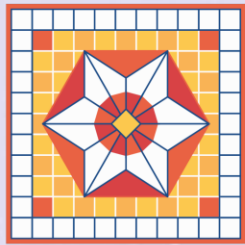


Low-scale Leptogenesis with Low-energy CP-Violation



FLASY

ROME 2025

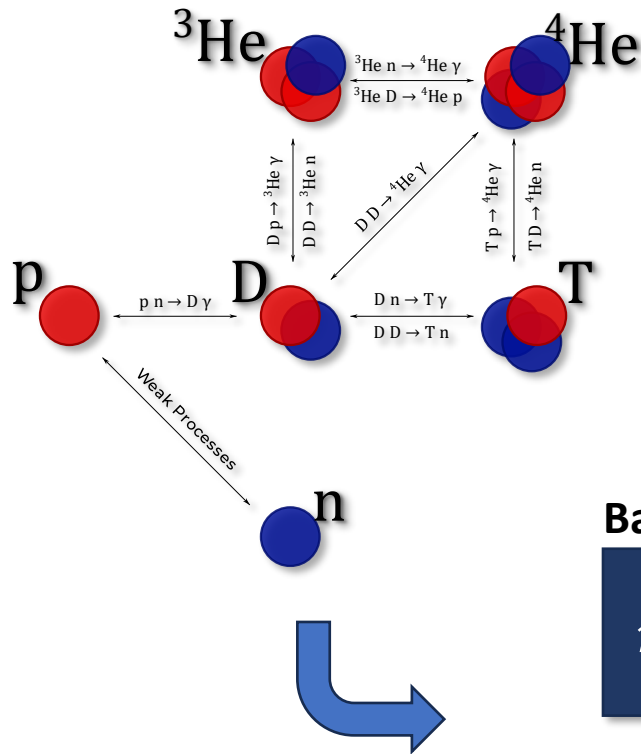
Speaker: **Alessandro Granelli**
Post-doc at University of
Bologna (Italy)



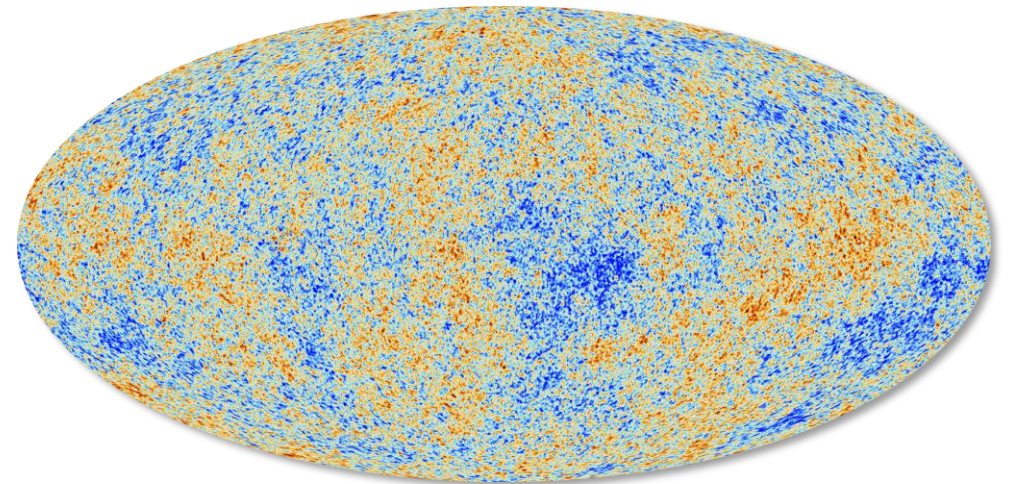
The Baryon Asymmetry of the Universe

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

Big Bang Nucleosynthesis (BBN)



Cosmic Microwave Background (CMB)



Baryon-to-photon ratio

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

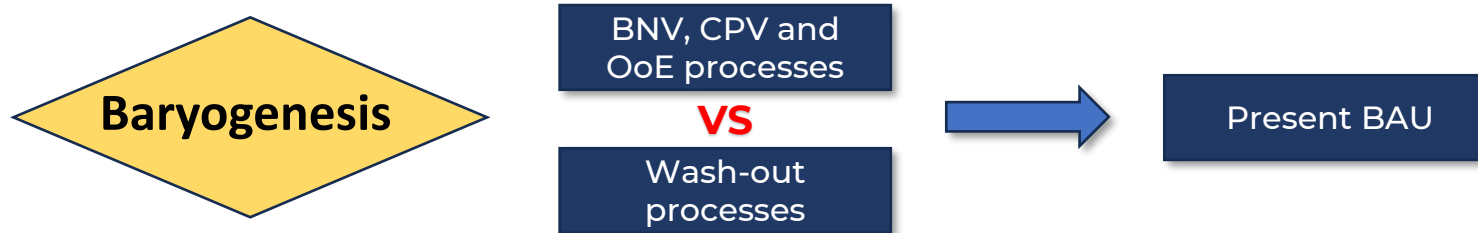
$\sim 2 \times 10^9 + 1$ baryons every 2×10^9 of antibaryons!

