keV scale sterile neutrino Dark Matter – theories and implications for experiment

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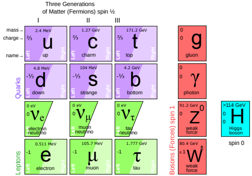
Outline

1. SM, Cosmology and sterile neutrinos
    - SM problems in particle physics and cosmology
    - Minimal extensions
    - Summary of important constraints on DM
2. Scenario I – *ν*MSM – just three sterile neutrinos
    - Generic description
    - DM constraints
    - Leptogenesys for baryogenesys and DM generation
3. Scenario II – *ν*MSM + DM generation
    - Adding the inflaton
    - DM production in inflaton decays
    - Bounds on the model
4. Scenario III – Left-Right symmetric models
    - Not so minimal model
    - Low scale window

Standard Model – describes nearly everything



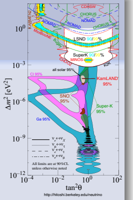
+

Einstein gravity

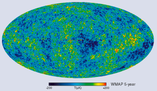
Describes

- 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



Can we describe everything with as small extension as possible?

- Minimal number of new particles
- No new scales before inflation/gravity

Great:

- Avoids (or reformulates) the hierarchy problem (in scale invariant formulations)
- Simple
- Predictive

One should agree to:

- Some (technical) fine-tuning

Some possible minimal models of everything

1. *ν*MSM – 2 sterile neutrino for leptogenesys, 1 for DM

   [Asaka, Shaposhnikov'05]

2. *ν*MSM + external DM generation mechanism

   [Shaposhnikov, Tkachev'06, FB, Gorbunov'10]

3. "sterile" neutrinos are charged under larger gauge group (Left-Right symmetric model)

   [FB, Hettmansperger, Lindner'10,
   Nemevsek, Senjanovic, Zhang'12]

Notes:

- something more is needed for inflation. Can be quite minimal eg. R^2 inflation, Higgs inflation, light inflaton
- Other minimal models are possible, say with scalar DM

Sterile neutrino role

Three sterile neutrinos present in all of the models

- N_1 – light unstable long-lived Dark Matter ($\sim$keV scale)
- $N_{2,3}$ – heavier
  - responsible for leptogenesys
  - responsible for active neutrino masses
  - responsible for (assist in) DM production

Summary of sterile neutrino Dark Matter constraints

Dark Matter

- Decay constraints – small enough radiative decay width (X-ray observations)

  always there
- Structure formation constraints
  - Heavy enough to form existing structures out of fermions

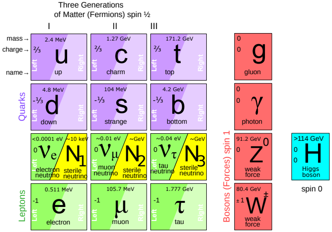
    always there
  - Cold enough to leave observed small scale structure intact

    depends in generation mechanism (spectrum)
- Production of proper DM abundance

  depends on generation mechanism

Scenario I – νMSM

Just three sterile neutrinos



Model action

$$\mathcal{L}_{\nu MSM} = \mathcal{L}_{SM} + i\bar{N}\partial\!\!\!/ N - \bar{L}_L F N \tilde{\Phi} - \bar{N} F^\dagger L_L \tilde{\Phi}^\dagger - \frac{1}{2}\left(\overline{N^c} M_M N + \bar{N} M_M^\dagger N^c\right).$$

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

νMSM description – neutrino masses

- $M_1 \sim 1$–$50\,\mathrm{keV}$ – Dark Matter
- $M_{2,3} \sim$ several GeV – Leptogenesys

$M_I \gg M^D = F\langle\Phi\rangle$ – “see-saw” formula is working:

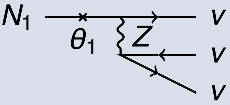
Light neutrino masses $$M^\nu = -(M^D)^T \frac{1}{M_I} M^D$$

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

DM properties – Radiative decay

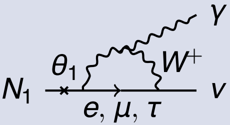
Leads to constraints from the X-ray observations

