Higgs Searches Illuminating Light Dark Matter

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RENCONTRES DU VIETNAM
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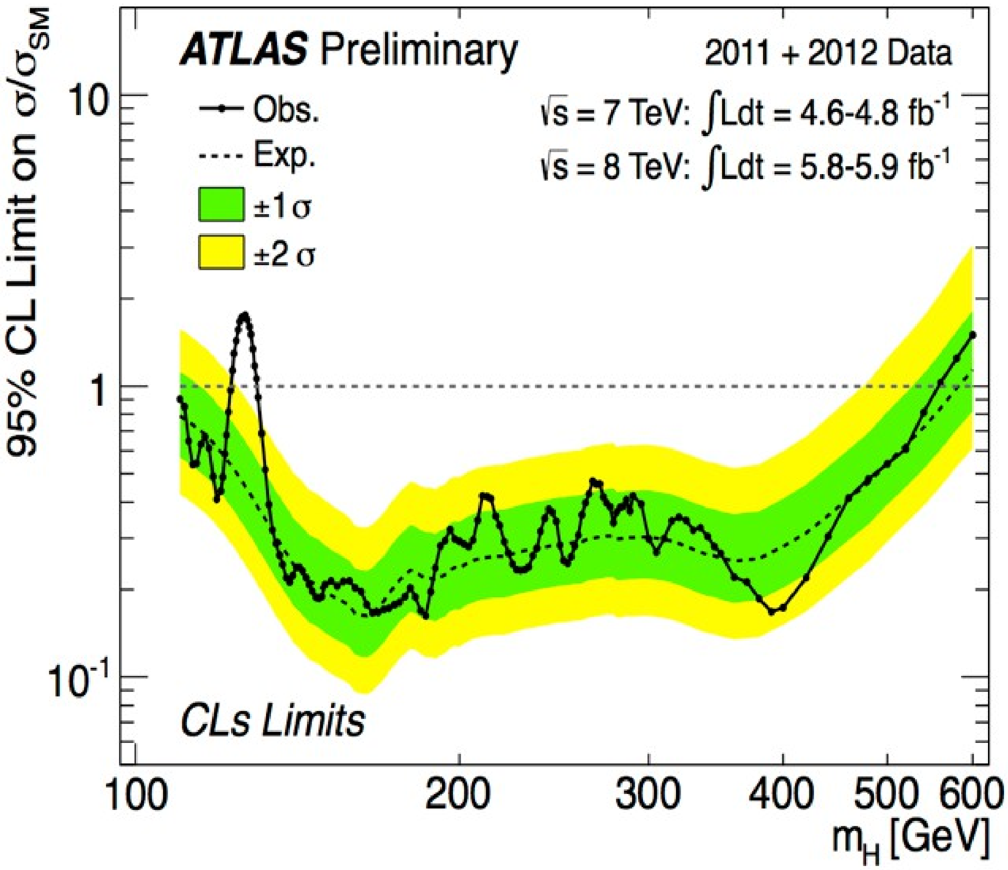
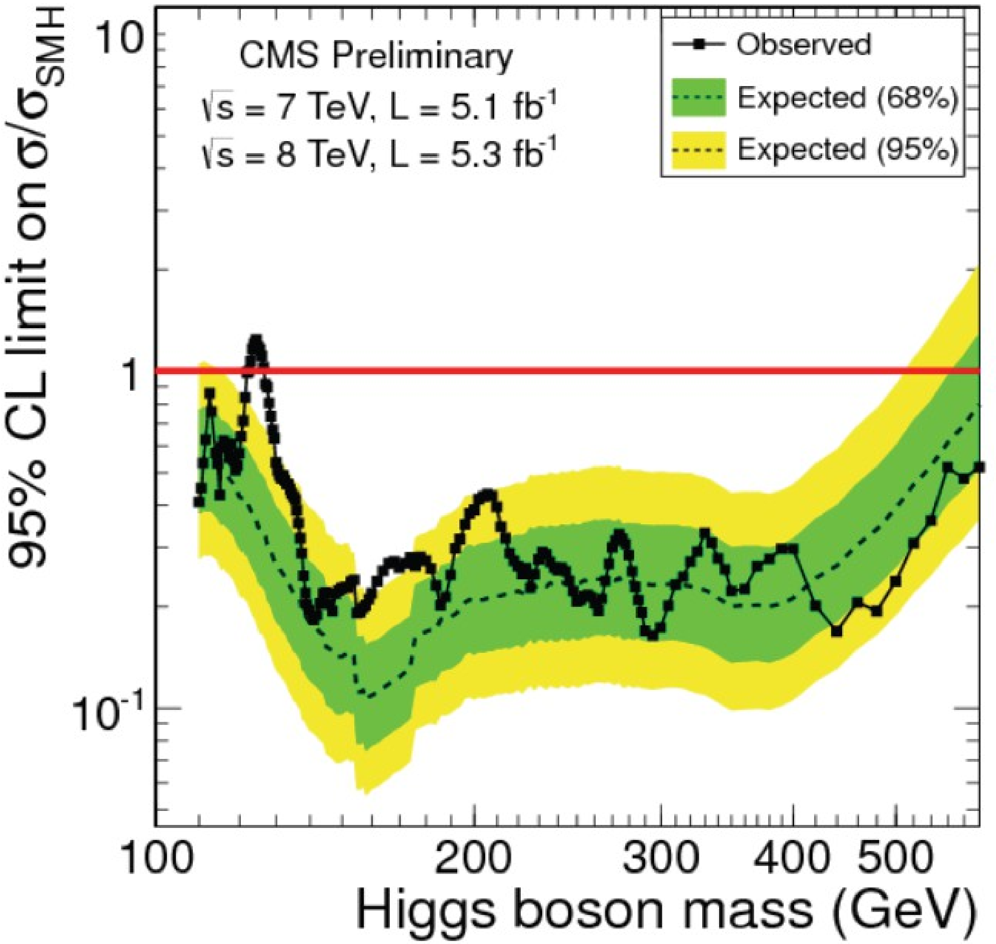
Outline

- Introduction
  - Higgs and DM direct searches
- Simplest WIMP DM model, SM+D
  - Implications of likely discovery of SM-like Higgs
- Somewhat enlarged model, THDM+D
  - SM-like Higgs & light-WIMP candidate
- Isospin-violating DM in THDM+D
- Conclusions

