Higgs Portal Dark Matter In Light Of The Recent PandaX-II And Lux Data

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In collaboration with Jusak Tandean, arXv:1609.03551

JHEP in press

NCTS Annual Theory Meeting

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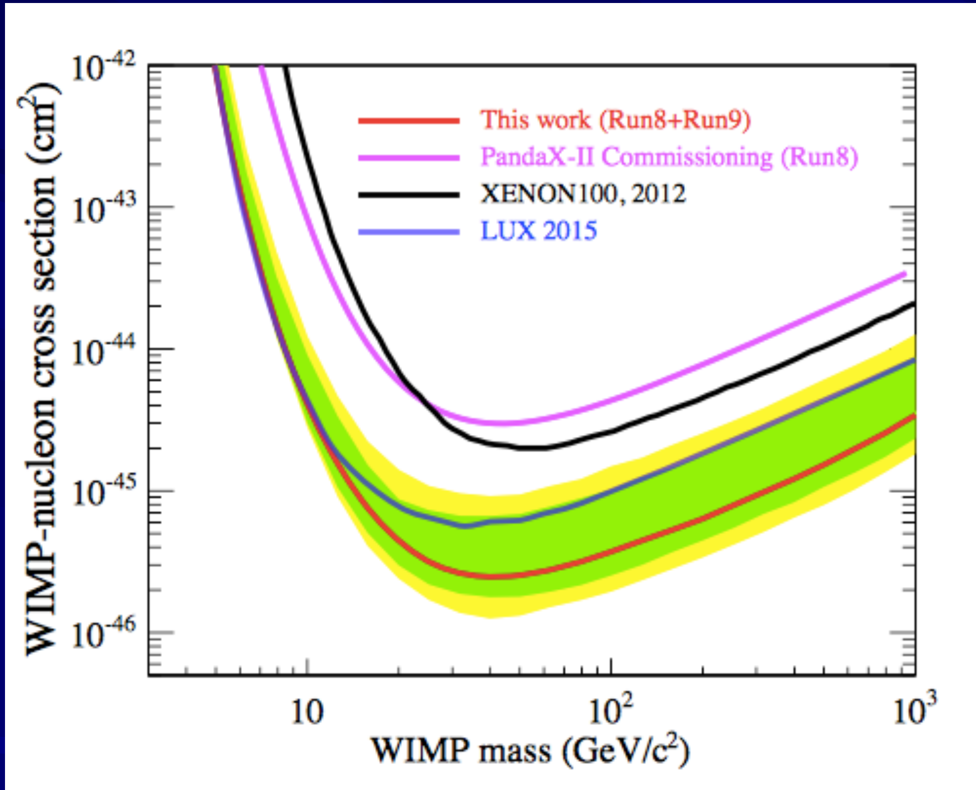
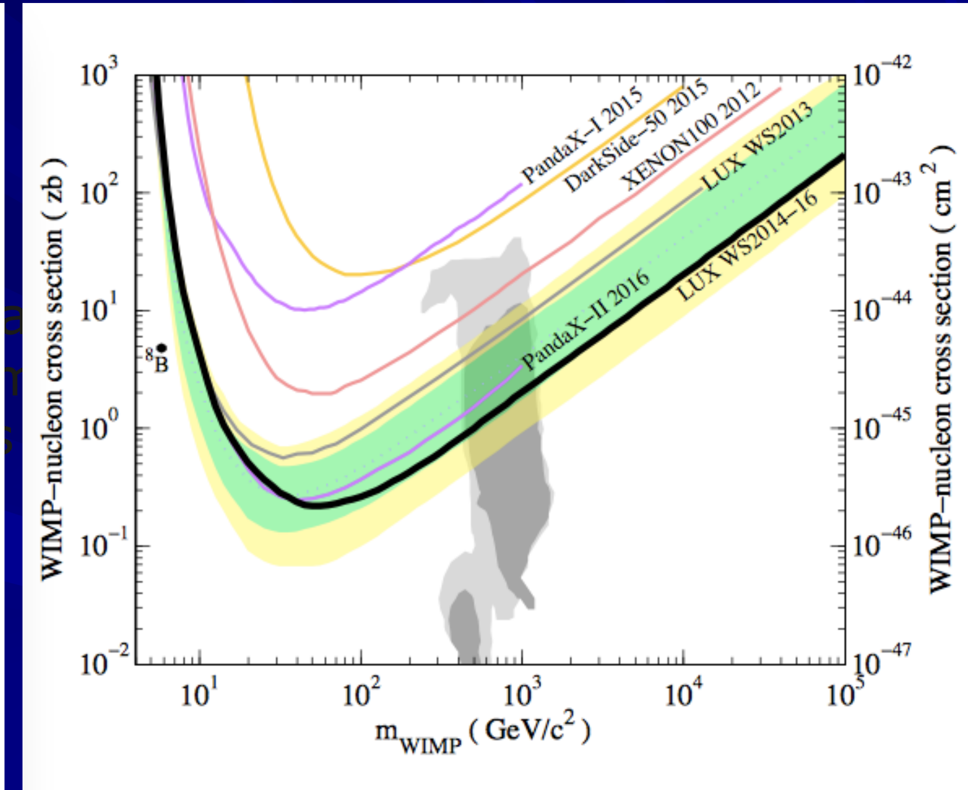
New results on Direct Dark Matter Search from Lux and PandaX-II





