Neutrinos and Dark Matter

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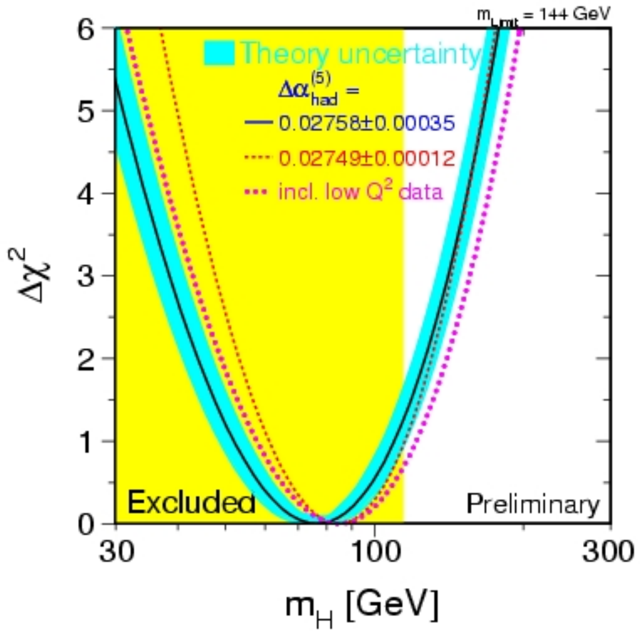
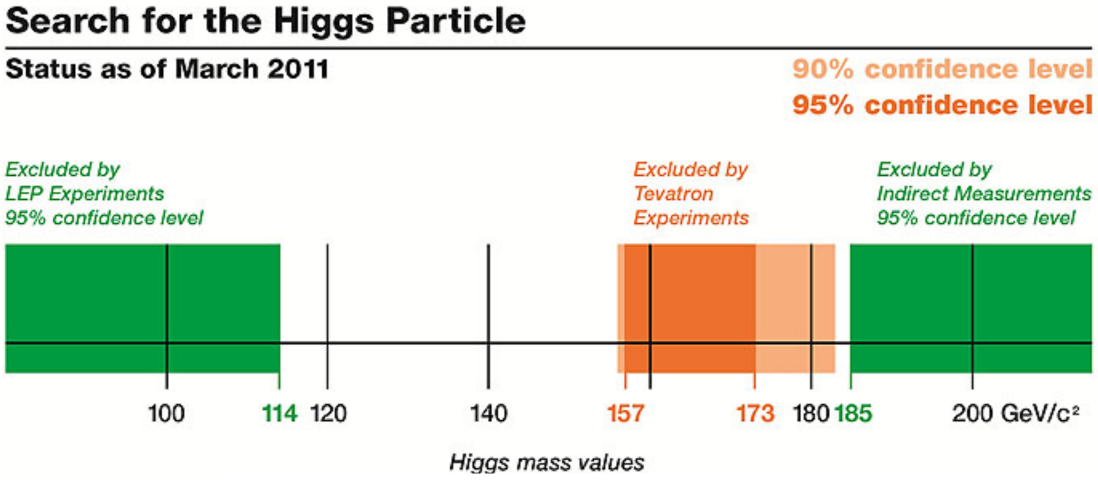
SM works perfect & Higgs Mass Range is converging

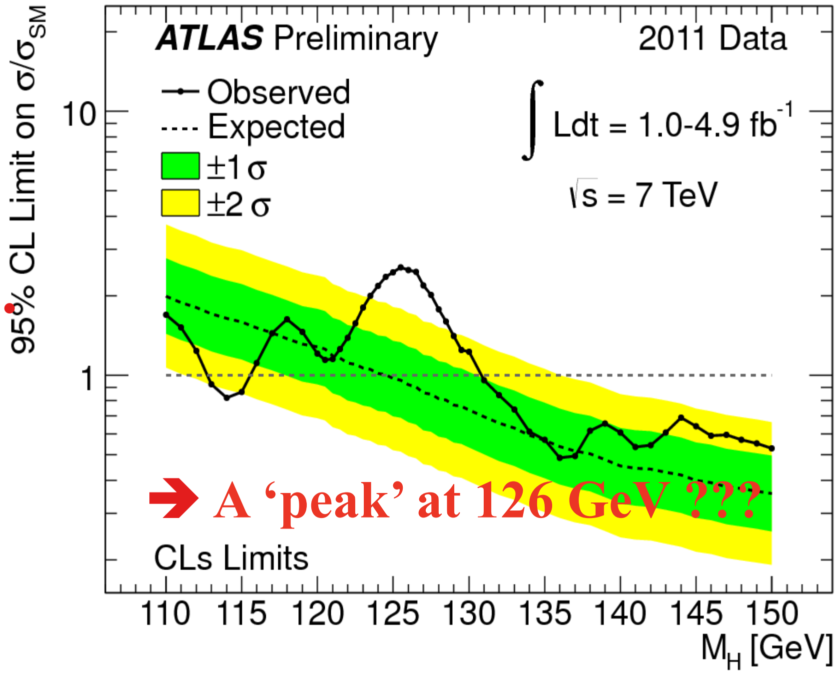




- allowed mass range is shrinking…
- if SM Higgs exists → light
- no (clear) signs for anything else

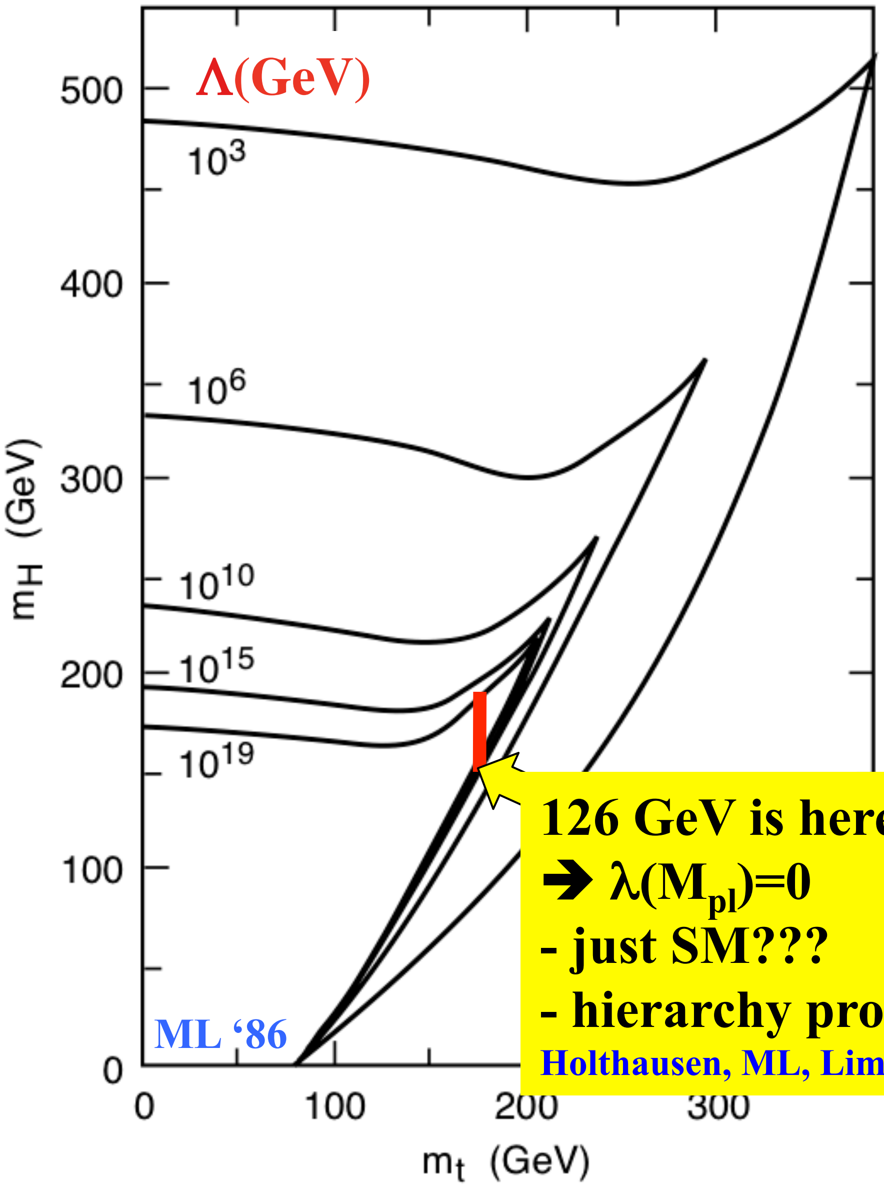
→ just the SM?

