EPFL

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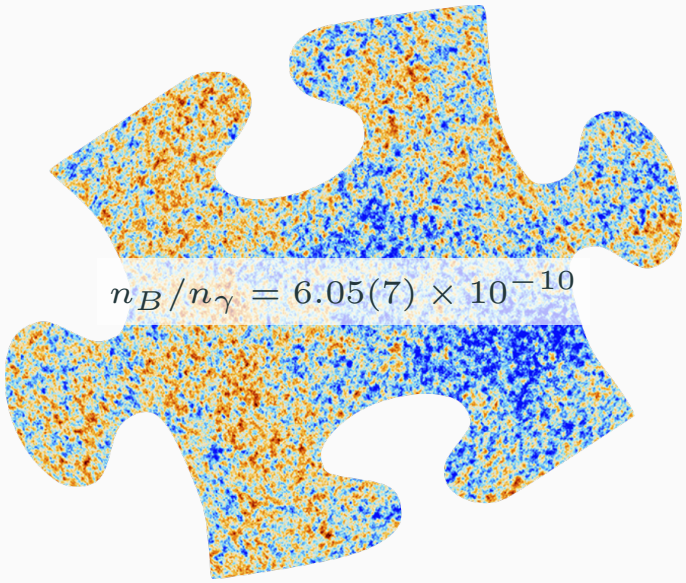
Low scale leptogenesis

Juraj Klarić

3 Neutrinos and beyond, XV. Rencontres du Vietnam, August 2019

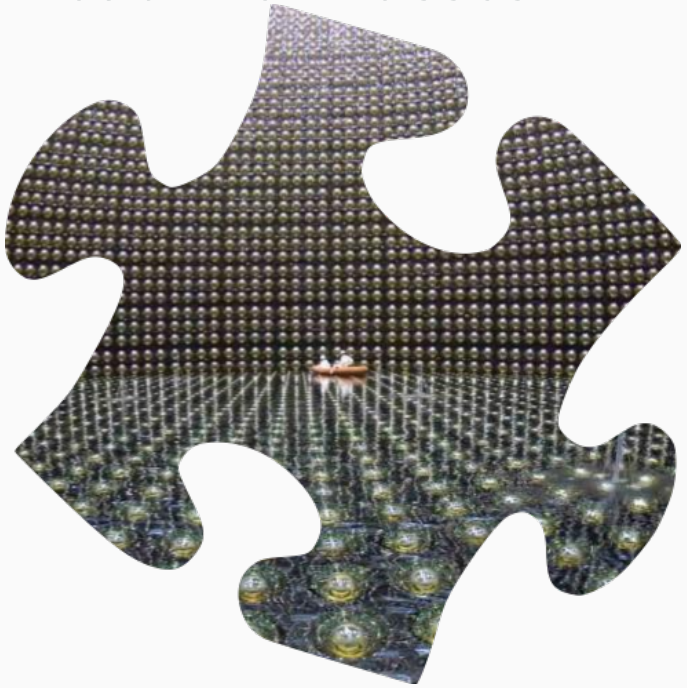
Some of the shortcomings of the standard model:

BAU baryon asymmetry of the universe



[Planck collaboration]

Neutrino masses



[Super-Kamiokande]

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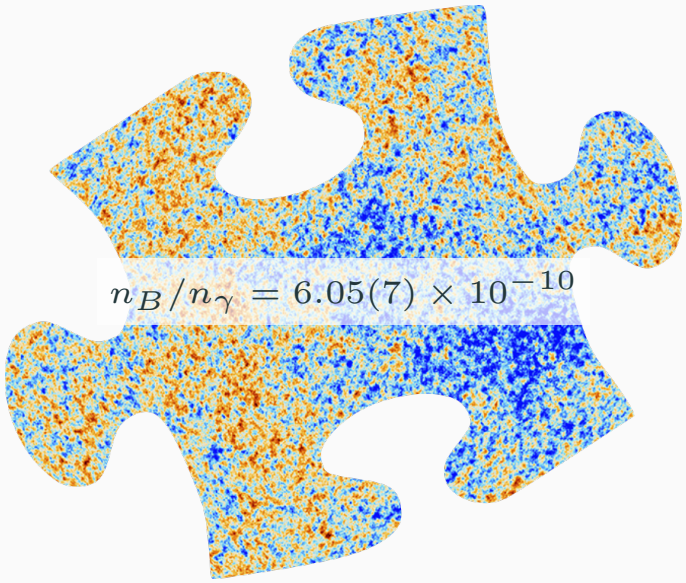

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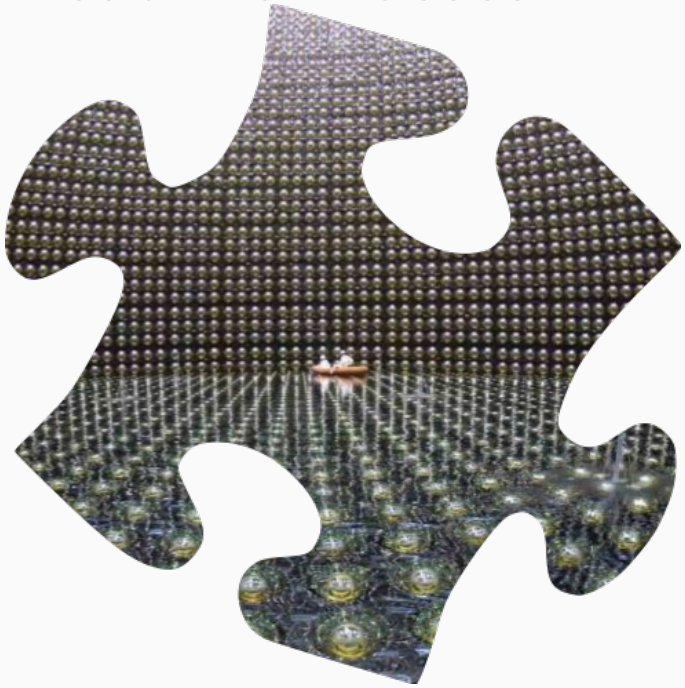
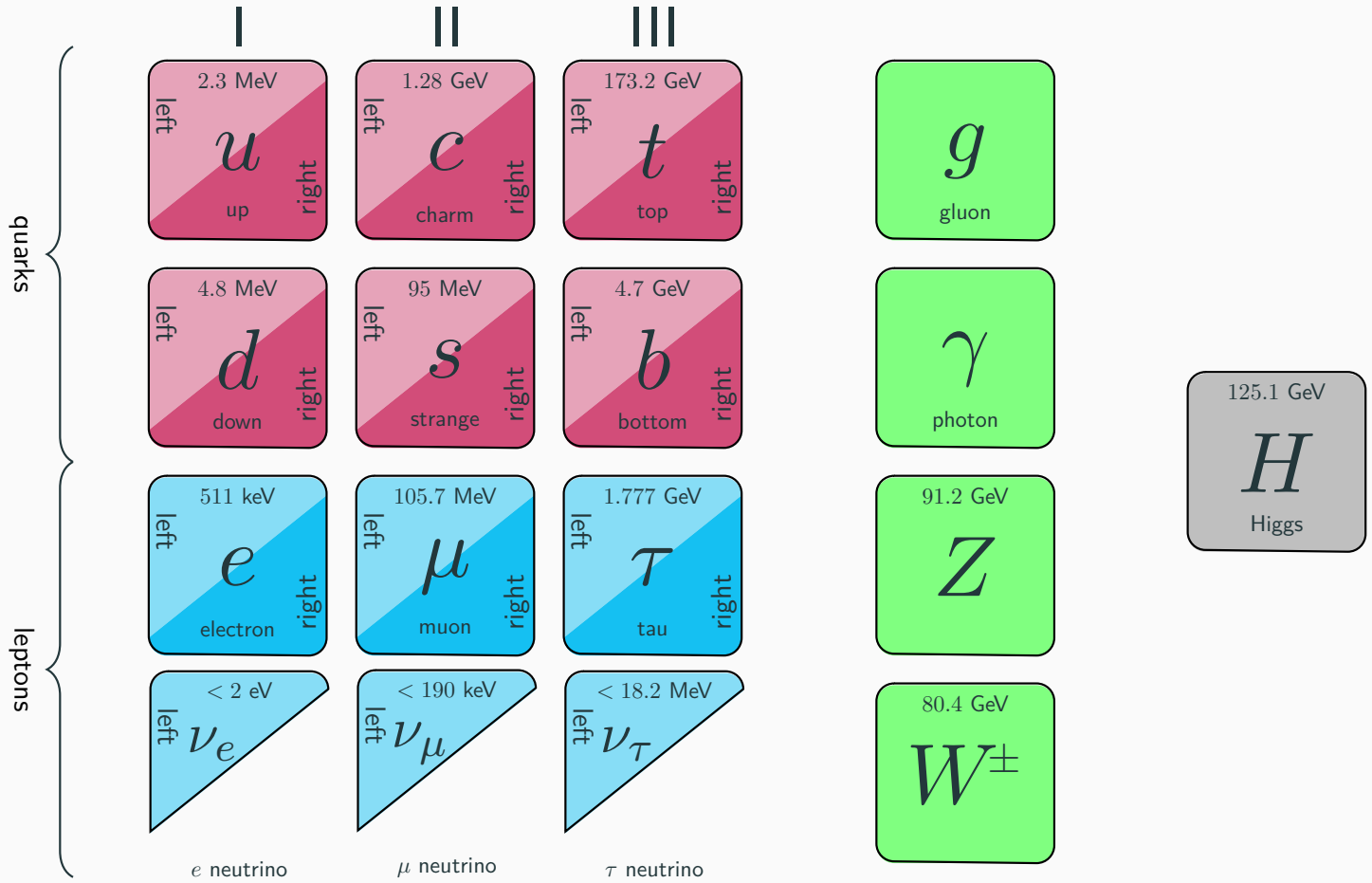


[Super-Kamiokande]

Is there a way to explain both?

Standard Model



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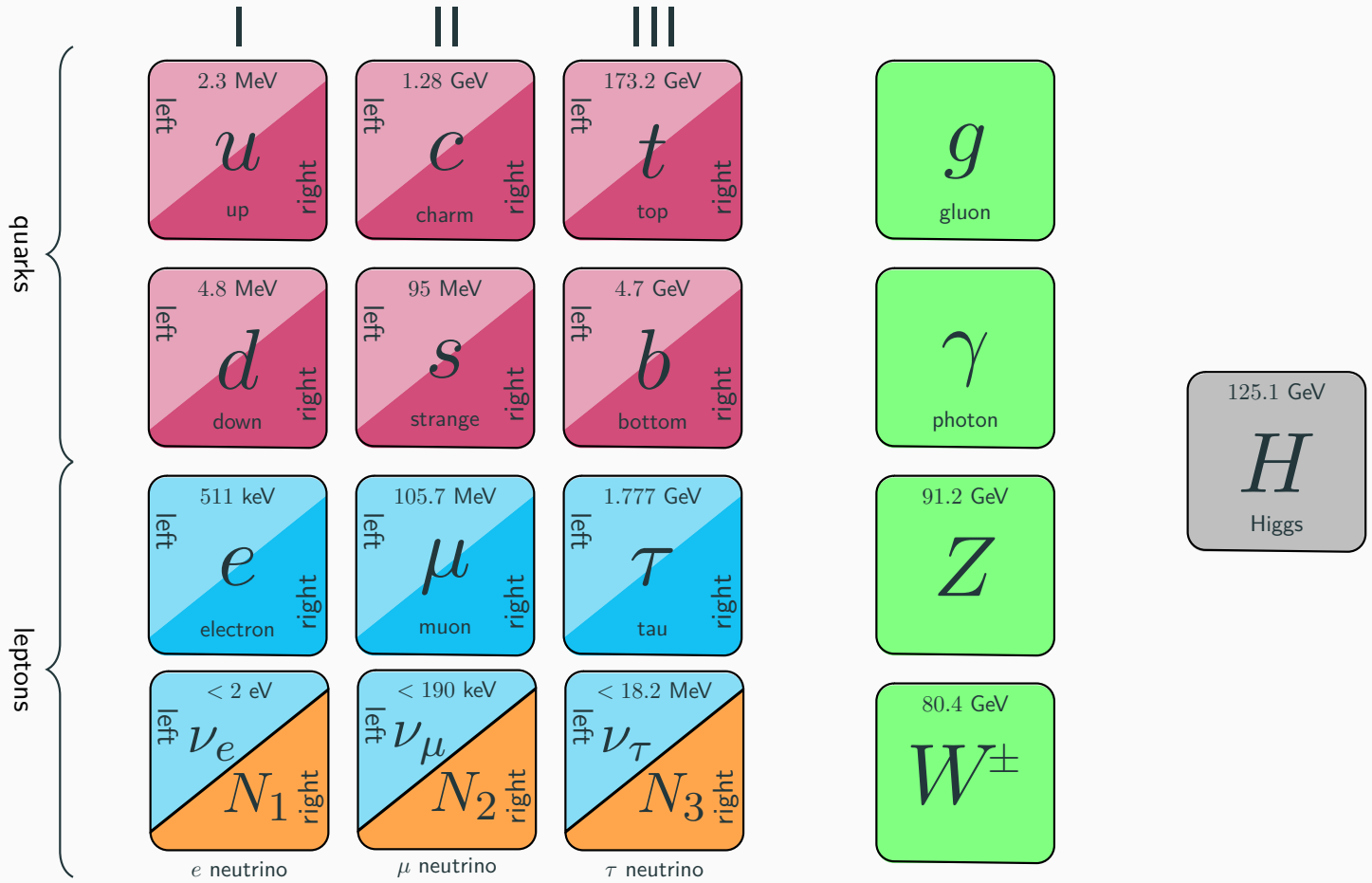

