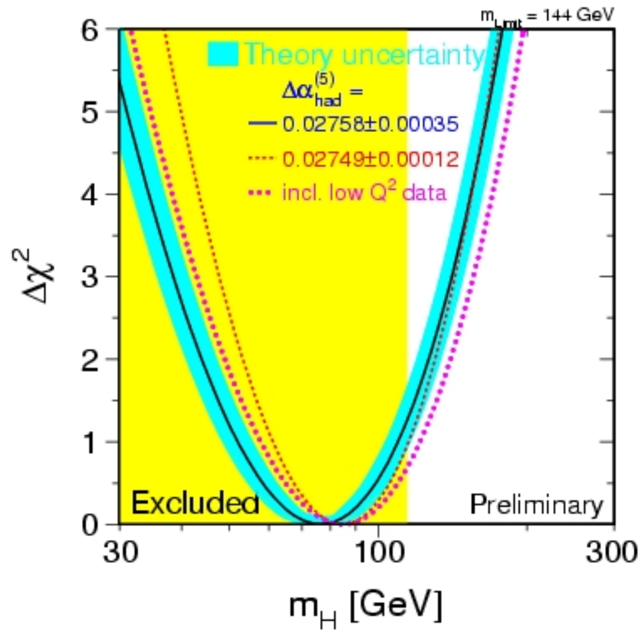
Sterile Neutrinos as Warm Dark Matter

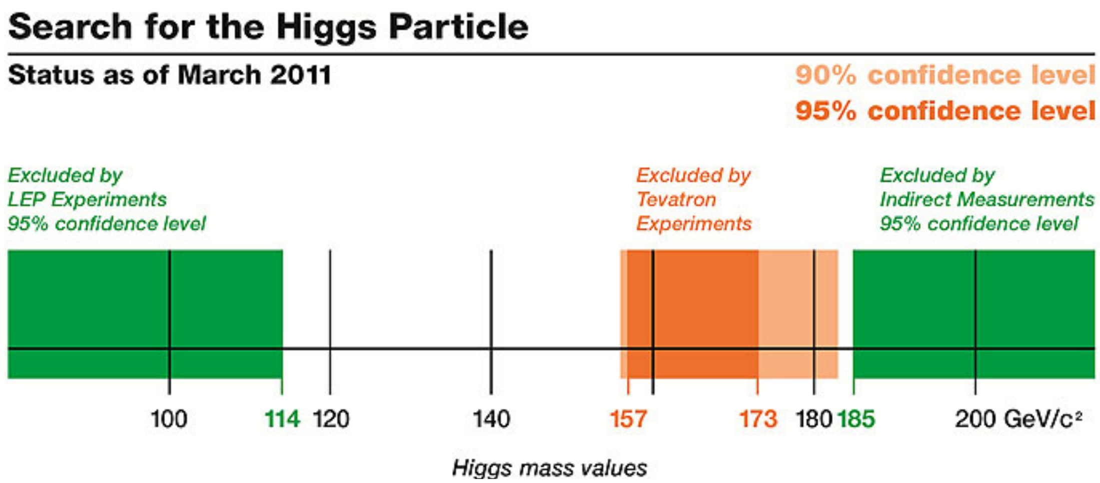
Manfred Lindner

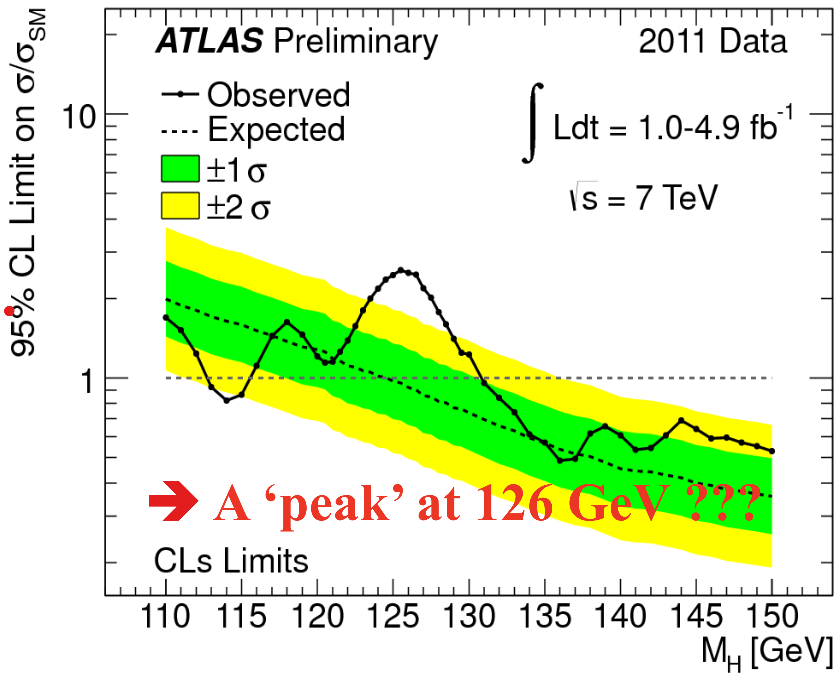
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

