University of Messina and INFN Catania

Update on Wimp Models with Loop Induced Direct Detection cross-section

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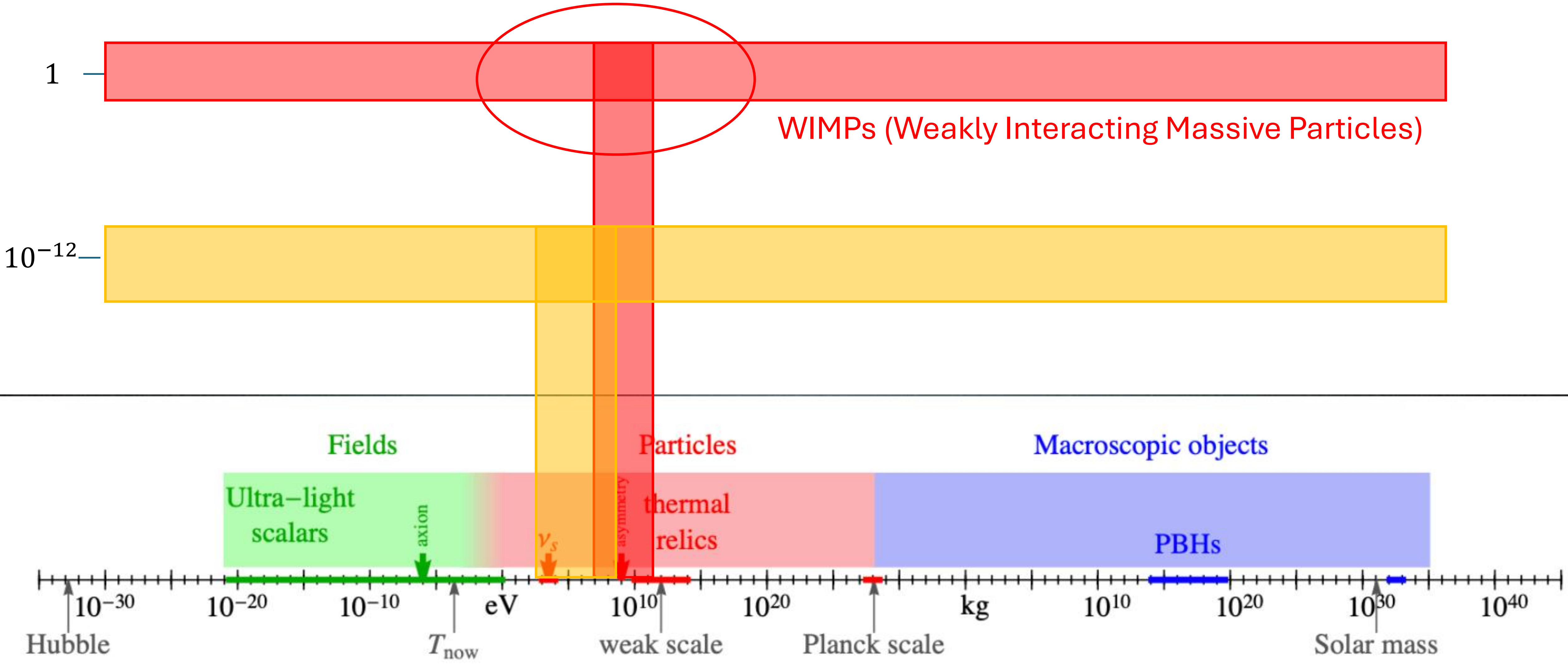
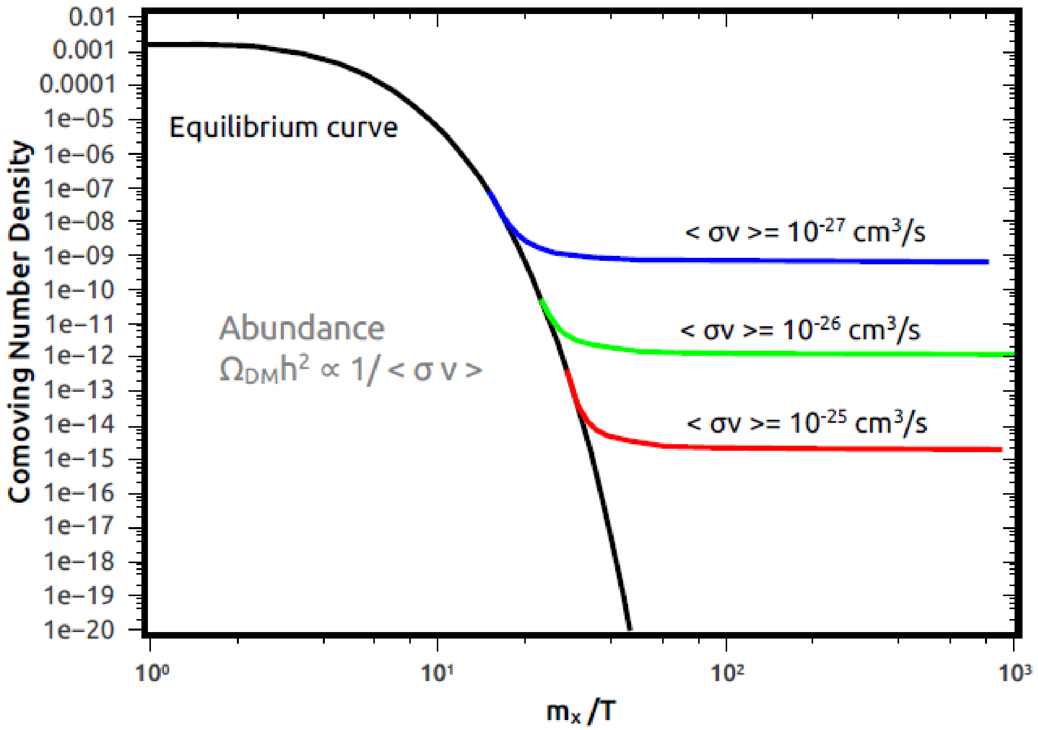
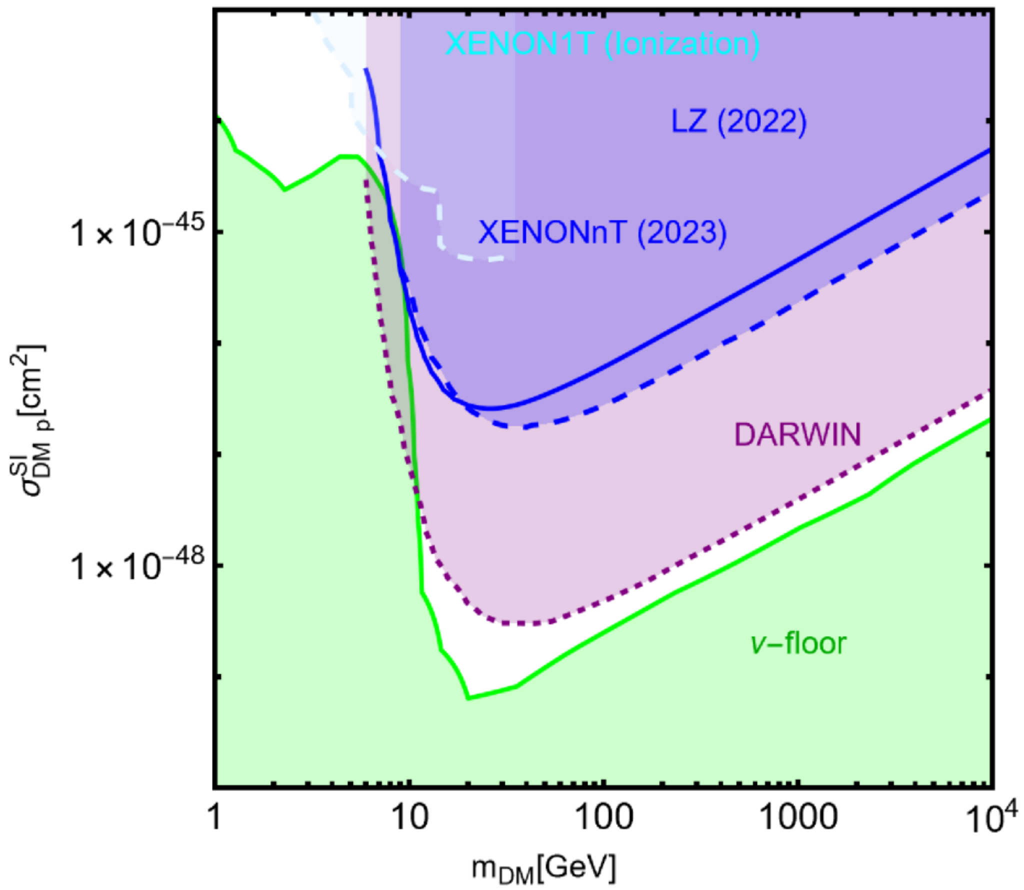
Landscape of Particle DM



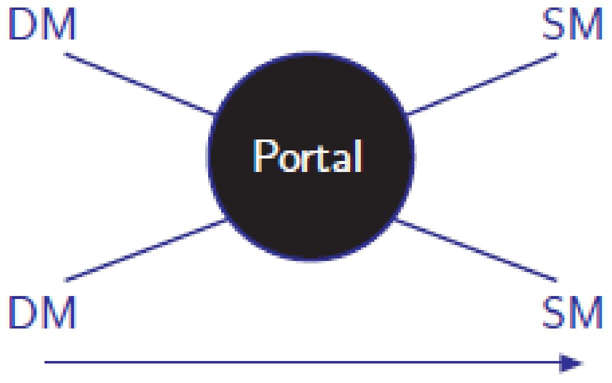
(Slide inspired from Marco Cirelli's talk at TAUP2023)

Relic Density vs DD

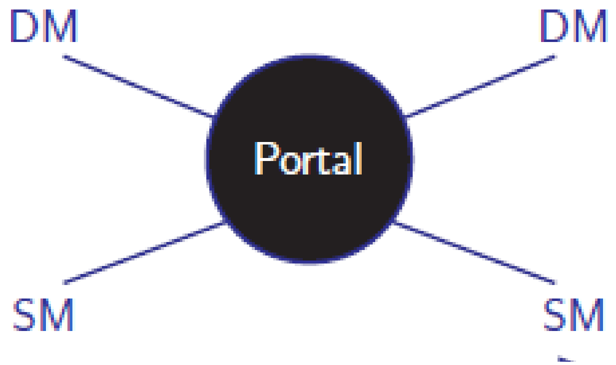




In most WIMP models DM annihilation cross-section (relic density (ID)) and scattering cross-section (DD) are related by cross-symmetric Feynman Diagrams.



Relic Density



Direct Dection

Very strong experimental constraints
(see e.g. G.A. et al 2403.15860)

Case of study: Model with relic density at tree level and DD cross-section at one-loop.

t-channel Portals

Built from Yukawa-type interactions between a DM candidate, an extra BSM states and a SM fermion. Interactions dictated by gauge invariance.

