Freeze-in $SU(2)$ vector dark matter at low reheating temperature

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Based on Dilip Kumar Ghosh, Sourav Gope, Xiao-Gang He, and Sk Jeesun

arXiv:2605.24473

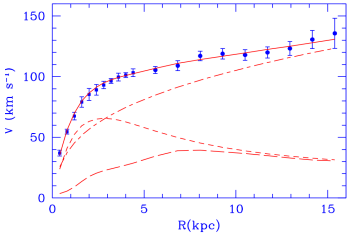
NEXUS 2026 – September 13, 2026

Outline

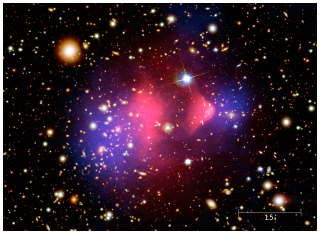
1. Introduction and motivation
2. Model
3. Results and constraints
4. Conclusion
5. Appendix

Dark Matter

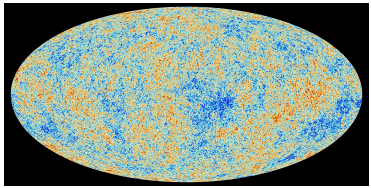
Galaxy rotation curves



The Bullet Cluster



Planck CMB

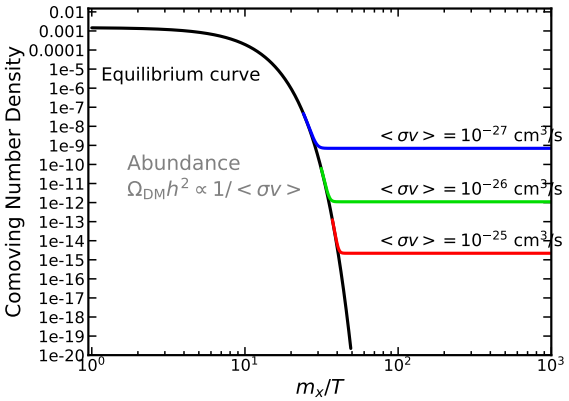


DM: $\Omega_c h^2 = 0.1200 \pm 0.0012$ **Baryons: $\Omega_b h^2 = 0.02237 \pm 0.00015$**

These results demand a new, non-baryonic matter component—but its particle identity remains unknown.

M33: Corbelli & Salucci, MNRAS 311 (2000) 441, astro-ph/9909252; Bullet Cluster: Clowe et al., ApJL 648 (2006) L109, astro-ph/0608407; CMB: Planck Collaboration VI, A&A 641 (2020) A6, arXiv:1807.06209

WIMP: Freeze-out



Freeze-out

- Initially, rapid interactions keep DM in **thermal equilibrium**: $n_\chi \simeq n_\chi^{\rm eq}$.
- As the Universe cools,the equilibrium abundance becomes Boltzmann suppressed, causing the annihilation rate $\Gamma_{\rm ann} = n_\chi \langle \sigma v \rangle$ to fall below H.
- Decoupling occurs when

$$\Gamma_{\rm ann} = n_\chi \langle \sigma v \rangle \sim H.$$

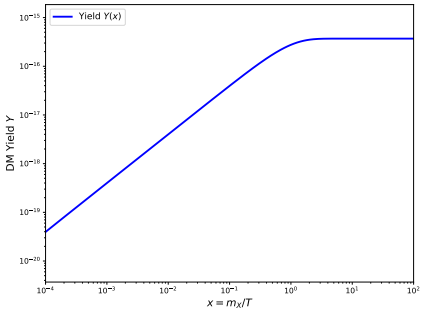
- Afterwards, the comoving abundance $Y_\chi = n_\chi / s$ becomes constant.

$$\Omega_\chi h^2 \propto \frac{1}{\langle \sigma v \rangle}.$$

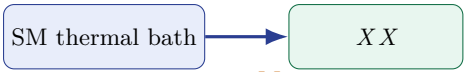
The feature of freeze out : stronger annihilation leaves a smaller relic abundance.

arXiv:1703.07364

FIMP: Freeze-in



$$Y_X \equiv \frac{n_X}{s}, \qquad x \equiv \frac{M_{\rm DM}}{T}$$



$$Y \sim \lambda^2 \frac{M_{pl}}{m}$$

The basic picture

1. The initial DM abundance is negligible.
2. The interaction is too weak to establish equilibrium:
$$Y_X < Y_X^{\rm eq}.$$
3. Bath particles slowly produce DM through decays or annihilations.
4. Production stops when the bath becomes too cold, leaving a frozen relic abundance.

