Nikhef

Radboud Universiteit

BARYOGENESIS

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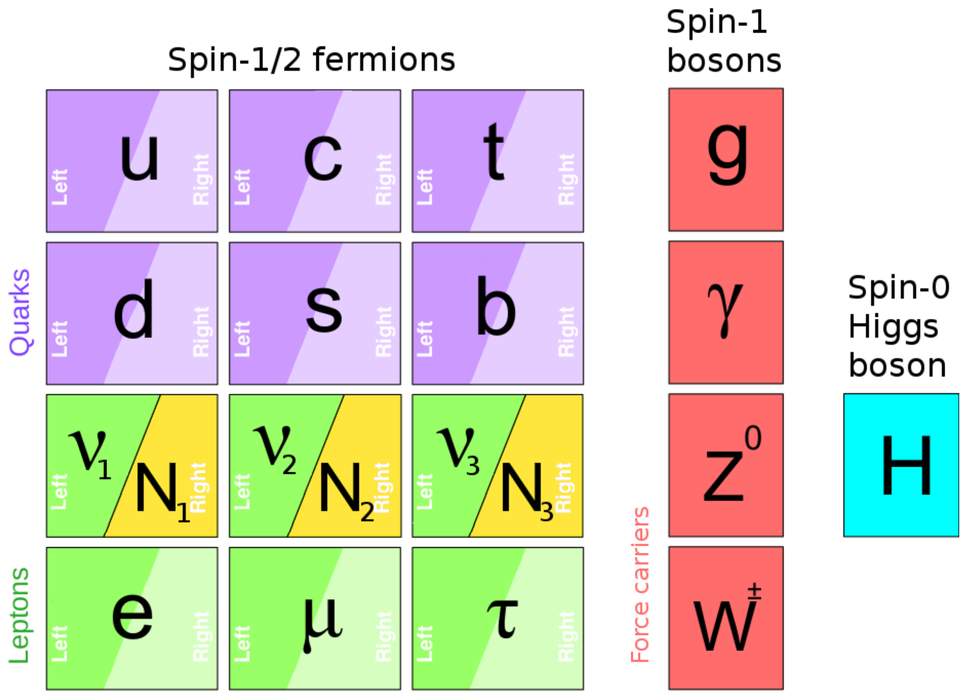
DRSTP June 2023

RIGHT-HANDED NEUTRINOS



$$Y_b = \frac{n_b - n_{\bar{b}}}{s} \sim 10^{-10}$$

- neutrino mass
- **leptogenesis**
- dark matter

PLAN

1. vanilla leptogenesis
2. low scale leptogenesis

NEUTRINO MASS

$$\mathcal{L} \supset -\bar{l}_L Y_\nu \tilde{H}\, \nu_R - \tfrac{1}{2} m_R \overline{\nu_R^c} \nu_R + \text{h.c.}$$

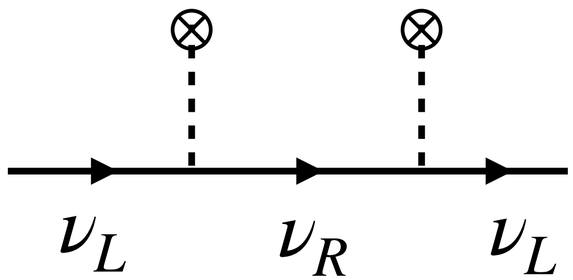
Dirac mass

Majorana mass

$$M = \begin{pmatrix} 0 & m_D \\ m_D^T & m_R \end{pmatrix}$$

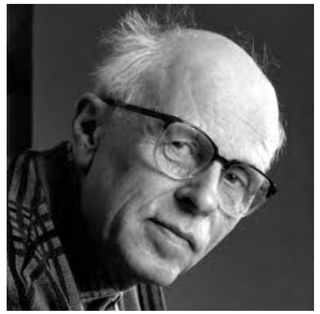
see saw mechanism

$m_\eta =$



$$= -m_D \frac{1}{m_R} m_D^T = -\theta m_R \theta^T \qquad \theta = m_D / m_R$$

SAKHAROV CONDITIONS



Sakharov 1976

$$\mathcal{L} \supset -\bar{l}_L Y_\nu \tilde{H}\, \nu_R - \tfrac{1}{2} m_R \overline{\nu_R^c} \nu_R + \text{h.c.}$$

