Light sterile neutrino dark matter in extensions of the Standard Model

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Workshop CIAS Meudon 2011
WARM DARK MATTER IN THE GALAXIES:
THEORETICAL AND OBSERVATIONAL PROGRESSES
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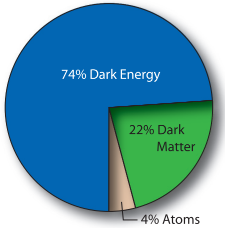
Outline

1. Dark Matter – what is needed and possible
2. νMSM – production during thermal evolution
   - The model content
   - DM generation from active neutrinos
   - X-ray bounds
   - Structure formation
   - Experimental consequences
3. νMSM with DM primordial abundance
   - Model with inflaton
   - DM production in inflaton decays
4. Guage chared "sterile" neutrinos
   - Model assumptions
   - DM abundance constraints on $N_{2,3}$
   - Structure formation bounds
   - Consequences and examples
5. Conclusions

Dark Matter variants

Warm Dark Matter is an interesting opportunity



22% of the Universe is Dark and Matter

- Cold Dark Matter – non-relativistic already at decoupling $T_f \gtrsim M_X$
  - 🙂 most common candidate
  - ☹ normally predicts cuspy DM profiles, and a lot of Dwarf satellites
- Hot Dark Matter – relativistic up to radiation to matter dominance transition $M_X \lesssim 1$ eV
  - ☹ Destroys small scale structure – contradicts observations
- Warm Dark Matter – relativistic at decoupling, non-relativistic at radiation to matter dominance transition
  - Intermediate – is ok for $M_X \gtrsim 1$ keV
  - reduces small scale structure
    - 🙂 smoother profiles
    - 🙂 less Dwarf Satellites

Sterile neutrino is a nice candidate for WDM

Sterile neutrino

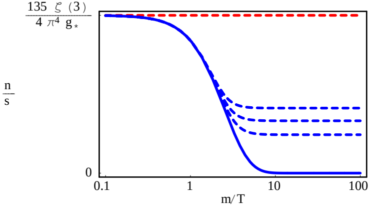
- may be rather light (and long living)
- interacts very weakly
- is present in most extensions of the SM

Note: this is not the only possibility, there are more, eg.

- light gravitino
- heavy particles with very non-thermal spectrum (hevy sterile neutrino produced in particle decays)
- …

DM abundance

“Usual” thermal case



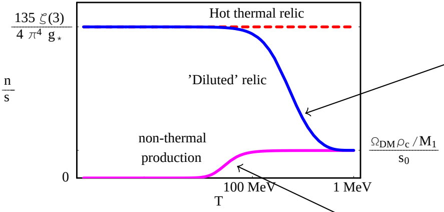
$$\frac{\Omega}{\Omega_{\mathrm{DM}}} \simeq \left(\frac{10}{g_{*\mathrm{f}}}\right)\left(\frac{M}{10\,\mathrm{eV}}\right)$$

Decoupled relativistic } HDM

$\Omega \sim \Omega_{\mathrm{DM}}$

Decoupled nonrelativistic } CDM ($M \gg$ MeV)

How to get keV mass?

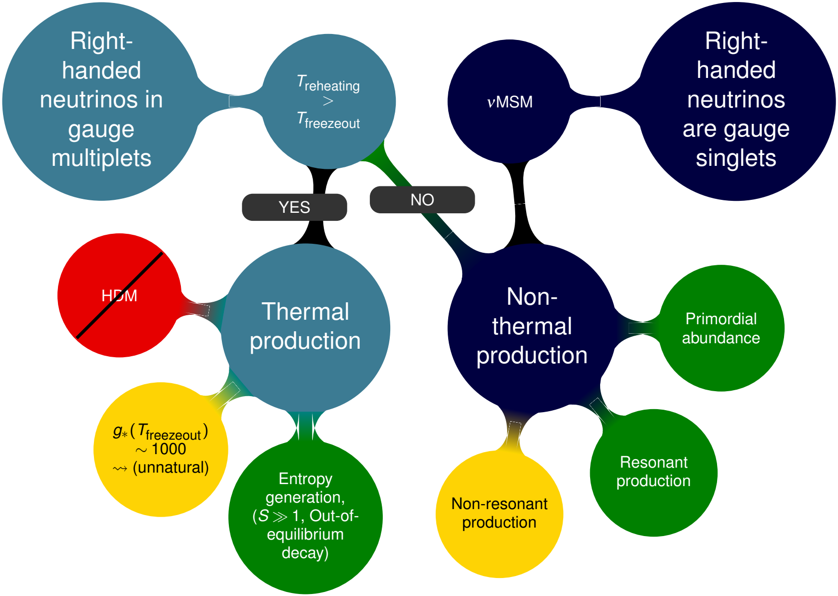


Diluted after decoupling (entropy generated by other particle decay)

