Neutrinos and Dark Matter

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➔ **F. Bezrukov, H. Hettmannsperger, ML, arxiv:0912.4415, PRD81,085032**

NEUTRINO OSCILLATION WORKSHOP

NOW 2010

Neutrino Oscillation Workshop

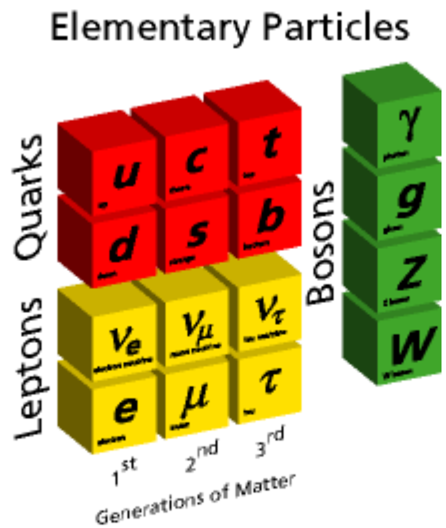
Conca Specchiulla (Otranto, Lecce, Italy)

Sept. 4-11, 2010

DM and Extensions of the Standard Model

SM = Success of renormalizable gauge field theories in d=4

QED	➔ QCD	➔ SM
$U(1)_{em}$	$SU(3)_C$	$SU(3)_C \times SU(2)_L \times U(1)_Y$



➔ **symmetry, renormalizability, no anomalies**

➔ **particle content (symmtery representations):**

- gauge sector – fixed by gauge group
- scalar sector – must break EW symmetry, $SB \sim 2_L$
- fermions – anomaly free combinations (least understood sector!!!)

➔ **different levels of SM extension…**

- add SM representations: scalars, fermions
- extend the gauge symmetry
- add supersymmetry
- extend/modify basic concepts: quantum fields, nature of space-time, ...

increasing level of speculation S:

1) new fields
2) follow gauge route
3) new concepts
4) wild speculation

Physics Beyond the Standard Model

Theoretical arguments:

SM does not exist without cutoff (triviality)
Higgs-doublett = only simplest extension
Gauge hierarchy problem
Gauge coupling unification
Charge quantization
Strong CP problem
Unification with gravity
Why: 3 generations , which representations
Many parameters (9+? masses, 4+? mixings)

Experimental facts:

- Electro weak scale << Planck scale
- Gauge couplings close to unification
- Neutrinos have masses & large mixings
- Dark Matter
- Dark Energy
- Baryon asymetry of the Universe
- Few $\geq 2\sigma$ deviations: g-2, ... ???

• a framework that solves all problems…

→ seems not (yet) to exist

… solve some problems:

→ pick your favourite problem
→ implications for other topics

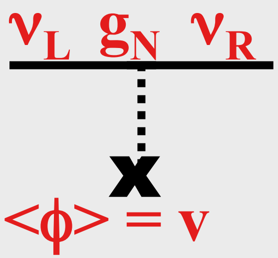
Gauge hierarchy:
→ e.g. SUSY (S=3)
→ Dark Matter, neutrinos, …

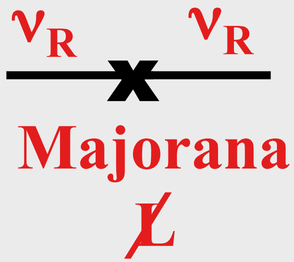
Strong CP problem: → Axions …

Neutrino masses and mixings:
→ extra fields / gauge groups (S=1.5)
→ Dark Matter, … ???

Adding Neutrino Mass Terms (S=1)

Simplest possibility: add 3 right handed neutrino fields





➔ $$\left(\bar{\nu}_L \quad \bar{\nu}_R^{\mathbf{c}}\right)\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \nu_L^{\mathbf{c}} \\ \nu_R \end{pmatrix}$$

New ingredients: 1) Majorana masses (2nd explicit scale) 2) L violation (global symmetry)

A natural consequence of the simplest, most suggestive and straight forward way to accommodate neutrino masses:

see-saw ➔ light active neutrinos and heavy sterile neutrinos

active ➔ naturally light ←➔ observed neutrinos
sterile ➔ masses $O(M_R)$ and mixings $O(m_D/M_R)$ → tiny!

➔ right handed neutrinos probably exist
➔ if viable, ν's are obvious, natural and most conservative DM candidates!

Could Neutrinos be Dark Matter?

