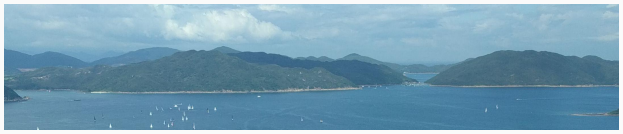
EPFL



European Research Council
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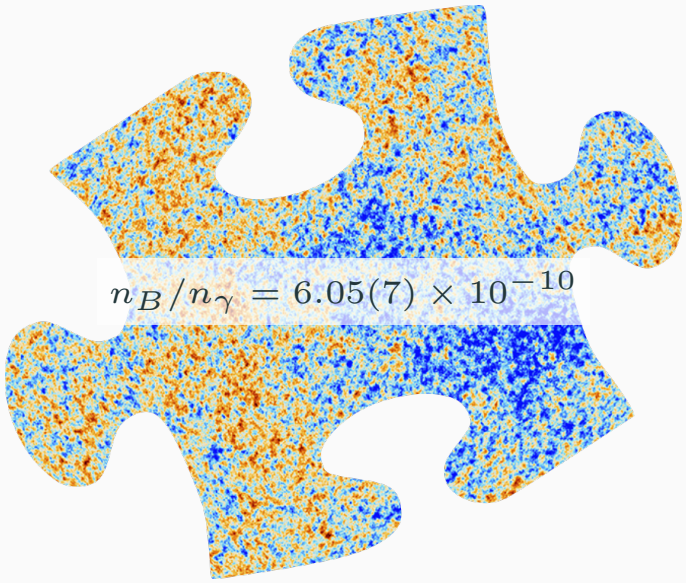
Low-scale leptogenesis with three heavy neutrinos

Juraj Klarić
based on work in collaboration with A. Abada, G. Arcadi, V. Domcke, M. Drewes and M. Lucente

HKUST IAS, Hong Kong, January 9, 2020

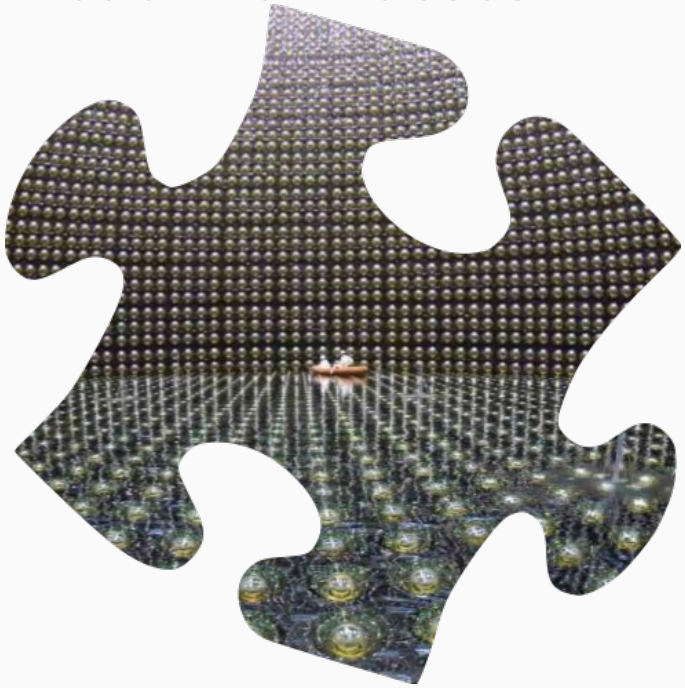
Some of the shortcomings of the standard model:

BAU baryon asymmetry of the universe



[Planck collaboration]

Neutrino masses



[Super-Kamiokande]

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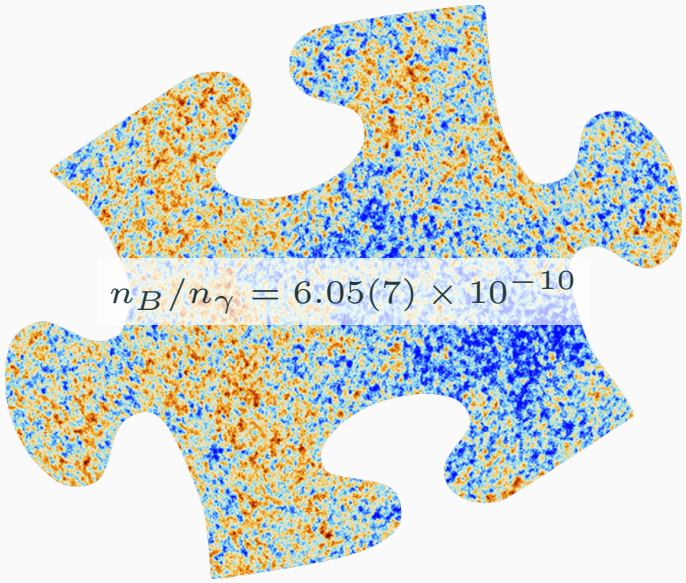

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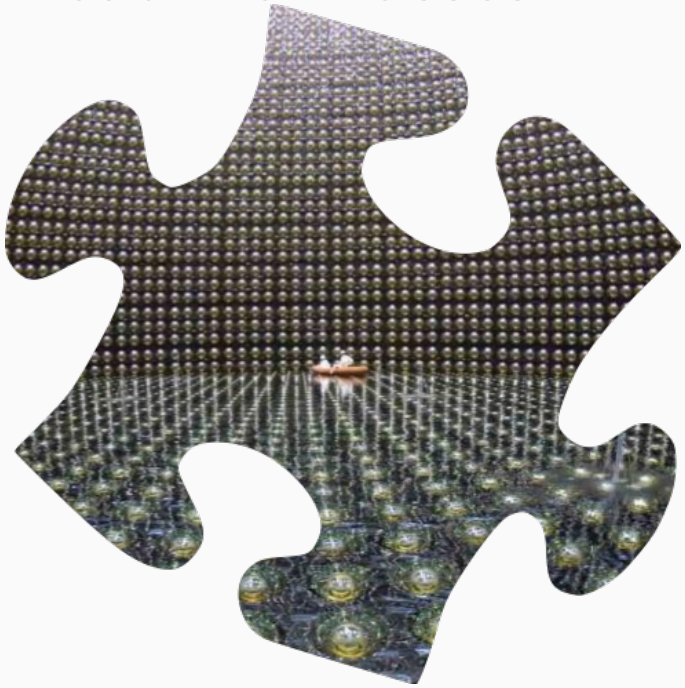
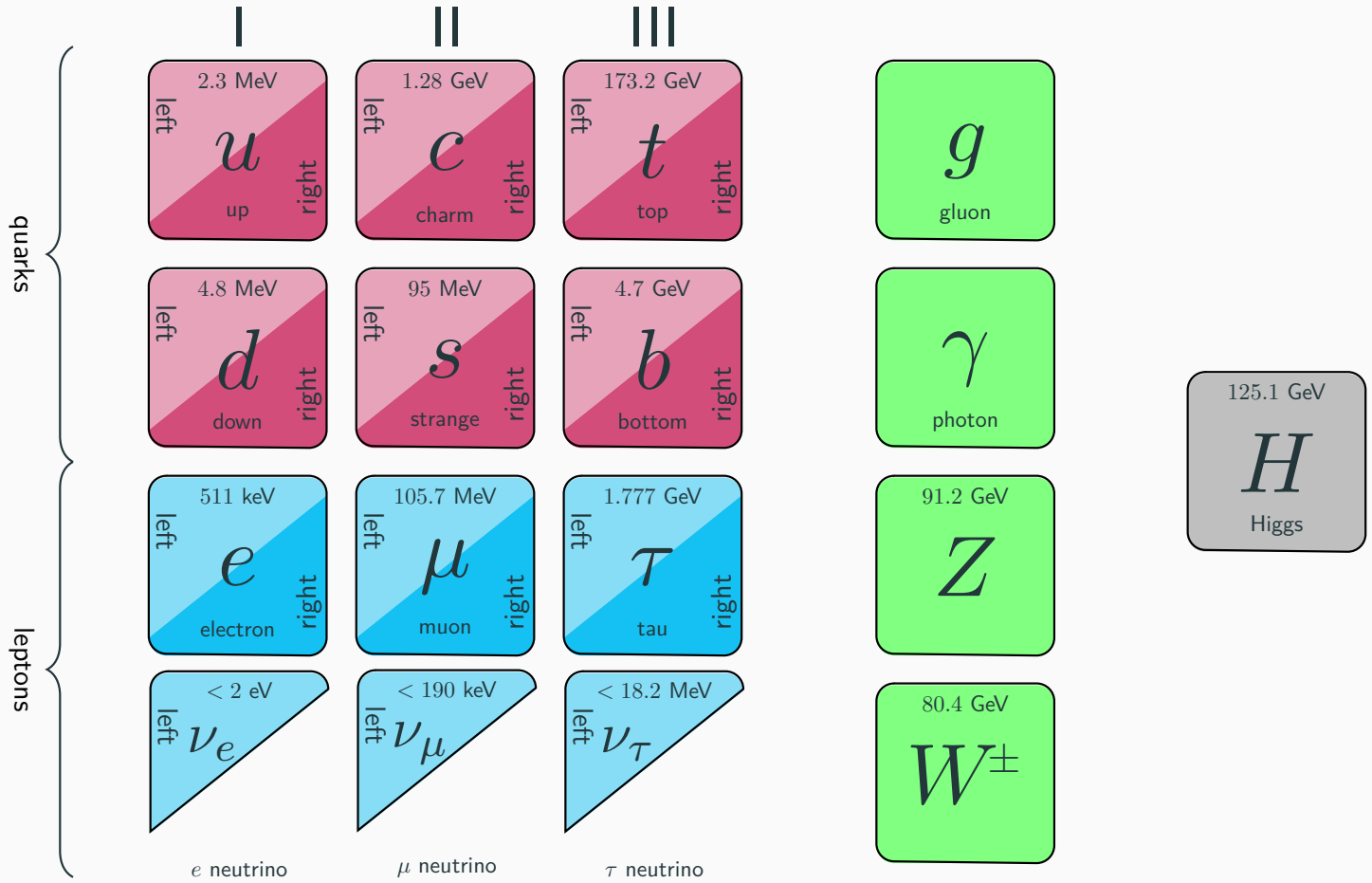


[Super-Kamiokande]

Is there a way to explain both?