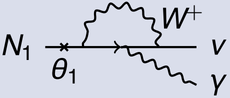
Main decay channel



- $\tau > \tau_{\text{Universe}}$ – easy!
- not visible, really…

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

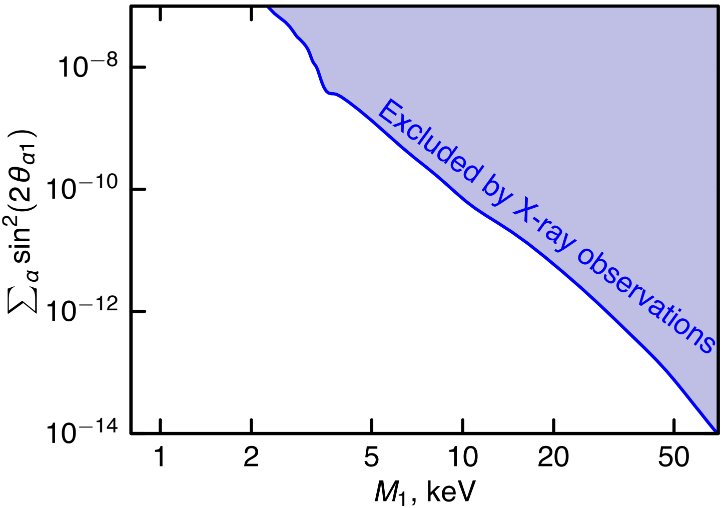




$$\Gamma \simeq 5.5 \times 10^{-27} \left(\frac{\theta_1^2}{10^{-5}}\right) \left(\frac{M_1}{1\text{keV}}\right)^5 \text{s}^{-1}$$

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

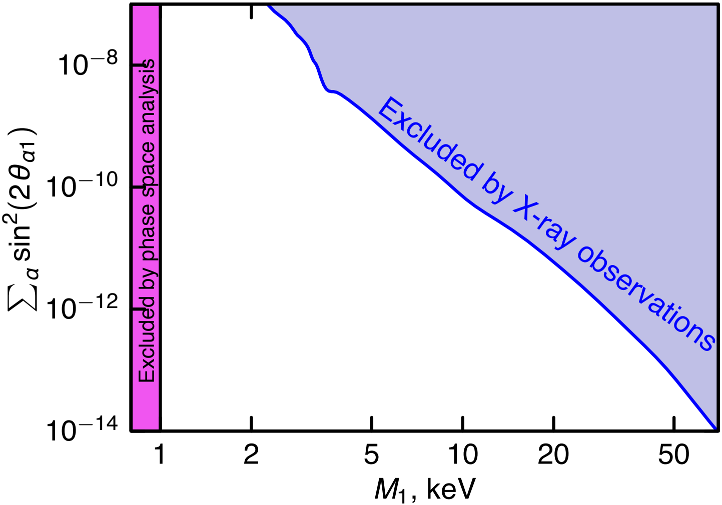
Bounds for the N_1 – DM sterile neutrino



Universal constraint for all models

[Boyarsky, Ruchayskiy, Shaposhnikov'09]

Bounds for the N_1 – DM sterile neutrino



Universal constraints for all models

DM generation in the early Universe

- Because of small mixing angle (X-ray constraints!) *never* enters thermal equilibrium
    - Good – does not overclose the Universe
    - Bad – abundance depends on initial conditions (or is it actually good?)

DM generation in the early Universe

Produced in $\bar{l}l \to \nu N_1$, $q\bar{q} \to \nu N_1$, 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 ($c \sim b$)

