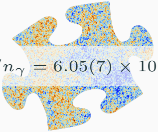
Uniting low-scale leptogeneses

Juraj Klarić
based on 2008.13771 in collaboration with M.E. Shaposhnikov and I. Timiryasov

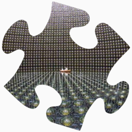
8^{th} LLP Workshop, 19.11.2020

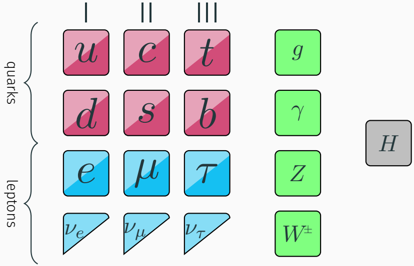
The Baryon Asymmetry of the Universe



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

Neutrino masses





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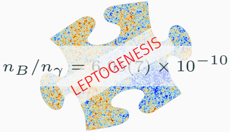

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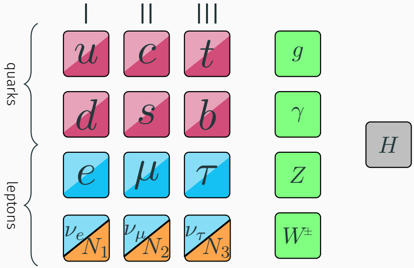


Neutrino masses and the type-I seesaw

The ν mass matrix

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

- ν_R are SM gauge singlets

Active neutrino masses

$$m_\nu = m_D?$$

[Minkowski 1977...]

[1]"Everything not forbidden is compulsory." - Murray Gell-Mann

Neutrino masses and the type-I seesaw

The ν mass matrix

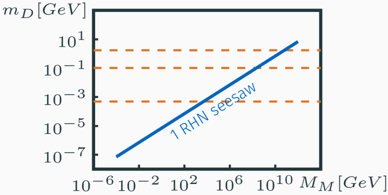
$$\mathcal{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

- ν_R are SM gauge singlets
- $m_D = vF$ and M_M[1] are free parameters
- minimal scenario: 2 right-handed neutrinos (RHN)

Active neutrino masses

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

[Minkowski 1977...]



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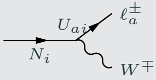
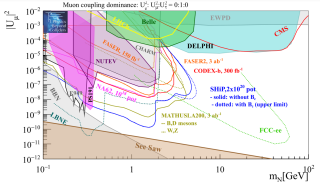
How can we search for heavy neutrinos?

Mixing with RHN



$$U_{ai}^2 \equiv \left|\left(m_D M_M^{-1}\right)_{ai}\right|^2$$

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



[PBC working group report 1901.09966]

17:05 → 18:55 **Heavy neutral leptons (HNLs) session**

Conveners: Albert De Roeck (CERN), Federico Leo Redi (EPFL - Ecole Polytechnique Federale Lausanne (CH))

17:05 **HNL Introduction**

Speaker: Federico Leo Redi (EPFL - Ecole Polytechnique Federale Lausanne (CH))

Slides

17:20 **News from FIPs workshop and discussions on HNLs**

Speaker: Marco Drewes (Universite Catholique de Louvain (UCL) (BE))

Drewes_LLP_HNL_...

17:40 **MeV-scale Seesaw and Leptogenesis**

Speaker: Michele Lucente (RWTH Aachen)

MeV seesaw leptog...

18:00 **A quantitative study on helicity inversion in Majorana neutrino decays at the LHC**

Speaker: Richard Ruiz (Universite Catholique de Louvain)

rruiz_LLP8_LNVHeli...

18:20 **Discussion round on MCs for HNLs**

Speakers: Jan Hajer (Université catholique de Louvain), Jean-Loup Tastet (University of Copenhagen (DK)), Lesya Shchutska (EPFL - Ecole Polytechnique Federale Lausanne (CH)), Sonia Amina Bouchiba (EPFL - Ecole Polytechnique Federale Lausanne (CH)), Various contributers

11-17-LLP-HNL-MC.... | HNLs in Pythia | JeanLoup_LLP_202... | LLP8_EPFL_HNL_st...

