Evading Dark Matter Bounds through NLSP-Assisted Freeze-Out with Long-Lived Signatures

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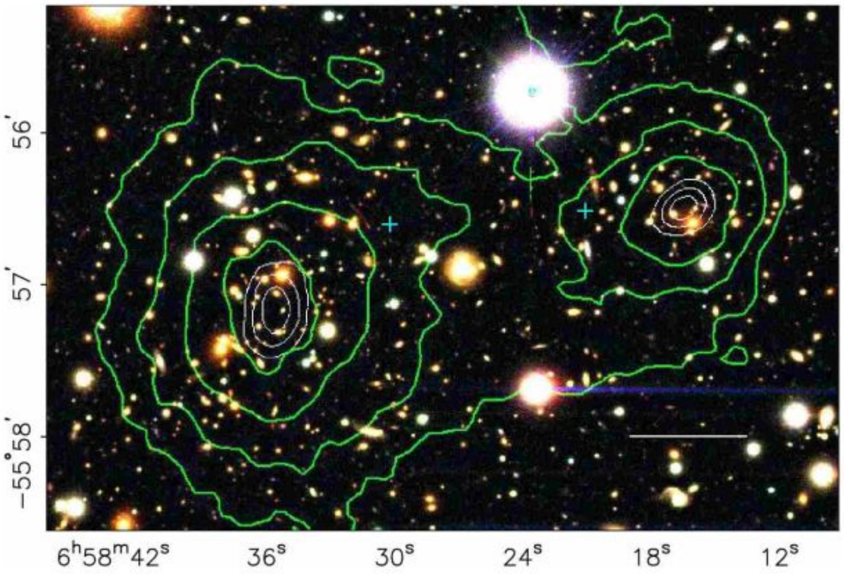
과학기술정보통신부

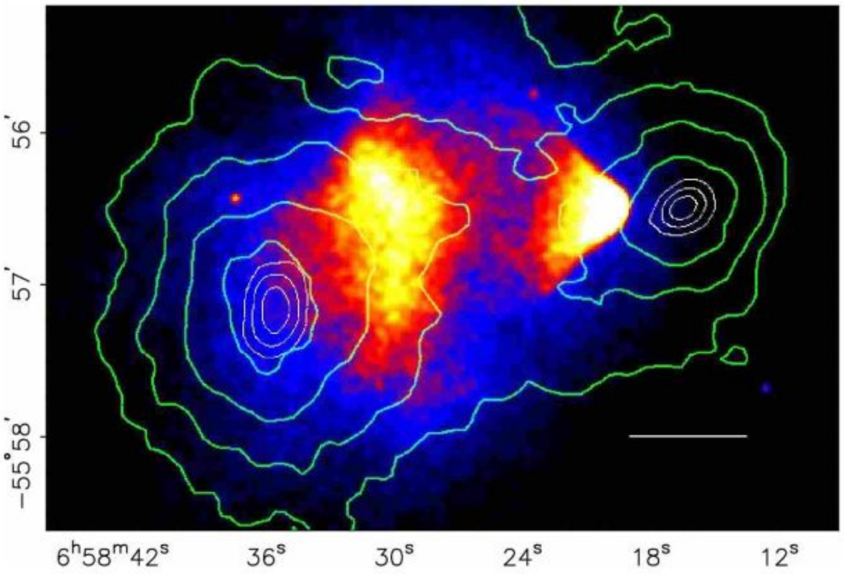
Tentative Plan

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

Bullet cluster 1E0657-558

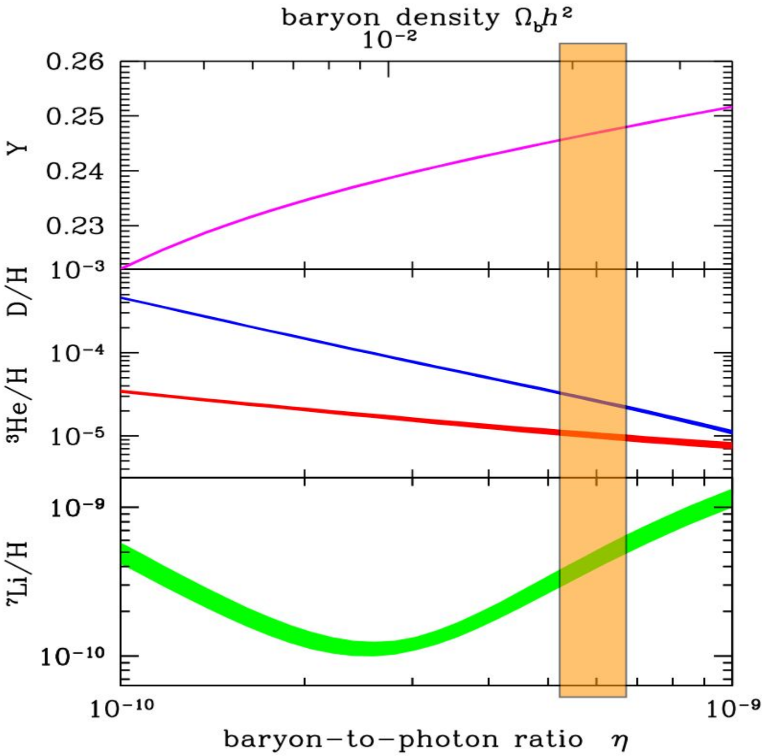
Astrophys. J. 648, L109 (2006)