Standard Model



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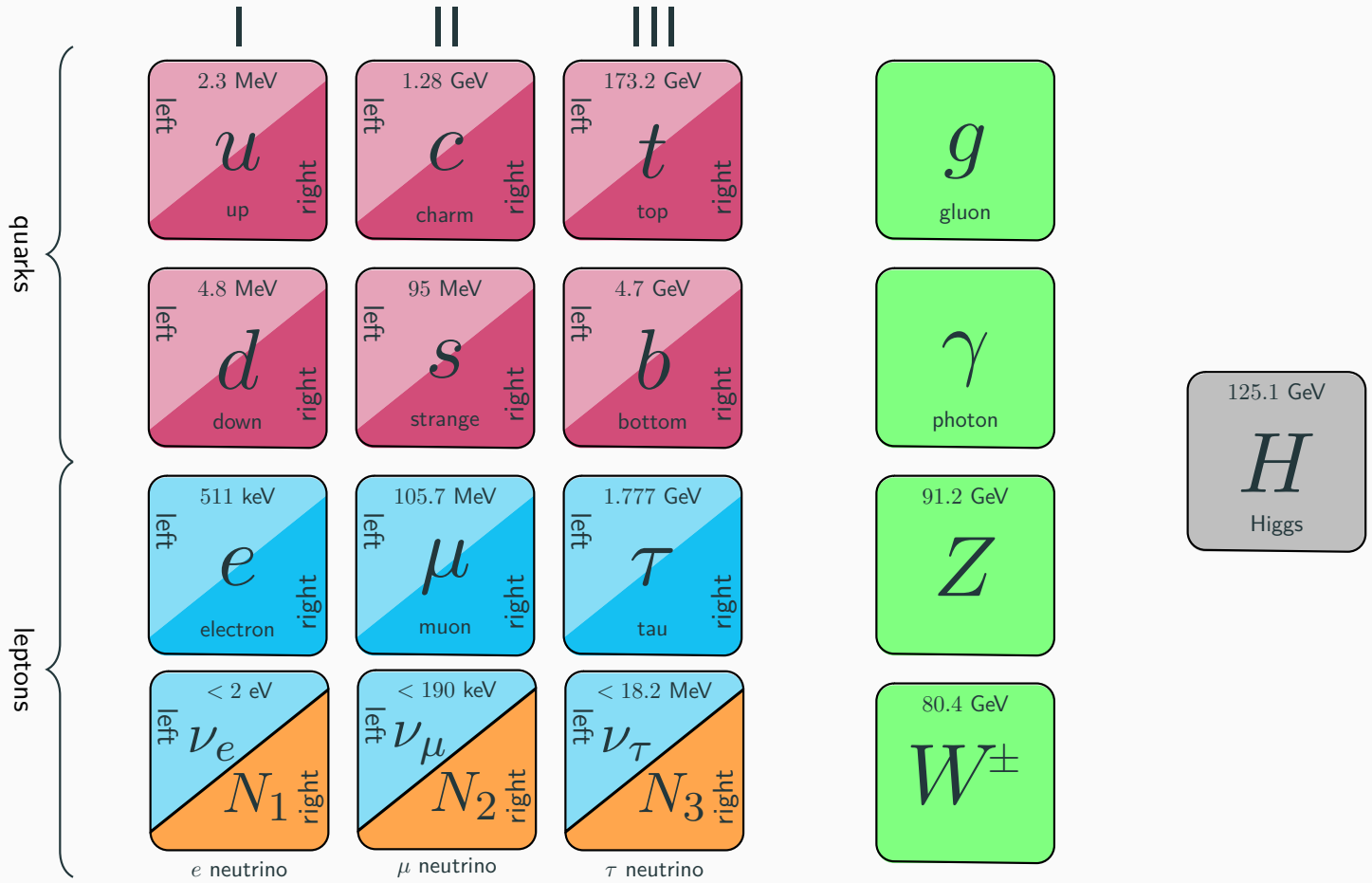

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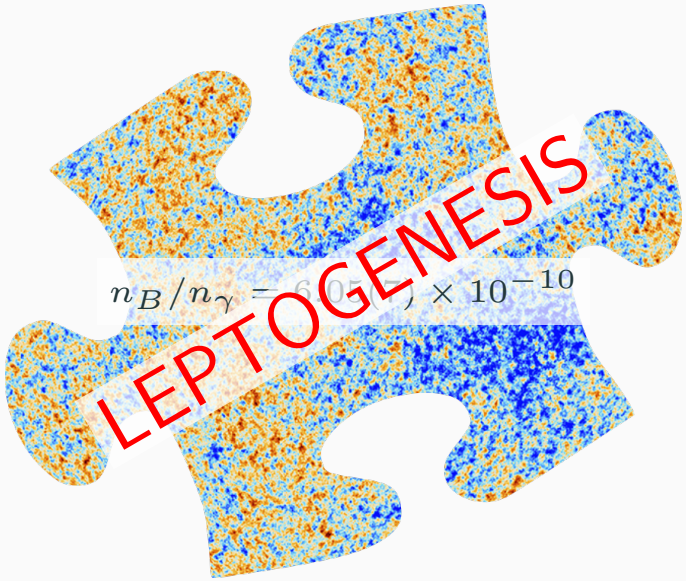

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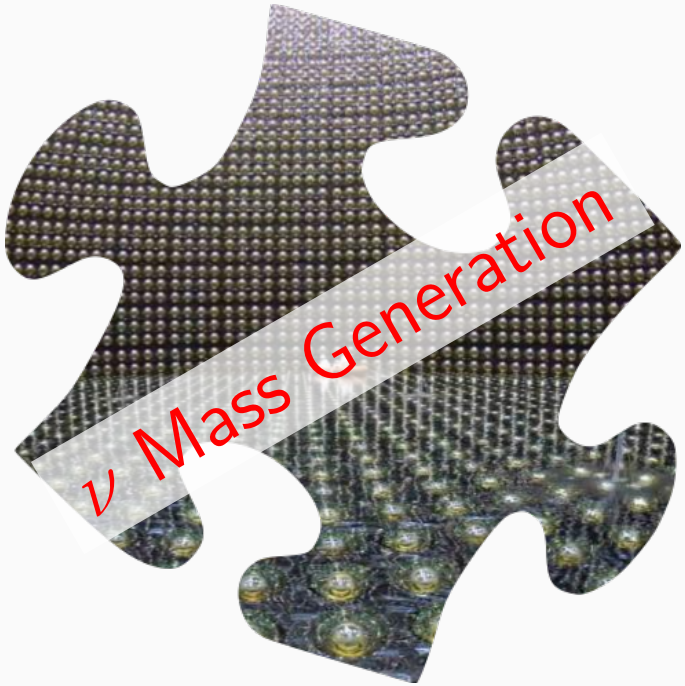


The "Seesaw" Relation

- Dirac Mass $m_D = vF$
- 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

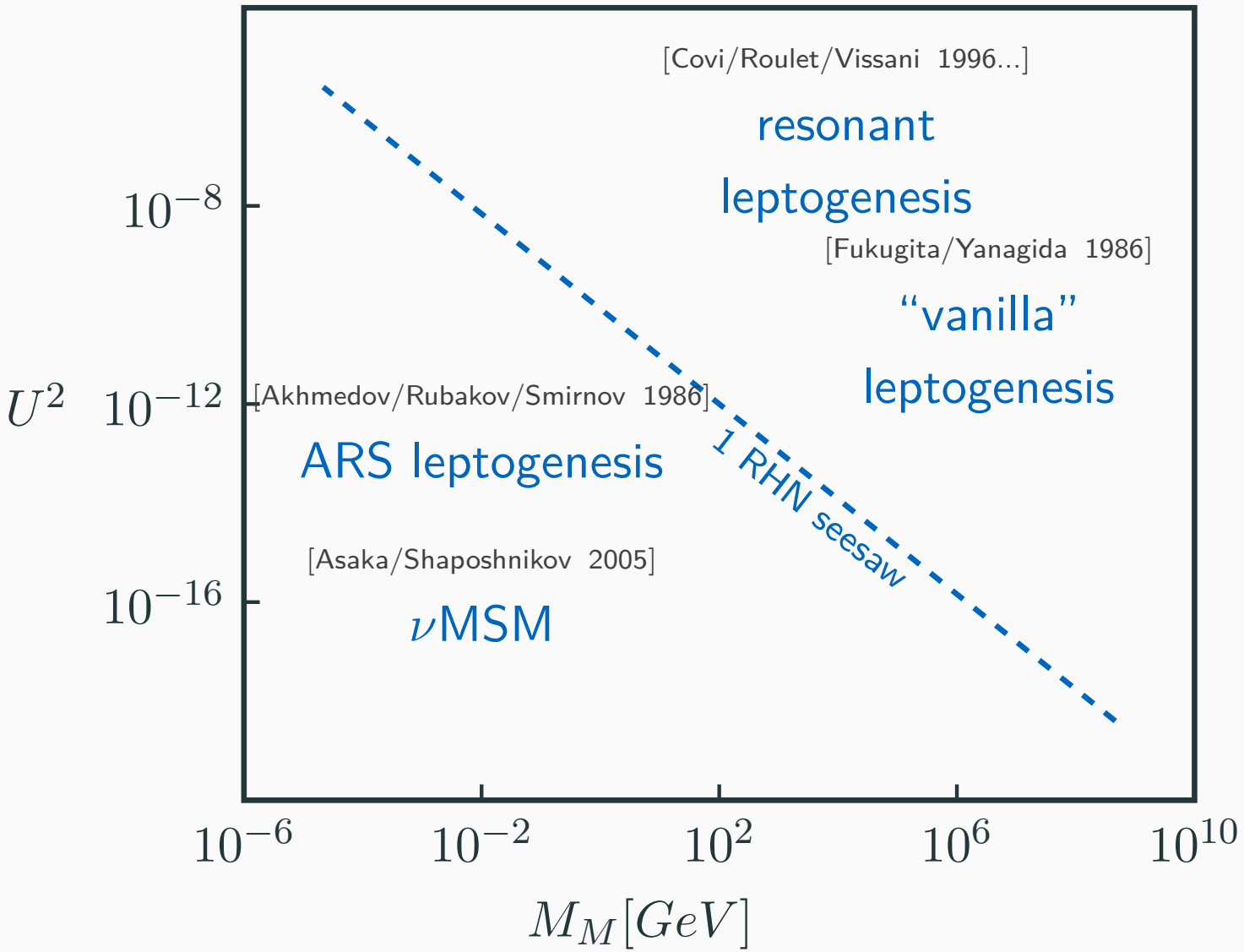
$$m_\nu = -m_D M_M^{-1} m_D^T$$

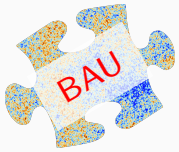
[Minkowski 1977...]

