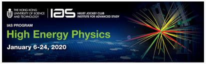


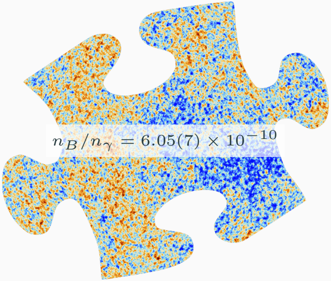
The Parameter Space of Low-scale Leptogenesis

Juraj Klarić

HKUST IAS, Hong Kong, January 20, 2020

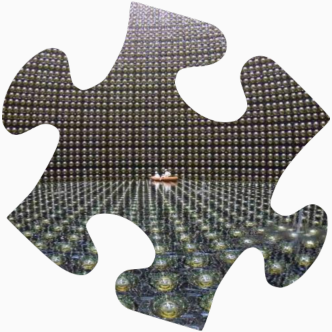
Some of the shortcomings of the standard model:

BAU baryon asymmetry of the universe



[Planck collaboration]

Neutrino masses



[Super-Kamiokande]

Some of the shortcomings of the standard model:

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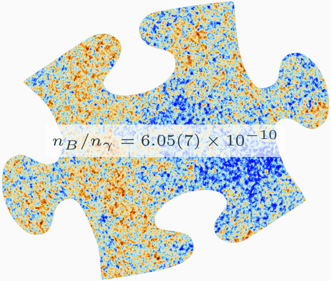

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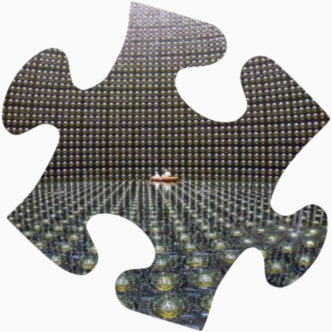
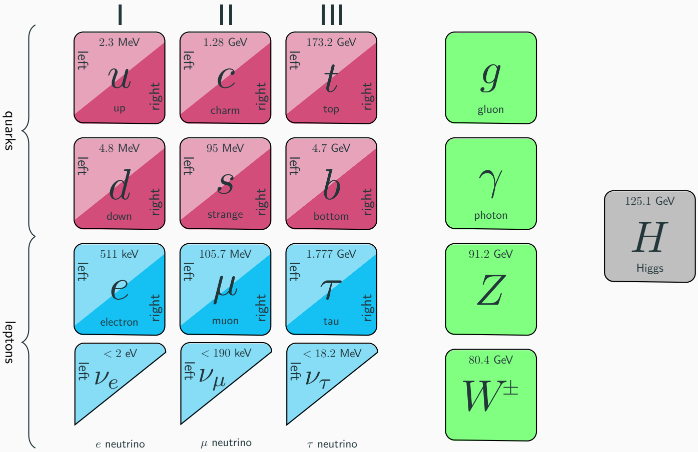


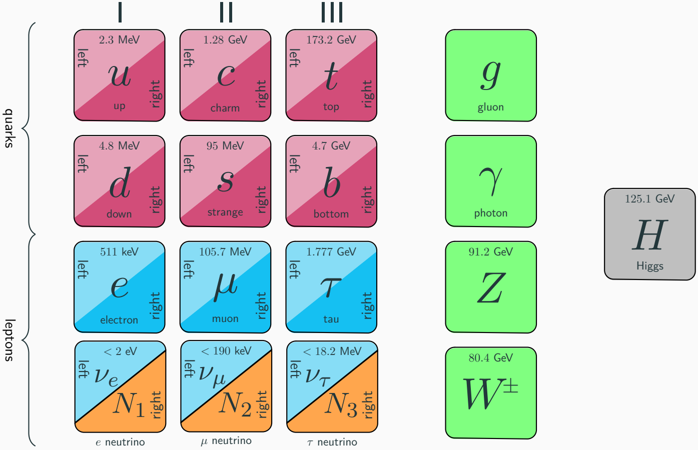
[Super-Kamiokande]

Is there a way to explain both?

