Isospin violating dark matter from double Higgs portals

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4th International Workshop on

Dark Matter, Dark Energy and Matter–Antimatter Asymmetry

暗物質、暗能量及物質-反物質不對稱

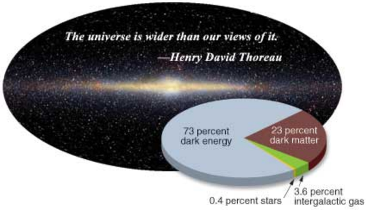
December 29–31, 2016 – Lecture Room 4A, NCTS, General 3rd Building, NTHU, Hsinchu, Taiwan

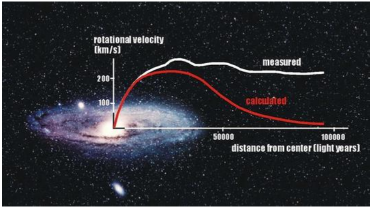
Outline

1. Motivation for IVDM
2. Mechanism of isospin-violation in the DM-nucleon scattering
   - Effective operator analysis
   - Some examples
3. Realization of IVDM from double Higgs portals
   (The discussion in this talk is mainly limited in the Higgs-portal models)
   - 2HDM+singlet model
   - DM phenomenology
   - Collider search signature
4. Conclusions

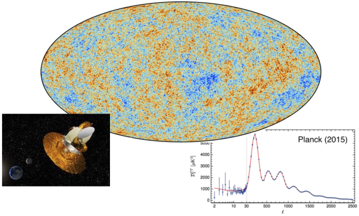
Based on JHEP **1411** (2014) 105; JCAP **1610** (2016) 040 with A. Drozd, B. Grzadkowski and J. F. Gunion.

The existence of DM at astrophysical and cosmological scales is well established.

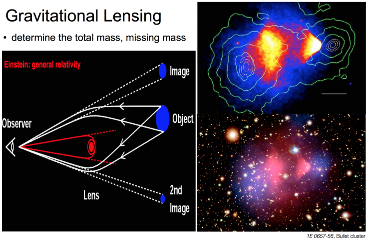




Galaxy rotation



CMB anisotropy



NO candidate for dark matter in the SM of particle physics.

Basics on dark matter

The identity of DM is still unknown including mass, spin (if it is a particle?) and we can classify

- HotDM: $\sim 10\,\mathrm{eV}$ neutrinos

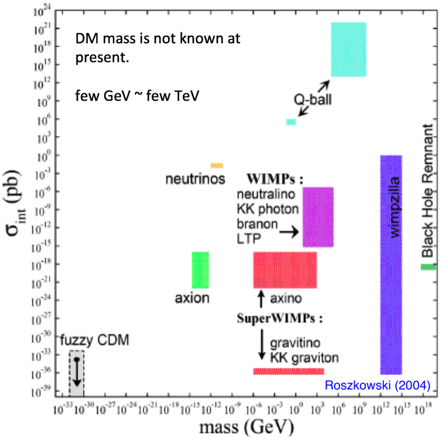
$$\Omega h^2 \approx \frac{m_\nu}{91.5\,\mathrm{eV}}$$

  kinetic temperature relatively high $\rightarrow$ fails to form galaxies at an early epoch

- WarmDM:
  1. $\sim 0.1\,\mathrm{keV}$ sterile neutrinos
  2. $\sim\ \mathrm{GeV}$ gravitinos

  density fluctuations damped out due to the large free streaming.

- CoolDM: $\sim 0.1 - 1\,\mathrm{keV}$ sterile neutrinos
- ColdDM: Axions, WIMPs
  - too big to fail problem
  - cuspy halo problem
  - missing satellites problem

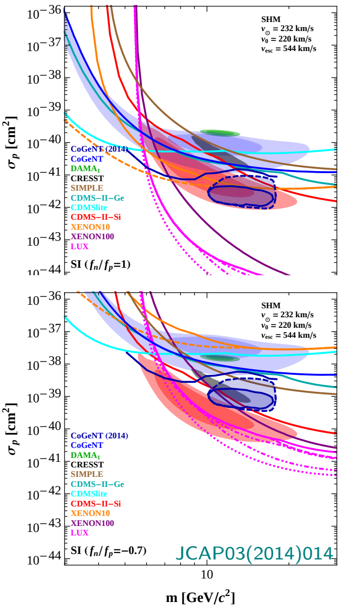


Motivation for IVDM from the direct detection

Experimental results are typically translated into the event rate (or limit) for the spin-independent cross section for DM scattering off a nucleon $\sigma^{\rm SI}_{{\rm DM}-N}$ as a function of DM mass.

