Light inflaton – connecting cosmology with experiment

Based on:
A.Anisimov, Y.Bartocci, FB, Phys. Lett. B **659**, 703 (2008)
FB, D.Gorbunov, JHEP **05** (2010) 010

Fedor Bezrukov
Ludwig-Maximilians-Universität München
ARNOLD SOMMERFELD CENTER for theoretical physics
Germany

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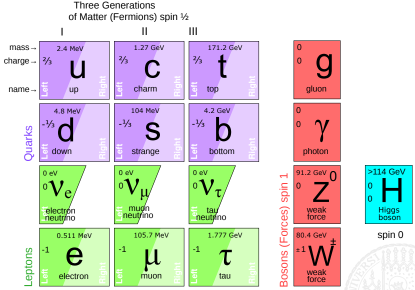
Outline

Standard Model – describes nearly everything that we know

Gauge theory $SU(3) \times SU(2) \times U(I)$
Describes (together with Einstein gravity)

- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ($T < 1$ MeV, $t > 1$ sec)

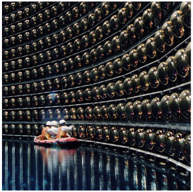


Standard Model has experimental problems

- Laboratory
  - Neutrino oscillations
- Cosmology
  - Baryon asymmetry of the Universe
  - Dark Matter
  - Dark Energy
  - Inflation
    - Horizon problem (and flatness, entropy, . . .)
    - Initial density perturbations

Neutrino oscillations

SAGE neutrino observatory (solar oscillations evidence $\nu_e \to \nu_\mu$)

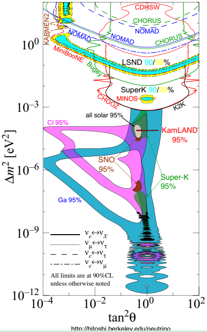


SuperKamiokande (atmospheric oscillations $\nu_\mu \to \nu_\tau$)

Reactor neutrinos, accelerator neutrinos

Oscillation parameters

Δm^2_{21}	$7.59{\pm 0.20} \times 10^{-5}$ eV^2
$\sin^2 2\theta_{12}$	0.87 ± 0.03
$\lvert\Delta m^2_{32}\rvert$	$2.43{\pm 0.13} \times 10^{-3}$ eV^2
$\sin^2 2\theta_{23}$	> 0.92
$\sin^2 2\theta_{13}$	< 0.15

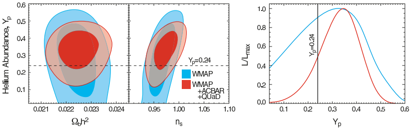


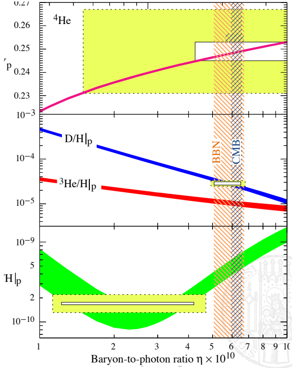
Baryon asymmetry of the Universe

- Current universe contains baryons and no antibarions
- Current baryon density

$$\eta_B \equiv \frac{n_B}{n_\gamma} \simeq 6.1 \times 10^{-10}$$

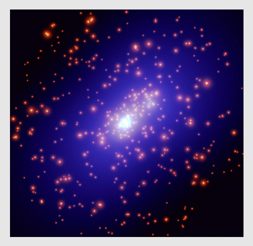
- Does not fit into the SM (too weak CP violation, too smooth phase transition)

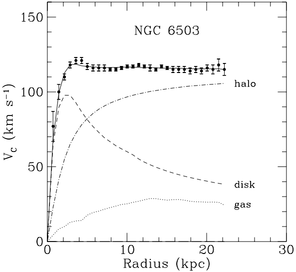




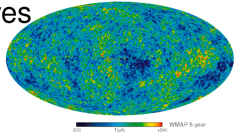
Dark Matter

Gravitational lensing





Rotation curves

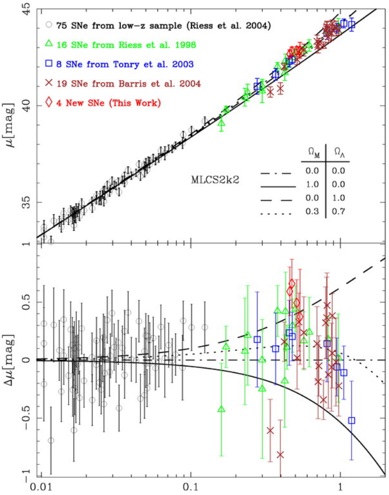


$\Omega_{DM} \simeq 0.21$

CMB fluctuations

“Bullet” cluster

Dark Energy



← Supernova type Ia redshifts

accelerated expansion of the Universe today

$$\Omega_\Lambda \simeq 0.74$$

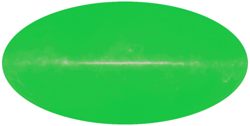
Different from inflation

- Much lower scale
- No need to stop it

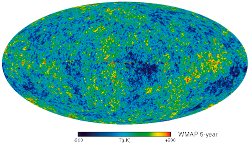
Can be explained "just" by a cosmological constant

