Minimal Consistent Fermion Dark Matter

NeXT Spring Workshop 2020

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In collaboration with A.Belyaev, G.Cacciapaglia
1) Why particle DM?
2) What are MCDM models?
   • Single DM multiplet case
   • Adding mediator multiplets
3) Exploring a two-component DM model - accidentally stable mediators
4) Conclusions & Outlook
Why DM?

- Galaxy rotation curves
- Bullet cluster
- Large Scale Structure
- Gravitational lensing

Pie chart showing the composition of the universe:
- Dark Energy 71.4%
- Dark Matter 24%
- Atoms 4.6%

CMB (Cosmic Microwave Background) image.
Experimental complementarity

mono-X+MET, multilepton+MET, multijet+MET, non-prompt searches.

**WIMP:**
thermalised DM freezes out, requiring (co)annihilation channel(s)

**FIMP:**
Non-thermalised DM freezes-in, requiring (feeble) production channel(s).
The model landscape

- Nonrenormalisable
- Light mediators can spoil interpretation
- May not be gauge-invariant
- May have anomalies

T.Tait 1506.03116
Why MCDM?

- EFT
  - Not valid at LHC if light mediators present

- Simplified models
  - Not always gauge-invariant, particles often treated as singlets
  - DM and/or mediator charged partners important for LHC phenomenology, coannihilation channels in early universe.

- MCDM
  - gauge-invariant, renormalisable and anomaly-free
  - Indirect mediators e.g higgs-portals, dark sectors
  - MFV only

\[ \frac{g_X g_{SM}}{M_{med}^2} \sim \frac{1}{\Lambda^2} \]
Single multiplet

\[ \mathcal{L} = i \bar{\psi} \gamma^\mu D_\mu \psi - m_D \bar{\psi} \psi \]

- Introduce non-chiral (vector-like) multiplet

\{I,Y\}={0,0}, \{\frac{1}{2},\frac{1}{2}\}, \{1,0\} may have yukawa to SM leptons

- forbid these couplings by imposing \(Z_2\)

\{0,0\} has no gauge-interactions – invisible to direct detection and collider but over(under) abundant if thermal(non-thermal)

Cirelli et al. hep-ph/0512090
Radiative Mass split

Phenomenology highly sensitive to the mass split between components of a multiplet

\[ M_Q - M_{Q'} = \frac{M_D g^2}{16\pi^2} (Q - Q') \left[(Q + Q' - 2Y)(f_W - f_Z) + (Q + Q')(f_Z - f_\gamma) s_w^2\right] \]

\[ f_a = \frac{r}{2} \left[2r^3 \log(r) - 2r + \sqrt{r^2 - 4} (r^2 + 2) \log(A)\right] - 4 \]

Max M for which $\gamma$ neutral lightest (if $Q=-1$ present; $I>Y$)

Excluded from Z decays

\[ r = \frac{m_a}{M} \]
Collider bounds

- LEP (209 GeV) constraint on charged particles
  \[ m_\psi^+ \gtrsim 100\text{GeV} \rightarrow m_\psi^0 \gtrsim 100\text{GeV} \quad (I \neq 0) \]

- Non-prompt searches for compressed spectra

\[
\Gamma(\chi^- \rightarrow \chi_0 f \bar{f}) = \frac{2 N_C G_F^2 \Delta_+^5}{15 \pi^3} \quad (\Delta_+ \gg m_f)
\]

\[
\Gamma(\chi^- \rightarrow \chi^0 \pi^-) = \frac{2 G_F^2 f_\pi^2 \cos^2(\theta_C)}{\pi} \Delta_+^3 \quad (\Delta_+ \gg m_\pi^-)
\]

Zurita et al. 1703.05327

Relic abundance

- Annihilation through Z, coannihilation with charged partners through W.

\[ \dot{n}_1(t) + 3H(t)n_1(t) \approx - \left( <\sigma v>_{\chi_1\chi_1} \right) + \left( <\sigma v>_{\chi_1\chi_2} \right) \frac{g_2}{g_1} \left( 1 + \frac{\Delta m}{m_{\chi_1}} \right)^{3/2} e^{-\Delta m/T} \left( n_1(t)^2 - n_{1,eq}(t)^2 \right) \]

\[ \Omega h^2 \approx \Omega h^2_{Planck} = 0.1188 \pm 0.0010 \quad \text{at } M_{DM} \sim \text{few TeV}^0 \]
Direct detection

\( Y \neq 0 \)

Excluded by DD

\( Y = 0 \)

loop suppressed nucleon scattering – close to DD bounds

If mass split < 100KeV, may also have inelastic scatterings. But this would require masses below nuclear threshold (\( Y=0 \)) if only from radiative split.
Direct detection loops

Y=0 minimal candidates (which are sizable piece of relic abundance) may be discovered or ruled out at next generation of DD experiments

+ box (WIP), expected to be O(triangle) in large MD limit
Dim-5 couplings to higgs?