15:50 **Probing the long lived heavy neutrinos at the colliders (12'+3')** 15m

The neutrino oscillation experiment has clearly pointed out that the Standard Model neutrinos have tiny masses and their flavors are mixed. There are a plenty of models which explain the mechanism of the generation of the neutrino mass. In this talk we will discuss about the simple neutrino mass generation process at the TeV scale which is often called the seesaw mechanism and its phenomenological aspects at the high energy colliders from the long-lived scenarios.

Speaker: Arindam Das (Osaka University)

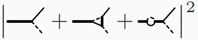
16:05 **Long-lived Sterile Neutrinos at the LHC in Effective Field Theory (12'+3')** 15m

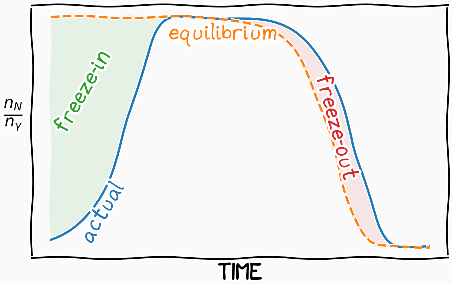
We study the prospects of a displaced-vertex search of sterile neutrinos at the Large Hadron Collider (LHC) in the framework of the neutrino-extended Standard Model Effective Field Theory. The production and decay of sterile neutrinos can proceed via the standard active-sterile neutrino mixing in the weak current, as well as through higher-dimensional operators arising from decoupled new physics. If sterile neutrinos are long-lived, their decay can lead to displaced vertices which can be reconstructed. We investigate the search sensitivities for the ATLAS/CMS detector, the future far-detector experiments: AL3X, ANUBIS, CODEX-b, FASER, MATHUSLA, and MoEDAL-MAPP, and at the proposed fixed-target experiment SHiP. We study scenarios where sterile neutrinos are predominantly produced via rare charm and bottom mesons decays through minimal mixing and/or dimension-six operators in the νSMEFT Lagrangian. We perform simulations to determine the potential reach of high-luminosity LHC experiments in probing the EFT operators, finding that these experiments are very competitive with other searches.

Speaker: Mr Guanghui Zhou (University of Massachusetts Amherst)

Baryogenesis through leptogenesis

Sakharov conditions

1. Baryon number violation
    - realized in the SM through sphaleron processes for $T \gtrsim 130$ GeV [D'Onofrio/Rummukainen/Tranberg 1404.3565]
2. C and CP violation
    - RHN oscillations and decays 
3. Deviation from thermal equilibrium
    - RHN freeze-in and freeze-out



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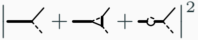
   - RHN oscillations and decays 
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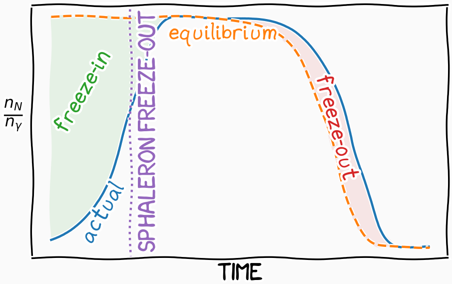

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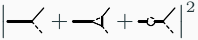
   - RHN oscillations and decays 
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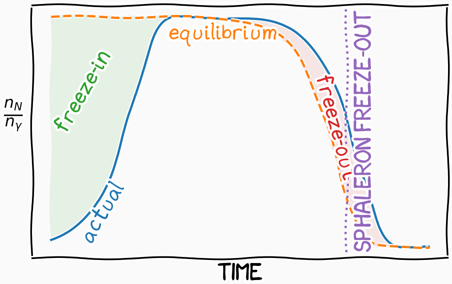
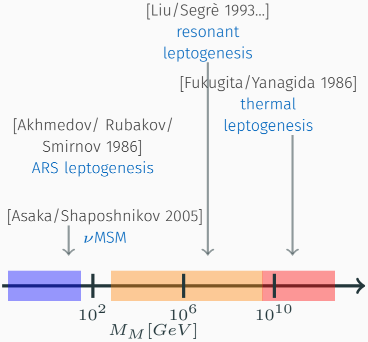


