Low-scale Leptogenesis with Dirac CP-Violation

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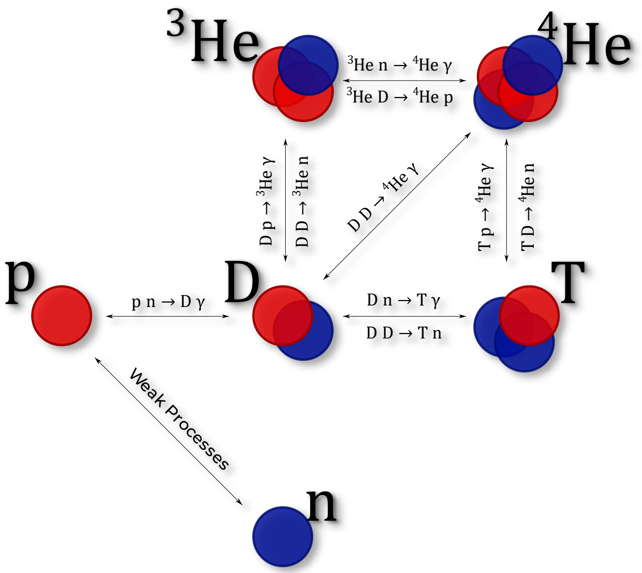
The Baryon Asymmetry of the Universe

In the present Universe we observe an **overabundance of matter** over antimatter. In terms of baryons: the **Baryon Asymmetry of the Universe (BAU)**.

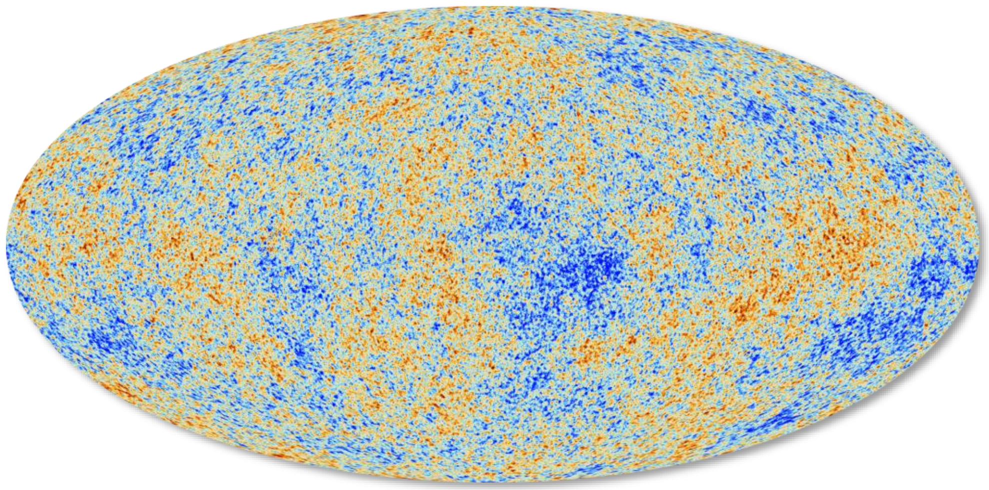
$$\eta_B = \frac{(n_B - n_{\bar{B}})}{n_\gamma} \simeq 6.1 \times 10^{-10}$$

$\sim 2 \times 10^9 + 1$ baryons every 2×10^9 of antibaryons!

Big Bang Nucleosynthesis (BBN)



Cosmic Microwave Background (CMB)



Sakharov's conditions and Baryo/Leptogenesis

The three **Sakharov's conditions** for a dynamical generation of a baryon (B) or lepton (L) asymmetry:

- **B (L) violation (BNV or LNV)**
- **C and CP violation (CPV)**
- **Out-of-equilibrium dynamics (OoE)**

A. D. Sakharov (1967)

Baryogenesis

BNV, CPV and OoE processes
VS
Wash-out processes

→ Present BAU

Recent Review: D. Bodeker, W. Buchmuller, 2009.07294

We need physics beyond the SM!

Leptogenesis

LNV, CPV and OoE processes
VS
Wash-out processes

→ Lepton Asymmetry → (**SM** **Sphalerons**) → Present BAU

Fukugita & Yanagida (1986)

Neutrino masses and mixing

Neutrinos have non-zero masses and mix: $\nu_{\alpha L}(x) = \sum_{a=1}^{3} U_{\alpha a} \nu_{aL}(x)$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{\frac{i\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{\frac{i\alpha_{31}}{2}} \end{pmatrix}$$

Summary of neutrinos observations:

- **Normal Ordering (NO):** $m_1 < m_2 < m_3$
- **Inverted Ordering (IO):** $m_3 < m_1 < m_2$

- **Normal Hierarchical (NH):** $0 \simeq m_1 < m_2 < m_3$
- **Inverted Hierarchical (IH):** $0 \simeq m_3 < m_1 < m_2$
- **Quasi Degenerate:** $m_1 \simeq m_2 \simeq m_3$

Ordering	θ_{12} (°)	θ_{13} (°)	θ_{23} (°, 3σ)	δ (°, 3σ)	Δm^2_{21} (10^{-5}eV^2)	$\Delta m^2_{31(32)}$ (10^{-3}eV^2)
NO	33.41	8.58	39.7 – 51.0	154 – 350	7.41	2.507
IO	33.41	8.57	39.9 – 51.5	194 – 344	7.41	-2.486

I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz and A. Zhou (2020), NuFIT 5.2 (2022), www.nu-fit.org

