LOW SCALE SEESAW MODELS AND LEPTOGENESIS

Michele Lucente

27th International Conference on Supersymmetry and Unification of Fundamental Interactions

22nd May 2019, Omni Hotel - Corpus Christi

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

Observational problems of the SM

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

NuFIT 3.2 (2018)

Neutrinos are massive and leptons mix

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler and T. Schwetz, arXiv:1611.01514 [hep-ph]

The Universe has a negligible amount of antimatter

$$\eta_{\Delta B} = (6.13 \pm 0.03) \times 10^{-10}$$

N. Aghanim *et al.* [Planck Collaboration], arXiv:1807.06209 [astro-ph.CO]

The natural (simple) way

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

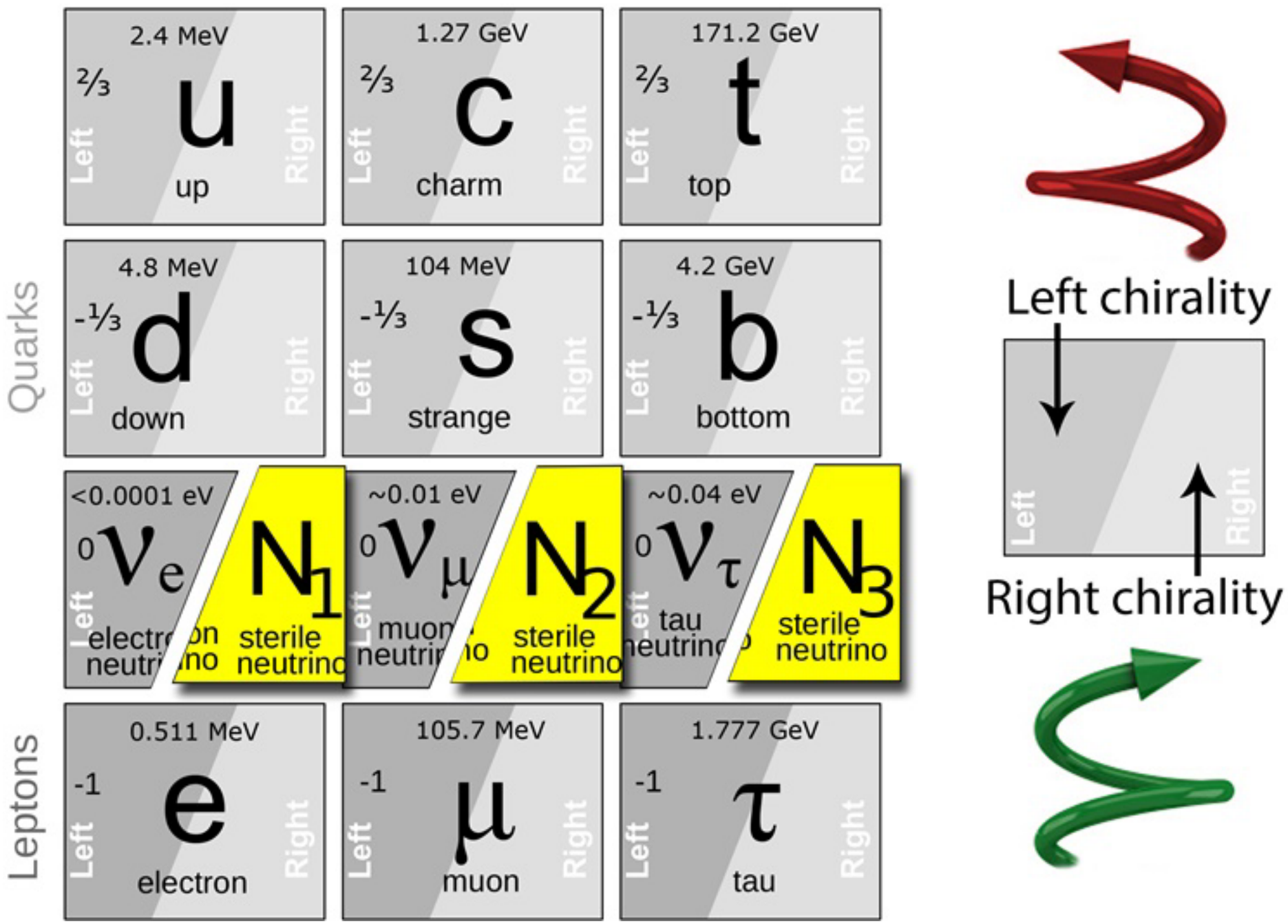


Figure from S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

Neutrino masses and leptogenesis

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

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

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

$$m_\nu = -v^2 F \frac{1}{M} F^T$$

The Lagrangian provides the ingredients for leptogenesis too

Sakharov conditions

- **Complex Yukawa** couplings ***F*** 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

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

After electroweak phase transition $\langle \Phi \rangle = v \simeq 174$ GeV

$$m_\nu = -v^2 F \frac{1}{M} F^T$$

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

Sakharov conditions

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

Leptogenesis realisations

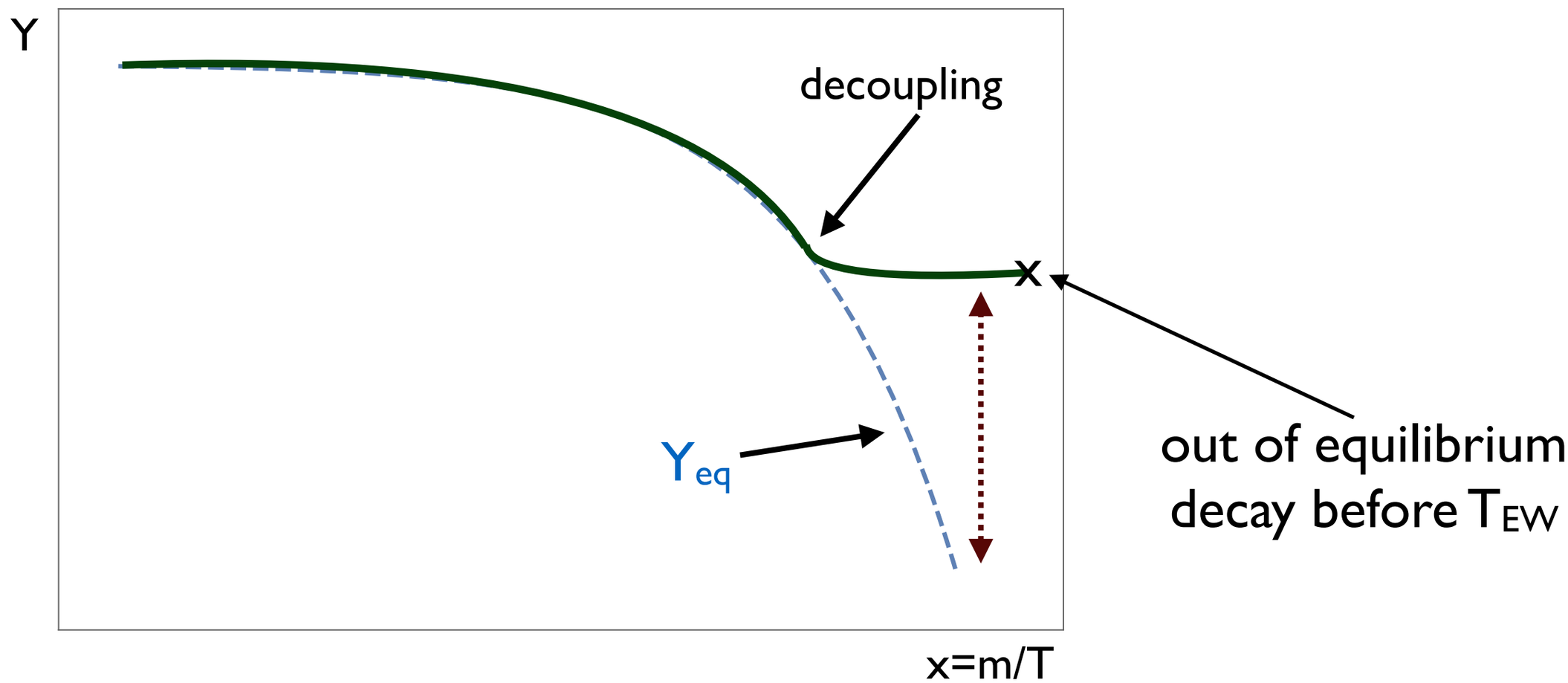
3rd Sakharov condition:
deviation from thermal equilibrium

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

BAU: Thermal leptogenesis

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

Thermal leptogenesis: sterile neutrinos in equilibrium at large temperatures



<u>Generation of a lepton asymmetry due to the CP-violating decay of the particles</u>

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

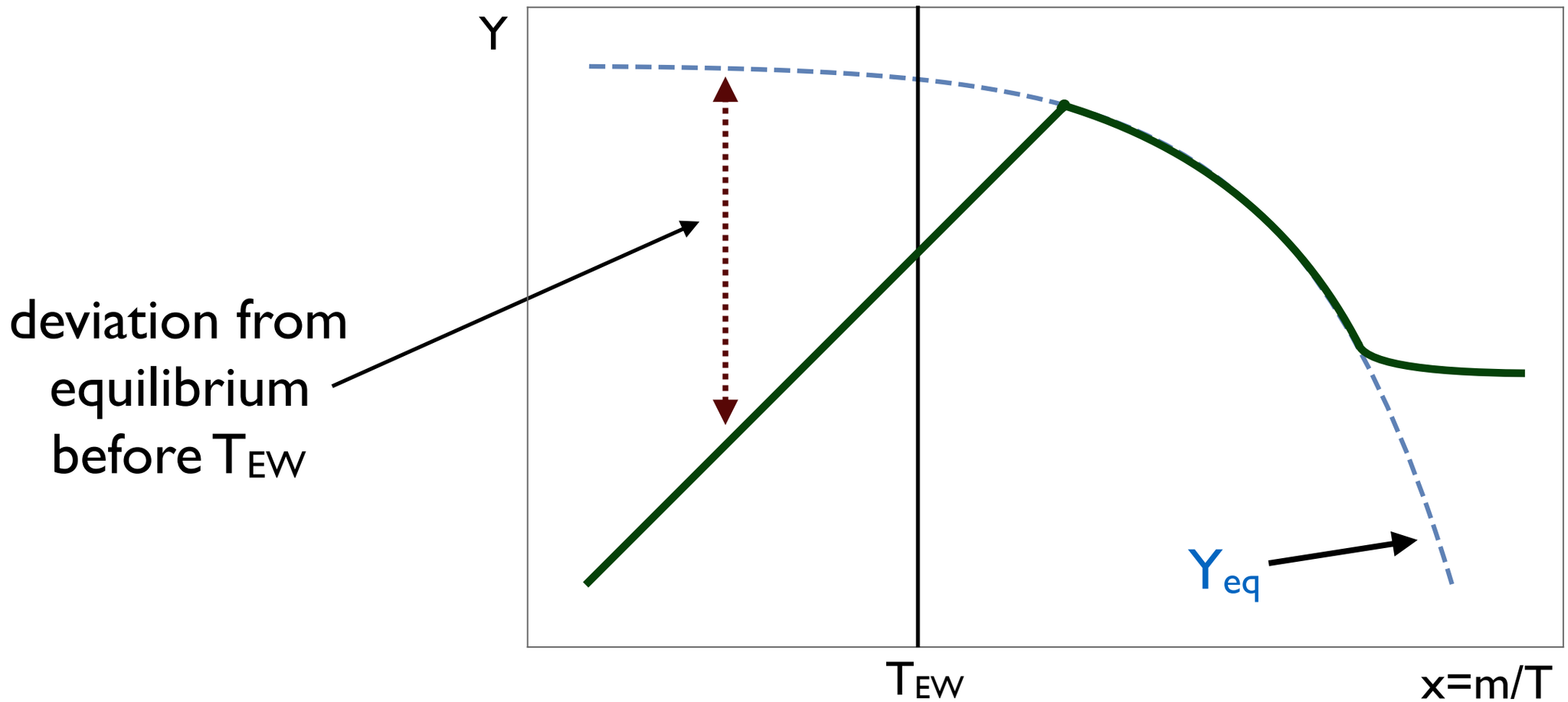
M > 10^6 GeV to reproduce observed BAU (relaxed to M > TeV for degenerate masses) → Difficult to test in laboratory

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
K. Moffat, S. Pascoli, S. T. Petcov, H. Schulz and J. Turner, arXiv:1804.05066 [hep-ph]

BAU: ARS mechanism

E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255
T. Asaka and M. Shaposhnikov, hep-ph/0505013

Sterile neutrinos out of equilibrium at large temperatures



From the seesaw relation

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

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

ARS leptogenesis

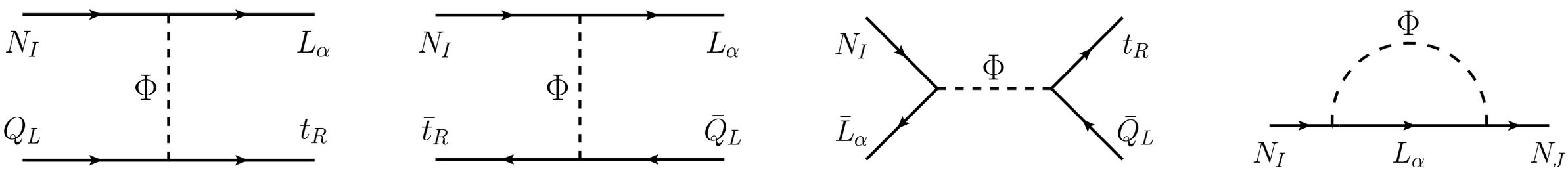
How does the mechanism work?