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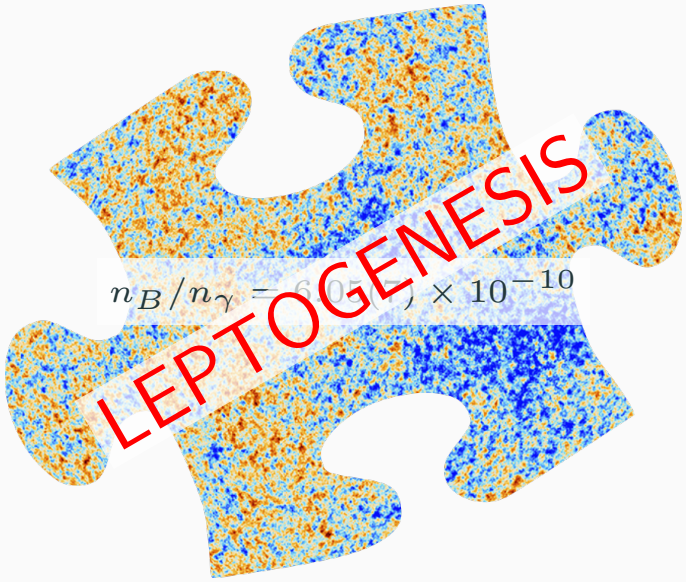

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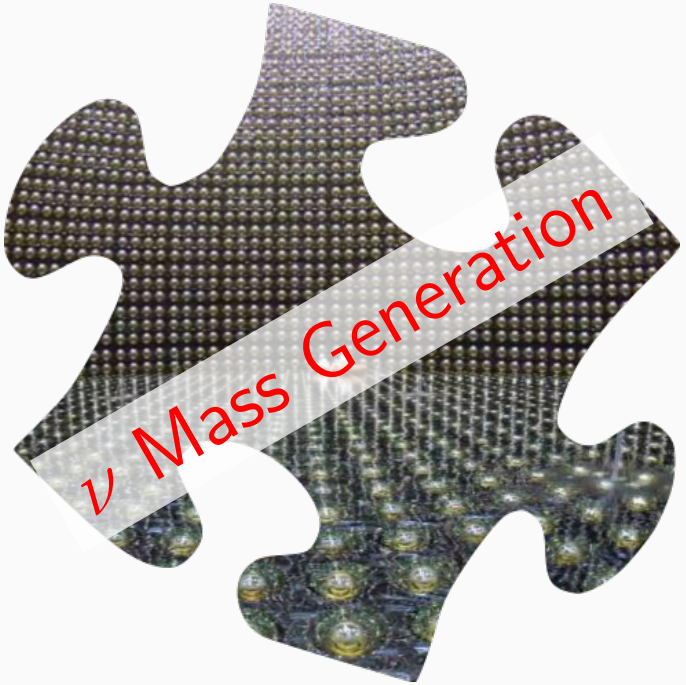


The "Seesaw" Relation

- Dirac Mass $m_D = vY^\dagger$
- Right handed neutrino (RHN) Majorana mass M_M

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

Active neutrino masses

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

see talk by Sin Kyu Kang

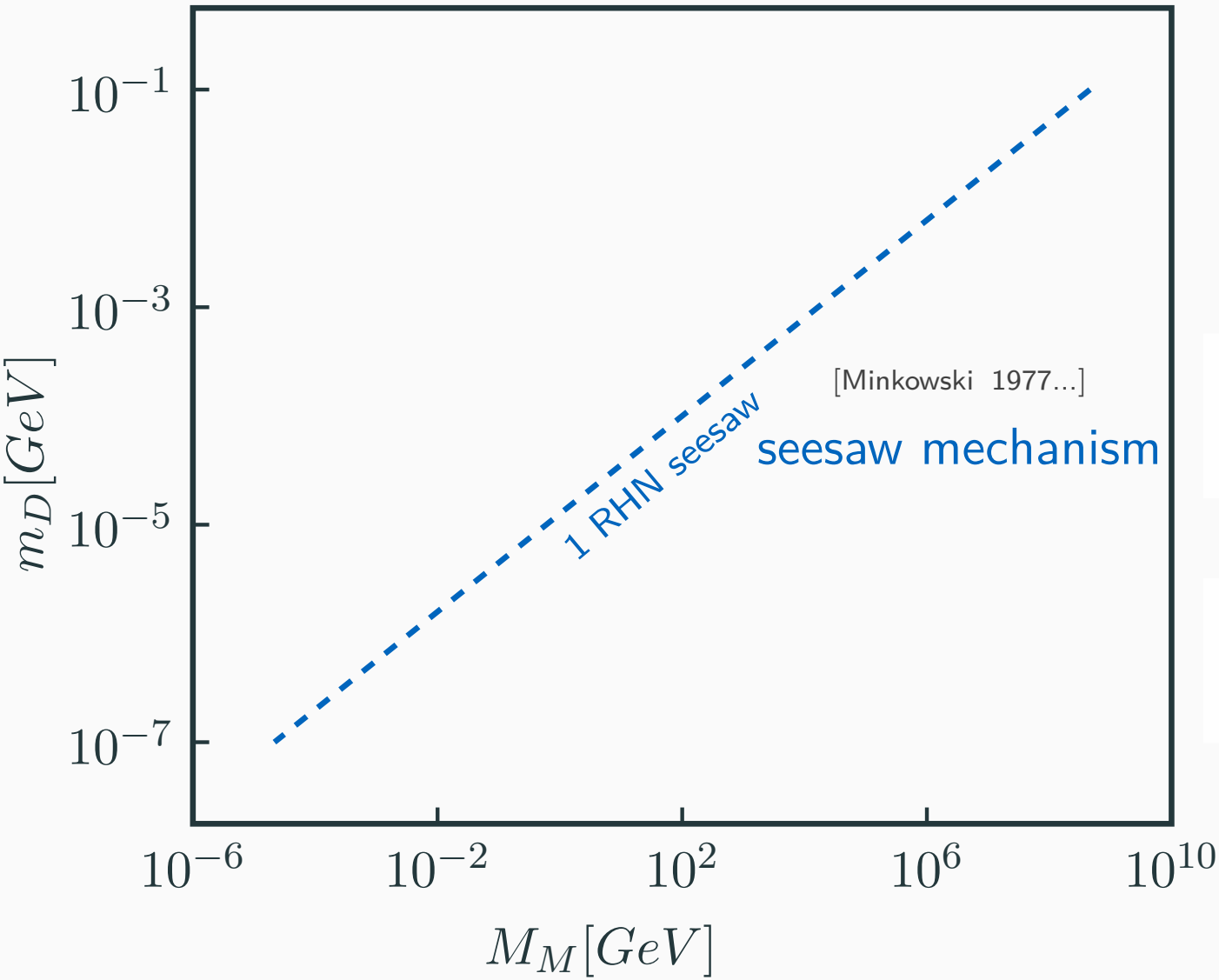
for other mechanisms see talk by R. Ruiz

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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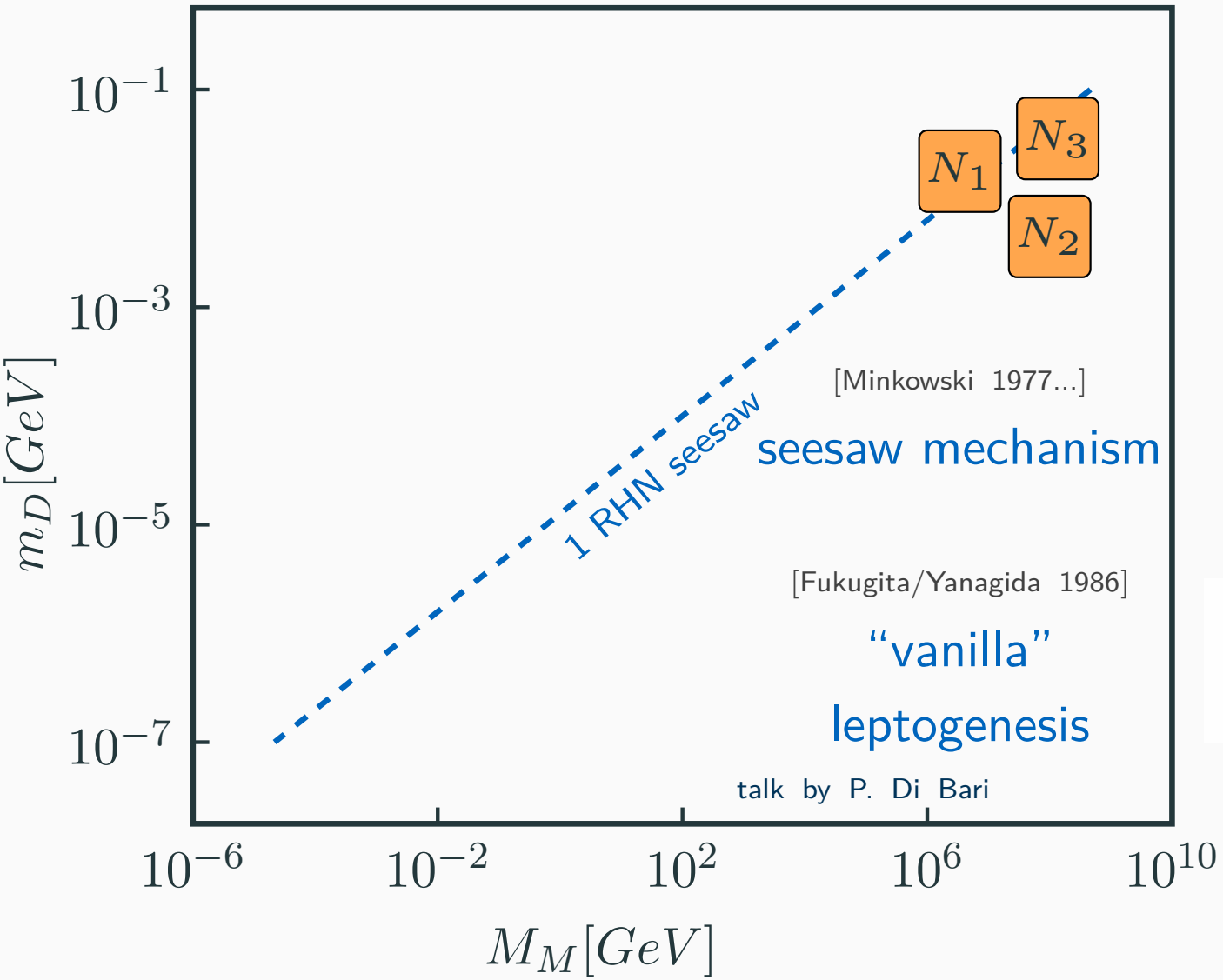

