WIMP-FIMP option and neutrino masses via a novel anomaly-free B−L symmetry

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Based On: 2503.02635

7th Mini-Workshop on
"CHIRALITY IN THE UNIVERSE BEYOND THE ELECTROWEAK SCALE"

25th April - 28th April 2025

The K-Hotel, Sandong, Gurye

National Research Foundation of Korea

중앙대학교 CHUNG-ANG UNIVERSITY

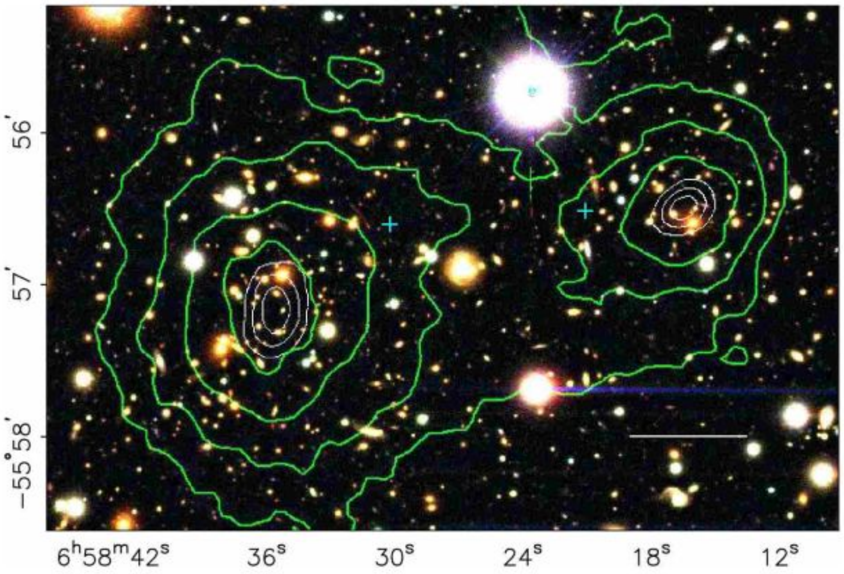
과학기술정보통신부

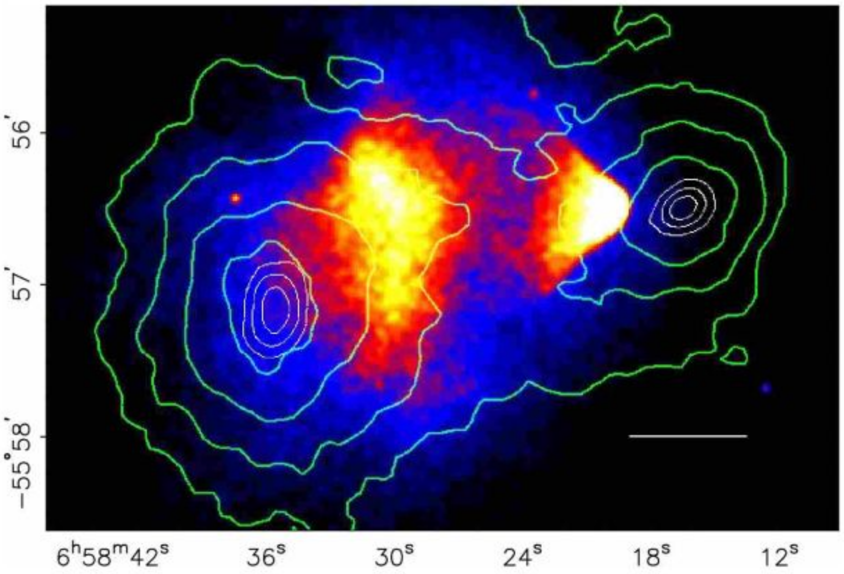
Tentative Plan

- Motivation for Dark Matter Study
- Dark matter status in direct detection
- Model Description
- Constraints
- Results
- Conclusion

Bullet cluster 1E0657-558

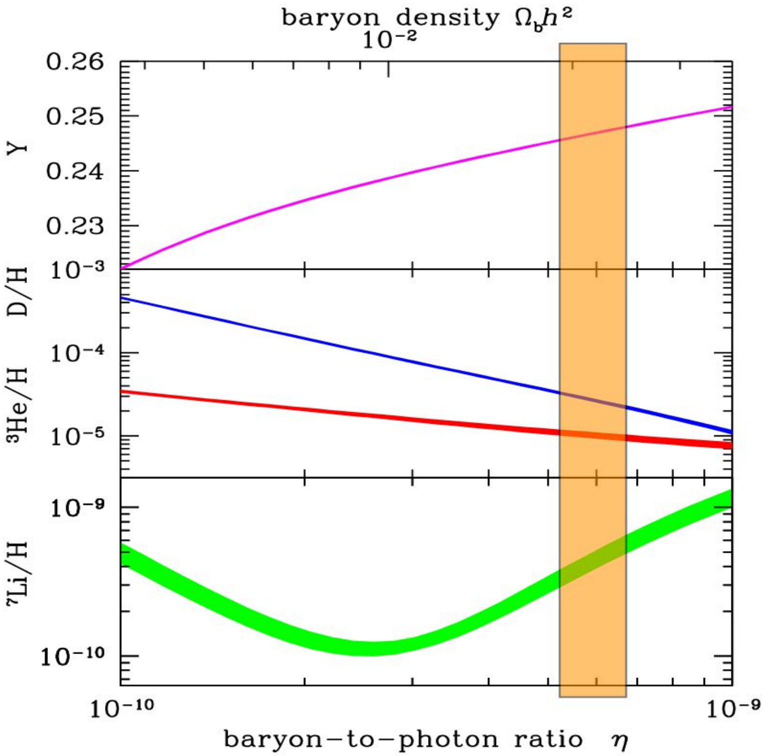
Astrophys. J. 648, L109 (2006)

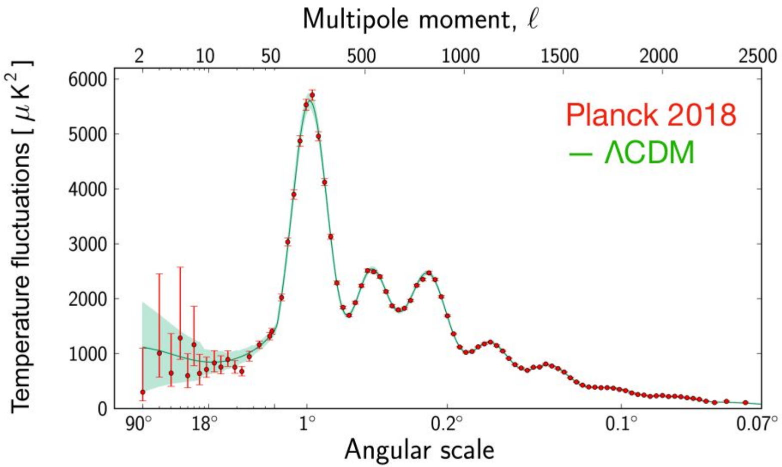




- ➢ Bullet cluster is a recent merging of galaxy clusters.
- ➢ The gravitational potential is not produced by baryons, but by DM.
- ➢ Hot gas is collisional and loses energy, so lags behind DM.
- ➢ DM clusters are collisionless and passed through each other