$\Omega \sim \Omega_{\mathrm{DM}}$

Never entered thermal equilibrium

Possible scenarios



Summary of useful constraints

- Production of proper DM abundance
- Decay constraints – small enough radiative decay width (X-ray observations)
- Structure formation constraints – cold enough to leave observed small scale structure intact

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Situation 1

DM Sterile neutrinos never enter the thermal equilibrium and are initially absent

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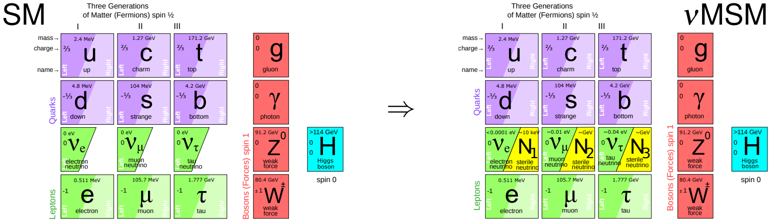
νMSM composition



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

Role of right ("sterile") neutrinos

- N_1 – Warm Dark Matter
  - Mass $M_1 \sim \text{keV}$
  - Lifetime $\tau_1 > \tau_{\text{Universe}} \sim 10^{17}$ s
- $N_{2,3}$ – Give mass to active neutrinos and generate baryon (and lepton) asymmetry
  - Mass $M_{2,3} > 100$ MeV – GeV
  - Lifetime $\tau_{2,3} \lesssim 0.1$ s

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 ($c \sim b$)

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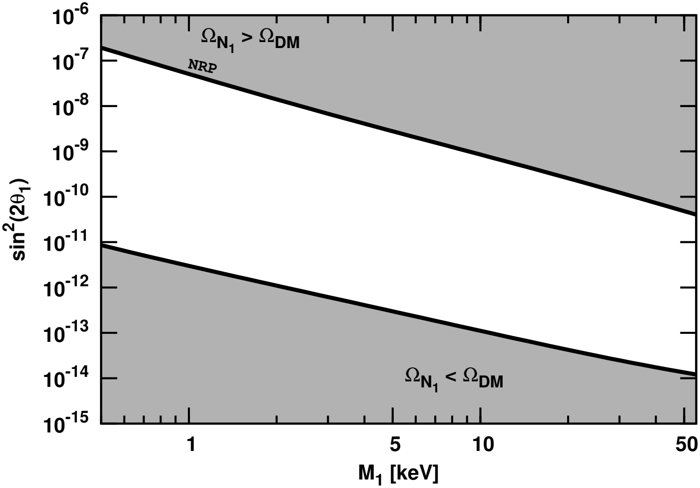
Astrophysical constraints

