Neutrino Masses
and a
Leptogenesis at the TeV scale
with a global U(1)

François-Xavier Josse-Michaux
CFTP, IST

in collaboration with E. Molinaro

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Neutrino Masses

$$\Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \times 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m^2_{31} = 2.45 \pm 0.09 \times 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m^2_{31} = -2.34^{-0.10}_{+0.09} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin(\theta_{12})^2 = 0.312^{+0.017}_{-0.015}$$

$$\sin(\theta_{23})^2 = 0.51 \pm 0.06$$

$$\sin(\theta_{13})^2 = 0.010^{+0.009}_{-0.006}$$

$$\sin(\theta_{13})^2 = 0.013^{+0.009}_{-0.007}$$

Schwetz *et al*, 1103

Experimentally Challenging

Absolute neutrino mass ?

Hierarchy ?

Nature of neutrinos ?

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Theoretically Challenging

SM-like Dirac-type mass: $y_\nu \,\bar{\ell}\, H \,\nu_R$ $\quad y_\nu \lesssim 10^{-13}$

GUT-liked mass:

new fermions
- type I seesaw — Minkowski; Gell-Mann, Ramond&Slansky; Yanagida; Mohapatra&Senjanovic;
- type III seesaw — Foot, Lew, He&Joshi; Ma;

new scalars
- type II seesaw — Magg&Wetterich; Lazarides, Shafi &Wetterich; Mohapatra&Senjanovic;

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Typically very heavy $\Lambda \gg \mathrm{TeV}$ and impossible to probe experimentally

Neutrino Masses

Low-energy (~TeV scale) models

In General: Suppressed Yukawas hard to probe

«Tuned» models: Large Yukawas +Cancellations suffer destabilizing radiative corrections

Aristizabal Sierra &Yaguna '11

«Stabilized» models: Large Yukawas +Symmetry mass is protected

The symmetry can be explicitely broken by small parameters or conserved above the EWSB

eg: Kersten&Smirnov '07

Branco, Grimus&Laboura '89

Mohapatra&Valle, '8

We study the UV-completion of the Inverse-Seesaw model imposing a conserved global U(1)

Neutrino Masses with a global U(1)

Add 3 RH neutrinos:

$$\begin{array}{c|cccc||cccccc||} & H_1 & Q & u_R & d_R & L & e_R & N_1 & N_2 & N_3 \\ U(1)_L & 0 & 0 & 0 & 0 & 1 & 1 & 1 & -1 & 0 \end{array}$$

Conserved L:

$$-\mathcal{L} \supset y_\nu^1 \, \overline{N_1} \, \tilde{H}_1 \, L + M \, \overline{N_1} \, N_2 + h.c.$$

$$M_\nu = \begin{pmatrix} 0 & m_{D_1}^T & 0 \\ m_{D_1} & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

$$m_\nu = 0$$

Neutrino Masses with a global U(1)

Add 3 RH neutrinos + 1 Scalar doublet H2 + 1 singlet H3

$$
\begin{array}{c|cccc||ccccc||cc}
 & H_1 & Q & u_R & d_R & L & e_R & N_1 & N_2 & N_3 & H_2 & H_3 \\
U(1)_L & 0 & 0 & 0 & 0 & 1 & 1 & 1 & -1 & 0 & -2 & 2
\end{array}
$$

Perturbate the zeros: add scalar representations

L is broken after EWSB

$$
M_\nu = \begin{pmatrix} 0 & m_{D_1}^T & \bullet \\ m_{D_1} & \bullet & M \\ \bullet & M & \bullet \end{pmatrix}
$$

$$
-\mathcal{L}_{eff} \supset -\frac{y_1^i y_2^j + y_1^j y_2^i}{2M} \left(\overline{\ell}_j^c . \widetilde{H}_2{}^*\right) \left(\widetilde{H}_1^\dagger . \ell_i\right)
+ \frac{y_1^i y_1^i \, \alpha^*}{\sqrt{2}\, M^2} \left(\overline{\ell}_j^c . \widetilde{H}_1^*\right) \left(\widetilde{H}_1^\dagger . \ell_i\right) H_3{}^*
+ \frac{y_2^i \, y_2^j \, \alpha}{\sqrt{2}\, M^2} \left(\overline{\ell}_\beta^c . \widetilde{H}_2{}^*\right) \left(\widetilde{H}_2{}^\dagger . \ell_\alpha\right) H_3 + h.c.
$$

$$
(m_\nu)_{i\,j} = -\left(y_1^i y_2^j + y_2^i y_1^j - y_1^i y_1^j \, \alpha^* \frac{v_1 v_3}{v_2 \, M} - y_2^i \, y_2^j \, \alpha \frac{v_2 v_3}{v_1 \, M} \right) \frac{v_1 v_2}{2M} \neq 0
$$

