The Simplest Higgs Portal Dark Matter Model and Its Extensions

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Work with Jusak Tandean

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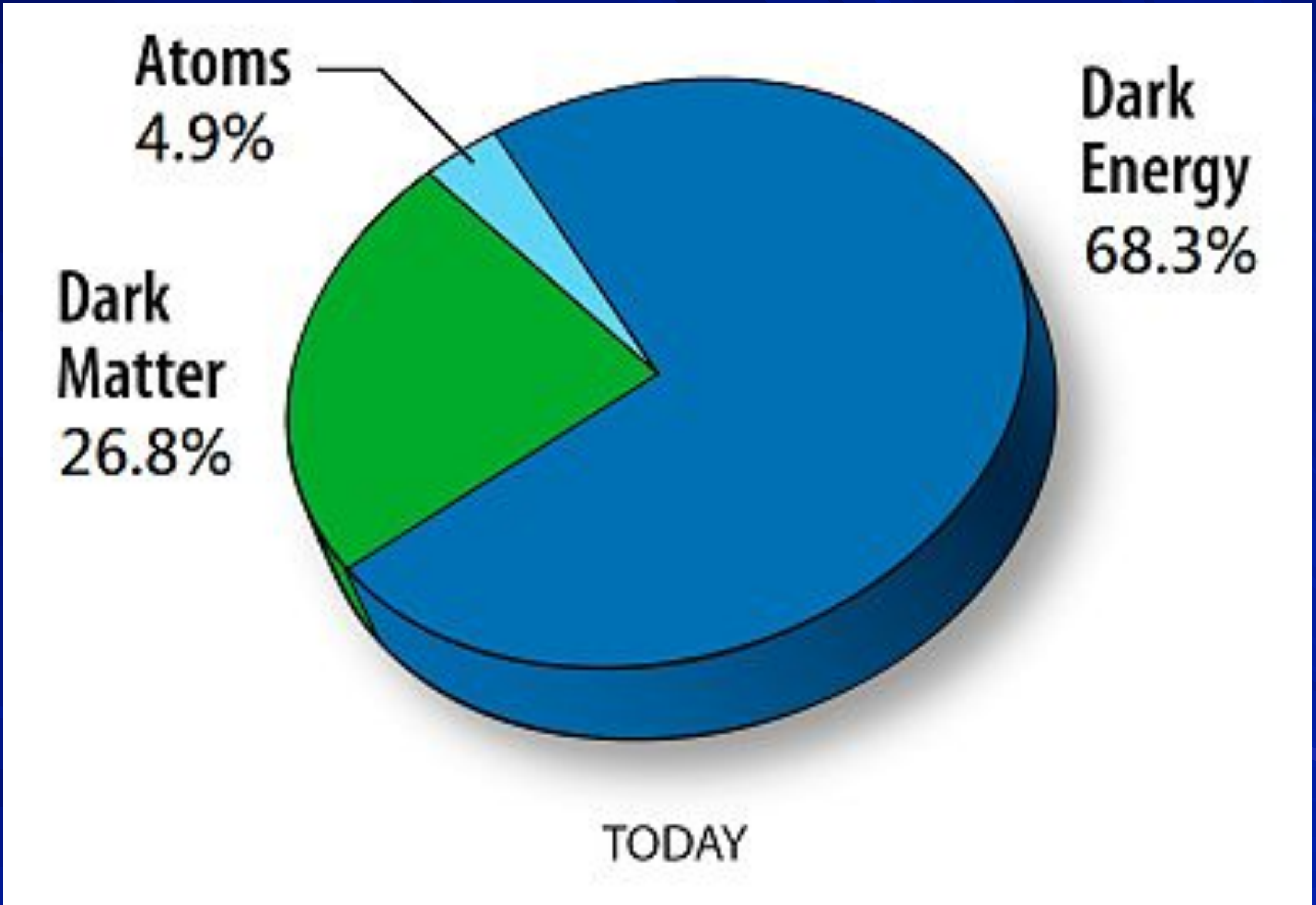
Higgs Portal Workshop

Umass, 05/01/2014


Atoms
4.9%
Dark
Energy
68.3%
Dark
Matter
26.8%
TODAY

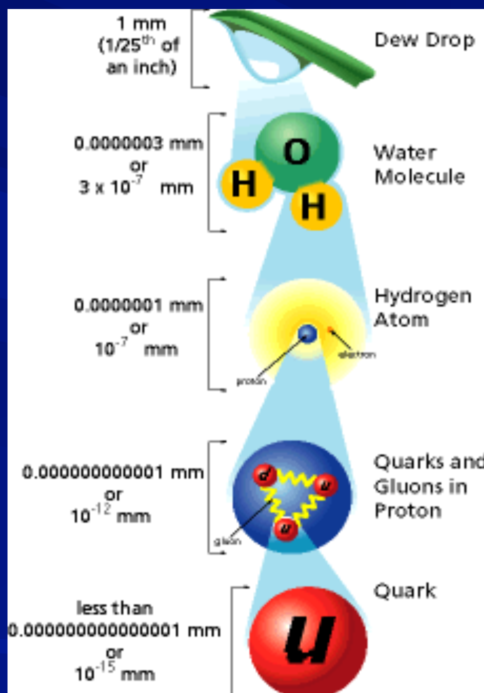
Dark Matter Properties

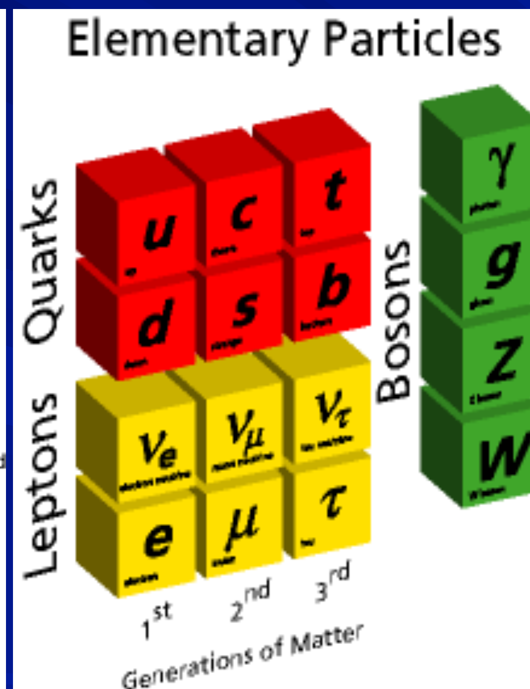
- Neutral (electric charge =0 and colorless)
- Very weakly interacting, no EM interaction
- Very long lived or absolutely stable
- Hot or warm or cold, prefer cold dark matter (CMD)
- Mass, spin not known

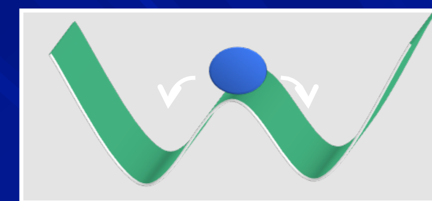
This talk will concentrate on WIMP CMD

Standard Model of Particles
SU(3) x SU(2) x U(1)