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

Two kinds of ~~CP~~ processes

Lepton number conserving

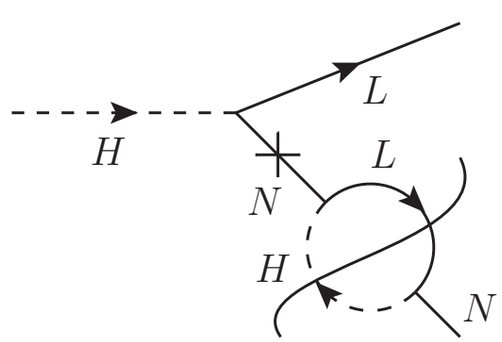
(neutrino generation and oscillations)



Lepton number violating

(thermal Higgs decay)

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

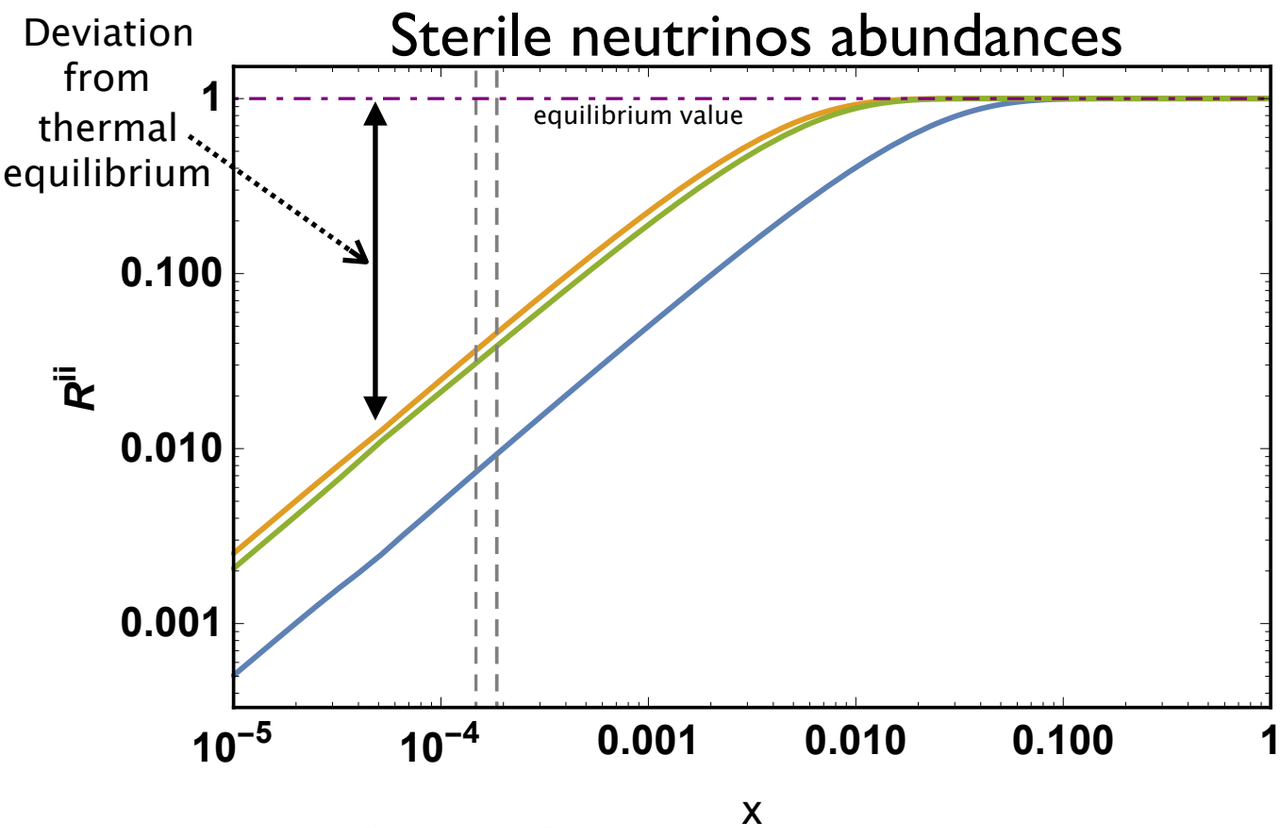


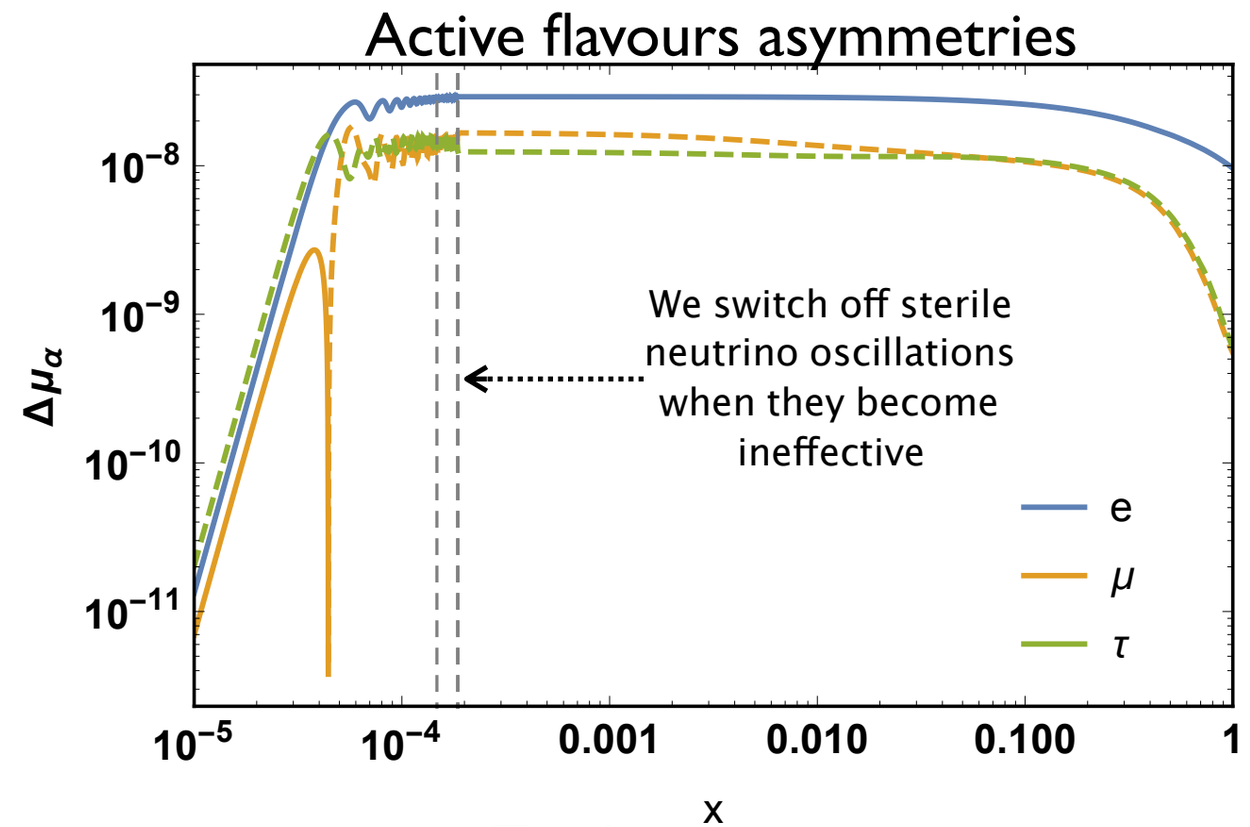
$$\propto \frac{M^2}{T^2}$$

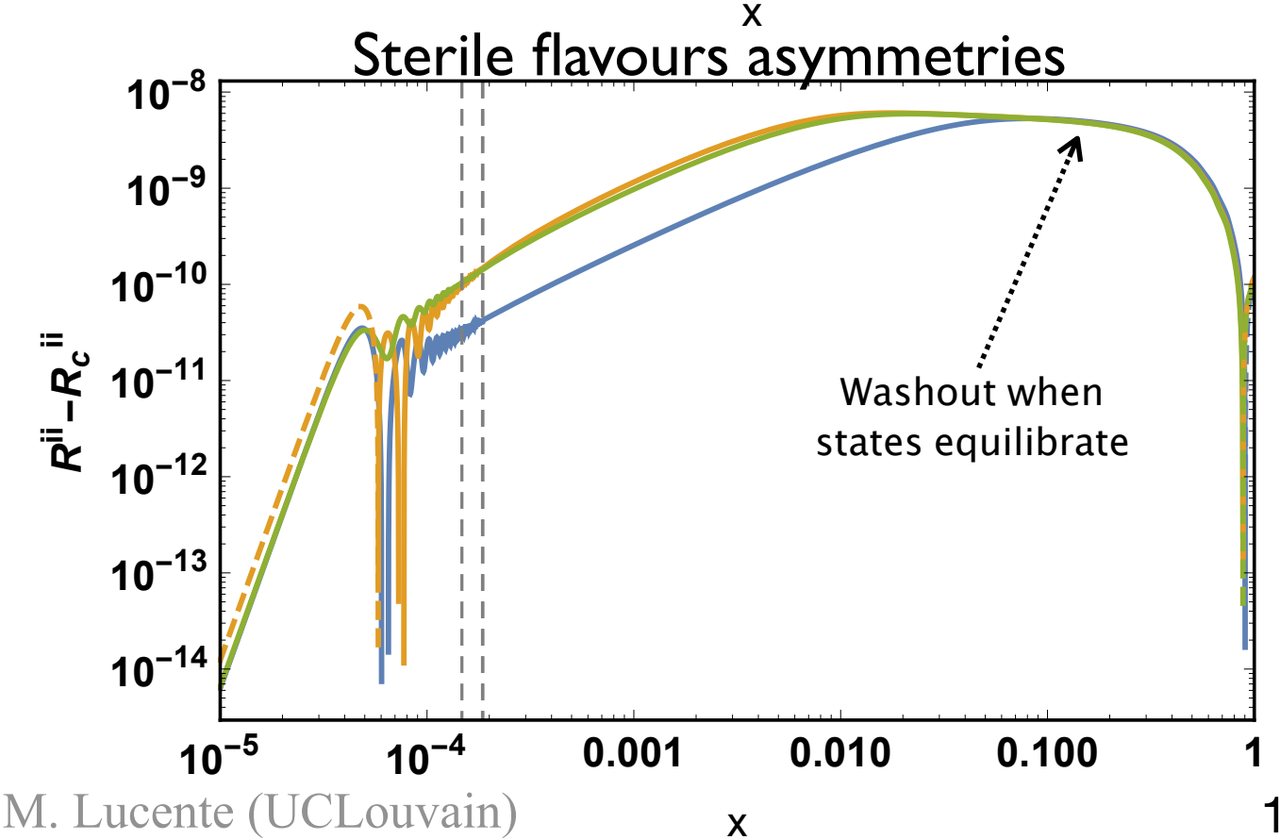
relevant at late times

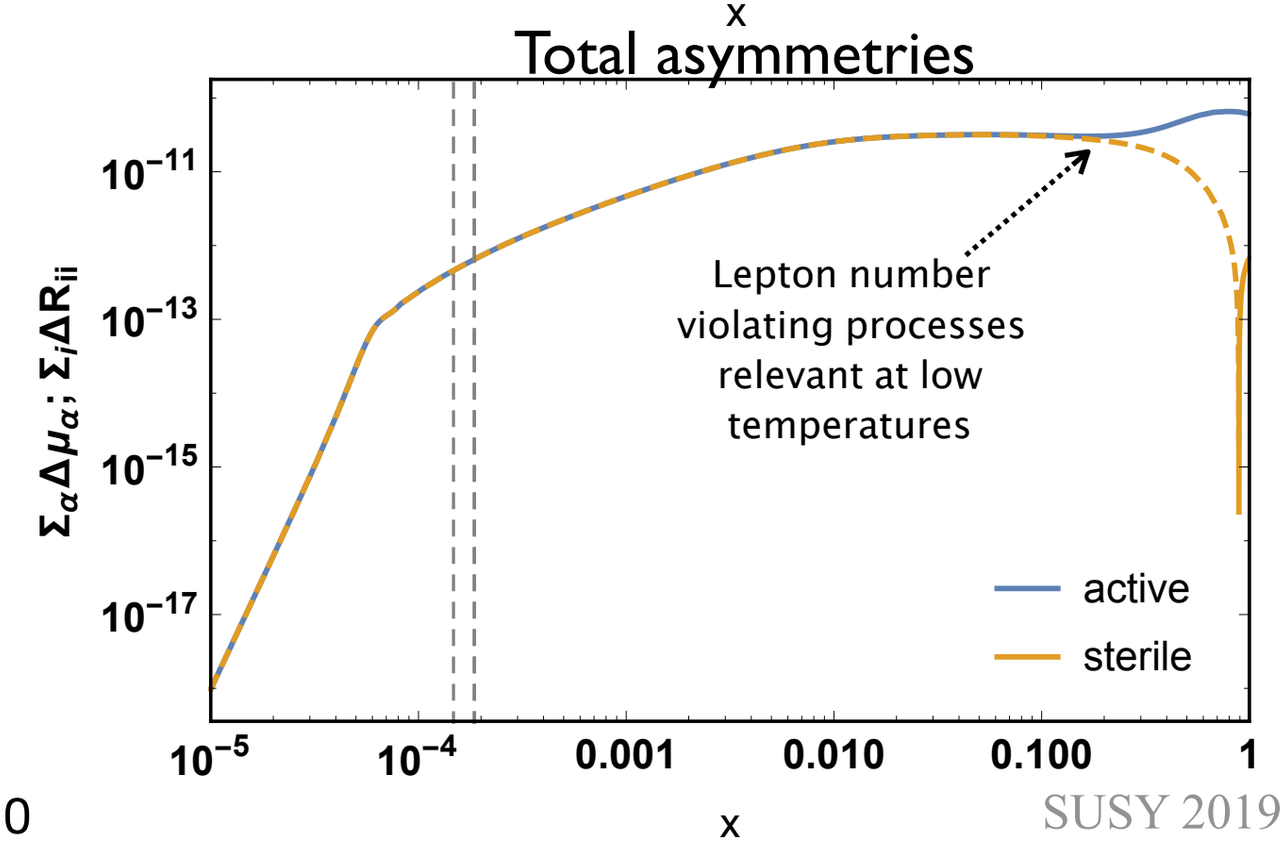
Asymmetry generation example with 3 RHN

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





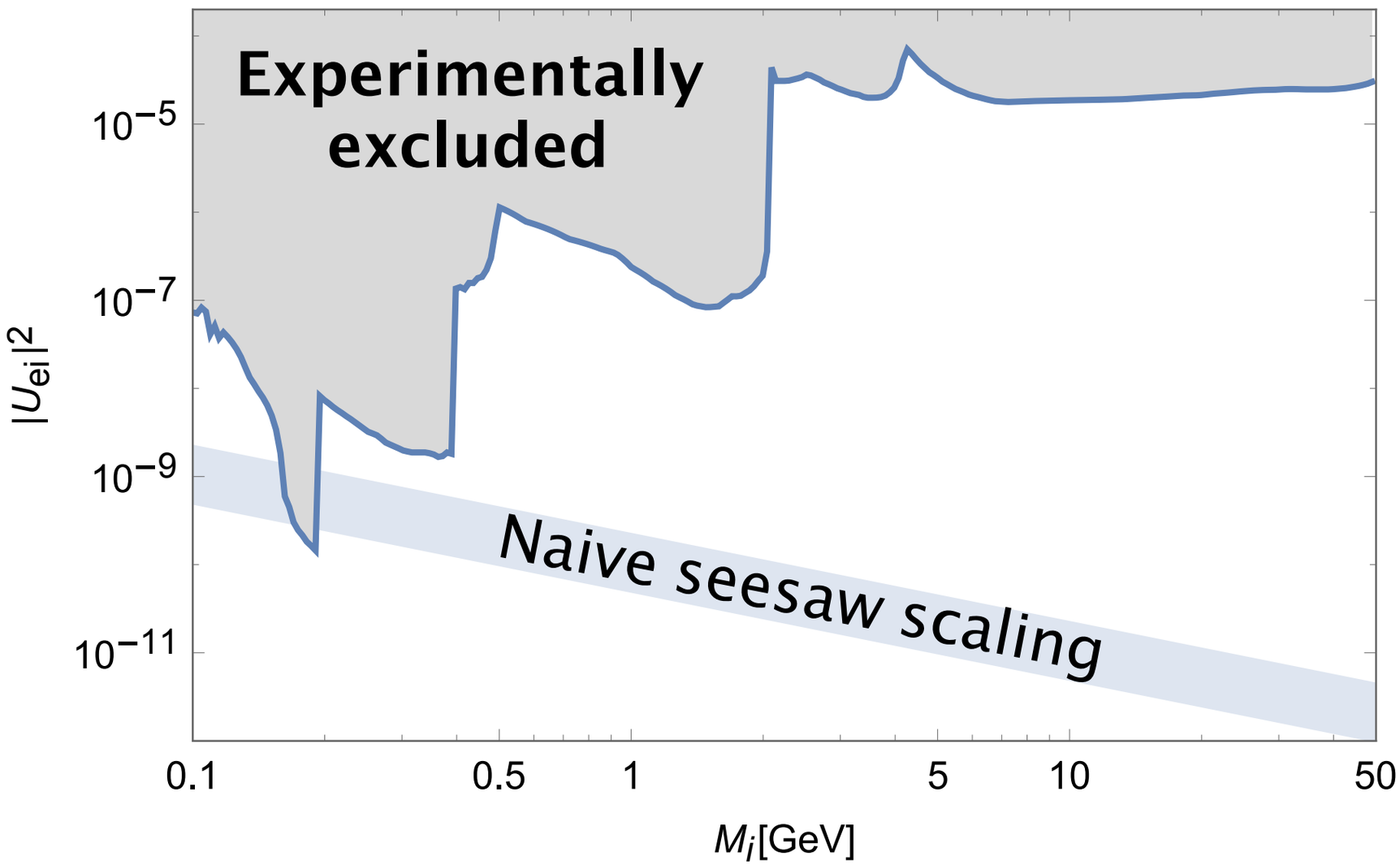




Testability?

Seesaw scaling $$m_\nu = -v^2 F \frac{1}{M} F^T$$

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

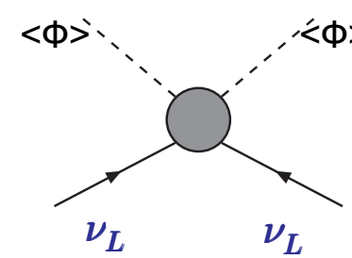
SM as an effective theory

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

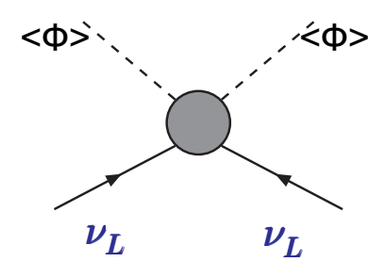
SM as an effective theory

