Bounds on Right-Handed Neutrino Parameters from Observable Leptogenesis

Based on [2207.01651]

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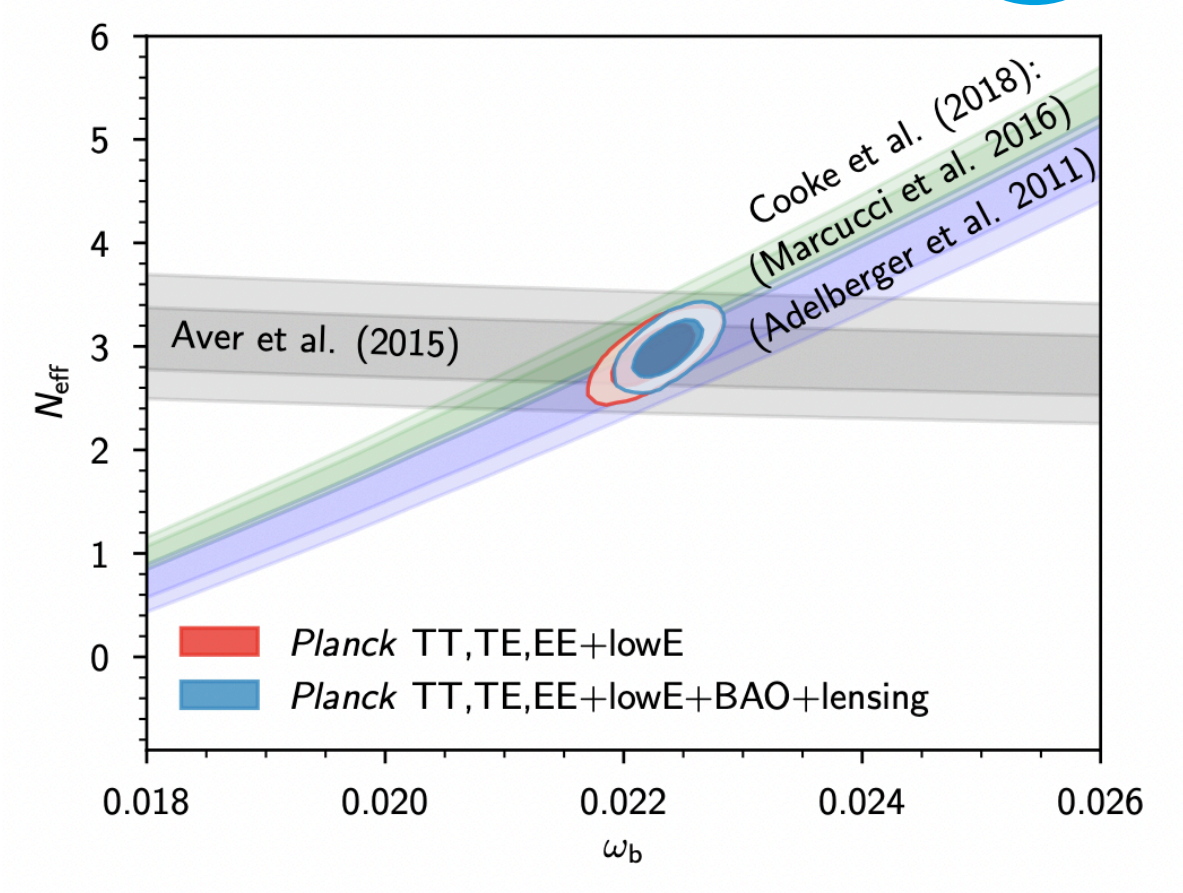
Prerequisite 1 - baryon asymmetry

