Sterile Neutrinos and Dark Matter

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INTERNATIONAL WORKSHOP ON MODELS OF NEUTRINO MASS

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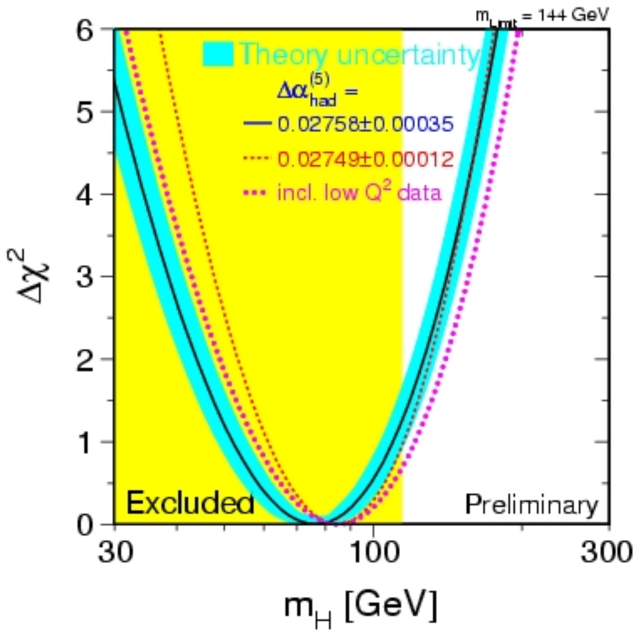
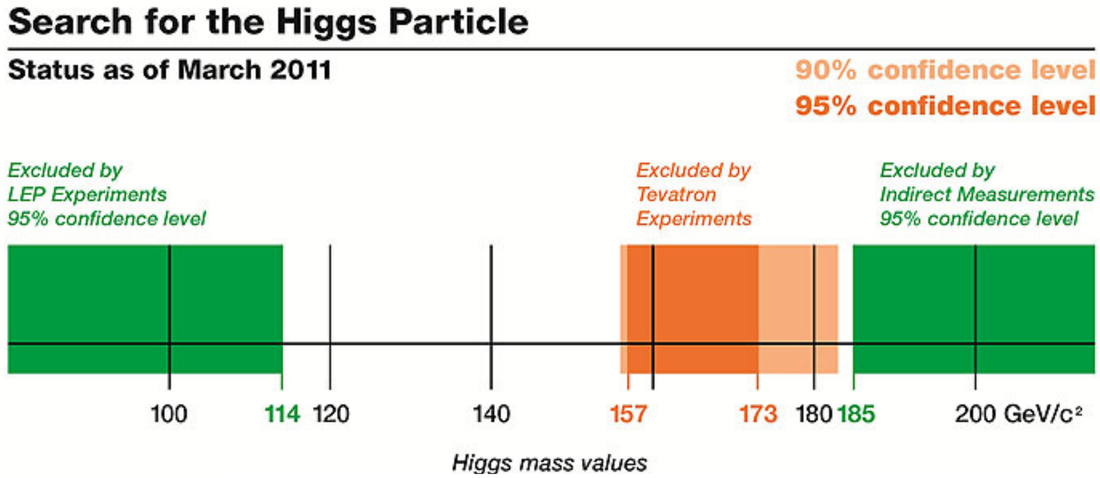
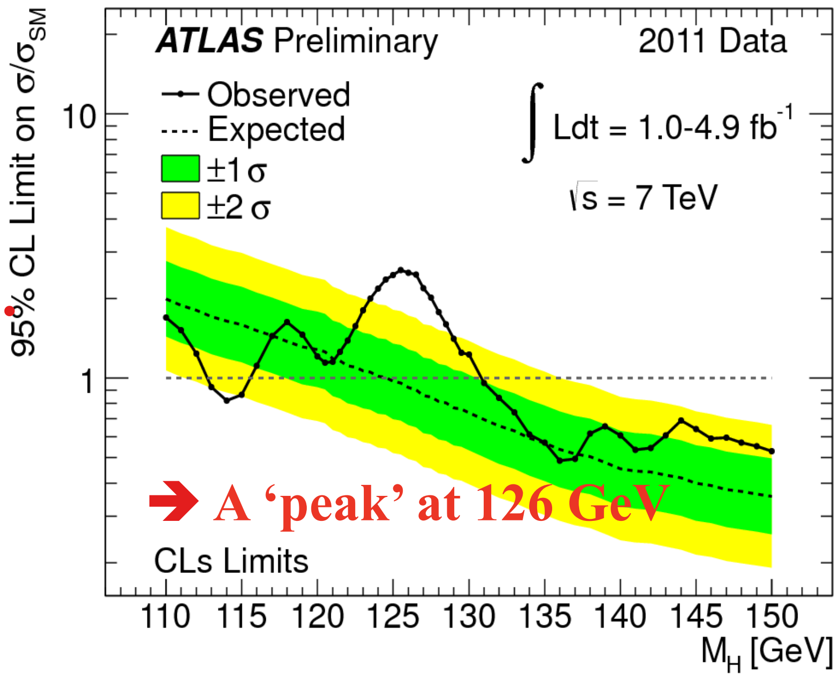
SM works perfectly & Higgs Mass