What is ν – June 25-29

SM works perfectly & Higgs Mass Range is converging







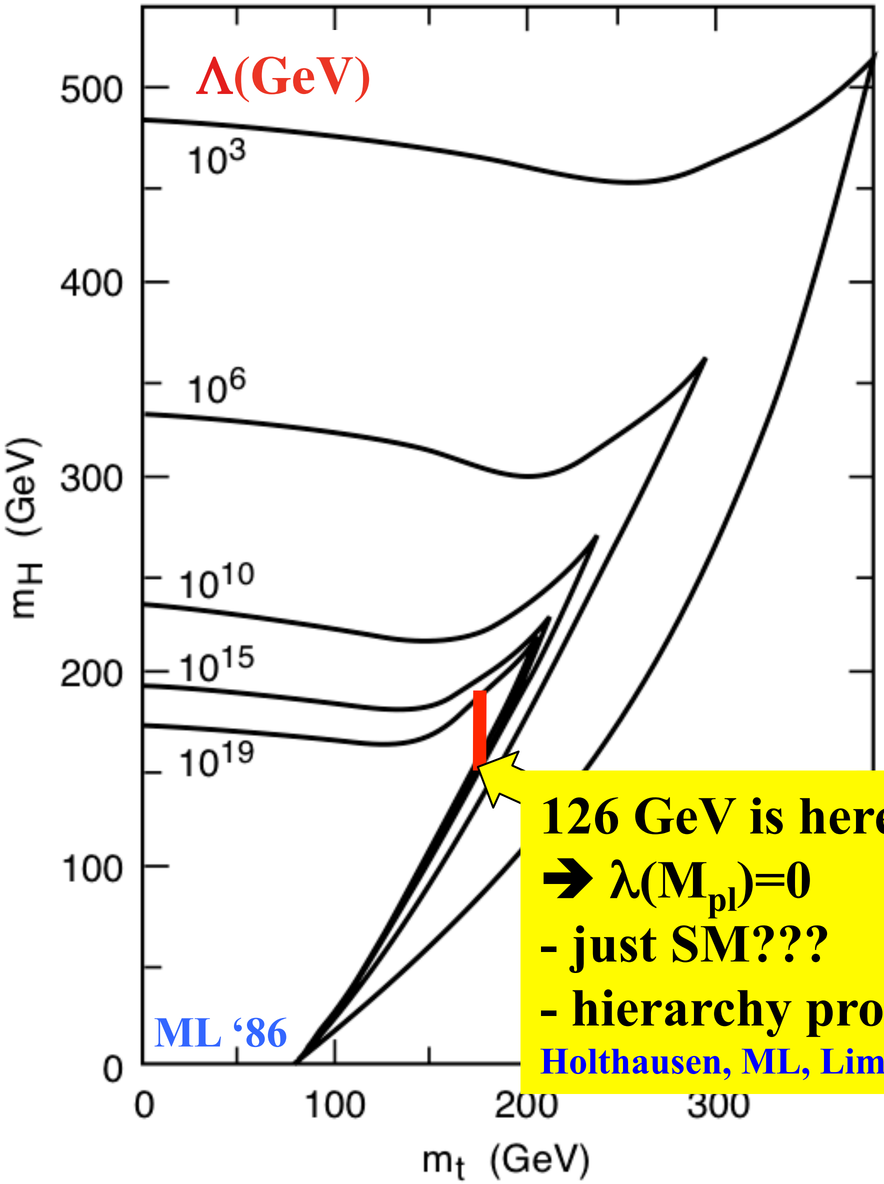
➔ A 'peak' at 126 GeV ???

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

➔ just the SM?

➔ Dark Matter?

Triviality and Vacuum Stability

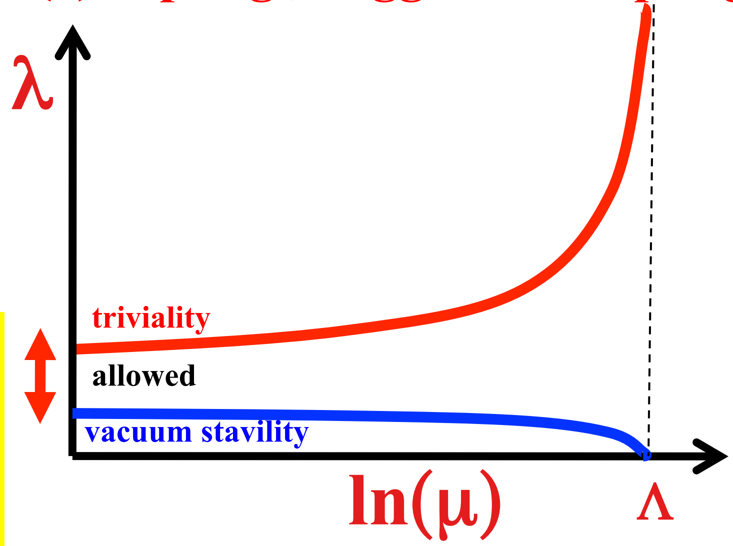


126 GeV < m_H < 174 GeV

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

Holthausen, ML, Lim

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



➔ RGE arguments seem to work
➔ we need some embedding

The SM works perfect but must be extended….

- **Hierarchy problem**
  - separation of two scalar scales is unstable… SUSY, TeV physics
  - Planck scale physics: New concepts … ???
- **Many theoretical reasons for BSM physics…**
- **SM cannot explain Baryon Asymmetry of the Universe (BAU)**

