Sterile Neutrinos as Dark Matter

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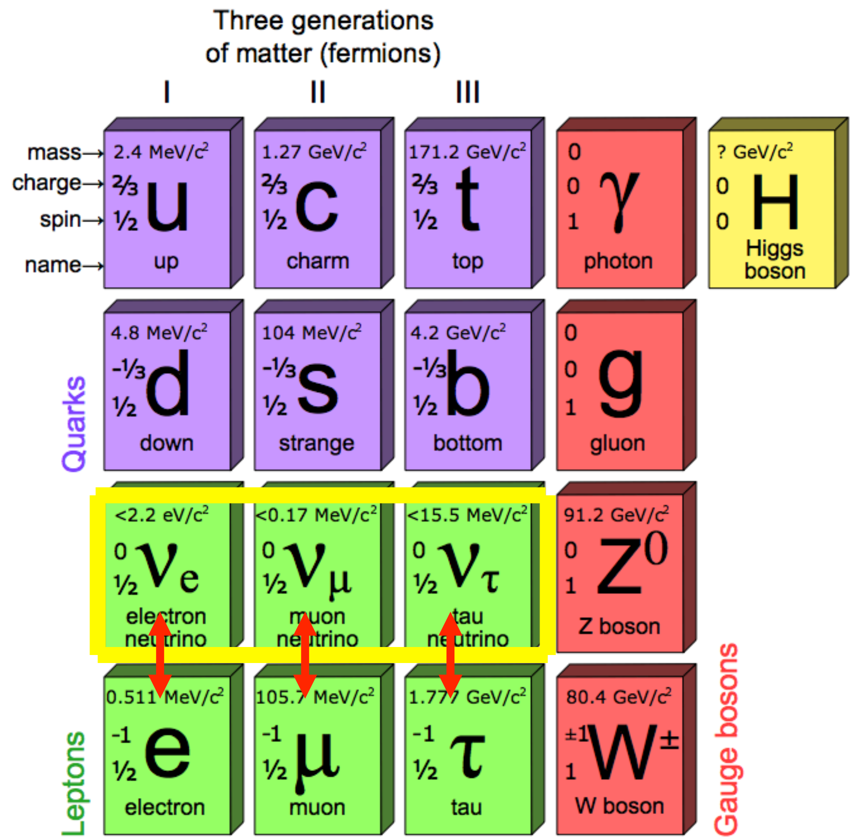
The Success of the SM

- **Standard Model:**
  - success of renormalizabel QFTs
  - 3 generations of quarks & leptons
  - including 3 left-handed neutrinos
    → textbooks: neutrinos massless



- **Massive neutrinos → extension**
  - → simplest solution: add three ν_R
  - → Dirac & Majorana masses
  - → see-saw, ... → 3 light neutrinos

<u>BUT:</u> Principle which selects/explains

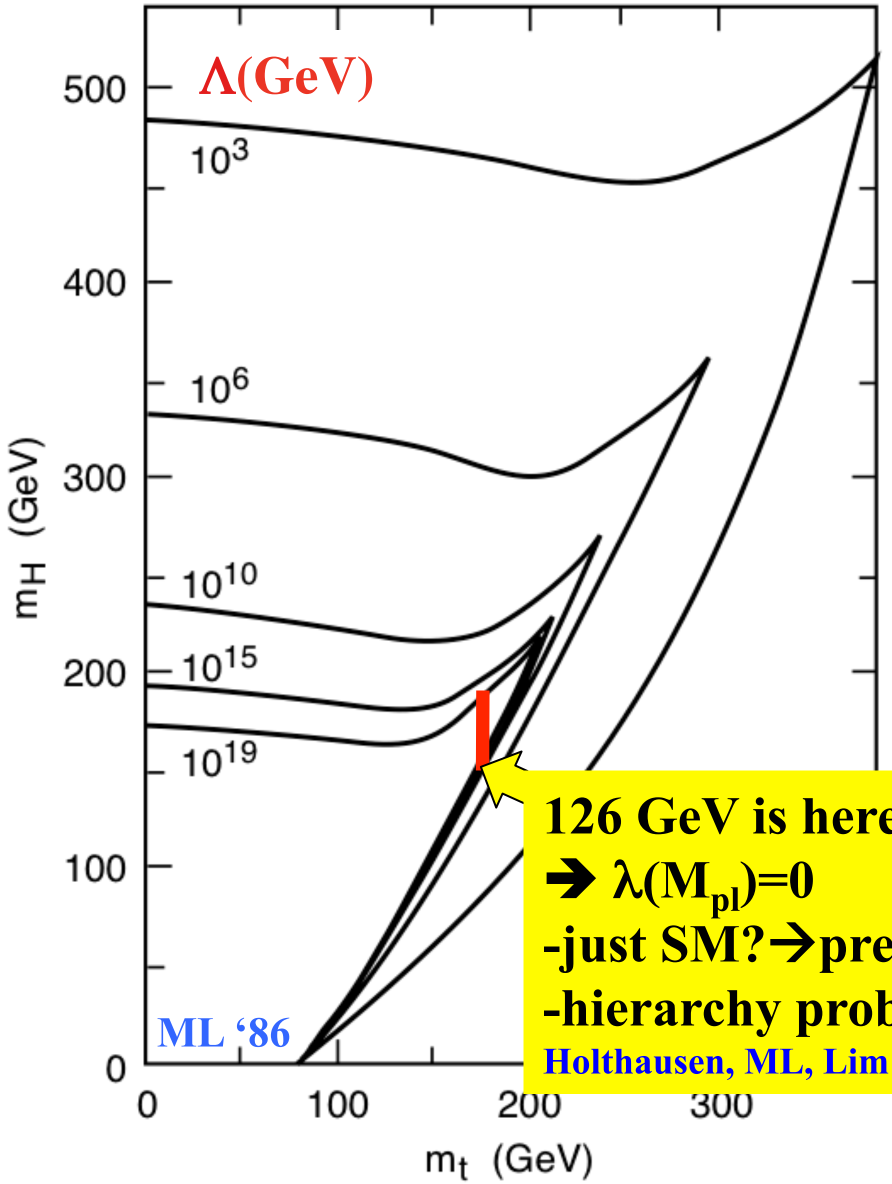
- **generations, particle representations, symmetries is UNKNOWN→ many alternatives**

  e.g. $N_R > 3$, new scalars, new fermions, extra symmetries, ...

- **various other reasons for BSM physics**

  → only hard fact: neutrinos are massive!

