Predicting the baryon asymmetry in the low scale type I see saw

Based on [2207.01651] & [2305.14427]

Pilar Hernandez, Jacobo López-Pavón, Nuria Rius and Stefan Sandner*
*stefan.sandner@ific.uv.es

IRN Neutrino meeting, June 20, 2023

IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT DE VALÈNCIA Facultat de Física
"la Caixa" Foundation

Outline

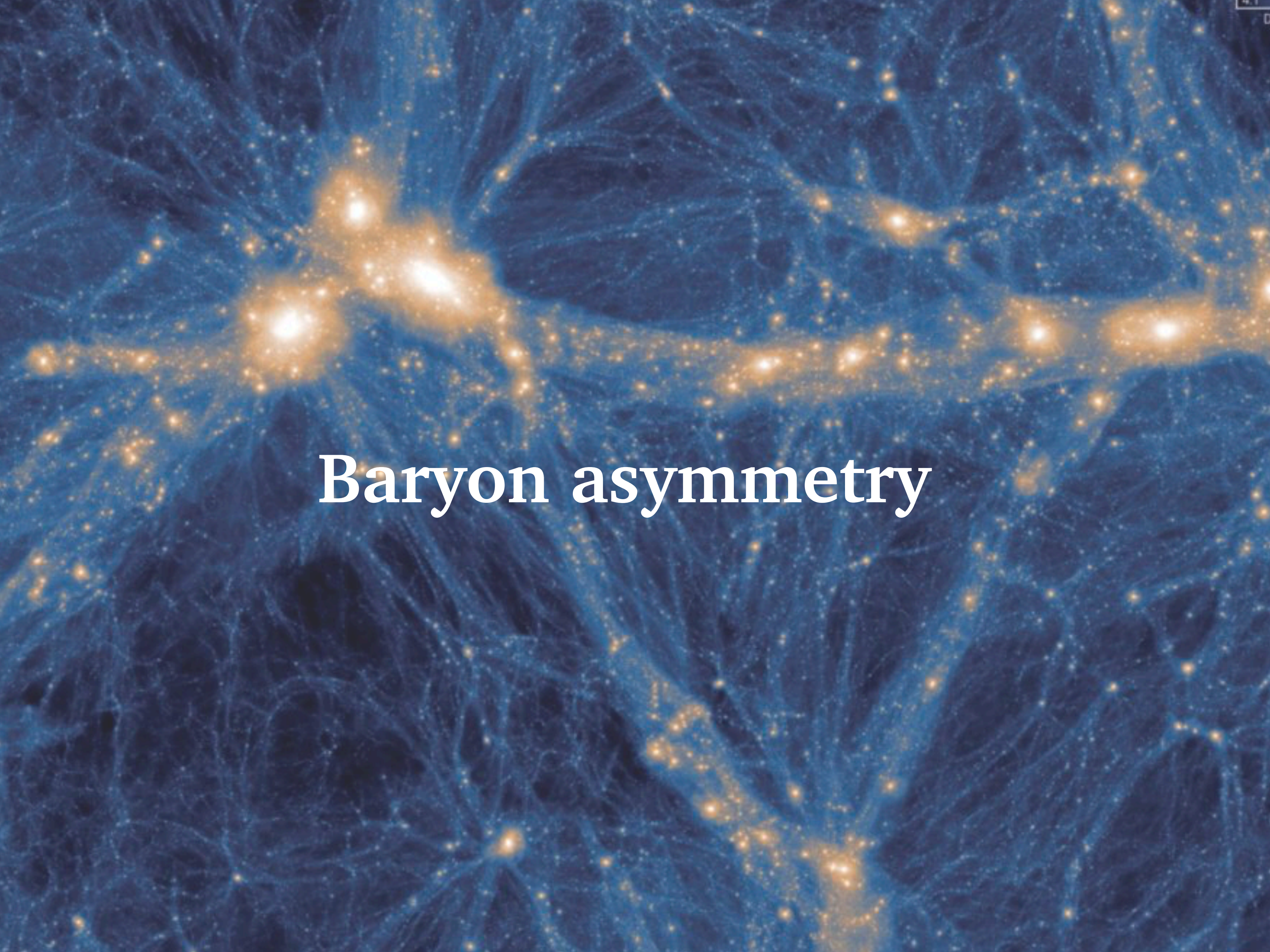
- The baryon asymmetry.
- Origin of neutrino masses.

The general problem we try to address.

Our work

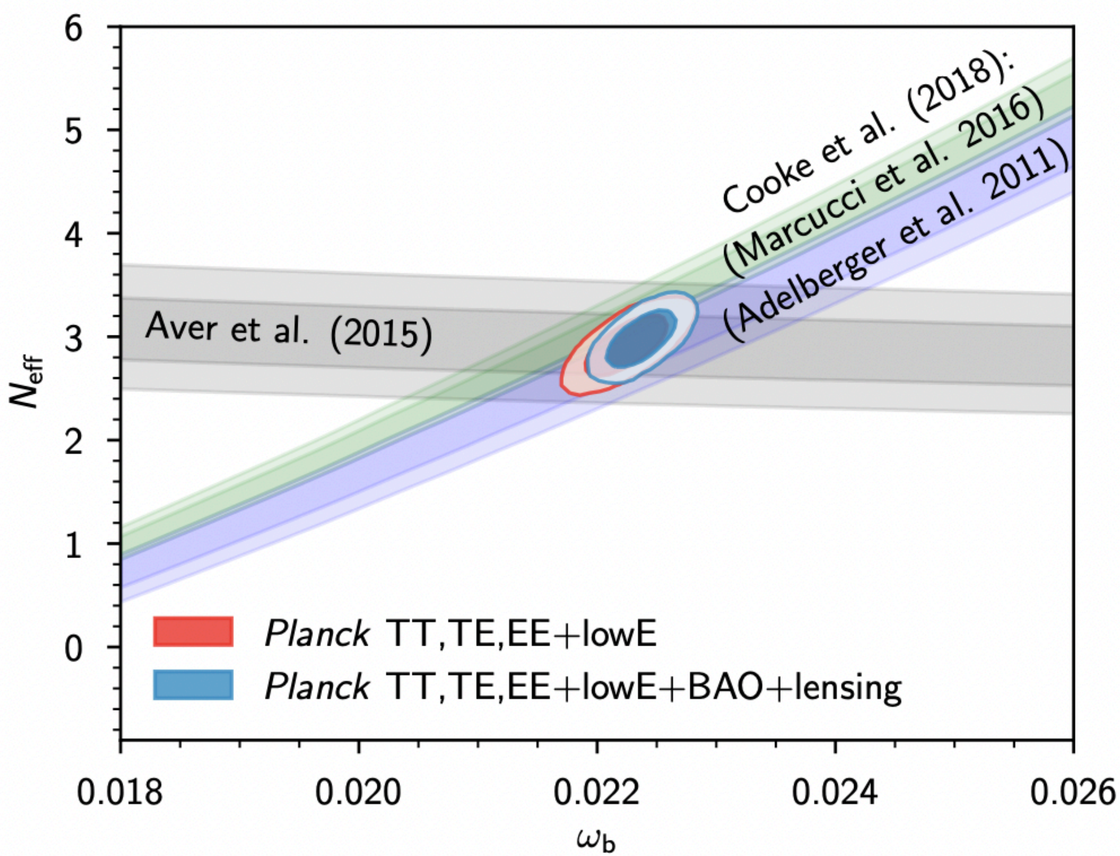
- Constraints from the asymmetry. **[2207.01651]**
- Predicting the asymmetry from the lab. **[2305.14427]**

Baryon asymmetry



Baryon asymmetry

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

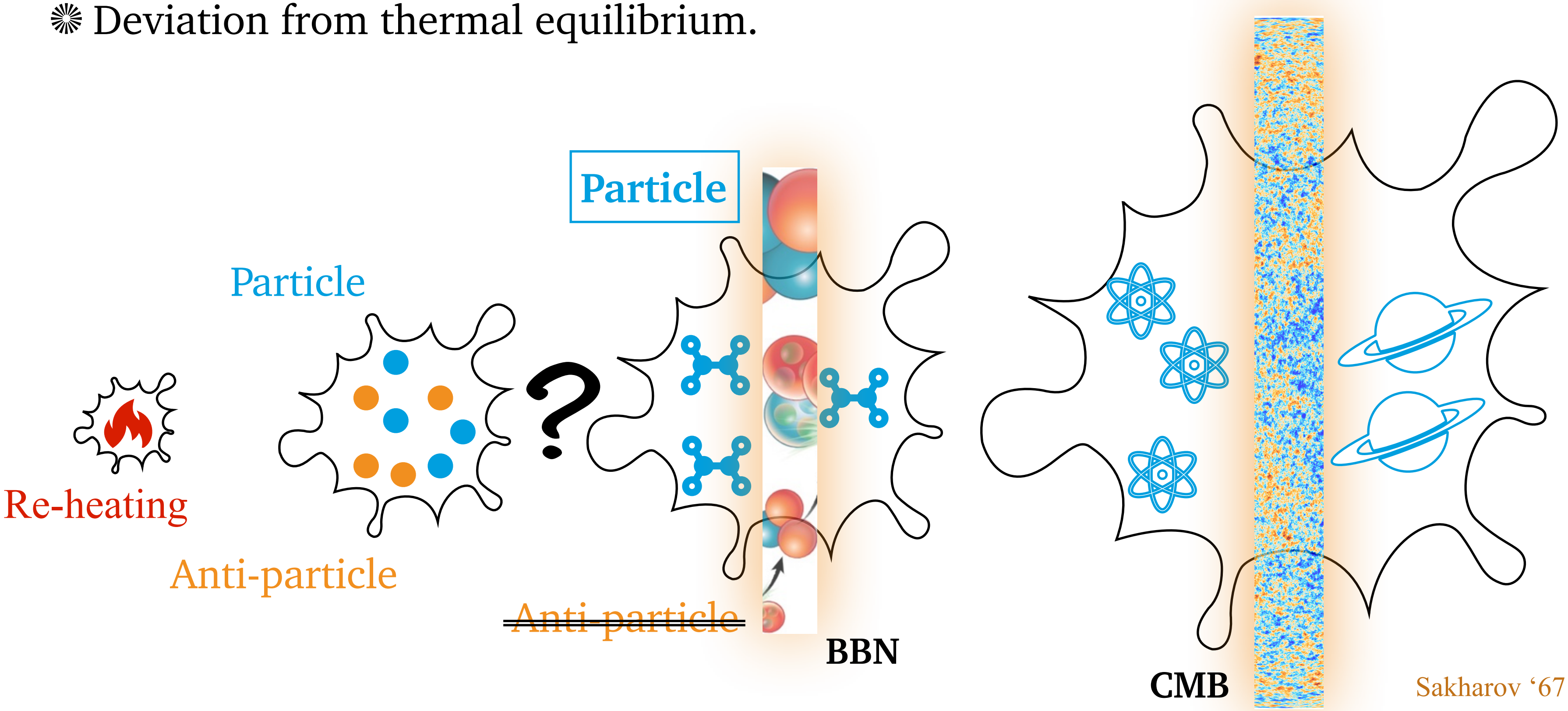


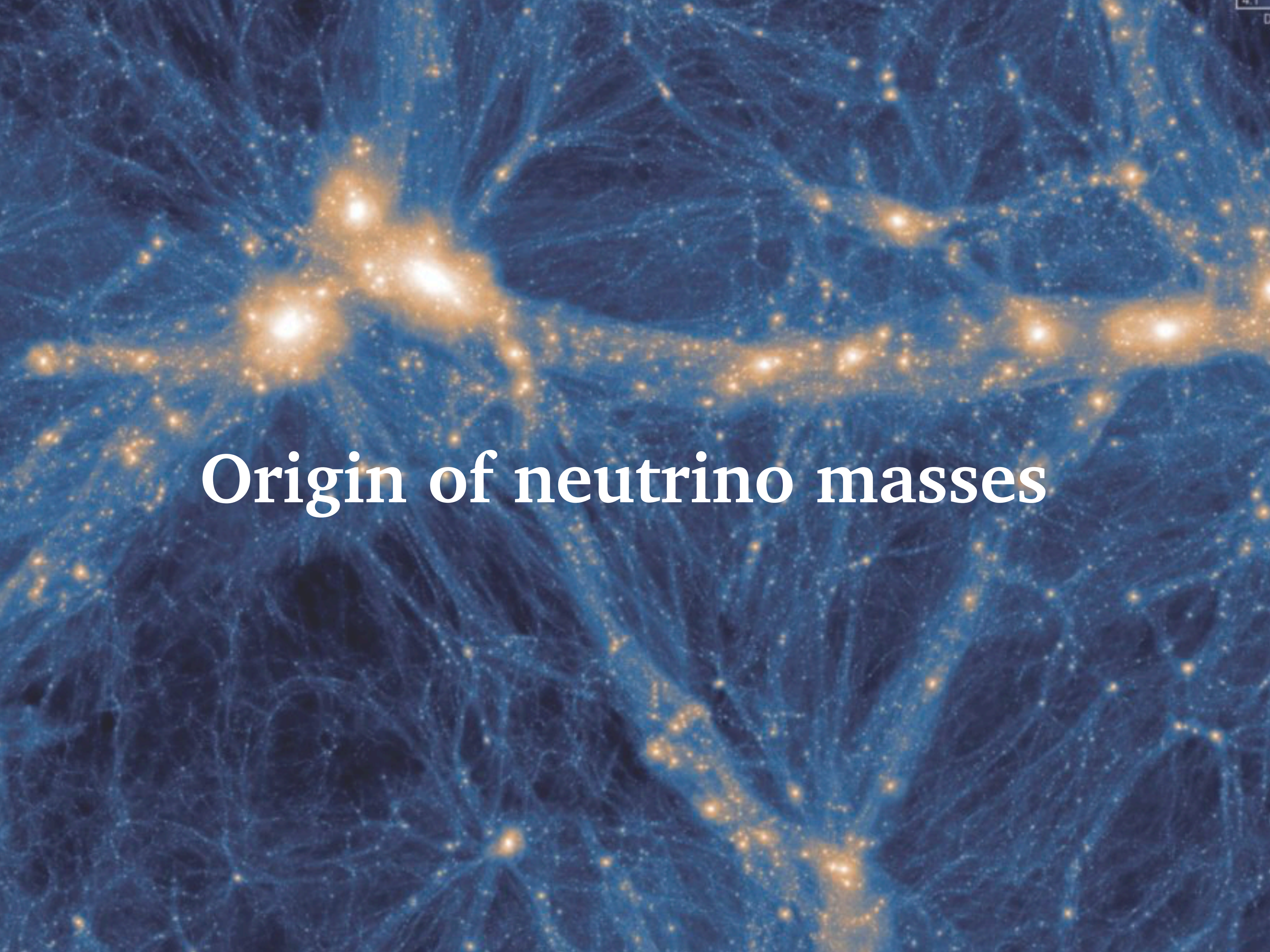
Every (dynamical) model needs to explain $Y_B|_{\text{today}} = (8.66 \pm 0.01) \times 10^{-11}$

Baryon asymmetry

Dynamical creation is fundamentally constrained. ➡ **Sakharov Conditions.**

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





Origin of neutrino masses

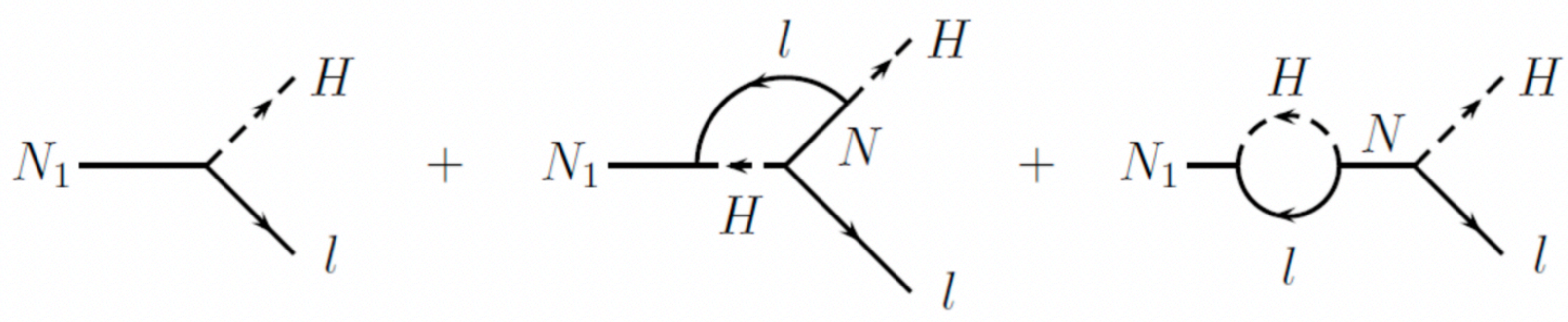
Neutrino masses — Minimal model

<u>Minimal scenario</u>: Type I see saw with 2 heavy neutrinos.