$$\frac{dR}{dE_R} = N_T \frac{\rho_0}{m_\chi} \int_{v_{\rm min}}^{+\infty} d^3v\, v \frac{d\sigma}{dE_R} \frac{f(v, v_e)}{v}$$

$$\boxed{\frac{d\sigma}{dE_R} = \frac{m_A \sigma_{0,A}}{2\mu_A} F^2(E_R)}$$



Standard assumptions:

1. "Standard Halo Model"
2. Short range interaction
3. Equal couplings to protons and neutrons
4. Elastic scattering

Relaxing the cond. #3, the tension between the null result of the LUX (2013)/SuperCDMS and the (tentative) positive signal regions favored by CDMS II and CoGeNT could be alleviated.

By definition, dark matter differently coupling to protons, f_p and to neutrons f_n.

$$\sigma^{Z}_{\mathrm{DM}-N} = \sigma_{\mathrm{DM}-p}\Theta_X(f_n/f_p)$$

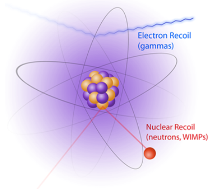
σ_p: DM-proton cross section
σ^Z_N: DM-nucleon cross section assuming $f_n/f_p = 1$

where the rescaling factor Θ_X is defined as

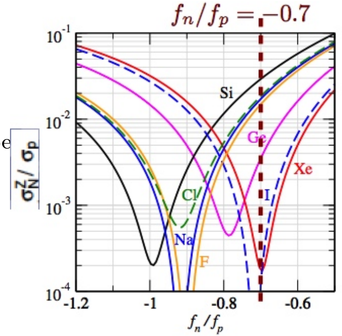
$$\Theta_X(f_n/f_p) \equiv \begin{cases} \left[\frac{Z}{A} + \frac{f_n}{f_p}\left(1-\frac{Z}{A}\right)\right]^2, & \text{single isotope} \\ \frac{\sum_I \eta_I \mu^2_{A_I}[Z+f_n/f_p(A_I-Z)]^2}{\sum_I \eta_I \mu^2_{A_I} A_I^2}, & \text{multiple isotope} \end{cases}$$

η: relative abundance of an isotope
μ_A: reduced nucleon-DM mass

Note that for $f_n/f_p = 1$, then $\Theta_X(f_n/f_p) = 1$.



Nucleon={proton, neutron}

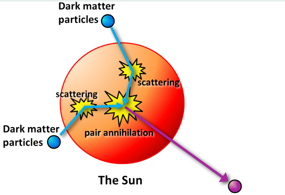


How to detect WIMP DM?

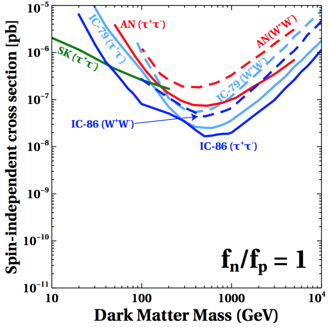
Neutrino detectors can constrain the DM spin-independent direct detection cross section by searching for the neutrinos produced by DM annihilations inside the Sun.
When the WIMP capture and annihilation processes in the Sun is in equilibrium, the neutrino signal is determined only by the annihilation final states and by the capture rate,

$$\Gamma_C = \sigma_p \, C_0(M_{DM}, f_n/f_p)$$

which is $\propto$ the direct detection cross section.



$$F_\odot = \frac{C_0(M_{DM}, f_n/f_p = 1)}{C_0(M_{DM}, f_n/f_p)}$$



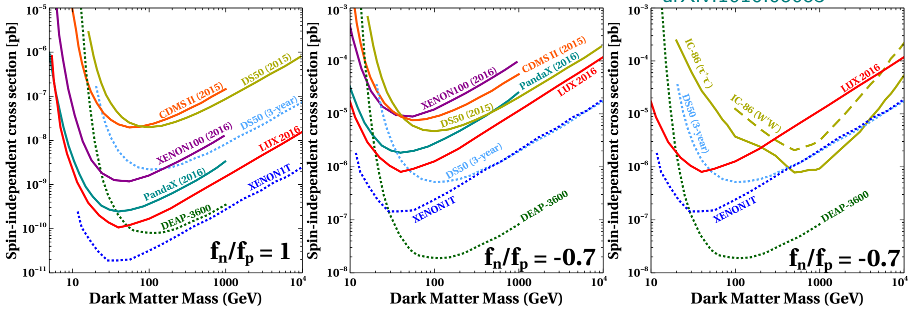
take into account the contributions from all nuclei up to ^{59}Ni