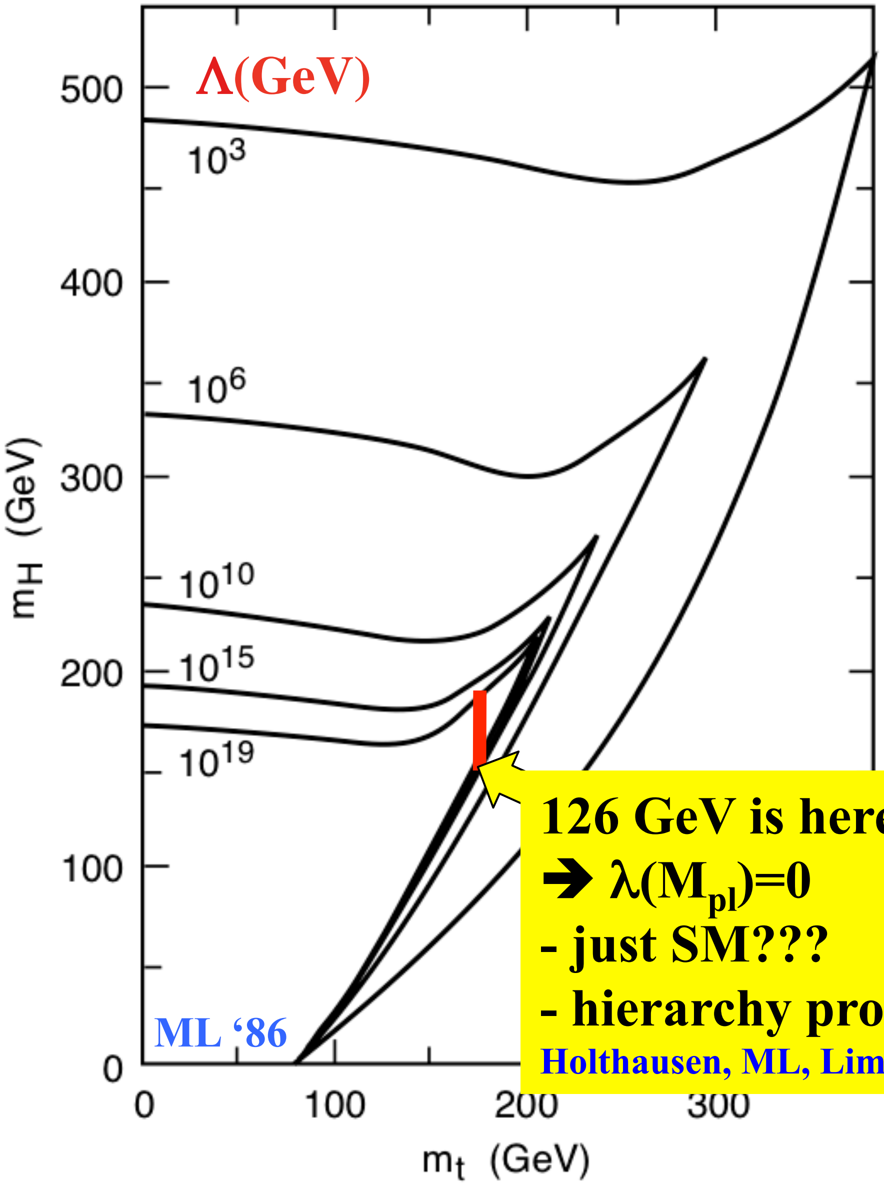
➔ A 'peak' at 126 GeV

- 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

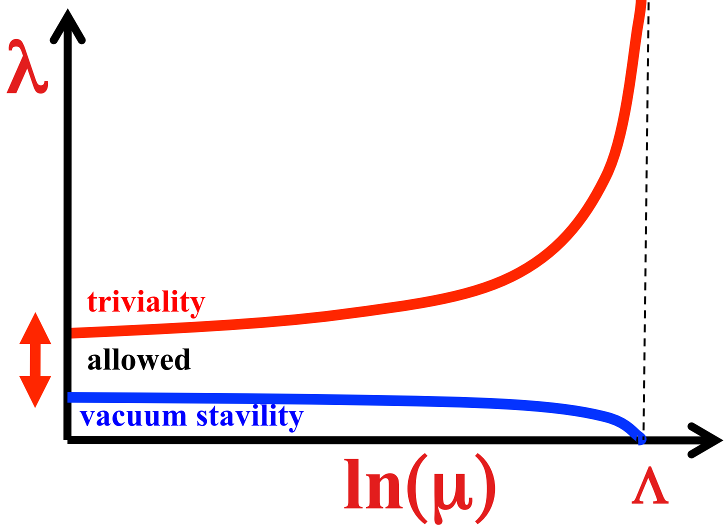


126 GeV is here!
➔ $\lambda(M_{pl})=0$
- just SM???
- hierarchy problem

Holthausen, ML, Lim

126 GeV < m_H < 174 GeV

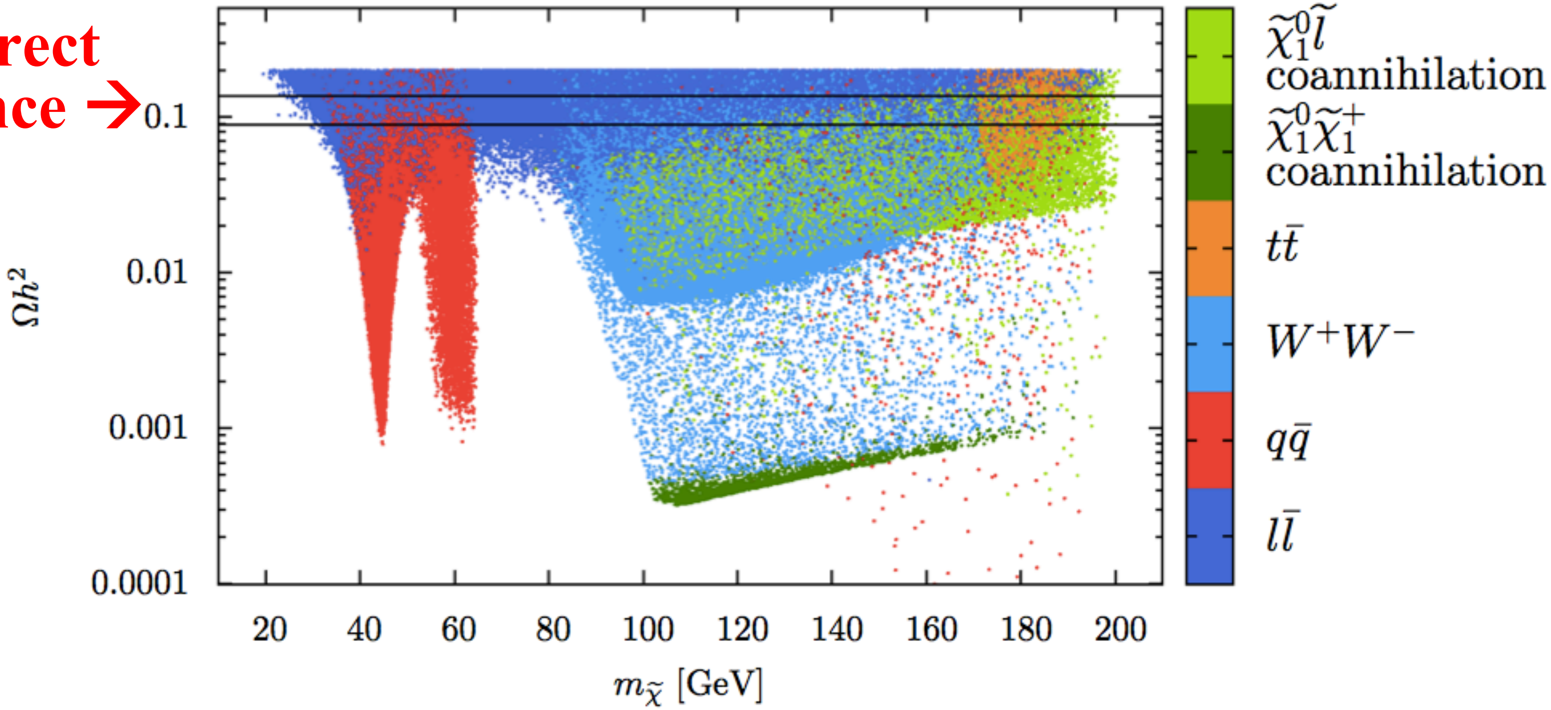
SM does not exist w/o embedding
- U(1) copling , Higgs self-coupling