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~~ $\Lambda \approx \text{GeV}$
- $c_{\alpha\beta} \ll 1$ 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

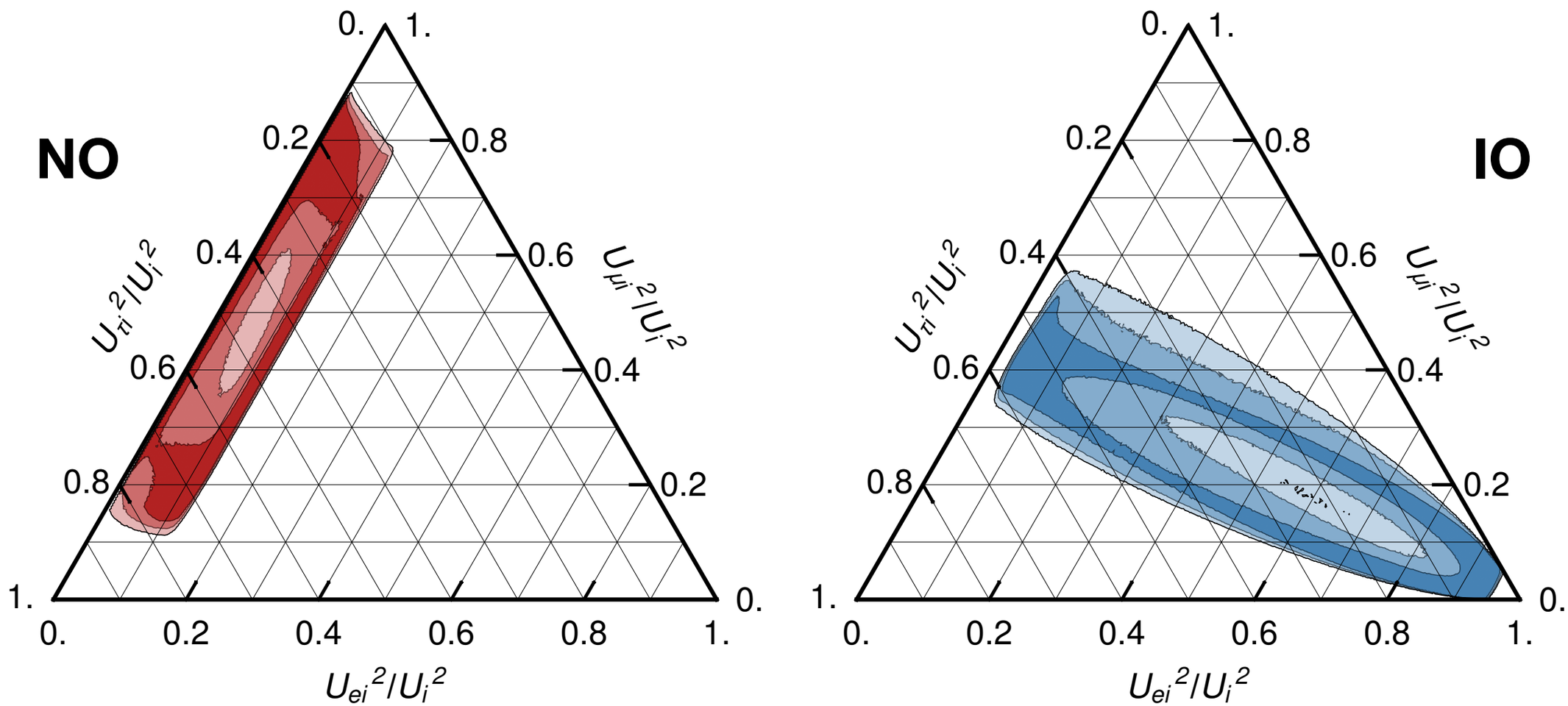
m_i^{tree}
tree-level neutrino mass spectrum

The minimal scenario: 2 RH-Neutrinos

Two RH-neutrinos suffice to account for neutrino oscillation data

S. F. King, hep-ph/9912492, hep-ph/0204360
P. H. Frampton, S. L. Glashow and T. Yanagida, hep-ph/0208157
A. Donini, P. Hernandez, J. Lopez-Pavon and M. Maltoni, arXiv:1106.0064 [hep-ph]

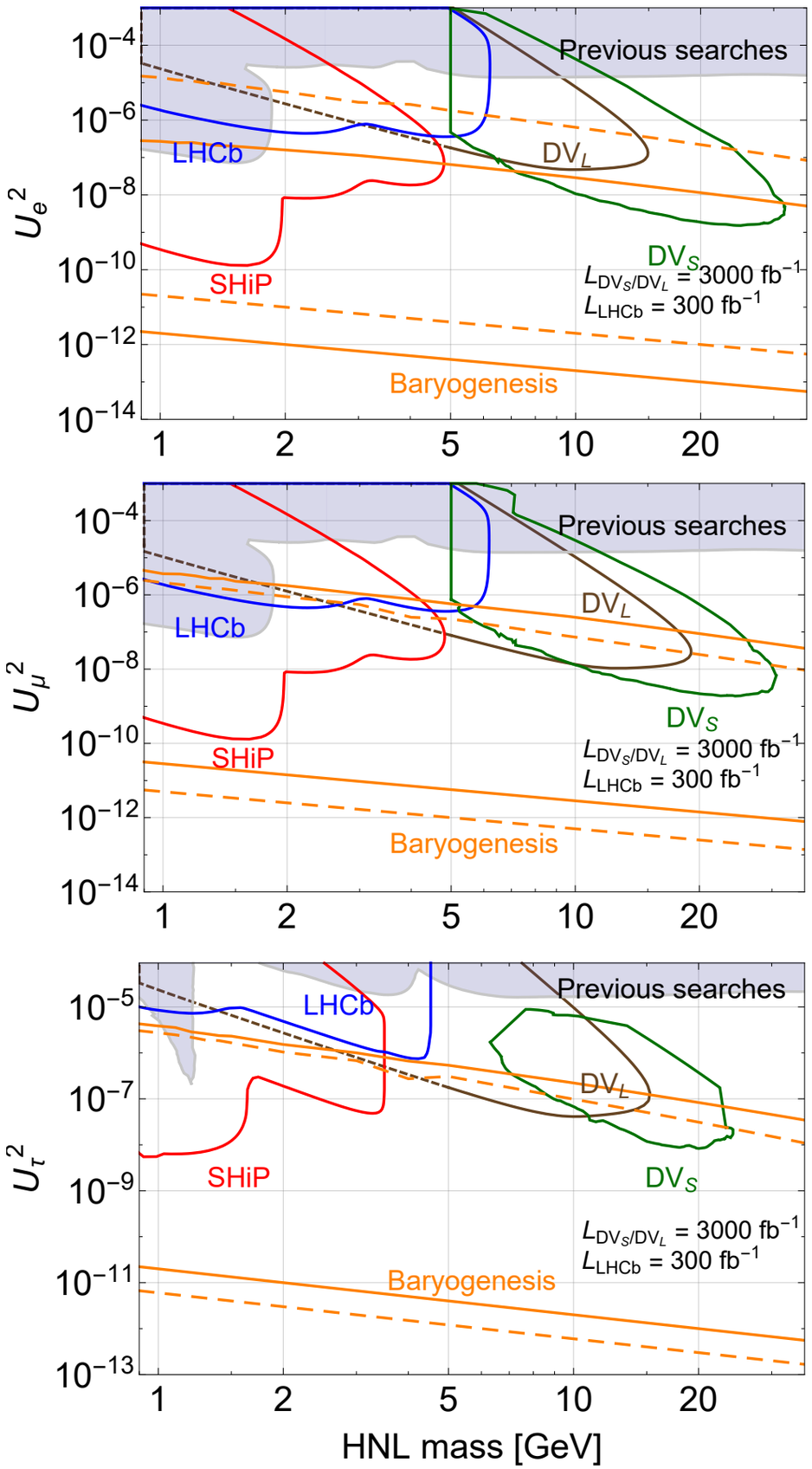
Constrained flavour pattern



M. Drewes, J. Hajer, J. Klaric and G. Lanfranchi, arXiv:1801.04207 [hep-ph]
A. Caputo, P. Hernandez, J. Lopez-Pavon and J. Salvado, arXiv:1704.08721 [hep-ph]

Large hierarchies in the couplings to different SM flavours not allowed

Leptogenesis with 2 RH-neutrinos



Too large active-sterile couplings enable equilibration of HNL and asymmetry washout