M_{DM} (GeV)	$f_n/f_p = -0.80$	-0.75	-0.70	-0.65	-0.60
10	43.5	35.9	29.4	24.1	19.9
20	65.0	49.5	38.0	29.7	23.6
30	76.2	55.6	41.5	31.7	24.8
40	82.8	58.9	43.2	32.7	25.4
50	87.1	61.0	44.2	33.2	25.7
60	90.2	62.3	44.9	33.5	25.9
70	92.4	63.3	45.3	33.8	26.0
80	94.2	64.0	45.7	33.9	26.1
90	95.6	64.6	45.9	34.1	26.2
100	96.7	65.1	46.1	34.1	26.2
200	101.8	66.9	46.9	34.5	26.3
1000	104.7	67.7	47.0	34.5	26.3
10000	105.1	67.7	47.0	34.4	26.2

arXiv:1610.08683

Impact of the IVDM on the direct detection

arXiv:1610.08683



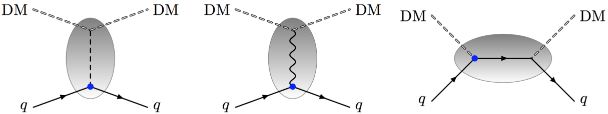
In the IVDM scenario, the interpretation of the experimental limits on the dark matter spin-independent cross section may be significantly modified.

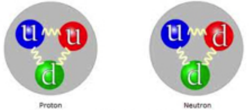
- On the one hand, the direct detection constraints are shifted depending on the target nucleus, possibly changing the hierarchy among different experiments.
- On the other hand, the relative strength between the bounds from neutrino detectors and those from direct detection experiments is altered, allowing the former to be more competitive.

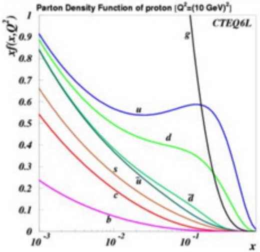
Mechanism of IV in the DM-nucleon scattering

IVDM is a generic framework that includes many dark matter candidates that interacts differently with up and down quarks *at Quark level realization.*

- Spin-0 WIMPs







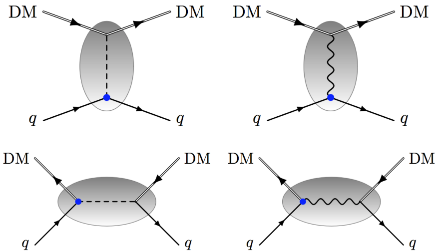
JHEP05(2014)086

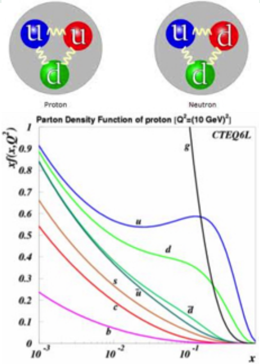
DM	operator $\mathcal{O}$	f_N
real	$\mathcal{O}^{(\mathrm{R})} \equiv \sum_{q=u,d} C_q^{(\mathrm{R})} \frac{1}{2}\phi^2 \cdot \bar{q}q$	$\sum_{q=u,d} B_q^{(N)} C_q^{(\mathrm{R})}$
complex (S)	$\mathcal{O}^{(\mathrm{Cs})} \equiv \sum_{q=u,d} C_q^{(\mathrm{Cs})} \phi^* \phi \cdot \bar{q}q$	$\sum_{q=u,d} B_q^{(N)} C_q^{(\mathrm{Cs})}$
complex (V)	$\mathcal{O}^{(\mathrm{Cv})} \equiv \sum_{q=u,d} C_q^{(\mathrm{Cv})} i(\phi^*\partial_\mu\phi - \phi\partial_\mu\phi^*)\bar{q}\gamma^\mu q$	$2m_{\mathrm{DM}} \times \begin{cases} 2C_u^{(\mathrm{Cv})} + C_d^{(\mathrm{Cv})} & (f_p) \\ C_u^{(\mathrm{Cv})} + 2C_d^{(\mathrm{Cv})} & (f_n) \end{cases}$

