ON LOW SCALE LEPTOGENESIS

Pilar Hernández, Jacobo López-Pavón, Stefan Sandner, NR

JHEP 12 (2022), arXiv:2305.14427

Workshop on Standard Model and Beyond

Corfu, Sept. 2023

IFIC INSTITUT DE FÍSICA CORPUSCULAR
VNIVERSITAT DE VALÈNCIA
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Motivation

BSM hints:

- Neutrino masses
- Baryon assymetry of the Universe (BAU)
- Dark matter
- …

Low scale Type I seesaw provides a minimal possible connection between 1 and 2, via leptogenesis through sterile neutrino oscillations, with observable signals.

ARS leptogenesis, Drewes et al. 2017

Outline

- Minimal type I seesaw model with 2 HNL
- Leptogenesis via HNL oscillations
  - Time scales and slow modes
- The importance of being CP violating flavour basis invariants
- $\mu \simeq 0$ case
- Numerical parameter scan
- Conclusions and outlook

1. Minimal type I seesaw model with 2 HNL

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

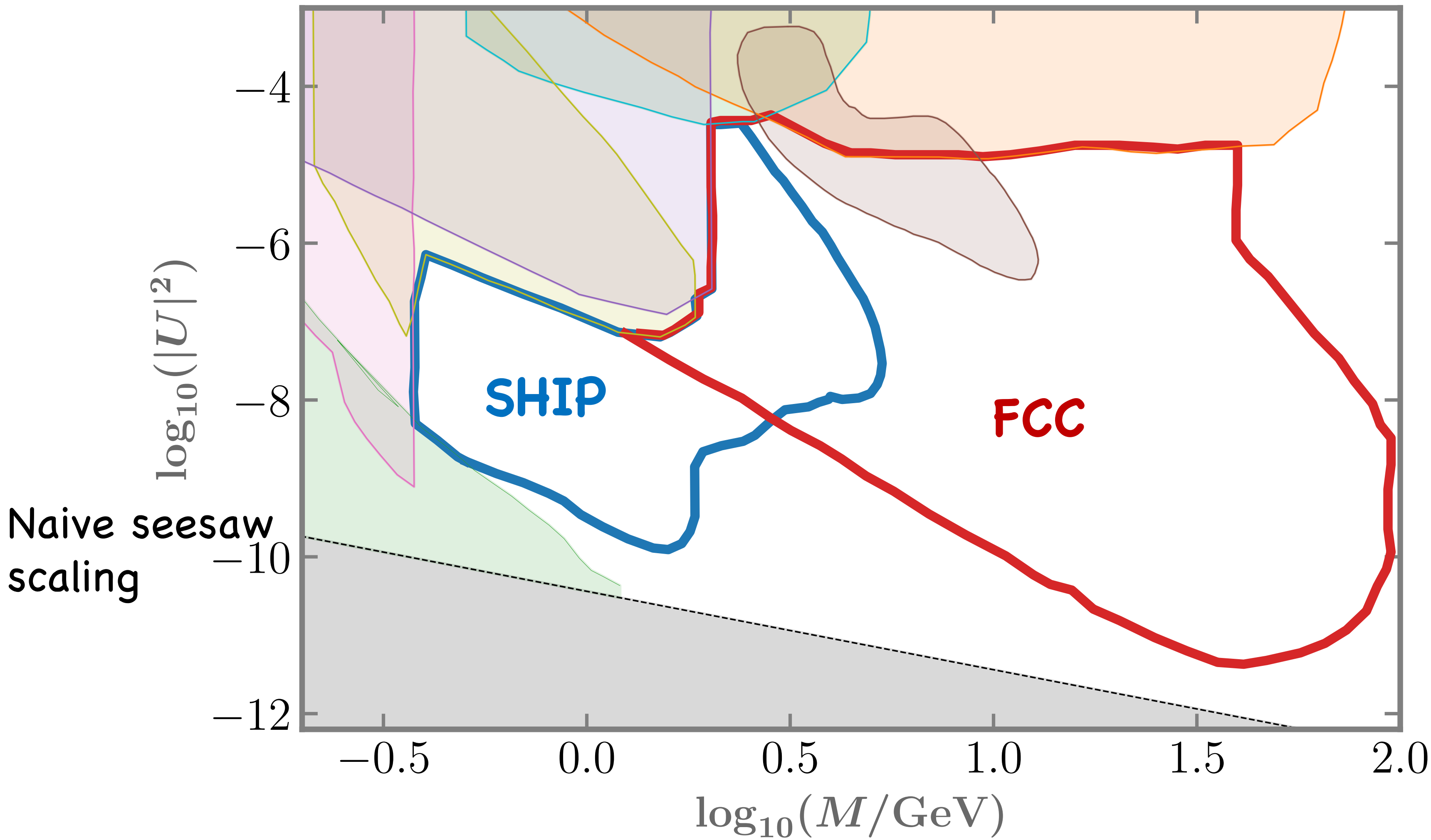
- $m_\nu = v^2 \, Y \, M^{-1} \, Y^T$, $v = \langle \Phi \rangle$
- one massless neutrino

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

$$M \in [0.1 - 100] \text{ GeV}$$

- Naive seesaw scaling of active neutrino-HNL mixing:

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


SHIP
FCC
Naive seesaw scaling
$\log_{10}(|U|^2)$
$\log_{10}(M/\mathrm{GeV})$
−4
−6
−8
−10
−12
−0.5
0.0
0.5
1.0
1.5
2.0

Approximately conserved lepton number limit

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

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

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

- 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:

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

2. Leptogenesis via HNL oscillations

Akhmedov, Rubakov, Smirnov 1998, Asaka,Shaposhnikov 2005, etc

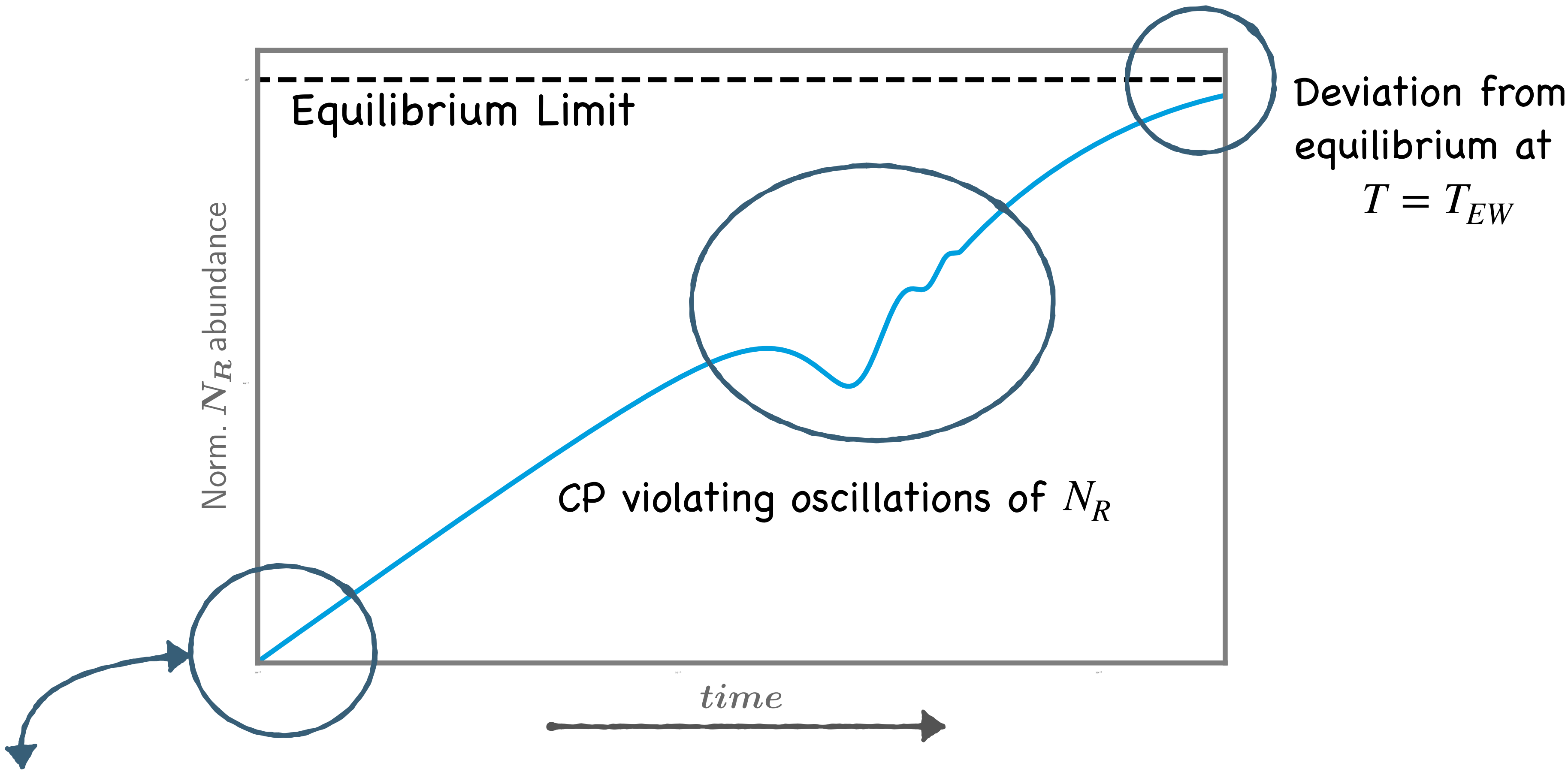
Sakharov conditions for baryogenesis:

- CP violating phases in Y, M
- B violated by sphaleron processes at $T > T_{EW}$
- At least one sterile neutrino 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 $M = O(\mathrm{GeV})$, $Y \sim 10^{-6} - 10^{-7}$, in the correct range to explain neutrino masses ! Freeze-in baryogenesis

