OBSERVABLE LEPTOGENESIS

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Outline

- Introduction
- Leptogenesis via HNL decay
- ν electroweak baryogenesis
- Leptogenesis via HNL oscillations
- Summary and Outlook

Reviews on leptogenesis:

Buchmüller, Peccei, Yanagida, 2005; Davidson, Nardi, Nir, 2008; Fong, Nardi, Riotto, 2012; Garbrecht, Molinaro et al., 2018

1. Introduction

- Baryon number density: determined from
  - Big Bang Nucleosynthesis: primordial abundances of light elements (D, ^{3}He, ^{4}He, ^{7}Li) mainly depend on one parameter, n_B/n_γ
  - CMB anisotropies

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} \simeq \frac{n_B}{s} = (8.66 \pm 0.01) \times 10^{-11}$$

Impressive consistency between both determinations, completely independent !

- Baryon asymmetry
  - Nucleons and antinucleons were in thermal equilibrium up to $T_{fo} \approx 22$ MeV, when $\Gamma_{ann} < H$
  - If the Universe were locally baryon-symmetric:

    $Y_{Bfo} < 10^{-20}$ ➔ there was a baryon asymmetry

- Sakharov's conditions to dinamically generate the baryon asymmetry (BAU)
  - Baryon number violation
  - C and CP violation
  - Departure from thermal equilibrium

2. Leptogenesis via HNL decay

2. Leptogenesis via HNL decay

- BAU generated in the decay of heavy Majorana neutrinos: Fukugita, Yanagida, 1986

  - Out of equilibrium decay
  - L and CP violating interactions ➔ lepton asymmetry, ΔL
  - (B+L)-violating, but (B-L) conserving, non-perturbative sphaleron interactions ΔL ➔ ΔB

- Non-equilibrium process → Boltzmann eqs.

$$\frac{dY_{N_1}}{dz} = -\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)(D+S)$$

$$\frac{dY_{B-L}}{dz} = -\epsilon\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)D - Y_{B-L}W$$

$$z \equiv M_1/T$$

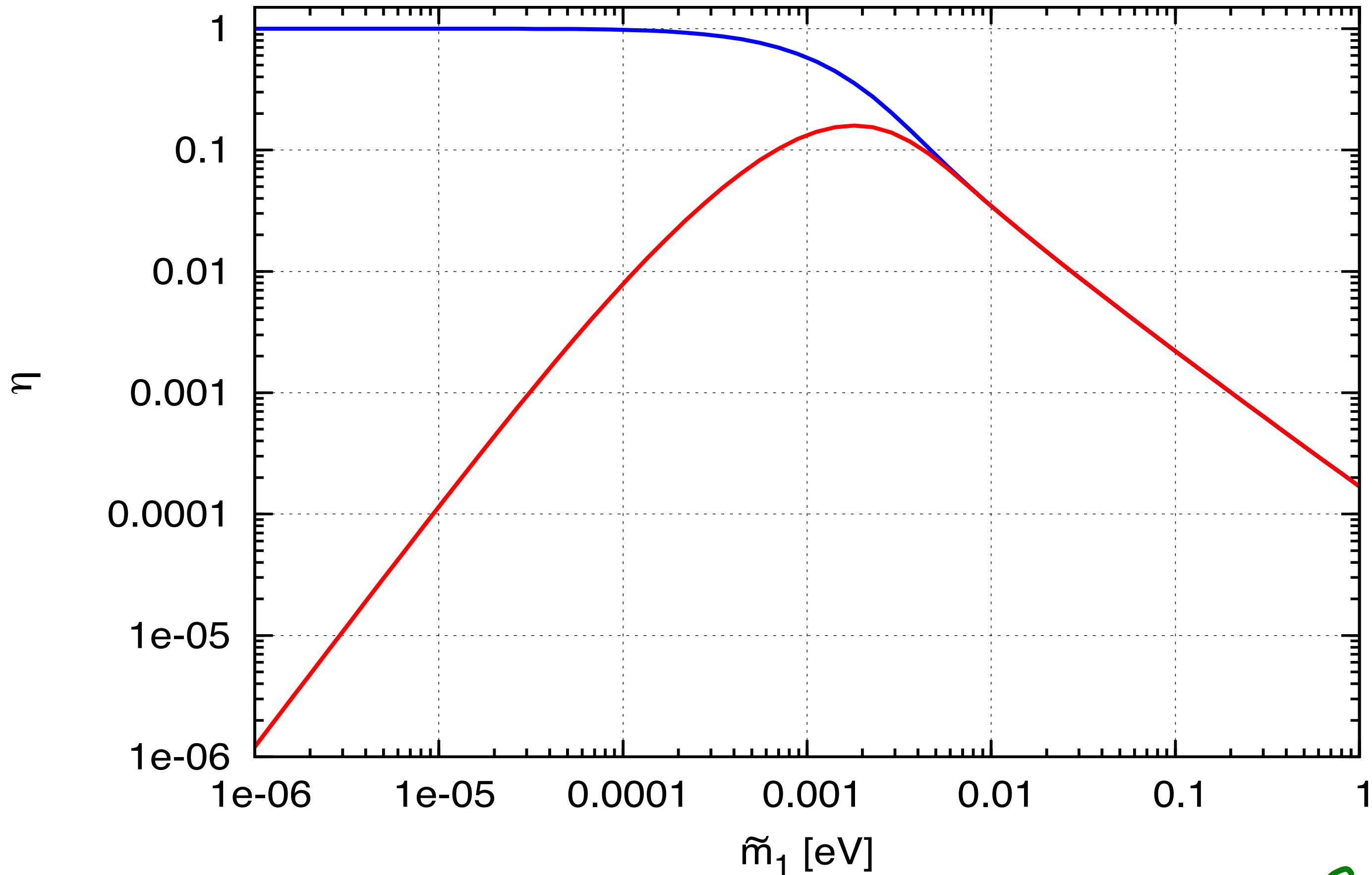
$$\epsilon = \sum_\alpha \epsilon_{\alpha 1} = \sum_\alpha \frac{\Gamma(N_1 \to \ell_\alpha h) - \Gamma(N_1 \to \bar{\ell}_\alpha \bar{h})}{\sum_\beta \Gamma(N_1 \to \ell_\beta h) + \Gamma(N_1 \to \bar{\ell}_\beta \bar{h})}$$

- Final baryon asymmetry:

$$Y_B = -\kappa\,\epsilon\,\eta$$

$$\kappa = \frac{28}{79} Y_{N_1}^{eq}(T \gg M_1) \sim 10^{-3}$$

η = efficiency : $0 \leq \eta \leq 1$



$Y_N^i = 0$ $Y_N^i = Y_N^{eq}$

Credit:
J. Racker

$$\tilde{m}_1 \equiv \frac{(\lambda^\dagger \lambda)_{11} v^2}{M_1}$$

Related to the contribution of N_1 to light neutrino masses

- η maximum for

$$\tilde{m}_1 = m_* = \frac{16}{3\sqrt{5}}\pi^{5/2}\sqrt{g_*}\frac{v^2}{M_P} \sim 10^{-3}\,\mathrm{eV}$$

m_* , defined by: $$\frac{\Gamma_N}{H(T = M_1)} = \frac{\tilde{m}_1}{m_*}$$

determines the amount of departure from thermal equilibrium and the strength of the washouts:

$\tilde{m}_1 \gg m_*$ ➔ strong washout:

- independence of initial conditions, $\eta \propto 1/\tilde{m}_1$

$\tilde{m}_1 \ll m_*$ ➔ weak washout:

- depends on initial conditions, if $Y_N^i = 0 \rightarrow \eta \propto \tilde{m}_1^2$

- Hierarchical heavy neutrinos: $\epsilon \sim \frac{3}{16\pi} \frac{\lambda_{\alpha 2}^2}{M_2} M_1$

- Connection to light neutrino masses (type I seesaw):

$$|\epsilon| \leq \epsilon_{DI} = \frac{3}{16\pi} \frac{M_1}{v^2} (m_3 - m_1)$$

Davidson, Ibarra, 2002

➔ $M_1 \gtrsim 10^9\,\mathrm{GeV}$

Detailed numerical analysis solving BEs:

➔ $M_1 \gtrsim (4\times) 10^8 \mathrm{GeV}$ for fine-tuned regions

Hambye et al. 2004

➔ bound on light neutrino masses, $m_\nu < 0.15$ eV

Buchmüller, Di Bari, Plümacher, 2004

Flavour effects

- At $T \lesssim 10^{12}$ GeV, the τ Yukawa interaction is fast, and there are (in general) 2 lepton flavour asymmetries evolving almost independently

- At $T \lesssim 10^{9}$ GeV, both τ and μ Yukawa interactions are in equilibrium ➔ 3 independent lepton flavour asymmetries, $Y_{\Delta(B/3-L\alpha)}$

Barbieri et al. 2000; Endoh et al. 2004; Abada et al. 2006; Nardi et al. 2006

Some consequences:

★Flavoured asymmetries ε_α depend on U_{PMNS} phases although in general leptogenesis is "insensitive" to them, even in SUSY Davidson, Garayoa, Palorini, NR, 2007

★ Bound on light neutrino masses $m_\nu < 0.15$ eV evaded

★ N_2 leptogenesis can survive N_1 washouts more easily:

➔ relevant for SO(10) models which predict $M_1 \ll 10^9$ GeV

★ Leptogenesis possible with $\epsilon = \sum_\alpha \epsilon_\alpha = 0$

➔ relevant for models with small B-L violation (inverse seesaw)

$$\epsilon_{\alpha i} \equiv \frac{\Gamma(N_i \to \ell_\alpha h) - \Gamma(N_i \to \bar{\ell}_\alpha \bar{h})}{\sum_\beta \Gamma(N_i \to \ell_\beta h) + \Gamma(N_i \to \bar{\ell}_\beta \bar{h})} = \epsilon^{\not L}_{\alpha i} + \epsilon^{L}_{\alpha i}$$

where:

Covi, Roulet, Vissani, 1996

$$\epsilon^{\not L}_{\alpha i} = \sum_{j \neq i} f(a_j) \mathrm{Im}[\lambda^*_{\alpha j} \lambda_{\alpha i} (\lambda^\dagger \lambda)_{ji}]$$

$$a_j \equiv M_j^2 / M_i^2$$

$$\epsilon^{L}_{\alpha i} = \sum_{j \neq i} g(a_j) \mathrm{Im}[\lambda^*_{\alpha j} \lambda_{\alpha i} (\lambda^\dagger \lambda)_{ij}]$$

related to L conserving d=6 operators ➔ escape the DI bound because they are not linked to neutrino masses (LNV d=5 Weinberg operator). $M_1 > 10^6$ GeV

Resonant leptogenesis

- Enhancement of the CP asymmetry for degenerate neutrinos, $M_2 - M_1 \approx \Gamma_2$

$$|\epsilon| \sim \frac{1}{2}\frac{\mathrm{Im}[(\lambda^\dagger\lambda)^2_{21}]}{(\lambda^\dagger\lambda)_{11}(\lambda^\dagger\lambda)_{22}} \leq \frac{1}{2}$$

Covi, Roulet, 1997; Pilaftsis, 1997; Pilaftsis, Underwood 2004

➔EW scale e-,μ-,τ- leptogenesis with observable LFV

Pilaftsis 2005; Deppisch, Pilaftsis 2011

- Approximate flavour symmetries + universal RHN masses at the GUT scale ➔ heavy neutrino mass splittings radiatively generated

Non-equilibrium QFT:

Kadanoff-Baym equations for spectral functions and statistical propagators of leptons and Majorana neutrinos

Anisimov et al., 2011; Drewes et al. 2013

★ Relevant in the weak washout regime

★ Very important for resonant leptogenesis: supression wrt classical Boltzmann result.