Mechanism of IV in the DM-nucleon scattering

Quark level realization

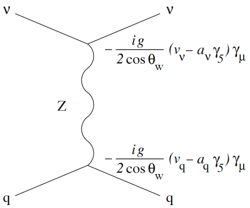
- Spin-$\frac{1}{2}$ WIMPs





DM	operator $\mathcal{O}$	f_N
Majorana	$\mathcal{O}^{(\mathrm{M})} \equiv \sum_{q=u,d} C_q^{(\mathrm{M})} \frac{1}{2}\bar{\chi}\chi \cdot \bar{q}q$	$2m_{\mathrm{DM}} \sum_{q=u,d} B_q^{(N)} C_q^{(\mathrm{M})}$
Dirac (S)	$\mathcal{O}^{(\mathrm{Ds})} \equiv \sum_{q=u,d} C_q^{(\mathrm{Ds})} \bar{\chi}\chi \cdot \bar{q}q$	$2m_{\mathrm{DM}} \sum_{q=u,d} B_q^{(N)} C_q^{(\mathrm{Ds})}$
Dirac (V)	$\mathcal{O}^{(\mathrm{Dv})} \equiv \sum_{q=u,d} C_q^{(\mathrm{Dv})} \bar{\chi}\gamma_\mu\chi \cdot \bar{q}\gamma^\mu q$	$2m_{\mathrm{DM}} \times \begin{cases} 2C_u^{(\mathrm{Dv})} + C_d^{(\mathrm{Dv})} & (f_p) \\ C_u^{(\mathrm{Dv})} + 2C_d^{(\mathrm{Dv})} & (f_n) \end{cases}$

An example of Dirac fermion DM: neutrino in the SM



f	c_V	c_A
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$	$-\frac{1}{2}$

At $q^2 \ll m_Z^2$, the Z propagator reduces to $ig^{\mu\nu}/m_Z^2$, and the four-fermion amplitude reads

$$\sqrt{2}G_F\,\bar{\nu}(v_\nu - a_\nu\gamma_5)\gamma_\mu\nu\,\bar{q}(v_q - a_q\gamma_5)\gamma^\mu q,$$

For a non-relativistic neutrino, only the time component of the vector current and the space components of the axial current survive.

- For the vector part, one obtains for protons and neutrons respectively

$$G_s^p = \frac{G_F}{\sqrt{2}}(1 - 4\sin^2\theta_W)v_\nu$$
$$G_s^n = -\frac{G_F}{\sqrt{2}}v_\nu$$

The interaction is mainly with the neutrons.

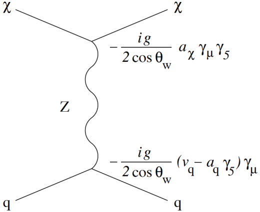
- The axial part leads to the four-fermion coupling constants

$$G_a^p = \sqrt{2}G_F a_\nu\,(a_u\Delta u + a_d\Delta d + a_s\Delta s)$$
$$G_a^n = \sqrt{2}G_F a_\nu\,(a_u\Delta d + a_d\Delta u + a_s\Delta s)$$

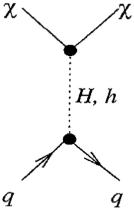
Here Δq is the fraction of the proton spin carried by quark q.

Majorana fermion DM: neutralino LSP in the SUSY

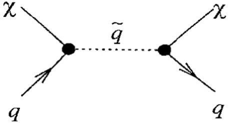
- A Majorana fermion is a spin-$\frac{1}{2}$ particle that coincides with its antiparticle.
- It has neither vector nor tensor currents.
- It has both spin-dependent and spin-independent interactions with nuclei, the former mediated by Z boson and squarks, the latter by Higgs bosons and squarks.



Z-portal



Higgs-portal



colored mediator

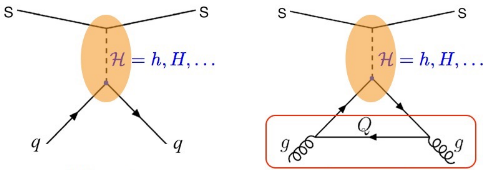
The paper JHEP 07(2015)129 investigated the following four scenarios:

- SM-like Higgs exchange (probably unlikely)
- Non SM-like (light and heavy) Higgs exchange
- SM-like Higgs and light squark exchange
- Generic Higgs and light squark exchange

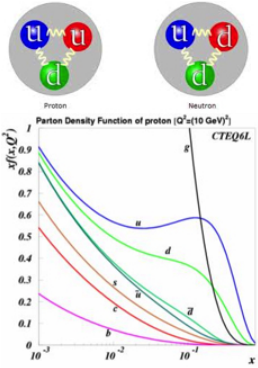
but the authors restricts the $m_{\tilde{\chi}_0^1} > 50$ GeV.

