WIMP Dark Matter: from Simplified to more Realistic Models

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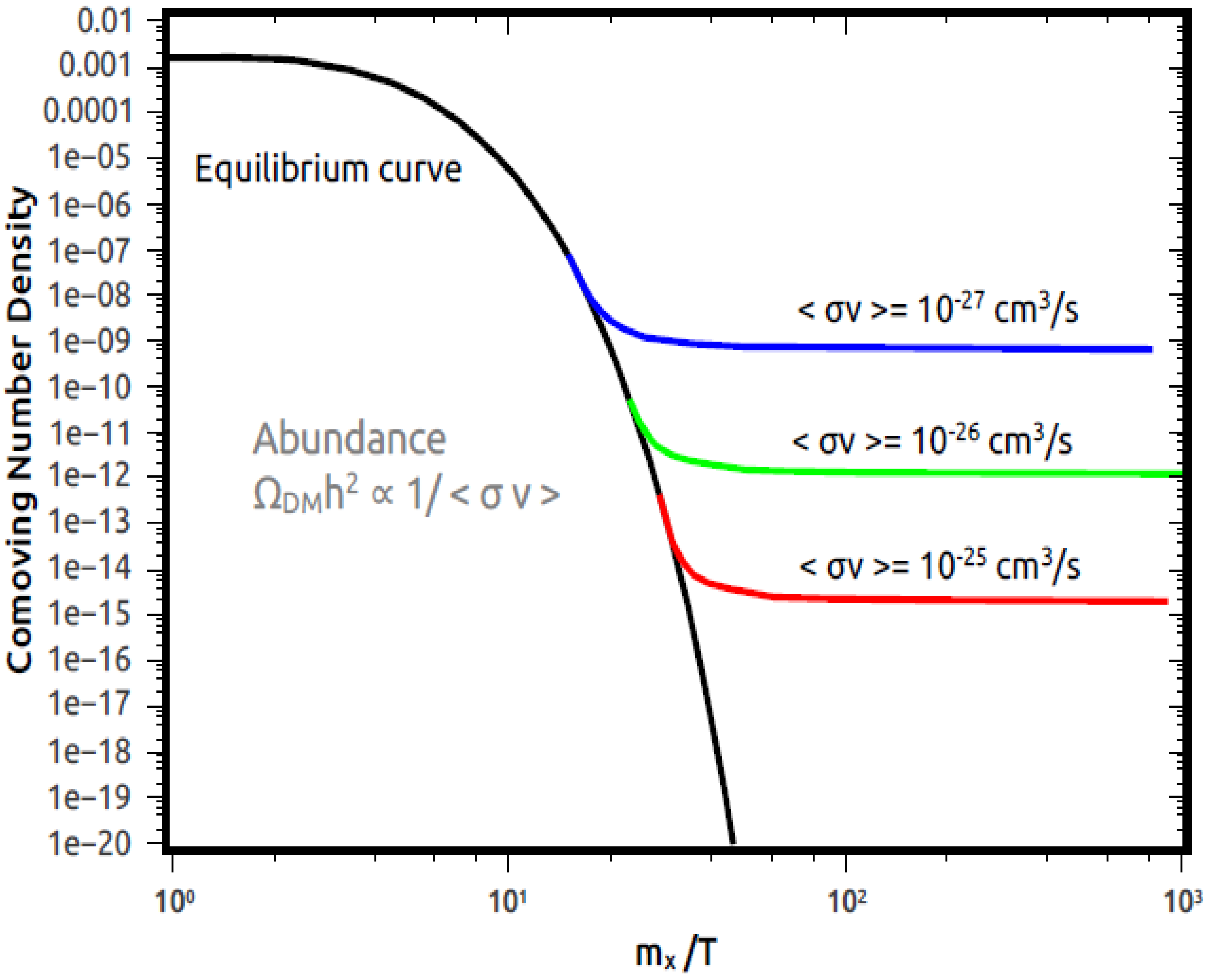
Dark Matter is one of the building blocks of the Standard Cosmological model.
Provides most of the matter contribution to the energy budget of the Universe.
Evidences from astrophysics and cosmology.

Stable on cosmological scales.
Weakly or SuperWeakly interacting with ordinary matter, photons.
Cold (up to warm) as opposed to hot.

No (confirmed) detection so far.

WIMP Paradigm



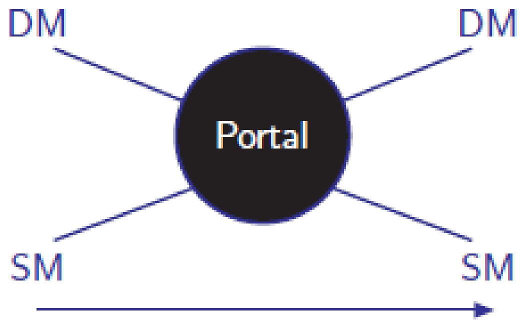
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\rm ann} v \rangle \left(n^2 - n_{\rm eq}^2\right)$$

$$\frac{dY}{dx} = \frac{1}{3H}\frac{ds}{dx}\langle \sigma v \rangle \left(Y^2 - Y_{eq}^2\right)$$

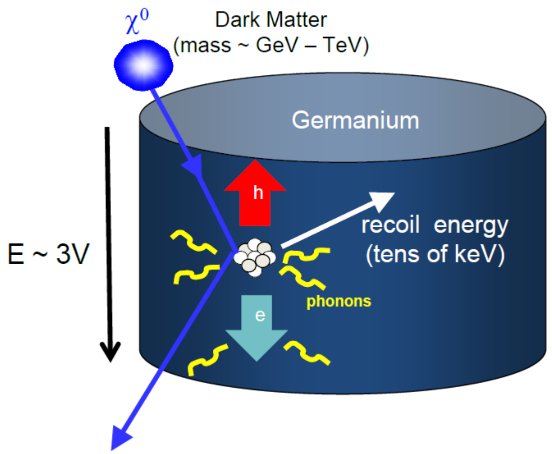
$$\Omega h^2 \theta^{-3} \approx 8.7661 \times 10^{-11}\,\mathrm{GeV}^{-2}\left[\int_{T_0}^{T_f} \overline{g_{\rm eff}}^{1/2} \langle \sigma v_{\rm M\o l} \rangle \frac{\mathrm{d}T}{m}\right]^{-1}$$

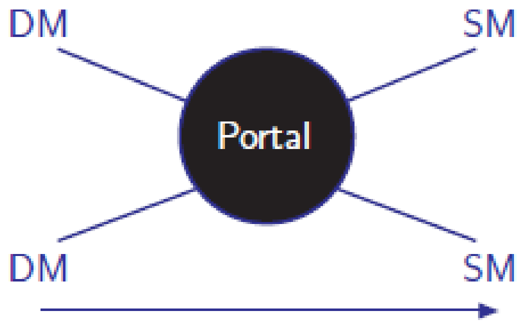
$$\langle \sigma v \rangle = a + bv^2$$

Simplified models: “Dark portals“

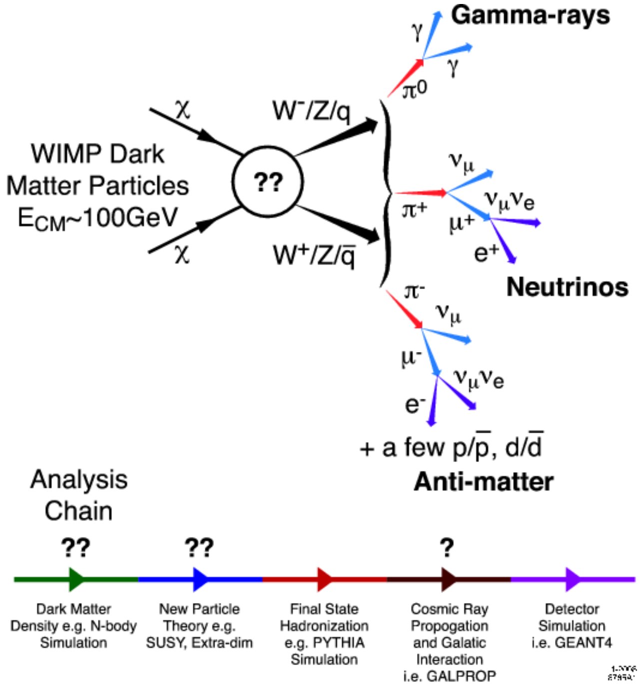


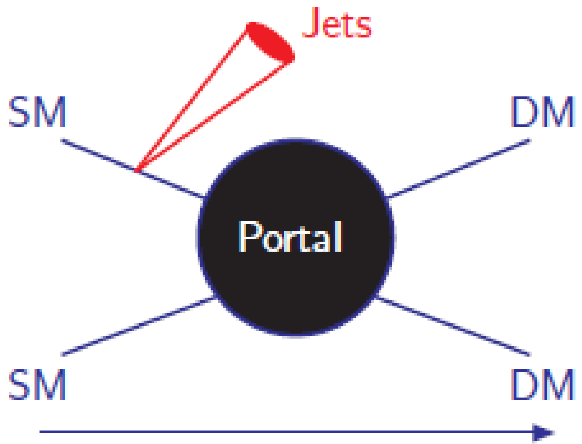
(a) Direct Detection



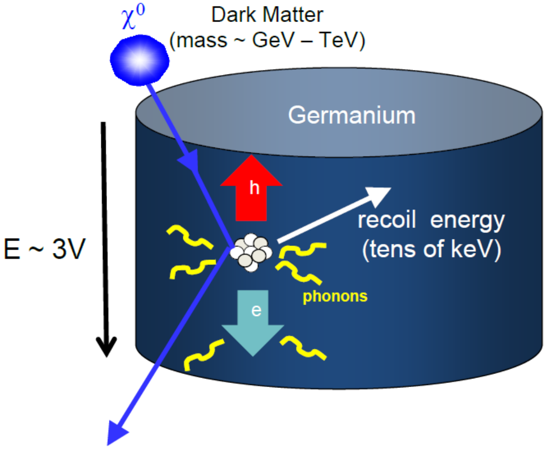


(b) Indirect Detection

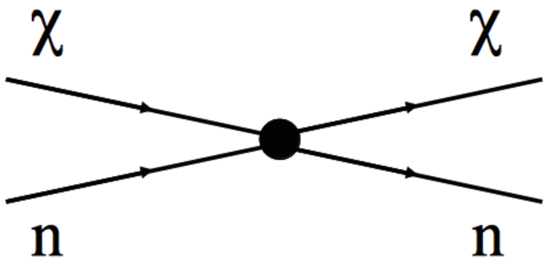


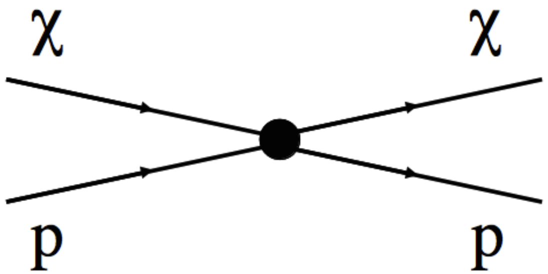


(c) Collider Detection

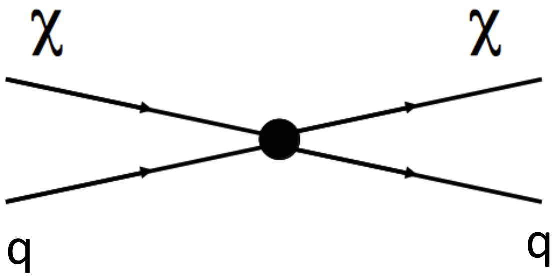


$$\sigma_{\chi T} = \frac{\mu_{\chi T}^2}{\pi m_{\rm med}^4} \sum_{c_N^i} c_N^j c_N^j |F^{ij}_{NN'}(q^2)|^2$$





$$\mathcal{L} = \sum_{ij} \frac{g_\chi^i g_N^j}{m_{\rm med}^2} \bar{\chi}\Gamma_i^\mu \chi \bar{N} \Gamma_{j\mu} N \longrightarrow \sigma_{\chi N}$$



$$\mathcal{L} = \sum_{ij} \frac{g_\chi^i g_q^j}{m_{\rm med}^2} \bar{\chi}\Gamma_i^\mu \chi \bar{q} \Gamma_{j\mu} q$$

$$\frac{dR(E_R,t)}{dE_R} = \frac{N_T \rho_\chi}{m_\chi m_T} \int_{v_{\min}}^{v_{\rm esc}} v f_E(\vec{v},t) \frac{d\sigma_{\chi T}(v,E_R)}{dE_R} d^3\vec{v} \qquad f_E(v) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{|v|^2}{2\sigma^2}\right]$$

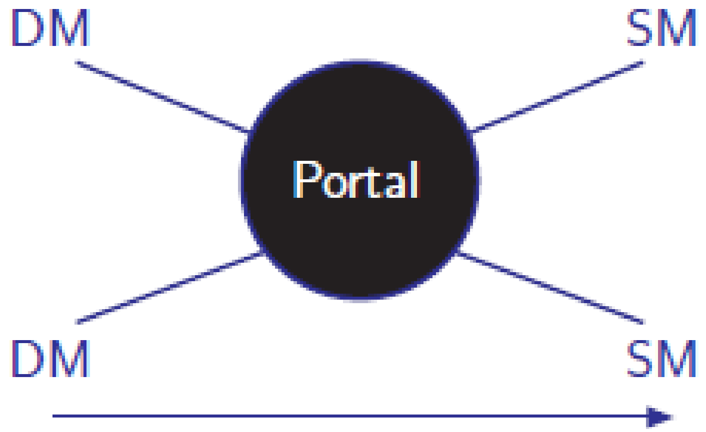
$$R = \int_{E_{\rm th}}^{E_{\max}} dE_R \frac{N_T \rho_\chi}{m_\chi m_T} \int_{v_{\min}}^{v_{\rm esc}} v f_E(\vec{v},t) \frac{d\sigma_{\chi T}(v,E_R)}{dE_R} d^3\vec{v}$$