Prerequisite I

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

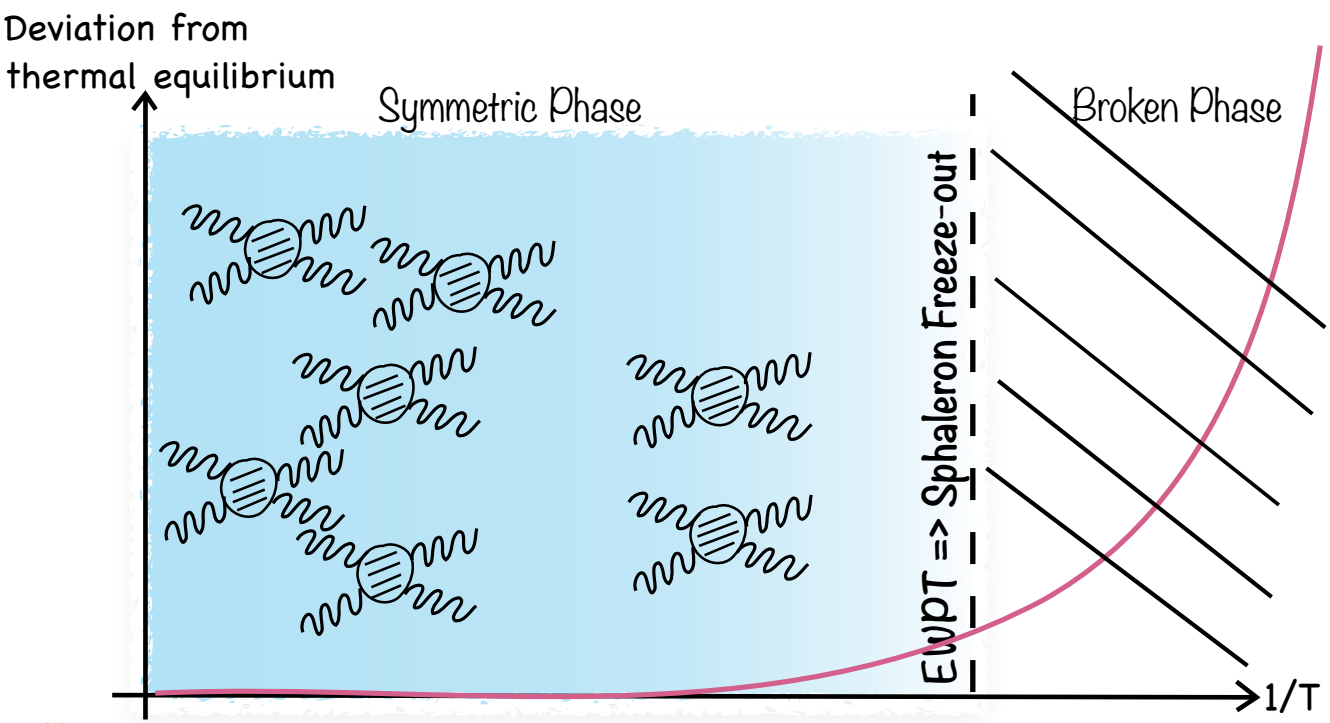


Every (dynamical) model needs to explain $Y_B|_{\rm today} = (8.66 \pm 0.01) \times 10^{-11}$

Prerequisite I

Dynamical creation of the BAU is fundamentally constrained => Sakharov Conditions

* Baryon number violation
* Fundamental distinctness of particle and anti-particle (C & CP violation)
* Time window in which dynamics falls out of equilibrium

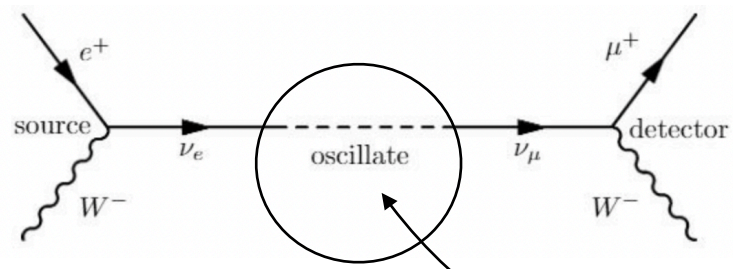


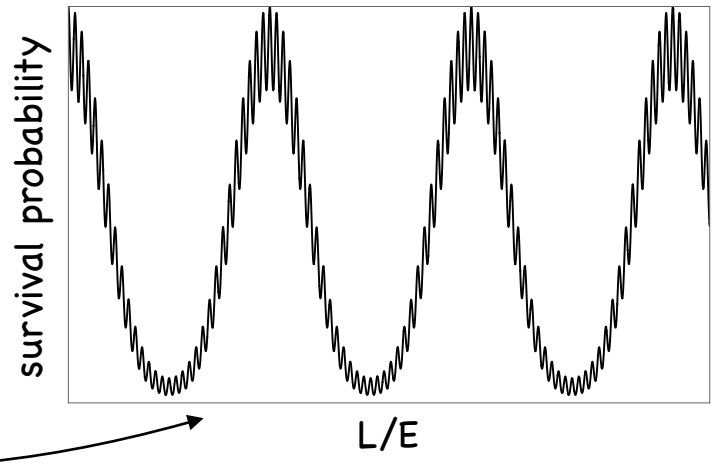
Sakharov '67

Prerequisite II - neutrino masses

Prerequisite II

Observed left-handed neutrino oscillations imply that they are massive.

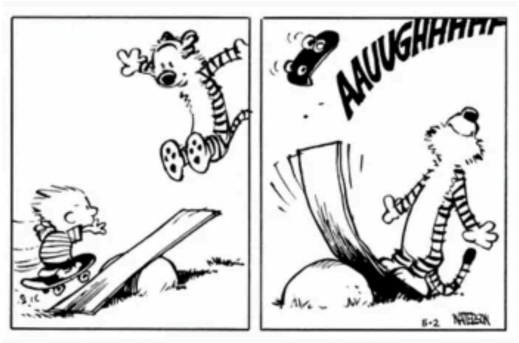




The possible Majorana nature of the neutrinos introduces the See-Saw framework!

We will focus on the minimal scenario with 2 right-handed neutrinos.