DM generation – NR production

- N_1 never enter thermal equilibrium
- Momentum distribution is not thermal

$$f_{N_1}(p) = \frac{\chi}{e^{p/T_\nu} + 1}$$

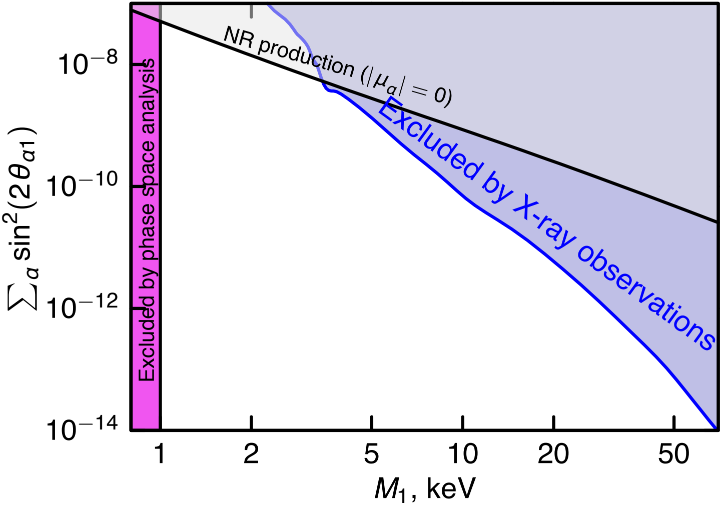
with $\chi \propto \theta_1^2$

  - This is much hotter, than the "Thermal Relic" with

$$f_{TR}(p) = \frac{1}{e^{p/T_{TR}} + 1}$$

  of low temperature $T_{TR} < T_\nu$ (c.f. M.Viel's talk on Wednesday)
  - The Lyman-α constraint is quite strong $m_{NRP,min} \propto (m_{TR,min})^{4/3}$

Bounds for the N_1 – DM sterile neutrino



Nearly universal constraints

DM generation – NR production

- N_1 never enter thermal equilibrium
- Momentum distribution is not thermal

$$f_{N_1}(p) = \frac{\chi}{e^{p/T_\nu}+1}$$

with $\chi \propto \theta_1^2$

  - This is much hotter, than the “Thermal Relic” with

$$f_{TR}(p) = \frac{1}{e^{p/T_{TR}}+1}$$

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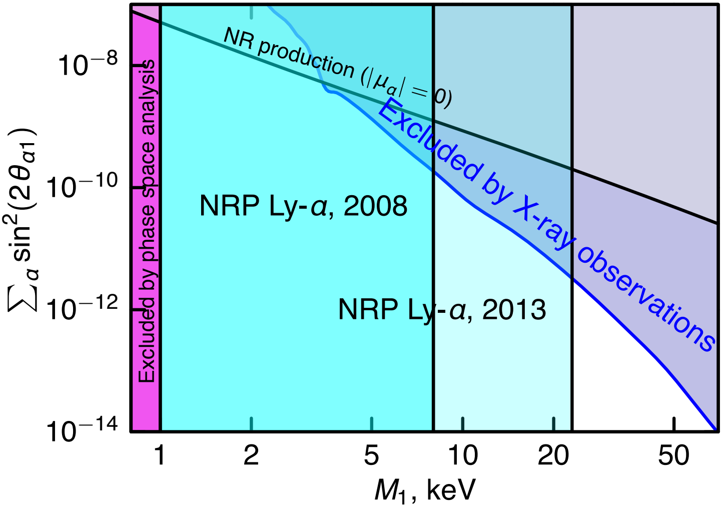
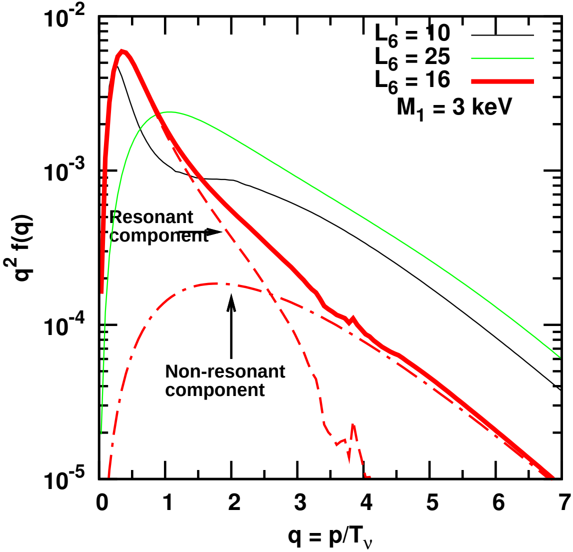
Bounds for the N_1 – DM sterile neutrino