Sakharov's conditions and Baryo/Leptogenesis

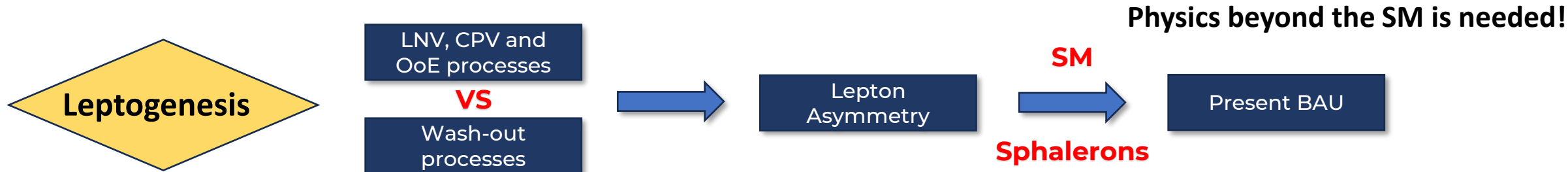
The three **Sakharov's conditions** for a dynamical generation of a baryon (B) or lepton (L) asymmetry:

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

A. D. Sakharov (1967)



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



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} (°, 3 σ)	δ (°, 3 σ)	Δm_{21}^2 (10 ⁻⁵ eV ²)	$\Delta m_{31(32)}^2$ (10 ⁻³ eV ²)
NO	33.67	8.58	39.9 – 51.1	139 – 350	7.41	2.505
IO	33.67	8.57	39.9 – 51.4	195 – 342	7.41	-2.487

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

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

Right-handed
neutrinos/sterile
neutrinos/ heavy
Majorana
neutrinos

Electroweak Symmetry Breaking

Neutrino mass generation



Neutrino mass matrix

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

Neutrino mixing

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

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

Mixing
angle/Coupling

Model Parameters



Casas-Ibarra Parameterisation

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

Casas-Ibarra matrix
 $OO^T = 1$

With 2 heavy Majorana neutrinos

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

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

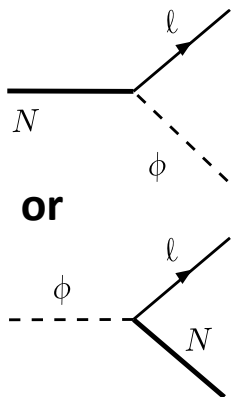
$$\theta = \omega + i \xi$$

$$\varphi = \pm 1$$

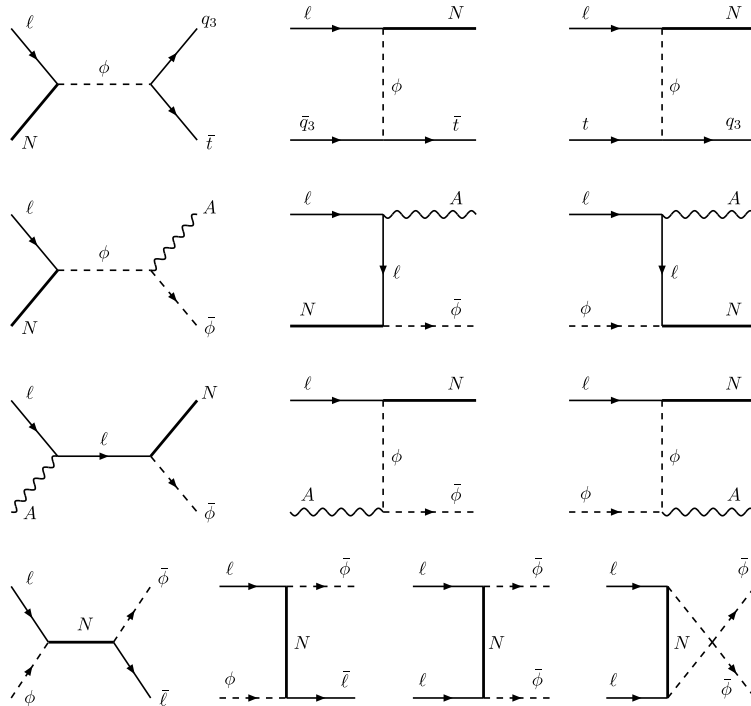
Leptogenesis within the type-I seesaw mechanism