➔ RGE arguments seem to work
➔ we need some embedding

Dark Matter: The WIMP Scenario

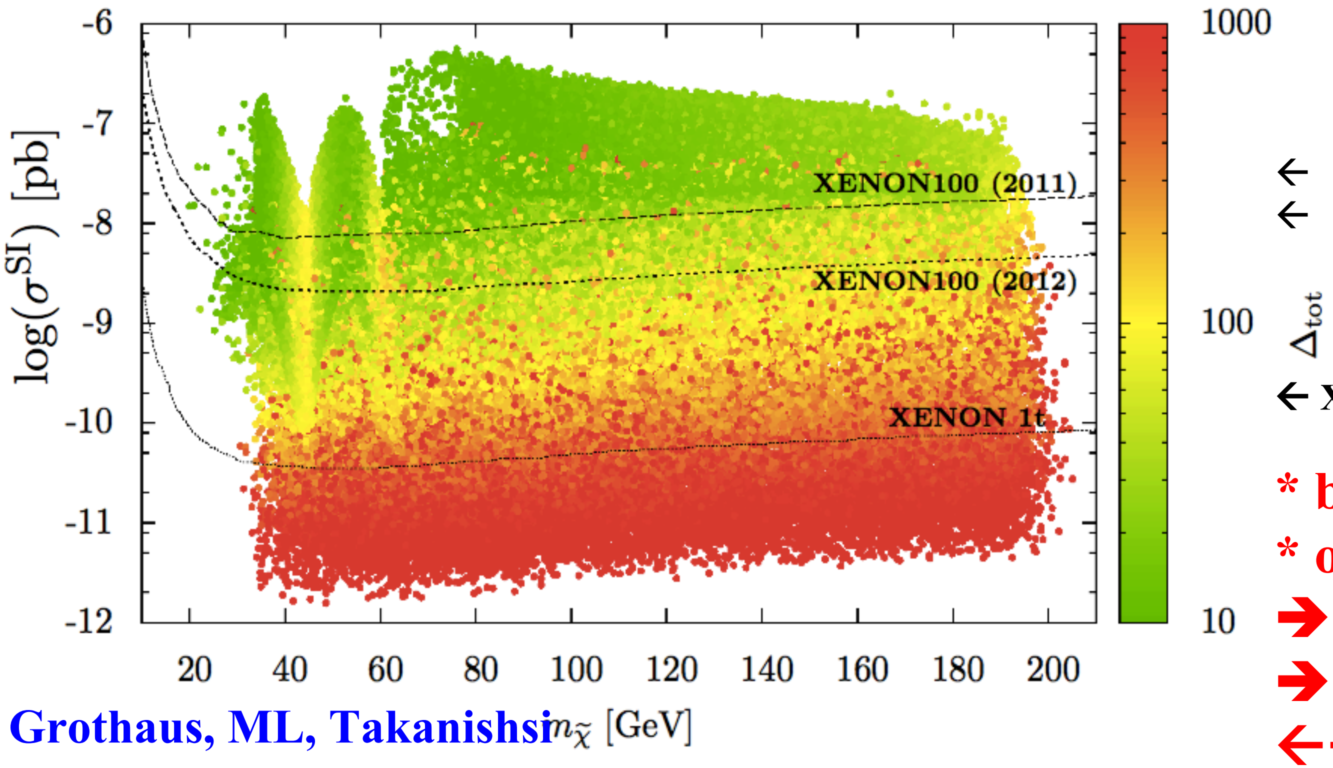
- DM candidates in BSM models
  ←→ hierarchy problem → SUSY: Neutralino
- WIMP miracle → correct abundance
- **MSSM @ EW scale → scan 11 dimensional parameter space:**
  $\tan\beta\,,\, M_1\,,\, M_2\,,\, M_3\,,\, M_A\,,\, \mu\,,\, m_{\tilde{\ell}_L}\,,\, m_{\tilde{\ell}_R}\,,\, m_{\tilde{q}_{1,2}}\,,\, m_{\tilde{q}_3}\,,\, a_0$
- **Pick correct abundance →**



