Mapping the parameter space of low-scale leptogenesis

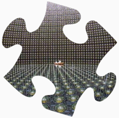
Juraj Klarić

NuFACT 2023

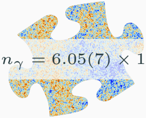
August 22nd 2023

Some puzzles for physics beyond the Standard Model

Neutrino masses



The Baryon Asymmetry of the Universe



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

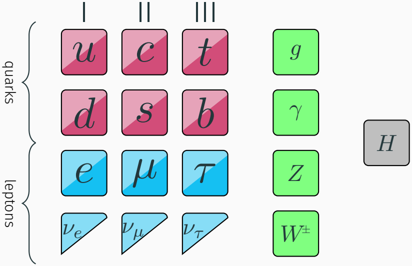


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

Neutrino masses

[Minkowski 1977...]

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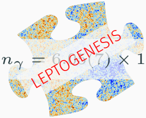
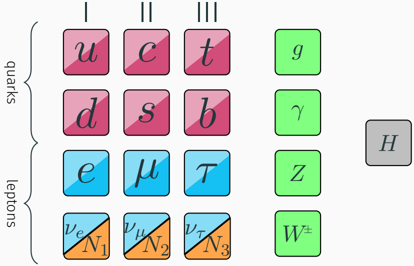


$n_B/n_\gamma = 6.$[illegible]$(7) \times 10^{-10}$

[Fukugita/Yanagida '86...]



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What does the seesaw tell us about HNL masses?

The Seesaw Lagrangian

$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

Active neutrino masses

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[Minkowski '77
Gell-Mann/Ramond/Slansky '79
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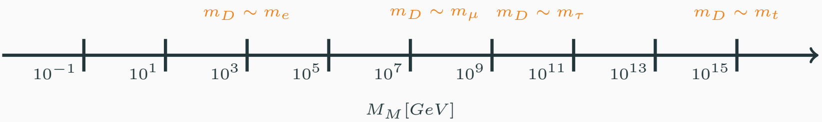
canonical type-I seesaw



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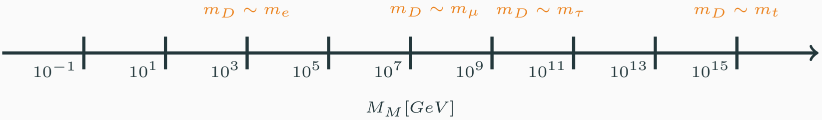

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[Mohapatra '93
Mohapatra/Valle '86
Bernabeu/Santamaria/Vidal/Mendez/Valle '86
Gavela/Hambye/Hernandez/Hernandez '09
Branco/Grimus/Lavoura '89
Malinsky/Romao/Lavoura '89]
low-scale
linear and inverse seesaws

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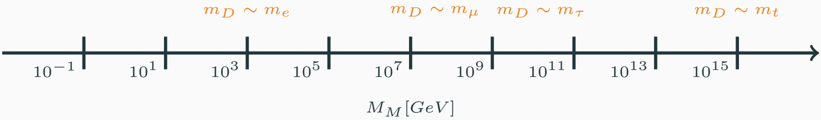


The Sakharov Conditions

1. Baryon number violation

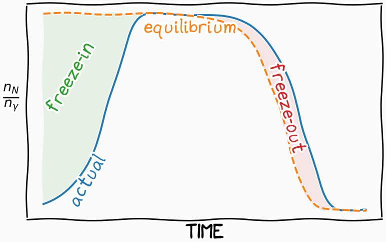
   sphaleron processes

2. C and CP violation

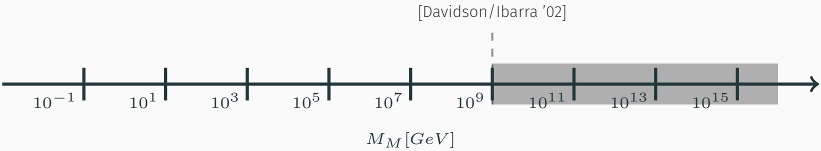
   RHN decays and oscillations

3. Deviation from equilibrium

   freeze-in and freeze-out of RHN



[Fukugita/Yanagida '86]
thermal leptogenesis



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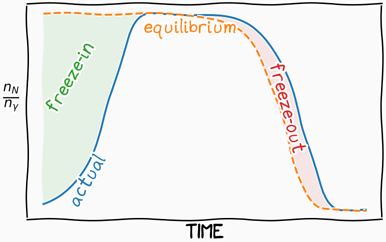