Inflation evidence – horizon problem

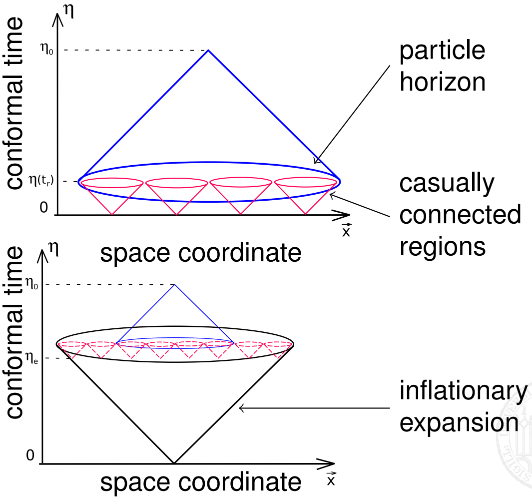
Microwave sky



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

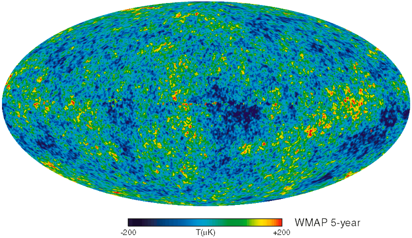


Universe is uniform!

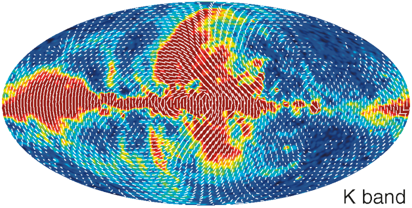


CMB gives measured predictions from inflation

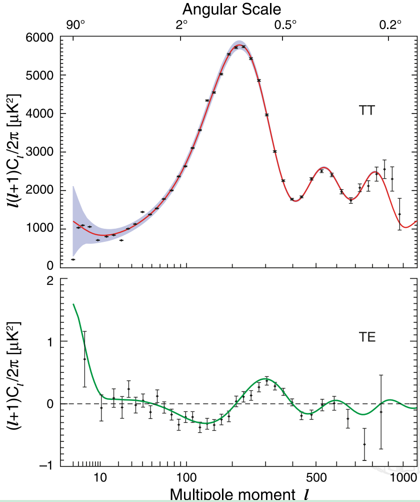
Temperature fluctuations



Polarization

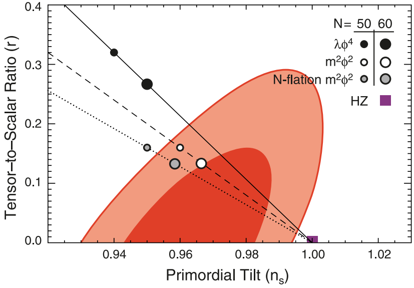


CMB spectrum



Inflationary parameters from CMB

- Spectrum of primordial scalar density perturbations is just a bit not flat $n_s - 1 \equiv \frac{d \log \mathcal{P}_{\mathcal{R}}}{d \log k}$
- Tensor perturbations are compatible with zero $r \equiv \frac{\mathcal{P}_{\text{grav}}}{\mathcal{P}_{\mathcal{R}}}$



(WMAP07 results)

Let us expand the model in a minimal way

I will follow a “Minimal” approach

Explain the experimental facts with

- minimal number of new particles
- no new physical scales

Different situation in usual approaches

Solve hierarchy problems first

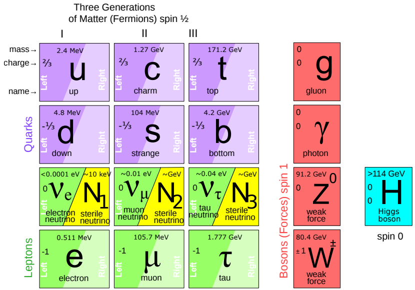
- Supersymmetry, Extra dimensions . . . } New physics at TeV energies – “masks” us from early Universe

νMSM — describes all, except for inflation

SM symmetrically extended by right handed (Majorana) neutrinos N_i

Describes

- DM by keV scale neutrino N_1
- BAU via leptogenesys by two heavier (GeV scale) neutrinos $N_{2,3}$