Schematic evolution of N_R abundance

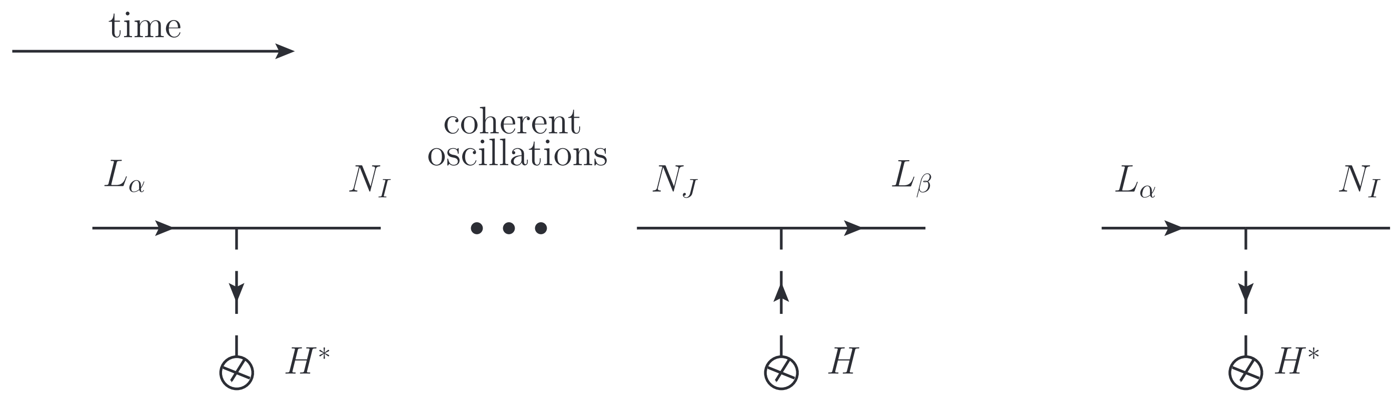


Initially 0 abundance == freeze-in

28

- Basic stages:

Shuve, Yavin 2014



$Y_{\Delta L_1} = 0$	$Y_{\Delta L_1} > 0$	$Y_{\Delta L_1} > 0$
$Y_{\Delta L_2}, Y_{\Delta L_3} = 0$	$Y_{\Delta L_2}, Y_{\Delta L_3} < 0$	$Y_{\Delta L_2}, Y_{\Delta L_3} < 0$
$\sum_\alpha Y_{\Delta L_\alpha} = 0$	$\sum_\alpha Y_{\Delta L_\alpha} = 0$	$\sum_\alpha Y_{\Delta L_\alpha} \neq 0$
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: $\bar{\rho}$, $H \Longrightarrow H^*$
- 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.

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

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

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

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

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

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

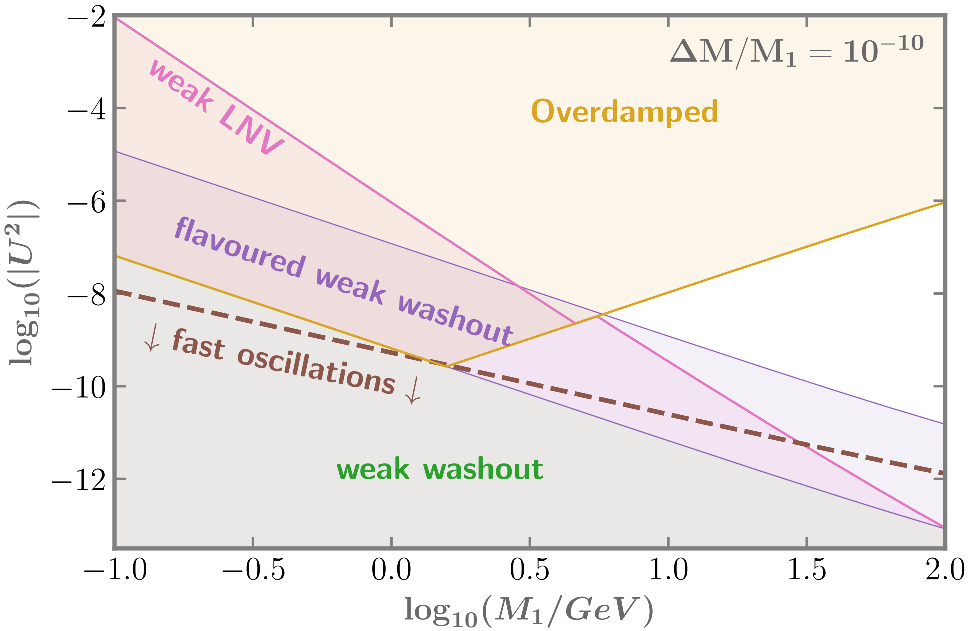
- Overdamped regime: when $\epsilon \propto \dfrac{\Delta M^2/T}{\Gamma(T)} \ll 1$ at $T \geq T_{EW}$,

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

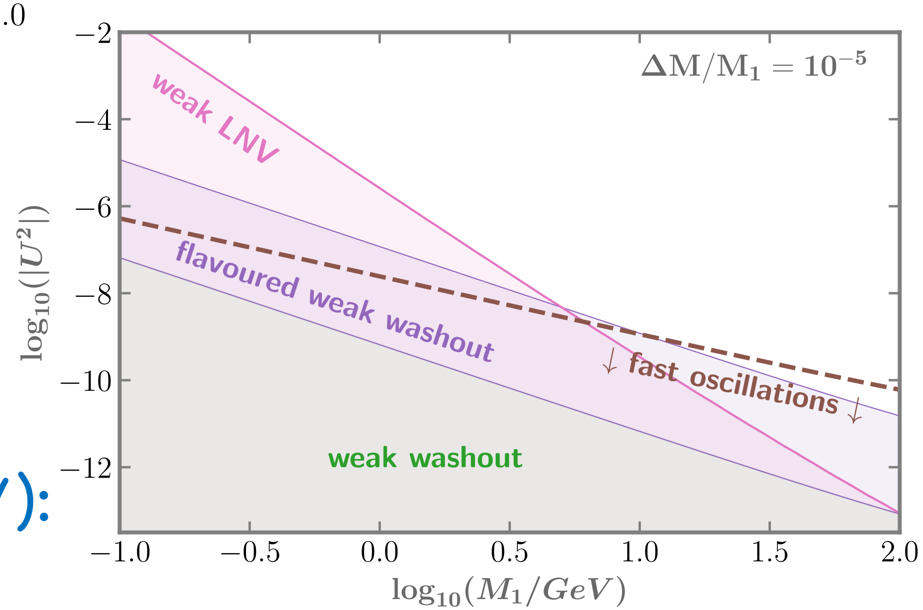
- Weak LNV (HC) regime:

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

- 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

3. The importance of being CP violating flavour basis invariants

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

Branco et al., 2001

- Change of weak basis:

$$Y \to V^\dagger Y W, Y_\ell \to V^\dagger Y_\ell U, M_R \to W^T M_R W$$

- Define Hermitian matrices:

$$h = Y^\dagger Y, \bar{h} = Y^\dagger Y_\ell Y_\ell^\dagger Y, H_M = M_R^\dagger M_R \to W^\dagger (h, \bar{h}, H_M) W$$

- LNC CP invariants: independent of HNL Majorana character

Hernández et al., 2015

$$I_0 = \mathrm{Im}\left(\mathrm{Tr}\left[h\, H_M \bar{h}\,\right]\right)$$

- 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}

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

- Overdamped regime (new): oscillations cutoff by Γ_α

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

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

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

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

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

- Flavoured weak washout regime:

$$\Delta^{\mathrm{int}\,(\alpha)}_{\mathrm{LNV}} = \frac{\Delta^M_\alpha}{\left[\mathrm{Tr}\left(Y^\dagger Y\right)\right]^2}$$

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

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

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

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

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

NH

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

- Free parameters: M, ΔM, y, and 3 phases: $\boldsymbol{\delta}$, $\boldsymbol{\phi}$ (U_{PMNS}), $\boldsymbol{\theta}$

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

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

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

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

$$\frac{\Delta^{\rm ov}_{\rm LNV}}{M_1 M_2 (M_2^2 - M_1^2)} \approx -\frac{\sqrt{\Delta m^2_{\rm atm}}}{4MU^2} s_\theta,$$

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

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

4. μ≃0 case

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

- Valid for

$$\mu \lesssim \rho y y' \frac{T^2}{8M} \sim \frac{T^2}{8v^2}\rho|\Delta m_{atm}|$$

NH: $\rho = \mathcal{O}(1)$

IH: $\rho = O(|\Delta m_{sol}|/|\Delta m_{atm}|)$

- Sterile neutrinos 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:

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

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

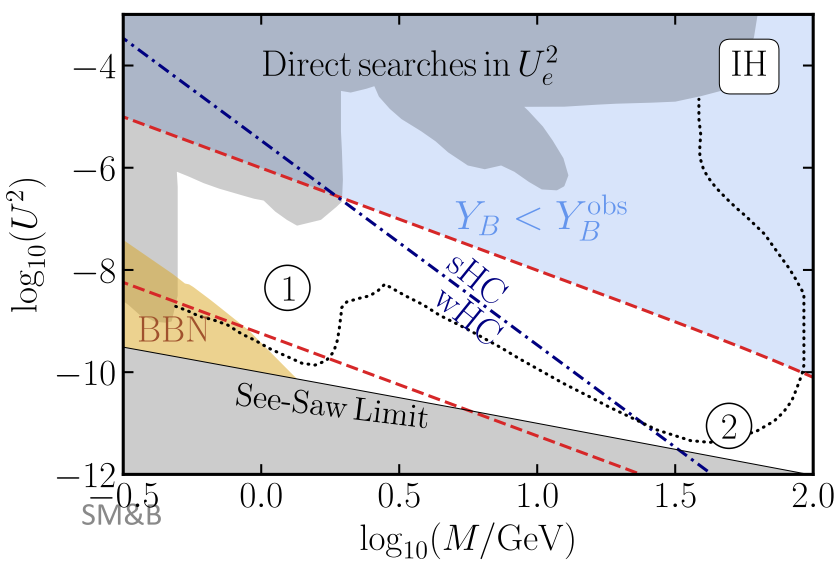
- Once active neutrino masses and mixings are fixed, only 4 free parameters: M, U^2 (or y^2), and PMNS phases, (δ, ϕ)