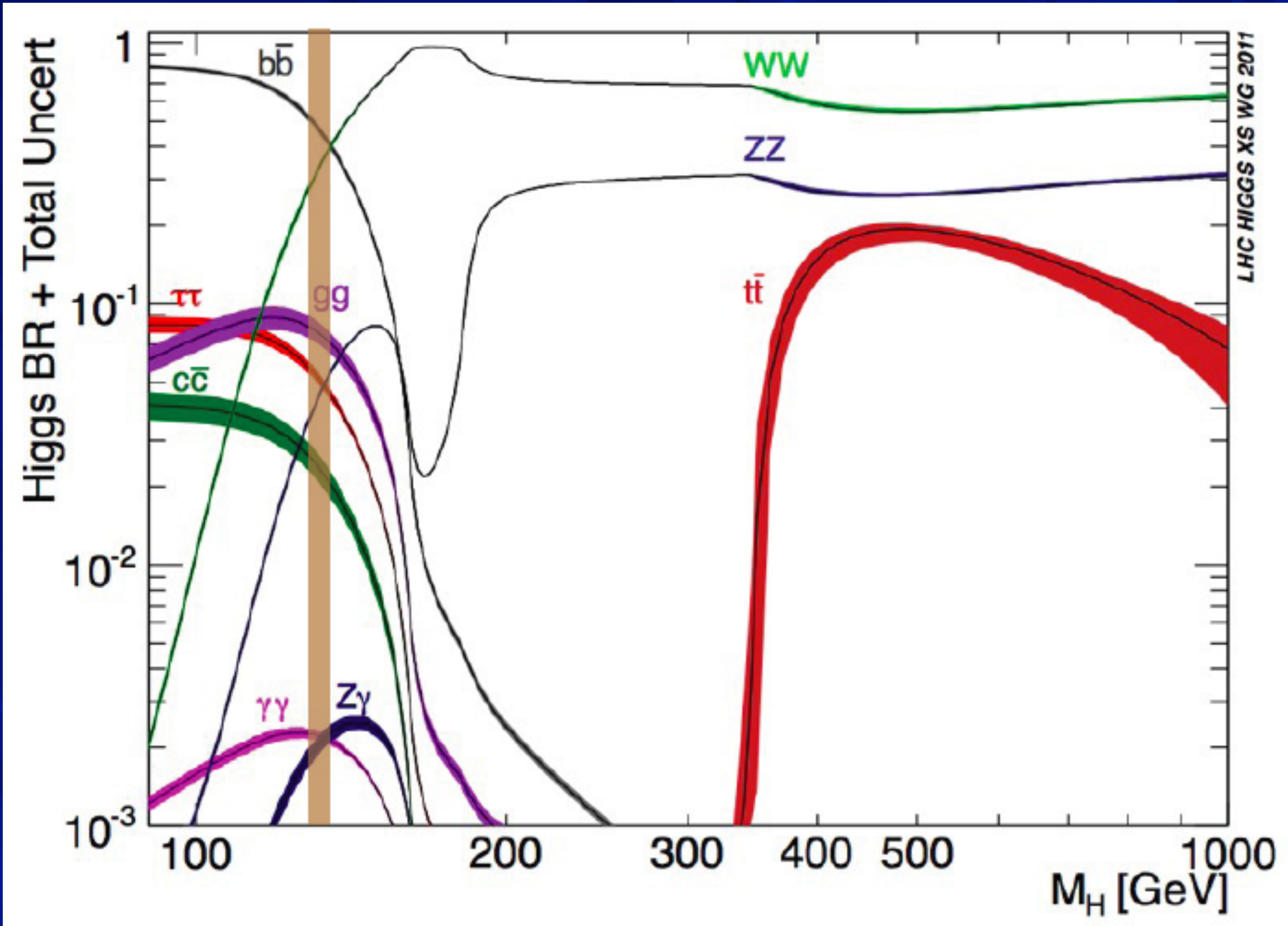
Inward Bound





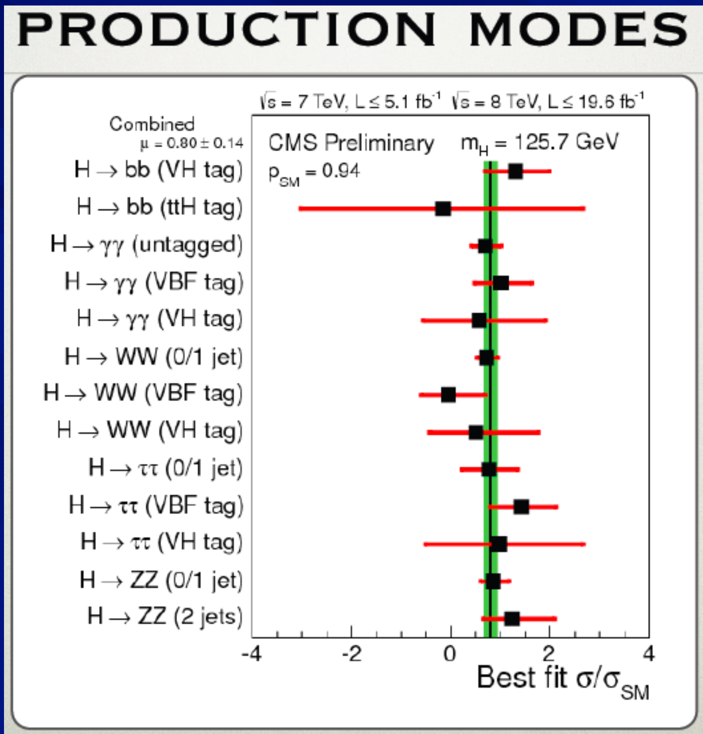


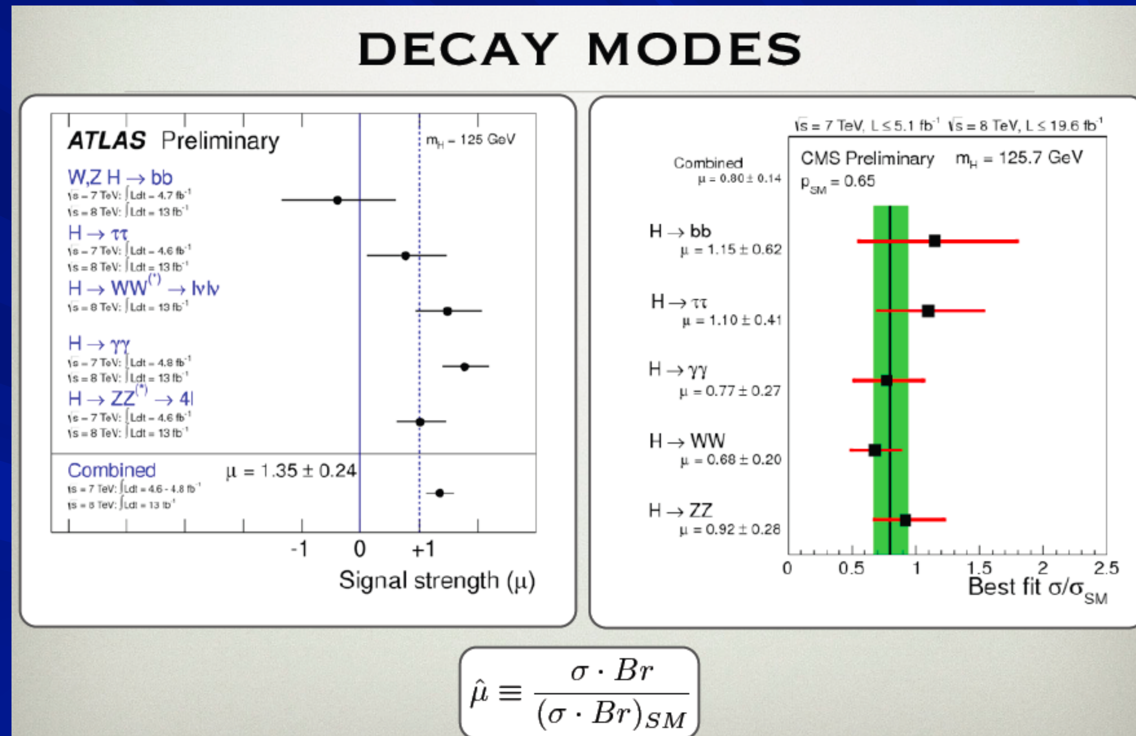
None of the SM particles can play the role of DM



Higgs BR + Total Uncert
1
10^{-1}
10^{-2}
10^{-3}
$b\bar{b}$
WW
ZZ
$\tau\tau$
gg
$c\bar{c}$
$t\bar{t}$
$\gamma\gamma$
$Z\gamma$
100
200
300
400
500
1000
M_H [GeV]
LHC HIGGS XS WG 2011

