Low-scale leptogenesis with 3 right-handed neutrinos

Michele Lucente

39th International Conference on High Energy Physics
ICHEP 2018 Seoul

July 6th 2018, Coex Center in Seoul

Based on work in collaboration with
A. Abada, G. Arcadi, V. Domcke, M. Drewes and J. Klaric

UCL
Université catholique de Louvain

Observational problems of the SM

Two seemingly unrelated observations cannot be accounted for in the Standard Model

Neutrinos are massive and leptons mix

$$|U| = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

M.C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, arXiv:1409.5439 [hep-ph]

The Universe has a negligible amount of antimatter

$$\eta_{\Delta B} = (6.10 \pm 0.04) \times 10^{-10}$$

The natural (simple) way

Complete the SM field pattern with **right-handed neutrinos**

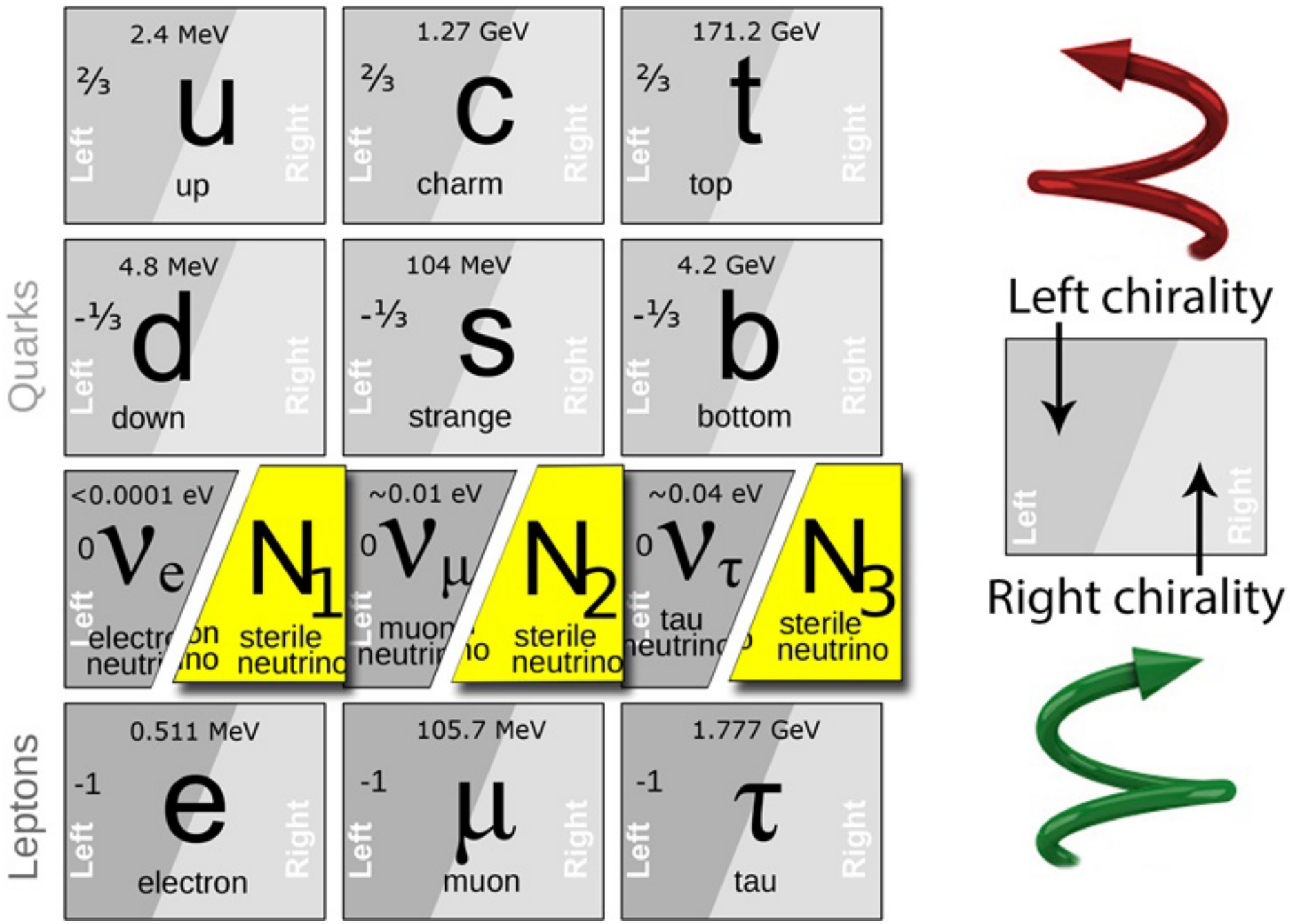


Figure from S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

Neutrino masses and leptogenesis

Type-I seesaw mechanism: SM + gauge singlet fermions N_I

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N_I}\partial\!\!\!/ N_I - \left(Y_{\alpha I}\overline{\ell_\alpha}\widetilde{\phi}N_I + \frac{M_{IJ}}{2}\overline{N_I^c}N_J + h.c. \right)$$

After electroweak phase transition $< \Phi > = v \simeq 174$ GeV

$$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger$$

The Lagrangian provides the ingredients for leptogenesis too

Sakharov conditions

- **Complex Yukawa** couplings ***Y*** as a source of ~~**CP**~~ ✓
- ~~***B***~~ from sphaleron transitions until $T_{EW} \simeq 140$ GeV ✓
- sterile neutrinos deviations from thermal equilibrium ✓

Neutrino masses and leptogenesis

Type-I seesaw mechanism: SM + gauge singlet fermions N_I

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N_I}\partial\!\!\!/ N_I - \left(Y_{\alpha I}\overline{\ell_\alpha}\widetilde{\phi} N_I + \frac{M_{IJ}}{2}\overline{N_I^c} N_J + h.c. \right)$$

After electroweak phase transition < Φ > = v ≃ 174 GeV

$$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger$$

<u>The Lagrangian provides the ingredients for leptogenesis too</u>

Sakharov conditions

- **Complex Yukawa** couplings ***Y*** as a source of ~~**CP**~~ ✓
- ~~***B***~~ from sphaleron transitions until $T_{EW} \simeq 140$ GeV ✓
- sterile neutrinos deviations from thermal equilibrium ✓