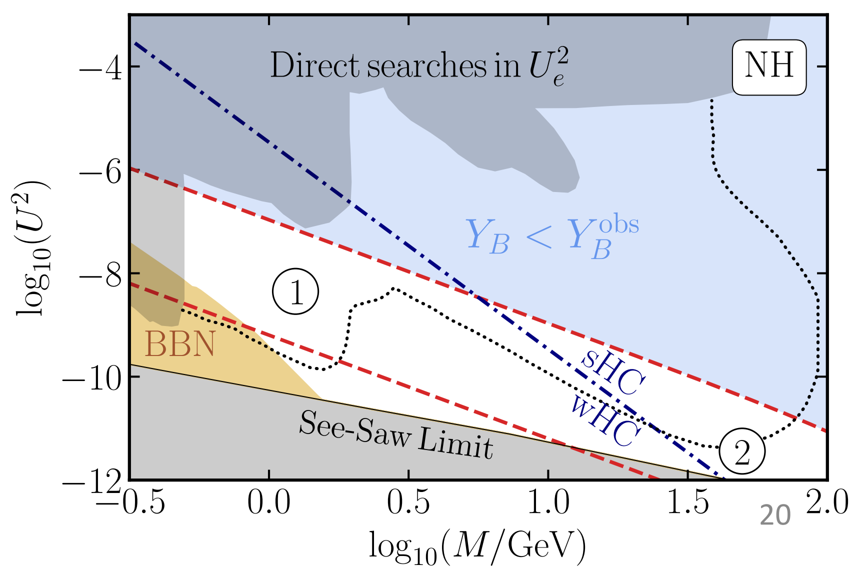
Slow modes

- Weak flavour α : $\Gamma_\alpha(T_{EW}) < H_u(T_{EW}) < \Gamma(T_{EW})$
- Weak HC : $\Gamma_M(T_{EW}) \propto (M/T_{EW})^2\, \Gamma(T_{EW}) < H_u(T_{EW})$
- LNV interactions: $$\Gamma_{\rm LN}^{\rm slow} \propto y'^2 T \sim \frac{m_\nu^2}{2^3 v^2 U^2} T$$

$\Rightarrow$ always out of equilibrium at T_{EW} for $U^2 > 10^{-11}$

- Successful baryogenesis only in weak flavoured regime:





CP violating flavour basis invariants

- All previous CP invariants vanish in the $\mu \simeq 0$
- 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:

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

- In terms of neutrino parameters, and at leading order in y'/y and

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

- NH

$$\Delta_e^{\rm fw} = -\frac{M^2 \Delta m^2_{\rm atm} \sqrt{r}}{2U^2 v^2}\, \theta_{13} s_{12} \sin(\delta + \phi)$$

- IH

$$\Delta_e^{\rm fw} = \frac{M^2 \Delta m^2_{\rm atm} r^2}{4U^2 v^2}\, c_{12} s_{12} \sin\phi, \qquad \Delta_\mu^{\rm fw} = \Delta_\tau^{\rm fw} = -\frac{1}{2}\Delta_e^{\rm fw}$$

5. Parameter scan

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

- Nested sampling algorithm UltraNest

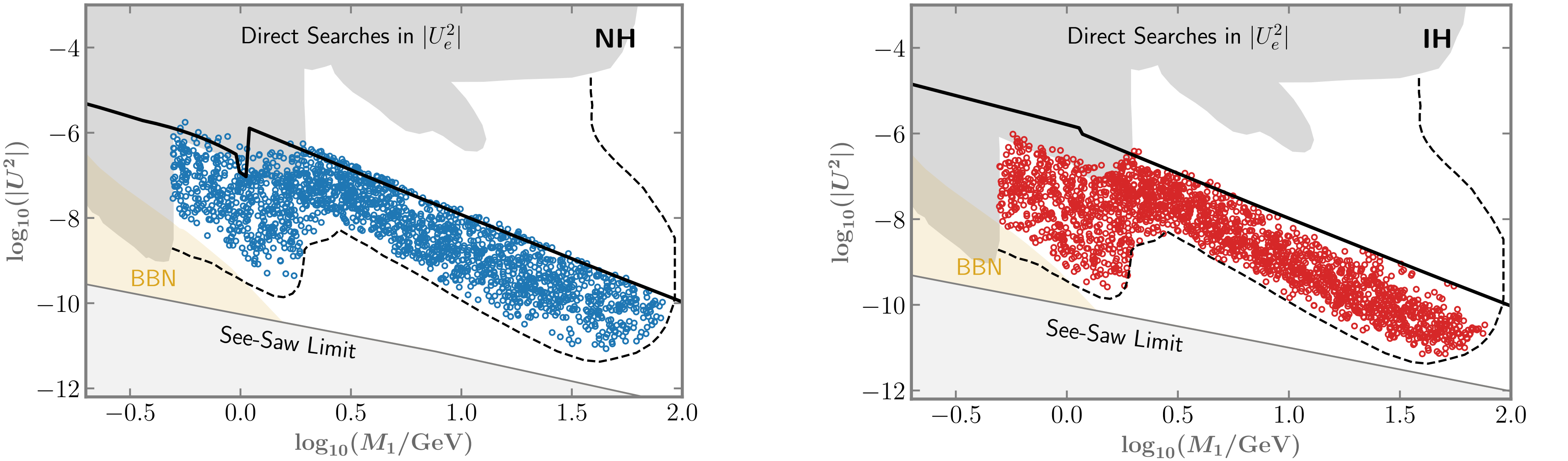
$$\log(\mathcal{L}) = -\frac{1}{2}\left(\frac{Y_B(T_{\rm EW}) - Y_B^{\rm exp}}{\sigma_{Y_B^{\rm exp}}}\right) \qquad Y_B^{\rm exp} = (8.66 \pm 0.05) \times 10^{-11}$$

- 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)

Full scan

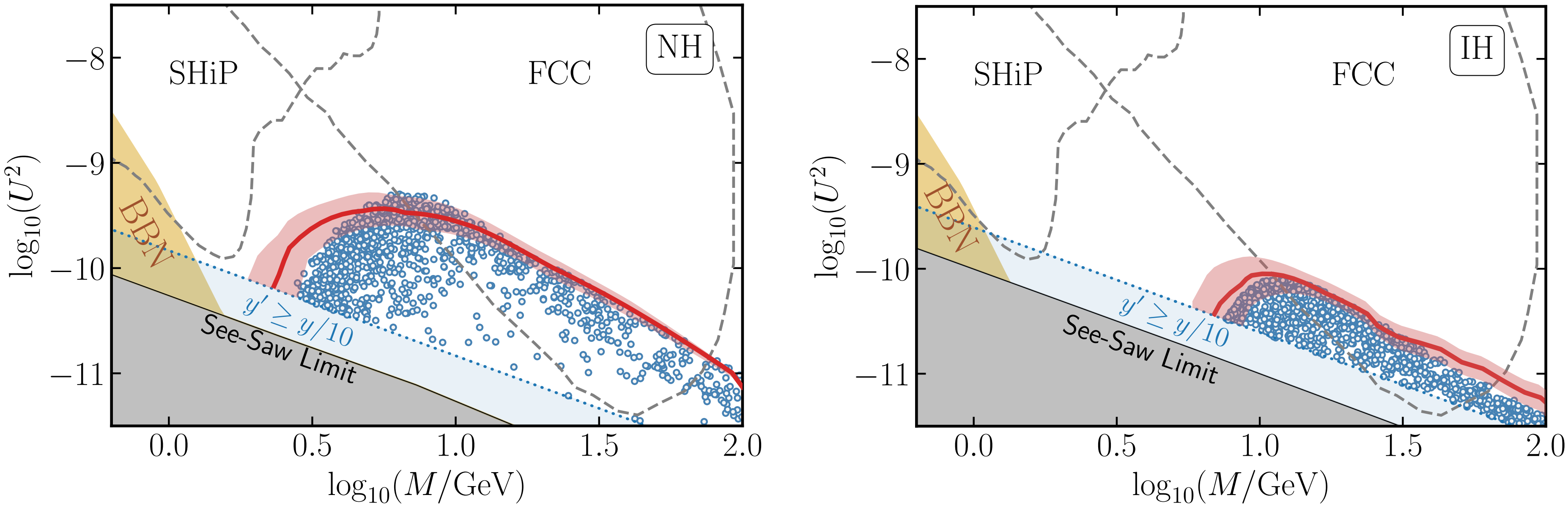


Absolute upper bound on U^2 from the overdamped regime:

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

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

$\mu \simeq 0$ case



Observable at FCC only in sHC regime

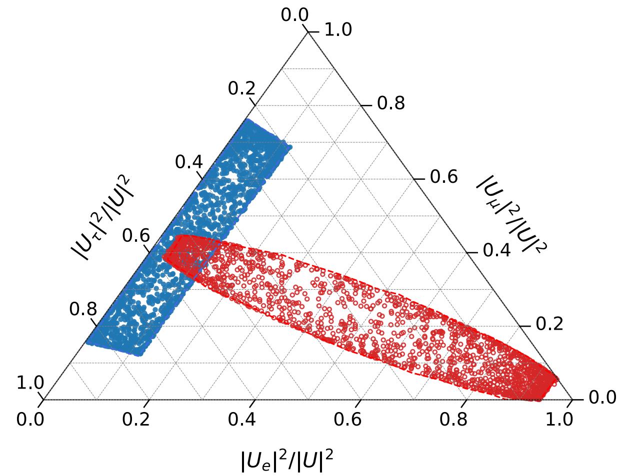
$$Y_B = -1.5 \times 10^{-25} \left(\frac{\mathrm{GeV}}{M}\right)^2 \left(\frac{1}{U^2}\right)^2 f_\alpha^{\mathrm{H}} \qquad U^2 \geq 1 \times 10^{-6} \left(\frac{1\,\mathrm{GeV}}{M}\right)^4$$