[Akhmedov/Rubakov/Smirnov '98
Asaka/Shaposhnikov '05]
leptogenesis via oscillations

[Liu/Segre '93
Pilaftsis '97
Pilaftsis/Underwood '04;'05]
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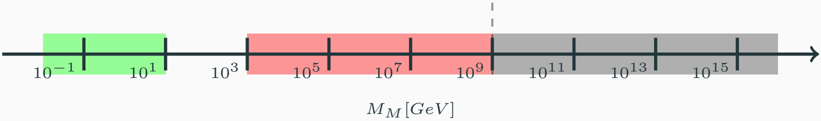
[Davidson/Ibarra '02]



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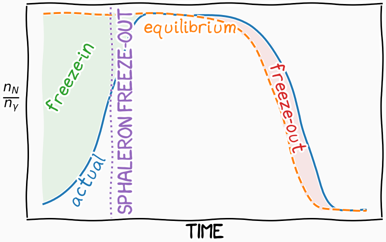

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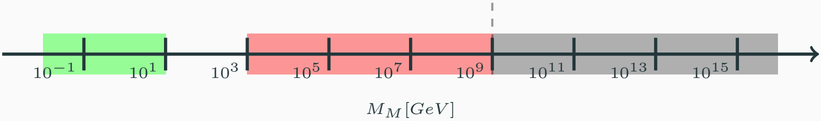

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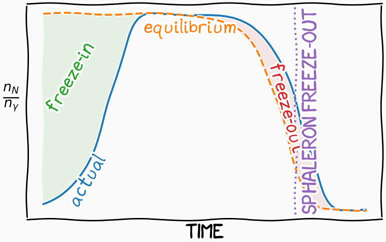

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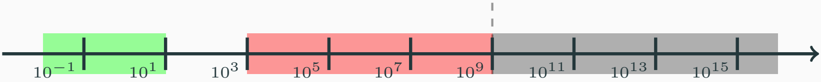
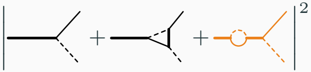


$M_M\,[GeV]$

The low-scale leptogenesis mechanisms

Resonant leptogenesis

- assymetry produced in HNL decays



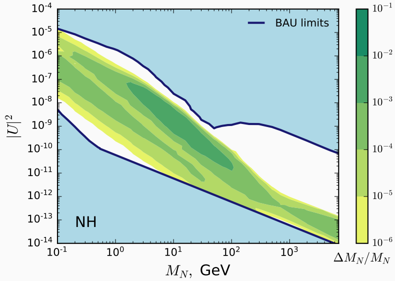
- asymmetry diverges when $M_2 \to M_1$
- relativistic effects can typically be neglected
- heavy neutrino decays require $M \gtrsim T$, not clear what happens for $M \lesssim 130$ GeV

Leptogenesis via oscillations

- all asymmetry is generated during RHN equilibration (freeze-in)
- HNL scatterings dominate over decays
- important to distinguish the helicities of the RHN
- the comoving HNL equilibrium distribution is approximately constant $\dot{Y}_N^{\text{eq}} \approx 0$

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

Results: The minimal model with 2 RHNs



[JK/Timiryasov/Shaposhnikov 2103.16545]

- baryogenesis possible for all masses above 100 MeV!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes
- results depend on low-energy CP phases:
  - optimal phases for NH: $\delta = 0$ and $\eta = \pi/2$
  - less overlap for e.g. $\delta = \pi$ and $\eta = 0$
  - maximal $\Delta M/M \lesssim 10^{-1} \rightarrow 10^{-3}$

