A consistent model for leptogenesis, dark matter and the IceCube signal

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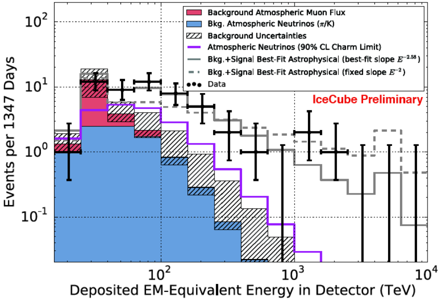
based on M. Re Fiorentin, V. Niro, N. Fornengo, arXiv:1606.04445 [hep-ph]

Energy spectrum

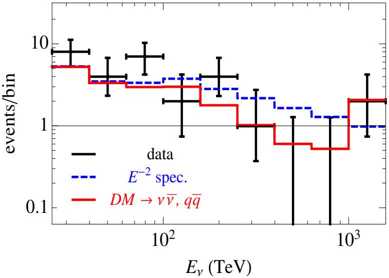


Aarsten, et. al, arXiv: 1609.04981

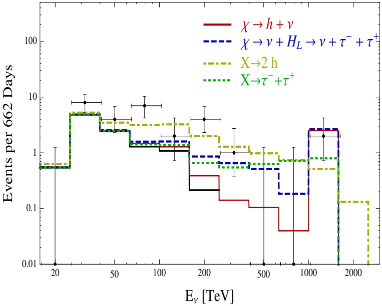
The best-fit astrophysical spectra (assuming an unbroken power-law model) are shown in gray.

The dashed line shows a fixed-index spectrum of E^{-2}, whereas the solid line shows a spectrum with a best-fit spectral index.

Neutrinos from Dark Matter decay?



A. Esmaili, P.D. Serpico, arXiv:1308.1105 [hep-ph]



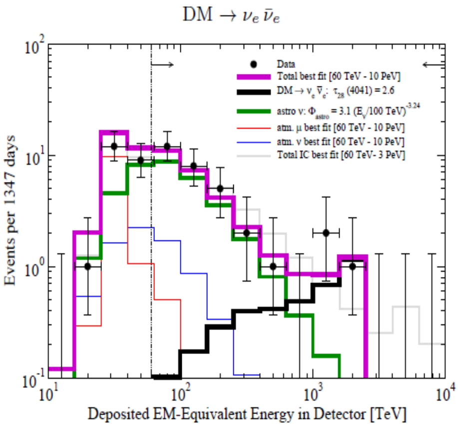
Y. Bai, R. Lu and J. Salvado, arXiv: 1311.5864 [hep-ph]

fermionic or scalar DM

Neutrinos from Dark Matter decay?

A. Bhattacharya, A. Esmaili, S. Palomares-Ruiz, I. Sarcevic, arXiv:1706.05746 [hep-ph]

Best fit values of the DM lifetime and mass [τ_{28} ($m_{\rm DM}$)] in units of 10^{28} s and TeV



The model

- We assume that the signal detected by IceCube is originated from DM decays $\Rightarrow N_1$: constitute the whole DM content of the Universe and at the same time produce the IceCube signal

- Standard minimal LRSM
$\Rightarrow$ the RH leptons are fitted into $SU(2)_R$ doublets:

$$R_i = \begin{pmatrix} N_{Ri} \\ \ell_{Ri} \end{pmatrix}$$

- The Yukawa sector then is:

$$\mathcal{L}_Y = -Y^{(1)}_{ij}\overline{L}_i \Phi R_j - Y^{(2)}_{ij}\overline{L}_i \tilde{\Phi} R_j - Y^{\Delta}_{ij}\left(L_i^T C i\tau_2 \Delta_L L_j + R_i^T C i\tau_2 \Delta_R R_j\right) + \text{h.c},$$

where Φ is a bi-doublet scalar field:

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}, \qquad \Delta_{L,R} = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta^+ & \delta^{++} \\ \delta^0 & -\frac{1}{\sqrt{2}}\delta^+ \end{pmatrix}_{L,R},$$

and $\tilde{\Phi} \equiv \tau_2 \Phi^* \tau_2$ (τ_2 being the second Pauli matrix)

Decay and IceCube signal

- N_1 decays only through the Yukawa couplings and the decay channels are:

$$N_1 \longrightarrow l_\alpha^\mp W^\pm; \qquad N_1 \longrightarrow \nu_\alpha Z, \bar{\nu}_\alpha Z; \qquad N_1 \longrightarrow \nu_\alpha h, \bar{\nu}_\alpha h.$$