Type-I seesaw mechanism

Seesaw lagrangian

Yukawa and mass terms

$$\mathcal{L}_{Y,M}(x) = -\left(Y_{\alpha j}\overline{\psi_{\alpha L}}(x)\, i\sigma_2\, \Phi^*(x)\, N_{jR}(x) + h.c.\right) - \frac{1}{2} M_j \overline{N_j}(x) N_j(x)$$

Right-handed neutrinos/sterile neutrinos/ heavy Majorana neutrinos

Electroweak Symmetry Breaking

Neutrino mass generation

Neutrino mass matrix

$$m_\nu \simeq -(v^2/2) Y \widehat{M}^{-1} Y^T$$

Neutrino mixing

$$\nu_{\alpha L} \simeq U_{\alpha a}\nu_{aL} + \Theta_{\alpha j} N^c_{jR}$$

$$\Theta_{\alpha j} \simeq \left(v/\sqrt{2}\right) Y_{\alpha j}/M_j$$

Mixing angle/Coupling

Model Parameters

Casas-Ibarra Parameterisation

$$Y = \pm i\left(\sqrt{2}/v\right) U \sqrt{\widehat{m}}\, O^T \sqrt{\widehat{M}}$$

Casas-Ibarra matrix

$$\boldsymbol{OO^T = 1_{2x2}}$$

With 2 heavy Majorana neutrinos

$$O^{(\mathrm{NH})} = \begin{pmatrix} 0 & \cos\theta & \varphi\sin\theta \\ 0 & -\sin\theta & \varphi\cos\theta \end{pmatrix}$$

$$O^{(\mathrm{IH})} = \begin{pmatrix} \cos\theta & \varphi\sin\theta & 0 \\ -\sin\theta & \varphi\cos\theta & 0 \end{pmatrix}$$

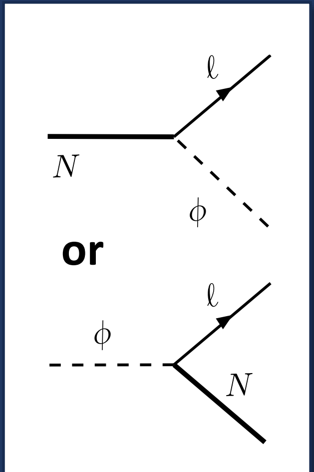
$$\theta = \omega + i\,\xi$$

$$\varphi = \pm 1$$

Leptogenesis within the type-I seesaw mechanism

Lepton Number violating processes via Yukawa coupling

Decays



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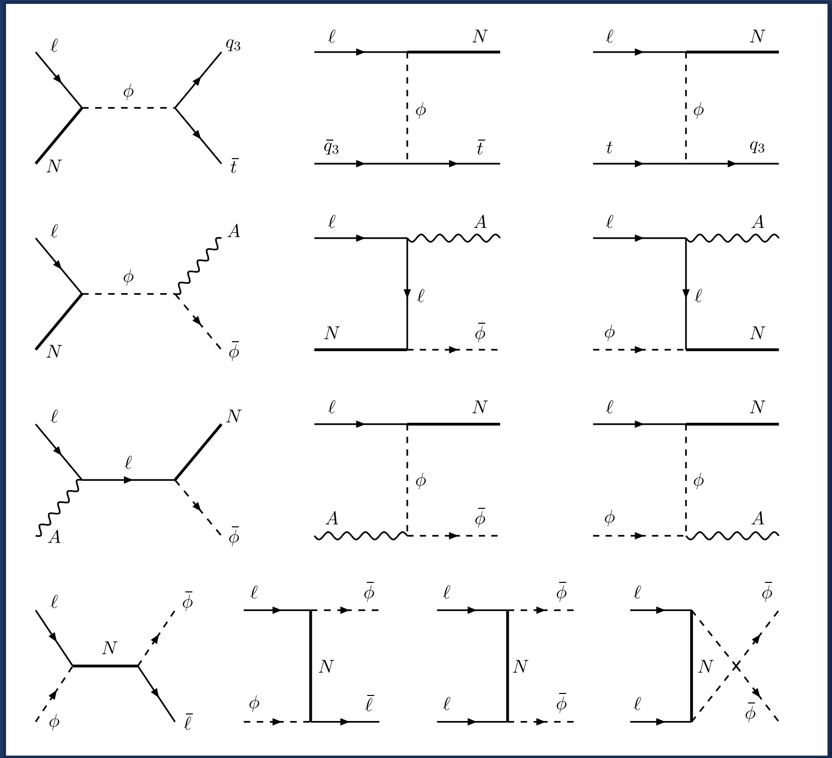
Scatterings



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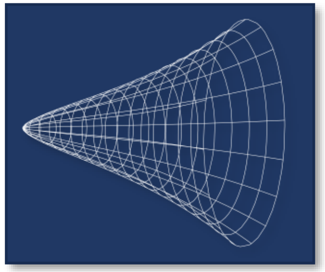
CP-violation

$$\epsilon^{CP} = \frac{\Gamma(N \to l \ldots) - \Gamma(N \to \bar{l} \ldots)}{\Gamma(N \to \text{anything})}$$