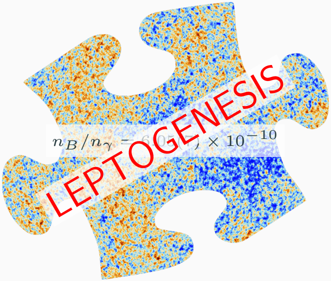
Standard Model



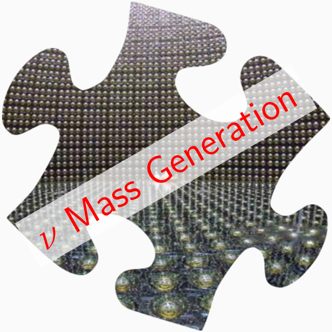
Standard Model



BAU baryon asymmetry of the universe



Neutrino masses



The "Seesaw" Relation

- Dirac Mass $m_D = vF$
- Right handed neutrino (RHN) Majorana mass M_M

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

Active neutrino masses

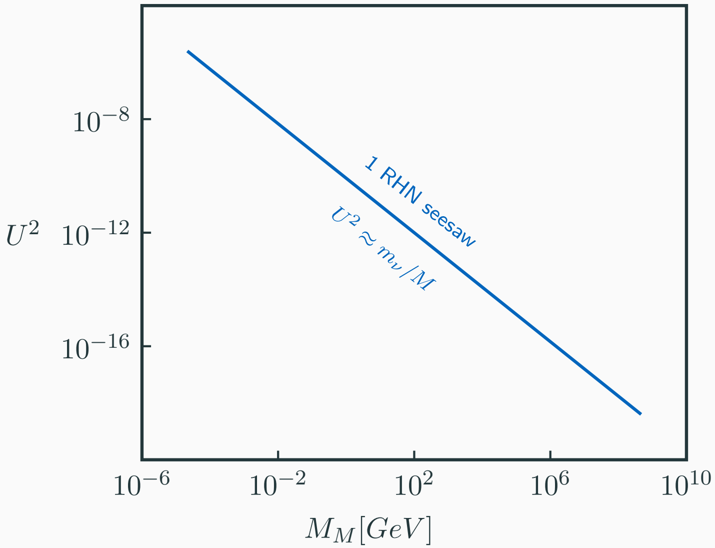
$$m_\nu = -m_D M_M^{-1} m_D^T$$

[Minkowski 1977, Yanagida 1980, $\cdots$]

Mixing with RHN

$$U_{ai}^2 \equiv \left| \left(m_D M_M^{-1} \right)_{ai} \right|^2$$
$$U^2 = \sum_{a\,,i} U_{ai}^2$$

Where could the RHN be hiding?



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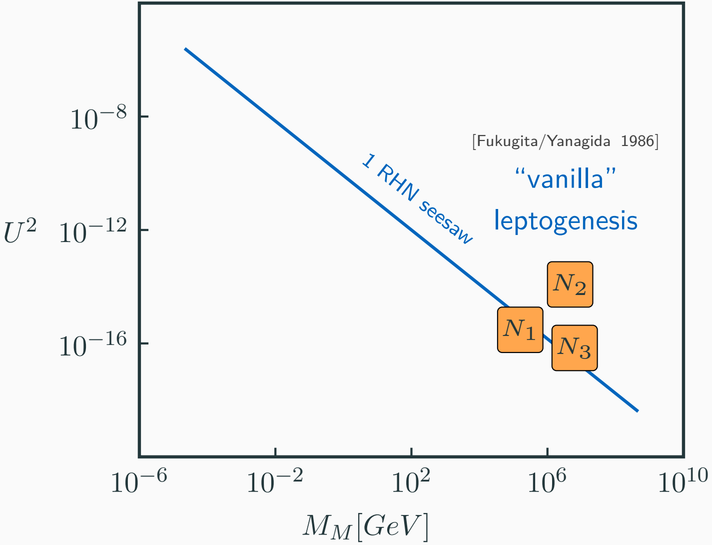

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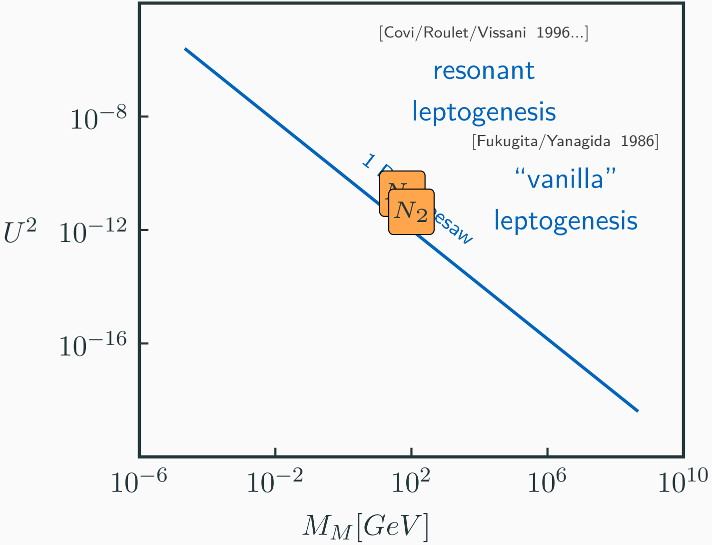