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

Lepton number violation
& CP violation

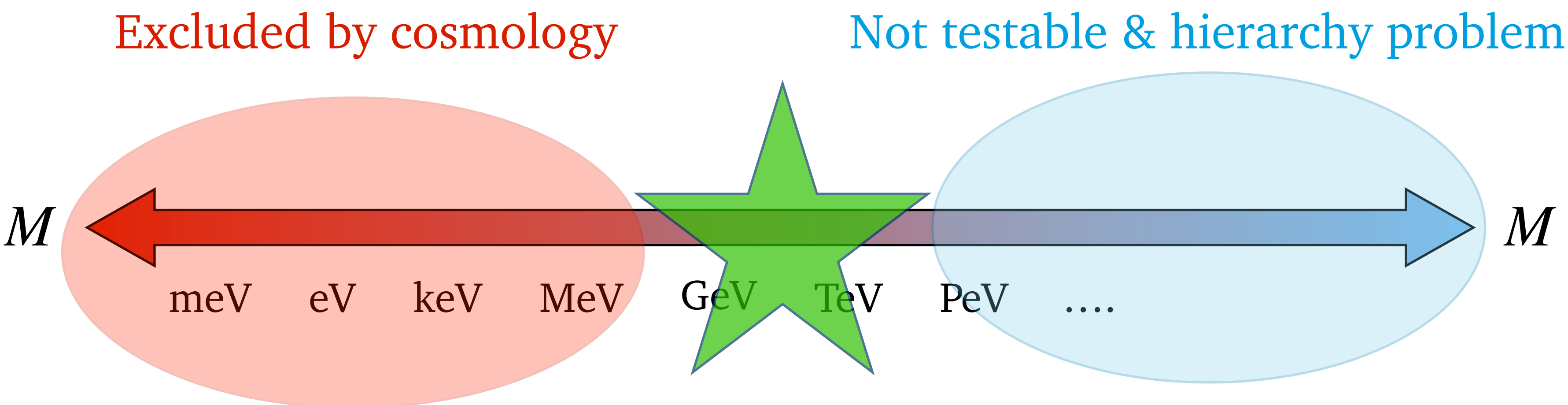
Complex Yukawas:
new CP violation

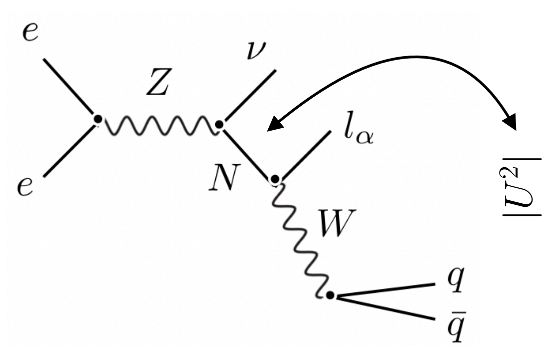


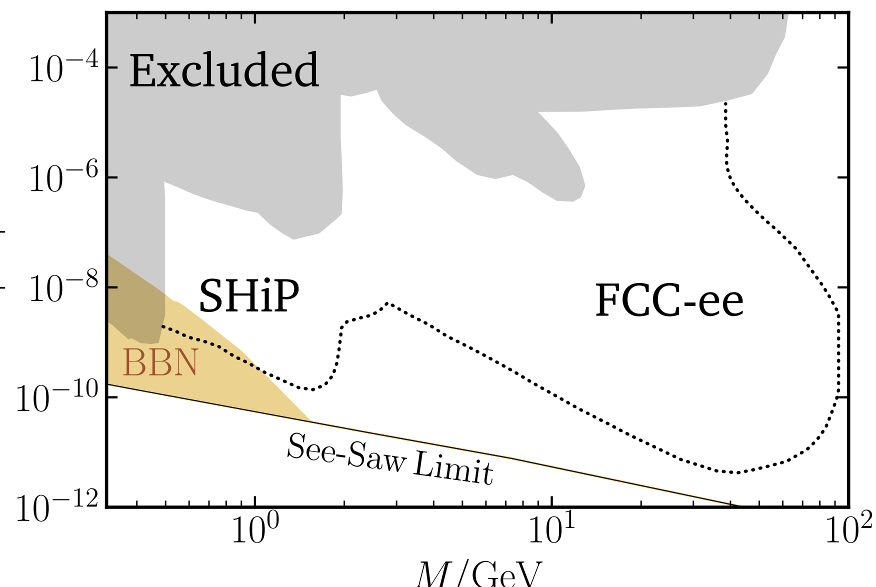
Possible to constrain M?

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

Neutrino masses — Minimal model







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

Neutrino masses — Minimal model

Testable mixings between light and heavy neutrinos.

Approximate **lepton number symmetry**.

Quasi-Dirac pairs.

$$
\begin{array}{c} \\ \\ M_\nu = \end{array}
\begin{array}{ccc} \overline{\nu^c} & \overline{N}_1 & \overline{N}_2 \\ 1 & -1 & 1 \end{array}
$$

$$
M_\nu = \begin{pmatrix} 0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} \\ Y_1 v/\sqrt{2} & \mu' & M \\ \epsilon Y_2 v/\sqrt{2} & M & \mu \end{pmatrix}
\qquad
\begin{array}{cc} L & \\ 1 & \nu \\ -1 & N_1^c \\ 1 & N_2^c \end{array}
$$

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.

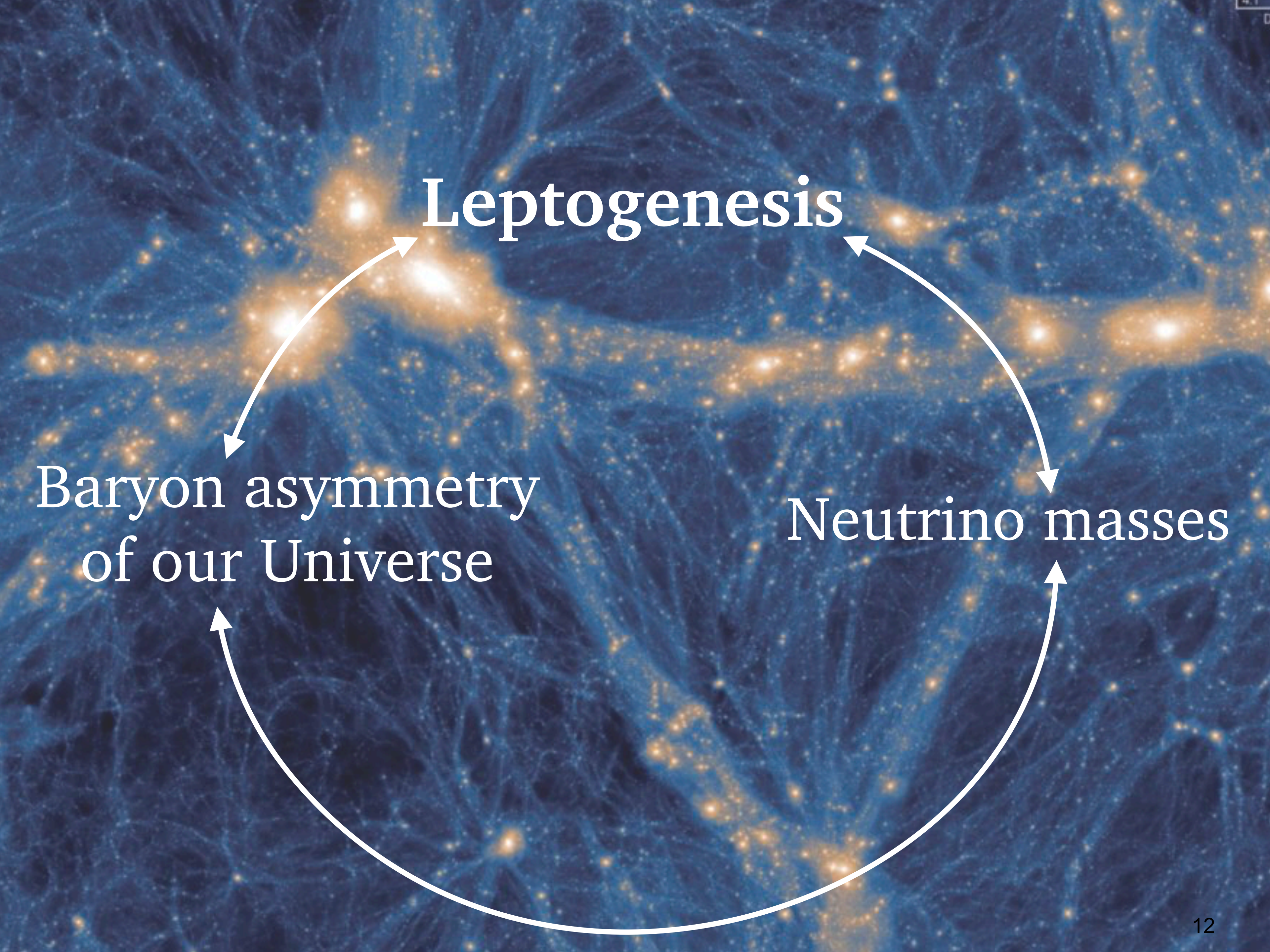
$$Y = f(U_{\rm PMNS}, U^2, m_\nu, M, \Delta M, \theta)$$

Light sector

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

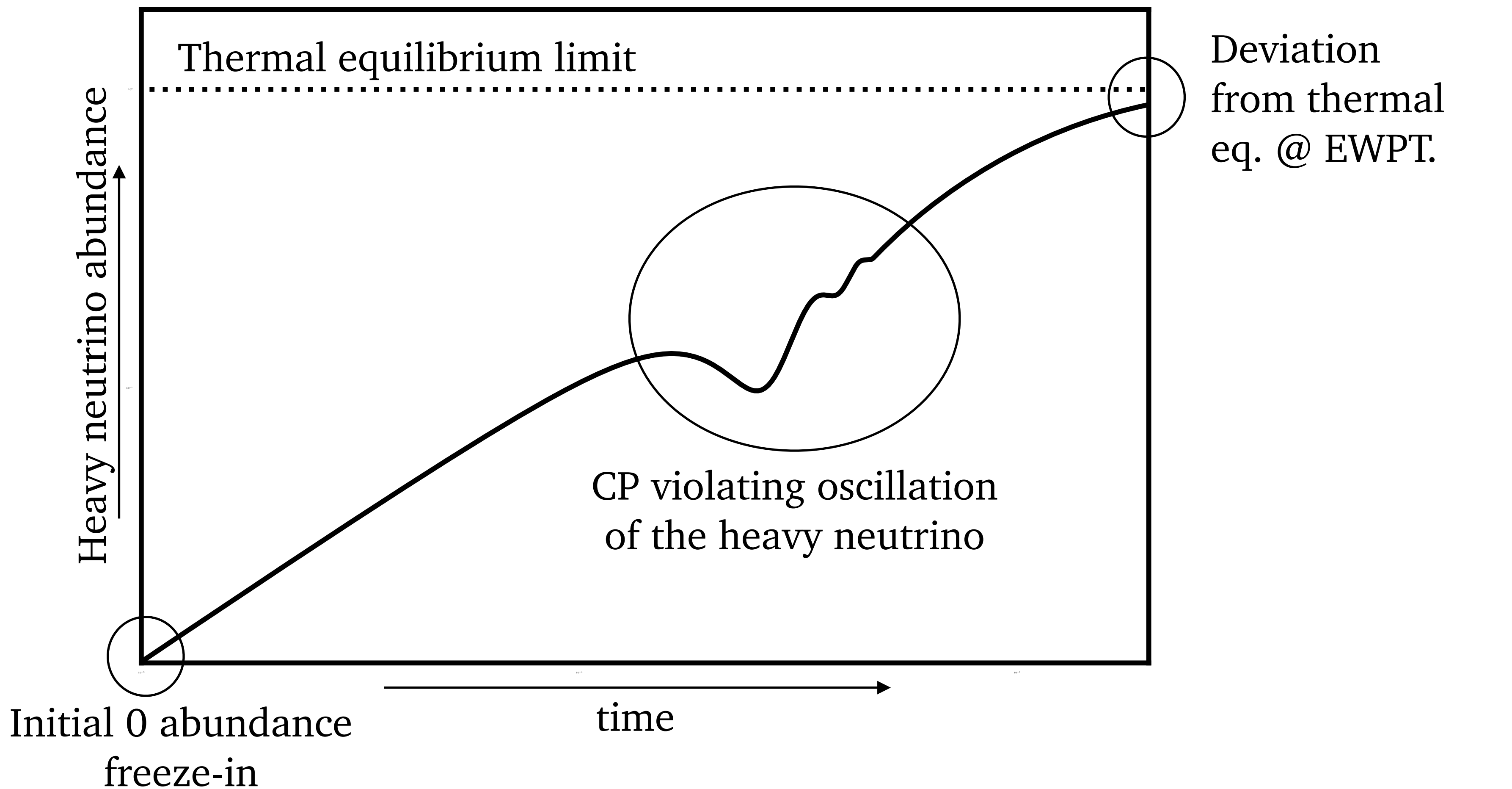
Heavy sector

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


Leptogenesis
Baryon asymmetry of our Universe
Neutrino masses

Leptogenesis via oscillations

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



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

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

$x = 1/T$

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

$$\begin{aligned}
xH_u \frac{\mathrm{d}r_{\bar N}}{\mathrm{d}x} =& -i[\langle H^*\rangle, r_{\bar N}] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{Y^TY^*, r_{\bar N}-1\} - x^2\frac{\langle s_N^{(0)}\rangle}{2}\{MY^\dagger YM, r_{\bar N}-1\} \\
&- \langle\gamma_N^{(1)}\rangle Y^T\mu Y^* + x^2\langle s_N^{(1)}\rangle MY^\dagger\mu YM \\
&+ \frac{\langle\gamma_N^{(2)}\rangle}{2}\{Y^T\mu Y^*, r_{\bar N}\} - x^2\frac{\langle s_N^{(2)}\rangle}{2}\{MY^\dagger\mu YM, r_{\bar N}\},
\end{aligned}$$

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

$\bar{r} \to r$ similar

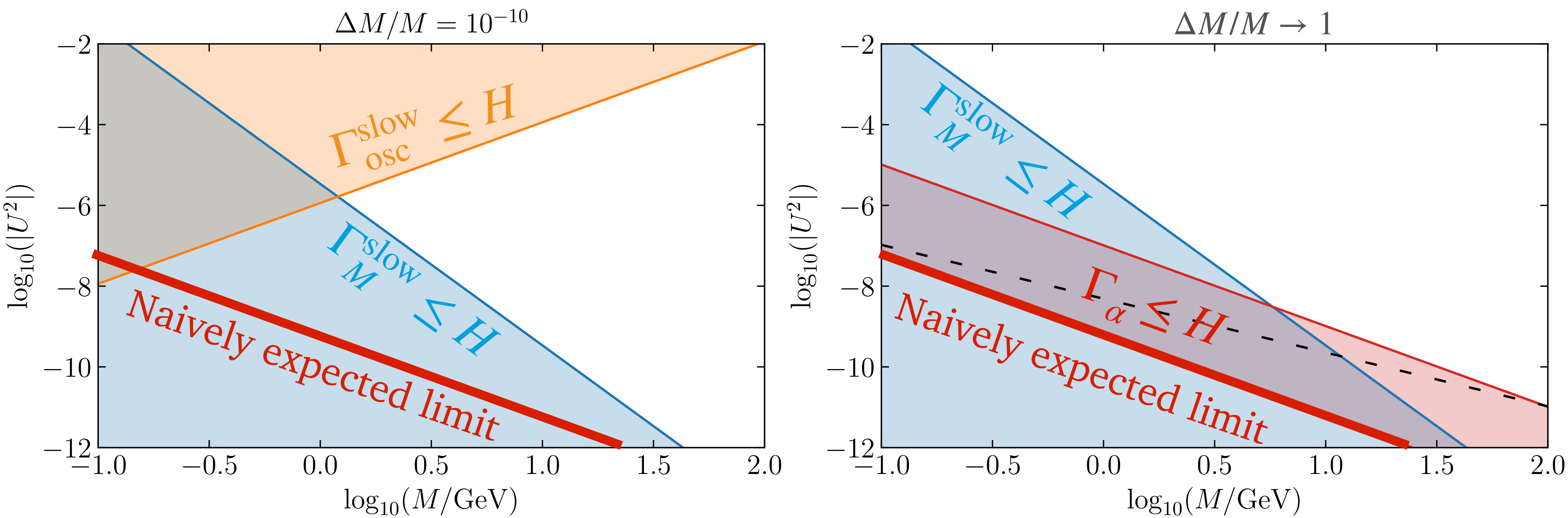
Raffelt, Sigl ’93; Ghiglieri, Laine ‘17

Washout regimes

Coloured regions in principle provide enough out of equilibrium.

Highly degenerate neutrinos

Less degenerate neutrinos



Sakharov conditions fulfilled in testable region of parameter space.

Hernandez, Lopez-Pavon, Rius, Sandner '22

CP violation

Same game as for SM Jarlskog invariant, but new playground: Y_l, Y, M.

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

$$\equiv \sum_\alpha y^2_{\ell_\alpha} \Delta_\alpha(\Delta m_{\mathrm{sol}}, \Delta m_{\mathrm{atm}}, \delta, \phi, U^2, M, \theta)$$

Hermitian combination —
Insensitive to Majorana character.