+

Expansion of the Universe

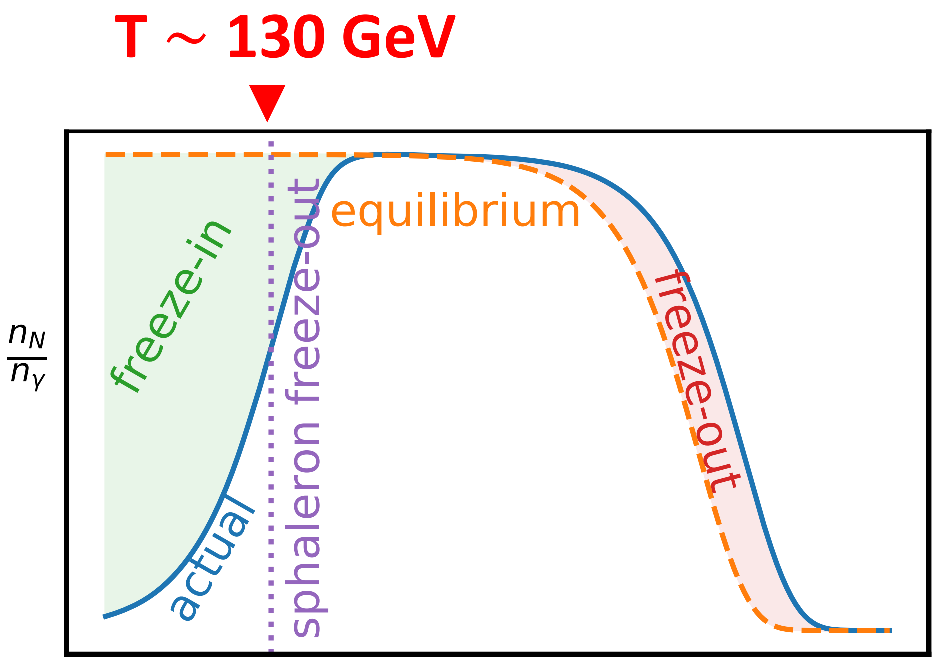


L. Covi, E. Roulet, F. Vissani hep-ph/9605319,
W. Buchmuller, M. Plumacher hep-ph/9710460,
A. Pilaftsis hep-ph/9702393,
...

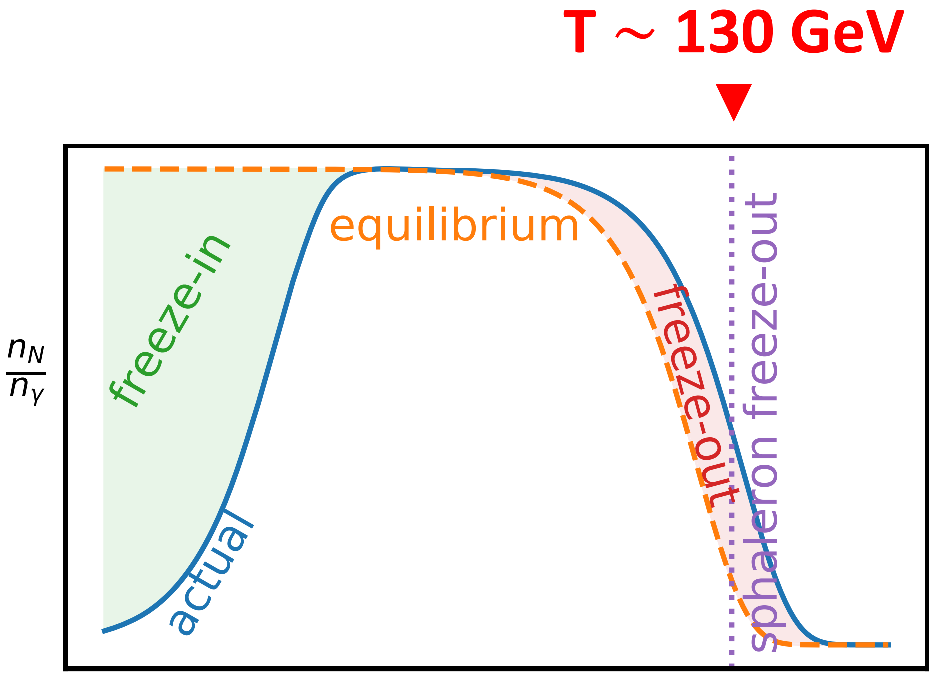
G. F. Giudice, A. Notari, M. Raidal, A. Riotto, A. Strumia hep-ph/0310123
S. Davidson, E. Nardi, Y. Nir arXiv:0802.2962

Leptogenesis within the type-I seesaw mechanism

Freeze-in Leptogenesis



Freeze-out Leptogenesis



J. Klarić, M. Shaposhnikov, I. Timiryasov, PRL.127.111802 and PRD.104.055010
A. G., K. Moffat, S. T. Petcov, arXiv:2009.03166

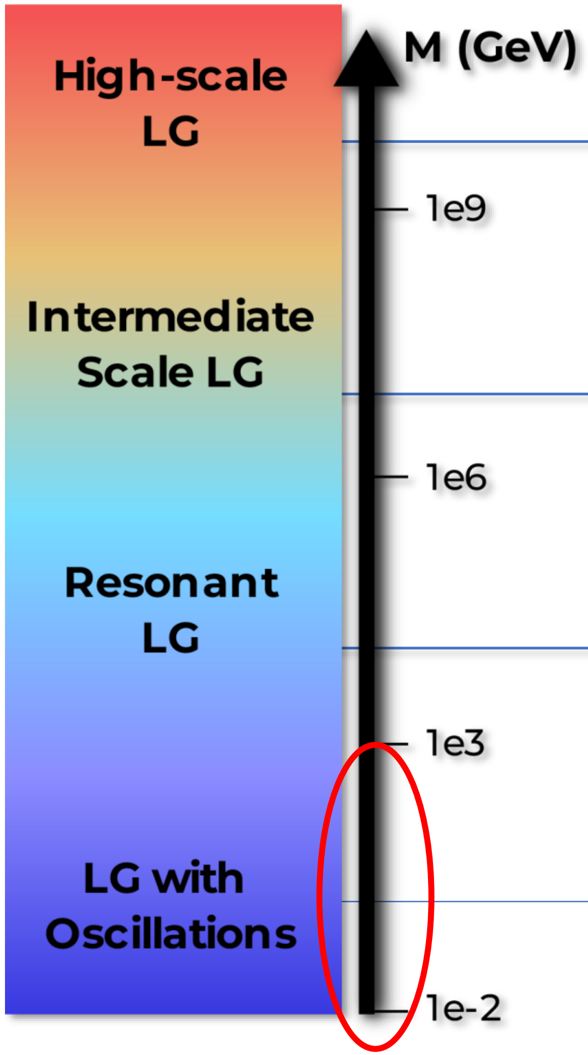
Leptogenesis scales

Fukugita & Yanagida (1986)

Racker, Rius & Pena (2012)

Pilaftsis & Underwood (2003)

Ahmedov, Rubakov & Smirnov (1998)



Accessible energies!

