Implication to (future) collider experiments from dark matter searches so far. The key question is “Where is a dark matter region attractive but not charted yet?”.
Thermal DM hypothesis

Many dark matter candidates due to little knowledge of its nature!

\[ \lambda = 2 \pi m < \text{Gal. size} \]

\[ \lambda = 2 \pi m \sim 2m/M_{\text{pl}}^2 \]

\[ m < \text{Gal. mass} \]

10^{-22} \text{ eV} \quad 10^{19} \text{ GeV} \quad 10^{40} \text{ g}

Particle dark matter

Dark matter searches are currently based on various hypotheses (e.g. WIMP, Axion, sterile ν, pBH, etc.) to cover such a huge DM mass region.

Thermal DM hypothesis

DM is a particle and its abundance today is fixed by the freeze-out mechanism.

Freeze-out MECH (BBN, Recombination)

Abundance of a species is determined by the competition between the expansion rate of the universe & the reaction rate maintaining an equilibrium of the species.
Which type of SM particle does the thermal DM mainly interacts with? Thermal DM does not have EM & color charges, thus it is classified by:

<table>
<thead>
<tr>
<th>Weak charge</th>
<th>Spin</th>
<th>Thermal dark matter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral</td>
<td>$0$</td>
<td>$1/2$</td>
</tr>
<tr>
<td>Mixed</td>
<td>$0$</td>
<td>$1/2$</td>
</tr>
<tr>
<td>Weak-charged</td>
<td>$0$</td>
<td>$1/2$</td>
</tr>
</tbody>
</table>

*From $\Delta N_{\text{eff}}$*
If thermal DM is assumed to be fermionic and has minimal interactions,

**Thermal DM hypothesis**

- From $\Delta N_{\text{eff}}$:
  - Weak charge $0$
  - Weak charge $0 - \frac{1}{2}$ mixing
  - Weak charge $\frac{1}{2}$
  - Weak charge $\frac{1}{2} - 1$ mixing
  - Weak charge $1$

- From unitarity:

**Which type of SM particle does the thermal DM mainly interacts with?**

Thermal DM does not have EM & color charges, thus it is classified by

**Thermal dark matter**

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</table>
Present status & Implications

Weak charge 0
Weak charge 0 – 1/2 mixing
Weak charge 1/2
Weak charge 1/2 – 1 mixing
Weak charge 1
Case 1: Thermal DM has a mixed weak charge (|DM⟩ = z_a |α⟩ + z_b |β⟩).

Mixed weak charge

DM Yukawa Interaction

Direct detection experiments are efficiently testing DMs of this kind.

Typical WIMPs in TeV-scale BSMs.

[S. Banerjee, S. M., K. Mukaida and Y. L. S. Tsai, JHEP1611]
**Present status & Implications**

- **Weak charge 0**
  - **Weak charge 0** — 1/2 mixing
- **Weak charge 1/2**
  - **Weak charge 1/2** — 1 mixing
- **Weak charge 1**

---

**Case 2:** Thermal DM has a non-0 weak charge (≈ a $SU(2)_L$ eigenstate).

**EW Interactions**

\[
\text{DM}^{(*)} \xrightarrow{V = W, Z, \gamma} \text{DM}^{(*)}
\]

**Annihilation boosted**

\[
\text{DM} \xrightarrow{V} \text{DM}
\]

[J. Hisano, S.M., M. Nojiri, 2004]

**Disappearing track**

\[
\text{q} \xrightarrow{V} \text{DM} \quad \text{g}
\]

\[
\text{q}' \xrightarrow{V} \text{DM}
\]

If signal is detected, …

A distinct signal at future Hadron colliders!

[M. Low, L. Wang, 2014; T. Han, S. Mukhopadhyay, X. Wang, 2018]

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**WIMP candidates in BSMs after Higgs discovery.**
Case 3: Thermal DM is singlet under the $SU(2)_L \times U(1)_Y$ symmetries. Recent searches remain CPV H-portal & leptophilic region uncharted.

**CPV H-portal**

No renormalizable interaction between DM and SM particles. $\implies$ New particle (Mediator)

Thermal DM region is covered by $H$-factories if $m_\chi < m_h/2$.

Lepton colliders can test the thermal DM region if $2m_\chi < s^{1/2}$.

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[S.M., S. Mukhopadhyay, Y. L. S. Tsai, JHEP 1410] [S. M., S. Mukhopadhyay, Y. L. S. Tsai, PRD94, 2016]
**Present status & Implications**

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Present status & Implications

Case 3: Thermal DM is singlet under the SU(2)_L × U(1)_Y symmetries.

Light DM — Light mediator — SM

Interactions w/ enough magnitudes.

Above interactions induce H—φ mixing and Higgs exotic decays.

⇒ High-L collider & H-factory!

