Recent developments in testable leptogenesis

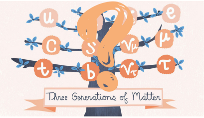
Yannis Georis

Theory Seminar Nikhef
November 23, 2023

Outline

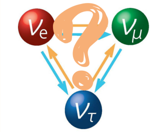
1. Neutrino masses and type-I seesaw
2. Low-scale leptogenesis
3. Effects of flavour- and CP-symmetries
4. Take-home

Open questions in the Standard Model

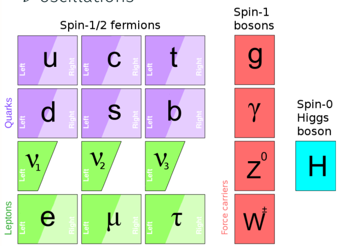


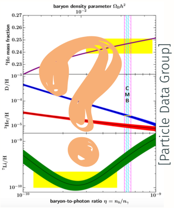
Origin of flavours

[Sandbox Studio, Chicago]



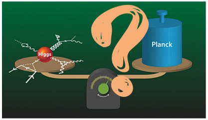
ν oscillations





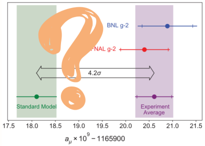
[Particle Data Group]

Baryon asymmetry



Hierarchy problem

[A. Stonebraker/APS]



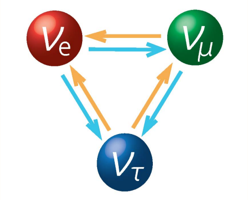
[Muon g-2 collaboration]

Muon $g - 2$

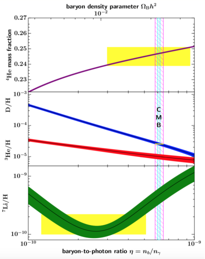
[Chandra]

Dark Matter

Right-handed neutrinos

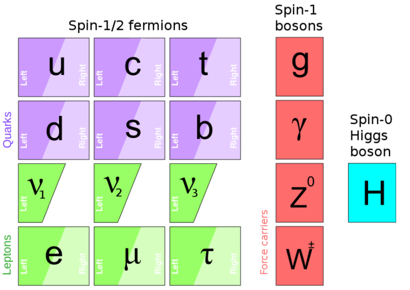


Neutrino oscillations/masses

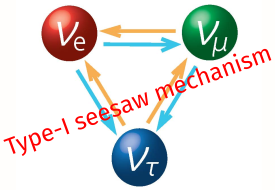


[Particle Data Group]

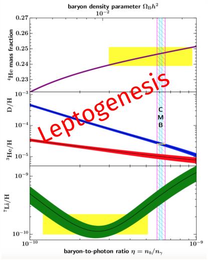
Baryon asymmetry



Right-handed neutrinos

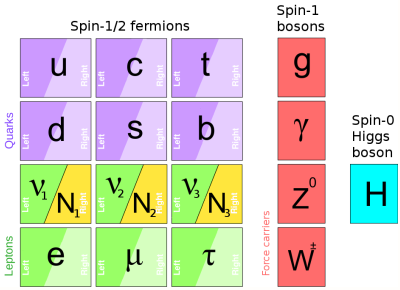


Neutrino oscillations/masses



[Particle Data Group]

Baryon asymmetry



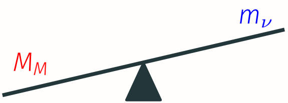
Type-I seesaw Lagrangian

$$\mathcal{L} \supset Y_{\alpha i}(\bar{\ell}_\alpha \tilde{\phi})\nu_{Ri} + \frac{1}{2}\bar{\nu}^c_{Ri}(M_M)_{ij}\nu_{Rj} + \text{h.c.}$$

Yukawa Majorana

Seesaw relation

$$m_\nu = -v^2\left(Y \cdot M_M{}^{-1} \cdot Y^t\right)$$



$$\nu \simeq U^\dagger_\nu(\nu_L - \theta\nu^c_R) + \text{h.c.}$$

Light neutrinos

$$N \simeq U^\dagger_N(\nu_R + \theta^t\nu^c_L) + \text{h.c.}$$

Heavy neutrinos (HNL)

- $n \geq 2$ HNL generations needed to explain light neutrino masses

Type-I seesaw mechanism

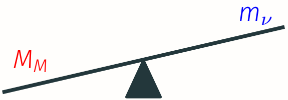
Type-I seesaw Lagrangian (below EWSB)

$$\mathcal{L} \supset \mathrm{v}Y_{\alpha i}\bar{\ell}_\alpha \nu_{Ri} + \frac{1}{2}\bar{\nu}^c_{Ri}(\mathrm{M}_M)_{ij}\nu_{Rj} + \text{h.c.}$$

Dirac **Majorana**

Seesaw relation

$$m_\nu = -v^2\left(Y\cdot {M_M}^{-1}\cdot Y^t\right)$$



$$\nu \simeq U_\nu^\dagger(\nu_L - \theta\nu_R^c) + \text{h.c.}$$

Light neutrinos

$$N \simeq U_N^\dagger(\nu_R + \theta^t\nu_L^c) + \text{h.c.}$$

Heavy neutrinos (HNL)

- $n \geq 2$ HNL generations needed to explain light neutrino masses
  - What is our prior on n ?
    - $n = 2$: Minimality (νMSM)
    - $n = 3$: Flavour symmetries, gauge extensions,... (LRSM,...)

Type-I seesaw mechanism

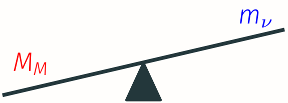
Type-I seesaw Lagrangian (below EWSB)

$$\mathcal{L} \supset vY_{\alpha i}\bar{\ell}_\alpha \nu_{Ri} + \frac{1}{2}\bar{\nu}^c_{Ri}(M_M)_{ij}\nu_{Rj} + \text{h.c.}$$

Dirac **Majorana**

Seesaw relation

$$m_\nu = -v^2\left(Y \cdot M_M{}^{-1} \cdot Y^t\right)$$



$$\nu \simeq U_\nu^\dagger(\nu_L - \theta\nu_R^c) + \text{h.c.}$$

Light neutrinos

$$N \simeq U_N^\dagger(\nu_R + \theta^t\nu_L^c) + \text{h.c.}$$

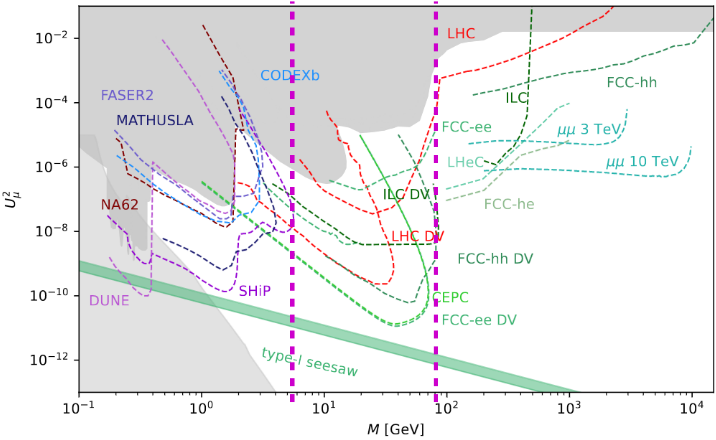
Heavy neutrinos (HNL)

- $n \geq 2$ HNL generations needed to explain light neutrino masses
- Experimental sensitivity expressed in terms of

$$U_\alpha^2 = \sum_i |\theta_{\alpha i}|^2 = \sum_i |v(Y \cdot M_M^{-1})_{\alpha i}|^2$$

Testing the type-I seesaw

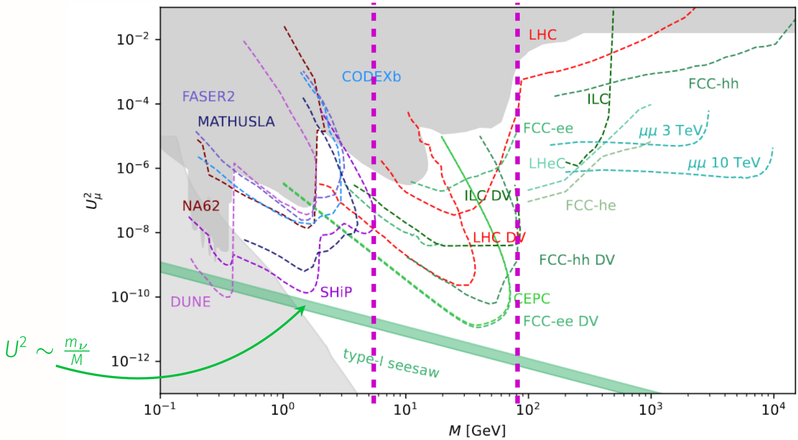
Many different ways to probe HNLs:



[Bose et al; 2209.13128]

Meson decays   W/Z decays   Virtual W/Z exchange

Many different ways to probe HNLs:



[Bose et al; 2209.13128]

Meson decays W/Z decays Virtual W/Z exchange

How to reach large coupling ? B-L approximate symmetry

Naive seesaw bound

$$m_\nu = -v^2 \left(Y \cdot M_M^{-1} \cdot Y^t \right) \Leftrightarrow U_i^2 \sim \frac{m_\nu}{M_i} \;\sim\; 10^{-10} \frac{\text{GeV}}{M_i}$$

How to reach large coupling ? B-L approximate symmetry

Naive seesaw bound

$$m_\nu = -v^2\left(Y \cdot M_M^{-1} \cdot Y^t\right) \Leftrightarrow U_i^2 \sim \frac{m_\nu}{M_i} \sim 10^{-10}\,\frac{\text{GeV}}{M_i}$$

B-L approximate symmetry

Majorana mass

$$\bar{M} \cdot \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

Yukawa coupling

$$\begin{pmatrix} f_e(1+\epsilon_e) & if_e(1-\epsilon_e) & f_e\epsilon_e' \\ f_\mu(1+\epsilon_\mu) & if_\mu(1-\epsilon_\mu) & f_\mu\epsilon_\mu' \\ f_\tau(1+\epsilon_\tau) & if_\tau(1-\epsilon_\tau) & f_\tau\epsilon_\tau' \end{pmatrix}$$

Technically natural: Small m_ν from small symmetry breaking parameters $\mu, \epsilon, \epsilon' \ll 1$

Consistent with large U^2.