M1<<M2<<M3 Davidson-Ibarra bound M1>1e9 GeV

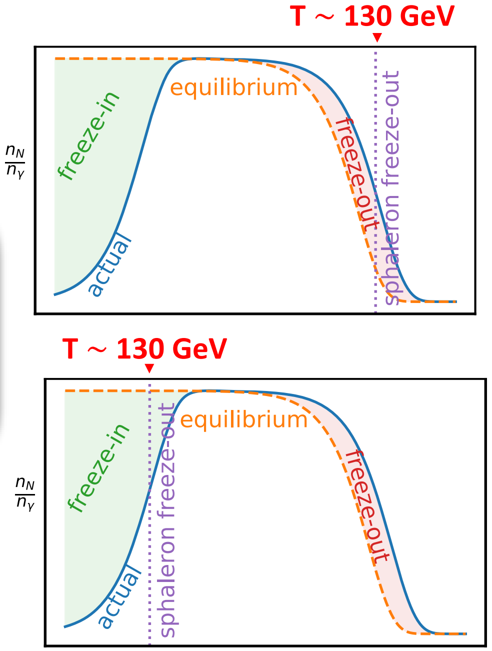
Flavour effects, Mild hierarchy: M2<3M1, M3<3M2

Quasi-degenerate Ns Non-relativistic regime (T<<M)

Quasi-degenerate Ns Relativistic (T>>M) Thermal effects

Low-energy CP-violation

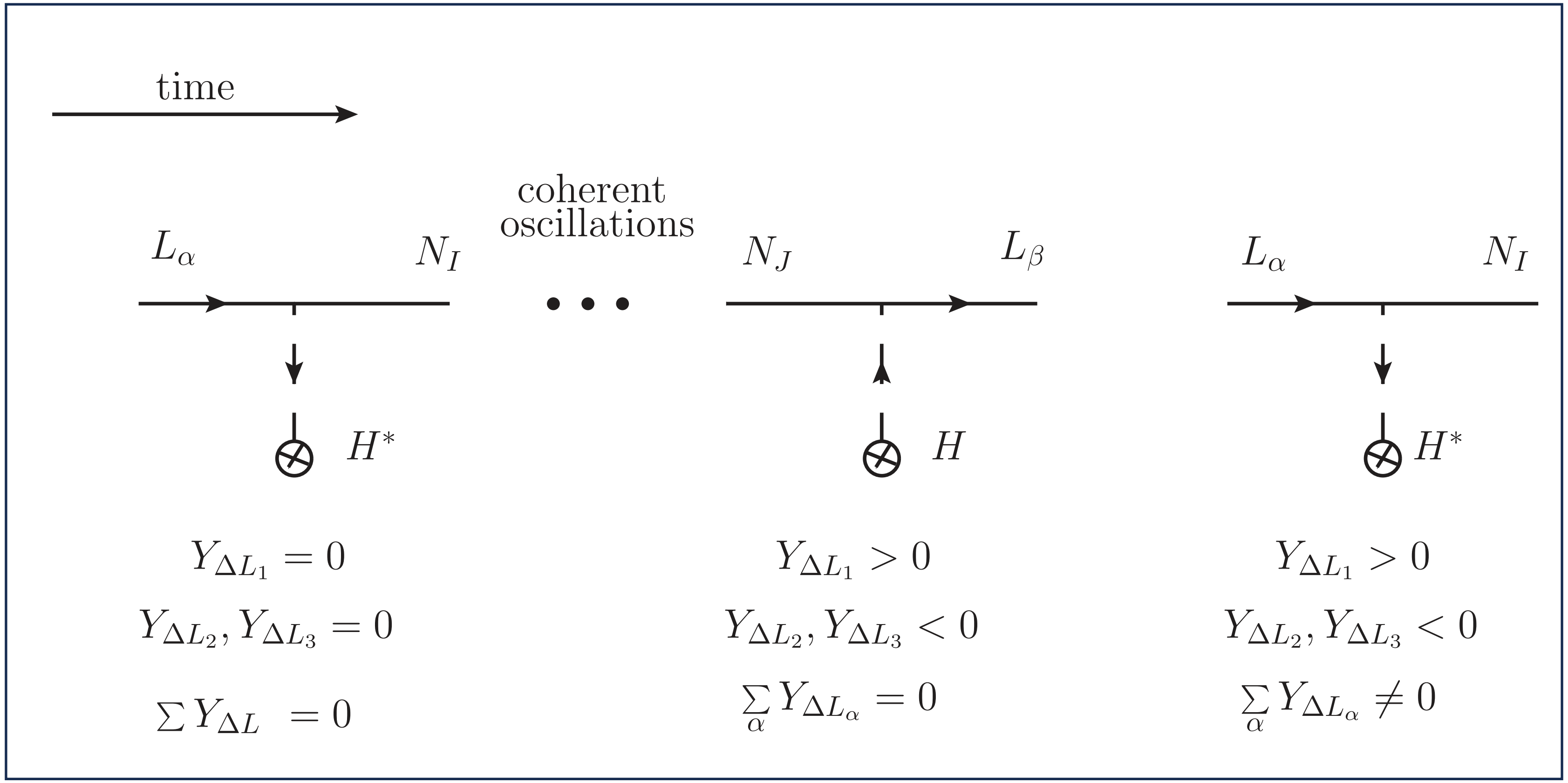
S. Pascoli, S. T. Petcov, A. Riotto (2007),
S. Blanchet. P. Di Bari (2007),
…,
K. Moffat, S. Pascoli, S. T Petcov, J. Turner (2018),
A.G., K. Moffat, S. T. Petcov (2022)