  BUT: Massive neutrinos require SM extension → SM+

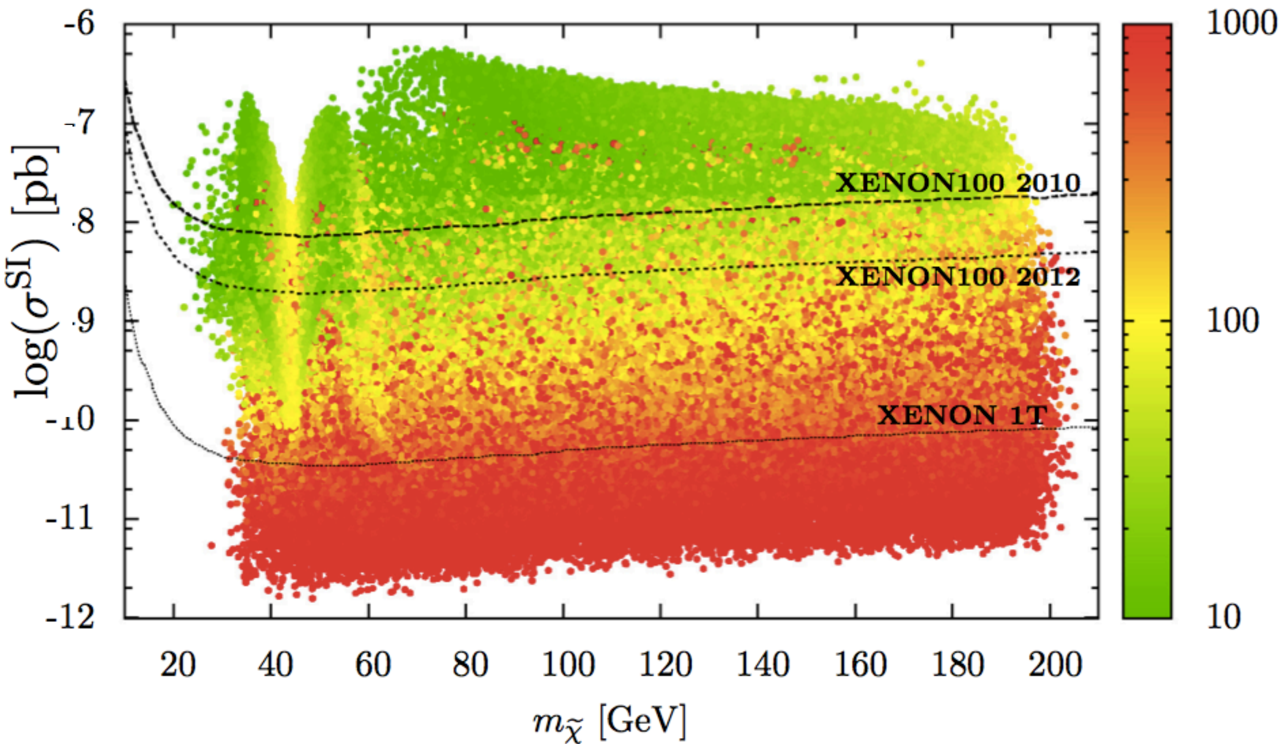
  → leptogenesis = one of the best BAU explanations

  → nothing else needed!
- **Dark Matter**
  - an extra particle is needed which is DM
  - particles connected to the hierarchy problem, strong CP, …
  - massive neutrinos require new physics ←→ DM?

Most favoured Dark Matter: WIMPs

- Candidates in BSM models ←→ hierarchy problem
- WIMP miracle → correct abundance
- MSSM neutralino: Level of fine-tuning → Δ_{tot}

$$\Delta p_i \equiv \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right| \qquad \Delta_{tot} \equiv \sqrt{\sum_{p_i=\mu^2, b, m_{H_u}^2, m_{H_d}^2} \{\Delta p_i\}^2}$$



XENON100-2010

XENON100-2012 ???