Garny et al., 2013

- If $M_2 - M_1 \approx \Gamma_2$ ➔ HNL oscillations

- Taken into account using "Flavour covariant transport equations" ➔ density matrix formalism

$$\dot{\rho} = -i[H, \rho]$$

Dev et al., 2014 (109 p.)

- Identify mixing contribution from diagonal ρ_N and heavy neutrino oscillation contribution from off-diagonal $(\rho_N)_{12}$

- Also in the Kadanoff-Baym approach Dev et al., 2015

3. ν electroweak baryogenesis

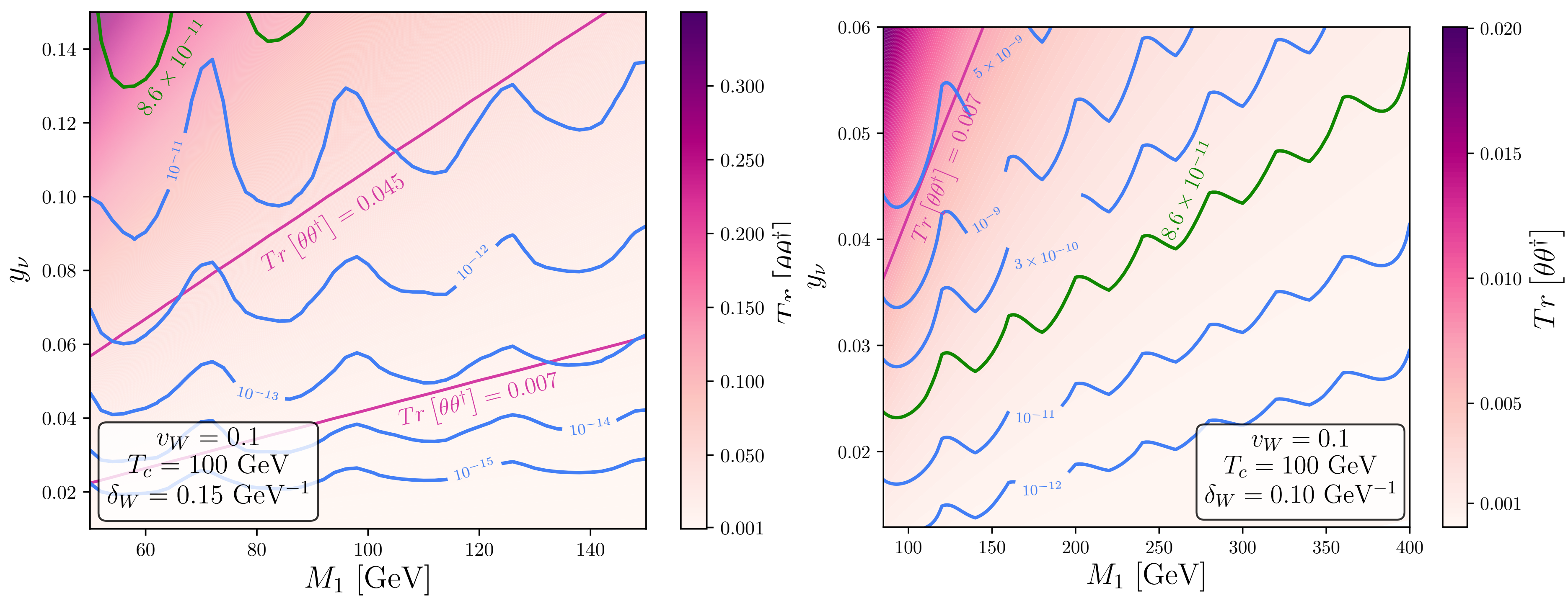
- Extra SM singlet scalar provides both: strongly first order EW phase transition (SFOPT) and HNL (Dirac) masses
- Inverse or linear seesaw ➔ large neutrino Yukawa couplings

$$\mathcal{L} = -\overline{L}_L \tilde{H} Y_\nu N_R - \overline{N}_L \phi Y_N N_R + h.c. - V(\phi^* \phi, H^\dagger H)$$

- Profiles of the vevs $v_H(z)$ and $v_\phi(z)$ along the bubble wall must be different

P. Hernández, NR, 1997

Importance of flavour effects: $\theta \equiv m_D M_N^{-1} = \frac{1}{\sqrt{2}} Y_\nu v_H Y_N^{-1} v_\phi$



Unflavoured　　　　With flavour

Regions of SFOPT consistent with current experimental bounds also identified

E. Fernández-Martínez et al. 2020, 2023

5. Leptogenesis via HNL oscillations

Akhmedov, Rubakov, Smirnov, 1998; Asaka,Shaposhnikov 2005; Hernández et al. 2016; Antusch et al. 2018; Drewes et al. 2018; Abada et al. 2019; Domcke et al. 2020; etc

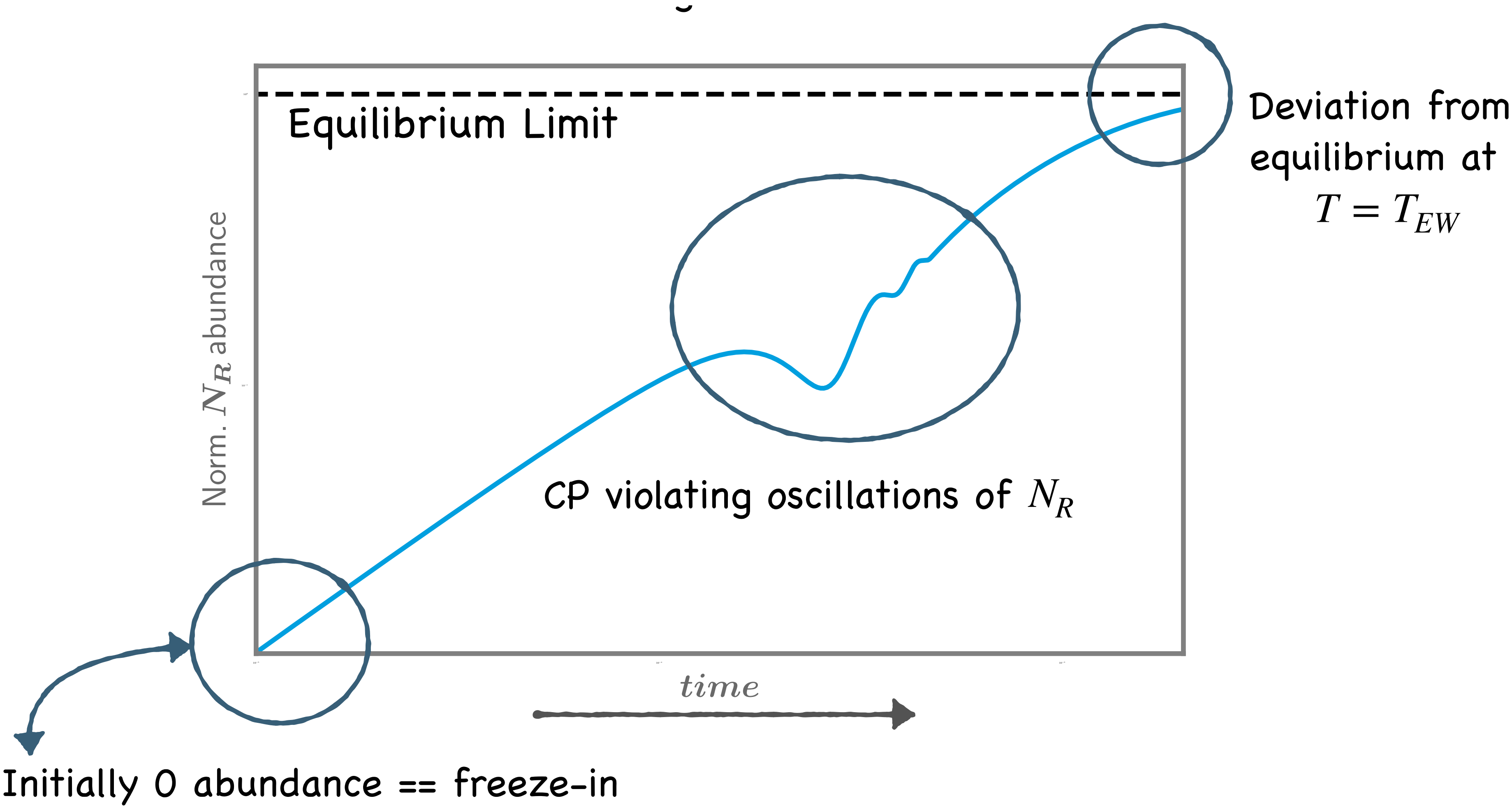
Sakharov conditions for baryogenesis:

- CP violating phases in Y, M
- B violated by sphaleron processes at $T > T_{EW}$
- At least one HNL does **NOT** equilibrate by T_{EW} , i.e. for some rate

$$\Gamma_i (T_{EW}) \leq H_u(T_{EW}) = T_{EW}^2 / M_P^*$$

Fulfilled for M = O(GeV), $Y \sim 10^{-6} - 10^{-7}$, in the correct range to explain neutrino masses ! Freeze-in baryogenesis

