



Baryon asymmetry of the universe via GeV-scale right-handed neutrinos

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GeV-scale right-handed neutrinos

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \overline{\nu_{RI}} i \partial_\mu \gamma^\mu \nu_{RI} - F_{\alpha I} \overline{L_\alpha} \tilde{\Phi} \nu_{RI} - \frac{(M_M)_I}{2} \overline{\nu_{RI}^C} \nu_{RI} + h.c. \quad \begin{array}{l} \alpha = e, \mu, \tau \\ I = 1, 2, \dots \end{array}$$

$$\hookrightarrow \text{Dirac mass : } [M_D]_{\alpha I} = v F_{\alpha I}$$

Neutrino oscillations: $\Delta m_{ij}^2 = m_i^2 - m_j^2 \neq 0$

“Seesaw mechanism”

If $M_M \sim \mathcal{O}(1)\text{GeV}$,

For $|M_D| \ll M_M$

$F \sim \mathcal{O}(10^{-8})$

$$\hat{M}_\nu = -M_D M_M^{-1} M_D^T \rightarrow m_\nu \sim \frac{v^2 F^2}{M_M}$$

$\Theta \equiv \frac{M_D}{M_M} \sim \mathcal{O}(10^{-6})$

Baryon asymmetry of the universe (BAU): $Y_B^{\text{obs}} = (8.677 \pm 0.054) \times 10^{-11}$

($Y_B \equiv n_B/s$, $n_B \equiv n_b - n_{\bar{b}}$)

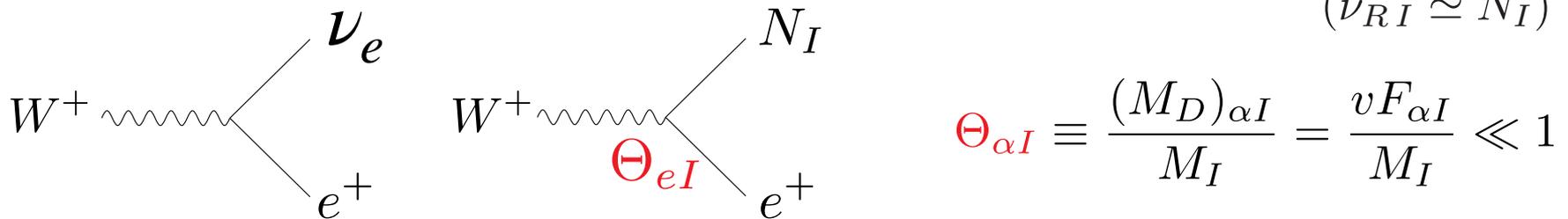
“Baryogenesis via right-handed neutrino oscillations”

[Akhmedov, Rubakov, Smirnov ('98)] [Asaka, Shaposhnikov ('05)]

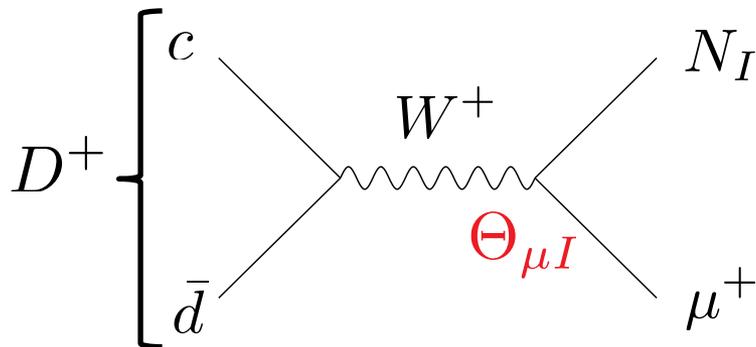
RH ν s have to be **quasi-degenerate** and have **CP-violating** interactions

Search for GeV-scale RH ν

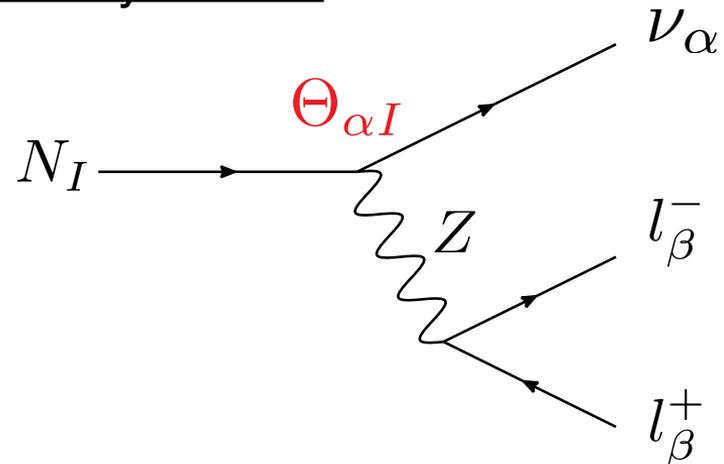
Weak interaction through neutrino mixing; $\nu_{L\alpha} = U_{\alpha i}\nu_i + \Theta_{\alpha I}N_I^c$
 ($\nu_{RI} \simeq N_I$)



