Review on dark portals

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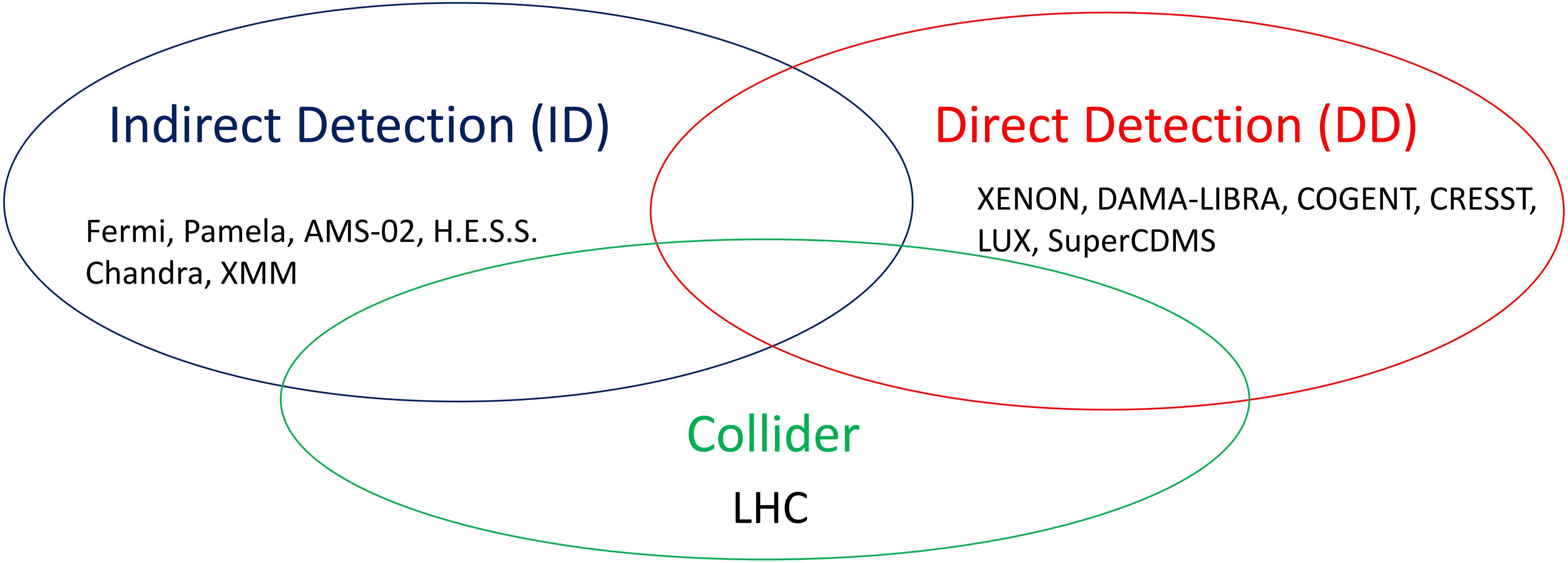
PARTICLE DM

Dark Matter is one of the building blocks of the Standard Cosmological model.
Contributes to around 27% of 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.

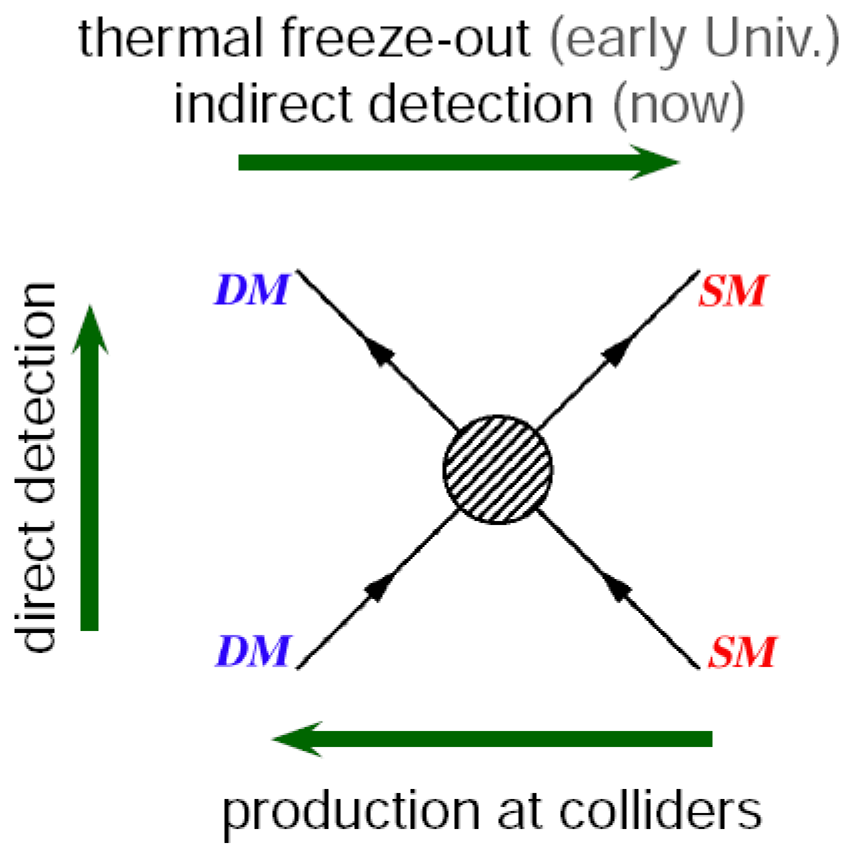
Three, possibly complementary, kinds of DM searches:



Complementary information from DM relic density. Case of study WIMP mechanism:

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

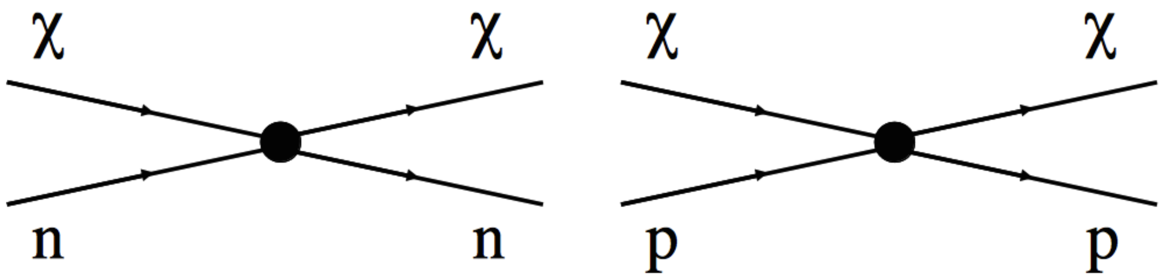
WIMP scenarios feature a strong complementarity between Dark Matter searches.

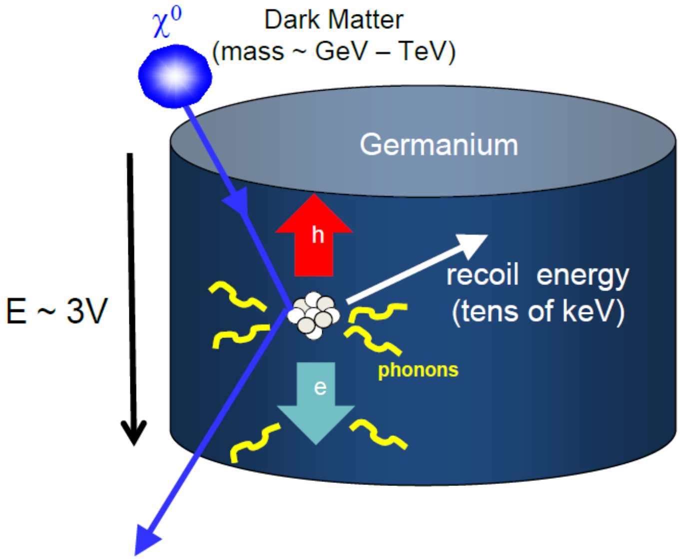


DM Direct Detection

Microscopic description through interactions of DM with quarks (or gluons)

Translated as effective interaction with nucleons.



