Singlet-Doublet Fermionic dark matter in gauge theory of Baryons

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Singlet-Doublet Fermionic dark matter in gauge theory of Baryons, Taramati with colloborators Dr. Kirtiman Ghosh(IOP Bhubaneshwar) JHEP01(2025)159

Outline

1. Introduction to DM
2. Evidences and properties
3. Detection techniques
4. Dark matter in a gauge theory of baryons
5. Phenomenonlogical analysis
6. Conclusions

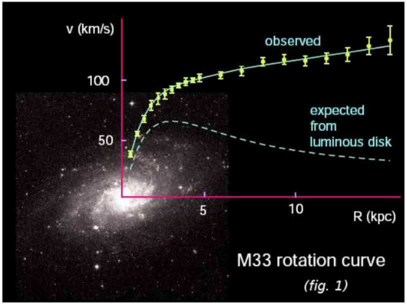
Introdution

Taken from www.secretsofuniverse.in

First discovery of dark matter

Fritz Zwicky is usually credited the first person to hypothesis the existence of Dark Matter, in 1933.

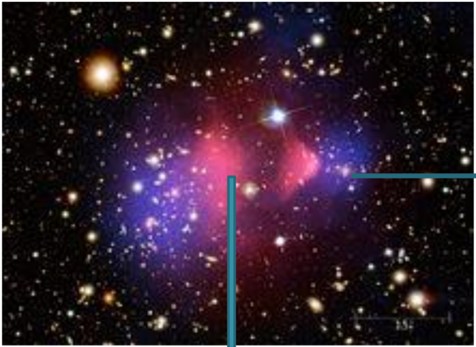
$$\frac{mv_r^2}{r} = \frac{GM_r m}{r^2}$$



$$v_r \sim \frac{1}{r^{1/2}} \quad \text{(Keplerian Decline)}$$

Evidence of dark matter

(Collision of galaxies in Bullet cluster1E 0657-56)

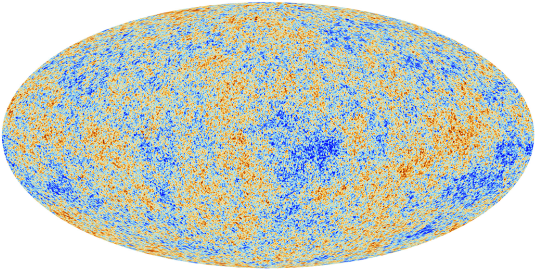


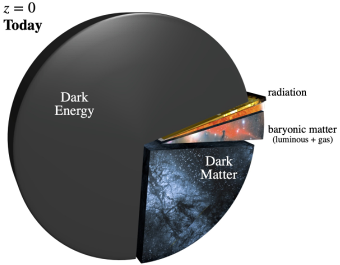
(Blue color) Dark matter seen through gravitational lensing and is found to be 7 times larger than baryonic mass.

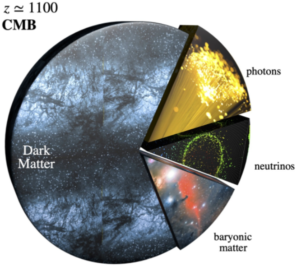
Markevitch et.al, Astro Phy J, 2004

(Pink color) Hot gas seen through X-ray by Chandra X-ray observatory at the central part

Continued...




$z = 0$
Today
Dark Energy
radiation
baryonic matter
(luminous + gas)
Dark Matter


$z \simeq 1100$
CMB
photons
neutrinos
baryonic matter
Dark Matter

Properties of dark matter

Nature of Dark Matter

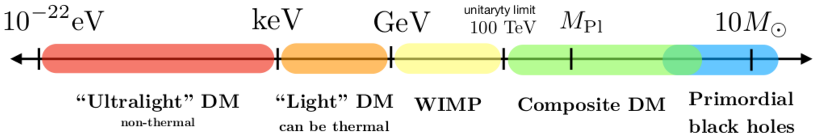
- DM should be a massive particles and hence interact gravitationally.
- It is electrically neutral and colourless. Therefore it could hide itself easily.
- It is stable on the Cosmological time scale and therefore the large scale.

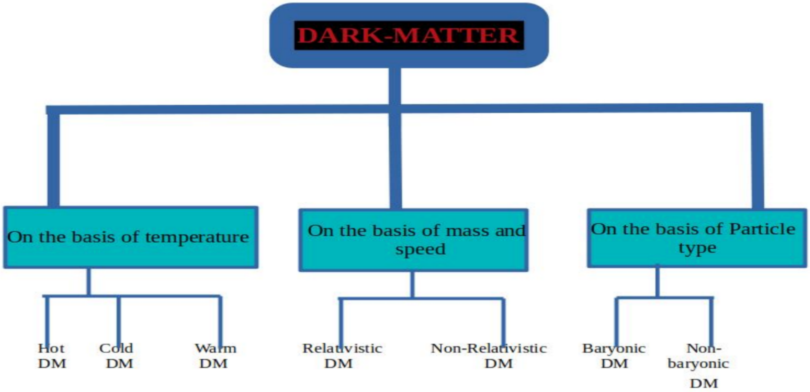
Mass of DM = ?
Spin = ?, Charge = ?
Interaction apart from gravity ?
Relic abundance
(Symmetric/ asymmetric?).

Many unaswered questions

Q. How to probe the DM, which is required for the existence of our universe ?

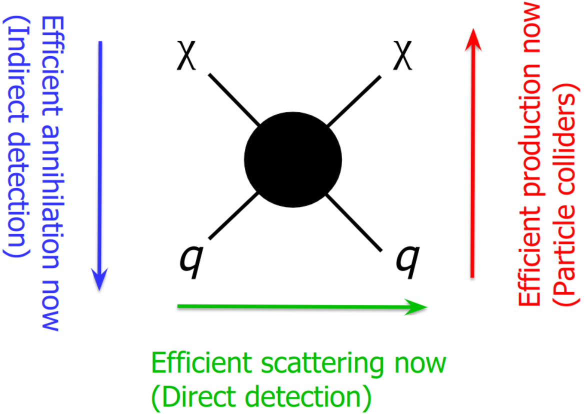
Types of dark matter





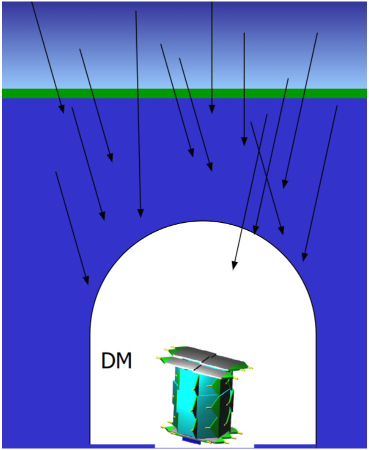
Detection Techniques for Dark Matter Particles

Correct relic density $\rightarrow$ Efficient annihilations then



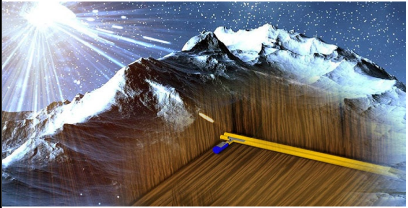
Direct Detection

- Searches for normal matter recoiling from DM collisions.
- WIMP properties:
  - $M_\chi \sim 100$ GeV
  - $v_\chi \sim 10^{-3}$
  - Recoil Energies $\sim 1 - 100$ KeV
- Typically focus on ultra-sensitive detectors placed deep underground.



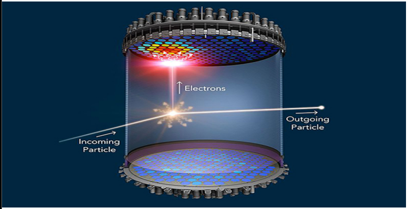
Few of the DD experiments

XENON1T (2018) [ITALY]



PandaX (2020) [CHINA]

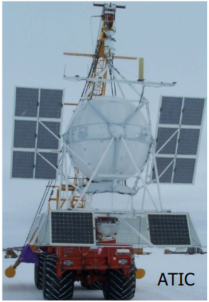
LUX-ZEPLIN (2017) [USA]



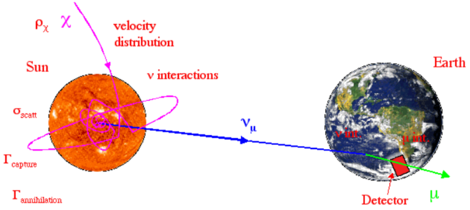
XENONnT (Data taking) [ITALY]

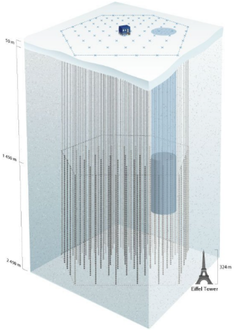
Indirect Detection

Dark Matter annihilates in the DM halo to positrons, which are detected by PAMELA/ATIC/Fermi.



Dark Matter annihilates in the center of the Sun to neutrinos, which are detected by IceCube.





Indirect Detection

Dark Matter annihilates in the galctic center to photons, which are detected by FermiLAT, HESS.

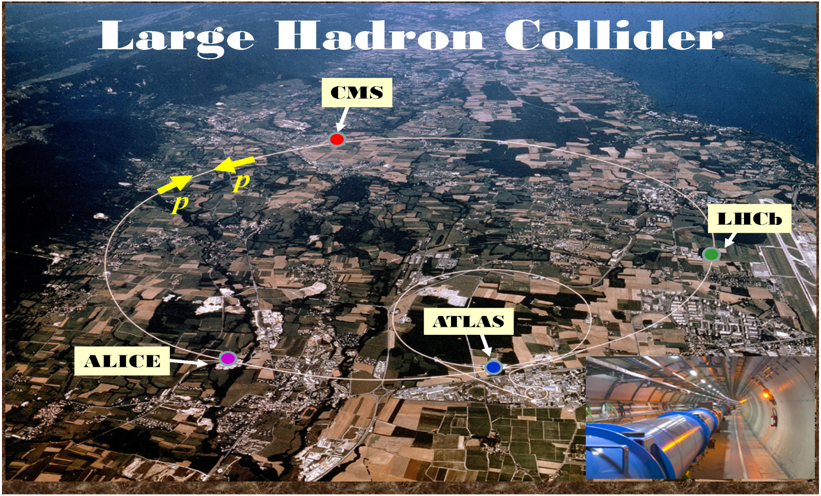
- Lines from XX → γγ, γZ
- Continuum from XX → ff → γ

$$\frac{d\Phi_\gamma}{d\Omega dE} = \sum_i \underbrace{\frac{dN_\gamma^i}{dE}\sigma_i v \frac{1}{4\pi m_\chi^2}}_{\text{Particle Physics}} \underbrace{\int_\psi \rho^2 dl}_{\text{Astro-Physics}}$$

Halo profiles are poorly understood near the galactic center

Production of collider

Dark Matter can also be produced via the annihilation of SM particles or as missing energy signals at particle colliders.

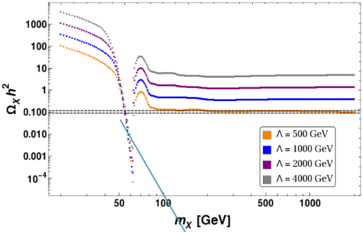


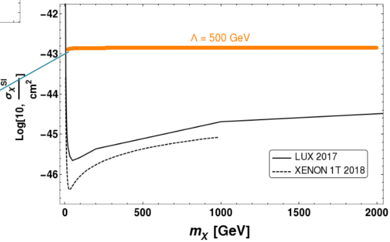
Incorporating Dark Matter in BSM frameworks

- **Few of the works already available in literature**
- Work done by us

Vector like leptonic Singlet DM Model

$$\mathcal{L}_{\mathrm{DM}} = \bar{\chi}(i\gamma^{\mu}\partial_{\mu} - m_{\chi})\chi - \frac{1}{\Lambda}\left(H^{\dagger}H - \frac{v^2}{2}\right)\bar{\chi}\chi$$



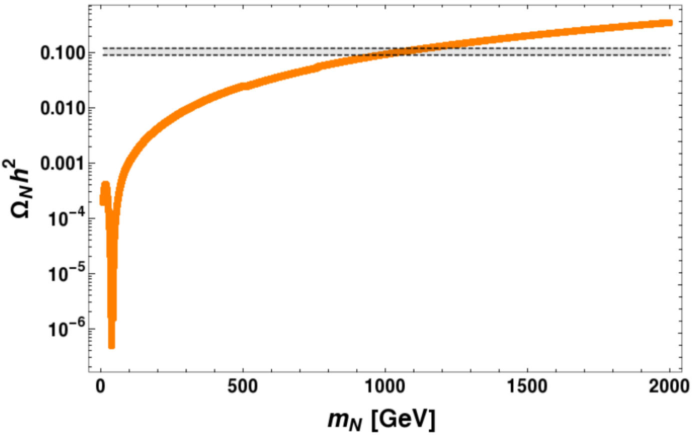


Allowed zone of valid DM

ariXiv:1801.04074

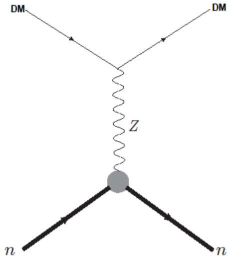
Inert lepton Doublet DM Model

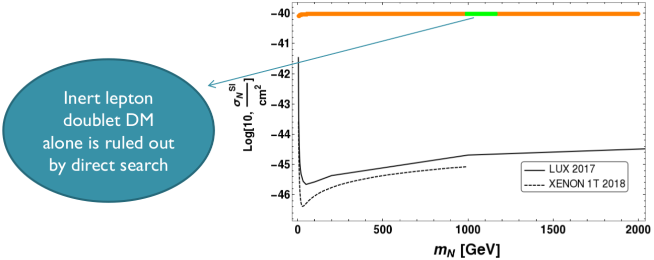
$$\mathcal{L}_{\mathrm{DM}} = \bar{N}(i\gamma^\mu D_\mu - m_N)N$$



arXiv:1812.06505

Inert lepton Doublet DM Model continued...





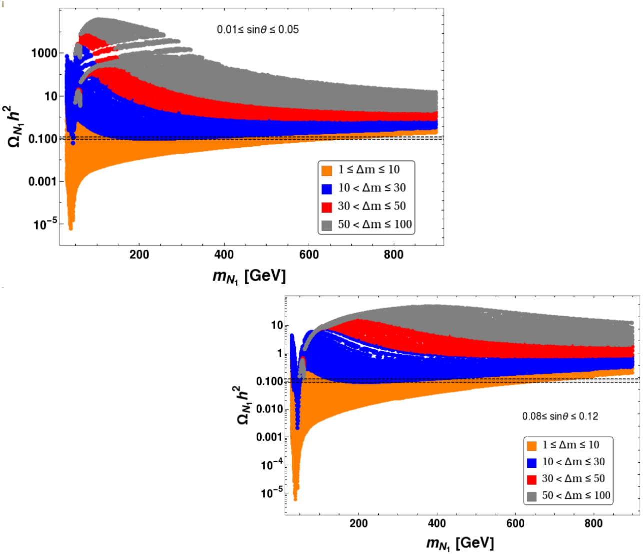
arXiv:1812.06505

Singlet-doublet leptonic DM Model

$$\mathcal{L}_{\text{DM}} = M_N \overline{N} N + M_\chi \overline{\chi^0} \chi^0 + [Y \overline{N} \tilde{H} \chi^0 + \text{h.c.}] + \overline{N} i \gamma^\mu D_\mu N + \overline{\chi^0} i \gamma^\mu \partial_\mu \chi^0$$

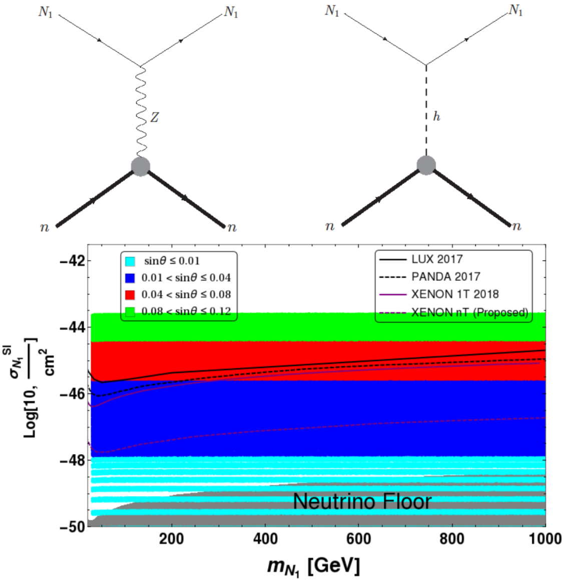
$$N = \begin{pmatrix} N^0 \\ N^- \end{pmatrix} \equiv (1, 2, -1), \quad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \equiv (1, 2, 1), \quad \chi^0 \equiv (1, 1, 0)$$

Singlet-doublet leptonic DM Model



arXiv:2204.09671

Singlet-doublet leptonic DM Model



arXiv: 2204.09671

Incorporating Dark Matter in BSM frameworks

- Few of the works already available in literature
- **Work done by us**

Singlet-Doublet fermionic dark matter in gauge theory of baryons

$$\Updownarrow$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B$$

Taramati et al., JHEP 01 (2025) 159
arXiv:2408.12424 (hep-ph)

Singlet-Doublet fermionic dark matter in a gauge theory of baryons

$$\mathcal{A}[SU(3)_C^2 \times U(1)_B] = 0$$

$$\mathcal{A}[SU(2)_L^2 \times U(1)_B] = \frac{3}{2}$$

$$\mathcal{A}[U(1)_Y^2 \times U(1)_B] = -\frac{3}{2}$$

$$\mathcal{A}[U(1)_Y \times U(1)_B^2] = 0$$

$$\mathcal{A}[U(1)_Y^2 \times U(1)_B] = 0$$

$$\mathcal{A}[U(1)_Y \times U(1)_B^2] = 0$$

$$B_1 - B_2 = -3$$

- Two non-vanishing anomalies.
- Adding 6 fermions to cancel them.

	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
Gauge fields	$\vec{W}_\mu$	B_μ	Z'_μ
$\Psi_L = \begin{pmatrix} \Psi_L^+ \\ \Psi_L^0 \end{pmatrix}$	**2**	$1/2$	B_1
$\Psi_R = \begin{pmatrix} \Psi_R^+ \\ \Psi_R^0 \end{pmatrix}$	**2**	$1/2$	B_2
$\xi_L = \xi_L^+$	**1**	1	B_2
$\xi_R = \xi_R^+$	**1**	1	B_1
$\chi_L = \chi_L^0$	**1**	0	B_2
$\chi_R = \chi_R^0$	**1**	0	B_1
H	**2**	$1/2$	0
S	**1**	0	$B_1 - B_2$

Model Framework

⋆ The complete Lagrangian for the gauge theory of baryons is given by:

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{SM} - \frac{g_B}{3}\left(\overline{q_L}\gamma_\mu Z_B^\mu q_L + \overline{u_R}\gamma_\mu Z_B^\mu u_R + \overline{d_R}\gamma_\mu Z_B^\mu d_R\right) \\ &+ \overline{\Psi_L} i \not{D} \Psi_L + \overline{\Psi_R} i \not{D} \Psi_R + \overline{\chi_L} i \not{D} \chi_L + \overline{\chi_R} i \not{D} \chi_R + \overline{\xi_L} i \not{D} \xi_L + \overline{\xi_R} i \not{D} \xi_R \\ &- h_1 \overline{\Psi_L} \tilde{H} \xi_R - h_2 \overline{\Psi_R} \tilde{H} \xi_L - h_3 \overline{\Psi_L} H \chi_R - h_4 \overline{\Psi_R} H \chi_L \\ &- \lambda_\Psi \overline{\Psi_L} S_B \Psi_R - \lambda_\xi \overline{\xi_L} S_B \xi_R - \lambda_\chi \overline{\chi_L} S_B \chi_R + \text{h.c.} \\ &+ (D_\mu S_B)^\dagger (D^\mu S_B) - V(H, S_B) \qquad (1)\end{aligned}$$

⋆ The Yukawa mass matrix for the neutral and charged fermions is given by:

$$\begin{aligned}\mathcal{L}_{NF}^B &= \overline{\begin{pmatrix}\Psi_L^+ & \xi_L^+\end{pmatrix}} \begin{pmatrix} M_\Psi & M_1 \\ M_2 & M_\xi \end{pmatrix} \begin{pmatrix} \Psi_R^+ \\ \xi_R^+ \end{pmatrix} \\ &+ \overline{\begin{pmatrix}\chi_L^0 & \Psi_L^0\end{pmatrix}} \begin{pmatrix} M_\chi & M_4 \\ M_3 & M_\Psi \end{pmatrix} \begin{pmatrix} \chi_R^0 \\ \Psi_R^0 \end{pmatrix} + \text{h.c.} \qquad (2)\end{aligned}$$

- The mass matrix terms in the previous slide are individually given as :

$$M_\Psi = \frac{\lambda_\Psi v_B}{\sqrt{2}}, \quad M_\xi = \frac{\lambda_\xi v_B}{\sqrt{2}}, \quad M_1 = \frac{h_1 v}{\sqrt{2}}, \quad M_2 = \frac{h_2 v}{\sqrt{2}},$$
$$M_3 = \frac{h_3 v}{\sqrt{2}}, \quad M_4 = \frac{h_4 v}{\sqrt{2}}.$$

- The unphysical flavor basis $\begin{pmatrix}\chi_L^0 & \Psi_L^0\end{pmatrix}^T$ is related to physical mass basis $\begin{pmatrix}\Psi_{1L} & \Psi_{2L}\end{pmatrix}^T$ basis as,

$$\begin{pmatrix}\Psi_{1L}\\ \Psi_{2L}\end{pmatrix} = \mathcal{V}\begin{pmatrix}\chi_L^0\\ \Psi_L^0\end{pmatrix}. \quad \text{Similarly, } \begin{pmatrix}\Psi_{1R}\\ \Psi_{2R}\end{pmatrix} = \mathcal{V}\begin{pmatrix}\chi_R^0\\ \Psi_R^0\end{pmatrix}.$$

Here, $\mathcal{V} = \begin{pmatrix}\cos\theta_{L/R} & \sin\theta_{L/R}\\ -\sin\theta_{L/R} & \cos\theta_{L/R}\end{pmatrix}$.

- Also, $\Psi_1 = \Psi_{1L} + \Psi_{1R}$ and $\Psi_2 = \Psi_{2L} + \Psi_{2R}$ with the lighter one among them being a viable DM candidate.

Continued...

- Equivalently:

$$\begin{aligned} \Psi_1 &= \cos\theta_{L/R}(\chi^0) + \sin\theta_{L/R}(\Psi^0) \\ \Psi_2 &= -\sin\theta_{L/R}(\chi^0) + \cos\theta_{L/R}(\Psi^0) \end{aligned} \tag{3}$$

with the mixing angle $\tan(2\theta_{DM}) = \frac{M_4+M_3}{M_\Psi - M_\chi}$ $(\theta_{DM} = \theta_{L/R})$.

- In the small angle approx. ($\sin\theta_{DM} \to 0$), the masses of Ψ_1 and Ψ_2 states can be written as:

$$\begin{aligned} m_{\Psi_1} &\simeq M_\chi - \frac{m}{2}\sin 2\theta_{DM} \equiv M_\chi - \frac{(m^2)}{(M_\Psi - M_\chi)}, \\ m_{\Psi_2} &\simeq M_\Psi + \frac{m}{2}\sin 2\theta_{DM} \equiv M_\Psi + \frac{m^2}{(M_\Psi - M\chi)}. \end{aligned} \tag{4}$$

- With $m \ll m_\chi < m_\Psi$, we get $m_{\Psi_1} < m_{\Psi_2}$ and thus, the Dirac fermion Ψ_1 is lightest and a stable dark matter candidate.

Direct detection bounds

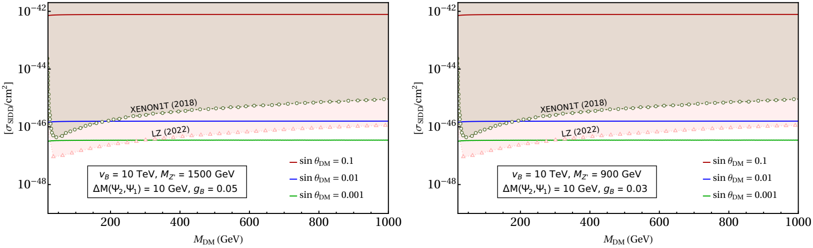


Figure 1: Spin-independent direct detection (SIDD) cross-section as a function of DM mass in the range 0–1500 GeV. Experimental limits from LZ (dashed black) and XENON1T (dot-dashed black) are shown for comparison. Left and right panels correspond to two different $M_{Z'}$ values. The curves represent different DM mixing angles, as labeled in the figure, with fixed values of other parameters.

Direct detection......

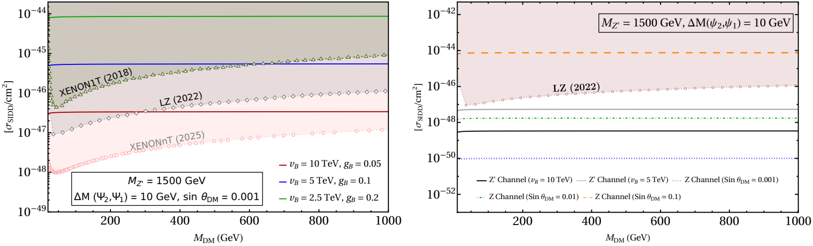


Figure 2: Spin-independent DM-neutron cross-section vs M_{DM} (30–1000 GeV). Left: Z and Z' contributions for various $\sin\theta_{DM}$ and v_B. Right: Comparison of Z and Z' channels with fixed $M_{Z'} = 1500$ GeV, $\Delta M = 10$ GeV. LZ bound and future sensitivities are shown. Results computed using micrOMEGAs.

Direct detection.......

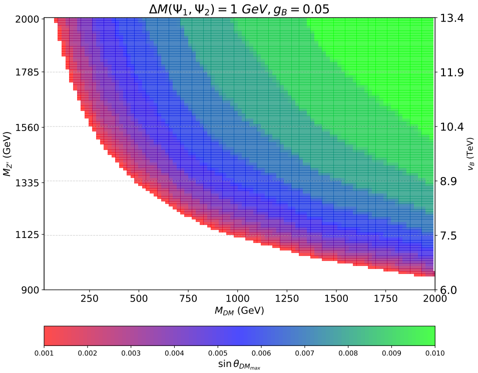
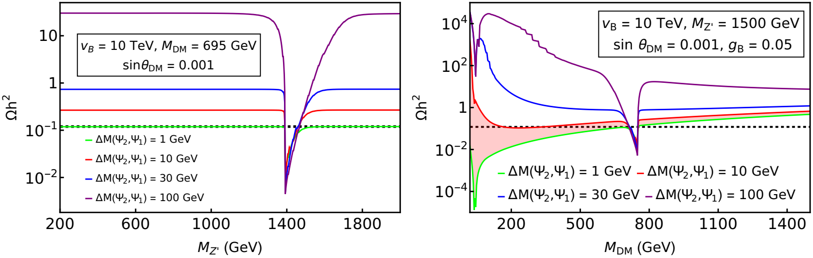


Figure 3: Heat map showing the allowed parameter space in the $M_{\rm DM}$–$M_{Z'}$ plane from direct detection (DD) constraints. The color scale indicates the maximum allowed value of the DM mixing angle $\sin\theta_{\rm DM}$ at each point. We fix $\Delta M(\Psi_2, \Psi_1) = 1$ GeV and $g_B = 0.05$. All axis values are in GeV.

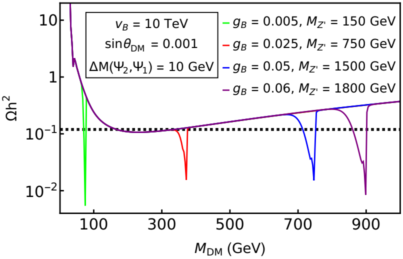
Relic density analysis



Relic density plot for the extended $U(1)_B$ Model. The plots depicts the value of relic density as a function of the mass of new mediator $M_{Z'}$. In this plot:

- Region of resonance : At $M_{DM} = M_{Z'}/2$, due to the enhancement of the dark matter annihilation cross section, the relic density of DM is strongly suppressed.
- Other values of $M_{Z'}$: Relic abundance is not strongly dependent on $M_{Z'}$ at mass values other than the resonance region.
- Mass splitting in the exotic neutral sector: Relic density $\propto$ mass spliting (due to the presence of co-annihilations with the next-to-lightest exotic fermion state (Ψ_2)).
- Breaking scale of $U(1)_B$: not strongly dependent to relic abundance.

Relic analysis continued...



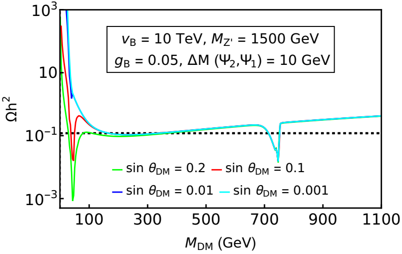


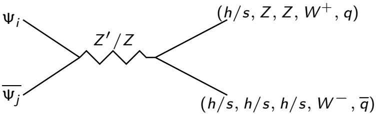
Figure shows DM relic density as a function of the DM mass with fixed $(g_B, v_B, M_{Z'}, \Delta m)$ but different mixing angle values. We see that the slope of resonance sharpens as we increase $M_{Z_,}$ and DM mass value. In this plots:

- location and width of the resonance region: location of the resonance region $\propto M_{Z'}$. **Width** $\propto$ **decay width of new gauge field** $\propto$ **coupling strength of new gauge** $\propto \frac{1}{\textbf{lifetime}}$. and can decay into a wider range of final states. As a result, the enhancement in the annihilation cross section due to the resonance is spread over a larger range of Z' masses.
- mass splitting: **mass spliting** $\propto$ **relic density**, co-annihilation and annihilation.

Feynman diagrams relevent with relic analysis:

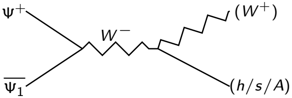
$$\mathcal{L}_{\text{int}} = ig\overline{\Psi}_i\gamma^\mu\Psi_j B_\mu$$

Here, $B = Z'/Z/W^+/W^-$

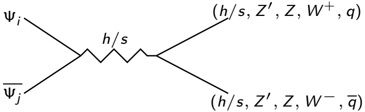


$$\mathcal{L}_{\text{int}} = ig\Psi^+\gamma^\mu\Psi_i B_\mu$$

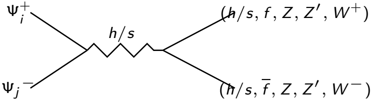
Here, $B = W^+/W^-$



$$\mathcal{L}_{\text{int}} = \lambda_h\overline{\Psi}_i\Psi_j H,\ \lambda_s\overline{\Psi}_i\Psi_j S_B$$



$$\mathcal{L}_{\text{int}} = \lambda_h\psi_i^+\psi_j H,\ \lambda_s\overline{\Psi}_i\Psi_j S_B$$



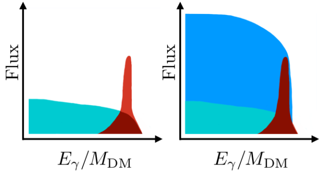
All the interaction channels verified by the CalcHEP HEP package.

Discussion on Indirect detection

There are two main requirements for detecting such gamma rays:

- A sufficiently high annihilation cross-section of DM, ensuring enough flux of these rays to be detectable using current gamma-ray telescopes.
- Suppression of the continuous spectrum from other physical processes, providing a clean signal with minimal background.

However, the above case applies only to Majorana-type dark matter. In our case, the dark matter is of Dirac type, which is not suppressed by the velocity of the FSR processes.



Conclusions....

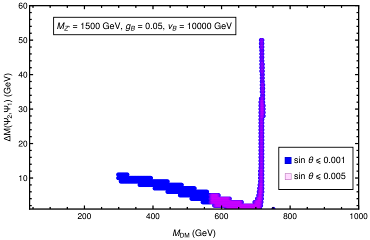


Figure 4: Scatter plots in the plane of $M_{\rm DM} - \Delta M\ (\Psi_2, \Psi_1)$ for $M_{Z'} = 1500$ GeV in the left panel and for $M_{Z'} = 900$ GeV in the right left panel. v_B is fixed at 10 TeV for both the plots. Plots show the allowed parameter space from DM relic, direct detection (LZ-2022) and collider constraints.

Conclusions....

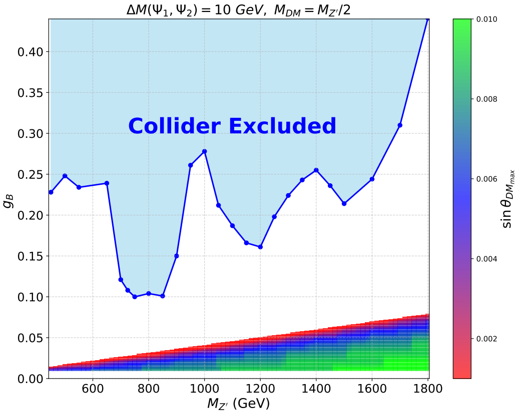


Figure 5: Scatter plot in the plane of $M_{Z'} - g_B$ with $\Delta M(\Psi_2, \Psi_1) = 10$ GeV and $M_{\rm DM} = M_{Z'}/2$. The plot shows color-coded region allowed from DM relic and SIDD constraints. The color value shows the maximum value of DM mixing angle for which the constraints are evaded. The blue-shaded region towards the top shows the parameter region already probed by the collider data.

Conclusion....

- The observed relic abundance of DM implies that its freeze-out cross-section (0.1 pb) is typically a weak interaction cross-section. Therefore, it is widely believed that DM is a WIMP.
- We studied the case of a mixed (singlet+doublet) leptonic DM, which satisfies the relic abundance within a large parameter space.
- The spin-independent direct detection cross-section is within the reach of the Xenon1T and LUX experimental data.
- In indirect detection, FSR processes are not suppressed by the velocity, making them irrelevant for our model.

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Thank You!

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