A model of light pseudo scalar Dark matter

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Chakdar, Ghosh, Hung, Khan & Nanda

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standard WIMP Freeze out scenario

- Most studied BSM DM scenario: WiMP → EW + weak coupling SM
- Produced thermally early Universe, thermal equilibrium with SM up to certain temp → decouples from thermal bath@ $T_f$, interaction rate drops below expansion rate of Universe ($H$) → $\Omega h^2 \approx 0.12$
- Observed abundance is set almost exclusively by annihilation crosssec, largely insensitive to unknown details of early Universe and to mass

- Null results at direct detection ⇒ Strong constraints WIMP paradigm
- Alternate possibilities: FIP, Axion, ALPs etc.
Dark matter Freeze out vs in

• Freeze-in as *opposite process* to freeze-out: as T drops below the mass of the relevant particle, DM is either heading away from (freeze-out) or towards (freeze-in) thermal equilibrium

• Freeze-in: DM interacts extremely weakly with SM particles, negligible initial abundance and never attain thermal equilibrium (*Feebly Interacting Particle*)

Fig 1: Evolution with temperature of DM abundance for conventional freeze-out and freeze-in mechanism.
**Theory Framework**

- $\text{EW}_R$ model contains non-sterile RH $\nu'$s with Majorana masses $\sim \text{EW}$
- Dirac mass term comes from a complex singlet scalar $\phi_s$, imaginary part of this singlet is a pseudo-NG (PNG) boson $A_s^0$ (light DM)
- When a global symmetry is spontaneously broken $A_s^0$ acquires mass from explicit breaking term in scalar potential
- $\text{EW}$ SSB scale of global symmetry & sub-MeV explicit breaking scale for $A_s^0$ makes this PNG boson naturally light DM candidate

\[
\mathcal{L}_M = g_M (\bar{l}_R^M \sigma_2)(i \tau_2 \bar{\chi}) l_R^M + h.c.
\]

$\bar{\chi} (3, \frac{Y}{2} = 1)$

\[
M_R = g_M v_M; < \chi^0 >= v_M \sim \Lambda_{\text{EW}}
\]

\[
\bar{\chi} = \begin{pmatrix}
\frac{1}{\sqrt{2}} \chi^+ & \chi^{++} \\
\chi^0 & -\frac{1}{\sqrt{2}} \chi^+
\end{pmatrix}
\]

\[
\mathcal{L}_S = g_{sI} \bar{l}_L \phi_s l_R^M + h.c.
\]

$\phi_s (1, \frac{Y}{2} = 0)$

\[
m_\nu^D = g_{sI} v_S \quad \text{where} \quad < \phi_s >= v_S
\]

$m_\nu \leq 1\text{eV} \quad \Rightarrow \quad v_S \sim 10^{5-6}\text{eV with } g_{sI} \sim \mathcal{O}(1)$

or $v_S \sim \Lambda_{\text{EW}}$ with $g_{sI} \sim \mathcal{O}(10^{-6})$
**Particle content: EWν<sub>R</sub> model**

SM+ mirror fermions+ extended scalar sector (DM)

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Gauge bosons</th>
<th>Mirror Quarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>u&lt;sub&gt;up&lt;/sub&gt;</td>
<td>Y</td>
<td>u&lt;sub&gt;M&lt;/sub&gt;</td>
</tr>
<tr>
<td>c&lt;sub&gt;charm&lt;/sub&gt;</td>
<td></td>
<td>c&lt;sub&gt;M&lt;/sub&gt;</td>
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<tr>
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<td></td>
<td>t&lt;sub&gt;M&lt;/sub&gt;</td>
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<td>d&lt;sub&gt;down&lt;/sub&gt;</td>
<td>D</td>
<td>d&lt;sub&gt;M&lt;/sub&gt;</td>
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<td>s&lt;sub&gt;strange&lt;/sub&gt;</td>
<td></td>
<td>s&lt;sub&gt;M&lt;/sub&gt;</td>
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<tr>
<td>b&lt;sub&gt;bottom&lt;/sub&gt;</td>
<td>b</td>
<td>b&lt;sub&gt;M&lt;/sub&gt;</td>
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</tbody>
</table>

**Refs:** Chakdar, Ghosh, Hoang, Hung, Nandi

Complete *Scalar* Sector

- **Singlet**
  - $\phi_s \langle \nu_s \rangle$
    - Dirac mass, DM

- **Doublet**
  - $\phi_1 \langle \nu_1 \rangle, \phi_2 \langle \nu_2 \rangle$
    - mass to SM
  - $\phi_1^M \langle \nu_1^M \rangle, \phi_2^M \langle \nu_2^M \rangle$
    - mass to Mirror Fermions

- **Triplet**
  - $\tilde{\chi} \langle \nu_M \rangle$
    - Majorana mass
  - $\xi \langle \nu_M \rangle$
    - Custodial symmetry
Scalar sector parameters

