Probing heavy neutrino physics

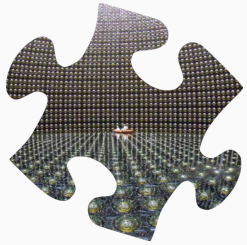
Juraj Klarić

34th Rencontres de Blois

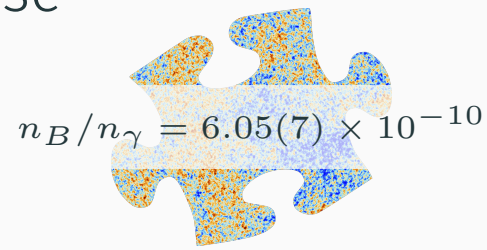
May 18th 2023

Some puzzles for physics beyond the Standard Model

Neutrino masses



The Baryon Asymmetry of the Universe



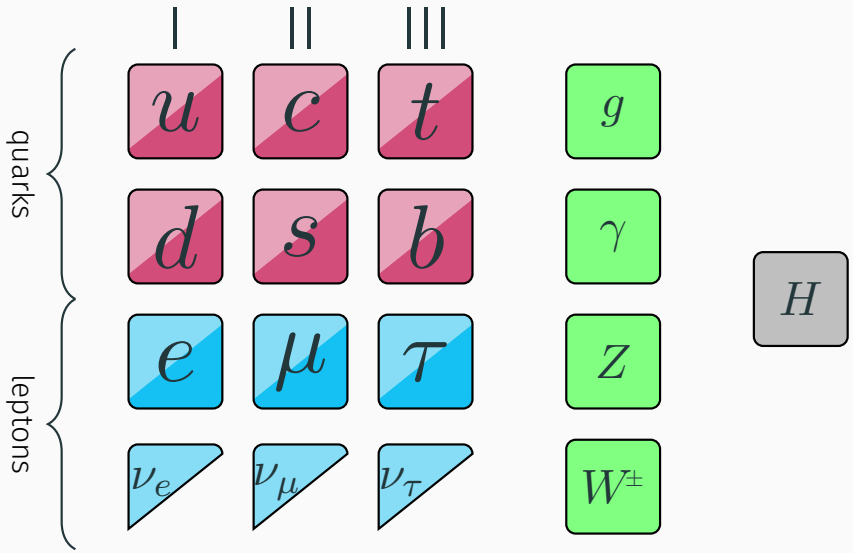


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

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[Minkowski 1977...]

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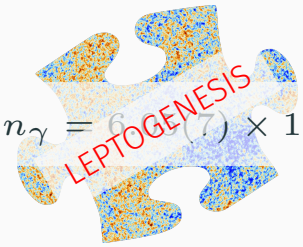
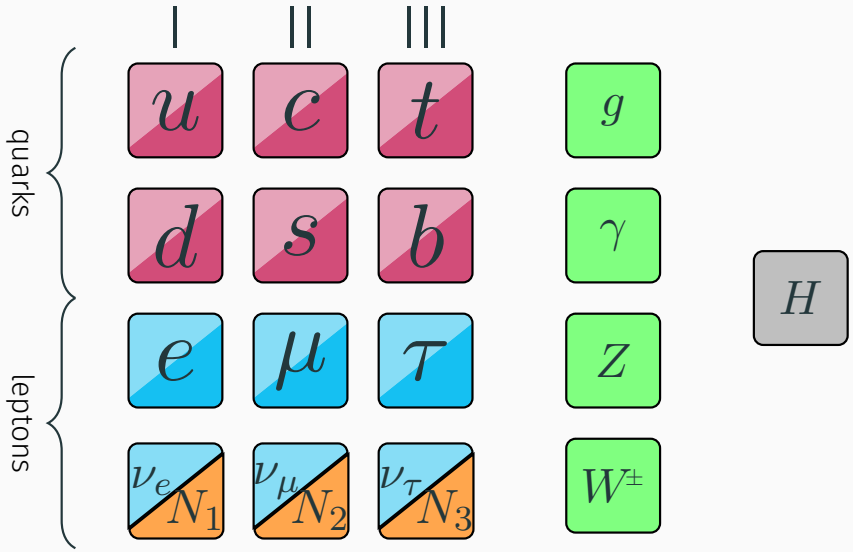


$$n_B/n_\gamma = 6(7) \times 10^{-10}$$

[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

$$m_\nu = m_D$$

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[Minkowski '77
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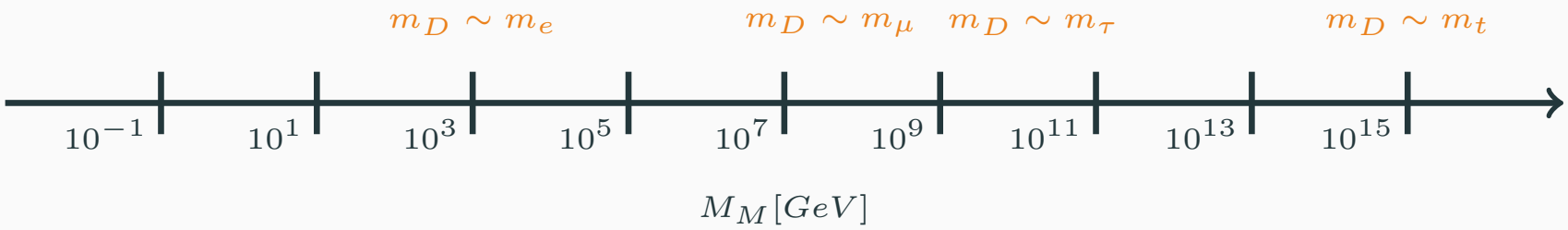
canonical type-I seesaw



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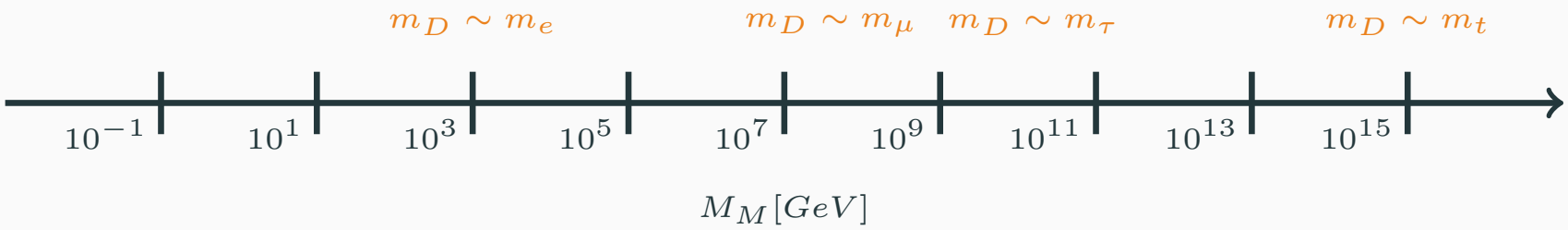

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Gavela/Hambye/Hernandez/Hernandez '09
Branco/Grimus/Lavoura '89
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low-scale
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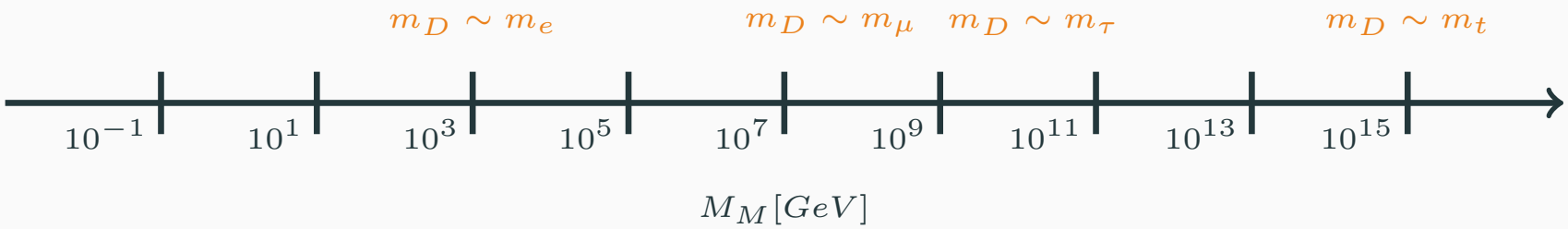


From High to Low-scale Leptogenesis

The Sakharov Conditions

1. Baryon number violation

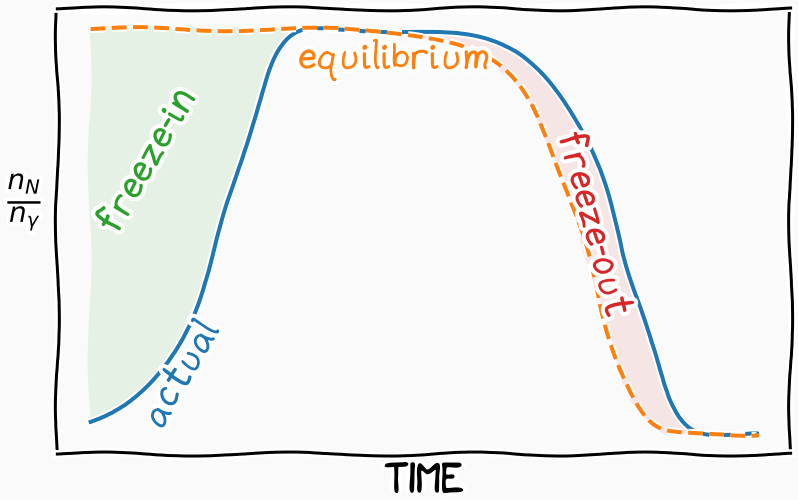
   sphaleron processes

2. C and CP violation

   RHN decays and oscillations

3. Deviation from equilibrium

   freeze-in and freeze-out of RHN



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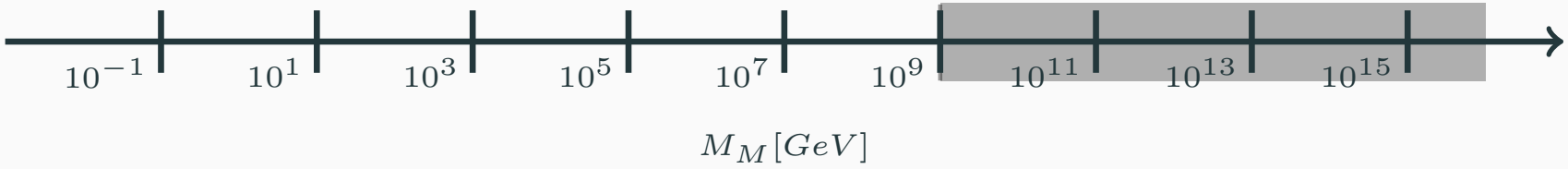

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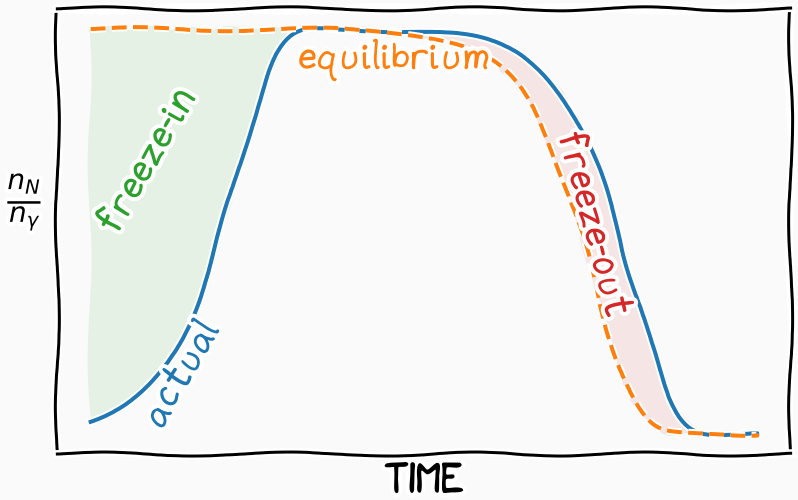