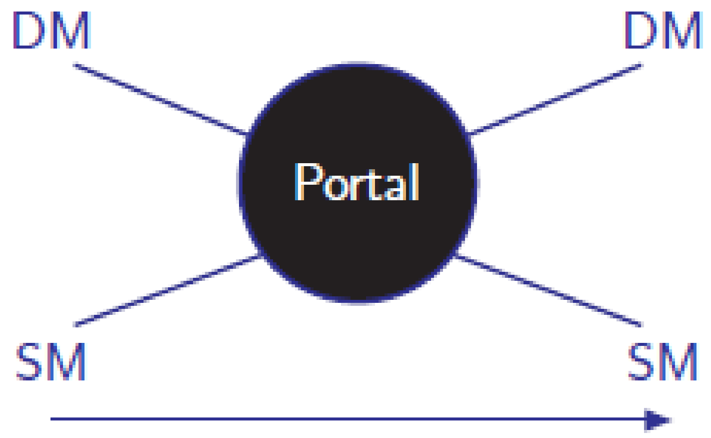
Conventionally:

$$\frac{d\sigma_{\chi T}}{dE_R} = \left(\frac{d\sigma_{\chi T}}{dE_R}\right)_{\rm SI} + \left(\frac{d\sigma_{\chi T}}{dE_R}\right)_{\rm SD} = \frac{m_T}{2\mu_T^2 v^2}(\sigma^{SI}_{\chi T,0}|F^{\rm SI}(q)|^2 + \sigma^{SD}_{\chi T,0}|F^{\rm SD}(q)|^2)$$

$$\sigma^{\rm SI}_{\chi T,0} \approx \left[\frac{\mu_{\chi T}}{\mu_{\chi p}} Z \sqrt{\sigma^{\rm SI}_{\chi p}} + \frac{\mu_{\chi T}}{\mu_{\chi n}} (A-Z) \sqrt{\sigma^{\rm SI}_{\chi n}}\right]^2$$

$$\sigma^{\rm SD}_{\chi T,0} \propto \left[S_p \frac{\mu_{\chi T}}{\mu_{\chi p}} \sqrt{\sigma^{\rm SD}_{\chi p}} + S_n \frac{\mu_{\chi T}}{\mu_{\chi p}} \sqrt{\sigma^{\rm SD}_{\chi n}}\right]^2$$





Relic Density

$$\langle \sigma v \rangle \approx \frac{\lambda_f^2 \lambda_\chi^2 m_\chi^2}{(4m_\chi^2 - m_{\rm med}^2)^2}(a + b v_{\rm f.o}^2)$$

$$\sigma_{\chi N} = \frac{\mu_{\chi N}^2}{\pi m_{\rm med}^4} f(\lambda_q)$$

$v_{\rm f.o} \sim 0.3$

s-wave

p-wave

Indirect Detection

$$\langle \sigma v \rangle \approx \frac{\lambda_f^2 \lambda_\chi^2 m_\chi^2}{(4m_\chi^2 - m_{\rm med}^2)^2}(a + b v_{\rm now}^2)$$

$v_{\rm now} \sim 10^{-3}$

Higgs portal

$$\mathcal{L}_\chi = \lambda_\chi^H \chi^* \chi H^\dagger H$$
$$\mathcal{L}_\psi = \frac{\lambda_\psi^H}{\Lambda} \overline{\psi} \psi H^\dagger H$$
$$\mathcal{L}_V = \lambda_V^H V^\mu V_\mu H^\dagger H$$

$$\Big\downarrow \quad H = \left(0, \frac{v_h + h}{\sqrt{2}}\right)^T$$

$$\mathcal{L}_\chi = \lambda_\chi^H v_h \chi^* \chi h + \lambda_\chi^H \chi^* \chi h h,$$
$$\mathcal{L}_\psi = \lambda_\psi^H v_h \overline{\psi} \psi h + \lambda_\psi^H \overline{\psi} \psi h h$$
$$\mathcal{L}_V = \lambda_V^H v V^\mu V_\mu h + \lambda_V^H V^\mu V_\mu h h$$

$$\langle \sigma v \rangle_{ff}^{\chi} = \sum_f n_f^c \frac{(\lambda_\chi^H)^2 m_f^2 \left(m_\chi^2 - m_f^2\right)^{3/2}}{8\pi m_\chi^3 v_h^2 \left(m_h^2 - 4m_\chi^2\right)^2}$$

$$\sigma_{\chi p}^{\mathrm{SI}} = \frac{\mu_{\chi p}^2}{4\pi} \frac{(\lambda_\chi^H)^2}{m_\chi^2} \frac{m_p^2}{m_h^4} \left[f_p \frac{Z}{A} + f_n \left(1 - \frac{Z}{A}\right)\right]^2$$

$$\langle \sigma v \rangle_{ff}^{\psi} = (\lambda_\psi^H)^2 \sum_f n_c^f \frac{(m_f)^2 \left(m_\psi^2 - m_f^2\right)^{3/2}}{4\pi m_\psi v_h^2 \left(m_h^2 - 4m_\psi^2\right)^2} v^2$$

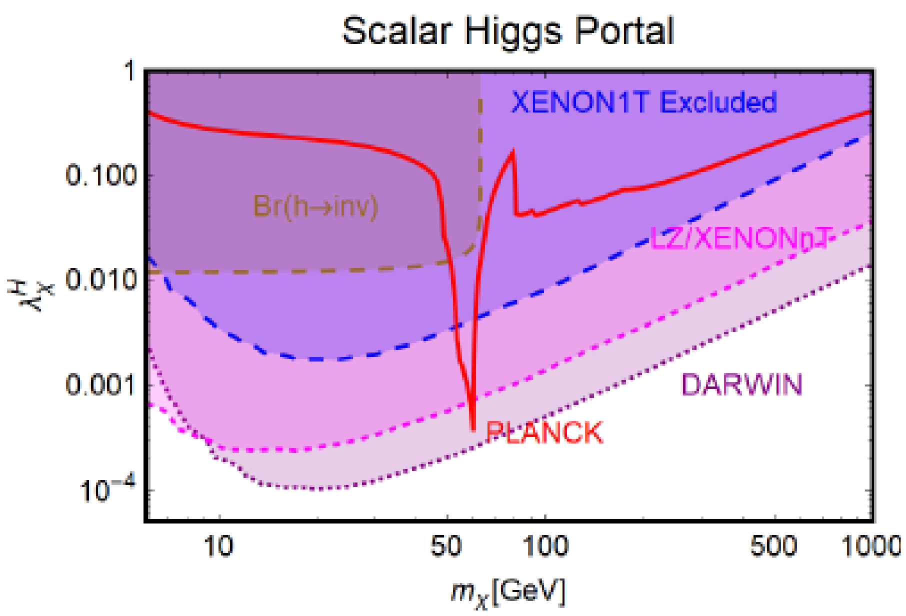
$$\sigma_{\psi p}^{\mathrm{SI}} = \frac{\mu_{\psi p}^2}{\pi} (\lambda_\psi^H)^2 \frac{m_p^2}{v_h^2 m_h^4} \left[f_p \frac{Z}{A} + f_n \left(1 - \frac{Z}{A}\right)\right]^2$$

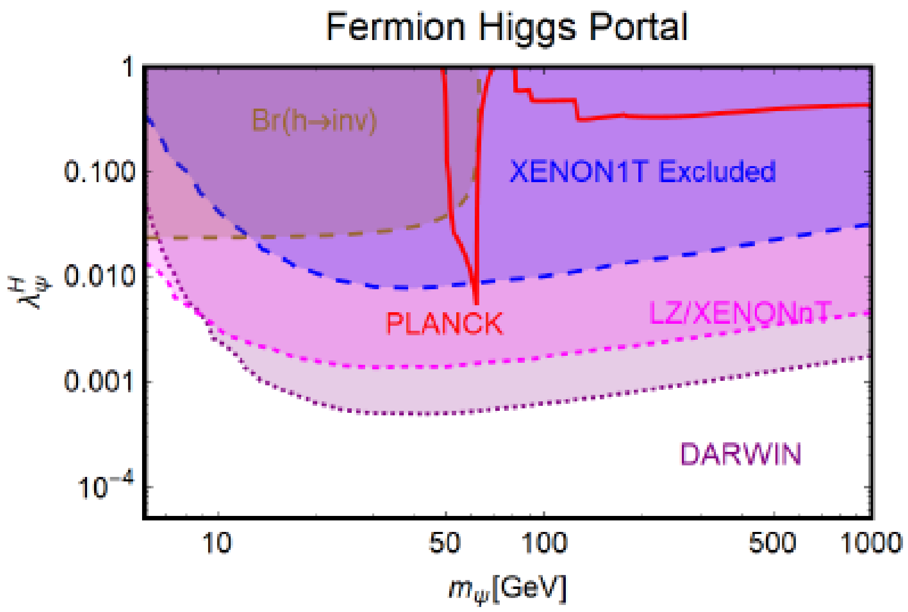
$$\langle \sigma v \rangle_{ff}^{V} = \sum_f n_c^f (\lambda_V^H)^2 m_f^2 \frac{\sqrt{4 - \frac{4m_f^2}{m_V^2}} \left(4m_V^2 - 4m_f^2\right)}{96\pi v_h^2 m_V^2 \left(4m_V^2 - m_h^2\right)^2}$$

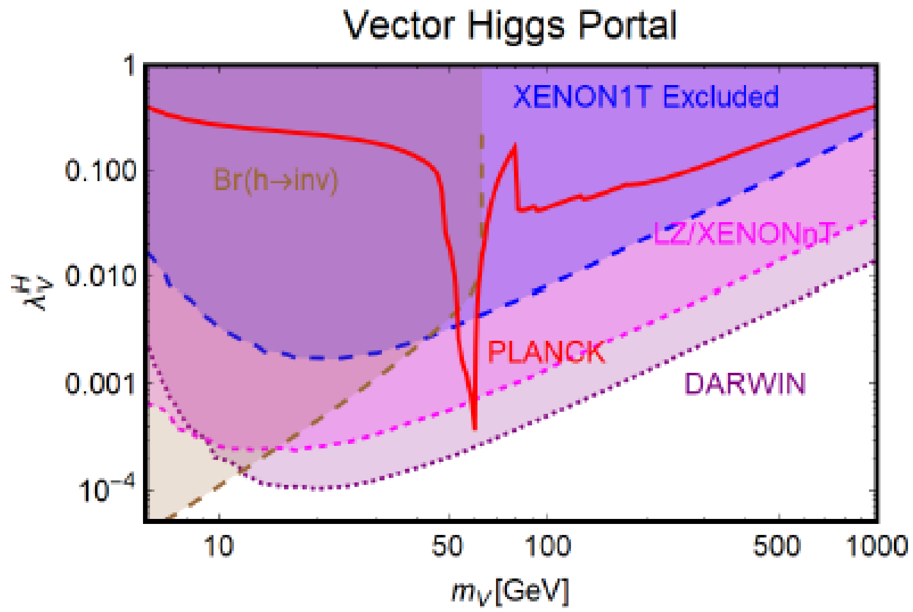
$$\sigma_{Vp}^{\mathrm{SI}} = \frac{\mu_{Vp}^2}{4\pi} (\lambda_V^H)^2 \frac{m_p^2}{m_h^4 m_V^2} \left[f_p \frac{Z}{A} + f_n \left(1 - \frac{Z}{A}\right)\right]^2$$

$$f_N = \sum_{q=u,d,s} f_q^N + \frac{6}{27} f_{\mathrm{TG}}^N,$$

$$f_{\mathrm{TG}}^N = 1 - \sum_{q=u,d,s} f_q^N, \quad N = p, n,$$


Scalar Higgs Portal
XENON1T Excluded
Br(h→inv)
LZ/XENONnT
DARWIN
PLANCK
λ_χ^H
m_χ[GeV]


Fermion Higgs Portal
Br(h→inv)
XENON1T Excluded
PLANCK
LZ/XENONnT
DARWIN
λ_ψ^H
m_ψ[GeV]


Vector Higgs Portal
XENON1T Excluded
Br(h→inv)
LZ/XENONnT
PLANCK
DARWIN
λ_V^H
m_V[GeV]

From Simplied to Realistic Models

Higgs portals, and more in general, simplified models with SI cross-section are under strong experimental pressure.

It is then worth asking whether these are overconstrained scenarios.

We should then investigate whether realistic models retain this feature or instead propose solutions to alleviate tensions with experimental constraints.

