Uniting low-scale leptogeneses

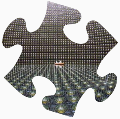
Juraj Klarić

based on 2008.13771, 2103.16545 in collaboration with M.E. Shaposhnikov and I. Timiryasov
and 2106.16226 in collaboration with M. Drewes and Y. Georis

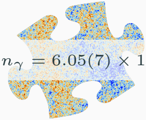
DESY Theory Workshop, September 24$^{\text{th}}$ 2021

Some puzzles for physics beyond the Standard Model

Neutrino masses



The Baryon Asymmetry of the Universe



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

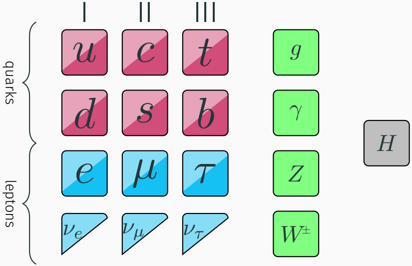


Image credits: Kamioka Observatory, ICRR, U. Tokyo; ESA and the Planck Collaboration

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Neutrino masses

[Minkowski 1977...]

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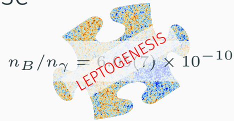
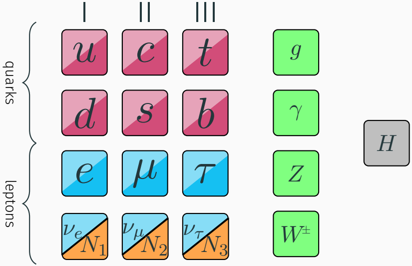


[Fukugita/Yanagida '86...]



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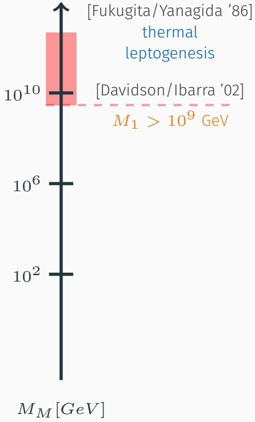
Leptogenesis mechanisms



Sakharov conditions

1. Baryon number violation

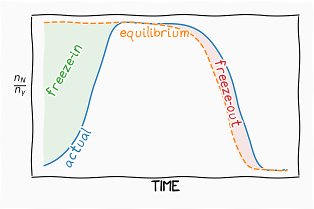
   sphaleron processes

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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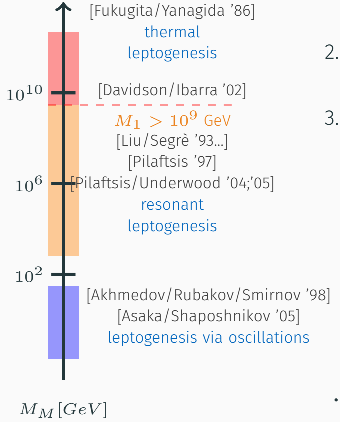

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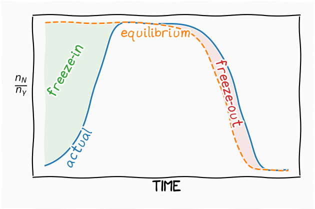
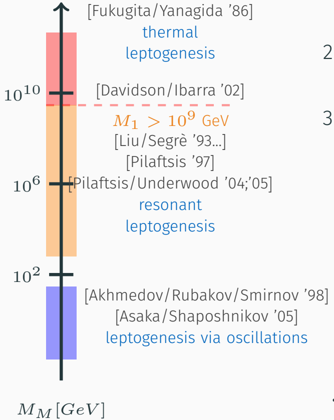


- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV
- leptogenesis works in a wide range of RHN masses



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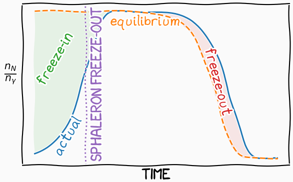

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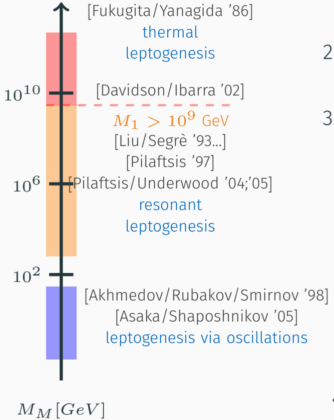

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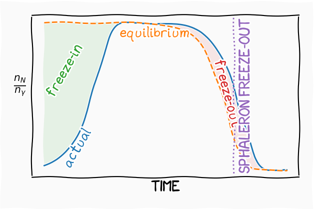

