

# Recent direct detection and LHC data illuminating simple Higgs-portal dark-matter models

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*Based on*

XG He & JT, JHEP 12 (2016) 074 [arXiv:1609.03551]

CF Chang, XG He, JT, JHEP 04 (2017) 107 [arXiv:1702.02924]

The 13th International Workshop on the Dark Side of the Universe  
Institute for Basic Science, Daejeon, Korea

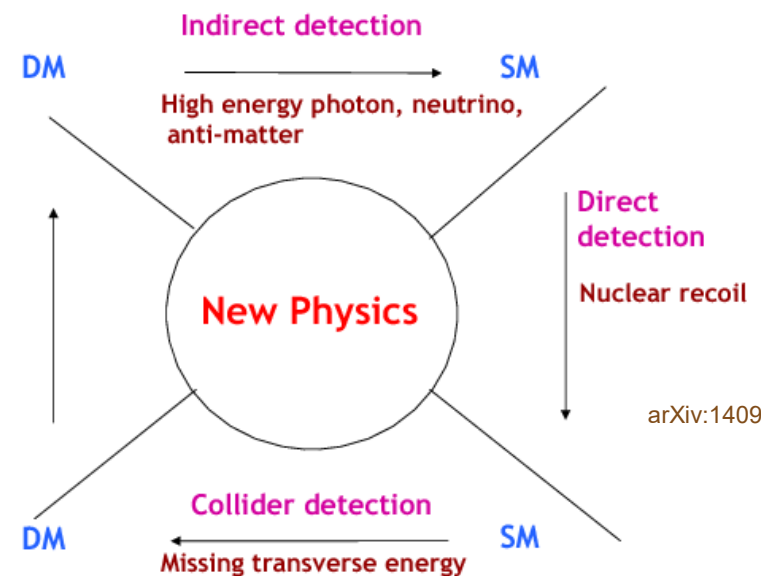
10 July 2017

## 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

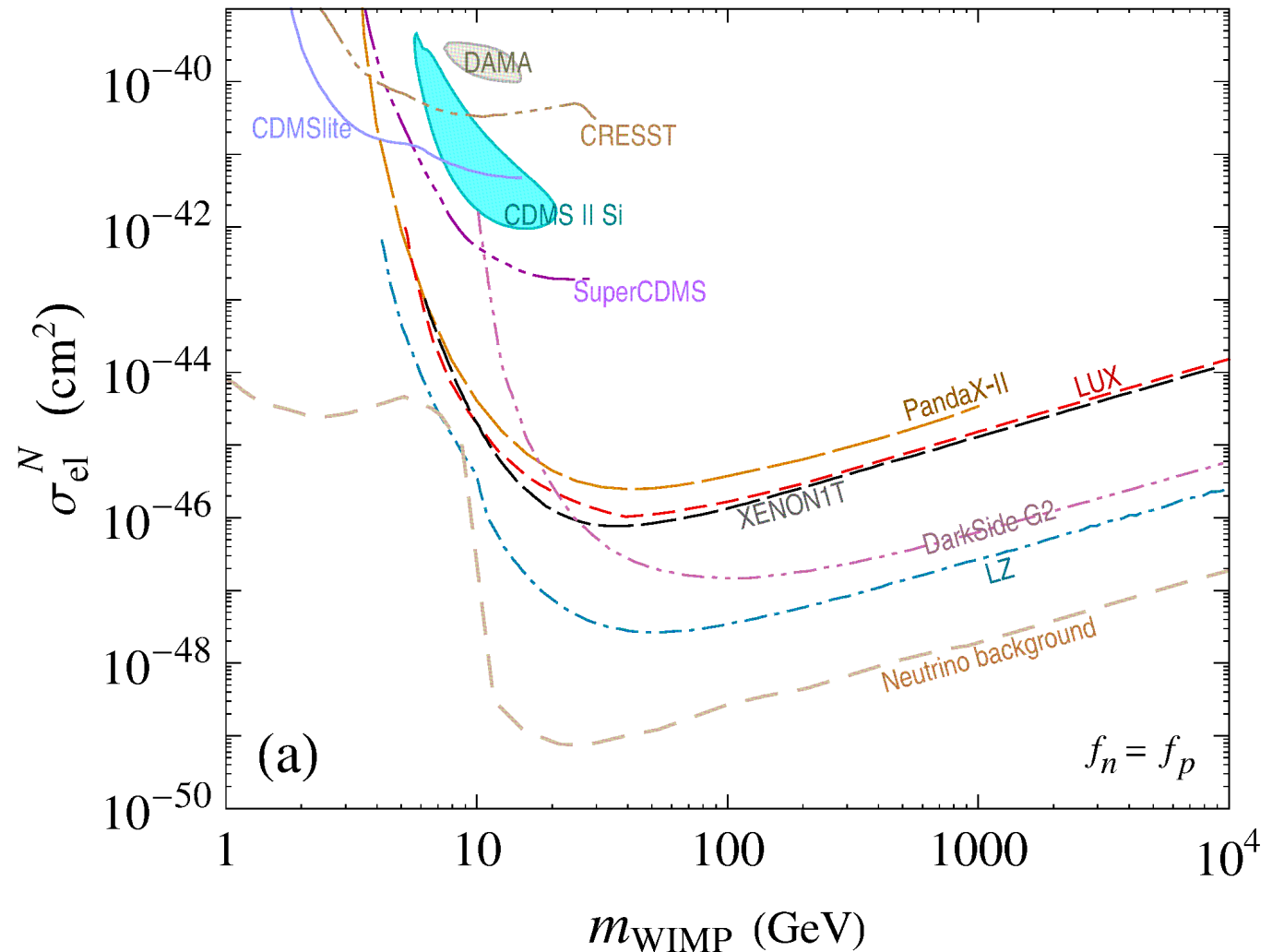
## Introduction

- 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



## DM direct detection experiments

- WIMPs may be directly detected via their interactions with nuclei.
- The plot shows the strictest 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

- Higgs' invisible decay

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

- Higgs' couplings to gauge bosons & fermions

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

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

$$\kappa_X^2 = \Gamma_{h \rightarrow X\bar{X}} / \Gamma_{h \rightarrow X\bar{X}}^{\text{SM}}$$

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

## Simplest WIMP DM model

- The simplest model having a WIMP candidate is the SM+D:
  - the standard model (SM) plus
  - a real scalar field called **darkon**,  $D$ , as the DM.
- The **darkon** is stable.
  - It's a **singlet** under the SM gauge groups.
  - Its Lagrangian is invariant under a discrete  $Z_2$  symmetry,  $D \rightarrow -D$ .
- Requiring also the **darkon** interactions be renormalizable implies  $D$  can couple only to the Higgs doublet field  $H$ .
- The renormalizable **darkon** Lagrangian is then

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

self-interaction  
coupling

mass  
parameter

darkon-Higgs  
coupling

- After electroweak symmetry breaking

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

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,  $-\lambda D^2 h v$ , is essential for determining the DM relic density in the SM+D.

## Relic density in 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 in the standard big-bang cosmology, according to

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

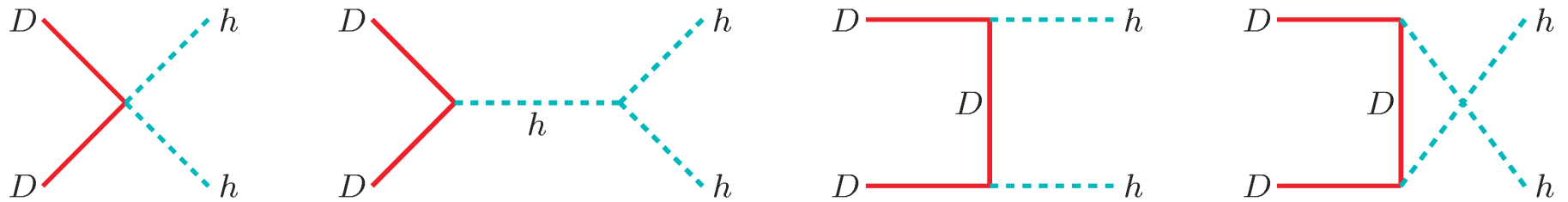
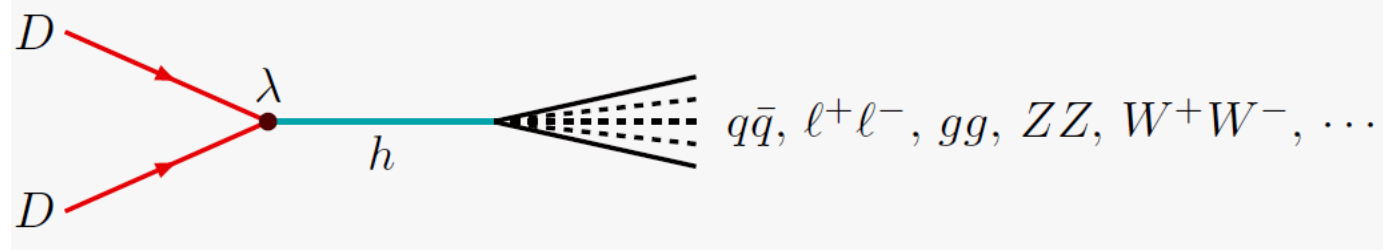
Kolb & Turner, 1990

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

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

## Darkon annihilation in SM+D

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



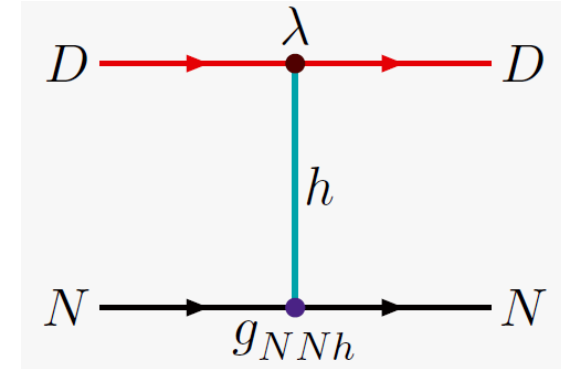
- The annihilation cross-section

$$\sigma_{\text{ann}} = \sigma(DD \rightarrow h^* \rightarrow X_{\text{SM}}) + \sigma(DD \rightarrow hh), \quad X_{\text{SM}} \neq hh$$

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

## Testing SM+D: direct detection of darkon

- 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  $DN \rightarrow DN$ .



- The amplitude for  $DN \rightarrow DN$

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

- The cross section of  $DN \rightarrow DN$

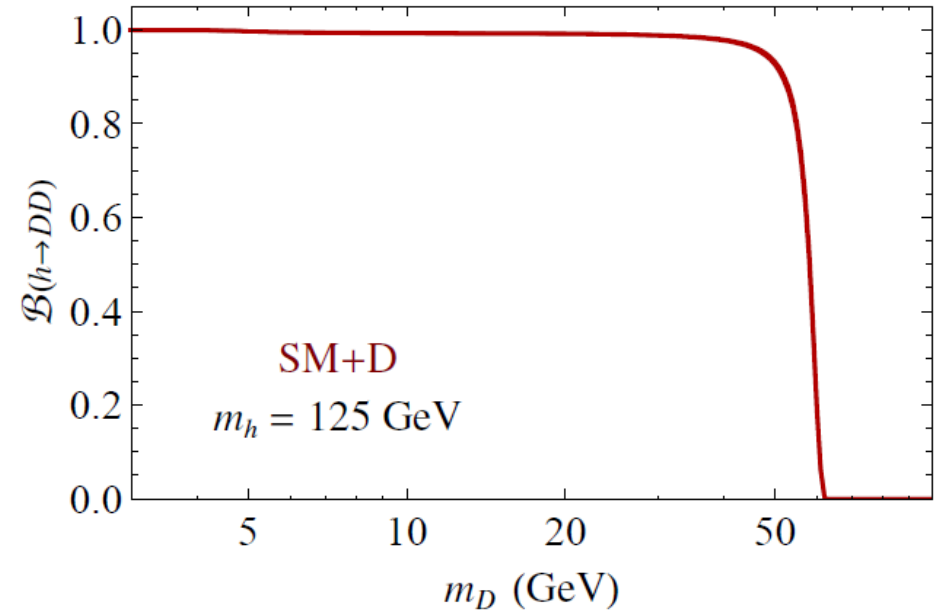
$$\sigma_{\text{el}}^N = \frac{\lambda^2 g_{NNh}^2 m_N^2 v^2}{\pi (m_D + m_N)^2 m_h^4}$$

- The effective Higgs-nucleon coupling  $g_{NNh} = 0.0011$

He, Li, Li, JT, Tsai, 2008

## Testing SM+D: invisible Higgs decay data

- For a 125-GeV Higgs, the invisible decay mode is highly dominant for low darkon masses,  $m_D < m_h/2$ 
  - except near  $m_h/2$
- Thus the discovery of the 125-GeV Higgs implies that the SM+D with a light darkon (under  $\sim 50$  GeV) is ruled out.



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

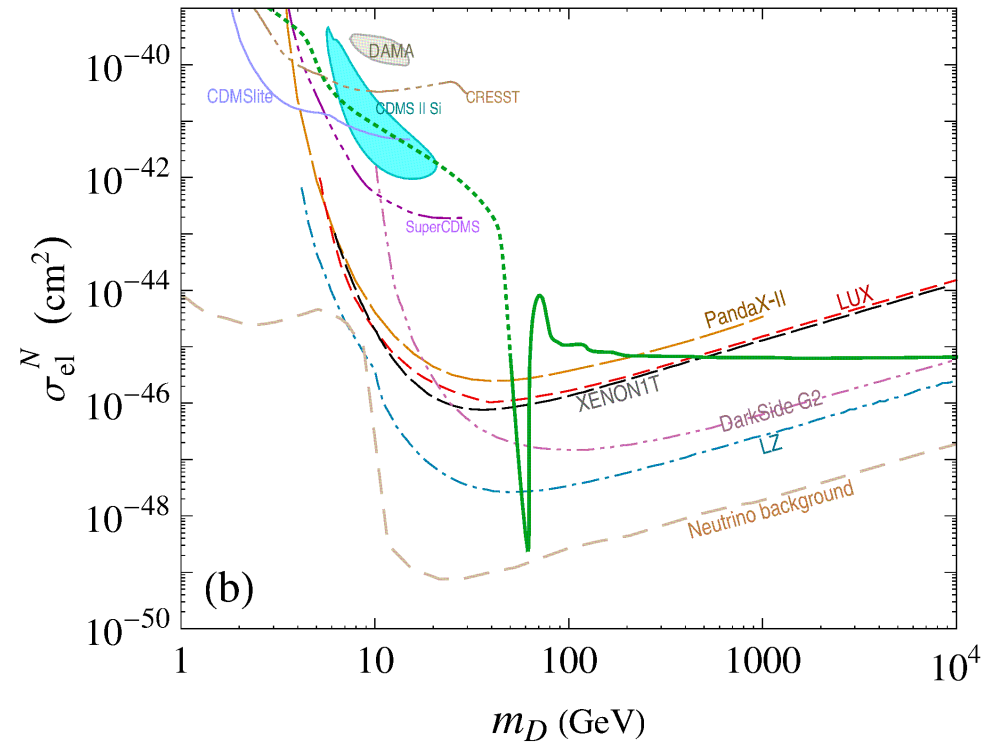
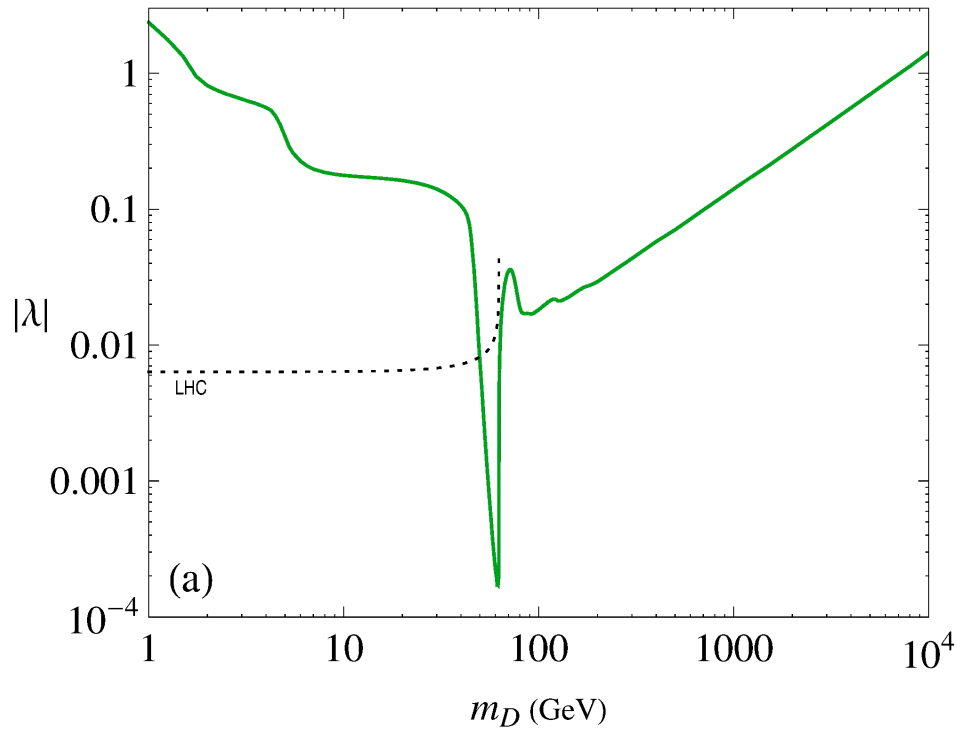
$$\Gamma(h \rightarrow DD) = \frac{\lambda^2 v^2}{8\pi m_h} \sqrt{1 - \frac{4m_D^2}{m_h^2}} \quad \text{for } 2m_D < m_h$$

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

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

ATLAS & CMS, 2016

## 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 52.1 GeV and from 62.6 GeV to  $\sim 500$  GeV.
- 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.

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

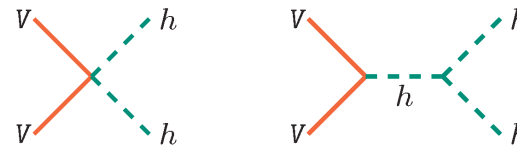
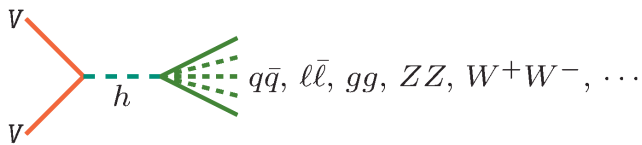
Kanemura *et al.*, 2010

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

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

- Cross section of DM annihilation

$$\sigma_{\text{ann}} = \sigma(VV \rightarrow h^* \rightarrow X_{\text{SM}}) + \sigma(VV \rightarrow hh), \quad X_{\text{SM}} \neq hh$$



$$\sigma(VV \rightarrow h^* \rightarrow X_{\text{SM}}) = \frac{\lambda_h^2 (\beta_V^2 s^2 + 12m_V^4) v^2 \sum_i \Gamma(\tilde{h} \rightarrow X_{i,\text{SM}})}{9\beta_V m_V^4 \sqrt{s} [(m_h^2 - s)^2 + \Gamma_h^2 m_h^2]}, \quad \beta_X = \sqrt{1 - \frac{4m_X^2}{s}}$$