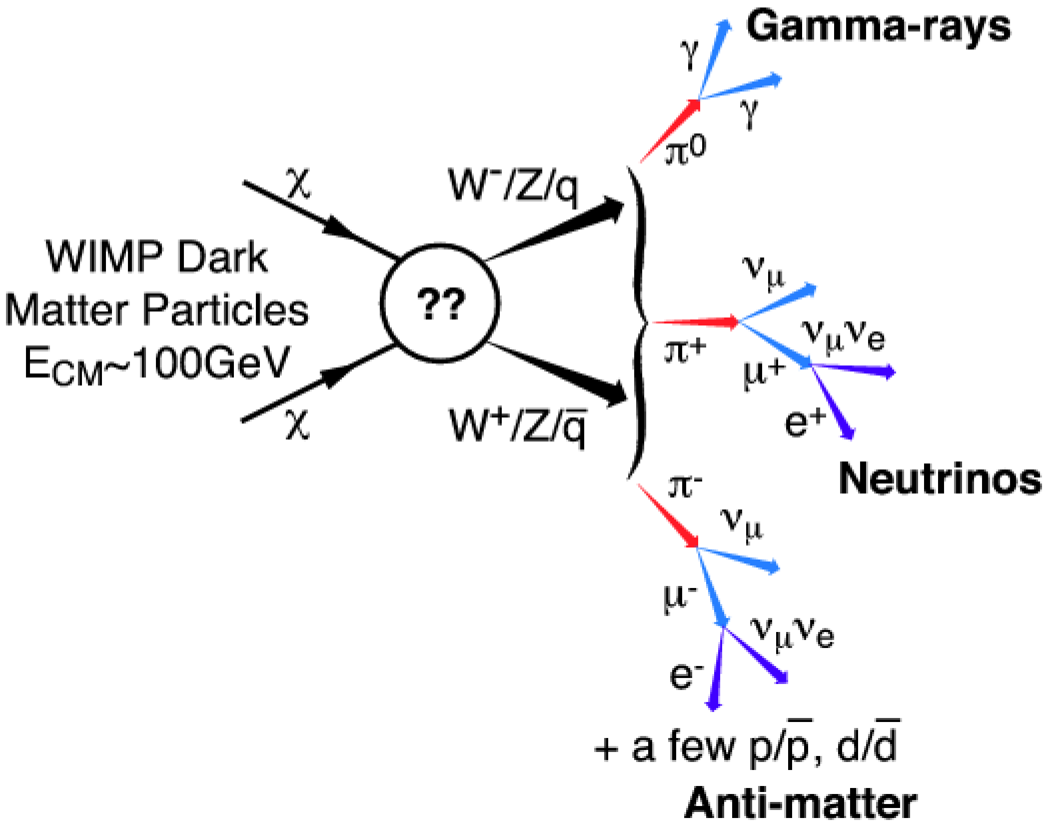


Two kinds of interactions customarily distinguished

Spin Indipendent (SI) interactions: Sum coherently among nucleons of the target

Spin Dependent (SD) interactions: Sensitive to the contributions from protons and nucleons to the nuclear spin.

Dark Matter Indirect Detection



Dark Matter Indirect Searches rely on the detection
Of the products of DM annihilations and decay.

Typically studied:
Antiprotons (AMS-02, PAMELA)
Electron/Positrons (PAMELA)
Photons (FERMI, XMM, CHANDRA, SUZAKU, HESS)

DM at colliders

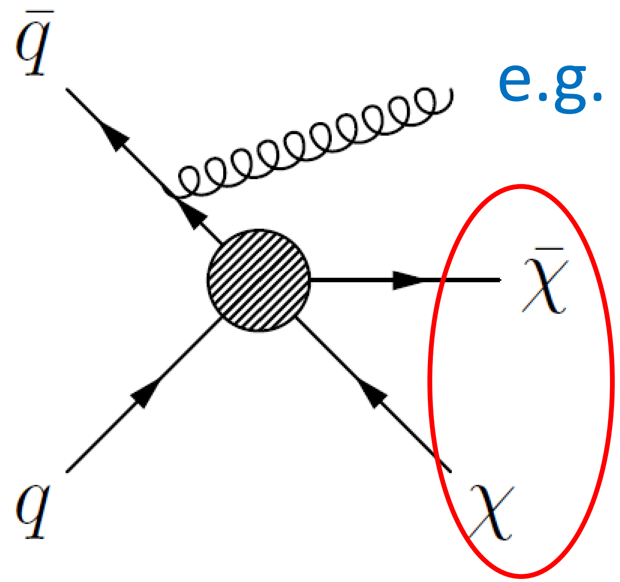
Increasing interest on recent times on the possibility of DM production at colliders (LHC)

Two possibilities

Production from decay of exotic particles.
Example: end of decay chains of supersymmetric particles.

Direct production at collider

Pair production of DM can be detected in events with missing energy and initial state radiation (ISR)

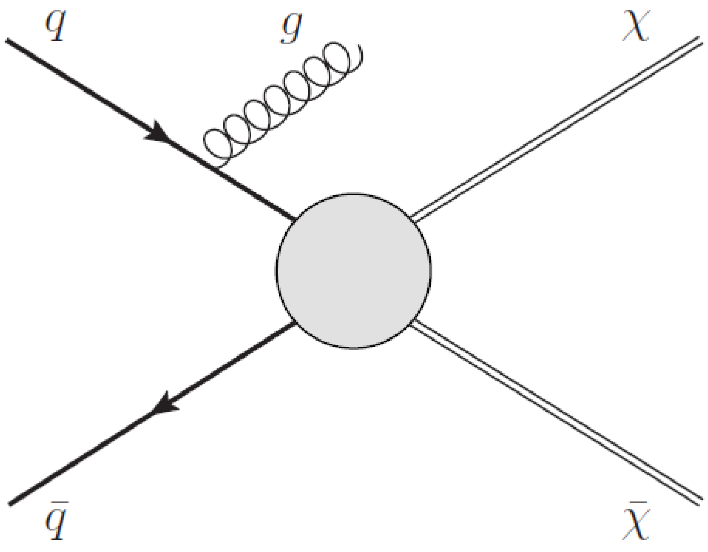


e.g. Monojet, monophoton, mono boson

Missing energy

In any case the DM miss direct detection at collider detectors. Complementary information from other searches is required.

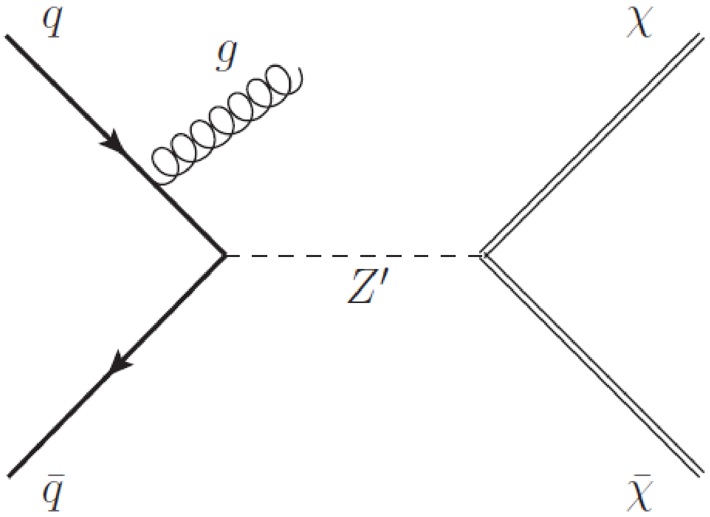
From EFT to simplified models



EFT provide a very simple way to express experimental limits (only one parameter)

The validity of EFT approach is controversial.

Some interesting scenarios are not described by EFT.

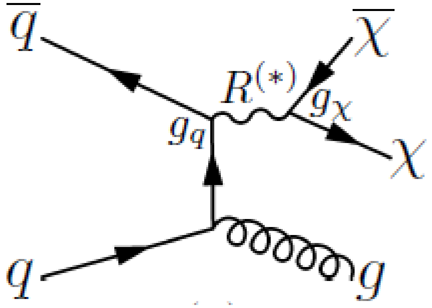


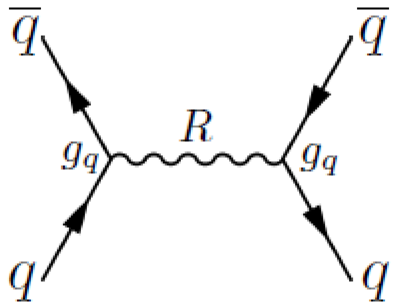
EFT analysis should be complemented by the use of simplified models.

Increased number of parameters.

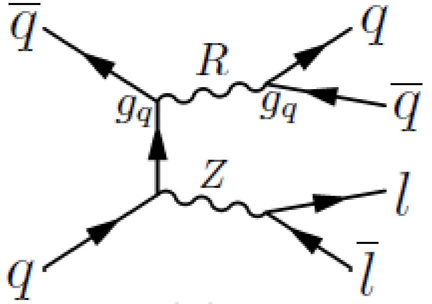
It is still possible to profit of complementarity with DM searches.

Complementarity in simplified models

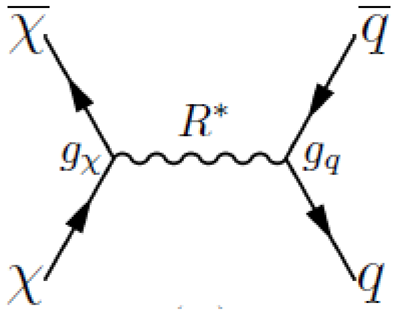




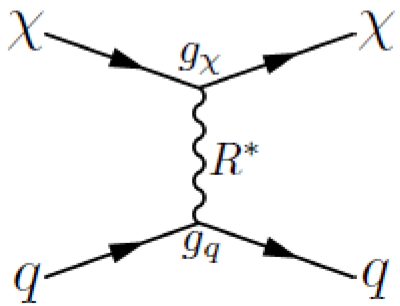
Chala et al. 1503.05916



Light mediators can be produced on shell. Additional signals (resonances) also from decays into SM particles.