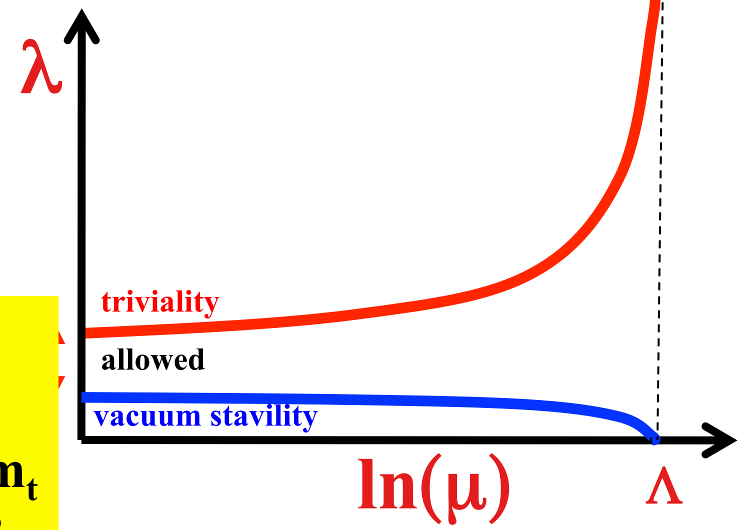
Triviality and Vacuum Stability



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

126 GeV < m_H < 174 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 works perfectly but it must be extended….

- **Many theoretical reasons for BSM physics:**

  - Flavour problem … ←→ maybe insights via neutrinos

  - Hierarchy problem

  - only a problem once the SM is embedded… → GUTs, …
  - separation of two scalar scales: SM Higgs and some other scalar at Λ
  - Planck scale physics → new concepts, spin 2, no new scalars?
    - ➔ no 2nd scalar for direct embeddings at the Planck scale?
    - ➔ SM boundary conditions that point to Λ_{Planck} → vacuum stability line!

- **Experimental facts:**

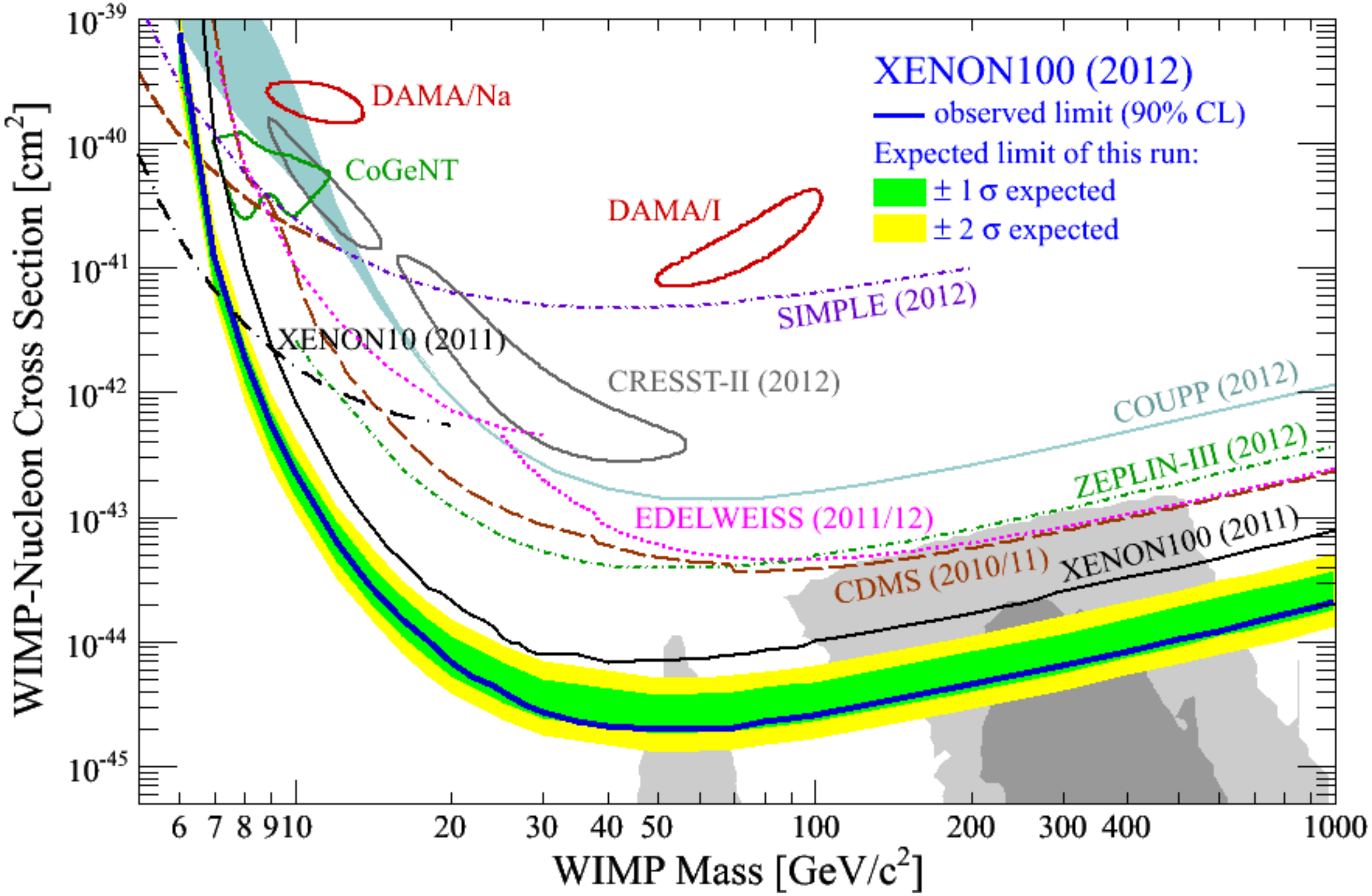
  - SM cannot explain Baryon Asymmetry of the Universe

  - BUT: neutrino masses require SM extension ➔ SM+➔
  - leptogenesis = one of the best BAU explanations

  - Dark Matter

  - some extra particle is required which is DM
  - hierarchy problem ➔ WIMPs, strong CP ➔ axions, …
  - massive neutrinos require new physics ←→ sterile neutrinos as DM?!

WIMP Searches versus CMSSM



How generic is this WIMP range?

