Light Inflaton – hunting for it from CMB through the Dark Matter and down to the colliders

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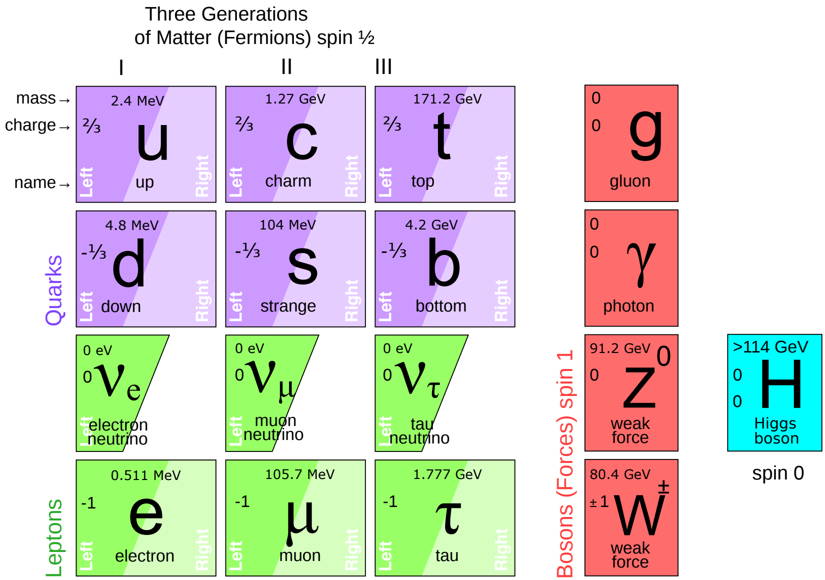
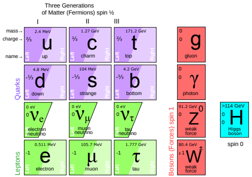
CERN TH Seminar
October 8, 2014

Outline

Standard Model of particle physics



Standard Model – describes nearly everything

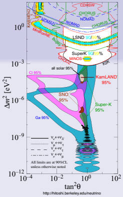


+ Einstein gravity

Describes

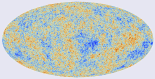
- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ($T < 1$ MeV, $t > 1$ sec)

Experimental problems:



- Laboratory
  - ? Neutrino oscillations
- Cosmology
  - ? Baryon asymmetry of the Universe
  - ? Dark Matter

  - ? Inflation



  - ? Dark Energy

Minimal extensions of the SM to account for everything

Should explain everything

- Neutrino oscillations
- Baryon asymmetry of the Universe
- Dark Matter
- Inflation

(first three: νMSM; last two: this talk)

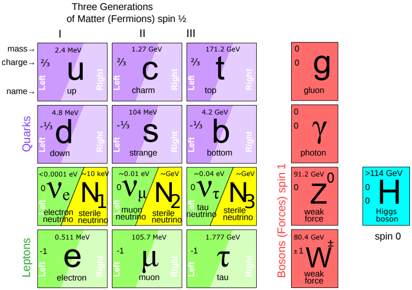
in a minimal way

- Introduce minimal amount of new particle/parameters
  - Simple
  - Predictive
- No new scales up to gravity/inflation
  - Allows to make relations between inflation and particle physics

Standard Model and nothing else above up to Planck scale?

- No heavy particles/scales
  - no physical high scale quadratic contributions to the Higgs boson mass
  - hierarchy problem is not that scary (however, the gravity should be generous enough not to give quadratically divergent contributions)
  - Processes at the highest energy (inflation) may be directly related to the low energy properties

Dark matter – νMSM setup used



Role of sterile neutrinos

N_1 (Warm) Dark Matter, $M_1 = 7\text{keV}$
Already seen in X-rays!

$N_{2,3}$ Baryogenesys, $M_{2,3} \sim$ several GeV

- Generation of DM abundance will be discussed later

[Asaka, Blanchet, Shaposhnikov'05]

Standard Model – extended for inflation

Some models that minimally expand the SM and have inflation

- Higgs inflation
  – No new particles, but: new scale M_P/ξ, UV corrections may mask inflation at $M_P/\sqrt{\xi}$ from particle physics
- R^2 inflation
  – purely gravitational solution, nothing interesting for the particle physics
- Light inflaton with non-minimal coupling
  – this talk, solution within renormalizable particle physics model

Important – the whole Universe evolution should be fully described within the model!