The Higgs fit SM very well



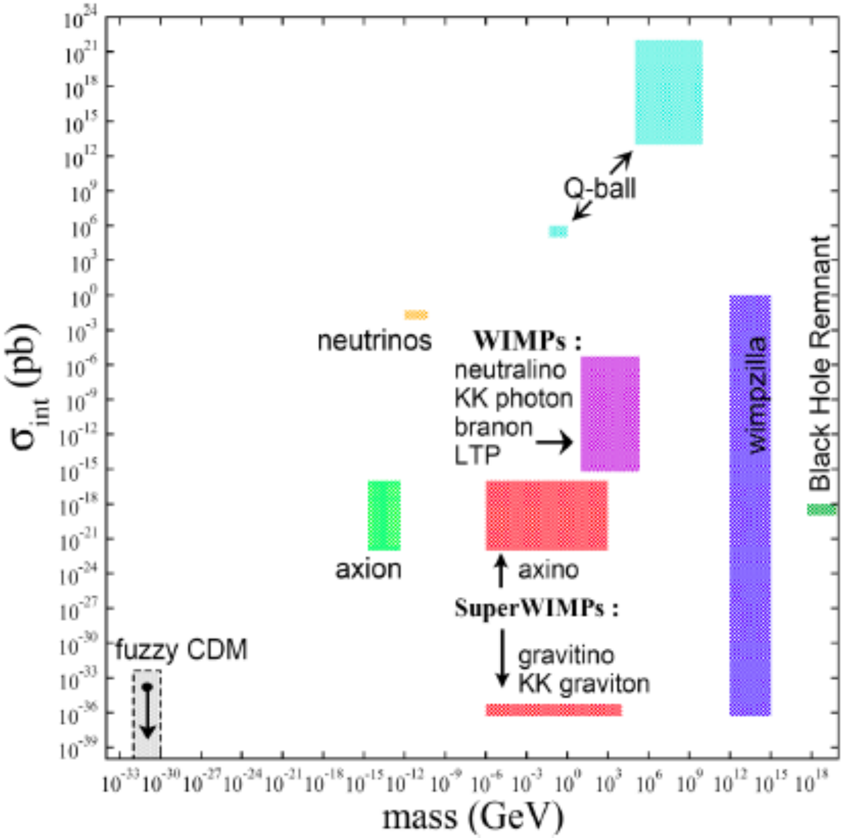


The LHC Higgs cannot have invisible branching ratio larger than 20 ~ 30%!

Constrain Higgs portal Dark Matter models.

DM Candidates in Particle Physics

- Many many candidates in fact
- Wide ranges of mass and coupling strengths
- If one tries to solve hierarchy problem, weak scale DM is well motivated
- Strong CP motivated axion



L.Roszkowski (2004)

The simplest: SM + a real scalar!
The Darkon Model

Thermal production of DM

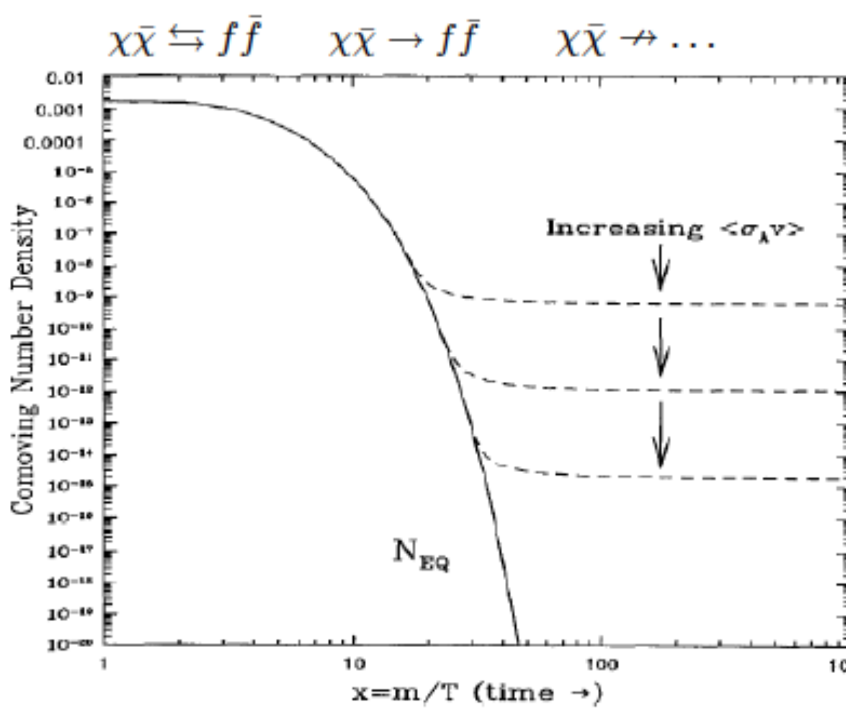
- Boltzmann Equation :

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{\rm eq}^2 \right]$$

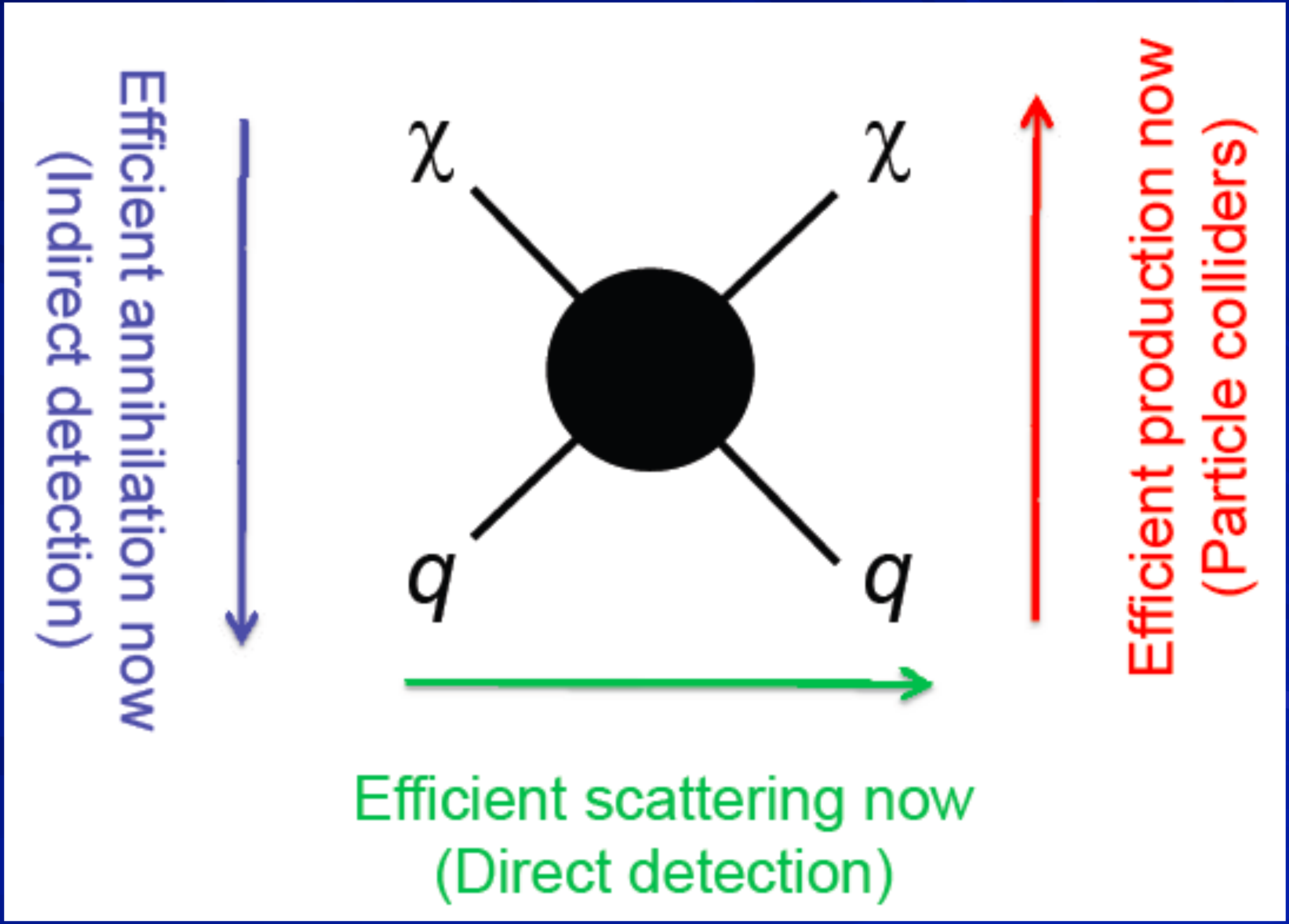
Dilution from expansion ($-3Hn$) $X + X \to SM + SM$ (n^2) $SM + SM \to X + X$ ($n_{\rm eq}^2$)

$$\Omega_X \approx \frac{6 \times 10^{27} cm^3 s^{-1}}{\langle \sigma_{\rm ann} v \rangle}$$