However – nothing about scalars – not to be told here

[Asaka, Blanchet, Shaposhnikov'05, Asaka, Shaposhnikov'05]

Examples of minimal extensions leading to inflation

νMSM (for DM and Baryogenesys) +

- Inflation with light inflaton [Shaposhnikov, Tkachev'06] [Anisimov, Bartocci, FB'08] [FB, Gorbunov'09]

  (Introduces new particle)

- Higgs boson inflation [FB, Shaposhnikov'08] [FB, Gorbunov, Shaposhnikv'08] [FB, Magnin, Shapshnikov'08]

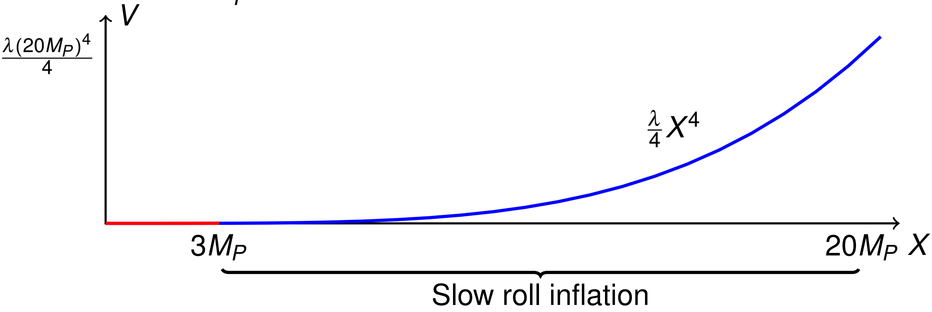
  (Modifies Higgs-gravity interaction, new scales M_P/ξ, $M_P/\sqrt{\xi}$)

- R^2 (scalaron) inflation [Starobinsky'80] [Gorbunov, Panin'10]

  (Modification only in the gravity sector)

Chaotic inflation – a scalar field

$$\mathscr{H}^2 \simeq \frac{1}{3M_P^2}\left(V(X)+\dot{X}^2/2\right) , \qquad \ddot{X}+3\mathscr{H}\dot{X}+V'(X)=0$$



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

quartic coupling: $\lambda \sim 10^{-13}$ (or mass: $m \sim 10^{13}$ GeV)

Light inflaton model adds one scalar particle to the SM

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \alpha H^\dagger H X^2 + \frac{\beta}{4} X^4$$

Standard Model — Interaction — Inflationary sector

(where $\beta \simeq \beta_0 = 1.5 \times 10^{-13}$ – inflationary requirement)

$m_\chi = m_h \sqrt{\frac{\beta}{2\alpha}}$ – the inflaton mass is defined by α

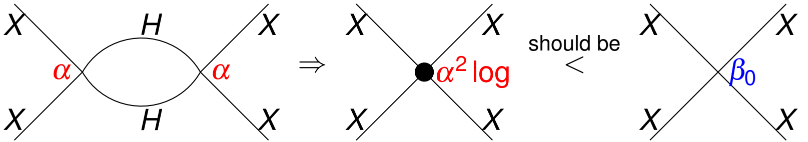
The Higgs-inflaton scalar potential is

$$V(H,X) = \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2 + \frac{\beta}{4} X^4 - \frac{1}{2}\mu^2 X^2 + V_0$$

[Anisimov, Bartocci, FB'08, FB, Gorbunov'09]

Radiative corrections require a small SM-inflaton coupling

Radiative corrections induce quartic coupling which should not spoil the flatness of the potential



This leads to an upper bound on the SM-inflaton interaction

$$\alpha \lesssim 10^{-7} \qquad \text{(roughly: } \alpha < \sqrt{\beta}\text{)}$$

Lower bound for the inflaton mass

$$m_\chi > 90\ \text{MeV}$$

Radiative corrections require a small SM-inflaton coupling

Radiative corrections induce quartic coupling which should not spoil the flatness of the potential

$$\delta V = \frac{m^4(X)}{64\pi^2} \log \frac{m^2(X)}{\mu^2} \quad \overset{\text{should be}}{<} \quad V_{\text{inflaton}} = \frac{\beta}{4} X^4$$

$m_h^2(X) = 4\alpha X^2$ (Higgs boson)

This leads to an upper bound on the SM-inflaton interaction

$$\alpha \lesssim 10^{-7} \qquad \text{(roughly: } \alpha < \sqrt{\beta}\text{)}$$