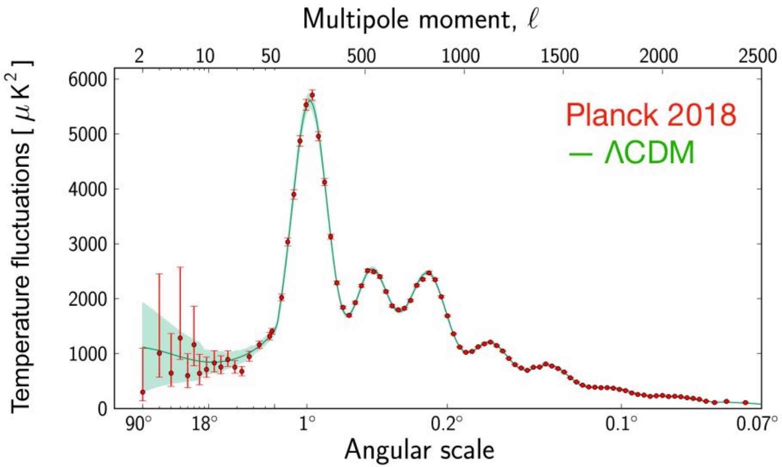




- Bullet cluster is a recent merging of galaxy clusters.
- The gravitational potential is not produced by baryons, but by DM.
- Hot gas is collisional and loses energy, so lags behind DM.
- DM clusters are collisionless and passed through each other

BBN and CMB

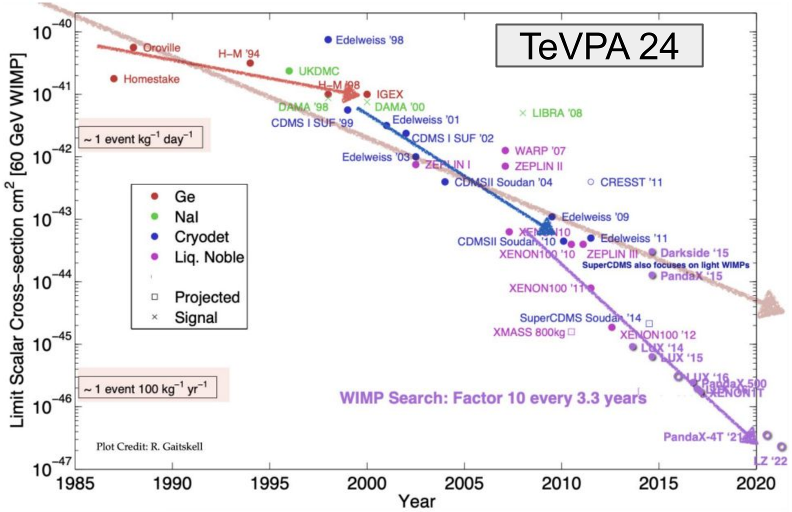


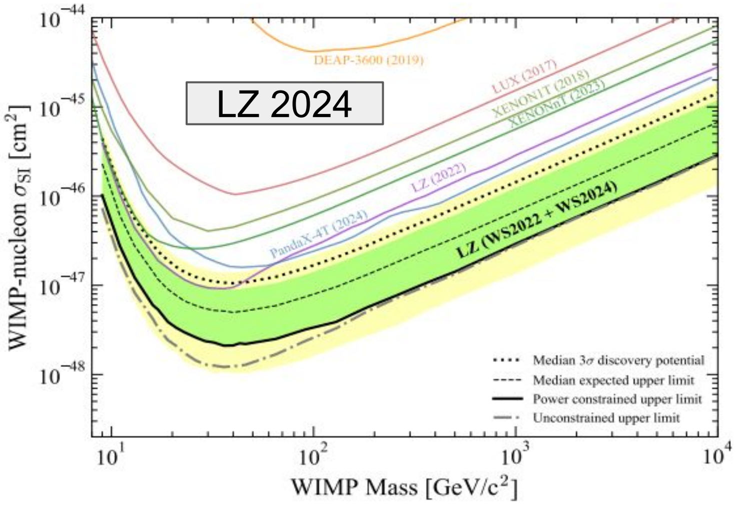


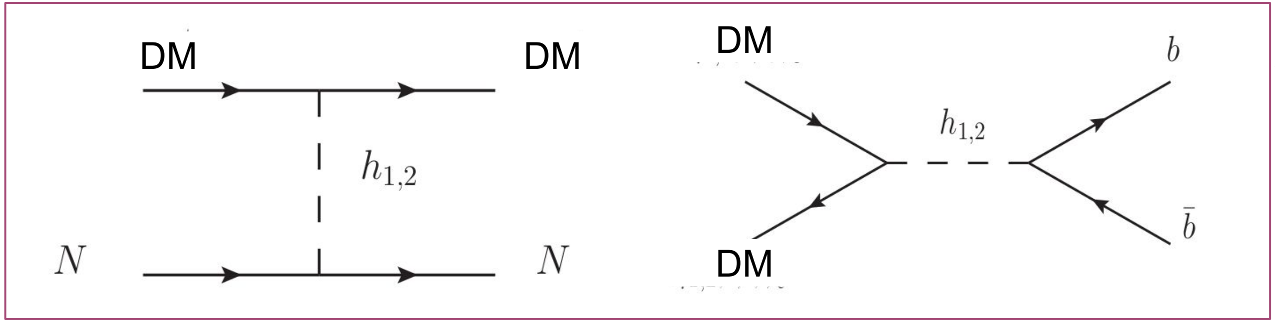
Parameter	Plik best fit	Plik [1]	CamSpec [2]	$([2]-[1])/\sigma_1$	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	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 in U1_B-L

