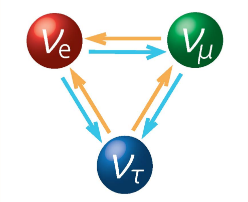
Testable leptogenesis with three right-handed neutrinos

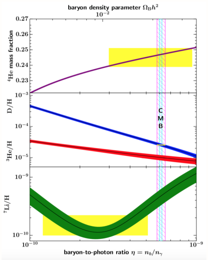
Yannis Georis (ヤニス・ジョリス)
Based on different works in collaborations with J. de Vries, M. Drewes, C. Hagedorn, J. Klarić, V. Plakkot and A. Wendels

KEK Theory Meeting on Particle Physics Phenomenology
February 17, 2026

Right-handed neutrinos

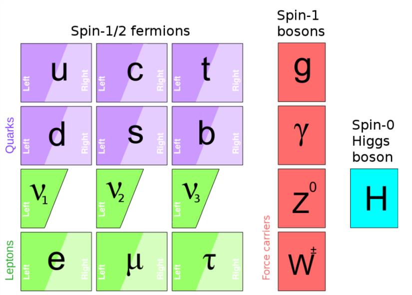


Neutrino oscillations/masses



[Particle Data Group]

Baryon asymmetry



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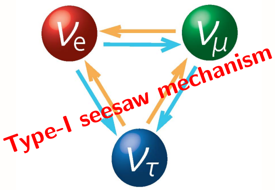

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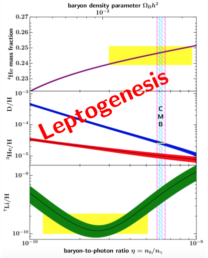

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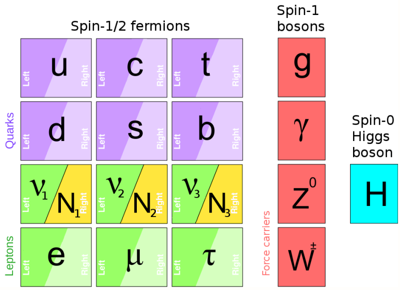
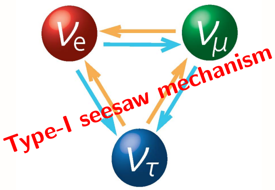


Philosophy:

⋆ Minimality
⋆ Testability

Right-handed neutrinos

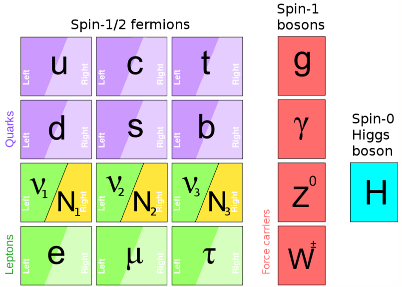


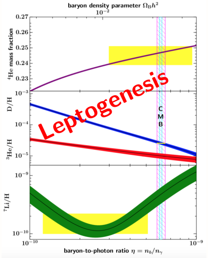
Neutrino oscillations/masses

⋆ Dark Matter
⋆ Large lepton asymmetries

↓

QCD 1$^{\rm st}$ order PT, PBHs, GWs?





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Outline

1. Neutrino masses and the type-I seesaw
2. Low-scale leptogenesis
3. Probing leptogenesis and the seesaw mechanism
4. Take-home

Neutrino masses and type-I seesaw

Type-I seesaw mechanism

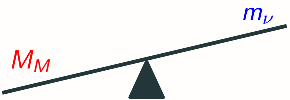
Type-I seesaw Lagrangian

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

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)

Type-I seesaw mechanism

Type-I seesaw Lagrangian (below EWSB)

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

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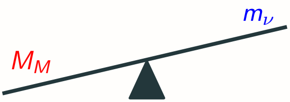

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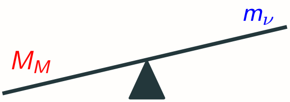

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Heavy neutrinos (HNL)

- $n \geq 2$ 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,...)

RHN landscape

- What is our prior on the RHN mass scale?

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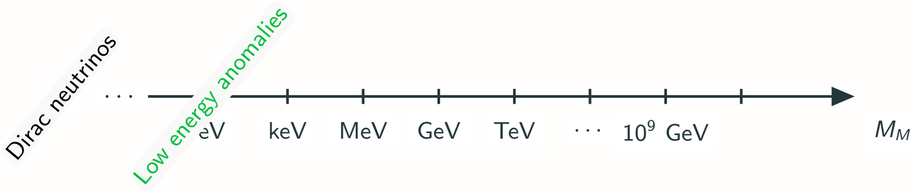

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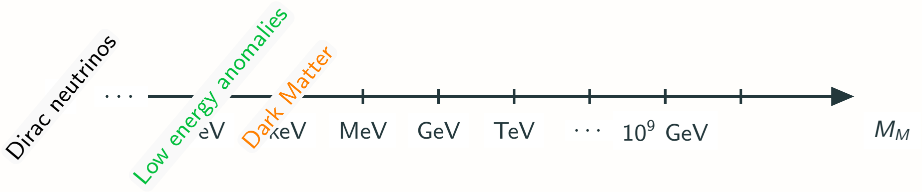

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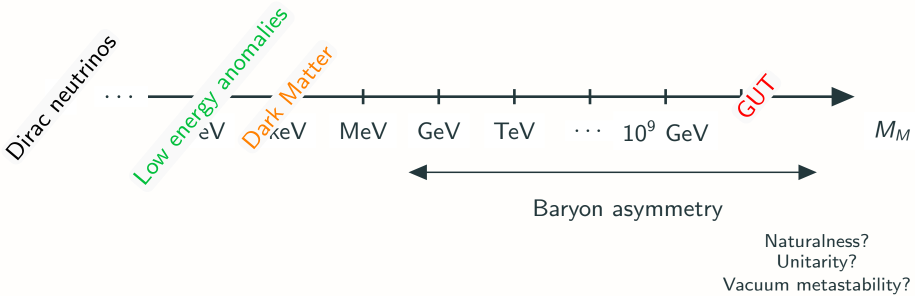