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

## Constraints from Higgs data, DM direct searches, and unitarity limit

- Higgs' invisible decay rate

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

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

- Cross section of DM-nucleon scattering  $\nu N \rightarrow \nu N$

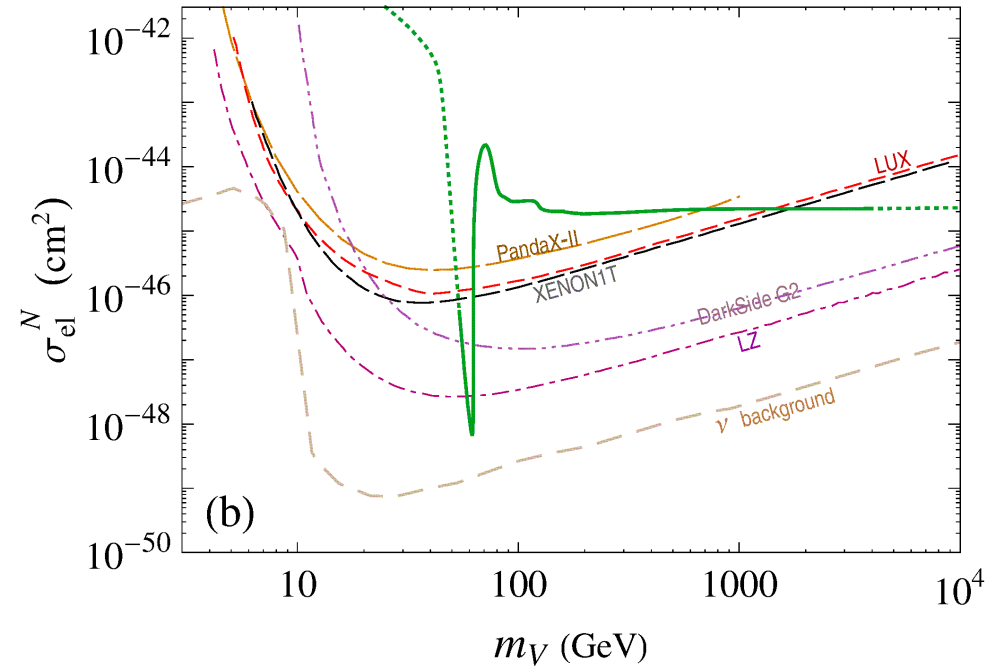
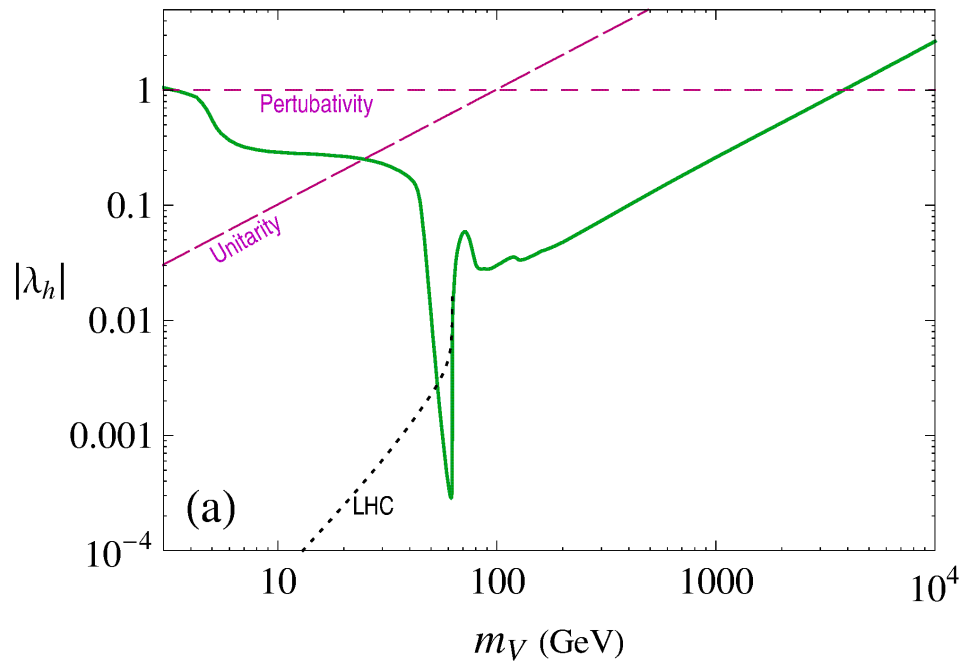
$$\sigma_{\text{el}}^N = \frac{\lambda_h^2 g_{NNh}^2 m_N^2 v^2}{\pi (m_V + m_N)^2 m_h^4}$$

- This model is actually nonrenormalizable and violates unitarity, implying that

unitarity conditions need to be applied and consequently  $\lambda_h < \frac{\sqrt{2\pi} m_V}{v}$

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:  $m_V \lesssim 54 \text{ GeV}$  and  $62.6 \text{ GeV} \lesssim m_V \lesssim 1.7 \text{ TeV}$

## Simplest Higgs-portal spin-1/2 DM model

- The WIMP DM candidate is a Dirac SM-singlet spin-1/2 fermion,  $\psi$ 
  - It's odd under a  $Z_2$  symmetry which does not affect SM particles.
- The leading-order **minimal** interaction of  $\psi$  with SM particles is via an effective dimension-5 scalar operator involving the Higgs doublet.

$$\mathcal{L}_\psi = \bar{\psi} i \not{\partial} \psi - \mu_\psi \bar{\psi} \psi - \frac{\bar{\psi} \psi H^\dagger H}{\Lambda_\psi}, \quad H^\dagger H = \frac{1}{2}(h + v)^2$$

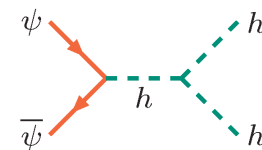
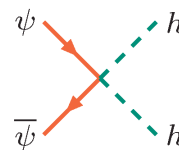
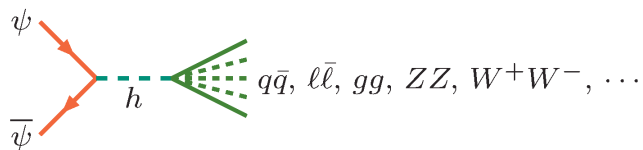
Kim & Lee, 2007

$\mu_\psi$  and  $\Lambda_\psi$  are real constants, and  $\Lambda_\psi$  represents the underlying heavy physics.

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

- Cross section of DM annihilation

$$\sigma_{\text{ann}} = \sigma(\bar{\psi} \psi \rightarrow h^* \rightarrow X_{\text{SM}}) + \sigma(\bar{\psi} \psi \rightarrow hh), \quad X_{\text{SM}} \neq hh$$



$$\sigma(\bar{\psi} \psi \rightarrow h^* \rightarrow X_{\text{SM}}) = \frac{\beta_\psi \lambda_{\psi h}^2 \sqrt{s} \sum_i \Gamma(\tilde{h} \rightarrow X_{i,\text{SM}})}{2[(m_h^2 - s)^2 + \Gamma_h^2 m_h^2]}, \quad \beta_x = \sqrt{1 - \frac{4m_x^2}{s}}$$

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

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

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

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

- Cross section of DM-nucleon scattering  $\psi N \rightarrow \psi N$

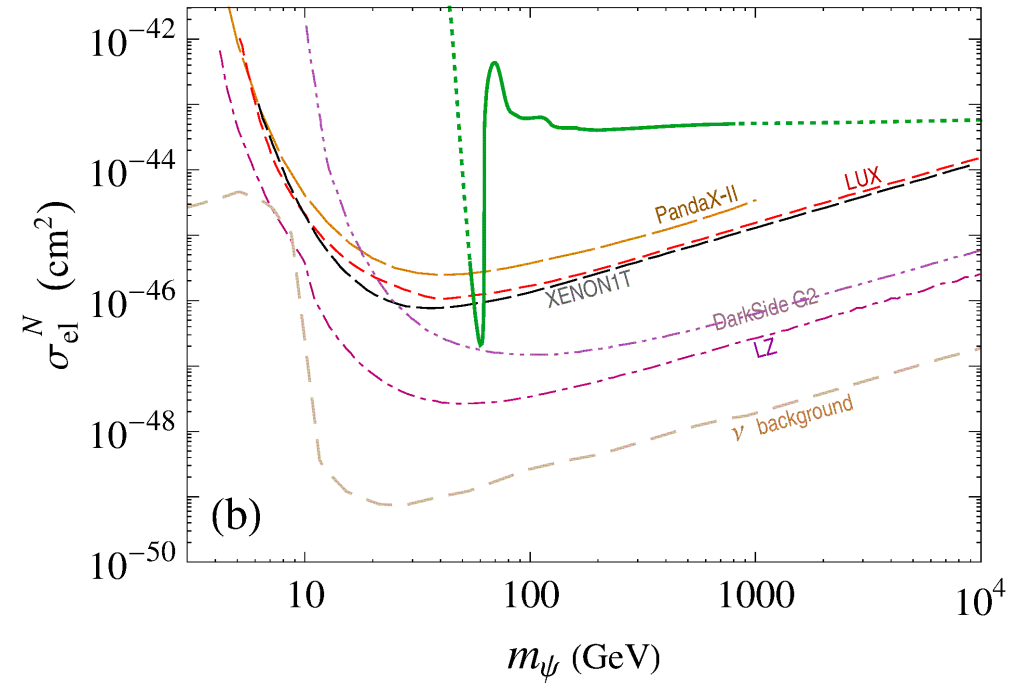
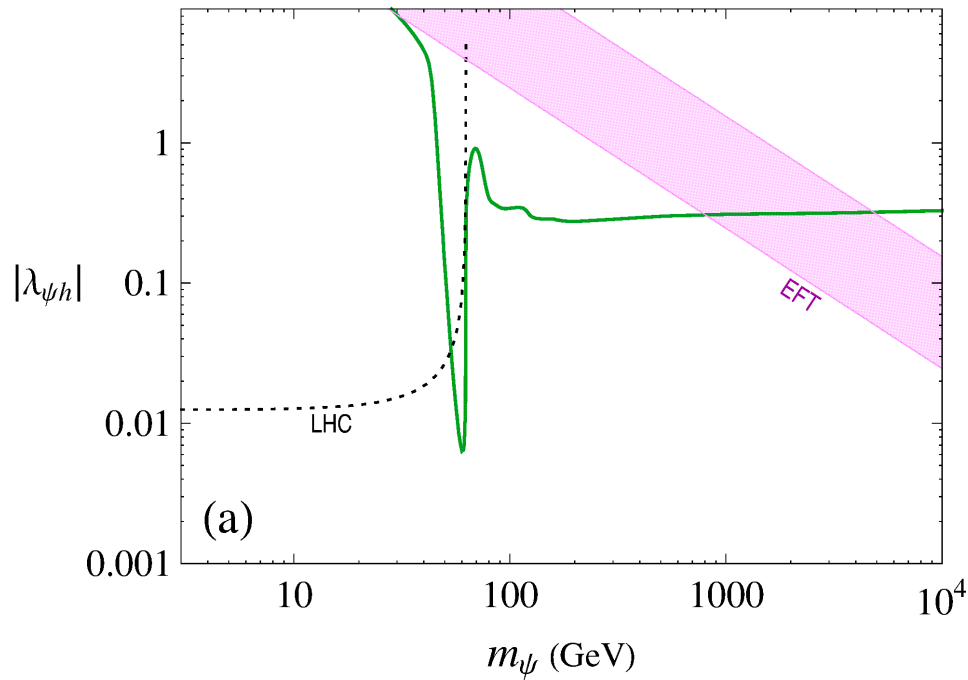
$$\sigma_{\text{el}}^N = \frac{\lambda_{\psi h}^2 g_{NNh}^2 m_\psi^2 m_N^2}{\pi (m_\psi + m_N)^2 m_h^4}$$

- The effective field theory (EFT) description of the  $\psi$ -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



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

- The Yukawa Lagrangian is

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

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

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

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

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

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

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

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

## Darkon's scalar interactions in THDM II+D

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

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

$$\mathcal{V}_H = m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - (m_{12}^2 H_1^\dagger H_2 + \text{H.c.}) + \frac{\lambda_1}{2} (H_1^\dagger H_1)^2 + \frac{\lambda_2}{2} (H_2^\dagger H_2)^2 \\ + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 + \frac{\lambda_5}{2} [(H_1^\dagger H_2)^2 + \text{H.c.}]$$

- 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  $D \rightarrow -D$ , whereas all the other fields are  $Z'_2$  even

• The scalar potential

$$\begin{aligned}
 \mathcal{V} &= \mathcal{V}_D + \mathcal{V}_H \\
 &\supset \frac{1}{2} m_D^2 D^2 + (\lambda_h h + \lambda_H H) D^2 v \\
 &\quad + \frac{1}{2} (\lambda_{hh} h^2 + 2\lambda_{hH} hH + \lambda_{HH} H^2 + \lambda_{AA} A^2 + 2\lambda_{H^+H^-} H^+ H^-) D^2 \\
 &\quad + \left( \frac{1}{6} \lambda_{hhh} h^3 + \frac{1}{2} \lambda_{hhH} h^2 H + \frac{1}{2} \lambda_{hHH} h H^2 + \frac{1}{2} \lambda_{hAA} h A^2 + \lambda_{hH^+H^-} h H^+ H^- \right) h v \\
 &\quad + \left( \frac{1}{6} \lambda_{HHH} H^3 + \frac{1}{2} \lambda_{HAA} H^2 A + \lambda_{HH^+H^-} H^+ H^- \right) H v
 \end{aligned}$$

contains the darkon mass & couplings

$$m_D^2 = m_0^2 + (\lambda_{1D} c_\beta^2 + \lambda_{2D} s_\beta^2) v^2$$

$$\lambda_h = \lambda_{2D} c_\alpha s_\beta - \lambda_{1D} s_\alpha c_\beta, \quad \lambda_H = \lambda_{1D} c_\alpha c_\beta + \lambda_{2D} s_\alpha s_\beta$$

$$\lambda_{hh} = \lambda_{1D} s_\alpha^2 + \lambda_{2D} c_\alpha^2 = \left( \frac{c_\alpha^3}{s_\beta} - \frac{s_\alpha^3}{c_\beta} \right) \lambda_h + \frac{s_{2\alpha} c_{\beta-\alpha}}{s_{2\beta}} \lambda_H$$

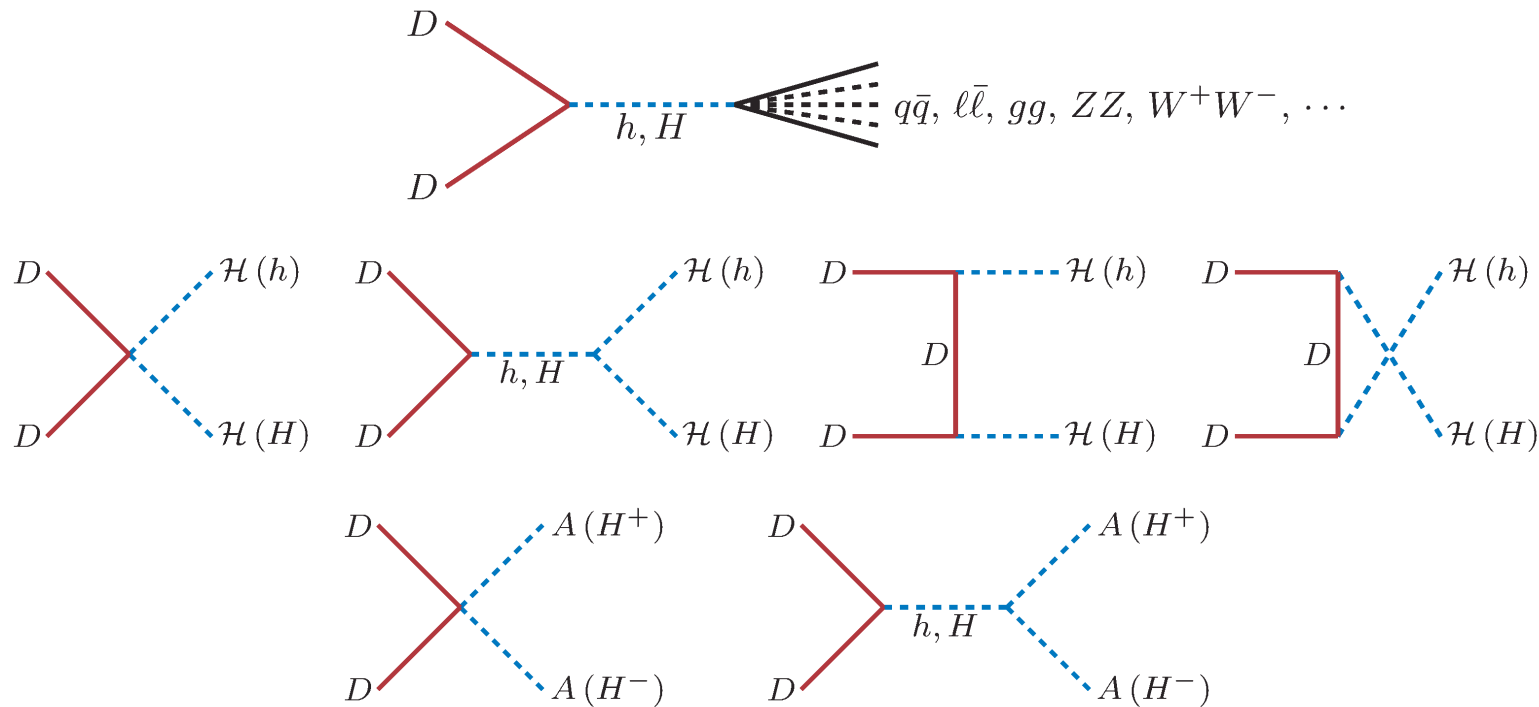
$$\lambda_{HH} = \lambda_{1D} c_\alpha^2 + \lambda_{2D} s_\alpha^2 = \left( \frac{c_\alpha^3}{c_\beta} + \frac{s_\alpha^3}{s_\beta} \right) \lambda_H - \frac{s_{2\alpha} s_{\beta-\alpha}}{s_{2\beta}} \lambda_h$$

$$\lambda_{hH} = (\lambda_{2D} - \lambda_{1D}) c_\alpha s_\alpha = \frac{s_{2\alpha}}{s_{2\beta}} (\lambda_h c_{\beta-\alpha} - \lambda_H s_{\beta-\alpha})$$

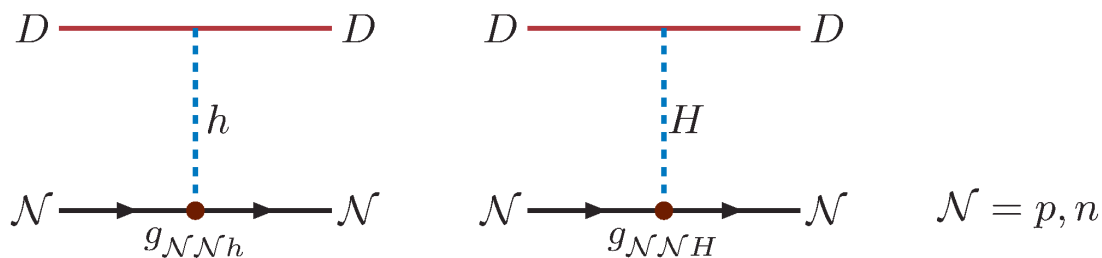
$$\lambda_{AA} = \lambda_{H^+H^-} = \lambda_{1D} s_\beta^2 + \lambda_{2D} c_\beta^2 = \frac{c_\alpha c_\beta^3 - s_\alpha s_\beta^3}{c_\beta s_\beta} \lambda_h + \frac{c_\alpha s_\beta^3 + s_\alpha c_\beta^3}{c_\beta s_\beta} \lambda_H$$

## Darkon annihilation & darkon-nucleon scattering in THDM II+D

### Darkon annihilation



### Darkon- $\mathcal{N}$ scattering



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

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

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

$$\mathcal{L}_{\mathcal{N}\mathcal{N}\mathcal{H}} = -g_{\mathcal{N}\mathcal{N}\mathcal{H}} \bar{\mathcal{N}}\mathcal{N}\mathcal{H}, \quad \mathcal{N} = p, n, \quad \mathcal{H} = h, H$$

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

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

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

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

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

- 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 ( $\sigma_{\text{el}}^p$  or  $\sigma_{\text{el}}^n$ ) rather than the darkon-nucleon one assuming isospin conservation