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

Equal to SM

Gauge Anomaly Conditions

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

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

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

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

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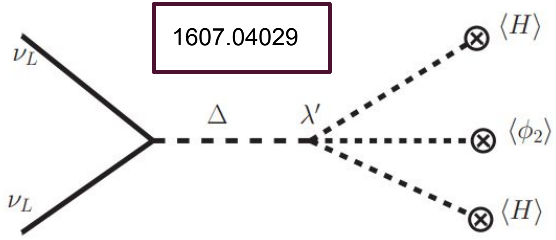


$$m_\nu = f\langle\Delta\rangle \simeq f\frac{\lambda' v^2 v_2}{M_\Delta^2}.$$

With additional gauge symmetry and scalar

1805.00568

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

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

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

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

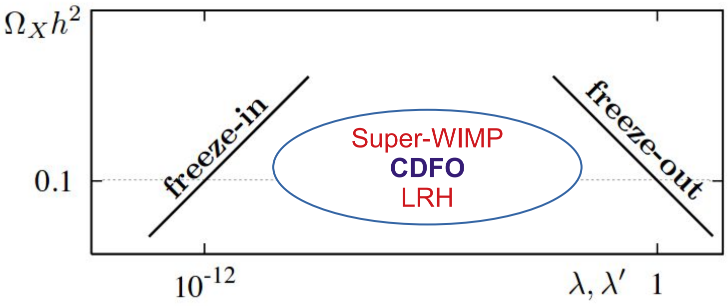
$$m_\nu \simeq -m_D^T M_R^{-1} m_D\,, \quad M_N \simeq M_R$$

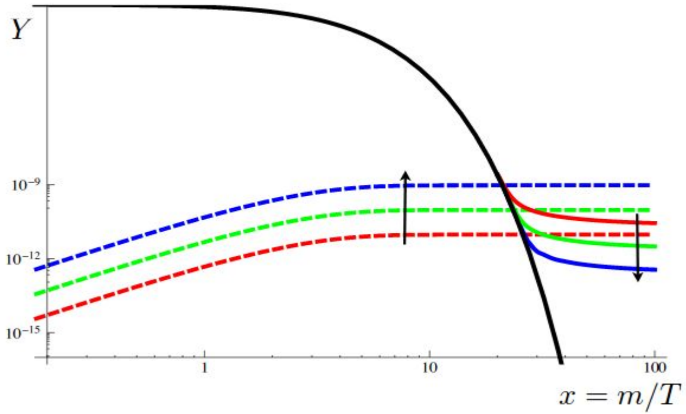
Constraints

- ➔ 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

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 conversion NLSP <-> DM.

- In the present work we have CDFO.
- The relic density can be fixed at any order of the DM direct coupling.
- DM is safe from all existing bounds naturally.

CDFO: Conversion Driven Freeze-Out
LRH: Low ReHeating

Contributing Diagrams and BE

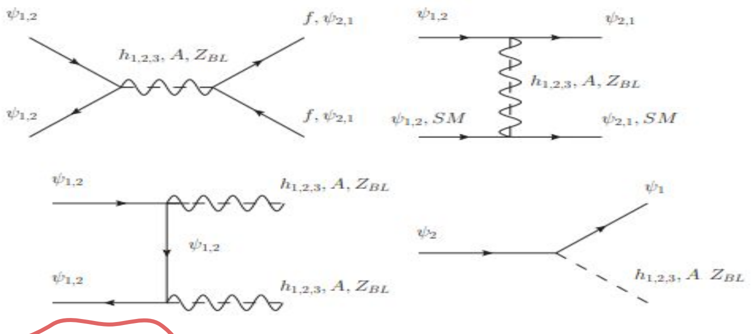


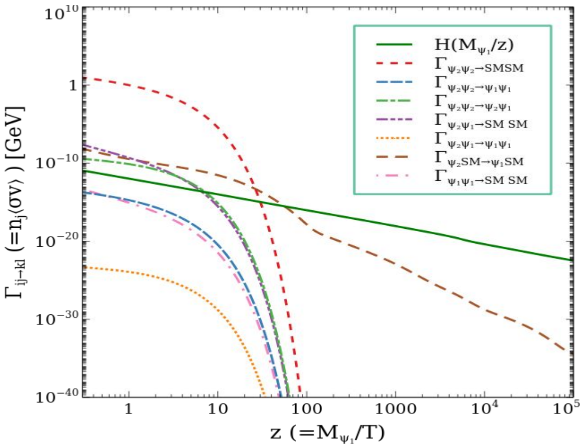
Figure 3: Diagrams relevant in setting the DM and NLSP abundances.

