The imprint of the matter-antimatter asymmetry in ν physics

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GENERALITAT VALENCIANA Conselleria d'Innovació, Universitats, Ciència i Societat Digital
HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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In collaboration with: J. López-Pavón, N. Rius and S. Sandner
arXiv: 2207.01651

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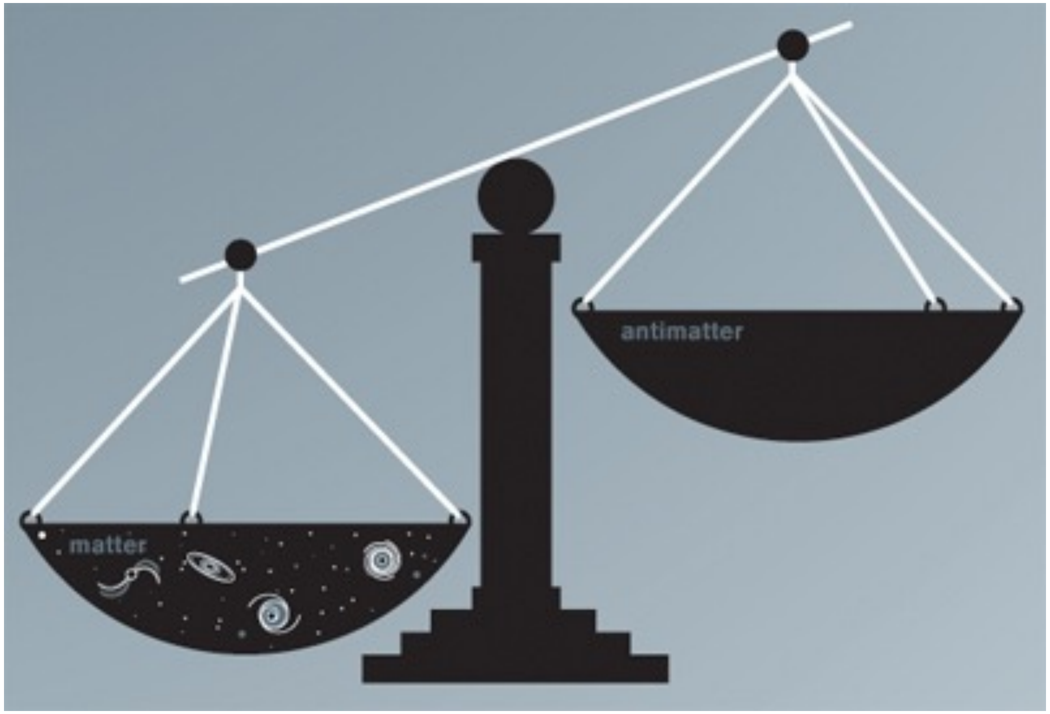
The matter-antimatter asymmetry

The Universe seems to be made of matter



$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21(16) \times 10^{-10}$$

A. Sakharov

Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

Three basic conditions for cosmological formation of baryonic asymmetry

I. Absence of baryonic charge conservation.

II. Difference between particles and antiparticles, manifesting itself in the violation of CP-invariance.

III. Nonstationarity. Formation of BA is only possible under nonstationary conditions in the absence of local thermodynamic equilibrium.

$$n_b \sim n_{\bar{b}} \propto e^{-m_b/T}$$

The Standard Model (subtly) complies

I Baryon Number

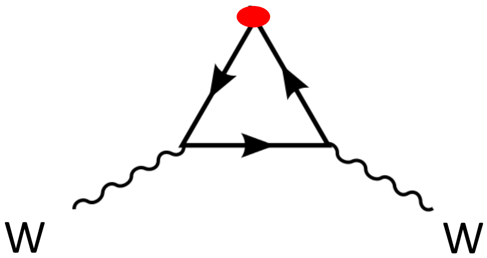
The SM Lagrangian preserves baryon number symmetry classically

$$p \not\to e^+ \pi_0$$

But the symmetry is broken by quantum vacuum effects: anomaly

t'Hooft '76, Klinkhammer, Manton '84;

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu$$



$$\mathrm{Rate}(\not{B}) \propto \begin{cases} e^{-\frac{4\pi}{\alpha_W}}, & T < T_{\mathrm{EW}} \\ \mathcal{O}(1), & T > T_{\mathrm{EW}} \end{cases}$$

Only B-L is conserved in the SM !

The Standard Model (subtly) complies

II CP violation

$$\mathcal{L}_{SM} = \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\mathrm{CP}\surd} + \underbrace{i\bar{\psi}\not{D}\psi}_{\mathrm{CP}\surd} + \underbrace{\bar{\psi}_i Y_{ij}\phi\psi_j}_{\mathrm{CP}\times \text{ iff } \mathrm{Y}\neq\mathrm{Y}^*} + \underbrace{D_\mu\phi D^\mu\phi - V(\phi)}_{CP\surd}$$

CP violation in the quark sector:

K-mesons 1964 Cronin-Fitsch
B-mesons 2001 BaBar & Belle
D-mesons 2019 LHCb

LHCb@ LHC

But the Standard Model fails

II CP violation

It is a subtle phenomenon that depends on many flavour parameters

$$Y_B \propto \Delta_{\mathrm{CP}}$$

$$\Delta_{CP}^{\mathrm{quarks}} = \begin{cases} \bullet \text{ Polynomial in } Y_u, Y_d \\ \bullet \text{ Has an imaginary part} \\ \bullet \text{ It is flavour-basis invariant} \end{cases}$$

But the Standard Model fails

II CP violation

It is a subtle phenomenon that depends on many flavour parameters

$$Y_B \propto \Delta_{\rm CP}$$

$$\Delta_{CP}^{\rm quarks} = \ {\rm Im}\left[\det\left([Y_u Y_u^\dagger, Y_d Y_d^\dagger]\right)\right] \propto J \prod_{i<j}(m_{d_i}^2 - m_{d_j}^2)\prod_{i<j}(m_{u_i}^2 - m_{u_j}^2)$$

$$J = {\rm Im}[V_{ij}^* V_{ii} V_{ji}^* V_{jj}] = c_{23} s_{23} c_{12} s_{12} c_{13}^2 s_{13} \sin\delta$$

Jarlskog '85

Three non-degenerate families of up and down quarks that mix are needed for there to be CP violation !

But the Standard Model fails

Too small CP violation in quark sector

Gavela, PH, Orloff, Pene ‘93

$$\frac{n_b}{n_\gamma} \sim \Delta_{CP}^{quarks} \sim 10^{-20}$$

New sources of CP violation are needed !

But the Standard Model fails

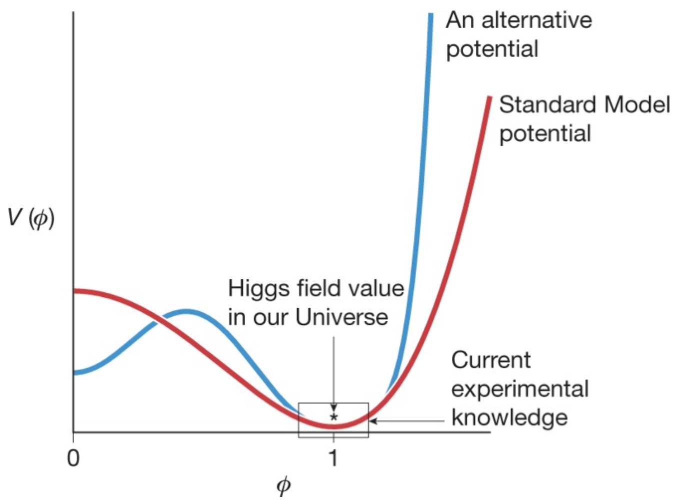
III Non-equilibrium

- First order phase transitions (EW symmetry is restored at high enough T)

It is a smooth crossover in the SM (too heavy higgs)

Kajantie, Laine, Rummukainen,Shaposhnikov '96

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 H^3 + \lambda_4 H^4$$



$$\lambda_3^{SM} = \frac{m_H^2}{\sqrt{2}v}, \lambda_4^{SM} = \frac{m_H^2}{4v^2}$$

