Simple Higgs-portal dark matter in light of direct search and LHC data

Jusak Tandean
National Taiwan University

Based on

CF Chang, XG He, JT, JHEP 04 (2017) 107 [arXiv:1702.02924]
PRD 96 (2017) 075026 [arXiv:1704.01904]
XG He & JT, JHEP 12 (2016) 074 [arXiv:1609.03551]

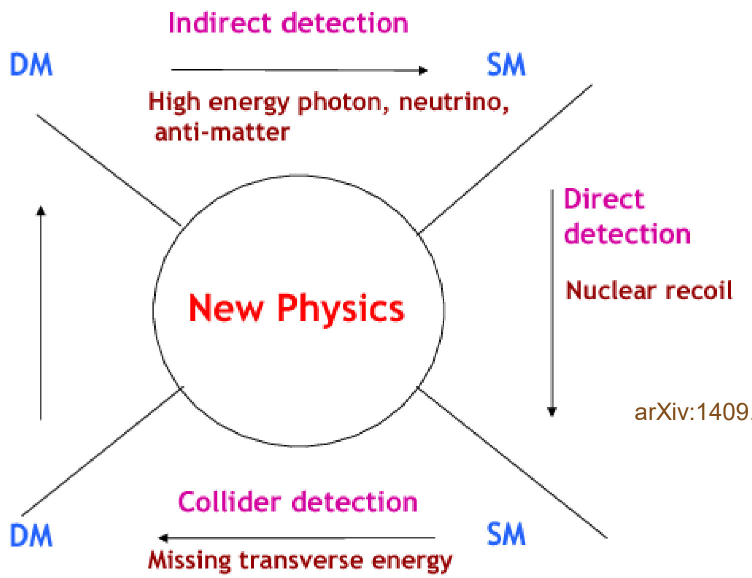
International Symposium on Cosmology and Particle Astrophysics
Yukawa Institute for Theoretical Physics, Kyoto, Japan

10 July 2017

Outline

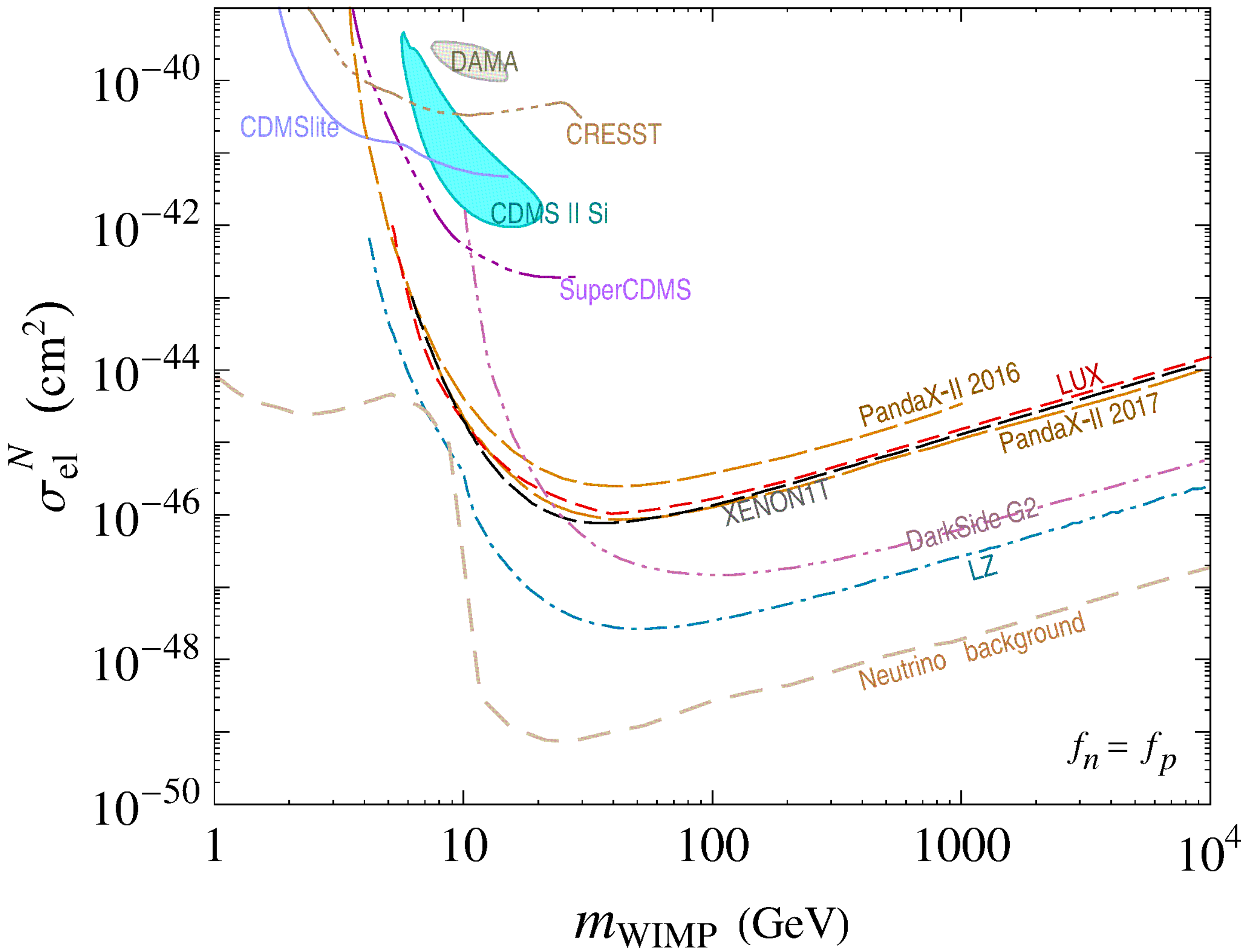
- Introduction
- Simplest Higgs-portal WIMP models
  - Bosonic (spin 0 or 1) DM
  - Fermionic (spin 1/2 or 3/2) DM
- Two-Higgs-doublet extensions of preceding models
- Conclusions

- The existence of dark matter in our Universe is now widely accepted
  - Dark matter (DM) makes up 26% of the total cosmic energy density
- But we're still in the dark about the particle identity of DM
- Among the most popular candidates for DM are the weakly interacting massive particles (WIMPs)
- Its detection is crucial for understanding the DM nature and for testing models of new physics beyond the standard model (SM)
- Ongoing and upcoming experiments are looking for signatures of WIMPs
- Focus: direct searches



arXiv:1409.4590

- WIMPs may be directly detected via their interactions with nuclei.
- The plot shows the data on WIMP-nucleon spin-independent elastic cross-section to date.
- Future searches: LZ, DarkSide G2



Implicit assumption of isospin symmetry: the effective WIMP couplings f_p and f_n to the proton and neutron are equal

ATLAS & CMS, 2016

- Higgs' invisible decay

$$\mathcal{B}(h \to \mathrm{BSM})_{\mathrm{exp}} < 0.16 \quad \Rightarrow \quad \mathcal{B}(h \to \mathrm{invisible}) = \frac{\Gamma(h \to \mathrm{invisible})}{\Gamma_h} < 0.16$$

- Higgs' couplings to gauge bosons & fermions

$$\kappa_W = 0.90 \pm 0.09\,, \quad \kappa_t = 1.43^{+0.23}_{-0.22}\,, \quad |\kappa_b| = 0.57 \pm 0.16\,, \quad |\kappa_\gamma| = 0.90^{+0.10}_{-0.09}$$

$$\kappa_Z = 1.00_{-0.08}\,, \quad |\kappa_g| = 0.81^{+0.13}_{-0.10}\,, \quad |\kappa_\tau| = 0.87^{+0.12}_{-0.11}$$

$$\kappa_X^2 = \Gamma_{h\to X\bar{X}} / \Gamma^{\mathrm{SM}}_{h\to X\bar{X}}$$

$$\kappa_\gamma^2 = 0.07\,\kappa_t^2 + 1.59\,\kappa_W^2 - 0.66\,\kappa_t\kappa_W$$

- The simplest model having a WIMP candidate is the SM+D: the SM plus a real scalar field called darkon, *D*, as the DM candidate.

Silveira & Zee, 1985

- It's a SM gauge singlet, stabilized by a discrete Z_2 symmetry, $D \to -D$.
- The renormalizable darkon Lagrangian

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

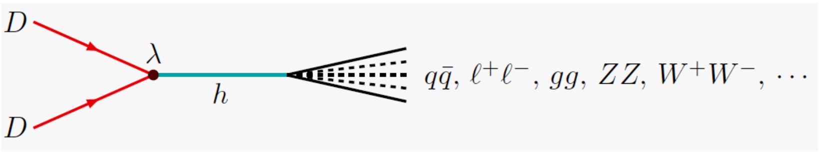
- After electroweak symmetry breaking

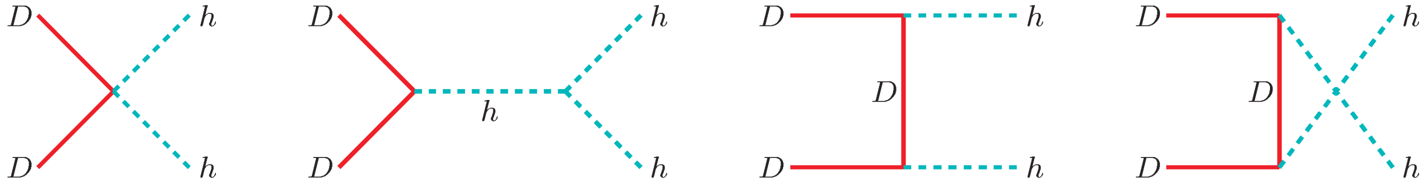
$$\mathcal{L}_D \supset -\tfrac{1}{4}\,\lambda_D\,D^4 - \tfrac{1}{2}\left(m_0^2 + \lambda v^2\right)D^2 - \tfrac{1}{2}\,\lambda\,D^2\,h^2 - \lambda\,D^2\,hv$$

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 $m_D = \sqrt{m_0^2 + \lambda v^2}$, and darkon self-interaction coupling λ_D.