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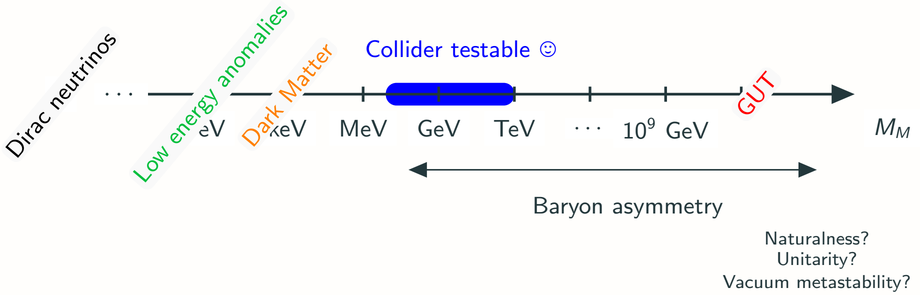
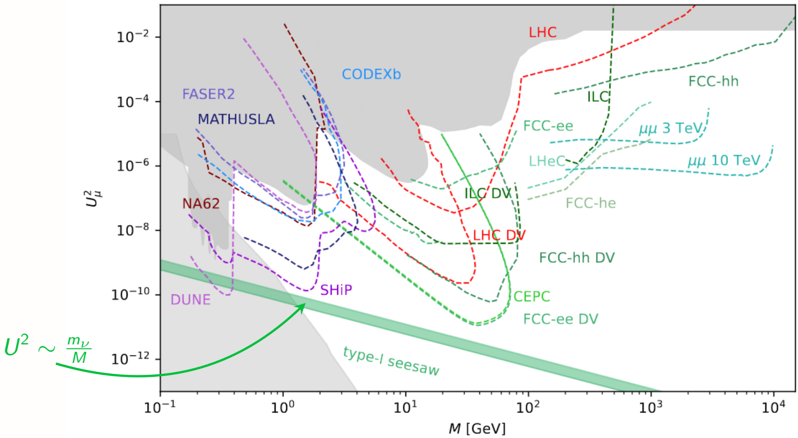


Probing the type-I seesaw

Many different ways to probe HNLs:



[Bose et al; 2209.13128]

Experimental sensitivity expressed in terms of

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

How to reach large coupling? B-L approximate symmetry

Naive seesaw bound

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

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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

$$\begin{pmatrix} y_e(1+\epsilon_e) & iy_e(1-\epsilon_e) & y_e\epsilon'_e \\ y_\mu(1+\epsilon_\mu) & iy_\mu(1-\epsilon_\mu) & y_\mu\epsilon'_\mu \\ y_\tau(1+\epsilon_\tau) & iy_\tau(1-\epsilon_\tau) & y_\tau\epsilon'_\tau \end{pmatrix}$$

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

Consistent with large production cross-section at colliders $\sigma \propto U^2$.

Probing the type-I seesaw

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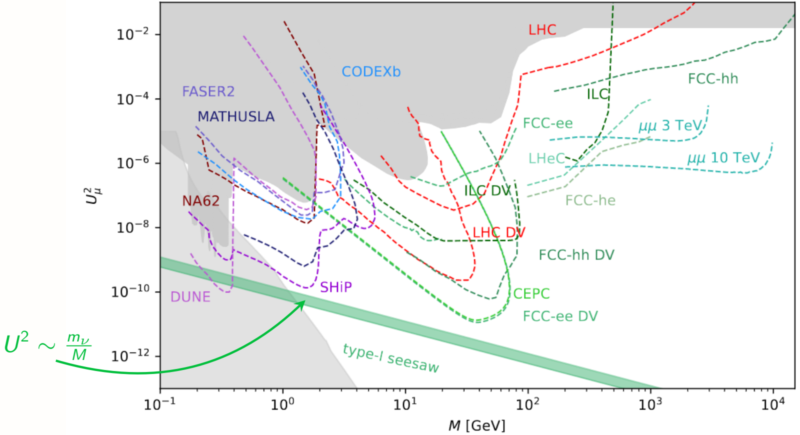

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Low-scale leptogenesis

Leptogenesis

Sakharov conditions:

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

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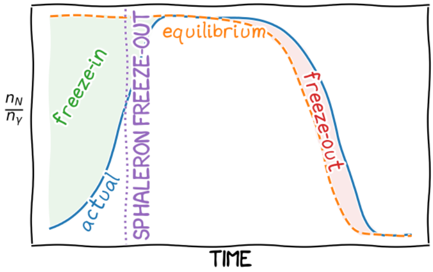

[Klarič/Shaposhnikov/Timiryasov, 2103.16545]

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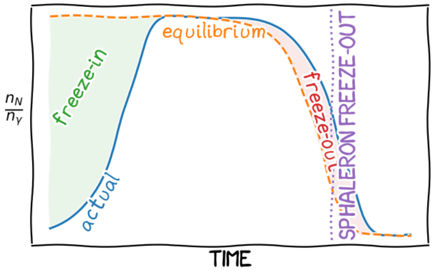

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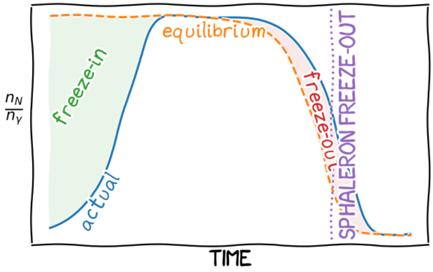
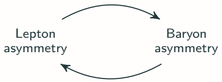
- ⋆ Baryon number violation
  - · Weak sphaleron process

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



[Klaric/Shaposhnikov/Timiryasov, 2103.16545]



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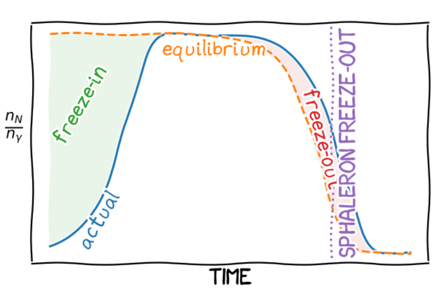

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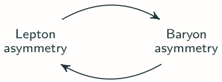

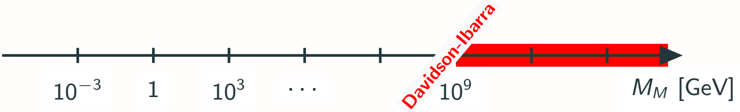

Thermal leptogenesis
[Fukugita/Yanagida '86]

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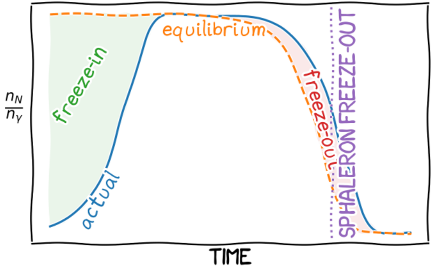

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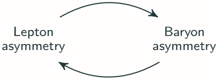


Low-scale leptogenesis
[Akhmedov/Rubakov/Smirnov '98, Pilaftsis/Underwood '03, Asaka/Shaposhnikov '05, ...]