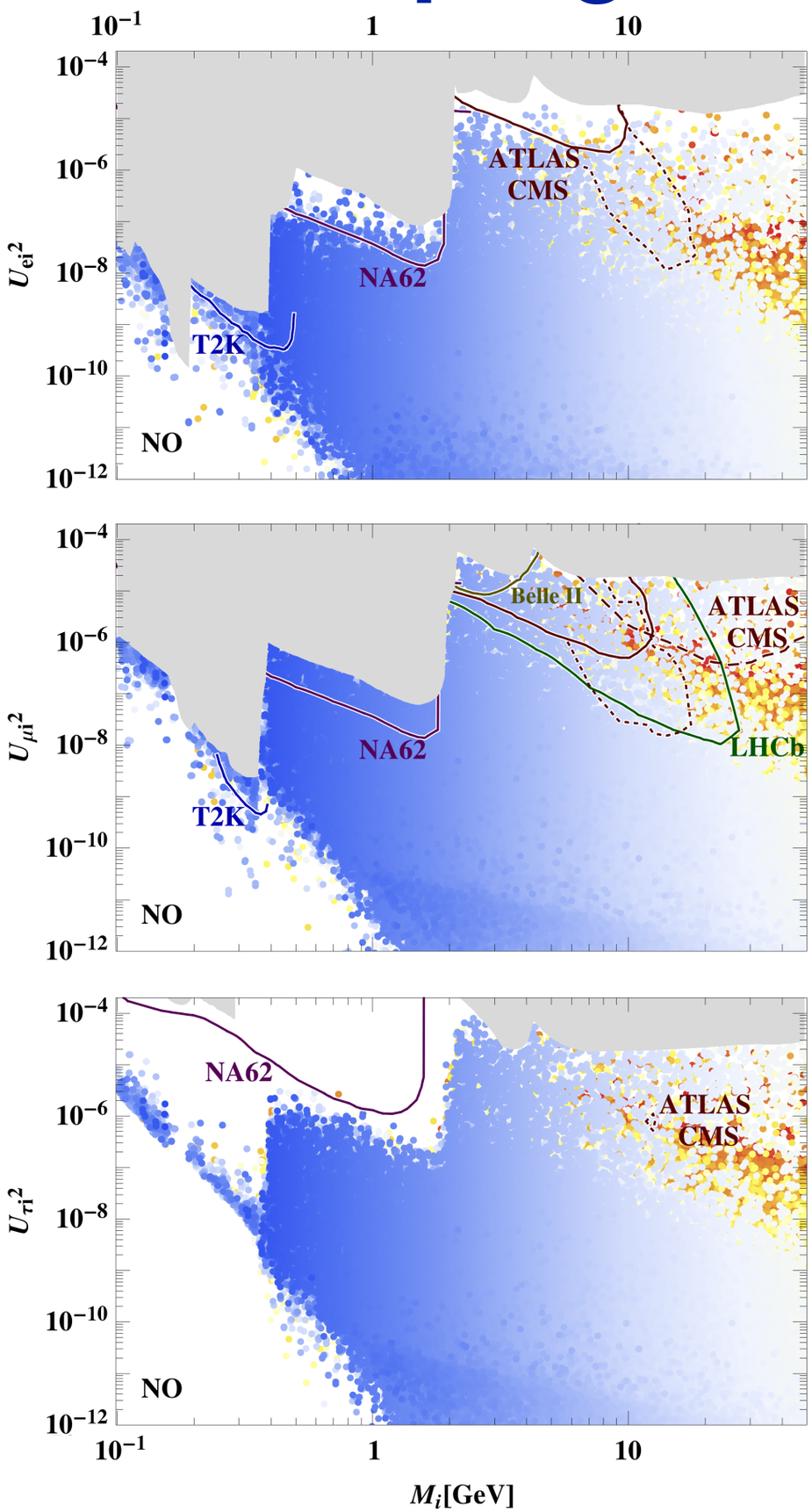
Washout is flavour-dependent, but "democratic" couplings for 2 RHN

Not possible to store the asymmetry in a feebly coupled flavour while the other mixings are large

Figures from I. Boiarska, K. Bondarenko, A. Boyarsky, S. Eijima, M. Ovchynnikov, O. Ruchayskiy and I. Timiryasov, arXiv:1902.04535 [hep-ph]

See also L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv: 1208.4607 [hep-ph]; A. Abada, G. Arcadi, V. Domcke and M.L., arXiv: 1507.06215, arXiv:1709.00415 [hep-ph]; P. Hernández, M. Kekic, J. López-Pavón, J. Racker and J. Salvado, arXiv:1508.03676, arXiv:1606.06719 [hep-ph]; S. Eijima, M. Shaposhnikov and I. Timiryasov, arXiv:1808.10833 [hep-ph]

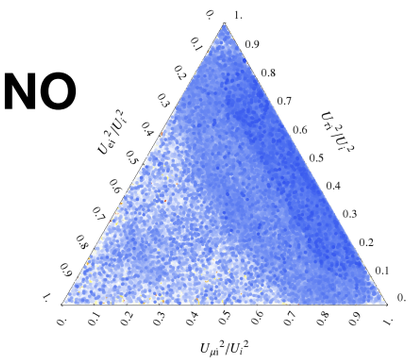
Leptogenesis with 3 RH-neutrinos



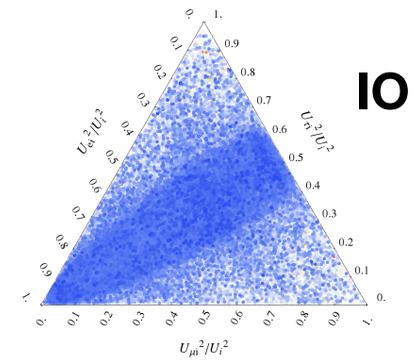
New effects peculiar to 3 RHN case

Larger flavour hierarchies are allowed

NO



IO



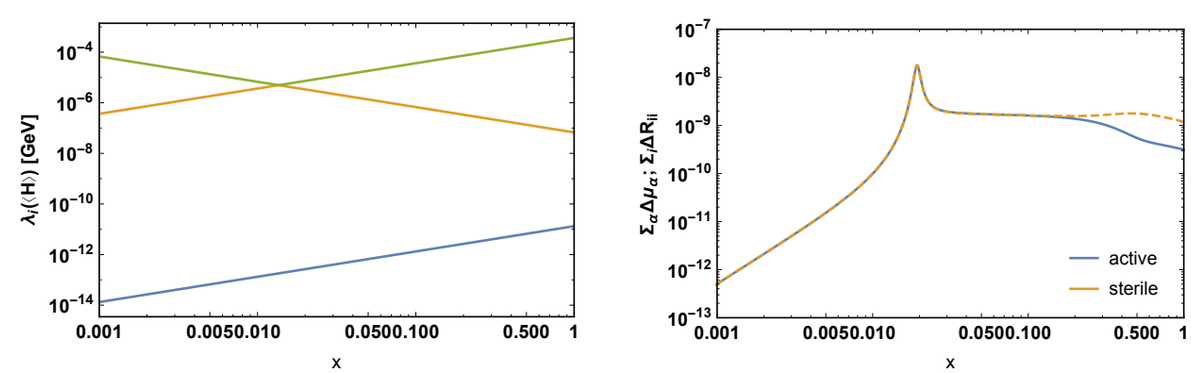
Asymmetry in the heavy neutrino oscillations

2 flavour oscillations are CP-conserving

3 flavour oscillations are CP-violating

→ New source term

Resonantly enhanced asymmetry



A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric and M.L., arXiv:1810.12463 [hep-ph]

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

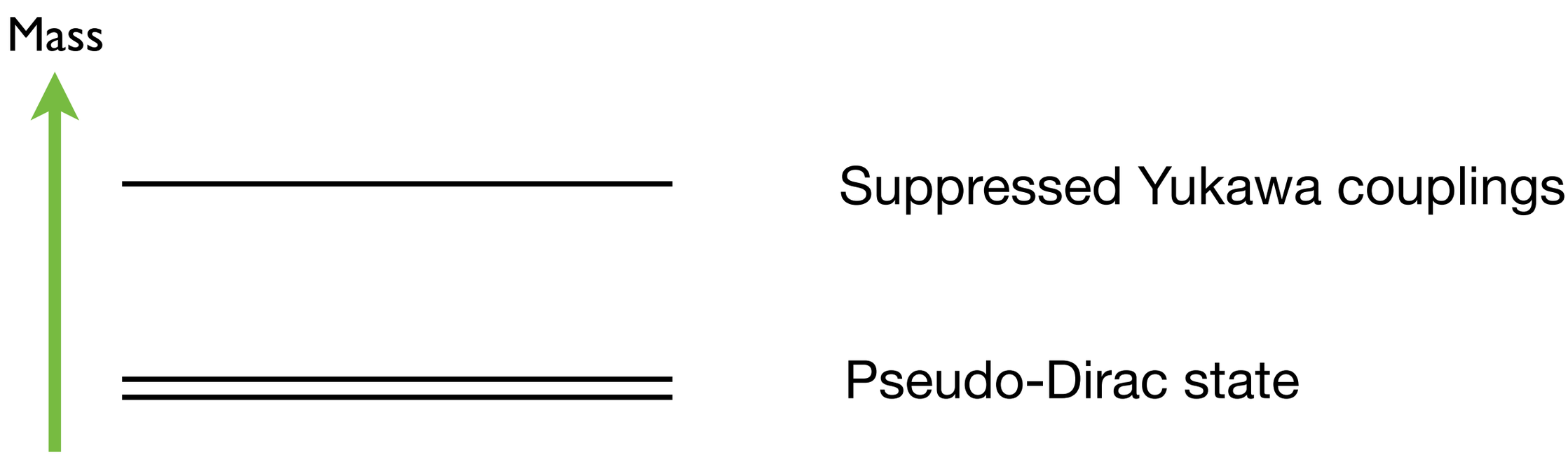
How to preserve lepton number with Majorana states?

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

or

Decouple a state

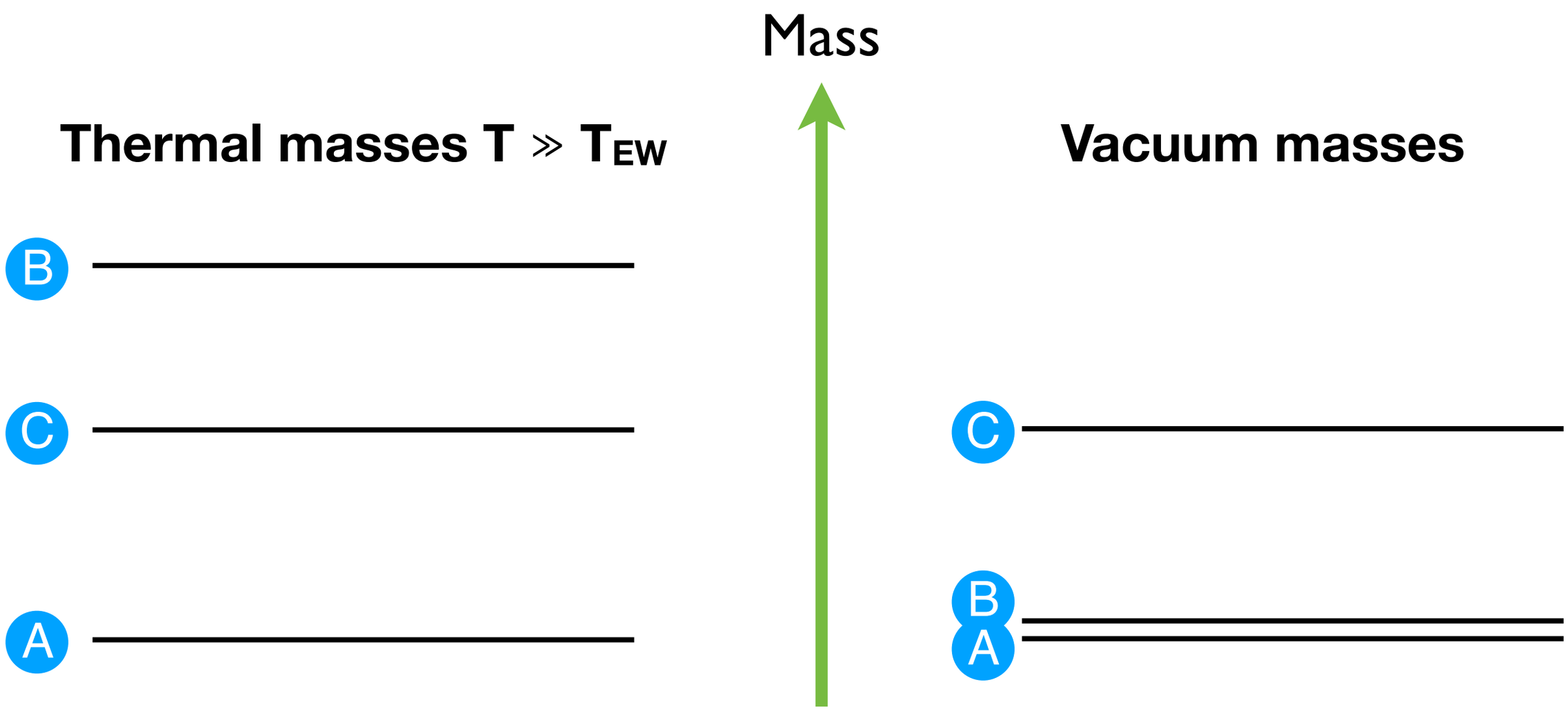
If there is an **odd number** of **right-handed neutrinos** and **B - L** approximate **symmetry**



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

$$T_{\text{crossing}} \approx \frac{2\sqrt{2}\bar{M}\sqrt{\mu'^2 - 1}}{\sqrt{\sum_a |F_a|^2}} = 2.8 \times 10^5 \text{ GeV} \left(\frac{\bar{M}}{\text{GeV}}\right) \frac{\sqrt{\mu'^2 - 1}}{\sqrt{\sum_a |(F_a/10^{-5})|^2}}$$

