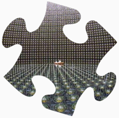
Heavy Neutral Leptons and Leptogenesis

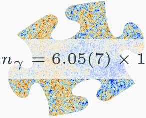
Juraj Klarić

March 21st, 2023

Neutrino masses



The Baryon Asymmetry of the Universe



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

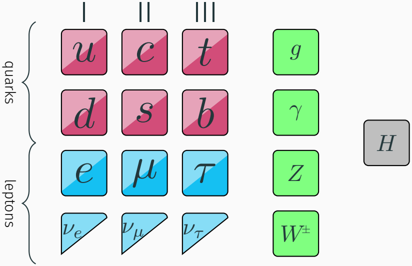


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

Some puzzles for physics beyond the Standard Model

Neutrino masses

[Minkowski 1977...]

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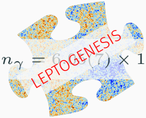

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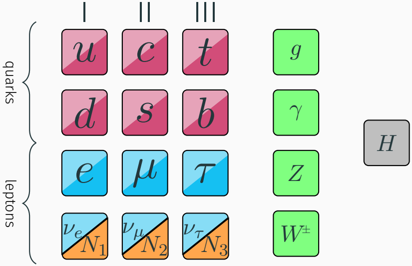
[Fukugita/Yanagida '86...]



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Where to look for HNLs?

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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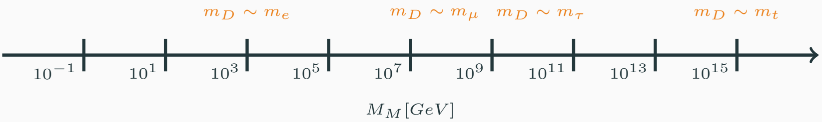
Yanagida ’79
Schechter/Valle ’80]
canonical type-I seesaw



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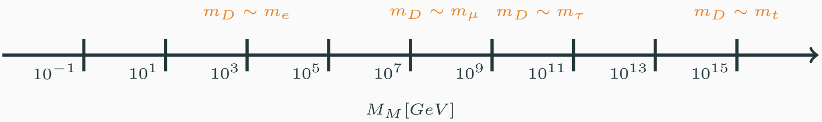

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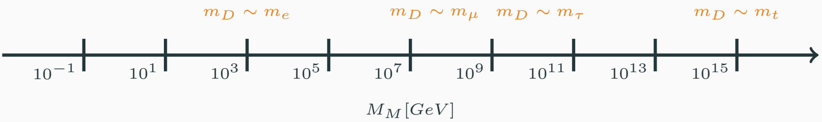
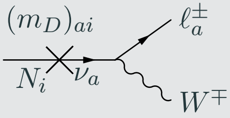
low-scale seesaw
linear and inverse seesaws



How to look for HNLs?

HNL mixing



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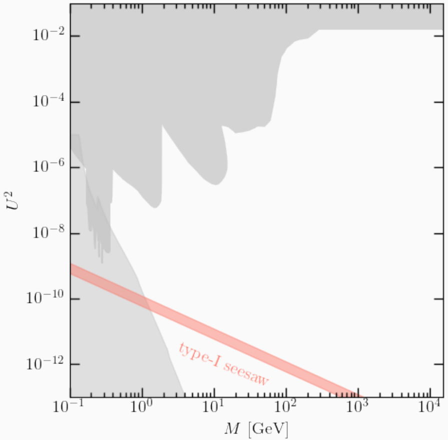
$$U^2 = \sum_{a,i} U_{ai}^2$$

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



[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

[see talks by Haifa Rejeb Sfar and Sophie Middleton]

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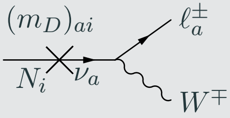

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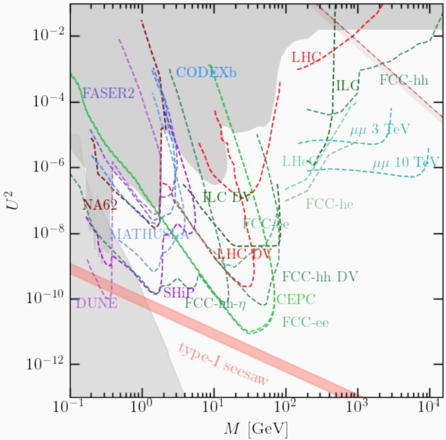

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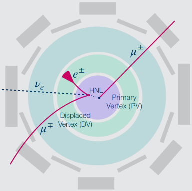
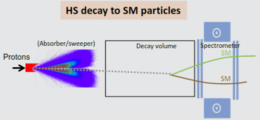


[graphic by D. Trischuk]

LLP experiments



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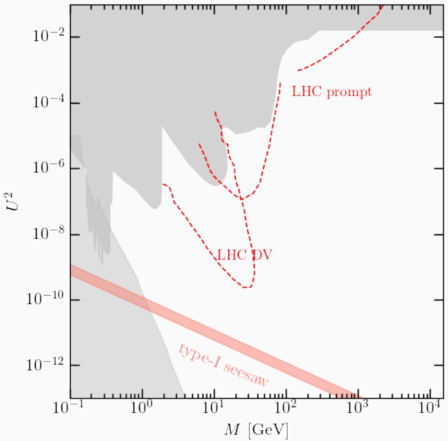

