Dark portals:from simplified models to theoretical embeddings

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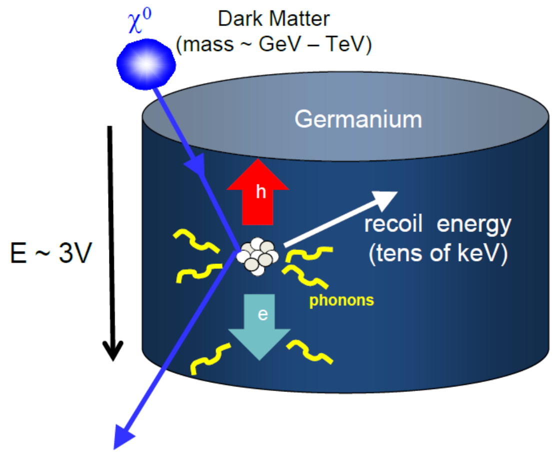
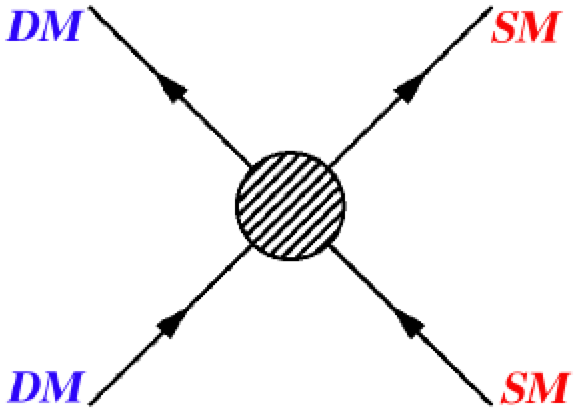
WIMP scenarios feature a strong complementarity between Dark Matter searches.

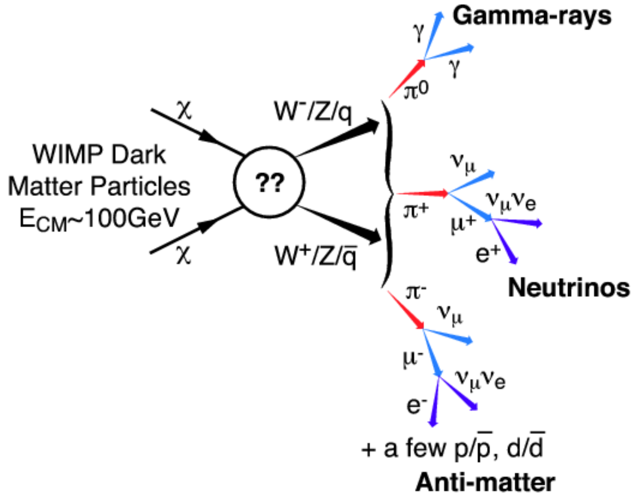


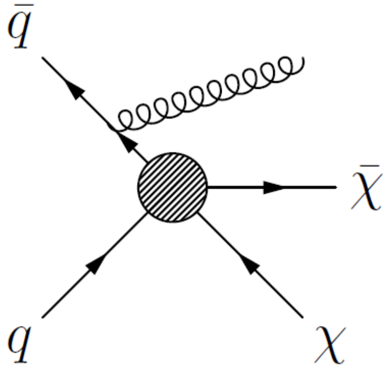
thermal freeze-out (early Univ.)
indirect detection (now)

direct detection



production at colliders





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

Dark Portals

“Dark Portals“ are simple extensions of the SM model with a DM candidate and a mediator of the interactions with the SM.

These are bottom-up models simple and manageable but still encode the most relevant aspects of DM (and BSM) phenomenology.

Their purpose is to provide an effective interface with experimental outcome (especially excesses) .

Can provide guidelines for model building.

Dark Portal to SM fermions

Dark portals are simple extensions of the SM with a DM candidate and a mediator interacting with the DM and SM fermions.

Scalar/pseudoscalar portal

$$\mathcal{L} = s\left[\lambda_s^{\chi}\bar{\chi}\chi + \lambda_s^f \bar{f} f\right] + a\left[i\lambda_a^{\chi}\bar{\chi}\gamma_5\chi + i\lambda_a^f \bar{f}\gamma_5 f\right]$$

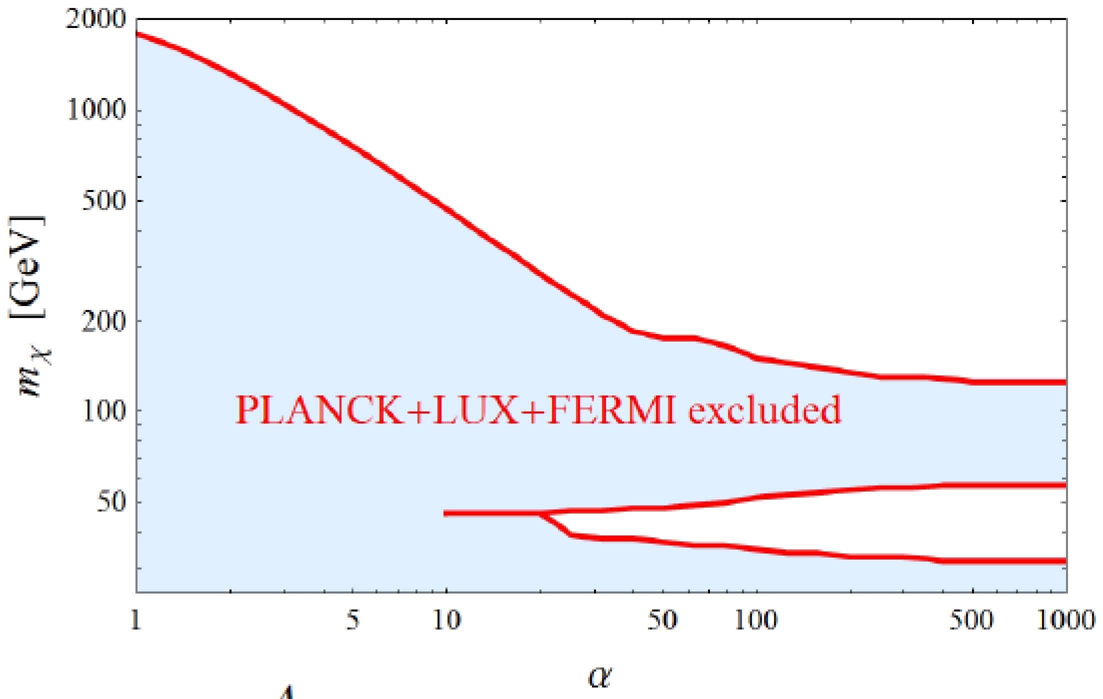
Vector/Axial portal

$$\mathcal{L} = g_D \bar{\chi}\gamma^{\mu}\left(V_{\chi} - A_{\chi}\gamma_5\right)\chi R_{\mu} + g_f \sum_f \bar{f}\gamma^{\mu}\left(V_f - A_f\gamma_5\right) f R_{\mu}$$