How to reduce the correlation between Relic Density and Direct Detection

Dominant annihilation into mediator pairs

$$\langle \sigma v \rangle \approx \frac{\lambda_\chi^4}{m_\chi^2}(a + b v^2)$$

Dominant annihilation into extra not SM states

$$\langle \sigma v \rangle \approx \frac{\lambda_\psi^2 \lambda_\chi^2 m_\chi^2}{(4 m_\chi^2 - m_{\rm med}^2)^2}(a + b v_{\rm f.o}^2)$$

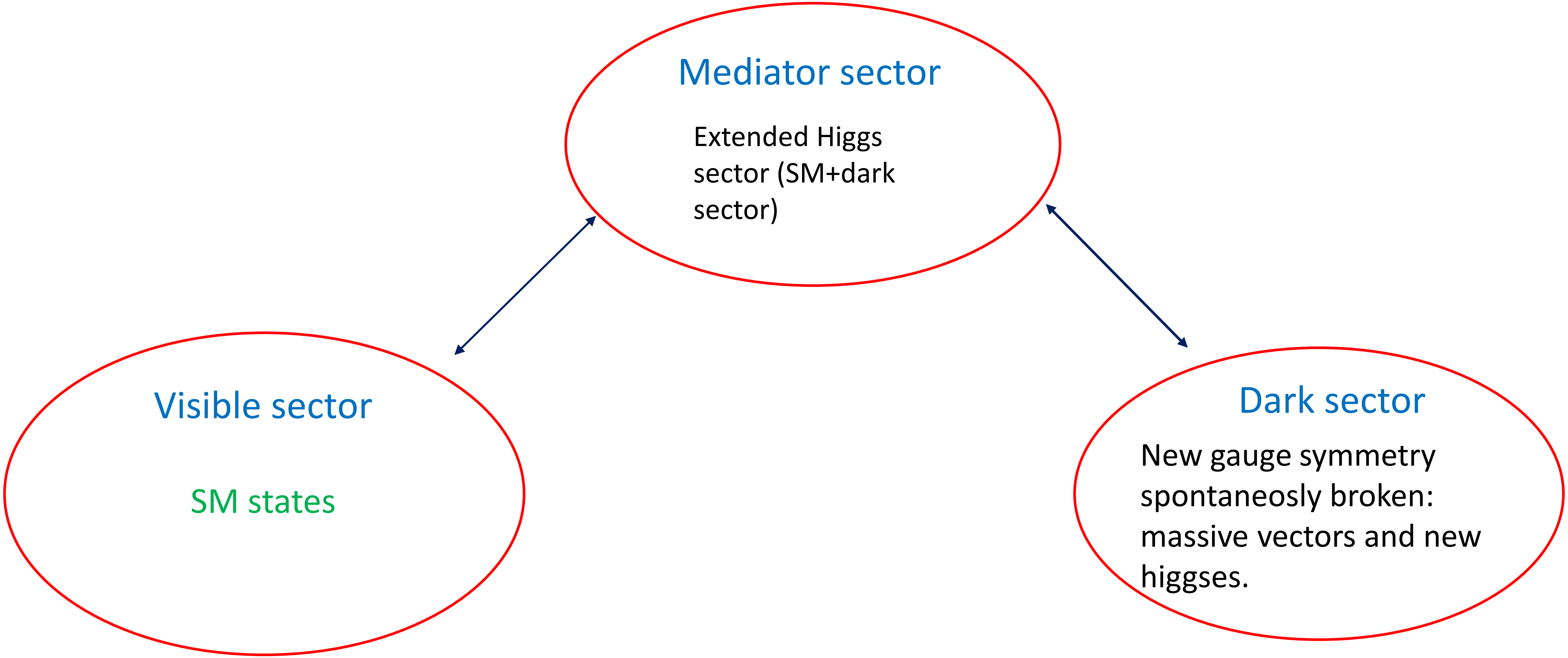
Secluded limit

Coannihilations

$$\langle \sigma v \rangle = \langle \sigma v \rangle(\chi_1 \chi_1 \rightarrow SMSM) + \sum_{i,j} \frac{g_i g_j}{g_{\rm DM}^2} \langle \sigma v \rangle(\chi_i \chi_j \rightarrow SMSM) \exp\left[-\frac{m_i - m_1}{T}\right] \exp\left[-\frac{m_j - m_1}{T}\right]$$

DM from gauge dark symmetry

C. Gross, O. Lebedev, Y. Mambrini, arXiv:1505.07480
G.A. , C. Gross, O. Lebedev, Y. Mambrini, S. Pokorski, T. Toma, arXiv:1611.00365

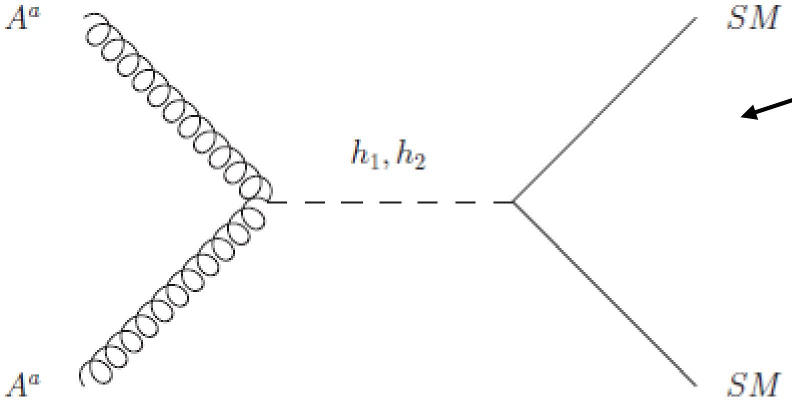


SM Higgs

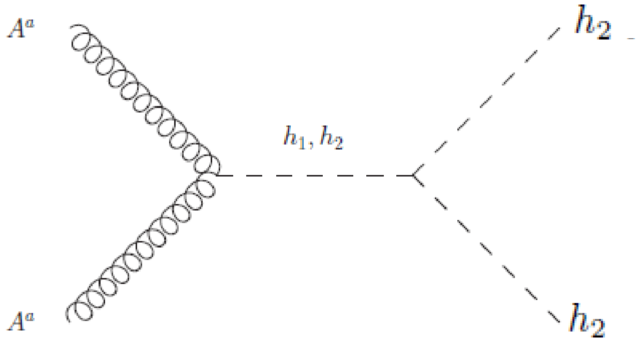
Dark Higgs

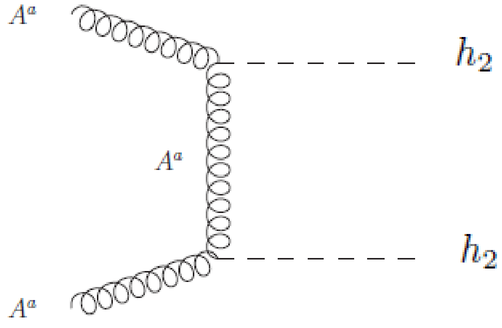
$$V_{\rm portal} = \sum_i \lambda_{H\phi_i} |H|^2 |\phi_i|^2$$

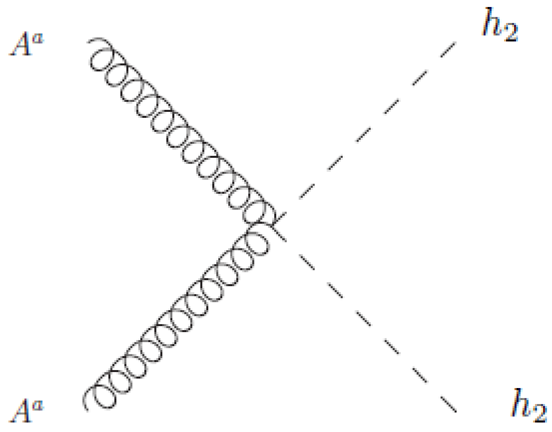
$$\rho = -h_1 \sin\theta + h_2 \cos\theta$$
$$h = h_1 \cos\theta + h_2 \sin\theta$$



Rates not dependent by small mixing angle







Annihilation rates scaling as $\sin^2\theta$ <<1

$$\sigma^{\rm SI}_{A-N} = \frac{g^2 \tilde{g}^2}{16\pi} \frac{m_N^4 f_N^2}{m_W^2} \frac{(m_{h_2}^2 - m_{h_1}^2)^2 \sin^2\theta \; \cos^2\theta}{m_{h_1}^4 m_{h_2}^4}$$

Simplest case U(1)

$$\mathcal{L}_{\rm hidden} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + (D_\mu \phi)^\dagger D^\mu \phi - V(\phi)$$

U(1) spontaneosly broken $\longrightarrow$ $A_\mu \to -A_\mu$

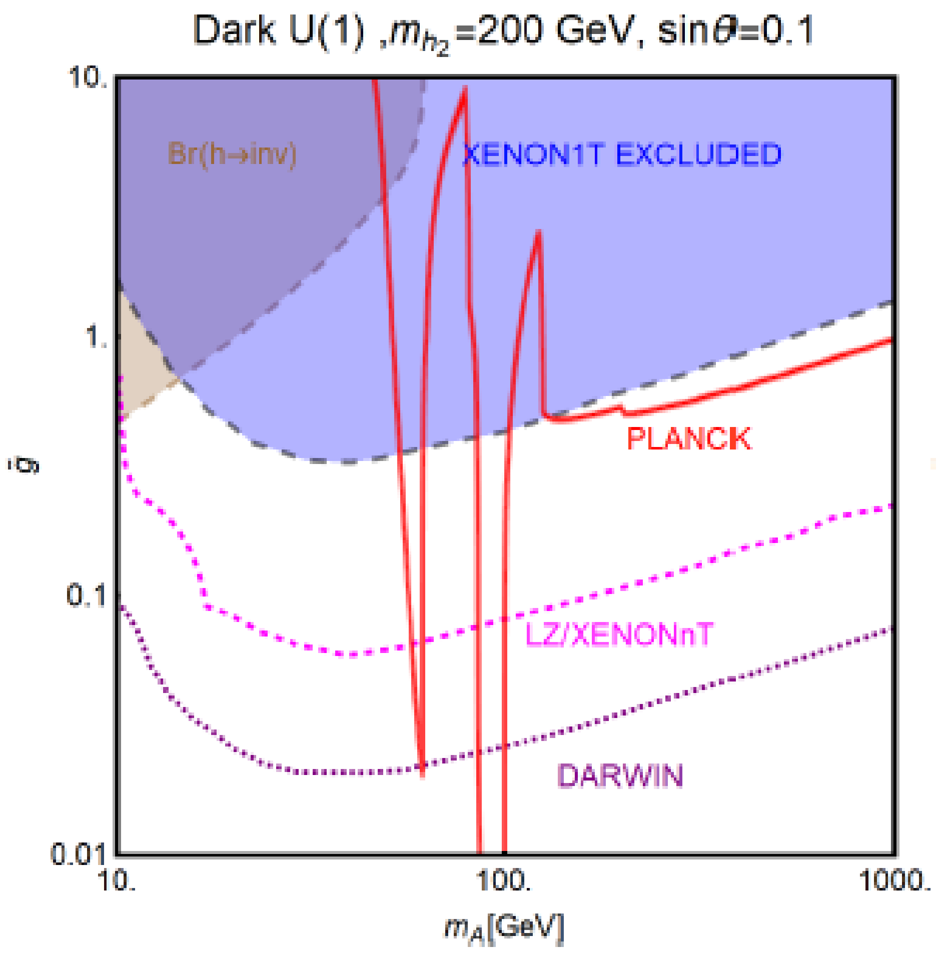
Spontaneous breaking leaves a residual Z_2 symmetry

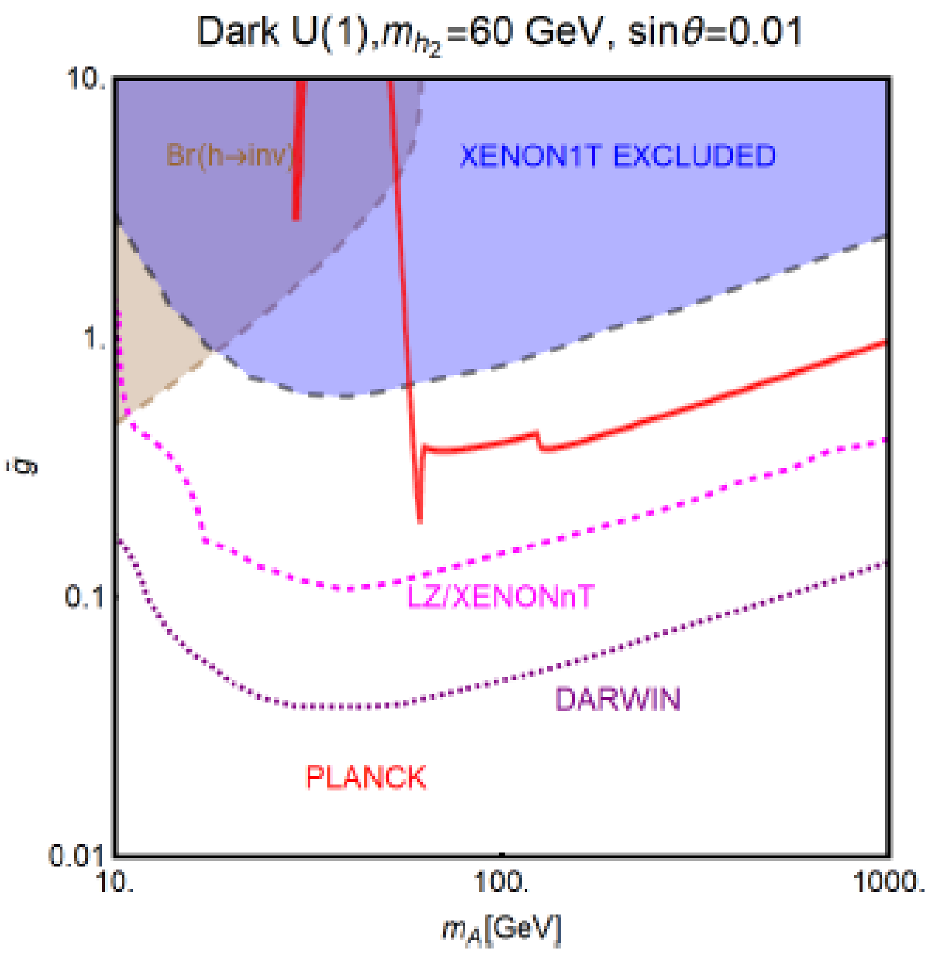
$$\mathcal{L}_{\rm portal} = -\lambda_{h\phi} |H|^2 |\phi|^2$$

$$\rho = -h_1 \ \sin\theta + h_2 \ \cos\theta$$
$$h = h_1 \ \cos\theta + h_2 \ \sin\theta$$

$$\Delta\mathcal{L}_{\rm s-g} = \frac{\tilde{g}^2}{4} \tilde{v} \rho \ A_\mu A^\mu + \frac{\tilde{g}^2}{8} \rho^2 \ A_\mu A^\mu$$

G.A., C. Gross, O. Lebedev, S. Pokorski, T. Toma, 1611.09675





DM annihilation is enhanced by dark Higgs final state without affecting the direct detection rate. LUX bounds are typically evaded at high DM masses.

SU(3) dark symmetry

$$-\mathcal{L}_{\rm portal} = V_{\rm portal} = \lambda_{H11}\,|H|^2|\phi_1|^2 + \lambda_{H22}\,|H|^2|\phi_2|^2 - (\lambda_{H12}\,|H|^2\phi_1^\dagger\phi_2 + \text{h.c.})$$

$$\mathcal{L}_{\rm hidden} = -\frac{1}{2}\text{tr}\{G_{\mu\nu}G^{\mu\nu}\} + |D_\mu\phi_1|^2 + |D_\mu\phi_2|^2 - V_{\rm hidden}$$

$$SU(3)_x \longrightarrow Z_2 x Z_2'$$

The minimal way to break the dark gauge group is through two fields in the fundamental representation

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ v_1+\varphi_1 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2+\varphi_2 \\ (v_3+\varphi_3)+i(\chi) \end{pmatrix}$$

Vector mass spectrum

$$m^2_{A^1} = m^2_{A^2} = \frac{\tilde{g}^2}{4} v_2^2$$

$$m^2_{A^4} = m^2_{A^5} = \frac{\tilde{g}^2}{4} v_1^2$$

$$m^2_{A^6} = m^2_{A^7} = \frac{\tilde{g}^2}{4} (v_1^2 + v_2^2)$$

$$m^2_{A^{8\prime}} = \frac{\tilde{g}^2 v_1^2}{3} \frac{1}{1 - \frac{\tan\alpha}{\sqrt{3}}}$$

$$m^2_{A^{3\prime}} = \frac{\tilde{g}^2 v_2^2}{4} \left(1 - \frac{\tan\alpha}{\sqrt{3}}\right)$$

$$A^{3\,\prime}_\mu = A^3_\mu \cos\alpha + A^8_\mu \sin\alpha$$
$$A^{8,\,\prime}_\mu = A^8_\mu \cos\alpha - A^3_\mu \sin\alpha$$

$$\alpha = \begin{cases} \frac{1}{2}\arctan\left(\frac{\sqrt{3}v_2^2}{2v_1^2 - v_2^2}\right) & \text{for} \quad v_2^2 \leq 2v_1^2 \\ \frac{1}{2}\arctan\left(\frac{\sqrt{3}v_2^2}{2v_1^2 - v_2^2}\right) + \frac{\pi}{2} & \text{for} \quad v_2^2 > 2v_1^2 \end{cases}$$

Scalar mass spectrum

$$\mathcal{L} = \frac{1}{2}\Phi^T m^2_{\mathrm{CP-even}}\Phi + \frac{1}{4}(\lambda_4 - \lambda_5)(v_1^2 + v_2^2)\chi^2 \qquad \Phi = (h, \varphi_1, \varphi_2, \tilde{\varphi}_3)^T$$

$$m^2_{\mathrm{CP-even}} \approx \begin{pmatrix} \lambda_H v^2 & \lambda_{H11} v v_1 & \lambda_{H22} v v_2 & 0 \\ \lambda_{H11} v v_1 & \lambda_1 v_1^2 & \lambda_3 v_1 v_2 & 0 \\ \lambda_{H22} v v_2 & \lambda_3 v_1 v_2 & \lambda_2 v_2^2 & 0 \\ 0 & 0 & 0 & (\lambda_4 + \lambda_5)(v_1^2 + v_2^2)/2 \end{pmatrix}$$

$$h_1 = \cos\theta h - \sin\theta \varphi_2$$
$$h_2 = \sin\theta h + \cos\theta \varphi_2$$

$$h_3 \simeq \varphi_1 \qquad m^2_{h_3} = \lambda_1 v_1^2$$

$$h_4 \simeq \varphi_3 \qquad m_{h_4} = \sqrt{(\lambda_4 + \lambda_5)(v_1^2 + v_2^2)/2}$$

gauge eigenstates	mass eigenstates	$\mathbb{Z}_2 \times \mathbb{Z}_2'$
h, φ_i, A^7_μ	$h_i, \tilde{h}_4, \tilde{A}^7_\mu$	$(+,+)$
A^1_μ, A^4_μ	A^1_μ, A^4_μ	$(-,-)$
A^2_μ, A^5_μ	A^2_μ, A^5_μ	$(-,+)$
$\chi, A^3_\mu, A^6_\mu, A^8_\mu$	$\tilde{\chi}, A'^3_\mu, \tilde{A}^6_\mu, A'^8_\mu$	$(+,-)$

Higgs Portal Embedding in Dark SU(3)

We can reduce the model to an extended Higgs portal in the limit:

$$v_3 \ll v_2 \ll v_1$$

$$\mathcal{L} = \frac{m_A^2}{2}\left(-\sin\theta h_1 + \cos\theta h_2\right)\left[\sum_{a=1,2} A_\mu A^{a\mu} + \left(\cos\alpha - \frac{\sin\alpha}{\sqrt{3}}\right)^2 A_\mu^3 A^{3\mu}\right]$$

$$+\tilde{g}\cos\alpha \sum_{a,b,c=1,2,3} \epsilon_{abc}\partial_\mu A_\nu A_\nu^a A^{b\mu} A^{c\nu} - \frac{\tilde{g}^2}{2}\cos^2\alpha \sum_{a=1,2}\left(A_\mu^a A^{a\mu} A_\nu^3 A^{3\nu} - (A_\mu^a A^{3\mu})^2\right)$$

$$-\frac{1}{2}m_\chi^2 \chi^2 + \left[\frac{\tilde{g}}{2m_A}\left(-\sin\theta h_1 + \cos\theta h_2\right) - \frac{1}{4}\left(\lambda_{\chi\chi 11} h_1^2 + 2\lambda_{\chi\chi 12} h_1 h_2 + \lambda_{\chi\chi 22} h_2^2\right)\right]\chi^2$$

$$-\frac{\kappa_{111}}{6} v_h h_1^3 - \frac{\kappa_{112}}{2} v_h h_1^2 h_2 - \frac{\kappa_{221}}{2} v_h h_1 h_2^2 - \frac{\kappa_{222}}{6} v_h h_2^3$$

$$\frac{h_1\cos\theta + h_2\sin\theta}{v_h}\left[2m_W^2 W_\mu^+ W^{\mu-} + m_Z^2 Z_\mu Z^\mu - \sum_f m_f \bar{f} f\right]$$

Possible stable states:

$A_1 = A_2 = A$ Always stable from the discrete symmetry

A_3 $m^2_{A^3{}'} = \frac{\tilde{g}^2 v_2^2}{4}\left(1 - \frac{\tan\alpha}{\sqrt{3}}\right)$ always lighter but unstable $A^3 \to \chi + SM$ if allowed

χ Stable if lightest particle of the hidden sector and CP is conserved

$$\frac{m^2_{\tilde{\chi}}}{m^2_{A'^3}} = 2\frac{\lambda_4 - \lambda_5}{\tilde{g}^2} f(v_2^2/v_1^2) \qquad f(r) = \frac{3}{2}\frac{r+1}{r+1-\sqrt{1+r(r-1)}}$$

Single component DM

CP-violated tiny violated

$Z_2 x Z_2'$ acts only on the vector states.

We can distinguish CP-even and CP-odd states but χ is unstable.

Single component Dark Matter with increased annihilation channels

Multi component DM

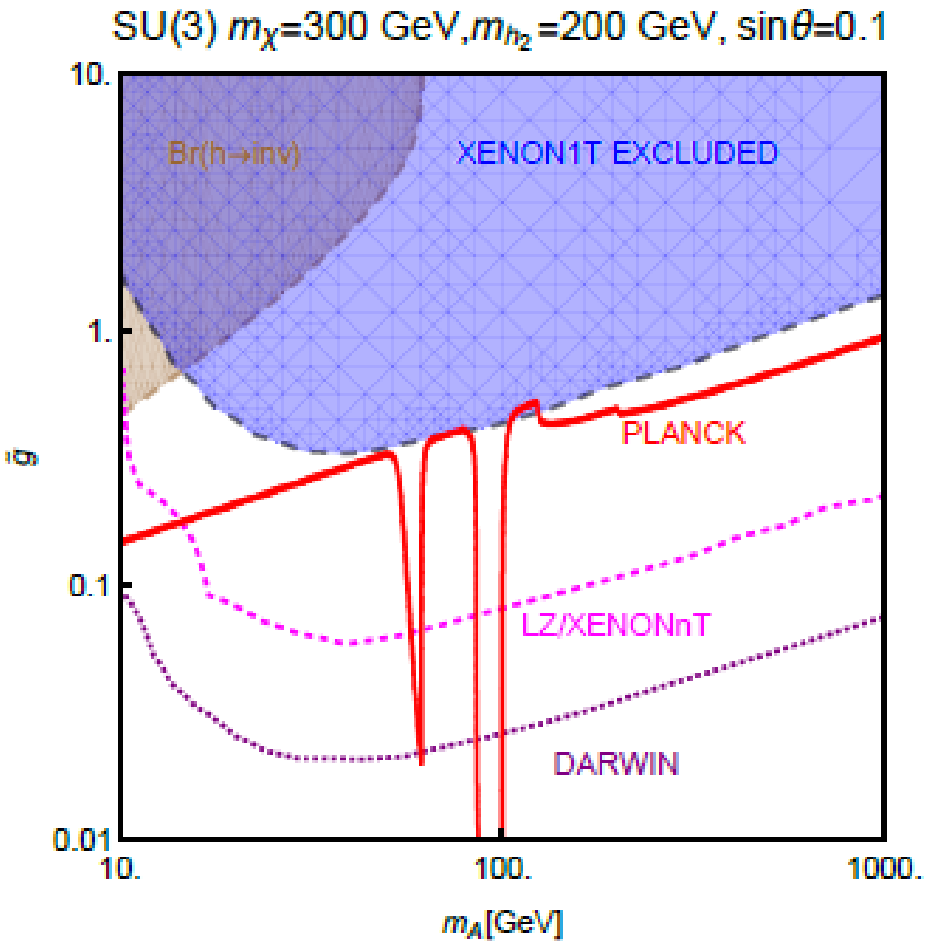
CP-conserved

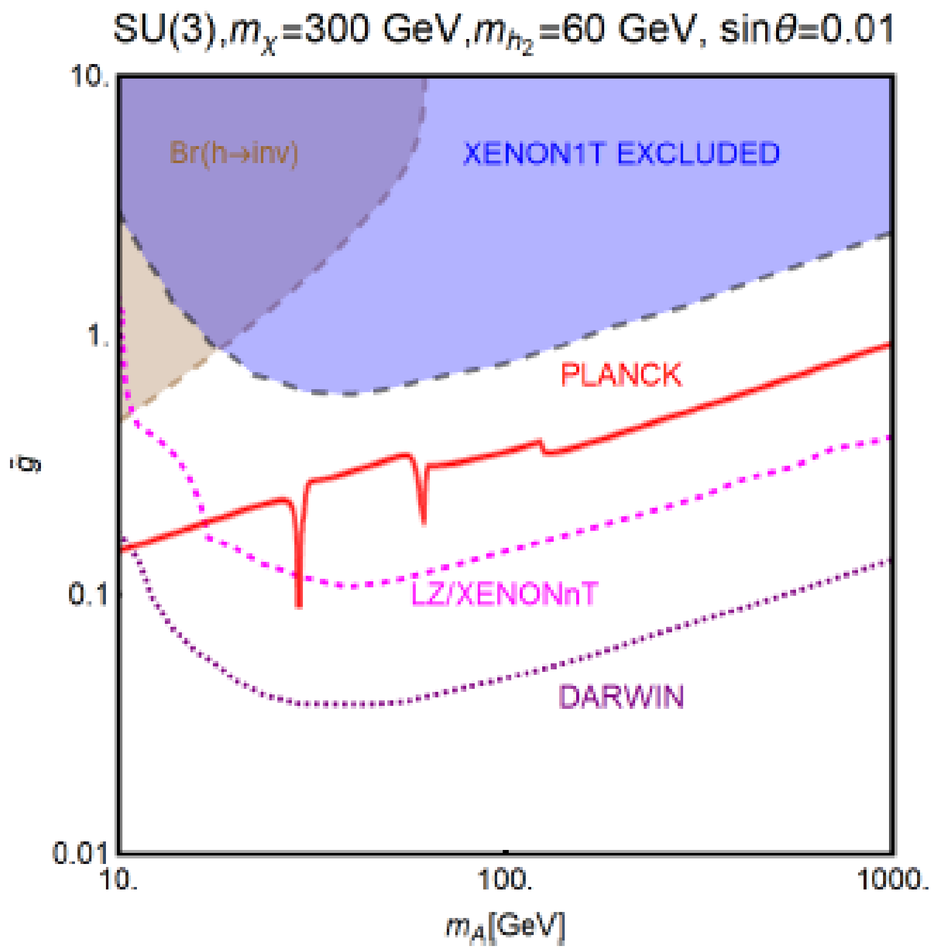
$Z_2 x Z_2'$ extends also to the scalar sector.

Spin-0/Spin-1 multi-component Dark Matter.

$$m_\chi < m_{A_3} < m_A$$

Multi-component DM





New annihilation channels:

$$AA \to \chi\chi \ , \ h_2 h_2$$

$$AA \to A^{3\,\prime} A^{3\,\prime}$$

Allow to evade direct detection constraints

Multi-component DM

In single component dark portals the relic density depends, through inverse proportionality relation, only on pair annihilations into SM states.

