

Higgs portal vector dark matter at a low reheating temperature

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To appear Soon

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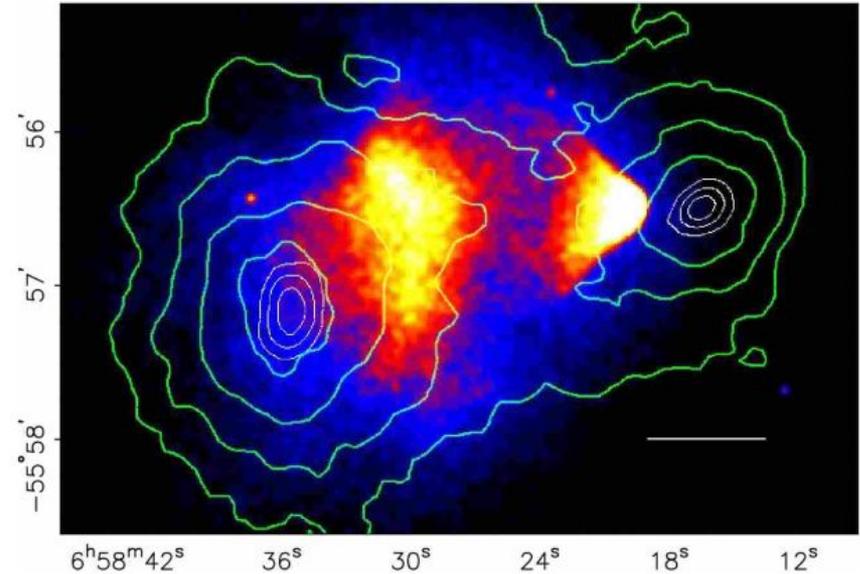
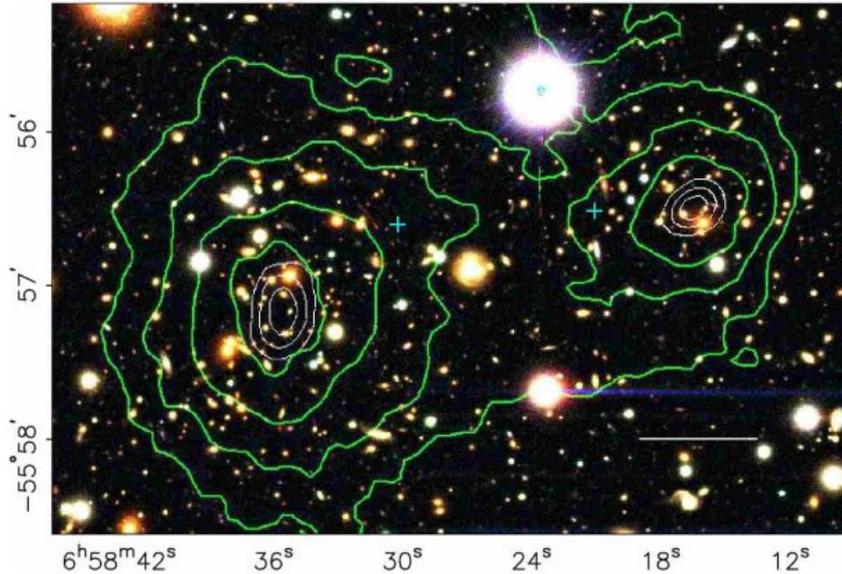


Talk Plan

- ❖ Motivation for Dark Matter Study
- ❖ Model Description
- ❖ Constraints
- ❖ Results
- ❖ Conclusion

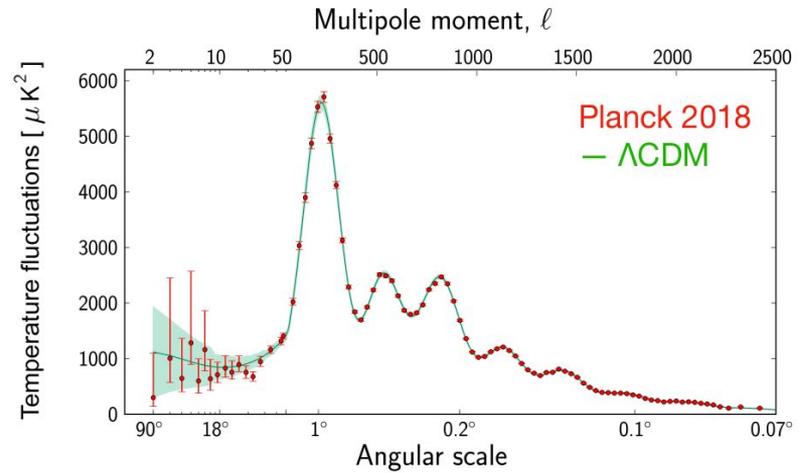
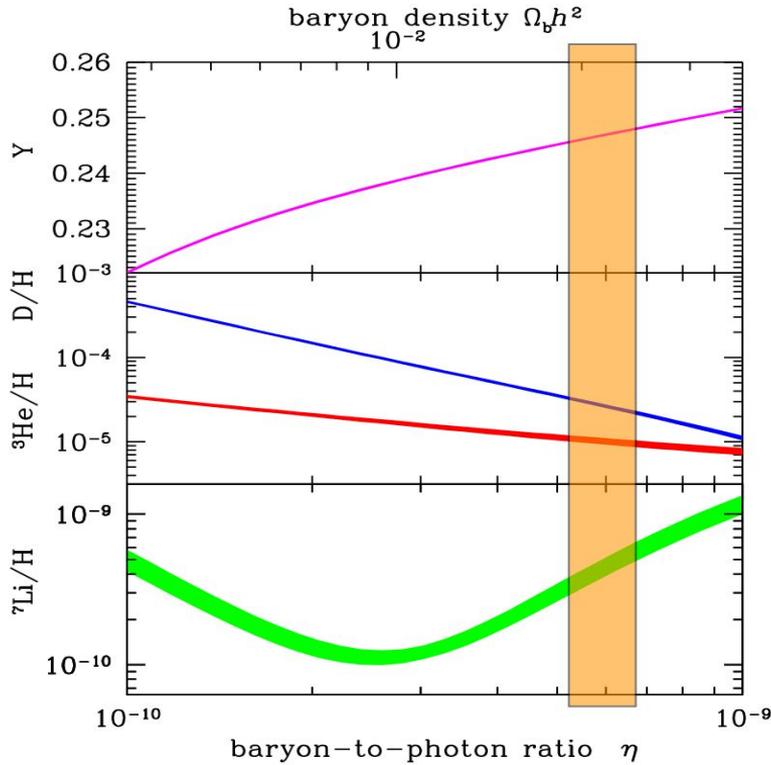
Bullet cluster 1E0657-558

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	Planck best fit	Planck [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
100θ _{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
100θ _s	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.