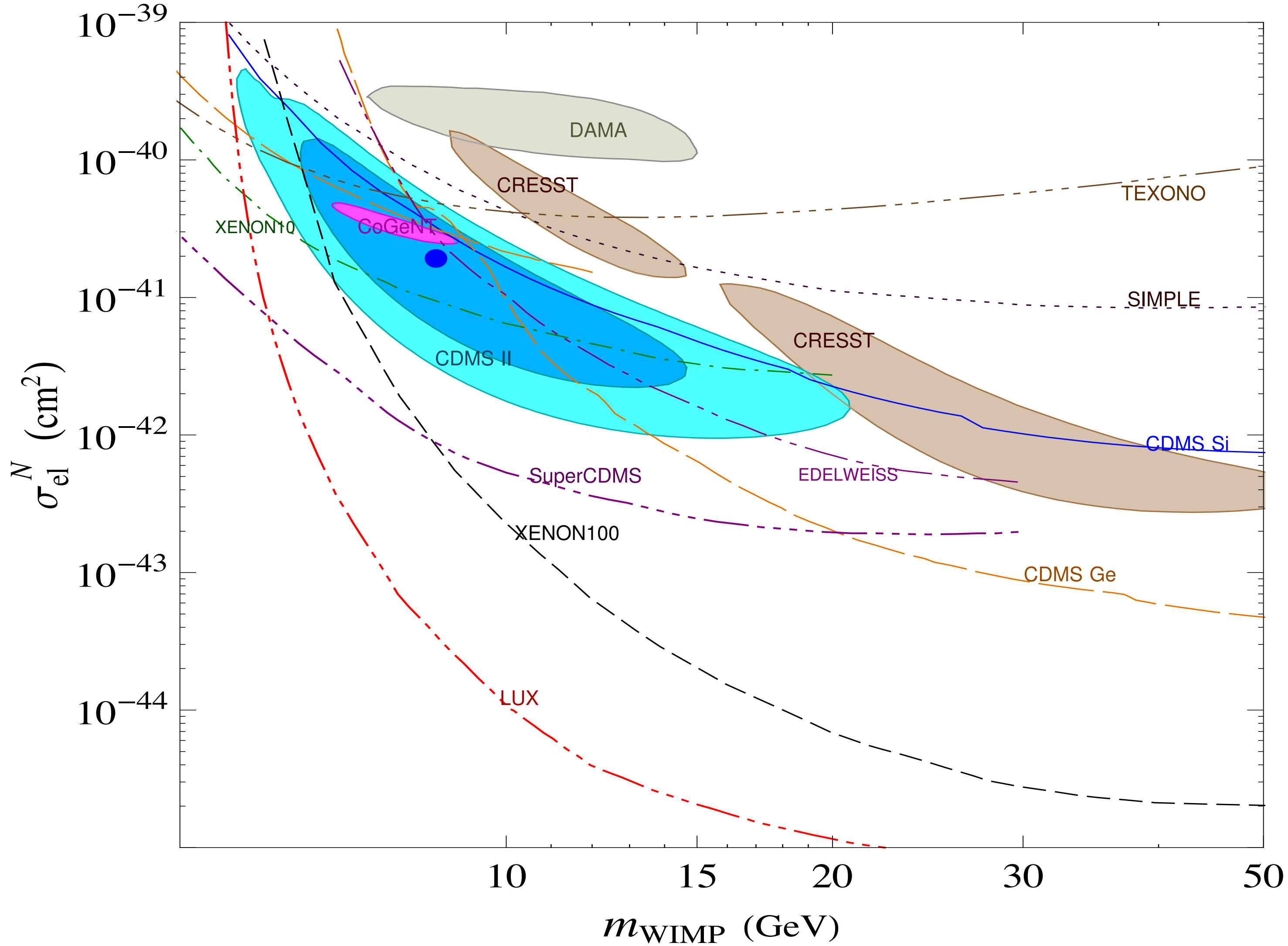
- X (CDM) is initially in thermal equilibrium
- As universe cools down, X only decreases by pair annihilation
- As universe expands, X eventually decouples from the SM



DM relic density, detection and DM production at colliders



Status of Direct DM detection



There are several indications of light DM of order 10 GeV, DAMA, CoGENT, CRESST, CDSMII…

It is often claimed that Xenon and Lux experiments rule out these possibilities.

But, the detection is target dependent. If interaction of DM with proton and neutron are different, Isopin Violating DM, it may happen that the nuclei-DM cross section for Xenon is small, but not for other nuclei.

Low mass DM of order 10 GeV mass is not completely ruled out!

The Darkon Model SM+D, the simplest Higgs portal model, as a realistic realization

SM+D: SM3 + a real SM singlet D darkon field (plays the role of dark matter).

Sileira&Zee, PLB (1985)

Beyond the SM part, the Lagrangian of the model

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

where λ_D, m_0, and λ are free parameters and H is the Higgs doublet containing the physical Higgs field h

Only two of its free parameters besides m_h are :

λ and the darkon mass $m_D = (m_0^2 + \lambda v^2)^{1/2}$

D is stable due to a D-> - D Z2 symmetry.

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

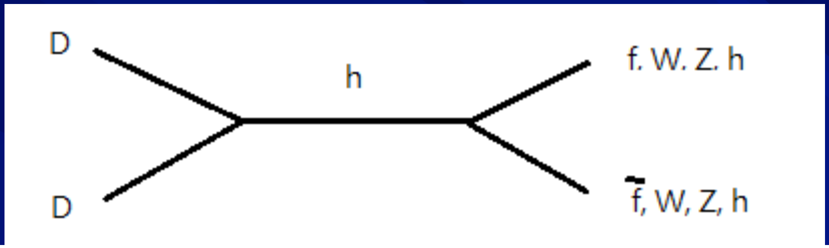
$v = 246\,\mathrm{GeV}$ vacuum of H. darkon mass $m_D = (m_0^2+\lambda v^2)^{1/2}$

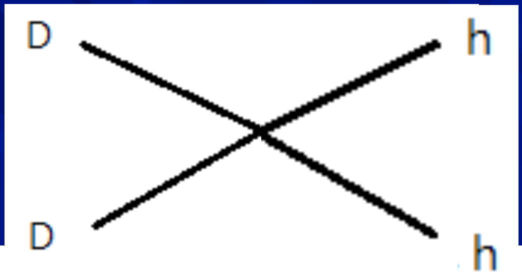
After H develops VEV, there is a term: v DD h.

This term is important for annihilation of D D -> h -> SM particle

This term also induce h -> DD if DM mass is less than half of the Higgs mass increasing the invisible decay width and make the LHC detection harder!