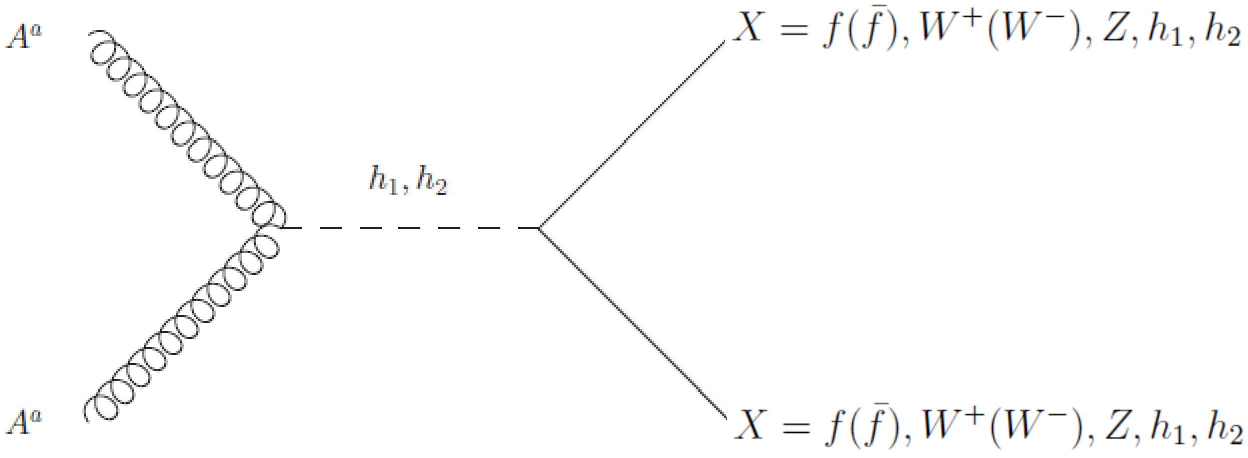
In multi-component DM from hidden sector one have different possible processes:

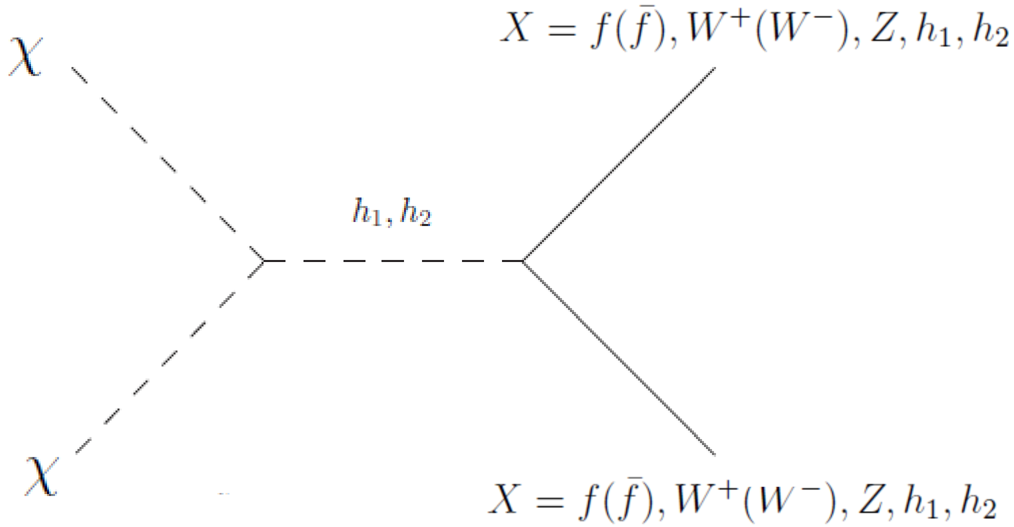
-pair annihilations of both components into SM states
-pair annihilations of the heavier DM component into the lightest one
-co-annihilations
-semi(co)-annihilations

Boltzmann equation for simplified system

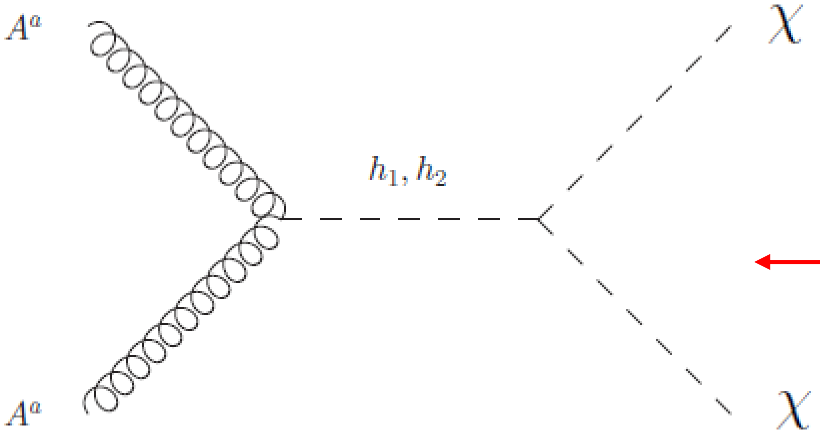
$$\frac{dY_A}{dx} = -\overline{\langle \sigma v \rangle}(AA \to XX)\left(Y_A^2 - Y_{A,\mathrm{eq}}^2\right) - \overline{\langle \sigma v \rangle}(AA \to \chi\chi)\left(Y_A^2 - \frac{Y_{A,\mathrm{eq}}^2}{Y_{\chi,\mathrm{eq}}^2} Y_\chi^2\right)$$
$$- \overline{\langle \sigma v \rangle}(AA \to A^3 h_{1,2})\left(Y_A^2 - \frac{Y_\chi}{Y_{\chi,\mathrm{eq}}} Y_{A,\mathrm{eq}}^2\right)$$

$$\frac{dY_\chi}{dx} = -\overline{\langle \sigma v \rangle}(\chi\chi \to XX)\left(Y_\chi^2 - Y_{\chi,\mathrm{eq}}^2\right) + \overline{\langle \sigma v \rangle}(AA \to \chi\chi)\left(Y_A^2 - \frac{Y_{A,\mathrm{eq}}^2}{Y_{\chi,\mathrm{eq}}^2} Y_\chi^2\right)$$
$$- \overline{\langle \sigma v \rangle}(AA^3 \to A h_{1,2}) Y_A Y_{A^3,\mathrm{eq}}\left(\frac{Y_\chi}{Y_{\chi,\mathrm{eq}}} - 1\right) + \overline{\langle \sigma v \rangle}(AA \to A^3 h_{1,3})\left(Y_A^2 - \frac{Y_\chi}{Y_{\chi,\mathrm{eq}}} Y_{A,\mathrm{eq}}^2\right)$$



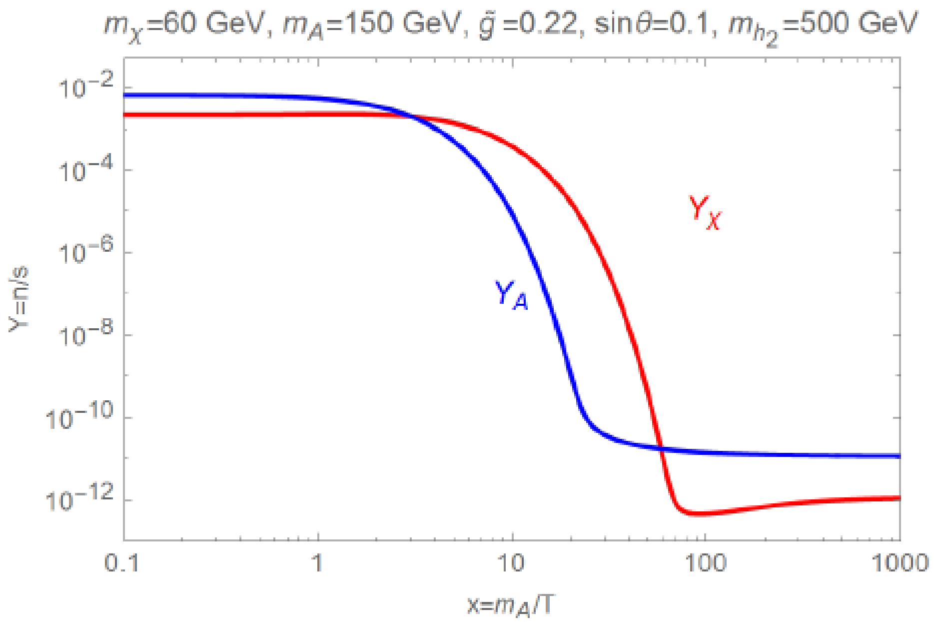


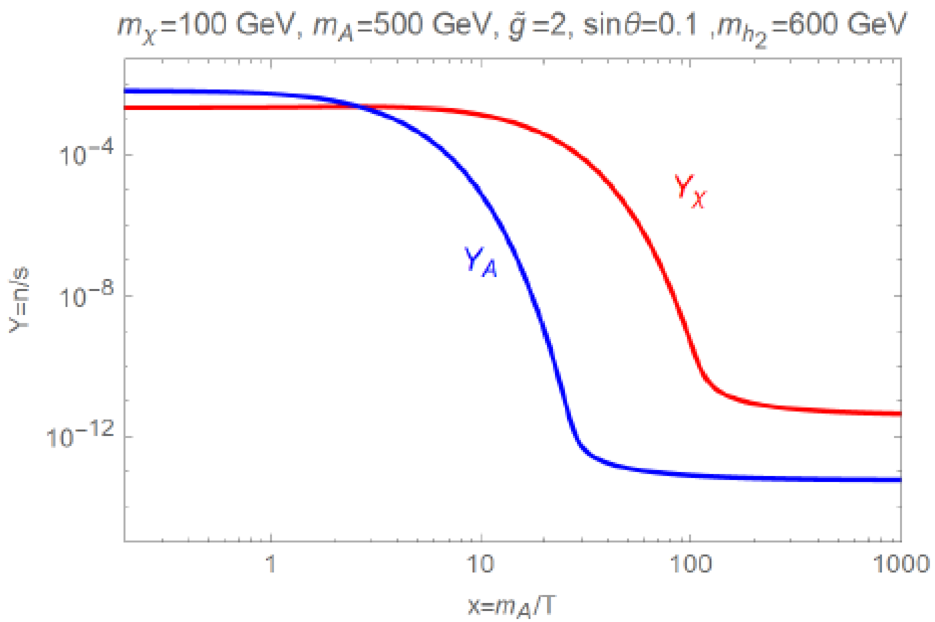
Conventional pair annihilations



Dark annihilation

The relic density is mostly determined by pair annihilations.



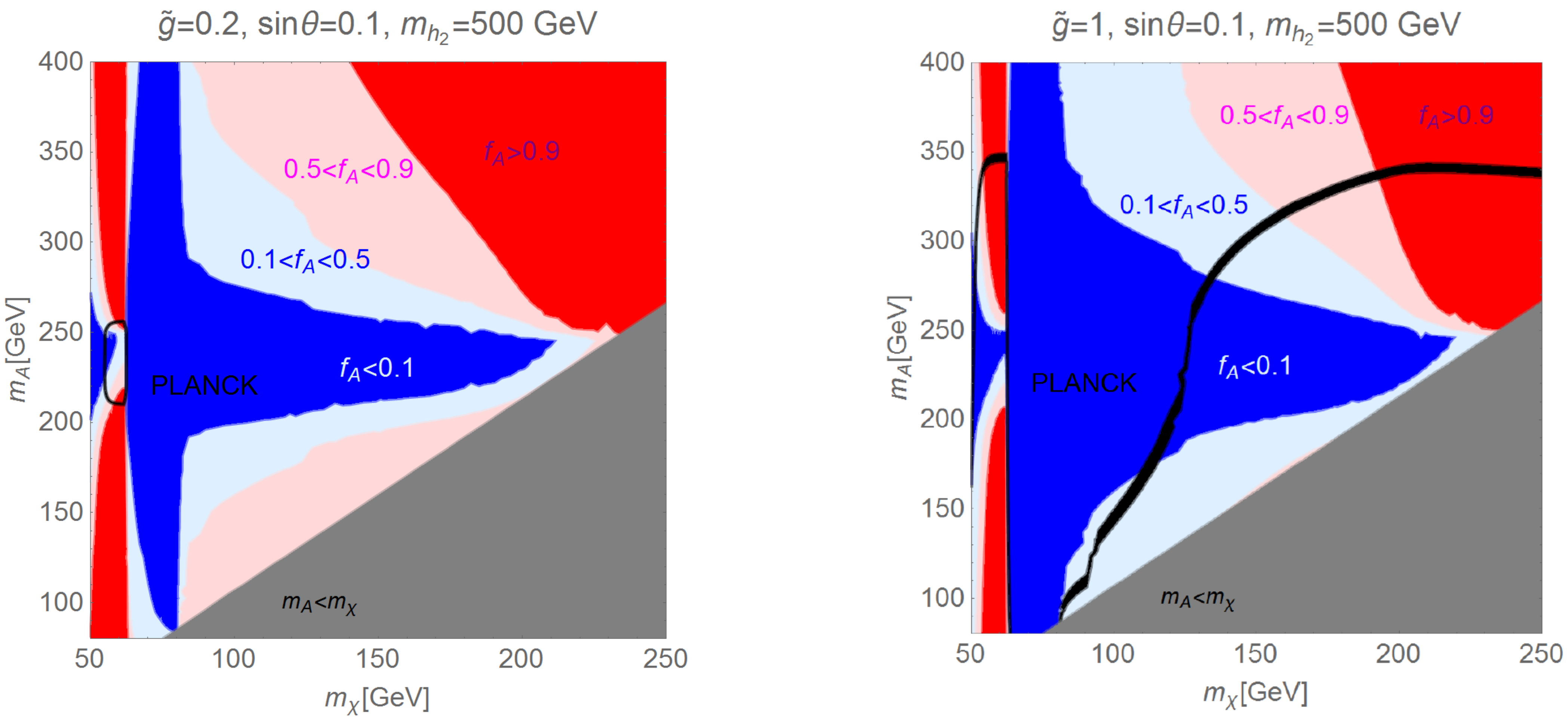


Relic density dominated by pair annihilations

Good approximation

$$\Omega_{\rm DM,tot}h^2 \approx 8.8\times 10^{-11}\,{\rm GeV}^{-2}\left[\left(\bar{g}_{\rm eff,A}^{1/2}\int_{T_0}^{T_{f,A}}\langle \sigma v\rangle_A \frac{dT}{m_A}\right)^{-1}+\left(\bar{g}_{\rm eff,\chi}^{1/2}\int_{T_0}^{T_{f,\chi}}\langle \sigma v\rangle_\chi \frac{dT}{m_\chi}\right)^{-1}\right]$$

$$\approx 8.8\times 10^{-11}\,{\rm GeV}^{-2}\left[\frac{x_{f,A}}{\bar{g}_{\rm eff,A}^{1/2}\left(a_A+x_{f,A}^{-1}b_A\right)}+\frac{x_{f,\chi}}{\bar{g}_{\rm eff,\chi}^{1/2}\left(a_\chi+x_{f,\chi}^{-1}b_\chi\right)}\right]$$



$\tilde{g}$=0.2, sinθ=0.1, m_{h_2}=500 GeV
$\tilde{g}$=1, sinθ=0.1, m_{h_2}=500 GeV
m_A[GeV]
m_χ[GeV]
0.5<f_A<0.9
f_A>0.9
0.1<f_A<0.5
f_A<0.1
PLANCK
m_A<m_χ