Relic density / ID



Direct Detection

Simplified models (Dark portals)

Z-portal

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

Z´ portal

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

Scalar/pseudoscalar portal

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

Correlation with Relic density

Away from thresolds and resonances the annihilation cross-section can be velocity expanded

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

s-wave contribution. Constant between freeze-out and present times

p-wave contribution. Sizable at freeze-out negligible at present times.

Indirect signal possible only in presence of sizable s-wave component.

Correlation with Direct Detection

The pair annihilation cross-section can be expressed in terms of observable quantities, i.e. DM scattering cross-sections.

s-wave or p-wave dominated according the nature of the DM coupling

DD constraints the relic abundance of DM.

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

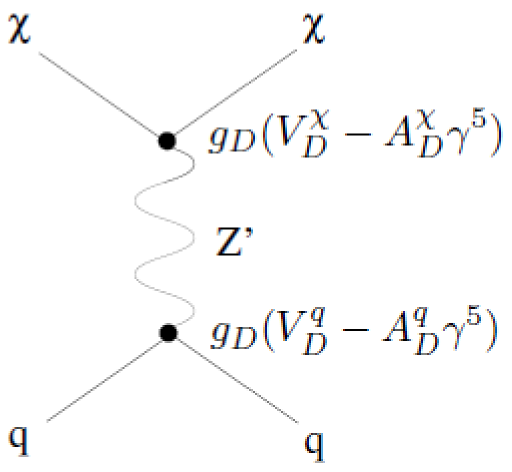
Possible constraints from ID

Prediction of the value of the scattering cross-section from the requirement the DM is thermal.

DM bilinear	*SM fermion bilinear*			
fermion DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2,\ \sigma_{\mathrm{SI}} \sim 1$	$\sigma v \sim v^2,\ \sigma_{\mathrm{SD}} \sim q^2$	–	–
$\bar{\chi}\gamma^5\chi$	$\sigma v \sim 1,\ \sigma_{\mathrm{SI}} \sim q^2$	$\sigma v \sim 1,\ \sigma_{\mathrm{SD}} \sim q^4$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1,\ \sigma_{\mathrm{SI}} \sim 1$	$\sigma v \sim 1,\ \sigma_{\mathrm{SD}} \sim v_\perp^2$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	$\sigma v \sim v^2,\ \sigma_{\mathrm{SI}} \sim v_\perp^2$	$\sigma v \sim 1,\ \sigma_{\mathrm{SD}} \sim 1$

(Berlin et al. 1404.0022)

DD for Z/Z′



$\sigma_{\chi q}$

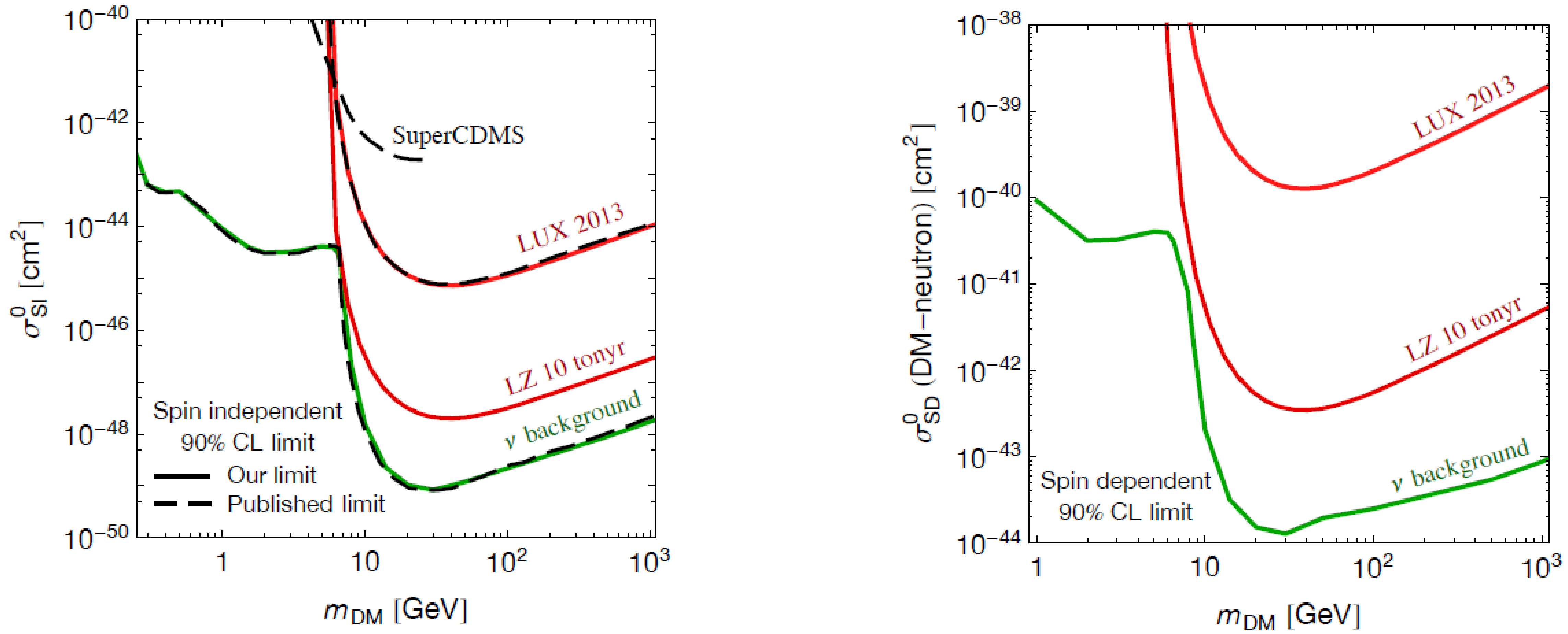
$$\sigma_{\chi N}^{\rm SI} = \frac{4 g_D^4 (V_D^\chi)^2 \mu_{\chi N}^2}{\pi M_{Z'}^4}\left[V_D^u\left(1+\frac{Z}{A}\right)+V_D^d\left(2-\frac{Z}{A}\right)\right]^2$$

$$\sigma_{\chi N}^{SD} = \frac{12 g_D^4 \mu_{\chi N}^2 |A_D^\chi|^2}{\pi M_{Z'}^4 (S_p^A + S_n^A)^2}\Big[A_D^u(\Delta_u^p S_p^A + \Delta_d^p S_n^A) + A_D^d\left((\Delta_d^p + \Delta_s^p)S_p^A + (\Delta_u^p + \Delta_s^p)S_n^A\right)\Big]^2$$

$$\alpha_{SI} = \frac{\sum_A \eta_A A^2 \left[V_u'\left(1+\frac{Z}{A}\right) + V_d'\left(2-\frac{Z}{A}\right)\right]^2}{\sum_A \eta_A A^2}$$

$$\alpha_{SD} = \frac{\sum_A \eta_A \left[A_u'(\Delta_u^p S_p^A + \Delta_d^p S_n^A) + A_d'\left((\Delta_d^p + \Delta_s^p)S_p^A + (\Delta_u^p + \Delta_s^p)S_n^A\right)\right]^2}{\sum_A \eta_A (S_p^A + S_n^A)^2}$$

Factor accounting for isospin violation



Buchmuller et al., 1407.8257

Annihilation into SM fermions final states can be expressed in terms of SI and SD cross-sections.