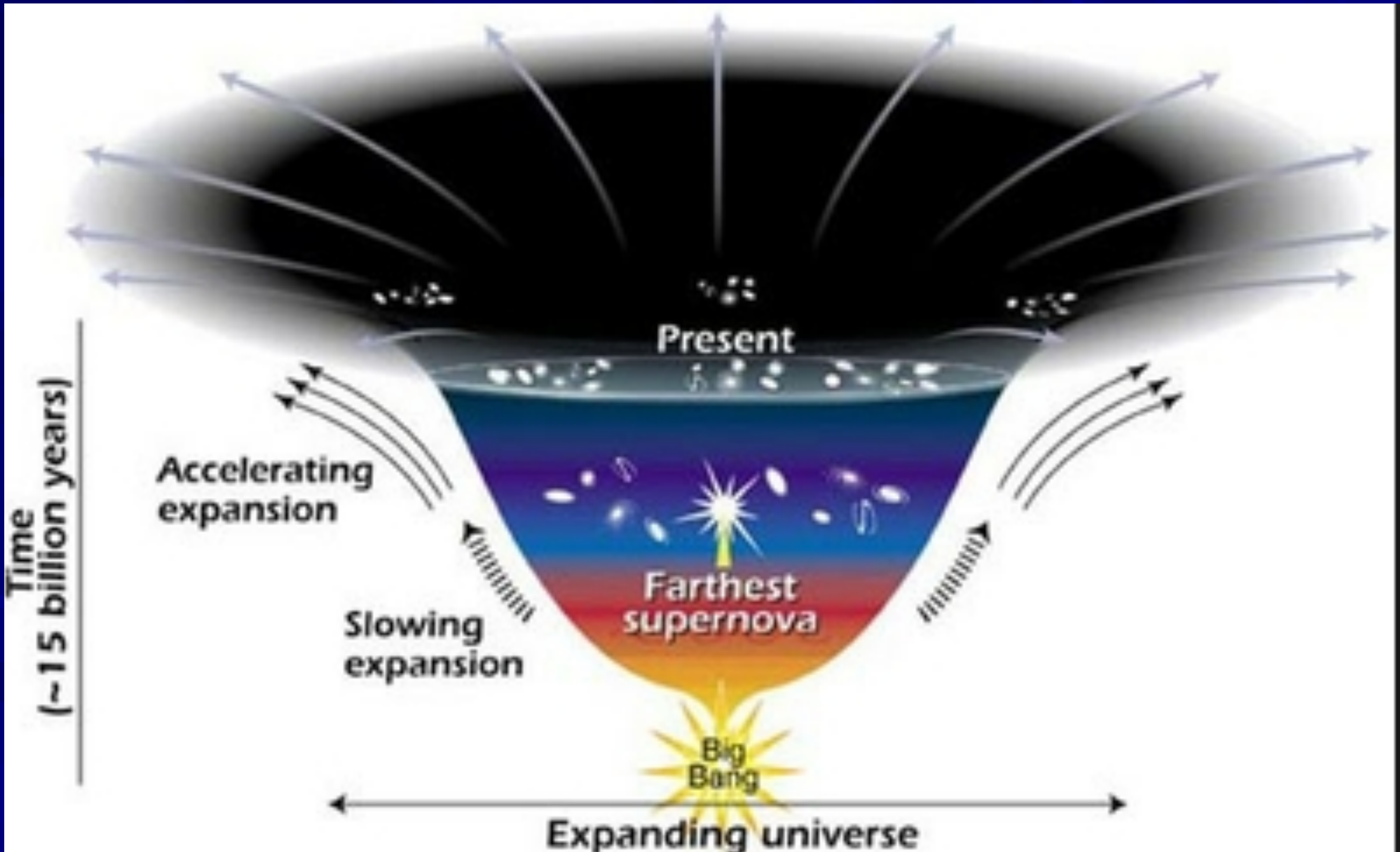
arXiv: 1607.07400

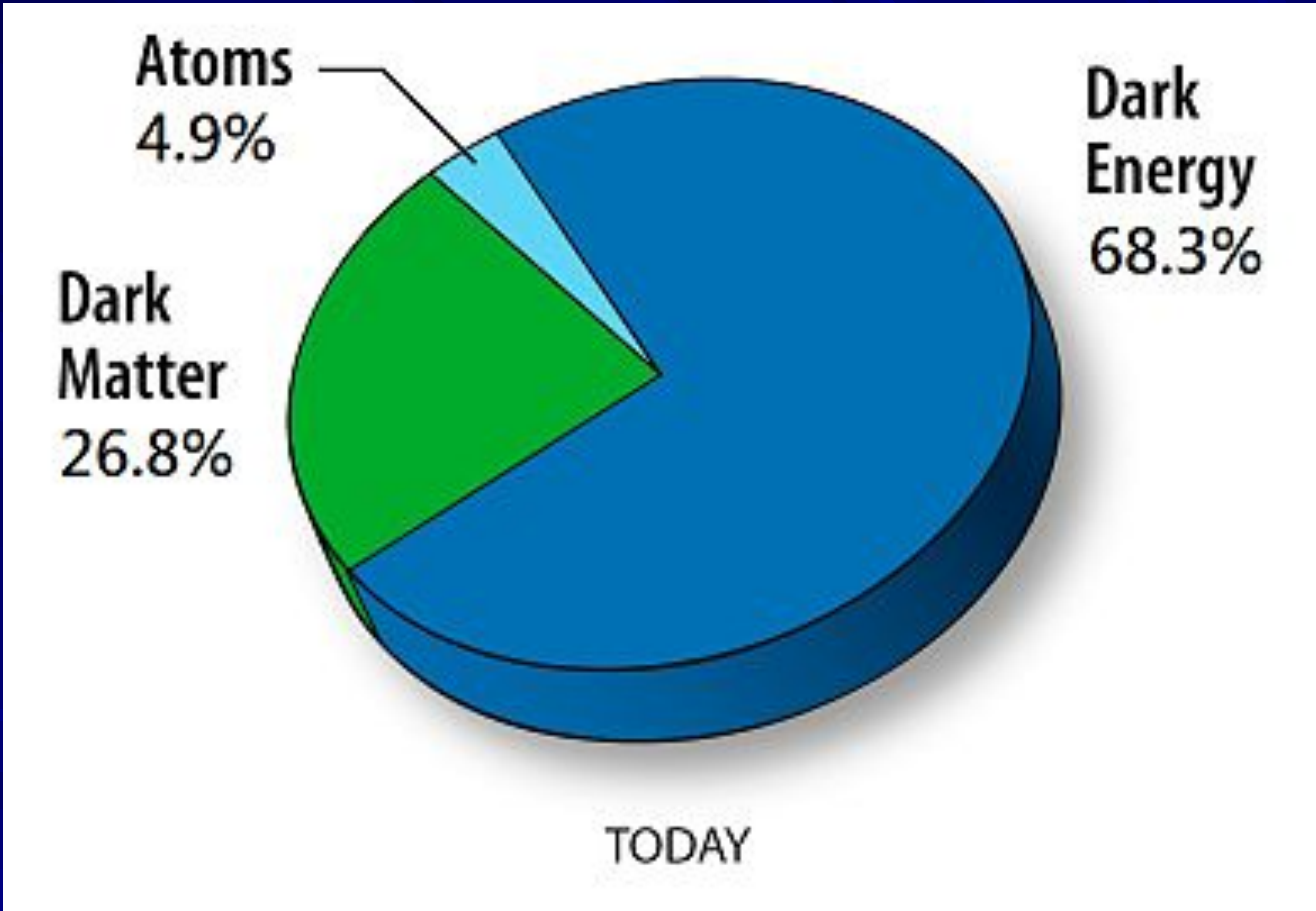
PRL117, 121303

arXiv:1608.07648

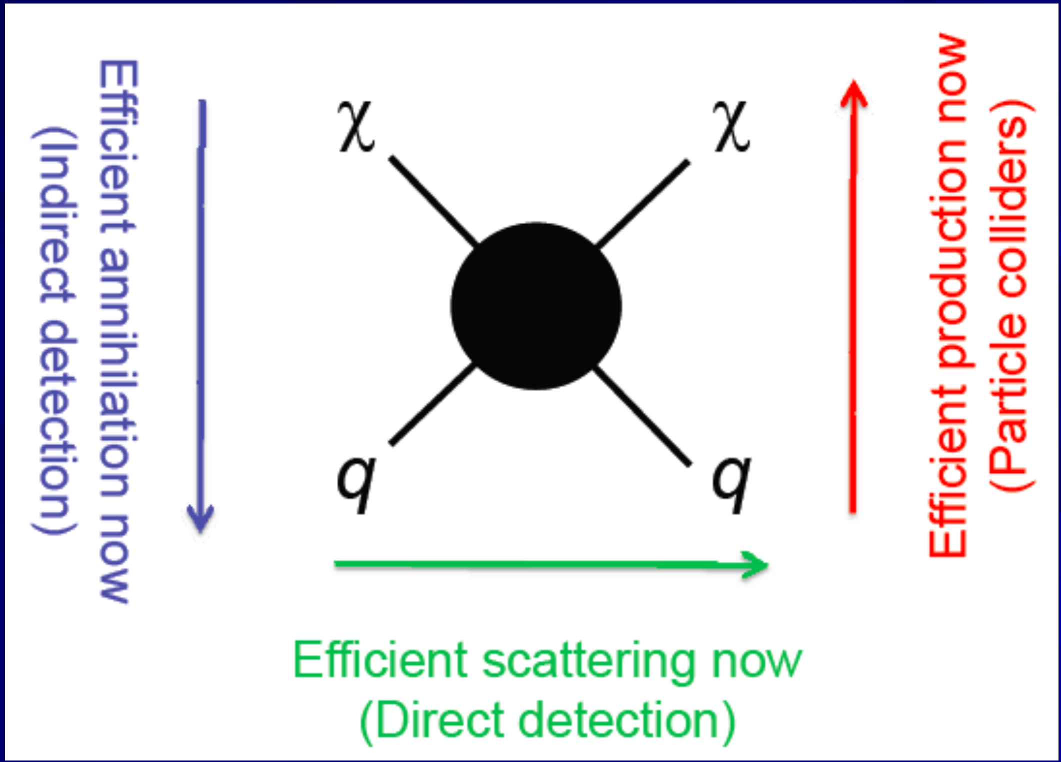
Standard Model for Cosmology

Inflation+FRW Big Bang +Cosmological Constant



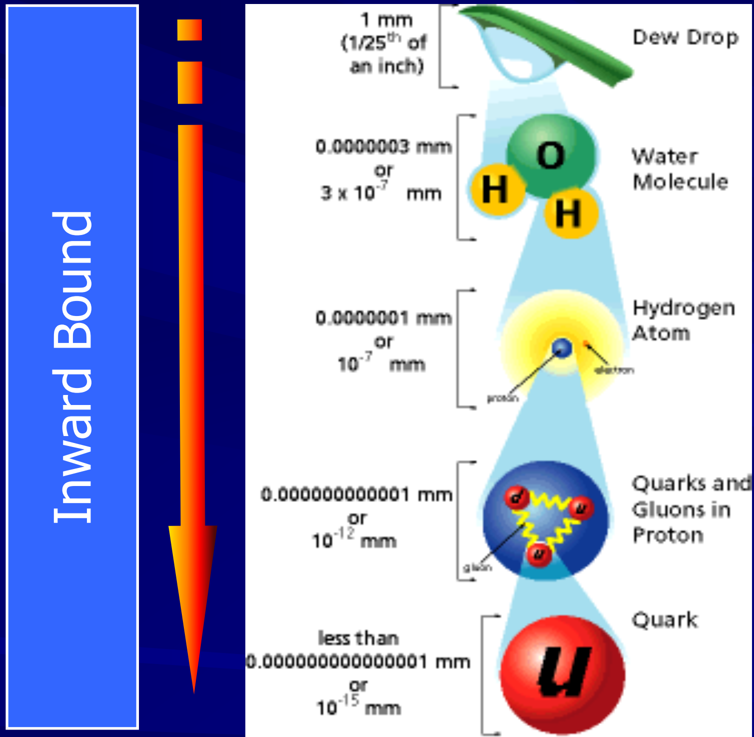

Atoms
4.9%
Dark
Energy
68.3%
Dark
Matter
26.8%
TODAY

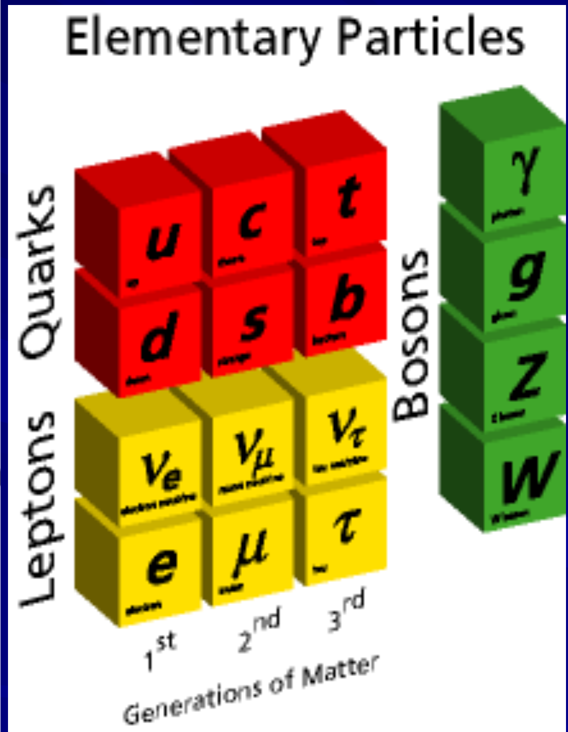
