Muon (g-2) and XENON1T Excess with Dark Matter in $L_\mu - L_\tau$ Model

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The $L_\mu - L_\tau$ Model

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{L_\mu - L_\tau}$$

- Well Motivated : Anomaly free; can have very interesting phenomenology related to neutrino mass; DM as well as flavour anomalies like the muon anomalous magnetic moment $(g-2)_\mu$
- Interesting DM phenomenology(DM-SM interaction happens without kinetic mixing.)
- Better prospects of detection.
- The symmetry of the model allows a kinetic mixing term between $U(1)_Y$ of SM and $U(1)_{L_\mu - L_\tau}$ as

$$\frac{\epsilon}{2} B^{\alpha\beta} Y_{\alpha\beta}$$

where $B^{\alpha\beta} = \partial^\alpha X^\beta - \partial^\beta X^\alpha$, $Y_{\alpha\beta}$ are the field strength tensors.

Anomalous Muon Magnetic Moment

- The magnetic moment of muon:

$$\overrightarrow{\mu_\mu} = g_\mu \left(\frac{q}{2m}\right) \overrightarrow{S}\ , \tag{1}$$

where g_μ : gyromagnetic ratio $= 2$

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- Any radiative correction, which couples the muon spin to the virtual fields, contributes to its magnetic moment:

$$a_\mu = \frac{1}{2}(g_\mu - 2) \tag{2}$$

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- One loop diagram mediated by Z' boson.

$$\Delta a_\mu = \frac{\alpha'}{2\pi}\int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)M_{Z'}^2} \approx \frac{\alpha'}{2\pi}\frac{2m_\mu^2}{3M_{Z'}^2} \tag{3}$$

where $\alpha' = g_x^2/(4\pi)$.

Anomalous Muon Magnetic Moment

The recent measurement of the muon anomalous magnetic moment, a_μ, by the E989 experiment at Fermilab shows a discrepancy with respect to the theoretical prediction of the Standard Model (SM)

$$a_\mu^{\mathrm{FNAL}} = 116592040(54) \times 10^{-11} \tag{4}$$

$$a_\mu^{\mathrm{SM}} = 116591810(43) \times 10^{-11} \tag{5}$$

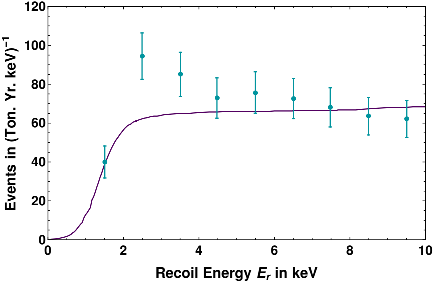
which when combined with the previous Brookhaven determination

$$a_\mu^{\mathrm{BNL}} = 116592089(63) \times 10^{-11} \tag{6}$$

leads to a 4.2 σ observed excess of $\Delta a_\mu = 251(59) \times 10^{-11}$.

XENON1T Electron Recoil Excess

Recent results from XENON1T collaboration
"Observation of Excess Electronic Recoil Events in XENON1T"
[arXiv: 2006.09721[hep-ex]]

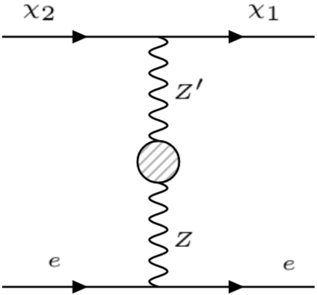


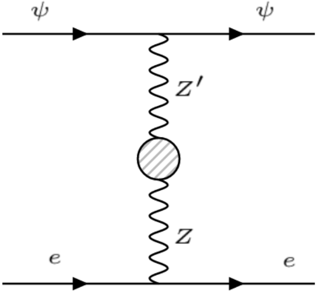
Possible interpretations : Solar Axions, Neutrino magnetic moment, Beta decay from Tritium and New Physics(DM and other).