BBN and CMB

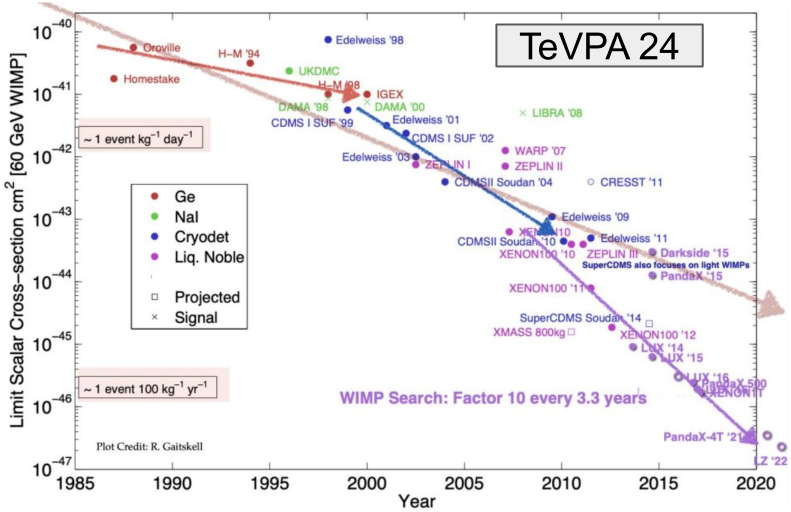


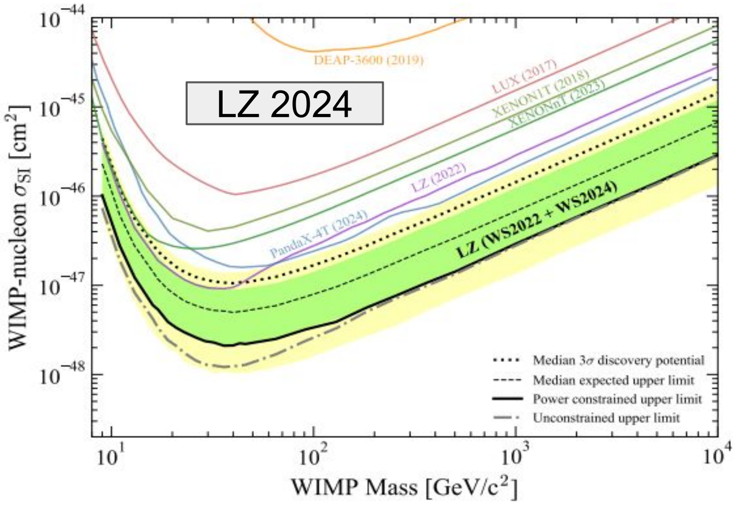


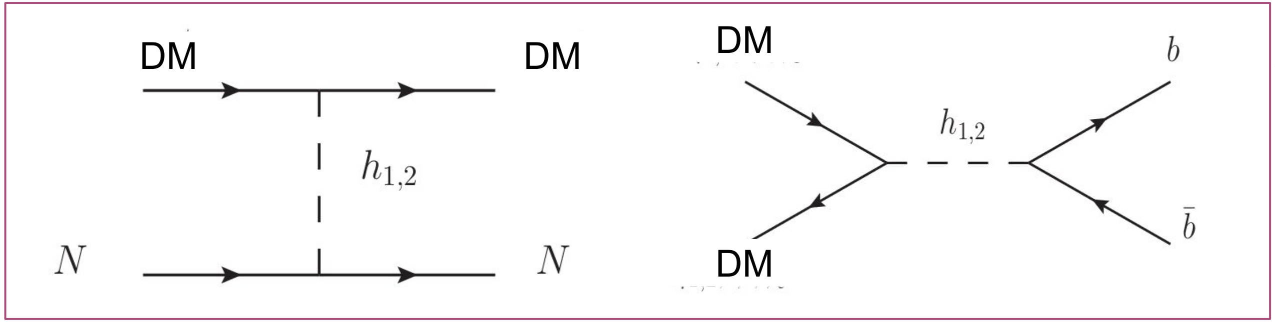
Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

➢ LSS suggests without DM, density perturbations would start to grow only after recombination, so today there would not be structures.

Direct Detection in Present time







Standard Scenario is Tightly Constrained

Alternative Mechanisms ???

Particle Content & SSB

Gauge Group	Extra fermions				Extra scalars	
	ξ_{1L}	ξ_{2L}	χ_{1L}	χ_{2L}	ϕ_1	ϕ_2
$SU(2)_L$	1	1	1	1	1	1
$U(1)_Y$	0	0	0	0	0	0
$U(1)_{B-L}$	a	b	c	c	n	$2n$

Gauge Anomaly Conditions

$$\begin{aligned} [U(1)_{B-L}]^3 &\rightarrow a^3 + b^3 - 2c^3 = 3\,, \\ [\text{Gravity}]^2 \times U(1)_{B-L} &\rightarrow a + b - 2c = 3\,, \\ \text{Yukawa terms} &\rightarrow a - c = 2n \text{ and } b - c = n\,. \end{aligned}$$

$$(a, b, c, n) = (1, 0, -1, 1) \text{ and } \left(\frac{4}{3}, \frac{1}{3}, -\frac{2}{3}, 1\right).$$

Usual Type-I

Will be used

$$\begin{aligned} \mathcal{V}(\phi_h, \phi_1, \phi_2) &= -\mu_h^2 \left(\phi_h^\dagger \phi_h\right) + \lambda_h \left(\phi_h^\dagger \phi_h\right)^2 - \mu_1^2 \left(\phi_1^\dagger \phi_1\right) + \lambda_1 \left(\phi_1^\dagger \phi_1\right)^2 - \mu_2^2 \left(\phi_2^\dagger \phi_2\right) \\ &+ \lambda_2 \left(\phi_2^\dagger \phi_2\right)^2 + \lambda_{h1} \left(\phi_h^\dagger \phi_h\right) \left(\phi_1^\dagger \phi_1\right) + \lambda_{h2} \left(\phi_h^\dagger \phi_h\right) \left(\phi_2^\dagger \phi_2\right) \\ &+ \lambda_{12} \left(\phi_1^\dagger \phi_1\right) \left(\phi_2^\dagger \phi_2\right) + \mu \left(\phi_2 \phi_1^{\dagger 2} + \phi_2^\dagger \phi_1^2\right) \end{aligned}$$

During SSB

$$\phi_h = \begin{pmatrix} G^+ \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix}, \quad \phi_1 = \frac{v_1 + H_1 + iA_1}{\sqrt{2}}, \quad \phi_2 = \frac{v_2 + H_2 + iA_2}{\sqrt{2}}.$$

$$M^2_{scalar} = \begin{pmatrix} 2\lambda_h v_h^2 & \lambda_{h1} v_h v_1 & \lambda_{h2} v_h v_2 \\ \lambda_{h1} v_h v_1 & 2\lambda_1 v_1^2 & v_1 \left(\sqrt{2}\mu + \lambda_{12} v_2\right) \\ \lambda_{h2} v_h v_2 & v_1 \left(\sqrt{2}\mu + \lambda_{12} v_2\right) & \left(-\frac{\mu v_1^2}{\sqrt{2} v_2} + 2\lambda_2 v_2^2\right) \end{pmatrix}.$$

$$M^2_{CP-odd} = \begin{pmatrix} -2\sqrt{2}\mu v_2 & \sqrt{2}\mu v_1 \\ \sqrt{2}\mu v_1 & -\frac{\mu v_1}{\sqrt{2} v_2} \end{pmatrix}.$$

Fermionic Dark Matter

$$\mathcal{L}_{BL}^{Kin} = \sum_{X=\xi_{1L},\xi_{2L},\xi_{1R},\chi_{2R}} \bar{X} i \not{D} X + \alpha_1 \bar{\xi}_{1L}\chi_{1R}\phi_2 + \alpha_2 \bar{\xi}_{2L}\chi_{2R}\phi_1 + \beta_1 \bar{\xi}_{2L}\chi_{1R}\phi_1 + \beta_2 \bar{\xi}_{1L}\chi_{2R}\phi_2 + h.c.$$

After SSB

$$\mathcal{L}_{\xi\chi} = \begin{pmatrix} \bar{\xi}_{1L} & \bar{\xi}_{2L} \end{pmatrix} \begin{pmatrix} \frac{\alpha_1 v_2}{\sqrt{2}} & \frac{\beta_2 v_2}{\sqrt{2}} \\ \frac{\beta_1 v_1}{\sqrt{2}} & \frac{\alpha_2 v_1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \chi_{1R} \\ \chi_{2R} \end{pmatrix} + h.c.$$

$$\tan\theta_R = \frac{M_1 v_2 \beta_2 + M_2 v_1 \beta_1}{M_2 v_1 \alpha_2 - M_1 v_2 \alpha_1},$$
$$\tan\theta_L = \frac{M_1}{M_2}\frac{\alpha_1 \tan\theta_R + \beta_1}{\alpha_1 - \beta_2 \tan\theta_R}.$$

