Direct Detection prospects for single- and multi-component Dark portals

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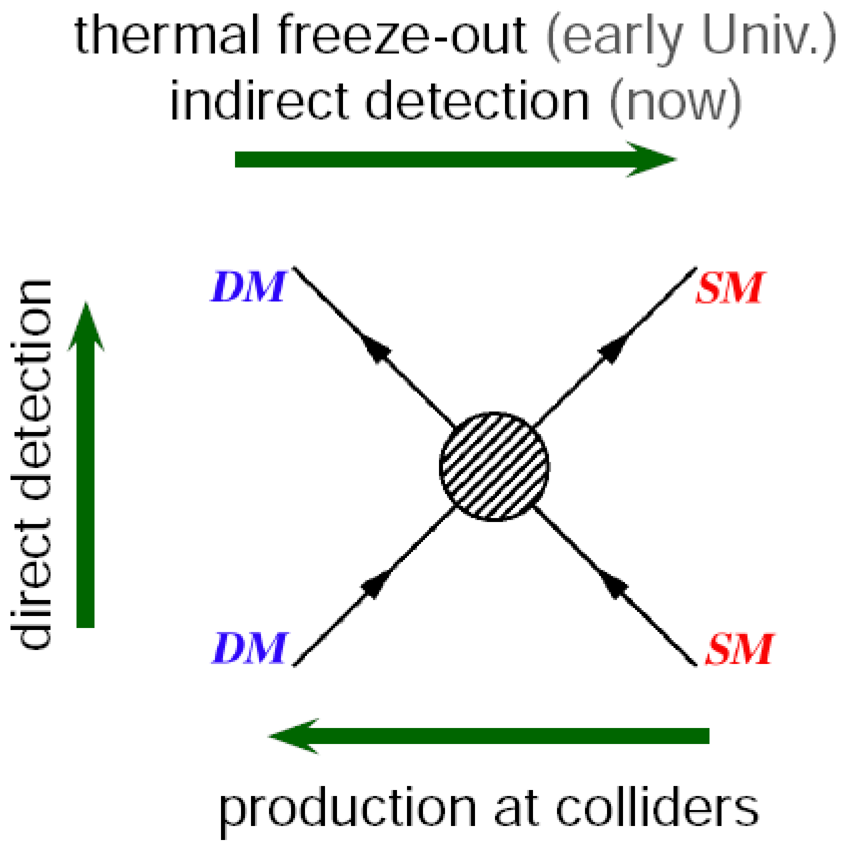
Outline and motivations

Investigate the capability of next future direct detection facilities of testing the WIMP hypothesis.

Cases of study:

-Dark Portals

-Two Component DM (Hidden SU(3))

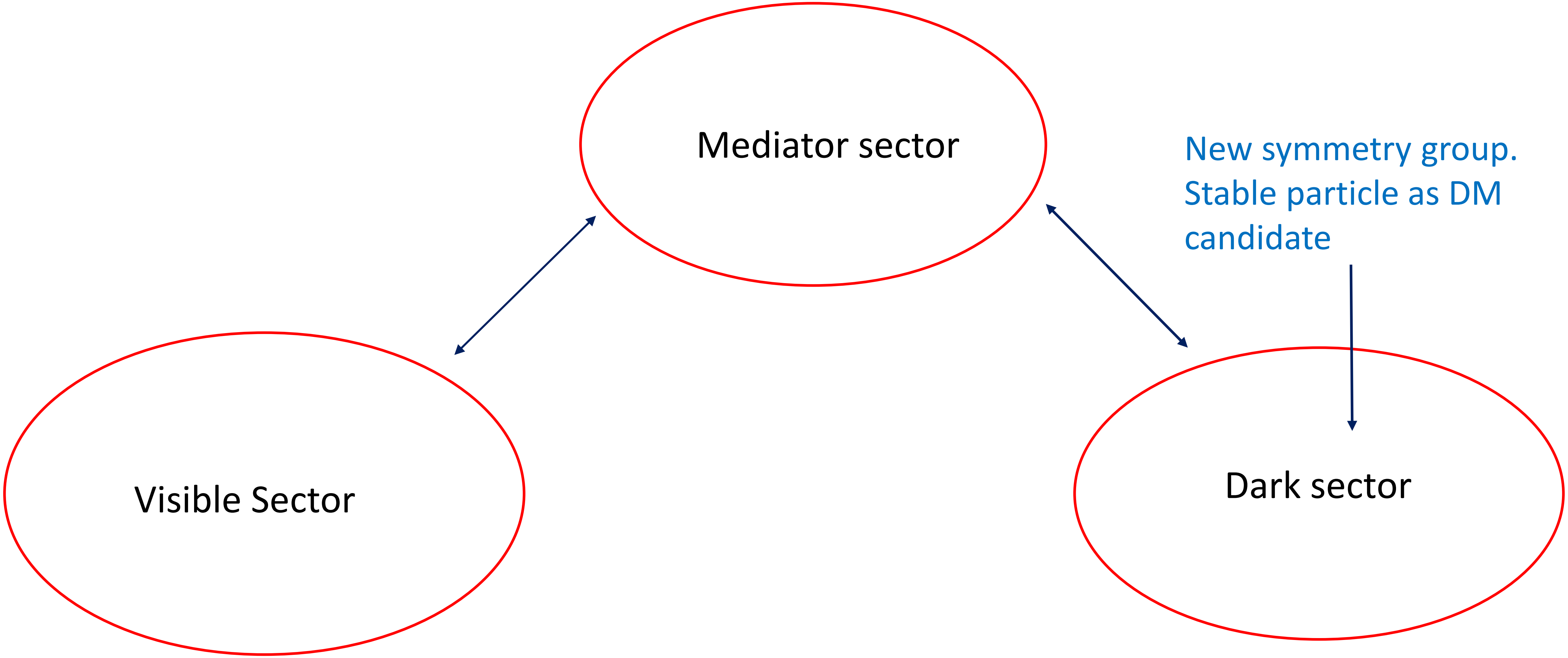


$$\Omega h^2 \simeq 0.12 \longrightarrow \langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

$$\langle \sigma v \rangle = f_1 \sigma_{\chi N}^{\mathrm{SI}} + f_2 \sigma_{\chi N}^{\mathrm{SD}}$$

Too strong limits from Direct Detection would imply a too much suppressed annihilation cross-section and overabundant Dark Matter.

Simple framework for DM Interactions



Dark Portals

Simplest setup: 1 particle in the Dark Sector, i.e. the DM candidate, 1 particle in the mediator sector.

$$\mathcal{L} = \xi \frac{\lambda_\chi^H}{\Lambda} H^\dagger H \left[\bar{\chi}\chi + i\alpha_\chi^H \bar{\chi}\gamma_5 \chi\right]$$

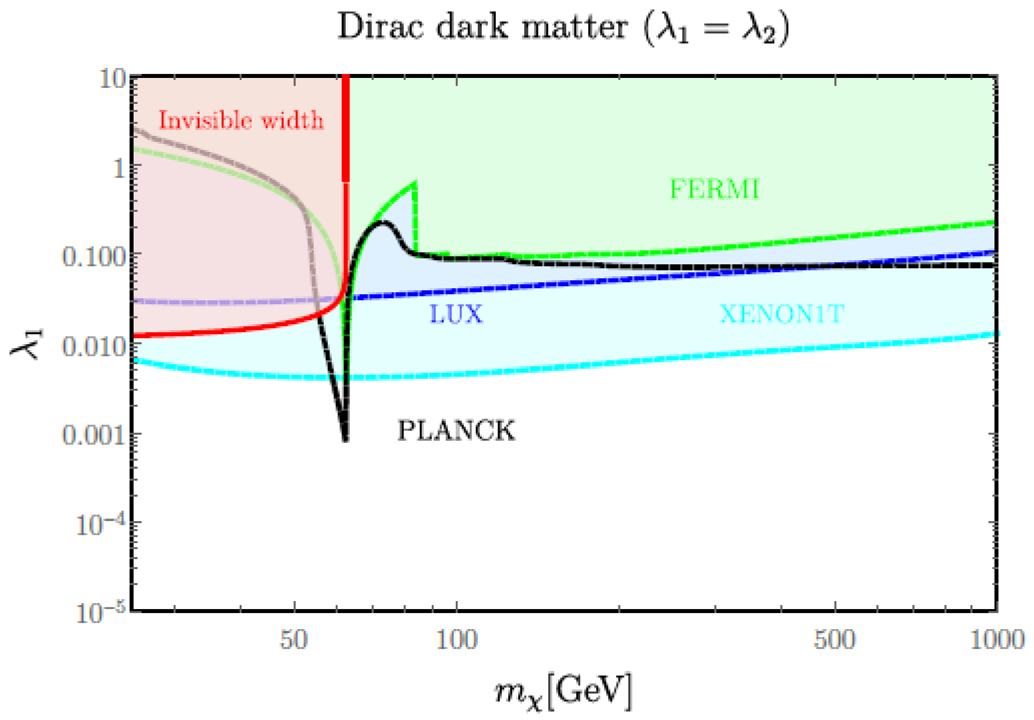
$$\mathcal{L} = \frac{g}{4\cos\theta_W} V_\chi^Z \left(\overline{\chi}\gamma^\mu \left(1-\alpha_\chi^Z \gamma^5\right)\chi Z_\mu + \overline{f}\gamma^\mu \left(V_f^Z - A_f^Z \gamma^5\right) f Z_\mu\right)$$