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

$$\equiv \sum_\alpha \Delta^M_\alpha(\Delta m_{\mathrm{sol}}, \Delta m_{\mathrm{atm}}, \delta, \phi, U^2, M, \theta)$$

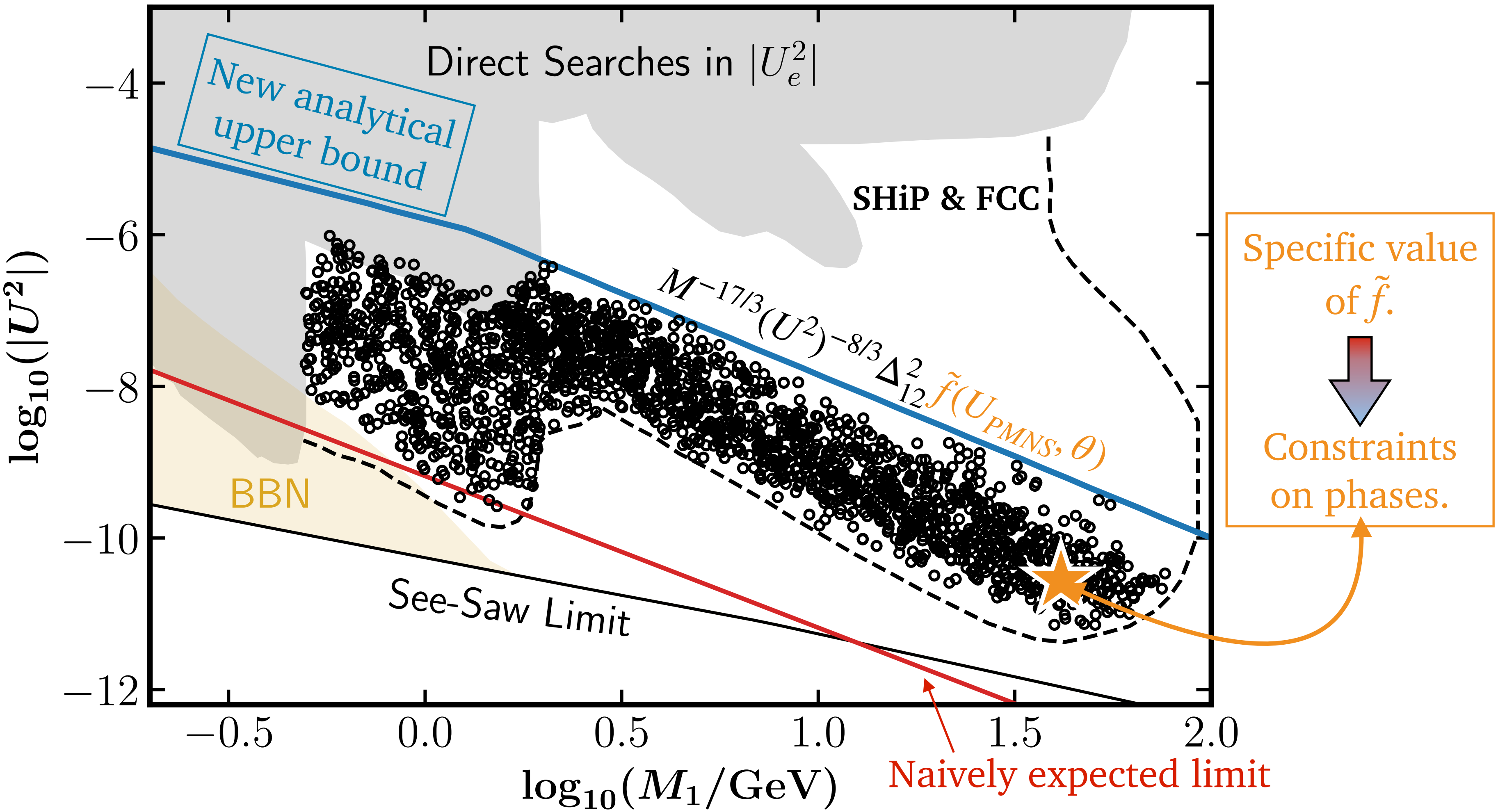
High scale phase —
Pure Majorana character.

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

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

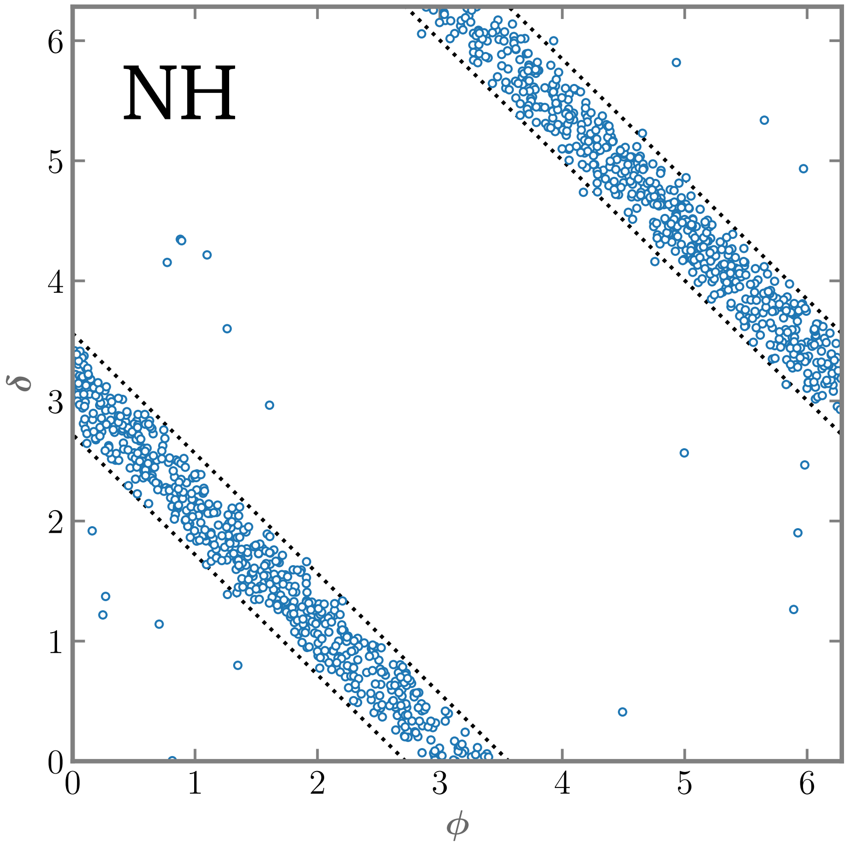
Hernandez, Lopez-Pavon, Rius, Sandner ‘22

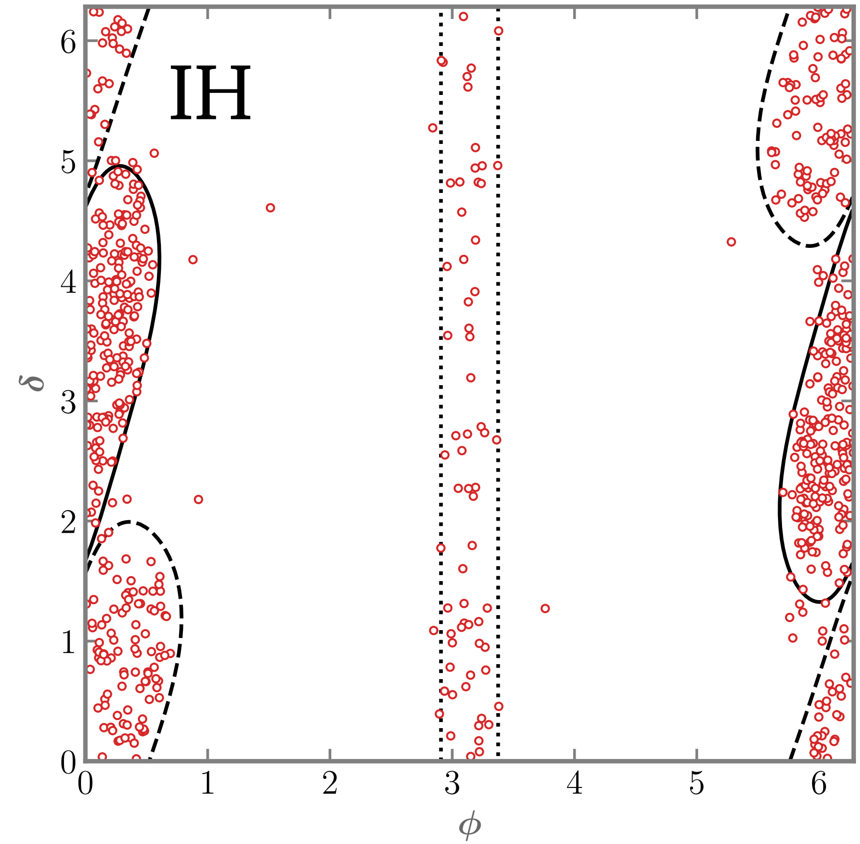
Upper bound on HNL mixing



Hernandez, Lopez-Pavon, Rius, Sandner '22

Constraints on CP phases



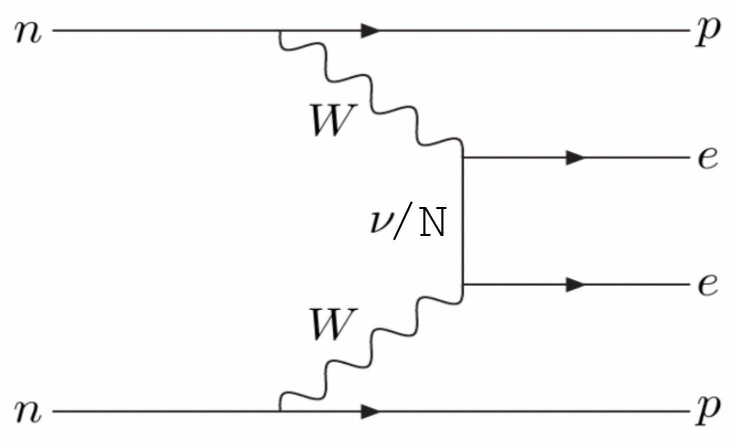


PMNS phases correlated by imposing the observed asymmetry.

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

Hernandez, Lopez-Pavon, Rius, Sandner '22

Implications on $0\nu\beta\beta$



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

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

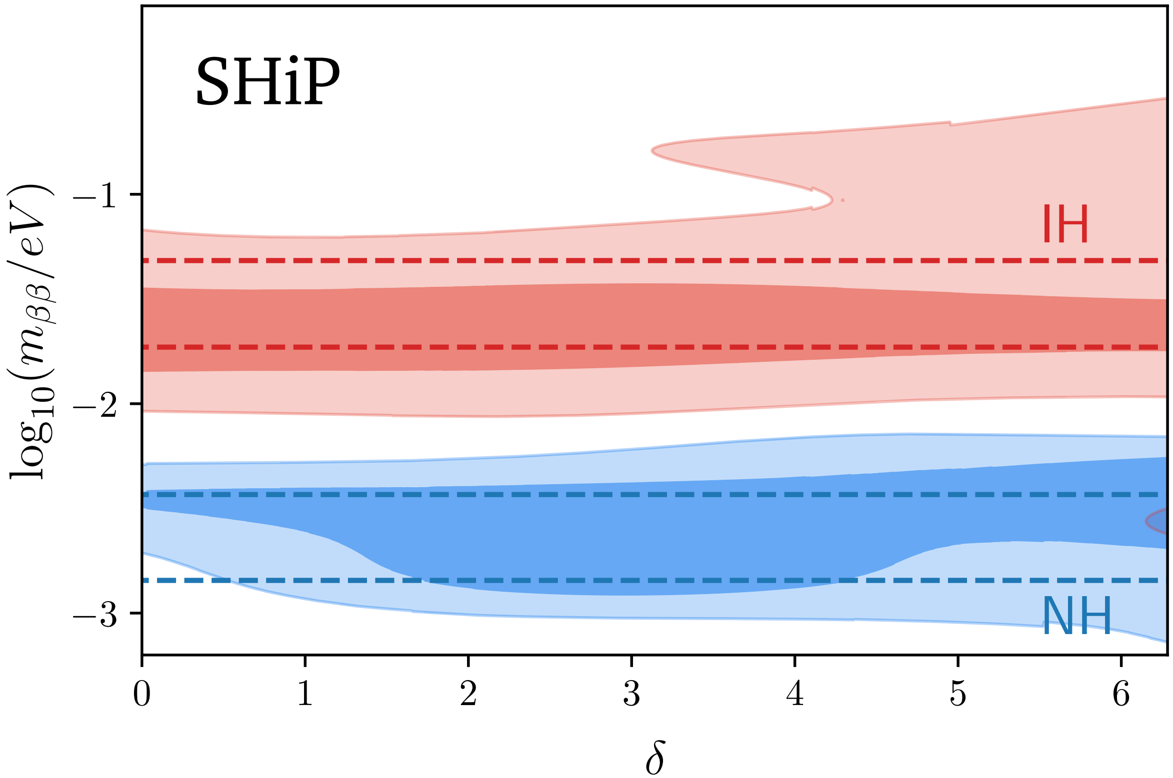
$$m_{\beta\beta} = \left| \sum_{i=\text{light}} U_{ei}^2 m_i + \sum_{I=\text{heavy}} \Theta_{eI}^2 M_I \mathcal{M}\left(M_I\right) / \mathcal{M}\left(0\right) \right|$$

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

Implications on $0\nu\beta\beta$

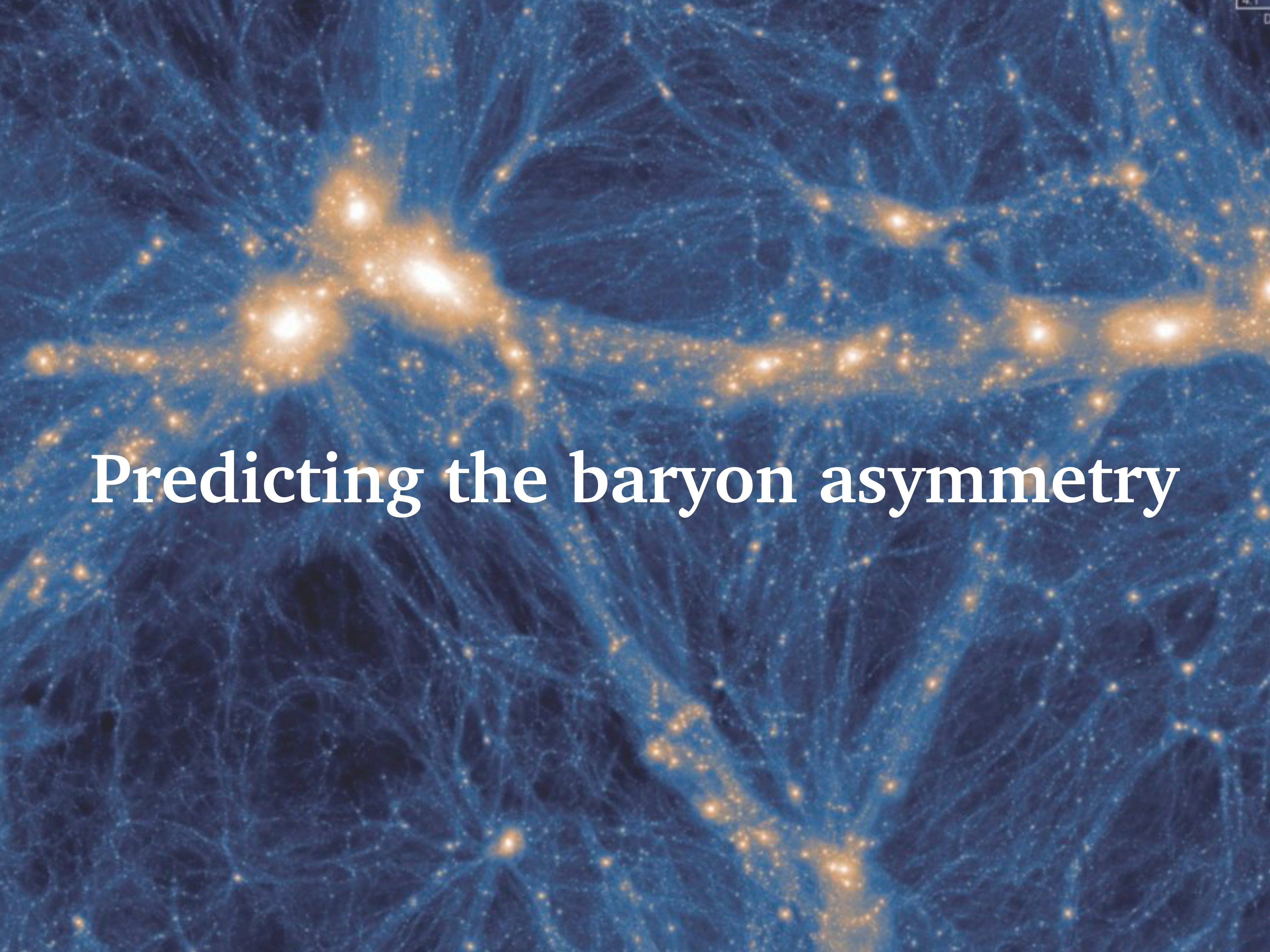
Example: Parameter space covered by SHiP with $\Delta M/M = 10^{-2}$.

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?

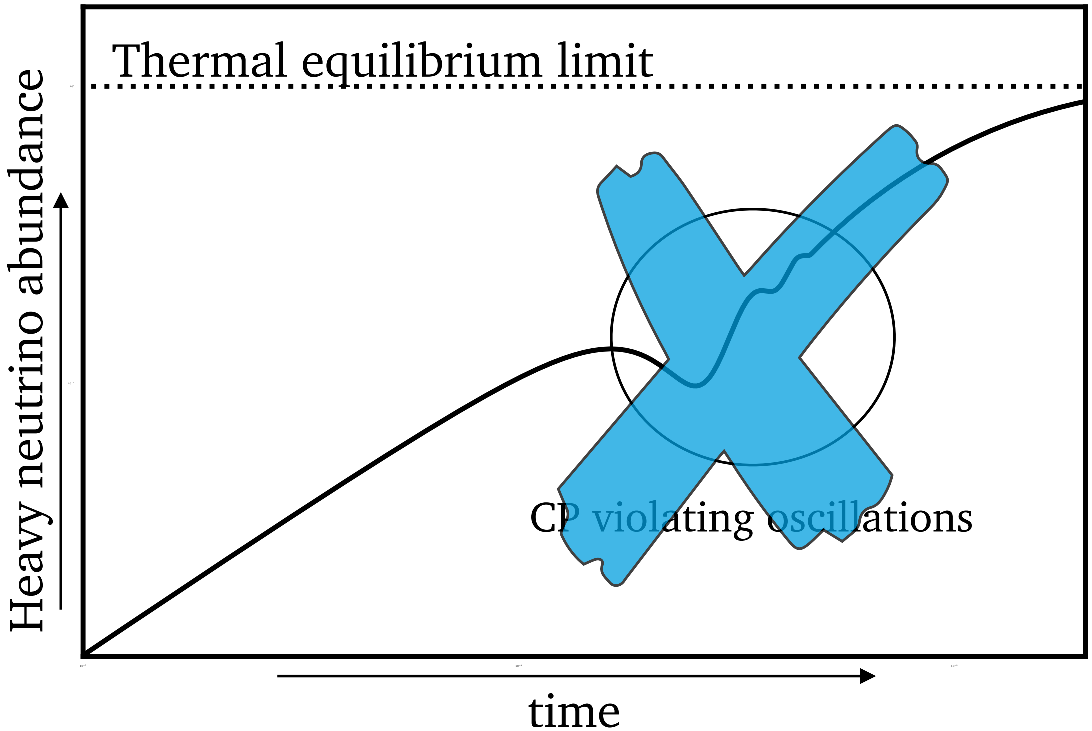
$$\begin{array}{c} \\ \\ M_\nu = \end{array} \begin{array}{ccc} \overline{\nu^c} & \overline{N}_1 & \overline{N}_2 \\ 1 & -1 & 1 \\ \end{array} \quad L$$

$$M_\nu = \begin{pmatrix} 0 & Y_1^T v/\sqrt{2} & \epsilon Y_2^T v/\sqrt{2} \\ Y_1 v/\sqrt{2} & \mu' & M \\ \epsilon Y_2 v/\sqrt{2} & M & \mu \end{pmatrix} \begin{array}{cc} 1 & \nu \\ -1 & N_1^c \\ 1 & N_2^c \end{array}$$

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: $M_1 = M_2$.