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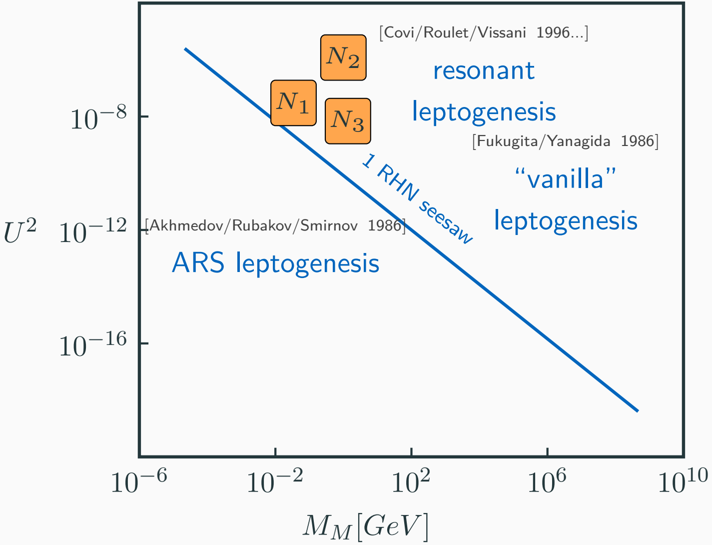

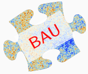

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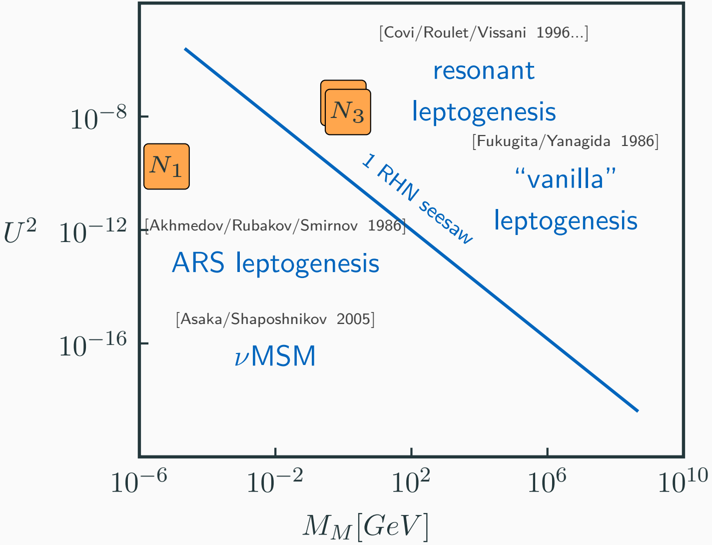

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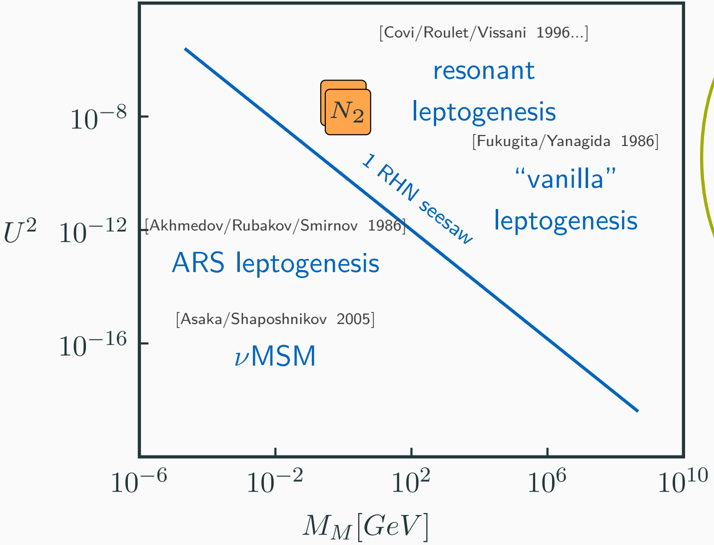