- The SM+D relic density results mainly from the annihilation of a darkon pair into SM particles through Higgs (*h*) exchange.





- The darkon annihilation cross-section

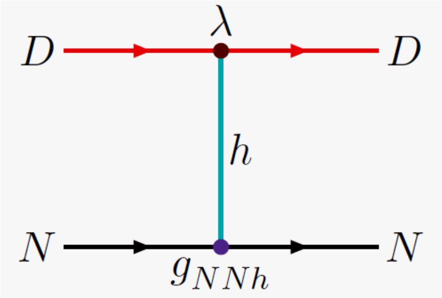
$$\sigma_{\rm ann} = \sigma(DD \to h^* \to X_{\rm SM}) + \sigma(DD \to hh)\,, \qquad X_{\rm SM} \neq hh$$

$$\sigma(DD \to h^* \to X_{\rm SM}) = \frac{4\lambda^2 v^2}{(m_h^2 - s)^2 + \Gamma_h^2 m_h^2}\,\frac{\sum_i \Gamma(\tilde{h} \to X_{i,\rm SM})}{\sqrt{s - 4m_D^2}}$$

- Observations (Planck) yield $\Omega_D h^2 = 0.1197 \pm 0.0022$

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

- The direct detection of darkon interactions relies on nuclear recoil effects due to darkon scattering with a nucleon N.



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

- The cross section of $DN \to DN$

$$\sigma_{\rm el}^{N} = \frac{\lambda^2 g_{NNh}^2 m_N^2 v^2}{\pi \left(m_D + m_N\right)^2 m_h^4}$$

- LHC measurements on Higgs decays imply constraints on the darkon-Higgs coupling.

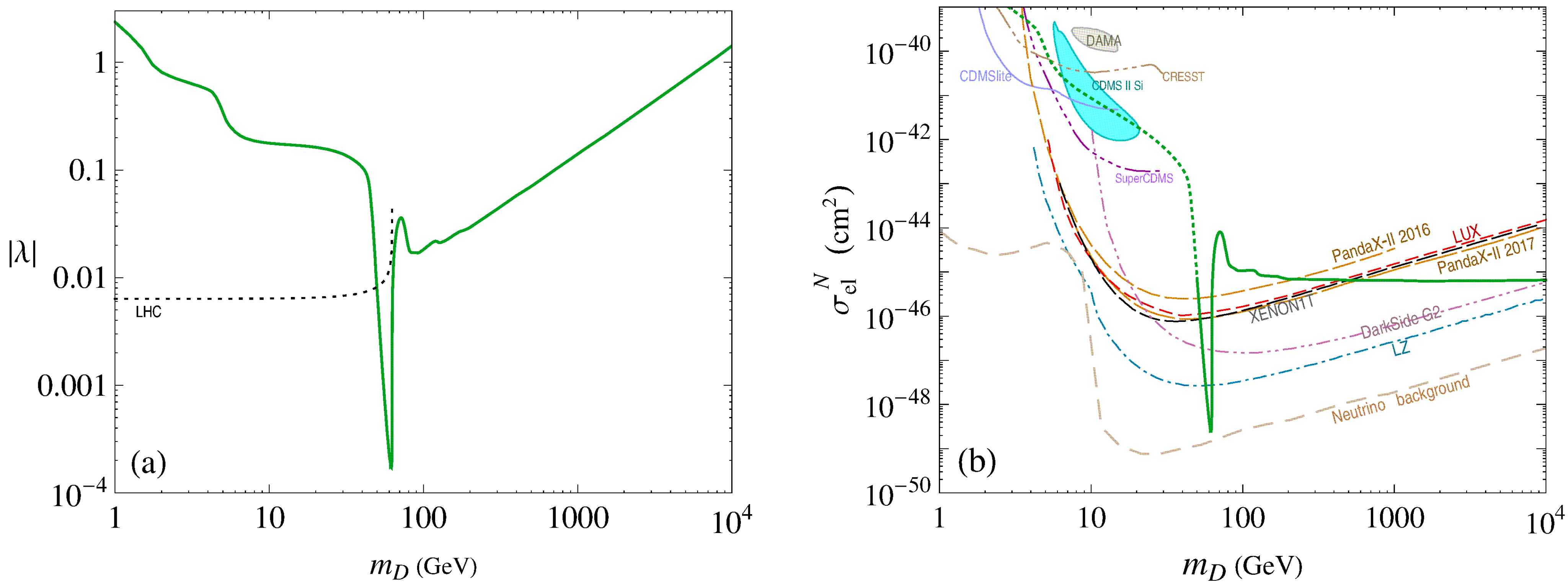
$$\Gamma(h \to DD) = \frac{\lambda^2 v^2}{8\pi m_h}\sqrt{1 - \frac{4m_D^2}{m_h^2}} \quad \text{for} \quad 2m_D < m_h$$

$$\Gamma_h = \Gamma_h^{\rm SM} + \Gamma(h \to DD)\,, \qquad \Gamma_h^{\rm SM} = 4.08\ \text{MeV} \quad \text{for} \quad m_h = 125.1\ \text{GeV}$$

ATLAS & CMS, 2016

$$\mathcal{B}(h \to \text{BSM})_{\rm exp} < 0.16 \quad \Rightarrow \quad \mathcal{B}(h \to DD) = \frac{\Gamma(h \to DD)}{\Gamma_h} < 0.16$$

Constraints on SM+D



- The dotted part of the green curve in the right plot is disallowed by LHC data on Higgs invisible decay.
- Together the Higgs data and the new limits from LUX, PandaX-II, and XENON1T rule out SM+D darkon masses below 52 GeV and from 63 GeV to 570 GeV.
- Ongoing & future searches: PandaX-II, XENON1T, DarkSide G2, and LZ can probe SM+D darkon masses up to roughly 20 TeV.

Simplest Higgs-portal vector DM model

- The WIMP DM candidate is a real SM-singlet spin-1 boson, *V*
  - It's odd under a Z_2 symmetry which does not affect SM particles.
- The minimal Higgs-*V* interaction is via a dimension-4 operator involving the Higgs doublet.

$$\mathcal{L}_V = -\frac{1}{4}V_{\kappa\nu}V^{\kappa\nu} + \frac{\mu_V^2}{2}V_\kappa V^\kappa + \frac{\lambda_V}{4}(V_\kappa V^\kappa)^2 + \lambda_h \mathrm{H}^\dagger\mathrm{H}\, V_\kappa V^\kappa$$

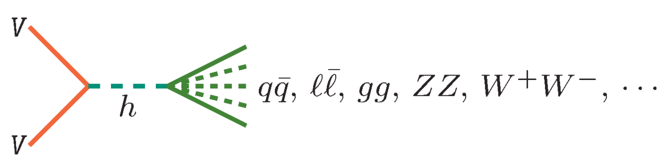
Kanemura *et al.*, 2010

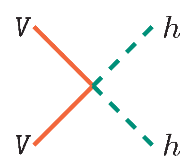
$V_{\kappa\nu} = \partial_\kappa V_\nu - \partial_\nu V_\kappa$, μ_V^2 and $\lambda_{V,h}$ are real constants, $\mathrm{H}^\dagger\mathrm{H} = \frac{1}{2}(h+v)^2$

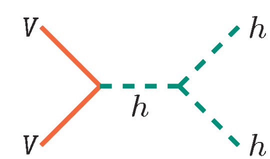
$$\mathcal{L}_V \supset \frac{m_V^2}{2}V_\kappa V^\kappa + \lambda_h\left(hv + \frac{h^2}{2}\right)V_\kappa V^\kappa , \qquad m_V = \left(\mu_V^2 + \lambda_h v^2\right)^{1/2}$$

- Cross section of DM annihilation

$$\sigma_{\rm ann} = \sigma(VV \to h^* \to X_{\rm SM}) + \sigma(VV \to hh) , \qquad X_{\rm SM} \neq hh$$







$$\sigma(VV \to h^* \to X_{\rm SM}) = \frac{\lambda_h^2\left(\beta_V^2 s^2 + 12 m_V^4\right)v^2 \sum_i \Gamma(\tilde{h} \to X_{i,\rm SM})}{9\beta_V m_V^4 \sqrt{s}\left[\left(m_h^2 - s\right)^2 + \Gamma_h^2 m_h^2\right]} , \qquad \beta_{\rm X} = \sqrt{1 - \frac{4m_{\rm X}^2}{s}}$$

$$\sigma(VV \to hh) \simeq \frac{\beta_h \lambda_h^2\left(\beta_V^2 s^2 + 12 m_V^4\right)}{288\beta_V \pi m_V^4 s}\left[1 + \frac{3m_h^2\left(s - m_h^2\right)}{\left(s - m_h^2\right)^2 + \Gamma_h^2 m_h^2}\right]^2$$

- Higgs' invisible decay rate

$$\Gamma(h \to VV) = \frac{\lambda_h^2 v^2}{8\pi m_h} \frac{\left(1 - 4R_V^2 + 12R_V^4\right)}{4R_V^4} \sqrt{1 - 4R_V^2}\,, \qquad R_V = \frac{m_V}{m_h}$$

