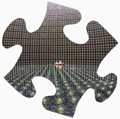
Mapping the parameter space of low-scale leptogenesis

Juraj Klarić

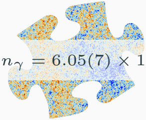
PASCOS, July 26th 2022

Some puzzles for physics beyond the Standard Model

Neutrino masses



The Baryon Asymmetry of the Universe



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

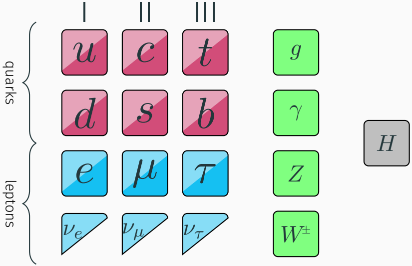


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

Some puzzles for physics beyond the Standard Model

Neutrino masses

[Minkowski 1977...]

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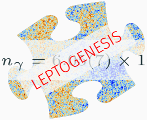

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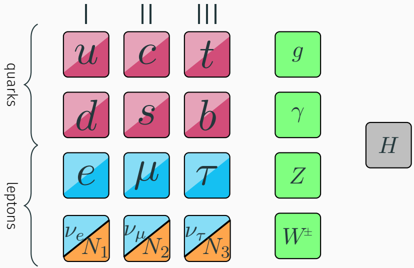
[Fukugita/Yanagida '86...]



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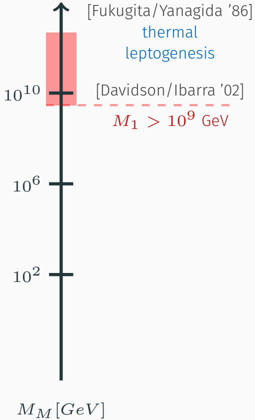
Leptogenesis mechanisms



Sakharov conditions

1. Baryon number violation

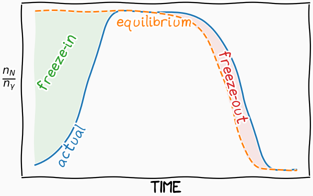
   sphaleron processes

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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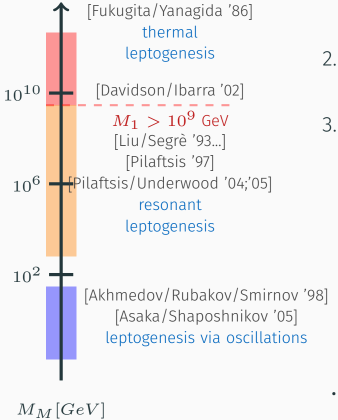

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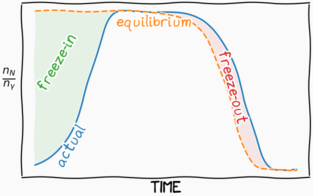

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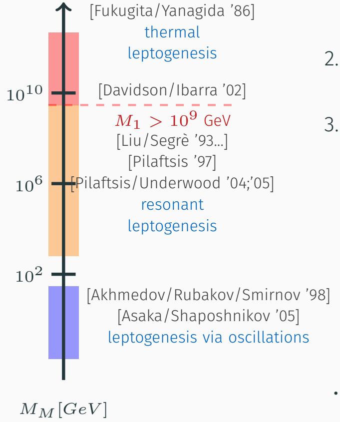

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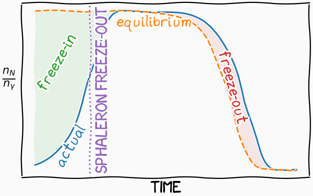

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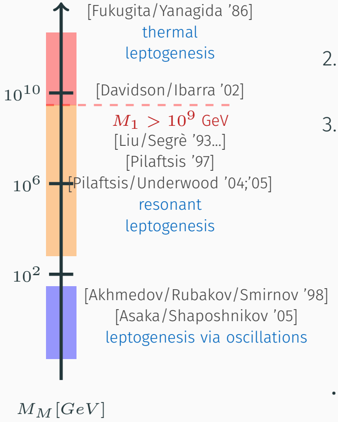

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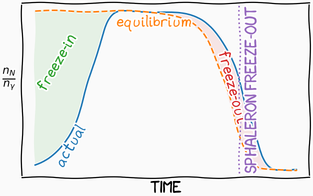