In one sentence

Freeze-in builds the relic abundance from almost nothing, without thermalizing dark matter.

Hall et al., arXiv:0911.1120;

Low Reheating Temperature Freeze-in

Experimental challenge

Traditional freeze-in usually requires a feeble coupling $\lambda \sim \mathcal{O}(10^{-10})$.
This small coupling makes laboratory signals **extremely difficult**.

Initial-condition challenge

Usually, freeze-in calculations assume $Y_\chi^{\rm ini} \simeq 0$. But feebly coupled particles can nevertheless be produced gravitationally during and immediately after inflation.

O. Lebedev, JCAP 02 (2023) 032, arXiv:2210.02293

What a low reheating temperature can change

Larger, testable couplings: if $T_{\rm RH} < M_{\rm DM}$, thermal production is Boltzmann suppressed,

$$\gamma_{\rm prod} \propto e^{-\mathcal{O}(M_{\rm DM}/T_{\rm RH})}.$$

Reproducing the observed abundance then requires a larger portal coupling.

A possible origin of a negligible initial abundance: a preceding inflaton-dominated reheating era and its entropy release can dilute primordial relics, motivating $Y_\chi(T_{\rm RH}) \simeq 0$ as an initial condition.

Testable low-$T_{\rm RH}$ freeze-in bridges the freeze-in and freeze-out regimes.

Cosme, Costa and Lebedev, arXiv:2306.13061

Motivation

Established: thermal $SU(2)$

- Hidden $SU(2)$ breaking leaves a custodial symmetry that stabilizes three degenerate vectors.
- Their thermal freeze-out and Higgs-portal phenomenology have been studied in detail.

Hambye, JHEP 01 (2009) 028;
Baouche et al., PRD 104 (2021) 075022

Recent: low-$T_{\rm RH}$ $U(1)$

- Low $T_{\rm RH}$ freeze-in of a Higgs-portal $U(1)$ model has been analyzed.
- Low reheating permits larger couplings and improved detection prospects.
- Additional Z_2 symmetry is required to ensure the stability of the DM.

Khan, Kim and Lee, JCAP 06 (2025) 040

This work: low-$T_{\rm RH}$ $SU(2)$

- custodial $SO(3)$ naturally stabilizes three degenerate vectors;
- We determine quantitatively how the Boltzmann-suppressed low-$T_{\rm RH}$ nonthermal regime is realized in this particular three-component $SU(2)_{\rm HS}$ theory.

We systematically characterize the strong-freeze-in regime, its thermalization boundary, and its experimental implications in the custodially stabilized three-component $SU(2)_{\rm HS}$ vector-DM model.

Thermal hidden $SU(2)$: arXiv:0811.0172, 2105.14387; low-$T_{\rm RH}$ $U(1)$ freeze-in: arXiv:2503.17621

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$SU(2)_{\rm HS}$ Vector Dark Matter Model

- The model is the SM plus a hidden non-Abelian gauge symmetry $SU(2)_{\rm HS}$ and a hidden scalar doublet ϕ.
- The DM can interact with the SM particles through a Higgs-portal interaction.

