Freeze-in sterile neutrino dark matter in a class of $U(1)'$ models with inverse seesaw

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Motivations

- **Neutrino Mass**: Neutrino is massless in SM. Several neutrino oscillation experiments confirm neutrino has mass.
- **Existance of dark matter**: The galaxy rotation curve and Bullet cluster experiment by Chandra X-ray observatory $\rightarrow$ Cannot be explained by standard model (SM) of particle physics (other alternative solution: Modified Gravity).
- **511keV line**:The long standing puzzle of 511 keV line observed by the INTEGRAL satellite at the Milky way centre needs to be explained.
- **WIMPs**: The non observations of any signal in the direct detection dark matter experiments put stringent bounds on WIMPs of masses $\gtrsim 1\mathrm{GeV}$.

The Model

	Q_{L_i}	u_{R_i}	d_{R_i}	ℓ_{L_i}	e_{R_i}	ν_{R_α}	H	Φ	S
$\mathrm{SU(3)_C}$	3	3	3	1	1	1	1	1	1
$\mathrm{SU(2)_L}$	2	1	1	2	1	1	2	1	1
$\mathrm{U(1)_Y}$	1/6	2/3	$-1/3$	$-1/2$	-1	0	1/2	0	0
$U(1)'$	x_q	x_u	x_d	x_l	x_e	x_ν	$\frac{x_h}{2}$	$-x_\phi$	0

The most general Yukawa Lagrangian invariant under this new gauge group is,

$$-\mathcal{L}_{\text{Yukawa}} = Y_e \bar{\ell_L} H e_R + Y_\nu \bar{\ell_L} \tilde{H} \nu_R + Y_u \bar{Q}_L \tilde{H} u_R + Y_d \bar{Q}_L H d_R + y_{NS} \bar{\nu_R} \Phi S + \frac{1}{2} \bar{S^c} M_\mu S + \text{h.c.}$$

$$x_\ell = -x_\Phi - \frac{x_H}{2}, x_e = -x_\Phi - x_H, x_q = \frac{1}{6}(2x_\Phi + x_H), x_u = \frac{1}{3}(2x_H + x_\Phi), x_d = \frac{1}{3}(x_\Phi - x_H)$$

Freeze-in production of dark matter:
The Boltzmann equation to solve the relic density

$$\dot{n} + 3Hn = < \sigma v(ab \to NN) > n_a n_b.$$

The final abundance of the RHN DM is,

$$\frac{dY}{dT} = \frac{< \sigma v(ab \to NN) > n_a n_b}{sHT}.$$

The thermal average dark matter annihilation cross section

$$< \sigma v > = \frac{1}{(sY_{EQ})^2} g_N^2 \frac{m_N}{64\pi^2 x} \int_{4m_N^2}^{\infty} ds \times 2(s - 4m_N^2)\sigma(s)\sqrt{s} K_1\left(\frac{\sqrt{s}}{T}\right),$$

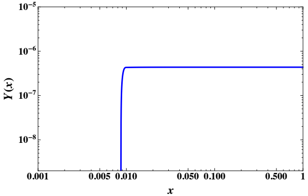
Dark matter in our $U(1)'$ model:

For the process $f\bar{f} \to NN$ in the s-channel mediated by the Z' as,

$$|\bar{\mathcal{M}}|^2 = \frac{g'^4 {y'_N}^2}{(s - M_{Z'}^2)^2 + M_{Z'}^2\Gamma_{Z'}^2}\Big[c_V^2\{s^2 + (s - 4m_f^2)(s - 4m_N^2)\cos^2\theta - 4s(m_N^2 - m_f^2) - 16m_N^2 m_f^2\} + c_A^2\{s^2 + (s - 4m_f^2)(s - 4m_N^2)\cos^2\theta - 4s(m_N^2 + m_f^2) + 16m_N^2 m_f^2 + \frac{16m_f^2 m_N^2}{M_{Z'}^4}(s - M_{Z'}^2)^2\}\Big]$$

Heavy Z' ($M_Z' \gg T_R \gg m_N$):

$$\Omega_N h^2 \simeq 0.12 \times \left(\frac{m_N}{1\mathrm{MeV}}\right)\left(\frac{10}{g_*}\right)^{\frac{3}{2}}\left(\frac{T_R}{5\mathrm{MeV}}\right)^3\left(\frac{9.7\mathrm{TeV}}{M_Z'/g'}\right)^4 \times \frac{x_\phi^2}{3}\left[2\left\{\left(\frac{3}{4}x_h + x_\phi\right)^2 + \left(\frac{x_h}{4}\right)^2\right\} + \left\{\left(x_\phi + \frac{x_h}{4}\right)^2 + \left(\frac{x_h}{4}\right)^2\right\}\right].$$



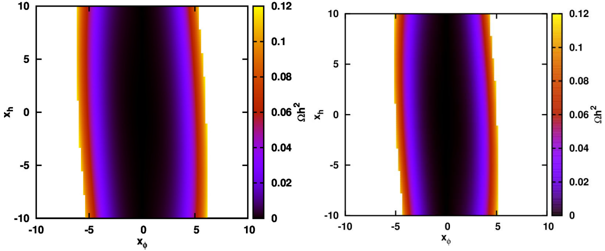


Figure: Relic density plot in the $x_h - x_\phi$ plane. In the left panel, we have fixed the values of the parameters as $m_N = 1$ MeV, $T_R = 10$ MeV, $M_{Z'} = 10$ TeV and $g' = 0.1$ whereas the right panel is for $m_N = 10$ MeV, $T_R = 50$ MeV, $M_{Z'} = 5$ TeV and $g' = 0.01$.

Light Z' ($M'_Z \ll m_N$):

$$\Omega_N h^2 = 0.12 \times \left(\frac{106.75}{g_*}\right)^{\frac{3}{2}} \left(\frac{g'}{3.04 \times 10^{-6}}\right)^4 x_\phi^2 (10x_h^2 + 13x_\phi^2 + 16x_H x_\phi).$$

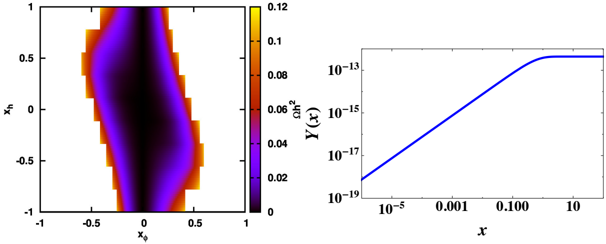


Figure: Relic density plot in $x_h - x_\phi$ plane. In the left panel, We have varied both x_h and x_ϕ from -1 to $+1$ for $g' = 3.04 \times 10^{-6}$ and in right panel, $M_{Z'} = 0.1\mathrm{GeV}$, $m_N = 1\mathrm{TeV}$, $x_\phi = 1$, $x_h = -1.2$ for $g' = 3.65 \times 10^{-6}$.

Intermediate Z' ($m_N \ll M_{Z'} \ll T_R$):

$$\Omega_N h^2 \simeq 0.12\left(\frac{g'}{6.54\times 10^{-9}}\right)^2\left(\frac{m_N}{10\mathrm{keV}}\right)\left(\frac{10\mathrm{GeV}}{M_{Z'}}\right)$$
$$\left[\frac{x_\phi^2(10x_h^2+13x_\phi^2+16x_hx_\phi)}{\frac{1}{36}(241x_h^2+418x_\phi^2+436x_hx_\phi)+x_\phi^2}\right].$$

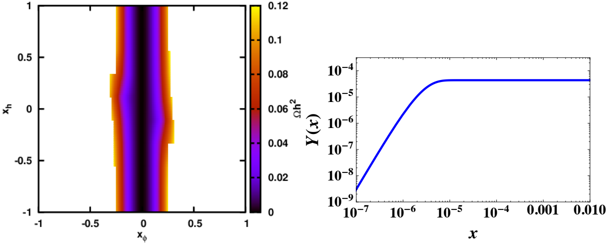
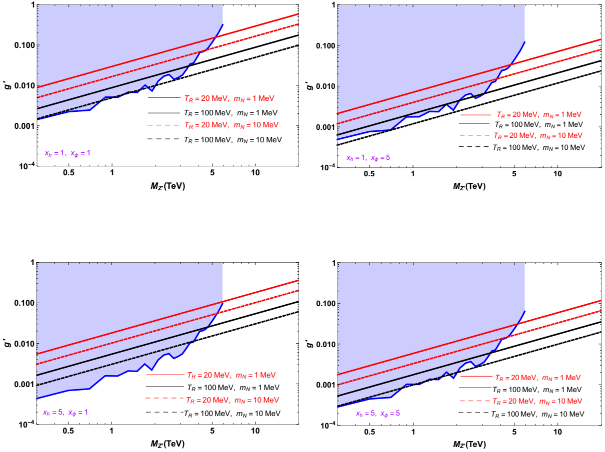


Figure: Relic density plot in $x_h - x_\phi$ plane. In the left panel, We have varied both x_h and x_ϕ from -1 to $+1$ for $g' = 6.54\times 10^{-9}$, $m_N = 10\mathrm{keV}$, $M_{Z'} = 1\mathrm{GeV}$ and in right panel, $x_\phi = 1$, $x_h = -1.2$ for $g' = 2\times 10^{-9}$, $m_N = 10\mathrm{keV}$, $M_{Z'} = 10\mathrm{GeV}$.

Bounds on coupling for heavy Z' from Experiments



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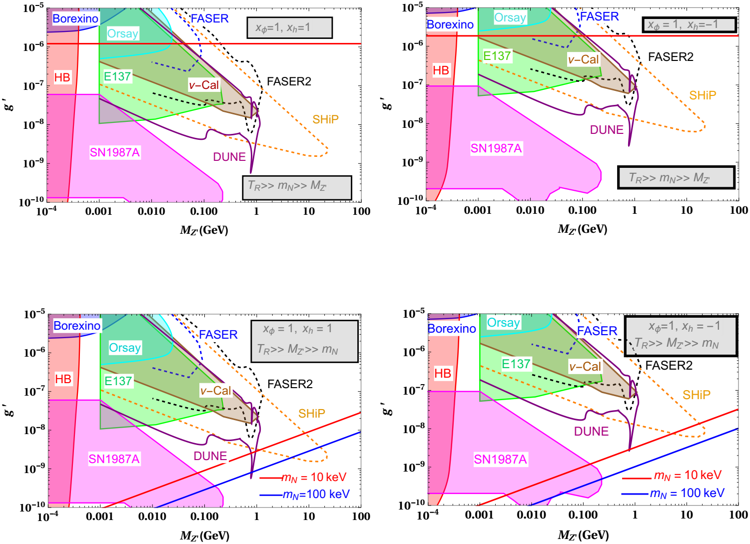

Discussions

- Detailed study of dark matter in $U(1)'$ model for a wide range of Z' mass.
- The heavy Z' can be probed in ATLAS, CMS whereas the light Z' can be probed from several lifetime frontier experiments like SHiP, FASERs etc.
- The decay of MeV scale dark matter can produce the long standing problem of galactic $511\mathrm{keV}$ line.

Thank You!