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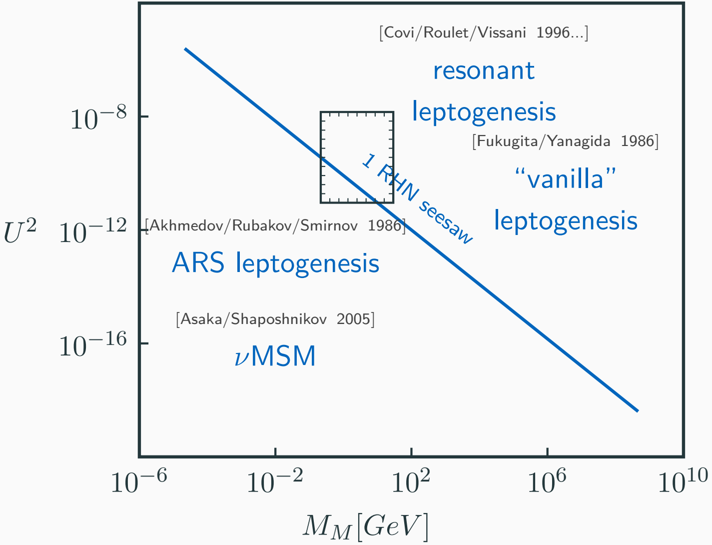
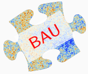
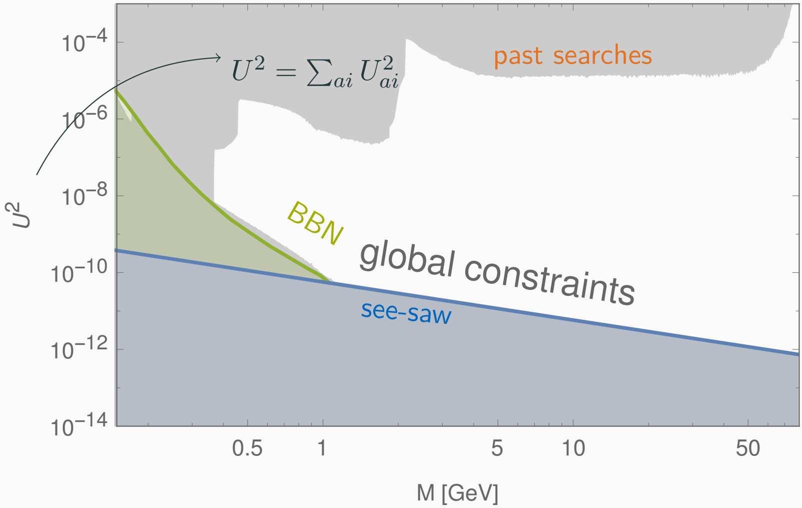




Constraints on RHN properties: 2 RHN, Normal Ordering



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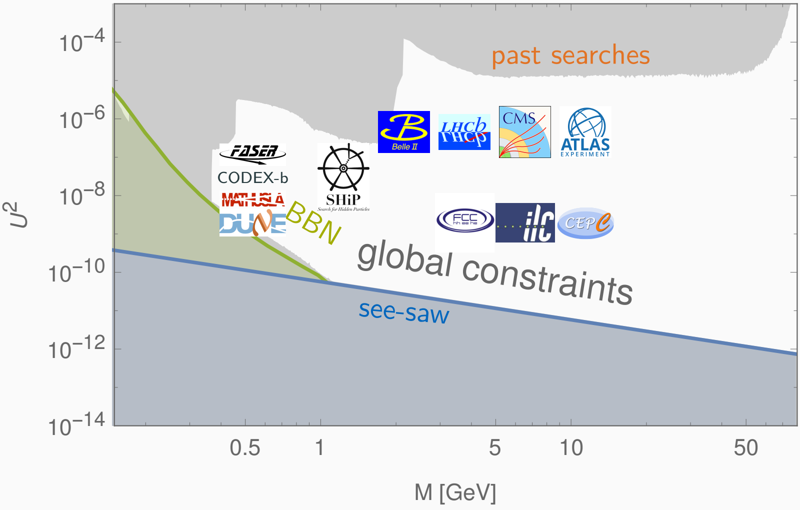
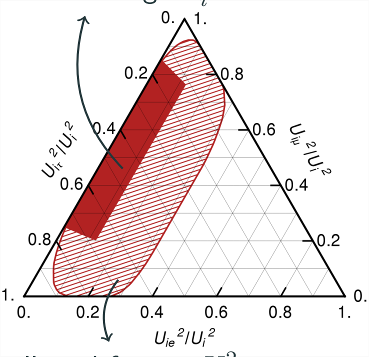


Testing the ν mass generation: Normal Ordering

Low energy parameters fixed to best fit, $\delta_{CP} \in [0, 2\pi]$ and Majorana phase $\alpha \in [0, 4\pi]$