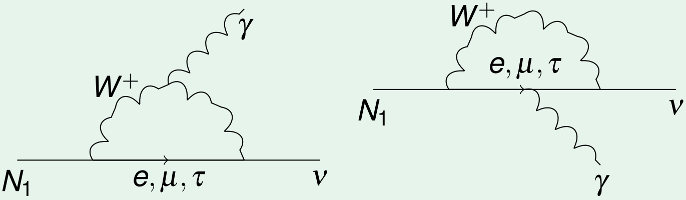
Pure νMSM case



Radiative decay

leads to constraints from the X-ray observations

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

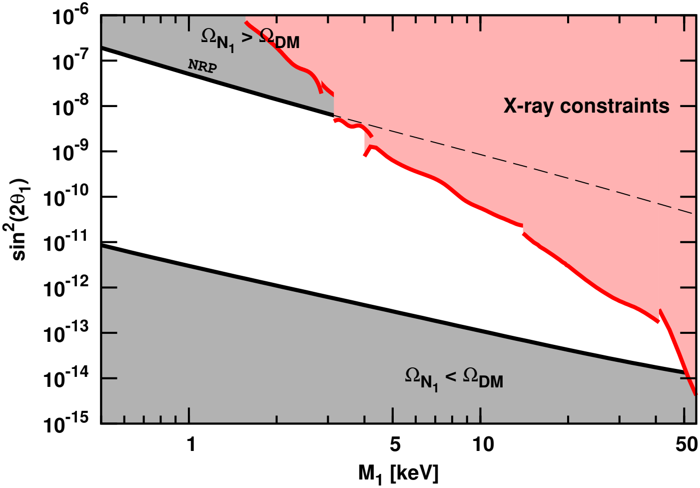


$$\Gamma \simeq 5.5 \times 10^{-27} \left(\frac{\theta_1^2}{10^{-5}}\right) \left(\frac{M_1}{1\text{keV}}\right)^5 \text{s}^{-1}$$

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

Astrophysical constraints

Pure νMSM case



Light sterile neutrino DM

F. Bezrukov

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Bounds from the observed structure formation

Small masses are forbidden

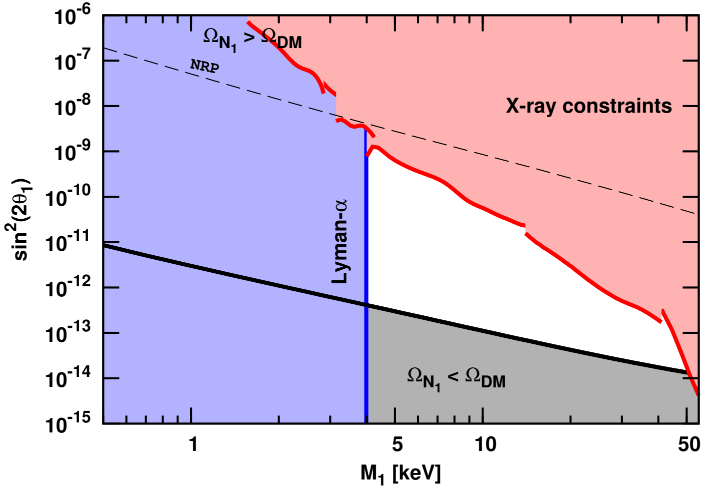
- Light sterile neutrino being relativistic after decoupling provides a cut off in the structure formation at smaller (sub-Mpc) scales.
- Presence of this cut off can be searched by the analysis of the Lyman-α absorption line of the intergallactic hydrogen.
- It bounds the velocity distribution, which depends on the primordial phase-space distribution

$$f(p) \sim \frac{\theta_M^2(p)}{\exp(p/T_\nu)+1}$$

  - For Non Resonant production – $m > 8$keV.
  - For Resonant production – bound is weaker, because the velocity distribution has a peak at lower momenta

[Boyarsky, Lessgourgues, Ruchayskiy, Viel'08]

Astrophysical constraints
Pure νMSM case



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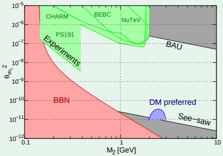
νMSM experimental consequences

DM sterile neutrino N_1, $M_1 \sim$ 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]

Lepton asymmetry generating $N_{2,3}$: $M_{2,3} \sim$ GeV, ΔM very small

- Neutrino production in hadron decays: kinematics
  - Missing energy in K decays
  - Peaks in momentum for two body decays
- Neutrino decays into SM particles
  - Beam target experiments



[Gorbunov, Shaposhnikov'07]

Situation 2

DM Sterile neutrinos never enter the thermal equilibrium and are present at the begining of the thermal evoluiton

Light inflaton model adds one scalar particle to the SM

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

Standard Model — Interaction — Inflationary sector

(where $\beta \simeq \beta_0 = 1.5 \times 10^{-13}$ – inflationary requirement) The Higgs-inflaton scalar potential is

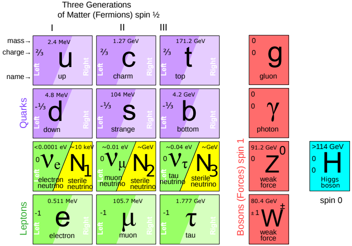
$$V(H,X) = \lambda \left(H^\dagger H - \frac{\alpha}{\lambda} X^2 \right)^2 + \frac{\beta}{4} X^4 - \frac{1}{2}\mu^2 X^2 + V_0$$