Mass and velocity suppressed

$$\langle \sigma v \rangle_{f\bar{f}} \simeq \frac{g_D^4 m_\chi^2}{2\pi m_{Z'}^4} \sum_f n_c^f \left(|V_f|^2 + |A_f|^2\right) \left(1 - \frac{4 m_\chi^2}{m_{Z'}^2}\right)^{-2} \left[2|V_\chi|^2 + |A_\chi|^2 \boxed{\left(\frac{m_b^2}{m_\chi^2} \frac{|A_b|^2}{\sum_f (|V_f|^2 + |A_f|^2)} + \frac{m_t^2}{m_\chi^2} \frac{|A_t|^2}{\sum_f (|V_f|^2 + |A_f|^2)} + \frac{v^2}{6}\right)}\right]$$

If final state kinematically allowed

$$= \frac{2 m_\chi^2}{\mu_{\chi p}^2} \sum_f n_c^f \left(|V_f|^2 + |A_f|^2\right) \left(1 - \frac{4 m_\chi^2}{m_{Z'}^2}\right)^{-2} \left[2 \frac{\sigma_{\chi p}^{\rm SI}}{\alpha_{\rm SI}} + \frac{\sigma_{\chi p}^{\rm SD}}{3 \alpha_{\rm SD}} \left(\frac{m_b^2}{m_\chi^2} \frac{|A_b|^2}{\sum_f (|V_f|^2 + |A_f|^2)} + \frac{m_t^2}{m_\chi^2} \frac{|A_t|^2}{\sum_f (|V_f|^2 + |A_f|^2)} + \frac{v^2}{6}\right)\right]$$

Relic density deeply tight to SI cross-section

Z-portal

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

General scenario. Need completion at high scales

Concrete examples

Effective operators

$$\mathcal{L} = \frac{ig}{\Lambda^2} H^\dagger D_\mu H \left[\overline{\chi}\gamma^\mu\left(v_\chi - a_\chi\gamma_5\right)\chi\right]$$

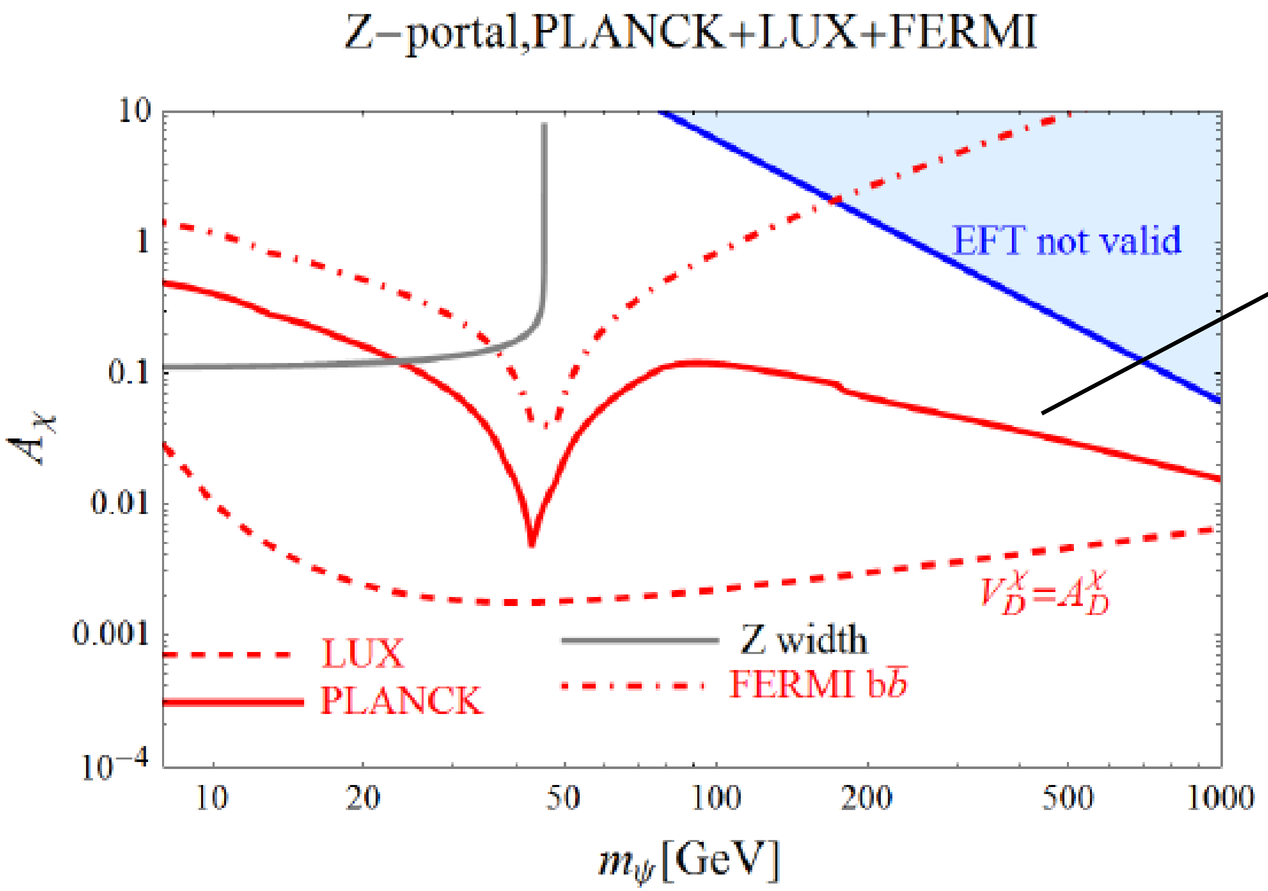
$$H^\dagger D_\mu H \rightarrow \frac{v_h^2}{4\cos\theta_W} Z_\mu \longrightarrow V_\chi = \frac{v_h^2}{\Lambda^2} v_\chi$$

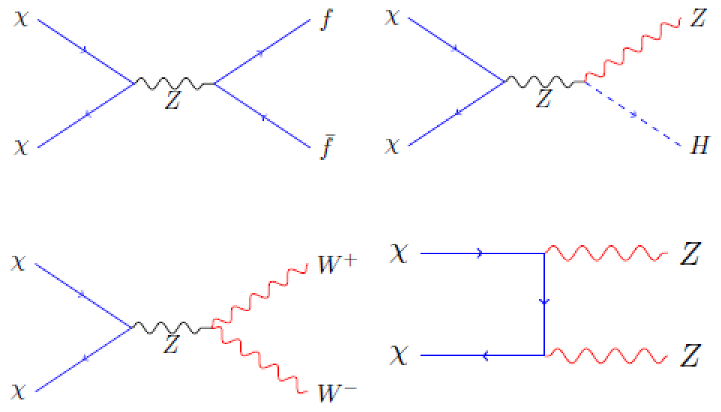
De Simone et al. JHEP1406 (2014) 081

Kinetic mixing

$$\delta B_{\mu\nu} B'^{\mu\nu} \qquad m_{Z'} \gg m_Z$$

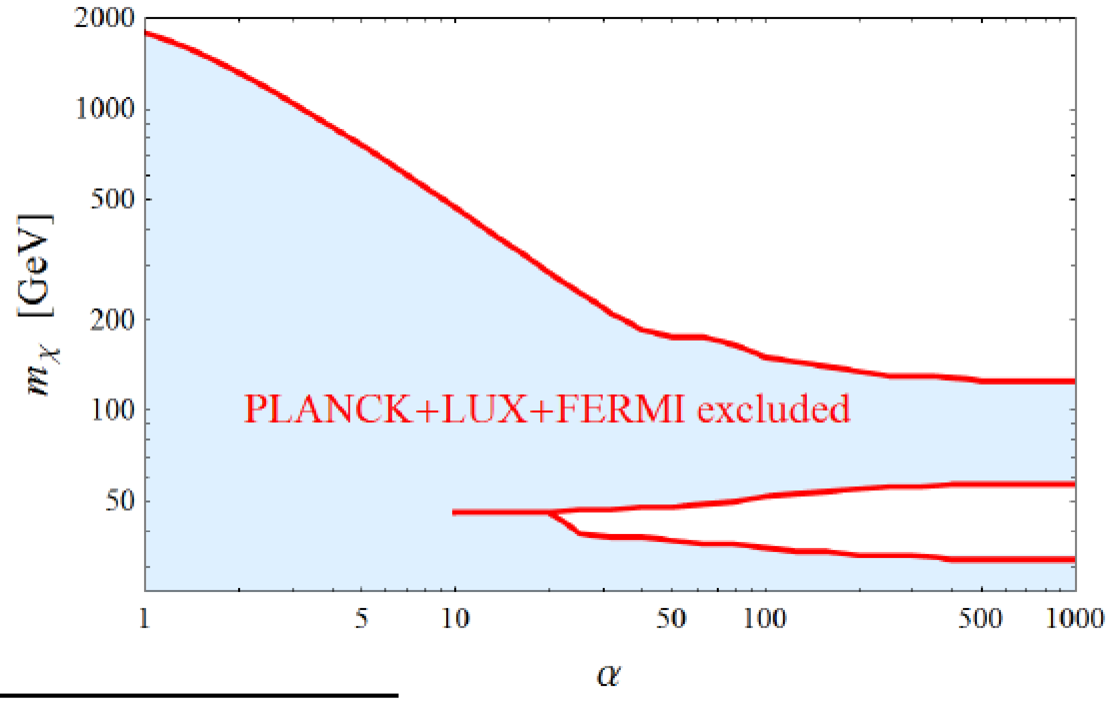
$$V_\chi = q_D \frac{g_D}{g} \tan\theta_W \delta \frac{m_Z}{m_{Z'}}$$





Additional annihilation channels

The case of comparable axial and vector couplings is excluded by limits from LUX (SI) and Z-width.