Neutrino Masses with a global U(1)

UV-completion of the Inverse-Seesaw:

Add 3 RH neutrinos + 1 Scalar doublet H2 + 1 singlet H3

Gain: 2 massive neutrinos

Neutrino Masses with a global U(1)

UV-completion of the Inverse-Seesaw:

Add 3 RH neutrinos + 1 Scalar doublet H2 + 1 singlet H3

Gain: 2 massive neutrinos

+ 1 singlet S: L(S)=1

Gain: 2 massive neutrinos
+ Leptogenesis
+ Dark Matter

2-Steps Leptogenesis

Reminder: standard Leptogenesis

Fukugita&Yanagida; Luty

$$-\mathcal{L} \supset \frac{1}{2}\, M\, \overline{N}\, N^c + \left(y_1\, \overline{N}\, \tilde{H}_1\, L + h.c. \right)$$

Majorana N   L-violating couplings

N

Liu&Segre; Covi, Roulet&Vissani

CP-violation in decays

Out-of-equilibrium decays

Kuzmin, Rubakov&Shaposhnikov

Sphalerons

$$\Delta L \longleftrightarrow \Delta B$$

Lepton asymmetry   Baryon asymmetry

Observed Baryon asymmetry

$$\Omega_B = 0.02255 \pm 0.00054$$

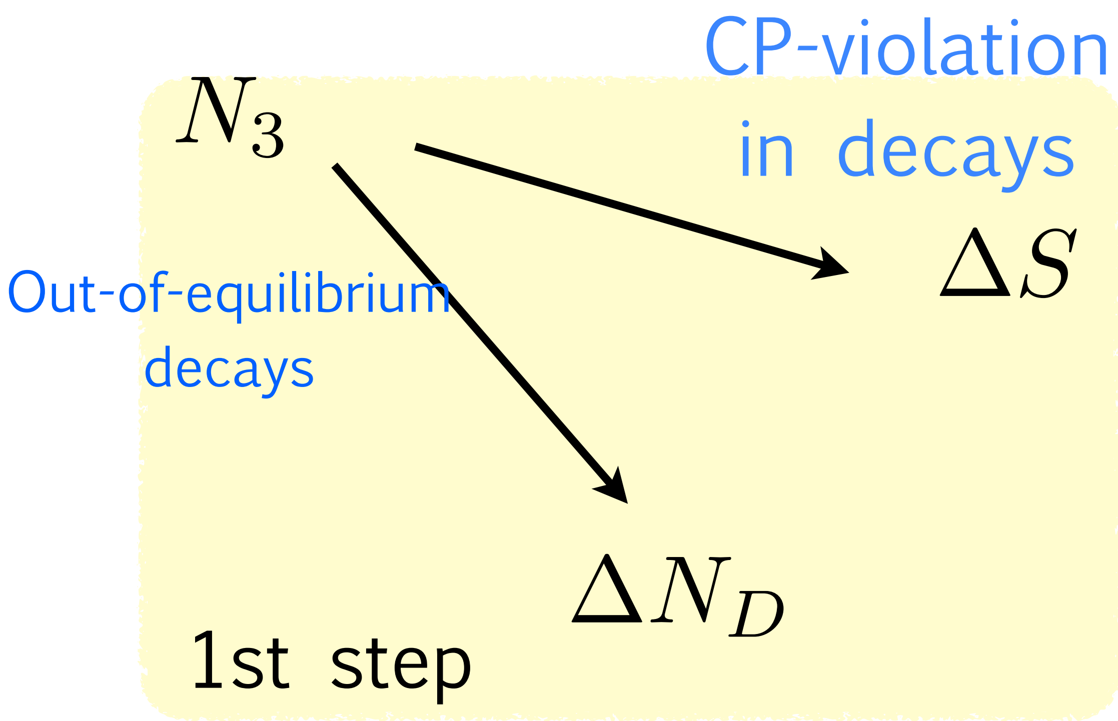
WMAP7

2-Steps Leptogenesis

$$-\mathcal{L}_{\rm int} \supset \quad \frac{1}{2} M_3 \, \overline{N}_3 \, N_3^c + \left(g \, \overline{N}_3 \, N_D \, S^* \; + \; \frac{\alpha}{\sqrt{2}} H_3 \, \overline{N}_D \, N_D^c - \frac{\mu''}{\sqrt{2}} S^2 \, H_3^* \; + h.c. \right)$$

$$+ M \, \overline{N}_D N_D + \left(y_1^i \, \overline{N}_D \, \tilde{H}_1^\dagger \, \ell_i \; + \; y_2^j \, \overline{N}_D^c \, \tilde{H}_2^\dagger \, \ell_j \; + \; h.c. \right)$$