But the Standard Model fails

III Non-equilibrium

- Expansion of the Universe when $\Gamma(T) \leq H(T)$

scattering rate < Hubble expansion

All particles in the SM (even neutrinos) satisfy

$$\Gamma_{SM}(T) \geq H(T), \quad T \geq T_{\rm EW}$$

The Standard Model+massive ν

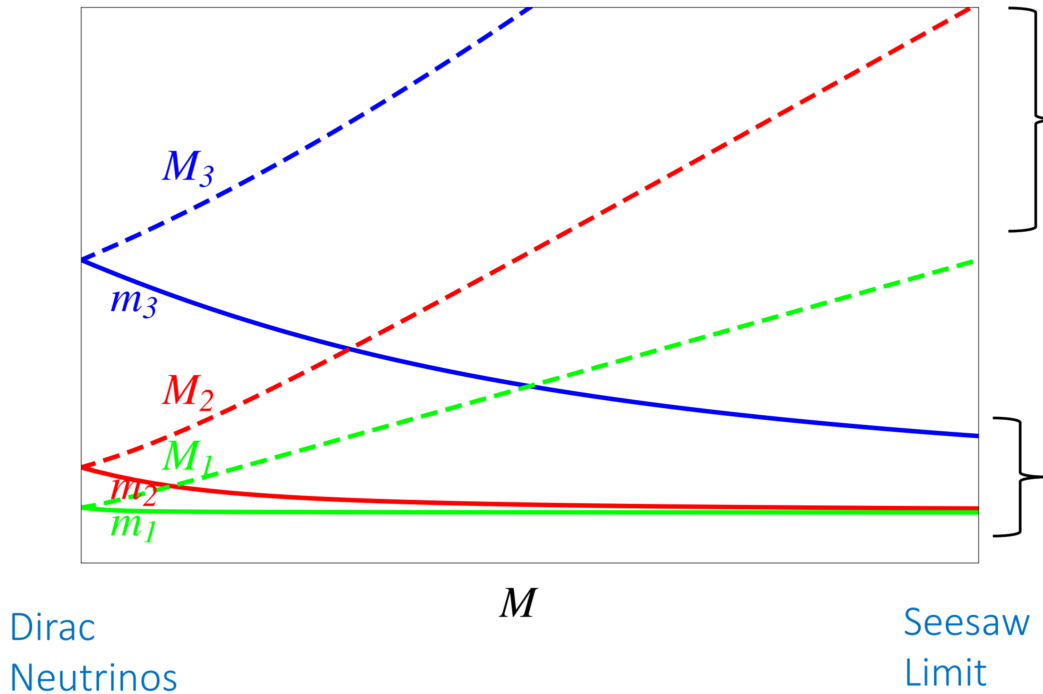
An extension of the SM table is mandatory

$(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$(\mathbf{3},\mathbf{2})_{-\frac{1}{6}}$	$(\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{3},\mathbf{1})_{-\frac{2}{3}}$	$(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$(\mathbf{1},\mathbf{1})_0$
$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$	$\begin{pmatrix}u^i\\ d^i\end{pmatrix}_L$	e_R	u^i_R	d^i_R	ν^1_R
$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$	$\begin{pmatrix}c^i\\ s^i\end{pmatrix}_L$	μ_R	c^i_R	s^i_R	ν^2_R
$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	$\begin{pmatrix}t^i\\ b^i\end{pmatrix}_L$	τ_R	t^i_R	b^i_R	ν^3_R

$$\mathcal{L}_{SM} \supset \bar{\nu}_{Li} Y_{ij} H \nu_{Rj} + \bar{\nu}_{Ri} M_{ij} \nu^c_{Rj}$$

The Standard Model+massive ν

M≠ 0 <-> 6 Majorana neutrinos (3 light, 3 heavy)



Heavy Neutral Leptons (N)

$$m_{\text{heavy}} \sim M$$

Light neutrinos (ν)

$$m_{\text{light}} \sim Y \frac{v^2}{M} Y^T$$

We can think of the heavy states as neutrino mass mediators

Fixing the light neutrino masses leaves us with a degeneracy

$$M \sim Y^2$$

The Standard Model+massive ν

New opportunities for baryogenesis!

- CP violation in the lepton sector potentially larger if M ≠ 0: new invariants

$$\Delta_{CP}^{\text{leptons}} = \text{Im}\left\{\text{Tr}[Y^\dagger Y M^\dagger M M^* (Y^\dagger Y)^* M]\right\}$$

Branco et al; Jenkins, Manohar;Wang, Yu Zhou…

- Heavy neutrino states might exit early/never reach thermal equilibrium at $T>T_{EW}$

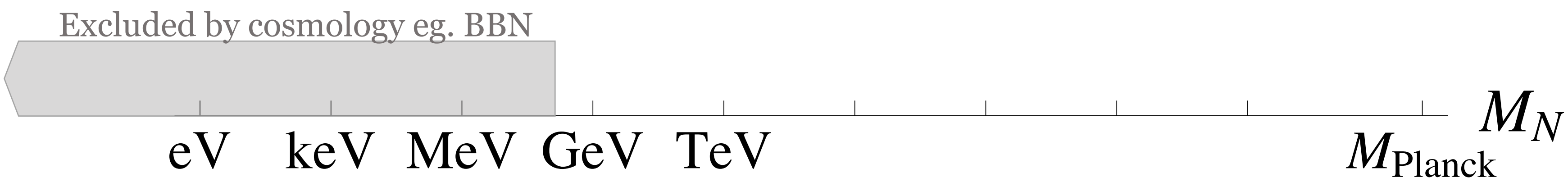
$$\Gamma_{N_i}(T) \leq H(T), T \geq T_{EW}$$

(Scattering rate < Hubble expansion rate)

The Standard Model+massive ν

Robust prediction: generation of a baryon asymmetry via leptogenesis for a wide range of M

Fukugita, Yanagida; ...Abada et al;..Pilaftsis...; Ahkmedov,Rubakov, Smirnov; Asaka, Shaposhnikov...



The Standard Model+massive ν

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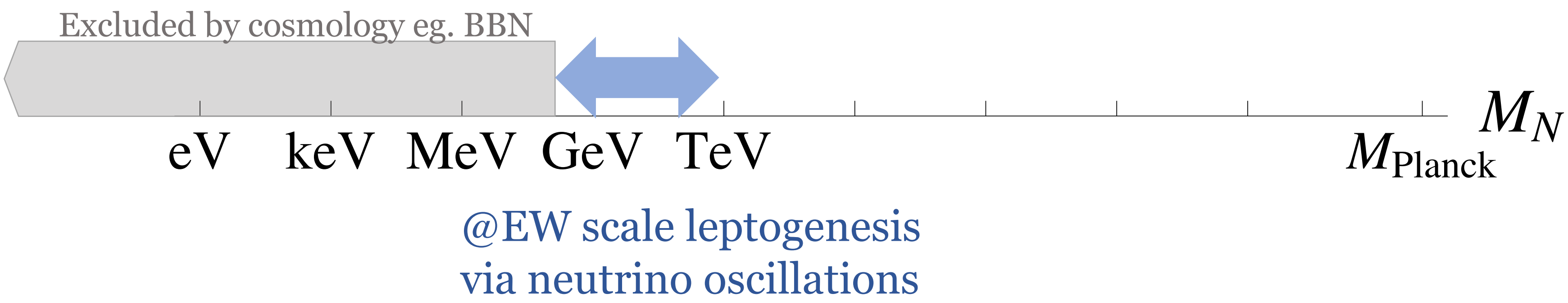

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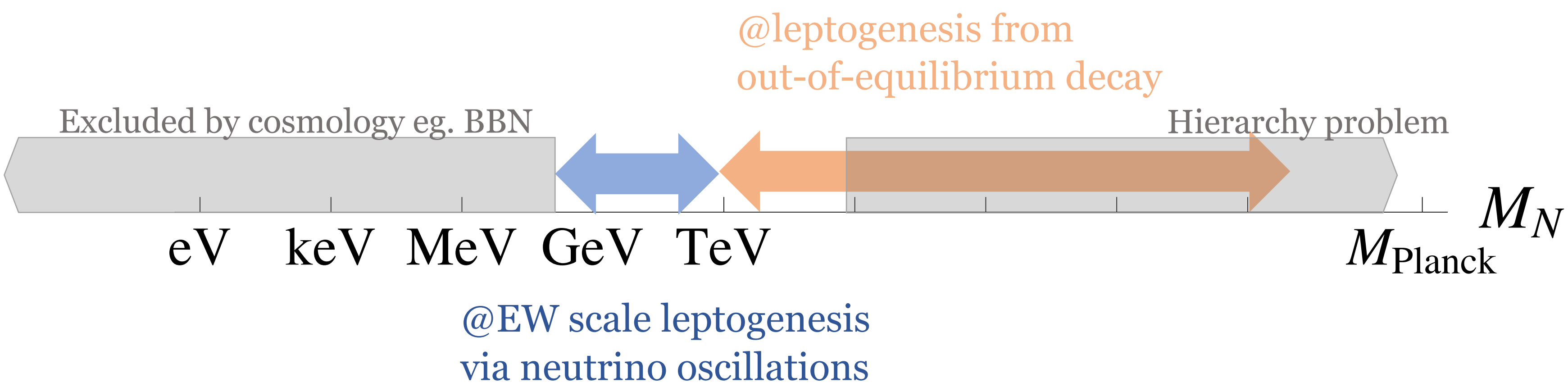


Heavy Neutral Leptons

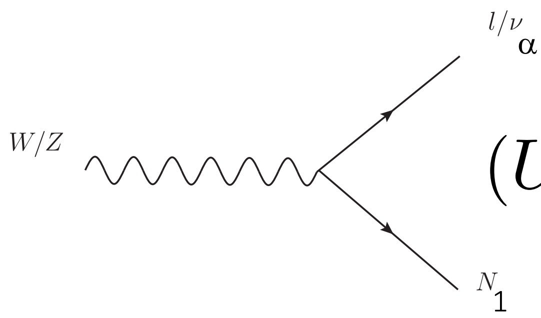
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{ll} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} + U_{lh} \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}$$