light active neutrino

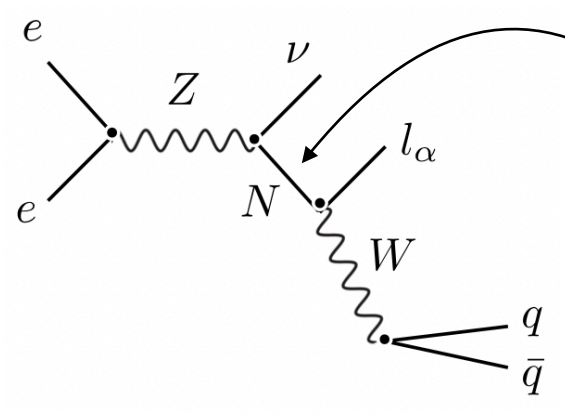


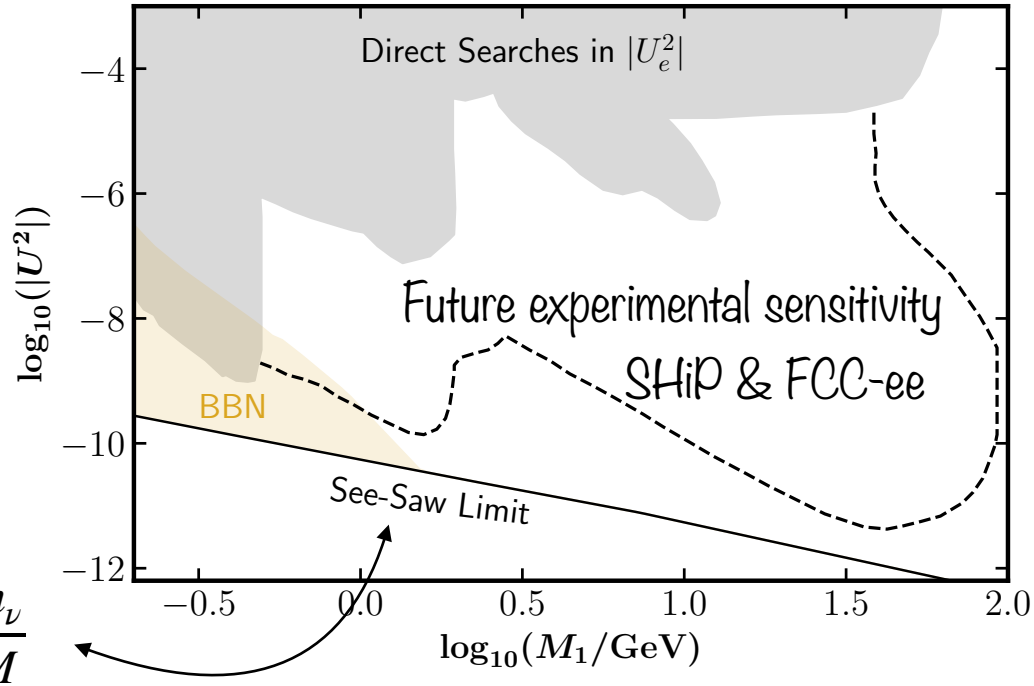
right-handed neutrino

Minkowski '77; Yanagida '79; …

Prerequisite II

Displaced vertex searches





Within naive see-saw scaling $U^2 \sim \frac{m_\nu}{M}$

Larger mixings can be achieved via an approximate Lepton Number symmetry!

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

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

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

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

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

$$\Delta M = 2\mu$$

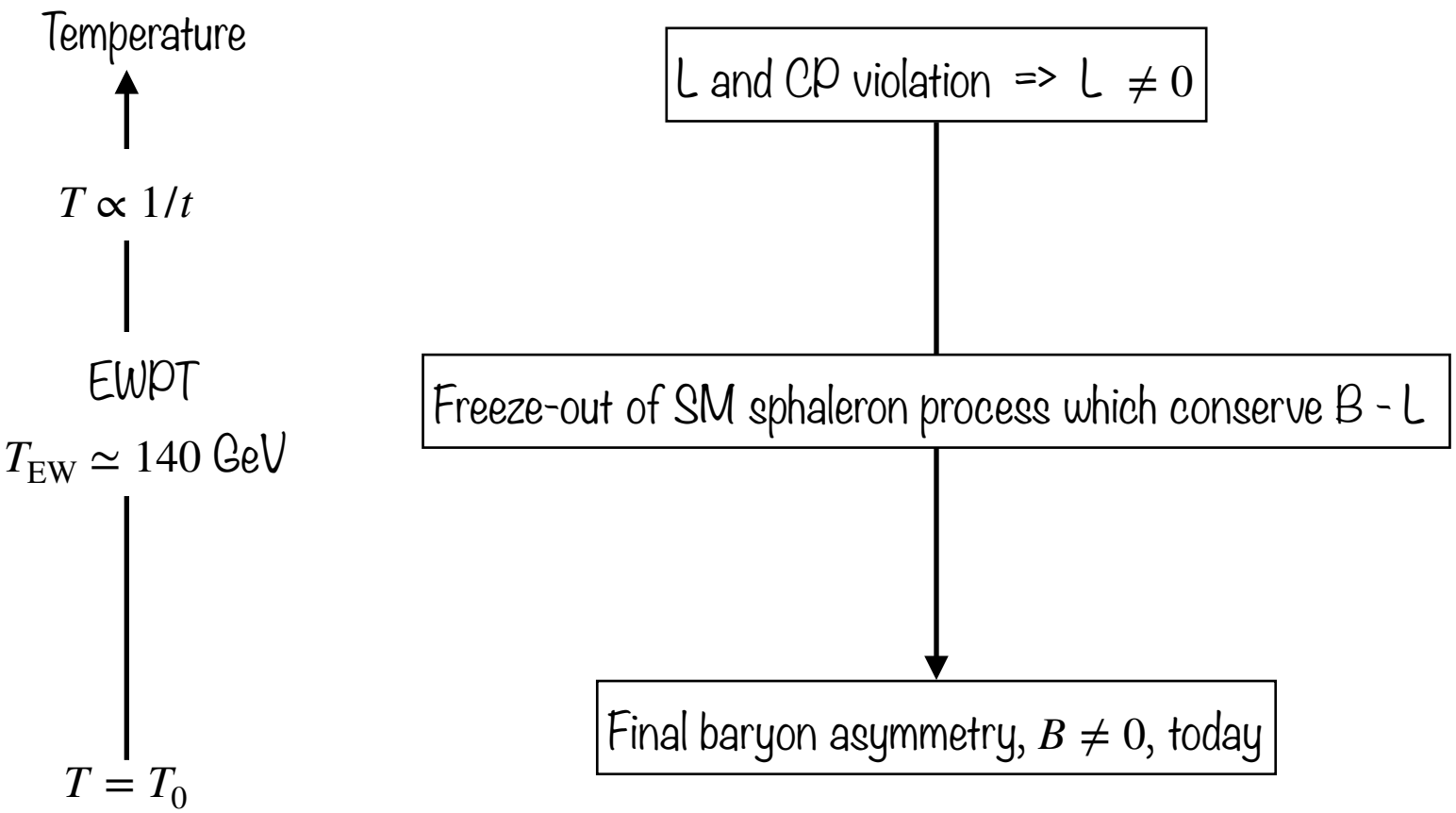
Wyler, Wolfenstein '83; Mohapatra, Valle '86

