Uniting low-scale leptogeneses

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

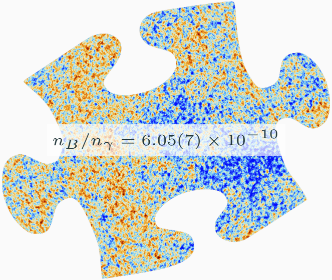
HiDDeN webinar, 17.11.2020

Outline

Introduction

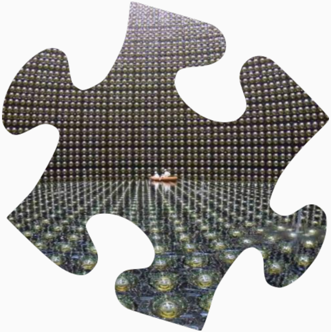
Some puzzles for physics beyond the Standard Model

BAU baryon asymmetry of the universe



[Planck collaboration]

Neutrino masses



[Super-Kamiokande]

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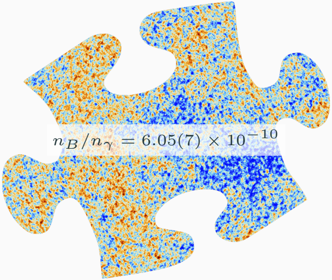

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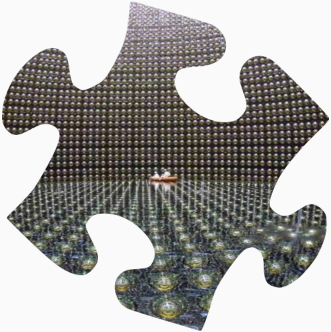
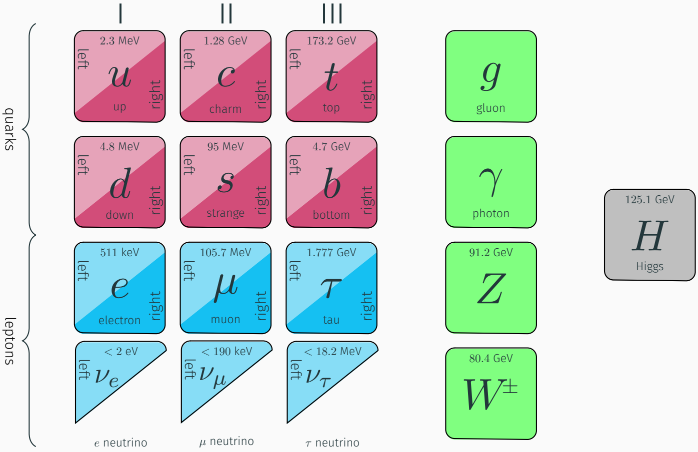


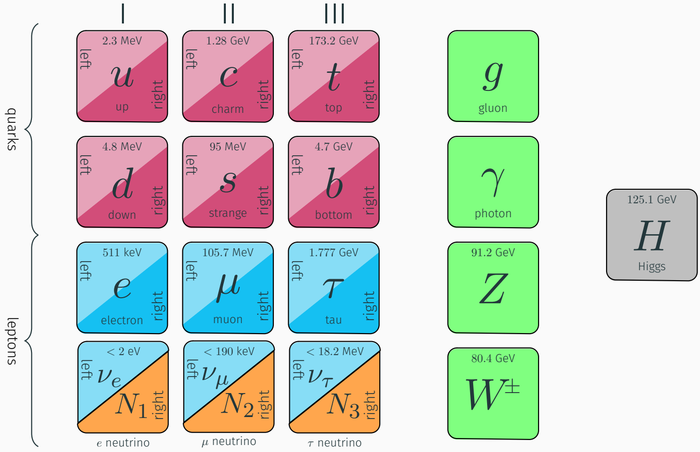
[Super-Kamiokande]

Is there a way to explain both?