Lower bound for the inflaton mass

$$m_\chi > 90 \text{ MeV}$$

Preheating requires large SM-inflaton coupling

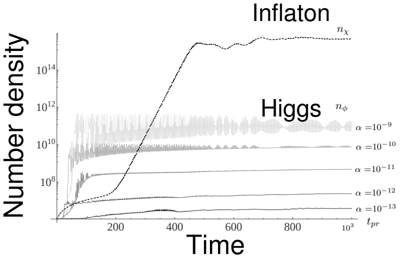
- After inflation: empty & cold
- Needed: hot, $T_r > 150$ GeV (to get baryogenesis)

Equating H production rate ($\propto \alpha^2$) to Hubble expansion rate ($\propto T^2$) $\Gamma_{XX\to HH} \sim \mathscr{H}$

Lower bound on α

$$\alpha \gtrsim 7 \times 10^{-10}$$

Parametric resonance?
Not so easy to create the Higgs



The large Higgs self interaction destroys coherence and spoils parametric resonance.

[Anisimov, Bartocci, FB'08]

Details

Inflaton is in the experimentally explorable range

Inflaton mass window (from Cosmology)

$$90\ \text{MeV} < m_\chi < 1.8\ \text{GeV}$$

Lower bound: radiative corrections

Upper bound: sufficient reheating

Also possible: $2m_H < m_\chi \lesssim 600$ GeV

Details

Inflaton-SM Interactions

As the Higgs boson, but light and suppressed by $\theta = \sqrt{2\beta} v/m_\chi$

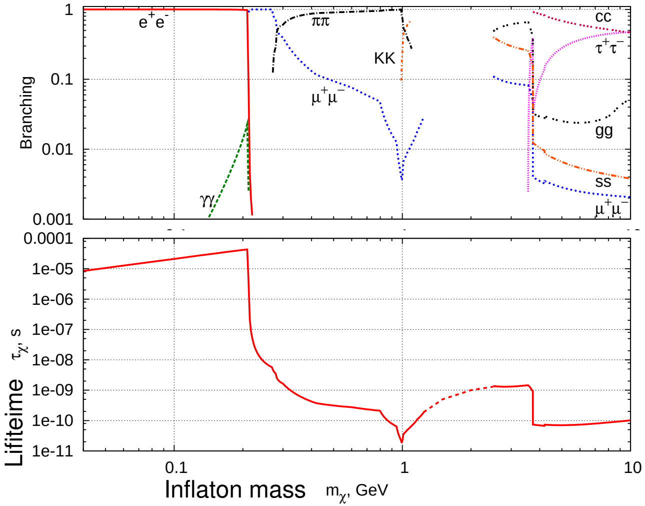
- Created: in meson decays
- Decays: the heaviest particle pairs (ee, $\pi\pi$, $\mu\mu$, KK)
- Interacts with media: extremely weakly

$$\mathscr{L}_{\chi\bar{f}f} = \theta \frac{m_f}{v} \chi \bar{f} f = \sqrt{2\beta} \frac{m_f}{m_\chi} \chi \bar{f} f$$

$$\mathscr{L}_{\chi\pi\pi} = 2\kappa\sqrt{2\beta} \cdot \frac{\chi}{m_\chi} \cdot \left(\frac{1}{2}\partial_\mu \pi^0 \partial^\mu \pi^0 + \partial_\mu \pi^+ \partial^\mu \pi^- \right)$$
$$- (3\kappa+1)\sqrt{2\beta} \cdot \frac{\chi}{m_\chi} \cdot m_\pi^2 \cdot \left(\frac{1}{2}\pi^0\pi^0 + \pi^+\pi^- \right) \qquad \left(\kappa = 2/9\right)$$

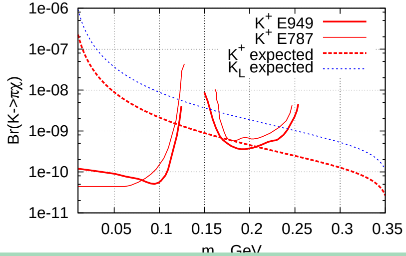
$$\mathscr{L}_{\chi\gamma\gamma} \approx \frac{F_{\gamma\gamma}\alpha}{4\pi} \frac{\sqrt{2\beta}}{m_\chi} \chi F_{\mu\nu} F^{\mu\nu} \qquad \mathscr{L}_{\chi gg} \approx \frac{F_{gg}\alpha_s}{4\sqrt{8}\pi} \frac{\sqrt{2\beta}}{m_\chi} \chi G^a_{\mu\nu} G^{a\mu\nu}$$

