

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

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Xiao-Gang He & JT, [arXiv:1304.6058](https://arxiv.org/abs/1304.6058) [PRD 88 (2013) 013020]

19th International Symposium on Particles, Strings, and Cosmology
Taipei, Taiwan

20 November 2013

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

arXiv:1304.4279

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.

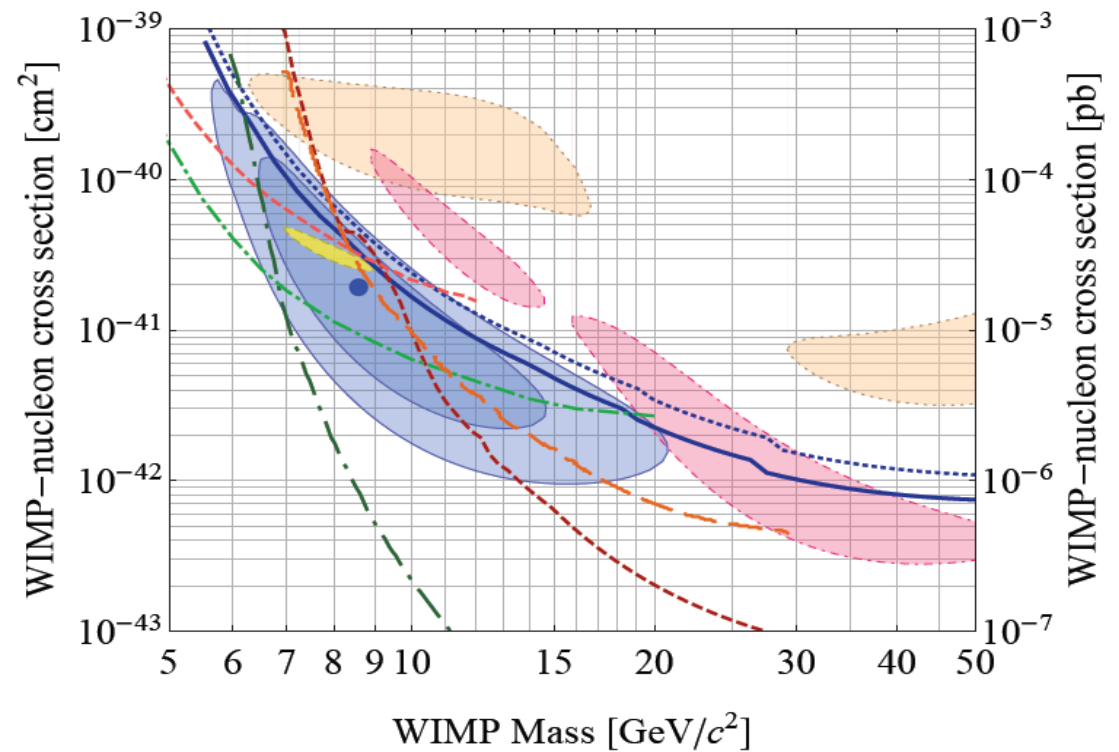
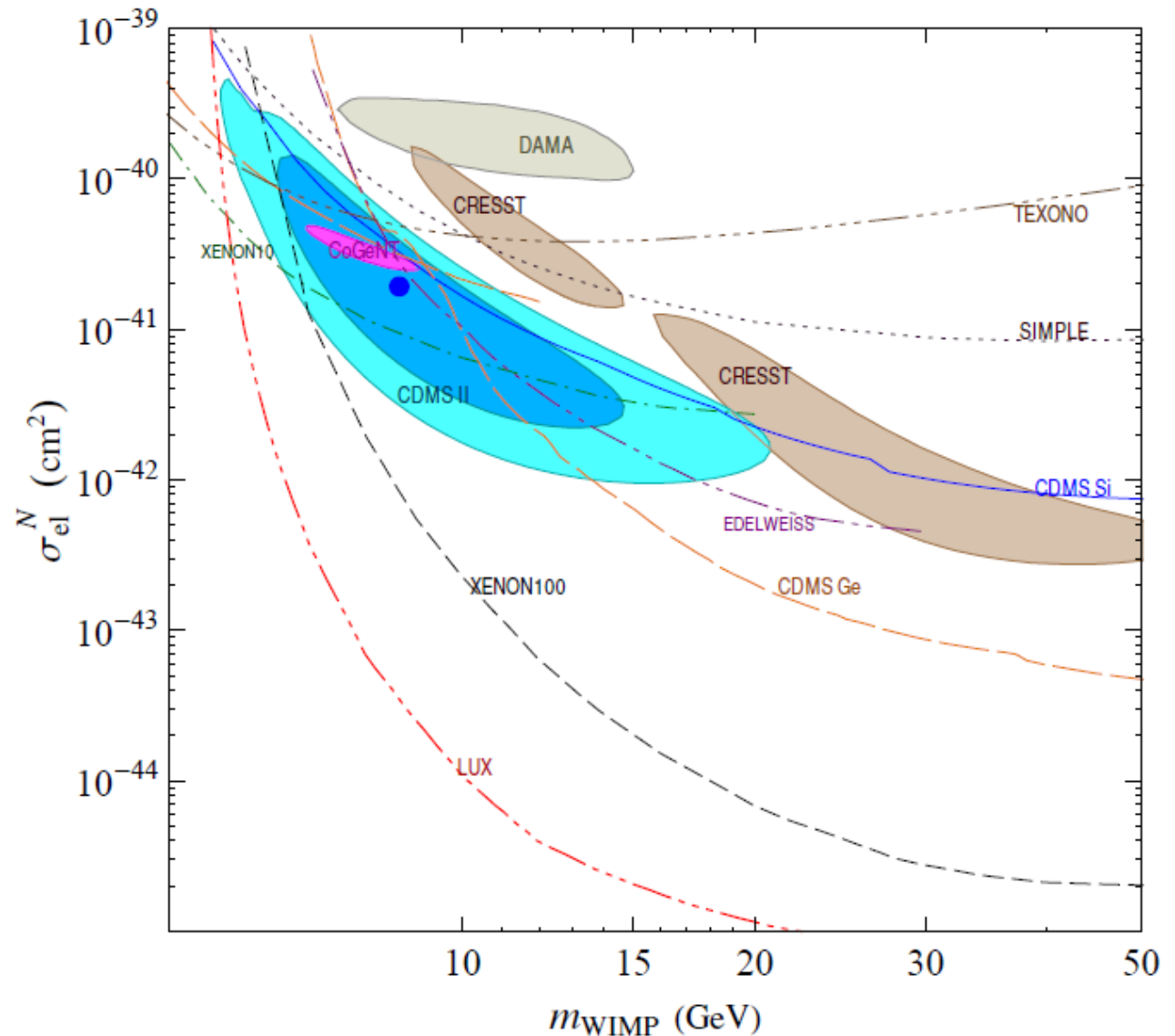