2) CP violation

1) lepton number violation $\Delta L = 2$

3) out of equilibrium production/decay of $N \approx \nu_R + \nu_R^c$

1) LEPTON NUMBER VIOLATION

sphalerons

$$(B-L)_f = (B-L)_i$$

$$(B+L)_f \sim 0$$

$$\Rightarrow \quad \boxed{B_f \sim -0.5 L_i}$$

2) CP VIOLATION

vanilla scenario $M_1 \ll M_2, M_3$

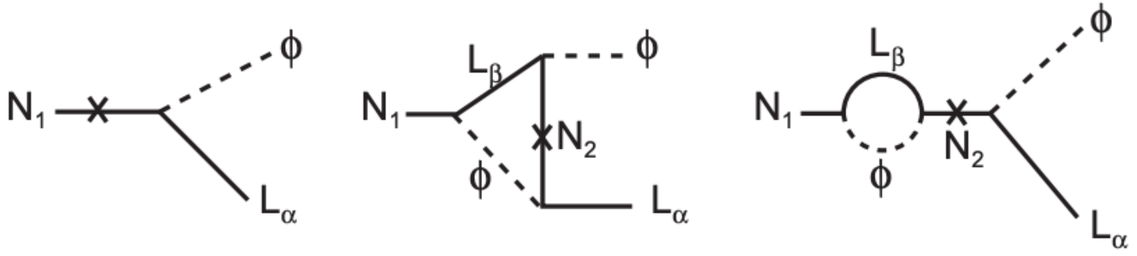
Fukugita and Yanagida 1986

$$\mathcal{L} \supset -\bar{l}_L Y_\nu \tilde{H}\, \nu_R - \tfrac{1}{2} m_R \overline{\nu_R^c} \nu_R + \text{h.c.}$$