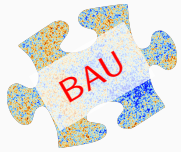

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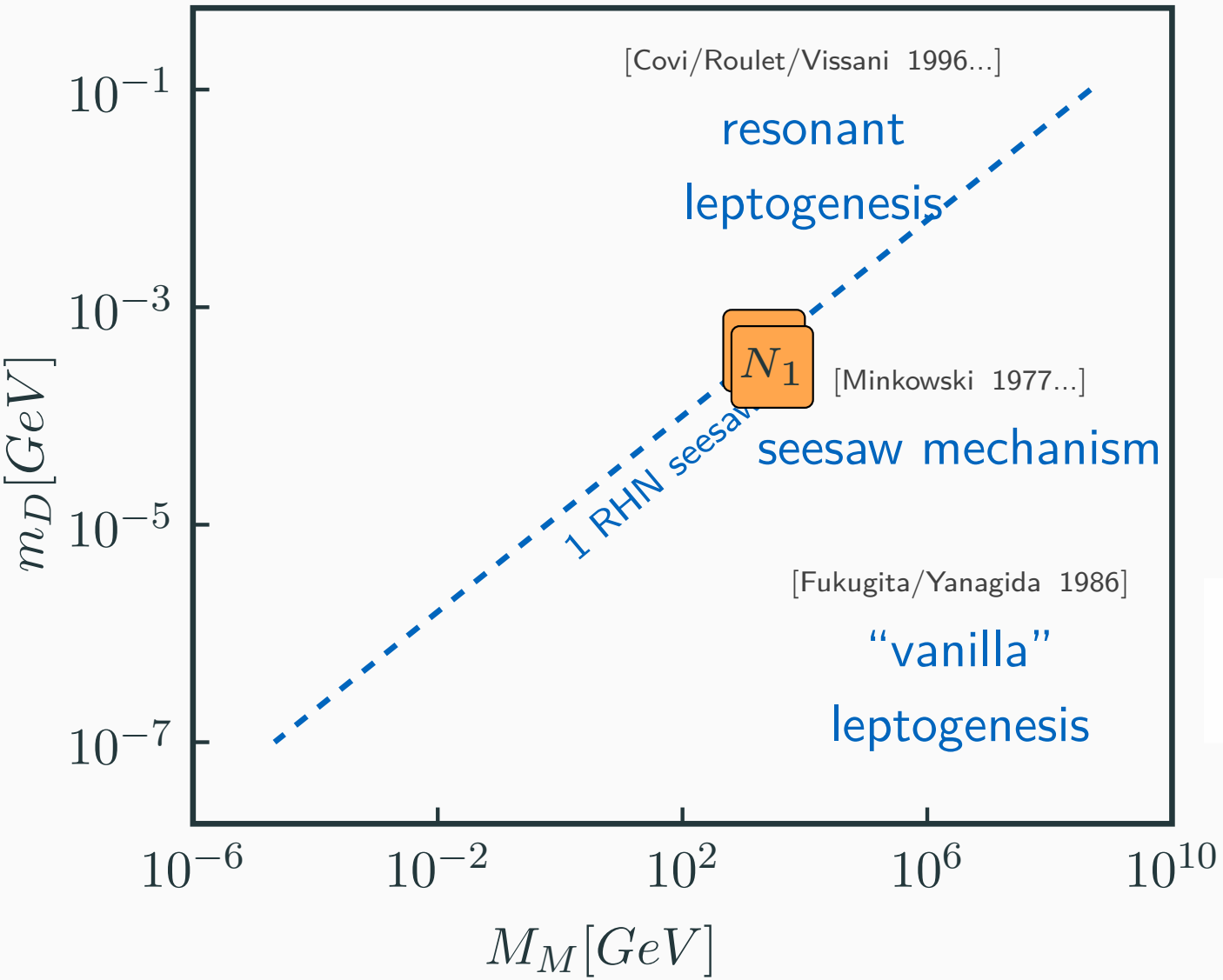

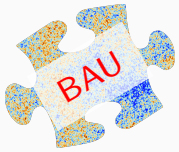

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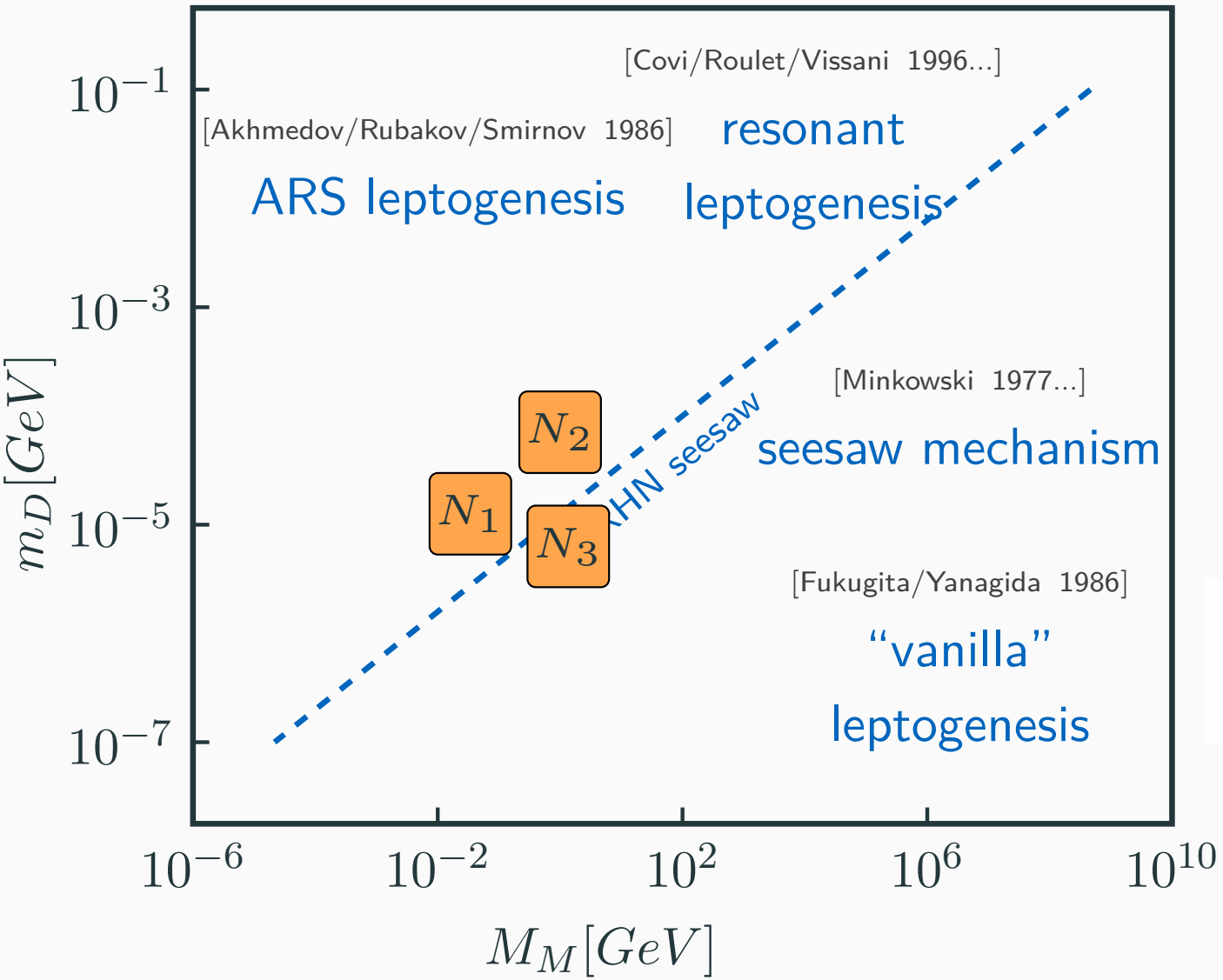

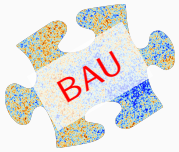

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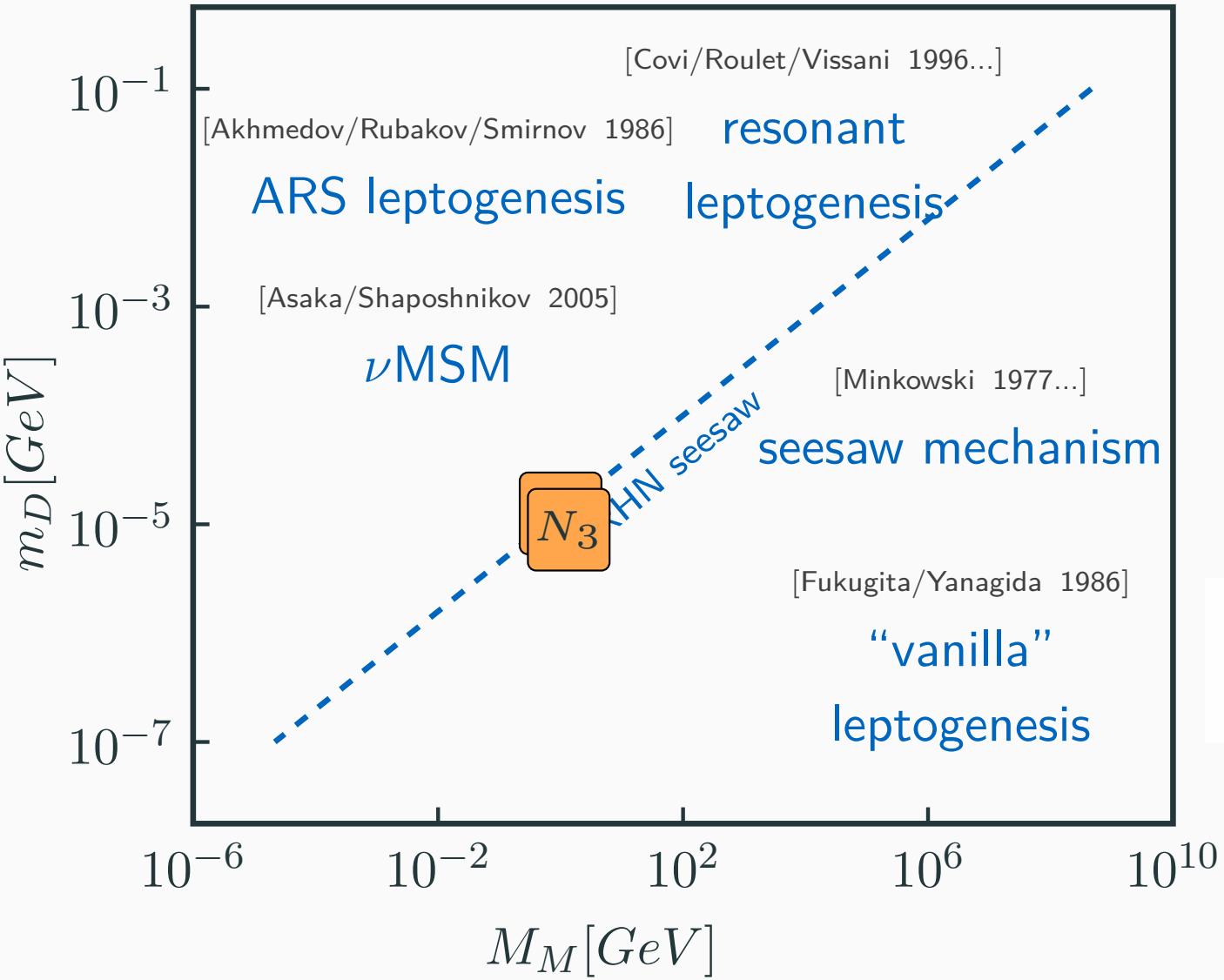

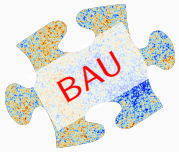

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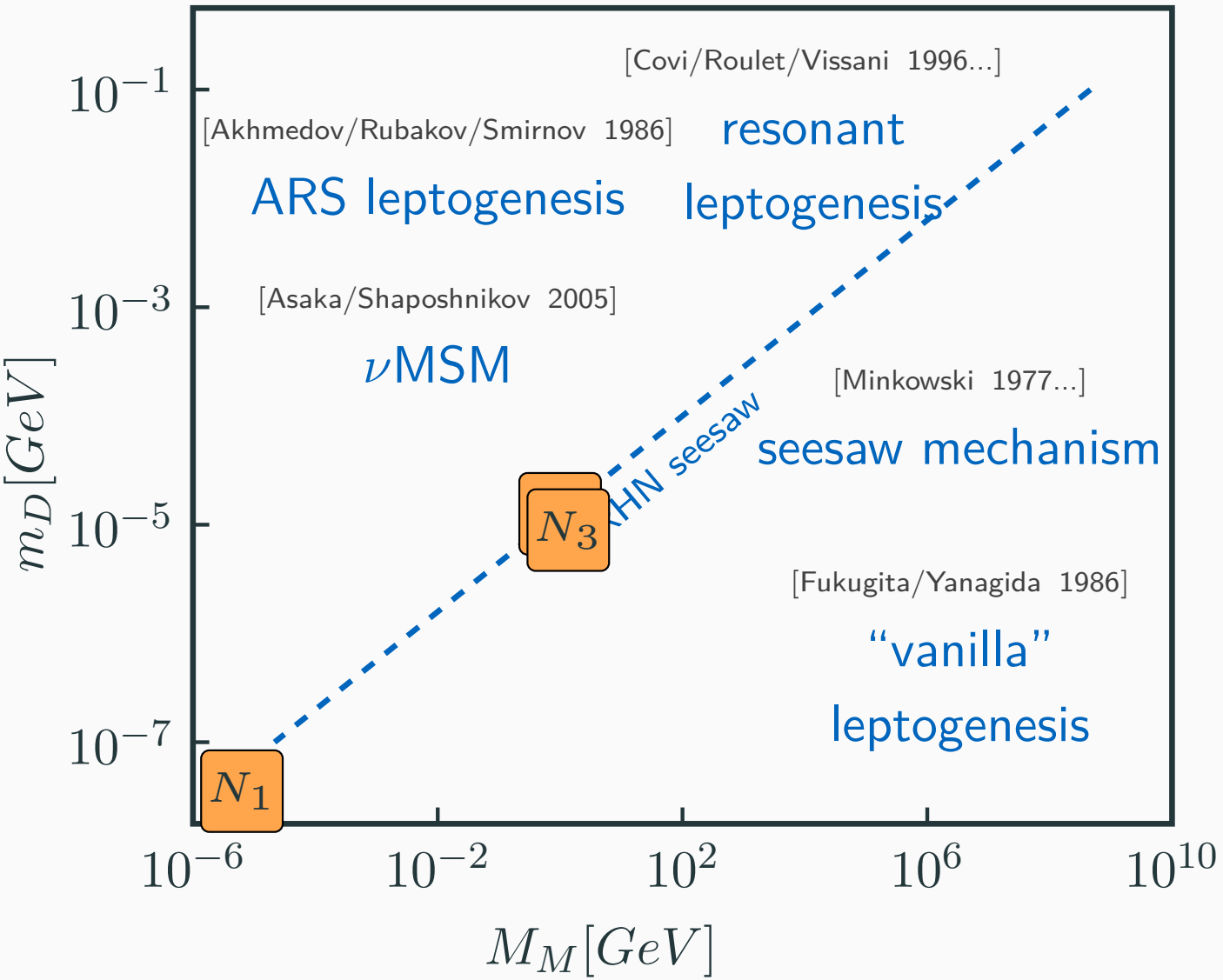