FIG. 4. Experimental upper limits (90% confidence level) for the WIMP-nucleon spin-independent cross section as a function of WIMP mass. We show the limit obtained from the exposure analyzed in this work alone (*blue dotted line*), and combined with the CDMS II Si data set reported in [23, 28] (*blue 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, 95.45% 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 $(8.6 \text{ GeV}/c^2, 1.9 \times 10^{-41} \text{ cm}^2)$.

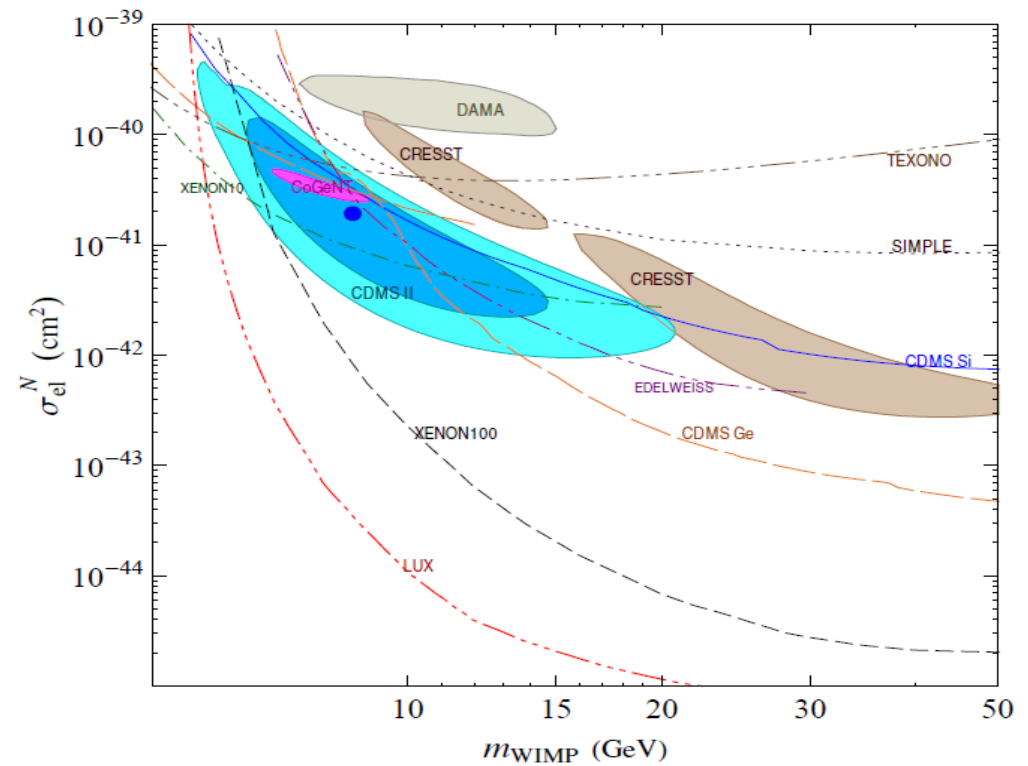
DM direct search experiments

- 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 $\sim 5\text{-}20$ 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.