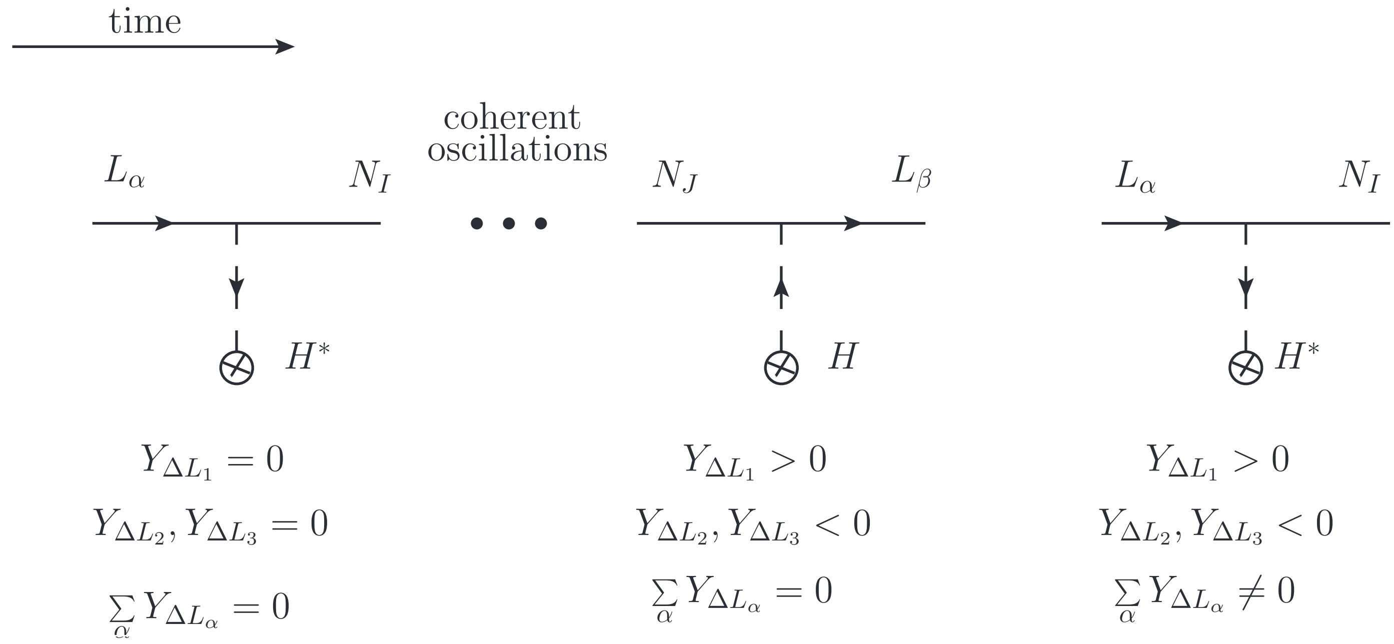
Schematic evolution of N_R abundance



Courtesy of S. Sandner

- Basic stages:

Shuve, Yavin 2014



Out of equilibrium HNL production

Asymmetries in lepton flavours

Different washout of flavoured asymmetries

- Inclusion of LNV (helicity conserving, HC) rates, suppressed by $(M/T)^2$

Hambye, Teresi 2016,2017

Density matrix formalism(*)

Raffelt & Sigl, 1993

$$\dot{\rho} = -i[H,\rho] - \frac{1}{2}\{\Gamma^a,\rho\} + \frac{1}{2}\{\Gamma^p,\rho_{eq}-\rho\}$$

- Hamiltonian term:

$$H = \frac{M^2}{2k^0} + \frac{T^2}{8k^0} Y^\dagger Y$$

- Annihilation and production rates of the N's: Γ^a, Γ^p

- For antineutrinos: $\bar{\rho}$, H ⟹ H*
- Diagonal density matrix for SM leptons, which are in thermal equilibrium, with chemical potential

$$f_\alpha(k^0) = \frac{1}{e^{(k^0-\mu_\alpha)/T}+1}$$

- For antileptons $\mu_\alpha \Longrightarrow -\mu_\alpha$

(*)Similar results in Closed-time-path formalism Drewes et al.

Minimal type I seesaw model with 2 HNL

Hernández, López-Pavón, NR, Sandner, 2022

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}_i \gamma^\mu \partial_\mu N_i - \left(Y_{\alpha i} \overline{L}_\alpha N_i \Phi + \frac{M_i}{2} \overline{N}_i^c N_i + h.c. \right)$$

- $m_\nu = v^2 \, Y \, M^{-1} \, Y^T$, $v = <\Phi>$
- one massless neutrino

- Low scale (testable at SHiP, FCC-ee):

  $M \in [0.1 - 100]$ GeV

- Naive seesaw scaling of active neutrino-HNL mixing:

  $U = v \, Y/M = O(\sqrt{m_\nu/M})$

Time scales and slow modes

$$\dot{\rho} = -i[H,\rho] - \frac{1}{2}\{\Gamma^a,\rho\} + \frac{1}{2}\{\Gamma^p,\rho_{eq}-\rho\}$$

- Annihilation and production rates of the N's: at T >> M,

$$\Gamma(T) \propto \mathrm{Tr}[YY^\dagger]\,T$$

Ghiglieri, Laine, 2017

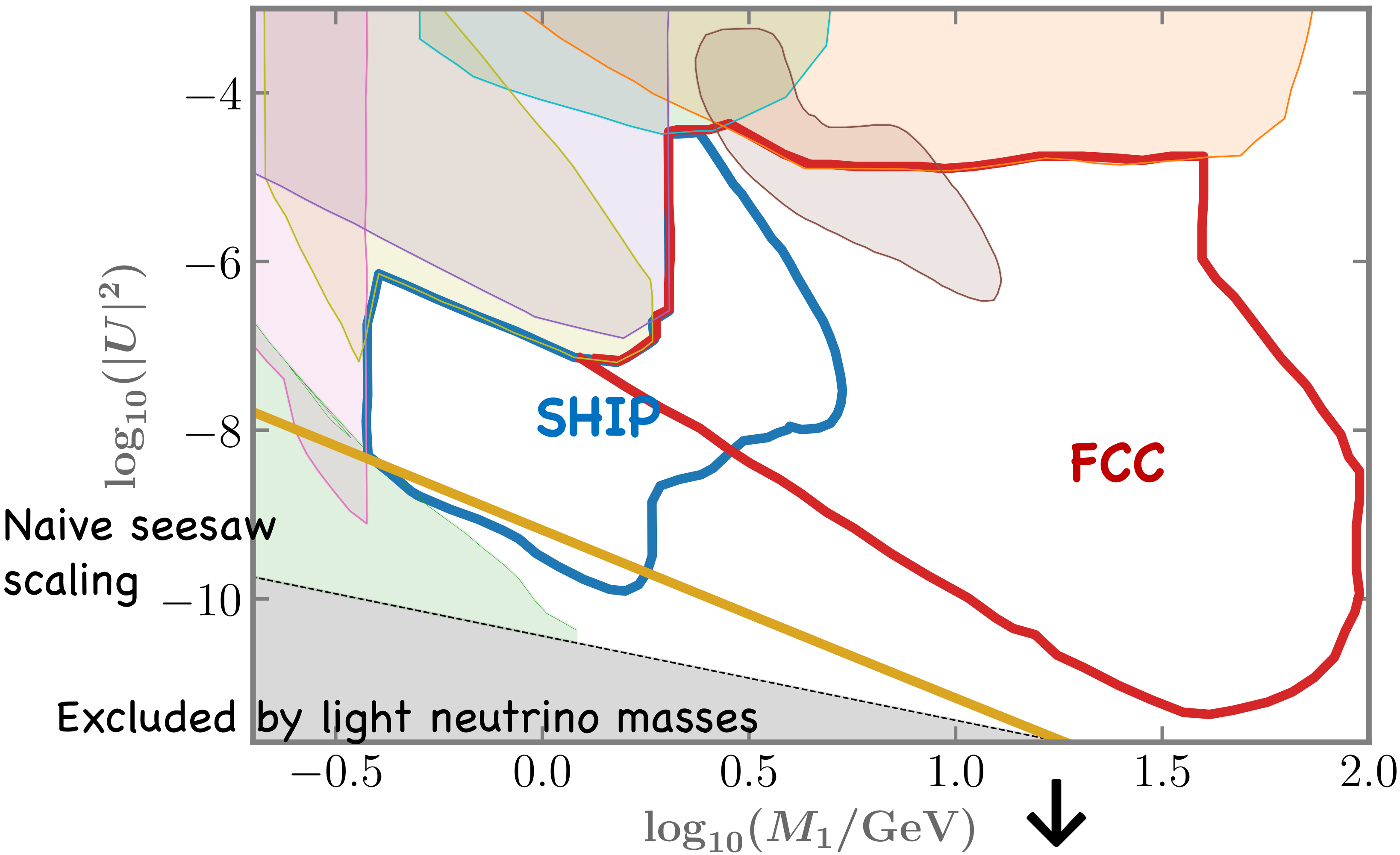
- Flavoured rates: $\Gamma_\alpha(T) \propto \epsilon_\alpha \Gamma(T)$ $\qquad \epsilon_\alpha \equiv \frac{(YY^\dagger)_{\alpha\alpha}}{\mathrm{Tr}[YY^\dagger]}$

- Oscillation rate: $\Gamma_{osc}(T) \propto \frac{\Delta M^2}{T}$

- LNV (HC) rate: $\Gamma_M \propto (M/T)^2\Gamma(T)$

- Asymmetry generated mostly at T_{osc}, defined as:

$\Gamma_{osc}(T_{osc}) = H_u(T_{osc})$



$\Gamma\,(T_{EW}) = H_u(T_{EW})$

Approximately conserved lepton number limit

- Inverse seesaw Wyler, Wolfenstein 1983;Mohapatra, Valle 1986

$$M = \begin{pmatrix} \mu_1 & \Lambda \\ \Lambda & \mu_2 \end{pmatrix}. \qquad Y = \begin{pmatrix} y_e & y'_e e^{i\beta'_e} \\ y_\mu & y'_\mu e^{i\beta'_\mu} \\ y_\tau & y'_\tau e^{i\beta'_\tau} \end{pmatrix}$$

$y'_\alpha \ll y_\alpha$, $\mu_i \ll \Lambda$

- Once neutrino masses and mixings are fixed, there are 6 free parameters:

- $y^2 \equiv \sum_\alpha y_\alpha^2$, or, equivalently $U^2 \simeq \frac{y^2 v^2}{2\Lambda^2}$

- Three independent phases ($\mu_1 = \mu_2 \equiv \mu$ can be chosen real)

- In terms of physical HNL masses:

$\Lambda = (M_1 + M_2)/2 = M$, $\mu = (M_2 - M_1)/2 = \Delta M/2$

Slow modes at T_{EW} (3rd Sakharov condition):

- Weak washout: $\Gamma_\alpha(T_{EW}) < \Gamma(T_{EW}) < H_u(T_{EW})$

- Flavoured weak washout: $\Gamma_\alpha(T_{EW}) < H_u(T_{EW}) < \Gamma(T_{EW})$

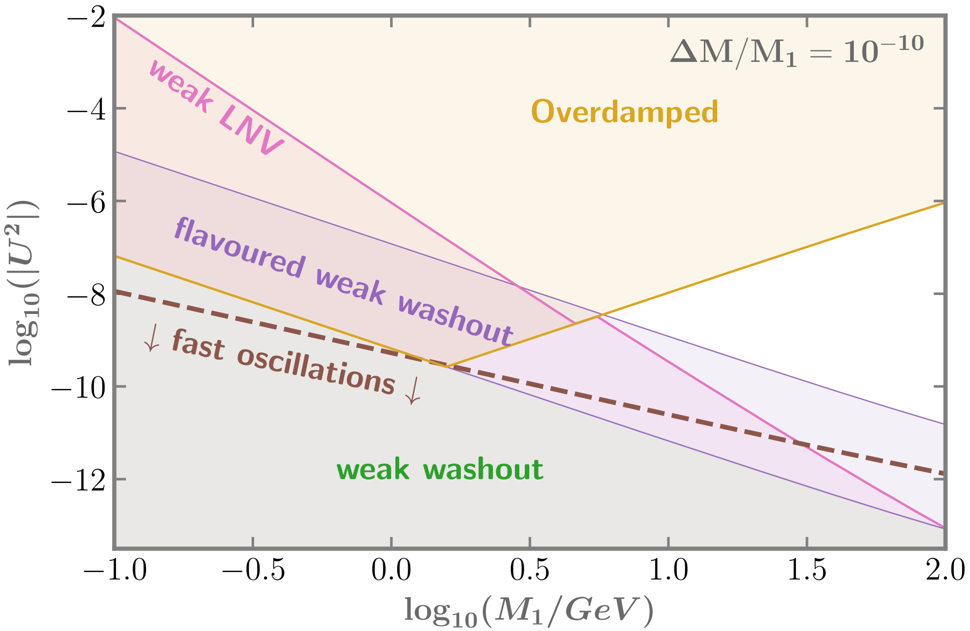
- Overdamped regime: when $\epsilon \propto \dfrac{\Delta M^2/T}{\Gamma(T)} \ll 1$ at $T \geq T_{EW}$,

$$\Gamma_{ov}(T_{EW}) \propto [\epsilon(T_{EW})]^2\, \Gamma(T_{EW}) < H_u(T_{EW})$$