→ Dark Matter?



→ A 'peak' at 126 GeV ???

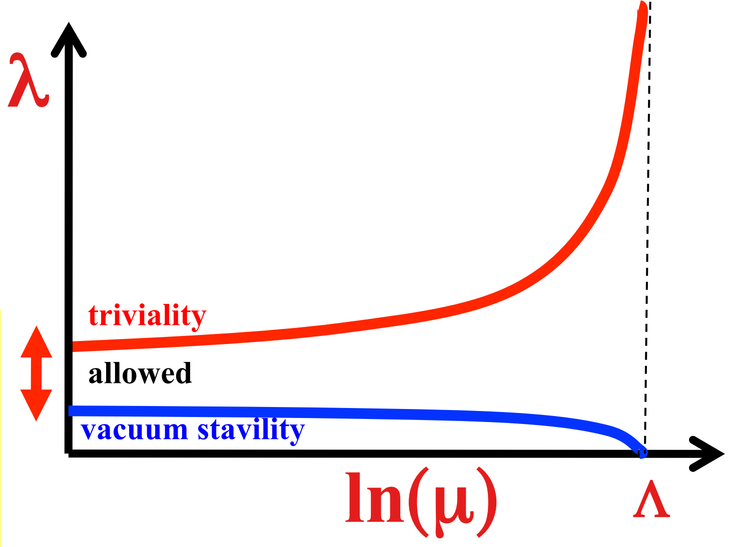
Triviality and Vacuum Stability



126 GeV is here!
➔ $\lambda(M_{pl})=0$
- just SM???
- hierarchy problem
Holthausen, ML, Lim

$126\ \text{GeV} < m_H < 174\ \text{GeV}$

SM does not exist w/o embedding
- U(1) copling , Higgs self-coupling



➔ RGE arguments seem to work
➔ we need some embedding

The SM must be extended….

- **Hierarchy problem**
  - separation of two scalar scales is unstable… SUSY, TeV physics
  - Planck scale physics: New concepts … ???
- **SM cannot explain Baryon Asymmetry of the Universe (BAU)**
  - massive neutrinos require SM extension ➔ SM+

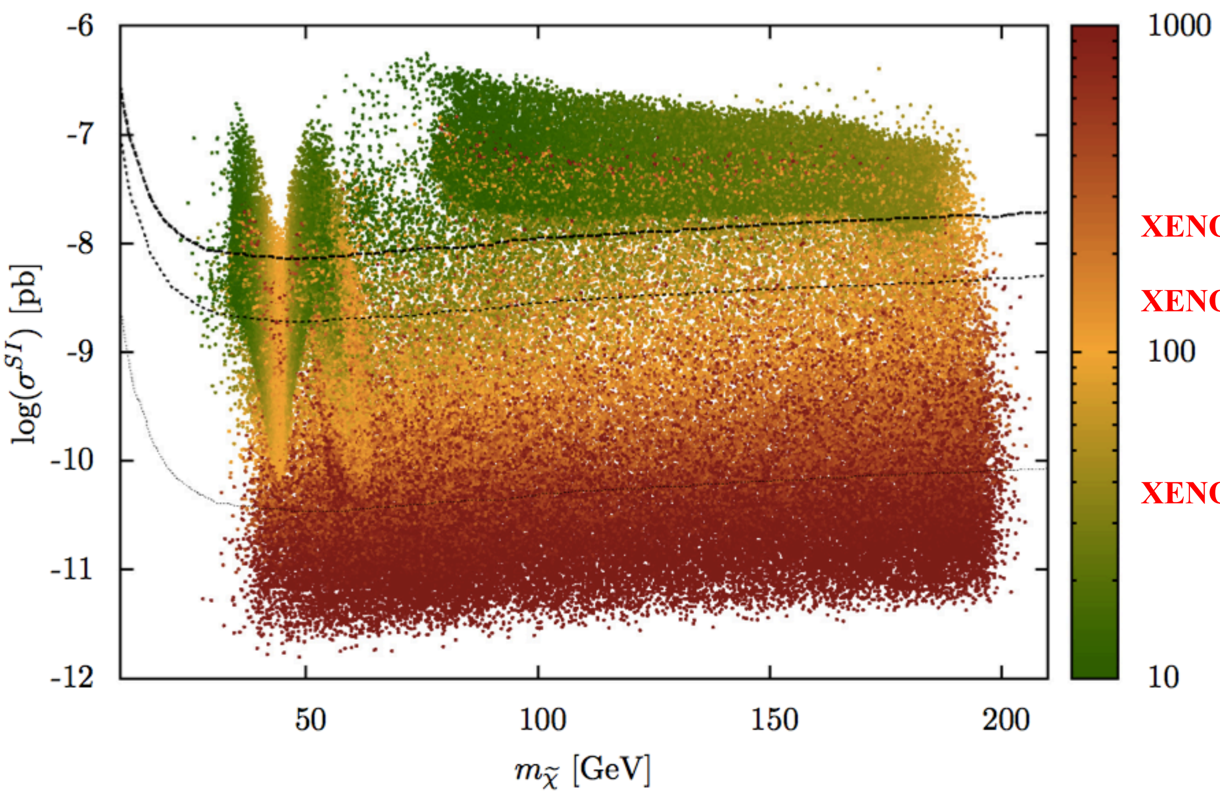
  ➔ leptogenesis = one of the best BAU explanations

  ➔ nothing else needed!
- **Dark Matter**
  - an extra particle is needed which is DM
  - particles connected to the hierarchy problem

Most favoured Dark Matter: WIMPs

- **Candidates in BSM models ←→ hierarchy problem**
- **WIMP miracle → correct abundance**
- **Direct searches ←→ neutralino & fine-tuning → Δ_{tot}**

$$\Delta p_i \equiv \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right|$$



XENON100-2010

XENON100-2012 ???