Leptogenesis realisations

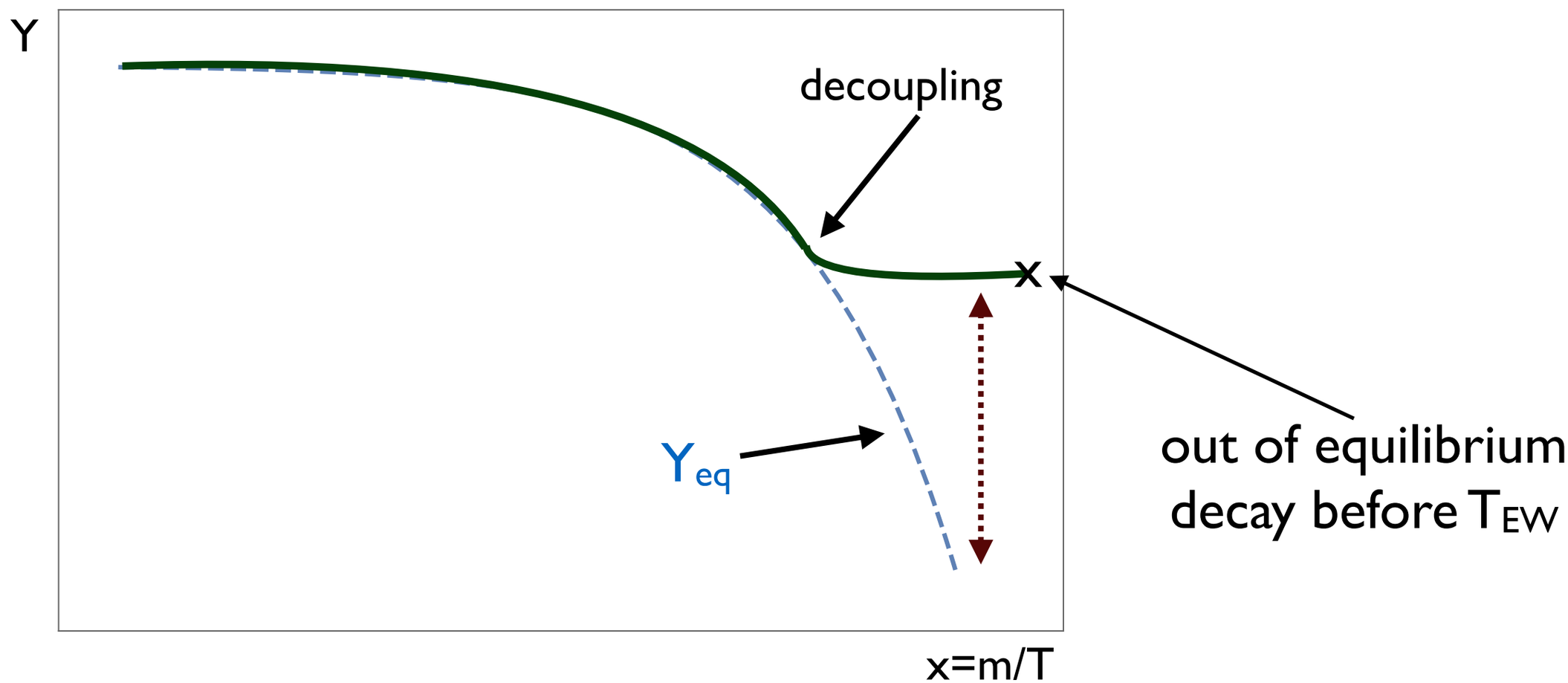
3rd Sakharov condition:
deviation from thermal equilibrium

At which temperature(s) do sterile neutrinos enter/deviate from thermal equilibrium?

BAU I: Thermal leptogenesis

Sterile neutrinos in thermal equilibrium if $|Y| \gtrsim 10^{-7}$

Thermal leptogenesis: sterile neutrinos in equilibrium at large temperatures



<u>Generation of a lepton asymmetry due to the Majorana character of the particles</u>

M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45

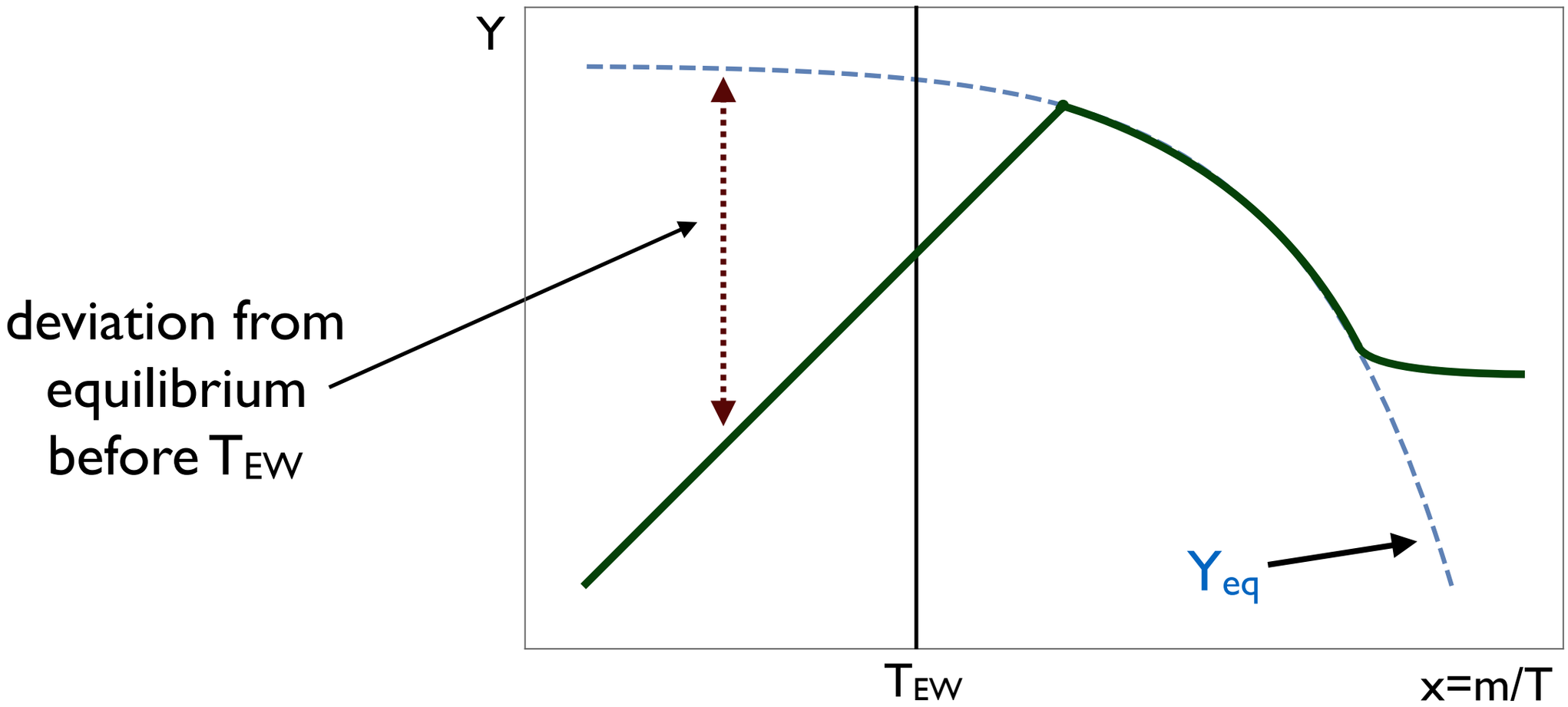
M > 10^8 GeV to reproduce observed BAU (relaxed to M > TeV for degenerate masses) → Difficult to test in laboratory

S. Davidson, E. Nardi and Y. Nir, arXiv:0802.2962 [hep-ph]
A. Abada, S. Davidson, A. Ibarra, F.-X. Josse-Michaux, M. Losada and A. Riotto, hep-ph/0605281
A. Pilaftsis and T. E. J. Underwood, hep-ph/0309342

BAU II: ARS mechanism

E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255

Sterile neutrinos out of equilibrium at large temperatures



From the seesaw relation

$$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger \simeq 0.3 \left(\frac{\mathrm{GeV}}{M}\right) \left(\frac{Y^2}{10^{-14}}\right) \mathrm{eV}$$

M ~ GeV to reproduce ν masses → **Testable**

ARS leptogenesis

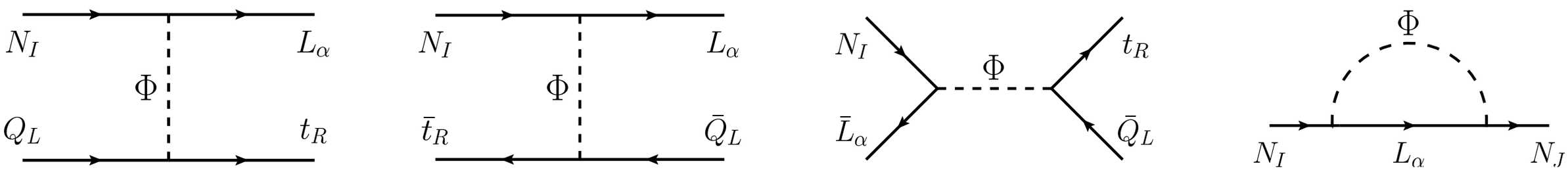
How does the mechanism work?