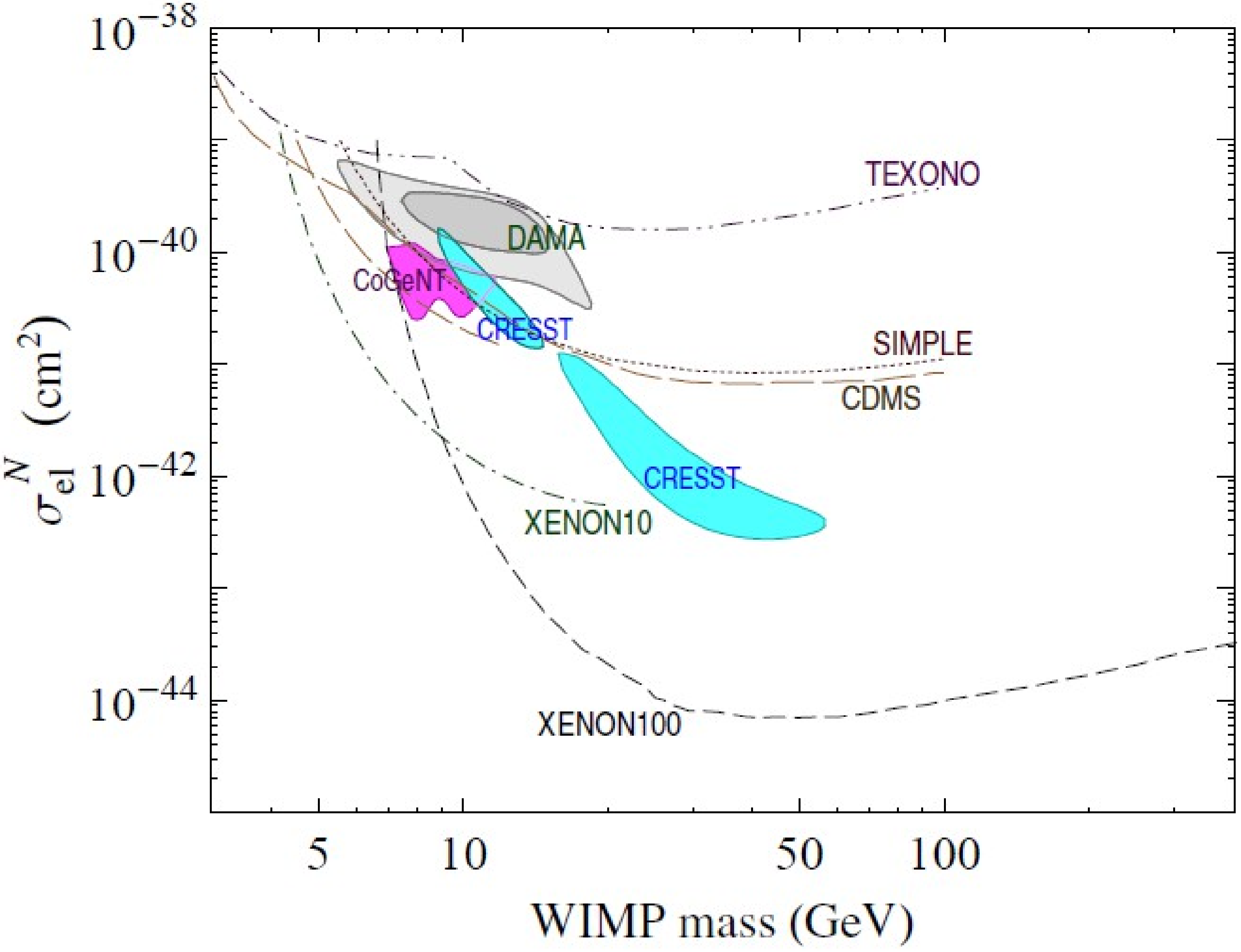
Discovery of particle consistent with SM Higgs





