Darkon models, light dark-matter hint from CDMS II, and Higgs boson at the LHC

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Outline

- Introduction
- Simplest WIMP DM model, SM+D
- Somewhat enlarged model, THDM+D
- Isospin-violating DM in THDM+D
- Conclusions
Potential WIMP hint in new CDMS II Si data

Their analysis resulted in 3 events and the estimated background is 0.7 events. The finding has 3-sigma CL and hence does not offer conclusive evidence for WIMPs.

FIG. 4. Experimental upper limits (90% confidence level) for the WIMP-nucleon spin-independent cross section as a function of WIMP mass. We show the limit obtained from the exposure analyzed in this work alone (blue dotted line), and combined with the CDMS II Si data set reported in [23, 28] (blue solid line). Also shown are limits from the CDMS II Ge standard [17] and low-threshold [29] analysis (dark and light dashed red), EDELWEISS low-threshold [30] (long-dashed orange), XENON10 S2-only [31] (dash-dotted green), and XENON100 [32] (long-dash-dotted green). The filled regions identify possible signal regions associated with data from CoGeNT [33] (dashed yellow, 90% C.L.), DAMA/LIBRA [10, 34] (dotted tan, 99.7% C.L.), and CRESST [12, 35] (dash-dotted pink, 95.4% C.L.) experiments. 68% and 90% C.L. contours for a possible signal from these data are shown in light blue. The blue dot shows the maximum likelihood point at (8.6 GeV/c², 1.9 × 10⁻⁴¹ cm²).
Weakly interacting massive particles (WIMPs) may be directly detected via their interactions with nuclei.

Recent data on WIMP-nucleon spin-independent elastic cross-section.

Light-WIMP data (mass ~5-20 GeV) remain controversial.

- DAMA, CoGeNT, and CRESST-II observed potential light-WIMP evidence (their data do not fully agree).

- But LUX, XENON, SIMPLE, and others have not seen any WIMP evidence, and hence provided only upper limits.
**Puzzle in light-WIMP data**

- There are inconsistencies among light-WIMP data from different direct detection experiments.

- One of the ideas proposed to resolve the puzzle: allow sizable isospin violation in WIMP-nucleon interactions.
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  $$f_n \approx -0.7 f_p$$

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Kurylov & Kamionkowski
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In IVDM case, some part of CDMS II (blue/cyan) area still escapes all current exclusion limits, in contrast to DAMA, CoGeNT, and CRESST-II
Interplay between Higgs & DM sectors

The two sectors may be intimately connected
- This is the case especially in darkon models

If so, detecting the signs of one of them could shine light on still hidden elements of the other.

It is of interest to explore some of the implications of recent developments in the hunts for the Higgs and for DM in the contexts of simple frameworks.
Simplest model: SM plus darkon

The **simplest model** having a WIMP candidate is the **SM+D**: 
- the **standard model** (SM) plus
- a real scalar field $D$, called **darkon**, as dark matter.

The **darkon** is stable.
- It's a **singlet** under the SM gauge groups.
- Its Lagrangian is **invariant** under a discrete $Z_2$ symmetry, $D \rightarrow -D$ (so $D$ can only be created or annihilated in pairs).

Requiring also the **darkon** interactions be renormalizable implies $D$ can couple only to the Higgs doublet field $H$.

The **darkon** Lagrangian then has the form

$$\mathcal{L}_D = \frac{1}{2} \partial^\mu D \partial_\mu D - \frac{1}{4} \lambda_D D^4 - \frac{1}{2} m_0^2 D^2 - \lambda D^2 H^\dagger H$$

- **self-interaction coupling**
- **mass parameter**
- **darkon-Higgs coupling**
Simplest Darkon model

After electroweak symmetry breaking

$$\mathcal{L}_D = \frac{1}{2} \partial^\mu D \partial^\mu D - \frac{1}{4} \lambda_D D^4 - \frac{1}{2} \left( m_0^2 + \lambda v^2 \right) D^2 - \frac{1}{2} \lambda D^2 h^2 - \lambda v D^2 h$$

$h$ is the physical Higgs field and $v = 246$ GeV the vev of $H$.

This Lagrangian has only 3 free parameters.