## Isospin-violating WIMP-nucleon interactions

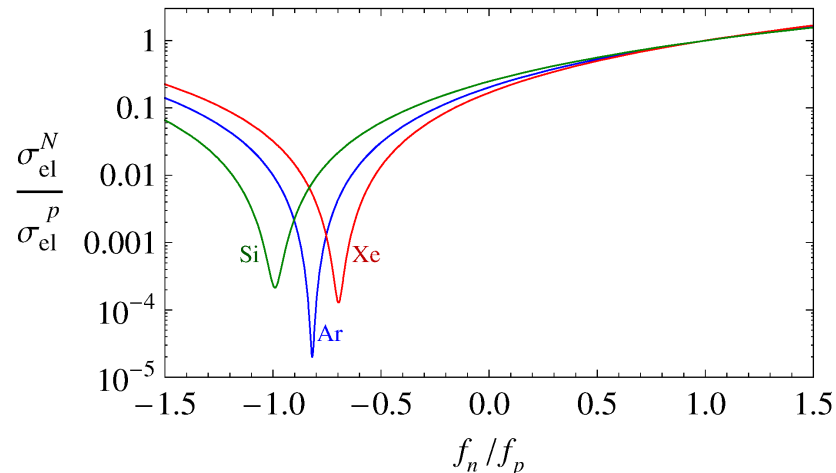
- The WIMP-nucleon cross-section in the isospin-symmetric limit can be converted to the WIMP-proton cross-section, and vice versa, using

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

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,  $A_i$  ( $\eta_i$ ) each denote the nucleon number (fractional abundance) of its isotopes,  $\mu_{A_i} = m_{A_i} m_{\text{WIMP}} / (m_{A_i} + m_{\text{WIMP}})$  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  $\sigma_{\text{el}}^N = \sigma_{\text{el}}^p$ .



In THDM II+D

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

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

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

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

He, Li, Li, JT, Tsai, 2008

$$\sigma_{\text{el}}^{\mathcal{N}} = \frac{m_{\mathcal{N}}^2 v^2}{\pi (m_D + m_{\mathcal{N}})^2} \left( \frac{\lambda_h g_{NNh}}{m_h^2} + \frac{\lambda_H g_{NNH}}{m_H^2} \right)^2$$

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

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

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

- Thus  $g_{NNh}$  and  $g_{NNH}$ , respectively, can vanish at certain values of

$$r_k^h = -\tan \alpha \tan \beta \quad \text{and} \quad r_k^H = \cot \alpha \tan \beta \quad \text{where} \quad r_k^{\mathcal{H}} = \frac{k_d^{\mathcal{H}}}{k_u^{\mathcal{H}}}$$

- The cross-section can also vanish from cancellation between the  $\lambda_h$  and  $\lambda_H$  terms.
- We choose  $h$  to be the 125-GeV Higgs and  $H$  heavier.

## LHC constraints on Yukawa couplings in THDM II

- From LHC measurements on Higgs decays

$$\kappa_X^2 = \Gamma_{h \rightarrow X\bar{X}} / \Gamma_{h \rightarrow X\bar{X}}^{\text{SM}}$$

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

$$\kappa_Z = 1.00_{-0.08}, \quad |\kappa_g| = 0.81_{-0.10}^{+0.13}, \quad |\kappa_\tau| = 0.87_{-0.11}^{+0.12} \quad \kappa_\gamma^2 = 0.07 \kappa_t^2 + 1.59 \kappa_W^2 - 0.66 \kappa_t \kappa_W$$

- 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

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

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

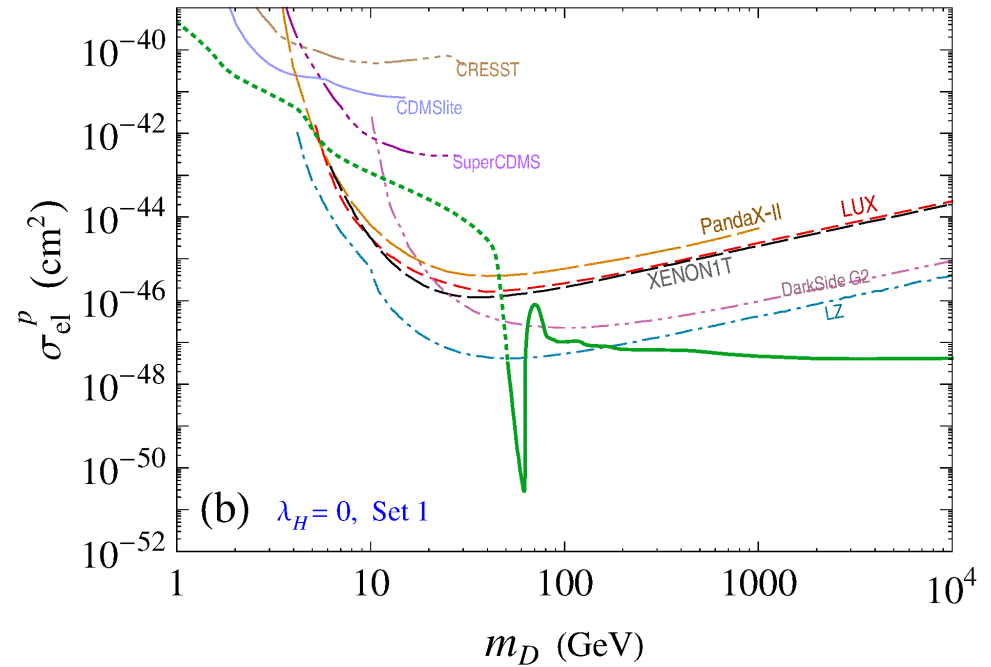
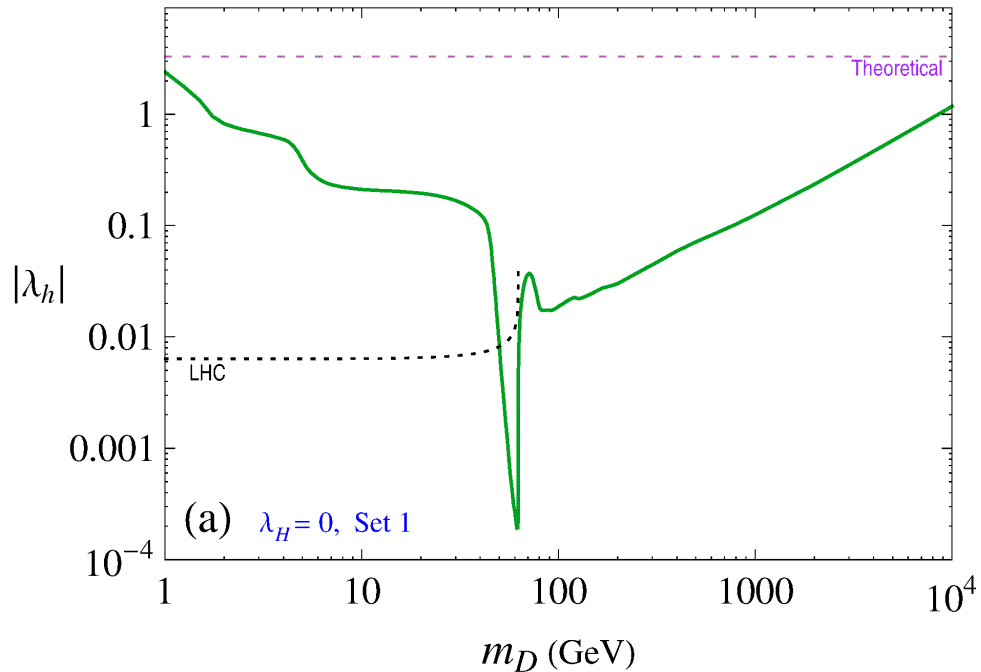
## *Additional constraints on THDM II+D*

- 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 ( $\lambda_H = 0$ ) examples

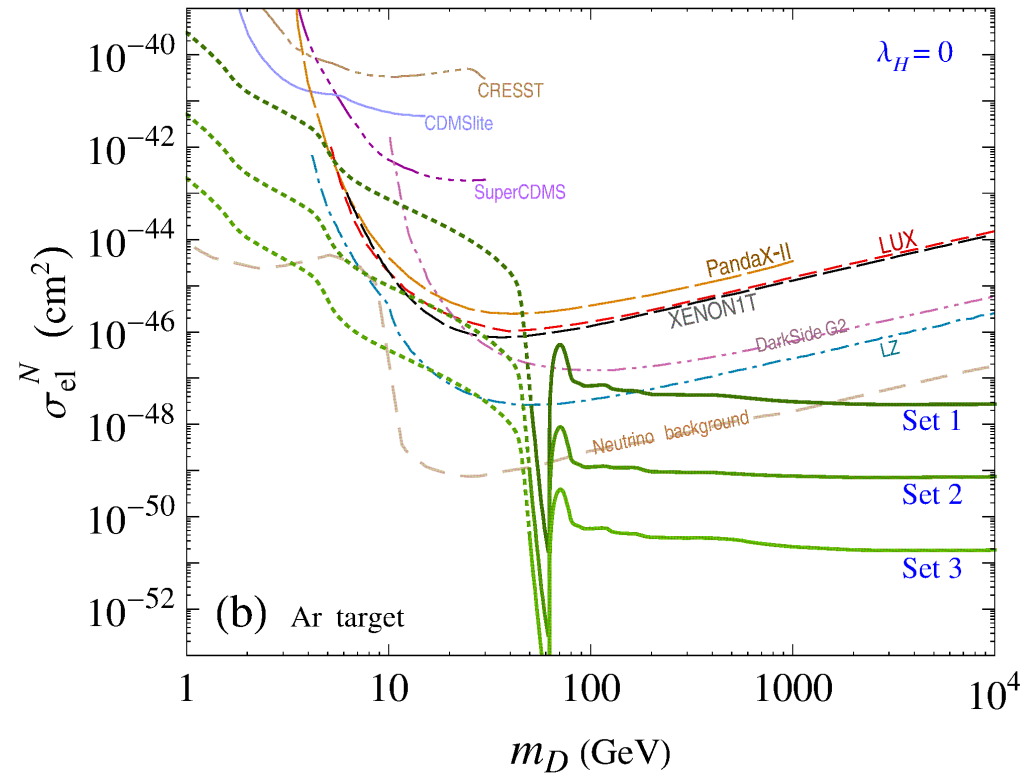
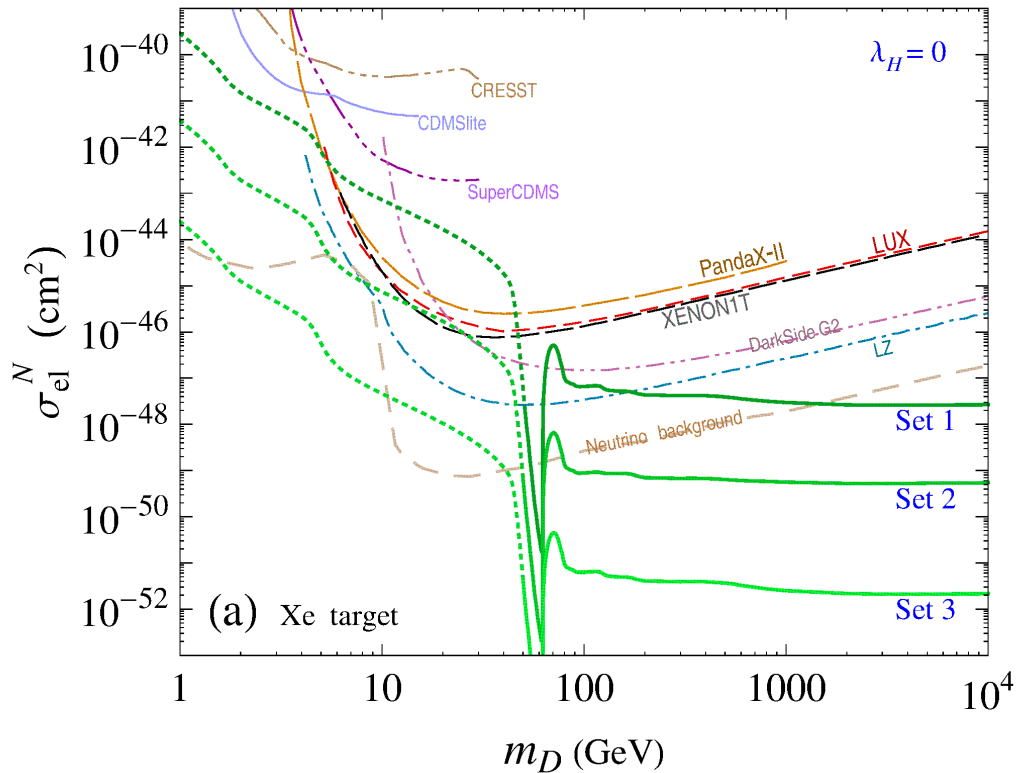
Set	$\alpha$	$\beta$	$\frac{m_H}{\text{GeV}}$	$\frac{m_A}{\text{GeV}}$	$\frac{m_{H^\pm}}{\text{GeV}}$	$\frac{m_{12}^2}{\text{GeV}^2}$	$k_V^h$	$k_u^h$	$\frac{k_d^h}{k_u^h}$	$k_V^H$	$k_u^H$	$k_d^H$	$\frac{g_{pph}}{10^{-5}}$	$\frac{f_n}{f_p}$
1	0.117	1.428	470	500	550	31000	0.966	1.003	-0.818	0.257	0.118	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  $\alpha$ ,  $\beta$ ,  $m_{H,A,H^\pm}$ , and  $m_{12}^2$  in the  $\lambda_H = 0$  scenario and the resulting values of several quantities, including  $f_n/f_p = g_{nnh}/g_{pph}$ .



## *h*-portal ( $\lambda_H = 0$ ) examples

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

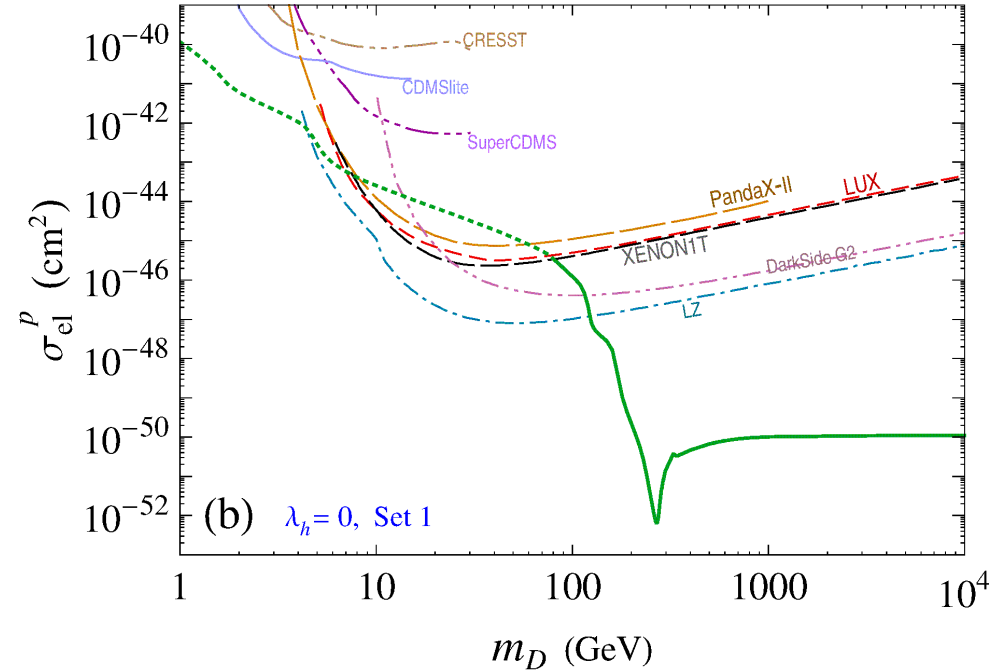
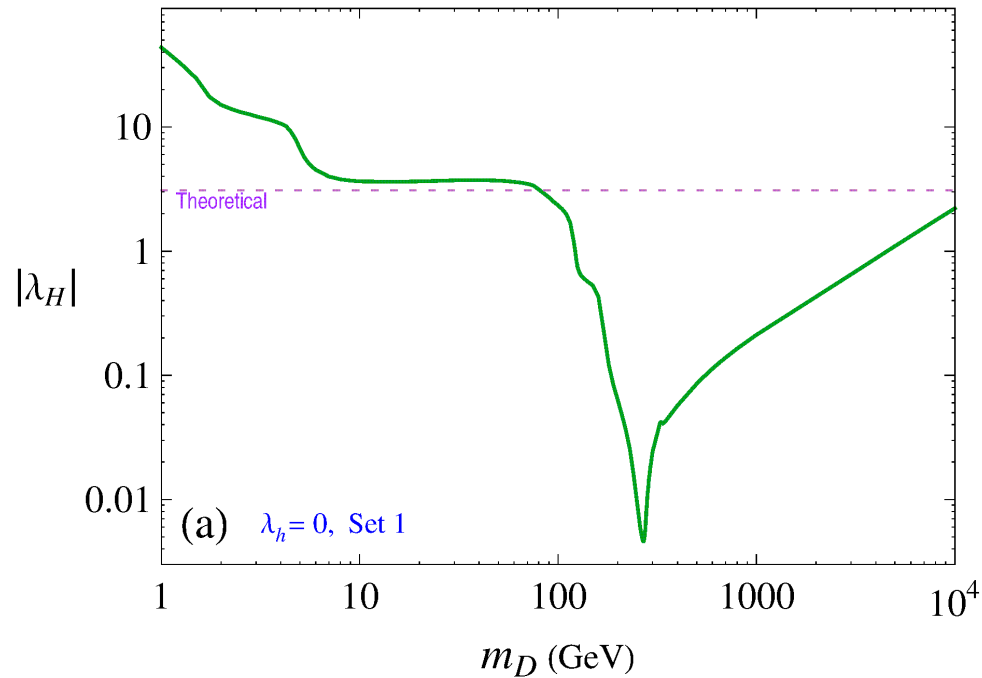


- The difference between xenon and argon targets can lead to visible effects if  $f_n/f_p$  is negative.
- There's ample parameter space that can evade present experimental constraints and perhaps even elude future direct searches.