Lepton Number violating processes via Yukawa coupling

Decays



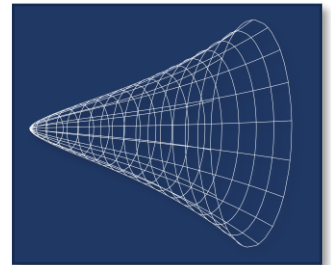
Scatterings



CP-violation

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

Expansion of the Universe



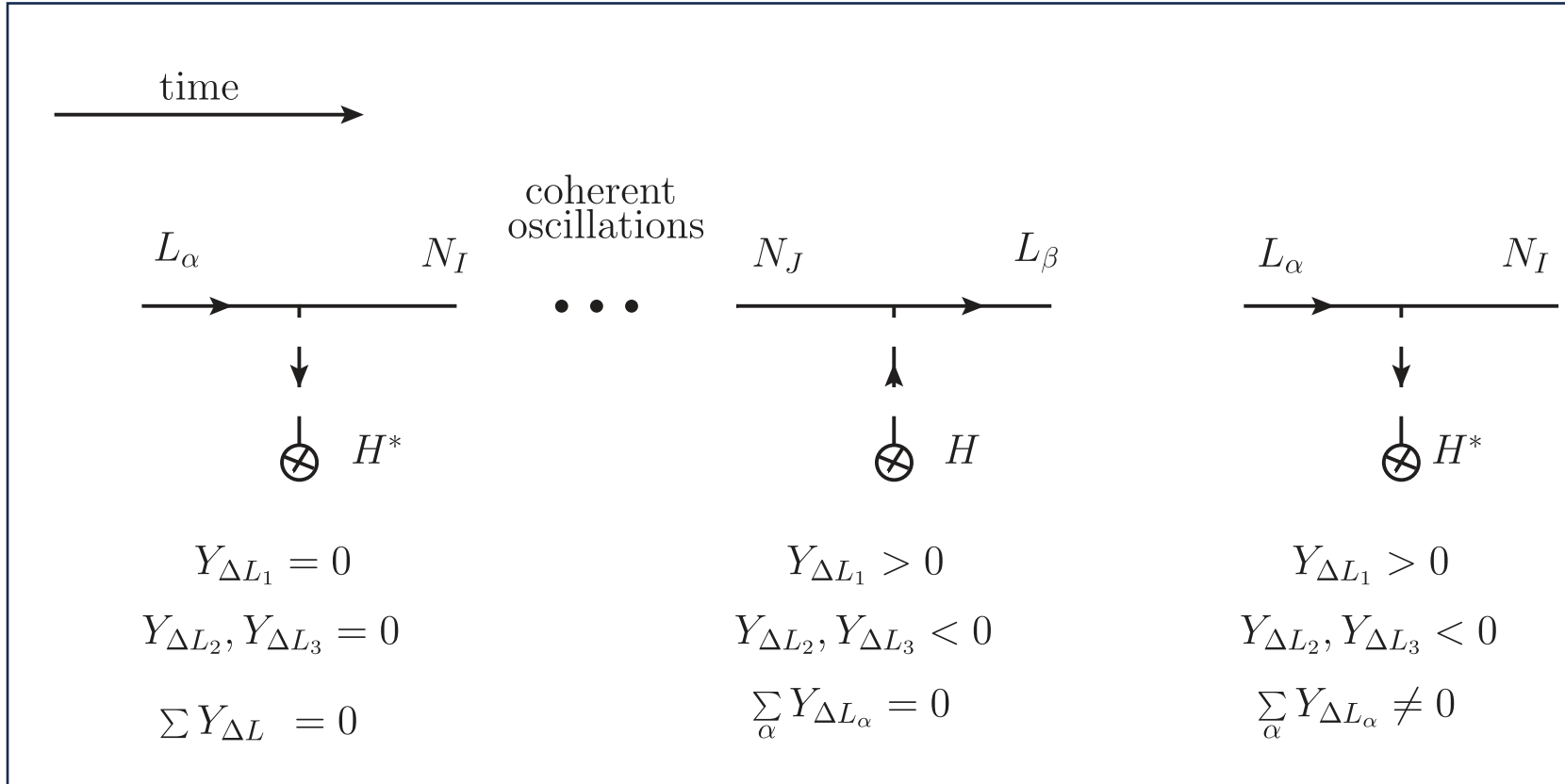
L. Covi, E. Roulet, F. Vissani
 hep-ph/9605319,
 W. Buchmuller, M. Plumacher
 hep-ph/9710460,
 A. Pilaftsis hep-ph/9702393,
 ...

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

Leptogenesis via oscillations

Leptogenesis via RHN oscillations

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



$T \sim 130 \text{ GeV}$



BAU

Sphaleron freeze-out

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

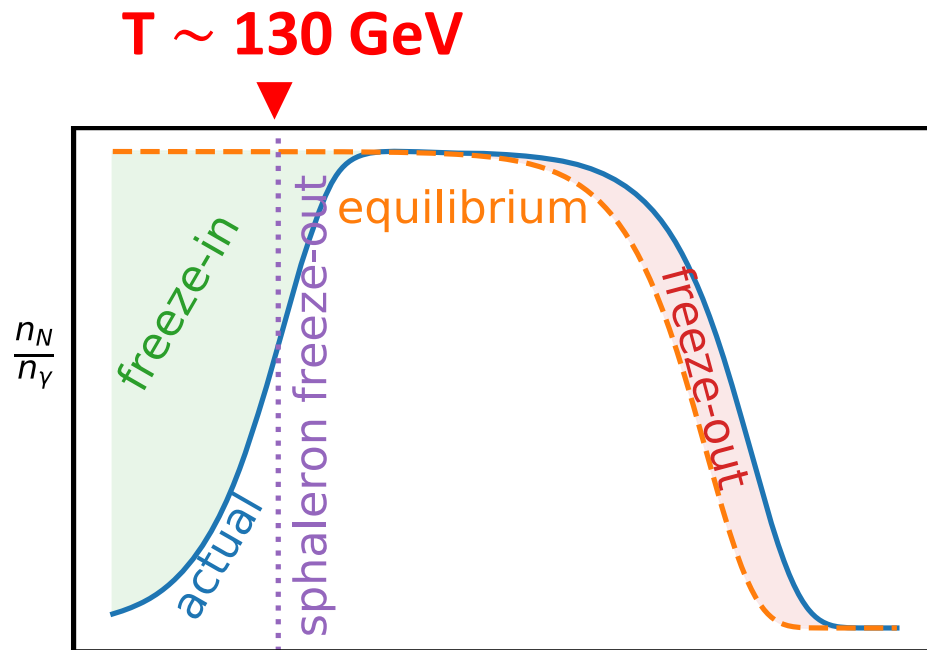
Leptogenesis within the type-I seesaw mechanism

Heavy neutrinos with either

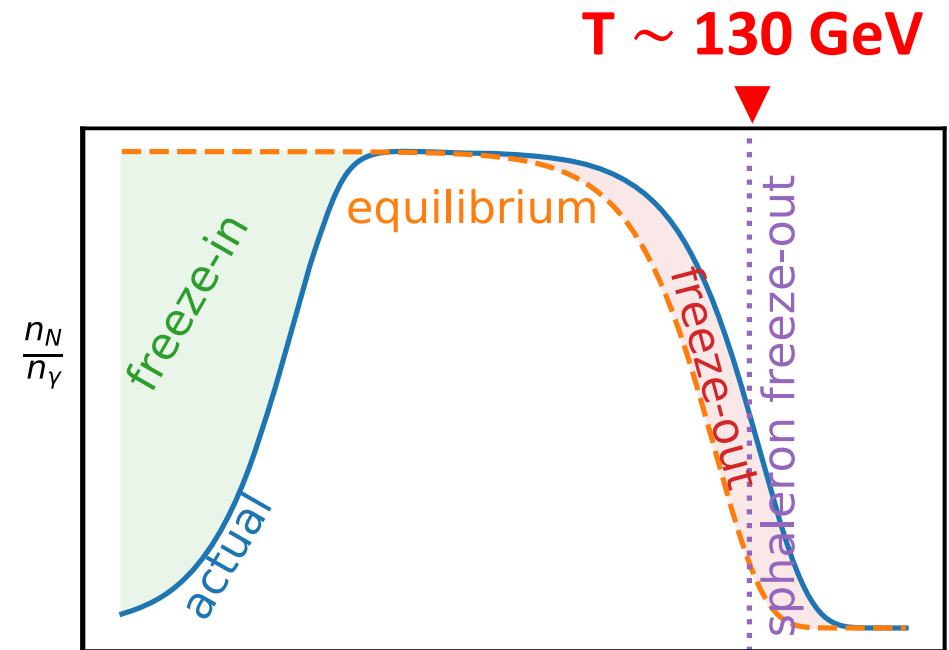
- **Thermal Initial Abundance (TIA);**
- **Vanishing Initial Abundance (VIA).**

