Low-scale Leptogenesis with Low-energy CP-Violation

NOW 2024
Neutrino Oscillation Workshop

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INFN

Theory and Phenomenology of Fundamental Interactions
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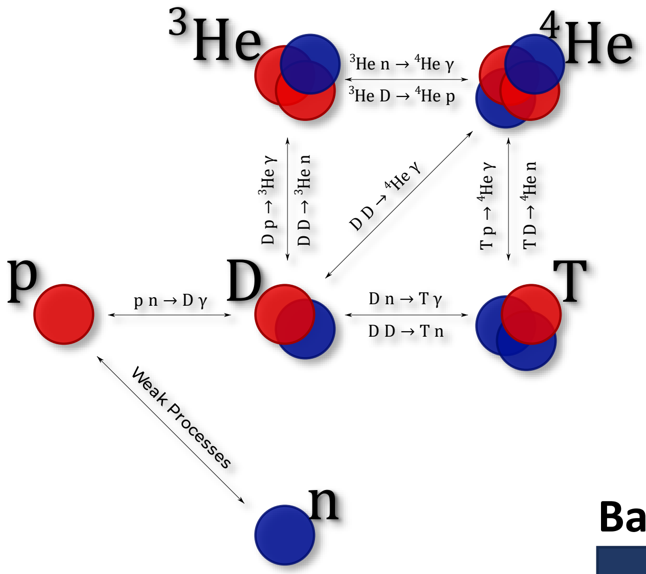
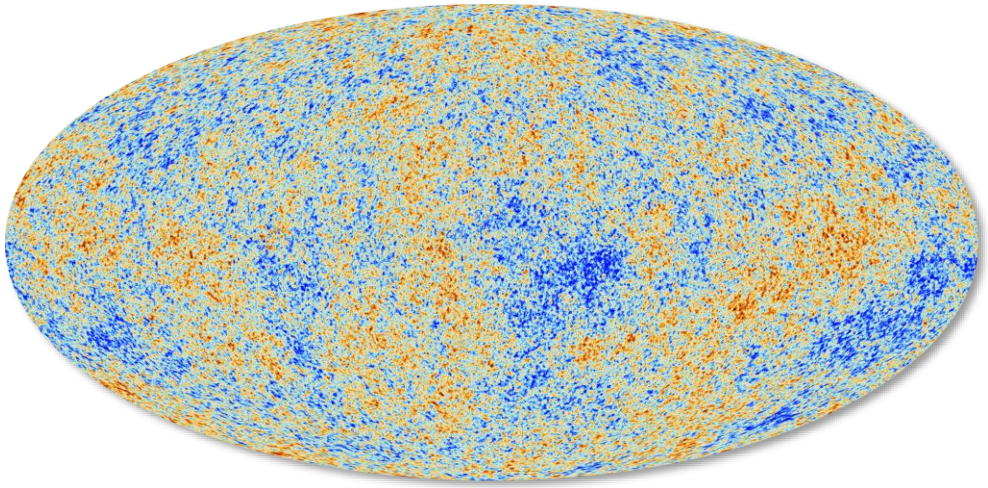
The Baryon Asymmetry of the Universe

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

Big Bang Nucleosynthesis (BBN)



Cosmic Microwave Background (CMB)



Baryon-to-photon ratio

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

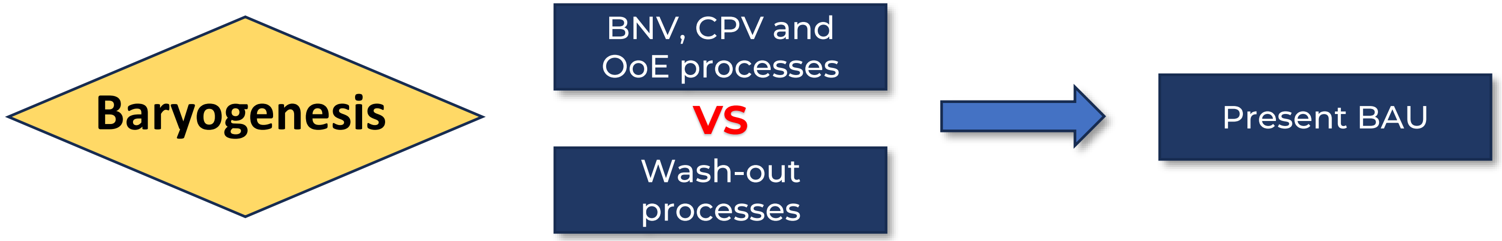
$\sim 2 \times 10^9 + 1$ baryons every 2×10^9 of antibaryons!

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)



Baryogenesis

BNV, CPV and OoE processes

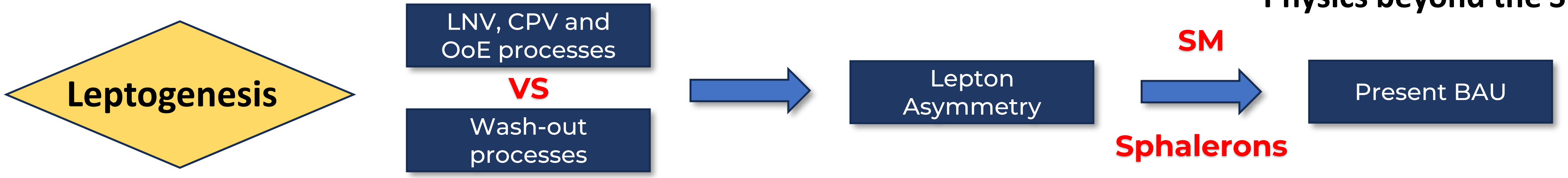
VS

Wash-out processes

Present BAU

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

Physics beyond the SM is needed!