A. Abada, S. Antusch, E. K. Akhmedov, G. Arcadi, T. Asaka, S. Blanchet, L. Canetti, E. Cazzato, V. Domcke, M. Drewes, S. Eijima, O. Fischer, T. Frossard, B. Garbrecht, D. Gueter, T. Hambye, P. Hernández, H. Ishida, M. Kekic, J. Klaric, J. López-Pavón, M.L., J. Racker, N. Rius, V. A. Rubakov, J. Salvado, M. Shaposhnikov, A. Y. Smirnov, D. Teresi…

Two kinds of ~~CP~~ processes

Lepton number conserving

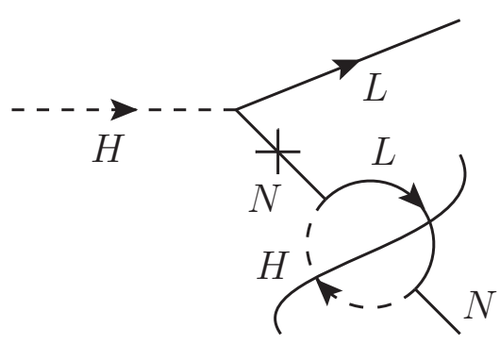
(neutrino generation and oscillations)



Lepton number violating

(thermal Higgs decay)

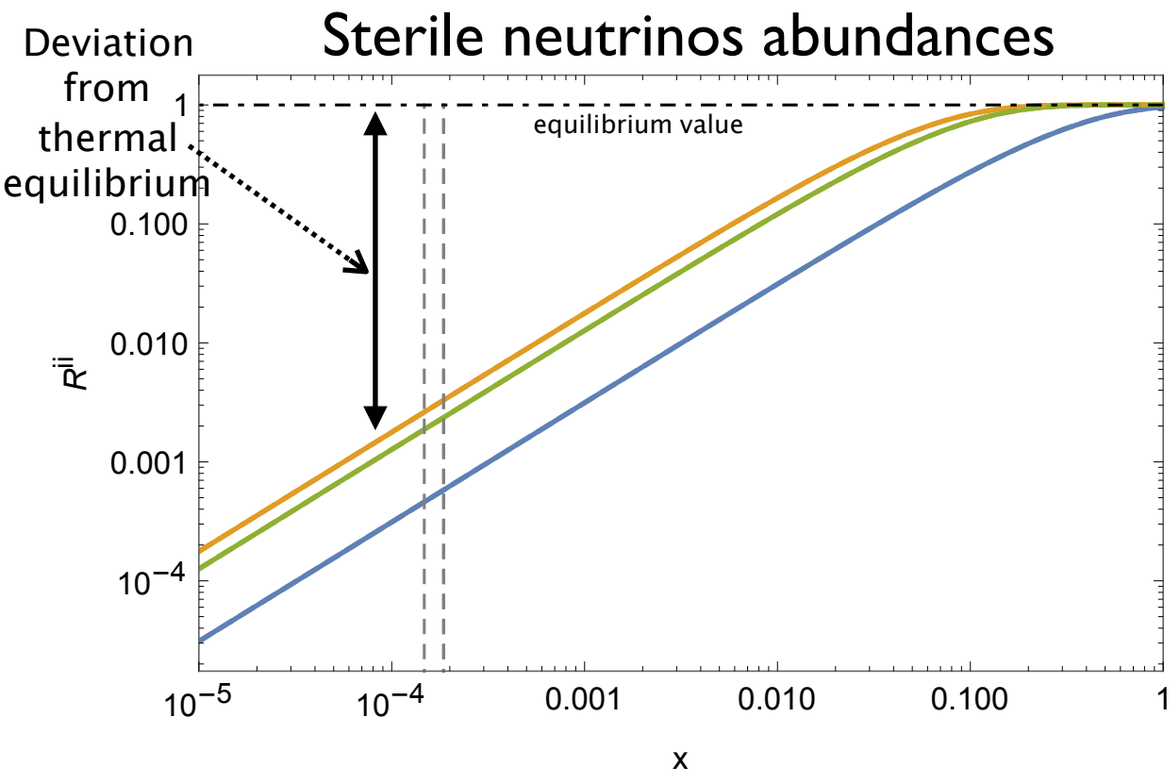
T. Hambye and D. Teresi, arXiv:1606.00017 [hep-ph], arXiv:1705.00016 [hep-ph]