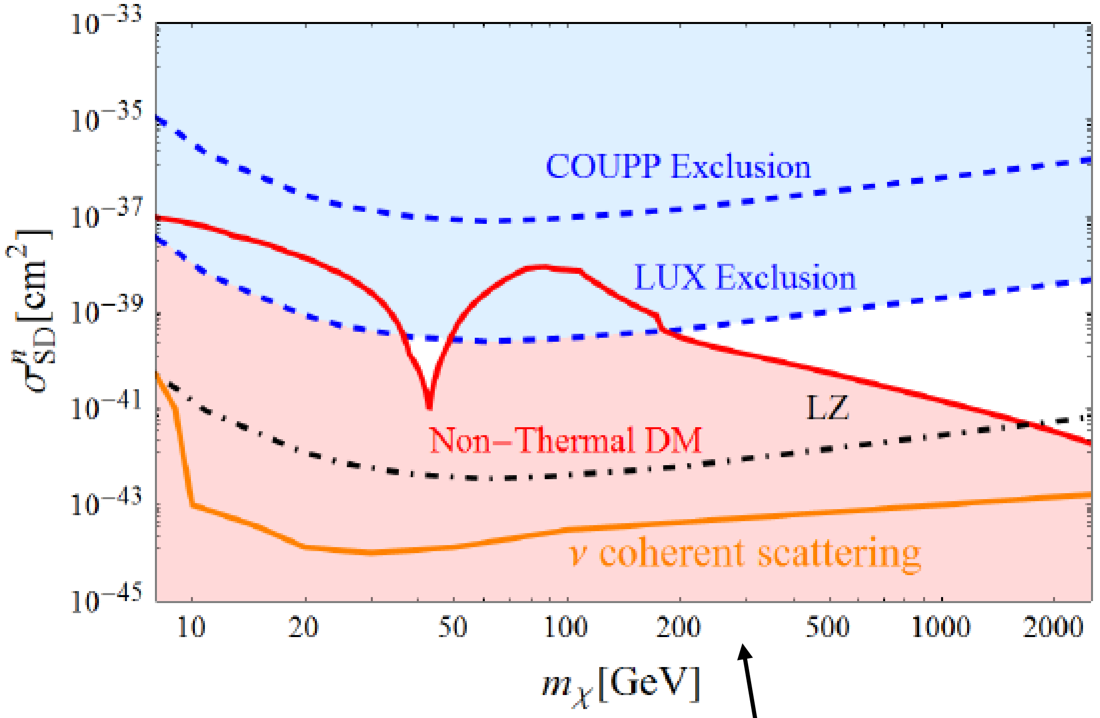
Simple example: Z-portal

(G.A., Y. Mambrini, F. Richard: 1411.2985)

Correct relic density (dominant axial interaction) ⟷ Lower bound on SD cross-section



$$\alpha = \frac{A_\chi}{V_\chi}$$



Next future experiments can completely probe Z-portal scenario

Dark Z´ models

General implementation: (See M. Pierre`s Talk)

$$\mathcal{L} = \sum_f g_f \bar{f}\gamma^\mu \left(\epsilon_L^f P_L + \epsilon_R^f P_R\right) f Z'_\mu + g_\chi \bar{\chi}\gamma^\mu \left(\epsilon_L^\chi P_L + \epsilon_R^\chi P_R\right) \chi Z'_\mu$$

$$\epsilon_{L,R}^f = \hat{\epsilon}_{L,R}^f / D$$

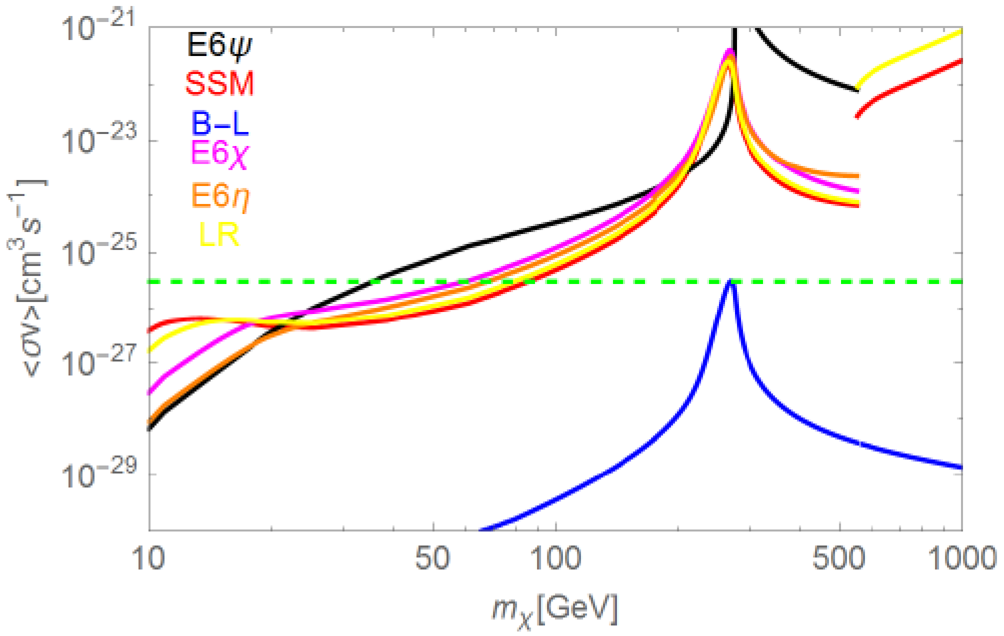
	χ	ψ	η	LR	B-L	SSM
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1
$\hat{\epsilon}_L^u$	-1	1	-2	-0.109	1/6	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}_L^d$	-1	1	-2	-0.109	1/6	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}_R^u$	1	-1	2	0.656	1/6	$-\frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}_R^d$	-3	-1	-1	-0.874	1/6	$\frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}_L^\nu$	3	1	1	0.327	-1/2	$\frac{1}{2}$
$\hat{\epsilon}_L^l$	3	1	1	0.327	-1/2	$-\frac{1}{2} + \sin^2\theta_W$
$\hat{\epsilon}_R^e$	1	-1	2	-0.438	-1/2	$\sin^2\theta_W$

Han et al. 1308.2738

DM phenomenology relies on vectorial and axial combinations.

