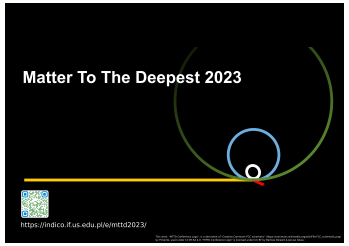
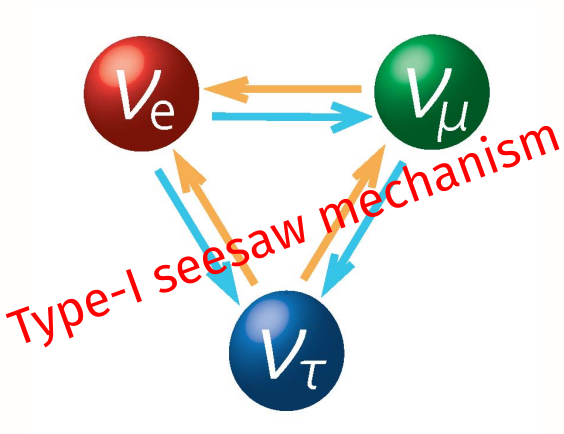
Recent developments in testable leptogenesis

Yannis Georis

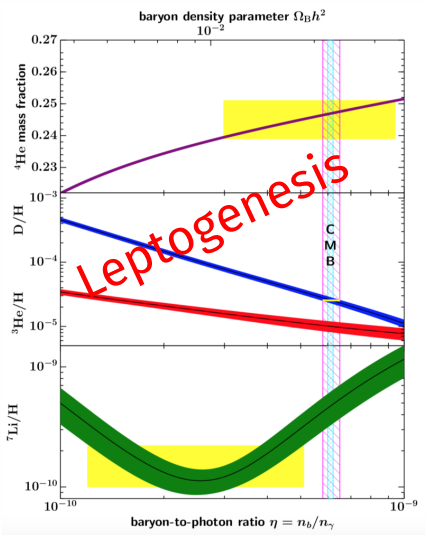
Matter To The Deepest 2023
September 22, 2023



Right-handed neutrinos (RHN)

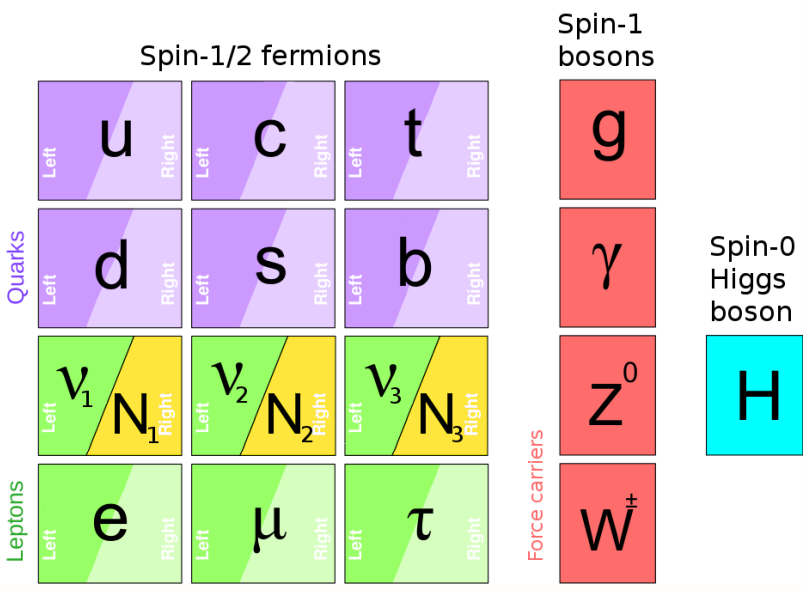


Neutrino masses



[Particle Data Group]

Baryon asymmetry



[See also talks by Suchita Kulkarni, Richard Ruiz, Claudia Hagedorn, Biswajit Karmakar, Arunansu Sil, Debasish Borah, Vytautas Dudenas, Frank Deppisch]

Type-I seesaw mechanism

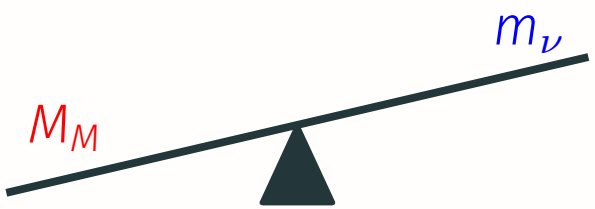
Type-I seesaw Lagrangian

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

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 (HNLs)

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

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

Leptogenesis

Sakharov conditions:

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

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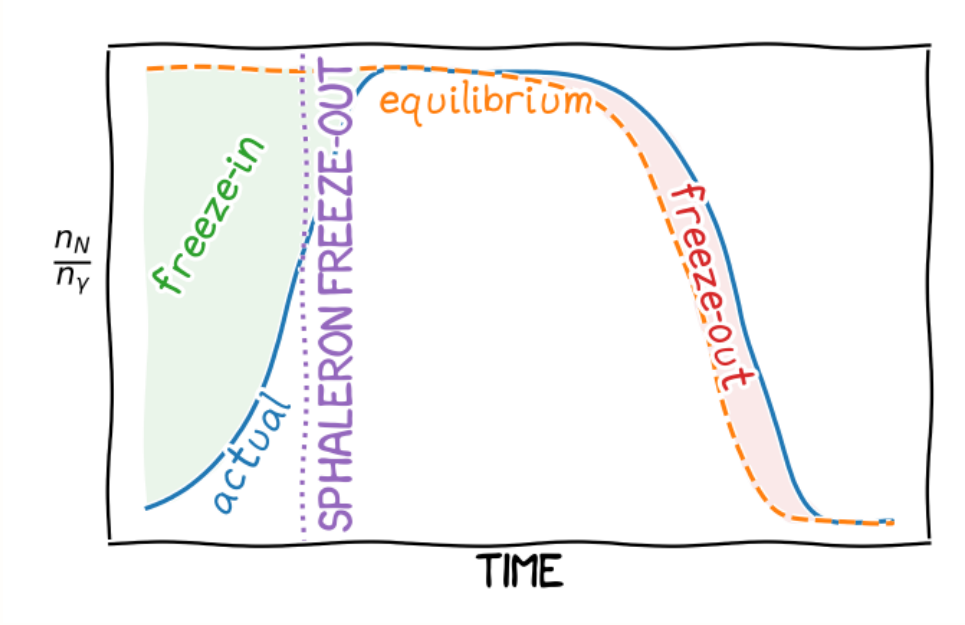

[Klarič/Shaposhnikov/Timiryasov, 2103.16545]

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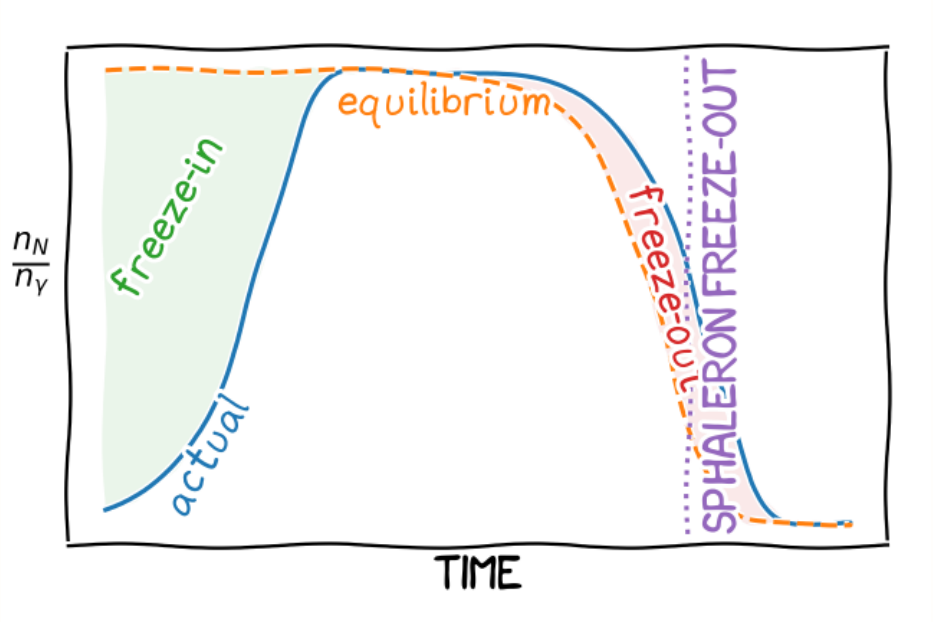

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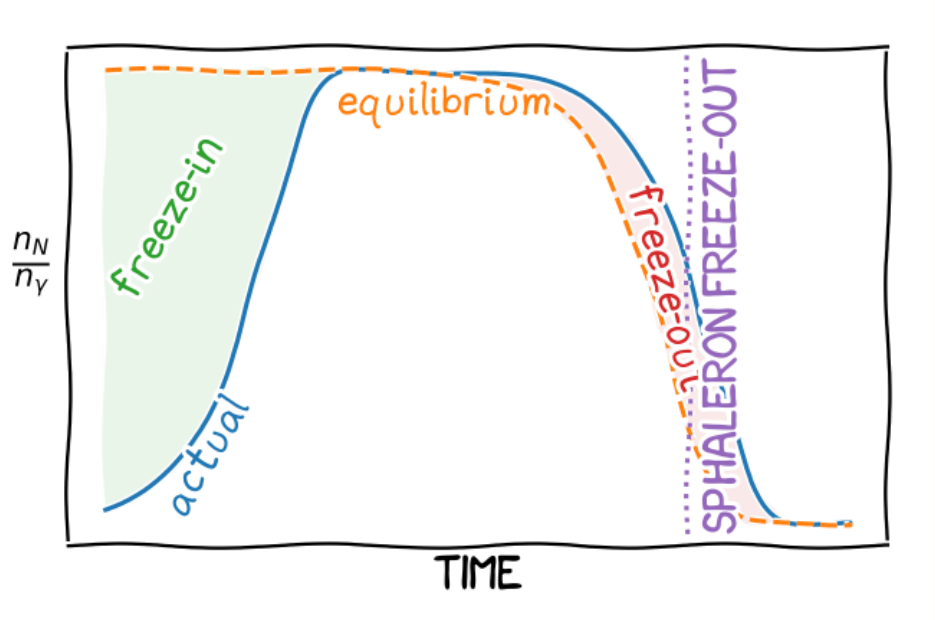

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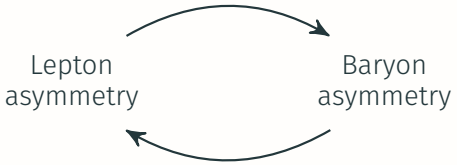