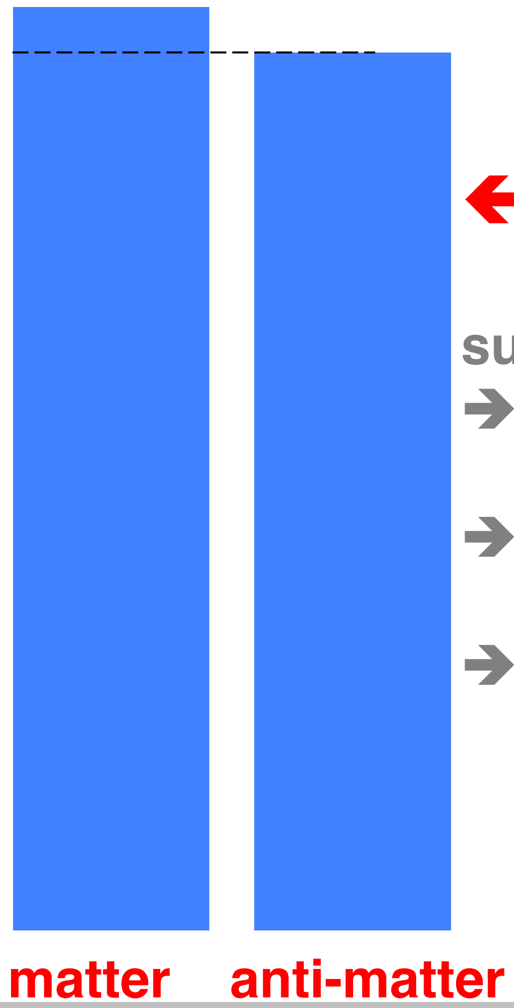
XENON1T

* becoming more tuned…
* other candiates..?
→ BSM
→ neutrinos?
←→ natural…

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

New Directions: Asymmetric Dark Matter

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



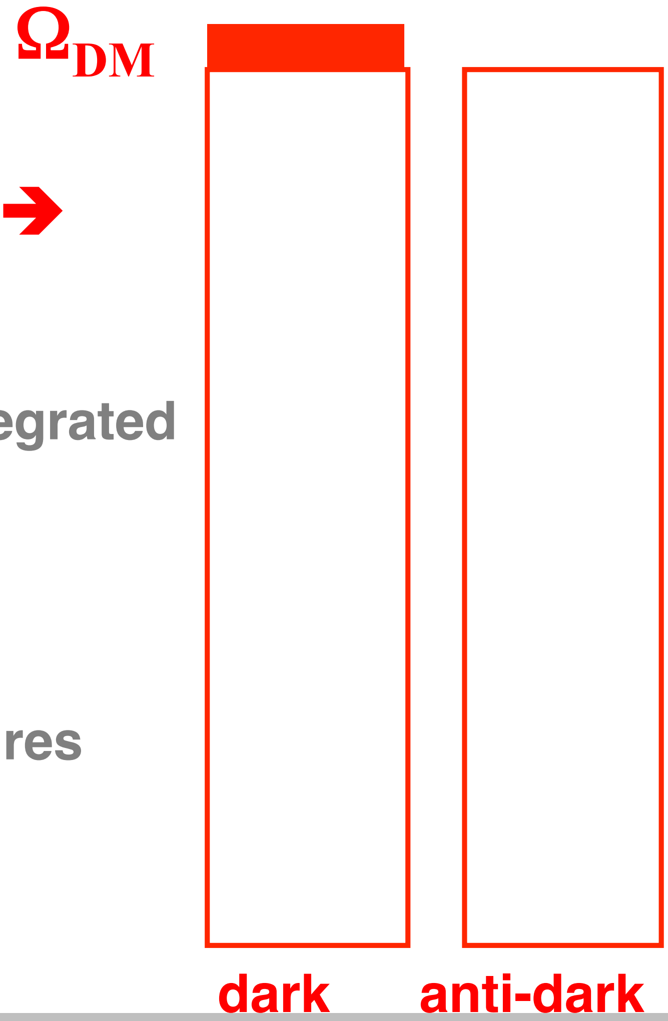
← SM x hidden sector →

suitable coupling

➔ heavy scale which is integrated out, but connects B, L

➔ links amount of DM to amount of matter

➔ various realizations = DM particles & sigantures



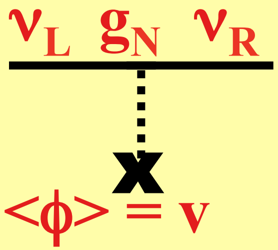
Most minimalistic: DM & Neutrino Mass

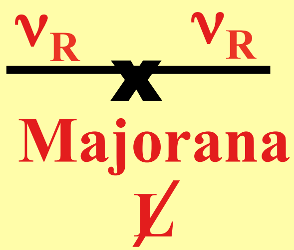
New Physics: Neutrino Mass Terms

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





→ $$\begin{pmatrix} \nu_L & \nu_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

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

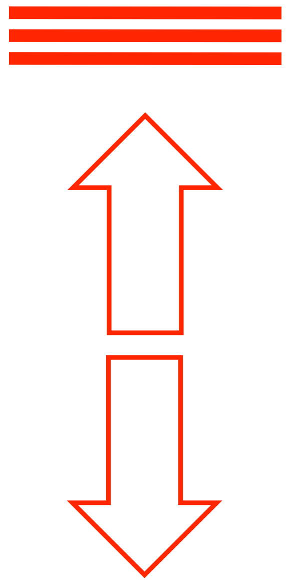
NEW ingredients, 9 parameters → SM+ and sea-saw

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, 2, … heavy states light?

➔ light sterile neutrino(s)

➔ tiny heavy-light mixing expected

$\theta^2 < O(m_\nu/m_s)$

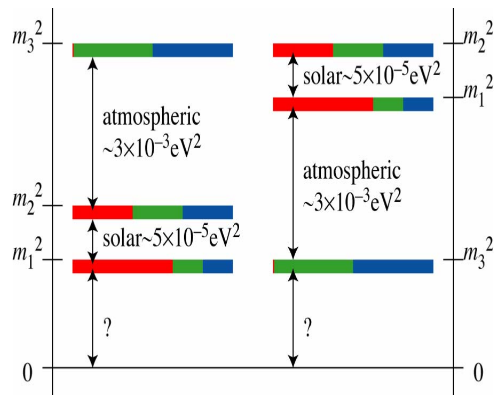
3 light active neutrinos

➔ this cold easily be wrong

- more than 3 N_R states, …

- M_R may have special eigenvalues, …

➔ light sterile neutrinos ?!



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 true! ➔ consequences?

Could Neutrinos be Dark Matter?

• **<u>Active neutrinos would be perfect Hot Dark Matter</u>** ➔ ruled out:

- **destroys small scale structures in cosmological evolution**
- **measured neutrino masses too small → maybe HDM component**

• **<u>keV sterile neutrinos: Warm Dark Matter</u>** ➔ 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 sterile Neutrinos as WDM

The νMSM

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

Particle content:

- Gauge fields of $SU(3)_c \times SU(2)_W \times U(1)_Y$: **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