Imposed bound $\mathcal{B}(h \to VV) = \dfrac{\Gamma(h \to VV)}{\Gamma_h} < 0.16$

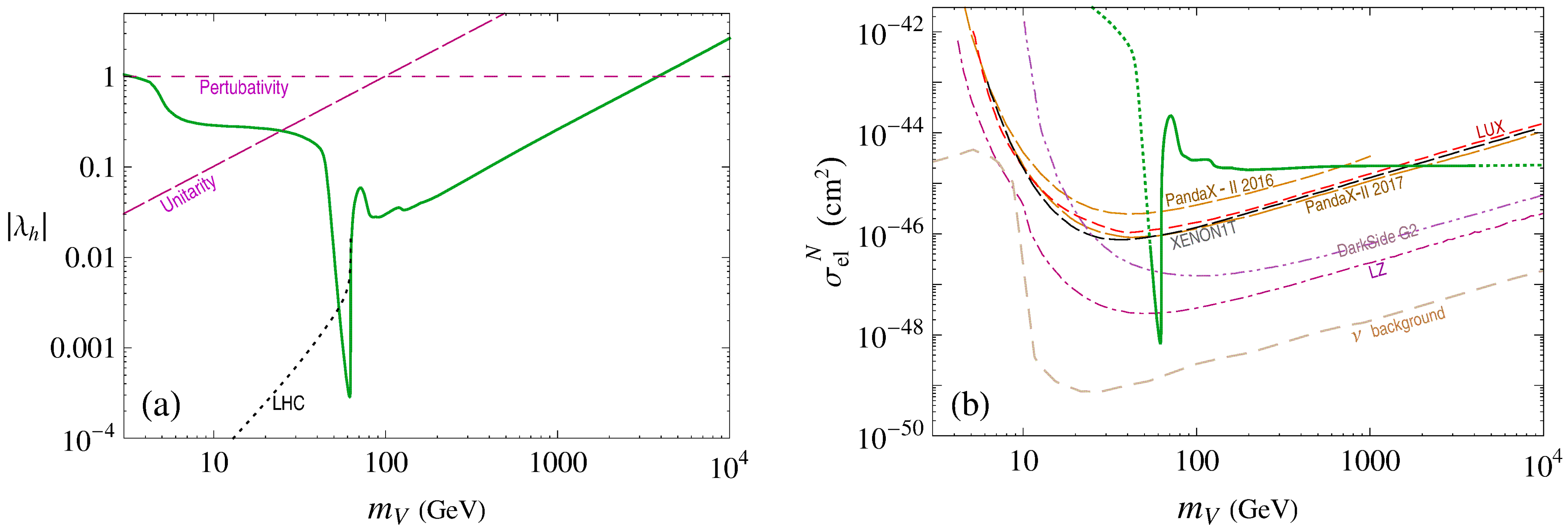
- Cross section of DM-nucleon scattering $VN \to VN$

$$\sigma_{\rm el}^N = \frac{\lambda_h^2 g_{NNh}^2 m_N^2 v^2}{\pi\,(m_V + m_N)^2 m_h^4}$$

- This model is actually nonrenormalizable and violates unitarity, implying that unitarity conditions need to be applied and consequently $\lambda_h < \dfrac{\sqrt{2\pi}\, m_V}{v}$

Lebedev, Lee, Mambrini, 2012

Viable parameter space of minimal vector-DM model



- The dotted part of the green curve in the right plot is disallowed by LHC data on Higgs invisible decay as well as perturbativity and unitarity considerations.

- Excluded regions: $m_V \lesssim 54$ GeV and 63 GeV $\lesssim m_V \lesssim 2.1$ TeV

Simplest Higgs-portal spin-1/2 DM model

- The WIMP DM candidate is a Dirac SM-singlet spin-½ fermion, ψ
  - It's odd under a Z_2 symmetry which does not affect SM particles.
- The leading-order minimal interaction of ψ with SM particles is via an effective dimension-5 scalar operator involving the Higgs doublet.

$$\mathcal{L}_\psi = \overline{\psi}\, i\partial\!\!\!/ \psi - \mu_\psi \overline{\psi}\psi - \frac{\overline{\psi}\psi\, \mathrm{H}^\dagger \mathrm{H}}{\Lambda_\psi}, \qquad \mathrm{H}^\dagger \mathrm{H} = \tfrac{1}{2}(h+v)^2$$

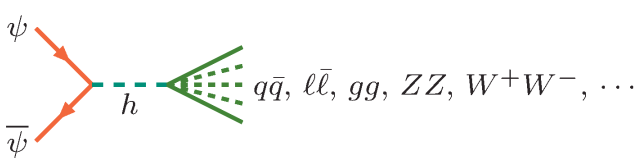
Kim & Lee, 2007

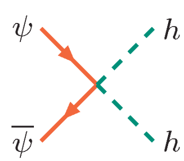
μ_ψ and Λ_ψ are real constants, and Λ_ψ represents the underlying heavy physics.

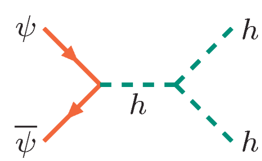
$$\mathcal{L}_\psi \supset -m_\psi \overline{\psi}\psi - \lambda_{\psi h}\, \overline{\psi}\psi \left(h + \frac{h^2}{2v}\right), \qquad m_\psi = \mu_\psi + \frac{\lambda_{\psi h} v}{2}, \qquad \lambda_{\psi h} = \frac{v}{\Lambda_\psi}$$

- Cross section of DM annihilation

$$\sigma_{\rm ann} = \sigma(\bar\psi\psi \to h^* \to X_{\rm SM}) + \sigma(\bar\psi\psi \to hh), \qquad X_{\rm SM} \neq hh$$







$$\sigma(\bar\psi\psi \to h^* \to X_{\rm SM}) = \frac{\beta_\psi \lambda_{\psi h}^2 \sqrt{s} \sum_i \Gamma(\tilde h \to X_{i,\rm SM})}{2\left[(m_h^2 - s)^2 + \Gamma_h^2 m_h^2\right]}, \qquad \beta_{\rm X} = \sqrt{1 - \frac{4m_{\rm X}^2}{s}}$$

$$\sigma(\bar\psi\psi \to hh) \simeq \frac{\beta_\psi \beta_h \lambda_{\psi h}^2}{64\pi v^2}\left[1 + \frac{3m_h^2(s - m_h^2)}{(s - m_h^2)^2 + \Gamma_h^2 m_h^2}\right]^2$$

Constraints from Higgs data, DM direct searches, and EFT validity limit

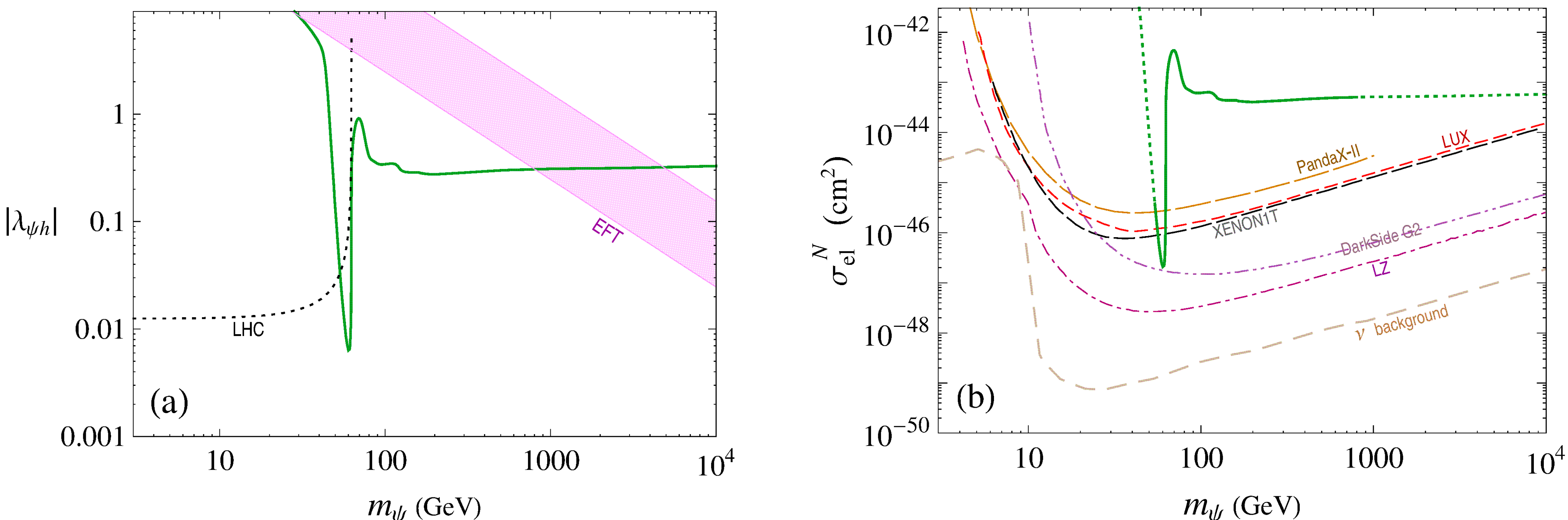
- Higgs' invisible decay rate
$$\Gamma(h \to \bar{\psi}\psi) = \frac{\lambda_{\psi h}^2 m_h}{8\pi}\left(1 - \frac{4m_\psi^2}{m_h^2}\right)^{3/2}$$

  Imposed constraint
$$\mathcal{B}(h \to \bar{\psi}\psi) = \frac{\Gamma(h \to \bar{\psi}\psi)}{\Gamma_h} < 0.16$$

- Cross section of DM-nucleon scattering $\psi N \to \psi N$
$$\sigma_{\rm el}^N = \frac{\lambda_{\psi h}^2 g_{NNh}^2 m_\psi^2 m_N^2}{\pi (m_\psi + m_N)^2 m_h^4}$$

- The effective field theory (EFT) description of the ψ-H interaction cannot be valid at arbitrarily high energies, implying the limitation
$$\lambda_{\psi h} < \frac{2\pi v}{m_\psi}$$
Busoni *et al.*, 2014

Viable parameter space of minimal spin-1/2 DM model



Chang, He, JT, 1702.02924

- The dotted portions of the green curve in the right plot are disallowed by LHC data on Higgs invisible decay and EFT limitation.