BAU generation after sphaleron decouple either during production (**freeze-in**) or departure from equilibrium (**freeze-out**)

Freeze-in Leptogenesis

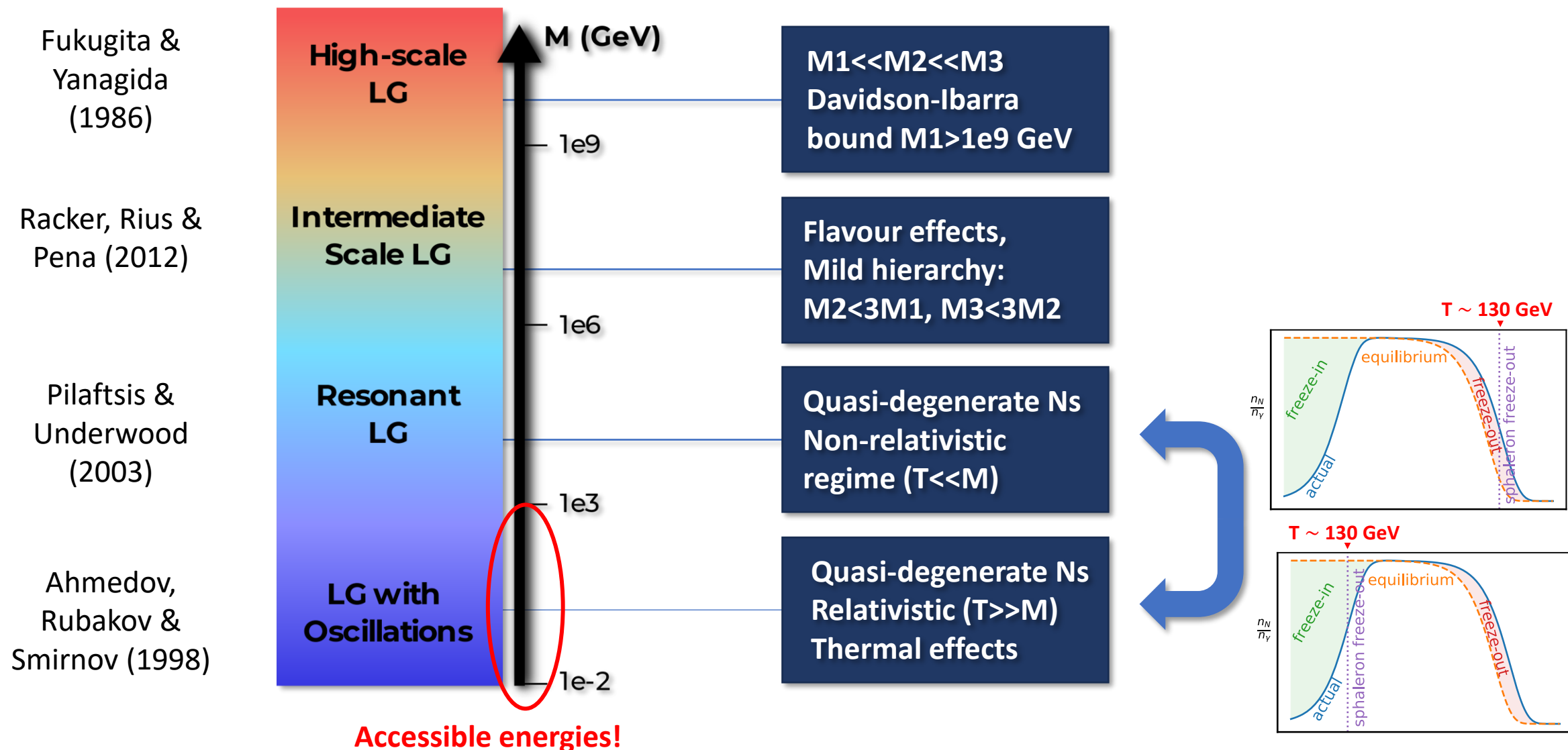


Freeze-out Leptogenesis



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



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

CP-violation in the Seesaw model

Casas-Ibarra Parameterisation

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

CP-violating phases in U and O!

CP-conservation implies : $Y_{\alpha j} = -iY_{\alpha j}^*\eta_j^{NCP}$



$$U_{a\alpha}^* = -iU_{a\alpha}\eta_a^{vCP} \text{ and } O_{aj} = -iO_{aj}^*\eta_j^{NCP}\eta_a^{vCP}$$

❖ Low-energy CP-violation: $O_{aj} = \pm O_{aj}^*$



The only CP-violating phases: **Dirac δ , Majorana α_{21}, α_{31}** .