allowed for large U_i^2

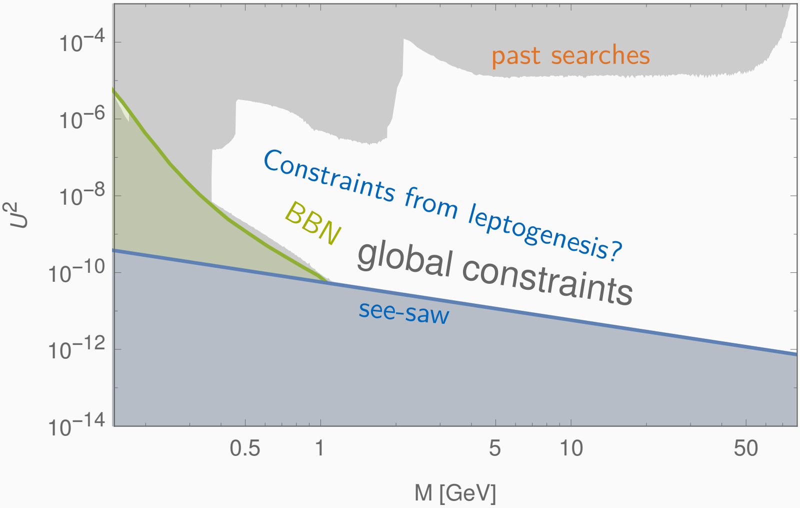


allowed for any U_i^2

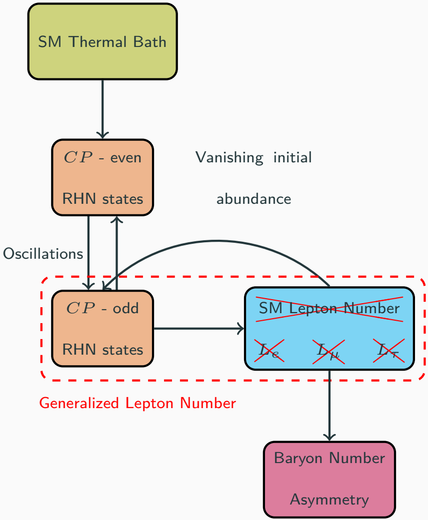
- the mixing angles U_{ai}^2 are related to the measured light neutrino parameters
- this constrains ratios U_{ai}^2/U_i^2
- constraints approach a limit for large U_i^2
- if we can measure individual U_{ai}^2 we have a consistency check for the seesaw mechanism

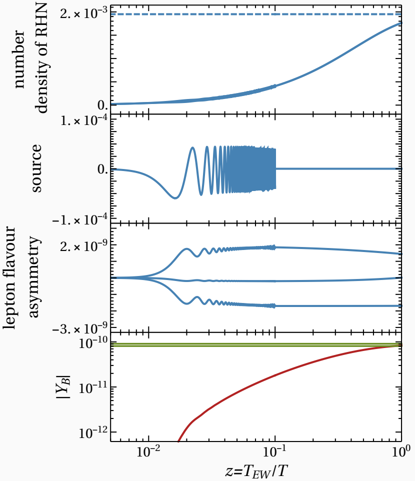
[Drewes/Hajer/JK/Lanfranchi 1801.04207]

Constraints on RHN properties: 2 RHN, Normal Ordering



Leptogenesis via Neutrino Oscillations





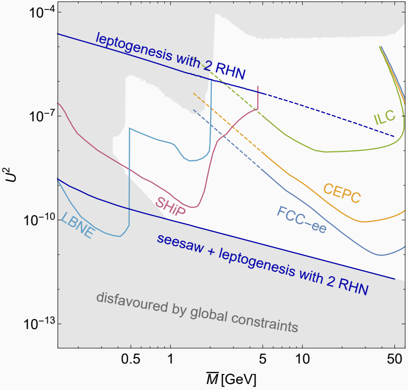
[Drewes/Garbrecht/Gueter/JK 1609.09069]

Theoretical challenges and progress:

- derivation of the **density matrix** equations from **first principles**
- **rate calculations** for RHN production at finite T
- **spectator effects**
- freezeout of the baryon number
- **analyitical approximations** for different regimes
- violation of generalized lepton number
- momentum dependence
- systematic studies of the parameter space/ phenomenological implications

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

Leptogenesis with 2 RHN

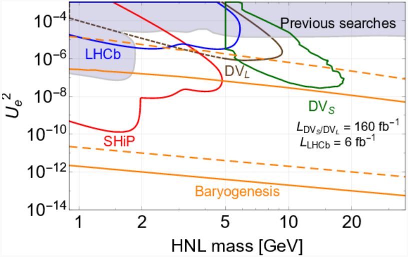


Inverted Ordering

[Drewes/Garbrecht/Gueter/JK 1609.09069]

- large mixing angle $U^2 \to$ large couplings $\to$ BAU can be erased before EWPT
- flavour asymmetric washout can help "hide" the BAU in one of the flavours
- **seesaw** allows for U_μ^2/U^2 up to a factor $\mathcal{O}(10^{-3})$ for IO

Leptogenesis with 2 RHN



[Eijima/Shaposhnikov/Timiryasov 1808.10833]
[Boiarska/Bondarenko/Boyarsky/Eijima/

Ovchynnikov/Ruchayskiy/Timiryasov 1902.04535]