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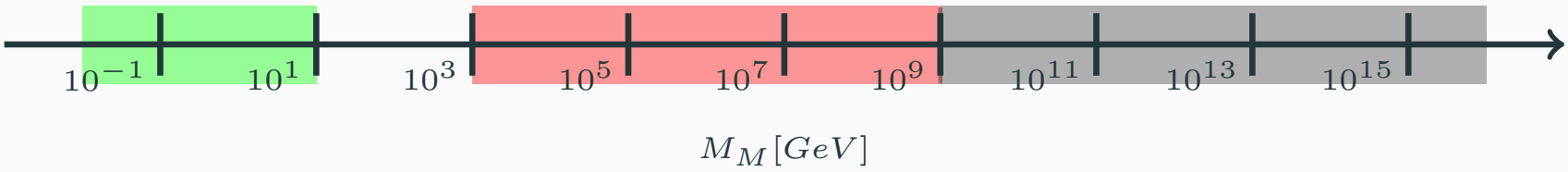

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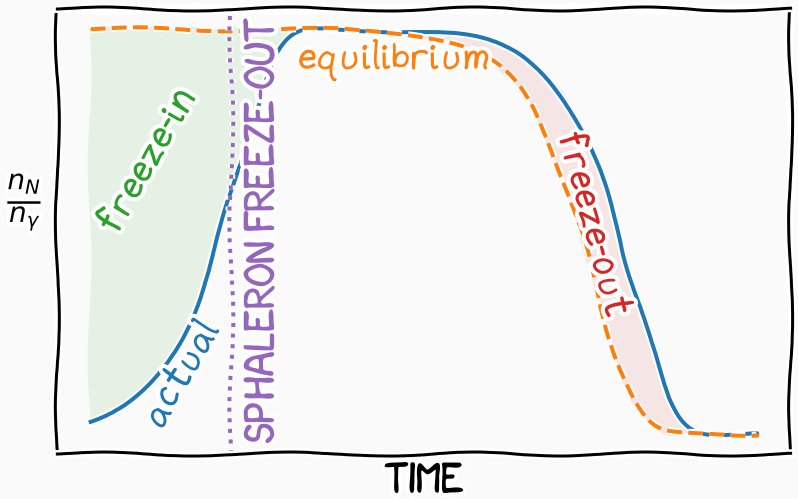

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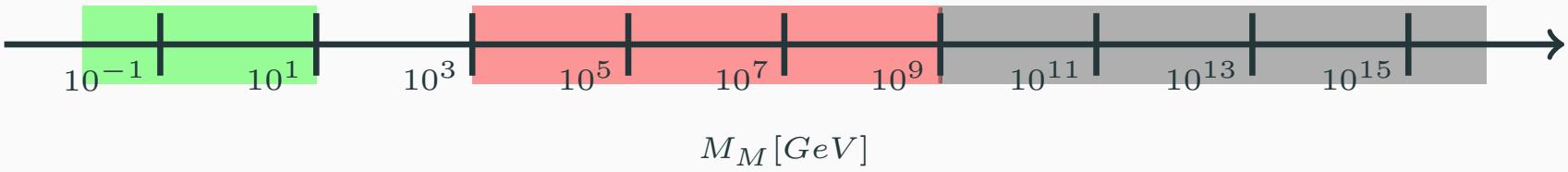

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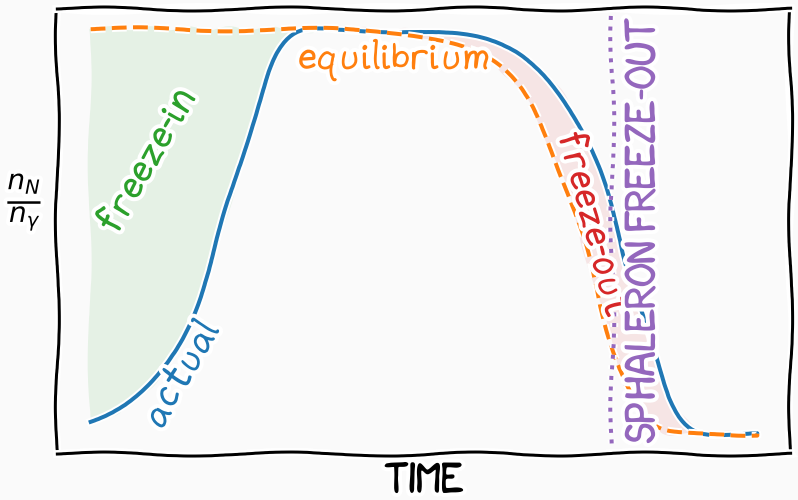

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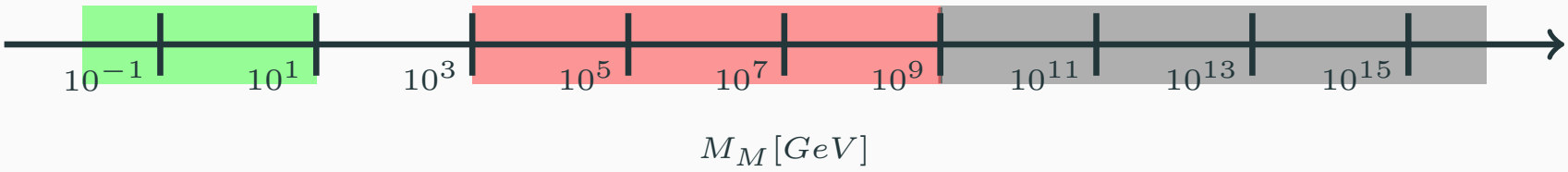
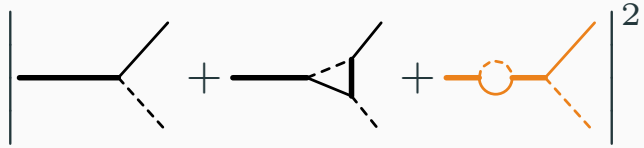


The low-scale leptogenesis mechanisms

Resonant leptogenesis

- assymetry produced in HNL decays



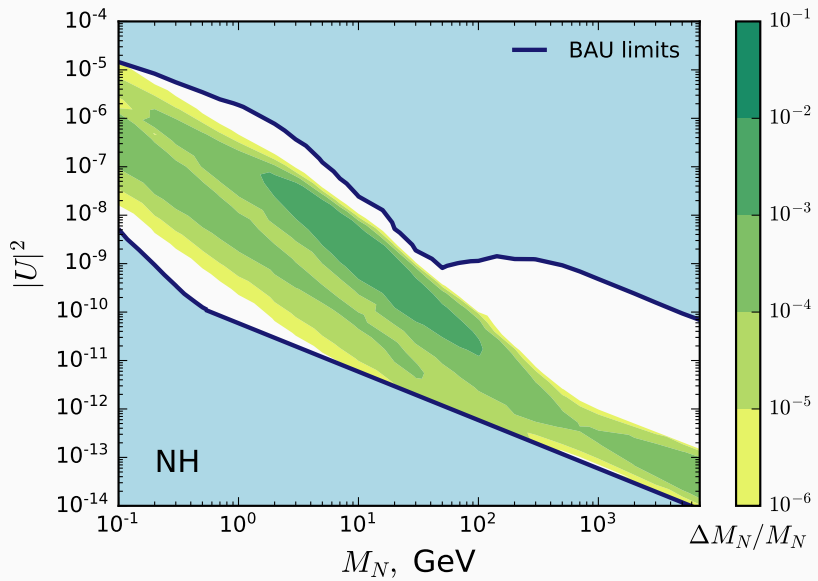
- asymmetry diverges when $M_2 \to M_1$
- relativistic effects can typically be neglected
- heavy neutrino decays require $M \gtrsim T$, not clear what happens for $M \lesssim 130$ GeV

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 $\dot{Y}_N^{\rm eq} \approx 0$

- 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 $\eta = \pi/2$
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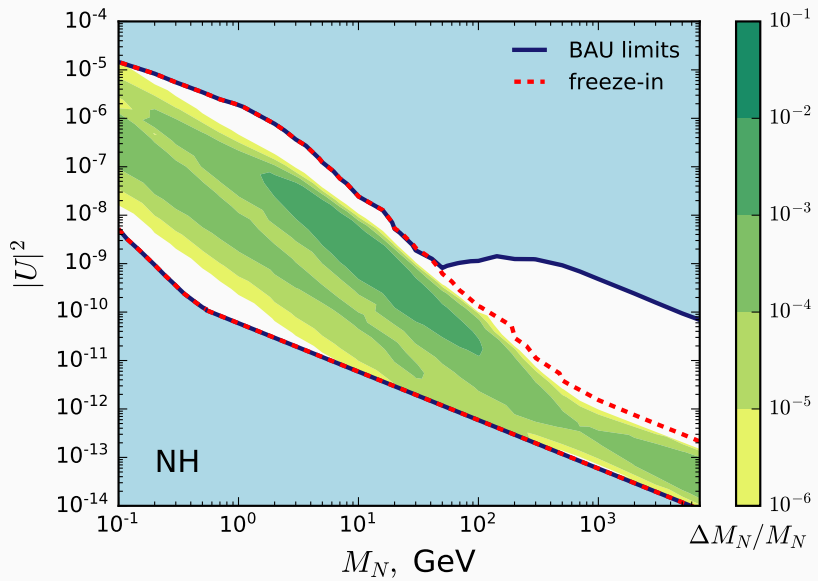

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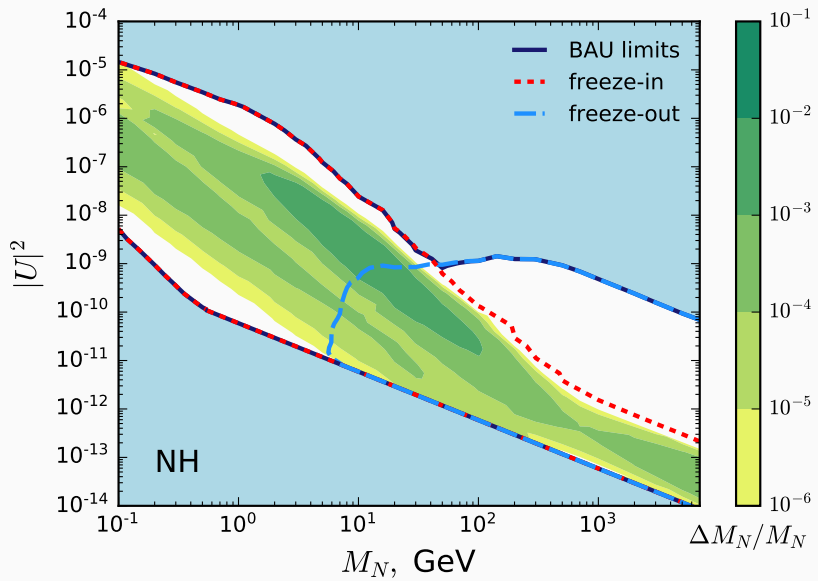

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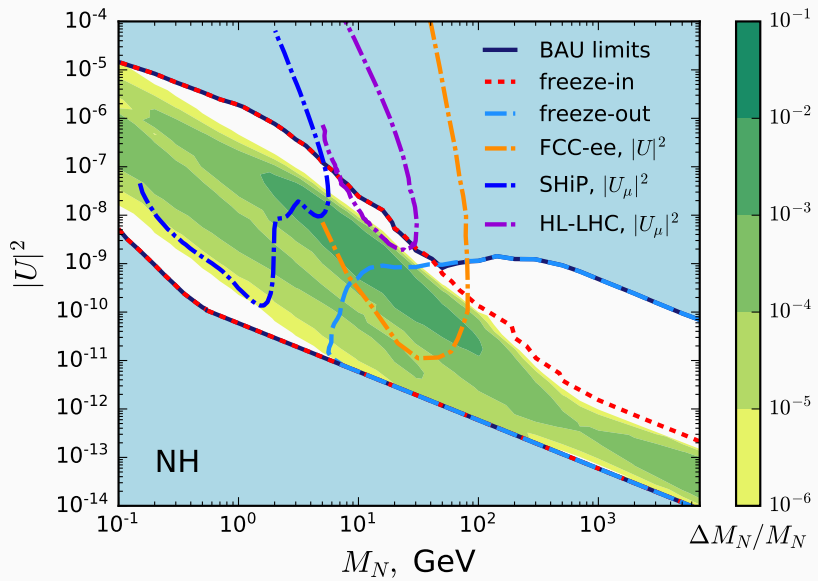