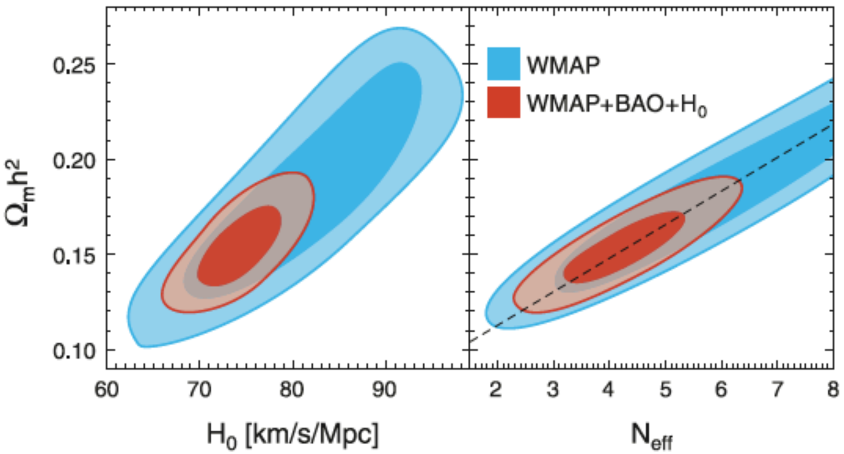
- **Active neutrinos would be Hot Dark Matter** → ruled out:
  - **- destroys small scale structure**
  - **- required neutrino masses much too small → maybe HDM component**

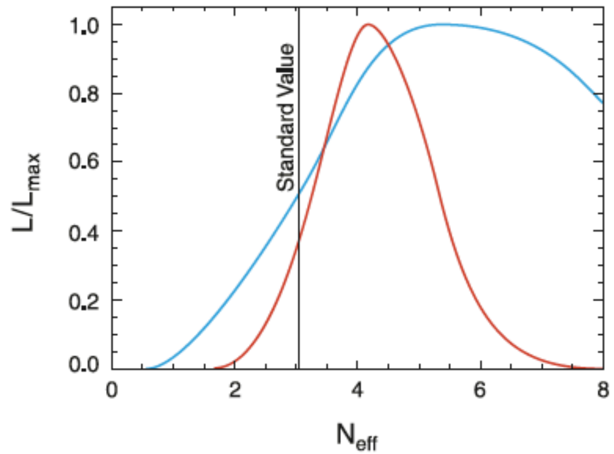
- **keV sterile neutrinos: Warm Dark Matter** → workes nicley:
  → relativistic at decoupling
  → non-relativistic at radiation to matter dominance transition
  - **OK for $M_X \simeq$ few keV**
  - **reduced small scale structure → smoother profile , less dwarf satellites**

- **Astronomy**
  -observations hint that a keV sterile particle may exist
  → right-handed neutrino
  Biermann, Kusenko & Segre, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …

More Indications for light DM Particle

CMB & cosmology:

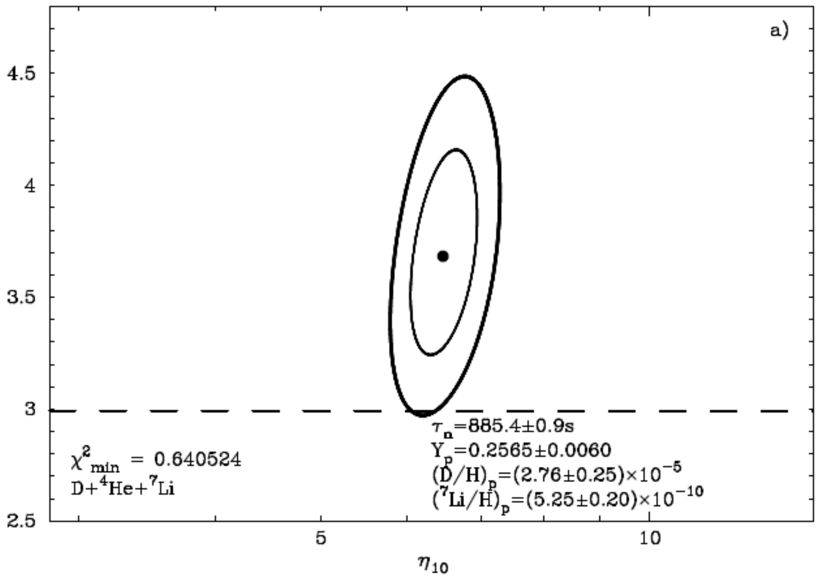




E. Komatsu et al. (2010)

BBN – 'feels' extra light particles:

N_ν



$N_\nu \simeq 3.7 \pm 1$

E. Aver, K. Olive, E. Skillman (2010)
Y. Izotov, T. Thuan(2010)

The νMSM

Asaka, Blanchet, Shaposhnikov, 2005 Asaka, Shaposhnikov, 2005

Particle content:

- Gauge fields of $SU(3)_c$ x $SU(2)_W$ x $U(1)_Y$: **γ, $W_\pm$, Z, g**
- Higgs doublet: **Φ=(1,2,1)**
- Matter

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{em}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	3	2	+1/3	$\begin{pmatrix} +2/3 \\ -1/3 \end{pmatrix}$
u_R	3	1	+4/3	+2/3
d_R	3	1	-2/3	-1/3
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	1	2	-1	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
e_R	1	1	-2	-1
N	1	1	0	0

x3 generations

➔ lepton sector more symmetric to the quark sector
➔ Majorana masses for N
➔ choose for one sterile ν ~keV mass ➔ exceeds lifetime of Universe

Abundance in the νMSM and in Alternatives

- **Virtue and problem of νMSM:**
  - scenario with sterile ν and tiny mixing ➔ never enters thermal equilibrium
  ➔ requires non-thermal production from other particles (avoid over-closure)
  ➔ new physics before the beginning of the thermal evolution sets abundance

- **Alternative scenario** **Bezrukov, Hettmannsperger, ML:**
  - sterile ν could be a non-singlet under some gauge extension
  ➔ extra scale between M_W and M_{Pl} : LR symmetry, …
  ➔ very simple possibility to get correct abundance
  - sterile ν is diluted after it drops out of thermal equilibrium
  ➔ long-lived particle decay out of TE after DM sterile ν freeze-out
  ➔ obvious candidate: one of the other (heavier) sterile neutrinos!
  ➔ very efficient reduction of amount of DM sterile neutrinos

➔ everything follows nicely from sterile neutrinos

Assumptions for the Alternative Scenario

- **Three right-handed neutrinos N_1 , N_2 , N_3**
- **Dirac and Majorana mass terms**
- **Charged under some (BSM) gauge group; gauge boson mass M**
- **Specific LR example:** $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Roles played by the sterile (~right-handed) 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

Sterile Neutrino DM Freeze-Out & Abundance

Decoupling of N_1 in early Universe: sterile neutrino DM is light
→ freezout while relativistic → calculation like for active neutrinos
+ suppression of annihilation x-section by M

Freeze-out temperature:

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

Abundance of N_1 today:

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

Required entropy generation factor:

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

Entropy Generation by out-of Equilibrium Decay

Heavy particle (here: N_3) dropping out of thermal equilibrium while relativistic $T_f > M_2$: ➔ **bounds gauge scale from below**

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

➔ **long lived** ➔ **becomes non-relativistic**

➔ **dominates expansion of Universe during its decay**

➔ **entropy generation factor** ➔

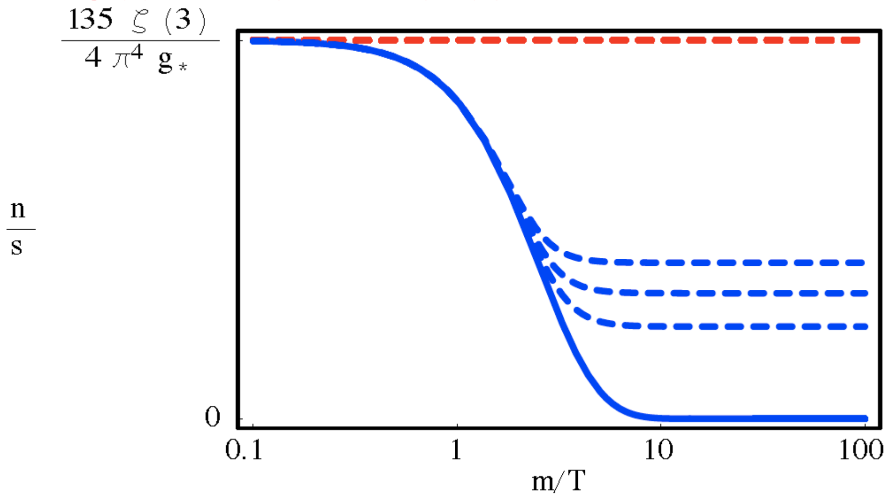
$$\frac{S_{\text{after}}}{S_{\text{before}}} = S \frac{a^3_{\text{before}}}{a^3_{\text{after}}}$$