Vector DM Model

Particle Content

Gauge Group	Baryon Fields			Lepton Fields		Scalar Field	
	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	H	Φ
$SU(2)_L$	2	1	1	2	1	2	1
$U(1)_Y$	1/6	2/3	-1/3	-1/2	-1	1/2	0
$U(1)_D$	0	0	0	0	0	0	1

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} W_{D\mu\nu} W^{D\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mathcal{V}(H, \Phi).$$

Lagrangian

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_H + h \end{pmatrix}, \quad \Phi = \frac{1}{\sqrt{2}} (v_\Phi + \phi).$$

During SSB

$$M_{h\phi} = \begin{pmatrix} 2\lambda_H v_H^2 & \lambda_{H\Phi} v_H v_\Phi \\ \lambda_{H\Phi} v_H v_\Phi & 2\lambda_\Phi v_\Phi^2 \end{pmatrix}.$$

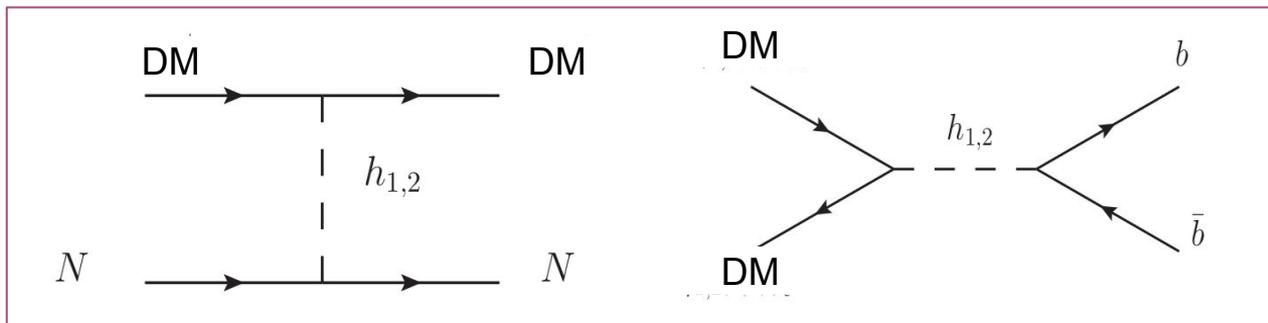
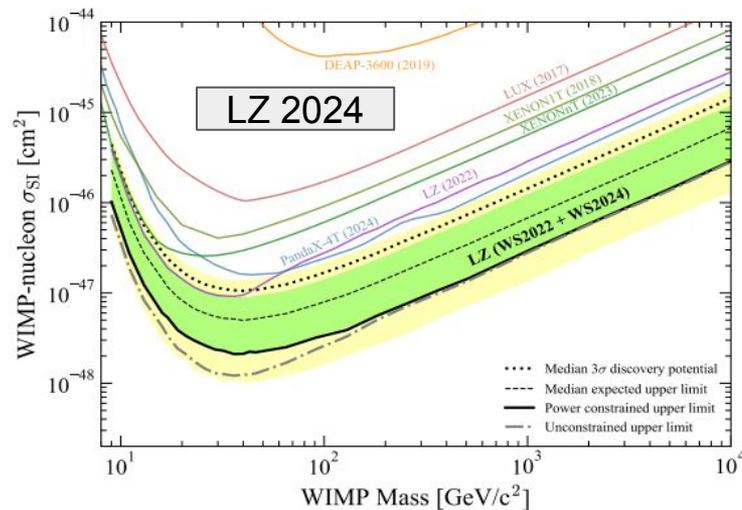
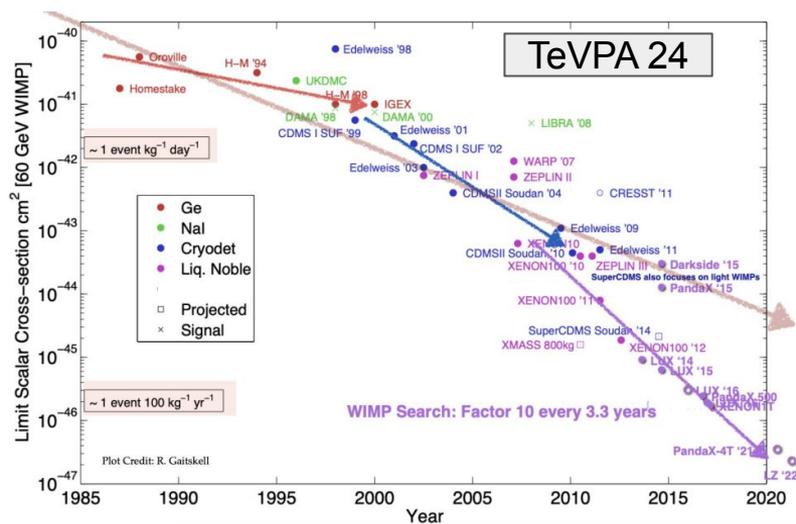
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

Higgses mass and mixing

Constraints

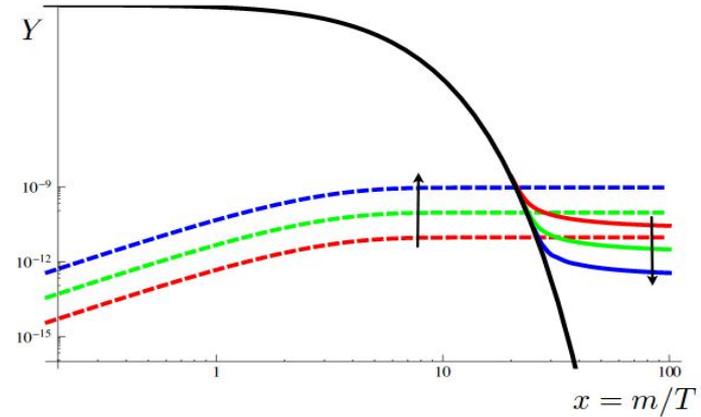
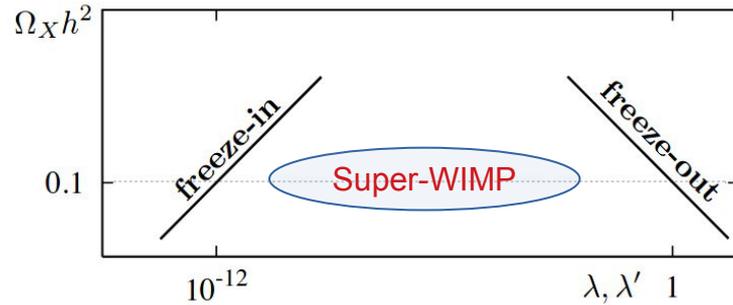
- Checked gauge anomaly condition -> To keep the symmetry
- Perturbativity Bound -> We can ignore higher order terms
- Potential Bound from Below -> To make potential bounded for high field value
- Direct Detection Bound -> Severe bound from LUX-ZEPLIN
- Indirect Detection Bound -> Avoided by WIMP annihilation to BSM sector
- Collider Bound mainly SM Higgs -> Higgs signal strength and Invisible decay
- BBN bound -> Reheat temperature above BBN scale
- Oblique parameters -> safe for the allowed mixing angle after Higgs data

Direct Detection in Present time



Standard Scenario is Tightly Constrained

DM Production Mechanisms



- 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 Equation

$$\frac{dY_{W_D}}{dz} = \frac{2M_{pl}z\sqrt{g_*(z)}}{1.66M_{sc}^2g_s(z)} [\langle\Gamma_{h_i\rightarrow W_D W_D}\rangle (Y_{h_i}^{eq} - Y_{W_D}^2)]$$

$$+ \frac{2M_{sc}s(T)}{z^2H(T)T} [Y_i^2\langle\sigma v\rangle_{ii\rightarrow W_D W_D} - Y_{W_D}^2\langle\sigma v\rangle_{W_D W_D\rightarrow ii}]$$

$$s(T) = \frac{2\pi^2}{45}g_*T^3, \quad H(T) = \sqrt{\frac{8\pi^3g_*}{90}}\frac{T^2}{M_{pl}}.$$

$$\langle\Gamma_{h_i\rightarrow W_D W_D}\rangle = \Gamma_{h_i\rightarrow W_D W_D}\frac{K_1(z)}{K_2(z)}$$

$$\langle\sigma v\rangle_{ii} = \frac{g_i^2T}{2(2\pi)^4n_i^2}\int_{4(\max[M_i, M_{W_D}])^2}^{\infty}\sigma_{ii\rightarrow W_D W_D}(s-4M_i^2)\sqrt{s}K_1\left(\frac{\sqrt{s}}{T}\right)ds$$