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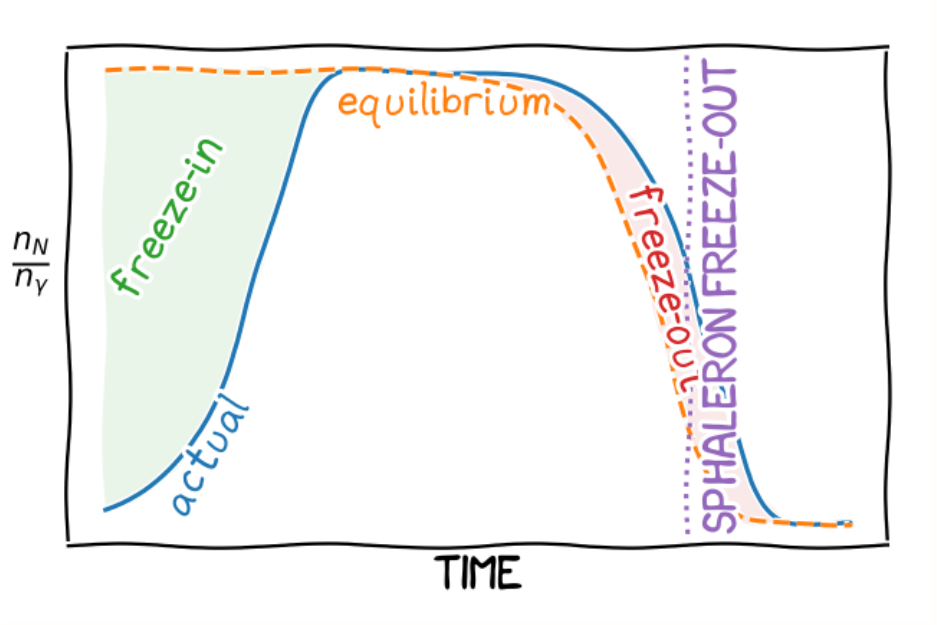

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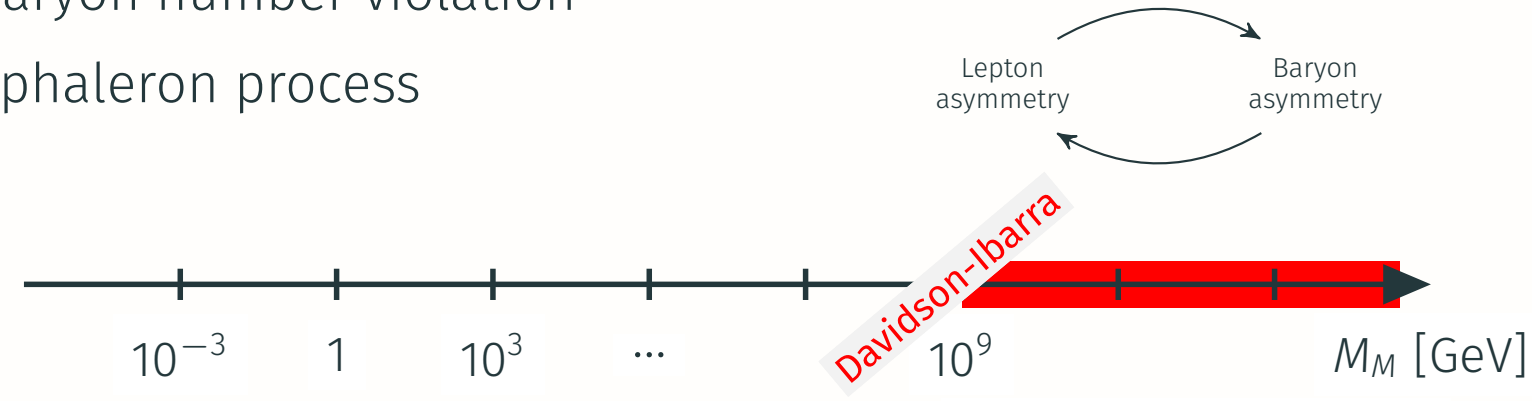

Thermal leptogenesis
[Fukugita/Yanagida '86]

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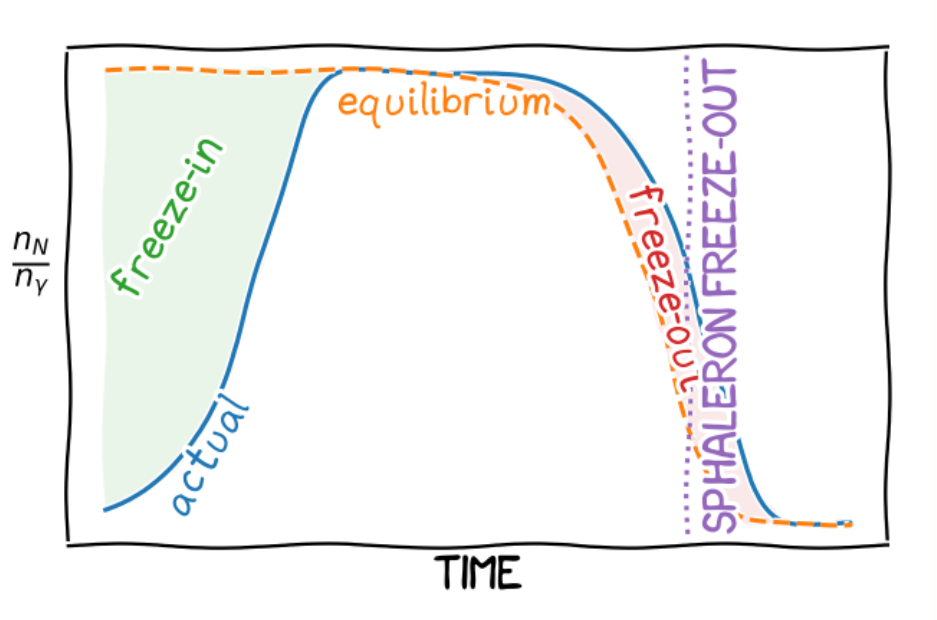

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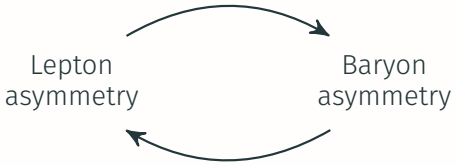
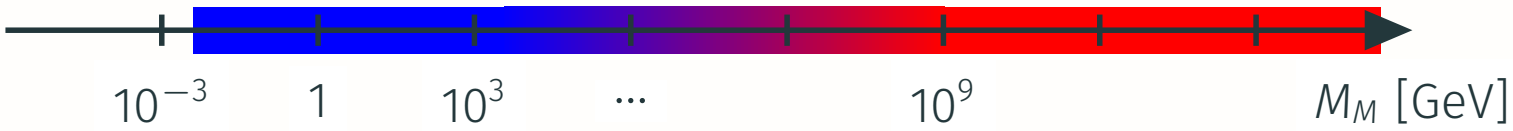




Low-scale leptogenesis

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

Thermal leptogenesis

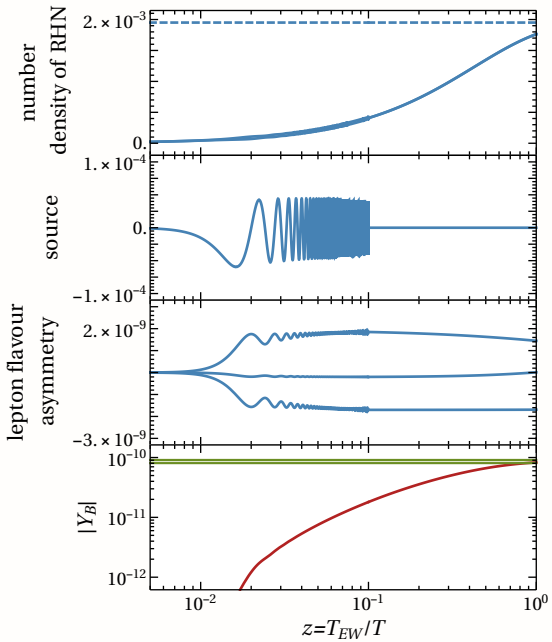
[Fukugita/Yanagida '86]

Low-scale models

- Traditionally, 2 main mechanisms:

ARS Leptogenesis

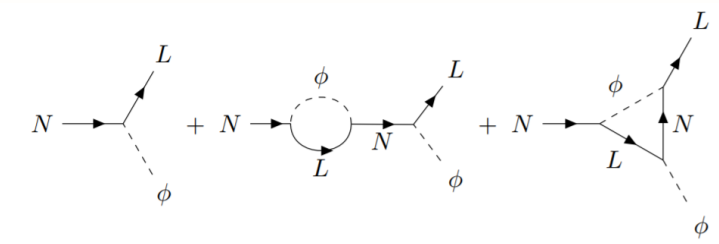
Asymmetry produced during freeze-in from CP-violating HNL oscillations



[Drewes/Garbrecht/Gueter/Klarič; 1606.06690]

Resonant leptogenesis

Resonant enhancement of CP-violation from small mass splittings



Decay asymmetry:

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

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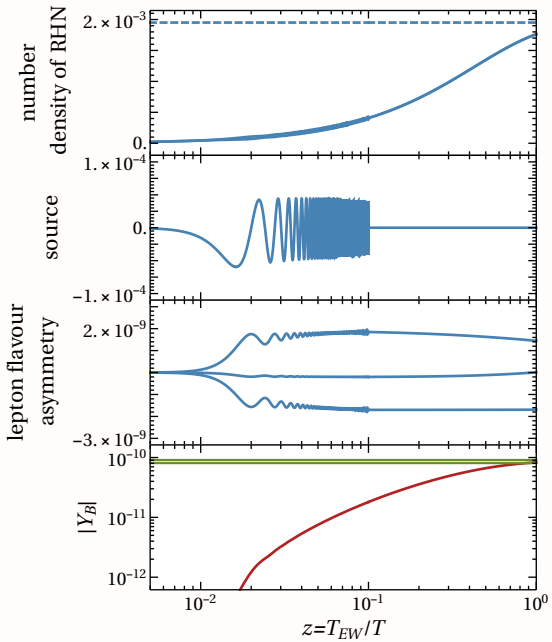

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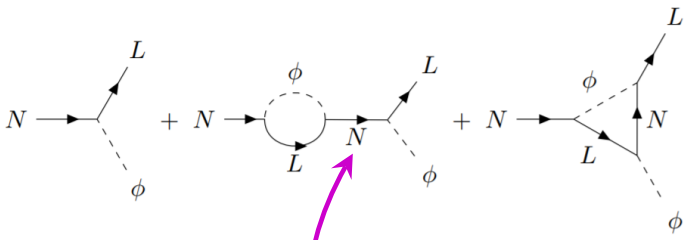

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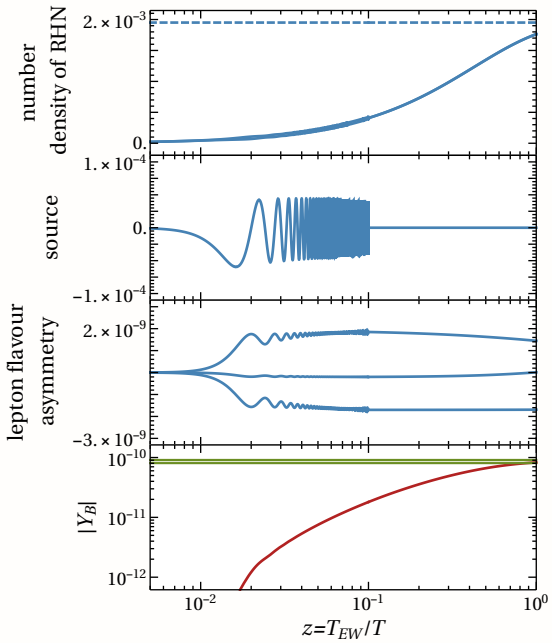

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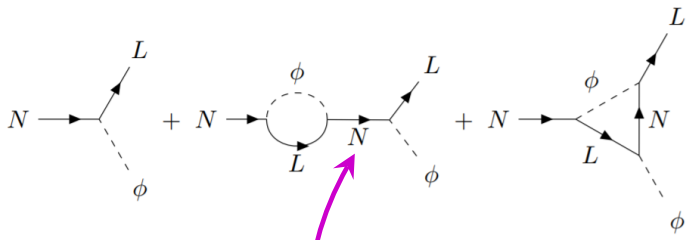