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

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

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_{21}^2 ($10^{-5}\mathrm{eV}^2$)	$\Delta m_{31(32)}^2$ ($10^{-3}\mathrm{eV}^2$)
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

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

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

$$\boldsymbol{OO^T = 1}$$

With 2 heavy Majorana neutrinos

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

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

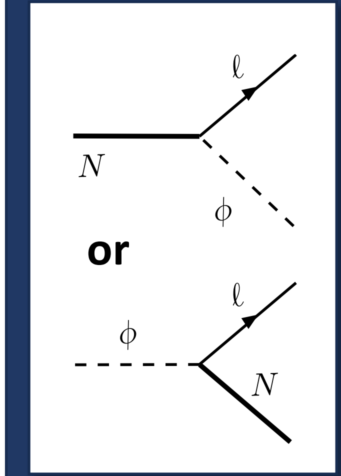
$\theta = \omega + i\,\xi$

$\varphi = \pm 1$

Leptogenesis within the type-I seesaw mechanism

Lepton Number violating processes via Yukawa coupling

Decays



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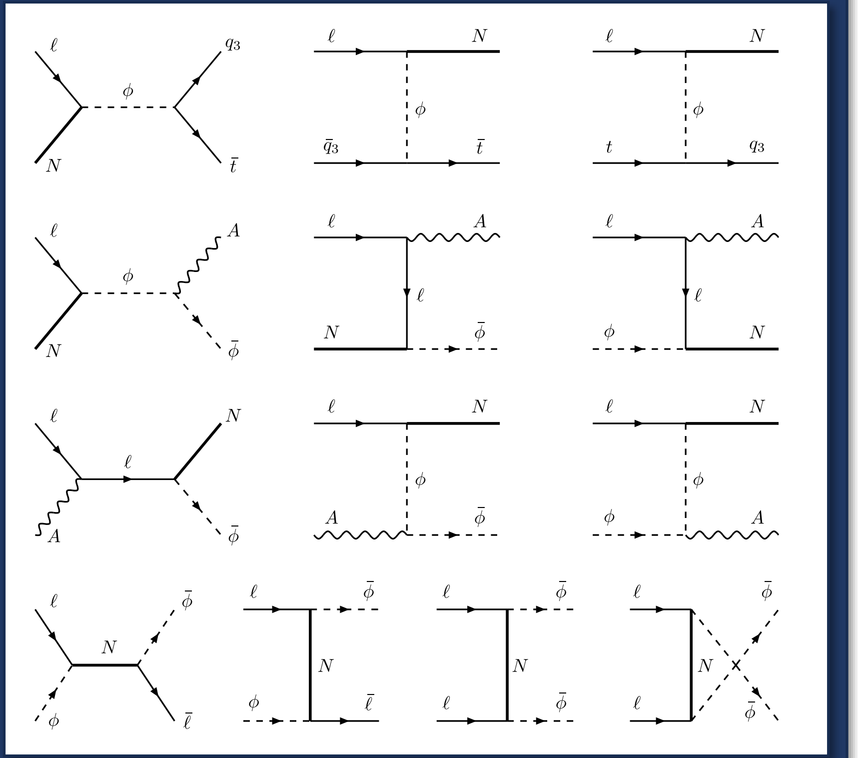
Scatterings