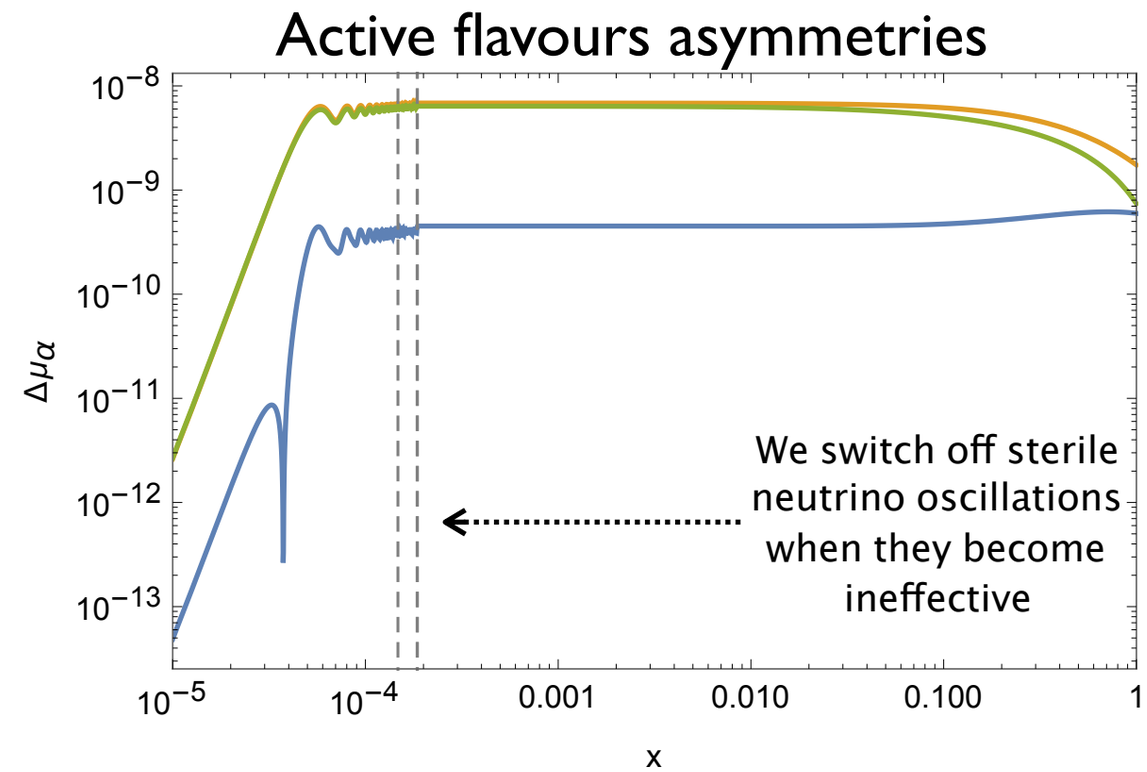


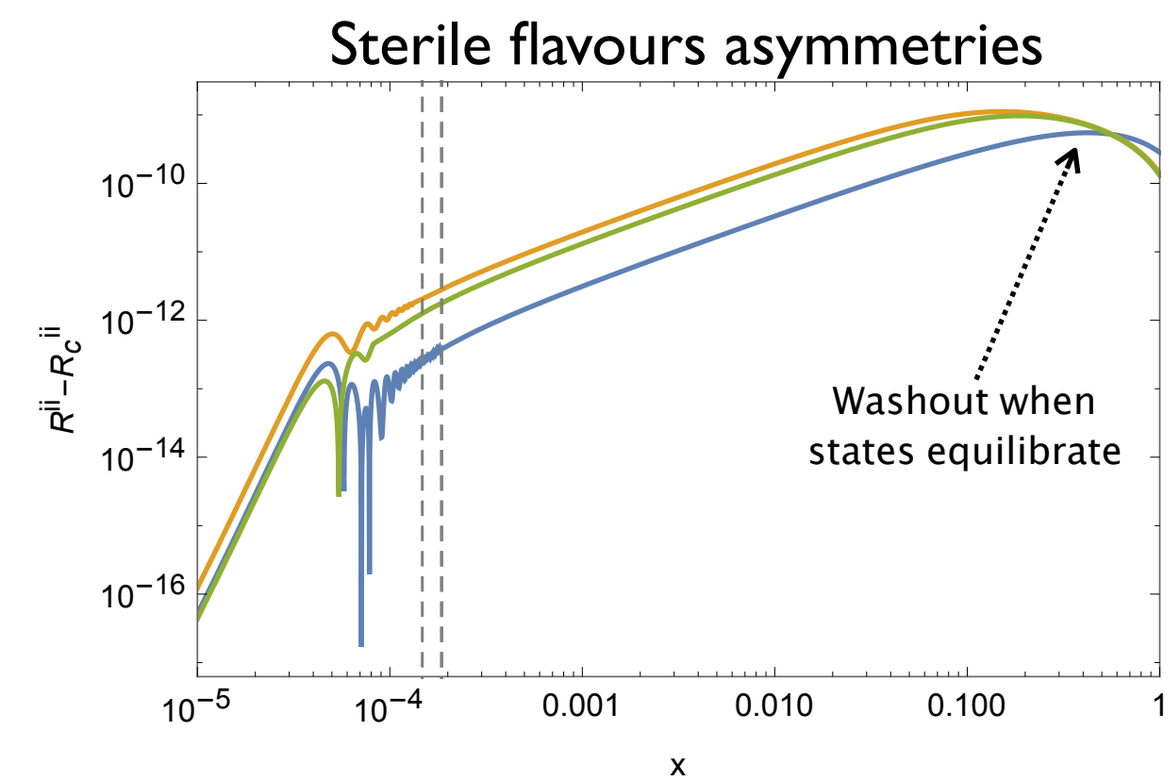
$$\propto \frac{M^2}{T^2}$$ relevant at late times

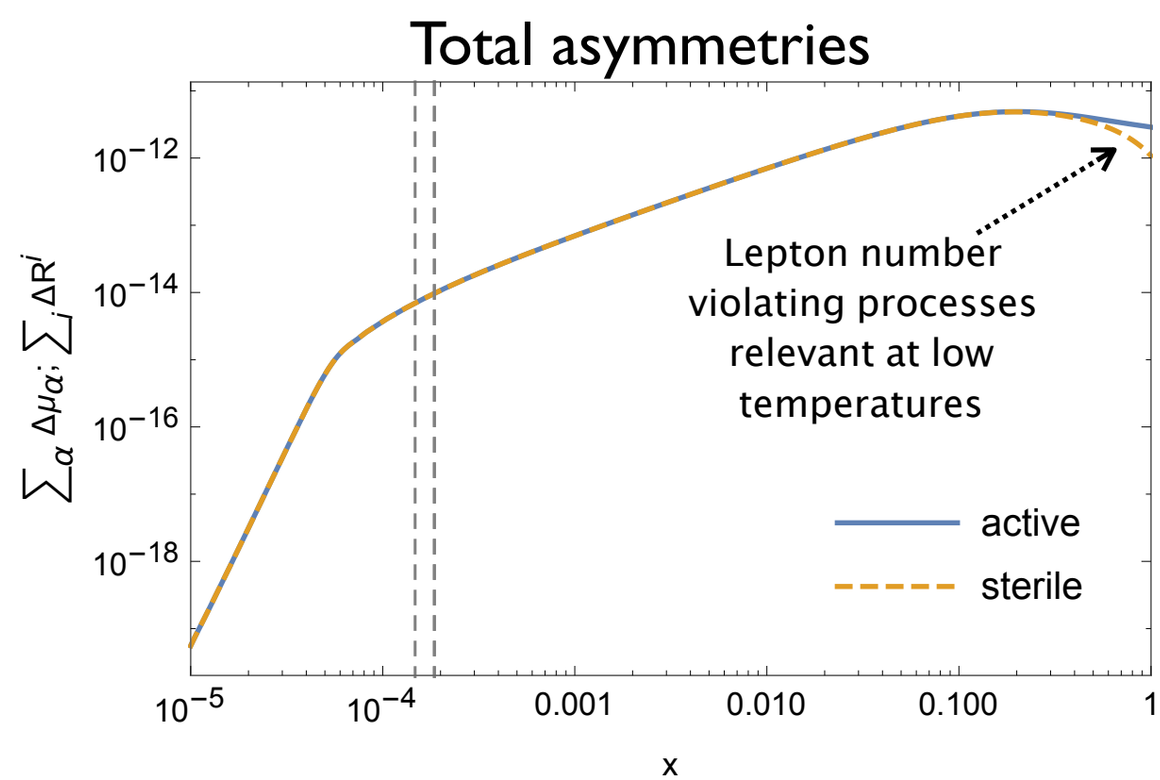
Asymmetry generation example with 3 RHN

$x = \frac{T}{T_{\rm EW}}$ T_{EW} = 140 GeV R :sterile neutrinos density matrix μ_α : active flavours chemical potentials