Inflaton mass window (from Cosmology – reheating and radiative corrections to inflation)

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

[Anisimov, Bartocci, FB'09, FB, Gorbunov'10]

Dark matter – add νMSM and stir

Light inflaton + 

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

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  - Lifetime $\tau_1 > \tau_{\text{Universe}} \sim 10^{17}$ s
- $N_{2,3}$ – Give mass to active neutrinos and generate (just) baryon asymmetry
  - Mass $M_{2,3} > 100$ MeV – GeV
  - Lifetime $\tau_{2,3} \lesssim 0.1$ s

DM production now happens from inflaton decays

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

m_χ – inflaton mass

DM neutrino mass bound from production mechanism

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

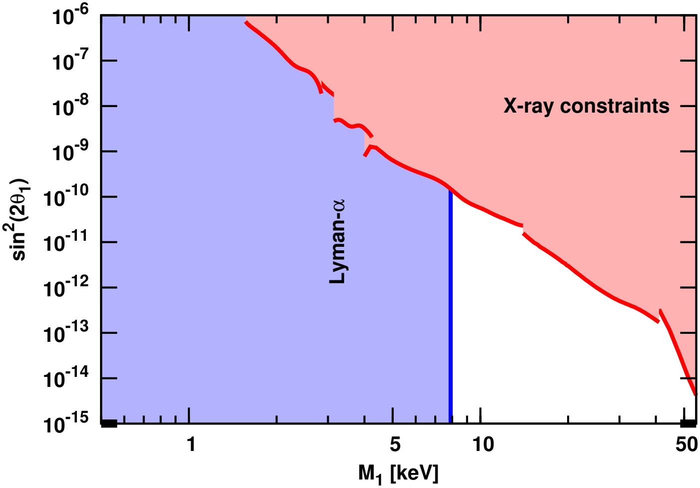
- Distribution is similar to that of the non-resonant production (just a bit cooler)

DM neutrino mass bound from Lyman-α

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

Astrophysical constraints

νMSM with inflaton decay into DM



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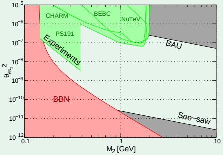


Inflaton search

Rare B decays [FB, Gorbunov'10]

Situation 3

DM Sterile neutrinos enter thermal equilibrium and their abundance is diluted later on

Model (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 (not GUT)

For concreteness – Left-Right symmetric model with gauge group $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Role of right ("sterile") neutrinos

- N_1 – Warm Dark Matter
  - Mass $M_1 \sim$ keV
  - Lifetime $\tau_1 > \tau_{\text{Universe}} \sim 10^{17}$ s
- $N_{2,3}$ – dilute entropy after DM decoupling
  - Mass $M_{2,3} >$ GeV
  - Lifetime $\tau_{2,3} \lesssim 0.1$ s

DM (sterile neutrino) freezeout and abundance

Temperature of freezeout

$$T_f \sim g_{*f}^{1/6} \left(\frac{M}{M_W}\right)^{4/3} (1 \div 2)\ \text{MeV}$$

Abundance of N_1 at present time

$$\frac{\Omega_N}{\Omega_{DM}} \simeq \frac{1}{S}\left(\frac{10.75}{g_{*f}}\right)\left(\frac{M_1}{1\text{keV}}\right) \times 100$$

Thus, required entropy generation factor is

$$S \simeq 100 \left(\frac{10.75}{g_{*f}}\right)\left(\frac{M_1}{1\text{keV}}\right)$$

Entropy generation by out-of equilibrium decay

If a heavy particle (eg. sterile neutrino N_3)

- drops out of thermal equilibrium while relativistic

$$T_\mathrm{f} > M_2$$

  - this bounds gauge scale from below (cross-section is defined by M)

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

- lives long, so that it becomes non-relativistic and dominates Universe expansion during its decay

Then entropy is generated (i.e. $\frac{s_\mathrm{after}}{s_\mathrm{before}} = S \frac{a^3_\mathrm{before}}{a^3_\mathrm{after}}$)

$$S \simeq 0.76 \frac{\bar{g}_*^{1/4} M_2}{g_* \sqrt{\Gamma_2 M_\mathrm{Pl}}}$$

This fixes the decay width Γ_2

BBN bound

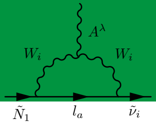
Non DM sterile neutrinos $N_{2,3}$ should decay before BBN