Standard Model – extended for inflation

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“Standard” chaotic inflation

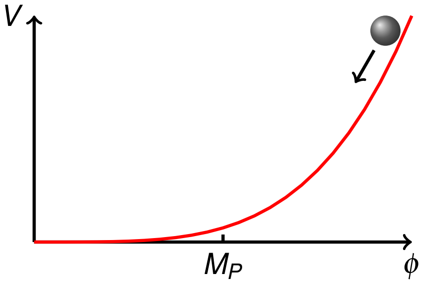
Scalar part of the action

$$S=\int d^4x\sqrt{-g}\left\{-\frac{M_P^2}{2}R+\frac{\partial_\mu\phi\partial^\mu\phi}{2}-\frac{\beta}{4}\phi^4\right\}$$

Required to get $\delta T/T \sim 10^{-5}$

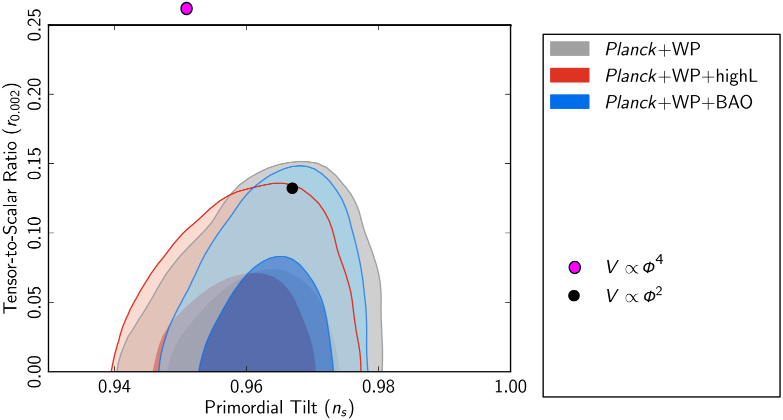
$$\beta \sim 10^{-13}$$

$$m \sim 10^{13}\text{ GeV}$$



Fields $\gtrsim M_P$, energy $\sim \lambda^{1/4} M_P$.

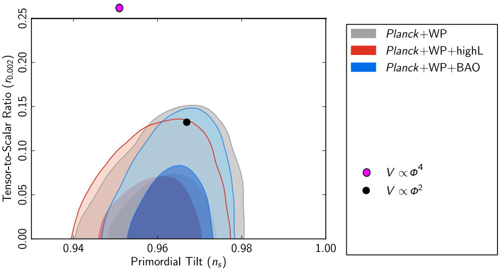
Planck results disfavor plain ϕ^4

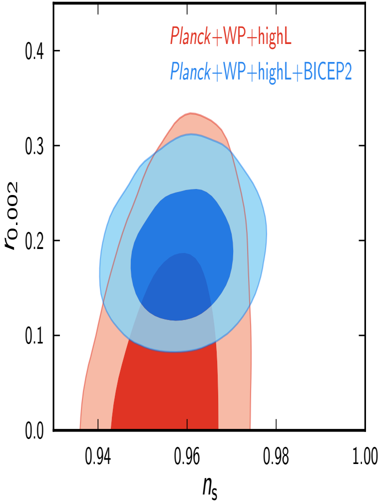


Obligatory BICEP2 remark

$$U_{\text{inflation}}^{1/4} \sim 1.9 \times 10^{16}\ \text{GeV} \left(\frac{r}{0.1}\right)^{1/4}$$

If BICEP2 measured anything – that would be fun!





Non-minimal coupling to gravity leads to good inflation

Scalar action with non-minimal coupling

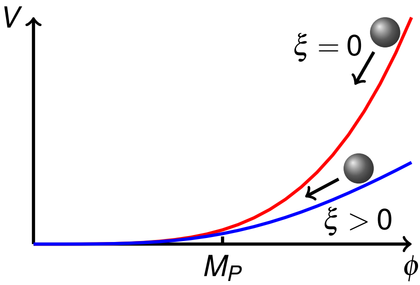
$$S = \int d^4x\sqrt{-g}\left\{ -\frac{M_P^2}{2}R - \frac{\xi}{2}\phi^2 R + \frac{\partial_\mu\phi\partial^\mu\phi}{2} - \frac{\lambda}{4}\phi^4 \right\}$$

Conformal transformation to the Einstein frame

$$\hat{g}_{\mu\nu} = \sqrt{1+\frac{\xi\phi^2}{M_P^2}}\, g_{\mu\nu},$$

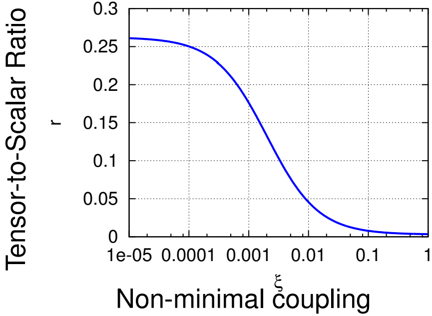
flattens the potential

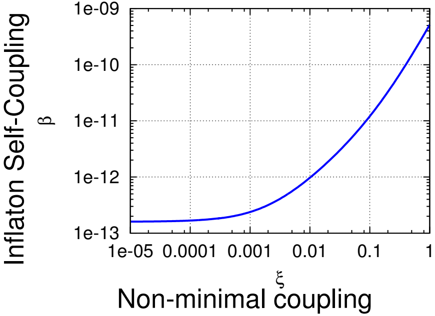
$$V(\phi) \to \hat{V}(\phi) = \frac{V(\phi)}{\left(1+\xi\phi^2/M_P^2\right)^2}$$