D is stable, but can annihilate through h exchange





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

$v_{\text{rel}} = 2\left|\boldsymbol{p}_D^{\text{cm}}\right|/m_D$ is the relative speed of the DD pair in their cm frame,

$\tilde{h}$ is a virtual having the same couplings to other states as h of mass m_h,

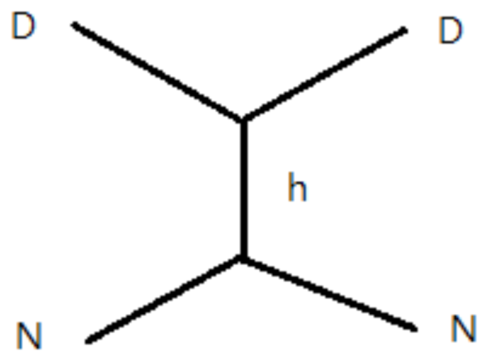
an invariant mass $\sqrt{s} = 2m_D$,

$$\Omega_D h^2 \simeq \frac{1.07 \times 10^9\, x_f}{\sqrt{g_*}\, m_{\text{Pl}} \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle \,\text{GeV}}, \qquad x_f \simeq \ln \frac{0.038\, m_{\text{Pl}}\, m_D \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle}{\sqrt{g_*\, x_f}},$$

h is the Hubble constant in units of $100\,\text{km}/(\text{s}{\cdot}\text{Mpc})$, $m_{\text{Pl}} = 1.22 \times 10^{19}\,\text{GeV}$

$x_f = m_D/T_f$ g_* number of relativistic degrees of freedom with masses less than T_f

Direct Search

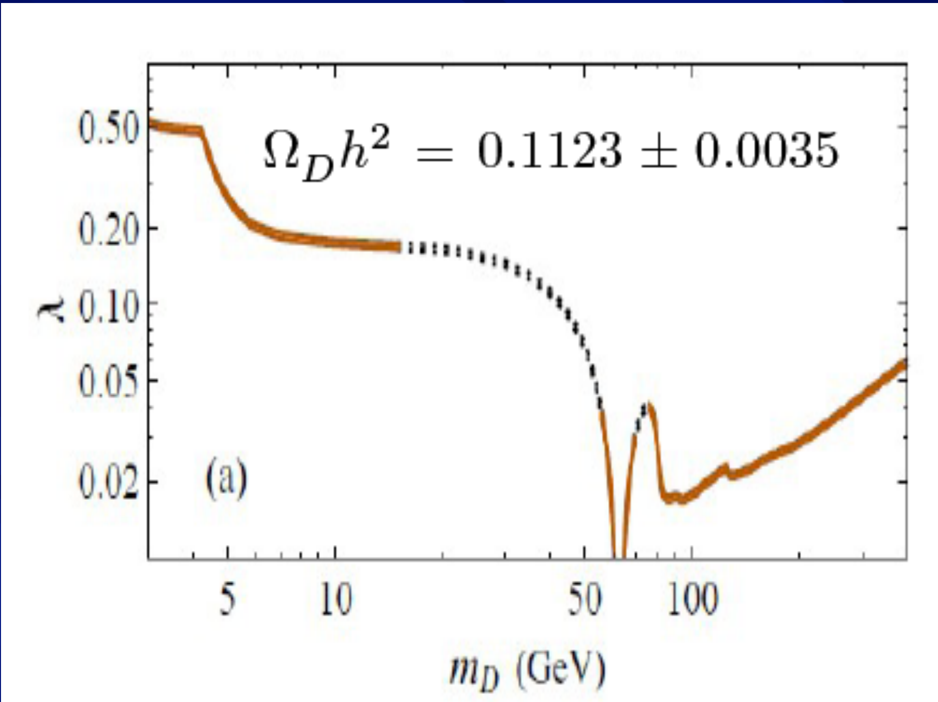


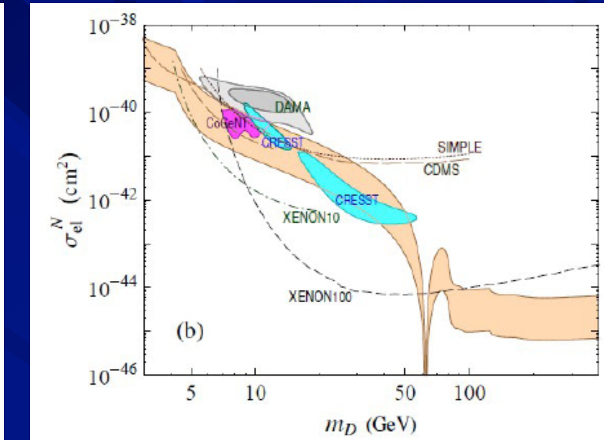
$$\sigma_{\rm el} \simeq \frac{\lambda^2 g_{NNh}^2 v^2 m_N^2}{\pi \left(m_D + m_N\right)^2 m_h^4} \cdot \quad \sigma_{\pi N} = 45\,\mathrm{MeV}$$

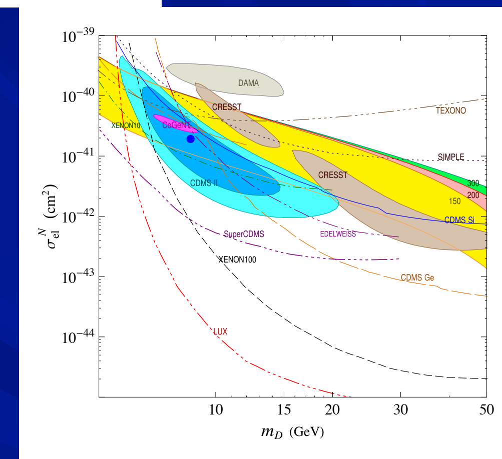
$$g_{NNh}, \quad \mathcal{L}_{qqh} = -\Sigma_q m_q \bar{q} q\, h/v, \quad g_{NNh}^{\rm SM3} = 1.71 \times 10^{-3}$$

$\sigma_{\pi N}$ 35 MeV to 80 MeV

$$1.3 \times 10^{-3} \lesssim g_{NNh}^{\rm SM3} \lesssim 3.2 \times 10^{-3}.$$







Tong Li et al, MPLA (2007), PRD(2009); PLB(2010).

If dark matter mass is heavy m_D > 300 GeV or around $m_h/2$ no problem for both relic density and direct detection. But is small than $m_h/2$, there are problems with direct detection and also invisible Higgs decay!

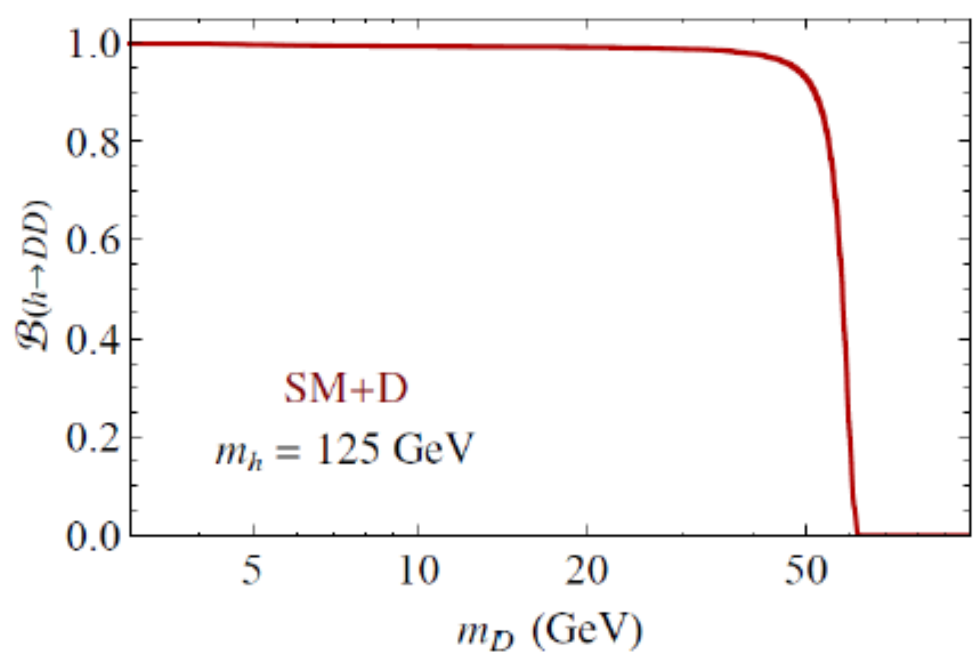
Dark matter relic density and direct detection allow solutions with dark matter mass less than half of Higgs mass. H -> DD allowed.