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

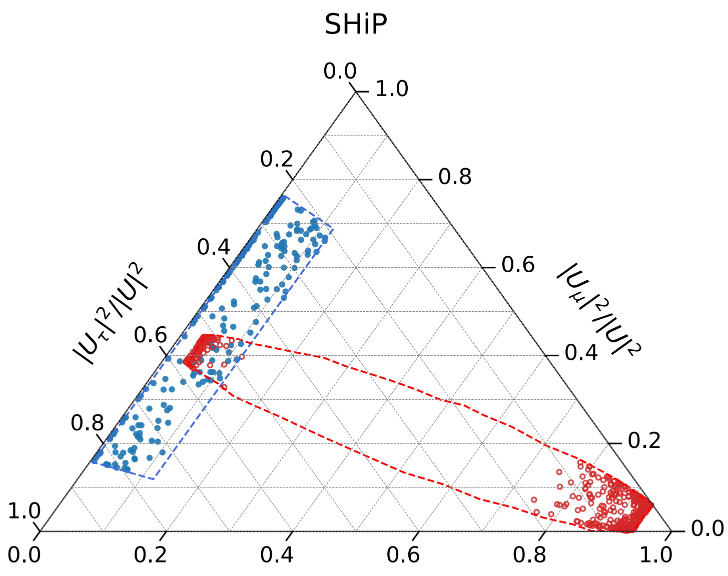
Relation to other observables

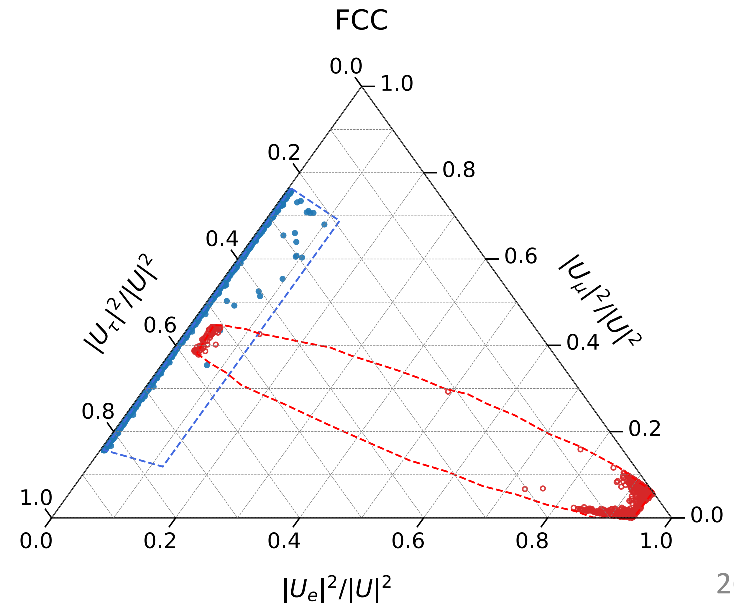
1. HNL flavour mixing

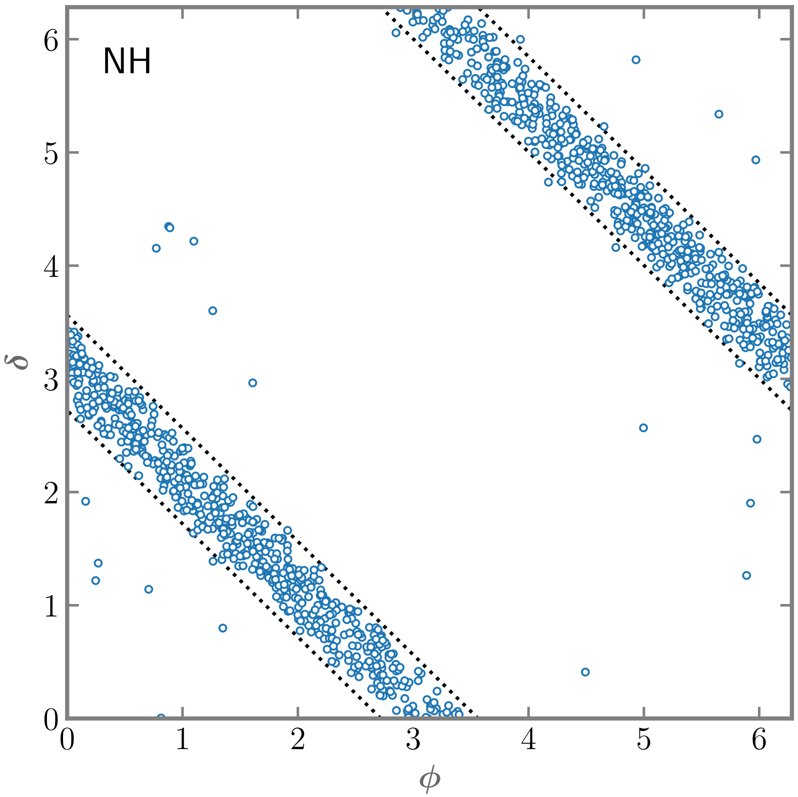
- Full scan: NH and IH

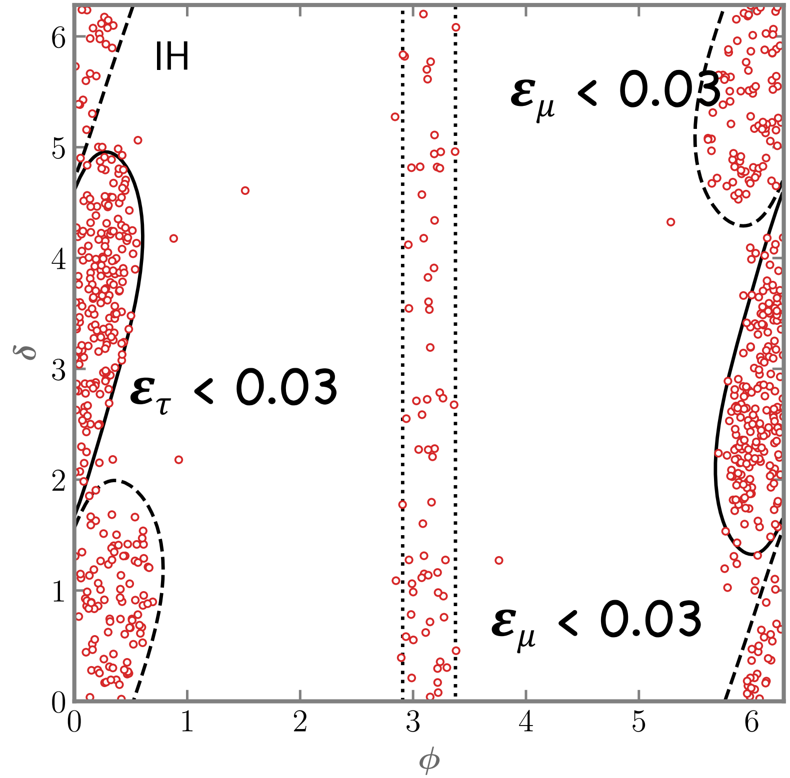


- $\Delta M/M = 10^{-2}$









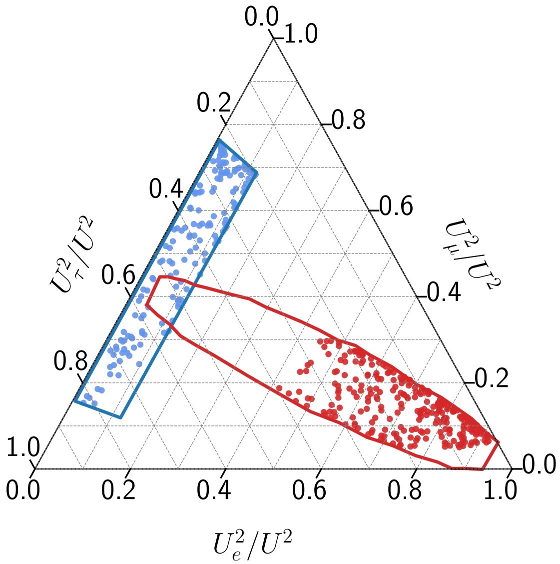
$\varepsilon_e < 0.01$ ($\delta+\phi \approx \pi$, 3π)

$\varepsilon_e < 0.05$

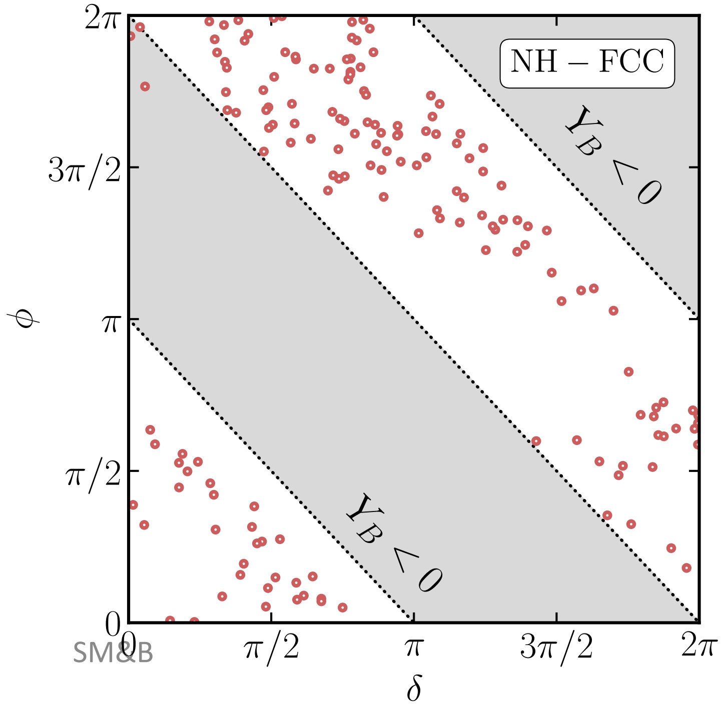
($\phi \approx \pi$)