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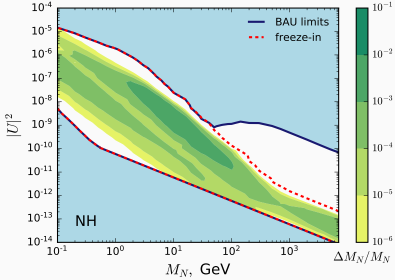

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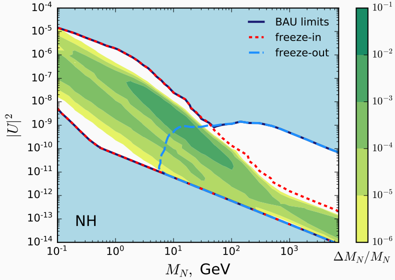

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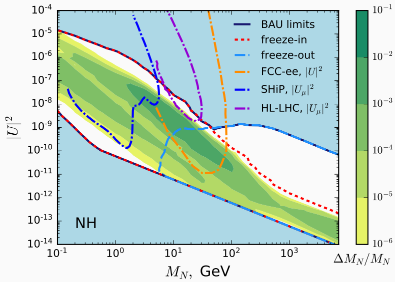

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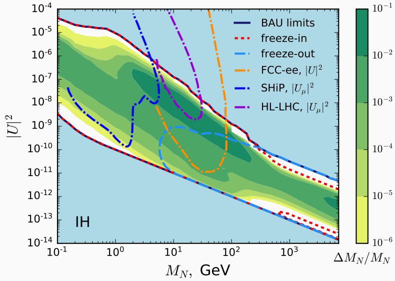

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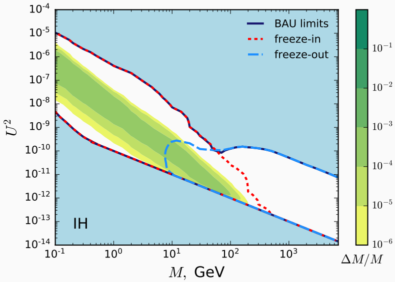

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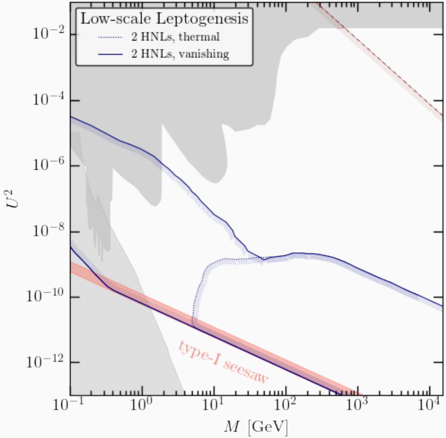

[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

[leptogenesis bounds from JK/Timiryasov/Shaposhnikov 2103.16545

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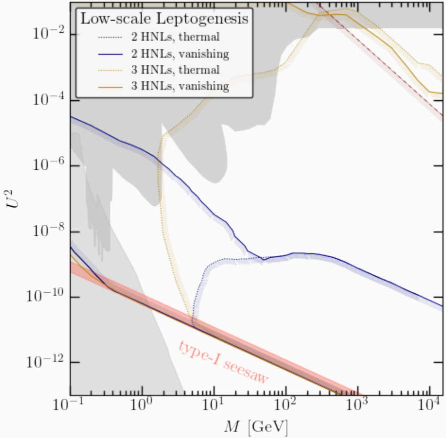

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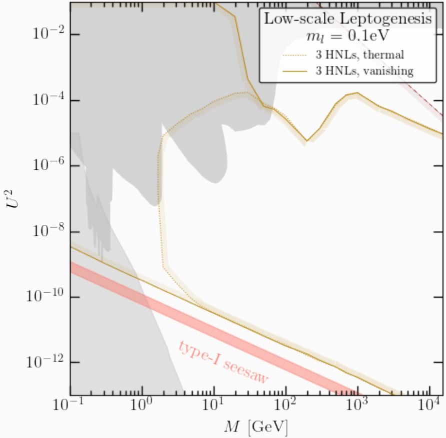