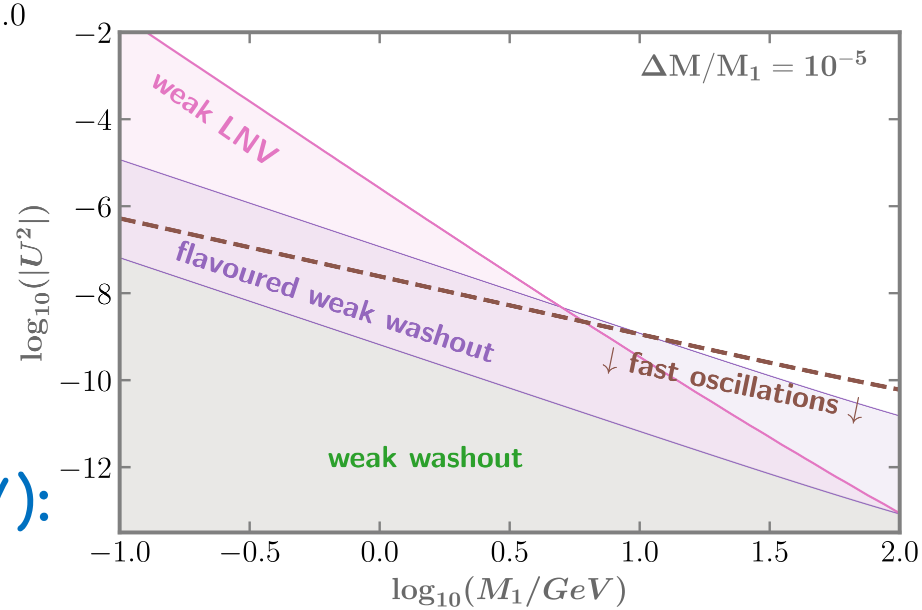
- Weak LNV (HC) regime:

$$\Gamma_M(T_{EW}) \propto (M/T_{EW})^2\, \Gamma(T_{EW}) < H_u(T_{EW})$$

- Fast oscillations: $\Gamma_{osc}(T) >> \Gamma(T)$ at $T = T_{osc}$



Asymmetry exponentially washed out in white regions



- Overdamped: lower bound on U^2
- Weak washout (flavoured, LNV): upper bound on U^2

CP violating flavour basis invariants

- All CP violating observables must be proportional to a combination of CP weak basis invariants

Branco et al., 2001

- LNC CP invariants: independent of HNL Majorana character

Hernández et al., 2015

$$I_0 = \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y M^\dagger M Y^\dagger Y_\ell Y_\ell^\dagger Y\right]\right)$$

$$\to \sum_\alpha y_{\ell_\alpha}^2 \sum_{i<j} (M_j^2 - M_i^2)\, \mathrm{Im}\left[Y_{\alpha j}^* Y_{\alpha i} \left(Y^\dagger Y\right)_{ij}\right] \equiv \sum_\alpha y_{\ell_\alpha}^2\, \Delta_\alpha$$

- LNV CP invariants: sensitive to Majorana character of HNLs, only appear when LNV interactions are included

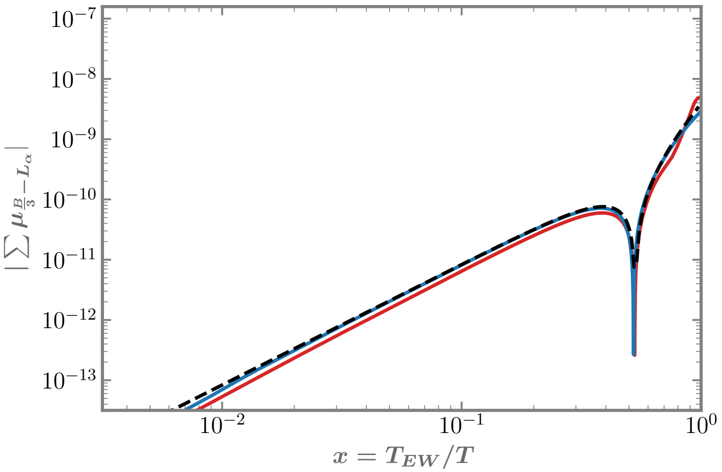
$$I_1 = \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y M^\dagger M M^* Y^T Y^* M\right]\right)$$

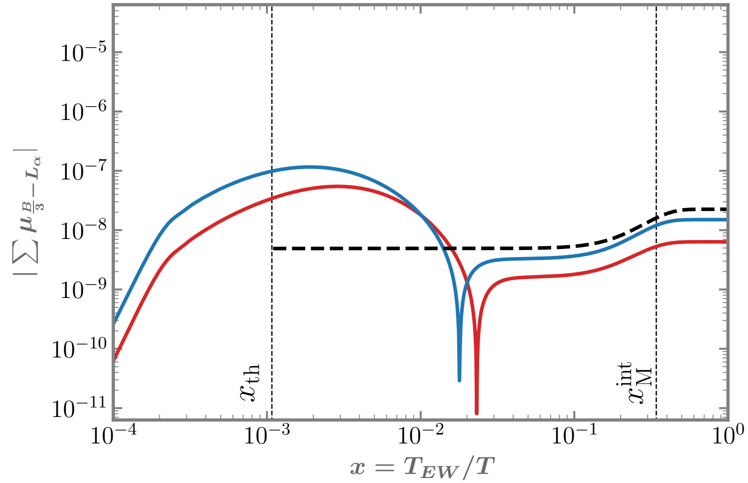
$$\to \sum_\alpha \sum_{i<j} (M_j^2 - M_i^2)\, M_i M_j \mathrm{Im}\left[Y_{\alpha j} Y_{\alpha i}^* \left(Y^\dagger Y\right)_{ij}\right] \equiv \sum_\alpha \Delta_\alpha^M$$

Analytic approach

- Identify the non-thermal modes and their characteristic time scales
- Solve the equations perturbatively, exploiting the weakly coupled modes
- Identify the CP-invariants that control Y_B

Overdamped regime: Slow flavour α :





$$\epsilon \propto \frac{\Delta M^2/T}{\Gamma(T)} \ll 1$$

$\Gamma_\alpha(T_{EW}) < H_u(T_{EW}) < \Gamma(T_{EW})$

---- analytical solution:
Perturbing in y' and in $(M/T)^2$
Linearized equations

—— numerical solution with same approximations

—— full numerical solution

CP invariants in terms of neutrino masses and U_{PMNS}

$$-\left(m_\nu\right)_{\alpha\beta} = \frac{v^2}{\Lambda}\left(Y_{\alpha 1} Y_{\beta 2} + Y_{\alpha 2} Y_{\beta 1} - Y_{\alpha 1} Y_{\beta 1}\frac{\mu_2}{\Lambda}\right) = \left(U^* m\, U^\dagger\right)_{\alpha\beta}$$

- $Y_{\beta 2} \propto y'$, and μ_2 violate LN
- Parametrization equivalent to Casas-Ibarra in the symmetry protected limit ($y'/y \approx e^{-2\mathrm{Im}[z]}$, θ=2Re[z]) Gavela et al. 2009

$$Y_{\alpha 1} = \frac{e^{-i\theta/2} y}{\sqrt{2}}\left(U^*_{\alpha 3}\sqrt{1+\rho} + U^*_{\alpha 2}\sqrt{1-\rho}\right)$$

NH

$$Y_{\alpha 2} = \frac{e^{i\theta/2} y'}{\sqrt{2}}\left(U^*_{\alpha 3}\sqrt{1+\rho} - U^*_{\alpha 2}\sqrt{1-\rho}\right) + \frac{\Delta M}{4M} Y_{\alpha 1}$$

$$\rho = \frac{\sqrt{\Delta m^2_{\rm atm}} - \sqrt{\Delta m^2_{\rm sol}}}{\sqrt{\Delta m^2_{\rm atm}} + \sqrt{\Delta m^2_{\rm sol}}}, \qquad y' = \frac{M}{2v^2 y}\left(\sqrt{\Delta m^2_{\rm atm}} + \sqrt{\Delta m^2_{\rm sol}}\right).$$

- Free parameters: M, ΔM, y, and 3 phases: δ, ϕ (U_{PMNS}), θ

$$U^2 \equiv \sum_\alpha |U_{\alpha i}|^2 \approx \frac{y^2 v^2}{2M^2}, |U_{\alpha 1}| \simeq |U_{\alpha 2}|$$

- For NH, at leading order in y'/y, ΔM/M and

$$r \equiv \frac{\sqrt{\Delta m^2_{\rm sol}}}{\sqrt{\Delta m^2_{\rm atm}}} \sim \theta_{13} \sim |\theta_{23} - \pi/4| \sim 10^{-1}$$

$$\frac{\Delta^{\rm ov}_{\rm LNC}}{M_2^2 - M_1^2} \approx -\frac{v^2\sqrt{\Delta m^2_{\rm atm}}}{8M^3U^4} s_\theta, \quad \frac{\Delta^{\rm ov}_{\rm LNV}}{M_1 M_2 (M_2^2 - M_1^2)} \approx -\frac{\sqrt{\Delta m^2_{\rm atm}}}{4MU^2} s_\theta,$$

$$\frac{\Delta^{e}_{\rm LNC}}{M_2^2 - M_1^2} \approx U^2 M^3 \frac{\sqrt{\Delta m^2_{\rm atm}}}{v^4} r\, s^2_{12} s_\theta,$$

$$\frac{\Delta^{\mu}_{\rm LNC}}{M_2^2 - M_1^2} \approx -\frac{\Delta^{\tau}_{\rm LNC}}{M_2^2 - M_1^2} \approx \frac{U^2 M^3}{2} \frac{\sqrt{\Delta m^2_{\rm atm}}}{v^4} \sqrt{r}\, c_{12} \sin(\theta - \phi)$$

Numerical parameter scan

Antusch et al. 2018; Abada et al. 2019; Klaric´ et al. 2020, 2021; Drewes et al. 2022