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

+

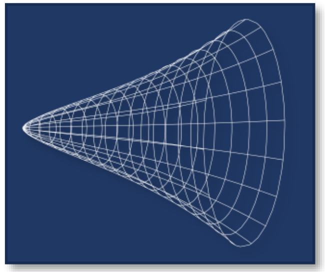
CP-violation

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

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

+

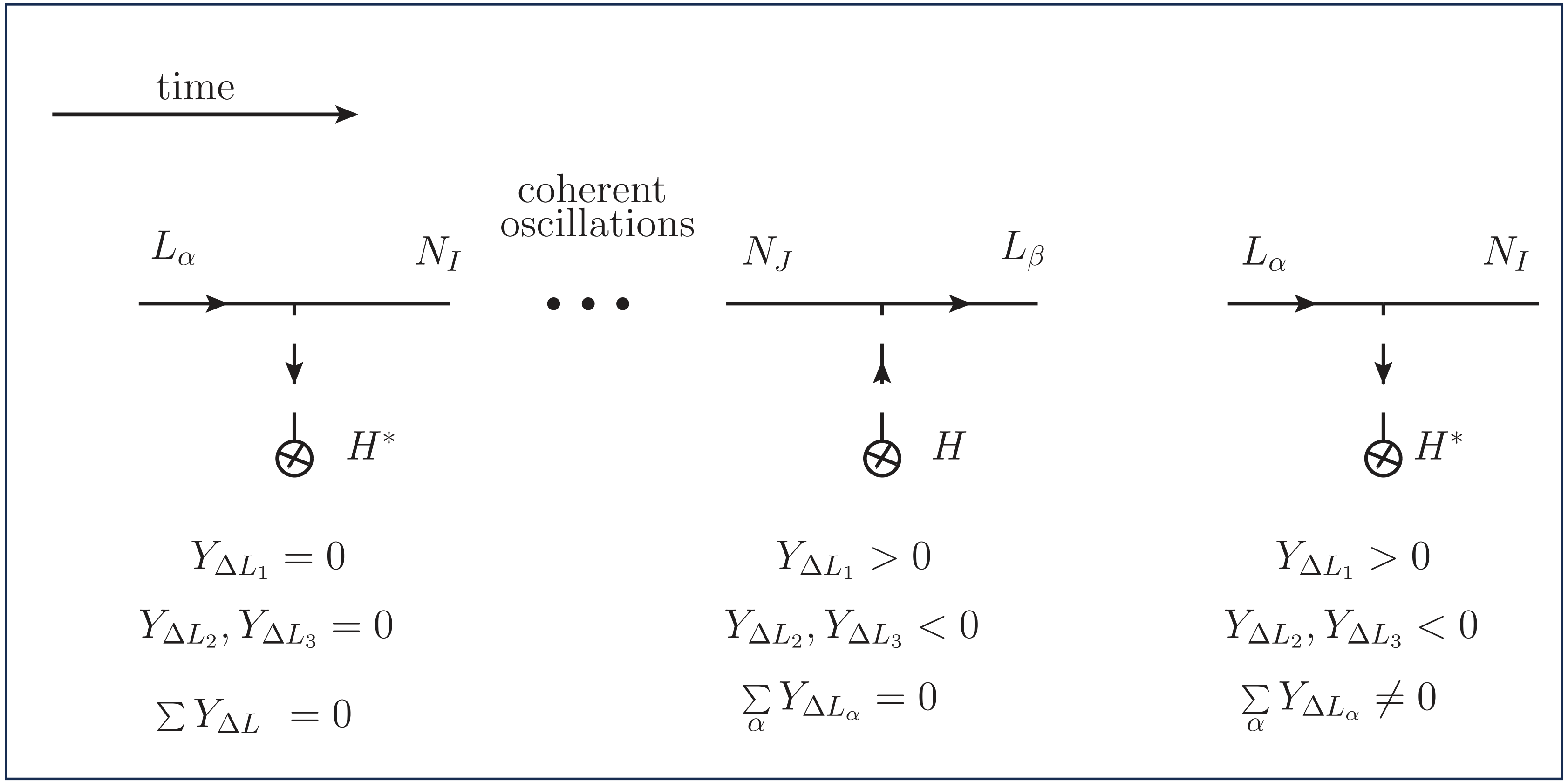
Expansion of the Universe

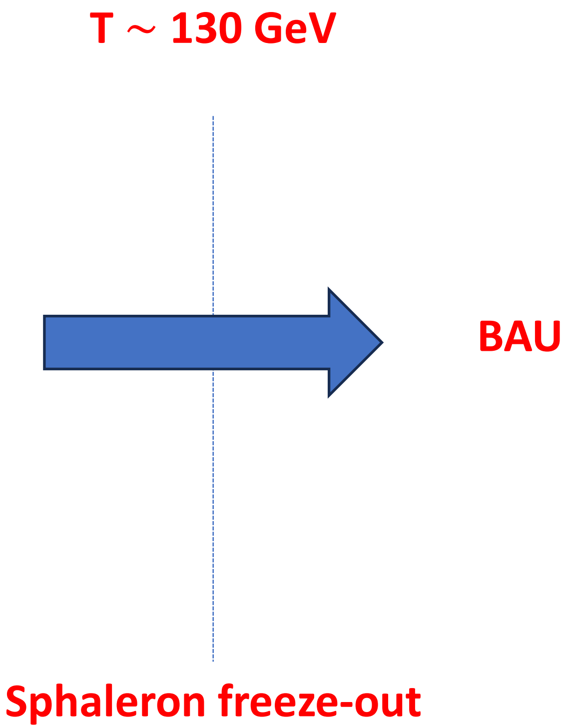


Leptogenesis via oscillations

Leptogenesis via RHN oscillations

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





T ~ 130 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

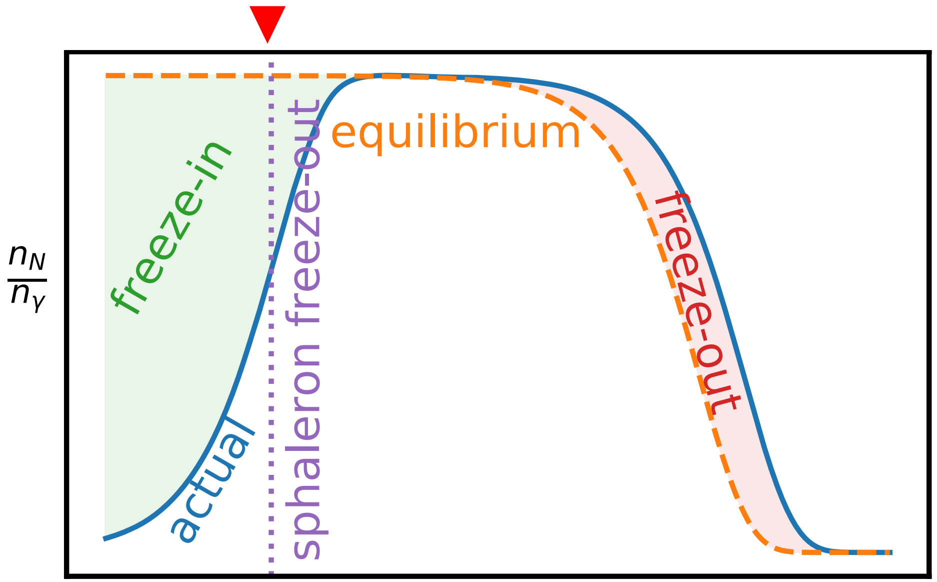