Most favoured Dark Matter: WIMPs

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

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



Grothaus, ML, Takanishsi

← XENON100-2010
← XENON100-2012
← XENON1T

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

New Directions: Asymmetric Dark Matter

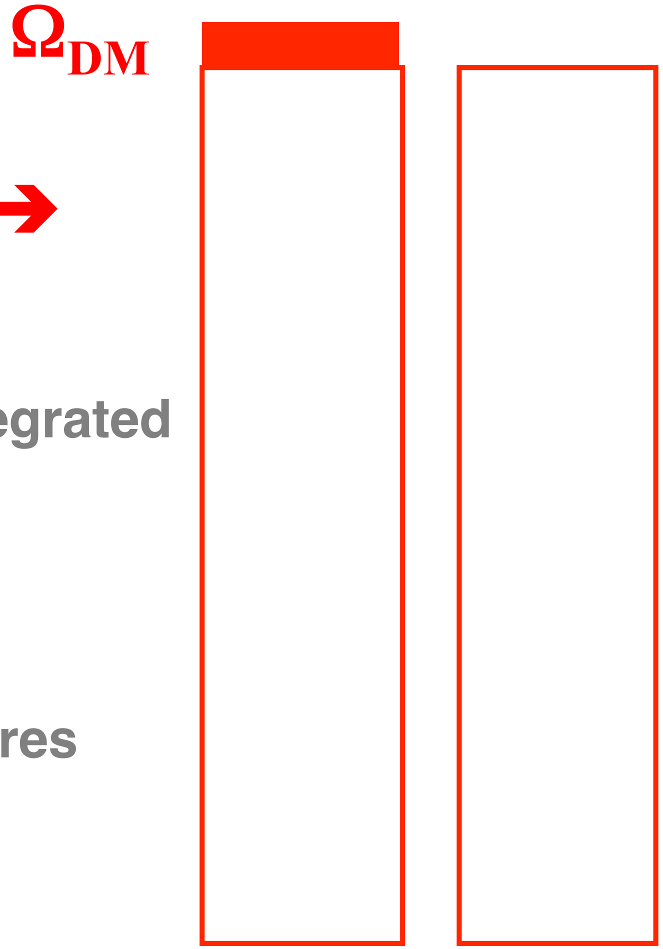
➔ Why is $\Omega_{DM} \simeq 5 * \Omega_{baryonic}$? (a factor 5 or 500?)

matter anti-matter

← 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

➔ new physics…



dark anti-dark

The SM works perfect but must be extended….

- **Many theoretical reasons for BSM physics:**
  - Hierarchy problem
    - separation of two scalar scales… SUSY, TeV physics
    - Planck scale physics: New concepts … ???
  - strong CP (axions), …
    - ➔ but experimentally no sign… ?
- **Experimental facts:**
  - SM cannot explain Baryon Asymmetry of the Universe
    - BUT: neutrino masses require SM extension ➔ SM+➔
    - leptogenesis = one of the best BAU explanations → OK
  - Dark Matter
    - some extra particle is needed which is DM
    - particles connected to the hierarchy problem, strong CP, …
    - massive neutrinos require new physics ←→ DM?

Most minimalistic: DM & Neutrino Mass

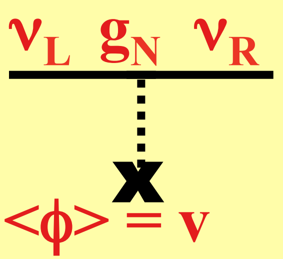
New Physics: Neutrino Mass Terms

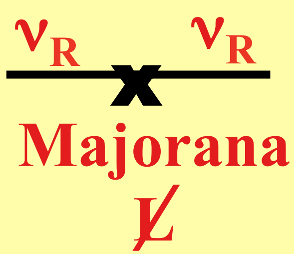
SM ~m$\phi\bar{L}$R = (2,1)

→ 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. $\geq 10^{13}$ GeV

➔ leptogenesis, role in GUTs, …

> **Some mechanism which makes 1, 2, … heavy states light?**
> **➔ light sterile neutrino(s)**
> **➔ tiny heavy-light mixing expected $\theta^2 < O(m_\nu/m_s)$**

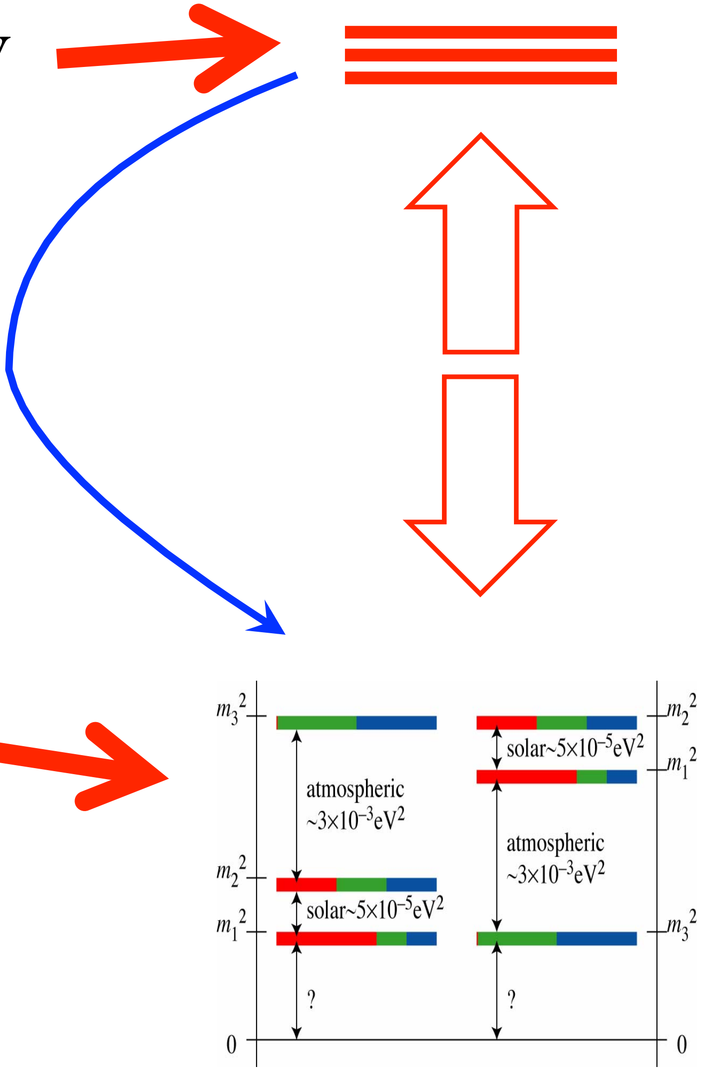
3 light active neutrinos

➔ 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… ➔ sterile ν's?
➔ New and better data / experiments are needed to clarify the situation
➔ eV scale and mixings up to a few percent

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

BBN: $N_\nu \simeq 3.7 \pm 1$ E. Aver, K. Olive, E. Skillman, Y. Izotov, T. Thuan

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, …

- Evidences point to different sterile states
- Most likely not all of them are true! ➔ consequences?
- Take all conceivable sterile scenarios serious!