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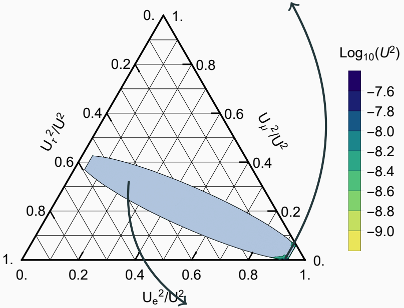
consistent with BAU



consistent with ν masses (IO)

$$\bar{M} = 30\,\mathrm{GeV}$$
$$U^2 = 4 \times 10^{-9}$$

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

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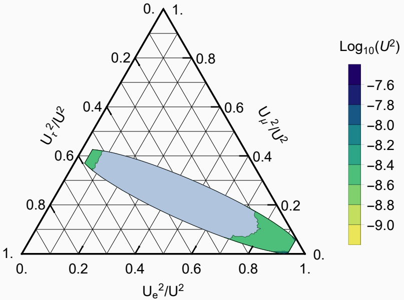

$$\bar{M} = 30\,\mathrm{GeV}$$
$$U^2 = 2.5 \times 10^{-9}$$

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

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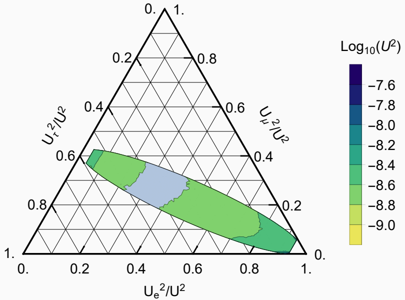
Leptogenesis with 2 RHN



$$\bar{M} = 30\,\mathrm{GeV}$$
$$U^2 = 1.6 \times 10^{-9}$$

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

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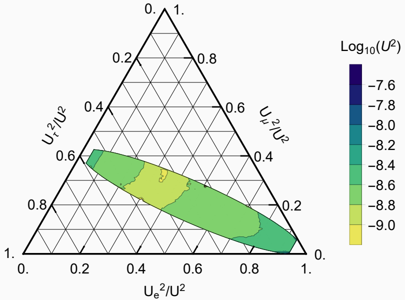
Leptogenesis with 2 RHN



$$\bar{M} = 30\,\mathrm{GeV}$$
$$U^2 < 1 \times 10^{-9}$$

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

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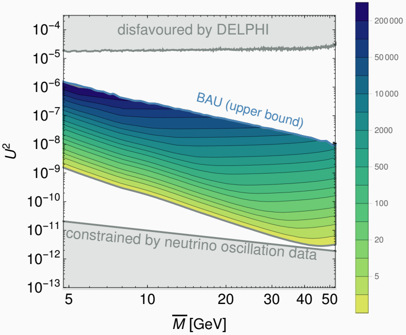
Measuring Flavour Ratios



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

- large mixing angles - up to $O(10^5)$ RHN can be produced at the FCC
- use this to measure the flavour ratios
- large M - fraction of semileptonic events with flavour a in the final state proportional to U_a^2/U^2

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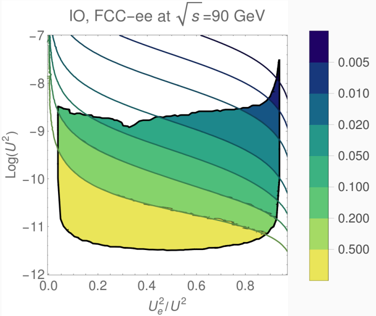

$\bar{M} = 30$ GeV

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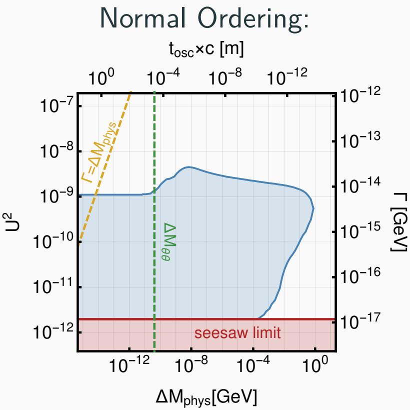
Measuring the mass splitting



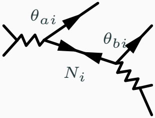
$M = 30$ GeV

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

- large range of viable ΔM consistent with leptogenesis
- energy resolution of planned experiments - $\Delta M/M \sim \mathcal{O}(\text{few}\%)$
- Higgs vev contribution to RHN mass difference $\Delta M_{\theta\theta}$ practically implies lower limit on the mass splitting
- more information possible from LNV observables?