SM portals

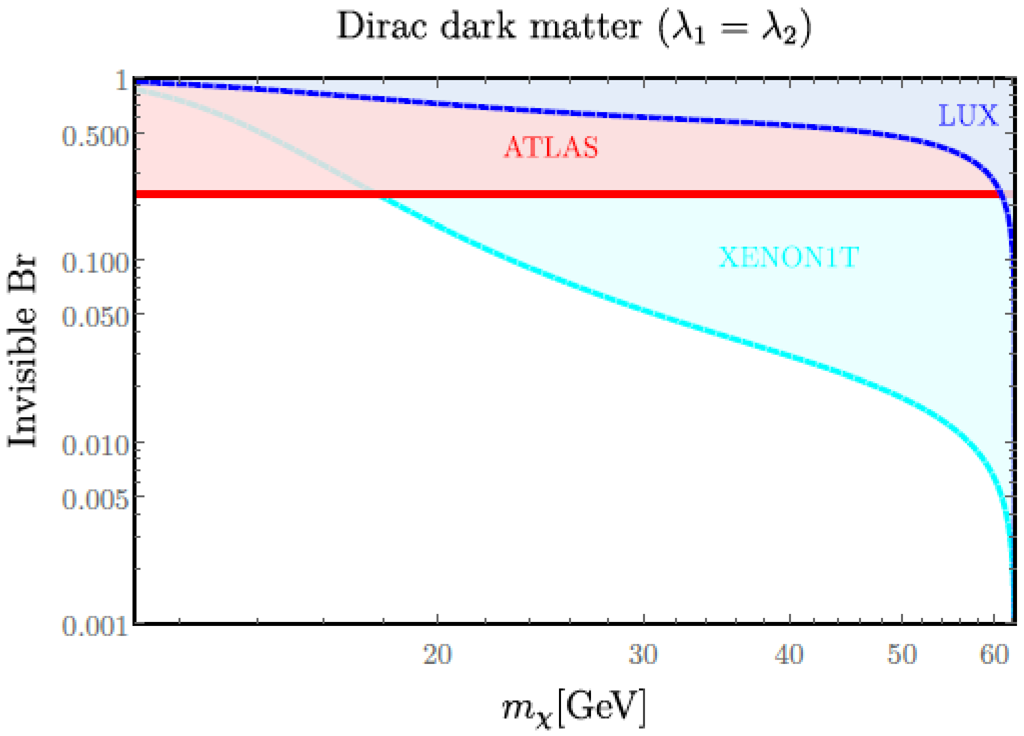
$$\mathcal{L} = \xi \lambda_\chi^\Phi (s\bar{\chi}\chi + ia\bar{\chi}\gamma_5\chi) + \sum_f \lambda_f^\Phi \left(s\bar{f}f + ia\bar{f}\gamma_5 f\right)$$

$$\mathcal{L} = g V_\chi^{Z'} \left(\overline{\chi}\gamma^\mu \left(1-\alpha_\chi^{Z'}\gamma^5\right)\chi Z'_\mu + \overline{f}\gamma^\mu \left(V_f^{Z'} - A_f^{Z'}\gamma^5\right) f Z'_\mu\right)$$

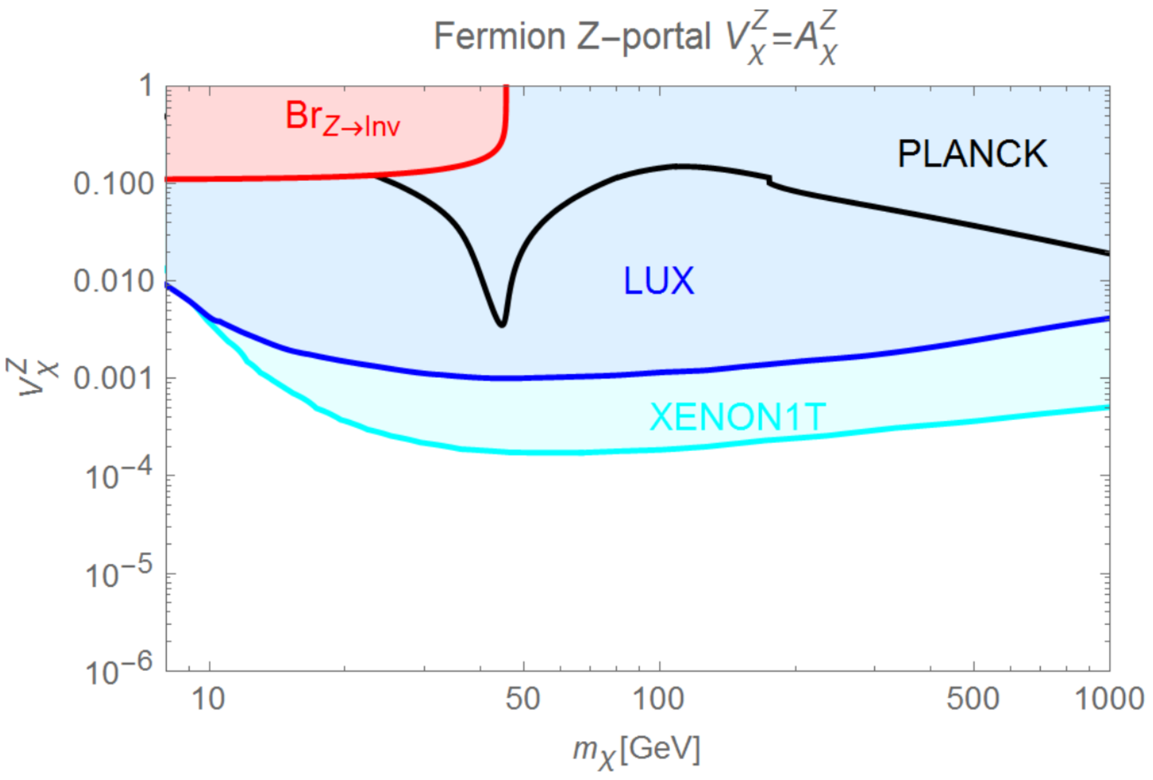
BSM Portals



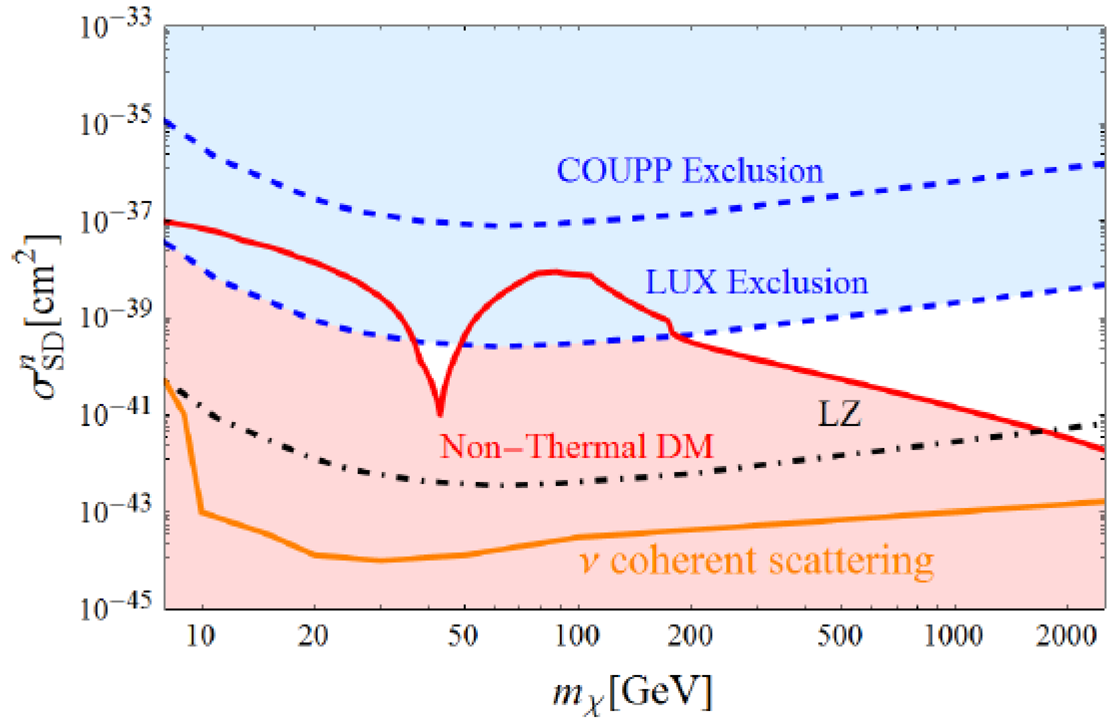
G.A., M. Dutra, P. Ghosh, Y. Mambrini, M. Pierre, F, Queiroz,
in preparation



New constraints on Direct Detection can complement limits from invisible branching ratio of the Higgs.