Scalar DM+ Fermion mediator

$$L_{scalar} = \Gamma_L^{f_i} \bar{f}_i P_R \Psi_{f_i} \phi_{DM} + \Gamma_R^{f_i} \bar{f}_i P_L \Psi_{f_i} \phi_{DM} + h.c. + \lambda_{1H\phi} \left(\phi_{DM}^\dagger \phi_{DM}\right) \left(H^\dagger H\right) + \lambda_{2H\phi} \left(\phi_{DM}^\dagger T_\phi^a \phi_{DM}\right) \left(H^\dagger \frac{\sigma^a}{2} H\right)$$

Fermionic DM+ Scalar mediator

$$L_{fermion} = \Gamma_L^{f_i} \bar{f}_i P_R \Phi_{f_i} \psi_{DM} + \Gamma_R^{f_i} \bar{f}_i P_L \Phi_{f_i} \psi_{DM} + h.c. + \lambda_{1H\phi} \left(\Phi_{f_i}^\dagger \Phi_{f_i}\right) \left(H^\dagger H\right) + \lambda_{2H\phi} \left(\Phi_{f_i}^\dagger T_\phi^a \Phi_{f_i}\right) \left(H^\dagger \frac{\sigma^a}{2} H\right)$$

$$\langle\sigma v\rangle_{eff} = \frac{1}{2}\langle\sigma v\rangle_{DM\,DM}\frac{g_{DM}^2}{g_{eff}^2} + \langle\sigma v\rangle_{DM\,M}\frac{g_{DM}g_M}{g_{eff}^2}\left(1+\widetilde{\Delta}\right)^{3/2}\exp\left[-x\widetilde{\Delta}\right] + \frac{1}{2}\langle\sigma v\rangle_{M^\dagger M}\frac{g_M^2}{g_{eff}^2}\left(1+\widetilde{\Delta}\right)^3\exp\left[-2x\widetilde{\Delta}\right]$$

$$\widetilde{\Delta} = \frac{M_M - M_{DM}}{M_{DM}}$$

$$\langle\sigma v\rangle_{Complex\ DM} = \sum_f N_c^f \frac{\left|\Gamma_{L,R}^f\right|^4 M_{\phi_{DM}}^2 v^2}{48\pi\left(M_{\phi_{DM}}^2 + M_{\psi_f}^2\right)^2}$$

$$\langle\sigma v\rangle_{Dirac\ DM} = \sum_f N_c^f \frac{\left|\Gamma_{L,R}^f\right|^4 M_{\psi_{DM}}^2}{32\pi\left(M_{\psi_{DM}}^2 + M_{\phi_f}^2\right)^2}$$

$$\langle\sigma v\rangle_{Real\ Scalar\ DM} = \sum_f N_c^f \frac{\left|\Gamma_{L,R}^f\right|^4 M_{\phi_{DM}}^6 v^4}{60\pi\left(M_{\phi_{DM}}^2 + M_{\psi_f}^2\right)^4}$$

$$\langle\sigma v\rangle_{Majorana\ DM} = \sum_f N_c^f \frac{\left|\Gamma_{L,R}^f\right|^4 M_{\psi_{DM}}^2\left(M_{\psi_{DM}}^4 + M_{\phi_f}^4\right) v^2}{48\pi\left(M_{\psi_{DM}}^2 + M_{\phi_f}^2\right)^4}$$

DD of Scalar DM

$$L_{scalar} = \Gamma_L^{f_i} \bar{f}_i P_R \Psi_{f_i} \phi_{DM} + \Gamma_R^{f_i} \bar{f}_i P_L \Psi_{f_i} \phi_{DM} + h.c. + \lambda_{1H\phi} \left(\phi_{DM}^\dagger \phi_{DM}\right)\left(H^\dagger H\right) + \lambda_{2H\phi} \left(\phi_{DM}^\dagger T_\phi^a \phi_{DM}\right)\left(H^\dagger \frac{\sigma^a}{2} H\right)$$

Non-relativistic Limit

Absent for real scalar DM

$$L_{eff}^{Scalar,q} = \sum_{q=u,d} c^q \left(\phi_{DM}^\dagger i\overleftrightarrow{\partial}_\mu \phi_{DM}\right) \bar{q}\gamma^\mu q + \sum_{q=u,d,s} d^q m_q \phi_{DM}^\dagger \phi_{DM} \bar{q} q + d^g \frac{\alpha_s}{\pi} \phi_{DM}^\dagger \phi_{DM} G^{a\mu\nu} G_{\mu\nu}^a + \sum_{q=u,d,s} \frac{g_1^q}{M_{\phi_{DM}}^2} \phi^\dagger (i\partial^\mu)(i\partial^\nu)\, \phi_{DM} O_{\mu\nu}^q + \frac{g_1^g}{M_{\phi_{DM}}^2} \phi_{DM}^\dagger (i\partial^\mu)(i\partial^\nu) \phi_{DM} O_{\mu\nu}^g$$

DD for fermionic DM

$$L_{fermion} = \Gamma_L^{f_i} \bar{f}_i P_R \Phi_{f_i} \psi_{DM} + \Gamma_R^{f_i} \bar{f}_i P_L \Phi_{f_i} \psi_{DM} + h.c. + \lambda_{1H\phi} \left(\Phi_{f_i}^\dagger \Phi_{f_i}\right) \left(H^\dagger H\right) + \lambda_{2H\phi} \left(\Phi_{f_i}^\dagger T_\phi^a \Phi_{f_i}\right) \left(H^\dagger \frac{\sigma^a}{2} H\right)$$

Absent for Majorana DM

Responsible for SD interactions

$$L_{eff}^{fermion,q} = \sum_{q=u,d} c^q \bar{\psi}_{DM} \gamma_\mu \psi_{DM} \bar{q} \gamma^\mu q + \sum_{q=u,d,s} \tilde{c}^q \bar{\psi}_{DM} \gamma_\mu \gamma_5 \psi_{DM} \bar{q} \gamma^\mu \gamma_5 q + \sum_{q=u,d,s} d^q m_q \bar{\psi}_{DM} \psi_{DM} \bar{q} q + \sum_{q=c,b,t} d^{g,q} \bar{\psi}_{DM} \psi_{DM} G^{a\mu\nu} G_{\mu\nu}^a$$

$$+ \sum_{q=u,d,s} \left(g_1^q \frac{\bar{\psi}_{DM} i\partial^\mu \gamma^\nu O_{\mu\nu}^q}{M_{\psi_{DM}}} + g_2^q \frac{\bar{\psi}_{DM} (i\partial^\mu)(i\partial^\nu) \psi_{DM} O_{\mu\nu}^g}{M_{\psi_{DM}}^2} \right)$$

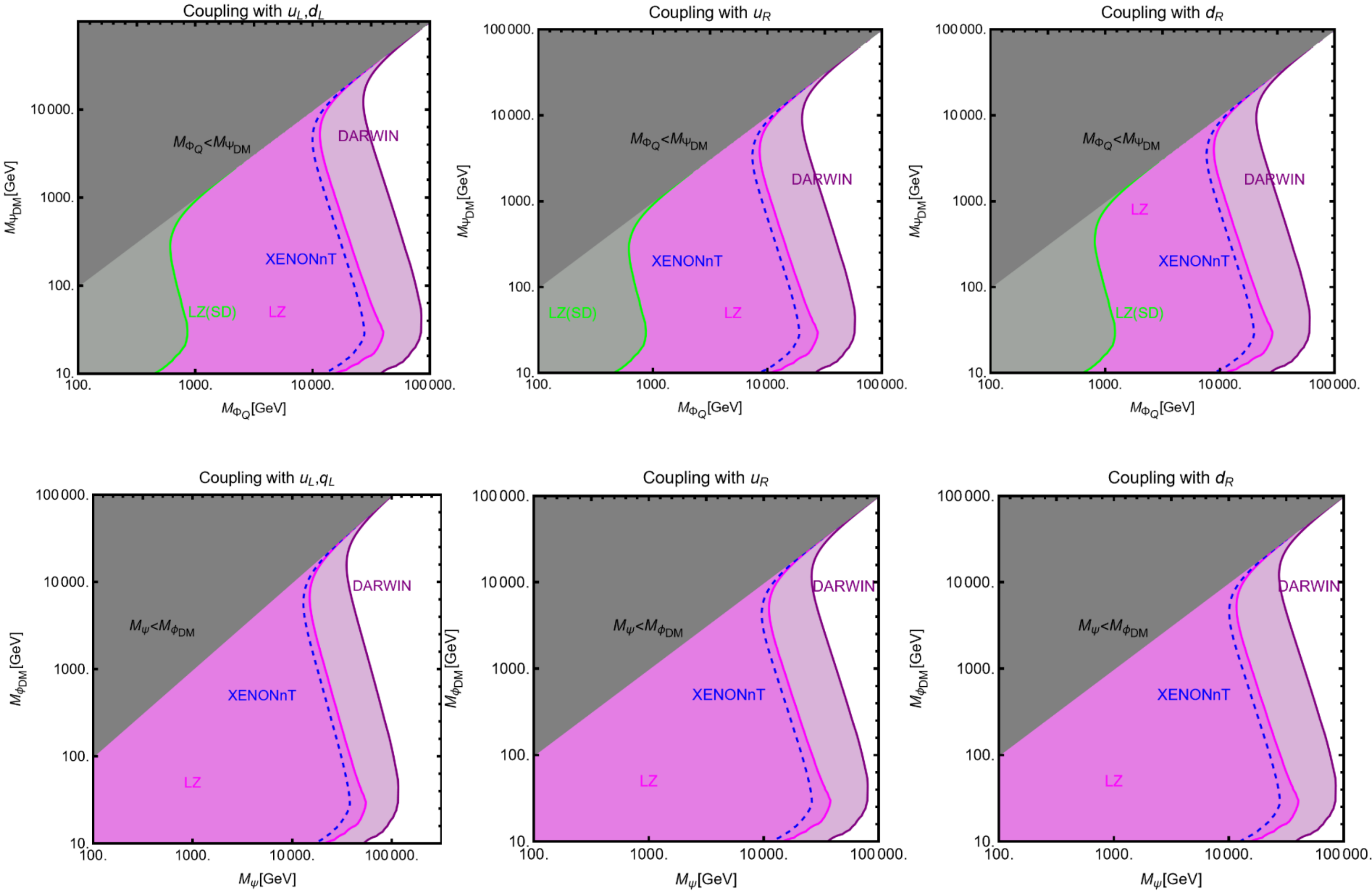
$$+ \sum_{q=c,b,t} \left(g_1^{g,q} \frac{\bar{\psi}_{DM} i\partial^\mu \gamma^\nu \psi_{DM} O_{\mu\nu}^g}{M_{\psi_{DM}}} + g_2^{g,q} \frac{\bar{\psi}_{DM} (i\partial^\mu)(i\partial^\nu) \psi_{DM} O_{\mu\nu}^g}{M_{\psi_{DM}}^2} \right) + \frac{\tilde{b}_\psi}{2} \bar{\psi}_{DM} \sigma^{\mu\nu} \psi_{DM} F_{\mu\nu} + b_\psi \bar{\psi}_{DM} \gamma^\mu \psi_{DM} \partial^\nu F_{\mu\nu}$$

Direct Detection

Complex scalar and Dirac DM interact at tree level with first generation quarks.