Lagrangian

$$\mathcal{L}_{\rm BSM} \supset -\frac{1}{4} V^{a\mu\nu} V^a_{\mu\nu} + (D_\mu \phi)^\dagger (D^\mu \phi) - V(H,\phi).$$

where $D^\mu \phi = \left(\partial^\mu - i g_\phi \frac{\tau^a}{2} X^{a\mu}\right) \phi$,

$$V(H,\phi) = \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_\phi^2 \phi^\dagger \phi + \lambda_\phi (\phi^\dagger \phi)^2 + \lambda_{\phi H} \phi^\dagger \phi \, H^\dagger H.$$

[arXiv:0811.0172]

Hidden sector

- All SM particles are singlets under $SU(2)_{\rm HS}$.
- ϕ is charged under $SU(2)_{\rm HS}$; its vev breaks the hidden gauge symmetry.
- The three gauge bosons X^a_μ $(a = 1,2,3)$ are the vector-DM candidates.

$$H = \begin{pmatrix} 0 \\ (v+S)/\sqrt{2} \end{pmatrix}, \qquad \phi = \begin{pmatrix} 0 \\ (v_\phi + \phi_0)/\sqrt{2} \end{pmatrix}.$$

Rotation to the scalar mass basis

$$\begin{pmatrix} h \\ \eta \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} S \\ \phi_0 \end{pmatrix}, \qquad \tan 2\beta = \frac{\lambda_{\phi H} v v_\phi}{\lambda_\phi v_\phi^2 - \lambda_H v^2}, \qquad m_h = 125 \text{ GeV}.$$

After electroweak and hidden-sector symmetry breaking

$$\begin{aligned}
\mathcal{L} \supset & -\frac{1}{4} V_{\mu\nu} \cdot V^{\mu\nu} + \frac{1}{2} m_X^2 X_\mu \cdot X^\mu - \frac{1}{2} m_h^2 h^2 - \frac{1}{2} m_\eta^2 \eta^2 - (h c_\beta + \eta s_\beta) \sum_f \frac{m_f}{v} \bar{f} f \\
& + \left[\frac{c_\beta^2 h^2 + s_\beta^2 \eta^2 + s_{2\beta} h\eta}{2v} + h c_\beta + \eta s_\beta \right] \left(\frac{2 m_W^2}{v} W_\mu^+ W^{-\mu} + \frac{m_Z^2}{v} Z_\mu Z^\mu \right) \\
& + \left[\frac{s_\beta^2 h^2 + c_\beta^2 \eta^2 - s_{2\beta} h\eta}{2 v_\phi} - h s_\beta + \eta c_\beta \right] \frac{m_X^2}{v_\phi} X_\mu \cdot X^\mu \\
& - \frac{1}{6} \rho_h h^3 - \frac{1}{6} \rho_\eta \eta^3 - \frac{1}{2} \rho_1 \eta^2 h - \frac{1}{2} \rho_2 h^2 \eta
\end{aligned}$$

arXiv:2105.14387

$SU(2)_{\rm HS}$ Vector Dark Matter Model

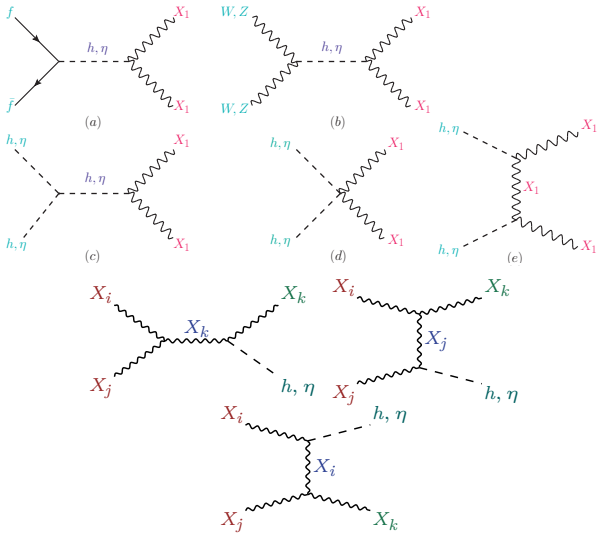
DM stability

$$m_{X_1} = m_{X_2} = m_{X_3} \equiv m_X = \frac{1}{2} g_\phi v_\phi$$

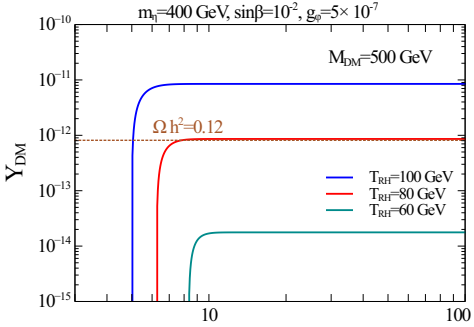
- The theory retains a custodial $SO(3)$ acting on X^a_μ.
- The three vector states remain exactly mass degenerate.