Mechanism of IV in the DM-nucleon scattering

Consider the scalar DM via Higgs-portal



light quarks   heavy quarks



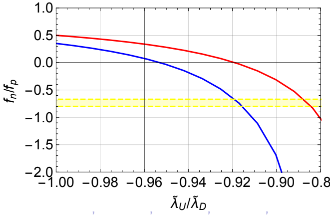
$$\frac{f_n}{f_p} = \frac{m_n}{m_p}\frac{F_u^n \tilde{\lambda}_U + F_d^n \tilde{\lambda}_D}{F_u^p \tilde{\lambda}_U + F_d^p \tilde{\lambda}_D}$$

where the combined form factors (including the QCD NLO) are

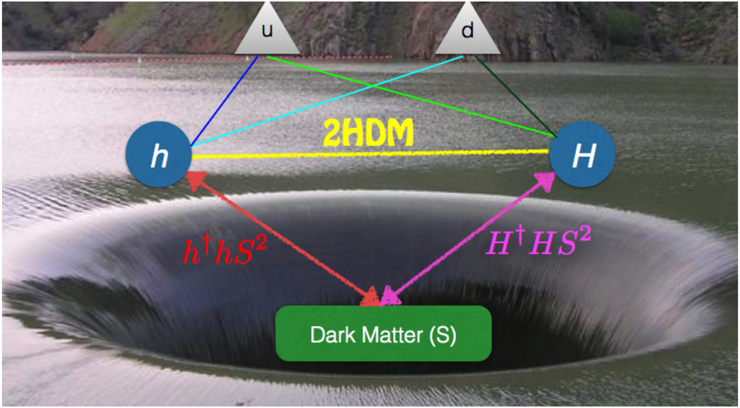
$$F_u^N = f_{Tu}^N + \sum_{q=c,t} \frac{2}{27} f_{TG}^N \left(1 + \frac{35}{36\pi}\alpha_S(m_q)\right)$$
$$F_d^N = f_{Td}^N + f_{Ts}^N + \frac{2}{27} f_{TG}^N \left(1 + \frac{35}{36\pi}\alpha_S(m_b)\right)$$

for which the nucleon form factor has the relation defined as $f_{TG}^N = 1 - \sum_{q=u,d,s} f_{Tq}^N$ and the DM-quark effective couplings

$$\tilde{\lambda}_U = \sum_{\mathcal{H}} \frac{\Lambda_{\mathcal{H}}}{m_{\mathcal{H}}^2} C_U^{\mathcal{H}}, \qquad \tilde{\lambda}_D = \sum_{\mathcal{H}} \frac{\Lambda_{\mathcal{H}}}{m_{\mathcal{H}}^2} C_D^{\mathcal{H}}$$



IVDM from two-Higgs-doublet portal



Double Higgs portals:

1. SM Higgs (at 125 GeV discovered at LHC) portal: OFF $\rightarrow$ NO invisible decay.
2. BSM Higgs portal: ON $\rightarrow$ responsible for producing thermal relics.

Type II Higgs Yukawa interaction: generate the isospin violation

2HDM+Singlet model (2HDMS)

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Adding a **real** gauge singlet scalar S to the two-Higgs-double model (2HDM)

The full potential (defined in the general basis) in the scalar sector is

$$\begin{aligned}V(\Phi_1,\Phi_2,S) = {} & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right] \\ & + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4|\Phi_1^\dagger\Phi_2|^2 \\ & + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + h.c.\right] \\ & + \frac{1}{2}m_0^2S^2 + \frac{1}{4!}\lambda_S S^4 + \kappa_1 S^2(\Phi_1^\dagger\Phi_1) + \kappa_2 S^2(\Phi_2^\dagger\Phi_2) + S^2(\kappa_3\Phi_1^\dagger\Phi_2 + h.c.)\end{aligned}$$

Symmetry: $\mathbb{Z}_2 \times \mathbb{Z}_2'$

- $\mathbb{Z}_2 : \Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$
- $\mathbb{Z}_2' : \Phi_1 \to \Phi_1, \Phi_2 \to \Phi_2, S \to -S$

S could be a dark matter candidate provide it does not acquire a VEV.