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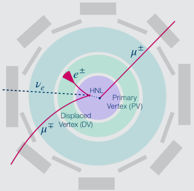

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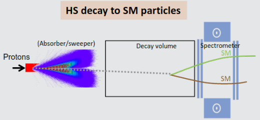

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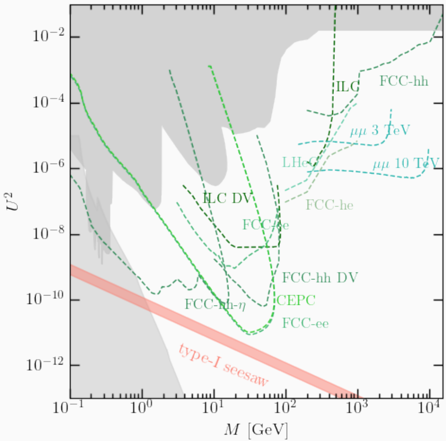

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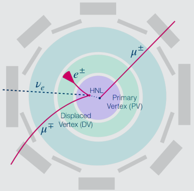

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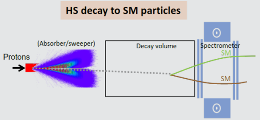

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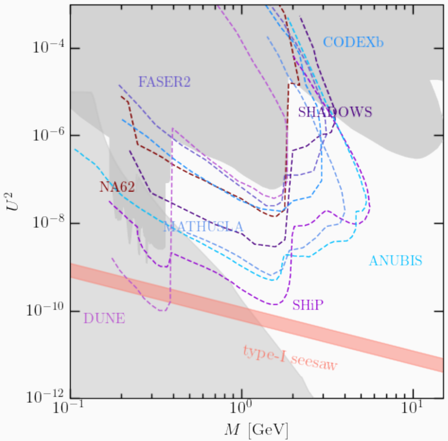

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Low-scale leptogenesis mechanisms

The Sakharov Conditions

1. Baryon number violation

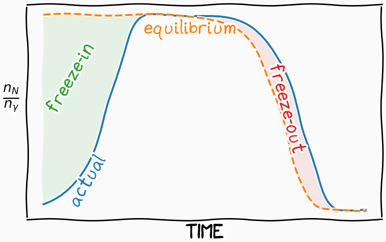
   sphaleron processes

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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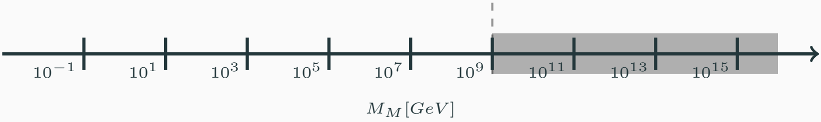

From High to Low-scale Leptogenesis

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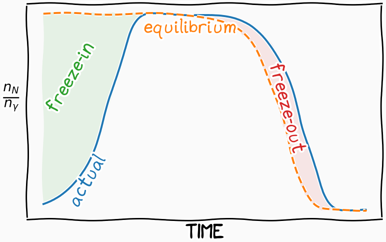

[Akhmedov/Rubakov/Smirnov ’98
Asaka/Shaposhnikov ’05]
leptogenesis via oscillations

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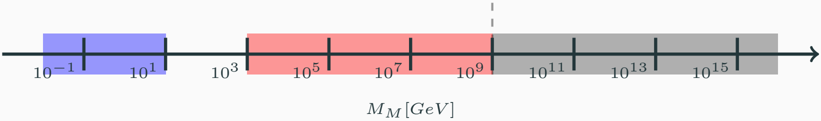

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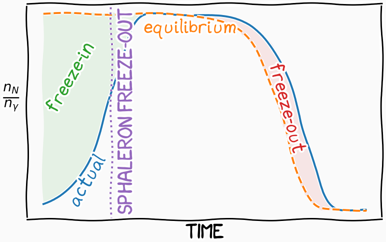

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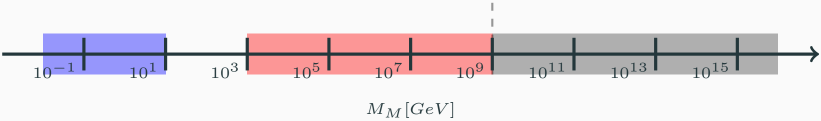

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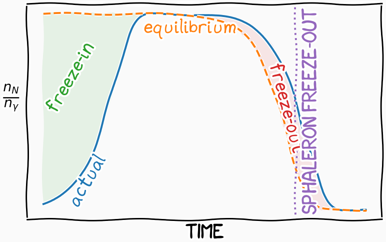

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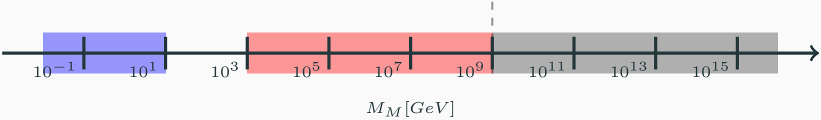

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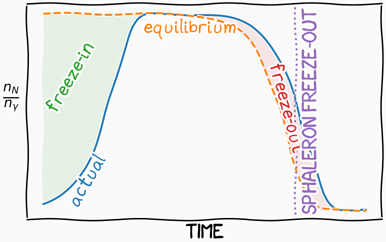

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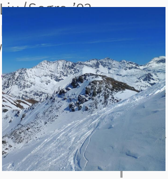

