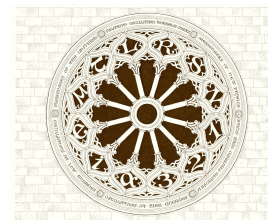


Sterile Neutrinos and Dark Matter

Manfred Lindner



NOW 2012

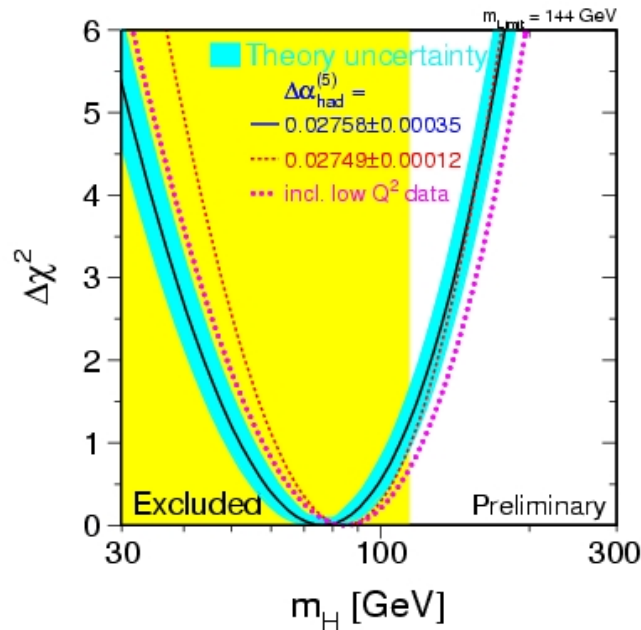


Neutrino Oscillation Workshop

Conca Specchiulla (Otranto, Lecce, Italy)

