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

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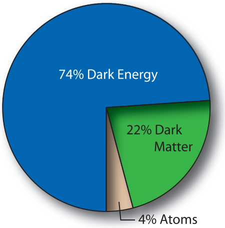
Outline

Dark Matter



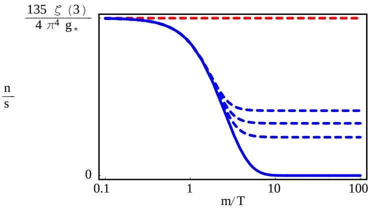
$\Omega_{DM} \simeq 0.22$ of the Universe is Dark and Matter

- 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 $M_X \lesssim 1$ 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

DM abundance

"Usual" thermal case



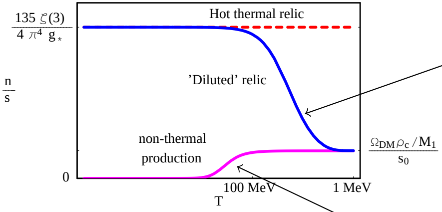
$$\frac{\Omega}{\Omega_{DM}} \simeq \left(\frac{10}{g_{*f}}\right)\left(\frac{M}{10\,\text{eV}}\right)$$

Decoupled relativistic } HDM

$\Omega \sim \Omega_{DM}$

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

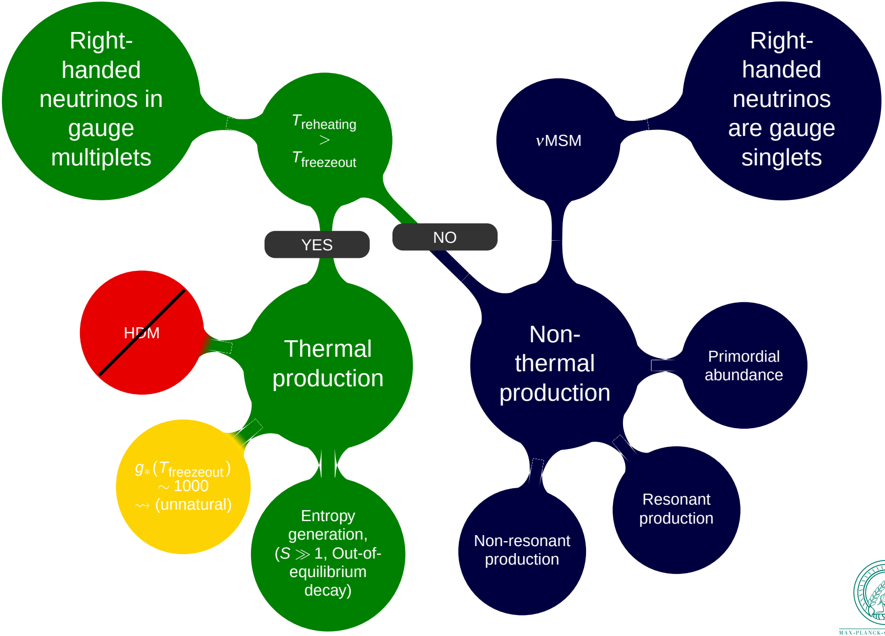
How to get keV mass?



Diluted after decoupling (entropy generated by other particle decay)

$\Omega \sim \Omega_{DM}$

Never entered thermal equilibrium


Right-handed neutrinos in gauge multiplets
$T_{\text{reheating}} > T_{\text{freezeout}}$
YES
NO
νMSM
Right-handed neutrinos are gauge singlets
HDM
Thermal production
Non-thermal production
Primordial abundance
$g_*(T_{\text{freezeout}}) \sim 1000$ ⇝ (unnatural)
Entropy generation, ($S \gg 1$, Out-of-equilibrium decay)
Non-resonant production
Resonant production

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

DM (sterile neutrino) freezeout and abundance

Temperature of freezeout

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

Abundance of N_1 at present time

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

Thus, required entropy generation factor is

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

DM mass bounds (from observed DM structure)

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

$$M_1 > 1\text{–}2\ \text{keV}$$

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, note 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

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

  - this bounds gauge scale from below

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

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

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

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

This fixes the decay width Γ_2

BBN bound

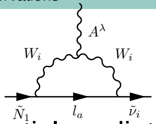
Non DM sterile neutrinos $N_{2,3}$ should decay before BBN

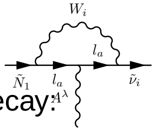
$$\tau \lesssim 0.1 \div 2 \text{ s}$$

Together with the fixed lifetime this leads to the mass bound

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

X-ray observations





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

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

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

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

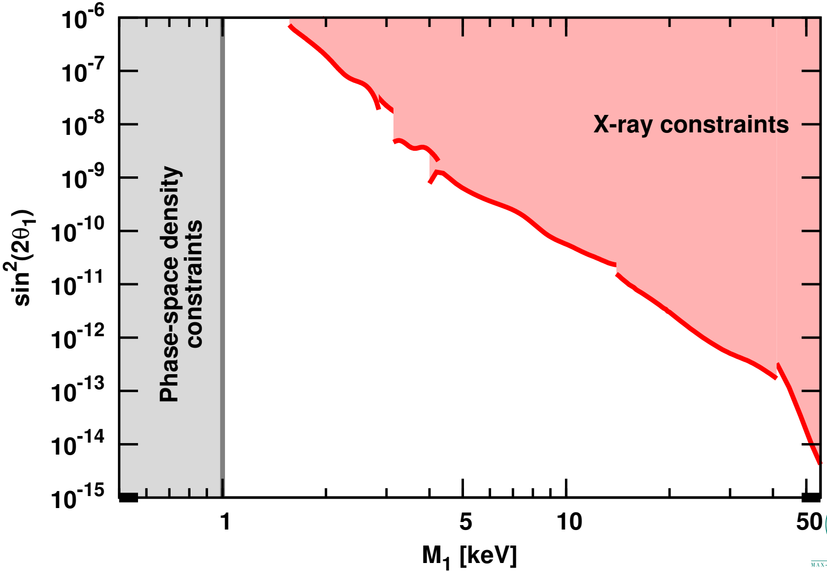
Dolgov, Hansen'00; Abazajian, Fuller, Tucker'01; Boyarsky, Ruchaysky, Shaposhnikov'06; etc.

- Additional contribution from W_R–W_L mixing ζ

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

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

Astrophysical constraints



Constraints summary

X/γ-ray

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

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

Ly-α bound

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

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 right abundance of the sterile neutrino N_1 is achieved if

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

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

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

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

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:	$\sqrt{\Delta m^2_{\text{sol}}}$	$= 8.7\times 10^{-3}$ eV

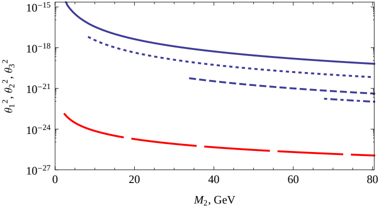
Impossible!

Working example with type II see-saw

Exactly LR-symmetric model:

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

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



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

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

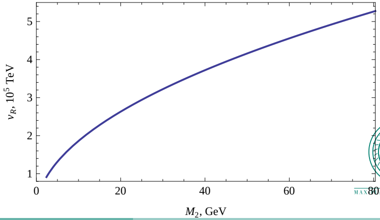
$M_1 = 1.6$keV

$M_2 = 2.7$ GeV $\qquad M_3 = 15.1$ GeV

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

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

$y = 0.027 f$



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!

MAX-PLANCK-GESELLSCHAFT

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