- Only the small region $56.3\ \text{GeV} \lesssim m_\psi \lesssim 62.2\ \text{GeV}$ remains viable.

- The enhancement of $\sigma_{\rm el}^N$ is due to enhanced $\lambda_{\psi h}$ which compensates for the suppression of the DM annihilation rate $\sigma_{\rm ann} v_{\rm rel}$ by $v_{\rm rel}^2$.

- The Yukawa Lagrangian is

$$\mathcal{L}_{\rm Y} = -\overline{Q}_{j,L}\left(\lambda_2^u\right)_{jl}\tilde{H}_2\mathcal{U}_{l,R} - \overline{Q}_{j,L}\left(\lambda_1^d\right)_{jl}H_1\mathcal{D}_{l,R} - \overline{L}_{j,L}\left(\lambda_1^\ell\right)_{jl}H_1E_{l,R} + \text{H.c.}$$

- It respects a discrete symmetry, Z_2, under which $H_2 \to -H_2$ and $\mathcal{U}_R \to -\mathcal{U}_R$ while all the other fields are not affected.

- The couplings of the CP-even Higgs bosons to fermions are given by

$$-\mathcal{L}_{\rm Y} \supset \sum_{\text{all quarks}} k_q^{\mathcal{H}} m_q \overline{q} q \frac{\mathcal{H}}{v}, \qquad k_{c,t}^{\mathcal{H}} = k_u^{\mathcal{H}}, \quad k_{s,b}^{\mathcal{H}} = k_d^{\mathcal{H}}, \qquad \mathcal{H} = h, H$$

$$k_u^h = \frac{c_\alpha}{s_\beta}, \qquad k_d^h = -\frac{s_\alpha}{c_\beta}, \qquad k_u^H = \frac{s_\alpha}{s_\beta}, \qquad k_d^H = \frac{c_\alpha}{c_\beta}$$

- The couplings of $\mathcal{H}$ to the weak bosons are given by

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

$$k_V^h = s_{\beta-\alpha}, \qquad k_V^H = c_{\beta-\alpha}$$

- The Lagrangian of the model, $\mathcal{L} \supset -\mathcal{V}_D - \mathcal{V}_H$, contains

$$\mathcal{V}_D = \frac{m_0^2}{2} D^2 + \frac{\lambda_D}{4} D^4 + \left(\lambda_{1D} H_1^\dagger H_1 + \lambda_{2D} H_2^\dagger H_2\right) D^2$$

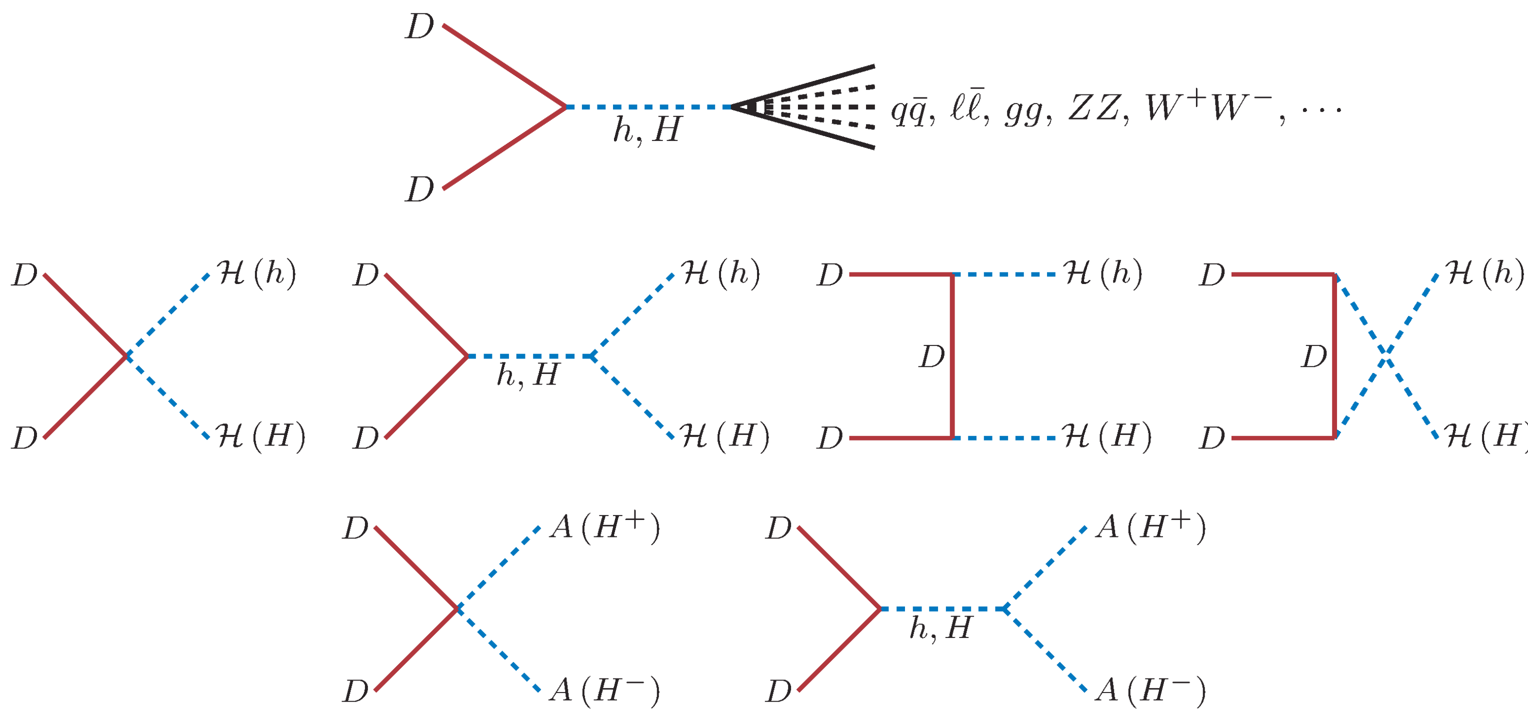
$$\mathcal{V}_H = m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - \left(m_{12}^2 H_1^\dagger H_2 + \mathrm{H.c.}\right) + \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2$$

$$+ \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \mathrm{H.c.}\right]$$

- The m_{12}^2 terms, important for relaxing the upper bounds on the Higgs masses, softly break Z_2

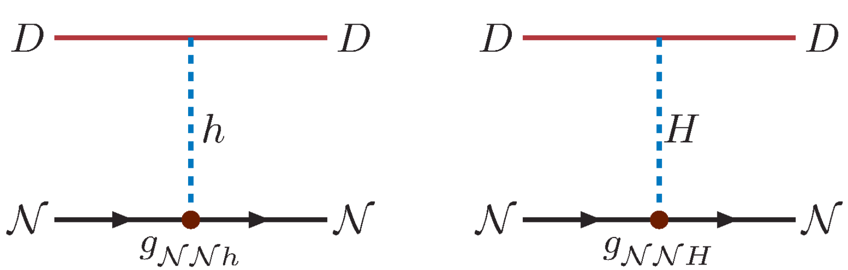
- Darkon's stability is maintained by another discrete symmetry, Z_2', under which $D \to -D$, whereas all the other fields are Z_2' even

- Darkon annihilation



- Darkon-$\mathcal{N}$ scattering

$$\sigma_{\rm el}^{\mathcal{N}} = \frac{m_{\mathcal{N}}^2\, v^2}{\pi\,(m_D + m_{\mathcal{N}})^2}\left(\frac{\lambda_h\, g_{\mathcal{N}\mathcal{N}h}}{m_h^2} + \frac{\lambda_H\, g_{\mathcal{N}\mathcal{N}H}}{m_H^2}\right)^2$$



$\mathcal{N} = p, n$

Effective couplings of h & H to nucleons in THDM II+D

- The effective Higgs couplings to the proton or neutron are given by

$$\mathcal{L}_{\mathcal{NNH}} = -g_{\mathcal{NNH}} \overline{\mathcal{N}} \mathcal{N} \mathcal{H} \,, \qquad \mathcal{N} = p, n \,, \qquad \mathcal{H} = h, H$$

$$g_{\mathcal{NNH}} = \frac{m_{\mathcal{N}}}{v} \left[\left(f_u^{\mathcal{N}} + f_c^{\mathcal{N}} + f_t^{\mathcal{N}} \right) k_u^{\mathcal{H}} + \left(f_d^{\mathcal{N}} + f_s^{\mathcal{N}} + f_b^{\mathcal{N}} \right) k_d^{\mathcal{H}} \right]$$

Shifman et al., 1978
Cheng, 1988
Cheng, 1989

where $f_q^{\mathcal{N}}$ is defined by $\langle \mathcal{N} | m_q \bar{q} q | \mathcal{N} \rangle = f_q^{\mathcal{N}} m_{\mathcal{N}} \bar{u}_{\mathcal{N}} u_{\mathcal{N}}$