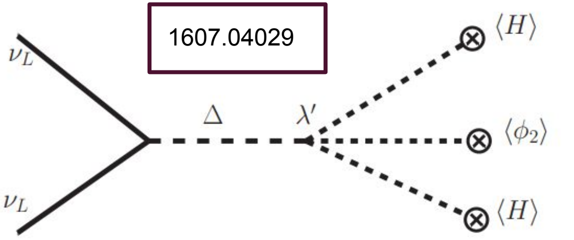
$$\mathcal{L}_{\psi}^{Yuk} = \sum_{i=1,2,3} \alpha_{11i}\bar{\psi}_{1L}\psi_{1R}h_i + \sum_{i=1,2,3} \alpha_{12i}\bar{\psi}_{1L}\psi_{2R}h_i + \sum_{i=1,2,3} \alpha_{21i}\bar{\psi}_{2L}\psi_{1R}h_i + \sum_{i=1,2,3} \alpha_{22i}\bar{\psi}_{2L}\psi_{2R}h_i + i\,\alpha_{11A}\,\bar{\psi}_{1L}\psi_{1R}A + i\,\alpha_{12A}\,\bar{\psi}_{1L}\psi_{2R}A + i\,\alpha_{21A}\,\bar{\psi}_{2L}\psi_{1R}A + i\,\alpha_{22A}\,\bar{\psi}_{2L}\psi_{2R}A + h.c..$$

$$\alpha_{11i} = \frac{M_1}{\sqrt{2}v_1 v_2}\left[U_{3i}v_1 + U_{2i}v_2 + (U_{3i}v_1 - U_{2i}v_2)\cos 2\theta_L\right],$$
$$\alpha_{12i} = \frac{\sqrt{2}M_2}{v_1 v_2}\left[(U_{3i}v_1 - U_{2i}v_2)\cos\theta_L \sin\theta_L\right],$$
$$\alpha_{21i} = \frac{\sqrt{2}M_1}{v_1 v_2}\left[(U_{3i}v_1 - U_{2i}v_2)\cos\theta_L \sin\theta_L\right],$$
$$\alpha_{22i} = \frac{M_2}{\sqrt{2}v_1 v_2}\left[U_{3i}v_1 + U_{2i}v_2 + (-U_{3i}v_1 + U_{2i}v_2)\cos 2\theta_L\right].$$

$$\mathcal{L}_{\psi Z_{BL}} = -\frac{g_{BL}}{3}\Big[\bar{\psi}_1\gamma^\mu\left((3\cos^2\theta_L + 1)P_L - 2P_R\right)\psi_1 + \bar{\psi}_2\gamma^\mu\left((3\sin^2\theta_L + 1)P_L - 2P_R\right)\psi_2 + \bar{\psi}_1\gamma^\mu(2\sin^2\theta_L)P_L\psi_2 + \bar{\psi}_2\gamma^\mu(2\sin^2\theta_L)P_L\psi_1\Big] Z_{BL\mu}. \quad ($$

Neutrino Mass

$$\mathcal{L}_{Neutrino} = \kappa_{ij}\frac{(L_i\phi_h)(L_j\phi_h)}{\Lambda}\frac{\phi_1^2}{\Lambda^2} + \kappa'_{ij}\frac{(L_i\phi_h)(L_j\phi_h)}{\Lambda}\frac{\phi_2}{\Lambda} + h.c..$$



$$m_\nu = f\langle\Delta\rangle \simeq f\frac{\lambda' v^2 v_2}{M_\Delta^2}.$$

With additional gauge symmetry and scalar

1805.00568

$$L_{ISS} = \sum_{\alpha,\beta=e,\mu,\tau} m_D^{\alpha\beta}\overline{\nu}_\alpha N_\beta + \overline{N^c_\alpha} M_N^{\alpha\beta} N'_\beta + \overline{N'^c_\alpha}\mu^{\alpha\beta}N'_\beta + h.c.$$

Gauge Group	Fermionic Fields		
	N_1	N_2	N_3
$SU(2)_L$	1	1	1
$U(1)_{B-L}$	1	-1	0

$$\begin{aligned}\mathcal{L}_N = {} & y_{e1}\bar{L}_e\tilde{\phi}_h N_1\frac{\phi_2}{\Lambda} + y_{e2}\bar{L}_e\tilde{\phi}_h N_2 + y_{e3}\bar{L}_e\tilde{\phi}_h N_3\frac{\phi_1}{\Lambda} + y_{\mu1}\bar{L}_\mu\tilde{\phi}_h N_1\frac{\phi_2}{\Lambda} + y_{\mu2}\bar{L}_\mu\tilde{\phi}_h N_2 \\ & + y_{\mu3}\bar{L}_\mu\tilde{\phi}_h N_3\frac{\phi_1}{\Lambda} + y_{\tau1}\bar{L}_\tau\tilde{\phi}_h N_1\frac{\phi_2}{\Lambda} + y_{\tau2}\bar{L}_\tau\tilde{\phi}_h N_2 + y_{\tau3}\bar{L}_\tau\tilde{\phi}_h N_3\frac{\phi_1}{\Lambda} + Y_{11}N_1N_1\phi_2 \\ & + Y_{12}N_1N_2\phi_2 + Y_{13}N_1N_3\phi_2 + Y_{22}N_2N_2\phi_2 + Y_{23}N_2N_3\phi_1 + M_{33}N_3N_3 + h.c..\end{aligned}$$

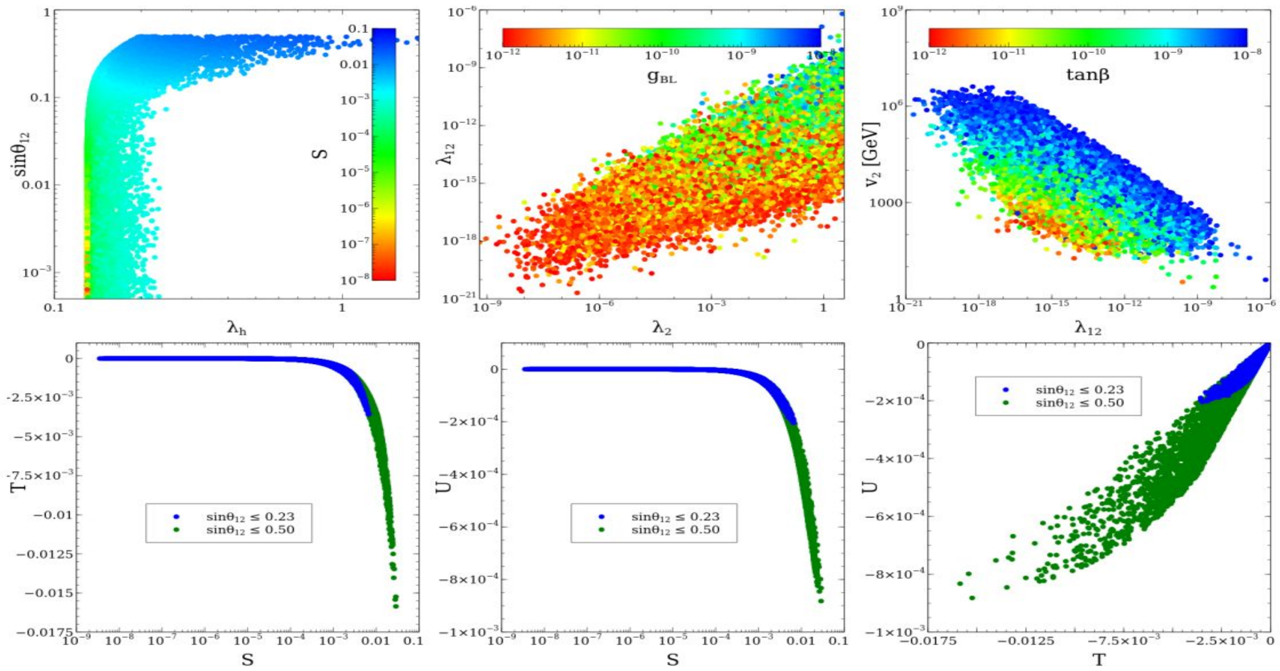
$$\mathcal{L}_{N-mass} = \begin{pmatrix}\bar{\nu}^c_{Li} & \bar{N}_i\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D^T & M_R\end{pmatrix}\begin{pmatrix}\nu_{Li} \\ N_i^c\end{pmatrix} + h.c.$$

$$m_\nu \simeq -m_D^T M_R^{-1} m_D\,, \quad M_N \simeq M_R$$

Constraints

- ➔ Checked gauge anomaly condition -> To keep the symmetry
- ➔ Perturbativity Bound -> We can ignore higher order terms
- ➔ Potential Bound from Below -> To make potential bounded for high field value
- ➔ Direct Detection Bound -> Severe bound from LUX-ZEPLIN
- ➔ Indirect Detection Bound -> Naturally small in present work
- ➔ Collider Bound mainly SM Higgs -> Higgs signal strength and Invisible decay
- ➔ BBN bound -> Decay before BBN time
- ➔ Oblique parameters -> safe for the allowed mixing angle after Higgs data