Thermal leptogenesis
[Fukugita/Yanagida '86]

Low-scale models

- Traditionally, 2 main mechanisms:

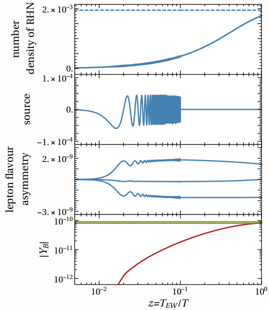
ARS Leptogenesis

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

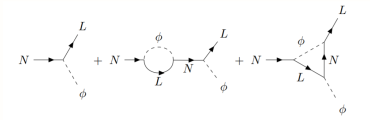
$\overset{?}{\longleftrightarrow}$

Resonant leptogenesis

Resonant enhancement of CP-violation from small mass splittings



[Drewes/Garbrecht/Gueter/Klarić; 1606.06690]



Decay asymmetry:

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

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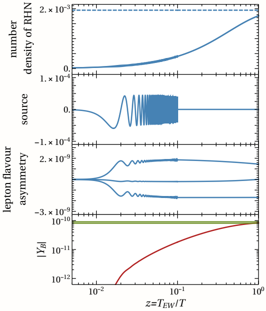

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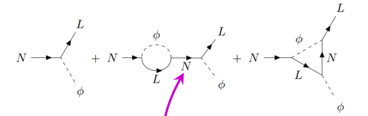

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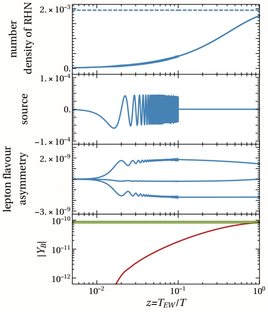

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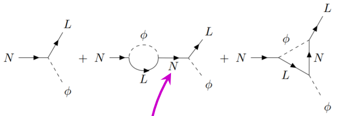

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$\longrightarrow$ Two regimes of the same mechanism! Represented by the same set of kinetic equations (cfr. [Garbrecht; 1812.02651] for a review)

Quantum kinetic equations

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

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Matrix of densities **Lepton asymmetry**

Effective Hamiltonian **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/Klarić '16, Hernandez/Kekic/Lopez-Pavon/Racker/Salvado '16, Ghiglieri/Laine '16 '18, Klarić/Shaposhnikov/Timiryasov '21, ...

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Washout term

Source term

Matrix of densities

Effective Hamiltonian

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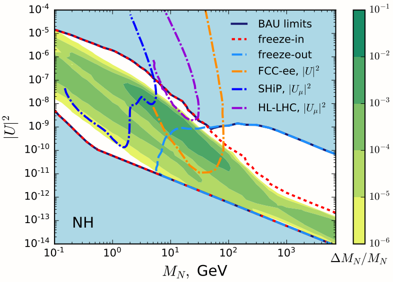
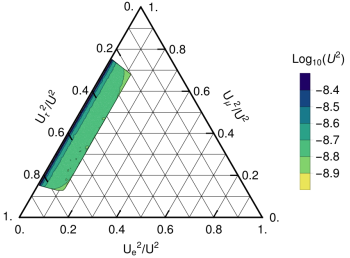
$n = 2$ (νMSM) parameter space

- 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



[Klarić/Shaposhnikov/Timiryasov; 2103.16545]



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

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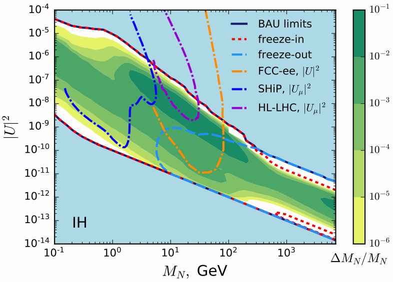
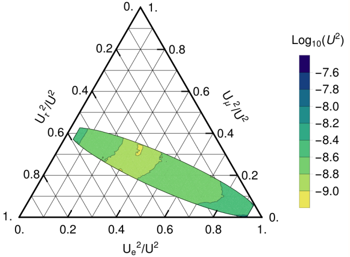
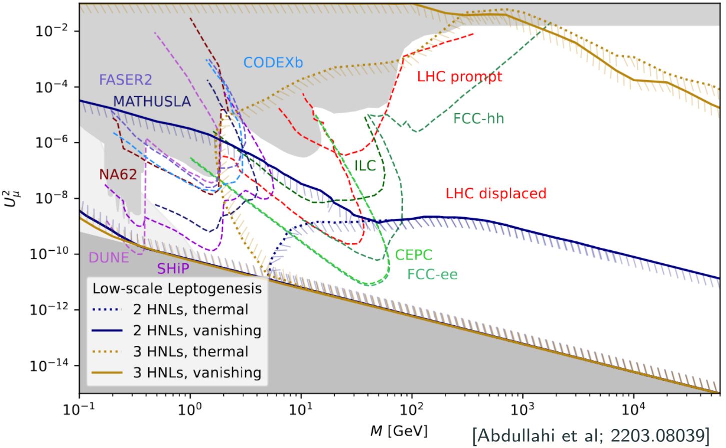


[Klarić/Shaposhnikov/Timiryasov; 2103.16545]



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



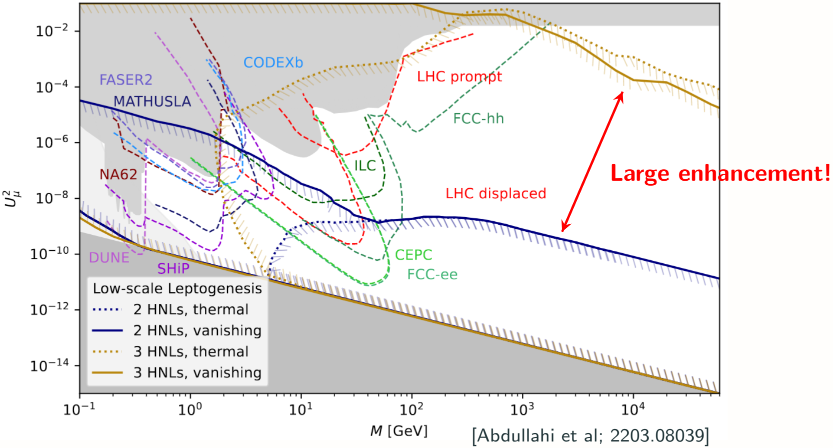
[Abdullahi et al; 2203.08039]

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

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

- Can potentially produce enough HNLs to test leptogenesis!