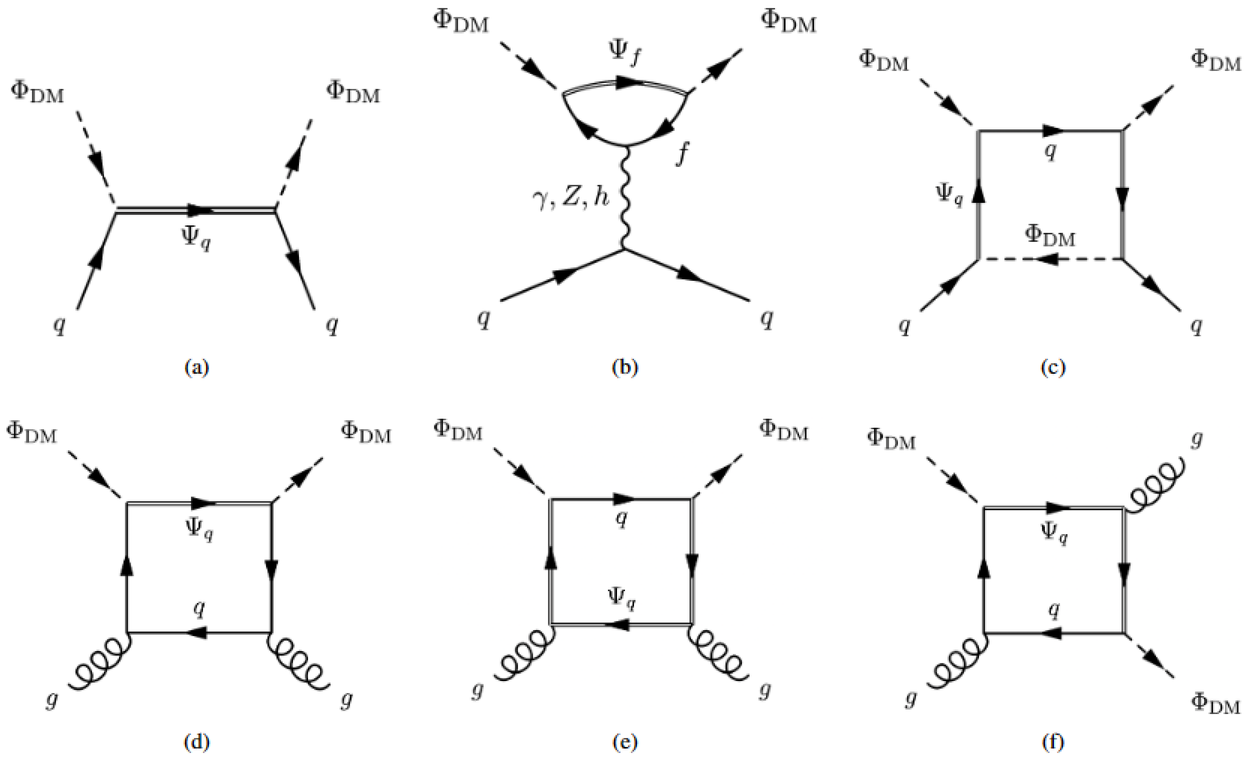
$$c^q \bar{\psi}_{DM} \gamma_\mu \psi_{DM} \bar{q} \gamma^\mu q$$

$$c^q \left(\phi_{DM}^\dagger i \overleftrightarrow{\partial}_\mu \phi_{DM} \right) \bar{q} \gamma^\mu q$$

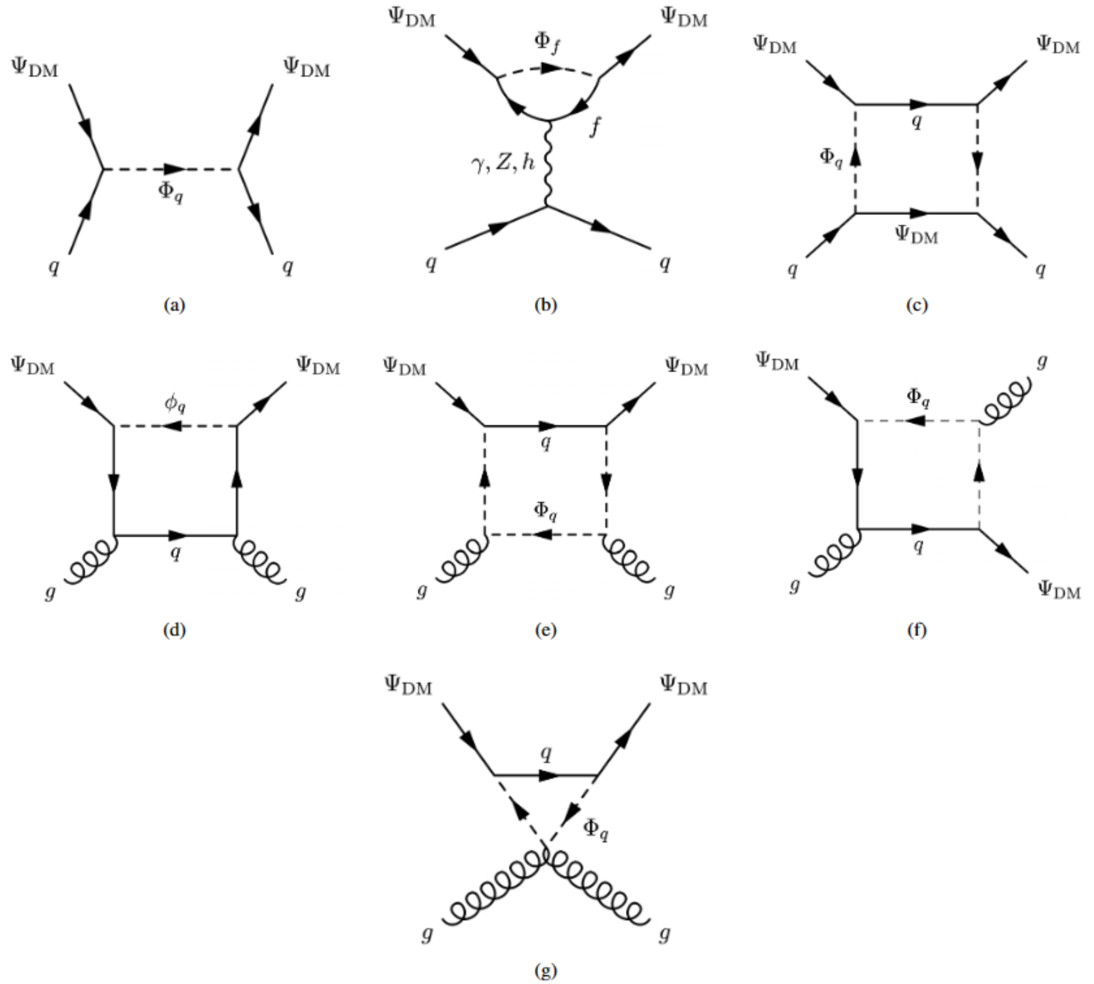


Other interactions arise at one-loop

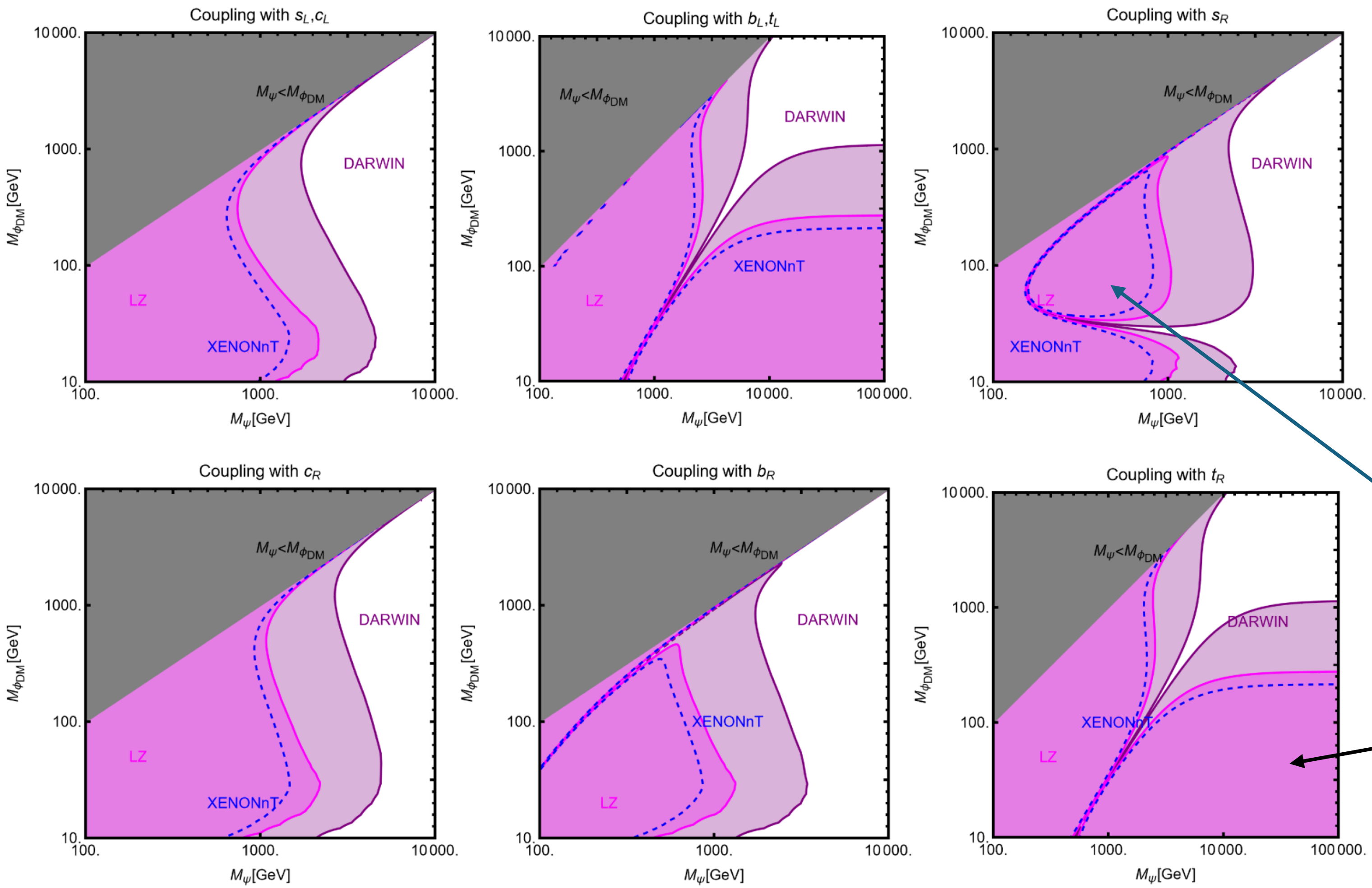
Scalar DM

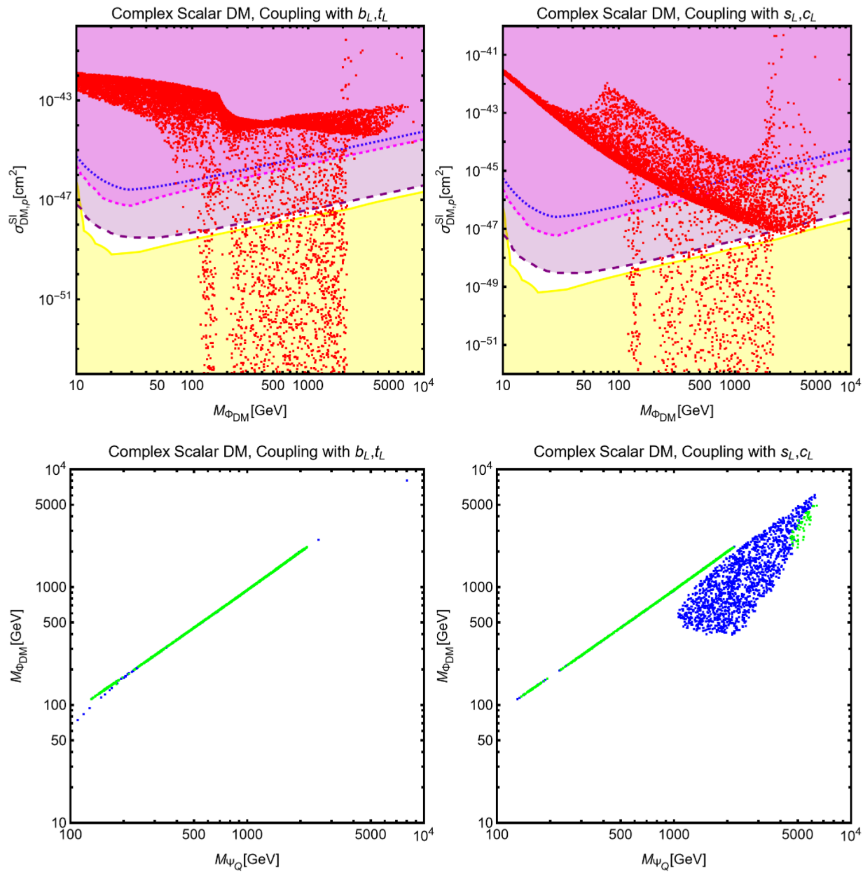


Fermionic DM

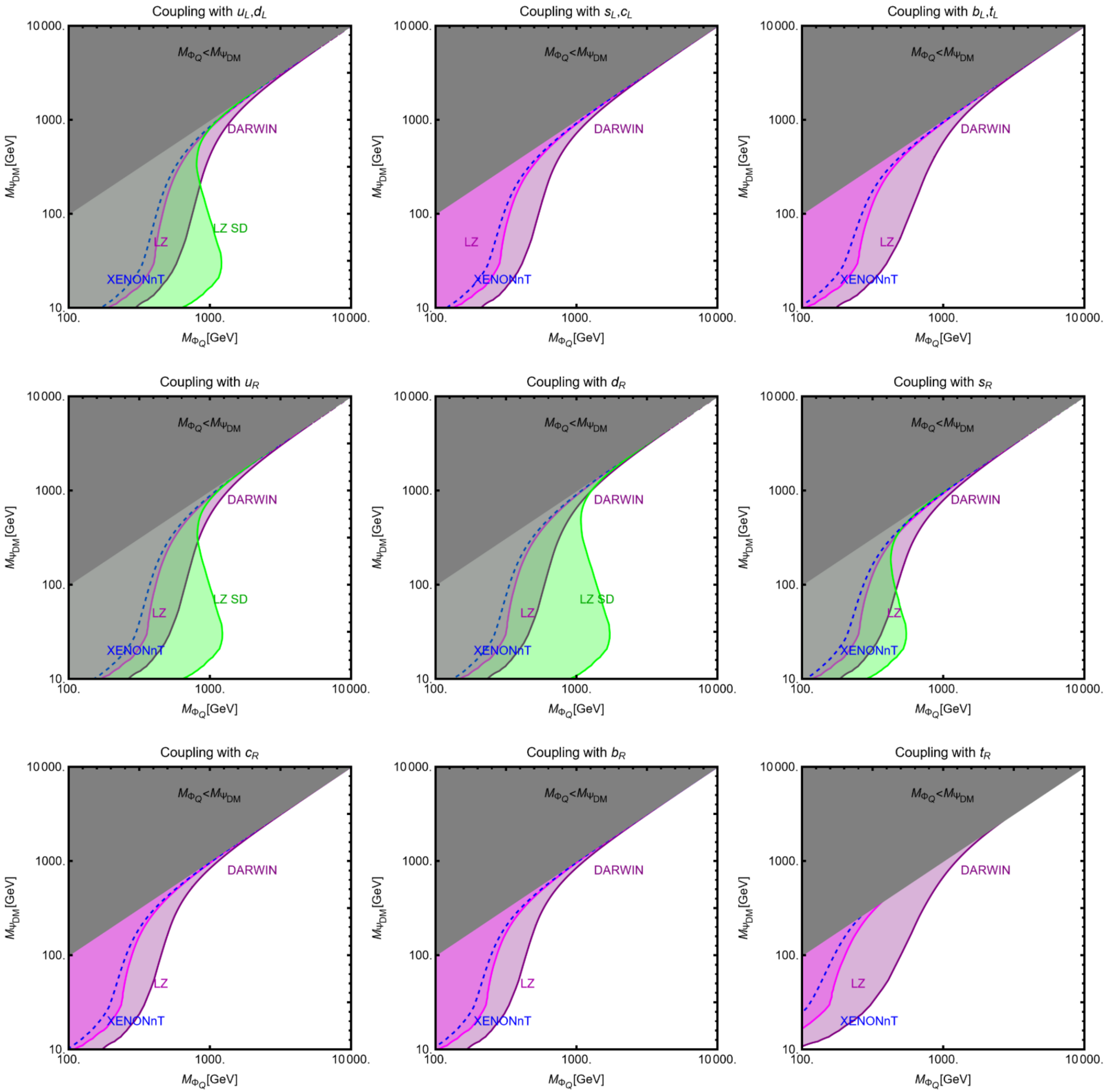


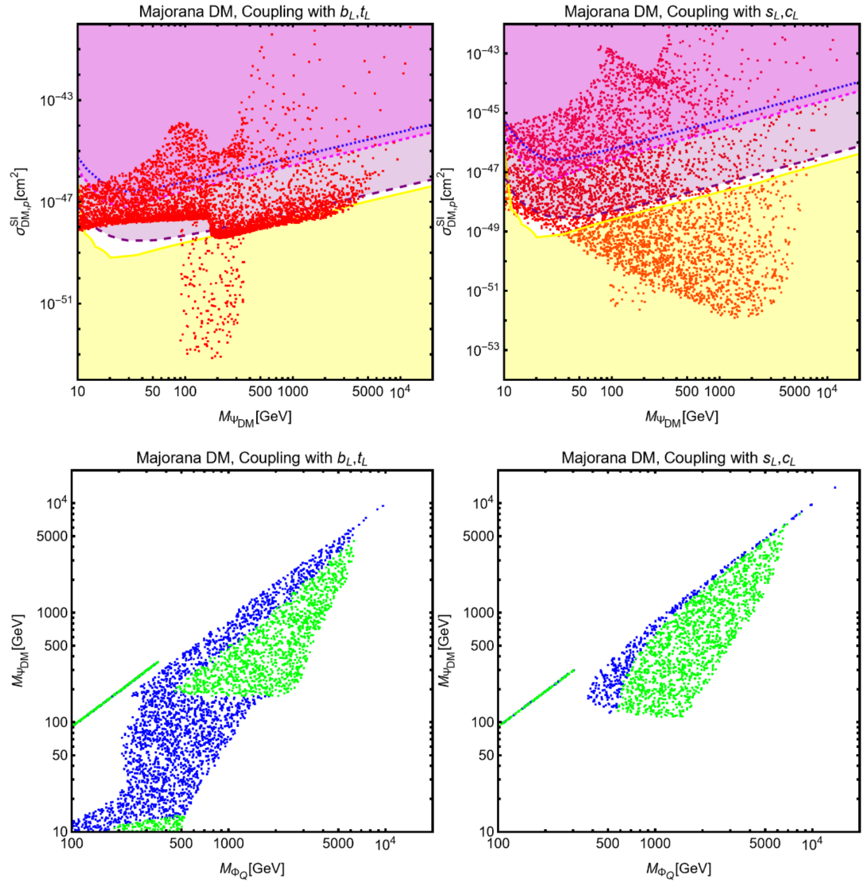
Complex Scalar DM coupled with 2°/3° generation quarks.





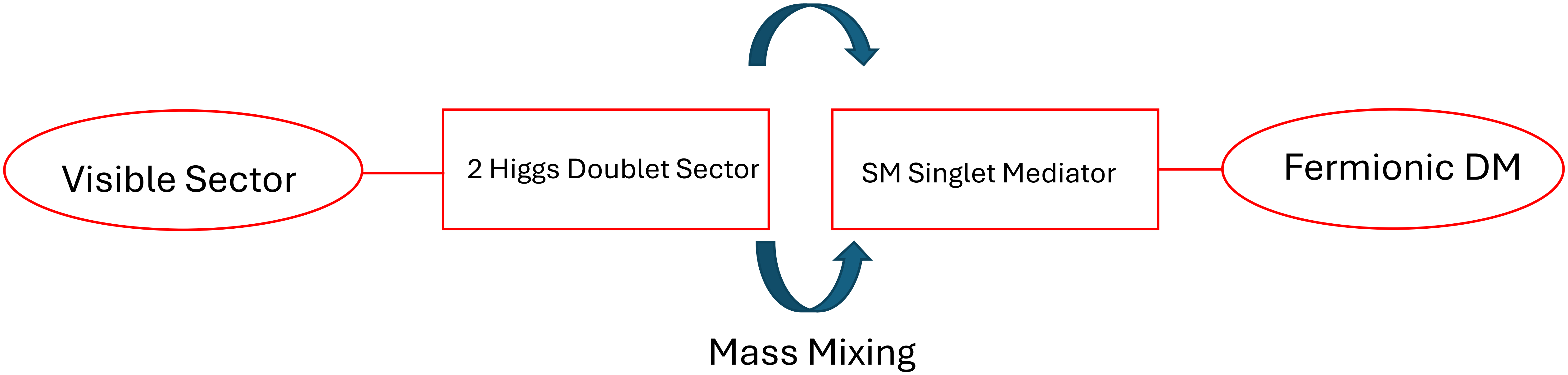
Strong constraints from the radiative Higgs portal





Majorana DM appears to be the favoured scenario as it features suppressed enough SI/SD interactions and, at the same time, enough efficient annihilation processes to ensure the correct relic density over large portions of the parameter space.

2HDM+a


Visible Sector
2 Higgs Doublet Sector
SM Singlet Mediator
Fermionic DM
Mass Mixing

Conventional (Z_2 symmetric)2HDM Potential

$$V_{2HDM} = m_1^2\phi_1^\dagger\phi_1 + m_2^2 m_1^2\phi_2^\dagger\phi_2 - m_3^2\left(\phi_1^\dagger\phi_2 + h.c.\right) + \frac{1}{2}\lambda_1\left(\phi_1^\dagger\phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\phi_2^\dagger\phi_2\right)^2 + \frac{1}{2}\lambda_5\left(\left(\phi_1^\dagger\phi_2\right)^2 + h.c.\right)$$
$$+\lambda_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \lambda_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right)$$

$$V(\Phi_1, \Phi_2, a_0) = V_{2HDM}(\phi_1, \phi_2) + V_{self}(a_0) + V_{a_0,2HDM}(\phi_1, \phi_2, a_0)$$

Self Interaction lagrangian

$$V_{self}(a_0) = \frac{1}{2}m_{a_0}^2 a_0^2 + \frac{1}{4}\lambda_a a_0^4$$

Singlet Doublet Interaction Lagrangian

$$V_{a_0,2HDM}(\phi_1, \phi_2, a_0) = \kappa\left(i\, a_0\phi_1^\dagger\phi_2 + h.c.\right) + \lambda_{1P} a_0^2\phi_1^\dagger\phi_1 + \lambda_{2P} a_0^2\phi_2^\dagger\phi_2$$

EW Symmetry Breaking

$$\langle \phi_1 \rangle = v_1$$

$$\langle \phi_2 \rangle = v_2$$

$$\frac{v_2}{v_1} = tan\beta$$

$$(\phi_1, \phi_2, a_0) \longrightarrow (h, a, H, A, H^{\pm})$$

Mixing between pseudoscalar states

$$\begin{pmatrix} A^0 \\ a^0 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix}$$

$$L_{Yuk} = \sum_f \frac{m_f}{v} [g_{hff} h\bar{f}f + g_{Hff} H\bar{f}f - i g_{aff} a\bar{f}\gamma_5 f - i g_{Aff} A\bar{f}\gamma_5 f]$$

$$g_{hff} = 1 \qquad g_{Aff} = cos\theta\, g_{A^0ff}$$

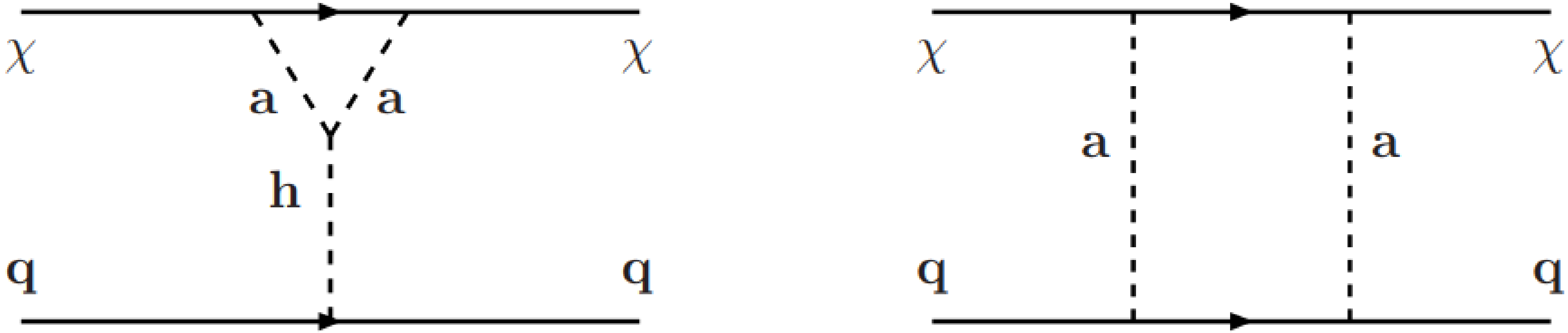
$$g_{aff} = sin\theta\, g_{A^0ff}$$

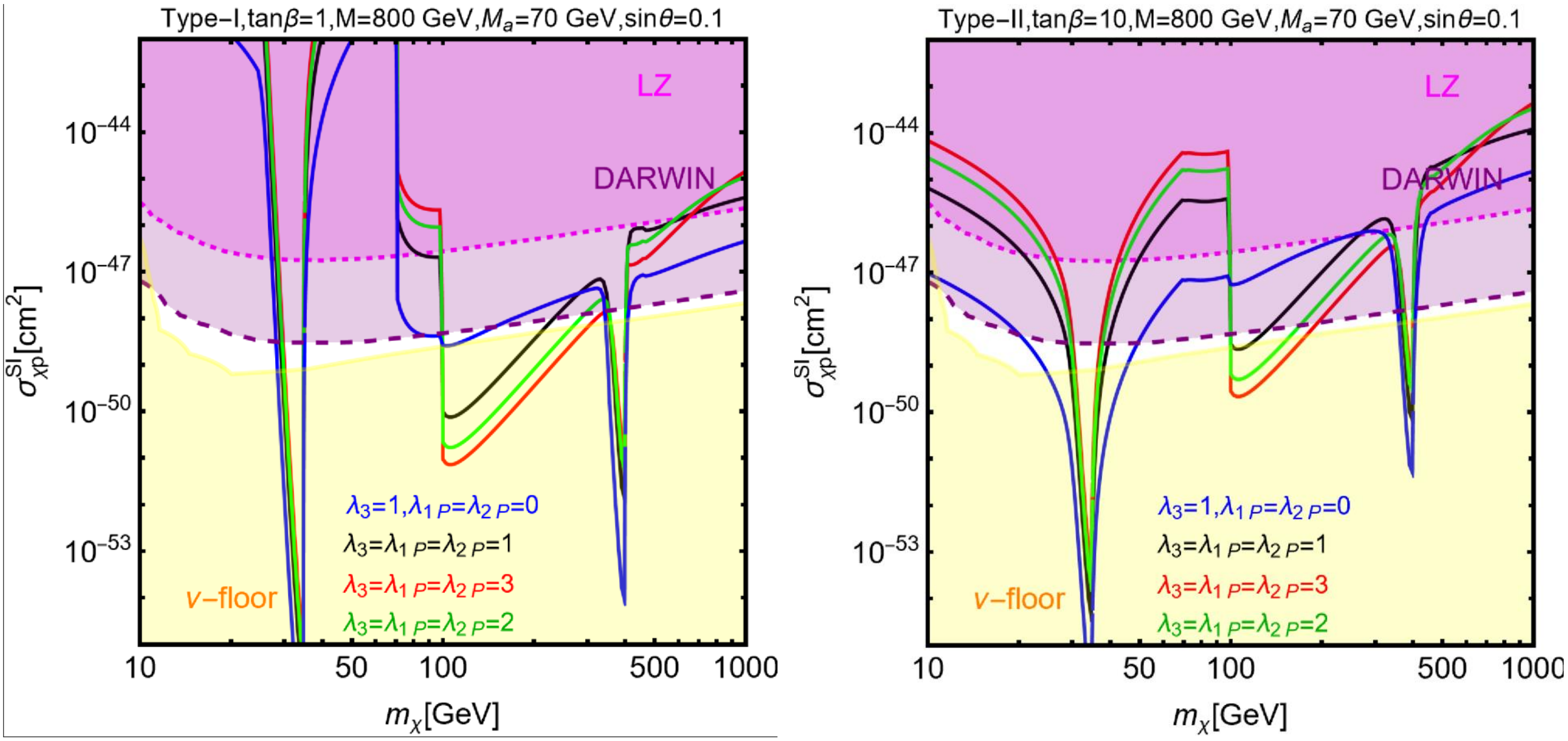
	Type I	Type II	Type X	Type Y
g_{htt}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$
g_{hbb}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$
$g_{h\tau\tau}$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$
g_{Htt}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$
g_{Hbb}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$
$g_{H\tau\tau}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$
g_{A^0tt}	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$
g_{A^0bb}	$-\frac{1}{\tan\beta}$	$\tan\beta$	$-\frac{1}{\tan\beta}$	$\tan\beta$
$g_{A^0\tau\tau}$	$-\frac{1}{\tan\beta}$	$\tan\beta$	$\tan\beta$	$-\frac{1}{\tan\beta}$

At tree level:

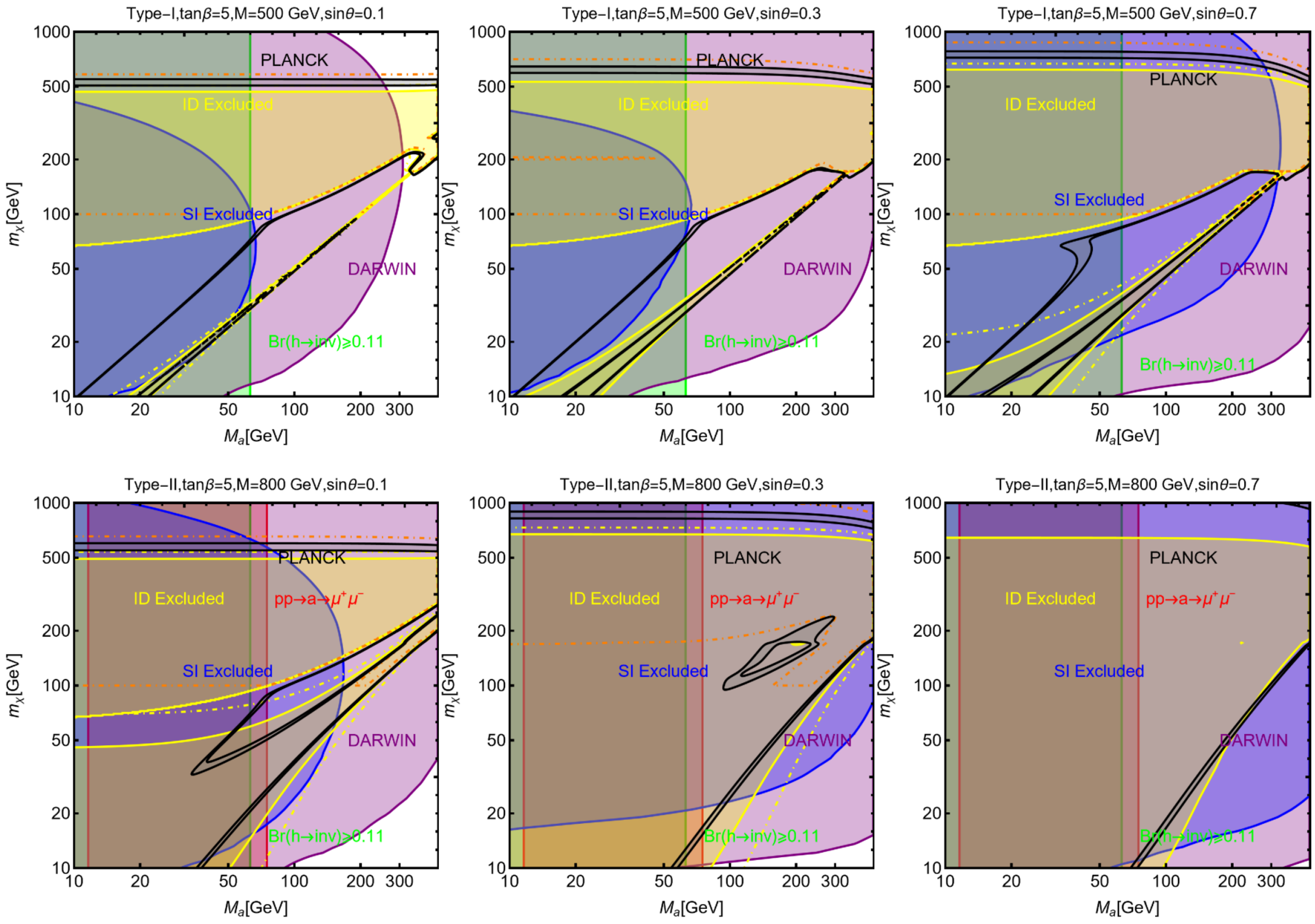
$$\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{f}\gamma_{\mu}\gamma_5 f \longrightarrow (\sigma_N\cdot\vec{q})(\sigma_\chi\cdot\vec{q}) \longrightarrow \frac{d\sigma}{dE_R}=\frac{g_\chi^2}{128\pi}\frac{q^4}{m_a^4}\frac{m_T^2}{m_\chi m_N}\frac{1}{v_E^2}\sum_{N.N'=p,n} g_N g_{N'} F_{\Sigma''}^{NN'}(q^2)$$

SI Cross section at loop level





Type−I,tanβ=1,M=800 GeV,M_a=70 GeV,sinθ=0.1
LZ
DARWIN
ν−floor
$\lambda_3=1,\lambda_{1P}=\lambda_{2P}=0$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=1$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=3$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=2$
$\sigma^{SI}_{\chi p}$[cm^2]
m_χ[GeV]
Type−II,tanβ=10,M=800 GeV,M_a=70 GeV,sinθ=0.1
LZ
DARWIN
ν−floor
$\lambda_3=1,\lambda_{1P}=\lambda_{2P}=0$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=1$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=3$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=2$
$\sigma^{SI}_{\chi p}$[cm^2]
m_χ[GeV]



Type−I,tanβ=5,M=500 GeV,sinθ=0.1
Type−I,tanβ=5,M=500 GeV,sinθ=0.3
Type−I,tanβ=5,M=500 GeV,sinθ=0.7
Type−II,tanβ=5,M=800 GeV,sinθ=0.1
Type−II,tanβ=5,M=800 GeV,sinθ=0.3
Type−II,tanβ=5,M=800 GeV,sinθ=0.7
PLANCK
ID Excluded
SI Excluded
DARWIN
Br(h→inv)≥0.11
pp→a→μ⁺μ⁻
m_χ[GeV]
M_a[GeV]

Conclusions

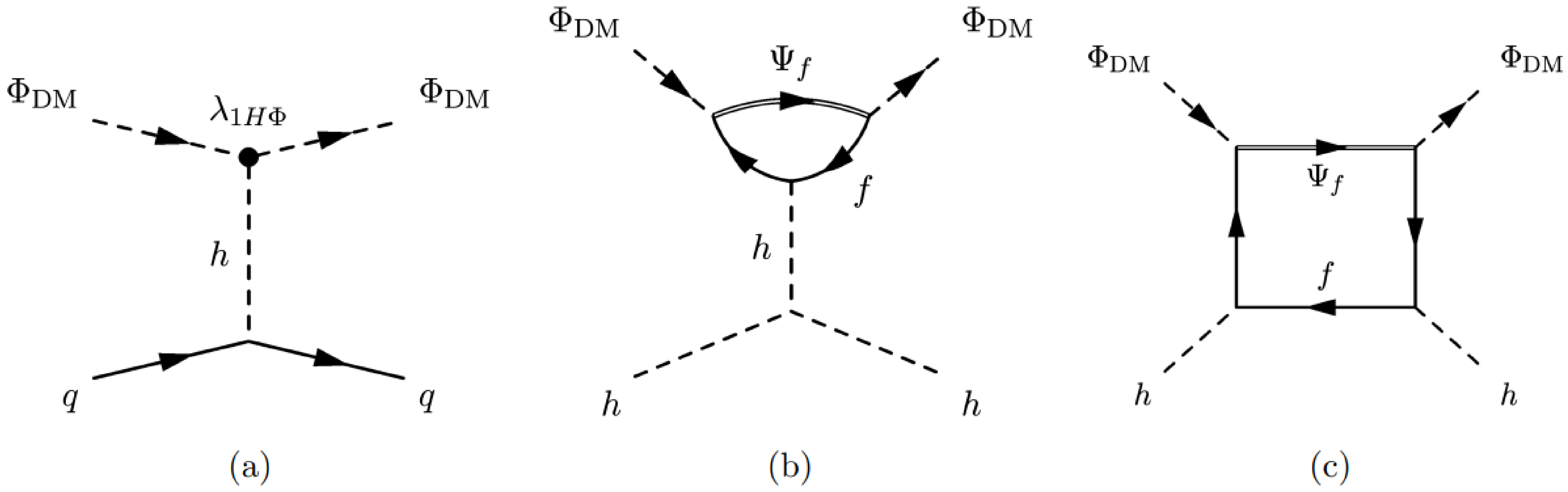
Dark Matter Direct Detection facilities have strong capability of testing WIMP models.

Models with loop-induced DD interactions are a potential benchmark for current and next generation experiments.

We have illustrated different models with potentially very suppressed cross-section but still capable of accounting for the correct DM relic density.

Back up

Radiatively induced Higgs Portal coupling



$$d_H^q = \sum_f \frac{g^2 \left|\Gamma_{L,R}^f\right|^2 M_{\psi_f}^2}{32\pi^2 m_H^2 m_W^2} F_H\left(\frac{m_f^2}{M_{\psi_f}^2}, \frac{M_{\phi_{DM}}^2}{M_{\psi_f}^2}\right)$$

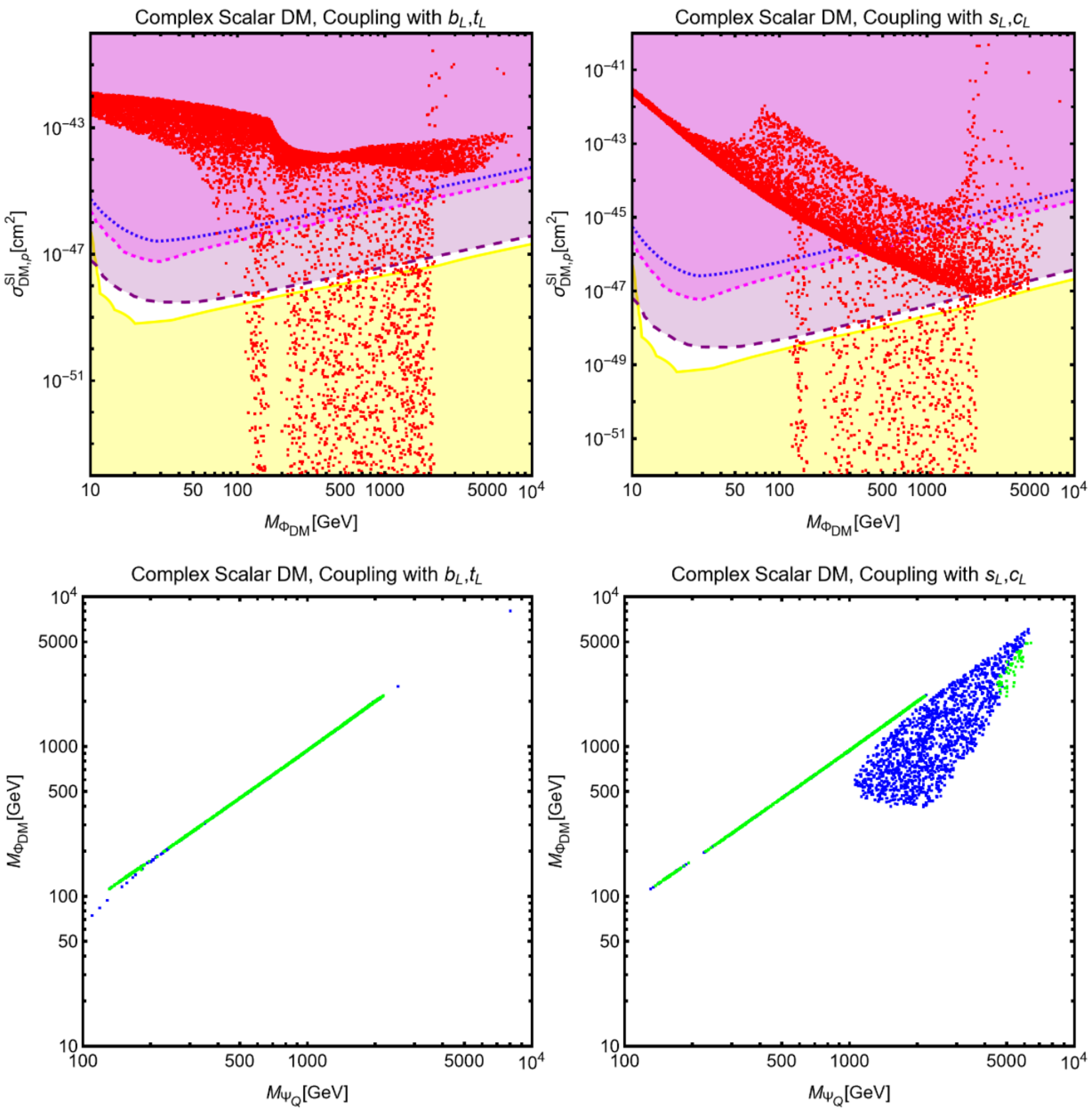
$$F_H(x_f, x_\phi) = 2x_f + 2x_f \frac{x_f^2 + (x_\phi - 1)x_\phi - x_f(1 + 2x_\phi)}{x_\phi\sqrt{\Delta}} \log\left[\frac{1 + x_f - x_\phi + \sqrt{\Delta}}{2\sqrt{x_f}}\right] + \frac{x_f(x_\phi - x_f)}{x_\phi} \log x_f + \frac{32\pi^2 m_W^2 \lambda_{1H\phi}^{(f)}(\mu)}{g^2 M_{\psi_f}^2 \left|\Gamma_{L,R}^f\right|^2} + 2x_f \log\frac{\mu^2}{m_f^2}$$

$$\lambda_{1H\phi}(\mu) = \lambda_{1H\phi}(M) - \log\frac{\mu^2}{M^2}\sum_f \frac{g^2 m_f^2 \left|\Gamma_{L,R}^f\right|^2}{16 m_W^2 \pi^2}$$

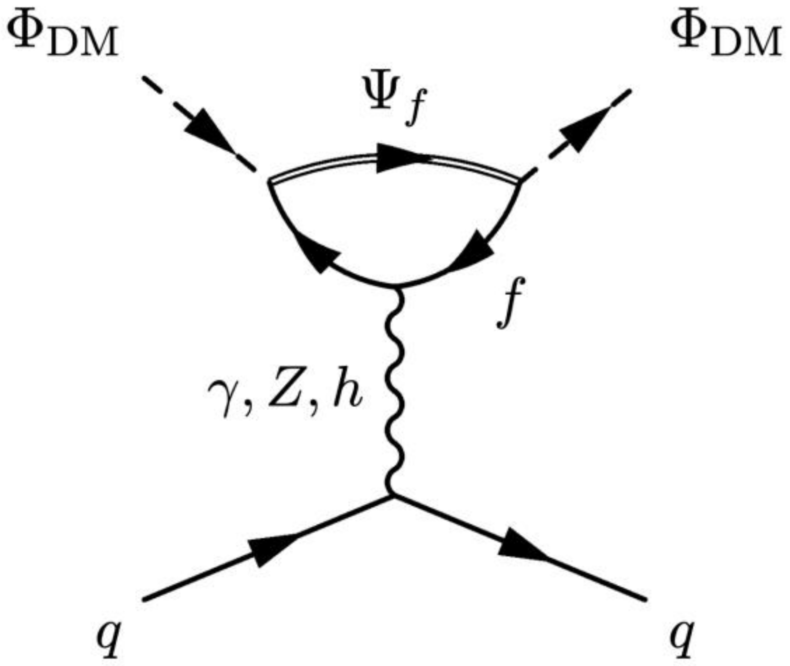
We assume

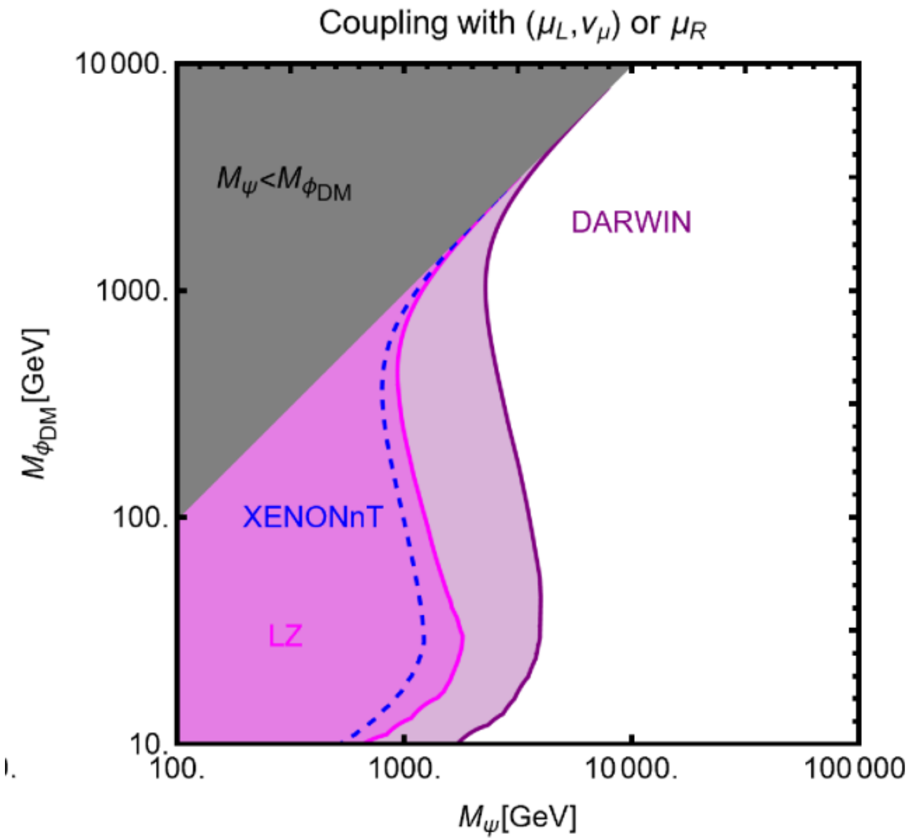
$$M = M_{\psi_f}$$

Interplay with the relic density.

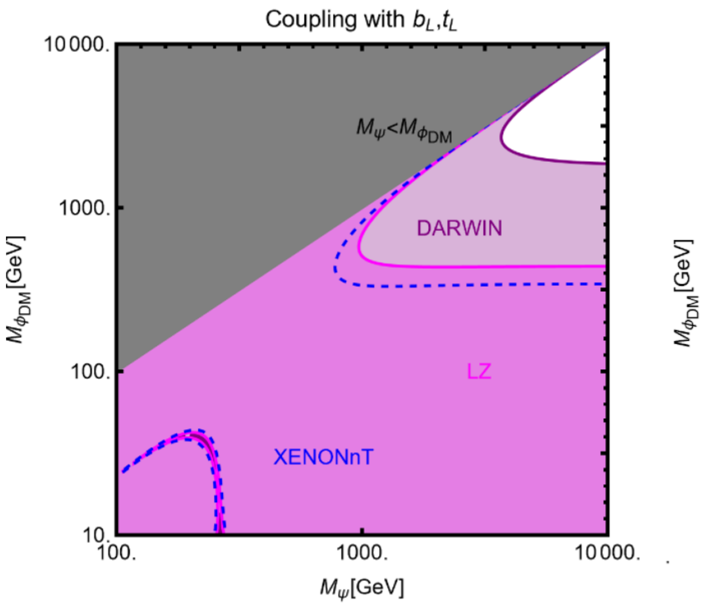


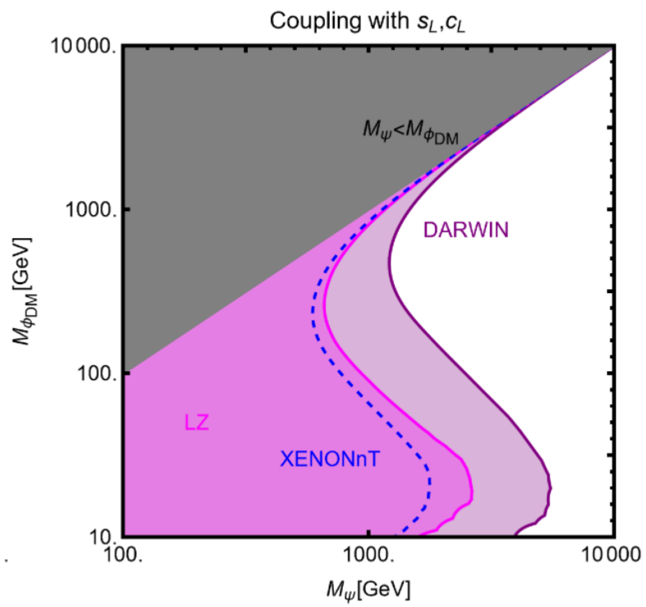
Penguin diagrams present also for couplings with leptons.



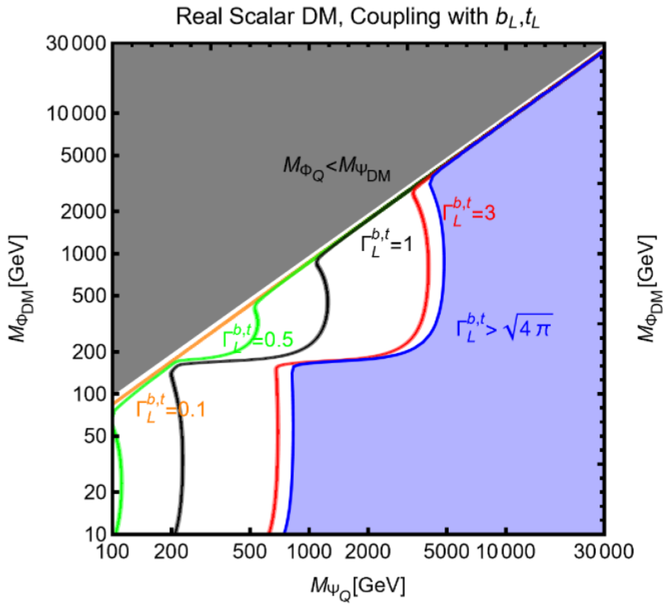


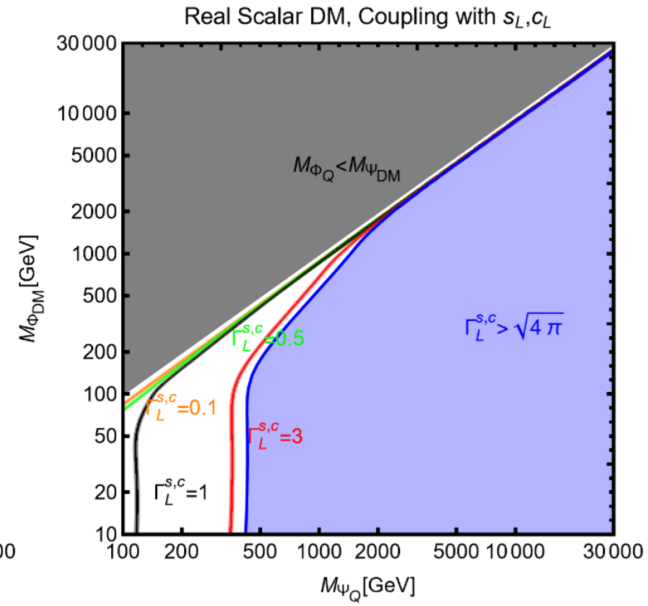
DD present also for leptophilic DM.





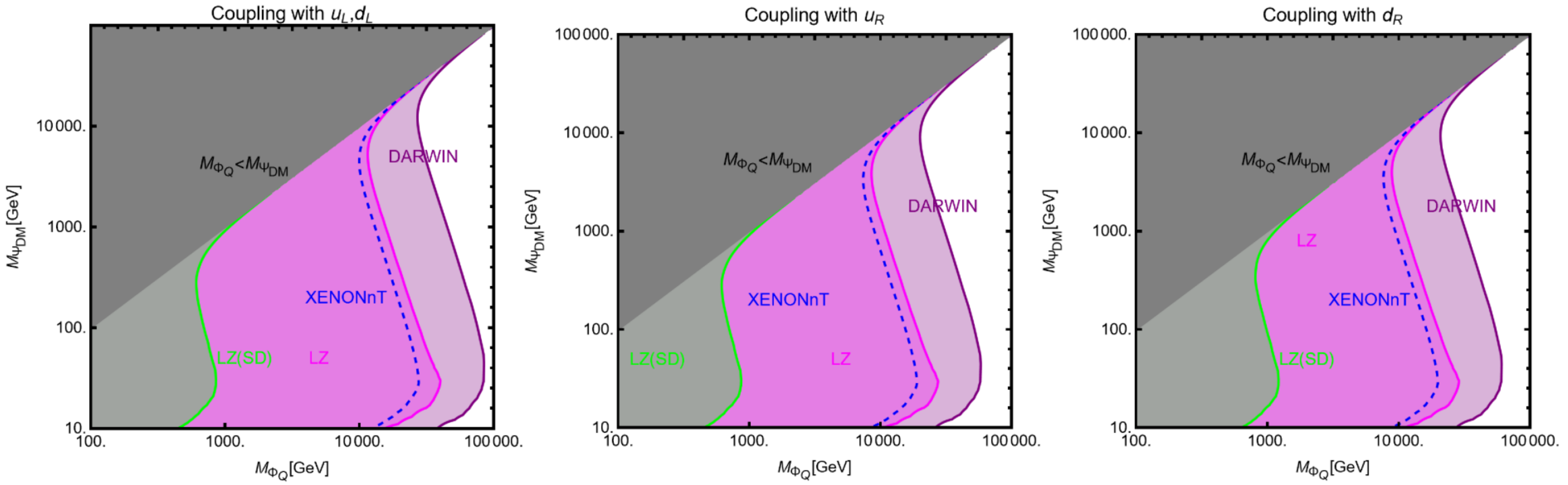
Except for couplings with top quarks real scalar DM has more suppressed DD (tree-level and penguin diagrams absent).

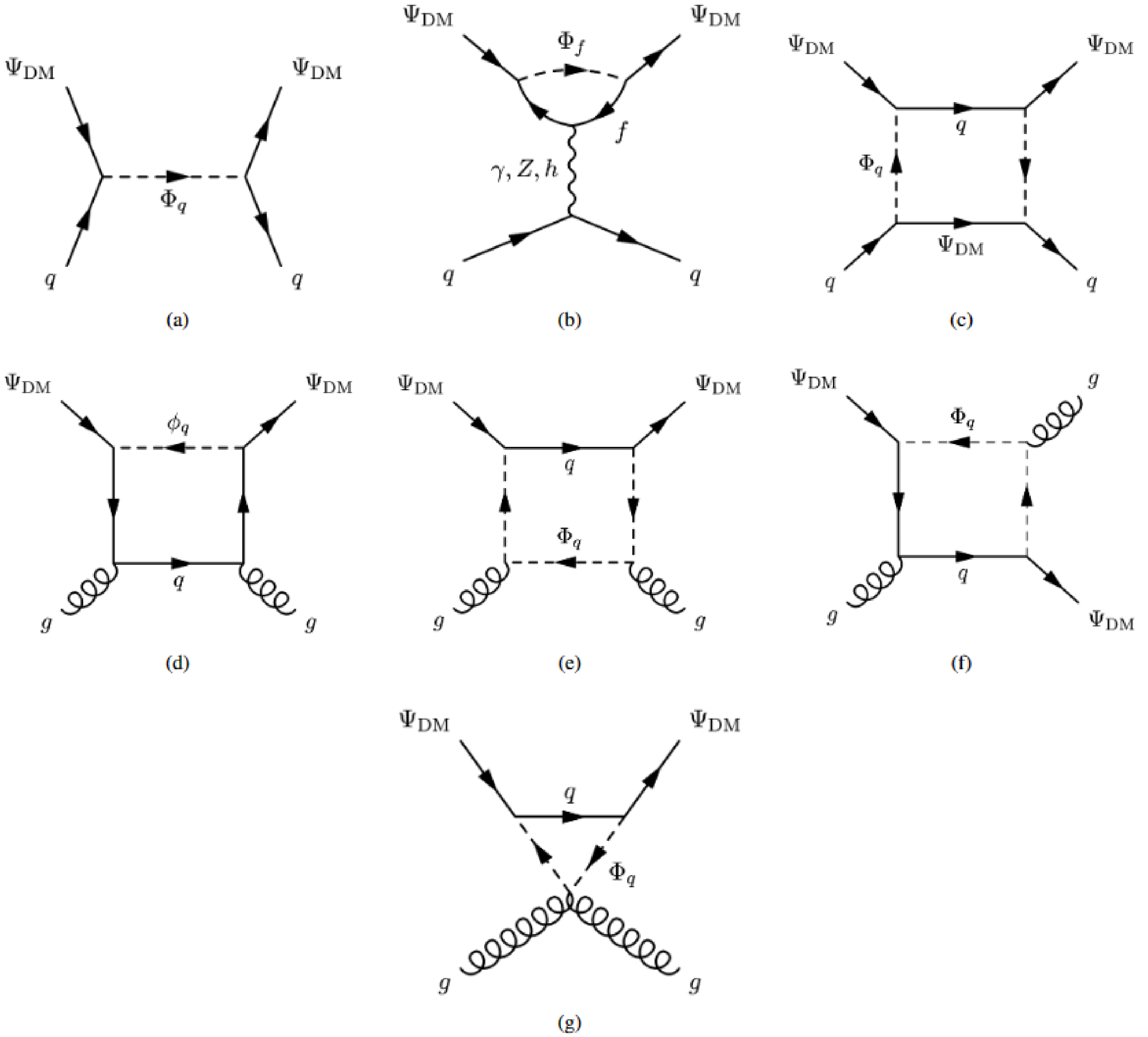




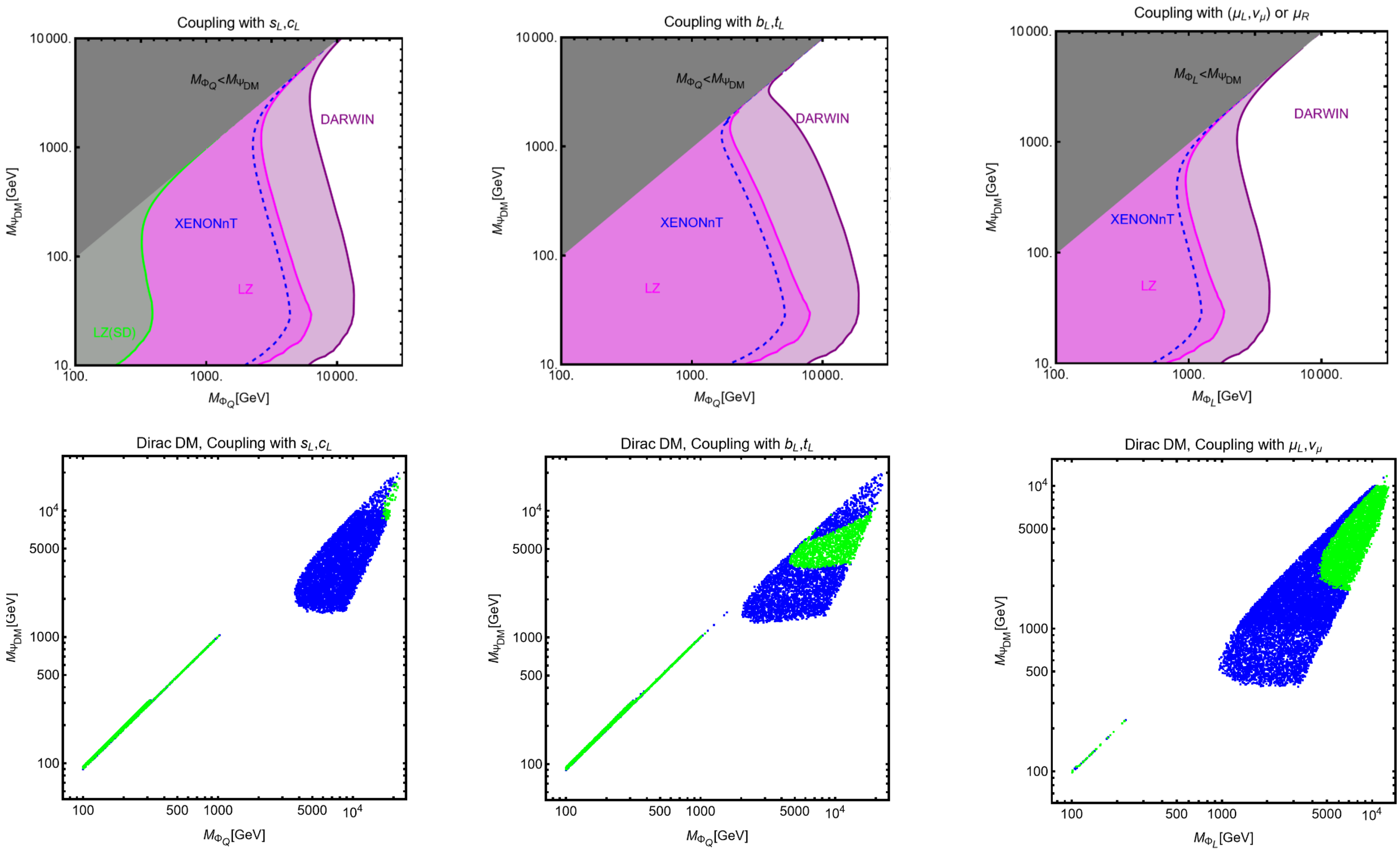
DM annihilation cross-section is, similarly, very suppressed (with exception of coupling with third generation quarks).

Couplings with first generations strongly constrained also for Dirac Dark Matter





Loop diagrams for couplings with second/third generation of quarks (and leptons).
No radiative portal induced for fermionic DM.


Coupling with s_L, c_L
$M_{\Phi_Q} < M_{\Psi_{DM}}$
DARWIN
XENONnT
LZ
LZ(SD)
$M_{\Psi_{DM}}$[GeV]
M_{Φ_Q}[GeV]
Coupling with b_L, t_L
$M_{\Phi_Q} < M_{\Psi_{DM}}$
DARWIN
XENONnT
LZ
Coupling with (μ_L, ν_μ) or μ_R
$M_{\Phi_L} < M_{\Psi_{DM}}$
DARWIN
XENONnT
LZ
M_{Φ_L}[GeV]
Dirac DM, Coupling with s_L, c_L
Dirac DM, Coupling with b_L, t_L
Dirac DM, Coupling with μ_L, ν_μ