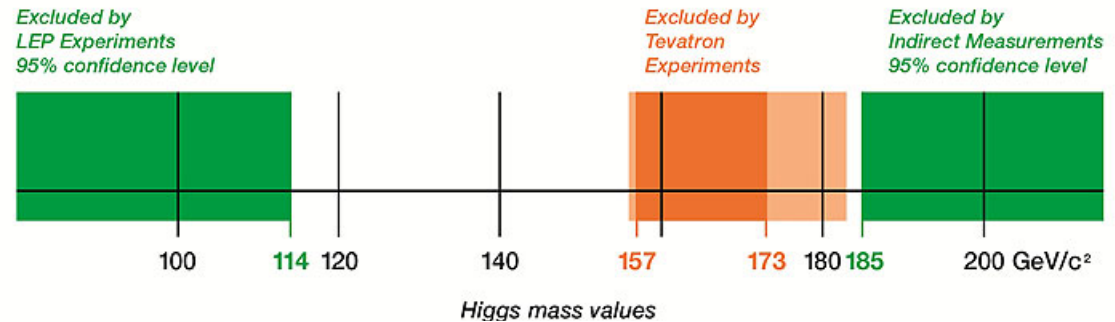
September 9-16, 2012

SM works perfectly & Higgs Mass

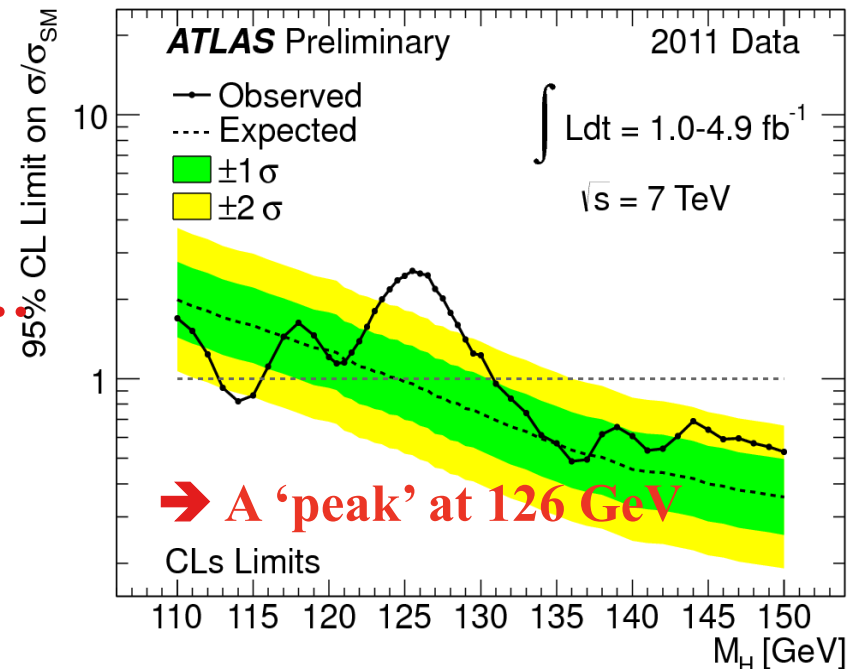


Search for the Higgs Particle

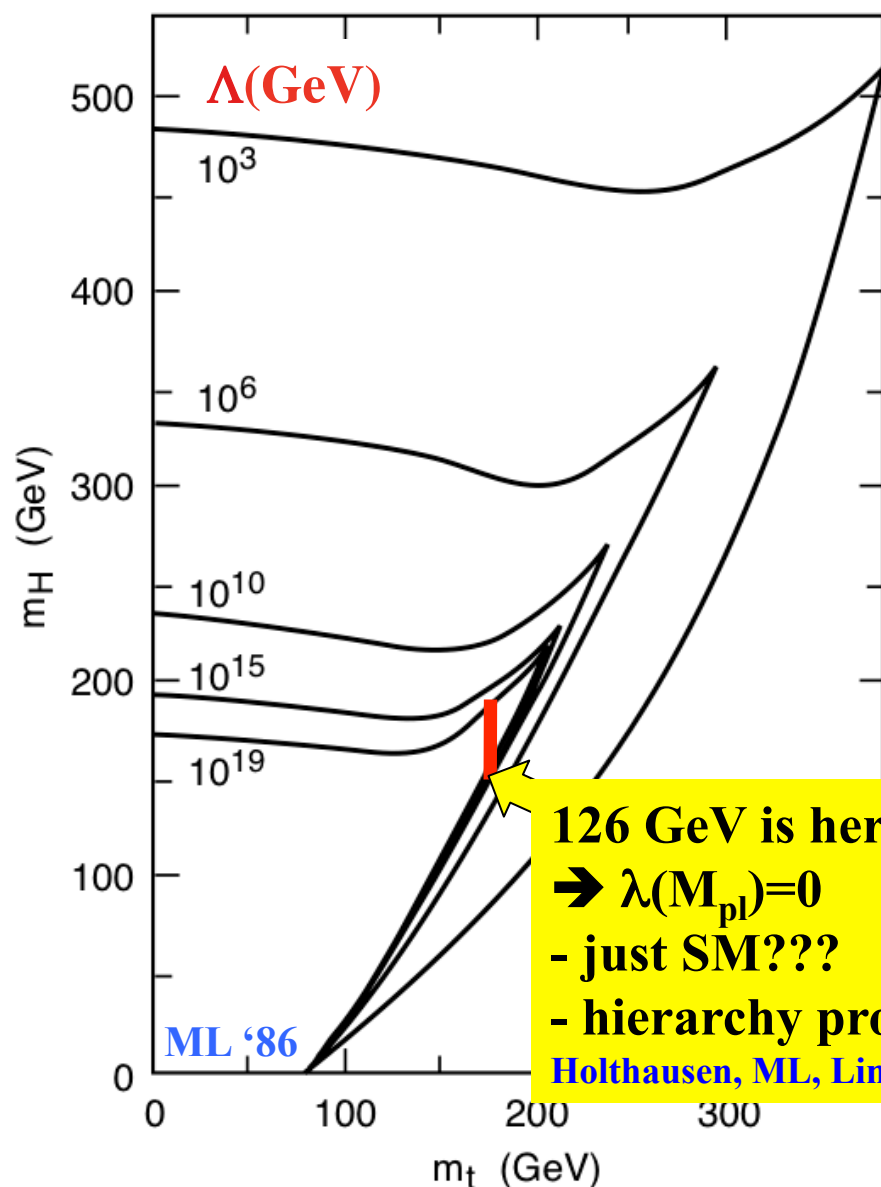
Status as of March 2011



- allowed mass range is shrinking...
- if SM Higgs exists → light
- no (clear) signs for anything else
- just the SM?
- Dark Matter?

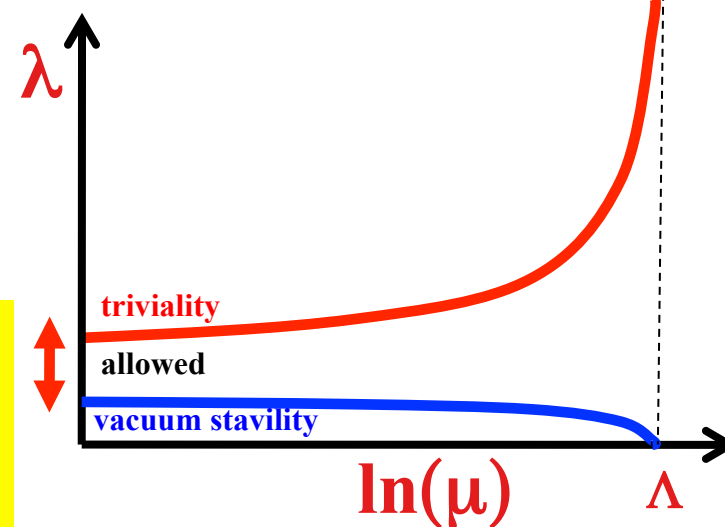


Triviality and Vacuum Stability