The $h \to DD$ decay width is given by

$$\Gamma(h \to DD) = \frac{1}{8\pi} \frac{\lambda^2 v^2}{m_h} \sqrt{1 - \left(\frac{2m_D}{m_h}\right)^2}.$$

Too large an invisible branching ratio. This model is out!

If the DM mass is indeed small, the model has to be extended!!



To have low DM mass ($m_D < m_h/2$), one must overcome two problems:

1. Reconcile various DM derect search constraints? Xeno and Lux exclude all indications of low DM mass from Dama, CoGENT, CRESST and CDMSII: Isospin Violating DM. (Fegn etal, PLB2011)
2. Avoid too large an invisible decay of Higgs boson.

More than one Higgs boson.(Cai, Ren &He PRD2011, Tandean & He, 2011, 2012)

Isospin Violating Dark Matter

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

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

Feng *et al.*

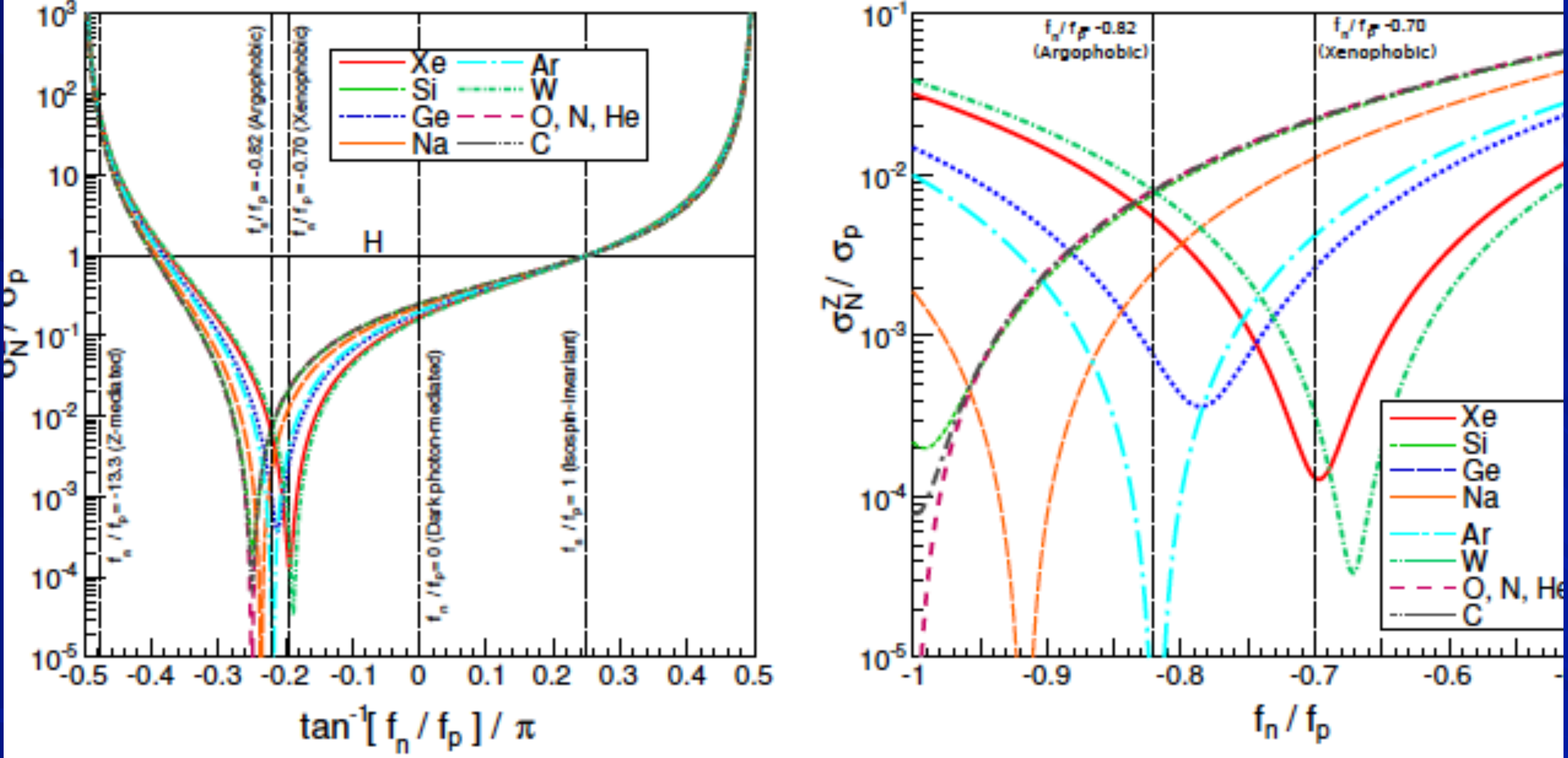
the sum is over isotopes of the element in the detector material with which the WIMP interacts dominantly, $\mathcal{Z}$ is proton number of the element, A_i (η_i) each denote the nucleon number (fractional abundance) of its isotopes, $\mu_{A_i} = m_{A_i} m_{\rm WIMP}/(m_{A_i} + m_{\rm WIMP})$ involving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