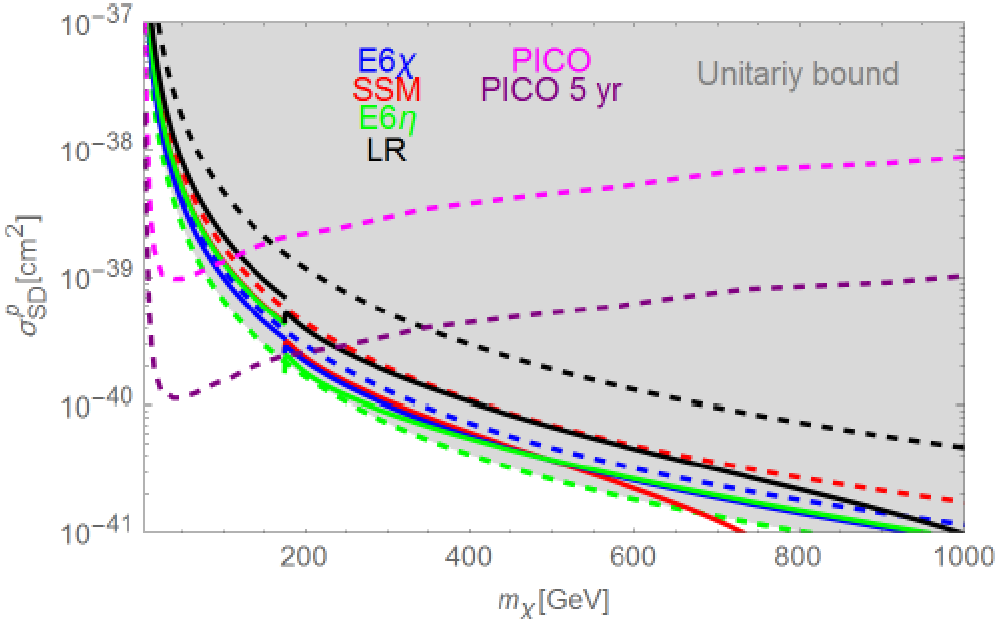
Fermionic Z-portal already excluded by current generation experiments ad exception of the pure axial limit.



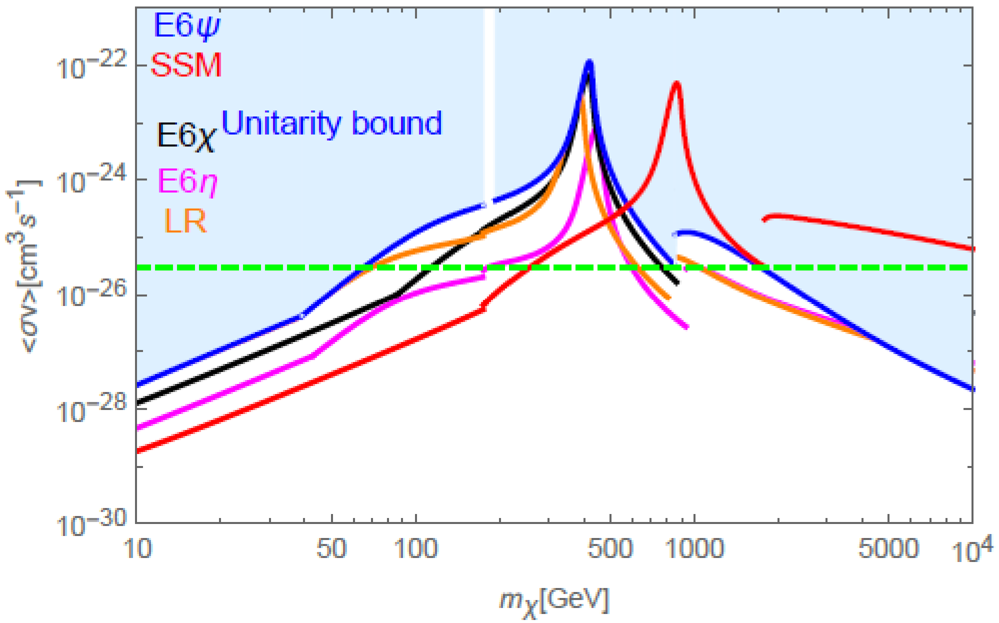
Next generation can completely probe the pure axial limit.

G. A., Y. Mambrini, F. Richard, JCAP 1503, 018

Z‘ portals

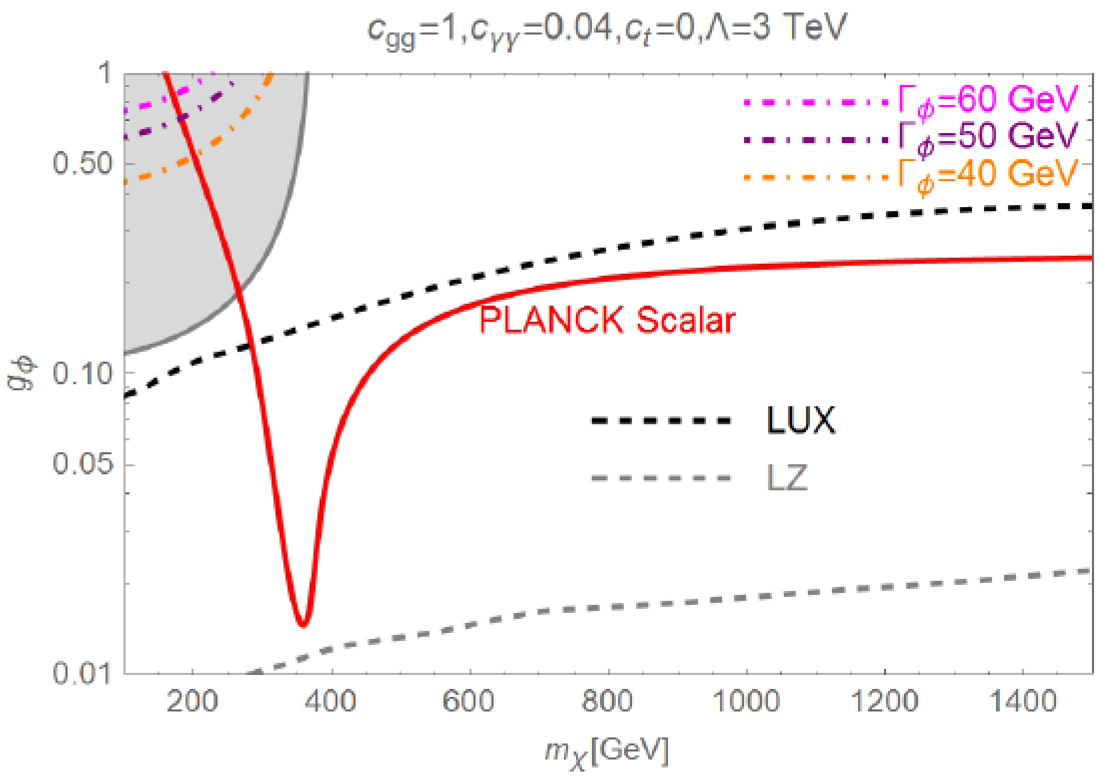


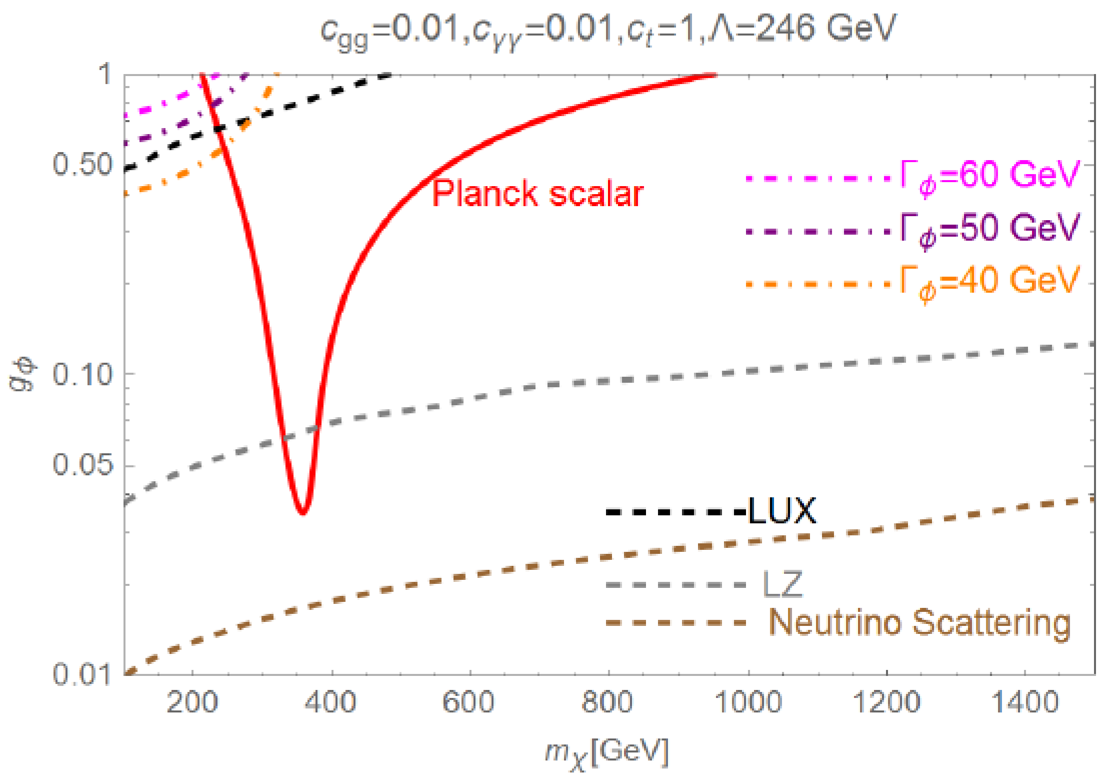
Z’ (fermionic portals) are also generically viable in the pure axial limit. Relation between relic density and DD is set by SD component.