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

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



$\rightarrow$ RGE arguments seem to work
 $\rightarrow$ 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**

BUT: Massive neutrinos require SM extension → SM+

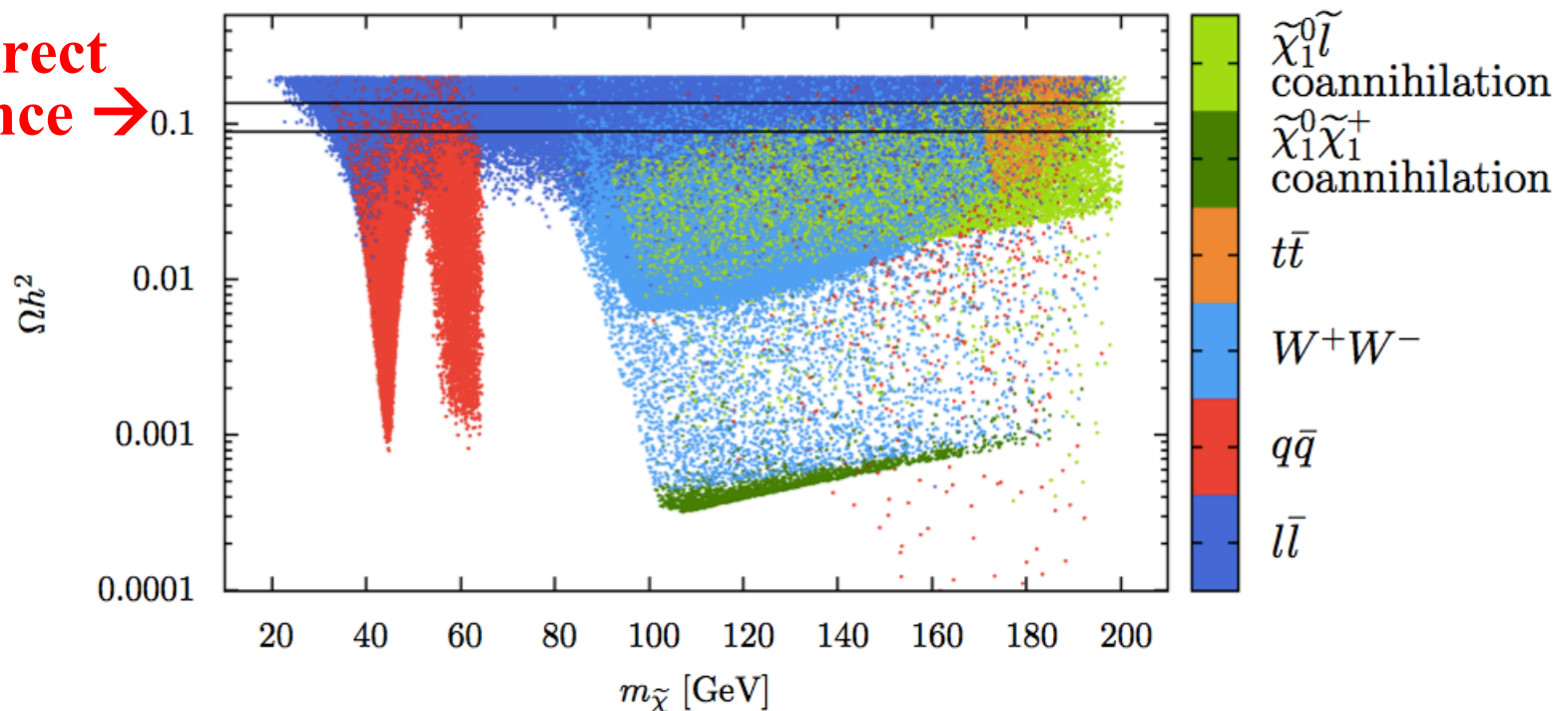
→ leptogenesis = one of the best BAU explanations

→ 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 $\leftrightarrow$ DM?