Heavy neutrinos with either

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

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

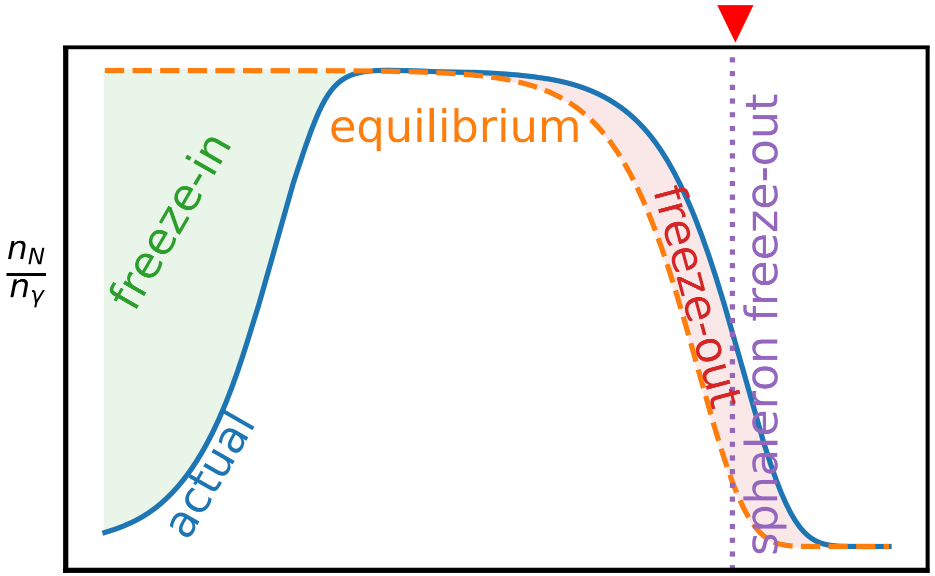
Freeze-in Leptogenesis

T ~ 130 GeV



Freeze-out Leptogenesis

T ~ 130 GeV



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

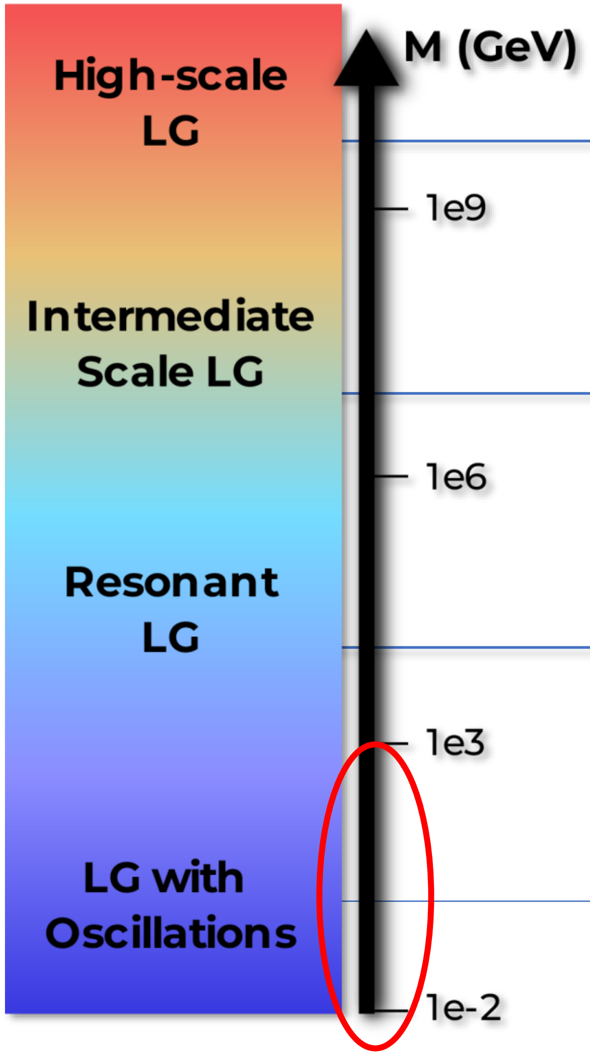
Leptogenesis scales

Fukugita & Yanagida (1986)

Racker, Rius & Pena (2012)

Pilaftsis & Underwood (2003)

Ahmedov, Rubakov & Smirnov (1998)



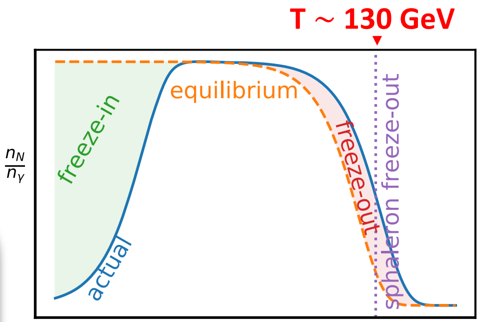
Accessible energies!

