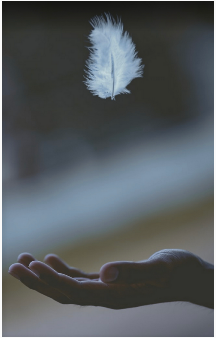


Heavy Neutral Leptons:

the FIP Physics Centre approach

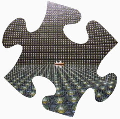
Juraj Klarić

FIPs workshop, October 21st 2022

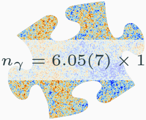
UCLouvain

Some puzzles for physics beyond the Standard Model

Neutrino masses



The Baryon Asymmetry of the Universe



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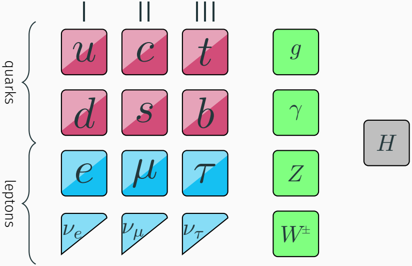

Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

Some puzzles for physics beyond the Standard Model

Neutrino masses

[Minkowski 1977...]

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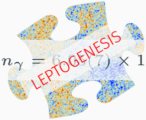

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[Fukugita/Yanagida '86...]

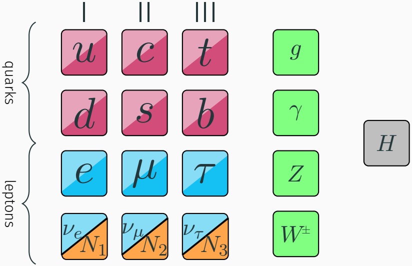


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

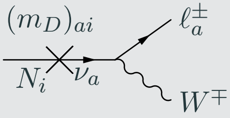
Discovering heavy neutral leptons

The seesaw mechanism and the Majorana neutrino mixing

Active neutrino masses

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

HNL mixing



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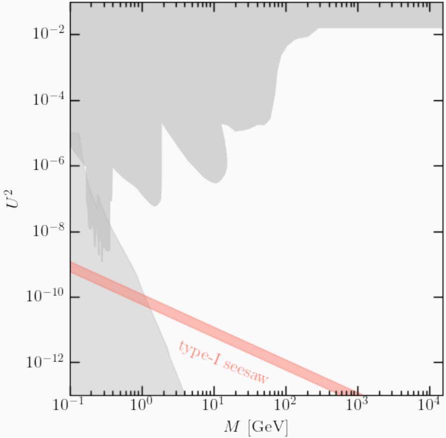

[figure adapted from Snowmass WPs 2203.08039 and 2203.05502]

[see talks by A. Marocco, B. Dey, A. Golutvin, E. Goudzovski, A. Paolini, J. Kopp, S. C. Middleton, JL Tastet, Giulia Ripellino]

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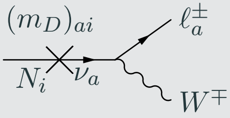

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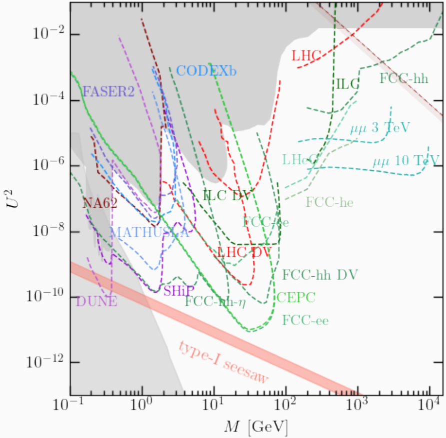

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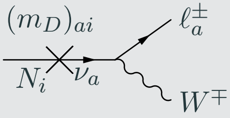

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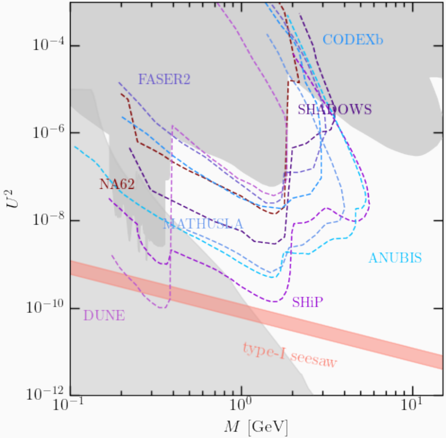

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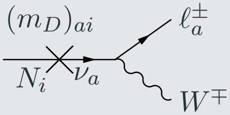

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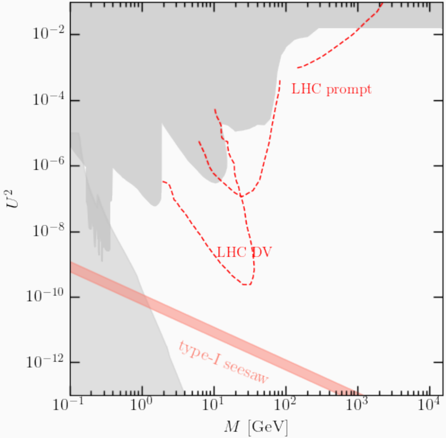