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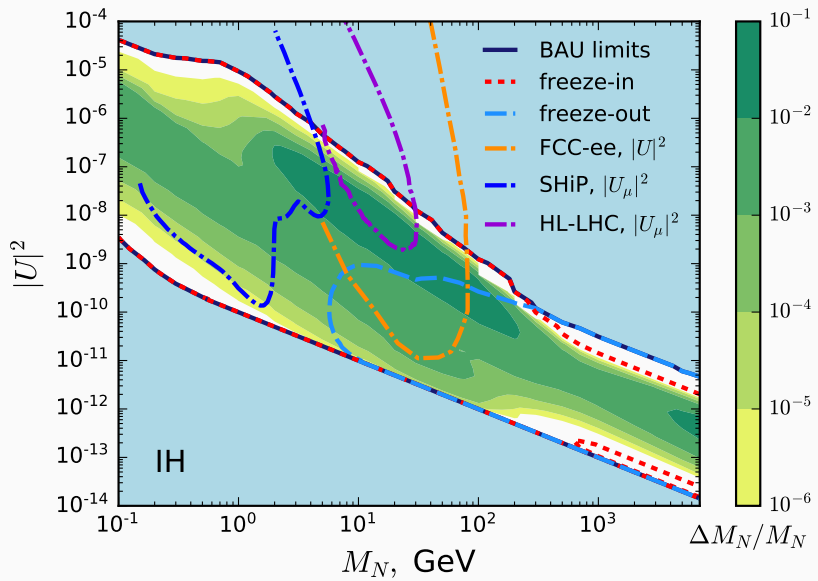

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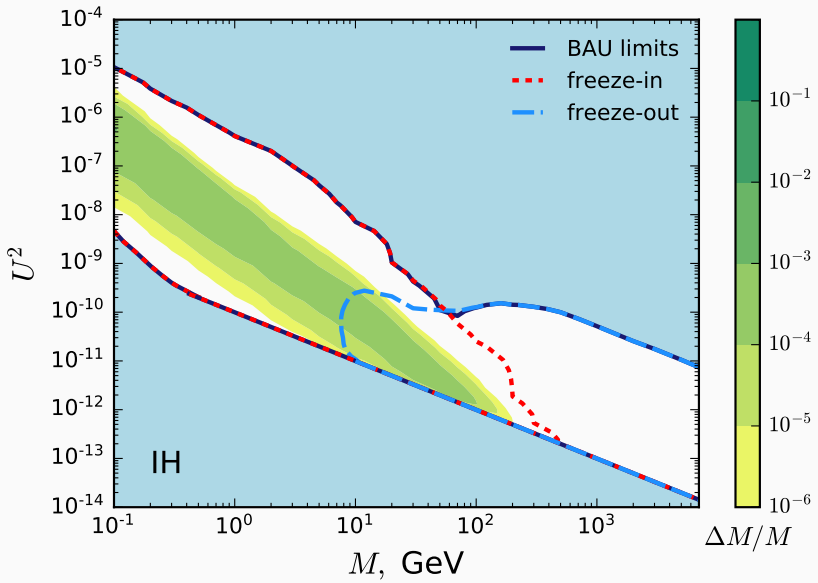

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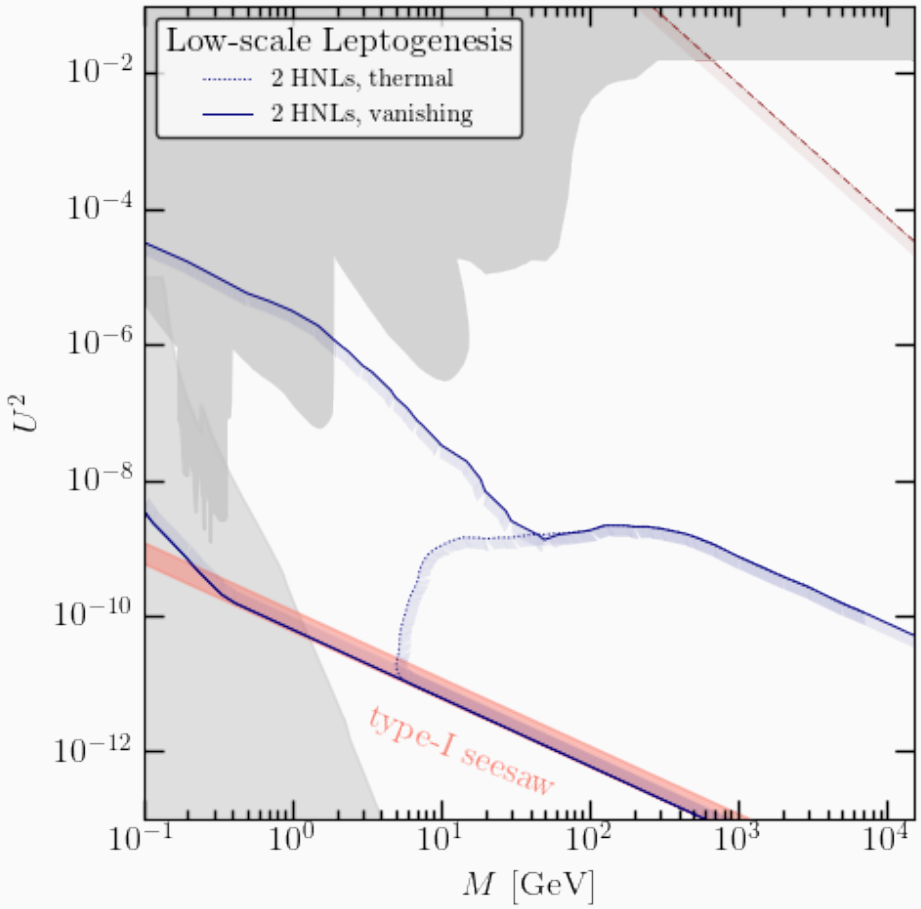

[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

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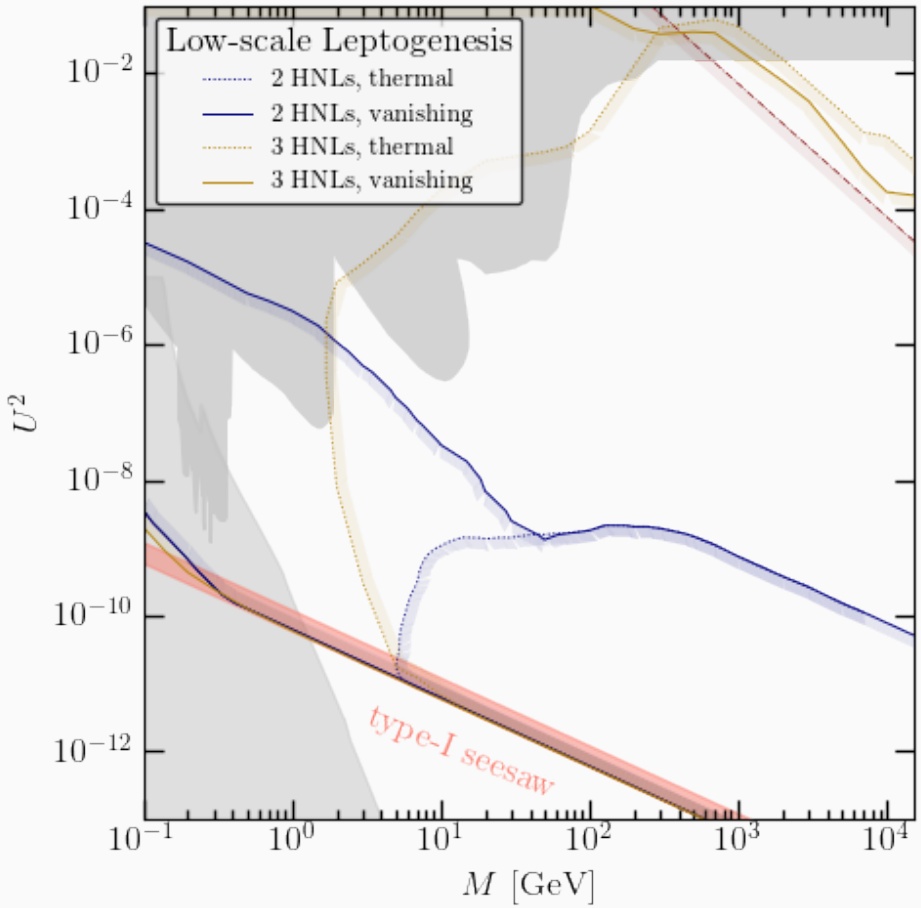

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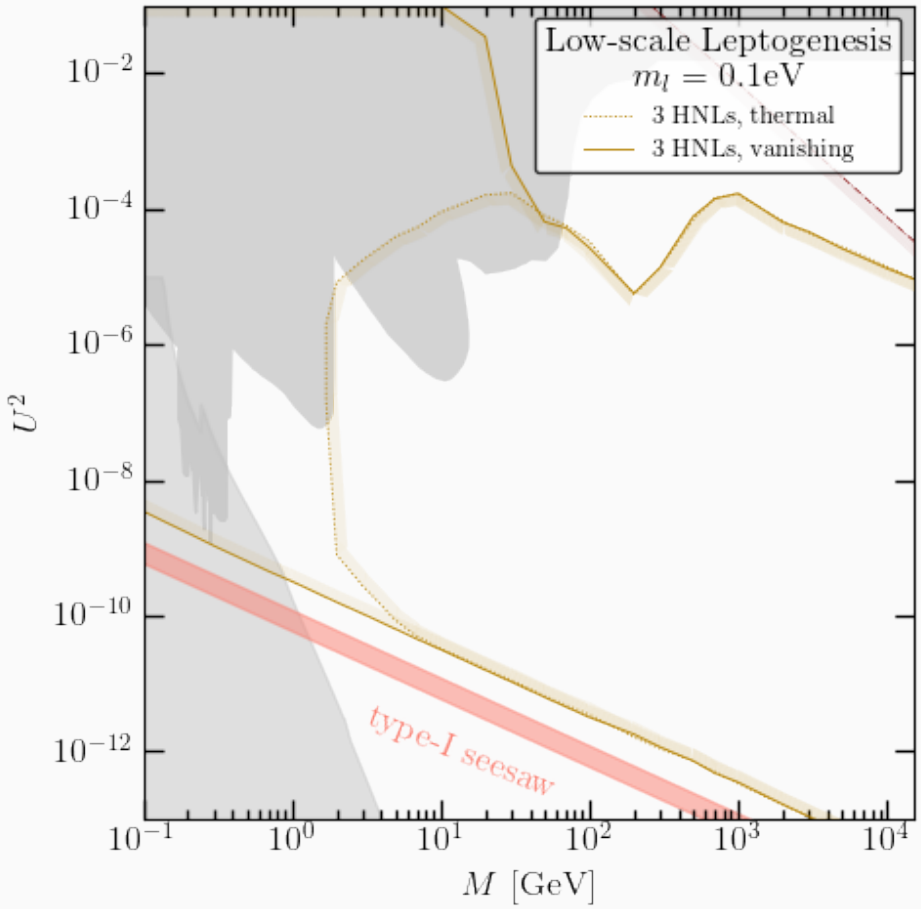