CP-parities, $\pm i$

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

CPV in LG in connection with that on neutrino oscillations and $0\nu\beta\beta$ -decay

CP-conserving values:

$$\begin{aligned}\delta &= k\pi, \\ \alpha_{21} &= k_2\pi, \\ \alpha_{31} &= k_3\pi, \\ k, k_1, k_2 &= 0, 1, 2 \dots\end{aligned}$$

S. Pascoli, S. T. Petcov, A. Riotto hep-ph/0611338

Models with generalised CP-symmetry at high-energy:

e.g., P. Chen, G.-J. Ding, S. F. King arXiv:1402.03873

Large couplings are allowed!

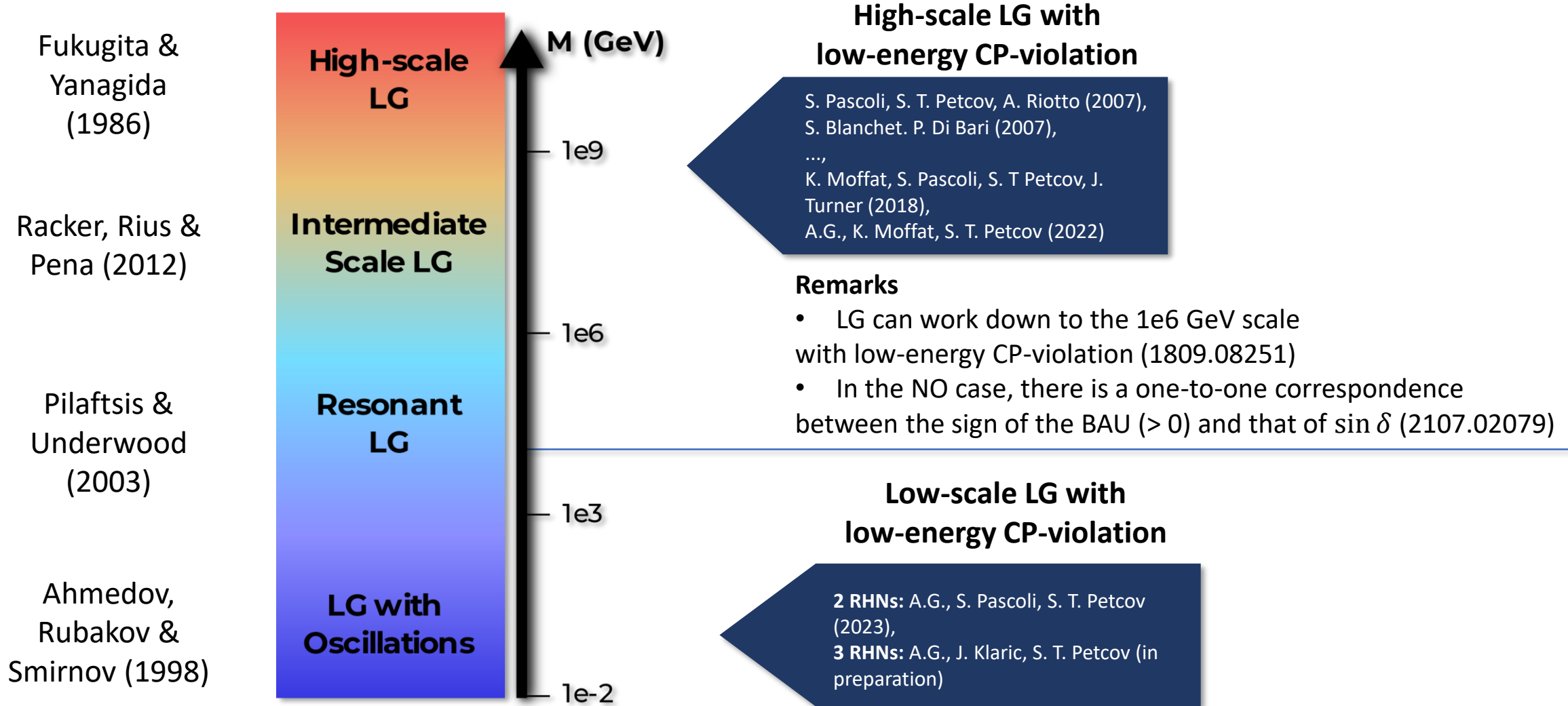
$$\text{E.g., } O^{(NH)} = \begin{pmatrix} 0 & \cosh \xi & \pm i \sinh \xi \\ 0 & -i \sinh \xi & \pm \cosh \xi \end{pmatrix}$$

Dirac CP-violation

The **Dirac phase** can be the **unique source of CP-violation** in the neutrino sector.

The Dirac phase alone can be responsible for the generation of the present **matter-antimatter asymmetry**.