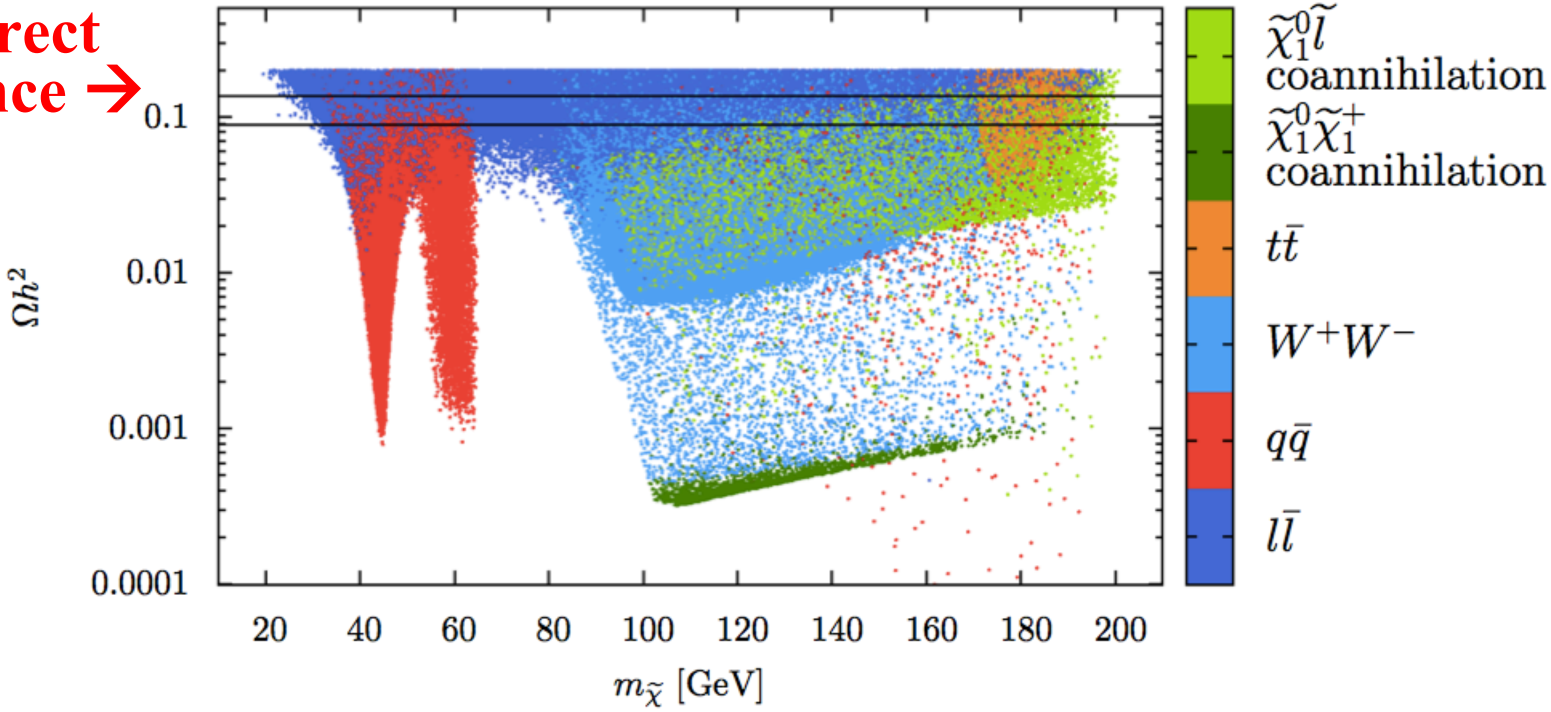
How small can the WIMP cross-section be?

WIMPs in the MSSM

- DM candidates in BSM models
  ←→ hierarchy problem → SUSY: Neutralino
- Correct abundance
  → MSSM @ EW scale → scan 11 dimensional parameter space:

$$\tan\beta\,,\, M_1\,,\, M_2\,,\, M_3\,,\, M_A\,,\, \mu\,,\, m_{\tilde{\ell}_L}\,,\, m_{\tilde{\ell}_R}\,,\, m_{\tilde{q}_{1,2}}\,,\, m_{\tilde{q}_3}\,,\, a_0$$

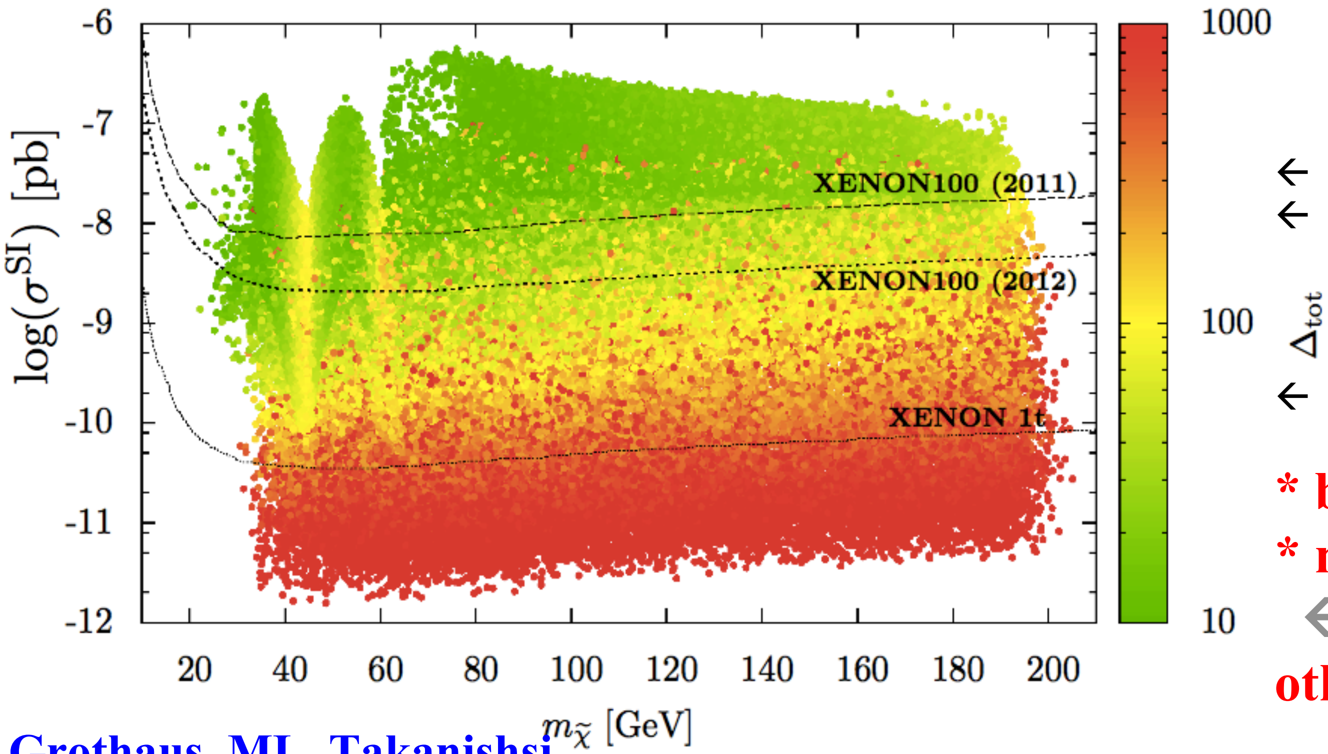
- Pick correct abundance →



Most favoured Dark Matter: WIMPs

- **MSSM neutralino: Level of fine-tuning → Δ_{tot}**

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



← XENON100-2010
← XENON100-2012
← future: XENON1T

* becoming more tuned…
* non-SUSY WIMPS worse
←→ neutalino is mixture
other candidates..?
…surprise for negative μ