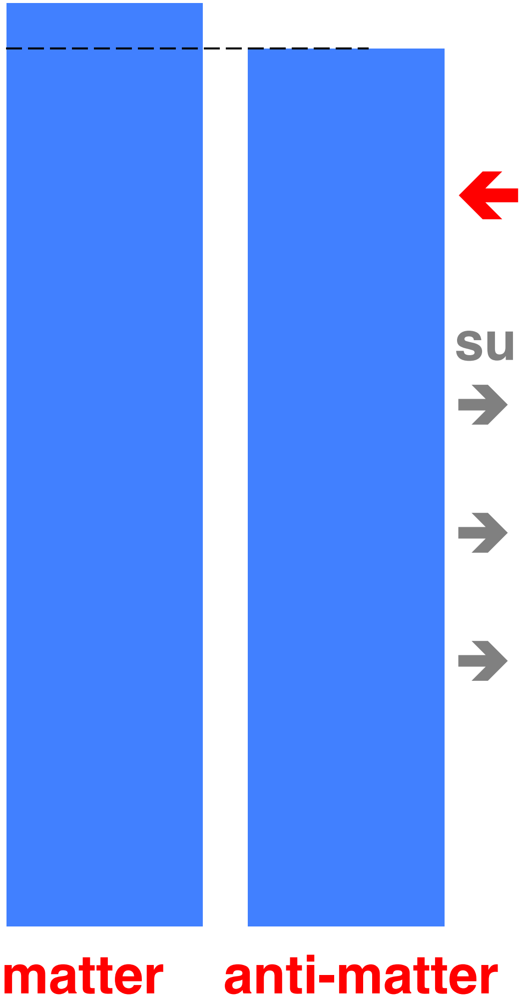
XENON1T

$$\Delta_{\rm tot} \equiv \sqrt{\sum_{p_i=\mu^2,b,m_{H_u}^2,m_{H_d}^2} \{\Delta p_i\}^2}$$

P. Grothaus, ML, Y. Takanishsi - to appear very soon

Other Ideas: Asymmetric Dark Matter

➔Why is $\Omega_{DM} \simeq 5 * \Omega_{baryonic}$? (a factor 5 or 500?)



🡐 SM x hidden sector ➔

suitably suppressed coupling
➔ heavy scale which is integrated out, but connects B, L
➔ links amount of DM to amount of matter
➔ various realizations = DM particles & sigantures

Could Neutrinos be Dark Matter?

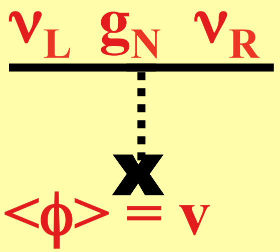
- Massive neutrinos required by experiment
  ➔ some new physics to explain masses
- Neutrino masses ←→ BAU: leptogenesis
- Could neutrinos also be Dark Matter?
  ➔ sterile neutrinos are a perfect
  Warm Dark Matter Candidate

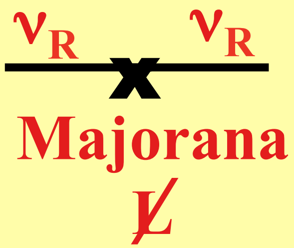
New Physics: Neutrino Mass Terms

Mass terms ~ m$\bar{L}$R = (2,1)

➔ Simplest possibility:
add 3 right handed neutrino fields

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$L_Q = \begin{pmatrix} l_u \\ l_d \end{pmatrix}$	3	2	1/3
r_u	3	1	4/3
r_d	3	1	-2/3
$L_L = \begin{pmatrix} l_\nu \\ l_e \end{pmatrix}$	1	2	-1
r_ν ???	1	1	0
r_e	1	1	-2





➔

$$\begin{pmatrix} \overline{\nu}_L & \overline{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

like quarks and charged leptons ➔ Dirac mass terms (including NMS mixing)

New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

6x6 block mass matrix
block diagonalization
M_R heavy ➔ 3 light ν's

NEW ingredients, 9 parameters ➔ SM+ and sea-saw

Evidences for Light Sterile Neutrinos

Particle Physics:

Reactor anomaly, LSND, MiniBooNE, MINOS, Gallex…

➔ evidences for light sterile ν's?

➔ New and better data / experiments are needed to clarify the situation

➔ maybe something exciting around the corner?

➔ but eV scale and sizable mixings

CMB: extra eV-ish neutrinos J. Hamann et al. , …

BBN: extra ν's possible: $N_\nu \simeq 3.7 \pm 1$

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

Astrophysics:

Effects of keV-ish sterile ν's on pulsar kicks, PN star kicks, …

Kusenko, Segre, Mocioiu, Pascoli, Fuller et al., Biermann & Kusenko, Stasielak et al., Loewenstein et al., Dodelson, Widrow, Dolgov, …

Most likely not all of them are correct! ➔ consequences?

Sterile Neutrino Spectrum

<u>The standard picture:</u>

3 heavy sterile neutrinos typ. $\geq 10^{13}$ GeV

➔ leptogenesis, role in GUTs, …

Some mechanism which makes
1 or 2 heavy sterile neutrinos light?
➔ keV sterile neutrino
➔ tiny heavy-light mixing expected
$\theta^2 < O(m_\nu/m_s)$

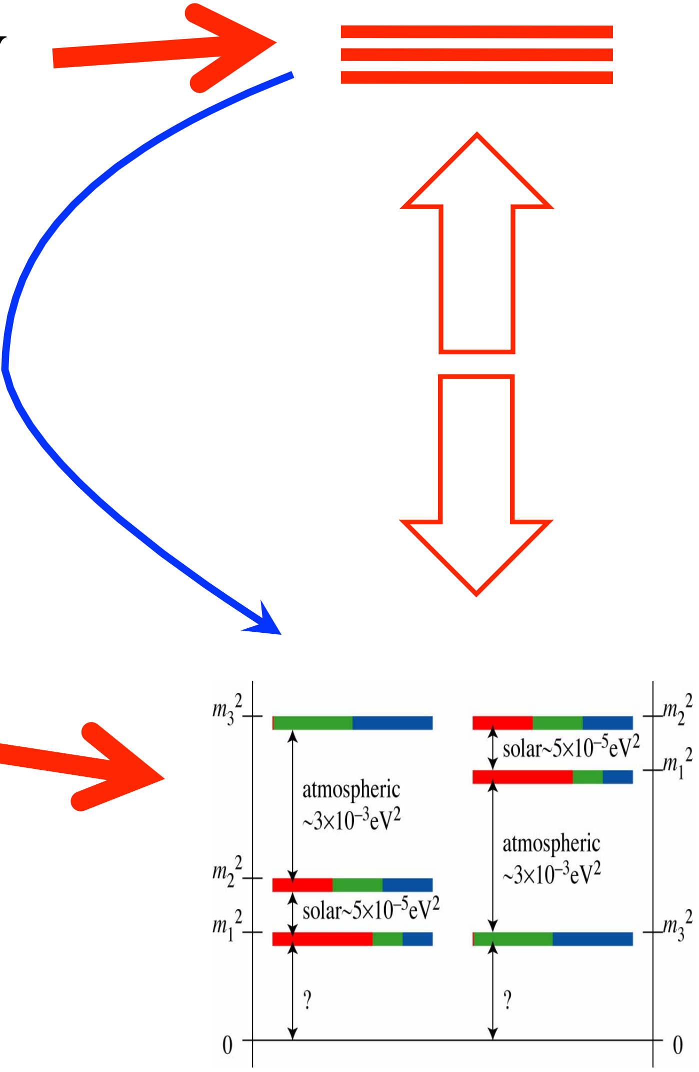
3 light active neutrinos

➔ this cold easily be wrong

- more than 3 N_R states, …

- M_R may have special eigenvalues, …

➔ light sterile neutrinos ?!