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

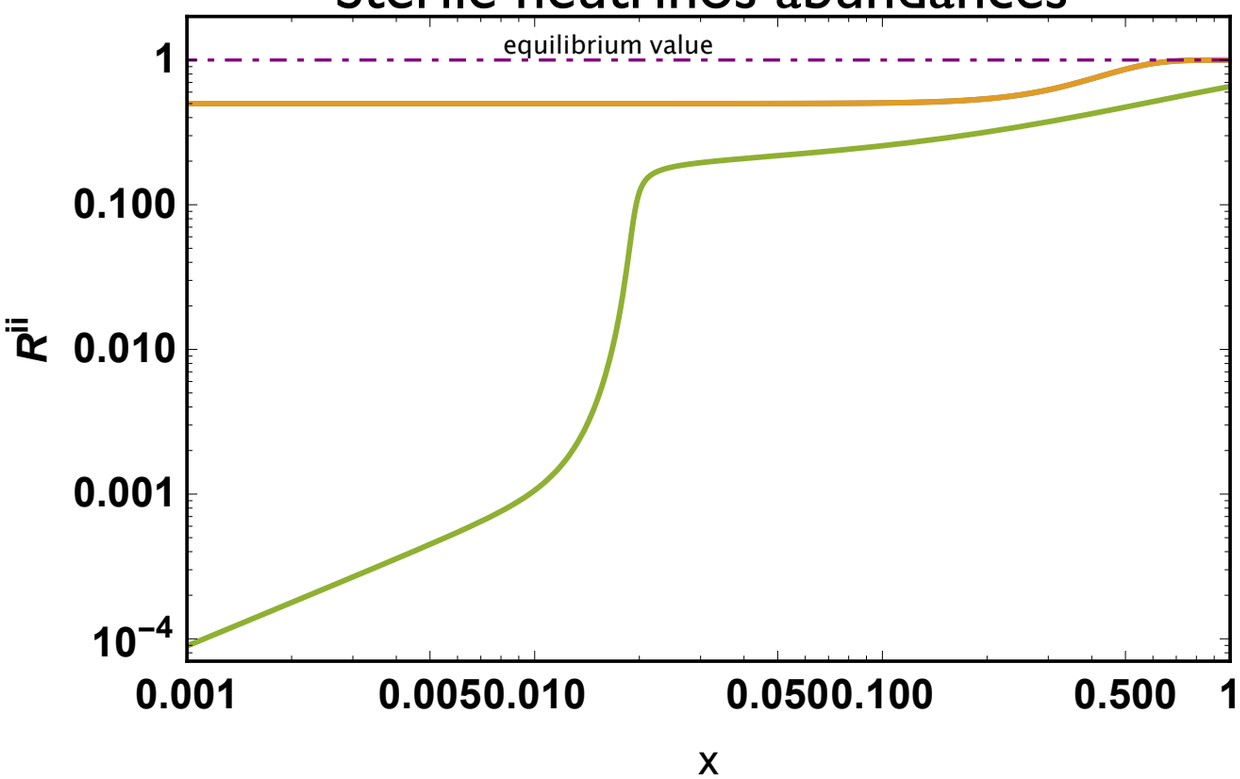


If the vacuum mass of the decoupled state is heavier than the pseudo-Dirac one, there is **necessarily** a level crossing at some finite temperature!

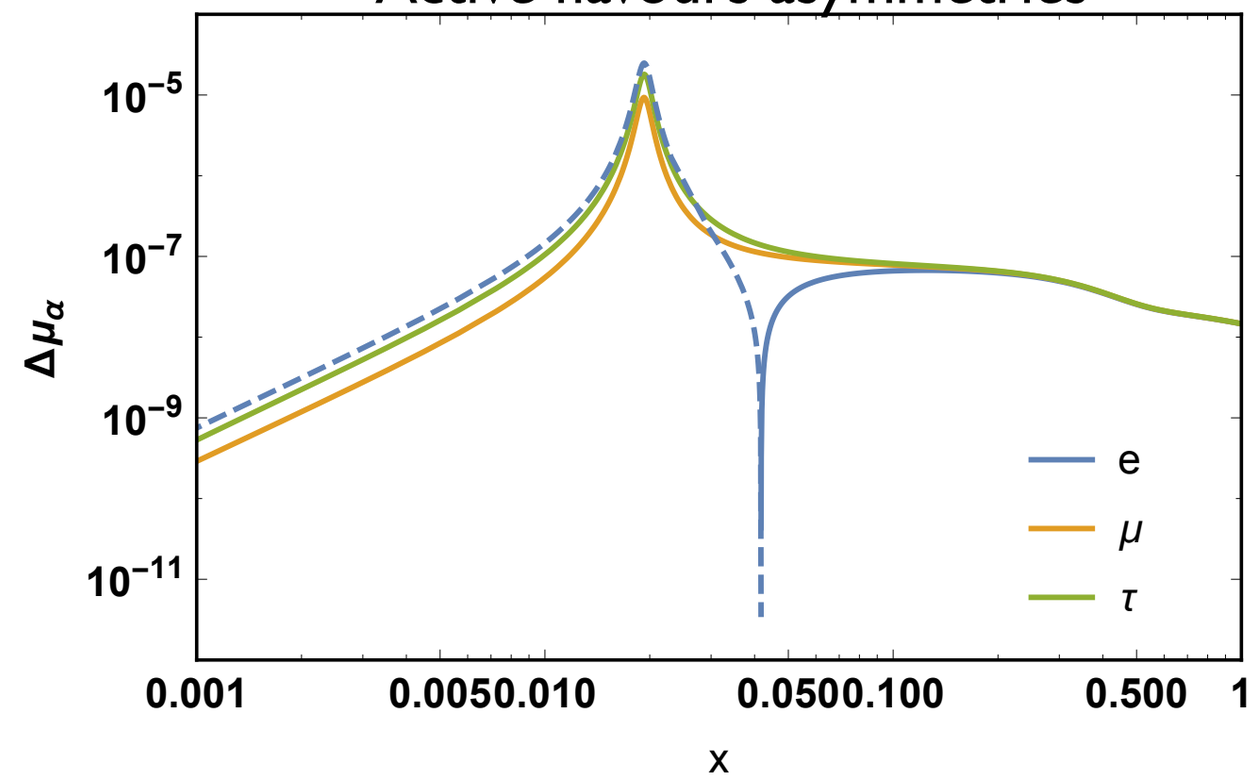
Level crossing: resonant asymmetry production

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

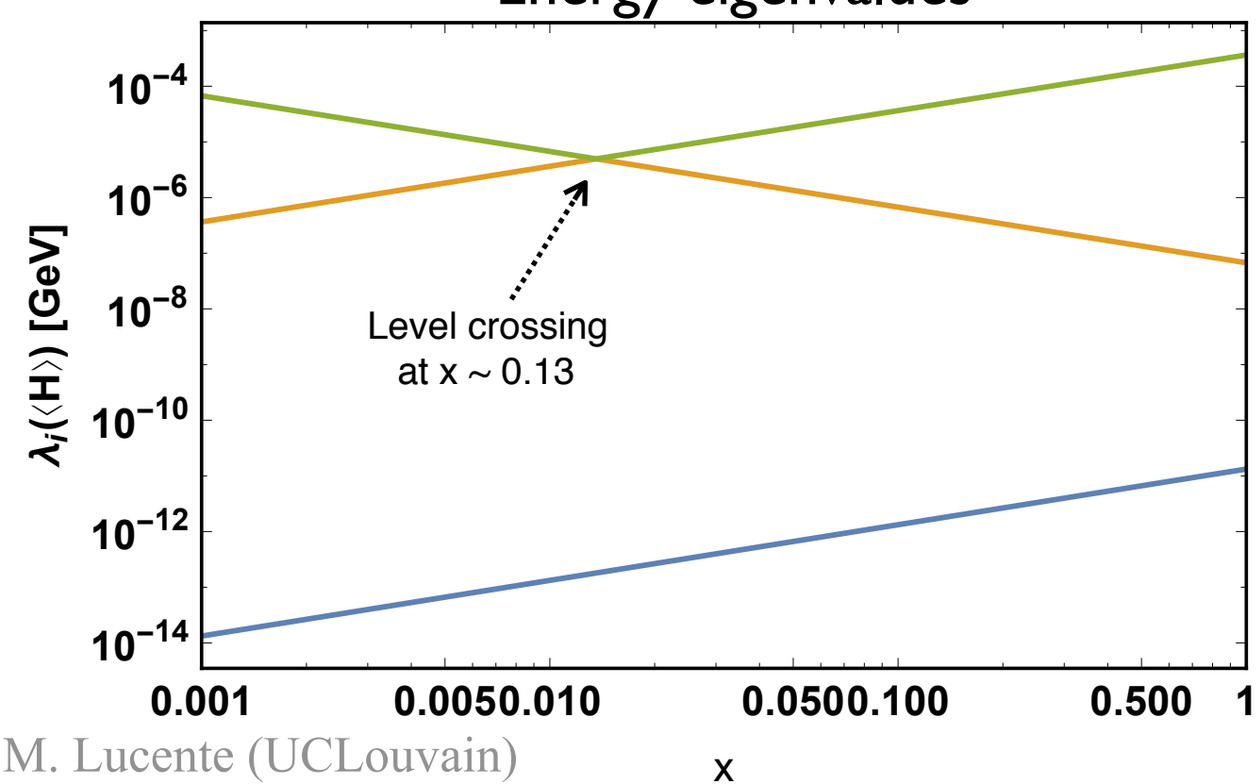
Sterile neutrinos abundances



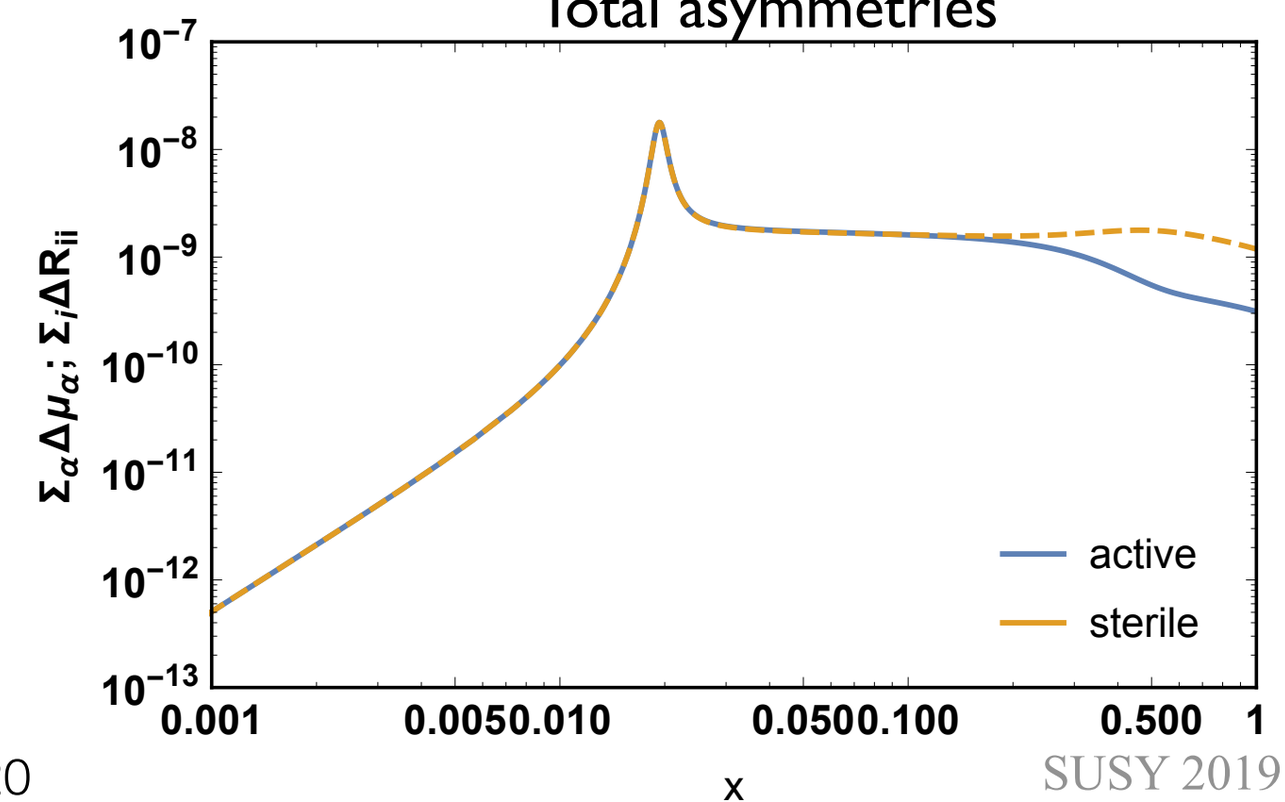
Active flavours asymmetries



Energy eigenvalues



Total asymmetries



Conclusion

Low-scale leptogenesis with **RH-neutrinos** at the **GeV scale** is an attractive mechanism for the BAU generation

We performed the **first systematic study** for low-scale leptogenesis in the Standard Model extended with **3 RH-neutrinos**

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

We find a **new mechanism** that:

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

Backup

Kinetic equations for freeze-in leptogenesis

G. Sigl and G. Raffelt, Nucl. Phys. B 406 (1993) 423; E. K. Akhmedov, V. A. Rubakov and A. Y. Smirnov, hep-ph/9803255; T. Asaka and M. Shaposhnikov, hep-ph/0505013; T. Asaka, S. Eijima and H. Ishida, arXiv:1112.5565 [hep-ph]; L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph]; P. Hernández, M. Kekic, J. López-Pavón, J. Racker and J. Salvado, arXiv:1606.06719 [hep-ph]; S. Antusch, E. Cazzato, M. Drewes, O. Fischer, B. Garbrecht, D. Gueter and J. Klaric, arXiv:1710.03744 [hep-ph]; A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric and M.L., arXiv:1810.12463 [hep-ph]

$$
\begin{aligned}
\frac{dR_N}{dt} = & -i\left[\langle H\rangle, R_N\right] - \frac{1}{2}\langle\gamma^{(0)}\rangle\left\{F^\dagger F, R_N - I\right\} - \frac{1}{2}\langle\gamma^{(1b)}\rangle\left\{F^\dagger\mu F, R_N\right\} + \langle\gamma^{(1a)}\rangle F^\dagger\mu F + \\
& - \frac{1}{2}\langle\widetilde{\gamma}^{(0)}\rangle\left\{M_M F^T F^* M_M, R_N - I\right\} + \frac{1}{2}\langle\widetilde{\gamma}^{(1b)}\rangle\left\{M_M F^T \mu F^* M_M, R_N\right\} + \\
& - \langle\widetilde{\gamma}^{(1a)}\rangle M_M F^T \mu F^* M_M\,, \\
\frac{d\mu_{\Delta a}}{dt} = & -\frac{9\,\zeta(3)}{2N_D\,\pi^2}\Big\{\langle\gamma^{(0)}\rangle\left(F R_N F^\dagger - F^* R_{\bar{N}} F^T\right) - 2\langle\gamma^{(1a)}\rangle\mu F F^\dagger + \\
& + \langle\gamma^{(1b)}\rangle\mu\left(F R_N F^\dagger + F^* R_{\bar{N}} F^T\right) \\
& + \langle\widetilde{\gamma}^{(0)}\rangle\left(F^* M_M R_{\bar{N}} M_M F^T - F M_M R_N M_M F^\dagger\right) - 2\langle\widetilde{\gamma}^{(1a)}\rangle\mu F^* M_M^2 F^T \\
& + \langle\widetilde{\gamma}^{(1b)}\rangle\mu\left(F^* M_M R_{\bar{N}} M_M F^T + F M_M R_N M_M F^\dagger\right)\Big\}_{aa}\,,
\end{aligned}
$$

The role of lepton number

M. Shaposhnikov, hep-ph/0605047
A. Abada, G. Arcadi, V. Domcke and M.L., arXiv:1507.06215, arXiv:1709.00415 [hep-ph]
A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric and M.L., arXiv:1810.12463 [hep-ph]

An approximate *B - L* symmetry:
- enhances the asymmetry production
- allows for large active-sterile mixings

General seesaw parametrisation

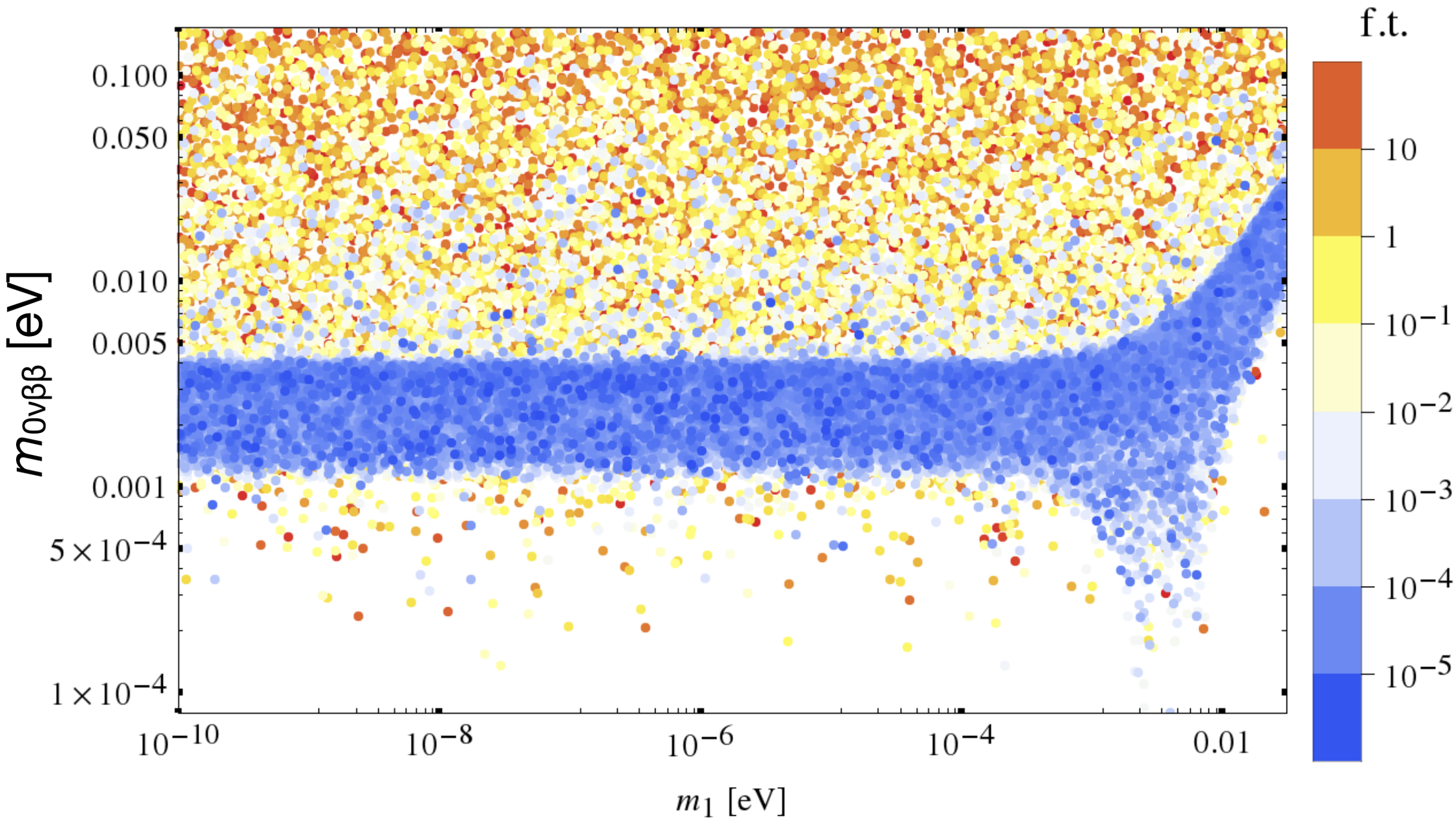
$$F = \frac{1}{\sqrt{2}} \begin{pmatrix} F_e(1+\epsilon_e) & \mathrm{i}F_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & \mathrm{i}F_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & \mathrm{i}F_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix} \qquad M_M = \bar{M} \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

In the limit $\varepsilon_\alpha, \varepsilon'_\alpha, \mu \ll 1$ → Approximate *B - L* conservation

Neutrinoless effective mass

0νββ decay is a lepton number violating process

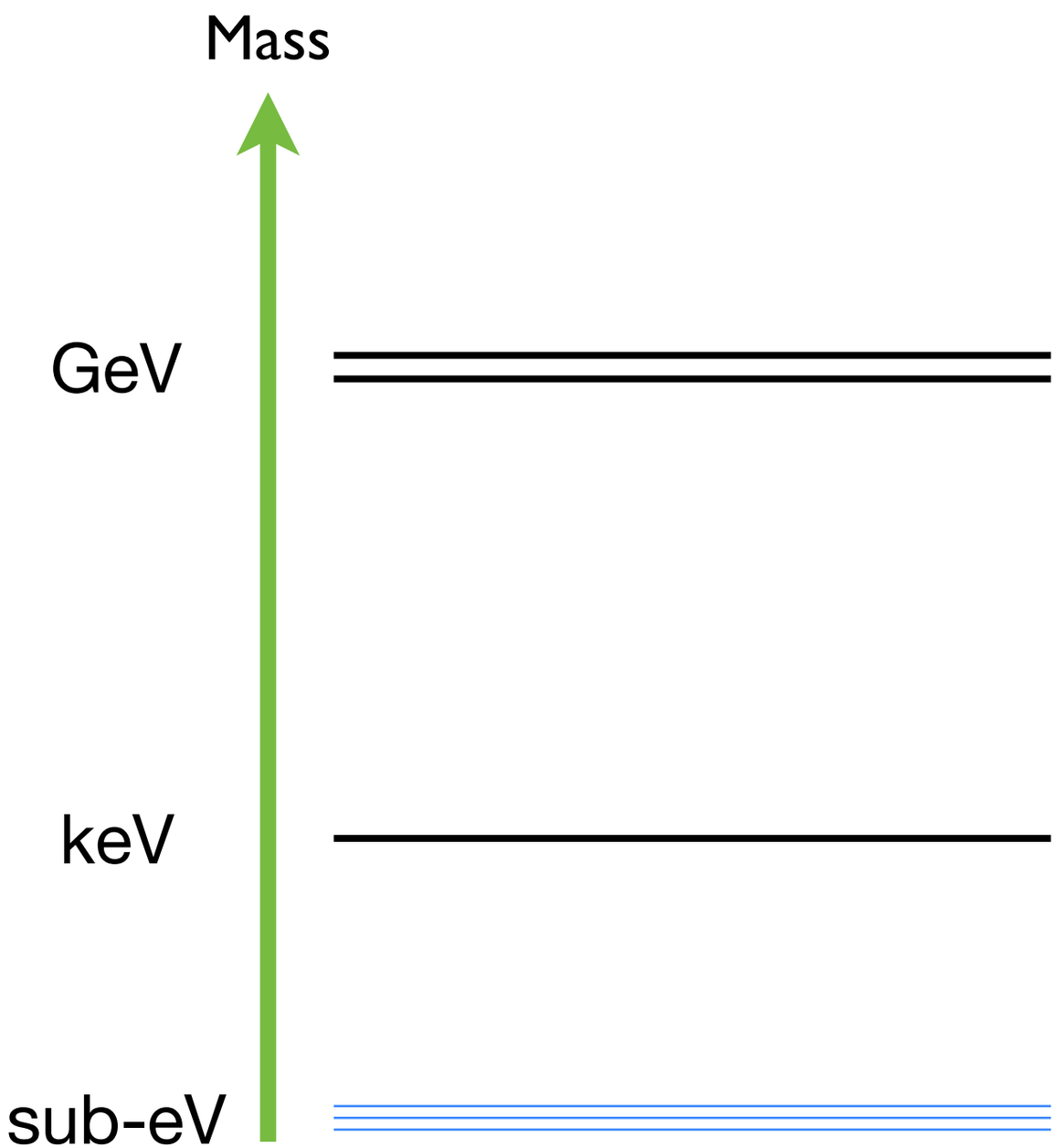
It violates the B - L symmetry



The νMSM

T. Asaka, S. Blanchet and M. Shaposhnikov, hep-ph/0503065
T. Asaka and M. Shaposhnikov, hep-ph/0505013
M. Shaposhnikov and I. Tkachev, hep-ph/0604236

Type-I Seesaw with a phenomenologically motivated mass spectrum



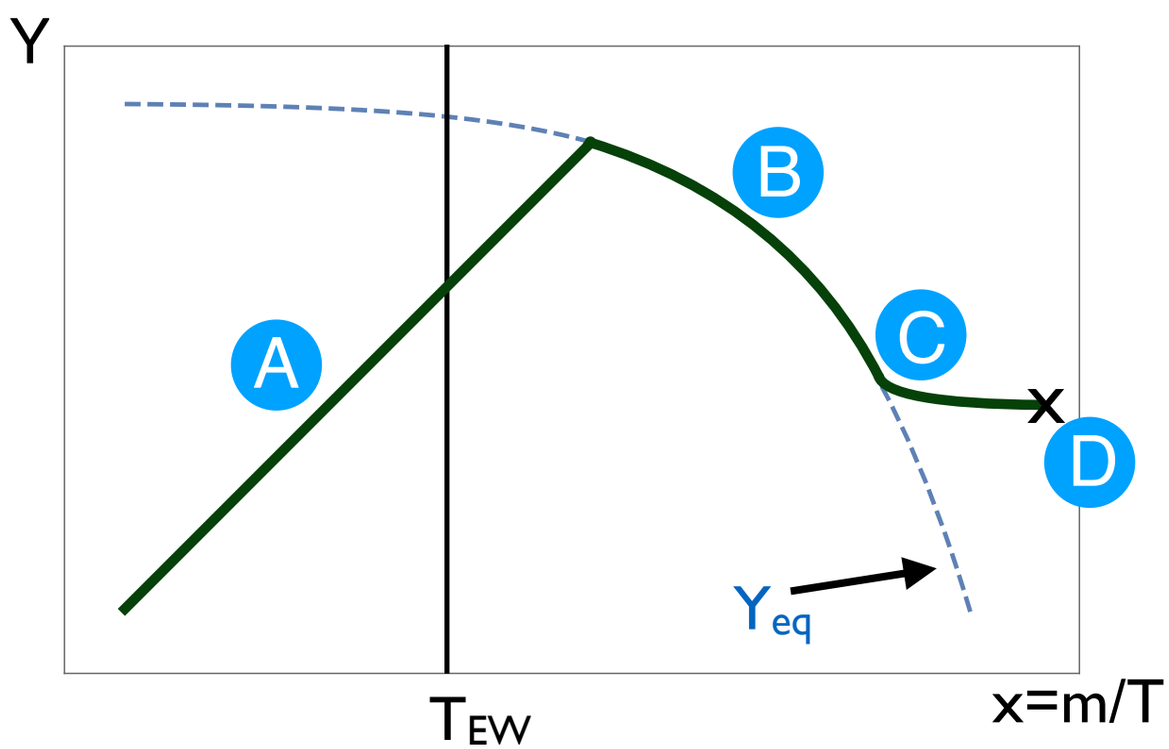
At the origin of the lepton **asymmetries** of the Universe and of **neutrino masses**