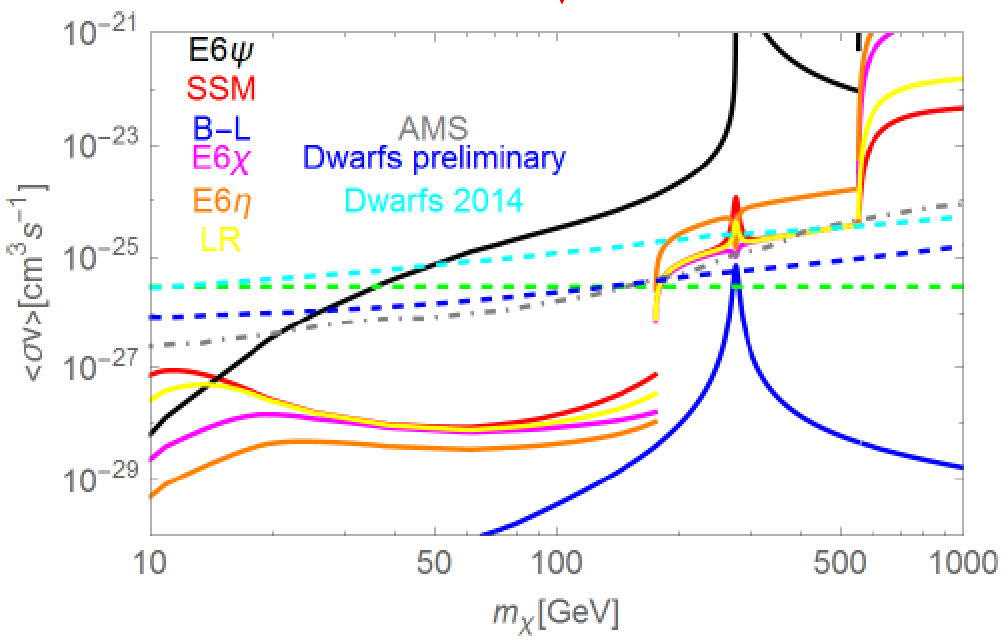
$$g_2 V_f = \frac{g_f}{2}\left(\epsilon_L^f + \epsilon_R^f\right) \qquad g_2 A_f = \frac{g_f}{2}\left(\epsilon_L^f - \epsilon_R^f\right)$$

$$g_2 V_\chi = \frac{g_\chi}{2}\left(\epsilon_L^\chi + \epsilon_R^\chi\right) \qquad g_2 A_\chi = \frac{g_\chi}{2}\left(\epsilon_L^\chi - \epsilon_R^\chi\right)$$



Decoupling time

Present time



s-wave component of the annihilation cross-section is proportional to the vectorial coupling suppressed by LUX.
Indirect signals suppressed.

Unitarity bound

$$m_\chi \lesssim \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_2 |A_\chi|}$$

In a not gauge invariant setup axial couplings lead to cross-sections which violate perturbative unitarity (Kahlhoefer et al: 1510.02110)

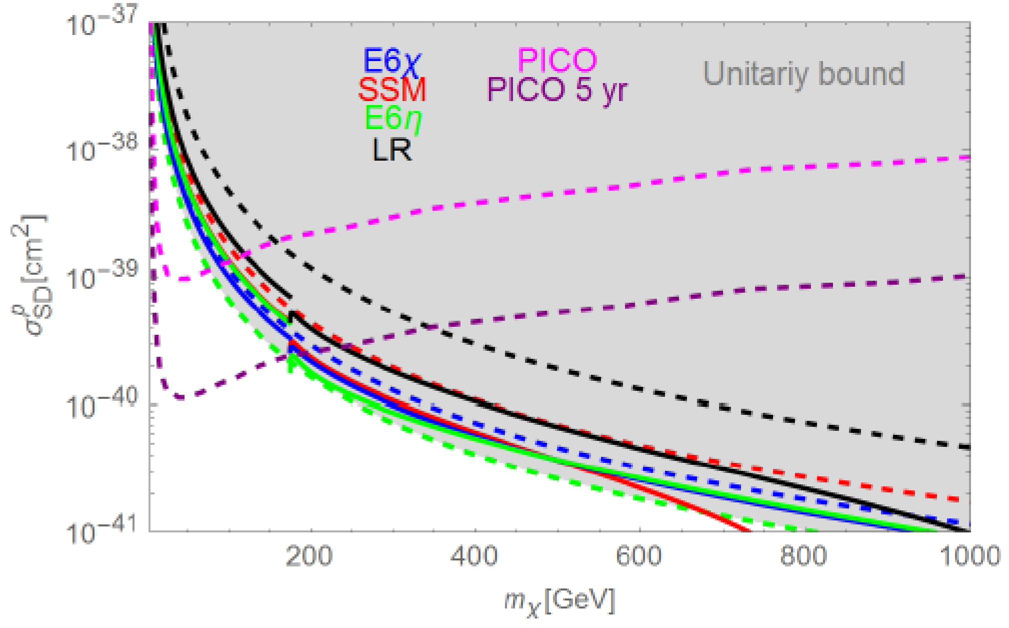
The bound is evaded by considering a theory with only vectorial couplings (e.g. kinetic mixing) or by explicitly introducing a higgs mechanism in the new U(1) sector.

$$m_s < \frac{\pi m_{Z'}^2}{g_2^2 |A_\chi|^2 m_\chi}$$

Possibly different phenomenology associated to a second scalar mediator

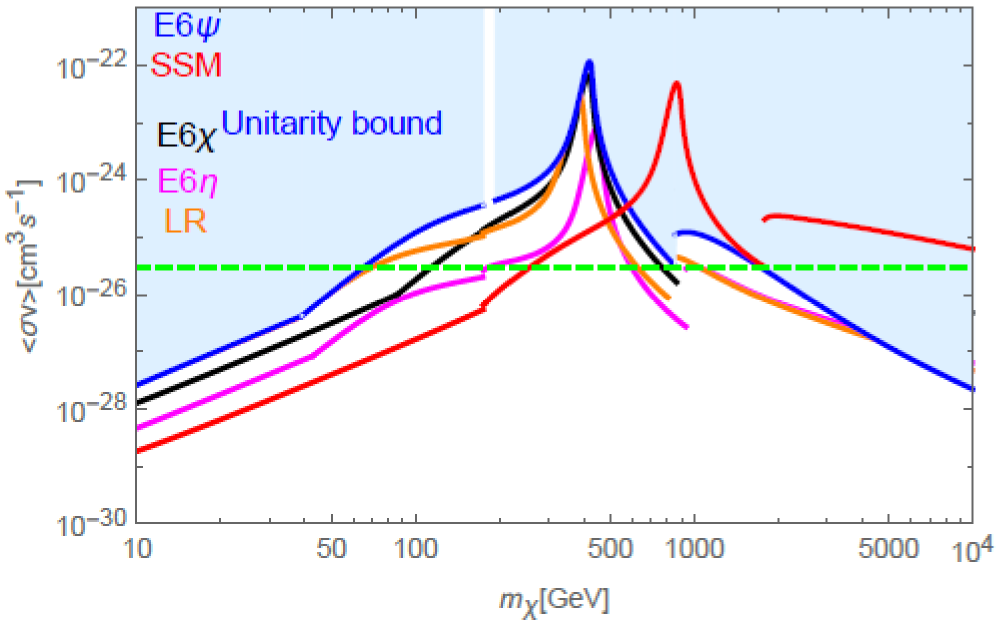
$$\delta m^2 = -\frac{1}{4} \frac{e\, g'\, q_H}{s_W\, c_W} v^2$$

In presence of axial couplings, gauge invariance implies that the SM higgs is charged under
the new U(1) and generates a Z/Z‘ mixing thus implying couplings with the gauge bosons.