Could Neutrinos be Dark Matter?

- **Active neutrinos would be perfect Hot Dark Matter** ➔ ruled out:
  - **destroys small scale structures in cosmological evolution**
  - **measured neutrino masses too small → maybe HDM component**

- **keV sterile neutrinos: Warm Dark Matter** ➔ workes very well:
  - ➔ relativistic at decoupling
  - ➔ non-relativistic at radiation to matter dominance transition
  - **OK for $M_X \simeq$ few keV with very tiny mixing**
  - **reduced small scale structure ➔ smoother profile, less dwarf satellites**
  - **➔ scenario where one sterile neutrino is keV-ish, the others heavy**
  - **➔ tiny active – sterile mixings $O(m_\nu/M_R)$**

⇔ observational hints from astronomy

- **hints that a keV sterile particle may exist ➔ right-handed neutrino?**

Note: Right-handed neutrinos exist probably anyway – just make one light!

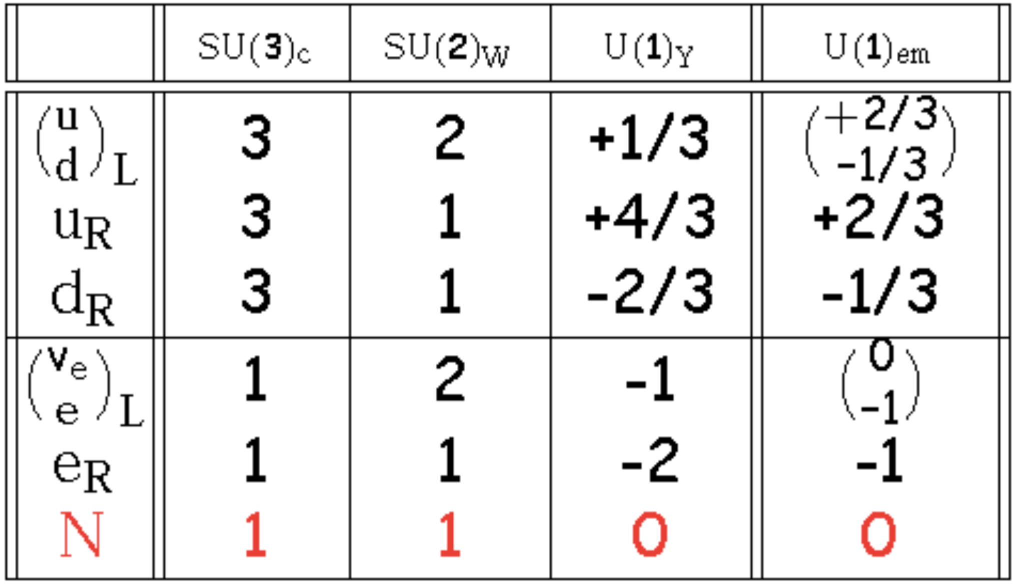
keV Neutrinos as WDM

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

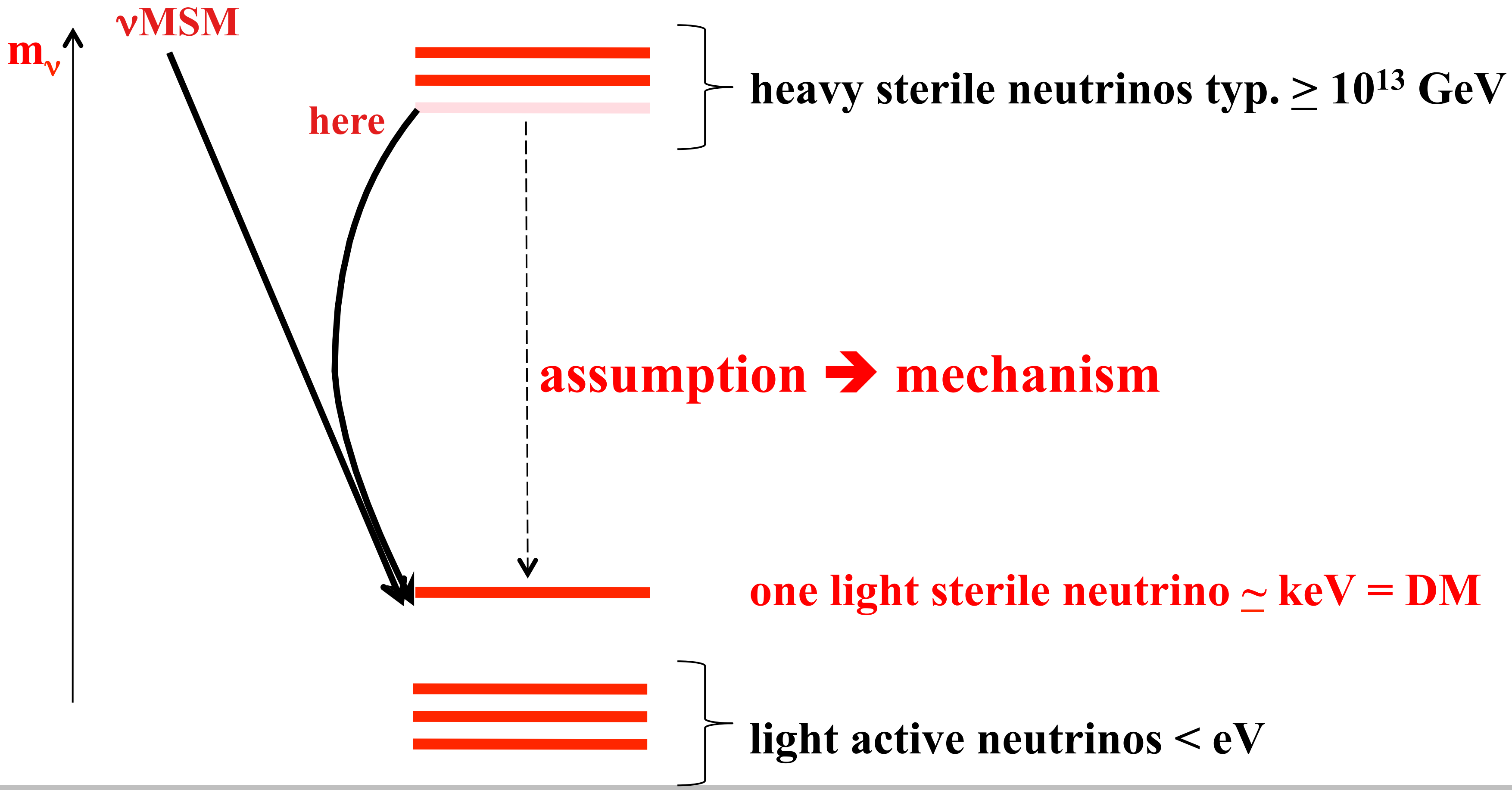
➔ lepton sector more symmetric to the quark sector