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$\longrightarrow$ Two regimes of the same mechanism ! Represented by the same set of kinetic equations (cfr. [Garbrecht; 1812.02651] for a review)

Quantum kinetic equations

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

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

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

Density matrix

Effective Hamiltonian

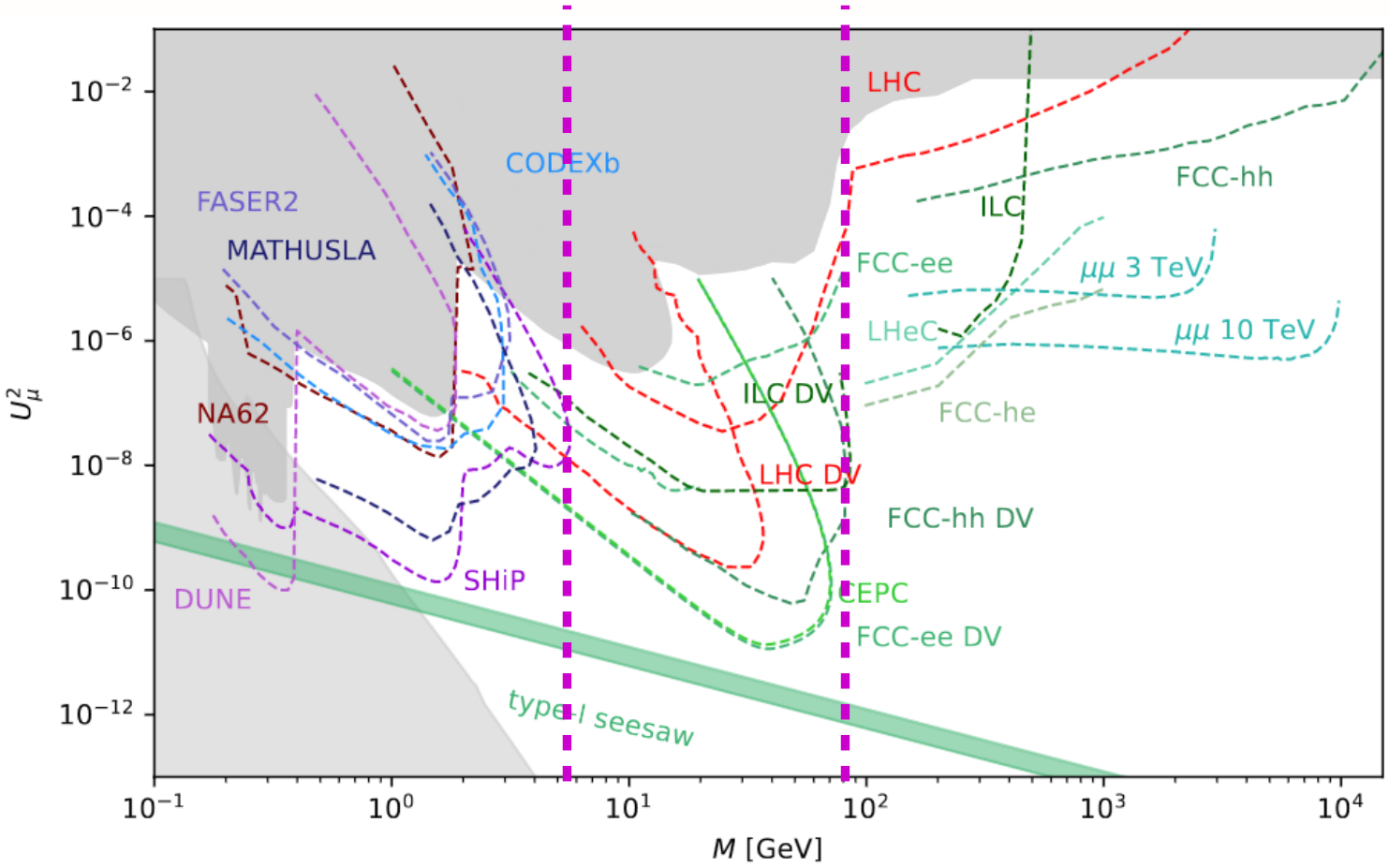
Interaction rates

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, ...

Testing leptogenesis

Many different ways to probe HNLs:



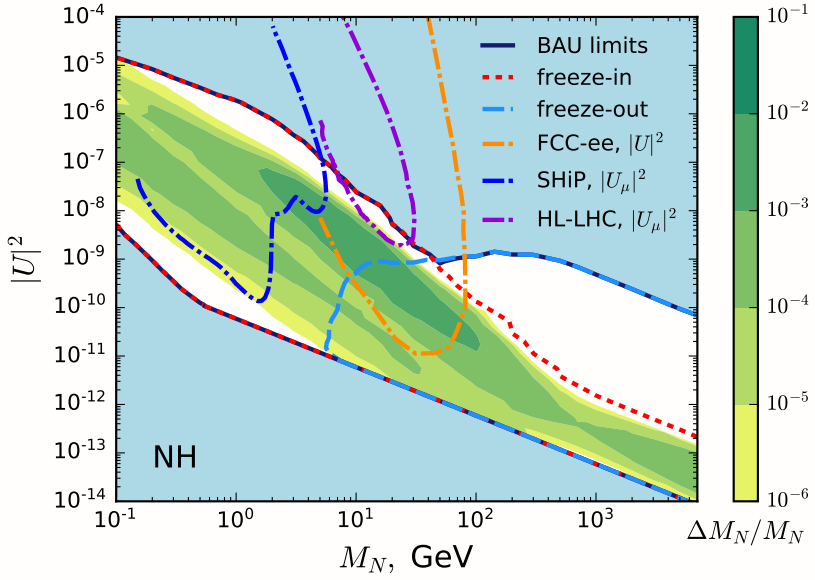
[Bose et al; 2209.13128]

Meson decays W/Z decays Virtual W/Z exchange

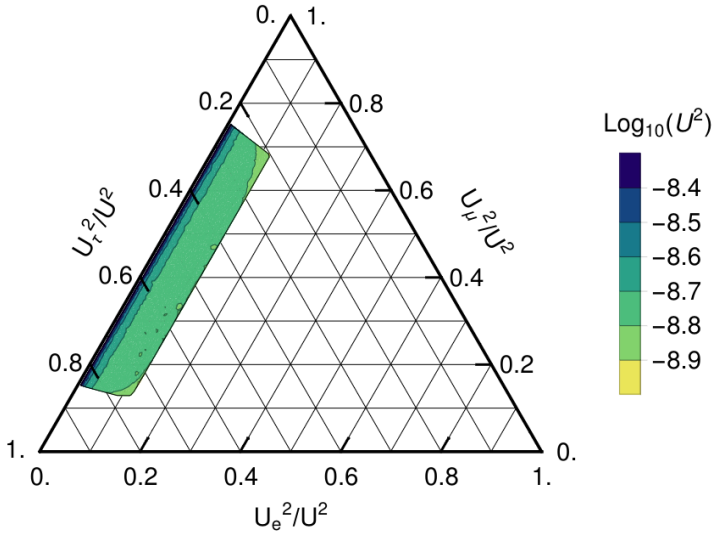
⟶ See Richard Ruiz' and Suchita Kulkarni's talk

$n = 2$ (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]

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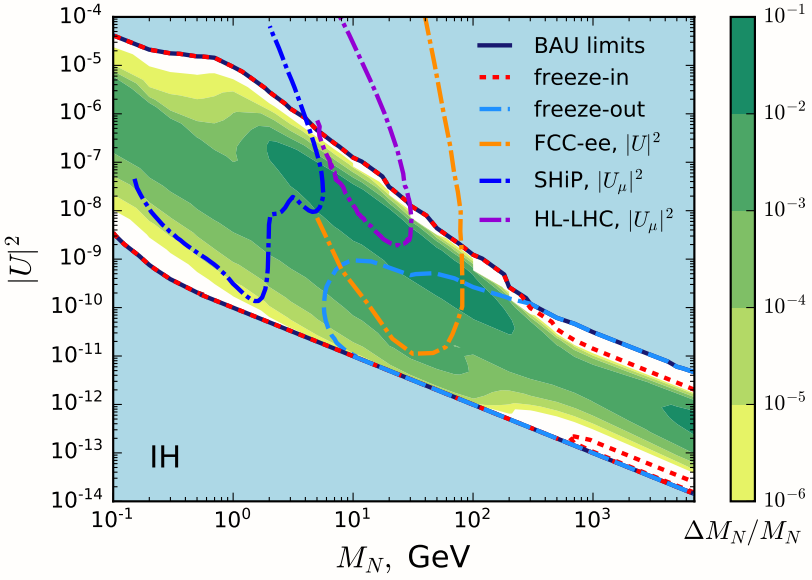

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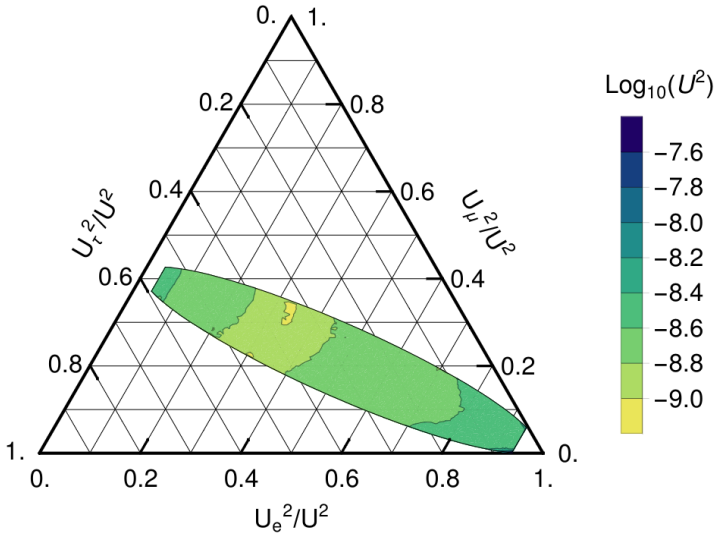