LNV and the RHN mass splitting

$$\Gamma_{X\to\ell_a\ell_b} \sim \left| \sum_i \quad \cdots \quad \right|^2$$



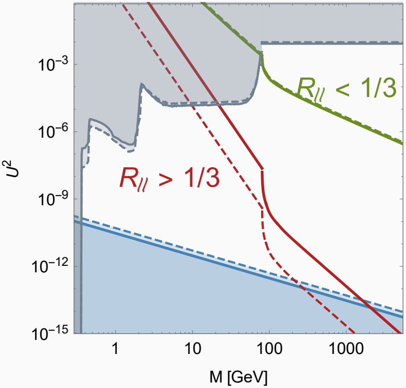
Same-to-opposite sign dilepton ratio

$$R_{\ell\ell} = \frac{\Delta M^2_{\rm phys}}{\Delta M^2_{\rm phys} + \Gamma^2_N}$$

[Anamiati/Hirsch/Nardi 1607.05641]

- ratio between RHN lifetime and mass splitting determines the number of LNV decays
- non-vanishing neutrino masses imply a lower limit on $\Delta M_{\rm phys}$
- radiative stability of ν masses implies an upper limit on $\Delta M_{\rm phys}$
- $R_{\ell\ell}$ can lead to information on the mass splitting

LNV and the RHN mass splitting



[Drewes/Klose/JK 1907.13034]

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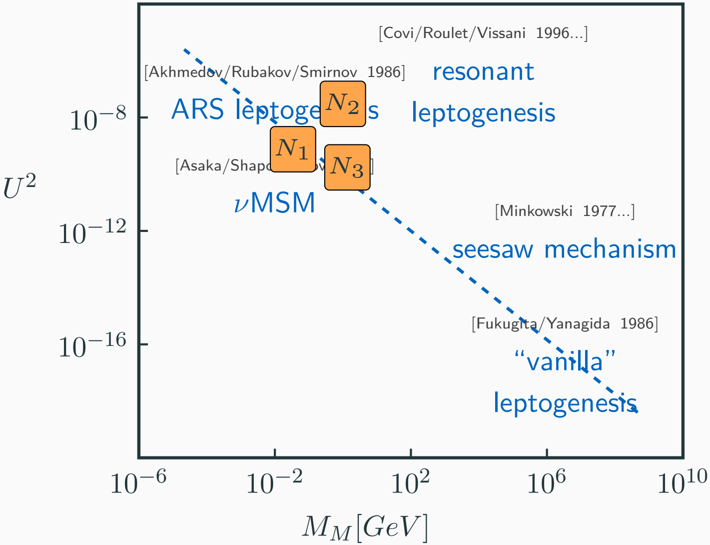
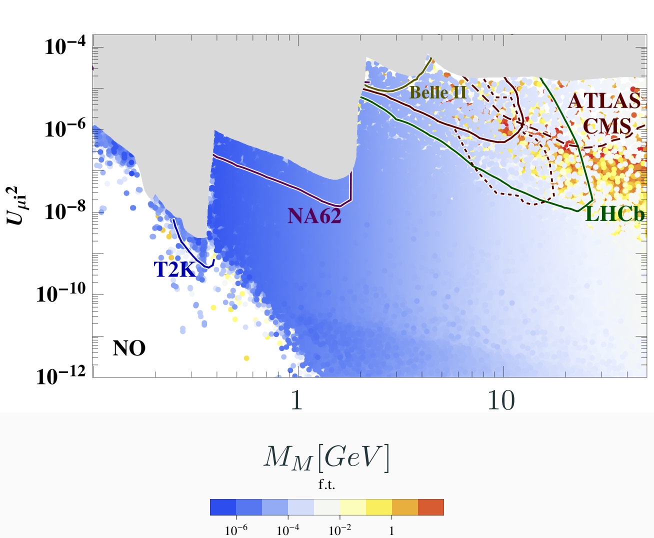
Leptogenesis with 3 RHN



Results: Leptogenesis with 3 RHN (Normal Ordering)



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

How is $3 \neq 2$?: Leptogenesis

- asymmetry can be generated even without washout

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

  more CP phases than in the case with two RHN

- large hierarchy in the washout is possible

  [Canetti/Drewes/Garbrecht 1404.7144]

- level crossing between the heavy neutrinos
  new effect!

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  Sakharov II: CP

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  [Canetti/Drewes/Garbrecht 1404.7144]

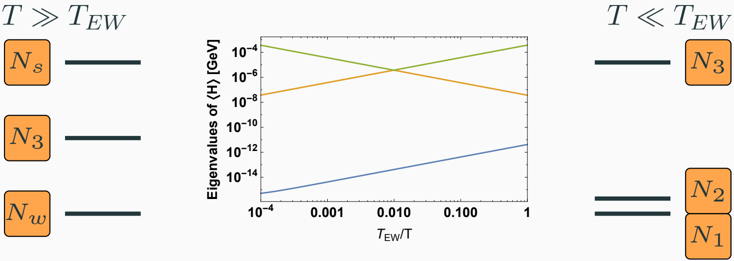
  Sakharov III: non-equilibrium

- level crossing between the heavy neutrinos
  new effect!