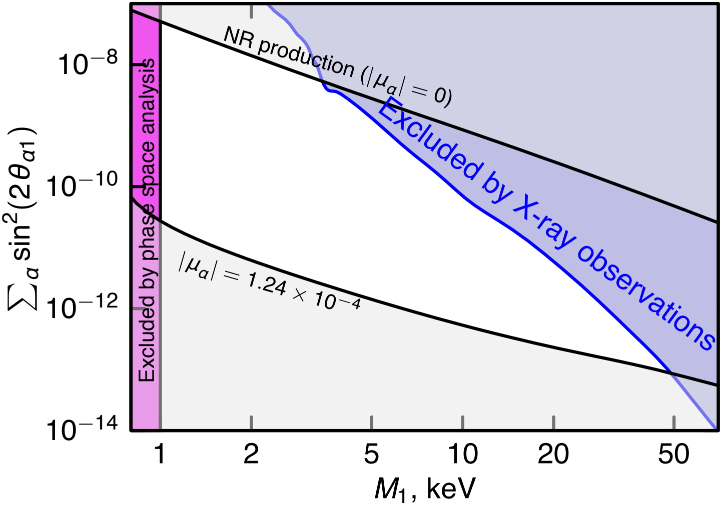
Nonresonant production is completely excluded

Resonant production – can provide much colder DM

And much more of it



Bounds for the N_1 – DM sterile neutrino



Only for “pure νMSM” – production with lepton asymmetries

[Canetti, Drewes, Shaposhnikov’13]

νMSM experimental consequences (DM)

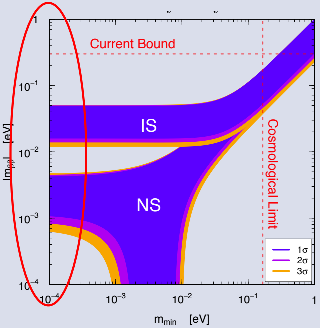
Active neutrino masses

- 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

T

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

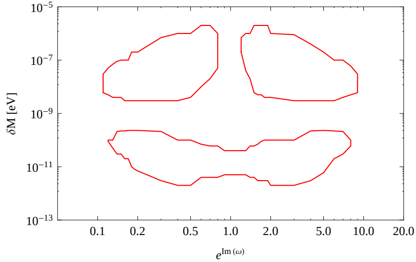
t

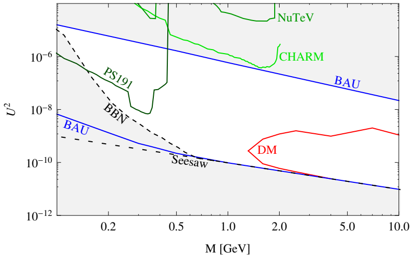
Bounds for the $N_{2,3}$ sterile neutrinos

$M_{1,2}$ very degenerate

$\Delta M \sim \delta m_{\text{active}}$

[Canetti, Drewes, Shaposhnikov'13]





Scenario II – νMSM + DM generation

- νMSM part
  - N_1 – Dark Matter
  - $N_{2,3}$ – leptogenesys (only)
- something else generates proper N_1 DM abundance

Example model

Light inflaton

$$\mathcal{L} = \mathcal{L}_{\nu\text{MSM0}} + \alpha H^\dagger H X^2 + \frac{\beta}{4} X^4 + f_I X \bar{N}^c N$$

- Reheating after inflation via $XX \to HH$ (Standard Model) and $X \to NN$ (Dark Matter)

[Shaposhnikov, Tkachev'06, FB, Gorbunov'10]

DM production now happens from inflaton decays

- At reheating inflaton decays both into SM and DM, providing *initial* abundance for N_1
- M_1 is determined from its decay width (assuming inflaton is the messenger of the scale invariance breaking, so f_1 determines both M_1 and inflaton decays to N_1)

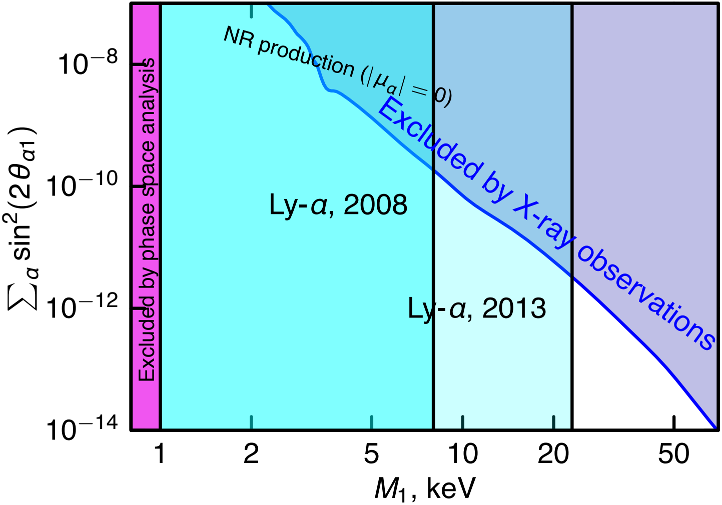
  $$M_1 \sim 13 \cdot \left(\frac{m_\chi}{300\ \text{MeV}}\right) \left(\frac{S}{4}\right)^{1/3} \cdot \left(\frac{0.9}{f(m_{\text{inflaton}})}\right)^{1/3} \text{keV}$$

  where $m_{\text{inflaton}} \simeq \text{GeV}$
- Distribution is similar to that of the non-resonant production (just a bit cooler)