No interference of CP phases at leading order.

Hernandez, Lopez-Pavon, Rius, Sandner '23

The θ phase

<u>Thermal corrections</u> 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: $\tilde{I}_0 \equiv \mathrm{Im}\left(\mathrm{Tr}\left[Y^\dagger Y M_R^* Y^T Y^* M_R Y^\dagger Y_l Y_l^\dagger Y\right]\right) \equiv \sum_\alpha y_{l_\alpha}^2 \Delta_\alpha^{th}$.

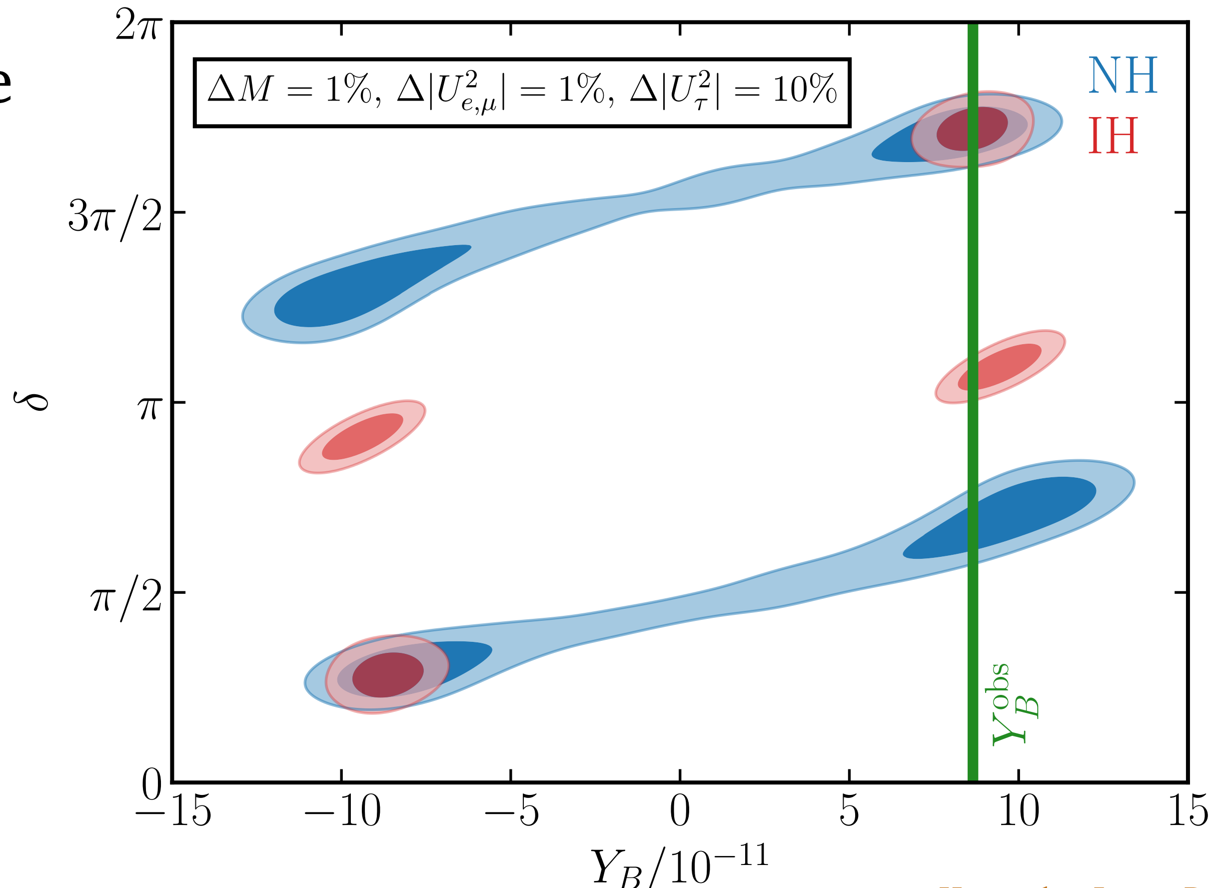
- Need flavour effects in Yukawa couplings since $\sum_\alpha \Delta_\alpha^{th} = 0$.
- Need explicit Majorana rates during thermalization.

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

The asymmetry from the lab

Can we predict the Y_B?

FCC-ee

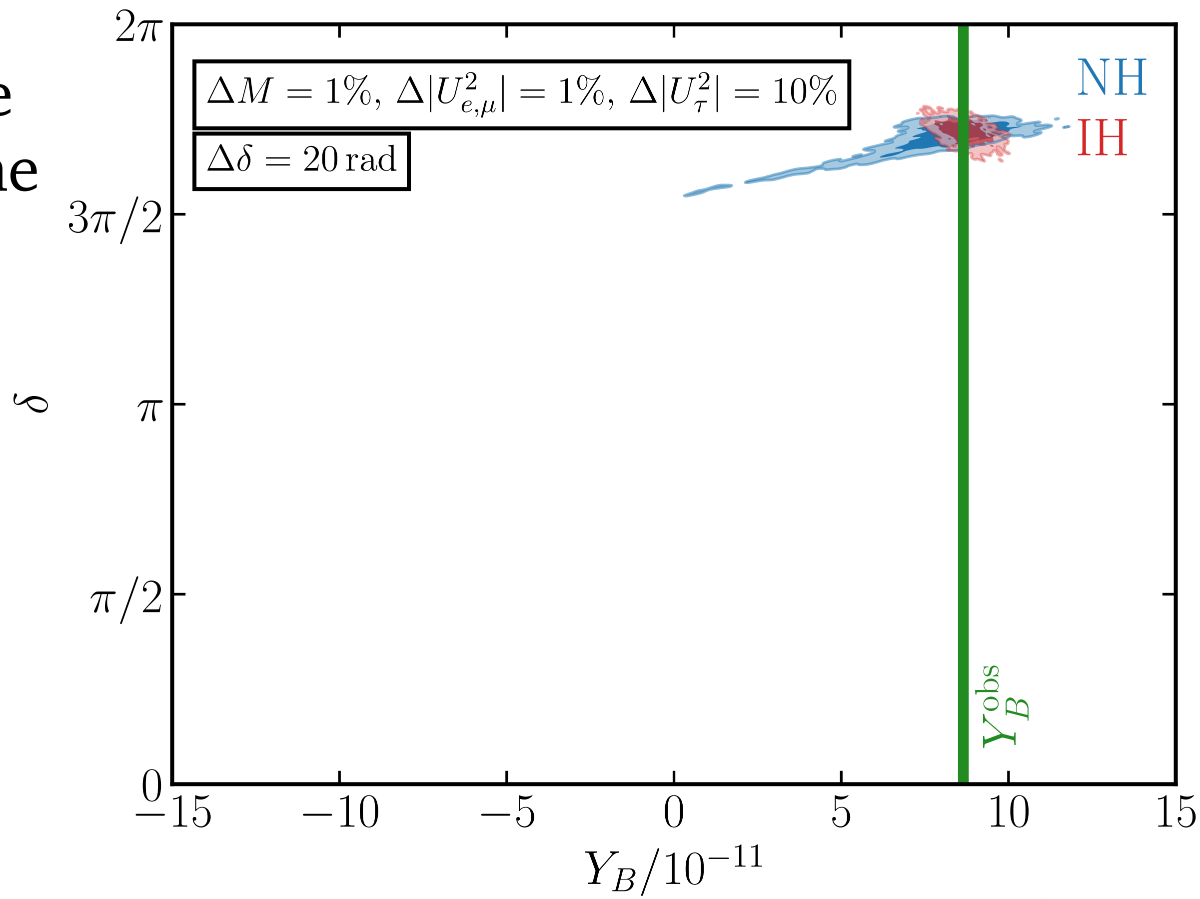


Hernandez, Lopez-Pavon, Rius, Sandner '23

The asymmetry from the lab

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

FCC-ee
HK, Dune

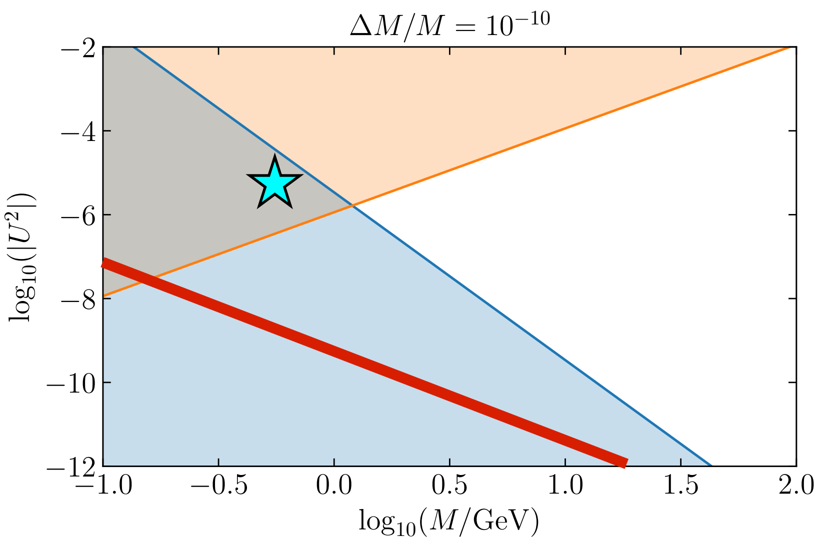


Hernandez, Lopez-Pavon, Rius, Sandner ‘23

Conclusions and Outlook

- Minimal neutrino mass models predict a baryon asymmetry even at accesible scales.

- Analytical approximation reveals **correlation** of leptogenesis with other observables.



Example

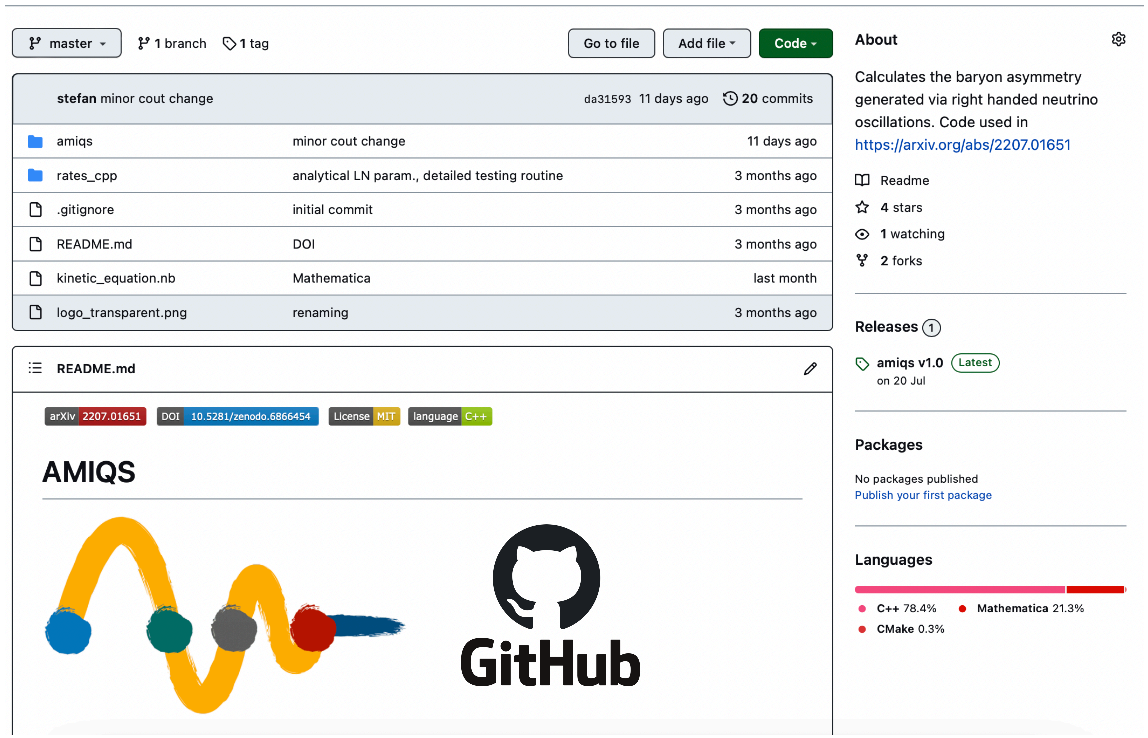
★ Y_B generation testable.
Derived constraints Y_B sets on:
CP phases,
flavour mixing,
and $0\nu\beta\beta$.

- Can measurably **predict** the asymmetry if the right-handed neutrinos are degenerate.

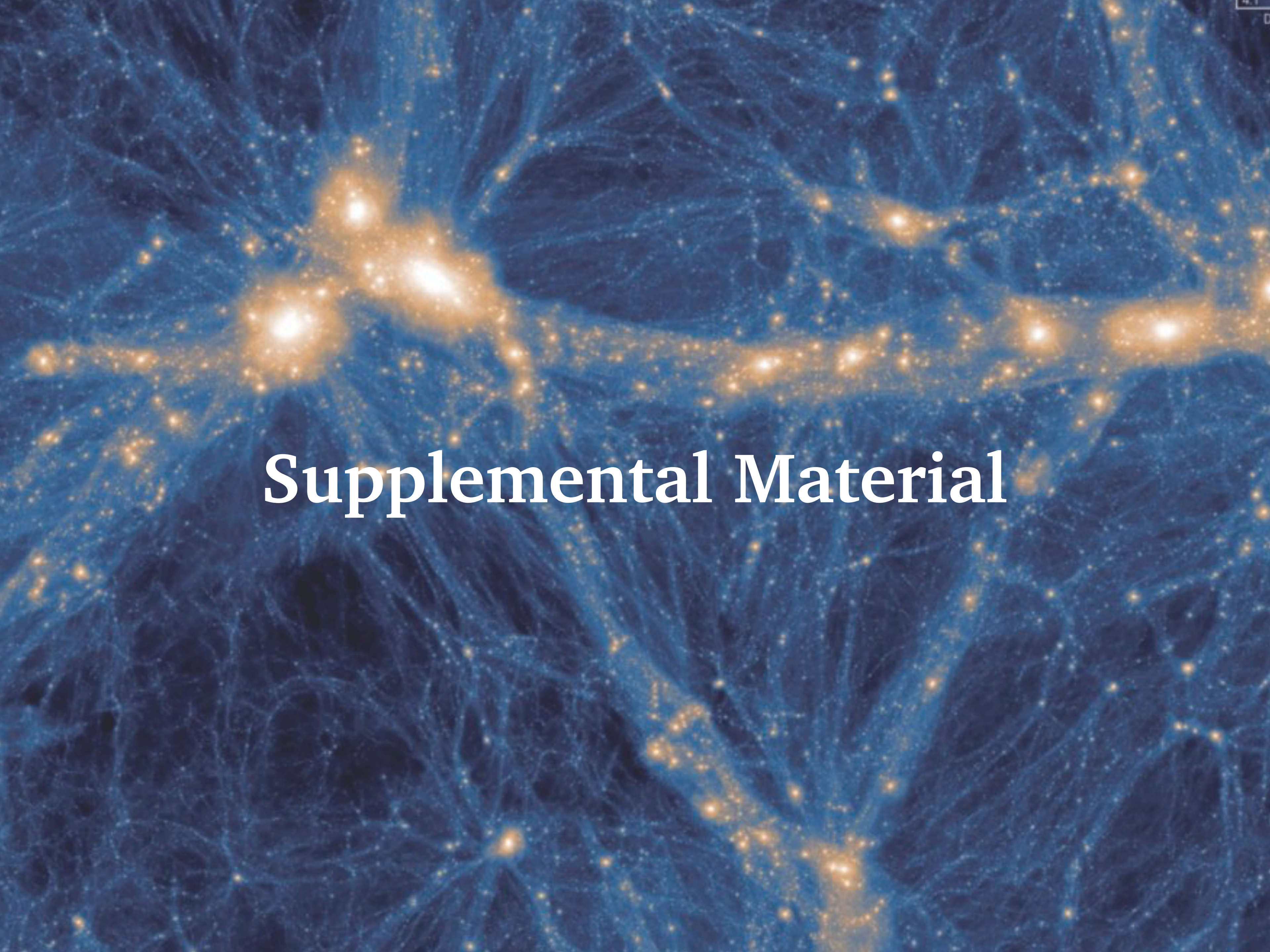
- Developed analytical method applicable to different problems.

Bonus

- Numerical code available on GitHub.



- Check out [2207.01651] & [2305.14427] for more details.