Including also LHC, perturbativity and unitarity, allowed regions typically lie around the s-channel resonances.

750 GeV scalar portal





Y.Mambrini, G.A., A. Djouadi, Phys. Lett. B755, 426-432

Next future direct detection experiments can exclude the possibility of fermionic WIMP coupled with a 750 GeV scalar resonance.

Intermediate summary

Current Direct Detection limits already constrain many Dark Portal configurations.

Absence of detection in the next future will rule out a sizable portion of them.

Possible way out:

- Do not rely on WIMP paradigm
- Consider setups with null/suppressed direct detection cross-section, e.g. pseudoscalar portal (Arina et al. 1406.5542)
- Break the strict relation between Direct Detection and annihilation cross-section, e.g. two component portal.

Multi-component dark portal

There are no a priori motivations to consider that a single particle accounts for the total DM component of the Universe.

Direct and Indirect DM signals depend on the relative density of the different components. It is possible to relax detection limits by assigning suitable values of the density fraction.

It is possible to control and correlate the density fractions of multi-component DM coming from a same hidden sector.

Simple example

$$\mathcal{L} = \left(\mu_\phi |\phi|^2 + \lambda_q \bar{q} q\right) S + \left(\mu_V V_\mu V^\mu + \lambda_q \bar{q} q\right) S$$

$$\langle \sigma v \rangle_\phi = \sum_q \frac{3\left(1 - \frac{m_f^2}{m_\phi^2}\right)^{3/2} |\mu_\phi|^2}{4\pi \left(m_S^2 - 4 m_\phi^2\right)^2}$$

$$\sigma_\phi^{\rm SI} = \frac{|\mu_\phi|^2 \mu_{N\phi}^2}{4\pi m_S^4 m_\phi^2} \frac{|Z f_p + (A-Z) f_n|^2}{A^2}$$

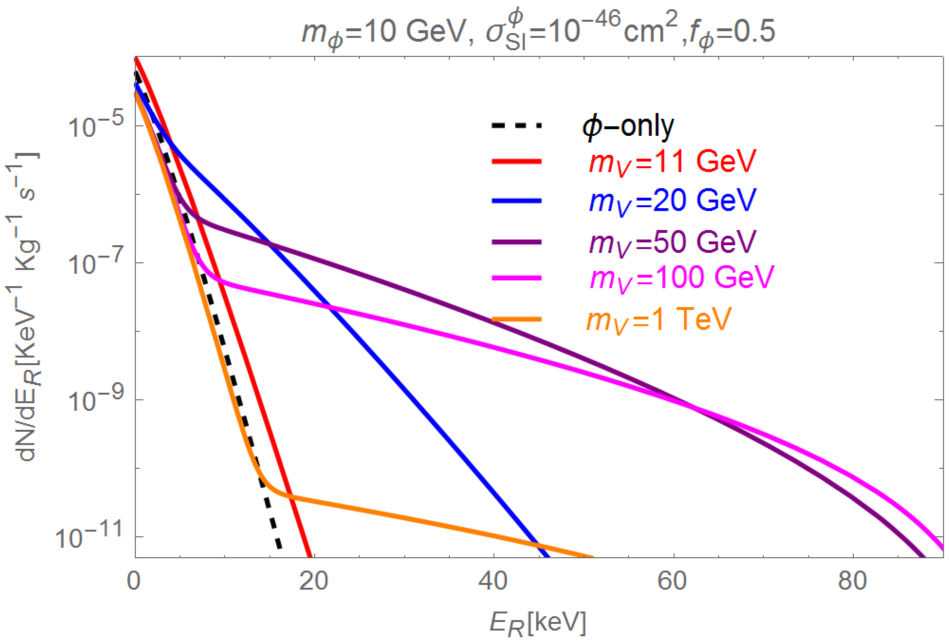
$$\langle \sigma v \rangle_V = \sum_q \frac{\left(1 - \frac{m_f^2}{m_V^2}\right)^{3/2} |\mu_V|^2}{4\pi \left(m_S^2 - 4 m_V^2\right)^2}$$

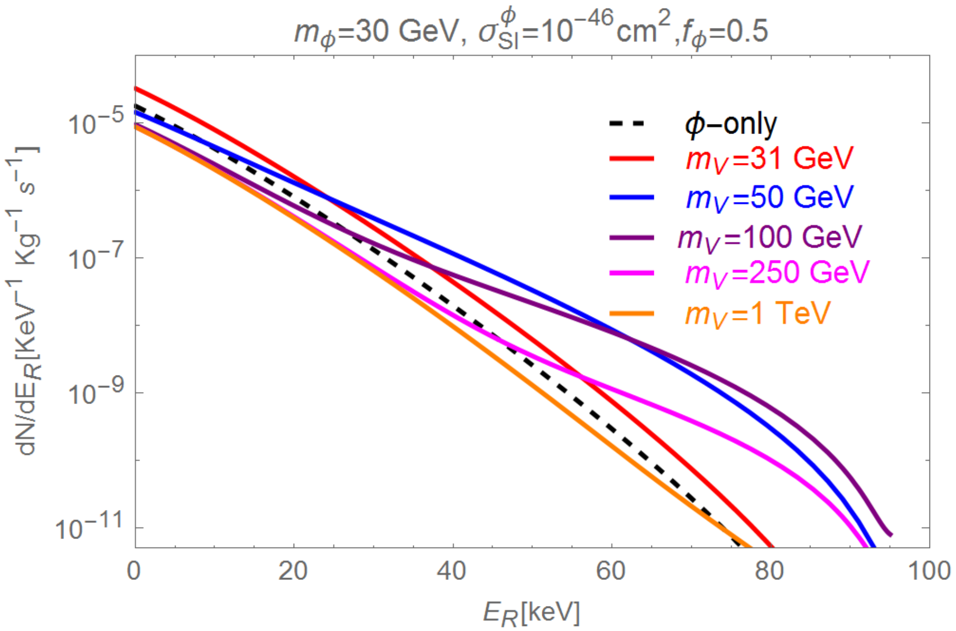
$$\sigma_V^{\rm SI} = \frac{|\mu_V|^2 \mu_{NV}^2}{4\pi m_S^4 m_V^2} \frac{|Z f_p + (A-Z) f_n|^2}{A^2}$$

$$\frac{\Omega_\phi}{\Omega_V} = \frac{\langle \sigma v \rangle_V}{\langle \sigma v \rangle_\phi} = \frac{|\mu_V|^2}{3|\mu_\phi|^2} = \frac{1}{3} \frac{\sigma_V^{\rm SI}}{\sigma_\phi^{\rm SI}} \frac{m_V^2}{m_\phi^2}$$

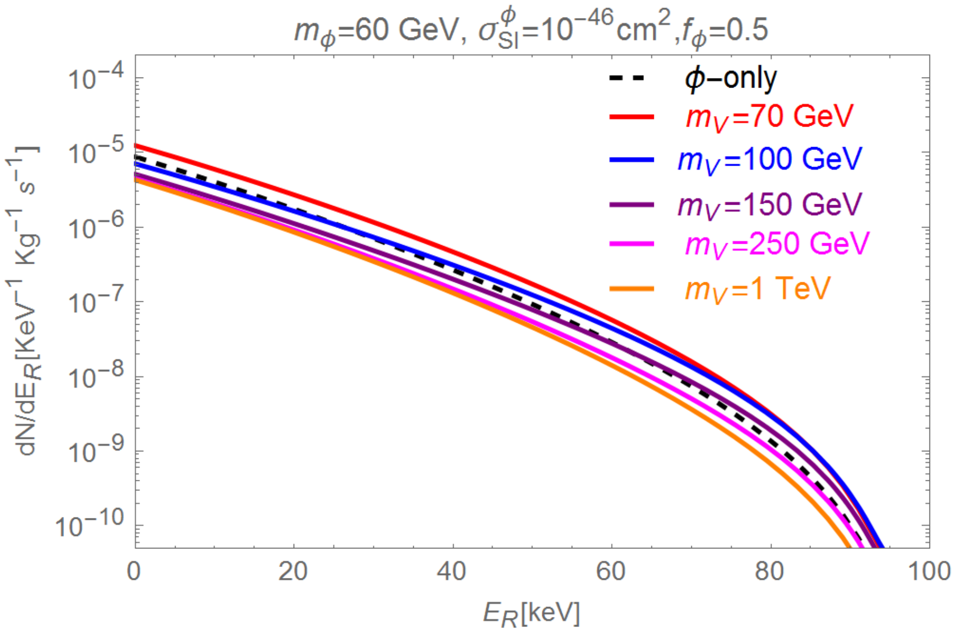
$$\frac{\sigma_V^{\rm SI}}{\sigma_\phi^{\rm SI}} = 3 \frac{m_\phi^2}{m_V^2} \frac{f_\phi}{1 - f_\phi}$$

$$\frac{dN}{dE_R} = \frac{\sigma_\phi^{\rm SI} \rho_0}{2 m_T^2 m_\phi} I_\phi(m_\phi, E_R) \left(f_\phi + (1 - f_\phi) \frac{m_\phi}{m_V} \frac{\sigma_V^{\rm SI}}{\sigma_\phi^{\rm SI}} \frac{I_V(m_V, E_R)}{I_\phi(m_\phi, E_R)} \right)$$