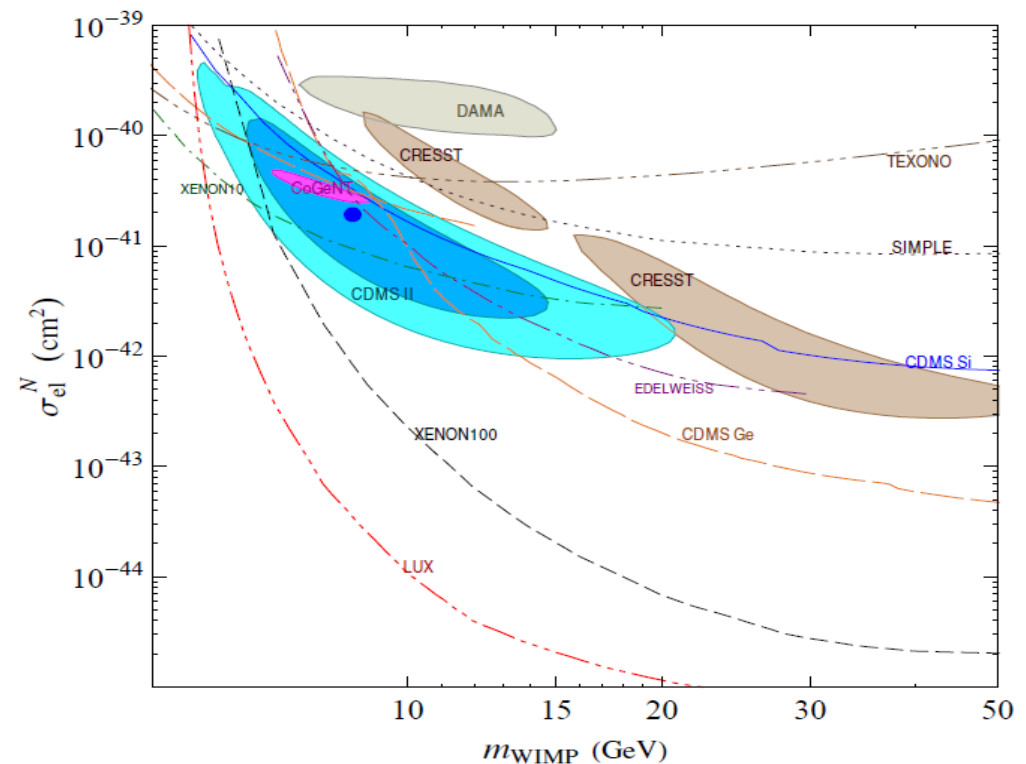


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- The tension in the light-WIMP data can be partially eased if the WIMP effective couplings f_p and f_n to the proton and neutron satisfy

$$f_n \approx -0.7 f_p$$

Bernabei *et al.*
Kurylov & Kamionkowski
Giuliani
Chang *et al.*
Feng *et al.*



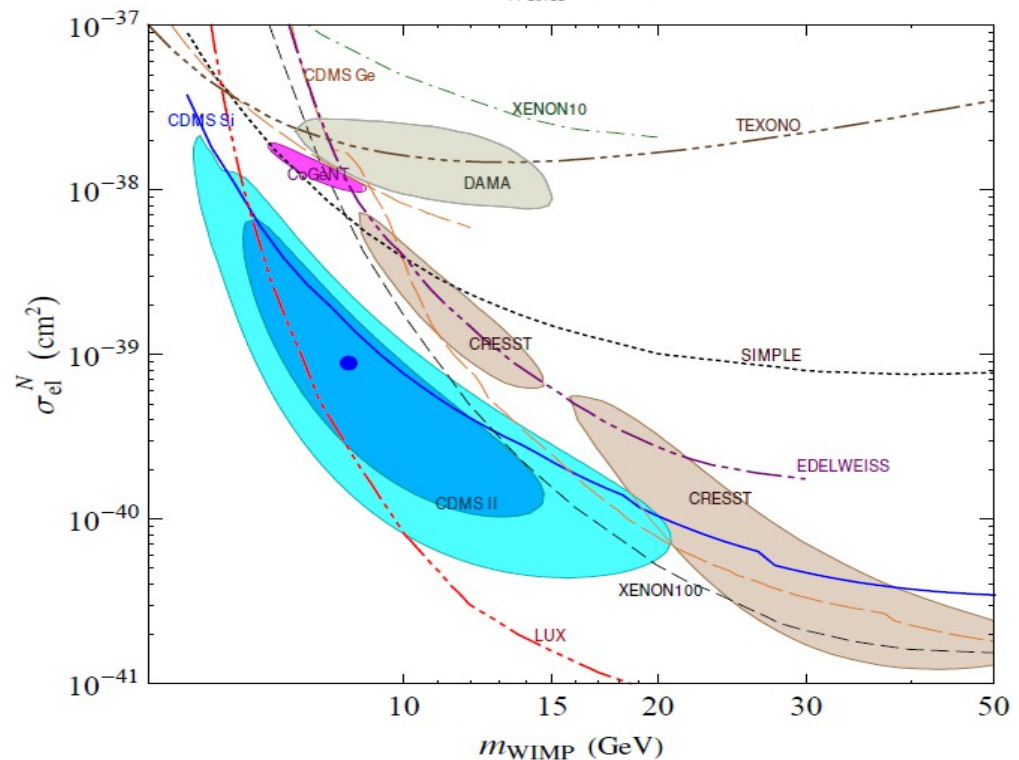
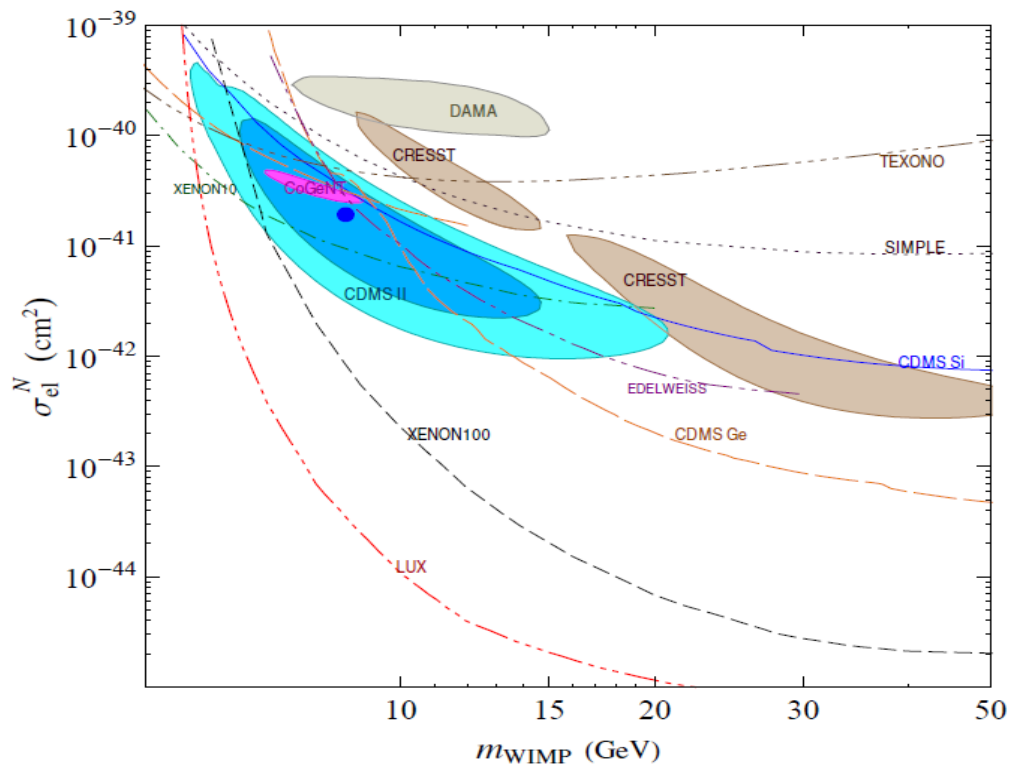
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In IVDM case, some part of CDMS II (blue/cyan) area still escapes all current exclusion limits, in contrast to DAMA, CoGeNT, and CRESST-II



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.

