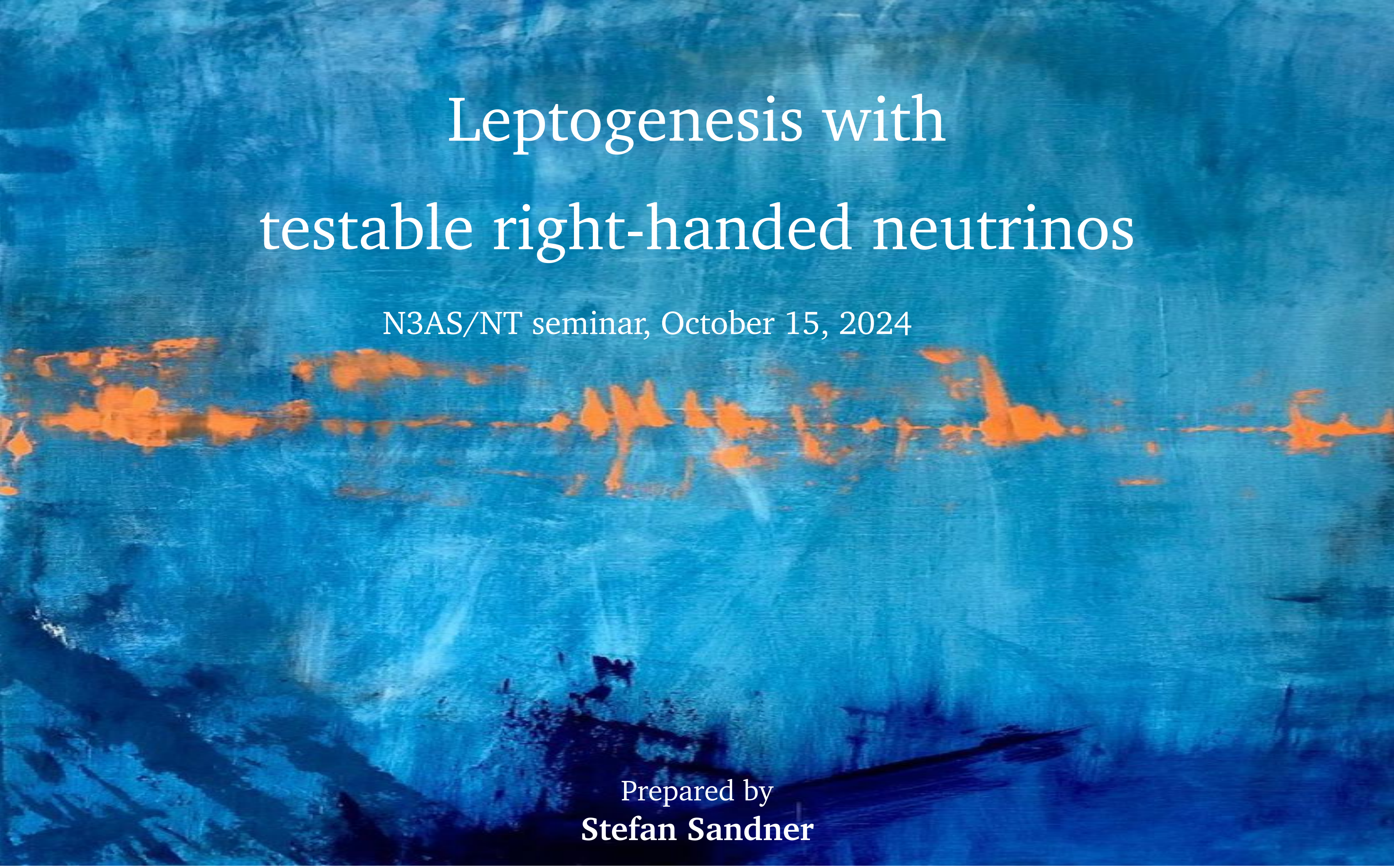

Leptogenesis with testable right-handed neutrinos

N3AS/NT seminar, October 15, 2024

Prepared by
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Outline

I. Baryon asymmetry

- Sakharov conditions
- Leptogenesis

II. Testing leptogenesis

- Correlations between the baryon asymmetry and other observables

New results

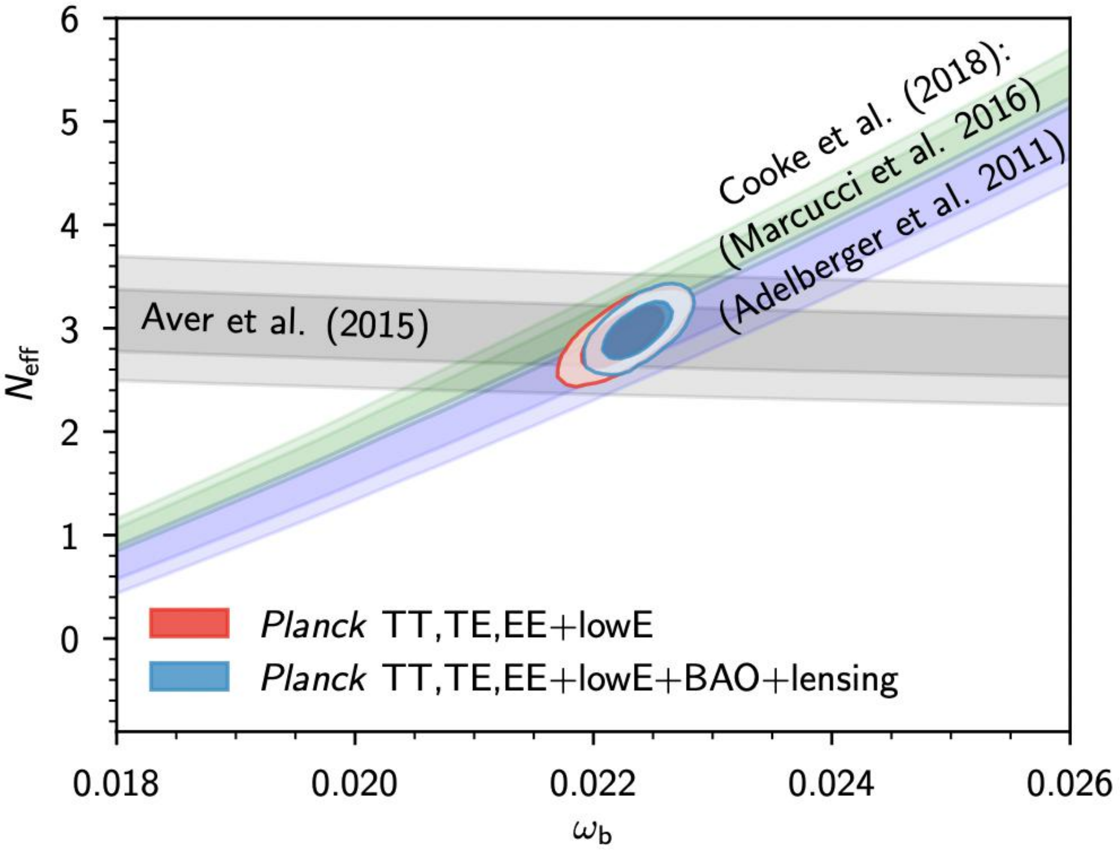
Based on References: arXiv 2207.01651 and arXiv 2305.14427

In collaboration with: Pilar Hernández, Jacobo López-Pavón and Nuria Rius

Part I: Baryon asymmetry

Baryon asymmetry

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

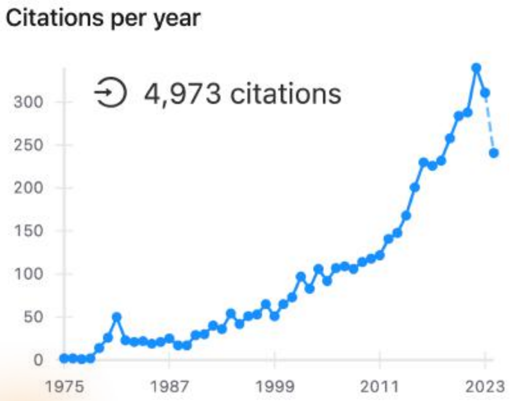


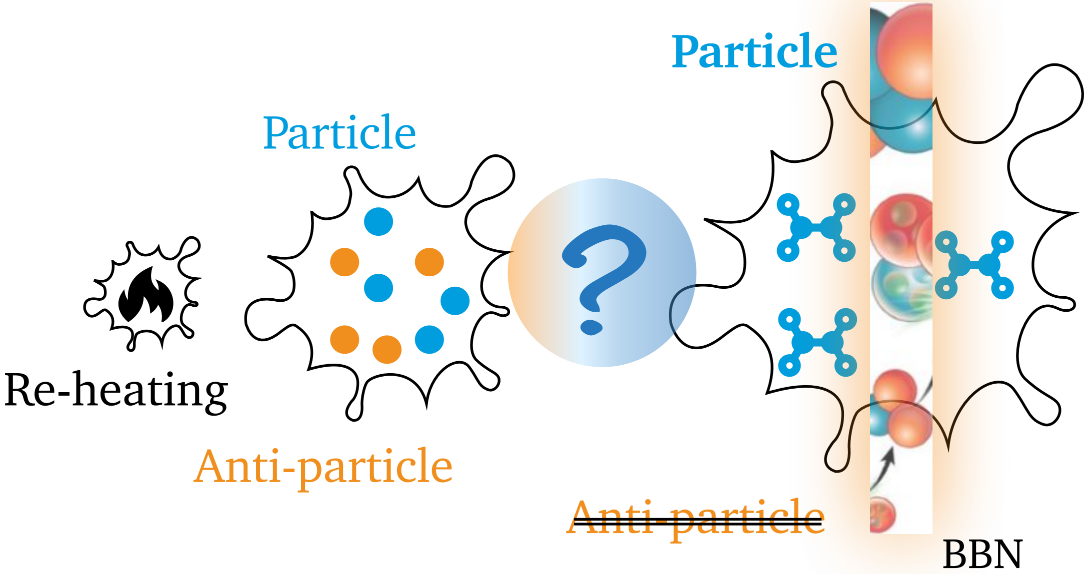
Every (dynamical) model needs to explain $\boxed{Y_B|_{\text{today}} = (8.66 \pm 0.01) \times 10^{-11}}$

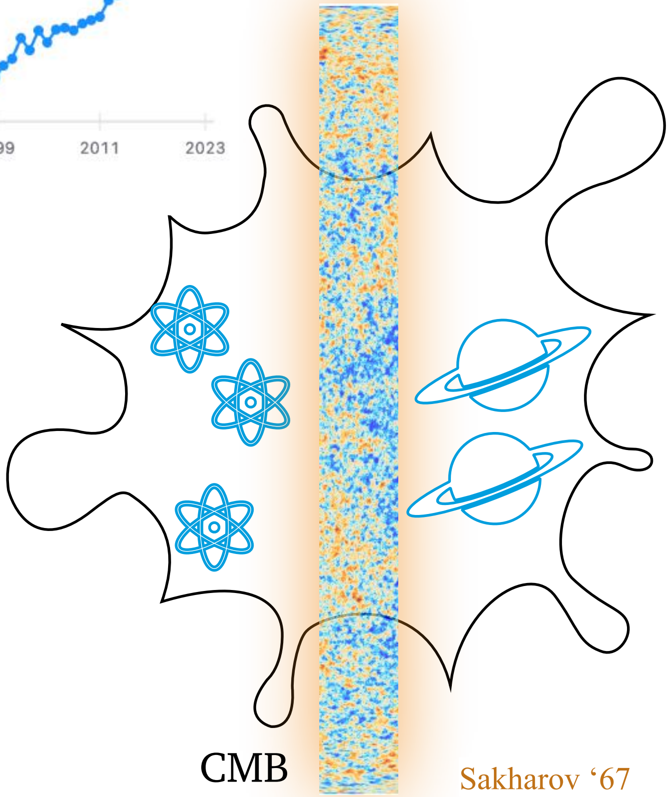
Baryon asymmetry

Dynamical creation is fundamentally constrained ➡ Sakharov Conditions

- ✺ Baryon number violation.
- ✺ C & CP violation.
- ✺ Deviation from thermal equilibrium.







Sakharov ‘67

Baryon asymmetry — in the SM

- CP violation controlled by *complex* CKM matrix.

$$Y_B \propto \Delta_{CP}^{quarks} = Im[det([Y_u Y_u^\dagger, Y_d Y_d^\dagger])]$$

$$\propto J \, \frac{1}{v^4} \prod_{i<j} (m_{u_i}^2 - m_{u_j}^2) \prod_{i<j} (m_{d_i}^2 - m_{d_j}^2)$$

Too small Jarlskog invariant: $J = s_{12} s_{23} s_{13} c_{12} c_{23} c_{13}^2 \sin \delta_{CKM}$

Jarlskog '83; Gavela, Hernandez, Orloff, Pene, Quimbay '94

- Out of equilibrium not strong enough with crossover phase transition.

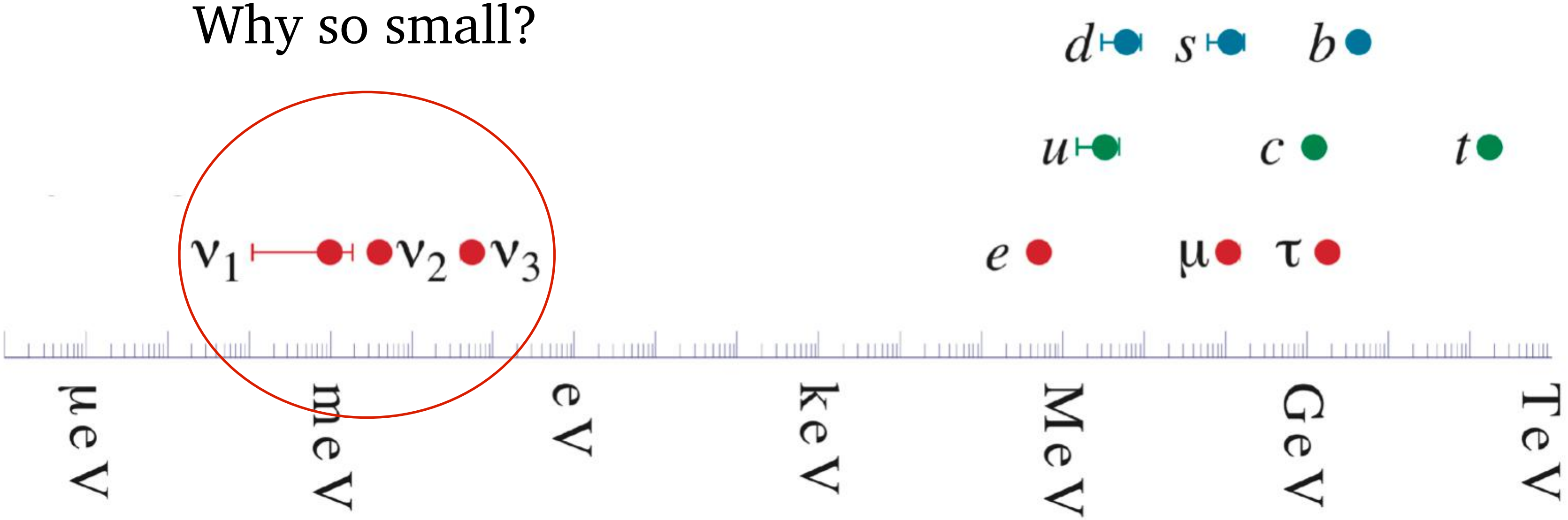
Kajantie, Laine, Rummukainen, Shaposhnikov '96

SM unable to explain observed Y_B.

Origin of neutrino masses

Neutrino masses

Why so small?



Cosmological *upper* bound: $\boxed{\sum m_\nu \leq 0.12\,\text{eV} \quad @\ 2\sigma}$

Neutrino oscillations *lower* bound: $\boxed{\sum m_\nu \geq 0.06\,\text{eV}\ @\ \gg 5\sigma}$

Planck 2018

Neutrino masses — Minimal model

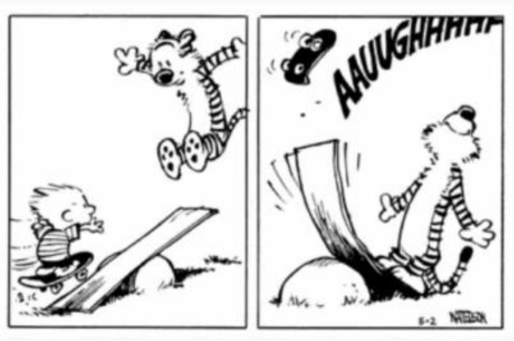
- Minimal scenario: Type-I seesaw with 2 heavy neutrinos.

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \mathscr{L}_K - \boxed{\frac{1}{2}\overline{N^c}_i M_{ij} N_j} - \boxed{Y_{i\alpha}\overline{L}_\alpha \tilde{H} N_i} + hc\,.$$

Lepton number violation
& CP violation

Complex Yukawas:
new CP violation

light
active
neutrino



heavy
sterile
neutrino

→ $m_\nu \sim y^2 \dfrac{v^2}{M}$

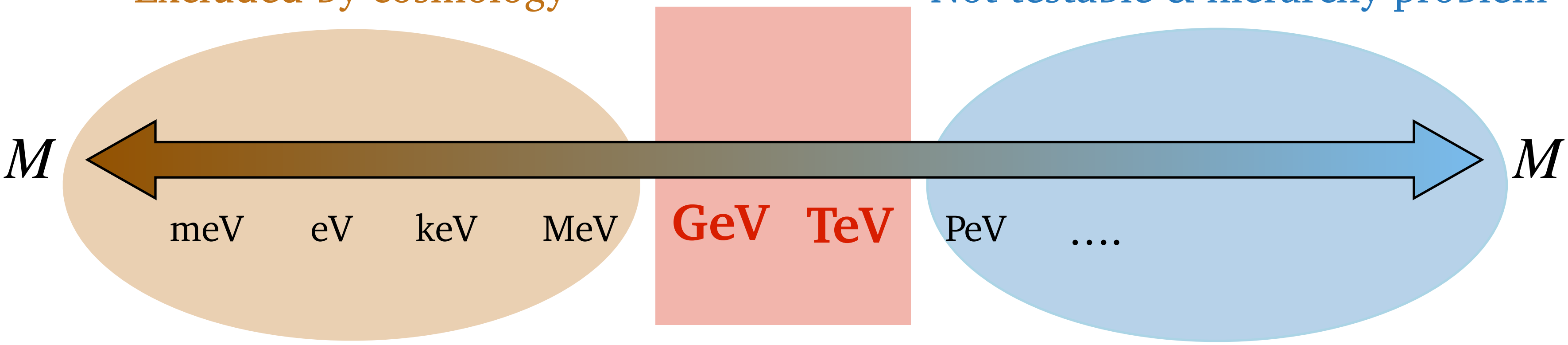
- Possible to constrain M?

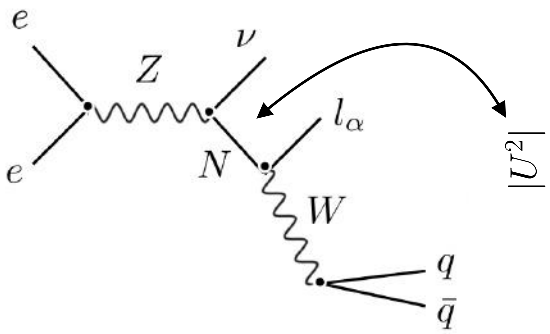
Minkowski ’77; Yanagida ’79; Wyler, Wolfenstein ’83; Mohapatra, Valle ’86; …

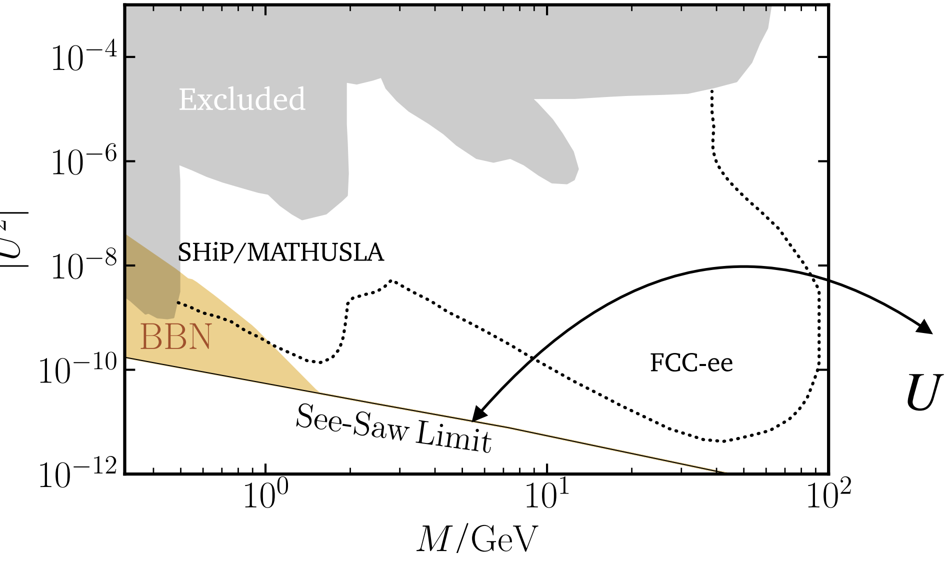
Neutrino masses — Minimal model

Excluded by cosmology

Not testable & hierarchy problem







$$U^2 \sim \frac{m_\nu}{M}$$

Dolgov et. al.; Hernandez, Kekic, López-Pavón; Vincent et al;….; Vissani '97; Coloma et. al. '20

Neutrino masses — Minimal model

Testable mixings between light and heavy neutrinos.

⇕

Approximate **lepton number symmetry**.

$$\begin{array}{cccccc} & \overline{\nu^c} & \overline{N}_1 & \overline{N}_2 & & \\ & 1 & -1 & 1 & L & \\ & 0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} & 1 & \nu \\ M_\nu = & Y_1 v/\sqrt{2} & \mu' & M & -1 & N_1^c \\ & \epsilon Y_2 v/\sqrt{2} & M & \mu & 1 & N_2^c \end{array}$$

Neutrino masses — Minimal model

- Light ν masses suppressed by LN violating parameters:

$$m_\nu = \mu \frac{v^2}{2M^2} Y_1^T Y_1 + \frac{v^2}{2M} \epsilon Y_2^T Y_1 + \frac{v^2}{2M} Y_1^T \epsilon Y_2$$

- Mixing between light and heavy neutrinos **unsuppressed**:

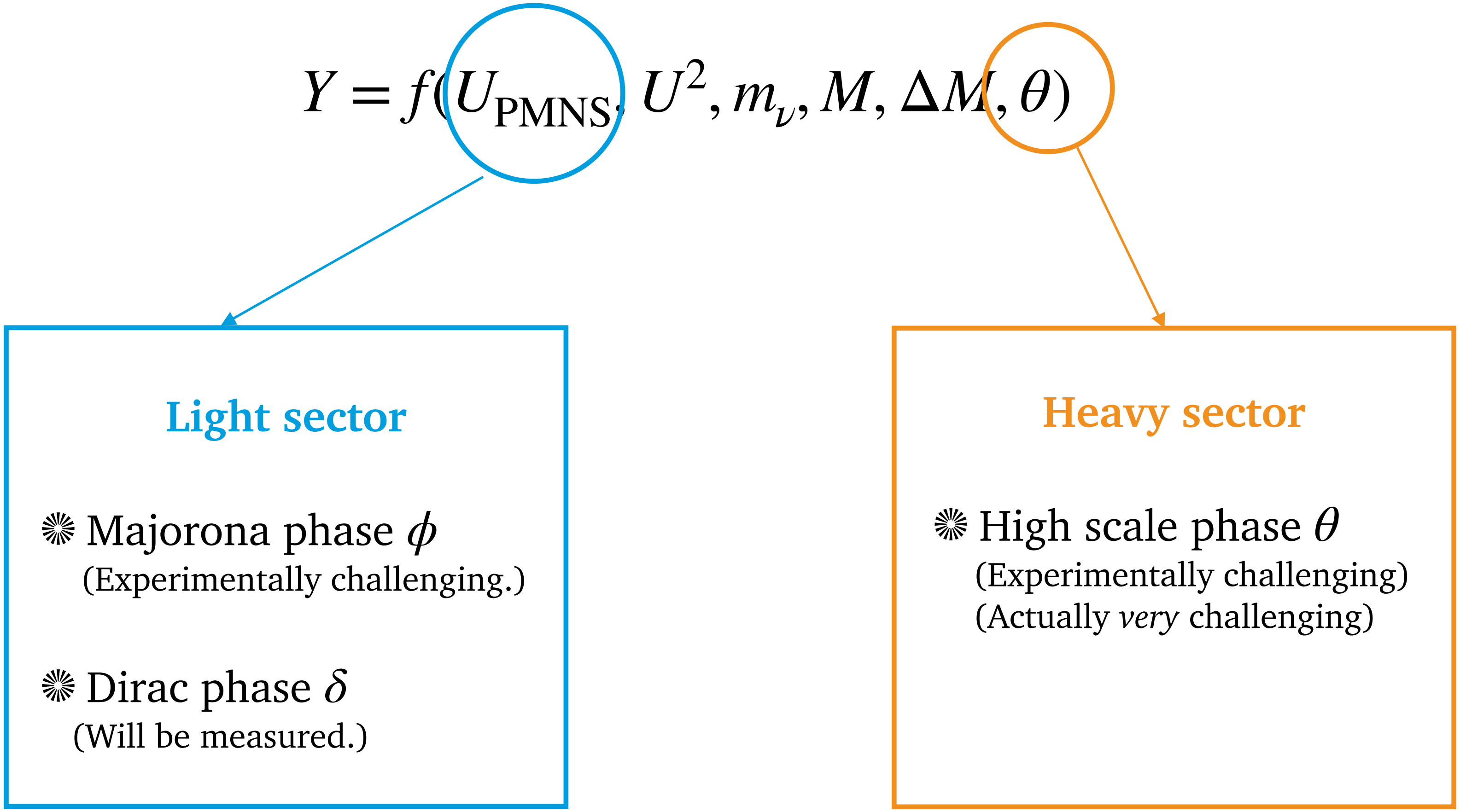
$$U_{\nu N} \simeq Y_1 v / M$$

- Heavy neutrino mass splitting:

$$\Delta M = \mu + \mu'$$

Neutrino masses — Minimal model

Dependence on leptonic CP phases encoded in Yukawa matrix.



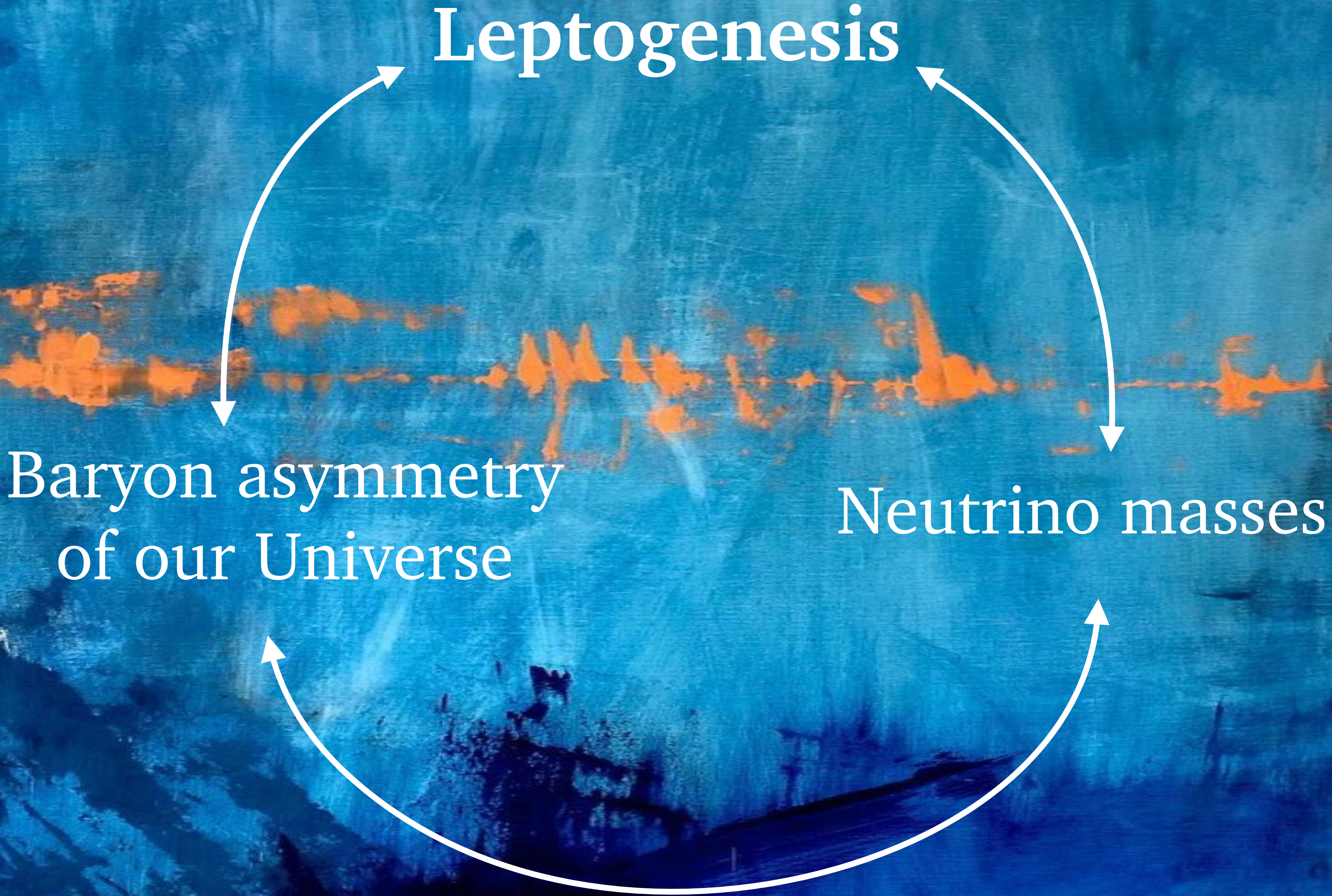
$$Y = f(U_{\mathrm{PMNS}}, U^2, m_\nu, M, \Delta M, \theta)$$

Light sector

- Majorona phase ϕ
  (Experimentally challenging.)
- Dirac phase δ
  (Will be measured.)

Heavy sector

- High scale phase θ
  (Experimentally challenging)
  (Actually *very* challenging)



Leptogenesis

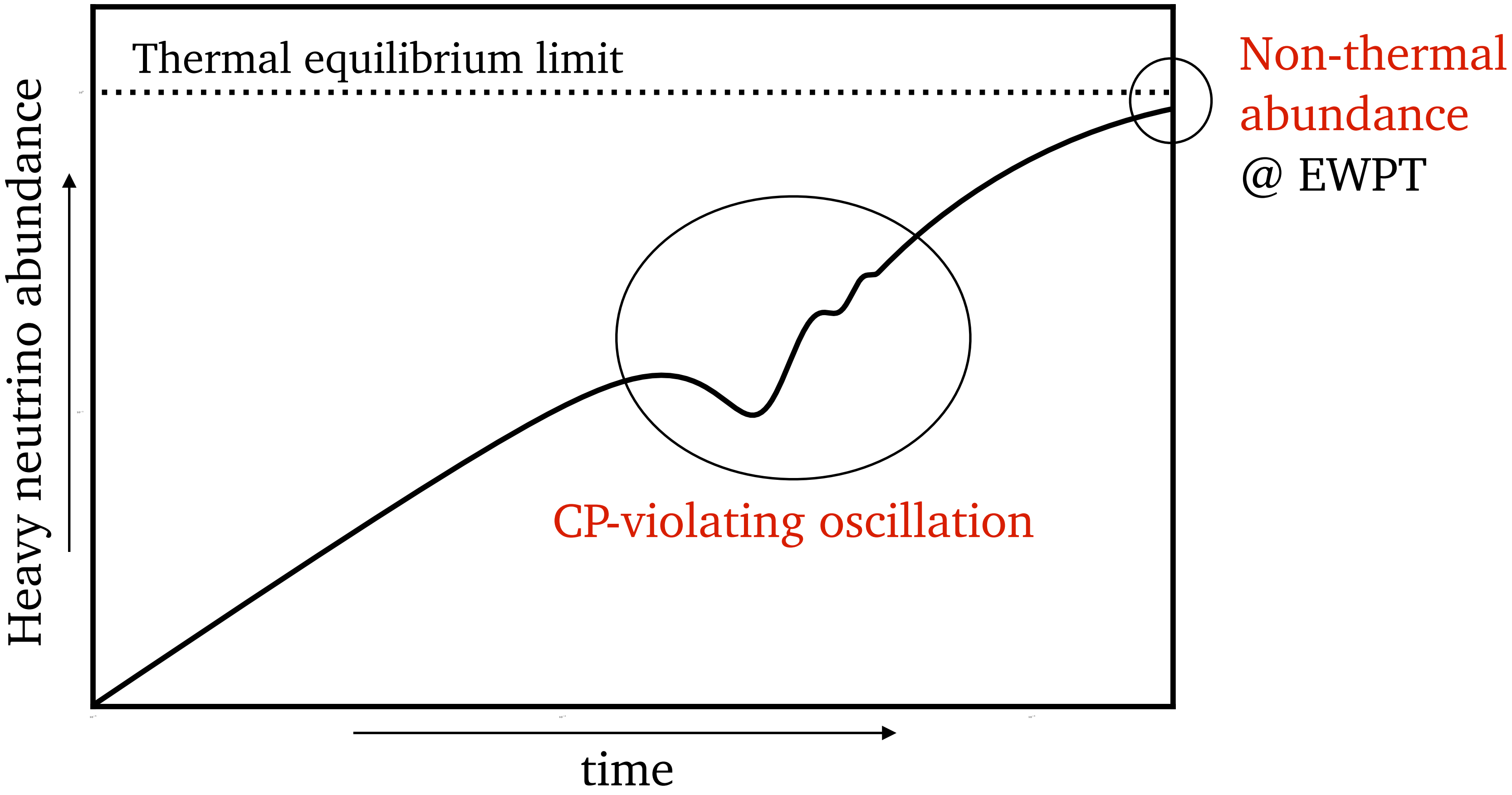
Baryon asymmetry
of our Universe

Neutrino masses

Leptogenesis via oscillations

- Heavy neutrinos at $\mathcal{O}(\text{GeV})$ scale.

$L \neq 0 \rightarrow$ active SM Sphalerons $(B - L \neq 0) \rightarrow B \neq 0$



Non-thermal abundance @ EWPT

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

Leptogenesis via oscillations

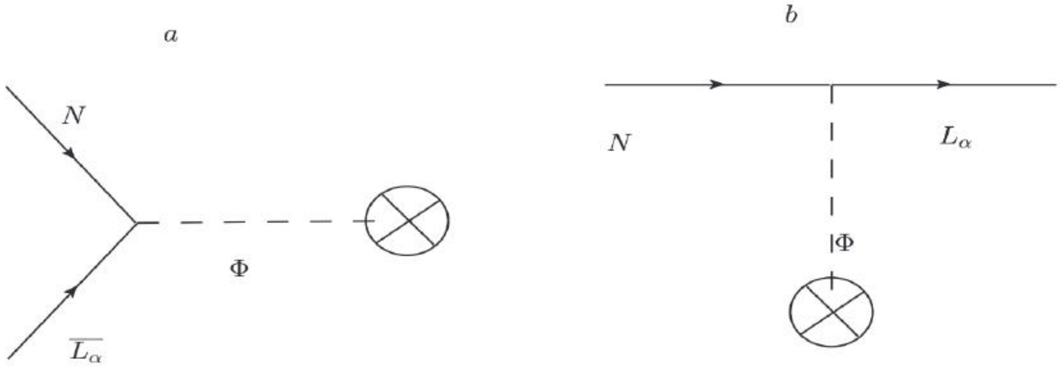
- Quantification of the asymmetry via quantum Boltzmann equation.

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

Quantum
density matrix

CP-violating
oscillations $H \propto \Delta M^2_{ij}/k_0$

Thermalization efficiency
$\Gamma^{a,p} = \epsilon Y Y^\dagger T$



Sakharov conditions fulfilled in testable region of parameter space.

Raffelt, Sigl ’93; Ghiglieri, Laine ’17; Hernandez, Lopez-Pavon, Rius, Sandner ‘22

Leptogenesis via oscillations

Quantification of the asymmetry via quantum Boltzmann equation

> **“Never make a calculation until you know the answer.”**
>
> John Archibald Wheeler, Spacetime Physics: Introduction to Special Relativity

Quantu

density ma

zation efficiency

$= \epsilon Y Y^\dagger T$

$r = \rho/\rho_{\mathrm{eq}}$

$x = 1/T$

$\gamma^{(i)}, s^{(i)}$:

rates

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

$\bar r \to r$

similar

Raffelt, Sigl ’93; Ghiglieri, Laine ‘17

CP-violating invariants

- CP invariants similar to SM Jarlskog invariant:

$$I_0 = \mathrm{Im}\left[\mathrm{Tr}\left(Y^\dagger Y M^\dagger M Y^\dagger Y_\ell Y_\ell^\dagger Y\right)\right] \equiv \sum_\alpha y_{\ell_\alpha}^2 \Delta_\alpha$$

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

Expectation: $Y_B = f_i\left(\Delta_\alpha\right) + \bar{f}_i\left(\Delta_\alpha^M\right)$

- Find $f, \bar{f}$ **analytically** and relate baryon asymmetry to observables.

Type-I seesaw relation: $\Delta_\alpha^{(M)} = \Delta_\alpha^{(M)}(\Delta m_{\mathrm{sol}}, \Delta m_{\mathrm{atm}}, \delta, \phi, U^2, M, \theta)$

Hernandez, Lopez-Pavon, Rius, Sandner '22

Adiabatic approximation

Kinetic equation in matrix representation:

$$r'(x) = A(x)r(x) + c(x) = [A^{(0)} + A^{(1)} + \mathcal{O}(\epsilon_{LNV}^2)]\, r(x) + [c^{(0)} + c^{(1)} + \mathcal{O}(\epsilon_{LNV}^2)]$$

$$A^{(0)} = V(x)\Lambda'(x)V^{-1}(x)$$

$$\epsilon_{LNV} = (\epsilon y_{2,\alpha}\, , M/T\,)$$

In the purely adiabatic limit[1]:

$$r_a(x) = V(x)\mathrm{e}^{\Lambda(\mathrm{x})}\int^{\mathrm{x}} \mathrm{dz}\, \mathrm{e}^{-\Lambda(\mathrm{z})}\mathrm{V}^{-1}(\mathrm{z})\mathrm{c}^{(0)}(\mathrm{z})$$

Leading order adiabatic perturbation[2]:

$$\delta r_a(x) = -\, V(x)\mathrm{e}^{\Lambda(\mathrm{x})}\int^{\mathrm{x}} \mathrm{dz}\, \mathrm{e}^{-\Lambda(\mathrm{z})}\mathrm{V}^{-1}(\mathrm{z})\mathrm{V}'(\mathrm{z})\mathrm{V}^{-1}(\mathrm{z})\; r_a(z)$$

Full solution

$$r^{(0)} = r_a + \delta r_a$$

Higher order corrections obtained similar via time-dependent perturbation theory.

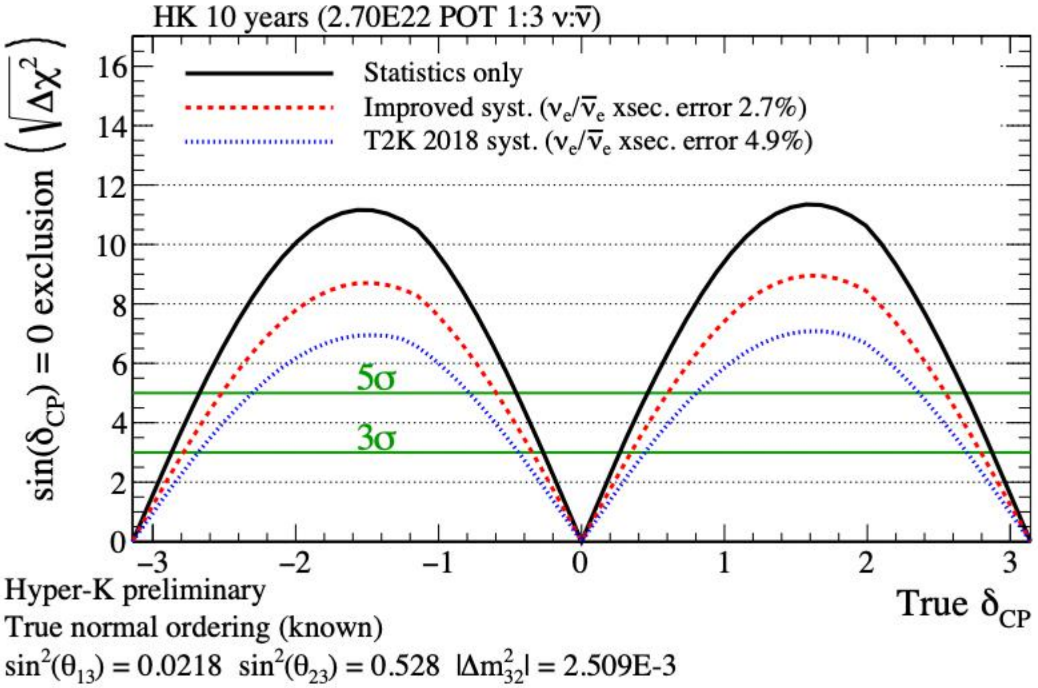
[1] Born, Fock **19**28; [2] Hernandez, Lopez-Pavon, Rius, Sandner **20**22

Part II: Testing leptogenesis

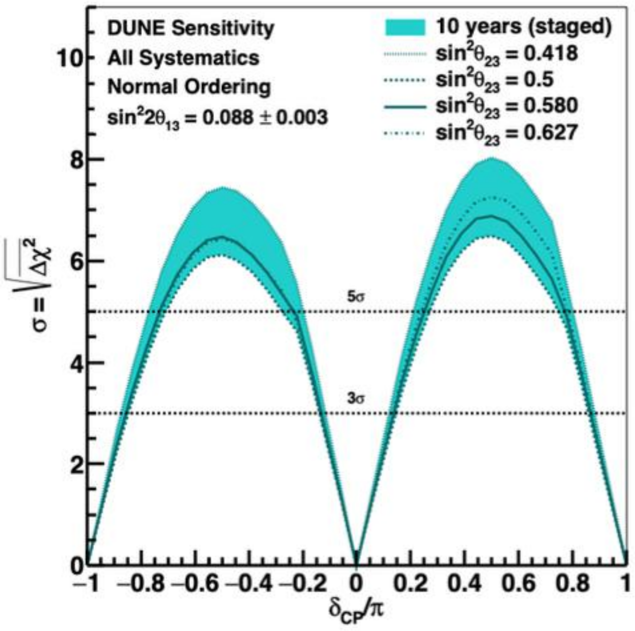
Relate to observables

$$\Delta_X(\Delta m_\nu, \delta, \phi, U^2, M, \Delta M, \theta)$$

Hyper Kamiokande (10y)



DUNE(10y)

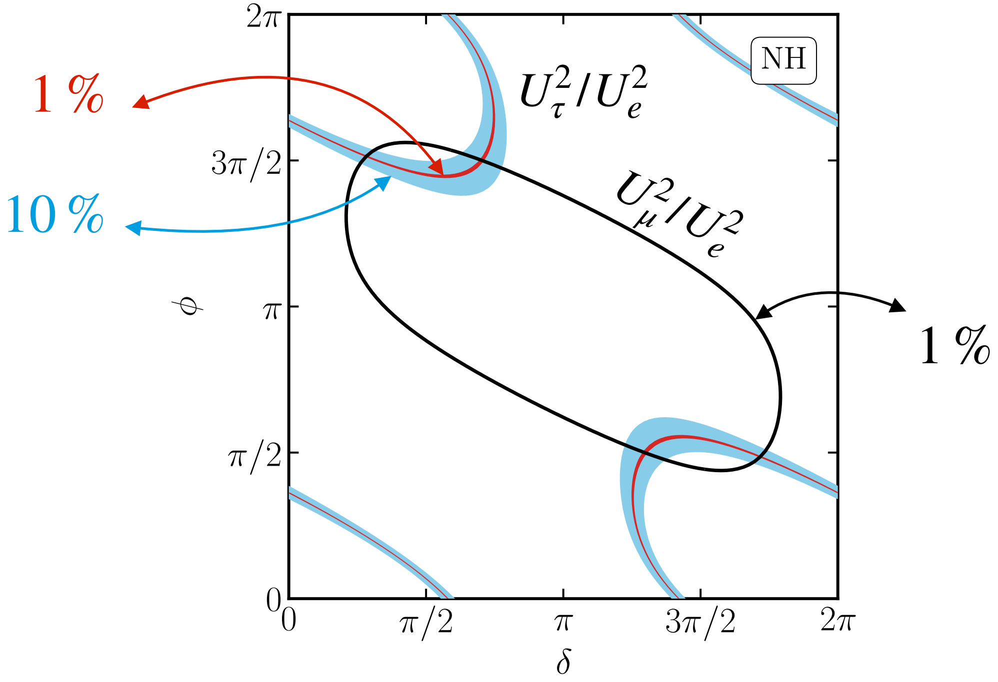


Relate to observables

$$\Delta_X(\Delta m_\nu, \delta, \phi, U^2, M, \Delta M, \theta)$$

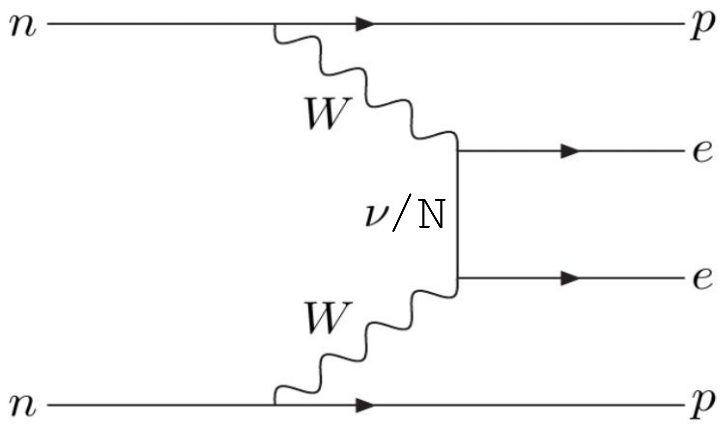
ϕ via i) $0\nu\beta\beta$ decay or ii) heavy neutrino flavor ratio depends on U_{PMNS} phases.

$(U_e^2)_{\text{true}}$	$(U_\mu^2)_{\text{true}}$	$(U_\tau^2)_{\text{true}}$
2.843×10^{-12}	1.087×10^{-11}	1.234×10^{-11}



Relate to observables

$$\Delta_X(\Delta m_\nu, \delta, \phi, U^2, M, \Delta M, \theta)$$



$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp}$$

Possibility in $0\nu\beta\beta$

$$\Gamma_{\beta\beta} \propto (U_{ei})^2 \propto e^{2i\theta} U^2 f(\delta, \phi, M_j)$$

Interference between ν/N contributions to $\Gamma_{\beta\beta}$ can reveal θ.

Realistically Y_B can not be fully predicted in general, but we can set constraints!

Lopez-Pavon, Pascoli, Wong ‘12

Relate to observables

- Light ν constraint: $\left(m_\nu\right)_{\alpha\beta} = v^2\left(Y^* \nu M^{-1} Y_\nu^\dagger\right)_{\alpha\beta} = \left(U^* m U^\dagger\right)_{\alpha\beta}$

- Exemplary **analytical** solution:

$$Y_B^{\text{damped osc}} \simeq \frac{\kappa x^2}{6\gamma_0 + \kappa\gamma_1} \frac{\gamma_0^2}{\gamma_0^2 + 4\omega^2} \frac{c_H M_P^*}{T_{EW}^3} \left(\Delta_{\text{LNC}}^{\text{ov}} - \frac{24}{5} \frac{s_0 x^3}{T_{\text{EW}}^2} \Delta_{\text{LNV}}^{\text{ov}} \right)$$

$\Delta_{\text{LNC}}^{\text{ov}}$ & $\Delta_{\text{LNV}}^{\text{ov}}$ expressed with **observable** quantities: $\Delta_X(\Delta m_\nu, \delta, \phi, U^2, M, \Delta M, \theta)$.

Neutrino oscillations
(Dune, T2HK, ..)

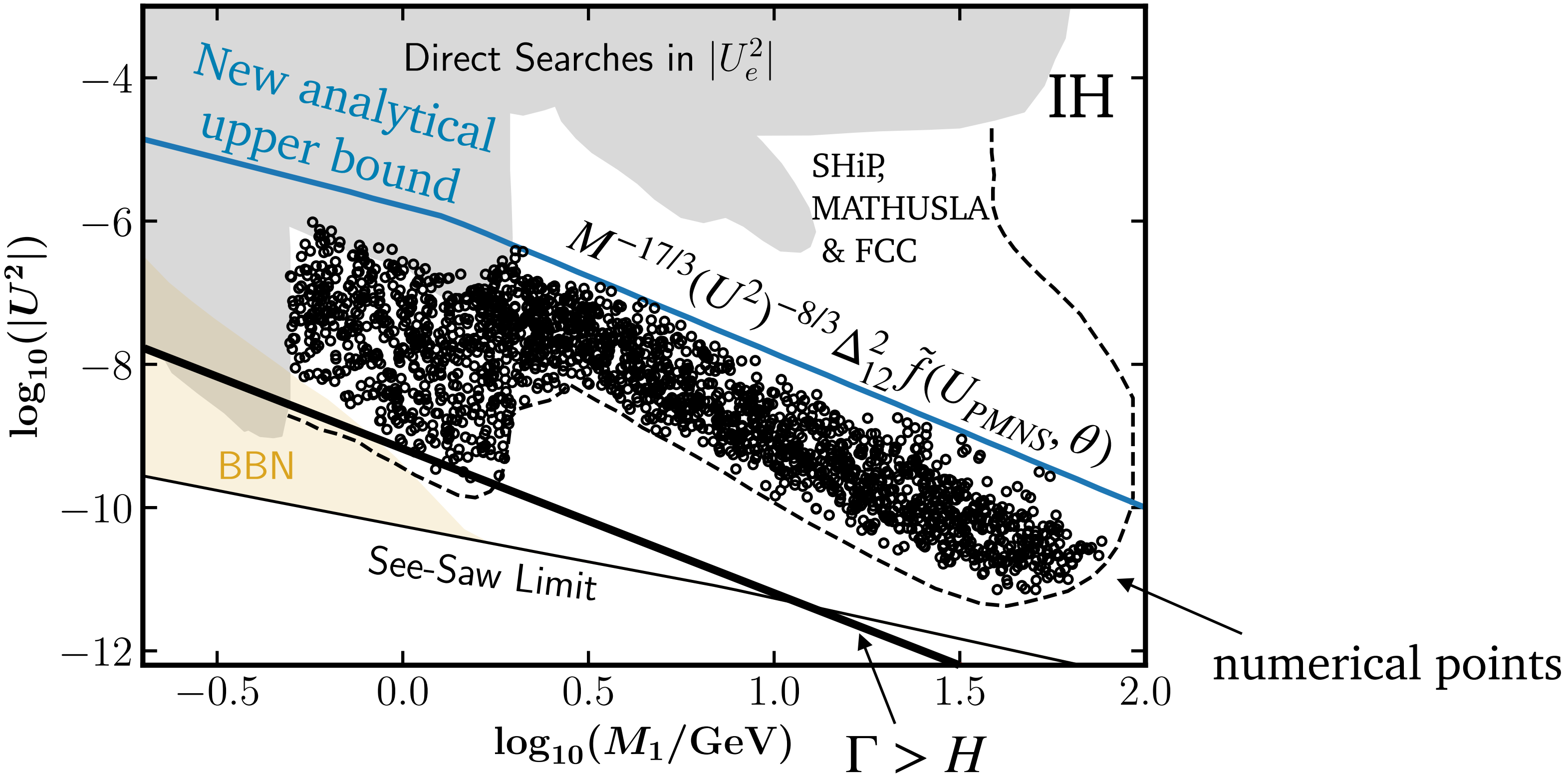
$\nu 0\beta\beta$ decay
(LEGEND, NEXT, ..)

Particle collider
(LHC, SHiP, FCC, ..)

Hernandez, Lopez-Pavon, Rius, Sandner '22

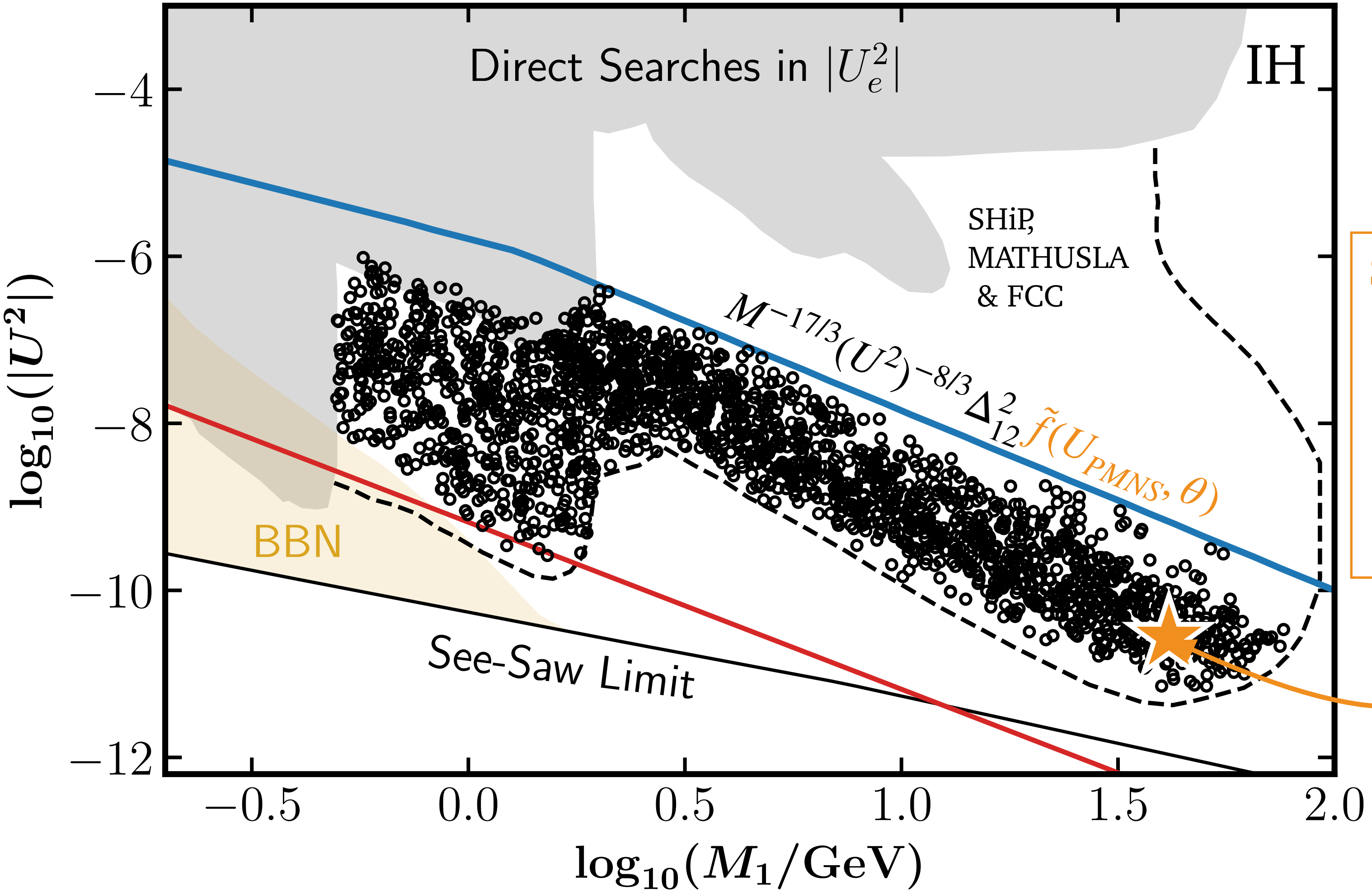
Upper bound from leptogenesis

Neutrino masses + baryon asymmetry explainable in testable region.



Hernandez, Lopez-Pavon, Rius, Sandner '22

Upper bound on HNL mixing

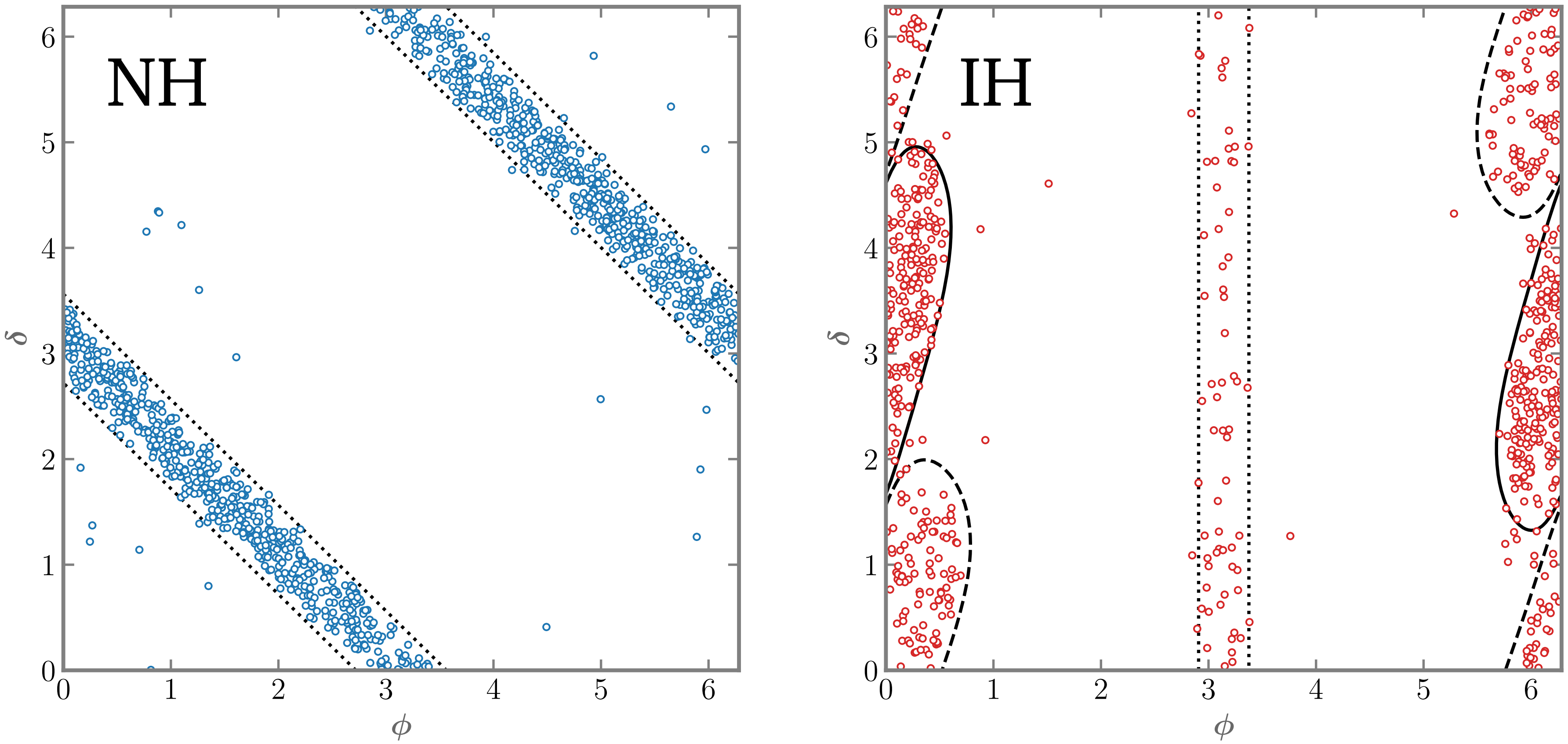


Specific value of $\tilde{f}$.

Constraints on phases.

Hernandez, Lopez-Pavon, Rius, Sandner ‘22

Constraints on CP phases



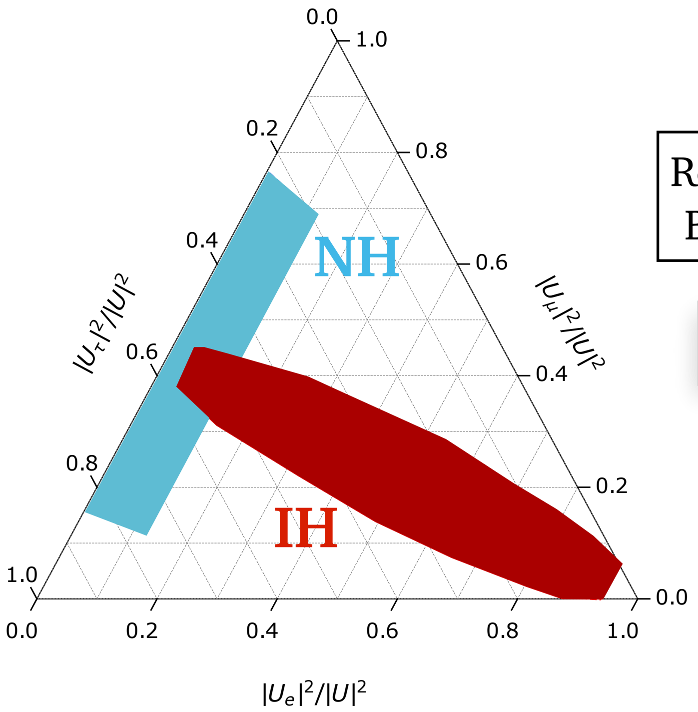
PMNS phases correlated by imposing the observed asymmetry.

Example: Parameter space covered by FCC-ee with $\Delta M/M = 10^{-2}$.

Hernandez, Lopez-Pavon, Rius, Sandner ‘22

Constraints on flavor structure

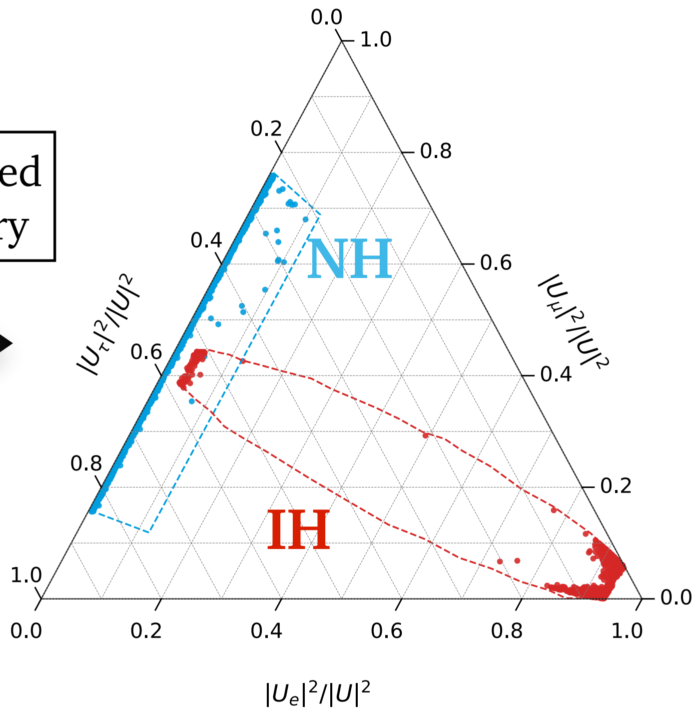
Neutrino Oscillation data



Reproduce observed Baryon asymmetry

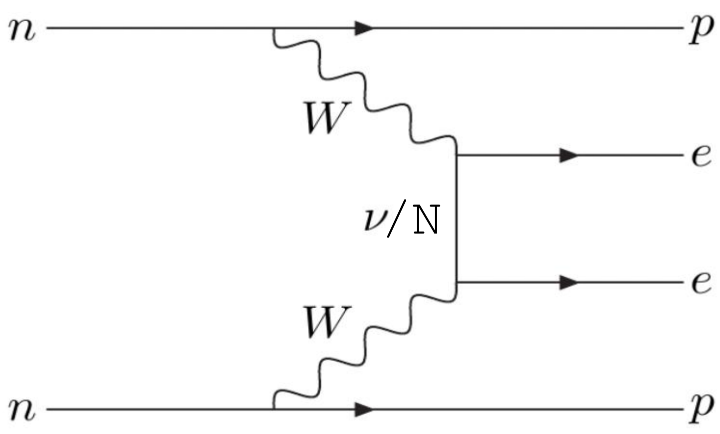
Example:

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



Hernandez, Lopez-Pavon, Rius, Sandner ‘22

Implications on $0\nu\beta\beta$



$$(Z, A) \Rightarrow (Z \pm 2, A) + 2e^{\mp}$$

$$\Rightarrow \quad \Gamma \propto |m_{\beta\beta}|^2$$

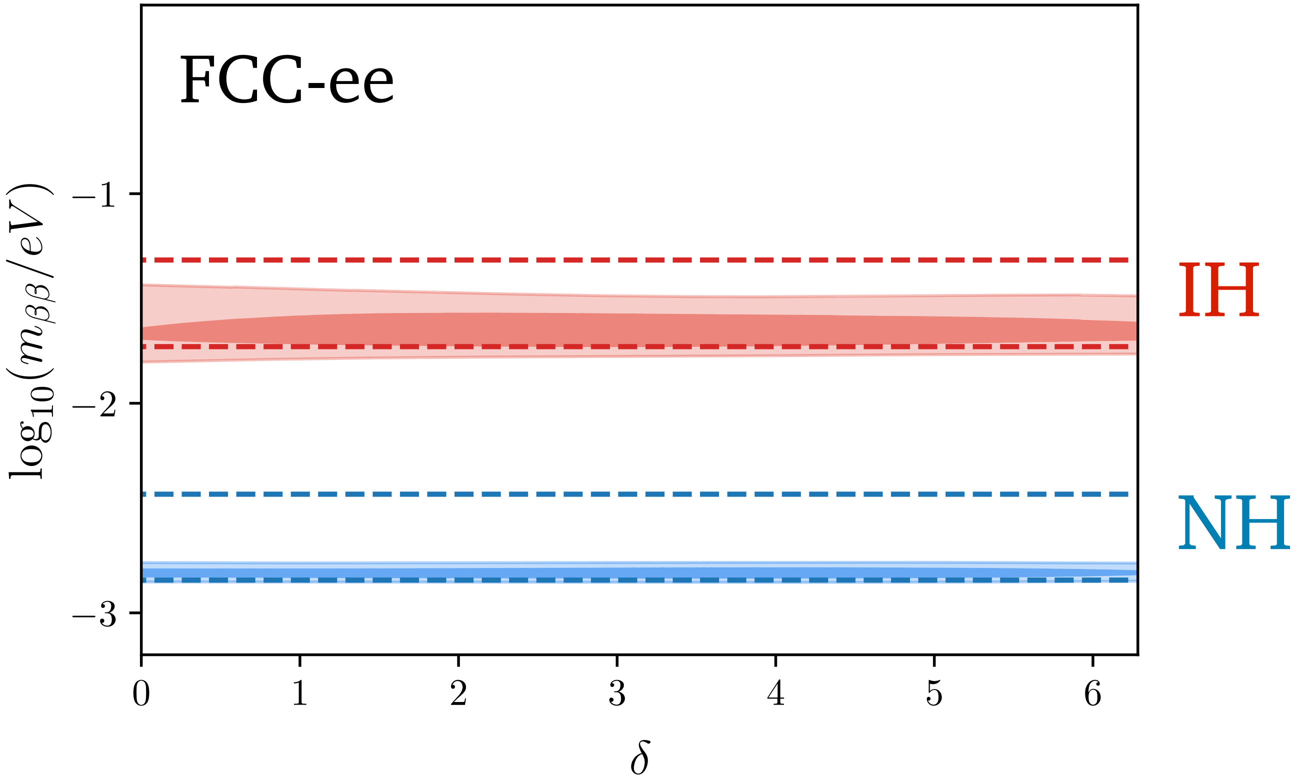
$$m_{\beta\beta} = \left| \sum_{i=\text{light}} U_{ei}^2 m_i + \sum_{I=\text{heavy}} \Theta_{eI}^2 M_I \mathscr{M}\left(M_I\right) \right| ,$$

$\mathcal{O}$(GeV) scale HNs + observed baryon asymmetry modify $m_{\beta\beta}$ in 2 ways.

Implications on $0\nu\beta\beta$

Example: Parameter space covered by FCC-ee with $\Delta M/M = 10^{-2}$.

Successful leptogenesis restricts expected $m_{\beta\beta}$ range.

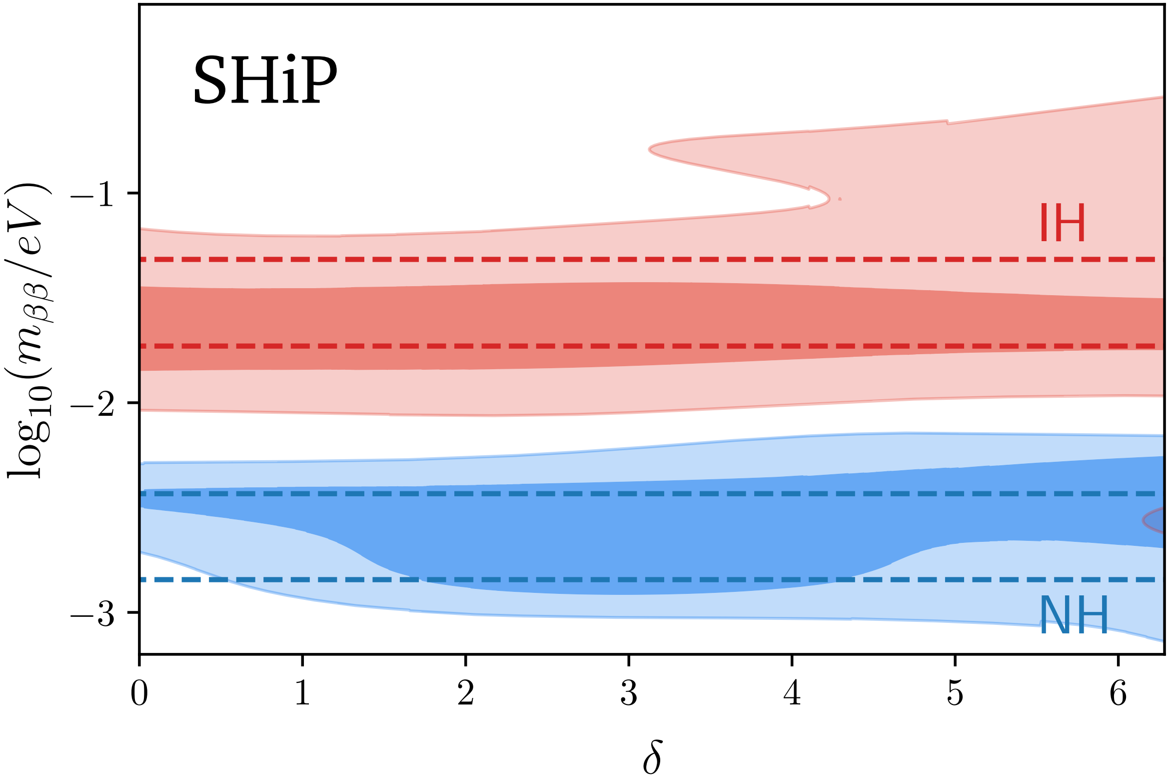


Hernandez, Lopez-Pavon, Rius, Sandner '22

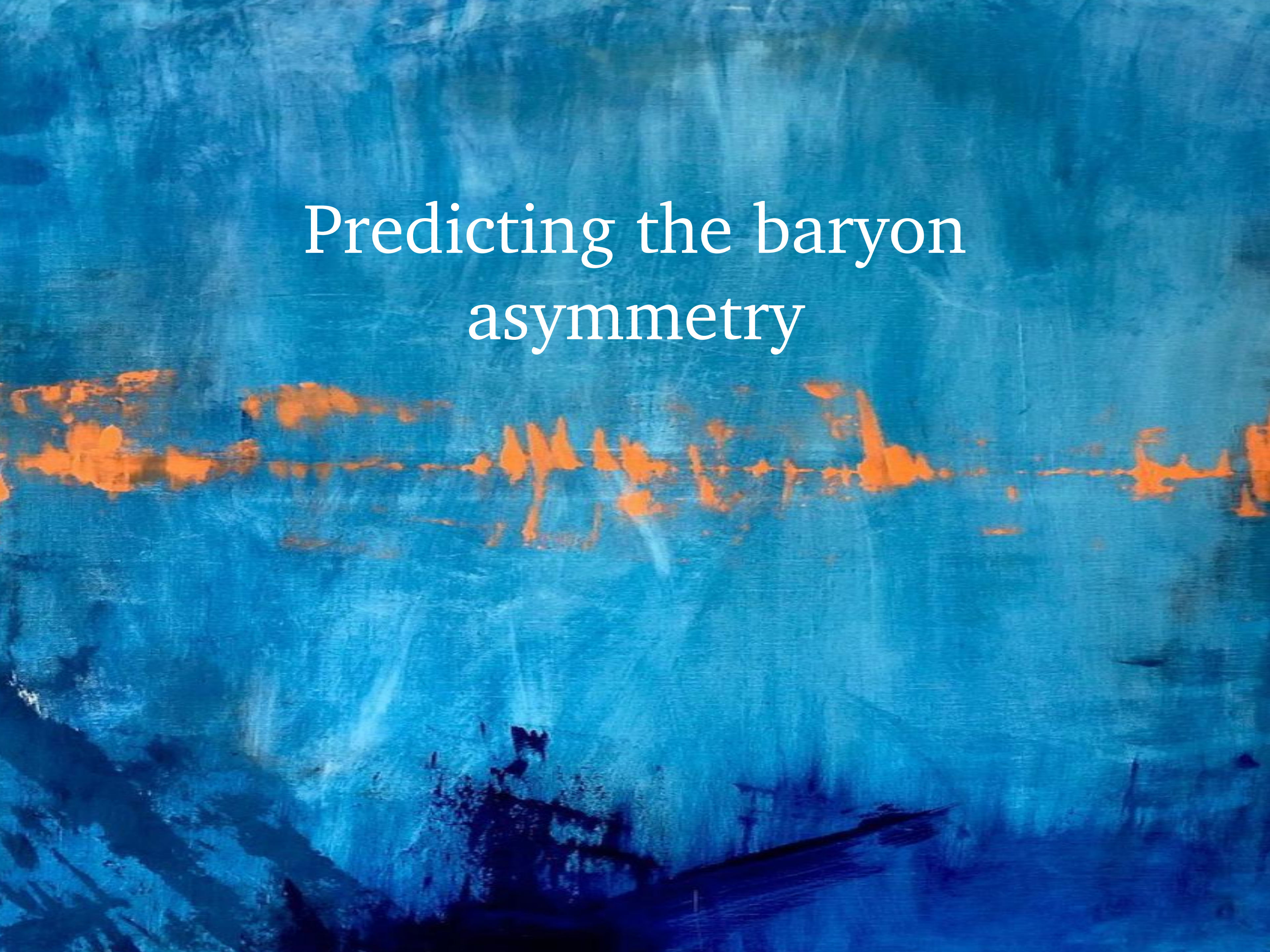
Implications on $0\nu\beta\beta$

Example: Parameter space covered by SHiP with $\Delta M/M = 10^{-2}$.

Large contribution from heavy neutrinos in accordance with observed asymmetry.



Hernandez, Lopez-Pavon, Rius, Sandner ‘22



Predicting the baryon asymmetry

The θ phase

θ mainly controls the Y_B and is *practically* not measurable.

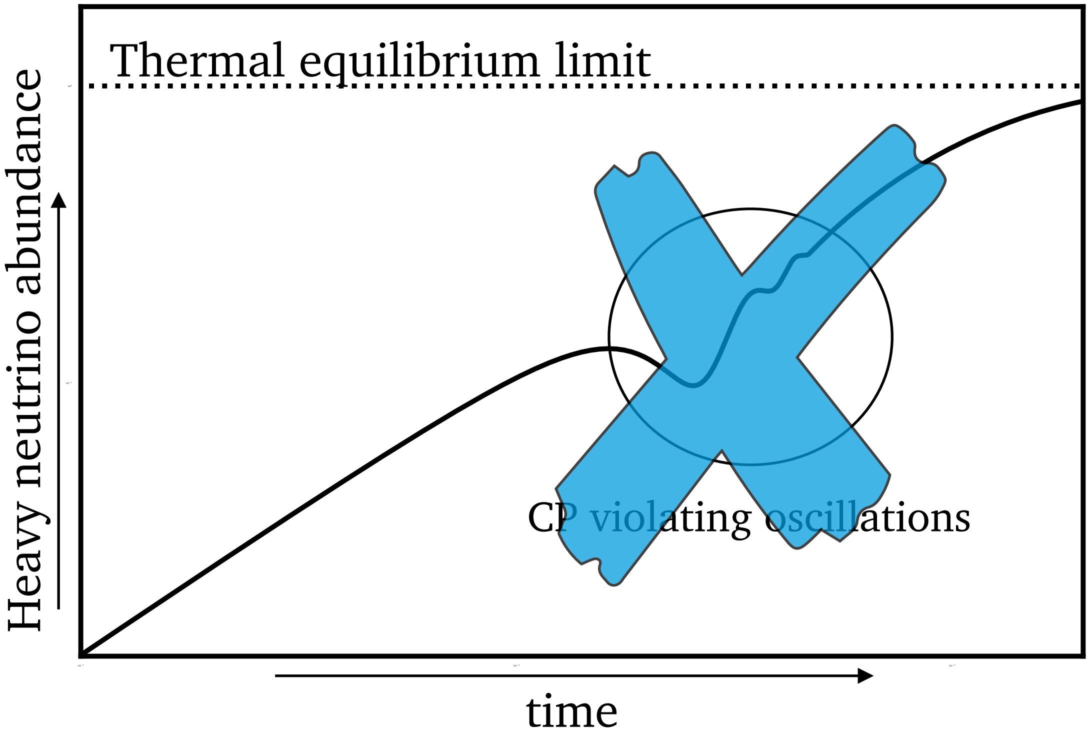
Where does θ actually come from?

$$M_\nu = \begin{array}{ccccc}
\overline{\nu^c} & \overline{N}_1 & \overline{N}_2 & & \\
1 & -1 & 1 & L & \\
0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} & 1 & \nu \\
Y_1 v/\sqrt{2} & \mu' & M & -1 & N_1^c \\
\epsilon Y_2 v/\sqrt{2} & M & \mu & 1 & N_2^c
\end{array}$$

If lepton number is exact in the heavy sector, θ is **not** physical.
All CP violation arises from the PMNS phases.

The θ phase

Exact lepton number symmetry in the heavy sector implies $M_1 = M_2$.



No interference of CP phases at leading order — previous CP invariants vanish *exactly*.

Hernandez, Lopez-Pavon, Rius, Sandner '23

The θ phase

Thermal corrections to free Hamiltonian lead to an effective "*mass difference*".

$$H \sim \boxed{\frac{M^2}{2k}} + \boxed{\frac{T^2}{8k}Y^\dagger Y + \frac{E-k}{16k}T}$$

Traditional oscillations

Thermal corrections

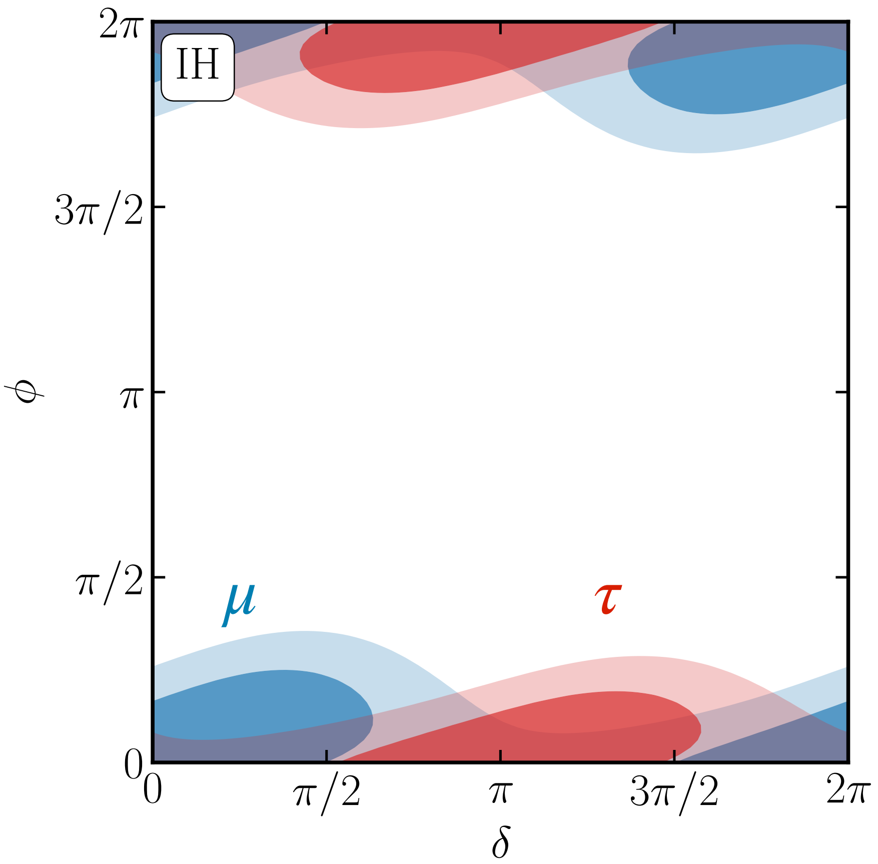
New CP invariant: $\tilde{I}_0 \equiv \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y M_R^* Y^T Y^* M_R Y^\dagger Y_l Y_l^\dagger Y\right]\right) \equiv \sum_\alpha y_{l_\alpha}^2 \Delta_\alpha^{th}.$

- Need flavor effects in Yukawa couplings since $\sum_\alpha \Delta_\alpha^{th} = 0$.
- Need explicit Majorana rates during thermalization.

Weldon '82; Drewes, Georis, Hagedorn, Klaric '22; Hernandez, Lopez-Pavon, Rius, Sandner '23

Relate to observables

How to achieve flavor effects?



Optimal phases for the asymmetry?

$$Y_B \sim 3 \times 10^{-28} \left(\frac{1}{|U^2|} \right)^2 \bar{f}_\alpha^{\mathrm{IH}}$$

Angular dependence of CP invariant.

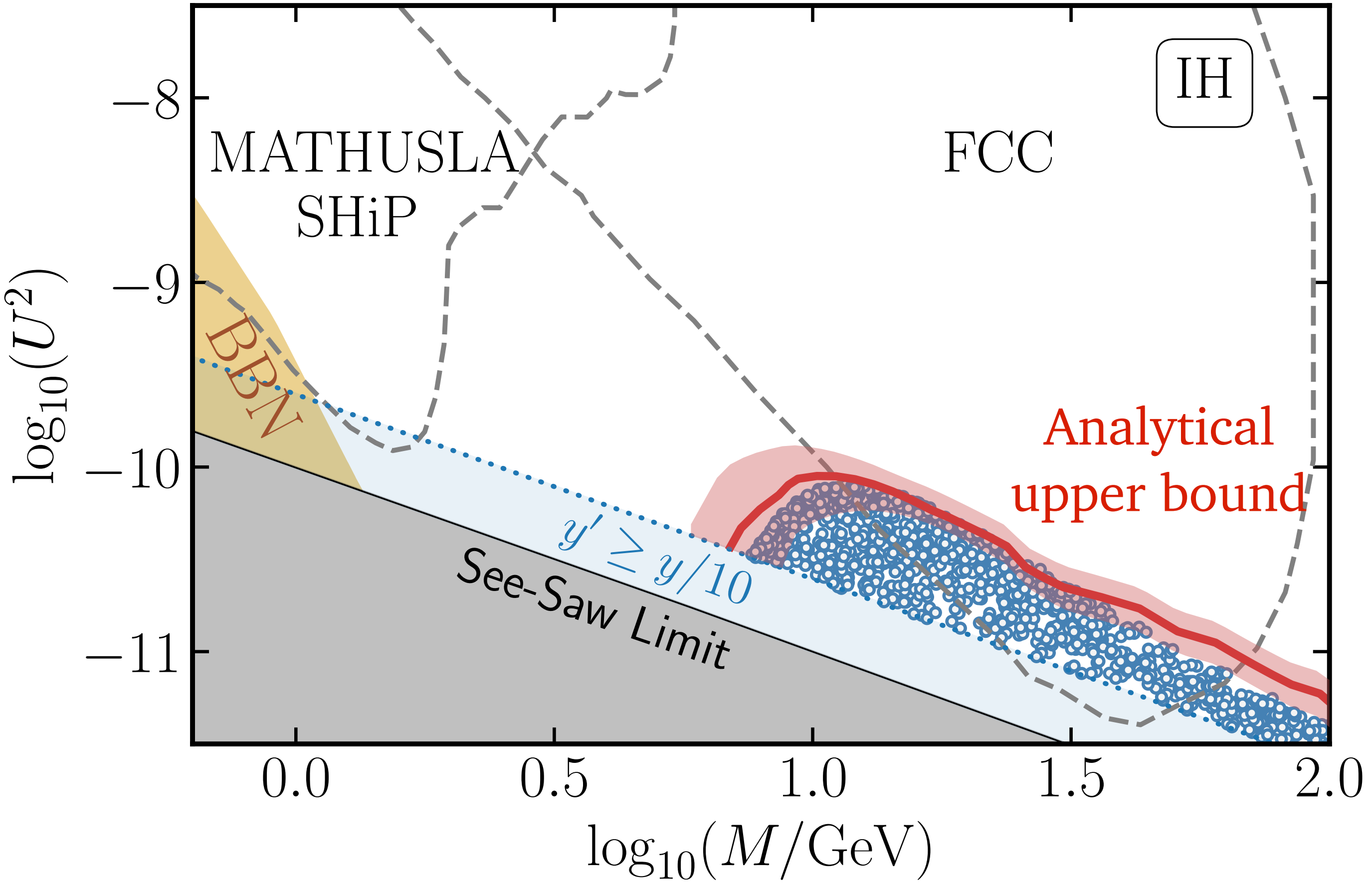
$$\bar{f}_\mu^{\mathrm{IH}} = \bar{f}_\tau^{\mathrm{IH}} = \frac{r^2 c_{12}^2 s_{12}^2 \sin(2\phi)}{2 - 8 c_{12}^2 s_{12}^2 \cos^2 \phi}$$

Baryon asymmetry vanishes *exactly* for maximal Yukawa flavor hierarchy.

Hernandez, Lopez-Pavon, Rius, Sandner '23

Upper bound on mixing

FCC-ee could see something.



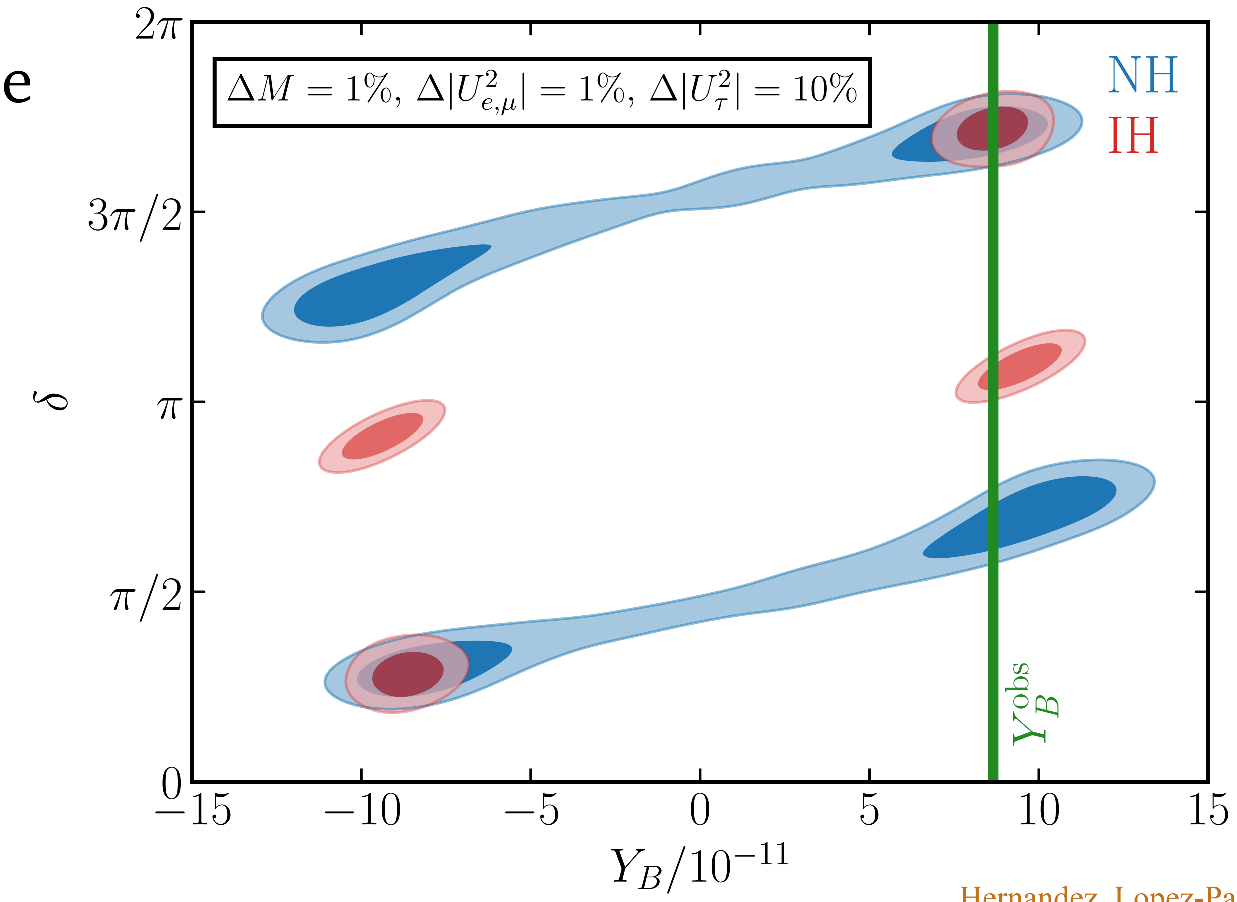
Numerical Points

Hernandez, Lopez-Pavon, Rius, Sandner ‘23

The asymmetry from the lab

Can we predict the Y_B?

FCC-ee

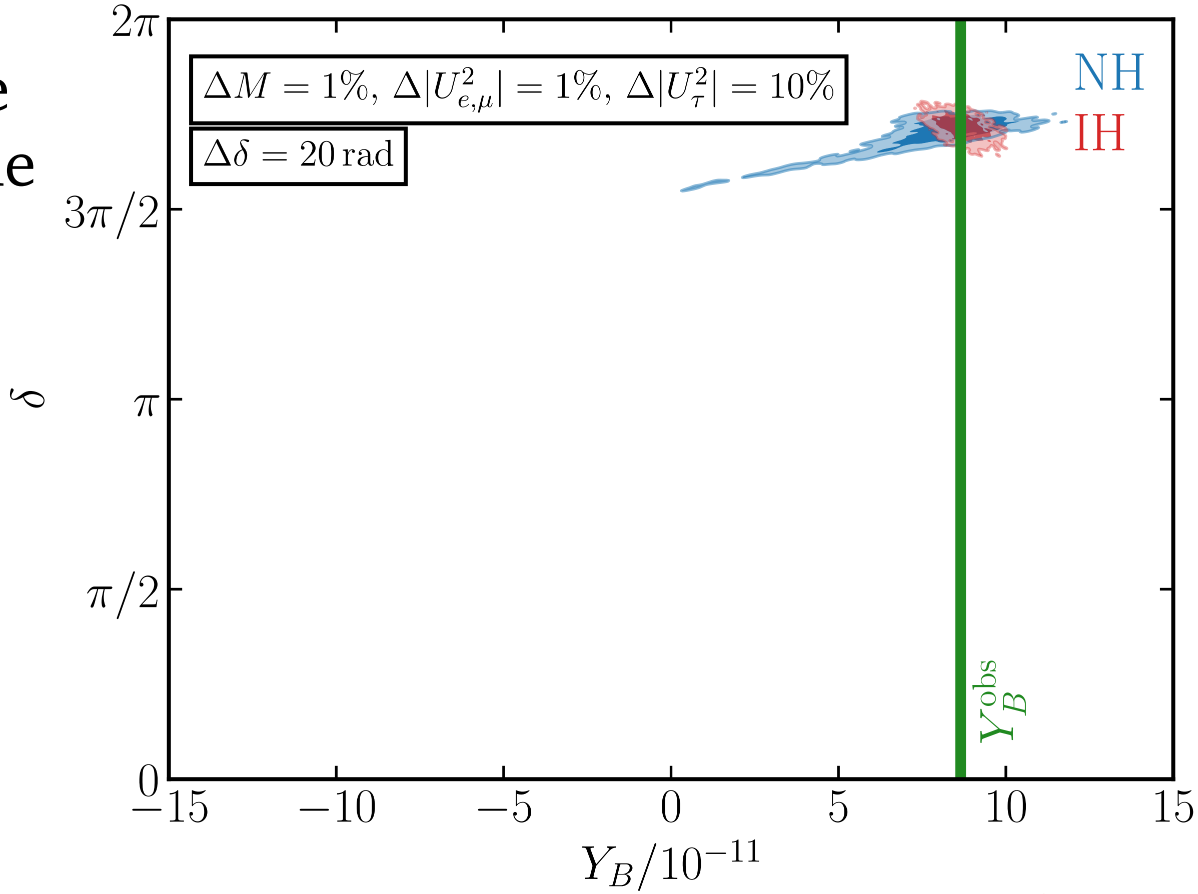


Hernandez, Lopez-Pavon, Rius, Sandner ‘23

The asymmetry from the lab

We can pin down Y_B with nothing more than lab measurements.

FCC-ee
HK, Dune



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Summary

✻ Leptogenesis possible for testable masses & mixings of ν_R.

✻ Analytical solution to kinetic eq. + Identification of relevant CP invariants.

→ Correlation of leptogenesis with other observables.

✻ Asymmetry can be predicted from lab measurements only.

✻ Method developed applicable to different problems.

Numerical code
publicly available

GitHub

arXiv 2207.01651

arXiv 2305.14427

Thank you

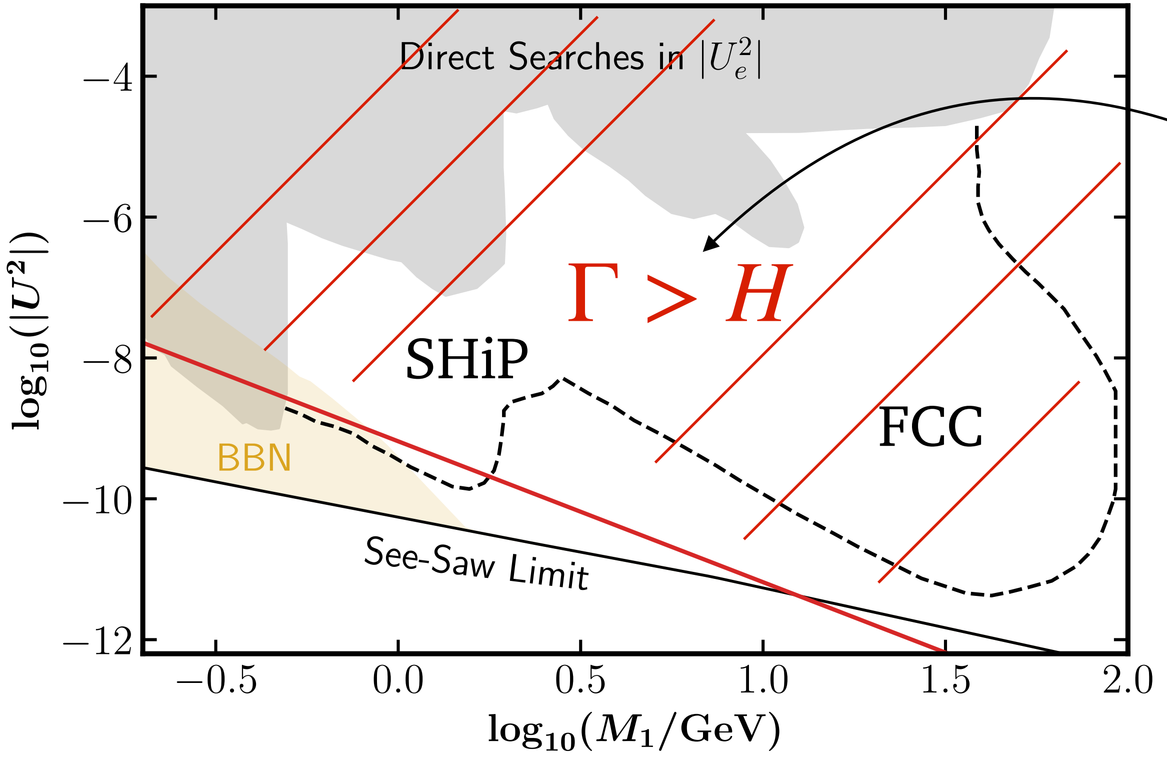
Supplemental material

Leptogenesis via oscillations

Very complex system — what should we expect?

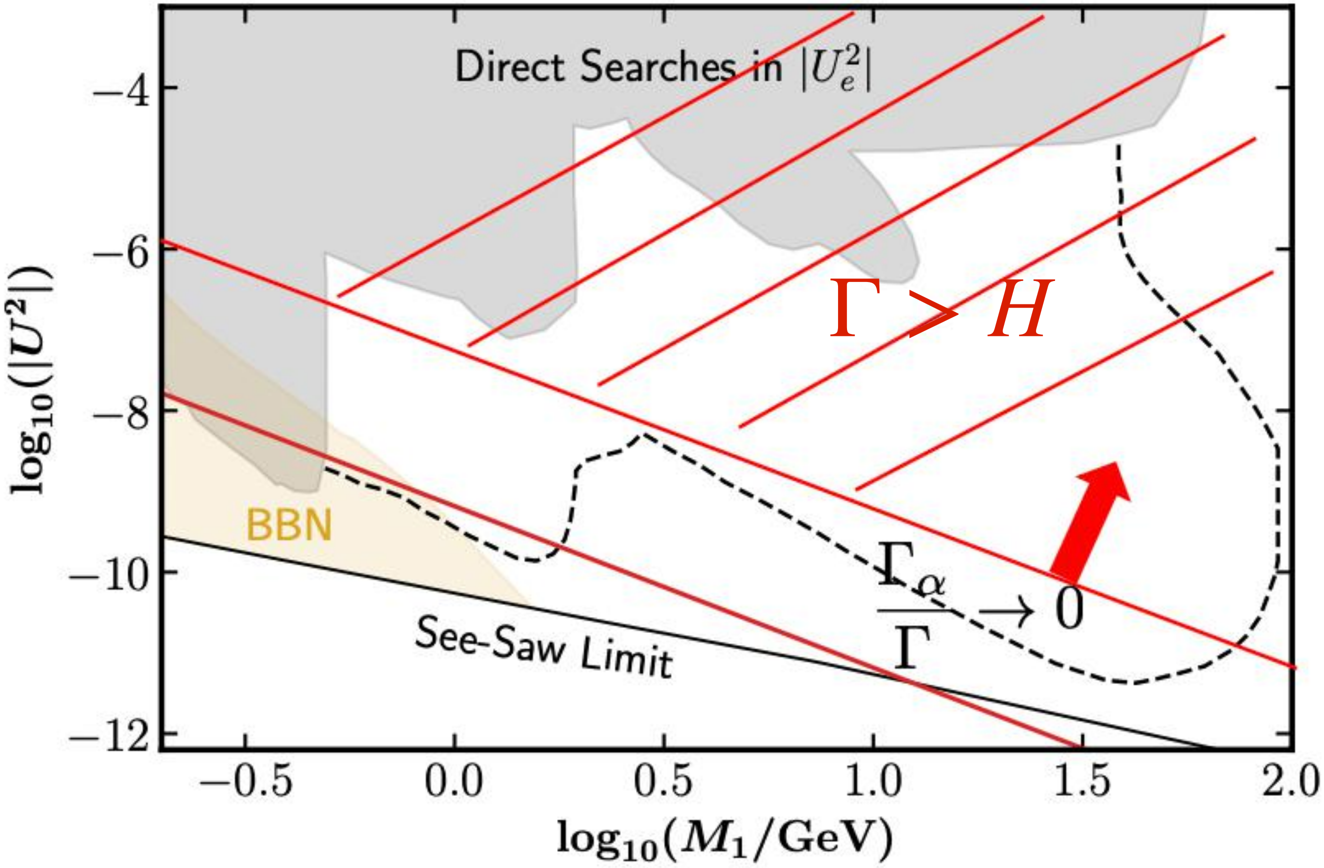
Estimated equilibration rate at EWPT:

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



Violation of Sakharov conditions!?

Washout regimes



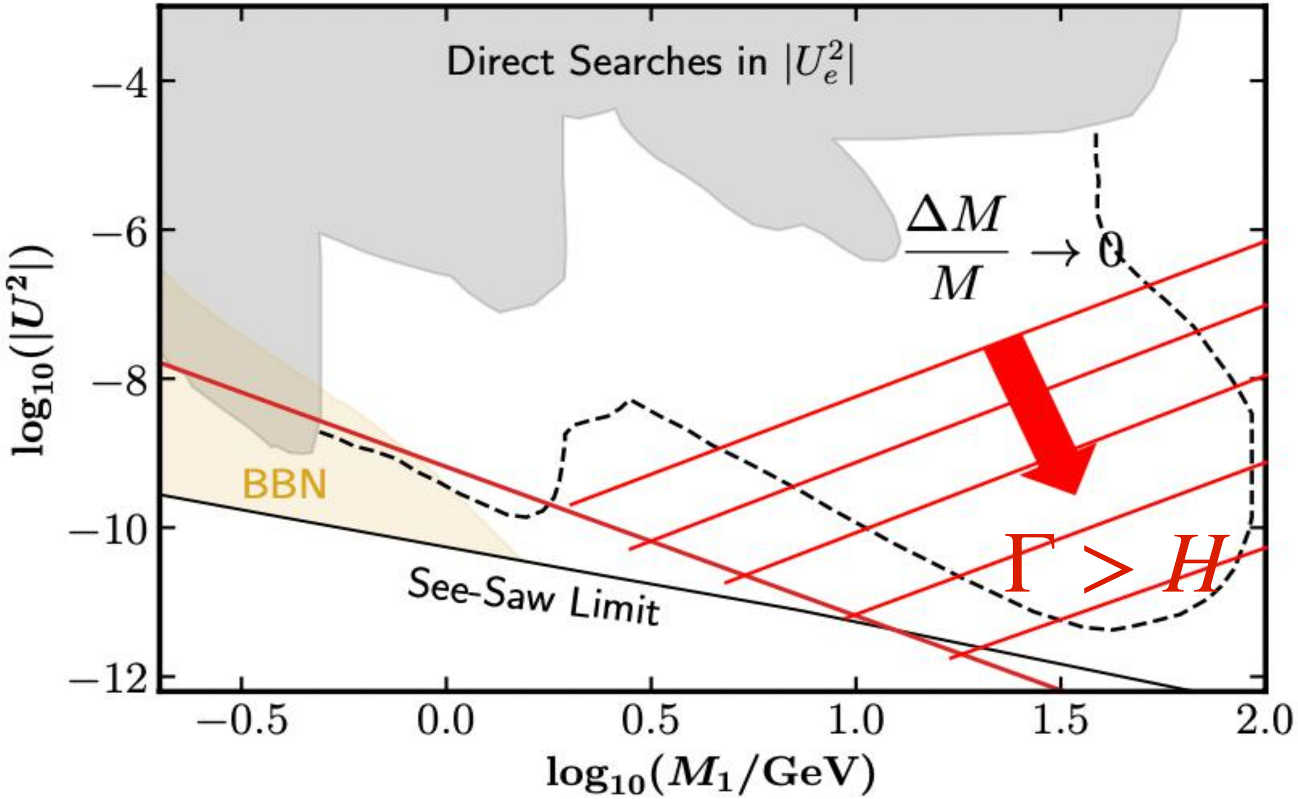
if $|y_\alpha| \ll |y_\beta|$

$\epsilon_\alpha \ll 1$

Flavoured weak washout:

$$\Gamma_\alpha \propto (YY^\dagger)_{\alpha\alpha} T = \frac{(YY^\dagger)_{\alpha\alpha}}{(YY^\dagger)} (YY^\dagger) T \equiv \epsilon_\alpha \Gamma$$

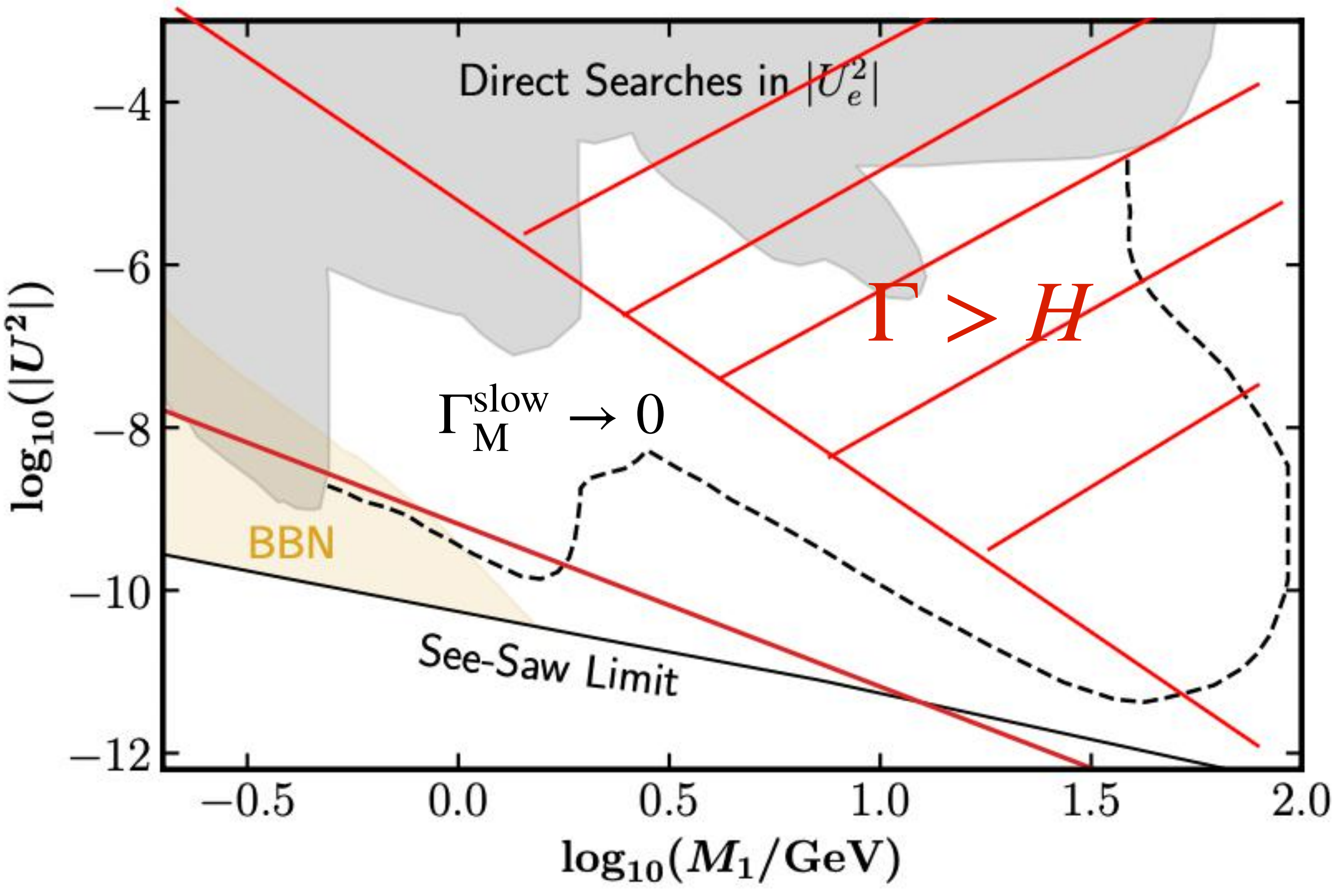
Washout regimes



Damped oscillations lead to weakly coupled lepton number.

$$\Gamma_{\text{osc}}^{\text{slow}} \propto \left(\frac{\Gamma_{\text{osc}}^{\text{vac}}}{\Gamma}\right)^2 \Gamma \equiv \epsilon^2 \Gamma \quad \text{with vacuum rate} \quad \Gamma_{\text{osc}}^{\text{vac}} \propto \frac{M_2^2 - M_1^2}{T} \propto \frac{\mu}{T}$$

Washout regimes

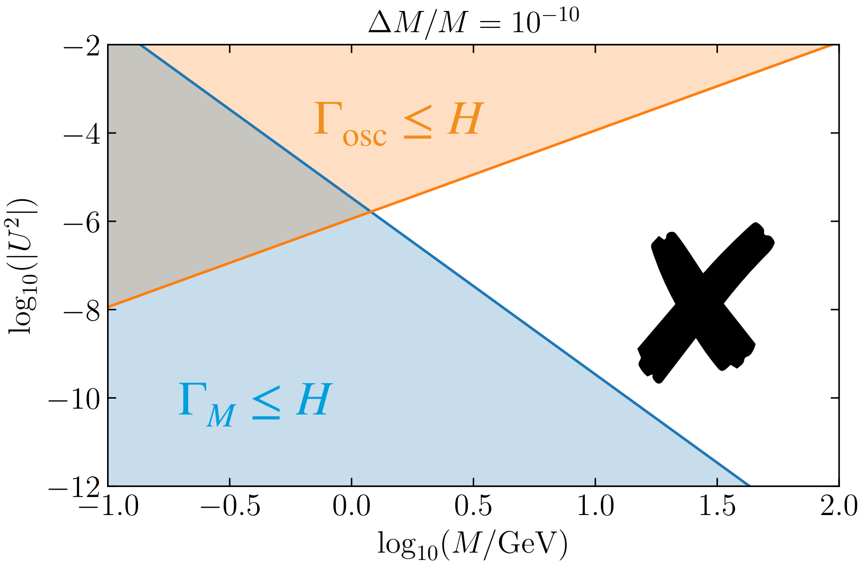


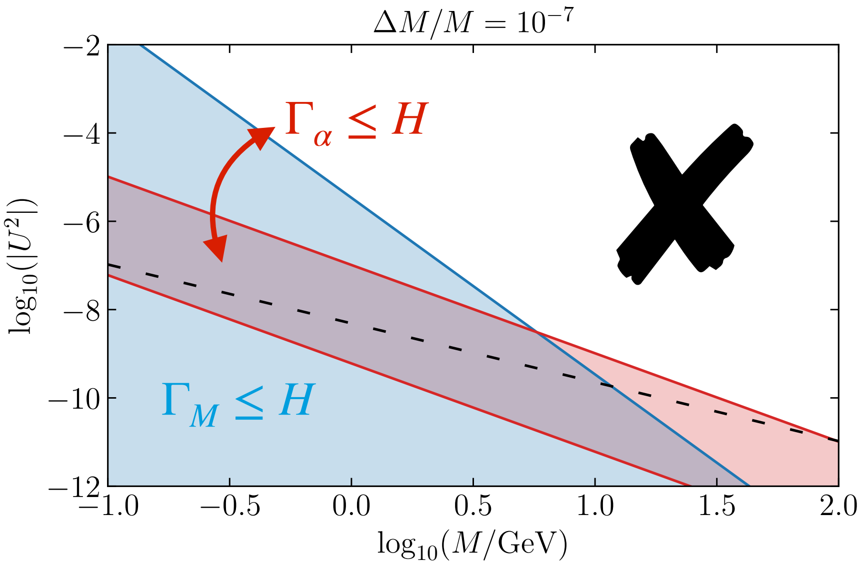
Weak helicity conserving due to $(M/T) \ll 1$: $\Gamma_{\rm M}^{\rm slow} \propto \left(\frac{M_i}{T}\right)^2 T$

Leptogenesis via oscillations

Projection onto 2D parameter space of $(M, |U^2|)$ for different ΔM

⇨ Identification of non-thermal regimes.





✗ System reaches thermal equilibrium. No asymmetry.
Major speed up of numerical sampling.

Each regime allows for adiabatic solution[1]**.**

[1] Hernandez, Lopez-Pavon, Rius, Sandner ‘22

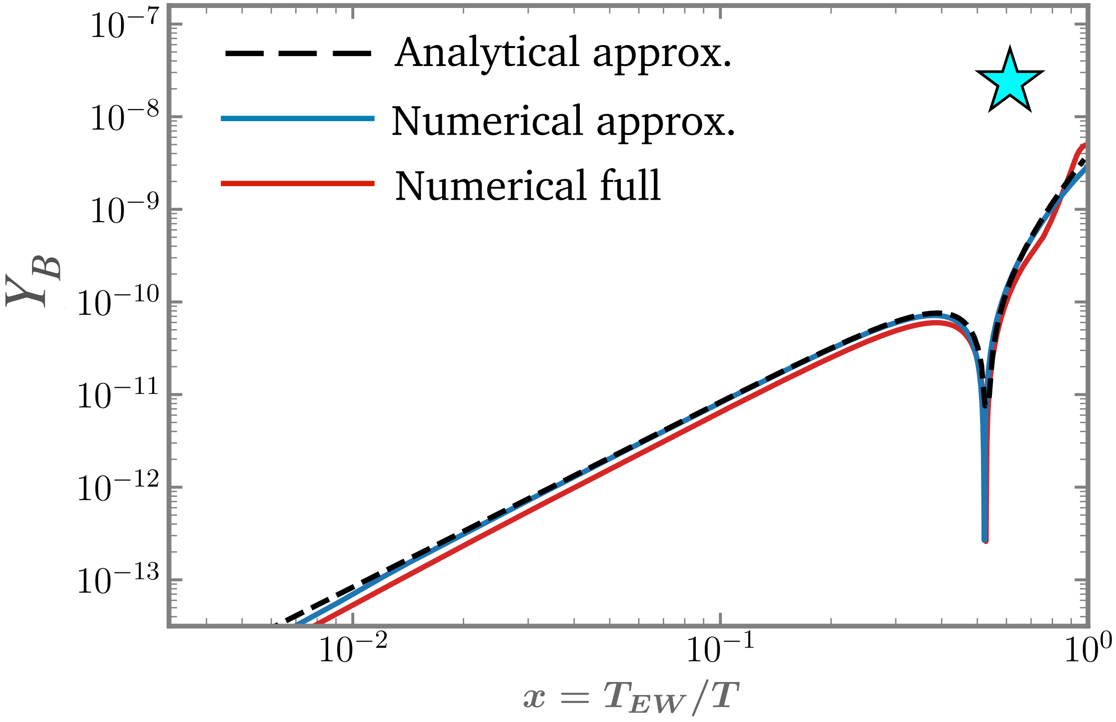
Leptogenesis via oscillations

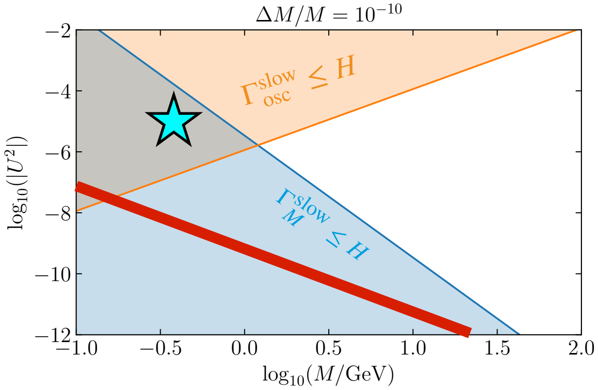
Recall expectation:

$Y_B = f_i\left(\Delta_\alpha\right) + \bar{f}_i\left(\Delta_\alpha^M\right)$

$$Y_B \simeq -\frac{4\kappa\Delta x^2}{6\gamma_0+\kappa\gamma_1}\frac{\gamma_0^2}{\gamma_0^2+4\omega^2}\boxed{\sum_\alpha \frac{y_\alpha y'_\alpha \sin\Delta\beta_\alpha}{y^2}\left(\frac{1}{y_\alpha^2}-\frac{3}{y^2}\right)} + \frac{48}{5}\frac{\kappa s_0\Delta x^5}{6\gamma_0+\kappa\gamma_1}\frac{\gamma_0^2}{\gamma_0^2+4\omega^2}\frac{M^2}{T_{\rm EW}^2}\boxed{\sum_\alpha\frac{y_\alpha y'_\alpha\sin\Delta\beta_\alpha}{y^2}},$$

CP invariants!



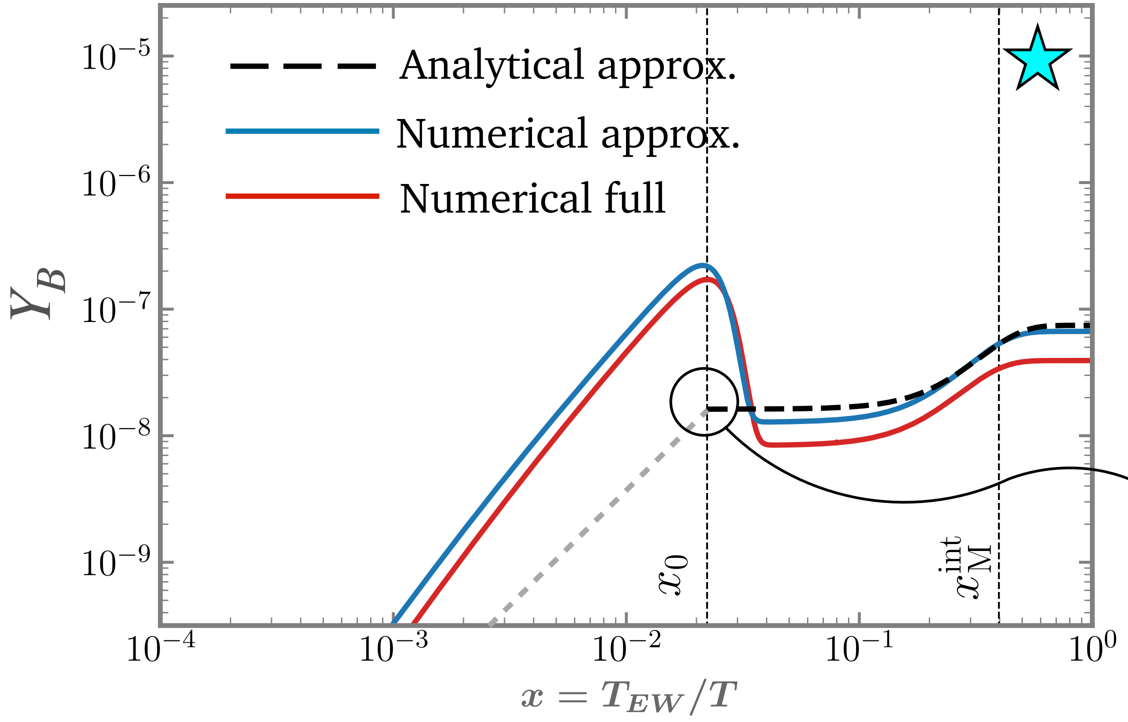


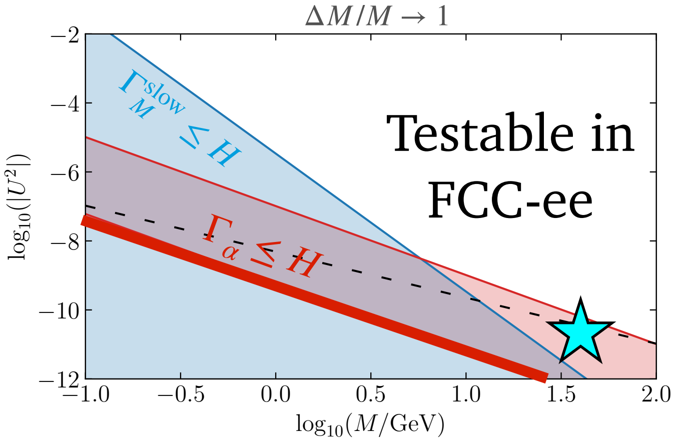
★ Testable in SHiP

Hernandez, Lopez-Pavon, Rius, Sandner '22

Leptogenesis via oscillations

Similar agreement in all other washout regimes.