## H-portal ( $\lambda_h = 0$ ) examples

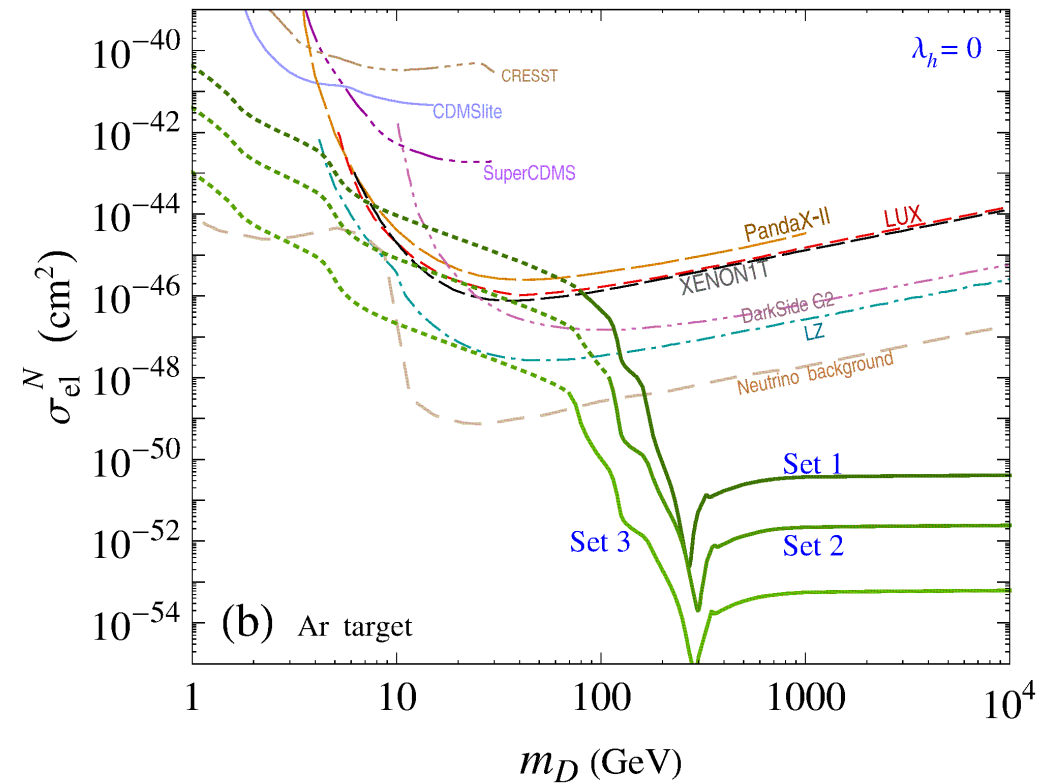
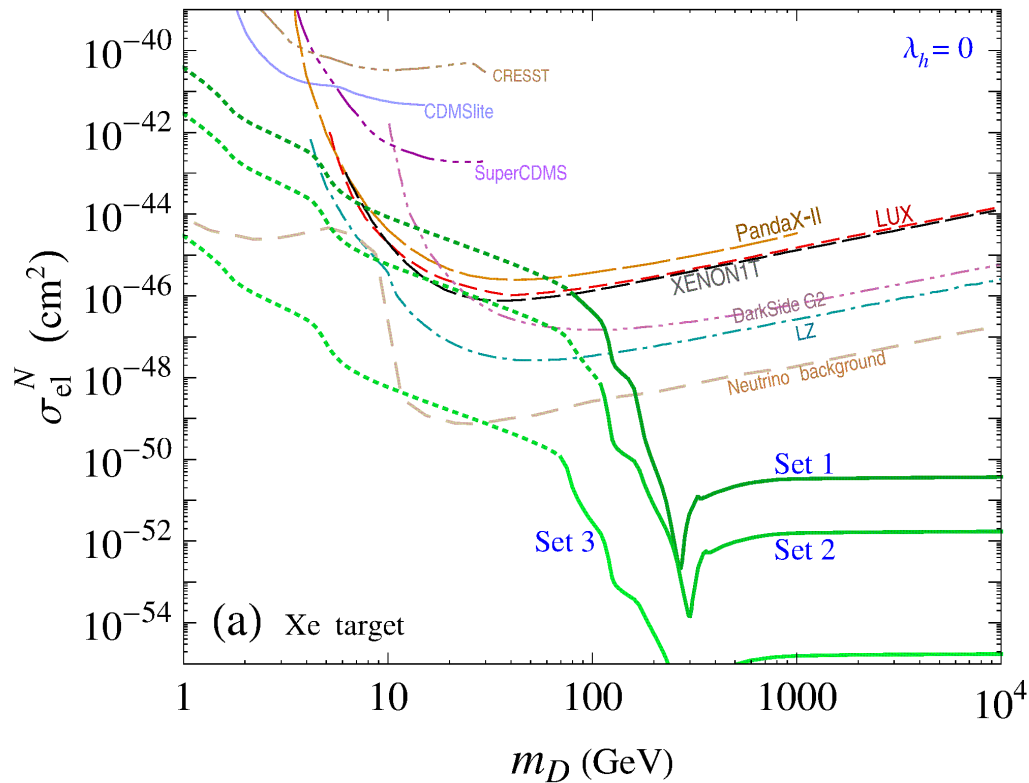
Set	$\alpha$	$\beta$	$\frac{m_H}{\text{GeV}}$	$\frac{m_A}{\text{GeV}}$	$\frac{m_{H^\pm}}{\text{GeV}}$	$\frac{m_{12}^2}{\text{GeV}^2}$	$k_V^h$	$k_u^h$	$k_d^h$	$k_V^H$	$k_u^H$	$\frac{k_d^H}{k_u^H}$	$\frac{g_{ppH}}{10^{-5}}$	$\frac{f_n}{f_p}$
1	-0.785	0.738	550	600	650	70000	0.999	1.051	0.955	0.048	-1.051	-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  $\alpha$ ,  $\beta$ ,  $m_{H,A,H^\pm}$ , and  $m_{12}^2$  in the  $\lambda_h = 0$  scenario and the resulting values of several quantities, including  $f_n/f_p = g_{nnH}/g_{ppH}$ .



## *H*-portal ( $\lambda_h = 0$ ) examples

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



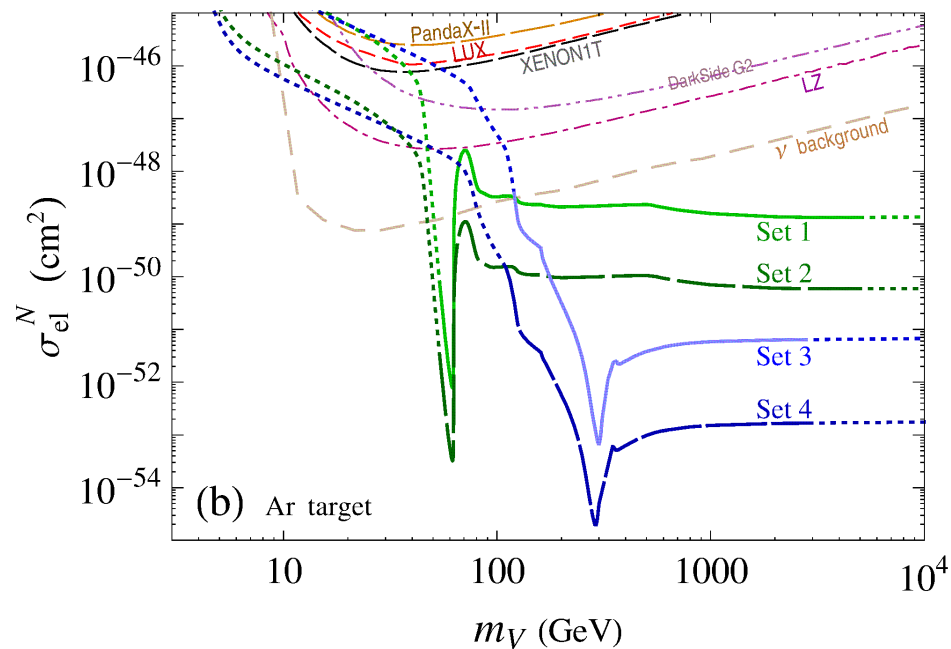
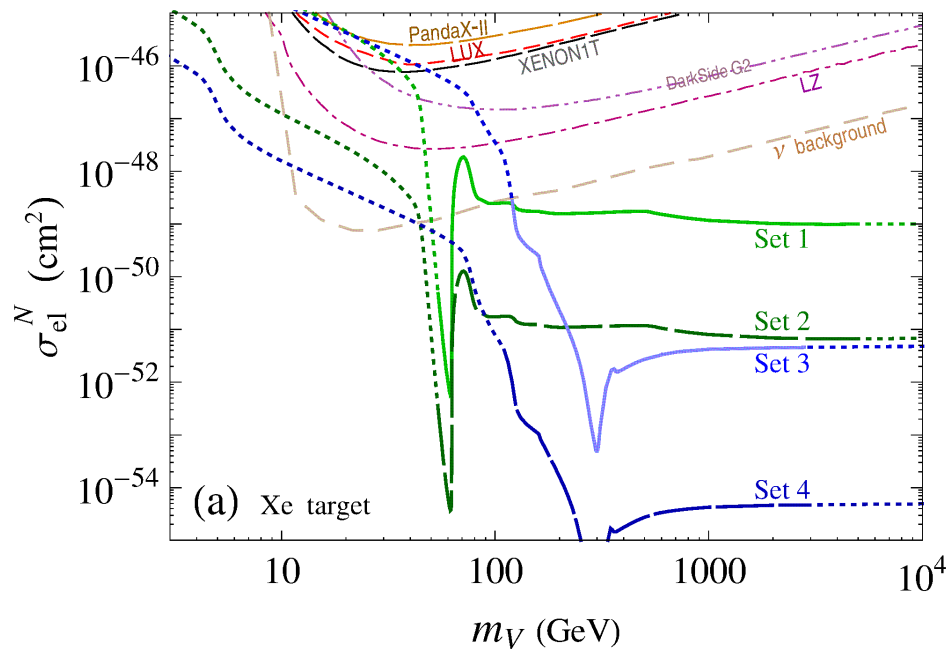
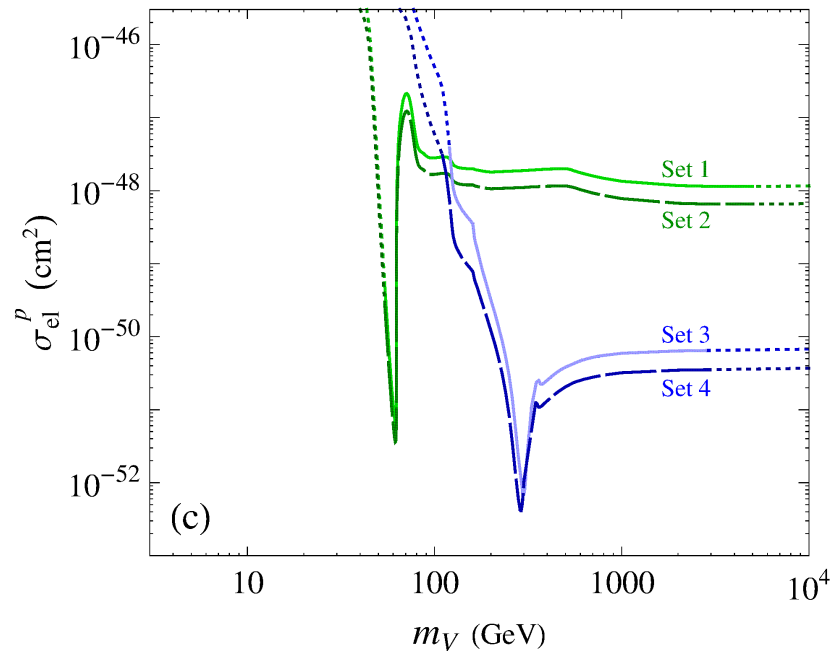
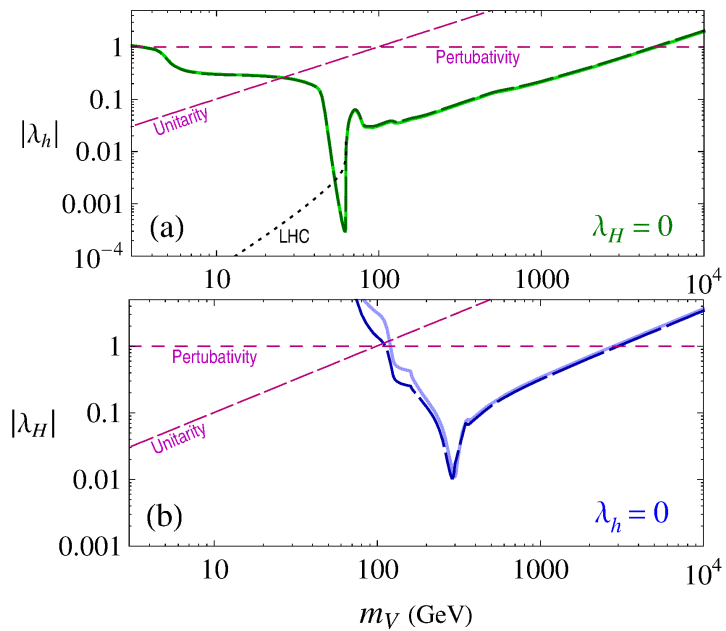
- The xenon-argon difference can again become visible if  $f_n/f_p < 0$ .
- There's more parameter space than in the *h*-portal ( $\lambda_H = 0$ ) case that can evade present experimental constraints and perhaps even elude future direct searches.