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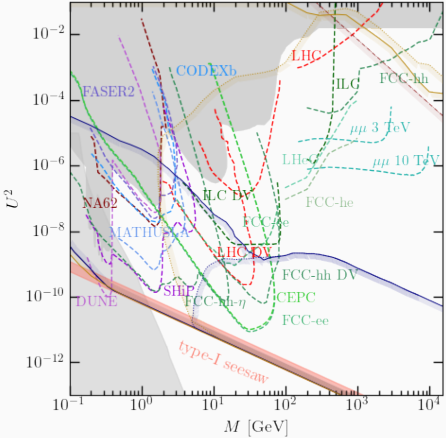

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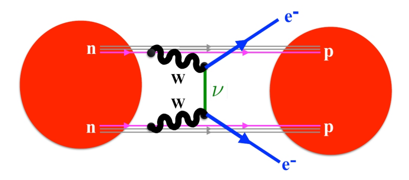
Probing HNLs in neutrinoless double β decay



[figure from 1910.04688]

HNL contribution to $0\nu\beta\beta$

$$m_{\beta\beta} \simeq \Big|[1 - f_A(\bar{M})]m^{\nu}_{\beta\beta} + 2f_A^2(\bar{M})\frac{\bar{M}^2}{\Lambda^2}\Delta M(\Theta^2_{e1} - \Theta^2_{e2})\Big|$$

- HNLs can contribute to $m_{\beta\beta}$ when $M \sim 100$ MeV
- the HNL contribution suppressed when $\Delta M \ll M$

  approximate lepton number conservation
- leptogenesis imposes bounds on the size of ΔM and Θ^2_{ei}
- parts of the leptogenesis parameter space can already be excluded in existing experiments
- much large parameter space with 3 HNLs
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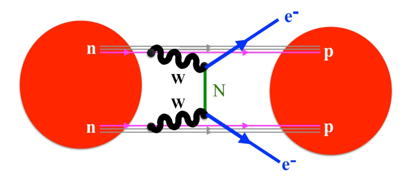

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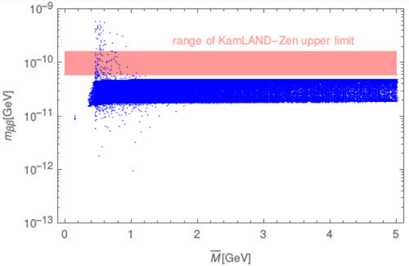

[Eijima/Drewes 1606.06221,

Hernández/Kekic/López-Pavón/Salvado 1606.06719]

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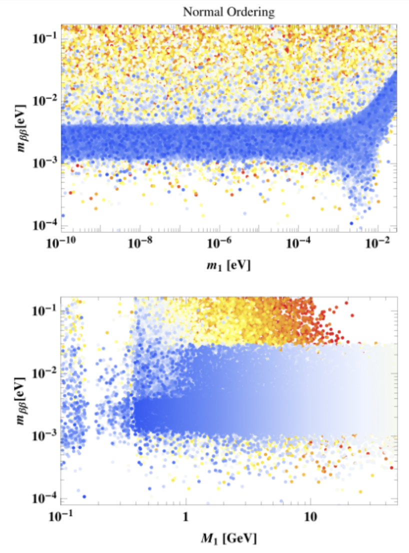

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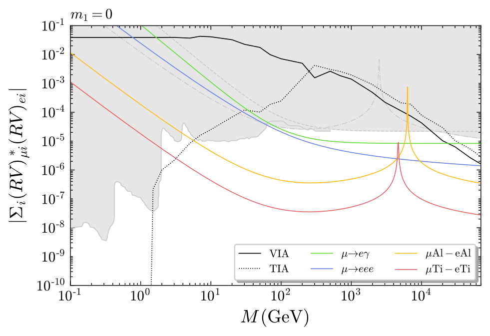
[Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