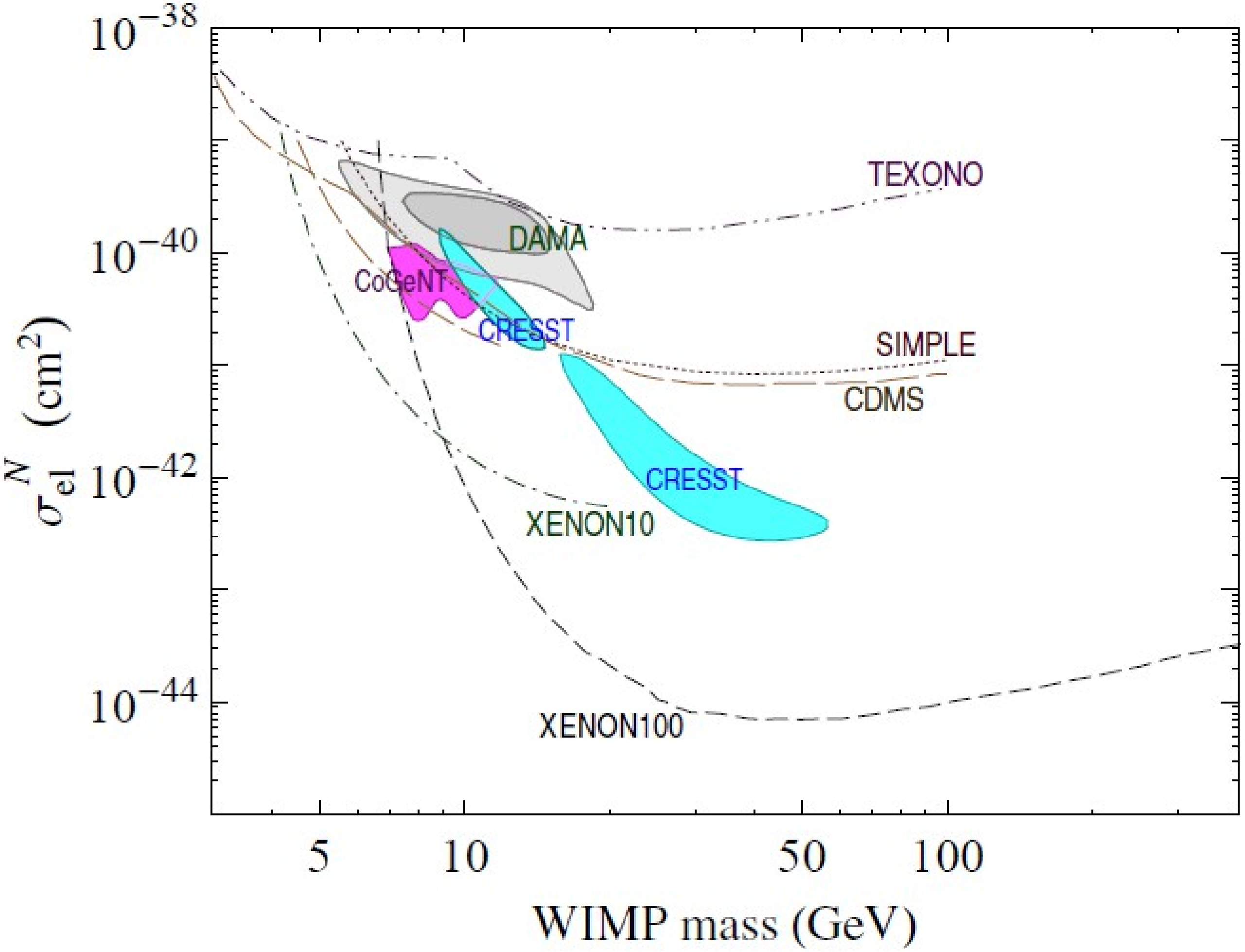
DM direct search experiments

- Weakly interacting massive particles (WIMPs) may be directly detected via their interactions with nuclei.
- Some recent data on WIMP-nucleon spin-independent elastic cross-section.



DM direct search experiments

- Weakly interacting massive particles (WIMPs) may be directly detected via their interactions with nuclei.
- Some recent data on WIMP-nucleon spin-independent elastic cross-section.
- Light-WIMP masses (~7-30 GeV) are still controversial.
  - DAMA, CoGeNT, and CRESST-II observed potential light-WIMP evidence (their data do not fully agree).
  - But CDMS, XENON, SIMPLE, and others have not seen any WIMP evidence, and hence provided only upper limits.



Potential resolution to light-WIMP puzzle

- One of the ideas proposed to resolve the puzzle: allow sizable isospin violation in WIMP-nucleon interactions.

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

$$f_n \approx -0.7\, f_p$$

Bernabei *et al*.
Kurylov & Kamionkowski
Giuliani
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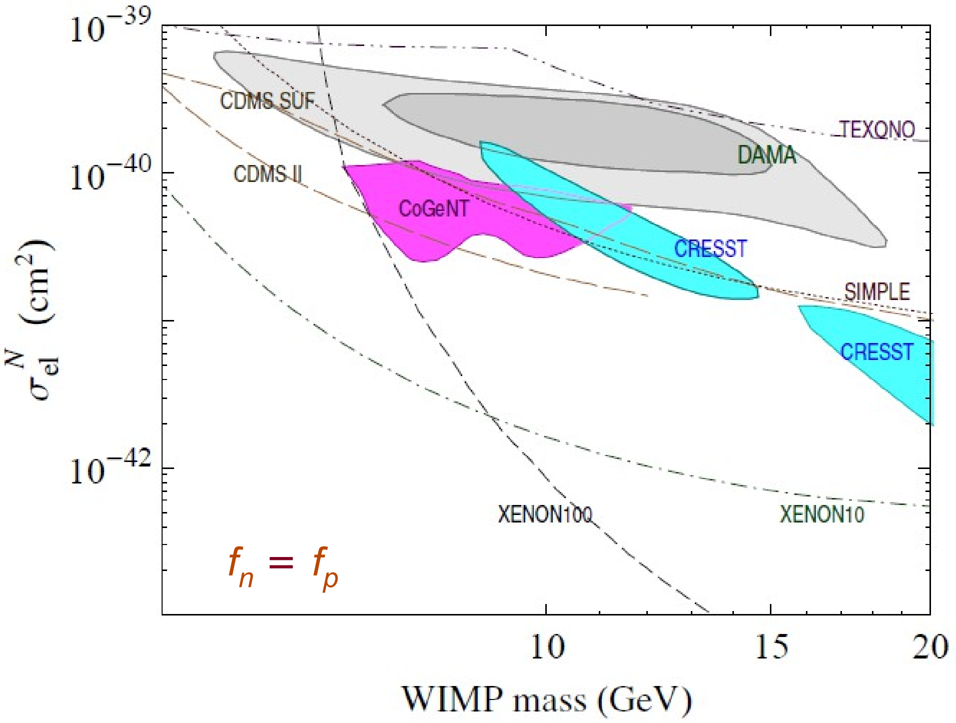
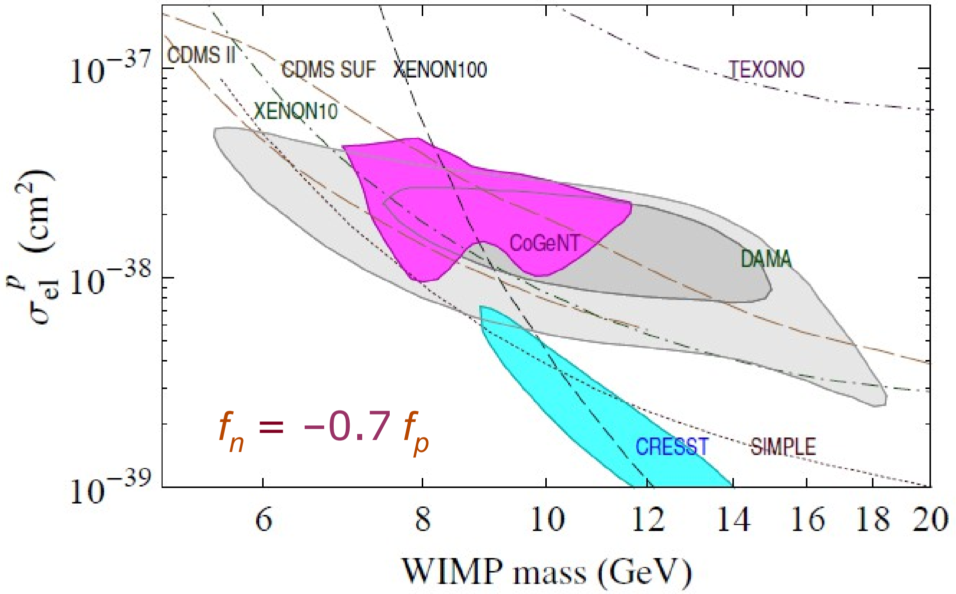




Interplay between Higgs & DM sectors

- The two sectors may be intimately connected
- 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.