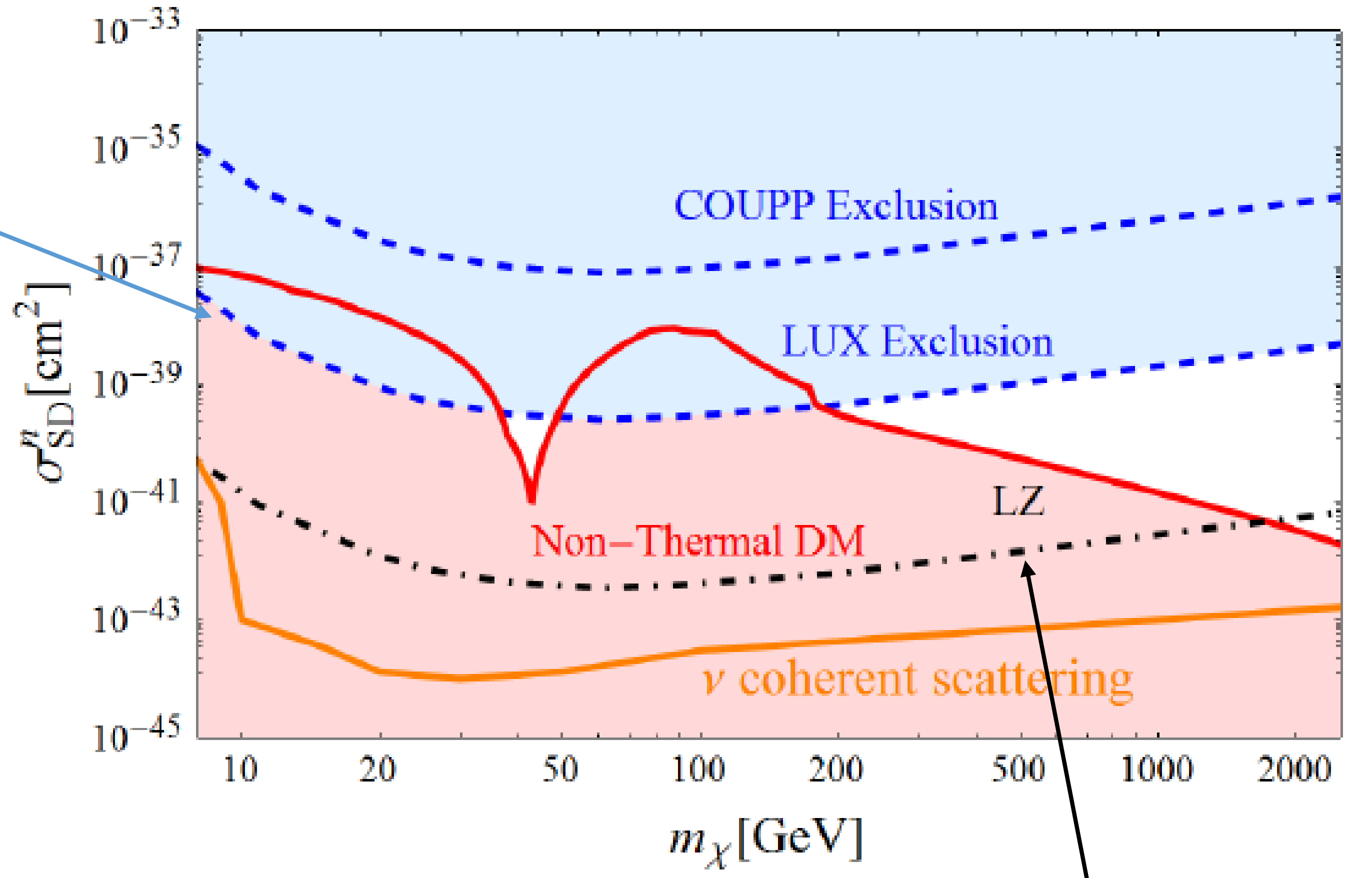


$$\alpha = \frac{A_\chi}{V_\chi}$$

Z-portal viable for almost pure axial couplings except for Z-pole and multi TeV regions.

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

Interaction of DM with neutrons



Next future experiments can completely probe Z portal scenario

Dark Z´ models

General implementation:

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

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

	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.

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

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

$$\sigma^{\mathrm{p}}_{\mathrm{SI}} = \frac{g'^{4}\mu_{\chi}^{2}}{\pi\, m_{Z'}^{4}} |V_{\chi}|^{2} \alpha_{\mathrm{SI}}$$

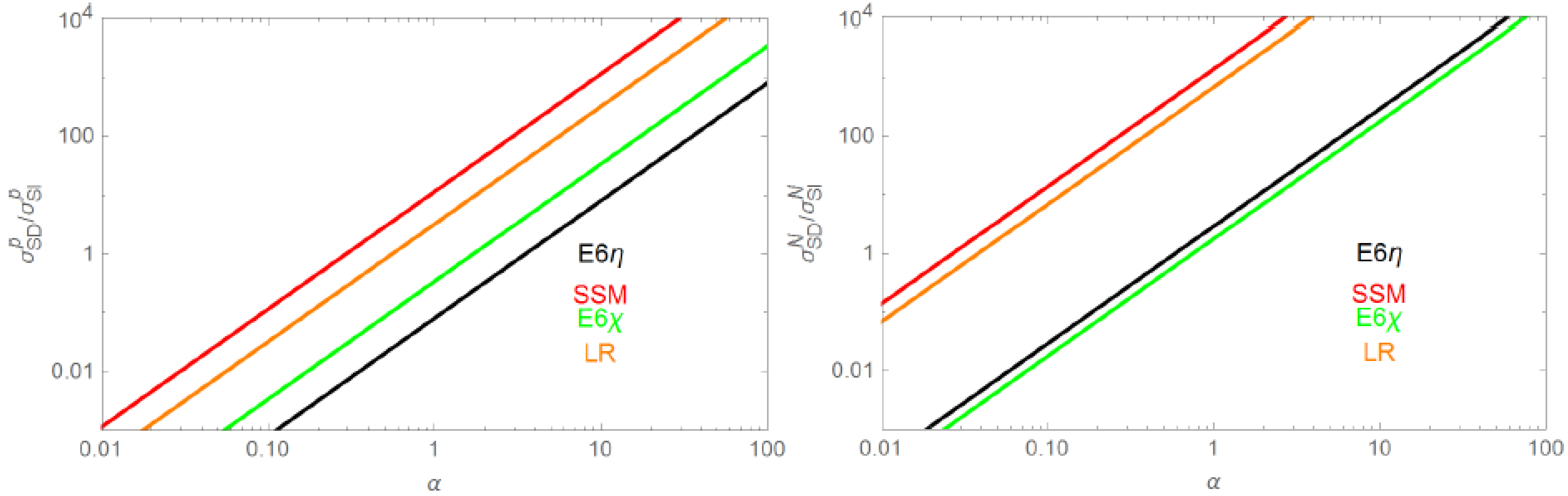
$$\sigma^{\mathrm{p}}_{\mathrm{SD}} = \frac{3g'^{4}\mu_{\chi}^{2}}{\pi\, m_{Z'}^{4}} |A_{\chi}|^{2} \alpha_{\mathrm{SD}}$$

Factors depending on the couplings with the fermions and the detector material

$$\frac{\sigma^{p}_{SD}}{\sigma^{p}_{SI}} = 3\alpha^{2}\frac{\alpha_{SD}}{\alpha_{SI}}$$

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

Different Z\` realizations might be distinguished by measuring both components of the DM scattering cross-section.



$$\langle \sigma v \rangle = \frac{m_\chi^2}{\pi m_{Z'}^4} |V_\chi|^2 \left[\left(a_V + b_V v^2 \right) + \alpha^2 \left(a_A + b_A v^2 \right) \right]$$

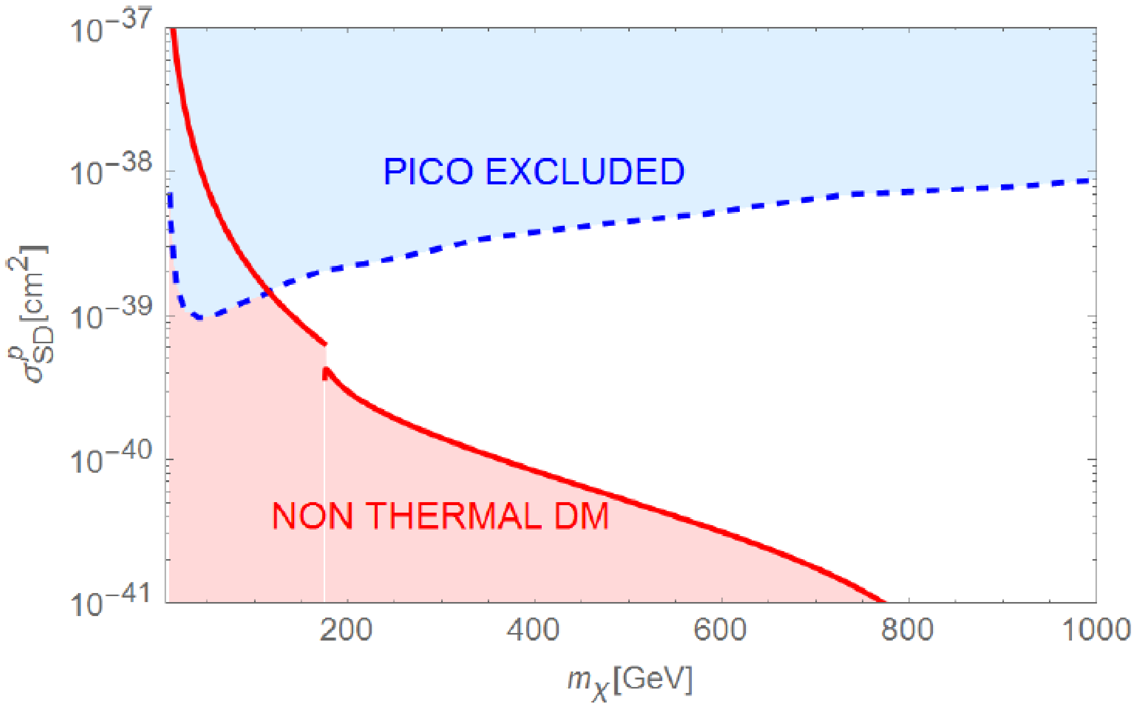
Very severe limits from direct detection (LUX) imply: $|V_\chi| \ll 1$