- Employing a chiral Lagrangian approach yields

$$g_{pp\mathcal{H}} \simeq \left(0.563 \, k_u^{\mathcal{H}} + 0.560 \, k_d^{\mathcal{H}} \right) \times 10^{-3}$$

$$g_{nn\mathcal{H}} \simeq \left(0.548 \, k_u^{\mathcal{H}} + 0.586 \, k_d^{\mathcal{H}} \right) \times 10^{-3}$$

He, Li, Li, JT, Tsai, 2008
He, Ren, JT, 2012

- Hence $g_{pp\mathcal{H}}$ and $g_{nn\mathcal{H}}$ can be very dissimilar, implying substantial breaking of isospin symmetry

- Thus, to evaluate DM-nucleon scattering in this model, it's more appropriate to work with either the darkon-proton or darkon-neutron cross-section $\left(\sigma_{\rm el}^p \text{ or } \sigma_{\rm el}^n \right)$ rather than the darkon-nucleon one assuming isospin conservation

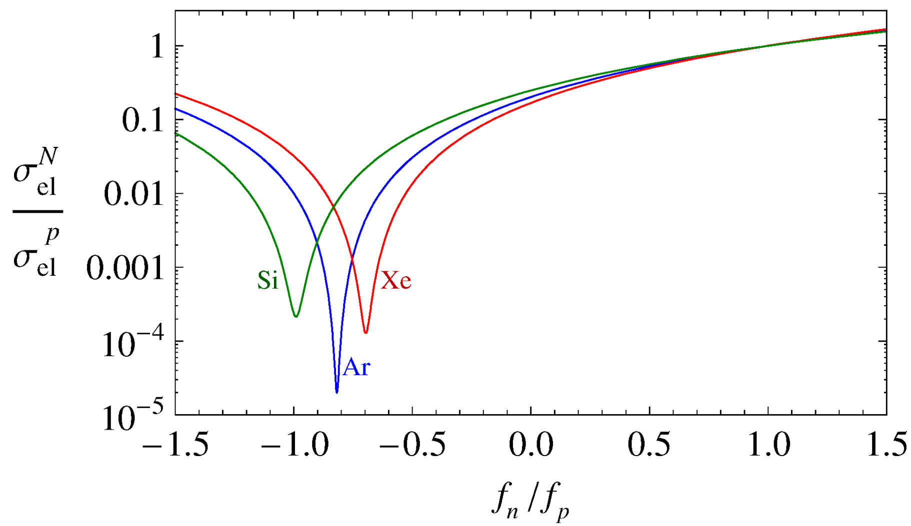
- The WIMP-nucleon cross-section in the isospin-symmetric limit can be converted to the WIMP-proton cross-section, and vice versa, using

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

Feng *et al.*, 2011

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 $\sigma_{\rm el}^N = \sigma_{\rm el}^p$.



Dependence of $\sigma_{\rm el}^N/\sigma_{\rm el}^p$ on f_n/f_p according to Eq. (20) for silicon, argon, and xenon targets.

In THDM II+D with only $\mathcal{H}$ = *h* or *H* as portal

$$f_n/f_p = g_{nn\mathcal{H}}/g_{pp\mathcal{H}}$$

Reduction of darkon-nucleon cross-section in THDM II+D

- It's possible for $g_{\mathcal{NNH}}$ to become very small or vanish, leading to a very small or vanishing darkon-$\mathcal{N}$ cross-section

He, Li, Li, JT, Tsai, 2008

$$\sigma_{\rm el}^{\mathcal{N}} = \frac{m_{\mathcal{N}}^2\, v^2}{\pi\,(m_D + m_{\mathcal{N}})^2}\left(\frac{\lambda_h\, g_{\mathcal{NN}h}}{m_h^2} + \frac{\lambda_H\, g_{\mathcal{NN}H}}{m_H^2}\right)^2$$

$$g_{pp\mathcal{H}} \simeq \left(0.563\, k_u^{\mathcal{H}} + 0.560\, k_d^{\mathcal{H}}\right) \times 10^{-3}$$

$$g_{nn\mathcal{H}} \simeq \left(0.548\, k_u^{\mathcal{H}} + 0.586\, k_d^{\mathcal{H}}\right) \times 10^{-3}$$

$$k_u^h = \frac{c_\alpha}{s_\beta}, \qquad k_d^h = -\frac{s_\alpha}{c_\beta}, \qquad k_u^H = \frac{s_\alpha}{s_\beta}, \qquad k_d^H = \frac{c_\alpha}{c_\beta}$$

- Thus $g_{\mathcal{NN}h}$ and $g_{\mathcal{NN}H}$, respectively, can vanish at certain values of

$r_k^h = -\tan\alpha\, \tan\beta$ and $r_k^H = \cot\alpha\, \tan\beta$ where $r_k^{\mathcal{H}} = \dfrac{k_d^{\mathcal{H}}}{k_u^{\mathcal{H}}}$

- The cross-section can also vanish from cancellation between the λ_h and λ_H terms.

- We choose *h* to be the 125-GeV Higgs and *H* heavier.

- From LHC measurements on Higgs decays $\kappa_X^2 = \Gamma_{h\to X\bar{X}}/\Gamma^{SM}_{h\to X\bar{X}}$

$$\kappa_W = 0.90 \pm 0.09\,, \quad \kappa_t = 1.43^{+0.23}_{-0.22}\,, \quad |\kappa_b| = 0.57 \pm 0.16\,, \quad |\kappa_\gamma| = 0.90^{+0.10}_{-0.09}$$

$$\kappa_Z = 1.00_{-0.08}\,, \quad |\kappa_g| = 0.81^{+0.13}_{-0.10}\,, \quad |\kappa_\tau| = 0.87^{+0.12}_{-0.11}$$

$$\kappa_\gamma^2 = 0.07\,\kappa_t^2 + 1.59\,\kappa_W^2 - 0.66\,\kappa_t\kappa_W$$

- THDM-II expectations: $k_V^h = \kappa_W = \kappa_Z\,, \quad k_u^h = \kappa_t \simeq \kappa_g\,, \quad k_d^h = \kappa_b = \kappa_\tau$
- Accordingly, we may impose

$$0.81 \le k_V^h \le 1\,, \quad 0.71 \le k_u^h \le 1.66\,, \quad 0.41 \le |k_d^h| \le 0.99\,, \quad 0.81 \le |k_\gamma^h| \le 1$$

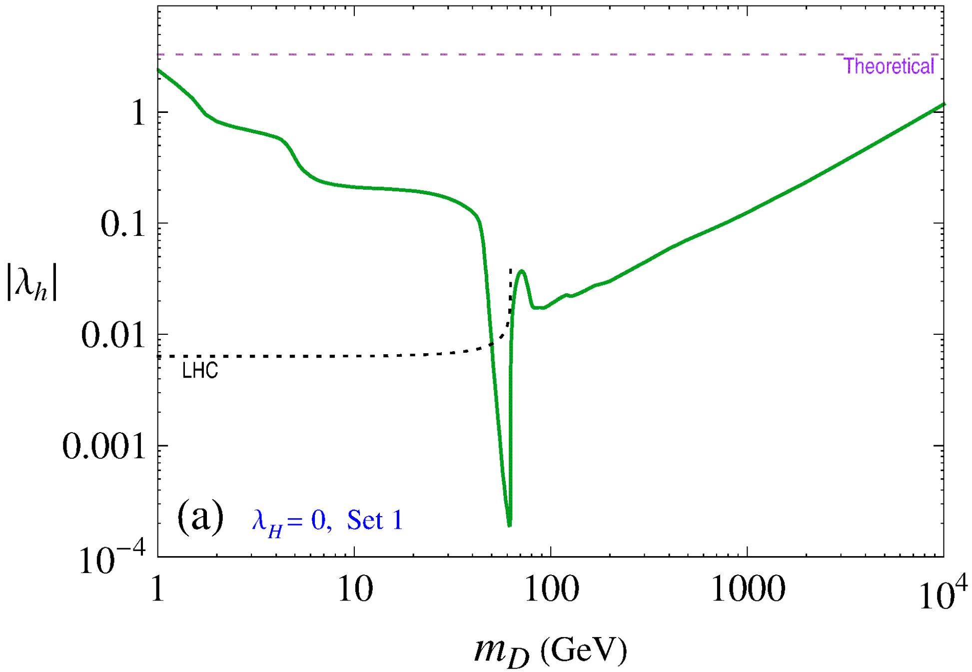
$$k_\gamma^h = 0.264\,k_u^h - 1.259\,k_V^h + 0.151\,\frac{\lambda_{hH^+H^-}v^2}{2m_{H^\pm}^2}\,A_0^{\gamma\gamma}(4m_{H^\pm}^2/m_h^2)$$