Production from meson decays



Decay of RH ν



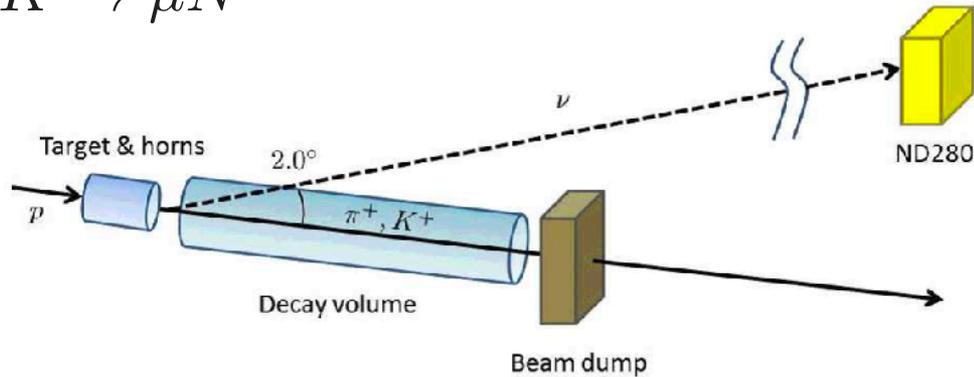
$$N \rightarrow \nu\nu\bar{\nu}, N \rightarrow \nu l\bar{l}, N \rightarrow l^+ M^- \dots$$

Search for GeV-scale RH ν in the T2K

With the T2K near detector ND280

$$K \rightarrow eN$$

$$K \rightarrow \mu N$$

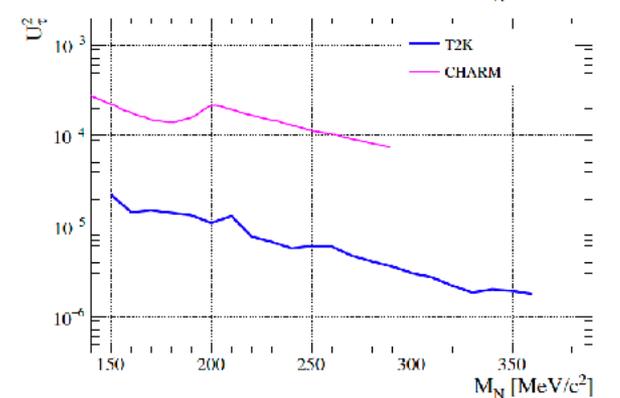
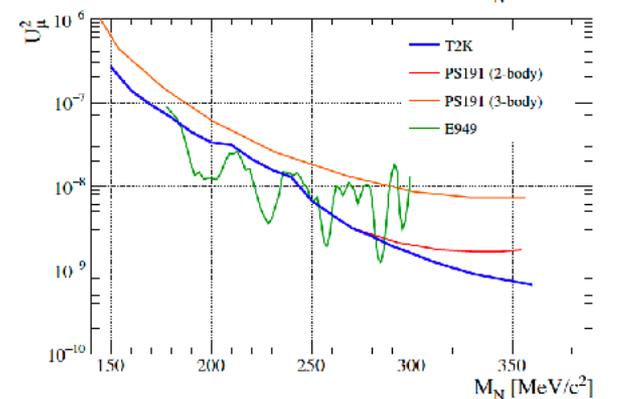
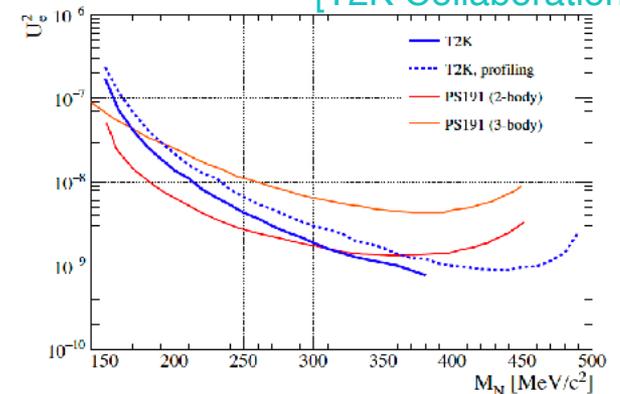