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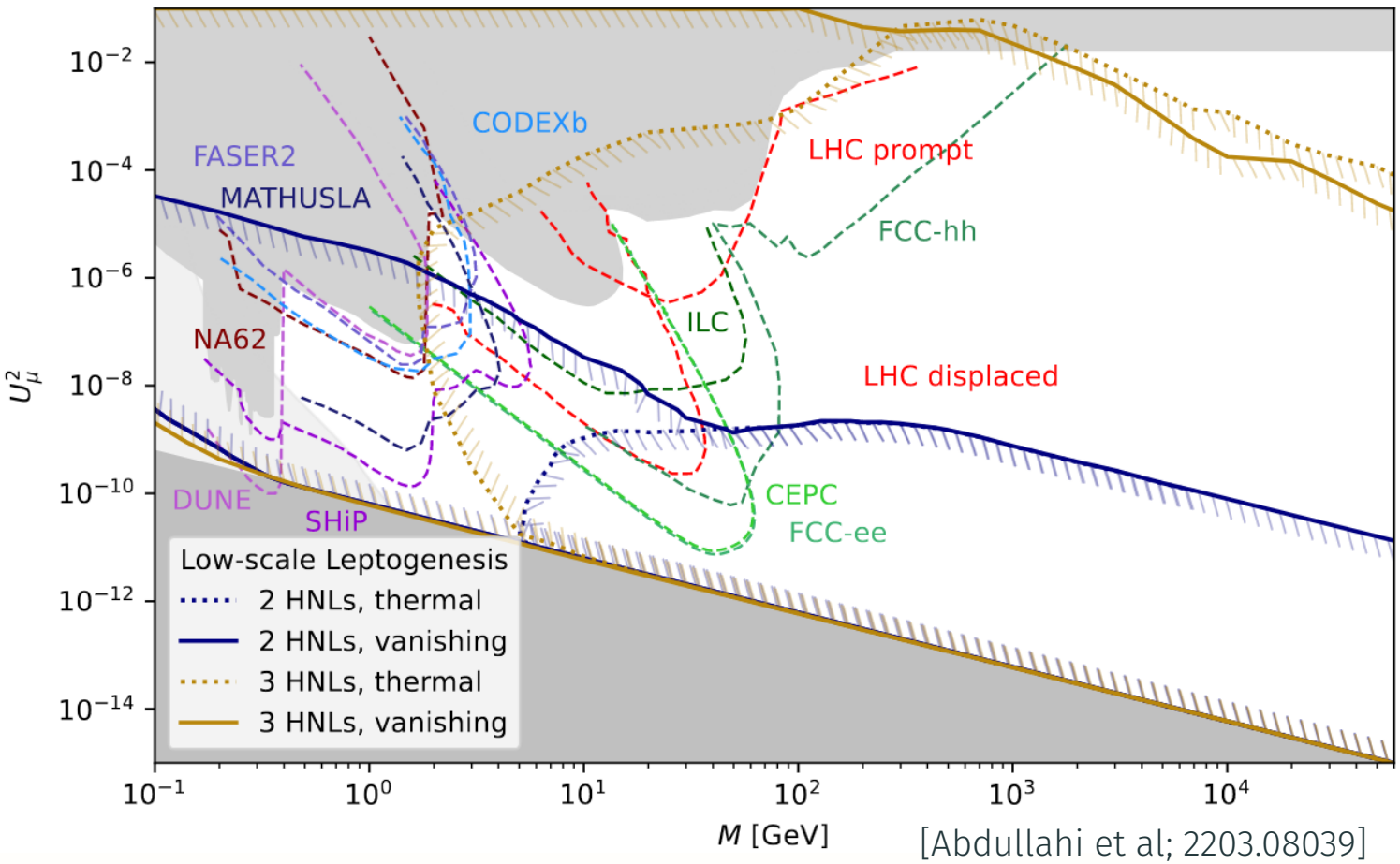
$n = 3$ parameter space, NH



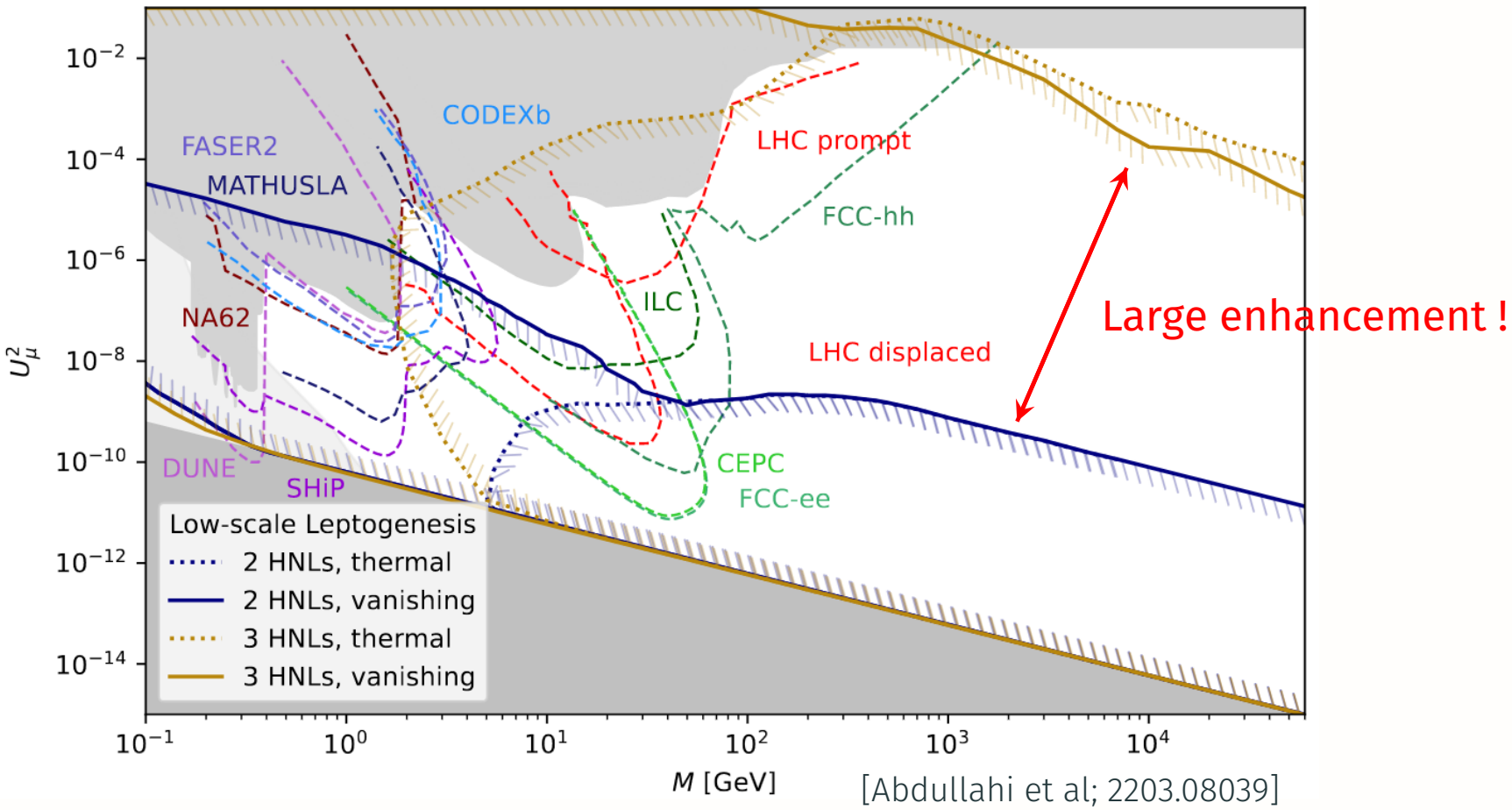
[Abdullahi et al; 2203.08039]

$n = 2$ 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



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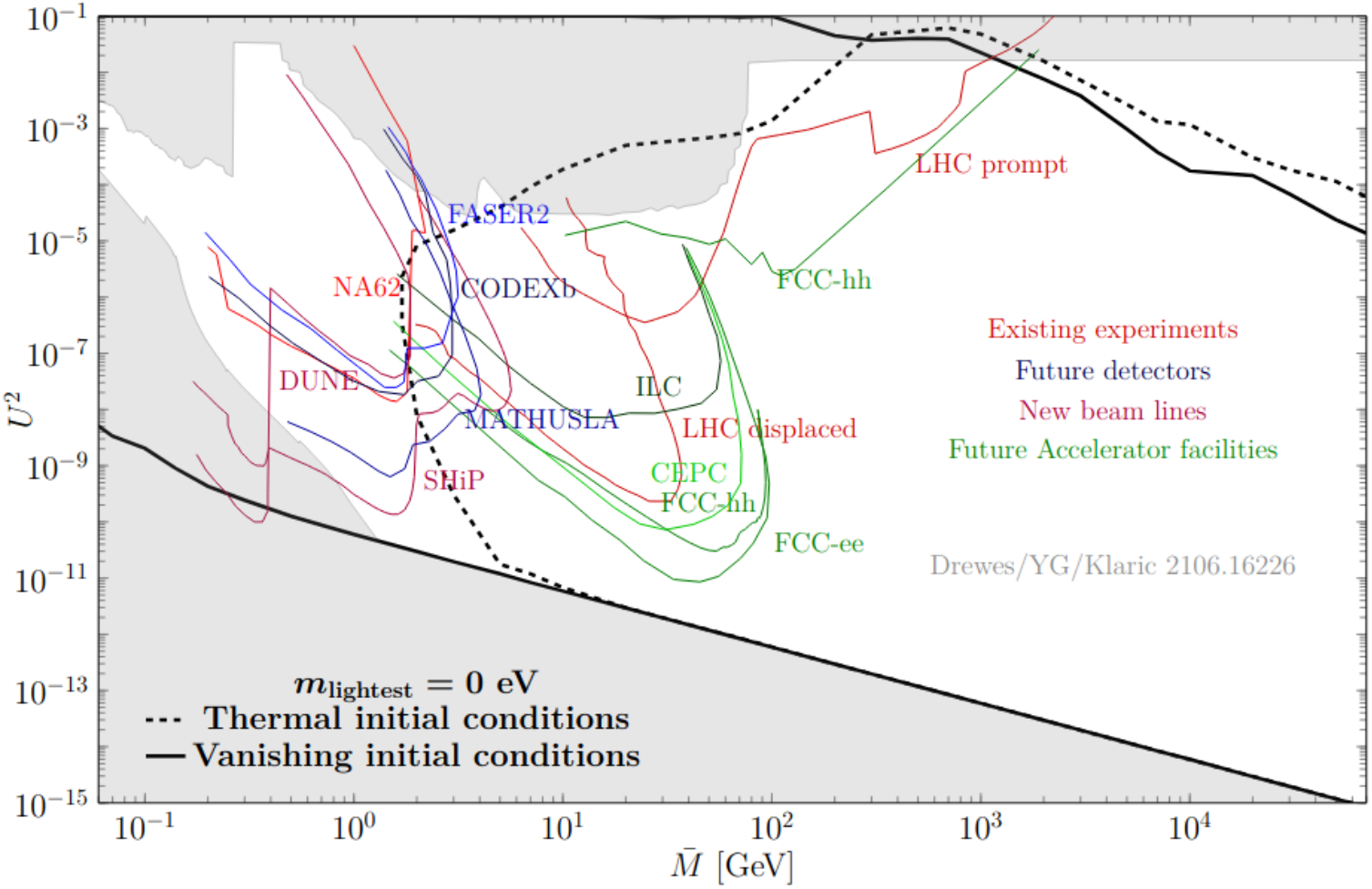