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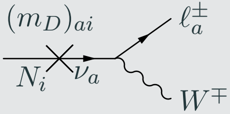

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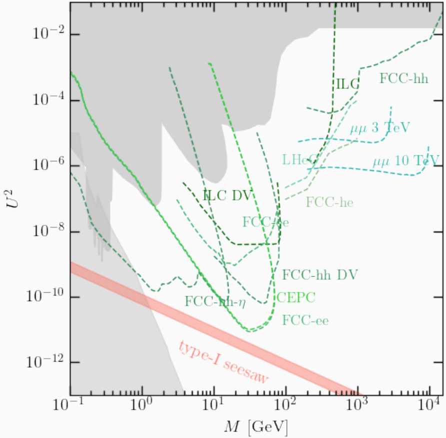

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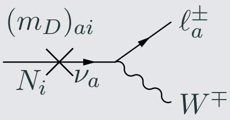

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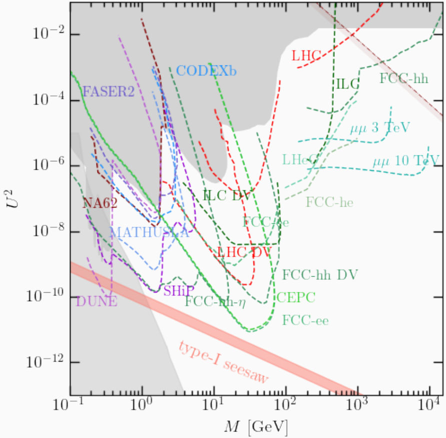

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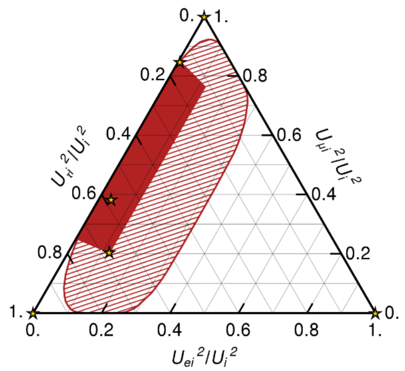
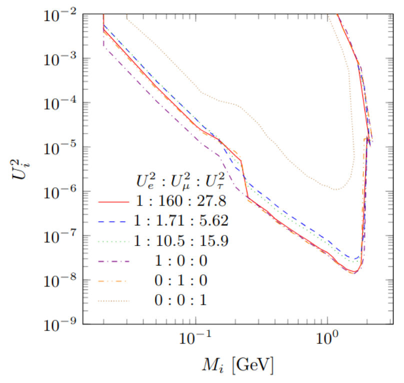
Realistic benchmarks

Sensitivity of experiments highly depends on mixing ratios:

NA62 in beam dump mode

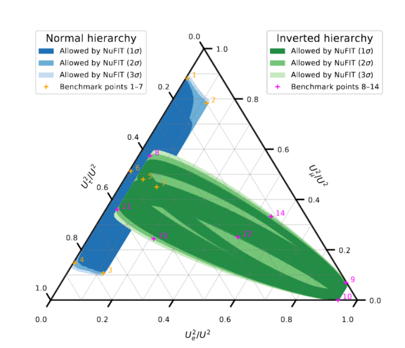


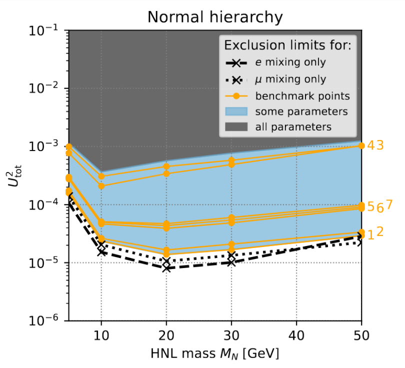


[Drewes/Hajer/JK/Lanfranchi 1801.04207]

Sensitivity of experiments highly depends on mixing ratios:

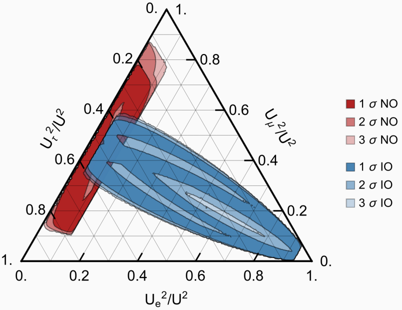
ATLAS





[Tastet/Ruchayskiy/Timiryasov 2107.12980] [see also talk by JL Tastet]

Constraints from the seesaw mechanism



[Drewes/JK/Lopez-Pavon 2207.02742]

[using nuFIT 5.1 2007.14792]

- in the minimal seesaw model the ratios are completely determined by U_{PMNS}
- ratios dominated by Majorana phase η, Dirac phase δ and θ_{23}
- allowed ratios become smaller as we pin down the PMNS parameters
- How to choose future-proof benchmarks?