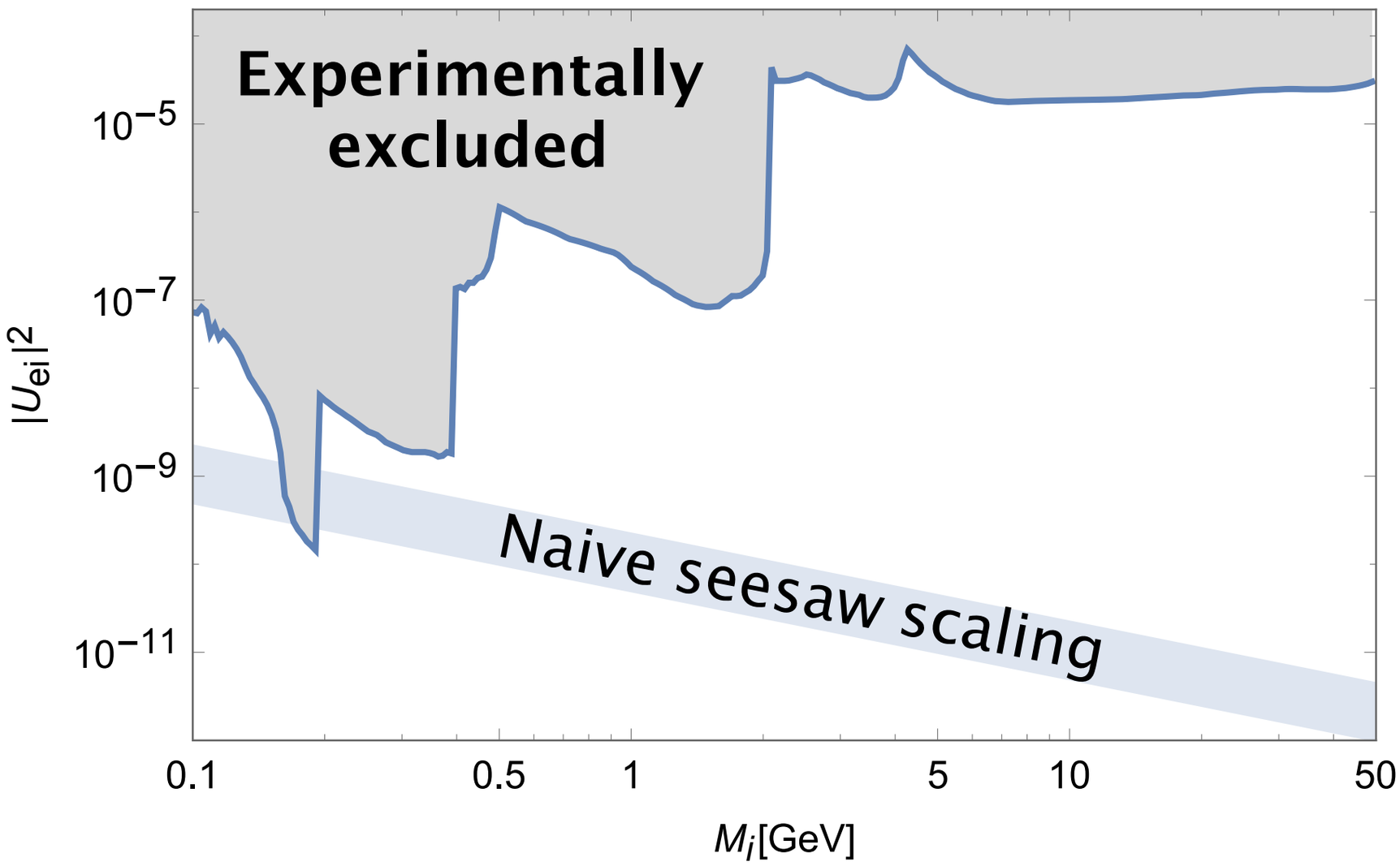




Testability?

Seesaw scaling $$m_\nu \simeq -\frac{v^2}{2} Y^* \frac{1}{M} Y^\dagger$$

In the **absence** of any **structure** in the *F* and *M* matrices $$|U_{\alpha i}| \lesssim \sqrt{\frac{m_\nu}{M}} \lesssim 10^{-5}\sqrt{\frac{\mathrm{GeV}}{M}}$$



But these are (complex) matrices: cancellations are possible

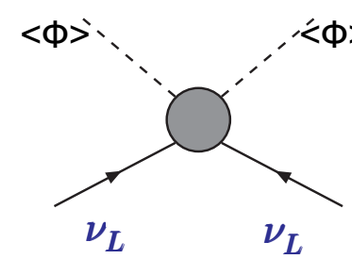
SM as an effective theory

Relaxing the renormalizability condition there is only one dim=5 gauge invariant operator (Weinberg operator) S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566

$\Delta L = 2$

$$\frac{1}{2}\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{l^c_{L\alpha}}\widetilde{\Phi}^*\right)\left(\widetilde{\Phi}^\dagger l^\beta_L\right) + h.c.$$

EWSB



$$\frac{v^2}{2}\frac{c_{\alpha\beta}}{\Lambda}\overline{\nu^c_{L\alpha}}\nu_{L\beta} + h.c.$$

New physics scale

$$c_{\alpha\beta}\,\frac{v}{\Lambda}\,v \lesssim \text{eV} \ll v$$

Why are neutrinos so light?

<u>Suppression mechanisms</u>

- $\frac{v}{\Lambda} \ll 1$ High NP scale
- $c_{\alpha\beta} \ll 1$ Symmetry (Lepton number)
- $c_{\alpha\beta} \ll 1$ Accidental cancellations

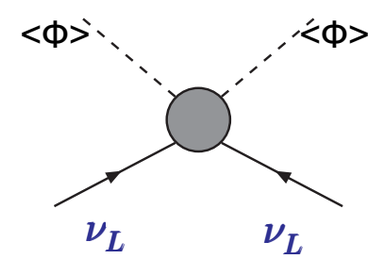
SM as an effective theory

Relaxing the renormalizability condition there is only one dim=5 gauge invariant operator (Weinberg operator) S. Weinberg, Phys. Rev. Lett. 43 (1979) 1566

$\Delta L = 2$

$$\frac{1}{2}\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{l^c_{L\alpha}}\widetilde{\Phi}^*\right)\left(\widetilde{\Phi}^\dagger l^\beta_L\right) + h.c.$$

EWSB



$$\frac{v^2}{2}\frac{c_{\alpha\beta}}{\Lambda}\overline{\nu^c_{L\alpha}}\nu_{L\beta} + h.c.$$

New physics scale

$$c_{\alpha\beta}\,\frac{v}{\Lambda}\,v \lesssim \text{eV} \ll v$$

Why are neutrinos so light?

Suppression mechanisms

- ~~$\frac{v}{\Lambda} \ll 1$ High NP scale~~ $\boxed{\Lambda \approx \text{GeV}}$
- $c_{\alpha\beta} \ll 1$ Symmetry (Lepton number)
- $c_{\alpha\beta} \ll 1$ Accidental cancellations

Fine tuning

If a symmetry is present in the Lagrangian, it will be manifest at any order in perturbation theory

The **neutrino mass scale** is **stable** under **radiative corrections**

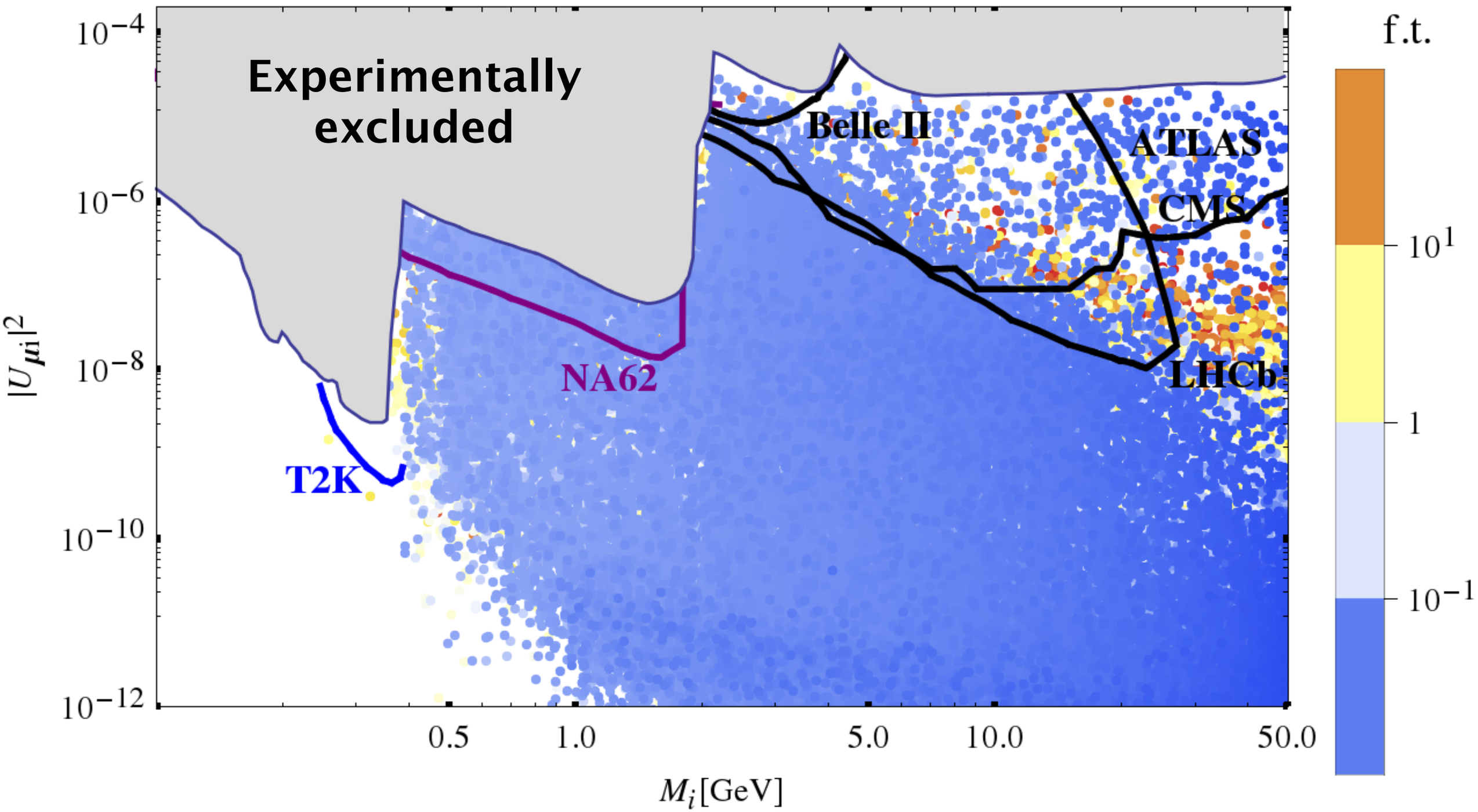
We compute neutrino masses m_ν at 1-loop, and quantify the level of fine-tuning of a solution as