Perturbative unitarity combined with collider limits strongly limits the range of viable DM masses.

$$\sigma^{\rm SD}_{\chi p,{\rm uni}} \approx 5.8\times 10^{-38}{\rm cm}^2 \alpha_{\rm SD}\left(\frac{m_\chi}{100\,{\rm GeV}}\right)^{-2}\left(\frac{m_{Z'}}{1\,{\rm TeV}}\right)^{-2}$$



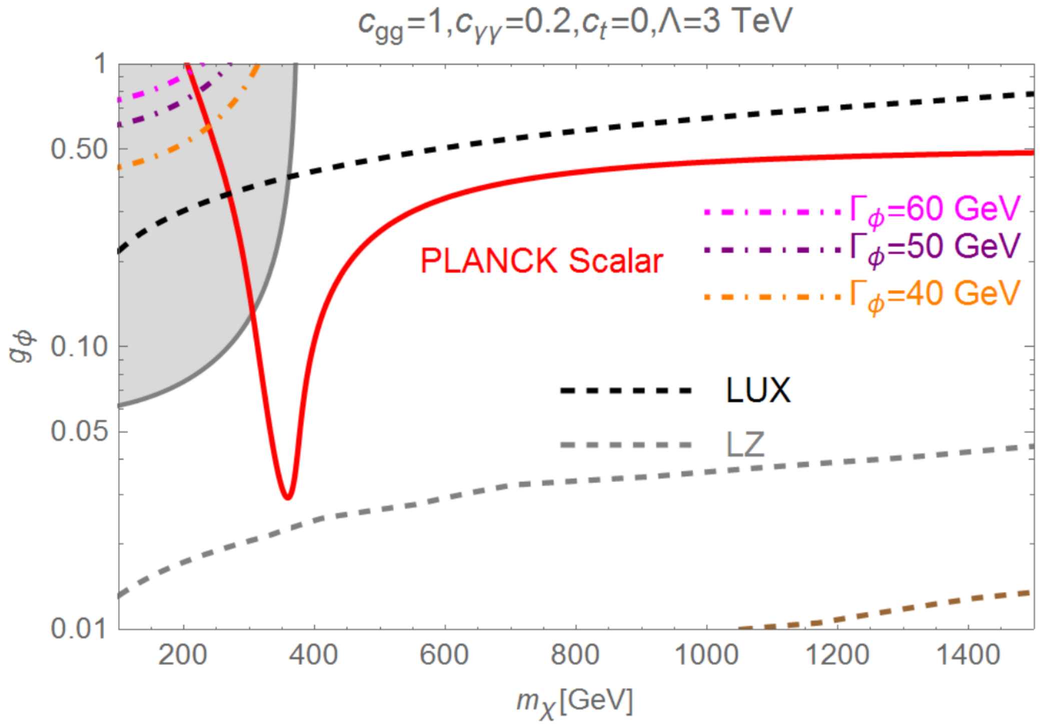
Dark Portal to Gauge Bosons

Example 1: 750 GeV Resonance

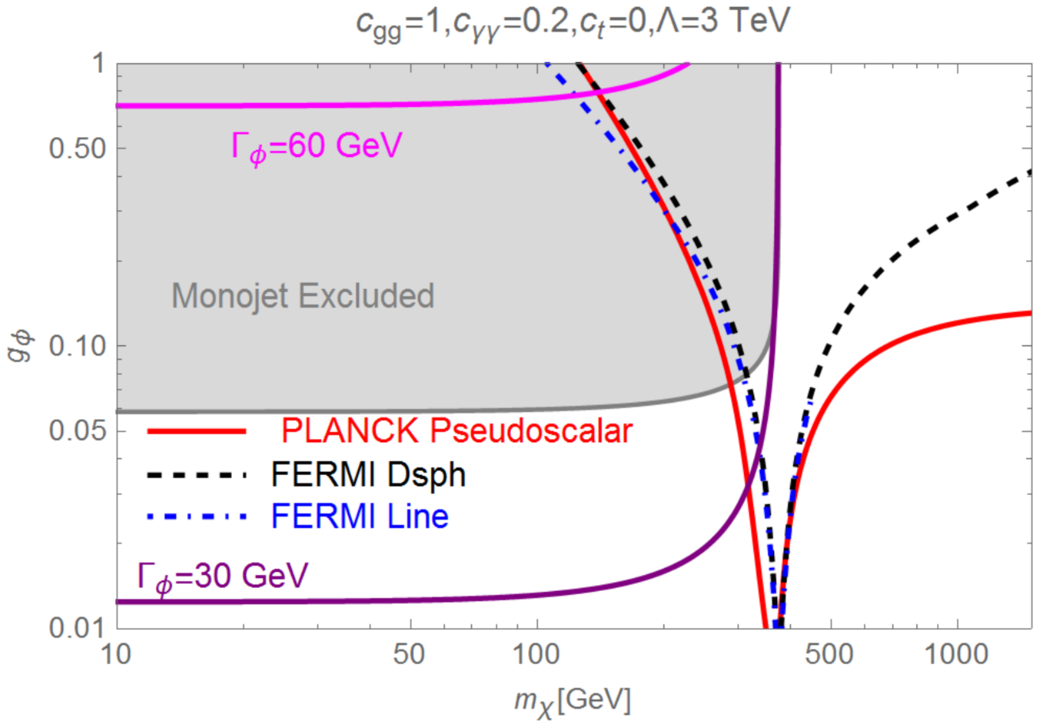
$$\mathcal{L}_{0+} = \frac{c_1}{\Lambda}\phi F_{\mu\nu}F^{\mu\nu} + \frac{c_2}{\Lambda}\phi W^{\mu\nu}W_{\mu\nu} + \frac{c_3}{\Lambda}\phi G^a_{\mu\nu}G^{\mu\nu}_a + g_\phi \phi\bar{\chi}\chi + m_\chi \bar{\chi}\chi$$

$$\mathcal{L}_{0-} = \frac{c_1}{\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{c_2}{\Lambda}\phi W^{\mu\nu}\tilde{W}_{\mu\nu} + \frac{c_3}{\Lambda}\phi G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a + i g_\phi \phi\bar{\chi}\gamma^5\chi + m_\chi \bar{\chi}\chi$$

$$c_{\gamma\gamma} = c_1 \cos^2\theta_W + c_2 \sin^2\theta_W\,, \;\; c_{ZZ} = c_1 \sin^2\theta_W + c_2 \cos^2\theta_W\,, c_{WW} = 2c_2,\; c_{gg} = c_3$$