(Change of the field $\frac{d\chi}{d\phi} = \sqrt{\frac{1+(\xi+6\xi^2)\phi^2/M_P^2}{(1+\xi\phi^2/M_P^2)^2}}$ is also needed)

The tensor perturbations are suppressed, inflaton self-coupling β is increased

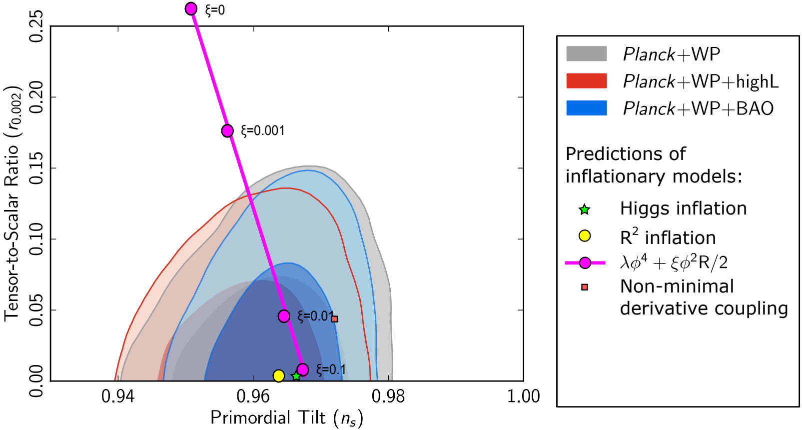




- For each ξ the self-coupling β is fixed by $\delta T/T \simeq 10^{-5}$ requirement.
- Measurement of not-too-small r measures ξ!

[Tsujikawa, Gumjudpai'04, FB'08]

Inflationary predictions are ok for $\xi \gtrsim 0.003$



Note: for small $\xi \lesssim 1$ no new scales in the model!

SM + Light Inflaton coupled in the Higgs sector only

$$\mathscr{L} = \mathscr{L}_{\text{SM,M=0}} + \alpha H^\dagger H \phi^2 +$$

Standard Model — Interaction

$$+ \frac{M_P^2}{2} R + \frac{(\partial\phi)^2}{2} + \frac{\xi\phi^2}{2} R + \frac{\beta}{4}\phi^4 - \frac{\mu^2}{2}\phi^2$$

Einstein gravity — Inflationary sector

Main assumption for today

- The scale invariance breaking is manifest *only in the inflaton sector*

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

Inflaton gets a vev $\to$ Higgs gets a vev

[Shaposhnikov, Tkachev'06, Anisimov, Bartocci, FB'09, FB, Gorbunov'13]

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Einstein gravity — Inflationary sector

Parameter counting:

- overall 5: λ, α, ξ, β, μ
  Fix in SM: Higgs mass m_H and vev $v^2 = 1/2\sqrt{2}G_F$
  Fix COBE normalization
- *2 free parameters*: α and β, or:
  inflaton mass $m_\chi = m_h \sqrt{\beta/2\alpha}$
  Higgs-inflaton mixing $\theta^2 = 2\alpha/\lambda$

[Shaposhnikov, Tkachev'06, Anisimov, Bartocci, FB'09, FB, Gorbunov'13]

All constants of the model are bound from cosmology

CMB normalization: $\beta(\xi)$

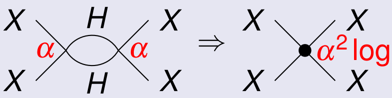
$$\beta = \frac{3\pi^2 \Delta^2_{\mathscr{R}}}{2} \frac{(1+6\xi)(1+6\xi+8(N+1)\xi)}{(1+8(N+1)\xi)(N+1)^3}$$

CMB tensor modes give ξ

$$r = \frac{16(1+6\xi)}{(N+1)(1+8(N+1)\xi)}$$

$\alpha^2 \lesssim \beta$ (mass lower bound)

Inflation is not spoiled by the radiative corrections



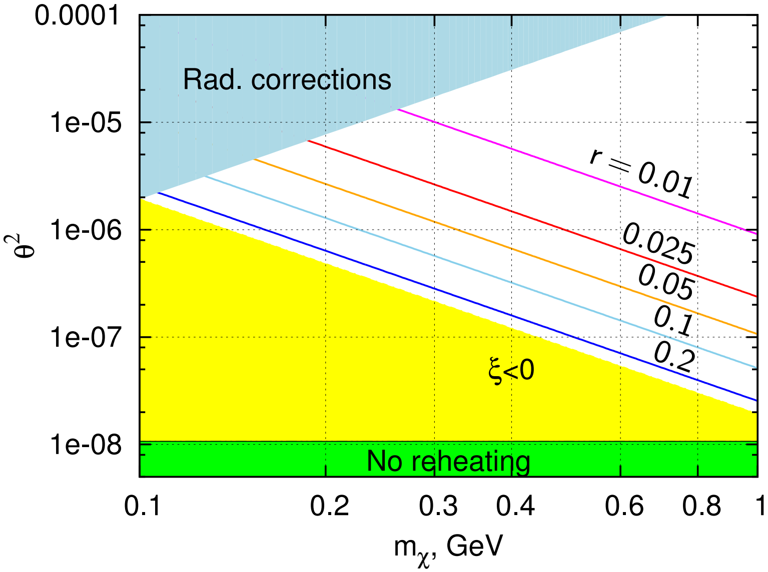
$\alpha > 10^{-7}$ (mass upper bound)