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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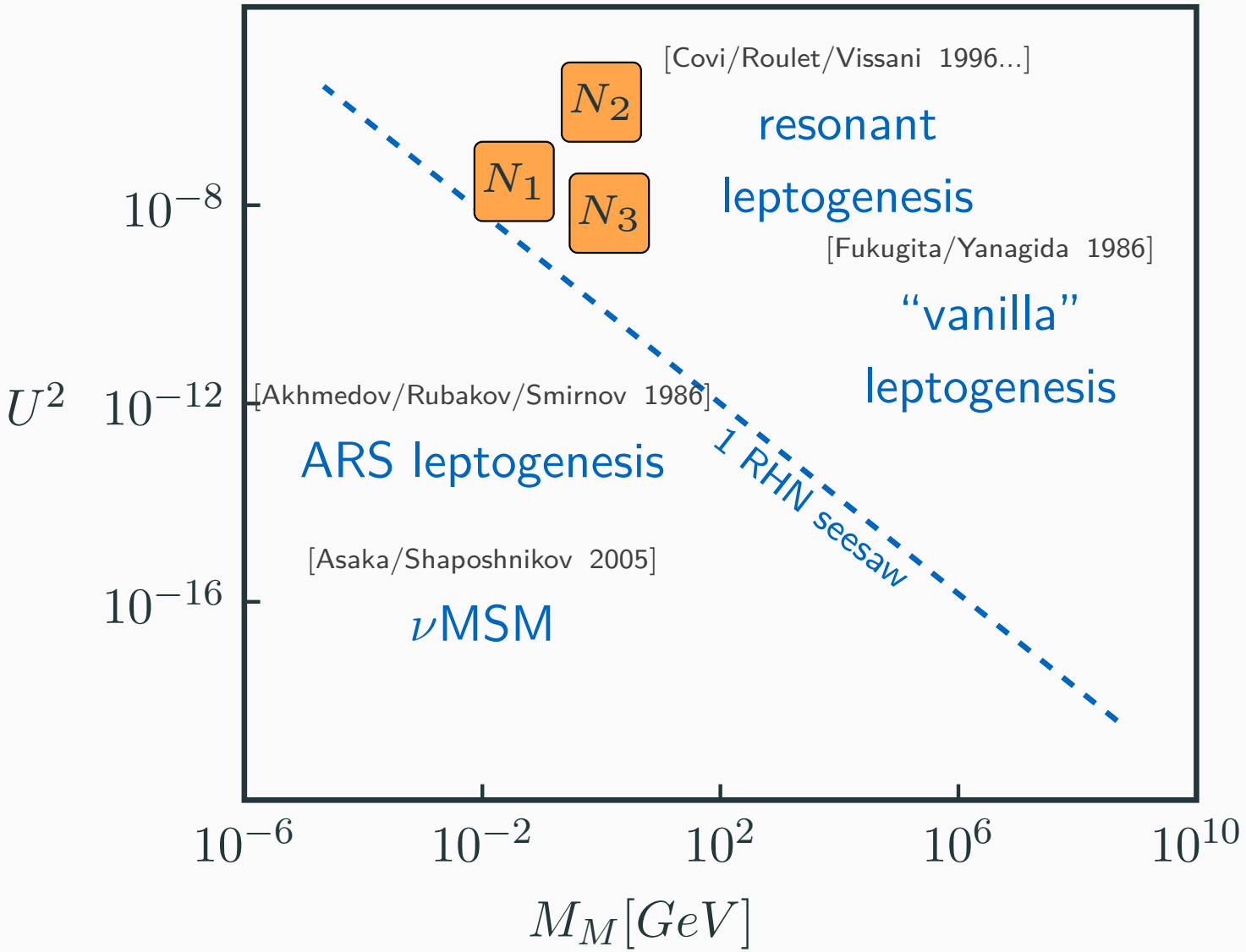

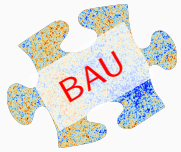

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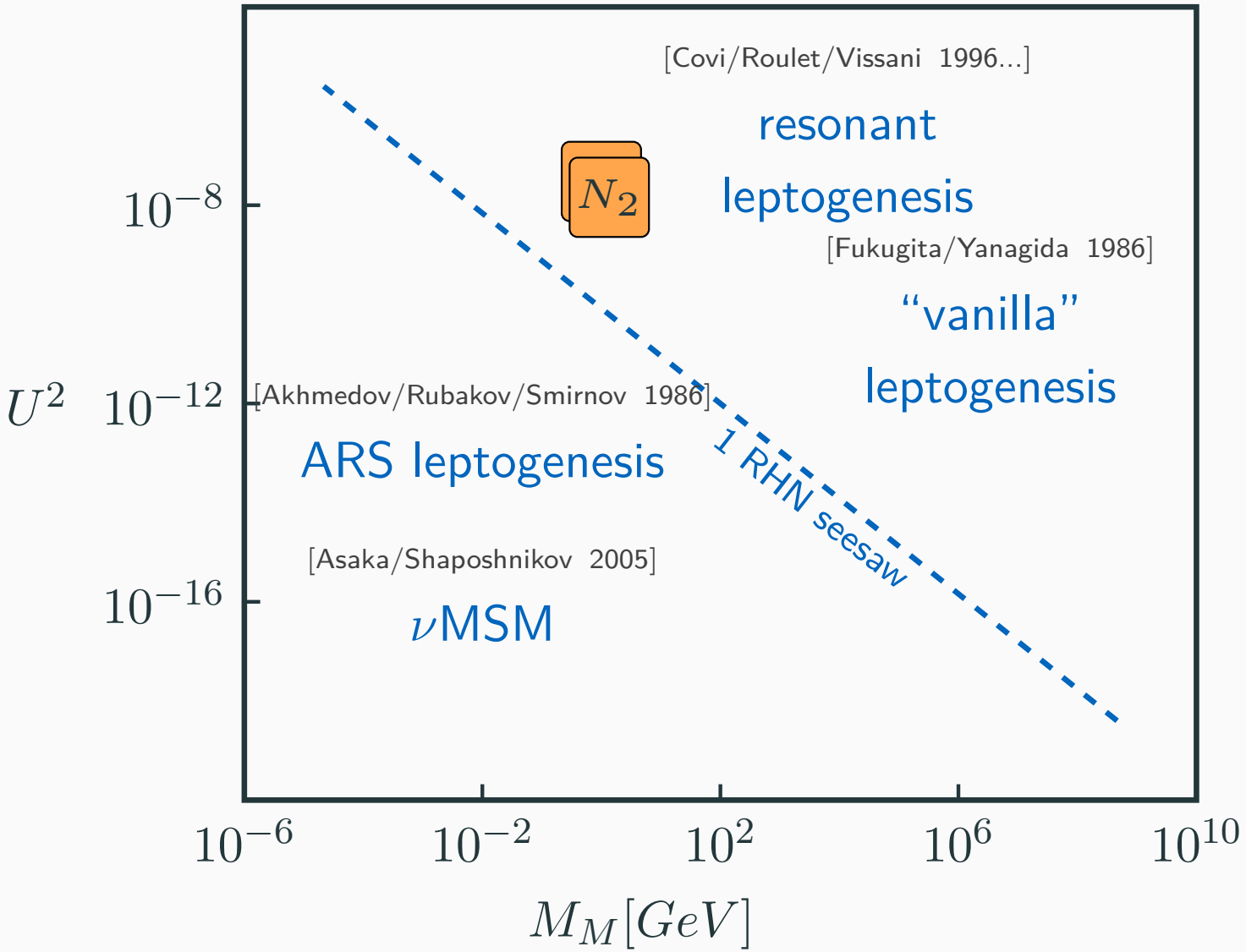

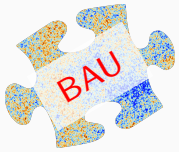

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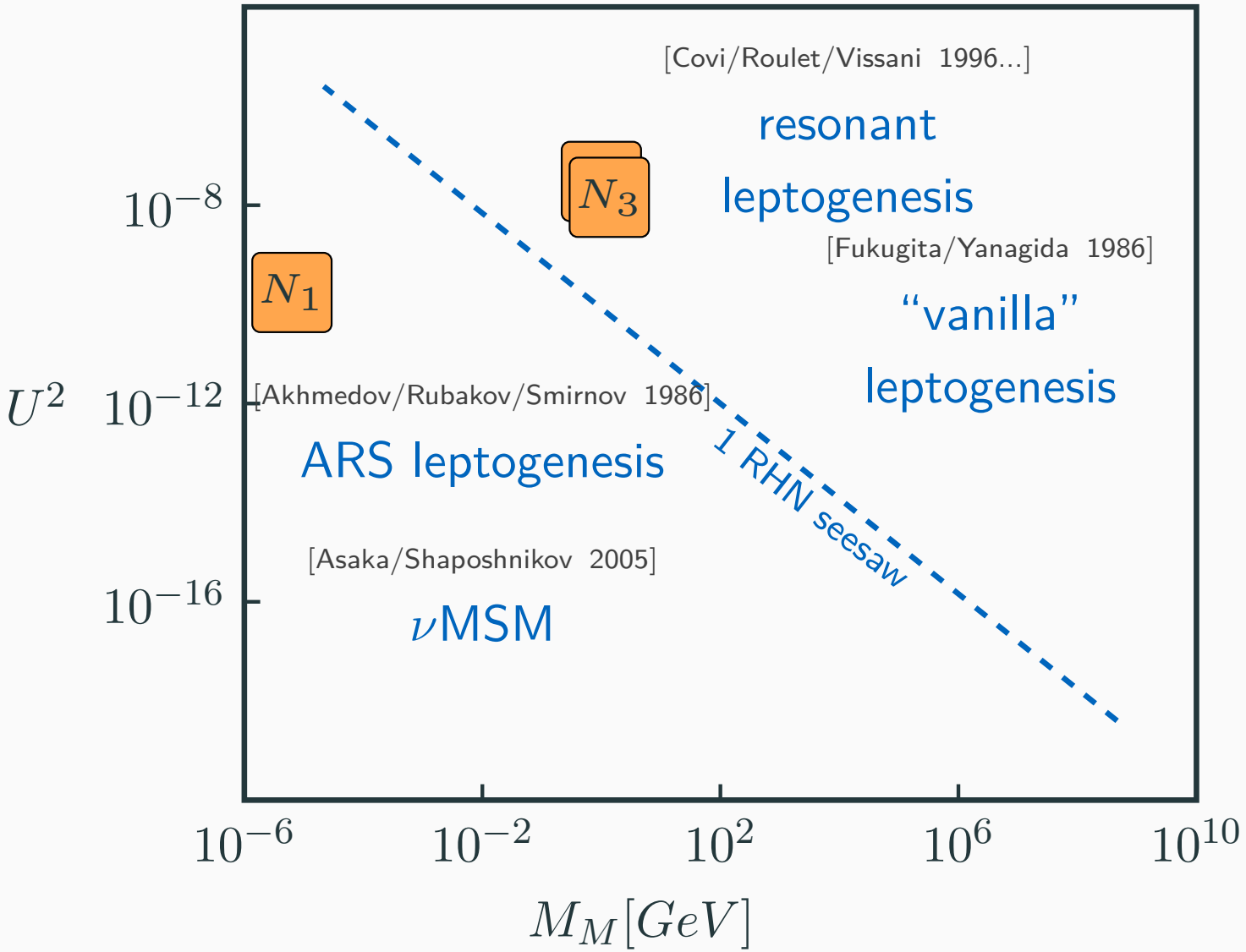