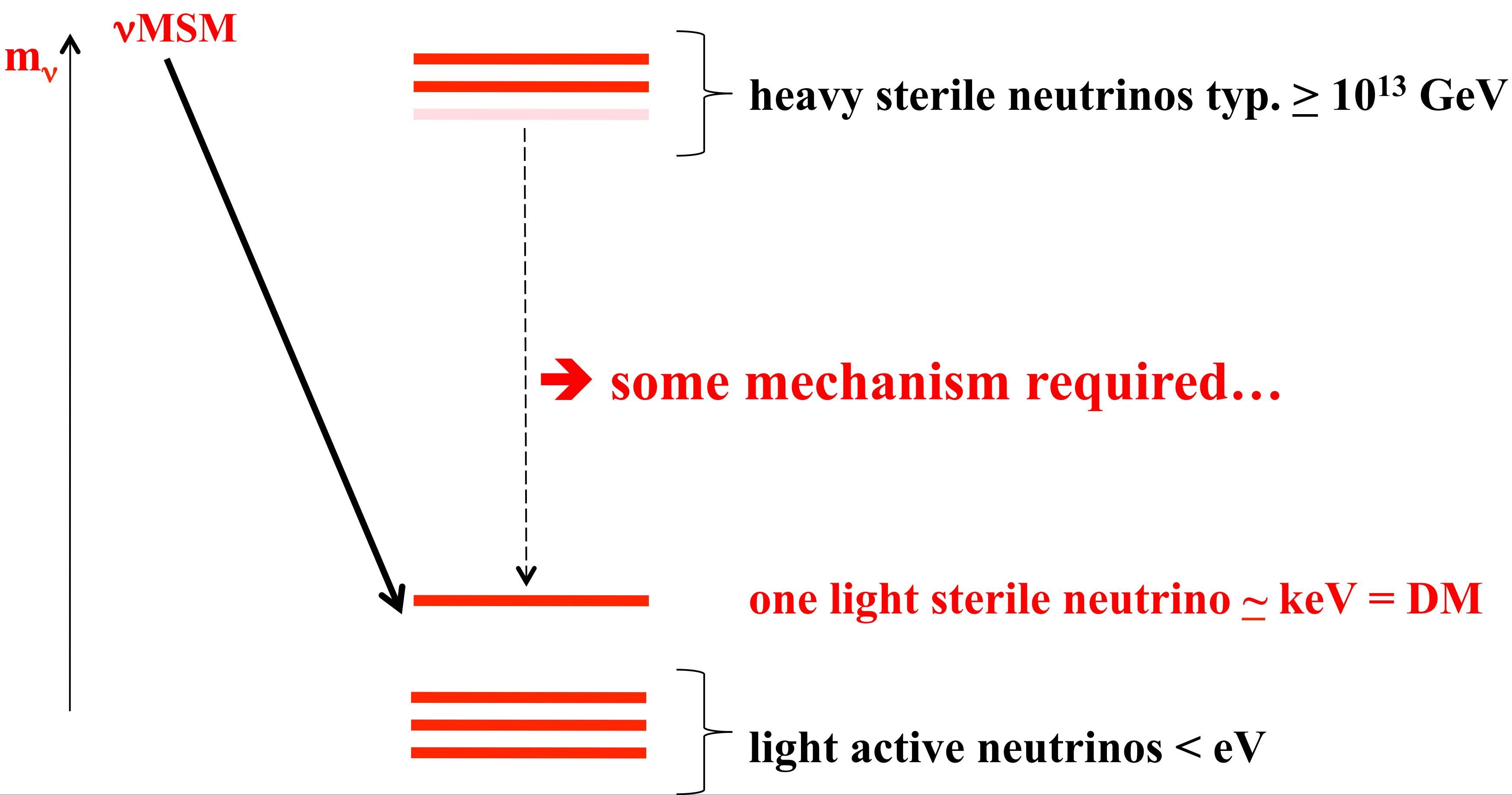
➔ Majorana masses for N

➔ 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**



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:

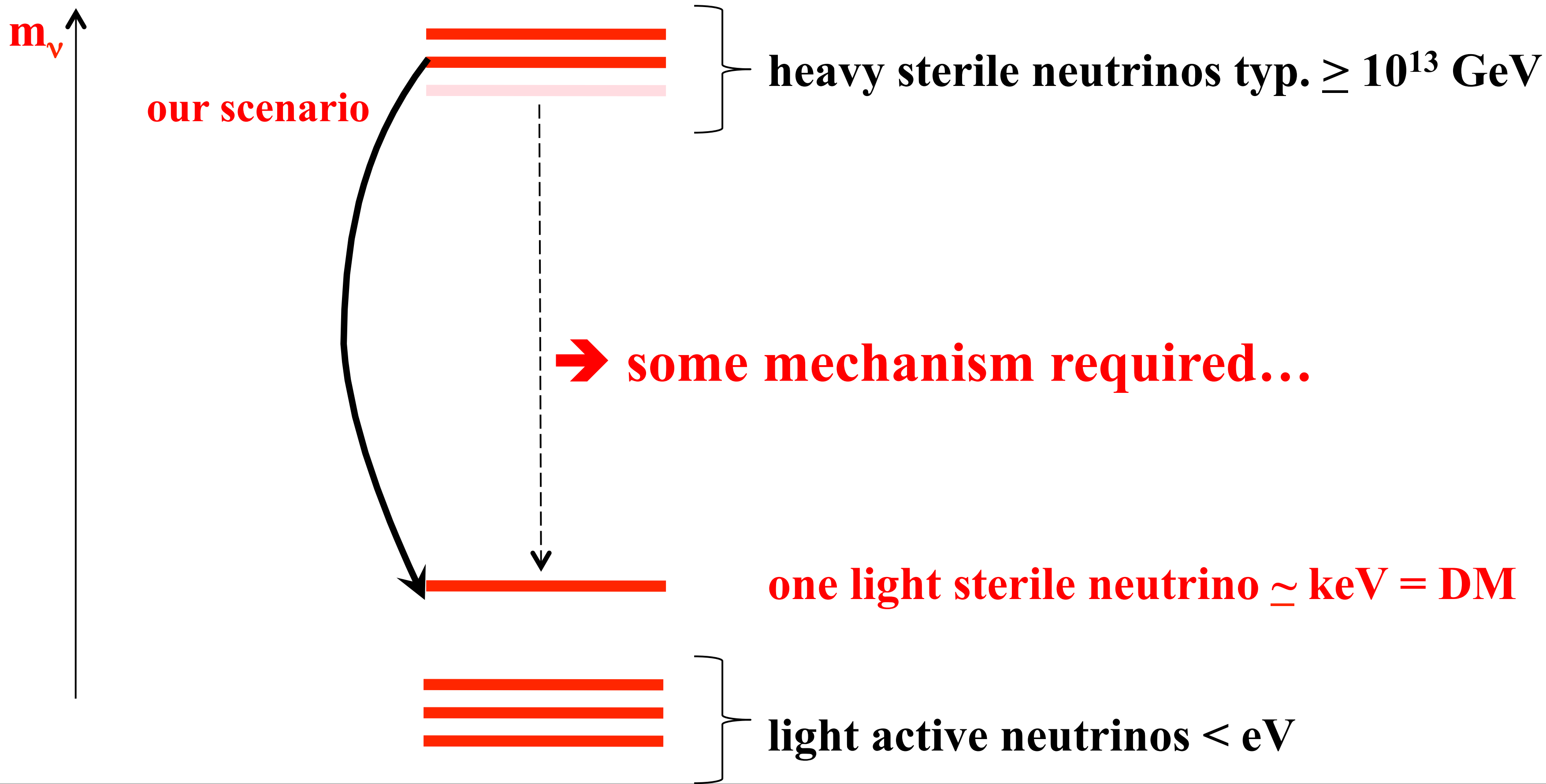
N_1 – Warm Dark Matter

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

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

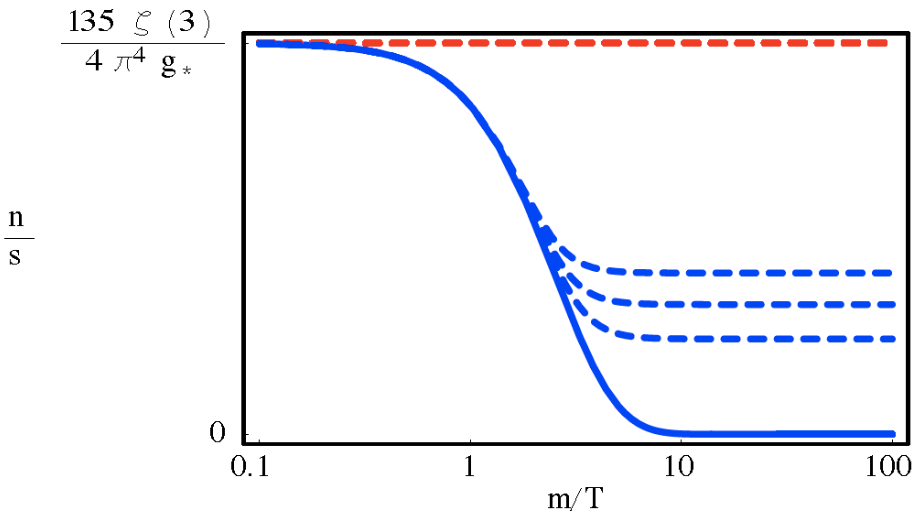
- Mass $M_{2,3} >$ GeV
- Lifetime $\tau_{2,3} \lesssim 0.1$ s

Thermal production of the correct abundance in our model:



Obtaining the correct Abundance

Usual thermal WIMP case:



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

Decoupled relativistic

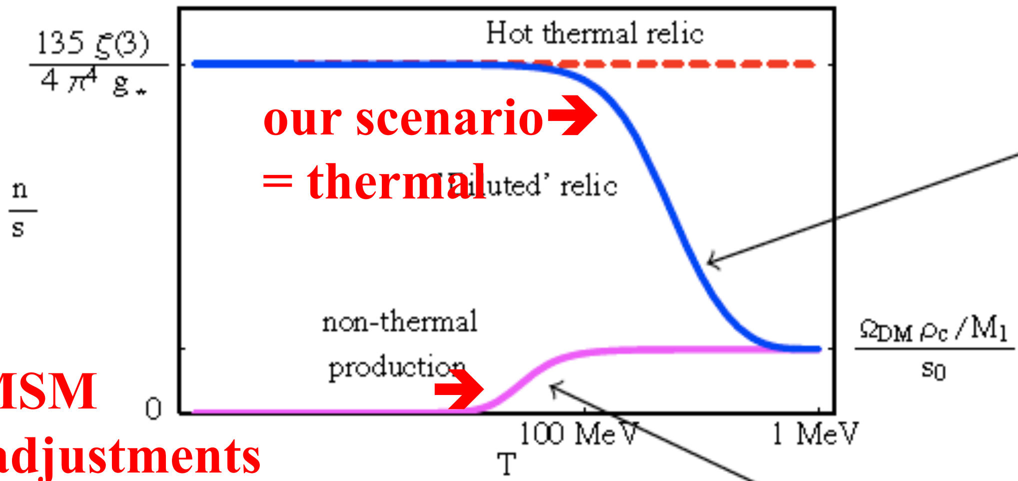
CDM:
(M>>MeV)

$\Omega \sim \Omega_{DM}$

Decoupled

nonrelativistic

keV sterile neutrinos:



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

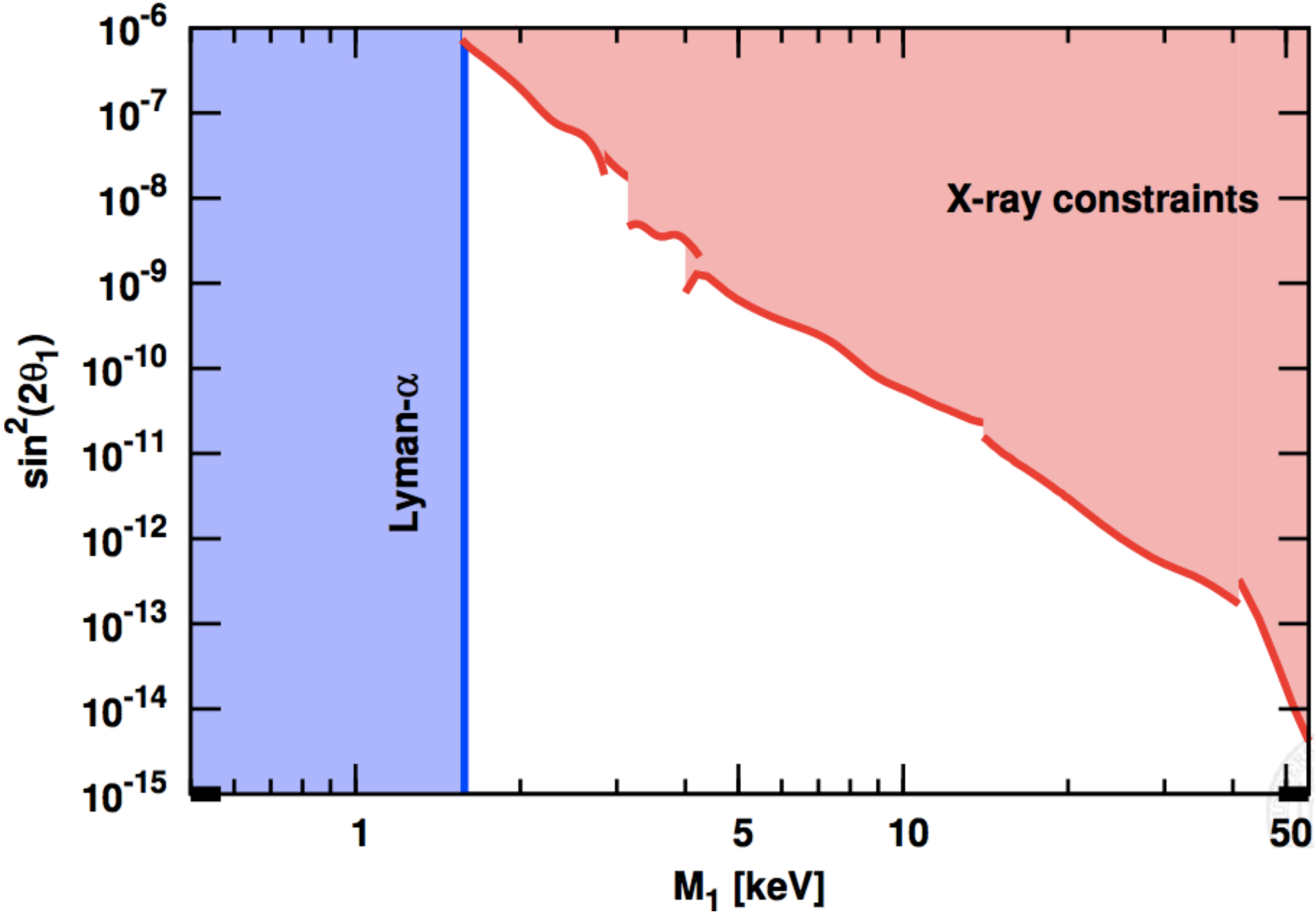
➔ entropy generation factor ➔

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

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

➔ fixes decay width Γ_2

Allowed Parameter Range



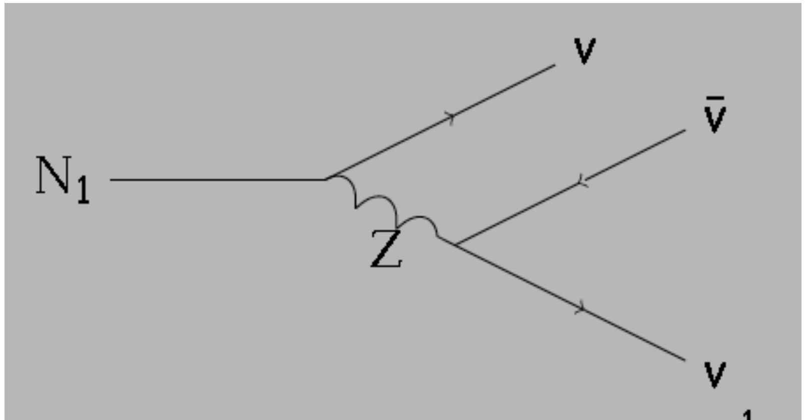
Observing keV-ish Neutrino DM

- **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 $N_1 \rightarrow \nu\bar{\nu}\nu$, $N_1 \rightarrow \nu\bar{\nu}\bar{\nu}$

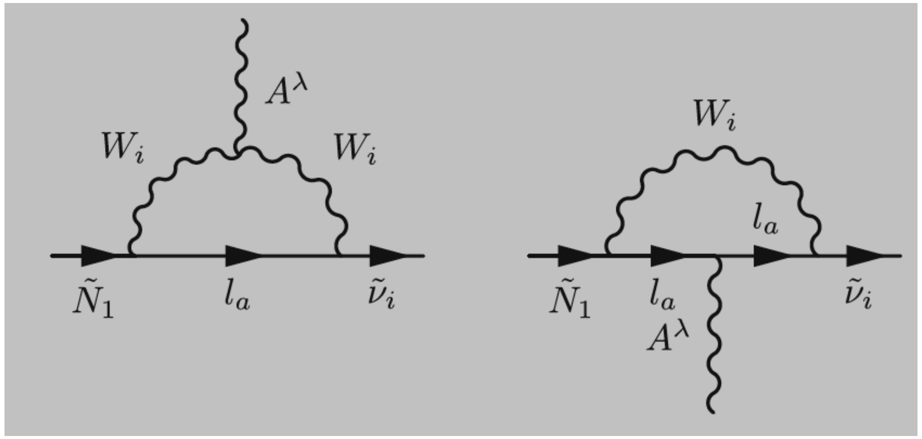
- not very constraining since $\tau \gg \tau_{Universe}$