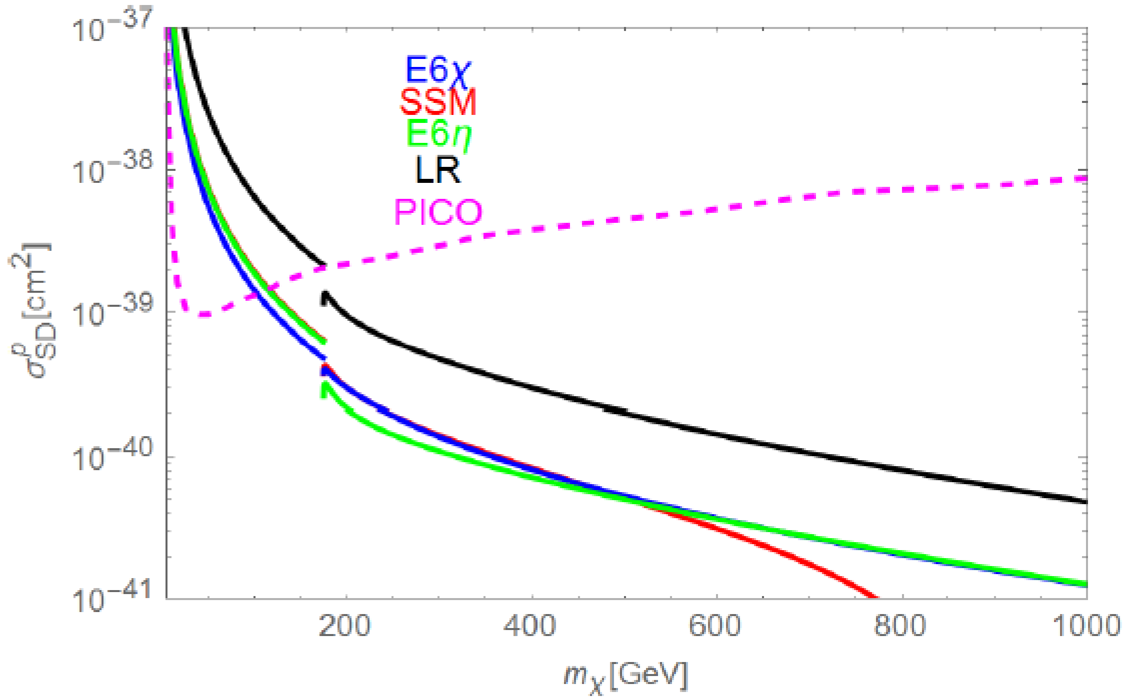
Correct relic density requires: $\alpha \gg 1$

$$\alpha \approx 1.1 \times 10^3 \sqrt{\frac{\alpha_{\rm SI}}{\sum_f n_c^f |V_f|^2 + |A_f|^2}} \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26}\,{\rm cm^3 s^{-1}}} \right)^{1/2} \left(\frac{\sigma_{N\chi}^{\rm SI}}{10^{-44}\,{\rm cm^2}} \right)^{-1/2} \left(\frac{m_\chi}{100\,{\rm GeV}} \right)^{-1}$$

Prediction for the SD cross-section:

$$\sigma_{N\chi}^{\rm SD} \approx 1.6 \times 10^{-37}\,{\rm cm}^2 \frac{\alpha_{\rm SD}}{n_c^f \sum_f |V_f|^2 + |A_f^2|} \left(\frac{\langle \sigma v \rangle}{3 \times 10^{-26}\,{\rm cm^3 s^{-1}}} \right) \left(\frac{m_\chi}{100\,{\rm GeV}} \right)^{-2}$$





Limit on SD cross-section can probe thermal Dark matter up to O(150-200) GeV.

Complementarity with collider searches

$$\sigma_{Z'll} \to \left(\frac{g'}{g}\right)^2 \times (1 - Br_\chi) \times \sigma_{Z'll}$$

Dilepton-Dijet production cross-section influenced by invisible branching fraction.

$$Br_\chi = \frac{\Gamma^\chi_{Z'}}{\Gamma^\chi_{Z'} + \sum_f \Gamma^f_{Z'}} = \left[1 + \left(\frac{2 g_D^2 \mu_{\chi N}}{M_{Z'}^2 \sqrt{\pi}}\right)^2 \frac{\sum_f c_f [|V_D^f|^2 + |A_D^f|^2]}{\sigma^{\mathrm{SI}}_{\chi N}/\alpha^{\mathrm{SI}}_{Z,A} + 1/3\sigma^{\mathrm{SD}}_{\chi N}/\alpha^{\mathrm{SD}}_{Z,A}}\right]^{-1}$$

Determined by DM relic density

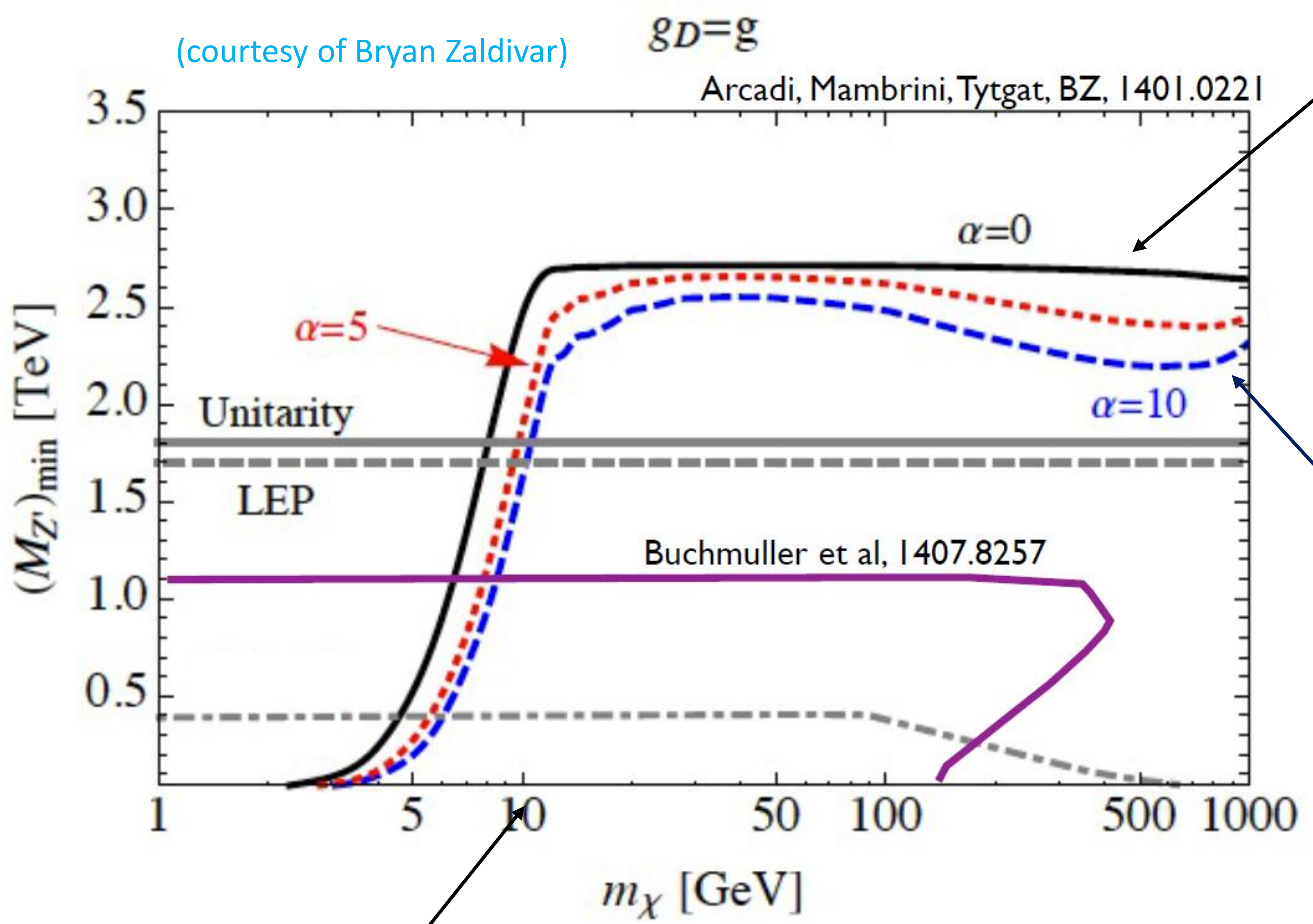
High invisible branching fraction:

monojet searches

Amount of invisible branching fraction depends on DM phenomenology.