Inflaton is relatively long lived



Production: hadron decays

$$\left.\begin{aligned} \mathrm{Br}\left(K^+ \to \pi^+\chi\right) &\approx 2.3\times 10^{-9} \\ \mathrm{Br}\left(K_L \to \pi^0\chi\right) &\approx 1.0\times 10^{-8} \\ \mathrm{Br}\left(\eta \to \pi^0\chi\right) &\approx 1.8\times 10^{-12} \\ \mathrm{Br}\left(B \to X_s\chi\right) &\approx 10^{-5} \end{aligned}\right\} \times \left(\frac{\beta}{\beta_0}\right)\cdot\left(\frac{100\text{ MeV}}{m_\chi}\right)^2\cdot\left(\frac{m_\chi}{m_{hadron}}\right)$$



Bound from $K^+ \to \pi^+ + \text{nothing}$

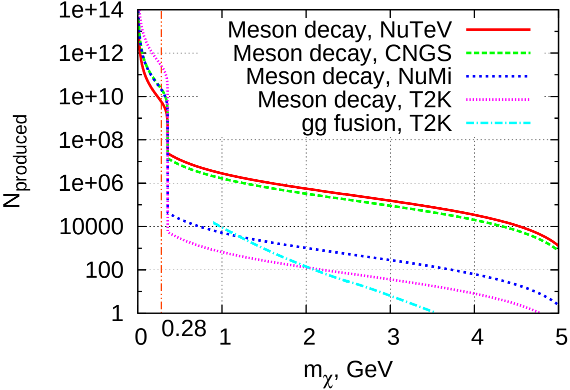
$$m_\chi > 120\text{ MeV}$$

Disfavoured:

$$170\text{ MeV} \lesssim m_\chi \lesssim 205\text{ MeV}$$

Production: beam dump, ideal luminosity

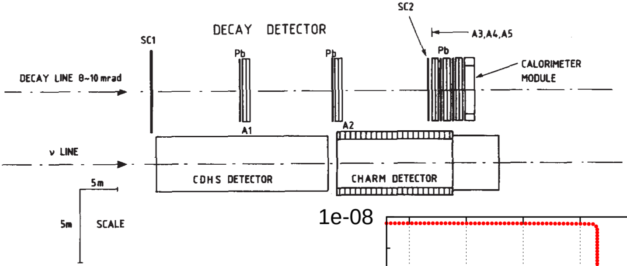
$$\frac{\sigma}{\sigma_{pp,\text{total}}} = M_{pp}\Big(\chi_s(0.5\,\text{Br}(K^+ \to \pi^+\chi) + 0.25\,\text{Br}(K_L \to \pi^0\chi)) + \chi_c\,\text{Br}(B \to \chi X_s)\Big)$$



	E, GeV
NuTeV	800
CNGS	400
NuMi	120
T2K	50

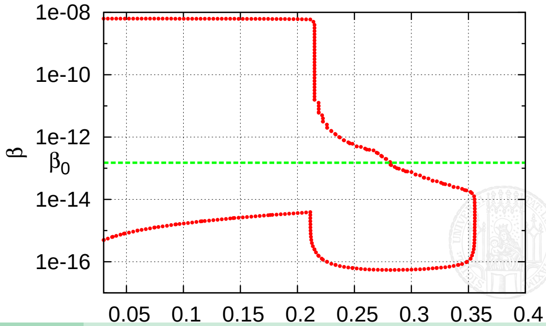
	N_{POT}, 10^{19}
NuTeV	1
CNGS	4.5
NuMi	5
T2K	100

Beam dump: CHARM bound is the best at present



Search for decays of something into $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$ $\Longrightarrow$

$m_\chi > 270$ MeV



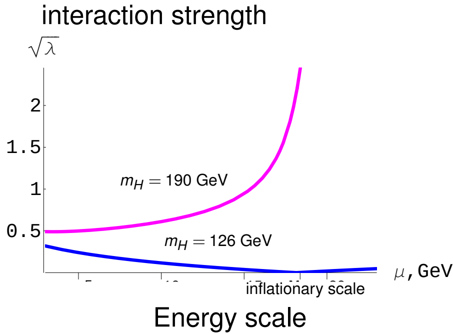
Production: search in B decays

$$\left.\begin{aligned} \mathrm{Br}\left(K^+ \to \pi^+ \chi\right) &\approx 2.3 \times 10^{-9} \\ \mathrm{Br}\left(K_L \to \pi^0 \chi\right) &\approx 1.0 \times 10^{-8} \\ \mathrm{Br}\left(\eta \to \pi^0 \chi\right) &\approx 1.8 \times 10^{-12} \\ \mathrm{Br}\left(B \to X_s \chi\right) &\approx 10^{-5} \end{aligned}\right\} \times \left(\frac{\beta}{\beta_0}\right) \cdot \left(\frac{100\,\mathrm{MeV}}{m_\chi}\right)^2 \cdot \left(\frac{m_\chi}{m_{hadron}}\right)$$

- Inflaton is produced quite abundant in B decays
- With typical lifetime of 10^{-9} s it decays at some distance but inside the detector
- Search for events with offset vertex in b-factories – BaBar, Belle
- LHCb !