Silveira & Zee, 1985
- 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 .

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

self-interaction
coupling

mass
parameter

darkon-Higgs
coupling

Simplest darkon model

- After electroweak symmetry breaking

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

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

- This Lagrangian has **only 3** free parameters.

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

- The last term, $-\lambda v D^2 h$, plays an **important** role in determining the **relic density** in the SM+D

Relic density of 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 Ω_D by the thermal dynamics of the Universe within the standard big-bang cosmology, according to

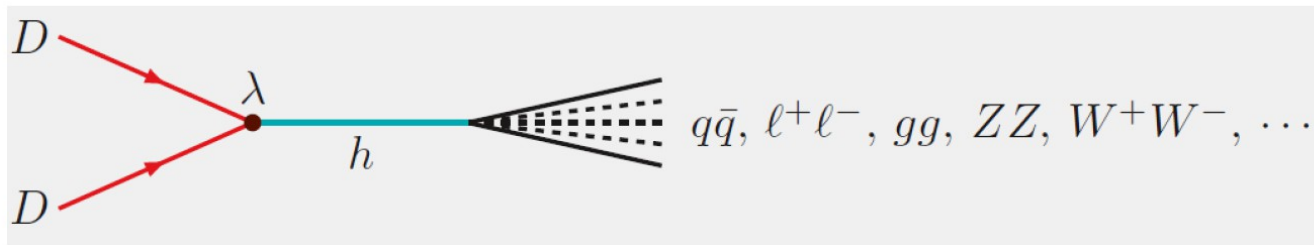
$$\Omega_D h^2 \sim \frac{0.1 \text{ pb}}{\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle}$$

Kolb & Turner, 1990

h is the Hubble constant in units of 100km/(s·Mpc),
 σ_{ann} the **darkon annihilation cross-section** into SM particles,
 v_{rel} the darkon-pair relative speed in their cm frame.

Darkon annihilation rate

- 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

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

\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 $\tilde{h} \rightarrow X_i$ any possible decay mode of \tilde{h} .

- For $m_D > m_h$ contributions from $DD \rightarrow hh$ need to be included in σ_{ann} .

Testing SM+D: direct detection of darkon

- 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** $DN \rightarrow DN$.