  For $M_1 \gg m_Z$, m_h, we have monochromatic neutrinos with energy $E_\nu \simeq M_1/2$

  $\Rightarrow$ Sharp peak and a cutoff in the neutrino energy spectrum, while neutrino cascades will provide a soft tail in the spectrum

- From the highest event detected by IceCube
  $\Rightarrow$ the DM mass scale can be directly determined:

$$M_1 \simeq 4\,\text{PeV}$$

  $\Rightarrow$ The N_1's lifetime τ_{N_1} can be directly derived:

$$\tau_{N_1} \simeq 10^{28}\,\text{s} \tag{1}$$

Decay and IceCube signal

The total decay rate $\Gamma_{D1} = \tau_{N_1}^{-1}$ at tree level is given as a function of the Yukawa parameters $Y^{\nu}_{\alpha 1}$ by the expression *S. Davidson, E. Nardi and Y. Nir [0802.2962], T. Hambye and G. Senjanovic, [hep-ph/0307237]* :

$$\Gamma_{D1} = \frac{M_1}{8\pi} \sum_{\alpha} |Y^{\nu}_{\alpha 1}|^2$$

Eq. (1) implies a constraint on the Yukawa couplings $Y^{\nu}_{\alpha 1}$

$$\sum_{\alpha} |Y^{\nu}_{\alpha 1}|^2 = \frac{8\pi}{M_1\, \tau_{N_1}} \ll 1$$

Due to the seesaw relation, this constraint will be reflected onto the other Yukawa couplings and the light neutrinos spectrum

Introducing the Casas-Ibarra parametrization *J. Casas and A. Ibarra, [hep-ph/0103065]*, considering light neutrinos mass spectrum with nonzero m_2 and m_3 $\Rightarrow$ we predict $m_1 \simeq 0$

Relic abundance

- Given the current values of Ω_{DM}, of the critical density ρ_c and entropy s_0, the current DM abundance $Y^0_{DM} \equiv n_{DM}/s_0$ is (for $M_1 = 4$ PeV):

$$Y^0_{DM} = \frac{\Omega_{DM}\, \rho_c}{M_1 s_0} \simeq 3.82 \times 10^{-10} \left(\frac{\text{GeV}}{M_1}\right) \simeq 9.5 \times 10^{-17}, \qquad (2)$$

- N_1 can be produced from the thermal bath through:
  $\rightarrow$ interactions given by the $SU(2)_R$ gauge bosons
  $\rightarrow$ Yukawa couplings to Higgs and lepton doublets

  If we assume the standard inflationary picture of the early Universe, charged leptons and LH neutrinos are part of the thermal bath: the $SU(2)_R$ interactions are able to produce the RH neutrinos

Relic abundance

- N_1's decay rate is strongly suppressed
  $\Rightarrow$ we can just consider $S(z)$ in the equation for the evolution for N_{N_1}
  $\Rightarrow$ Assuming vanishing initial abundance for N_1 at the end of inflation, i.e. $N_{N_1}(z_{RH}) = 0$ where $z_{RH} = M_1/T_{RH}$ corresponds to the reheating temperature:

$$\frac{dN_{N_1}}{dz} = S(z) N_{N_1}^{\text{eq}}(z),$$

  and $S(z)$ for the scattering:

$$S(z) \equiv \frac{\Gamma_S(z)}{H(z)z}$$

- The RH neutrinos are subject to the $SU(2)_R$ gauge interactions:

$$\Gamma_S(T) \equiv n_{N_1}^{\text{eq}}(T)\langle\sigma|v|\rangle(T),$$

  where $n_{N_1}^{\text{eq}}$ is the equilibrium number density of N_1 and $\langle\sigma|v|\rangle$ is the thermally averaged cross section times velocity *F. Bezrukov, H. Hettmansperger and M. Lindner, [0912.4415]*:

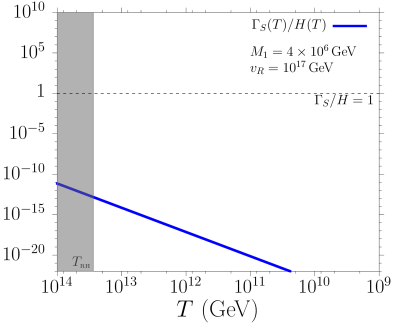
$$\langle\sigma|v|\rangle(T) \simeq G_F^2 T^2 \left(\frac{m_W}{m_{W_R}}\right)^4 \sim G_F^2 T^2 \left(\frac{m_W}{v_R}\right)^4,$$

  where m_W is the W boson mass and G_F the Fermi constant

Evolution in temperature of the ratio Γ_S/H

Expression of the Hubble rate in the radiation-dominated epoch:

$$H(z) = 1.66 g_*^{1/2} \frac{M_1^2}{M_{Pl}\, z^2},$$

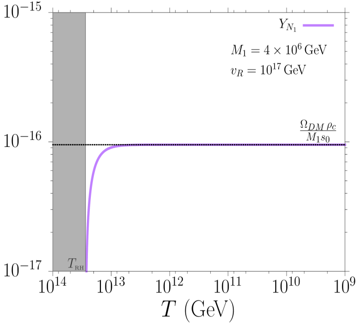


Evolution in temperature of the ratio Γ_S/H between scattering rate and the Hubble parameter (measures the efficiency of the scattering reaction)

This ratio is well below one even at the reheating temperature T_{RH}

N_1 abundance as a function of temperature T

$S(z)$: we may expect a value $\bar{z}$ at which $S(z)$ becomes negligible
$\Rightarrow$ the abundance of N_1 *freezes-in*

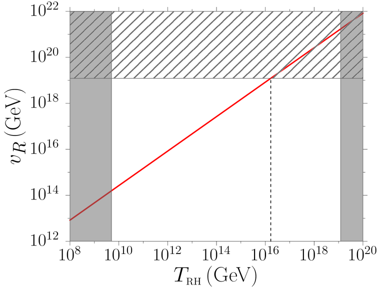


$\Rightarrow$ Production of N_1, exploiting the freeze-in mechanism
The scattering processes mediated by $SU(2)_R$ gauge bosons never become efficient after inflation
The abundance of N_1 is then preserved due to the absence of any other interaction

v_R and T_{RH}

From Eq. (2), we can obtain a relation between v_R and the reheating temperature T_{RH} such that $Y^0_{N_1} = Y^0_{DM}$:

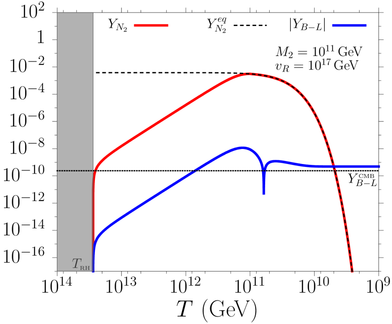
$$v_R = \left[\frac{1}{4 \times 2.40 g_*} \frac{\zeta(3) G_F^2 M_{Pl}}{1.66 \pi^2 g_*^{1/2} \, Y^0_{DM}} \right]^{\frac{1}{4}} m_W \, T_{RH}^{3/4} \simeq 8.3 \times 10^6 \, T_{RH}^{3/4},$$



The vertical shadowed region on the right: temperatures above the Planck scale
The upper hatched region: transplanckian values of v_R are excluded
The vertical shaded region on the left: the lower bound given by leptogenesis

The baryon asymmetry

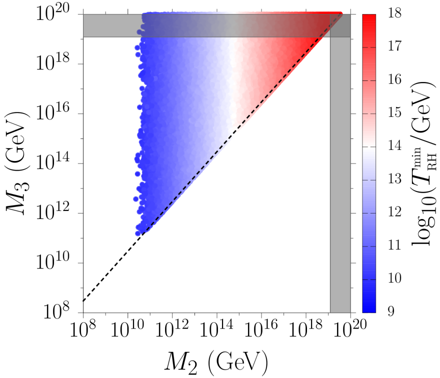
Given the constraint on N_1's Yukawa couplings that completely decouples the lightest neutrino N_1, and the fact that $M_1 \ll 10^9$ GeV, the asymmetry must be produced by N_2



Evolution of N_2 and $B-L$ asymmetry abundances as a function of temperature. We consider $M_2 = 10^{11}$ GeV, $T_{RH} = 2.7 \times 10^{13}$ GeV and $v_R = 10^{17}$ GeV

Values of M_2 and M_3

Expect on M_2 the same lower bound that applies on M_1 in N_1-dominated leptogenesis, i.e. $M_2 \gtrsim 5 \times 10^8$ GeV *S. Davidson and A. Ibarra, [hep-ph/0202239], S. Blanchet and P. Di Bari, [0807.0743]*
We will always consider hierarchical leptogenesis, obtained by imposing $M_3 \geq 3M_2$.



Scatter plot of points in the plane M_2-M_3 that give successful leptogenesis. The dashed line shows the hierarchical limit $M_3 = 3M_2$. The shaded regions exclude $M_i \geq M_{Pl}$.

Value of $T_{RH}^{\min}$

We obtained a lower bound entirely given by leptogenesis:

$$T_{RH}^{\min} \gtrsim 7 \times 10^{9}\ \text{GeV}.$$

Using this lower bound on $T_{RH}^{\min}$, we can find a range of allowed values of v_R:

$\Rightarrow 2 \times 10^{14}$ GeV $\lesssim v_R \lesssim 2 \times 10^{21}$ GeV, or
$\Rightarrow 2 \times 10^{14}$ GeV $\lesssim v_R \lesssim 10^{19}$ GeV if we require $v_R < M_{Pl}$.

The lower bound on v_R agrees with our assumptions of a very high symmetry breaking scale

Avoid unwanted low-energy effects due to the $SU(2)_R$ gauge interactions
$\Rightarrow$ the $SU(2)_R \otimes SU(2)_L \otimes U(1)_{\tilde{Y}} \to SU(2)_L \otimes U(1)_Y$ breaking must take place at very high energies
$\Rightarrow$ large $\langle \Delta_R \rangle \equiv v_R$

Constraints on the model from W_R-mediated decays of N_1

N_1 has also an hadronic decay through the mediation of the W_R gauge boson into right-handed charged leptons and quarks: $N_1 \to l_R q_R \bar{q}'_R$ *P. S. Bhupal Dev, C.-H. Lee and R. N. Mohapatra, [1408.2820], J. Gluza and T. Jeliski, [arXiv:1504.05568 [hep-ph]]* :

$$\Gamma(N_1 \to l_R q_R \bar{q}'_R) \simeq \frac{3 g_R^4}{2^{10}\pi^3 M_1^3} \int_0^{M_1^2} ds \frac{M_1^6 - 3M_1^2 s^2 + 2s^3}{\left(s - M_{W_R}^2\right)^2 + M_{W_R}^4 \frac{g_R^4}{(4\pi)^2}} .$$

Considering $M_1 \ll M_{W_R}$ and the usual condition $M_{W_R} = g_R v_R$, the total decay width is given by:

$$\Gamma(N_1 \to l_R q_R \bar{q}'_R) + \Gamma(N_1 \to \bar{l}_R \bar{q}_R q'_R) \simeq \frac{3\, M_1^5}{2^{10}\pi^3\, v_R^4}$$

This decay rate implies a lifetime for N_1 larger than the age of the Universe for $v_R > 5 \times 10^{17}$ GeV.
Antiproton bounds on heavy-DM decays and bounds from gamma-rays *M. Garny, A. Ibarra and D. Tran, [1205.6783], K. Murase and J. F. Beacom, [1206.2595], A. Esmaili and P. D. Serpico, [1505.06486]* set much stronger constraints on this decay channel: larger than $10^{26}\,\mathrm{s} - 10^{27}\,\mathrm{s}$

$\to$ v_R in a transplanckian regime

"Hadrophobic" LRSM

$\Rightarrow$ prevents the decay of N_1 through W_R

	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_{\tilde{Y}}$
L	**1**	**2**	**1**	$-1/2$
Q	**3**	**2**	**1**	$1/6$
R	**1**	**1**	**2**	$-1/2$
u	**3**	**1**	**1**	$2/3$
d	**3**	**1**	**1**	$-1/3$

L and R are fermionic doublets, Q is a quark doublet and u and d stand for the up quark and down quark singlets

This model accommodates the right-handed quarks into singlets of $SU(2)_R$, with a suitable choice of their $\tilde{Y}$ quantum number in order to satisfy the condition $Q = T_{3L} + T_{3R} + \tilde{Y}$ *A. Donini, F. Feruglio, J. Matias and F. Zwirner, [hep-ph/9705450], K. Hsieh, K. Schmitz, J.-H. Yu and C. P. Yuan, [1003.3482]*

Conclusions

- LR symmetric extension of the SM: the three additional right-handed neutrinos play a role in explaining the baryon asymmetry of the Universe, the DM abundance and the ultra energetic signal detected by the IceCube experiment
- The production of N_1 in the primordial thermal bath occurs via a freeze-in mechanism driven by the additional $SU(2)_R$ interactions
- The constraints imposed by IceCube and the DM abundance allow the heavier right-handed neutrinos to realize a standard type-I seesaw leptogenesis