Standard model 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, $D \to -D$ (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

$$\mathcal{L}_D = \tfrac{1}{2}\partial^\mu D\,\partial_\mu D - \underbrace{\tfrac{1}{4}\lambda_D}_{\text{self-interaction coupling}} D^4 - \tfrac{1}{2}\underbrace{m_0^2}_{\text{mass parameter}} D^2 - \underbrace{\lambda}_{\text{darkon-Higgs coupling}} D^2\, H^\dagger H$$

Darkon model

- After electroweak symmetry breaking

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

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

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

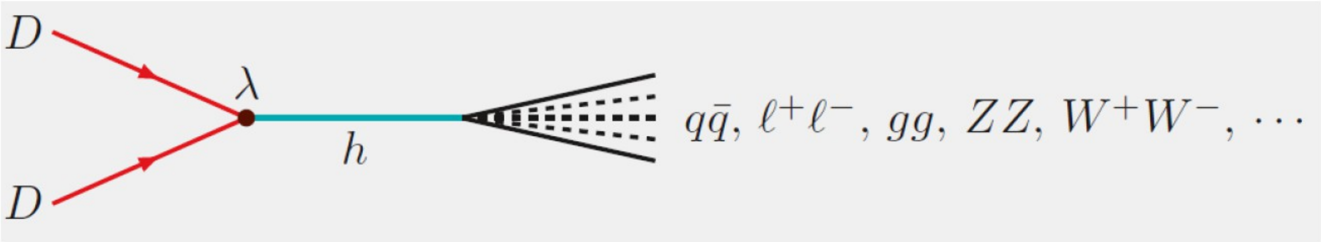
Kolb & Turner, 1990

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.

- WMAP7 & other data yield $\Omega_D h^2 = 0.1123 \pm 0.0035$ Komatsu *et al.*, 2010
- We use the 90%-C.L. range $0.1065 \le \Omega_D h^2 \le 0.1181$

Darkon annihilation rate

- For $m_D \le m_h$ the relic density results from darkon annihilation into SM3 particles via Higgs (h) exchange.



- The h-mediated annihilation cross-section

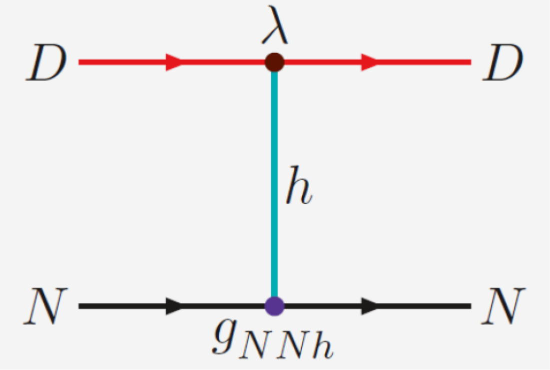
$$\sigma_{\rm ann}\, v_{\rm rel} \;=\; \frac{8\lambda^2 v^2}{\left(4m_D^2 - m_h^2\right)^2 + \Gamma_h^2\, m_h^2}\; \frac{\sum_i \Gamma\left(\tilde{h} \to X_i\right)}{2m_D}$$

$\tilde{h}$ 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 $\sigma_{\rm ann}$.

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 $DN \to DN$.



- Amplitude for $DN \to DN$

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

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

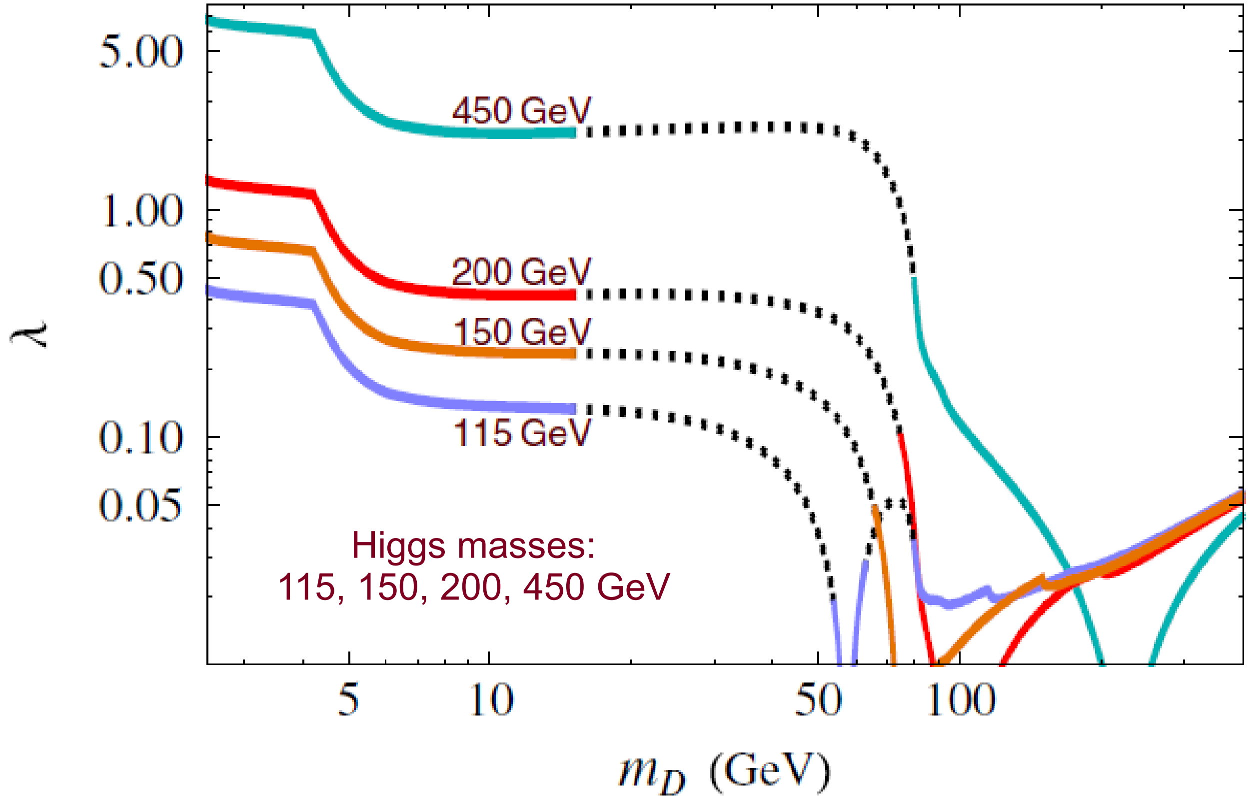
- Cross section of $DN \to DN$

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

Darkon masses allowed by direct searches & rare decays

- Allowed darkon masses in SM+D with 3 fermion generations (SM3+D)
  - From 2.5 GeV to ~15 GeV
  - Regions close to, but less than, $m_h/2$
  - Beyond ~80 GeV