- Complex part of singlet scalar $A^0_S$ does not mix with other scalars
- Mass of complex singlet scalar
  \[ M^2_{A^0_S} = 8 \lambda_{5c} (v_1 + v_2) (v_{1M} + v_{2M}) \]
- \[ \sqrt{(v_1^2 + v_{1M}^2 + v_2^2 + v_{2M}^2 + 8v_M^2)} = 246 \text{ GeV} \]
- After Spontaneous EW symmetry breaking $\rightarrow$ SU(2)$_D$ singlet mass eigenstates denoted by $\tilde{H}_S$, $\tilde{H}$, $\tilde{H}'$, $\tilde{H}''$, $\tilde{H}''$, $\tilde{H}'''$
- $\tilde{H}_S \rightarrow$ lightest, singlet DM, next heavier ones are $\tilde{H}'$, $\tilde{H}''$, $\tilde{H}'''$, with heaviest state $\tilde{H}''''$ and $\tilde{H}$ being the 125 GeV Higgs
- The decay rate of $\tilde{H}$ into two lightest CP-even scalars $\tilde{H}_S$ ($A^0_S$) can contribute to the Higgs invisible decay width depending on mixing, i.e., the value of the quartic coupling $\lambda_{4a}$ and vevs
- Singlet scalar $v_S \sim 10^4 \text{ GeV, } y_{sl} \sim 10^{-8}$ chosen $\rightarrow$ $v$ mass $\sim 0.1 \text{ eV}$
**BP’s and $\mu'$s: Scalar mass spectrum**

<table>
<thead>
<tr>
<th>Benchmark Points</th>
<th>VEV of the scalar fields (GeV)</th>
<th>Scalar quartic couplings $\lambda$'s</th>
<th>Masses of the scalar fields (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v_1$</td>
<td>$v_2$</td>
<td>$v_{1M}$</td>
</tr>
<tr>
<td>BP-1</td>
<td>140</td>
<td>145</td>
<td>43.5</td>
</tr>
<tr>
<td>BP-2</td>
<td>138</td>
<td>142</td>
<td>51.07</td>
</tr>
<tr>
<td>BP-3</td>
<td>152</td>
<td>145</td>
<td>42.99</td>
</tr>
<tr>
<td>BP-4</td>
<td>130</td>
<td>135</td>
<td>68.19</td>
</tr>
<tr>
<td>BP-5</td>
<td>130</td>
<td>140</td>
<td>62.95</td>
</tr>
</tbody>
</table>

**TABLE I**: BPs obtained fitting for constraints with $m_H$ at 125 GeV in conjunction with other heavier scalars

<table>
<thead>
<tr>
<th>Signal Strength</th>
<th>Benchmark Points and Signal strength of SM like Higgs</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$\mu_{bb}$</td>
</tr>
<tr>
<td>$\mu_{Best-Fit}$</td>
<td>2.51$^{+2.43}_{-2.01}$</td>
</tr>
<tr>
<td>$\mu_{BP-1}$</td>
<td>1.70</td>
</tr>
<tr>
<td>$\mu_{BP-2}$</td>
<td>1.81</td>
</tr>
<tr>
<td>$\mu_{BP-3}$</td>
<td>1.42</td>
</tr>
<tr>
<td>$\mu_{BP-4}$</td>
<td>1.85</td>
</tr>
<tr>
<td>$\mu_{BP-5}$</td>
<td>2.06</td>
</tr>
</tbody>
</table>

**TABLE II**: 125 GeV Higgs signal strengths corresponding to the BP’s shown in Table I
Why NOT Freeze out?

- For viable sub-MeV DM, corresponding quartic coupling $\lambda_{5c} < 10^{-12}$
- Allowed annihilation channels are: $A_S^0 A_S^0 \rightarrow \tilde{H}_A^0 \tilde{u} \rightarrow \bar{\nu}_l \nu_l / l\bar{l}$

- Large Higgs portal couplings produce relic density at right ballpark through freeze-out mechanism, but violates direct detection limits
- DM unable to remain in thermal bath at MeV due to BBN, forcing it to decouple from thermal bath at some higher temperature
- For such relativistic decoupling, the relic density can be calculated by

$$\Omega h^2 = 7.83 \times 10^4 \left( \frac{g_i}{g_{*s}(T_{dec})} \frac{M_{DM}}{\text{MeV}} \right)$$

- Turns out to be Overabundant by a few orders of magnitude!
Freeze in relic density

- DM is produced from annihilations of SM particles: $a + b \rightarrow \chi + \chi$ or decay of heavier particle in equilibrium with thermal bath: $Y \rightarrow \chi + \chi$

- In this model, FIP DM is produced dominantly from the decay of the mirror fermions and heavy Higgs (scattering processes negligible)

