Update on WIMP Models with loop-induced Direct Detection cross-section

Giorgio Arcadi

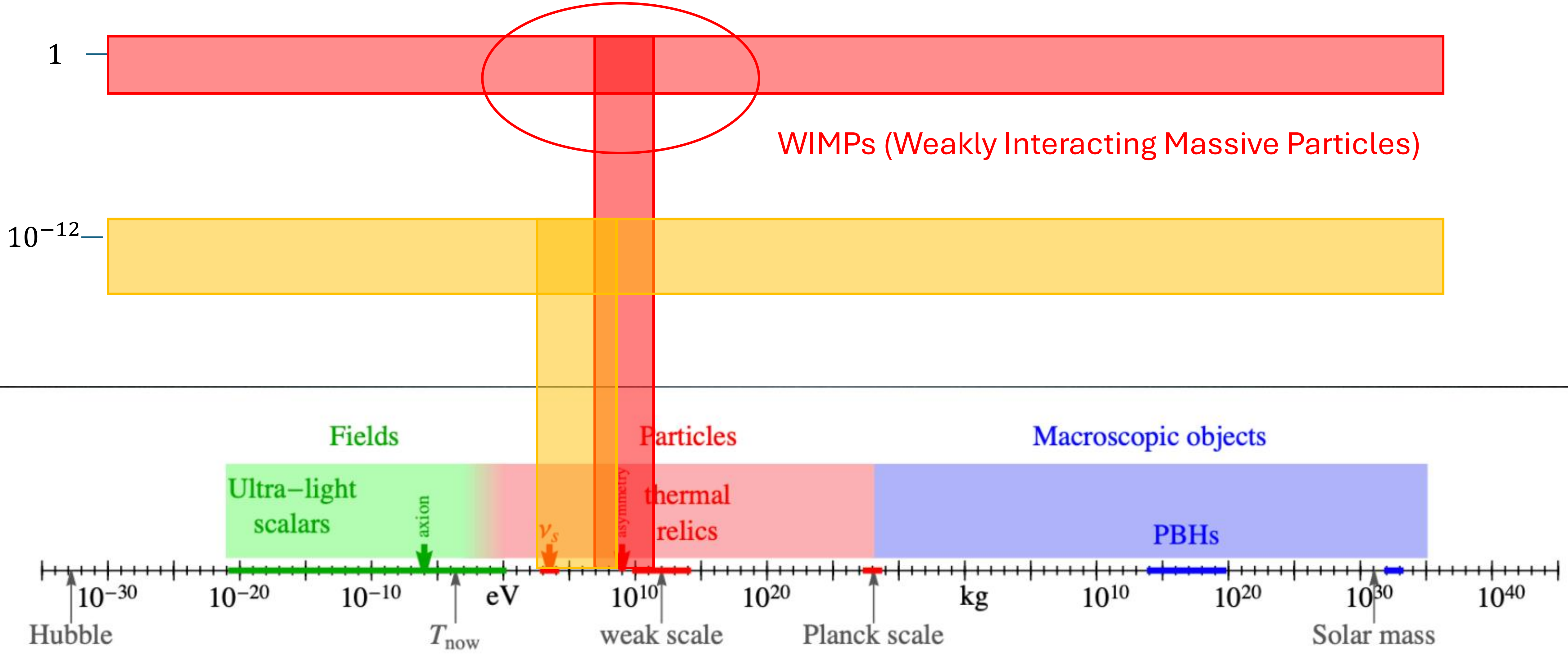
University of Messina

Particle DM

Solution to Dark Matter Puzzle from Particle Physics is a widely accepted conjecture.