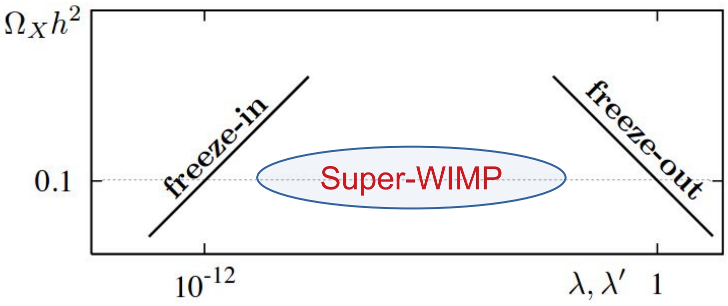
Allowed range (w/o using DM bound)

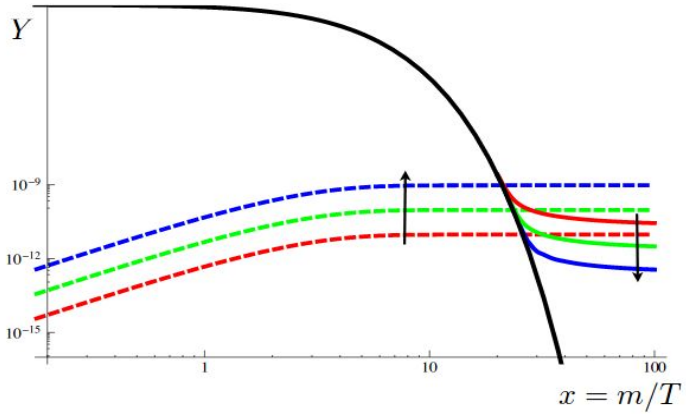


$$10^{-4} \leq \theta_{12} \leq 0.23\,,\ 10^{-4} \leq \theta_{13,23} \leq 0.1\,,\ 10^{-12} \leq g_{BL} \leq 10^{-8}\,,\ \theta_{L,R} = 0,$$
$$1 \leq \left(M_{h_{2,3}} - M_{h_1}\right)[\mathrm{GeV}] \leq 10^3,\ 1 \leq (M_A - M_{h_1})\,[\mathrm{GeV}] \leq 10^3\,,$$
$$1 \leq M_{Z_{BL}}[\mathrm{GeV}] \leq 10^3\,,\ 10^{-12} \leq \tan\beta \leq 10^{-8}\,.$$

DM Production Mechanisms

Hall et al' 09





- WIMP DM is easy to detect but no signal puts bound on its parameter space.
- FIMP DM is difficult to probe in different experiments due to its feeble interaction.
- In this work, we focus on production via freeze-in at low reheating.

- In the present work we have FIMP DM at the strong coupling.
- The relic density at strong coupling makes FIMP DM detectable.

Boltzmann Equations

Bath Particles

SM, ψ_1, h_i, A

Non-thermal Particles

ψ_2, Z_{BL}

$$\hat{L} f_{Z_{BL}} = \sum_{i=1,2,3} \mathcal{C}^{h_i \to Z_{BL} Z_{BL}} + \sum_{B,C=A,h_i} \mathcal{C}^{B \to Z_{BL} C} + \mathcal{C}^{Z_{BL} \to All}$$

$$\hat{L} = zH \left(1 + \frac{T g_s'}{3 g_s}\right) \frac{\partial}{\partial z}$$

$$\begin{aligned}
\frac{dY_{\psi_1}}{dz} &= -\frac{S(z_{\psi_1})\langle\sigma v\rangle_{\psi_1\psi_1}}{z_{\psi_1} H(z_{\psi_1})}\left(Y_{\psi_1}^2 - Y_{\psi_1}^{eq\,2}\right) \\
&\quad - \sum_{A=h_i,Z_{BL}} \theta(M_{\psi_1} - M_{\psi_2} - M_A)\frac{M_{pl} z\sqrt{g_{eff}}}{0.33 M_{sc}^2 g_{*,s}(z)}\left(\langle\Gamma_{\psi_1\to\psi_2 A}\rangle\left(Y_{\psi_1}^{eq} - Y_{\psi_2} Y_A\right)\right) \\
\frac{dY_{Z_{BL}}}{dz} &= \sum_{B=h_i} \theta(M_B - 2M_{Z_{BL}})\frac{2M_{pl} z\sqrt{g_{eff}}}{0.33 M_{sc}^2 g_{*,s}(z)}\langle\Gamma_{B\to Z_{BL} Z_{BL}}\rangle\left(Y_B^{eq} - Y_{Z_{BL}}^2\right)\Big] \\
&\quad + \sum_{B,C=h_i,A,\psi_1} \theta(M_B - M_C - M_{Z_{BL}})\frac{M_{pl} z\sqrt{g_{eff}}}{0.33 M_{sc}^2 g_{*,s}(z)}\left(\langle\Gamma_{B\to C Z_{BL}}\rangle\left(Y_B^{eq} - Y_C Y_{Z_{BL}}\right)\right) \\
&\quad - \sum_{C=All} \theta(M_{Z_{BL}} - 2M_C)\frac{M_{pl} z\sqrt{g_{eff}}}{0.33 M_{sc}^2 g_{*,s}(z)}\langle\Gamma_{Z_{BL}\to CC}\rangle_{NTH}\left(Y_{Z_{BL}} - Y_C^2\right)\Big] \\
\frac{dY_{\psi_2}}{dz} &= \sum_{B=h_i} \theta(M_B - 2M_{\psi_2})\frac{2M_{pl} z\sqrt{g_{eff}}}{0.33 M_{sc}^2 g_{*,s}(z)}\langle\Gamma_{B\to\psi_2\psi_2}\rangle\left(Y_B^{eq} - Y_{\psi_2}^2\right)\Big] \\
&\quad + \theta(M_{Z_{BL}} - 2M_{\psi_2})\frac{2M_{pl} z\sqrt{g_{eff}}}{0.33 M_{sc}^2 g_{*,s}(z)}\langle\Gamma_{Z_{BL}\to\psi_2\psi_2}\rangle_{NTH}\left(Y_{Z_{BL}} - Y_{\psi_2}^2\right)\Big] \\
&\quad + \sum_{A=h_i,Z_{BL}} \theta(M_{\psi_1} - M_{\psi_2} - M_A)\frac{M_{pl} z\sqrt{g_{eff}}}{0.33 M_{sc}^2 g_{*,s}(z)}\left(\langle\Gamma_{\psi_1\to\psi_2 A}\rangle\left(Y_{\psi_1}^{eq} - Y_{\psi_2} Y_A\right)\right) \qquad (28)
\end{aligned}$$

$$\langle\Gamma_{X\to BC}\rangle = \Gamma_{X\to BC}\frac{K_1(z_X)}{K_2(z_X)}, \quad \langle\Gamma_{Z_{BL}\to BC}\rangle = M_{Z_{BL}}\Gamma_{Z_{BL}\to BC}\frac{\int \frac{f_{Z_{BL}} d^3p}{\sqrt{p^2 + M_{Z_{BL}}^2}}}{\int f_{Z_{BL}} d^3p}$$