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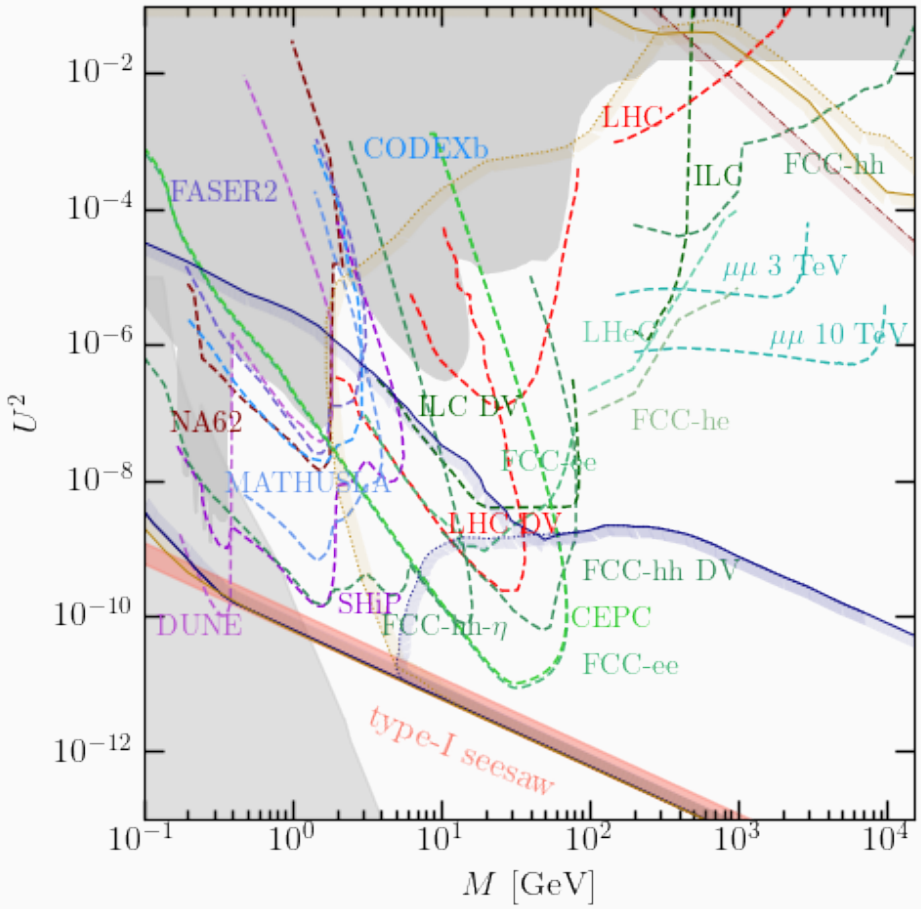

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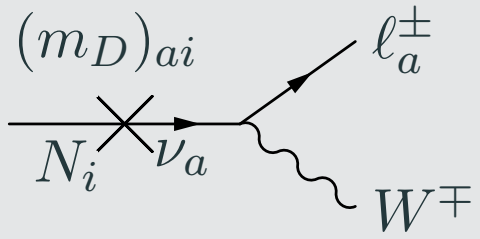
Direct probes of HNLs

Direct probes of the HNL parameter space

HNL mixing



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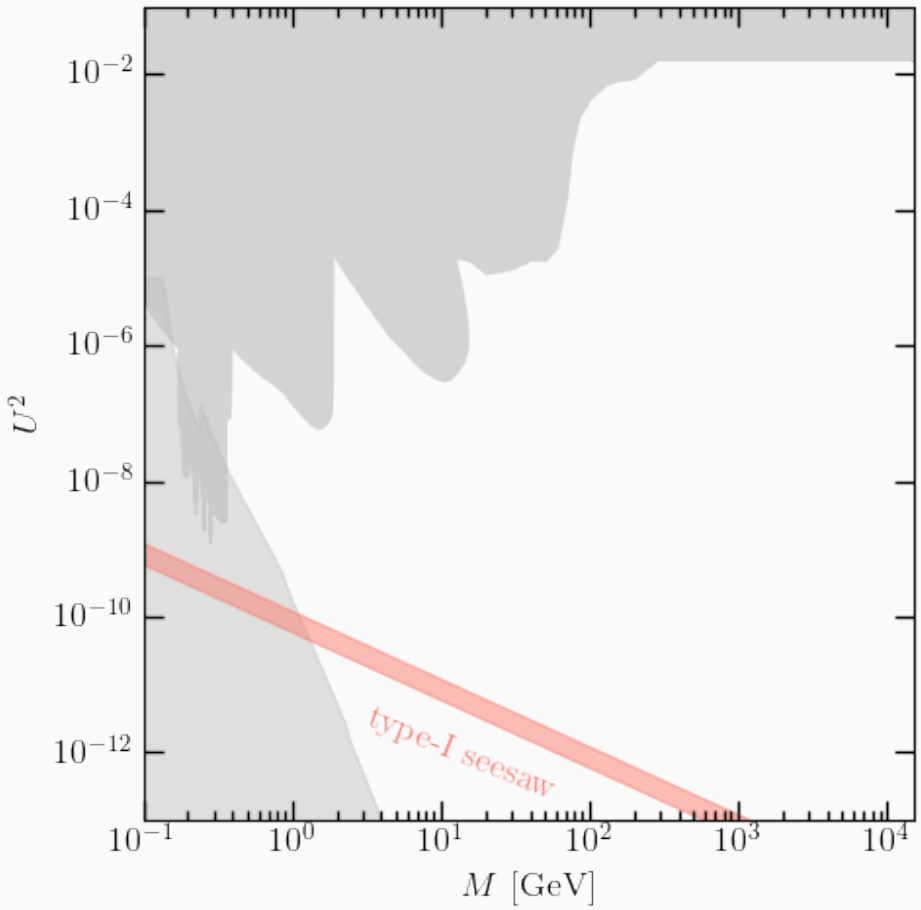

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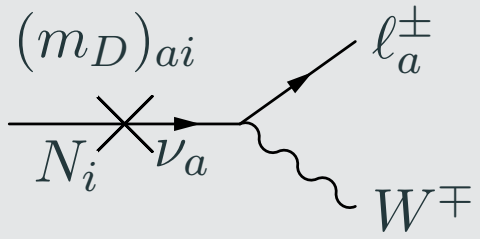

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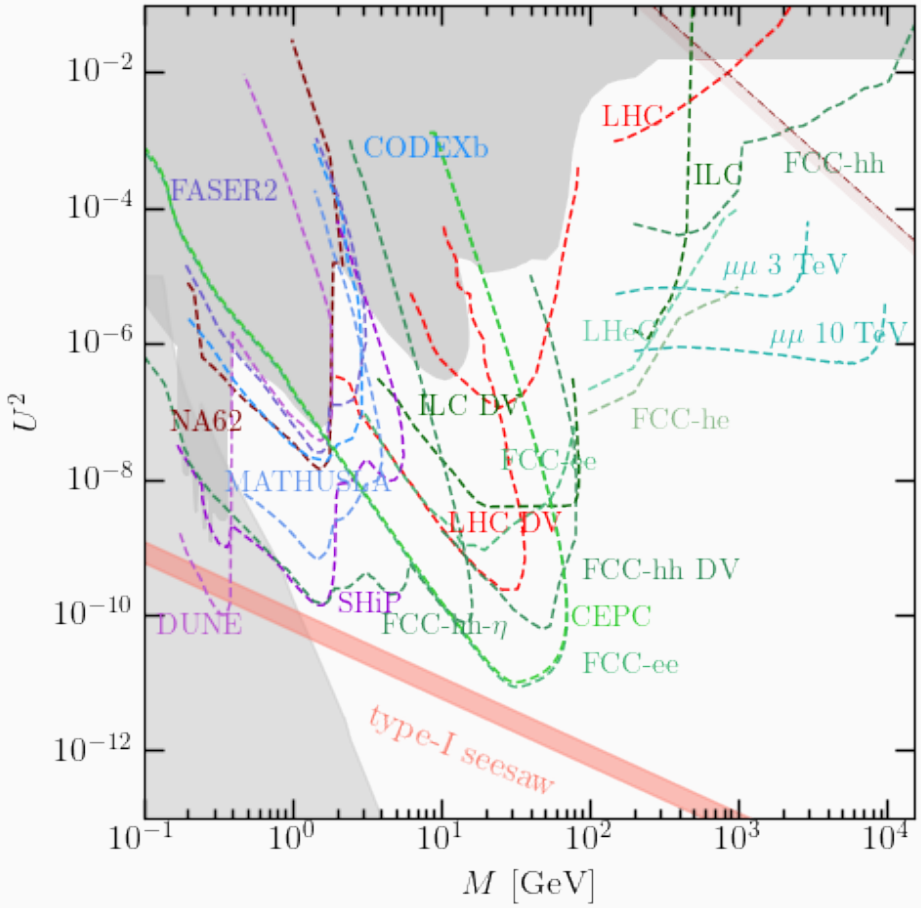

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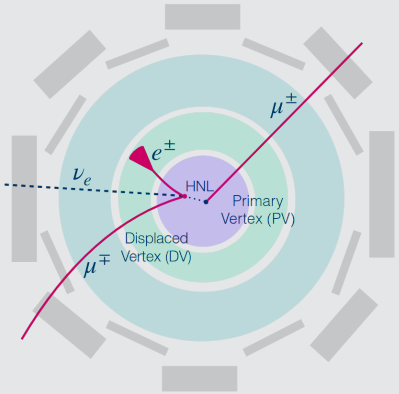
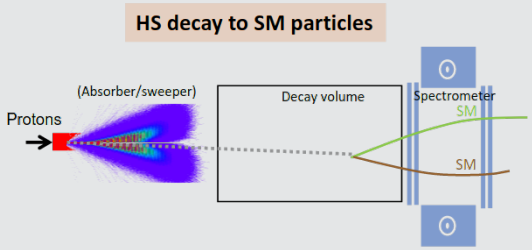
Direct probes of the HNL parameter space

Displaced Vertices

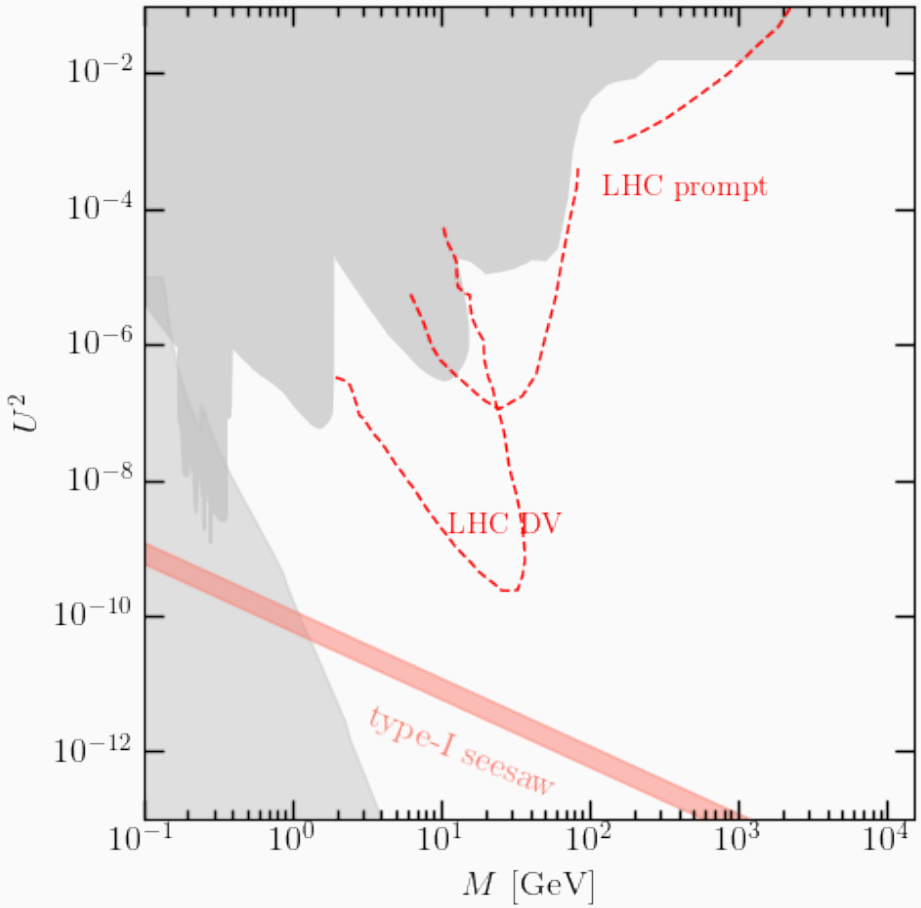


[graphic by D. Trischuk]

LLP experiments



[graphic by A. Golutvin]



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

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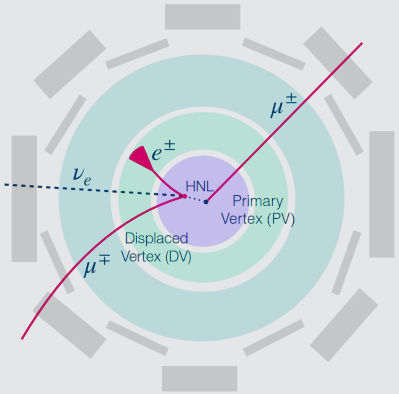

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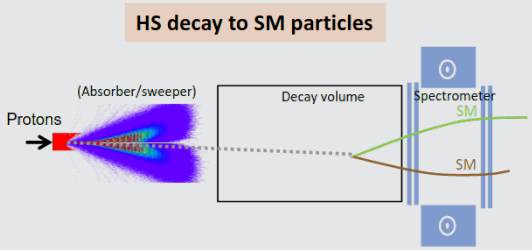