Leptogenesis mechanisms



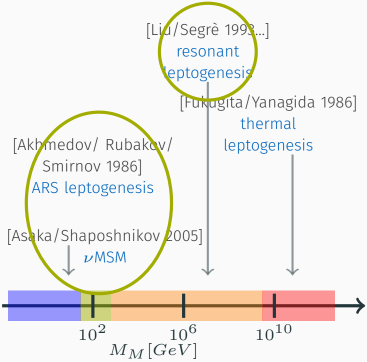
- several leptogenesis mechanisms exist for different masses
- for hierarchical RHN ($M_1 \ll M_2 \ll M_3$) the Davidson-Ibarra bound applies with:

$$M_1 \gtrsim 10^9 GeV$$

Loopholes:

- Resonant leptogenesis $M_M \gtrsim \mathrm{TeV}$
- Leptogenesis via RHN oscillations $M_M \sim \mathrm{GeV}$

Leptogenesis mechanisms



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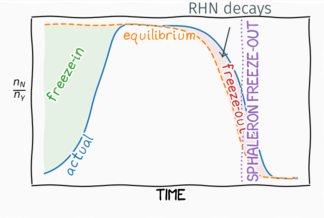
} Are these mechanisms connected?

Resonant leptogenesis

- the BAU is mainly produced in RHN decays
- The lepton asymmetries follow the equation

$$\frac{dY_{\ell_a}}{dz} = -\epsilon_a \frac{\Gamma_N}{Hz}(Y_N - Y_N^{\rm eq}) - W_{ab} Y_{\ell_b}$$



The key quantity determining the BAU is the decay asymmetry

$$\epsilon_a \equiv \frac{\Gamma_{N\to l_a} - \Gamma_{N\to \bar{l}_a}}{\Gamma_{N\to l_a} + \Gamma_{N\to \bar{l}_a}} = \frac{1}{8\pi}\frac{{\rm Im}(F^\dagger F)^2_{12}}{(F^\dagger F)_{11}}\frac{M_1 M_2}{M_1^2 - M_2^2}$$

Becomes enhanced if $M_2 \to M_1$ [Kuzmin 1970 (baryogenesis);(leptogenesis:) Liu/Segrè/Flanz/Paschos/Sarkar/Weiss/Covi/Roulet/Vissani/Pilaftsis/Underwood/Buchmüller/Plumacher...]

This enhancement is known as resonant leptogenesis.

- divergent when $M_2 = M_1$?

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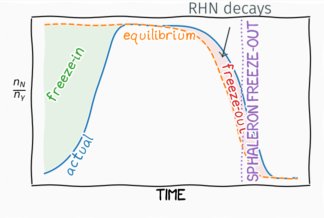

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Becomes enhanced if $M_2 \to M_1$ [Kuzmin 1970 (baryogenesis);(leptogenesis:)

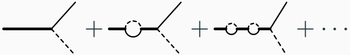
Liu/Segrè/Flanz/Paschos/Sarkar/Weiss/Covi/Roulet/Vissani/Pilaftsis/Underwood/Buchmüller/Plumacher...]

This enhancement is known as resonant leptogenesis.

- divergent when $M_2 = M_1$?
- divergence is unphysical — it needs to be regulated!

Resonant leptogenesis and RHN oscillations

- in the degenerate limit perturbation theory breaks down

$\Gamma_N \supset$ 

- to resolve this we need to go beyond the S-matrix formalism, RHN are unstable particles $\rightarrow$ no asymptotic states!
- another way of describing the same process is to use density matrix equations (derived from the *Schwinger-Kelydish* formalism)

RHN density matrix

$$\frac{\mathrm{d}\rho}{\mathrm{d}z} = -i\,[H,\rho] - \frac{1}{2}\,\{\Gamma, \rho - n^{\mathrm{eq}}\}$$

Active lepton equations

$$\frac{\mathrm{d}Y_\ell}{\mathrm{d}z} = \mathrm{Tr}\left[\tilde{\Gamma}(\rho - \rho^*)\right] - W Y_\ell$$

