Mapping the parameter space of low-scale leptogenesis

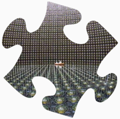
Juraj Klarić

based on 2008.13771, 2103.16545 in collaboration with M.E. Shaposhnikov and I. Timiryasov,
2106.16226 in collaboration with M. Drewes and Y. Georis,
and 2206.04342 in collaboration with A. Granelli and S.T. Petcov

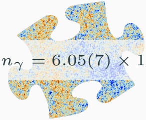
FPCapri, June 12th 2022

Some puzzles for physics beyond the Standard Model

Neutrino masses



The Baryon Asymmetry of the Universe



$$n_B/n_\gamma = 6.05(7) \times 10^{-10}$$

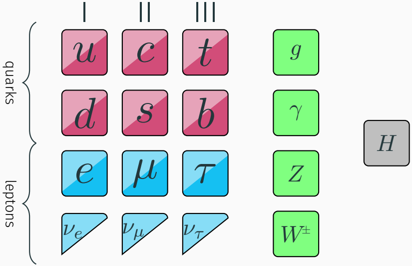


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

Some puzzles for physics beyond the Standard Model

Neutrino masses

[Minkowski 1977...]

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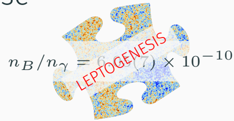
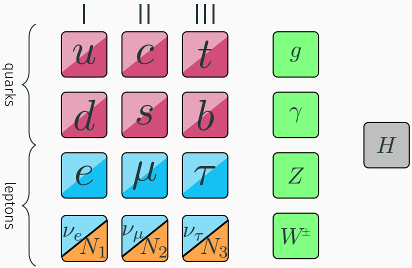


[Fukugita/Yanagida ’86...]



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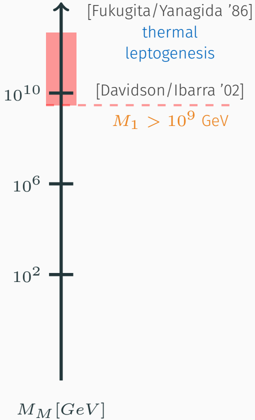
Leptogenesis mechanisms



Sakharov conditions

1. Baryon number violation

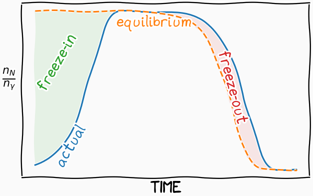
   sphaleron processes

2. C and CP violation

   RHN decays and oscillations

3. Deviation from thermal equilibrium

   freeze-in and freeze-out of RHN



- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV

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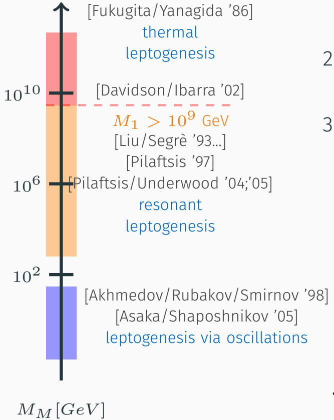

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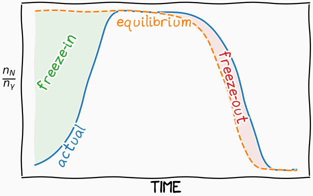

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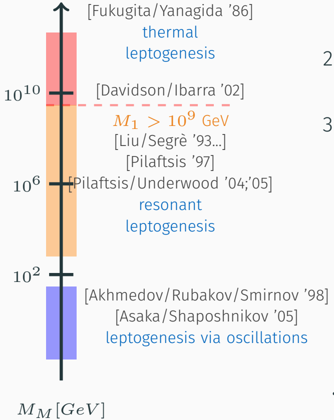

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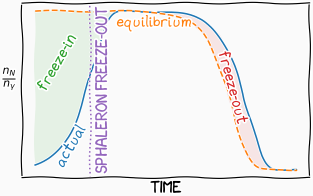