Standard Model



Standard Model



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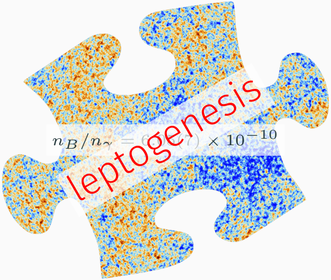


Neutrino masses

The Neutrino Masses

The neutrino masses

- the observed neutrino masses are surprisingly small

$$m_\nu \lesssim 1\,\mathrm{eV}$$

- if the masses are even partly Dirac $\rightarrow$ right-handed neutrinos (RHN) exist

$$\mathcal{L} \supset \frac{1}{2}\overline{\nu_L} m_D \nu_R$$

- RHN are SM gauge singlets
- they can be their own antiparticles $\rightarrow$ they *can*[1] have a Majorana mass term M_M
- the full mass matrix:

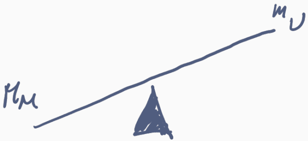
$$\mathcal{L} \supset \frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D^T & M_M\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix}$$

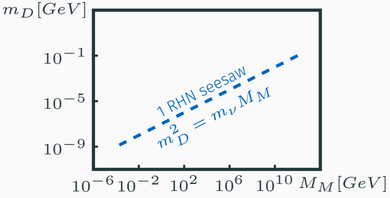
[1] "Everything not forbidden is compulsory." - Murray Gell-Mann

Active neutrino masses

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

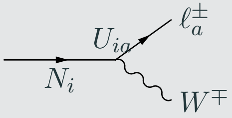
- m_D and M_M are related through the seesaw formula
- for $m_D \sim 1\,\mathrm{GeV} \to M_M \sim 10^{10}\,\mathrm{GeV}$
- but for $m_D \sim 10^{-6}\,\mathrm{GeV} \to M_M \sim 1\,\mathrm{GeV}$





[Minkowski 1977...]

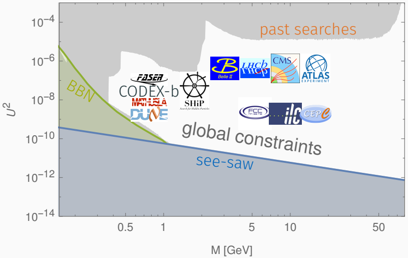
Mixing with RHN



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

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

GeV range is especially interesting!



Low-scale Leptogeneses

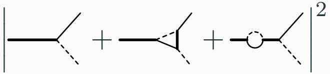
Baryogenesis

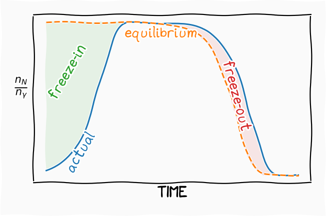
Sakharov conditions

1. Baryon number violation
   - realized in the SM through sphaleron processes ✓
2. C and CP violation
   - coming from the quark sector too small in SM ✗
3. Deviation from thermal equilibrium
   - second order phase transition too small in SM ✗

Sakharov conditions

1. Baryon number violation
    - realized in the SM through sphaleron processes ✓
2. C and CP violation
    - coming from the quark sector too small in SM ✗
    - RHN oscillations and decays ✓
3. Deviation from thermal equilibrium
    - second order phase transition too small in SM ✗
    - RHN freeze-in and freeze-out ✓

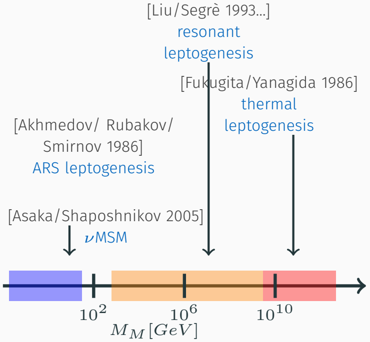




Baryogenesis through leptogenesis

- many different 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 $M_M \sim \mathrm{GeV}$

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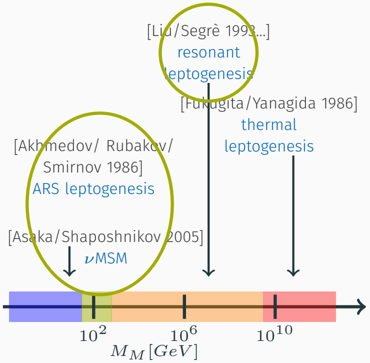

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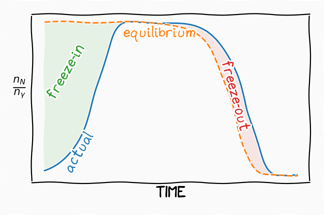
Are these mechanisms connected?

