No arguments to forbid $\xi \lesssim 1$

Critical point: where EW-vacuum becomes unstable





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

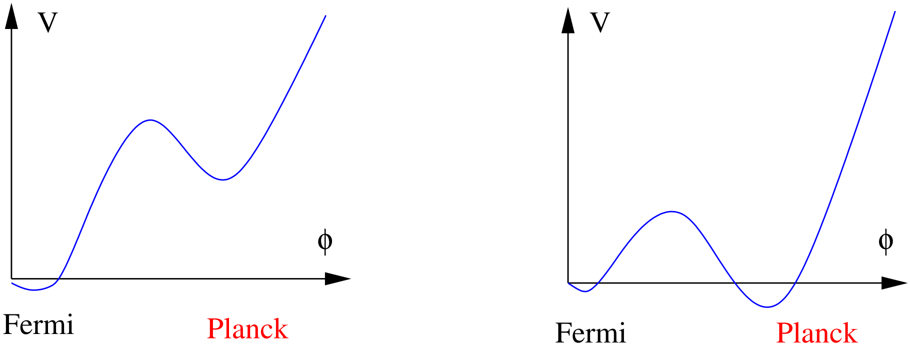


$$m_h^{\rm H} > \left[129.0 + \frac{m_t - 172.9\,\text{GeV}}{1.1\,\text{GeV}} \times 2.2 - \frac{\alpha_s(M_Z) - 0.1181}{0.0007} \times 0.56\right] \text{GeV}$$

present measurements at CMS and ATLAS:

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

Update at HCP2012, Nov.12-16



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

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

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