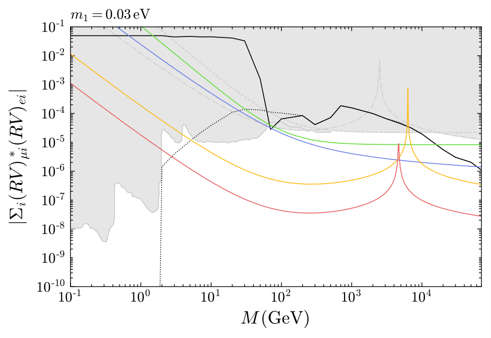
Indirect probes: Charged LFV with 3 HNLs



[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 leptogenesis parameter space with 3 HNLs
- simultaneous LFV possible in several channels

Indirect probes: Charged LFV with 3 HNLs



[Granelli/JK/Petcov 2206.04342]

- parameters space in the TeV region already severly constrained by cLFV observables
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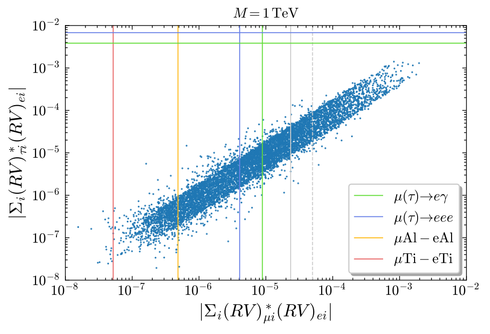

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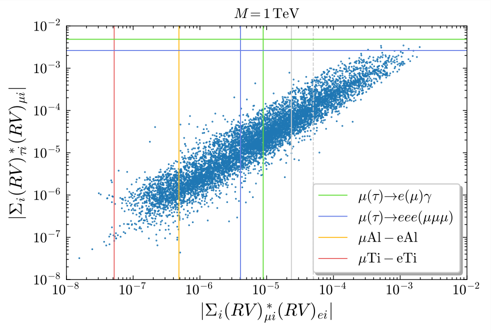

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Conclusions

- right-handed neutrinos can offer a minimal solution to the origins of neutrino masses and the baryon asymmetry of the Universe
- the existence right-handed neutrinos can be tested at existing and near-future experiments
    - excellent synergy between direct and indirect probes!
- leptogenesis is a viable baryogenesis mechanism for all heavy neutrino masses above the $\mathcal{O}(100)$ MeV scale
- HNLs could lead to very rich phenomenology

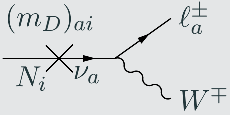
  displaced vertices, LFV ($\mu \to e\gamma$), LNV ($0\nu\beta\beta$), HNL oscillations...

Thank you!

Direct searches for HNLs

Direct probes of the HNL parameter space

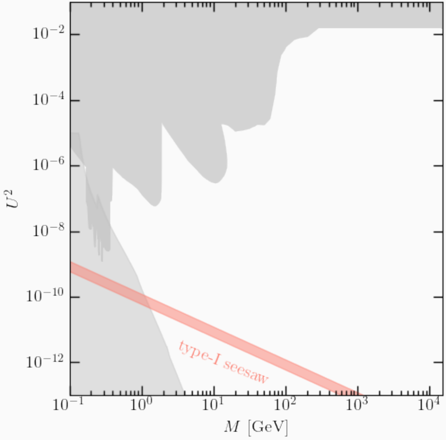
HNL mixing



$$U_{ai}^2 \equiv \left| \left(m_D M_M^{-1} \right)_{ai} \right|^2$$

$$U^2 = \sum_{a,i} U_{ai}^2$$

$$U^2 \gtrsim m_\nu / M$$



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

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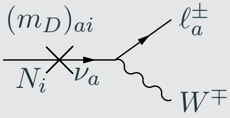

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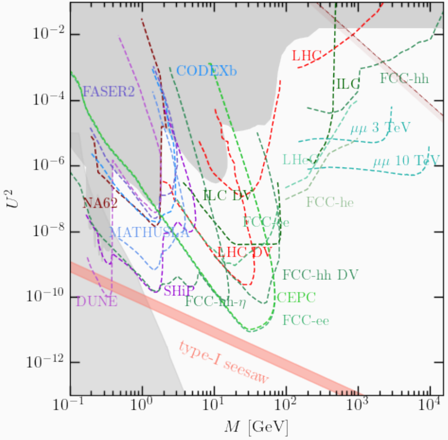