➔ Majorana masses for N

➔ choose for one sterile ν ~keV mass ➔ exceeds lifetime of Universe

Virtue and Problem of the νMSM

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



heavy sterile neutrinos typ. $\geq 10^{13}$ GeV

assumption ➔ mechanism

one light sterile neutrino $\simeq$ keV = DM

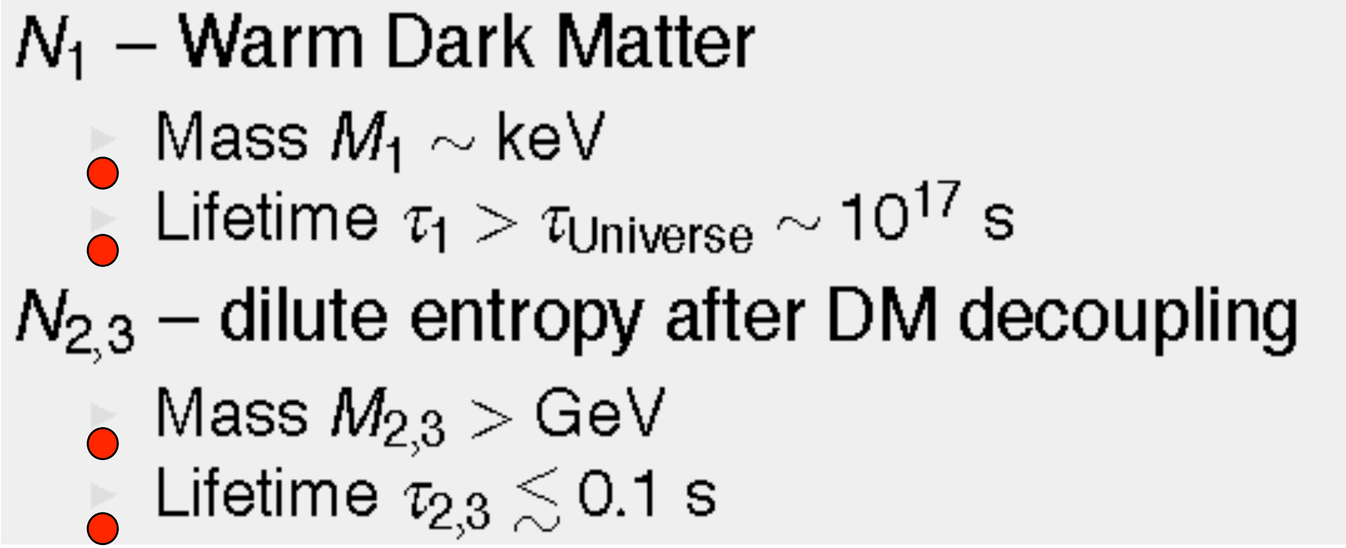
light active neutrinos < eV

Alternative Scenario with Thermal Abundance

An alternative scenario: Bezrukov, Hettmannsperger, ML

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

Roles played by the sterile (~right-handed) neutrinos:



N_1 – Warm Dark Matter

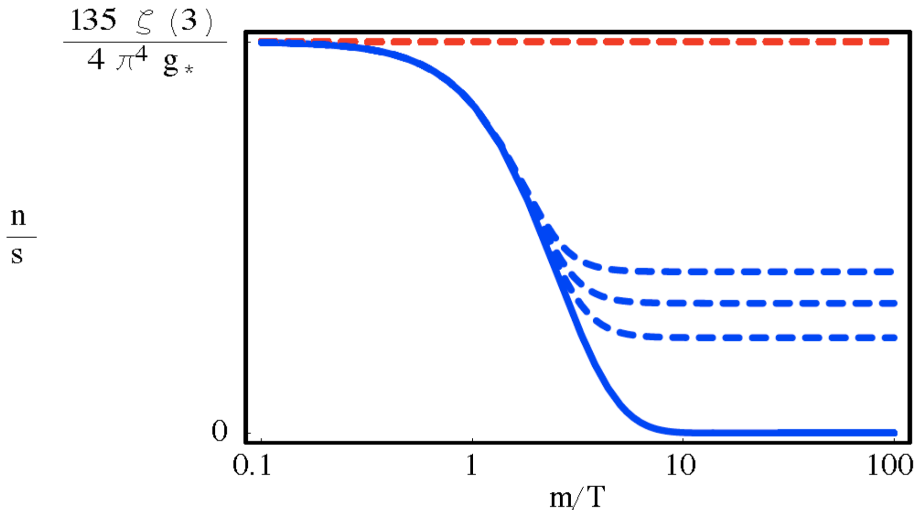
- Mass $M_1 \sim \text{keV}$
- Lifetime $\tau_1 > \tau_{\text{Universe}} \sim 10^{17}$ s

$N_{2,3}$ – dilute entropy after DM decoupling

- Mass $M_{2,3} > \text{GeV}$
- Lifetime $\tau_{2,3} \lesssim 0.1$ s

Obtaining the correct Abundance

Usual thermal case:



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

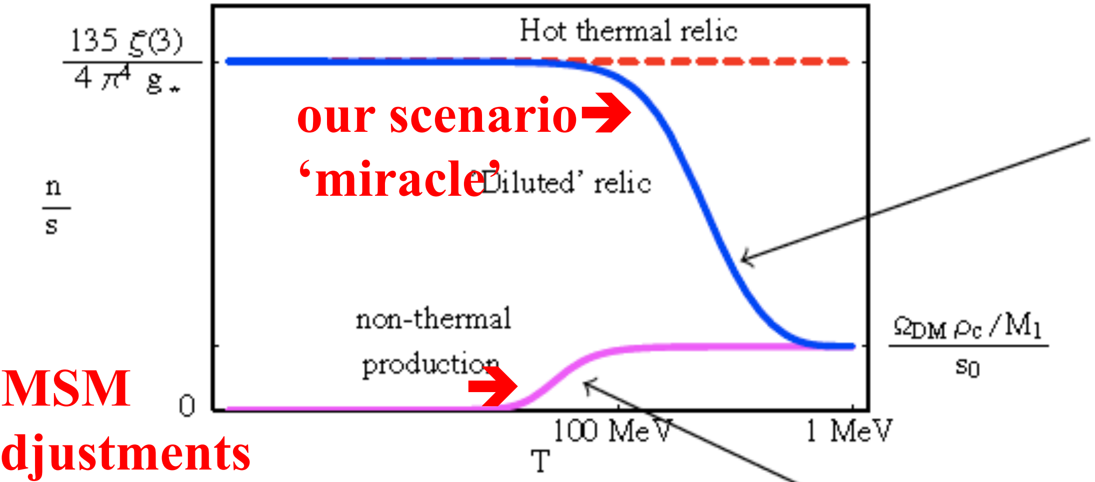
Decoupled relativistic

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

Decoupled

nonrelativistic

keV sterile neutrinos:



our scenario ➔
'miracle'