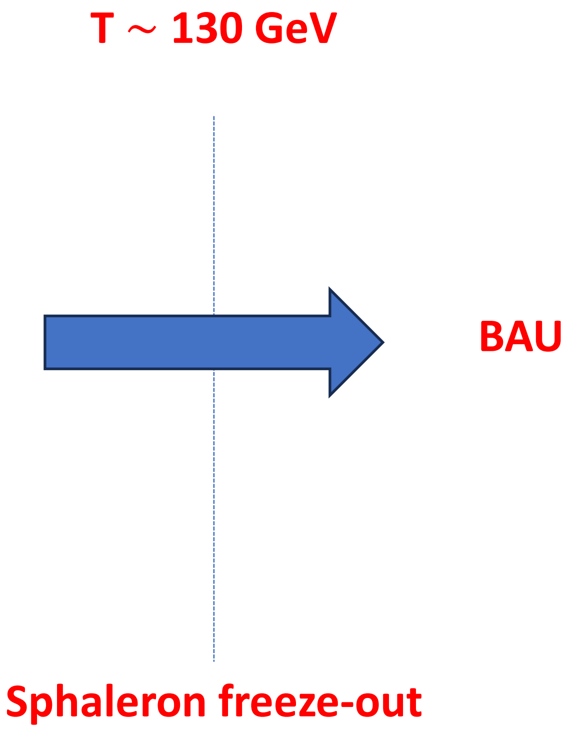


J. Klarić, M. Shaposhnikov, I. Timiryasov, PRL.127.111802 and PRD.104.055010

Freeze-in Leptogenesis

Fig. from B. Shuve, I. Yavin arXiv:1401.2459





+ thermal effects (thermal masses and soft emission of gauge bosons)
+ helicity states behave differently

Density Matrix Equations

$$Hx\frac{dr_N}{dx} = -i\left[\langle\mathcal{H}\rangle, r_N\right] - Hx\frac{r_N}{N_N^{\rm eq}}\frac{dN_N^{\rm eq}}{dx} - \frac{\langle\gamma_N^{(0)}\rangle}{2}\left\{Y^\dagger Y, r_N - 1\right\} + \langle\gamma_N^{(1)}\rangle Y^\dagger \mu Y - \frac{\langle\gamma_N^{(2)}\rangle}{2}\left\{Y^\dagger \mu Y, r_N\right\} +$$

$$- \frac{\langle S_N^{(0)}\rangle}{2T^2}\left\{MY^{\rm T}Y^* M, r_N - 1\right\} - \frac{\langle S_N^{(1)}\rangle}{T^2} MY^{\rm T}\mu Y^* M + \frac{\langle S_N^{(2)}\rangle}{2T^2}\left\{MY^{\rm T}\mu Y^* M, r_N\right\},$$

$$\kappa Hx\frac{d\mu_{\Delta_\alpha}}{dx} = -\frac{\langle\gamma_N^{(0)}\rangle}{2}\left(Y r_N Y^\dagger - Y^* r_{\overline{N}} Y^{\rm T}\right)_{\alpha\alpha} + \langle\gamma_N^{(1)}\rangle\left(YY^\dagger\right)_{\alpha\alpha}\mu_\alpha - \frac{\langle\gamma_N^{(2)}\rangle}{2}\left(Y r_N Y^\dagger + Y^* r_{\overline{N}} Y^{\rm T}\right)_{\alpha\alpha}\mu_\alpha +$$

$$+ \frac{\langle S_N^{(0)}\rangle}{2T^2}\left(Y^* M r_N M Y^{\rm T} - Y M r_{\overline{N}} M Y^\dagger\right)_{\alpha\alpha} + \frac{\langle S_N^{(1)}\rangle}{T^2}\left(Y M^2 Y^\dagger\right)_{\alpha\alpha}\mu_\alpha +$$

$$- \frac{\langle S_N^{(2)}\rangle}{2T^2}\left(Y M r_{\overline{N}} M Y^\dagger + Y^* M r_N M Y^{\rm T}\right)_{\alpha\alpha}\mu_\alpha,$$

$$Hx\frac{dr_{\overline{N}}}{dx} = r_N \to r_{\overline{N}},\ \mu \to -\mu,\ Y \to Y^*$$

Computationally very demanding!

Thermal averaged rates

J. Ghiglieri, M. Laine arXiv:1703.06087 and 1711.08469
http://www.laine.itp.unibe.ch/leptogenesis/

Freely available codes!