Dim-5 operators generated by e.g Dirac mediator multiplet

\[
\mathcal{L}_{\text{dim-5}} \supset -\frac{\kappa}{\Lambda} \phi_H^* T_{1/2}^a \phi_H \bar{\Psi} T_I^a \Psi - \frac{\kappa'}{\Lambda} \phi_H^* \phi_H \bar{\Psi} \Psi,
\]

\[
m_D' = m_D + \frac{\kappa'}{2\Lambda} v^2,
\]

\[
M_Q - M_{Q'} \big|_{\text{Higgs}} = \mu_D (Q - Q') \quad \mu_D = -\frac{\kappa v^2}{4\Lambda}
\]

Special case – Y=1/2:

\[
\Delta \mathcal{L}_{\text{dim5}} = -\frac{1}{2} \frac{\kappa_M}{\Lambda} \phi_H^* T_{1/2}^a \phi_H \bar{\Psi} T_I^a \Psi^C + \text{h.c.}
\]

\[
m_{1/2}^0 = m_D - \frac{1}{2} \mu_D \pm c_{1/2} \mu_M,
\]

\[
c_{I+1/2} = I + 1/2.
\]

\[
\mu_M = \frac{\kappa_M v^2}{4\Lambda}
\]
Dim-5 couplings to Higgs?

- Larger mass splits $\rightarrow$ larger dim5 couplings $\rightarrow$ larger DD signals

- NOTE: loops not included here, this example is $Y=1/2$, $I=1/2$
## +Mediator

<table>
<thead>
<tr>
<th>Spin of Dark Matter</th>
<th>0</th>
<th>1/2</th>
<th>1</th>
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<tbody>
<tr>
<td>Spin of Mediator</td>
<td></td>
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<tr>
<td>spin 0 even mediator</td>
<td>$\tilde{S}_Y S_Y'$, $\tilde{F}_Y S_Y'$</td>
<td>$\tilde{F}_Y S_Y'$</td>
<td>$\tilde{V}_Y S_Y'$</td>
</tr>
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\[ \tilde{F}_Y^I S_Y^I, \]

Even scalar mediator

\[ \Delta \mathcal{L}_{\text{real}} = \frac{1}{2} (D_\mu \Phi)^2 - V(\Phi) - \frac{1}{2} \lambda (\Phi^2)(\phi_H^\dagger \phi_H) + V_{\text{linear}} \]

\[ \Delta \mathcal{L}_{\text{com.}} = |D_\mu \Phi|^2 - V(\Phi) - \lambda (\Phi^\dagger \Phi)(\phi_H^\dagger \phi_H) - \lambda' (\Phi^\dagger T^a \Phi)(\phi_H^\dagger \tau^a \phi_H) + V_{\text{linear}} \]

\[ \Delta \mathcal{L}_{D1} = -y_1 \Phi \bar{\psi} \psi \quad \text{Real CP-even scalar} \]

\[ \Delta \mathcal{L}_{D2} = -iy_2 \Phi \bar{\psi} \gamma^5 \psi \quad \text{Real CP-odd scalar} \]

\[ Y' = 0 \]

\[ I' = 0, \ldots, 2I \]

\[ \Delta \mathcal{L}_{D3} = -y_3 \Phi \bar{\psi}^c \psi + h.c. \quad \text{Real CP-even scalar} \]

\[ \Delta \mathcal{L}_{D4} = -iy_4 \Phi \bar{\psi}^c \gamma^5 \psi + h.c. \quad \text{CP-odd scalar} \]

\[ Y' = 2Y \]

\[ I' = 0, \ldots, 2I \]

**Majorana DM:** \( Y=0; \) LD2, LD4 vanish and LD1 & LD3 coincide by Majorana condition.
Even scalar mediator

If \( \Phi \) acquires VEV there are eventual linear couplings of \( \Phi \) to Higgs doublet, possible only in 3 cases:

\[
\begin{align*}
S^0_0 \Rightarrow V_{\text{linear}} &= -\mu \, \Phi \, \phi_H^\dagger \phi_H, \quad (\text{CP-even}) ; \\
S^1_0 \Rightarrow V_{\text{linear}} &= -\mu \, \Phi^a \, \phi_H^\dagger \tau^a \phi_H , \quad (\text{CP-even}) ; \\
S^1_1 \Rightarrow V_{\text{linear}} &= -\mu \, \Phi^a \, \phi_H^\dagger \tau^a \phi_H + \text{h.c.}.
\end{align*}
\]