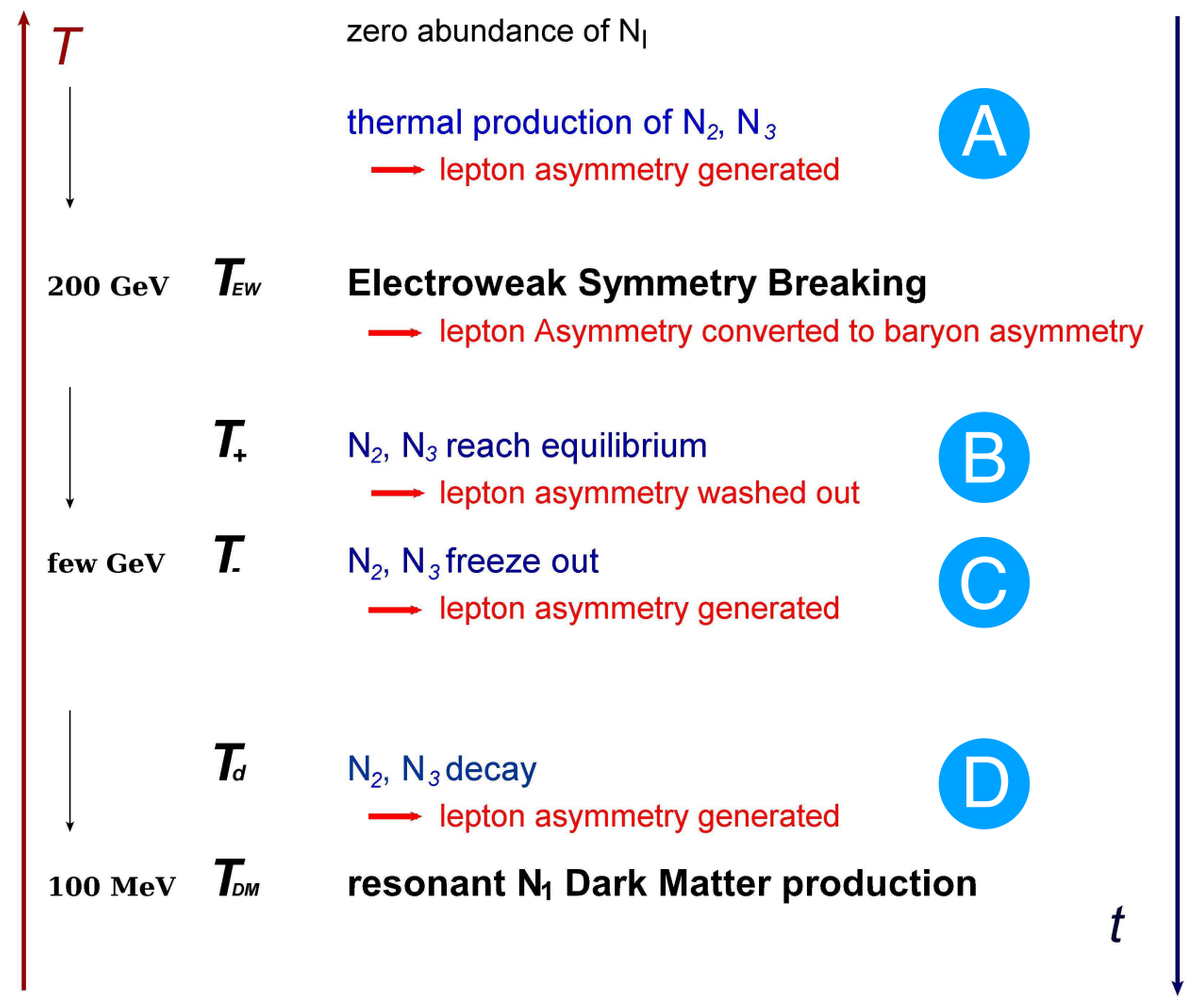
Dark matter candidate
(does not significantly contribute to ν masses)

Active neutrinos

νMSM thermal history

L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, arXiv:1208.4607 [hep-ph]

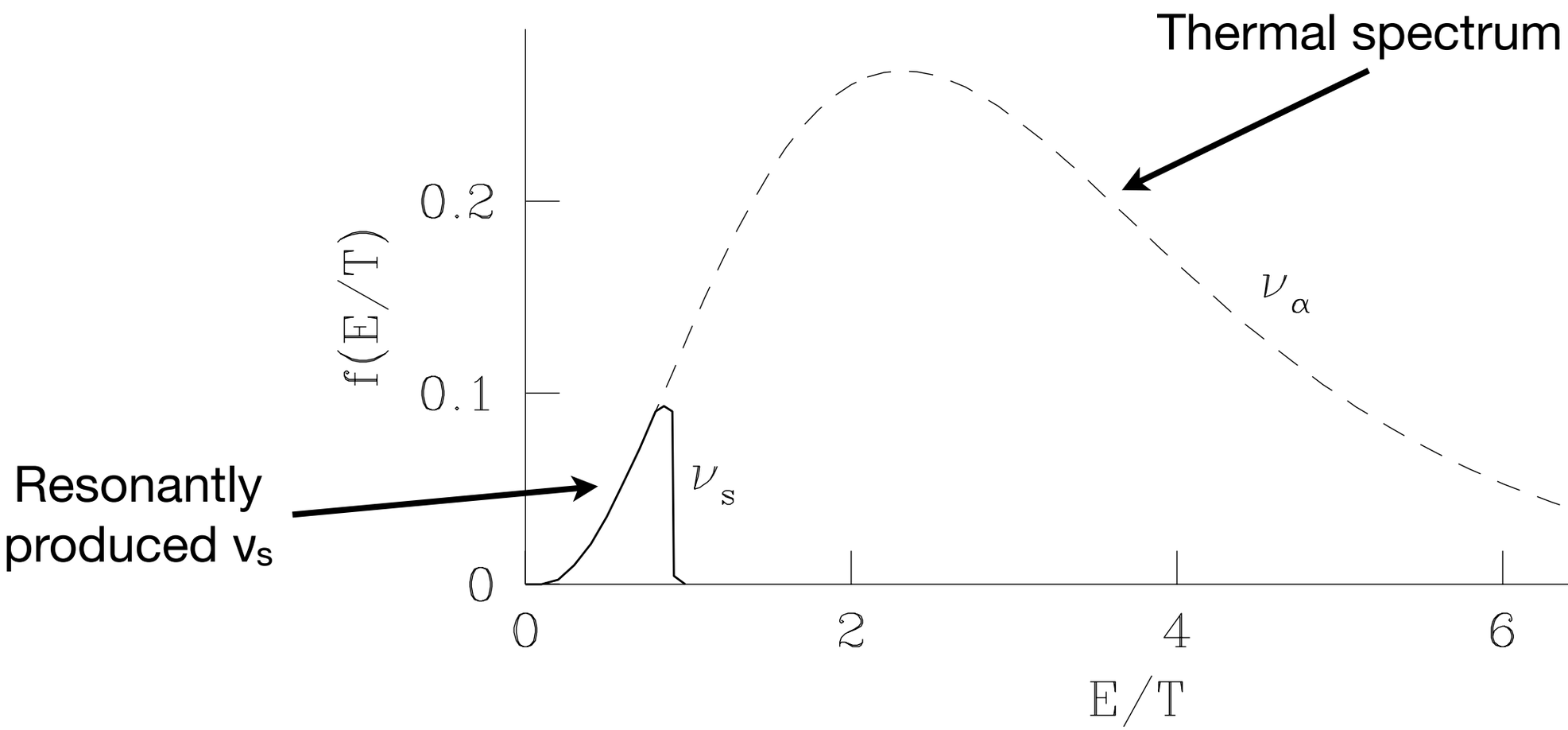




νMSM dark matter solution

Shi-Fuller mechanism: **lepton number-driven resonant** MSW conversion of active neutrinos

X. D. Shi and G. M. Fuller, astro-ph/9810076



Required lepton asymmetry

$$\mu_\alpha = \frac{n_\alpha}{s} \gtrsim 8 \cdot 10^{-6}$$

Required mass degeneracy

$$\frac{\delta M}{M} \lesssim 10^{-14}$$

The Inverse Seesaw (ISS)

R. N. Mohapatra and J. W. F. Valle, Phys. Rev. D 34 (1986) 1642

M. C. Gonzalez-Garcia and J. W. F. Valle, Phys. Lett. B 216 (1989) 360

F. Deppisch and J. W. F. Valle, hep-ph/0406040

Enlarge the SM field content with:
- right handed neutrino fields, ν_R
- fermionic sterile singlets, s

In the basis $n_L \equiv (\nu_L, \nu_R^C, s)^T$ the ISS neutrino mass terms read:

$$-\mathcal{L}_{m_\nu} = \frac{1}{2} \overset{+1}{n_L^T} \overset{-1}{C} \overset{+1}{\mathcal{M}} n_L + h.c., \qquad \mathcal{M} = \begin{pmatrix} 0 & d & 0 \\ d^{\mathrm{T}} & 0 & n \\ 0 & n^{\mathrm{T}} & \mu \end{pmatrix} \qquad d = \frac{v}{\sqrt{2}} Y^*$$

t'Hooft naturalness criterium: terms violating L are "small", i.e.
$|\mu| \ll |n|, |d|$

Neutrino masses in the limit $|\mu| \ll |d| \ll |n|$: $$m_\nu \simeq d \left(n^{-1}\right)^{\mathrm{T}} \mu \left(n^{-1}\right) d^{\mathrm{T}}$$

One could link the smallness of μ with the one of m_ν (mechanism viable with large Yukawas), thus interesting phenomenology

Presence of sterile states (ν anomalies or DM candidates)

ISS mass scales

For each ISS realisation:
- $\#\nu_L + (\#s - \#\nu_R)$ light states
- $\#\nu_R$ pseudo-Dirac couples

Mass

E.g.

2 $\#\nu_R$ heavy states
(pseudo-Dirac pairs)

$\approx \mathcal{O}(n)$

TeV
(testable)