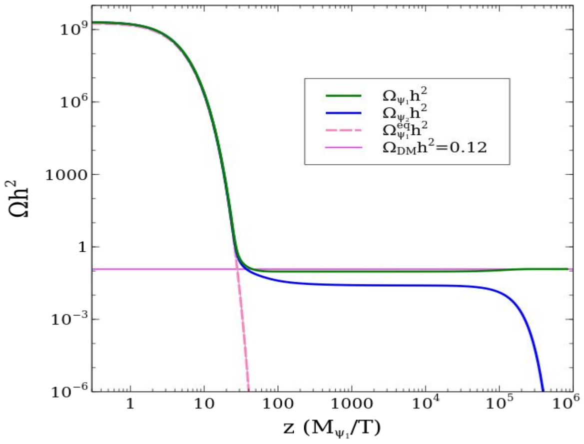
$$Y^{eq}_{\psi_1} = \frac{45 z^2}{2\pi^2 g_s(M_{\psi_1}/z)} K_2(z), \quad Y^{eq}_{\psi_2} = \frac{45 z^2}{2\pi^2 g_s(M_{\psi_1}/z)} K_2\left(\frac{M_{\psi_2}}{M_{\psi_1}} z\right)$$

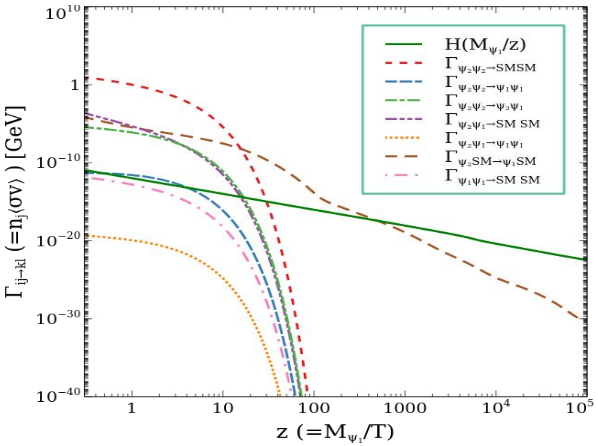
$\psi_2\, SM \leftrightarrow \psi_1\, SM$

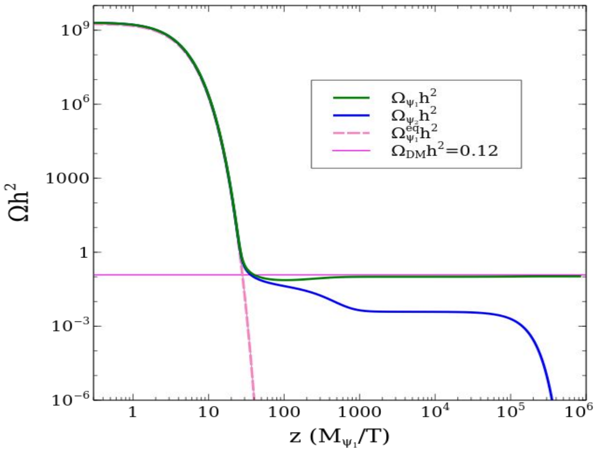
$$\begin{aligned}
\frac{dY_{\psi_1}}{dz} &= -\frac{s}{Hz}\Bigg[\langle\sigma v\rangle_{\psi_1\psi_1\to f\bar{f}}\left(Y^2_{\psi_1} - (Y^{eq}_{\psi_1})^2\right) + \langle\sigma v\rangle_{\psi_1\psi_2\to f\bar{f}}\left(Y_{\psi_1}Y_{\psi_2} - Y^{eq}_{\psi_1}Y^{eq}_{\psi_2}\right) \\
&- \frac{\Gamma_{\psi_2\to\psi_1}}{s(T)}\left(Y_{\psi_2} - Y_{\psi_1}\frac{Y^{eq}_{\psi_2}}{Y^{eq}_{\psi_1}}\right) - \langle\sigma v\rangle_{\psi_2\psi_2\to\psi_1\psi_1}\left(Y^2_{\psi_2} - \frac{(Y^{eq}_{\psi_2})^2}{(Y^{eq}_{\psi_1})^2}Y^2_{\psi_1}\right) - \langle\sigma v\rangle_{\psi_1\psi_2\to\psi_1\psi_1}\left(Y_{\psi_1}Y_{\psi_2} - \frac{Y^{eq}_{\psi_2}}{Y^{eq}_{\psi_1}}Y^2_{\psi_1}\right) \\
&- \langle\sigma v\rangle_{\psi_2\psi_2\to\psi_1\psi_2}\left(Y^2_{\psi_2} - \frac{Y^{eq}_{\psi_2}}{Y^{eq}_{\psi_1}}Y_{\psi_1}Y_{\psi_2}\right) - \frac{\widetilde{\Gamma}_{\psi_2\to\psi_1 X}}{s(T)}\left(Y_{\psi_2} - \frac{Y^{eq}_{\psi_2}}{Y^{eq}_{\psi_1}}Y_{\psi_1}\right)\Bigg], \\
\frac{dY_{\psi_2}}{dz} &= -\frac{s}{Hz}\Bigg[\langle\sigma v\rangle_{\psi_2\psi_2\to f\bar{f}}\left(Y^2_{\psi_2} - (Y^{eq}_{\psi_2})^2\right) + \langle\sigma v\rangle_{\psi_1\psi_2\to f\bar{f}}\left(Y_{\psi_1}Y_{\psi_2} - Y^{eq}_{\psi_1}Y^{eq}_{\psi_2}\right) \\
&+ \frac{\Gamma_{\psi_2\to\psi_1}}{s(T)}\left(Y_{\psi_2} - Y_{\psi_1}\frac{Y^{eq}_{\psi_2}}{Y^{eq}_{\psi_1}}\right) + \langle\sigma v\rangle_{\psi_2\psi_2\to\psi_1\psi_1}\left(Y^2_{\psi_2} - \frac{(Y^{eq}_{\psi_2})^2}{(Y^{eq}_{\psi_1})^2}Y^2_{\psi_1}\right) + \langle\sigma v\rangle_{\psi_1\psi_2\to\psi_1\psi_1}\left(Y_{\psi_1}Y_{\psi_2} - \frac{Y^{eq}_{\psi_2}}{Y^{eq}_{\psi_1}}Y^2_{\psi_1}\right) \\
&+ \langle\sigma v\rangle_{\psi_2\psi_2\to\psi_1\psi_2}\left(Y^2_{\psi_2} - \frac{Y^{eq}_{\psi_2}}{Y^{eq}_{\psi_1}}Y_{\psi_1}Y_{\psi_2}\right) + \frac{\widetilde{\Gamma}_{\psi_2\to\psi_1 X}}{s(T)}\left(Y_{\psi_2} - \frac{Y^{eq}_{\psi_2}}{Y^{eq}_{\psi_1}}Y_{\psi_1}\right)\Bigg].
\end{aligned} \tag{20}$$