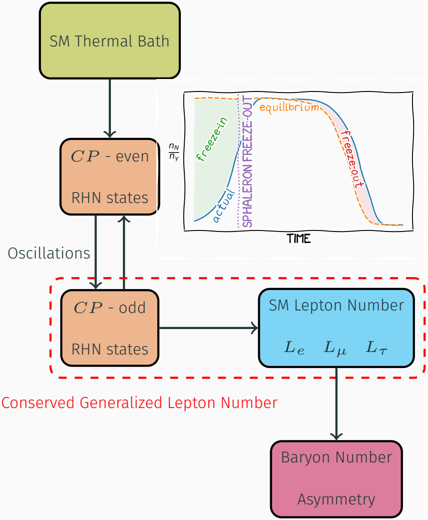
Resonant leptogenesis - summary

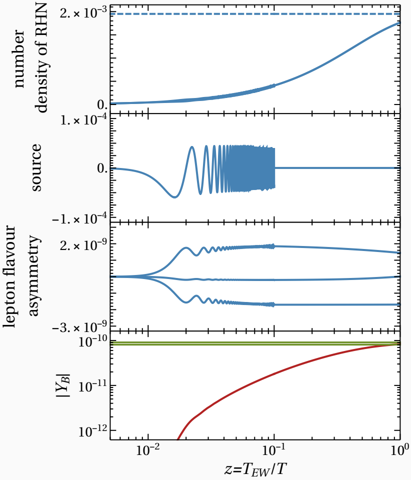
- resonant leptogenesis allows RHN below $10^9\,\mathrm{GeV}$
- we run into conceptual problems for $M_2 \to M_1$
- these issues can be resolved with non-perturbative methods
  - resonant leptogenesis can be described through RHN oscillations

Issues:

- existing studies typically assume non-relativistic RHN and neglect relativistic effects
- non-thermal initial conditions still require solving the full density matrix equations
- RHN decays require $M \gtrsim T$ $\to$ not clear what happens for $M \lesssim 130\,\mathrm{GeV}$

Leptogenesis via oscillations





Evolution Equations

System of kinetic equations

$$i\frac{dn_{\Delta_\alpha}}{dt} = -2i\frac{\mu_\alpha}{T}\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\Gamma_\alpha\right] f_N\,(1-f_N) \quad + i\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}\left[\tilde{\Gamma}_\alpha\,(\bar{\rho}_N-\rho_N)\right],$$

$$i\,\frac{d\rho_N}{dt} = [H_N,\rho_N] - \frac{i}{2}\left\{\Gamma,\rho_N-\rho_N^{eq}\right\} - \frac{i}{2}\sum_\alpha \tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N\,(1-f_N)\right],$$

$$i\,\frac{d\bar{\rho}_N}{dt} = -\,[H_N,\bar{\rho}_N] - \frac{i}{2}\left\{\Gamma,\bar{\rho}_N-\rho_N^{eq}\right\} + \frac{i}{2}\sum_\alpha \tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N\,(1-f_N)\right],$$

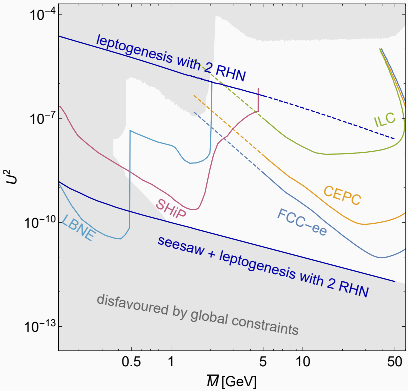
- equations very similar to those used for resonant leptogenesis
- notably there are twice as many equations for the RHN $\rightarrow$ helicity taken into account $(\rho_N\,,\rho_{\bar{N}})$
- temperature dependence of the equilibrium distributions often neglected

Leptogenesis via oscillations - summary

Compared to resonant leptogenesis, there exist a few important differences:

- initial conditions are crucial, all BAU is generated during RHN equilibration
- it is important to distinguish between the helicities of the RHN, as it carries an approximately conserved lepton number
- the decay of the RHN equilibrium distribution can typically be neglected $\dot{Y}_N^{\mathrm{eq}} \approx 0$

The parameter space of low-scale leptogenesis

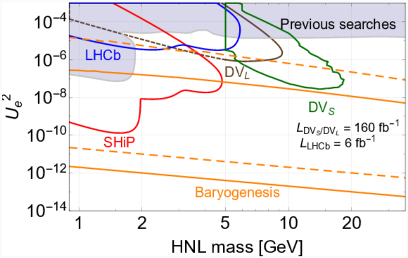


Inverted Ordering

[Drewes/Garbrecht/Gueter/JK 1609.09069]

- several systematic studies over the past years
- leptogenesis is within reach of future experiments
- most studies stop around $\mathcal{O}(50)\,\mathrm{GeV}$
- why is this?