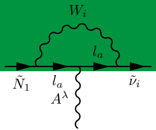
$$\tau \lesssim 0.1 \div 2 \text{ s}$$

This means, that proper entropy can be generated only for (or the required lifetime will be too long)

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

X-ray observations





- Second main N_1 decay mode is two particle radiative decay:

$$\Gamma_{N_1\to\nu\gamma} \simeq 5.5\times 10^{-22}\theta_1^2\left(\frac{M_1}{1\text{keV}}\right)^5 \text{s}^{-1}$$

  - Leads to an X-ray line with $E = M_1/2$ which is emitted from the Dark Matter objects
  - Experiments (XMM-Newton, Chandra, INTEGRAL, etc.) give

$$\Gamma_{N_1\to\gamma\nu} \lesssim 9.9\times 10^{-27}\ \text{s}^{-1} \quad \text{or} \quad \theta_1^2 \lesssim 1.8\times 10^{-5}\left(\frac{1\text{keV}}{M_1}\right)^5$$

Dolgov, Hansen'00; Abazajian, Fuller, Tucker'01; Boyarsky, Ruchaysky, Shaposhnikov'06; etc.

- Additional contribution from W_R–W_L mixing ζ

$$\Gamma_{N_1\to\gamma\nu} \simeq 1.1\times 10^{-8}\zeta^2 \frac{\sum\limits_{a=e,\mu,\tau}|m_{l_a}(V_R)_{a1}|^2}{m_{l_a}^2}\left(\frac{M_1}{\text{keV}}\right)^3 \text{s}^{-1}$$

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*

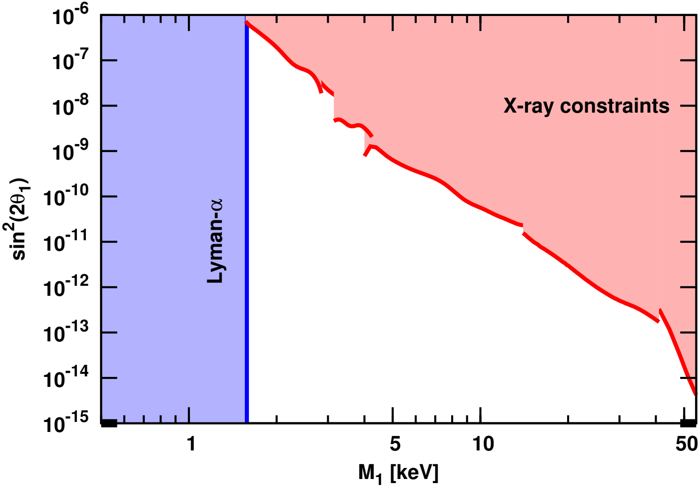
Ly-α bound – structure formation

[Boyarsky, Lessgourgues, Ruchayskiy, Viel'08, Seljak etal'06]

$$M_1 > 1.6 \text{ keV}$$

Astrophysical constraints

Sterile neutrino in beyond SM gauge multiplets



Constraints summary

X/γ-ray

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

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

Ly-α bound

$$M_1 > 1.6\text{keV}$$

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

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

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

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

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

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

Active neutrino masses are given by type I see-saw

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2}\left(\ \overline{\nu^c_{aL}}, \overline{N_{aR}}\ \right)\begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_{aL} \\ N^c_{aR} \end{pmatrix}$$

Light neutrino masses and mixings

$$m^\nu = -(M^D)^T \frac{1}{M_I} M^D \qquad \theta_I^2 = \sum_{\alpha=e,\mu,\tau} \frac{M^D_{I\alpha}(M^D)^\dagger_{\alpha I}}{M_I^2} \ll 1$$

$$M_1\theta_1^2 + M_2\theta_2^2 \geq m_2 \geq \Delta m_{\text{sol}}$$

S generation:	$M_2\theta_2^2$	$\lesssim 1.8\times 10^{-3}\bar{g}_*^{1/2}\left(\frac{\text{GeV}}{M_2}\right)^2\left(\frac{\text{keV}}{M_1}\right)^2$
X-ray bound:	$M_1\theta_1^2$	$\lesssim 2.7\times 10^{-3}\left(\frac{1.6\ \text{keV}}{M_1}\right)^4$
Δm_{solar}:	$\sqrt{\Delta m^2_{\text{sol}}}$	$= 8.7\times 10^{-3}$ eV

Impossible!