Contribution of different Channels

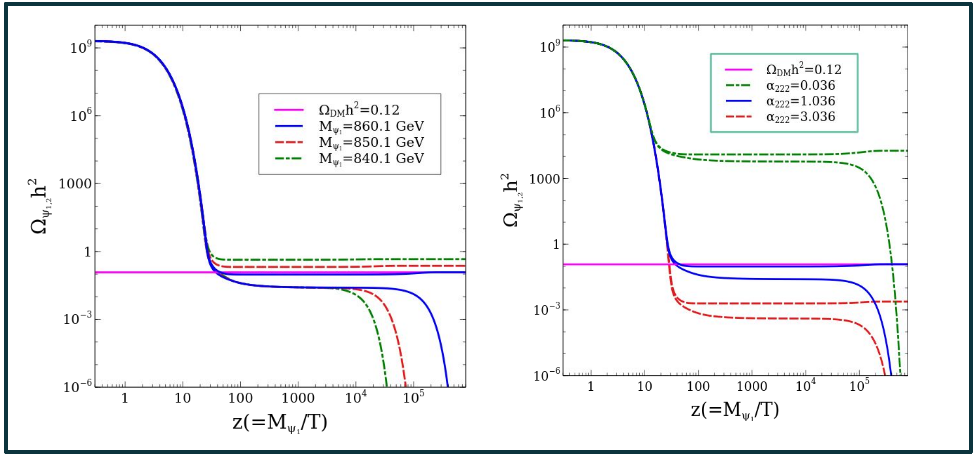


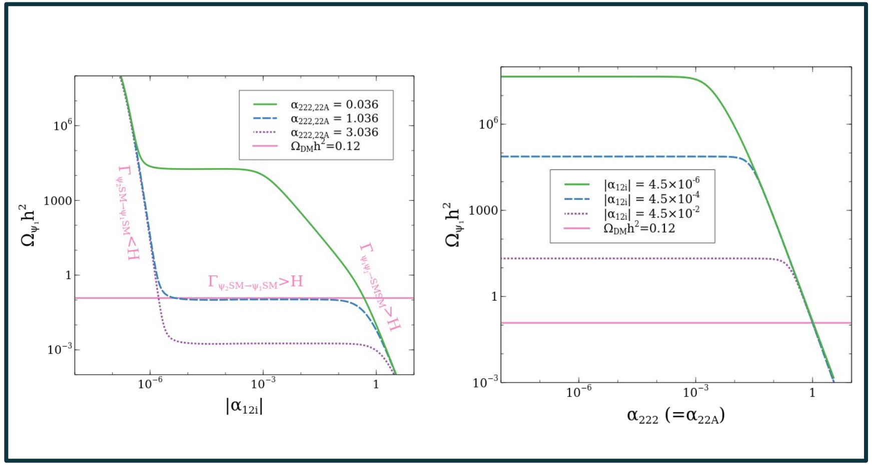


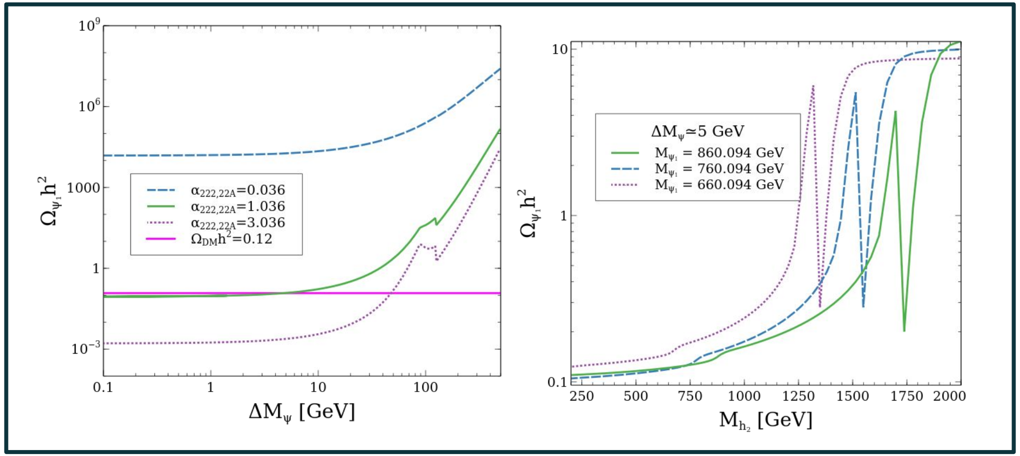


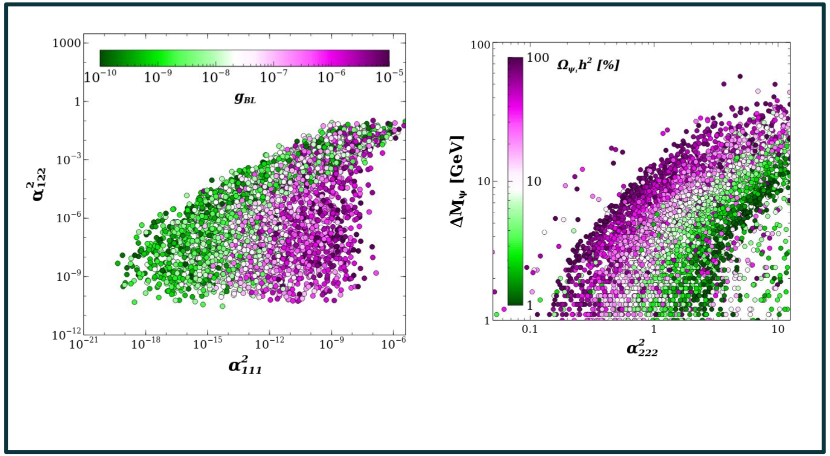


DM relic density response with model parameters

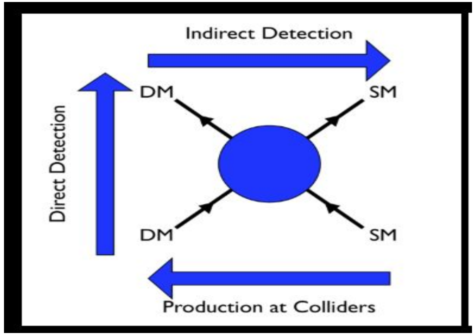


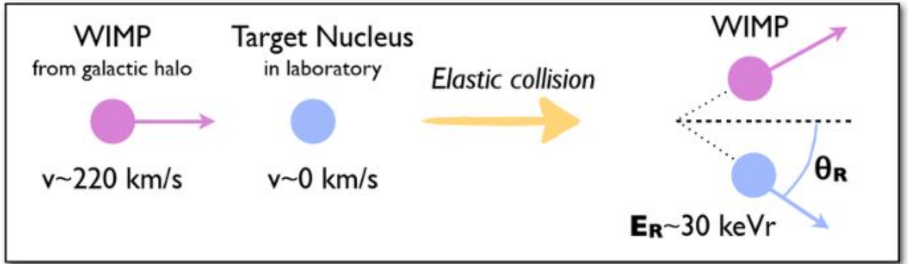


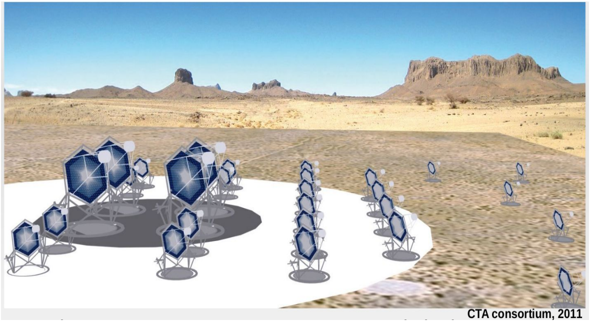