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

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

  ➔ photon line $E_\gamma = m_s/2$



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

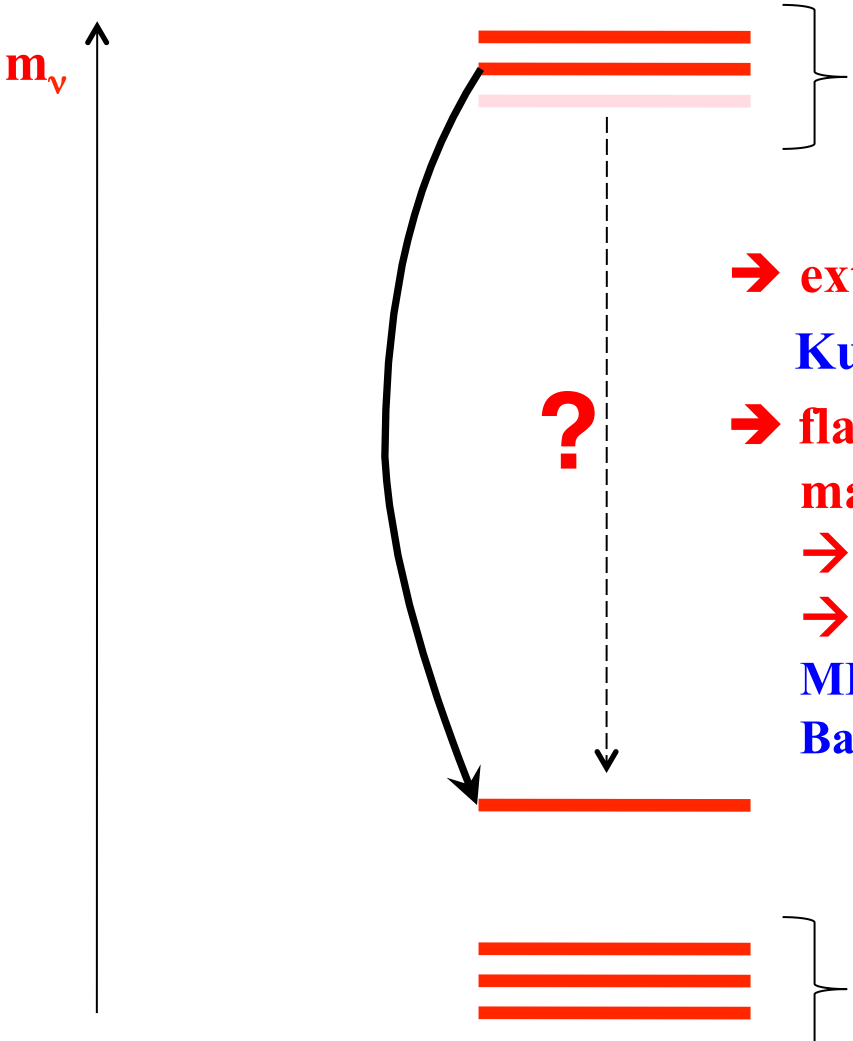
$$\Gamma_{N_1 \rightarrow \nu\gamma} \simeq 5.5 \times 10^{-22} \theta_1^2 \left(\frac{M_1}{1\ \mathrm{keV}} \right)^5 \mathrm{s}^{-1}$$

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

- 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

How it may work…

Neutrino mass matrix:

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

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

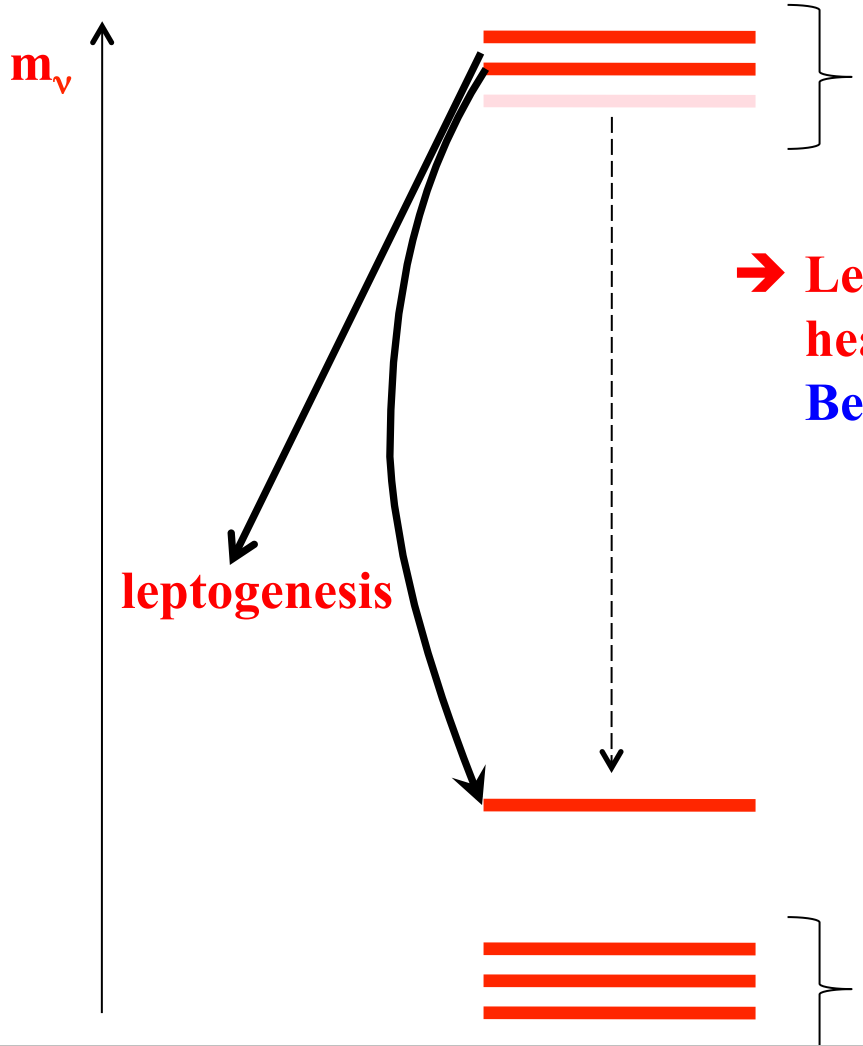
det(M_{ij}) =0 ➔ M_1=0

➔ massless sterile state + soft breaking

➔ light sterile ν

Leptogenesis

…there still exist heavy sterile states …



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

➔ **Leptogenesis from the decay of the remaining heavy sterile neutrinos works perfectly!**
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**
- **Our scenario: 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: just invent some mechanism which 'naturally' explains light sterile neutrinos