The SUSY WIMP Scenario

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

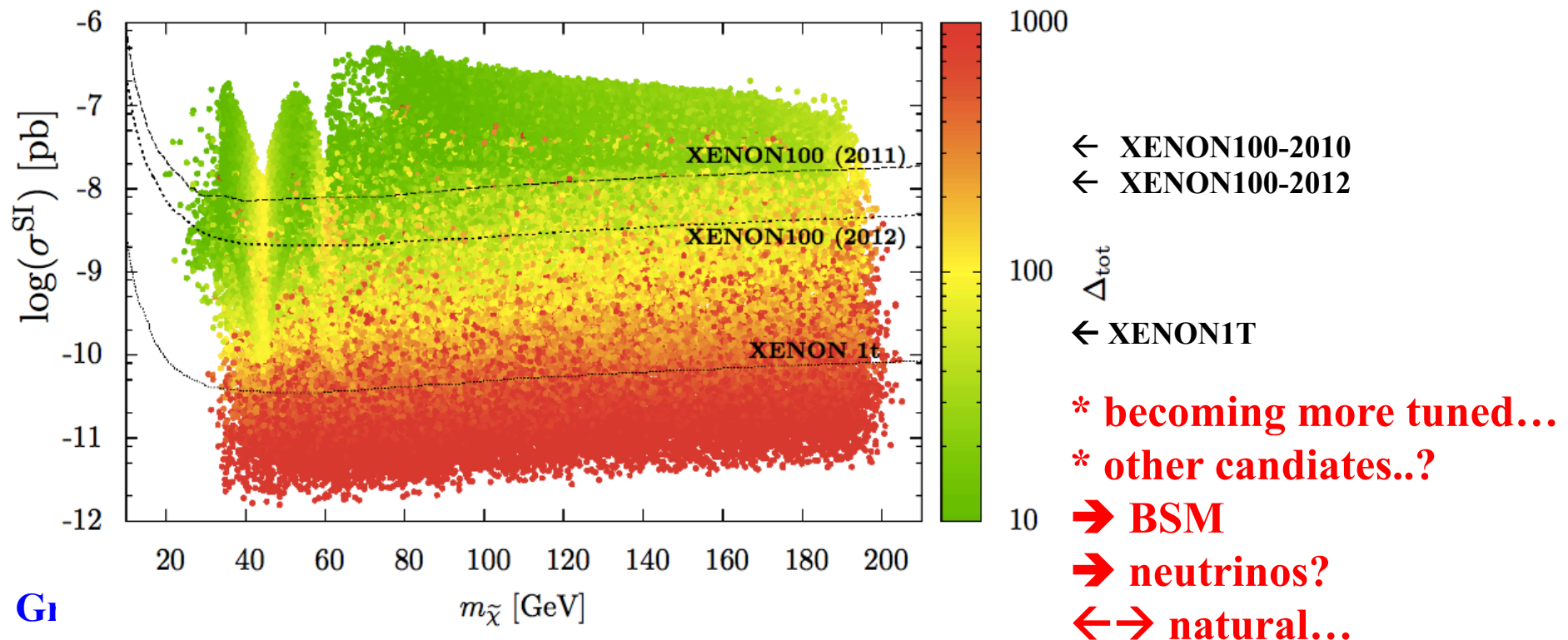
- **Pick correct abundance $\rightarrow$**



Most favoured Dark Matter: WIMPs

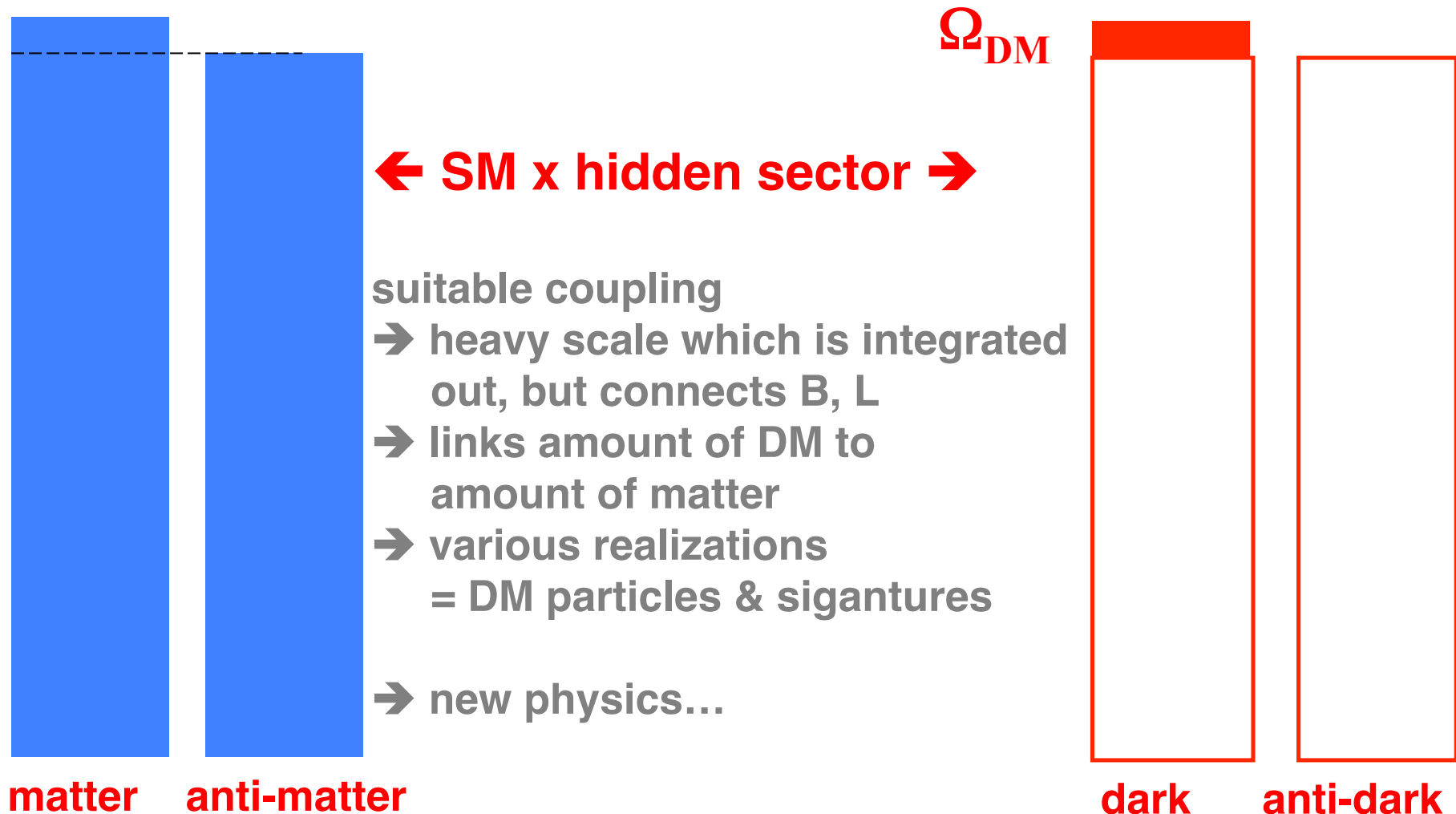
- **MSSM neutralino: Level of fine-tuning $\rightarrow \Delta_{\text{tot}}$**