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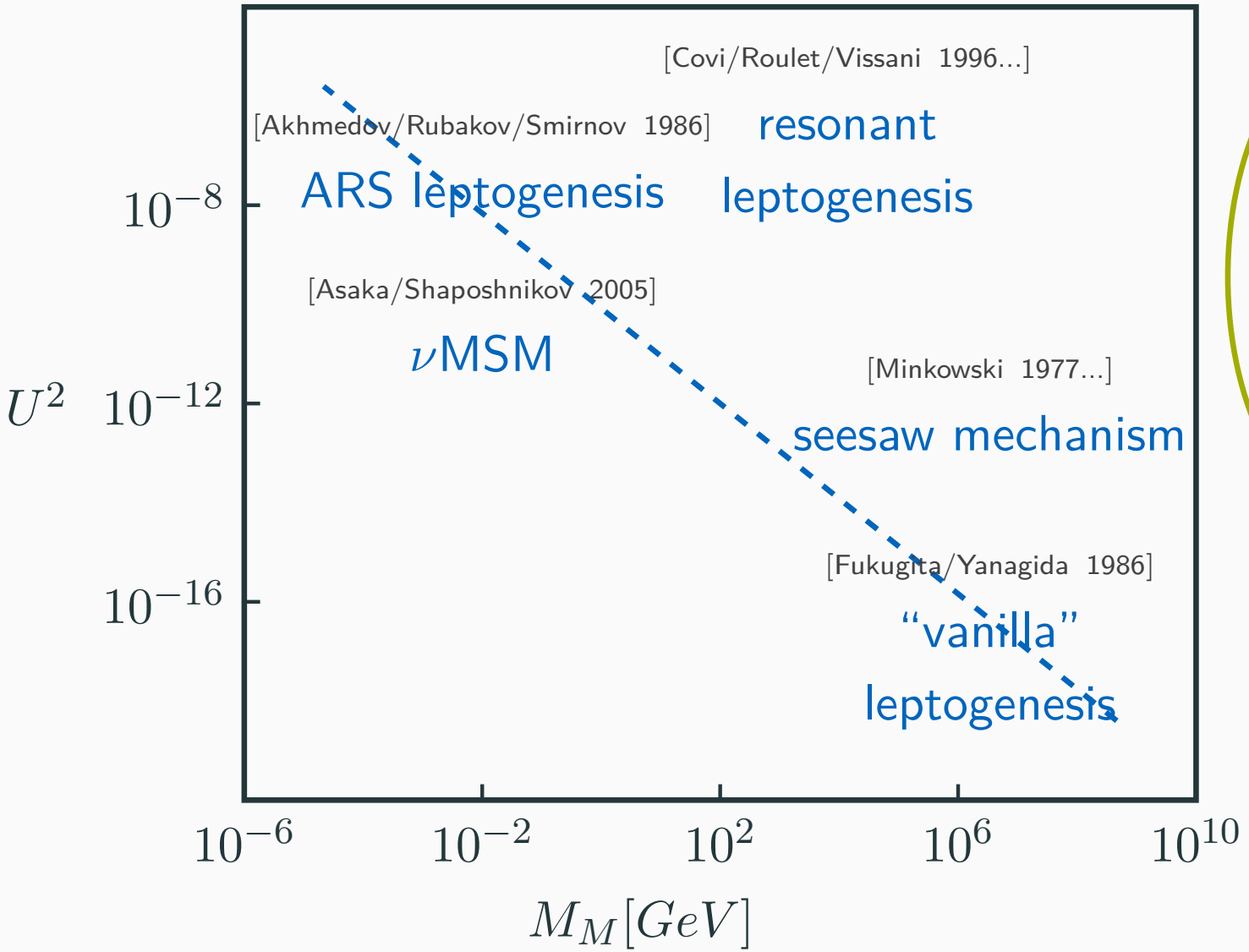
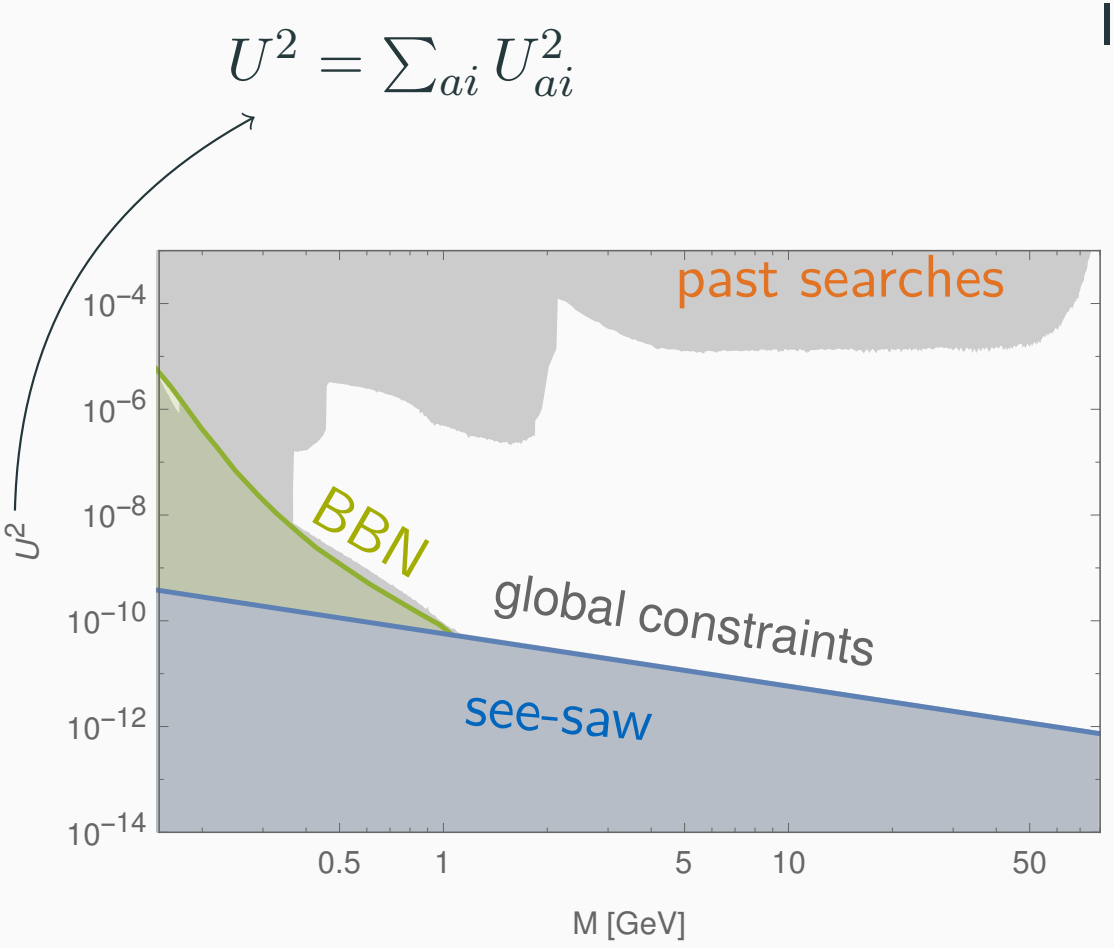


Constraints on RHN properties: 2 RHN, Normal Ordering



Indirect constraints:

- neutrinoless double β decay
- lepton universality
- CKM universality
- electroweak precision data
- LFV in rare lepton decays:
  - $\mu \to e\gamma$
  - $\tau \to e\gamma$
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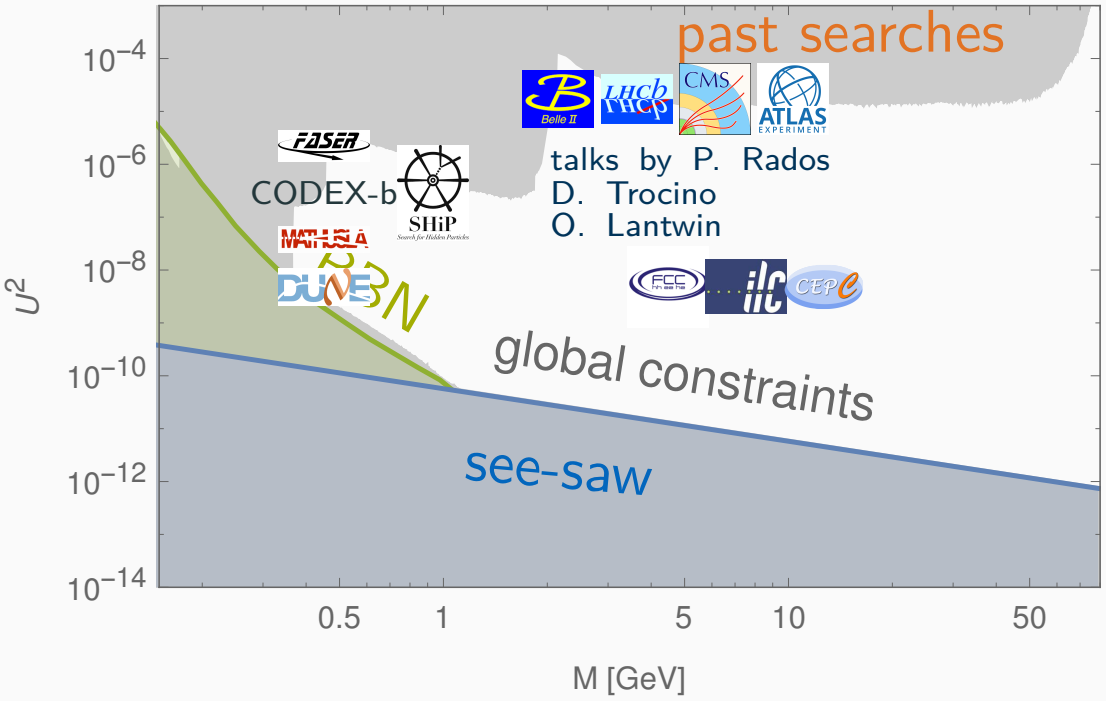

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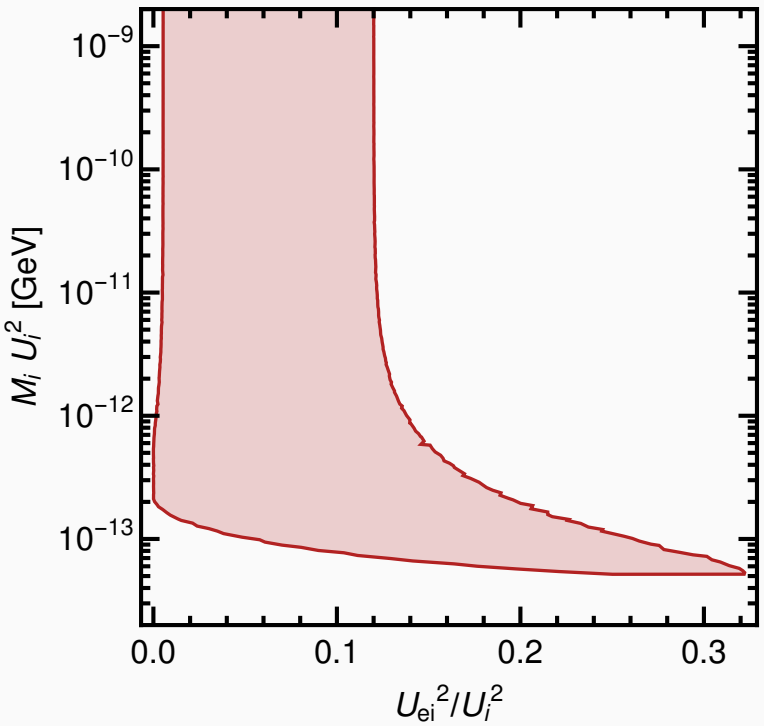
Testing the ν mass generation: Normal Ordering

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



- 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]