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$M_M\,[GeV]$

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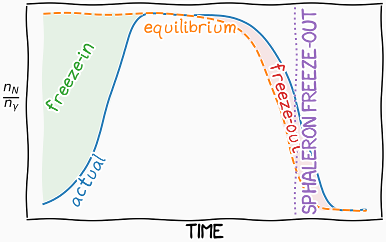

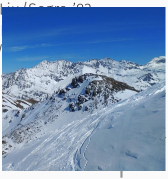

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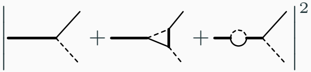
The low-scale leptogenesis mechanisms

Resonant leptogenesis

- assymetry produced in HNL decays



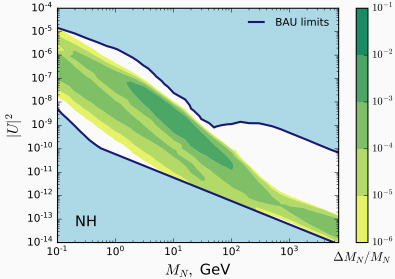
- asymmetry diverges when $M_2 \to M_1$
- relativistic effects can typically be neglected
- heavy neutrino decays require $M \gtrsim T$, not clear what happens for $M \lesssim 130$ GeV

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

- 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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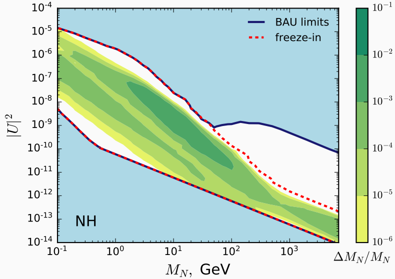

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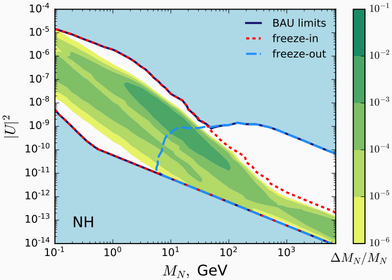

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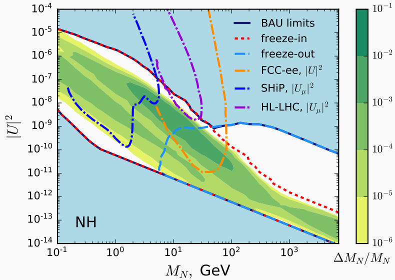

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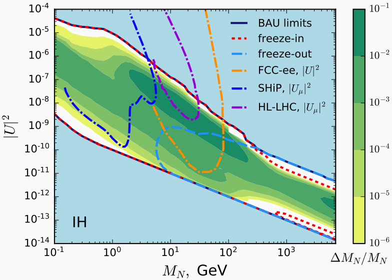

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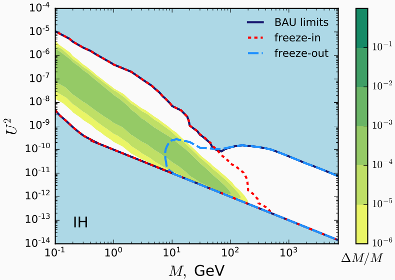

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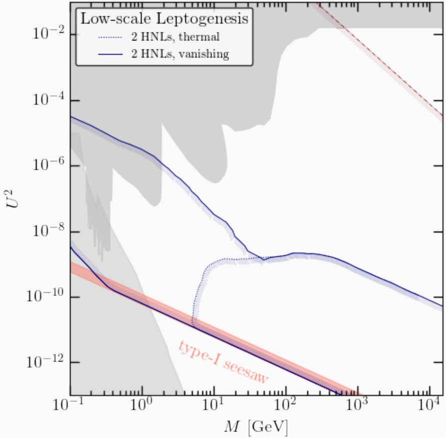
- all U^2 are allowed for experimentally accessible masses
- [see the talk by Yannis Georis]



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[leptogenesis bounds from JK/Timiryasov/Shaposhnikov 2103.16545 and Drewes/Georis/JK 2106.16226]

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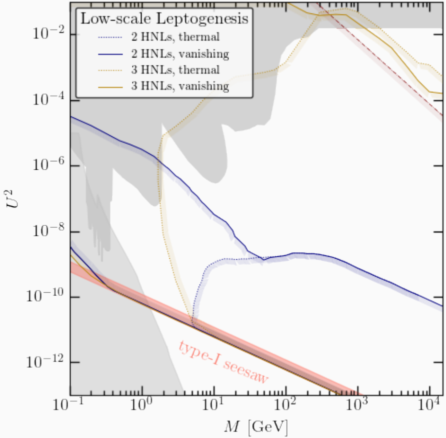


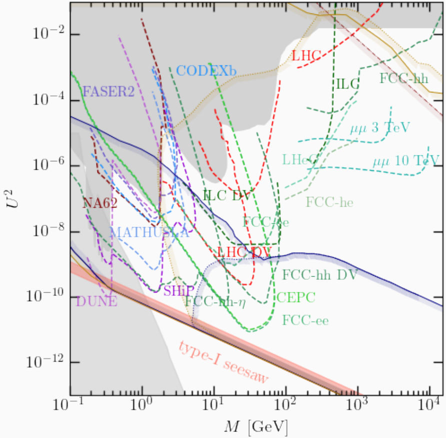
[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