DM neutrino mass bound from Lyman-α

$$M_1 > 8\text{keV}$$

Bounds for the N_1 – DM sterile neutrino



Production in inflaton decays

Astrophysical constraints

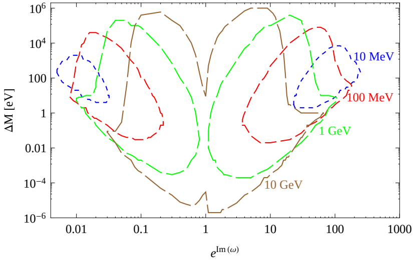
νMSM with inflaton decay into DM

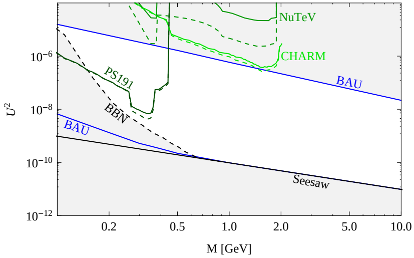
- Dark Matter N_1
    - θ_1 can be very small
    - stronger mass bounds from structure formation
- Leptogenesys by $N_{2,3}$

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

- 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

[Gorbunov, Shaposhnikov'07]





Situation 3 – a lot of new physics

Assumptions

- There are three right-handed neutrinos N_1, N_2, N_3
- At low energies they have Dirac and Majorana mass terms
- They are charged under some (non-SM) gauge group, with the (right) gauge boson mass M

Example – $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model

Thermal history

- DM Sterile neutrinos N_1 enter thermal equilibrium
- Their abundance later diluted S times by out of equilibrium decay of $N_{2,3}$
- Leptogenesys – usual (resonant) in $N_{2,3}$ decays.

[FB, Hettmansperger, Lindner'10, Nemevsek, Senjanovic, Zhang'12]

Constraints summary

X/γ-ray

$$\theta_1^2 \lesssim 1.8\times 10^{-5}\left(\frac{1\mathrm{keV}}{M_1}\right)^5$$

$$\zeta^2 \lesssim 10^{-18}\ldots(\mathrm{keV}/M_1)^3$$

Ly-α bound

$$M_1 > 1.5 - 3.3\mathrm{keV}$$

$\Omega_{N_1} = \Omega_{DM}$ if

$$\Gamma_2 \simeq 0.50\times 10^{-6}\,\bar{g}_*^{1/2}\frac{M_2^2}{M_{Pl}}\left(\frac{1\mathrm{keV}}{M_1}\right)^2$$

BBN $\tau_2 > 0.1 \div 2\,\mathrm{sec}$

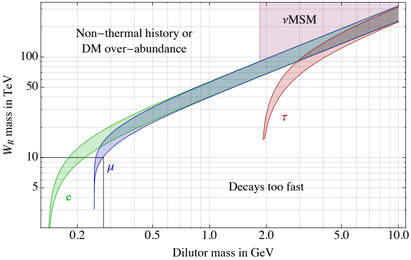
$$M_2 > \left(\frac{M_1}{1\mathrm{keV}}\right)(1.7\div 10)\ \mathrm{GeV}$$

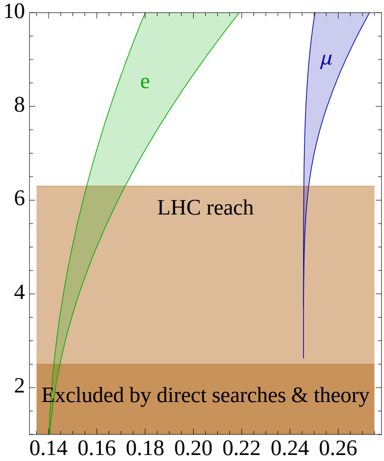
The entropy is effectively generated if the right-handed gauge scale is

$$M > g_{*f}^{-1/8}\left(\frac{M_2}{1\ \mathrm{GeV}}\right)^{3/4}(10\div 16)\ \mathrm{TeV}$$

