A sub-GeV dark matter model: $U(1)_{T3R}$ extension of SM

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w/ Bhaskar Dutta, Jason Kumar
WHY LOW MASS DARK MATTER MODEL

- Lack of evidence for WIMP miracle and recent interest in sub-GeV DM.

- DM with mass $\mathcal{O}(1 - 100)$ MeV evades tight constraints from the current direct detection experiments and can get right relic density.

- Why $m_{DM} \sim \mathcal{O}(1 - 100)$ MeV? DM arise from a new physics associated with the light flavor sectors.

- Connect the DM to the light flavor sector through a dark photon/Higgs interactions for right handed SM fermions.

- Can solve the Yukawa sector hierarchy problem in the light flavor sector.
• Gauge symmetry: $SU(2)_L \times U(1)_Y \times U(1)_{T3R}$. The electric charge, $Q = T_{3L} + Y$.

• Anomalies cancel if we choose: one $q^u_R$, one $q^d_R$, one $\ell_R$ and one $\nu_R$. need not be in same generation. Yukawa terms need $\phi$ insertion.

• $\phi$ gets VEV $V$:
  1. breaks $U(1)_{T3R}$ down to $Z_2$ parity.
  2. SM fermion masses is proportional to $V$.
  3. Only $\eta_{L,R}$ are odd under parity.
  4. we get physical bosons: $\phi'$ and $A'$.

• $\eta$ has both Majorana and Dirac mass term.
  1. we take $m_D < < \lambda_M V$
  2. two physical states $\eta_{1,2}$ with $\Delta m = m_1 - m_2 = 2m_D$.
  3. $m_{1,2}$ scale with $V$.

<table>
<thead>
<tr>
<th>Field</th>
<th>$q_{T3R}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q^u_R$</td>
<td>-2</td>
</tr>
<tr>
<td>$q^d_R$</td>
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<tr>
<td>$\ell_R$</td>
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<tr>
<td>$\nu_R$</td>
<td>-2</td>
</tr>
<tr>
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</tr>
<tr>
<td>$\eta_R$</td>
<td>-1</td>
</tr>
<tr>
<td>$\phi$</td>
<td>-2</td>
</tr>
</tbody>
</table>

$$M_{\eta} = \begin{bmatrix} \lambda_M V & m_D \\ m_D & \lambda_M V \end{bmatrix}$$
If $V \sim \mathcal{O}(1 - 10)$ GeV, then SM fermions, $\eta_{1,2}$, $\phi'$ and $A'$ are all sub-GeV.

$\phi'$ coupling to $\eta_{1,2}$ is diagonal, while $A'$ coupling is off-diagonal.

New particles:
1. $A'$ (dark photon), $\phi'$ (dark Higgs).
2. sterile neutrino, $\nu_s$ (mostly $\nu_R$)
3. $\eta_{1,2}$ (Majorana fermion DM, comes from the mixing of $\eta_{L,R}$).

$\phi'$, $A'$, $\nu_s$ are not stabilized by any symmetry. They will decay to SM particles.

Two specific models with $V = 10$ GeV:
1. For $\ell = \mu$: $u_R, d_R, \mu_R, \nu_R, \eta_1, \eta_2, \phi', A'$.
2. For $\ell = e$: $u_R, d_R, e_R, \nu_R, \eta_1, \eta_2, \phi', A'$. 
**CONSTRAINTS**

- Main Constraints:
  1. $e^+e^-$ colliders: BaBar
  2. Electron beam dump expts.: $A', \phi' \rightarrow e^+e^-$
  4. Fifth force, APV, BBN.

- We take $V \sim 10$ GeV and small neutrino mixing angle.
- Three benchmark points which we will see get the relic density right also.
- $g - 2$: $\phi'$ (positive) and $A'$ (negative) in one-loop can be fine-tuned against each other or heavy new physics.
DIRECT DETECTION

• Two channels:
  1. $\phi'$ mediated: SI, elastic, isospin-invariant.