- Darkon-Higgs coupling $\lambda$
- Darkon mass $m_D = \sqrt{m_0^2 + \lambda v^2}$
- Darkon self-interaction coupling $\lambda_D$.

The last term, $-\lambda v D^2 h$, plays an important role in determining the relic density in the SM+D.
The interactions of any WIMP candidate with SM particles must satisfy constraints from relic-density data.

The darkon annihilation rate into SM particles is related to its relic density $\Omega_D$ by the thermal dynamics of the Universe within the standard big-bang cosmology, according to

$$\Omega_D h^2 \sim \frac{0.1 \text{ pb}}{\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle}$$

$h$ is the Hubble constant in units of 100km/(s·Mpc), $\sigma_{\text{ann}}$ the darkon annihilation cross-section into SM particles, $v_{\text{rel}}$ the darkon-pair relative speed in their cm frame.
For $m_D \leq m_h$, the relic density results from darkon annihilation into SM3 particles via Higgs ($h$) exchange.

**The $h$-mediated annihilation cross-section**

$$
\sigma_{\text{ann}} v_{\text{rel}} = \frac{8\lambda^2 v^2}{(4m_D^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \sum_i \frac{\Gamma(\tilde{h} \to X_i)}{2m_D}.
$$

$\tilde{h}$ is a virtual Higgs boson having the same couplings to other states as the physical $h$ of mass $m_h > m_D$, but with invariant mass $\sqrt{s} = 2m_D$, and $\tilde{h} \to X_i$ any possible decay mode of $\tilde{h}$.

For $m_D > m_h$ contributions from $DD \to hh$ need to be included in $\sigma_{\text{ann}}$. 
The direct detection of dark matter is through the recoil of nuclei when a darkon hits a nucleon $N$.

In SM+D, this occurs via Higgs exchange in the $t$-channel elastic scattering $DN \rightarrow DN$.

Amplitude for $DN \rightarrow DN$

\[ \mathcal{M}_{el} \approx \frac{2\lambda g_{NNh} v}{m_h^2} \bar{NN} \]

as $t << m_h^2$ for slow $D$ and $N$

Cross section of $DN \rightarrow DN$

\[ \sigma_{el} \approx \frac{\lambda^2 g_{NNh}^2 v^2 m_N^2}{\pi (m_D + m_N)^2 m_h^4} \]
- SM+D with Higgs mass $m_h = 125$ GeV
- The prediction accommodates well the light-WIMP hypothesis.
Invisible Higgs in SM+D with light darkon

For a 125-GeV Higgs, the invisible decay mode is highly dominant for darkon masses $m_D < m_h/2$

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Thus the discovery of a 125-GeV Higgs implies that SM+D with a light darkon (under ~40 GeV) is ruled out.

To keep a light darkon, SM+D needs to be expanded.
Two-Higgs-doublet model plus darkon

- The Higgs sector is the THDM of type III
  - Both Higgs doublets couple to the fermions.
  - Neutral physical scalar Higgs fields $h$ & $H$

$$\begin{pmatrix} h_1^0 \\ h_2^0 \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

- Darkon Lagrangian

$$\mathcal{L}_D = \frac{1}{2} \partial^\mu D \partial_\mu D - \frac{1}{4} \lambda_D D^4 - \frac{1}{2} m_0^2 D^2 - \left[ \lambda_1 H_1^\dagger H_1 + \lambda_2 H_2^\dagger H_2 + \lambda_3 (H_1^\dagger H_2 + H_2^\dagger H_1) \right] D^2$$

- Darkon mass & darkon-Higgs couplings

$$m_D^2 = m_0^2 + [\lambda_1 \cos^2 \beta + \lambda_2 \sin^2 \beta + \lambda_3 \sin(2\beta)] v^2$$

$$\lambda_h = -\lambda_1 \sin \alpha \cos \beta + \lambda_2 \cos \alpha \sin \beta + \lambda_3 \cos(\alpha + \beta)$$

$$\lambda_H = \lambda_1 \cos \alpha \cos \beta + \lambda_2 \sin \alpha \sin \beta + \lambda_3 \sin(\alpha + \beta)$$