- Nested sampling algorithm UltraNest

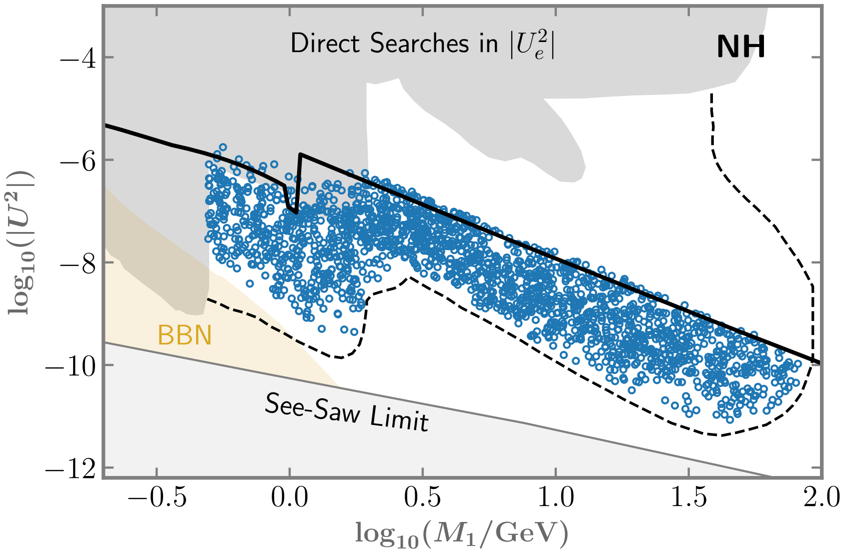
$$\log(\mathcal{L}) = -\frac{1}{2}\left(\frac{Y_B(T_{\rm EW}) - Y_B^{\rm exp}}{\sigma_{Y_B^{\rm exp}}}\right) \qquad Y_B^{\rm exp} = (8.66 \pm 0.05) \times 10^{-11}$$

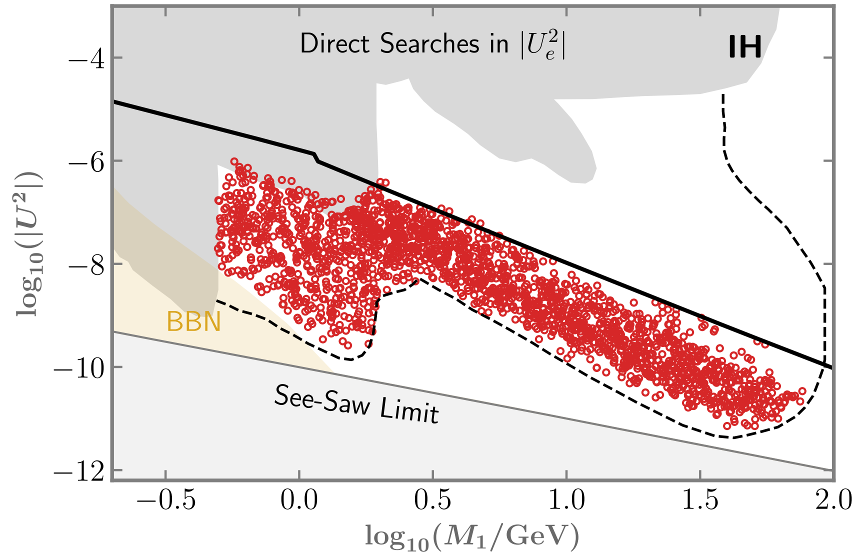
- Priors:

$\log_{10}(M_1)$	$\log_{10}(\Delta M/M_1)$	$\log_{10}(y)$	θ	δ	α
$[-1, 2]$	$[-14, -1]$	$[-8, -4]$	$[0, 2\pi]$	$[0, 2\pi]$	$[0, 2\pi]$

- y'/y < 0.1 , to ensure approximate LNC limit
- Restricted to region testable at SHIP, FCC-ee.
- Publicly available code *amiqs* in GitHub (S. Sandner)

Numerical scan





Absolute upper bound on U^2 from the overdamped regime:

- Weak LNV
  $M \lesssim O(1\ \mathrm{GeV})$

$$(U^2)^{\mathrm{wLNV}}_{\mathrm{ov}} \lesssim 4(17) \times 10^{-7} \left(\frac{1\,\mathrm{GeV}}{M}\right)^{4/3} \quad \mathrm{NH(IH)}$$

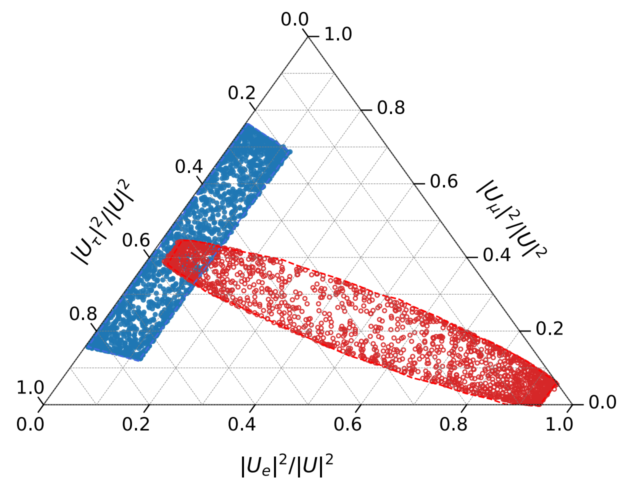
- Strong LNV
  $M \gtrsim O(1\ \mathrm{GeV})$

$$(U^2)^{\mathrm{sLNV}}_{\mathrm{ov}} \lesssim 16(2.3) \times 10^{-7} \left(\frac{1\,\mathrm{GeV}}{M}\right)^{28/13} \quad \mathrm{NH(IH)}$$