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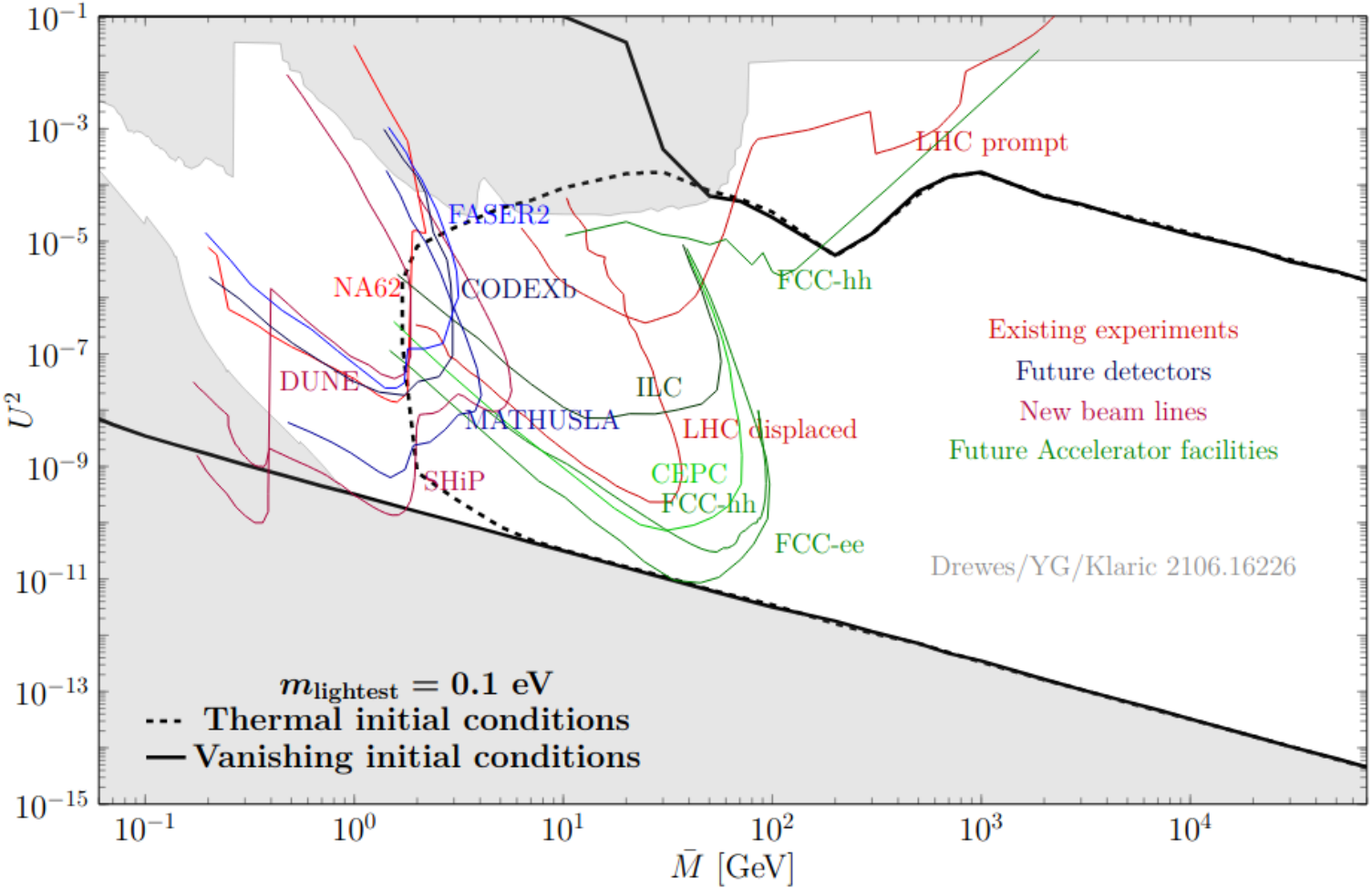

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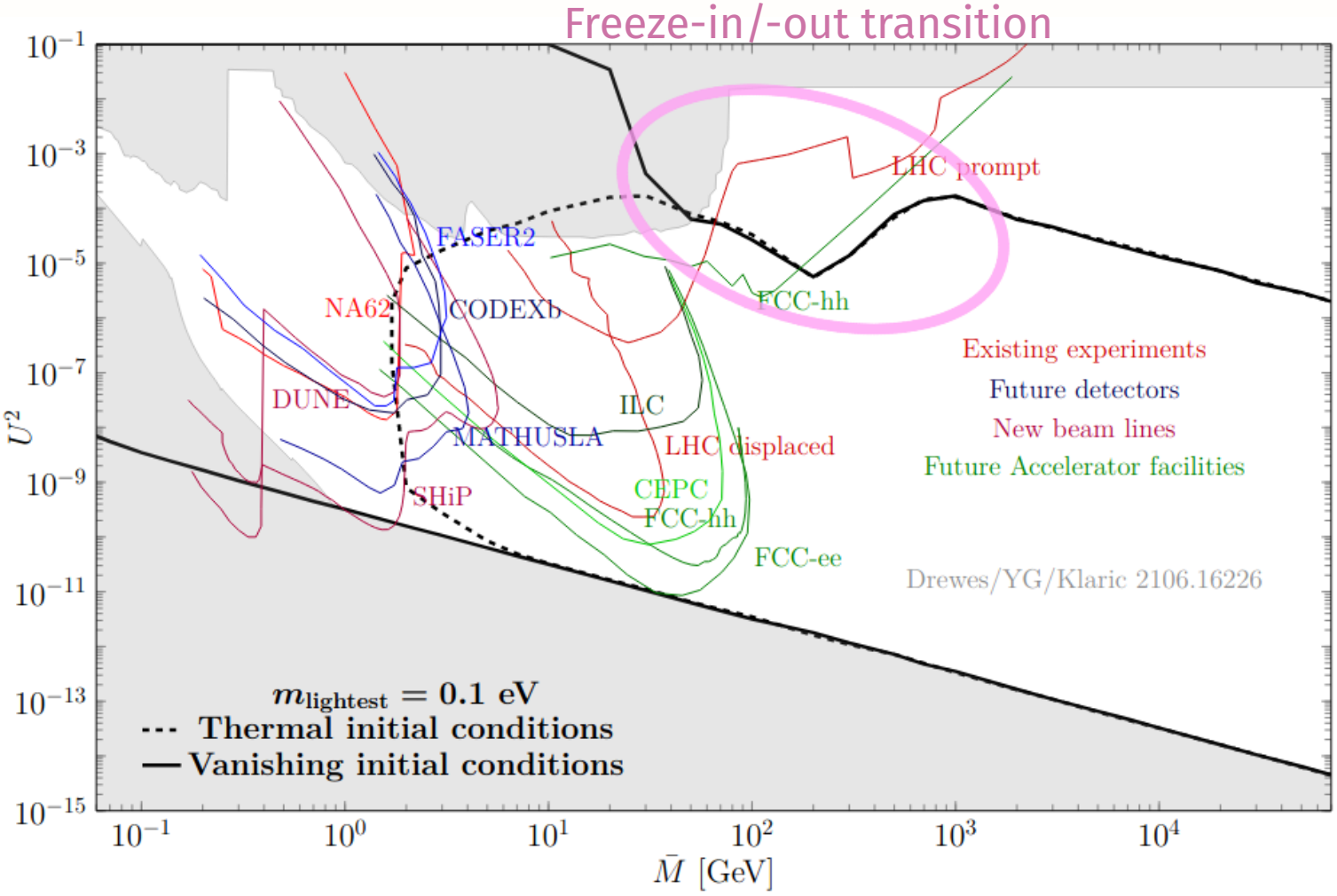

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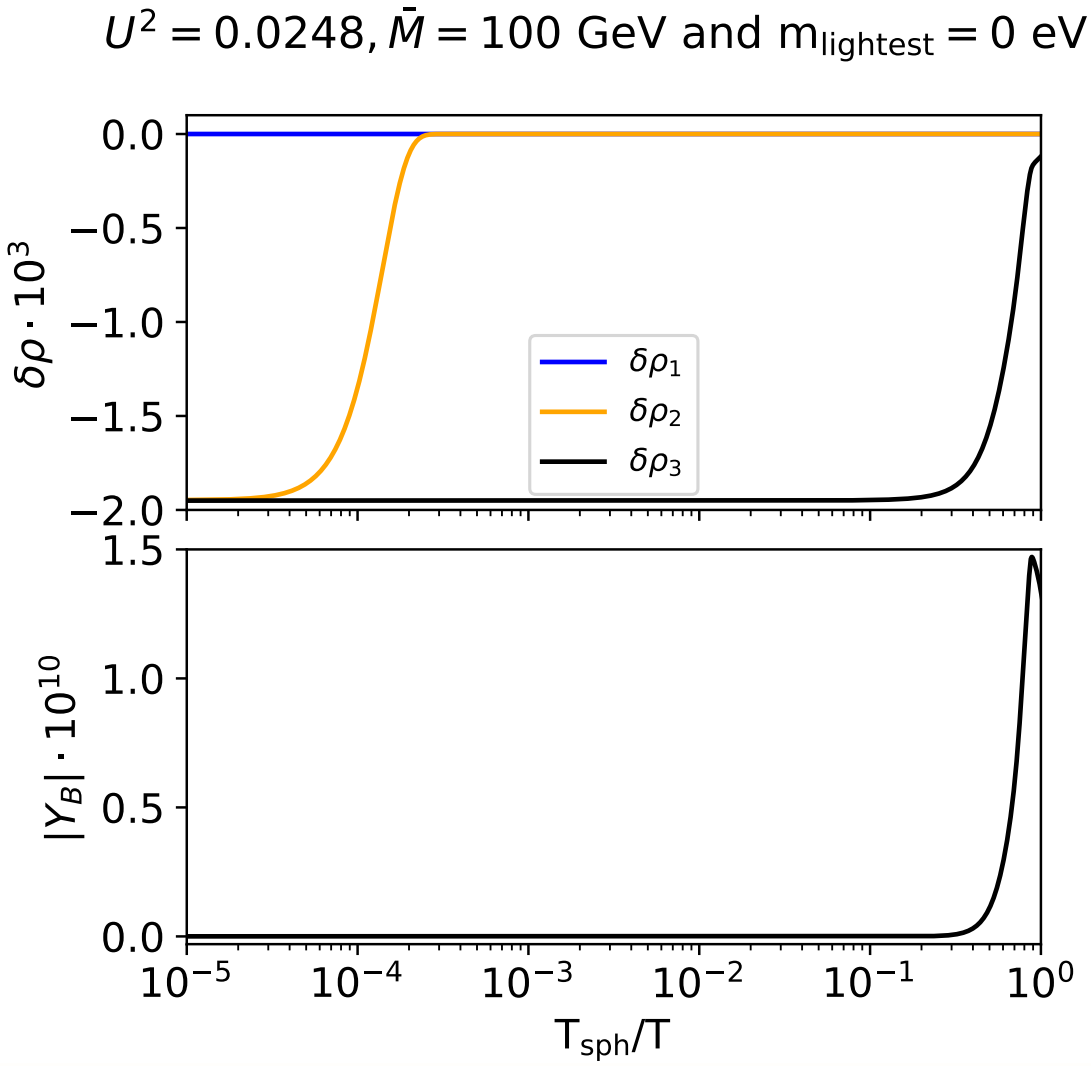
Why such large mixings ?