How to reach large coupling ? B-L approximate symmetry

Naive seesaw bound

$$m_\nu = -v^2\left(Y \cdot M_M^{-1} \cdot Y^t\right) \Leftrightarrow U_i^2 \sim \frac{m_\nu}{M_i} \sim 10^{-10}\frac{\text{GeV}}{M_i}$$

B-L approximate symmetry

Majorana mass

$$\bar{M} \cdot \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

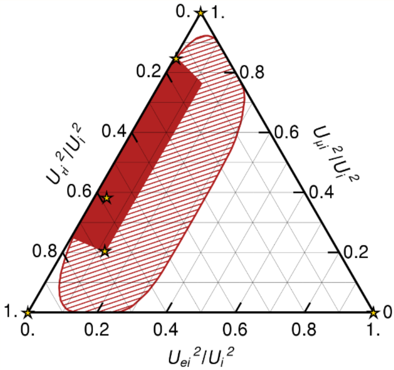
Yukawa coupling

Pseudo-Dirac pair — Decoupled

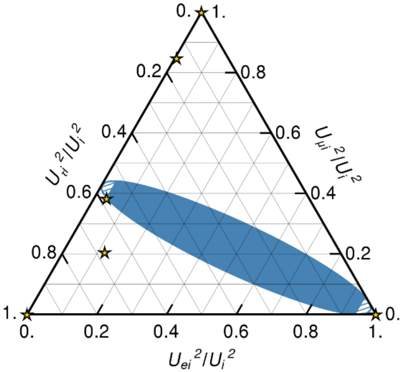
$$\begin{pmatrix} f_e(1+\epsilon_e) & if_e(1-\epsilon_e) & f_e\epsilon'_e \\ f_\mu(1+\epsilon_\mu) & if_\mu(1-\epsilon_\mu) & f_\mu\epsilon'_\mu \\ f_\tau(1+\epsilon_\tau) & if_\tau(1-\epsilon_\tau) & f_\tau\epsilon'_\tau \end{pmatrix}$$

Technically natural: Small m_ν from small symmetry breaking parameters $\mu, \epsilon, \epsilon' \ll 1$
Consistent with large U^2.

Flavour triangle



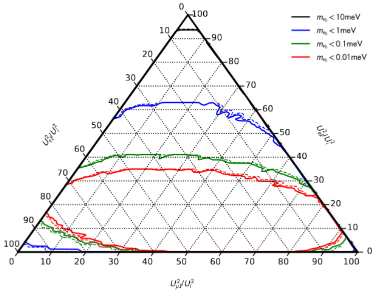
(a) Normal ordering.



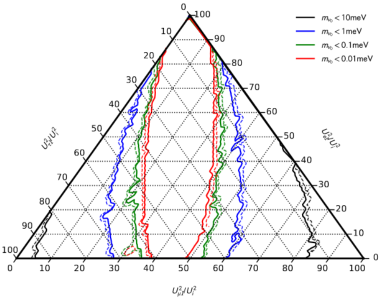
(b) Inverted ordering.

[Drewes/Hajer/Klarič/Lafranchi; 1801.04207]

- Branching ratios constrained for $n = 2$: Can test HNLs as origin of ν masses.
- For $m_0 \neq 0$ (only possible for $n = 3$), almost all flavour ratios are allowed.



Normal ordering



Inverted ordering

[Chrzaszcz et al; 1908.02302]

- Branching ratios constrained for $n = 2$: Can test HNLs as origin of ν masses.
- For $m_0 \neq 0$ (only possible for $n = 3$), almost all flavour ratios are allowed.

Low-scale leptogenesis

Leptogenesis

Sakharov conditions:

- ⋆ C- and CP-violation
- ⋆ Deviation from thermal equilibrium
- ⋆ Baryon number violation

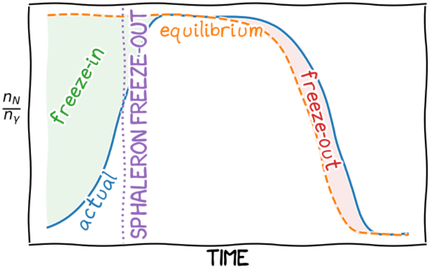
Leptogenesis

Sakharov conditions:

- ⋆ C- and CP-violation
  - · HNL oscillations and decay
- ⋆ Deviation from thermal equilibrium
  - · Freeze-in and freeze-out of the HNL
- ⋆ Baryon number violation

Sakharov conditions:

- ⋆ C- and CP-violation
  - · HNL oscillations and decay
- ⋆ Deviation from thermal equilibrium
  - · Freeze-in and freeze-out of the HNL
- ⋆ Baryon number violation

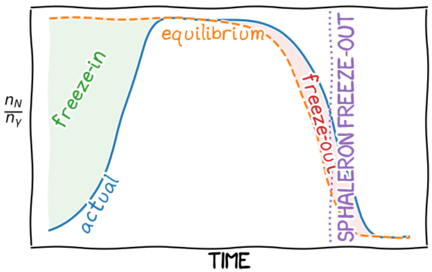


[Klarič/Shaposhnikov/Timiryasov, 2103.16545]

Leptogenesis

Sakharov conditions:

- ⋆ C- and CP-violation
  - HNL oscillations and decay
- ⋆ Deviation from thermal equilibrium
  - Freeze-in and freeze-out of the HNL
- ⋆ Baryon number violation



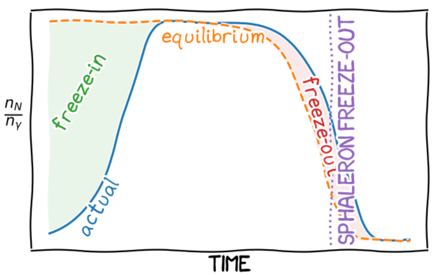
[Klarič/Shaposhnikov/Timiryasov, 2103.16545]

Leptogenesis

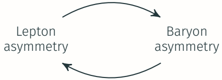
Sakharov conditions:

- ⋆ C- and CP-violation
  - HNL oscillations and decay
- ⋆ Deviation from thermal equilibrium
  - Freeze-in and freeze-out of the HNL
- ⋆ Baryon number violation
  - Sphaleron process

Efficient for 130 GeV $\lesssim T \lesssim 10^{12}$ GeV

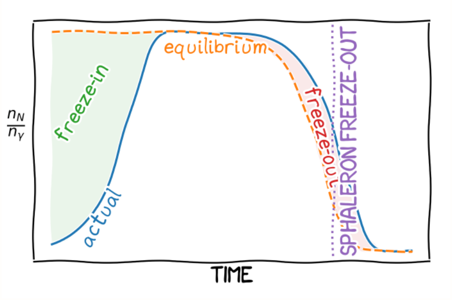


[Klarič/Shaposhnikov/Timiryasov, 2103.16545]

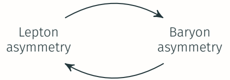


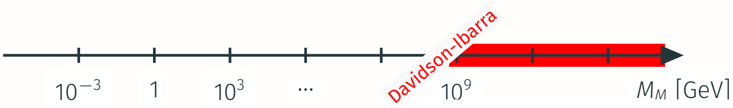
Sakharov conditions:

- ⋆ C- and CP-violation
  - HNL oscillations and decay
- ⋆ Deviation from thermal equilibrium
  - Freeze-in and freeze-out of the HNL
- ⋆ Baryon number violation
  - Sphaleron process



[Klarič/Shaposhnikov/Timiryasov, 2103.16545]





Vanilla thermal leptogenesis

[Fukugita/Yanagida '86]

Vanilla thermal leptogenesis

Assumptions:

* Asymmetry generated by heavy neutrino decays
* Hierarchical mass spectrum $M_1 \ll M_i$
* Unflavoured

Vanilla thermal leptogenesis

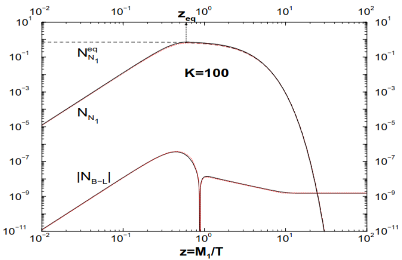
Assumptions:

* Asymmetry generated by heavy neutrino decays
* Hierarchical mass spectrum $M_1 \ll M_i$
* Unflavoured

Boltzmann equations

$$\frac{\mathrm{d}}{\mathrm{d}z} n_1 = -\frac{\Gamma_D}{Hz}(n_1 - n_1^{eq})$$

$$\frac{\mathrm{d}}{\mathrm{d}z} n_{B-L} = \epsilon_1 \frac{\Gamma_D}{Hz}(n_1 - n_1^{eq}) - \frac{\Gamma_W}{Hz} n_{B-L}$$



[Buchmüller/Di Bari/Plümacher; '04]

Vanilla thermal leptogenesis

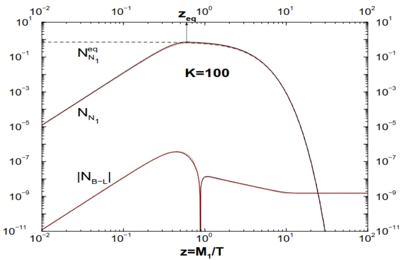
Assumptions:

- ∗ Asymmetry generated by heavy neutrino decays
- ∗ Hierarchical mass spectrum $M_1 \ll M_i$
- ∗ Unflavoured

Boltzmann equations

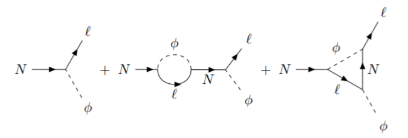
$$\frac{\mathrm{d}}{\mathrm{d}z} n_1 = -\frac{\Gamma_D}{Hz}(n_1 - n_1^{eq})$$

$$\frac{\mathrm{d}}{\mathrm{d}z} n_{B-L} = \epsilon_1 \frac{\Gamma_D}{Hz}(n_1 - n_1^{eq}) - \frac{\Gamma_W}{Hz} n_{B-L}$$



[Buchmüller/Di Bari/Plümacher; '04]

· Decay asymmetry $\epsilon_1 \equiv \frac{\Gamma_{N_1\to\ell+\phi} - \Gamma_{N_1\to\bar\ell+\phi^*}}{\Gamma_{N_1\to\ell+\phi} + \Gamma_{N_1\to\bar\ell+\phi^*}}$



Vanilla thermal leptogenesis

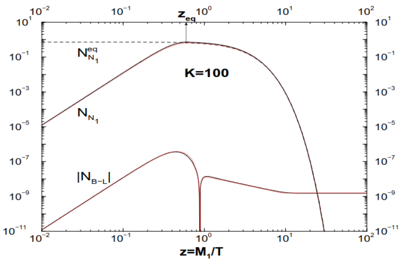
Assumptions:

- ∗ Asymmetry generated by heavy neutrino decays
- ∗ Hierarchical mass spectrum $M_1 \ll M_i$
- ∗ Unflavoured

Boltzmann equations

$$\frac{\mathrm{d}}{\mathrm{d}z} n_1 = -\frac{\Gamma_D}{Hz}(n_1 - n_1^{eq})$$

$$\frac{\mathrm{d}}{\mathrm{d}z} n_{B-L} = \epsilon_1 \frac{\Gamma_D}{Hz}(n_1 - n_1^{eq}) - \frac{\Gamma_W}{Hz} n_{B-L}$$



[Buchmüller/Di Bari/Plümacher; '04]

- Decay asymmetry $\epsilon_1 \equiv \frac{\Gamma_{N_1 \to \ell+\phi} - \Gamma_{N_1 \to \bar{\ell}+\phi^*}}{\Gamma_{N_1 \to \ell+\phi} + \Gamma_{N_1 \to \bar{\ell}+\phi^*}}$
- For large mass splittings $|\epsilon_1| \lesssim \frac{3}{8\pi}\frac{M_1}{v^2}\sqrt{\Delta m_{23}^2}$ leading to the Davidson-Ibarra bound

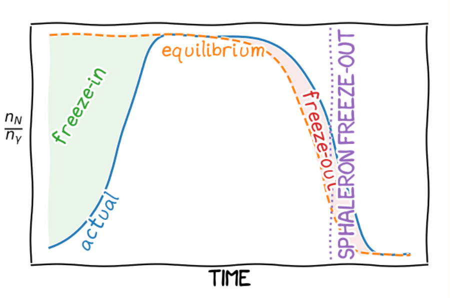
$$M_1 \gtrsim 4 \cdot 10^8 \text{ GeV}$$

$\hookrightarrow$ Direct detection ☹

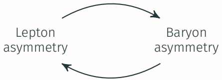
Leptogenesis

Sakharov conditions:

- ⋆ C- and CP-violation
  - HNL oscillations and decay
- ⋆ Deviation from thermal equilibrium
  - Freeze-in and freeze-out of the HNL
- ⋆ Baryon number violation
  - Sphaleron process



[Klarič/Shaposhnikov/Timiryasov, 2103.16545]



Low-scale leptogenesis
[Akhmedov/Rubakov/Smirnov '98, Pilaftsis/Underwood '03, Asaka/Shaposhnikov '05, ...]

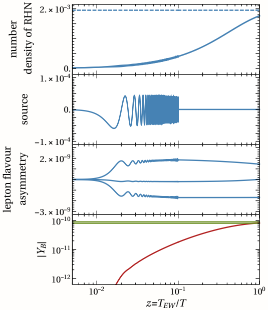
Vanilla thermal leptogenesis
[Fukugita/Yanagida '86]

Low-scale models

- Traditionally, 2 main mechanisms:

ARS Leptogenesis

Asymmetry produced during freeze-in from CP-violating HNL oscillations

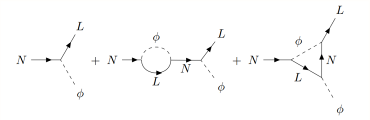


[Drewes/Garbrecht/Gueter/Klarič; 1606.06690]

$\overset{?}{\longleftrightarrow}$

Resonant leptogenesis

Resonant enhancement of CP-violation from small mass splittings



Decay asymmetry:

$$\epsilon_i \simeq \frac{\mathrm{Im}(Y^\dagger Y)^2_{ij}}{(Y^\dagger Y)_{ii}(Y^\dagger Y)_{jj}} \frac{(M^2_{N_i} - M^2_{N_j}) \cdot M_{N_i} \Gamma_N}{(M^2_{N_i} - M^2_{N_j})^2 + M^2_{N_i} \Gamma^2_N}$$

Low-scale models

- Traditionally, 2 main mechanisms:

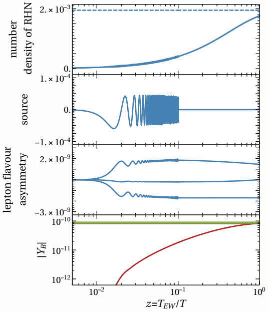
ARS Leptogenesis

Asymmetry produced during freeze-in from CP-violating HNL oscillations

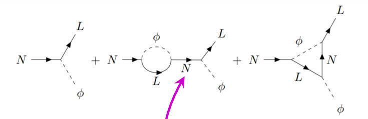
$\overset{?}{\longleftrightarrow}$

Resonant leptogenesis

Resonant enhancement of CP-violation from small mass splittings



[Drewes/Garbrecht/Gueter/Klarič; 1606.06690]



Decay asymmetry:

$$\epsilon_i \simeq \frac{\mathrm{Im}(Y^\dagger Y)^2_{ij}}{(Y^\dagger Y)_{ii}(Y^\dagger Y)_{jj}} \frac{(M^2_{N_i} - M^2_{N_j}) \cdot M_{N_i} \Gamma_N}{(M^2_{N_i} - M^2_{N_j})^2 + M^2_{N_i} \Gamma^2_N}$$

- Traditionally, 2 main mechanisms:

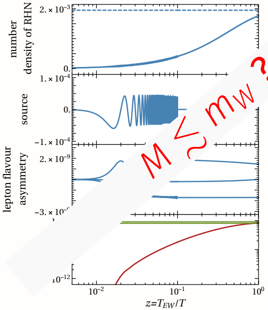
ARS Leptogenesis

Asymmetry produced during freeze-in from CP-violating HNL oscillations

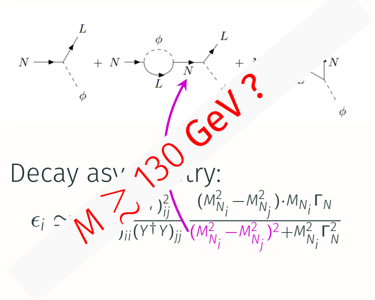
$\overset{?}{\longleftrightarrow}$

Resonant leptogenesis

Resonant enhancement of CP-violation from small mass splittings



[Drewes/Garbrecht/Gueter/Klarič; 1606.06690]

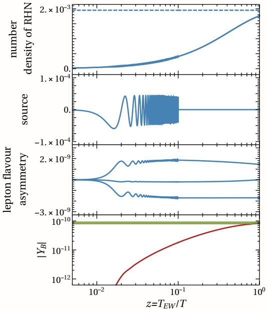


Low-scale models

- Traditionally, 2 main mechanisms:

ARS Leptogenesis

Asymmetry produced during freeze-in from CP-violating HNL oscillations

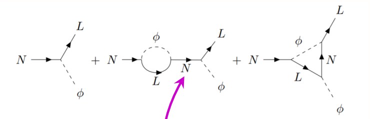


[Drewes/Garbrecht/Gueter/Klarič; 1606.06690]

$\leftrightarrow$?