$$N \rightarrow l_{\alpha}^{\pm} \pi^{\mp}$$

$$N \rightarrow l_{\alpha}^{\pm} l_{\beta}^{\mp} \nu_{\beta}$$

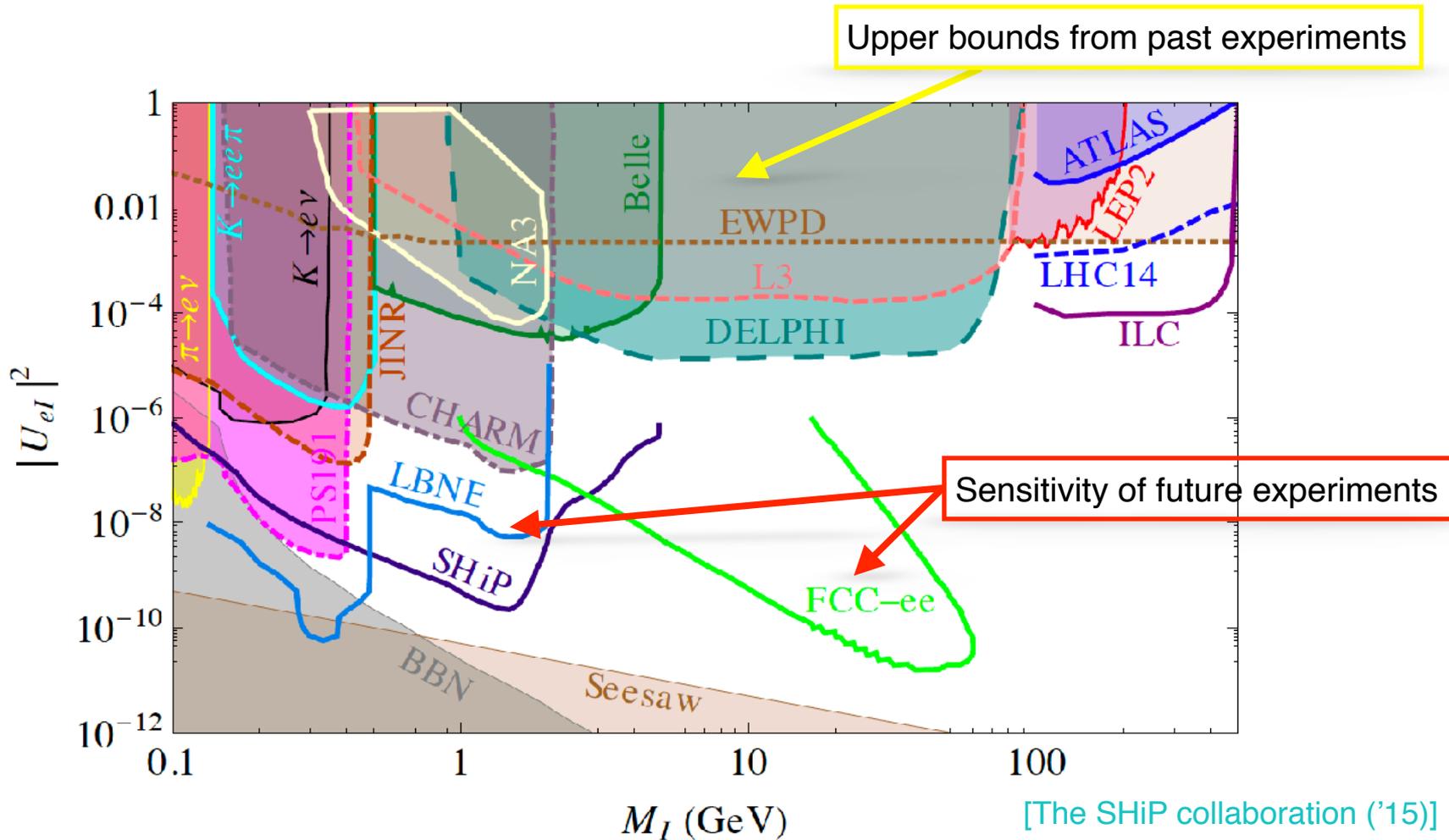
$$N \rightarrow \nu_{\alpha} l_{\beta}^{\pm} l_{\beta}^{\mp}$$

[T2K Collaboration ('19)]



[Asaka, SE, Watanabe ('12)]

Past and future experiments

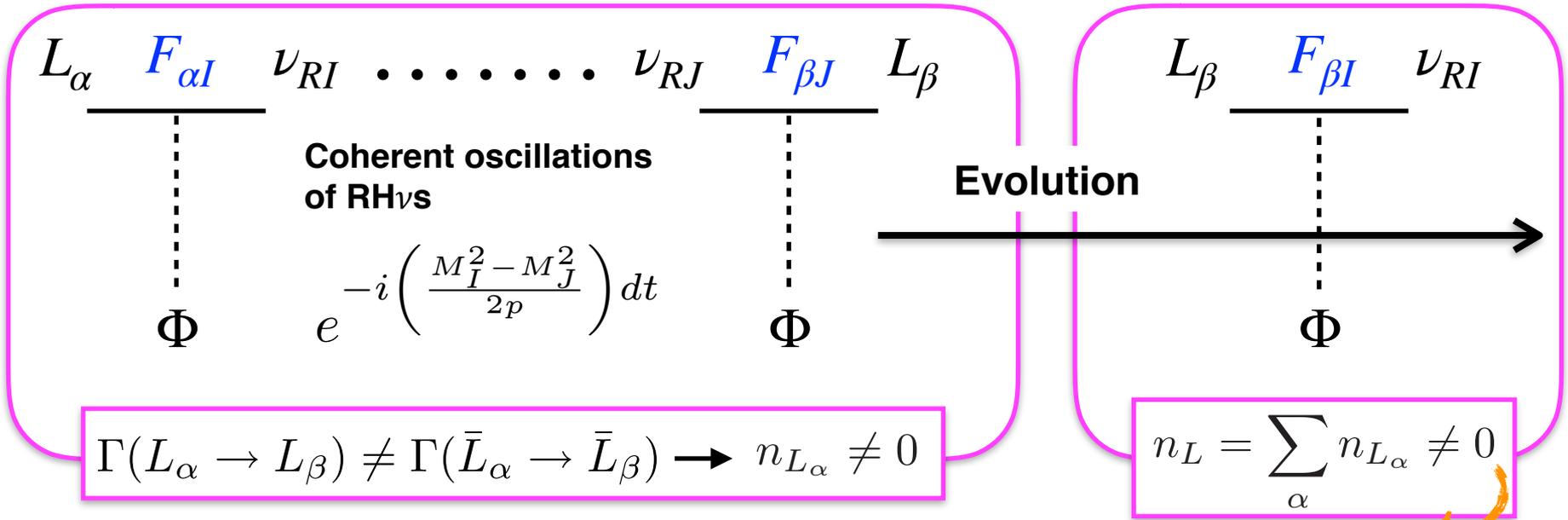
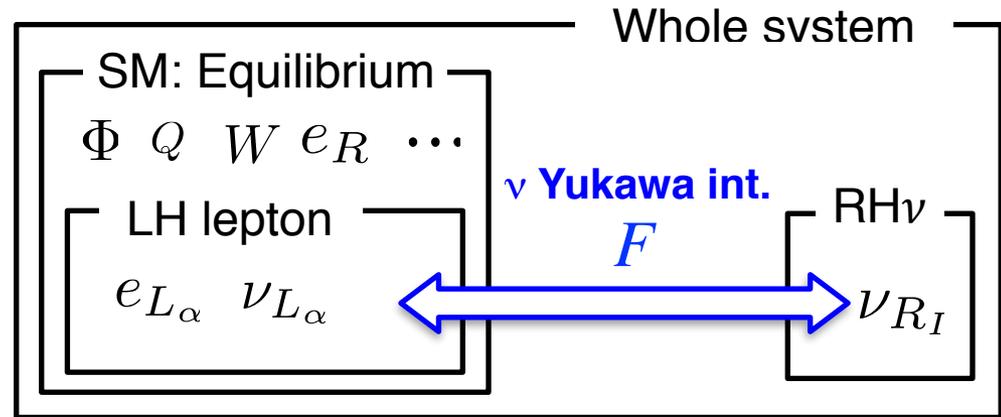


Can GeV-scale RH ν s responsible for the BAU be probed?