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

➔ **fixes decay width Γ_2**

Obtaining the right Abundance

Usual thermal case:



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

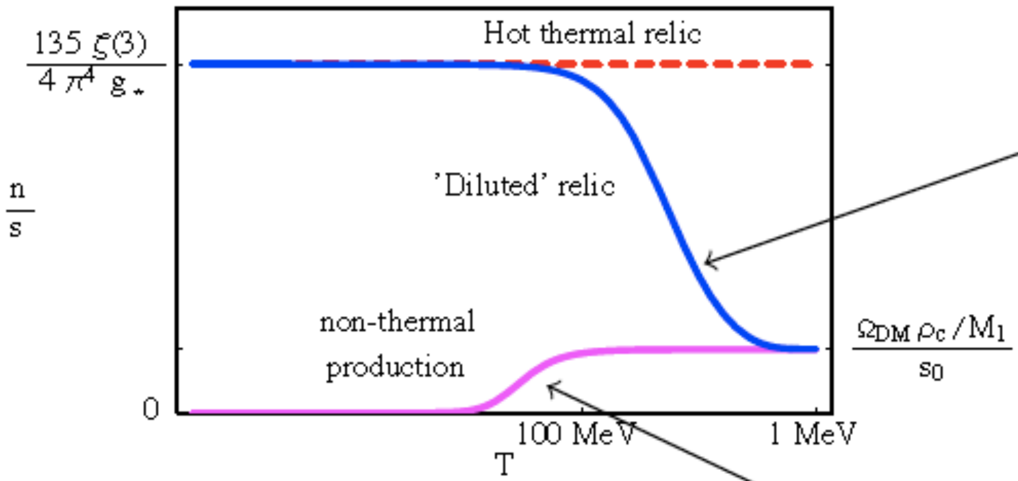
Decoupled relativistic

CDM: (M>>MeV) $\Omega \sim \Omega_{DM}$

Decoupled

nonrelativistic

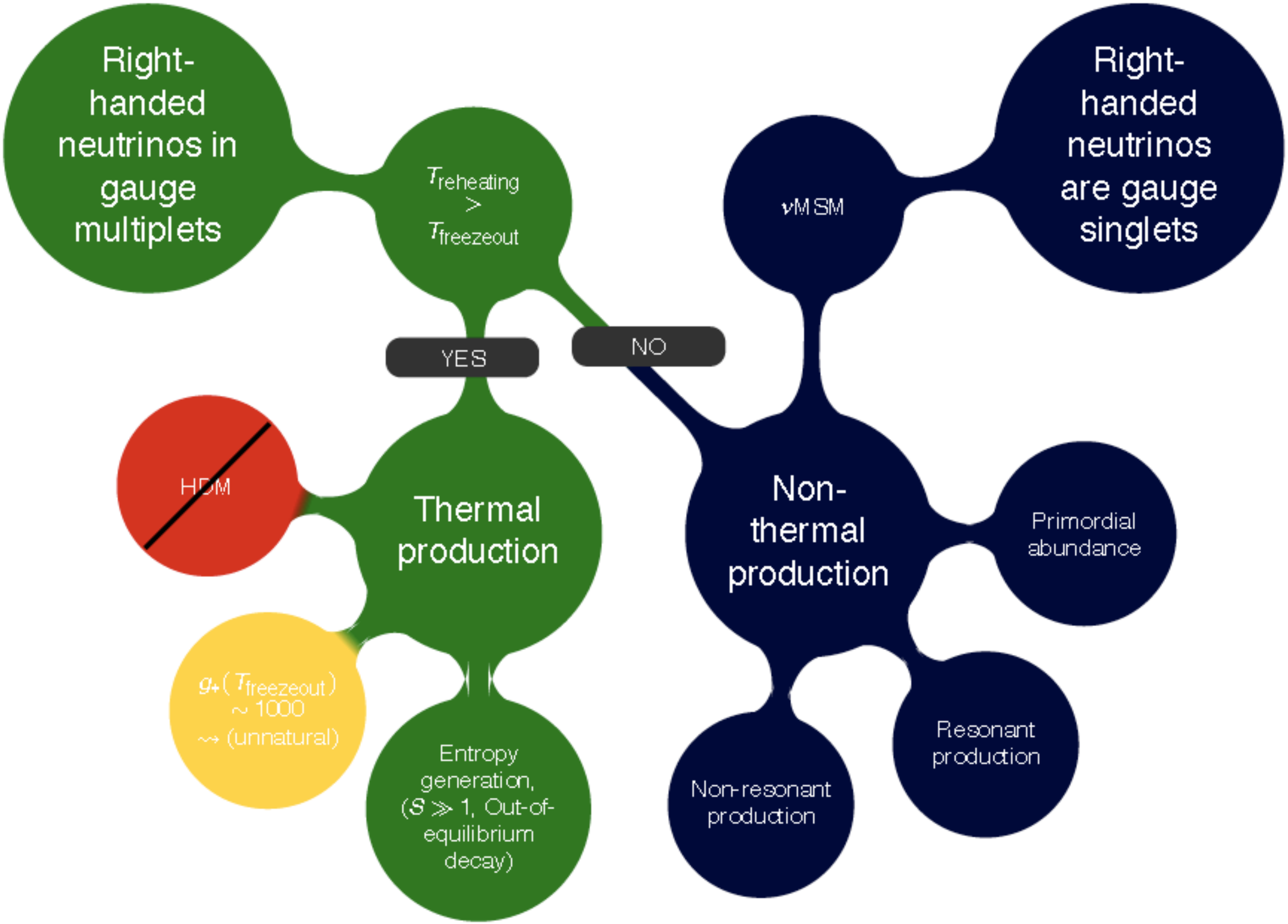
keV sterile neutrinos:



Diluted after decoupling (entropy generated by other particle decay)

$\Omega \sim \Omega_{DM}$

Never entered thermal equilibrium



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

Summary of Constraints

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

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

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 right abundance of the sterile neutrino N_1 is achieved if

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

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

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

Implications for See-Saw

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}(\overline{\tilde{\nu}^c_{aL}}, \overline{\tilde{N}_{aR}})\begin{pmatrix} M_L & m_D \\ m_D^T & M_R \end{pmatrix}\begin{pmatrix} \tilde{\nu}_{aL} \\ \tilde{N}^c_{aR} \end{pmatrix} + \text{H.c.}$$

- **Usual flavour (=tilde) to mass basis rotation**

$$\begin{pmatrix} \tilde{\nu}_{aL} \\ \tilde{N}^c_{aR} \end{pmatrix} \simeq \begin{pmatrix} 1 & (M_R^{-1} m_D^T)^\dagger \\ -M_R^{-1} m_D^T & 1 \end{pmatrix}\begin{pmatrix} U & 0 \\ 0 & V_R \end{pmatrix}\begin{pmatrix} \nu_{iL} \\ N^c_{IR} \end{pmatrix}$$

- **U = PMNS matrix, V_R = mixing in right-handed sector**

$$M_L - m_D M_R^{-1} m_D^T = U^\star \cdot \text{diag}(m_1, m_2, m_3) \cdot U^\dagger$$ **➔M_L = 0: Type-I**

$$M_R = V_R^\star \cdot \text{diag}(M_1, M_2, M_3) \cdot V_R^\dagger$$

- **Mixing angles between mass states, sterile neutrinos and flavour states:**

$$\theta_{aI} \equiv \frac{(m_D V_R)_{aI}}{M_I} \quad \textbf{and} \quad \theta_I^2 \equiv \sum_{a=e,\mu,\tau} |\theta_{aI}|^2$$

⇔ strength of interaction (decay) of sterile neutrinos

- **Current best fit values:**

$$\Delta m^2_{\rm sol} = (7.65^{+0.69}_{-0.6}) \times 10^{-5}\ {\rm eV}^2$$
$$\Delta m^2_{\rm atm} = (2.4^{+0.35}_{-0.33}) \times 10^{-3}\ {\rm eV}^2.$$

- **Casas-Ibarra parametrization for type-I and II** (Akhmedov, Rodejohann)

$$\theta_I^2 = \frac{[\sqrt{M_R} R^T m_\nu^{\rm diag} R^\star \sqrt{M_R}]_{II}}{M_I^2} \quad , \quad m_\nu^{\rm diag} = {\rm diag}(m_1, m_2, m_3)$$