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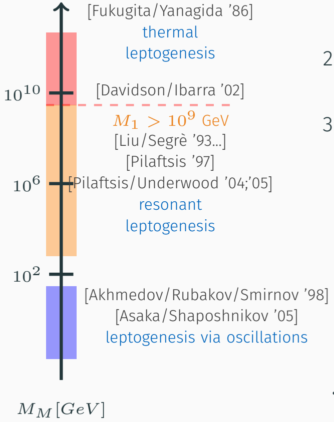

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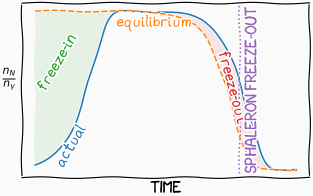

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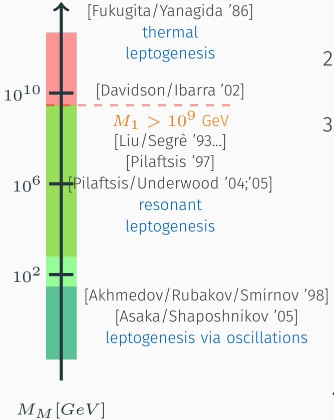

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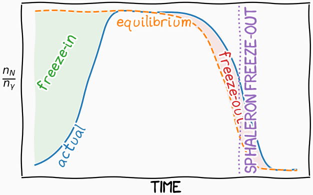
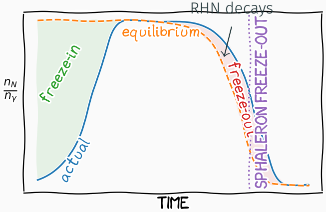


- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV
- leptogenesis works in a wide range of RHN masses
- how are the low-scale mechanisms connected?

Resonant leptogenesis

- the BAU is mainly produced in RHN decays
- The lepton asymmetries follow the equation

$$\frac{dY_{\ell_a}}{dz} = -\epsilon_a \frac{\Gamma_N}{Hz}(Y_N - Y_N^{\mathrm{eq}}) - W_{ab} Y_{\ell_b}$$



The key quantity determining the BAU is the decay asymmetry

$$\epsilon_a \equiv \frac{\Gamma_{N\to l_a} - \Gamma_{N\to \bar{l}_a}}{\Gamma_{N\to l_a} + \Gamma_{N\to \bar{l}_a}} = \frac{1}{8\pi} \frac{\mathrm{Im}(F^\dagger F)^2_{12}}{(F^\dagger F)_{11}} \frac{M_1 M_2}{M_1^2 - M_2^2}$$

Becomes enhanced if $M_2 \to M_1$ [(baryogenesis) Kuzmin '70] [(leptogenesis:)

Liu/Segrè/Flanz/Paschos/Sarkar/Weiss/Covi/Roulet/Vissani/Pilaftsis/Underwood/Buchmüller/Plumacher...]

This enhancement is known as resonant leptogenesis.

- divergent when $M_2 = M_1$?

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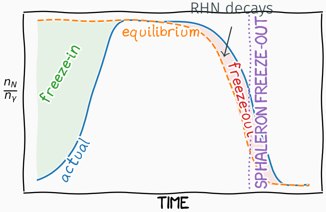

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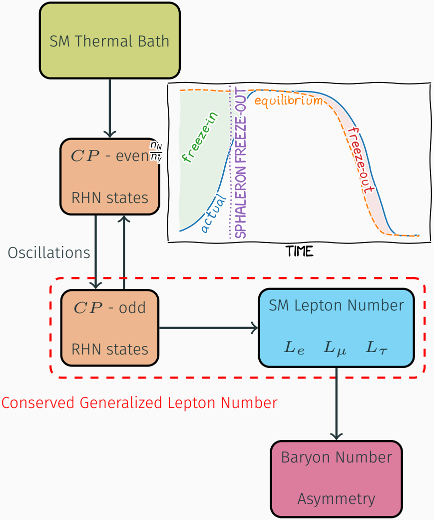
This enhancement is known as resonant leptogenesis.