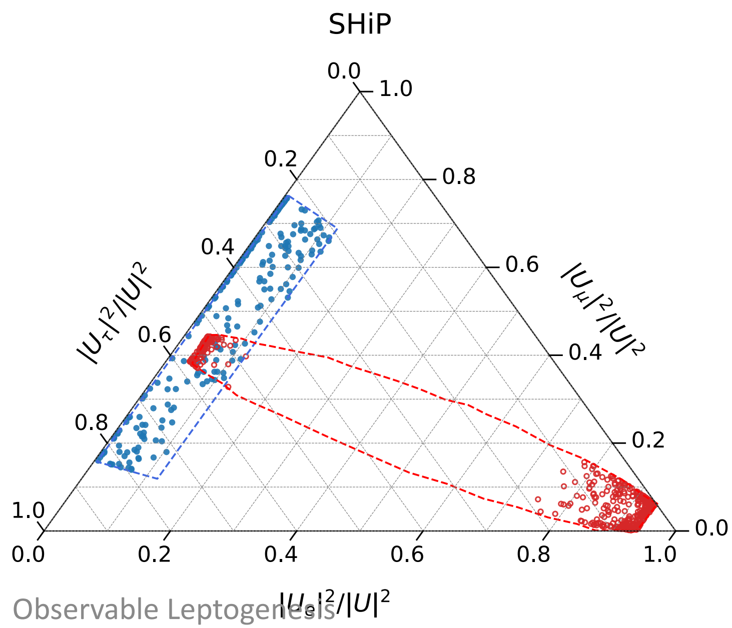
Relation to other observables

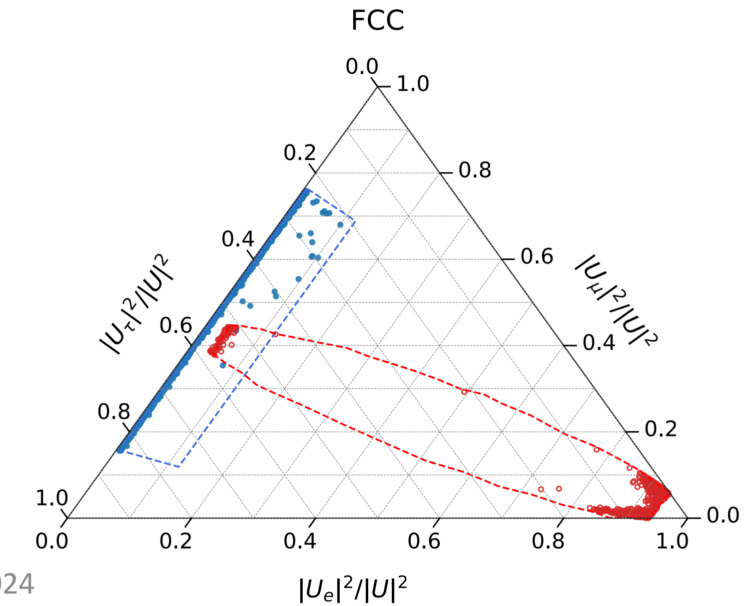
1. HNL flavour mixing

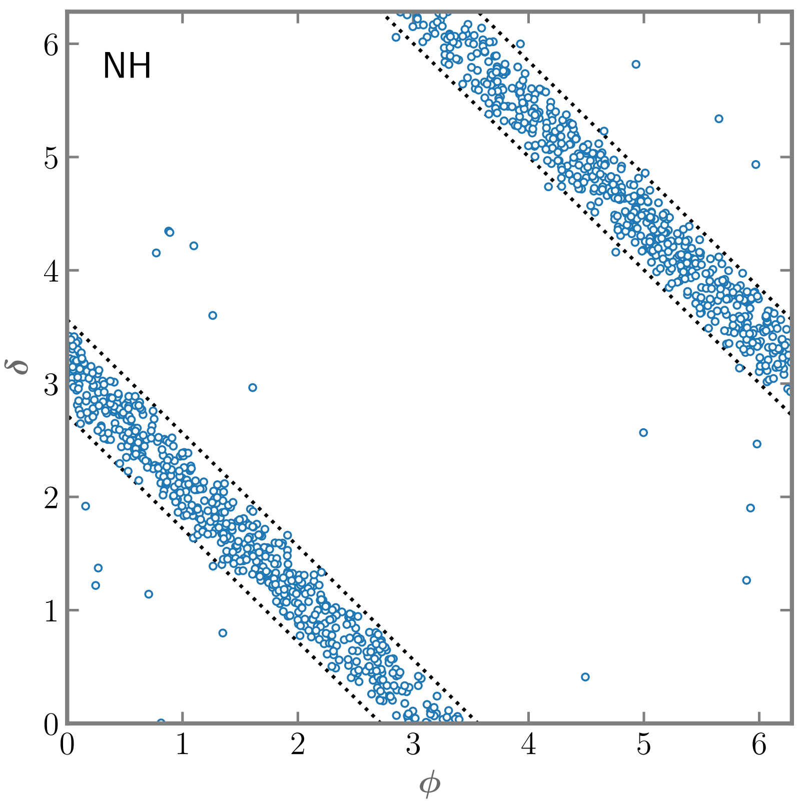
- Full scan: NH and IH

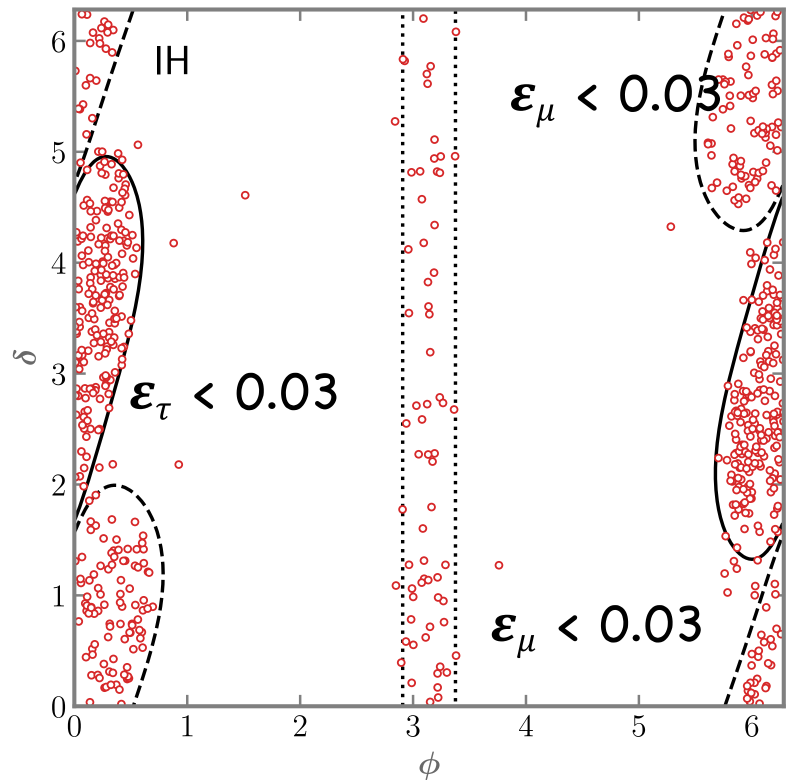


- $\Delta M/M = 10^{-2}$









$\varepsilon_e < 0.01$ ($\delta+\phi \approx \pi, 3\pi$)

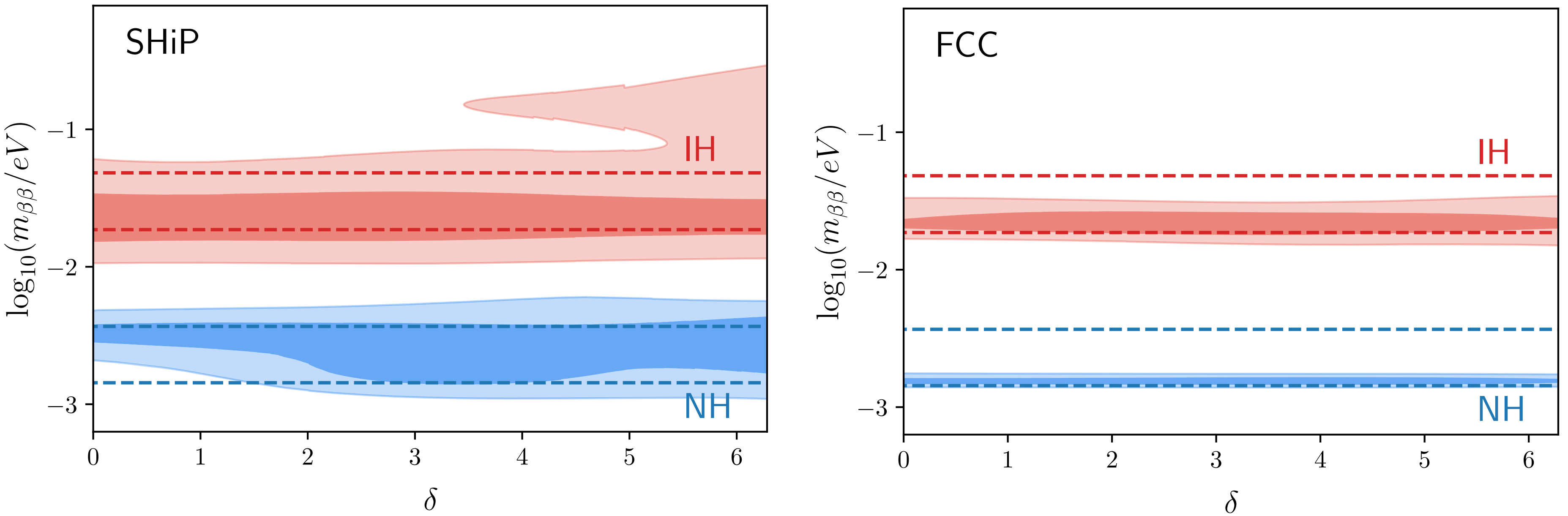
$\varepsilon_e < 0.05$

($\phi \approx \pi$)

$$\epsilon_\alpha \equiv \frac{(YY^\dagger)_{\alpha\alpha}}{\mathrm{Tr}[YY^\dagger]}$$

2. Neutrinoless double beta decay: ΔM/M = 10^{-2}

Effect of HNL only in SHIP range



$\mu \simeq 0$ case

$$M = \begin{pmatrix} 0 & \Lambda \\ \Lambda & 0 \end{pmatrix} \qquad Y = \begin{pmatrix} y_e & y'_e e^{i\beta'_e} \\ y_\mu & y'_\mu e^{i\beta'_\mu} \\ y_\tau & y'_\tau e^{i\beta'_\tau} \end{pmatrix}$$

- HNLs degenerate at T > T_{EW}, except for small loop correction

$$\Delta\mu \propto yy'\rho M/(4\pi)^2 \ll yy'\rho T^2/(8M)$$

- At T=0:

$$\Delta M_{NH} = |m_3| - |m_2| = \sqrt{\Delta m^2_{atm}} - \sqrt{\Delta m^2_{sol}}$$

$$\Delta M_{IH} = |m_2| - |m_1| = \sqrt{\Delta m^2_{atm}} - \sqrt{\Delta m^2_{atm} - \Delta m^2_{sol}}$$

- Once active neutrino masses and mixings are fixed, only 4 free parameters: M, U^2 (or y^2), and PMNS phases, (δ, ϕ)

CP violating flavour basis invariants

- All previous CP invariants vanish in the $\mu \simeq 0$ limit
- Higher order in the Yukawa couplings:

$$\tilde{I}_0 \equiv \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y M_R^* Y^T Y^* M_R Y^\dagger Y_\ell Y_\ell^\dagger Y\right]\right) \equiv \sum_\alpha y_{\ell_\alpha}^2 \Delta_\alpha$$

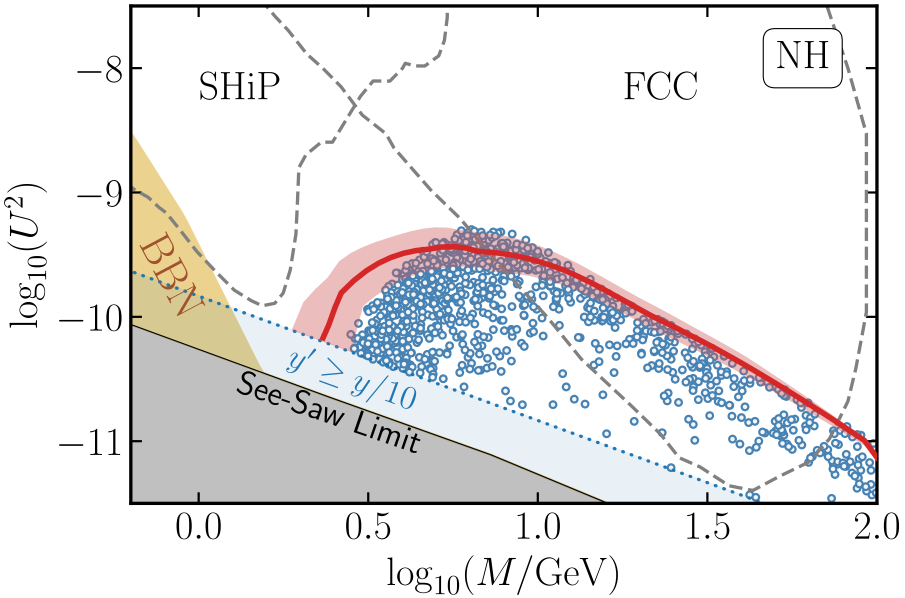
with

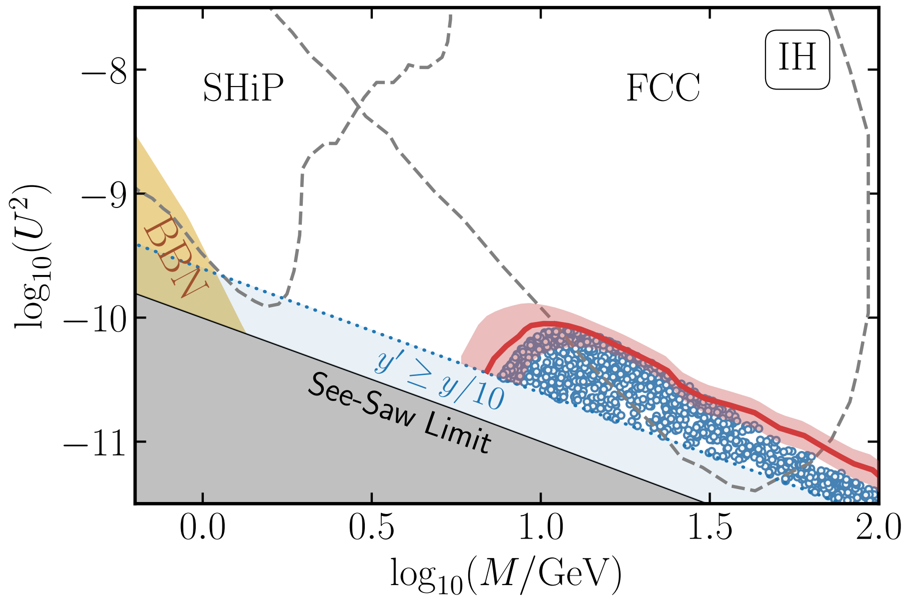
$$\Delta_\alpha = \mathrm{Im}\left[\left(Y Y^\dagger Y M_R^* Y^T Y^* M_R Y^\dagger\right)_{\alpha\alpha}\right] \qquad \sum_\alpha \Delta_\alpha = 0$$

We find contribution from weak flavour:

$$\Delta_\alpha^{\mathrm{fw}} = \frac{1}{\mathrm{Tr}\left(\mathrm{Y}^\dagger \mathrm{Y}\right)^2} \Delta_\alpha \,,$$