Resonant leptogenesis

Resonant enhancement of CP-violation from small mass splittings



Decay asymmetry:

$$\epsilon_i \simeq \frac{\mathrm{Im}(Y^\dagger Y)^2_{ij}}{(Y^\dagger Y)_{ii}(Y^\dagger Y)_{jj}} \frac{(M^2_{N_i} - M^2_{N_j}) \cdot M_{N_i} \Gamma_N}{(M^2_{N_i} - M^2_{N_j})^2 + M^2_{N_i} \Gamma^2_N}$$

⟶ Two regimes of the same mechanism ! Represented by the same set of kinetic equations (cfr. [Garbrecht; 1812.02651] for a review)

Quantum kinetic equations

$$i\,\frac{\mathrm{d}}{\mathrm{d}t}\rho = [H, \delta\rho] - \frac{i}{2}\{\Gamma, \delta\rho\} - i \sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

$$i\,\frac{\mathrm{d}}{\mathrm{d}t}\bar{\rho} = -[H, \delta\bar{\rho}] - \frac{i}{2}\{\Gamma, \delta\bar{\rho}\} + i \sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

$$\frac{\mathrm{d}}{\mathrm{d}t} n_{\Delta_a} = -\frac{2i\mu_a}{T}\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3}\mathrm{Tr}[\Gamma_a] f_F(1-f_F) + i\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3}\mathrm{Tr}[\tilde{\Gamma}_a(\delta\bar{\rho} - \delta\rho)].$$

Density matrix

Effective Hamiltonian

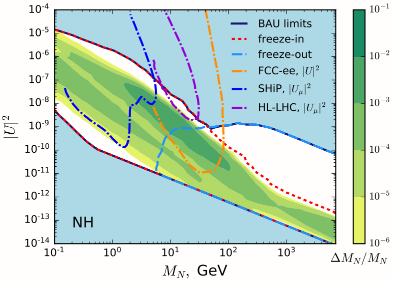
Interaction rates

Lepton asymmetry

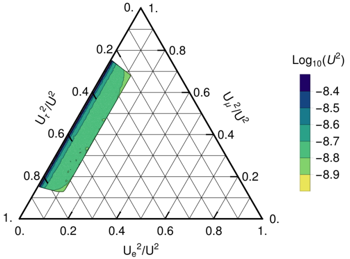
- Interaction rates can be
  - ⋆ Fermion number **conserving** $\sim (Y^\dagger Y)T$
  - ⋆ Fermion number **violating** $\sim (Y^t Y^*)\frac{M^2}{T}$
- Refined calculation subject to intensive studies over the last years, e.g. Anisimov/Bedak/Bödeker ’10, Garny/Kartavtsev/Hohenegger ’11, Drewes/Garbrecht/Gueter/Klarič ’16, Hernandez/Kekic/Lopez-Pavon/Racker/Salvado ’16, Laine/Ghiglieri ’16 ’18, Klarič/Shaposhnikov/Timiryasov ’21, ...

$n = 2$ (νMSM) parameter space

- Parameter space for freeze-in and freeze-out are connected
- Sizeable fraction of the parameter space can be tested at colliders or fixed target experiments
- Relies on flavour hierarchies to reach large U^2
- IH parameter space larger than for NH for $M \lesssim \mathcal{O}(100)$ GeV due to stronger washout



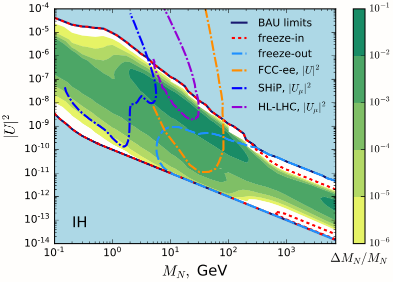
[Klarič/Shaposhnikov/Timiryasov; 2103.16545]



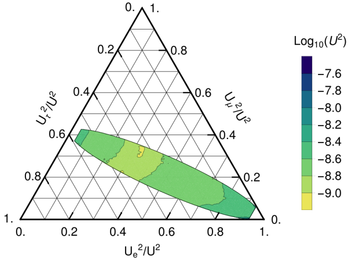
[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/Klarič; 1710.03744]

$n = 2$ (νMSM) parameter space

- Parameter space for freeze-in and freeze-out are connected
- Sizeable fraction of the parameter space can be tested at colliders or fixed target experiments
- Relies on flavour hierarchies to reach large U^2
- IH parameter space larger than for NH for $M \lesssim \mathcal{O}(100)$ GeV due to stronger washout

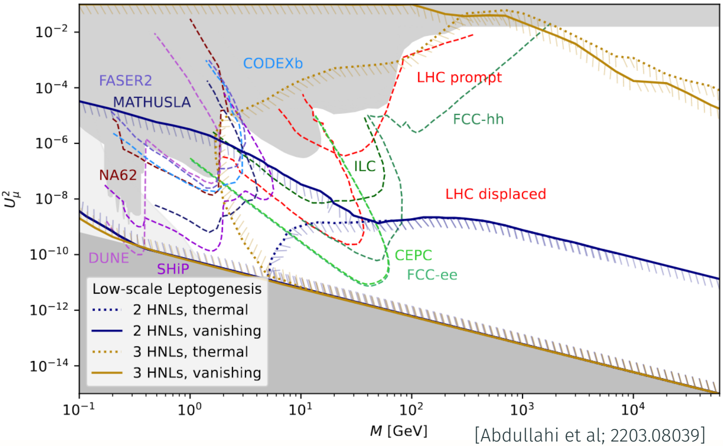


[Klarič/Shaposhnikov/Timiryasov; 2103.16545]



[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/Klarič; 1710.03744]

$n = 3$ parameter space, NH



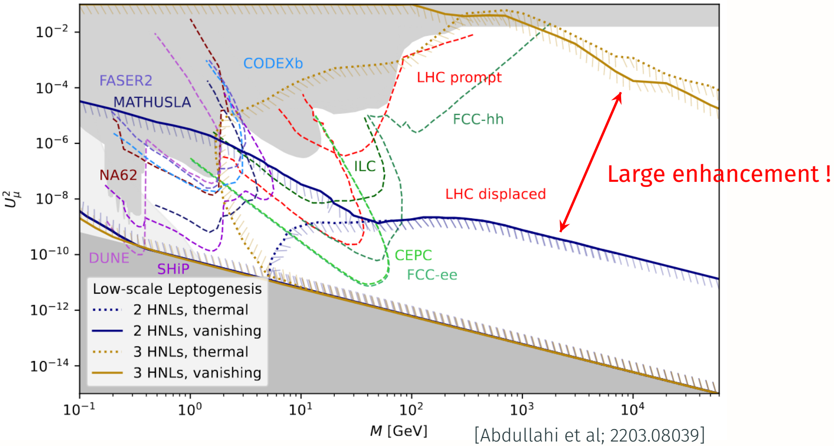
[Abdullahi et al; 2203.08039]

$n = 2$ lines from [Klarič/Shaposhnikov/Timiryasov, 2103.16545]

$n = 3$ lines from [Drewes/YG/Klarič; 2106.16226]

- Can potentially produce enough HNLs to test leptogenesis !

$n = 3$ parameter space, NH



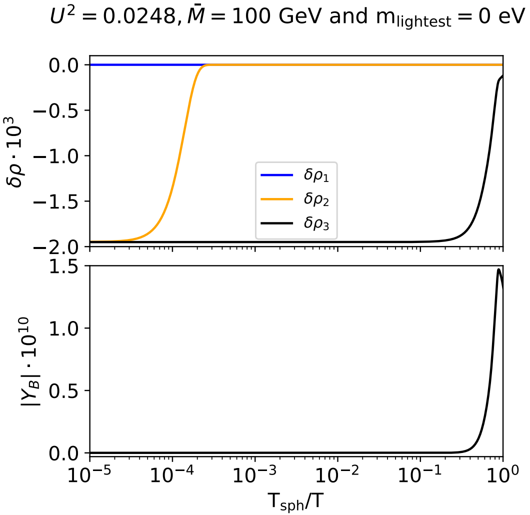
[Abdullahi et al; 2203.08039]

$n = 2$ lines from [Klarič/Shaposhnikov/Timiryasov, 2103.16545]

$n = 3$ lines from [Drewes/YG/Klarič; 2106.16226]

- Can potentially produce enough HNLs to test leptogenesis !