$z \ll 1$

$$K_1(z) = \frac{1}{z}\sqrt{1+\frac{\pi}{2}}z e^{-z}$$

$$K_1(z) = \frac{1}{z^2}\left(\frac{15}{8}+z\right)\sqrt{1+\frac{\pi}{2}}z e^{-z}$$

$z \gg 1$

$$K_1(z) = \sqrt{\frac{\pi}{2z}}e^{-z}$$

$$K_1(z) = \frac{1}{z}\left(\frac{15}{8}+z\right)\sqrt{\frac{\pi}{2z}}e^{-z}$$

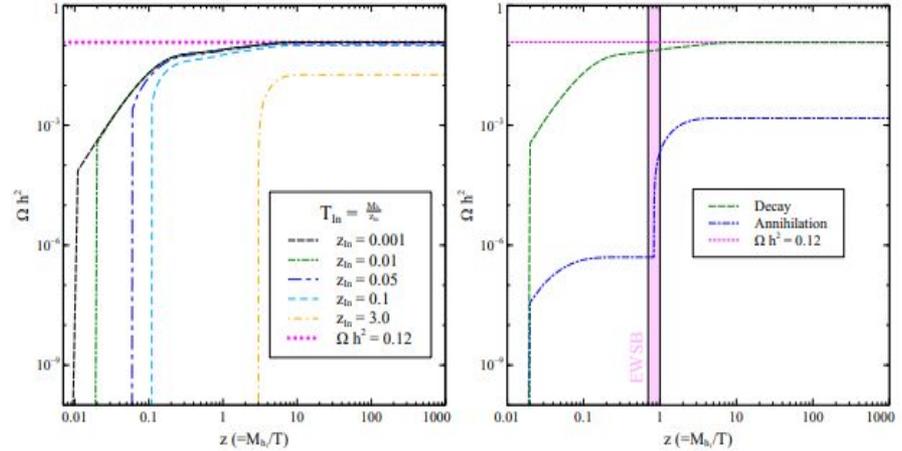
Decay Contribution

Equilibrium comoving number density

$$Y_{eq} = \frac{45}{2\pi^2} \frac{g_A}{g_*(T)} \left(\frac{x_A}{2\pi}\right)^{3/2} e^{-\frac{M_A}{T}}$$

Boltzmann Equation

$$Y_{W_D}^{dec} = \frac{0.17\Gamma_{h_i} g_{h_i} M_{pl}}{M_{h_i}^2 g_s^{3/2}} \int_{z_0}^{\infty} z^{5/2} e^{-z} dz$$



$$Y_{W_D}^{Dec} = \sum_{i=1,2} \frac{0.17\Gamma_{h_i} g_{h_i} M_{pl}}{g_*^{3/2} M_{h_i}^2} \left[\frac{1}{4} \sqrt{\frac{M_{h_i}}{T_R}} \left(15 + \frac{2M_{h_i}}{T_R} \left(5 + \frac{2M_{h_i}}{T_R} \right) \right) e^{-\frac{M_{h_i}}{T_R}} + \frac{15}{8} \sqrt{\pi} \text{Erfc} \left(\sqrt{\frac{M_{h_i}}{T_R}} \right) \right]$$

Hall et al' 09

$$z_{ini} \rightarrow 0 \Rightarrow \Omega_{W_D} h^2 = \frac{2.18 \times 10^{18}}{g_s^{3/2}} \frac{M_{W_D} \Gamma_{h_i}}{M_{h_i}^2}$$

$$\text{Erfc}(x) \simeq \frac{2e^{-x^2}}{\sqrt{\pi} \left(x + \sqrt{x^2 + \frac{4}{\pi}} \right)}$$

$$\Gamma_{h_i \rightarrow W_D W_D} = \frac{M_{h_i}^3 g_{h_i}^2 g_{W_D W_D}}{128\pi M_{W_D}^4} \sqrt{1 - \frac{4M_{W_D}^2}{M_{h_i}^2}} \left(1 - \frac{4M_{W_D}^2}{M_{h_i}^2} + \frac{12M_{W_D}^4}{M_{h_i}^4} \right)$$

Annihilation Contribution

Costa, Cosme, Lebedev PRD 24, JCAP 24
 Malpartida, Bernal, Perez, Lineros JCAP 23
 Arcadi, Costa, Goudelis, Lebedev JHEP 24
 Arcadi, Almeida, Lebedev, Almeida PLB 25
 Lee, Park, Sanz 2412.07850
 + Many more

Cross Section for $h_2 h_2 \rightarrow W_D W_D$

$$\sigma_{h_i h_j \rightarrow W_D W_D} \simeq \frac{g_{h_i h_j W_D W_D}^2}{16\pi s} \left(\frac{s(s - 4M_{W_D}^2)}{(s - (M_{h_i} + M_{h_j})^2)(s - (M_{h_i} - M_{h_j})^2)} \right)^{1/2} \left(1 + \frac{(s - 2M_{W_D}^2)^2}{8M_{W_D}^4} \right) \quad (27)$$

Thermal average cross section

$$n_{AB} \langle \sigma v \rangle = \frac{g_A g_B T}{2(2\pi)^4} \frac{g_{W_D W_D h_2 h_2}^2}{16\pi} \int_{4M_1^2}^{\infty} \frac{ds}{s} (s - 4M_{W_D}^2)^{1/2} (s - 4M_{h_2}^2)^{1/2} \left[1 + \frac{(s - 2M_{W_D}^2)^2}{8M_{W_D}^4} \right] \sqrt{s} K_1 \left(\frac{\sqrt{s}}{T} \right)$$

where $M_1 = \max [M_{W_D}, M_{h_2}]$

↓

$$s = 4M_1^2 + p^2$$

↓

$$K_1(\sqrt{s}/T) = \sqrt{\frac{\pi T}{2(p^2 + 4M_1^2)}} e^{-\frac{2M_1}{T}} e^{-\frac{p^2}{4M_1 T}}$$