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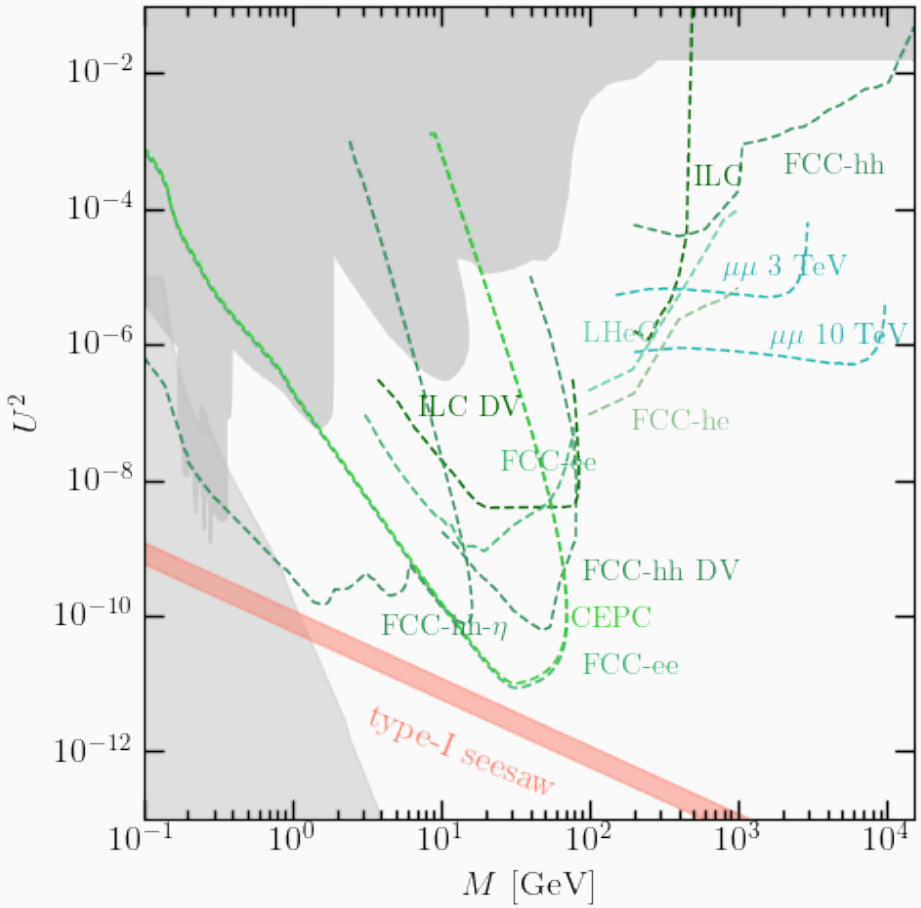

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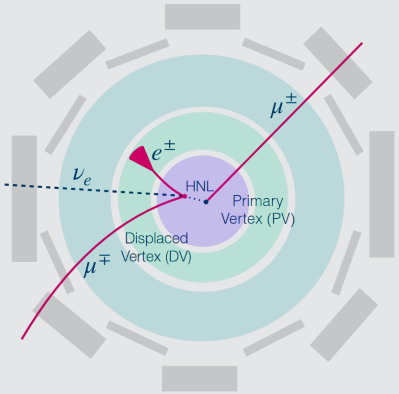

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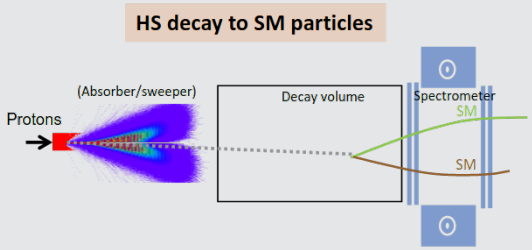

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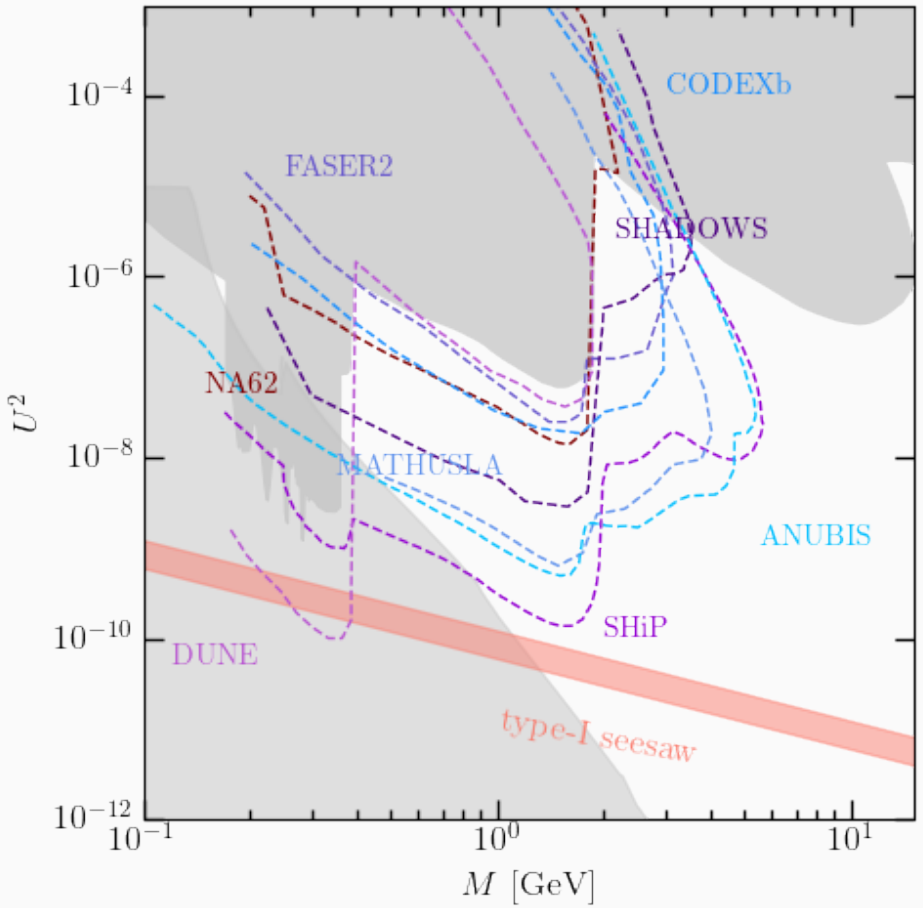

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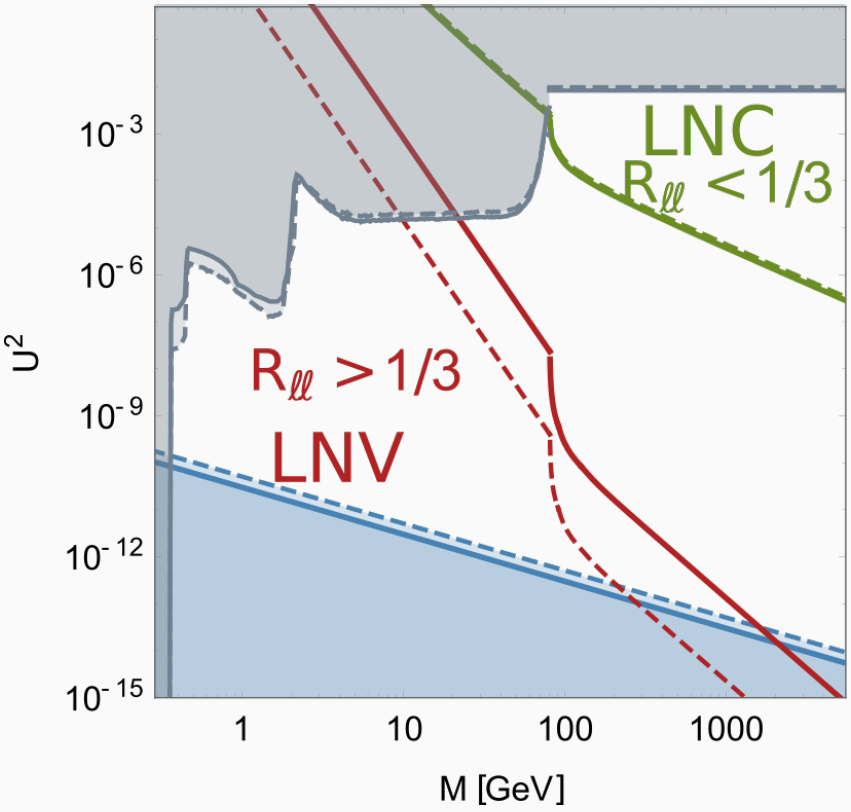
Lepton Number violation in HNL decays



[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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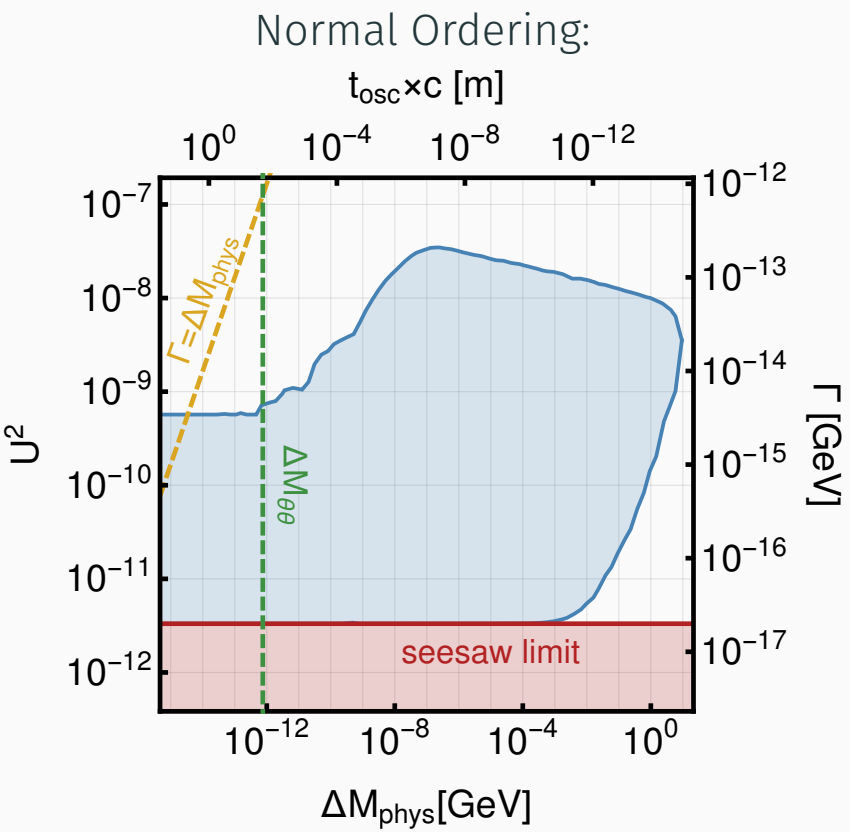

$M = 30$ GeV

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

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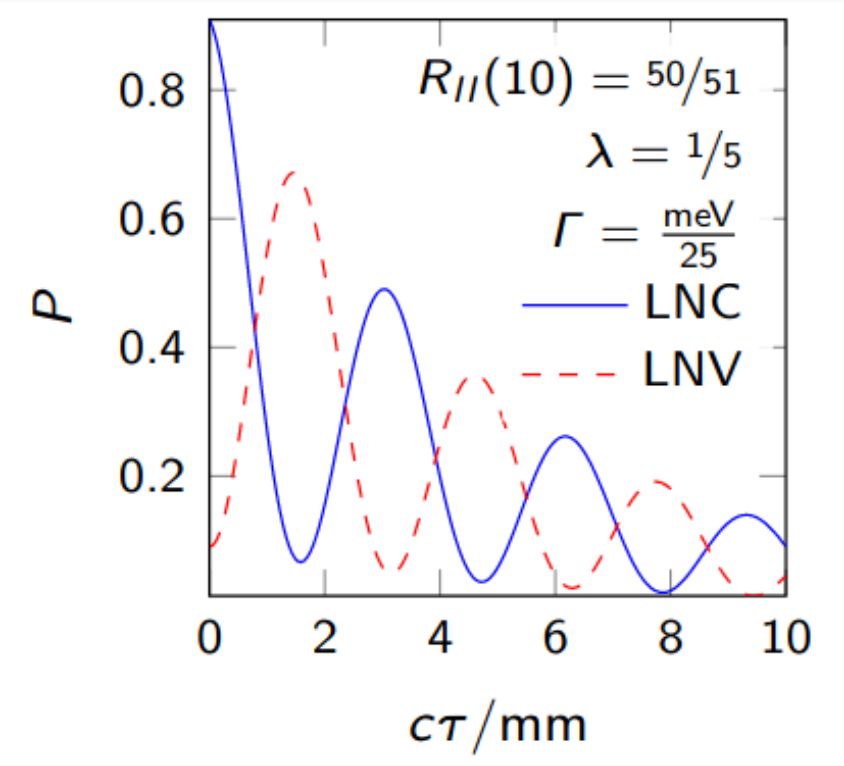