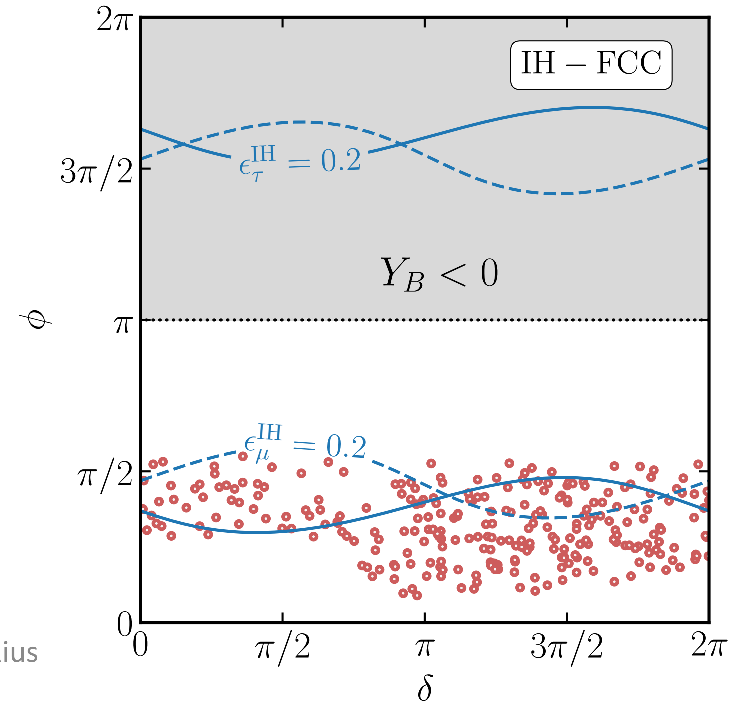
$$\epsilon_\alpha \equiv \frac{(YY^\dagger)_{\alpha\alpha}}{\mathrm{Tr}[YY^\dagger]}$$

$\mu \simeq 0$ case

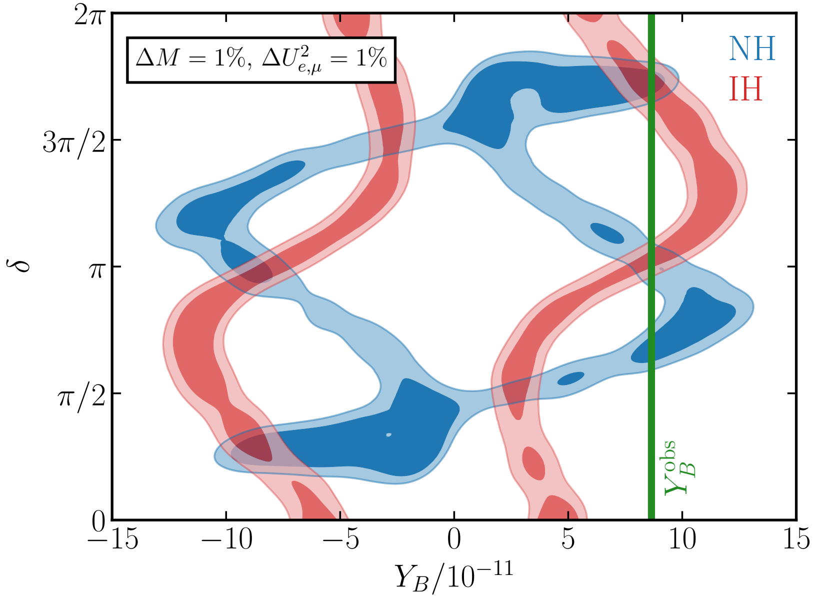


NH and IH



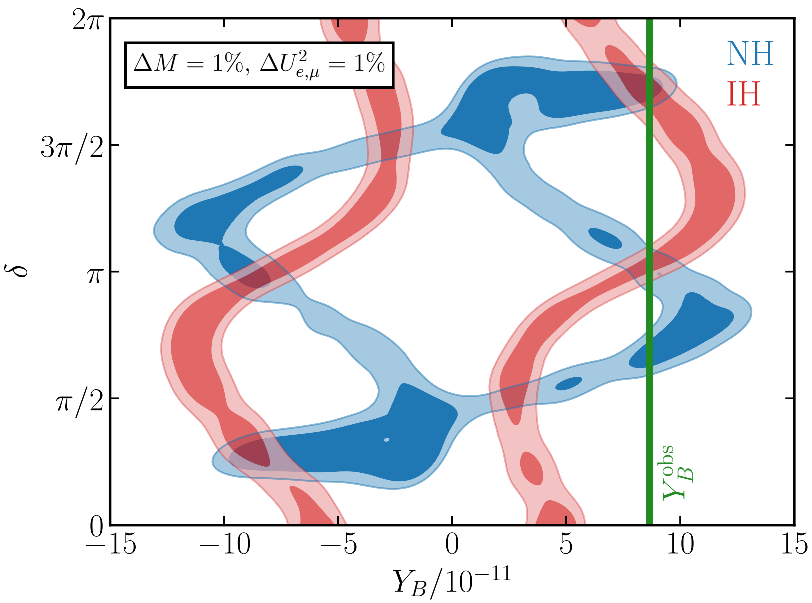


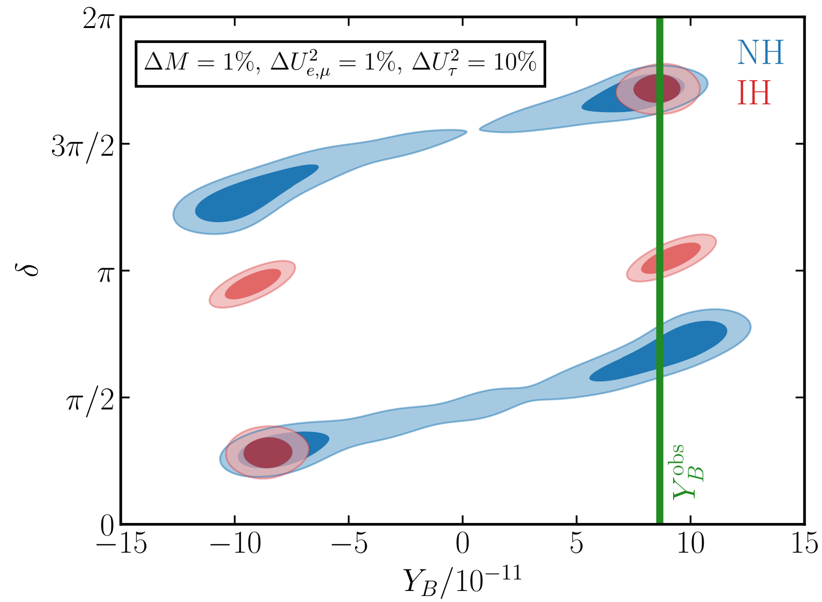
Numerical likelihood inference in the case of measuring HNL-active neutrino mixings



	M^{true}/GeV	$(U_e^2)_{true}$	$(U_\mu^2)_{true}$	$(U_\tau^2)_{true}$	$\delta^{true}/\mathrm{rad}$
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

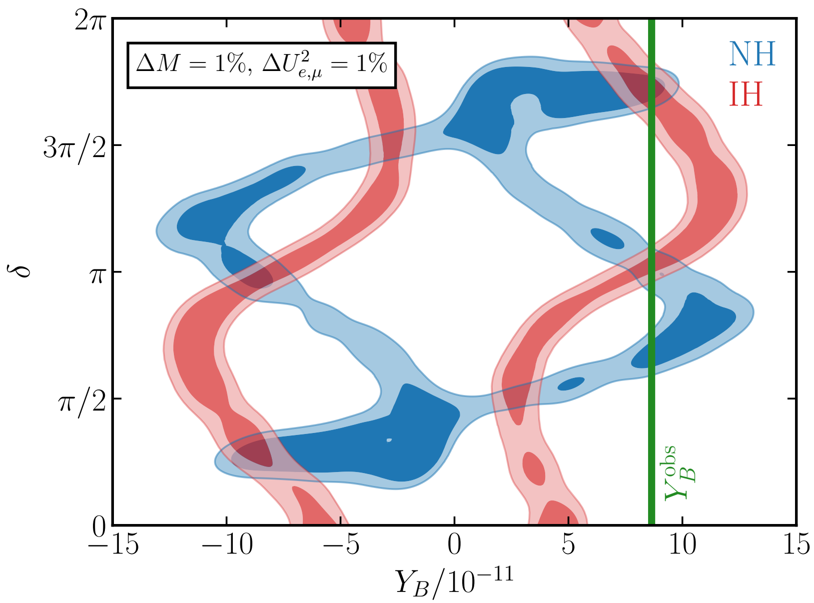
Numerical likelihood inference in the case of measuring HNL-active neutrino mixings