Four independent BSM parameters

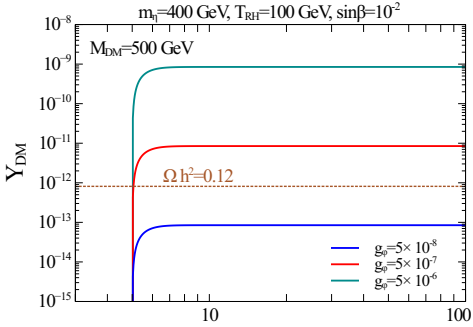
$$m_X, \quad g_\phi, \quad \sin\beta, \quad m_\eta$$



DM Yield



$T_{\rm RH} \downarrow \Rightarrow\ Y_{\rm DM} \downarrow$



$g_\phi \uparrow \Rightarrow\ Y_{\rm DM} \uparrow$

To keep $\Omega_{\rm DM}h^2 \simeq 0.12$ while lowering $T_{\rm RH}$, the portal interaction must become stronger.

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Theoretical and collider constraints

The model parameters are constrained by unitarity, perturbativity, and vacuum stability.

- **Perturbative unitarity**

$$|\lambda_{\phi H}| \leq 8\pi, \qquad |\lambda_H| \leq 4\pi, \qquad |\lambda_\phi| \leq 4\pi,$$
$$\left|3(\lambda_H + \lambda_\phi) \pm \sqrt{9(\lambda_H - \lambda_\phi)^2 + 4\lambda_{\phi H}^2}\right| \leq 8\pi.$$

- **Vacuum stability and perturbativity**

$$\lambda_H > 0, \qquad \lambda_\phi > 0, \qquad \lambda_{\phi H} > -2\sqrt{\lambda_H \lambda_\phi}, \qquad g_\phi < \sqrt{4\pi}.$$

Collider bounds from Higgs decays

$h \to X_i X_i$ and $h \to \eta\eta$ contribute through $\Gamma_X = 3\Gamma(h \to X_i X_i)$ and $\Gamma_{\eta\eta} = \Gamma(h \to \eta\eta)$:

$$\Gamma_h^{\rm tot} = c_\beta^2 \Gamma_h^{\rm SM} + \Gamma_X + \Gamma_{\eta\eta}, \qquad \Gamma_{\rm inv} = \Gamma_X + \Gamma_{\eta\eta} {\rm BR}^2(\eta \to XX).$$

$$B_{\rm inv} = \frac{\Gamma_{\rm inv}}{\Gamma_h^{\rm tot}} < 0.13, \qquad B_{\rm undet}^{\rm model} = \frac{\Gamma_{\eta\eta}}{\Gamma_h^{\rm tot}} < 0.21 \quad (m_\eta < 2m_X).$$
$$1.0 \text{ MeV} < \Gamma_h^{\rm tot} < 6.0 \text{ MeV}, \qquad \sin\beta < 0.23.$$

CMS Run 2: arXiv:2602.18611; arXiv:1606.02266

Direct Detection

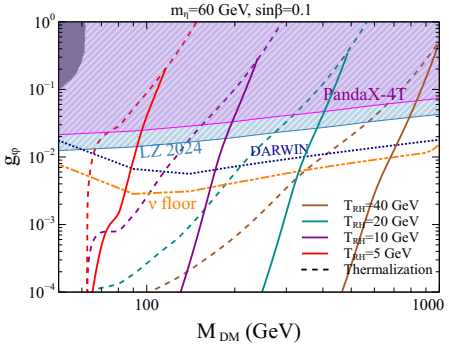
- Direct DM detection seeks to measure the nuclear recoil imparted by the scattering of the DM particle.