Equilibrium vs Nonequilibrium DM distribution

$$\hat{L} f_{Z_{BL}} = \sum_{i=1,2,3} \mathcal{C}^{h_i \to Z_{BL} Z_{BL}} + \sum_{B,C=A,h_i} \mathcal{C}^{B \to Z_{BL} C} + \mathcal{C}^{Z_{BL} \to All}$$

where the Lioville's operator, $\hat{L}$, can be expressed as,

$$\hat{L} = zH \left(1 + \frac{T g_s'}{3 g_s}\right) \frac{\partial}{\partial z} .$$

$$z \gg 1 \Rightarrow p \ll M_{Z_{BL}}$$

$$\Downarrow$$

$$< \sigma v >_{NTH} \simeq < \sigma v >_{TH} \simeq \Gamma_{Z_{BL}}$$

$$\mathcal{C}^{X \to Z_{BL} Y} = \frac{z}{16 \pi M_{sc}} \frac{\mathcal{B}^{-1}(z)}{\xi_p \sqrt{\xi_p^2 \mathcal{B}(z)^2 + \left(\frac{M_{Z_{BL}} z}{M_{sc}}\right)^2}} \frac{|M|^2_{X \to Z_{BL} Y}}{g_{Z_{BL}}} \times \left(e^{-\sqrt{\left(\xi_k^{\min}\right)^2 \mathcal{B}(z)^2 + \left(\frac{M_{h_2} z}{M_{sc}}\right)^2}} - e^{-\sqrt{\left(\xi_k^{\max}\right)^2 \mathcal{B}(z)^2 + \left(\frac{M_{h_2} z}{M_{sc}}\right)^2}}\right) .$$

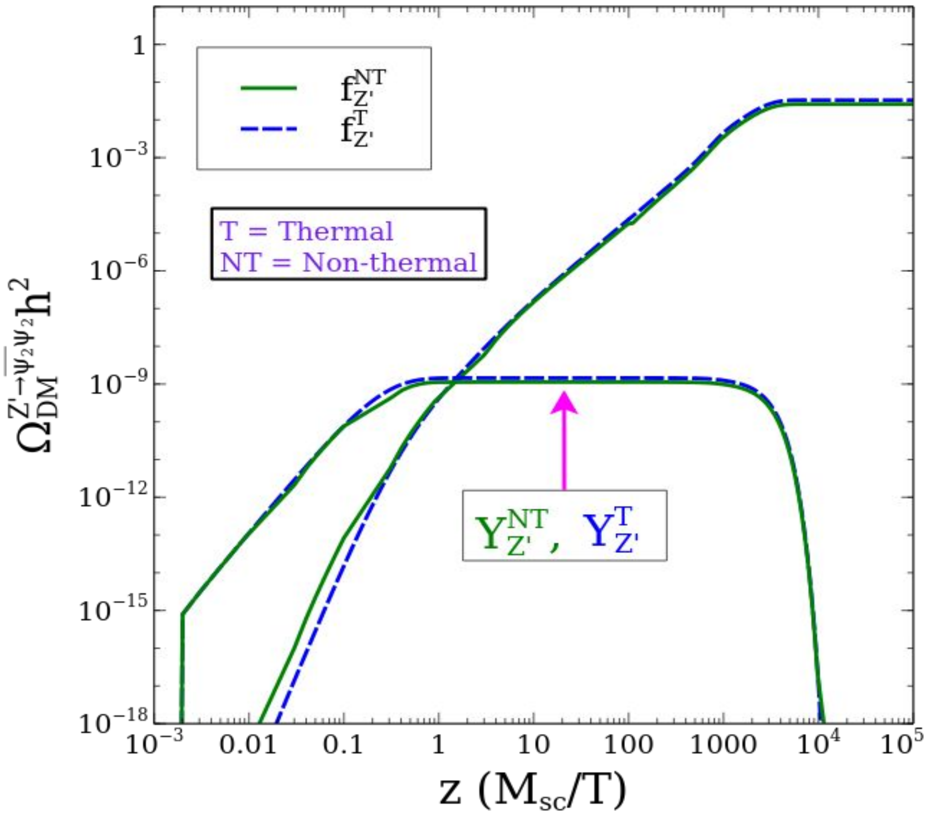
$$\xi_k^{\min}(\xi_p, z) = \frac{M_{sc}}{2\,\mathcal{B}(z)\, z\, M_{Z_{BL}}} \left| \eta(\xi_p, z) - \frac{\mathcal{B}(z) \times M_{h_2}^2}{M_{Z_{BL}} \times M_{sc}} \xi_p\, z \right| ,$$

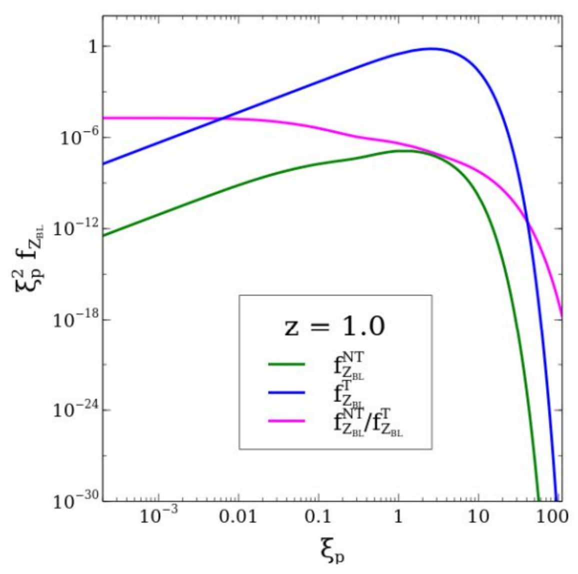
$$\xi_k^{\max}(\xi_p, z) = \frac{M_{sc}}{2\,\mathcal{B}(z)\, z\, M_{Z_{BL}}} \left(\eta(\xi_p, z) + \frac{\mathcal{B}(z) \times M_{h_2}^2}{M_{Z_{BL}} \times M_{sc}} \xi_p\, z \right) ,$$

$$\eta(\xi_p, z) = \left(\frac{M_{h_2} z}{M_{sc}}\right) \sqrt{\left[\left(\frac{M_X}{M_{Z_{BL}}} + 1\right)^2 - \left(\frac{M_Y}{M_{Z_{BL}}}\right)^2\right]\left[\left(1 - \frac{M_{Z_{BL}}}{M_X}\right)^2 - \left(\frac{M_{Z_{BL}}}{M_X}\right)^2\right]} \times \sqrt{\xi_p^2\, \mathcal{B}(z)^2 + \left(\frac{M_{Z_{BL}} z}{M_{sc}}\right)^2} . \quad (52)$$

$$\langle \Gamma_{X \to BC} \rangle = \Gamma_{X \to BC} \frac{K_1(z_X)}{K_2(z_X)} , \quad \langle \Gamma_{Z_{BL} \to BC} \rangle_{NTH} = M_{Z_{BL}} \Gamma_{Z_{BL} \to BC} \frac{\int \frac{f_{Z_{BL}} d^3 p}{\sqrt{p^2 + M_{Z_{BL}}^2}}}{\int f_{Z_{BL}} d^3 p} .$$

Thermal and Non-thermal Distribution





- Thermal and Non-thermal distribution produce same amount of DM
- Non-thermal distribution code runs very longer, so it is enough to consider the thermal distribution and proceed.