[YG; 2305.06663]

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

Lepton number violation (LNV) at colliders

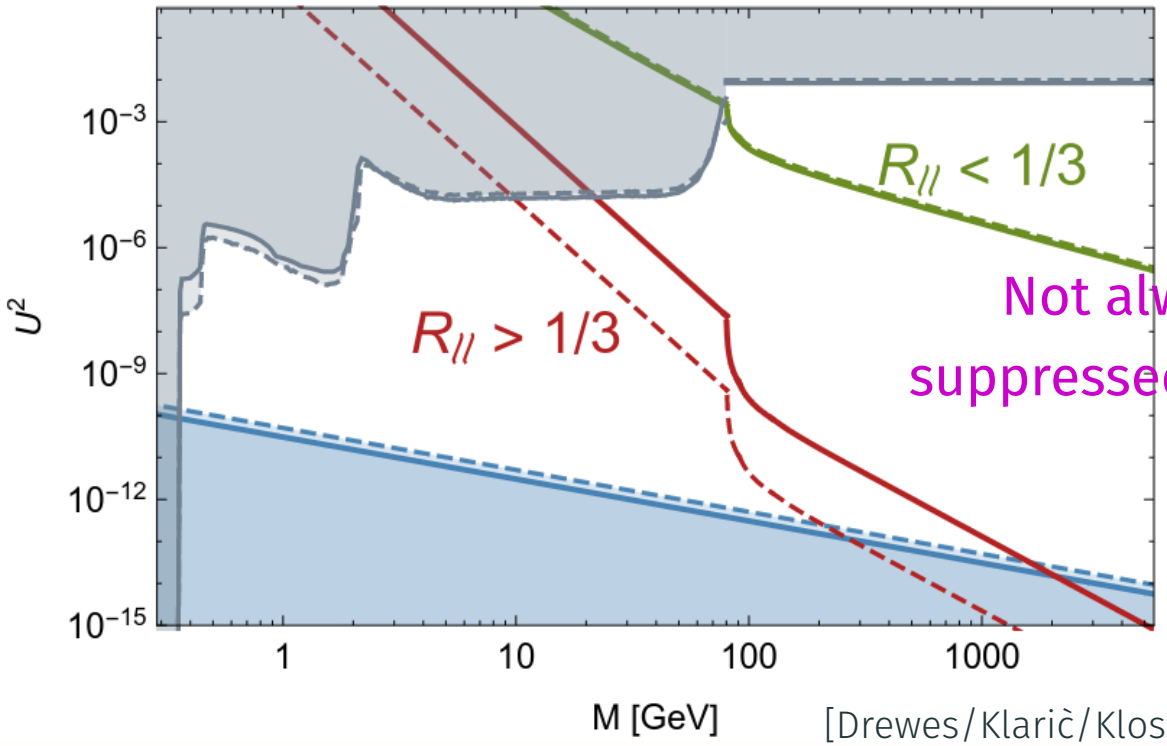
Approximate B-L symmetry

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

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

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

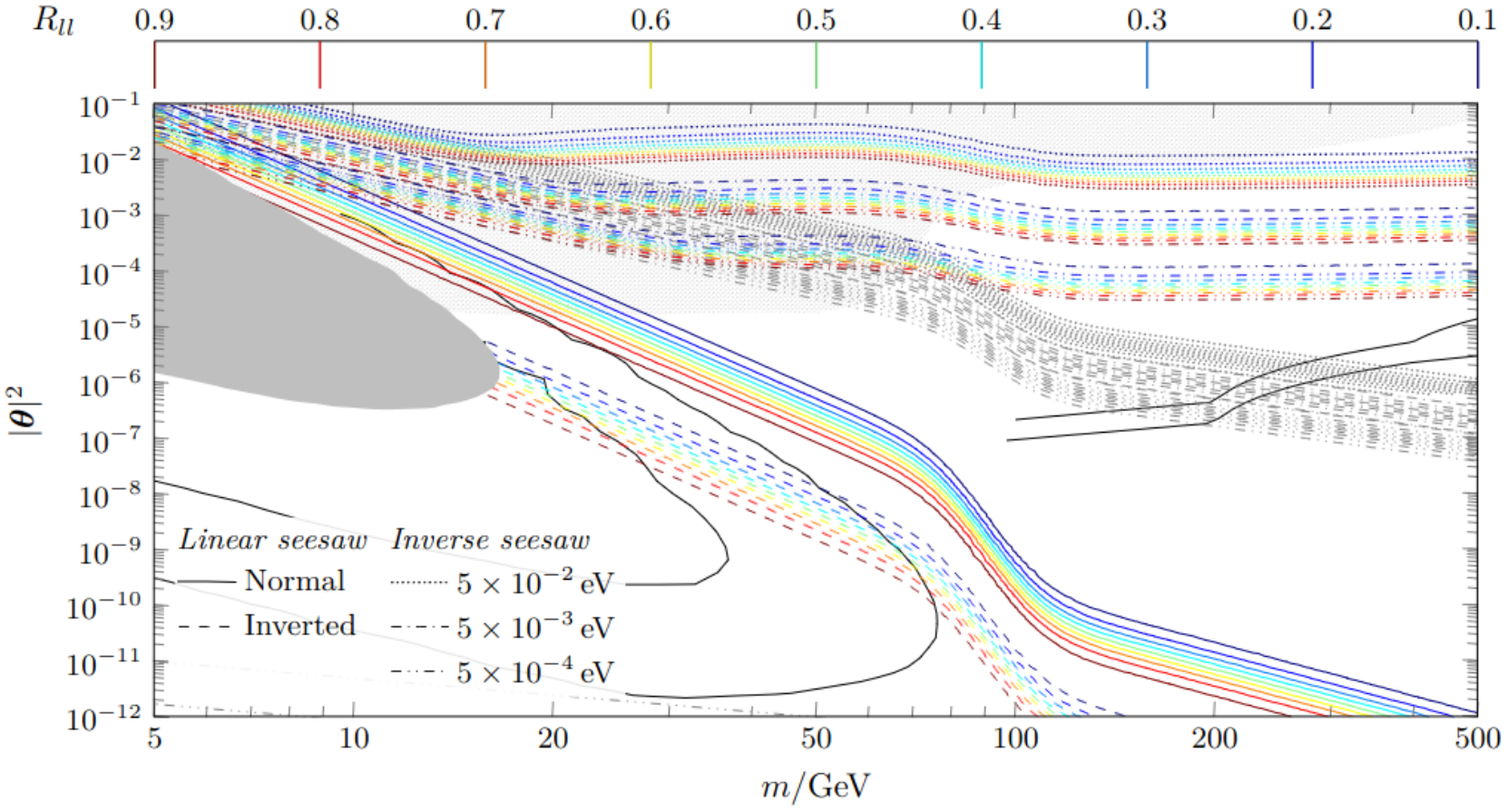
$$R_{ll} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$



Not always strongly suppressed for sizeable U^2!

[Drewes/Klarič/Klose; 1907.13034]

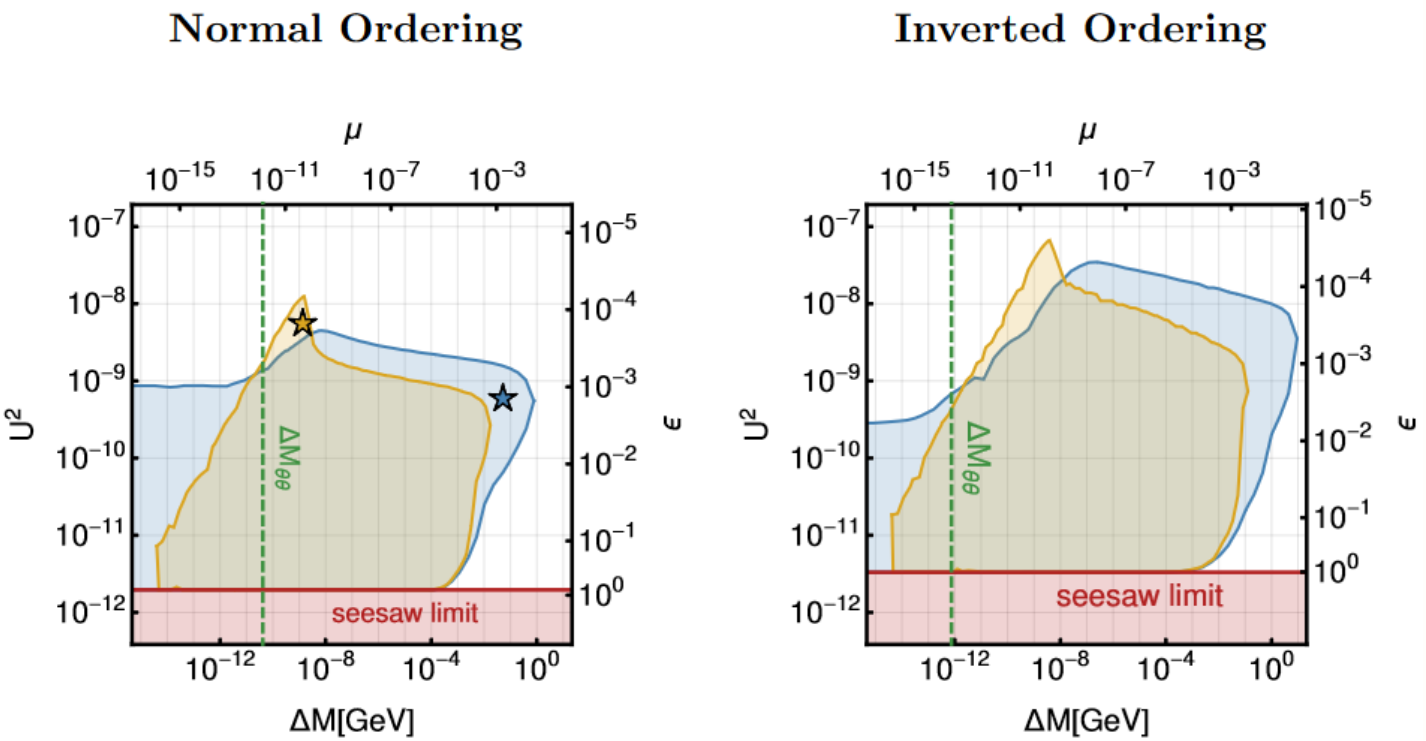
Lepton number violation (LNV) at colliders



[Antusch/Hajer/Rosskopp, 2307.06208]

In practice, prospects can be even more optimistic !

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

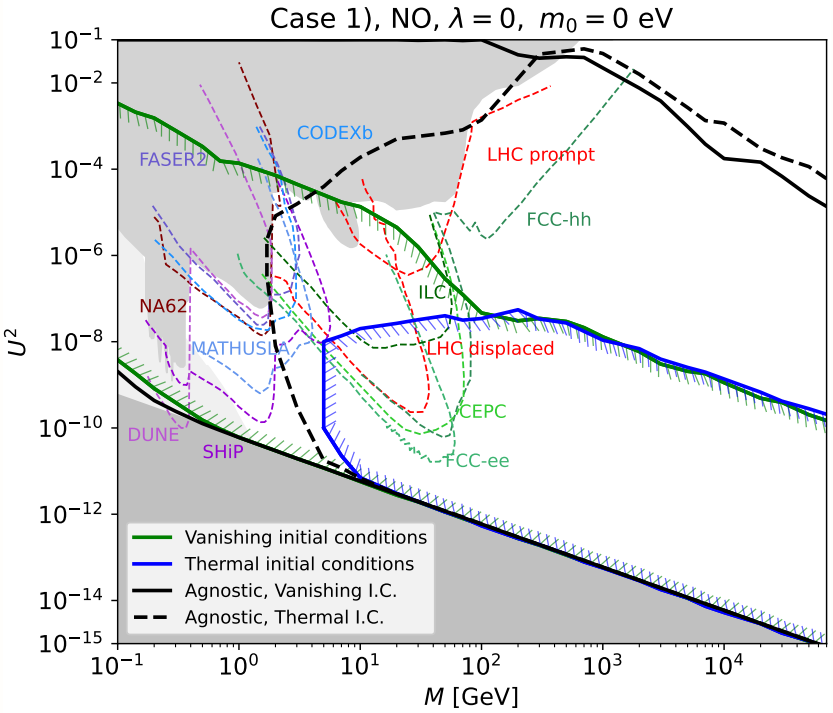
$$\Delta M_{\rm phys} \sim h_+(T) Y^\dagger Y + h_-(T) Y^t Y^*$$