Baryogenesis via RH ν oscillations

Mechanism

- **CP violation**
- **Out-of-equilibrium process**

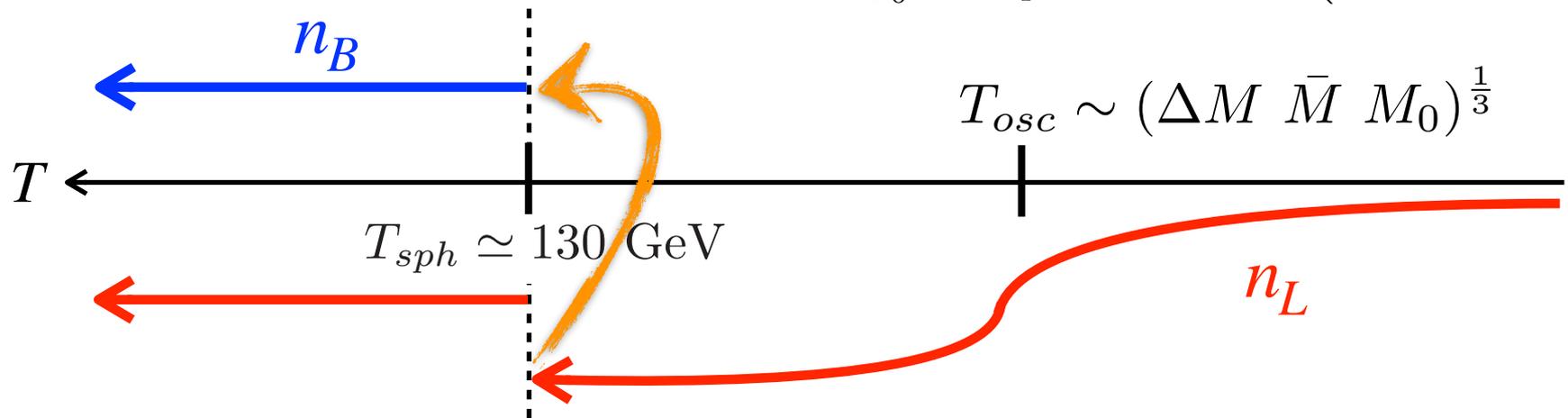


$$n_B(T_{sph}) = -\frac{28}{79}n_L(T_{sph}) \quad \text{at} \quad T_{sph} \simeq 130 \text{ GeV}$$

T_{osc} of Baryogenesis

Evolution of asymmetries

$$\int_0^t \frac{M_2^2 - M_1^2}{2p} dt' \sim 1 \quad \left(t = \frac{1}{2H} = \frac{M_0}{2T^2} \right)$$



$T_{osc} \ll T_{sph}$: can not be effective to generate n_B

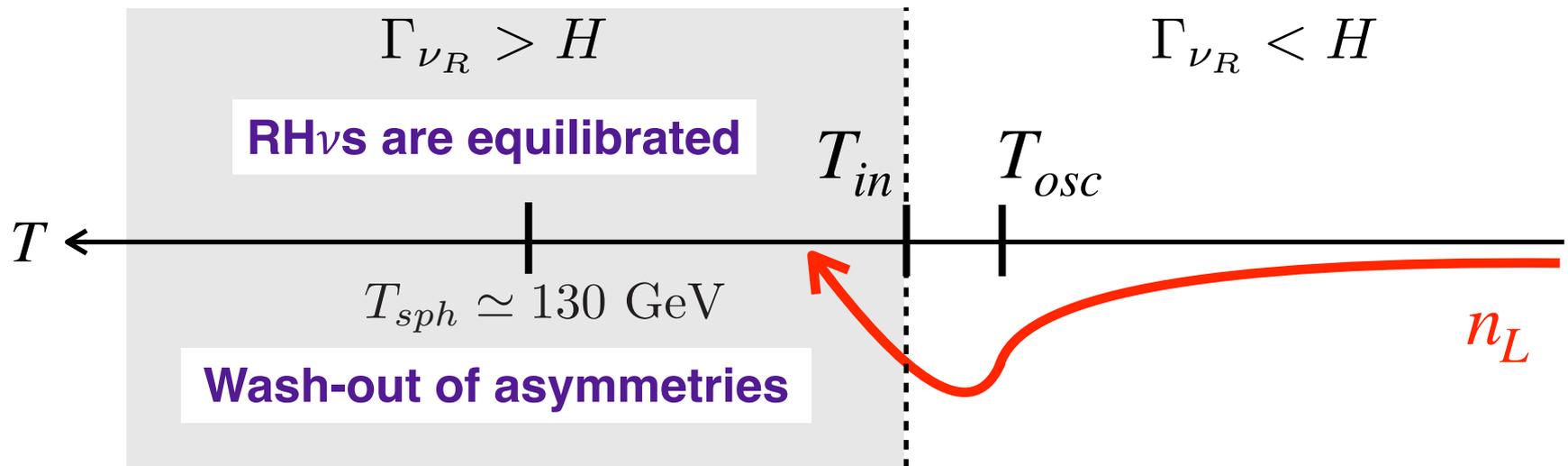
$T_{osc} \gg T_{sph}$: less amount of RH ν s to oscillate