Supplemental Material

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 $\left|\phi_2 - \phi_1\right| = 0 \text{ or } \left|\delta_2 - \delta_1\right| = 0$

In the context of ARS leptogenesis:

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

P. Hernandez '23, Dublin Theoretical Physics Colloquia

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

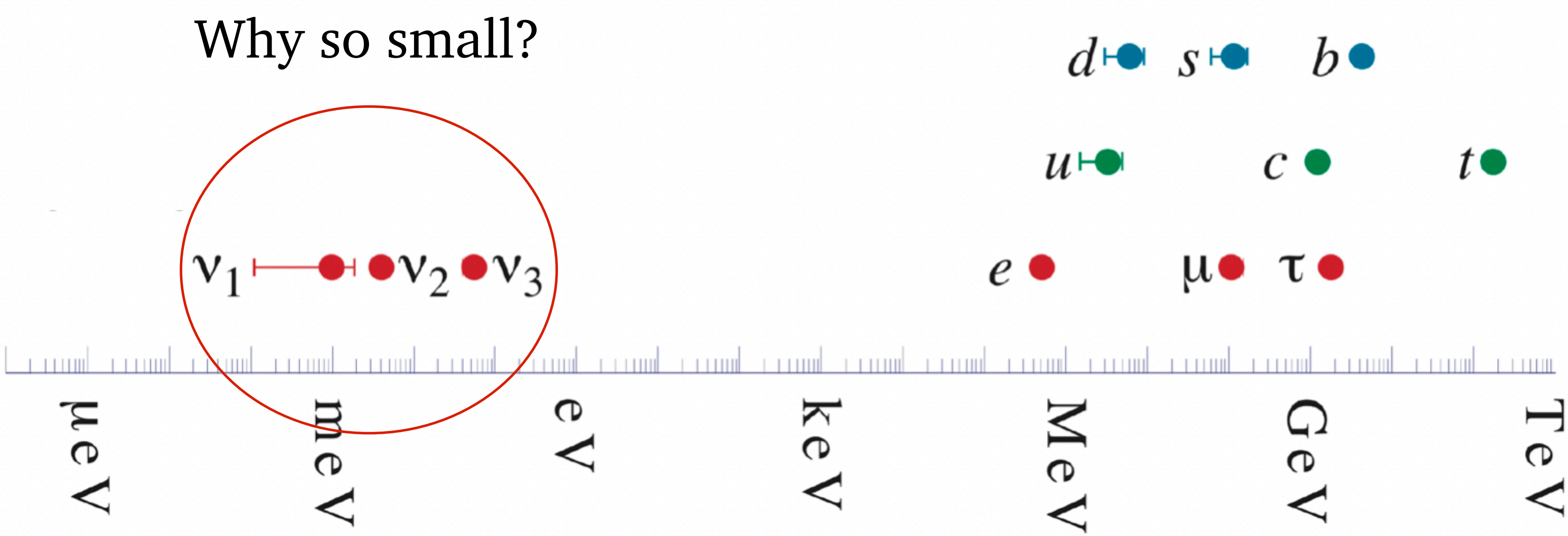
Jarlskog '83; Gavela, Hernandez, Orloff, Pene, Quimbay '94

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

Kajantie, Laine, Rummukainen, Shaposhnikov '96

SM unable to explain observed Y_B.

Neutrino masses



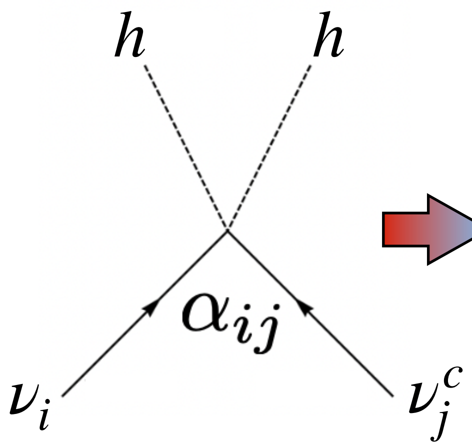
Cosmological *upper* bound: $\sum m_\nu \leq 0.12\,\text{eV} \;\; @ \; 2\sigma$

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

Planck 2018

Neutrino masses

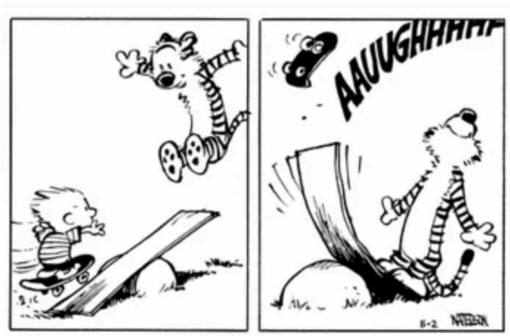
Weinberg operator: $\mathscr{L}_M \subset \bar{L}\tilde{\Phi}\,\alpha\,\tilde{\Phi}L^c + h.c.$



$$\alpha = \frac{Y_\nu}{M}$$

$$m_\nu = Y\frac{v^2}{M}$$

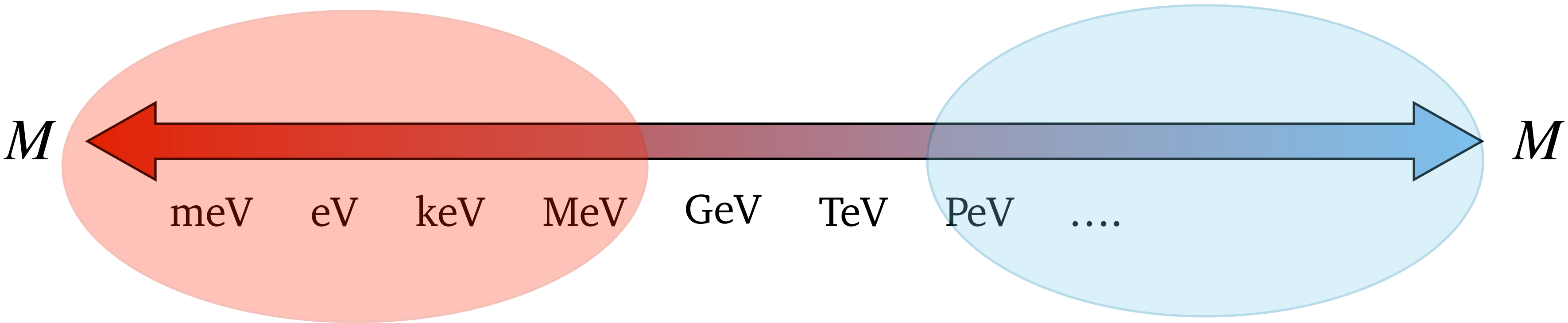
light active neutrino



heavy sterile neutrino

Minkowski ’77; Gell-Mann, Ramond, Slansky ’79; Yanagida ’79; Mohapatra, Senjanovic ’80 …

Neutrino masses — Minimal model

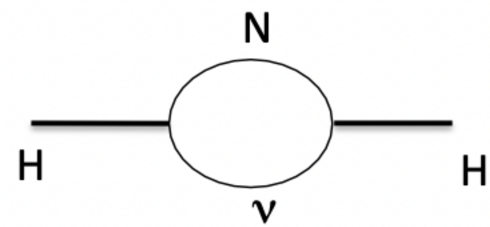


Excluded by cosmology

Not testable & hierarchy problem

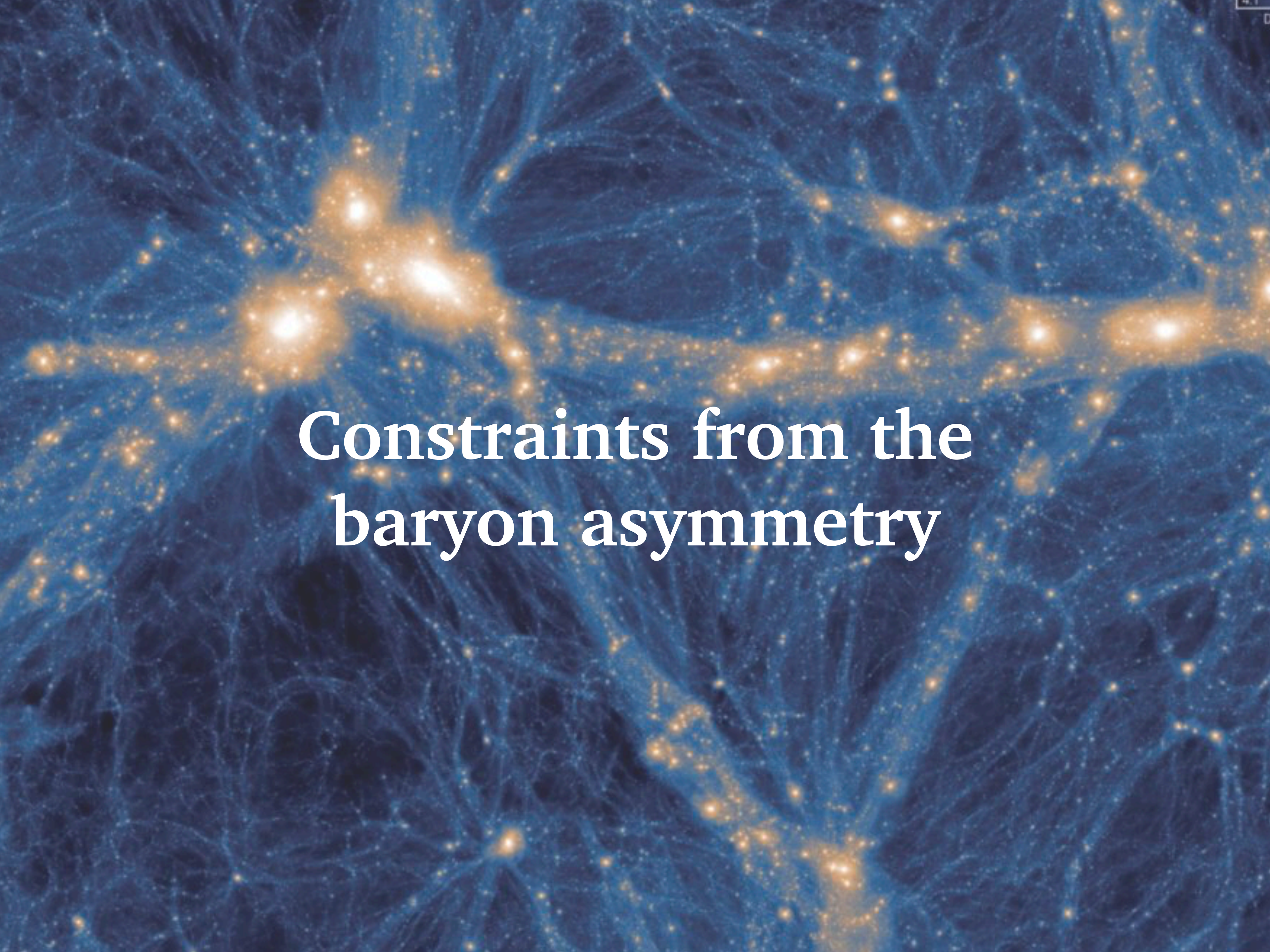
Dark matter / dark radiation

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



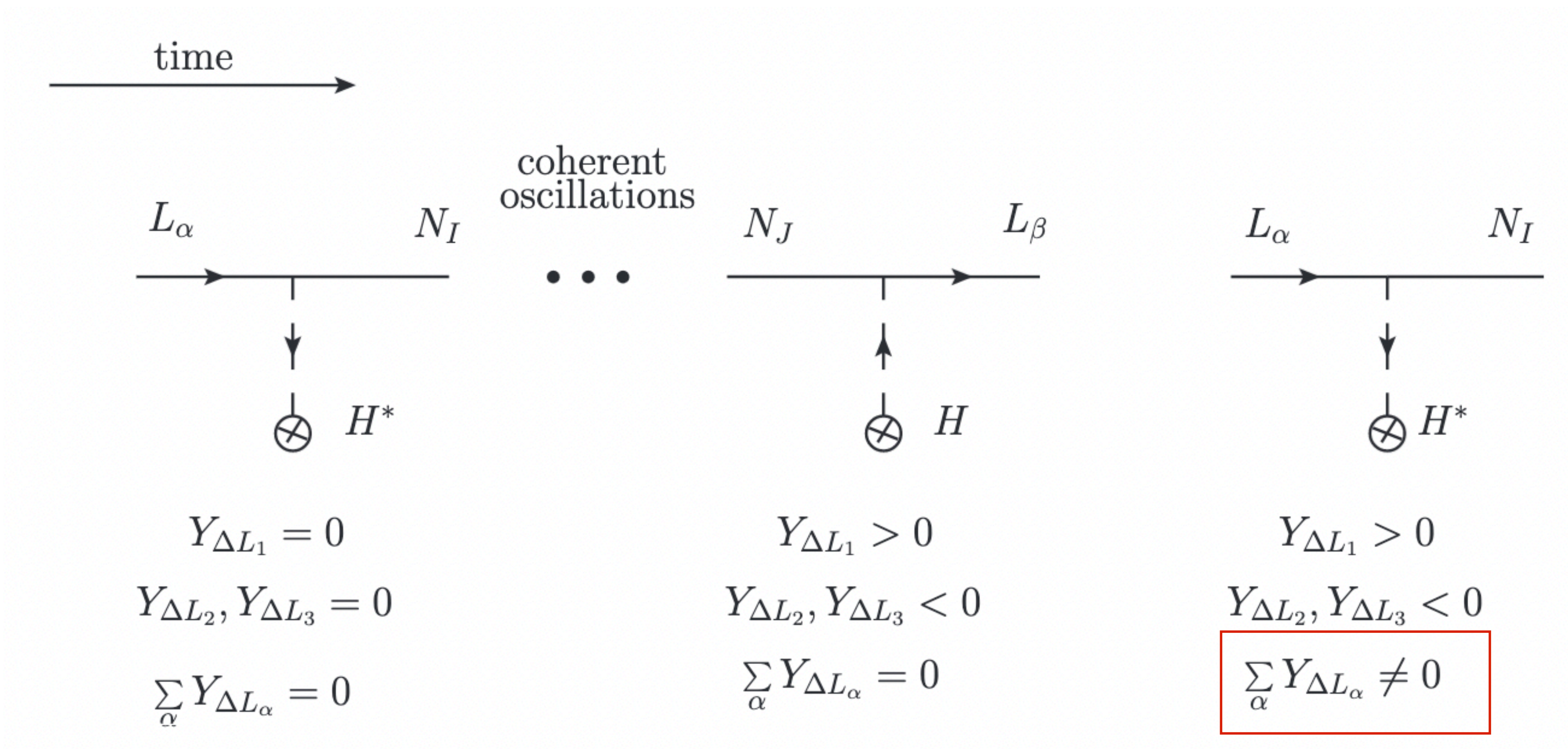
$$\delta m_h^2 = \frac{YY^\dagger}{4\pi^2} M^2 \log \frac{M}{\mu}$$

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



Constraints from the baryon asymmetry

Leptogenesis via oscillations



Out of equilibrium HNL production

Asymmetry in lepton flavours

Different washout of flavour 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
$$\begin{cases} M_R & \rightarrow W^T M_R W \\ Y & \rightarrow V^\dagger Y W \\ Y_\ell & \rightarrow V^\dagger Y_\ell U \end{cases}$$

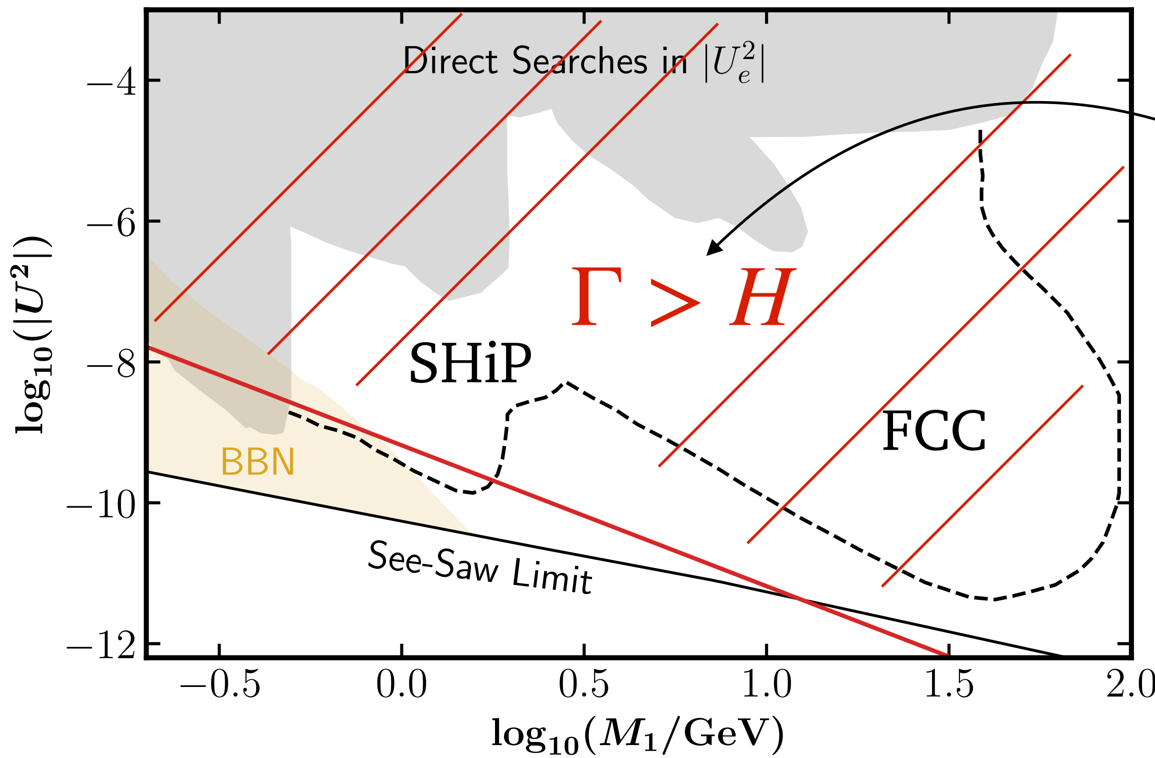
Can distinguish two types of CP violating sources — High scale or mixture.

Leptogenesis via oscillations

Very complex system — what should we expect?