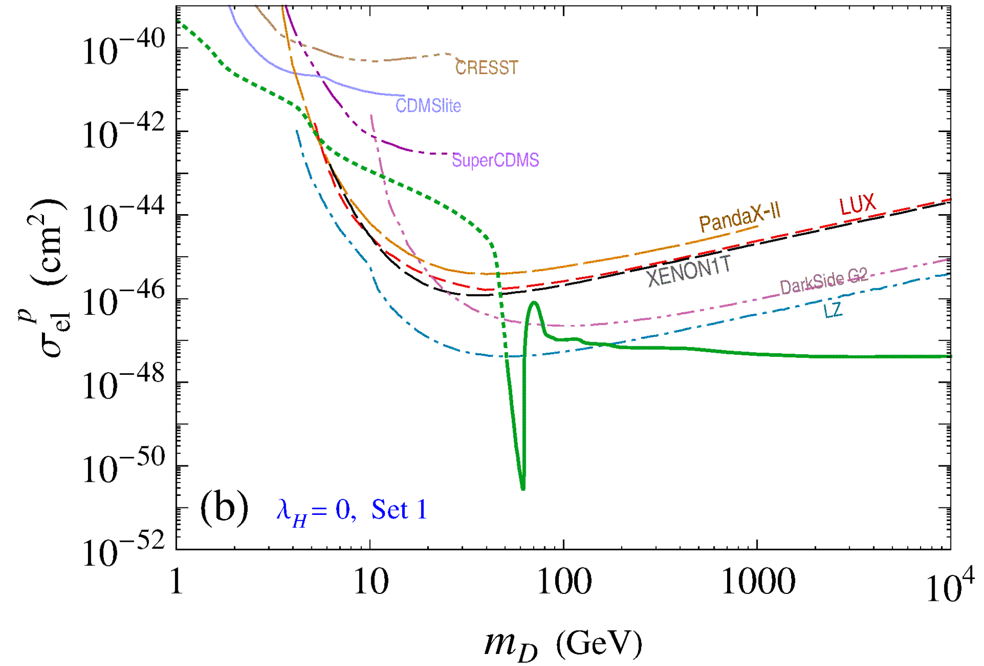
- The LHC bound on the invisible decay of the 125-GeV Higgs boson applies to h, but not to the heavier H.
- Since the new scalars arise from the presence of a second Higgs doublet, their effects must satisfy the constraints on oblique parameters from electroweak precision measurements.
- Theoretical requirements on the scalar potential can be important
  - Perturbativity
  - Vacuum stability
  - Unitarity of scalar scattering amplitudes

h-portal (λ_H = 0) examples

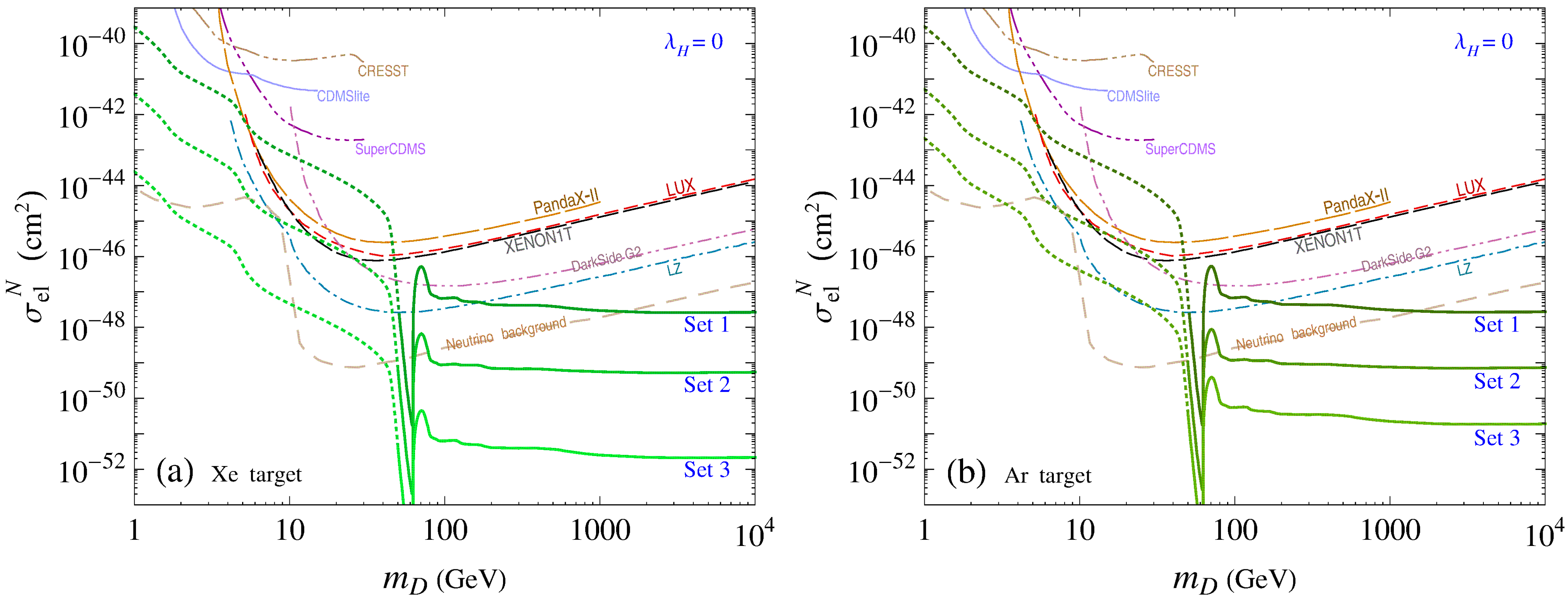
Set	α	β	$\frac{m_H}{\text{GeV}}$	$\frac{m_A}{\text{GeV}}$	$\frac{m_{H^\pm}}{\text{GeV}}$	$\frac{m_{12}^2}{\text{GeV}^2}$	k_V^h	k_u^h	$\frac{k_d^h}{k_u^h}$	k_V^H	k_u^H	k_d^H	$\frac{g_{pph}}{10^{-5}}$	$\frac{f_n}{f_p}$
1	0.117	1.428	470	500	550	31000	0.966	1.003	−0.818	0.257	0.118	6.98	10.6	+0.658
2	0.141	1.422	550	520	540	44000	0.958	1.001	−0.947	0.286	0.142	6.68	3.29	−0.197
3	0.206	1.357	515	560	570	55000	0.913	1.002	−0.962	0.408	0.209	4.61	2.42	−0.646

TABLE I: Sample values of input parameters α, β, $m_{H,A,H^\pm}$, and m_{12}^2 in the $\lambda_H = 0$ scenario and the resulting values of several quantities, including $f_n/f_p = g_{nnh}/g_{pph}$.





- Predictions for darkon-nucleon cross-section for (a) xenon and (b) argon target materials

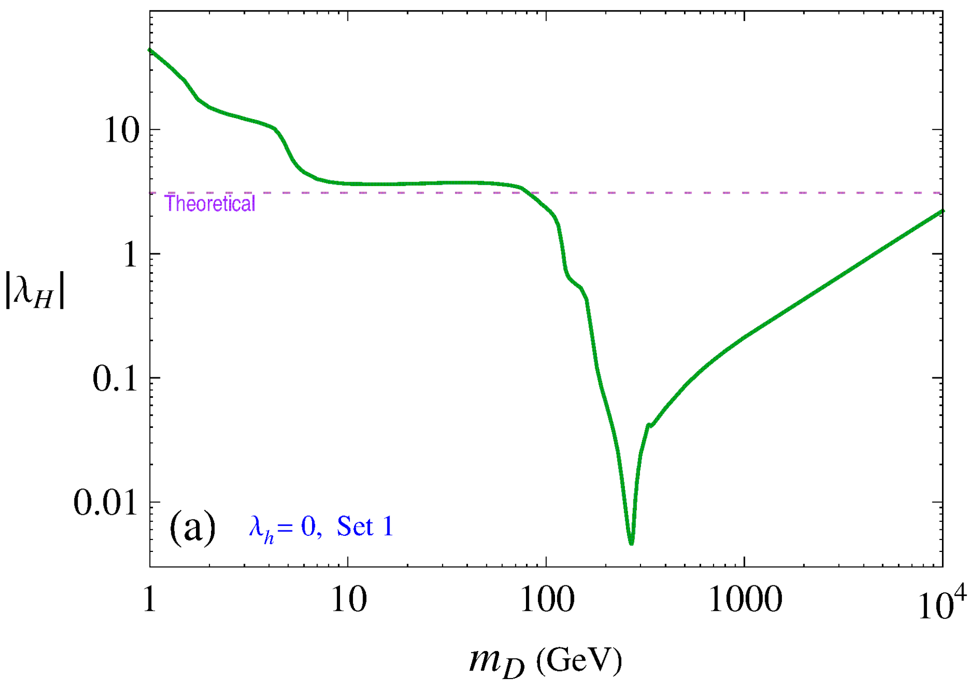


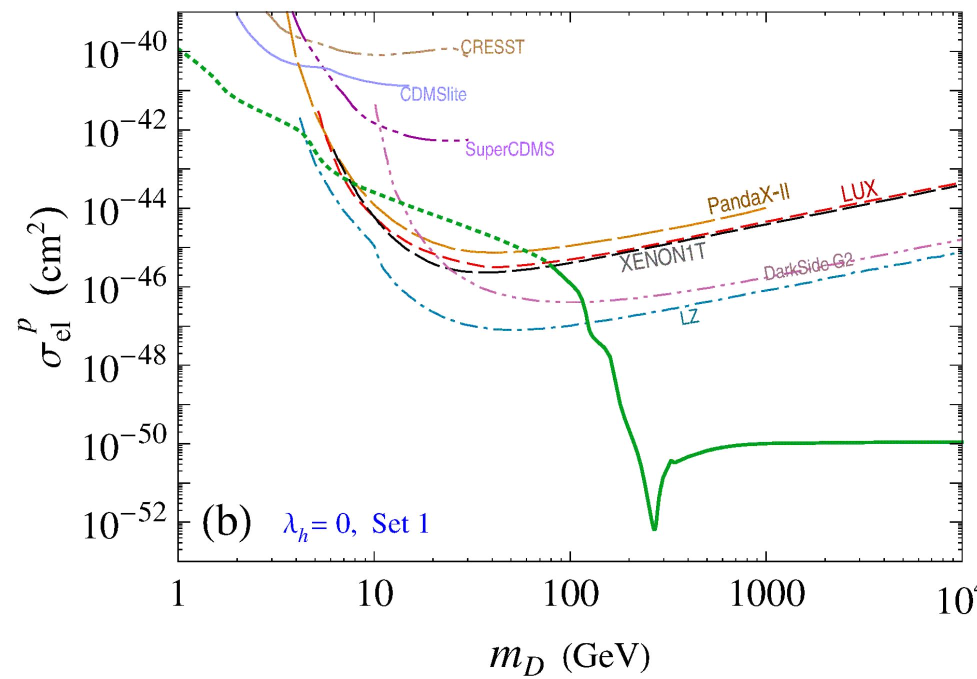
- The difference between xenon and argon targets can lead to visible effects if f_n/f_p is negative.
- There's ample parameter space that can evade present experimental constraints and perhaps even elude future direct searches.