The parameter space of low-scale leptogenesis



[Eijima/Shaposhnikov/Timiryasov 1808.10833] [Boiarska et. al. 1902.04535]

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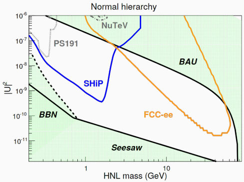
- why is this?

What lies beyond $\mathcal{O}(50)$ GeV?

- for $M_M > M_W$ new channels open up in low-scale leptogenesis
  - large equilibration rates for both FNV and FNC processes
  - generically we have $\Gamma_N/H \gtrsim 30$ for $T \sim 150\,\mathrm{GeV}$, $M \sim 80\,\mathrm{GeV}$
  - we should never underestimate large exponents $Y_L \sim \mathrm{e}^{-t\Gamma_N/H} \times Y_L^{\mathrm{init}}$
  - early estimate [Blondel/Graverini/Serra/Shaposhnikov 2014]



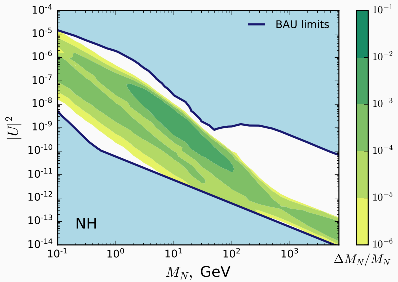
Baryogenesis window closes at $M_M \sim 80\,\mathrm{GeV}$?

- there is no established lower bound from resonant leptogenesis
  - early estimates gave successful leptogenesis for $\mathcal{O}(200)$ GeV [Pilaftsis/Underwood 2005]
  - updated study suggests $\mathcal{O}(2)$ GeV [Hambye/Teresi 2016]
    however: not completely consistent with results of leptogenesis via RHN oscillations

Study of the parameter space

- we use a single set of equations for both leptogeneses
  - for $M \gg T$ we recover resonant leptogenesis
  - for $M \ll T$ we recover leptogenesis via oscillations
- we separate the freeze-in and freeze-out regimes
  - for thermal initial conditions freeze-out is the only source of BAU: “resonant” leptogenesis dominates
  - for vanishing initial conditions with $\dot{Y}_N^{eq} \to 0$ freeze-in is the only source of BAU: LG via oscillations dominates
- biggest challenge: rates!
  - so far estimates of the rates only exist for $M \ll T$ and $M \gg T$
  - we combine the two by *extrapolating* the relativistic rate and adding it to the non-relativistic decays
- we perform a comprehensive numerical scan over the parameters between $0.1\text{GeV} < M_M < 10\,\text{TeV}$

Results



- the baryogenesis window remains open!
- there is significant overlap the two mechanisms

How to distinguish the contributions of freeze-in and freeze-out?

- they are described by the same equations
- in resonant leptogenesis decays, *i.e.* freeze-out dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\mathrm{eq}}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the “source” term to $\dot{Y}_N^{\mathrm{eq}} \to 0$ by hand

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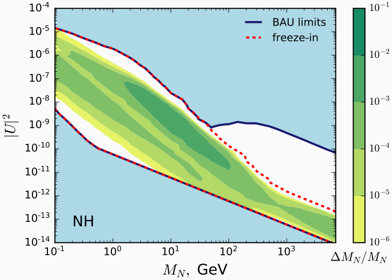

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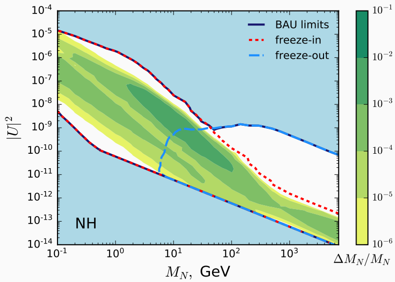

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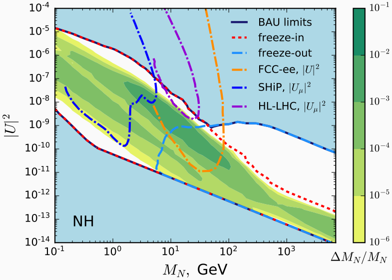

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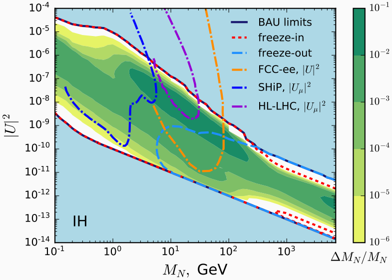