Direct Detection

Both components feature a SI cross-section:

$$\sigma_{A_1 N} = \frac{\tilde{g}^2 \mu^2_{\mathrm{A_1 N}}}{4\pi} \sin^2\theta \cos^2\theta \left(\frac{1}{m^2_{h_1}} - \frac{1}{m^2_{h_2}}\right)^2 \frac{\left[Z f_p + (A-Z) f_n\right]^2}{A^2}$$

Trilinear couplings of the scalar potential generate a null coupling in the not-relativistic limit (« blind spot »)

$$\lambda_2 v_2 (-\sin\theta h_1 + \cos\theta h_2) + \lambda_{H22} (\cos\theta h_1 + \sin\theta h_2) \tilde{\chi}^2 = \frac{\tilde{g}}{4 m_A} \sin\theta \cos\theta \left(-h_1 m^2_{h_1} \sin\theta + h_2 m^2_{h_2} \cos\theta\right)$$

Cross-section generated by scalar vector mixing

$$\sigma_{\chi N} = \frac{\mu^2_{\chi N}}{4\pi} \frac{m^2_\chi m^2_A}{m^4_{A_6}} \sin^2\theta \cos^2\theta \left(\frac{1}{m^2_{h_1}} - \frac{1}{m^2_{h_2}}\right)^2 \frac{\left[Z f_p + (A-Z) f_n\right]^2}{A^2} \xrightarrow[v_1 \gg v_2]{} 0$$

$$\frac{dR(E_R,t)}{dE_R} = \frac{N_T \rho_\chi}{m_\chi\, m_T} \int_{v_{\min}}^{v_{\rm esc}} v f_E(\vec{v},t) \frac{d\sigma_{\chi T}(v,E_R)}{dE_R} d^3\vec{v}$$

The recoil rate depends on the DM local energy density.
While the scattering cross-section is in principle independent from the DM relic density one makes assumption on it while evaluating a DD signal.

$$\frac{dN}{dE_R} = \sum_{i=\chi,A} f_i \left(\frac{dN}{dE_R}\right)_i$$

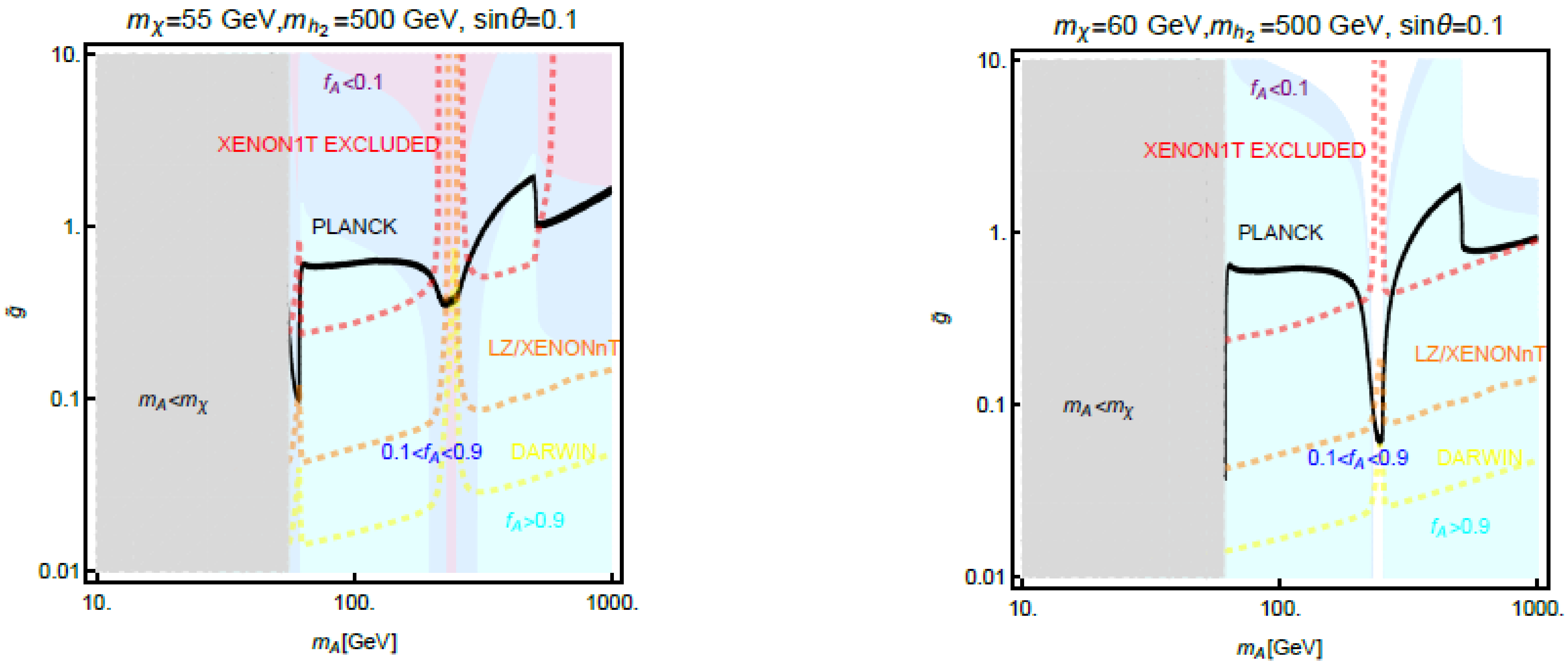
$$f_A = \Omega_A/\Omega_{\rm DM,tot} \qquad f_A \approx \frac{\frac{\langle\sigma v\rangle_\chi}{\langle\sigma v\rangle_A}}{1+\frac{\langle\sigma v\rangle_\chi}{\langle\sigma v\rangle_A}}$$

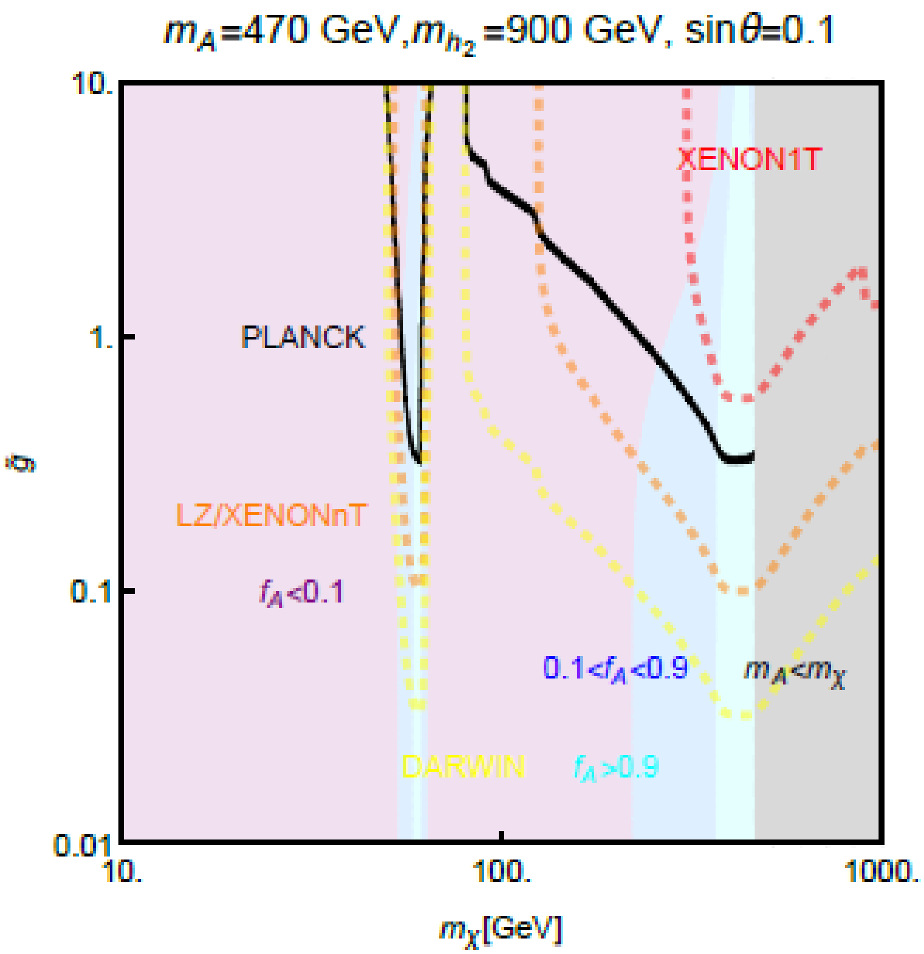
Evading DD limits:

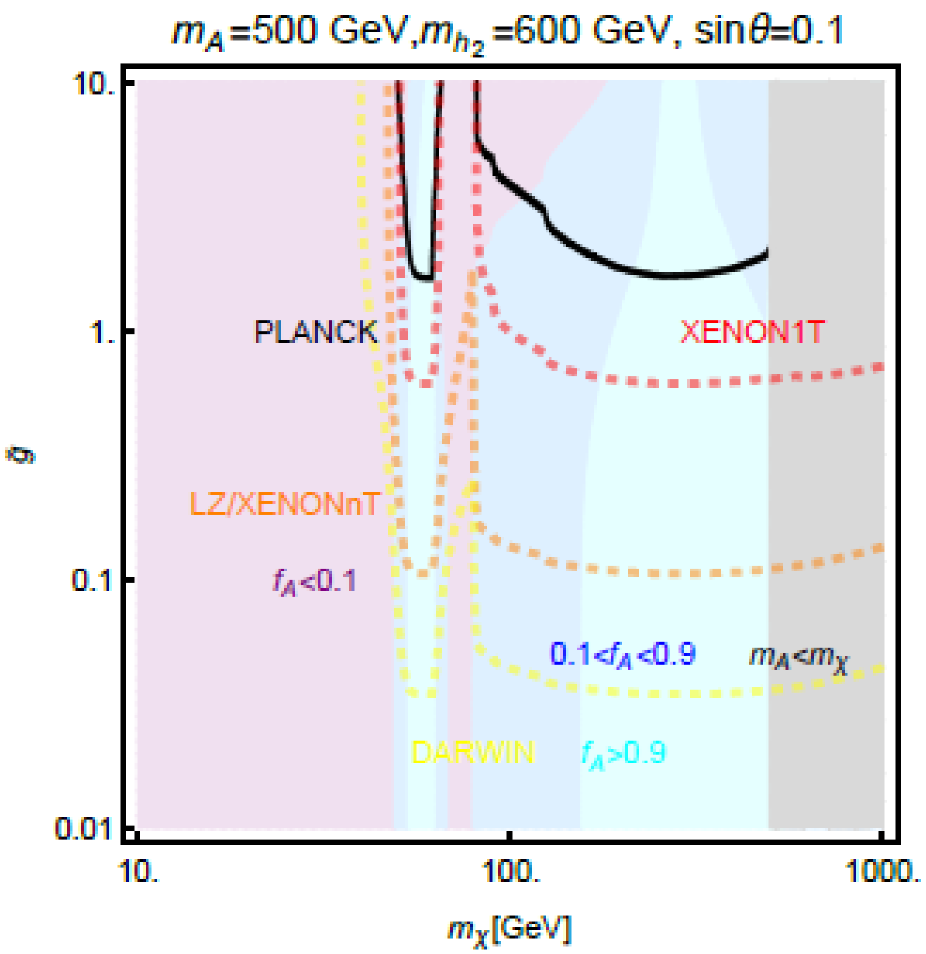
The scalar component has suppressed scattering cross-section.

One can reduce the signal of the vectorial DM in the case it is a subdominant DM component.

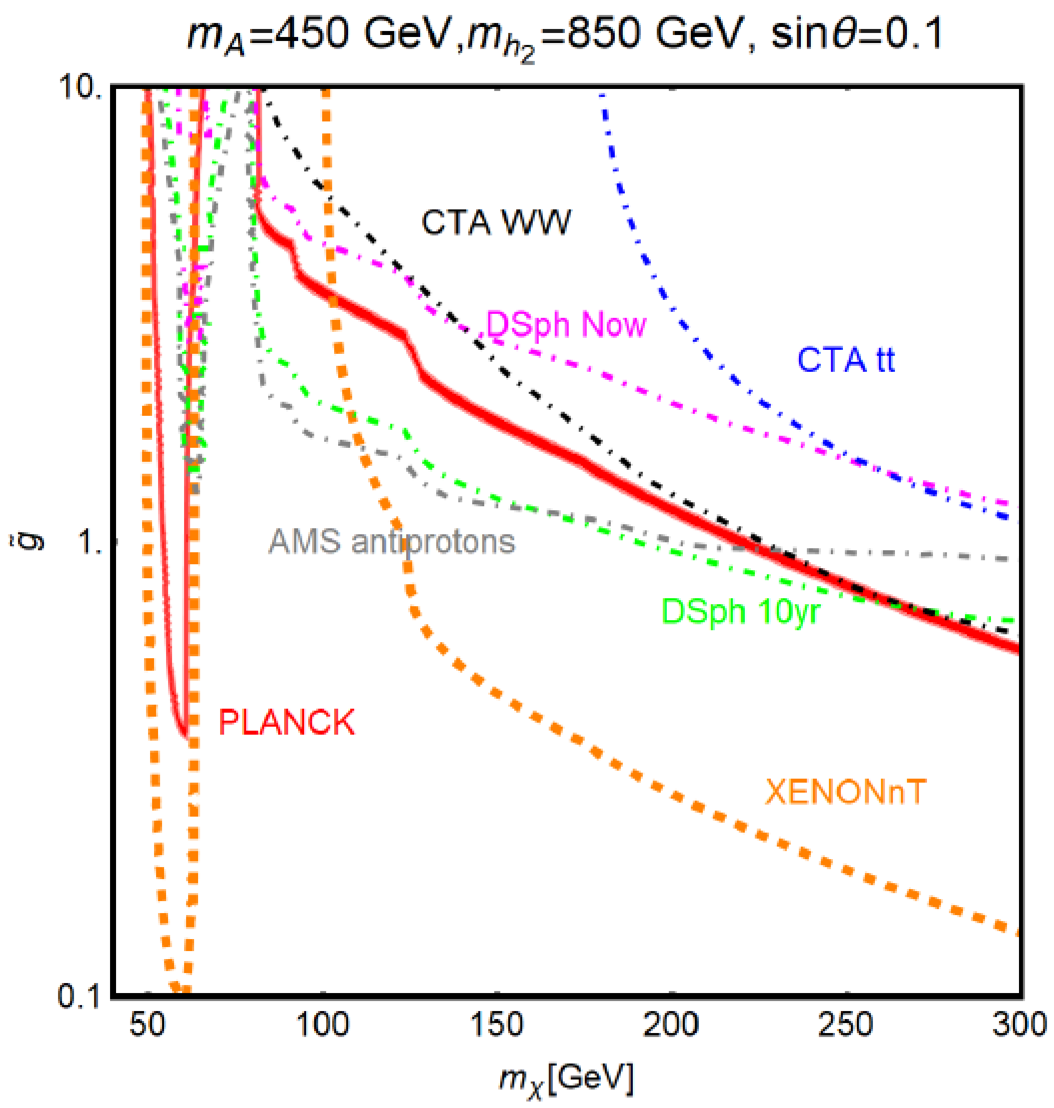
Scalar component is « coy » with respect to direct detection. For vector component the SI cross-section is suppressed by a small mixing angle with respect to the main annihilation channel.