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

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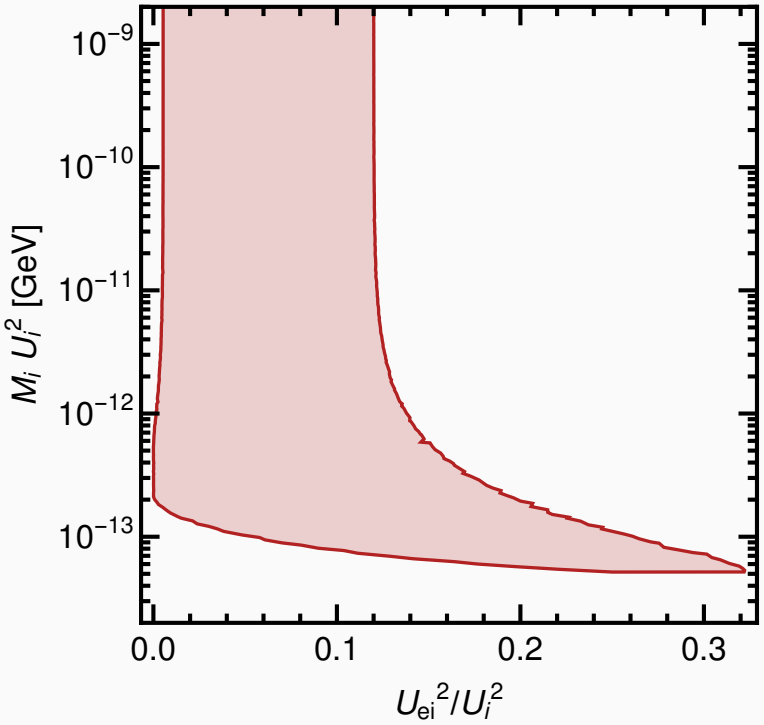
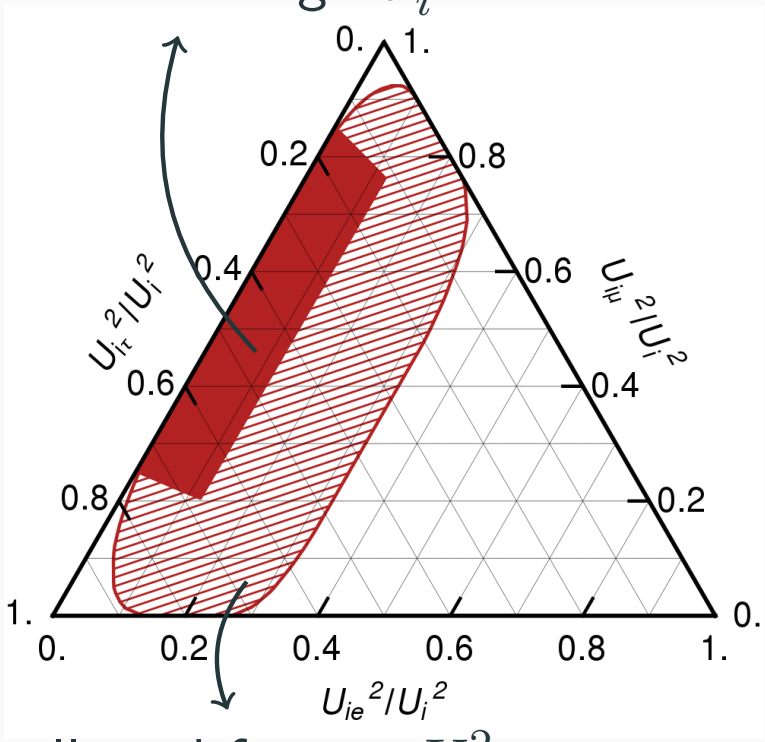


allowed for large U_i^2



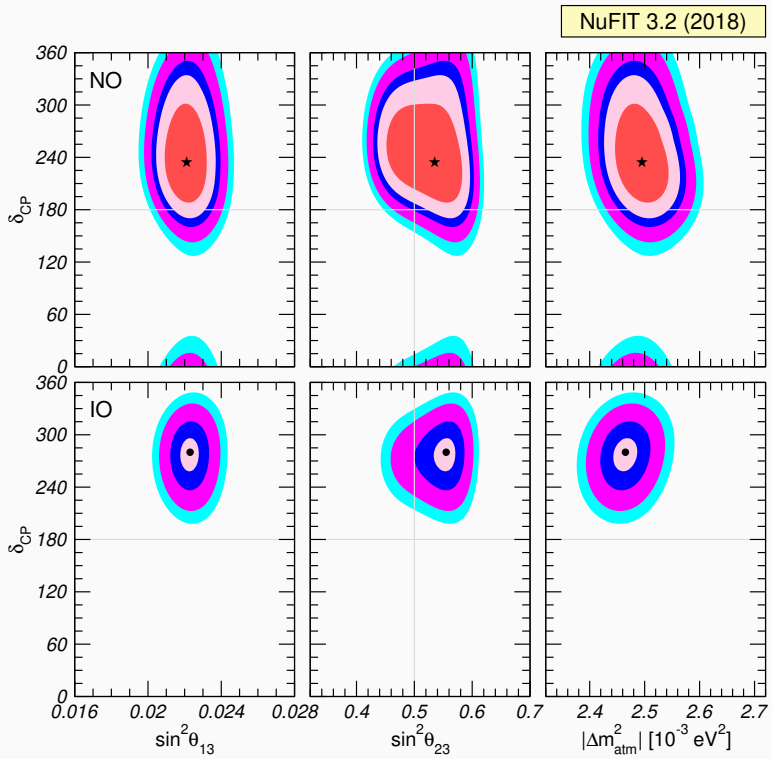
allowed for any U_i^2

[Drewes/Hajer/JK/Lanfranchi 1801.04207]

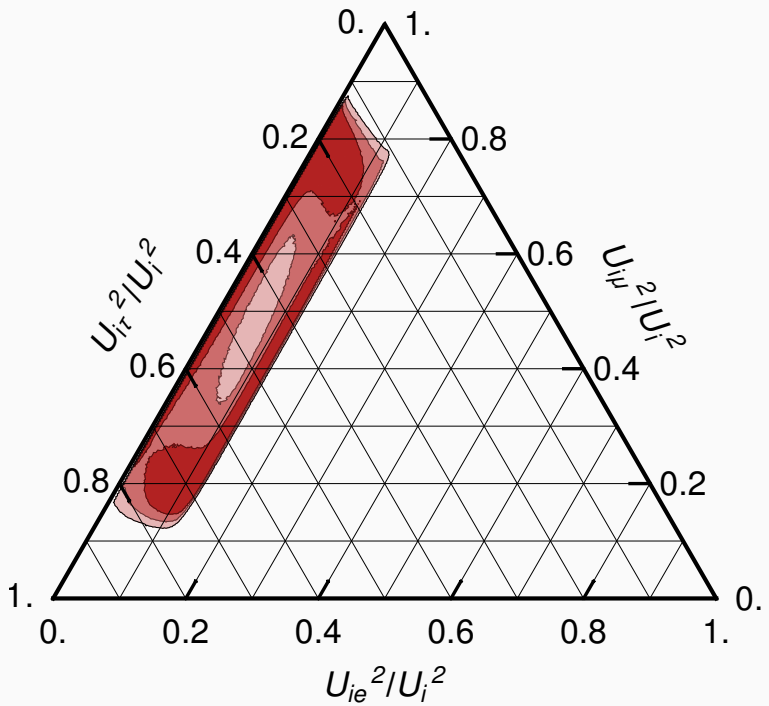
[Drewes/Garbrecht/Gueter/JK 1609.09069] [Caputo/Hernandez/Lopez-Pavon/Salvado 1704.08721]

Testing the ν mass generation: Normal Ordering

Measurement of δ_{CP} improves the prediction:



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



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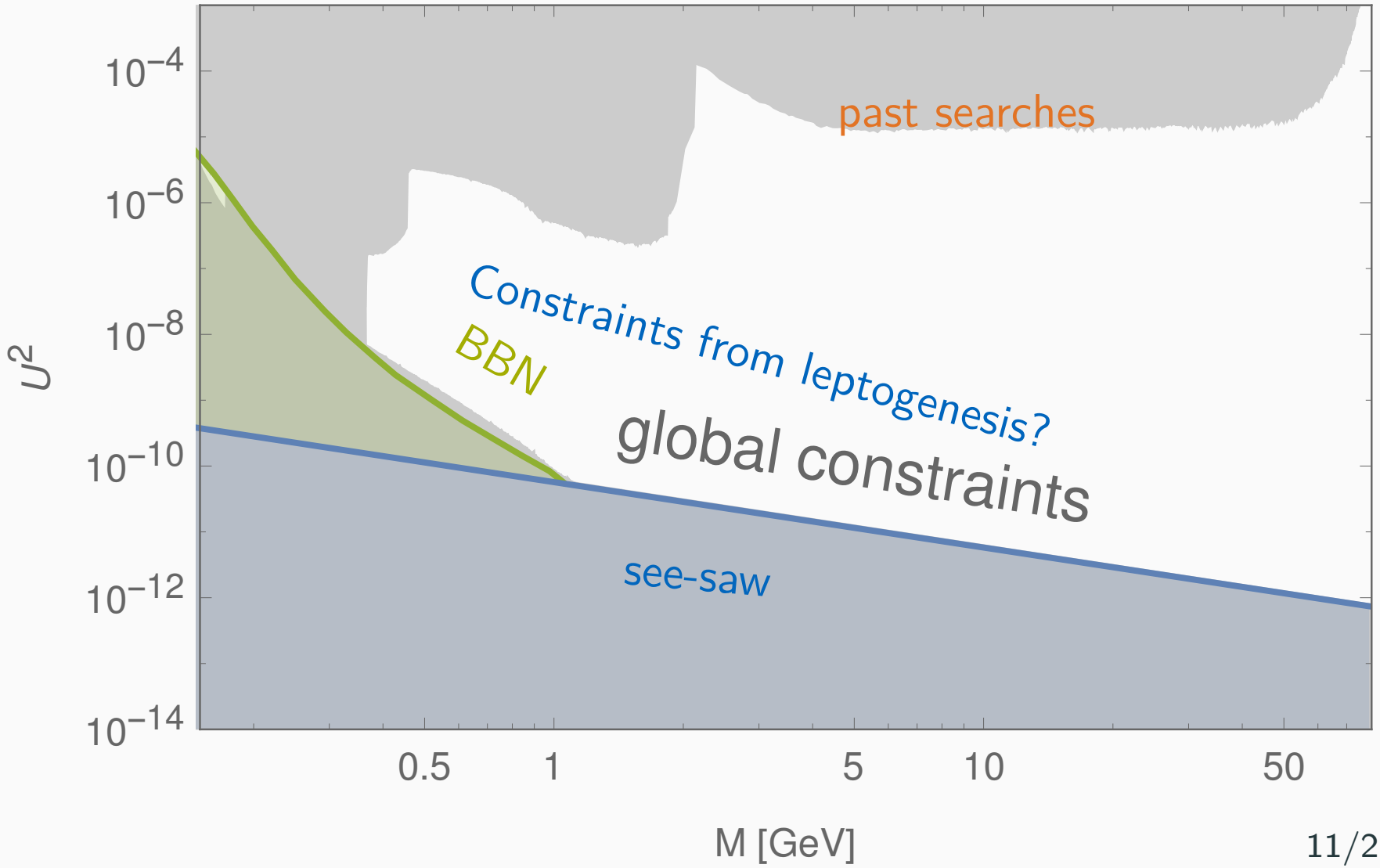
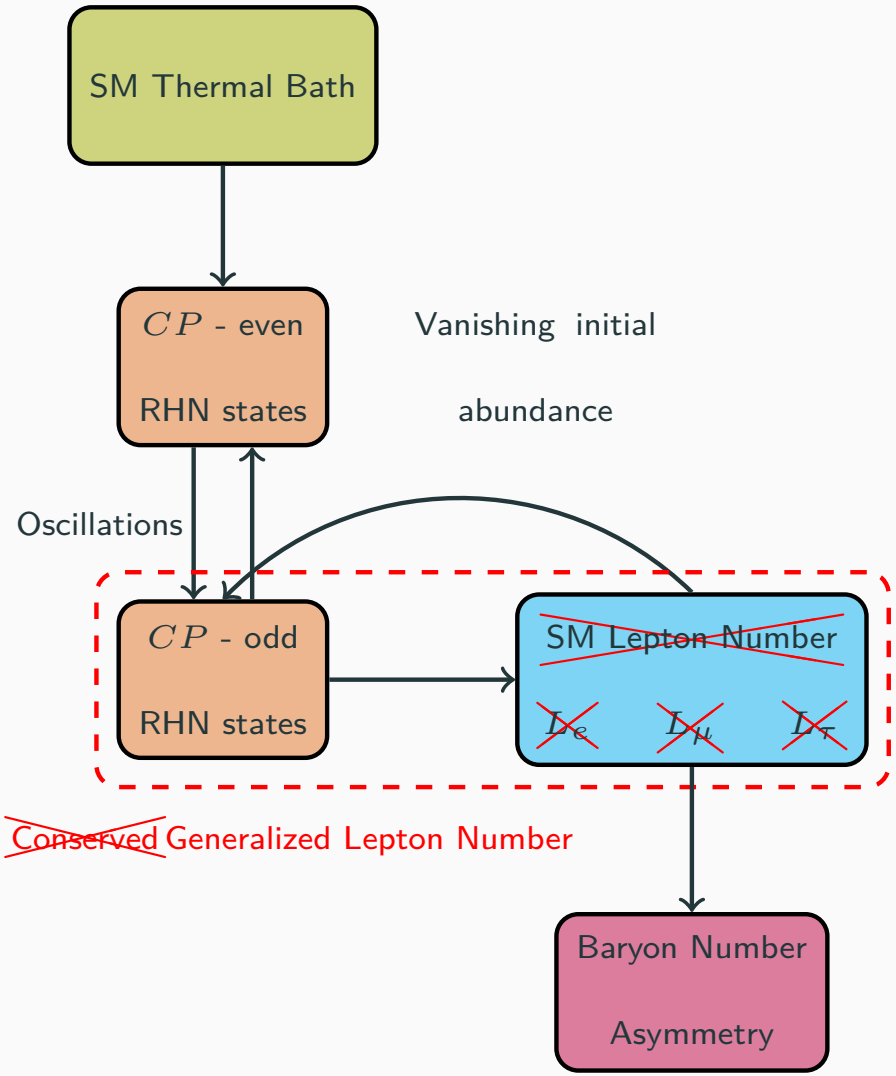
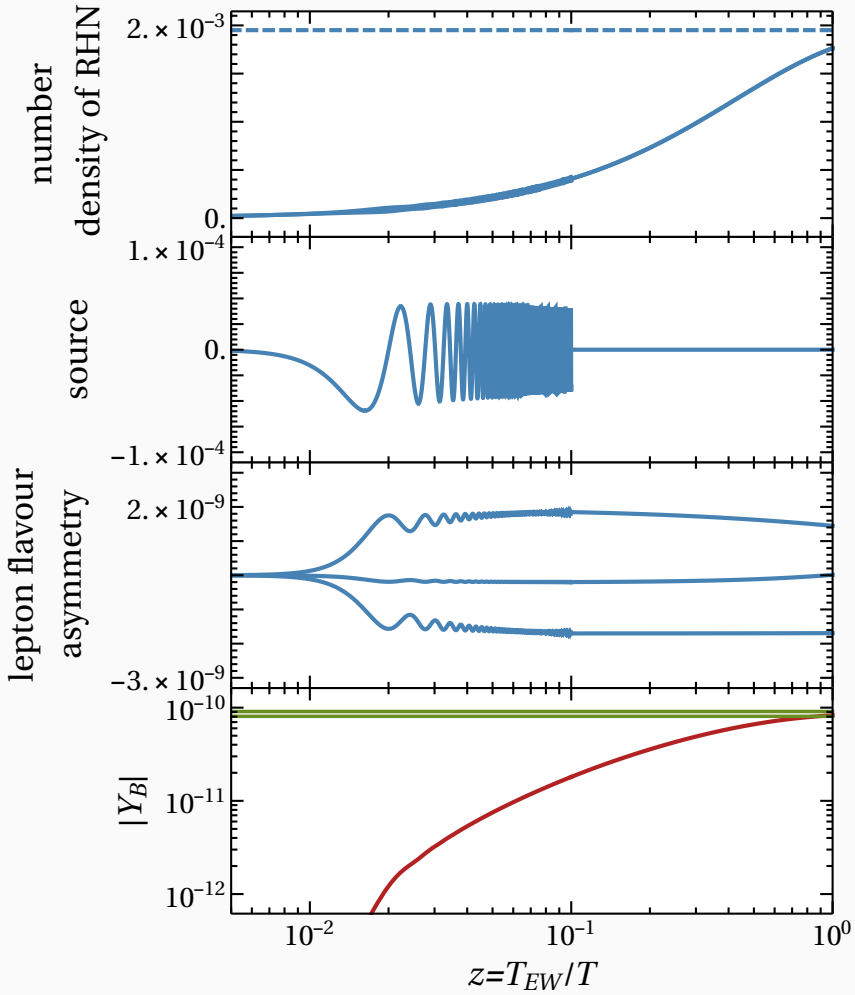