νMSM adjustments ➔

Diluted after decoupling (entropy generated by other particle decay)

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

Never entered thermal equilibrium

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

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

➔ sufficiently long lived ➔ become 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

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

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

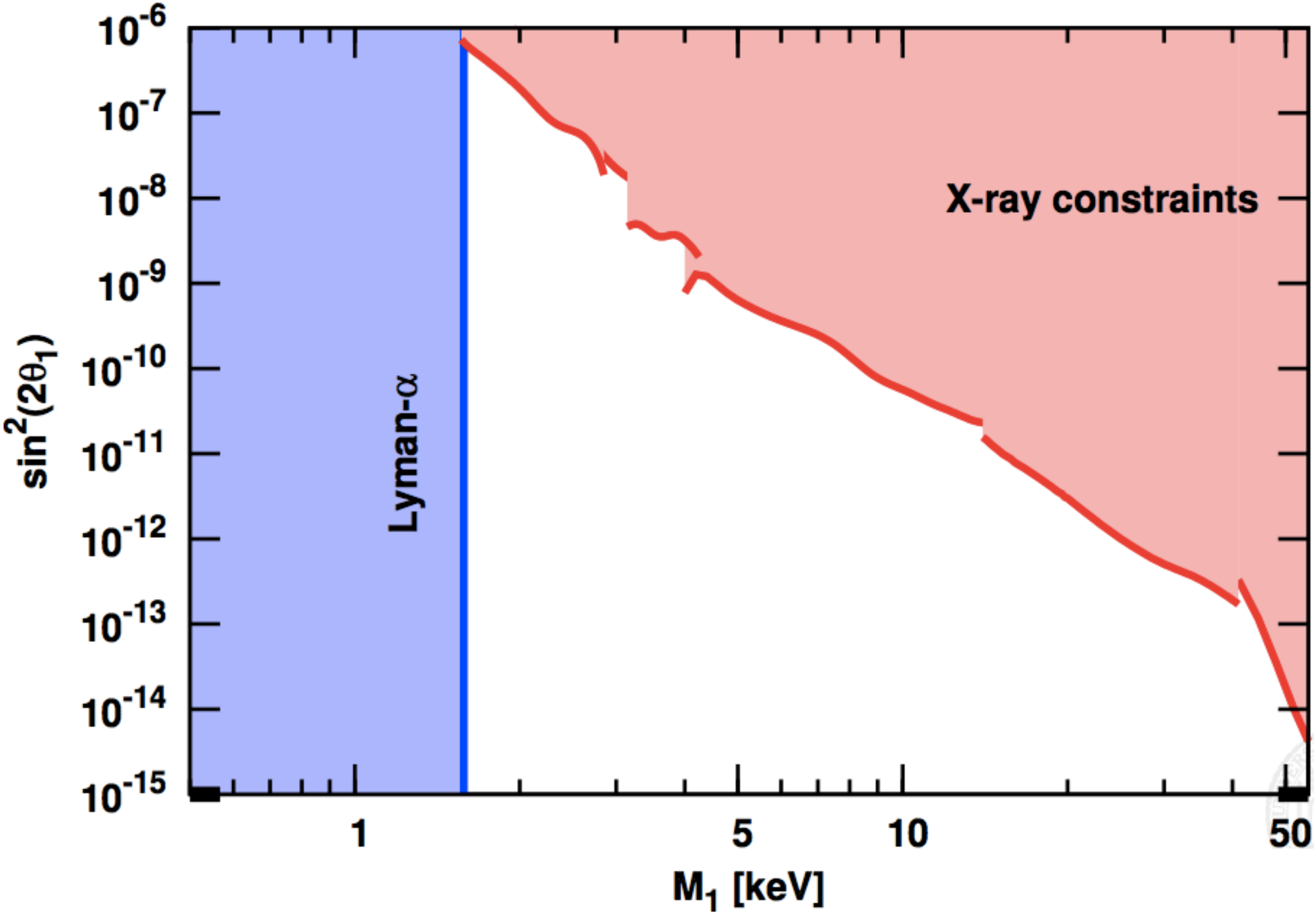
The right abundance of the sterile neutrino N_1 is achieved if

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

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

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

Allowed Parameter Range



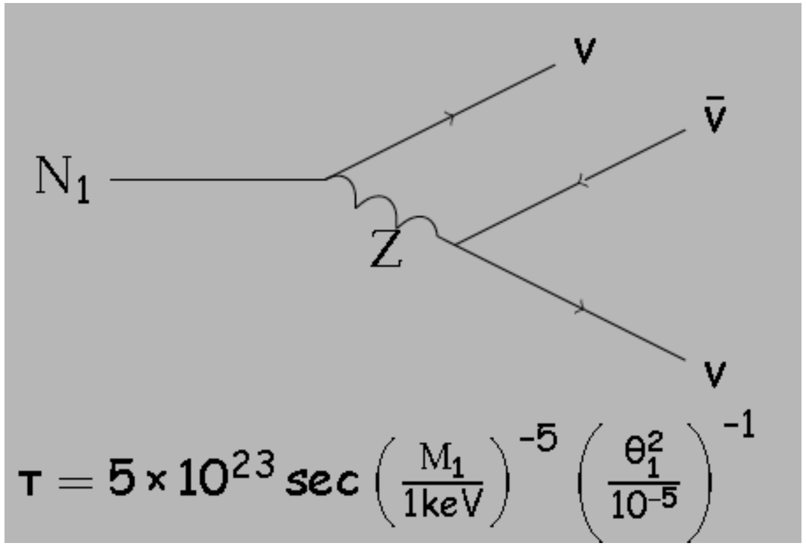
Observing keV-ish Neutrino DM

- LHC
  - sterile neutrino DM is not observable
  - WIMP-like particles still possible – but not DM
- direct searches
  - sterile ν DM extremely difficult; maybe in β-decay (MARE)
- astrophysics/cosmology ➔ at some level: keV X-rays

  ➔ sterile neutrino DM is decaying into active neutrinos

  - decay $N_1 \rightarrow \nu\bar{\nu}\nu$, $N_1 \rightarrow \nu\bar{\nu}\bar{\nu}$
  - not very constraining since

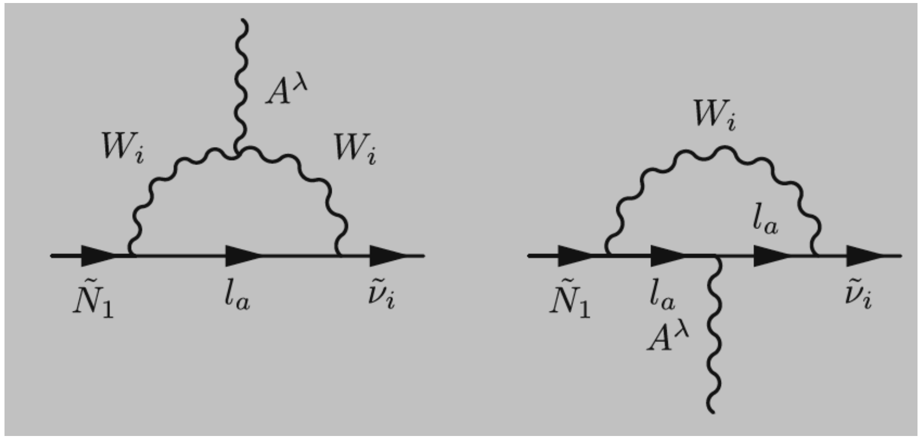
    $\tau >> \tau_{\text{Universe}}$



$$\tau = 5\times10^{23}\,\text{sec}\left(\frac{M_1}{1\text{keV}}\right)^{-5}\left(\frac{\theta_1^2}{10^{-5}}\right)^{-1}$$