Working example with type II see-saw

Exactly LR-symmetric model:

$$\mathscr{L}_{\text{mass}} = -\frac{1}{2}\left(\;\overline{\nu^c_{aL}}, \overline{N_{aR}}\;\right)\begin{pmatrix} f\,v_L & y\,v \\ y\,v & f\,v_R \end{pmatrix}\begin{pmatrix} \nu_{aL} \\ N^c_{aR} \end{pmatrix}$$

$$m_\nu = v_L f - \frac{v^2}{v_R} y f^{-1} y\;, \qquad M_I = f_I v_R$$

$$m_1 = 5.2\times 10^{-9}\text{ eV}$$

$$m_2 = 8.7\times 10^{-3}\text{ eV} \quad m_3 = 4.9\times 10^{-2}\text{ eV}$$

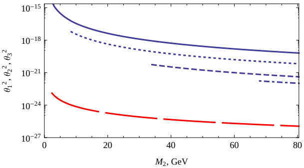
$$M_1 = 1.6\text{keV}$$

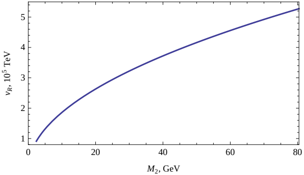
$$M_2 = 2.7\text{ GeV} \qquad M_3 = 15.1\text{ GeV}$$

$$\theta_1^2 = \theta_2^2 = \theta_3^2 = 2.3\times 10^{-15}$$

$$v_R = 9.67\times 10^4\text{ TeV} \quad v_L = 313\text{ keV}$$

$$y = 0.027 f$$





Conclusions

- One can generate sterile neutrino DM by
  - Out of thermal equilibrium – νMSM
  - Primordialy – νMSM+inflaton decays
  - In thermal equilibrium with entropy dilution – gauge charged sterile neutrinos
- All models require strong hierarchies in the sterile neutrino sector
- Most important bounds on the model goes from
  - DM abundance
  - X-ray from raiative decays
  - Structure formation

T. Asaka, M. Shaposhnikov, Phys. Lett. B **620** (2005) 17

T. Asaka, S. Blanchet, M. Shaposhnikov, Phys. Lett. B **631** (2005) 151

D. Gorbunov, A. Khmelnitsky and V. Rubakov,
JCAP **0810**, 041 (2008), [arXiv:0808.3910 [hep-ph]].

A. Boyarsky, O. Ruchayskiy and D. Iakubovskyi,
arXiv:0808.3902 [hep-ph].

A. Boyarsky, J. Lesgourgues, O. Ruchayskiy and M. Viel,
arXiv:0812.0010 [astro-ph].

U. Seljak, A. Makarov, P. McDonald and H. Trac,
Phys. Rev. Lett. **97**, 191303 (2006), [astro-ph/0602430].

A. Anisimov, Y. Bartocci, F. L. Bezrukov, Phys. Lett. B **671**, 211 (2009)

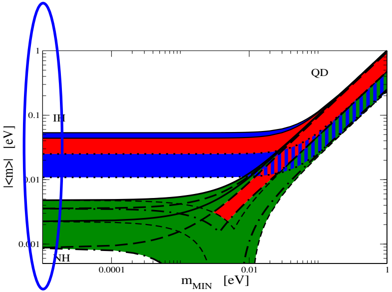
FB, D. Gorbunov, JHEP **05** (2010) 010

D. Gorbunov, M. Shaposhnikov, JHEP **0710** (2007) 015

F. L. Bezrukov, Phys. Rev. **D72** (2005) 071303

$0\nu\beta\beta$ 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

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

[FB'05]

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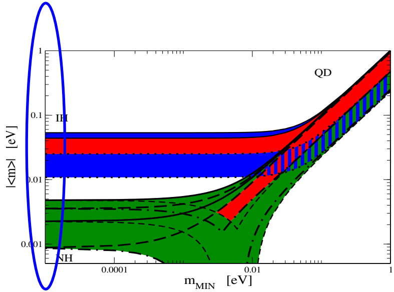

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