Higgs portal interactions if CP-even – present if VEV induced for scalar → dangerous for rho parameter

\[
\rho = \frac{m_W^2}{m_Z^2 \cos^2(\theta_W)} \sim 1 \quad \rightarrow \quad \frac{\Sigma_i 4Y_i^2 v_i^2}{\Sigma_i (I_i (I_i + 1) - Y_i (Y_i - 1)) v_i^2} \sim 1
\]

If scalar mixes with Higgs, SM-like Higgs couplings modified → couplings to SM fermions must be small. There are exceptions to this, where direct couplings can exist:

\[
\begin{align*}
S^0_2 \Rightarrow V_{\text{ferm.}} &= -y_s \, \Phi \, \bar{e}_R^c e_R \\
S^1_1 \Rightarrow V_{\text{ferm.}} &= -y_s \, \Phi^a \, l_L^c \tau^a l_L
\end{align*}
\]

Type-II see saw like, breaks lepton number conservation
Important cases

• Linear couplings present $\Phi \phi_H^2$
  - generated by $\Phi$ VEV $\rightarrow$ mixes with Higgs (Higgs portal)
  - Experiment strongly limits size of VEV through rho parameter

• Bi-linear couplings only $\Phi^2 \phi_H^2$
  - $\Phi$ VEV forbidden $\rightarrow$ scalar not a direct mediator
  - $\Phi$ may be accidentally stable $\rightarrow$ 2-component DM

• Lepton couplings
  - allowed in 2 special cases $S_2^0$, $S_1^1$
Two component models

- If only bilinear couplings of mediator to SM:
  
  \[ m_\Phi < 2m_\psi \]
  
  \( \Phi \) accidentally stable

- \( m_\Phi < 2m_\psi \) \& \( \tilde{F}_Y^0 \)
  
  \( \Phi \psi \) only couple through \( Y \).

  \[ Y \lesssim 10^{-8} \]
  
  \( \psi \) FIMP

- \( m_\Phi > 2m_\psi \) \& \( \tilde{F}_Y^0 \)
  
  \( \psi \) will not thermalise, \( \Phi \) obtains thermal relic which decays into \( \psi \) after freeze-out

  \[ Y \lesssim 10^{-10} \]
  
  \( \psi \) superWIMP

  \[ Y \sim 1 \]
  
  \( \Omega_\Phi \sim 0 \)
Two-component DM model

- We explore a minimal model with accidentally stable pseudo-scalar mediator, with interesting interplays

\[ \tilde{F}_0^0 S_0^0 (CP - odd) \]

\[ \mathcal{L} \supset i Y_\psi a \bar{\psi} \gamma^5 \psi - \frac{\lambda a H}{4} |a|^2 \phi_H^\dagger \phi_H \]

- \(a\) does not acquire VEV \(\rightarrow\) no linear coupling to Higgs
- \(m_a < 2m_\psi\) \(\rightarrow\) “secluded DM”
- Model implemented in LanHEP, and numerical scan performed using micrOMEGAs.

4 relevant parameters:

\[ m_\psi, \ Y_\psi, \ m_a, \ \lambda a H \]
(co)Annihilation channels

$m_\psi \gtrsim \frac{m_a + m_h}{2} \gtrsim \frac{3m_H}{4} \sim 90\text{GeV}$

$m_a \sim m_\psi \gtrsim m_H$

$\sigma_{a\rightarrow f f} \sim \frac{\lambda^2 m_f^2}{(4m_a^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$

- $aa \rightarrow WW$  $m_a > 80\text{GeV}$
- $aa \rightarrow ZZ$  $m_a > 90\text{GeV}$
- $aa \rightarrow tt$  $m_a > 173\text{GeV}$
\[ \sigma_{SI}(aN \to aN) \sim \frac{\lambda_a^2 f_N^2 A^2 m_N^4}{m_H^4 m_a^2} \approx 3 \times 10^{-7} \frac{\lambda_a^2}{m_a^2} \]
Metastable a

\[ \Gamma(a \rightarrow \bar{\psi} \psi) = \frac{Y^2_\psi}{4\pi} m_a \left(1 - \frac{4m^2_\psi}{m^2_a}\right)^{\frac{3}{2}} \]