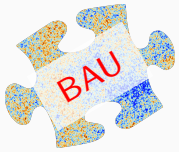

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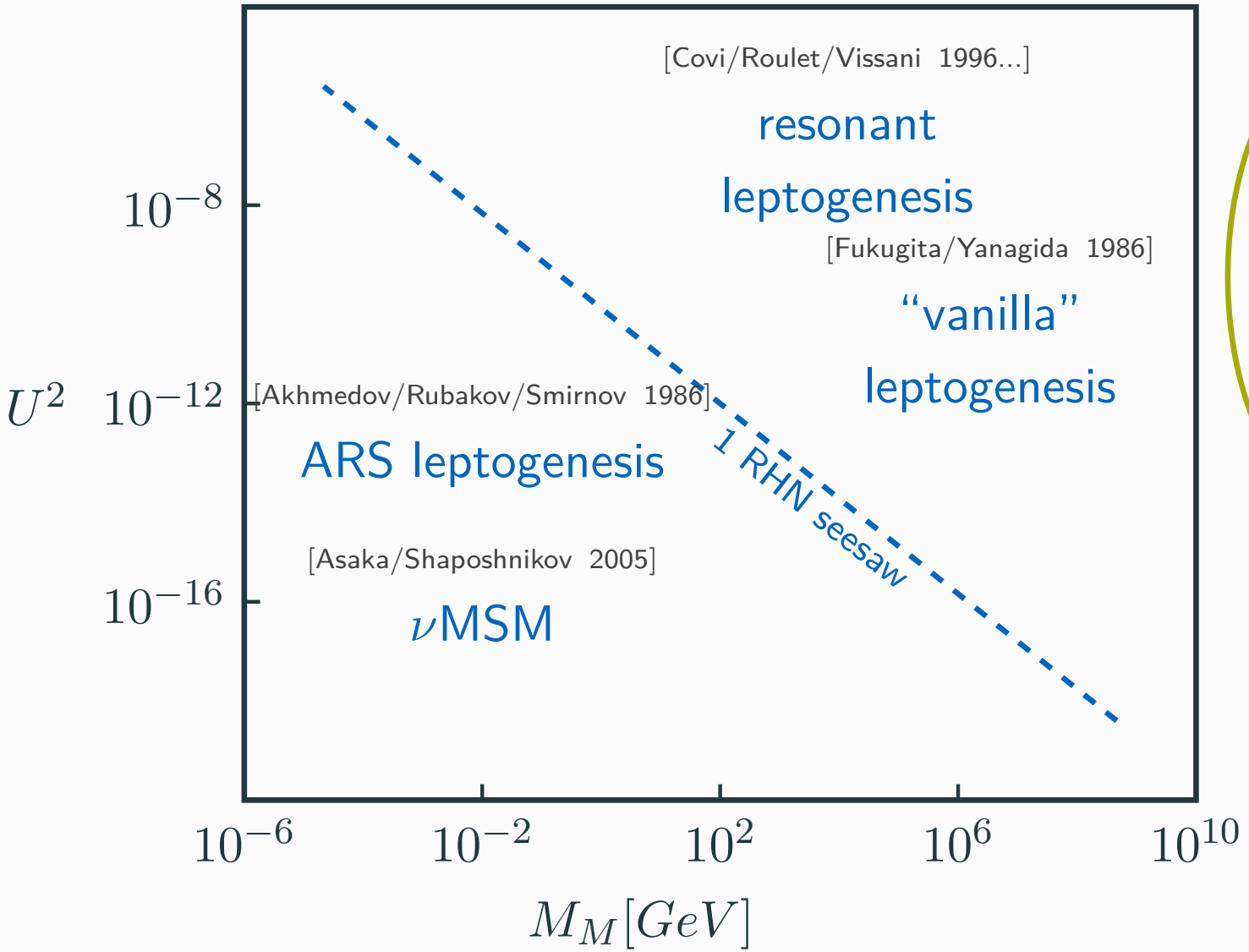
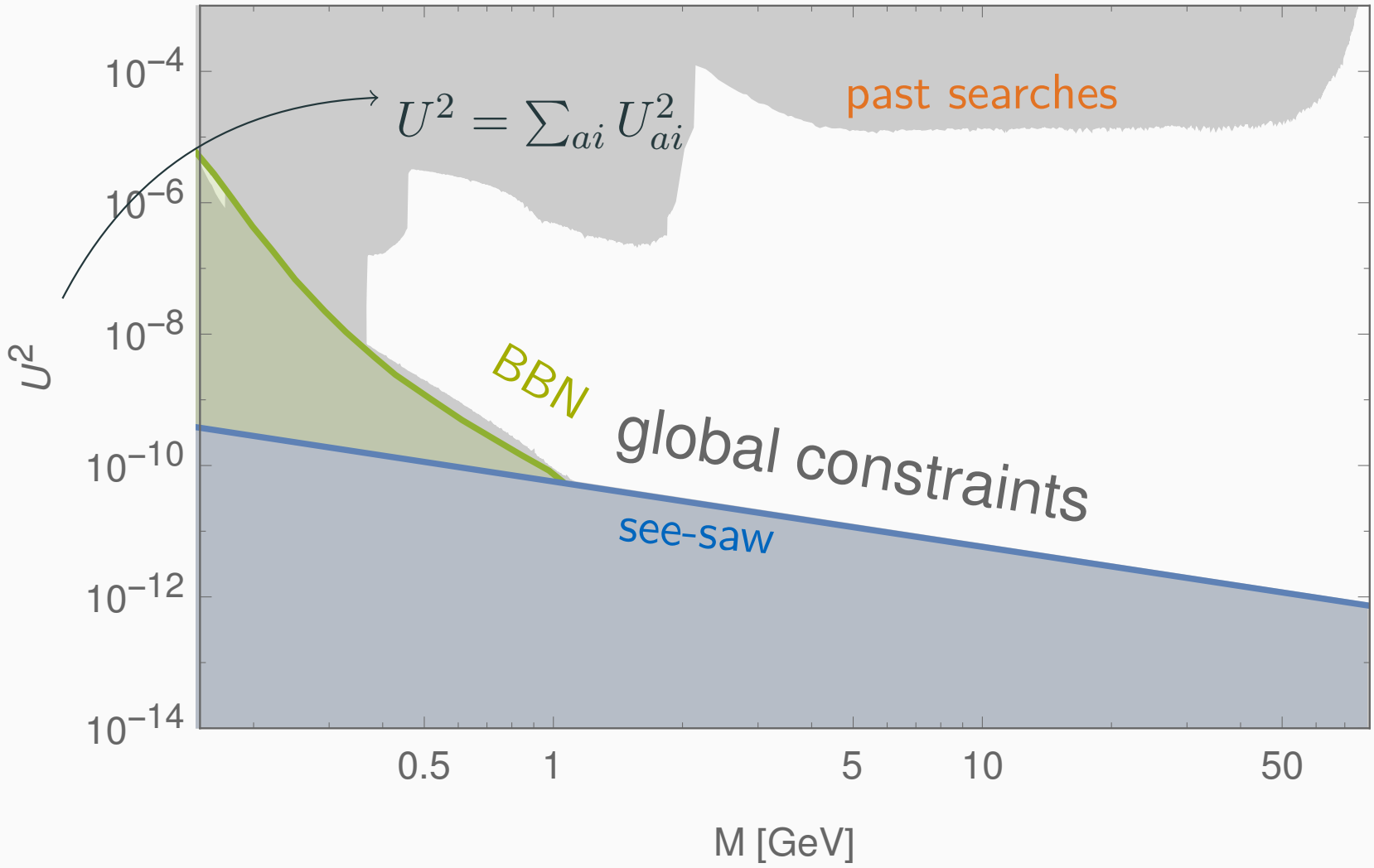


How is $3 \neq 2$?: Allowed mixing angles (2 RHN)