2HDM+Singlet model (2HDMS)

the S-dependent part (after the EWSB)

$$V_S = \frac{1}{2} m_S^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \lambda_h v h S^2 + \lambda_H v H S^2 + S^2(\lambda_{HH} HH + \lambda_{hH} hH + \lambda_{hh} hh + \lambda_{AA} AA + \lambda_{H^+H^-} H^+ H^-) \tag{1}$$

where

$$m_S^2 = m_0^2 + (\kappa_1 \cos^2\beta + \kappa_2 \sin^2\beta) v^2 \tag{2}$$

$$\lambda_h = -\kappa_1 \sin\alpha \cos\beta + \kappa_2 \cos\alpha \sin\beta \tag{3}$$

$$\lambda_H = \kappa_1 \cos\alpha \cos\beta + \kappa_2 \sin\alpha \sin\beta \tag{4}$$

$$\lambda_{AA} = \tfrac{1}{2}\lambda_{H^+H^-} = \tfrac{1}{2}(\kappa_1 \sin^2\beta + \kappa_2 \cos^2\beta) \tag{5}$$

$$\lambda_{hh} = \tfrac{1}{2}(\kappa_2 \cos^2\alpha + \kappa_1 \sin^2\alpha) \tag{6}$$

$$\lambda_{HH} = \tfrac{1}{2}(\kappa_1 \cos^2\alpha + \kappa_2 \sin^2\alpha) \tag{7}$$

$$\lambda_{hH} = \tfrac{1}{2}(\kappa_2 - \kappa_1) \sin 2\alpha\,. \tag{8}$$

Remarks

- NO AS^2 interaction, so A cannot be a portal in this model.
- The set of independent inputs:
  $\{m_S, \lambda_h, \lambda_H, \lambda_S\}$ + $\{m_h, m_H, m_A, m_{H\pm}, \sin(\beta-\alpha), \tan\beta, m_{12}^2\}$

Phenomenology discussion

Both h-125 and H-125 scenarios could fit very well with cosmological observation.

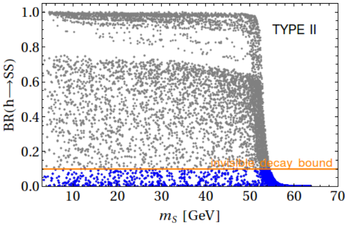
- Fully suppressed the invisible decay for the SM-like Higgs.
- Produce proper relic abundance
- Direct detection
- Indirection detection

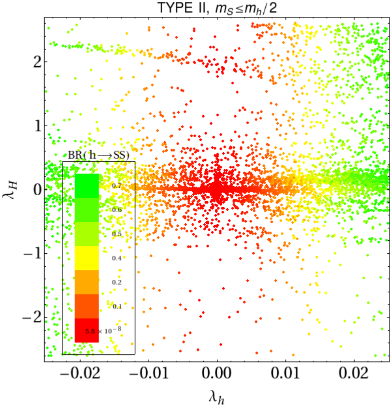
Our focus: light dark matter

$$m_S < 50\ \text{GeV}$$

The invisible decay width for the SM-like Higgs $\mathcal{H}$ is

$$\Gamma(\mathcal{H} \to SS) = \frac{1}{2\pi}\frac{4\lambda_{\mathcal{H}}^2 v^2}{m_{\mathcal{H}}}\sqrt{1 - \frac{4m_S^2}{m_{\mathcal{H}}^2}}$$





Portal coupling $\lambda_{\mathcal{H}}$ for the SM-like Higgs being constrained very small.

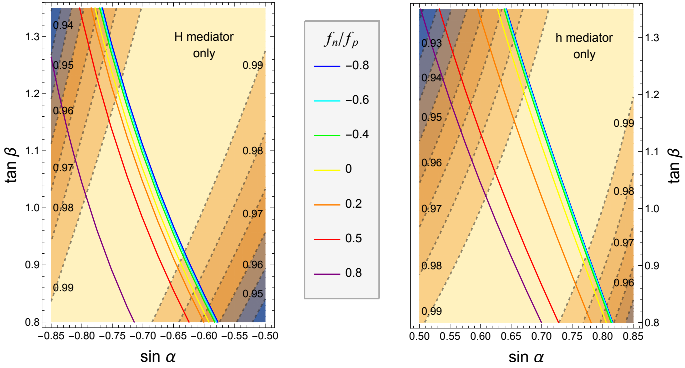
Finding a IVDM, a really challengeable job

Applying the Higgs-quark coupling pattern into the generic f_n/f_p already derived yields

Higgs	C_V	C_U	C_D
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

$$\tan\beta = -\frac{\frac{f_n}{f_p}F_u^p - \frac{m_n}{m_p}F_u^n}{\frac{f_n}{f_p}F_d^p - \frac{m_n}{m_p}F_d^n}\,\frac{w+\tan\alpha}{1-w\tan\alpha}$$

where the weight parameter is defined by $w = \frac{\Lambda_h}{\Lambda_H}\frac{m_H^2}{m_h^2}$, $(\Lambda_{h,H} = -2\lambda_{h,H})$.