$$f.t.(m_\nu) = \sqrt{\sum_{i=1}^{3} \left(\frac{m_i^{\text{loop}} - m_i^{\text{tree}}}{m_i^{\text{loop}}} \right)^2}$$

m_i^{loop}
1-loop neutrino mass spectrum

m_i^{tree}
tree-level neutrino mass spectrum

Results



Solutions with sizeable mixing exhibit a small degree of fine-tuning

Why?

Mass spectrum with 3 right-handed neutrinos and B - L approximate symmetry

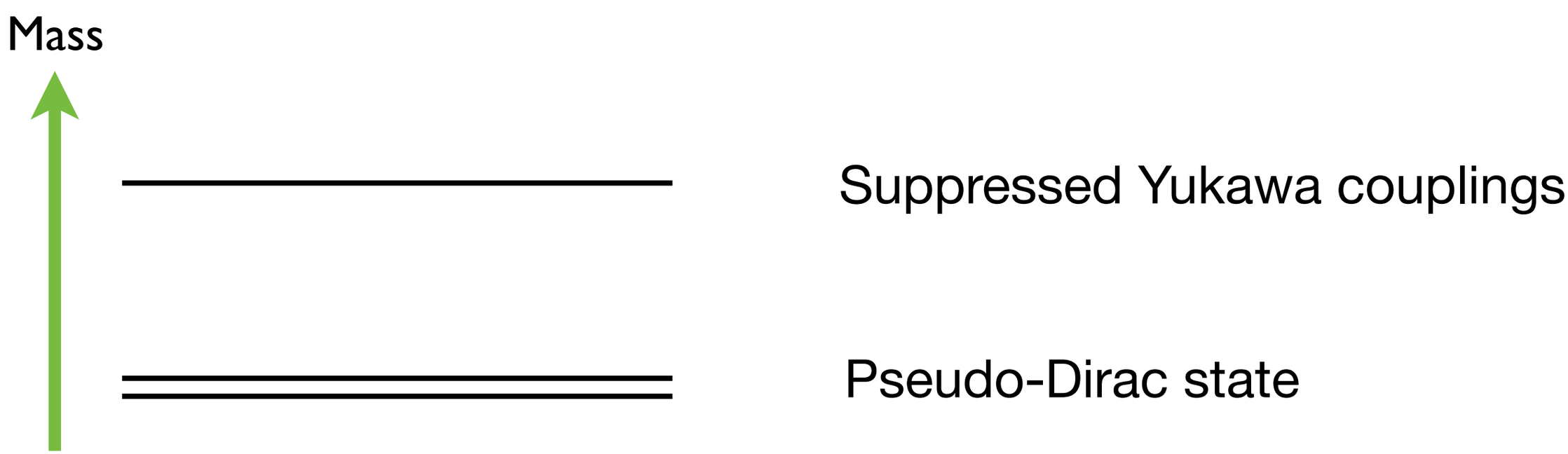
How to preserve lepton number with Majorana states?

Pair two states to form a Dirac state
(*equal masses, maximal mixing, opposite CP*)

or

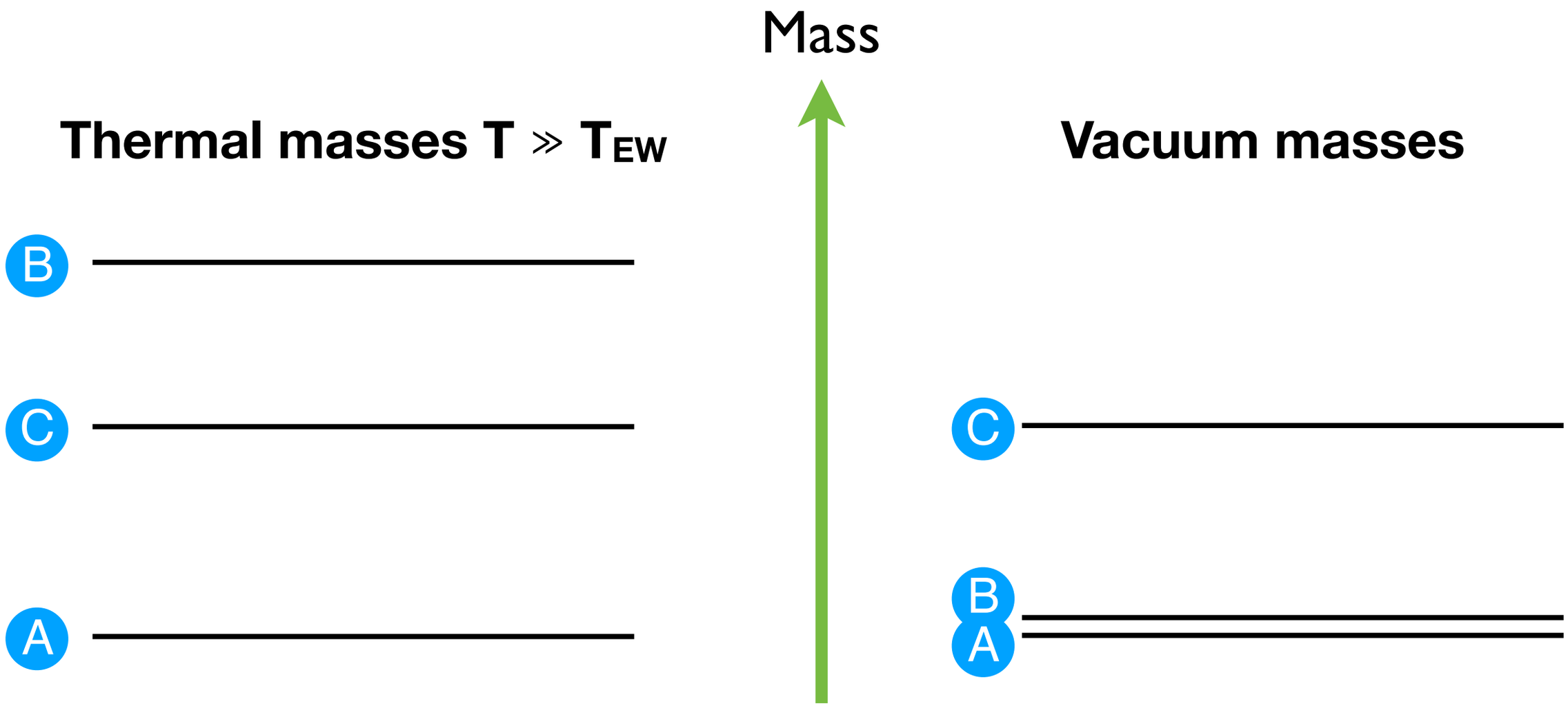
Decouple a state

If there is an **odd number** of **right-handed neutrinos** and **B - L** approximate **symmetry**