Leptogenesis scales



Viable LG with 2 RHNs and Dirac CPV

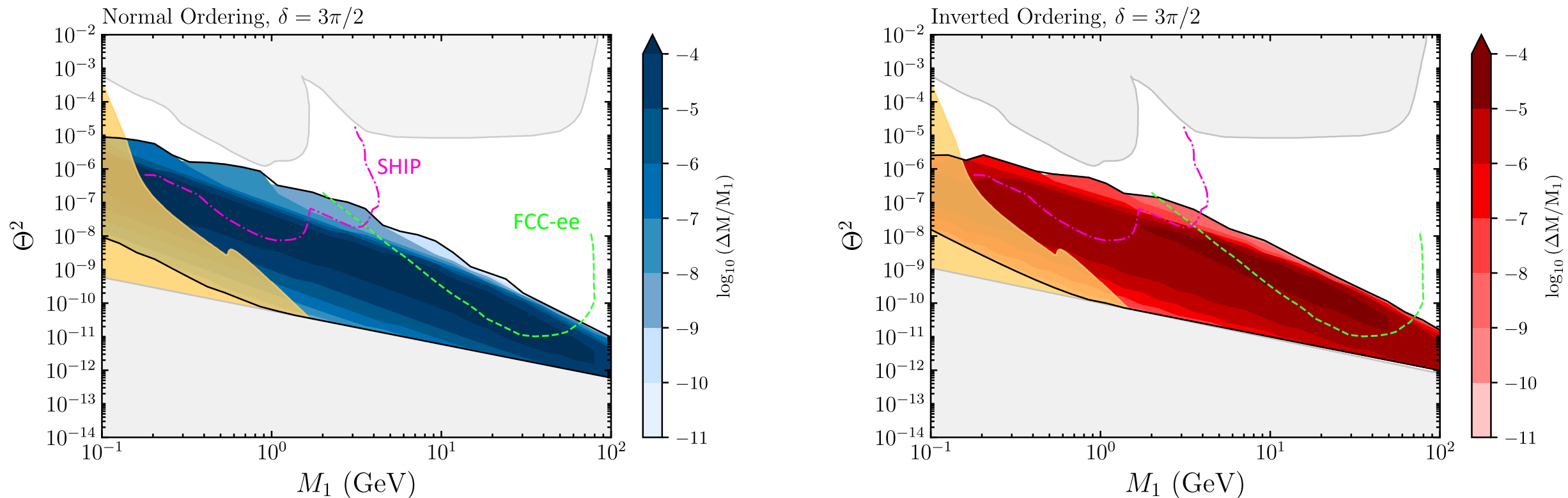
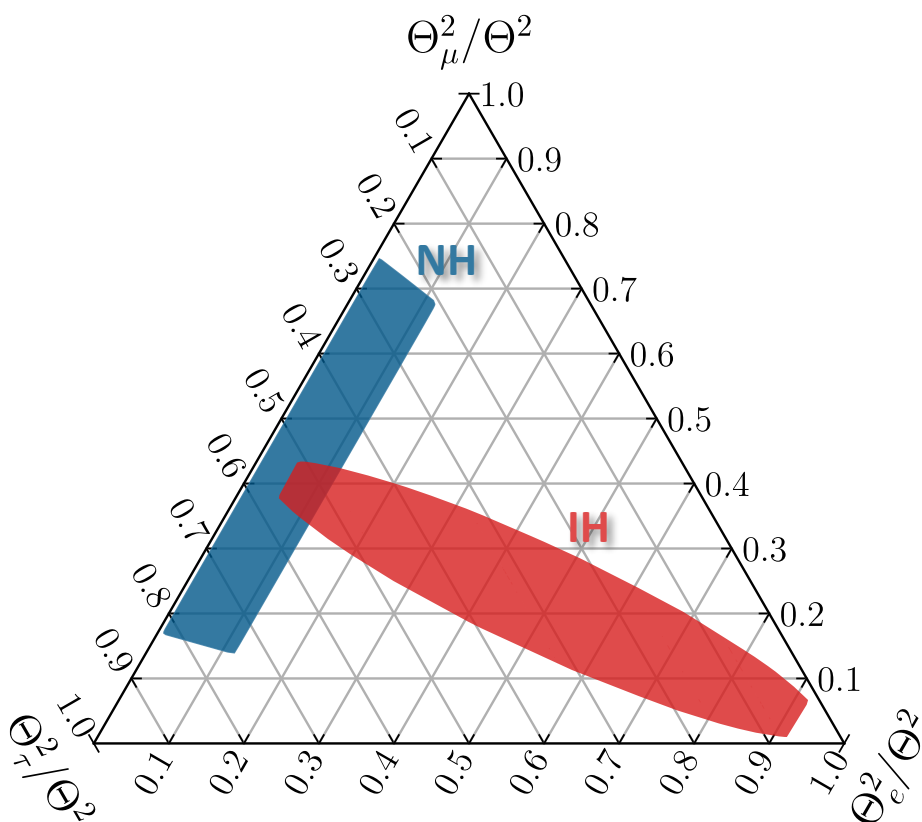


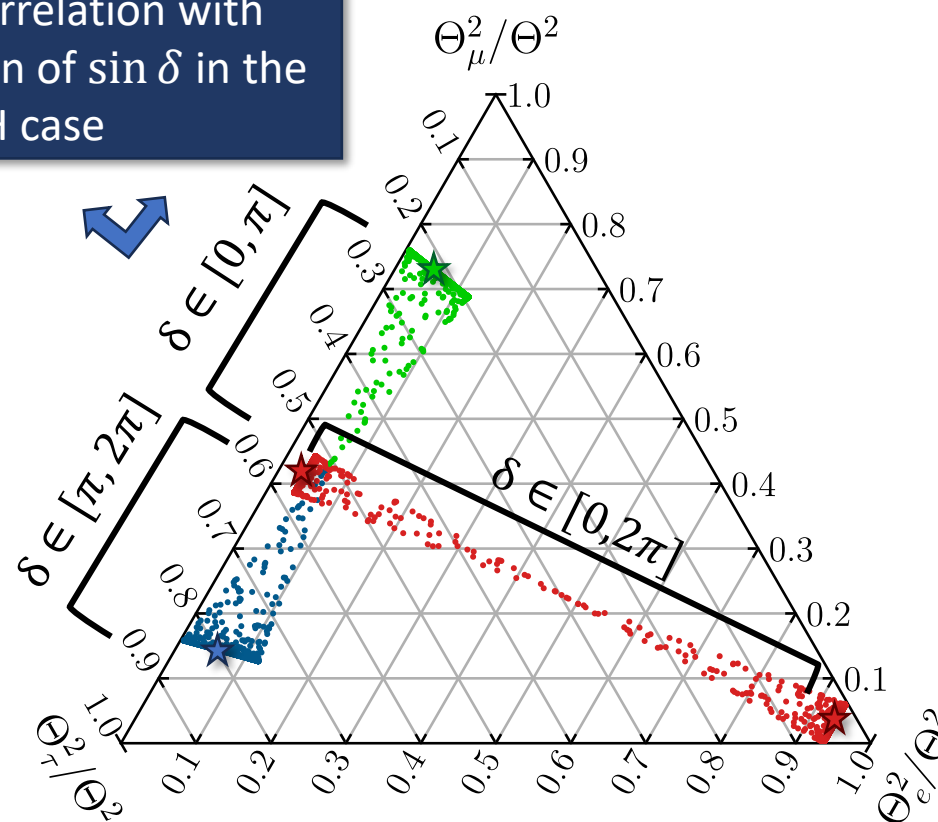
Fig. from A. G., S. Pascoli, S. T. Petcov, *Low-Scale LG with Low-Energy Dirac CPV*, arXiv:2307.07476.