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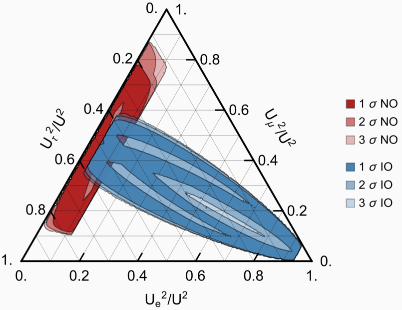

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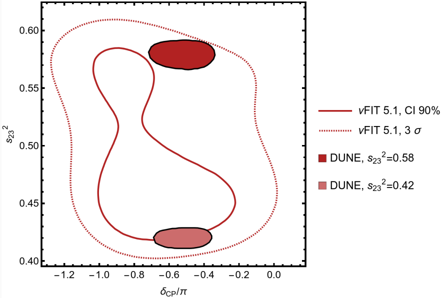
Future sensitivity?

- 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]

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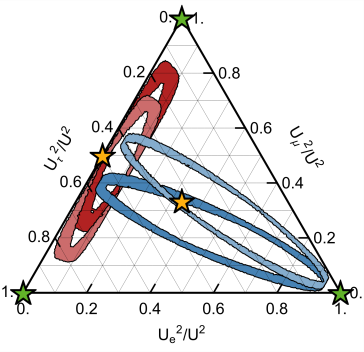
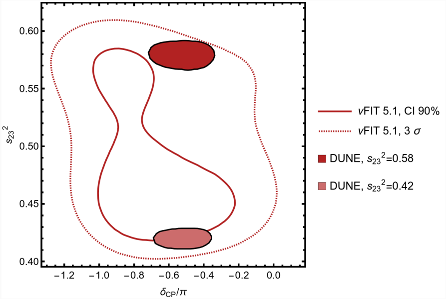


[Figure from 2207.02742]



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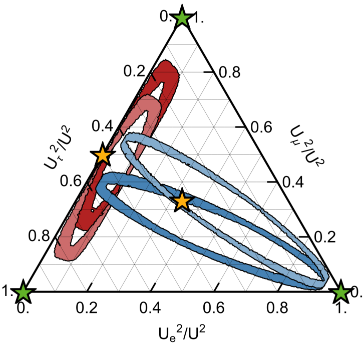
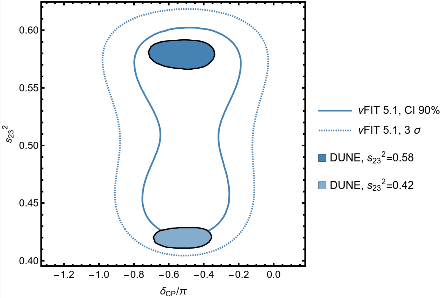


[Figure from 2207.02742]



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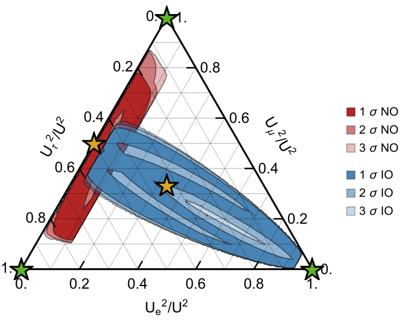
New Benckmark Points



[Figure from 2207.02742]

- 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:
  - $U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 1$
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- Reinterpretations still highly desirable [see talk by JL Tastet]

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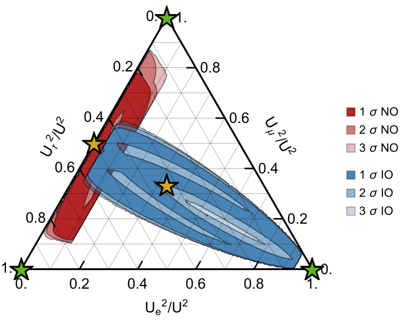

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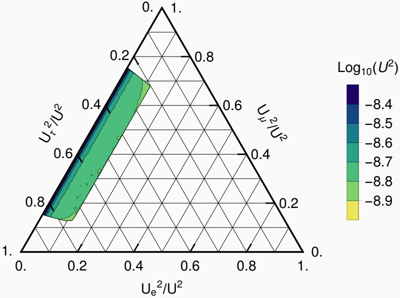
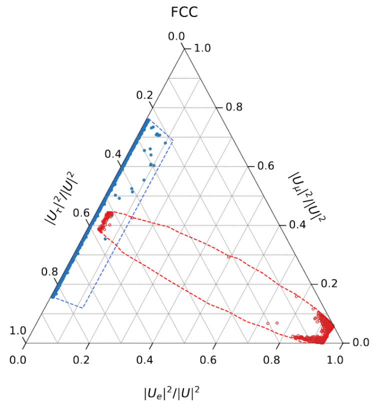
Flavor constraints from leptogenesis