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



New Directions: Asymmetric Dark Matter

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



Most minimalistic: DM & Neutrino Mass

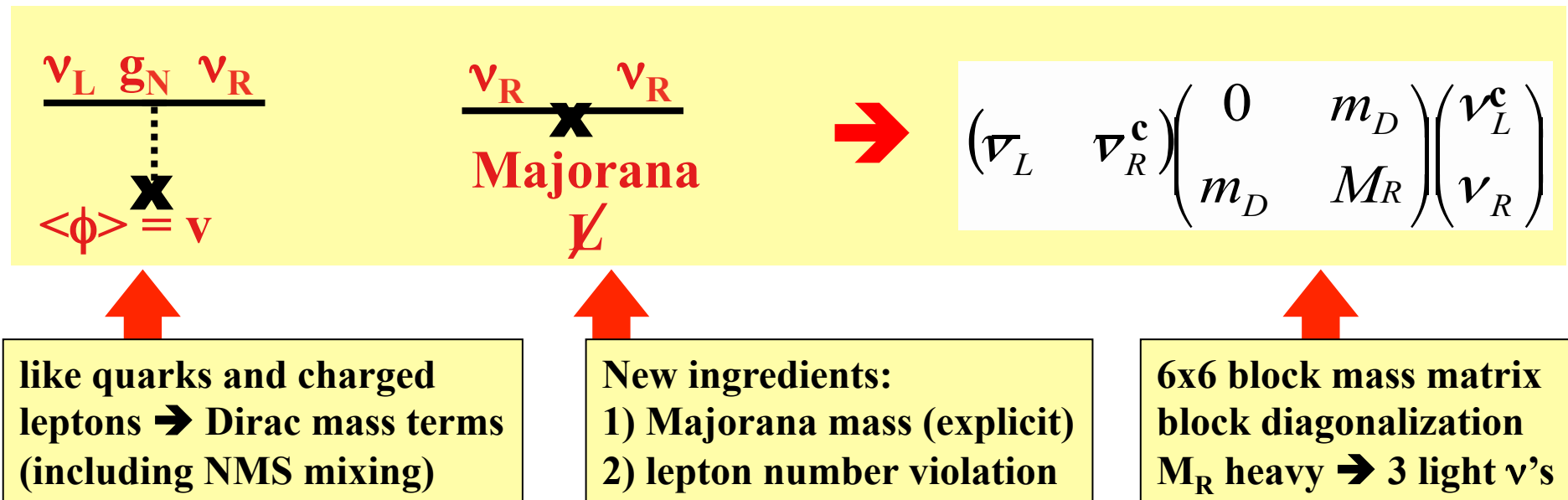
New Physics: Neutrino Mass Terms

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

→ 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
$r_\nu ???$	1	1	0
r_e	1	1	-2



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

The Neutrino Spectrum

The standard picture:

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
 $\theta^2 < O(m_v/m_s)$

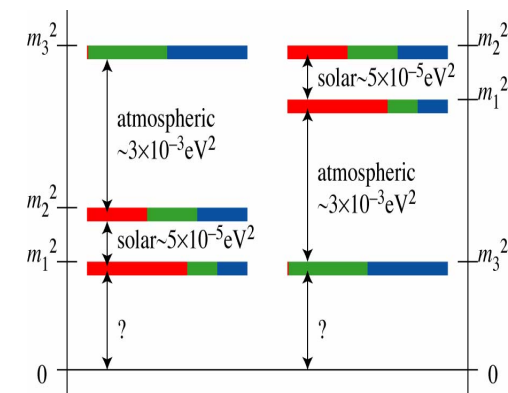
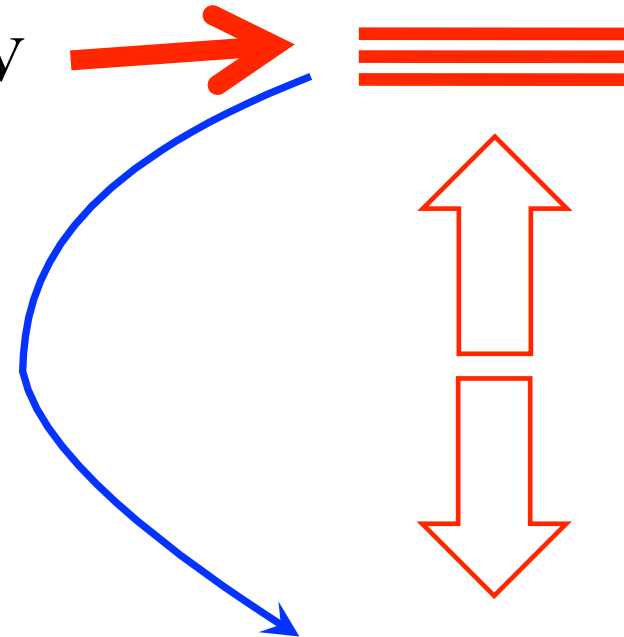
3 light active neutrinos

→ this could 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?

- 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 $M_X \simeq \text{few keV}$ 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 ν MSM

Asaka, Blanchet, Shaposhnikov, Asaka, Shaposhnikov

Particle content:

- Gauge fields of $SU(3)_c \times SU(2)_W \times U(1)_Y$: $\gamma, W_{\pm}, Z, g$
- Higgs doublet: $\Phi=(1,2,1)$

• Matter

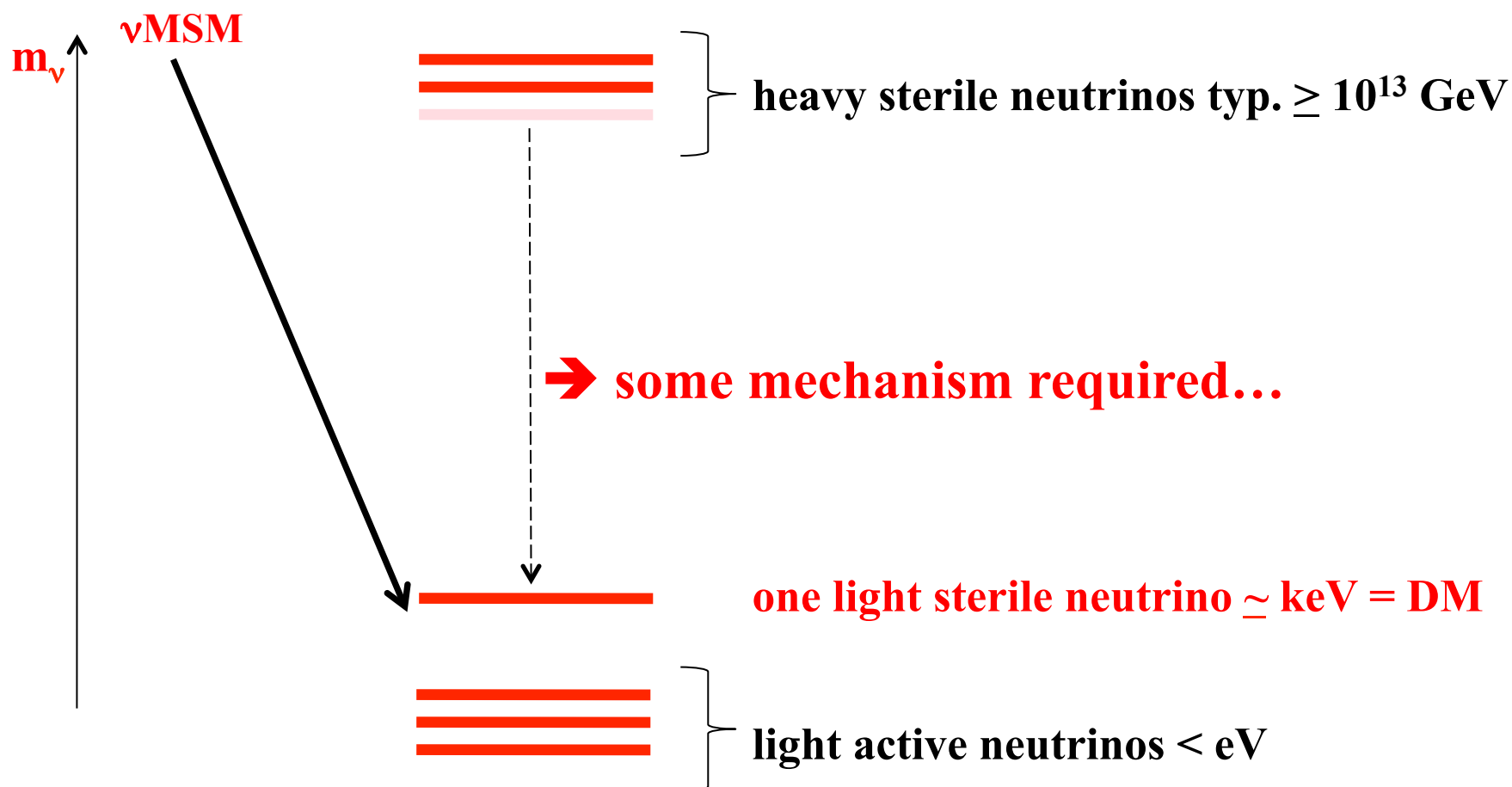
	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{em}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	3	2	+1/3	$\begin{pmatrix} +2/3 \\ -1/3 \end{pmatrix}$
u_R	3	1	+4/3	+2/3
d_R	3	1	-2/3	-1/3
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	1	2	-1	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
e_R	1	1	-2	-1
N	1	1	0	0