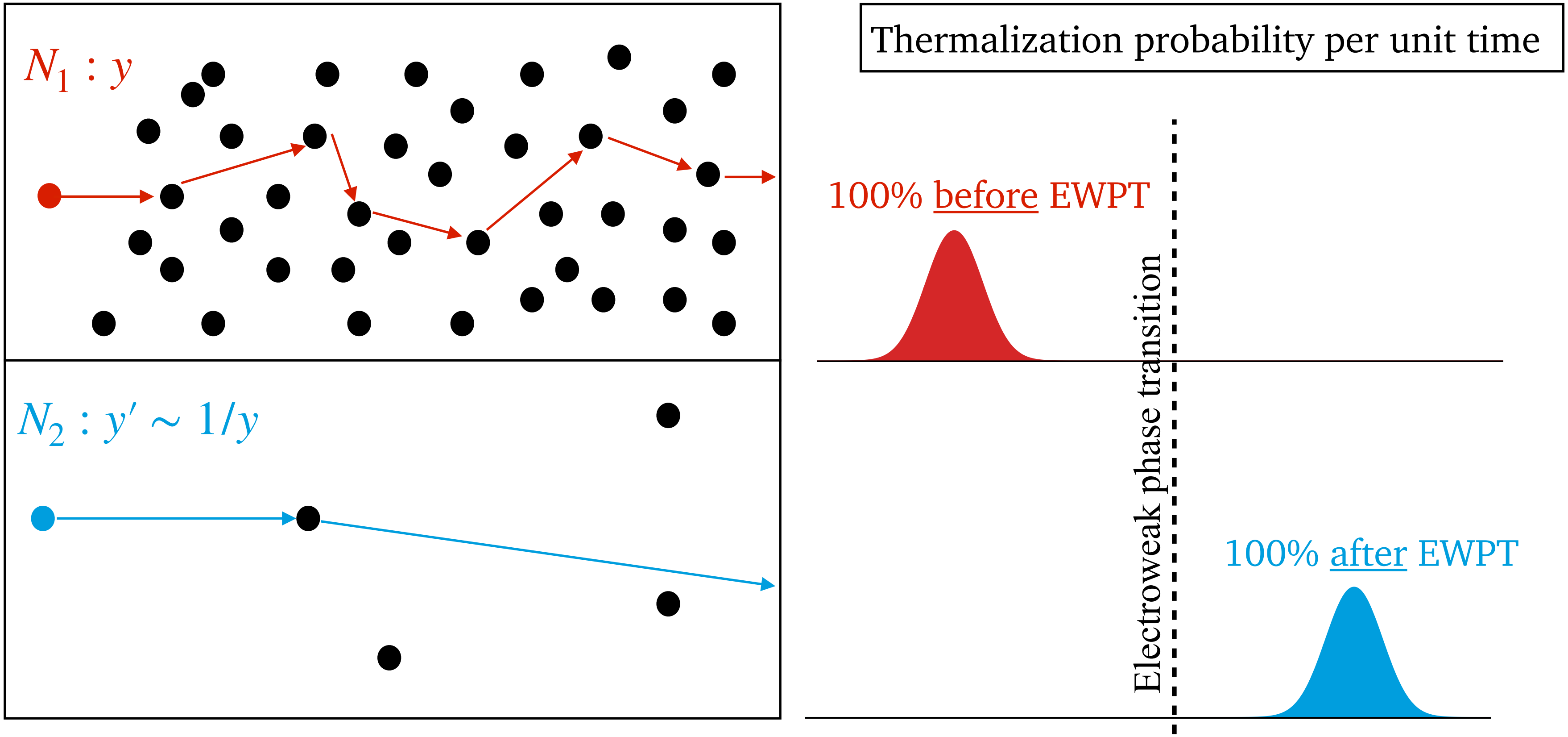
Testable in FCC-ee

Derived new analytical *projection method* for when adiabatic hierarchy flips over time.

Hernandez, Lopez-Pavon, Rius, Sandner ‘22

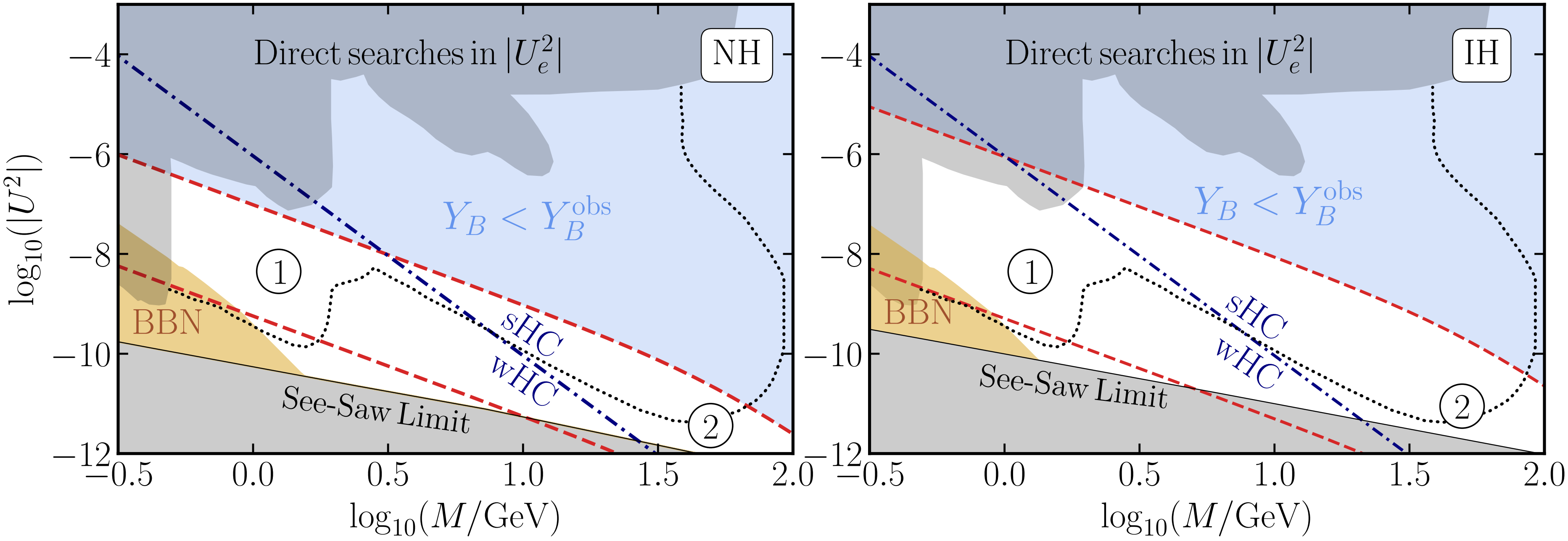
Leptogenesis via oscillations

<u>Example</u>: If *oscillations are damped* $\Gamma^{\mathrm{th}}_{osc} \simeq P_{osc}\Gamma \lesssim H$ is realizable until EWPT.
Physical motivation: softly broken LN symmetry.



Washout regimes

Within red band we expect a non-vanishing baryon asymmetry.



Solve for Y_B *analytically* in regions ① and ② — similar as before but higher order.

Hernandez, Lopez-Pavon, Rius, Sandner ‘23

Analytical approximation

Recall expectation:

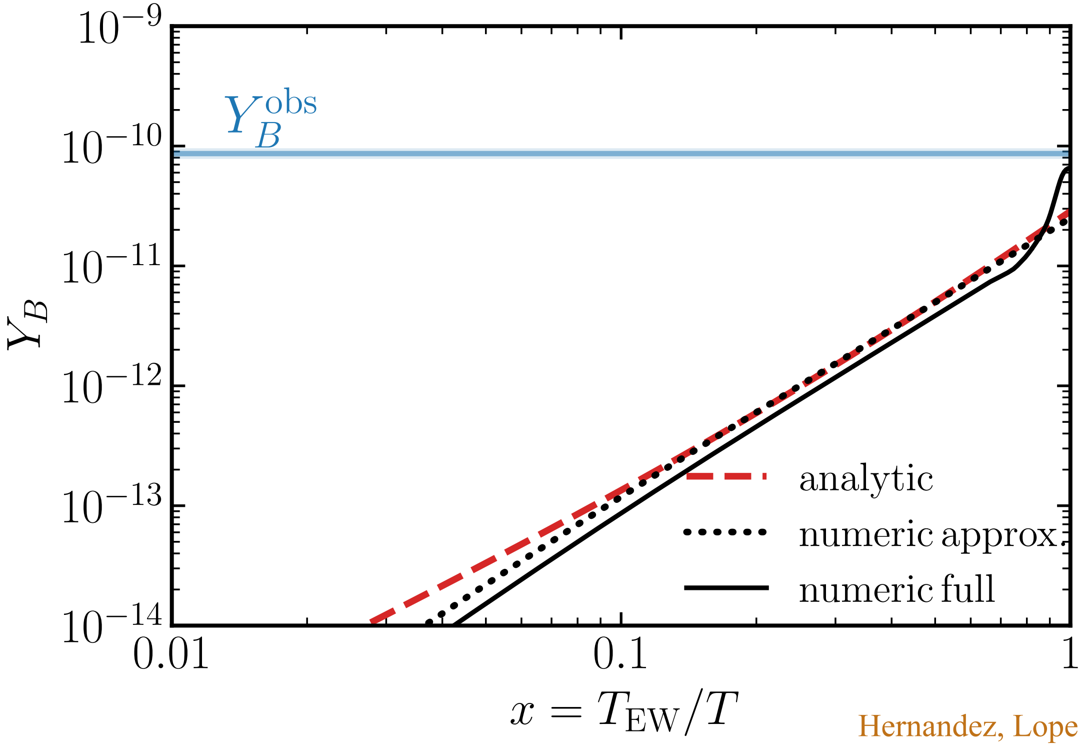
$Y_B = f_i\left(\Delta_\alpha^{th}\right) + \bar{f}_i\left(\Delta_\alpha^{th}\right)$

$$Y_B \simeq -\frac{\chi}{T_{\rm EW}^2}\frac{4\gamma_0\kappa(s_0\omega+\gamma_0\omega_M)}{(4\gamma_0+\gamma_1\kappa)(\gamma_0^2+4\omega^2)}\left(\frac{\gamma_1\kappa}{3}\bar{\Delta}_\alpha + 2\sum_{\beta\neq\alpha}\bar{\Delta}^M_\beta\right)$$

Weak flavor CP invariant

Strong flavor CP invariant

✓



Hernandez, Lopez-Pavon, Rius, Sandner ‘23

Sakharov conditions

- If C or CP are conserved: $\Gamma(A \to B + C) = \Gamma(\bar{A} \to \bar{B} + \bar{C})$

- Production and destruction rates in equilibrium: $\Gamma(A \to B + C) = \Gamma(B + C \to A)$

CP violation

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

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

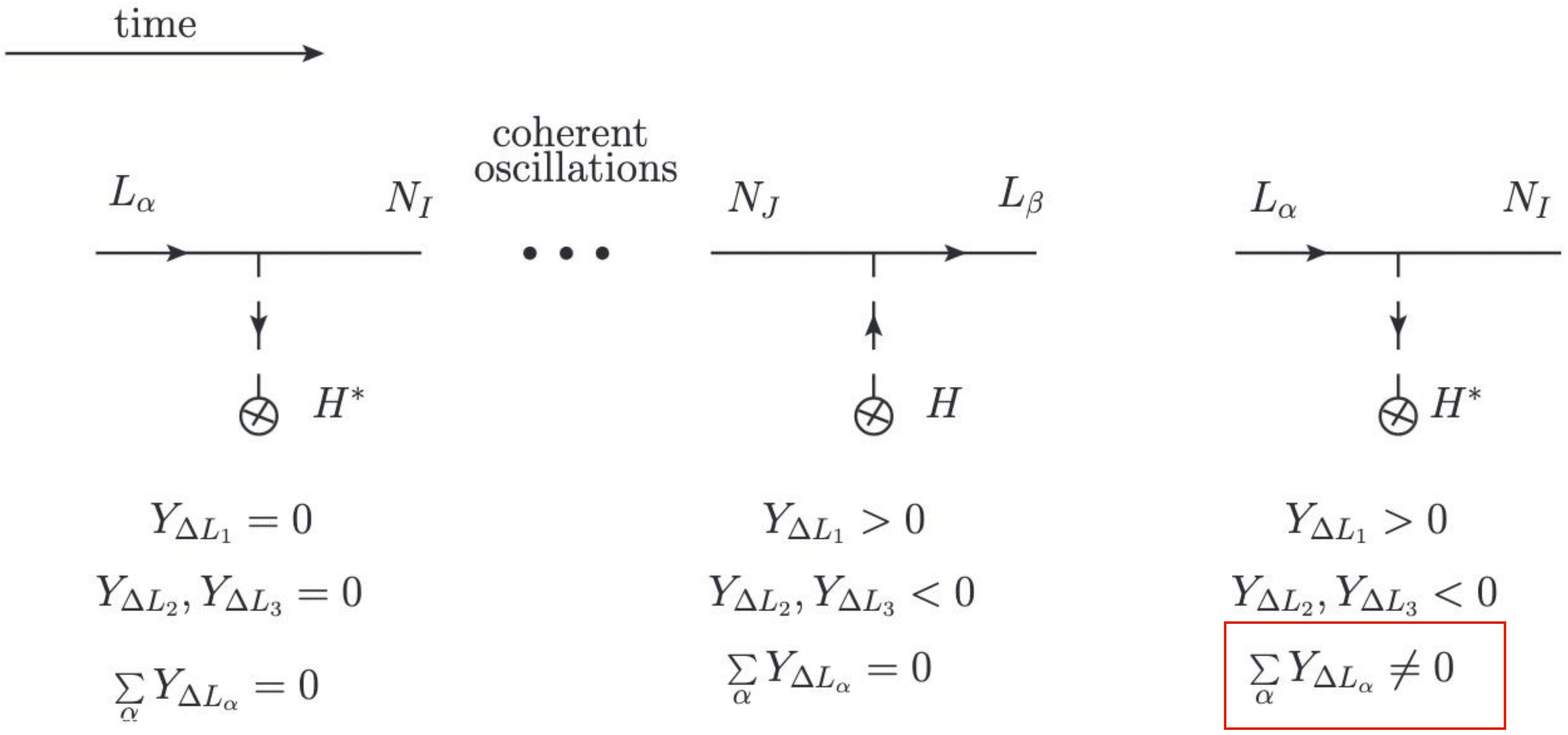
Vanishes if $|\phi_2 - \phi_1| = 0$ or $|\delta_2 - \delta_1| = 0$

In the context of ARS leptogenesis:

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

P. Hernandez ’23, Dublin Theoretical Physics Colloquia

Leptogenesis via oscillations



$$Y_{\Delta L_1} = 0$$
$$Y_{\Delta L_2}, Y_{\Delta L_3} = 0$$
$$\sum_\alpha Y_{\Delta L_\alpha} = 0$$

$$Y_{\Delta L_1} > 0$$
$$Y_{\Delta L_2}, Y_{\Delta L_3} < 0$$
$$\sum_\alpha Y_{\Delta L_\alpha} = 0$$

$$Y_{\Delta L_1} > 0$$
$$Y_{\Delta L_2}, Y_{\Delta L_3} < 0$$
$$\boxed{\sum_\alpha Y_{\Delta L_\alpha} \neq 0}$$

Out of equilibrium HNL production

Asymmetry in lepton flavors

Different washout of flavor asymmetries

Shuve, Yavin '14

CP violation

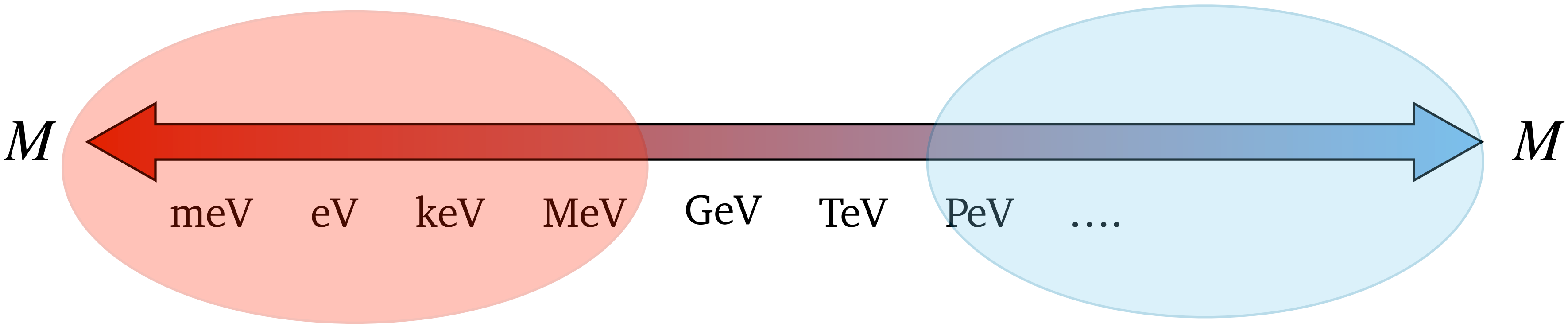
CP violating observable. → Weak basis independent CP invariants.

Same game as for SM Jarlskog invariant, but new playground: (M_R, Y, Y_ℓ)

Generic invariant transformation of flavour basis
$$\begin{cases} M_R & \rightarrow W^T M_R W \\ Y & \rightarrow V^\dagger Y W \\ Y_\ell & \rightarrow V^\dagger Y_\ell U \end{cases}$$

Can distinguish two types of CP violating sources — High scale or mixture.

Neutrino masses — Minimal model

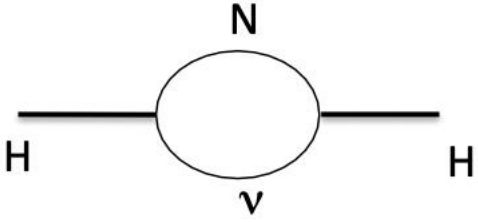


Excluded by cosmology

Not testable & hierarchy problem

Dark matter / dark radiation

- Big Bang Nucleosynthesis
- Cosmic microwave background
- Large scale structure



$$\delta m_h^2 = \frac{YY^\dagger}{4\pi^2} M^2 \log \frac{M}{\mu}$$

Dolgov, Hansen, Raffelt, Semikoz; Ruchayskiy, Ivashko; Hernandez, Kekic, López-Pavón; Vincent et al;….; Vissani ’97

Relate to observables

$$\Delta_X(\Delta m_\nu, \delta, \phi, U^2, M, \Delta M, \theta)$$

ϕ via i) $0\nu\beta\beta$ decay or ii) heavy neutrino flavor ratio depends on U_{PMNS} phases.