- Yukawa Lagrangian

$$\mathcal{L}_Y = -\bar{Q}_{j,L} (\lambda_1^U)_{jl} H_1 U_{l,R} - \bar{Q}_{j,L} (\lambda_2^U)_{jl} H_1 D_{l,R} - \bar{Q}_{j,L} (\lambda_1^D)_{jl} H_2 U_{l,R} - \bar{Q}_{j,L} (\lambda_2^D)_{jl} H_2 D_{l,R}$$

$$- \bar{L}_{j,L} (\lambda_1^E)_{jl} H_1 E_{l,R} - \bar{L}_{j,L} (\lambda_2^E)_{jl} H_2 E_{l,R} + \text{H.c.}$$
Yukawa terms

After fermion mass matrices $M_{\mu,D,E} = \frac{1}{\sqrt{2}}(\lambda_{1,U,D,E}^{u}v_{1} + \lambda_{2,U,D,E}^{u}v_{2})$ are diagonalized, $h_{1,2}^{0}$ couple to fermions according to

$$\mathcal{L}_{Y} = -\bar{U}_{L} \left[ \left( M_{\mu} - \frac{\lambda_{1}^{u}v_{2}}{\sqrt{2}} \right) \frac{h_{1}^{0}}{v_{1}} + \left( M_{\mu} - \frac{\lambda_{1}^{u}v_{1}}{\sqrt{2}} \right) \frac{h_{2}^{0}}{v_{2}} \right] U_{R} - \bar{D}_{L} \left[ \left( M_{D} - \frac{\lambda_{2}^{D}v_{2}}{\sqrt{2}} \right) \frac{h_{1}^{0}}{v_{1}} + \left( M_{D} - \frac{\lambda_{1}^{D}v_{1}}{\sqrt{2}} \right) \frac{h_{2}^{0}}{v_{2}} \right] D_{R}$$

$$- \bar{E}_{L} \left[ \left( M_{E} - \frac{\lambda_{2}^{E}v_{2}}{\sqrt{2}} \right) \frac{h_{1}^{0}}{v_{1}} + \left( M_{E} - \frac{\lambda_{1}^{E}v_{1}}{\sqrt{2}} \right) \frac{h_{2}^{0}}{v_{2}} \right] E_{R} + \text{H.c.}$$

where now $M_{\mu} = \text{diag}(m_{u}, m_{c}, m_{t})$, etc., and $U = (u \ c \ t)^{T}$, etc., contain mass eigenstates, but $\lambda_{1,2}^{u,D,E}$ in general are not also diagonal separately.

For each flavor-diagonal coupling, then in terms of the physical field $\mathcal{H} = h$ or $H$

$$\mathcal{L}_{\text{ffH}} = -k_{f}^{\mathcal{H}} m_{f} \bar{f} f \frac{\mathcal{H}}{v}$$

$$k_{u}^{h} = \frac{\cos \alpha}{\sin \beta} - \lambda_{1}^{u} \frac{v \cos(\alpha - \beta)}{\sqrt{2} m_{u} \sin \beta}, \quad k_{u}^{H} = \frac{\sin \alpha}{\sin \beta} - \lambda_{1}^{u} \frac{v \sin(\alpha - \beta)}{\sqrt{2} m_{u} \sin \beta}$$

$$k_{d}^{h} = -\frac{\sin \alpha}{\cos \beta} + \lambda_{2}^{d} \frac{v \cos(\alpha - \beta)}{\sqrt{2} m_{d} \cos \beta}, \quad k_{d}^{H} = \frac{\cos \alpha}{\cos \beta} + \lambda_{2}^{d} \frac{v \sin(\alpha - \beta)}{\sqrt{2} m_{d} \cos \beta}$$

$$k_{e}^{h} = -\frac{\sin \alpha}{\cos \beta} + \lambda_{2}^{e} \frac{v \cos(\alpha - \beta)}{\sqrt{2} m_{e} \cos \beta}, \quad k_{e}^{H} = \frac{\cos \alpha}{\cos \beta} + \lambda_{2}^{e} \frac{v \sin(\alpha - \beta)}{\sqrt{2} m_{e} \cos \beta}$$

$$\lambda_{a}^{u,d,e} = (\lambda_{a}^{U,D,E})_{11}, \quad \text{etc.}$$
**Higgs couplings**