only if $\#s > \#\nu_R$
$(\#s - \#\nu_R)$ light sterile states

$\sim \mathcal{O}(\mu)$

eV

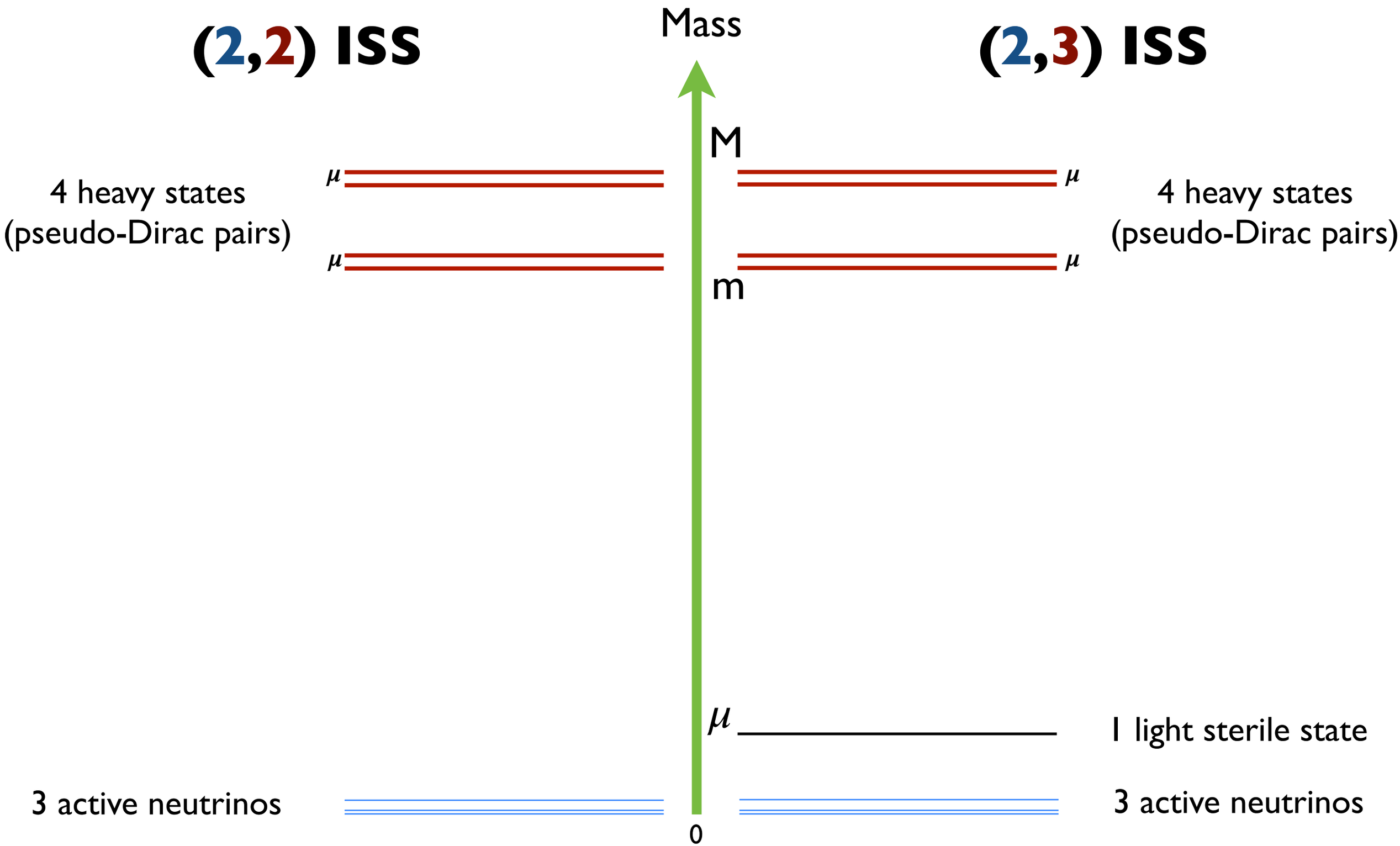
$\#\nu_L$ active neutrinos

$\sim \mathcal{O}(\mu)\mathcal{O}(k)$

meV

$$k = \frac{|d|}{|n|}$$

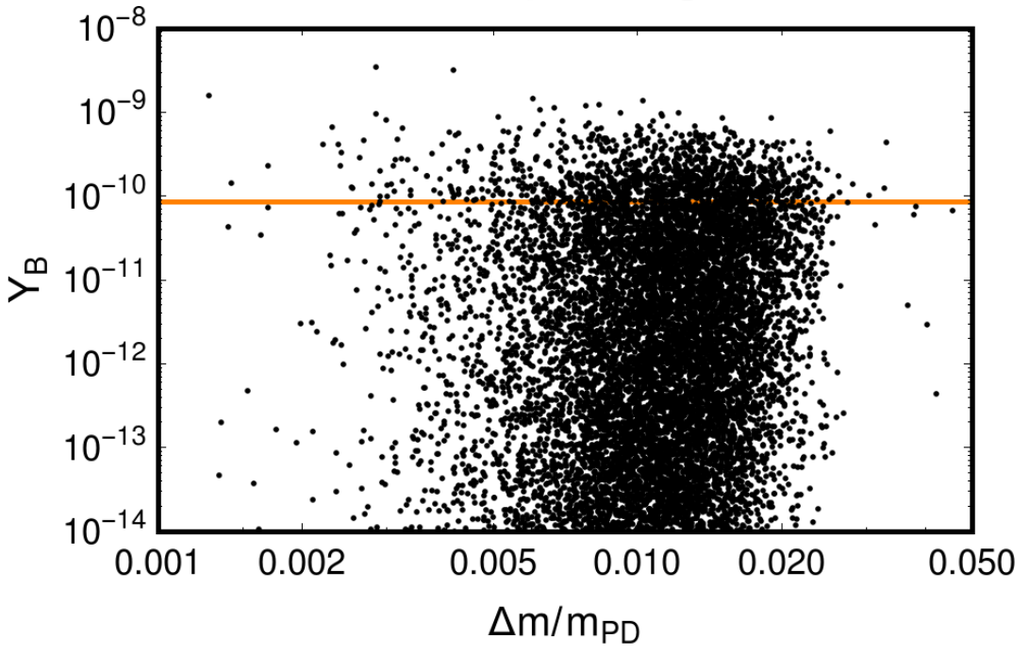
Minimal ISS spectra



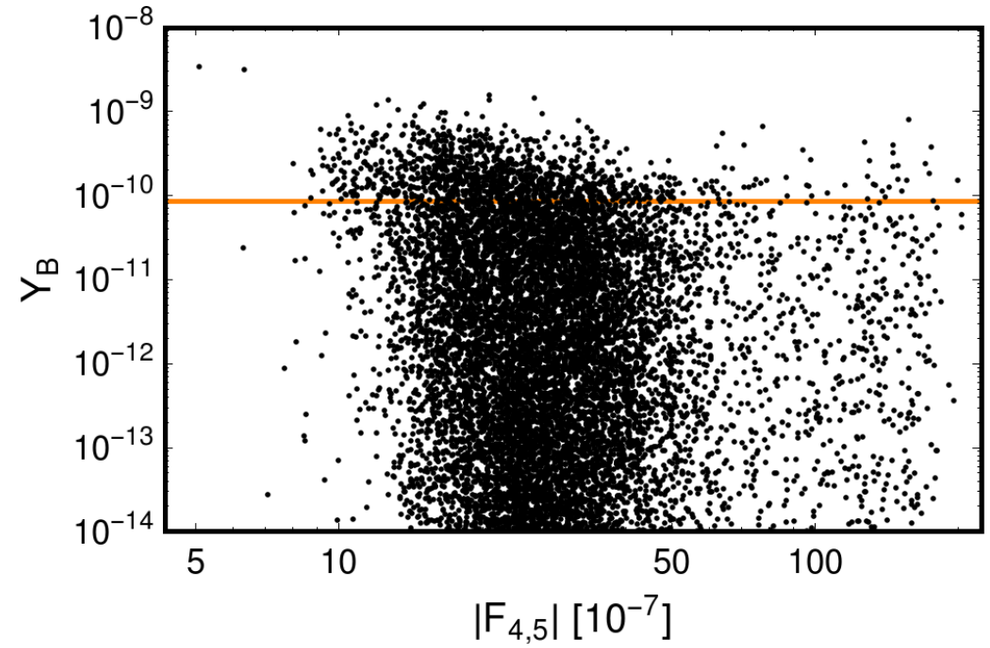
ARS leptogenesis in the (2,2) ISS

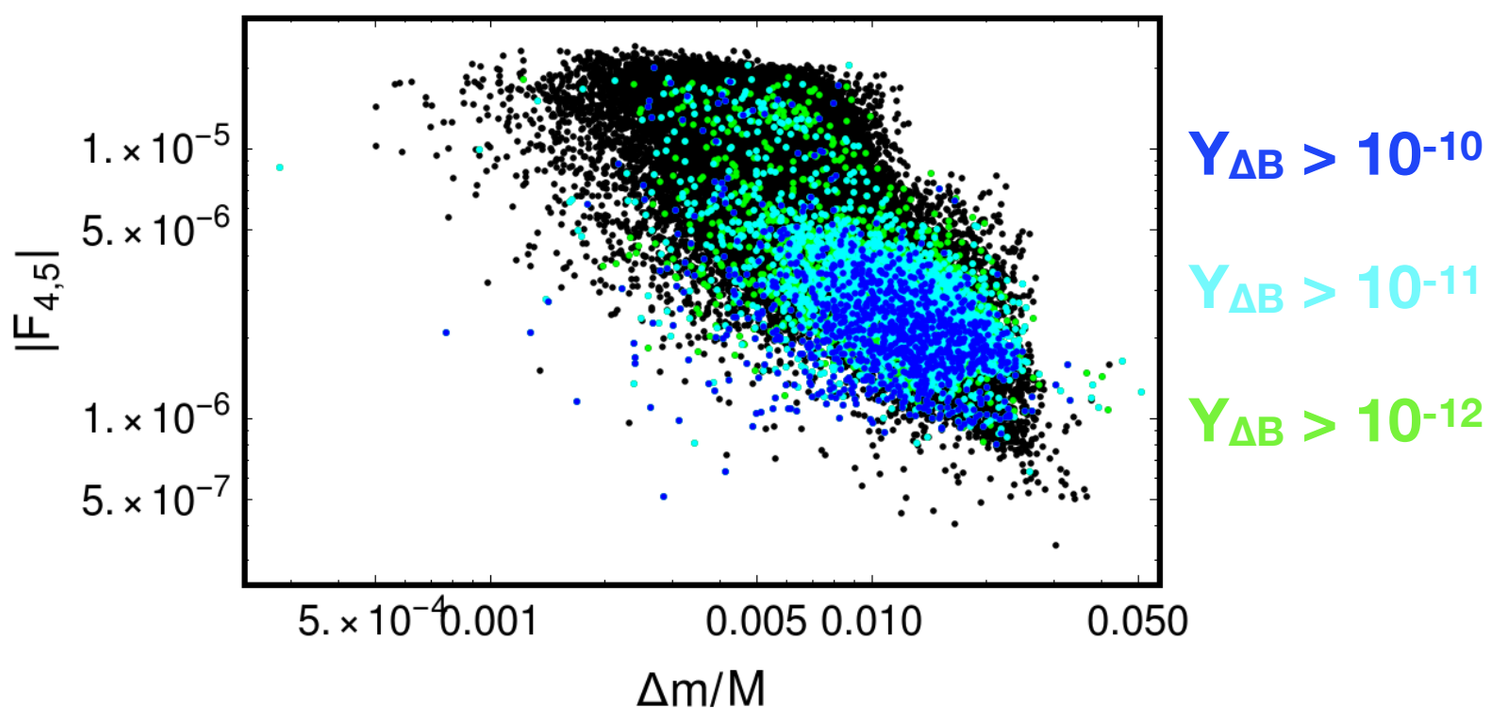
A. Abada, G. Arcadi, V. Domcke and M.L., arXiv:1709.00415 [hep-ph]

Mass splitting



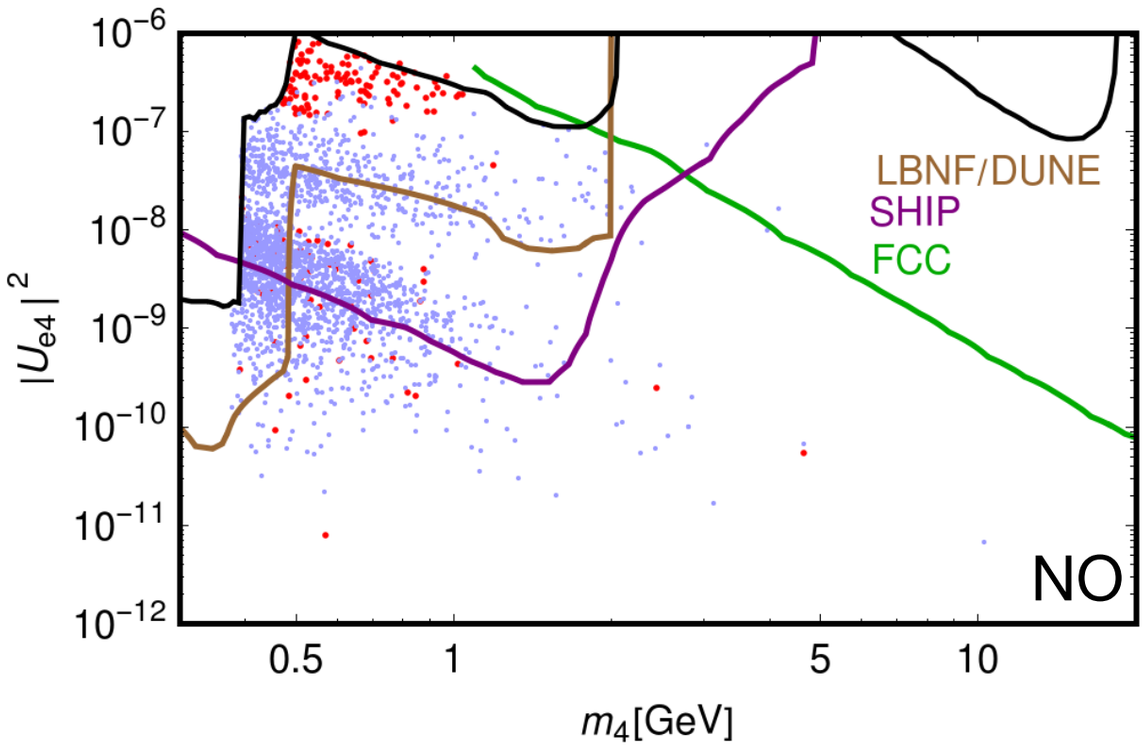
Yukawas

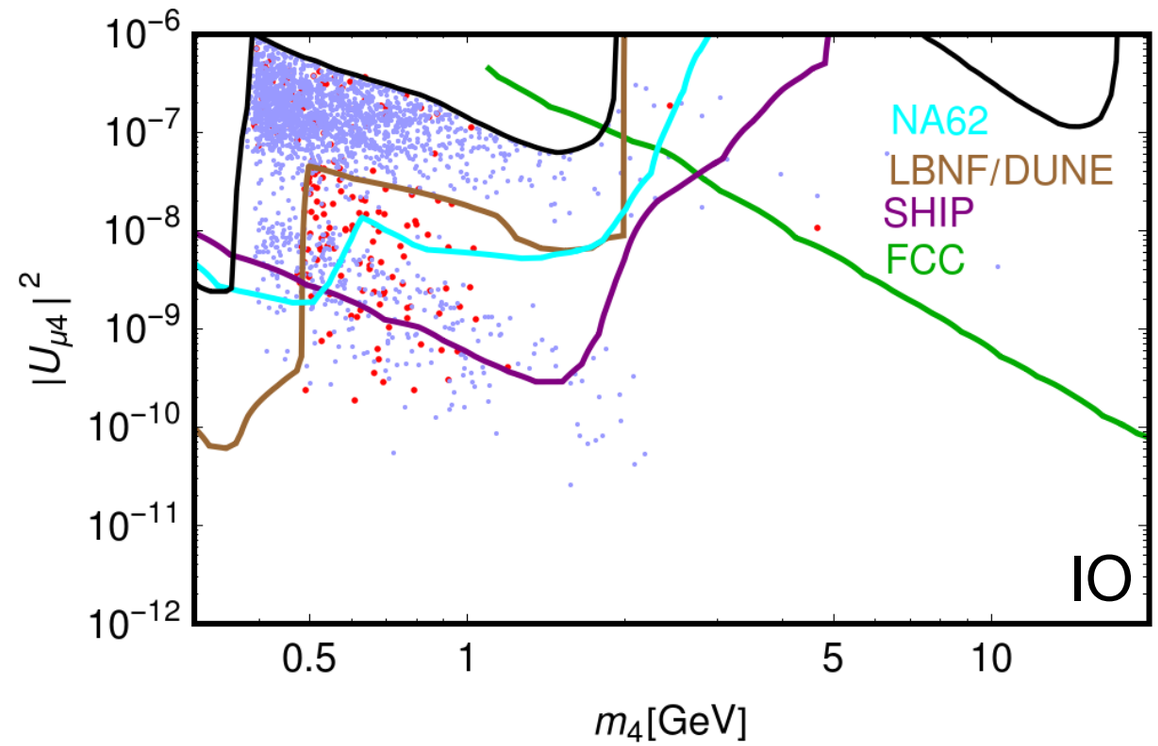




Testability

A. Abada, G. Arcadi, V. Domcke and M.L., arXiv:1709.00415 [hep-ph]





A large fraction of solutions is testable in future experiments