- divergent when $M_2 = M_1$?
- divergence is unphysical — it needs to be regulated!
- this process can instead be described with density matrix equations

Leptogenesis via oscillations



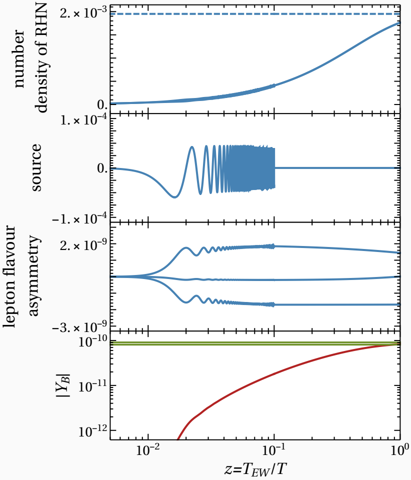


figure from [Drewes/Garbrecht/Gueter/JK 1606.06690]

Quantum Kinetic Equations (QKEs)

System of QKEs

$$i\frac{dn_{\Delta_\alpha}}{dt} = -2i\frac{\mu_\alpha}{T}\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\Gamma_\alpha\right] f_N\left(1-f_N\right)$$
$$+\,i\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\tilde{\Gamma}_\alpha\left(\bar{\rho}_N-\rho_N\right)\right],$$
$$i\,\frac{d\rho_N}{dt} = \left[H_N\,,\rho_N\right]-\frac{i}{2}\left\{\Gamma,\rho_N-\rho_N^{eq}\right\}$$
$$-\,\frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N\left(1-f_N\right)\right],$$
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$$+\,\frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N\left(1-f_N\right)\right],$$

- coupled system of integro-differential equations for the lepton flavor asymmetries n_{Δ_α}, and the helicity-dependent HNL density matrices ρ_N and $\bar{\rho}_N$
- HNL oscillations described by the effective hamiltonian H_N
- equilibration described by helicity and flavor-dependent matrices Γ

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- similar sets of equations derived using different strategies for both regimes
- for resonant leptogenesis relativistic corrections were typically negligible
  helicity effects could be neglected $\rho_N \approx \bar{\rho_N}^*$
- leptogenesis via oscillations assumed ultra-relativistic HNLs
  non-relativistic corrections found to be important in recent years
  [Hambye/Teresi '16; Laine/Ghiglieri '17; Eijima/Shaposhnikov '17]
- gradual convergence towards the same set of equations

The low-scale leptogenesis mechanisms

Resonant leptogenesis

- often sufficient to use decay asymmetries ϵ_a
- conceptual issues arise when $M_2 \to M_1$
- relativistic effects can typically be neglected
- heavy neutrino decays require $M \gtrsim T$, not clear what happens for $M \lesssim 130$ GeV

Leptogenesis via oscillations

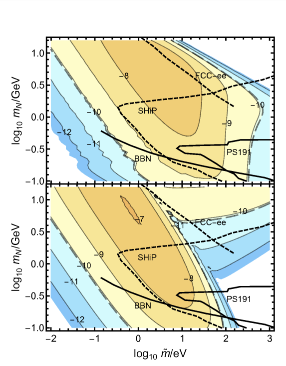
- initial conditions are crucial, all BAU is generated during RHN equilibration (freeze-in)
- important to distinguish the helicities of the RHN
- the decay of the RHN equilibrium distribution can typically be neglected $\dot{Y}_N^{\text{eq}} \approx 0$

- both can be described by the same density-matrix equations

The parameter space of low-scale leptogenesis

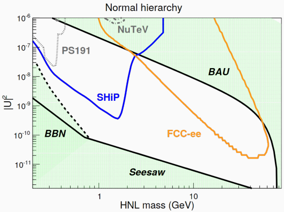
Resonant leptogenesis

- early estimates lead to successful leptogenesis for $\mathcal{O}(200)$ GeV [Pilaftsis/Underwood '05]
- Higgs decay leptogenesis mechanism proposed in [Hambye/Teresi '16; '17]