Favoured condition: $T_{sph} \sim T_{osc}$ $\left(M_0 \equiv \sqrt{\frac{90}{\pi^2 g_*}} M_p \approx 7 \times 10^{17} \text{ GeV} \right)$

$$\longrightarrow \Delta M \sim 3 \times 10^{-12} \text{ GeV} \left(\frac{\text{GeV}}{M} \right)$$

T_{in} of $\text{RH}\nu$

Evolution of asymmetries



T_{in} : $\text{RH}\nu$ enters thermal equilibrium

$$\Gamma_{\nu_R}(T_{in}) = H(T_{in})$$

$$\Gamma_{\nu_R}(T) \simeq 0.012 [F^\dagger F] T$$

Requirement: Upper bound on Yukawa couplings

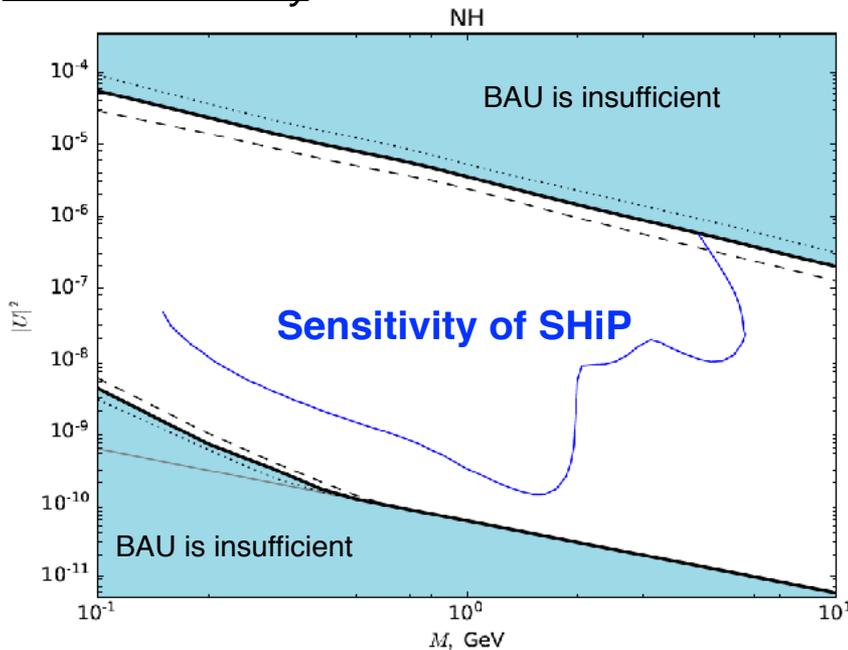
$$F^{\text{Max}}(M) \longrightarrow \Theta^{\text{Max}}(M) = \frac{v F^{\text{Max}}(M)}{M}$$

Direct search and the BAU with RH ν s

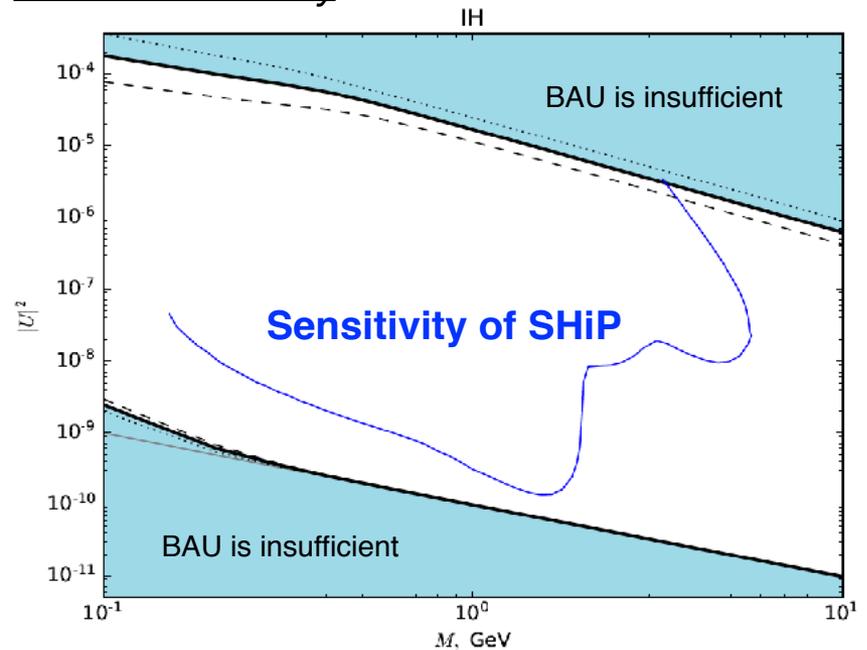
Latest results of parameter space required from the successful BAU.

Typical mixing of HNLs : $U^2 \equiv \sum_{\alpha I} |\Theta_{\alpha I}|^2$

Normal hierarchy



Inverted hierarchy

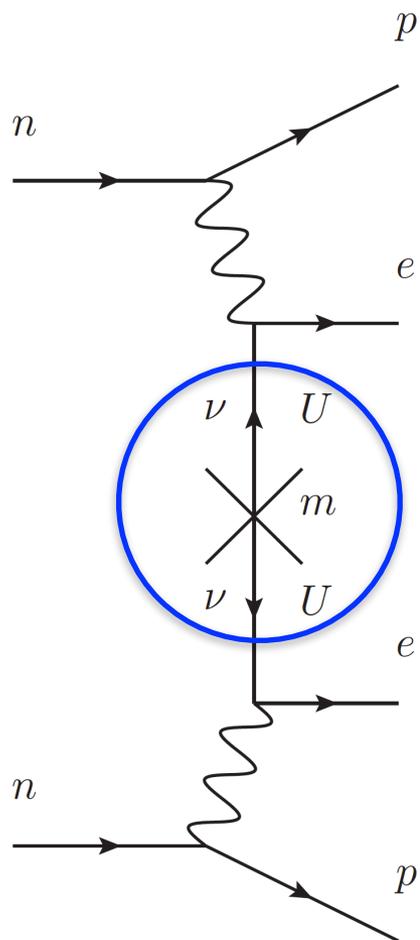


[SE, Shaposhnikov, Timiryasov ('18)]

For GeV-scale mass the SHiP experiment will probe the wide region in the suggested parameter space!