phases

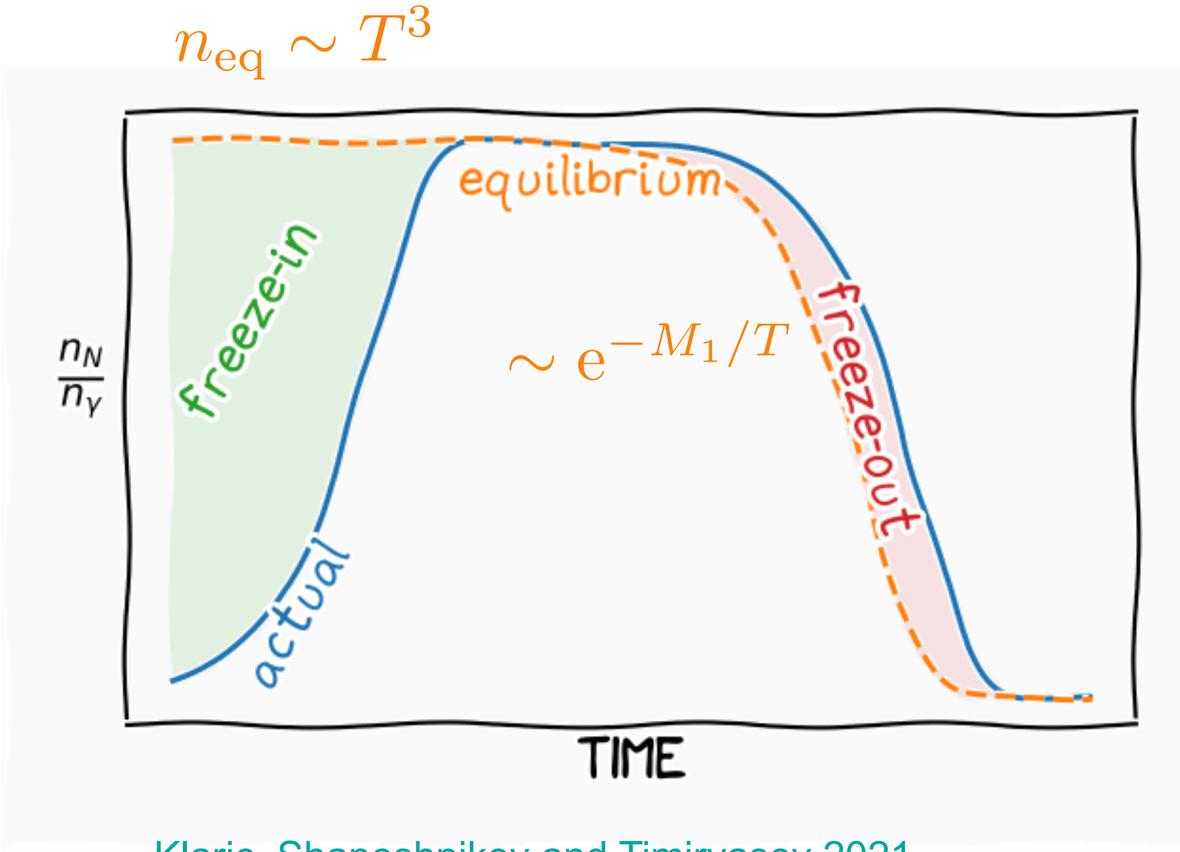
$$\epsilon_1 = \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to \bar{l} H^*)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to \bar{l} H^*)} \sim \frac{M_1 m_\eta}{4\pi v^2}$$

Interference term



3) OUT OF EQUILIBRIUM DECAY

vanilla scenario $M_1 \ll M_2, M_3$



Klaric, Shaposhnikov and Timiryasov 2021

assumed $K = \frac{\Gamma_1}{H}\Big|_{T=M_1} \gtrsim 1$

SIMPLE ESTIMATE

vanilla scenario $M_1 \ll M_2, M_3$

total lepton number from decays

$$Y_b = \frac{n_b}{s} = \eta \, \frac{\epsilon_1 \, n_{N_1}^{\rm eq}}{s} \, K^{-1}$$

sphalerons $B_f = \eta L_i$

$n_{N_1}^{\rm eq}/s \sim 10^{-3}$

washout

SIMPLE ESTIMATE

vanilla scenario $M_1 \ll M_2, M_3$

$$Y_b = \frac{n_b}{s} = \eta \, \frac{\epsilon_1 \, n_{N_1}^{\rm eq}}{s} \, K^{-1} \overset{?}{\sim} 10^{-10}$$

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

TESTABILITY

vanilla scenario $M_1 \ll M_2, M_3$

- heavy RHN $M_1 \gtrsim 10^9$ GeV

- small mixing angle $\theta = \frac{m_D}{m_R}$

- 6 (2) phases at high energy, 3 (2) phases at low energies for $n_{\text{RHN}} = 3$ (2)

- indirect: majorana nature $0\nu\beta\beta$-decay

PLAN

1. vanilla leptogenesis hard/impossible to test
2. low scale leptogenesis

LOW SCALE LEPTOGENESIS

$M_1 \sim M_2, M_3$

lower RHN mass

- flavor oscillations $M_1 \gtrsim 10^6 \mathrm{GeV}$
- resonant leptogenesis $M_1 \gtrsim 10^2 \mathrm{GeV}$
- ARS leptogenesis $M_1 \sim 10^{-1} - 10^2 \mathrm{GeV}$

larger θ -approximate lepton number symmetry $m_\eta = -m_D m_R^{-1} m_D^T$

APPROXIMATE LEPTON SYMMETRY

RHNs combine in Dirac neutrino

$$Y = \begin{pmatrix} y_e & 0 \\ y_\mu & 0 \\ y_\tau & 0 \end{pmatrix} \qquad m_R = \begin{pmatrix} 0 & M \\ M & 0 \end{pmatrix}$$