[leptogenesis bounds from JK/Timiryasov/Shaposhnikov 2103.16545

and Drewes/Georis/JK 2106.16226]

Results: Leptogenesis with 3 RHNs

- both freeze-in and freeze-out leptogeneses within reach of existing experiments
- all U^2 are allowed for experimentally accessible masses
- [see the talk by Yannis Georis]



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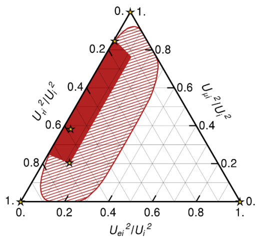
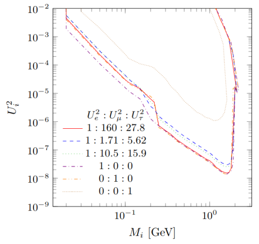
What kind of HNLs to look for?

Sensitivity of experiments highly depends on mixing ratios

NA62 in beam dump

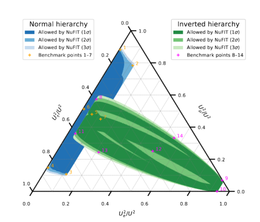


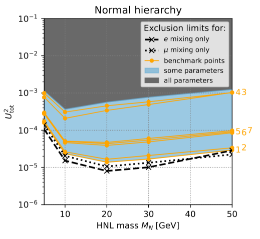


[Drewes/Hajer/JK/Lanfranchi

1801.04207]

ATLAS

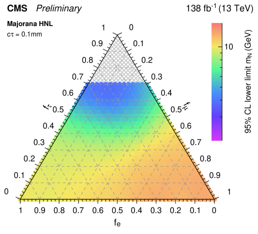


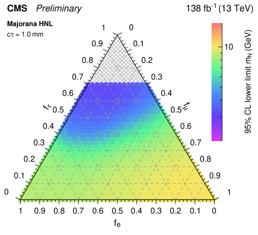


[Tastet/Ruchayskiy/Timiryasov

2107.12980]

CMS

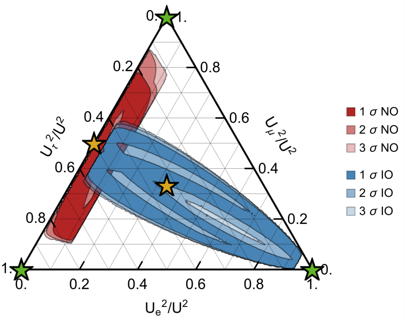




[CMS-PAS-EXO-21-013]

[from the talk by Haifa Rejeb Sfar]

New Benckmark Flavour Ratios



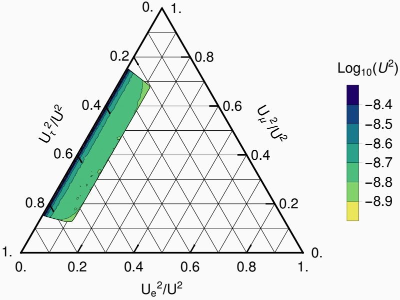
[Drewes/JK/Lopez-Pavon 2207.02742]

- in the minimal seesaw model the flavour ratios are determined by U_{PMNS}
- uncertainty dominated by Majorana phase η, Dirac phase δ and θ_{23}

- new benchmarks prepared for the HNL WG of the FIPs physics centre
- selection criteria:
  1. consistency with ν-osc. data
  2. added value
  3. symmetry considerations
  4. simplicity
  5. leptogenesis
- in addition to the single flavor benchmarks, we propose the new points:
  - $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 1$
  - $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 1 : 1$
- Common benchmarks can used to compare the reach of different searches

New Benckmark Flavour Ratios

NO, $M = 30$ GeV



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

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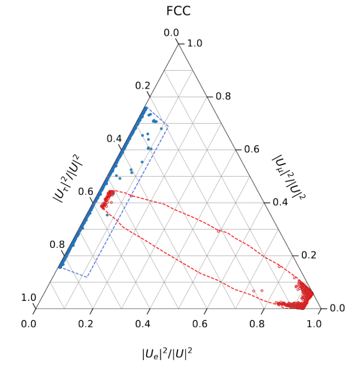

$\Delta M/M = 10^{-2}$

[Hernandez/Lopez-Pavon/Rius/Sandner 2207.01651]

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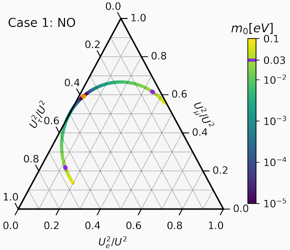

3HNLs with flavour symmetries

[Drewes/Georis/HagedornKlaric 2203.08538]

[Drewes/Georis/HagedornKlaric 230a.bcde]

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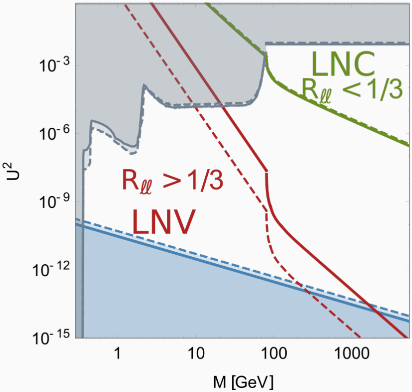
Dirac or Majorana HNLs?