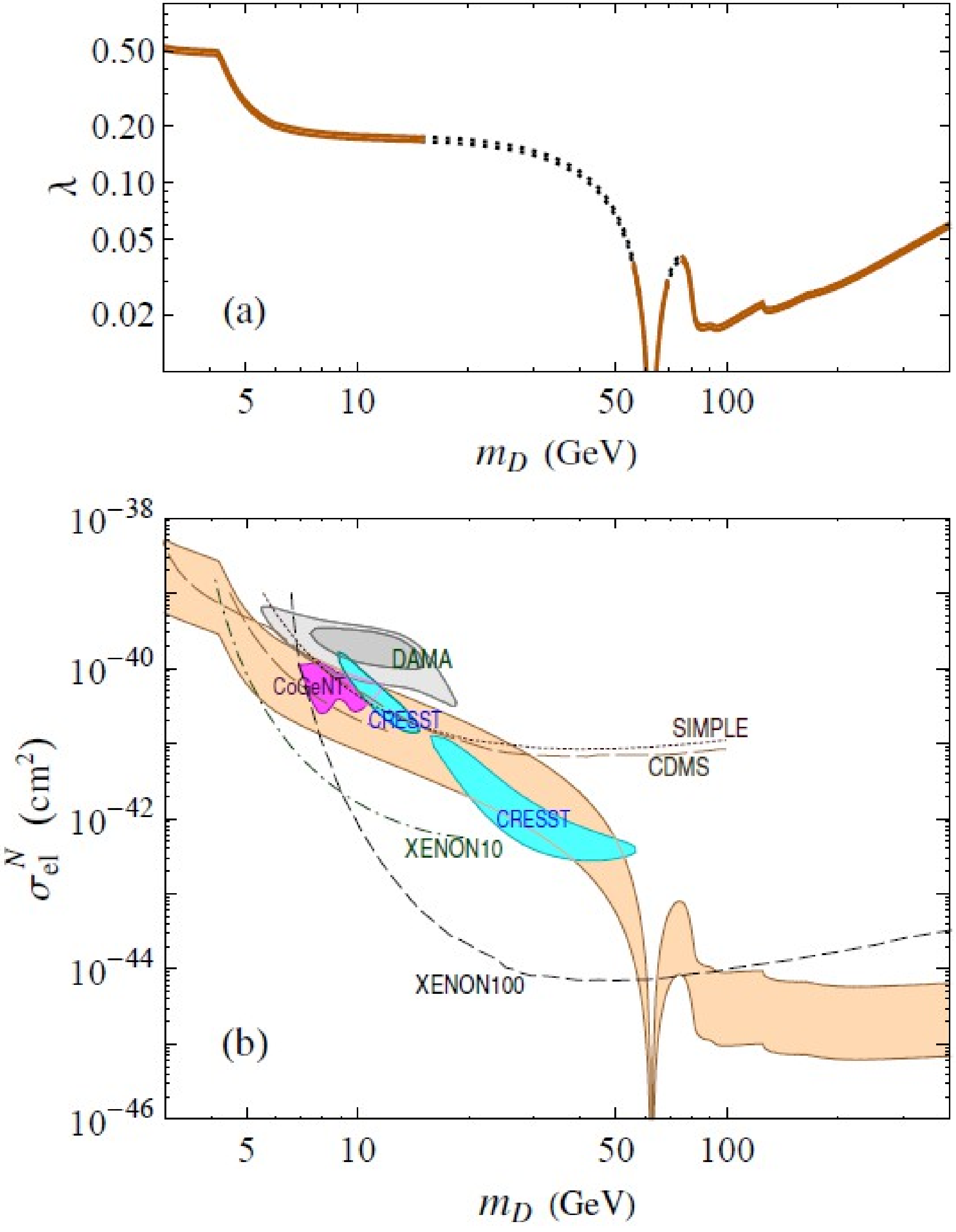
He & JT



- The black-dotted sections are disallowed by direct search data.

SM3+D & SM4+D

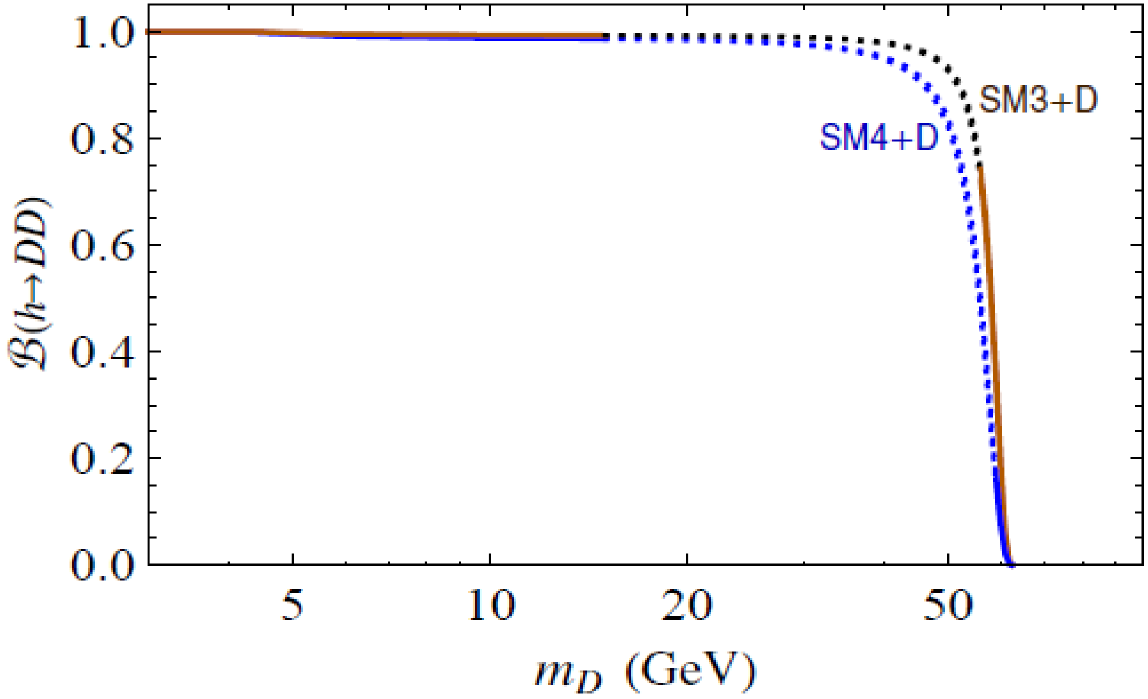
- In SM3+D with Higgs mass m_h = 125 GeV
- The prediction accommodates well the light-WIMP hypothesis.
- The black-dotted sections of the curves are disallowed by direct search data.
- Their counterparts in SM+D with 4 sequential generations (SM4+D) are roughly similar.