Sufficient reheating

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

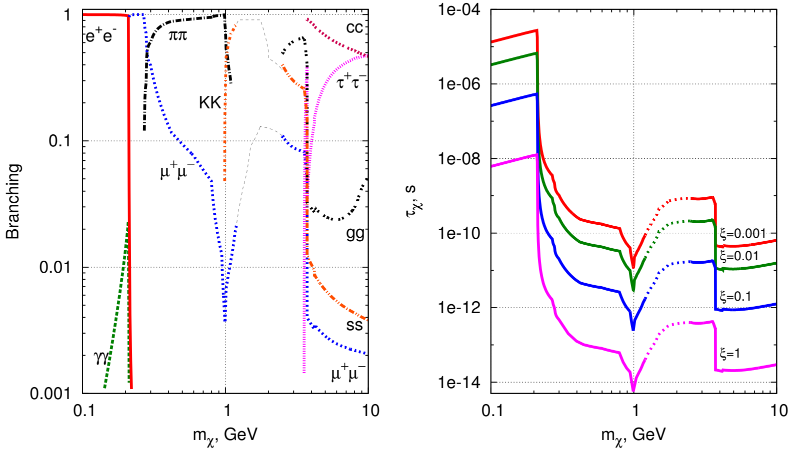
[Anisimov, Bartocci, FB'09]

Parameter region is constraint from cosmology



Inflaton decays and lifetime

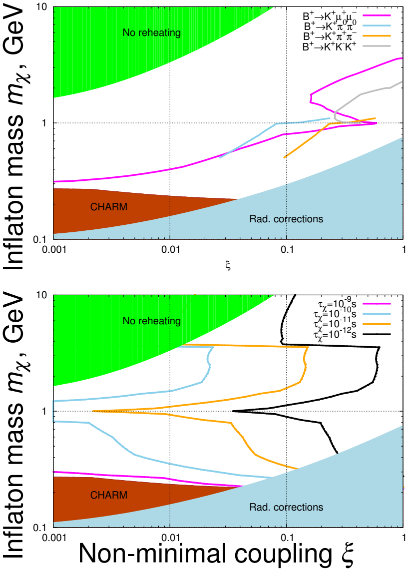
Coupled to everything proportional particle mass



Created in meson decays:

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

Experimental searches are possible



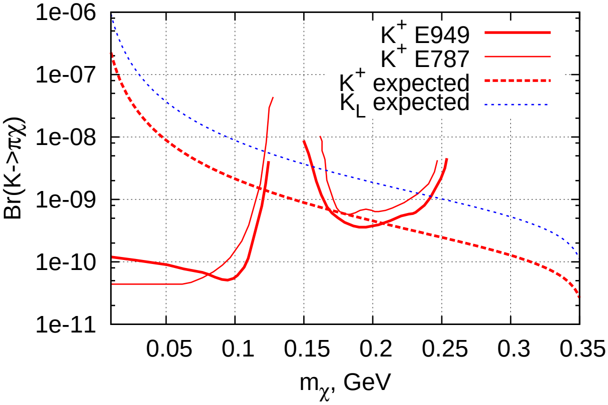
Behaves as light "Higgs" boson, suppresed by $\theta = \sqrt{2\beta}\, v/m_\chi$

- Created in meson decays
- Decays: KK, $\pi\pi$, $\mu\mu$, ee, ...
- Interacts with media: extremely weakly

Search (LHCb, Belle)

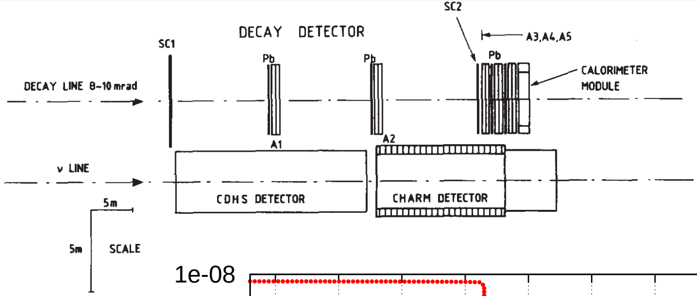
- Events with offset vertices in B decays
- Peaks in Daltiz plot of three body B decays