Leptogenesis

Baryon asymmetry of our Universe

Neutrino masses

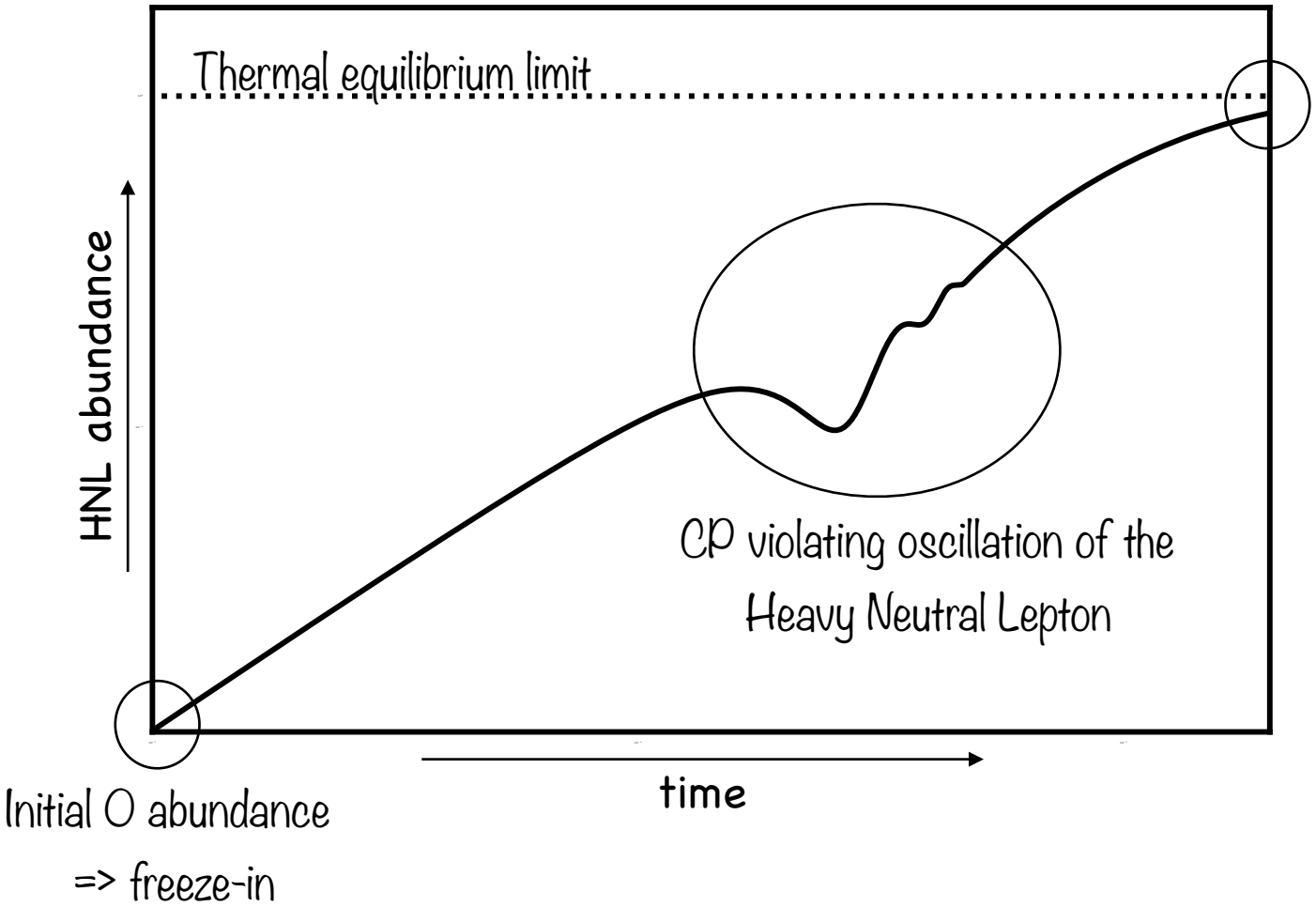
Leptogenesis



* Realization of this idea at testable right-handed neutrino mass scales via oscillations

Fukugida, Yanagida '86

Leptogenesis via oscillations



Deviation from thermal equilibrium at EWPT

Akmedov, Rubakov, Smirnov '98; Asaka, Shaposhnikov '05

Leptogenesis via oscillations

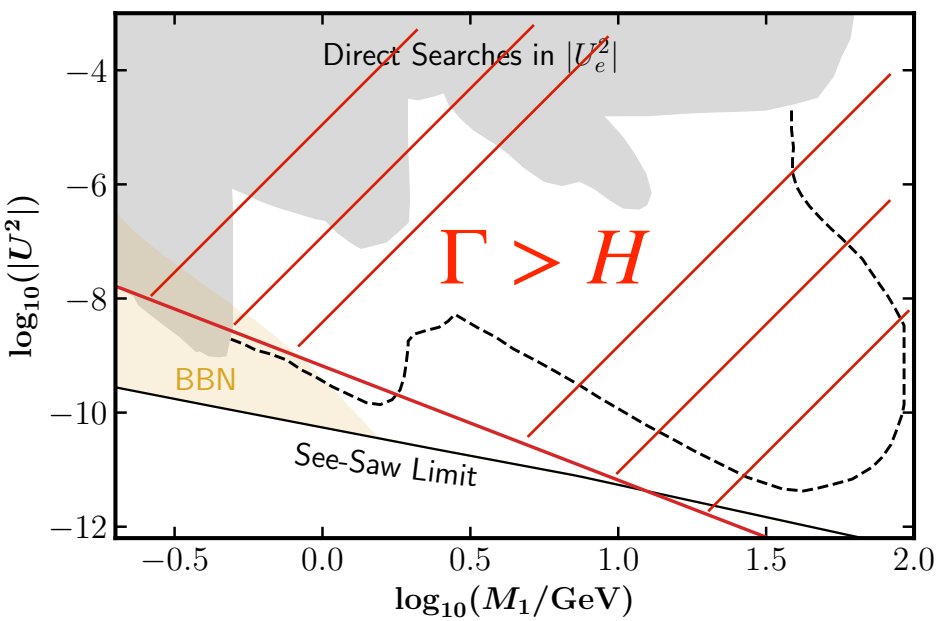
Quantification of the asymmetry via quantum Boltzmann equation

