Breaking leptonic symmetries with a Majoron: When Lepton Flavour Violation meets warm Dark Matter

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Paris, Nov 2016

Based on :

- L.H., D. Teresi, Arxiv : 1607.01798
  Dark matter and observable Lepton Flavour Violation

- L.H., Y. Zhang, ArXiv : 1609.05882
  Supernova Constraints on Massive (Pseudo)Scalar Coupling to Neutrinos

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- And so many more...

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- Right Handed friends? ✔
- Dark Matter? ✔
- Inflaton? ✗
- Hierarchy problem? ✗
- And so many more... ✗

Neutrino masses : Seesaw Mechanism?

$$\mathcal{L}_\nu = -\frac{g}{\sqrt{2}}\, \bar{\nu}_R^c \Sigma \nu_R - \frac{h}{\sqrt{2}}\, \bar{\nu}_L H \nu_R + h.c..$$

$$\theta \approx \frac{m_D}{M^R} = \frac{hv}{2gv_\Sigma}.$$

$$\begin{aligned} h &\approx \frac{(m_1 M_R)^{1/2}}{v}, \\ &\sim 1,3\times 10^{-9}\left(\frac{m_1}{0,1\mathrm{eV}}\right)^{1/2}\left(\frac{M_R}{\mathrm{MeV}}\right)^{1/2}\left(\frac{246\mathrm{GeV}}{v}\right). \end{aligned}$$

Seesaw process ⇒ Tiny Yukawa couplings

Idea : Assign global $U(1)_l$ charges to leptons, RH and LH neutrinos [Branco et. al. '89, Babu, Ma, '89, Pilaftsis '05]

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$\hookrightarrow$ Phenomenological observables...

Example

For instance :

	N_1	$N_\pm = (N_2 \pm iN_3)/\sqrt{2}$	L	e_R
$U(1)_l$	$q \neq 1$	$\pm\, 1$	$+1$	$+1$

Yukawas become :

$$h = v \begin{pmatrix} 0 & a & ia \\ 0 & b & ib \\ 0 & c & ic \end{pmatrix}$$

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$m_\nu = 0$ **at all orders...**

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Yukawas become :

$$h = v \begin{pmatrix} 0 & a & ia \\ 0 & b & ib \\ 0 & c & ic \end{pmatrix} + \delta h$$

$\hookrightarrow$ **Need to break $U(1)_l$**

Until now : Plug it in by hand...

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Suggestion : Break it spontaneously !

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- ↪ Bonus : Assign charges such that N_1 is stable

	N_1	$N_+ = \frac{N_2 + iN_3}{\sqrt{2}}$	L	e_R	Σ	Φ
$U(1)_l$	even	$+1$	$+1$	$+1$	even	0

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_y$$

where

$$\begin{aligned} \mathcal{L}_y &= \lambda_{abc} \bar{N}_+^c \bar{L} \Phi + h.c. \\ \mathcal{L}_N &= -2 M_R \bar{N}_+^c N_- - 2\, g_{++} \Sigma^\dagger \bar{N}_+^c N_+ - 2\, g_{--} \Sigma \bar{N}_-^c N_- + h.c. \end{aligned}$$

$$\mathcal{M}_M = \begin{pmatrix} 0 & 0 & 0 \\ 0 & M_R + u\kappa_R & iu\ \delta_R \\ 0 & iu\ \delta_R & M_R - u\kappa_R \end{pmatrix}$$

$$\begin{aligned} \kappa_R &\equiv g_{++} + g_{--} \\ \delta_R &\equiv g_{++} - g_{--} \end{aligned}$$

$$\mathcal{M}_D = v \begin{pmatrix} 0 & a & ia \\ 0 & b & ib \\ 0 & c & ic \end{pmatrix}$$

At the ren. level :

$m_\nu = m_{N_1} = 0$

Ingredients :