Analytical estimate and range

0911.1120

$$\Omega_{P_{DM}} h^2 \simeq \frac{1.09\times 10^{27}}{g_\rho^{3/2}} \frac{M_{P_{DM}} \Gamma_X}{M_X^2}$$

1807.06209

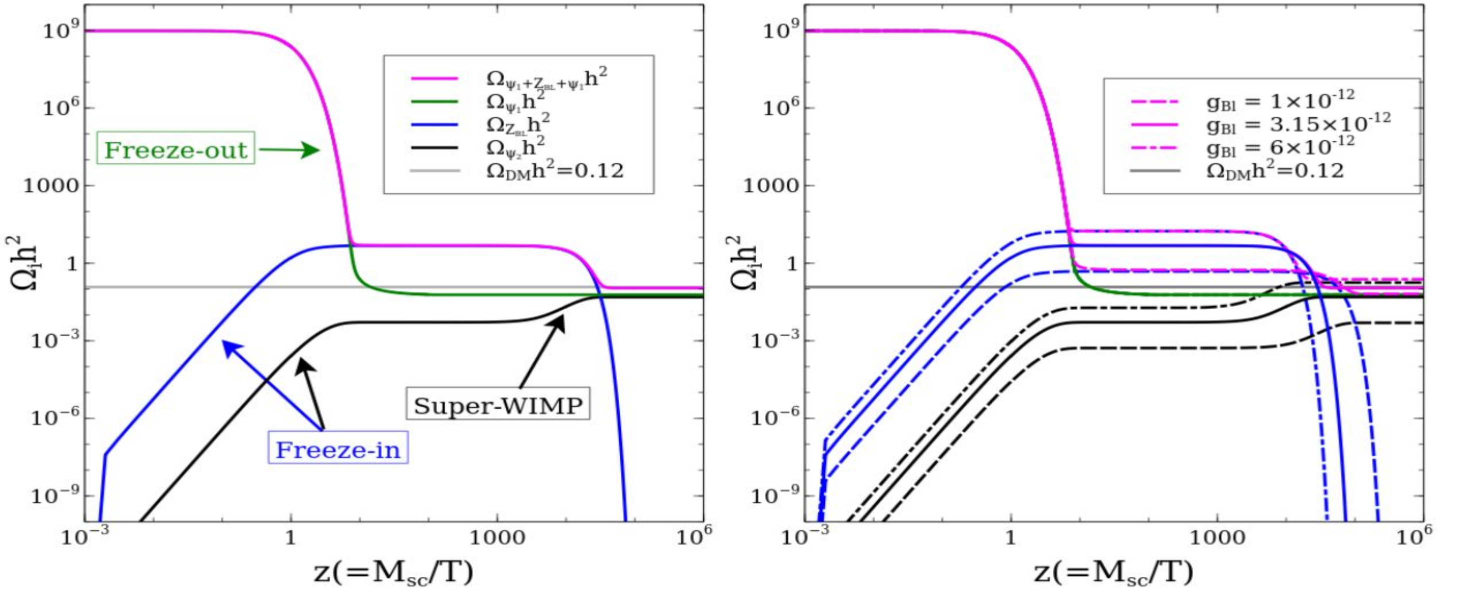
$$0.1116 \leq (\Omega_{\psi_1} + \Omega_{\psi_2})\, h^2 \leq 0.1284\,.$$

$$\Omega_{Z_{BL}} h^2 \simeq \sum_{X=h_{1,2,3}} \frac{2.18\times 10^{27}}{g_\rho^{3/2}} \frac{M_{Z_{BL}} \Gamma_{X\to Z_{BL} Z_{BL}}}{M_X^2} + \sum_{X,Q=h_{1,2,3},A} \frac{1.09\times 10^{27}}{g_\rho^{3/2}} \frac{M_{Z_{BL}} \Gamma_{X\to Z_{BL} Q}}{M_X^2}$$

$$\Omega_{\psi_2} h^2 \simeq \sum_{X=h_{1,2,3},A} \frac{2.18\times 10^{27}}{g_\rho^{3/2}} \frac{M_{\psi_2} \Gamma_{X\to\psi_2\psi_2}}{M_X^2} + 2\, Br(Z_{BL}\to\psi_2\psi_2)\, \frac{M_{\psi_2}}{M_{Z_{BL}}} \left(\Omega_{Z_{BL}} h^2\right)\,. \qquad (44)$$

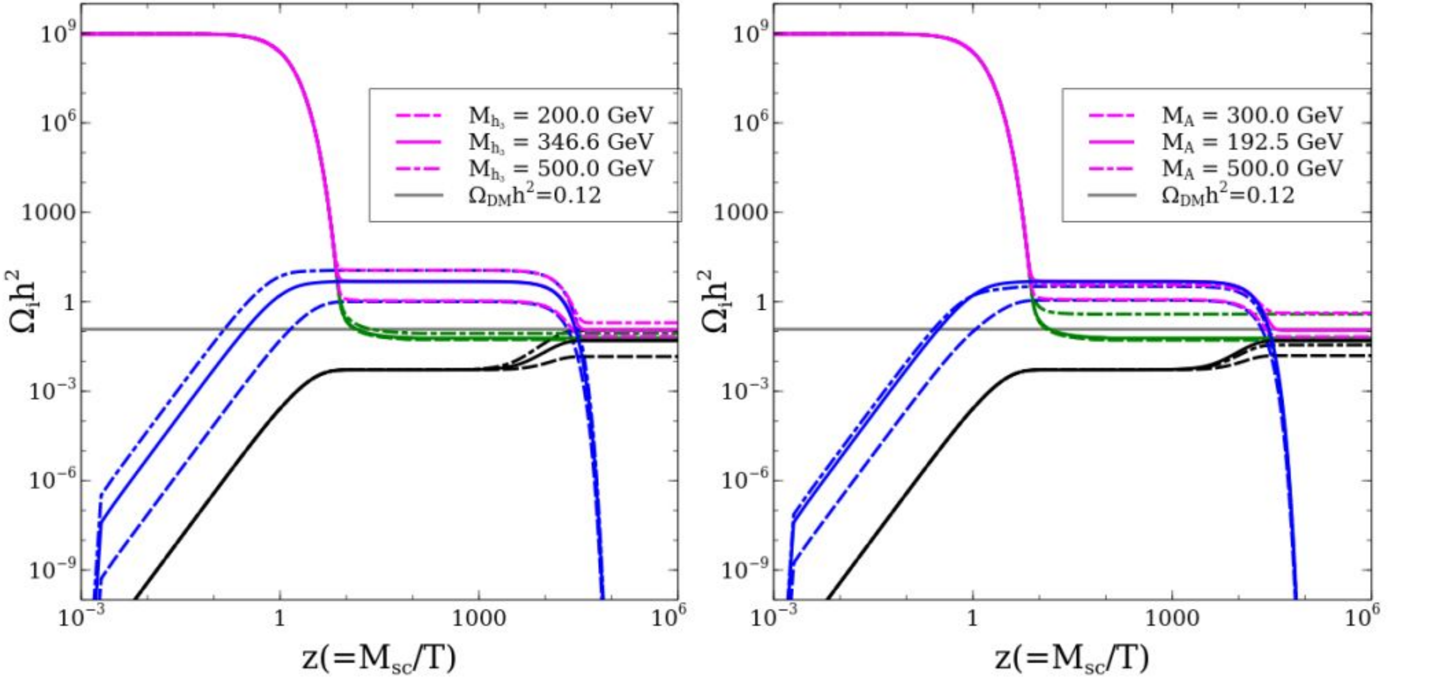
$$10^{-4} \leq \theta_{ij}\ (i,j=1,2,3) \leq 10^{-1}\,, 1 \leq \left(M_{h_{2,3}} - M_{h_1}\right)\ [\mathrm{GeV}] \leq 10^3\,, 10^{-12} \leq g_{BL} \leq 10^{-8}\,,$$
$$1 \leq M_{Z_{BL}}\ [\mathrm{GeV}] \leq 10^3\,, 1 \leq (M_A - (M_{Z_{BL}} + M_{h_1}))\ [\mathrm{GeV}] \leq 10^3\,, 10^{-12} \leq \tan\beta \leq 10^{-6}\,,$$
$$1 \leq M_{\psi_1}\ [\mathrm{GeV}] \leq 10^3\,, 1 \leq M_{\psi_2}\ [\mathrm{GeV}] \leq 10^3\,, \theta_L = 0\,. \qquad ($$