Production: bound from $K^+ \to \pi^+ + \text{nothing}$

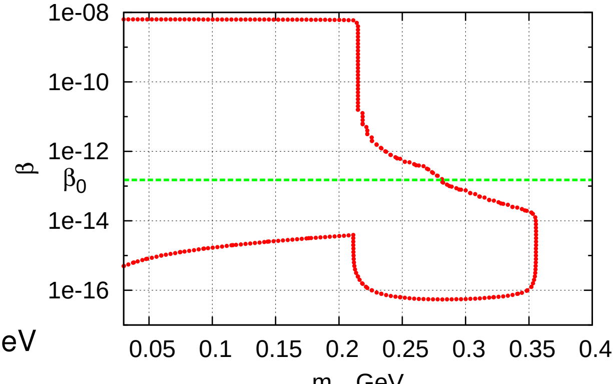


Excluded: $m_\chi \lesssim 120$ MeV
Disfavoured: 170 MeV $\lesssim m_\chi \lesssim$ 205 MeV

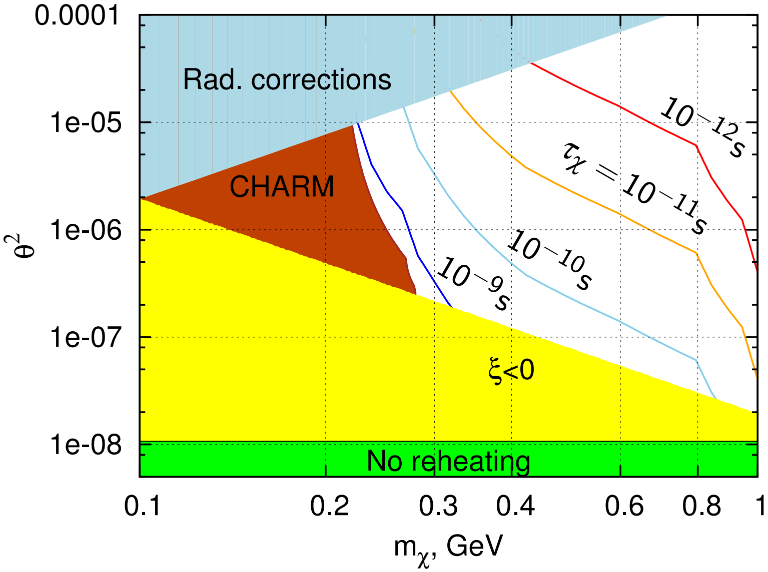
CHARM – bound



Search for decays of something into $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$ $\Longrightarrow$ $m_\chi < 270$ MeV



Longer lifetimes are excluded by CHARM



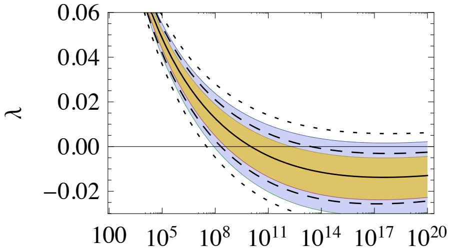
Future experimental searches

- For the longer lifetimes – SHIP
- For the shorter lifetimes – LHCb, BELLE (some constraints are there, just awaiting for proper analysis)

Another prediction: The Higgs boson can not be light

Inflation proceeds along $H^\dagger H = \frac{\alpha}{\lambda} X^2 \quad \Rightarrow H$ is large at inflation

- The Higgs self-coupling λ: must be positive up to inflationary scales



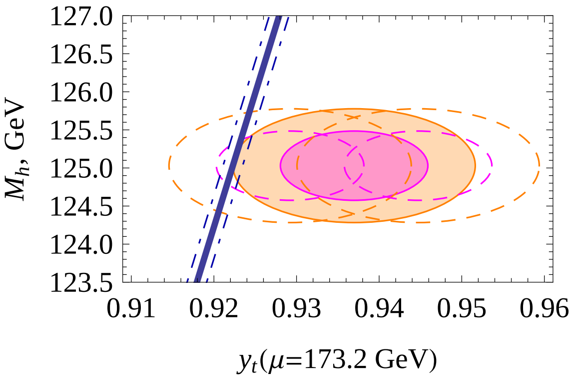
Higgs mass
$m_H = 125.3\,\text{GeV}$

yScale μ, GeV

Current experimental value: $m_H = 125.7 \pm 0.4\,\text{GeV}$ (CMS)

[FB, Kalmykov, Kniehl„ Shaposhnikov'12,
Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori„ Strumia'12]

Current top quark Yukawa is compatible with stable Higgs within experimental errors



DM and Baryogenesys: Adding sterile neutrinos N_I

$$\mathscr{L} = \mathscr{L}_{\text{SM,M=0}} + \alpha H^\dagger H \phi^2 +$$

Standard Model — Interaction

$$+ \frac{M_P^2}{2} R + \frac{(\partial\phi)^2}{2} + \frac{\xi\phi^2}{2} R + \frac{\beta}{4}\phi^4 - \frac{\mu^2}{2}\phi^2$$