Light neutrino mixing
(~PMNS)

HNL mixing

Naïve seesaw scaling: $$|U_{lh}|^2 \sim \frac{m_l}{M_N}$$

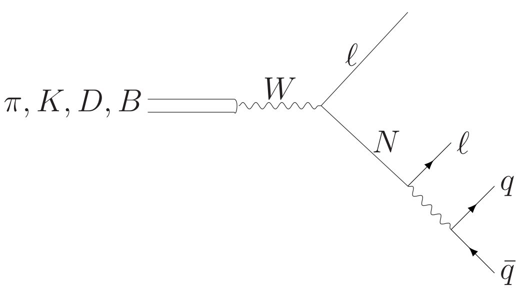
Heavy Neutral Leptons



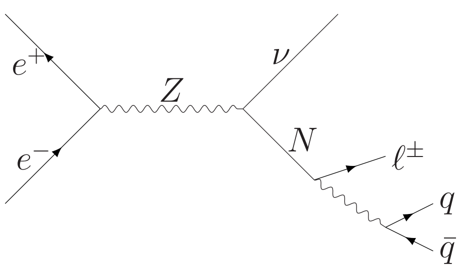
$$(U_{hl})_{\alpha 1}$$

$$U^2 = \sum_\alpha |(U_{hl})_{\alpha 1}|^2$$

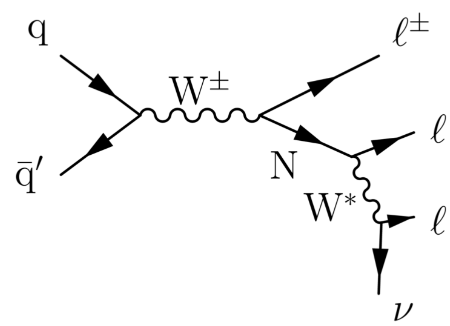
Meson decays



e+e-@Z peak

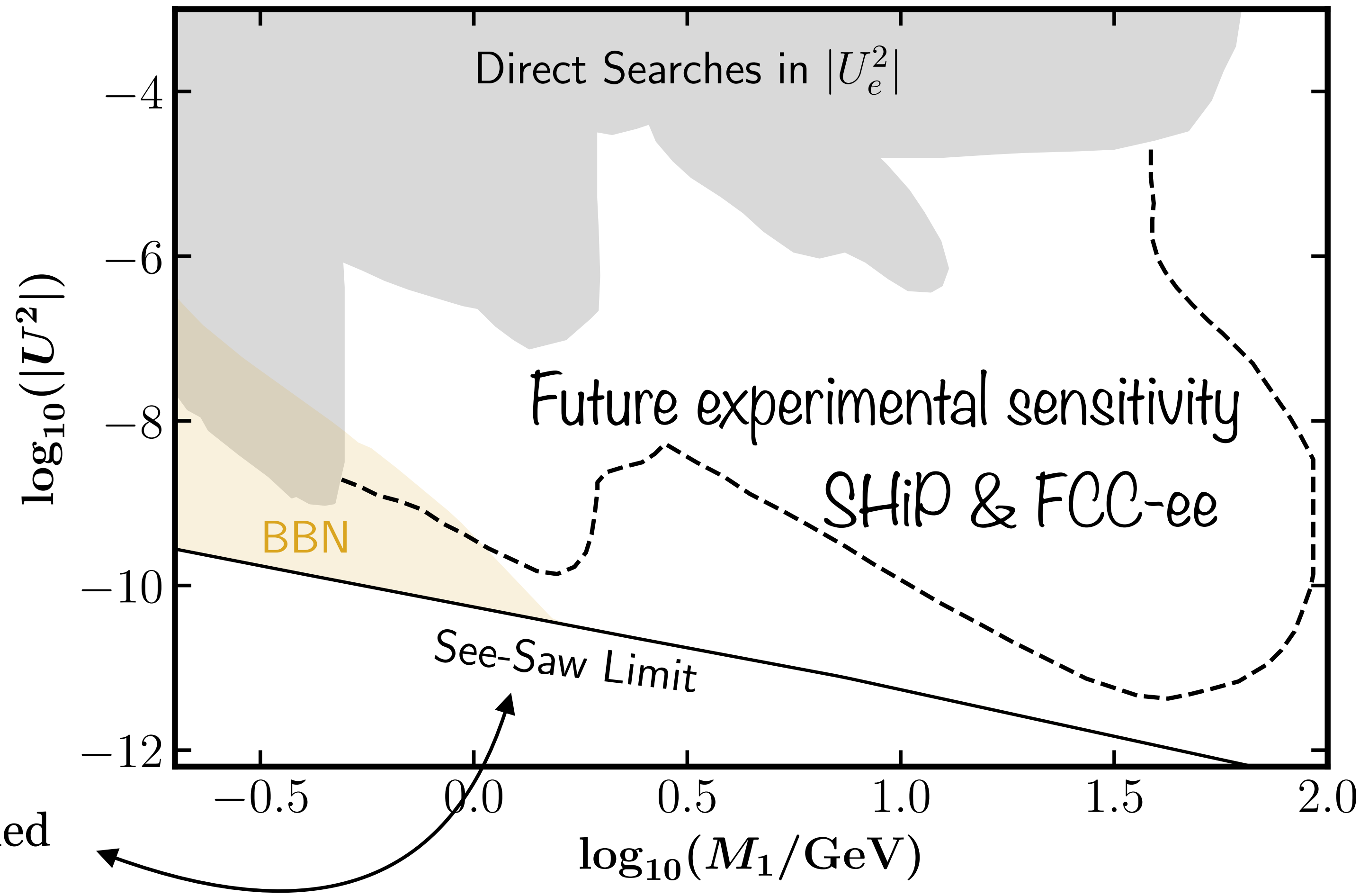


Hadron colliders



@Laboratory (fixed target, colliders) and cosmic rays

Heavy Neutral Leptons



ν masses
not explained

Most of the accessible region is quite far from the seesaw limit … $|U|^2 \gg \frac{m_l}{M}$

Heavy Neutral Leptons

Strongly mixed HNL that explain neutrino masses iff approximate global symmetry $U(1)_L$

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao;Kersten, Smirnov; Abada et al; Gavela et al….many others

Minimal Model two neutrinos: $L(N_1) = +1, \; L(N_2) = -1$

$$M = \begin{pmatrix} 0 & \Lambda \\ \Lambda & 0 \end{pmatrix} \qquad Y = \begin{pmatrix} y_e & 0 \\ y_\mu & 0 \\ y_\tau & 0 \end{pmatrix}$$

Degenerate heavy neutrinos, massless light neutrinos, no CP violation…

Heavy Neutral Leptons

Strongly mixed HNL that explain neutrino masses iff approximate global symmetry $U(1)_L$

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao;Kersten, Smirnov; Abada et al; Gavela et al....many others

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

Expansion parameters $\quad y' \ll y, \mu \ll \Lambda, \;\; \Delta M \propto \mu$

Neutrino masses:

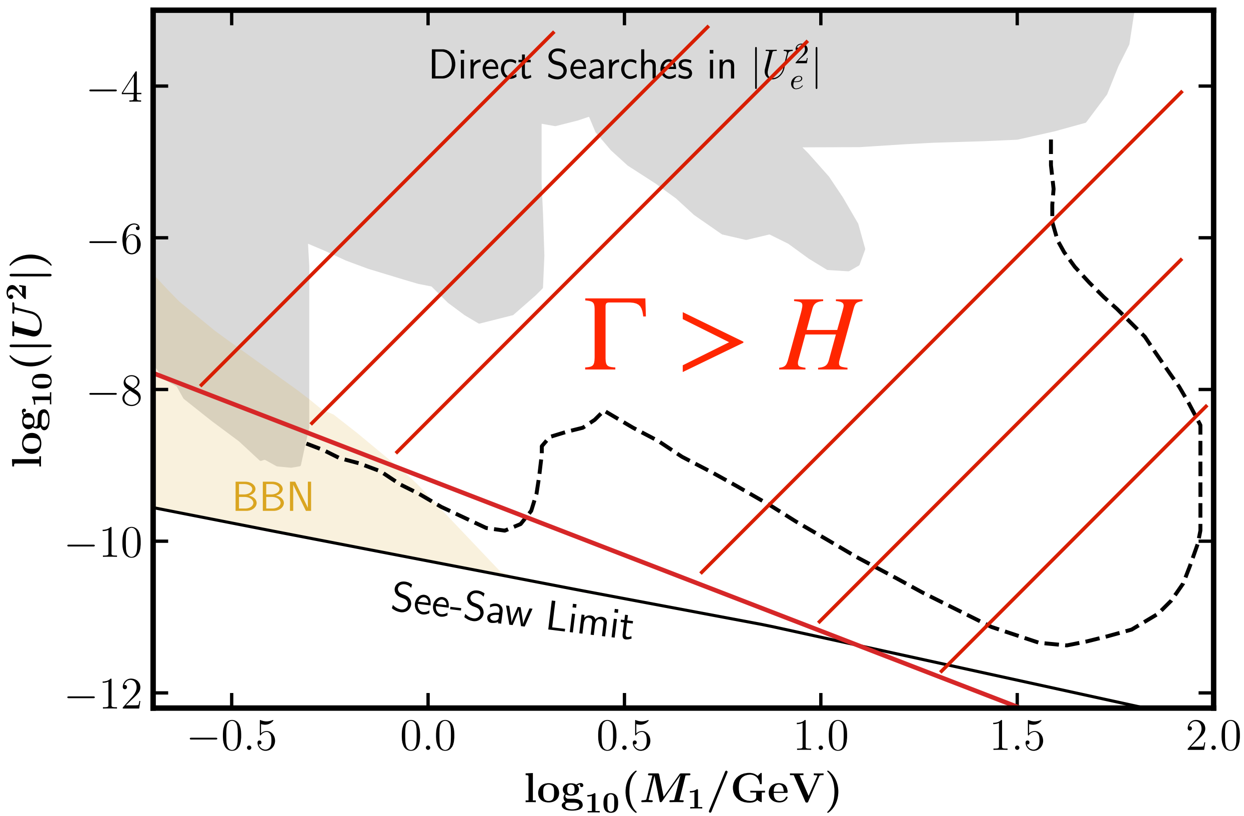
$$(m_\nu)_{\alpha\beta} \propto \frac{v^2}{\Lambda}\left(y_\alpha y'_\beta + y_\beta y'_\alpha - y_\alpha y_\beta \frac{\mu_2}{\Lambda}\right)$$