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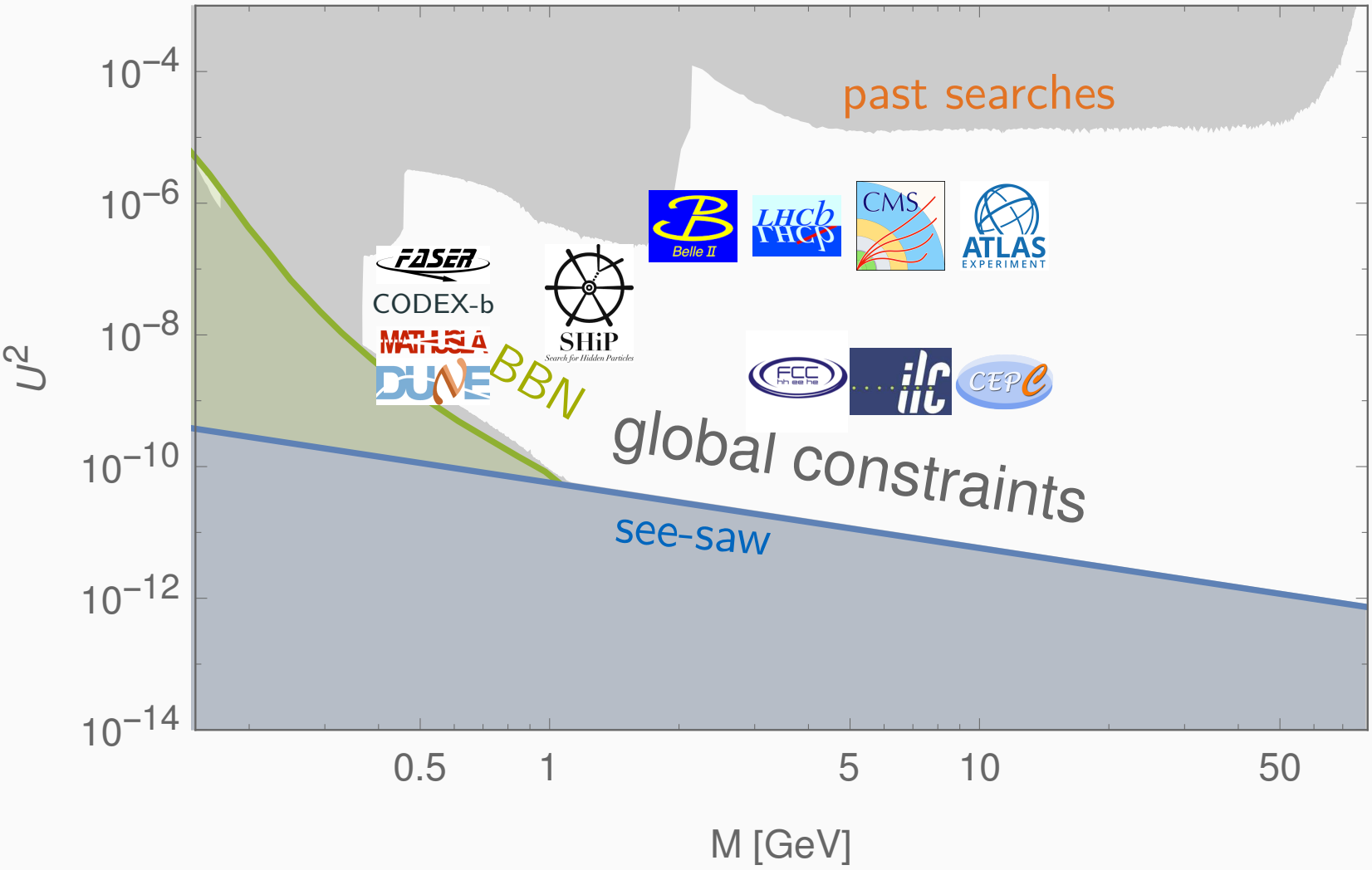
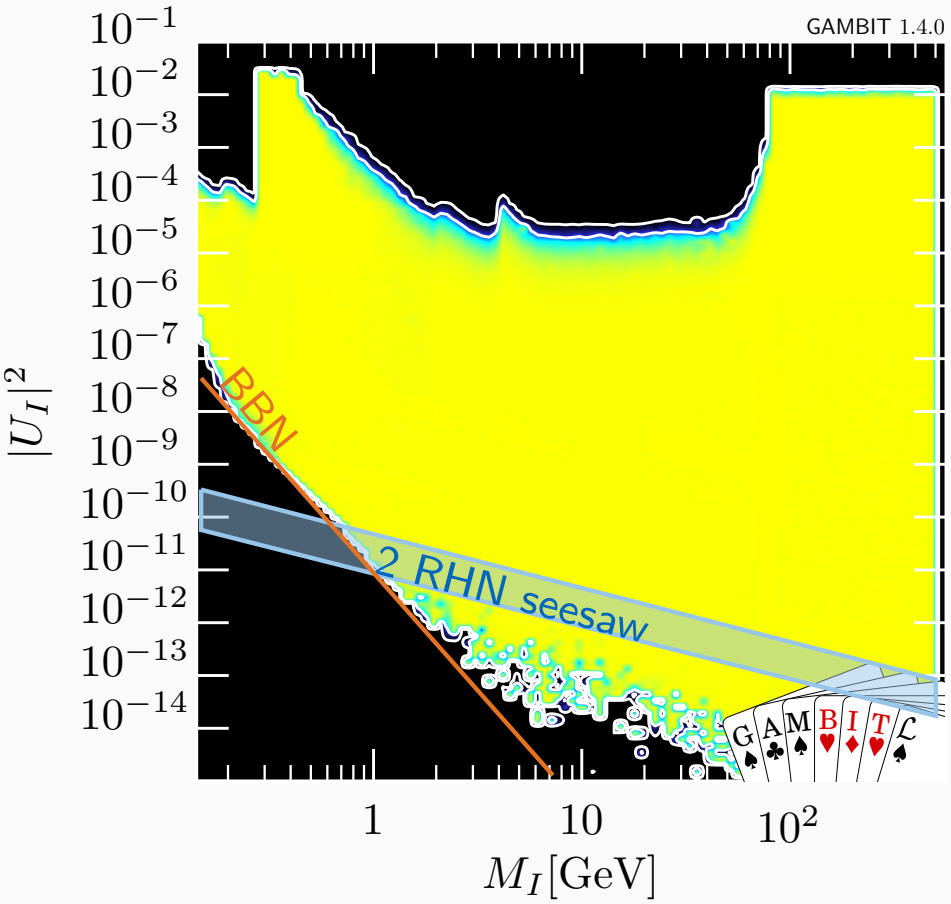


How is $3 \neq 2$?: Allowed mixing angles (3 RHN)

- smallest $U_i^2 \sim m_1/M$, can be $\ll m_{\rm sol}/M_i$
- lower limit from BBN
- weaker combined bounds from past experimental searches
  - mainly correspond to $U_i^2 \sim U_{\tau i}^2$



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

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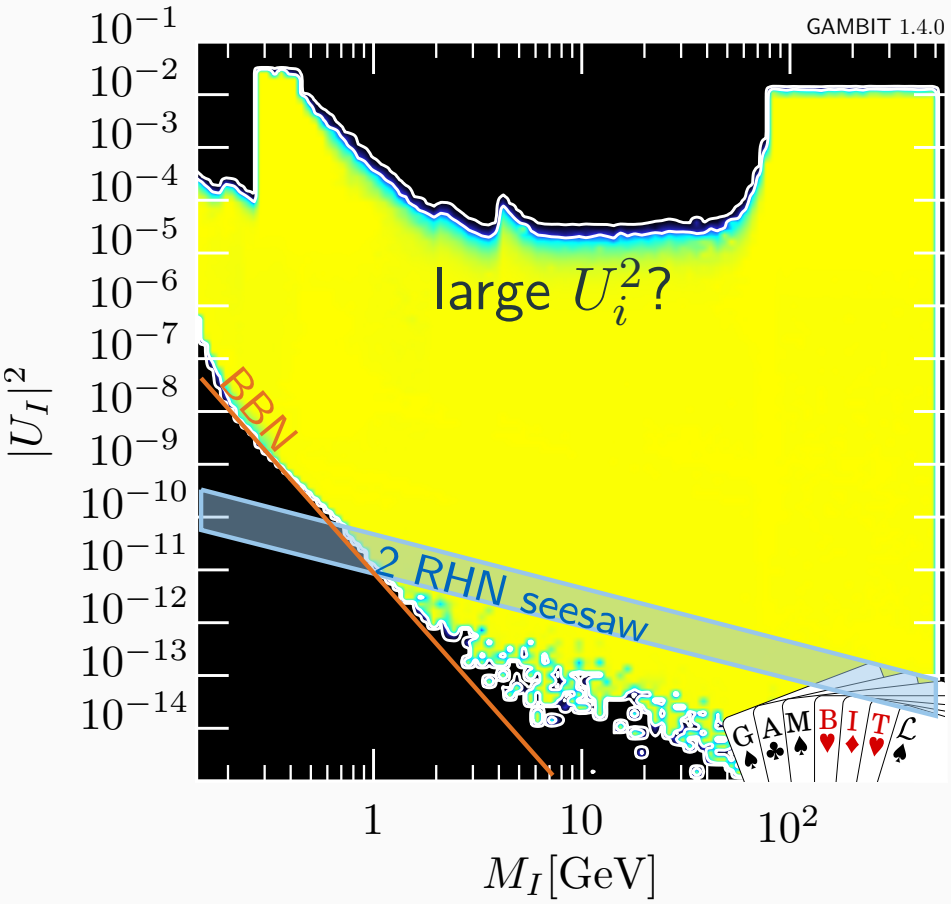

[Chrzaszcz/Drewes/Gonzalo/Harz/Krishnamurthy/Weniger 1908.02302]

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

$$M_M = \bar{M} \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

$$F = \frac{1}{\sqrt{2}} \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix}$$

How is $3 \neq 2$?: Parameter space

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\text{diag}}} \mathcal{R} \sqrt{M_M}$$

[Casas, Ibarra 2001]

2 Heavy Neutrinos (νMSM)

$+$ 2 RHN masses

2 parameters

3 Heavy Neutrinos

$+$ 3 RHN masses

3 parameters

How is $3 \neq 2$?: Parameter space

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\text{diag}}}\, \mathcal{R} \sqrt{M_M}$$

[Casas, Ibarra 2001]

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3 parameters

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$+$ 3 *complex* $(\times 2)$ angles

6 parameters

How is $3 \neq 2$?: Parameter space

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\text{diag}}} \mathcal{R} \sqrt{M_M}$$

[Casas, Ibarra 2001]

2 Heavy Neutrinos (νMSM)

$+$ 2 RHN masses

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$+$ **2 light neutrino masses**

5 parameters

3 Heavy Neutrinos

$+$ 3 RHN masses

$+$ 3 *complex* $(\times 2)$ angles

$+$ **$2+1$ light neutrino masses**

9 parameters

How is $3 \neq 2$?: Parameter space

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\text{diag}}} \mathcal{R} \sqrt{M_M}$$

[Casas, Ibarra 2001]

2 Heavy Neutrinos (νMSM)
$+$ 2 RHN masses
$+$ 1 *complex* $(\times 2)$ angle
$+$ **2 light neutrino masses**
$+$ **3 PMNS angles**
$+$ 1 CP phase δ
$+$ 1 Majorana phase α
11 (6 free) parameters

3 Heavy Neutrinos
$+$ 3 RHN masses
$+$ 3 *complex* $(\times 2)$ angles
$+$ **2+1 light neutrino masses**
$+$ **3 PMNS angles**
$+$ 1 CP phase δ
$+$ 2 Majorana phases $\alpha_{1,2}$
18 (13 free) parameters