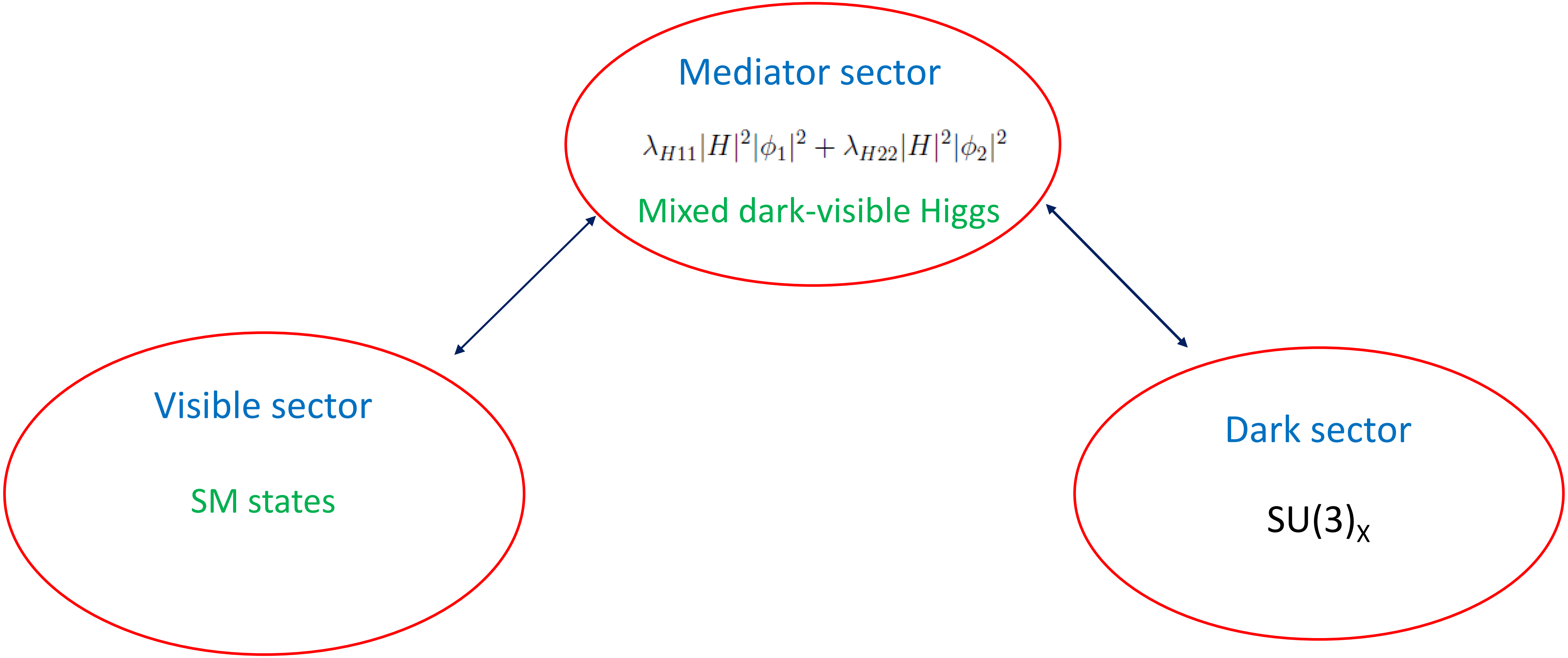


(see also e.g. 0907.4374
1208.0336)



Hidden SU(3) model

C. Gross, O. Lebedev, Y. Mambrini, arXiv:1505.07480



$$\mathcal{L}_{\rm SM} + \mathcal{L}_{\rm portal} + \mathcal{L}_{\rm hidden}$$

$$-\mathcal{L}_{\rm SM} \supset V_{\rm SM} = \frac{\lambda_H}{2}|H|^4 + m_H^2|H|^2$$

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

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

$$G_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + i\tilde{g}[A_\mu, A_\nu] \qquad D_\mu\phi_i = \partial_\mu\phi_i + i\tilde{g}A_\mu\phi_i$$

$SU(3)_X \longrightarrow Z_2 \times Z_2'$

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

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

$$V_{\text{hidden}}(\phi_1, \phi_2) = m_{11}^2 |\phi_1|^2 + m_{22}^2 |\phi_2|^2 - (m_{12}^2 \phi_1^\dagger \phi_2 + \text{h.c.}) + \frac{\lambda_1}{2} |\phi_1|^4 + \frac{\lambda_2}{2} |\phi_2|^4 + \lambda_3 |\phi_1|^2 |\phi_2|^2 + \lambda_4 |\phi_1^\dagger \phi_2|^2$$

$$+ \left[\frac{\lambda_5}{2} (\phi_1^\dagger \phi_2)^2 + \lambda_6 |\phi_1|^2 (\phi_1^\dagger \phi_2) + \lambda_7 |\phi_2|^2 (\phi_1^\dagger \phi_2) + \text{h.c.} \right]$$

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	$(-,+)$
$\chi, A^3_\mu, A^6_\mu, A^8_\mu$	$\tilde{\chi}, A'^3_\mu, \tilde{A}^6_\mu, A'^8_\mu$	$(+,-)$

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

Simplified model $v_1 >> v_2 >> v_3$

$$\mathcal{L} \supset \frac{1}{2} m_A^2 \sum_{a=1,2} A_\mu^a A^{a\mu} + \frac{1}{2} m_{\tilde{\chi}}^2 \tilde{\chi}^2$$
$$+ \frac{\tilde{g}\, m_A}{2} (-h_1 \sin\theta + h_2 \cos\theta) \sum_{a=1,2} A_\mu^a A^{a\mu}$$
$$+ (1+r)\lambda_2 v_2 (-\sin\theta h_1 + \cos\theta h_2) + (1+r)\lambda_{H22} (\cos\theta h_1 + \sin\theta h_2) \tilde{\chi}^2$$

Case I can be reduced to a two component scalar portal

$$\lambda_2 = \frac{\cos\theta m_{h_2}^2 + \sin^2\theta m_{h_1}^2}{v_2^2} = \tilde{g}^2 \frac{\cos^2\theta m_{h_2}^2 + \sin^2\theta m_{h_1}^2}{4 m_A^2}$$
$$\lambda_{H22} = \frac{(m_{h_1}^2 - m_{h_2}^2)\sin\theta\cos\theta}{v v_2} = \tilde{g} \frac{(m_{h_1}^2 - m_{h_2}^2)\sin\theta\cos\theta}{2 v m_A}$$

The model has only one fundamental parameter, the « dark » gauge coupling.

Relic density

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

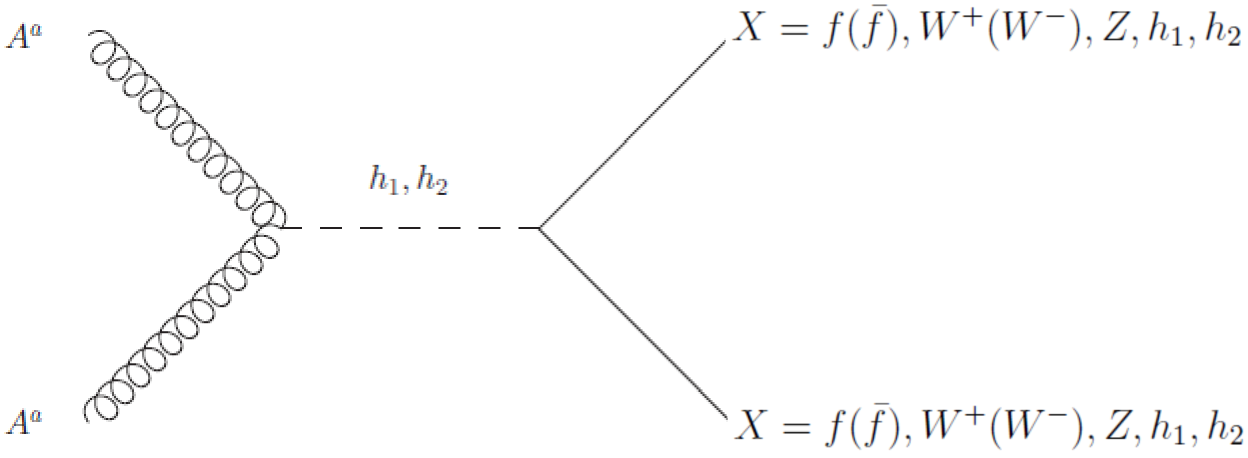
In multi-component DM from hidden sector one have different possible processes:

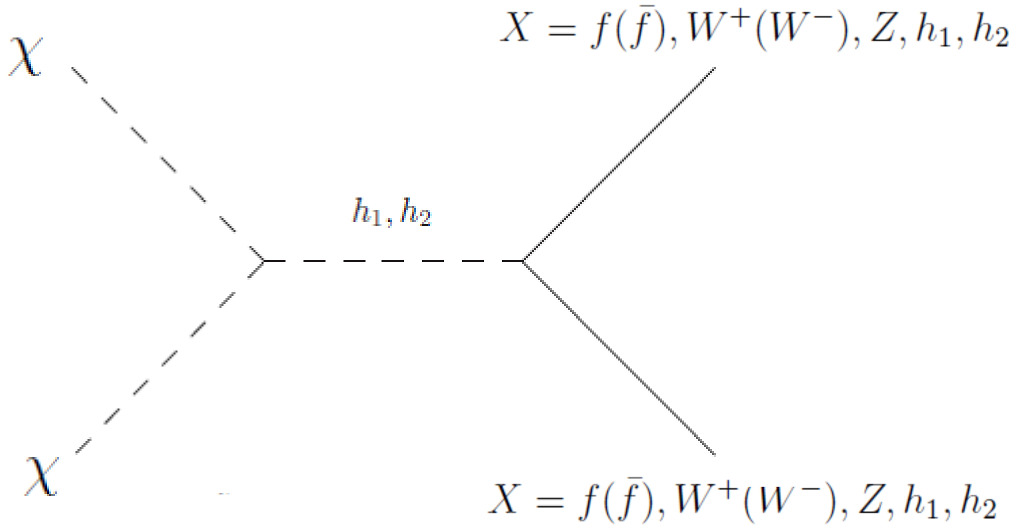
-pair annihilations of both components into SM states
-pair annihilations of the heavier DM component into the lightest one
-co-annihilations
-semi(co)-annihilations