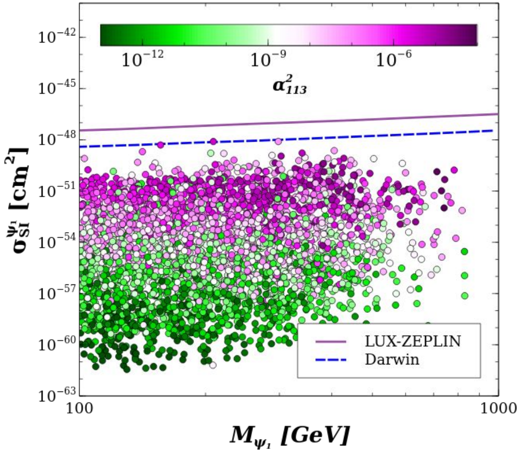


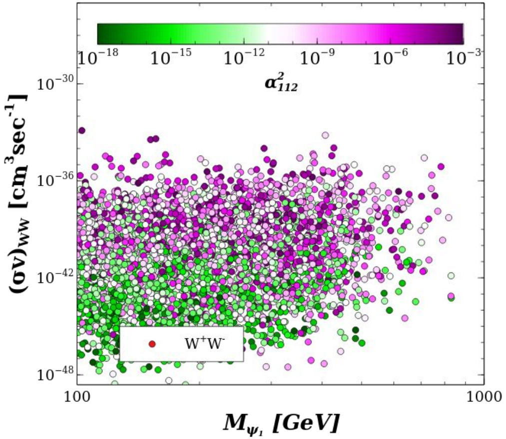
Direct and Indirect Detections



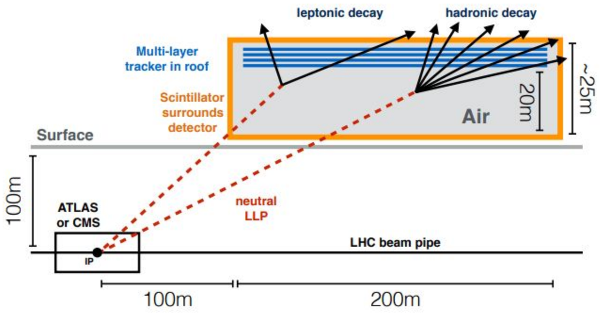


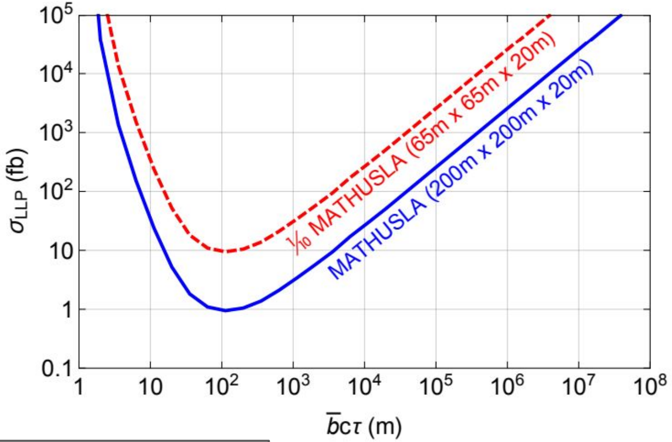


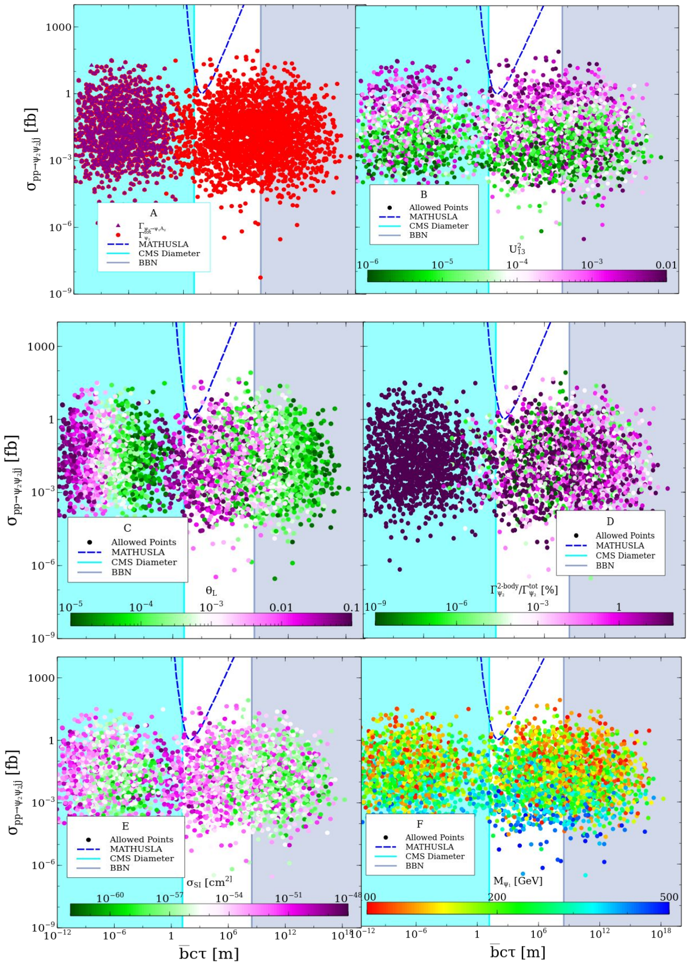




Detection at MATHUSLA



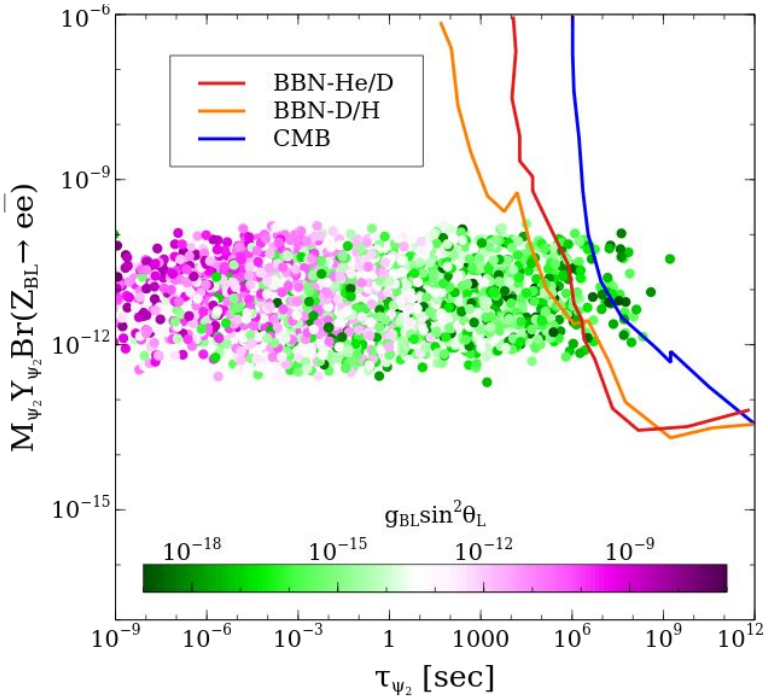


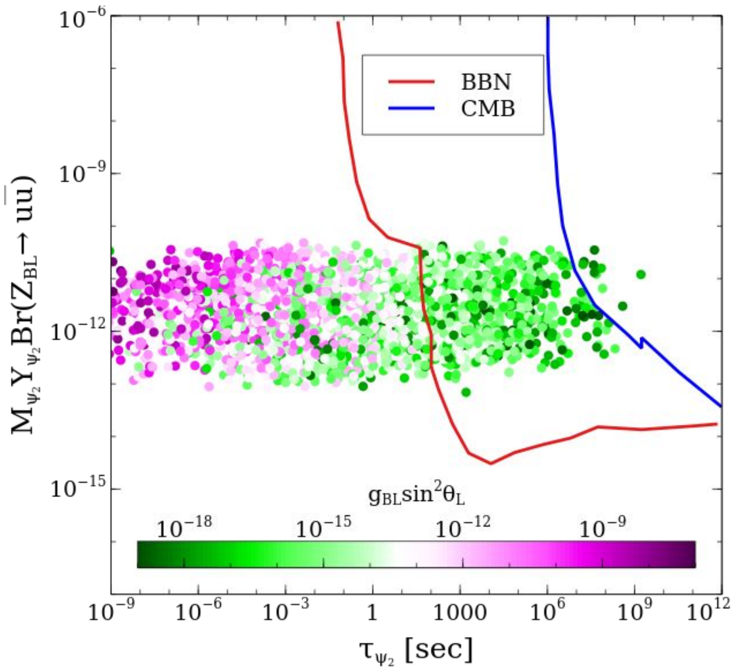


MATHUSLA: 1806.07396