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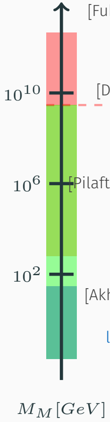

[Fukugita/Yanagida ’86]
thermal leptogenesis

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

[Liu/Segrè ’93...]
[Pilaftsis ’97]
[Pilaftsis/Underwood ’04;’05]
resonant leptogenesis

[Akhmedov/Rubakov/Smirnov ’98]
[Asaka/Shaposhnikov ’05]
leptogenesis via oscillations

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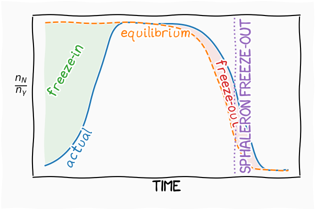
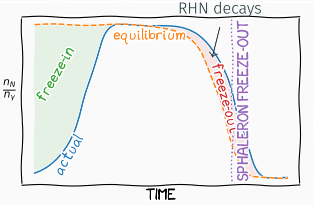


- for hierarchical RHN $M_1 \gtrsim 10^9$ GeV
- leptogenesis works in a wide range of RHN masses
- how are the low-scale mechanisms connected?

Resonant leptogenesis

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

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



The key quantity determining the BAU is the decay asymmetry

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

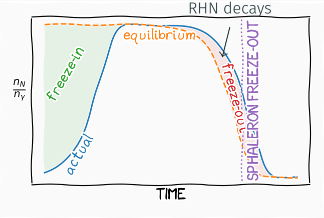
Becomes enhanced if $M_2 \to M_1$ [(baryogenesis) Kuzmin '70] [(leptogenesis:)

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

This enhancement is known as resonant leptogenesis.

- divergent when $M_2 = M_1$?

Resonant leptogenesis



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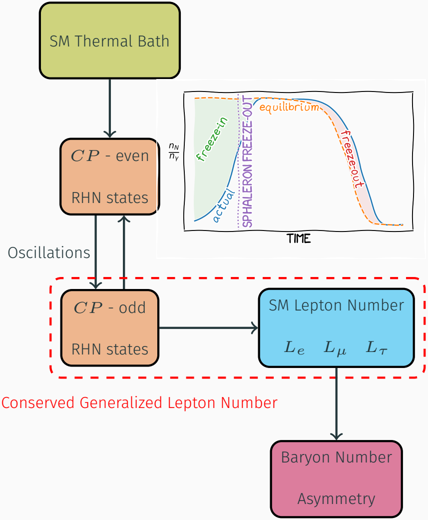
This enhancement is known as resonant leptogenesis.

- 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



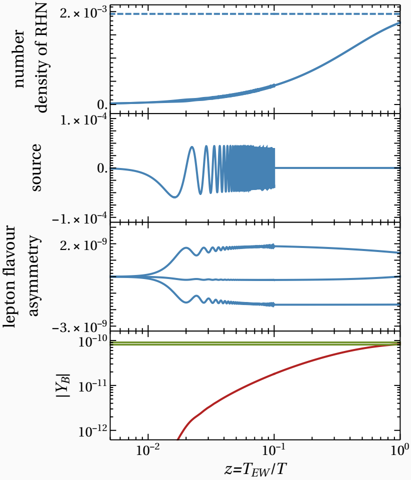


figure from [Drewes/Garbrecht/Gueter/JK 1606.06690]

Quantum Kinetic Equations (QKEs)

System of QKEs

$$
\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\} \\
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\end{aligned}
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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 [see Mikko Laine's talk]

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$$+\frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N\left(1-f_N\right)\right],$$

- similar sets of equations derived using different strategies for both regimes
- for resonant leptogenesis relativistic corrections were typically negligible helicity effects could be neglected $\rho_N \approx \bar{\rho_N}^*$
- 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
  [also see Giovanni Zattera's talk]

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

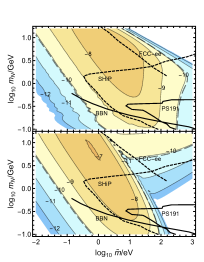
- initial conditions are crucial, all BAU is generated during RHN equilibration (freeze-in)
- important to distinguish the helicities of the RHN
- the decay of the RHN equilibrium distribution can typically be neglected $\dot{Y}_N^{\mathrm{eq}} \approx 0$

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

The parameter space of low-scale leptogenesis

Resonant leptogenesis

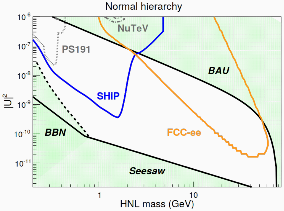
- early estimates lead to successful leptogenesis for $\mathcal{O}(200)$ GeV [Pilaftsis/Underwood '05]
- *different* GeV-scale mechanism proposed in [Hambye/Teresi '16; '17]



- results not fully consistent with the density-matrix treatment at the O(10) GeV scale?