[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
- energy resolution of planned experiments - $\Delta M/M \sim \mathcal{O}(\text{few}\%)$
- tiny mass splittings can be probed via HNL oscillations

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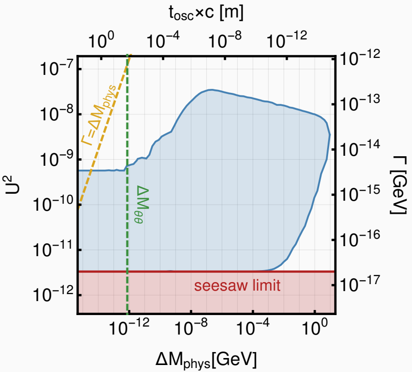

$M = 30$ GeV

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

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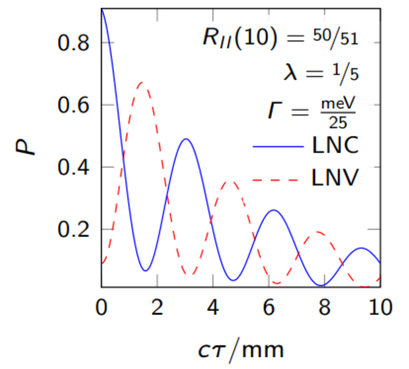

[Antusch/Hajer/Rosskopp 2210.10738]

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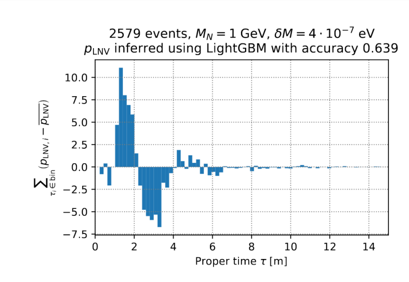

[Tastet/Timiryasov 1912.05520]

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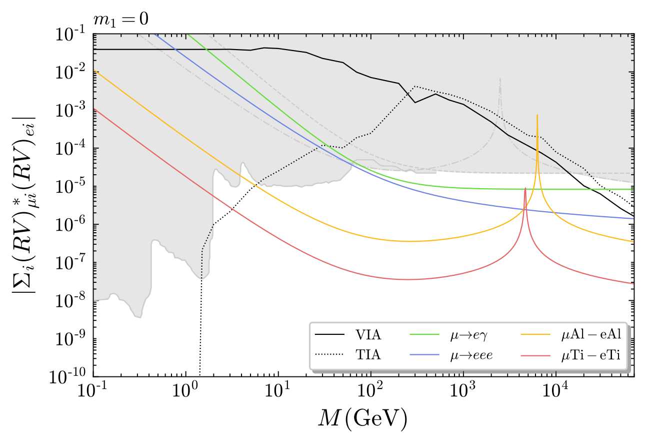
Conclusions

- 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 high-energy and high-intensity experiments!
- leptogenesis is a viable baryogenesis mechanism for all heavy neutrino masses above the $\mathcal{O}(100)$ MeV scale
- HNLs have a very rich phenomenology

  displaced vertices, LNV, LFV, HNL oscillations...

Thank you!

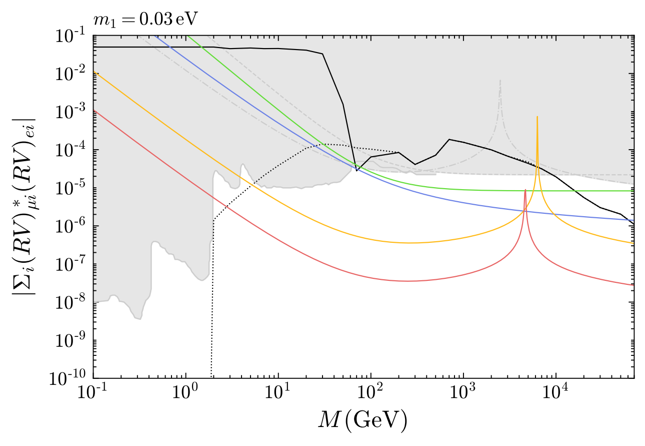
Indirect probes: Charged LFV



[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

Indirect probes: Charged LFV



[Granelli/JK/Petcov 2206.04342]

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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

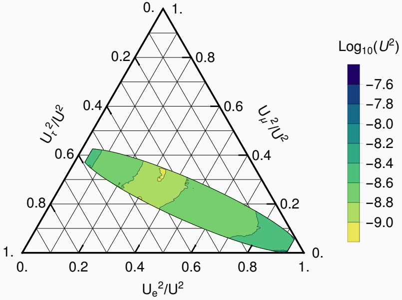
Fine Tuning

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

Measuring flavor ratios at experiments

- the HNL branching ratios are constrained for a fixed U^2
- large number of HNLs possible at FCC-ee allow for measurement of U_e^2/U^2
- similar sensitivity @ SHiP

IO, $M = 30$ GeV



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

1710.03744]

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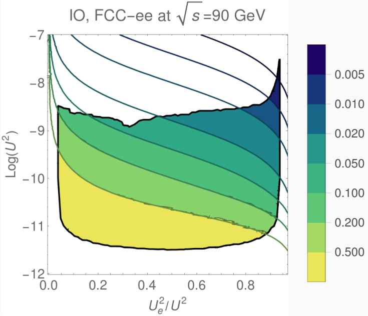
$M_N = 30$ GeV @ FCC-ee