BBN Bound

Kawasaki,Kohri,Moroi,Takaesu PRD 18

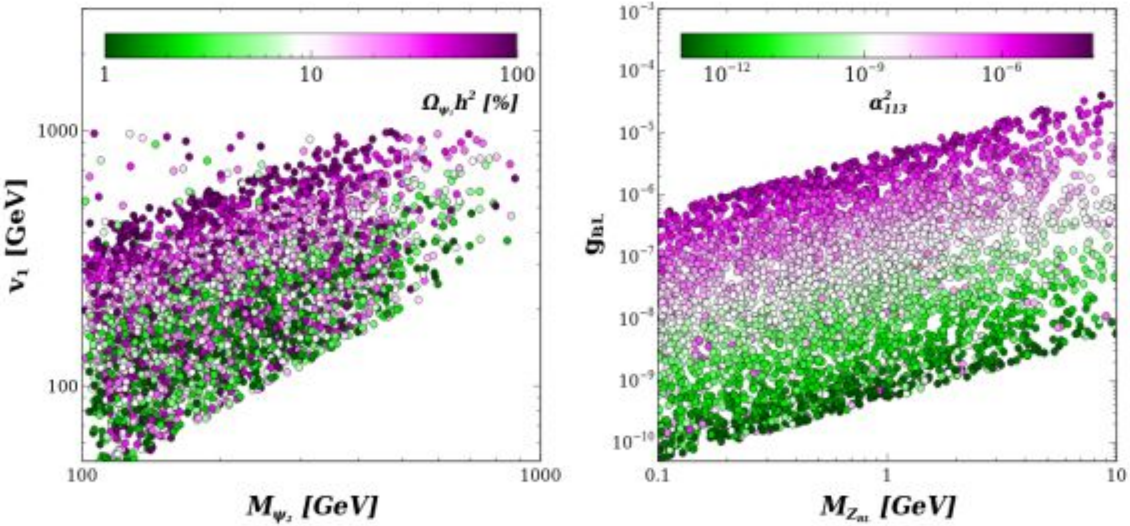




Conclusion

- ★ Studied fermionic dark matter produced from NLSP assisted freeze-out and super WIMP.
- ★ DM remains in thermal equilibrium for longer due to NLSP SM <-> DM SM interaction.
- ★ Direct detection is naturally suppressed.
- ★ Indirect detection is suppressed by velocity square due to fermionic DM.
- ★ We have studied possible detection prospects of DM at MATHUSLA.
- ★ Potential effect on the successful BBN predictions.

Thank you for listening



1
10
100
$\Omega_{\psi}h^2$ [%]
1000
100
v_1 [GeV]
100
1000
M_{ψ} [GeV]
10^{-12}
10^{-9}
10^{-6}
α^2_{113}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
g_{BL}
0.1
1
10
$M_{Z_{BL}}$ [GeV]