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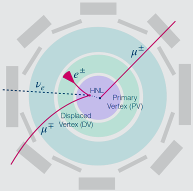
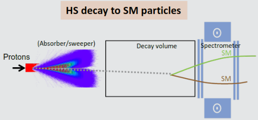
Direct probes of the HNL parameter space

Displaced Vertices

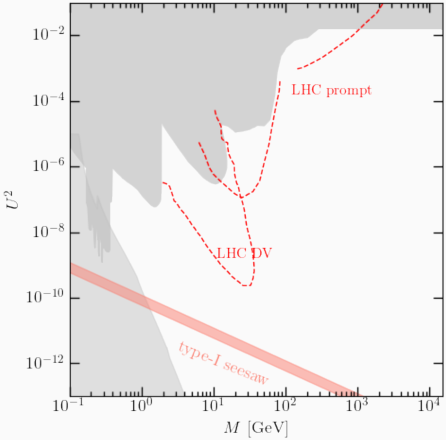


[graphic by D. Trischuk]

LLP experiments



[graphic by A. Golutvin]



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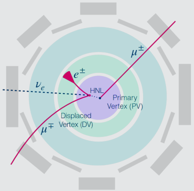

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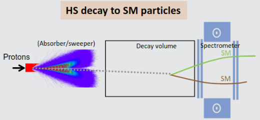

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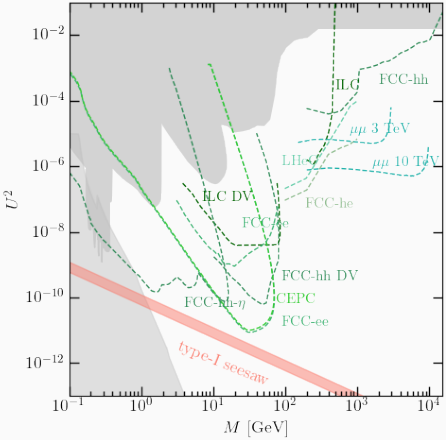

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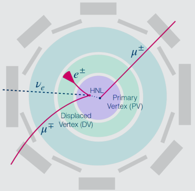

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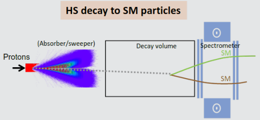

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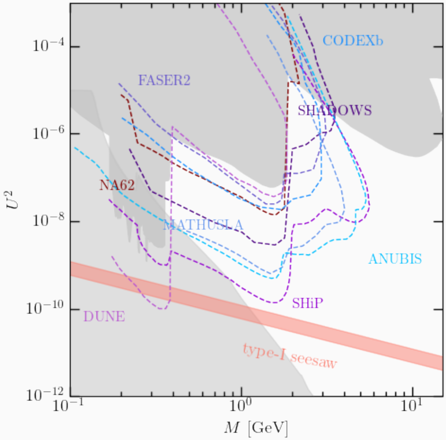

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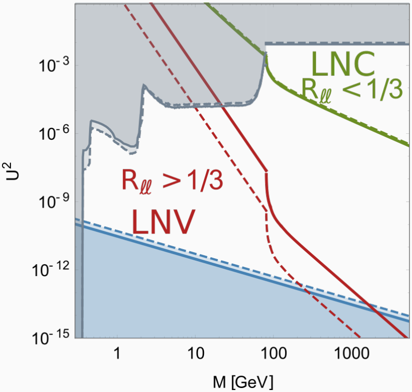
Lepton Number violation in HNL decays



[Drewes/Klose/JK 1907.13034]