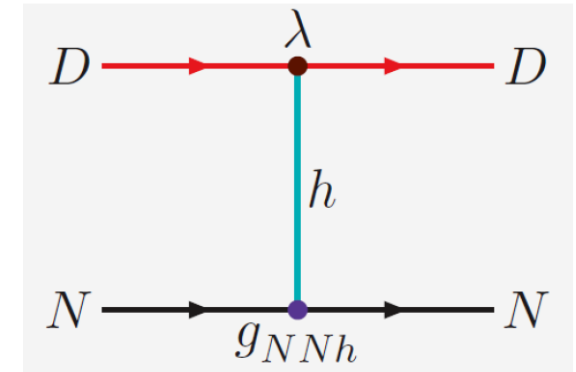
- Amplitude for $DN \rightarrow DN$

$$\mathcal{M}_{\text{el}} \simeq \frac{2\lambda g_{NNh} v}{m_h^2} \bar{N}N$$

as $t \ll m_h^2$ for slow D and N

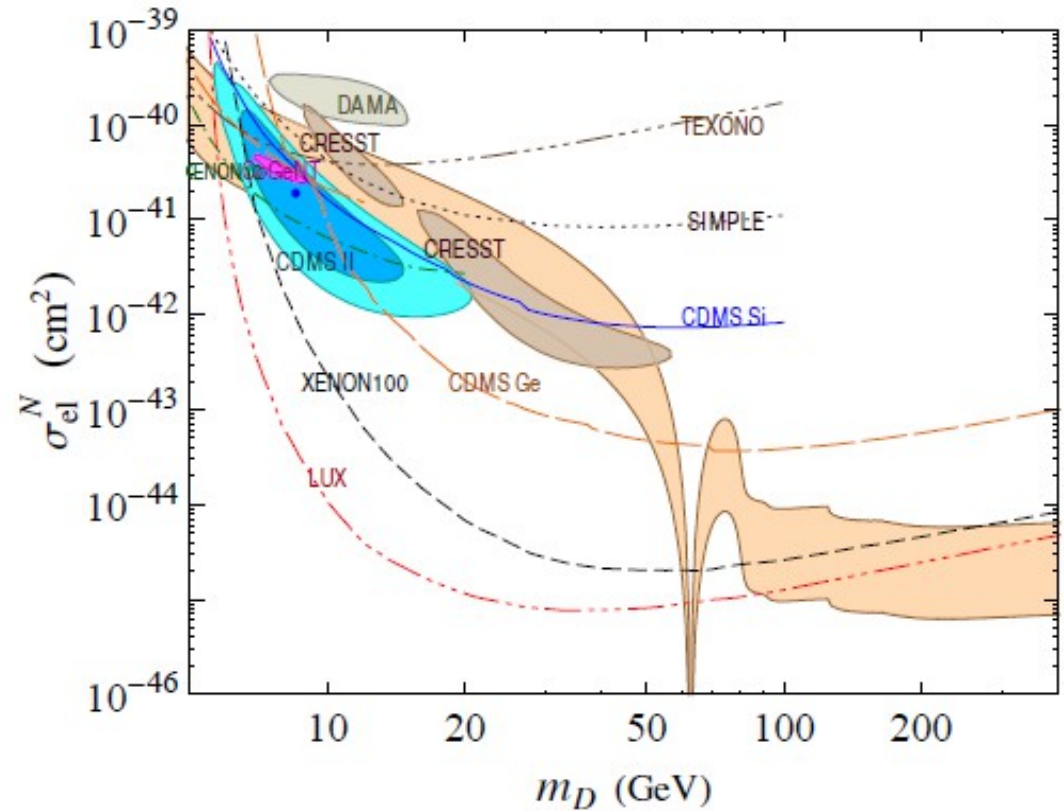
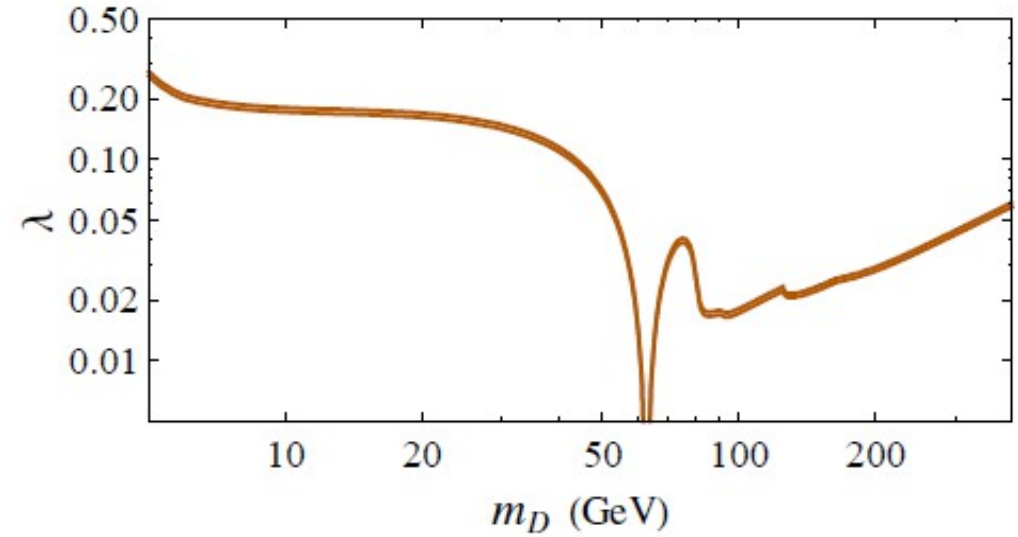
- Cross section of $DN \rightarrow DN$

$$\sigma_{\text{el}} \simeq \frac{\lambda^2 g_{NNh}^2 v^2 m_N^2}{\pi (m_D + m_N)^2 m_h^4}$$



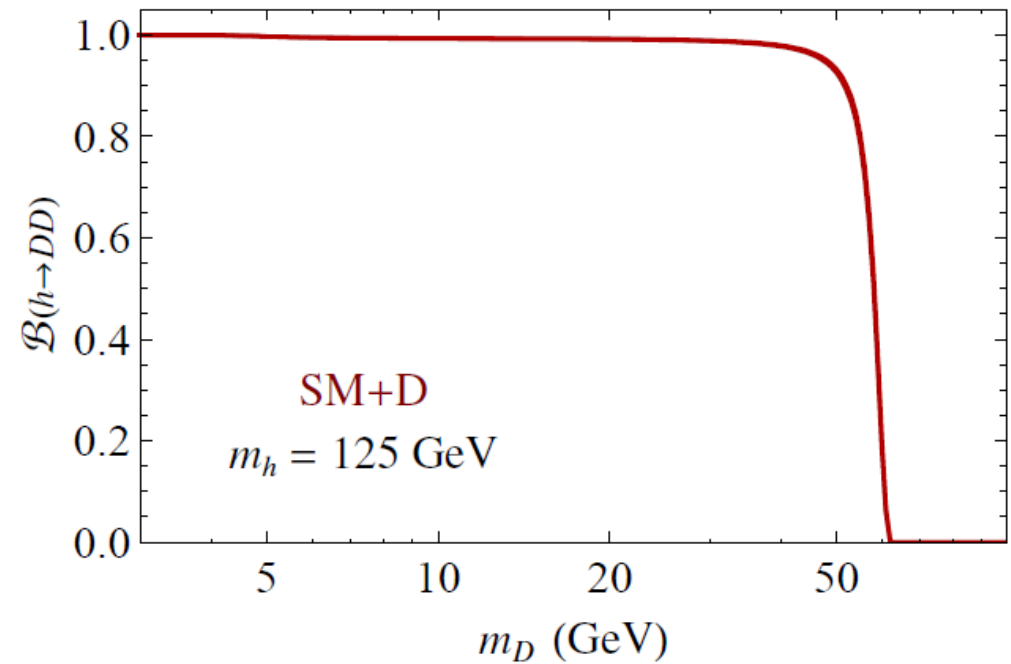
SM+D

- SM+D with Higgs mass $m_h = 125$ GeV
- The prediction accommodates well the light-WIMP hypothesis.