Leptogenesis via Neutrino Oscillations



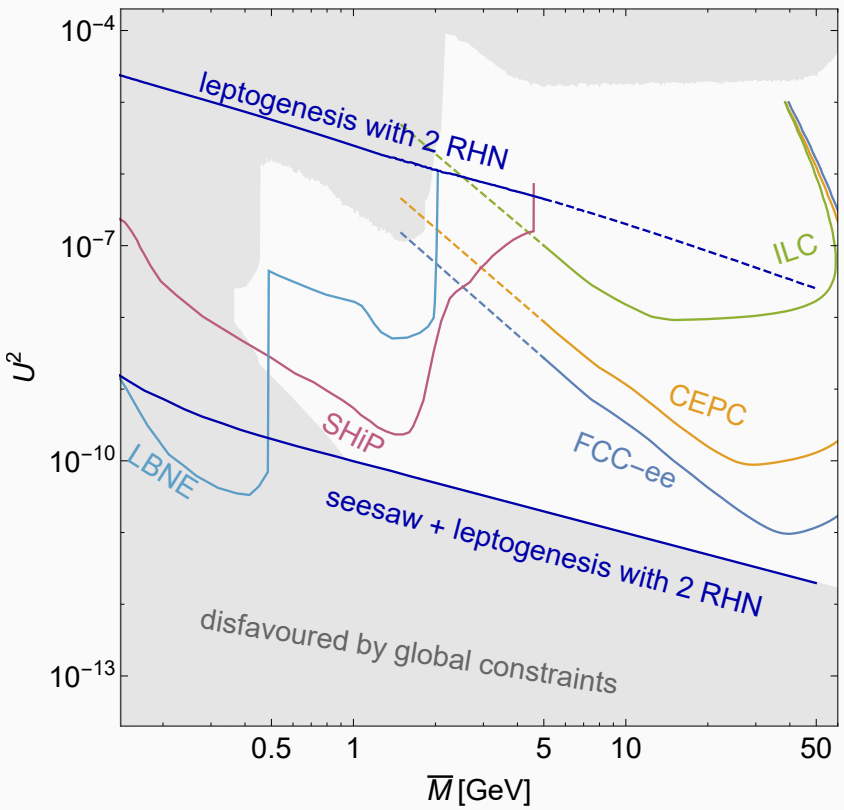


Theoretical challenges and progress:

- 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

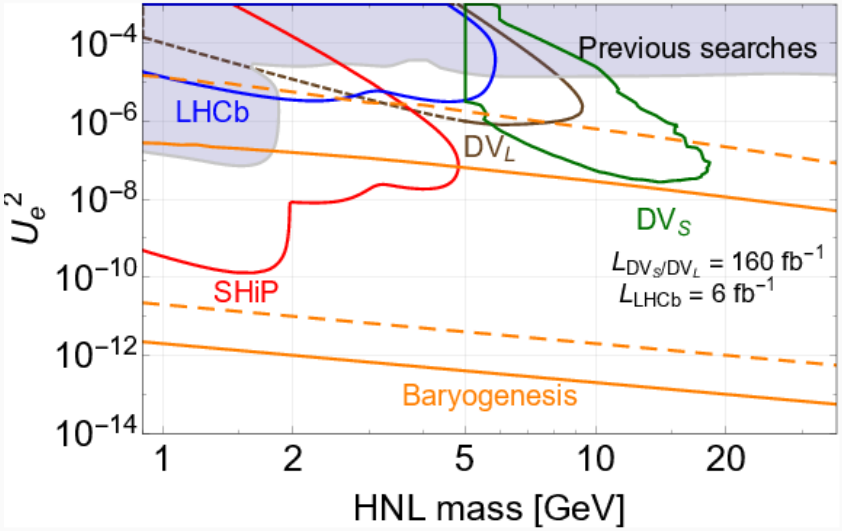


Inverted Ordering

[Drewes/Garbrecht/Gueter/JK 1609.09069]

- large mixing angle $U^2 \rightarrow$ large couplings $\rightarrow$ 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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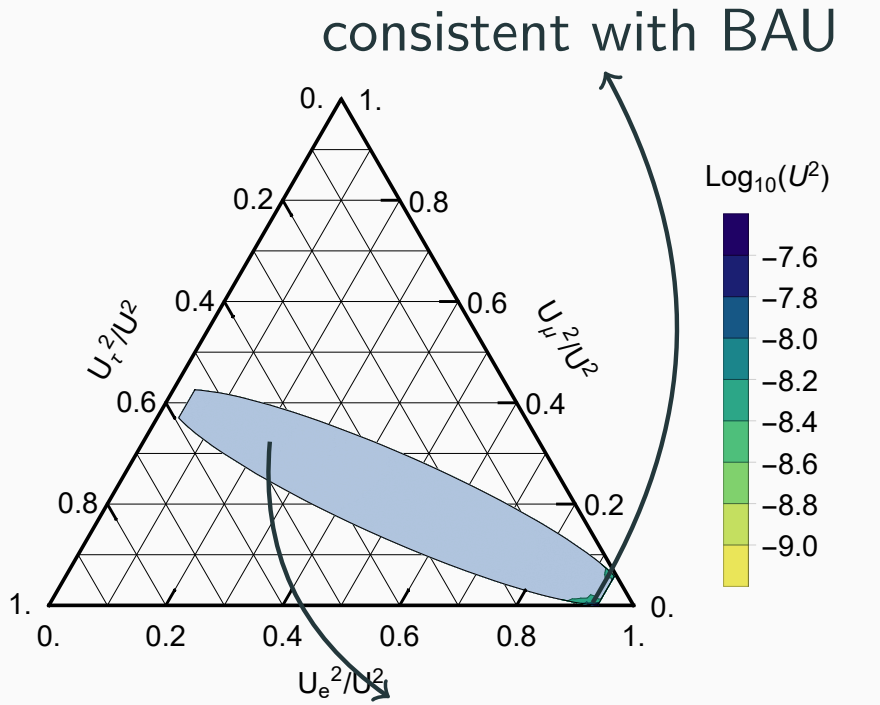

$$\bar{M} = 30\,\mathrm{GeV}$$
$$U^2 = 4 \times 10^{-9}$$

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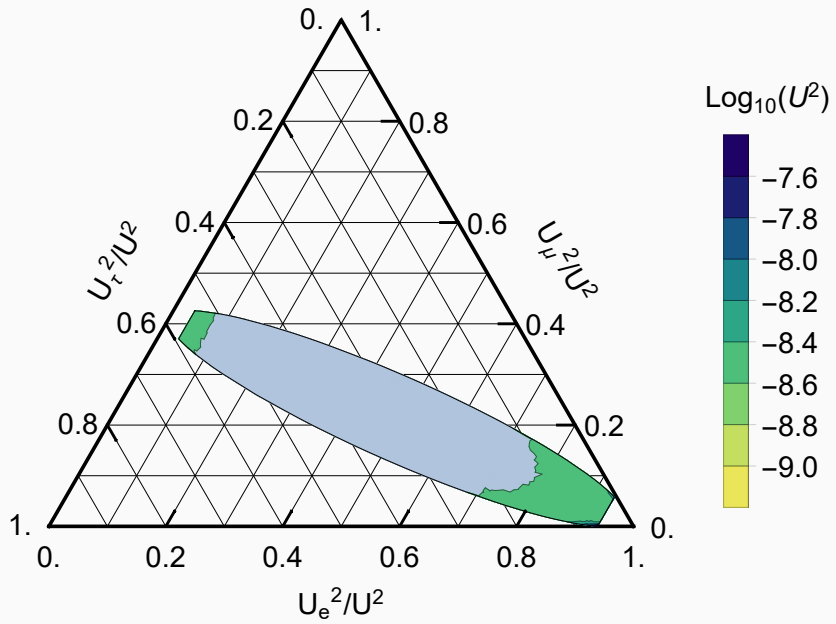
[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]

