Radiative Light Dark Matter

Dimitrios Karamitros

University of Ioannina,
Greece

8/4/2017

In collaboration with
Athanasios Dedes and Apostolos Pilaftsis

arXiv:1704.01497
Evidence for Dark Matter: The Bullet Cluster
There is extra matter in the universe with relic abundance\textsuperscript{1}
\[ \Omega_{DM} h^2 \approx 0.12. \]

\textsuperscript{1}P. Ade et al. Astron. Astrophys. \textbf{571}, A16 (2014) [arXiv:1303.5076].
WIMPs at the electroweak scale seem natural ("WIMP miracle").

One way to explain the missing WIMP signal: Move to sub-GeV masses.

Dimitrios Karamitros
sub-GeV Dark Matter

Characteristics:

- Stable and neutral.
- Lowest allowed\(^2\) Dark Matter mass \(\sim 10\) keV.
- Relativistic at freeze-out \((\Omega_{DM}h^2 \gg 0.12) \rightarrow\) out of thermal equilibrium production.

**Why is it light?**
Symmetry \(\rightarrow\) soft breaking \(\rightarrow\) radiative mass generation.

---

\(^2\)V. Iri et al., *New Constraints on the free-streaming of warm dark matter from intermediate and small scale Lyman-\(\alpha\) forest data*, arXiv:1702.01764
**Minimal Model**

|     | $SU(2)_L$ | $U(1)_Y$ | $U(1)_{PQ}$ | $\mathbb{Z}_2$ |
|-----|-----------|-----------|--------------|---------------|
| $S$ | $1$       | $0$       | $-1$         | odd           |
| $D_1$ | $2$       | $-1$      | $0$          | odd           |
| $D_2$ | $2$       | $1$       | $0$          | odd           |
| $\Phi_1$ | $2$       | $1$       | $1$          | even          |
| $\Phi_2$ | $2$       | $1$       | $-1$         | even          |

\[ -\mathcal{L}^Y = Y_1 \Phi_1^T \epsilon D_1 S + Y_2 \Phi_2^\dagger D_2 S + M_D D_1^T \epsilon D_2 + \text{H.c.}, \]
\[ V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{H.c}) + \ldots \]

From minimization conditions for $m_{12} \gg \nu$:

\[ m_{11}^2 \approx m_{12}^2 t_\beta + \mathcal{O}(\nu^2), \quad m_{22}^2 \approx m_{12}^2 t_\beta^{-1} + \mathcal{O}(\nu^2), \]

with $t_\beta \equiv \langle \Phi_2 \rangle / \langle \Phi_1 \rangle$.

---

$^3$R. D. Peccei and H. R. Quinn, *Phys. Rev.* D16 (1977) 1791–1797 and R. D. Peccei and H. R. Quinn, *Phys. Rev. Lett.* 38 (1977) 1440–1443.
Mass Generation

\[ M_{S}^{\text{rad}} = \frac{2y^2}{(4\pi)^2} \frac{M_D}{t_\beta - t_\beta^{-1}} \left[ \frac{t_\beta \ln \left( t_\beta / r^2 \right)}{t_\beta - r^2} - \frac{t_\beta^{-1} \ln \left( t_\beta^{-1} / r^2 \right)}{t_\beta^{-1} - r^2} \right], \]

\[ r \equiv \frac{M_D}{m_{12}}, \quad y^2 \equiv Y_1 Y_2. \]

Assuming that \( M_D \gg v \):

\[ \frac{M_{S}^{\text{tree}}}{M_{S}^{\text{rad}}} \sim \frac{8\pi^2 v^2}{M_D^2} < 1. \]
$M_D = 10^{-2} \times m_{12}, \tan\beta = 1$
The Freeze-in mechanism:

- DM particle absent and out of thermal equilibrium.
- DM particle produced from plasma particles (say $B$).
- Production stops usually at $T_{FI} \sim M_B$ (renormalizable operators) or $T_{FI} \sim T_{RH}$ (non-renormalizable operators).
Freeze-in of $S$

Assuming:
- $D_{1,2}$ are decoupled, i.e. $M_D \gg T_{RH}$.
- $T_{RH} \gtrsim T_C$.
- Mass is radiatively dominated, i.e. $M_S^{\text{rad}} \gg M_S^{\text{tree}}$.
- Alignment limit of 2HDM.

The production is described by:

$$-\mathcal{L}_{\text{eff}}^{d=5} = \frac{y^2}{M_D} \frac{t_\beta}{1 + t_\beta^2} \left( H_1^\dagger H_1 - H_2^\dagger H_2 - t_\beta H_1^\dagger H_2 + t_\beta^{-1} H_2^\dagger H_1 \right) SS + \text{H.c.},$$

$\langle H_1 \rangle = \nu$ and $\langle H_2 \rangle = 0$.

Then the dominant production channels of $S$ are:

- $H_i^\dagger H_j \rightarrow SS$ for $T_C \leq T < T_{RH}$,
- $h \rightarrow SS$ for $T < T_C$. 

Dimitrios Karamitros
Results

\[ M_D = 10^{-2} \times m_{12}, \tan \beta = 1 \]

Interesting Implication: Solving the strong CP problem.

DFSZ\textsuperscript{4} model: \( \langle \Sigma \rangle \equiv f_{PQ} \approx m_{12} \gtrsim 10^9 \) GeV.