Grothaus, ML, Takanishsi

Most minimalistic: SM + Neutrino Masses

Simplest Neutrino Mass Terms

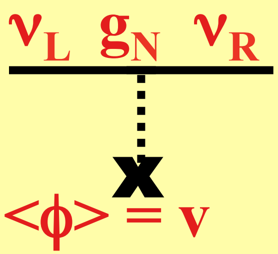
SM ~m$\phi\bar{L}$R = (2,1)

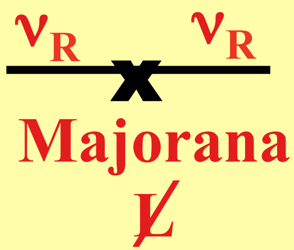
→ new fields

→ **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

The Neutrino Spectrum

<u>The standard picture:</u>

3 heavy sterile neutrinos typ. ≥ 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 $\theta^2 < O(m_\nu/m_s)$

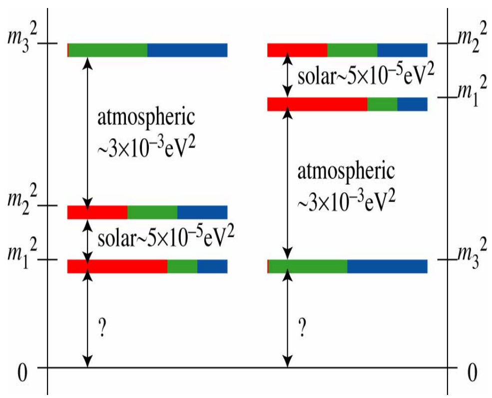
3 light active neutrinos

➔ this cold easily be wrong

- more than 3 N_R states, …

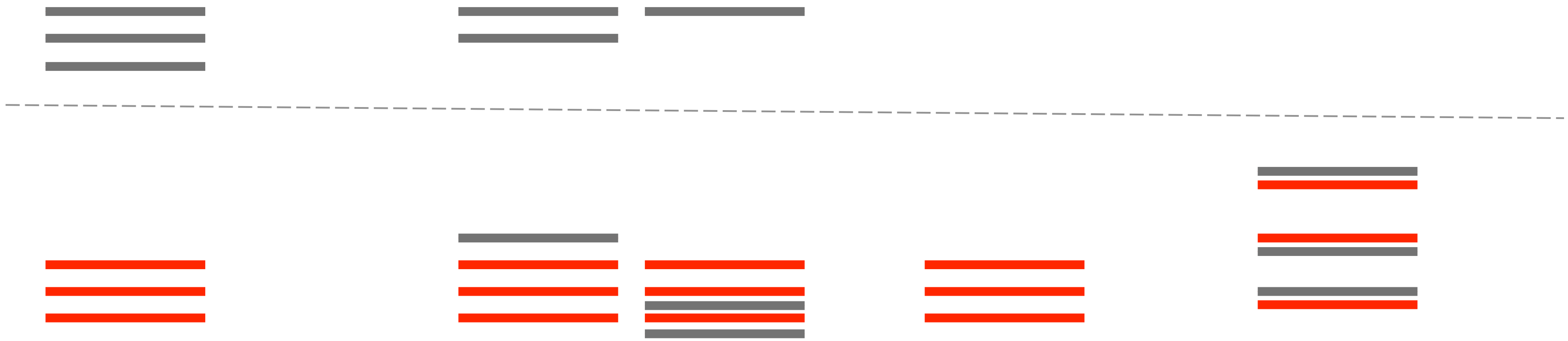
- M_R may have special eigenvalues, …

➔ light sterile neutrinos ?!



Alternative Neutrino Mass Scenarios

$M_L=0$, $m_D = M_W$, M_R=high: see-saw	M_R singular singular-SS	$M_L = M_R = 0$ Dirac	$M_L = M_R = \varepsilon$ pseudo Dirac



Evidences/hints/arguments:

reactor anomaly, LSND, Gallium, MiniBooNE, TeV-EW-fits, keV as WDM, …

Most likely not all true, but one is enough:

VERY IMPORTANT! ➔ tests

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!

Sterile Neutrinos after PLANCK

Are sterile neutrinos excluded? ➔ NO assumptions: thermalization

Planck analysis of 3+1 neutrino scenarios (m_ν^{eff}). Two cases: extra state with T_s or with rescaled spectrum

for $m_{\rm sterile}^{\rm thermal} < 10\,{\rm eV}$

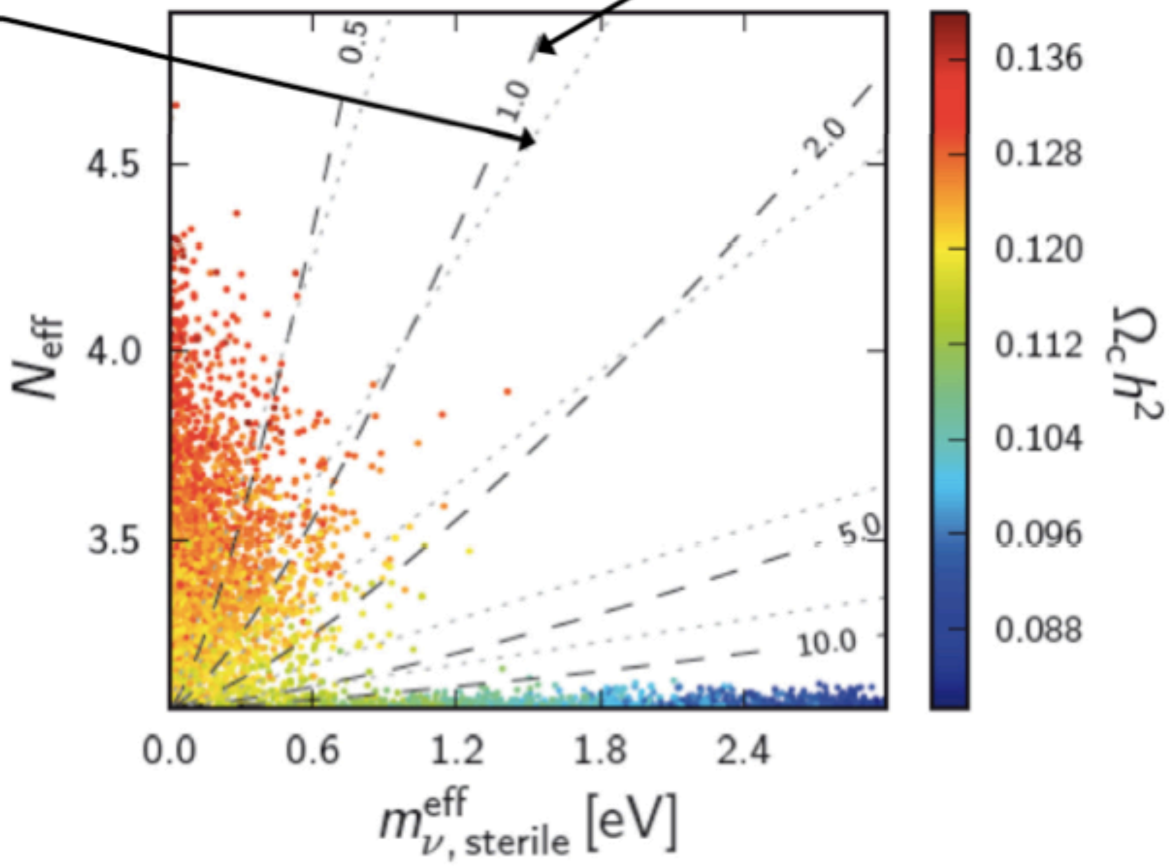
CMB alone (Planck+WP+HighL):