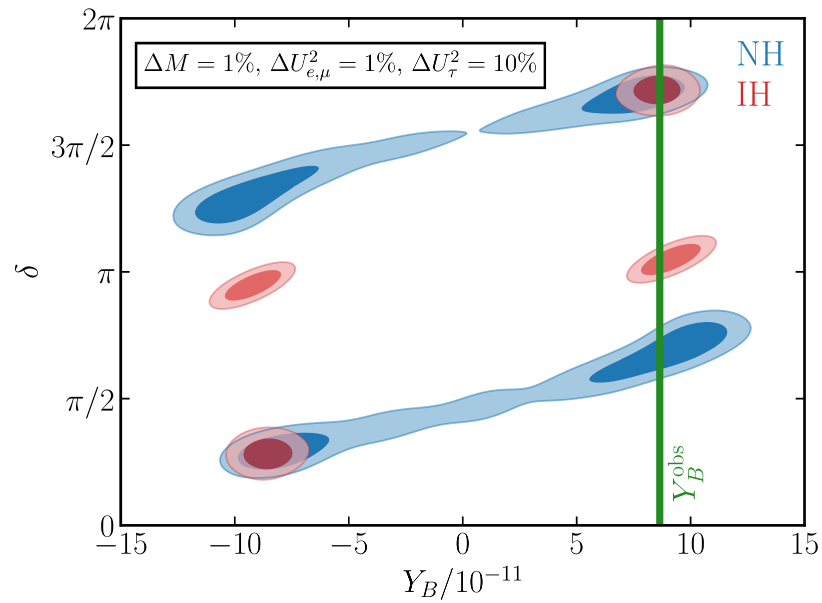


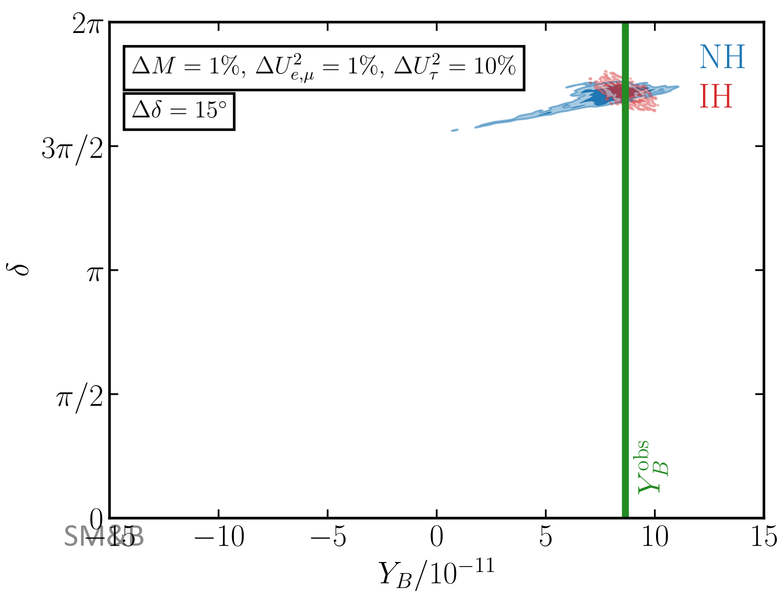


	$M^{\rm true}/{\rm GeV}$	$(U_e^2)_{\rm true}$	$(U_\mu^2)_{\rm true}$	$(U_\tau^2)_{\rm true}$	$\delta^{\rm true}/{\rm rad}$
NH	31.60	2.843×10^{-12}	1.087×10^{-11}	1.234×10^{-11}	5.396
IH	20.731	3.291×10^{-11}	4.823×10^{-12}	3.465×10^{-12}	5.402

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







ϕ determined by Y_B

$$\Delta M \gg \Gamma$$

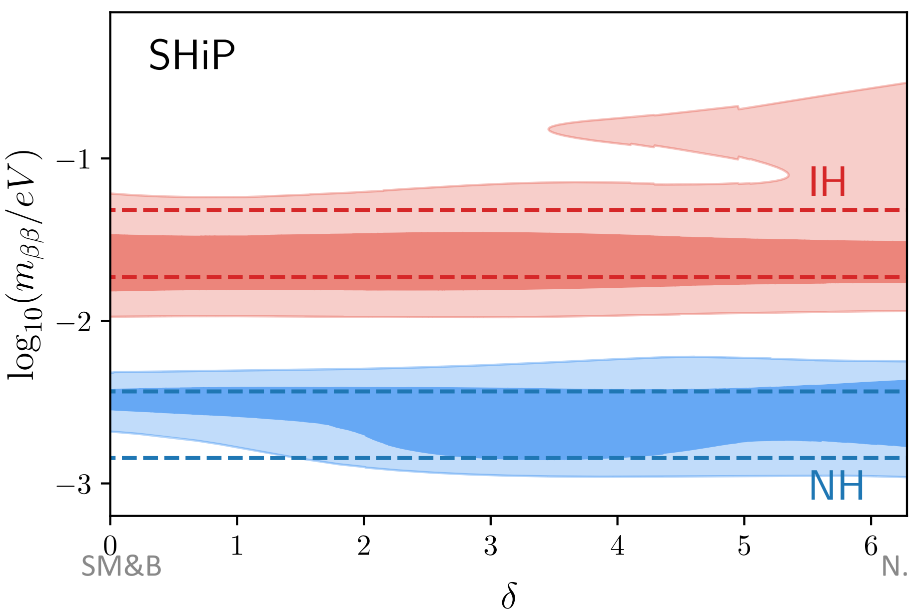
HNL oscillations can not be observed at FCC but LNV processes can

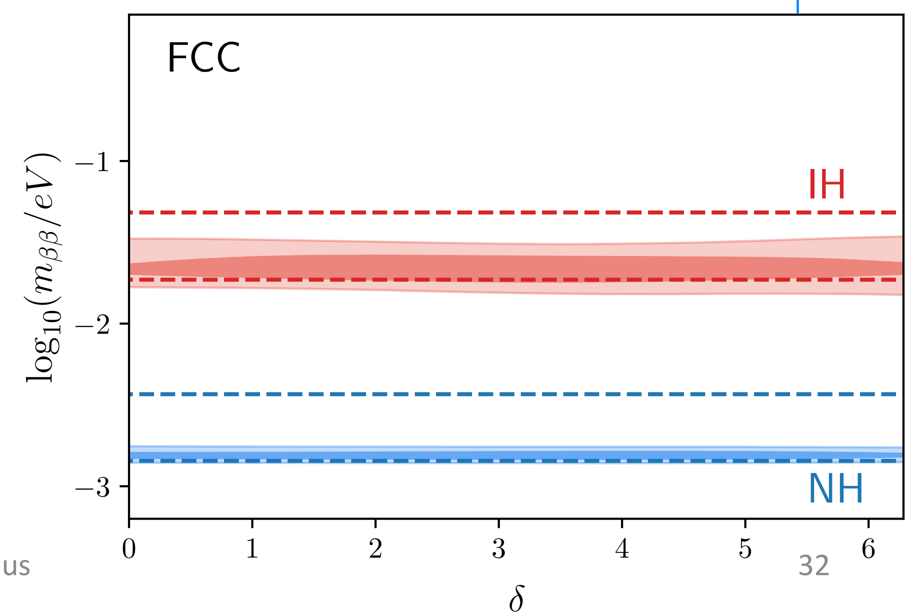
2. Neutrinoless double beta decay: $\Delta M/M = 10^{-2}$

Effect of HNL only in SHIP range

$$m_{\beta\beta}^{NH} = \Bigg| \sqrt{\Delta m^2_{\rm atm}} \left(c_{12}^2 c_{13}^2 r - e^{-2i(\delta+\phi)} s_{13}^2 \right)$$
$$- 2e^{i\theta} U^2 \Delta M f(A) \left(\frac{0.9\text{GeV}}{M}\right)^2 \left(r s_{12}^2 + 2\sqrt{r} s_{12} s_{13} e^{-i(\delta+\phi)} + s_{13}^2 e^{-2i(\delta+\phi)} \right) \Bigg| ,$$

$$m_{\beta\beta}^{IH} = \Bigg| \sqrt{\Delta m^2_{\rm atm}} c_{13}^2 \left(c_{12}^2 - s_{12}^2 e^{2i\phi} + \mathcal{O}\left(r^2\right) \right)$$
$$- e^{i\theta} U^2 \Delta M f(A) \left(\frac{0.9\text{GeV}}{M}\right)^2 \left(c_{12} + s_{12}^{i\phi} \right)^2 \left(1 + \mathcal{O}\left(r^2\right)\right) \Bigg| ,$$





SM&B

Conclusions and outlook

- Precise analytic understanding of numerical scan for successful baryogenesis via heavy neutral lepton (HNL) oscillations in the minimal seesaw (2 HNL)

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

- 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 to 3 HNL

Thank you !