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

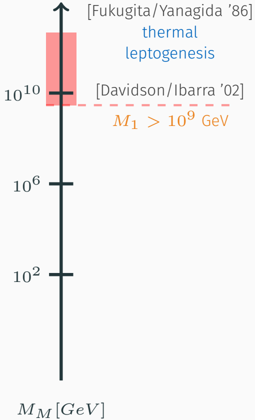


$$\Delta M/M = 10^{-2}$$

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

Input from cosmology: low-scale leptogenesis

Leptogenesis mechanisms



[Fukugita/Yanagida ’86]

thermal leptogenesis

[Davidson/Ibarra ’02]

$M_1 > 10^9$ GeV

Sakharov conditions

1. Baryon number violation

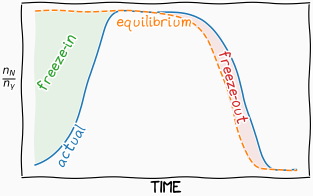
   sphaleron processes

2. C and CP violation

   RHN decays and oscillations

3. Deviation from thermal equilibrium

   freeze-in and freeze-out of RHN



- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV

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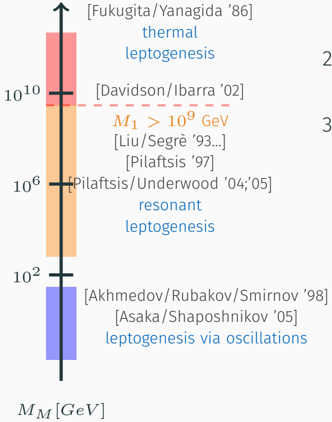

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[Pilaftsis ’97]
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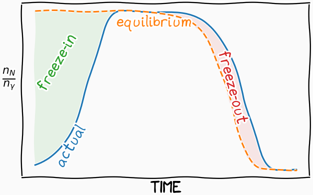

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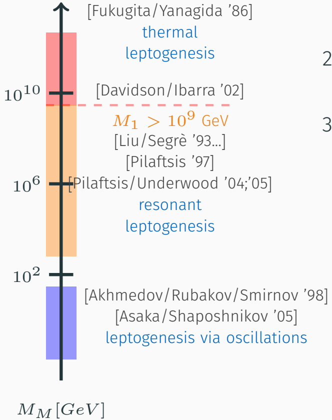

[Fukugita/Yanagida ’86]
thermal leptogenesis

10^{10}

[Davidson/Ibarra ’02]
$M_1 > 10^9$ GeV

[Liu/Segrè ’93...]
[Pilaftsis ’97]

10^6

[Pilaftsis/Underwood ’04;’05]
resonant leptogenesis

10^2

[Akhmedov/Rubakov/Smirnov ’98]
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leptogenesis via oscillations

$M_M\,[GeV]$

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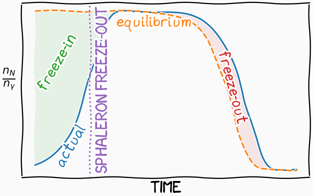

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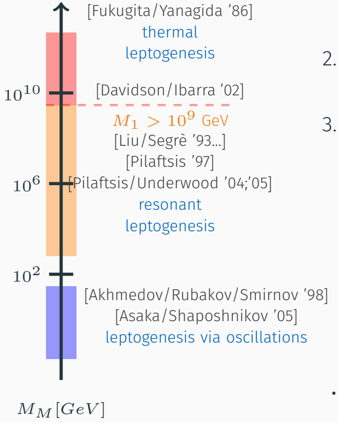

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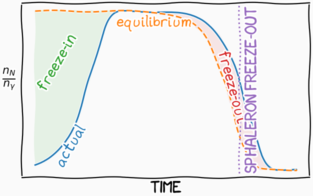

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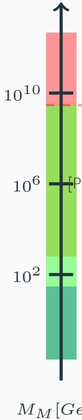

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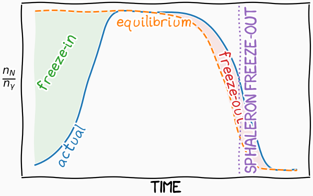
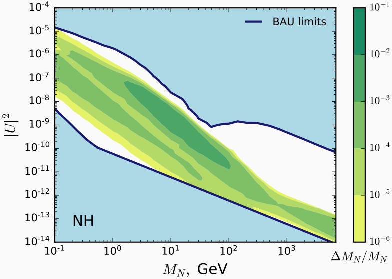


- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV
- leptogenesis works in a wide range of RHN masses
- how are the low-scale mechanisms connected?