- $\hookrightarrow$ Three generations of RH neutrinos
- $\hookrightarrow$ New scalar field Σ
- $\hookrightarrow$ Break spontaneously the global $U(1)_l$: $\Sigma = u + (S + iJ)/\sqrt{2}$
- $\hookrightarrow$ Bonus : Assign charges such that N_1 is stable
- $\hookrightarrow$ Write all dimension 5 operators preserving $U(1)_l$: Mass scale Λ of some UV completion sector

The Model

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_y \; + \mathcal{L}_5$$

$$\mathcal{L}_5 = -2c_{11}\frac{\left(\Sigma^\dagger\right)^2}{\Lambda}\bar{N}_1^c N_1 - c_h\frac{\Sigma^\dagger}{\Lambda}\bar{N}_+^c(L\bar{\Phi}) + h.c.\,,$$

$$\mathcal{M}_M = \begin{pmatrix} g_{11}\frac{u}{\Lambda} & 0 & 0 \\ 0 & M_R + u\kappa_R & iu\;\delta_R \\ 0 & iu\;\delta_R & M_R - u\kappa_R \end{pmatrix}$$

$$\kappa_R \equiv g_{++} + g_{--}$$
$$\delta_R \equiv g_{++} - g_{--}$$

$$\mathcal{M}_D = v\begin{pmatrix} 0 & a & ia + \delta a \\ 0 & b & ib + \delta b \\ 0 & c & ic + \delta c \end{pmatrix}$$

$$\delta h = \begin{pmatrix} \delta a \\ \delta b \\ \delta c \end{pmatrix} = c_h\frac{u}{\Lambda}$$

Dark Matter Sector

In this set up :

	N_1	$N_+ = \frac{N_2+iN_3}{\sqrt{2}}$	L	e_R	Σ	Φ
$U(1)_l$	even	$+1$	$+1$	$+1$	even	0

- N_1 is stable : dark matter candidate
- Production mechanism : $S \longrightarrow N_1 N_1$ (Freeze In Scenario)
- Relic density reached for

$$\left(\frac{u}{\Lambda}\right)^2 \frac{m_{N_1}}{m_S} \approx 3 \times 10^{-24}$$

Parameter Space

Relic density :

$$\frac{u}{\Lambda} \approx 5.5 \times 10^{-10} \left(\frac{m_S}{100\mathrm{MeV}} \right)^{1/2} \left(\frac{\mathrm{keV}}{m_{N_1}} \right)^{1/2}$$

Dark matter mass : $m_{N_1} \equiv \frac{u^2}{\Lambda}$ (set $c_{11} = 1$)

$$u \approx 1.8\ \mathrm{TeV} \left(\frac{m_{N_1}}{\mathrm{keV}} \right)^{3/2} \left(\frac{100\mathrm{MeV}}{m_S} \right)^{1/2}$$

$$\Lambda \approx 3.3 \times 10^{12}\ \mathrm{GeV} \left(\frac{m_{N_1}}{\mathrm{keV}} \right)^{2} \left(\frac{100\mathrm{MeV}}{m_S} \right)$$

Neutrino masses

Parameters entering the seesaw : g_{--}, c_h, M_R, h_0

$$c_h\ h_0 \approx 3.7\times 10^{-7}\left(\frac{M_R}{\mathrm{GeV}}\right)\left(\frac{m_{N_1}}{\mathrm{keV}}\right)^{1/2}\left(\frac{100\mathrm{MeV}}{m_S}\right)^{1/2}$$

$$\frac{g_{--}}{c_h^2} \approx 2.6\times 10^{-7}\left(\frac{m_S}{100\mathrm{MeV}}\right)^{3/2}\left(\frac{\mathrm{keV}}{m_{N_1}}\right)^{5/2}$$

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- $\rightarrow$ Short lived RH neutrinos accessible to detection

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Underlying leptonic symmetry

Large Yukawas allowed by construction

$\hookrightarrow$ **sizable *lepton flavour* violation**

$\rightarrow$ observable $\mu \rightarrow e\gamma$

$\rightarrow$ $\mu \rightarrow e$ conversion

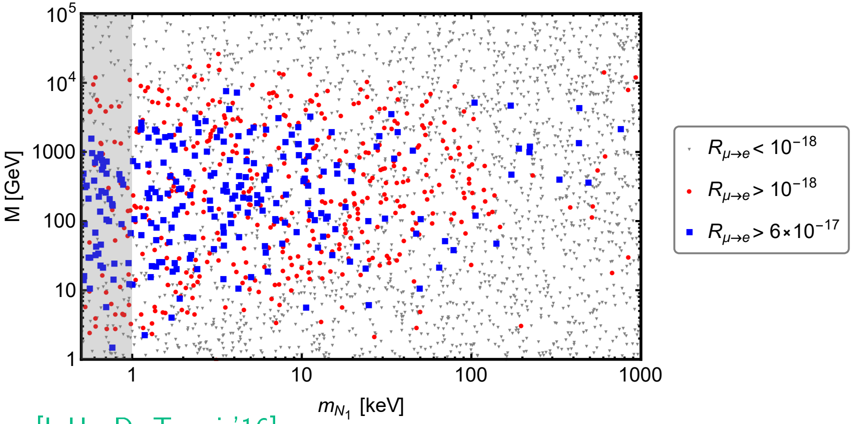
$\rightarrow$ Short lived RH neutrinos accessible to detection

Underlying leptonic symmetry

$\hookrightarrow$ **small neutrino masses, small *lepton number* violation**

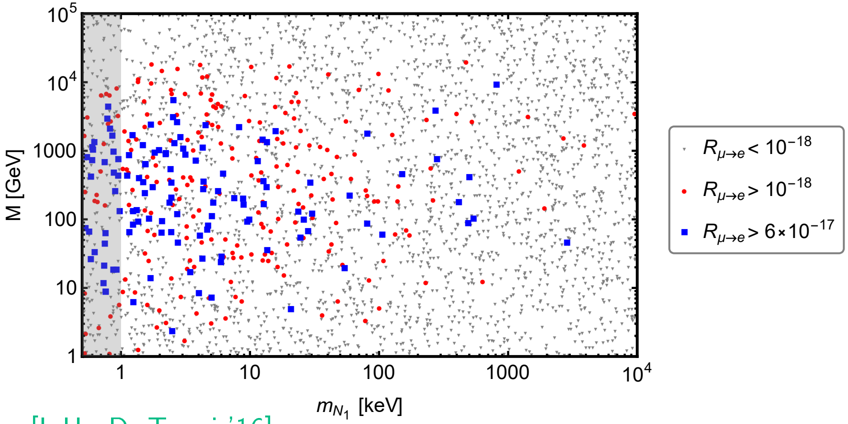
$\rightarrow$ No constraint from double β decay...

$$\Lambda = 10^{14}\,\mathrm{GeV}\,, \quad c_h = 1\,,$$



[L.H., D. Teresi '16]

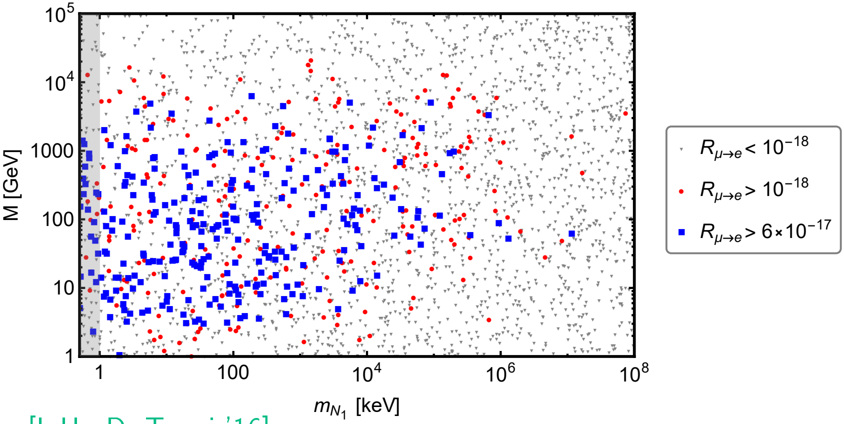
$$\Lambda = 10^{16}\,\mathrm{GeV}\,, \quad c_h = 1\,,$$



[L.H., D. Teresi '16]

Prospection

$$\Lambda = 10^{14}\,\text{GeV}\,, \qquad c_h = 0.01\,,$$



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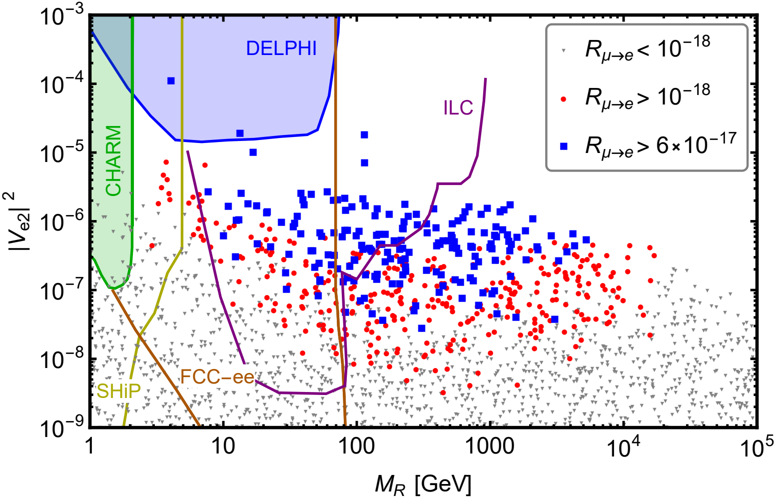

Scalar phenomenology

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- Production in Supernovae?

Supernovae bounds

$$T_{SN} \sim 10\mathrm{MeV}, \qquad \text{production via} \qquad \nu\nu \longrightarrow S$$

- Massless Majoron : Such channel suppressed
- $g_{J\nu\nu} \lesssim 4 \times 10^{-7}$

↪ far from being reached here

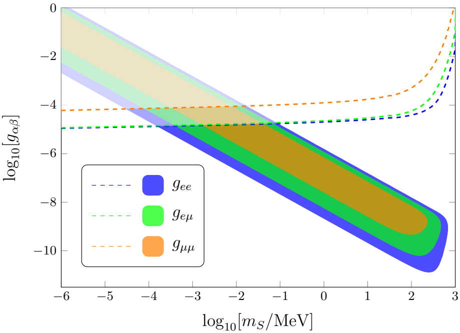
- What for massive particle ($\sim \mathrm{MeV}$) production?

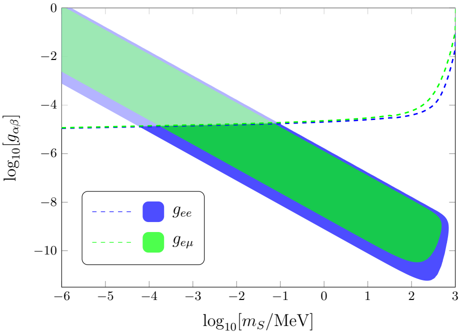
$$\begin{aligned} g_{J\nu_e\nu_e} &= \frac{-4\sqrt{2}\ a^2 g_{--} v^2}{M_R^2 - 4 g_{--} g_{++} u^2}, \\ g_{S\nu_e\nu_e} &= \frac{-4\sqrt{2}\ a^2 g_{--} v^2 \left(M_R^2 + 4 g_{--} g_{++} u^2\right)}{\left(M_R^2 - 4 g_{--} g_{++} u^2\right)^2}. \end{aligned} \tag{0.1}$$

Two different effects :

- Slightly too high coupling $g_{S\nu\nu} \rightarrow$ too much energy loss
- Significantly too high coupling $g_{S\nu\nu} \rightarrow$ decay or scattering of the scalar back in the core : no energy loss

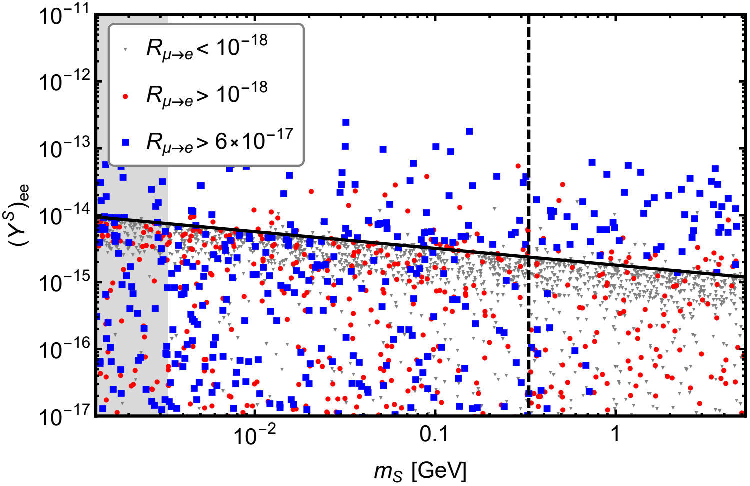
Constraint from SN1987a : $\mathcal{L} \lesssim 5 \times 10^{52}$erg/s





[L.H., Y. Zhang '16]

In our model :



$R_{\mu\to e} < 10^{-18}$
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$R_{\mu\to e} > 6\times10^{-17}$
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
$(Y^S)_{ee}$
10^{-2}
0.1
1
m_S [GeV]

Supernovae probe : prospection

- SN1987a : Only twelve events...
- In the case of future explosion ($d \approx 0.2$ kpc, $M = 18 M_\odot$) :

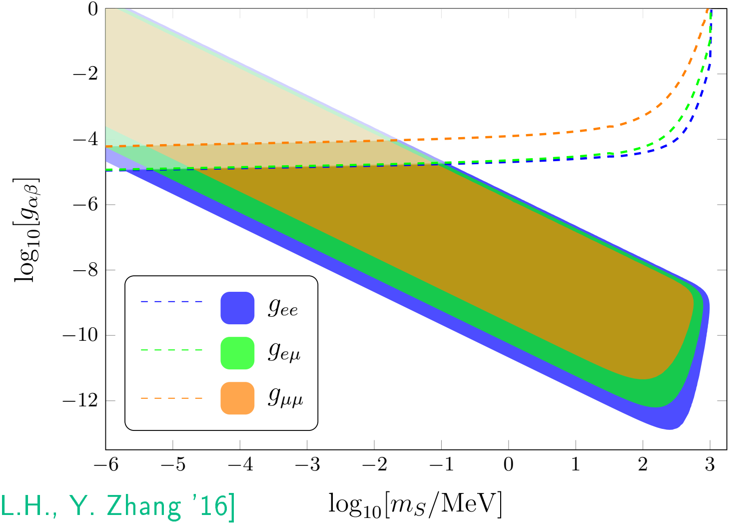
$$N^{SK}_{events} \sim 10^5 \,, \qquad N^{IC}_{events} \sim 10^8$$

[Fischer, Ringwald et al. '16]

- Prospective constraint :

$$\mathcal{L}^{S}_{\Delta t} < \frac{1}{\sqrt{N_{event}}} \mathcal{L}^{\nu, simu}_{\Delta t} \tag{0.2}$$

Supernovae probe : prospection



[L.H., Y. Zhang '16]

Conclusion

- A model of "spontaneous" neutrino mass generation...
- ...with large Yukawas!
- Breaking of the leptonic symmetry triggered by SSB
- One isolated RH generation : Dark matter candidate
- Observable lepton flavour violation in future experiments
- RH neutrino searches as well
- May (not) be observable in SN neutrino burst detection...

The End

Thank you!