- lepton number conserved
- degenerate RHN mass
- vanishing light neutrino mass

APPROXIMATE LEPTON SYMMETRY

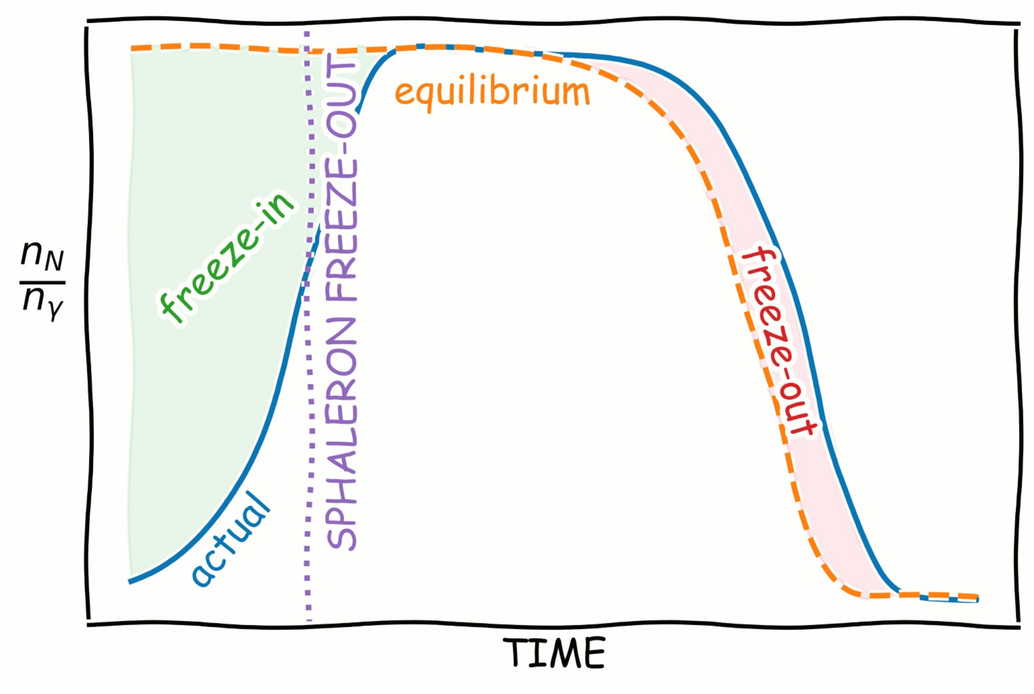
RHNs combine in Dirac neutrino

$$Y = \begin{pmatrix} y_e & y'_e \\ y_\mu & y'_\mu \\ y_\tau & y'_\tau \end{pmatrix} \qquad m_R = \begin{pmatrix} \mu & M \\ M & \mu \end{pmatrix}$$

small symmetry breaking

- almost lepton number conserved
- almost degenerate RHN mass
- almost vanishing light neutrino