$n = 3$ parameter space, NH



[Abdullahi et al; 2203.08039]

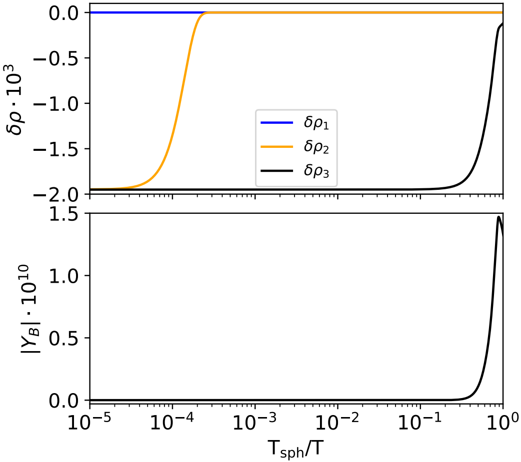
$n = 2$ lines from [Klarić/Shaposhnikov/Timiryasov, 2103.16545]

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

- Can potentially produce enough HNLs to test leptogenesis!

Why such large mixings?

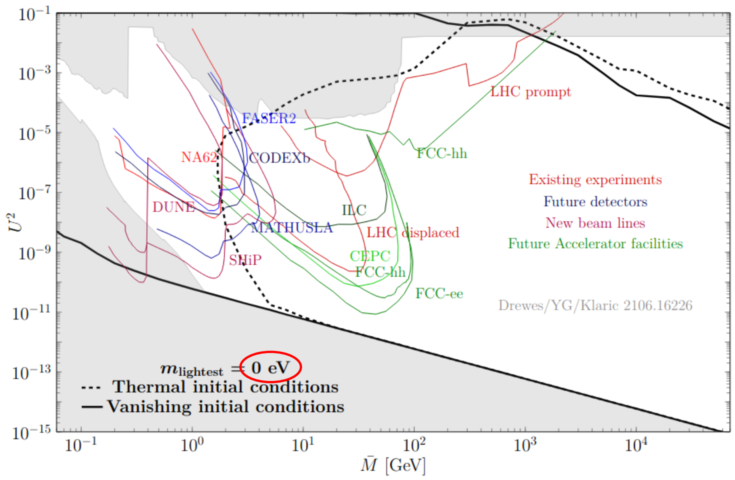
$U^2 = 0.0248, \bar{M} = 100$ GeV and $m_{\text{lightest}} = 0$ eV



[YG; 2305.06663]

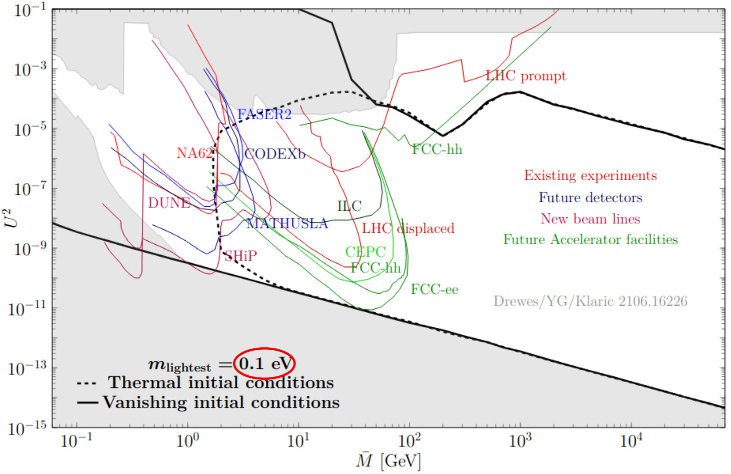
- Large mixing angles allow late equilibration of one HNL $U_i^2 \ll 1$
  $\hookrightarrow$ Late BAU production, less time for washout

$n = 3$ parameter space, NH



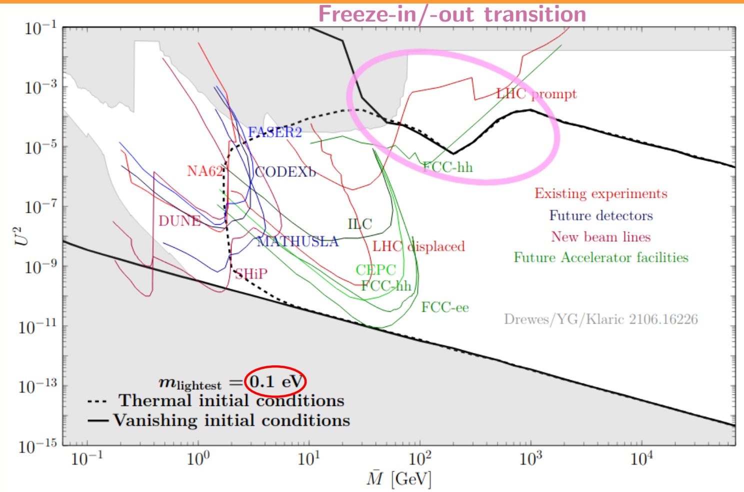
- Can potentially produce enough HNLs to test leptogenesis!