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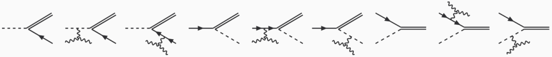
Conclusions

- resonant leptogenesis and leptogenesis through neutrino oscillations are really two realizations of the same mechanism
- freeze-out leptogenesis is already possible for GeV-scale heavy neutrinos
- freeze-in leptogenesis remains important at the TeV-scale and beyond
- leptogenesis is a viable baryogenesis mechanism for all heavy neutrino masses above the $\mathcal{O}(100)$ MeV scale
- leptogenesis is testable at planned future experiments
  - there is synergy between high-energy and high-intensity experiments!
  - together they will cover a large portion of the low-scale leptogenesis parameter space

Thank you!

Rates for leptogenesis

- one of the major challenges is to estimate the coefficients H_N and Γ_N
- unlike resonant leptogenesis, where it is often assumed that the rates are dominated by RHN decays, the main contribution comes from thermal effects



[Ghiglieri/Laine 2017]

Two main types of rates:

Fermion number conserving

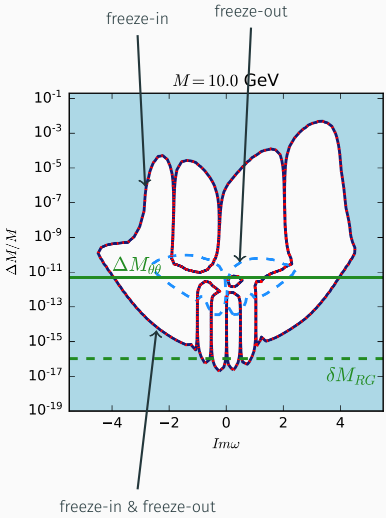
$$\Gamma_+ \sim F^2 T \sim H$$

Fermion number violating

$$\Gamma_- \sim F^2 \frac{M^2}{T} \ll H$$

[Ghiglieri/Laine 2017, Eijima/Shaposhnikov 2017]

Slices of the parameter space



- slices of the parameter space for fixed M, $\mathrm{Re}\omega$ and phases in the PMNS matrix
- both mechanisms contribute at all masses
- large ΔM region is highly sensitive to initial conditions
- freeze-out leptogenesis requires small mass splitting $\Delta M/M \lesssim 10^-8$

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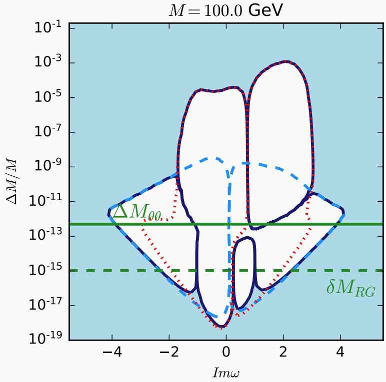

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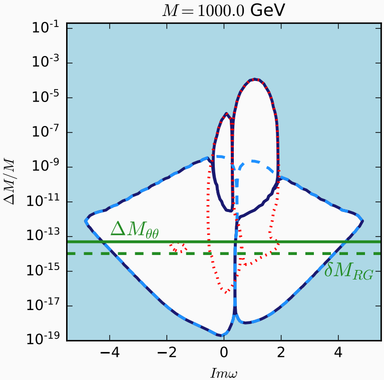

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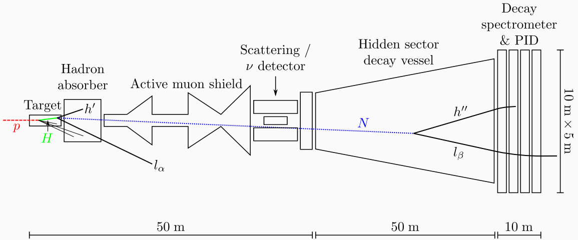
RHN searches at the Intensity Frontier

Example of an IF experiment: SHiP



- RHN can be produced in D and B meson decays

  [Gorbunov/Shaposhnikov 2007]
- GeV-scale RHN are very long lived—they decay into charged particles in the vacuum vessel
- SHiP can be very sensitive to HNLs [SHiP collaboration 2018]