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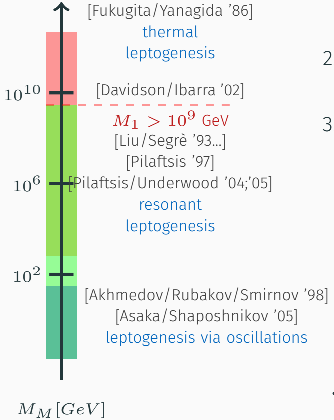

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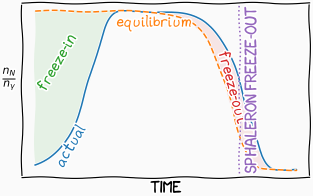
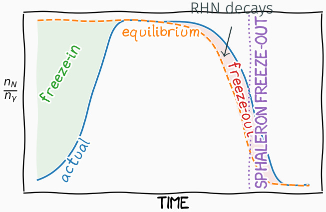


- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV
- leptogenesis works in a wide range of RHN masses
- how are the low-scale mechanisms connected?

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

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

Becomes enhanced if $M_2 \to M_1$ [(baryogenesis) Kuzmin '70] [(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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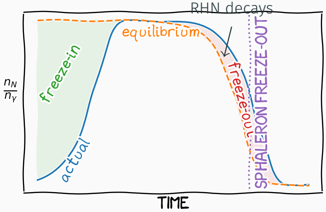

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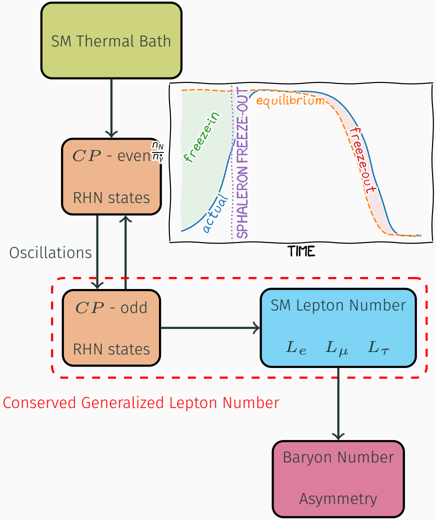
This enhancement is known as resonant leptogenesis.

- divergent when $M_2 = M_1$?
- divergence is unphysical — it needs to be regulated!
- this process can instead be described with density matrix equations

Leptogenesis via oscillations



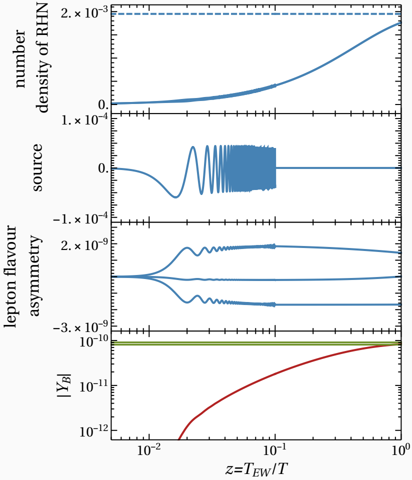


figure from [Drewes/Garbrecht/Gueter/JK 1606.06690]

Quantum Kinetic Equations (QKEs)

System of QKEs

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

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

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- coupled system of integro-differential equations for the lepton flavor asymmetries n_{Δ_α}, and the helicity-dependent HNL density matrices ρ_N and $\bar{\rho}_N$
- HNL oscillations described by the effective hamiltonian H_N
- equilibration described by helicity and flavor-dependent matrices Γ

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\begin{aligned}
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- similar sets of equations derived using different strategies for both regimes
- for resonant leptogenesis relativistic corrections were typically negligible
  helicity effects could be neglected $\rho_N \approx \rho_{\bar{N}}^*$
- leptogenesis via oscillations assumed ultra-relativistic HNLs
  non-relativistic corrections found to be important in recent years
  [Hambye/Teresi '16; Laine/Ghiglieri '17; Eijima/Shaposhnikov '17]
- gradual convergence towards the same set of equations

The low-scale leptogenesis mechanisms

Resonant leptogenesis

- often sufficient to use decay asymmetries ϵ_a
- conceptual issues arise when $M_2 \to M_1$
- relativistic effects can typically be neglected
- heavy neutrino decays require $M \gtrsim T$, not clear what happens for $M \lesssim 130$ GeV

Leptogenesis via oscillations

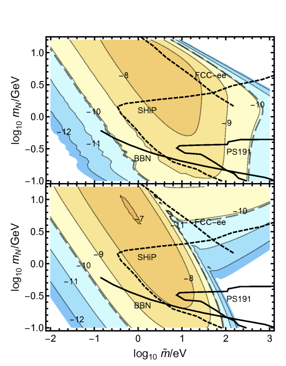
- initial conditions are crucial, all BAU is generated during RHN equilibration (freeze-in)
- important to distinguish the helicities of the RHN
- the decay of the RHN equilibrium distribution can typically be neglected $\dot{Y}_N^{\text{eq}} \approx 0$