DM relic density, detection and DM production at colliders

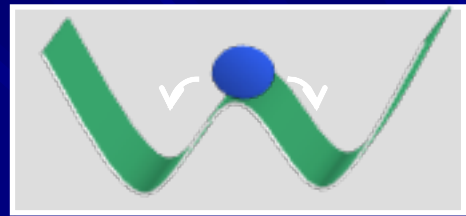


Status of the Simplest Dark Matter Model

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



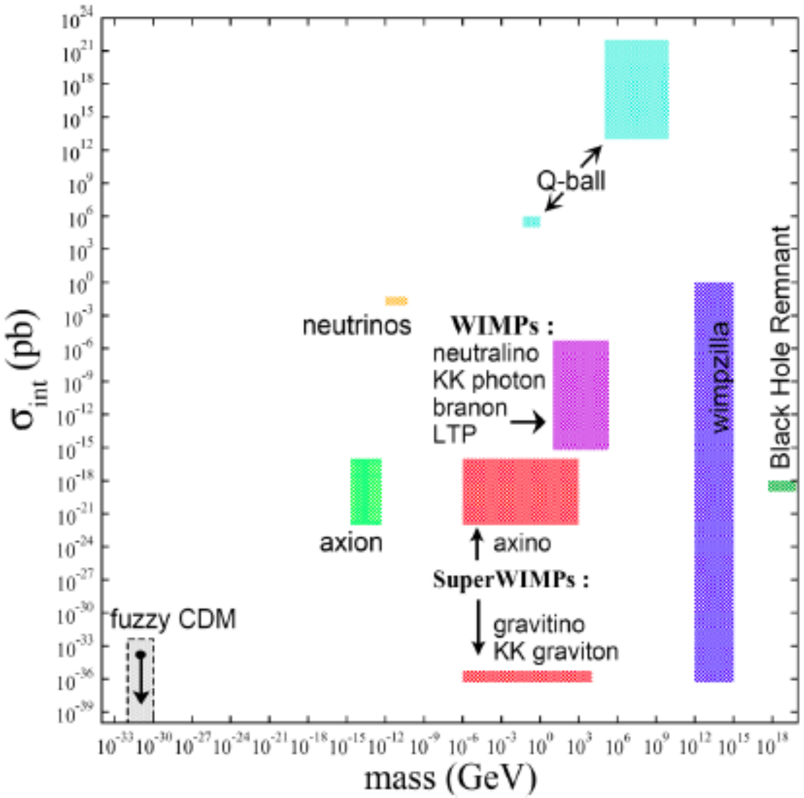




None of the SM particles can play the role of DM

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

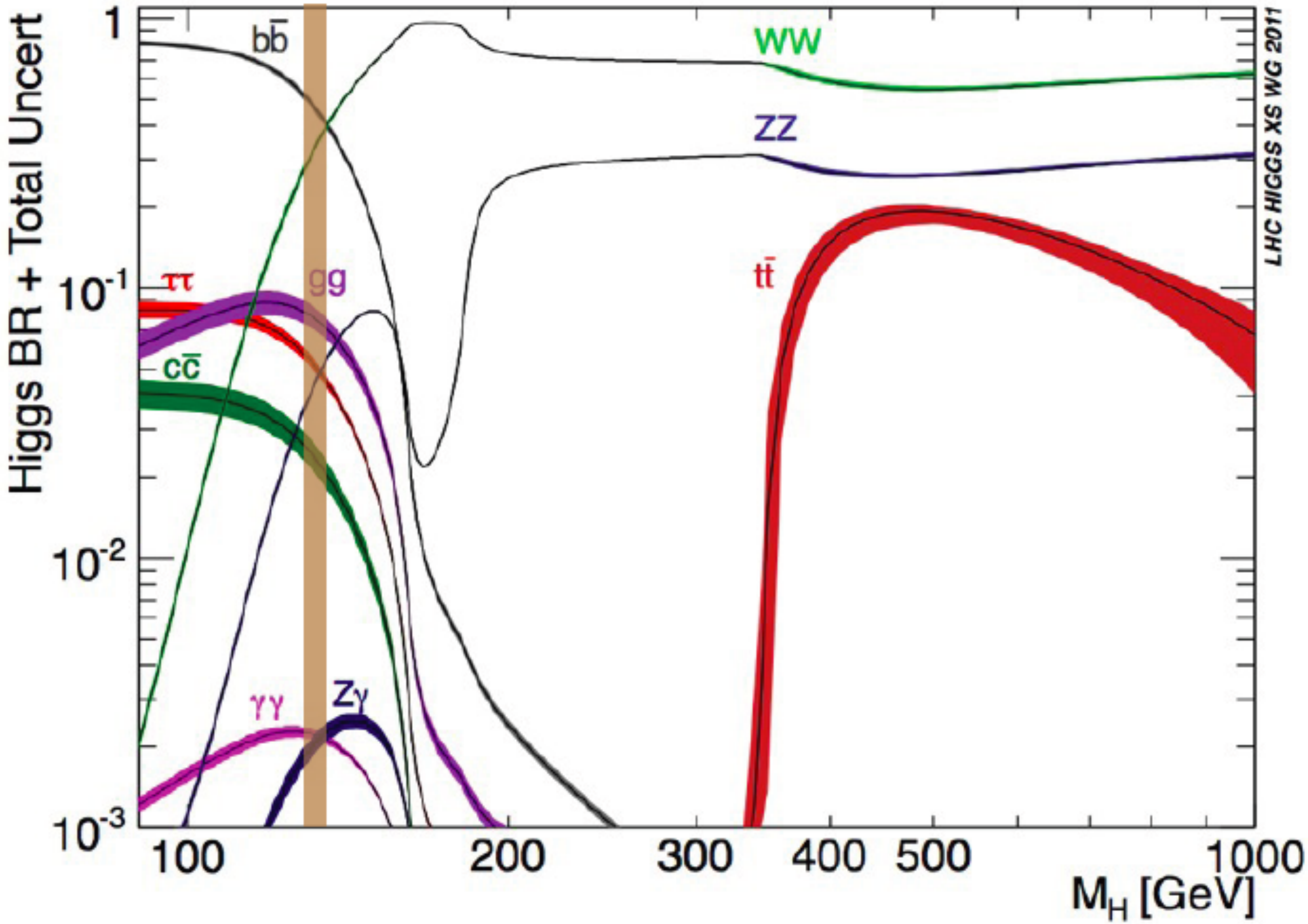


L.Roszkowski (2004)

The simplest: SM + a real scalar!