Thermal leptogenesis

- the BAU is mainly produced in the decays of RHN
- as the universe expands, cools down to $T \leq M_M$ the RHN become non-relativistic and begin to decay



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

$$\epsilon_a \equiv \frac{\Gamma_{N\to l_a} - \Gamma_{N\to \bar{l}_a}}{\Gamma_{N\to l_a} + \Gamma_{N\to \bar{l}_a}}$$

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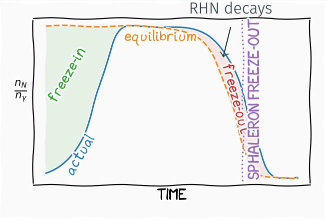

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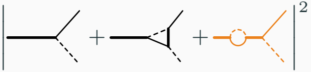
- for hierarchical neutrinos, the decay asymmetry is limited by the Davidson-Ibarra bound

$$|\epsilon| \lesssim \frac{3M_1 m_\nu}{8\pi v^2}$$

[Davidson/Ibarra 2002]

- however, if we carefully look at the diagrams

$$\Gamma_{N\to\ell\bar{\phi}} \sim$$



we find that the wave-function diagram becomes enhanced for $M_2 \to M_1$

$$\epsilon = \frac{1}{8\pi} \frac{\mathrm{Im}(F^\dagger F)^2_{12}}{(F^\dagger F)_{11}} \frac{M_1 M_2}{M_1^2 - M_2^2}$$

[Kuzmin 1970]

In the context of *leptogenesis*:

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

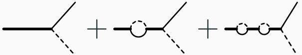
This enhancement is known as resonant leptogenesis.

Resonant Leptogenesis and RHN oscillations

- the effective decay asymmetry ϵ appears divergent for $M_2 \to M_1$
- this divergence is unphysical, it needs to be regulated

$$\epsilon = \frac{1}{8\pi} \frac{\mathrm{Im}(F^\dagger F)_{12}^2}{(F^\dagger F)_{11}} \frac{M_1 M_2}{M_1^2 - M_2^2 + A^2}$$

- in the degenerate limit perturbation theory breaks down

$\Gamma_N \supset$  $+ \cdots$

- to resolve this we have to go beyond the S-matrix formalism, RHN are unstable particles $\to$ no asymptotic states!

Evolution equations for resonant leptogenesis

- another way of describing the same process is to use density matrix equations
- instead of number densities, we include correlations of the RHN flavours:

RHN density matrix

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

Active lepton equations

$$\frac{\mathrm{d}Y_\ell}{\mathrm{d}z} = S_\ell(n) - W Y_\ell$$

- Density matrix of the RHN $n = \begin{pmatrix} n_{11} & n_{12} \\ n_{21} & n_{22} \end{pmatrix}$
- Effective Hamiltonian H of the RHN $\sim M^2/T + Y^2 T$
- Production rate $\Gamma \sim Y^2 T$
- Source term S_ℓ of the active neutrinos
- Washout term W