  Sakharov II: CP

Enhancement due to level crossing

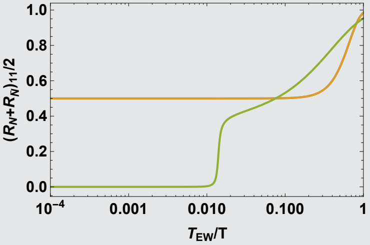
- in the $B - L$ symmetric limit two heavy neutrinos form a pseudo-Dirac pair
- the "3rd" heavy neutrino can be heavier than the pseudo-Dirac pair
- for $T \gg T_{EW}$, the pseudo-Dirac pair also has a thermal mass



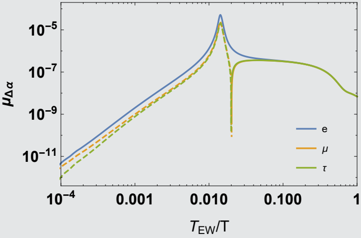
[Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

Enhancement due to level crossing

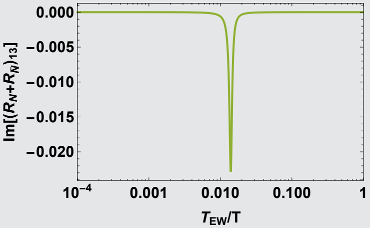
Heavy Neutrino Densities



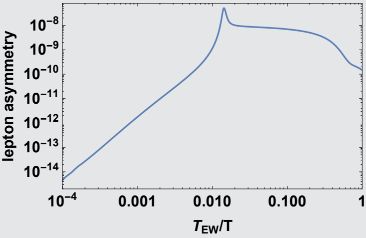
Lepton flavour asymmetries



Heavy Neutrino correlations



Lepton number asymmetry



Conclusions

- GeV-scale RHN are a viable solution to the questions of the BAU and neutrino masses
- the minimal model with 2 RHN imposes strong constraints on the properties of the RHN
- 3 RHN - larger parameter space, weaker predictions
- measurements of the branching ratios $N \to Xa$ are complementary with the low-energy neutrino oscillation experiments
- leptogenesis is within reach of existing experiments and future lepton colliders
- leptogenesis with large mixing angles implies strong constraints on the RHN branching ratios
- full testability is in principle possible, difficult in practice

Backup

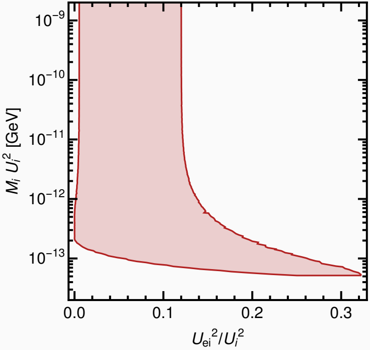
Fine tuning

- 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

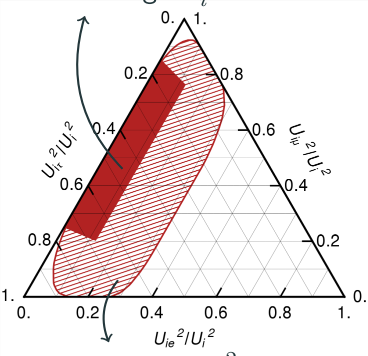
Fine Tuning

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

Testing the ν mass generation: Normal Ordering



allowed for large U_i^2



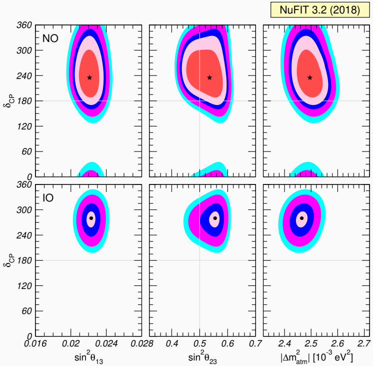
allowed for any U_i^2

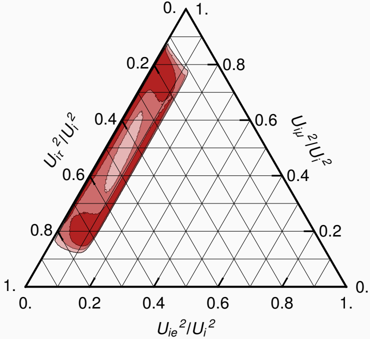
[Drewes/Hajer/JK/Lanfranchi 1801.04207]

[Drewes/Garbrecht/Gueter/JK 1609.09069] [Caputo/Hernandez/Lopez-Pavon/Salvado 1704.08721]

Testing the ν mass generation: Normal Ordering

Measurement of δ_{CP} improves the prediction:





[Esteban/Gonzalez-Garcia/Maltoni/Martinez-Soler/Schwetz 1611.01514]

[Drewes/Hajer/JK/Lanfranchi 1801.04207]