- both can be described by the same density-matrix equations

The parameter space of low-scale leptogenesis

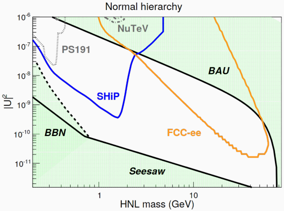
Resonant leptogenesis

- early estimates lead to successful leptogenesis for $\mathcal{O}(200)$ GeV [Pilaftsis/Underwood '05]
- Higgs decay leptogenesis mechanism proposed in [Hambye/Teresi '16; '17]



Leptogenesis via oscillations

- for $M_M > M_W$ new channels open up
- large equilibration rates for both FNV and FNC processes
- generically we have $\Gamma_N/H \gtrsim 30$ for $T \sim 150\,\mathrm{GeV}$, $M \sim 80\,\mathrm{GeV}$
- early estimate [Blondel/Graverini/Serra/Shaposhnikov 2014]



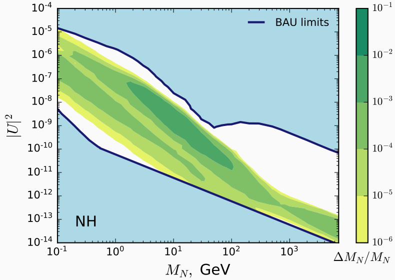
- Baryogenesis window closes at $M_M \sim 80\,\mathrm{GeV}$?
- with three RHN shown to work for $M_M \geq TeV$ [Garbrecht 2014]

A quantitative study is necessary!

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

Results: Minimal model with 2 heavy neutrinos



[JK/Shaposhnikov/Timiryasov 2008.13771 and 2103.16545]

- the baryogenesis window remains open!
- 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 $Y_N(0) = Y_N^{\text{eq}}$
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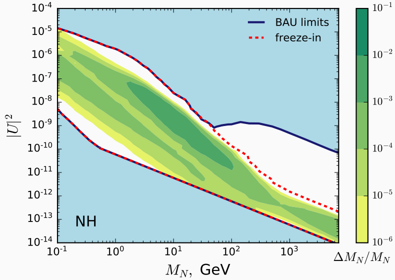

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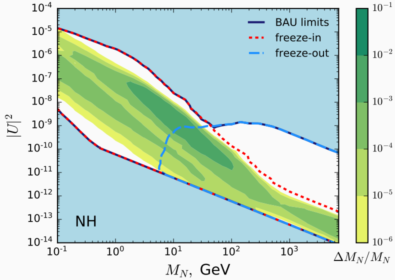

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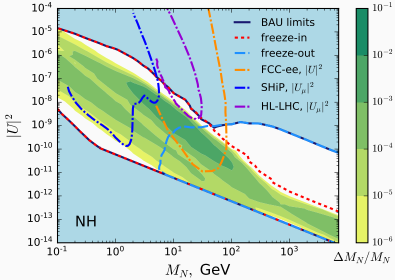

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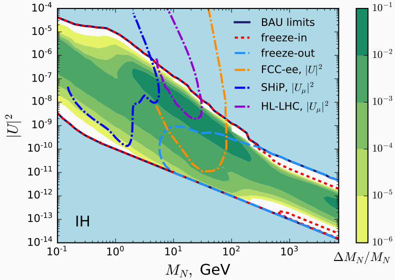

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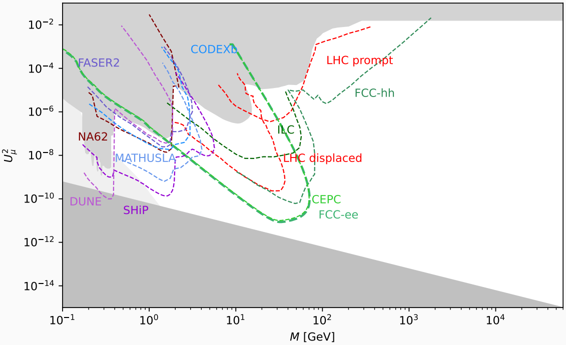
Results: Model with 3 heavy neutrinos



[Snowmass White Paper 2203.08039]

leptogenesis lines from [Drewes/Georis/JK 2106.16226]