Boltzmann equation for simplified system

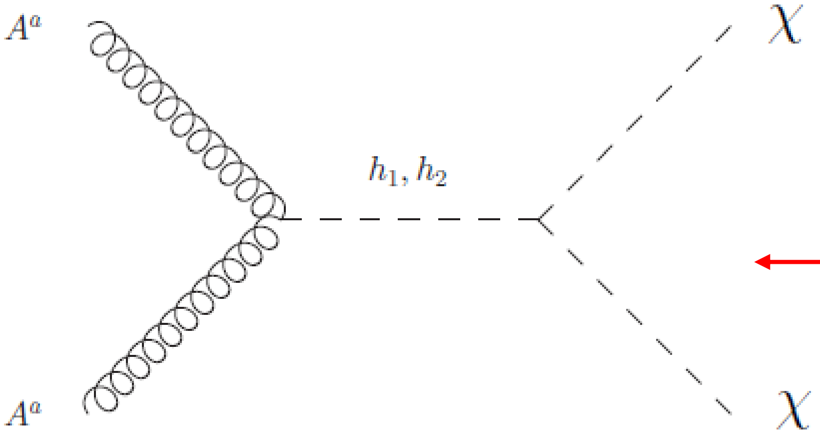
$$\frac{dY_A}{dx} = -\overline{\langle \sigma v \rangle}(AA \to XX)\left(Y_A^2 - Y_{A,\text{eq}}^2\right) - \overline{\langle \sigma v \rangle}(AA \to \chi\chi)\left(Y_A^2 - \frac{Y_{A,\text{eq}}^2}{Y_{\chi,\text{eq}}^2} Y_\chi^2\right)$$
$$- \overline{\langle \sigma v \rangle}(AA \to A^3 h_{1,2})\left(Y_A^2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

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



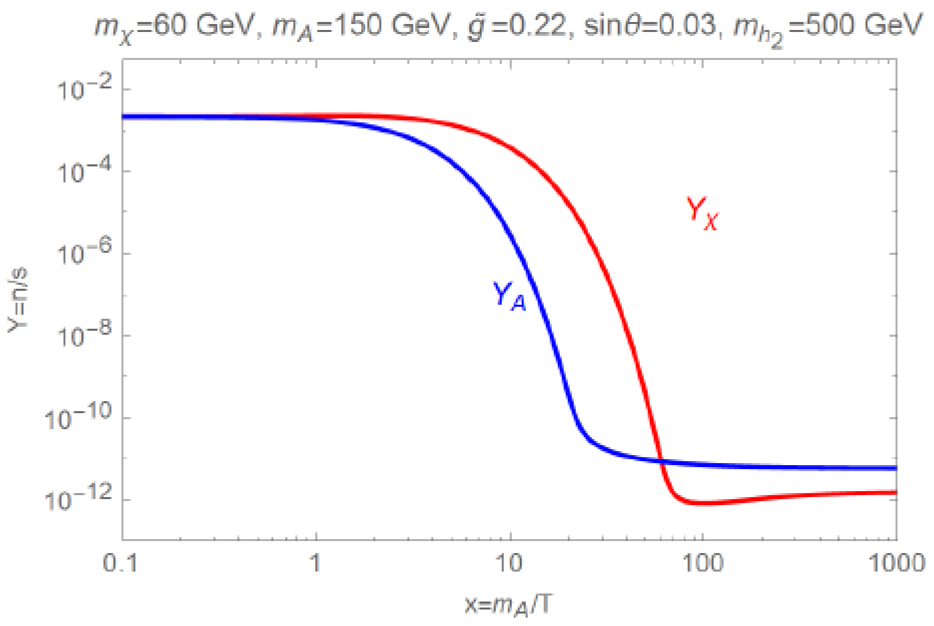


Conventional pair annihilations

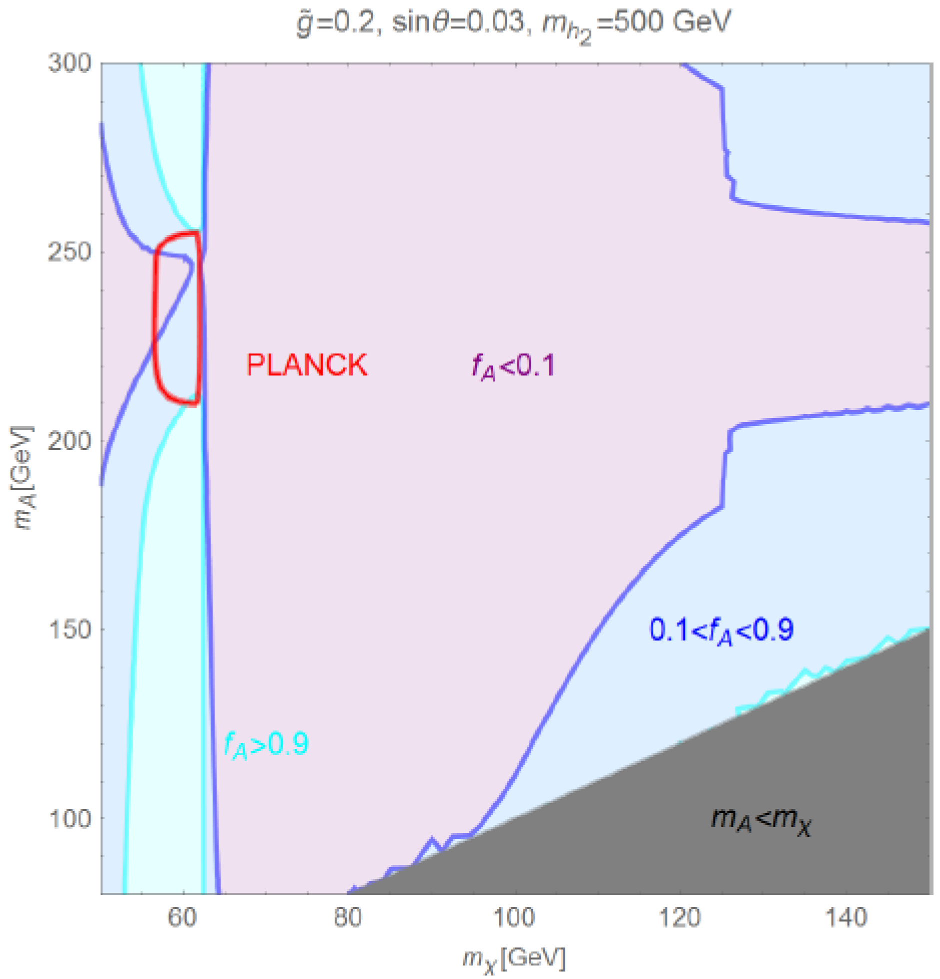


The relic density is mostly determined by pair annihilations.

Dark annihilation



G.A., C. Gross, O. Lebedev, Y. Mambrini, S. Pokorsky, T. Toma, in preparation



$$AA \to \chi\chi$$

Suppresses the relic density of vector component unless its mass close to the scalar one of a s-channel resonance is met.

Direct Detection

Both components feature a SI cross-section:

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

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

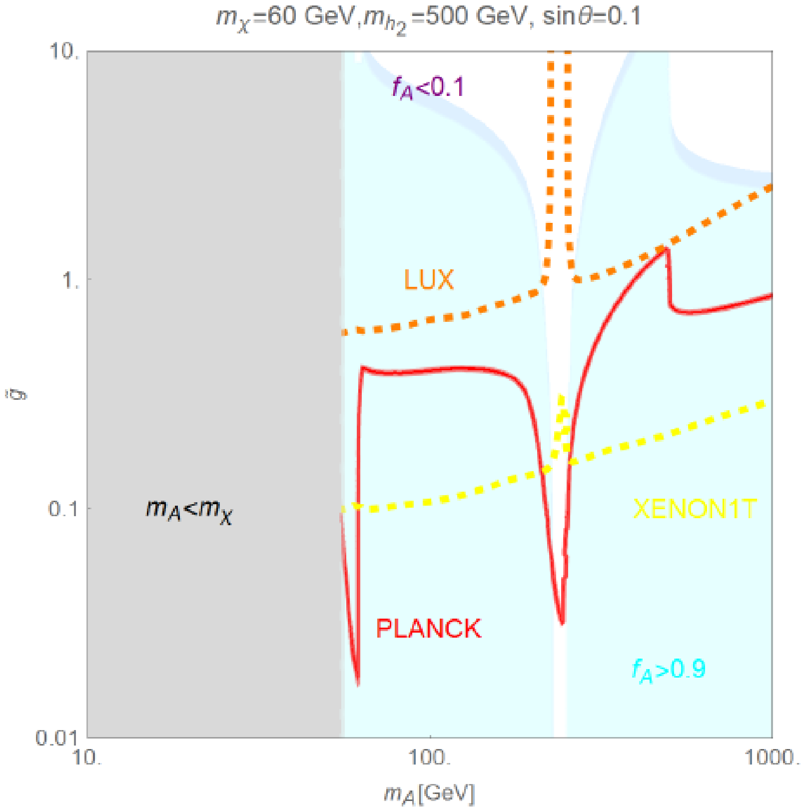
$$\lambda_2 v_2(-\sin\theta h_1 + \cos\theta h_2) + \lambda_{H22}(\cos\theta h_1 + \sin\theta h_2)\tilde{\chi}^2 = \frac{\tilde{g}}{4 m_A} \sin\theta\cos\theta \left(-h_1 m_{h_1}^2 \sin\theta + h_2 m_{h_2}^2 \cos\theta\right)$$