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

1710.03744]

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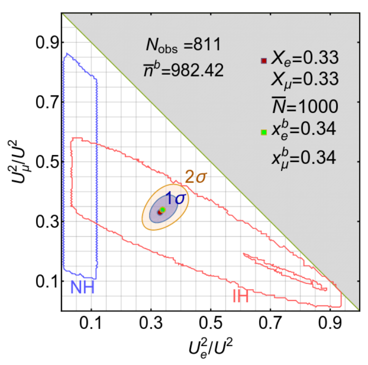
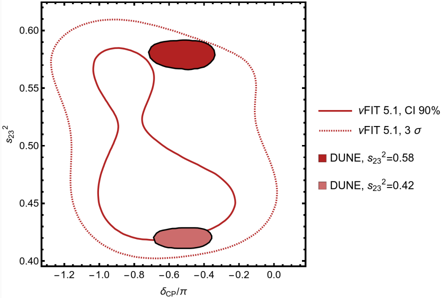
$M_N = 1$ GeV @ SHiP



[Snowmass HNL WP 2203.08039]

Future sensitivity to PMNS parameters?

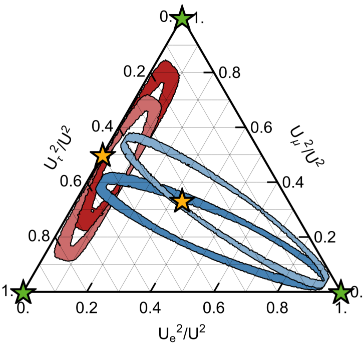
- significant improvement expected with DUNE and HyperK
- we can use the sensitivity estimates to estimate how the allowed flavor ratios change



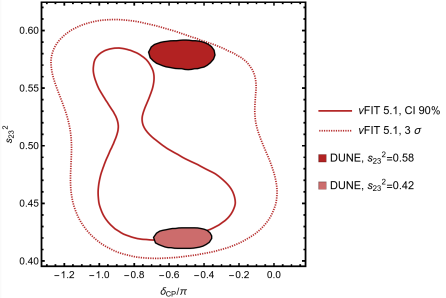
[nuFIT 5.1 2007.14792]

[DUNE TDR 2002.03005]

Future sensitivity to PMNS parameters?



[Drewes/JK/Lopez-Pavon 2207.02742]



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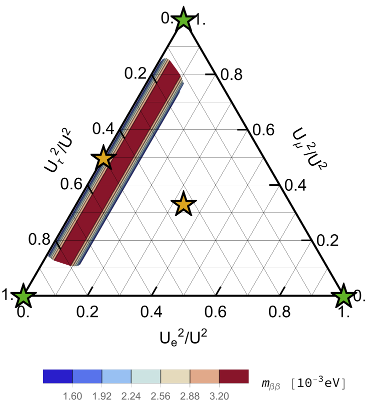
Complementarity with neutrinoless double beta decay



- $m_{\beta\beta}$ is a complementary probe of the flavor mixing ratios for $M_N \gg 100 MeV$
- excluding $m_{\beta\beta}$ limits allowed flavour ratios

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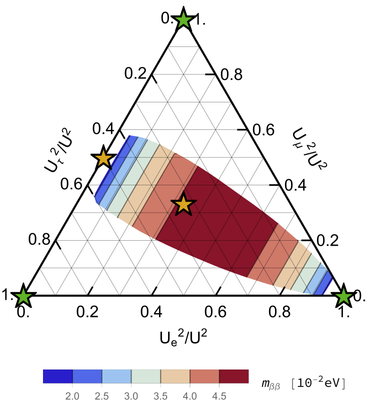

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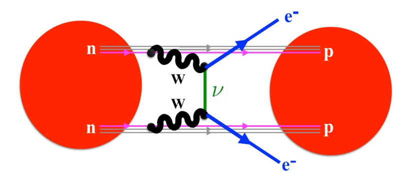
HNL contribution to neutrinoless double β decay



[figure from 1910.04688]

- RHN can contribute to $m_{\beta\beta}$
- large mass splitting is required to have an observable effect (not always compatible with leptogenesis)
- some leptogenesis scenarios can already be excluded by current results

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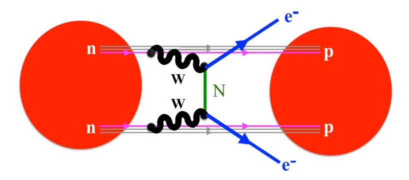

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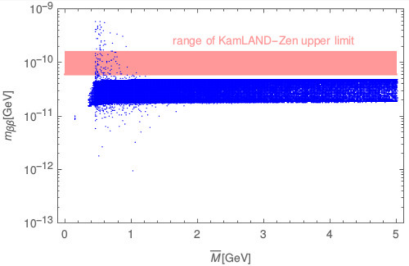

[Eijima/Drewes 1606.06221,

Hernández/Kekic/López-Pavón/Salvado 1606.06719]