The h and H couplings to W and Z may be relevant depending on $m_D$ and are given by

$$\mathcal{L}_{VVH} = \frac{1}{v} \left( 2m_W^2 W^+ W^- + m_Z^2 Z^+ Z^- \right) \left[ h \sin(\beta - \alpha) + H \cos(\beta - \alpha) \right]$$

Inspired by the discovery of a 125-GeV SM-like Higgs at the LHC, we adopt

$$\cos(\beta - \alpha) = 0$$

Applying one of its solutions, $\beta - \alpha = \pi/2$, yields

$$k_u^h = k_d^h = k_e^h = 1$$

$$k_u^H = -\cot \beta + \frac{\lambda_1^u v}{\sqrt{2} m_u \sin \beta}$$

$$k_d^H = \tan \beta - \frac{\lambda_2^d v}{\sqrt{2} m_d \cos \beta}$$

$$k_e^H = \tan \beta - \frac{\lambda_2^e v}{\sqrt{2} m_e \cos \beta}$$

$$\lambda_h = \lambda_1 \cos^2 \beta + \lambda_2 \sin^2 \beta + \lambda_3 \sin(2\beta)$$

$$\lambda_H = \frac{1}{2} (\lambda_1 - \lambda_2) \sin(2\beta) - \lambda_3 \cos(2\beta)$$

$$\mathcal{L}_{VVH} = \left( 2m_W^2 W^+ W^- + m_Z^2 Z^+ Z^- \right) \frac{h}{v}$$

Now the couplings of h to SM fermions and gauge bosons are identical to those of SM Higgs.
**Prediction of THDM+D**

- The prediction can accommodate well the light-WIMP hypothesis.

- The model has a SM-like Higgs, $h$

- The heavier Higgs, $H$, is largely invisible.
  - This is consistent with LHC data.
The observed relic density and $f_n = -0.7 f_p$ requirements lead to limitations on the predicted darkon-proton scattering cross-section.

We find that to enhance $\sigma_{el}^p$ by a few orders of magnitude under these restrictions implies that $k_{u,d}^H$ have to be big, $k_u^H \sim -2k_d^H$, and the other $k_f^H$ become negligible by comparison.

For example, with $m_H = 200$ (300) GeV we find $0.6 \times 10^3 \leq \lambda_H k_u^H \leq 0.8 \times 10^3$ corresponding to $5 \text{ GeV} \leq m_D \leq 20 \text{ GeV}$.

Thus in general $k_u^H = \mathcal{O}(10^3)$ if $\lambda_H = \mathcal{O}(1)$ and $m_H$ is a few hundred GeV.

For such large $k_{u,d}^H$, one expects that $k_u^H \sim \lambda_1^u v_1 / m_u$ and $k_d^H \sim \lambda_2^d v_2 / m_d$. Consequently, since $\lambda_1^u v_1 + \lambda_2^d v_2 = \sqrt{2} m_u$ and $\lambda_1^d v_1 + \lambda_2^d v_2 = \sqrt{2} m_d$, some degree of fine cancelations between the $\lambda_{a,d}^u v_a$ terms is needed to reproduce the small $u$ and $d$ masses. This is the price one has to pay for the greatly amplified $\sigma_{el}^p$. 
The maximum prediction (orange) curve is lower than the DAMA and CoGeNT favored regions, but by only a factor of a few.

The prediction range (light orange) can easily accommodate the CRESST-II and CDMS II favored regions.

Much of the prediction (light orange) also escapes the LUX limit.
**Conclusions**

- The discovery of the SM-like Higgs boson at the LHC implies that the simplest WIMP DM model, SM+D, with a light darkon (under ~40 GeV) is ruled out.

- To keep a light darkon in the presence of a SM-like Higgs, one needs to enlarge SM+D.

- This is achievable in THDM+D.

- THDM+D can also offer isospin violation in the WIMP-nucleon interactions at the desired level.

- THDM+D can accommodate well the new possible hint of low-mass WIMPs from CDMS II, whether the WIMP-nucleon interactions conserve isospin or not, although there is partial conflict with the LUX result.