Leptogenesis via oscillations

- for $M_M > M_W$ new channels open up
- large equilibration rates for both FNV and FNC processes
- generically we have $\Gamma_N/H \gtrsim 30$ for $T \sim 150\,\mathrm{GeV}$, $M \sim 80\,\mathrm{GeV}$
- early estimate [Blondel/Graverini/Serra/Shaposhnikov 2014]



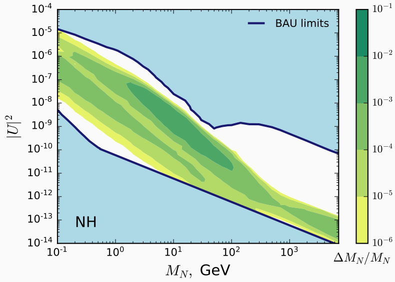
- Baryogenesis window closes at $M_M \sim 80\,\mathrm{GeV}$?

A quantitative study is necessary!

How to navigate the parameter space

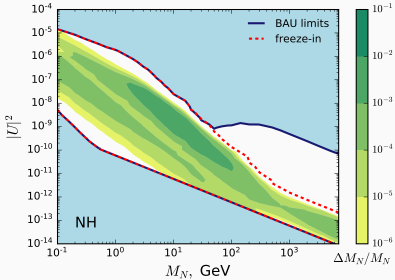
- we use a single set of equations for both leptogeneses
  - for $M \gg T$ we recover resonant leptogenesis
  - for $M \ll T$ we recover leptogenesis via oscillations
- we separate the freeze-in and freeze-out regimes
  - for thermal initial conditions freeze-out is the only source of BAU: "resonant" leptogenesis dominates
  - for vanishing initial conditions with $\dot{Y}_N^{eq} \to 0$ freeze-in is the only source of BAU: LG via oscillations dominates
- biggest challenge: rates!
  - so far estimates of the rates only exist for $M \ll T$ and $M \gg T$
  - we combine the two by *extrapolating* the relativistic rate and adding it to the non-relativistic decays
- we perform a comprehensive numerical scan over the parameters between $100\,\mathrm{MeV} < M_M < 10\,\mathrm{TeV}$

Results: The minimal model with 2 RHNs



- the baryogenesis window remains open!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\text{eq}}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the "source" term to $dY_N^{\text{eq}}/dz \to 0$ by hand
- success is not guaranteed: for different phases the overlap can be much smaller



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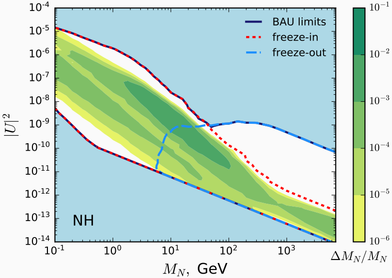

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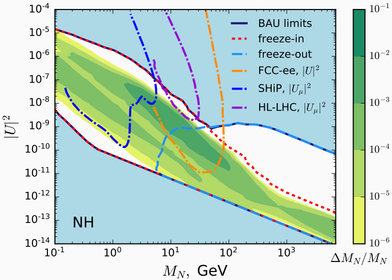

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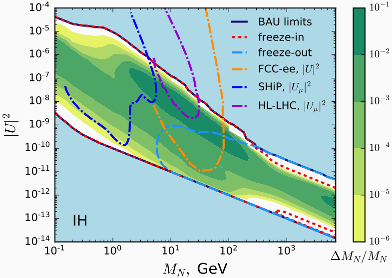