We have systematically investigated the thermal dark matter (WIMP) to find a parameter region that is attractive but not charged yet. Implications to (future) collider experiments are obtained as follows:

<table>
<thead>
<tr>
<th>DM candidates</th>
<th>Collide signatures</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ TeV-scale DM</td>
<td>Disappearing track</td>
<td>BSM after H discovery</td>
</tr>
<tr>
<td>✓ H-funnel (CPV) DM</td>
<td>Invisible H-decay</td>
<td>G.C. γ-ray anomaly</td>
</tr>
<tr>
<td>✓ Leptophilic DM</td>
<td>Mono-γ search</td>
<td>g_μ - 2 anomaly</td>
</tr>
<tr>
<td>✓ Light DM</td>
<td>Exotic H-decay</td>
<td>Small scale crisis</td>
</tr>
</tbody>
</table>

Since our investigation is based on the minimal setup for dark matter interactions at each quantum number of the dark matter field, there must exist other attractive DM regions if we go beyond the minimality.
Backup Slides
Singlet Scalar Thermal Dark Matter

\[ \mathcal{L}_{\text{SHP}} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_0^2 S^2 - \frac{1}{2} \lambda S |H|^2 S^2 - \frac{1}{4!} \lambda_4 S^4 \]

\[ G_2 \rightarrow G_3 \]

@ Present

@ Near future

[J. A. Casas, et. al, 2017]
Mixed $(1_0 - 2_{±1/2})$ Fermion Thermal DM

$$\mathcal{L}_{SD} = \mathcal{L}_{\text{kin}} - \left[ \frac{1}{2} M_S S S + M_D D_1 \cdot D_2 + y_1 S D_1 \cdot \tilde{H} + y_2 S D_2 \cdot H + \text{H.c.} \right]$$

Direct dark matter detection @ Under ground laboratories

[S. Banerjee, S. M., K. Mukaida and Y. L. S. Tsai, JHEP1611]
\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \bar{T} (\mathcal{D} - M_T) T \]

Non-perturbative Sommerfeld Effect (SE)

SE + Perturbative one-loop correction

SE + Perturbative Sudakov logarithms (LL & NLL)

SE + NL + NLL + Inclusive effects

[J. Hisano, S.M., M. Nojiri, 2004]
[A. Hryczuk, R. Iengo, 2013]
Singlet Fermion Thermal DM (CPV H-portal)

\[ \mathcal{L}_{\text{EFT}} \supset \frac{c_S}{2\Lambda} (\bar{\chi}\chi)|H|^2 + \frac{c_P}{2\Lambda} (\bar{\chi}i\gamma_5\chi)|H|^2 + \sum_f \frac{c_f}{2\Lambda^2} (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{f}\gamma_\mu f) + \frac{c_H}{2\Lambda^2} (\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger \overset{\rightarrow}{D}_\mu H) \]

Direct dark matter detection @ Under ground laboratories (Spin-dependent scattering)

[S.M., S. Mukhopadhyay, Y. L. S. Tsai, JHEP 1410]
Singlet Fermion Thermal DM (Leptophilic)

\[ \mathcal{L}_{\text{EFT}} \supset \frac{C_S}{2 \Lambda} (\bar{\chi} \chi) |H|^2 + \frac{C_p}{2 \Lambda^2} (\bar{\chi} \gamma_5 \chi) |H|^2 + \sum_f \frac{C_f}{2 \Lambda^2} (\bar{\chi} \gamma^\mu \gamma_5 \chi) (\bar{f} \gamma_\mu f) + \frac{C_H}{2 \Lambda^2} (\bar{\chi} \gamma^\mu \gamma_5 \chi) (H^+ i \tilde{D}_\mu H) \]

*Flavor blindness assumed.*

Direct dark matter detection @ Under ground laboratories
Mono-jet search @ Hi-Luminosity Large Hadron Collider.

Light mediator region

[S. M., S. Mukhopadhyay, Y. L. S. Tsai, PRD94, 2016]
\[
\mathcal{L} = - \frac{c_s}{2} \phi \bar{\chi} \chi - \frac{c_p}{2} i \phi \bar{\chi} \gamma^5 \chi + A_\phi \phi H^\dagger H + \frac{\lambda_\phi}{2} \phi^2 H^\dagger H + \mu_1^3 \phi^3 + \frac{\mu_3^2}{2} \phi^2 + \frac{\mu_3}{3!} \phi^3 + \frac{\lambda_4}{4!} \phi^4
\]
Answer to the question why a singlet scalar mediator is introduced?

**SM + DM system** → No renormalizable interaction (SM, $Z_2$ symmetries).

New particle (mediator) must be introduced to have the interaction.

The mediator is as light as DM to explain DM density observed today.

The mediator must be singlet under the SM gauge group and bosonic.

The vector mediator is difficult to evade the constraint from CMB.

(A careful model building is required.)