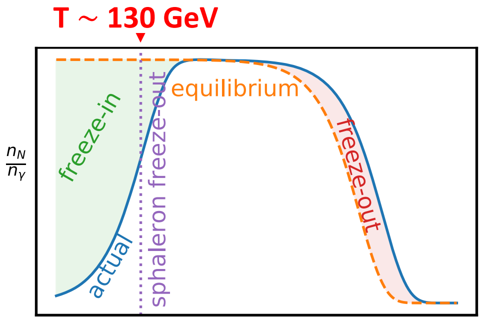
M1<<M2<<M3
Davidson-Ibarra bound M1>1e9 GeV

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

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

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





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

CP-violation in the Seesaw model

Casas-Ibarra Parameterisation

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

CP-violating phases in U and O!

CP-parities, $\pm i$

CP-conservation implies : $\mathrm{Y}_{\alpha j} = -i\mathrm{Y}^{*}_{\alpha j}\eta_{j}^{NCP}$ ⟹ $\mathrm{U}^{*}_{\alpha a} = -i\mathrm{U}_{\alpha a}\eta_{a}^{\upsilon\mathrm{CP}}$ and $\mathrm{O}_{aj} = -i\mathrm{O}^{*}_{aj}\eta_{j}^{NCP}\eta_{a}^{\upsilon\mathrm{CP}}$

- **Low-energy CP-violation:** $\mathrm{O}_{aj} = \pm\mathrm{O}^{*}_{aj}$ ⟹ The only CP-violating phases: **Dirac $\boldsymbol{\delta}$, Majorana $\boldsymbol{\alpha_{21}}$, $\boldsymbol{\alpha_{31}}$.**

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 0νββ-decay

CP-conserving values:
$\boldsymbol{\delta = k\pi}$,
$\boldsymbol{\alpha_{21} = k_2\pi}$,
$\boldsymbol{\alpha_{31} = k_3\pi}$,
$\boldsymbol{k, k_1, k_2 = 0, 1, 2 \ldots}$

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!

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

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.**

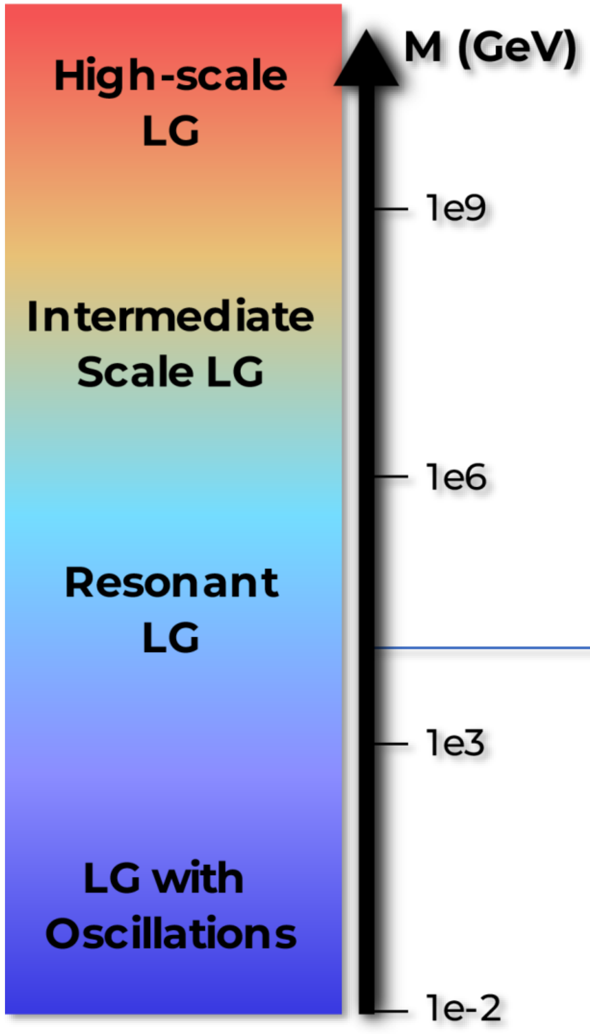
Leptogenesis scales

Fukugita & Yanagida (1986)

Racker, Rius & Pena (2012)

Pilaftsis & Underwood (2003)

Ahmedov, Rubakov & Smirnov (1998)



High-scale LG with 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)

Remarks

- LG can work down to the 1e6 GeV scale with low-energy CP-violation (1809.08251)
- In the NO case, there is a one-to-one correspondence between the sign of the BAU (> 0) and that of $\sin\delta$ (2107.02079)

Low-scale LG with low-energy CP-violation

2 RHNs: A.G., S. Pascoli, S. T. Petcov (2023),
3 RHNs: A.G., J. Klaric, S. T. Petcov (in preparation)

Parameter space of viable LG

Viable LG with 2 RHNs and Dirac CPV

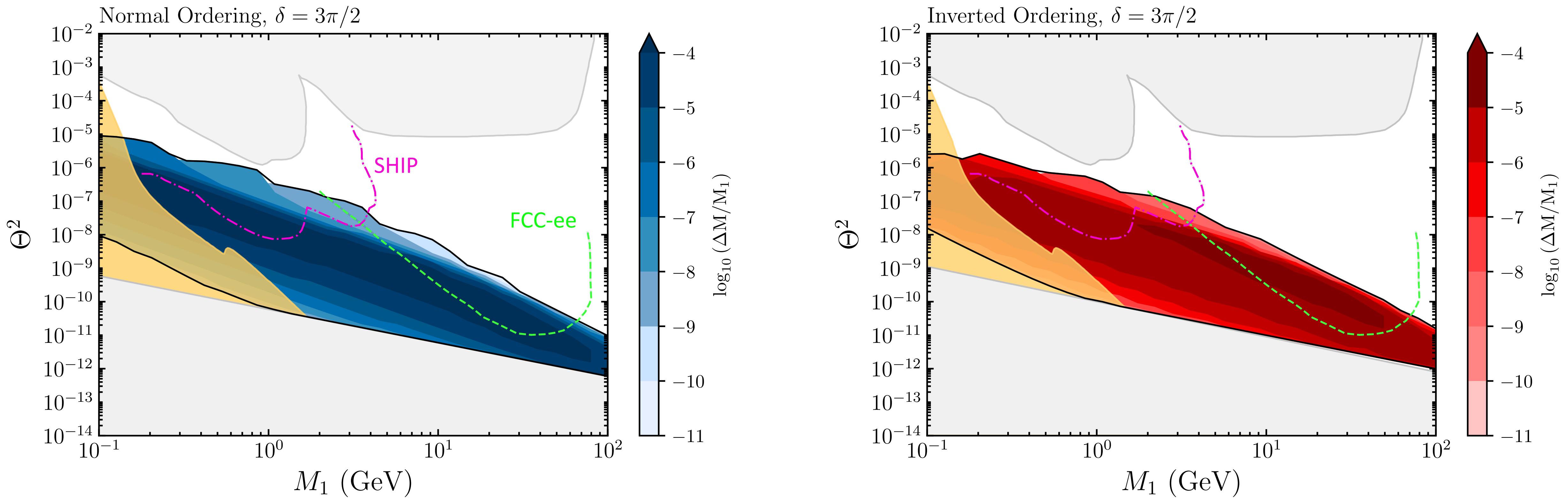
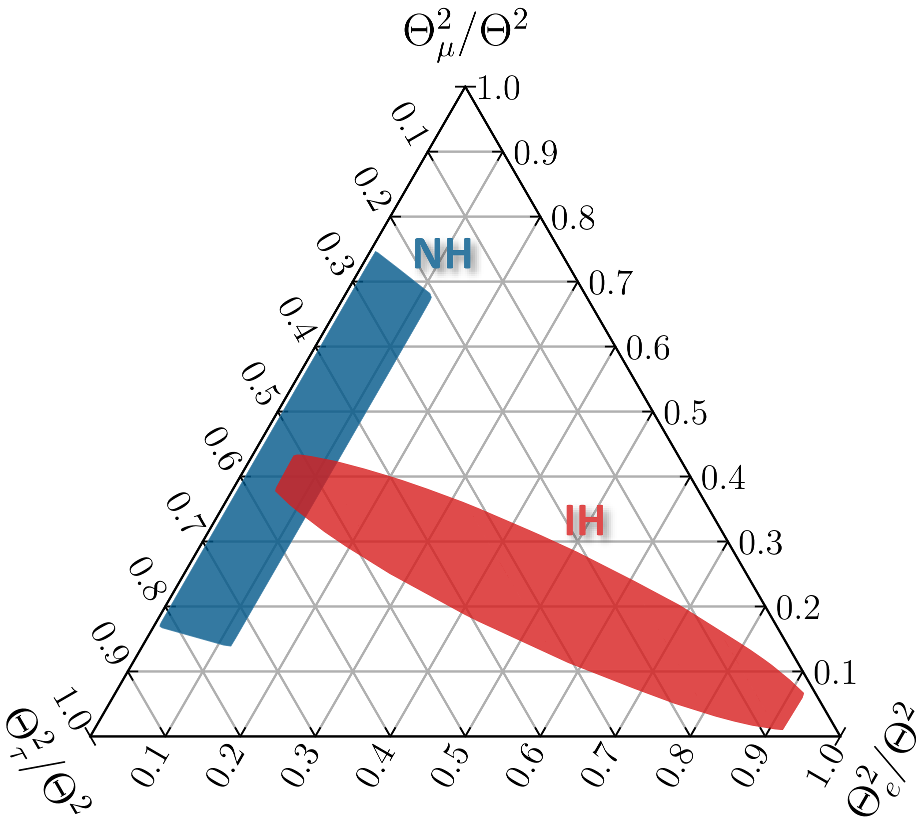
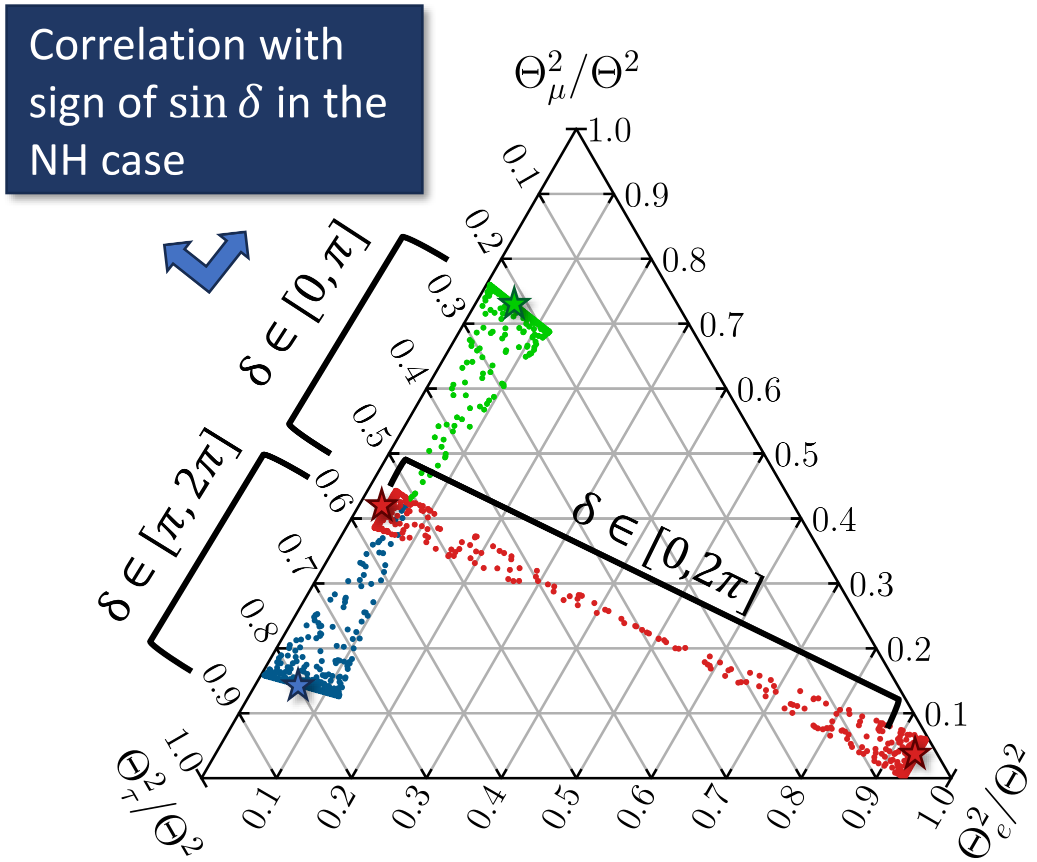