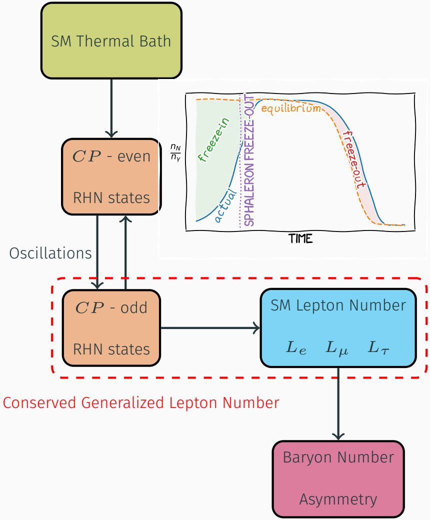
Resonant leptogenesis - summary

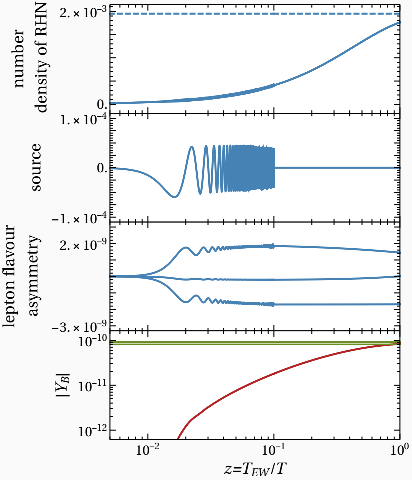
- resonant leptogenesis allows RHN below $10^9\,\mathrm{GeV}$
- we run into conceptual problems for $M_2 \to M_1$
- these issues can be resolved with non-perturbative methods
  - resonant leptogenesis can be described through RHN oscillations

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 through Neutrino Oscillations





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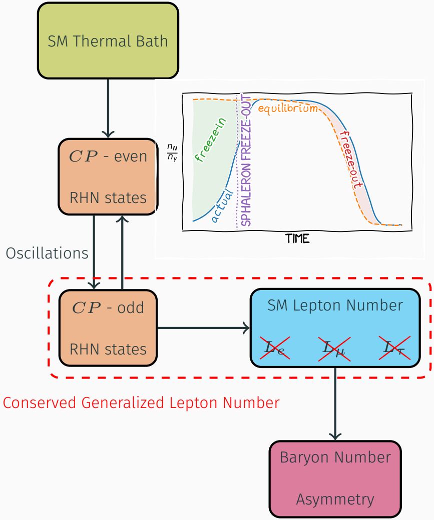

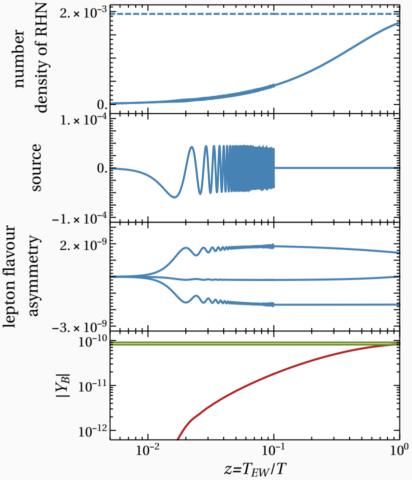

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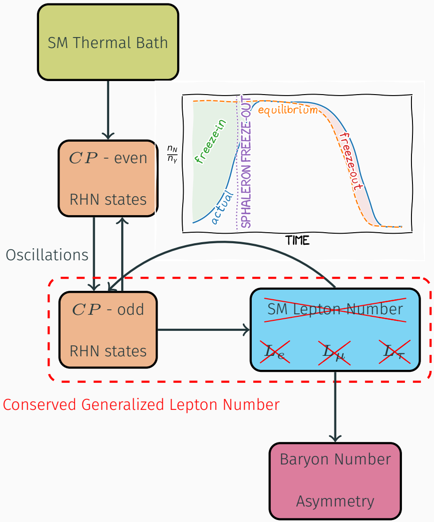