XENON1T Electron Recoil Excess

Two Possible solutions:

- Inelastic DM scenario
- Boosted DM scenario





Inelastic Dark Matter Scenario

- Scalar field: $\phi_1 \sim (1,1,0,1)$; $\langle\phi_1\rangle = v_1$
- The DM field $\rightarrow \chi_{L,R} \sim (1,1,0,\frac{1}{2})$ (Dirac fermion)
- Choice of $L_\mu - L_\tau$ charge stabilise it.(No additional symmetries required.)

The relevant part of the DM Lagrangian:

$$-\mathcal{L}_Y = M_\chi(\bar{\chi_L}\chi_R + \bar{\chi_R}\chi_L) + \frac{1}{2}(f_1\overline{\chi_L^c}\chi_L\phi_1^* + f_2\overline{\chi_R^c}\chi_R\phi_1^* + \mathrm{h.c.}) \tag{7}$$

$$\begin{aligned}\mathcal{L}_{\rm DM} &= \frac{1}{2}\bar{\chi_1}i\gamma^\mu\partial_\mu\chi_1 - \frac{1}{2}M_1\bar{\chi_1^c}\chi_1 + \frac{1}{2}\bar{\chi_2}i\gamma^\mu\partial_\mu\chi_2 - \frac{1}{2}M_2\bar{\chi_2^c}\chi_2 \\ &+ (i\frac{1}{2}g_x\bar{\chi_2}\gamma^\mu\chi_1 Z'_\mu + \mathrm{h.c.}) + \frac{1}{4}g_x\frac{m_-}{M_\chi}(\bar{\chi_2}\gamma^\mu\gamma^5\chi_2 - \bar{\chi_1}\gamma^\mu\gamma^5\chi_1)Z'_\mu \\ &+ \frac{1}{2}(f_1\cos^2\theta - f_2\sin^2\theta)\bar{\chi_1}\chi_1\phi_1 + \frac{1}{2}(f_2\cos^2\theta - f_1\sin^2\theta)\bar{\chi_2}\chi_2\phi_1\end{aligned} \tag{8}$$

where

$M_1 = M_\chi - m_+$, $M_2 = M_\chi + m_+$, $m_\pm = (m_L \pm m_R)/2$, $m_{L,R} = f_{1,2}v_1$.
and $\delta = M_2 - M_1 = 2m_+$

Relic Abundance of DM

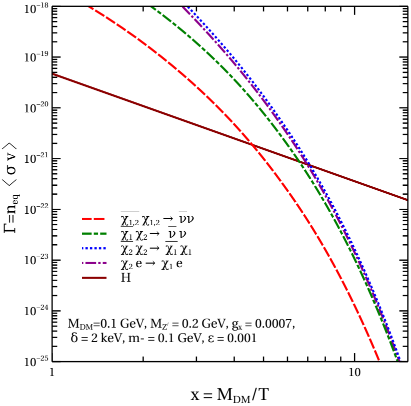
Relic abundance of two component DM in our model $\chi_{1,2}$ can be found by numerically solving the corresponding Boltzmann equations.

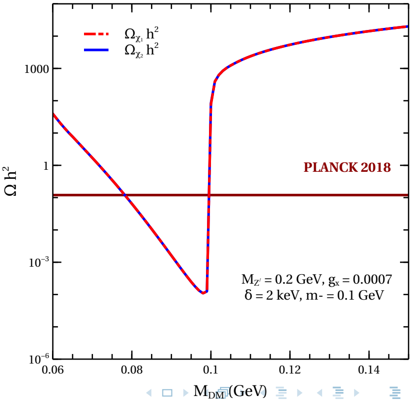
$$
\begin{aligned}
\frac{dn_2}{dt} + 3n_2 H &= -\langle \sigma \mathrm{v}_{\chi_2\bar{\chi_2}\to X\bar{X}} \rangle \left(n_2^2 - (n_2^{\mathrm{eq}})^2\right) \\
&- \langle \sigma \mathrm{v}_{\chi_2\bar{\chi_2}\to \chi_1\bar{\chi_1}} \rangle \left(n_2^2 - \frac{(n_2^{\mathrm{eq}})^2}{(n_1^{\mathrm{eq}})^2} n_1^2\right) \\
&- \langle \sigma \mathrm{v}_{\chi_2\bar{\chi_1}\to X\bar{X}} \rangle \left(n_1 n_2 - n_1^{\mathrm{eq}} n_2^{\mathrm{eq}}\right) , \\
\frac{dn_1}{dt} + 3n_1 H &= -\langle \sigma \mathrm{v}_{\chi_1\bar{\chi_1}\to X\bar{X}} \rangle \left(n_1^2 - (n_1^{\mathrm{eq}})^2\right) \\
&+ \langle \sigma \mathrm{v}_{\chi_2\bar{\chi_2}\to \chi_1\bar{\chi_1}} \rangle \left(n_2^2 - \frac{(n_2^{\mathrm{eq}})^2}{(n_1^{\mathrm{eq}})^2} n_1^2\right) \\
&- \langle \sigma \mathrm{v}_{\chi_2\bar{\chi_1}\to X\bar{X}} \rangle \left(n_1 n_2 - n_1^{\mathrm{eq}} n_2^{\mathrm{eq}}\right) ,
\end{aligned}
\tag{9}
$$

Relic Density of Inelastic DM

- Due to tiny mass splitting, almost identical annihilation channels and sub-dominant conversion processes → almost identical relic abundance of two DM candidates.
-

$$\Omega_{\chi_1} = \Omega_{\chi_2} = \Omega_{DM}/2$$





- Since the mass splitting between χ_2 and χ_1 is kept at keV scale $\delta \sim \mathcal{O}(\mathrm{keV})$, there can be decay modes like $\chi_2 \to \chi_1 \nu \bar{\nu}$ primarily mediated by Z'.
- If both the DM components are to be there in the present universe, this lifetime has to be more than the age of the universe that is $\tau_{\chi_2} > \tau_{\rm age} \approx 4 \times 10^{17}$ s.
- The decay width of this process is

$$\Gamma_{\chi_2 \to \chi_1 \nu \bar{\nu}} \approx \frac{g_x^4 \delta^5}{(160\pi^3 M_{Z'}^4)} \tag{10}$$

- Thus, imposing the lifetime constraint on heavier DM component puts additional constraints on the model parameters.

XENON1T Electron Recoil Excess

- $\chi_2 e \to \chi_1 e$ process responsible for XENON1T excess.
- The differential cross section is given by

$$\frac{d\langle \sigma v \rangle}{dE_r} = \frac{\sigma_e}{2m_e} \int_0^{v_{esc}} dv \frac{f(v)}{v} \int_{q-}^{q+} a_0^2 q dq |F(q)|^2 K(E_r, q) \,. \qquad (11)$$

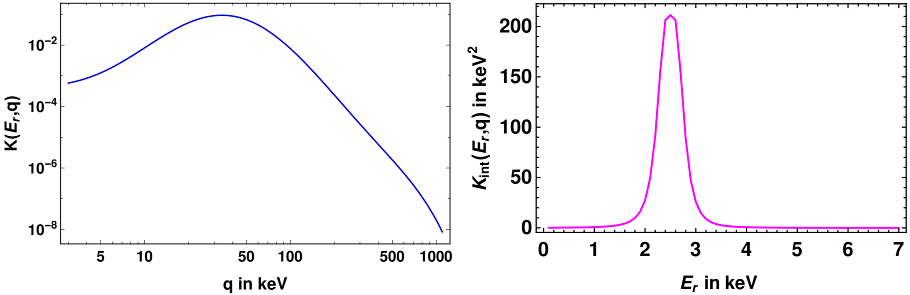
$K(E_r, q)$: Atomic excitation factor, $\sigma_e = \frac{16\pi\alpha_z\alpha_x\epsilon^2 m_e^2}{M_{Z'}^4}$: The free electron cross-section.

- Maxwellian velocity distribution boosted in earth's rest frame(After angular integration)

$$f(v) = Av\mathrm{Exp}[-3(v - v_m)^2/2\sigma_v^2] \,, \qquad (12)$$

- The limits of integration are determined depending on the relative values of E_r and $\delta = M_2 - M_1$.
  For $E_r \geq \delta, \quad q_{\pm} = M_2 v \pm \sqrt{M_2^2 v^2 - 2M_2(E_r - \delta)}$
  And for $E_r \leq \delta, \quad q_{\pm} = \sqrt{M_2^2 v^2 - 2M_2(E_r - \delta)} \pm M_2 v$.

Atomic Excitation Factor



$$K_{int}(E_r, q) = \int_{q-}^{q+} q \; dq \; K(E_r, q)$$

- The differential event rate for the inelastic DM scattering with electrons in Xenon atom, *i.e* $\chi_2 e \to \chi_1 e$, can be given as:

$$\frac{dR}{dE_r} = n_T n_{\chi_2} \frac{d\langle \sigma v \rangle}{dE_r} \tag{13}$$

where $n_T = 4 \times 10^{27}\ \mathrm{Ton}^{-1}$, $n_{\chi_2} \approx n_{\chi_1} \approx n_{\mathrm{DM}}/2$

- Incorporating the detector efficiency $\gamma(E)$, the energy resolution of the detector is given by a Gaussian distribution with an energy dependent width,

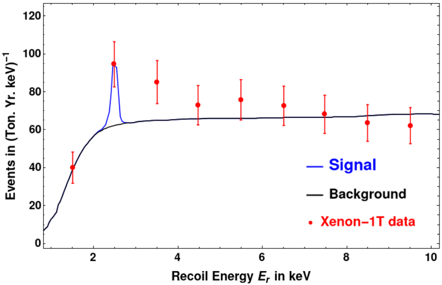
$$\zeta(E, E_r) = \frac{1}{\sqrt{2\pi\sigma_{\mathrm{det}}^2}} \mathrm{Exp}\Big[- \frac{(E - E_r)^2}{2\sigma_{\mathrm{det}}^2} \Big] \times \gamma(E) \tag{14}$$

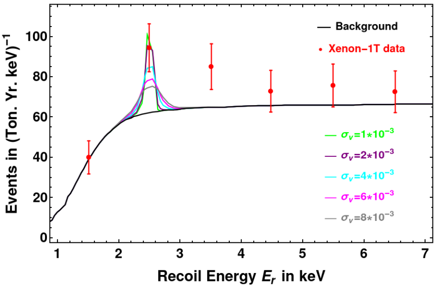
where $\sigma_{\mathrm{det}}(E) = a\sqrt{E} + bE$ with $a = 0.3171$ and $b = 0.0037$.

- Thus the final detected recoil energy spectrum is given by

$$\frac{dR_{\mathrm{det}}}{dE_r} = \frac{n_T n_{\mathrm{DM}} \sigma_e a_0^2}{2m_e} \int dE\ \ \zeta(E, E_r) \Bigg[\int_0^{v_{esc}} dv \frac{f(v)}{v} \int_{q-}^{q+} dq\ \ qK(E_r, q) \Bigg] \tag{15}$$

XENON1T Electron Recoil Excess

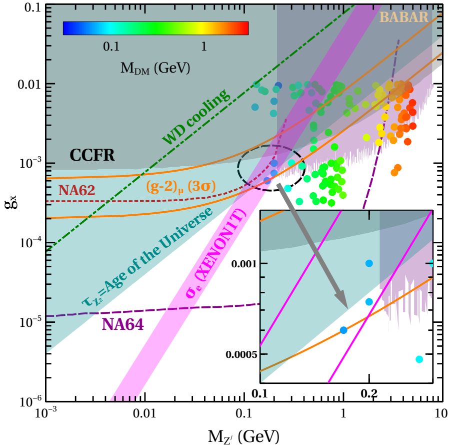




Relevant Parameters used :$\delta = 2.5$ keV , $m_{\chi 2}= 0.1$ GeV, $v \approx 1 \times 10^{-3}$, $g_x = 7 \times 10^{-4}$, $M_{Z'} = 0.2$ GeV, $\epsilon = 5 \times 10^{-3}$ which corresponds to $\sigma_e = 3.47 \times 10^{-17}\ \mathrm{GeV}^{-2}$.

Results and Discussion

- Final result is summarised in terms of parameter space $g_x - M_{Z'}$.



- Main obstacle in satisfying both the excess in Inelastic DM scenario $\rightarrow$ the constraint on heavier DM lifetime.

Boosted Dark Matter Scenario

- Single component DM scenario.
- DM annihilate into boosted lighter particles which scatter off electron elastically, giving rise to the required excess.
- Two additional vector like fermions $\psi_{A,B}$ and an additional singlet scalar η.
- The $L_\mu - L_\tau$ gauge coupling of ψ_A, ψ_B, η are taken to be $0, g_B, 0$ respectively.
- The relevant Lagrangian can be written as follows.

$$\mathcal{L} \supseteq \overline{\psi_A} i\gamma^\mu \partial_\mu \psi_A - m_A \overline{\psi_A}\psi_A + \overline{\psi_B} i\gamma^\mu D_\mu \psi_B - m_B \overline{\psi_B}\psi_B - y_A \eta \overline{\psi_A}\psi_A - y_B \eta \overline{\psi_B}\psi_B + \mathrm{h.c.} \tag{16}$$

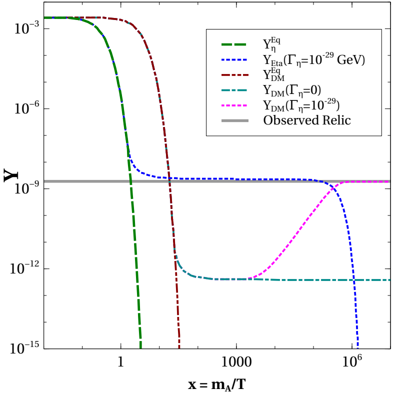
$D_\mu \psi_B = (\partial_\mu - i g_B Z'_\mu)\psi_B$. $g_B = n_B g_{\mu\tau}$ with
n_B: gauge charge of vector like fermion ψ_B.

- For simplicity, we take $y_B = 0$ whereas y_A is taken to be small to realise the desired DM phenomenology.

Relic Density of DM

$$\frac{dY_{\psi_A}}{dx} = -\frac{s(m_A)}{x^2 H(m_A)}\langle\sigma(\psi_A\psi_A \to \psi_B\psi_B)v\rangle\left(Y_{\psi_A}^2 - \left(Y_{\psi_A}^{eq}\right)^2\right) + \frac{2x}{H(m_A)}\left(\langle\Gamma_{\eta\to\psi_A\psi_A}\rangle Y_\eta\right)$$

$$\frac{dY_{\eta}}{dx} = -\frac{s(m_A)}{x^2 H(m_A)}\langle\sigma(\eta\eta \to XX)v\rangle\left(Y_{\eta}^2 - \left(Y_{\eta}^{eq}\right)^2\right) - \frac{2x}{H(m_A)}\left(\langle\Gamma_{\eta\to\psi_A\psi_A}\rangle Y_\eta\right) \quad (17)$$



- $m_\eta = 1$ GeV, m_A=0.1 GeV, $\Gamma_{\eta\to\psi_A\psi_A} = 10^{-29}$ GeV, $\sigma(\eta\eta \to XX) = 10^{-9}$ GeV^{-2} $\sigma(\psi_A\psi_A \to \psi_B\psi_B) = 10^{-4}$ GeV^{-2}.
- we have kept $\sigma(\psi_A\psi_A \to \psi_B\psi_B), \sigma(\eta\eta \to XX)$ as free parameters (within unitarity limits) without specifying the details, and adjust them to achieve the desired XENON1T fit and DM relic

XENON1T Electron Recoil Excess

- We consider $\psi_B e \to \psi_B e$ as the process responsible for XENON1T excess.

$$\frac{d\langle \sigma v \rangle}{dE_r} = \frac{\sigma_e}{2m_e v} \int_{q-}^{q+} a_0^2 \; q \; dq |F(q)|^2 K(E_r, q) \,, \qquad (18)$$

where $\sigma_e = \frac{g_B^2 \epsilon^2 g^2 m_e^2}{\pi M_{Z'}^4}$ and $q_\pm = m_B v \pm \sqrt{m_B^2 v^2 - 2 m_B E_r}$

- ψ_A is the dominant DM component. Annihilation in DM dense regions like the Galactic center (GC) or the Sun produces boosted ψ_B particles.
- Boost determined by the mass difference between ψ_A and ψ_B.
- If one considers the GC to be the source of boosted dark fermion then the obtained flux is

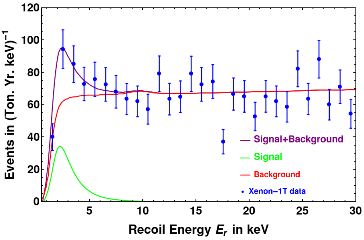
$$\Phi_{\psi_B}^{\mathrm{GC}} = 1.6 \times 10^5 \ \mathrm{cm}^{-2}\mathrm{s}^{-1} \left(\frac{\langle \sigma_{\psi_A \psi_A \to \psi_B \psi_B} v \rangle}{10^{-29} \ \mathrm{cm}^2} \right) \left(\frac{0.1 \ \mathrm{GeV}}{m_A} \right)^2 \qquad (19)$$

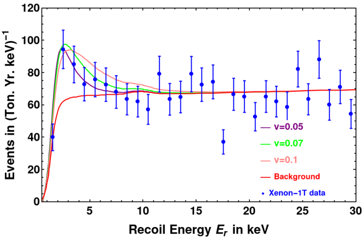
XENON1T Electron Recoil Excess

$$\frac{dR}{dE_r} = n_T \Phi_{\psi_B} \frac{d\langle \sigma v \rangle}{dE_r} \quad (20)$$

The differential event rate for the scattering of ψ_B with electrons in Xenon atom at XENON1T:

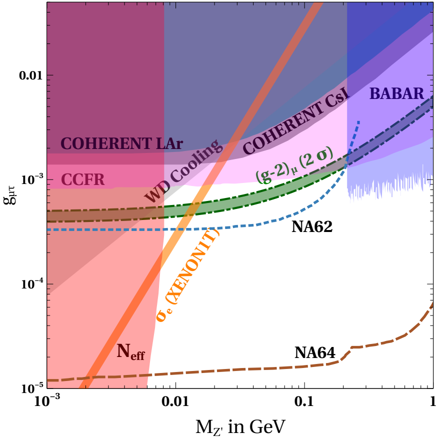
$$\frac{dR_{\rm det}}{dE_r} = \frac{n_T \Phi_{\psi_B} \sigma_e a_0^2}{2 m_e v} \int dE \ \ \zeta(E, E_r) \left[\int_{q-}^{q+} dq \ \ q K(E_r, q) \right] \quad (21)$$

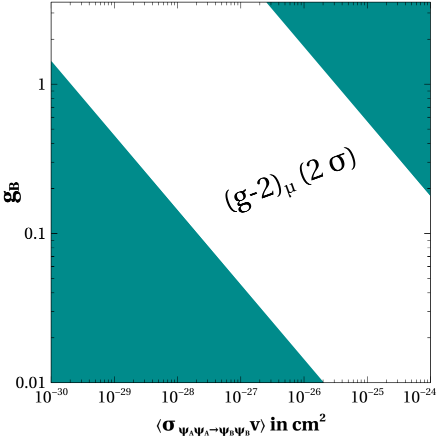




$\sigma_e = 7.2 \times 10^{-11} \text{GeV}^{-2}, \ m_B = 0.1 \text{ GeV}, \ v = 0.05, \ \ m_A \approx m_B.$

Summary





Future data from ongoing and near future experiments can probe the entire parameter space of this minimal and very predictive model.

Thank You !!!