Comoving number density

$$Y_{W_D}^{Anni} = \frac{0.34 M_{pl} \cos^4 \alpha g_D^4}{(2\pi)^4 g_*^{3/2}} \frac{M_1}{M_{W_D}^4} \left[(4M_1^4 + 3M_{W_D}^4 - 4M_1^2 M_{W_D}^2) \frac{e^{-\frac{2M_1}{T_R}}}{4M_1^2} \left(1 + \frac{2M_1}{T_R} \right) + (12M_1^3 - 6M_1 M_{W_D}^2) \frac{e^{-\frac{2M_1}{T_R}}}{2M_1} + 15M_1^2 \Gamma \left(0, \frac{2M_1}{T_R} \right) \right]$$

suppression

Reheat Temperature

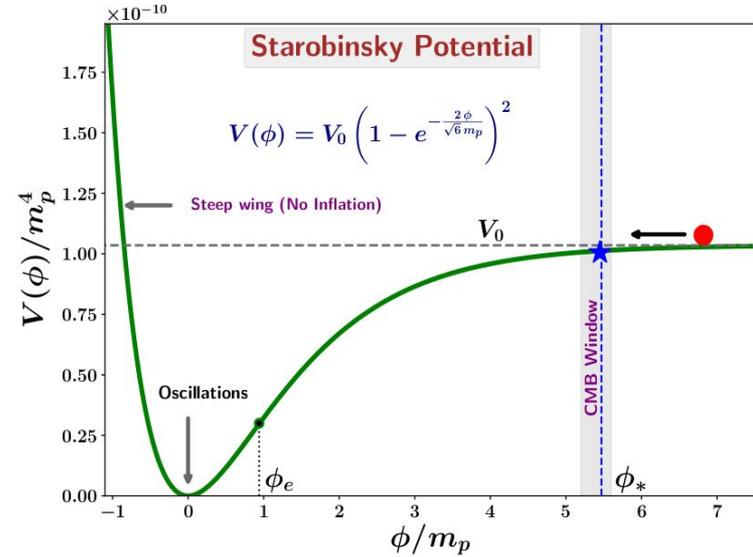
Inflation Potential during reheating

$$V(\chi) = \lambda_\chi \frac{\chi^n}{\Lambda^{n-4}}$$

Background Equations

$$\frac{d\rho_\chi}{da} + \frac{6n}{n+2} \frac{\rho_\chi}{a} = -\frac{2n}{2+n} \frac{\Gamma_\chi \rho_\chi}{H a},$$
$$\frac{d\rho_R}{da} + 4 \frac{\rho_R}{a} = \frac{2n}{2+n} \frac{\Gamma_\chi \rho_\chi}{H a}.$$

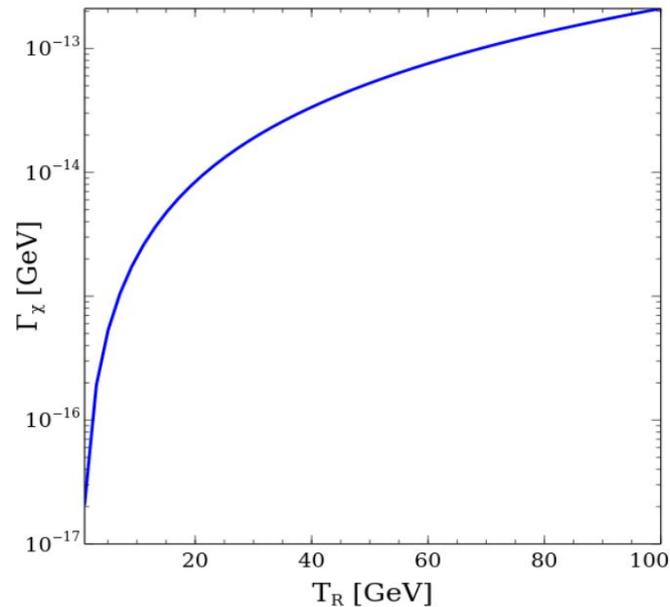
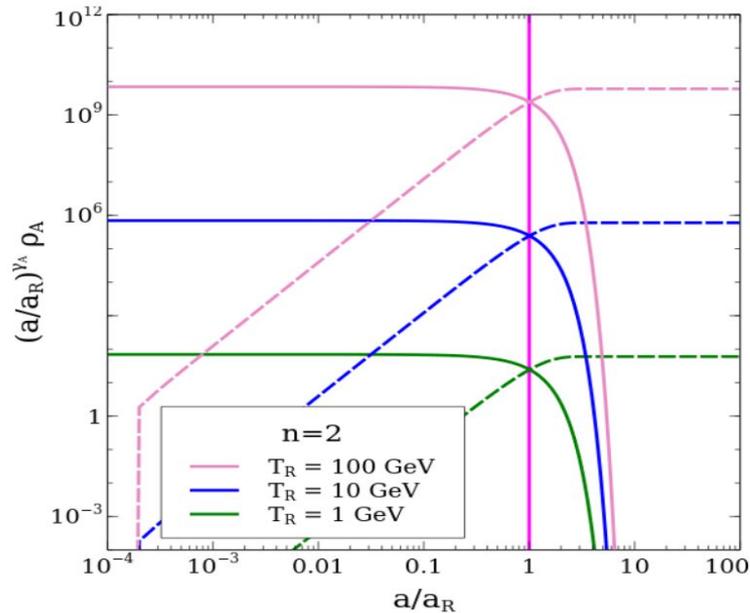
$$H = \sqrt{\frac{8\pi(\rho_\chi + \rho_\phi)}{3M_{pl}^2}}$$



$$T_R = \left(\frac{\Gamma_\chi M_{pl}}{g_*^{1/2}} \sqrt{\frac{45}{8\pi^3}} \right)^{1/2}$$

Turner PRD 83
Mishra 2403.10606

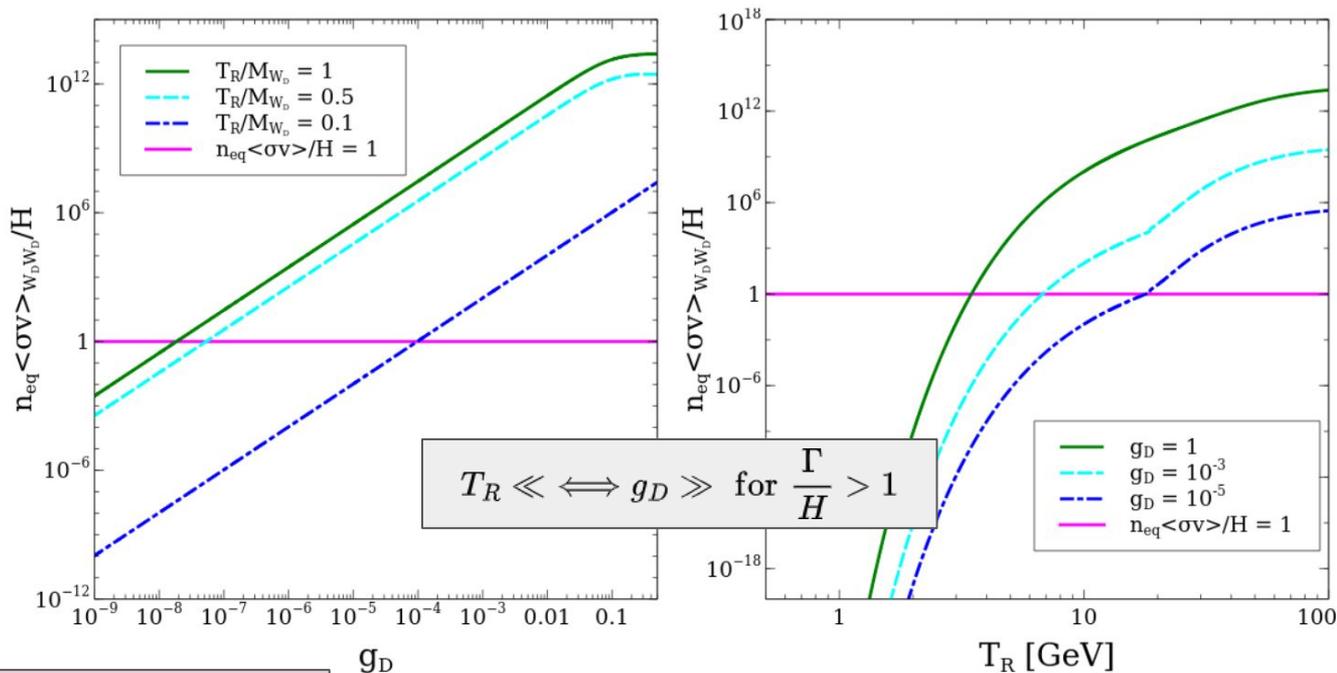
Thermal Bath Production



$$\rho_R = 0 \text{ and } \rho_\chi = \rho_\chi(a_R) \left(\frac{a}{a_R}\right)^{-\frac{2n}{2+n}}$$