Low Invisible branching fraction

Resonance searches



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

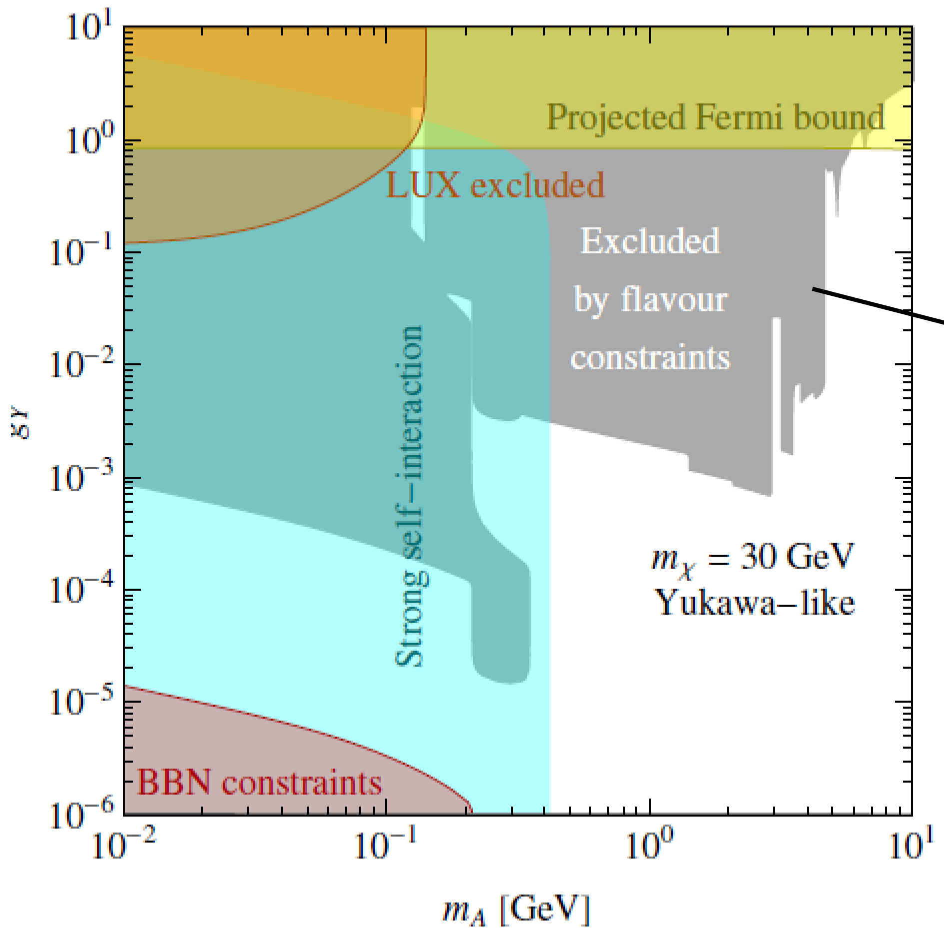
Weaker limits in presence of
axial couplings

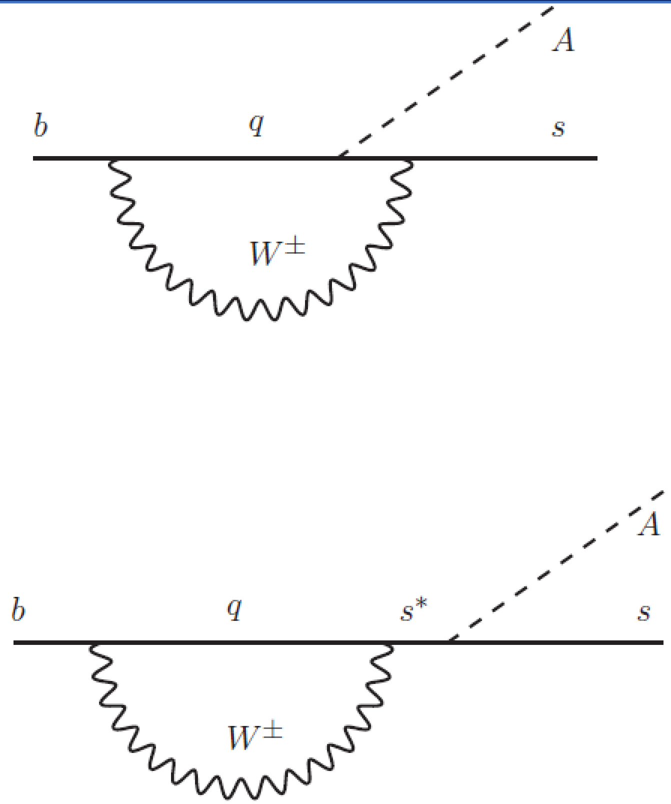
Low DM masses. Sensitive invisible branching fraction allowed. LHC limits should be modified.

Pseudo-scalar portal

$$\mathcal{L}_{\rm DM} = i\, g_\chi\, A\, \bar{\chi}\gamma^5\chi$$

$$\mathcal{L}_{\rm SM} = \sum_{f=q,\ell,\nu} i\, g_f\, A\, \bar{f}\gamma^5 f$$





(Dolan et al. arXiv 1412.5174)

GC signal

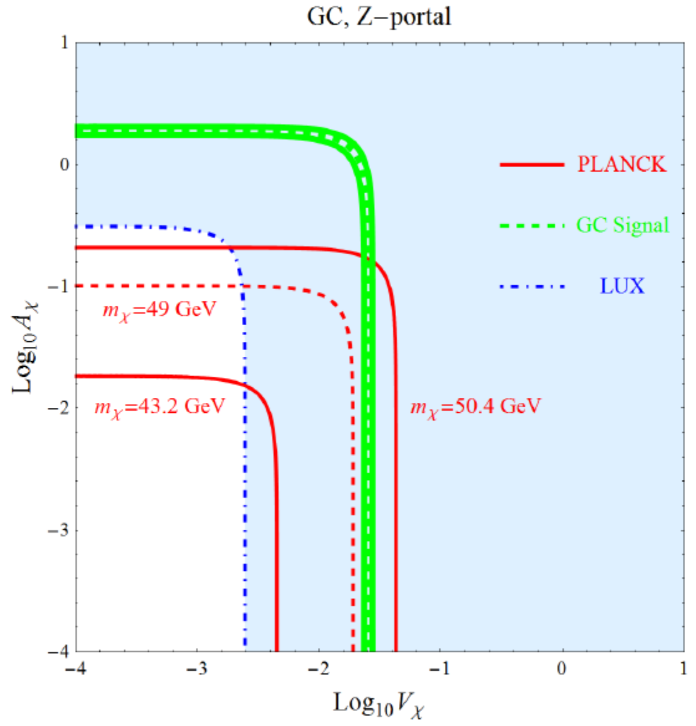
Recent studies have reported an excess in gamma-rays (Daylan et al. arXiv:1402.6703). The presence of an unknown component in the gamma-ray spectrum is confirmed by FERMI collaboration.

The signal is compatible with a DM annihilating into bb and mass between 30 (Berlin et al. 1404.0022) and 50 GeV (Calore et al. 1409.0042) (Astrophysical interpretation is also feasible)

New analysis have enlarged the range of candidate masses and final states including WW, ZZ, tt and hh. (In these cases the DM mass is close to the kinematical thresold) (Agrawal et al. 1411.2592 and Calore et al 1411.4647).