DM Production Mechanisms

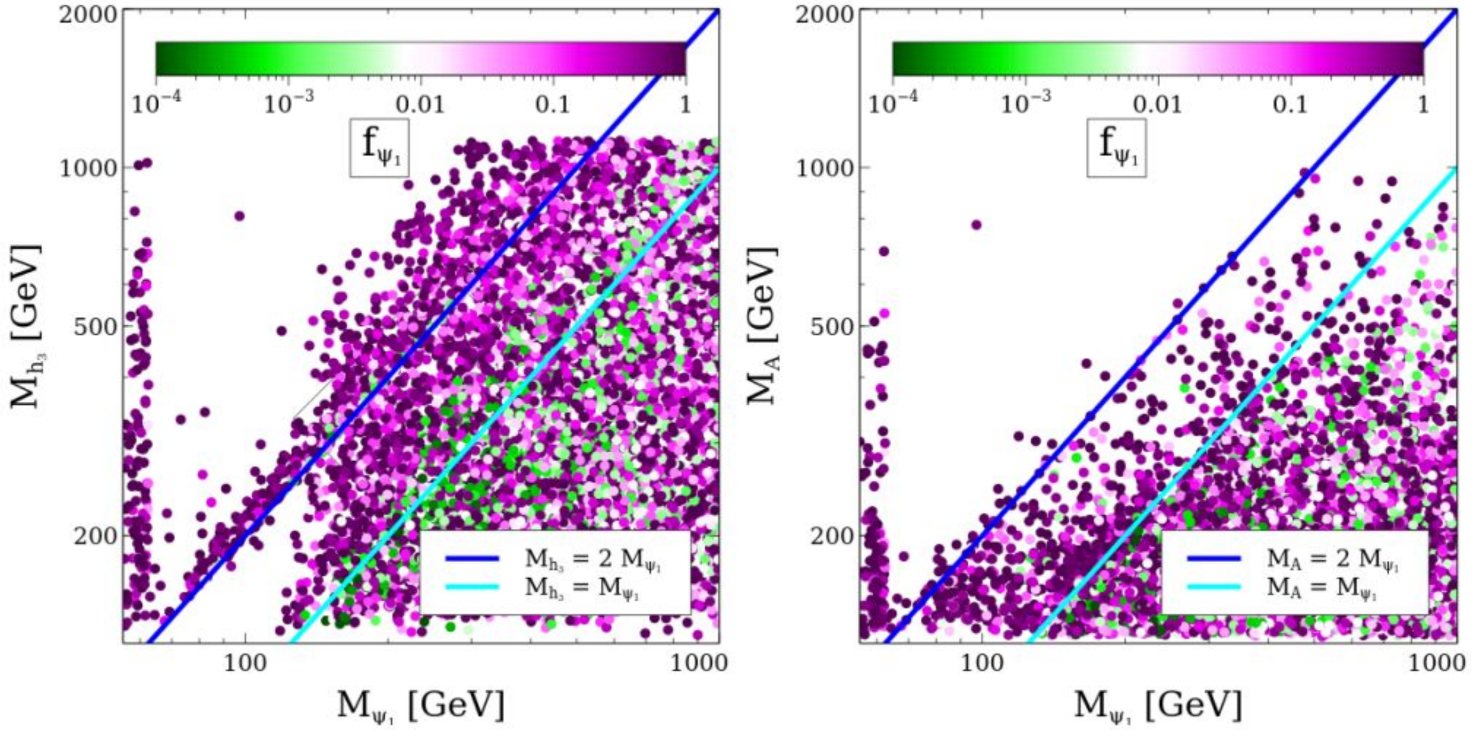


- ➢ LP shows the WIMP and FIMP DM productions by different mechanisms
- ➢ RP shows the dependence of DM relic density with the change of the gauge coupling