Validity up to inflationary scale

Radiative corrections – "screening" of the Higgs self-interaction depending on scale

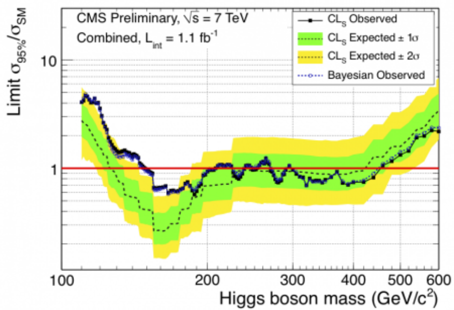


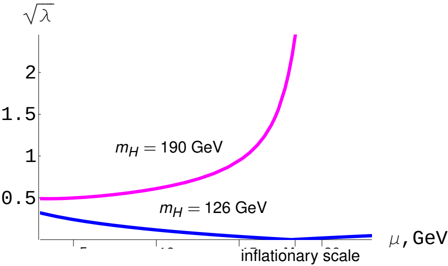
Higgs mass bounds

$$126\,\text{GeV} \lesssim m_H \lesssim 190\,\text{GeV}$$

Validity up to inflationary scale

Recent CMS bounds

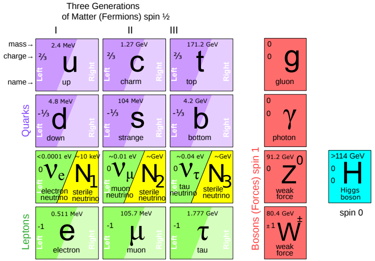




Higgs mass bounds

$$126\,\text{GeV} \lesssim m_H \lesssim 190\,\text{GeV}$$

Dark matter – add νMSM and stir

Light inflaton + 

$+f_I X \bar{N}^c N$

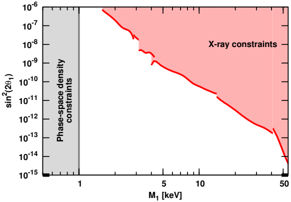
[Asaka, Blanchet, Shaposhnikov'05, Shaposhnikov, Tkachev'06]

- DM sterile neutrinos are produced in inflaton decays
- BAU via leptogenesis with two heavier sterile neutrinos

DM neutrino mass bound from production mechanism

$$M_1 \lesssim 80\text{keV}$$

Possible search for νMSM neutrino in the lab and in the Universe



- DM sterile neutrino N_1, $M_1 \sim 1 - 80$keV
  - X-ray line from the DM radiative decay $N_1 \to \nu\gamma$
  - Neutrinoless double beta decay $m_{ee} < 50 \times 10^{-3}$ eV

  [FB'05] Details
- Lepton asymmetry generating $N_{2,3}$, $M_{2,3} \sim$ GeV
  - Neutrino production hadron decays: kinematics
    - Missing energy in K decays
    - Peaks in momentum of charged leptons for two body decays
  - Neutrino decays into SM particles: “nothing” to leptons and hadrons
    - Beam target experiments with high intensity proton beam, detector (preferably not dense) after the shielding.

[D. Gorbunov, M.Shaposhnikov'07]

Summary

Start from:

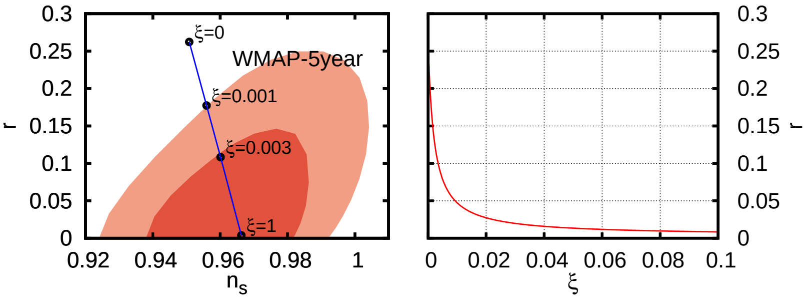
- Explain every experimental fact
- Expand the Standard Model in a minimal way

Arrive to:

- Predictions for low energy experiments!