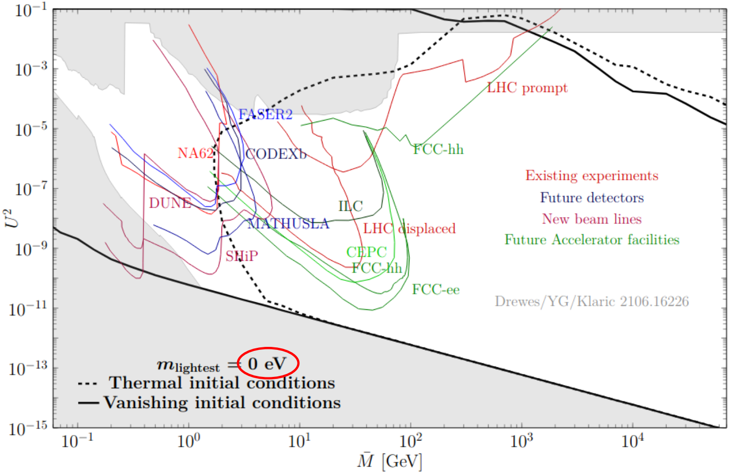
Why such large mixings ?



[YG; 2305.06663]

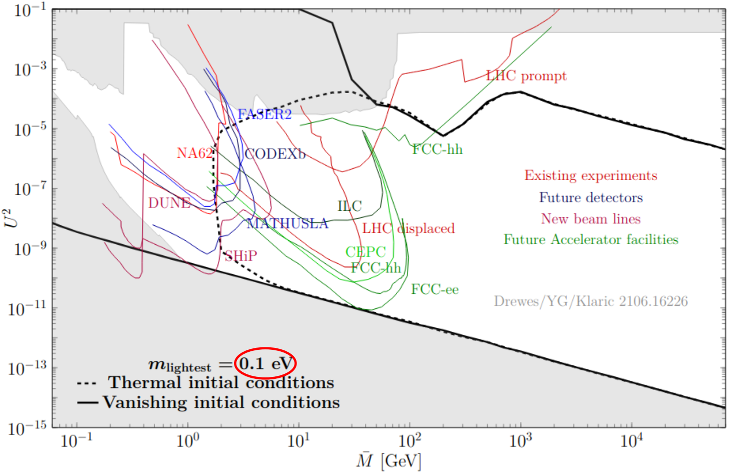
- Large mixing angles allow late equilibration of one HNL $U_i^2 \ll 1$
  $\hookrightarrow$ Late BAU production, less time for washout

$n = 3$ parameter space, NH



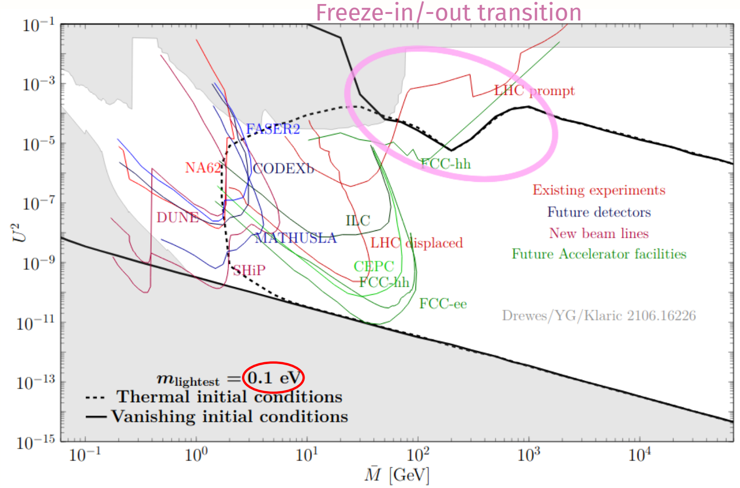
- Can potentially produce enough HNLs to test leptogenesis !

$n = 3$ parameter space, NH

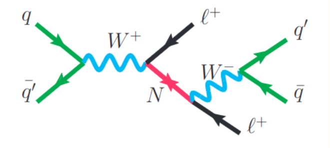


- Can potentially produce enough HNLs to test leptogenesis !

$n = 3$ parameter space, NH



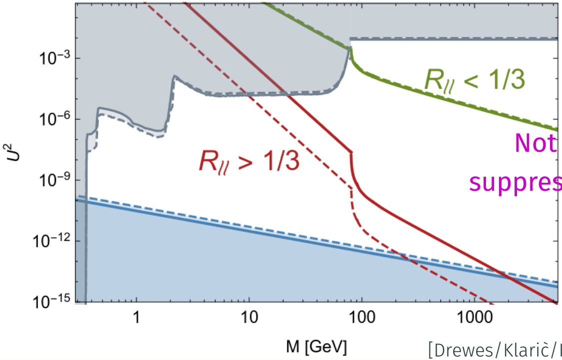
- Can potentially produce enough HNLs to test leptogenesis !



[CMS collaboration; 1806.10905]

- Large U^2 but lepton number conserved if $\mu, \epsilon \to 0$
- Ratio of lepton number violating to conserving decays parametrised by

$$R_{ll} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$



Not always strongly suppressed for sizeable U^2!

[Drewes/Klarič/Klose; 1907.13034]

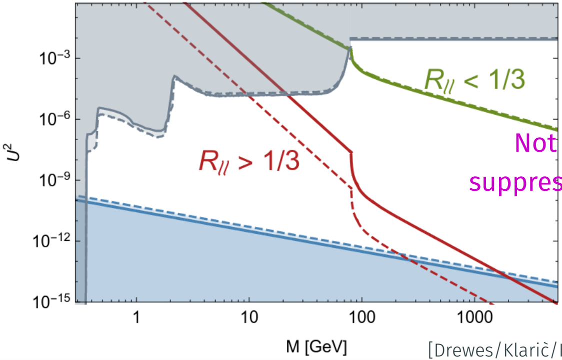
Approximate B-L symmetry

$$M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 \\ 0 & \bar{M}(1+\mu) \end{pmatrix},$$

$$Y = \begin{pmatrix} f_e(1+\epsilon_e) & if_e(1-\epsilon_e) \\ f_\mu(1+\epsilon_\mu) & if_\mu(1-\epsilon_\mu) \\ f_\tau(1+\epsilon_\tau) & if_\tau(1-\epsilon_\tau) \end{pmatrix}$$

- Large U^2 but lepton number conserved if $\mu, \epsilon \to 0$
- Ratio of lepton number violating to conserving decays parametrised by

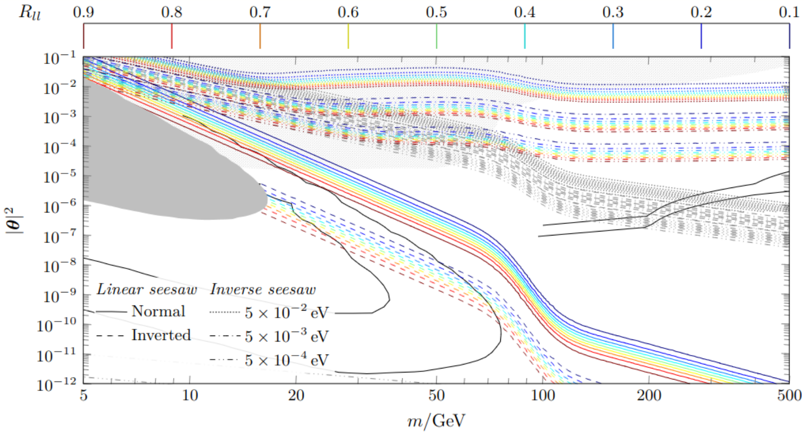
$$R_{ll} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$



Not always strongly suppressed for sizeable U^2!

[Drewes/Klarič/Klose; 1907.13034]

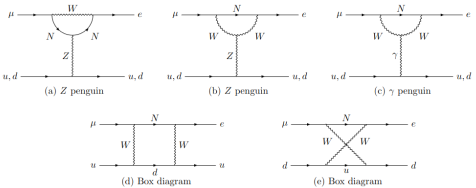
Lepton number violation at colliders



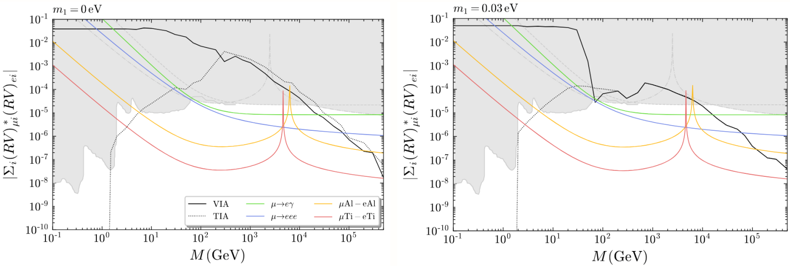
[Antusch/Hajer/Rosskopp, 2307.06208]

In practice, decoherence effects can make testability prospects even more optimistic !

- HNLs also lead to charge lepton flavour violation.