The Darkon Model

A typical Higgs portal model



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

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 Z'_2 symmetry.

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

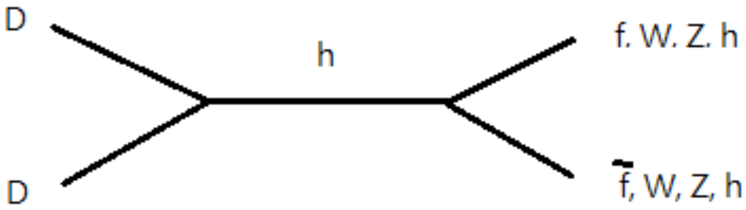
$v = 246\,\text{GeV}$ vacuum of H. darkon mass $m_D = (m_0^2 + \lambda v^2)^{1/2}$

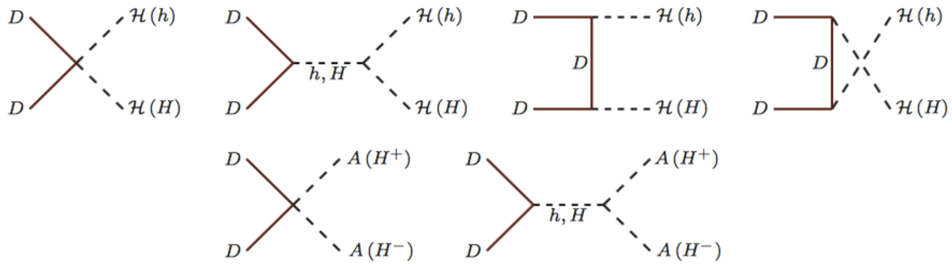
After H develops VEV, there is a term: v DD h.

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





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

$v_{\rm rel} = 2\left|\boldsymbol{p}_D^{\rm cm}\right|/m_D$ 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,

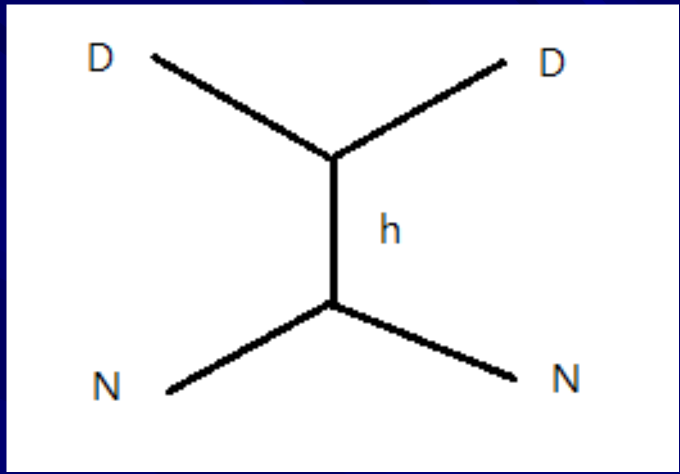
an invariant mass $\sqrt{s} = 2m_D$,

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

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

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

Direct Search



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

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

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

$$1.1 \times 10^{-3} \lesssim g_{NNh}^{\rm SM3} \lesssim 3.2 \times 10^{-3}.$$

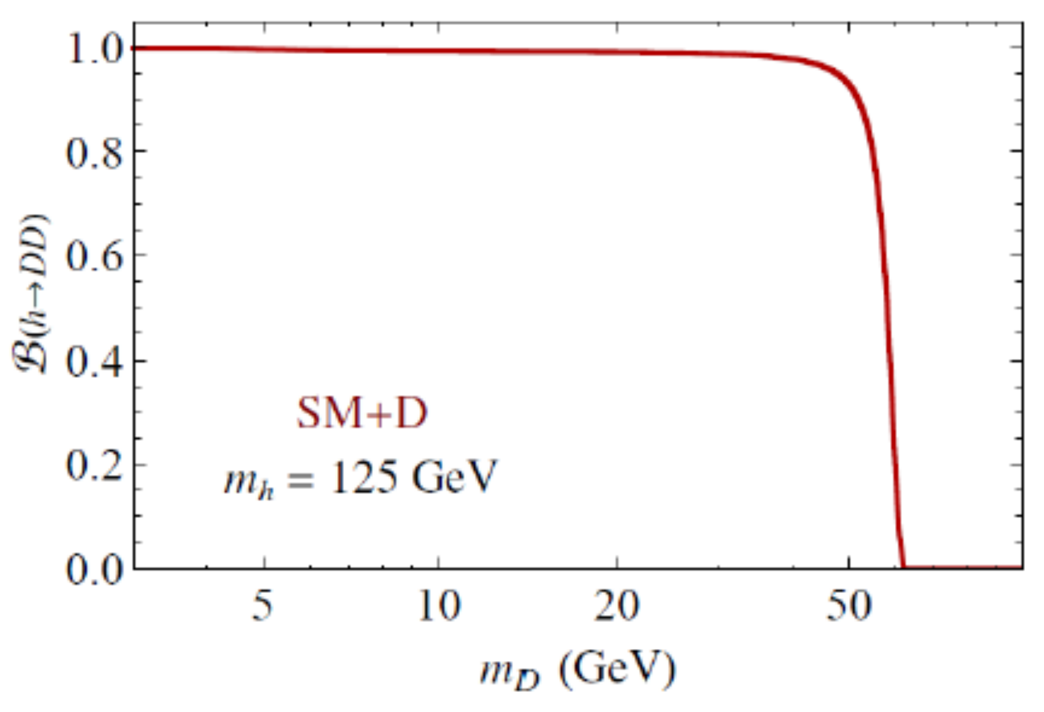
Dark matter relic density and direct detection allow solutions with dark matter mass less than half of Higgs mass. H -> DD allowed.