`Python`: A. G., C. Leslie, Y. F. Perez-Gonzalez, H. Schulz, B. Shuve, J. Turner, R. Walker, `ULYSSESv2`, arXiv:2301.05722
`C++`: P. Hernández, J. López-Pávon, N. Rius and S. Sandner, `amiqs`, arXiv:2207.01651

Parameter Space of low-scale LG

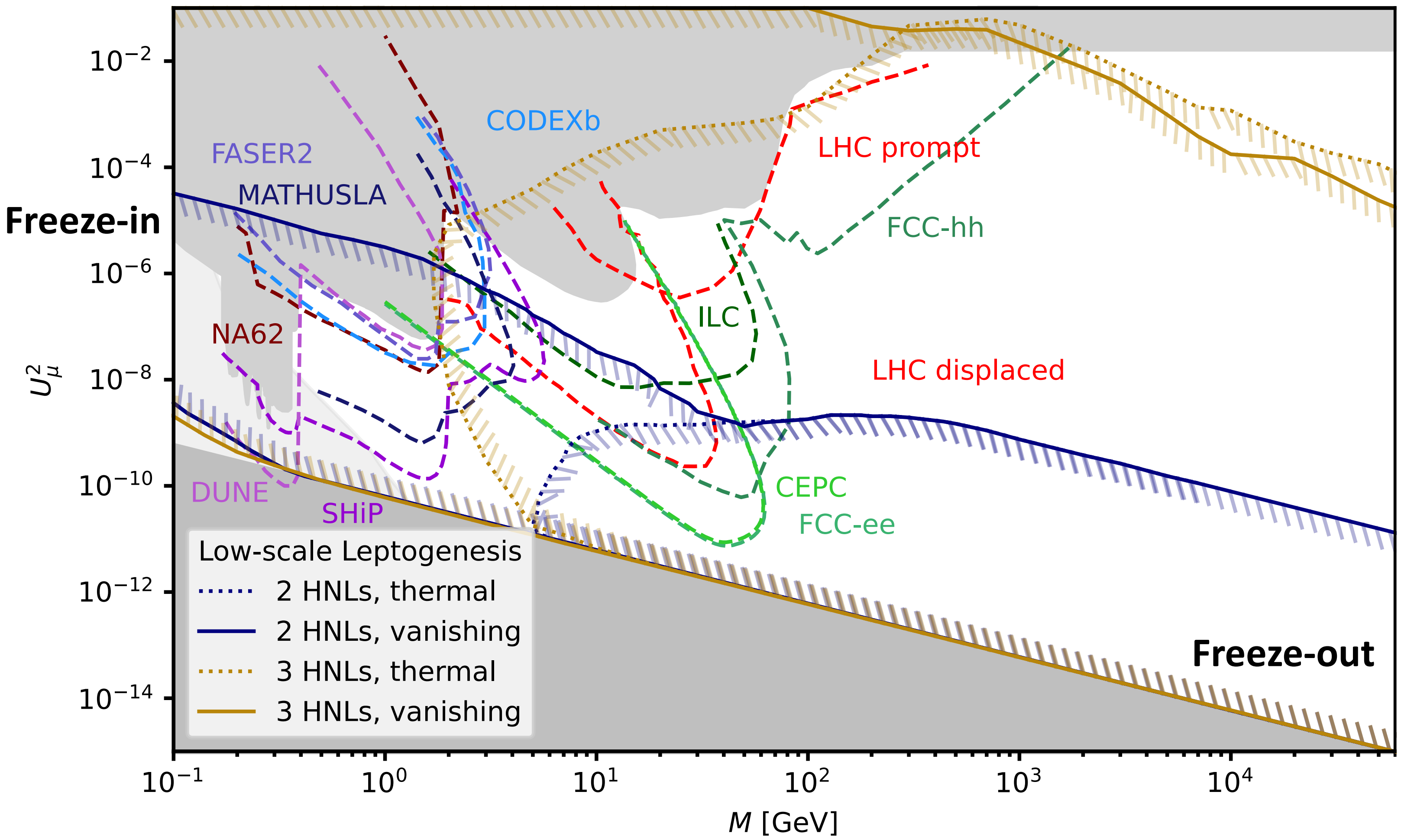


Fig. from A. M. Abdullahi et al., arXiv:2203.08039

Parameter Space of low-scale LG

- Experiments looking at **charged lepton flavour violating processes** involving muons will be able to probe the LG parameter space.