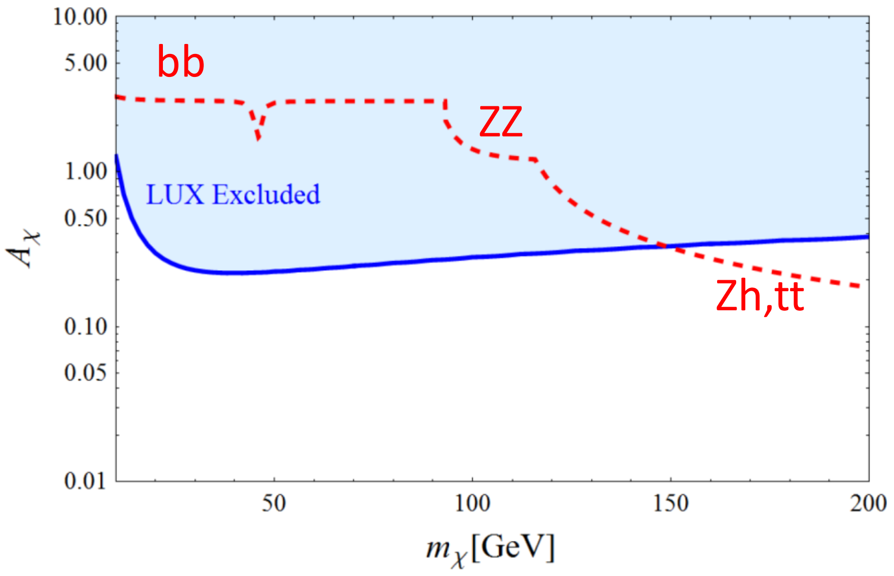
Annihilation into bb mass and velocity suppressed in the pure axial limit.

$$\frac{\langle \sigma v \rangle_{v\to 0}}{\langle \sigma v \rangle_{\text{f.o.}}} \approx \frac{3}{2v_{\text{f.o.}}^2} \frac{m_b^2}{m_\chi^2} \frac{\left(m_Z^2 - 4m_\chi^2\right)^2}{m_Z^4} \frac{|A_b|^2}{\sum_{m_\chi > m_f} \left(|V_f|^2 + |A_f|^2\right)} \simeq O\left(10^{-3}\right)$$



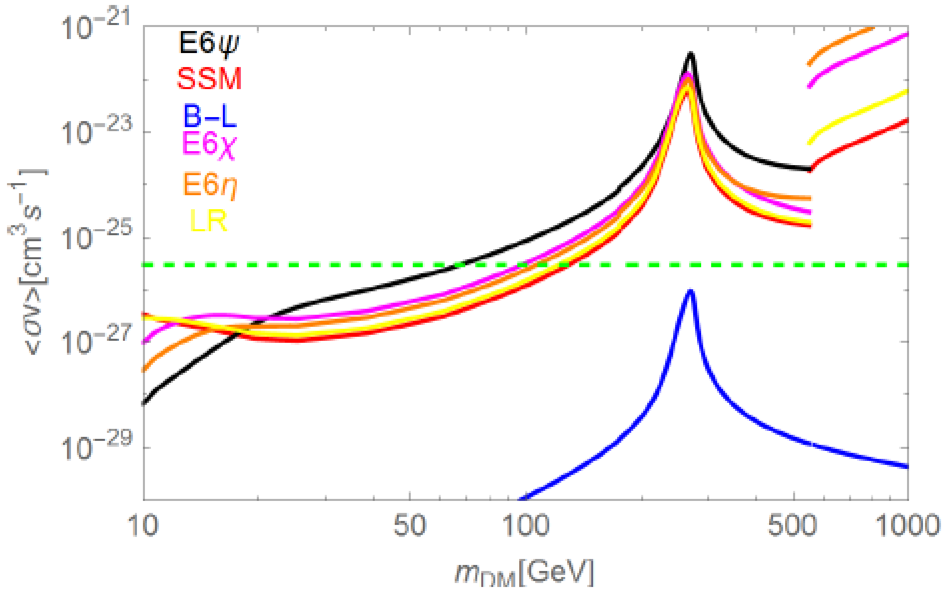
GC signal requires instead:

$$\frac{\langle \sigma v \rangle_{v\to 0}}{\langle \sigma v \rangle_{\text{f.o.}}} \simeq 1$$

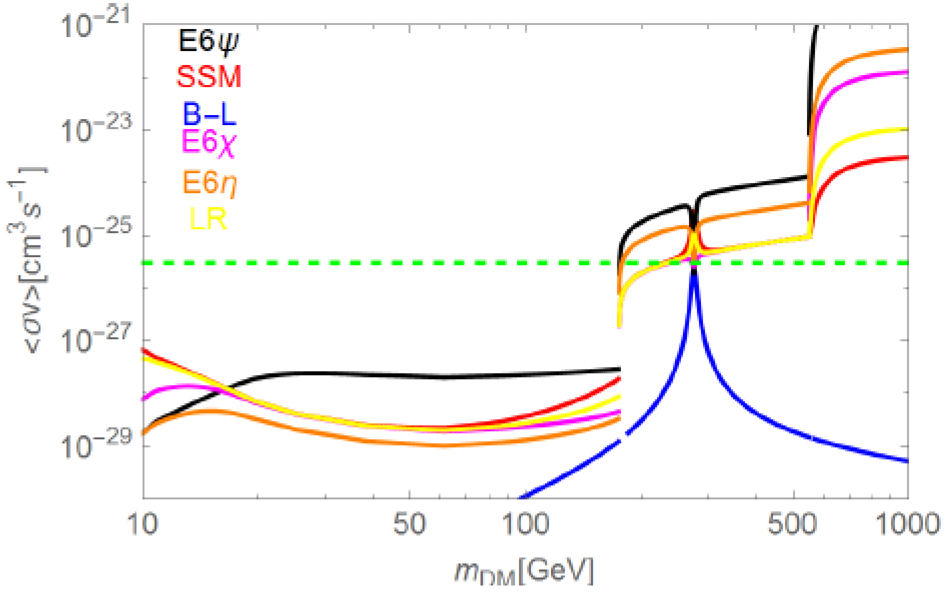


For axial Z-portal is not possible to reproduce the GC signal with bb annihilation because of the velocity suppression of the cross-section.

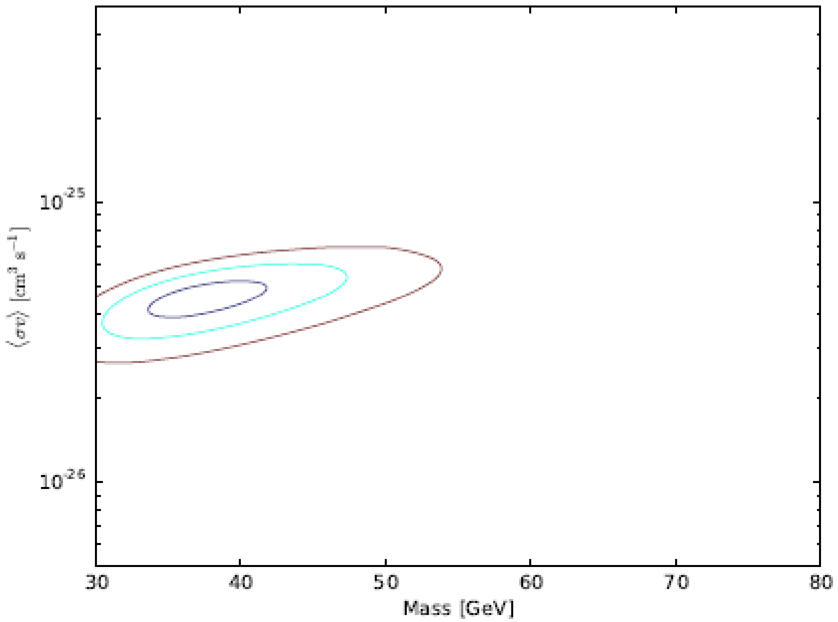
GC signal for Z`



Freeze-out



Now



Conclusion

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.

BACK UP

$$\langle \sigma v \rangle = \frac{m_\chi^2}{\pi m_{Z'}^4} |V_\chi|^2 \left[\left(a_V + b_V v^2\right) + \alpha^2 \left(a_A + b_A v^2\right) \right]$$

$$\frac{\langle \sigma v \rangle}{\sigma_\chi^{\rm SI}} = \frac{m_\chi^2}{\mu_{\chi N}^2 \alpha_{\rm SI}} \left[\left(a_V + b_V v^2\right) + \alpha^2 \left(a_A + b_A v^2\right) \right]$$

For light DM

$$\frac{\langle \sigma v \rangle}{\sigma_{N\chi}^{\rm SI}} \simeq \frac{m_\chi^2}{\mu_{\chi N}^2 \alpha_{\rm SI}} \left[1 + \frac{\alpha^2}{2} \left[\frac{m_b^2}{m_\chi^2} \frac{|A_b|^2}{\sum_f |V_f|^2 + |A_f|^2} + \frac{v^2}{6} \right] \right] n_c^f \sum_f |V_f|^2 + |A_f|^2$$

$$\simeq \frac{m_\chi^2}{\mu_{\chi N}^2 \alpha_{\rm SI}} \left[1 + \frac{\alpha^2}{12} \right] n_c^f \sum_f |V_f|^2 + |A_f|^2$$