He, Ho, JT, Tsai

Invisible Higgs in SM3+D & SM4+D

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



- Thus if the newly discovered boson of mass ~125 GeV is the SM3 Higgs, SM3+D & SM4+D with a light darkon will both be ruled out

Two-Higgs-doublet model plus darkon

- The Higgs sector is the THDM of type III
  - Both Higgs doublets give mass to the fermions.
  - Neutral physical 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

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

- Mass & darkon-Higgs couplings

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

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

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

- Yukawa Lagrangian

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

Yukawa terms

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

$$\mathcal{L}'_{\rm Y} = -\bar{\mathcal{U}}_L \left[\left(M_{\mathcal{U}} - \frac{\lambda_2^{\mathcal{U}} v_2}{\sqrt{2}}\right)\frac{h_1^0}{v_1} + \left(M_{\mathcal{U}} - \frac{\lambda_1^{\mathcal{U}} v_1}{\sqrt{2}}\right)\frac{h_2^0}{v_2}\right]\mathcal{U}_R - \bar{\mathcal{D}}_L \left[\left(M_{\mathcal{D}} - \frac{\lambda_2^{\mathcal{D}} v_2}{\sqrt{2}}\right)\frac{h_1^0}{v_1} + \left(M_{\mathcal{D}} - \frac{\lambda_1^{\mathcal{D}} v_1}{\sqrt{2}}\right)\frac{h_2^0}{v_2}\right]\mathcal{D}_R$$

$$- \bar{E}_L \left[\left(M_E - \frac{\lambda_2^E v_2}{\sqrt{2}}\right)\frac{h_1^0}{v_1} + \left(M_E - \frac{\lambda_1^E v_1}{\sqrt{2}}\right)\frac{h_2^0}{v_2}\right]\mathcal{D}_R + \text{H.c.}$$

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

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

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

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

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

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

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

Yukawa terms

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

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

- Inspired by the likely discovery for a 125-GeV SM-like Higgs in the LHC data, we adopt

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

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

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

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

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

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

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

- Now the couplings of h to SM fermions and gauge bosons are identical to those of SM Higgs.

SM-like Higgs & another scalar Higgs

- To render h more SM-like, we require the hDD coupling

  $$\lambda_h = 0$$

  Thus for $m_D < m_h < m_H$ the darkon contribution to the DM relic density comes only from H-mediated diagrams.

  Since λ_1^u and $\lambda_2^{d,e}$ in $k_{u,d,e}^H$ are free parameters, for illustration we pick

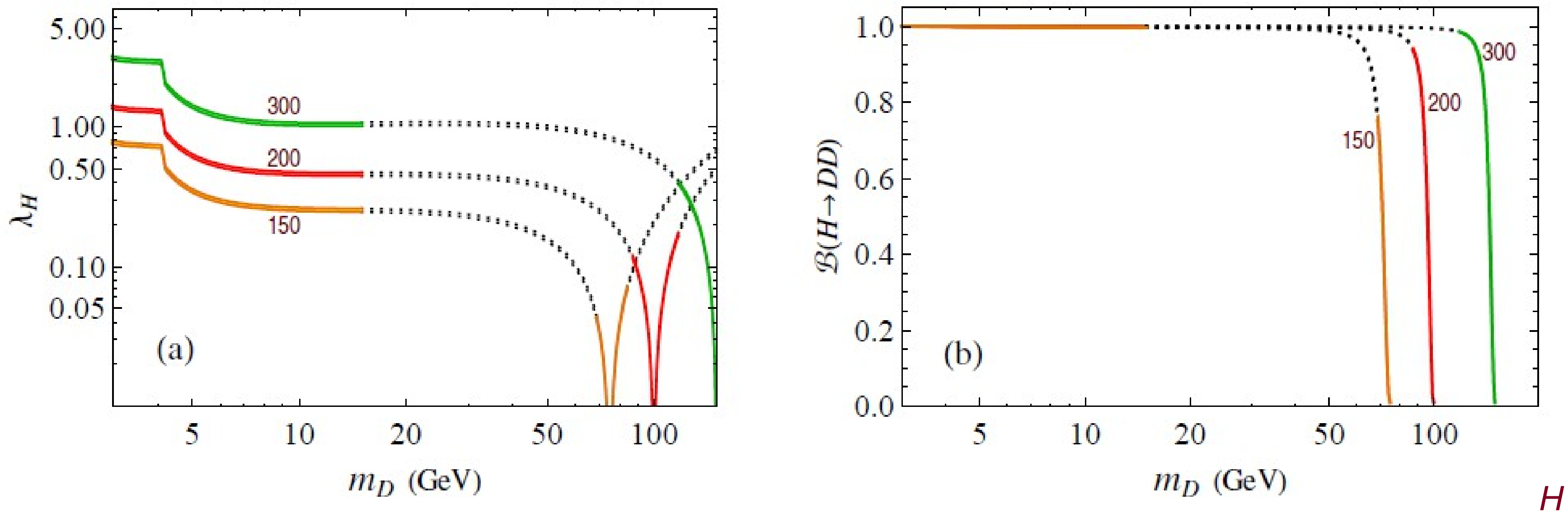
  $$k_u^H = k_d^H = k_e^H = 1$$

  and similarly for k_f^H belonging to the second and third families.

  With these specific selections, H share with h the same couplings to the fermions, but H does not couple to W and Z at tree level, unlike h.