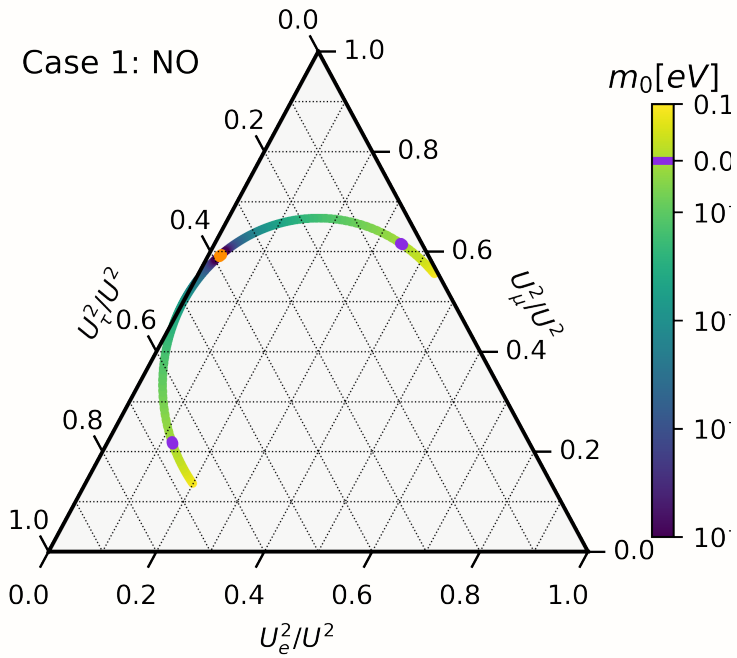
- Lepton asymmetry proportional to CP-violating combination

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

Leptogenesis with flavour symmetries

- Flavour symmetries ($\Delta(6n^2)$) have reduced parameter space but highly predictive ! (See Claudia Hagedorn's talk)

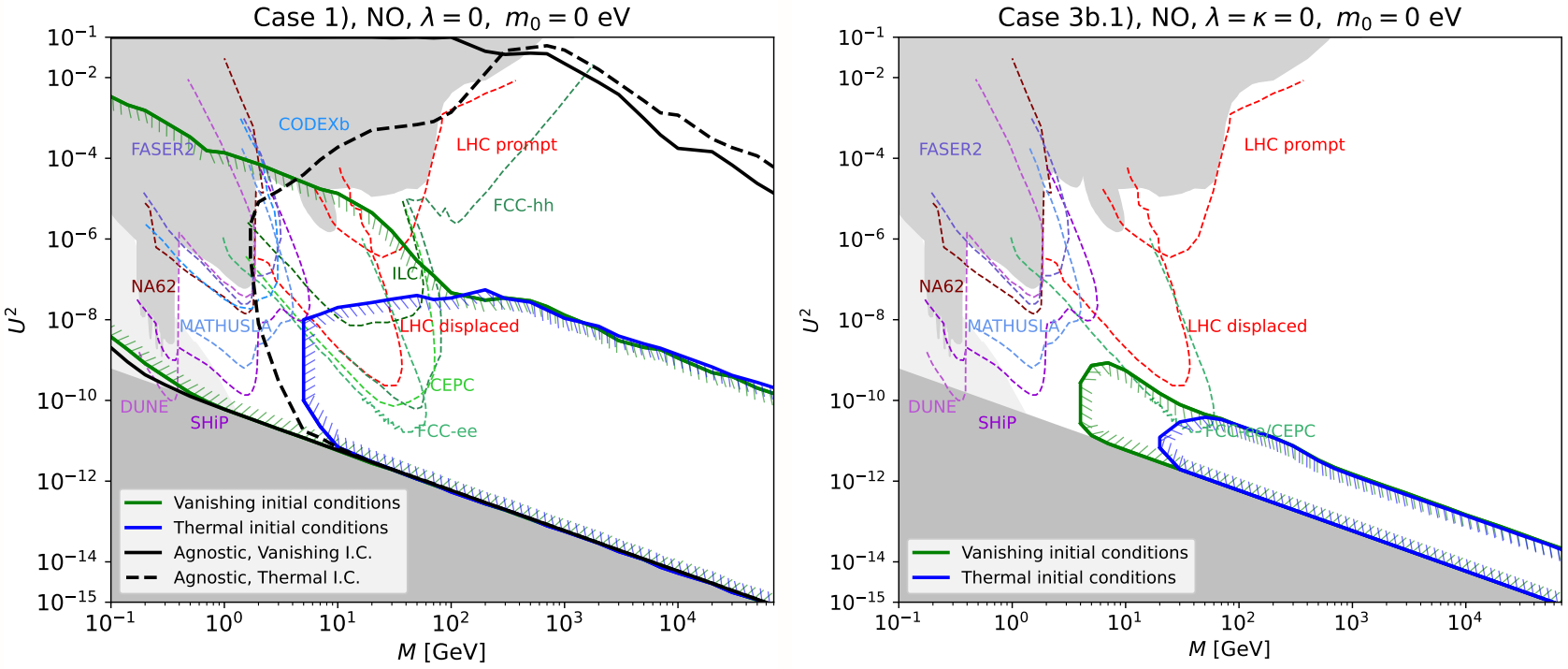




[Drewes/YG/Hagedorn/Klarič; 23xx.xxxxx]

Leptogenesis with flavour symmetries

- Flavour symmetries ($\Delta(6n^2)$) have reduced parameter space but highly predictive ! (See Claudia Hagedorn's talk)



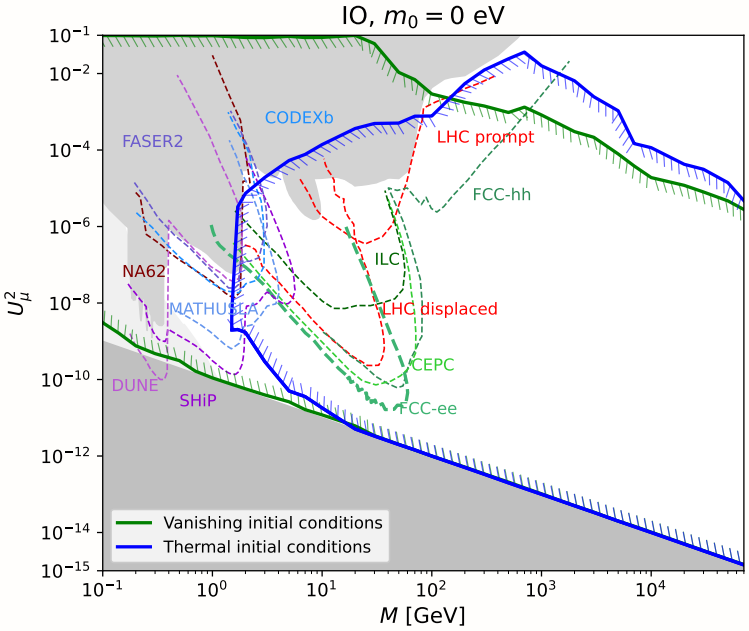
[Drewes/YG/Hagedorn/Klarič; 23xx.xxxxx]

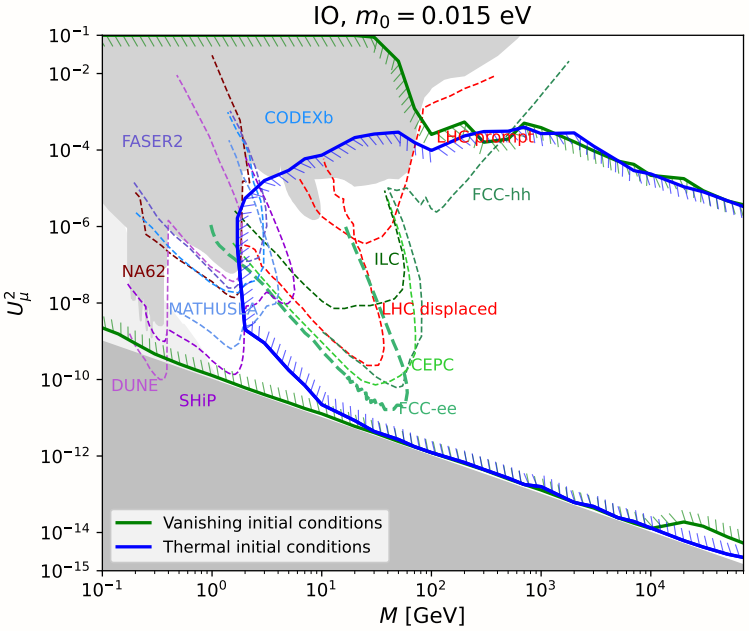
Take home and outlook

- Leptogenesis highly testable solution for ν masses + baryon asymmetry
- Degenerate leptogenesis possible due to Higgs and thermal effects
- 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, ...
- Collider testability of $n = 3$ scenario to be further explored

Thanks for your attention!

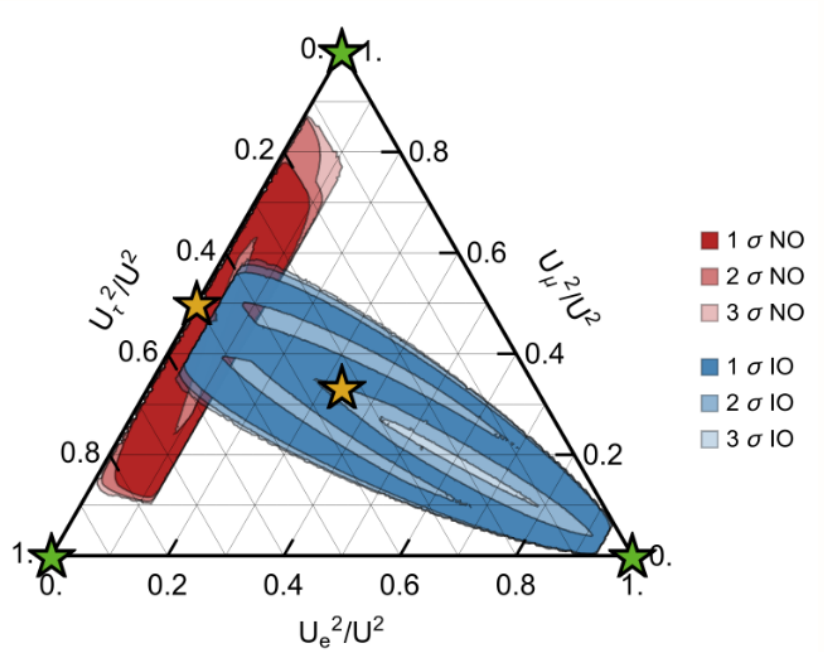
$n = 3$ parameter space, IO



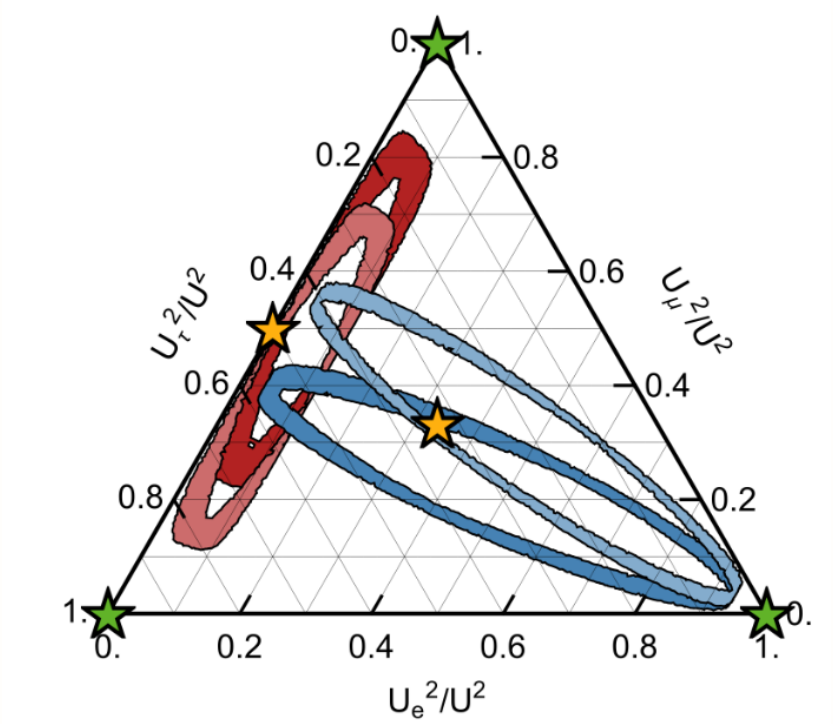


- Similar enhancement of the parameter space for IO.