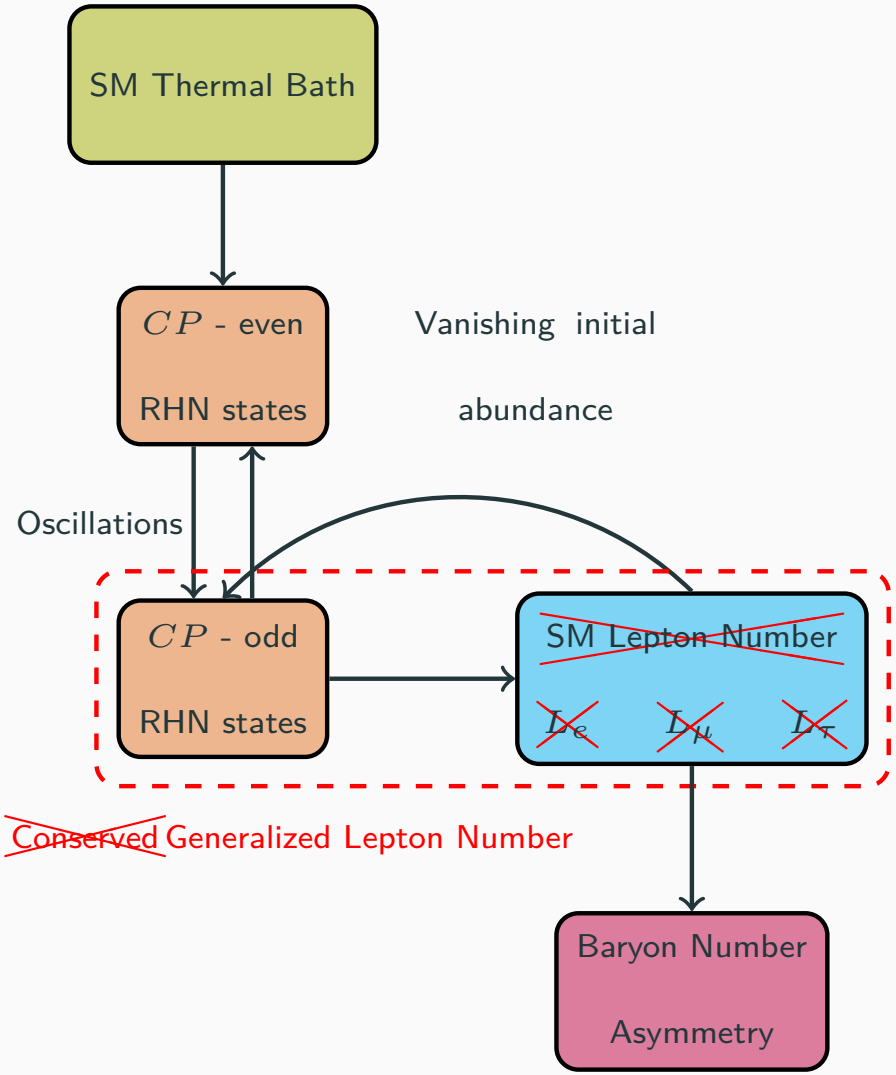
Fine tuning

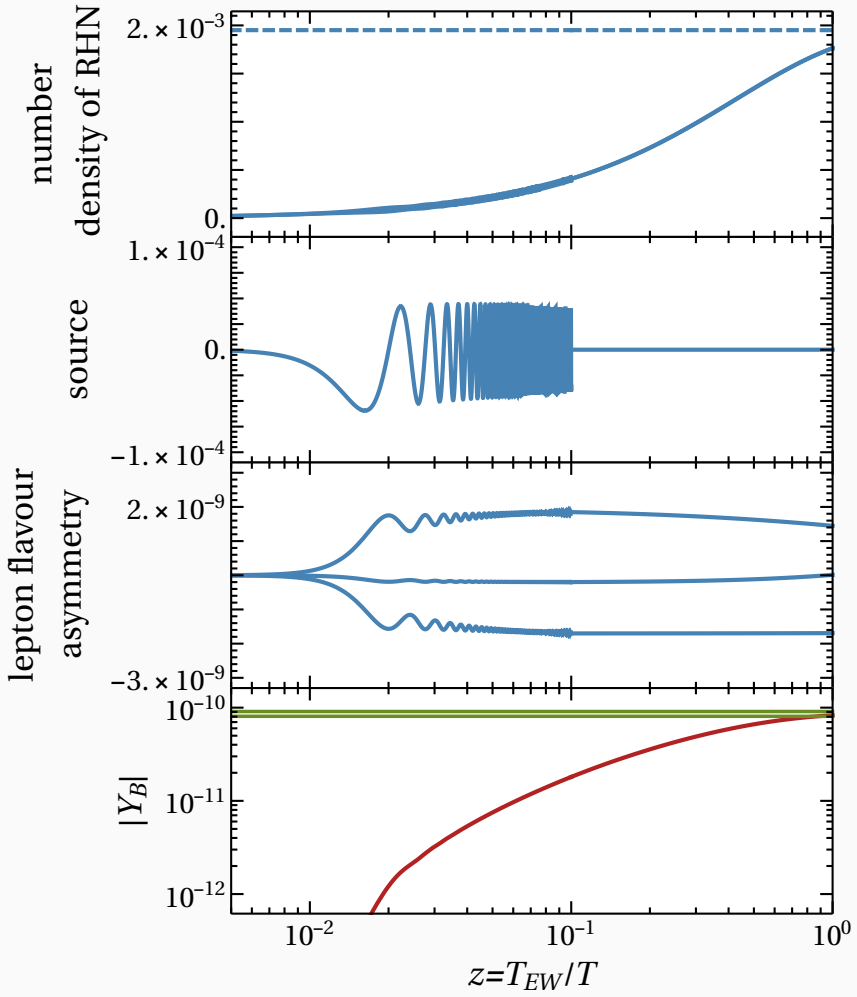
- if present, symmetries are manifest to all orders in p.t.
- in the case of a large B-L breaking, radiative corrections can cause large neutrino masses
- we can use the size of radiative corrections to the light neutrino masses to quantify tuning

Fine Tuning

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

Leptogenesis via Neutrino Oscillations



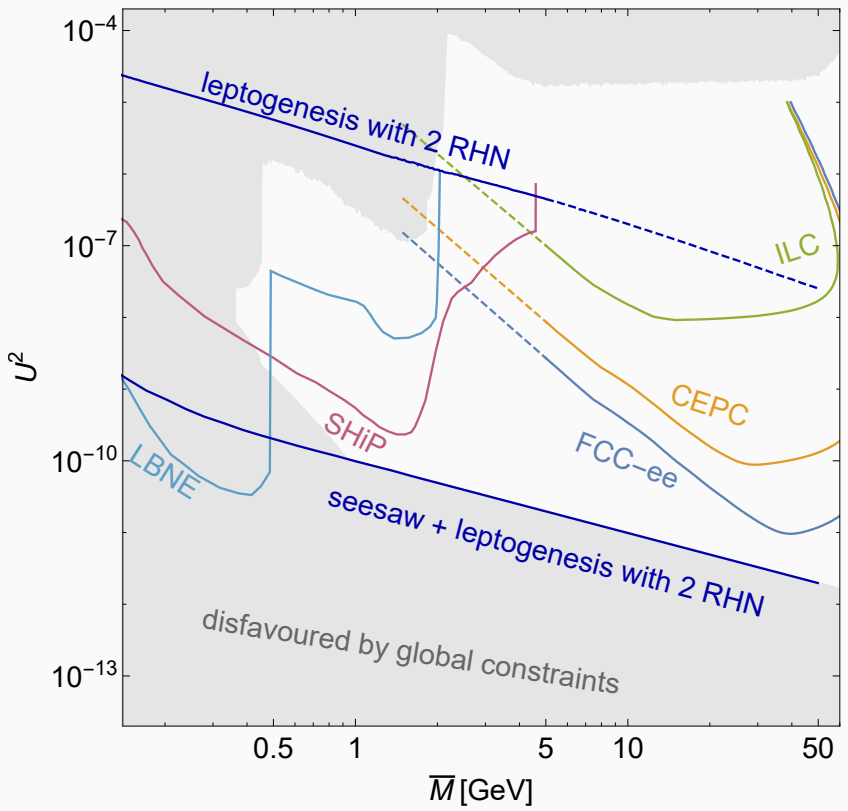


Theoretical challenges and progress:

- 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

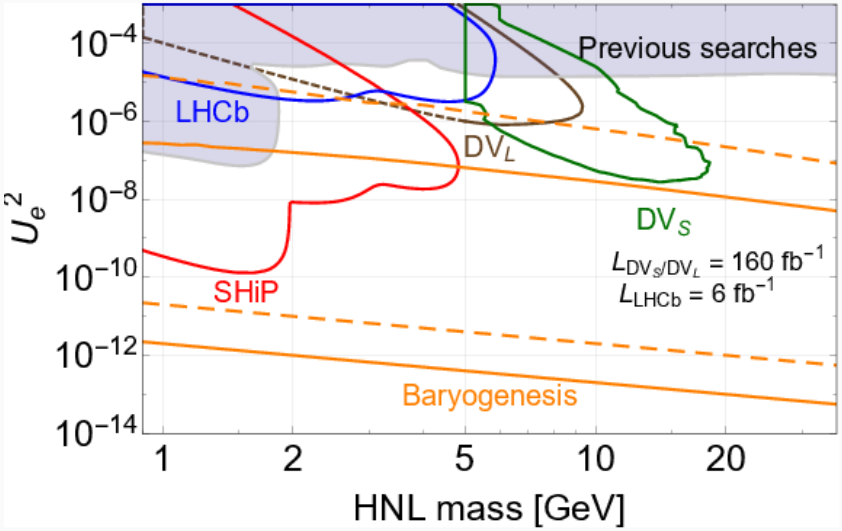


Inverted Ordering

[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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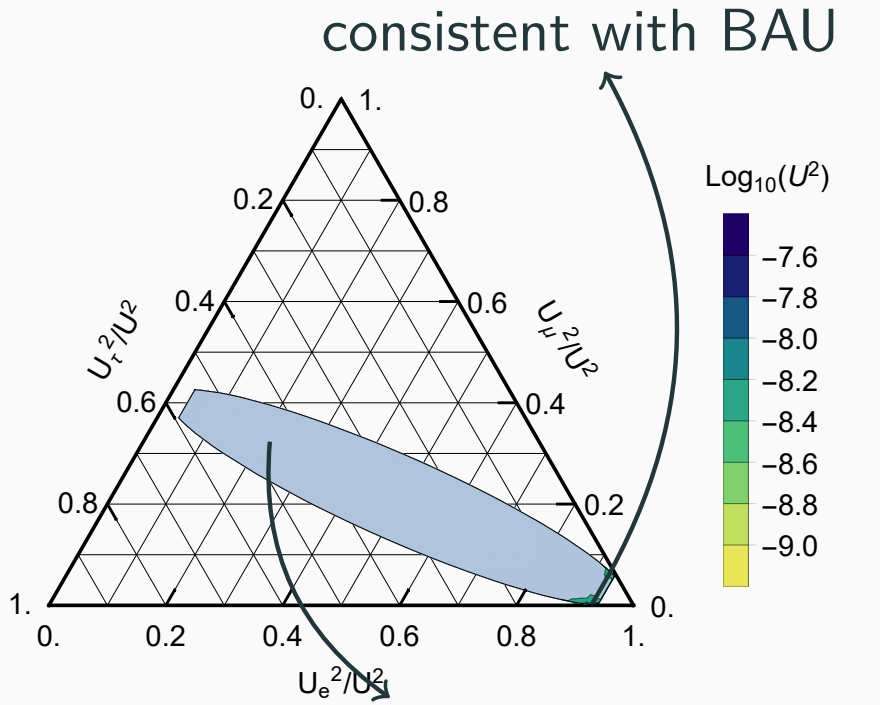