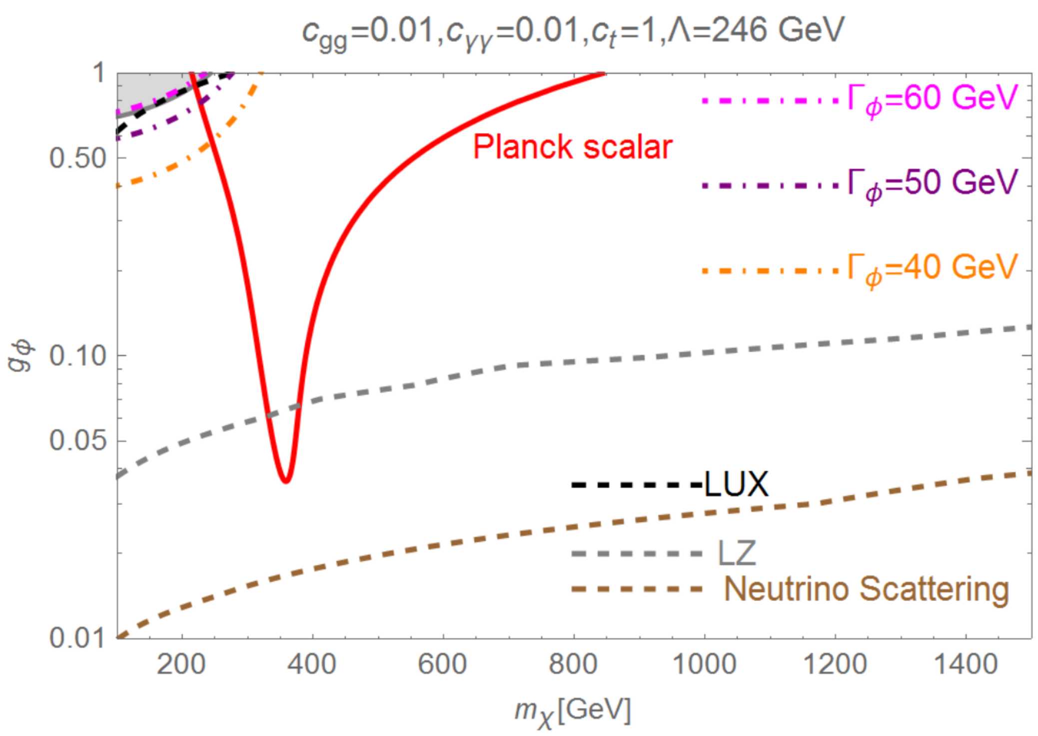
$$g_{\phi NN} = \sum_{f=u,d,s} \bar{c}_f \frac{m_N}{\Lambda} f_{Tf}^N + \frac{2}{27} f_{TG}^N \left(\sum_{f=c,b,t} \bar{c}_f \frac{m_N}{\Lambda} - \bar{c}_{gg} \frac{m_N}{\Lambda} \right)$$



Y. Mambrini, G.A. and Abdelak Djouadi 1512.04913,
See also 1512.04917, 1512.06842, 1601.01571

$$\langle \sigma v \rangle_{gg}^{0^+} \simeq \frac{32 g_\phi^2 c_{gg}^2 m_\chi^4 v^2}{\pi \Lambda^2 (s - M_\phi^2)^2}$$

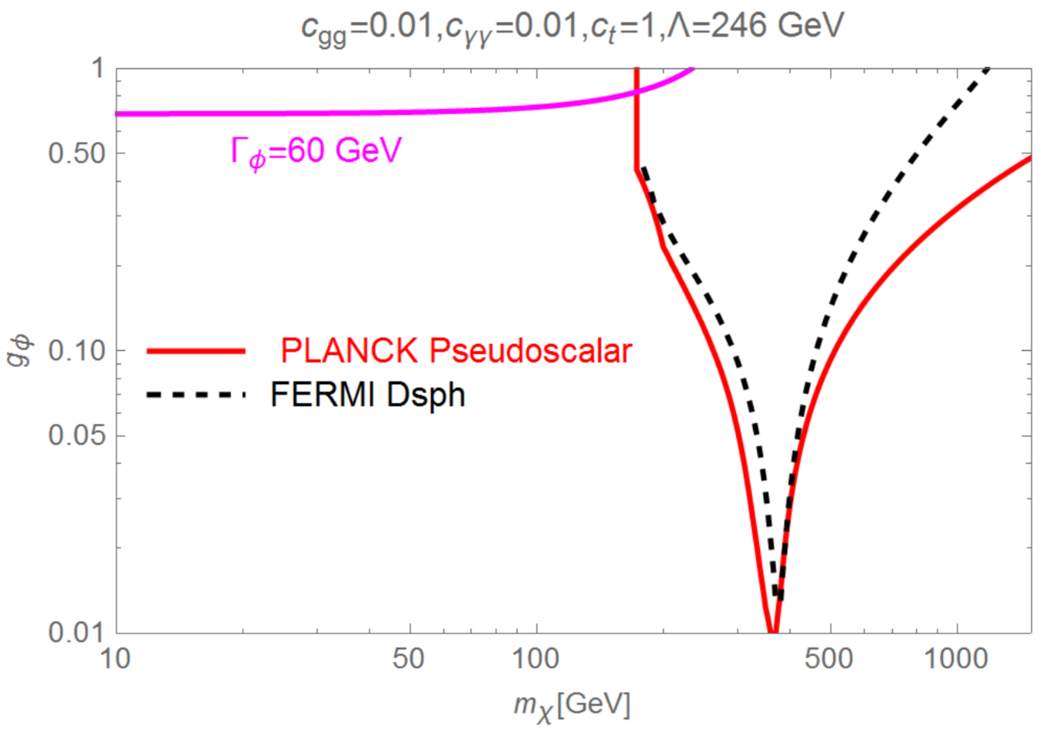
$$\langle \sigma v \rangle_{gg}^{0^-} = \frac{32 g_\phi^2 c_{gg}^2 s^2}{\pi \Lambda^2 (s - M_\phi^2)^2}$$



$$\langle \sigma v \rangle^{+}_{\bar{t}t} \approx \frac{g_\phi^2 m_t^2 v^2}{64\pi v_h^2 m_\chi^2}$$

$$m_\chi > M_\phi$$

$$\langle \sigma v \rangle^{-}_{\bar{t}t} \approx \frac{g_\phi^2 m_t^2}{16\pi v_h^2 m_\chi^2}$$



$$\langle \sigma v \rangle^{0^+}_{\bar{t}t} \approx \frac{g_\phi^2 m_t^2 m_\chi^2 v^2}{4\pi v_h^2 M_\phi^4} \left(1 - \frac{4m_t^2}{m_\chi^2}\right)^{3/2}$$

$$m_\chi < M_\phi$$

$$\langle \sigma v \rangle^{0^-}_{\bar{t}t} \approx \frac{g_\phi^2 m_t^2 s}{4\pi v_h^2 M_\phi^4} \sqrt{1 - \frac{4m_t^2}{m_\chi^2}}$$