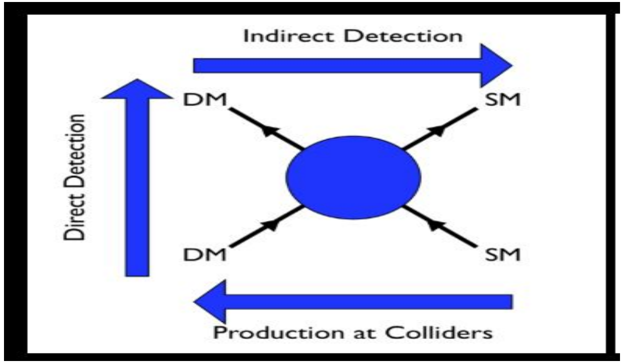
DM Variation with M_h2 and M_A

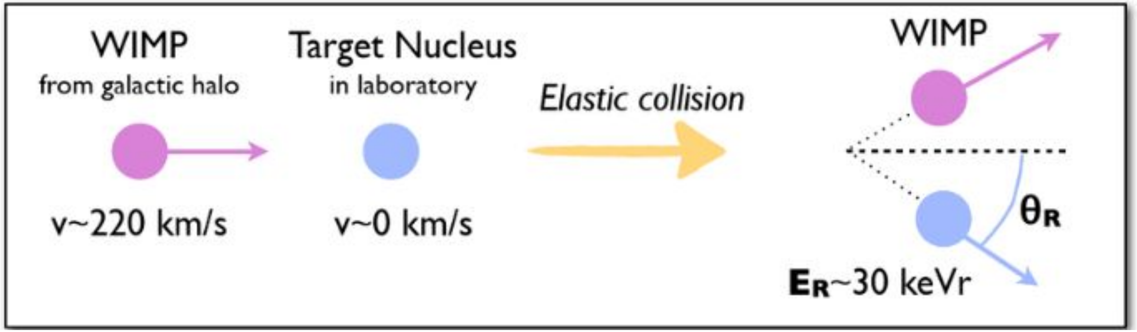


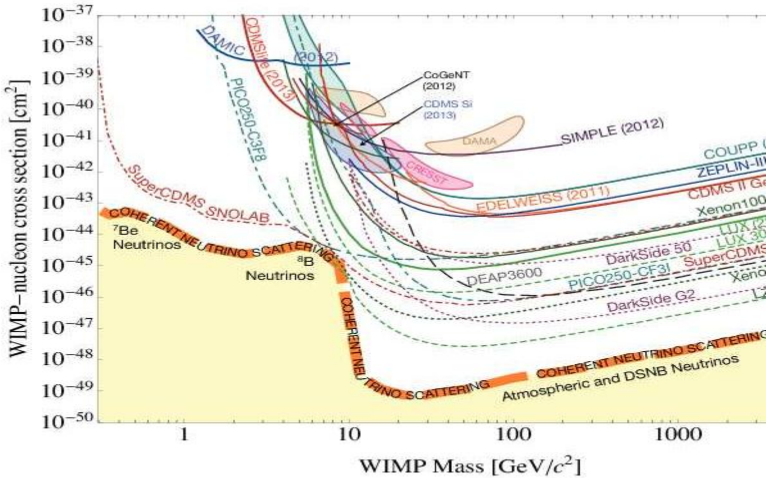
Variation in DM mass and Higgs mass

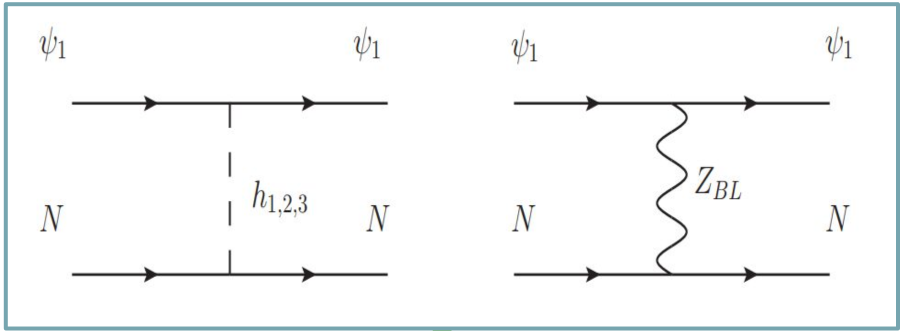


Direct Detection



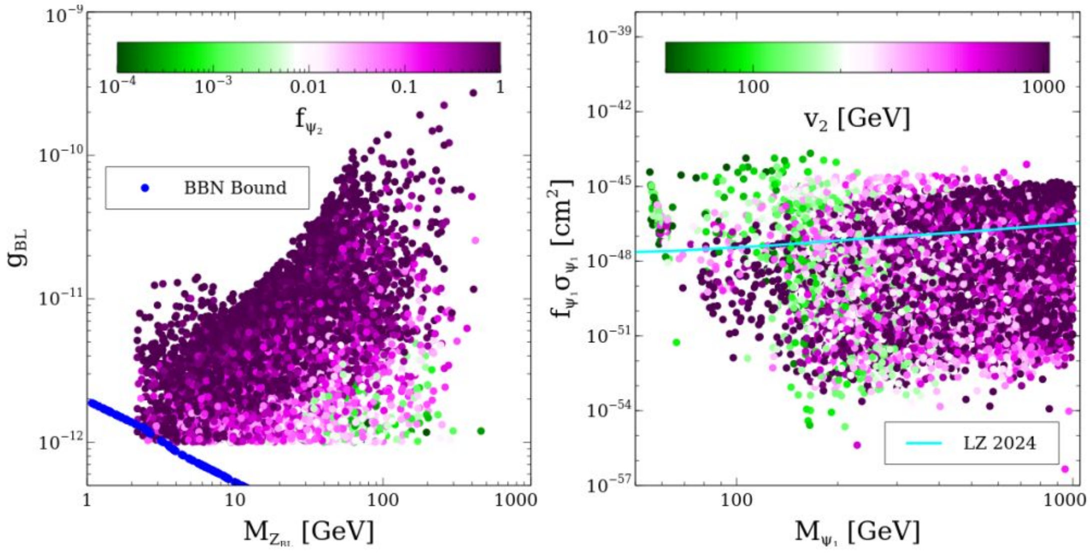






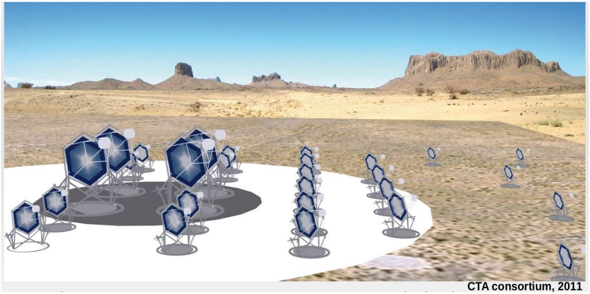
$$\sigma_{\psi_1} = \frac{\mu^2}{\pi}\left[\frac{f_N M_N}{v}\sum_{i=1,2,3}\frac{U_{1i}\alpha_{11i}}{M_{h_i}^2} + \frac{f_{Z_{BL}} g_{BL}^2\left(3\cos^2\theta_L - 1\right)}{18 M_{Z_{BL}}^2}\right]^2$$

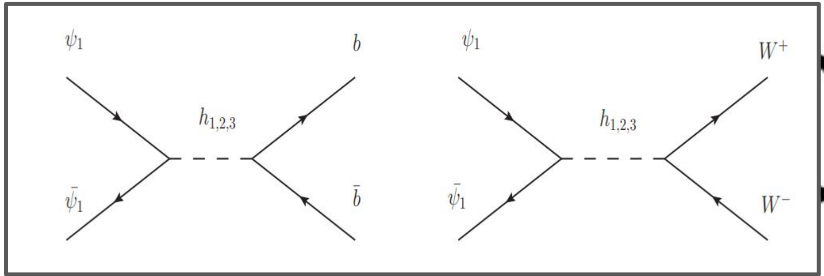
Direct Detection Prospects



A. LP: Variation in the M_ZBL - g_BL plane, some part is close to the BBN time.
B. RP: We see variation in the M_DM - sigma_SI plane, some part has been explored by LZ.

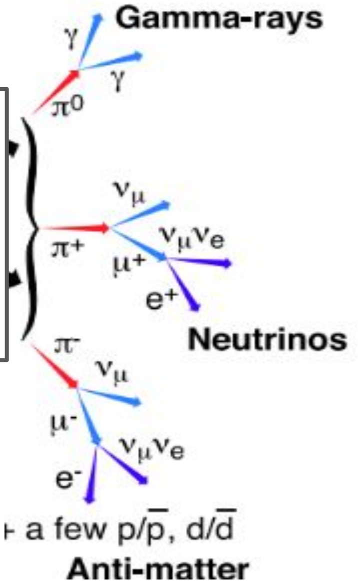
Indirect Detection

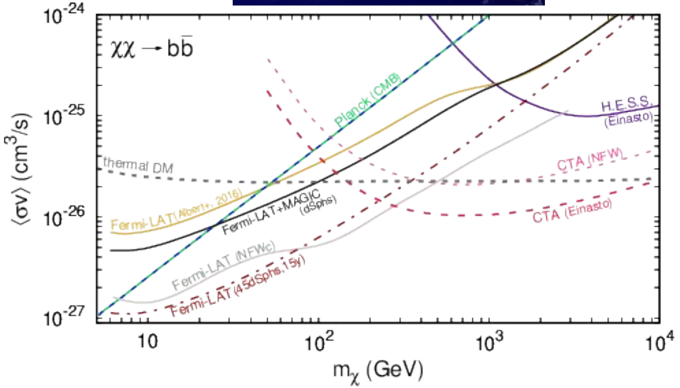




$$< \sigma v > \propto (s - 4M_{DM}^2)$$
$$\Downarrow$$
$$< \sigma v > \Rightarrow \underrightarrow{s \to 4M_{DM}^2 + M_{DM}^2 v_{rel}^2} \propto M_{DM}^2 v_{rel}^2$$

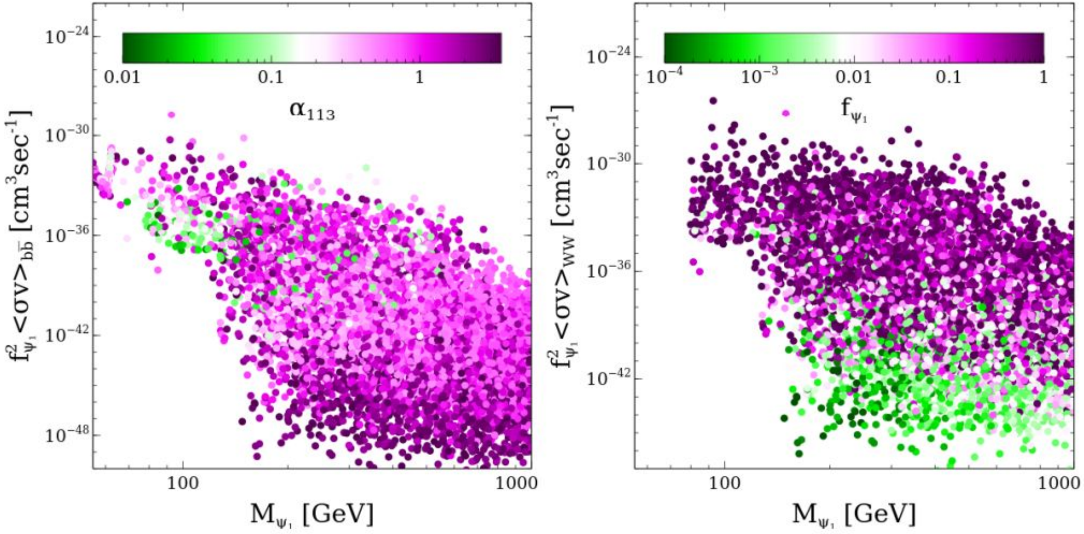
$$(\sigma v)_{kk} \simeq \frac{n_c v_{rel}^2 M_b^2 M_{\psi_1}^2 \left(1 - \frac{M_b^2}{M_{\psi_1}^2}\right)^{3/2}}{8\pi v^2} \sum_{i,j=1,2,3} A_i A_j^* \,, \text{ for } k - b \,,$$
$$\simeq \frac{v_{rel}^2 M_W^4 \sqrt{1 - \frac{M_W^2}{M_{\psi_1}^2}}}{16\pi v^2} \left(3 - \frac{4M_{\psi_1}^2}{M_W^2} + \frac{4M_{\psi_1}^4}{M_W^4}\right) \sum_{i,j=1,2,3} A_i A_j^* \,, \text{ for } k = W^\pm \,.$$





$$A_i = \frac{\alpha_{11i} U_{1i}}{(4M_{\psi_1}^2 - M_{h_i}^2) + i\Gamma_{h_i} M_{h_i}} \,.$$

Indirect Detection Prospects



A. LP:DM mass vs cross section for the bb channel which ic below the thermal CS for velocity suppress.
B. RP: We have shown the variation for the WW chanel.

Conclusion

- ★ We have studied fermionic dark matter produced from the freeze-out and super WIMP.
- ★ Some part of the region has been explored in the direct detection experiments
- ★ For fermionic DM, we have indirect detection which is suppressed by velocity
- ★ At collider we can expect similar search as WIMP type DM
- ★ We have shown for delayed decay it is not necessary to determine the distribution function which is cumbersome.
- ★ By changing the mass ordering we can easily accommodate FIMP type DM with less detection prospects.

Thank you for listening