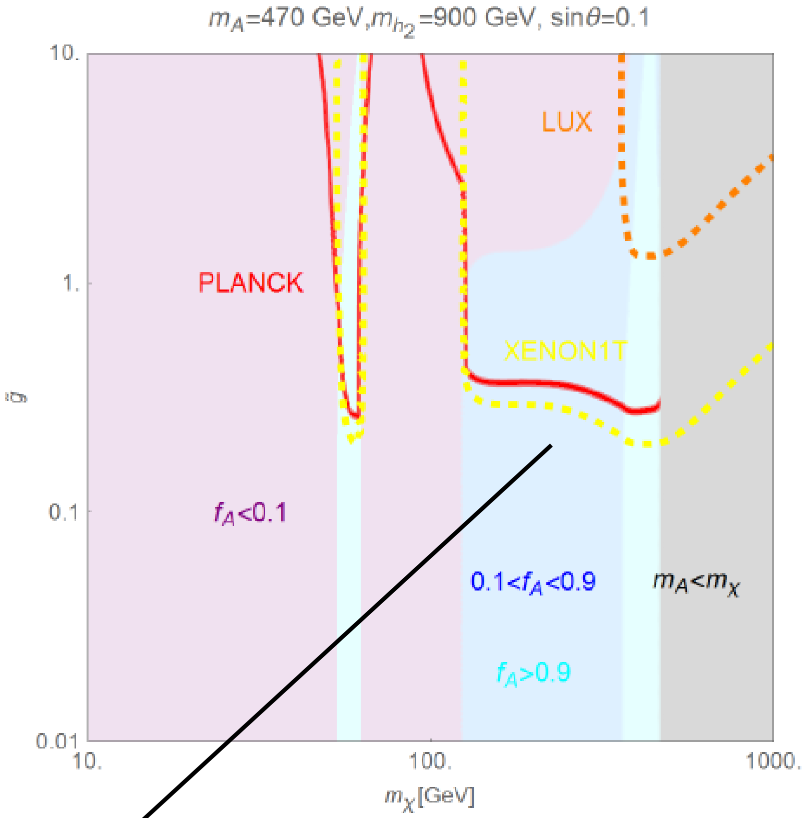
(see also 1406.0617)

Cross-section generated by scalar vector mixing

$$\sigma_{\chi N} = \frac{\mu_{\chi N}^2}{4\pi} \frac{m_\chi^2 m_A^2}{m_{A_6}^4} \sin^2\theta \cos^2\theta \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2}\right)^2 \frac{\left[Z f_p + (A-Z) f_n\right]^2}{A^2} \xrightarrow{\text{Simplified limit}} 0$$

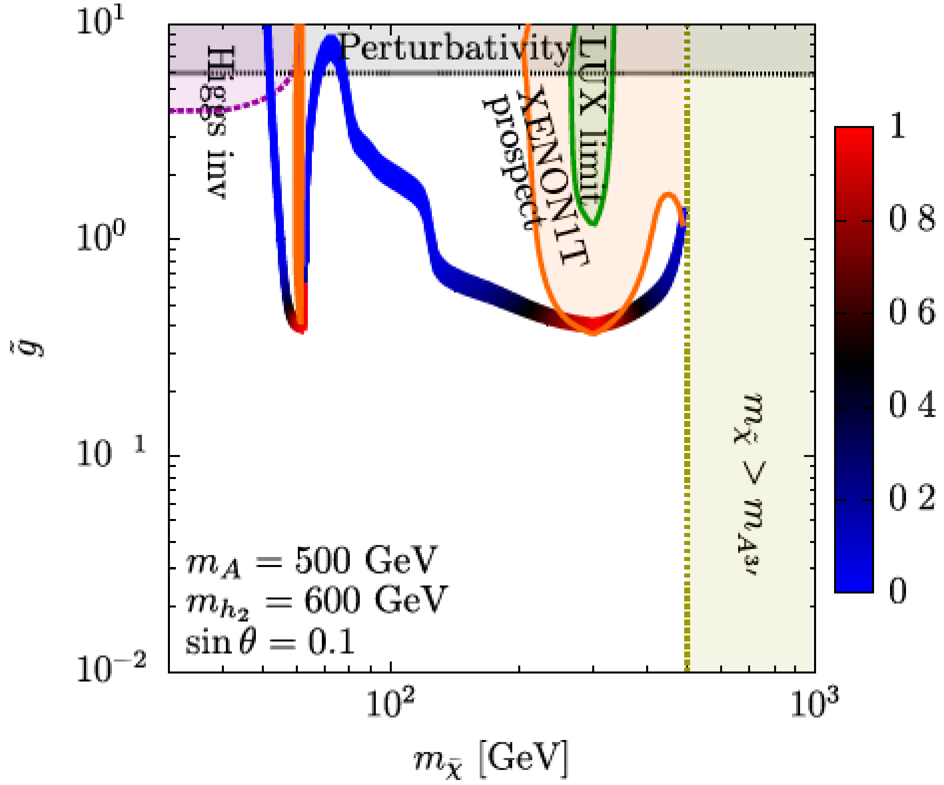
Scalar component is « coy » with respect to direct detection. For vector component the SI cross-section is suppressed by a
small mixing angle with respect to the main annihilation channel.