Fig. from A. G., S. Pascoli, S. T. Petcov, *Low-Scale LG with Low-Energy Dirac CPV,* arXiv:2307.07476.

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^2in the accessible region

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

Parameter Space of low-scale LG with 3RHNs

LG with 3 RHNs is even more promising!

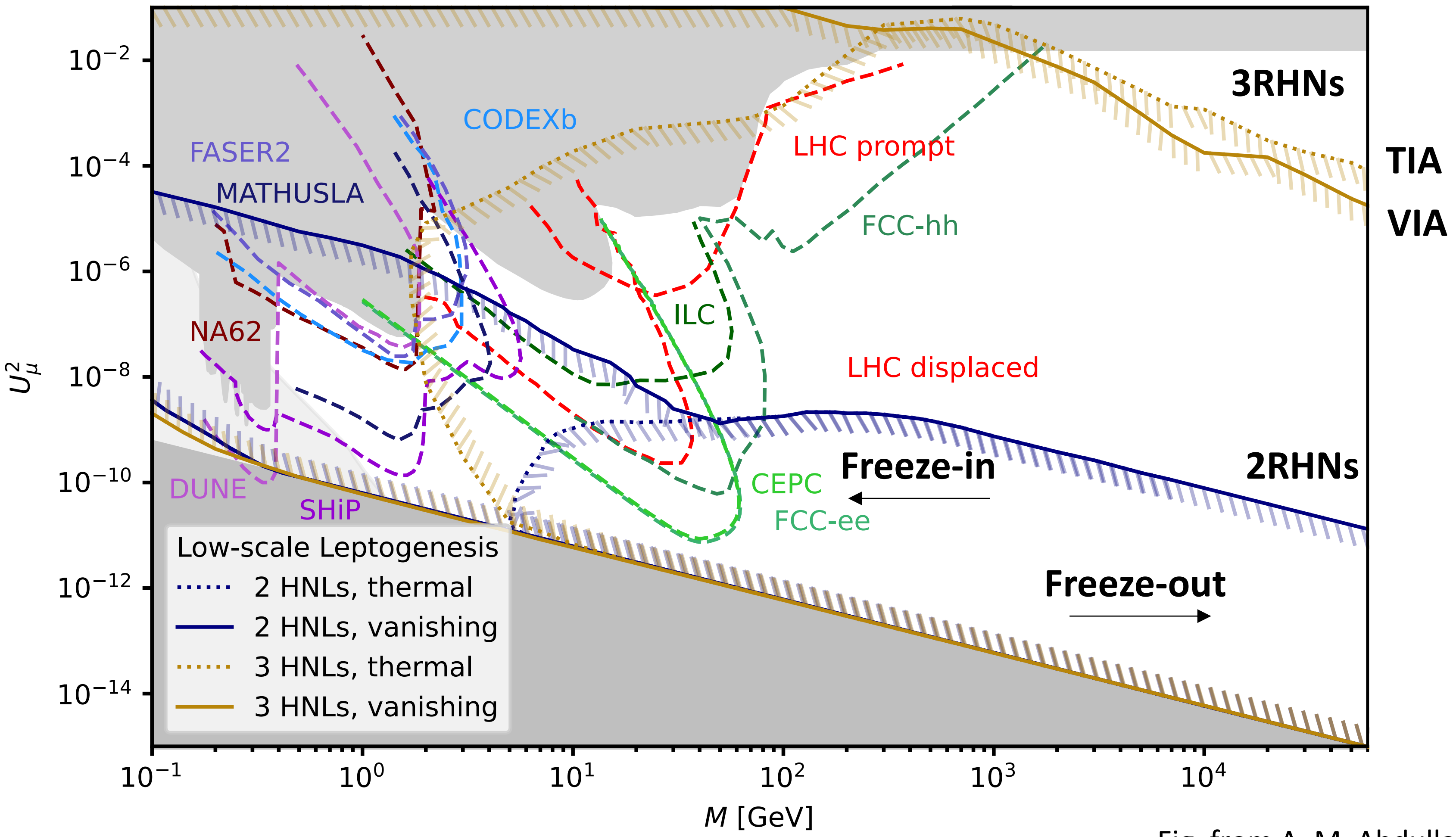
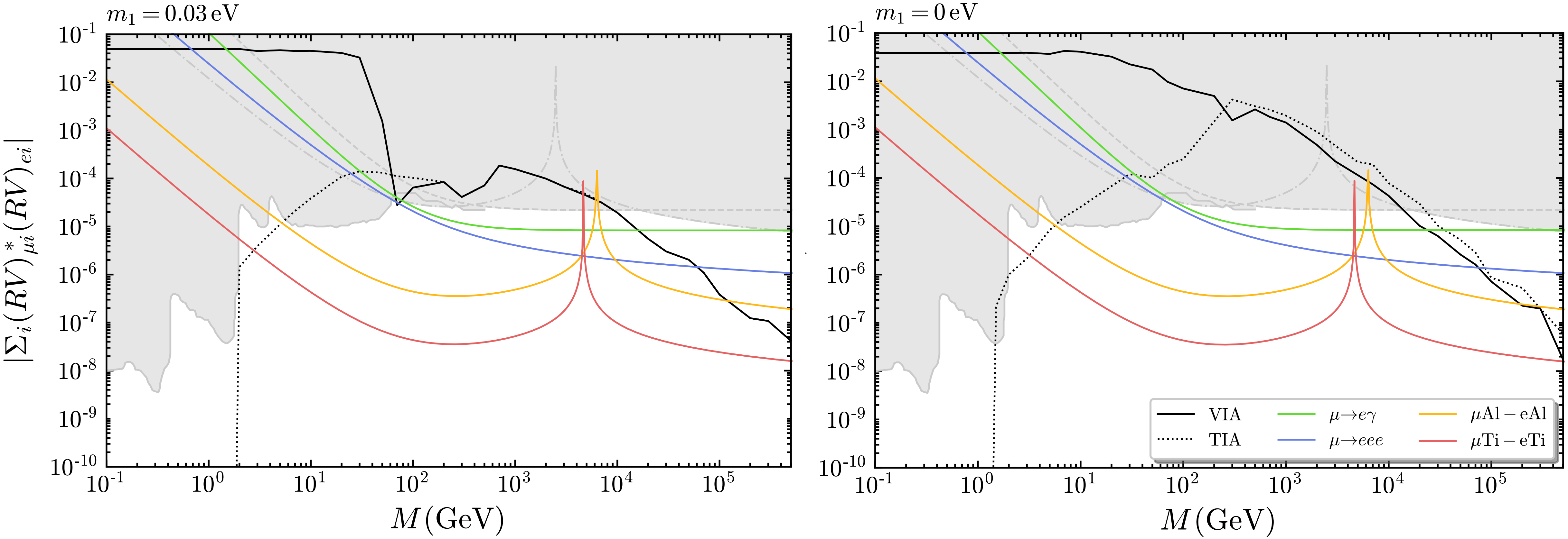


Fig. from A. M. Abdullahi et al., arXiv:2203.08039

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.



- 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 μ→eγ decay, Mu3e on μ→eee decay, Mu2e and COMET (PRISM/PRIME) on μ−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

$$\begin{aligned}
Hx\frac{dr_N}{dx} &= -\,i\left[\langle\mathcal{H}\rangle, r_N\right] - Hx\frac{r_N}{N_N^{\rm eq}}\frac{dN_N^{\rm eq}}{dx} - \frac{\langle\gamma_N^{(0)}\rangle}{2}\left\{Y^\dagger Y, r_N - 1\right\} + \langle\gamma_N^{(1)}\rangle Y^\dagger\mu Y - \frac{\langle\gamma_N^{(2)}\rangle}{2}\left\{Y^\dagger\mu Y, r_N\right\} + \\
&\quad - \frac{\langle S_N^{(0)}\rangle}{2T^2}\left\{MY^{\rm T}Y^* M, r_N - 1\right\} - \frac{\langle S_N^{(1)}\rangle}{T^2} MY^{\rm T}\mu Y^* M + \frac{\langle S_N^{(2)}\rangle}{2T^2}\left\{MY^{\rm T}\mu Y^* M, r_N\right\},
\end{aligned}$$

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

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

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