Kinetic mixing

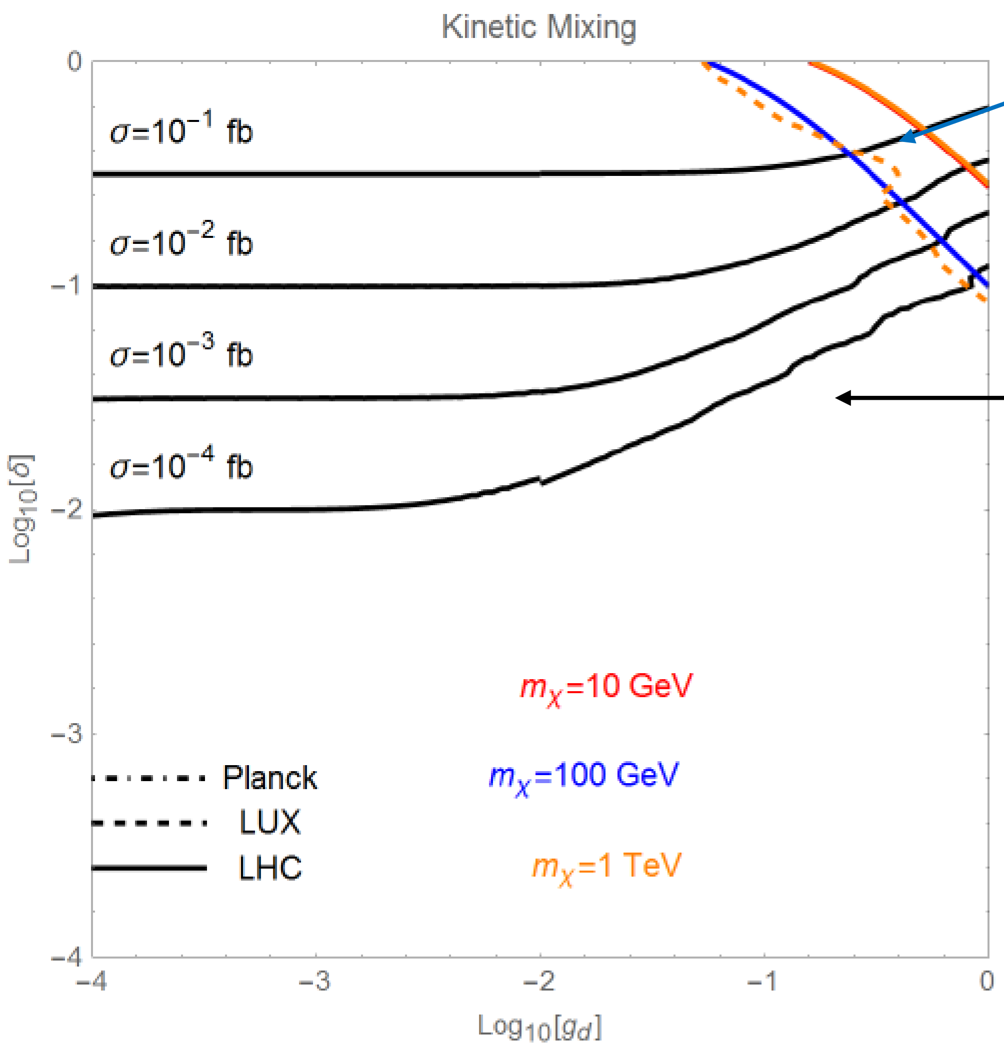
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm DM}$$

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\sin\delta B^{\mu\nu}X_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu}$$

$$\mathcal{L}_{\rm DM} = \bar{\chi}D^{\mu}\chi\gamma_{\mu}, \quad D^{\mu} = \partial^{\mu} + ig_d X^{\mu}$$

$$\begin{pmatrix} B_\mu \\ W^3_\mu \\ X_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\tan\delta \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1}{\cos\delta} \end{pmatrix} \begin{pmatrix} \hat{c}_W & -\hat{s}_W\cos\xi & \hat{s}_W\sin\xi \\ \hat{s}_W & \hat{c}_W\cos\xi & -\hat{c}_W\sin\xi \\ 0 & \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

The Z‘ (and the DM) can be coupled under the SM even if it is not charged under the new U(1). The kinetic mixing induces couplings with the SM fermions and gauge bosons.



$$m_{Z'} = 1.8\text{TeV}$$

LUX excluded

$$pp \to Z' \to W^+W^-$$

($pp \to Z' \to Zh$ also present)

Correct relic density is achieved only for DM masses of the order of 1 TeV, close to the s-channel resonance.