LR-symmetric low scale window

- Tuning of flavour structure can separate N_1 and $N_{2,3}$ decoupling over QCD phase transition
- Allows for $M_{W_R} \gtrsim 4 - 5\,\mathrm{TeV}$
- $M_2 \approx m_\pi + m_\mu$,
  $M_3 \approx m_\pi + m_e$





[Nemevsek, Senjanovic, Zhang'12]

DM mass bounds (from observed DM structure)

Phase space distribution is now different, and corresponds to the *thermal relic case*

$$f(p) = \frac{1}{\exp\left(\frac{p}{T_\nu/S}\right) + 1}$$

So, N_1 are now *cooled*

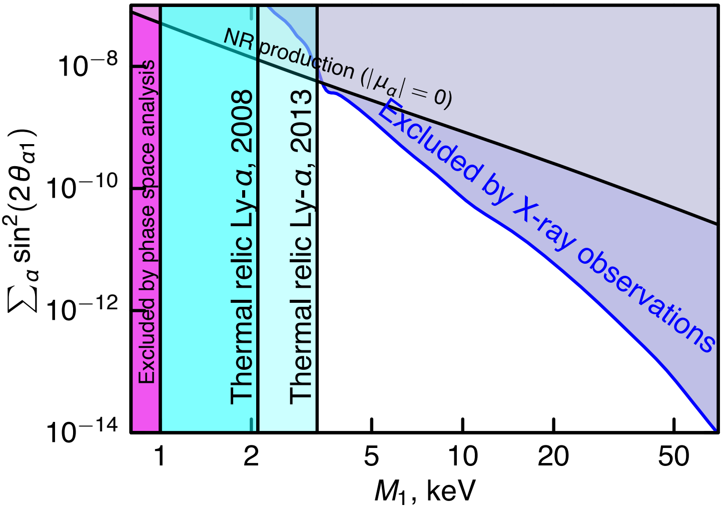
Ly-α bound – structure formation

[Boyarsky, Lesgourgues, Ruchayskiy,, Viel'09, Viel, Becker, Bolton,, Haehnelt'13]

$$M_1 > 1.5 - 3.3 \text{ keV}$$

Astrophysical constraints

Sterile neutrino in beyond SM gauge multiplets



For entropy diluted sterile neutrinos

Constraints for particle physics

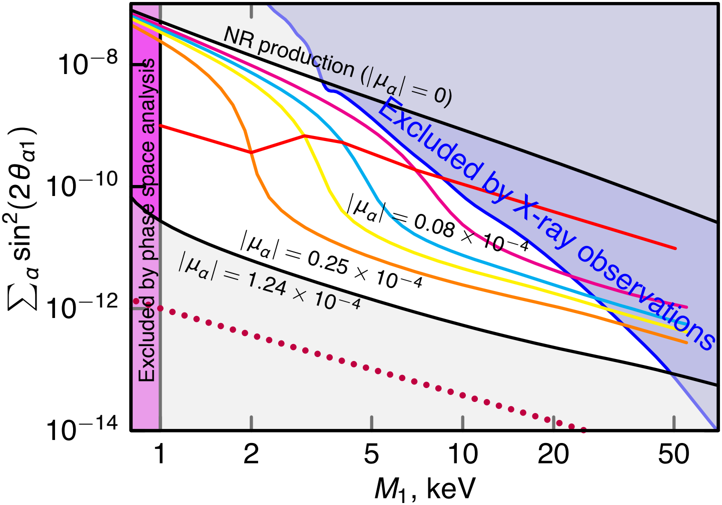
- Yukawa couplings for *all three* N_I are very small
  - type I see-saw like mechanism is impossible
- Active neutrino masses are generated by some type II mechanism
- In the generic case:
  - $N_{2,3}$ masses are high
  - W_R is heavy
  - $0\nu\beta\beta$ – standard
  - X-ray decay of N_1 DM can be arbitrary small
- Low scale case with special flavour structure
  - $N_{2,3}$ masses are low (particle physics experiments?)
  - W_R is within collider reach
  - $0\nu\beta\beta$ – has new physics contributions
  - May have lower bound on X-ray N_1 decay
  - Baryogenesys?