$$\rho_\chi(a_R) = \rho_R(a_R) = \frac{\pi^2}{30} g_* (T_R) T_R^4$$

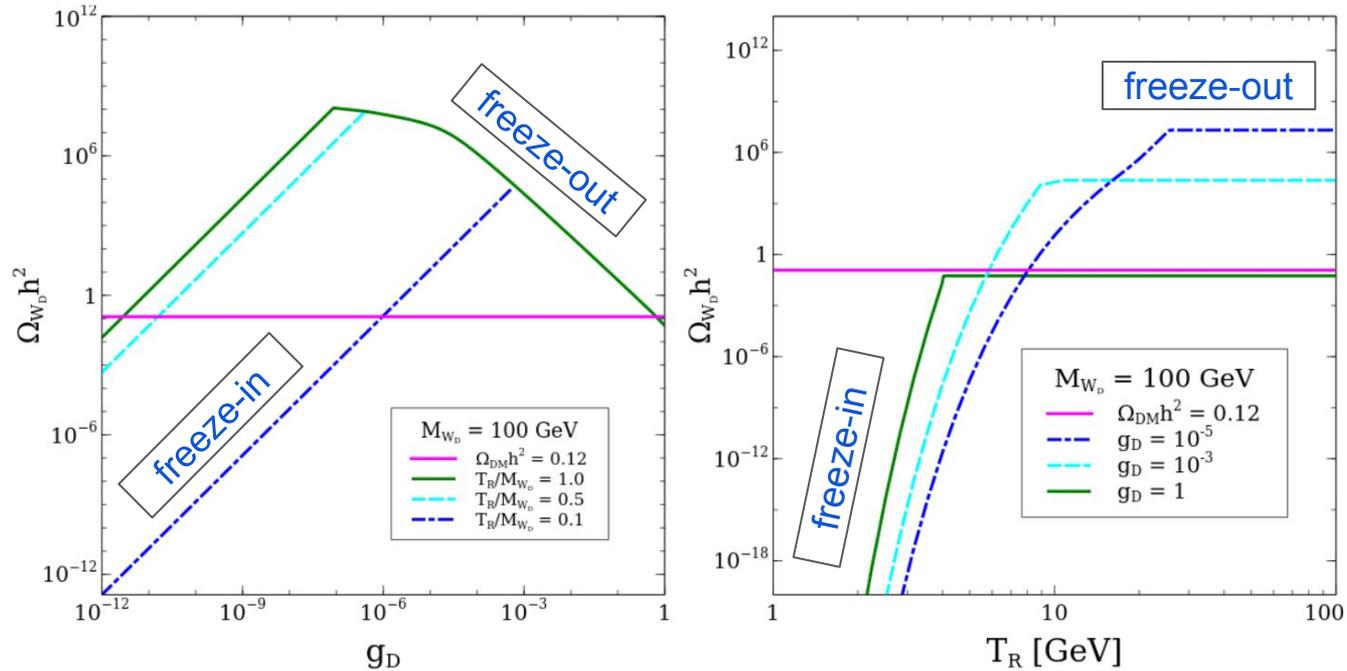
Equilibrium variation with g_D and T_R



Model Parameters Value

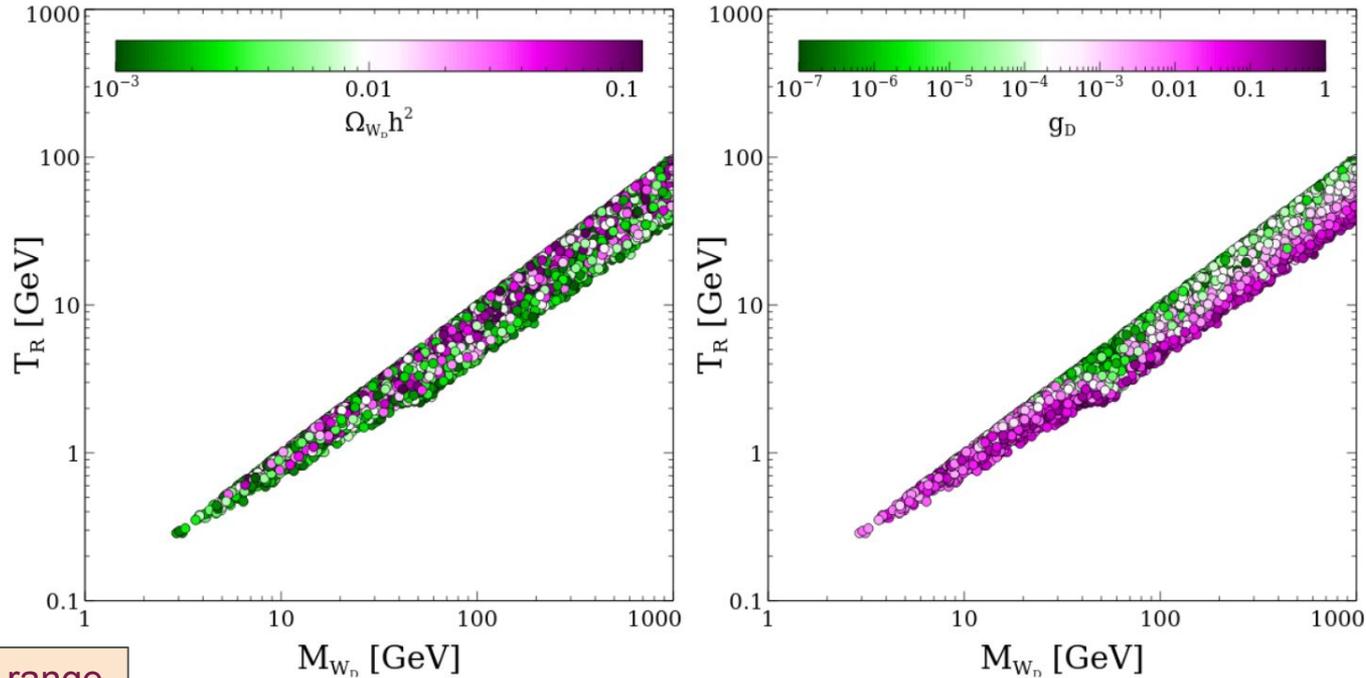
$$M_{W_D} = 100 \text{ GeV}, M_{h_2} = 500 \text{ GeV}, \sin \alpha = 0.1, g_D = 10^{-5}, \frac{T_R}{M_{W_D}} = 0.1$$

Relic density variation with g_D and T_R



- LP: As the g_D increases freeze-in regime production increases and opposite for the freeze-out case.
- RP: Depending on the value of g_D , we can have FI and FO dominated regime for different T_R .