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 sterile Neutrinos as WDM

The νMSM

Asaka, Blanchet, Shaposhnikov, Asaka, Shaposhnikov

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

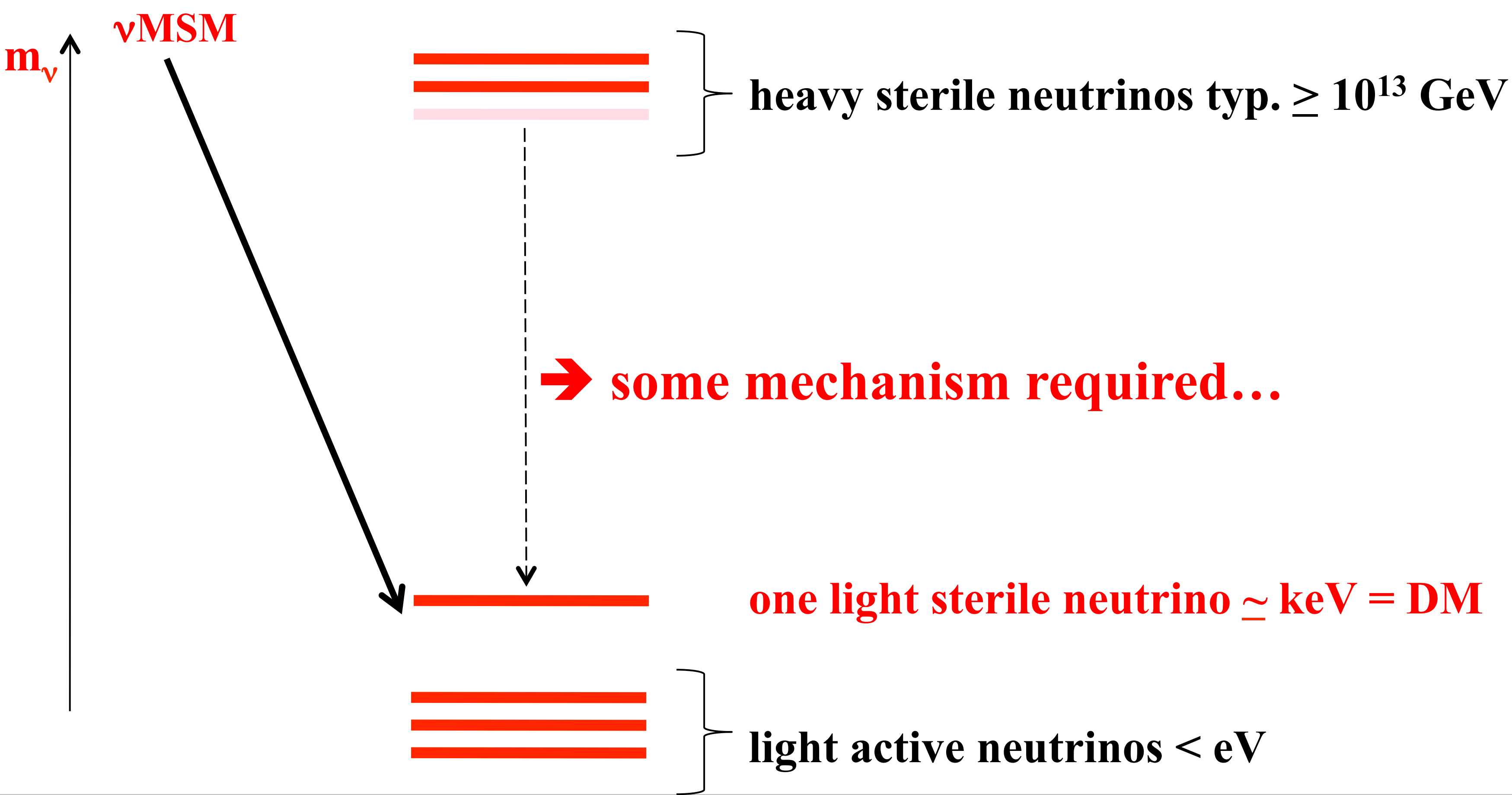
➔ lepton sector more symmetric to the quark sector

➔ 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



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:

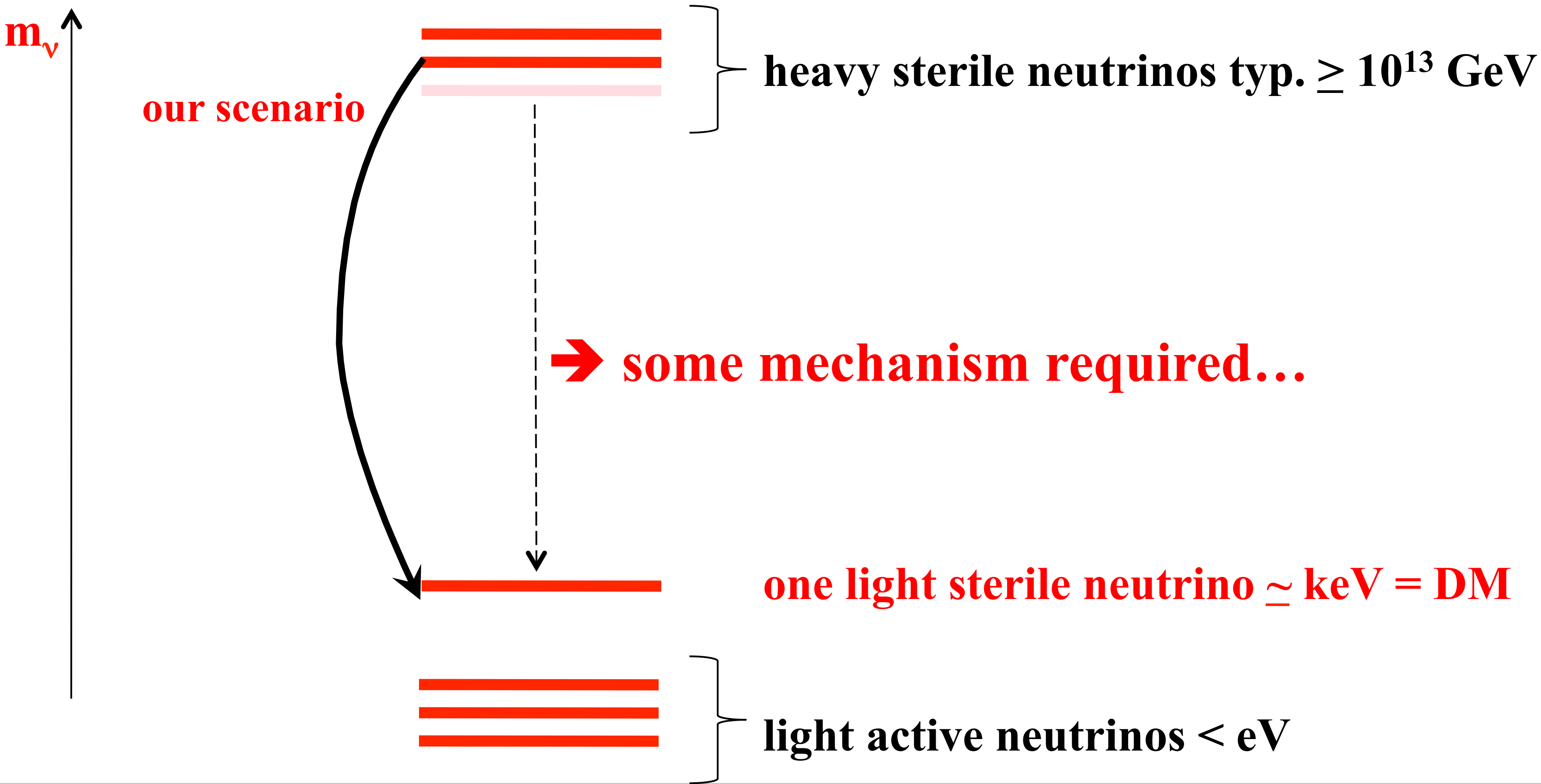
N_1 – Warm Dark Matter

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

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

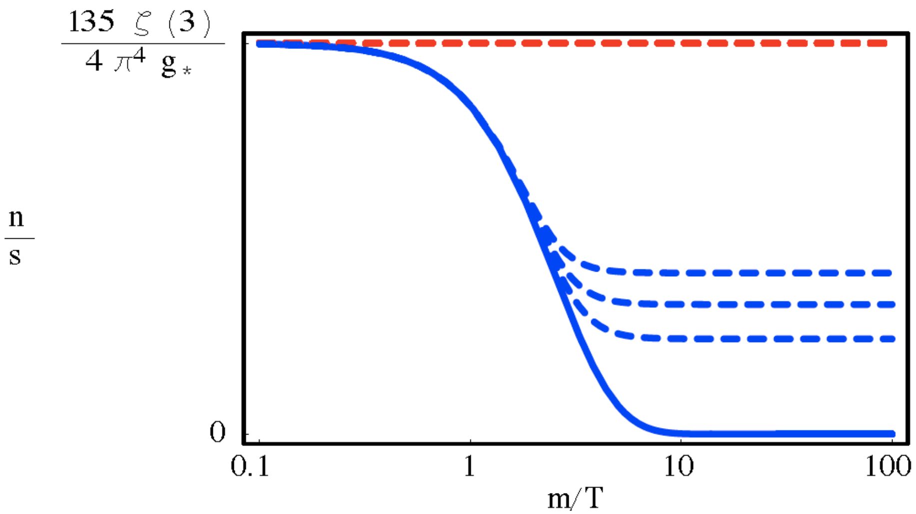
- Mass $M_{2,3} >$ GeV
- Lifetime $\tau_{2,3} \lesssim 0.1$ s

Thermal production of the correct abundance in our model:



Obtaining the correct Abundance

Usual thermal WIMP case:



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

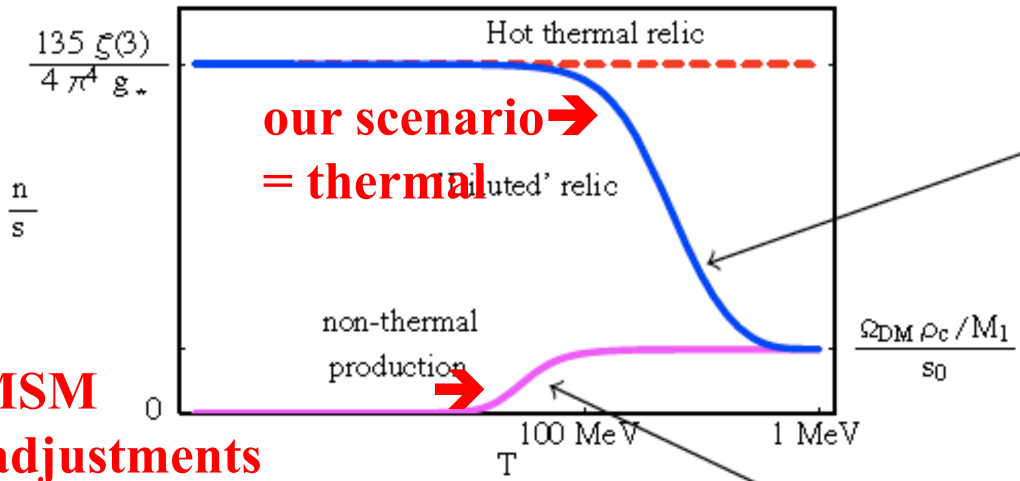
Decoupled relativistic

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

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

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

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

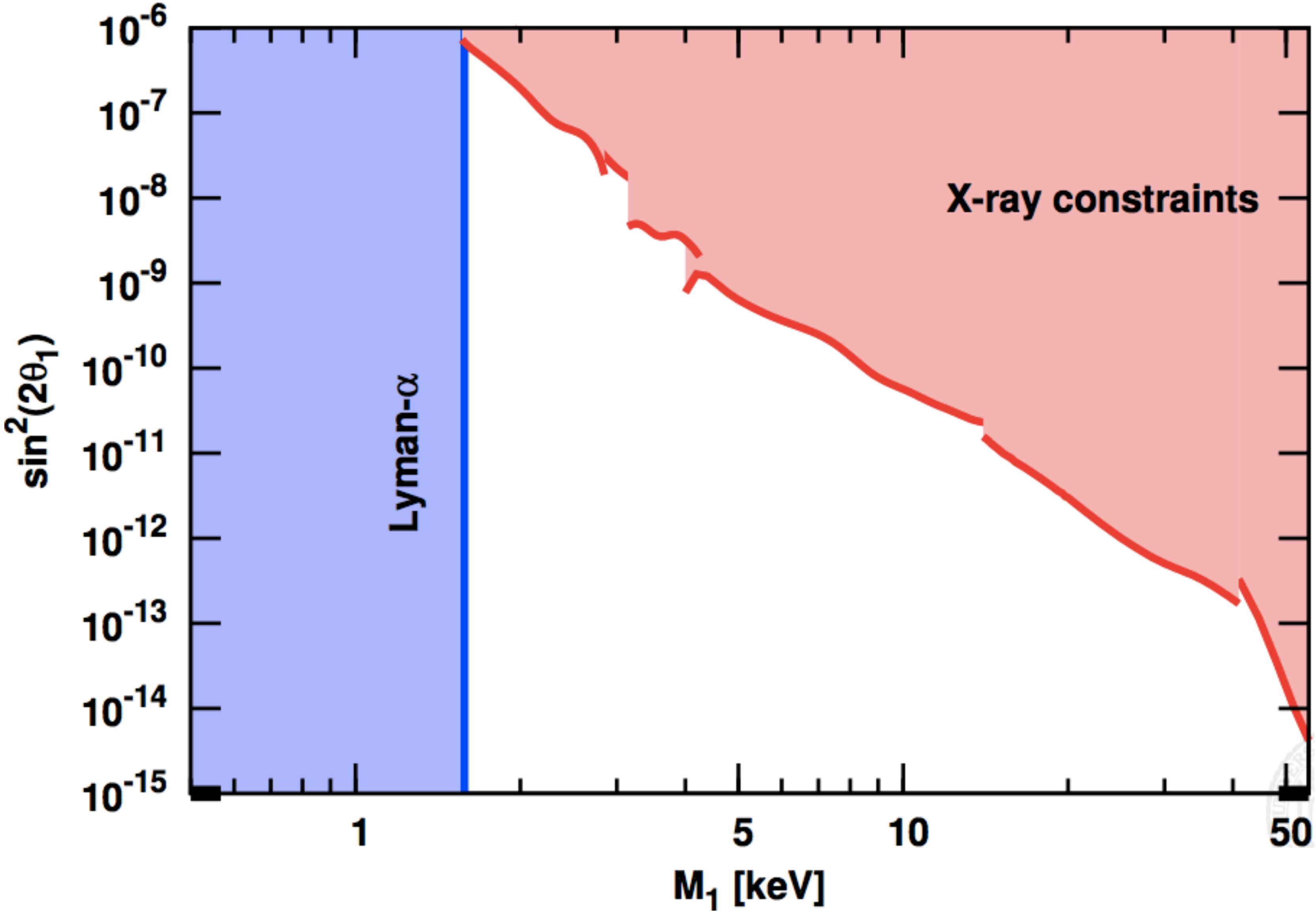
➔ **entropy generation factor ➔**

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

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

➔ **fixes decay width Γ_2**

Allowed Parameter Range

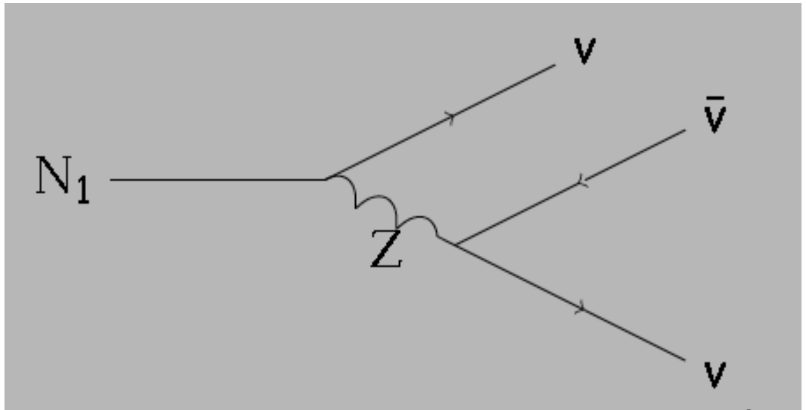


Observing keV-ish Neutrino DM

- **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

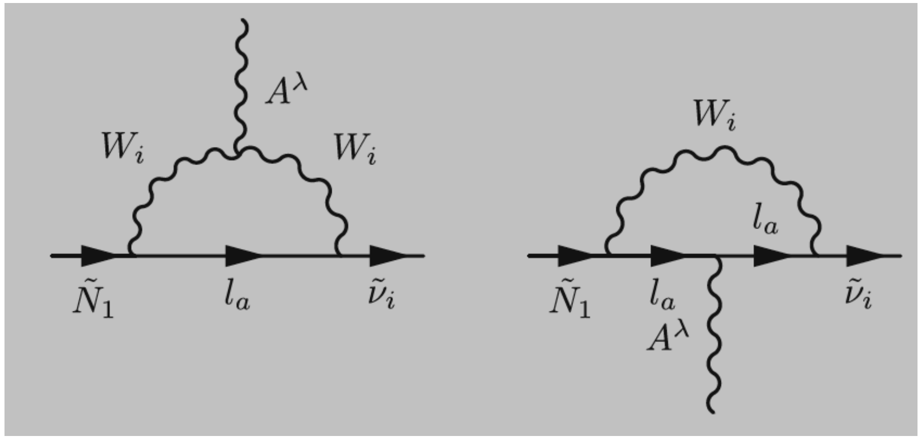
  - decay $N_1 \rightarrow \nu\bar{\nu}\nu$, $N_1 \rightarrow \nu\bar{\nu}\bar{\nu}$
  - not very constraining since $\tau \gg \tau_{Universe}$