Time scales and regimes

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

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

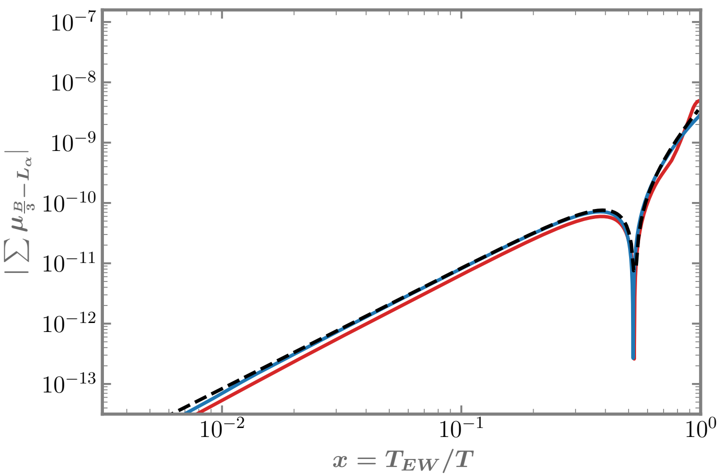
- Fast oscillations: $\Gamma_{osc}(T) \gg \Gamma(T)$ at $T = T_{osc}$

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

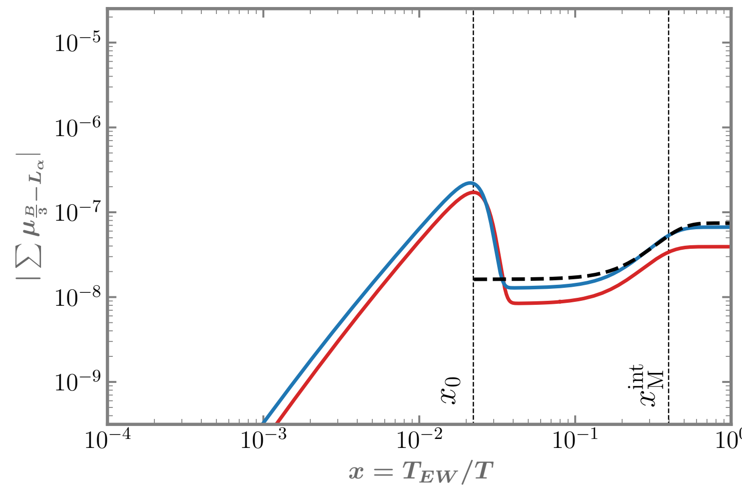
- Overdamped regime: $\Gamma_{osc}(T) \ll \Gamma(T)$ at $T = T_{osc}, T_{EW}$

4. Analytical solutions

Overdamped weak LNV



Intermediate slow flavour α

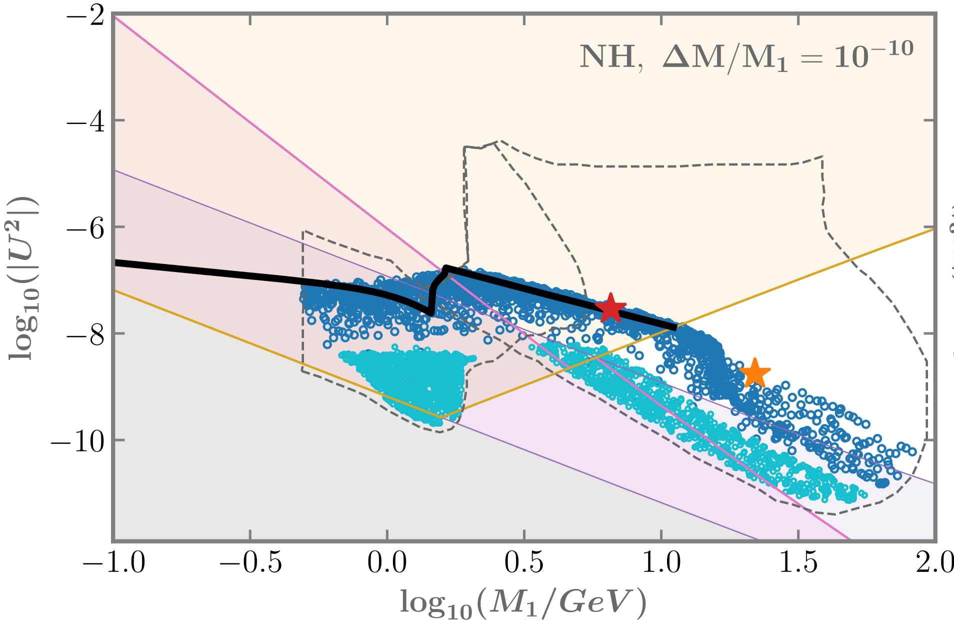


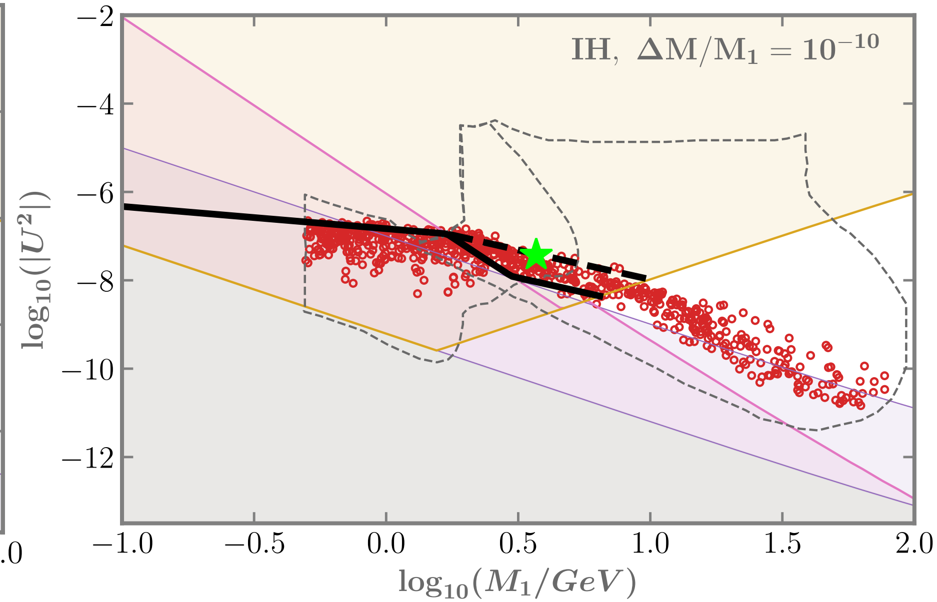
---- analytical solution: Perturbing in y' and in $(M/T)^2$

Linearized equations

—— numerical solution same approximations

—— full numerical solution





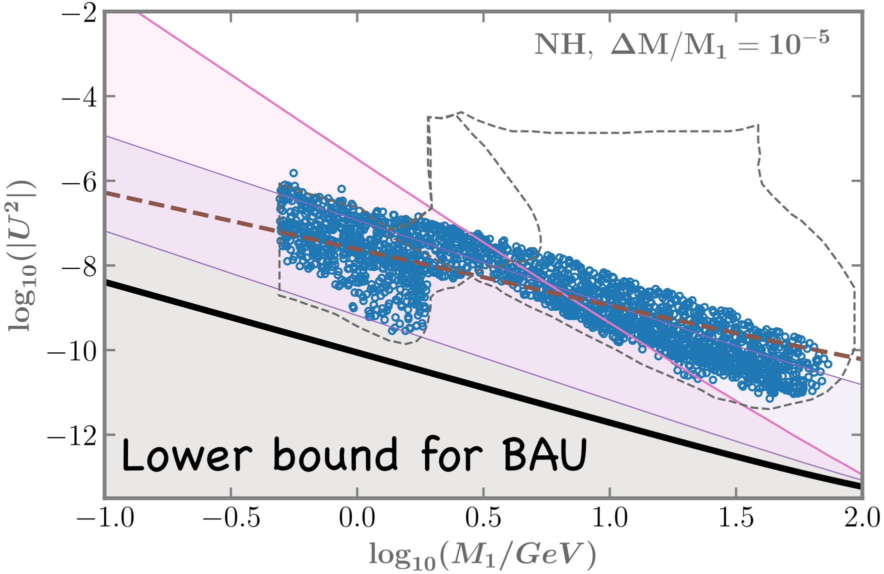
- Overdamped regime: $(U^2)_{\rm ov} \geq 8 \times 10^9 \left(\frac{\Delta M}{M}\frac{M}{1{\rm GeV}}\right)^2$
- For M ≲ O(1 GeV), weak LNV(HC):

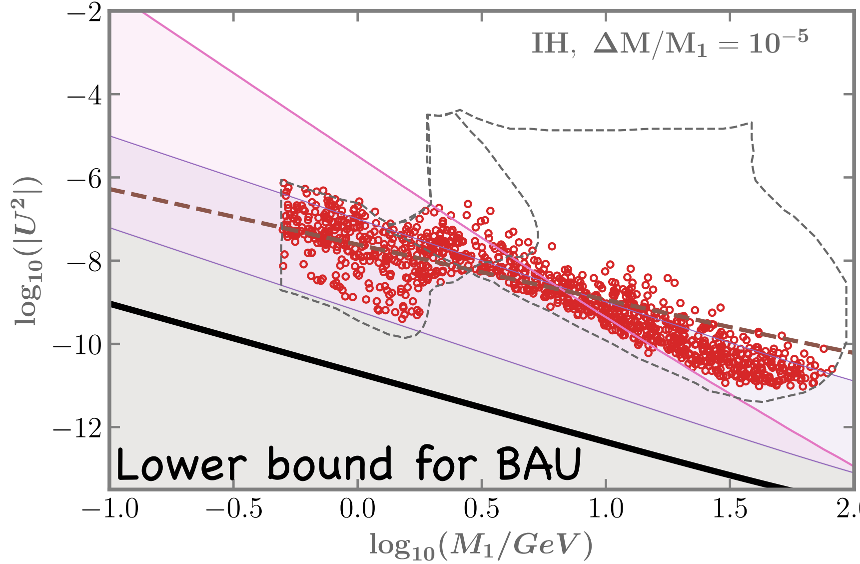
$$(Y_B)^{\rm wLNV}_{\rm ov} \simeq 2 \times 10^{-1}\,\frac{\Delta M}{M}\left(\frac{10^{-7}}{U^2}\right)\frac{1\,{\rm GeV}}{M}\left(\left(\frac{M}{1\,{\rm GeV}}\right)^4 f^{\rm H}_{\rm LNV} - \left(\frac{10^{-7}}{U^2}\right) f^{\rm H}_{\rm LNC}\right)$$

- $f^{\rm H}_{\rm LNC/LNV}$ are the angular part of the CP invariants:

$$f^{\rm IH}_{\rm LNC} = \frac{(1+3c_\phi \sin 2\theta_{12})(c_\theta s_\phi \sin 2\theta_{12} + s_\theta \cos 2\theta_{12})}{1 - c_\phi^2 \sin^2 2\theta_{12}}$$

$$f^{\rm NH}_{\rm LNC} = f^{\rm NH}_{\rm LNV} = 2/r^2 f^{\rm IH}_{\rm LNV} = s_\theta$$