$$\bar{M} = 30\,\mathrm{GeV}$$
$$U^2 = 4 \times 10^{-9}$$

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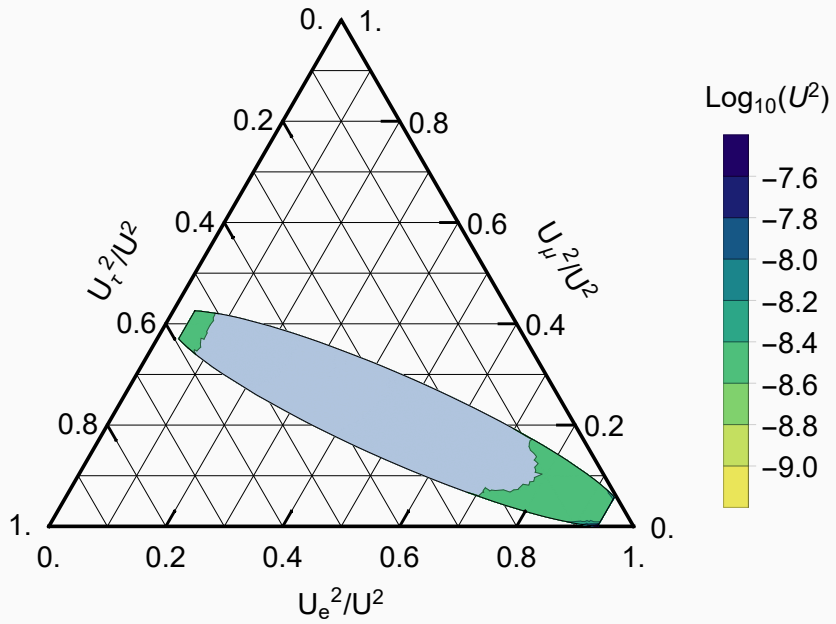
[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]

Leptogenesis with 2 RHN



$$\bar{M} = 30\,\mathrm{GeV}$$
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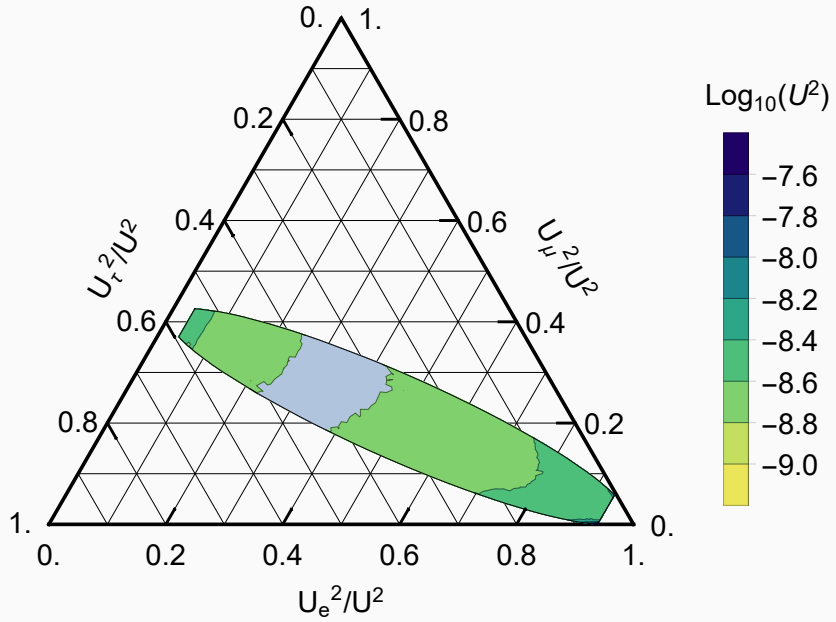

$$\bar{M} = 30\,\mathrm{GeV}$$
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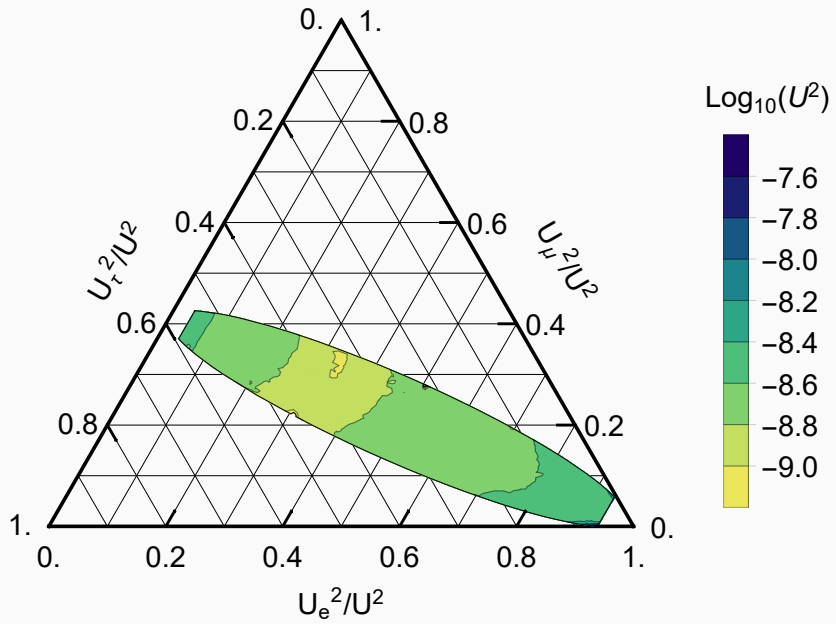

$$\bar{M} = 30\,\mathrm{GeV}$$
$$U^2 < 1 \times 10^{-9}$$

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

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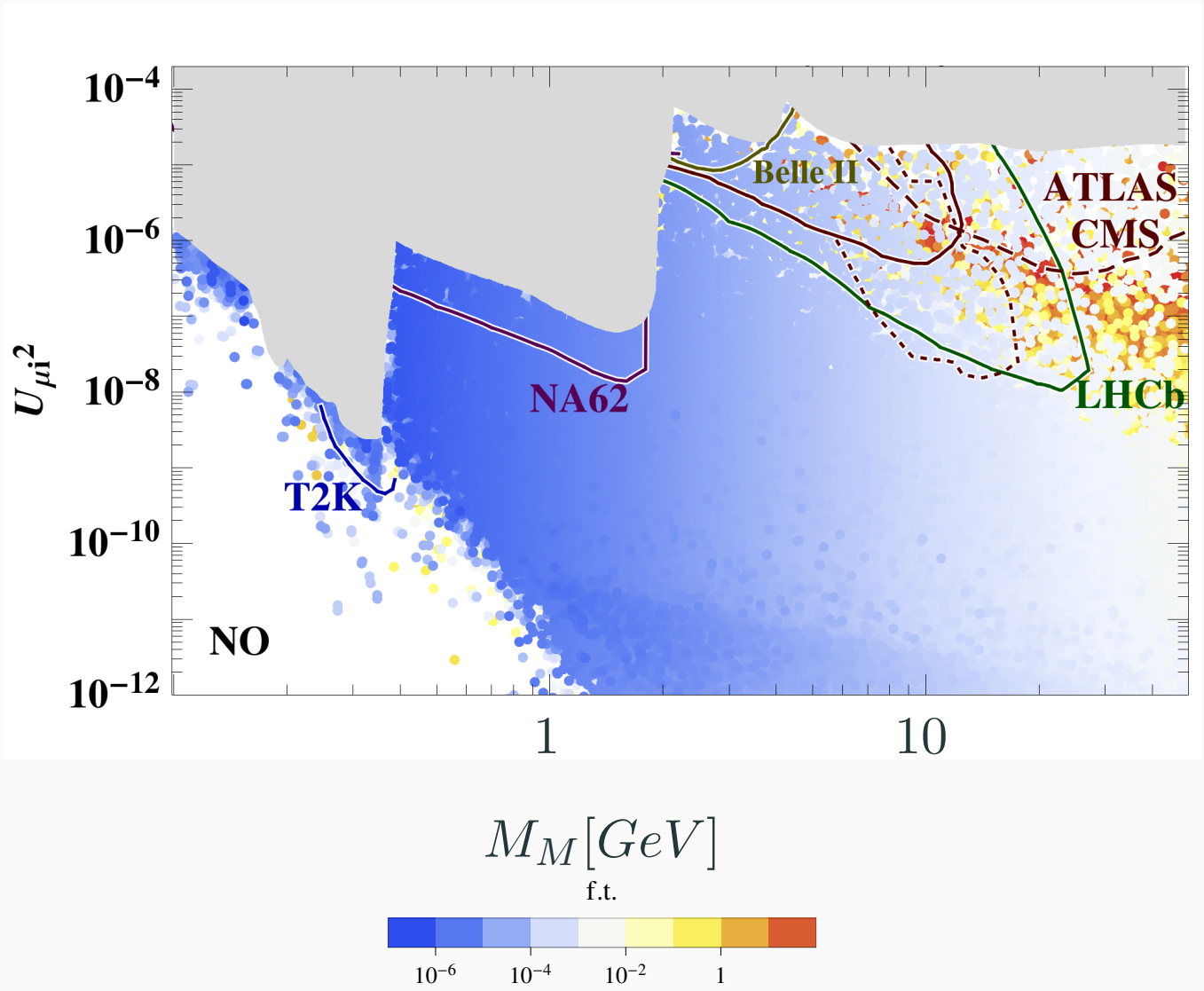
Results: Leptogenesis with 3 RHN (Normal Ordering)



[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

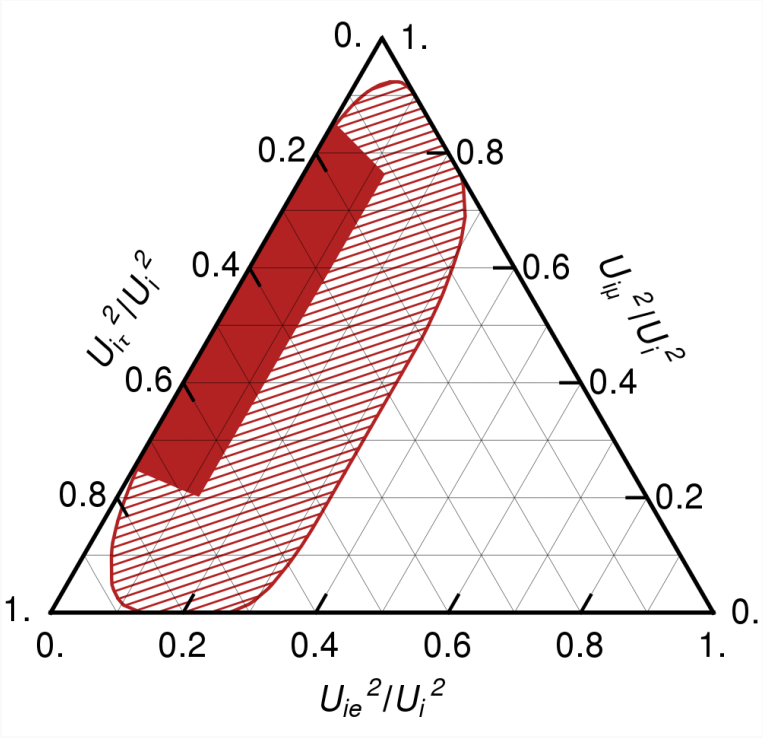
- level crossing between the heavy neutrinos

  new effect!