- Model with additional scalar inflaton
  - Inflaton is light, $90\,\mathrm{MeV} < m_\chi < 1.8\,\mathrm{GeV}$
  - Higgs boson mass is in the window $126 - 190\,\mathrm{GeV}$
  - Inflaton can be searched in rare decays! (LHCb)

WMAP-5 bounds



Message

With non-minimal coupling it is very natural for $\beta\phi^4$ inflation to be compatible with observations!

Return

Dark matter – add νMSM and stir

A νMSM inspired model with inflation χ (Shaposhnikov&Tkachev'06)

$$\mathscr{L} = (\mathscr{L}_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\bar{L}_\alpha N_I \Phi - \frac{f_I}{2}\bar{N}_I^c N_I X + \text{h.c.}) + \frac{1}{2}(\partial_\mu X)^2 - V(\Phi, X)$$

$$\Omega_N = \frac{1.6 f(m_\chi)}{S} \cdot \frac{\beta}{1.5 \times 10^{-13}} \cdot \left(\frac{M_1}{10\text{keV}}\right)^3 \cdot \left(\frac{100\text{ MeV}}{m_\chi}\right)^3 ,$$

DM sterile neutrino mass bound

$$M_1 \lesssim 13 \cdot \left(\frac{m_\chi}{300\text{ MeV}}\right) \left(\frac{S}{4}\right)^{1/3} \cdot \left(\frac{0.9}{f(m_\chi)}\right)^{1/3} \text{keV} .$$

Parametric enchancement

Let us suppose again that there is an inflaton X coupled to some particle ϕ. Then, during inflaton oscillations, for the ϕ modes with momentum k we have

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \left(\frac{k^2}{a^2(t)} + g^2 X(t)^2\right)\phi_k = 0$$

- Important – $X(t)$ oscillates
- Let us neglect the Universe expansion, and say that $X(t) = A\sin(\omega t)$, then

Mathieu equation

$$\frac{d^2\phi_k}{d\eta^2} + (A_k - 2q\cos 2\eta) = 0$$

where $A_k = k^2/\omega^2 + 2q$, $q = g^2 X_0^2/4\omega^2$, $\eta = \omega t$.

Temperature estimate for the reheating

Equating mean free path $n\sigma_{2l\to 2H} v \sim n\frac{\alpha^2}{\pi p_{\rm avg}^2}$ with the Hubble rate $H = \frac{T^2}{m_{\rm Pl}}\sqrt{\frac{\pi^2 g_*}{90}}$ we get

$$T_R \approx \frac{\zeta(3)\alpha^2}{\pi^4}\sqrt{\frac{90}{g_*}} m_{\rm Pl}$$

Requiring $T_R > 150\,\text{GeV}$ we can obtain the lower bound on α

$$\alpha \geq 7.3\times 10^{-8}\,,$$

Return

Temperature estimate for the reheating II

However, $p_{avg} \not\approx T$, the cross-section is enhanced, so

$$\frac{\zeta(3)\alpha^2}{\pi^3}\frac{T^4}{p_{avg}^3} \sim \frac{T^2}{\sqrt{\frac{90}{8\pi^3 g^*}}M_{Pl}}$$

For this estimate the bound is *weaker*

$$\alpha \geq 7\times 10^{-10}$$

Upper bound for the inflaton mass

$$m_\chi \leq 1.5\left(\frac{m_H}{150\,\text{GeV}}\right)\sqrt{\frac{\beta}{1.5\times 10^{-13}}}\,\text{GeV}$$

Return

Inflaton mass window

Flatness from radiative corrections

$$m_\chi > 120 \left(\frac{m_h}{150\ \text{GeV}}\right) \left(\frac{\beta}{1.5\times 10^{-13}}\right)^{\frac{1}{2}}\ \text{MeV}$$

Sufficient reheating

$$m_\chi \leq 1.5 \left(\frac{m_H}{150\,\text{GeV}}\right) \left(\frac{\beta}{1.5\times 10^{-13}}\right)^{\frac{1}{2}}\ \text{GeV}$$

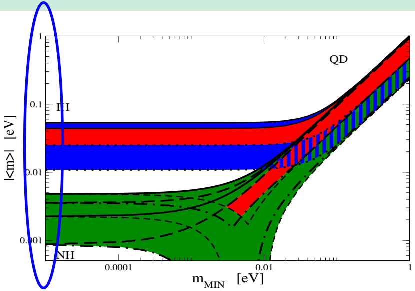
To be precise, the window also exists

$$2m_H < m_\chi \lesssim 460 \cdot \left(\frac{m_h}{150\ \text{GeV}}\right)^{4/3} \cdot \left(\frac{\beta}{1.5\times 10^{-13}}\right)^{1/3}\ \text{GeV}$$