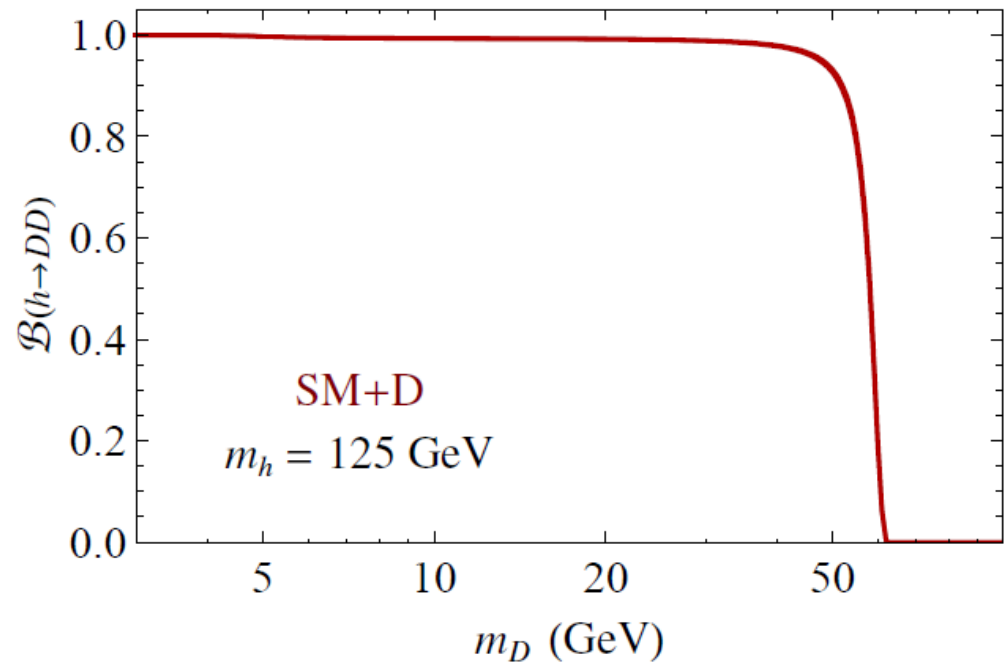
Invisible Higgs in SM+D with light darkon

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



Invisible Higgs in SM+D with light darkon

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 - except near $m_h/2$



- 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

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

- Darkon mass & darkon-Higgs couplings

$$\begin{aligned} m_D^2 &= m_0^2 + [\lambda_1 \cos^2 \beta + \lambda_2 \sin^2 \beta + \lambda_3 \sin(2\beta)] v^2 \\ \lambda_h &= -\lambda_1 \sin \alpha \cos \beta + \lambda_2 \cos \alpha \sin \beta + \lambda_3 \cos(\alpha + \beta) \\ \lambda_H &= \lambda_1 \cos \alpha \cos \beta + \lambda_2 \sin \alpha \sin \beta + \lambda_3 \sin(\alpha + \beta) \end{aligned}$$

- Yukawa Lagrangian

$$\begin{aligned} \mathcal{L}_Y &= -\bar{Q}_{j,L} (\lambda_1^U)_{jl} \tilde{H}_1 \mathcal{U}_{l,R} - \bar{Q}_{j,L} (\lambda_1^D)_{jl} H_1 \mathcal{D}_{l,R} - \bar{Q}_{j,L} (\lambda_2^U)_{jl} \tilde{H}_2 \mathcal{U}_{l,R} - \bar{Q}_{j,L} (\lambda_2^D)_{jl} H_2 \mathcal{D}_{l,R} \\ &\quad - \bar{L}_{j,L} (\lambda_1^E)_{jl} H_1 E_{l,R} - \bar{L}_{j,L} (\lambda_2^E)_{jl} H_2 E_{l,R} + \text{H.c.} \end{aligned}$$

Yukawa terms

After fermion mass matrices $M_{U,D,E} = \frac{1}{\sqrt{2}}(\lambda_1^{U,D,E} v_1 + \lambda_2^{U,D,E} v_2)$ are diagonalized, $h_{1,2}^0$ couple to fermions according to

$$\mathcal{L}'_Y = -\bar{U}_L \left[\left(M_U - \frac{\lambda_2^U v_2}{\sqrt{2}} \right) \frac{h_1^0}{v_1} + \left(M_U - \frac{\lambda_1^U v_1}{\sqrt{2}} \right) \frac{h_2^0}{v_2} \right] U_R - \bar{D}_L \left[\left(M_D - \frac{\lambda_2^D v_2}{\sqrt{2}} \right) \frac{h_1^0}{v_1} + \left(M_D - \frac{\lambda_1^D v_1}{\sqrt{2}} \right) \frac{h_2^0}{v_2} \right] D_R - \bar{E}_L \left[\left(M_E - \frac{\lambda_2^E v_2}{\sqrt{2}} \right) \frac{h_1^0}{v_1} + \left(M_E - \frac{\lambda_1^E v_1}{\sqrt{2}} \right) \frac{h_2^0}{v_2} \right] D_R + \text{H.c.}$$

where now $M_U = \text{diag}(m_u, m_c, m_t)$, 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

$$\mathcal{L}_{ff\mathcal{H}} = -k_f^{\mathcal{H}} m_f \bar{f} f \frac{\mathcal{H}}{v}$$

$$k_u^h = \frac{\cos \alpha}{\sin \beta} - \frac{\lambda_1^u v \cos(\alpha - \beta)}{\sqrt{2} m_u \sin \beta}, \quad k_u^H = \frac{\sin \alpha}{\sin \beta} - \frac{\lambda_1^u v \sin(\alpha - \beta)}{\sqrt{2} m_u \sin \beta}$$

$$k_d^h = -\frac{\sin \alpha}{\cos \beta} + \frac{\lambda_2^d v \cos(\alpha - \beta)}{\sqrt{2} m_d \cos \beta}, \quad k_d^H = \frac{\cos \alpha}{\cos \beta} + \frac{\lambda_2^d v \sin(\alpha - \beta)}{\sqrt{2} m_d \cos \beta}$$

$$k_e^h = -\frac{\sin \alpha}{\cos \beta} + \frac{\lambda_2^e v \cos(\alpha - \beta)}{\sqrt{2} m_e \cos \beta}, \quad k_e^H = \frac{\cos \alpha}{\cos \beta} + \frac{\lambda_2^e v \sin(\alpha - \beta)}{\sqrt{2} m_e \cos \beta}$$

$$\lambda_a^{u,d,e} = (\lambda_a^{U,D,E})_{11}, \quad \text{etc.}$$

Higgs couplings

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

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

- 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

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

$$k_u^H = -\cot \beta + \frac{\lambda_1^u v}{\sqrt{2} m_u \sin \beta}, \quad k_d^H = \tan \beta - \frac{\lambda_2^d v}{\sqrt{2} m_d \cos \beta}$$