- Scalar **unstable** if \( m_a > 2m_\psi \)
- Can be **metastable** with width order of universe age – either fine tune mass or
  \[ Y_\psi \lesssim 10^{-12} \]
- Can have DM mostly thermal \( a \) at freeze-out (DD visible), with small part non-thermal \( \psi \) (superWIMP)
- Decays to \( \psi \) make DM less visible to DD
- These decays to warm \( \psi \) can change velocity distributions of DM \( \rightarrow \) mass ratio limited by LSS formation
- WIMPs predict overdense cores, order of magnitude more dwarf galaxies in local group than observed and disk galaxies with less angular momentum. Velocity and angular momentum of DM halos can increase naturally in superWIMP scenarios (J. Cembranos eta l. hep-ph/0603067)
Non-thermal

\[ m_a < 2m_\psi \]
Conclusions & Outlook

- Systematic classification of MCDM reveals interesting models even for simplest case: two component DM with pseudoscalar mediator.

- $Y=0$ minimal fermionic DM models not yet fully excluded by experiment - non-singlets can be probed via non prompt searches or SUSY-like cascades at colliders. Observables highly dependent on mass-split.

- Consistent models with additional mediators may have rich phenomenology. Interesting scenarios may arise even from very simple models, even singlet cases → Portals and dark sectors.
Backup – loop details

\[ a(x, y) = 2 + (y^2 - x^2) \log \left( \frac{x^2}{(y+1)^2} \right) \]
\[ + \frac{2 \left( x^4 - 2x^3 (y^2 + y + 1) + y^2 (y + 2) - 4y - 2 \right) \log \left( \frac{x^2 + \sqrt{(x-y-2)(x+y)(x+y+2)}}{2(x+y+1)} \right)}{\sqrt{(x-y-2)(x+y)(x+y+2)}} \]

Now notice that, in limit of zero mass split \( y = 0 \), expanding around \( x = 0 \) - corresponding to \( M_D \gg M_W \):

\[ \lim_{y \to 0} a(x, y) \big|_{x=0} = -\pi + 3x - \frac{9}{8} x^2 + O(x^3) \]

For the full scattering process for DM and nucleon, \( DN \to DN \), using \( g_{\nu NN} = \frac{g_M}{2M_W} \) and \( \alpha_2 = \frac{\pi}{4} \):

\[ iM_{2-2} = iM_{DNN} \times \frac{g_{\nu NN}}{2M_W} \times \frac{i}{(h_1 + h_2)^2 - M_W^2} \好事 \left( p_1 \right) \left( p_2 \right) \]
\[ = \frac{i}{2 \alpha_2 \alpha_2} M_N \times \frac{1}{M_W} \left( Y^2 \cdot \overline{x}^2 a(x_1, y_1) \right. \]
\[ + \left. \frac{x_1}{8} \left[ (n^2 - (1 - 2Y^2)^2) a(x_1, y_1) + 2n^2 (n^2 - (1 - 2Y^2)^2) a(x_1, y_1) \right] \right] \left( \overline{p_1} \right) \left( \overline{p_2} \right) \left( p_1 \right) \left( p_2 \right) \]

\[ x_V = \frac{M_V}{M_D} \]
\[ y_i = \frac{M_i - M_D}{M_D} \]

Figure 3. Triangle loop function \(-x.a(x,y)\) against \(x\) (inversely proportional to MDM)

Figure 4. Triangle loop function \(-x.a(x,y)\) against \(y\) (mass split between MDM and fermion in loop / MDM)
Direct Detection & Higgs invisible decays

\[ \sigma_{SI} \times \Omega_\phi/\Omega_{\text{Planck}} < \sigma_{SI}^{\text{Xenon1T}} \]

- \( BR(H\to inv) < 24\% \)
- \( BR(H\to inv) < 3.8\% \)
- \( BR(H\to inv) < 0.4\% \)

\[ \sigma_{SI}(aN \to aN) \sim \frac{\lambda_{aH}^2 f_N^2 A^2 m_N^4}{m_H^4 m_a^2} \]

\[ \approx 3 \times 10^{-7} \frac{\lambda_{aH}^2}{m_a^2} \]

\[ \Gamma_{H\to aa} = \frac{\lambda_{aH}^2 v^2}{128\pi m_H} \sqrt{1 - \frac{4m_a^2}{m_H^2}} \]