Results: The minimal model with 2 RHNs

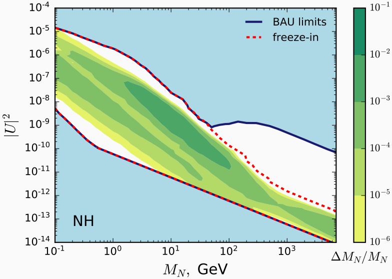


[JK/Timiryasov/Shaposhnikov 2103.16545]

- 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

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions
- leptogenesis via oscillations is freeze-in dominated, we neglect HNLs falling out of equilibrium
- results depend on low-energy CP phases:
  - optimal phases $\delta = 0$ and $\eta = \pi/2$
  - less overlap for e.g. $\delta = \pi$ and $\eta = 0$
  - maximal $\Delta M/M \lesssim 10^{-1} \rightarrow 10^{-3}$
- overall agreement with analytic approximations from [2207.01651] [see talk by S. Sandner]

Results: The minimal model with 2 RHNs



[JK/Timiryasov/Shaposhnikov 2103.16545]

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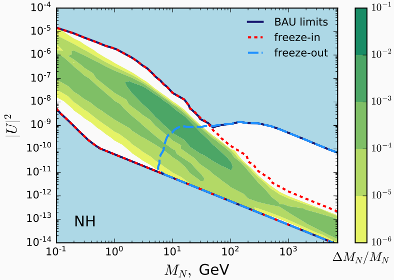

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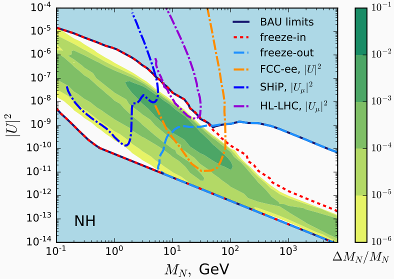

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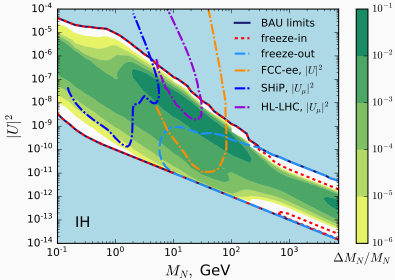

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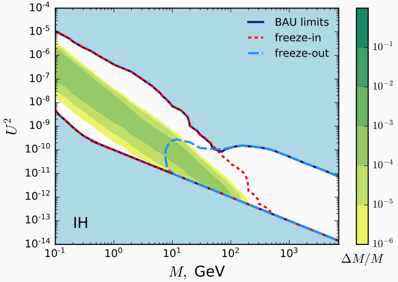

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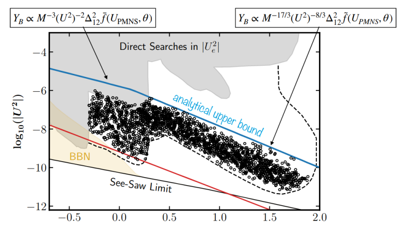

[Hernandez/Lopez-Pavon/Rius/Sandner 2207.01651]

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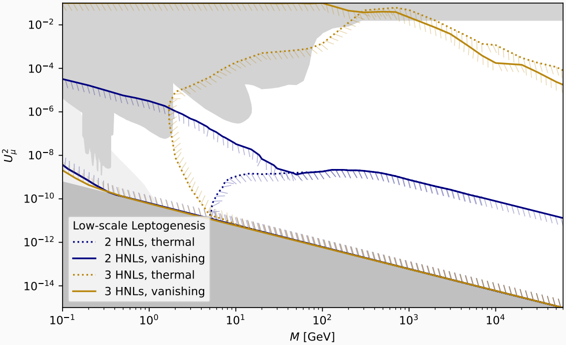

[Snowmass White Paper 2203.08039]

leptogenesis bounds from [Drewes/Georis/JK 2106.16226]

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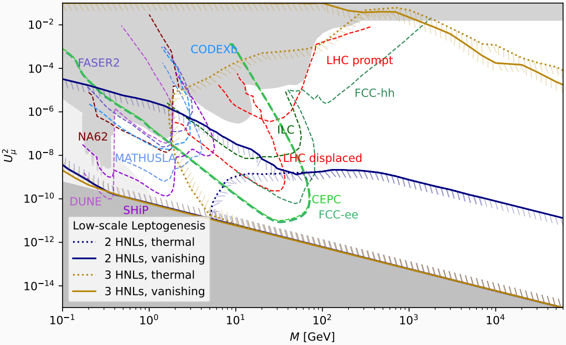

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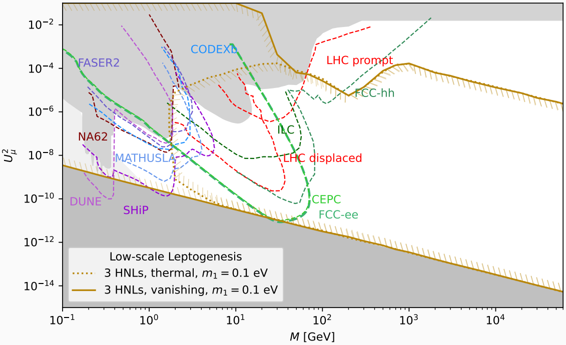

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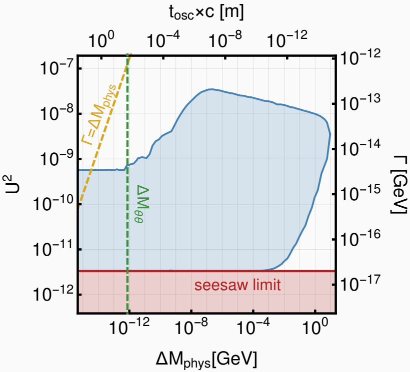
From discovery to tests