Boltzmann equation:

$$\frac{dn}{dt} + 3Hn = -\sum_i S \left(X_{Heavy,i} \rightarrow A_s^0 A_s^0, A_s^0 f_{SM}\right)$$

& corresponding relic density:

$$\Omega h^2 = \frac{h^2}{3H_0^2 M_{Pl}^2} M_{A_s^0} \sum_i \frac{g_{X_{Heavy,i}} \Gamma(X_{Heavy,i} \rightarrow A_s^0 A_s^0, A_s^0 f_{SM})}{M_{X_{Heavy,i}}^2}$$
Freeze in relic density

- Decay of heavy Higgs into DM & decay of mirror fermion to SM + DM,
  \[ \Gamma (\tilde{H}_i \to A_s^0 A_s^0) = \frac{y_{H_i}^2 A_s^0 A_s^0}{32 \pi M_{\tilde{H}_i}} (1 - \frac{M_{A_s^0}^2}{M_{\tilde{H}_i}^2})^{1/2}, \Gamma (f_{MF} \to f_{SM} A_s^0) = \frac{M_{f_{MF}}}{8\pi} y_{f_{MF} f_{SM} A_s^0}^2 \]

- Decay of heavy scalars and Mirror fermions can be controlled by \( \lambda_{5c}, \lambda_{4a}, \lambda_s, y_{sl} \) and VEVs with \( M_{A_s^0} \) mainly depending on \( \lambda_{5c} \) and VEVs

Fig: Variation of the parameters \( \lambda_{5c} \) and \( \lambda_{4a} \) and dark matter mass \( M_{A_s^0} \) against \( \lambda_{4a} \) variation

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Evolution of FIP DM with T

Freeze-in effect: initially density of DM being zero and increasing during the cooling of Universe and after a certain temperature DM density becoming constant.

Fig: The variation of Yield $Y(x)$ against $x$ for contributions coming from heavy Higgs and Mirror fermion decay ($M_{A^0_S} = 10$ keV)
**Bounds and Searches**

- $A_s^0 \rightarrow f f$ not possible at tree level, $A_s^0 \rightarrow \gamma \gamma$ via charged particles

- Lifetime of the decay (dominated by $e$): $\tau_{A_s^0} = \frac{6.582 \times 10^{-25}}{\Gamma_{tot}(A_s^0 \rightarrow \gamma \gamma) GeV}$ sec

- DM can remain stable for $\gamma_{sl} \sim O(10^{-2})$ for keV mass scale and $\gamma_{sl} \sim O(10^{-5})$ for MeV scales respectively ($\gamma_{sl} < 10^{-4}$ from rare decays)

- **Indirect detection**: weak scale DM (100 MeV) constrained by FERMI-LAT ($\tau_{A_s^0} > 10^{26}$ s); HEAO-1 and INTEGRAL able to put stringent constraints on parameter space preferring DM lifetime $\tau > 10^{29}$ s

- **Direct detection**: due to feeble interactions hard to get the signature of DM from the direct-detection experiments through nucleon-dark matter scattering ($\sigma \sim 10^{-61}$ cm$^2$)
• Blue dashed line relic density $\Omega h^2 = 0.1198 \pm 0.0026$.
• DM is stable in the region below the red-line, $\tau_{A^0} > \tau_U$ (3 red lines correspond to $g_u^M = 1; \sqrt{4\pi}$ and 4$\pi$).
• Grey region is excluded from $\mu \rightarrow e \gamma$ and $\mu 2e$ implying $g_{sl} < 10^{-4}$.
• Indirect detection bounds are shown preferring lifetime $\tau > 10^{29}$ s

Fig: $y_{sl}$ vs $M_{A^0}$ exclusion plot showing the relic density constraints
Freeze in in Colliders

- Can be searched in Colliders using charged track forming due to the decay of mirror fermions into SM fermion and DM.

\[
\text{Very weak couplings imply long lifetimes for the parent particle}
\]

- Not so long-lived
- "Very" long-lived

- Requires new experiments like MATHUSLA: construction of detector on surface above ATLAS/CMS (surface ~ 40000 \(m^2\), ~ height 25m)
- Large luminosity + energy to get significant event MATHUSLA100/200 detector for this scenario (prod cross-section of mother particle < O(10^{-10}) fb.)
Outlook

• Investigated prospect of a light (sub-MeV) scalar as a FIP DM
• Freeze in: DM interacts very weakly with SM & never attain thermal equilibrium
• DM sector gets populated through decay (or annihilation) of SM until the number density of SM species becomes Boltzmann-suppressed
• Mechanism needs feeble interactions → naturally suppressed coupling
• Successfully identified exclusion region for sub-MeV FIP, consistent with rare decay constraints, relic density and direct/indirect searches
• Tricky to search through direct detections, indirect detections have some handle, large energy & luminosity needed for MATHUSLA

Thank You!