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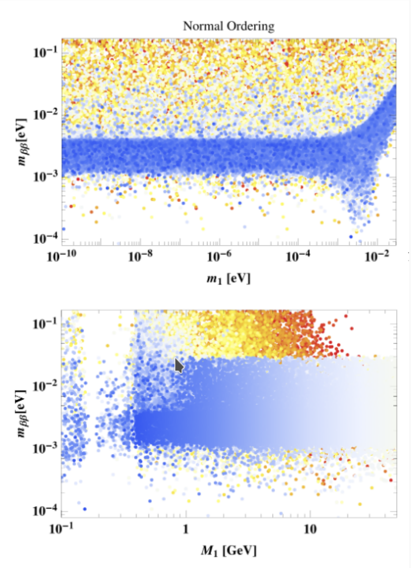

[Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

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Measuring the mass splitting in model with 2 HNLs

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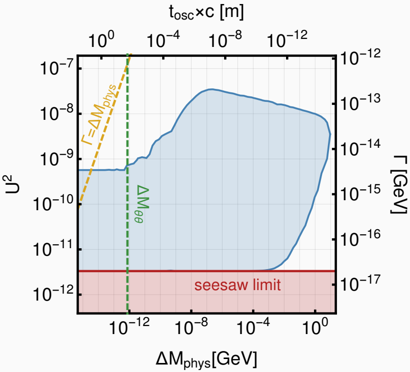

$M = 30$ GeV

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

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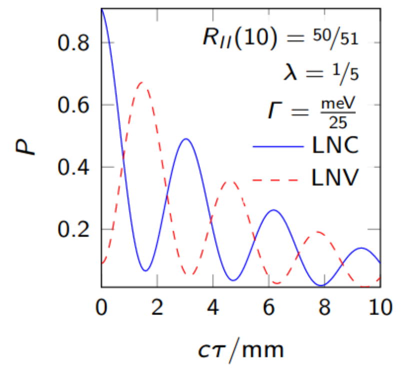

[Antusch/Hajer/Rosskopp 2210.10738]

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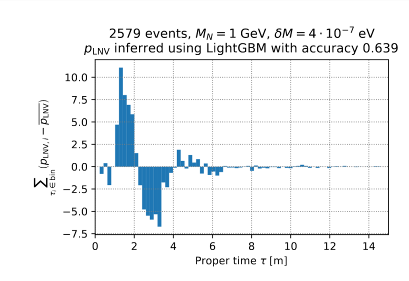

[Tastet/Timiryasov 1912.05520]

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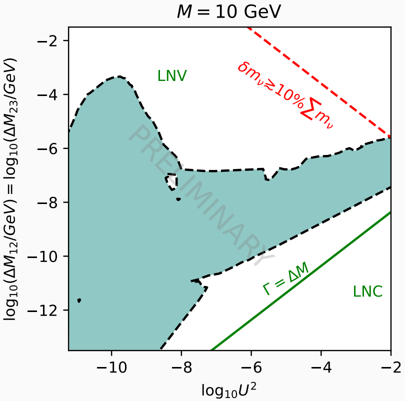
Mass splittings with 3 HNLs



- benchmark with fixed $U^2_{\alpha I}/U^2$
- upper bound on U^2 arises through a combination of baryogenesis + fine tuning constraints
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[Drewes/Georis/JK 230x.xxxx]

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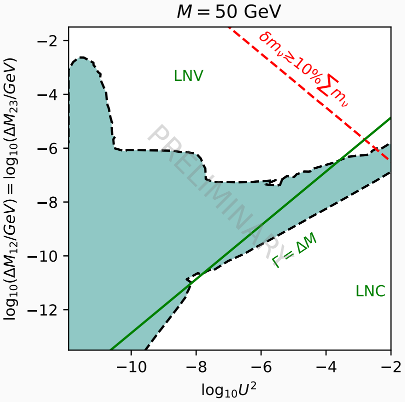

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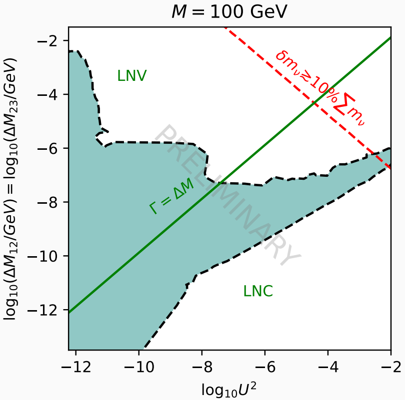

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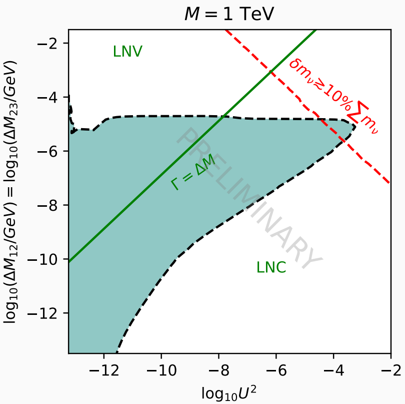

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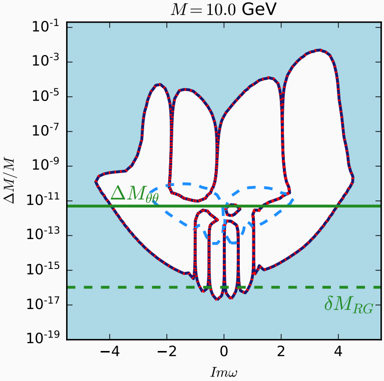
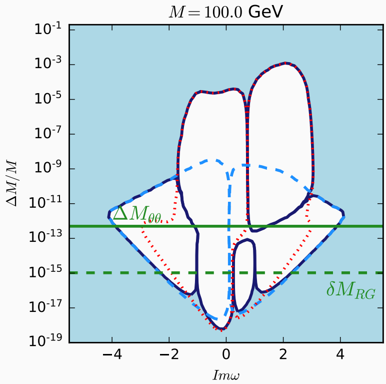
Slices of the parameter space