H-portal (λ_h = 0) examples

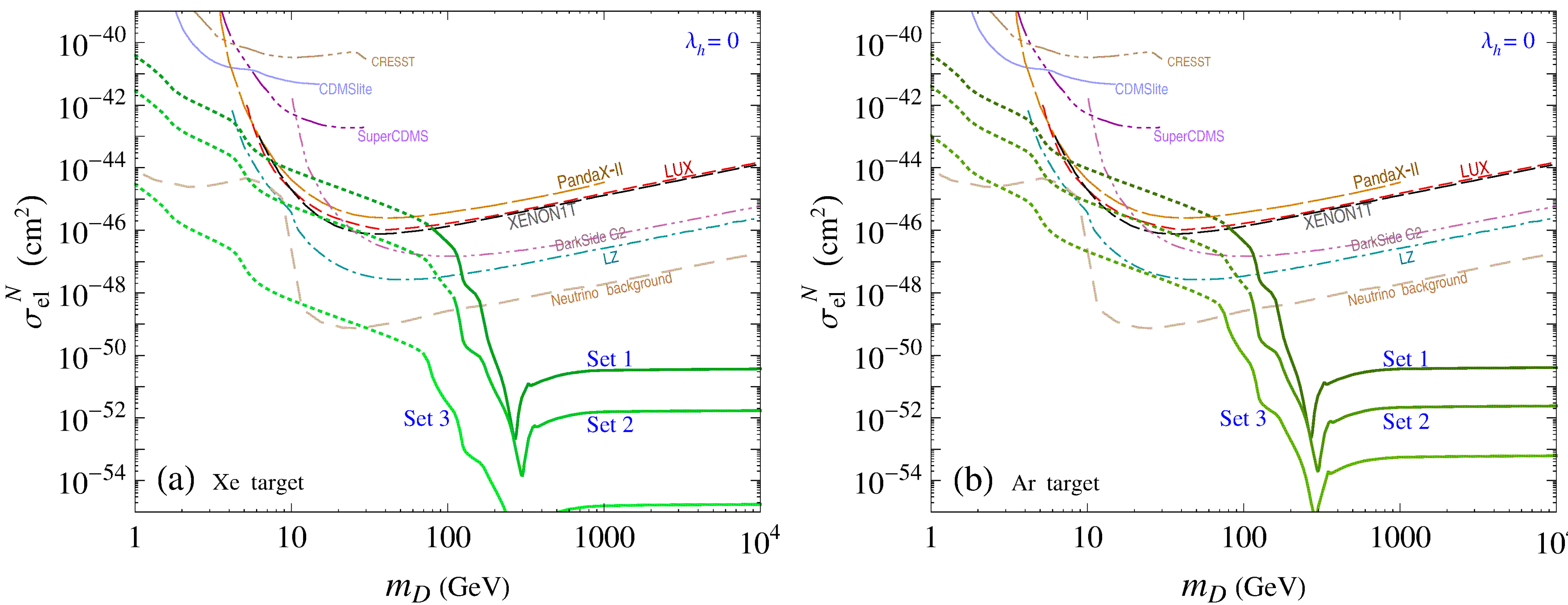
Set	α	β	$\frac{m_H}{\text{GeV}}$	$\frac{m_A}{\text{GeV}}$	$\frac{m_{H^\pm}}{\text{GeV}}$	$\frac{m_{12}^2}{\text{GeV}^2}$	k_V^h	k_u^h	k_d^h	k_V^H	k_u^H	$\frac{k_d^H}{k_u^H}$	$\frac{g_{ppH}}{10^{-5}}$	$\frac{f_n}{f_p}$
1	−0.785	0.738	550	600	650	70000	0.999	1.051	0.955	0.048	−1.051	−0.910	−5.62	+0.281
2	−0.749	0.723	610	750	760	91000	0.995	1.107	0.908	0.099	−1.029	−0.949	−3.26	−0.245
3	−0.676	0.658	590	610	640	60000	0.972	1.276	0.791	0.235	−1.023	−0.964	−2.40	−0.693

TABLE II: Samples values of input parameters α, β, $m_{H,A,H^\pm}$, and m_{12}^2 in the $\lambda_h = 0$ scenario and the resulting values of several quantities, including $f_n/f_p = g_{nnH}/g_{ppH}$.





- Predictions for darkon-nucleon cross-section for (a) xenon and (b) argon target materials



- The xenon-argon difference can again become visible if $f_n/f_p < 0$.
- There's more parameter space than in the h-portal ($\lambda_H = 0$) case that can evade present experimental constraints and perhaps even elude future direct searches.

THDM II plus vector or fermionic DM

Chang, He, JT, 2017

Set	α	β	$\frac{m_H}{\text{GeV}}$	$\frac{m_A}{\text{GeV}}$	$\frac{m_{H^\pm}}{\text{GeV}}$	$\frac{m_{12}^2}{\text{GeV}^2}$	k_V^h	k_u^h	$\frac{k_d^h}{k_u^h}$	k_V^H	k_u^H	k_d^H	$\frac{g_{pph}}{10^{-5}}$	$\frac{f_n}{f_p}$
1	0.141	1.422	550	520	540	44000	0.958	1.001	−0.947	0.286	0.142	6.68	3.29	−0.197
2	0.206	1.357	515	560	570	55000	0.913	1.002	−0.962	0.408	0.209	4.61	2.42	−0.646

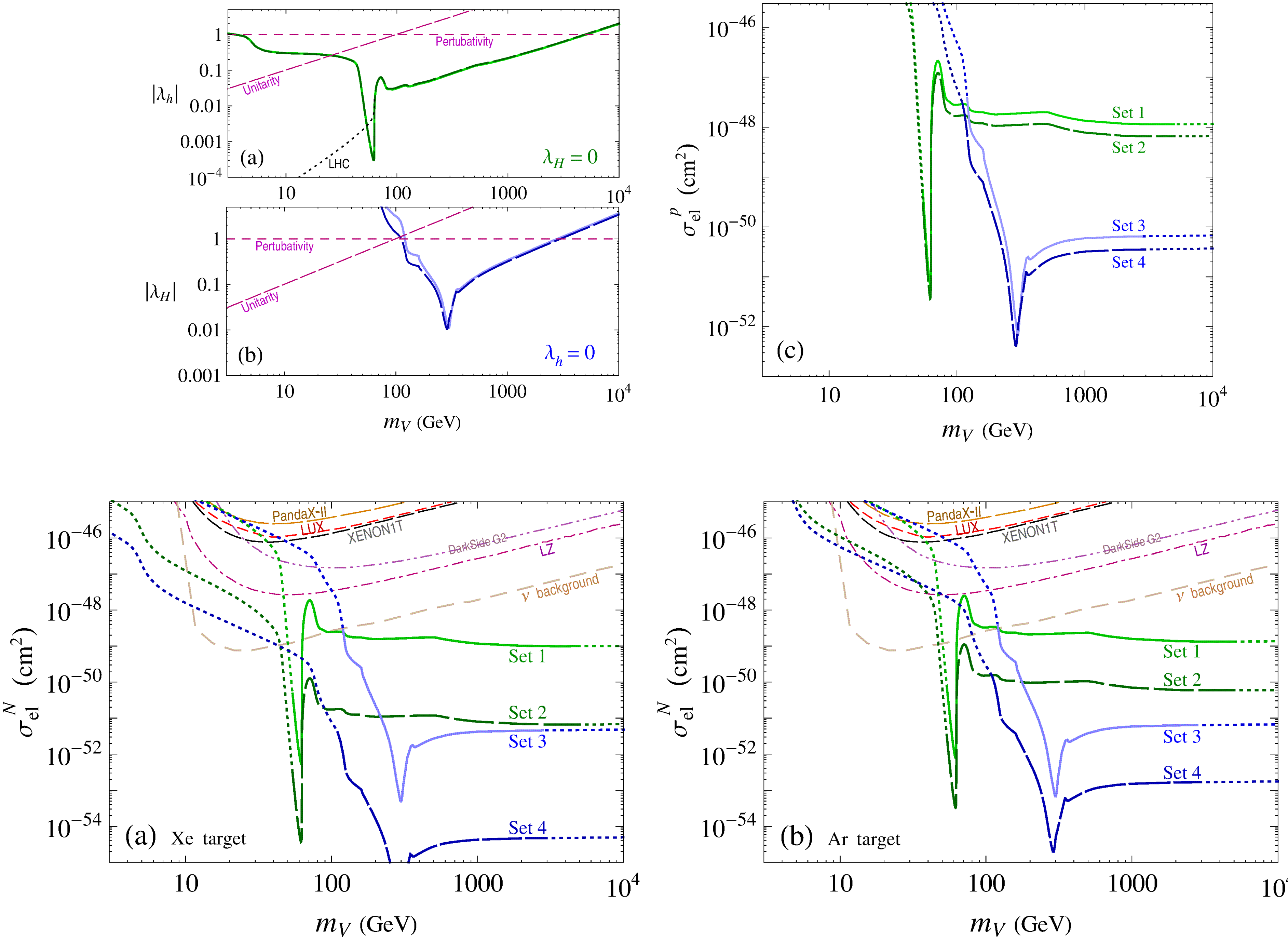
TABLE I: Sample values of input parameters α, β, $m_{H,A,H^\pm}$, and m_{12}^2 in the h-portal scenarios ($\lambda_{\psi H} = \lambda_{\Psi H} = \lambda_H = 0$) and the resulting values of several quantities, including $f_n/f_p = g_{nnh}/g_{pph}$.