Einstein gravity — Inflationary sector

$$+ i\bar{N}_I \partial\!\!\!/ N_I - F_{\alpha I} \bar{L}_\alpha N_I H - \frac{f_I}{2} \bar{N}_I^c N_I \phi$$

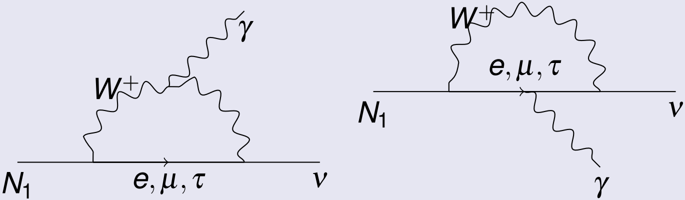
Dirac masses — Majorana masses

- f_I control both Majorana masses $M_I = f_I \langle\phi\rangle$ and inflaton-sterile neutrino coupling in the early Universe
- $F_{\alpha I}$ control active neutrino masses $m_i \sim m_D^2/M$ and sterile-active neutrino mixing $\theta_I \sim m_D^2/M_I^2$ (see-saw formula)

DM properties – Radiative decay

leads to constraints from the X-ray observations

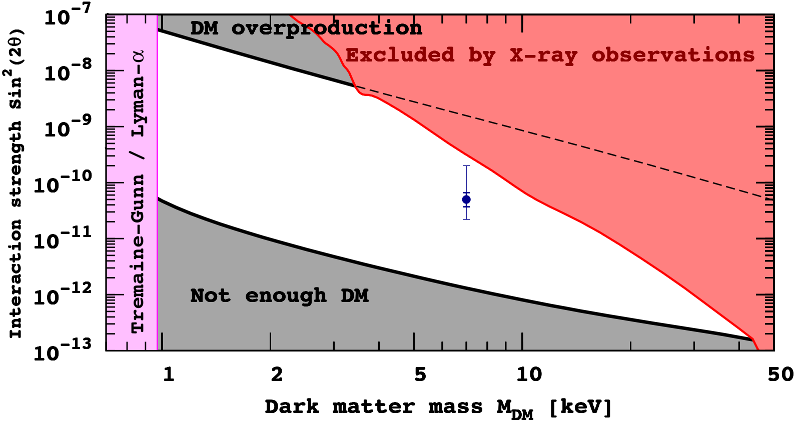
Second decay channel: $N_1 \to \nu\gamma$



$$\Gamma \simeq 5.5 \times 10^{-27} \left(\frac{\theta_1^2}{10^{-5}}\right) \left(\frac{M_1}{1\text{keV}}\right)^5 \text{s}^{-1}$$

- Monochromatic: $E_\gamma = M_1/2$
- We should see an X-ray ($\sim$ keV) line coming from everywhere in the sky

Sterile-active mixing θ_1 is bound (discovered?!) in X-ray observations



3.5 keV X-ray hint–mixing θ_1^2 (Dirak Yukawa F) too small mixing to produce DM via non-resonantly enhanced oscillations

DM is produced in inflaton decays

- Light inflaton is in thermal equilibrium down to small temperature $T_f \ll m_\chi$ (reactions $\chi \leftrightarrow e^+e^-, \mu^+\mu^-$, etc.)
- Maximal production happens at $T \simeq m_\chi$

$$\frac{\partial n}{\partial t} - \mathscr{H} p \frac{\partial n}{\partial p} = \frac{2m_\chi \Gamma_{\chi\to N_1 N_1}}{p^2} \int_{p+m_\chi^2/4p}^{\infty} n_\chi(E) dE$$

- Amount of DM produced

$$\Omega_{DM} \propto \frac{\Gamma_{\chi\to N_1 N_1} M_1}{m_\chi^2} \propto \frac{f_1^3 \theta^2}{m_\chi}$$

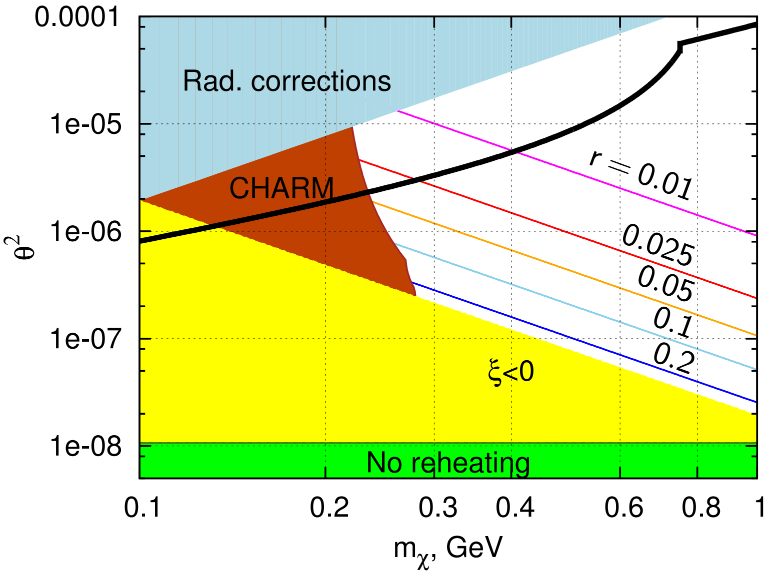
DM mass $M_1 = f_1 \langle \chi \rangle$ defines the inflaton-higgs mixing θ

$$\theta^2 \simeq 2.7 \times 10^{-6} \left(\frac{7\text{keV}}{M_1}\right)^3 \left(\frac{S}{1.5\, f(m_\chi)}\right) \left(\frac{\Omega_N}{0.22}\right) \left(\frac{m_\chi}{250\text{ MeV}}\right)$$