$\mu \simeq 0$ case



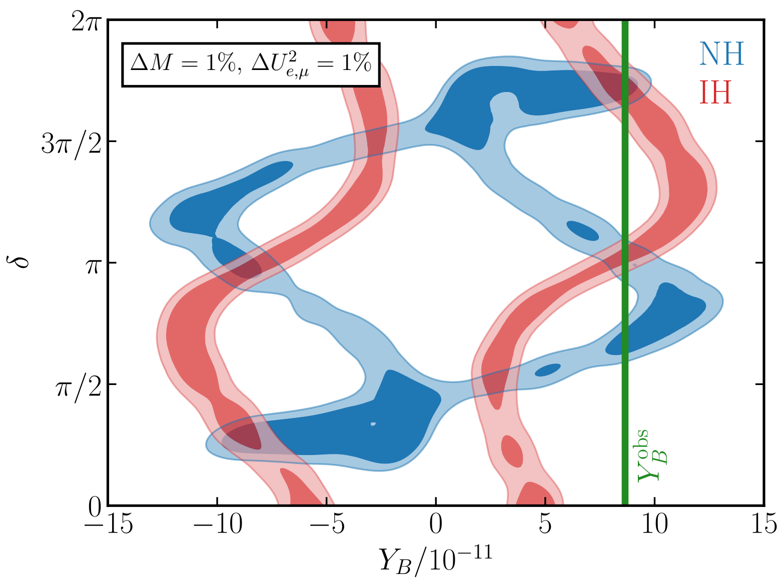


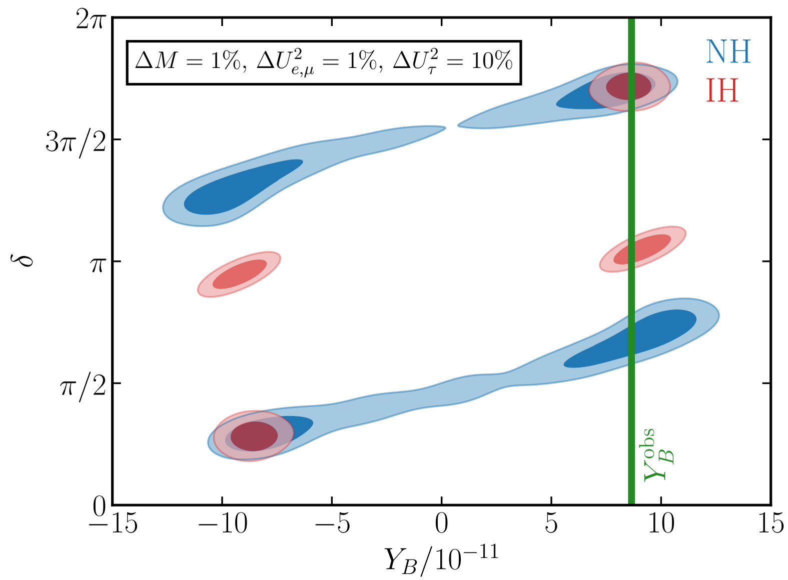
Observable at FCC only in sHC regime

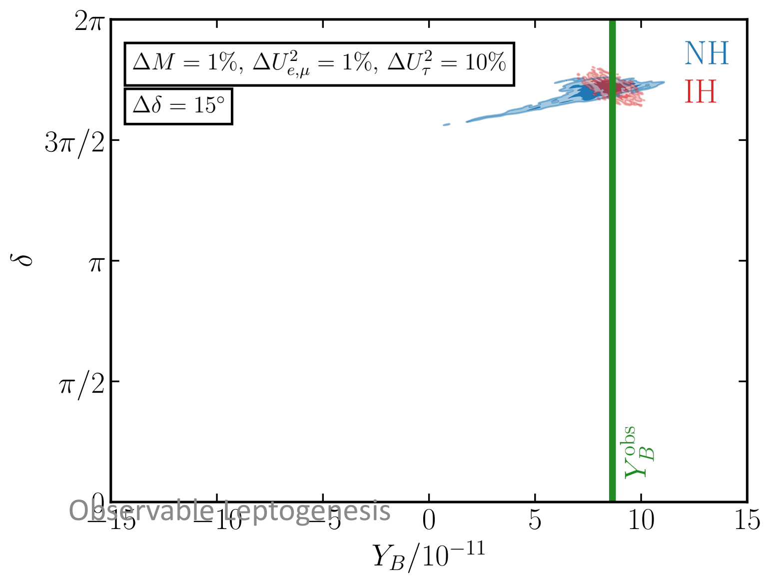
$$Y_B = -1.5 \times 10^{-25} \left(\frac{\mathrm{GeV}}{M}\right)^2 \left(\frac{1}{U^2}\right)^2 f_\alpha^{\mathrm{H}} \qquad U^2 \geq 1 \times 10^{-6} \left(\frac{1\,\mathrm{GeV}}{M}\right)^4$$

$$f_e^{\mathrm{NH}} = -\frac{\sqrt{r}}{2}\theta_{13} s_{12} \sin(\delta + \phi)\,, \qquad f_\mu^{\mathrm{IH}} = f_\tau^{\mathrm{IH}} = -\frac{r^2}{8} c_{12} s_{12} \sin\phi$$

Numerical likelihood inference in the case of measuring HNL-active neutrino mixings







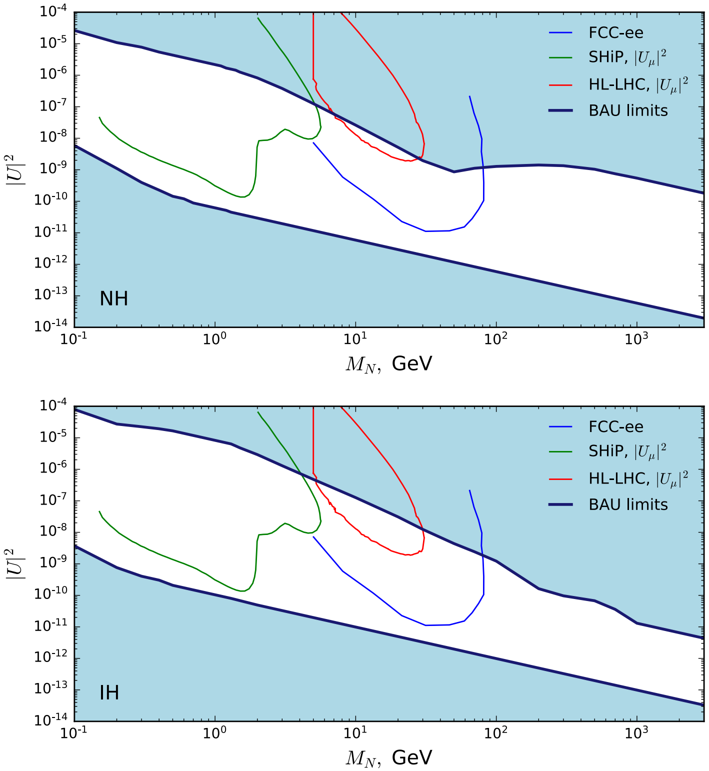
ϕ determined by Y_B

$$\Delta M \gg \Gamma$$

HNL oscillations can not be observed at FCC but LNV processes can

Extension to larger HNL masses:

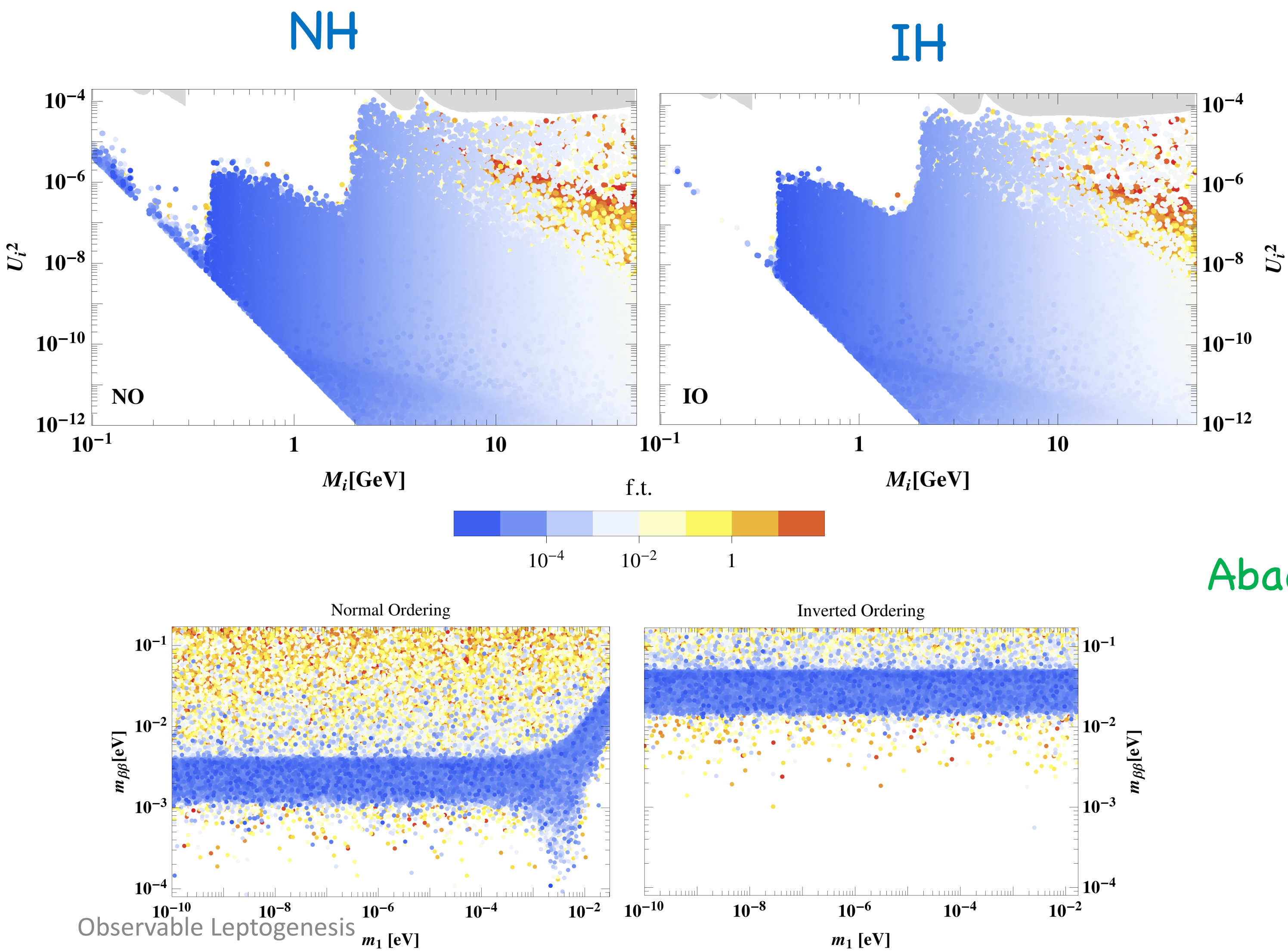
unifying resonant leptogenesis and baryogenesis via neutrino oscillations



Klaric et al. 2020, 21

N=3 HNL

Larger values of HNL mass splittings allowed



Abada et al. 2019

5. Summary and outlook

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- Thermal leptogenesis in generic type I seesaw: simple, appealing ... but difficult to test.