Measuring the mass splitting in model with 2 HNLs

Normal Ordering:



$M = 30$ GeV

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

1710.03744]

- large range of ΔM consistent with leptogenesis
- energy resolution of planned experiments - $\Delta M/M \sim \mathcal{O}(\text{few}\%)$
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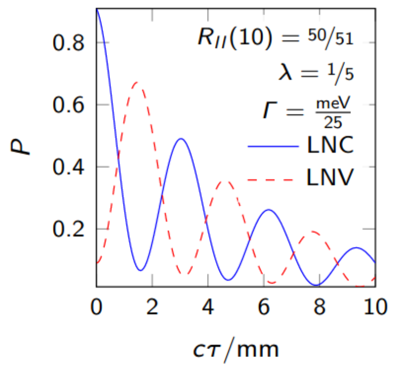

[Antusch/Hajer/Rosskopp 2210.10738]

[see talk by J. Hajer]

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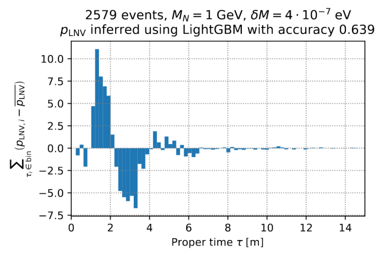

[Tastet/Timiryasov 1912.05520]

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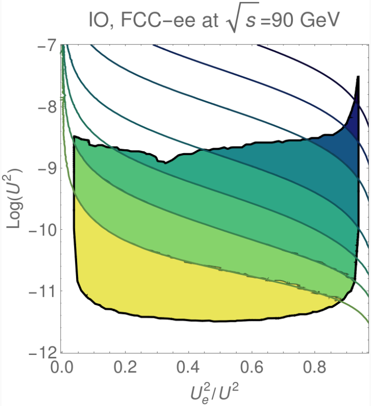
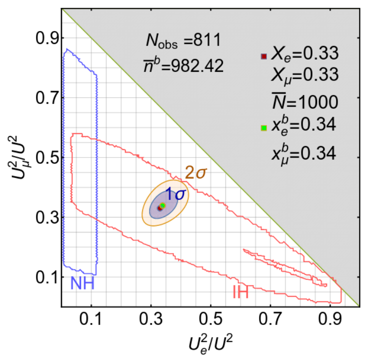
Measuring flavor ratios at experiments

$M_N = 30$ GeV @ FCC-ee



$M_N = 1$ GeV @ SHiP

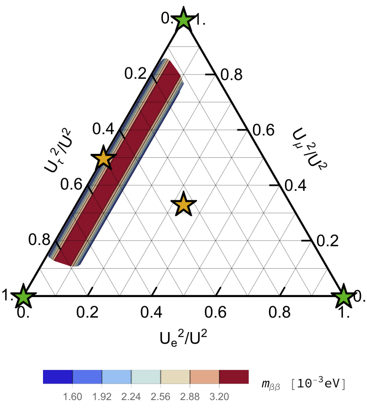


[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK

1710.03744]

[Snowmass HNL WP 2203.08039]

Complementarity with neutrinoless double beta decay



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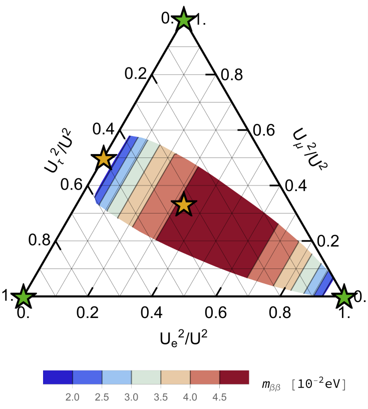

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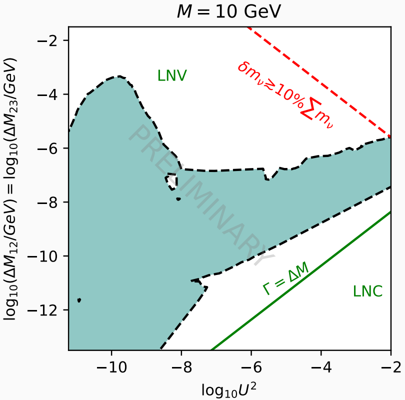
3 HNLs: range of mixing angles U^2 and mass splittings ΔM



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- upper bound on U^2 arises through a combination of baryogenesis + fine tuning constraints
- leptogenesis consistent with both LNV and LNC RHN decays
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[Drewes/Georis/JK 22Xx.xxxx]

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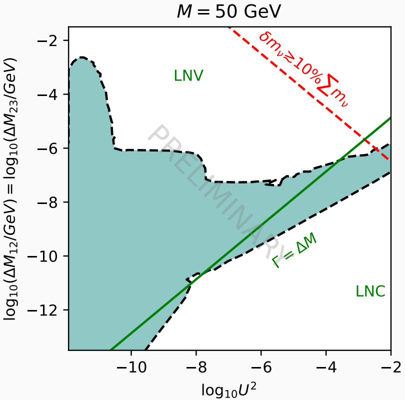