Feng etal arxiv:1307.1758

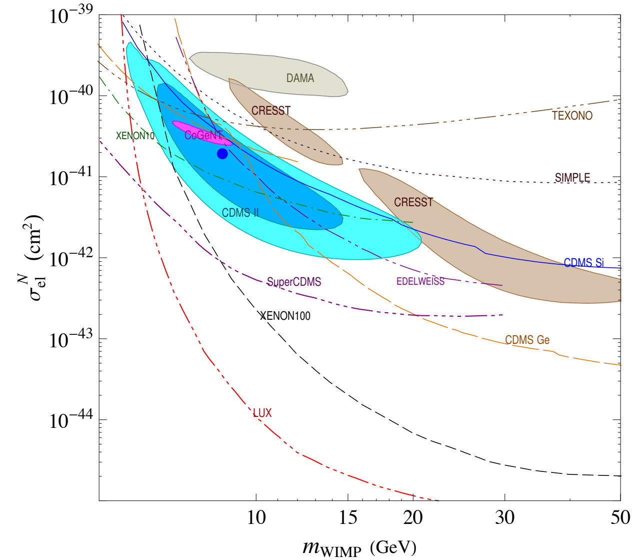


(a) Entire f_n/f_p range

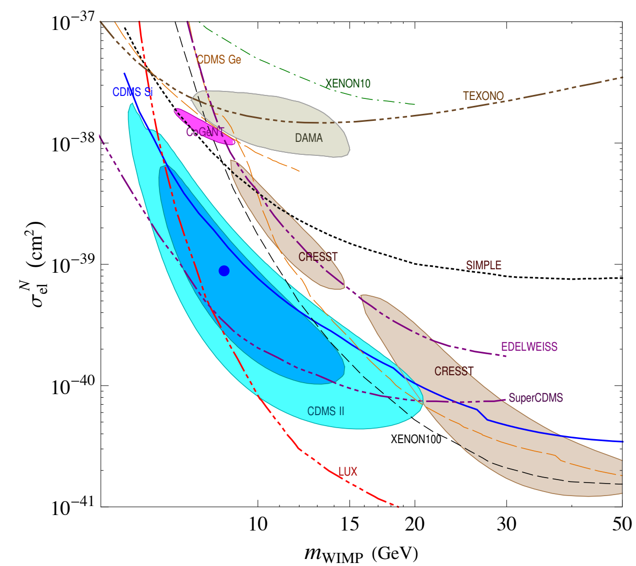
(b) Xenophobic region

Isospin symmetric

$f_n/f_p = -0.7$



Isospin-conserving DM: data only



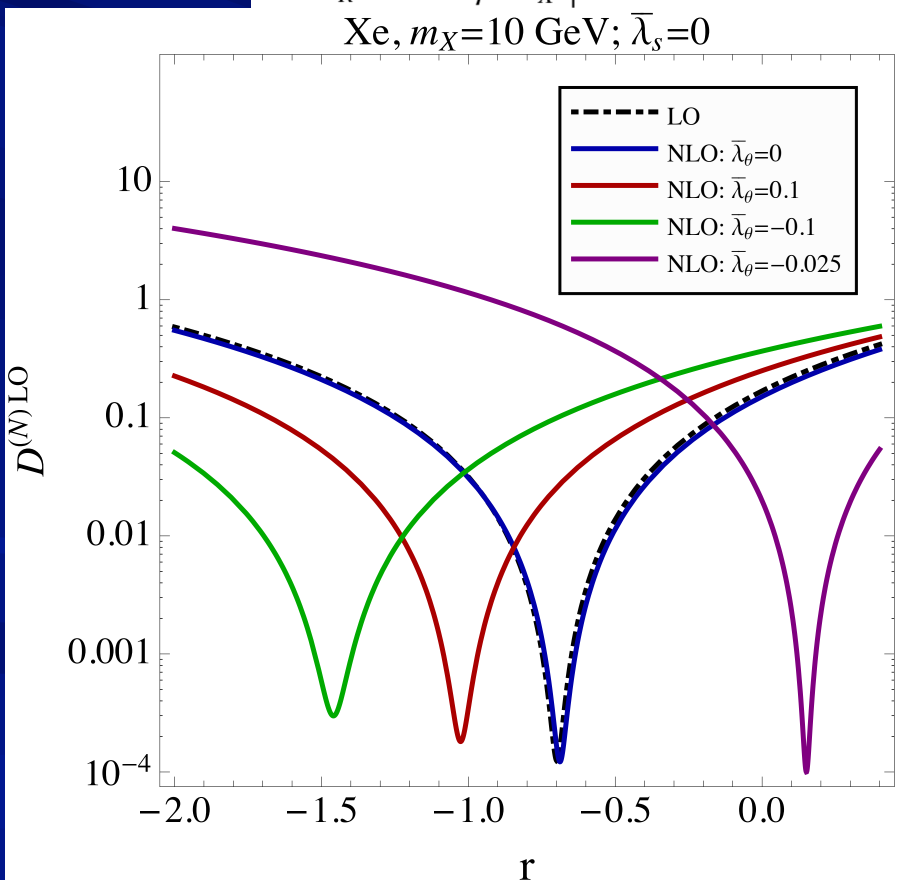
IVDM: data only

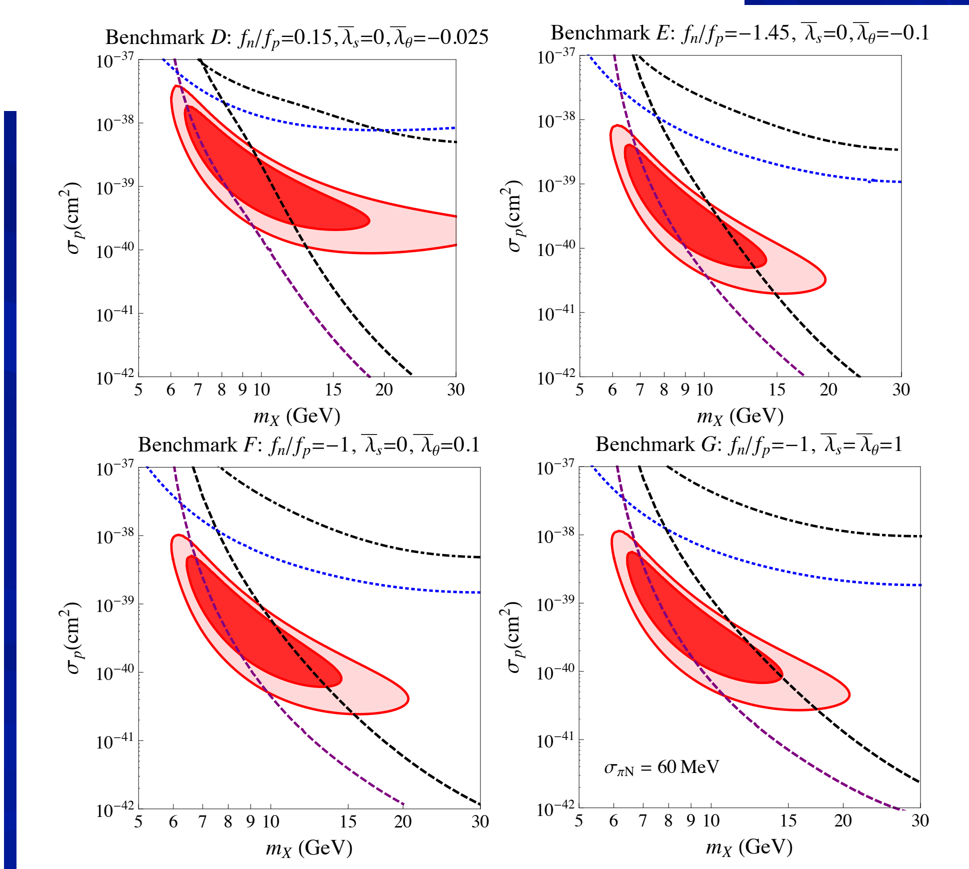
NLO corrections for nucleon couplings

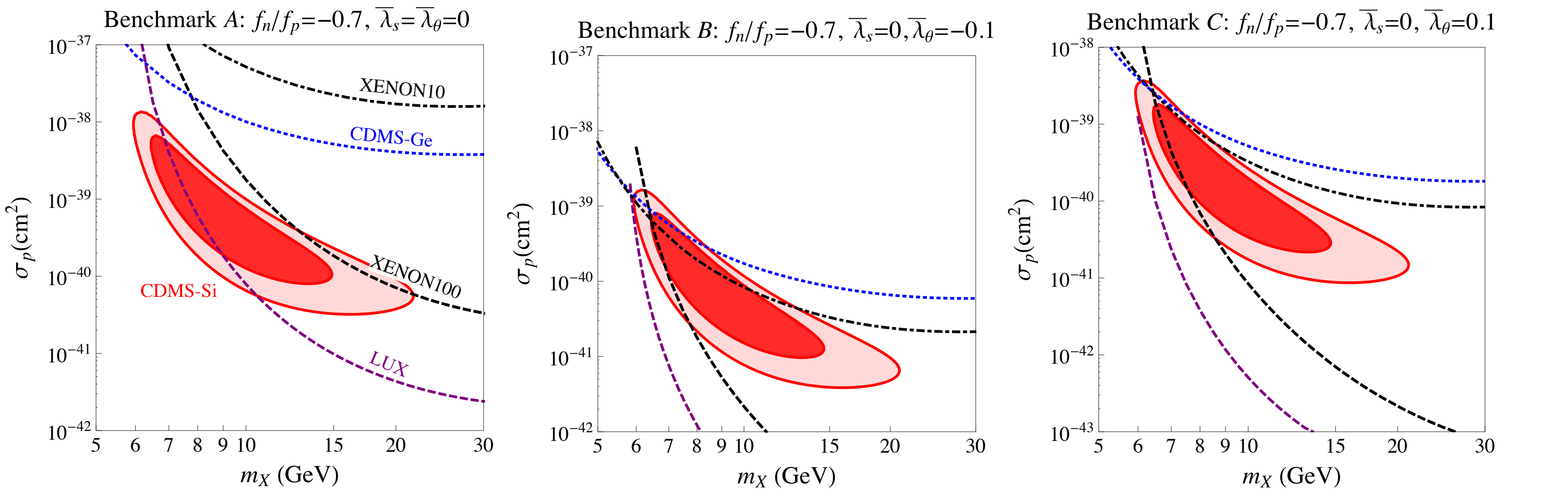
Vincenzo Cirigliano[a], Michael L. Graesser[a], Grigory Ovanesyan[a,b], Ian M. Shoemaker[a,c]

arXiv:1311.5886

$$\frac{dR}{dE_R}^{\mathrm{NLO}} = \frac{\sigma_p \rho_0}{2\mu^2 m_X} \left| \left[Z\left(1 + s_p E_R\right) + \left(A - Z\right)\left(r + s_n E_R\right)\right] F(E_R) + A_2(E_R) \right|^2 \times \eta\left(E_R, m_X, m_A\right) \; ,$$