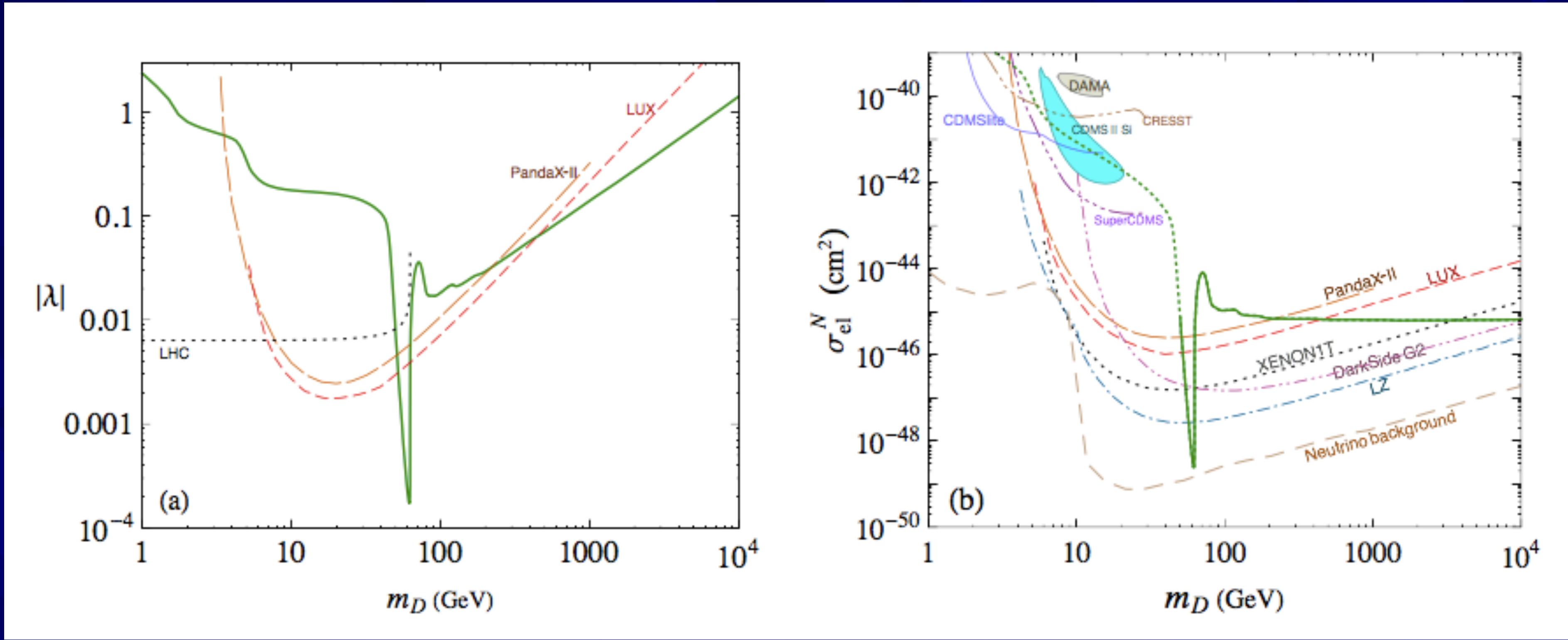
The $h \to DD$ decay width is given by

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

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

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





$\Omega_{DM}h^2$ =0.1189+- 0.0031

If dark matter mass is heavy m_D > 450 GeV 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!

When going beyond the simplest model, how much one can recover regions ruled out in SM + Darkon model?

Two Higgs Doublet Models

Depending on how the Higgs doublets ($\Phi_1 = H_1$ and $\Phi_2 = H_2$) couple to fermions, there are different types.

Models which lead to natural flavour conservation. The superscript i is a generation index. By convention, the u_R^i always couple to Φ_2.

Branco *et al.*, 2012

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Take THDM II for illustration.

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

Z_2 symmetry: H_2 -> - H_2, U_R -> - U_R

Other fields do not change sign.

THDM II + D D play the role of DM

Potential: L = - VD -VH

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

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

Z'_2 ensure D stable: D -> -D, other fields do not change.

M_{12} term breaks Z_2, required by phenomenology

$$H_r = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, h_r^+ \\ v_r + h_r^0 + i I_r^0 \end{pmatrix}, \qquad r = 1, 2,$$

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

$$\begin{pmatrix} h_1^+ \\ h_2^+ \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} w^+ \\ H^+ \end{pmatrix}, \qquad \begin{pmatrix} I_1^0 \\ I_2^0 \end{pmatrix} = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} z \\ A \end{pmatrix},$$

$$\begin{pmatrix} h_1^0 \\ h_2^0 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}, \qquad c_\mathcal{X} = \cos \mathcal{X}, \quad s_\mathcal{X} = \sin \mathcal{X},$$

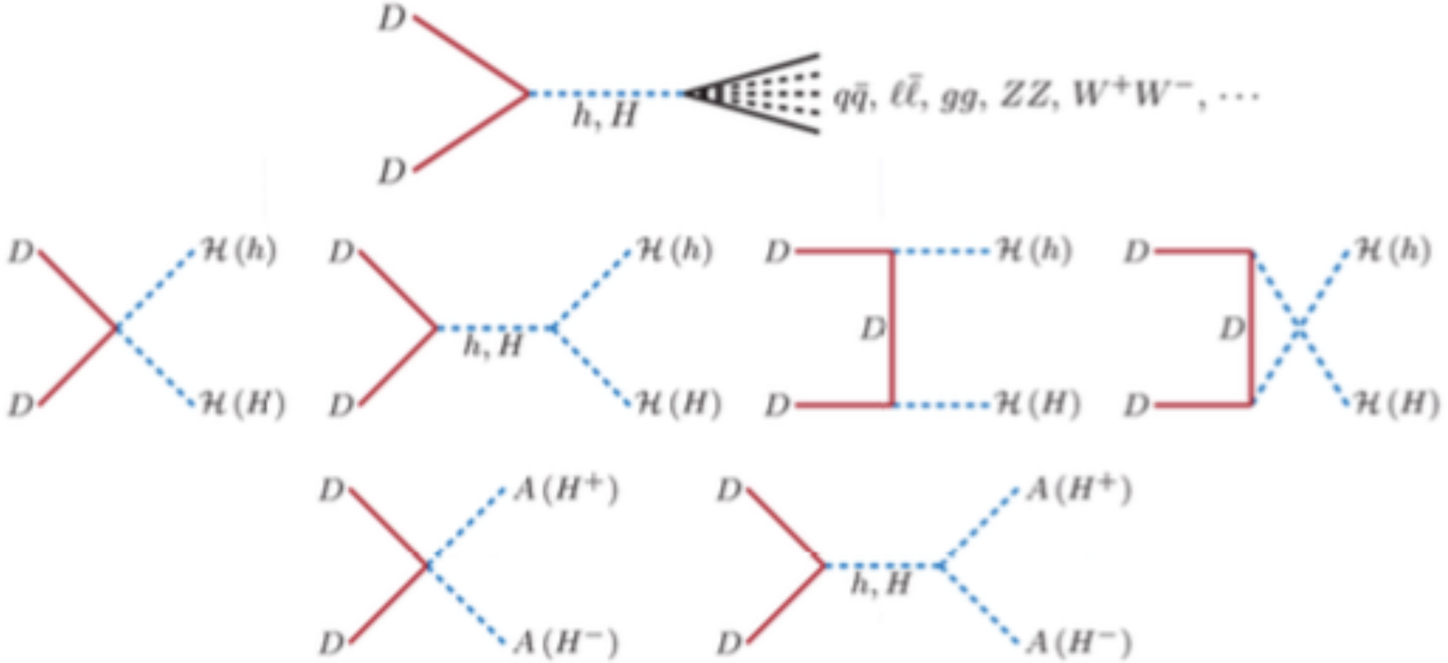
$$\begin{aligned} \mathcal{V} \supset\ & \tfrac{1}{2} m_D^2 D^2 + (\lambda_h h + \lambda_H H) D^2 v \\ & + \tfrac{1}{2}(\lambda_{hh} h^2 + 2\lambda_{hH}\, hH + \lambda_{HH} H^2 + \lambda_{AA} A^2 + 2\lambda_{H^+H^-} H^+ H^-) D^2 \\ & + \left(\tfrac{1}{6}\lambda_{hhh} h^2 + \tfrac{1}{2}\lambda_{hhH} hH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

$$\begin{aligned} \lambda_h &= \lambda_{2D}\, c_\alpha s_\beta - \lambda_{1D}\, s_\alpha c_\beta, & \lambda_H &= \lambda_{1D}\, c_\alpha c_\beta + \lambda_{2D}\, s_\alpha s_\beta, \\ \lambda_{hh} &= \lambda_{1D}\, s_\alpha^2 + \lambda_{2D}\, c_\alpha^2, & \lambda_{HH} &= \lambda_{1D}\, c_\alpha^2 + \lambda_{2D}\, s_\alpha^2, \\ \lambda_{hH} &= (\lambda_{2D} - \lambda_{1D}) c_\alpha s_\alpha, & \lambda_{AA} &= \lambda_{H^+H^-} = \lambda_{1D}\, s_\beta^2 + \lambda_{2D}\, c_\beta^2, \end{aligned}$$

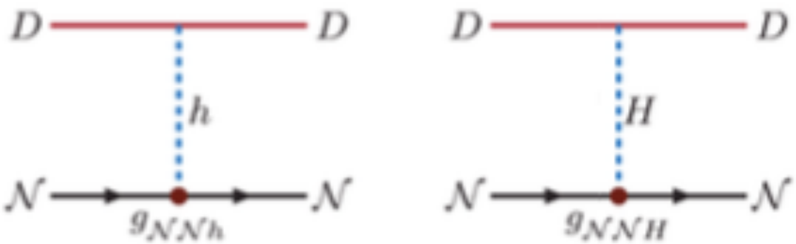
$$\lambda_{hh} = \left(\frac{c_\alpha^3}{s_\beta} - \frac{s_\alpha^3}{c_\beta} \right) \lambda_h + \frac{s_{2\alpha} c_{\beta-\alpha}}{s_{2\beta}} \lambda_H, \qquad \lambda_{HH} = \left(\frac{c_\alpha^3}{c_\beta} + \frac{s_\alpha^3}{s_\beta} \right) \lambda_H - \frac{s_{2\alpha} s_{\beta-\alpha}}{s_{2\beta}}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

$$\lambda_{hH} = \frac{s_{2\alpha}}{s_{2\beta}} (\lambda_h c_{\beta-\alpha} - \lambda_H s_{\beta-\alpha}), \qquad \lambda_{AA} = \lambda_{H^+H^-} = \frac{c_\alpha c_\beta^3 - s_\alpha s_\beta^3}{c_\beta s_\beta} \lambda_h + \frac{c_\alpha s_\beta^3 + s_\alpha c_\beta^3}{c_\beta s_\beta} \lambda_H.$$