$f(m_\chi) \sim 1$ depends on d.o.f. around $T \sim m_\chi/3$

[Shaposhnikov, Tkachev'06, FB, Gorbunov'13]

Parameters are completely fixed after DM discovery and measurement of r

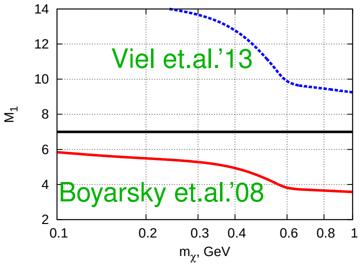


How cold is the Warm DM produced?

- Average momentum of the DM neutrino

$$\langle p \rangle \simeq 2.45\, T \left(\frac{10.75}{g_*(m_\chi/3)} \right)^{1/3}$$

Ly-α mass *lower* bounds



- Average momentum of particles with temperature T (more or less that of non-resonantly produced sterile neutrinos)

$$p_T = 3.15\, T$$

- On the edge!

Constraints and searches for heavier sterile $N_{2,3}$

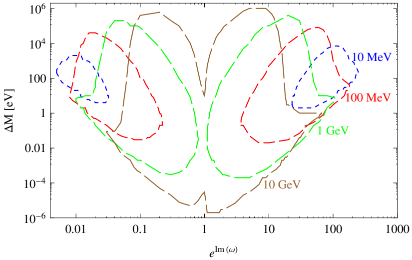
νMSM with inflaton decay into DM

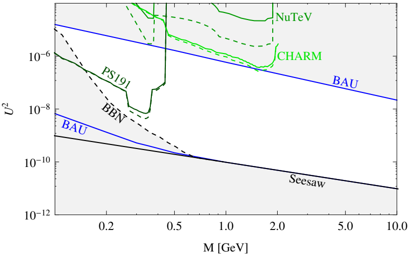
- Leptogenesys by $N_{2,3}$

  $$\Delta M/M \sim 10^{-3}$$

- Experimental searches
  - $N_{2,3}$ production in hadron decays:
    - Missing energy in K decays
    - Peaks in Dalitz plot
  - $N_{2,3}$ decays into SM
    - Beam target experiments – SHIP

[Gorbunov, Shaposhnikov'07]





Caveats

- Why this specific pattern of scale symmetry breaking?
- Domain wall problem

Conclusions

- A minimal model without any new scales can
  - Fully describe the Universe
  - Can be constrained from *a combination* of cosmological and laboratory experiments
- Example model: light non-minimally coupled inflaton
  - Cosmology – essential measurement of r, search for DM decays in X-rays
  - Laboratory
    - Inflaton – search in rare decays of B (LHCb, SHIP)
    - Sterile neutrinos – no large neutrinoless double beta decay, search in rare decays, SHIP
- Invent a better model?

Backup slides

How to reheat the Universe after inflation?

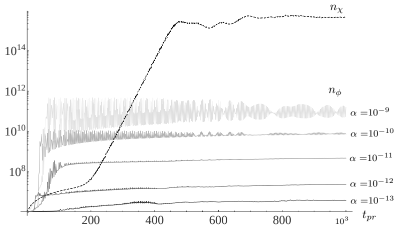
- After inflation: empty & cold
- Needed: hot, $T_r > 150$ GeV (to get baryogenesis, eg. via leptogenesis)

The estimate:

- Require, that at $T_r \sim 150$ GeV $\chi\chi \to HH$ process enters thermal equilibrium

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

Parametric resonance?
Not so easy to create the Higgs



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

DM generation in the early Universe

Produced in $l\bar{l} \to \nu N_1$, $q\bar{q} \to \nu N_1$, etc.