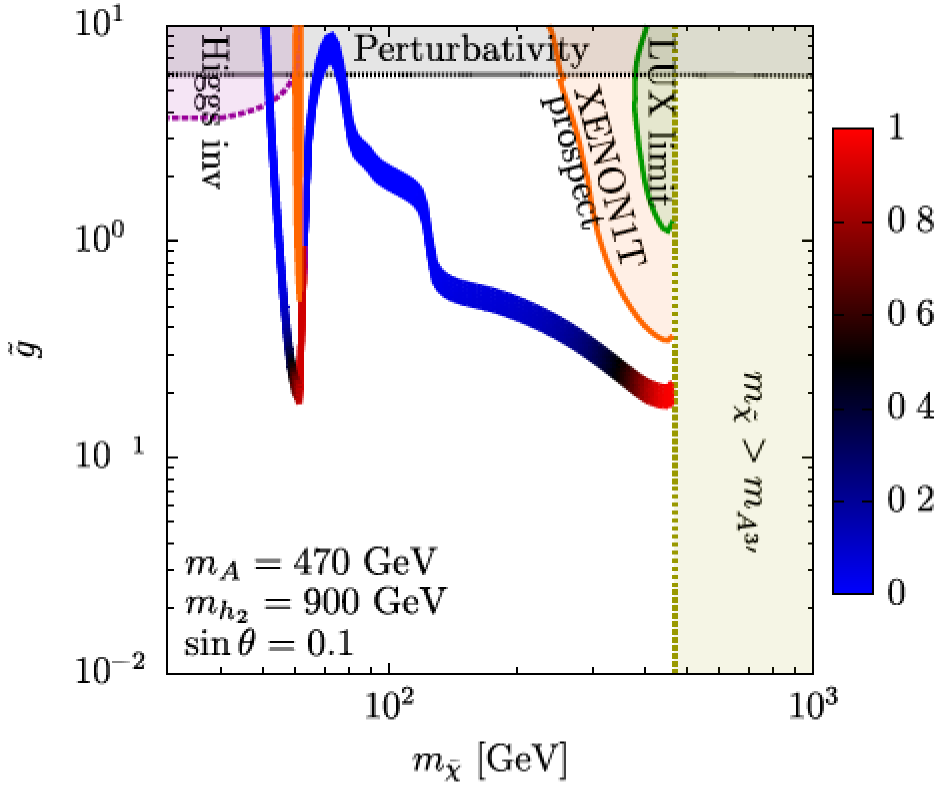




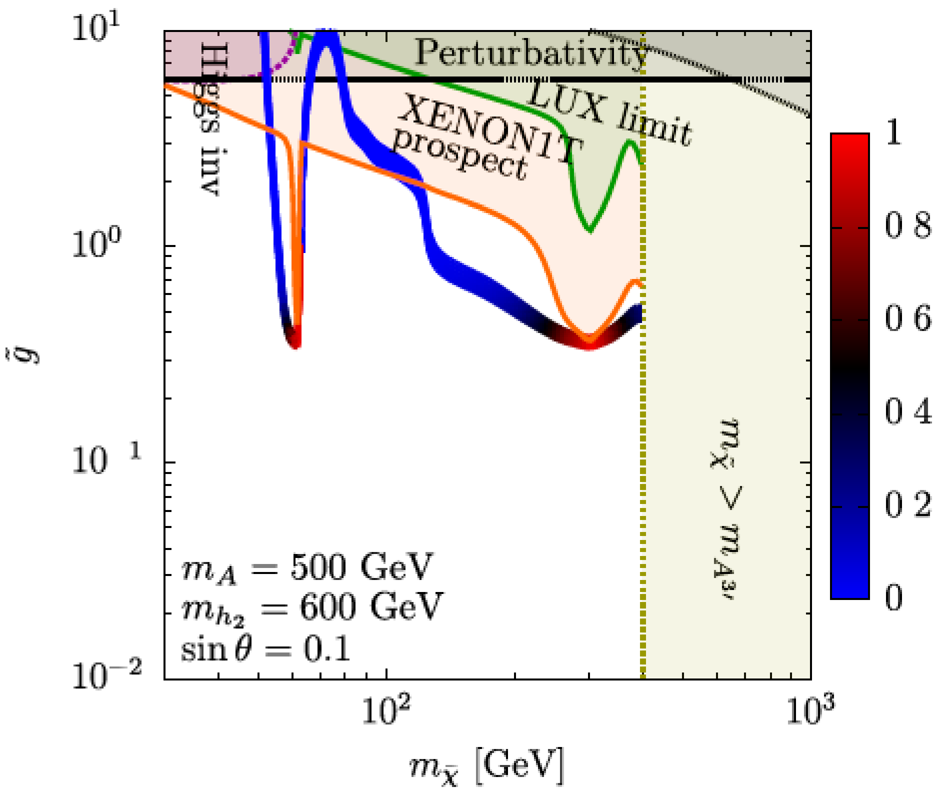
Xenon1T can probe subdominant component DM

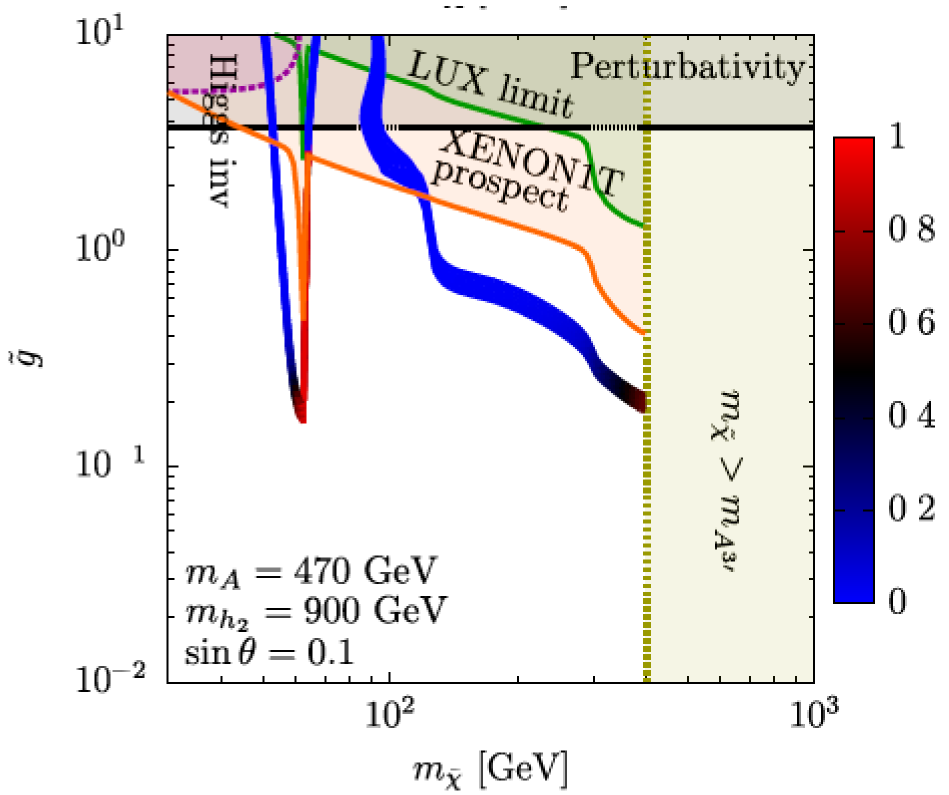
Numerical analysis

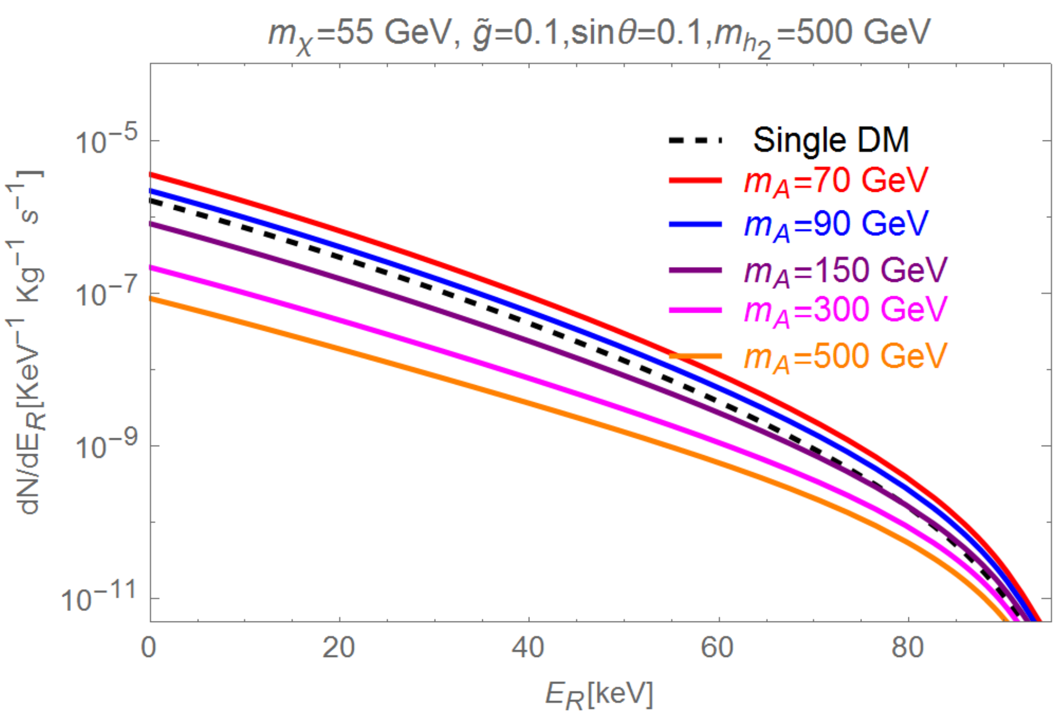




Case $v_1 \approx v_2$

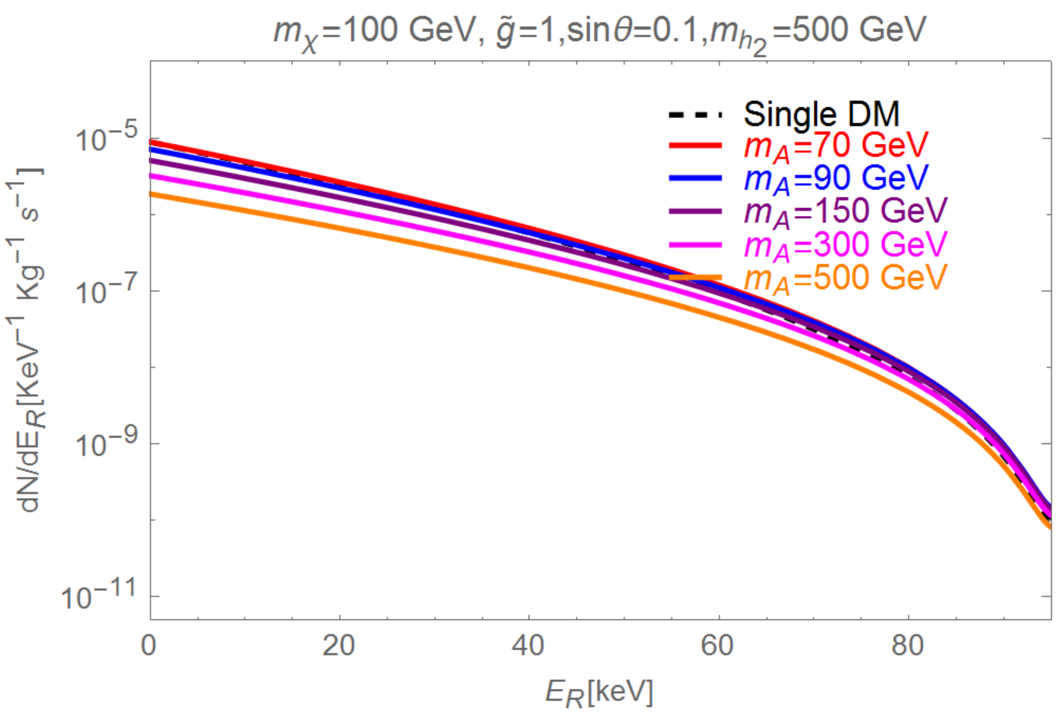






Limits from invisible Higgs width forbid to have a too light component. Component discrimination in DD not trivial.

Quantitative analysis required.



Conclusions

We have investigated the capability of next future detector of testing the WIMP hypothesis.

Dark portals represent the simplest case of study. Next future experiments can probe, and exclude in case of absence of signal many model configurations.

Two component DM setups can help to accommodate DM relic density with Direct Detection limits. Next future experiments can partially probe the interactions of subdominant DM components.