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

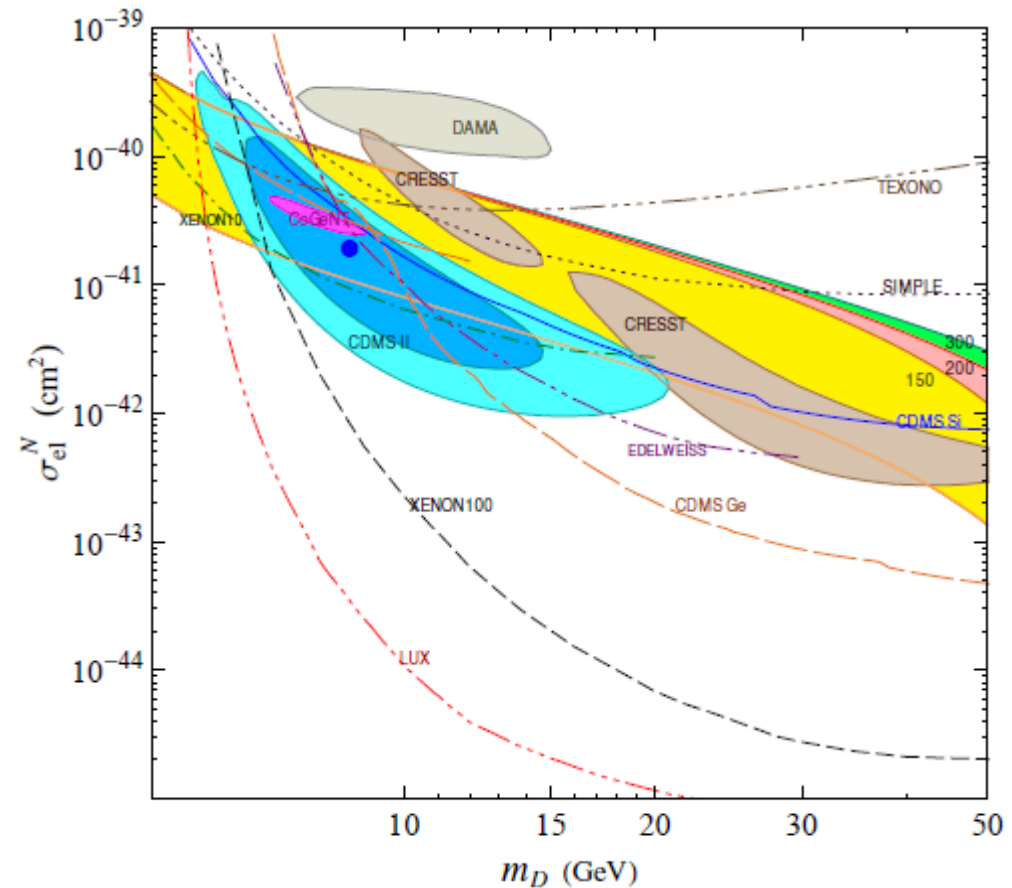
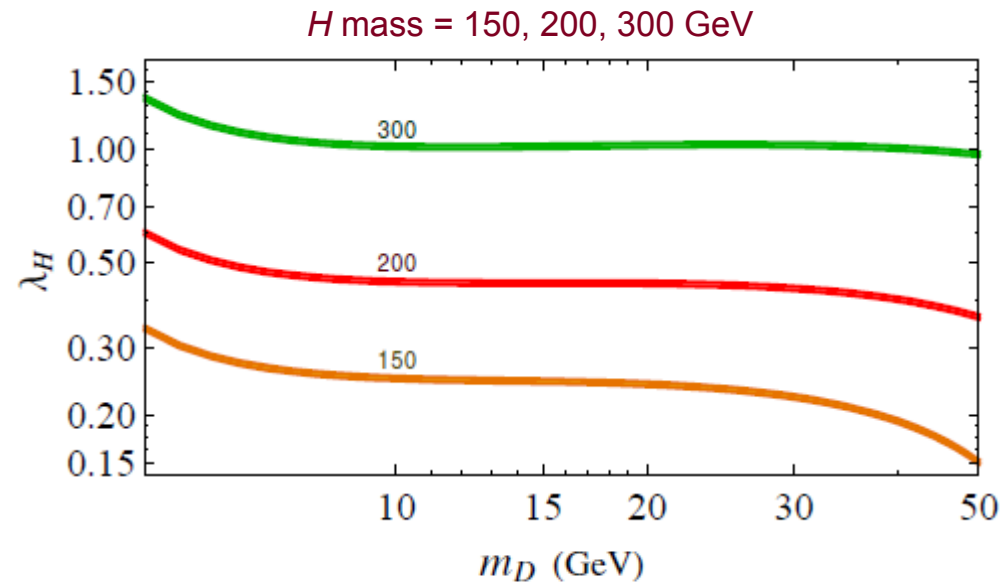
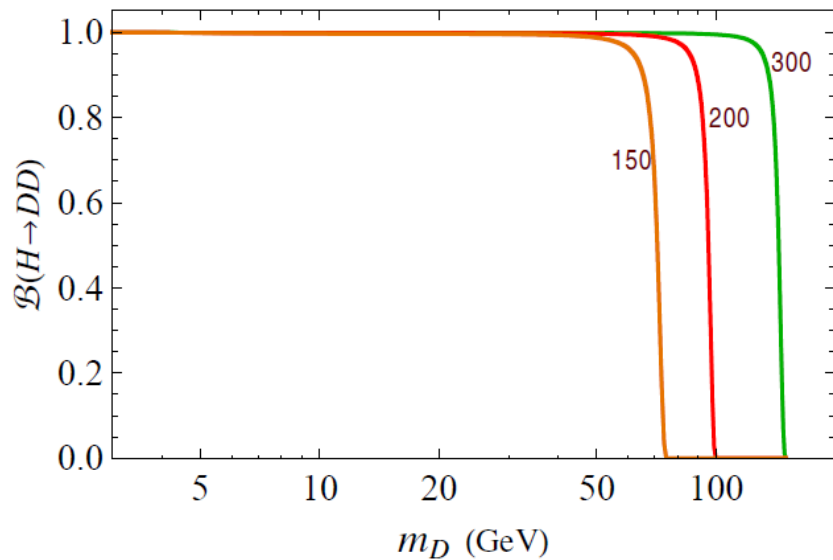
$$\lambda_h = \lambda_1 \cos^2 \beta + \lambda_2 \sin^2 \beta + \lambda_3 \sin(2\beta), \quad \lambda_H = \frac{1}{2}(\lambda_1 - \lambda_2) \sin(2\beta) - \lambda_3 \cos(2\beta)$$