Leptogenesis with 2 RHN



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

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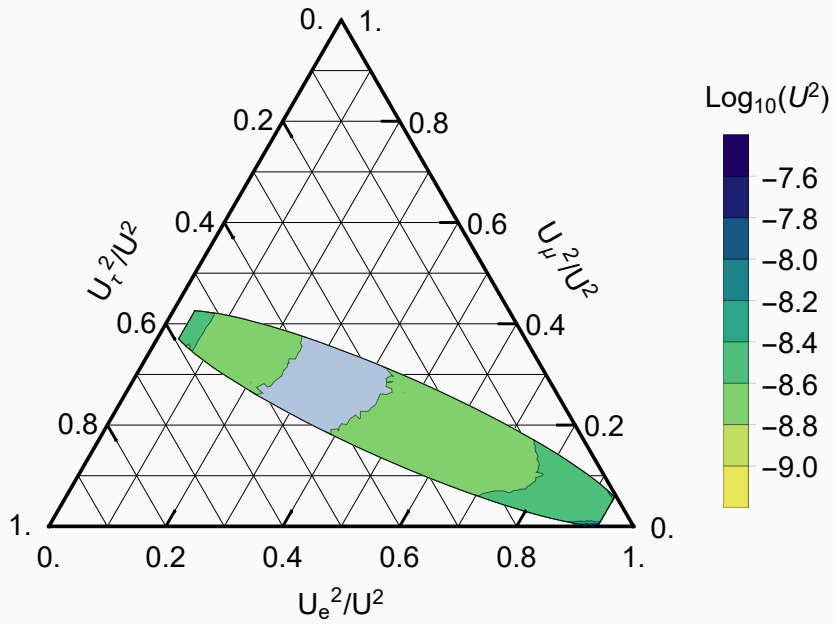

$$\bar{M} = 30\,\mathrm{GeV}$$
$$U^2 = 1.6 \times 10^{-9}$$

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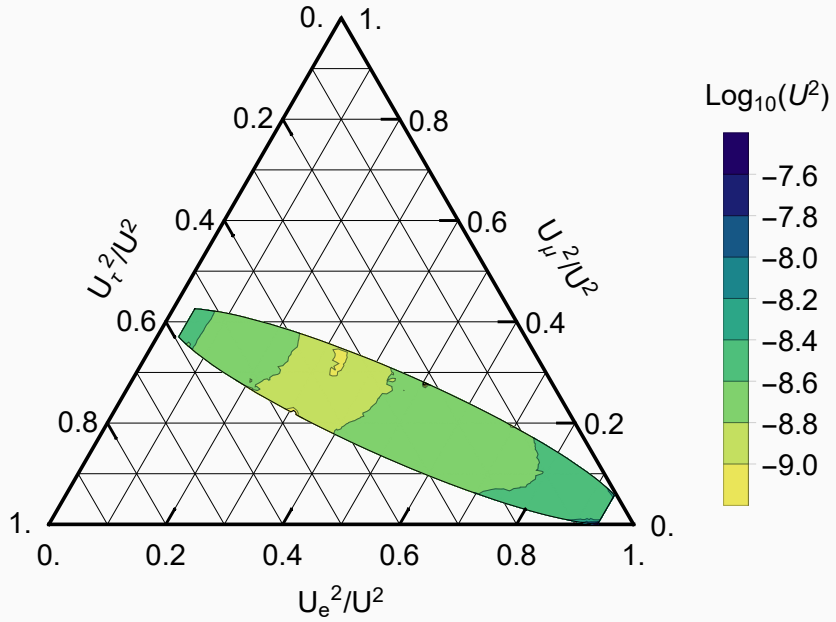
Leptogenesis with 2 RHN



$$\bar{M} = 30\,\mathrm{GeV}$$
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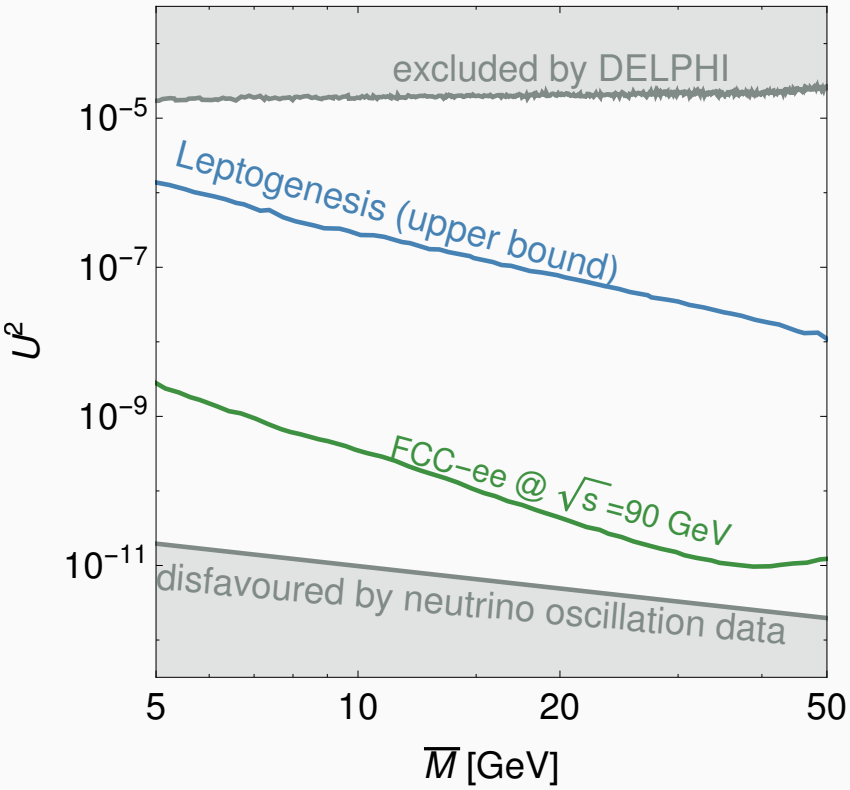
[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]

Sensitivity at Future lepton colliders: IO



- displaced vertex searches
- sensitivity calculated for each point consistent with leptogenesis
- guaranteed discovery - all points in a given M-U^2 bin have > 4 events
- potential discovery - some points have > 4 events
- for Z-pole run expected reach independent of flavour ratios
- away from the Z-pole, production through U_e^2

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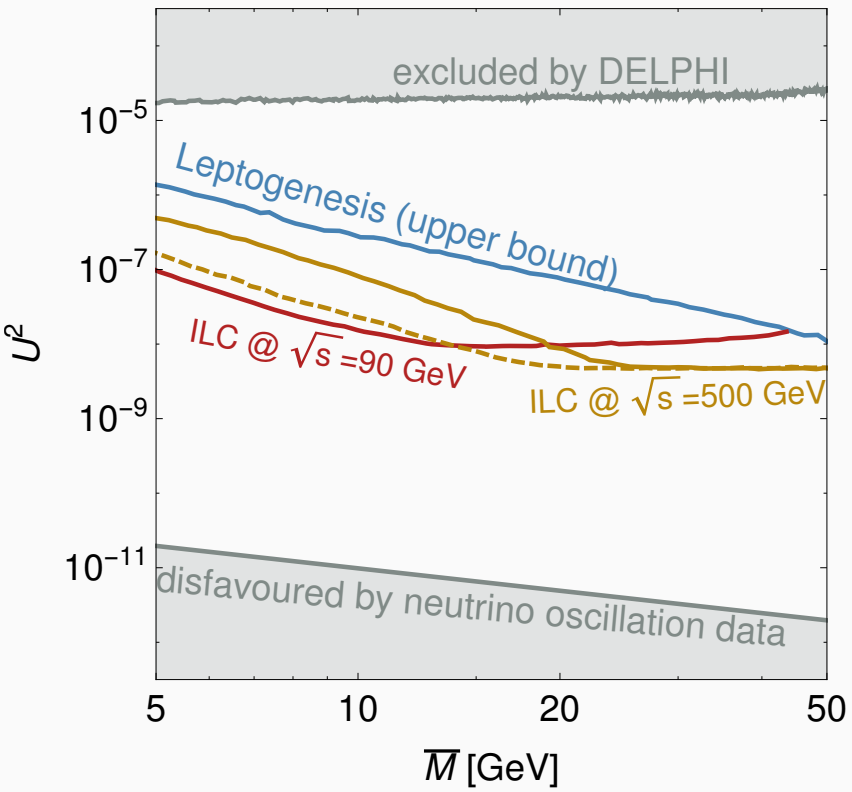

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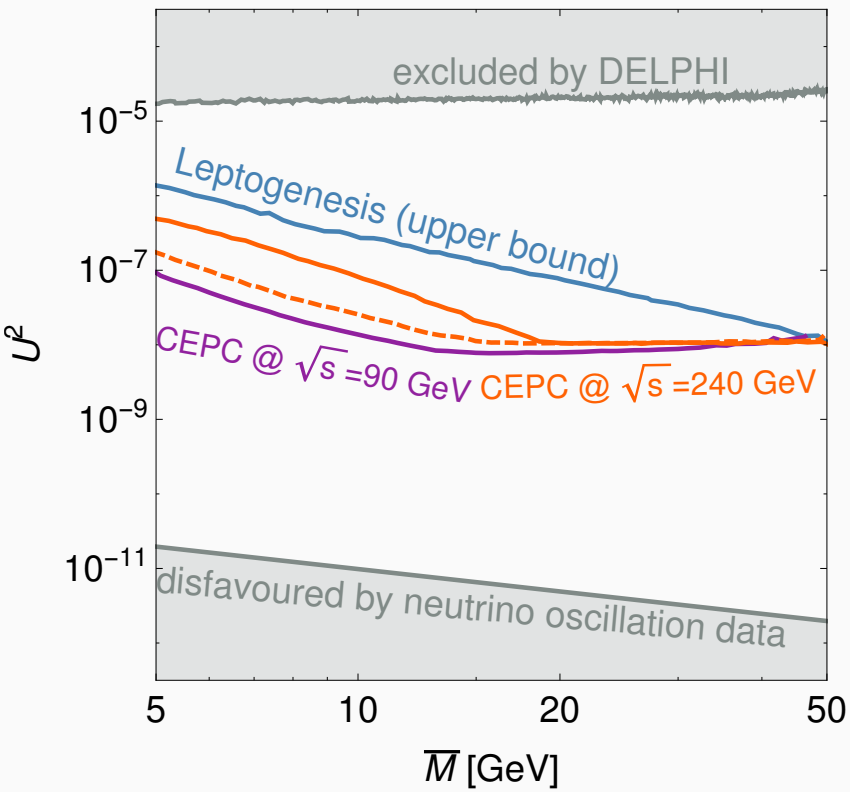

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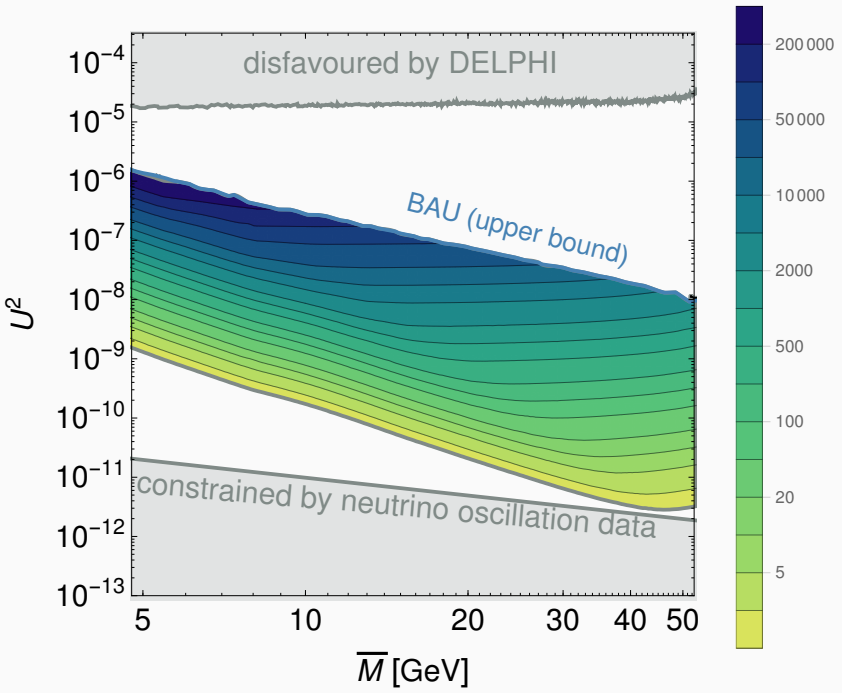
Measuring Flavour Ratios



[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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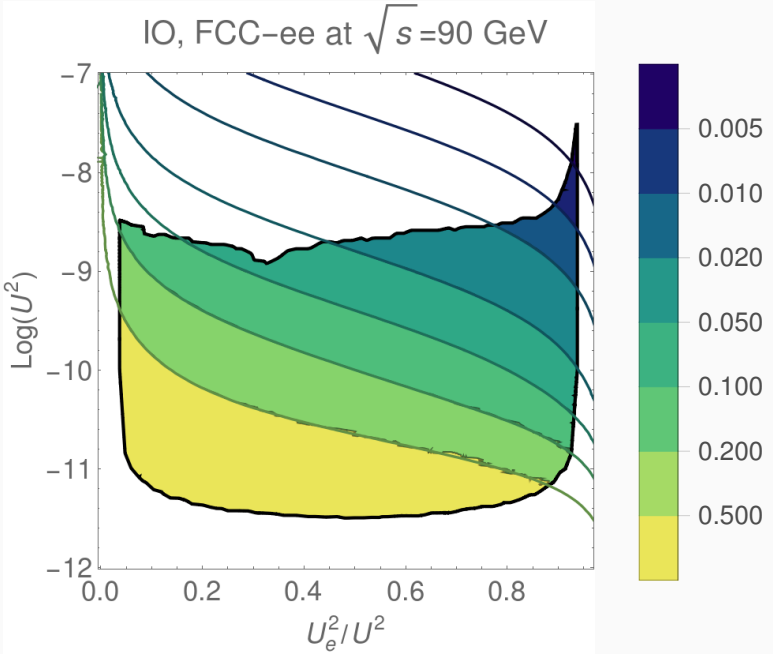