HNL Mixing:

$$U^2 \sim \frac{y^2 v^2}{2M^2}$$

Non thermal equilibration?

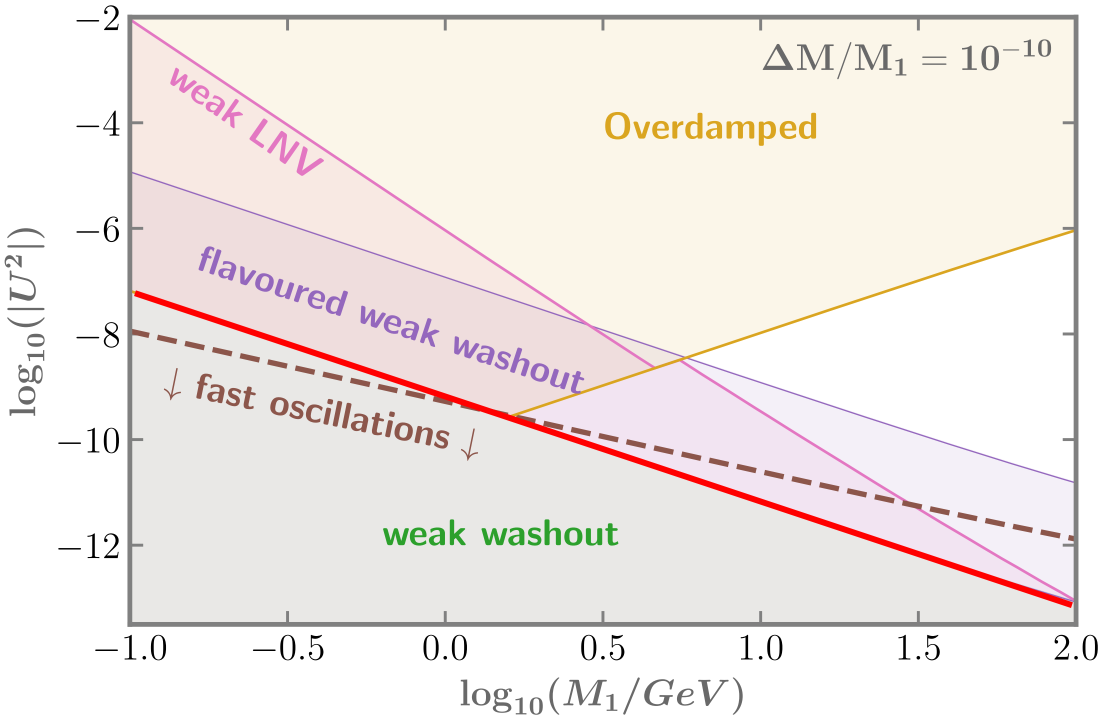
$\Gamma(T_{\rm EW}) \leq H(T_{\rm EW})$ is required $\Gamma \propto {\rm Tr}[Y^\dagger Y] T$



BUT approximate LN symmetry and flavour effects can lead to other slow modes

Highly-degenerate regime

Shaded regions have slow thermalizing modes

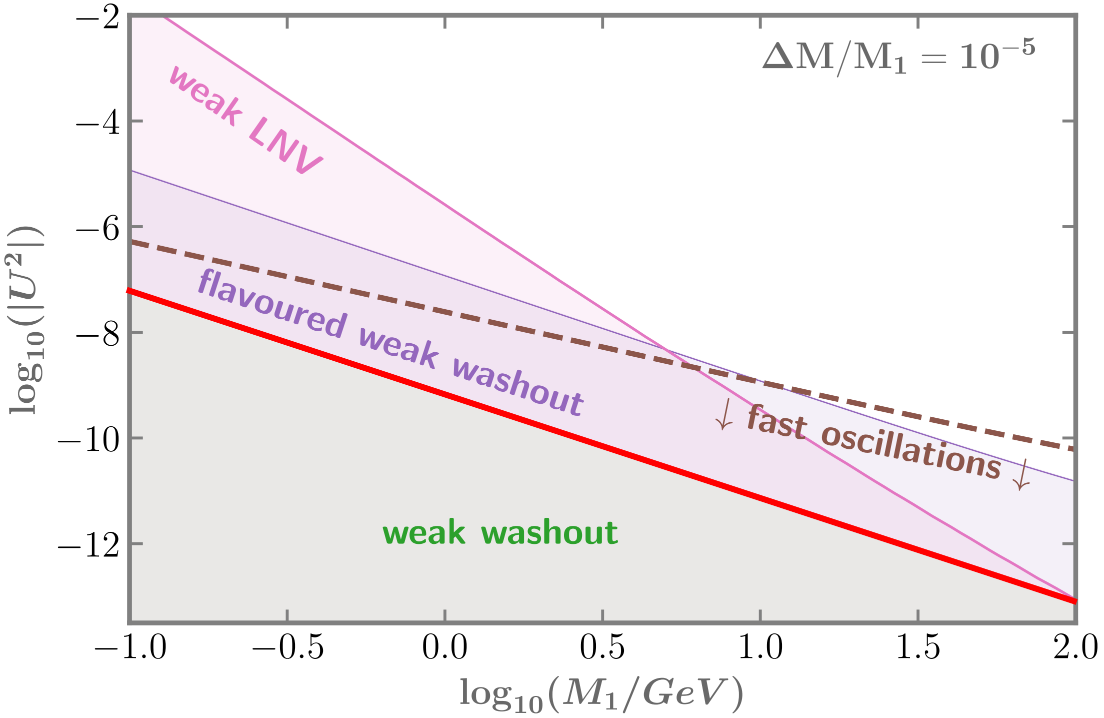


Overdamped: $\Delta M \ll M$

$$\Gamma_{\rm osc}^{\rm slow} = \epsilon^2 \Gamma \qquad \epsilon \equiv \frac{\Gamma_{osc}}{\Gamma} \qquad \Gamma_{\rm osc}(T) \propto \frac{M_2^2 - M_1^2}{T}$$

Not-so-degenerate regime

Shaded regions have slow thermalizing modes



Flavoured: $y_\alpha \ll y_\beta$

wLNV: $M \ll T$

$$\Gamma_\alpha \propto (YY^\dagger)_{\alpha\alpha} T$$

$$\Gamma_M^{\text{slow}} \propto \left(\frac{M_i}{T}\right)^2 \Gamma$$

(CP violation primer)

Any CP violating observable requires the interference of at least two amplitudes that differ in CP-even or CP-odd phases