[Urquia-Calderon/Timiryasov/Ruchayskiy; 2206.04540]



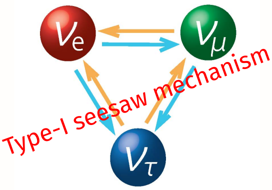
[Granelli/Klaric/Petcov; 2206.04342]

Intermediate summary

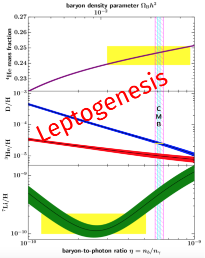
- Right-handed neutrinos provide minimal solution for ν masses + baryon asymmetry
- Parameter space largely enhanced for $n = 3$ due to decoupled 3^{rd} HNL
- Large mixing angle opens up the possibility of testing leptogenesis by combining information from colliders, $0\nu\beta\beta$, ν oscillations, ...
- Collider testability of $n = 3$ scenario to be further explored

Effects of flavour and CP-symmetries

Right-handed neutrinos

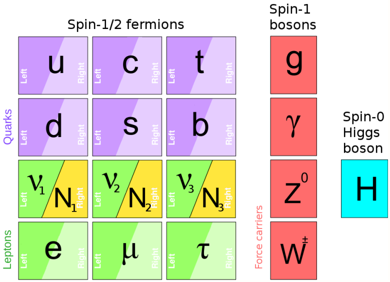


Neutrino masses

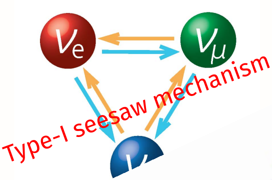


[Particle Data Group]

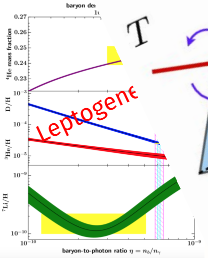
Baryon asymmetry



Right-handed neutrinos

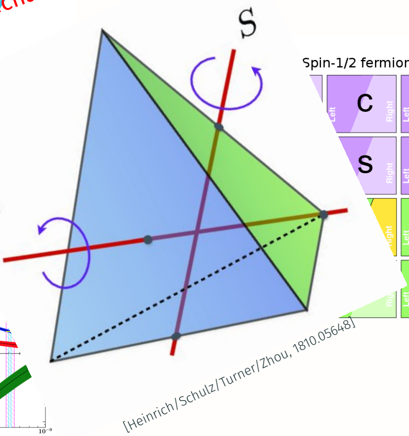


Neutr

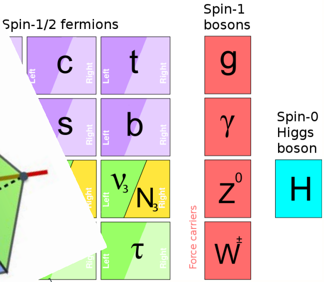


[Particle Data Group]

Baryon asymmetry

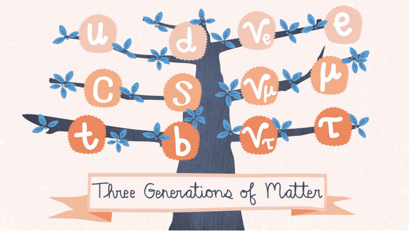


[Heinrich/Schulz/Turner/Zhou, 1810.05648]



Motivations for flavour symmetries

- Why 3 generations in the Standard Model ?



[Sandbox Studio, Chicago]

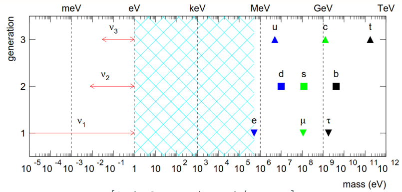
Motivations for flavour symmetries

- Why 3 generations in the Standard Model ?
- Hierarchy in the CKM matrix structure ?

$$|U_{\rm CKM}| \approx \begin{pmatrix} 0.97 & 0.22 & 0.004 \\ 0.22 & 0.99 & 0.04 \\ 0.008 & 0.04 & 1.01. \end{pmatrix}$$

Motivations for flavour symmetries

- Why 3 generations in the Standard Model ?
- Hierarchy in the CKM matrix structure ?
- Hierarchy in the fermion masses ?



[A. de Gouvea; hep-ph/0411274]

Motivations for flavour symmetries

- Why 3 generations in the Standard Model ?
- Hierarchy in the CKM matrix structure ?
- Hierarchy in the fermion masses ?
- Why such neutrino mixing pattern ? In particular, why the PMNS matrix

$$|U_{\mathrm{PMNS}}| \approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.29 & 0.59 & 0.75 \\ 0.49 & 0.59 & 0.64. \end{pmatrix}$$

is so close to a tri-bimaximal mixing

$$U_{\mathrm{TB}} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \end{pmatrix}.$$

Motivations for flavour symmetries

- Why 3 generations in the Standard Model ?
- Hierarchy in the CKM matrix structure ?
- Hierarchy in the fermion masses ?
- **Why such neutrino mixing pattern ?** In particular, why the PMNS matrix

$$|U_{\mathrm{PMNS}}| \approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.29 & 0.59 & 0.75 \\ 0.49 & 0.59 & 0.64. \end{pmatrix}$$

is so close to a tri-bimaximal mixing

$$U_{\mathrm{TB}} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \end{pmatrix}.$$

Discrete flavour symmetries

- Discrete symmetry G_f at high scale, broken at low scale into residual symmetries G_l, $G_\nu \subset G_f$.

$G_f \times \mathrm{CP}$

G_l — Charged lepton sector

$G_\nu \times \mathrm{CP}$ — Neutrino sector

- What group to choose ?
  * G_f discrete subgroup of U(3) (not always necessary)
  * G_f non-abelian to avoid texture zero
  * G_l abelian and minimal to avoid imposing too strong constraints on the charged lepton masses
  * G_ν as minimal as possible

Discrete flavour symmetries

- Discrete symmetry G_f at high scale, broken at low scale into residual symmetries $G_l, G_\nu \subset G_f$.

$$\Delta(6n^2)\times\mathrm{CP} \sim ((\mathcal{Z}_n \times \mathcal{Z}_n) \rtimes \mathcal{S}_3) \times \mathrm{CP}$$

$\mathcal{Z}_3$

Charged lepton sector

$\mathcal{Z}_2\times\mathrm{CP}$

Neutrino sector

In our setup

Prediction

$$U_{\mathrm{PMNS}} = \Omega(\mathbf{3}) R_{ij}(\theta_L) K_\nu$$

$$Y = \Omega(\mathbf{3})\, R_{ij}(\theta_L)\, \mathrm{diag}(y_1, y_2, y_3)\, P^{ij}_{kl}\, R_{kl}(-\theta_R)\, \Omega(\mathbf{3}')^\dagger$$

Parametrisation of flavour symmetries

- 4 qualitatively different scenarios:

  Case 1), Case 2), Case 3 a) and Case 3 b.1).

- 13 $\rightarrow$ 6 or 7 free parameters: For Case 1),

$$\phi_s,\ \theta_R,\ M_1 \approx M_2 \approx M_3,\ m_0.$$

  $\longrightarrow$ Better analytical understanding of the parameter space.

- Total coupling proportional to

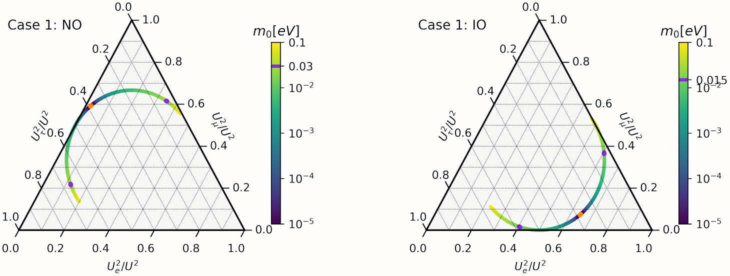
$$U^2 \propto \frac{1}{|\cos(2\theta_R)|}, \frac{1}{|\sin(2\theta_R)|}.$$

  $\hookrightarrow$ $\theta_R \rightarrow k\frac{\pi}{4}, k \in \mathbb{Z}$ (but enhanced residual symmetry) leads to experimentally testable scenarios !

- Can relate low- and high-scale parameters. For Case 1):

$$\sin(\delta) = 0,\ |\sin(\alpha)| = |\sin(6\phi_s)|,\ \sin(\beta) = 0.$$

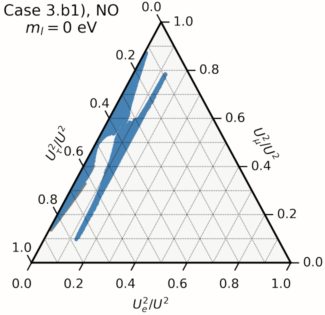
Ternary plots for Case 1)

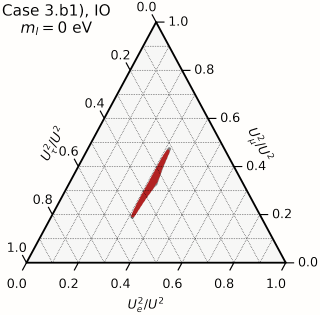


[Drewes/Hagedorn/YG/Klaric; 24xx.xxxxx]

- Enhanced predictivity compared to the agnostic scenario
- Branching ratio fixed (or 2 possibilities) for fixed m_0
  $\hookrightarrow$ Can pinpoint m_0 at colliders just by measuring the HNs branching ratio.
- Other cases are slightly less predictive.

Ternary plots for Case 3 b.1)





[Drewes/Hagedorn/YG/Klaric; 24xx.xxxxx]

- Enhanced predictivity compared to the agnostic scenario
- Branching ratio fixed (or 2 possibilities) for fixed m_0
  $\hookrightarrow$ Can pinpoint m_0 at colliders just by measuring the HNs branching ratio.
- Other cases are slightly less predictive.