x3 generations

- lepton sector more symmetric to the quark sector
- Majorana masses for N
- choose for one sterile $\nu \sim \text{keV}$ mass → exceeds lifetime of Universe

Virtue and Problem of the ν MSM

- ν MSM:** Scenario with sterile ν and tiny mixing $\rightarrow$ never enters thermal equilibrium
- $\rightarrow$ requires **non-thermal production** from other particles (avoid over-closure)
 - $\rightarrow$ **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 $\rightarrow$ scale M ($\sim$ 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 ($\sim$ right-handed) neutrinos:

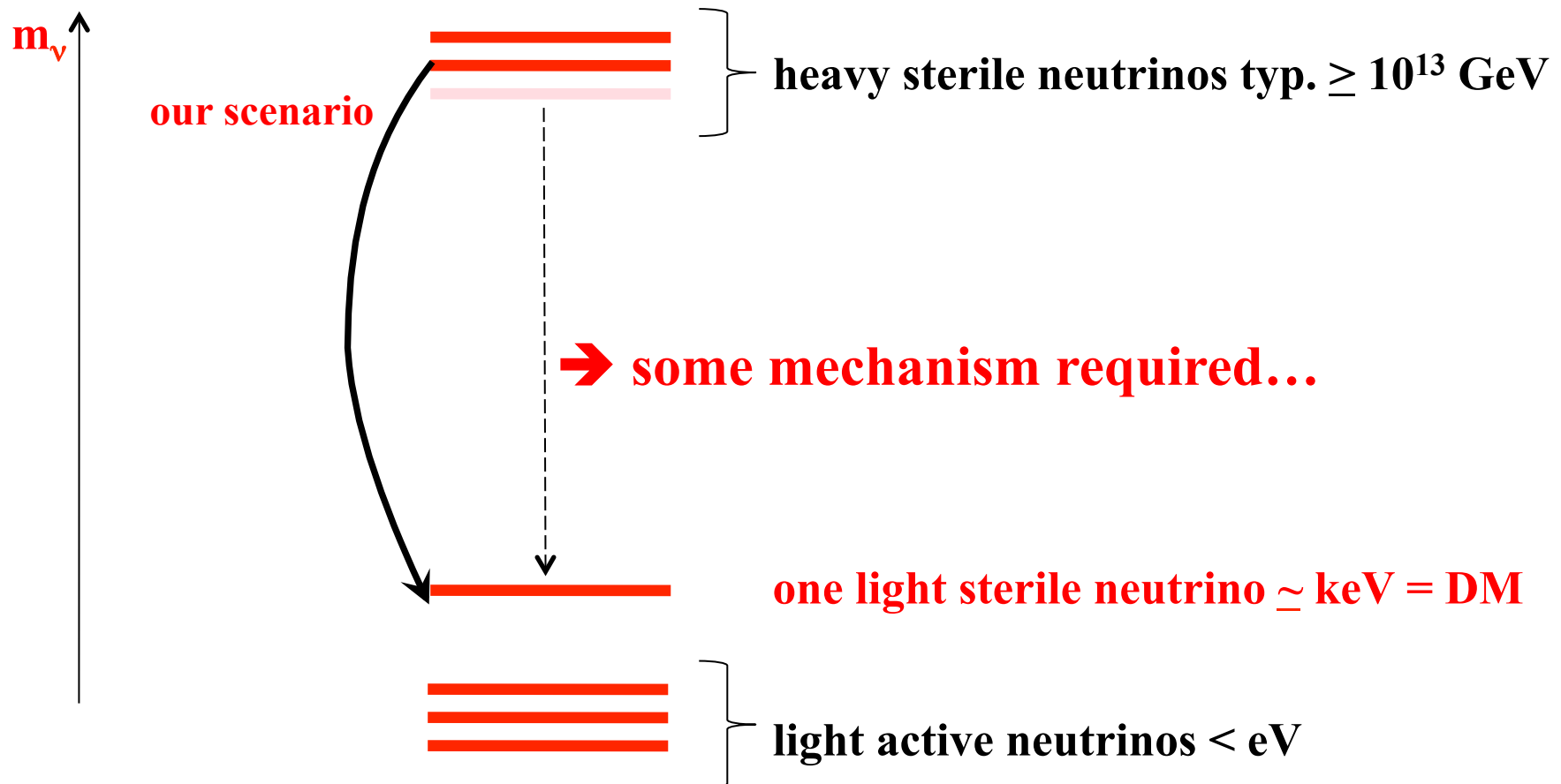
N_1 – Warm Dark Matter

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

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

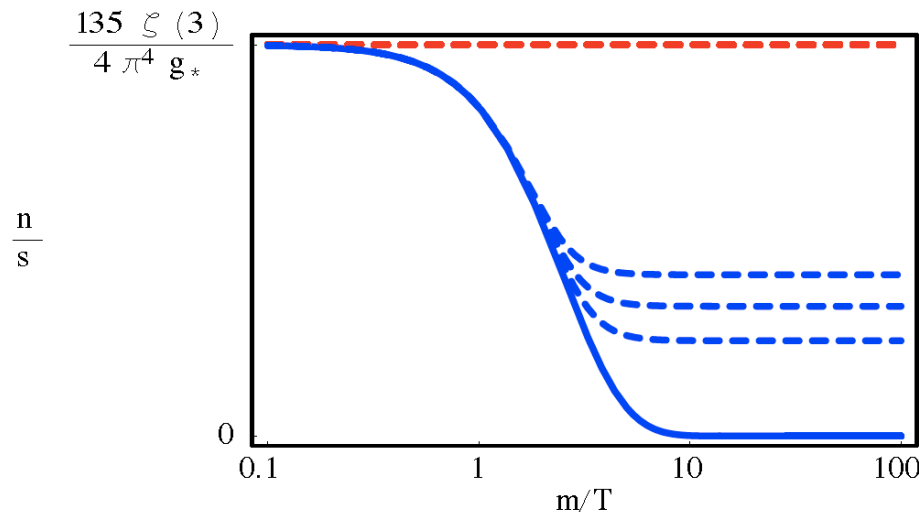
- Mass $M_{2,3} > \text{GeV}$
- Lifetime $\tau_{2,3} \lesssim 0.1 \text{ s}$

Thermal production of the correct abundance in our model:



Obtaining the correct Abundance

Usual thermal WIMP case:



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

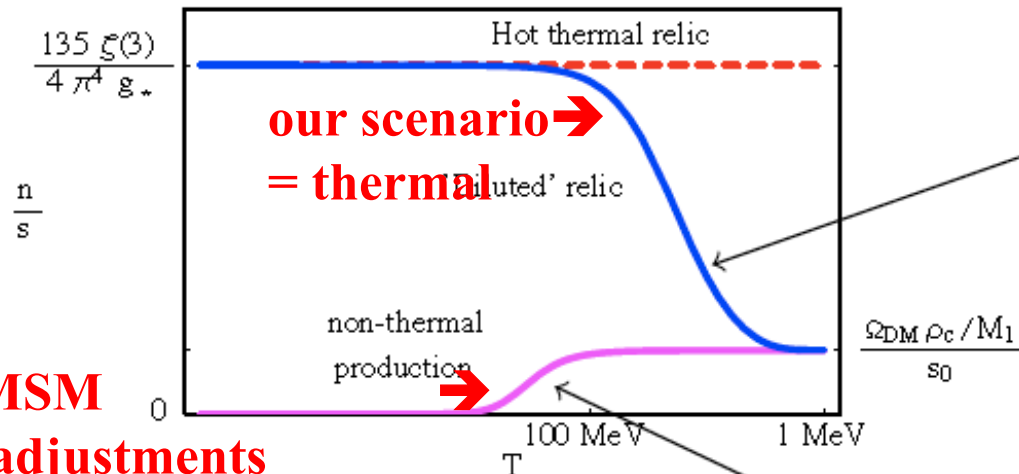
Decoupled relativistic

CDM:
($M \gg \text{MeV}$)

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

Decoupled
nonrelativistic

keV sterile neutrinos:



Diluted after decoupling
(entropy generated by other
particle decay)

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

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:

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

Abundance of N_1 today:

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

Required entropy generation factor:

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

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**

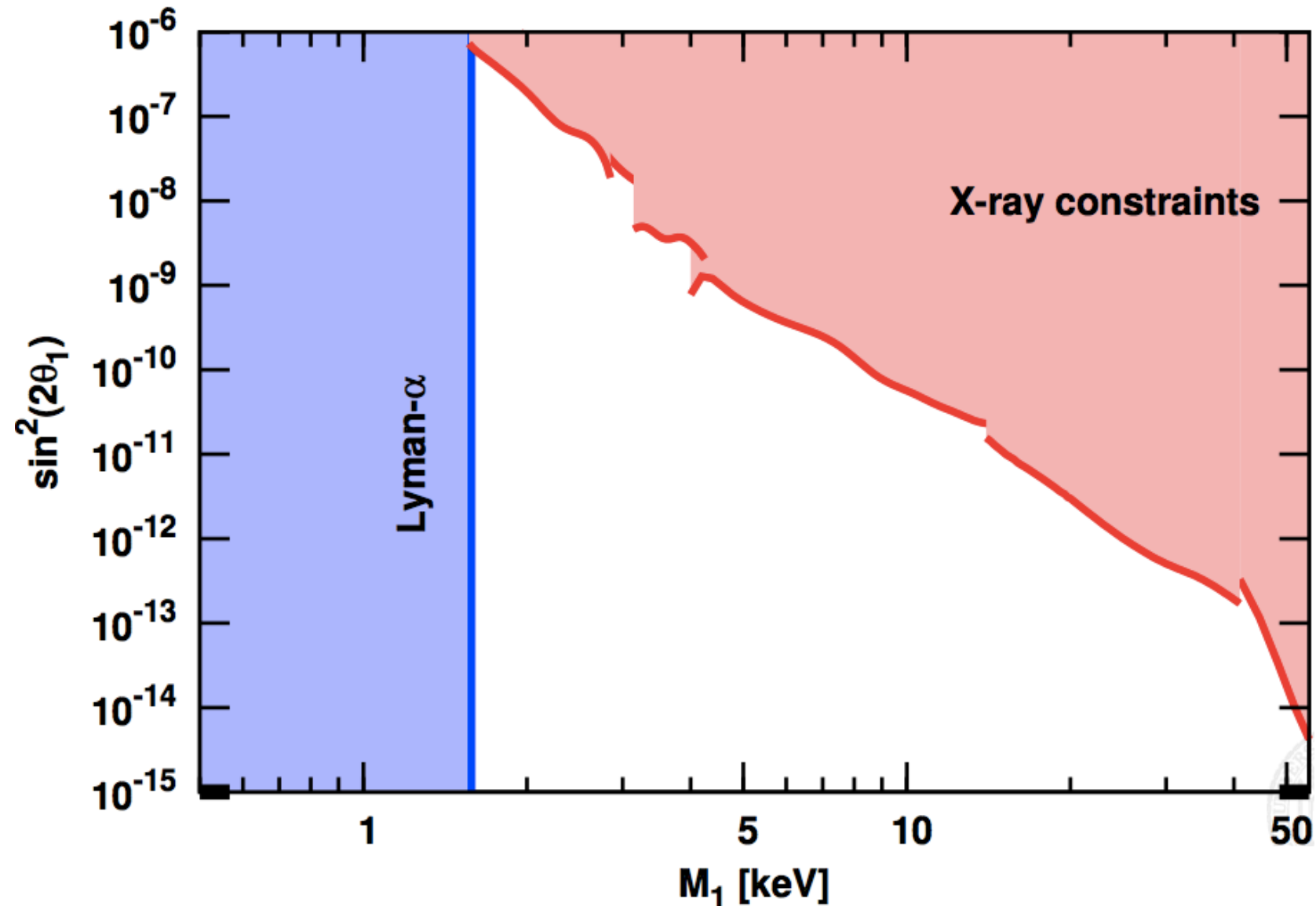
- entropy generation factor →**

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

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

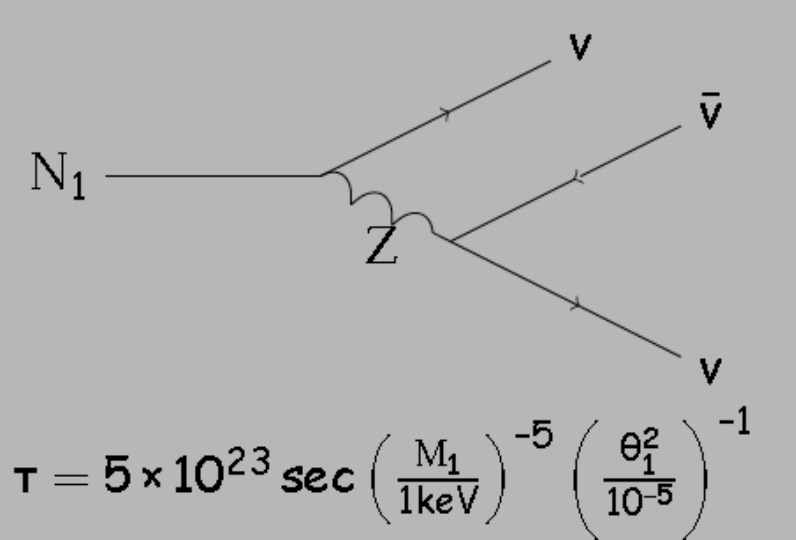
- fixes decay width Γ_2**

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 $\Rightarrow$ at some level: keV X-rays
 - $\Rightarrow$ 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 $\tau \gg \tau_{\text{Universe}}$

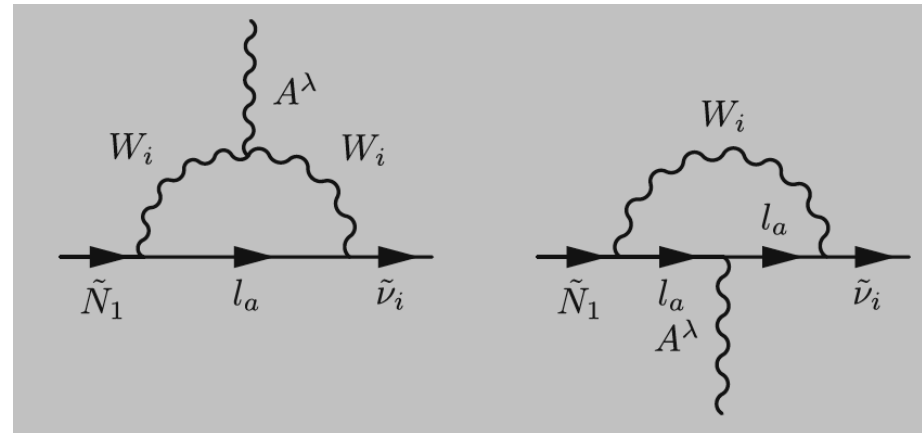


The diagram shows a horizontal line on the left labeled N_1 . A vertical wavy line labeled Z connects this to a vertex. From this vertex, three lines branch out to the right: one labeled ν (top), one labeled $\bar{\nu}$ (middle), and one labeled ν (bottom). Below the diagram, the decay lifetime is given by the equation:

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

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

→ photon line $E_\gamma = m_s/2$



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

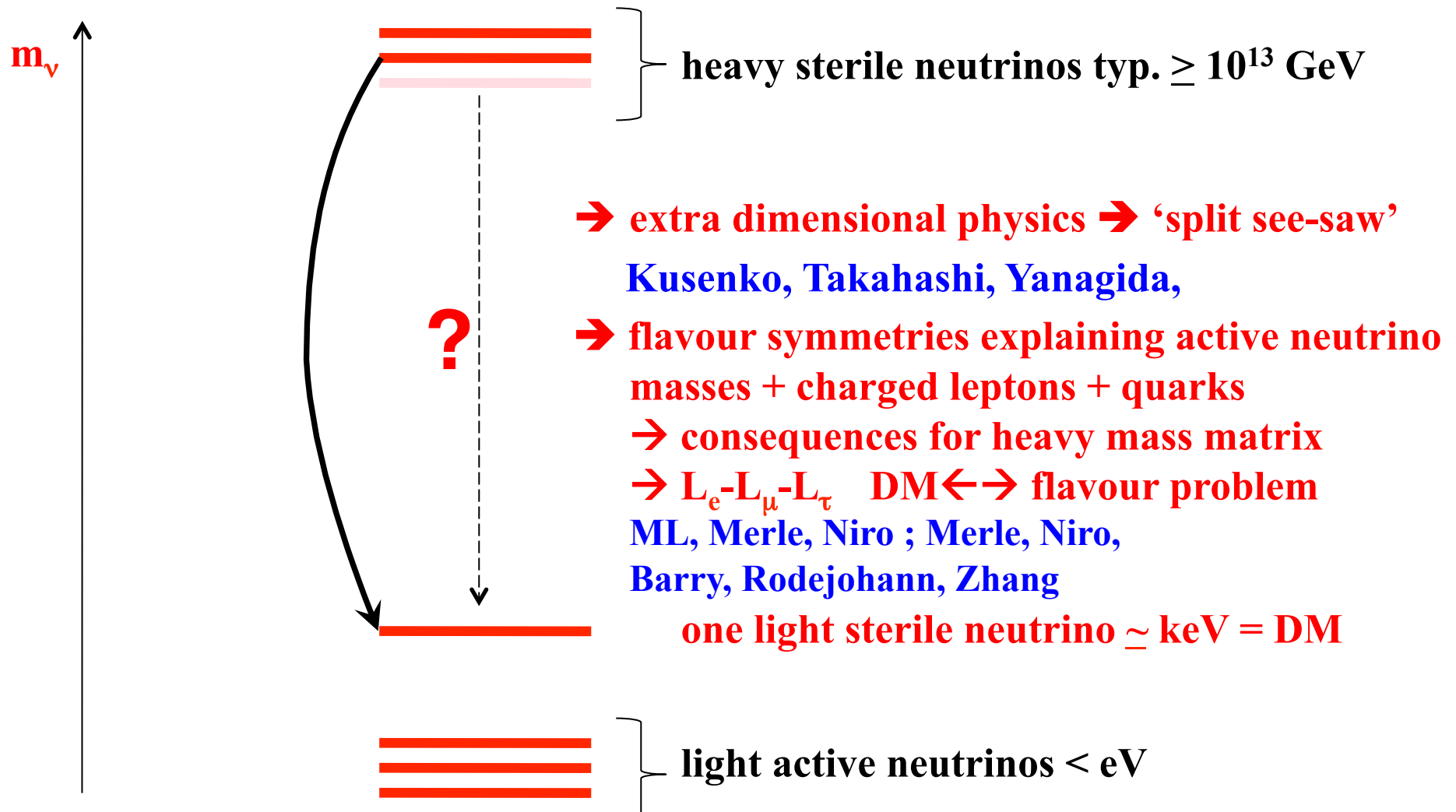
$$\Gamma_{N_1 \rightarrow \nu \gamma} \simeq 5.5 \times 10^{-22} \theta_1^2 \left(\frac{M_1}{1 \text{ keV}} \right)^5 \text{ s}^{-1}$$