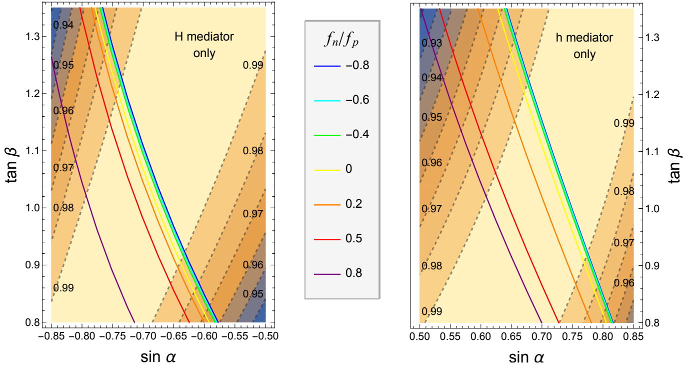


Applying the Higgs-quark coupling pattern into the generic f_n/f_p already derived yields

$$\tan\beta = -\frac{\frac{f_n}{f_p}F_u^p - \frac{m_n}{m_p}F_u^n}{\frac{f_n}{f_p}F_d^p - \frac{m_n}{m_p}F_d^n}\frac{w+\tan\alpha}{1-w\tan\alpha}$$

Higgs	C_V	C_U	C_D
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

where the weight parameter is defined by $w = \frac{\Lambda_h}{\Lambda_H}\frac{m_H^2}{m_h^2}$, $(\Lambda_{h,H} = -2\lambda_{h,H})$.



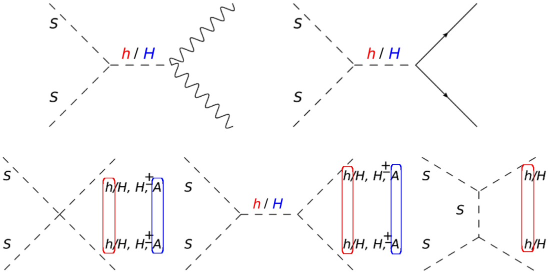
The solution ($\tan\beta \sim 1$ and $\sin\alpha \sim \mp 0.7$)

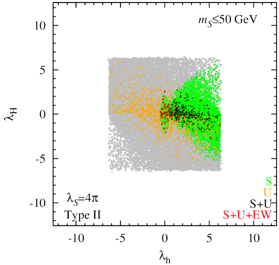
- very tuned
- induces a symmetry $\Phi_1 \to \Phi_2$.
- the mediator Higgs has quark couplings that maximally violate isospin.

Dark matter physics

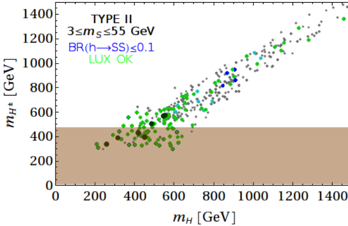
Relic abundance for Cold DM:

$$\Omega_S \simeq 1.07 \times 10^9 \frac{m_S/T_f}{\sqrt{g_*}\, M_{\rm Pl} \langle \sigma_{\rm ann} v_{\rm rel} \rangle} \; {\rm GeV}^{-1}$$





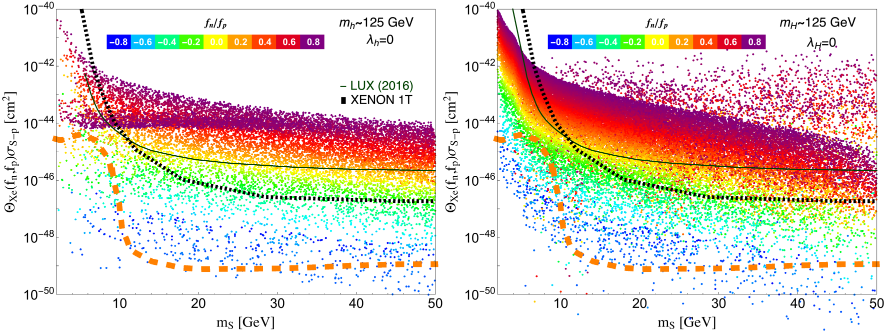
$|\lambda_H| \lesssim 2.5$ due to the model theoretical constraints. $\Longrightarrow$ m_H has an upper bound