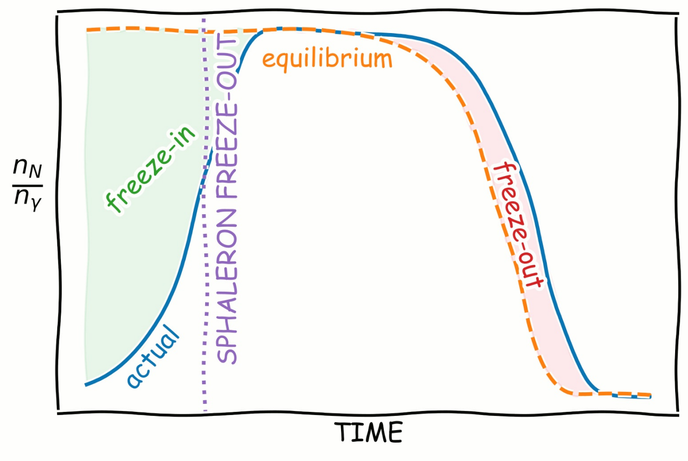
ARS LEPTOGENESIS



Klaric, Shaposhnikov and Timiryasov 2021

ARS LEPTOGENESIS

$\Gamma_1 > H \quad \& \quad \Gamma_2 < H \quad$ at $\quad T_{\mathrm{EW}}$



bath $\longrightarrow$ N_1 $\xrightarrow{\text{oscillations}}$ N_2, $L_2 \neq 0$; N_1, $L_1 \neq 0$