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

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

  ➔ photon line $E_\gamma = m_s/2$



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

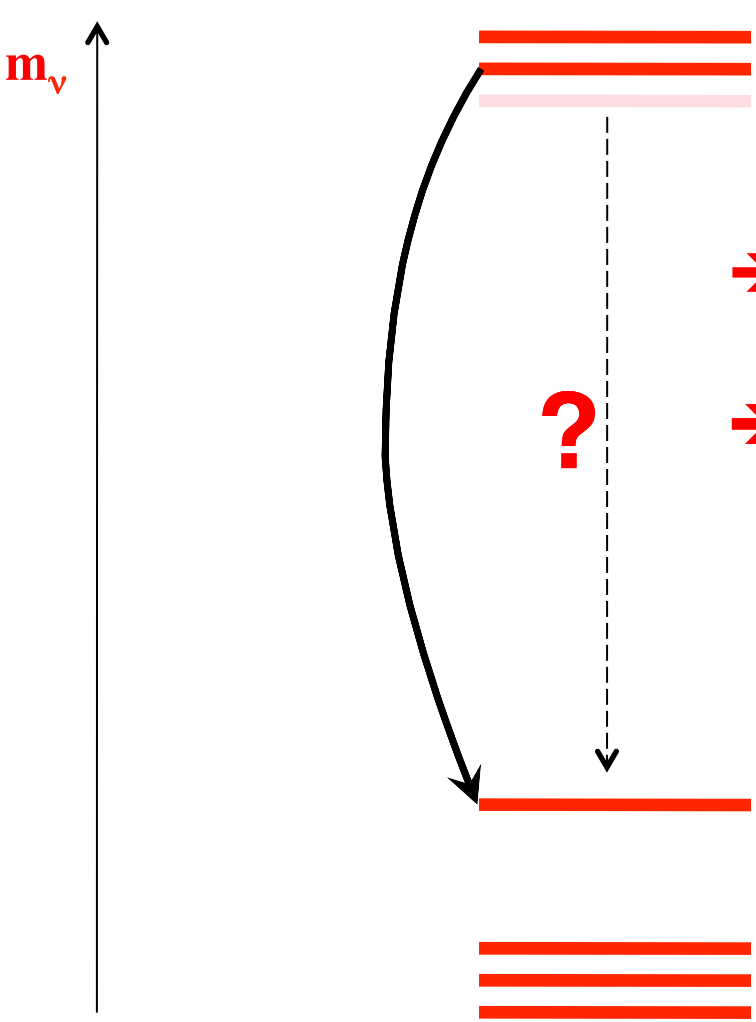
$$\Gamma_{N_1 \to \nu\gamma} \simeq 5.5 \times 10^{-22} \theta_1^2 \left(\frac{M_1}{1\ \text{keV}} \right)^5 \text{s}^{-1}$$

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

- 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,
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:

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

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

$\det(M_{ij}) = 0$ ➔ $M_1 = 0$

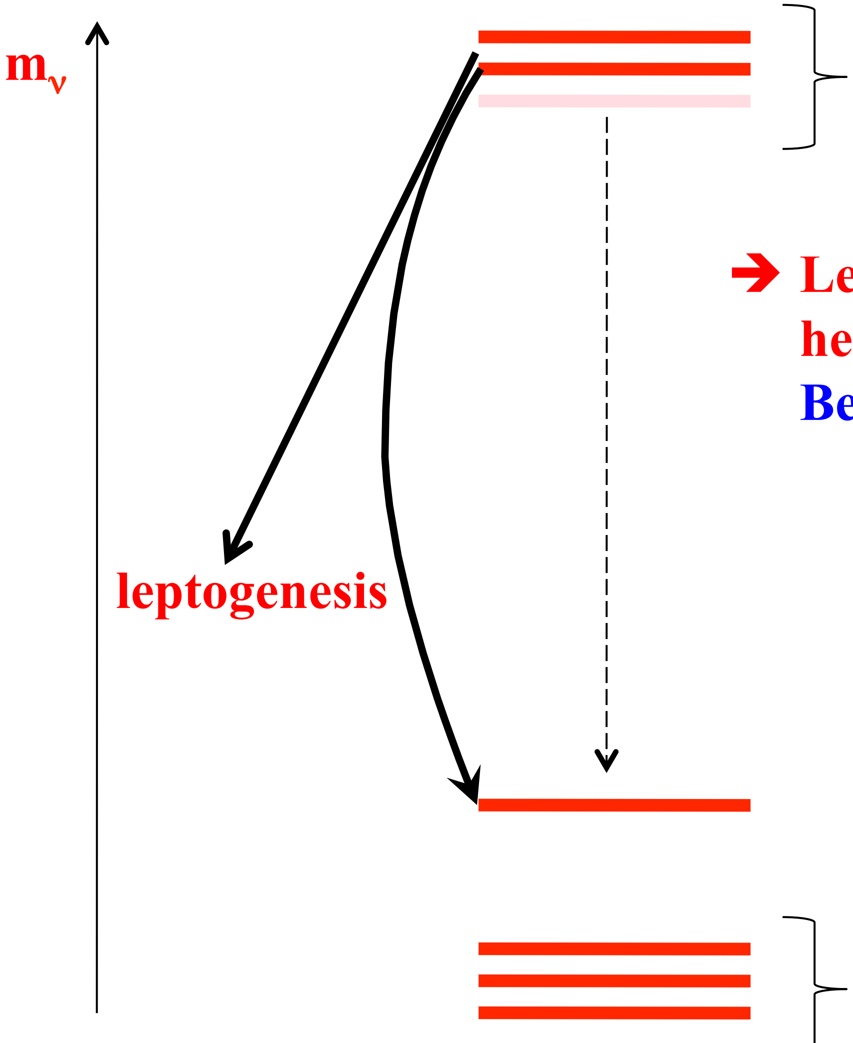
➔ massless sterile state + soft breaking

➔ 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-massesr**
- **Right handed neutrinos probably exist**
  → 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**
  → interesting constrains
  - small mixings from X-ray constraints and entropy generation (DM abundance)
  - masses bound by BBN

→ Combination with Leptogenses → BAU

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