Conclusions

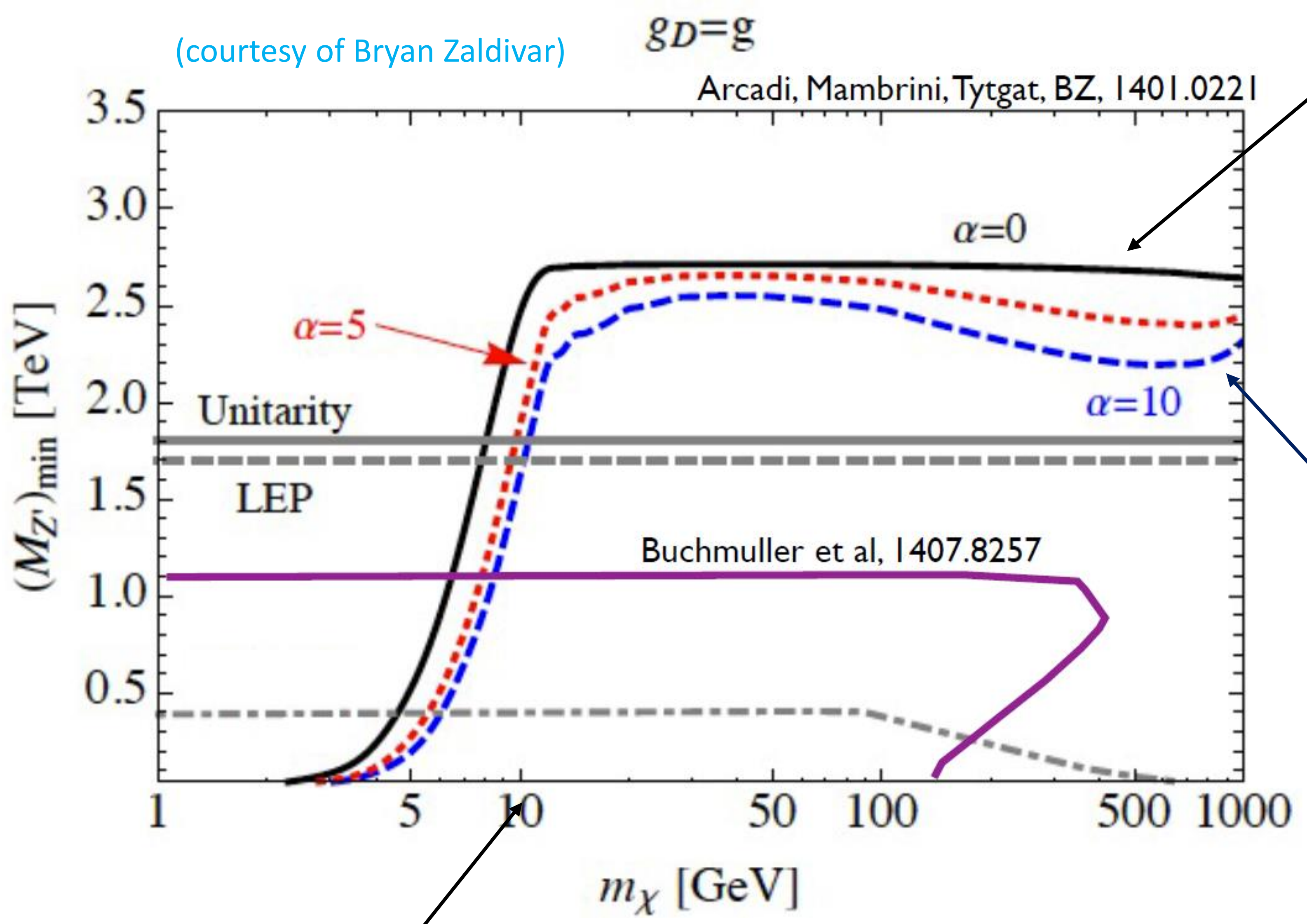
Simplified dark portals are optimal benchmarks for the study of new particles and interactions.

Combination of different DM search strategies is a powerfull tool.

Correlation with other searches of New Physics can be enforced as well.

Progress in model building is similarly relevant.

Back up



High DM masses. LUX limit implies
low invisible branching fraction.
LHC Dilepton limit
applies (indipendent from DM mass)

Weaker limits in presence of
axial couplings

Low DM masses. Sensitive invisible branching fraction allowed. LHC limits should be modified.

Bigger extra symmetry groups: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Two extra gauge bosons: W' and Z'

$$W' = \sin\phi_W W_L + \cos\phi_W W_R$$

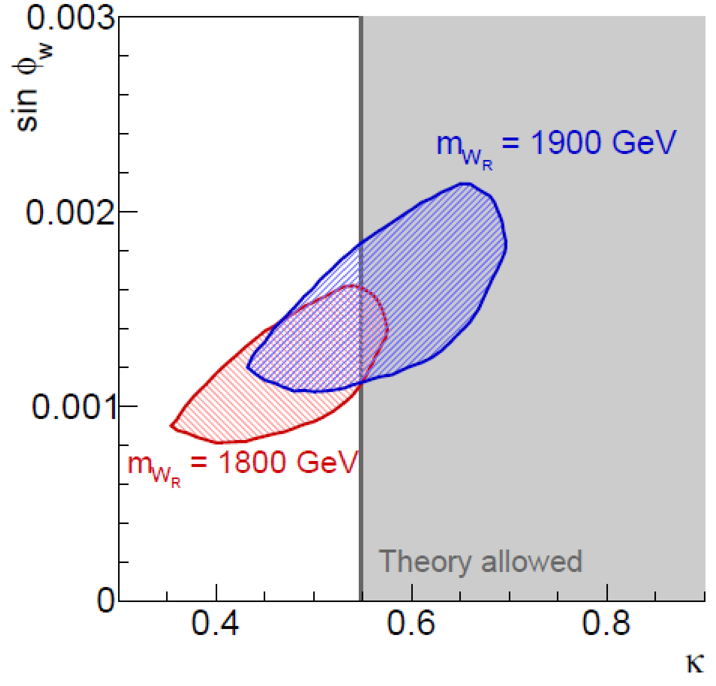
$$Z' = \sin\phi_Z Z + \cos\phi_Z Z_R$$

$$\mathcal{L} = \frac{g_R}{\sqrt{2}} W_{R,\mu} \sum_{f,f'} \left(\bar{f}' \gamma^\mu f + h.c.\right)$$

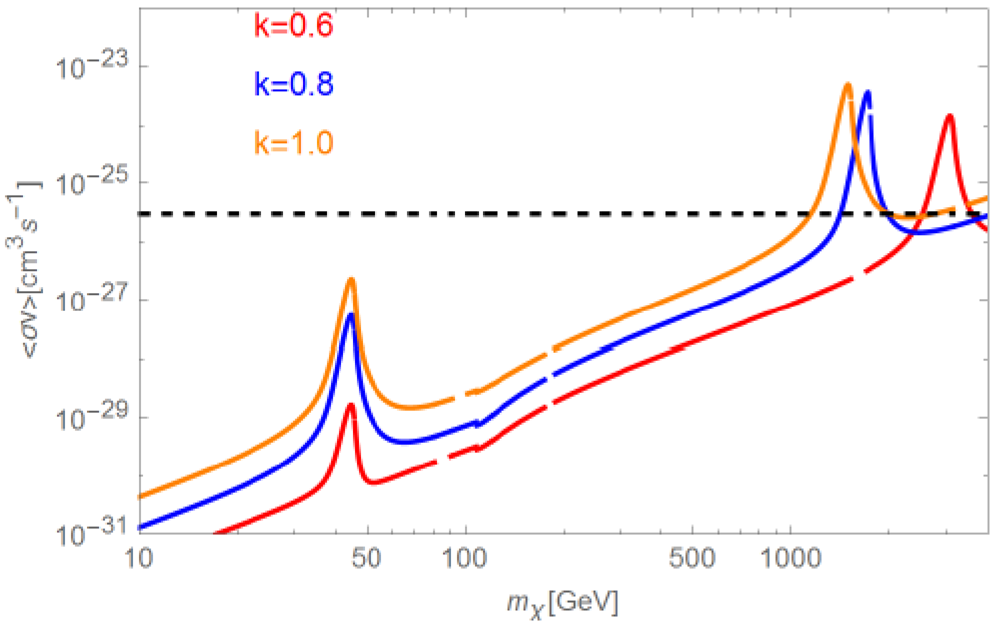
$$\mathcal{L} = \frac{g_R}{c_R} \left(T_R^3 - Y s_R\right) Z_{R,\mu} \sum_f \bar{f} \gamma^\mu f$$

$$g_R = k g_L$$

Di boson excess accounted by resonant production of a W' boson.