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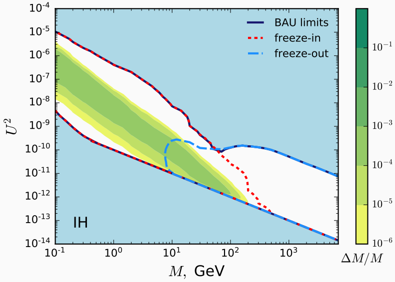
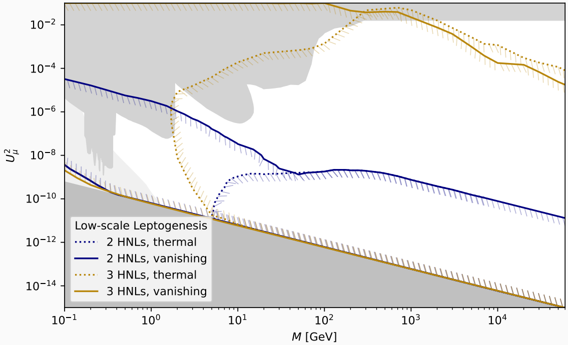


- the baryogenesis window remains open!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\text{eq}}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the "source" term to $dY_N^{\text{eq}}/dz \to 0$ by hand
- success is not guaranteed: for different phases the overlap can be much smaller

Results: Leptogenesis with 3 RHNs



[Snowmass White Paper 2203.08039]

leptogenesis lines from [Drewes/Georis/JK 2106.16226]

- for experimentally accessible heavy neutrino masses, all U^2 are allowed
- both freeze-in and freeze-out leptogeneses already testable at existing experiments
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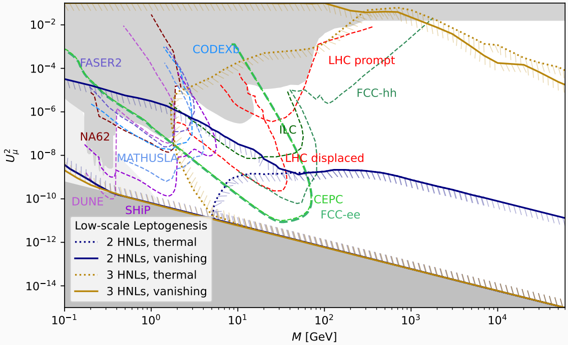

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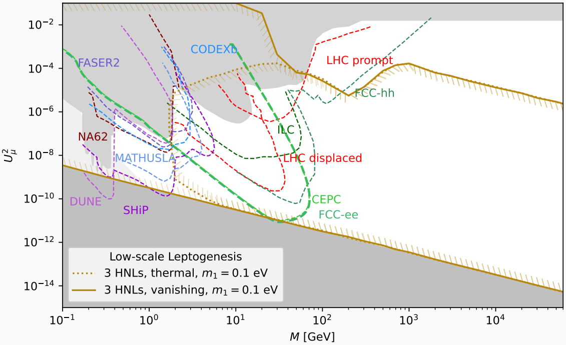

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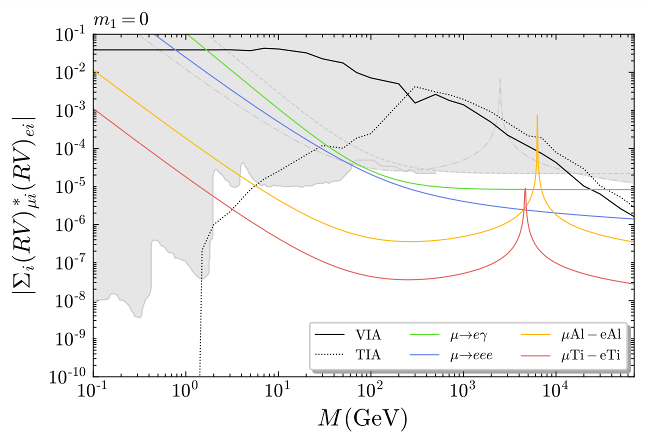
Indirect probes: Charged LFV



[Granelli/JK/Petcov 2206.04342]

- parameters space in the TeV region already severly constrained by cLFV observables
- future $\mu \to e$ conversion experiments can probe a large part of the $N = 3$ parameter space