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

- mixing tiny, but naturally expected to be tiny: $O(\text{scale ratio})$

Explaining keV-ish Sterile Neutrinos

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



Light Sterile Neutrinos from $L_e-L_\mu-L_\tau$

- **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 $L_e-L_\mu-L_\tau$ symmetry:

by **Lavoura & Grimus** → extended: **ML, Merle, Niro**

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

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

	$L_e L$	$L_\mu L$	$L_\tau L$	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:**

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

- **Dirac masses**

$$\begin{aligned} \mathcal{L}_{\text{mass}} = & -Y_D^{e1} \overline{L_{eL}} \tilde{\phi} N_{1R} - Y_D^{\mu2} \overline{L_{\mu L}} \tilde{\phi} N_{2R} - Y_D^{\mu3} \overline{L_{\mu L}} \tilde{\phi} N_{3R} - \\ & -Y_D^{\tau2} \overline{L_{\tau L}} \tilde{\phi} N_{2R} - Y_D^{\tau3} \overline{L_{\tau L}} \tilde{\phi} N_{3R} + h.c., \end{aligned}$$

- **In addition: Triplet masses**

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

Neutrino mass matrix:

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

$$\mathcal{M}_\nu = \left(\begin{array}{ccc|ccc} 0 & m_L^{e\mu} & m_L^{e\tau} & m_D^{e1} & 0 & 0 \\ m_L^{e\mu} & 0 & 0 & 0 & m_D^{\mu2} & m_D^{\mu3} \\ m_L^{e\tau} & 0 & 0 & 0 & m_D^{\tau2} & m_D^{\tau3} \\ \hline m_D^{e1} & 0 & 0 & 0 & M_R^{12} & M_R^{13} \\ 0 & m_D^{\mu2} & m_D^{\tau2} & M_R^{12} & 0 & 0 \\ 0 & m_D^{\mu3} & m_D^{\tau3} & M_R^{13} & 0 & 0 \end{array} \right)$$


$$\det(M_{ij}) = 0 \rightarrow M_1 = 0$$

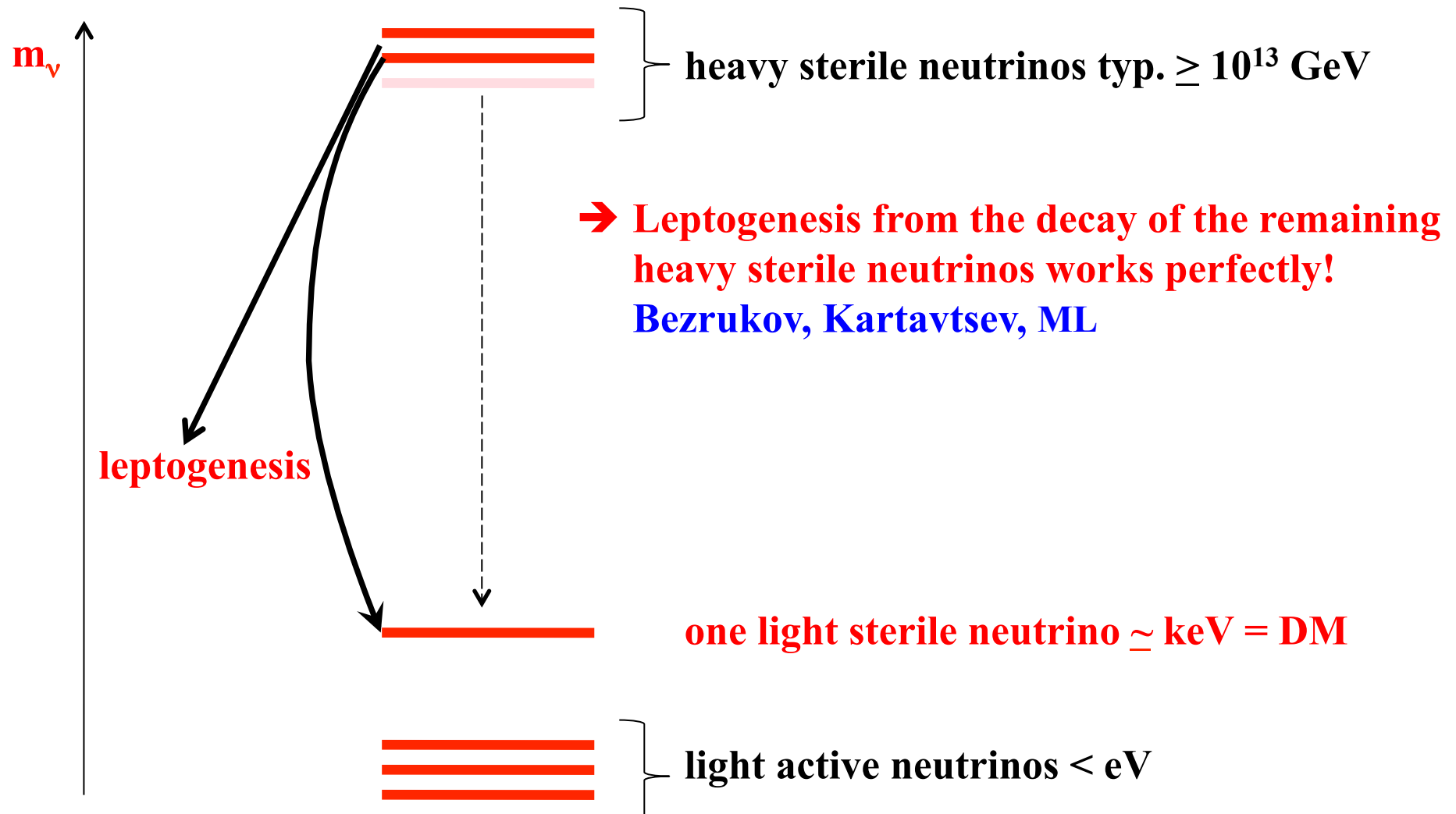
→ massless sterile state + soft breaking

→ naturally light sterile ν

→ mechanism possible in models

Leptogenesis

...there still exist heavy sterile states ...



Conclusions

- A **keV-ish sterile neutrino** is a very well motivated and good working **Warm Dark Matter candidate** $\leftrightarrow$ finite ν -masses
 - Right handed neutrinos probably exist
 $\rightarrow$ requires only some mechanism for light sterile mass $O(\text{keV})$
 - Simplest realization: $\nu\text{MSM} \rightarrow$ requires non-thermal production
 - Our scenario: **Sterile ν 's which are charged under some extended gauge group** $\rightarrow$ abundance from thermal production
 $\rightarrow$ interesting constraints
 - small mixings from X-ray constraints and entropy generation (DM abundance)
 - masses bound by BBN
- $\rightarrow$ Combination with Leptogenesis $\rightarrow$ BAU
- $\rightarrow$ More general scenarios: any mechanism which ‘naturally’ explains light sterile neutrinos