Majorana N_3



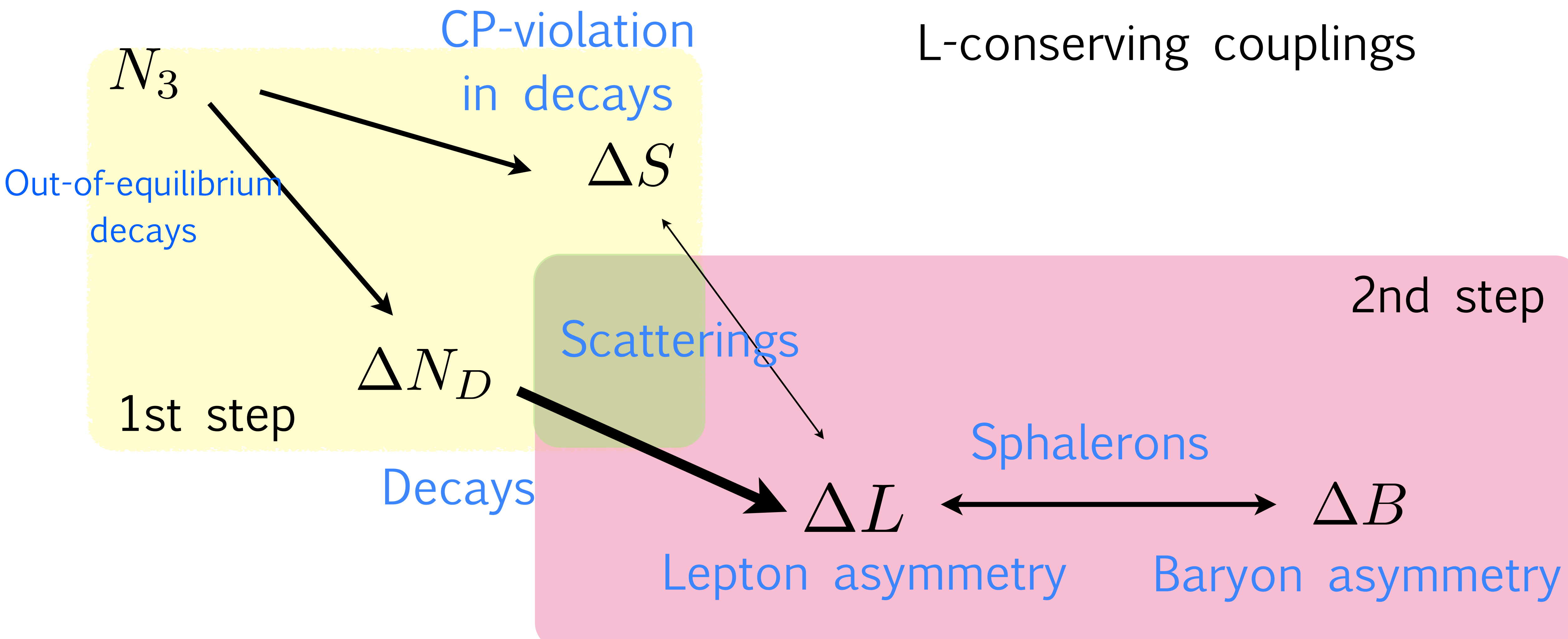
L-conserving couplings

2-Steps Leptogenesis

$$-\mathcal{L}_{\rm int} \supset \frac{1}{2} M_3 \overline{N}_3 N_3^c + \left(g \overline{N}_3 N_D S^* + \frac{\alpha}{\sqrt{2}} H_3 \overline{N}_D N_D^c - \frac{\mu''}{\sqrt{2}} S^2 H_3^* + h.c.\right)$$
$$+ M \overline{N}_D N_D + \left(y_1^i \overline{N}_D \tilde{H}_1^\dagger \ell_i + y_2^j \overline{N}_D^c \tilde{H}_2^\dagger \ell_j + h.c.\right)$$

Majorana N_3

L-conserving couplings



Observed Baryon asymmetry

$$\Omega_B = 0.02255 \pm 0.00054$$

WMAP7

2-Steps Leptogenesis

Relevant processes: $\mathcal{O}(g^2), \mathcal{O}(g^2\,\alpha^2)\,, \mathcal{O}(g^4)\,, \mathcal{O}(y^2)\,, \mathcal{O}(g^2\,y^2)$

1st Step

Decays / Inverse decays

$[N_3 \leftrightarrow N_D\, S^*]$

$\Delta N_D = 2$ scatterings

$[N_D\, S^* \leftrightarrow \overline{N_D}\, S]$ $[N_D\, N_D \leftrightarrow S\, S]$

Scatterings on N3: CP violation is included

$[N_3\, N_D \leftrightarrow S^*\, H_3]$ $[N_3\, S \leftrightarrow N_D\, H_3^*]$ $[N_D\, S \leftrightarrow N_3\, H_3]$

2nd Step

Decays / Inverse decays of ND

$[N_D \leftrightarrow \ell\, H_1]$ $[N_D \leftrightarrow \overline{\ell}\, H_2^*]$

Scatterings on top quarks

$[N_D \overline{\ell} \leftrightarrow \overline{t}\, Q_3]$ $[N_D\, q \leftrightarrow \ell\, q]$

Scatterings on N3

$[N_3\, S \leftrightarrow \ell\, H_1]$ $[N_3\, S \leftrightarrow \overline{\ell}\, H_2^*]$

Boltzmann Equations

$$Y_{N_3}{}' = (1 - y_{N_3}) \left(\gamma_D + 2 \sum_{k=a,\ldots,e} \gamma^k_{N_3} \right)$$

$$\begin{aligned}
y_{\Delta N_D}{}' = & -\epsilon_{CP}\, \gamma_D\, (1 - y_{N_3}) - 2\, \epsilon^a_{CP}\, \gamma^a_{N_3}\, (1 - y_{N_3}) + 2\, \epsilon^b_{CP}\, \gamma^b_{N_3}\, (1 - y_{N_3}) + 2\, \epsilon^c_{CP}\, \gamma^c_{N_3}\, (1 - y_{N_3}) \\
& -2 \left(\gamma^a_{\Delta\, 2} + 2\gamma^b_{\Delta\, 2}\right) (y_{\Delta N_D} - y_{\Delta S}) - \gamma_{D\ell}\, (-y_{\Delta H_1} - y_{\Delta \ell} + y_{\Delta N_D}) - \gamma_{D\bar{\ell}}\, (y_{\Delta H_2} + y_{\Delta \ell} + y_{\Delta N_D}) \\
& - \left(\gamma^s_{N_D} + 2\gamma^t_{N_3}\right) (y_{\Delta N_D} - y_{\Delta \ell}) + \gamma^a_{N_3}\, (y_{\Delta H_3} - y_{\Delta S} - y_{N_3} y_{\Delta N_D}) + \gamma^b_{N_3}\, (y_{\Delta H_3} - y_{\Delta N_D} - y_{N_3} y_{\Delta S}) \\
& + \gamma^c_{N_3}\, (y_{N_3} y_{\Delta H_3} - y_{\Delta N_D} - y_{\Delta S})
\end{aligned}$$

$$\begin{aligned}
Y_{\Delta S}{}' = & \ \epsilon_{CP}\, \gamma_D\, (1 - y_{N_3}) - 2\, \epsilon^a_{CP}\, \gamma^a_{N_3}\, (1 - y_{N_3}) + 2\, \epsilon^b_{CP}\, \gamma^b_{N_3}\, (1 - y_{N_3}) + 2\, \epsilon^c_{CP}\, \gamma^c_{N_3}\, (1 - y_{N_3}) \\
& -2\, \epsilon_{CP}\, \gamma^d_{N_3}\, (1 - y_{N_3}) - 2\, \epsilon_{CP}\, \gamma^e_{N_3}\, (1 - y_{N_3}) + 2 \left(\gamma^a_{\Delta\, 2} + 2\gamma^b_{\Delta\, 2}\right) (y_{\Delta N_D} - y_{\Delta S}) \\
& +2\gamma_{SS}\, (y_{\Delta H_1} - y_{\Delta H_2} - 2 y_{\Delta S}) + \gamma^a_{N_3}\, (y_{\Delta H_3} - y_{\Delta S} - y_{N_3} y_{\Delta N_D}) + \gamma^b_{N_3}\, (y_{\Delta H_3} - y_{\Delta N_D} - y_{N_3} y_{\Delta S}) \\
& + \gamma^c_{N_3}\, (y_{N_3} y_{\Delta H_3} - y_{\Delta N_D} - y_{\Delta S}) + \gamma^d_{N_3}\, (y_{\Delta H_1} + y_{\Delta \ell} - y_{N_3} y_{\Delta S}) \\
& - \gamma^e_{N_3}\, (y_{\Delta H_2} + y_{\Delta \ell} + y_{N_3} y_{\Delta S})
\end{aligned}$$

$$\begin{aligned}
Y_{\Delta \ell}{}' = & \ 2\, \epsilon_{CP}\, \gamma^d_{N_3}\, (1 - y_{N_3}) - 2\, \epsilon_{CP}\, \gamma^e_{N_3}\, (1 - y_{N_3}) + \left(\gamma^s_{N_D} + 2\gamma^t_{N_3}\right) (y_{\Delta N_D} - y_{\Delta \ell}) \\
& -\gamma_{D\,\ell}\, (y_{\Delta H_1} + y_{\Delta \ell} - y_{\Delta N_D}) - \gamma_{D\,\bar{\ell}}\, (y_{\Delta H_2} + y_{\Delta \ell} + y_{\Delta N_D}) - \gamma_{\Delta L=2}\, (y_{\Delta H_1} + y_{\Delta H_2} + 2\, y_{\Delta \ell}) \\
& - \gamma^d_{N_3}\, (y_{\Delta H_1} + y_{\Delta \ell} - y_{N_3} y_{\Delta S}) - \gamma^e_{N_3}\, (y_{\Delta H_2} + y_{\Delta \ell} + y_{N_3} y_{\Delta S})
\end{aligned}$$

$$Y_{\Delta H_1}{}' = \ldots \quad Y_{\Delta H_2}{}' = \ldots \quad Y_{\Delta H_3}{}' \quad \ldots$$

2-Steps Leptogenesis

$$-\mathcal{L}_{\rm int} \supset \quad \frac{1}{2} M_3 \, \overline{N}_3 \, N_3^c + \left(g \, \overline{N}_3 \, N_D \, S^* \; + \; \frac{\alpha}{\sqrt{2}} H_3 \, \overline{N}_D \, N_D^c - \frac{\mu''}{\sqrt{2}} S^2 \, H_3^* \; + h.c. \right)$$

$$+ M \, \overline{N}_D N_D + \left(y_1^i \, \overline{N}_D \, \tilde{H}_1^\dagger \, \ell_i \; + \; y_2^j \, \overline{N}_D^c \, \tilde{H}_2^\dagger \, \ell_j \; + \; h.c. \right)$$

CP asymmetry in N3 decays: $\epsilon_{CP} \simeq \dfrac{\mathrm{Im}(\alpha)}{16\,\pi} \dfrac{\mu''}{M_3}$

ND asymmetry@ 1st step: $Y^{1st}_{\Delta N_D} \propto \epsilon_{CP} \, \times \eta_1(g)$

L asymmetry@ 2nd step: $Y^{1st}_{\Delta L} \propto Y^{1st}_{\Delta N_D} \times \; \eta_2(y_1 , y_2) \sim Y^{1st}_{\Delta N_D}$

Final Baryon asymmetry:

$$Y_{\Delta B} \propto \epsilon_{CP} \, \eta_1(g) \, \eta_2(y_1 , y_2)$$

Successful Leptogenesis

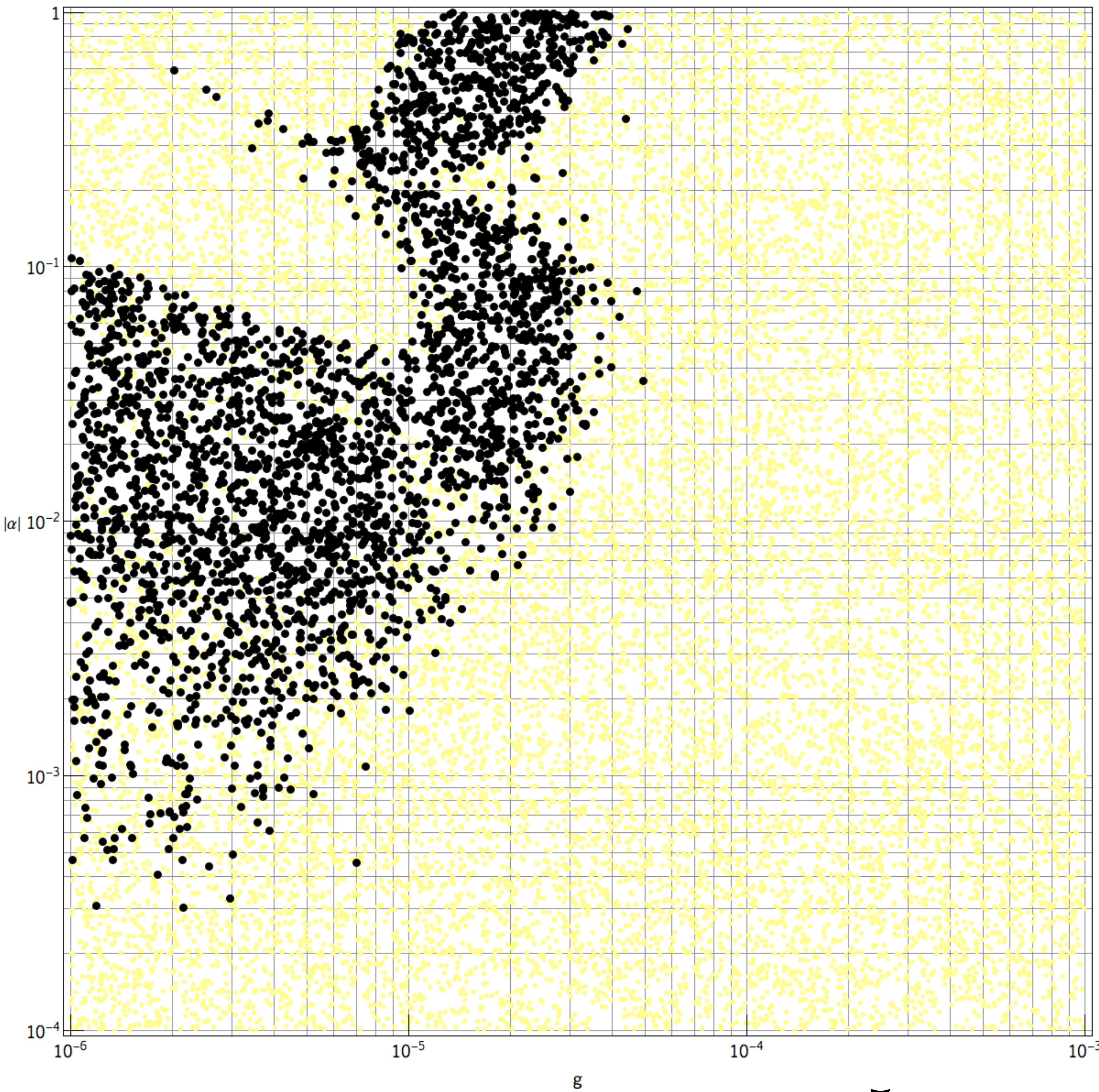
eg: $M_3 \sim 50\,\mathrm{TeV} \qquad \mu'' \sim 100\,\mathrm{GeV}$

$M \sim 1\,\mathrm{TeV}$

$y_1 \sim 10^{-4} \quad y_2 \sim 10^{-7}$

$$|\alpha| \gtrsim \text{few} \times 10^{-4}$$

or the CP asymmetry
is too small

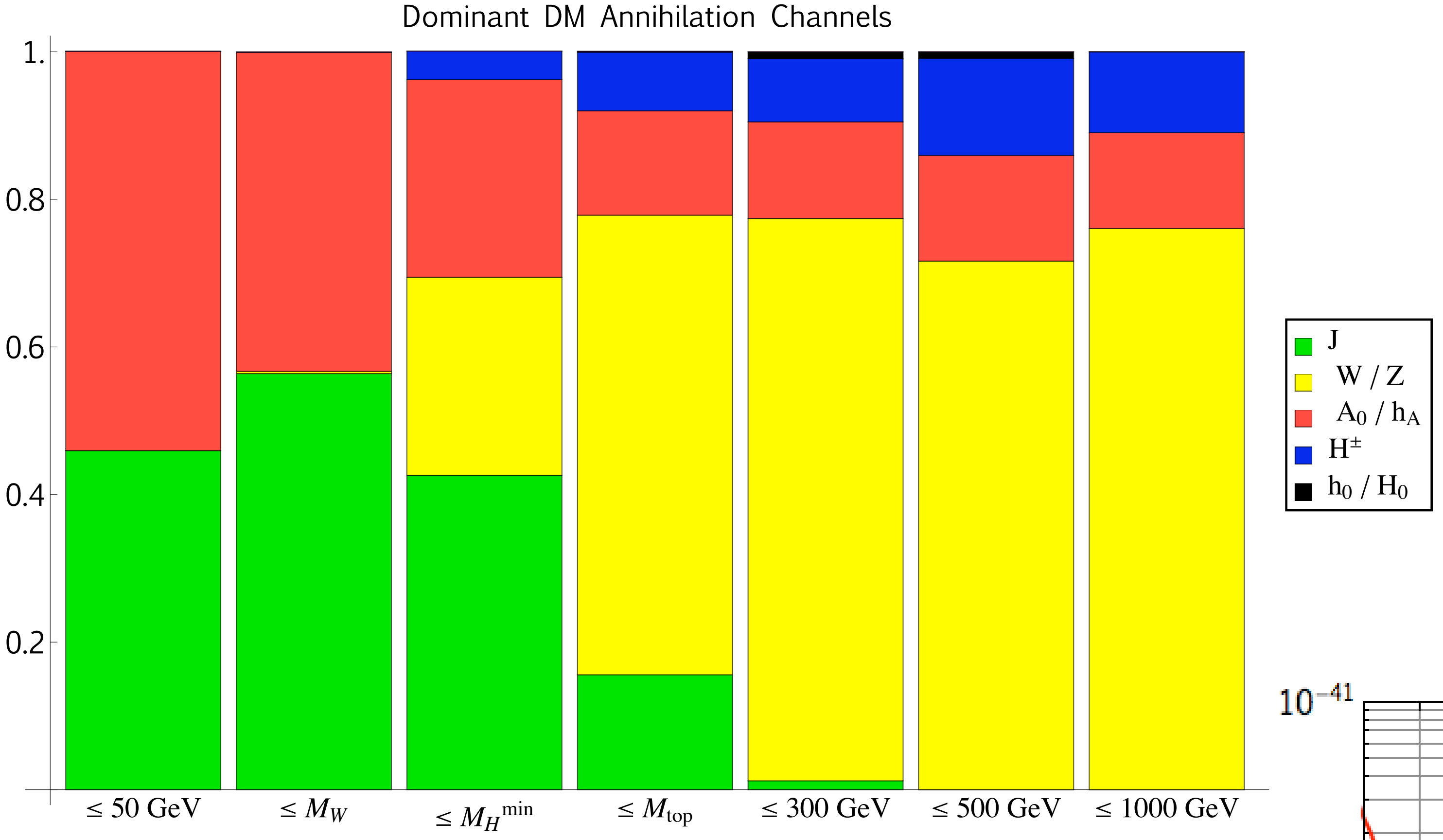


$$g \lesssim \text{few} \times 10^{-5}$$

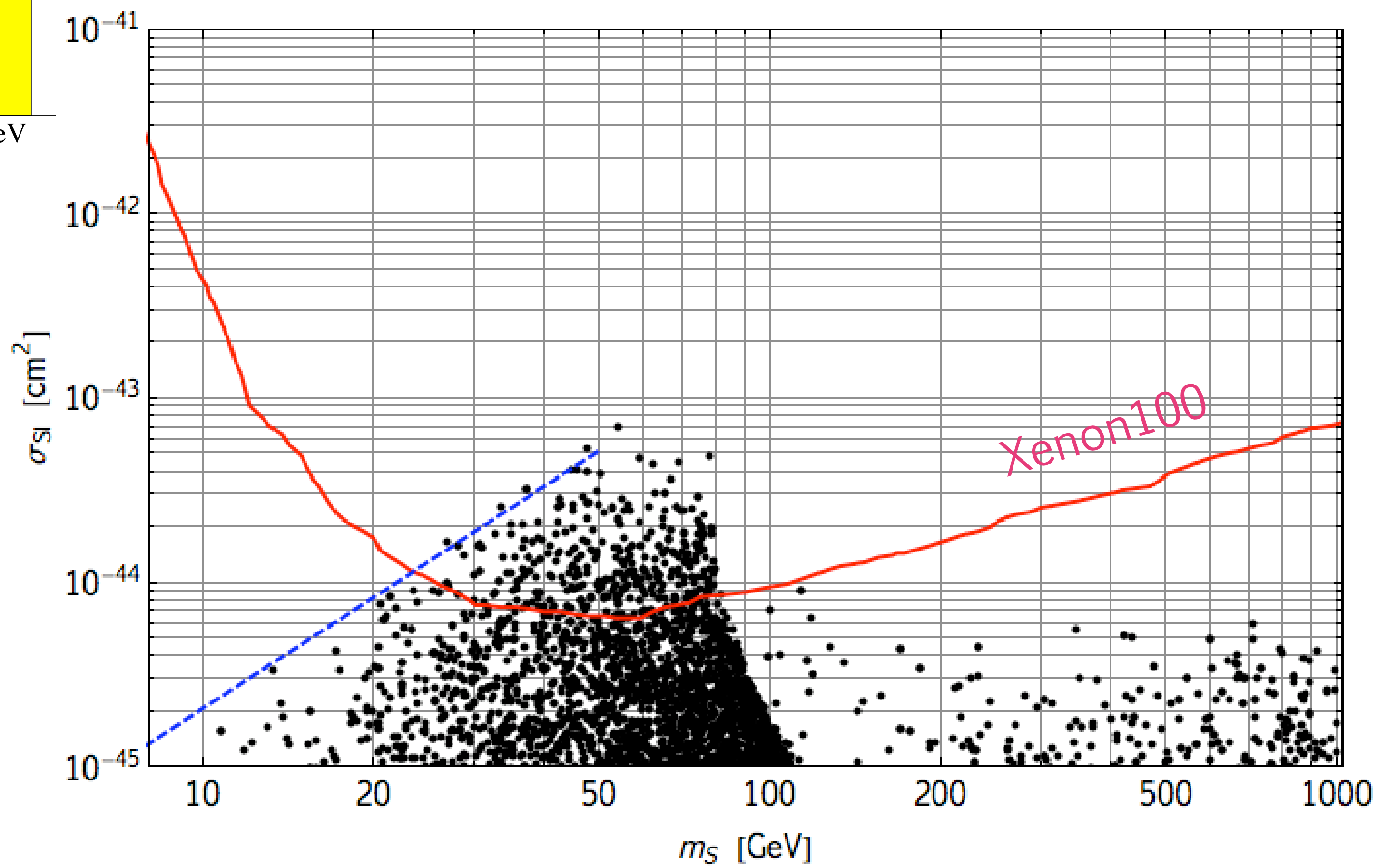
or the depletion processes are too big

Dark Matter

S mostly annihilates to Majoron J and to WW



SI cross-section upper-bounded at low Ms



S viable singlet scalar DM

Conclusion

We construct a UV-completion of the Inverse-Seesaw
imposing a conserved global Lepton number

1 scalar doublet & 1 scalar singlet added (+RHNs)

We add a scalar singlet

a new-scenario of Leptogenesis emerges

a viable Dark Matter candidate (S) exists

As long as N is charged under a conserved (lepton) number,
any asymmetry in N transfers to the lepton sector
through the neutrino Yukawa couplings

Addendum: Model Lagrangian

Lagrangian:
$$\mathcal{L}_{\rm int} = \mathcal{L}_{\rm int}^{\rm SM} - \mathcal{V}_{\rm Sca} - M\,\overline{N}_D N_D - \frac{1}{2} M_3\,\overline{N}_3\,N_3$$
$$-\left(y_1^i\,\overline{N}_D\,\widetilde{H}_1^\dagger\,\ell_i + y_2^j\,\overline{N}_D^c\,\widetilde{H}_2^\dagger\,\ell_j + \frac{\alpha}{\sqrt{2}}\,H_3\,\overline{N}_D\,N_D^c + g\,S\,\overline{N}_D\,N_3^c + \text{h.c.}\right),$$

Scalar Potential:

$$\begin{aligned}\mathcal{V}_{\rm Sca} = -\mu_1^2\,H_1^\dagger\,H_1 + \lambda_1\,(H_1^\dagger\,H_1)^2 - \mu_2^2\,H_2^\dagger\,H_2 + \lambda_2\,(H_2^\dagger\,H_2)^2 - \mu_3^2\,H_3^* H_3 + \lambda_3\,(H_3^* H_3)^2 \\ +\kappa_{12}\,H_1^\dagger\,H_1 H_2^\dagger\,H_2 + \kappa_{12}'\,H_1^\dagger\,H_2 H_2^\dagger\,H_1 + \kappa_{13}\,H_1^\dagger\,H_1 H_3^* H_3 + \kappa_{23}\,H_2^\dagger\,H_2 H_3^* H_3 \\ +\mu_S^2\,S^* S + \lambda_S\,(S^* S)^2 + \mathcal{F}_1\,H_1^\dagger\,H_1 S^* S + \mathcal{F}_2\,H_2^\dagger\,H_2 S^* S + \mathcal{F}_3\,H_3^* H_3 S^* S \\ +h\,S^2 H_1^\dagger\,H_2 + h^*\,S^{*2} H_2^\dagger\,H_1 - \frac{\mu'}{\sqrt{2}}\left(H_1^\dagger\,H_2 H_3 + H_2^\dagger\,H_1 H_3^*\right) - \frac{\mu''}{\sqrt{2}}(S^2 H_3^* + S^{*2} H_3)\,.\end{aligned}$$

Addendum: Higgs Sector

2 doublets + 1 complex singlet

3 CP-even neutral	$h^0\,,H^0$	LEP+Tevatron+LHC constrained
2 CP-odd neutral	h_A A^0	~degenerate and unconstrained
	$\mathcal{J}$	Majoron : massless Goldstone of U(1)
1 charged	$H^\pm$	

Lightest CPE h0 has suppressed couplings to SM

SM-like H0 has additionnal decay channels:

H0-> J J is important before H0->WW channel opens