- for experimentally accessible heavy neutrino masses, all U^2 are allowed
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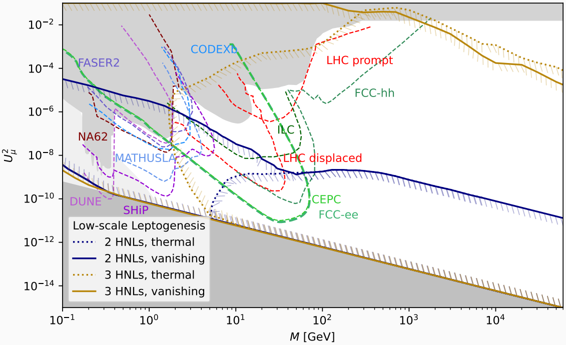

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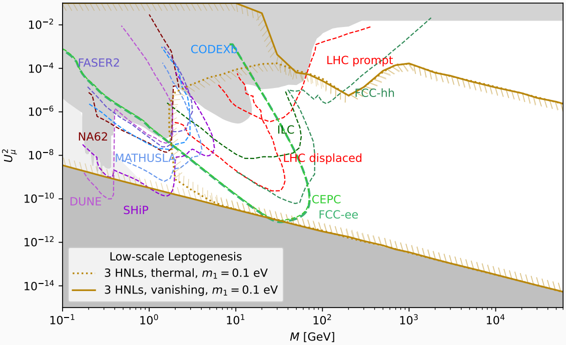

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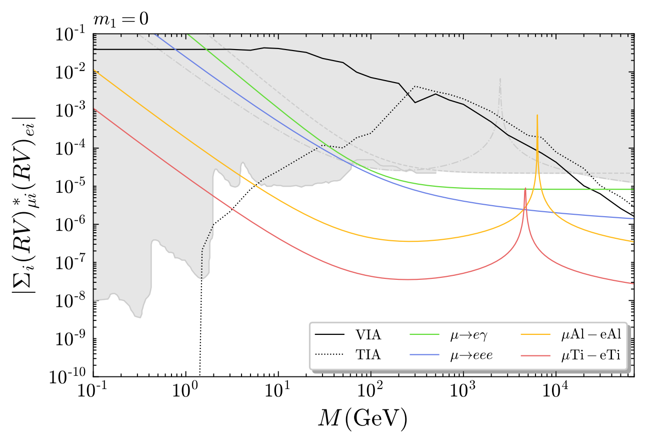

[Granelli/JK/Petcov 2206.04342]

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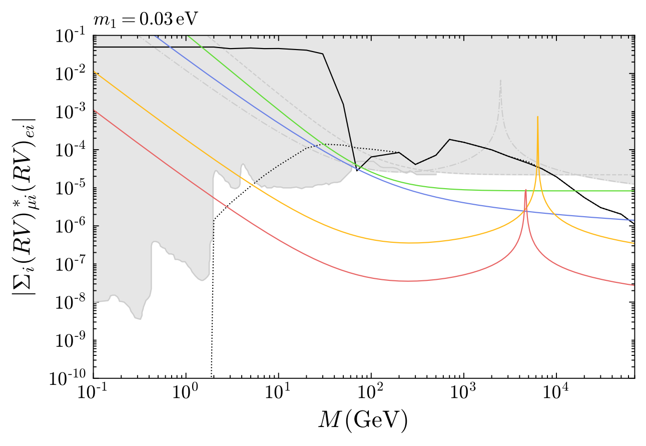

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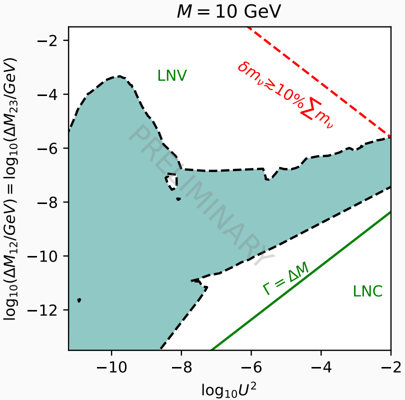
Slice of the parameter space



- benchmark with fixed $U^2_{\alpha I}/U^2$
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[Drewes/Georis/JK 220x.xxxx]

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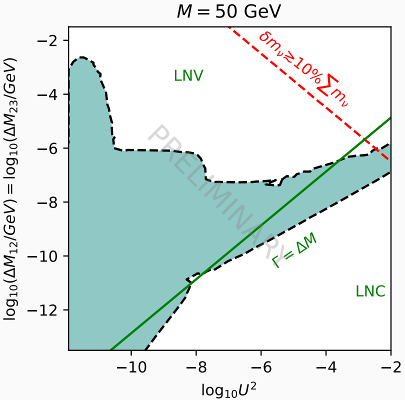

