

keV sterile neutrino Dark Matter in gauge extensions of the Standard Model

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Outline

- 1 Dark Matter – what is needed and possible
- 2 Constraints on gauged models with keV sterile (right) neutrinos
 - Mass bounds
 - Generation of entropy
 - X-ray observations
- 3 Consequences and examples
 - Type I see-saw
 - Type II see-saw
- 4 Conclusions



Dark Matter

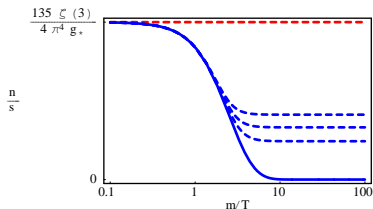
$\Omega_{DM} \simeq 0.22$ of the Universe is

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 $M_X \lesssim 1 \text{ eV}$
 - 😞 Destroys small scale structure – contradicts observations
- Warm Dark Matter – relativistic at decoupling, non-relativistic at radiation to matter dominance transition
 - ▶ Intermediate – is ok for $M_X \gtrsim 1 \text{ keV}$
 - ▶ reduces small scale structure
 - 😊 smoother profiles
 - 😊 less Dwarf Satellites

DM abundance

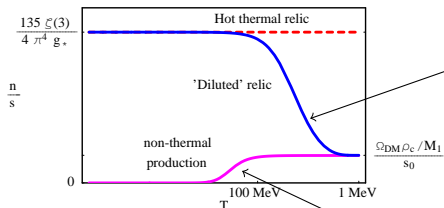
“Usual”
thermal
case



$$\left. \begin{aligned} \frac{\Omega}{\Omega_{\text{DM}}} &\simeq \left(\frac{10}{g_{*f}} \right) \left(\frac{M}{10\text{eV}} \right) \\ \text{Decoupled relativistic} \end{aligned} \right\} \text{HDM}$$

$$\left. \begin{aligned} \Omega &\sim \Omega_{\text{DM}} \\ \text{Decoupled} \\ \text{nonrelativistic} \end{aligned} \right\} \text{CDM} \quad (M \gg \text{MeV})$$

How to get keV mass?

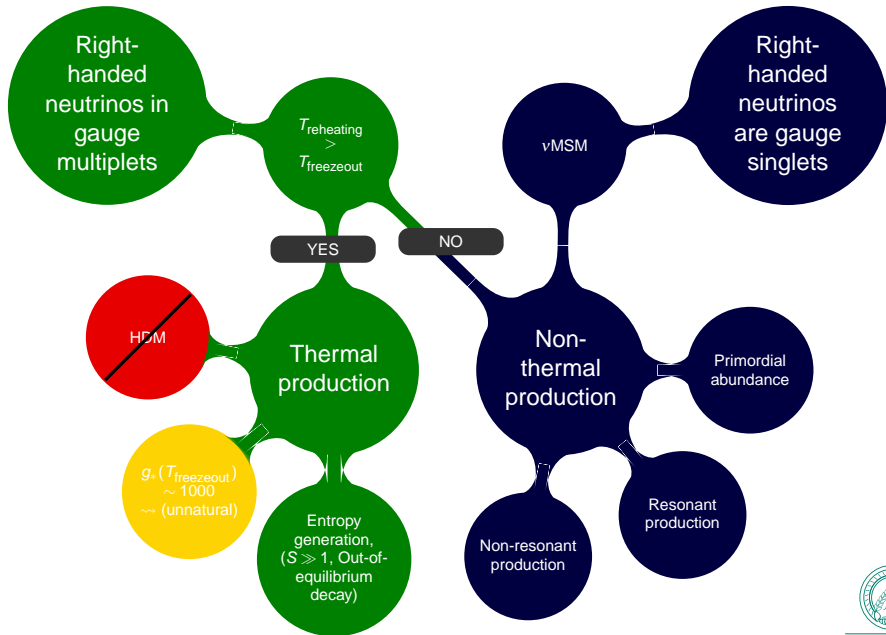


Diluted after decoupling
(entropy generated by other
particle decay)

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

Never entered thermal equilibrium





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

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

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

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

Thus, required entropy generation factor is

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



DM mass bounds (from observed DM structure)

Phase space density bound [Gorbunov etal'08, Boyarsky etal'08]

$$M_1 > 1-2 \text{ keV}$$

Ly- α bound – structure formation

[Boyarsky etal'08, Seljak etal'06]

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

(Note – this corresponds to *thermal relic* case in the language of Ly- α papers, not sterile neutrino case)



Entropy generation by out-of equilibrium decay

If a heavy particle (eg. sterile neutrino N_3)