- Fast oscillation/intermediate regime

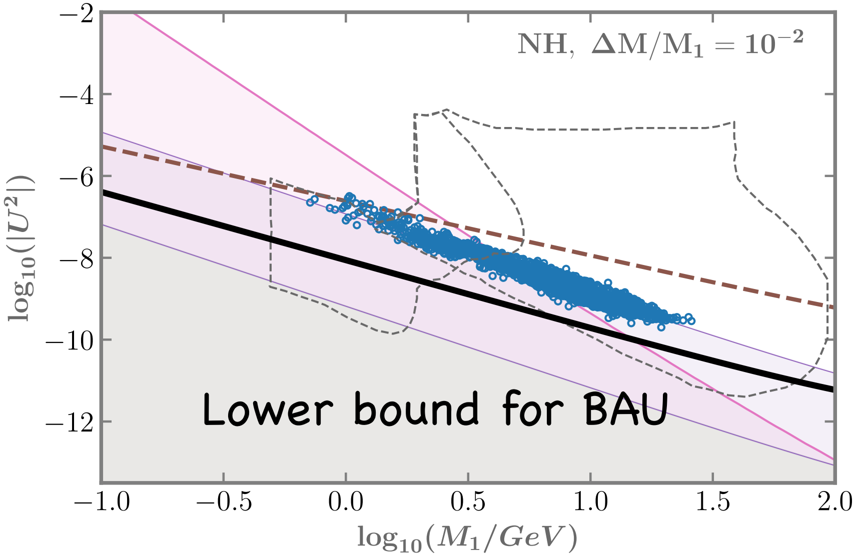
$$\epsilon_\alpha \equiv \frac{(YY^\dagger)_{\alpha\alpha}}{\mathrm{Tr}[YY^\dagger]}$$

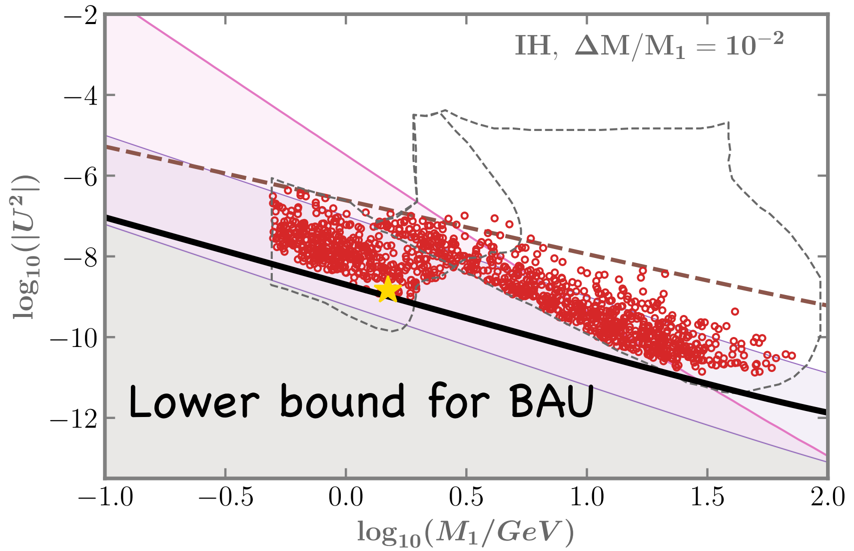
- One flavour α remains weak at T_{EW}

$$10^{-9}\left(\frac{1\mathrm{GeV}}{M}\right)^2 \frac{1}{\mathrm{Max}(\epsilon_\alpha)} \leq (U^2)_{\mathrm{fw}} \leq 10^{-9}\left(\frac{1\mathrm{GeV}}{M}\right)^2 \frac{1}{\mathrm{Min}(\epsilon_\alpha)}$$

- NH : $\alpha = e$ ($\delta + \phi \approx \pi$) , IH: $\alpha = e, \mu, \tau$, depending on (δ,ϕ)

$$\mathrm{Min}(\epsilon_e)_{\mathrm{NH}} \simeq \mathrm{Min}(\epsilon_\alpha)_{\mathrm{IH}} = 5 \times 10^{-3}$$





- Only fast oscillation, one slow flavour at T_{EW}:

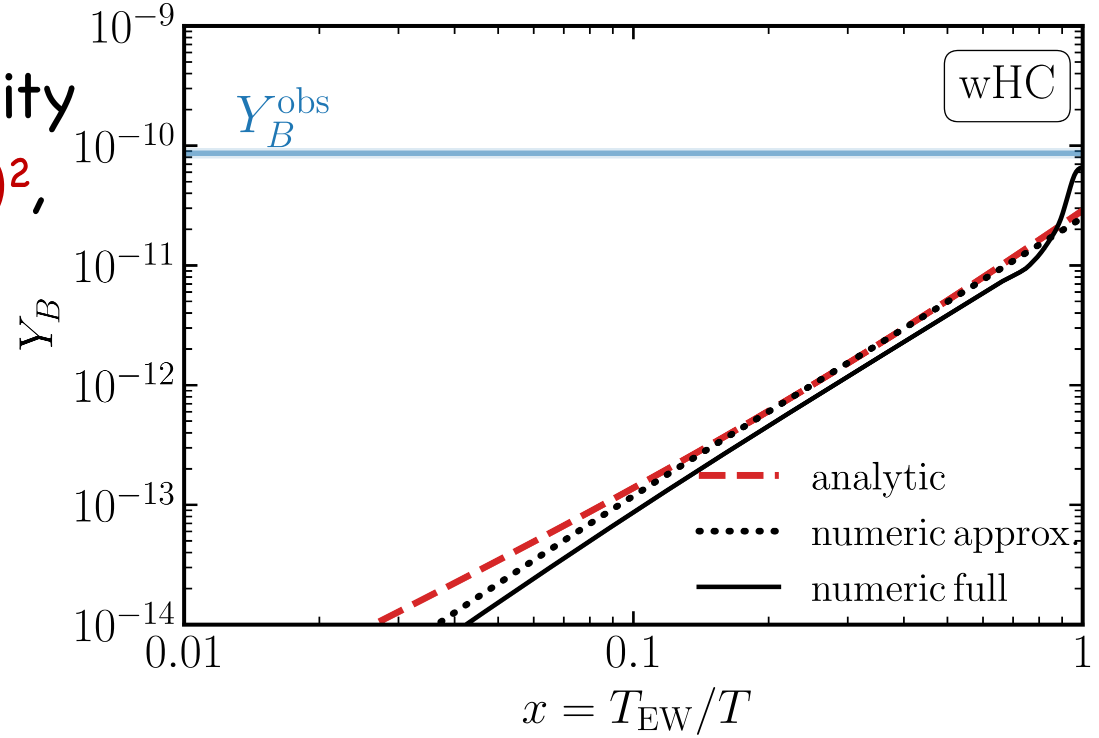
$$(Y_B)_{\rm fw-osc} = -4.3\times 10^{-12}\eta \tilde{f}^{\alpha}_{\rm NH/IH}\left(\frac{U^2}{10^{-9}}\right)\left(\frac{\Delta M}{M}\right)^{-2/3}\left(\frac{M}{1{\rm GeV}}\right)^{5/3}$$

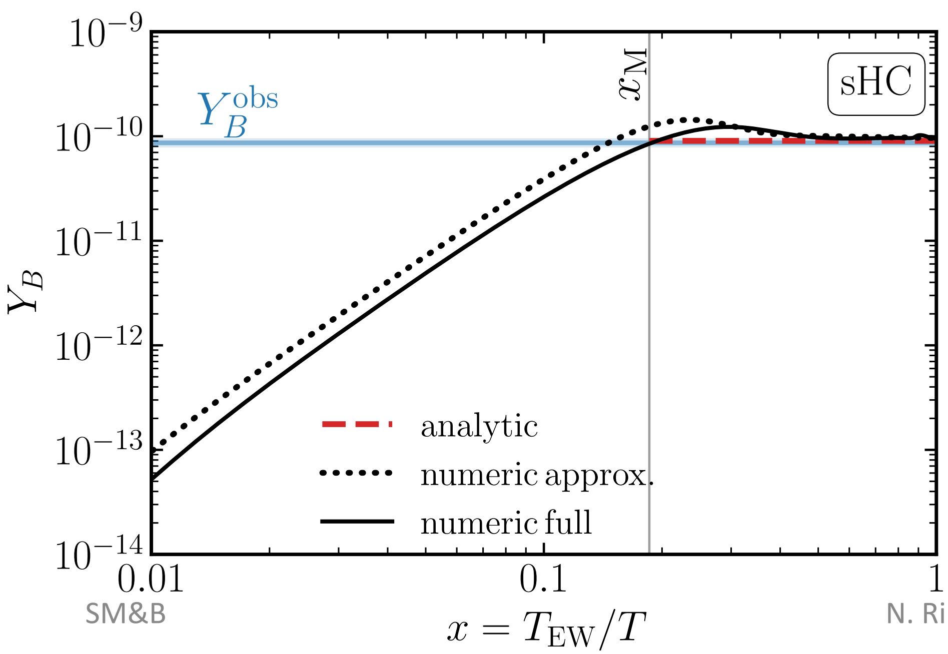
$$\tilde{f}^{e}_{\rm NH} = r s_{12}^2 s_\theta, \quad \tilde{f}^{\mu,\tau}_{\rm IH} = -\tilde{f}^{e}_{\rm IH}/2 = -\frac{1}{4}(\sin 2\theta_{12} s_\phi c_\theta + \cos 2\theta_{12} s_\theta)$$

- Y_B in weak LNV(HC) regime too small

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

Ghiglieri, Laine, 2017





0νββ decay in $\mu \simeq 0$ case