- Progress in leptogenesis via HNL oscillations

  – Precise analytic understanding of numerical scan in the minimal seesaw (2 HNL)

  – Focus on parameter region testable at SHiP, FCC-ee and correlations with other observables

  – Importance of determining ΔM

  – $\mu \simeq 0$ case: leptogenesis only possible in FCC-ee mass range, falsified if HNL oscillations were observed

- Future: extension of the analytic approach to 3 HNL

Backup slides

- In the basis where M_R, Y_l are diagonal:

$$I_0 = \sum_\alpha y_{\ell_\alpha}^2 \sum_{i<j} (M_j^2 - M_i^2)\,\mathrm{Im}\left[Y_{\alpha j}^* Y_{\alpha i} \left(Y^\dagger Y\right)_{ij}\right] \equiv \sum_\alpha y_{\ell_\alpha}^2 \Delta_\alpha$$

$$\sum_\alpha \Delta_\alpha = 0$$

- Flavoured weak washout: weakly coupled flavour α at T_{EW}

$$\Delta_{\rm LNC}^\alpha = \Delta_\alpha$$

- Overdamped regime (new): oscillations cutoff by Γ_α

$$\Delta_{\rm LNC}^{\rm ov} \propto \sum_\alpha \frac{\Delta_\alpha}{\Gamma_\alpha}$$

- LNV CP invariants: sensitive to Majorana character of HNLs, only appear when LNV interactions are included

$$I_1 = \mathrm{Im}\,\{\mathrm{Tr}\,[h\,H_M\,M^* h^* M\,]\}$$

$$I_1 = \sum_{\alpha}\sum_{i<j}\left(M_j^2 - M_i^2\right) M_i M_j \mathrm{Im}\left[Y_{\alpha j} Y_{\alpha i}^* \left(Y^\dagger Y\right)_{ij}\right] \equiv \sum_{\alpha} \Delta_\alpha^M$$

- Overdamped regime: $\Delta_{\rm LNV}^{\rm ov} = \dfrac{1}{\left[\mathrm{Tr}\left(Y^\dagger Y\right)\right]^2}\sum_{\alpha}\Delta_\alpha^M$

- Flavoured weak washout regime:

$$\Delta_{\rm LNV}^{\mathrm{int}\,(\alpha)} = \frac{\Delta_\alpha^M}{\left[\mathrm{Tr}\left(Y^\dagger Y\right)\right]^2}$$

Time scales and regimes

- Asymmetry generated mostly at T_{osc}, defined as:

$$\Gamma_{osc}(T_{osc}) = H_u(T_{osc})$$

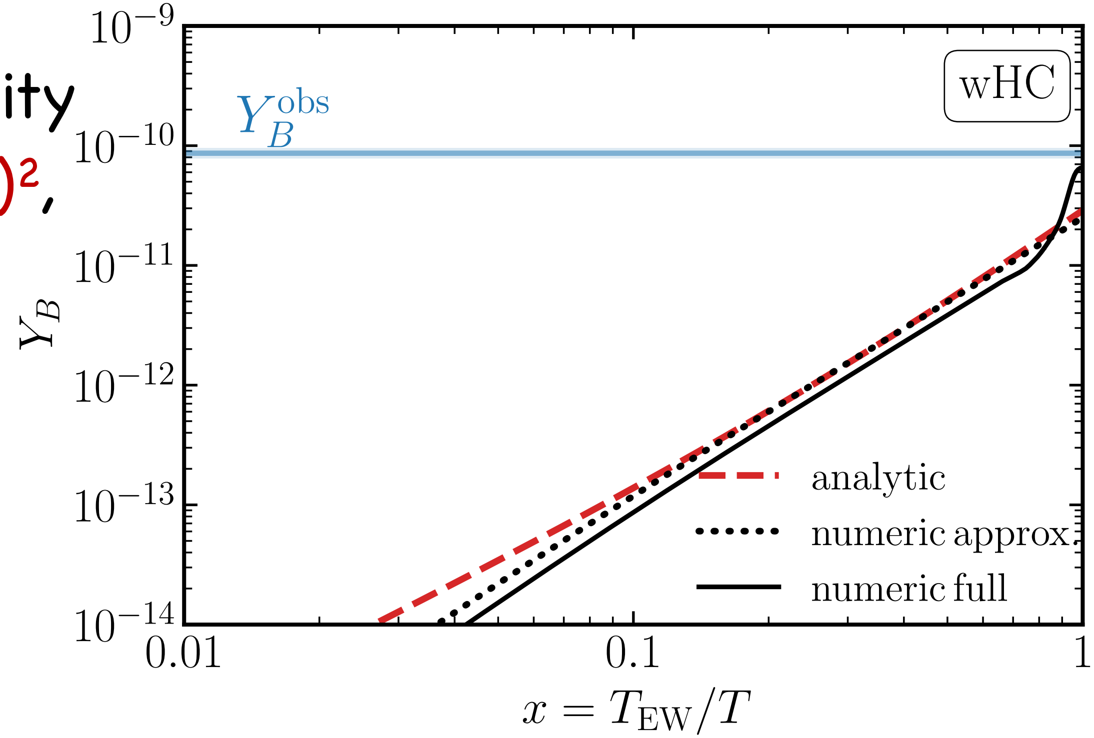
- Fast oscillations: $\Gamma_{osc}(T) >> \Gamma(T)$ at $T = T_{osc}$

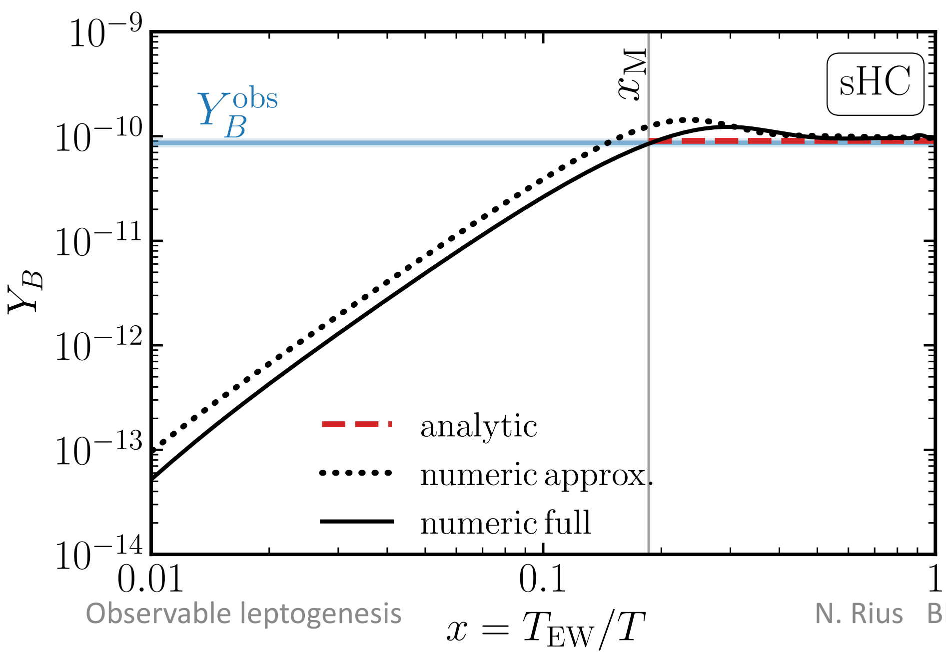
- Intermediate regime: $\Gamma_{osc}(T) << \Gamma(T)$ at $T = T_{osc}$, but
  $\Gamma_{osc}(T) > \Gamma(T)$ at $T = T_{EW}$

- Overdamped regime: $\Gamma_{osc}(T) << \Gamma(T)$ at $T = T_{osc}, T_{EW}$

Important effect of Helicity Conserving rates ∝ $(M/T)^2$, that grow near T_{EW}

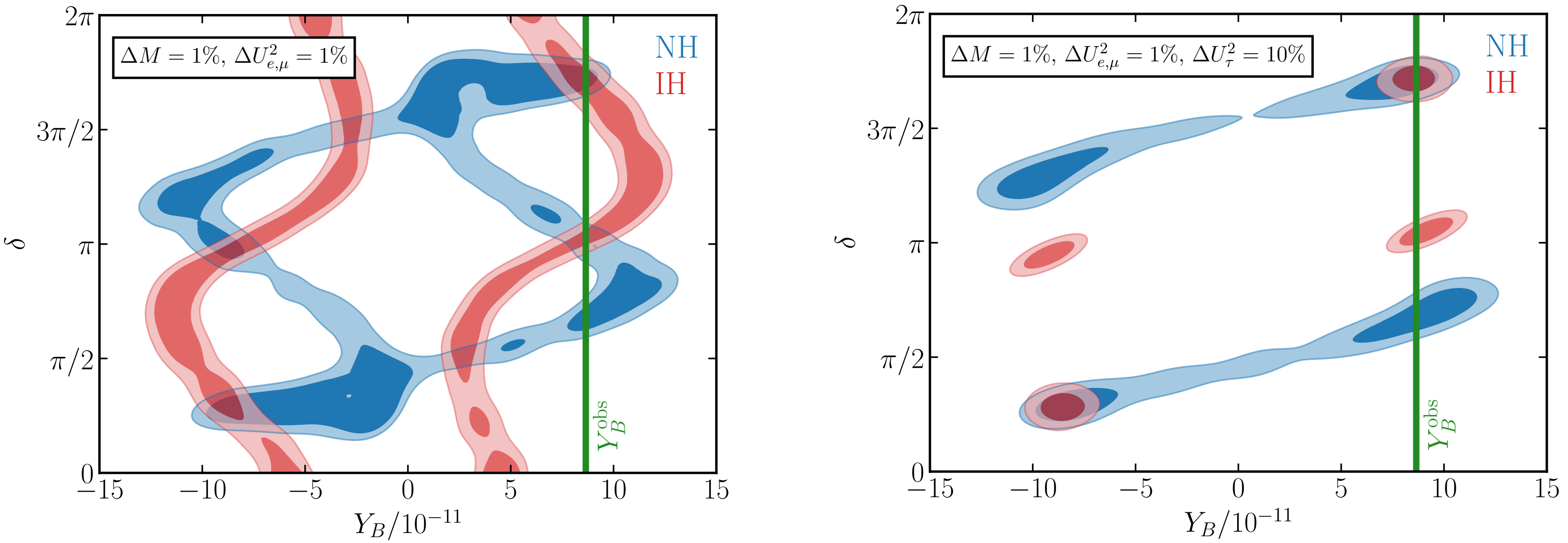
Ghiglieri, Laine, 2017





$\mu \simeq 0$ case

Numerical likelihood inference in the case of measuring HNL-active neutrino mixings



	$M^{\rm true}/{\rm GeV}$	$(U_e^2)_{\rm true}$	$(U_\mu^2)_{\rm true}$	$(U_\tau^2)_{\rm true}$	$\delta^{\rm true}/{\rm rad}$
NH	31.60	2.843×10^{-12}	1.087×10^{-11}	1.234×10^{-11}	5.396
IH	20.731	3.291×10^{-11}	4.823×10^{-12}	3.465×10^{-12}	5.402

0νββ decay in $\mu \simeq 0$ case