Allowed region in M_{WD} and T_R plane



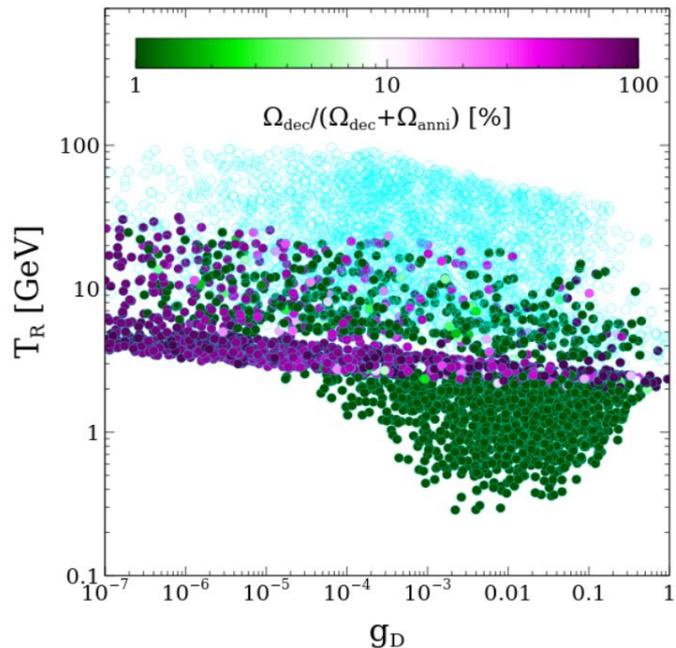
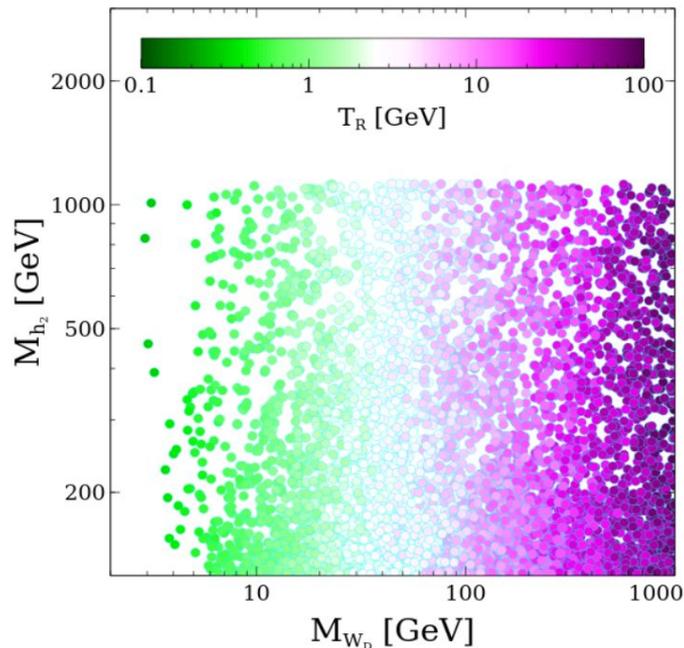
Parameters range

$$10^{-3} \leq \sin \alpha \leq 0.2, \quad 1 \leq (M_{h_2} - M_{h_1}) [\text{GeV}] \leq 1000, \quad 10^{-7} \leq g_D \leq 1$$

$$1 \leq M_{WD} [\text{GeV}] \leq 1000, \quad 10^{-4} \leq \frac{T_R}{M_{WD}} \leq 10^{-1}.$$

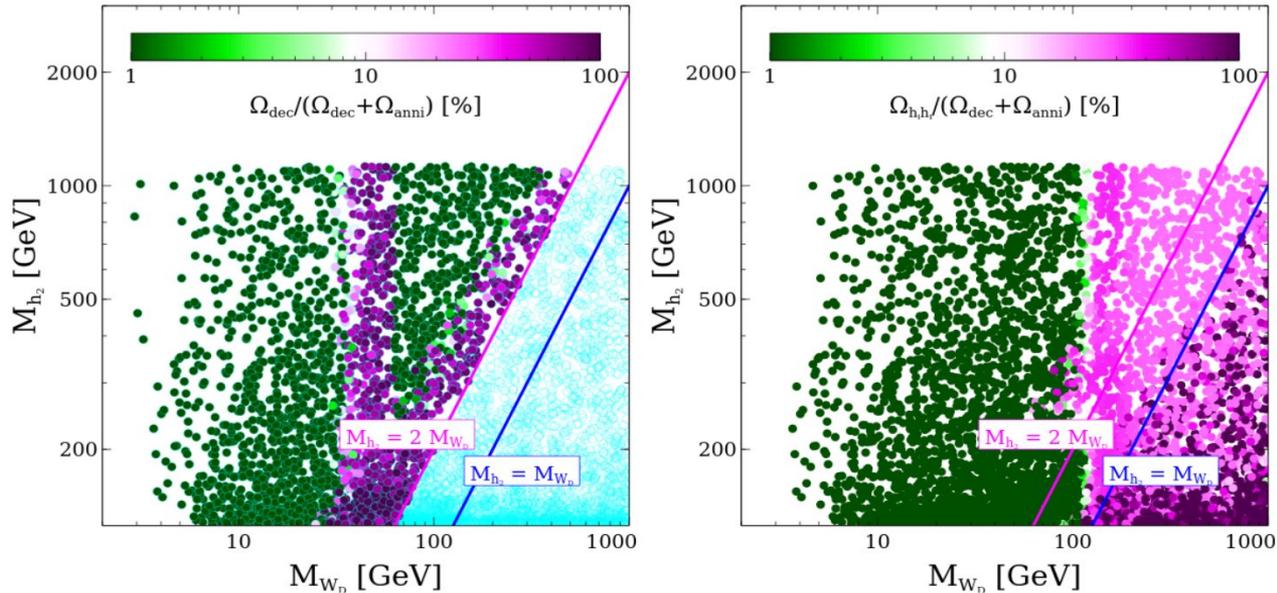
- A. We see sharp correlation between T_R and M_{WD} .
- B. RP green points are mainly from decay due to phase space suppression

Scatter plots in different plane



- A. LP: All values of M_{h_2} can produce WD dark matter with the suitable values of T_R .
- B. RP: The magenta points are for the decay contribution and cyan region is zero decay contribution.