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

Quantum density matrix

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

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



Estimated equilibration rate at EWPT

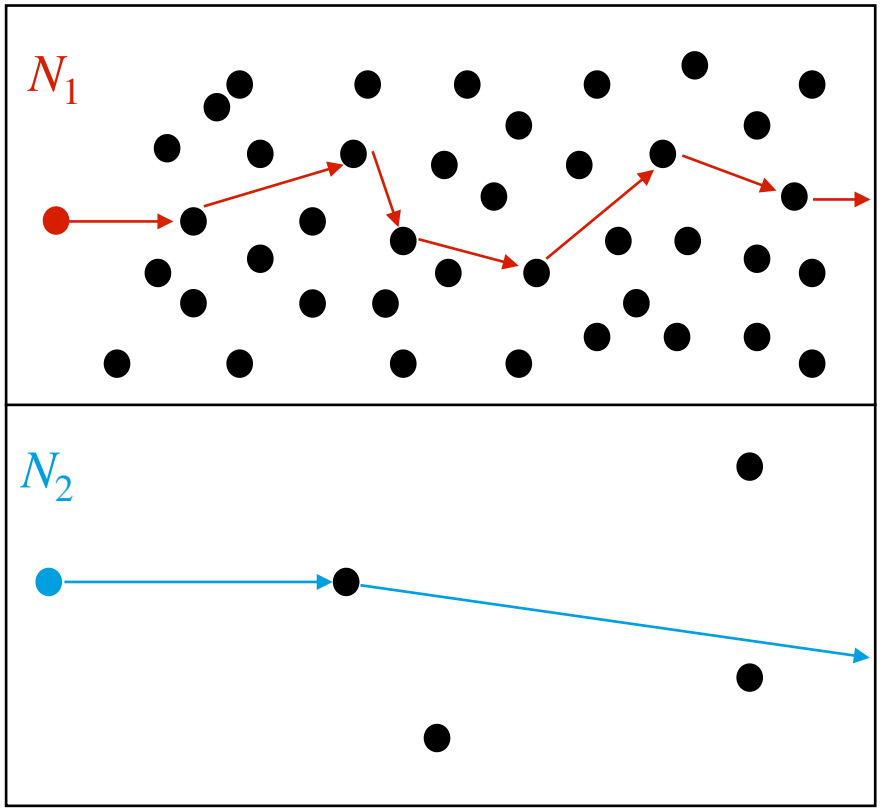
$$\Gamma \propto U^2 \frac{M^2}{v^2} T_{EW} \lesssim H_U = T_{EW}^2/M_p^*$$

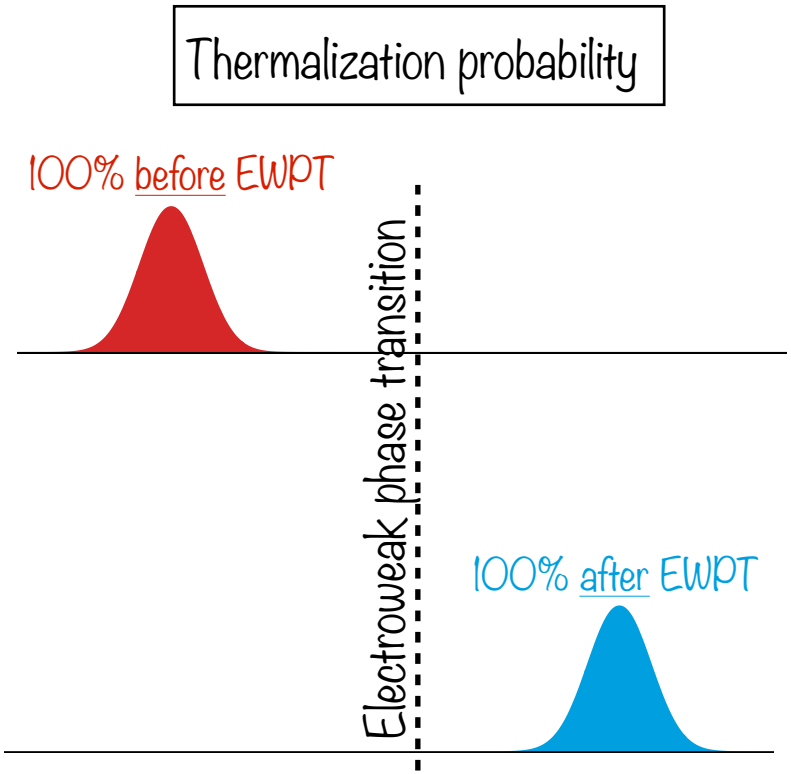
Part I - Damped oscillations

Leptogenesis via oscillations I

If **oscillations are damped** one mode remains weak until EWPT => BAU can be stored

Use approximate Lepton Number symmetry to ensure: i) $\mu \ll \Lambda \leftrightarrow \Delta M \ll M$ & ii) $y' \ll y$