m_A=470 GeV,m_{h_2}=900 GeV, sinθ=0.1
XENON1T
PLANCK
LZ/XENONnT
f_A<0.1
0.1<f_A<0.9
m_A<m_χ
DARWIN
f_A>0.9
10.
1.
0.1
0.01
10.
100.
1000.
m_χ[GeV]
$\tilde{g}$


m_A=500 GeV,m_{h_2}=600 GeV, sinθ=0.1
PLANCK
XENON1T
LZ/XENONnT
f_A<0.1
0.1<f_A<0.9
m_A<m_χ
DARWIN
f_A>0.9
10.
1.
0.1
0.01
10.
100.
1000.
m_χ[GeV]
$\tilde{g}$

Detection of both components



Dominant scalar DM component producing sizable Indirect Detection signal.

Subdominant vector component with sizable Direct Detection signal.

Conclusions

DM simplified models are predictive but most probably overconstrainted.

Next-to-minimal realizations, dictated by theoretical reasons lead to potentially sensitive (and interesting) differencies in the phenomenology.

Back up

Towards UV complete models:mixing with a singlet

$$V(H,\Phi)=\lambda_{hS}H^\dagger H\Phi^2+\lambda_\Phi\Phi^4+\mu_\Phi^2\Phi^2 \longrightarrow \begin{pmatrix} h \\ S \end{pmatrix}=\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \Re H(0) \\ \phi \end{pmatrix}$$

$$\tan 2\theta=\frac{\lambda_{hS}v_h v_\Phi}{\lambda_h v_h^2-\lambda_\Phi v_\Phi^2} \qquad v_\Phi=\frac{(m_h^2-m_S^2)\sin 2\theta}{2\lambda_{hS}v_h}$$

$$\begin{aligned}
\kappa_{hhh} &= \frac{m_h^2}{v_h^2\cos\theta}\left(\cos^4\theta+\sin^2\theta\frac{\lambda_{hS}v_h^2}{(m_h^2-m_S^2)}\right),\\
\kappa_{SSS} &= \frac{m_S^2}{v_h^2\sin\theta}\left(\sin^4\theta+\cos^2\theta\frac{\lambda_{hS}v_h^2}{(m_S^2-m_h^2)}\right),\\
\kappa_{hhS} &= \frac{2m_h^2+m_S^2}{v_h^2}\left(\cos^2\theta+\frac{\lambda_{hS}v_h^2}{(m_S^2-m_h^2)}\right),\\
\kappa_{hSS} &= \frac{2m_S^2+m_h^2}{v_h^2}\left(\sin^2\theta+\frac{\lambda_{hS}v_h^2}{(m_h^2-m_S^2)}\right).
\end{aligned}$$

$$\mathcal{L}_{\rm SM}^{hS}=\frac{h\cos\theta-S\sin\theta}{v_h}\left[2m_W^2W_\mu^+W^{\mu-}+m_Z^2Z^\mu Z_\mu-\sum_f m_f\bar{f}f\right]$$

$$\mathcal{L}_{hS}=-\frac{\kappa_{hhh}v_h}{2}\,h^3-\frac{\kappa_{hhS}v_h}{2}\sin\theta\;h^2S-\frac{\kappa_{hSS}v_h}{2}\cos\theta\;hS^2-\frac{\kappa_{SSS}v_h}{2}\,S^3$$

DM Interactions

Scalar DM

$$-\mathcal{L}_\chi = \lambda_H^\chi |\chi|^2 H^\dagger H + \lambda_\Phi^\chi |\chi|^2 \Phi^2 + \mu_\chi^2 |\chi|^2$$

$$\downarrow$$

$$-\mathcal{L}_\chi = g_{\chi\chi h}|\chi|^2 h + g_{\chi\chi S}|\chi|^2 S + g_{\chi\chi hh}|\chi|^2 h^2 + g_{\chi\chi hS}|\chi|^2 hS + g_{\chi\chi SS}|\chi|^2 S^2 + m_\chi^2 |\chi|^2$$

Fermion DM

$$\mathcal{L}_\psi = -y_\psi \overline{\psi}\psi\Phi$$

$$y_\psi \propto m_\psi / v_\Phi$$

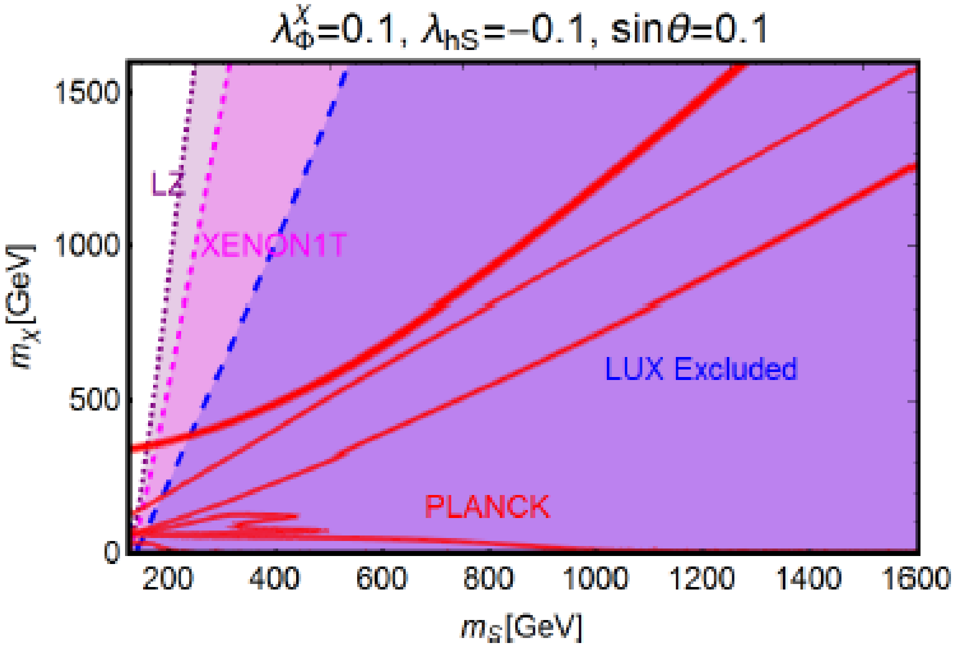
Vector DM

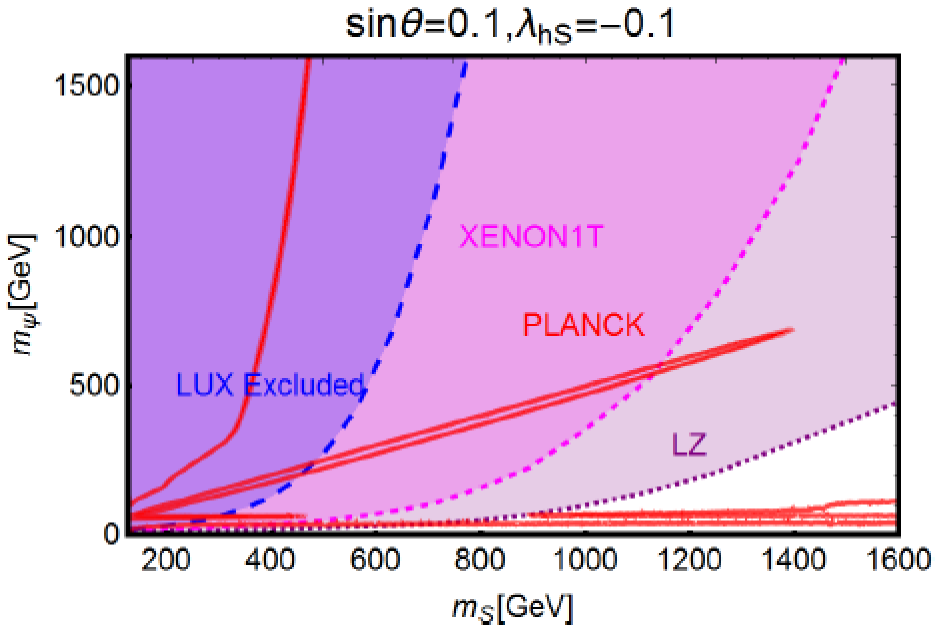
$$(D_\mu \Phi)^* D^\mu \Phi \longrightarrow D_\mu = \partial_\mu - i\frac{\eta_V^S}{2} V_\mu$$

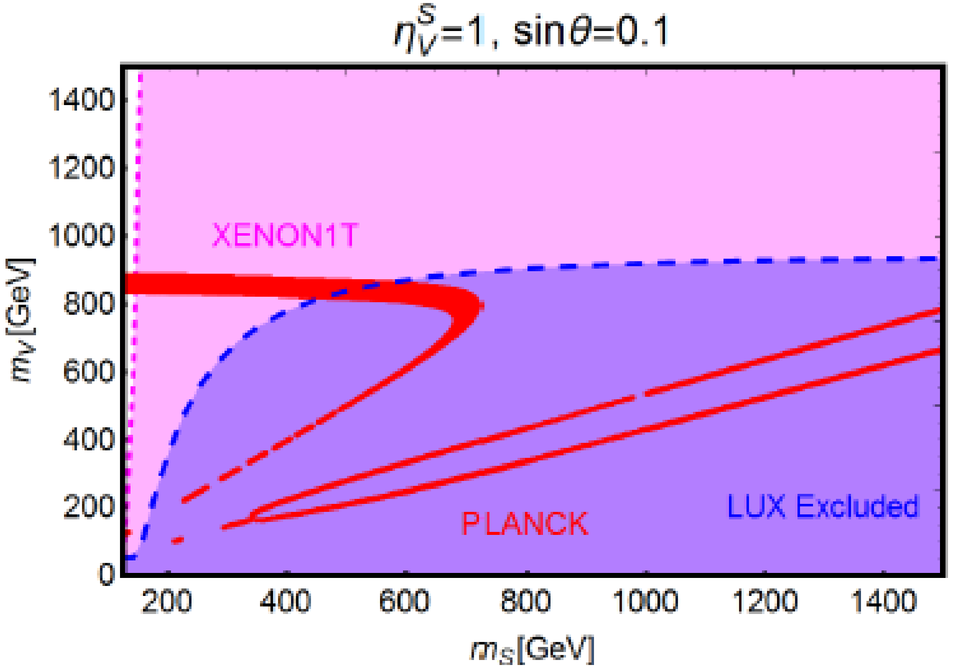
$$\downarrow$$

$$\mathcal{L}_V = \frac{1}{2}\eta_V^S m_V V^\mu V_\mu \phi + \frac{(\eta_V^S)^2}{8}\phi^2 V^\mu V_\mu + \frac{1}{2} m_V^2 V^\mu V_\mu$$

$$v_\Phi = 2m_V/\eta_V^S \qquad \lambda_{hS} = \frac{(m_h^2 - m_S^2)\sin 2\theta}{2 v_h} \times \frac{\eta_V^S}{2 m_V}$$







G.A., M. Dutra, P. Ghosh, M. Lindner, Y. Mambrini, M. Pierre, F. Queiroz, 1703.07364

Higgs portal

$$\xi \lambda_\chi^H \chi^* \chi H^\dagger H$$

$$\langle \sigma v \rangle_{ff}^{\chi} = \sum_f n_f^c \frac{(\lambda_\chi^S)^2 m_f^2 \left(m_\chi^2 - m_f^2\right)^{3/2}}{8\pi m_\chi^3 v_h^2 \left(m_h^2 - 4m_\chi^2\right)^2}$$

$$\langle \sigma v \rangle_{WW}^{\chi} = \frac{g^2 (\lambda_\chi^H)^2 \sqrt{m_\chi^2 - m_W^2}}{16\pi m_\chi^3 v_h^2 \left(m_h^2 - 4m_\chi^2\right)^2} \left(-4m_\chi^2 m_W^2 + 4m_\chi^4 + 3m_W^4\right)$$

$$\langle \sigma v \rangle_{ZZ}^{\chi} = \frac{g^2 (\lambda_\chi^H)^2 \sqrt{m_\chi^2 - m_Z^2}}{32\pi m_\chi^3 v_h^2 \left(m_h^2 - 4m_\chi^2\right)^2} \left(-4m_\chi^2 m_Z^2 + 4m_\chi^4 + 3m_Z^4\right).$$

$$\sigma_{\chi p}^{\rm SI} = \frac{\mu_{\chi p}^2}{4\pi} \frac{(\lambda_\chi^H)^2}{m_\chi^2} \frac{m_p^2}{m_h^4} \left[f_p \frac{Z}{A} + f_n \left(1 - \frac{Z}{A}\right)\right]^2$$

$$\xi \frac{\lambda_\Psi^H}{\Lambda} \overline{\Psi} \psi H^\dagger H$$

$$\langle \sigma v \rangle_{ff}^{V} = \sum_f n_c^f (\lambda_H^2)^2 m_f^2 \frac{\sqrt{4 - \frac{4m_f^2}{m_V^2}} \left(4m_V^2 - 4m_f^2\right)}{96\pi v_h^2 m_V^2 \left(4m_V^2 - m_h^2\right)^2}$$

$$\langle \sigma v \rangle_{WW}^{V} = g^2 (\lambda_V^H)^2 \frac{\sqrt{4 - \frac{4m_W^2}{m_V^2}} \left(16m_V^4 - 16m_V^2 m_W^2 + 12m_W^4\right)}{768\pi m_V^2 v_h^2 \left(4m_V^2 - m_S^2\right)^2}$$

$$\langle \sigma v \rangle_{ZZ}^{V} = g^2 (\lambda_V^H)^2 \frac{\sqrt{4 - \frac{4m_Z^2}{m_V^2}} \left(16m_V^4 - 16m_V^2 m_Z^2 + 12m_Z^4\right)}{1536\pi m_V^2 v_h^2 \left(4m_V^2 - m_h^2\right)^2}$$

$$\sigma_{Vp}^{\rm SI} = \frac{\mu_{Vp}^2}{4\pi} (\lambda_V^H)^2 \frac{m_p^2}{m_h^4 m_V^2} \left[f_p \frac{Z}{A} + f_n \left(1 - \frac{Z}{A}\right)\right]^2$$