Quantum kinetic equations

$$i\,\frac{\mathrm{d}}{\mathrm{d}t}\rho = [H, \delta\rho] - \frac{i}{2}\{\Gamma, \delta\rho\} - i \sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

$$i\,\frac{\mathrm{d}}{\mathrm{d}t}\bar{\rho} = -[H, \delta\bar{\rho}] - \frac{i}{2}\{\Gamma, \delta\bar{\rho}\} + i \sum_{a\in\{e,\mu,\tau\}} \tilde{\Gamma}_a \frac{\mu_a}{T} f_F(1-f_F),$$

Source term

$$\frac{\mathrm{d}}{\mathrm{d}t} n_{\Delta_a} = -\frac{2i\mu_a}{T}\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3}\mathrm{Tr}[\Gamma_a] f_F(1-f_F) + i\int \frac{\mathrm{d}^3\vec{k}}{(2\pi)^3}\mathrm{Tr}[\tilde{\Gamma}_a(\delta\bar{\rho} - \delta\rho)].$$

Density matrix

Effective Hamiltonian

Lepton asymmetry

Interaction rates

- Interaction rates can be
  - ⋆ Fermion number **conserving** $\sim (Y^\dagger Y)T$
  - ⋆ Fermion number **violating** $\sim (Y^t Y^*)\frac{M^2}{T}$
- Refined calculation subject to intensive studies over the last years, e.g. Anisimov/Bedak/Bödeker ’10, Garny/Kartavtsev/Hohenegger ’11, Drewes/Garbrecht/Gueter/Klarič ’16, Hernandez/Kekic/Lopez-Pavon/Racker/Salvado ’16, Laine/Ghiglieri ’16 ’18, Klarič/Shaposhnikov/Timiryasov ’21, …

CP-violation combinations

- Perturbatively,

$$Y_B \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ (\delta\rho - \delta\bar{\rho})\right) \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ [H_N, \Gamma]\right)$$

$$H_N = \frac{M_M^2}{2E} + h_+(T) Y^\dagger Y + h_-(T) Y^t Y^*, \ \ \Gamma, \tilde{\Gamma} = \pm\gamma_+(T) Y^\dagger Y + \gamma_-(T) Y^t Y^*$$

- BAU production governed by

$$C_{\mathrm{LFV},\alpha} = i\,\mathrm{Tr}\Big(\left[M_M^2, Y^\dagger\, Y\right]\ Y^\dagger\, P_\alpha\, Y\Big)\ ,$$
$$C_{\mathrm{LNV},\alpha} = i\,\mathrm{Tr}\Big(\left[M_M^2, Y^\dagger\, Y\right]\ Y^T\, P_\alpha\, Y^*\Big)\ ,$$
$$C_{\mathrm{DEG},\alpha} = i\,\mathrm{Tr}\Big(\left[Y^T\, Y^*, Y^\dagger\, Y\right]\ Y^T\, P_\alpha\, Y^*\Big)\ ,$$

CP-violation combinations

- Perturbatively,

$$Y_B \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ (\delta\rho - \delta\bar{\rho})\right) \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ [H_N, \Gamma]\right)$$

$$H_N = \frac{M_M^2}{2E} + h_+(T)Y^\dagger Y + h_-(T)Y^t Y^*,\ \ \Gamma, \tilde{\Gamma} = \pm\gamma_+(T)Y^\dagger Y + \gamma_-(T)Y^t Y^*$$

- BAU production governed by

$$C_{\mathrm{LFV},\alpha} = i\,\mathrm{Tr}\Big(\left[M_M^2, Y^\dagger Y\right]\ Y^\dagger P_\alpha Y\Big)\ ,$$

$$C_{\mathrm{LNV},\alpha} = i\,\mathrm{Tr}\Big(\left[M_M^2, Y^\dagger Y\right]\ Y^T P_\alpha Y^*\Big)\ ,$$

$$C_{\mathrm{DEG},\alpha} = i\,\mathrm{Tr}\Big(\left[Y^T Y^*, Y^\dagger Y\right]\ Y^T P_\alpha Y^*\Big)\ ,$$

Flavour violating only

$\sum_\alpha C_{\mathrm{LFV},\alpha} = 0$

Violates lepton number

$\sum_\alpha C_{\mathrm{LNV},\alpha} \neq 0$

Flavour violating only, can be $\neq 0$ for $\Delta M = 0$!

CP-violation combinations

- Perturbatively,

$$Y_B \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ (\delta\rho - \delta\bar{\rho})\right) \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ [H_N, \Gamma]\right)$$

$$H_N = \frac{M_M^2}{2E} + h_+(T) Y^\dagger Y + h_-(T) Y^t Y^*, \ \ \Gamma, \tilde{\Gamma} = \pm\gamma_+(T) Y^\dagger Y + \gamma_-(T) Y^t Y^*$$

- For Case 1,

$$C_{\mathrm{LFV},\alpha} \sim \frac{8}{3} M^2\, \kappa\, y_2 y_3\, (y_2^2 - y_3^2)\ \sin\theta_{L,\alpha}\ \sin\theta_R\ \cos 3\,\phi_s,$$

$$C_{\mathrm{LNV},\alpha} \sim \frac{8}{3} M^2 \kappa y_2 y_3 \left(y_3^2 \cos(2\theta_R) - y_2^2\right) \sin\theta_{L,\alpha}\ \sin\theta_R\ \cos 3\,\phi_s,$$

$$C_{\mathrm{DEG},\alpha} = 0,$$

where

$$\theta_{L,\alpha} = \theta_L + \rho_\alpha \frac{4\,\pi}{3} \text{ with } \rho_e = 0,\ \rho_\mu = +1,\ \rho_\tau = -1\,.$$

CP-violation combinations

- Perturbatively,

$$Y_B \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ (\delta\rho - \delta\bar{\rho})\right) \propto \mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ [H_N, \Gamma]\right)$$

$$H_N = \frac{M_M^2}{2E} + h_+(T) Y^\dagger Y + h_-(T) Y^t Y^*, \ \ \Gamma, \tilde{\Gamma} = \pm\gamma_+(T) Y^\dagger Y + \gamma_-(T) Y^t Y^*$$

- For Case 1,

$$C_{\mathrm{LFV},\alpha} \sim \frac{8}{3} M^2\, \kappa\, y_2 y_3\, (y_2^2 - y_3^2)\ \sin\theta_{L,\alpha}\ \sin\theta_R\ \cos 3\,\phi_s,$$

$$C_{\mathrm{LNV},\alpha} \sim \frac{8}{3} M^2 \kappa y_2 y_3 \left(y_3^2 \cos(2\theta_R) - y_2^2\right) \sin\theta_{L,\alpha}\ \sin\theta_R\ \cos 3\,\phi_s,$$

$$C_{\mathrm{DEG},\alpha} = 0,$$

where

$$\theta_{L,\alpha} = \theta_L + \rho_\alpha\, \frac{4\,\pi}{3}\ \text{with}\ \rho_e = 0,\ \rho_\mu = +1,\ \rho_\tau = -1\,.$$

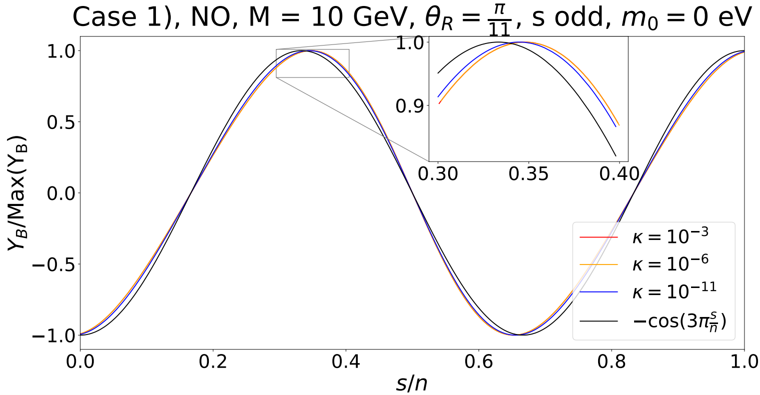


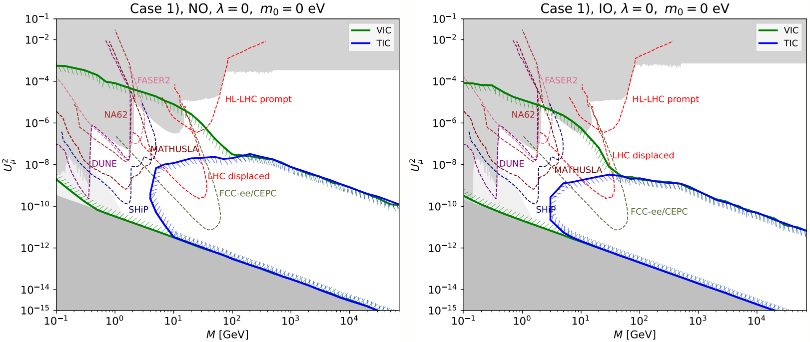
Figure 1: Vanishing initial conditions, $\lambda = 0$

[Drewes/Hagedorn/YG/Klaric; 2203.08538]