Darkon annihilation



Darkon-*N* scattering



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

$\mathcal{N} = p, n$

$$\mathcal{L} \supset \left(2m_W^2 W^{+\mu} W_\mu^- + m_Z^2 Z^\mu Z_\mu\right)\left(k_V^h \frac{h}{v} + k_V^H \frac{H}{v}\right), \qquad k_V^h = s_{\beta-\alpha}, \qquad k_V^H = c_{\beta-\alpha}.$$

$$\mathcal{L}_Y \supset -\sum_q k_q^{\mathcal{H}} m_q \bar{q} q \frac{\mathcal{H}}{v}, \qquad k_{c,t}^{\mathcal{H}} = k_u^{\mathcal{H}}, \qquad k_{s,b}^{\mathcal{H}} = k_d^{\mathcal{H}},$$

$$k_u^h = \frac{\cos\alpha}{\sin\beta}, \qquad k_d^h = -\frac{\sin\alpha}{\cos\beta}, \qquad k_u^H = \frac{\sin\alpha}{\sin\beta}, \qquad k_d^H = \frac{\cos\alpha}{\cos\beta}.$$

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

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

$$g_{pp\mathcal{H}} = \left(0.5631\, k_u^{\mathcal{H}} + 0.5599\, k_d^{\mathcal{H}}\right) \times 10^{-3}, \qquad g_{nn\mathcal{H}} = \left(0.5481\, k_u^{\mathcal{H}} + 0.5857\, k_d^{\mathcal{H}}\right) \times 10^{-3}.$$

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

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

Possibilities to have large enough relic density, but smaller direct detection of DM

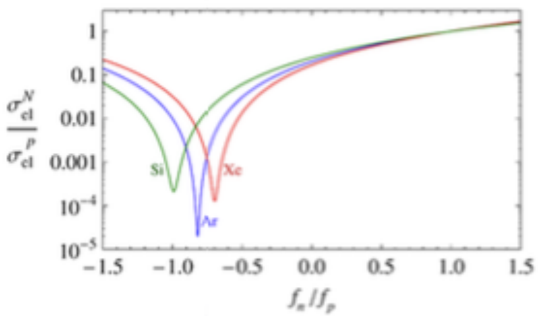
The WIMP-nucleon cross-section in the isospin-symmetric limit can be converted to the WIMP-proton cross-section, and vice versa, using

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

Feng *et al.*, 2011

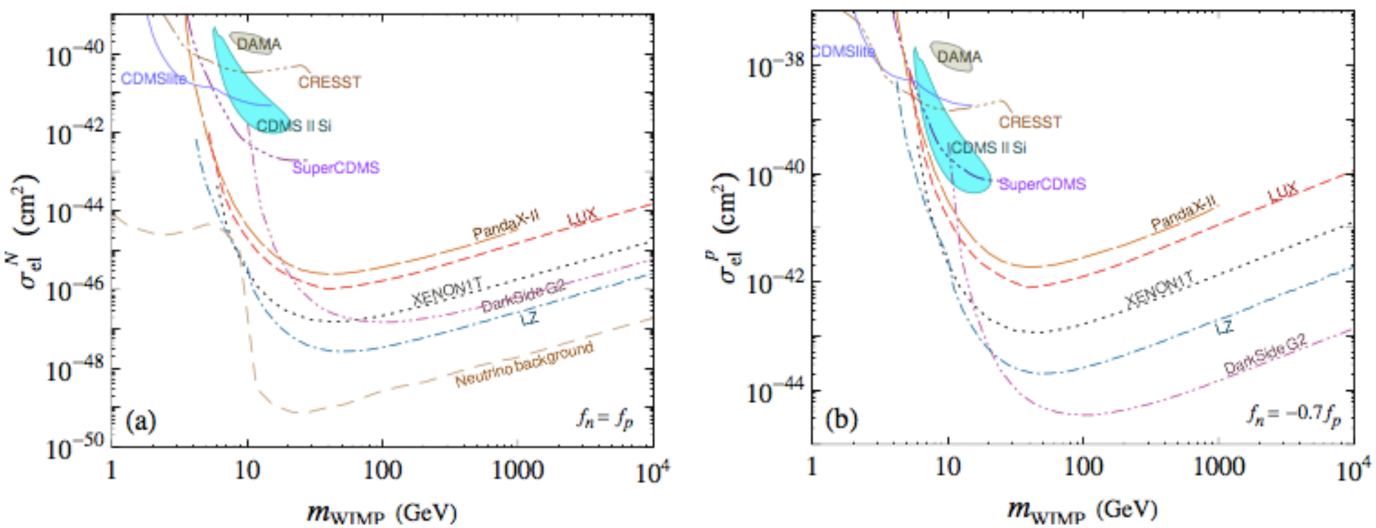
the sum is over isotopes of the element in the detector material with which the WIMP interacts dominantly, $\mathcal{Z}$ is proton number of the element, A_i (η_i) each denote the nucleon number (fractional abundance) of its isotopes, $\mu_{A_i} = m_{A_i} m_{\rm WIMP}/(m_{A_i} + m_{\rm WIMP})$ involving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

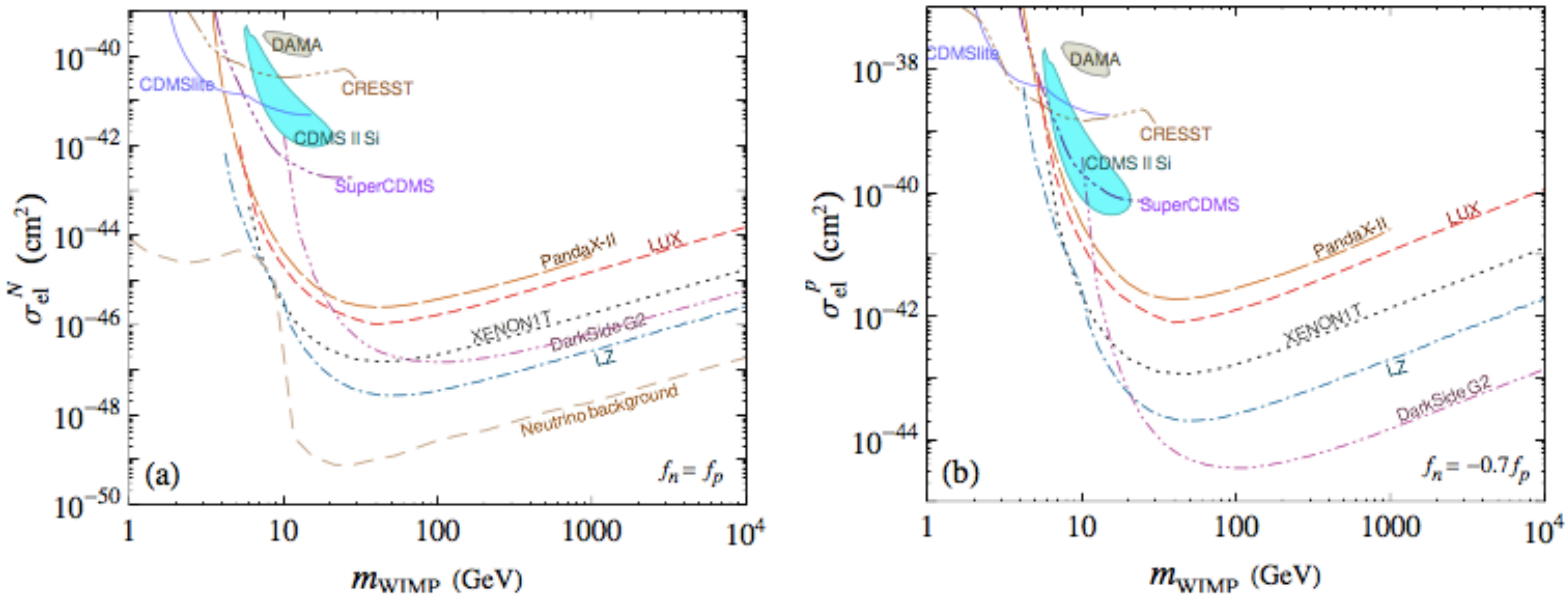


In THDM II+D

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



(a) (b)