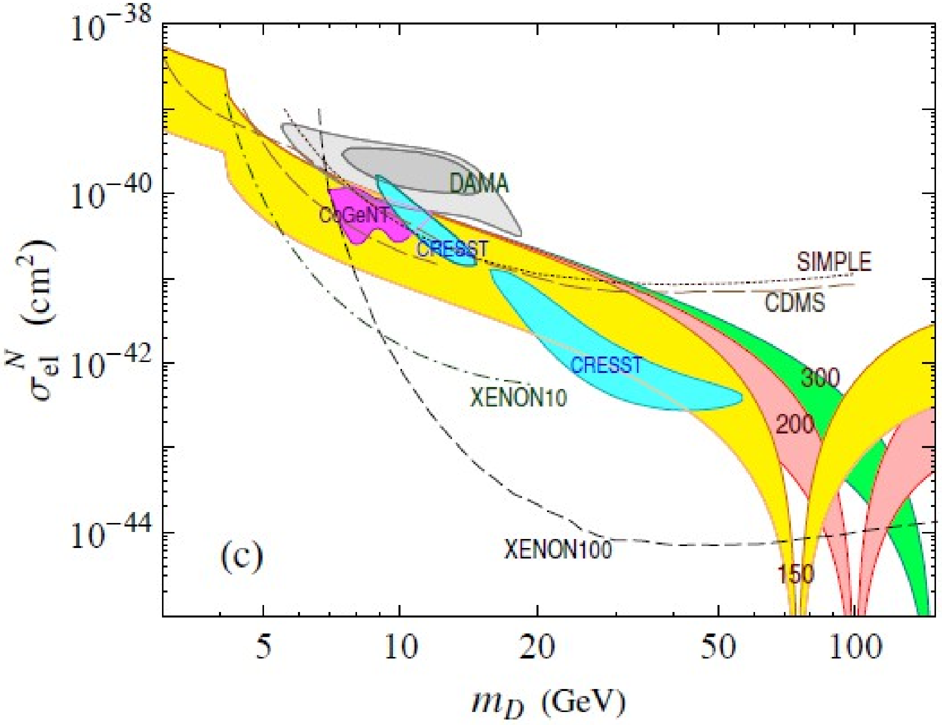
- Only *H* mediates the darkon annihilation.

Predictions of THDM+D



H mass =
150, 200, 300 GeV

- *H* is mostly invisible.
- The predictions also accommodate well the light-WIMP hypothesis.
- The model has a SM-like Higgs, *h*



THDM+D with isospin-violating DN couplings

The THDM+D can realize large isospin violation in darkon-nucleon interactions with the freedom still available in k_f^H.

The WIMP-nucleon cross-section $\sigma_{\rm el}^N$ in the isospin-symmetric limit is related to the WIMP-proton elastic cross-section $\sigma_{\rm el}^p$ in the presence of isospin violation by

$$\sigma_{\rm el}^N\, f_p^2 \sum_i \eta_i\, \mu_{A_i}^2\, A_i^2 \;=\; \sigma_{\rm el}^p \sum_i \eta_i\, \mu_{A_i}^2 \left[\mathcal{Z} f_p + \left(A_i - \mathcal{Z}\right) f_n\right]^2$$

Feng *et al.*

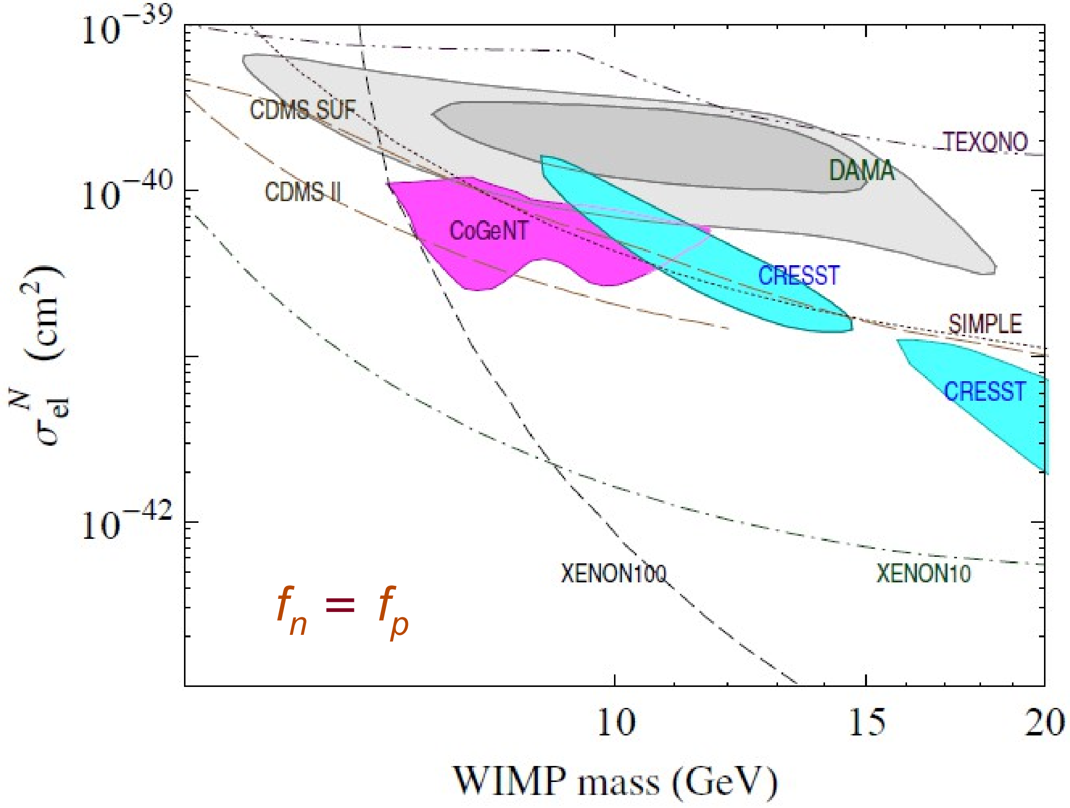
the sum is over isotopes of the element in the detector material with which the WIMP interacts dominantly, $\mathcal{Z}$ is proton number of the element, A_i (η_i) each denote the nucleon number (fractional abundance) of its isotopes, $\mu_{A_i} = m_{A_i} m_{\rm WIMP}/(m_{A_i} + m_{\rm WIMP})$ involving the isotope and WIMP masses.

If isospin is conserved, $f_n = f_p$, the measurement of event rates of WIMP-nucleus scattering will translate into the usual $\sigma_{\rm el}^N = \sigma_{\rm el}^p$.