  Sakharov II: CP

Hierarchy in the washout

- lepton asymmetry can survive washout if hidden in a particular flavor
- washout supression $W \sim \mathfrak{f} \sim \min(|F_a|)/\max(|F_a|)$
- for 2 RHN $\mathfrak{f} > 5 \times 10^{-3}$
- for 3 RHN $\mathfrak{f} \ll 1$ possible



[Drewes/Hajer/JK/Lanfranchi 1801.04207]

[Drewes/Garbrecht/Gueter/JK 1609.09069]

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

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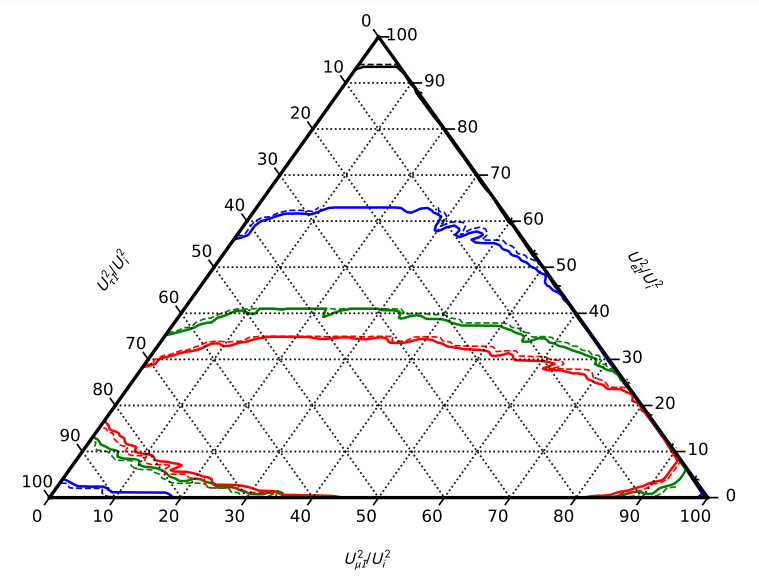
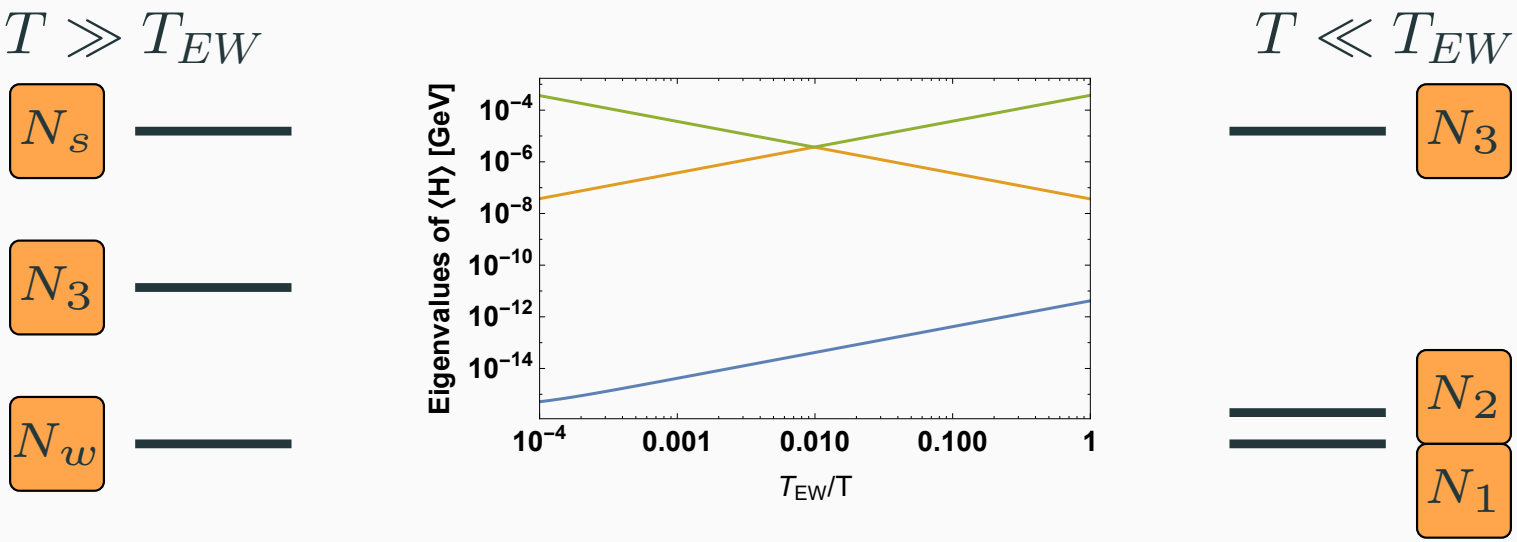
- for 2 RHN $\mathfrak{f} > 5 \times 10^{-3}$
- for 3 RHN $\mathfrak{f} \ll 1$ possible



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

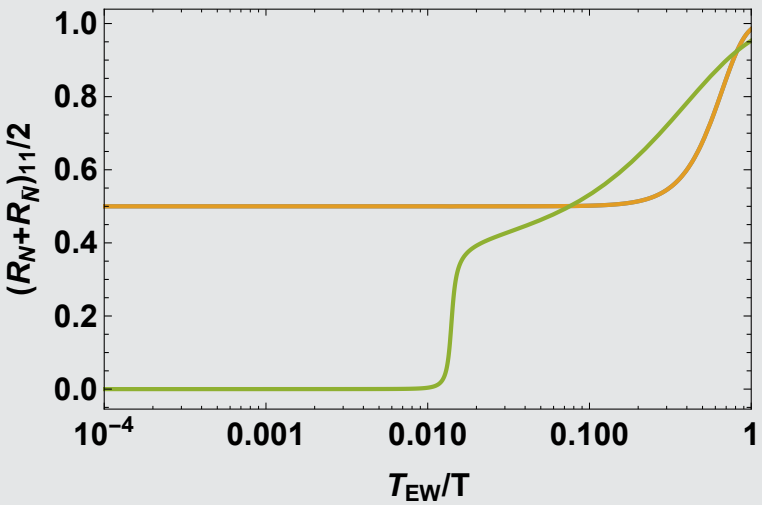
Enhancement due to level crossing

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

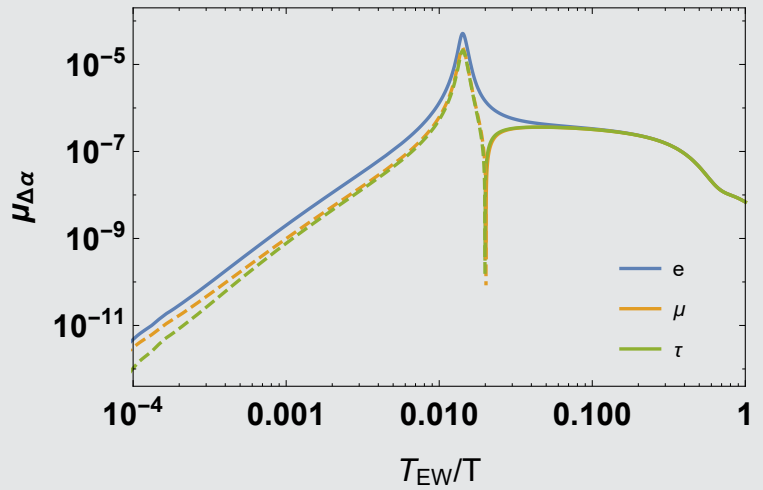


Enhancement due to level crossing

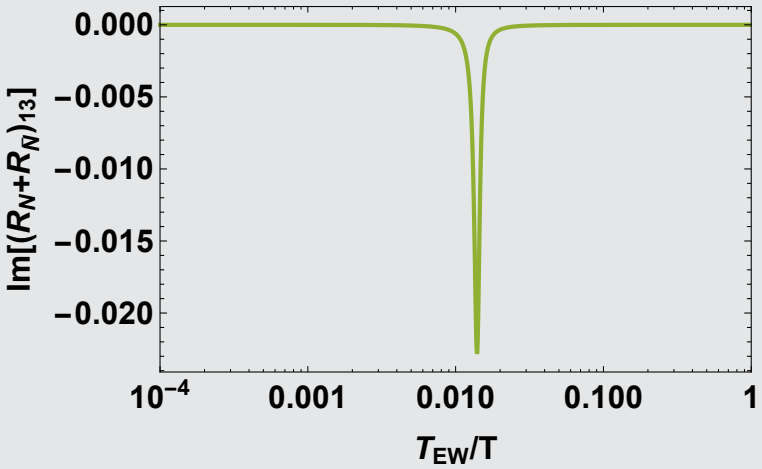
Heavy Neutrino Densities



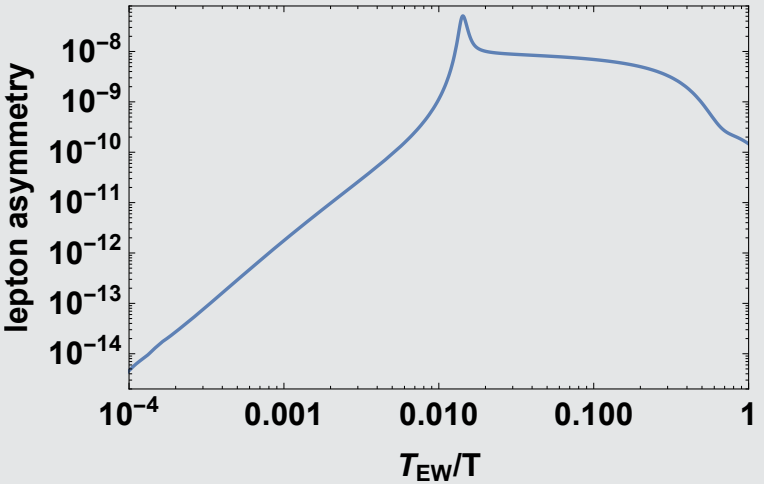
Lepton flavour asymmetries



Heavy Neutrino correlations



Lepton number asymmetry



Conclusions

Summary

- GeV-scale RHN are a viable solution to the questions of the BAU and neutrino masses
- first systematic study of the parameter space with three RHN
- no upper bound on U_i^2 from leptogenesis!
- **new mechanism** with resonantly enhanced production of the baryon asymmetry!