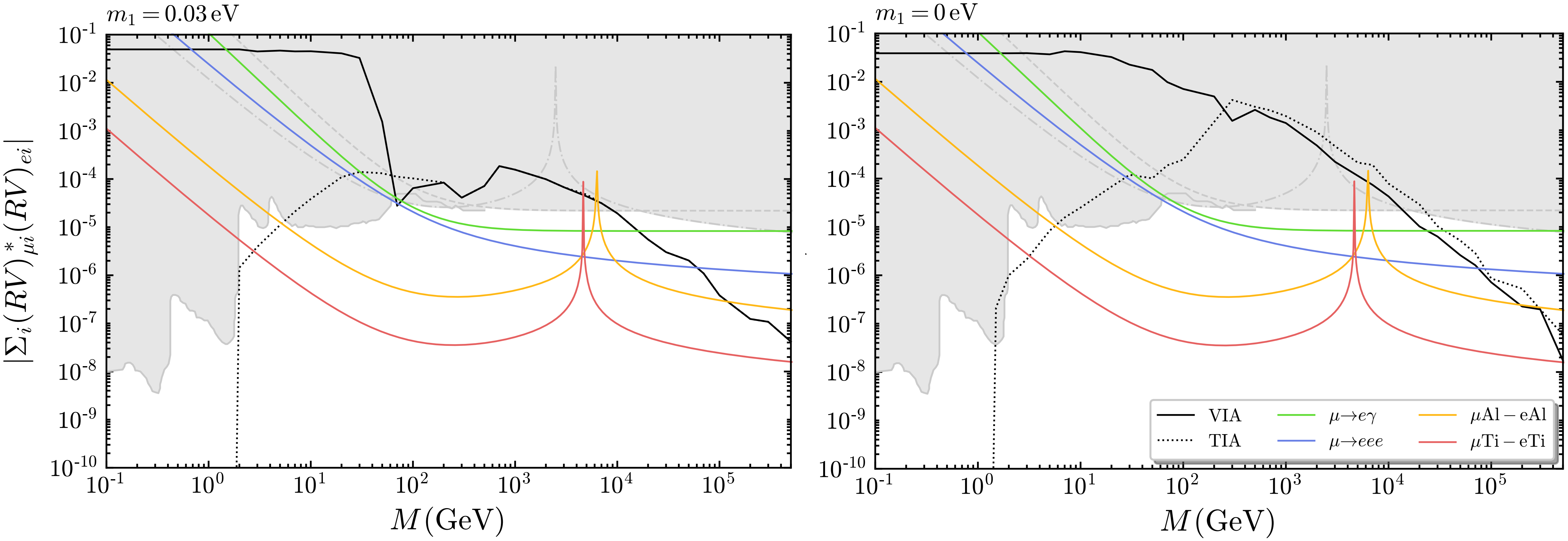


Fig. from A.G., J. Klarić, S. T. Petcov, *Phys. Lett. B, 837 (2023) 137643* [2206.04342]

CP-violation in the Seesaw model

Casas-Ibarra Parameterisation

$$Y = \pm i(\sqrt{2}/v) U \sqrt{\hat{m}} O^T \sqrt{\hat{M}}$$

Dirac phase δ
Majorana phases α_{21}, α_{31}

Low-energy CP-violation

Direct connection with low-energy experiments on neutrino oscillations and 0νββ-decay

Casas-Ibarra CP-violating phases

CP-conserving Casas-Ibarra matrix

Casas-Ibarra angle real or purely imaginary:
Real $\xi = 0, \omega \neq 0$
Imaginary $\omega = 0, \xi \neq 0$

S. Pascoli, S. T. Petcov, A. Riotto hep-ph/0611338
Model: P. Chen, G.-J. Ding, S. F. King arXiv:1402.03873

Large couplings!

Dirac CP-violation:
the **Dirac phase** may very well be **the only CP-violating phase** in the neutrino sector.
Is the Dirac CP-violation enough for LG?

Parameter space of viable LG with Dirac CP-violation

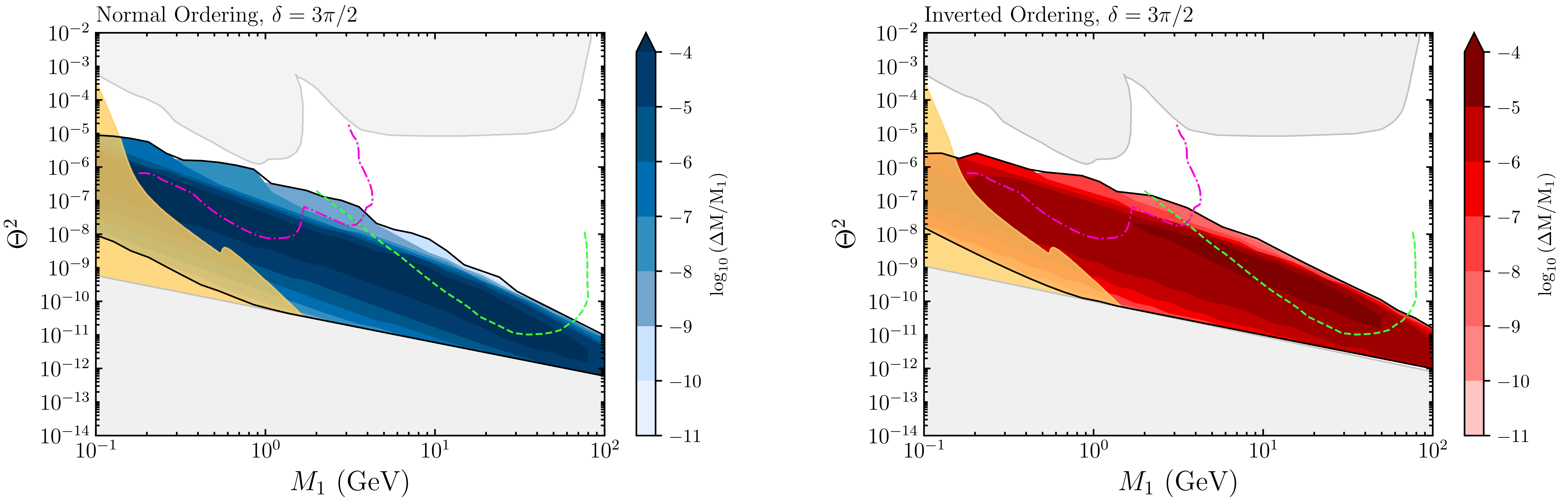
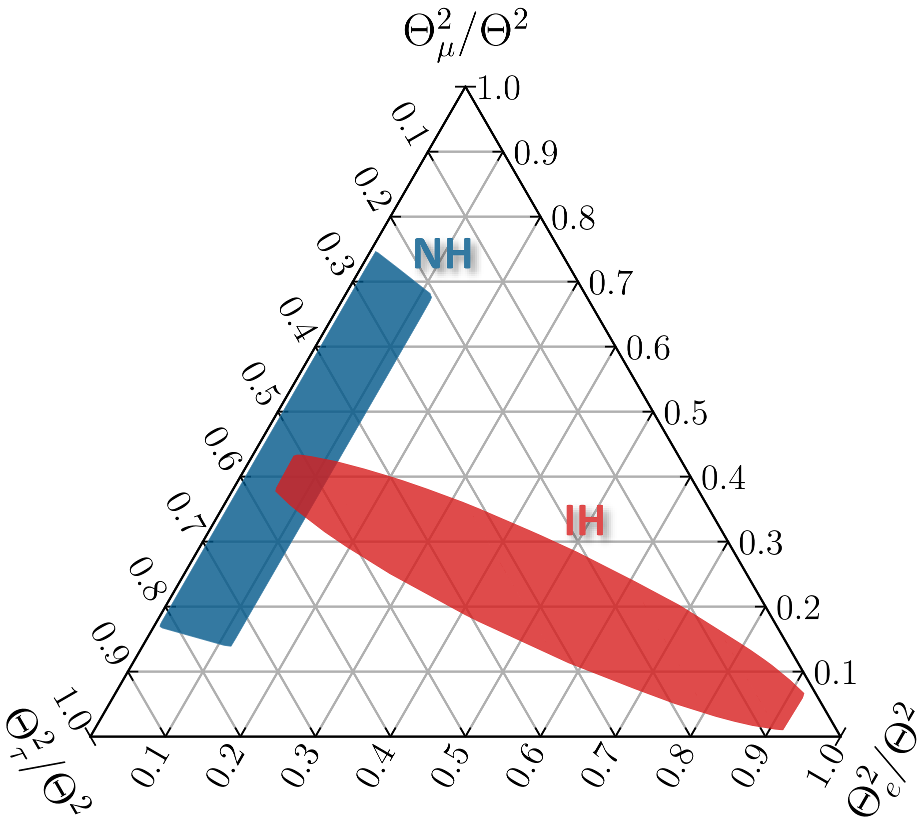