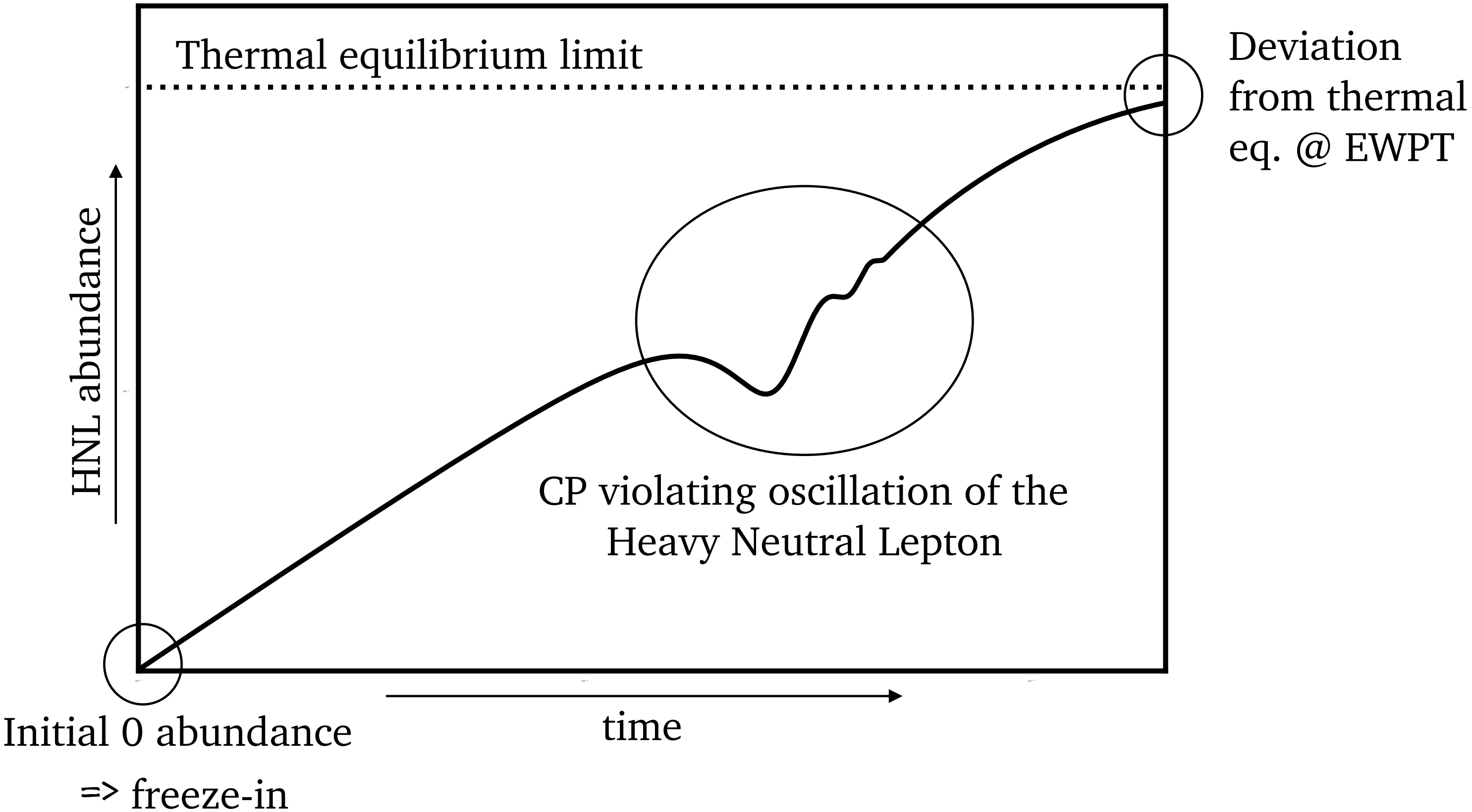
$$\Delta_{CP} \sim |A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2}|^2 - |A_1 e^{i\phi_1} e^{-i\delta_1} + A_2 e^{i\phi_2} e^{-i\delta_2}|^2$$

Vanishes if $|\phi_2 - \phi_1| = 0 \text{ or } |\delta_2 - \delta_1| = 0$

In the context of ARS leptogenesis:

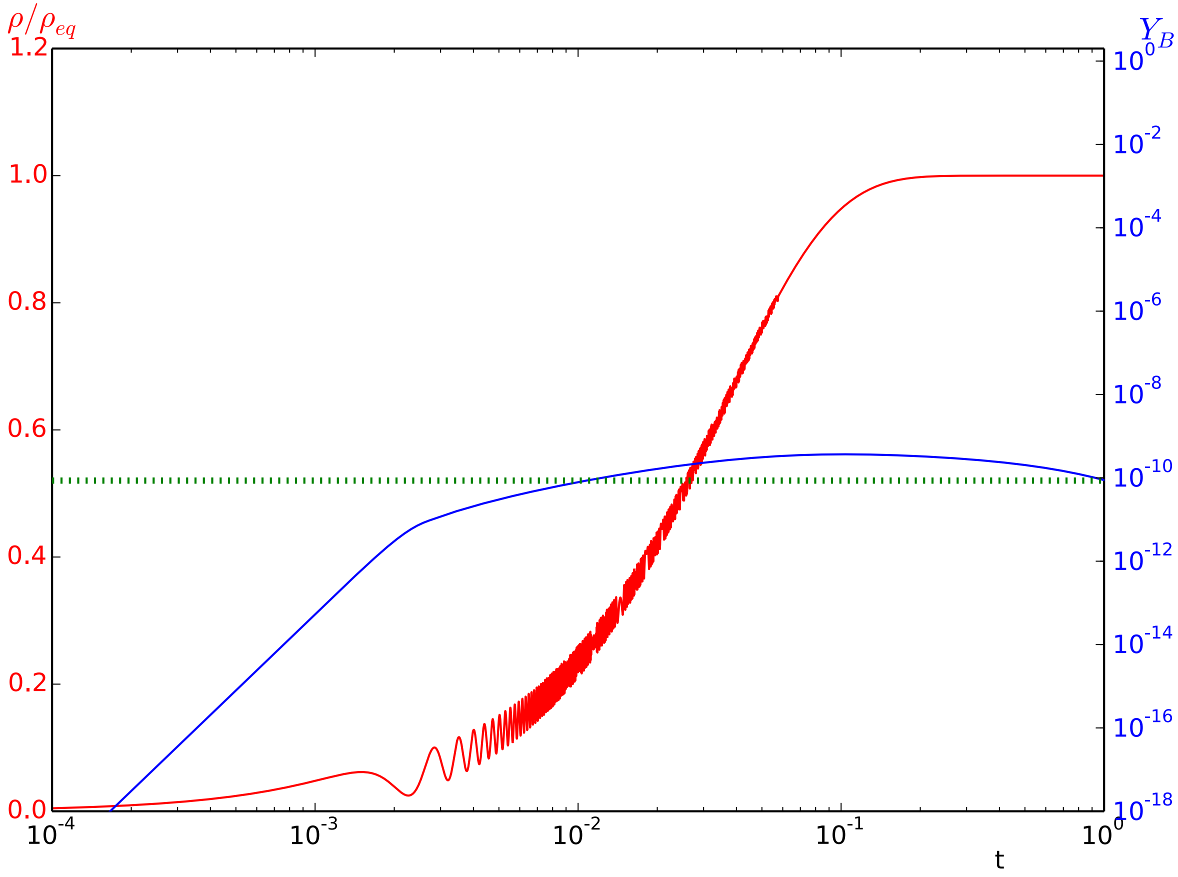
$\Delta\phi$ Oscillations/space-time phases

Freeze-in Leptogenesis



Courtesy of S. Sandner

Freeze-in Leptogenesis



The Standard Model+massive ν

Quantum kinetic equations describe the evolution of the N density matrix and the B/3-L_α chemical potentials

Raffelt-Sigl

$$\frac{d\rho_N(k)}{dt} = -i[H, \rho_N(k)] - \underbrace{\frac{1}{2}\{\Gamma_N^a, \rho_N\} + \frac{1}{2}\{\Gamma_N^p, 1-\rho_N\}}$$

Oscillations

Scattering

$$\bar{\rho}_N(H \to H^*)$$

$$\frac{d\mu_{B/3-L_\alpha}}{dt} = f(\rho_N, \rho_{\bar{N}}, \mu_{B/3-L_\alpha})$$

Stiff non-linear system with several relevant time scales: hard to explore parameter space !

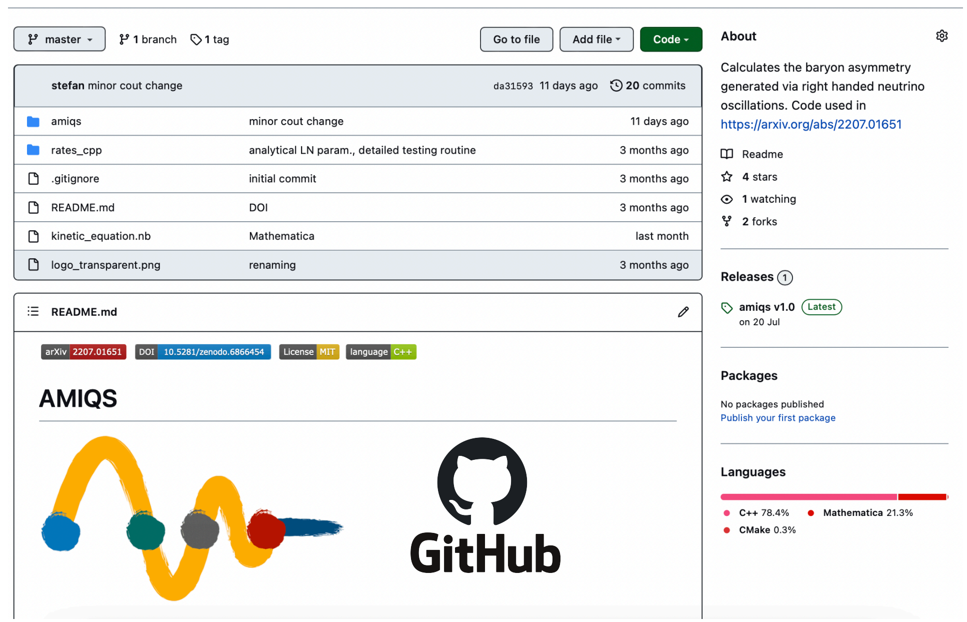
Many numerical studies before

Antusch et al.; Abada et al. ; Drewes et al.; Ghiglieri, Laine; PH et al ;Klaric et al.

Our latest refinements: inclusion of full M/T corrections to the scattering rates, v(T) close to T_{EW}

Stephan Sandner

Numerical code available on GitHub



State-of-the-art kinetic equations

$$
\begin{aligned}
xH_u \frac{\mathrm{d}r_N}{\mathrm{d}x} &= -i[\langle H\rangle, r_N] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{Y^\dagger Y, r_N - 1\} - x^2\frac{\langle s_N^{(0)}\rangle}{2}\{MY^T Y^* M, r_N - 1\} \\
&+ \langle\gamma_N^{(1)}\rangle Y^\dagger \mu Y - x^2\langle s_N^{(1)}\rangle MY^T\mu Y^* M \\
&- \frac{\langle\gamma_N^{(2)}\rangle}{2}\left\{Y^\dagger\mu Y, r_N\right\} + x^2\frac{\langle s_N^{(2)}\rangle}{2}\{MY^T\mu Y^* M, r_N\}\,, \\
xH_u \frac{\mathrm{d}r_{\bar N}}{\mathrm{d}x} &= -i[\langle H^*\rangle, r_{\bar N}] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{Y^T Y^*, r_{\bar N} - 1\} - x^2\frac{\langle s_N^{(0)}\rangle}{2}\{MY^\dagger Y M, r_{\bar N} - 1\} \\
&- \langle\gamma_N^{(1)}\rangle Y^T \mu Y^* + x^2\langle s_N^{(1)}\rangle MY^\dagger\mu Y M \\
&+ \frac{\langle\gamma_N^{(2)}\rangle}{2}\left\{Y^T\mu Y^*, r_{\bar N}\right\} - x^2\frac{\langle s_N^{(2)}\rangle}{2}\{MY^\dagger\mu Y M, r_{\bar N}\}\,, \\
xH_u \frac{\mathrm{d}\mu_{B/3-L_\alpha}}{\mathrm{d}x} &= \frac{\int_k \rho_F}{\int_k \rho_F'}\Bigg[\frac{\langle\gamma_N^{(0)}\rangle}{2}(Yr_NY^\dagger - Y^* r_{\bar N} Y^T) - x^2\frac{\langle s_N^{(0)}\rangle}{2}(Y^* M r_N M Y^T - YMr_{\bar N}MY^\dagger) \\
&- \mu_\alpha\left(\langle\gamma_N^{(1)}\rangle YY^\dagger + x^2\langle s_N^{(1)}\rangle YM^2Y^\dagger\right) + \frac{\langle\gamma_N^{(2)}\rangle}{2}\mu_\alpha(Yr_NY^\dagger + Y^* r_{\bar N} Y^T) \\
&+ x^2\frac{\langle s_N^{(2)}\rangle}{2}\mu_\alpha\left(YMr_{\bar N}MY^\dagger + Y^* M r_N M Y^T\right)\Bigg]_{\alpha\alpha}\,, \qquad (4.2)
\end{aligned}
$$

Towards an analytical understanding

PH, Lopez-Pavon, Rius, Sandner, arxiv: 2207.01651

- Identify the different non-thermal regimes and their characteristic time-scales
- Set up a perturbative approximation of the equations exploiting $y' << y$, $\mu << \Lambda$
- Identify the CP invariants that control the parameter dependences of Y_B

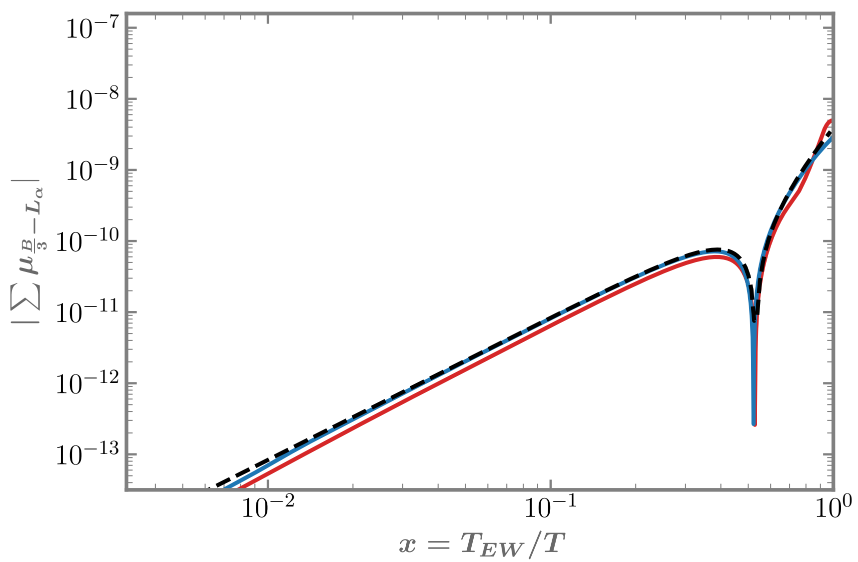
Branco et al, Manohar, Jenkins

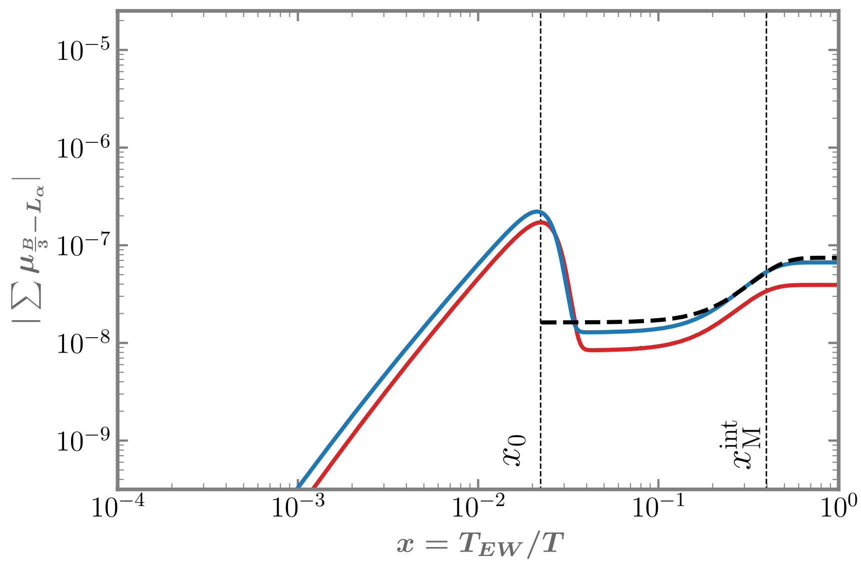
$$I_0 = \mathrm{Im}\left(\mathrm{Tr}[Y^\dagger Y M^\dagger M Y^\dagger Y_l Y_l^\dagger Y]\right)$$

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

- Write the CP invariants in terms of observable parameters: find bounds and correlations implied by the matter-antimatter asymmetry

Analytical vs numerical solution in overdamped regime





$$\left(\sum_\alpha \mu_{B/3-L_\alpha}\right)^{\mathrm{ov-wLNV}} \simeq \frac{\kappa x^2}{6\gamma_0+\kappa\gamma_1}\frac{\gamma_0^2}{\gamma_0^2+4\omega^2}\frac{c_H M_P^*}{T_{EW}^3}\left(\Delta_{\mathrm{LNC}}^{\mathrm{ov}} - \frac{24}{5}\frac{s_0 x^3}{T_{\mathrm{EW}}^2}\Delta_{\mathrm{LNV}}^{\mathrm{ov}}\right)$$

$$\Delta_{\mathrm{LNC}}^{\mathrm{ov}} = \frac{1}{[\mathrm{Tr}\,(Y^\dagger Y)]^2}\sum_\alpha \frac{1}{(YY^\dagger)_{\alpha\alpha}}\sum_{i<j}\left(M_j^2-M_i^2\right)\mathrm{Im}\left[Y_{\alpha j}^* Y_{\alpha i}\left(Y^\dagger Y\right)_{ij}\right]$$

$$\Delta_{\mathrm{LNV}}^{\mathrm{ov}} = \frac{1}{[\mathrm{Tr}\,(Y^\dagger Y)]^2}\sum_\alpha\sum_{i<j}\left(M_j^2-M_i^2\right)M_iM_j\mathrm{Im}\left[Y_{\alpha j}Y_{\alpha i}^*\left(Y^\dagger Y\right)_{ij}\right]$$

Connecting to observables

For Inverted Ordering:

Gavela, Hambye, PH, DH

$$Y = \begin{pmatrix} y_e & y'_e e^{i\beta_e} \\ y_\mu & y'_\mu e^{i\beta_\mu} \\ y_\tau & y'_\tau e^{i\beta_\tau} \end{pmatrix}$$

m_ν

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

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

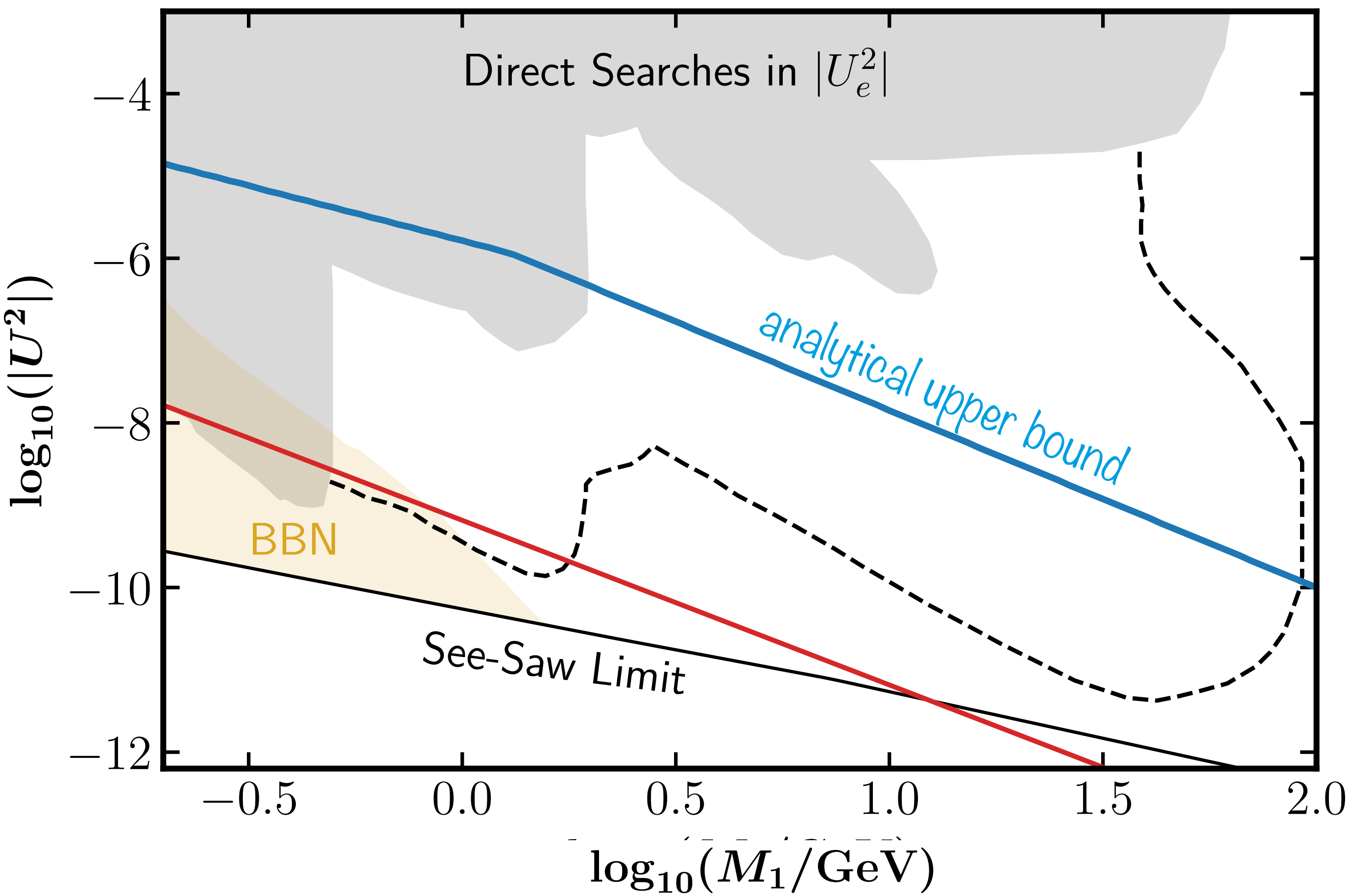
$$\rho = \frac{\sqrt{\Delta m^2_{\rm atm}} - \sqrt{\Delta m^2_{\rm sol}}}{\sqrt{\Delta m^2_{\rm atm}} + \sqrt{\Delta m^2_{\rm sol}}}, \qquad y' = \frac{M}{2v^2 y}\left(\sqrt{\Delta m^2_{\rm atm}} + \sqrt{\Delta m^2_{\rm sol}} \right)$$

$$\frac{\Delta^{\rm ov}_{\rm LNC}}{M_2^2 - M_1^2} \approx \frac{v^2\sqrt{\Delta m^2_{\rm atm}}}{8M^3U^4} \frac{(1 + 3c_\phi \sin 2\theta_{12})\,(c_\theta s_\phi \sin 2\theta_{12} + s_\theta \cos 2\theta_{12})}{-1 + c_\phi^2 \sin^2 2\theta_{12}}$$

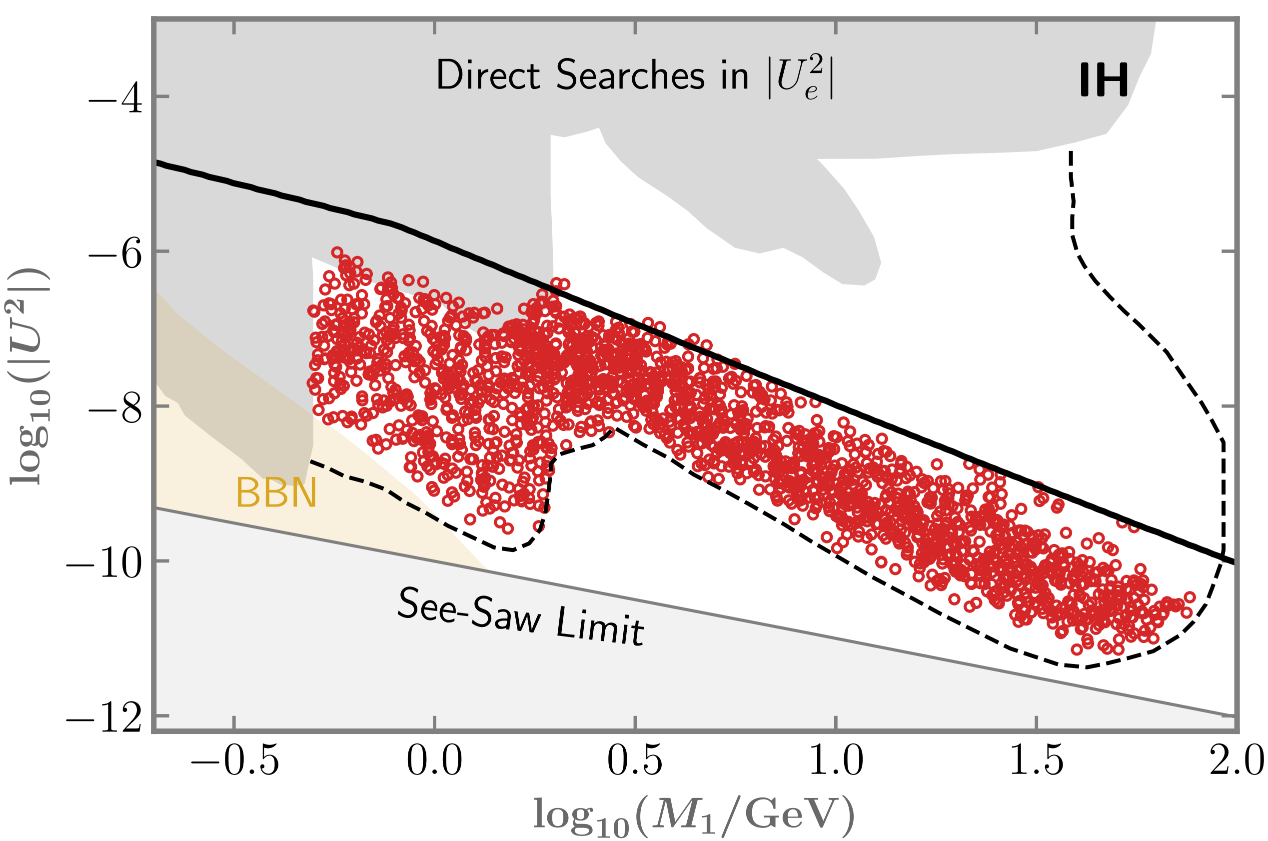
$$\frac{\Delta^{\rm ov}_{\rm LNV}}{M_1 M_2 (M_2^2 - M_1^2)} \approx -\frac{\sqrt{\Delta m^2_{\rm atm}}}{8MU^2} r^2 s_\theta$$

Depend on M, U, θ not accessible at low energies, and the PMNS Majorana phase ϕ

Upper bound on the HNL mixing



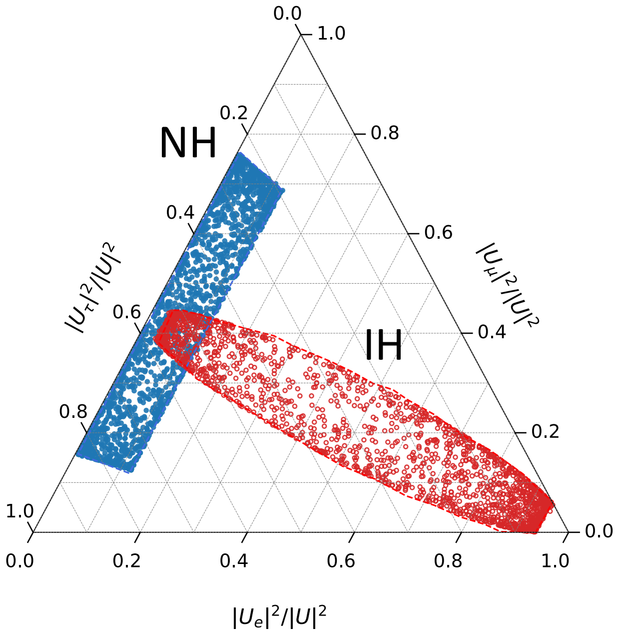
Upper bound on the HNL mixing



Numerical scan within the sensitivity region of SHIP and FCCee

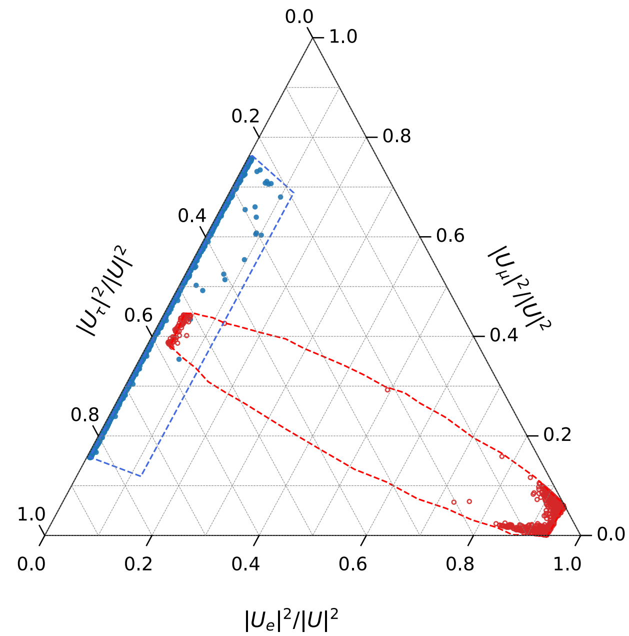
Implications for HNL mixings

In the not-so-degenerate case Y_B constrains significantly flavour ratios because flavour effects are necessary



Constrained by ν masses

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

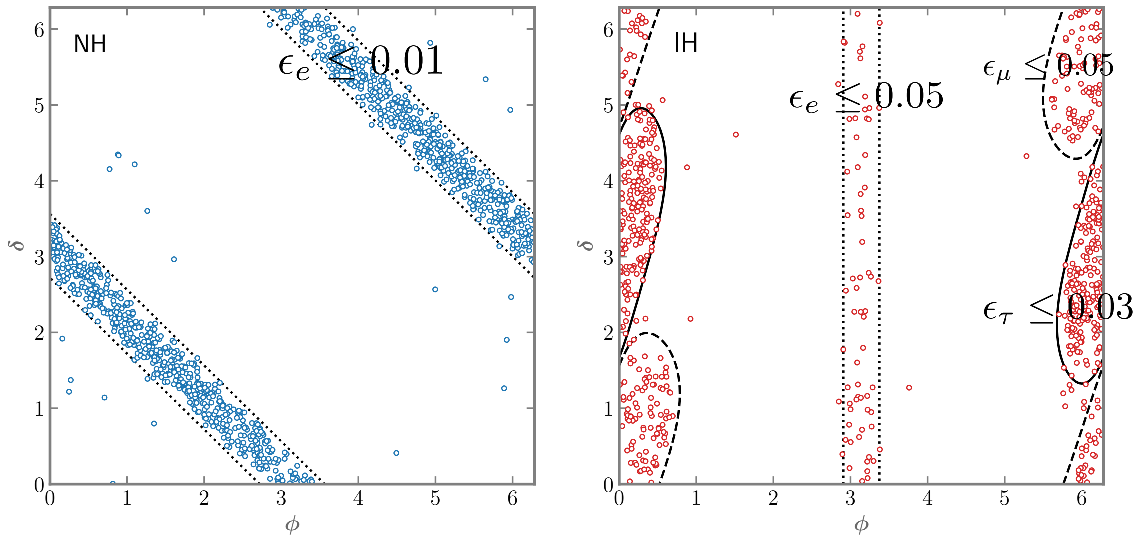


$$+ \ \frac{n_b}{n_\gamma} \sqrt{}$$

Implications for PMNS CP violation

In the not-so-degenerate case strong correlations with U_{PMNS} CP phases because flavour effects are necessary

$$\frac{\Delta M}{M} = 10^{-2} \qquad \frac{n_b}{n_\gamma} \checkmark$$



CP violation in ν oscillations

Majorana phase

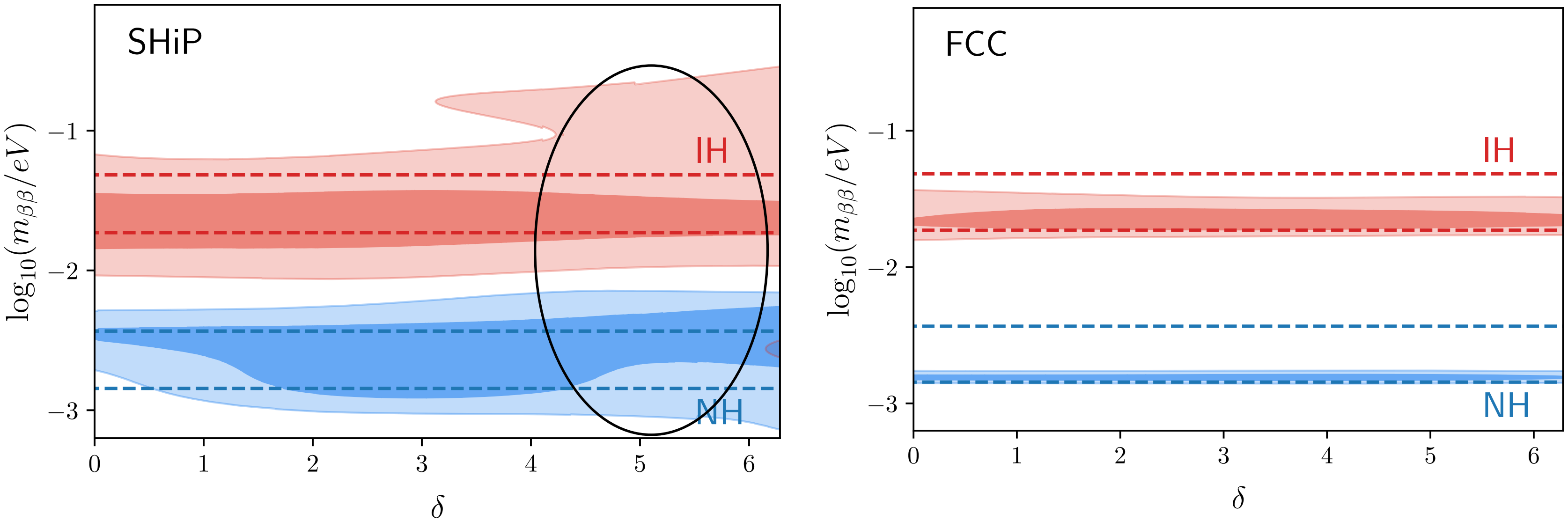
δ+ϕ in ββ0ν

Implications for ββ0ν

$$m_{\beta\beta} = \left| \sum_{i=\text{light}} U_{ei}^2 m_i + \sum_{I=\text{heavy}} \Theta_{eI}^2 M_I \mathcal{M}(M_I)/\mathcal{M}(0) \right|$$

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

$$\frac{n_b}{n_\gamma} \checkmark$$



- HNL effects on the amplitude within SHIP: no trivial dependence on phases
- Flavour effects needed for Y_B constrain the light contribution within FCC

Conclusions

- Neutrino mass models robustly predict a matter-antimatter asymmetry even at accesible scales

- Searches for the neutrino mass mediators (HNLs) could provide essential info about CP violation, the non-thermal condition and Y_B

- We have identified the CP invariants involved in low-scale leptogenesis

- CP invariants allow connecting Y_B to other observables: neutrino masses, CP violation in neutrino oscillations, $\beta\beta 0\nu$ and HNL masses and mixings

- Methods developed can be applied to more complex scenarios: understanding how Y_B constrains the more complex parameter space