New mechanism: resonant asymmetry production in the B - L symmetry

Mass spectrum with 3 right-handed neutrinos and B - L symmetry

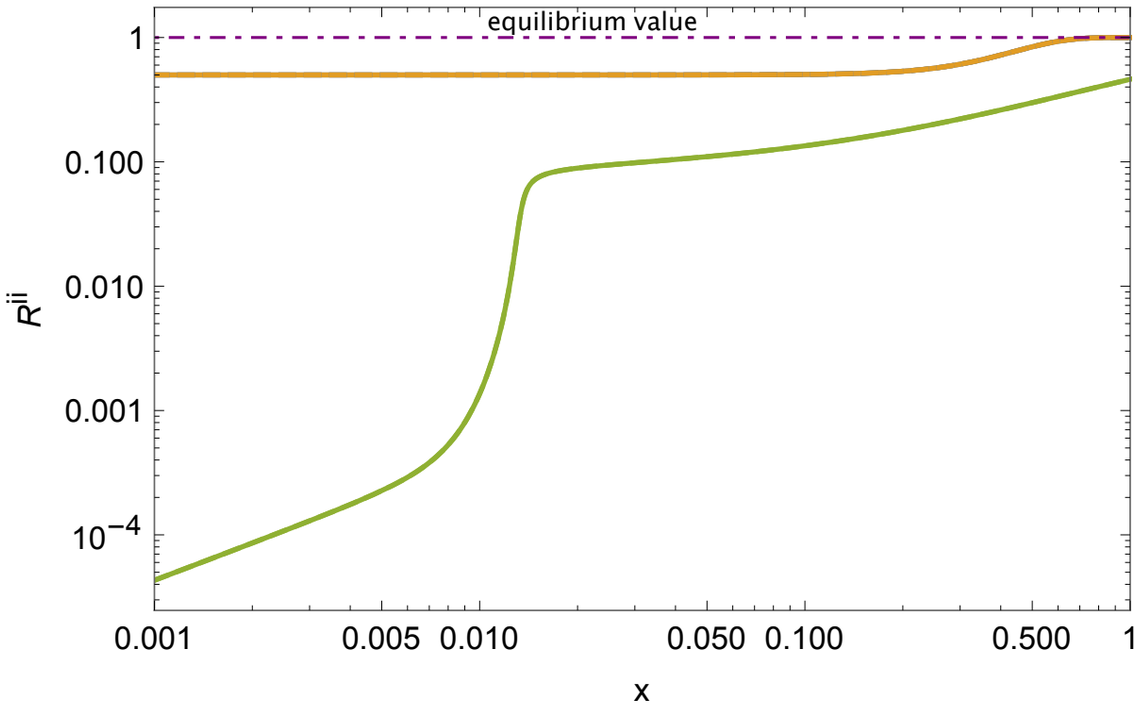


If the vacuum mass of the decoupled state is heavier than the pseudo-Dirac one, there is **necessarily** a level crossing at some finite temperature!

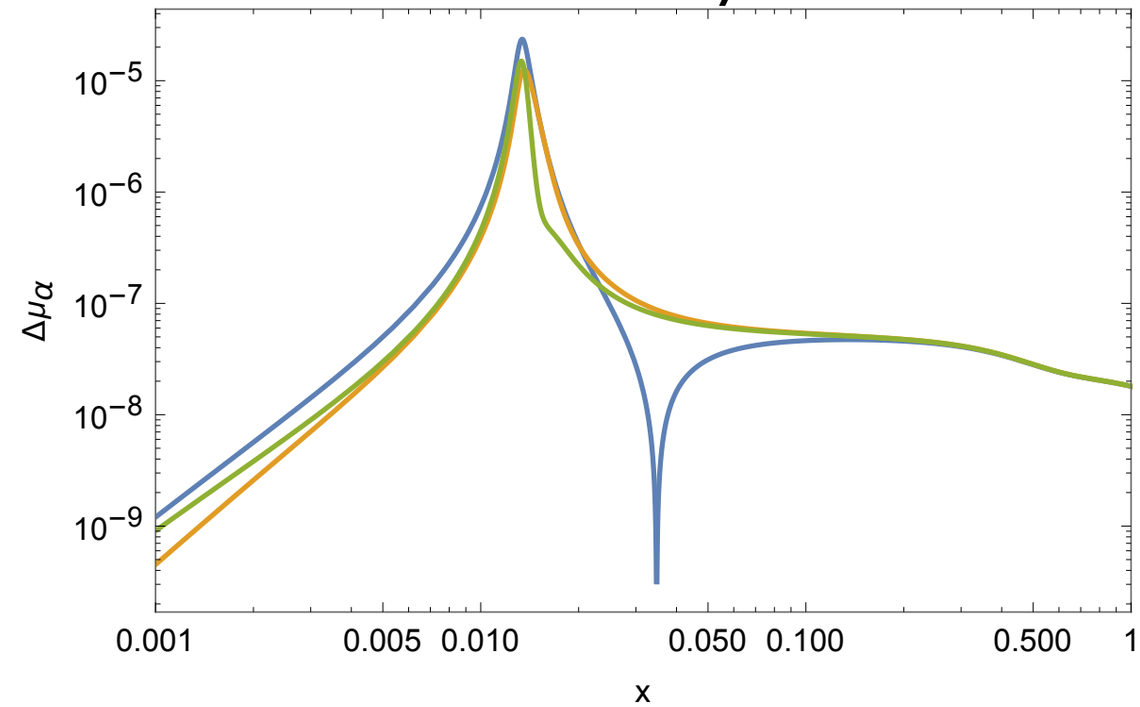
Level crossing: resonant asymmetry production

$x = \frac{T}{T_{\rm EW}}$ T_{EW} = 140 GeV R :sterile neutrinos density matrix μ_α : active flavours chemical potentials