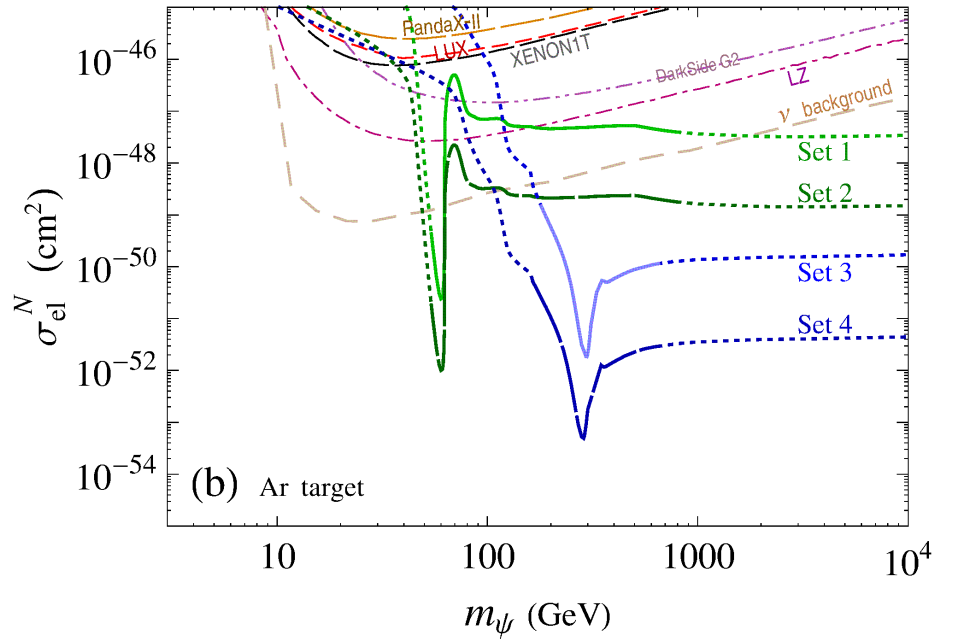
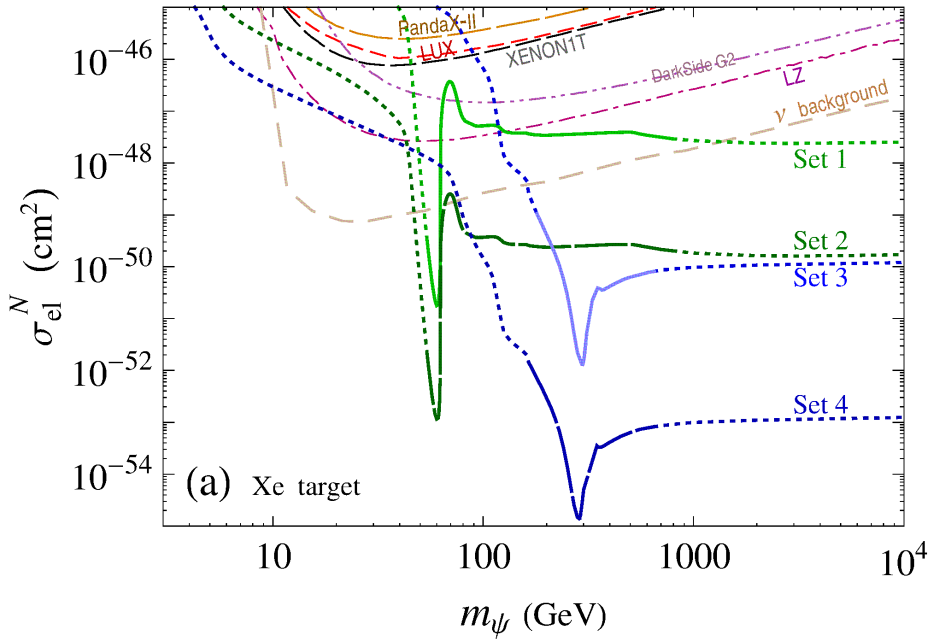
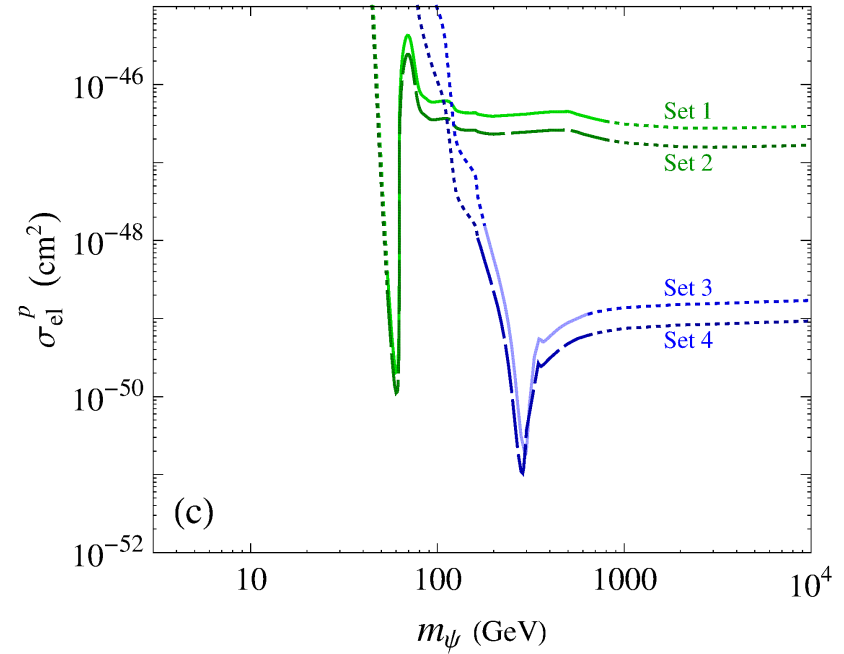
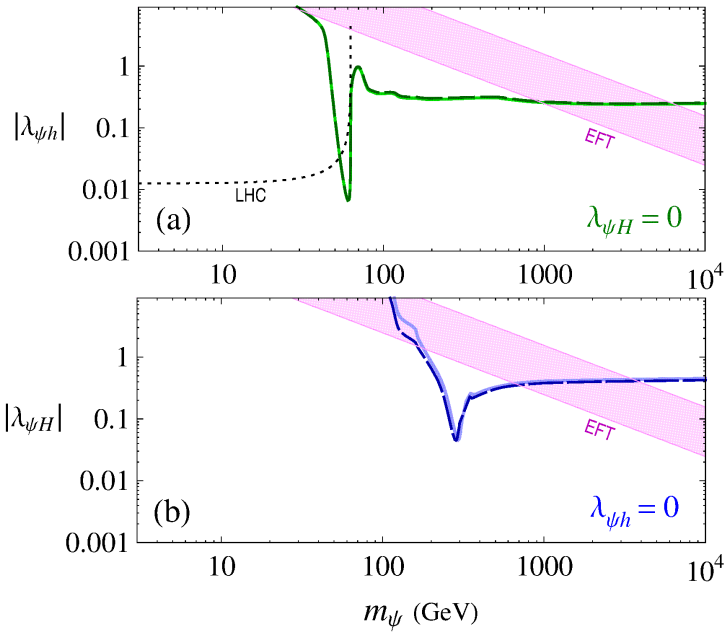
Set	$\alpha$	$\beta$	$\frac{m_H}{\text{GeV}}$	$\frac{m_A}{\text{GeV}}$	$\frac{m_{H^\pm}}{\text{GeV}}$	$\frac{m_{12}^2}{\text{GeV}^2}$	$k_V^h$	$k_u^h$	$\frac{k_d^h}{k_u^h}$	$k_V^H$	$k_u^H$	$k_d^H$	$\frac{g_{pph}}{10^{-5}}$	$\frac{f_n}{f_p}$
1	0.141	1.422	550	520	540	44000	0.958	1.001	-0.947	0.286	0.142	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  $\alpha$ ,  $\beta$ ,  $m_{H,A,H^\pm}$ , 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	$\alpha$	$\beta$	$\frac{m_H}{\text{GeV}}$	$\frac{m_A}{\text{GeV}}$	$\frac{m_{H^\pm}}{\text{GeV}}$	$\frac{m_{12}^2}{\text{GeV}^2}$	$k_V^h$	$k_u^h$	$k_d^h$	$k_V^H$	$k_u^H$	$\frac{k_d^H}{k_u^H}$	$\frac{g_{ppH}}{10^{-5}}$	$\frac{f_n}{f_p}$
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 ( $\lambda_{\psi h} = \lambda_{\Psi h} = \lambda_h = 0$ ).





## 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  $\sim 100$  GeV.