Benchmark A: f_n/f_p=−0.7, $\overline{\lambda}_s$=$\overline{\lambda}_\theta$=0
XENON10
CDMS-Ge
XENON100
CDMS-Si
LUX
σ_p(cm^2)
m_X (GeV)
Benchmark B: f_n/f_p=−0.7, $\overline{\lambda}_s$=0, $\overline{\lambda}_\theta$=−0.1
σ_p(cm^2)
m_X (GeV)
Benchmark C: f_n/f_p=−0.7, $\overline{\lambda}_s$=0, $\overline{\lambda}_\theta$=0.1
σ_p(cm^2)
m_X (GeV)

Two Higgs doublets + Darkon Model

- The Higgs sector is the THDM of type III
  - Both Higgs doublets couple to the fermions.
  - Neutral physical scalar Higgs fields *h* & *H*

$$\begin{pmatrix} h_1^0 \\ h_2^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

- Darkon Lagrangian

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

- Darkon 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

$$\mathcal{L}_Y = -\bar{Q}_{j,L}\left(\lambda_1^{\mathcal{U}}\right)_{jl}\tilde{H}_1\mathcal{U}_{l,R} - \bar{Q}_{j,L}\left(\lambda_1^{\mathcal{D}}\right)_{jl}H_1\mathcal{D}_{l,R} - \bar{Q}_{j,L}\left(\lambda_2^{\mathcal{U}}\right)_{jl}\tilde{H}_2\mathcal{U}_{l,R} - \bar{Q}_{j,L}\left(\lambda_2^{\mathcal{D}}\right)_{jl}H_2\mathcal{D}_{l,R} - \bar{L}_{j,L}\left(\lambda_1^{E}\right)_{jl}H_1E_{l,R} - \bar{L}_{j,L}\left(\lambda_2^{E}\right)_{jl}H_2E_{l,R} + \text{H.c.}$$

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

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

where now $M_{\mathcal{U}} = \text{diag}(m_u, m_c, m_t)$, etc., and $\mathcal{U} = (u\ c\ t)^{\text{T}}$, 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

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

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

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

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

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

If H is the Higgs mediating DM interacctions, whose couplings to up and down quarks are different and can lead to IVDM interaction. (the role of H and h can be switched)

Higgs couplings

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

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

- Inspired by the discovery of a 125-GeV SM-like Higgs at the LHC, we adopt

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

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

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

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

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

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

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

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

h is the SM like Higgs. If $\lambda_h = 0$ h does not interacts with DM, no problem with invisible Higgs decay width. H does the job fo DM physics!

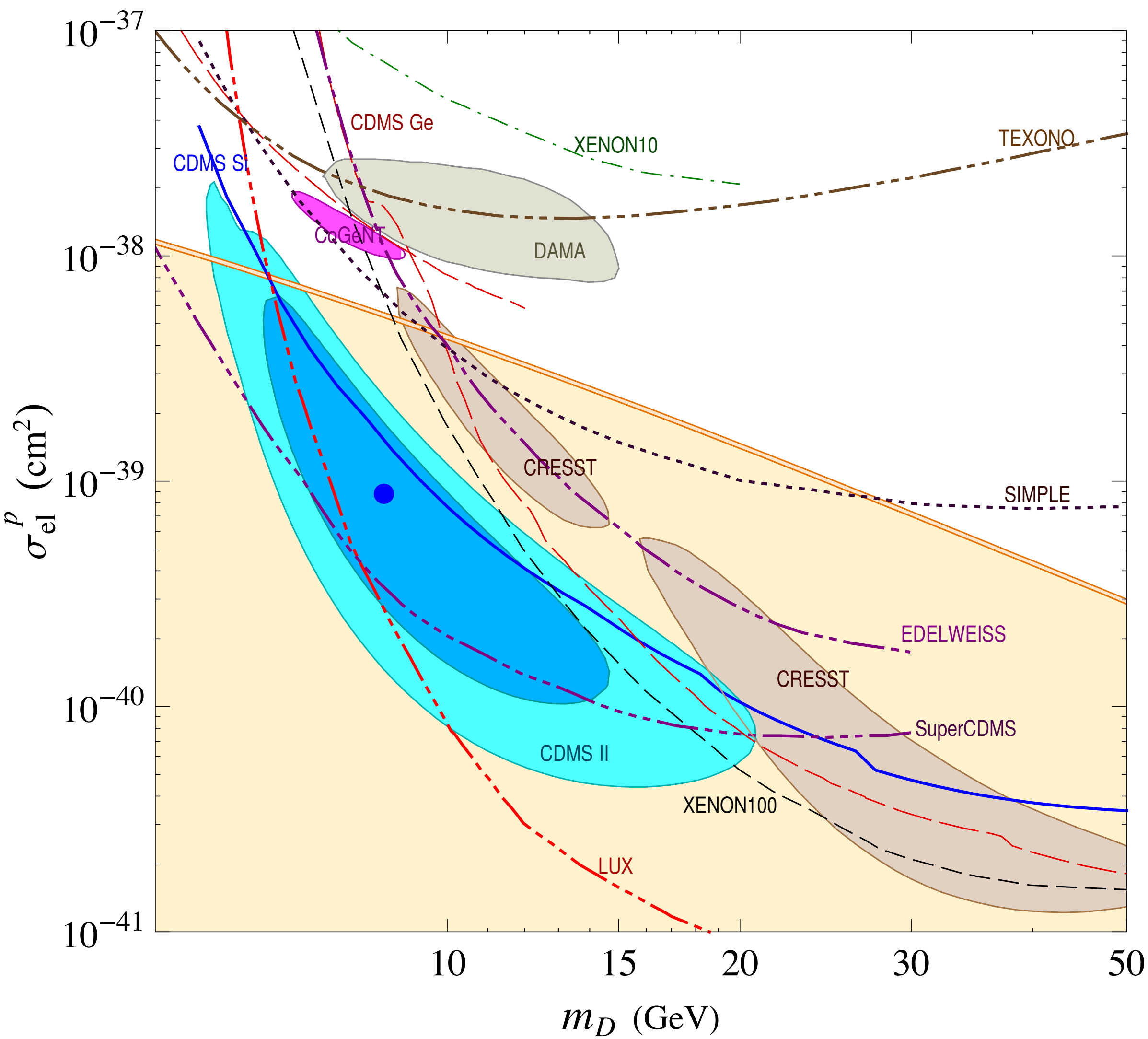
- The observed relic density and $f_n = -0.7 f_p$ requirements lead to limitations on the predicted darkon-proton scattering cross-section.

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 $m_H = 200\ (300)\,{\rm GeV}$ 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 $5\,{\rm GeV} \le m_D \le 20\,{\rm GeV}$.

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



IVDM: data & THDM+D

Conclusions

- Dark Matter exists, properties are not known completely.
- There are constraints from direct detections of DM. There are indications that DM has low mass of order 10 GeV, but excluded naively by Xenon experiments. One can reconcile the Xenon data with some of the low mass DM indications, via Isospin Violating DM.
- The properties of the Higgs boson discovered at the LHC can put stringent constraints on DM models.
- Possible to construct model to explain the low mass of DM indicated by the recent CDSMII and consistent with Xenon data, example: TypeIII 2HDM.