\textsuperscript{4}A. R. Zhitnitsky, \textit{Sov. J. Nucl. Phys.} \textbf{31} (1980) 260. and M. Dine, W. Fischler, M. Srednicki, \textit{Phys. Lett.} \textbf{B104} (1981) 199–202.
\[ M_D = 10^5 \times m_{12}, \ \tan\beta = 1 \]

Interesting Implication: LHC can produce the heavy scalars.
Detection of $S$

Direct detection sensitivity\textsuperscript{5} $\bar{\sigma}_{Se}^{\text{exp}} \simeq 10^{-38}$ cm\textsuperscript{2}.

In RLDM suppressed due to $\frac{m_e}{m_h}$:

$$\bar{\sigma}_{Se} \approx 10^{-50} \times \frac{y^4 t^2_\beta}{(1 + t^2_\beta)^2} \left(\frac{1 \text{ GeV}}{M_D}\right)^2 \text{cm}^2.$$  

$S$ particles Seem to be undetectable.

\textsuperscript{5}R. Essig, T. Volansky, and T.-T. Yu, \textit{New Constraints and Prospects for sub-GeV Dark Matter Scattering off Electrons in Xenon}, arXiv:1703.00910
Conclusions

- Natural Dark Matter at 10 keV – 1 GeV.
- Radiative mechanism compatible with Freeze-in, without fine tuning.
- Possible connection to the solution of the strong CP problem.
- Possible detection of the heavy scalars at the LHC.
Future Directions

- $T_{RH} = ?$
- $m_{12} = ?$
- Explore the connection to axion and other models.
- Direct detection of $S$?
$10\text{keV} - 1\text{GeV}$  \hspace{1cm} $\Omega h^2 \approx 0.12$

**Radiative**  \hspace{1cm} **Light**  \hspace{1cm} **Dark Matter**
bcp...
For $t_\beta = 1$,

\[ M_S^{\text{rad}} \approx \frac{2y^2}{(4\pi)^2} M_D \quad \text{for } r \ll 1 , \]

\[ M_S^{\text{rad}} \approx \frac{y^2}{(4\pi)^2} M_D \quad \text{for } r \sim 1 , \]

\[ M_S^{\text{rad}} \approx \frac{2y^2}{(4\pi)^2} \frac{M_D \ln r^2}{r^2} \quad \text{for } r \gg 1 . \]
Approximate Relic Abundance

$$\Omega_s h^2 \approx 0.12 \times \left( \frac{M_S}{10^{-5} \text{GeV}} \right) \left( \frac{2 \times 10^8 \text{GeV}}{M_D} \right)^2 \left( \frac{y}{4.7 \times 10^{-2}} \right)^4 \times \left[ \left( \frac{t_\beta}{1 + t_\beta^2} \right)^2 + \left( \frac{T_{\text{RH}}}{10^4 \text{GeV}} \right) \right], \text{ for } T_{\text{RH}} \gg m_{12}$$

$$\Omega_s h^2 \approx 0.12 \times \left( \frac{M_S}{10^{-3} \text{GeV}} \right) \left( \frac{2 \times 10^5 \text{GeV}}{M_D} \right)^2 \left( \frac{y}{4.7 \times 10^{-4}} \right)^4 \times \left( \frac{t_\beta}{1 + t_\beta^2} \right)^2 \left[ 1 + \left( \frac{T_{\text{RH}}}{10^4 \text{GeV}} \right) \right], \text{ for } T_{\text{RH}} \ll m_{12}$$
Example:\n\[
\lambda_\Sigma \Sigma^2 \Phi_1^\dagger \Phi_2 + \text{H.c.} \subset V(\Phi_1, \Phi_2, \Sigma),
\]
\[
\langle \Sigma \rangle \equiv f_{PQ} \approx m_{12}, \text{ with } \lambda_\Sigma \approx 1.
\]
Yukawa for \( r = 10^{-2} \)

\[ M_D = m_{12} \times 10^{-2}, \quad \tan(\beta) = 1 \]

\[ T_{\text{RH}} \text{ [GeV]} \]

- \( M_S = 1 \text{ GeV} \)
- \( M_S = 10^{-1} \text{ GeV} \)
- \( M_S = 10^{-2} \text{ GeV} \)
- \( M_S = 10^{-3} \text{ GeV} \)
- \( M_S = 10^{-4} \text{ GeV} \)
- \( M_S = 10^{-5} \text{ GeV} \)
Yukawa for $r = 10^5$

\[ M_D = m_{12} \times 10^5, \tan(\beta) = 1 \]
$M_{S}^{\text{tree}}$ for $r = 10^{-2}$

$M_D = m_12 \times 10^{-2}$, $\tan(\beta) = 1$
\[ M^\text{tree}_S \text{ for } r = 10^5 \]

\[ M_D = m_{12} \times 10^5, \tan(\beta) = 1 \]

\[ M_S = 1 \text{ GeV} \]
\[ M_S = 10^{-1} \text{ GeV} \]
\[ M_S = 10^{-2} \text{ GeV} \]
\[ M_S = 10^{-3} \text{ GeV} \]
\[ M_S = 10^{-4} \text{ GeV} \]
\[ M_S = 10^{-5} \text{ GeV} \]
Production using $H^\dagger HSS$ EFT

Approximate

Exact

$10^1$  $10^2$  $10^3$

$Y$

$10^{-5}$  $10^{-6}$  $10^{-7}$

$T [\text{GeV}]$

Dimitrios Karamitros
Decoupling using $H^\dagger HSS$ EFT

\[ L = 10^4 \text{GeV} \]
\[ L = 10^5 \text{GeV} \]
\[ L = 10^6 \text{GeV} \]
\[ L = 10^7 \text{GeV} \]
\[ L = 10^8 \text{GeV} \]