- drops out of thermal equilibrium while relativistic

$$T_f > M_2$$

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

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

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

Then entropy is generated (i.e. $\frac{S_{\text{after}}}{S_{\text{before}}} = S \frac{a_{\text{before}}^3}{a_{\text{after}}^3}$)

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

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:

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

- ▶ 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

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

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

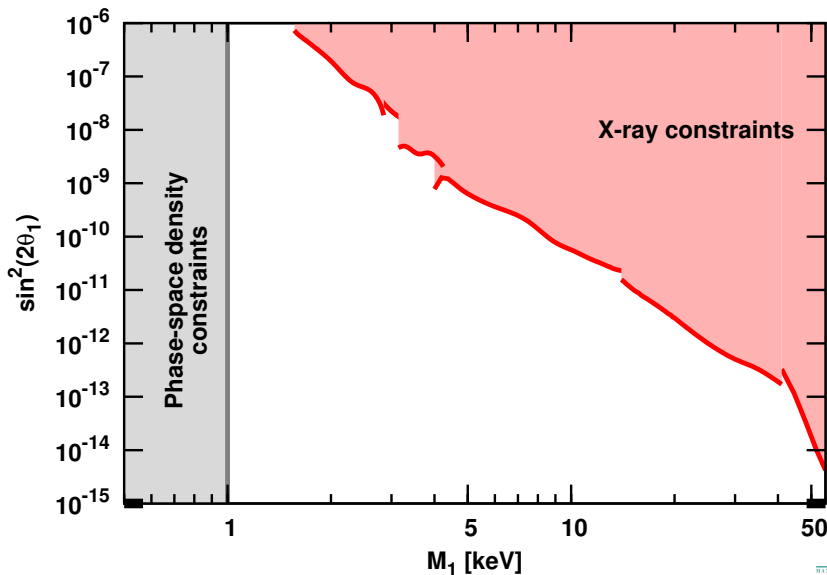
- Additional contribution from W_R - W_L mixing ζ

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

- ▶ No mixing allowed: $\zeta^2 \lesssim 10^{-18} \dots (\text{keV}/M_1)^3$



Astrophysical constraints



Constraints summary

X/ γ -ray

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

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

Ly- α bound

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

The right abundance of the sterile neutrino N_1 is achieved 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

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

Light neutrino masses and mixings

$$m^\nu = -(M^D)^T \frac{1}{M_I} M^D \quad \theta_I^2 = \sum_{\alpha=e,\mu,\tau} \frac{M_{I\alpha}^D (M^D)_{\alpha I}^\dagger}{M_I^2} \ll 1$$

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

Entropy 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: $M_1 \theta_1^2 \lesssim 2.7 \times 10^{-3} \left(\frac{1.6 \text{ keV}}{M_1} \right)^4$

Solar mass difference: $\sqrt{\Delta m_{\text{sol}}^2} = 8.7 \times 10^{-3} \text{ eV}$

Impossible!



Working example with type II see-saw

Exactly LR-symmetric model:

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2} \left(\overline{\nu_{aL}^c}, \overline{N_{aR}} \right) \begin{pmatrix} f \nu_L & y \nu \\ y \nu & f \nu_R \end{pmatrix} \begin{pmatrix} \nu_{aL} \\ N_{aR}^c \end{pmatrix}$$

$$m_\nu = \nu_L f - \frac{\nu^2}{\nu_R} y f^{-1} y, \quad M_I = f_I \nu_R$$

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

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

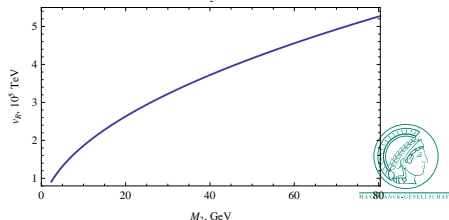
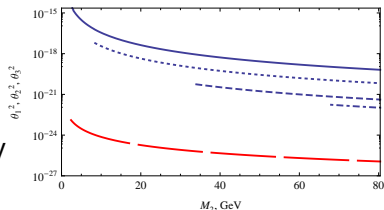
$$M_1 = 1.6 \text{ keV}$$

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

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

$$\nu_R = 9.67 \times 10^4 \text{ TeV} \quad \nu_L = 313 \text{ keV}$$

$$y = 0.027f$$







Conclusions

- keV scale sterile neutrino can be a good WDM candidate
- If they are charged under some extended gauge group, the model is *very* constrained
 - ▶ small mixings for keV neutrino from X-ray constraints
 - ▶ small mixings for other sterile neutrinos from entropy generation (DM abundance)
 - ▶ mass scales bounded from BBN

“Checklist” for viability of such models is formulated.

- This excludes a lot of models, and can leave out only very specific realisations
Search for good ones!



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