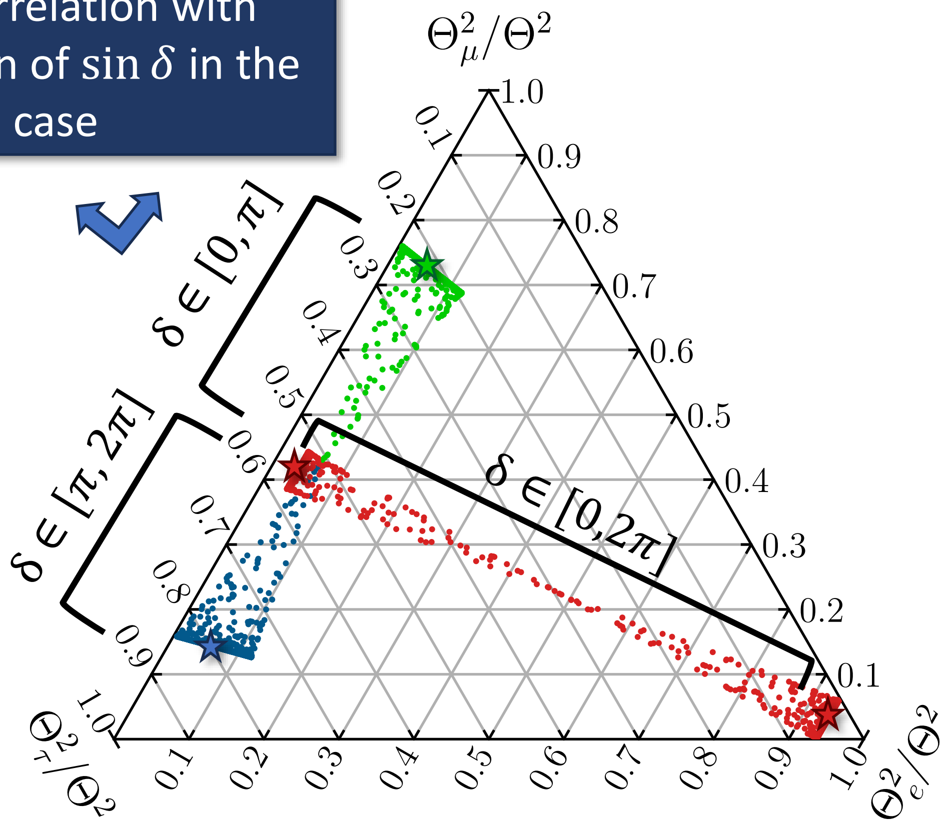
Fig. from A. G., S. Pascoli, S. T. Petcov, *Low-Scale LG with Low-Energy Dirac CPV,* arXiv:2307.07476 and follow-up in preparation.

Flavour ratios compatible with viable LG



LG with low- or high-energy CP-violation

Correlation with sign of $\sin\delta$ in the NH case



Low-energy Dirac CP-violation

★ Large mixings $\xi > 1, \Theta^2$ in the experimental region

A. G., S. Pascoli, S. T. Petcov arXiv:2307.07476 and follow-up in preparation.

Summary and conclusions

- The parameter space of **low-scale LG via oscillations** with **two/three quasi degenerate heavy Majorana neutrinos** can be **probed by future collider searches,** including **FCC,** of heavy neutral leptons in the mass range **[100 MeV, 100 GeV]**.

- Experiments looking at **charged lepton flavour violation processes**, such as MEG II on the $\mu \to e\gamma$ decay, Mu3e on $\mu \to eee$ decay, Mu2e and COMET (PRISM/PRIME) on $\mu - e$ conversion in Al (Ti), can **probe** the parameter space of **low-scale LG via oscillations** with **three quasi degenerate heavy Majorana neutrinos**.

- The **Dirac CP-violating phase** can **alone** provide the requisite **CP-violation** necessary **for successful LG; a future measurements of the CP-violation in neutrino oscilaltions would be in favour of low-scale LG.**

- It is important to have **complementarity** between different experiments to call for a discovery.

Thanks for your attention!