$m_h \sim 125$ GeV scenario:

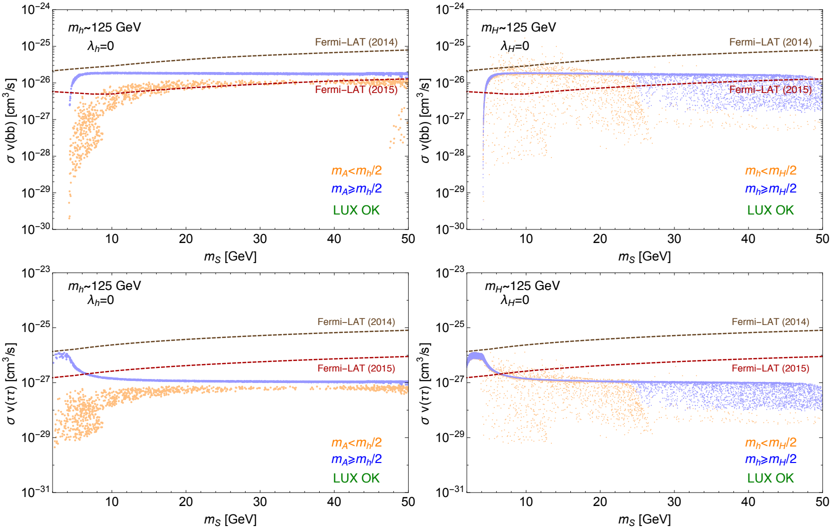
1. the ratio $\frac{\lambda_H}{m_H^2}$ is crucial.
2. A could be so light that $SS \to AA$ channel opens.

Direct detection



- After including isospin-violation, the 2HDMS could easily be consistent both with the LUX (2013) limits and also with the limits anticipated for XENON1T.
- Conversely, future improved exclusion limits or positive signals will either place an upper bound on f_n/f_p or favor a particular value of f_n/f_p.

Indirect detection



- Fermi-LAT (2015) (arXiv:1503.02641) excludes the $m_A \geq m_h/2$ solution (bb and $\tau\tau$ in combination).
- Due to the presence of the DM annihilation into the BSM mode $SS \to AA$, the $m_A < m_h/2$ solution is allowed. (To produce a proper relic density, $m_A < m_S$ for all the points in our analysis.)

Collider search signature

- Non-SM Higgs bosons *all* lie in definite mass ranges below 650 GeV.

Scenario	m_S	m_h	m_H	m_A	$m_{H^\pm}$
$h125$	$\lesssim 12$	125	$440-650$ $H \to SS, AZ, t\bar{t}$	$\lesssim 62.5$ $A \to b\bar{b}\ (\tau\tau)$	$485-630$ $H^\pm \to tb$
$H125$	$\gtrsim 4$	$10-62.5$ $h \to SS, b\bar{b}$	125	$420-650$ $A \to Zh, t\bar{t}$	$485-630$ $H^\pm \to hW^\pm, tb$
$H125$	$\gtrsim 25$	$62.5-125$	125	$420-650$	$485-630$

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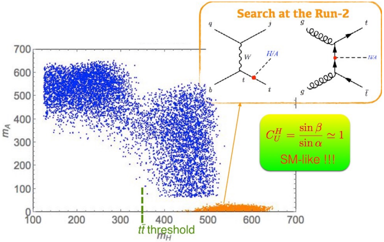

The paper arXiv:1507.07004 claims that $t\bar{t}A$ production with $A \to b\bar{b}$ will be detectable at the Run 2 for $\tan\beta = 1$ if $m_A \in [20, 100]$ GeV.

Conclusions

1. The Higgs and DM sectors may be intimately connected. If so, detecting the signs of one of sectors could shine light on still hidden elements of the other.

2. Isospin-violating effect is possible in many (but not ALL) models and dramatically changes the analysis of dark matter direct detection.

3. In this model, the non-SM-like Higgs bosons will be detectable at LHC Run 2 due to the fact that their masses and couplings are strongly restricted.

4. If DM were discovered in the future, our fine study of the IVDM scenario will determine the DM coupling strength and provide an efficient way for experiments to discover the nature of particle DM.

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