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 $\xi > 1$, Θ^2 in the accessible region

A. G., S. Pascoli, S. T. Petcov arXiv:2307.07476.

LG with 3 RHNs is even more promising!

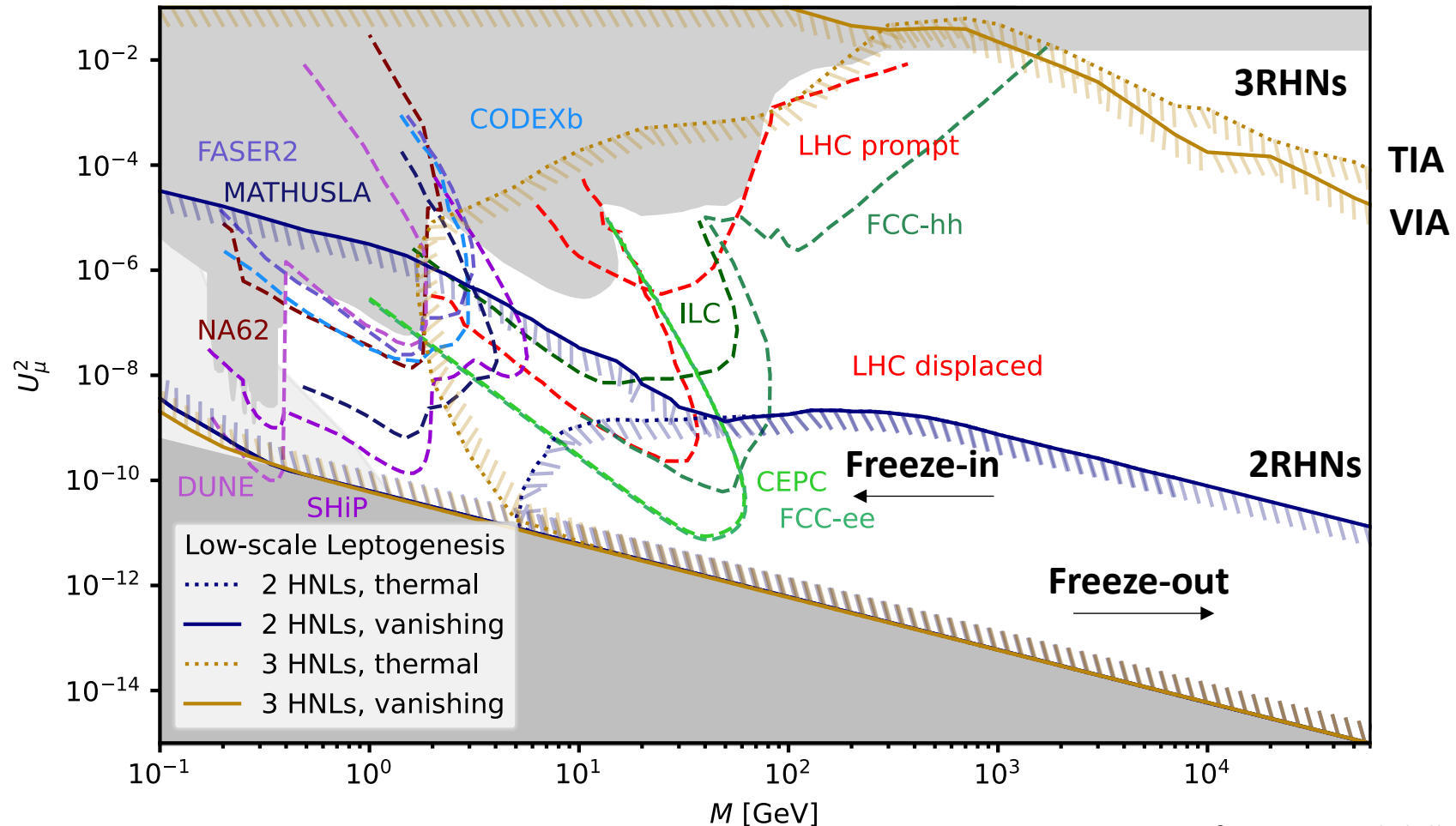
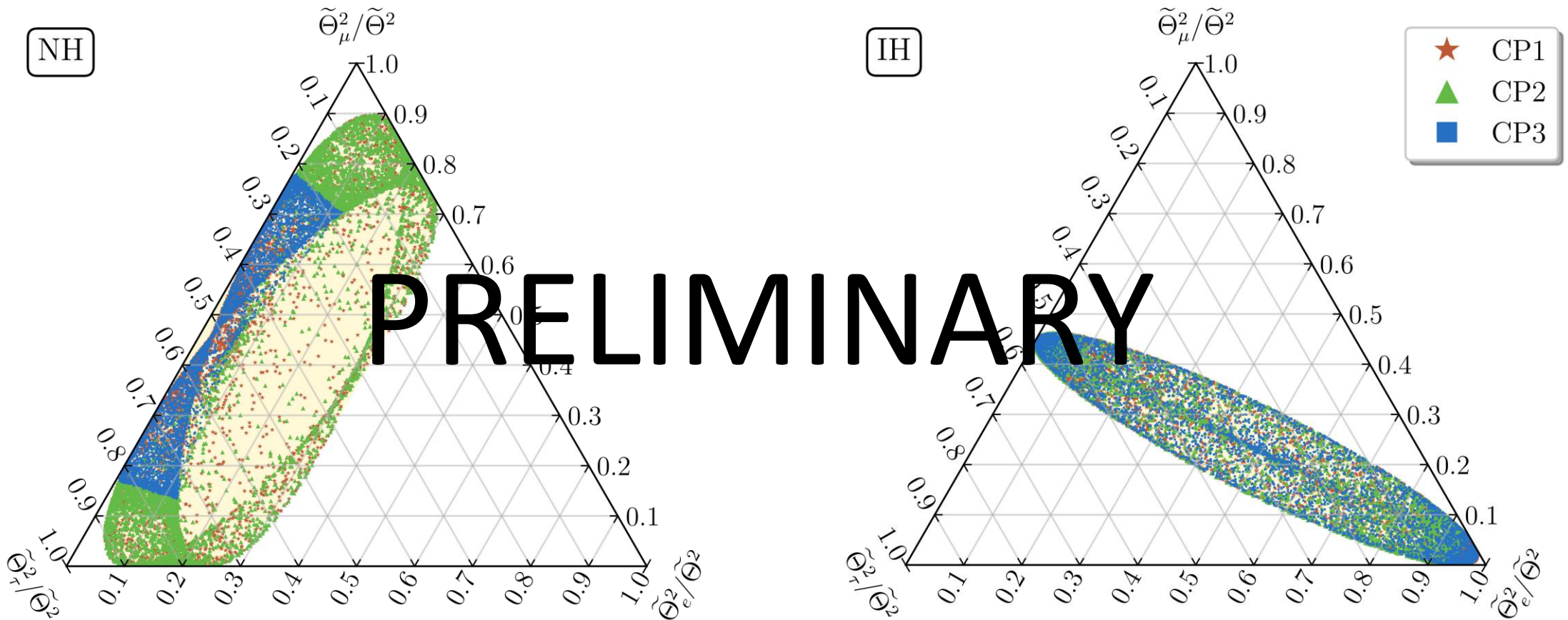