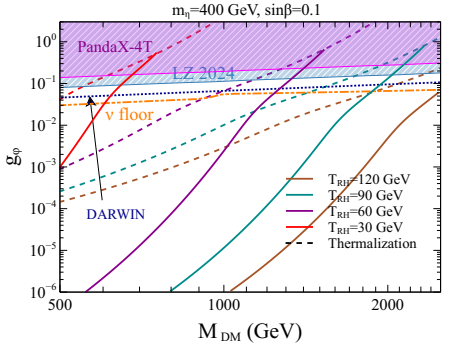
$$DM + N \to DM + N$$

- Here X scatters with nucleons through the scalar mediators h and η.

$$\sigma_{\rm SI} = \frac{f^2 m_N^2}{64\pi} \frac{v_\phi^2}{v^2} g_\phi^4 s_{2\beta}^2 \frac{(m_\eta^2 - m_h^2)^2}{m_\eta^4 m_h^4} \frac{\mu_r^2}{m_X^2}, \quad \mu_r = \frac{m_N m_X}{m_N + m_X}, \quad f \simeq 0.3$$

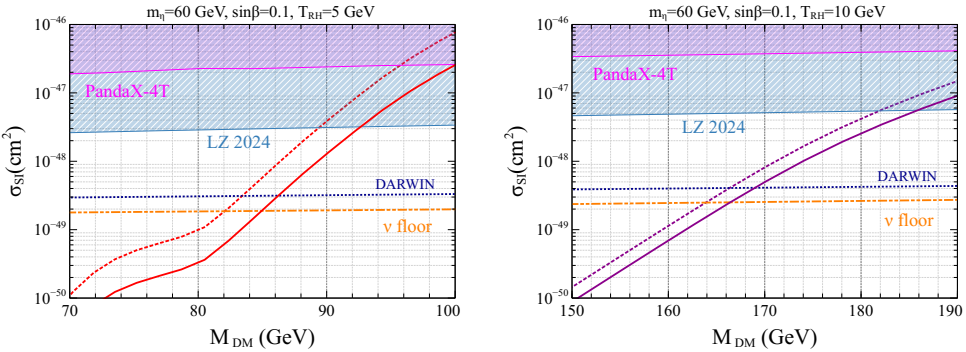
arxiv: 0811.0172





Direct Detection

- **Solid:** three-component $SU(2)_{\rm HS}$; **dotted:** one-component $U(1)_X$. Since $Y_{\rm DM} = 3\,Y_X$, the $SU(2)_{\rm HS}$ relic density requires a smaller coupling and predicts a lower $\sigma_{\rm SI}$.

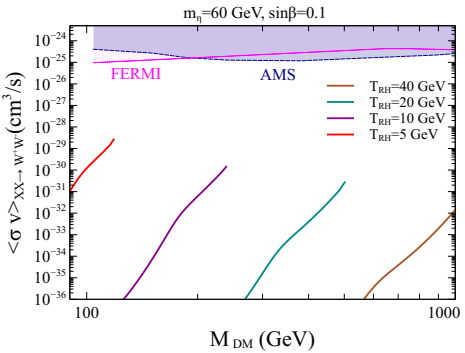


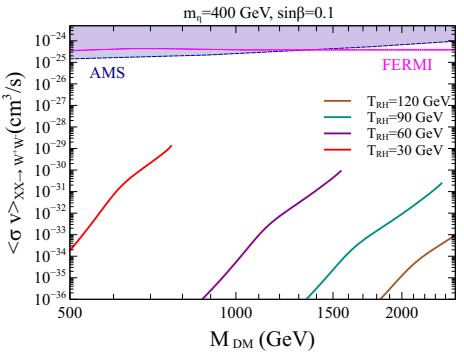
LZ allows $m_X \lesssim 92$ (184) GeV for $T_{\rm RH} = 5$ (10) GeV, versus 89 (180) GeV for one component.

$U(1)_X$: arXiv:2503.17621; $SU(2)_{\rm HS}$ comparison and benchmark values: arXiv:2605.24473

Indirect Detection

Indirect detection seeks to investigate the effects of dark matter annihilation processes, such as cosmic rays and gamma rays.