- for $\Delta M_N \ll \Gamma_N$ lepton number is conserved - Dirac HNLs
- for $\Delta M_N \gtrsim \Gamma_N$ lepton number is violated - Majorana HNLs
- fine tuning practically implies lower limit on the mass splitting $\Delta M_N \gtrsim \Delta m_\nu$
- large range of ΔM_N are consistent with leptogenesis
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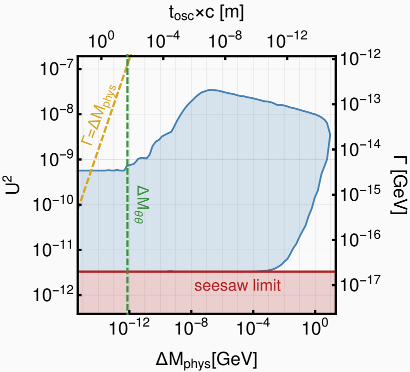
Lepton Number violation in HNL decays

Normal Ordering:



$M = 30$ GeV

[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]

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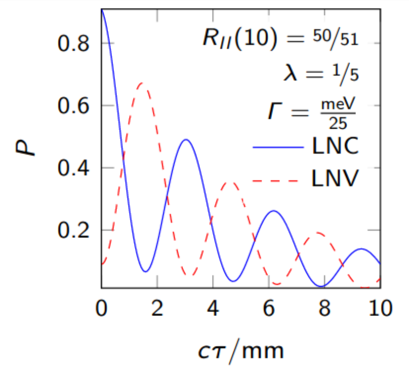

[Antusch/Hajer/Rosskopp 2210.10738]

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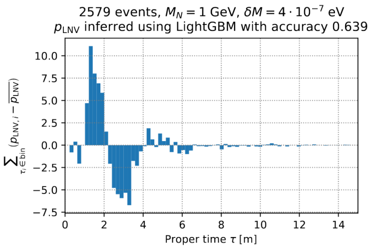

[Tastet/Timiryasov 1912.05520]

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Measuring flavor ratios at experiments

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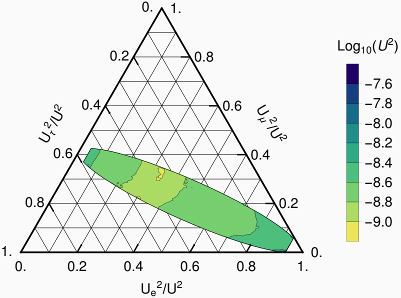

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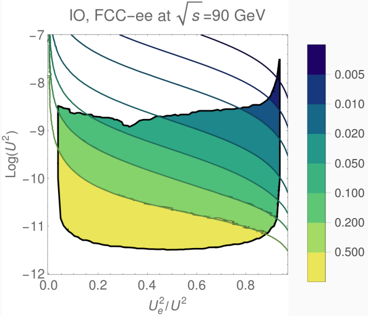

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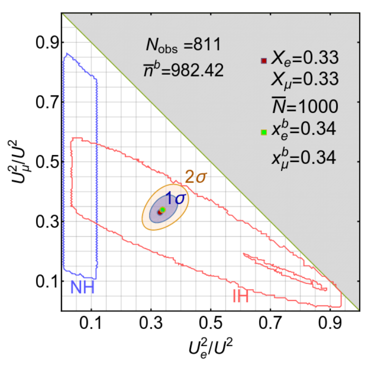
$M_N = 1$ GeV @ SHiP



[Snowmass HNL WP 2203.08039]

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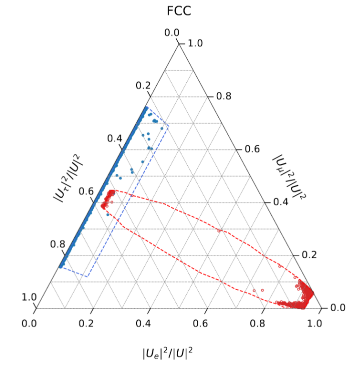

$$\Delta M/M = 10^{-2}$$

[Hernández/López-Pavón/Rius/Sandner 2207.01651]

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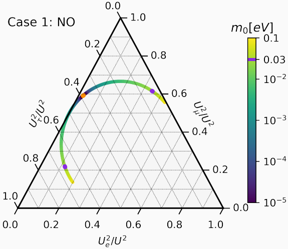

[Drewes/Georis/HagedornKlaric 2203.08538]

[Drewes/Georis/HagedornKlaric 230a.bcde]