- Correlation between Y_B and low-energy observables. Here,

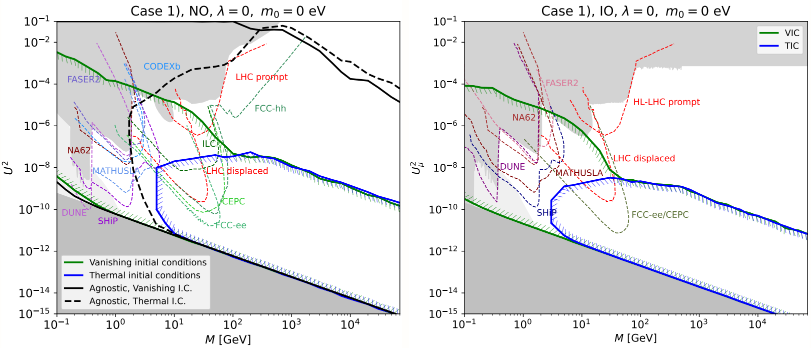
$$\sin(\alpha) = \sin(6\pi\frac{s}{n}).$$

Leptogenesis with flavour symmetries



[Drewes/YG/Hagedorn/Klarič; 24xx.xxxxx]

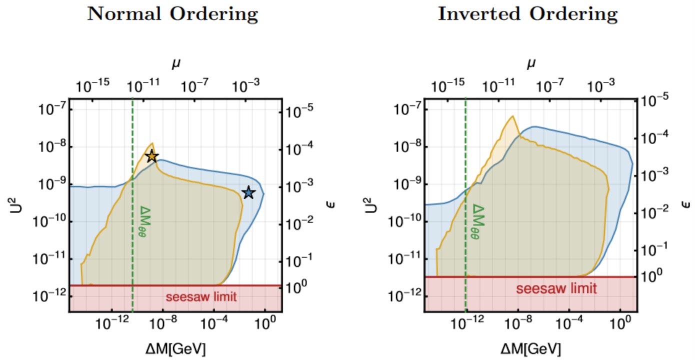
- Reduced parameter space but remains testable



[Drewes/YG/Hagedorn/Klarič; 24xx.xxxxx]

- Reduced parameter space but remains testable

Leptogenesis in the mass degenerate case



[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/Klarič; 1710.03744]
See also [Sandner/Hernandez/Lopez-Pavon/Rius; 2305.14427]

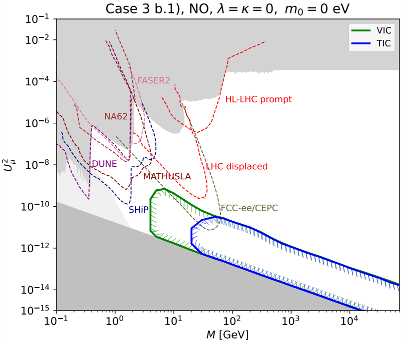
- Leptogenesis possible for $\Delta M = 0$ thanks to Higgs and thermal mass splittings

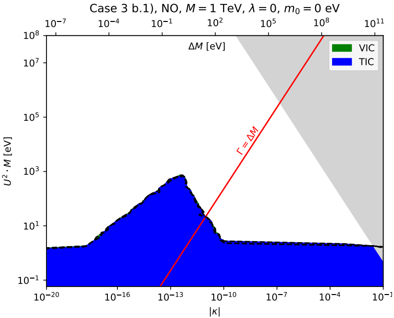
$$\Delta M_{\rm phys} \sim h_+(T) Y^\dagger Y + h_-(T) Y^t Y^*$$

- Lepton asymmetry proportional to CP-violating combination

$$\mathrm{Tr}\left(\tilde{\Gamma}_\alpha\ [H_N, \Gamma]\right) \sim \mathrm{Tr}\left(\left[\hat{Y}^t\,\hat{Y}^*, \hat{Y}^\dagger\,\hat{Y}\right]\ \hat{Y}^t\,P_\alpha\,\hat{Y}^*\right) \neq 0!$$

Flavour symmetries and degenerate leptogenesis





[Drewes/YG/Hagedorn/Klarič; 24xx.xxxxx]

- For Case 3 b.1), $C_{\mathrm{DEG},\alpha} \neq 0$! Leptogenesis viable for $\Delta M_M = 0$.

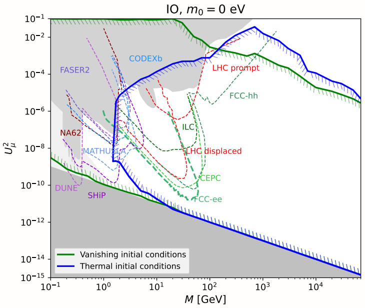
What should I take home ?

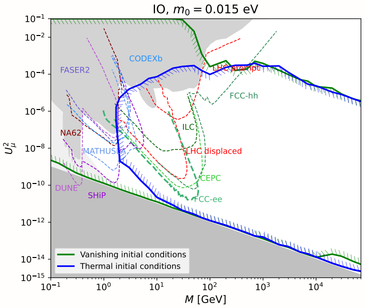
- Right-handed neutrinos provide minimal solution for ν masses + baryon asymmetry
- Leptogenesis parameter space largely enhanced for $n = 3$
- Large mixing angle opens up the possibility of testing leptogenesis by combining information from colliders, $0\nu\beta\beta$, ν oscillations, ...
- Combined with flavour symmetric explanation of PMNS: very predictive !
- Degenerate leptogenesis possible due to Higgs and thermal effects
- Collider testability of $n = 3$ scenario to be further explored

Thanks for your attention!

Appendix

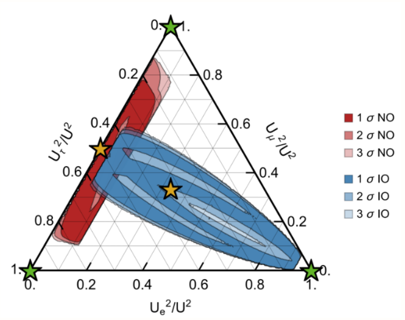
$n = 3$ parameter space, IO



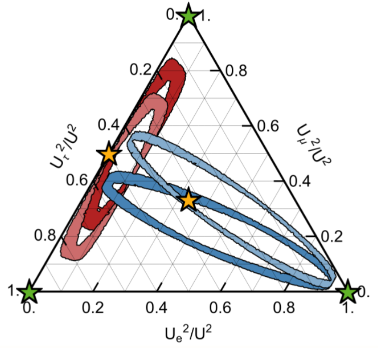


- Similar enhancement of the parameter space for IO.

Impact of low energy measurements on $\frac{U_\alpha^2}{U^2}$



Current ν oscillation data



DUNE projections

- New (more realistic) benchmarks proposed beyond the 1-flavour approximation
- DUNE measurement of δ could constrain the mixing to each SM flavour, hence leptogenesis

Seesaw parameter space

Consistency with ν-oscillation data induced by Casas-Ibarra parametrisation

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}} \mathrm{R} \sqrt{M_M}$$

Seesaw relation: $m_\nu = -v^2 F \cdot {M_M}^{-1} \cdot F^t$.

Seesaw parameter space

Consistency with ν-oscillation data induced by Casas-Ibarra parametrisation

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}} \mathrm{R} \sqrt{M_M}$$

R is a complex rotation matrix

n=3

3 CP-violating phases

3 PMNS angles (fixed)

3 light neutrino masses (2 fixed)

3 complex Euler angles

3 Majorana masses

13 free parameters

Seesaw parameter space

Consistency with ν-oscillation data induced by Casas-Ibarra parametrisation

$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}} \mathrm{R} \sqrt{M_M}$$

n=2

- 2 CP-violating phases
- 3 PMNS angles (fixed)
- 2 light neutrino masses (fixed)
- 1 complex Euler angle
- 2 Majorana masses

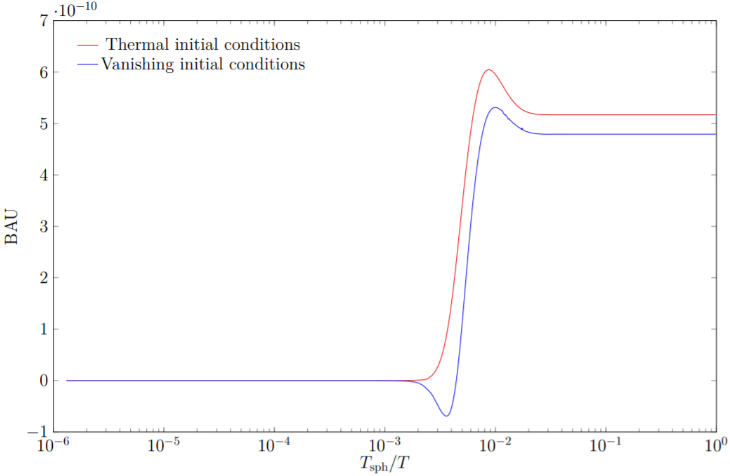
6 free parameters

n=3

- 3 CP-violating phases
- 3 PMNS angles (fixed)
- 3 light neutrino masses (2 fixed)
- 3 complex Euler angles
- 3 Majorana masses

13 free parameters

Thermal vs vanishing initial conditions



At large $\bar{M}$, parameter space for thermal I.C. is larger because asymmetry produced during freeze-in and freeze-out have opposite signs.