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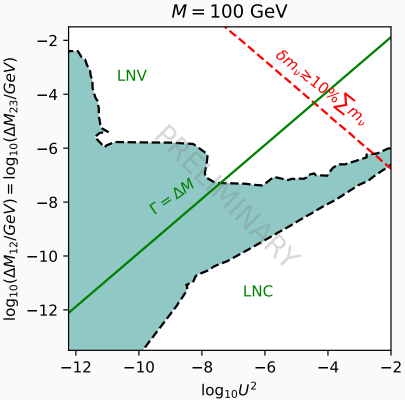

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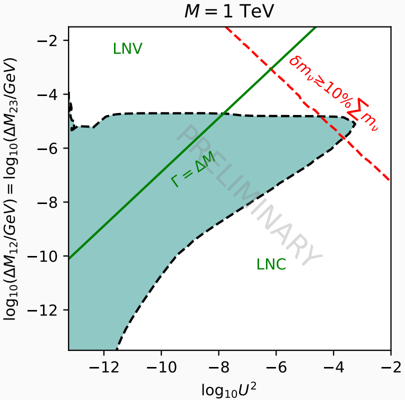

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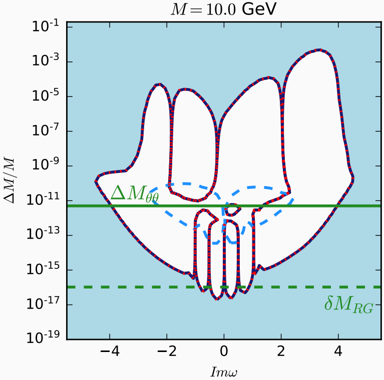
Conclusions

- resonant leptogenesis and leptogenesis through neutrino oscillations are really two regimes of the same mechanism
- freeze-out is already possible for GeV-scale RHNs
- freeze-in 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!

Slices of the parameter space



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- mass splitting induced by the Higgs $\Delta M_{\theta\theta}$
- mass splitting induced by RG running δM_{RG}

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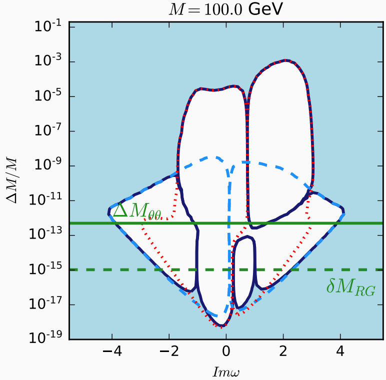

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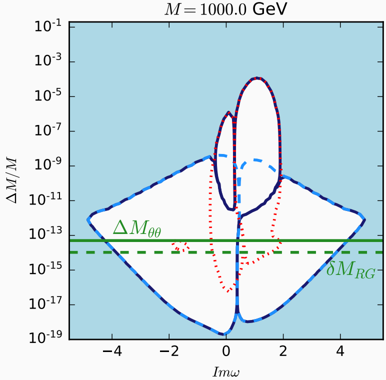

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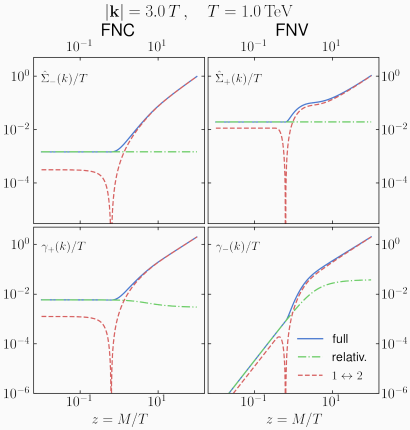
Extrapolating the rates to the non-relativistic regime

- helicity-dependent rates unknown outside of the relativistic regime
- we extrapolate the relativistic rate
- combine this result with the $1 \leftrightarrow 2$ rate

Symmetric phase of the SM:



Extrapolating the rates to the non-relativistic regime

- helicity-dependent rates unknown outside of the relativistic regime
- we extrapolate the relativistic rate
- combine this result with the $1 \leftrightarrow 2$ rate
- in the broken phase the situation is more involved
- large FNV contribution from mixing with light neutrinos
- indirect contribution is enhanced when $M_N \sim g^2 T$

Broken phase of the SM: