Bounds on Right-Handed Neutrino Parameters from Observable Leptogenesis

Based on [2207.01651]

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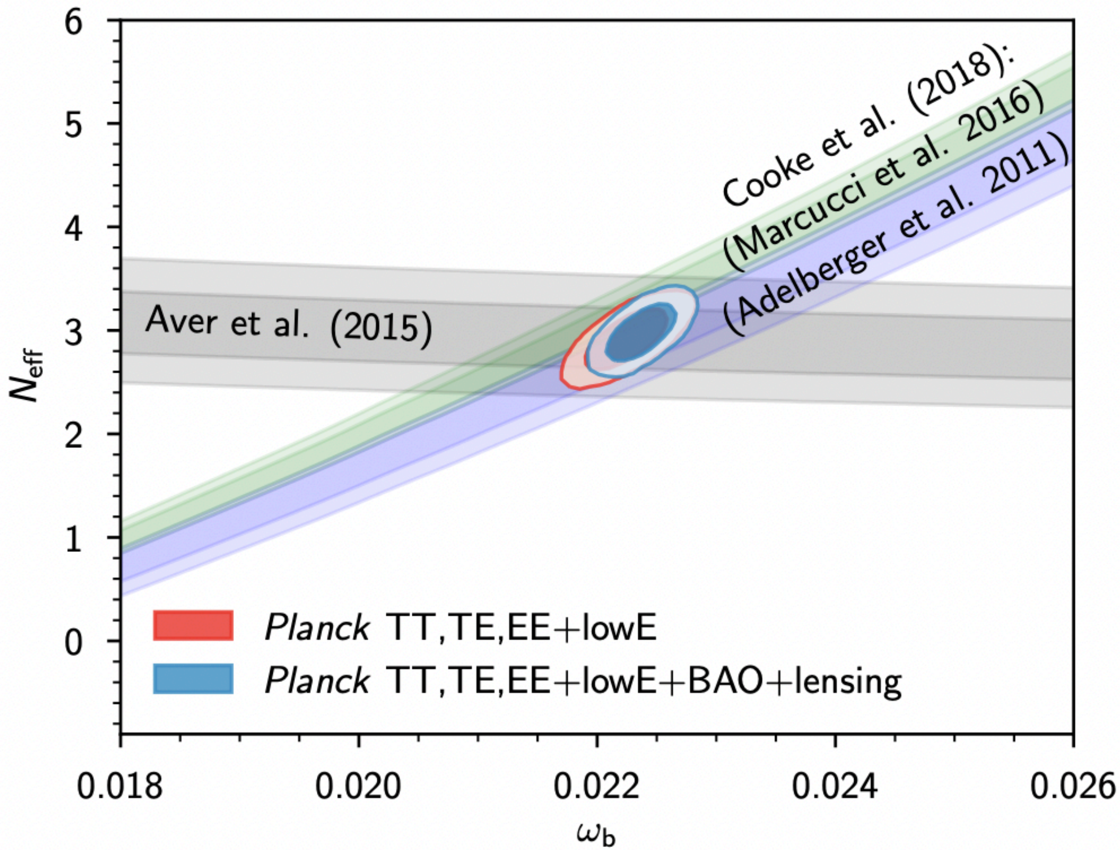
Prerequisite 1 - baryon asymmetry

Baryon asymmetry

Quantified via baryon to entropy density: $Y_B \equiv n_B/s = \frac{6.95 \times 10^{-9}}{2 + 0.8375 \times N_{eff}^{3/4}} \omega_b$

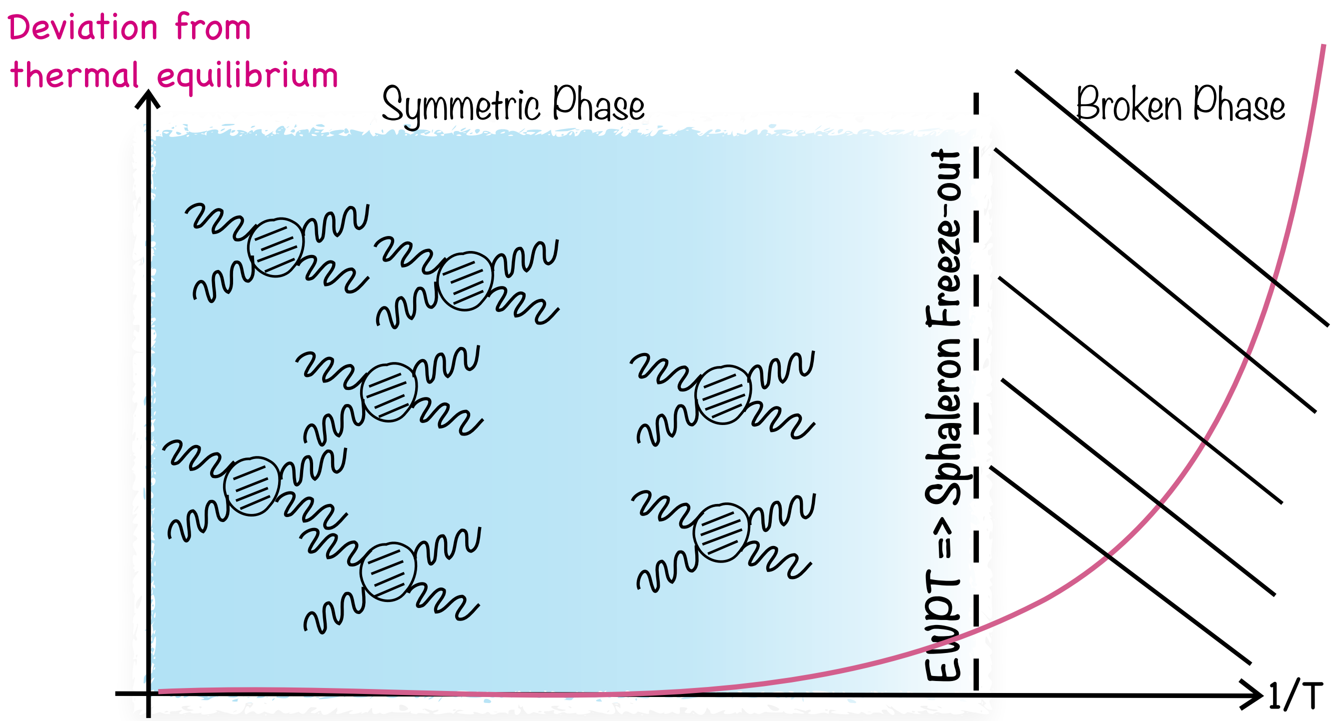


Every (dynamical) model needs to explain $Y_B|_{\text{today}} = (8.66 \pm 0.01) \times 10^{-11}$

Baryon asymmetry

Dynamical creation is fundamentally constrained => **Sakharov Conditions**

* Baryon number violation
* C & CP violation
* Deviation from thermal equilibrium



Sakharov '67

Prerequisite II - neutrino masses

Neutrino masses

heavy neutral leptons

light active neutrino

The possible Majorana nature of the neutrinos leads to the **<u>See-Saw</u>** framework!

We will focus on the minimal scenario with 2 heavy neutral leptons (HNLs)

Large mixings (U^2) between active neutrinos and HNLs are achieved via an **<u>approximate lepton number</u>** symmetry

$$Y = (\underline{y}, \underline{0}) + (\underline{0}, \underline{y'})$$

$$M = \begin{pmatrix} 0 & \Lambda \\ \Lambda & 0 \end{pmatrix} + \mathrm{diag}(\mu)$$

$$y' \ll y, \;\; \mu \ll \Lambda$$

$$\boxed{U^2 \simeq y^2 \frac{v^2}{M^2}}$$

$$m_\nu = f(y'/y, \mu/\Lambda)$$

$$\Delta M = 2\mu$$

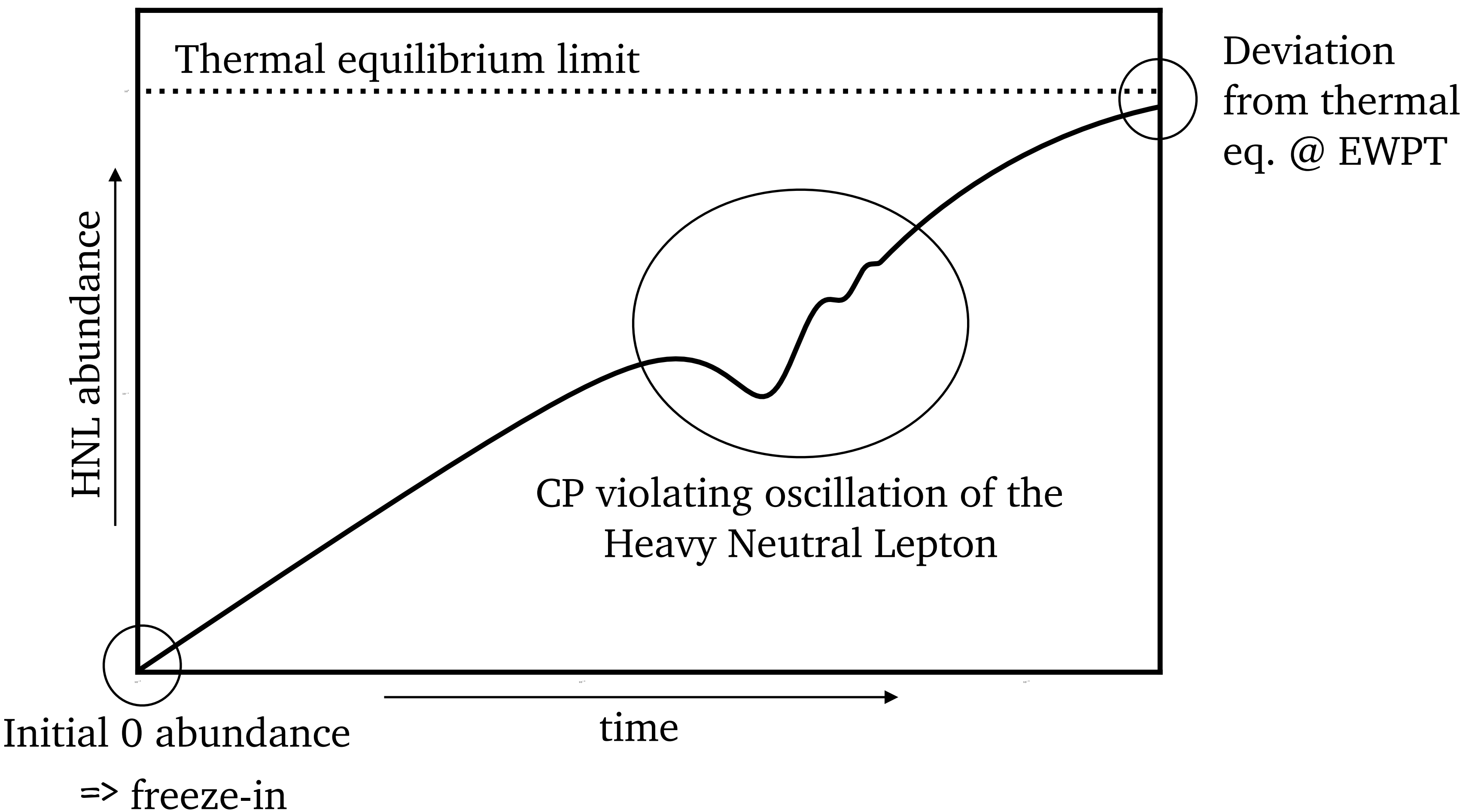
Minkowski ’77; Yanagida ’79; Wyler, Wolfenstein ’83; Mohapatra, Valle ’86; …

Leptogenesis

Baryon asymmetry

Neutrino masses

Leptogenesis via oscillations



Akmedov, Rubakov, Smirnov ’98; Asaka, Shaposhnikov ‘05

Leptogenesis via oscillations

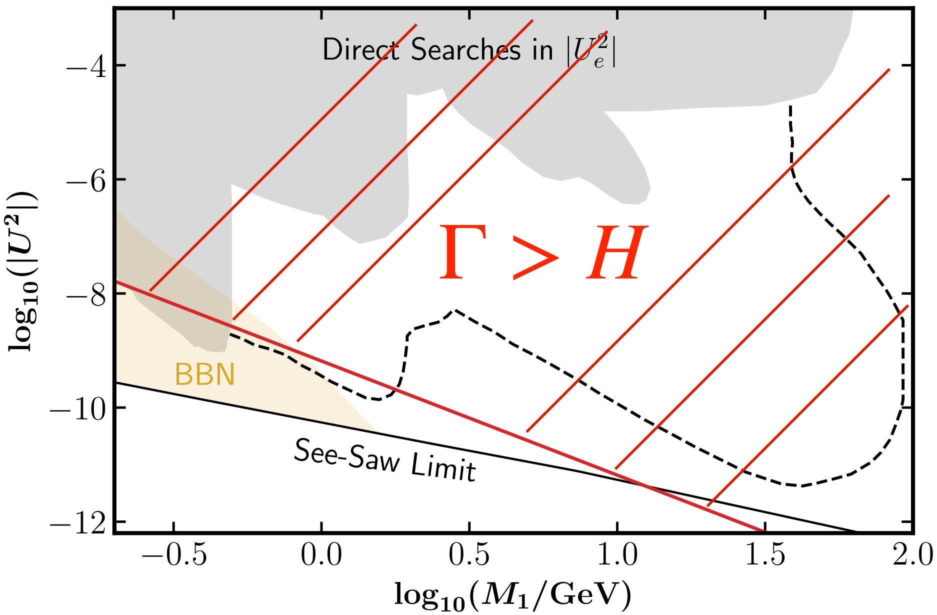
Quantification of the asymmetry via quantum Boltzmann equation

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

Quantum density matrix

CP violating oscillations $H \propto \Delta M_{ij}^2 / k_0$

Thermalization efficiency $\Gamma^{a,p} \propto YY^\dagger T$



Estimated equilibration rate at EWPT

$$\Gamma \propto U^2 \frac{M^2}{v^2} T_{EW} \lesssim H = T_{EW}^2 / M_p^*$$

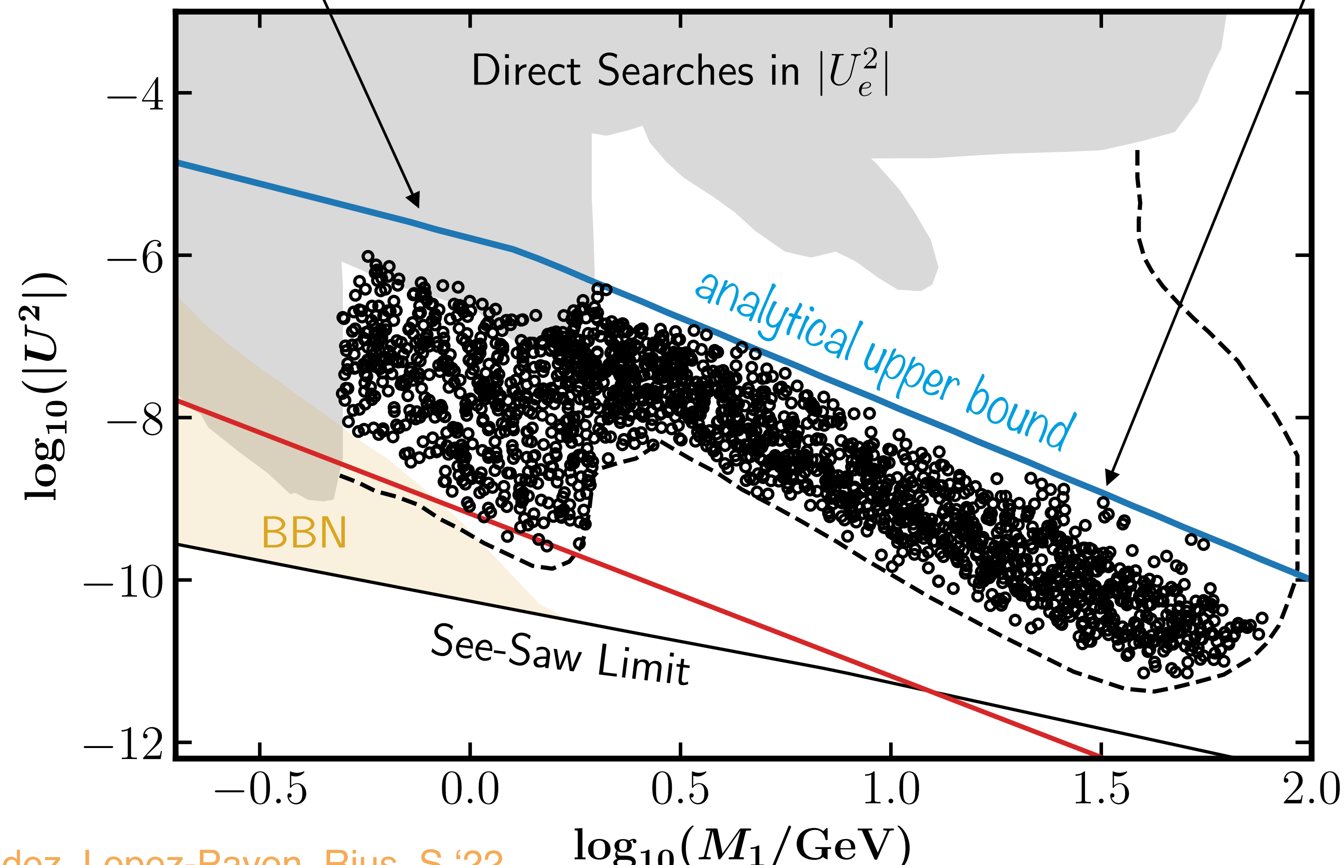
Damped oscillations

If oscillations are damped $\Gamma^{slow}_{osc} \simeq P_{osc}\Gamma \lesssim H$ is realizable until EWPT

Adiabatic perturbation around $\Gamma_{osc}/\Gamma \ll 1$ leads to **analytical upper bound**

$Y_B \propto M^{-3}(U^2)^{-2}\Delta^2_{12}\bar{f}(U_{\rm PMNS},\theta)$

$Y_B \propto M^{-17/3}(U^2)^{-8/3}\Delta^2_{12}\tilde{f}(U_{PMNS},\theta)$



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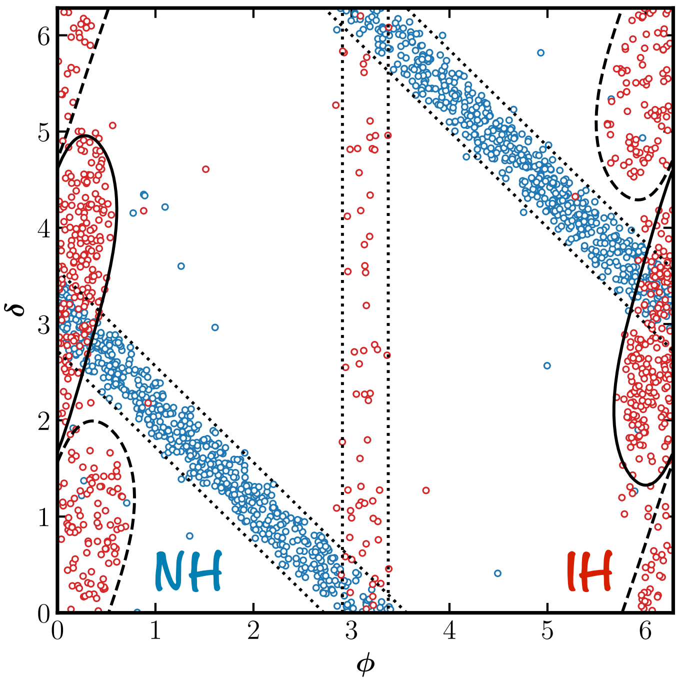
Fast oscillations

If $\Gamma_{osc}/\Gamma \gg 1$ the analytic solution can predict the PMNS phases, flavour mixing and implications on neutrinoless double beta decay

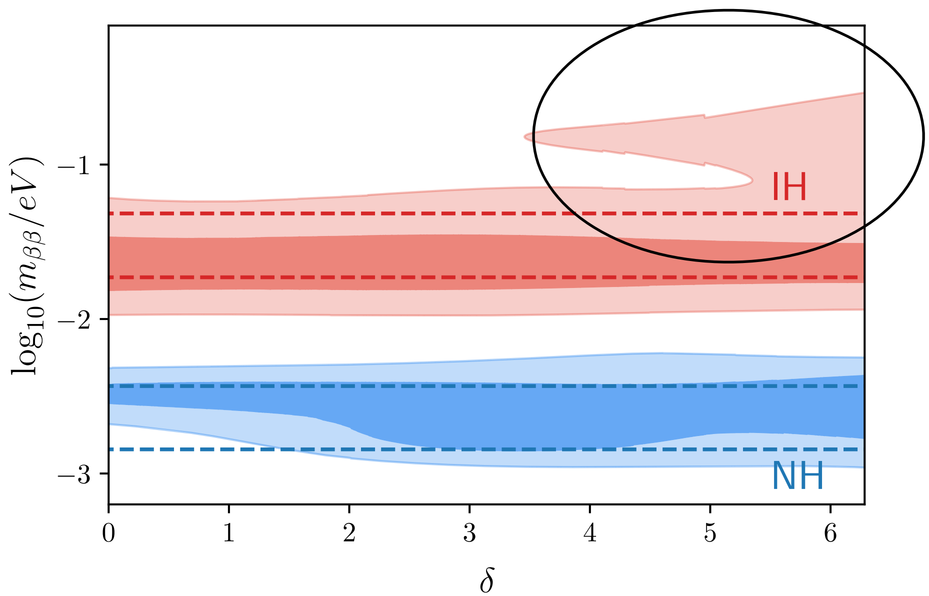
Flavour selection

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



$m_{\beta\beta}$ **enhancement**

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



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Conclusions and Outlook

- Developed analytical approximation reveals correlation of Leptogenesis with other observables

Upper bound on the right-handed neutrino interaction with the SM content!

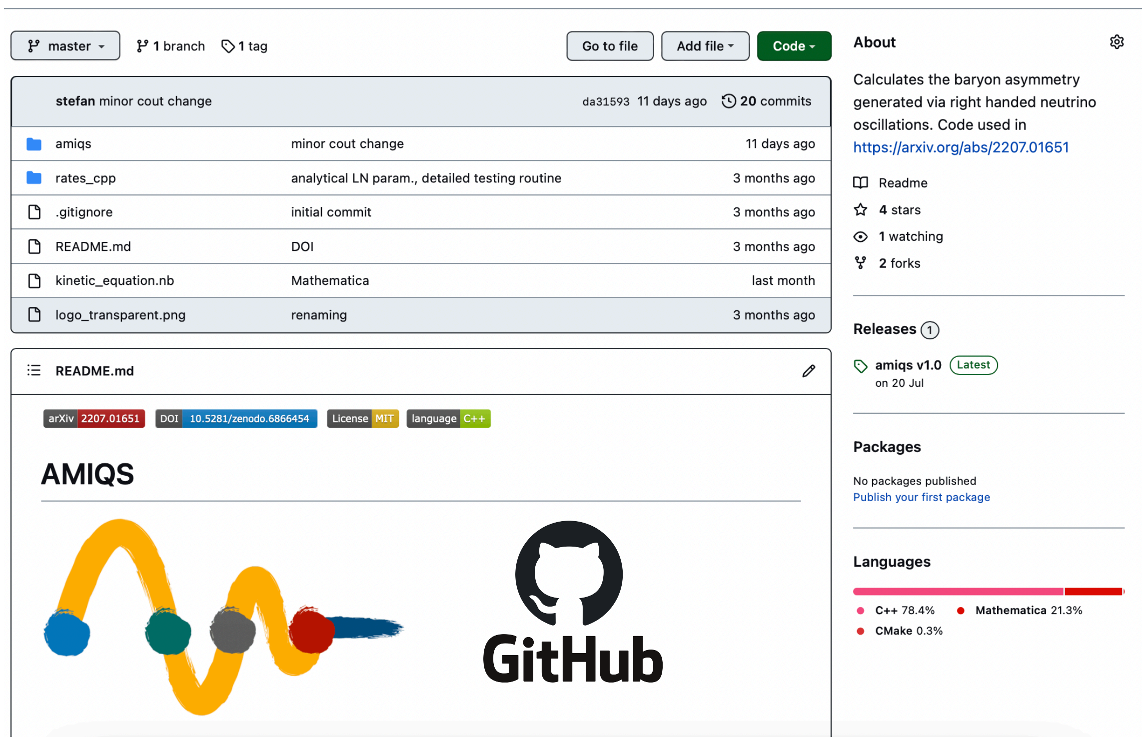
Right-handed neutrinos with $\Delta M/M \to 1$ need to realize a concrete flavour composition & impact the neutrinoless double-beta decay rate!

- Method developed can help to explore non-minimal scenarios

- Check out [2207.01651] for more details

Bonus

* Numerical code available on GitHub

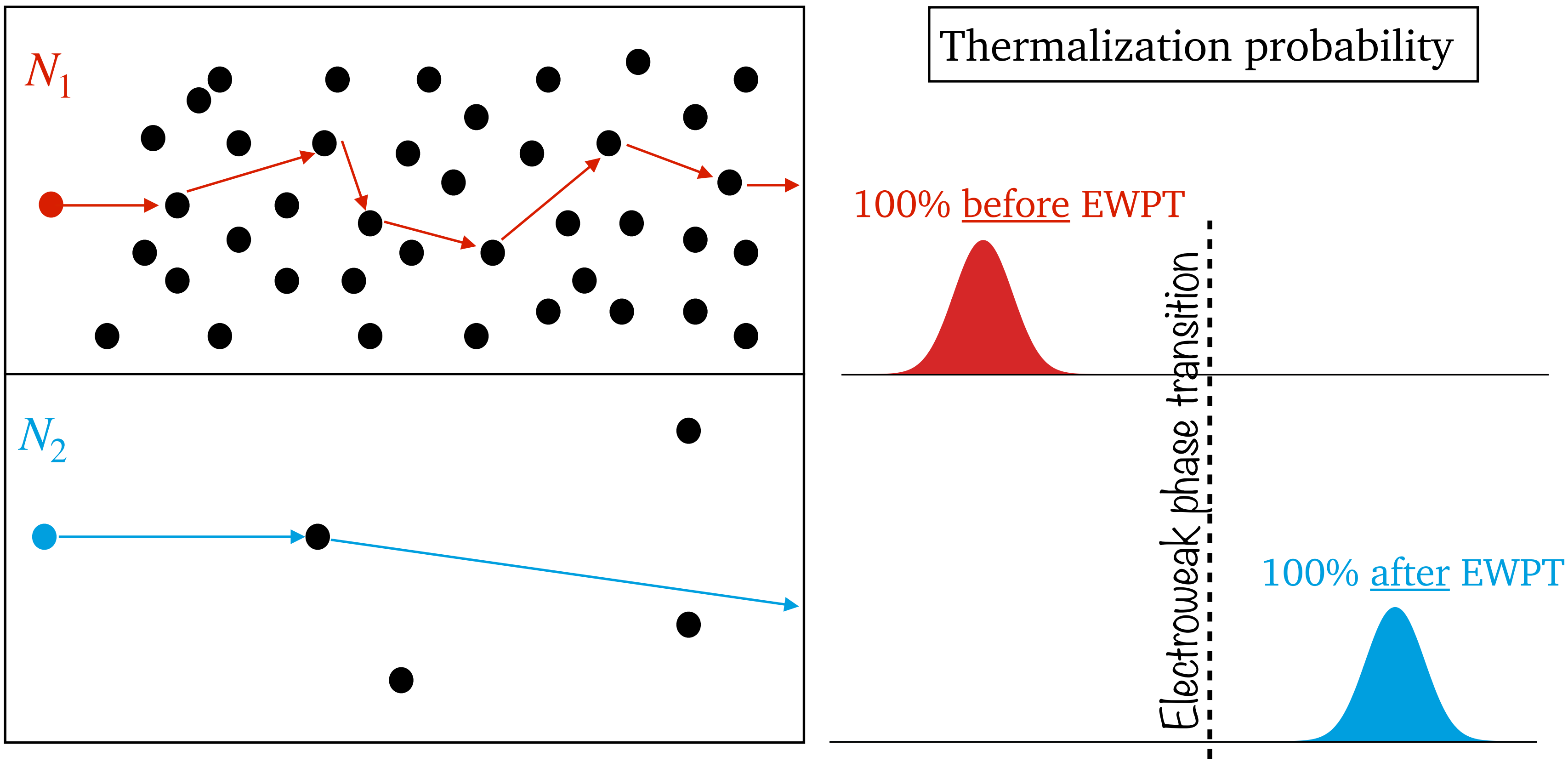


* Check out [2207.01651] for more details

Damped oscillations

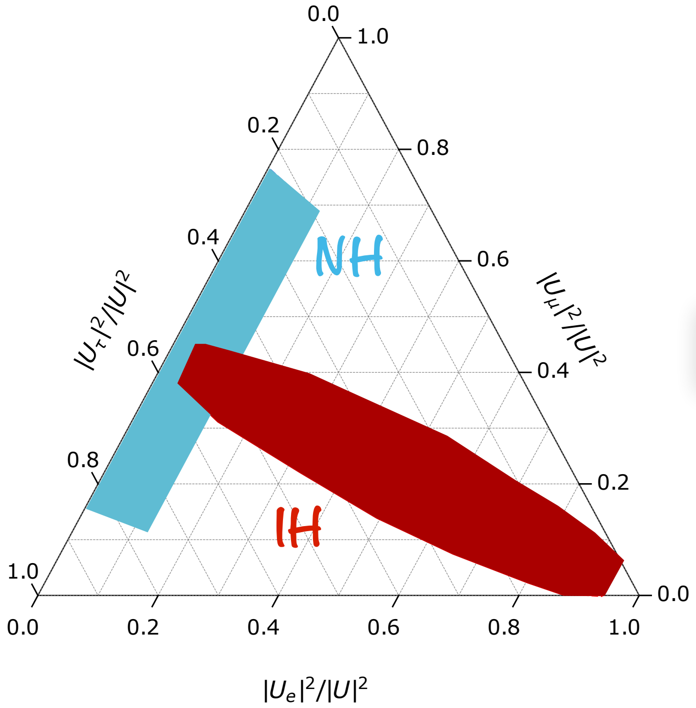
If **oscillations are damped** $\Gamma_{osc}^{slow} \simeq P_{osc}\Gamma \lesssim H$ is realizable until EWPT

Use approximate LN symmetry to ensure: i) $\Delta M \ll M$ & ii) $y' \ll y$

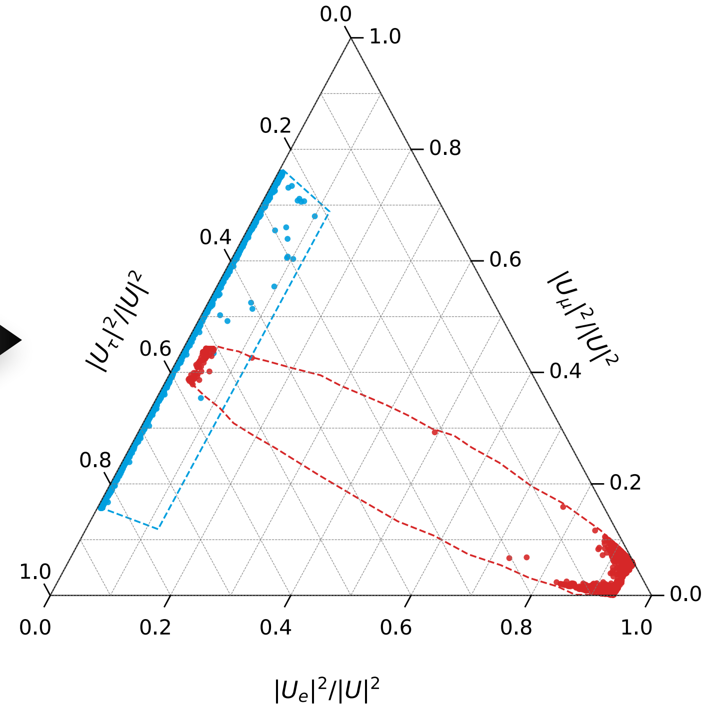


Fast oscillations

Neutrino Oscillation data

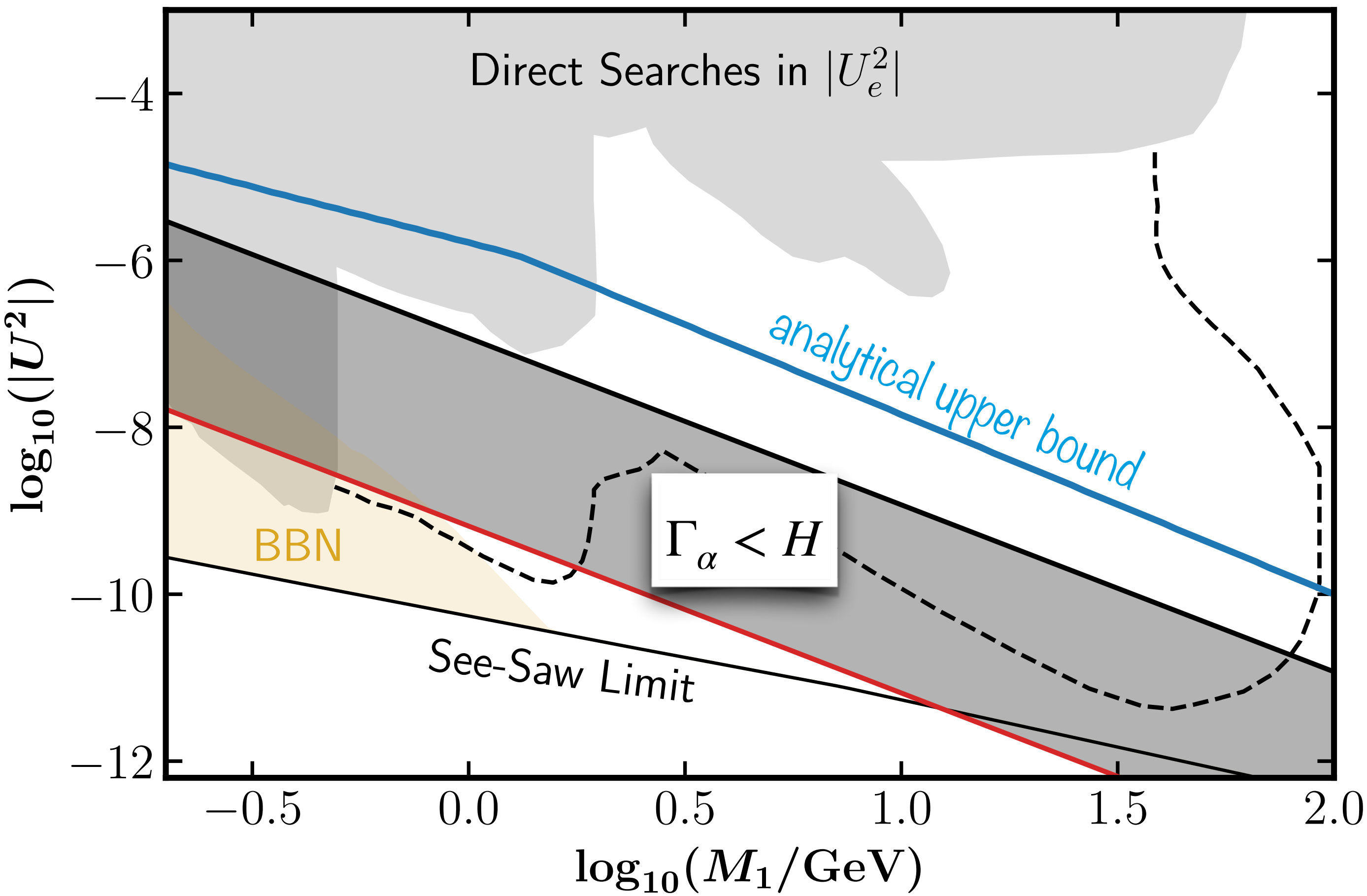


Flavour selection via Leptogenesis
with $\Delta M/M = 10^{-2}$ within FCC



Fast oscillations

One mode can remain weak only via flavour hierarchical interactions



CP Invariants

NORMAL HIERARCHY

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

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

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

$$\frac{\Delta^{\rm int(\tau)}_{\rm LNC}}{M_2^2-M_1^2} = \frac{\Delta^{\rm osc\,(\tau)}_{\rm LNC}}{g(M_1,M_2)} \approx -\frac{\Delta^{\rm int(\mu)}_{\rm LNC}}{M_2^2-M_1^2},$$

$$\frac{\Delta^{\rm ov}_{\rm LNV}}{M_1M_2(M_2^2-M_1^2)} = \frac{v^2}{2U^2M^2}\,\frac{\Delta^{\rm osc}_{\rm LNV}}{g_M(M_1,M_2)} \approx -\frac{\sqrt{\Delta m^2_{\rm atm}}}{4MU^2}s_\theta\,.$$

INVERTED HIERARCHY

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

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

$$\frac{\Delta^{\rm int(\mu)}_{\rm LNC}}{M_2^2-M_1^2} = \frac{\Delta^{\rm osc\,(\mu)}_{\rm LNC}}{g(M_1,M_2)} \approx \frac{\Delta^{\rm int(\tau)}_{\rm LNC}}{M_2^2-M_1^2} = \frac{\Delta^{\rm osc\,(\tau)}_{\rm LNC}}{g(M_1,M_2)} \approx -\frac{1}{2}\,\frac{\Delta^{\rm int(e)}_{\rm LNC}}{M_2^2-M_1^2}\,,$$

$$\frac{\Delta^{\rm ov}_{\rm LNV}}{M_1M_2(M_2^2-M_1^2)} = \frac{v^2}{2U^2M^2}\,\frac{\Delta^{\rm osc}_{\rm LNV}}{g_M(M_1,M_2)} \approx -\frac{\sqrt{\Delta m^2_{\rm atm}}}{8MU^2}r^2 s_\theta\,.$$