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]



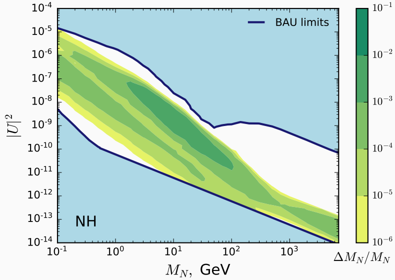
- Baryogenesis window closes at $M_M \sim 80\,\mathrm{GeV}$?
- with three RHN shown to work for $M_M \geq TeV$ [Garbrecht 2014]

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

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 $Y_N(0) = Y_N^{\mathrm{eq}}$
- leptogenesis via oscillations 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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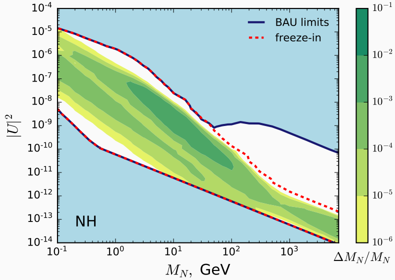

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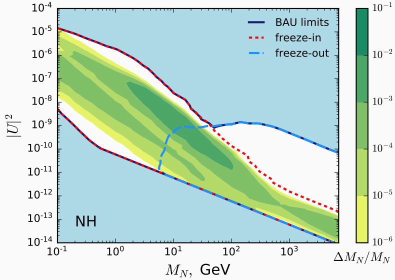

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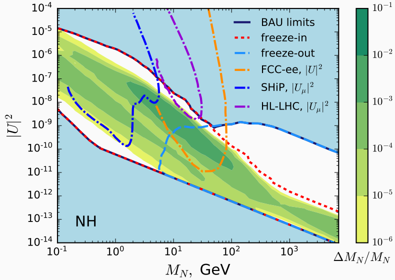

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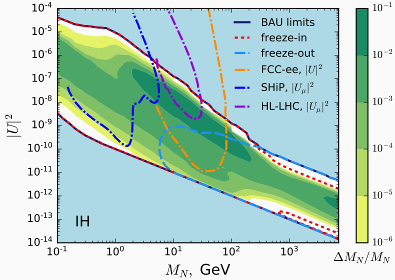
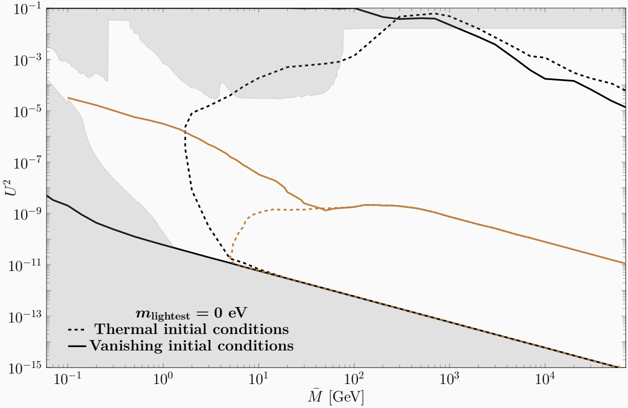


- the baryogenesis window remains open!
- two main contributions to the BAU, from freeze-in and freeze-out
- there is significant overlap of the two regimes

[JK/Shaposhnikov/Timiryasov 2008.13771 and 2103.16545]

- in resonant leptogenesis freeze-out (HNL decays) dominates, we can start with thermal initial conditions $Y_N(0) = Y_N^{\rm eq}$
- leptogenesis via oscillations is freeze-in dominated, $Y_N(0) = 0$, we set the “source” term to $dY_N^{\rm eq}/dz \to 0$ by hand

Results: Model with 3 heavy neutrinos



[Drewes/Georis/JK 2106.16226]

- for experimentally accessible heavy neutrino masses, all U^2 are allowed
- both freeze-in and freeze-out leptogeneses already testable at existing experiments
- the maximal value of U^2 depends on m_{lightest}