- **assume (convention) $m_1 < m_2 < m_3$ ➔ we get for the first two sterile ν's**

$$\begin{aligned} M_1 \theta_1^2 &= m_3 |\sin\omega_{13}|^2 + m_2 |\cos\omega_{13}|^2 |\sin\omega_{12}|^2 \\ &\quad + m_1 |\cos\omega_{13}|^2 |\cos\omega_{12}|^2, \\ M_2 \theta_2^2 &= m_3 |\cos\omega_{13}|^2 |\sin\omega_{23}|^2 + m_2 |\cos\omega_{23} \cos\omega_{12} \\ &\quad - \sin\omega_{23} \sin\omega_{13} \sin\omega_{12}|^2 + m_1 |\cos\omega_{23} \sin\omega_{12} \\ &\quad + \sin\omega_{23} \sin\omega_{13} \cos\omega_{12}|^2. \end{aligned}$$

- **The relation |z-w| ≥ ||z| - |w|| leads then to the following inequalities:**

$$M_1\theta_1^2 \geq m_2\{\sin^2\omega_{13} + \cos^2\omega_{13}\sin^2\omega_{12}\},$$
$$M_2\theta_2^2 \geq m_2\{\cos^2\omega_{13}\sin^2\omega_{23} + (|\cos\omega_{23}||\cos\omega_{12}| - |\sin\omega_{23}||\sin\omega_{13}||\sin\omega_{12}|)^2\}.$$

- **The minimum of the sum on the *rhs* is m_2 ➔**

$$M_1\theta_1^2 + M_2\theta_2^2 \geq m_2 \geq \Delta m_{\rm sol} \quad (*)$$

In words: One cannot generate active ν masses with type-I see-saw without sufficient mixings between active and sterile neutrinos

➔ conflict with bounds:

Entropy generation: $M_2\theta_2^2 \lesssim 1.8\times 10^{-3}\bar{g}_*^{1/2}\left(\frac{\rm GeV}{M_2}\right)^2\left(\frac{\rm keV}{M_1}\right)^2$

X-ray bound: $M_1\theta_1^2 \lesssim 2.7\times 10^{-3}\left(\frac{1.6\ \rm keV}{M_1}\right)^4$

➔ violates bound (*) **➔ type-I see-saw impossible**

Working example with type II see-saw

Exactly LR-symmetric model:

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

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

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

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

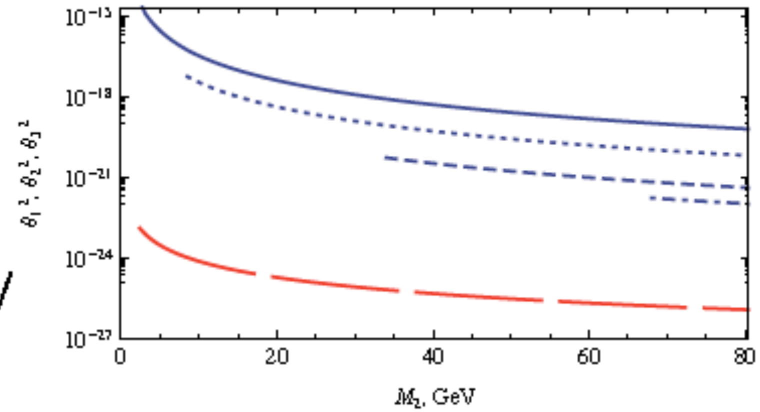
$$M_1 = 1.6\text{keV}$$

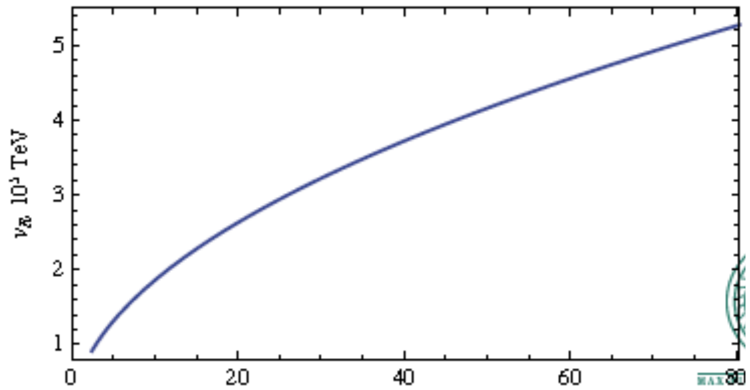
$$M_2 = 2.7\ \text{GeV} \qquad M_3 = 15.1\ \text{GeV}$$