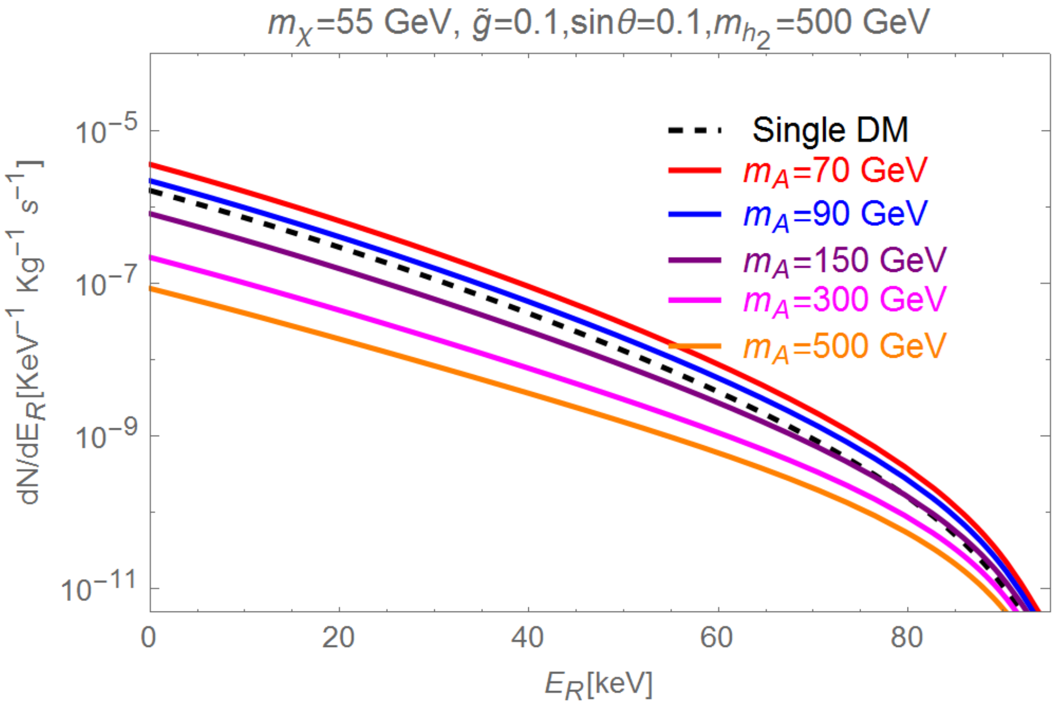
$$\langle \sigma v \rangle_{ff}^{\psi} = (\lambda_\psi^S)^2 \sum_f n_c^f \frac{(m_f)^2 \left(m_\psi^2 - m_f^2\right)^{3/2}}{4\pi m_\psi v_h^2 \left(m_h^2 - 4m_\psi^2\right)^2} v^2$$

$$\xi \lambda_V^H V^\mu V_\mu H^\dagger H$$

$$\langle \sigma v \rangle_{WW}^{\psi} = g^2 (\lambda_\psi^H)^2 v^2 \frac{\sqrt{m_\psi^2 - m_W^2}}{64\pi m_\psi v_h^2 \left(m_h^2 - 4m_\psi^2\right)^2} \left(-4m_\psi^2 m_W^2 + 4m_\psi^4 + 3m_W^4\right)$$

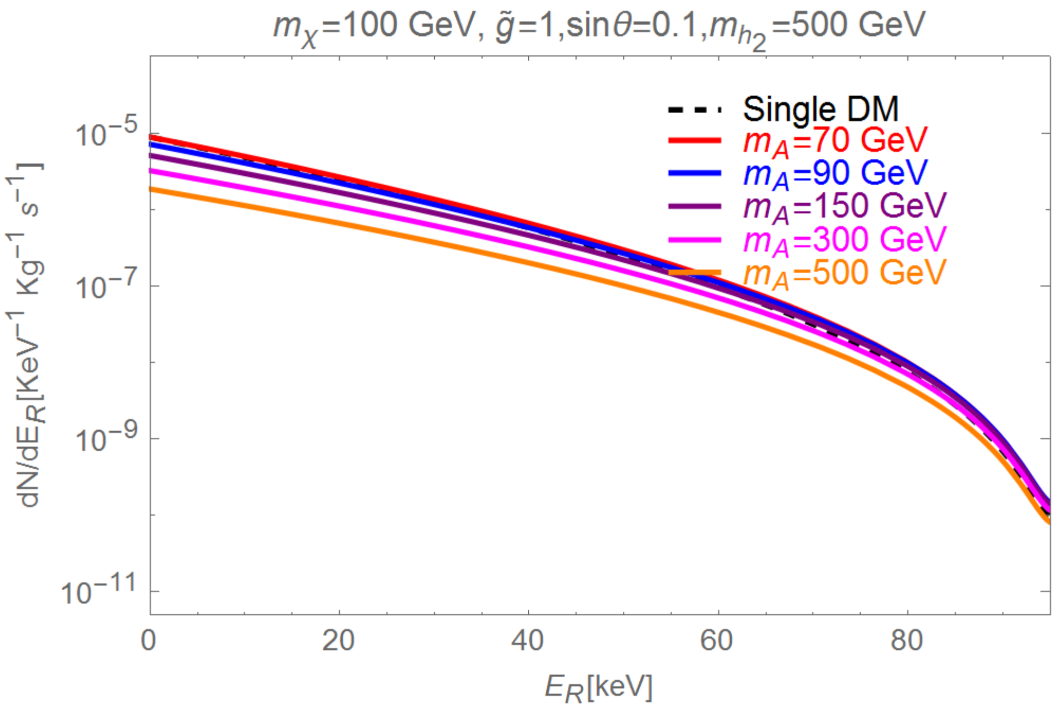
$$\langle \sigma v \rangle_{ZZ}^{\psi} = g^2 (\lambda_\psi^H)^2 v^2 \frac{\sqrt{m_\psi^2 - m_Z^2}}{128\pi m_\psi v_h^2 \left(m_h^2 - 4m_\psi^2\right)^2} \left(-4m_\psi^2 m_Z^2 + 4m_\psi^4 + 3m_Z^4\right)$$

$$\sigma_{\psi p}^{\rm SI} = \frac{\mu_{\psi p}^2}{\pi} (\lambda_\psi^H)^2 \frac{m_p^2}{v_h^2 m_h^4} \left[f_p \frac{Z}{A} + f_n \left(1 - \frac{Z}{A}\right)\right]^2$$

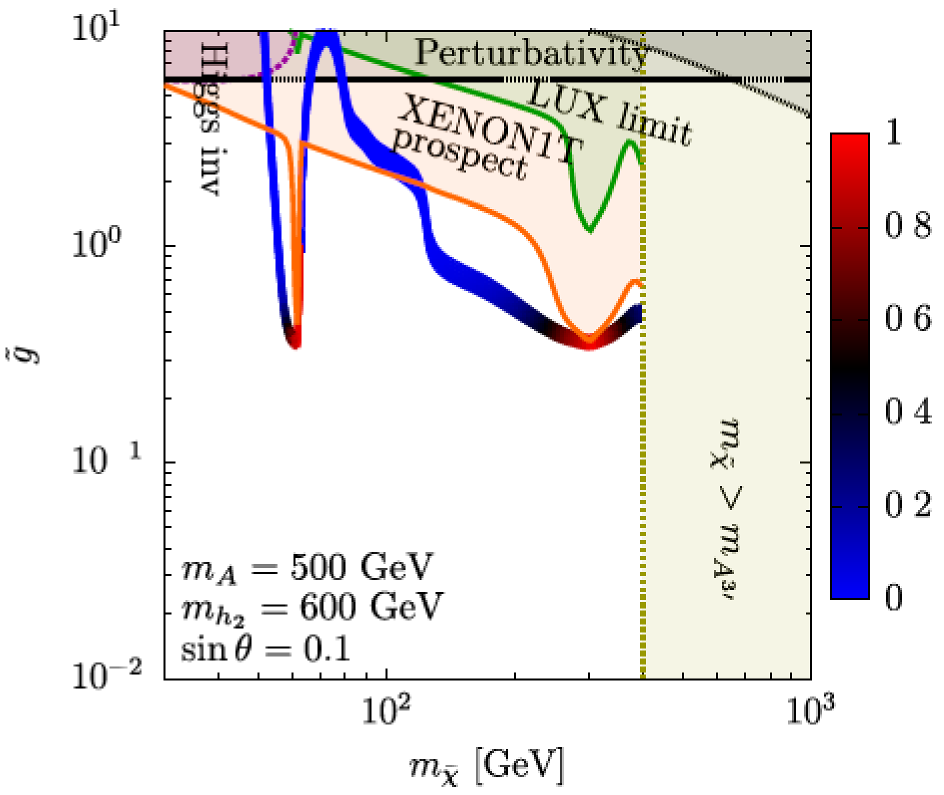


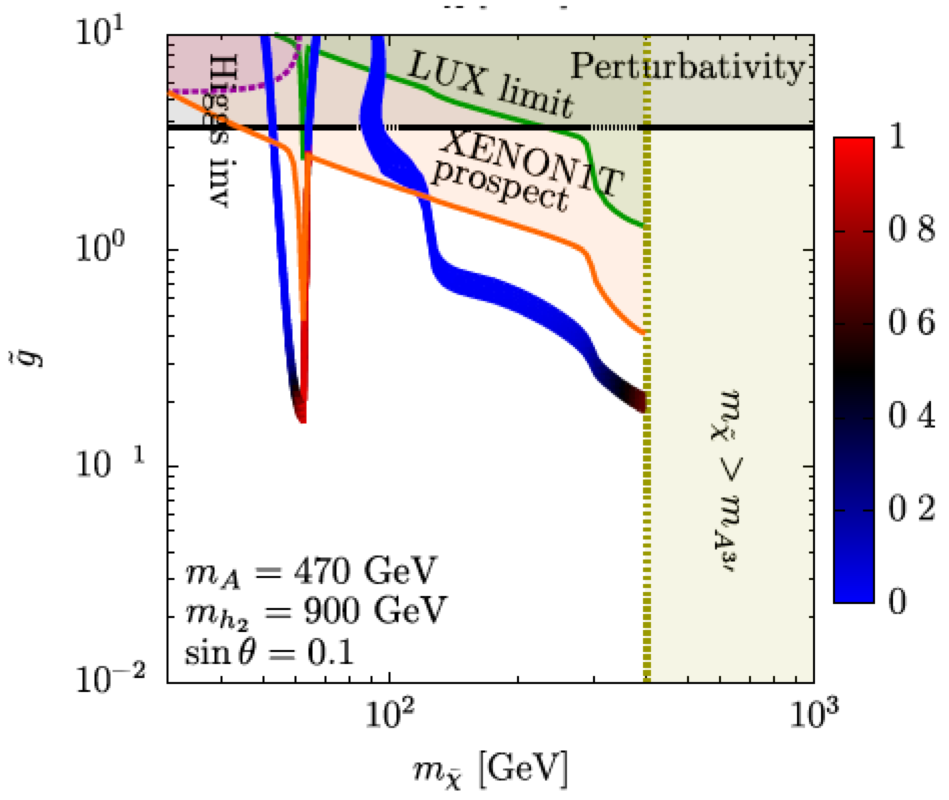
Limits from invisible Higgs width forbid to have a too light component. Component discrimination in DD not trivial.

Quantitative analysis required.



Case $v_1 \approx v_2$





gauge eigenstates	mass eigenstates	$\mathbb{Z}_2 \times \mathbb{Z}_2'$
h, φ_i, A_μ^7	$h_i, \tilde{h}_4, \tilde{A}_\mu^7$	$(+,+)$
A_μ^1, A_μ^4	A_μ^1, A_μ^4	$(-,-)$
A_μ^2, A_μ^5	A_μ^2, A_μ^5	$(-,+)$
$\chi, A_\mu^3, A_\mu^6, A_\mu^8$	$\tilde{\chi}, A_\mu'^3, \tilde{A}_\mu^6, A_\mu'^8$	$(+,-)$

Multi-component DM in general predicted

	Case I	Case II	Case III	Case IV
dark matter	$(A_\mu^1, A_\mu^2, \tilde{\chi})$	$(A_\mu^4, A_\mu^5, \tilde{\chi})$	$(A_\mu^1, A_\mu^2, A_\mu'^3)$	$(A_\mu^4, A_\mu^5, A_\mu'^3)$
parameter	$v_2/v_1 < 1$	$v_2/v_1 > 1$	$v_2/v_1 < 1$	$v_2/v_1 > 1$
choice	$\lambda_4 - \lambda_5 \ll 1$	$\lambda_4 - \lambda_5 \ll 1$	$\lambda_4 - \lambda_5 = \mathcal{O}(1)$	$\lambda_4 - \lambda_5 = \mathcal{O}(1)$