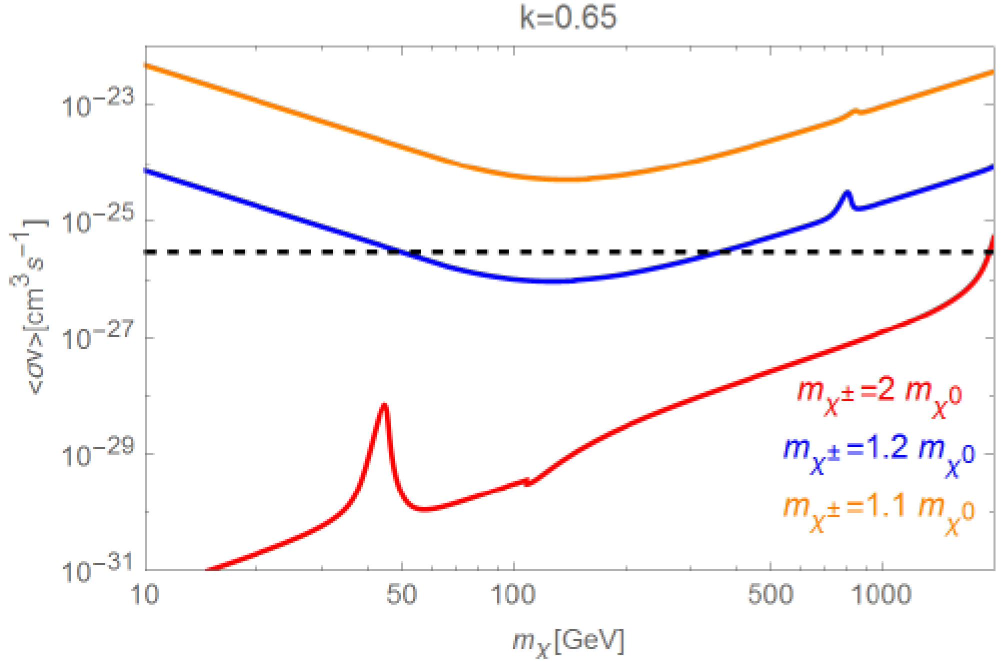
(Brehmer et al. 1507.00013)

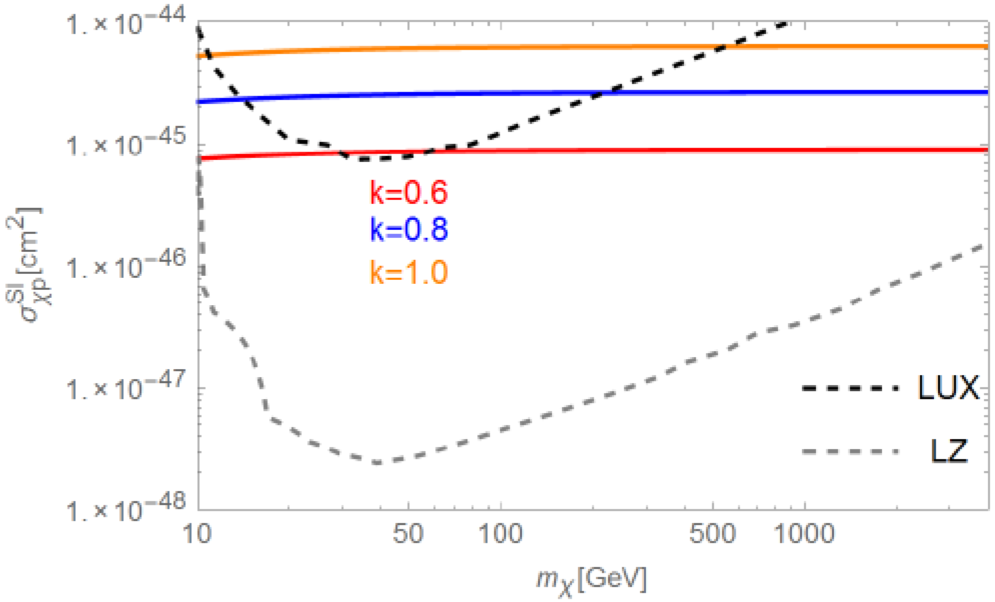


Correct relic density obtained only at resonance in case the DM is coupled only with the Z'.

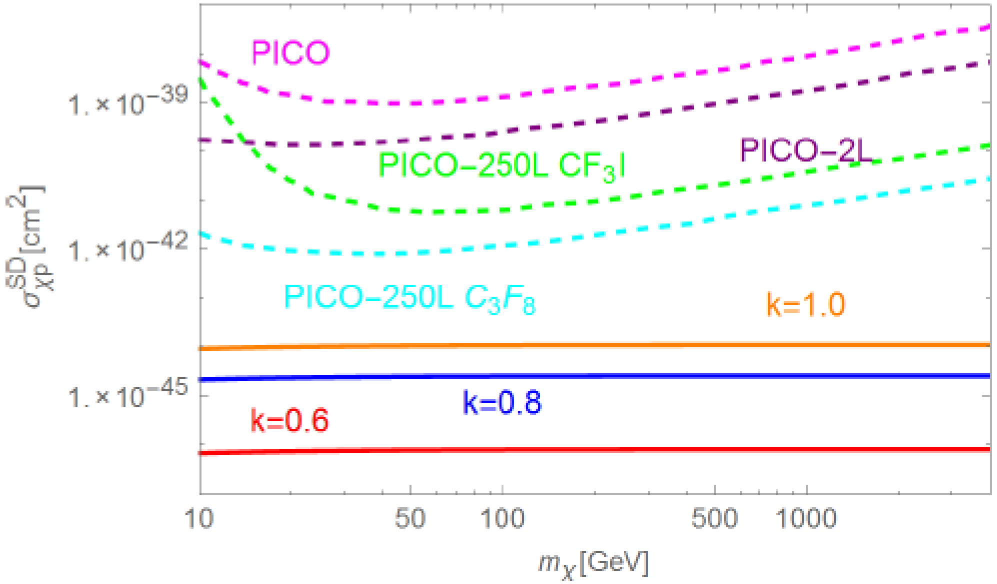
Annihilation can be enhanced by coannihilation effects.

E.g.: DM is in a multiplet (1,2,-1) under $SU(2)_L$ x $SU(2)_R$ x $U(1)_{B-L}$





Present and next future SI experiments can completely probe the relevant parameter space.



SD interactions are not accessible to present and next future experiments.