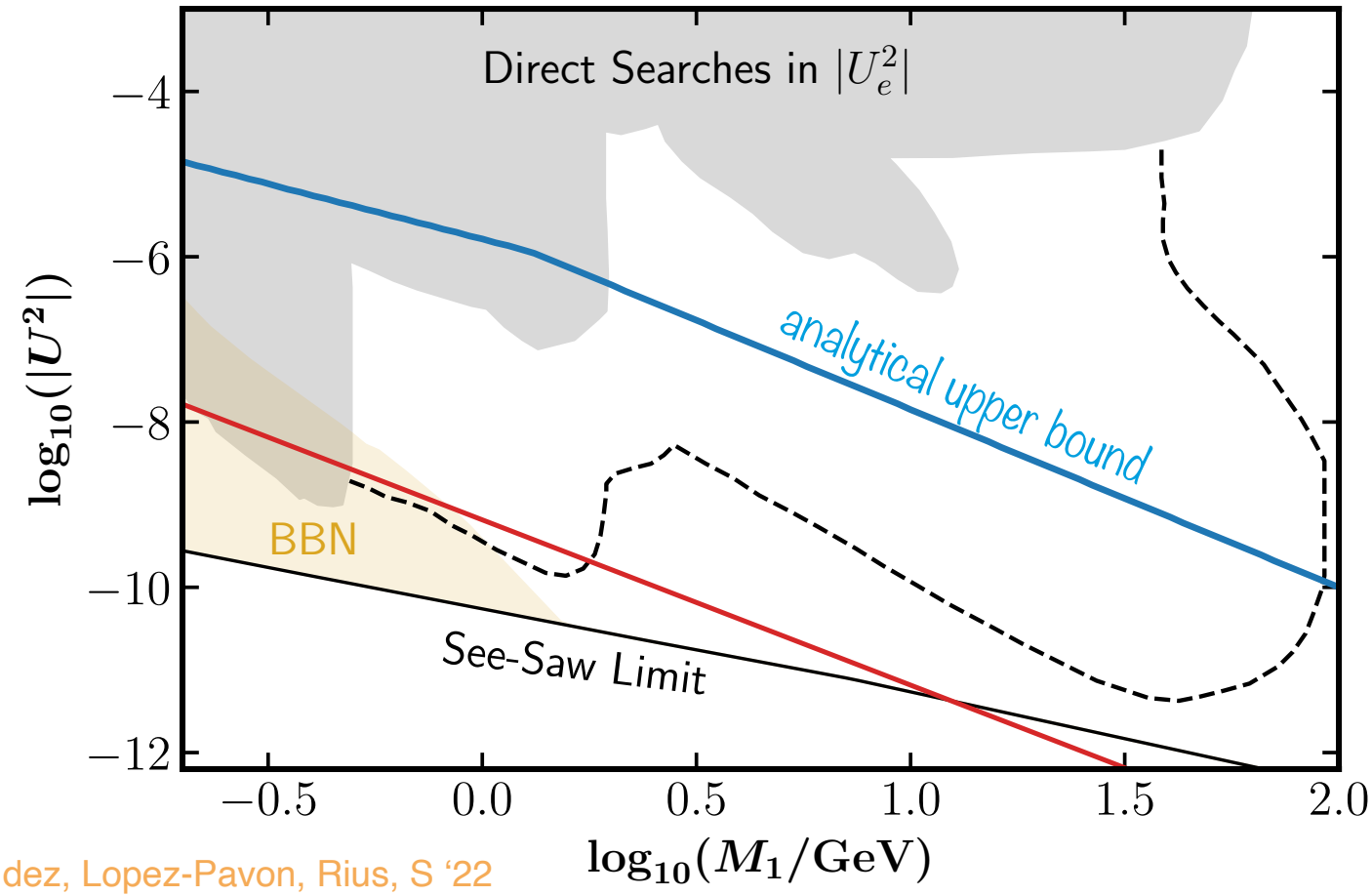




Leptogenesis via oscillations I

Adiabatic perturbation around slow oscillation mode => Analytical solution of BAU

=> Leptogenesis is possible for **mixings far larger than naively expected!**



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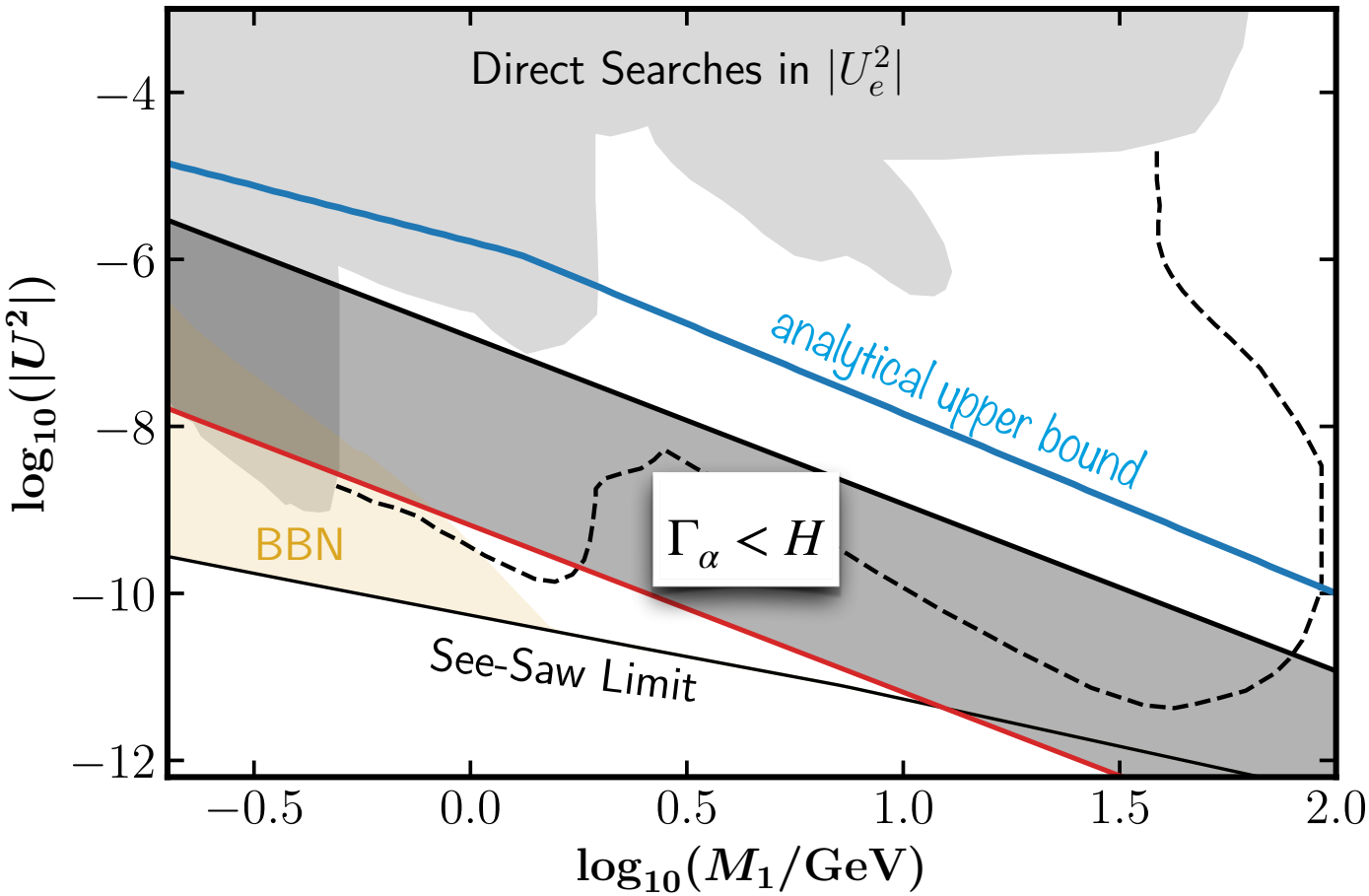
Part II - Fast oscillations

Leptogenesis via oscillations II

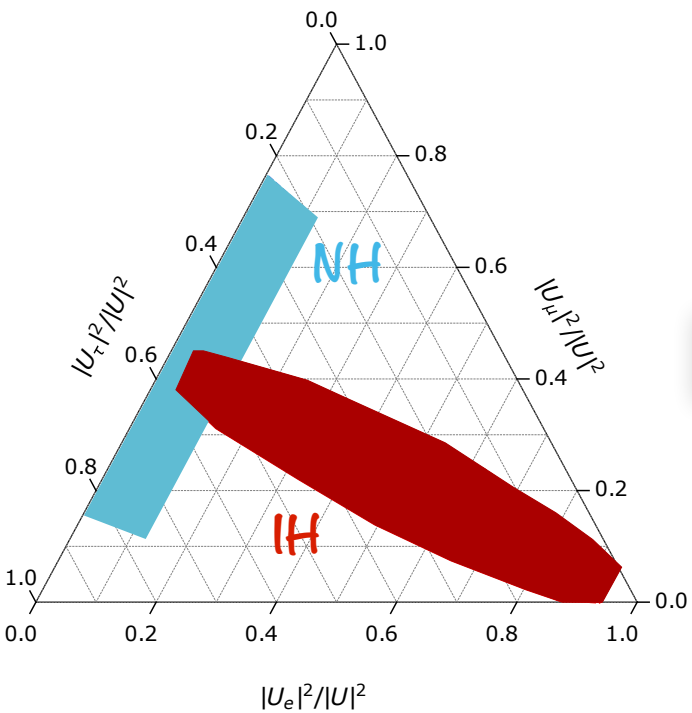
If **oscillations are fast** one mode can remain weak only via flavour hierarchical interactions



Leptogenesis via oscillations II

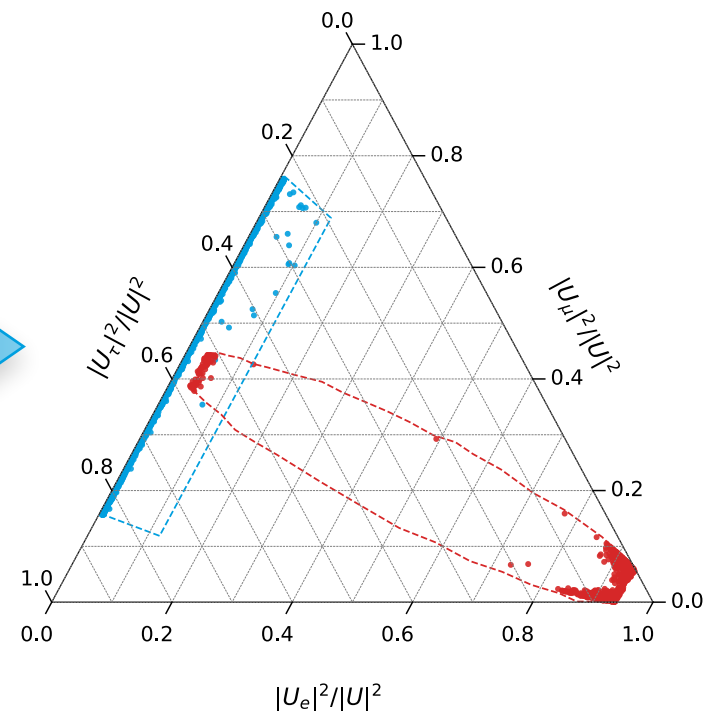
* Leptogenesis can make clear prediction on the PMNS phases & flavour mixing

Neutrino Oscillation data



Flavour selection via Leptogenesis

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



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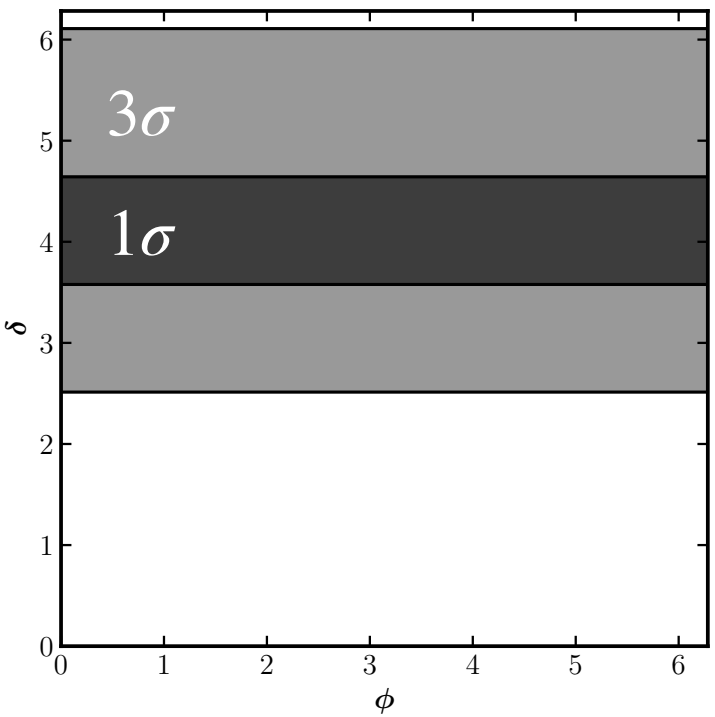