• Current constraints for low mass DM:
  1. CRESST III: $\sigma_{SI} \sim 10^{-35}$ cm$^2$ for $m \sim 200$ MeV.
  2. XENON1T: $\sigma_{SI} \sim 10^{-29} - 10^{-30}$ cm$^2$ for $m \sim \mathcal{O}(1 - 100)$ MeV.
  3. CDEX-1B: $\sigma_{SI} \sim 10^{-32} - 10^{-34}$ cm$^2$ for $m \sim (50 - 180)$ MeV.
  4. DM-electron scattering: XENON10, SuperCDMS and SENSEI: $\sigma_{SI} \leq 10^{-38}$ cm$^2$ for $m \sim \mathcal{O}(1 - 100)$ MeV.

• Our benchmark models satisfy all the constraints.
• We try to get the thermal relic abundance from the (co-)annihilation to SM particles or dark sector particles.

• The dominant two body final states are: \( \bar{\ell} \ell, \bar{\nu} \nu, \pi \pi, \pi^0(\phi', A', \gamma) \) and the purely dark sector channels \( A' A', \phi' \phi' \) and \( \phi' A' \).

• Three benchmark models:

<table>
<thead>
<tr>
<th>Case</th>
<th>( m_{A'} ) (MeV)</th>
<th>( m_{\phi'} ) (MeV)</th>
<th>( m_\eta ) (MeV)</th>
<th>( m_{\nu_s} ) (MeV)</th>
<th>( m_{\nu_D} ) (MeV)</th>
<th>( \langle \sigma v \rangle ) (cm(^3)/sec)</th>
<th>( \sigma_{SI}^{scalar} ) (pb)</th>
<th>( \sigma_{SI}^{vector} ) (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon case</td>
<td>55</td>
<td>200</td>
<td>100</td>
<td>10</td>
<td>( 10^{-3} )</td>
<td>( 3 \times 10^{-26} )</td>
<td>0.51</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>( 10^4 )</td>
<td>50</td>
<td>( 10^{16} )</td>
<td>( 10^4 )</td>
<td>( 3 \times 10^{-26} )</td>
<td>5.67( \times 10^{-9} )</td>
<td>1.80</td>
</tr>
<tr>
<td>electron case</td>
<td>( 5 \times 10^{-6} )</td>
<td>200</td>
<td>100</td>
<td>10</td>
<td>( 10^{-3} )</td>
<td>( 3 \times 10^{-26} )</td>
<td>0.51</td>
<td>6.50</td>
</tr>
</tbody>
</table>

• The first and third becnhmark gets relic density via \( \phi' \) resonance (\( p - \) wave supressed).

• The second benchmark gets the relic density from co-annihilation via \( A' \).
CONTRIBUTION TO $\Delta N_{\text{eff}}$ FROM $A'$

- We studied for $\ell = \mu$ model: $\mu \bar{\mu} \rightarrow \gamma A'$.
- The constraints are much more severe than $U(1)_{L_\mu-L_\tau}$ because $A'$ couples to chiral fermions.
- No matter how weak the coupling, the Goldstone mode (longitudinal polarization) does not decouple and equilibrates in the early universe.

- Even extremely light and weakly coupled $A'$ of $U(1)_{T3R}$ is ruled out, unless the symmetry breaking scale is $\geq 10^7$ GeV.
- $H_0$ tension can be resolved for $\Delta N_{\text{eff}} \approx 0.2$ by choosing $V$ appropriately for $m_{A'} \leq 1$ MeV.
- For $1 \leq m_{A'} \leq 10$ MeV, this can be done by choosing neutrino mass matrix appropriately.

![Graph showing $\Delta N_{\text{eff}}$ vs. $m_{A'}$](image-url)
CONCLUSIONS

- The experiments are now focusing on sub-GeV dark matter.

- We present a sub-GeV DM model with $m_{DM} \sim \mathcal{O}(1 - 100) \text{ MeV}$ naturally connected to the light flavor sector of SM and gives correct thermal relic density.

- Can solve the Yukawa sector hierarchy problem.

- Low mass mediator $\leq \mathcal{O}(10) \text{ GeV}$, consistent with the current experiments and can be probed in the future experiments.