$n = 3$ parameter space, NH



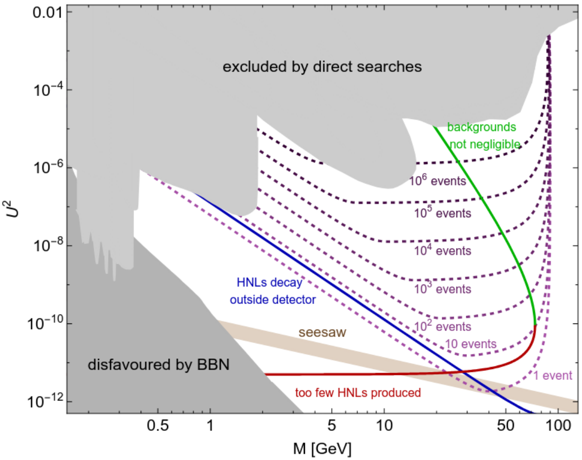
- Can potentially produce enough HNLs to test leptogenesis!

$n = 3$ parameter space, NH



- Can potentially produce enough HNLs to test leptogenesis!

Potential number of events at FCC-ee



[Drewes/Klarić/Li; 2511.23461]

- Can potentially produce enough HNLs to test leptogenesis!

Probing leptogenesis and the seesaw mechanism

Seesaw parameter space

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

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

n=2

2 CP-violating phases

3 PMNS angles (3/3 fixed)

2 light neutrino masses (2/2 fixed)

1 complex Euler angle

2 Majorana masses

6 free parameters

n=3

3 CP-violating phases

3 PMNS angles (3/3 fixed)

3 light neutrino masses (2/3 fixed)

3 complex Euler angles

3 Majorana masses

13 free parameters

Seesaw parameter space

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

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

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2 Majorana masses

6 free parameters

n=3

3 CP-violating phases

3 PMNS angles (3/3 fixed)

3 light neutrino masses (2/3 fixed)

3 complex Euler angles

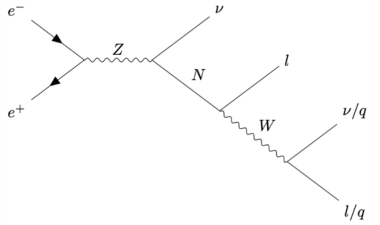
3 Majorana masses

13 free parameters

How much can we constrain the remaining parameters?

Constraining model parameters from collider observables

- Flavour composition of semileptonic decays gives information on the flavour ratios $U^2_{\alpha i}/U^2$ & seesaw parameters!



[Credit: Lovisa Rygaard]

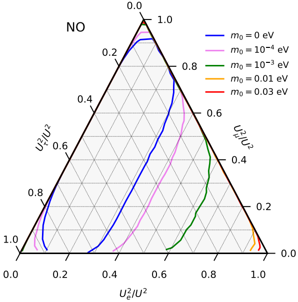
- Number of events governed by

$$\epsilon \sim e^{-2\gamma} \sim \frac{U^2}{m_\nu/\bar{M}}$$

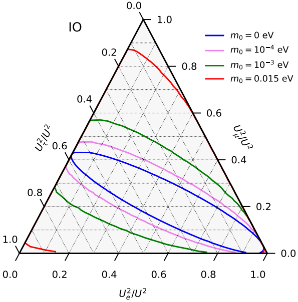
- For $n = 2$, $U^2_{\alpha i} \sim \mathcal{O}(1/\epsilon) + \mathcal{O}(1) + \ldots$
- For $n = 3$, $U^2_{\alpha i} \sim \mathcal{O}(1/\epsilon) + \mathcal{O}(1/\sqrt{\epsilon}) + \mathcal{O}(1) + \ldots$

$\implies$ Better parameter reconstruction (partly) compensates the larger dimensionality!

Constraining m_0



Normal ordering



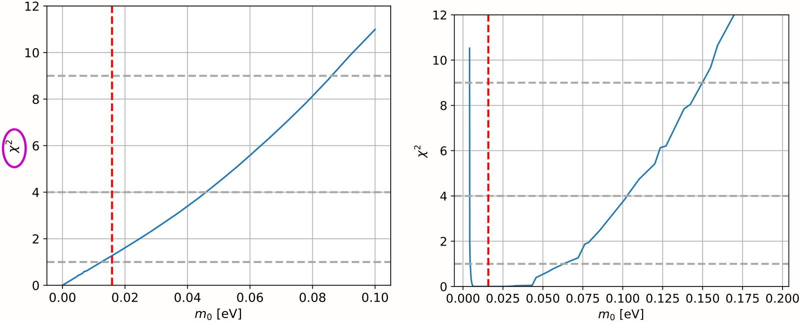
Inverted ordering

[Drewes/YG/Klarić/Wendels; 2407.13620]

- For optimistic scenarios ($\sim 10^5$ events at FCC-ee), can measure flavour ratios $\frac{U_\alpha^2}{U^2}$ at percent level!
- Can give a hint on value of m_0!

Constraining m_0

Idealised detector
Only statistical uncertainty
Based on number of events



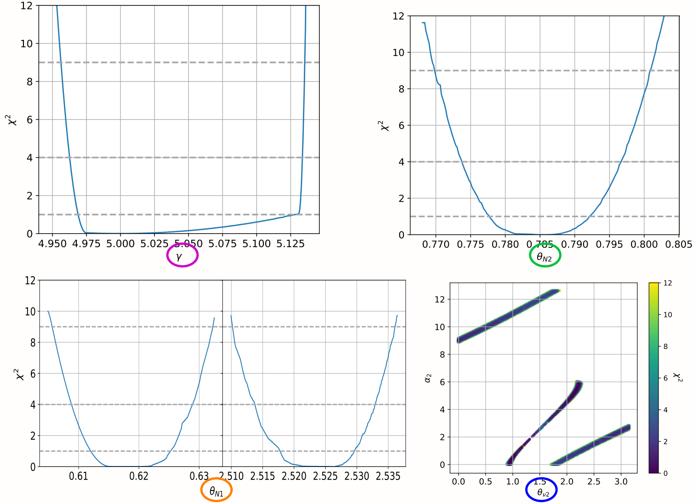
$m_0 = 0$ eV $\quad$ $m_0 = 0.01$ eV

[Drewes/YG/Klarić/Wendels; 2407.13620]

- Constraints on m_0 will not match Planck but better than KATRIN (though more indirect + model dependent): Complementarity!
- Can exclude $m_0 = 0$ if flavour ratios outside typical $m_0 = 0$ region.