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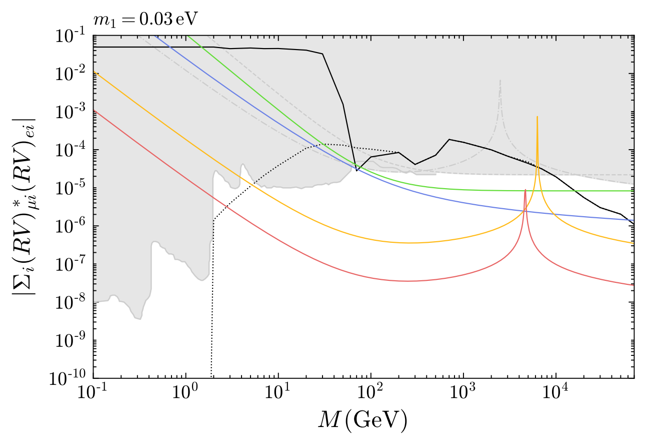

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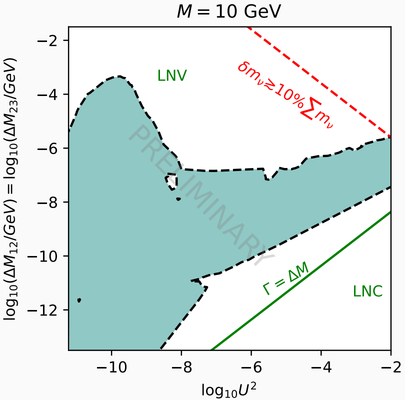
Allowed ranges of mixing angles U^2 and mass splittings ΔM



- benchmark with fixed $U^2_{\alpha I}/U^2$
- upper bound on U^2 arises through a combination of baryogenesis + fine tuning constraints
- leptogenesis consistent with both LNV and LNC RHN decays
- nontrivial LNV/LNC ratios can further constrain the RHN parameters

[Drewes/Georis/JK 220x.xxxx]

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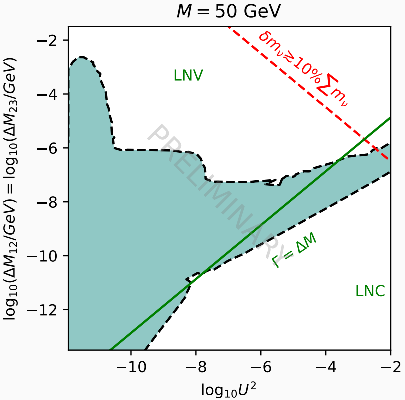

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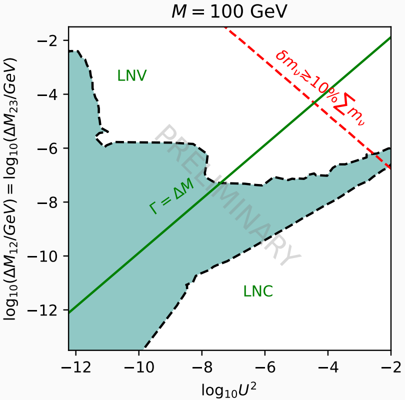

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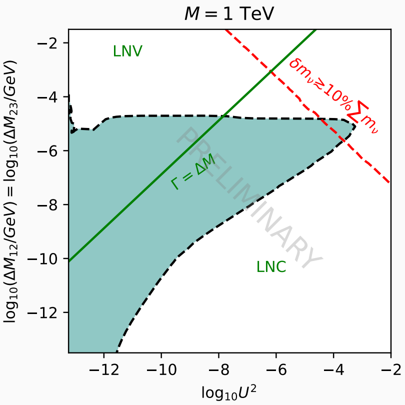

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[Drewes/Georis/JK 220x.xxxx]

Conclusions

- resonant leptogenesis and leptogenesis through neutrino oscillations are really two regimes of the same mechanism
- freeze-out is already possible for GeV-scale RHNs
- freeze-in remains important at the TeV-scale and beyond
- leptogenesis is a viable baryogenesis mechanism for all heavy neutrino masses above the $\mathcal{O}(100)$ MeV scale
- leptogenesis is testable at planned future experiments
  - synergy between high-energy and high-intensity searches!
  - together they can cover a large portion of the low-scale leptogenesis parameter space

Thank you!