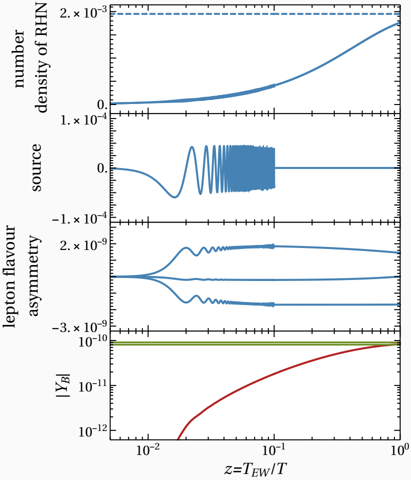

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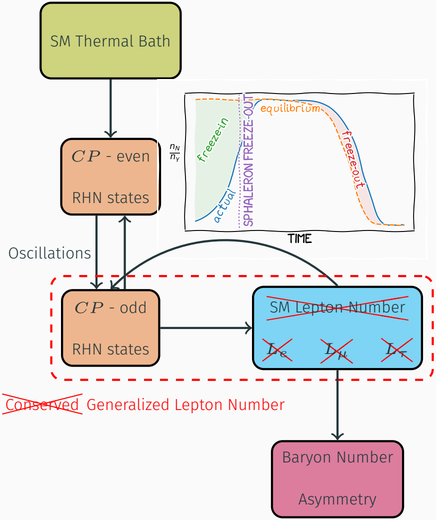
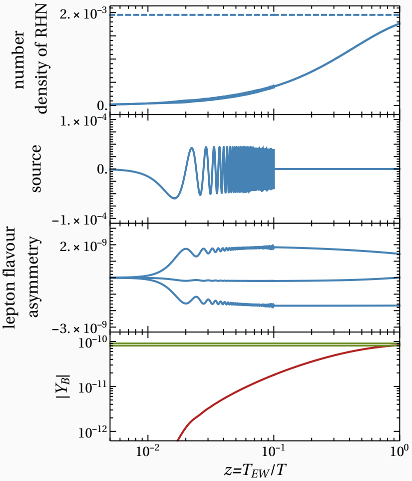




Leptogenesis through Neutrino Oscillations - differences

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 $\dot{Y}_N^{\text{eq}} \approx 0$

Evolution Equations

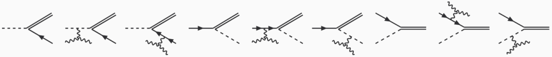
System of kinetic equations

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

- 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

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

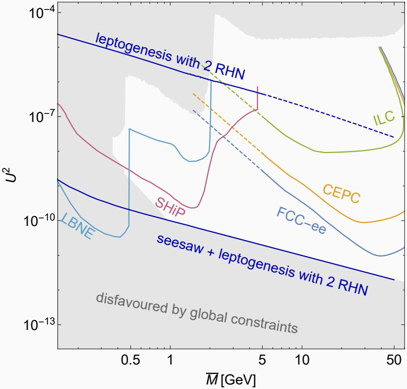
$$\Gamma_+ \sim Y^2 T \sim H$$

Fermion number violating

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

[Ghiglieri/Laine 2017, Eijima/Shaposhnikov 2017]

The parameter space of leptogenesis

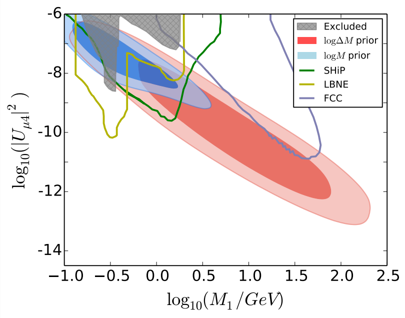


Inverted Ordering

[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?

Parameter space of low-scale leptogenesis



[Hernández/Kekic/López-Pavón/Racker/Salvado

1609.06719]

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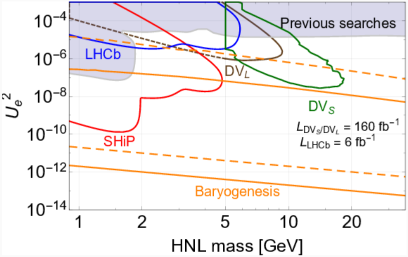

[Eijima/Shaposhnikov/Timiryasov 1808.10833] [Boiarska et. al. 1902.04535]

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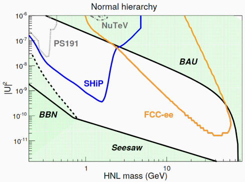
- most studies stop around $\mathcal{O}(50)\,\mathrm{GeV}$
- why is this?

What lies beyond $\mathcal{O}(50)$ 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
- 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]

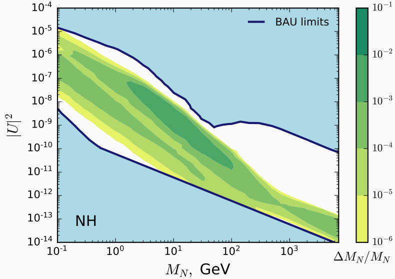


Baryogenesis window closes at $M_M \sim 80$ GeV?

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 $0.1\text{GeV} < M_M < 10\,\text{TeV}$

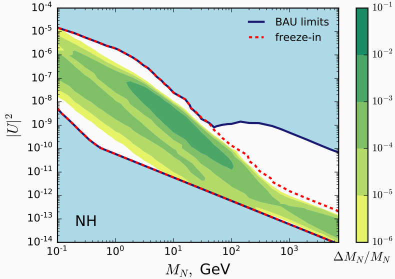
Results



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

How do we distinguish the two contributions?