Return

$0\nu\beta\beta$ effective Majorana mass is small

$$m_{ee} = \left| \sum_i m_i V_{ei}^2 \right|$$



- contribution from N_1 is negligible $|M_1 \theta_{e1}^2| \leq 10^{-5}$ eV
- For heavier active neutrinos the contribution is always negative $m_{ee} < \left|\sum_i m_i V_{ei}^2\right|$ smaller prediction

$m_{ee} < 50 \times 10^{-3}$ eV

F.B., 2006

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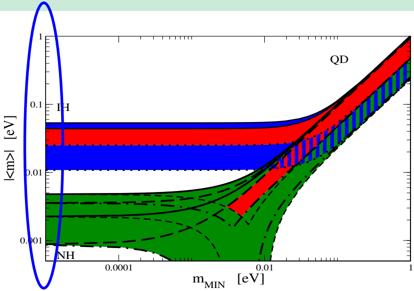

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Field dependent cut-off makes the model consistent

Inflationary regime – EW chiral theory

$$\mathscr{L}_{\text{chiral}} = \frac{1}{2}(\partial_\mu \chi)^2 - U(\chi) - \frac{1}{2g^2}\text{tr}[W_{\mu\nu}^2] - \frac{v^2}{4}\text{tr}[V_\mu^2] + i\bar{Q}_{L,R}\not{D}Q_{L,R} - (\frac{y_t v}{\sqrt{2}}\bar{Q}_L\tilde{\mathscr{U}}Q_R + \cdots + \text{h.c.})$$

with

$$\mathscr{U} = \exp[2i\pi^a T^a], \quad V_\mu = (\partial_\mu \mathscr{U})\mathscr{U}^\dagger + iW_\mu - i\mathscr{U}B_\mu^Y\mathscr{U}^\dagger$$

and

$$v^2 = \frac{h^2}{\Omega^2(h)} = \frac{M_P^2}{\xi}\left(1 - e^{-2\chi/\sqrt{6}M_P}\right)^{-1}$$

RG equations in the inflationary regime

$$16\pi^2\mu\frac{\partial}{\partial\mu}g' = \left(\frac{1}{6} - \frac{1}{12} + \frac{20n_f}{9}\right)g'^3\,, \tag{1}$$

$$16\pi^2\mu\frac{\partial}{\partial\mu}g = -\left(\frac{43}{6} + \frac{1}{12} - \frac{4n_f}{3}\right)g^3\,. \tag{2}$$

$$16\pi^2\mu\frac{\partial}{\partial\mu}g_3 = -7g_3^2\,. \tag{3}$$

$$16\pi^2\mu\frac{\partial}{\partial\mu}\xi = -\left(\frac{3}{2}g'^2 + 3g^2 - 6y_t^2\right)\xi\,. \qquad (v^2 \propto 1/\xi) \tag{4}$$

$$16\pi^2\mu\frac{\partial}{\partial\mu}y_t = \left(-\frac{17}{12}g'^2 - \frac{3}{2}g^2 - 8g_3^2 + 3y_t^2\right)y_t\,. \tag{5}$$

$$16\pi^2\mu\frac{\partial}{\partial\mu}\left(\frac{\lambda}{\xi^2}\right) = \frac{1}{\xi^2}\left(-6y_t^4 + \frac{3}{8}\left(2g^2 + (g'^2 + g^2)^2\right)\right)\,. \tag{6}$$

Effective potential

can be obtained from the SM one by

- removing the terms corresponding to the Higgs scalar loops
- setting Goldstone boson masses to zero

- FB, M. Shaposhnikov, Phys. Lett. B **659**, 703 (2008)
- FB, D. Gorbunov, M. Shaposhnikov, JCAP **06**, 029 (2009)
- FB, A. Magnin, M. Shaposhnikov, Phys. Lett. B **675**, 88 (2009)
- FB, A. Magnin, M. Shaposhnikov, S. Sibiryakov, JHEP **1101**, 016 (2011).
- FB, M. Shaposhnikov, JHEP **0907** (2009) 089
- A. Anisimov, Y. Bartocci, F. L. Bezrukov, Phys. Lett. B **671**, 211 (2009)
- FB, D. Gorbunov, JHEP **05** (2010) 010
- T. Asaka, M. Shaposhnikov, Phys. Lett. B **620** (2005) 17
- T. Asaka, S. Blanchet, M. Shaposhnikov, Phys. Lett. B **631** (2005) 151
- M. Shaposhnikov, I. Tkachev, Phys. Lett. B **639** (2006) 414
- A. A. Starobinsky, Phys. Lett. **B91** (1980) 99-102
- D. S. Gorbunov, A. G. Panin, [arXiv:1009.2448 [hep-ph]]