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



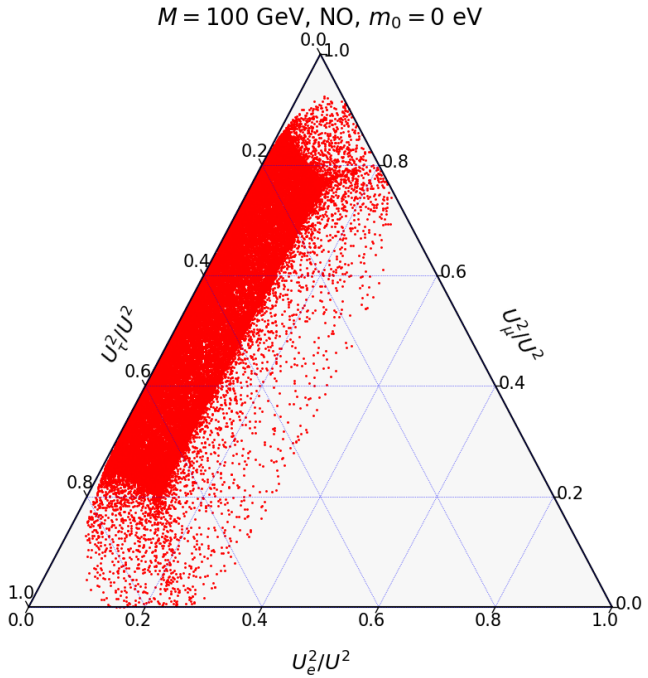
Current ν oscillation data

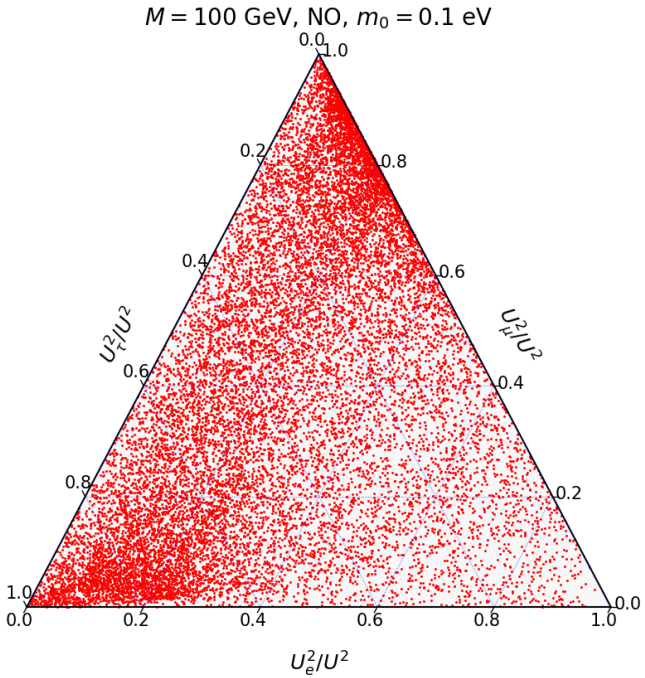


DUNE projections

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

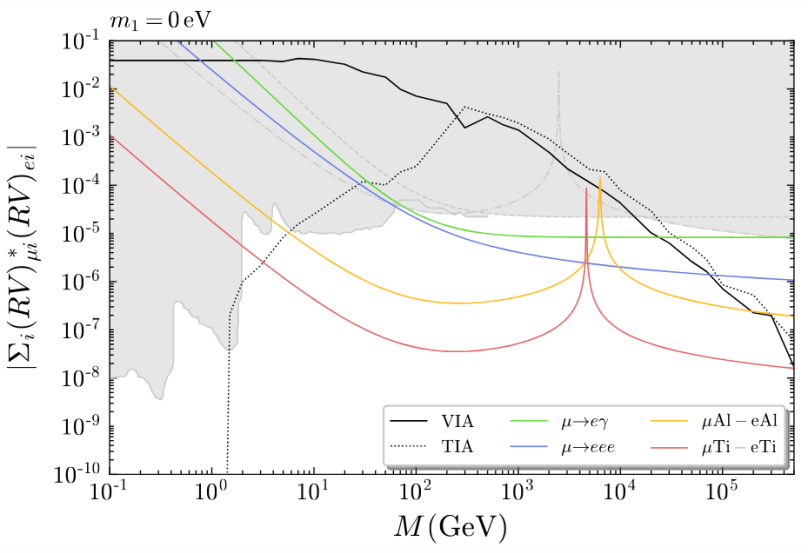
Flavour triangle, $n = 3$, NO

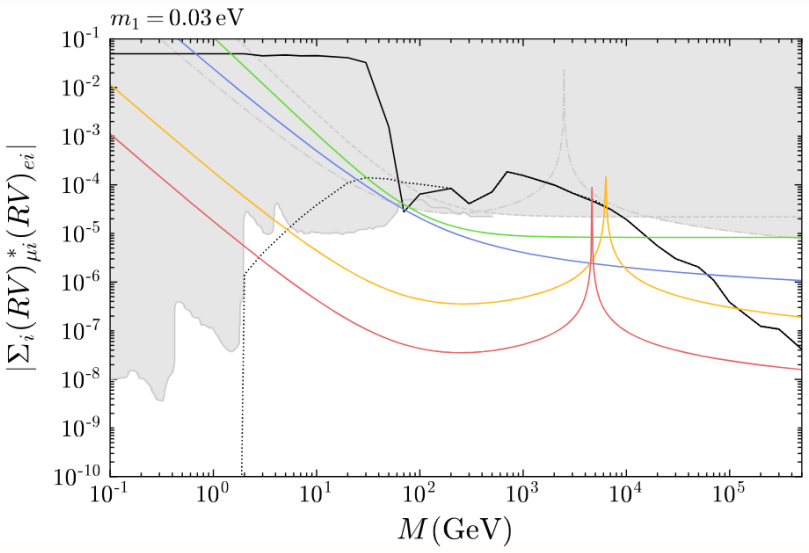




- Can fill (almost) the entire triangle for $m_0 \neq 0$!
- For $m_0 = 0$ eV, $\frac{U_e^2}{U^2}$ limited to be smaller than $\sim 1/3$.

Testing leptogenesis through CLFV experiments





- CLFV experiments can probe leptogenesis with $n = 3$ RHN generations for $M \gtrsim 10$ GeV.

Seesaw parameter space

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

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

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

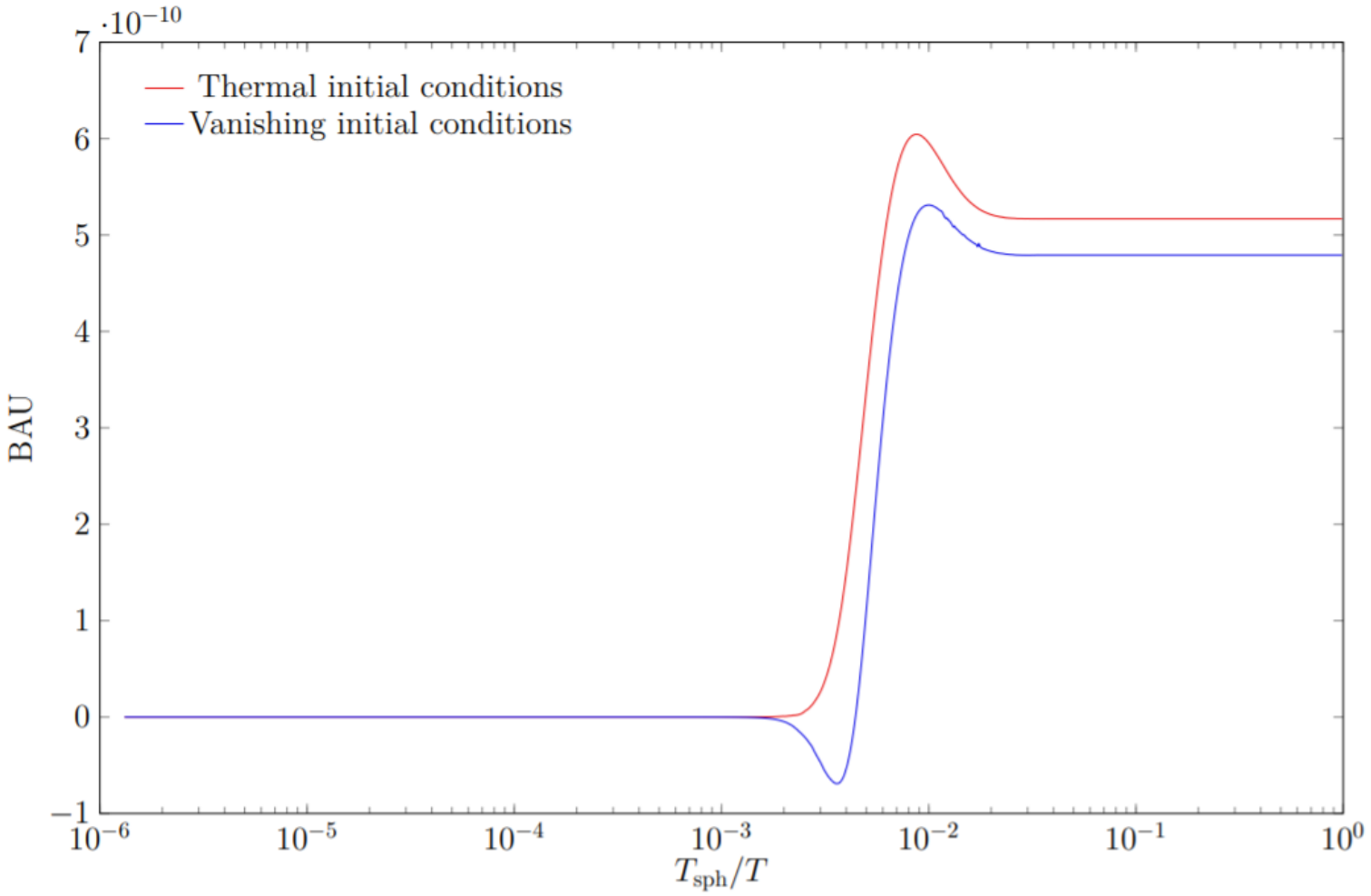
Seesaw parameter space

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	n=3
2 CP-violating phases	3 CP-violating phases
3 PMNS angles (fixed)	3 PMNS angles (fixed)
2 light neutrino masses (fixed)	3 light neutrino masses (2 fixed)
1 complex Euler angle	3 complex Euler angles
2 Majorana masses	3 Majorana masses
6 free parameters	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.