$$N_{\rm eff} < 3.91, \quad m_{\nu,\,\rm sterile}^{\rm eff} < 0.59\,{\rm eV}$$

With BAO:

$$N_{\rm eff} < 3.80, \quad m_{\nu,\,\rm sterile}^{\rm eff} < 0.42\,{\rm eV}$$

All 95% CL



Contours of equal m_ν^{eff}

keV sterile Neutrinos as WDM

The νMSM

Asaka, Blanchet, Shaposhnikov, Asaka, Shaposhnikov

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

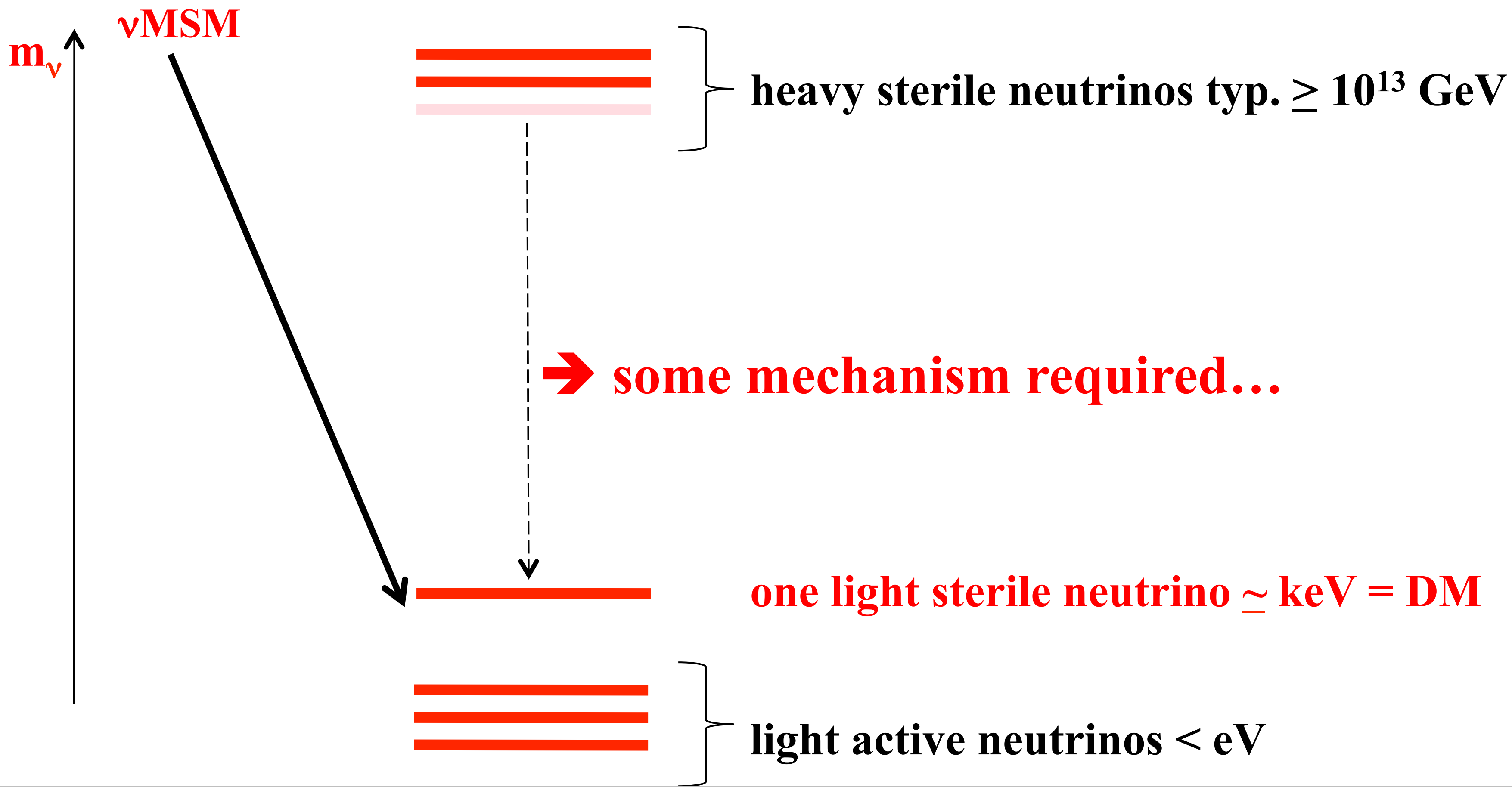
➔ lepton sector more symmetric to the quark sector

➔ 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:

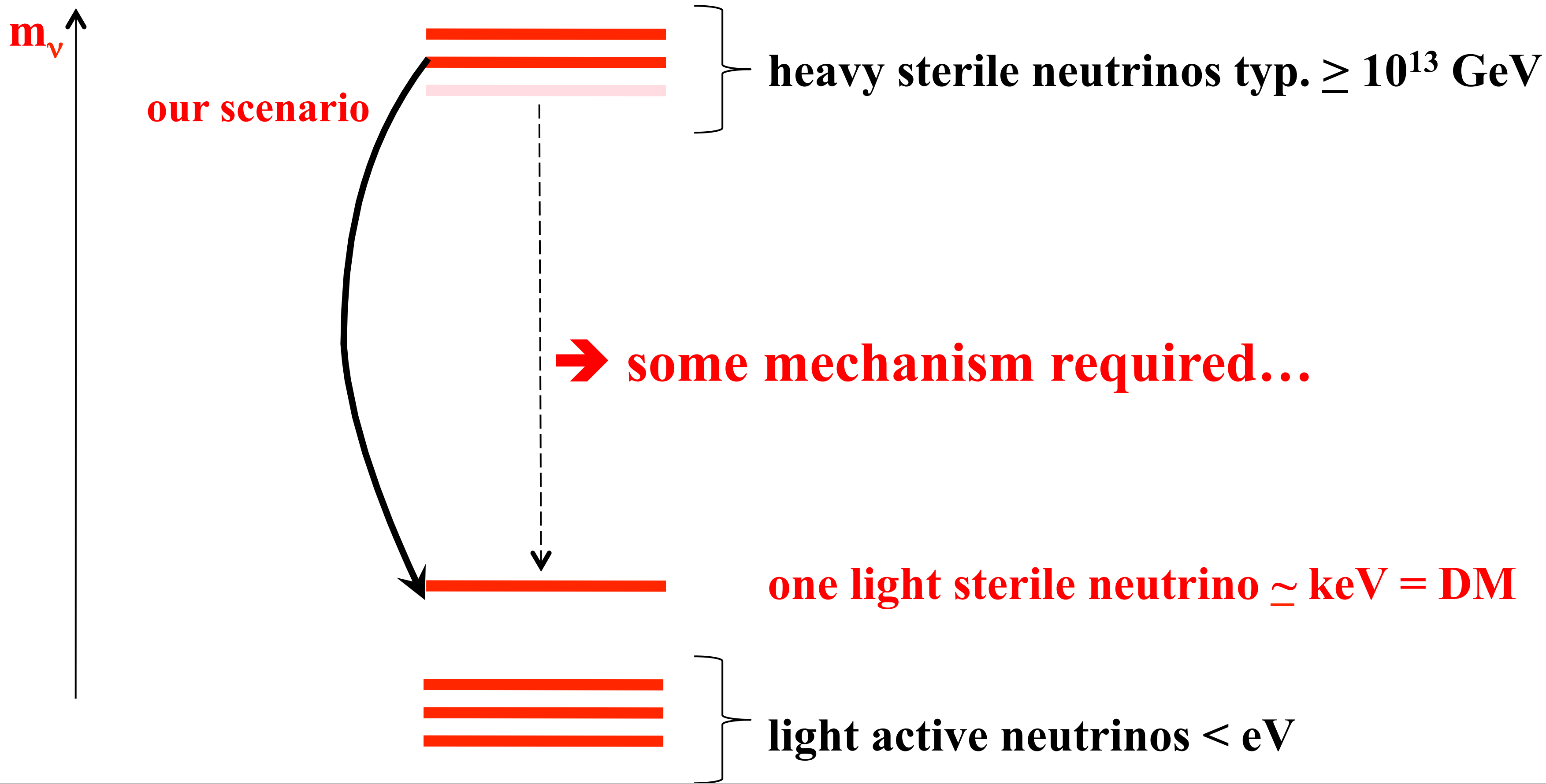
N_1 – Warm Dark Matter

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

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

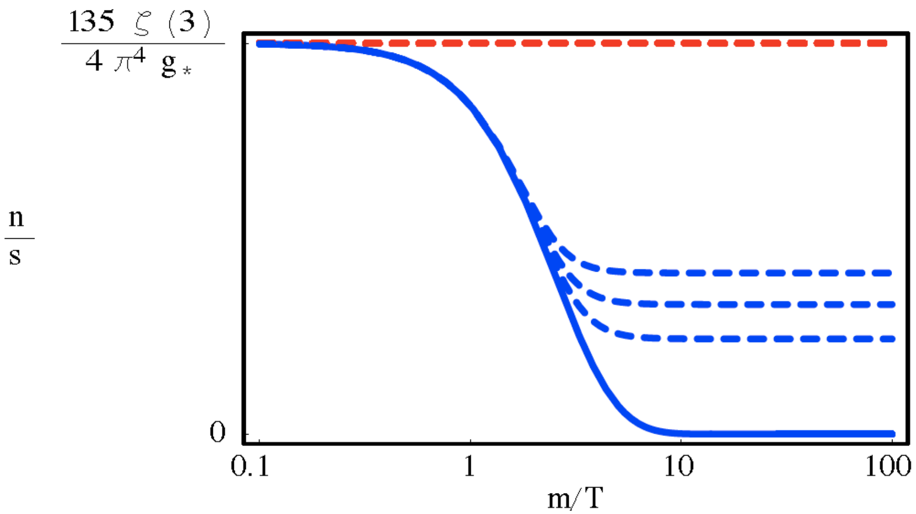
- Mass $M_{2,3} >$ GeV
- Lifetime $\tau_{2,3} \lesssim 0.1$ s

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

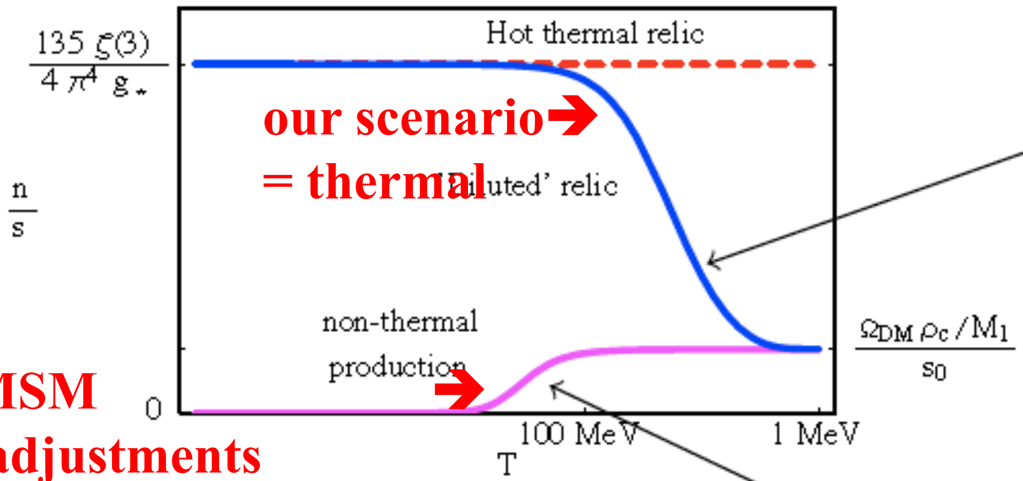
CDM:
(M>>MeV)

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

Decoupled

nonrelativistic

keV sterile neutrinos:



Diluted after decoupling (entropy generated by other particle decay)