Set	α	β	$\frac{m_H}{\text{GeV}}$	$\frac{m_A}{\text{GeV}}$	$\frac{m_{H^\pm}}{\text{GeV}}$	$\frac{m_{12}^2}{\text{GeV}^2}$	k_V^h	k_u^h	k_d^h	k_V^H	k_u^H	$\frac{k_d^H}{k_u^H}$	$\frac{g_{ppH}}{10^{-5}}$	$\frac{f_n}{f_p}$
3	−0.749	0.723	610	750	760	91000	0.995	1.107	0.908	0.099	−1.029	−0.949	−3.26	−0.245
4	−0.676	0.658	590	610	640	60000	0.972	1.276	0.791	0.235	−1.023	−0.964	−2.40	−0.693

TABLE II: The same as Table I, but for the H-portal scenarios ($\lambda_{\psi h} = \lambda_{\Psi h} = \lambda_h = 0$).

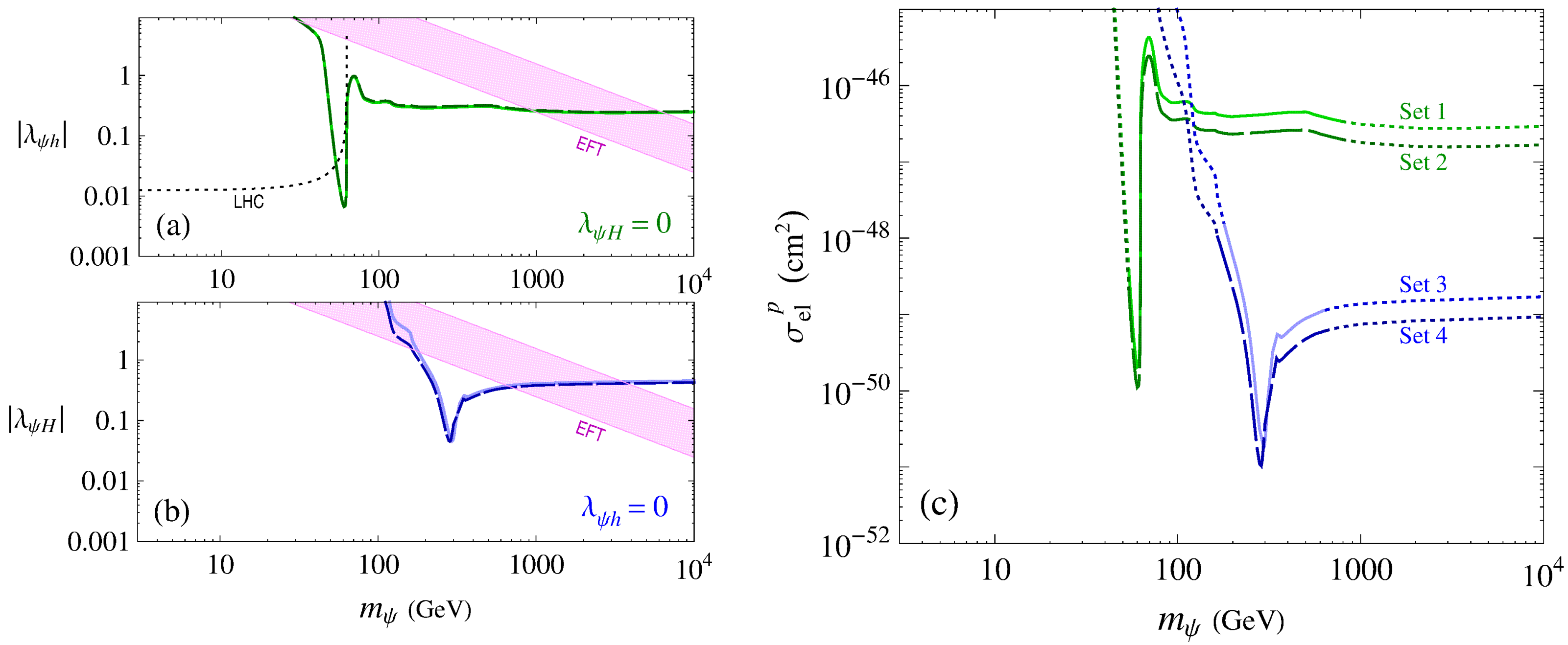
THDM II plus vector DM

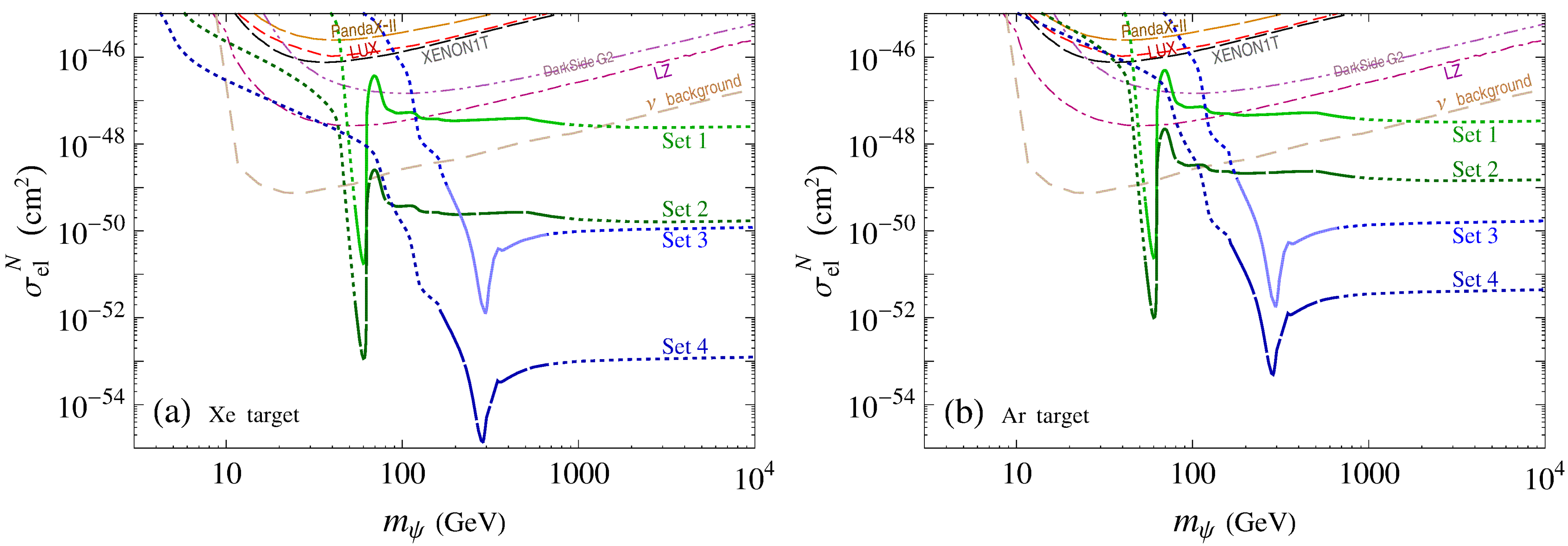
Chang, He, JT, 2017



THDM II plus spin-1/2 DM

Chang, He, JT, 2017





Conclusions

- Minimal Higgs-portal scalar and vector DM models, with only one Higgs doublet, may be ruled out in the not-too-distant future if the DM mass is below several tens TeV.
- In contrast, minimal Higgs-portal spin-1/2 (& spin-3/2) DM models are almost excluded now and will likely be fully excluded in the near future.
- However, if these Higgs-portal DM models each have (at least) two Higgs doublets instead, the DM-nucleon interaction may get highly suppressed (depending on the THDM type), and it may be very challenging to probe the parameter space corresponding to a DM mass exceeding ~100 GeV.

Conclusions

- Minimal Higgs-portal scalar and vector DM models, with only one Higgs doublet, may be ruled out in the not-too-distant future if the DM mass is below several tens TeV.
- In contrast, minimal Higgs-portal spin-1/2 (& spin-3/2) DM models are almost excluded now and will likely be fully excluded in the near future.
- However, if these Higgs-portal DM models each have (at least) two Higgs doublets instead, the DM-nucleon interaction may get highly suppressed (depending on the THDM type), and it may be very challenging to probe the parameter space corresponding to a DM mass exceeding ~100 GeV.
- For fermionic (spin 1/2 or 3/2) DM, if the simplest Higgs-portal model is supplemented with a pseudoscalar effective Higgs coupling, most of the DM mass range from ~58 GeV to ~2.3 TeV can be recovered and evade all the current constraints and maybe even future ones.