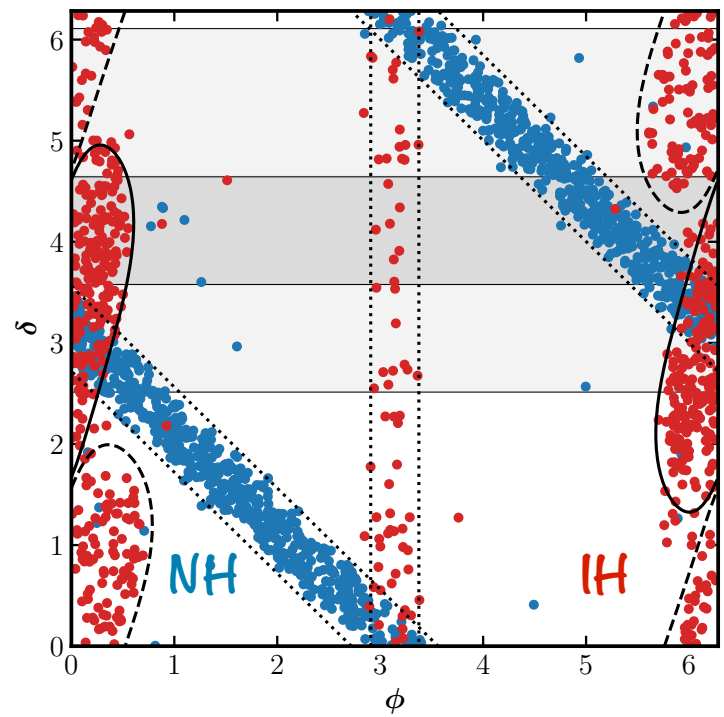

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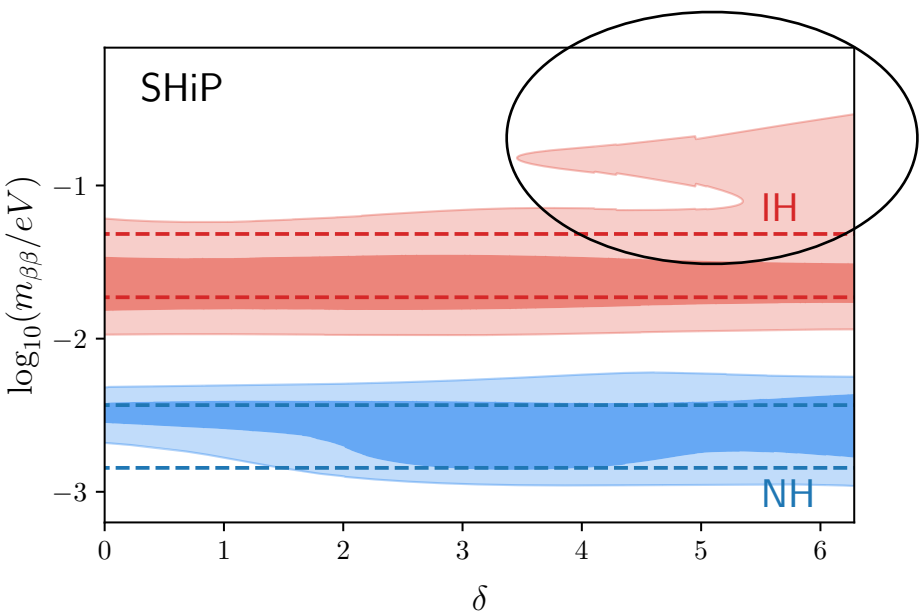
Leptogenesis via oscillations II

- Non-trivial implication on a possible observation of neutrino less double-beta decay!*

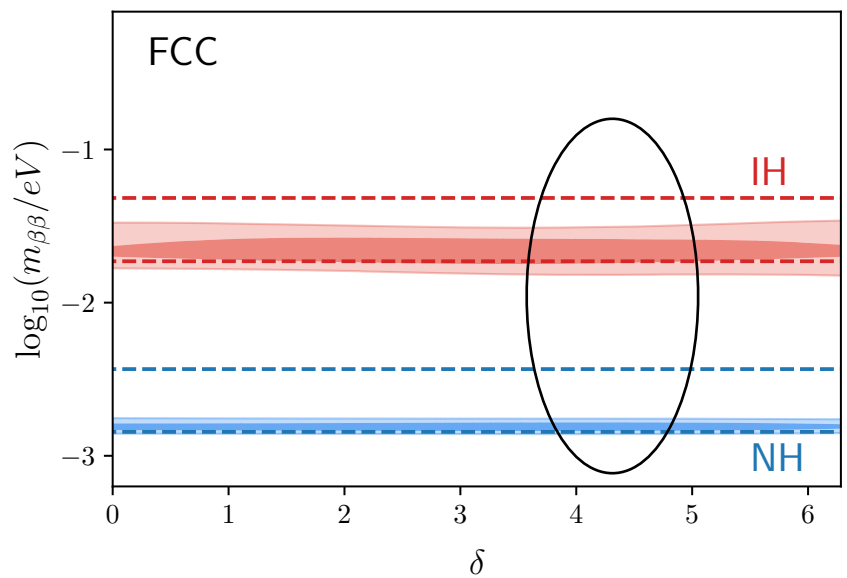
*Prediction dependent on the results of ongoing nuclear matrix element research

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

Significant **enhancement** of expected standard signal



Significant **restriction** of expected standard signal



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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 strength 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, e.g. 3 right-handed neutrinos

* Exact characterisation of the parameter-space volume, derivation of fundamental CP basis invariants, full numerical Bayesian analysis, implication of direct lepton number violating rates,... and for much more see [2207.01651]