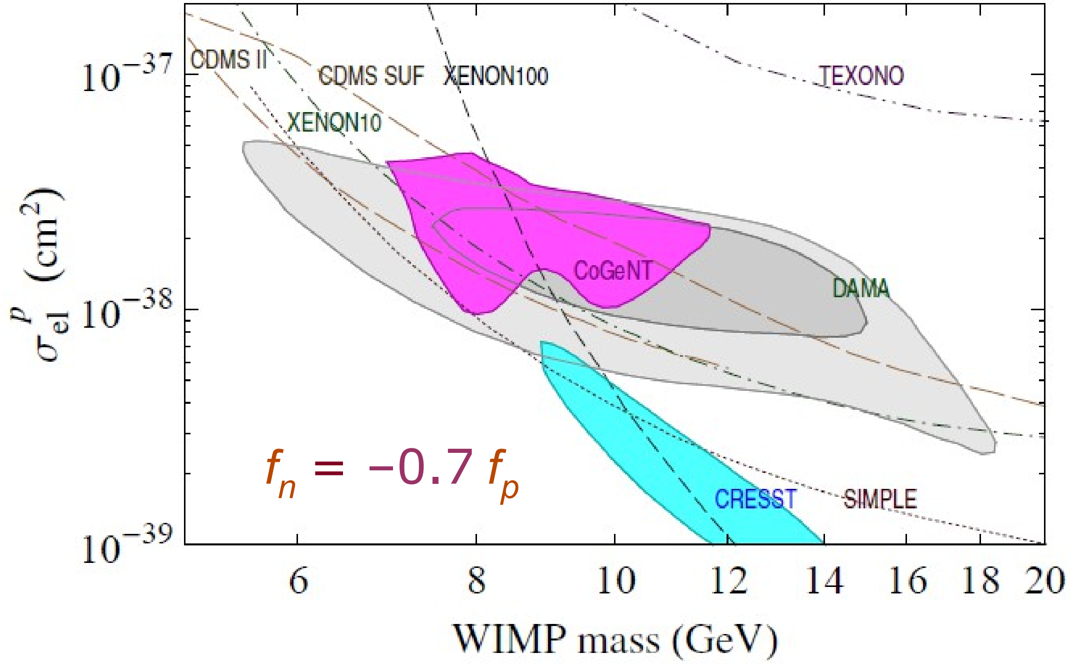
For $f_n = -0.7 f_p$, accounting for the A_i and $\mathcal{Z}$ numbers for the different detector materials, one can transform some of the contradictory data on WIMP-nucleon cross-sections into $\sigma_{\rm el}^p$ numbers which overlap with each other.

But this also makes the extracted $\sigma_{\rm el}^p$ enhanced relative to the current measured values of $\sigma_{\rm el}^N$ by up to 4 orders of magnitude, depending on A_i and $\mathcal{Z}$.

Isospin-violating WIMP-nucleon interactions



$f_n = f_p$



$f_n = -0.7\, f_p$

Isospin-violating darkon-nucleon couplings

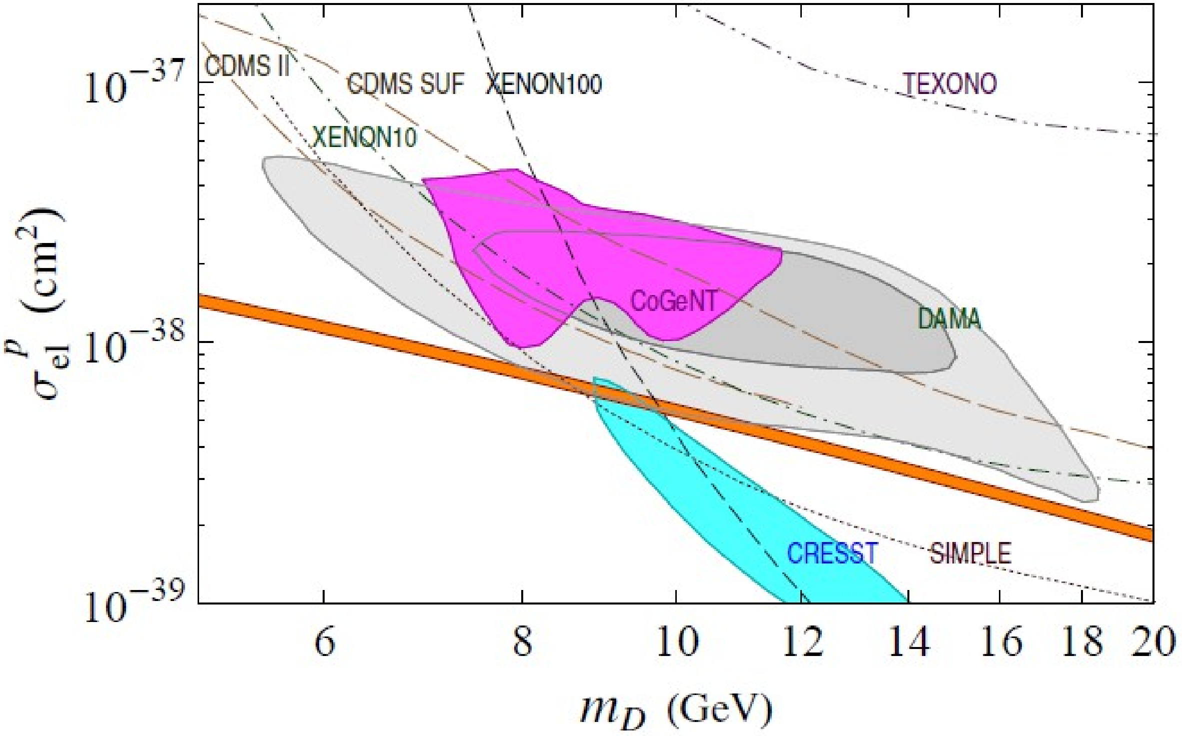
We find that to enhance $\sigma_{\rm el}^p$ by a few orders of magnitude under these restrictions implies that $k_{u,d}^H$ have to be big, $k_u^H \sim -2k_d^H$, and the other k_f^H become negligible by comparison.

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

Thus in general $k_u^H = \mathcal{O}\big(10^3\big)$ 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 $\sigma_{\rm el}^p$.

Prediction of THDM+D with isospin-violating DN couplings



- The prediction (orange) curve is lower than the DAMA & CoGeNT regions, but by only a factor of a few.
- The prediction can easily accommodate the CRESST-II data and has improved compatibility with the XENON limits.
- However, puzzles remain which likely need additional ingredients and/or future direct-search data to resolve.

Conclusions

- If the newly discovered boson is the SM Higgs, the simplest WIMP DM models, SM3+D & SM4+D, with a light darkon (under 15 GeV) will be ruled out.
- To keep a light darkon in the presence of a SM-like Higgs, one needs to enlarge SM+D.
- This can be achieved in THDM+D.
- THDM+D can also offer isospin violation in the WIMP-nucleon interactions at roughly the desired level, albeit with some degree of fine tuning.