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

  ➔ photon line $E_\gamma = m_s/2$



- so far: observational limit on active-sterile mixing angle

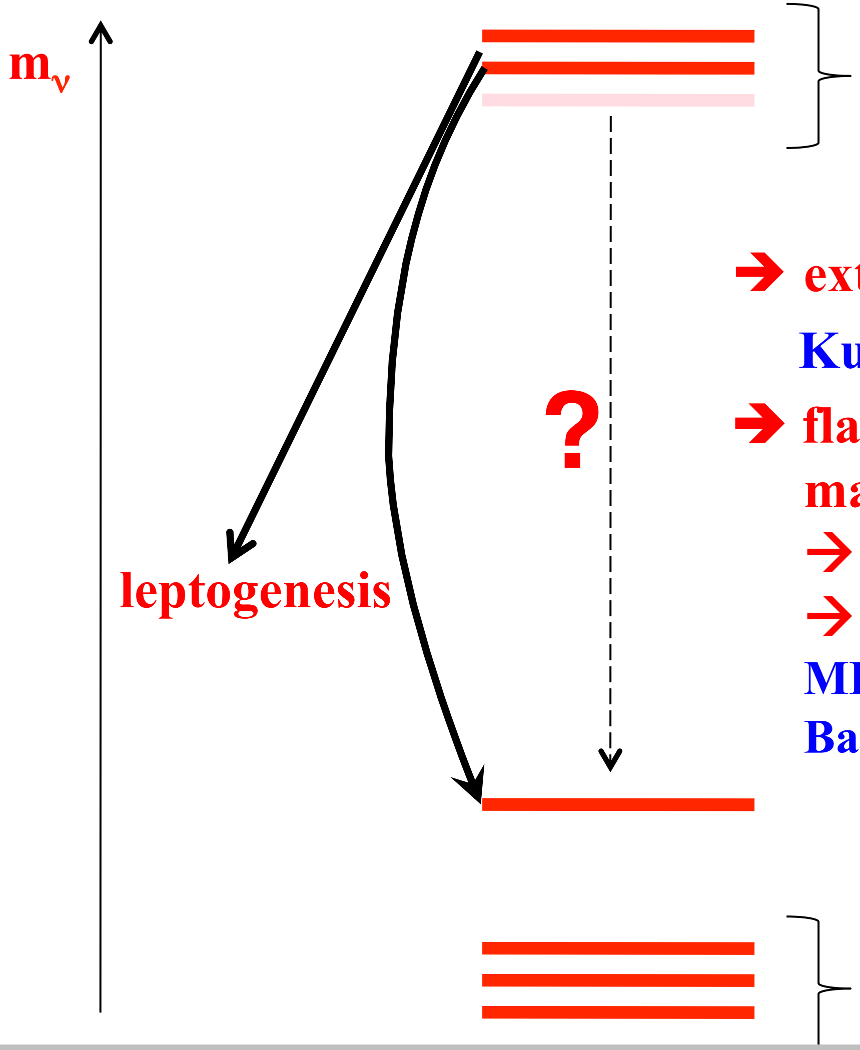
$$\Gamma_{N_1\to\nu\gamma} \simeq 5.5\times 10^{-22}\theta_1^2\left(\frac{M_1}{1\ \mathrm{keV}}\right)^5 \mathrm{s}^{-1}$$

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

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

Explaining keV-ish Sterile Neutrinos

Possible scenario: See-saw + a reason why 1 sterile ν is light



heavy sterile neutrinos typ. $\geq 10^{13}$ GeV

➔ extra dimensional physics ➔ 'split see-saw'

Kusenko, Takahashi, Yanagida,

➔ flavour symmetries explaining active neutrino masses + charged leptons + quarks

→ consequences for heavy mass matrix

→ L_e-L_μ-L_τ DM←→ flavour problem

ML, Merle, Niro ; Merle, Niro,

Barry, Rodejohann, Zhang

one light sterile neutrino $\simeq$ keV = DM

light active neutrinos < eV

Light Sterile Neutrinos from L_e-L_μ-L_τ

- Flavour symmetries have been studied to explain apparent regularities of masses and mixing: A4, S3, D5, …
  ➔ implications for sterile sector?
  ➔ could the same symmetries explain a keV-ish sterile ν ?

Model by Lavoura & Grimus ➔ extended: ML, Merle, Niro

SM + ν_{iR} + softly broken U(1) ←→ $\mathcal{F} \equiv L_e - L_\mu - L_\tau$

type II see-saw ➔ +Higgs triplet $\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$

	L_{eL}	$L_{\mu L}$	$L_{\tau L}$	e_R	μ_R	τ_R	N_{1R}	N_{2R}	N_{3R}	ϕ	Δ
$\mathcal{F}$	1	−1	−1	1	−1	−1	1	−1	−1	0	0

Neutrino Mass Terms

- **Mass matric for right-handed neutrinos:**

$$\mathcal{L}_{\text{mass}} = -M_R^{12}\,\overline{(N_{1R})^C}\,N_{2R} - M_R^{13}\,\overline{(N_{1R})^C}\,N_{3R} + h.c.$$

- **Dirac masses**

$$\begin{aligned}\mathcal{L}_{\text{mass}} \quad = \quad & -Y_D^{e1}\,\overline{L_{eL}}\,\tilde{\phi}\,N_{1R} - Y_D^{\mu 2}\,\overline{L_{\mu L}}\,\tilde{\phi}\,N_{2R} - Y_D^{\mu 3}\,\overline{L_{\mu L}}\,\tilde{\phi}\,N_{3R} - \\ & -Y_D^{\tau 2}\,\overline{L_{\tau L}}\,\tilde{\phi}\,N_{2R} - Y_D^{\tau 3}\,\overline{L_{\tau L}}\,\tilde{\phi}\,N_{3R} + h.c.,\end{aligned}$$

- **In addition: Triplet masses**

$$\mathcal{L}_{\text{mass}} = -Y_L^{e\mu}\,\overline{(L_{eL})^C}\,(i\sigma_2\Delta)\,L_{\mu L} - Y_L^{e\tau}\,\overline{(L_{eL})^C}\,(i\sigma_2\Delta)\,L_{\tau L} + h.c.$$

- **Mass matrix in the basis**

$$\Psi \equiv \left((\nu_{eL})^C, (\nu_{\mu L})^C, (\nu_{\tau L})^C, N_{1R}, N_{2R}, N_{3R}\right)^T$$