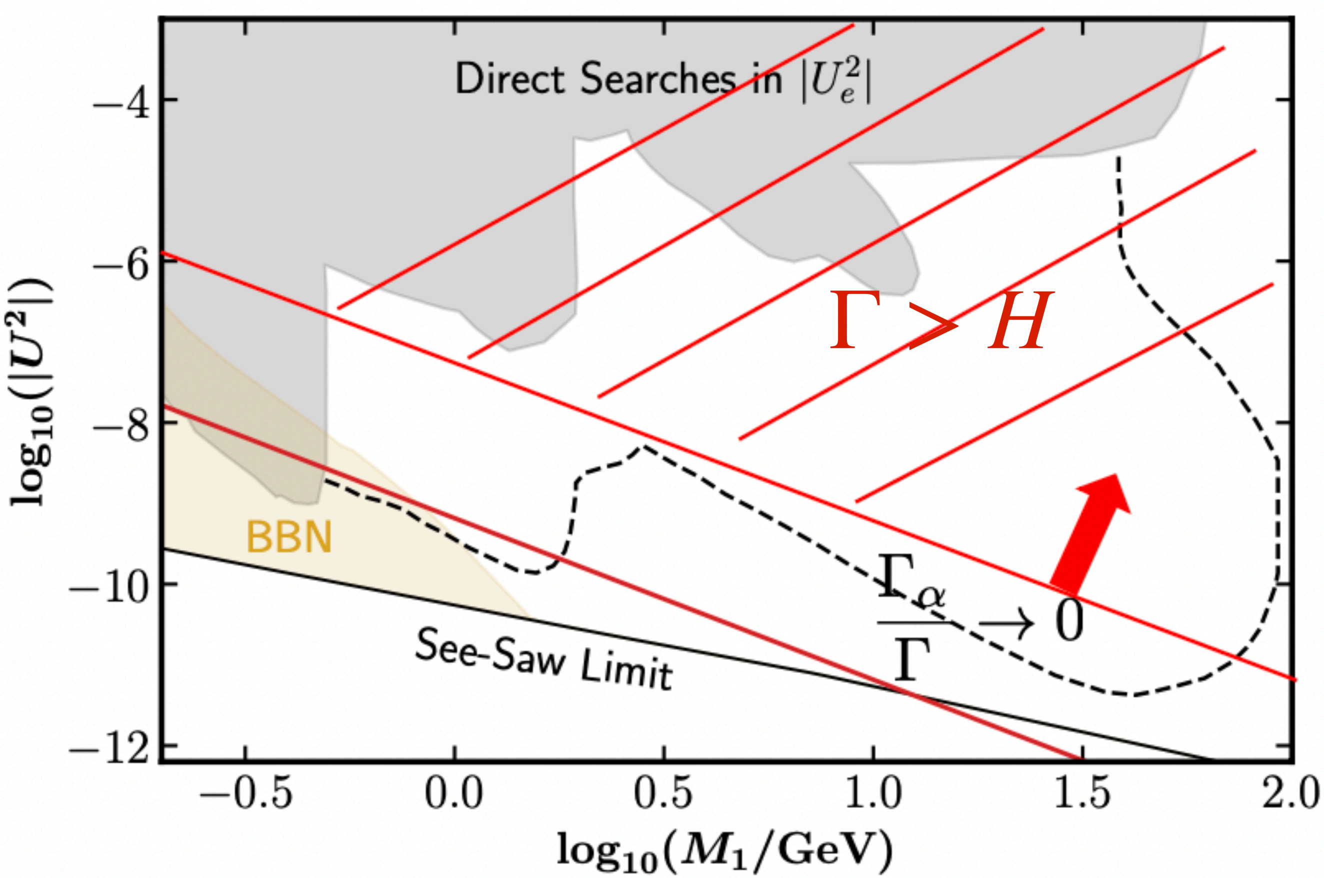
Estimated equilibration rate at EWPT:

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



Violation of Sakharov conditions!?

Washout regimes

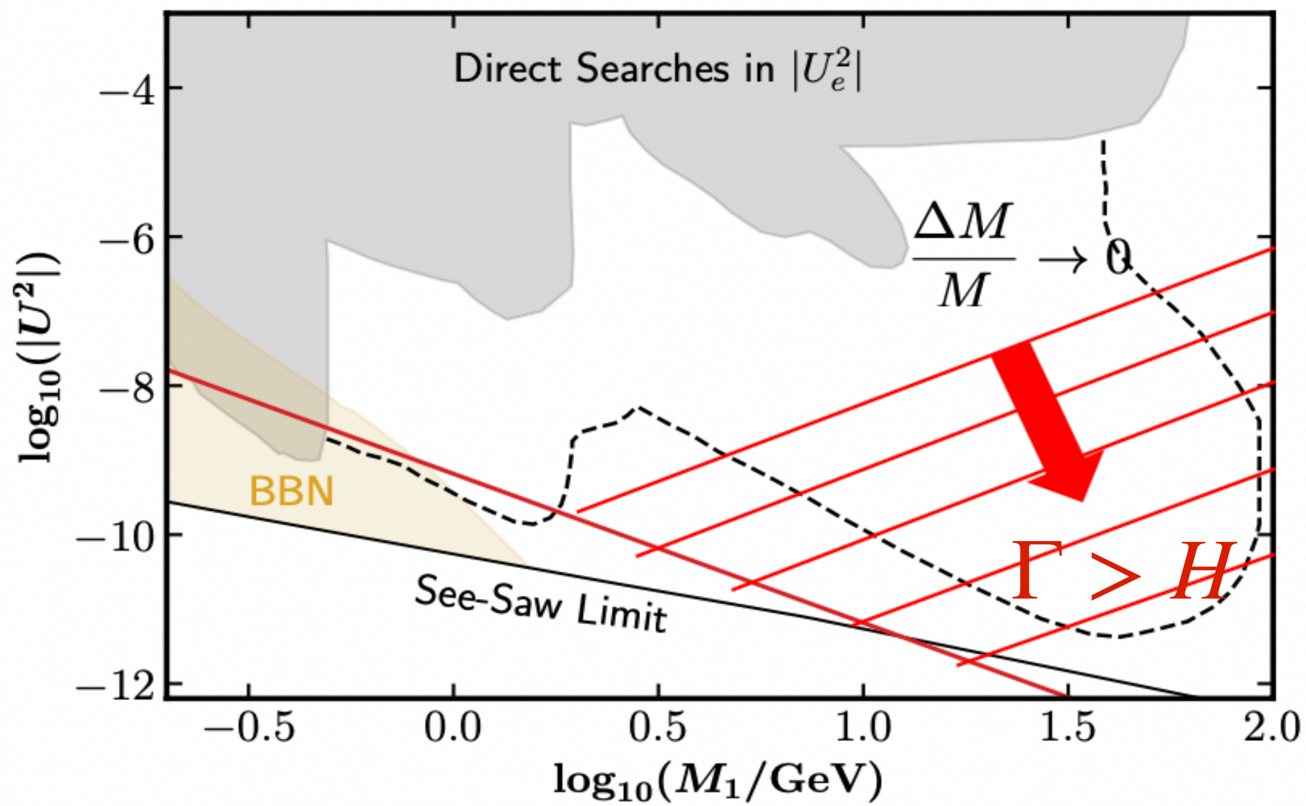


if $|y_\alpha| \ll |y_\beta|$

$\epsilon_\alpha \ll 1$

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

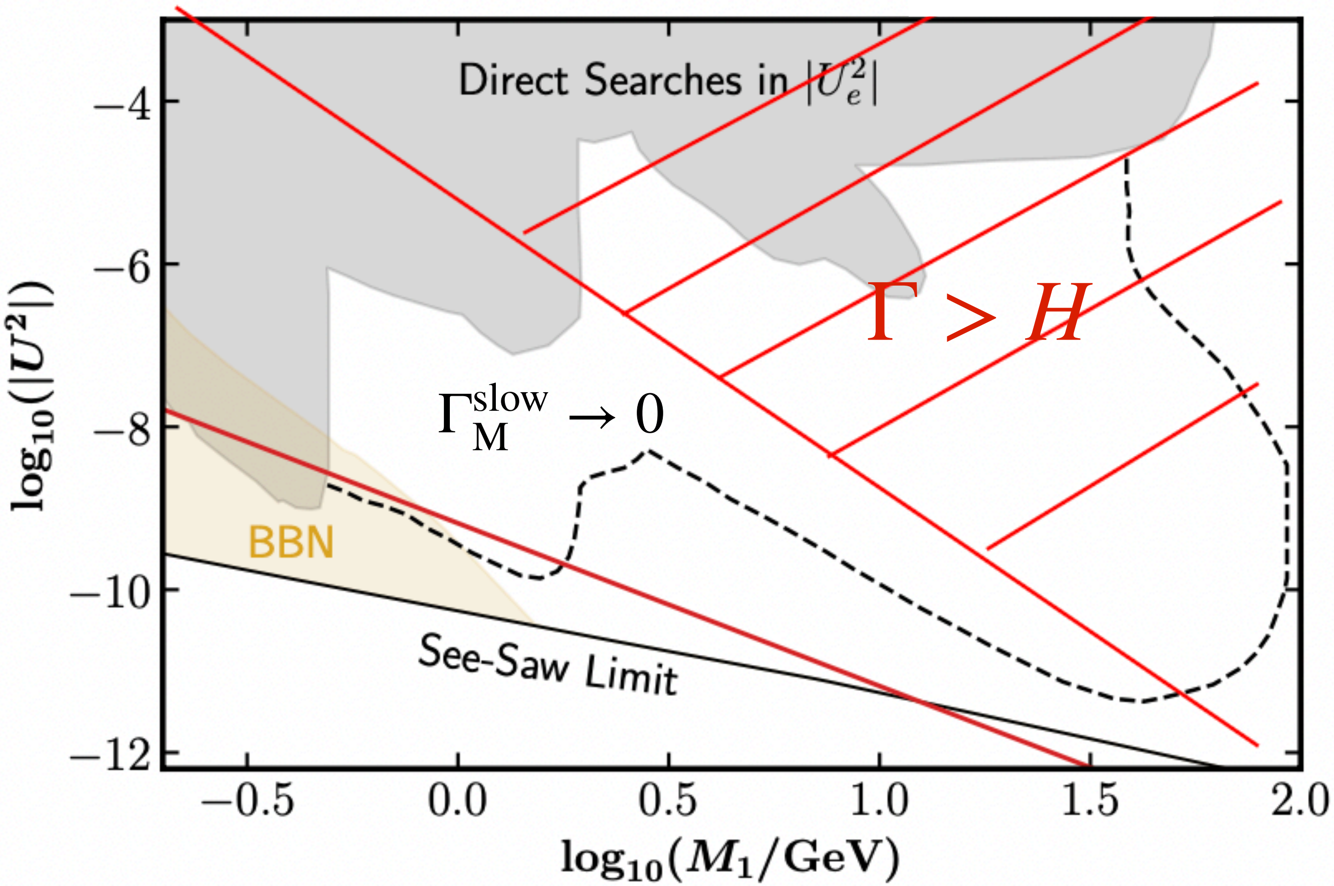
Washout regimes



Damped oscillations lead to weakly coupled lepton number.

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

Washout regimes



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

Adiabatic approximation

Kinetic equation in matrix representation:

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

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

$$\epsilon_{LNV} = (y'_\alpha, (M/T)^2)$$

In the purely adiabatic limit[1]:

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

Leading order adiabatic perturbation[2]:

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

→ Full solution

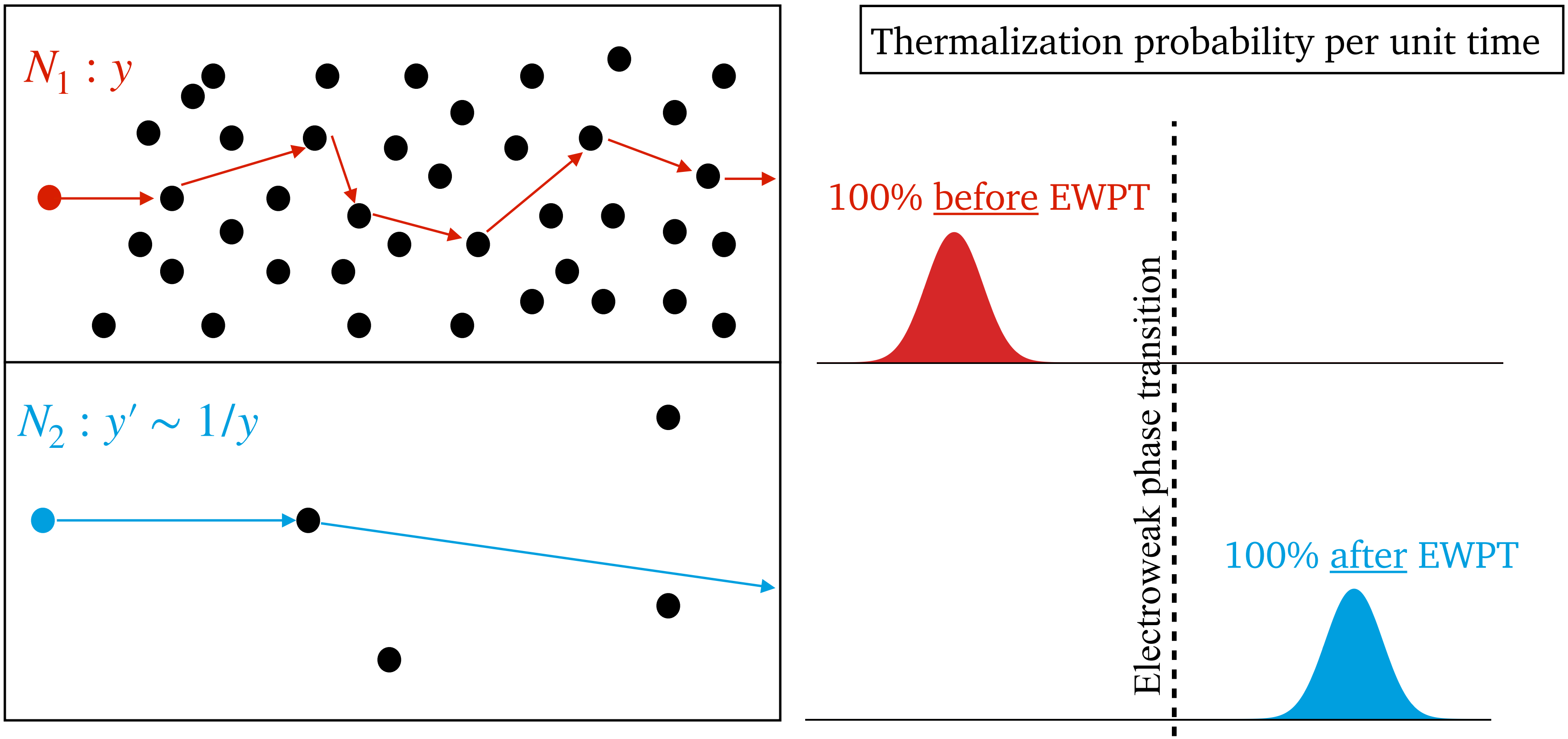
$$r^{(0)} = r_a + \delta r_a$$

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

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

Leptogenesis via oscillations

Example: If *oscillations are damped* $\Gamma_{osc}^{\text{th}} \simeq P_{osc}\Gamma \lesssim H$ is realizable until EWPT.
Physical motivation: softly broken LN symmetry.

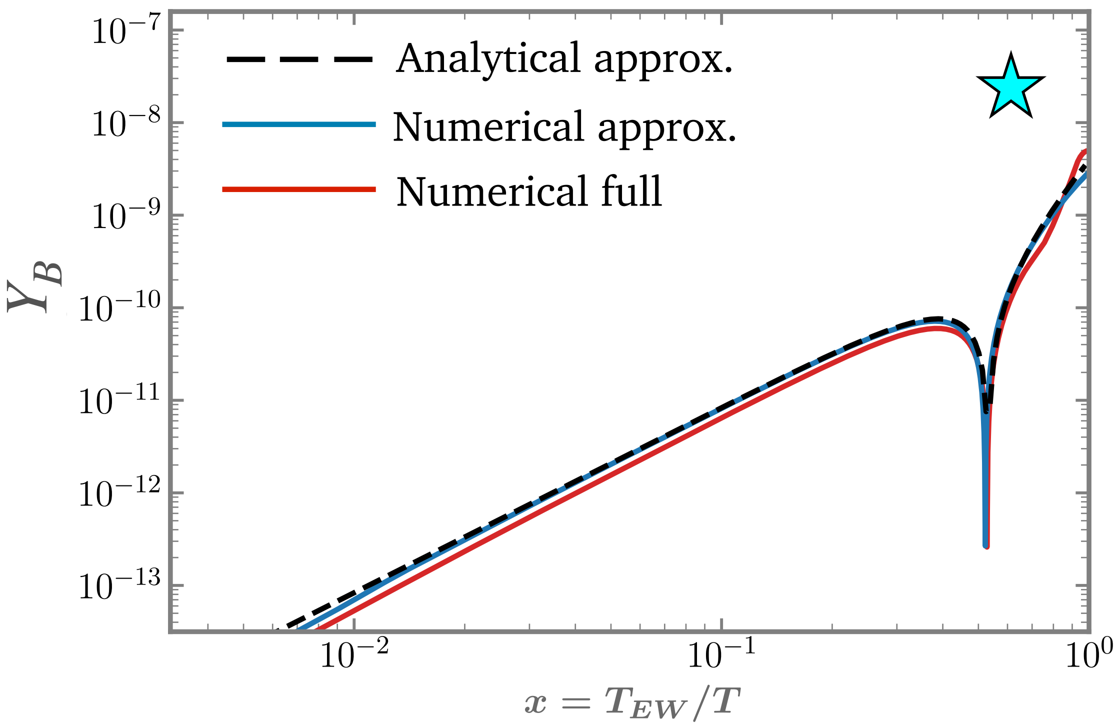


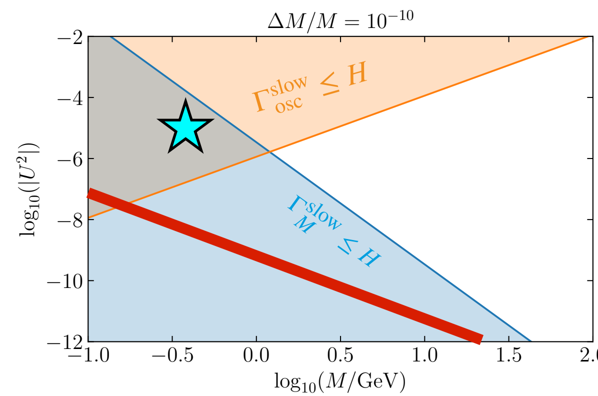
Leptogenesis via oscillations

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

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

CP invariants!