Production is proportionol to the effective active-sterile mixing angle

$$\theta_M^2(T) \simeq \frac{\theta_1^2}{\left(1 + \frac{2p}{M_1^2}\left(b(p,T) \pm c(T)\right)\right)^2 + \theta_1^2} \,.$$

$$b(p,T) = \frac{16 G_F^2}{\pi \alpha_W} p(2 + \cos^2\theta_W) \frac{7\pi^2 T^4}{360}$$

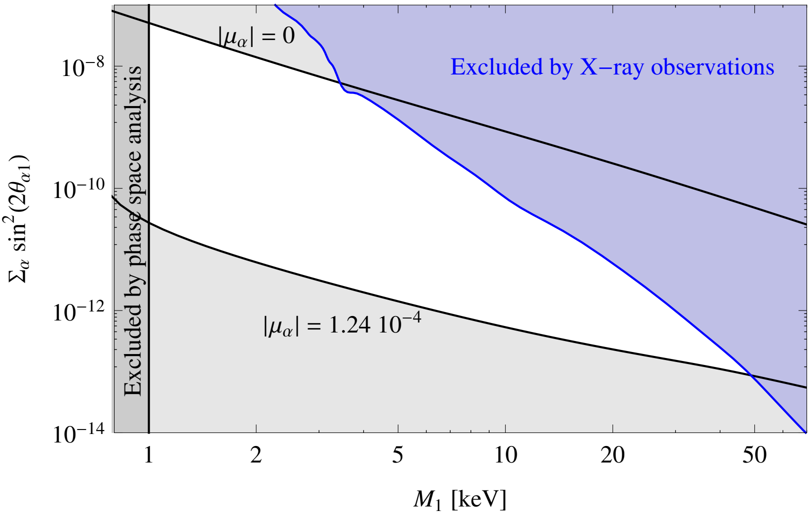
$$c(T) = 3\sqrt{2} G_F \left(1 + \sin^2\theta_W\right)(n_{\nu_e} - n_{\bar{\nu}_e})$$

(θ_1 – vacuum mixing angle of N_1 and active ν)

Production can be

Non-resonant (b dominates) or Resonant ($c \sim b$)

Bounds for the N_1 – DM sterile neutrino



[Canetti, Drewes, Shaposhnikov'13]

νMSM experimental consequences (DM)

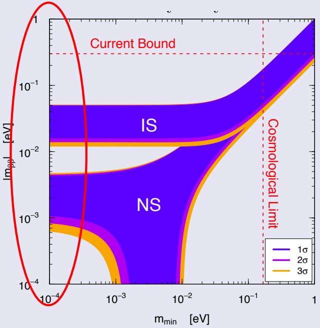
Active neutrino masses

- X-rays require very small N_1 mixing angle θ_1, so

$$m_1 < 10^{-5}\text{eV}$$

Neutrinoless double beta decay

- Additional contributions are negligible
  - N_1 – X-ray constraints
  - $N_{2,3}$ – mass $> 100\,\text{MeV}$
- Mass spectrum strongly hierarchical – X-ray constraints



$$m_{0\nu\beta\beta} < 50\times 10^{-3}\ \text{eV}$$

[FB'05]

Low T and low M leptogenesys

CP violation present in Yukawa matrices F

non-equilibrium process are for sterile neutrino N_I

- production
- freeze-out
- decay

Note – for $M_I/T \ll 1$ the asymmetries can be generated in active and sterile sectors with opposite signs

$$
\begin{aligned}
i\frac{d\rho_N}{dT} &= [H,\rho_N] - \frac{i}{2}\{\Gamma_N, \rho_N - \rho^{eq}\} + \frac{i}{2}\mu_\alpha \tilde{\Gamma}^\alpha_N \,, \\
i\frac{d\rho_{\bar{N}}}{dT} &= [H^*,\rho_{\bar{N}}] - \frac{i}{2}\{\Gamma^*_N, \rho_{\bar{N}} - \rho^{eq}\} - \frac{i}{2}\mu_\alpha \tilde{\Gamma}^{\alpha *}_N \,, \\
i\frac{d\mu_\alpha}{dT} &= -i\Gamma^\alpha_L \mu_\alpha + i\mathrm{tr}\left[\tilde{\Gamma}^\alpha_L(\rho_N - \rho^{eq})\right] \\
&\quad - i\mathrm{tr}\left[\tilde{\Gamma}^{\alpha *}_L(\rho_{\bar{N}} - \rho^{eq})\right] .
\end{aligned}
$$

[Asaka, Blanchet, Shaposhnikov'05, Canetti, Drewes, Shaposhnikov'13]

Thermal history of the Universe

		zero abundance of $N_{1,2,3}$
		thermal production of $N_{2,3}$
		$\Rightarrow$ lepton asymmetry generated
		$\mu_\alpha \sim 10^{-10}$
200 GeV	T_{EW}	Electroweak Symmetry Breaking
		$\Rightarrow$ lepton asymmetry converted to baryon asymmetry
		$\Delta_B \sim 0.86 \times 10^{-10}$
	T_+	$N_{2,3}$ reach equilibrium
		$\Rightarrow$ lepton asymmetry washed out
few GeV	T_-	$N_{2,3}$ freeze out
		$\Rightarrow$ lepton asymmetry generated
	T_d	$N_{2,3}$ decay
		$\Rightarrow$ lepton asymmetry generated
		$\mu_\alpha \gtrsim 8 \times 10^{-6}$
100 MeV	T_{DM}	resonant N_1 Dark Matter production

T ↑ t ↓

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