$$\mathcal{L}_{VV\mathcal{H}} = (2m_W^2 W^{+\mu} W_{\mu}^{-} + m_Z^2 Z^{\mu} Z_{\mu}) \frac{h}{v}$$

- 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.



THDM+D with isospin-violating DN couplings

- The observed relic density and $f_n = -0.7f_p$ requirements lead to limitations on the predicted darkon-proton scattering cross-section.

We find that to enhance σ_{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.

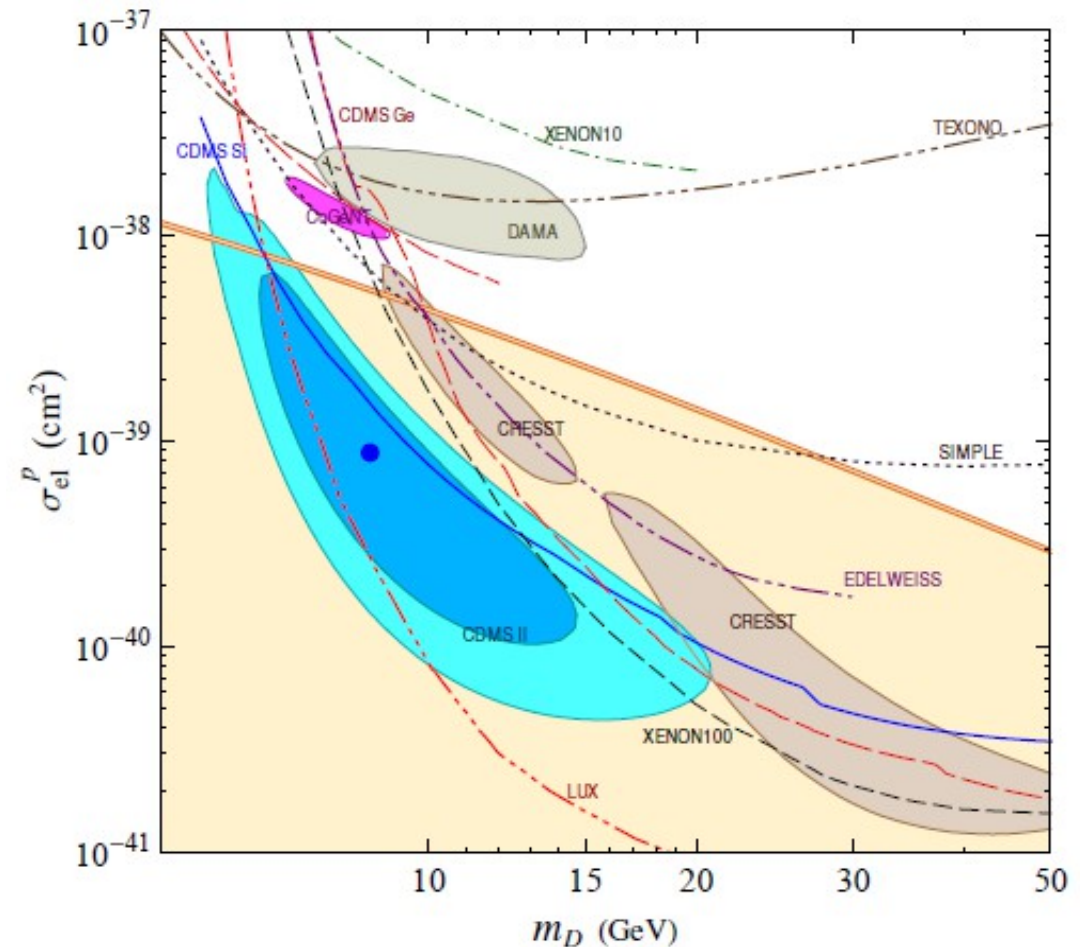
For example, with $m_H = 200$ (300) GeV we find 0.6 (1.4) $\times 10^3 \leq \lambda_H k_u^H \leq 0.8$ (1.8) $\times 10^3$ corresponding to 5 GeV $\leq m_D \leq 20$ GeV.

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 $\lambda_1^u v_1 + \lambda_2^u v_2 = \sqrt{2} m_u$ and $\lambda_1^d v_1 + \lambda_2^d v_2 = \sqrt{2} m_d$, some degree of fine cancelations between the $\lambda_a^{u,d} v_a$ terms is needed to reproduce the small u and d masses. This is the price one has to pay for the greatly amplified σ_{el}^p .

Prediction of THDM+D with isospin-violating DN couplings

- 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.