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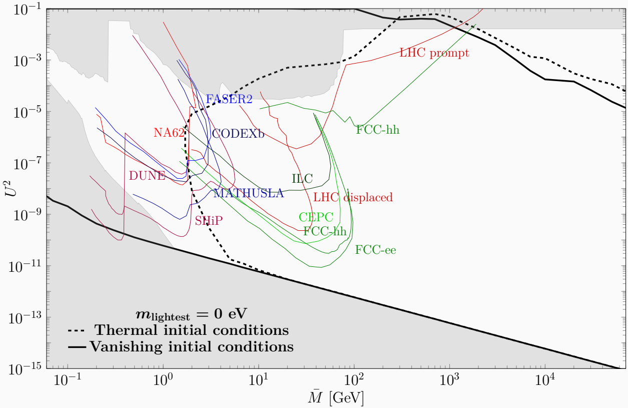

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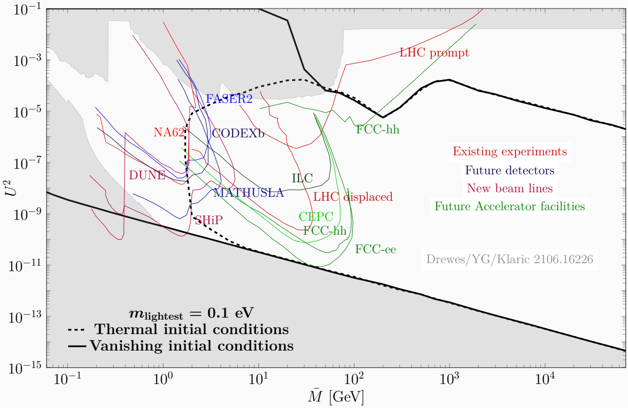

[Drewes/Georis/JK 2106.16226]

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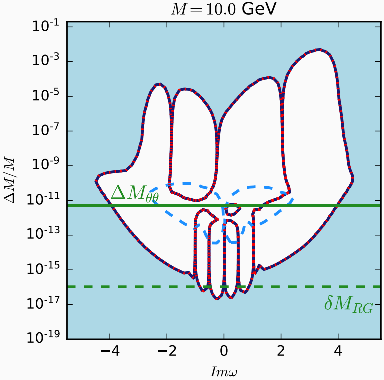
Conclusions

- resonant leptogenesis and leptogenesis through neutrino oscillations are really two regimes of the same mechanism
- freeze-out (thermal initial conditions) leptogenesis is already possible for GeV-scale heavy neutrinos
- freeze-in leptogenesis remains important at the TeV-scale and beyond (initial conditions matter)
- leptogenesis is a viable baryogenesis mechanism for all experimentally accessible heavy neutrino masses
- for three neutrinos, allowed mixing angles can be several orders of magnitude larger
- leptogenesis is testable at existing and planned future experiments
    - there is synergy between high-energy and high-intensity experiments!
    - together they cover a significant portion of the parameter space of low-scale leptogenesis

Thank you!

Slices of the parameter space



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

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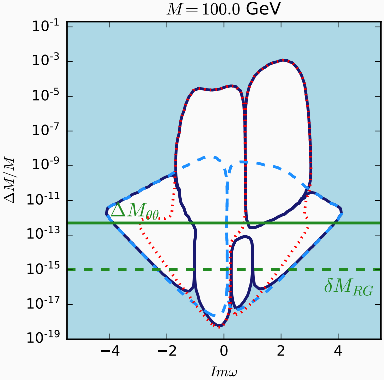

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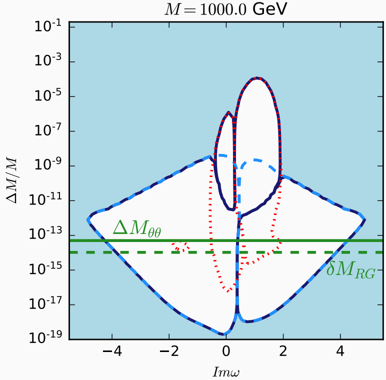

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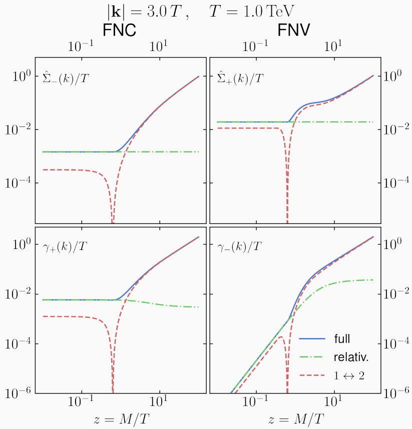
Extrapolating the rates to the non-relativistic regime

- 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: