WIMPs: Status and prospects

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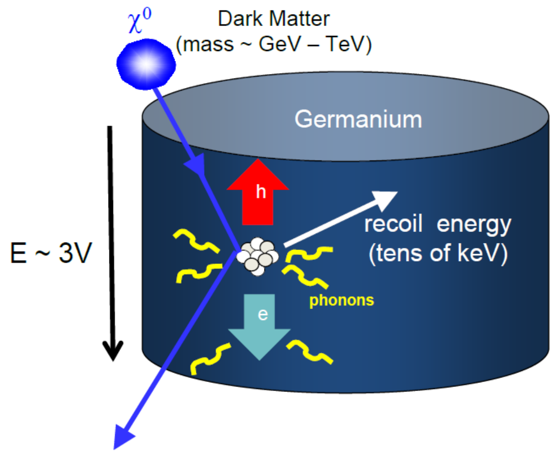
Motivation and overview

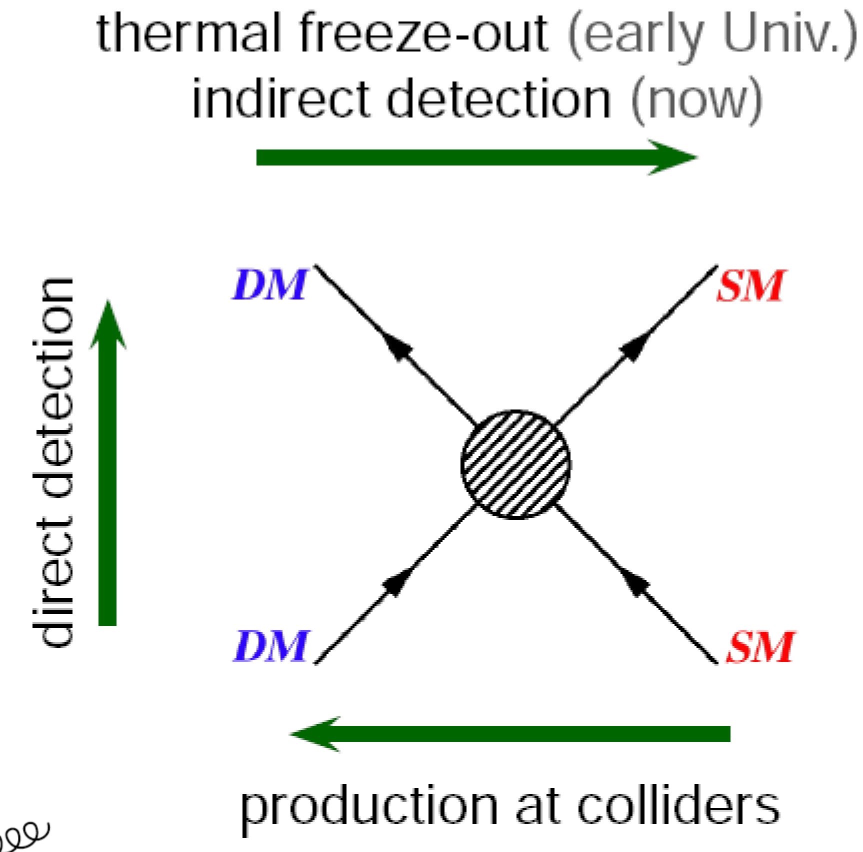
WIMP paradigm is an elegant solution for the Dark Matter problem.

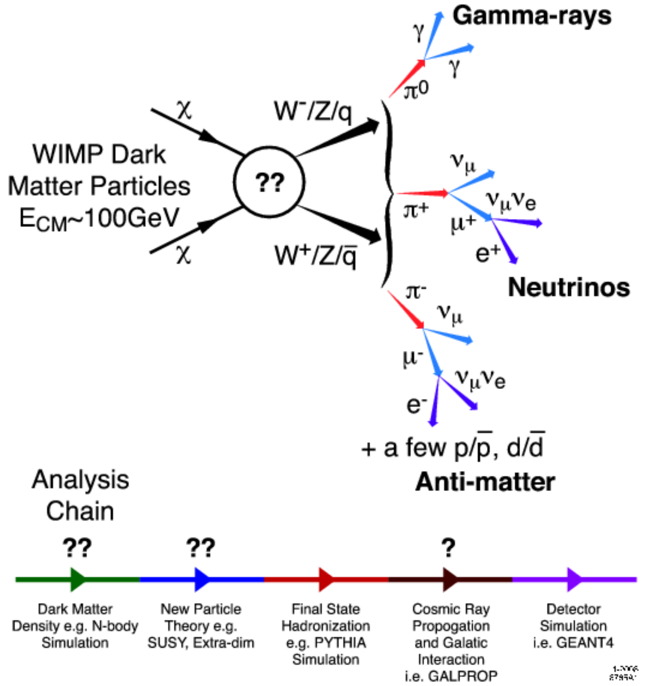
We provide an overview of the capability of current and future Direct Detection experiments of testing the WIMP paradigm
Case of study:‘‘Dark Portals‘‘

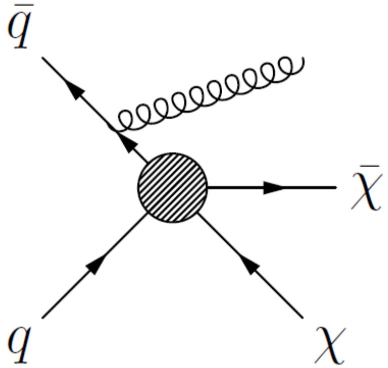
Critical assement about the theoretical limitations of ‘‘simplified‘‘ dark matter models and the possibility of embedding in UV complete setups.

WIMP scenarios feature a strong complementarity between Dark Matter searches.

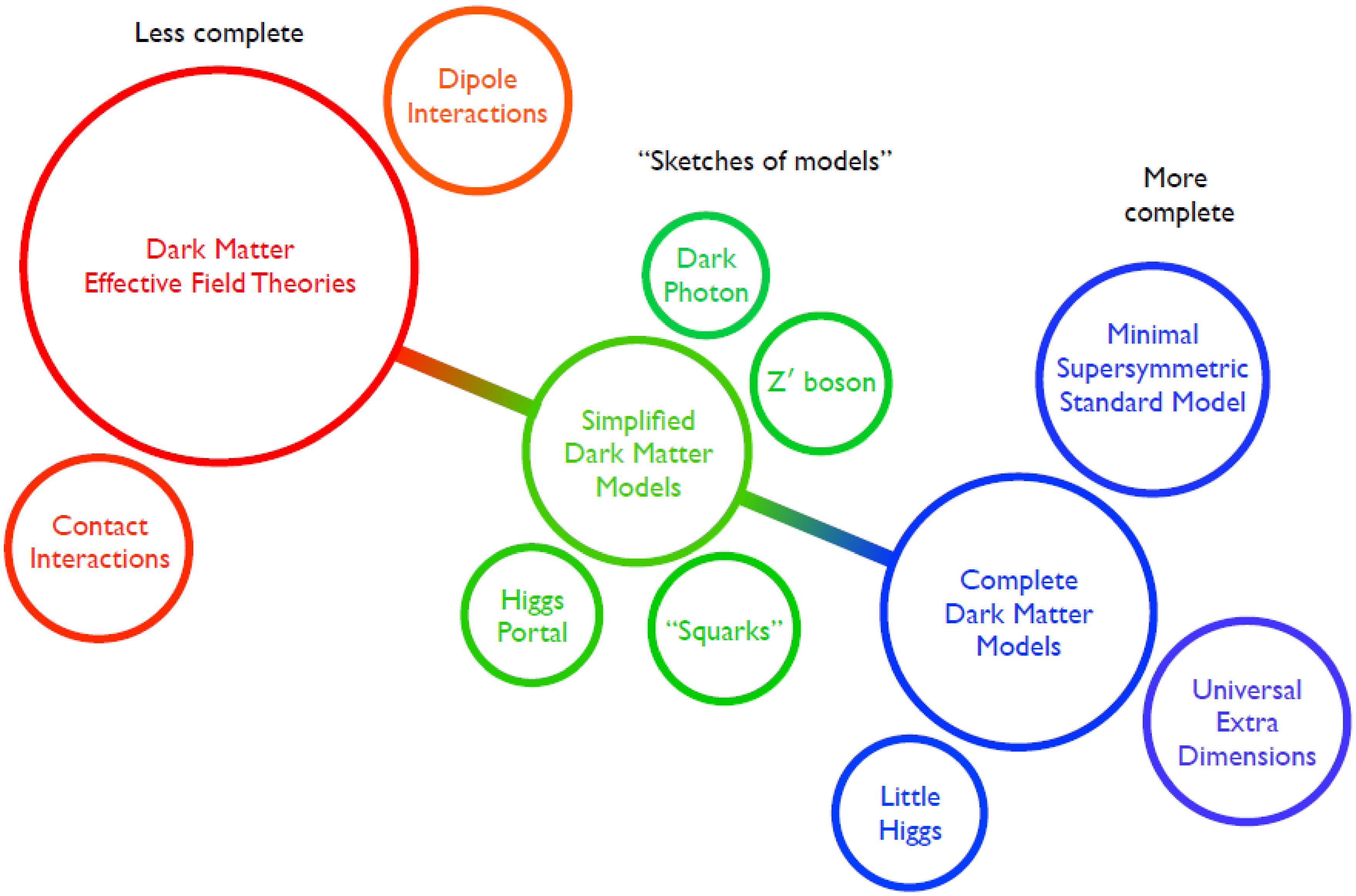








$$\Omega h^2 \simeq 0.12 \longrightarrow \langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$



Abdallah et al. arXiv:1506.03316

Simplified models: “Dark portals“

Mediator sector

Single state interacting with DM and fermion pairs.
Optional: neutral SM mediators (Higgs, Z, might do the job)

Visible sector

SM states

Trivial dark sector

Only the DM candidate
Stabilized by a global symmetry

Simplified vs UV complete models

+ Few free parameters: efficient interface with experimental output

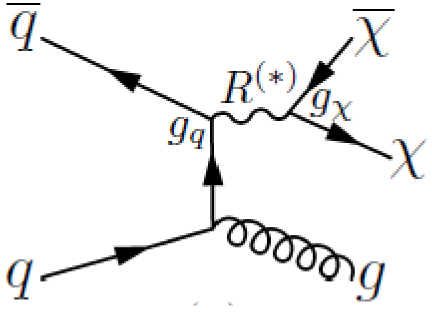
- Overconstrained

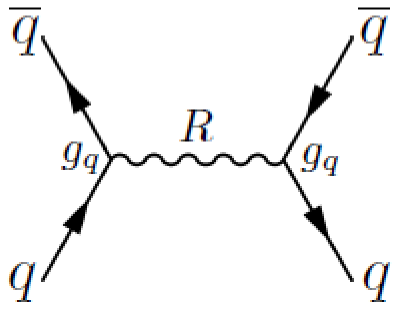
- Lack of theoretical consistency might affect theoretical predictions.

+More solid predictions.

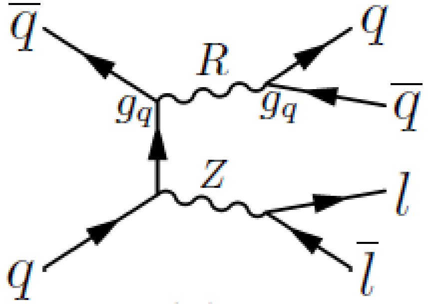
-Potentially high number of free parameters

Complementarity in simplified models

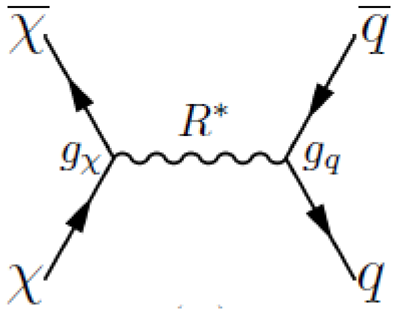




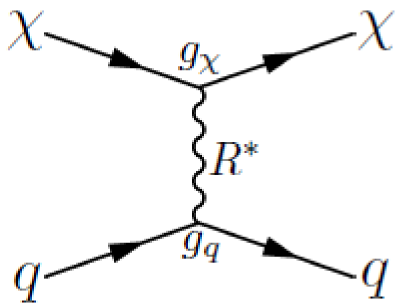
Chala et al. 1503.05916



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



Relic density / ID



Direct Detection

Examples of Dark portals

$$\mathcal{L} = \xi \mu_\chi^S \chi\chi S + \xi \lambda_\chi^{S\,2} |\chi|^2 |S|^2 + \frac{c_S}{\sqrt{2}} \frac{m_f}{v_h} \bar{f} f S$$

Spin-0 mediator

$$\mathcal{L} = \xi g_\psi \bar{\psi}\psi S + \frac{c_S}{\sqrt{2}} \frac{m_f}{v_h} \bar{f} f S$$

Spin-1 mediator

$$\mathcal{L} = m_V \eta_V^S V^\mu V_\mu S + \frac{1}{2} \eta_S^{V\,2} V^\mu V_\mu S S + \frac{c_S}{\sqrt{2}} \frac{m_f}{v_h} S \bar{f} f$$

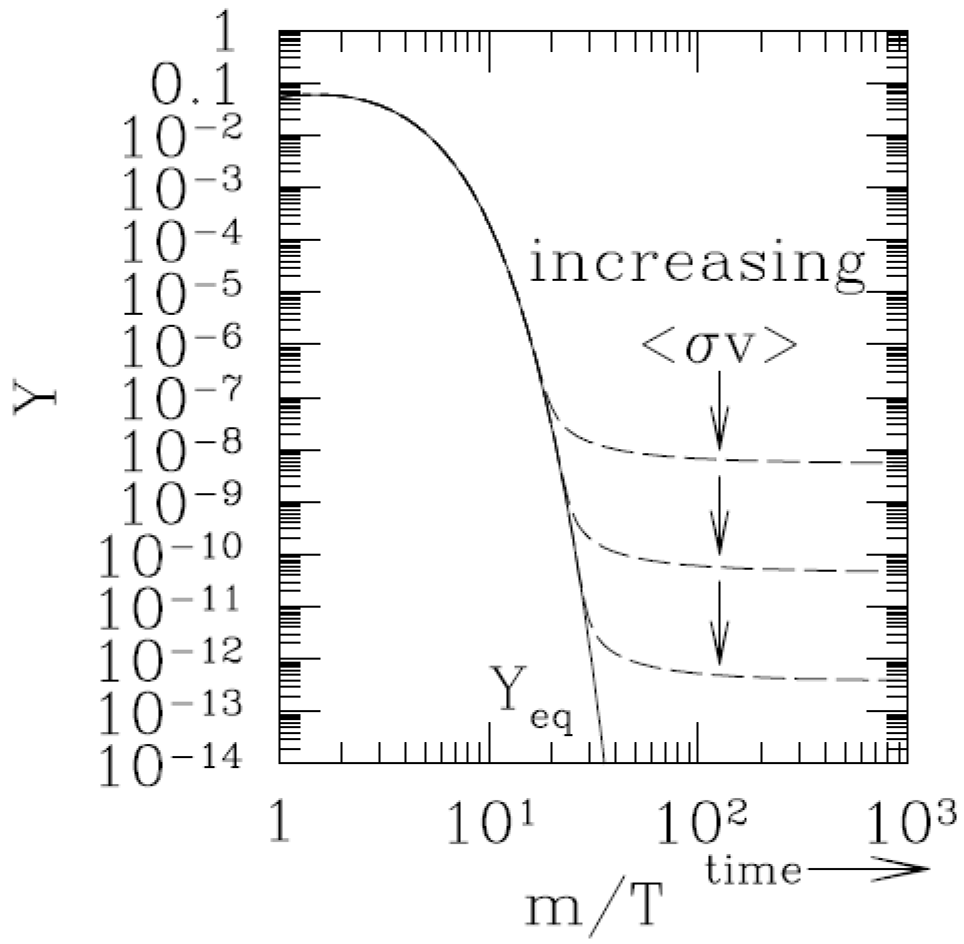
$$\mathcal{L} = i g' \lambda_\chi^{Z'} \left(\chi^* \partial_\mu \chi - \chi \partial_\mu \chi^*\right) Z'^\mu + g'^2 \lambda_\chi^{Z'\,2} \chi\chi^* Z'_\mu Z'^\mu + g' \sum_f \bar{f} \gamma^\mu \left(V_f^{Z'} - A_f^{Z'} \gamma_5\right) f Z'_\mu$$

$$\mathcal{L} = g' \xi \bar{\psi} \left(\boxed{V_\psi^{Z'}} - A_\psi^{Z'} \gamma_5\right) \psi Z'^\mu + g' \sum_f \bar{f} \gamma^\mu \left(V_f^{Z'} - A_f^{Z'} \gamma_5\right) f Z'_\mu$$

Not present for Majorana fermions

$$\mathcal{L} = g \eta_V^{Z'} [[VVZ]] + \bar{f} \gamma^\mu \left(V_f^{Z'} - A_f^{Z'} \gamma^5\right) f Z'_\mu$$

WIMP Paradigm



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

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

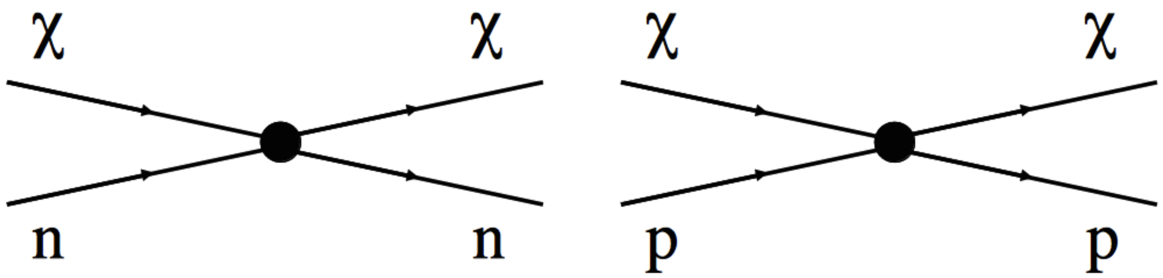
$$\Omega h^2 \theta^{-3} \approx 8.7661 \times 10^{-11} \mathrm{GeV}^{-2} \left[\overline{g_{\rm eff}}^{1/2} \int_{T_0}^{T_f} \langle \sigma v_{\rm M\o l} \rangle \frac{\mathrm{d}T}{m} \right]^{-1}$$

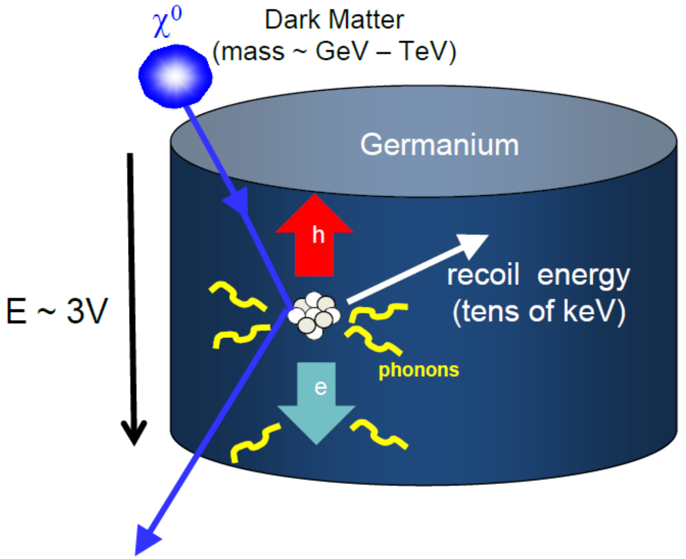
$$\langle \sigma v \rangle = a + b v^2$$

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.

$$\sigma^{\rm SI}_{\rm DM,p} \propto \frac{\mu_\chi^2}{m_S^4}\left[\lambda_p \frac{Z}{A} + \lambda_n \left(1-\frac{Z}{A}\right)\right]^2$$

Spin-0 Mediator

$$\lambda_N = \sum_{q=u,d,s} \frac{m_N}{m_q} y_q f_q^N + \frac{2}{27} f_{\rm TG} \frac{m_N}{m_q} \sum_{q=c,b,t} y_q$$

$$\sigma^{\rm SI}_{\psi,p} = \frac{g'^4 \mu^2_{\psi,p}}{\pi m^4_{Z'}} (V_\psi^{Z'})^2 \frac{[Z f_p + (A-Z) f_n]^2}{A^2} \longleftarrow \sigma^{\rm SI}_{\rm DM,p} \propto \frac{\mu^2_{\rm DM,p}}{\pi m^4_{Z'}} \frac{[Z f_p + (A-Z) f_n]^2}{A^2}$$

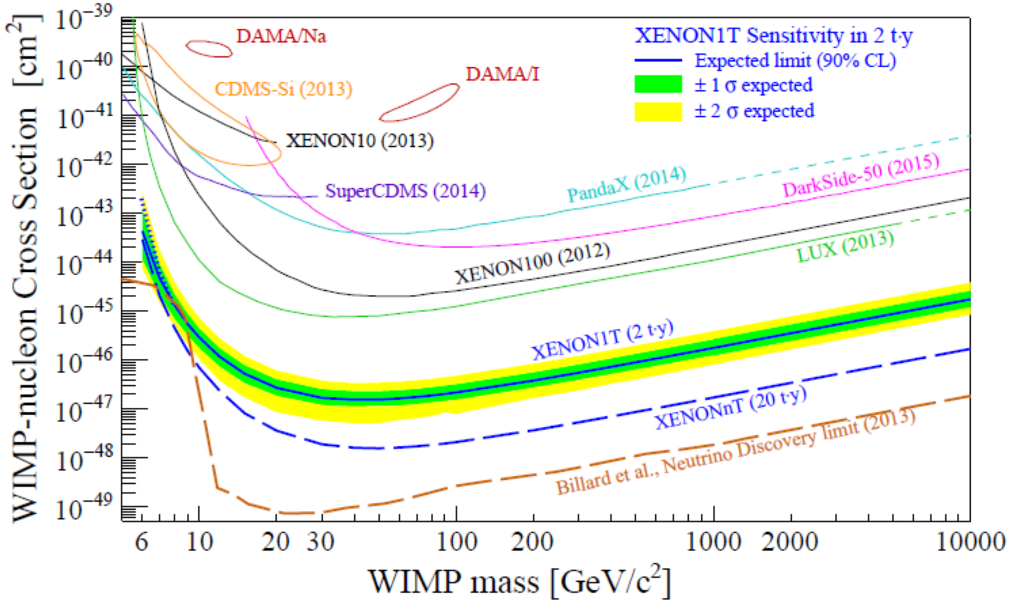
Zero for Majorana fermions

$$f_p = 2V_u^{Z'} + V_d^{Z'}$$

$$f_n = V_u^{Z'} + 2V_d^{Z'}$$

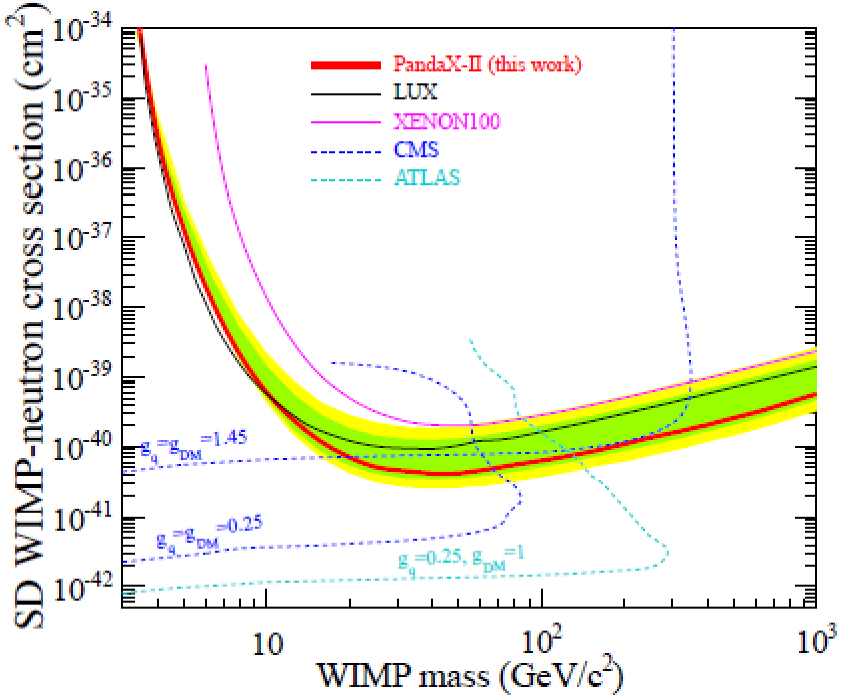
Spin-1 Mediator

$$\sigma^{\rm SD}_{\rm DM,p} \propto \frac{3\mu_\chi^2}{m^4_{Z'}}\left[A_u^{Z'} \Delta_u^p + A_d^{Z'} (\Delta_d^p + \Delta_s^p)\right]^2$$

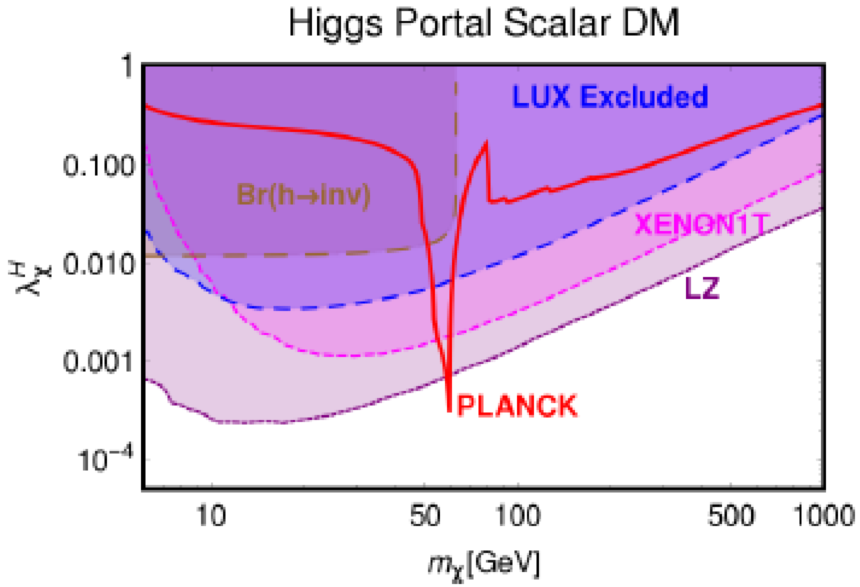


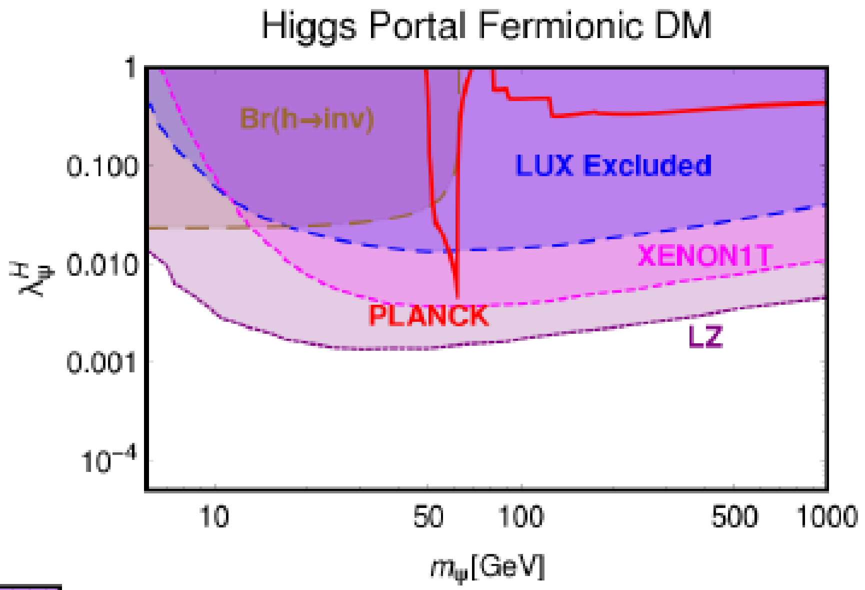
(Xenon Collaboration, 1512.07501)

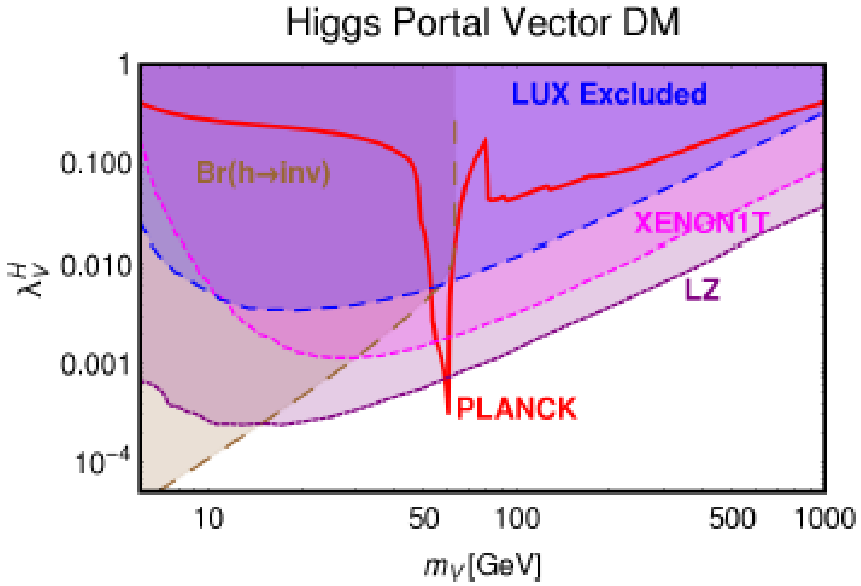
Panda-X Collaboration, 1611.06553



Higgs portal

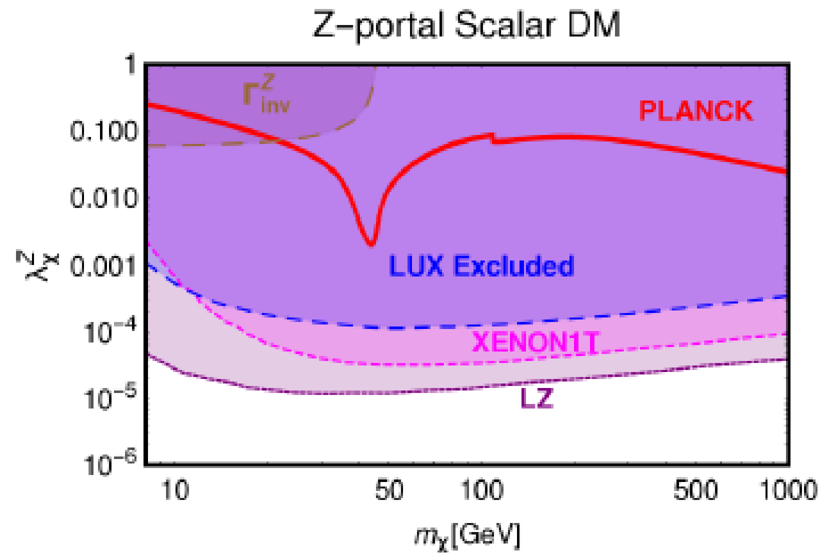




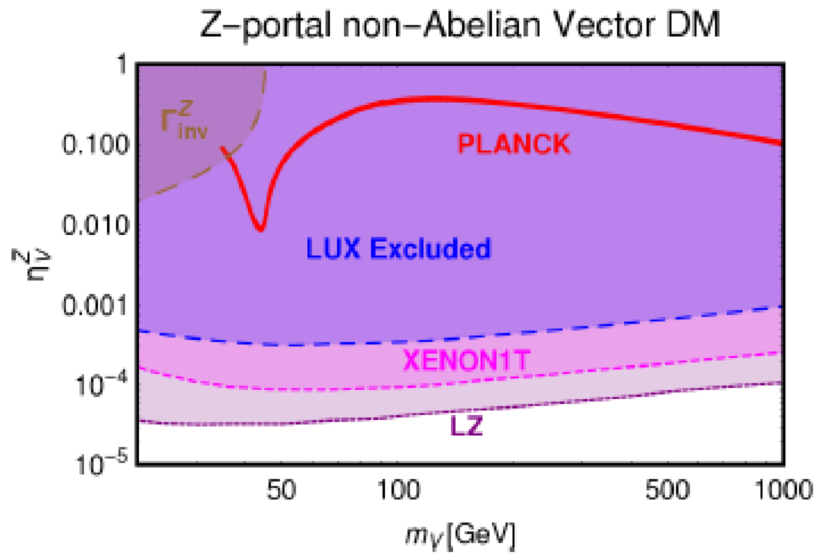


G.A., M. Dutra, P. Ghosh, M. Lindner, Y. Mambrini, M. Pierre, F. Queiroz, 1703.07364

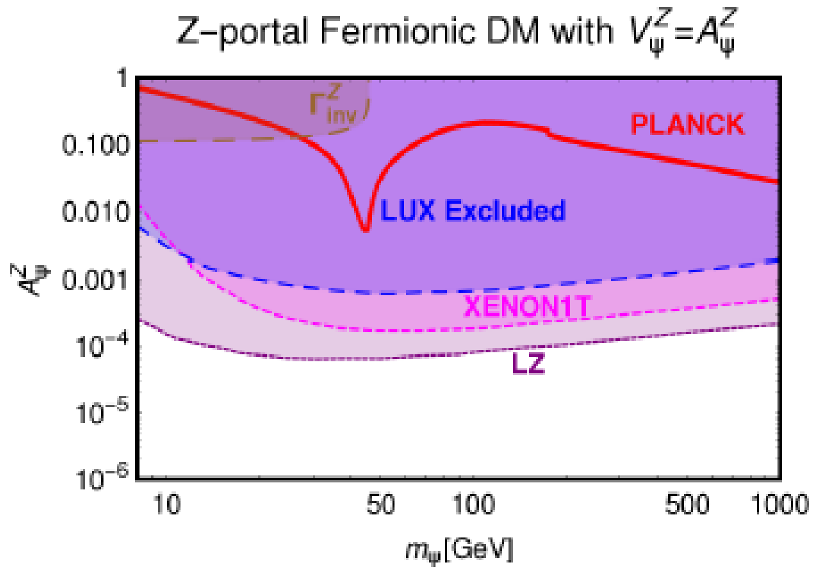
Z-portal



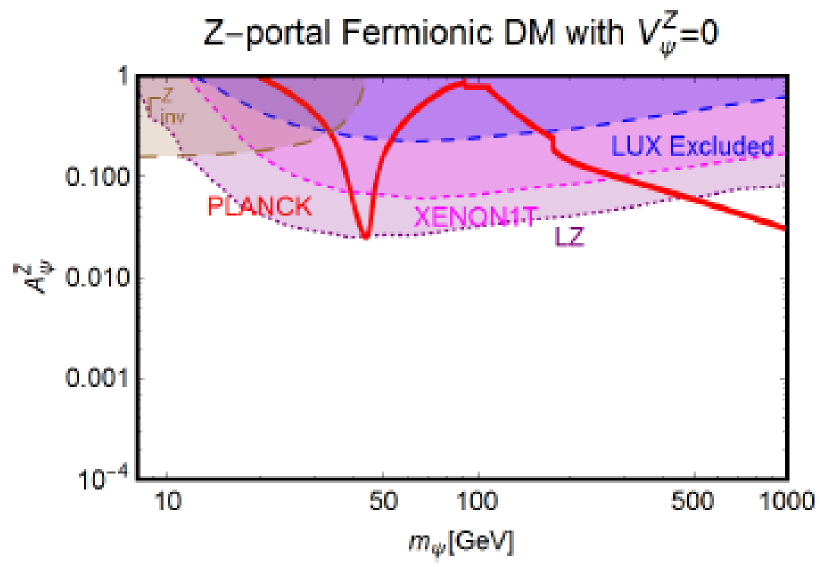
Z−portal Scalar DM
PLANCK
LUX Excluded
XENON1T
LZ
Γ_{inv}^{Z}
λ_{χ}^{Z}
m_{χ}[GeV]



Z−portal non−Abelian Vector DM
PLANCK
LUX Excluded
XENON1T
LZ
Γ_{inv}^{Z}
η_{V}^{Z}
m_{V}[GeV]

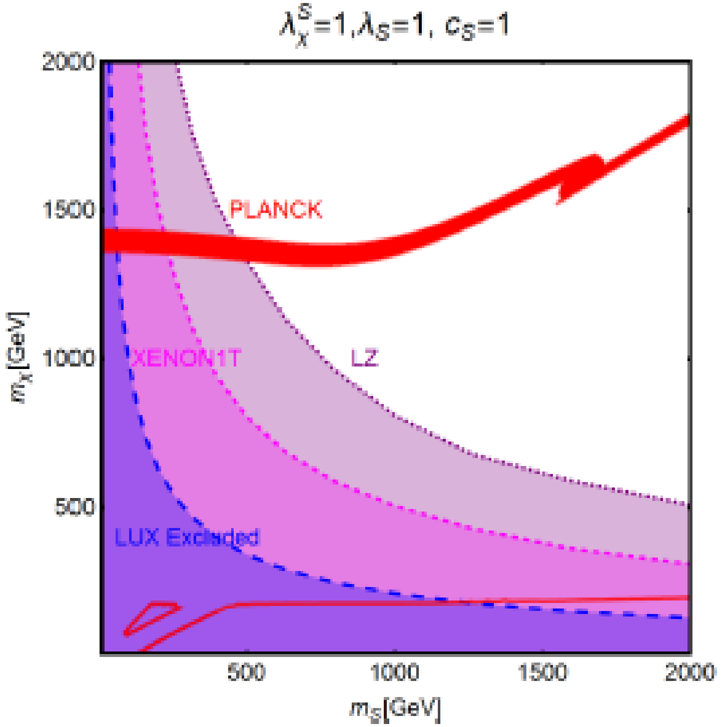


Z−portal Fermionic DM with $V_{\psi}^{Z}=A_{\psi}^{Z}$
PLANCK
LUX Excluded
XENON1T
LZ
Γ_{inv}^{Z}
A_{ψ}^{Z}
m_{ψ}[GeV]



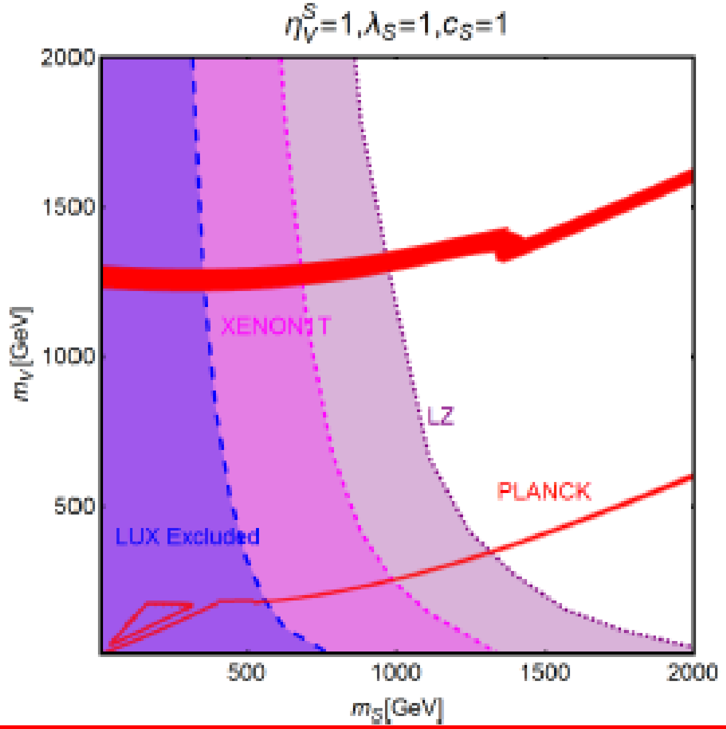
Z−portal Fermionic DM with $V_{\psi}^{Z}=0$
LUX Excluded
PLANCK
XENON1T
LZ
Γ_{inv}^{Z}
A_{ψ}^{Z}
m_{ψ}[GeV]

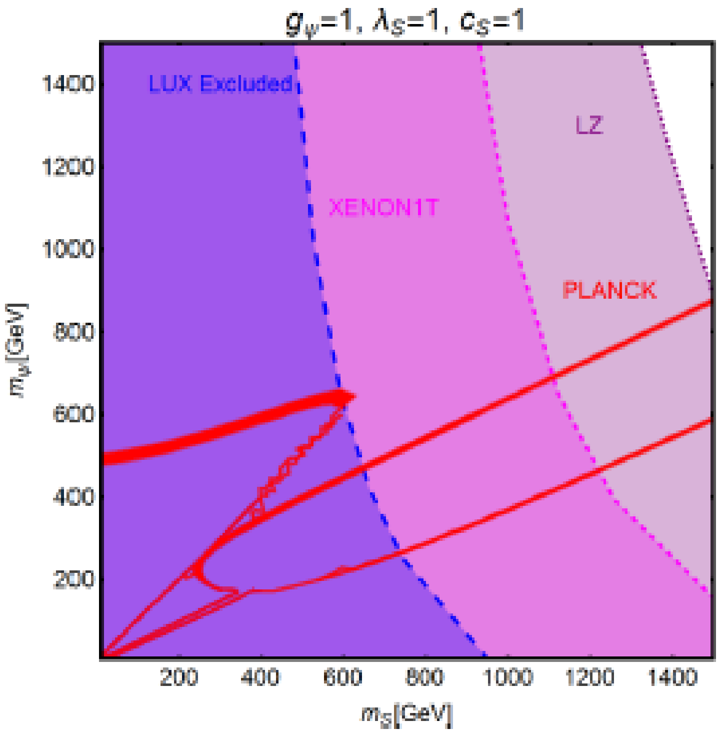
Spin-0 (real) mediator



Scalar DM

Vector DM

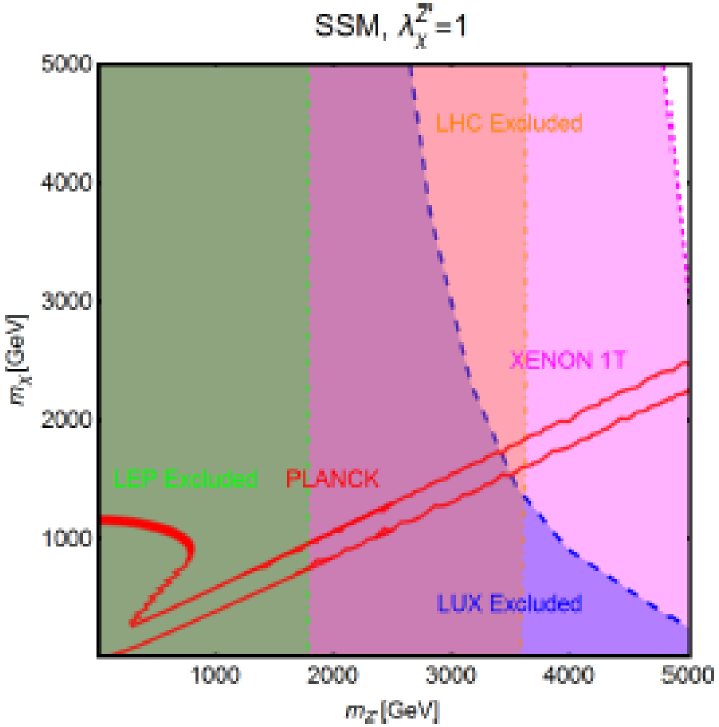




Fermion DM

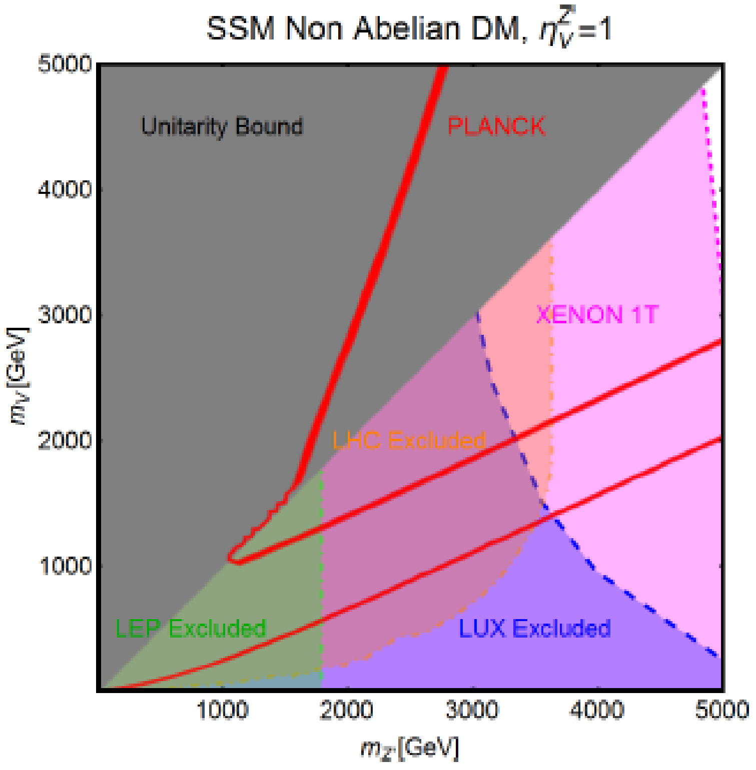
G.A., M. Dutra, P. Ghosh, M. Lindner, Y. Mambrini, M. Pierre, F. Queiroz, 1703.07364

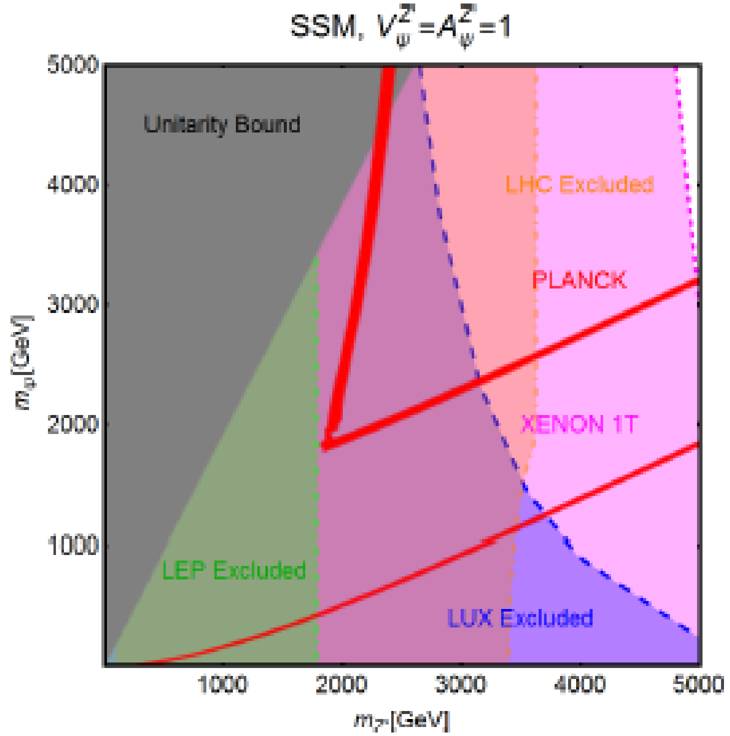
Spin-1 mediator



Complex scalar DM

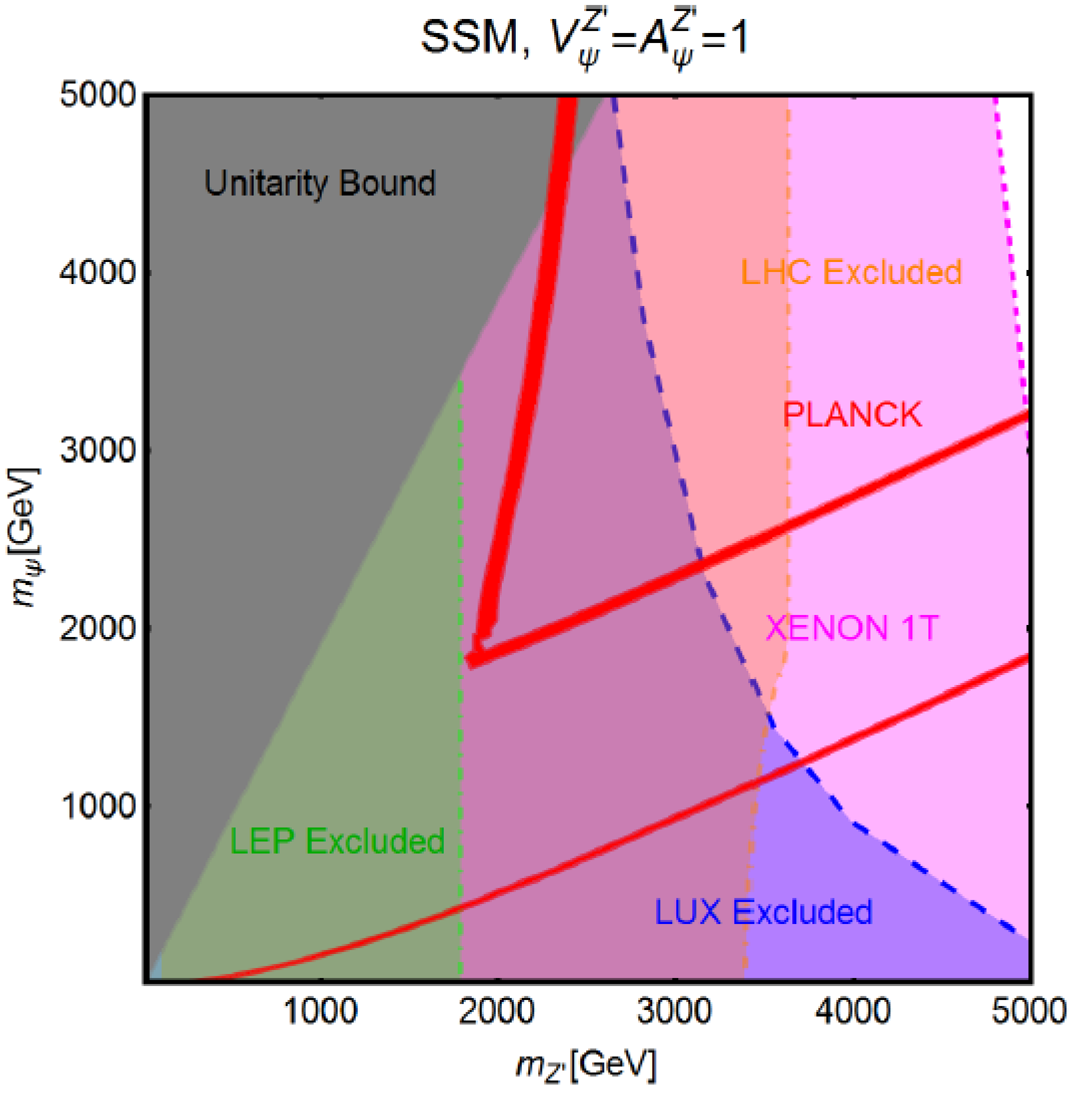
Non abelian vector DM

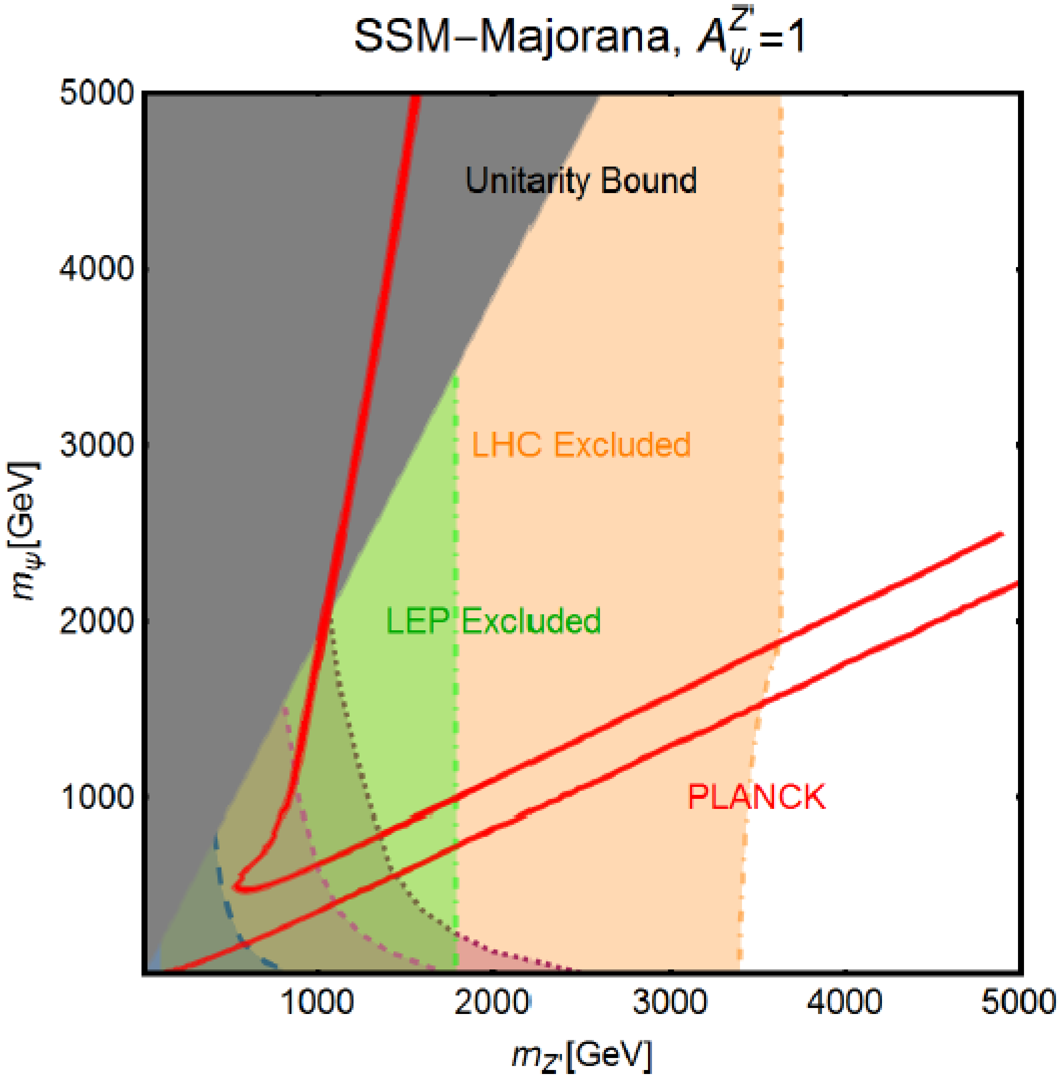




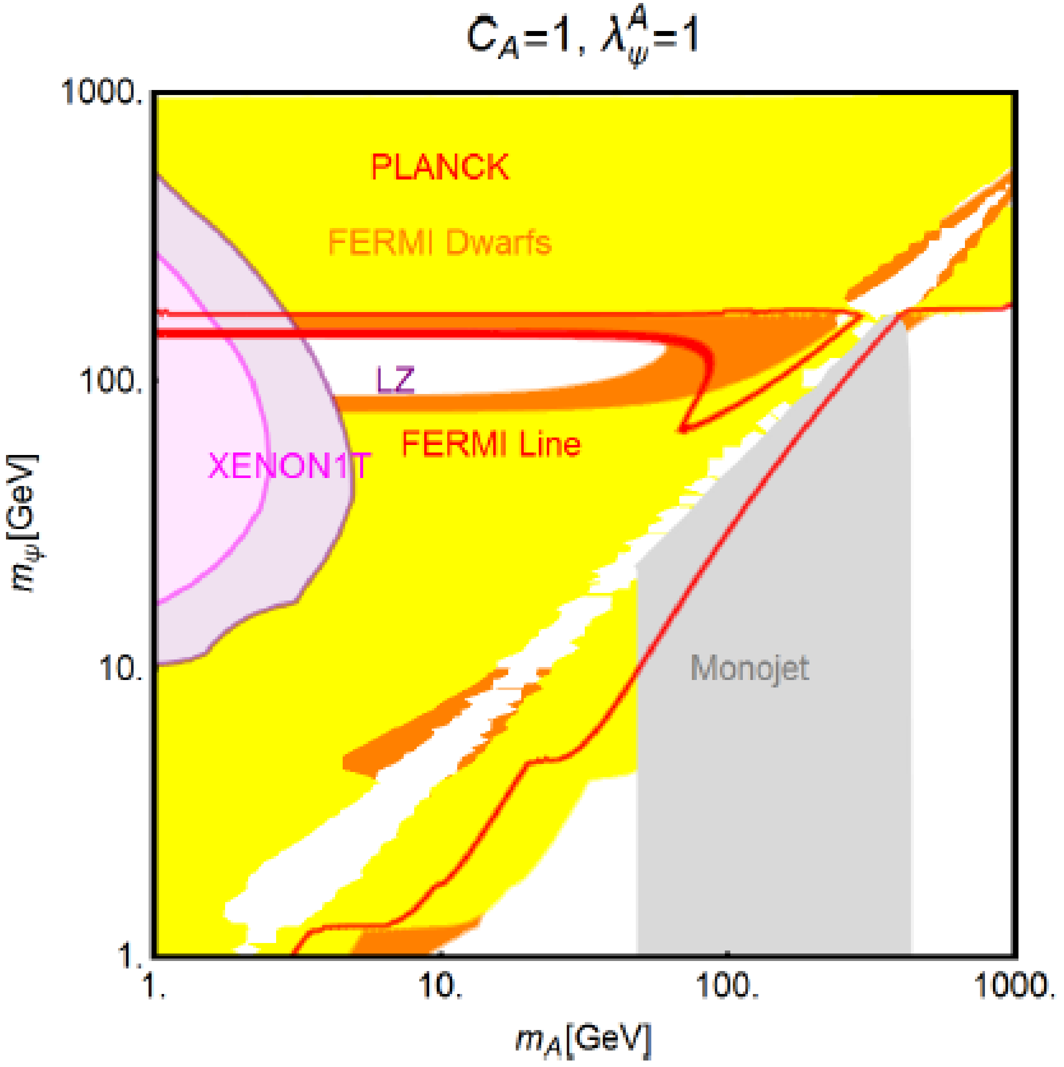
Dirac fermion DM

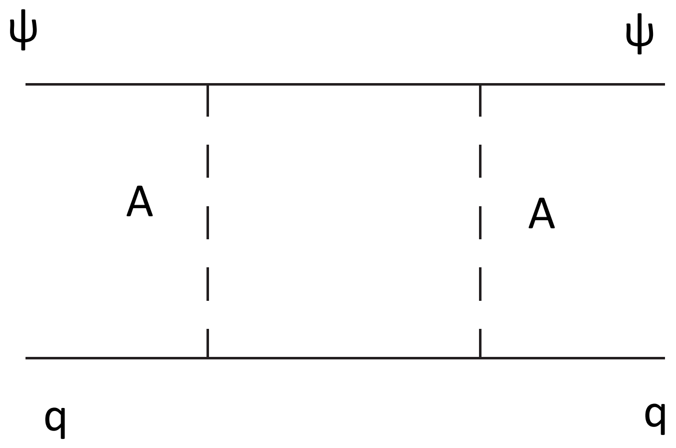
Dirac vs Majorana





Pseudo-scalar portal





SI cross-section induced only at one loop

S. Ipek, D. Mckenn and A. Nelson, 1404.3716

Scalar+(light pseudoscalar mediator)

$$\mathcal{L}_\Phi = \partial_\mu \Phi \partial^\mu \Phi^* + \mu_\Phi^2 |\Phi|^2 - \lambda |\Phi|^4 + \frac{\epsilon_\Phi^2}{2}\left(\Phi^2 + \mathrm{h.c.}\right)$$

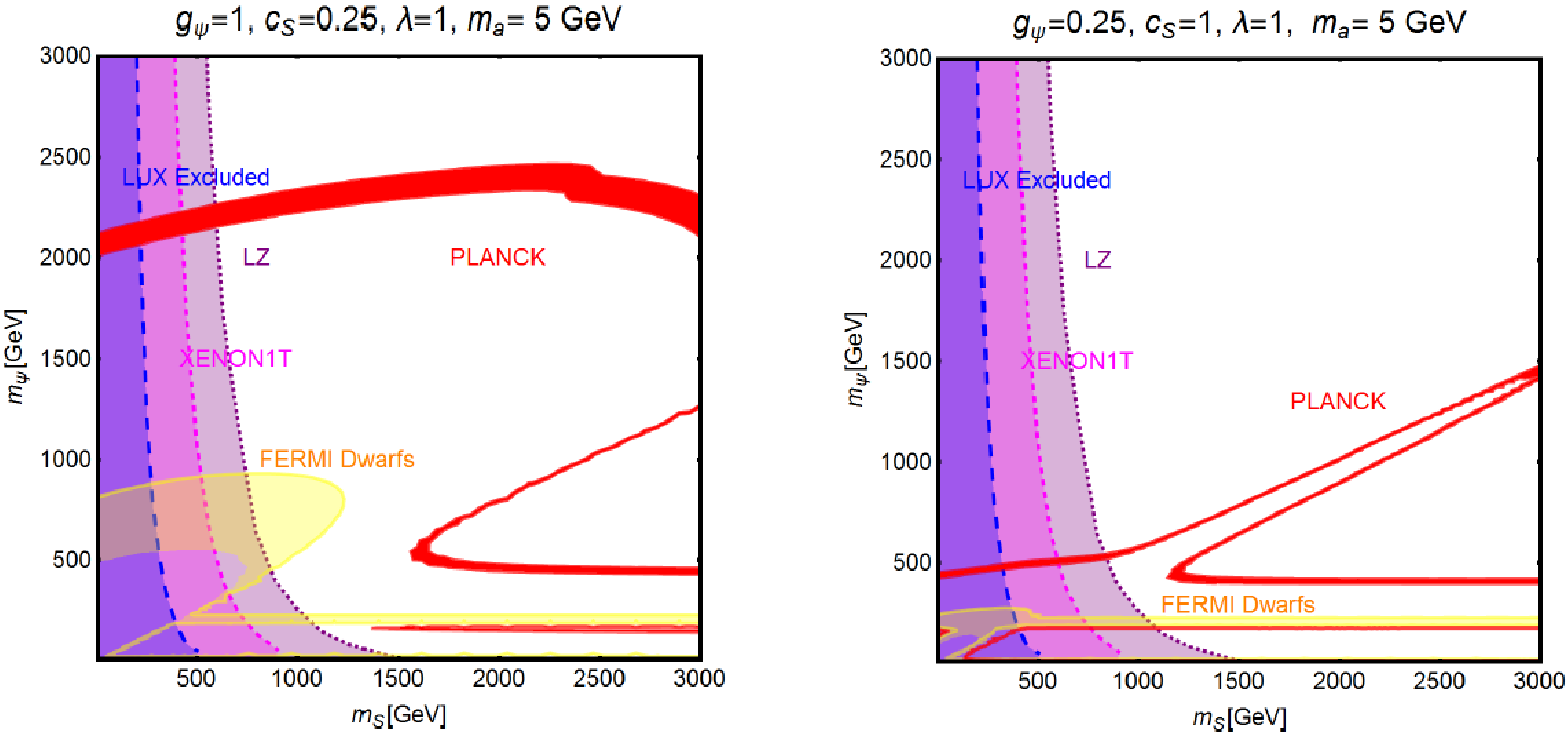
$$\Phi \rightarrow (S + ia)/\sqrt{2}$$

Pseudoscalar interpreted as pseudo-goldstone boson of a U(1) global symmetry

$$-\mathcal{L} = \frac{m_S^2}{2} S^2 + \frac{m_a^2}{2} a^2 + \sqrt{\frac{\lambda}{2}} m_S S a^2 + \sqrt{\frac{\lambda}{2}} m_S S^3 + \frac{\lambda}{4}\left(S^2 + a^2\right)^2 + m_\psi \overline{\psi}\psi + g_\psi \left(S\overline{\psi}\psi + ia\overline{\psi}\gamma^5\psi\right) + \sum_f c_S \frac{m_f}{v_h}\left(S\overline{f}f + ia\overline{f}\gamma^5 f\right)$$

$$\langle \sigma v \rangle (\overline{\psi}\psi \rightarrow Sa) = \begin{cases} \frac{g_\psi^2 \lambda m_S^4}{512\pi m_\psi^6} \approx 1.6 \times 10^{-25} \mathrm{cm}^3 \mathrm{s}^{-1} g_\psi^2 \lambda \left(\frac{m_S}{1\,\mathrm{TeV}}\right)^4 \left(\frac{600\,\mathrm{GeV}}{m_\psi}\right)^6 & m_\psi < m_S, \\ \frac{g_\psi^4}{16\pi m_\psi^2} \approx 2.3 \times 10^{-25} \mathrm{cm}^3 \mathrm{s}^{-1} g_\psi^4 \left(\frac{1\,\mathrm{TeV}}{m_\psi}\right)^2 & m_\psi > m_S. \end{cases}$$

Enhanchement of DM annihilation cross-section by light final states.



g_ψ=1, c_S=0.25, λ=1, m_a= 5 GeV
LUX Excluded
LZ
PLANCK
XENON1T
FERMI Dwarfs
m_ψ[GeV]
m_S[GeV]
3000
2500
2000
1500
1000
500
g_ψ=0.25, c_S=1, λ=1, m_a= 5 GeV
LUX Excluded
LZ
XENON1T
PLANCK
FERMI Dwarfs
m_ψ[GeV]
m_S[GeV]

RGE Corrections

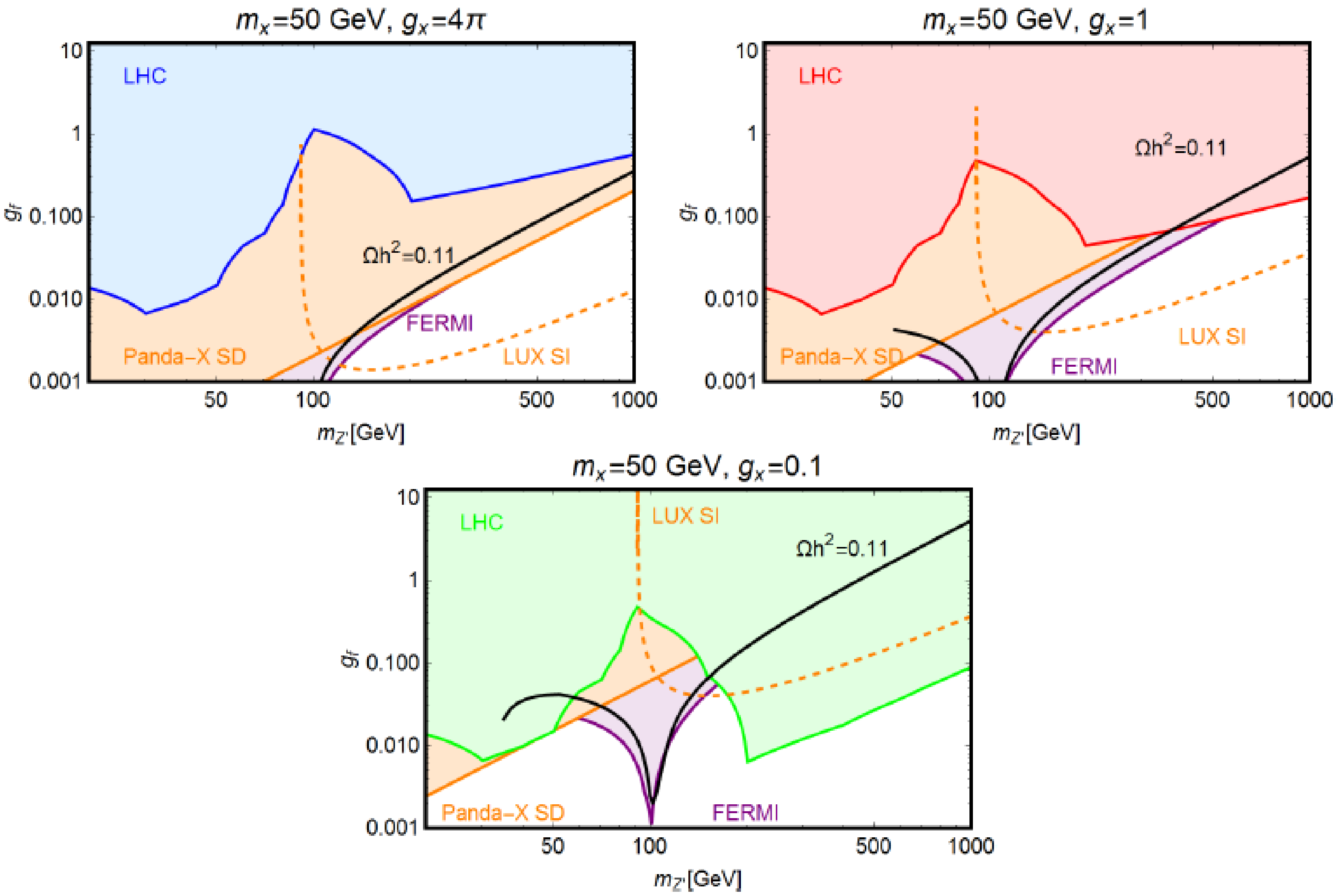
$$\mathcal{L} \supset \left[\bar{\chi}\gamma^\mu(g_{\chi v} + g_{\chi a}\gamma^5)\chi + g_f \bar{f}\gamma^\mu\gamma^5 f\right] Z'_\mu$$

$$\downarrow$$

$$\tilde{V}_u^{Z'} = \frac{\alpha_t}{2\pi}(3 - 8s_W^2)A_u^{Z'} \log\left(\frac{m_{Z'}}{m_Z}\right) - (3 - 8s_W^2)\left[\frac{\alpha_b}{2\pi}A_d^{Z'} + \frac{\alpha_\tau}{6\pi}A_e^{Z'}\right]\log\left(\frac{m_{Z'}}{\mu_N}\right)$$

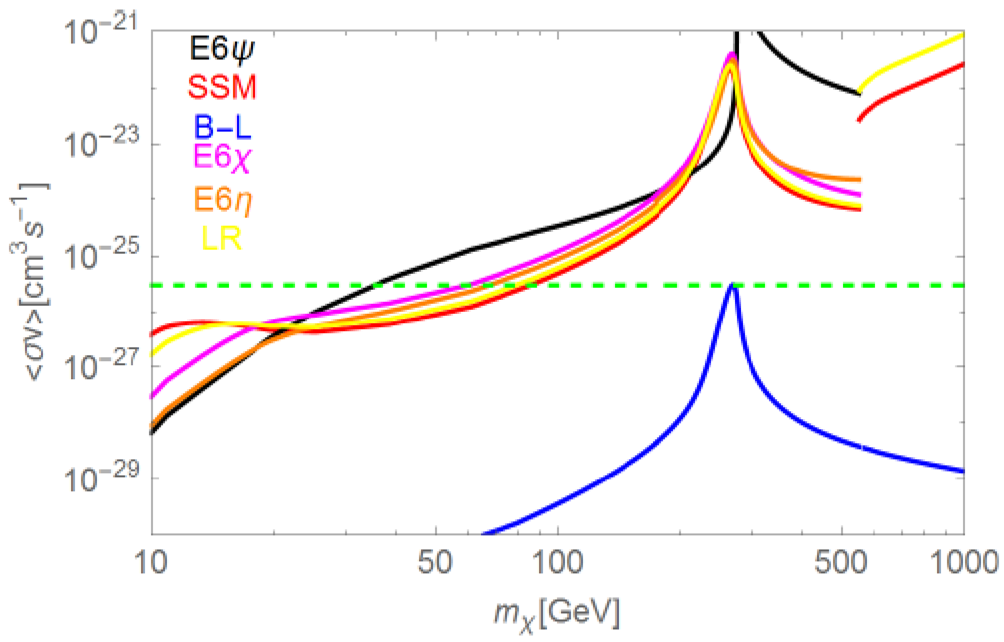
$$\tilde{V}_d^{Z'} = -\frac{\alpha_t}{2\pi}(3 - 4s_W^2)A_u^{Z'} \log\left(\frac{m_{Z'}}{m_Z}\right) + (3 - 4s_W^2)\left[\frac{\alpha_b}{2\pi}A_d^{Z'} + \frac{\alpha_\tau}{6\pi}A_e^{Z'}\right]\log\left(\frac{m_{Z'}}{\mu_N}\right)$$

F. d’Eramo, B. J. Kavanagh, P. Panci 1605.04917



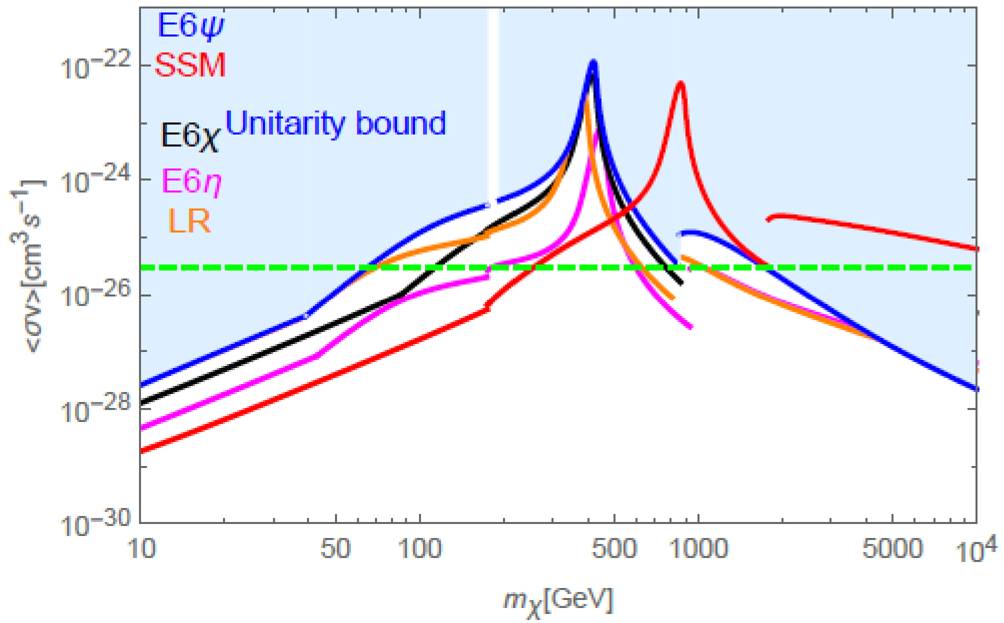
A. Alves, G.A., Y. Mambrini, S. Profumo, F. Queiroz, 1612.07282

Unitarity bound



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

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



Towards UV complete models:spin-0 mediators

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

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

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

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

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

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

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

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

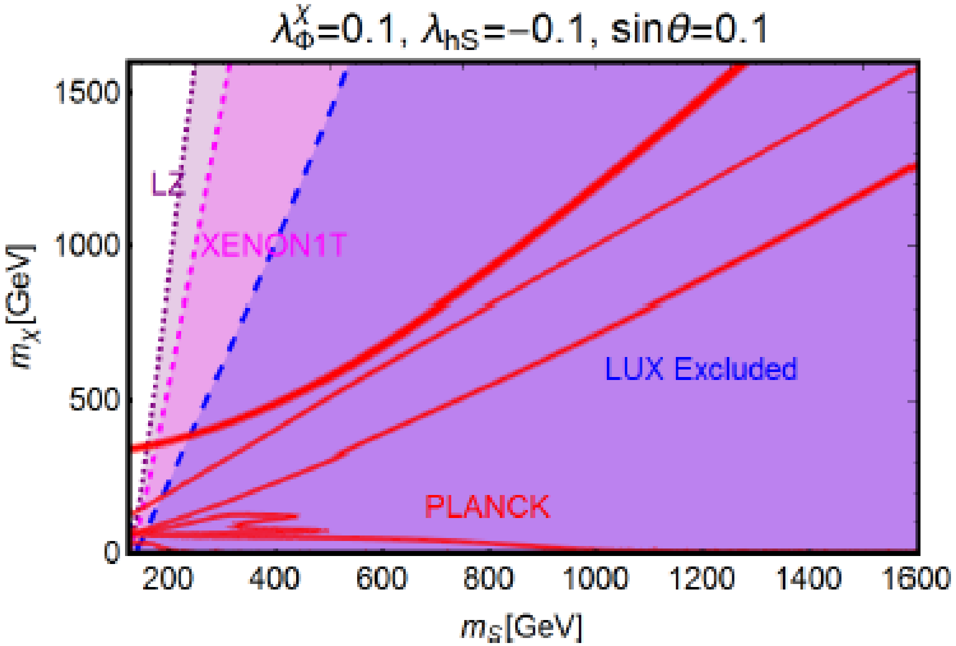
Vector DM

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

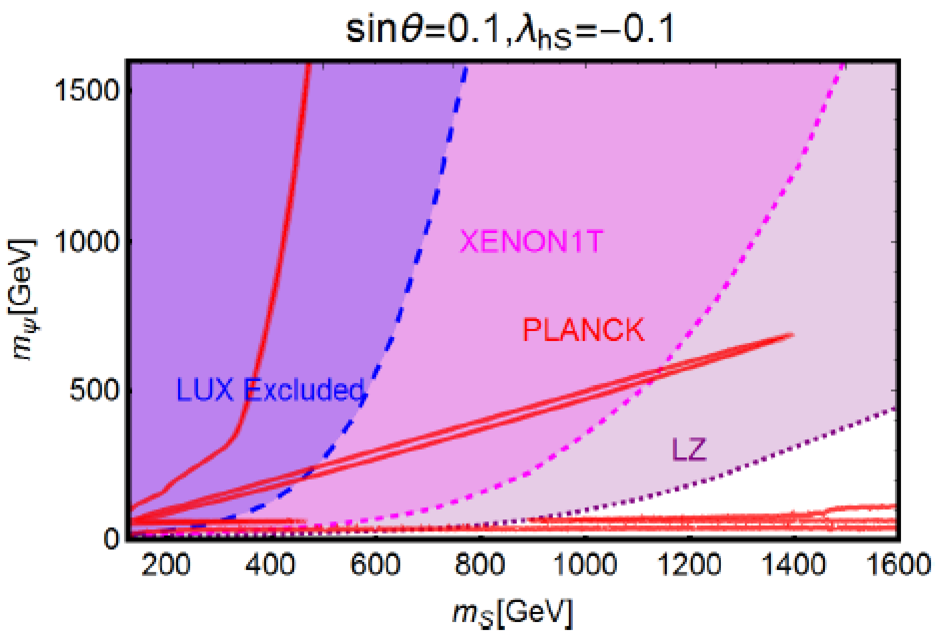
$$\downarrow$$

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

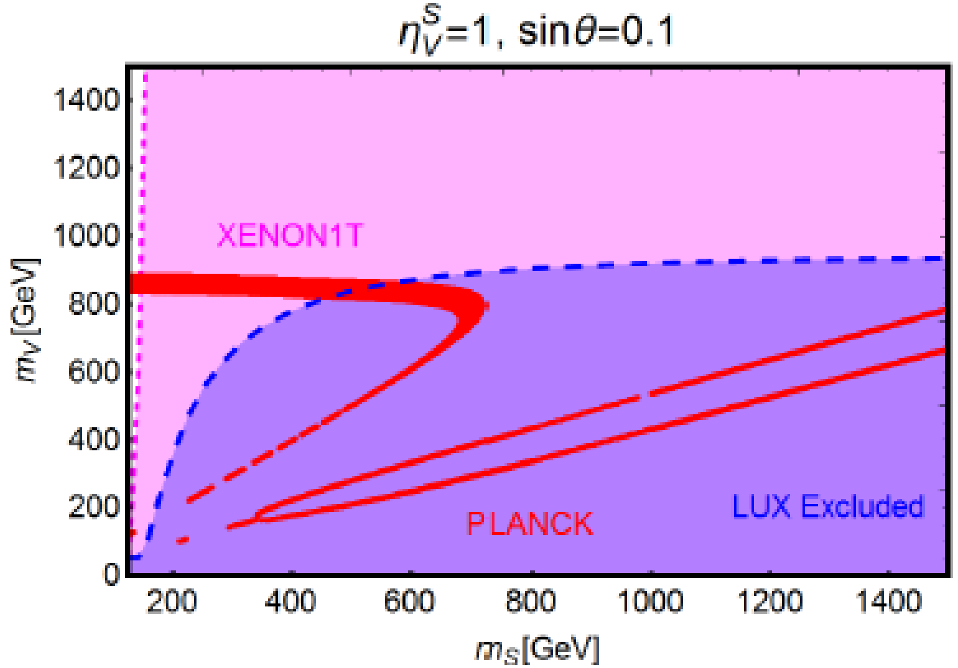
$$v_\Phi = 2m_V/\eta_V^S \qquad \lambda_{hS} = \frac{(m_h^2 - m_S^2)\sin 2\theta}{2v_h} \times \frac{\eta_V^S}{2m_V}$$



λ_Φ^χ=0.1, λ_{hS}=−0.1, sinθ=0.1
LZ
XENON1T
LUX Excluded
PLANCK
m_χ[GeV]
m_S[GeV]



sinθ=0.1,λ_{hS}=−0.1
XENON1T
PLANCK
LUX Excluded
LZ
m_ψ[GeV]
m_S[GeV]



η_V^S=1, sinθ=0.1
XENON1T
PLANCK
LUX Excluded
m_V[GeV]
m_S[GeV]

Spin-1 as new gauge bosons

Spin-1 BSM mediators can be interpreted as gauge bosons of extra symmetry groups

$$E_6 \to SO(10) \times U(1)_\psi \longrightarrow \text{Extra U(1) from Grand Unified theories}$$

$$SO(10) \to SU(5) \times U(1)_\chi$$

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(2) \times U(1)_Y \times U(1)_{LR}$$

General implementation:

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

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

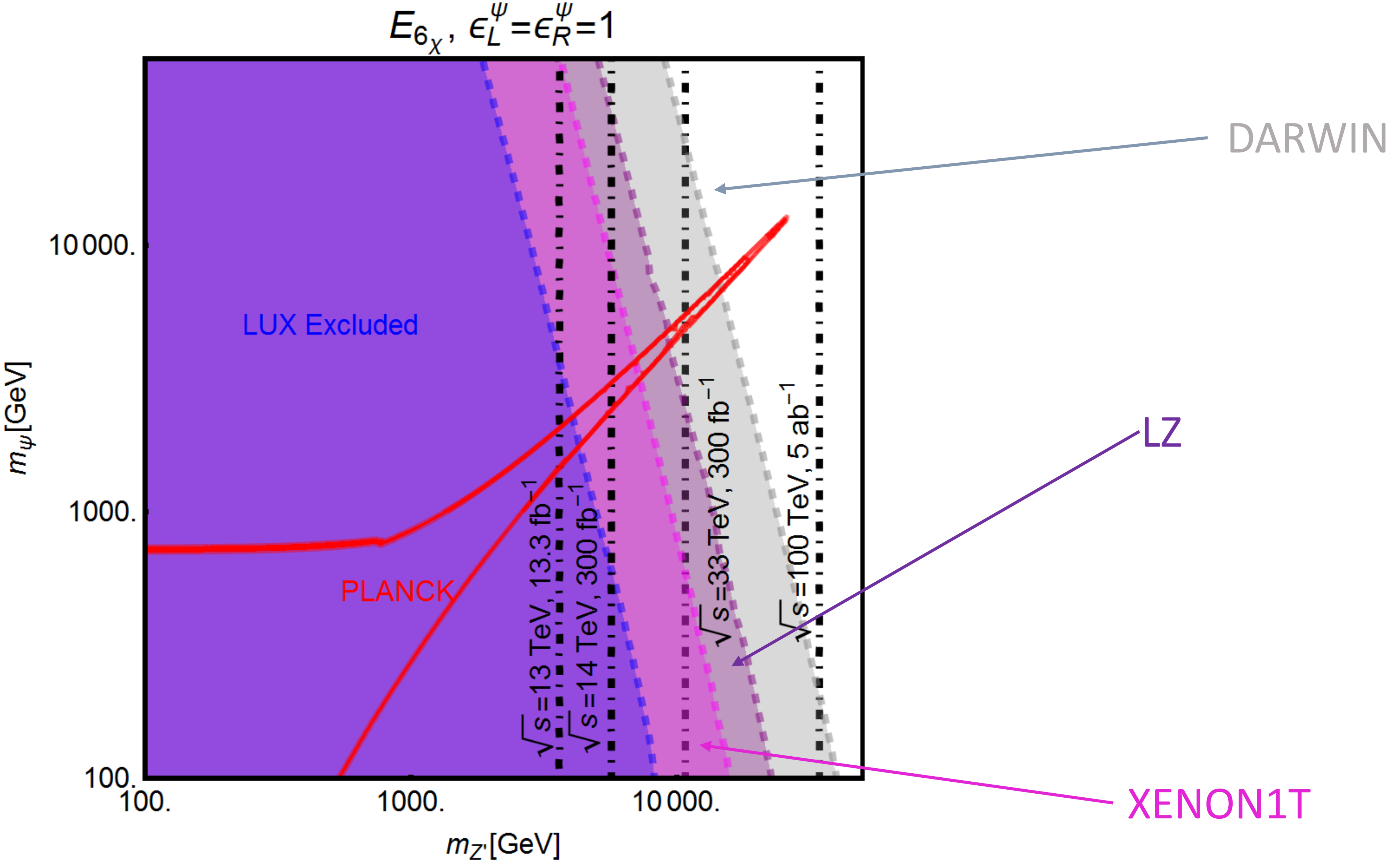
	χ	ψ	η	LR	B-L	SSM
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1
$\hat{\epsilon}_L^u$	-1	1	-2	-0.109	1/6	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}_L^d$	-1	1	-2	-0.109	1/6	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}_R^u$	1	-1	2	0.656	1/6	$-\frac{2}{3}\sin^2\theta_W$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

Vectorial and axial couplings are actually combinations of left-handed and right-handed currents

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

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



G.A., M. Lindner, Y. Mambrini, M. Pierre, F. Queiroz, 1704.023028

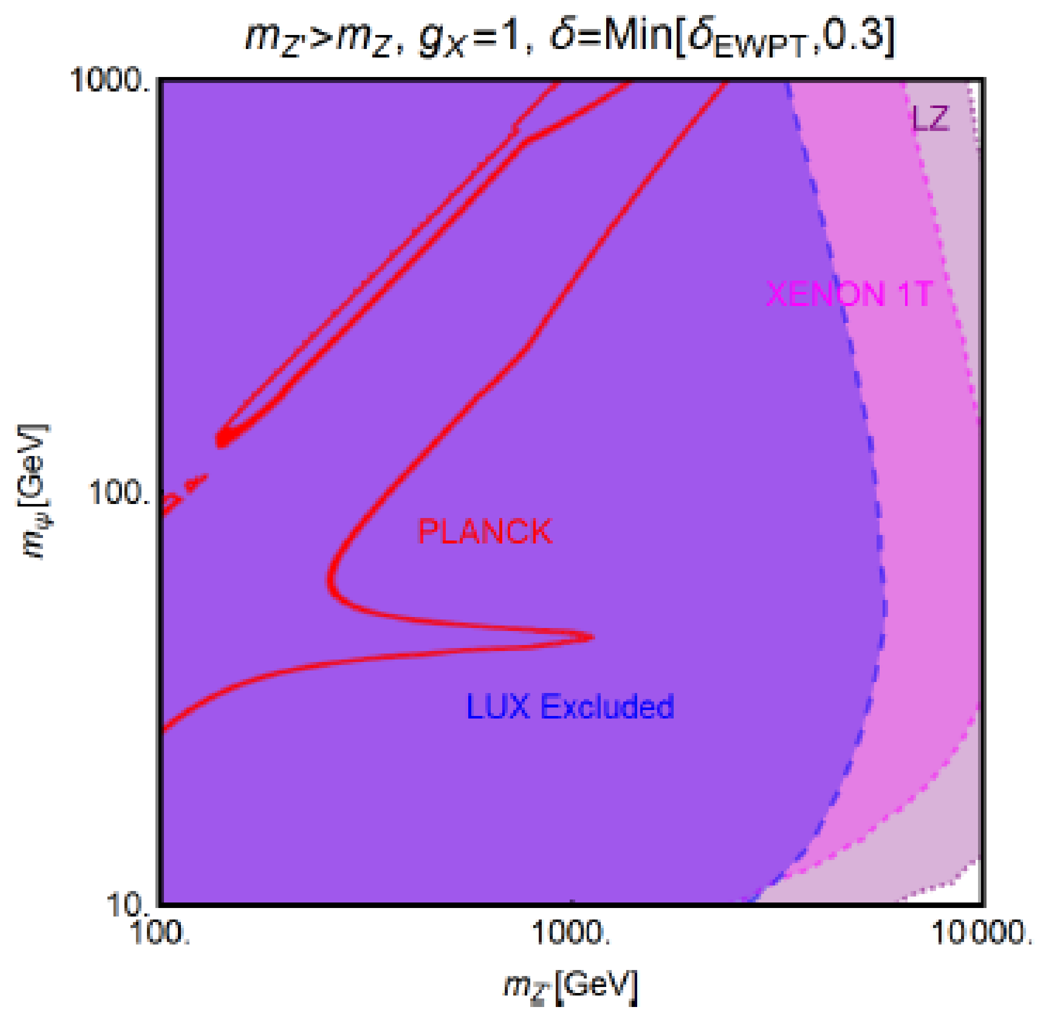
Coupling with the visible sector throught kinetic mixing

$$\mathcal{L} = -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} - \frac{1}{2}\sin\delta B^{\mu\nu}X_{\mu\nu} + \frac{1}{2}m_X^2 X^\mu X_\mu + \mathcal{L}'_{\rm SM} + \mathcal{L}_{\rm DM}$$

$$\begin{pmatrix} B_\mu \\ W_\mu^3 \\ X_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\tan\delta \\ 0 & 1 & 0 \\ 0 & 0 & 1/\cos\delta \end{pmatrix} \begin{pmatrix} c_{\hat{W}} & -s_{\hat{W}}\cos\xi & s_{\hat{W}}\sin\xi \\ s_{\hat{W}} & c_{\hat{W}}\cos\xi & -c_{\hat{W}}\sin\xi \\ 0 & \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix} \longrightarrow \quad \tan 2\xi = \frac{-2m_{\hat{Z}}^2 s_{\hat{W}}\cos\delta\sin\delta}{m_X^2 - m_{\hat{Z}}^2\cos\delta^2 + m_{\hat{Z}}^2 s_{\hat{W}}^2\sin\delta^2}$$

$$\begin{aligned}\mathcal{L}_{Z/Z',SM} &= \bar{f}\gamma^\mu\left(g_{f_L}^Z P_L + g_{f_R}^Z P_R\right) f Z_\mu + \bar{f}\gamma^\mu\left(g_{f_L}^{Z'} P_L + g_{f_R}^{Z'} P_R\right) f Z'_\mu + g_W^Z[[W^+W^-Z]] \\ &+ g_W^{Z'}[[W^+W^-Z']] + g_{hZZ}Z^\mu Z_\mu h + g_{hZZ'}Z'_\mu Z^\mu h + g_{hZ'Z'}Z'_\mu Z'^\mu h,\end{aligned}$$

$$\mathcal{L}_{\rm DM} = \begin{cases} \mathcal{L}_{\rm DM} = (D^\mu\chi)^* D_\mu\chi - m_\chi^2\chi^*\chi & \text{(complex scalar)}, \\ \mathcal{L}_{\rm DM} = \bar{\psi}\gamma^\mu D_\mu\psi - m_\psi\bar{\psi}\psi & \text{(Dirac fermion)}, \\ \mathcal{L}_{\rm DM} = \eta_V^X[[VVX]] + m_V^2 V_\mu^\dagger V^\mu & \text{(non-Abelian vector)} \end{cases}$$


$m_{Z'}>m_Z$, g_X=1, δ=Min[δ_{EWPT},0.3]
1000.
100.
10.
100.
1000.
10000.
m_ψ[GeV]
$m_{Z'}$[GeV]
LZ
XENON 1T
PLANCK
LUX Excluded

t-channel mediators

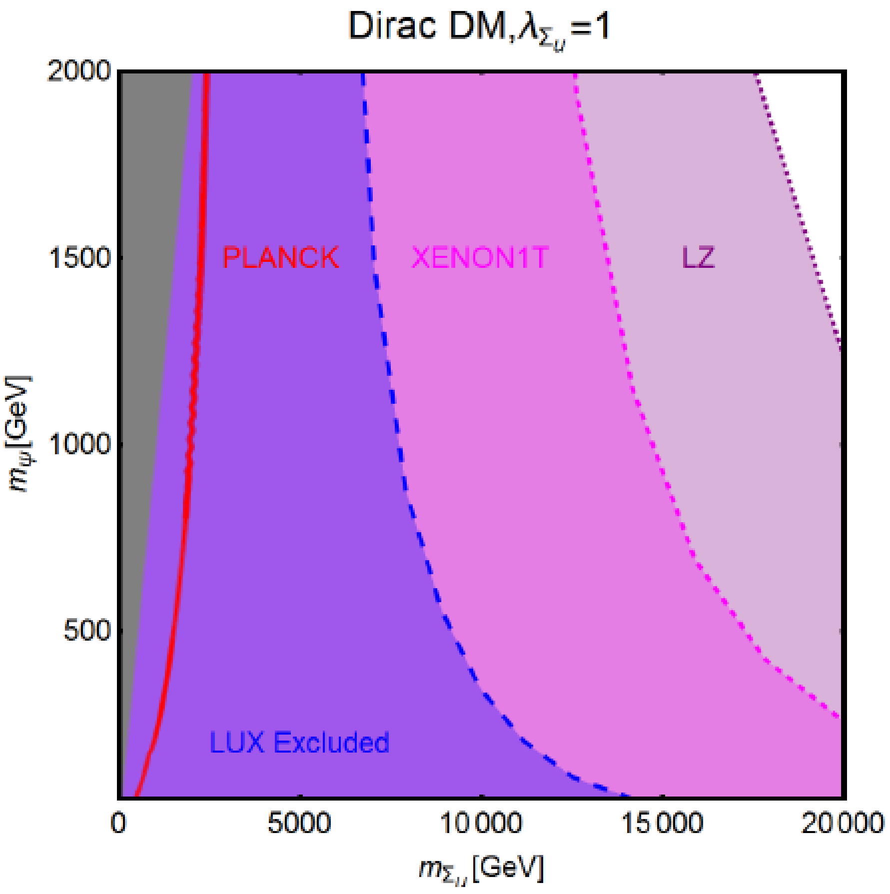
$$\mathcal{L} = -\lambda_{\Psi_q} \overline{\Psi}_q \chi q_R + h.c.$$

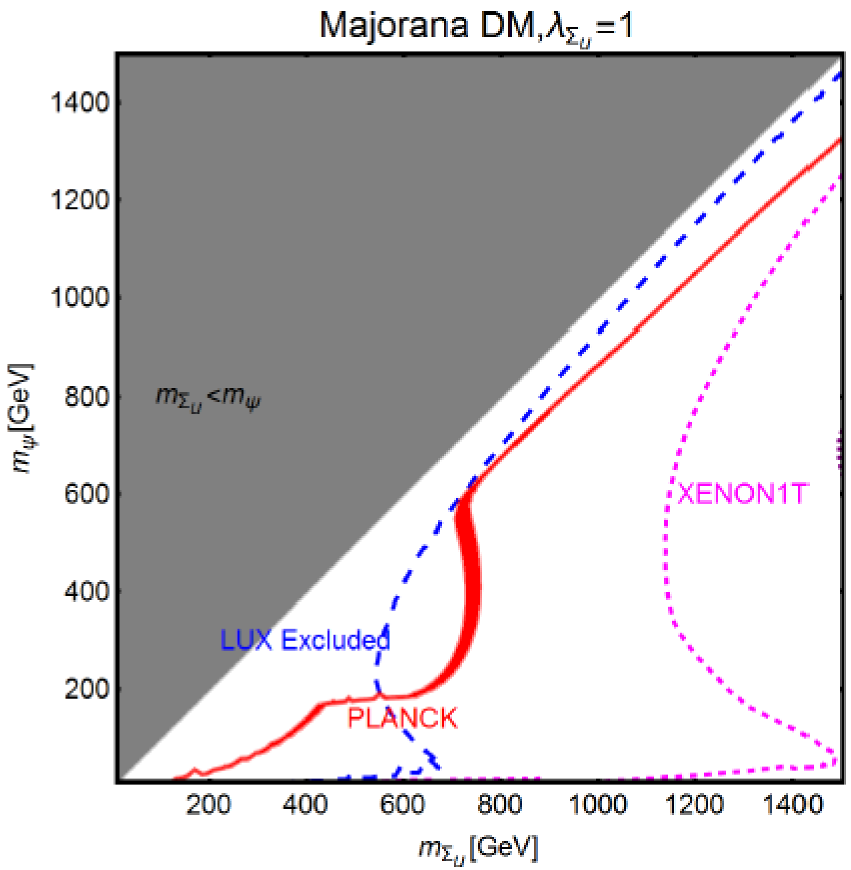
$$\mathcal{L} = -\lambda_{\Sigma_q} \overline{\psi} \Sigma_q q_R + h.c.$$

Mediator is (partially) charged under the SM group. Possible complementarity with LHC.

Dark Matter stable only if lighter than the mediator.

Coannihilations possibly relevant for the relic density.


Dirac DM,λ_{Σ_u}=1
PLANCK
XENON1T
LZ
LUX Excluded
2000
1500
1000
500
m_ψ[GeV]
0
5000
10 000
15 000
20 000
m_{Σ_u}[GeV]


Majorana DM,λ_{Σ_u}=1
$m_{\Sigma_u}<m_\psi$
XENON1T
LUX Excluded
PLANCK
1400
1200
1000
800
600
400
200
m_ψ[GeV]
200
400
600
800
1000
1200
1400
m_{Σ_u}[GeV]

Conclusions

We have provided an overview of current and next generation Direct Detection facilities of probing the WIMP hypothesis.

Simplest realizations suffer increasing experimental pressure.

Definite statements require to go beyond the ‘simplified models’ level.