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

Slices of the parameter space



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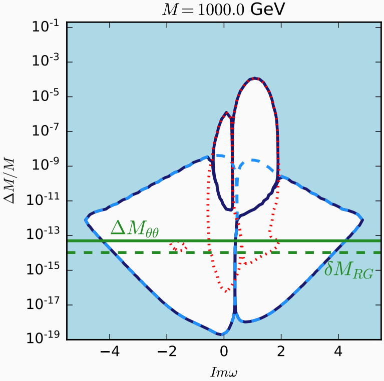

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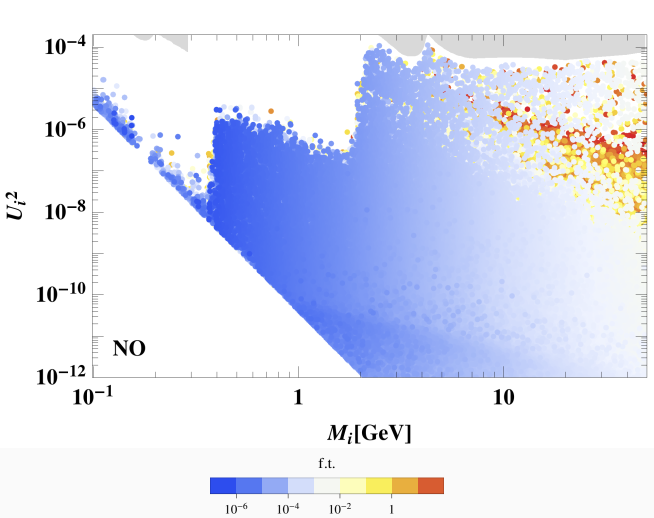
Results: Leptogenesis with 3 RHN (Normal Ordering)



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

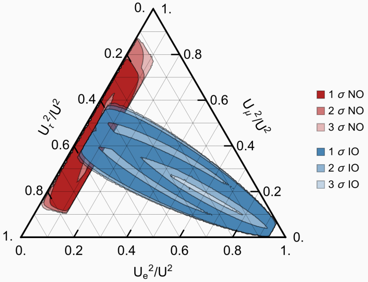
Hierarchy in the washout

- 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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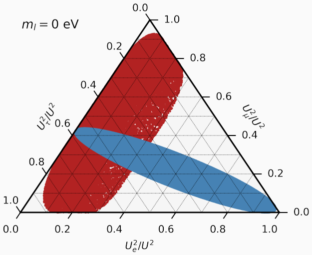

[Drewes/Georis/JK 220x.xxxx]

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

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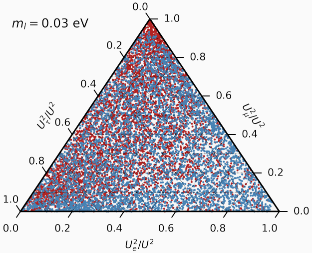


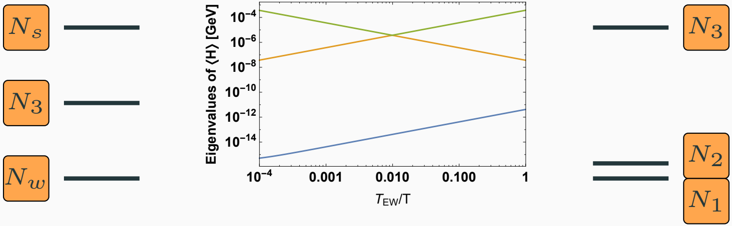
[Drewes/Georis/JK 220x.xxxx]

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

Enhancement due to level crossing

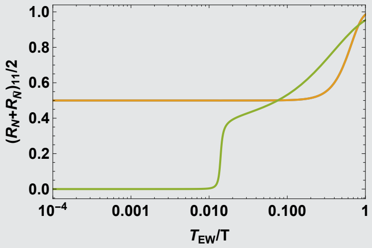
- in the $B - L$ symmetric limit two heavy neutrinos form a pseudo-Dirac pair
- the "3rd" heavy neutrino can be heavier than the pseudo-Dirac pair
- for $T \gg T_{EW}$, the pseudo-Dirac pair also has a thermal mass

$T \gg T_{EW}$ $T \ll T_{EW}$

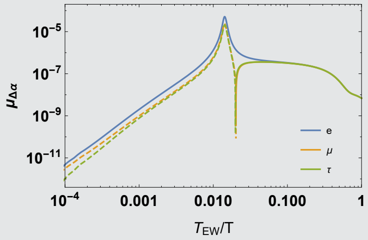


Enhancement due to level crossing

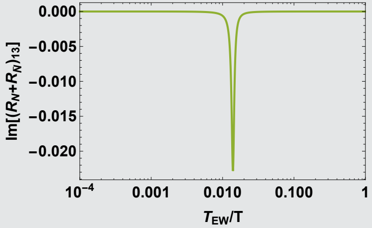
Heavy Neutrino Densities



Lepton flavour asymmetries



Heavy Neutrino correlations



Lepton number asymmetry