$0\nu 2\beta$ decay

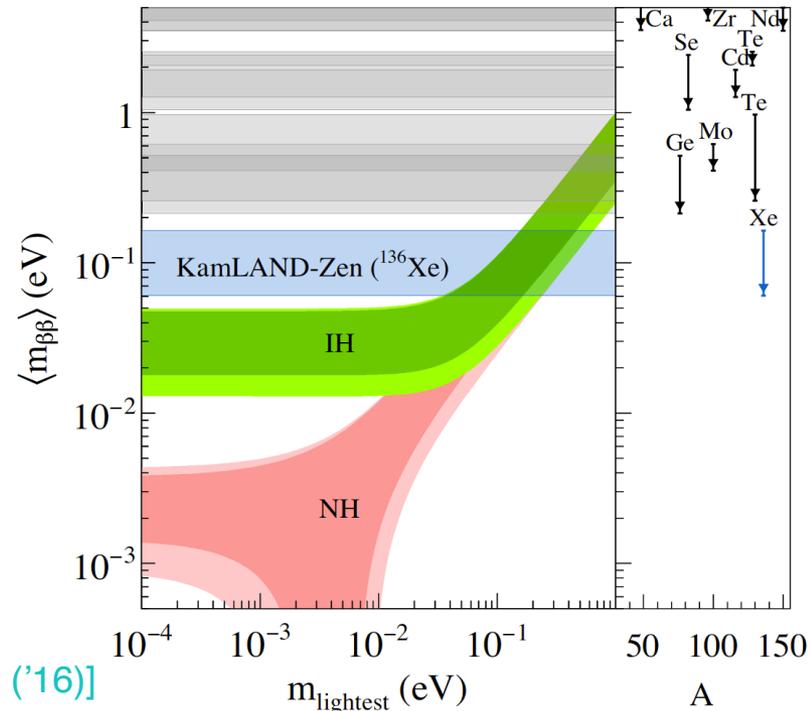
Lepton number violating process induced by **massive, Majorana neutrinos**



Effective neutrino mass : $[T_{1/2}^{0\nu}]^{-1} \propto (m_{\beta\beta})^2$

Active neutrino contribution : $m_{\beta\beta}^\nu = \left| \sum_i m_i U_{ei}^2 \right|$

Experimental bound :



$0\nu 2\beta$ decay with $RH\nu$

Effective neutrino mass with $RH\nu$:

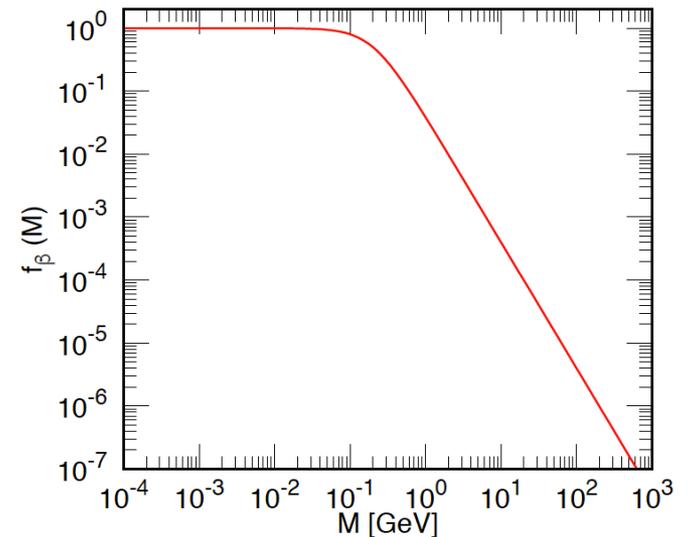
$$m_{\beta\beta} = \left| \sum_{i=1,2,3} m_i U_{ei}^2 + \sum_{I=1,2,\dots,n} f_{\beta}(M_I) M_I \Theta_{eI}^2 \right|$$

Mixing angle of $RH\nu$: $\Theta_{\alpha I} = \langle \Phi \rangle F_{\alpha I} / M_I$

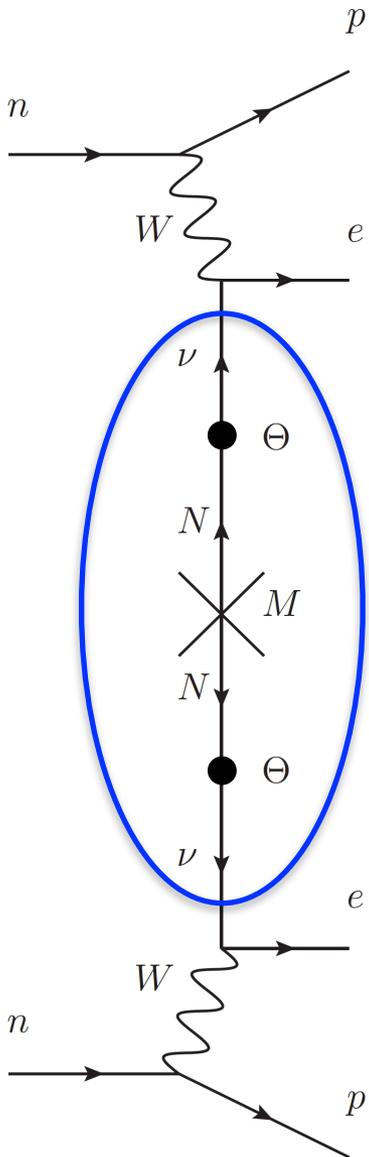
Suppression factor of nuclear matrix element:

$$f_{\beta}(M) = \frac{\langle p^2 \rangle}{\langle p^2 \rangle + M^2}$$

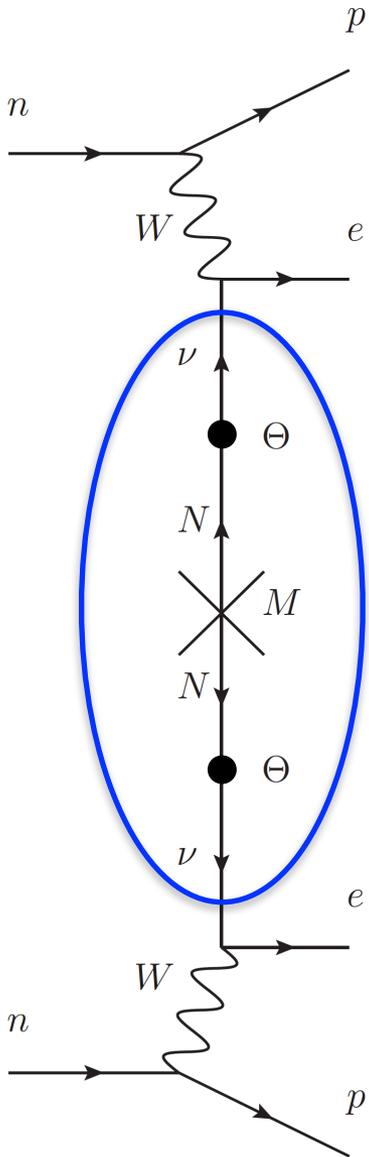
$$\langle p^2 \rangle \simeq (200 \text{ MeV})^2$$



For $M \gg \sqrt{\langle p^2 \rangle}$ contribution of $RH\nu$ is suppressed



$0\nu 2\beta$ decay with $RH\nu$ for baryogenesis



For $I = 1, 2$ and $\Delta M / \bar{M} \ll 1$

$$\begin{aligned}
 m_{\beta\beta}^N &= \sum_{1,2} f_{\beta}(M_I) M_I \Theta_{eI}^2 \\
 &\simeq f_{\beta}(\bar{M}) \sum_{I=1,2} M_I \Theta_{eI}^2 + \underline{\Delta M} f'_{\beta}(\bar{M}) (M_2 \Theta_{e2}^2 - M_1 \Theta_{e1}^2) \\
 &= \underline{-f_{\beta}(\bar{M})} \sum_{I=1,2,3} m_i U_{ei}^2 + \delta m_{\beta\beta}^N
 \end{aligned}$$

$$\left(\sum_{I=1,2} M_I \Theta_{eI}^2 = - \sum_{i=1,2,3} m_i U_{ei}^2 \right)$$

For $\Delta M \rightarrow 0$ limit

$$m_{\beta\beta} = [1 - f_{\beta}(\bar{M})] m_{\beta\beta}^{\nu}$$

Contribution of $RH\nu$ to the effective neutrino mass seems to be always destructive...

$0\nu 2\beta$ decay and the BAU with $RH\nu$

Numerical results under fixed CP phases maximizing $|\delta m_{\beta\beta}^N|$

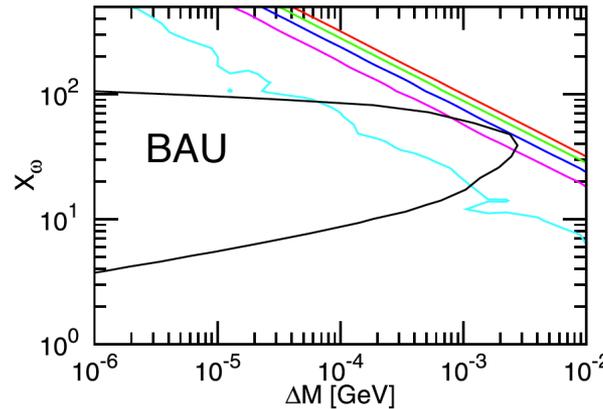
Inverted hierarchy $U^2 \propto (X_\omega^2 + X_\omega^{-2})$

Left from cyan line;

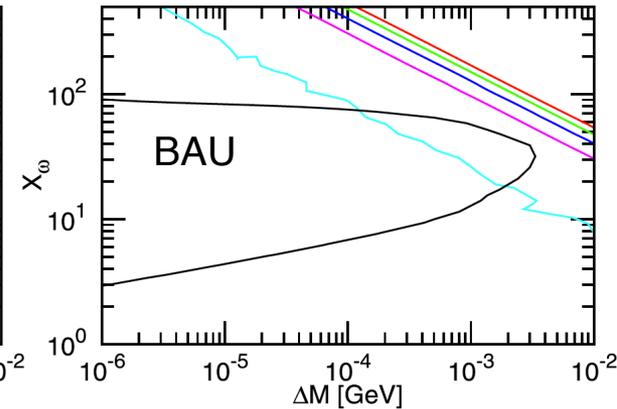
$$m_{\beta\beta} = [1 - f_\beta(\bar{M})] m_{\beta\beta}^\nu$$