Constraining model parameters from collider observables

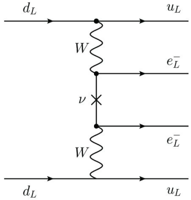
$$Y = \frac{i}{v} U_\nu \sqrt{m_\nu^{diag}} R_{13}(\theta_{\nu 2}) R_{23}(\theta_{\nu 1}) R_{12}(\omega + i\gamma) R_{23}(\theta_{N1}) R_{13}(\theta_{N2}) \sqrt{M_M}$$



[Drewes/YG/Klarić/Wendels; 2407.13620]

$0\nu\beta\beta$

- Majorana nature of neutrinos leads to neutrinoless double beta decay ($0\nu\beta\beta$)



- Lifetime $T_{1/2}^{0\nu}$ parametrised by the effective mass

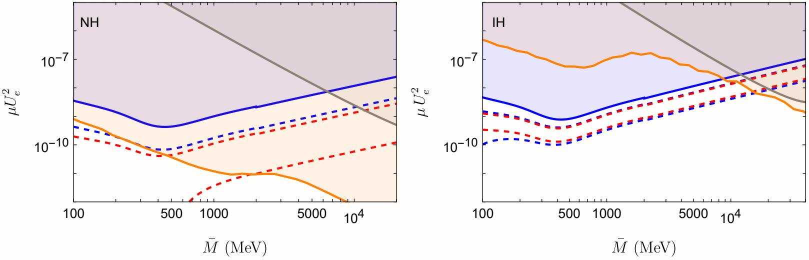
$$T_{1/2}^{0\nu} \propto \left(\bar{m}_{\beta\beta} = \frac{1}{\mathcal{A}(0)} \sum_{i=1}^{5} \mathcal{U}_{ei}^2 m_i \mathcal{A}(m_i) \right)^{-1} .$$

- Heavy neutrino can have a sizeable and direct impact

$$\bar{m}_{\beta\beta} \simeq e^{i \arg(m_{\beta\beta})} \left(|m_{\beta\beta}| \left[1 - \frac{\mathcal{A}(\bar{M})}{\mathcal{A}(0)} \right] - \frac{1}{2} e^{i\lambda} \bar{M}^2 \mu \, U_e^2 \left| \frac{\mathcal{A}'(\bar{M})}{\mathcal{A}(0)} \right| \right) ,$$

$\longrightarrow$ $0\nu\beta\beta$ can provide information on the Majorana phases α as well as ω!

- For $n = 2$:



[de Vries/Drewes/YG/Klarić/Plakkot; 2407.10560]

- For IH, constraints from $0\nu\beta\beta$ stronger for large splitting and $\bar{M} \lesssim 10$ GeV.
- Non-observation of $0\nu\beta\beta$ in the future would severely constrain μU_e^2.

Discrete flavour symmetries

- Discrete symmetries provide dynamical origin to ν mixing pattern

$$G_f \times \text{CP}$$

G_l — Charged lepton sector

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

Discrete flavour symmetries

- Discrete symmetries provide dynamical origin to ν mixing pattern

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

$\mathcal{Z}_3$ — Charged lepton sector

$\mathcal{Z}_2 \times \mathrm{CP}$ — Neutrino sector

In our setup

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

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

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

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

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

Case 1), BAU vs ϕ_s

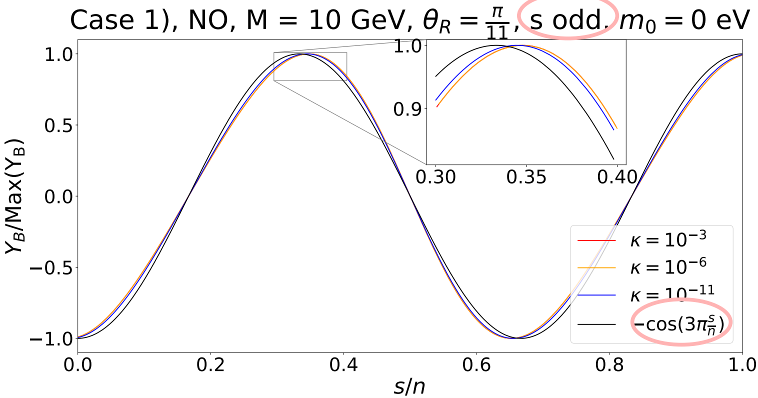


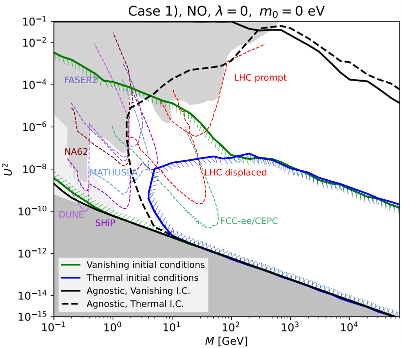
Figure 1: Vanishing initial conditions, $\lambda = 0$

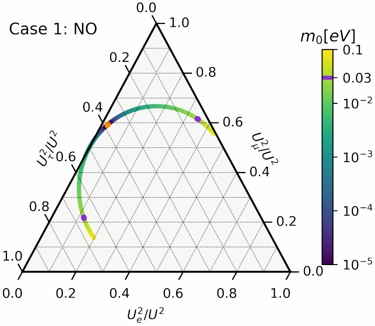
[Drewes/YG/Hagedorn/Klarić; 2203.08538]

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

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

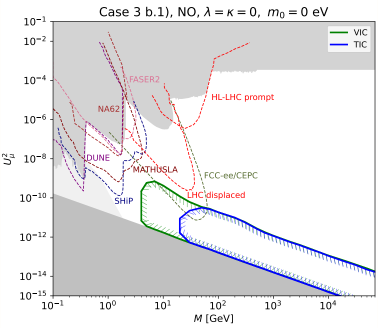
- Flavour symmetries have reduced parameter space but highly predictive!

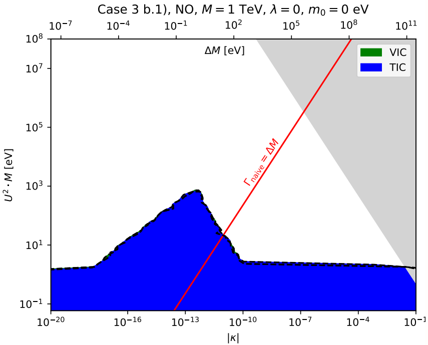




[Drewes/YG/Hagedorn/Klarić; 2412.10254]

Flavour symmetries and degenerate leptogenesis





[Drewes/YG/Hagedorn/Klarić, 2412.10254]

- Leptogenesis possible for $\Delta M_M = 0$ thanks to Higgs and thermal mass splittings
$$\Delta M_{\rm phys} \sim h_+(T) Y^\dagger Y + h_-(T) Y^t Y^*$$
- Only viable for masses above ~ 10 GeV.