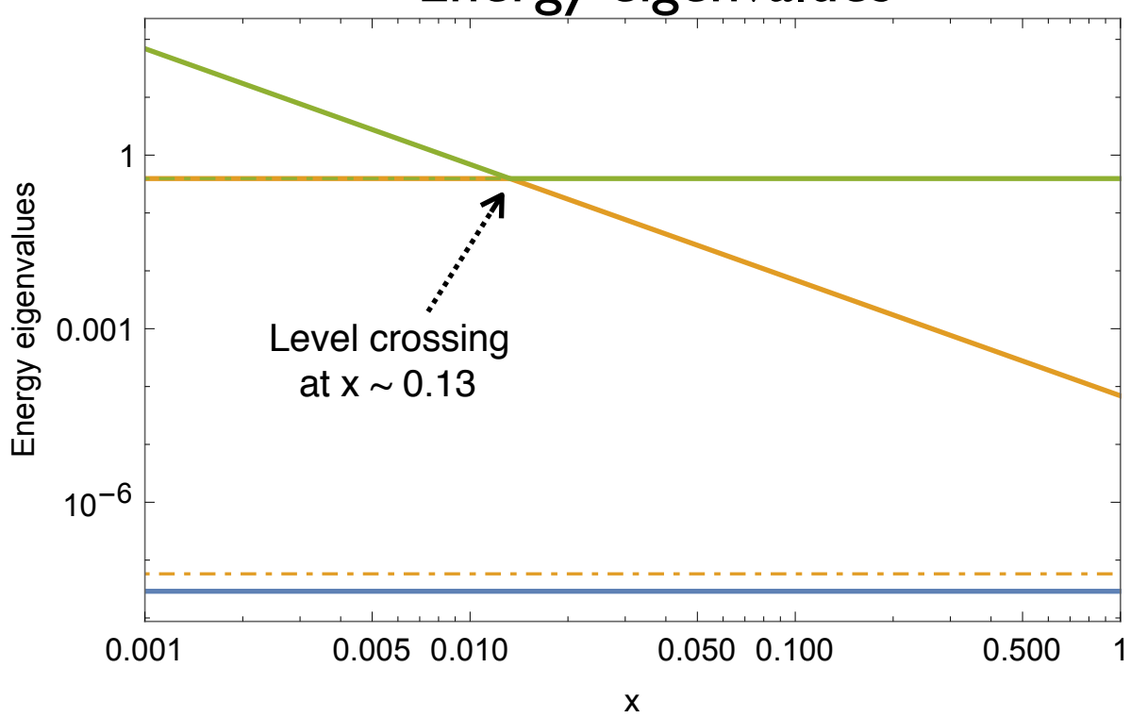
Sterile neutrinos abundances



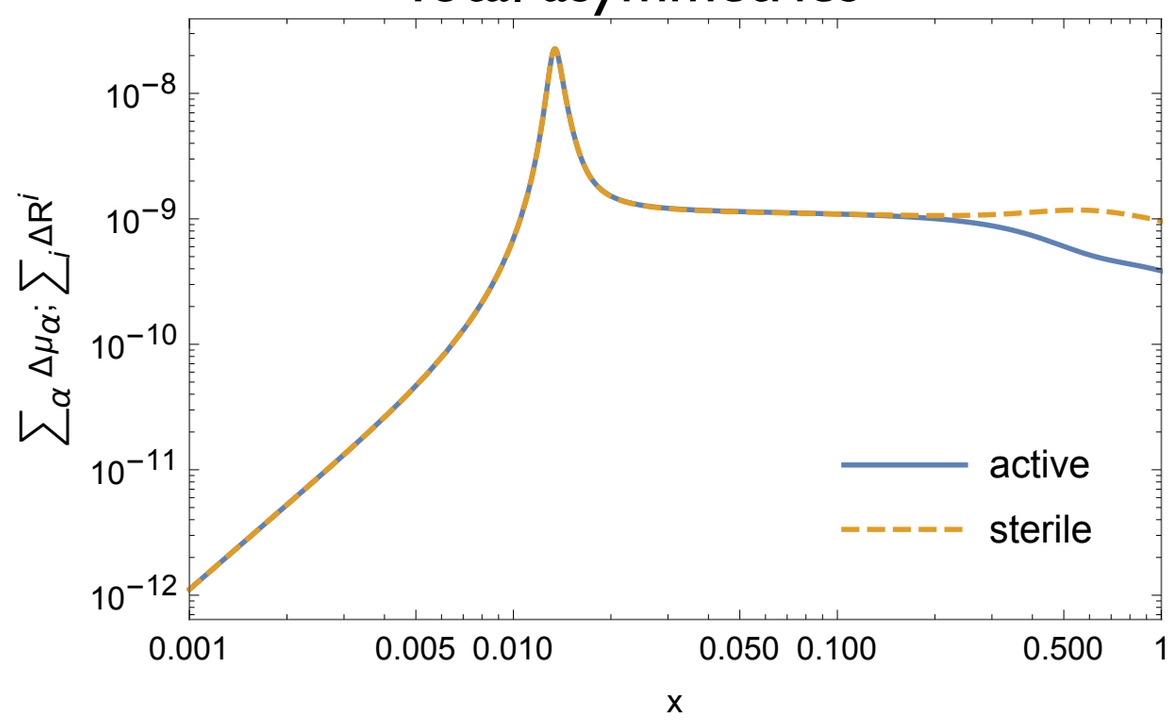
Active flavours asymmetries



Energy eigenvalues



Total asymmetries



Conclusion

We performed the **first systematic study** of the **low-scale leptogenesis** scenario in the minimal Standard Model extended with **3 right-handed neutrinos** having masses at the **GeV scale**

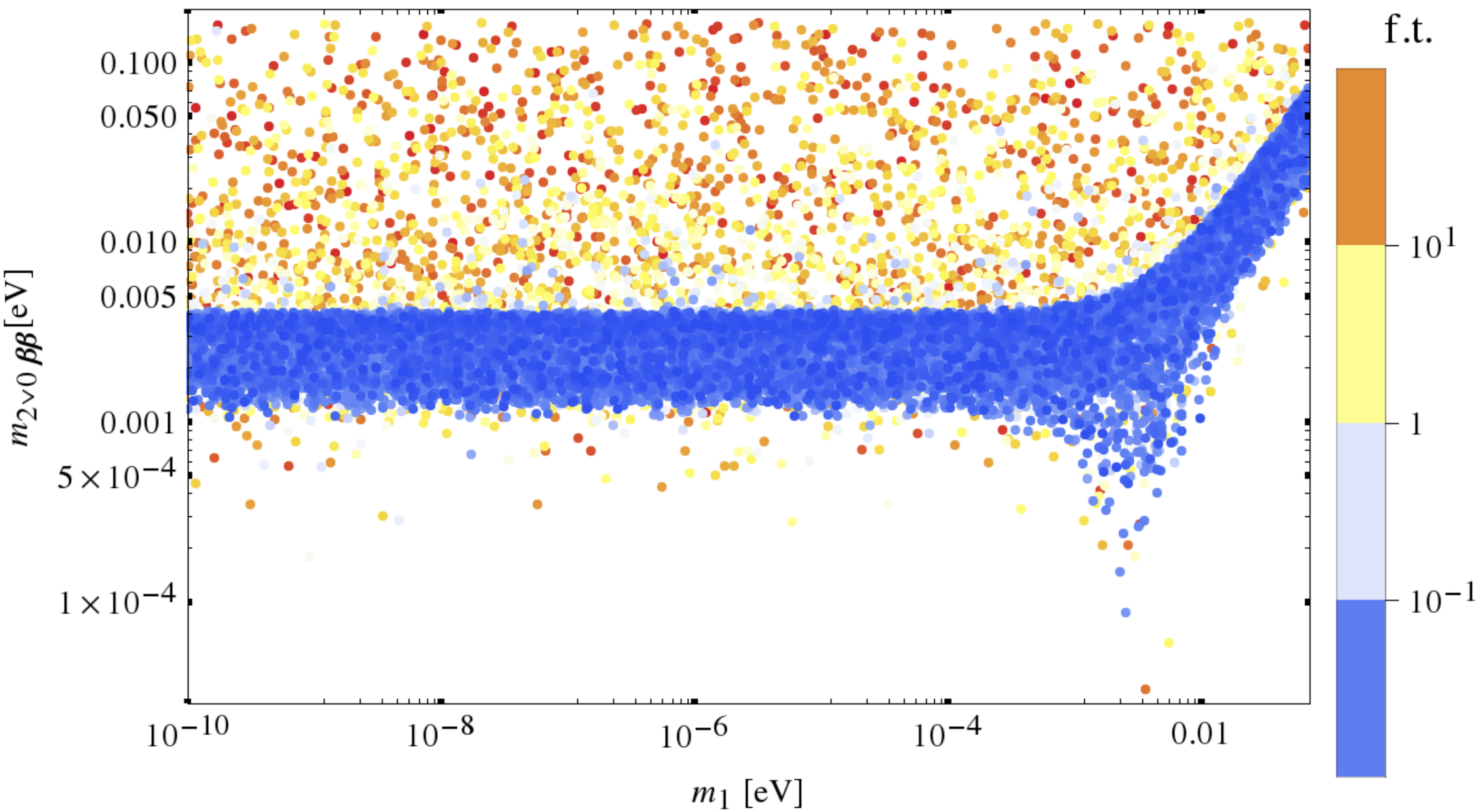
Low-scale solutions are **testable** in **current experiments** in the large-mixing region

Large mixings can result from fine-tuning or from an **underlying B - L symmetry**

We find a **new mechanism** that:

- dynamically creates resonantly enhanced asymmetries
- protects them from washout
- works precisely in the B - L approximate symmetry

Backup

Neutrinoless effective mass

0νββ decay is a lepton number violating process → It violates the B - L symmetry