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

νMSM
= adjustments

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**

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

➔ **sufficiently long lived** ➔ **become non-relativistic**

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

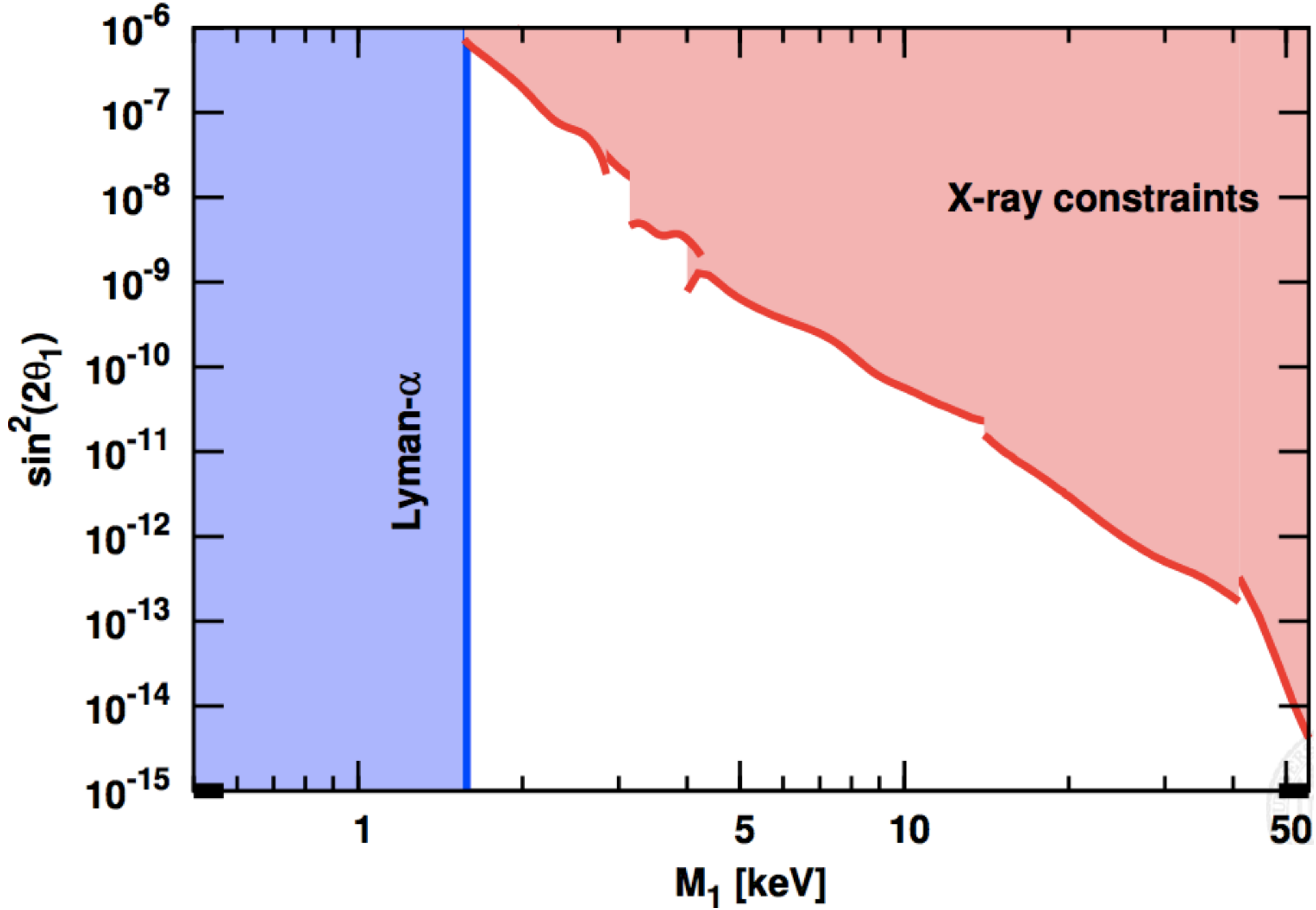
➔ **entropy generation factor** ➔

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

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

➔ **fixes decay width Γ_2**

Allowed Parameter Range



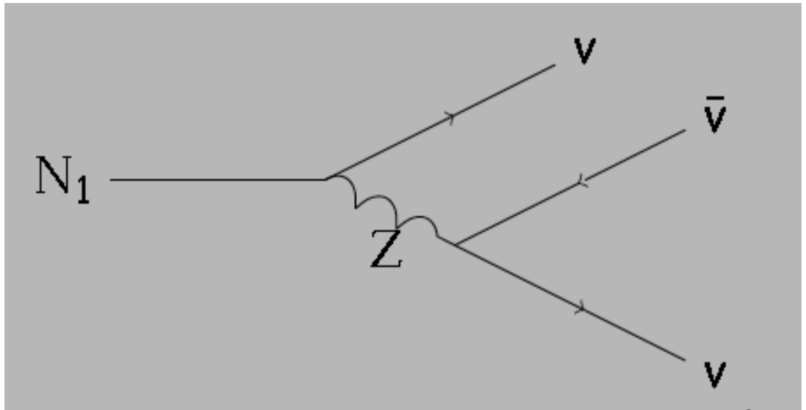
Observing keV-ish Neutrino DM

- **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

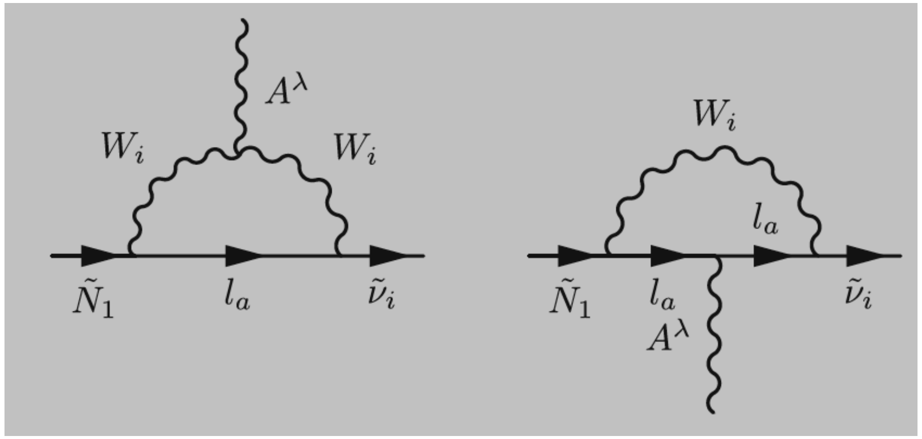
- decay $N_1 \rightarrow \nu\bar{\nu}\nu$, $N_1 \rightarrow \nu\bar{\nu}\bar{\nu}$