Right from cyan line;

$$m_{\beta\beta} \simeq |\delta m_{\beta\beta}^N|$$



(a) IH, $M_N = 0.5$ GeV

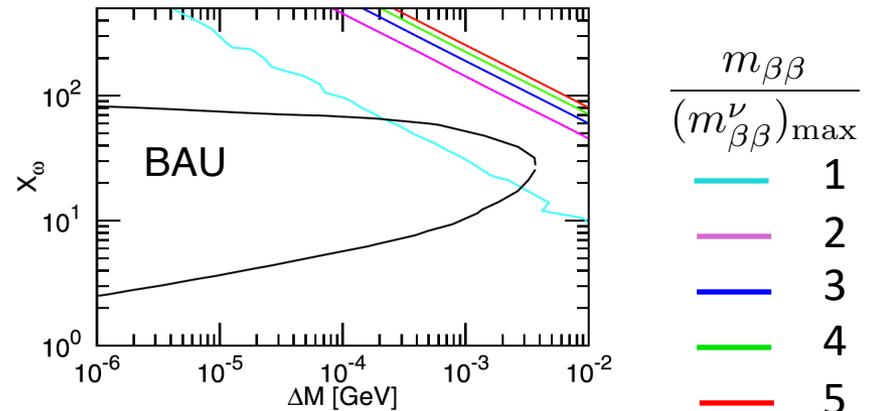


(b) IH, $M_N = 0.75$ GeV

In the inverted hierarchy case

- Mass close to $\langle p^2 \rangle \simeq (200 \text{ MeV})^2$
- Weak degeneracy $\Delta M/\bar{M} \sim 10^{-2}$

The rate of $0\nu 2\beta$ decay in this framework can be greater than that only from active neutrino contributions



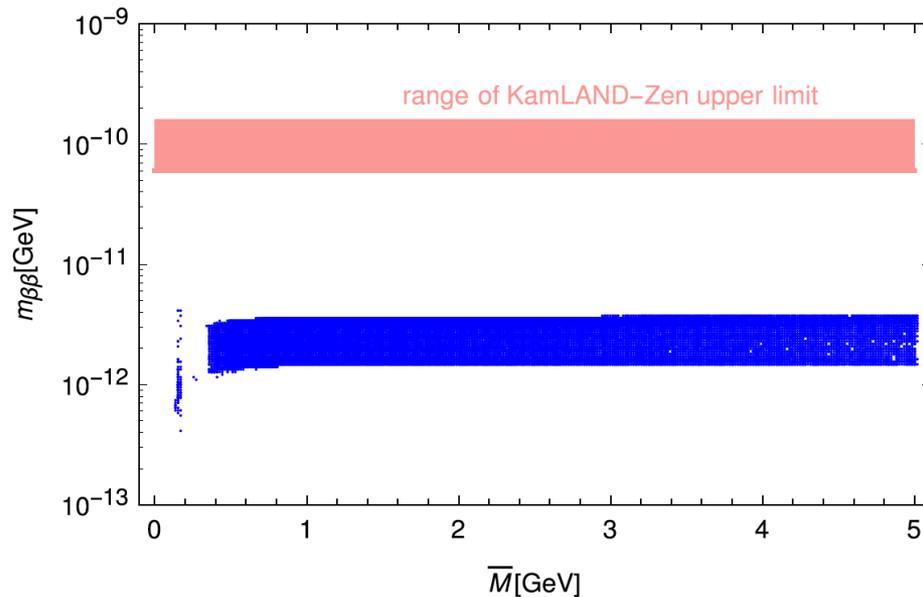
(c) IH, $M_N = 1.0$ GeV

[Asaka, SE, Ishida ('16)]

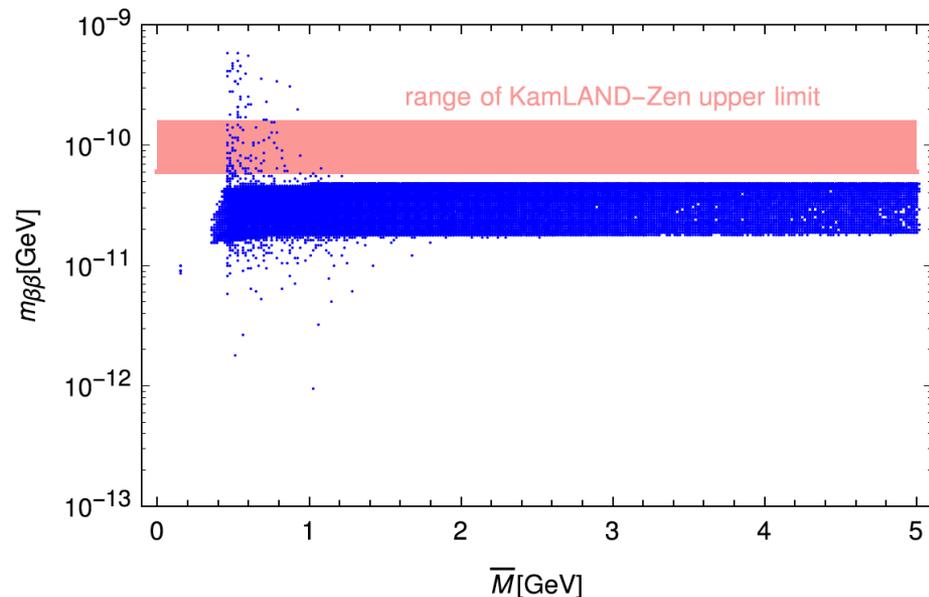
$0\nu 2\beta$ decay and the BAU with $RH\nu$

Effective neutrino mass under successful baryogenesis

Normal hierarchy



Inverted hierarchy



[Drewes, SE('16)]

- For $\bar{M} \lesssim 2\text{GeV}$ contributions from $RH\nu$ are effective.
- Current upper bound of $0\nu 2\beta$ decay already gives a restriction to the baryogenesis

Summary

GeV-scale right-handed neutrinos can be the origin of neutrino masses and the baryon asymmetry of the universe.

The weak-interacting particles are testable in both direct and indirect search experiments and might be found in near future!