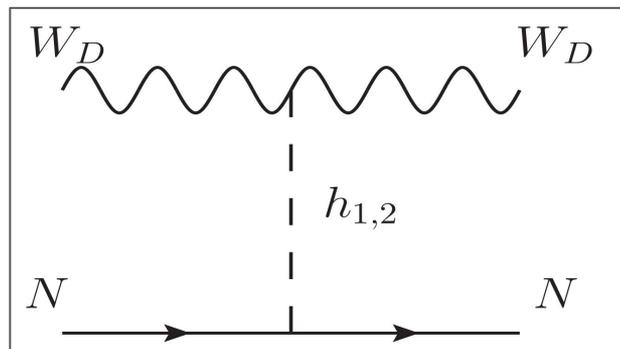
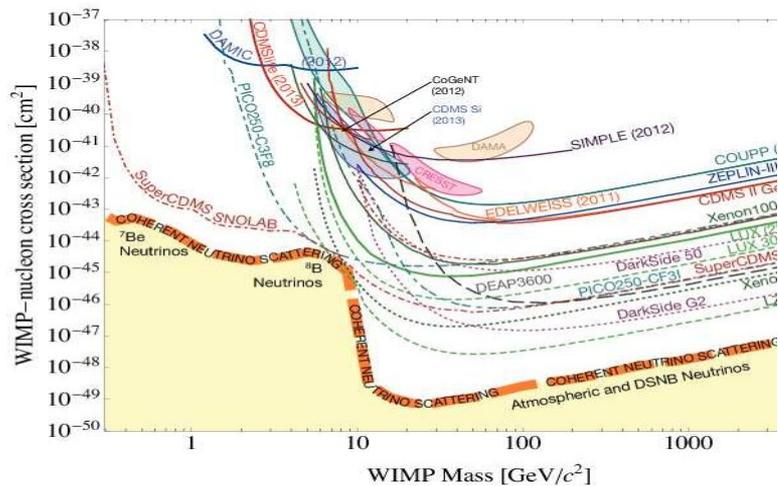
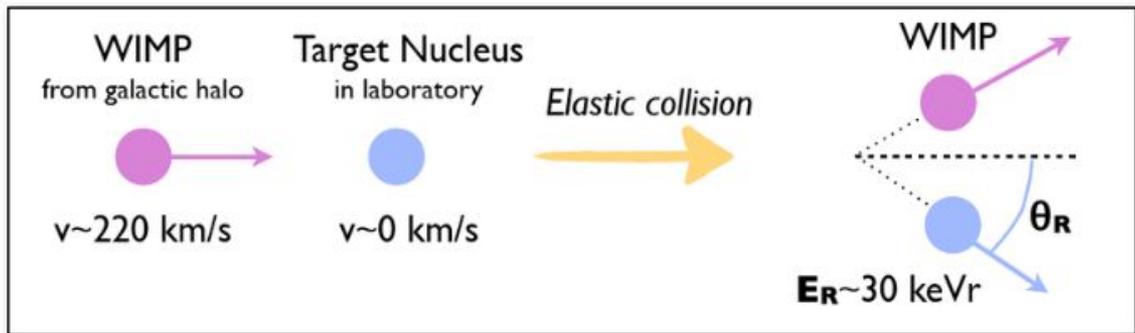
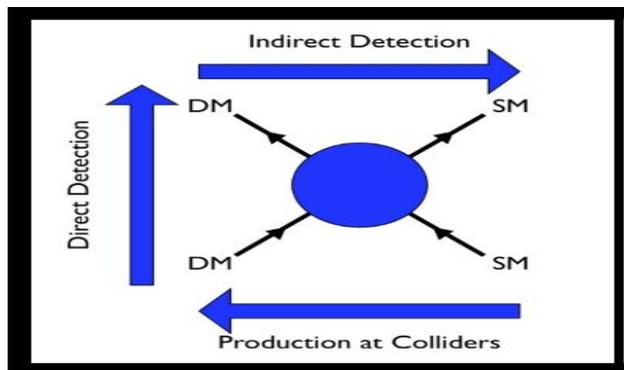
Different channels dominance in DM production



LP: Magenta points are coming from the decay contribution due to phase space suppression and cyan points are for zero decay contribution.

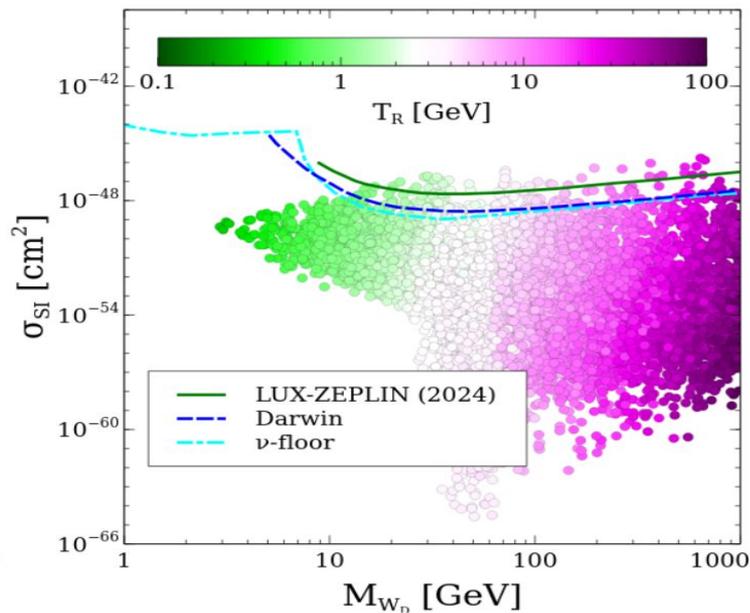
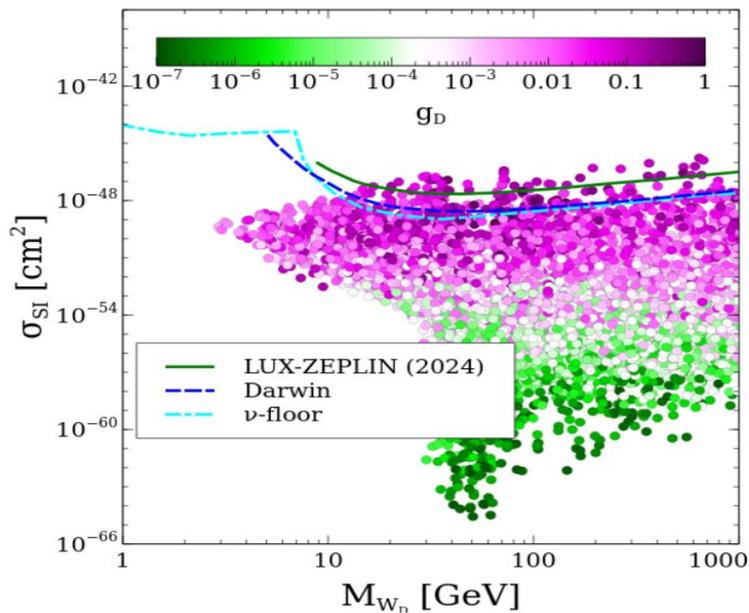
RP: Green points are either coming from the decay or the fermion annihilation and light magenta point coming due to SM Higgs annihilation whereas dark magenta points are coming due to BSM annihilations.