DAMA
CRESST
CDMSlite
CDMS II Si
SuperCDMS
PandaX-II
LUX
XENON1T
DarkSide G2
LZ
Neutrino background
(a)
$f_n = f_p$
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
σ_{el}^{N} (cm^2)
1
10
100
1000
10^4
m_{WIMP} (GeV)
DAMA
CDMSlite
CRESST
CDMS II Si
SuperCDMS
PandaX-II
LUX
XENON1T
LZ
DarkSide G2
(b)
$f_n = -0.7 f_p$
10^{-38}
10^{-40}
10^{-42}
10^{-44}
σ_{el}^{p} (cm^2)
1
10
100
1000
10^4
m_{WIMP} (GeV)

(a) **(b)**

Constraints on the couplings

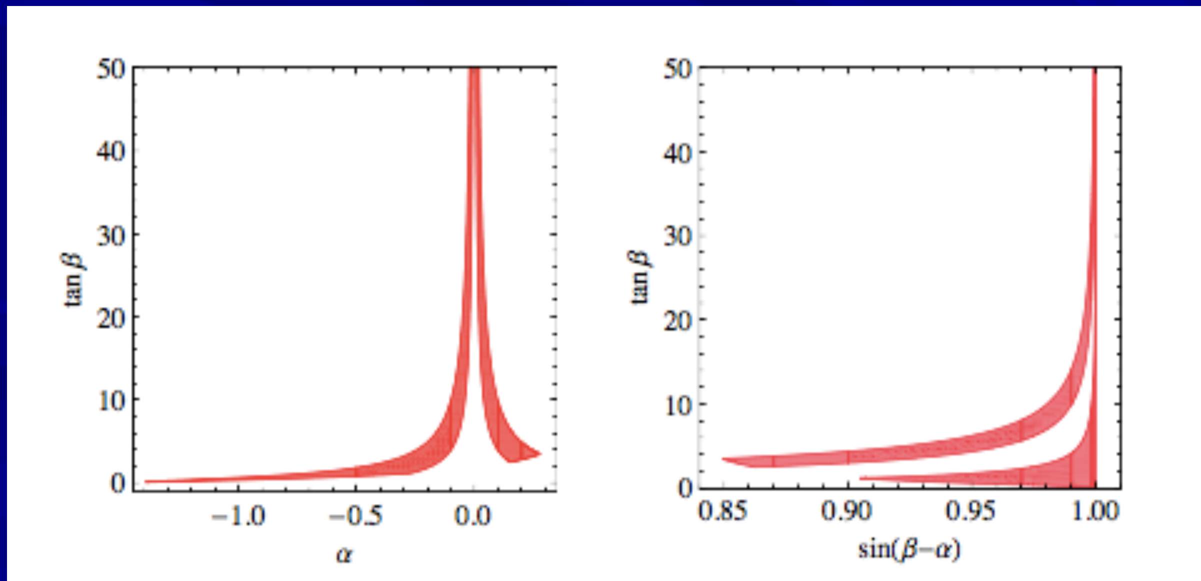
ATLAS and CMS

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

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

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

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



Additional constraints on THDM II+D

The LHC bound on the invisible decay of the 125-GeV Higgs boson applies to *h*.

Since the new scalars arise from the presence of a second Higgs doublet, their effects must satisfy oblique electroweak constraints.

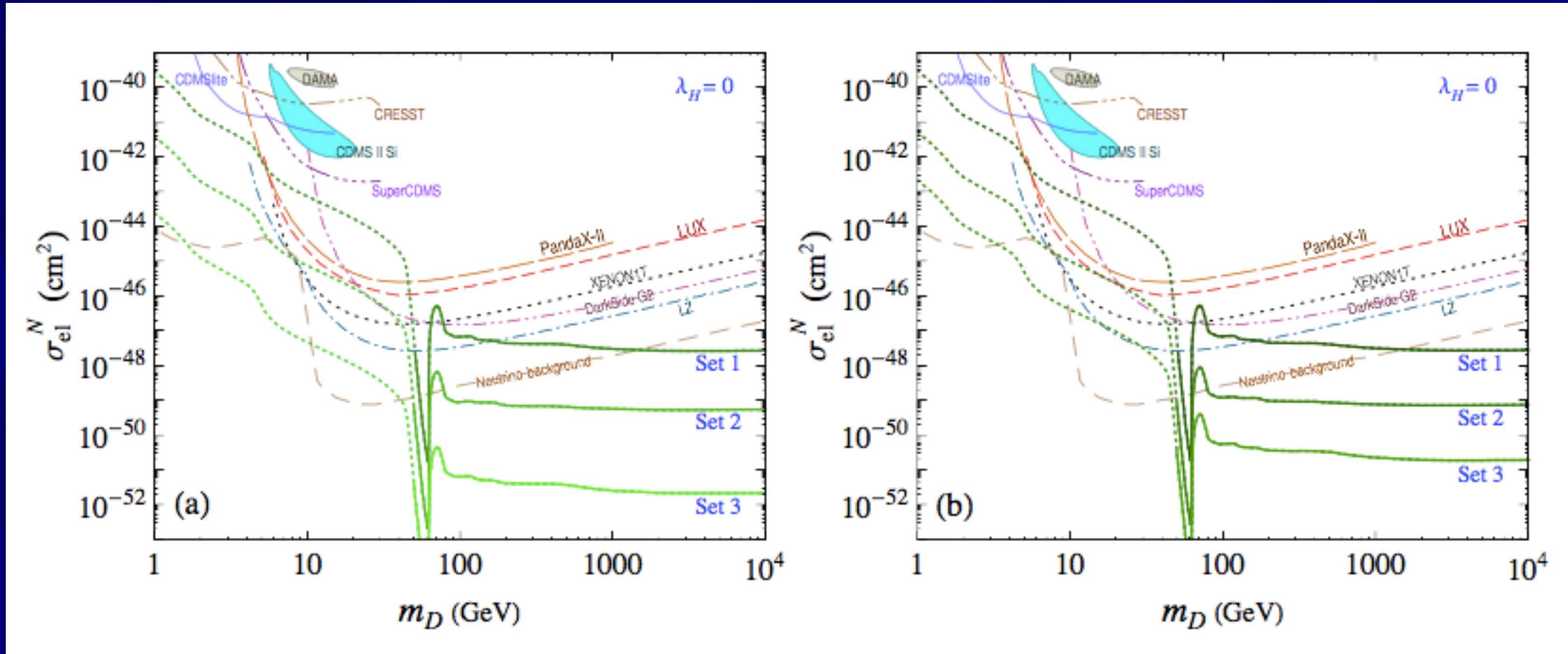
Theoretical requirements on the scalar potential can be important

- Perturbativity
- Vacuum stability
- Unitarity of scalar scattering amplitudes

Case studies

$\lambda_H=0$ h is the portal

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	$\frac{k_d^h}{k_u^h}$	$\frac{g_{pph}}{10^{-5}}$	$\frac{f_n}{f_p}$
1	0.147	1.370	470	500	550	43000	0.940	1.010	−0.727	15.7	+0.784
2	0.145	1.417	550	520	540	45800	0.956	1.001	−0.942	3.57	−0.101
3	0.206	1.357	515	560	570	55000	0.913	1.002	−0.962	2.42	−0.646



Important constraints from LHC:

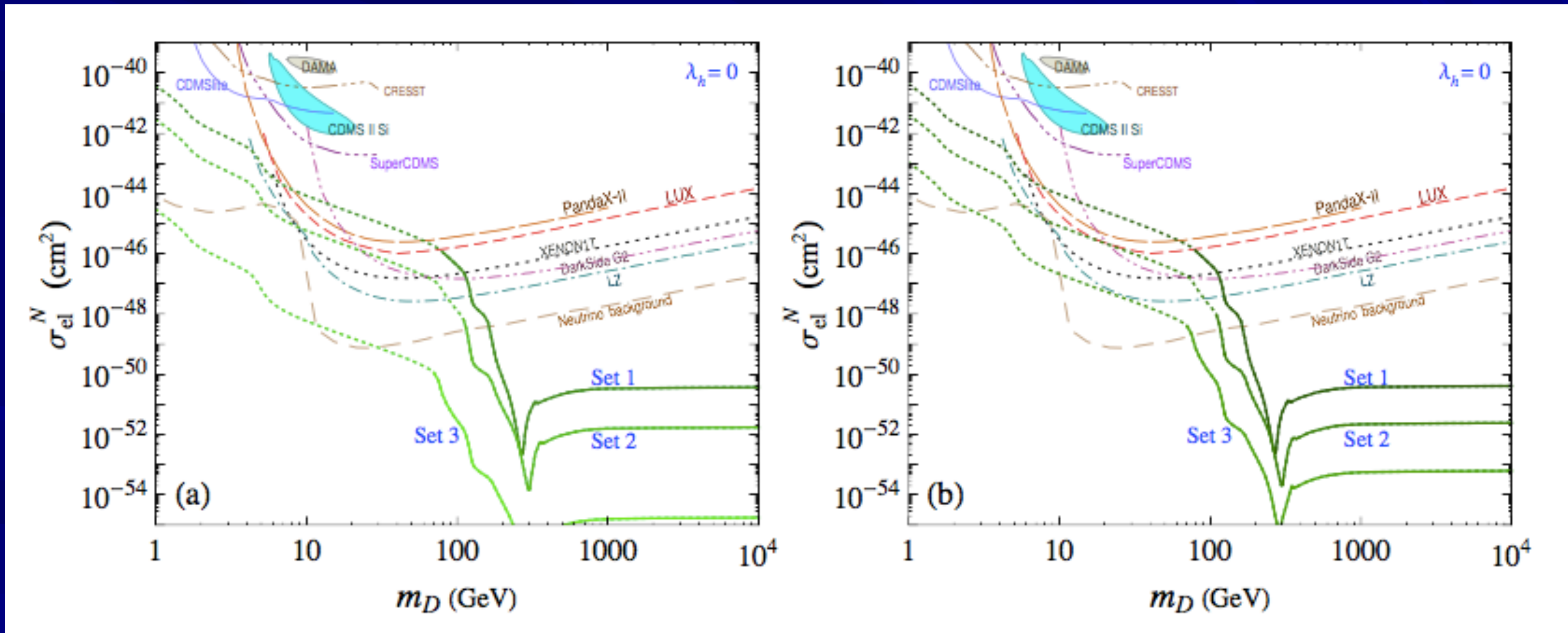
Invisible width less than 16% rule out DM mass less than about half of Higgs Mass!

Indicated by balck dashed line.

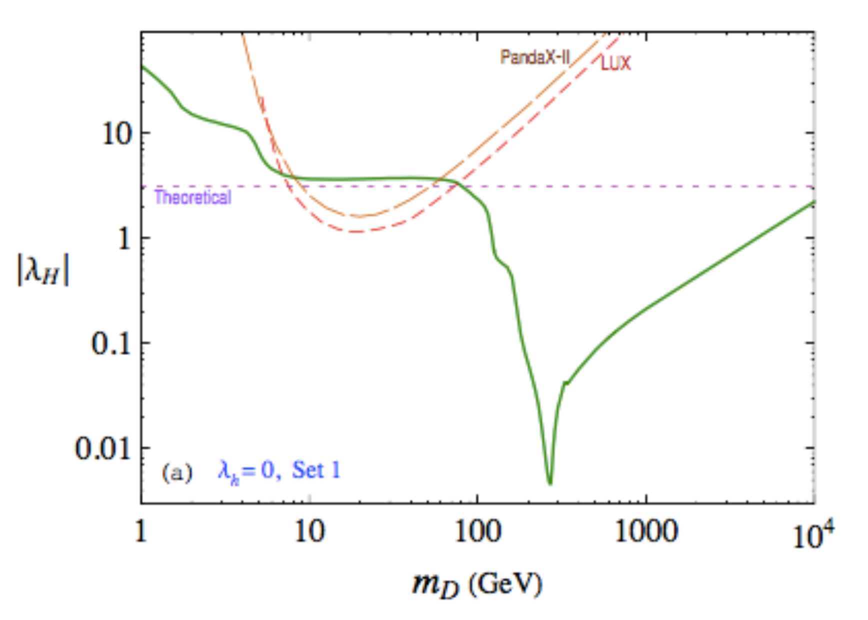
$\lambda_h = 0.$

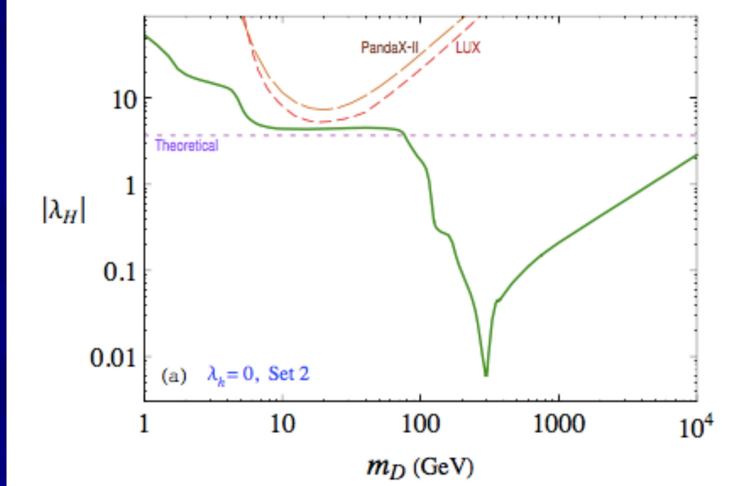
H is the portal

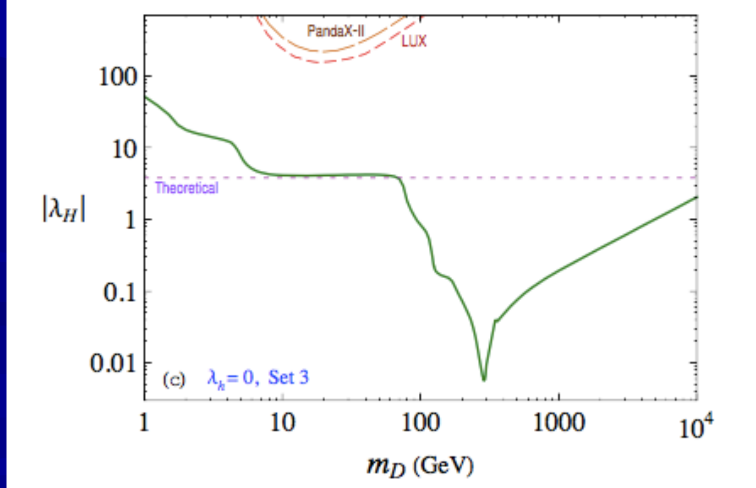
Set	α	β	$\frac{m_H}{\text{GeV}}$	$\frac{m_A}{\text{GeV}}$	$\frac{m_{H^\pm}}{\text{GeV}}$	$\frac{m_{12}^2}{\text{GeV}^2}$	k_V^h	k_u^h	k_d^h	k_V^H	k_u^H	$\frac{k_d^H}{k_u^H}$	$\frac{g_{ppH}}{10^{-5}}$	$\frac{f_n}{f_p}$
1	−0.785	0.738	550	600	650	70000	0.999	1.051	0.955	0.048	−1.051	−0.910	−5.62	+0.281
2	−0.793	0.764	610	750	740	80000	1.000	1.014	0.987	0.014	−1.030	−0.944	−3.57	−0.132
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



There are also considerations from perturbativity, vacuum stability and unitarity.







Conclusions

- In the Simplest darkon model, DM mass below 450 GeV is ruled out, except a small region near half of Higgs mass. There the cross section is close to the neutrino back ground floor.

- In THDM II + D model, a portion of DM range can be recovered, but LHC data and also theoretical considerations from perturbativity, vacuum stability and unitarity rule out DM mass below 60 GeV if the 125 GeV Higgs is the DM portal and 100 GeV if a heavy Higgs is the DM portal.