➔ $$\mathcal{M}_\nu = \left(\begin{array}{ccc|ccc} 0 & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\ m_L^{e\mu} & 0 & 0 & 0 & m_D^{\mu 2} & m_D^{\mu 3} \\ m_L^{e\tau} & 0 & 0 & 0 & m_D^{\tau 2} & m_D^{\tau 3} \\ \hline m_D^{e1} & 0 & 0 & 0 & M_R^{12} & M_R^{13} \\ 0 & m_D^{\mu 2} & m_D^{\tau 2} & M_R^{12} & 0 & 0 \\ 0 & m_D^{\mu 3} & m_D^{\tau 3} & M_R^{13} & 0 & 0 \end{array}\right)$$

➔ **three scenarios**

- $m_D^{\alpha i} \ll m_L^{\alpha\beta} \ll M_R^{ij}$ (separation scenario),
- $m_L^{\alpha\beta} \ll m_D^{\alpha i} \ll M_R^{ij}$ (type II see-saw scenario),
- $m_L^{\alpha\beta} \sim m_D^{\alpha i} \ll M_R^{ij}$ (hybrid scenario).

det(M_{ij}) =0
➔ M_1=0
➔ massless sterile state + soft breaking
➔ light sterile ν

Implications for See-Saw

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

- **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**

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

- **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 →**

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

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

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

→ violates bound (*)

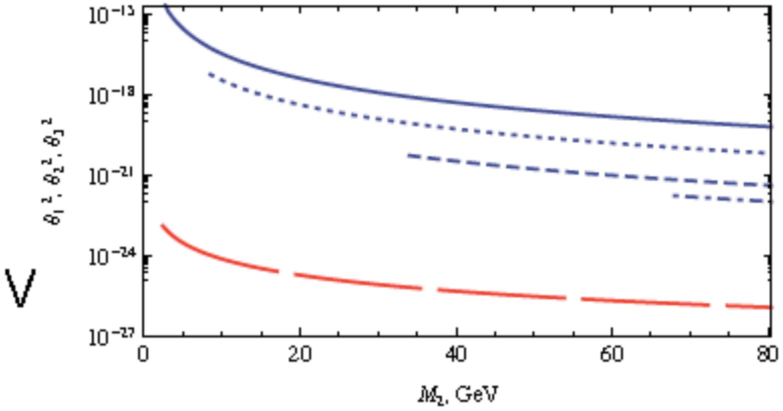
→ type-I see-saw impossible → type II

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

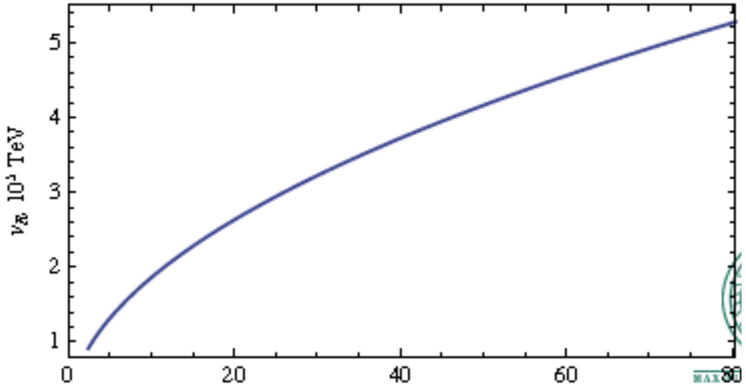
$M_1 = 1.6$keV

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

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

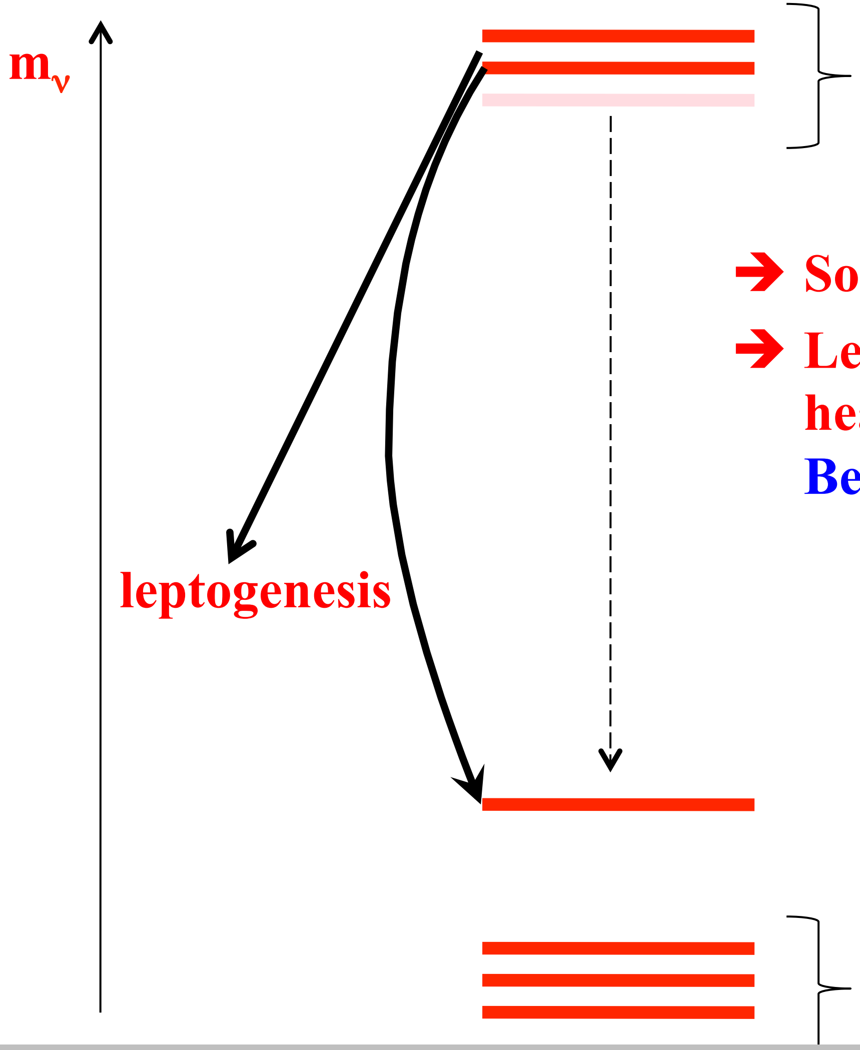
$v_R = 9.67 \times 10^4$ TeV $\quad v_L = 313$ keV

$y = 0.027 f$



Leptogenesis

Possible scenario: See-saw + a reason why 1 sterile ν is light



heavy sterile neutrinos typ. ≥ 10^{13} GeV

- ➔ **Some mechanism to explain the spectrum**
- ➔ **Leptogenesis from the decay of the remaining heavy sterile neutrinos**
  Bezrukov, Kartavtsev, ML

one light sterile neutrino ≃ keV = DM

light active neutrinos < eV

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 → abundance from thermal production → interesting constrains**
  - small mixings from X-ray constraints and 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

→ Combination with Leptogenses → BAU

→ More general scenarios require just some mechanism which 'naturally' explains light sterile neutrinos