Direct Detection



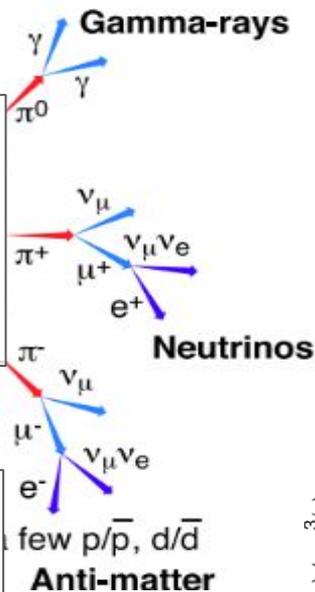
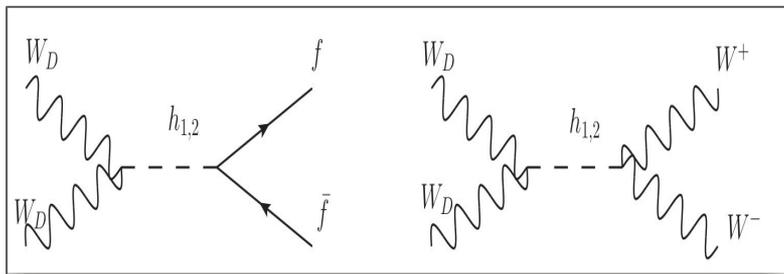
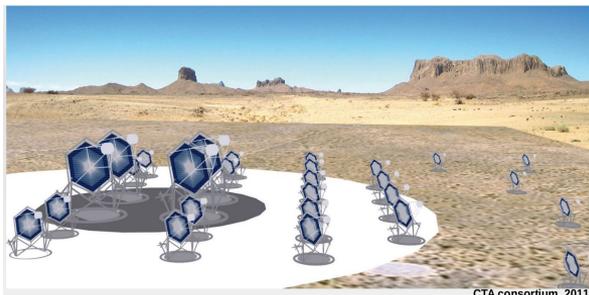
$$\sigma_{\text{SI}} = \frac{\mu^2 \sin^2(2\theta) g_D^2}{4\pi v_H^2} \left(\frac{1}{M_{h_1}^2} - \frac{1}{M_{h_2}^2} \right)^2 \left[\frac{Z f_\alpha^p + (A - Z) f_\alpha^n}{A} \right]^2,$$

Direct Detection Prospects



- A. LP: DM direct detection cross section varies with gauge coupling and some part already ruled and rest can be explored in future.
- B. RP: We see no dependence of T_R on the cross section but needed in particular range of DM mass to have DM relic density.

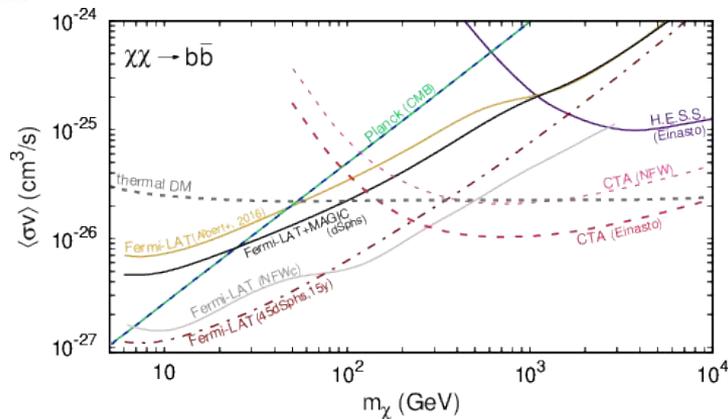
Indirect Detection



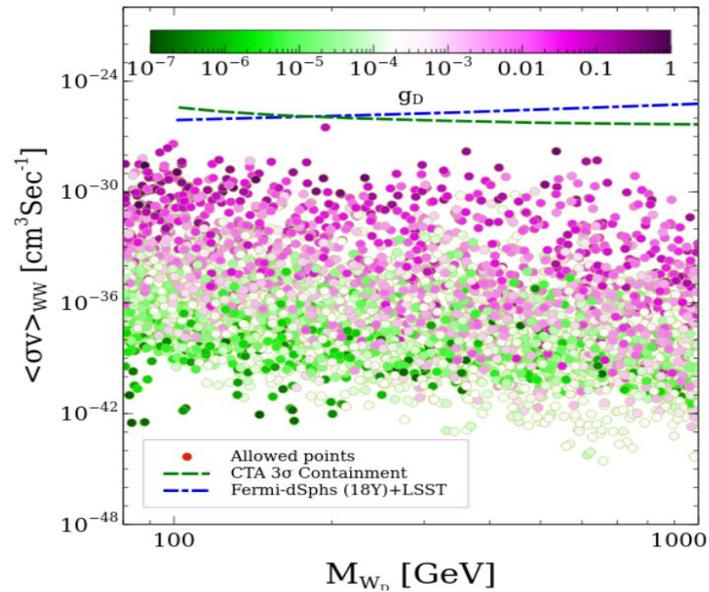
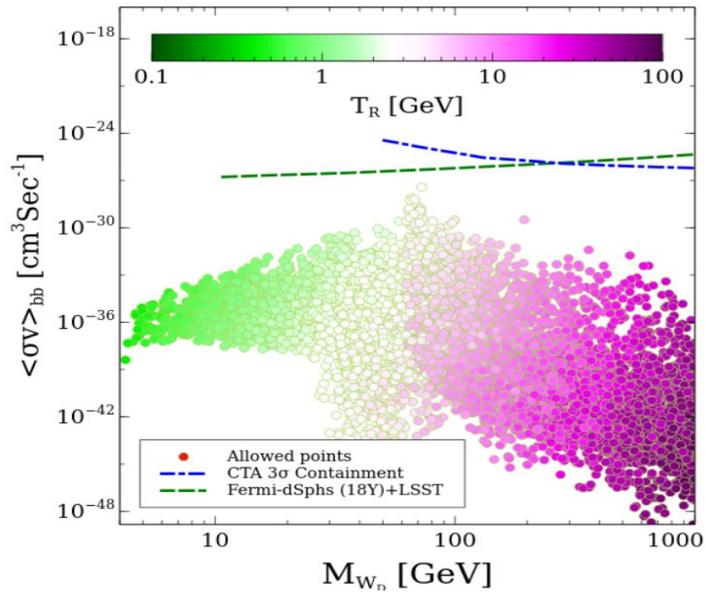
$$\langle \sigma v \rangle_{WW} \simeq \frac{4M_{W_D}^4 - 4M_{W_D}^2 M_W^2 + 3M_W^4}{96\pi M_{W_D}^2 M_W^4} \sqrt{1 - \left(\frac{M_W}{M_{W_D}}\right)^2} \left| \sum_{i=1,2} \frac{g_{h_i W_D W_D} g_{h_i W W}}{(4M_{W_D}^2 - M_{h_i}^2) + i\Gamma_{h_i} M_{h_i}} \right|^2$$

$$\langle \sigma v \rangle_{ff} \simeq \frac{n_c}{12\pi} \left(1 - \left(\frac{M_f}{M_{W_D}}\right)^2\right)^{3/2} \left| \sum_{i=1,2} \frac{g_{h_i W_D W_D} g_{h_i f f}}{(4M_{W_D}^2 - M_{h_i}^2) + i\Gamma_{h_i} M_{h_i}} \right|^2 \quad (19)$$

$$g_{h_{1(2)} W_D W_D} = -2g_D M_{W_D} \sin\theta(-\cos\theta), g_{h_{1(2)} W W} = \frac{e^2 v_H}{2 \sin^2 \theta_w} \cos\theta(\sin\theta), g_{h_{1(2)} f f} = \frac{M_f}{v_H} \cos\theta(\sin\theta),$$



Indirect Detection Prospects



- A. LP: We can see there is a possibility of DM detection in the future indirect detection experiments and T_R only important to fit the DM density.
- B. RP: Annihilation to WW final state and linearly vary with the g_D with some deflection due to the suppression from mixing angle and same.

Conclusion

- ★ We have studied vector dark matter for the low reheating case.
- ★ We focus on the freeze-in production at the strong coupling
- ★ We have found that to obtain DM density, DM mass and T_R need to be correlated
- ★ We have found in narrow region due to phase space suppression decay can dominate.
- ★ DM mass below SM Higgs mass mainly dominated by fermion annihilation whenever decay is subdominant and beyond by Higgses annihilation
- ★ We have found that for the freeze-in DM, we can have detection prospects at the direct, indirect and collider experiments.

Thank you for listening