Fig. from A. M. Abdullahi et al., arXiv:2203.08039

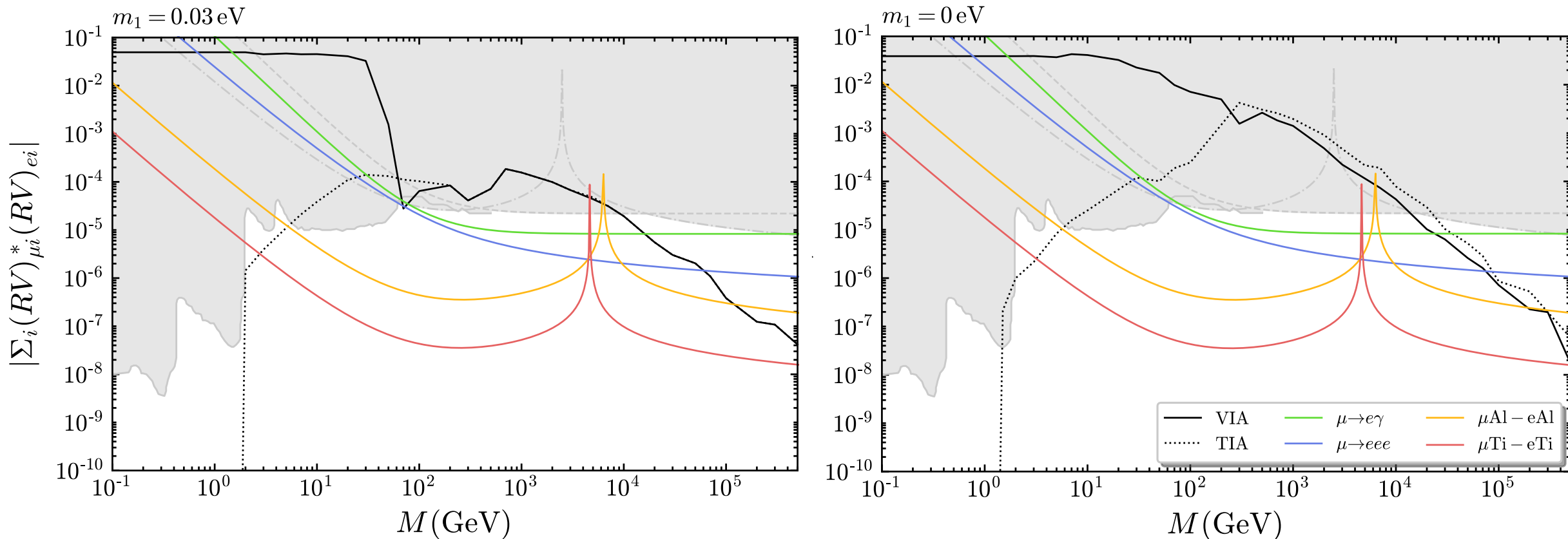
Flavour structure with low-energy CP-violation



Work in preparation, S. T. Petcov, J. Klarić, A. G.

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.



- A study on LG with 3RHNs and low-energy CP-violation is on its way (A.G., J. Klarić, S. T. Petcov, in preparation)!

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

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 $\mu \rightarrow e \gamma$ decay, Mu3e on $\mu \rightarrow e e e$ 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 with 2 RHNs**; a **future measurements of the CP-violation in neutrino oscillations would be in favour of low-scale LG**. The case with 3RHNs is even more promising, a study with low-energy CPV is in preparation (A.G., J. Klarić, S. T. Petcov, in preparation)

Thanks for your attention!

Back-up slides

Density Matrix Equations

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

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

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

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

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

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

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