[Antusch/Hajer/Rosskopp 2210.10738]

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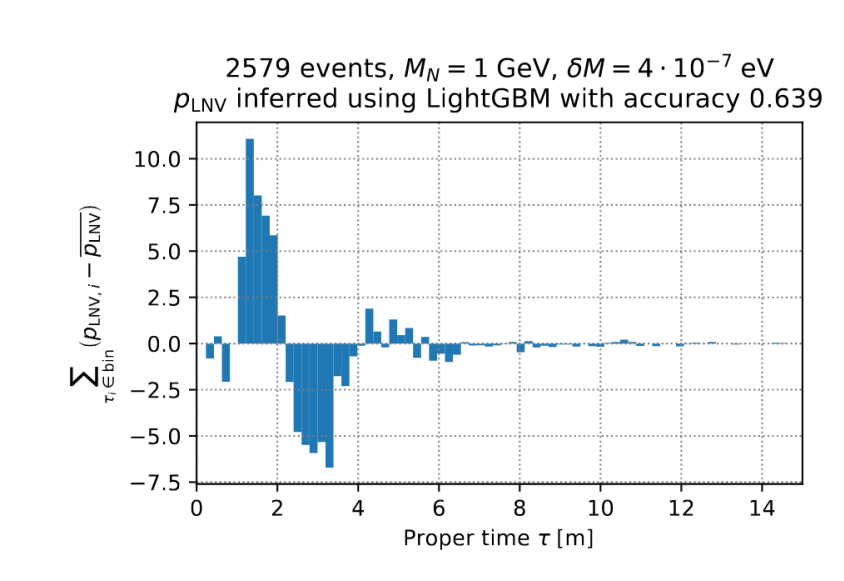

[Tastet/Timiryasov 1912.05520]

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Measuring flavor ratios at experiments

- the HNL branching ratios are constrained for a fixed U^2
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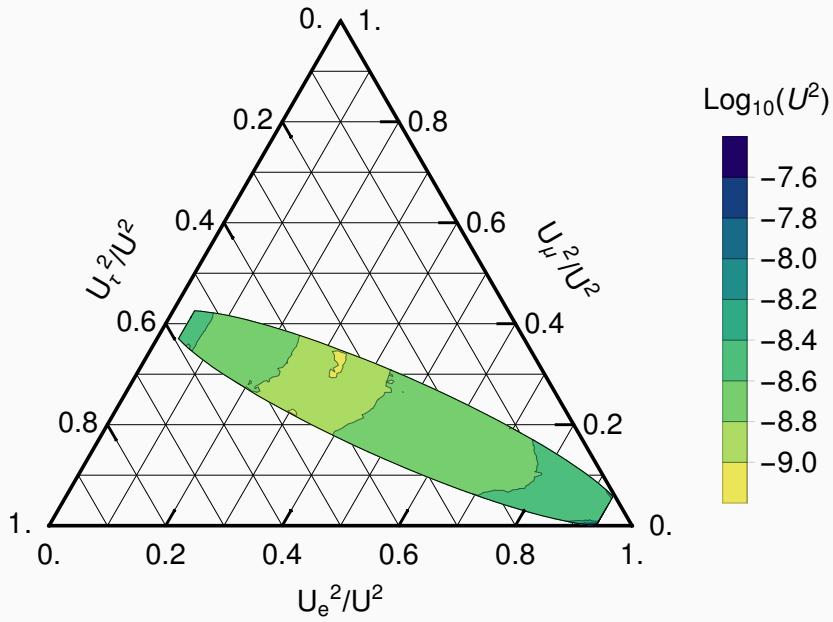

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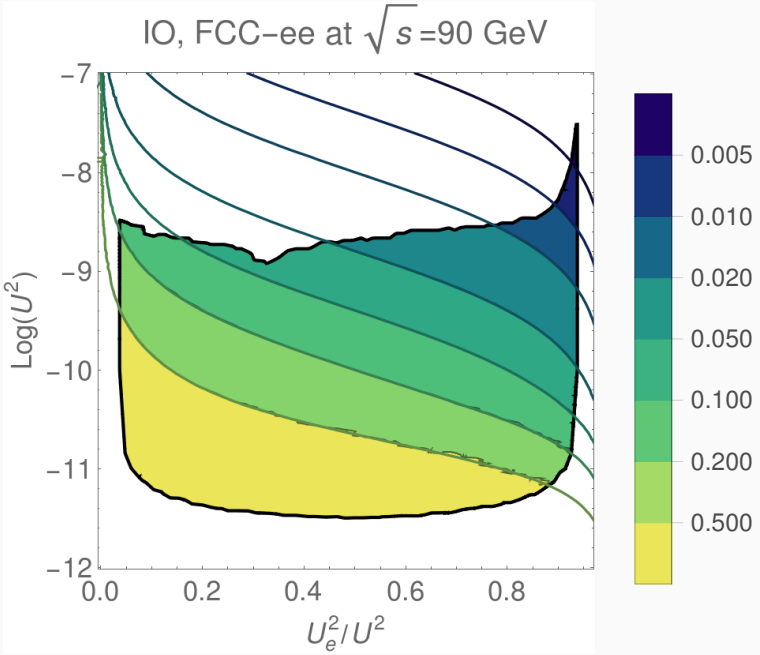

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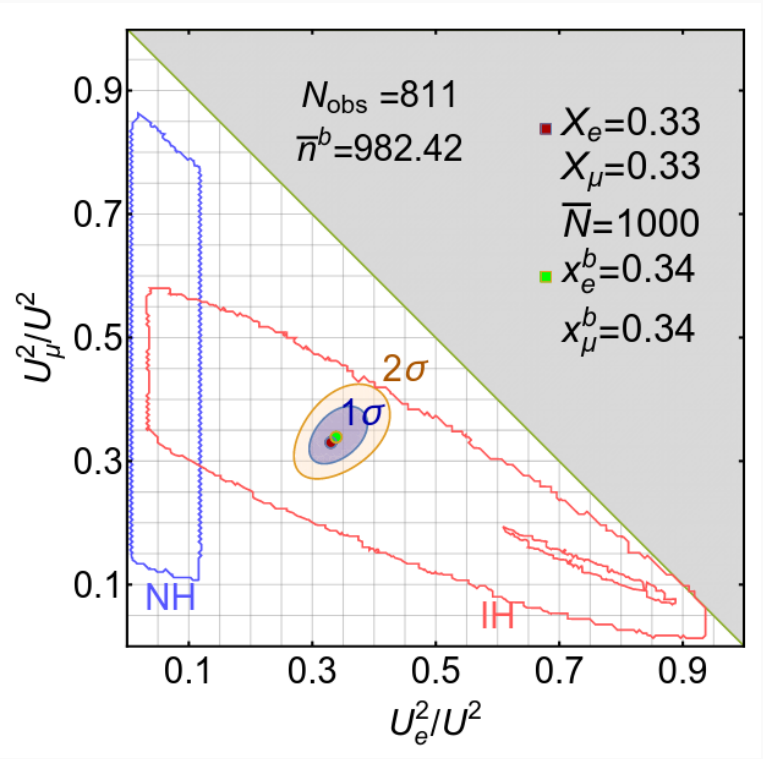
$M_N = 1$ GeV @ SHiP



[Snowmass HNL WP 2203.08039]

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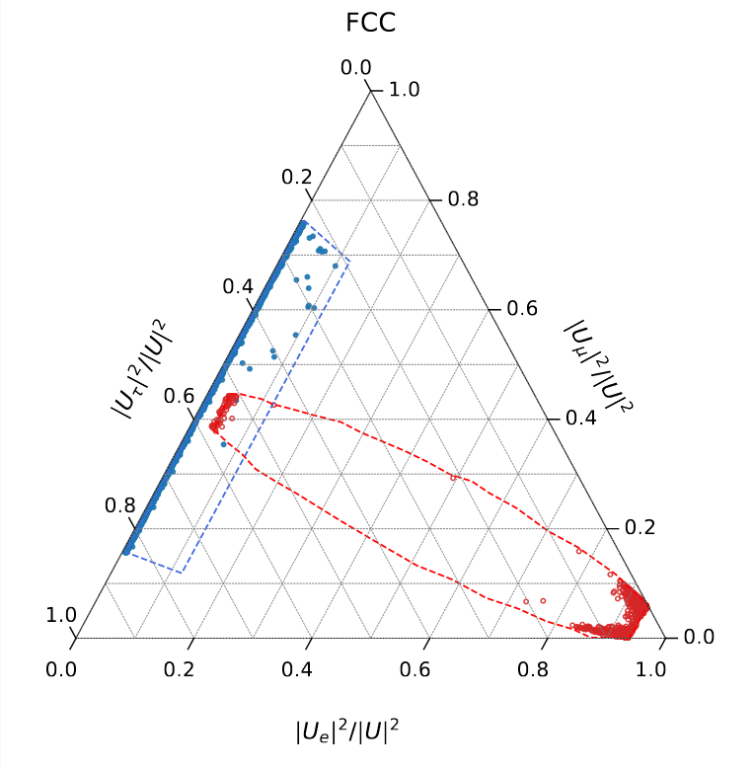

$$\Delta M/M = 10^{-2}$$

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

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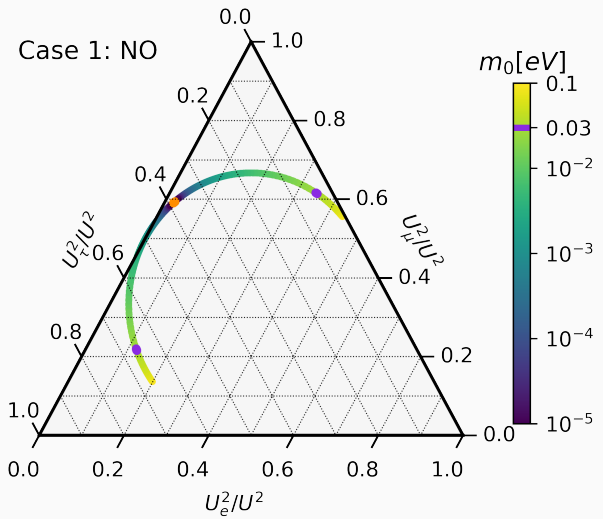
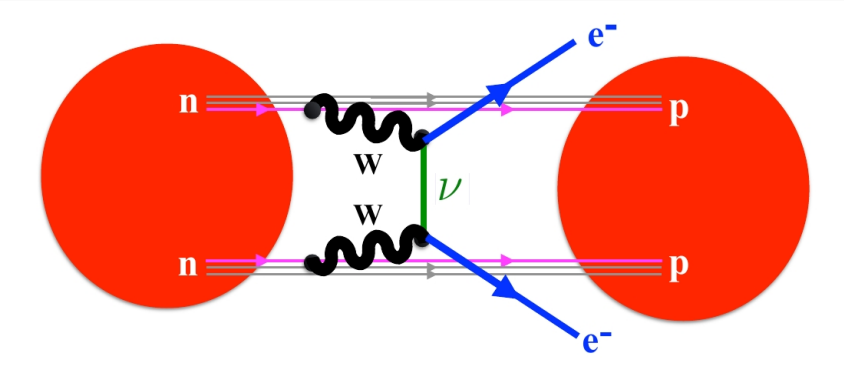


[Drewes/Georis/HagedornKlaric 2203.08538]

[Drewes/Georis/HagedornKlaric 230a.bcde]