Conclusions

- keV scale sterile neutrino dark matter has
  - universal constraints: X-rays, phase space density
  - model dependent ones: lower bounds on mixing angle, structure formation constraints on the mass

  Important to analyze all the properties – decay, production, structure formation!
- Minimal extensions of the SM by right handed sterile neutrinos can be very promising, leading to experimental signatures
  - X-rays
  - rare processes, beam target experiments
  - neutrinoless double beta decay
- A bit more of new physics may be welcome (reduce some fine tunings)
- A lot more of new physics is more complicated
  - may provide some experimental consequences

Bounds for the N_1 – DM sterile neutrino



Only for “pure νMSM” – production with lepton asymmetries

[Canetti, Drewes, Shaposhnikov’13]

$0\nu\beta\beta$ in νMSM in general

See saw and $0\nu\beta\beta$

- See-saw constraint

$$\sum_{\text{active}} m_i U_{ei}^2 + \sum_{\text{light}} M_I U_{eI}^2 + \sum_{\text{heavy}} M_I U_{eI}^2 = 0.$$

- Contributes to $0\nu\beta\beta$ (light means $M_I < Q_{\text{nuclear}} \sim 100\,\text{MeV}$)

$$\sum_{\text{active}} m_i U_{ei}^2 + \sum_{\text{light}} M_I U_{eI}^2$$

Neutrinoless double beta decay

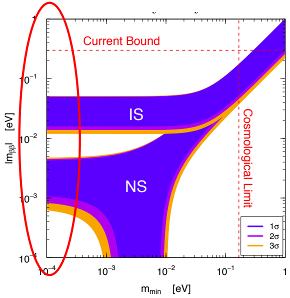
- Both $M_{2,3} > 100\,\text{MeV}$

  $m_{ee} < 50 \times 10^{-3}$ eV
- Both $M_{2,3} < 100\,\text{MeV}$

  $m_{ee} \sim 0$
- $M_2 < 100\,\text{MeV}$, $M_3 > 100\,\text{MeV}$

  $m_{ee} \sim ?$

  But – definitely no leptogenesys



SM + Light Inflaton coupled in the Higgs sector only

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \alpha H^\dagger H \phi^2 + \frac{\beta}{4}\phi^4 + \frac{\xi\phi^2}{2}R$$

Standard Model	Interaction	Inflationary sector

Inflaton mass depends on interaction strength: $m_\chi = m_h \sqrt{\beta/2\alpha}$

Specifically: the Higgs-inflaton scalar potential is

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

We assumed here, that the scale invariance is broken *in the inflaton sector only*

[Shaposhnikov, Tkachev'06, Anisimov, Bartocci, FB'09, FB, Gorbunov'11, FB, Gorbunov'13]

All constants of the model are bound from cosmology

CMB normalization sets $\beta(\xi)$

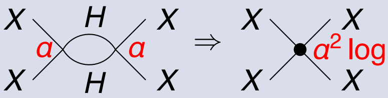
$$\beta = \frac{3\pi^2\,\Delta_{\mathcal{R}}^2}{2}\,\frac{(1+6\xi)(1+6\xi+8(N+1)\xi)}{(1+8(N+1)\xi)(N+1)^3}$$

CMB tensor modes bound ξ

$$r = \frac{16(1+6\xi)}{(N+1)(1+8(N+1)\xi)} \lesssim 0.15$$

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

Inflation is not spoiled by the radiative corrections



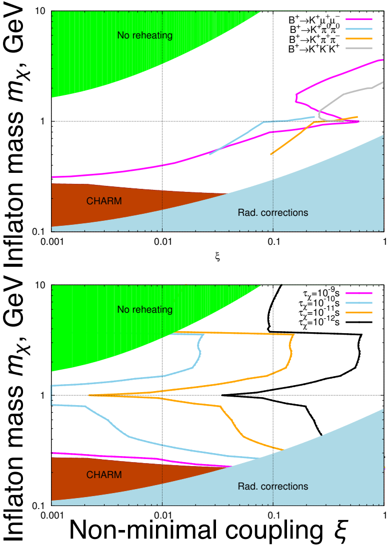
$\alpha > 10^{-7}$ (mass upper bound)

Sufficient reheating

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

[Anisimov, Bartocci, FB'09]

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

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