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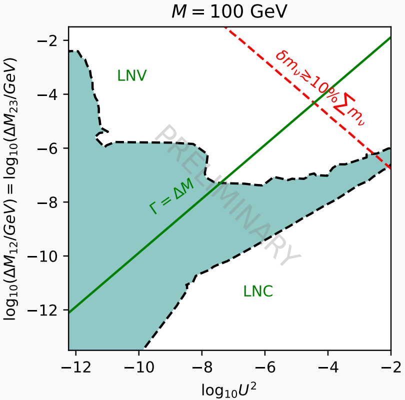

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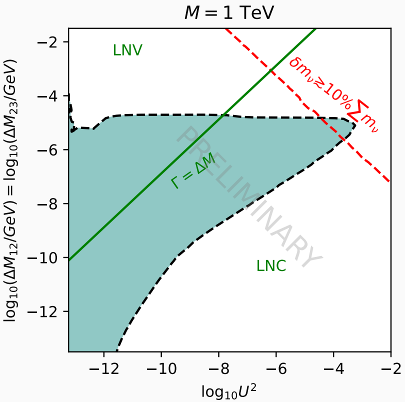

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[Drewes/Georis/JK 22Xx.xxxx]

Conclusions

- experimental sensitivities differ depending on flavor ratios
- tools for reinterpretation are highly desirable
- proposed new benchmarks for HNL searches
- when accesible LNV is an important observable $R_{\ell\ell}$
- leptogenesis is a viable baryogenesis mechanism for all heavy neutrino masses above the $\mathcal{O}(100)$ MeV scale
- leptogenesis is within reach at planned future experiments
  - synergy between high-energy and high-intensity frontiers!
  - together they can cover a large portion of the low-scale leptogenesis parameter space

Thank you!

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

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

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

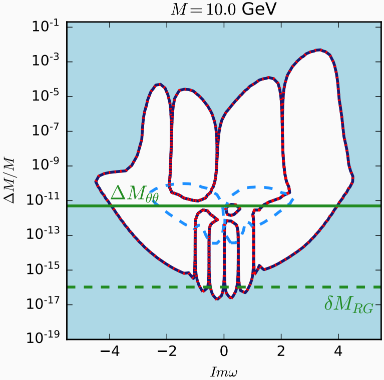
Fine tuning

- 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

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

Slices of the parameter space



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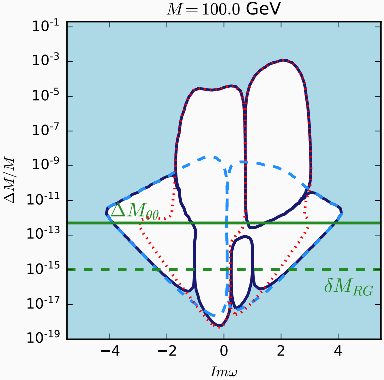

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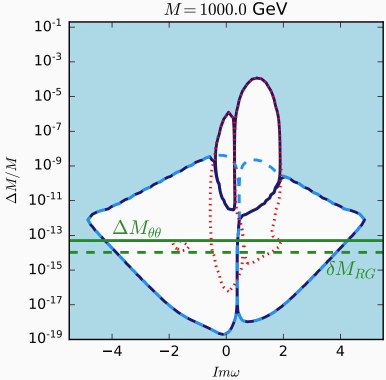

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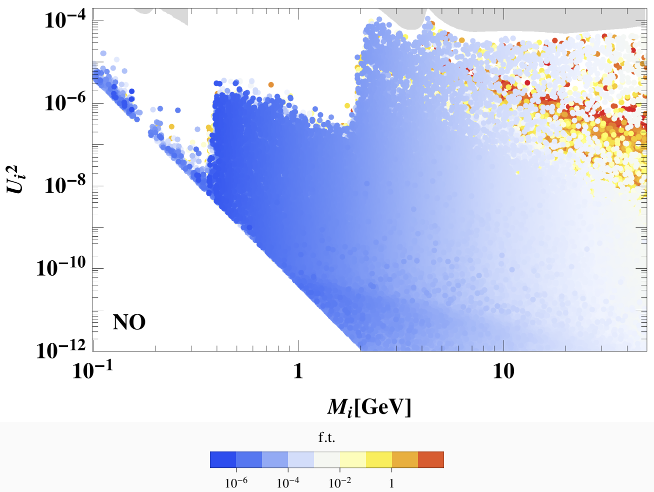

[Abada/Arcadi/Domcke/Drewes/JK/Lucente 1810.12463]

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

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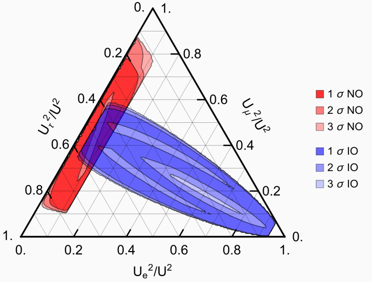

[Snowmass White Paper 2203.08039]