Large mixing angles and approximate B-L symmetry

- large U^2 require cancellations between different entries of the Yukawa matrices F
- this cancellation can be associated with an approximate lepton number symmetry

  [Shaposhnikov hep-ph/0605047, Kersten Smirnov 0705.3221, Moffat Pascoli Weiland 1712.07611]
- symmetry broken by small parameters $\epsilon, \epsilon', \mu, \mu'$

Pseudo-Dirac pairs

$$N_s = \frac{N_1 + iN_2}{\sqrt{2}}\,,\, N_w = \frac{N_1 - iN_2}{\sqrt{2}}$$

B-L parametrisation

$$M_M = \bar{M}\begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

$$F = \frac{1}{\sqrt{2}}\begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix}$$

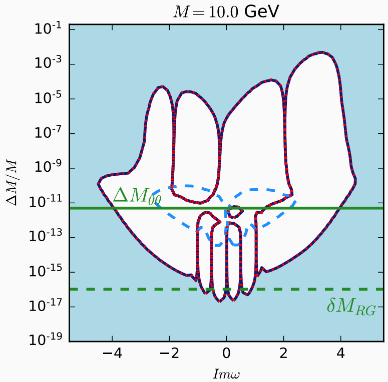
Fine tuning

- if present, symmetries are manifest to all orders in p.t.
- in the case of a large B-L breaking, radiative corrections can cause large neutrino masses
- we can use the size of radiative corrections to the light neutrino masses to quantify tuning

Fine Tuning

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

Slices of the parameter space



- two characteritic mass splittings
- mass splitting induced by the Higgs $\Delta M_{\theta\theta}$
- mass splitting induced by RG running δM_{RG}

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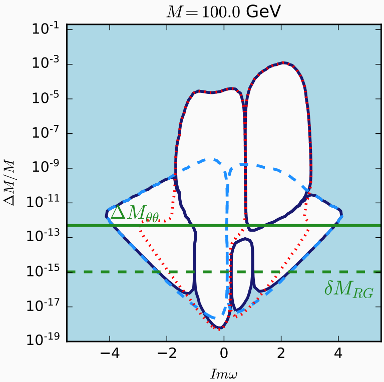

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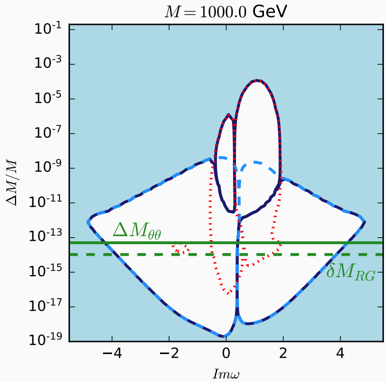

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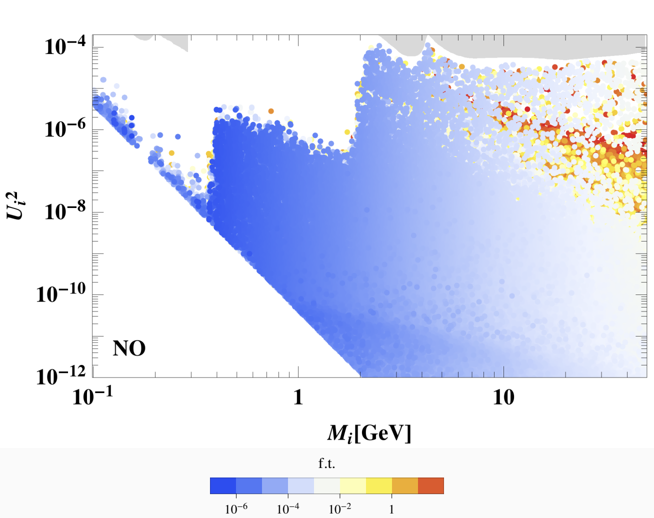
Results: Leptogenesis with 3 RHN (Normal Ordering)



[Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

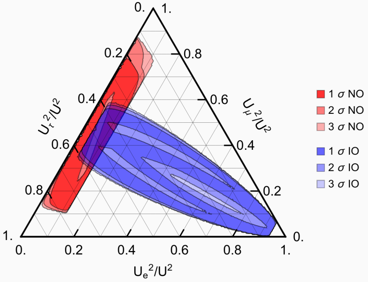
Hierarchy in the washout

- lepton asymmetry can survive washout if hidden in a particular flavor
- washout suppression

$$\mathfrak{f} \equiv \frac{\Gamma_a}{\Gamma} \sim \frac{U_a^2}{U^2}$$

- for 2 RHN $\mathfrak{f} > 5 \times 10^{-3}$
- for 3 RHN $\mathfrak{f} \ll 1$ possible

2 RHNs:



[Snowmass White Paper 2203.08039]

[Drewes/Garbrecht/Gueter/JK 1609.09069]

[Caputo/Hernandez/Lopez-Pavon/Salvado 1704.08721]

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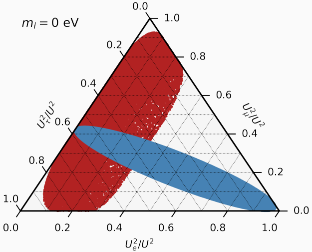

[Drewes/Georis/JK 220x.xxxx]

[Chrzaszcz/Drewes/Gonzalo/Harz/Krishnamurthy/Weniger 1908.02302]

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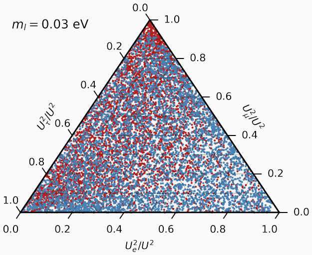
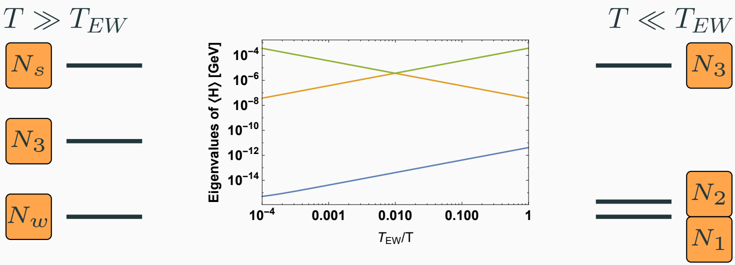


[Drewes/Georis/JK 220x.xxxx]

[Chrzaszcz/Drewes/Gonzalo/Harz/Krishnamurthy/Weniger 1908.02302]

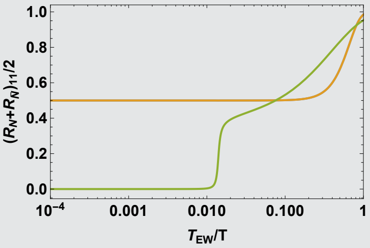
Enhancement due to level crossing

- in the $B-L$ symmetric limit two heavy neutrinos form a pseudo-Dirac pair
- the “3rd” heavy neutrino can be heavier than the pseudo-Dirac pair
- for $T \gg T_{EW}$, the pseudo-Dirac pair also has a thermal mass

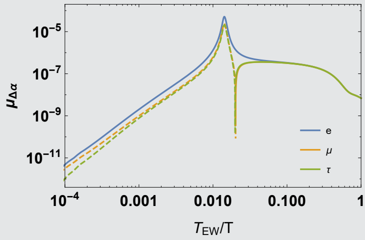


Enhancement due to level crossing

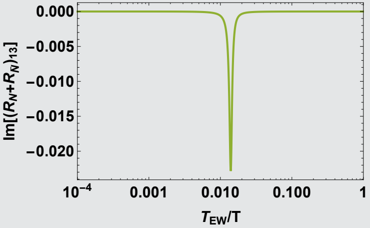
Heavy Neutrino Densities



Lepton flavour asymmetries



Heavy Neutrino correlations



Lepton number asymmetry