$L_i = 0$

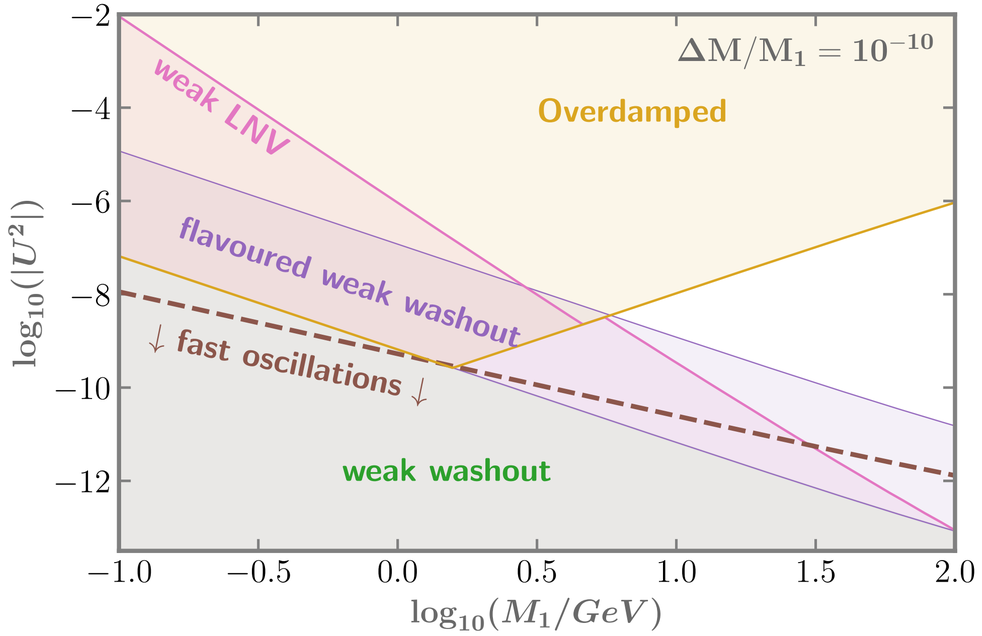
$\cancel{CP}$

N_1, $L_1 \neq 0$ $\longleftrightarrow$ bath $\longleftrightarrow$ $B \neq 0$

sphalerons

PARAMETER SPACE FOR 2 RHN

- 5 free parameters



Hernandez, Lopez-Pavon, Rius and S. Sandner 2022

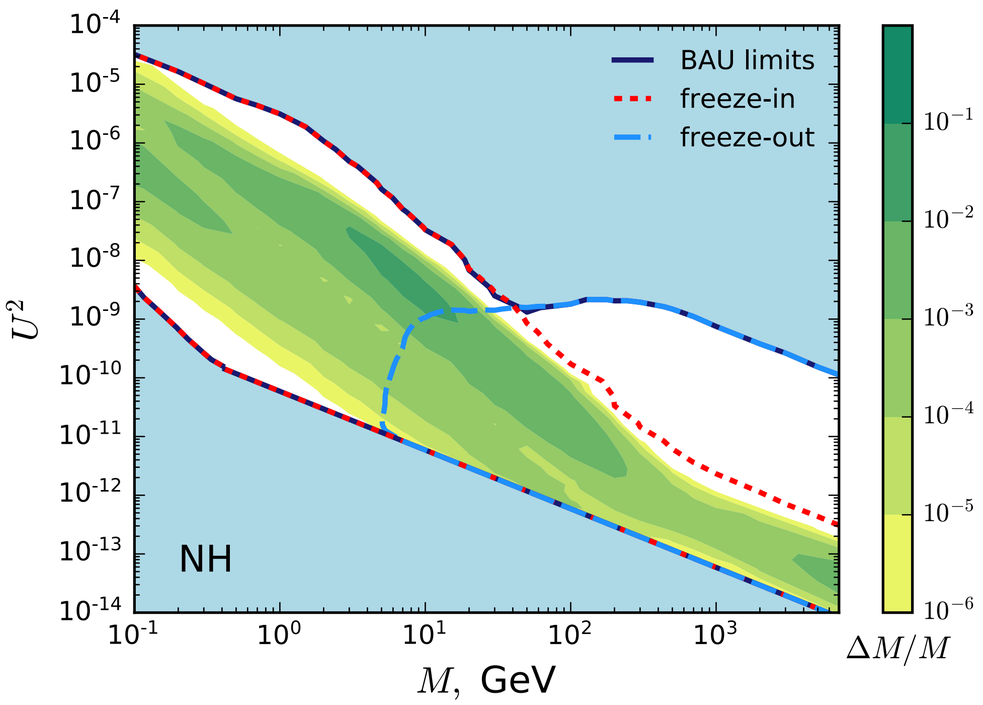
$$\nu_{L\alpha} = U^{\rm PMNS}_{\alpha i}\nu_i + \theta_{\alpha I} N^c_I$$

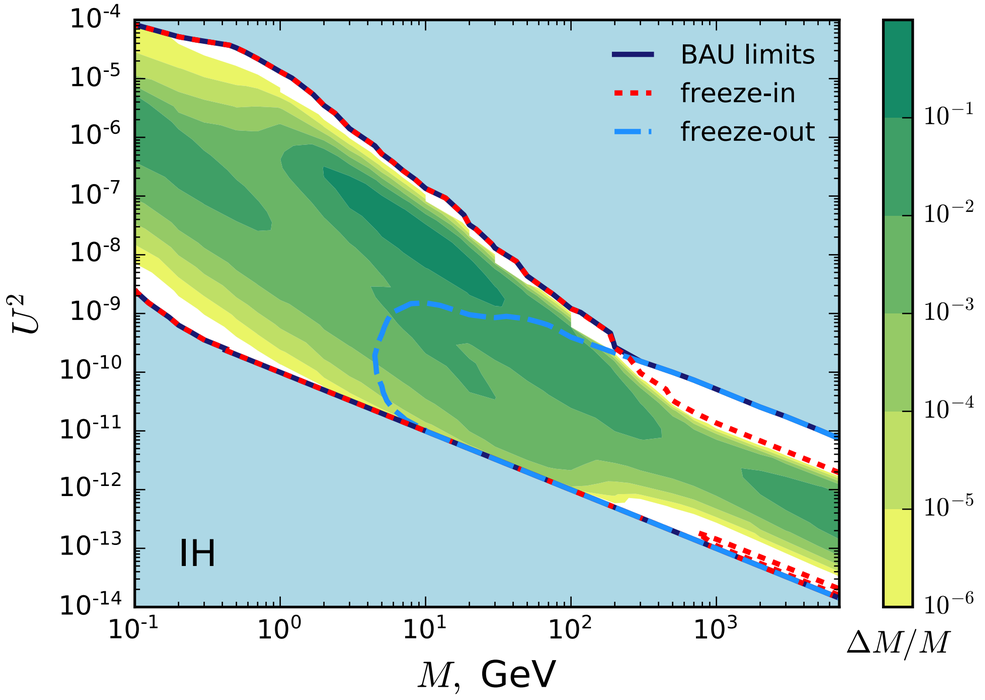
$$U^2_\alpha = \sum_I |\theta_{\alpha I}|^2, \qquad U^2 = \sum_\alpha U^2_\alpha$$

complicated parameter space!

PARAMETER SPACE FOR 2 RHN

Klaric, Shaposhnikov and Timiryasov 2021

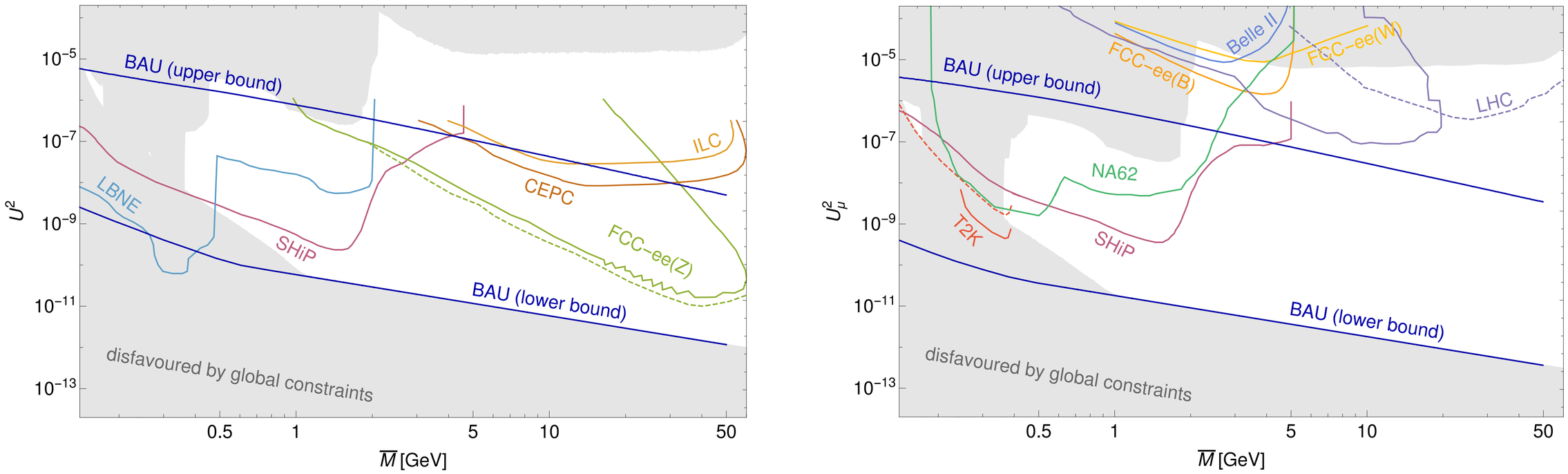




black, solid: leptogenesis with vanishing initial RHN density
blue, dashed: leptogenesis with thermal initial conditions.
red, dotted: neglecting universe expansion/freeze-out