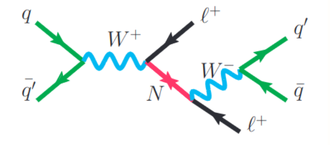
What should I take home?

- 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, ...
- In particular, future lepton colliders can act as discovery and precision machines in one
- Combined with flavour symmetric explanation of PMNS: very predictive!

Thanks for your attention!
ご清聴ありがとうございました。

Appendix

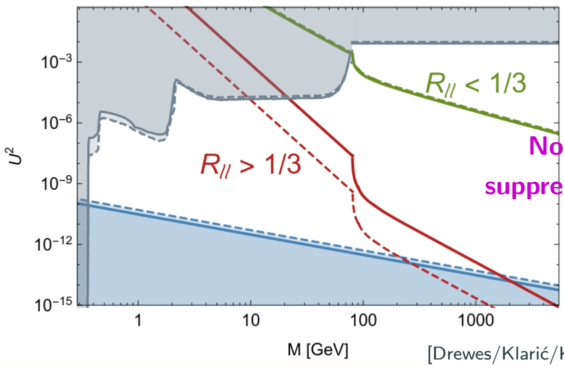
Lepton number violation at colliders



[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

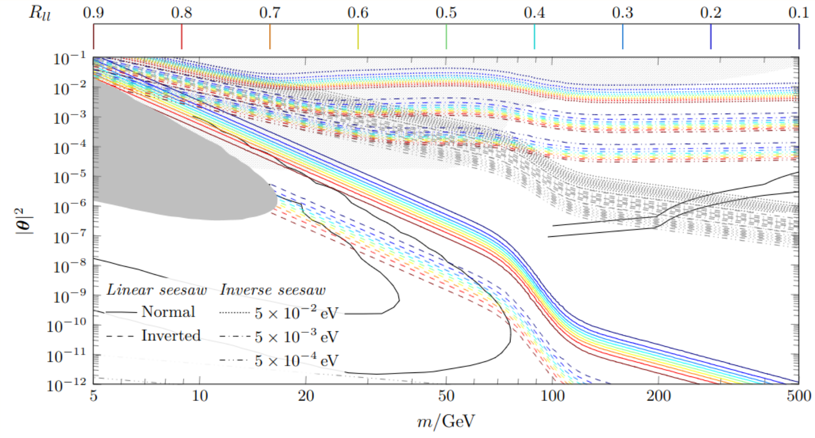
$$R_{ll} = \frac{\Delta M^2_{\text{phys}}}{2\Gamma_N^2 + \Delta M^2_{\text{phys}}}$$



Not always strongly suppressed for sizeable U^2!

[Drewes/Klarić/Klose; 1907.13034]

Lepton number violation at colliders

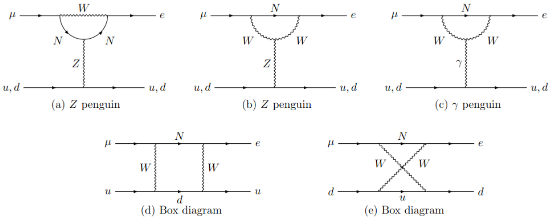


[Antusch/Hajer/Rosskopp, 2307.06208]

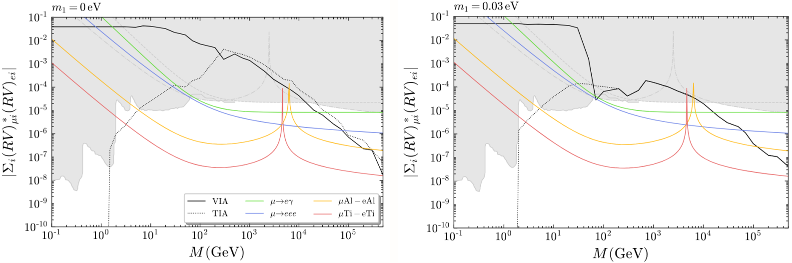
In practice, decoherence effects can make testability prospects even more optimistic!

Testing leptogenesis through CLFV experiments

- HNLs also lead to charge lepton flavour violation.

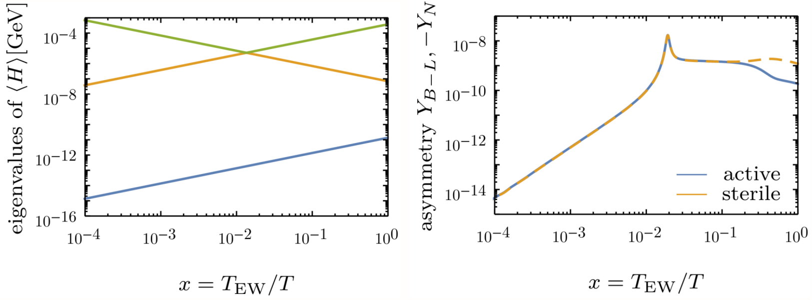


[Urquia-Calderon/Timiryasov/Ruchayskiy; 2206.04540]



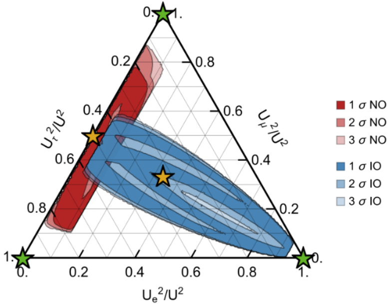
[Granelli/Klarić/Petcov; 2206.04342]

Dynamical resonance

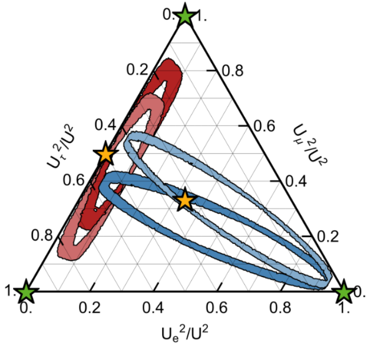


[Abada/Arcadi/Domcke/Drewes/Klaric/Lucente '18]