[Drewes/Garbrecht/Gueter/JK 1609.09069]

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

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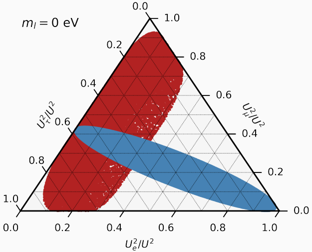

[Drewes/Georis/JK 220x.xxxx]

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

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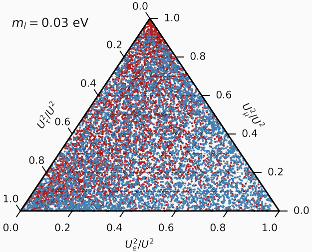
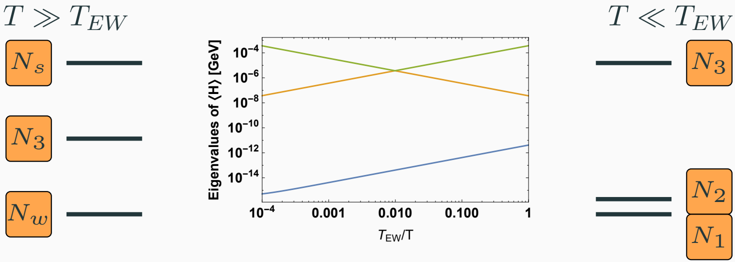


[Drewes/Georis/JK 220x.xxxx]

[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



$T \gg T_{EW}$

N_s

N_3

N_w

$T \ll T_{EW}$

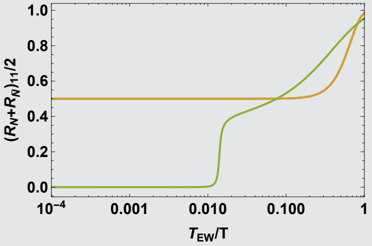
N_3

N_2

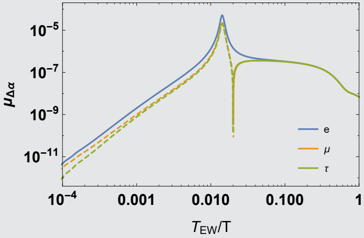
N_1

Enhancement due to level crossing

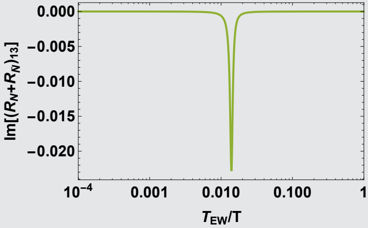
Heavy Neutrino Densities



Lepton flavour asymmetries



Heavy Neutrino correlations



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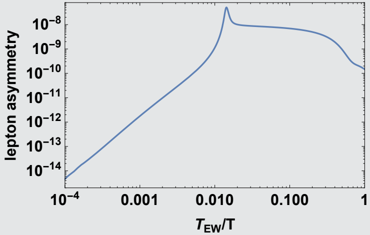
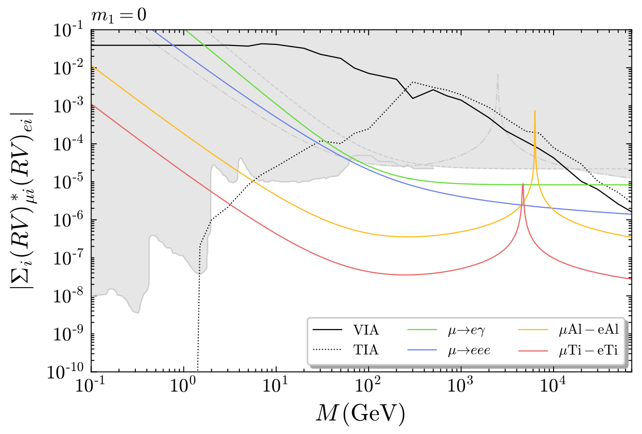


Indirect probes: Charged LFV



[Granelli/JK/Petcov 2206.04342]

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- future $\mu \to e$ conversion experiments can probe a large part of the $N = 3$ parameter space

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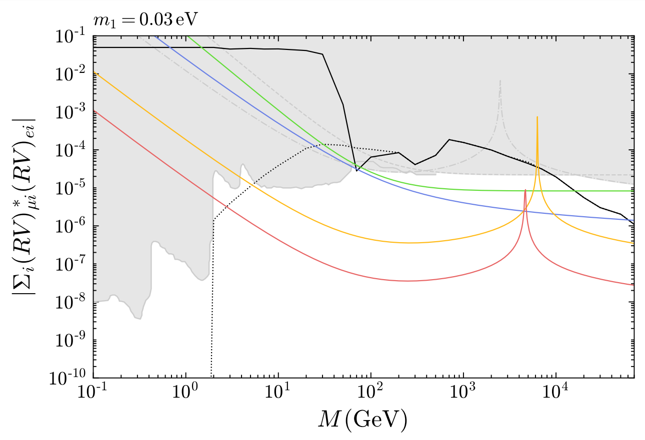

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