- The 90 %C.L. bounds on the thermal average cross-section for the process $X_i X_i \to W^+ W^-$ from the Fermi-LAT and AMS.
- The curves satisfy the dark matter abundance constraint.
- For the chosen set of BP, the relic satisfying contours lie below the existing indirect-detection

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Conclusion

- We studied freeze-in production of vector DM in an $SU(2)_{\rm HS}$ hidden sector for low reheating temperature.
- The three gauge bosons X_i are stable due to the residual custodial symmetry, without imposing an extra $\mathcal{Z}_2$ symmetry.
- For $T_{\rm RH} < M_{\rm DM}$, Boltzmann suppression allows the observed relic density to be obtained with comparatively larger g_ϕ.
- Larger couplings make the scenario testable: current LZ and PandaX-4T limits exclude the relic-satisfying region with roughly $M_{\rm DM}/T_{\rm RH} \sim 15 - 20$, while DARWIN can probe further.
- Indirect-detection constraints from $X_i X_i \to W^+ W^-$ are weaker for the chosen benchmarks, leaving viable parameter space.
- Low-$T_{\rm RH}$ VDM in hidden non-Abelian sectors can offer useful experimental and phenomenological insights; extensions to $SU(N)_{\rm HS}$ with $N \geq 3$ may open a broader dark-matter model-building landscape.

Thanks for your listening!

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Appendix: Boltzmann equation

$$
\begin{aligned}
\frac{dY_X}{dT} = & -\frac{S_{\rm ent}}{HT}\sum_{i=f,h,\eta,\,V}\Big[(\,Y_i^{\rm eq})^2\langle\sigma v\rangle_{ii\to XX} - \,Y_X^2\langle\sigma v\rangle_{XX\to ii}\Big] \\
& -\frac{S_{\rm ent}}{HT}\Big[\,Y_h^{\rm eq}\,Y_\eta^{\rm eq}\langle\sigma v\rangle_{h\eta\to XX} - \,Y_X^2\langle\sigma v\rangle_{XX\to h\eta}\Big] \\
& -\frac{S_{\rm ent}}{HT}\sum_{i=h,\eta}\langle\sigma v\rangle_{XX\to Xi}\Big[\,Y_X\,Y_X^{\rm eq} - \,Y_X^2\Big] \\
& -\frac{1}{HT}\sum_{j=h,\eta}\big[\,Y_j^{\rm eq}\langle\Gamma\rangle_{j\to XX} - \,Y_X\langle\Gamma\rangle_{XX\to j}\big]\,.
\end{aligned}
$$

- Instantaneous reheating and radiation domination are assumed for $T \le T_{\rm RH}$.
- The initial condition is $Y_X(\,T_{\rm RH}) = 0$.
- For the three degenerate vectors, $Y_{\rm DM} = \,Y_{X_1} + \,Y_{X_2} + \,Y_{X_3} = 3\,Y_X$.

Boltzmann equation and initial condition: arXiv:2605.24473

Appendix: thermal average and Boltzmann suppression

For $ij \to XX$, the thermally averaged cross section is

$$\begin{aligned}
\langle \sigma v \rangle_{ij\to XX} &= \frac{g_i g_j T}{2(2\pi)^4 n_i^{\rm eq} n_j^{\rm eq}} \int_{s_{\rm min}}^{\infty} ds\, \sigma_{ij\to XX}(s) \frac{\lambda(s, m_i^2, m_j^2)}{\sqrt{s}} K_1\left(\frac{\sqrt{s}}{T}\right), \\
s_{\rm min} &= \max\left[4m_X^2, (m_i + m_j)^2\right], \\
\lambda(s, m_i^2, m_j^2) &= \left[s - (m_i + m_j)^2\right]\left[s - (m_i - m_j)^2\right].
\end{aligned}$$

- For $T \ll m_X$, the integral is dominated near $s \simeq 4m_X^2$, with

$$K_1(z) \simeq \sqrt{\frac{\pi}{2z}} e^{-z}, \qquad z \simeq \frac{2m_X}{T}.$$

- The collision term samples only the energetic tail of the thermal bath and is approximately suppressed as

$$C_{ij\to XX} \propto e^{-2m_X/T}.$$

- Therefore decreasing $T_{\rm RH}$ requires a larger portal coupling to reproduce $\Omega_{\rm DM} h^2 \simeq 0.12$.

Thermal average and low-T interpretation: arXiv:2605.24473, Eq. (3.6)