How is $3 \neq 2$?: Leptogenesis

- asymmetry can be generated even without washout

  [Akhmedov/Rubakov/Smirnov hep-ph/9803255]

- large hierarchy in the washout is possible

  [Canetti/Drewes/Garbrecht 1404.7144]

- level crossing between the heavy neutrinos

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

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  [Akhmedov/Rubakov/Smirnov hep-ph/9803255]

  - Sakharov II: CP
  - more CP phases than in the case with two RHN

- large hierarchy in the washout is possible

  [Canetti/Drewes/Garbrecht 1404.7144]

  - Sakharov III: non-equilibrium

- level crossing between the heavy neutrinos

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

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Hierarchy in the washout

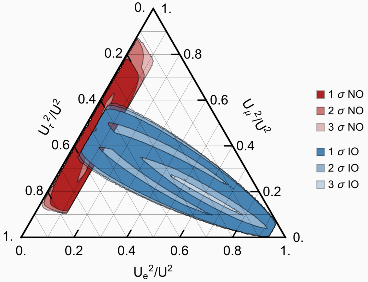
- lepton asymmetry can survive washout if hidden in a particular flavor
- washout suppression

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

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

$$\frac{\Gamma_I}{\Gamma} \sim \frac{U_I^2}{U^2}$$

2 RHNs:



[Snowmass White Paper 2203.08039]

[Drewes/Garbrecht/Gueter/JK 1609.09069]

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

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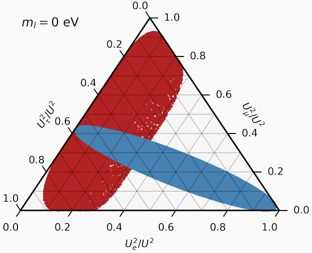

[Drewes/Georis/JK 230x.xxxx]

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

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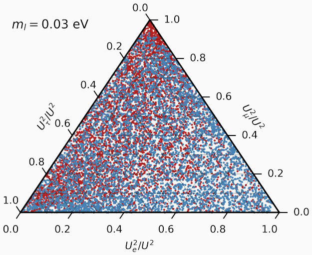
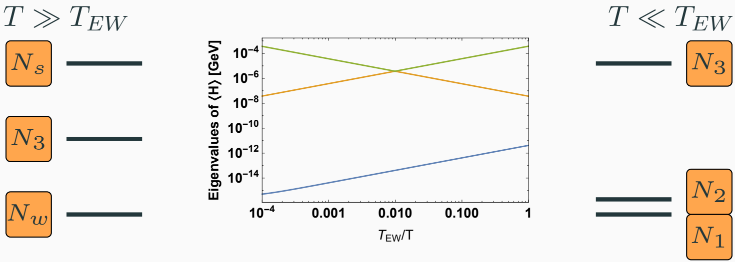


[Drewes/Georis/JK 230x.xxxx]

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

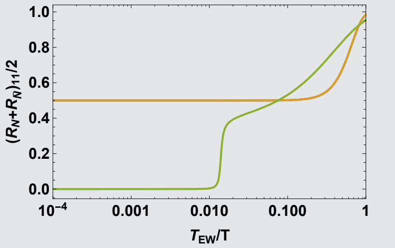
Enhancement due to level crossing

- 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

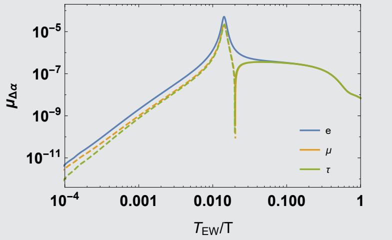


Enhancement due to level crossing

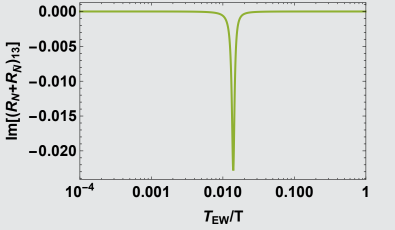
Heavy Neutrino Densities



Lepton flavour asymmetries



Heavy Neutrino correlations



Lepton number asymmetry