- two main contributions to the BAU, from 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 $Y_N(0) = Y_N^{\mathrm{eq}}$
- low-scale leptogenesis is freeze-in dominated, $Y_N(0) = 0$, we set the "source" term to $dY_N^{\mathrm{eq}}/dz \to 0$ by hand



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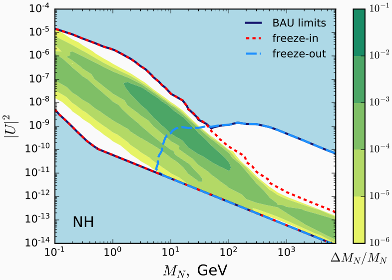

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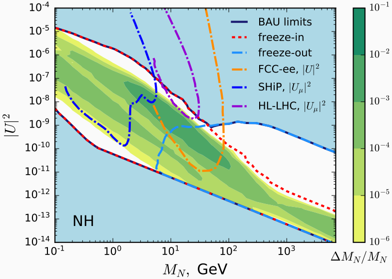

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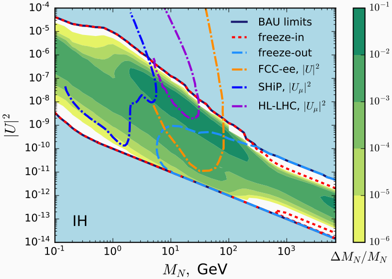

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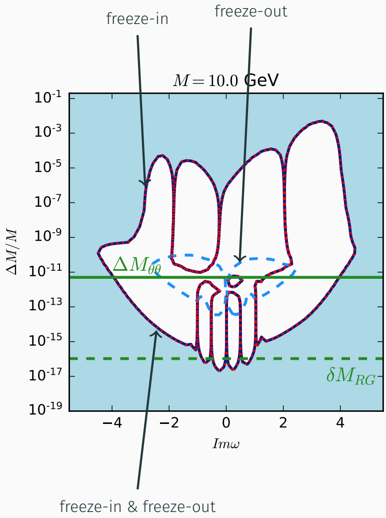
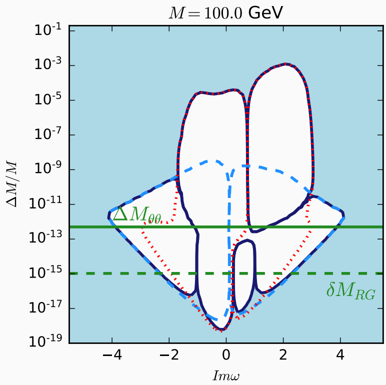
- they are described by the same equations
- in resonant leptogenesis decays, *i.e.* freeze-out dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\text{eq}}$
- low-scale leptogenesis is freeze-in dominated, $Y_N(0) = 0$, we set the “source” term to $dY_N^{\text{eq}}/dz \to 0$ by hand

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 $\Delta M/M \lesssim 10^{-}8$

Slices of the parameter space



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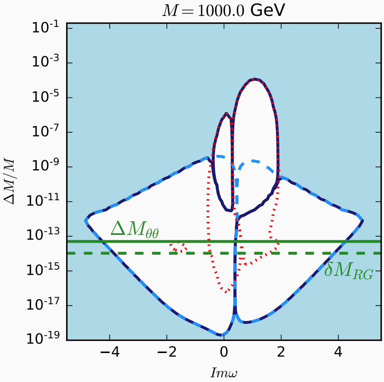

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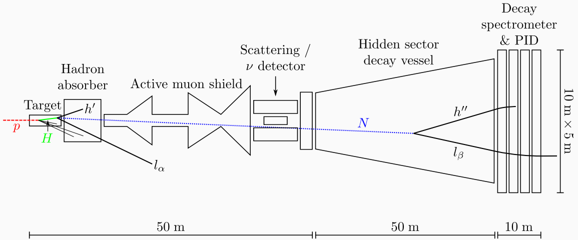
Conclusions

- 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!

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]