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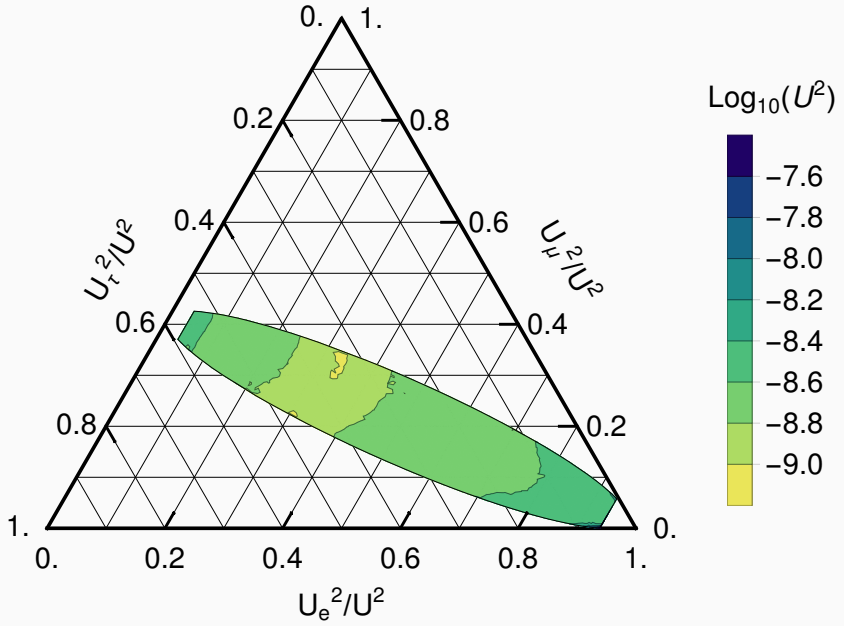

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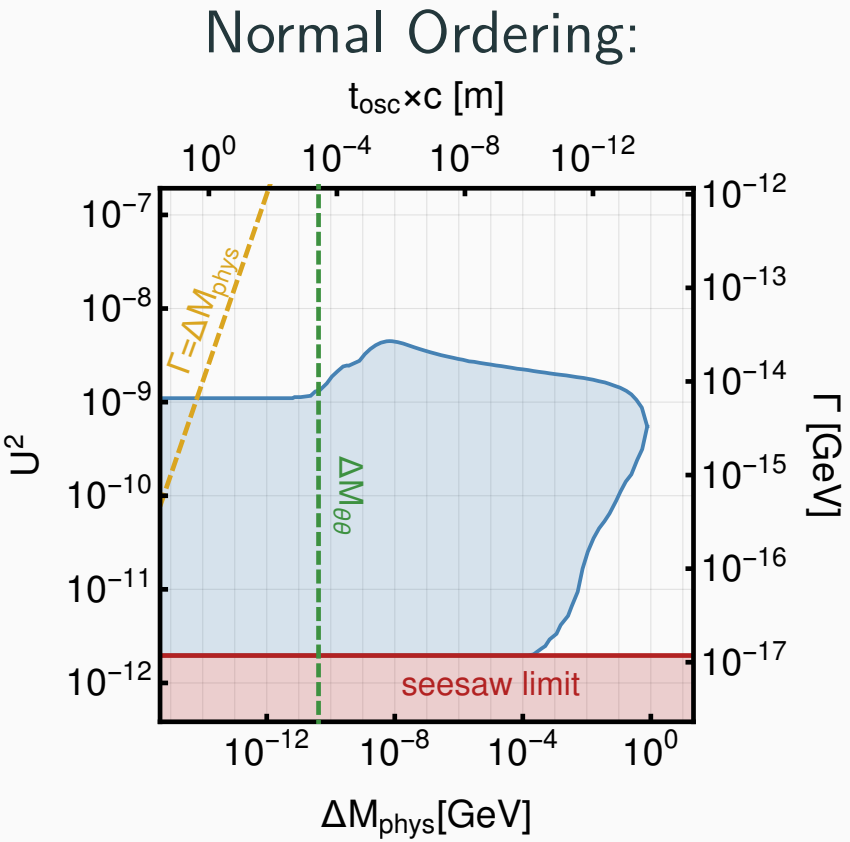
- large M - fraction of semileptonic events with flavour a in the final state proportional to U_a^2/U^2

Measuring the mass splitting



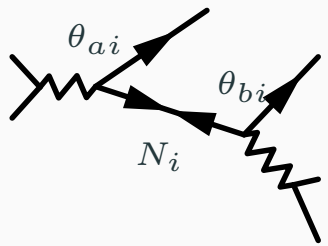
$M = 30$ GeV

[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

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



Same-to-opposite sign dilepton ratio

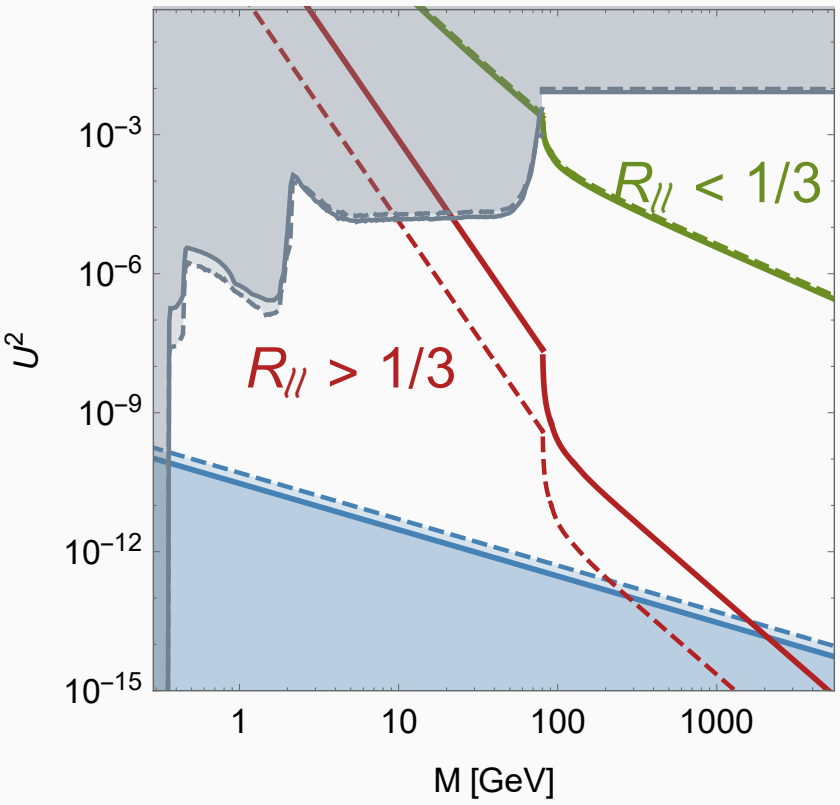
$$R_{\ell\ell} = \frac{\Delta M^2_{\rm phys}}{\Delta M^2_{\rm phys} + \Gamma^2_N}$$

[Anamiati/Hirsch/Nardi 1607.05641]

see talk by R. Ruiz

- 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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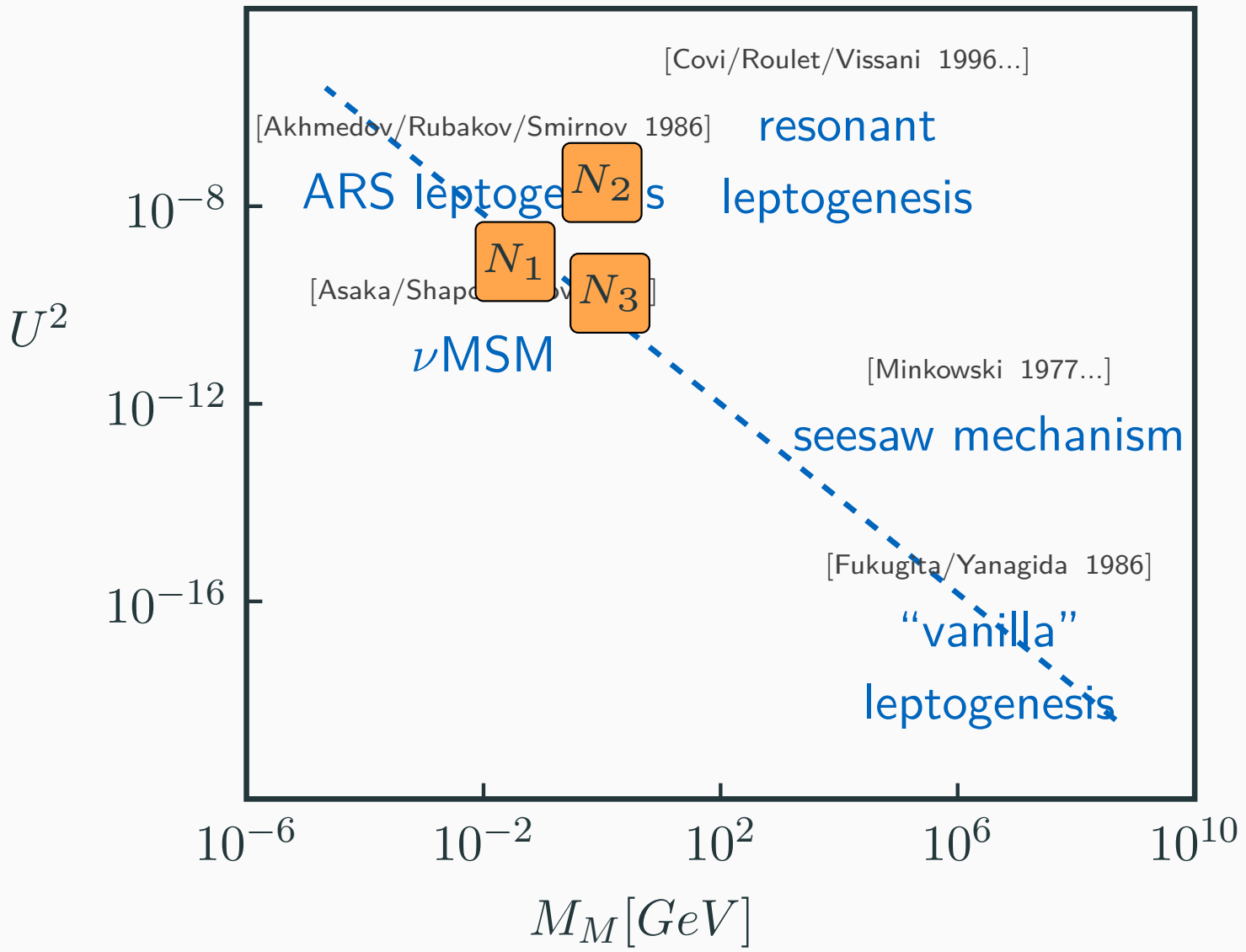
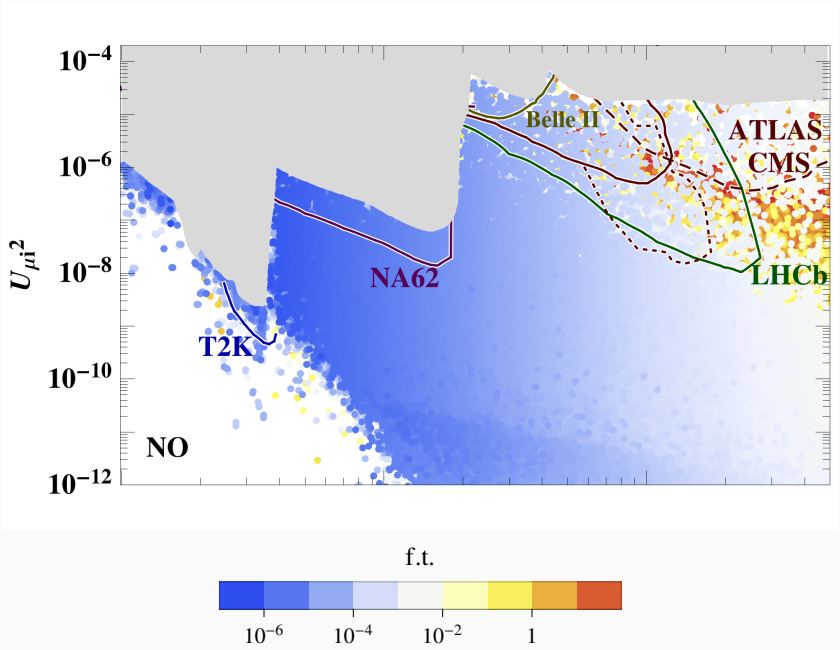
Leptogenesis with 3 RHN



Leptogenesis with 3 RHN Normal Ordering



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

- no constraints on mixing angles from the seesaw mechanism, possible to avoid washout
- new sources of CP violation with 3 RHN
- possible level crossing between the RHN energies $\rightarrow$ resonant enhancement!

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