PARAMETER SPACE FOR 2 RHN

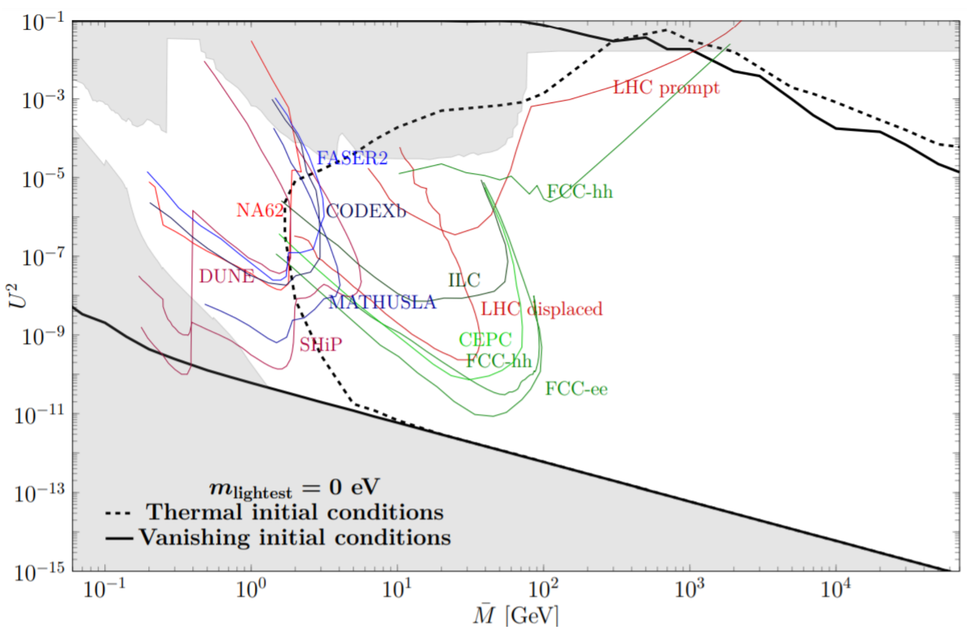
Drewes, Garbrecht, Gueter and Klaric 2016

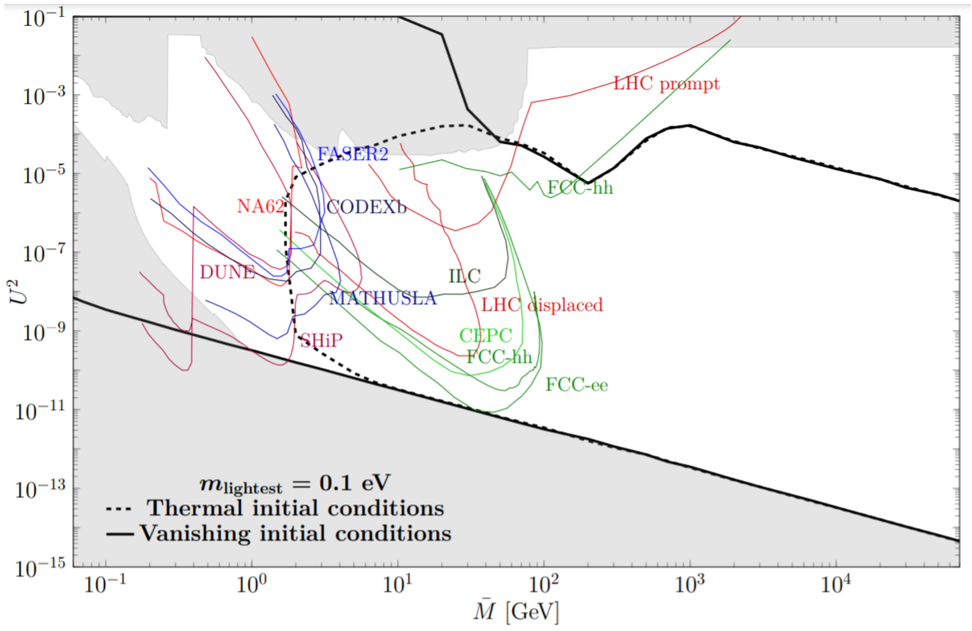


Normal hierarchy. The grey area disfavoured by direct (LHC, beam dump, Belle, kaon decays,..), and inderect searches ($0\nu\beta\beta$, lepton universality, LNV decays,..), and cosmology (BBN)

PARAMETER SPACE FOR 3 RHN

Drewes, Georic and Klaric 2022





larger mixing angles possible: more parameters to tune & possible level crossing resonances

PLAN

1. vanilla leptogenesis — hard/impossible to test
2. low scale leptogenesis — large part of parameter space can be probed
   low scale RHN mass + degenerate spectrum