Indirect probes of HNLs

Probing HNLs in neutrinoless double β decay



[figure from 1910.04688]

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

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

- 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
  - $m_{lightest} \neq 0$
  - larger rates due to wider range of ΔM_{ij}
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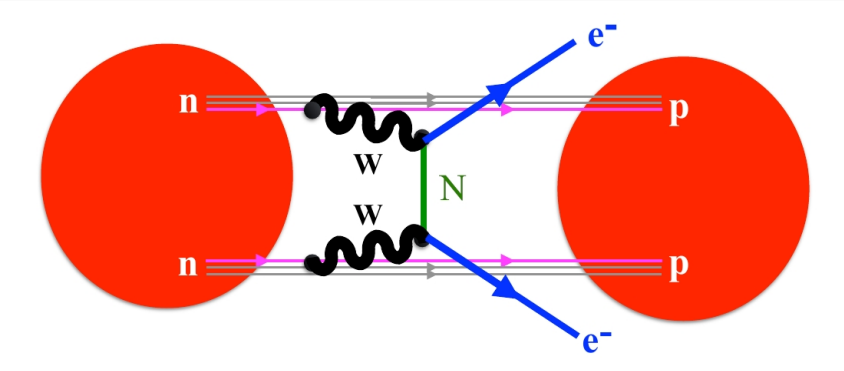

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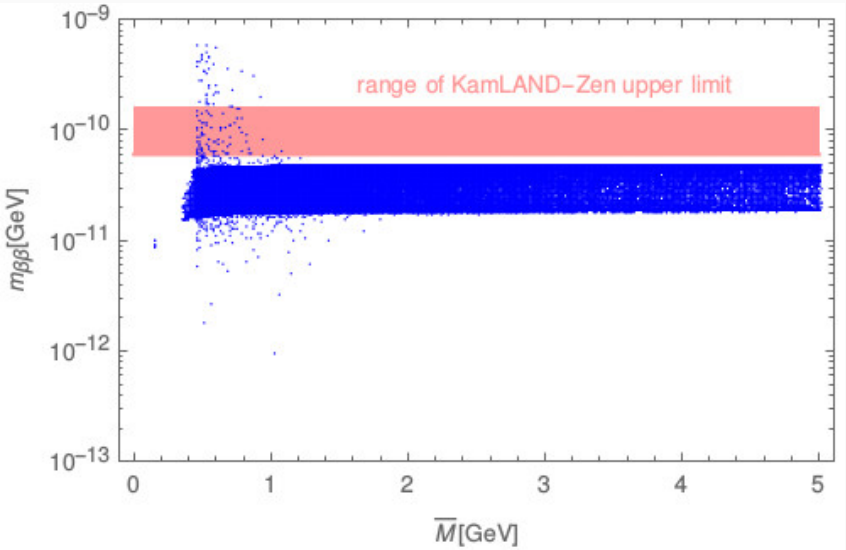

[Eijima/Drewes 1606.06221,

Hernández/Kekic/López-Pavón/Salvado 1606.06719]

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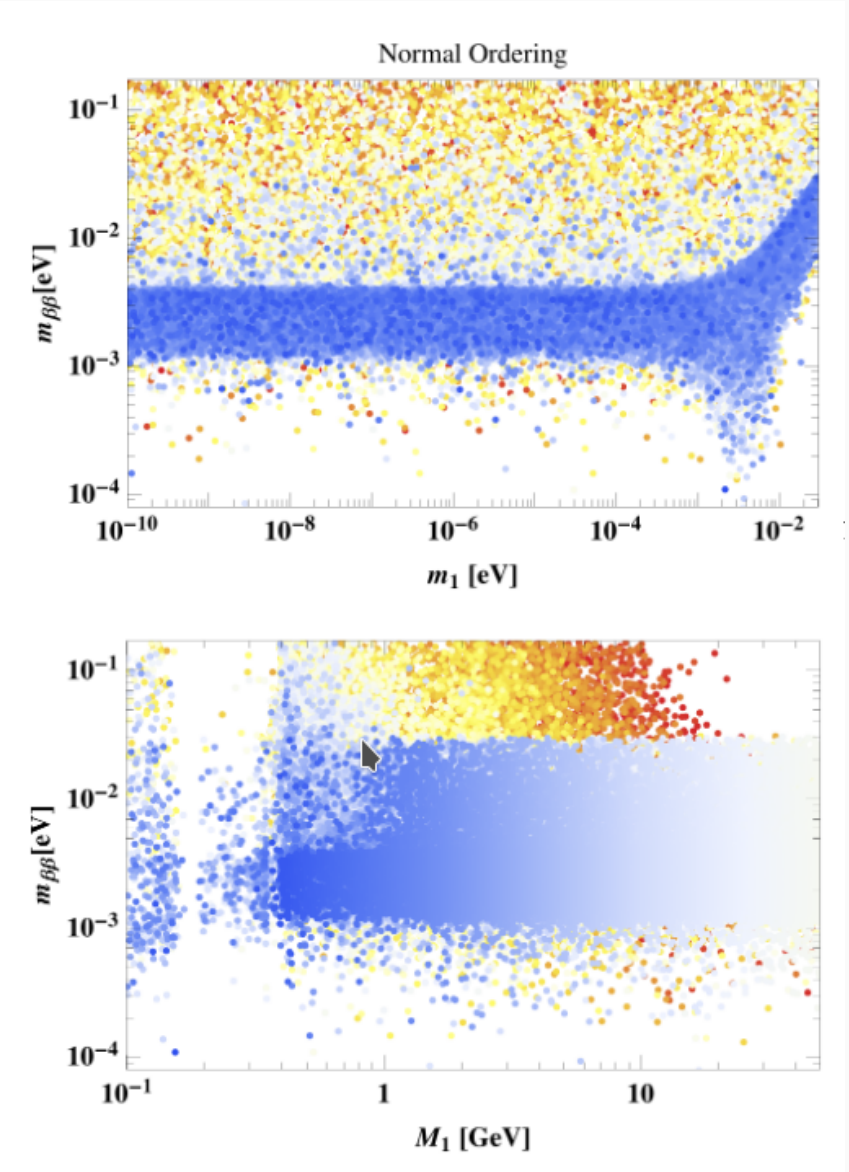

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[Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

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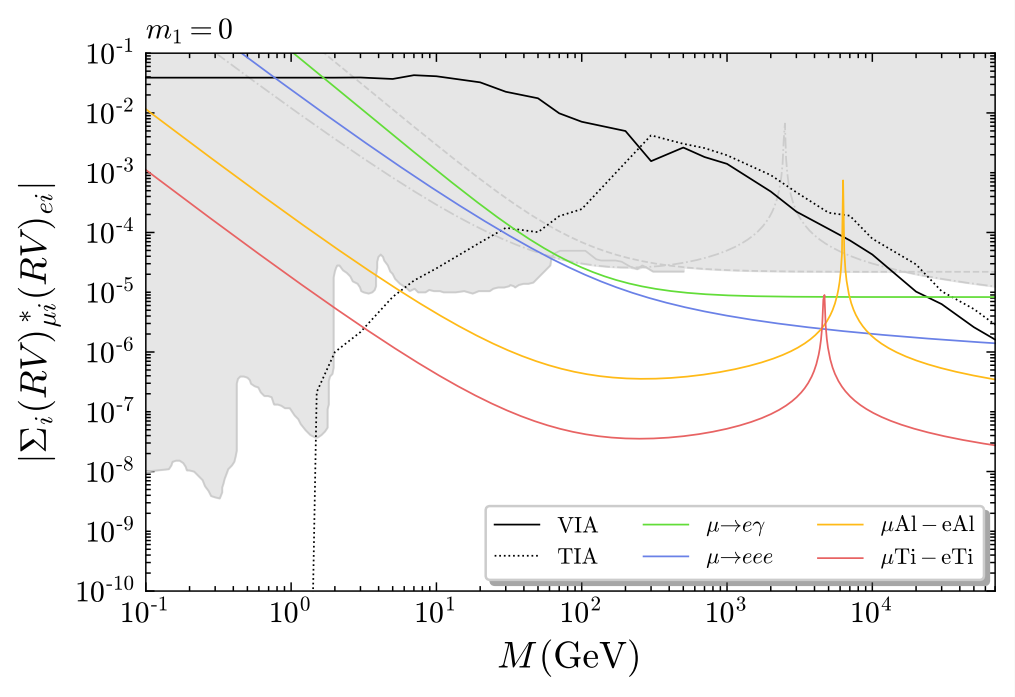

[Granelli/JK/Petcov 2206.04342]

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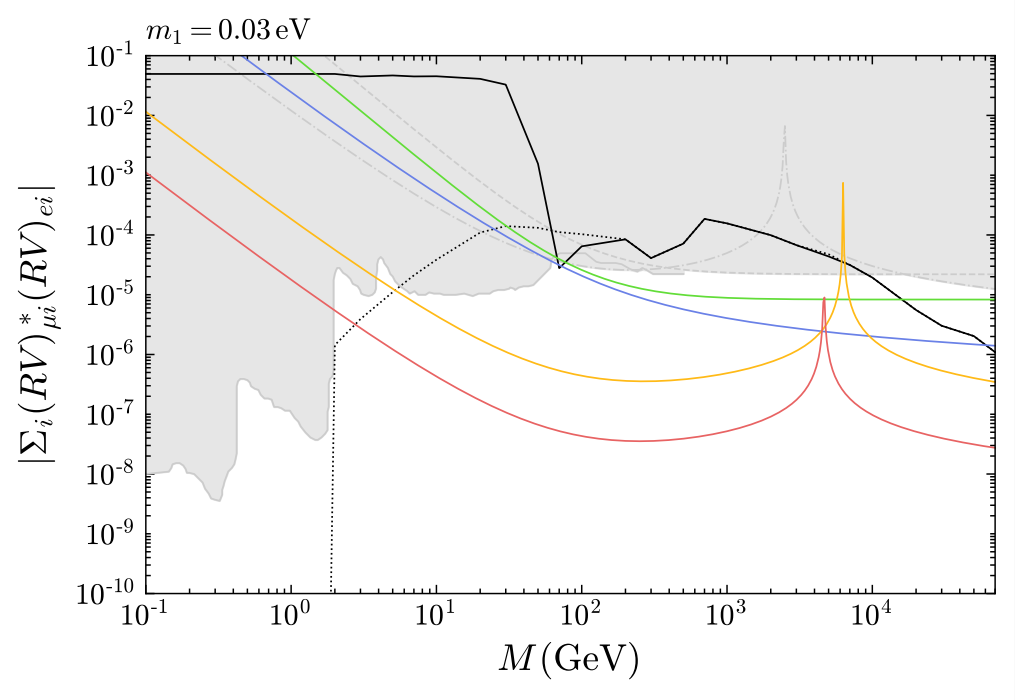

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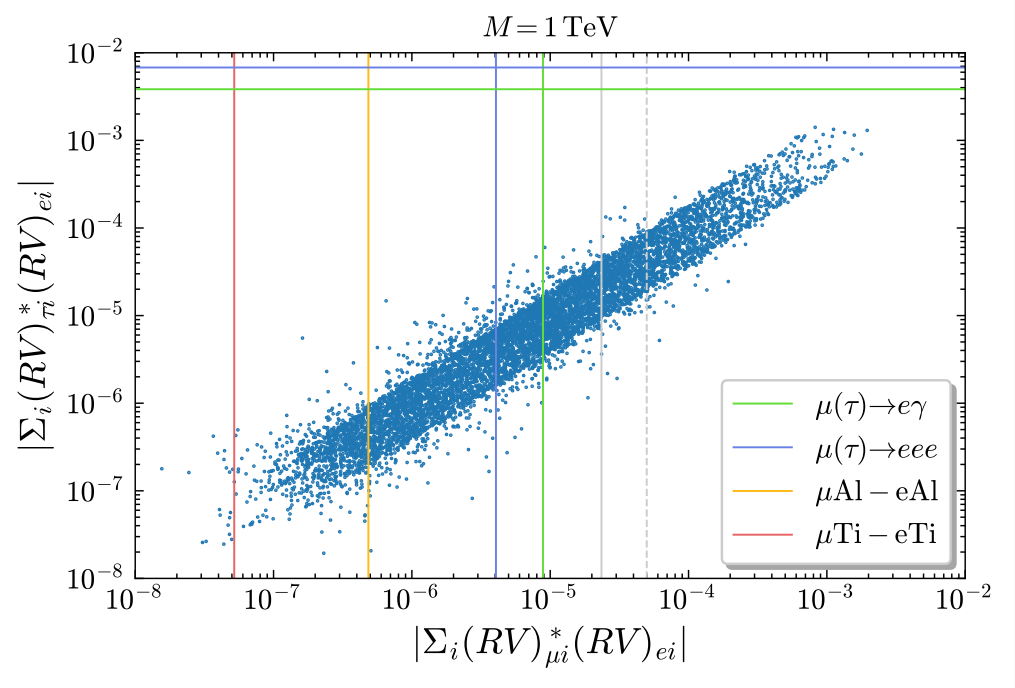