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

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

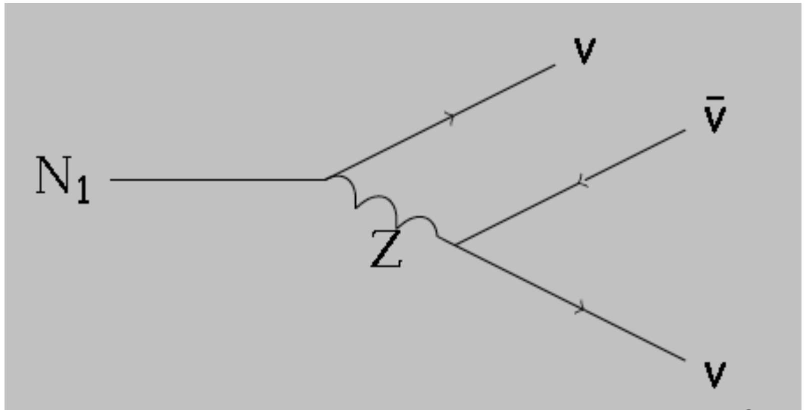
$$y = 0.027 f$$





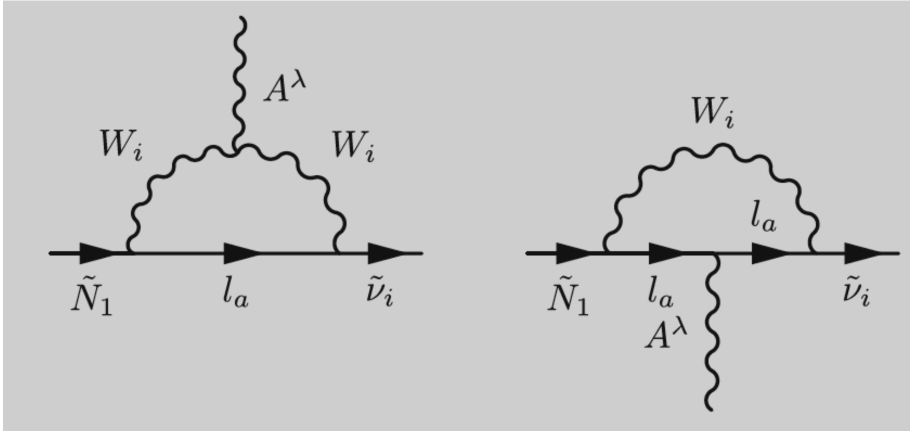
Observing keV-ish Neutrino DM

- LHC
  - sterile neutrino DM is not observable
  - WIMP-like particles still possible – but not DM
- direct searches
  - sterile neutrino DM is not observable
- astrophysics/cosmology → at some level: keV X-rays
  - sterile neutrino DM is decaying into active neutrinos
  - decay $N_1 \rightarrow \bar{\nu}\nu\nu$, $N_1 \rightarrow \bar{\nu}\bar{\nu}\nu$
  - not very constraining since $\tau >> \tau_{Universe}$



$$\tau = 5 \times 10^{23}\,\mathrm{sec} \left(\frac{M_1}{1\mathrm{keV}}\right)^{-5} \left(\frac{\theta_1^2}{10^{-5}}\right)^{-1}$$

- - radiative decays $N_1 \rightarrow \nu\gamma$



- so far: observations limit active-sterile mixing angle

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

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

- mixing tiny, but naturally expected to be tiny: O(scale ratio)

- **Other indirect effects of keV-ish sterile neutrino DM:**
  - pulsar kicks Kusenko, Segre, Fuller, Mocioiu, Pascoli
  - ...

Sumary & Conclusions

- **A keV-ish sterile neutrino is a very well motivated and good working Warm Dark Matter candidate ⇔ finite ν-masses**

- **Simplest realization: νMSM ➔ requires non-thermal production**

- **Alternative: Sterile ν's which are charged under some extended gauge group ➔ interesting constrains**
  - small mixings for keV neutrino from X-ray constraints
  - small mixings for other sterile neutrinos from entropy generation (DM abundance)
  - masses bound by BBN

➔ Implications for neutrino mass generation:

- type-I see-saw not possible
- type-II works ⇔ very natural in gauge extensions
- requires one sterile neutrino to be light

  ➔ flavour symmetries **ML, Merle, Niro to appear very soon**