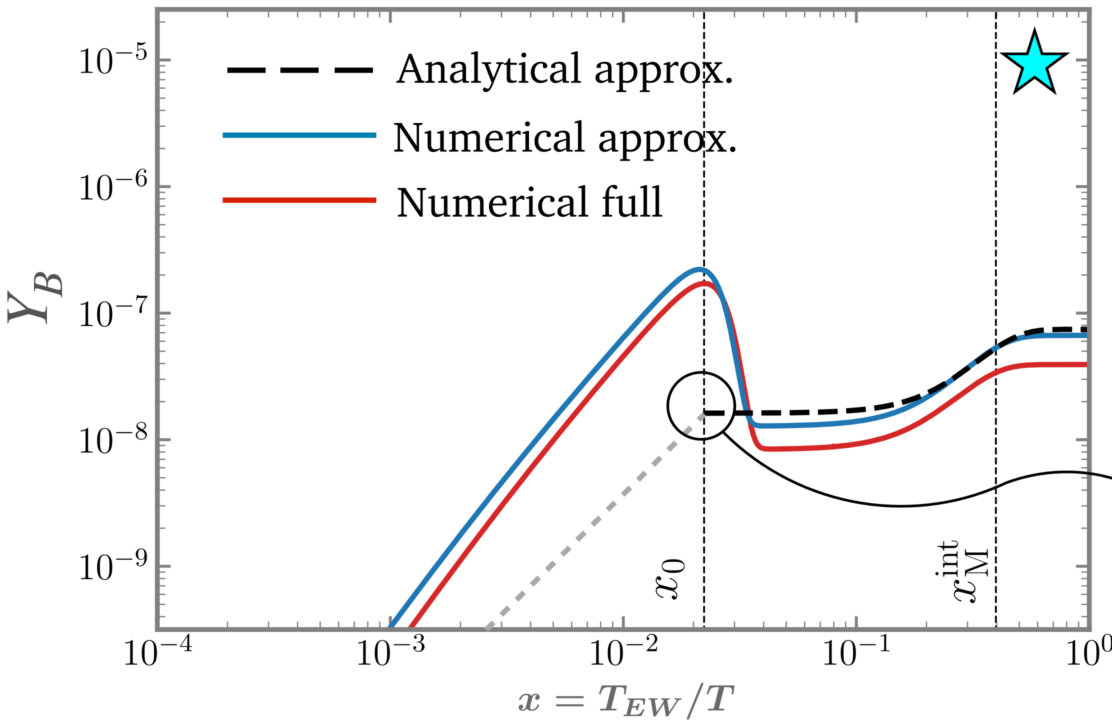


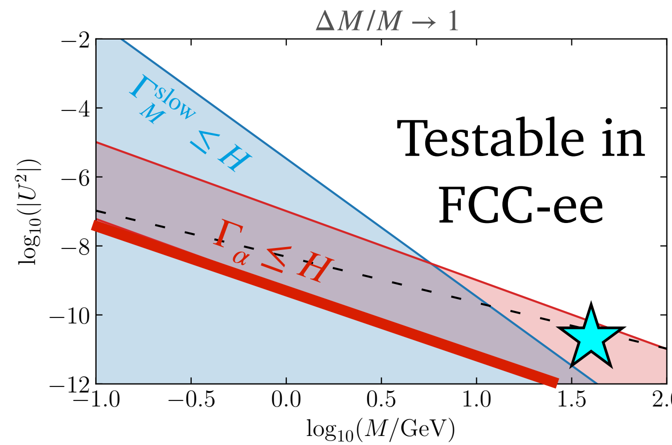
★ Testable in SHiP

Hernandez, Lopez-Pavon, Rius, Sandner '22

Leptogenesis via oscillations

Similar agreement in all other washout regimes.





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

Hernandez, Lopez-Pavon, Rius, Sandner '22

Relate to observables

Light neutrino data constraint: $-(m_\nu)_{\alpha\beta} = \frac{v^2}{M}(Y_{\alpha 1}Y_{\beta 2} - Y_{\alpha 2}Y_{\beta 1} - Y_{\alpha 1}Y_{\beta 1}\frac{\Delta M}{M}) = (U^* m U^\dagger)_{\alpha\beta}\,.$

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

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

↓

Neutrino oscillations
(Dune, T2K, HK, ..)

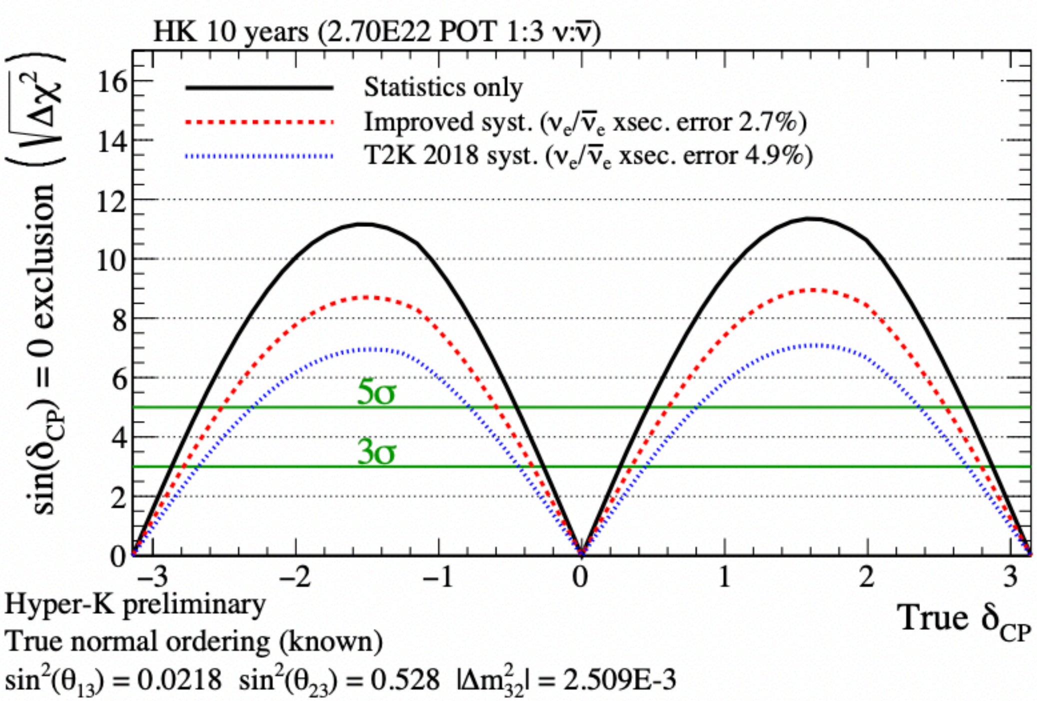
$\nu 0\beta\beta$ decay
(LEGEND, NEXT, ..)

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

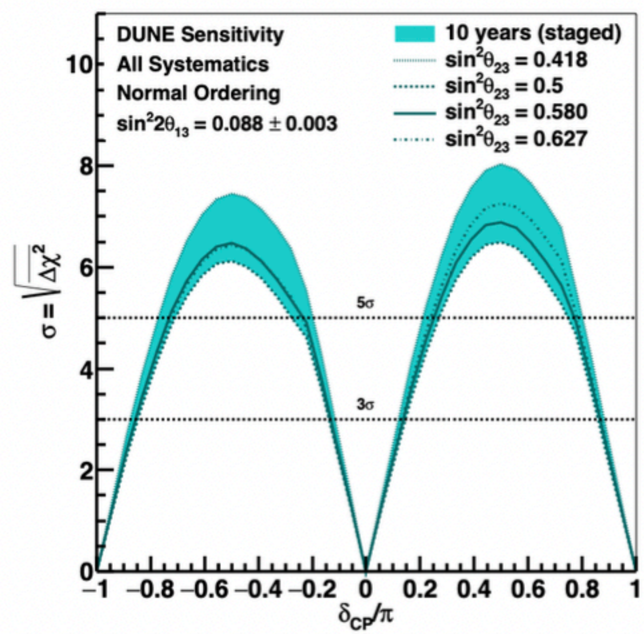
Relate to observables

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

Hyper Kamiokande (10y)



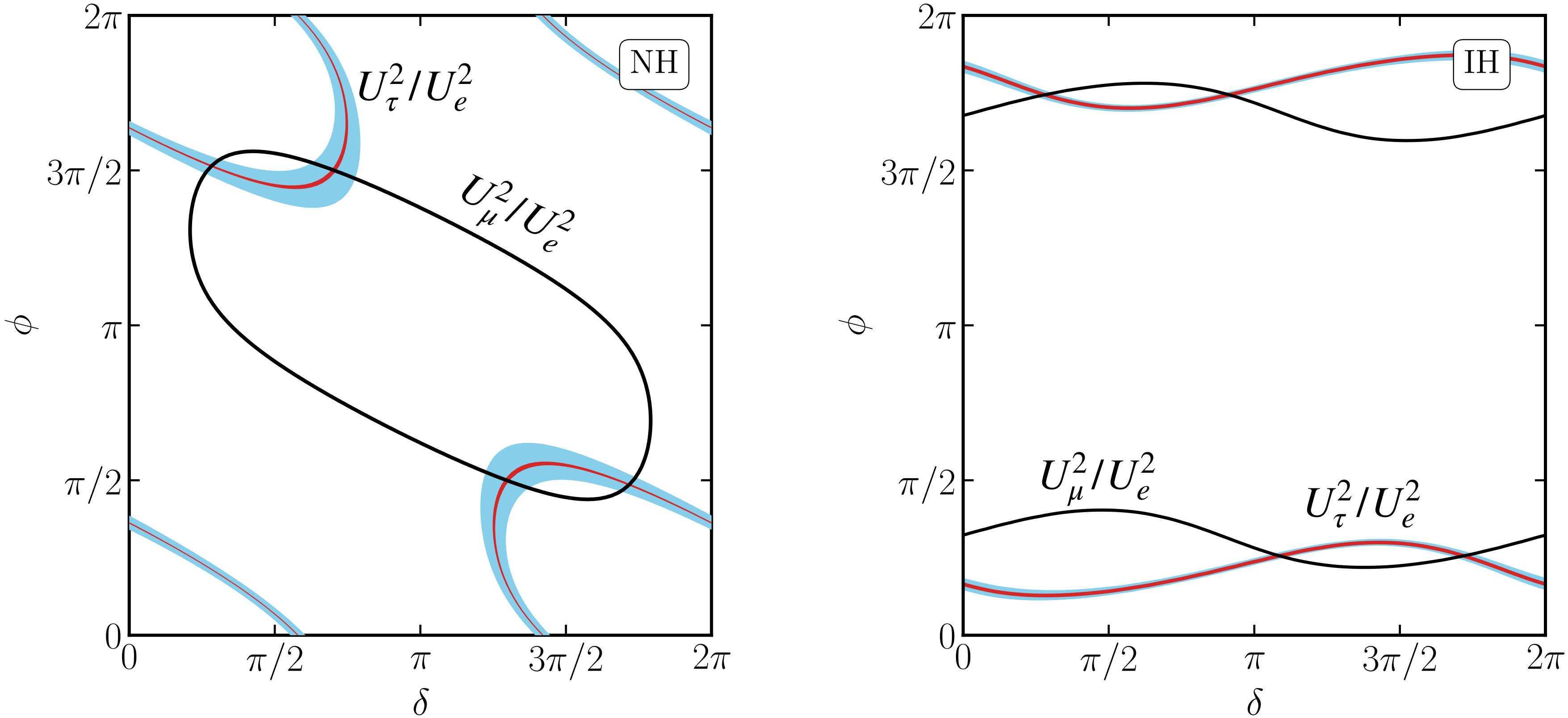
DUNE(10y)



Relate to observables

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

ϕ via $0\nu\beta\beta$ decay or … heavy neutrino flavour ratio depends on U_{PMNS} phases.



Relate to observables

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

In general Y_B still depends on the high scale phase θ — difficult to pin down.

<u>Possibility in $0\nu\beta\beta$</u>

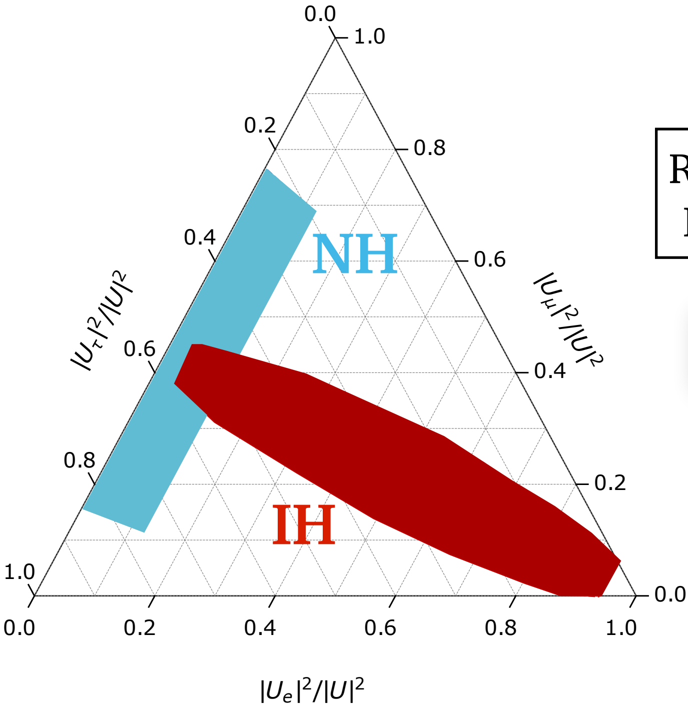
$$(U_\alpha)^2 \propto e^{2i\theta} U^2 f(\delta, \phi, M_j)$$

Interference effects between light and heavy neutrino contributions to $m_{\beta\beta}$ can reveal θ — theoretically…

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

Constraints on flavour structure

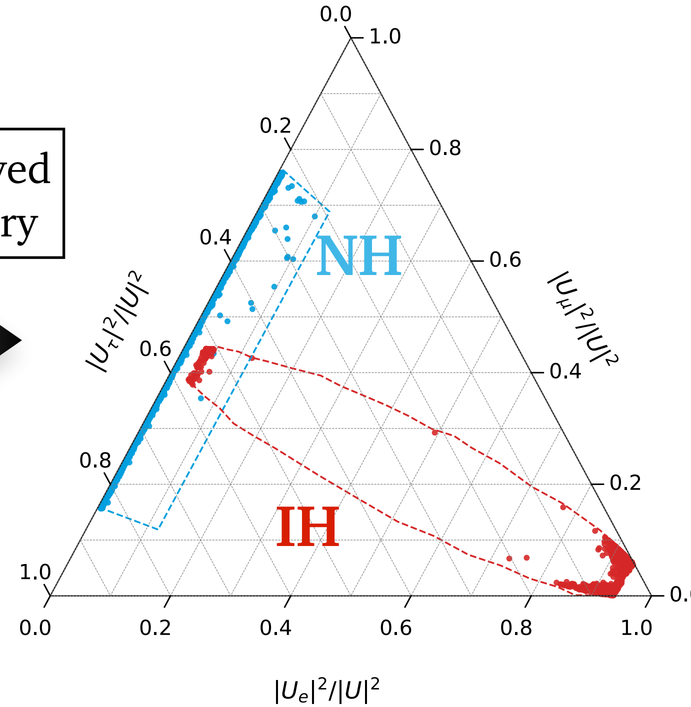
Neutrino Oscillation data



Reproduce observed Baryon asymmetry

Example:

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

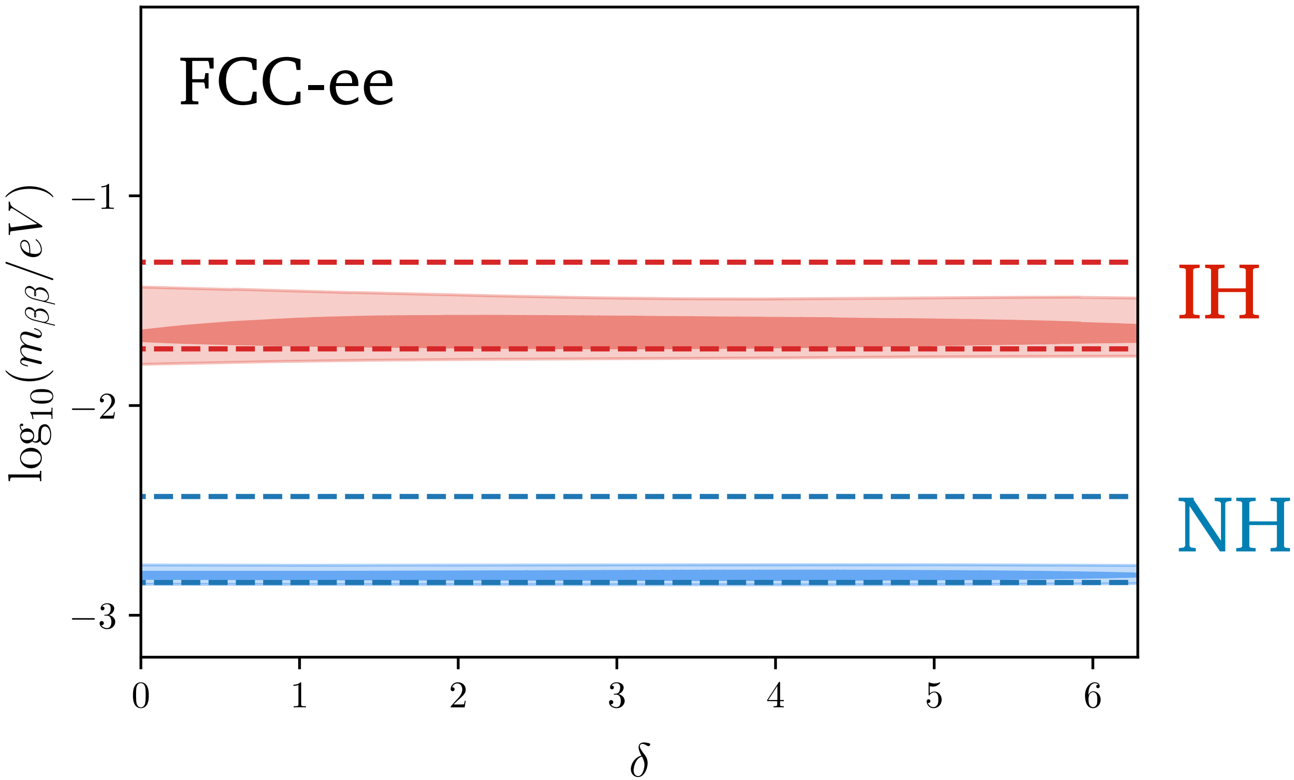


Hernandez, Lopez-Pavon, Rius, Sandner '22

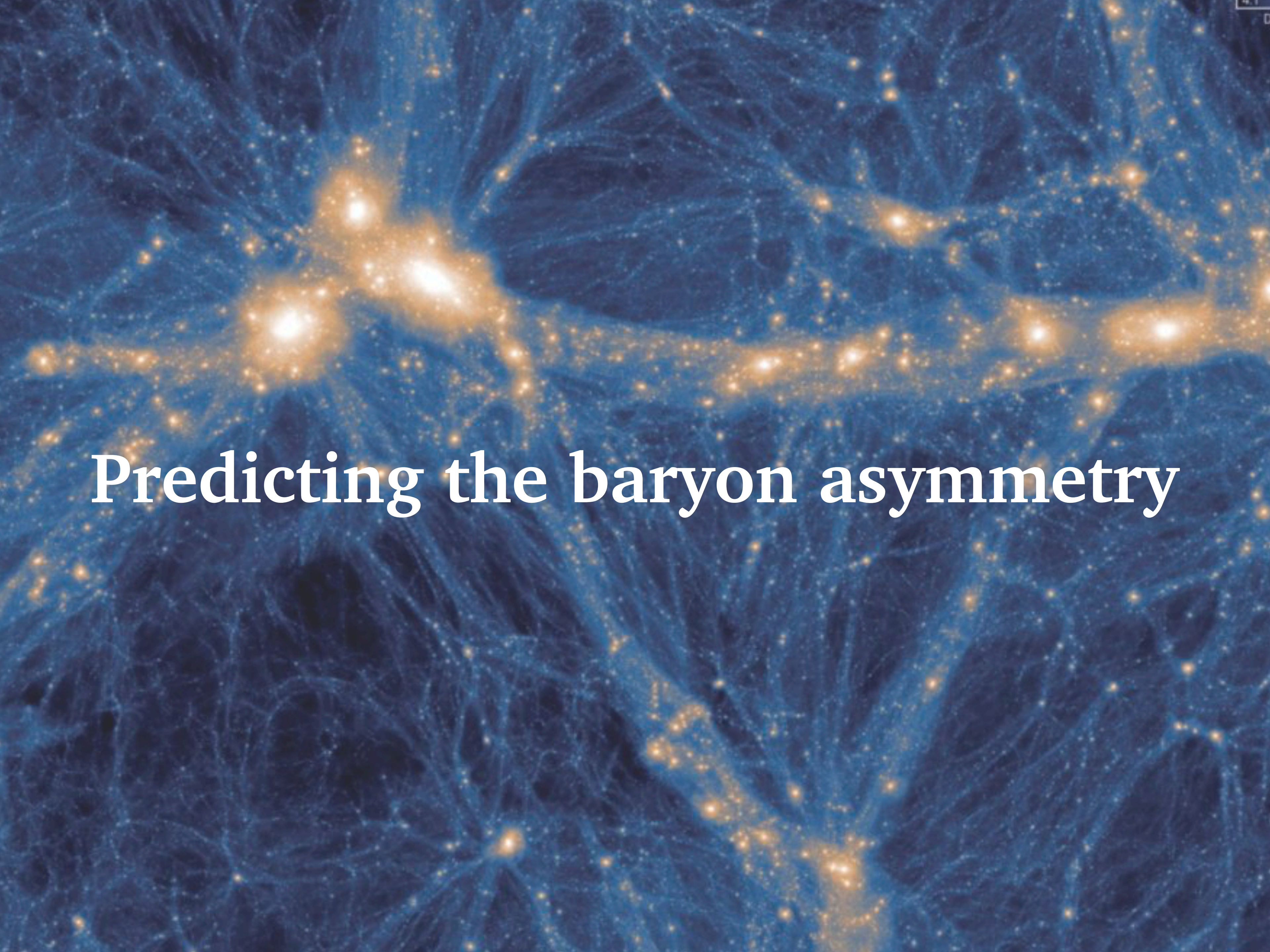
Implications on $0\nu\beta\beta$

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

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

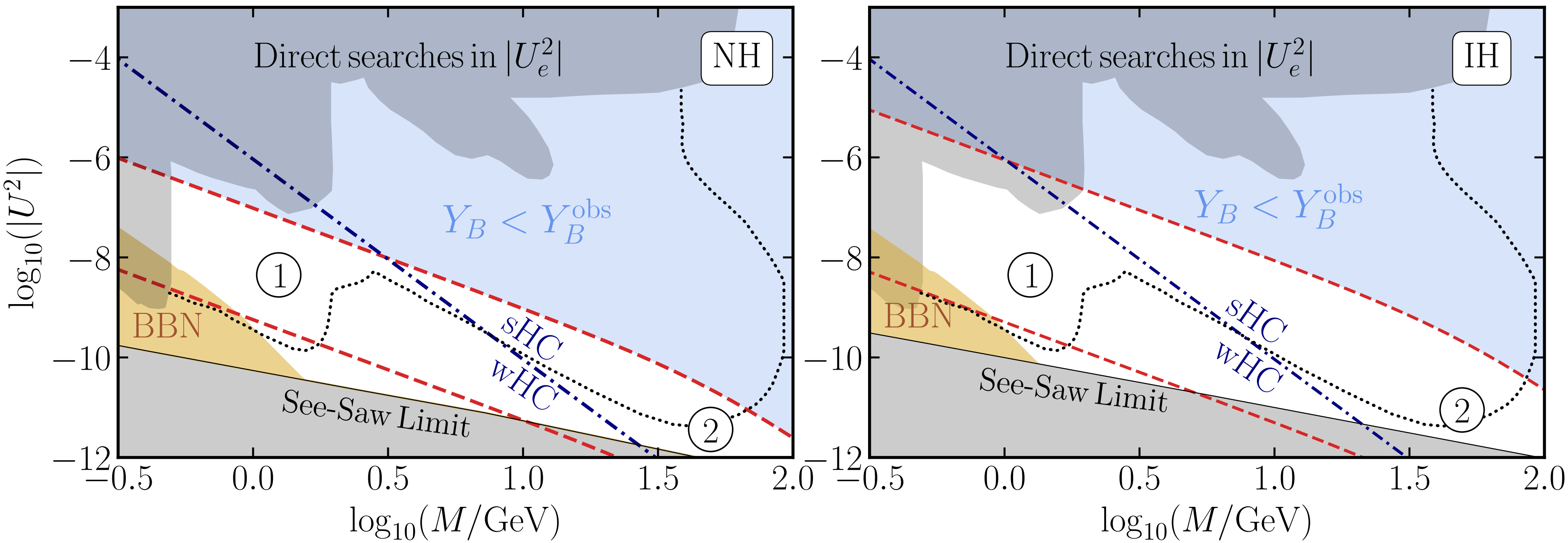


Hernandez, Lopez-Pavon, Rius, Sandner '22


Predicting the baryon asymmetry

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

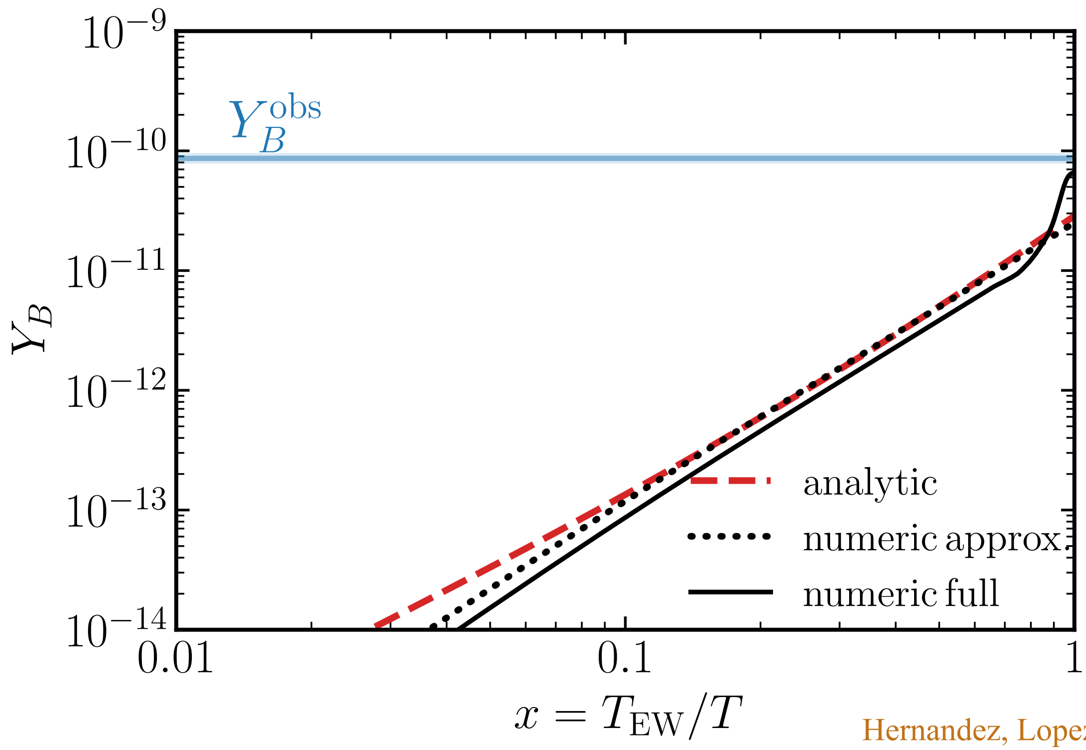
Analytical approximation

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 flavour CP invariant

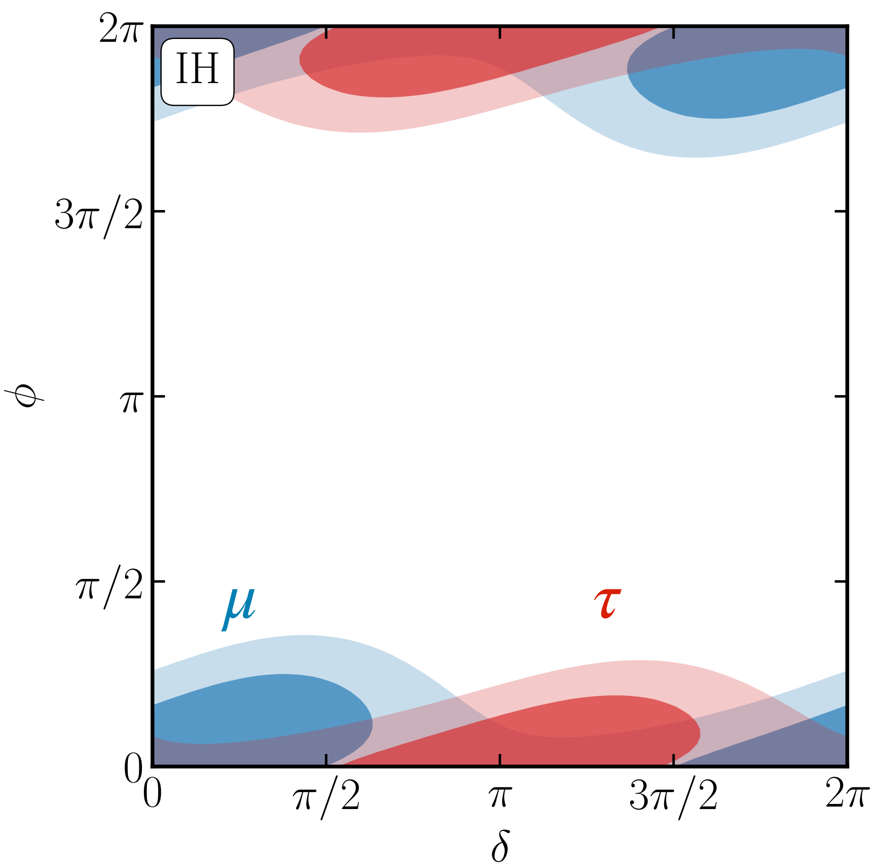
Strong flavour CP invariant



Hernandez, Lopez-Pavon, Rius, Sandner '23

Relate to observables

How to achieve flavour 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.

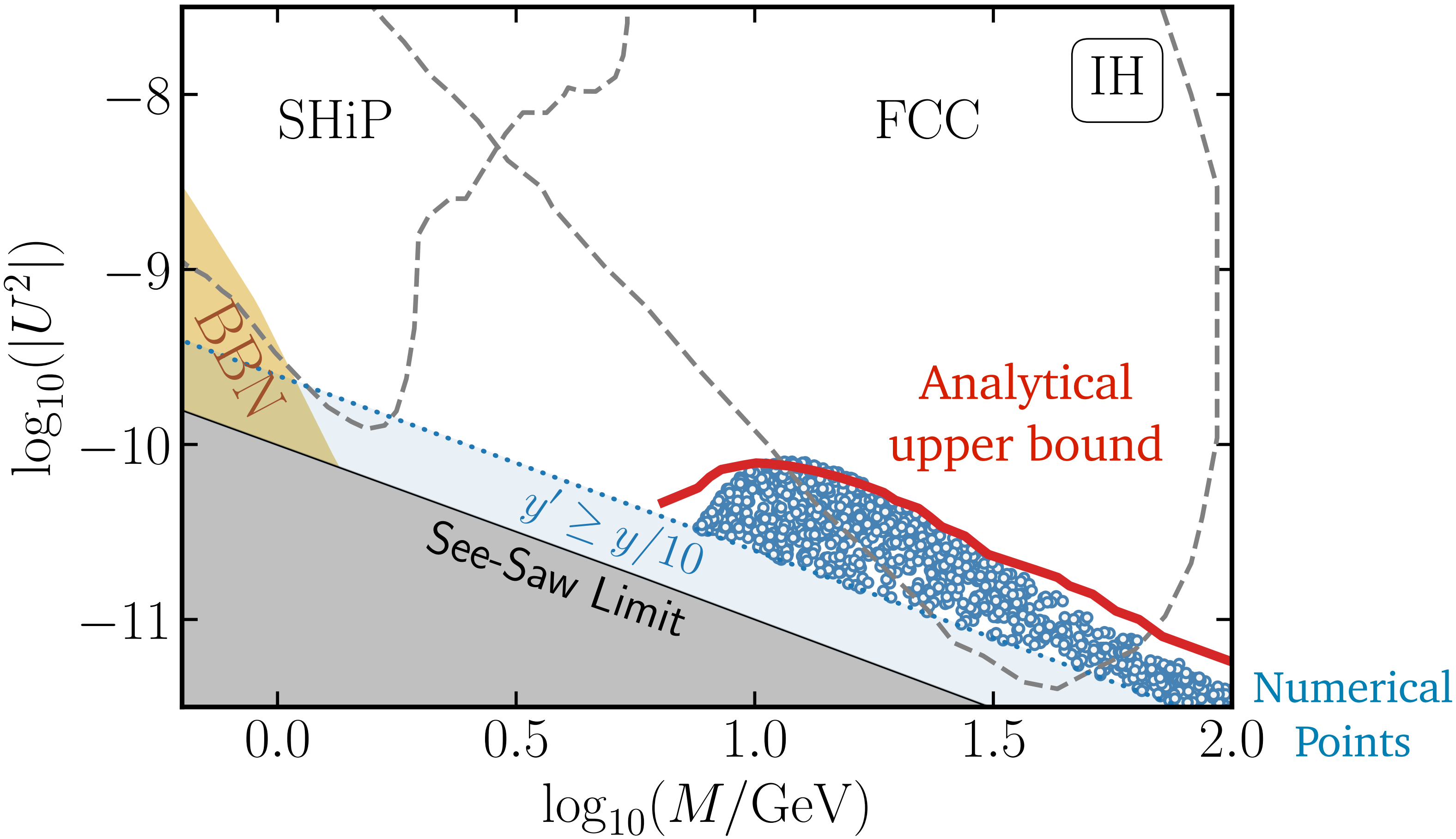
$$\bar{f}_\mu^{\mathrm{IH}} = \bar{f}_\tau^{\mathrm{IH}} = \frac{r^2 c_{12}^2 s_{12}^2 \sin(2\phi)}{2 - 8 c_{12}^2 s_{12}^2 \cos^2\phi}$$

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

Hernandez, Lopez-Pavon, Rius, Sandner '23

Upper bound on mixing

FCC-ee could see something.



Hernandez, Lopez-Pavon, Rius, Sandner '23