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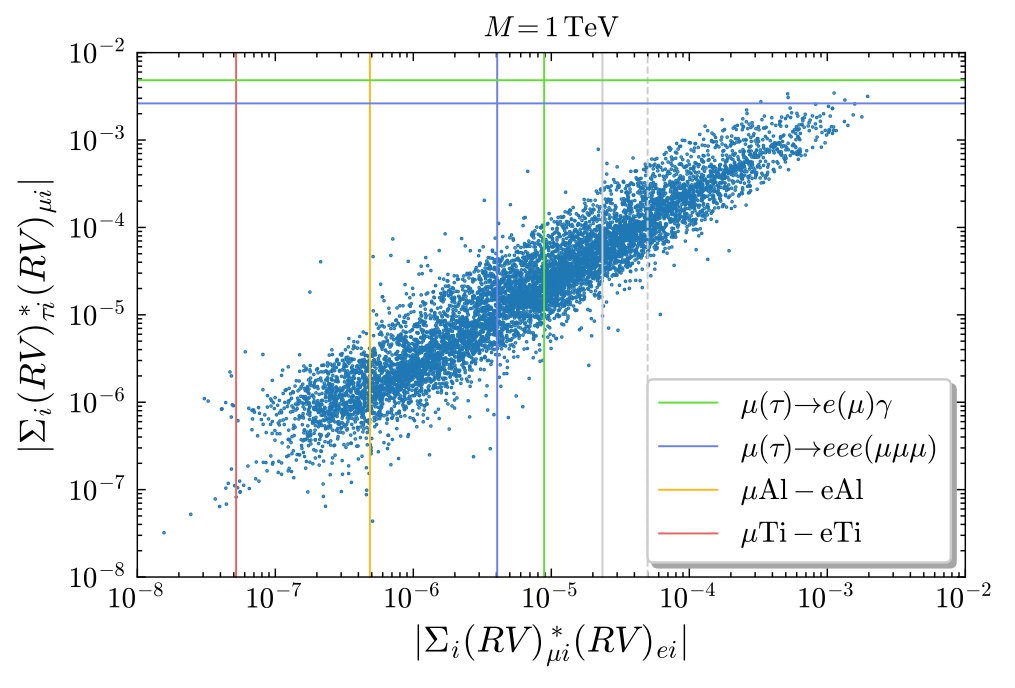

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Conclusions

- 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!

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

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Hierarchy in the washout

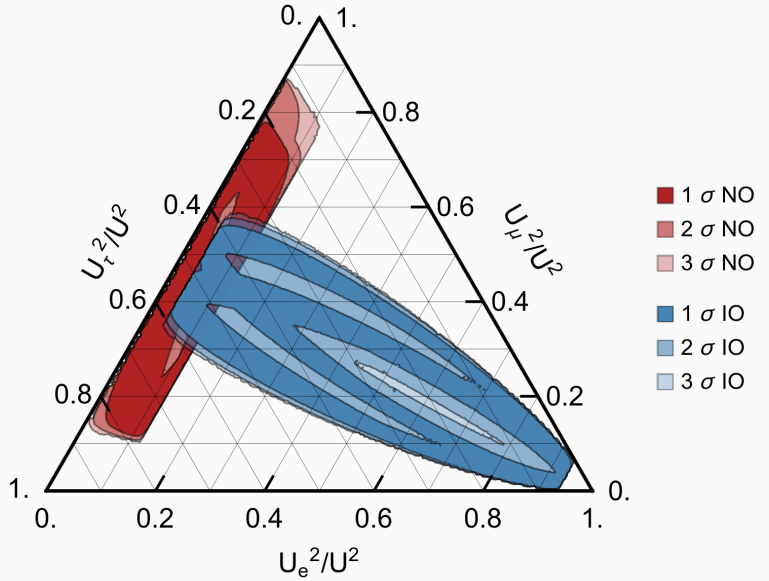
- lepton asymmetry can survive washout if hidden in a particular flavor
- washout suppression

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

- 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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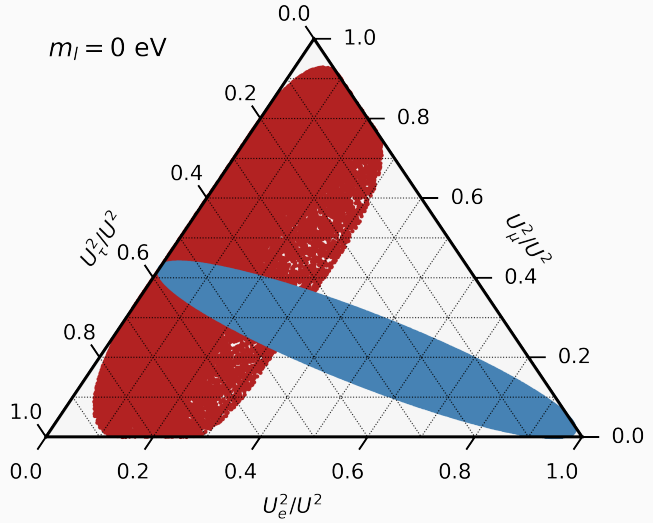

[Drewes/Georis/JK 230x.xxxx]

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

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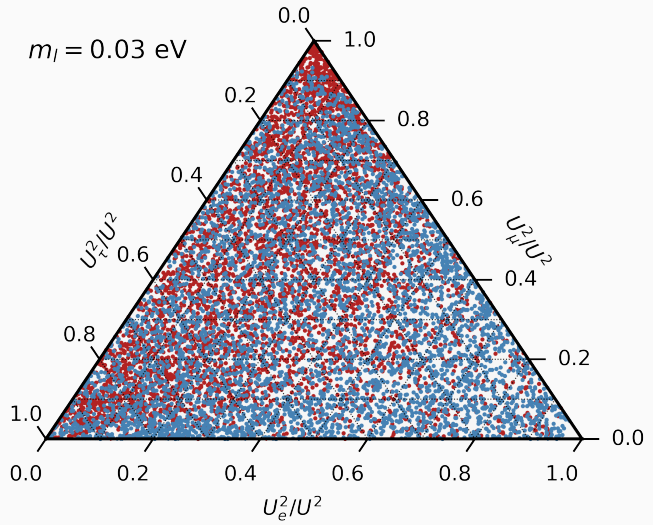


[Drewes/Georis/JK 230x.xxxx]

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

Enhancement due to level crossing

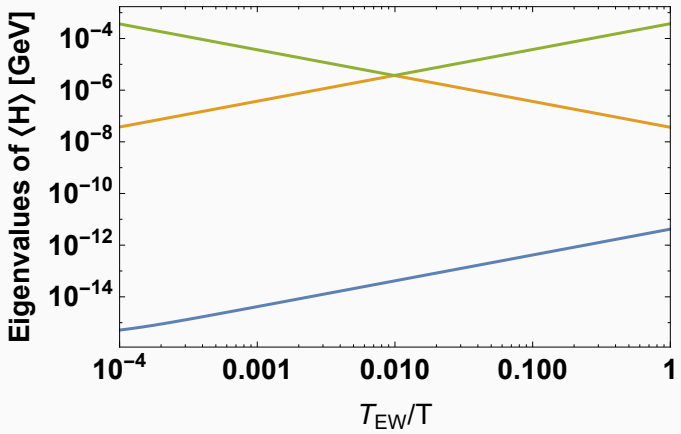
- in the $B - L$ symmetric limit two heavy neutrinos form a pseudo-Dirac pair
- the “3rd” heavy neutrino can be heavier than the pseudo-Dirac pair
- for $T \gg T_{EW}$, the pseudo-Dirac pair also has a thermal mass

$T \gg T_{EW}$

N_s

N_3

N_w



$T \ll T_{EW}$

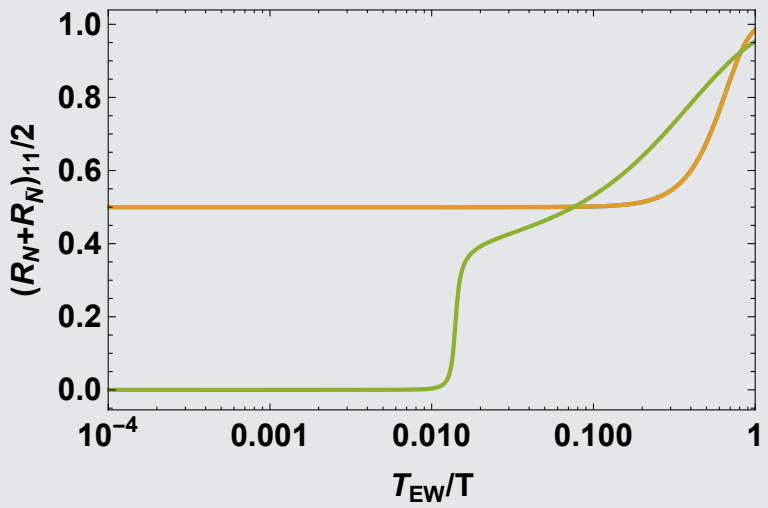
N_3

N_2

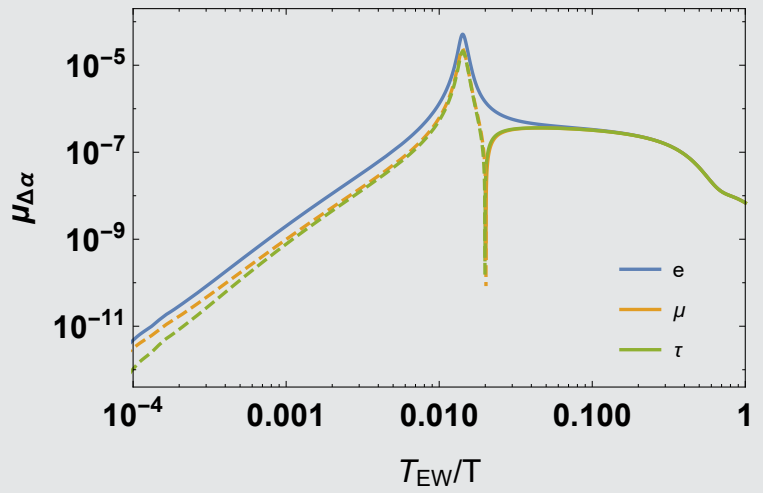
N_1

Enhancement due to level crossing

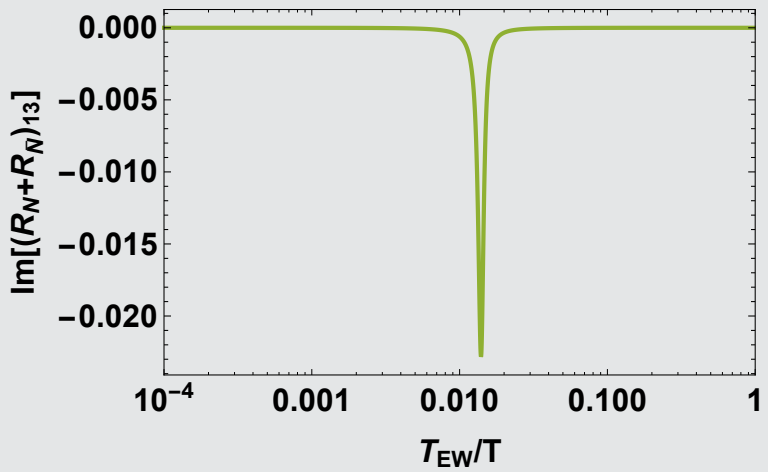
Heavy Neutrino Densities



Lepton flavour asymmetries



Heavy Neutrino correlations



Lepton number asymmetry