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



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

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



➔ photon line $E_\gamma = m_s/2$

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

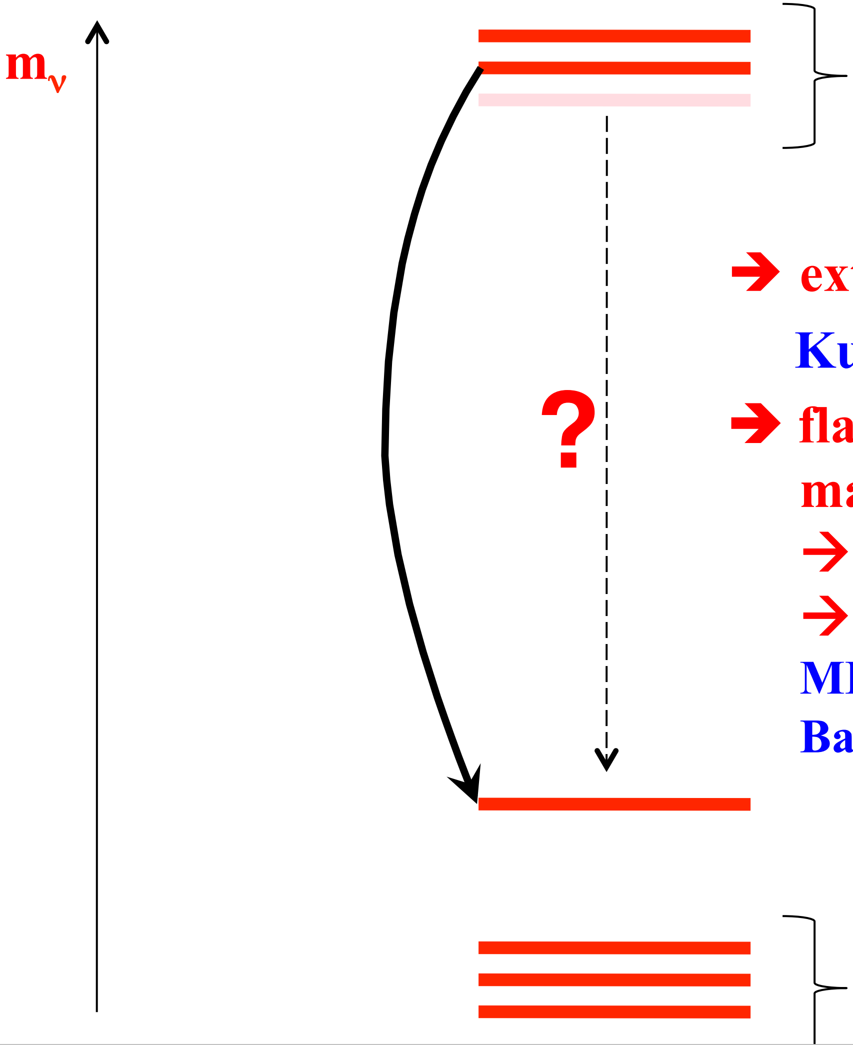
$$\Gamma_{N_1 \to \nu\gamma} \simeq 5.5 \times 10^{-22} \theta_1^2 \left(\frac{M_1}{1 \text{ keV}} \right)^5 \text{s}^{-1}$$

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

- 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. ≥ 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 ; Merle Niro Schmidt

Barry, Rodejohann, Zhang

one light sterile neutrino ≃ 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 with L_e-L_μ-L_τ symmetry:

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

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

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

- **Dirac masses**

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

- **In addition: Triplet masses**

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

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

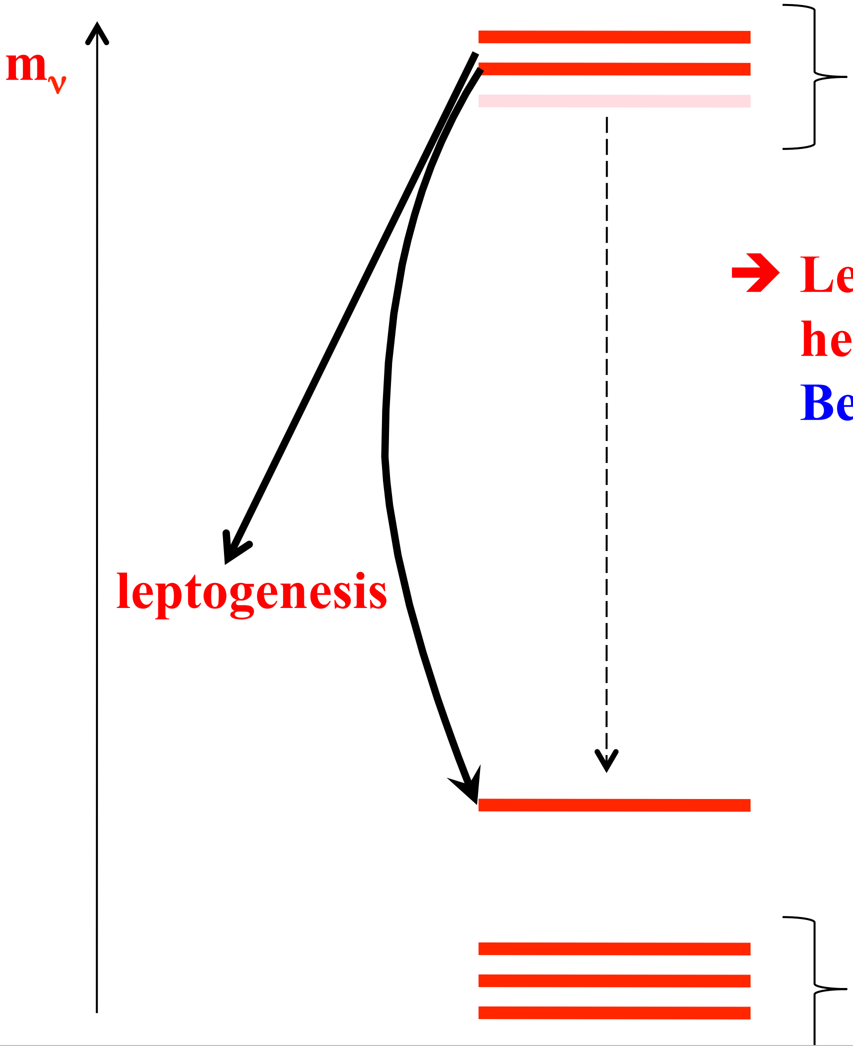
➔ massless sterile state + soft breaking

➔ naturally light sterile ν

➔ mechanism possible in models

Leptogenesis

…there still exist heavy sterile states …



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

➔ Leptogenesis from the decay of the remaining heavy sterile neutrinos works perfectly!
Bezrukov, Kartavtsev, ML

one light sterile neutrino $\simeq$ 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
- Right handed neutrinos probably exist anyway
  ➔ **requires only some mechanism for light sterile mass O(keV)**
- Simplest realization: νMSM ➔ requires non-thermal production
- Our scenario: **Sterile ν's which are charged under some extended gauge group** ➔ abundance from thermal production
- Combination with Leptogenesis ➔ DM + BAU

➔ More general scenarios: any mechanism which 'naturally' explains light sterile neutrinos