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



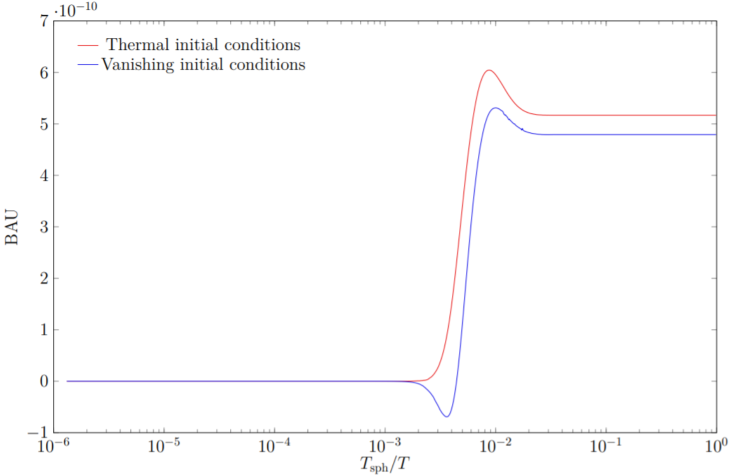
Current ν oscillation data



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

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.

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

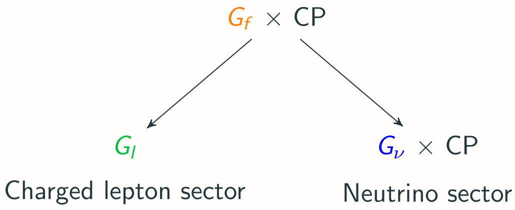
$$|U_{\mathrm{PMNS}}| \approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.29 & 0.59 & 0.75 \\ 0.49 & 0.59 & 0.64. \end{pmatrix}$$

  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, $G_\nu \subset G_f$.



- 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

[See also Hagedorn/Meroni/Molinaro '14]

Prediction

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

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

CP-violating 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 ($C_{\mathrm{LFV},\alpha}$)

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

Violates lepton number ($C_{\mathrm{LNV},\alpha}$)

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

Flavour violating only, can be $\neq 0$ for $\Delta M = 0$! ($C_{\mathrm{DEG},\alpha}$)

CP-violating combinations

- Perturbatively,

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

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

- For Case 1) and s odd,

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

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

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

where

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

Case 1), BAU vs ϕ_s

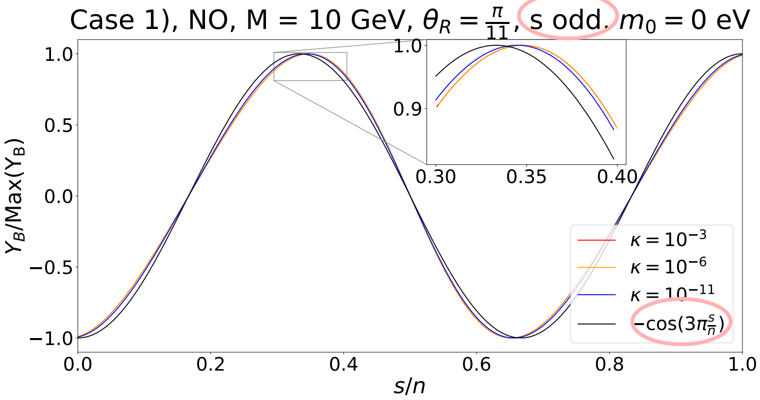


Figure 2: Vanishing initial conditions, $\lambda = 0$

[Drewes/YG/Hagedorn/Klarić; 2203.08538]

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

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

CP-violating combinations

- Perturbatively,

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

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

- For Case 1) and s even,

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

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

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

where

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

Case 1), BAU vs ϕ_s

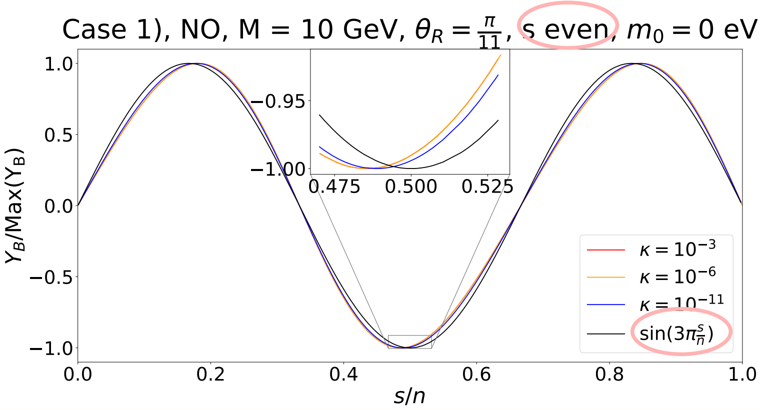


Figure 3: Vanishing initial conditions, $\lambda = 0$

[Drewes/YG/Hagedorn/Klarić; 2203.08538]

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

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

Vanilla thermal leptogenesis

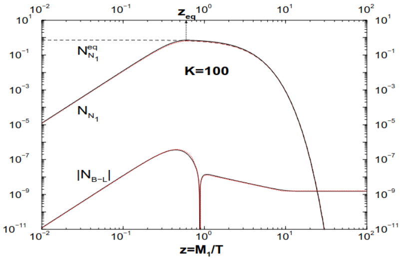
Assumptions:

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

Boltzmann equations

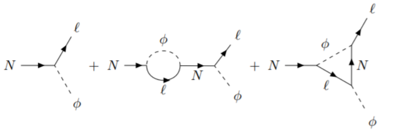
$$\frac{\mathrm{d}}{\mathrm{d}z} n_1 = -\frac{\Gamma_D}{Hz}(n_1 - n_1^{eq})$$

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



[Buchmüller/Di Bari/Plümacher; '04]

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



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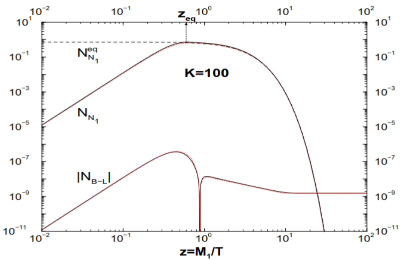

[Buchmüller/Di Bari/Plümacher; '04]

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· 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

$$M_1 \gtrsim 2 \times 10^9 \text{ GeV}$$

$\hookrightarrow$ Direct detection ☹