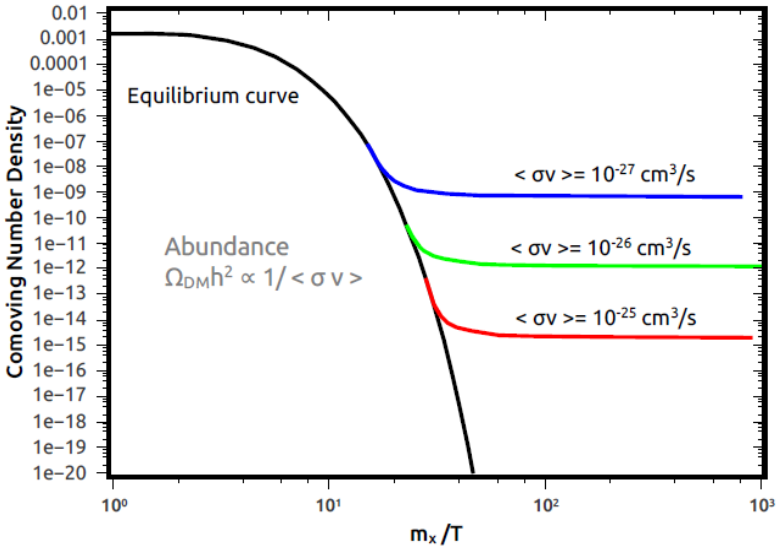
A particle DM is (typically) a Beyond the Standard Model state.

Stable on cosmological scales.
Weakly or SuperWeakly interacting with ordinary matter, photons.
Cold (up to warm) as opposed to hot.

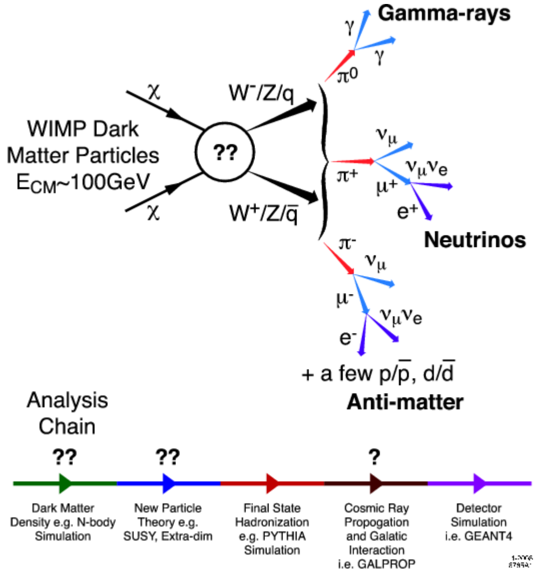


(Slide inspired from Marco Cirelli's talk at TAUP2023)

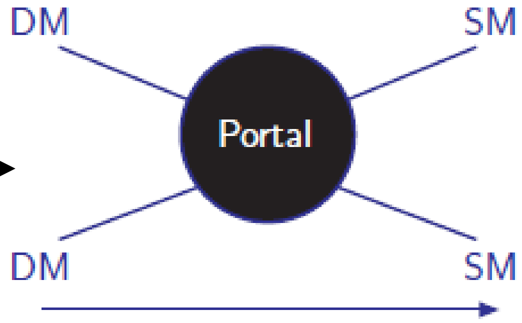
Portals for WIMPs



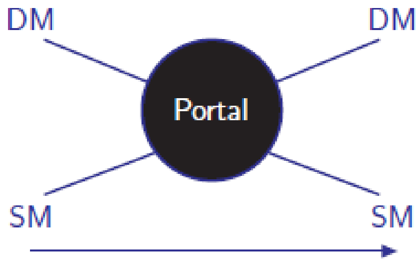
Relic Density



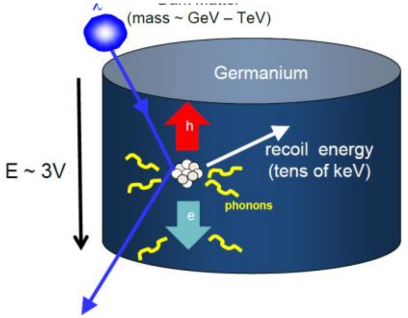
Indirect Detection

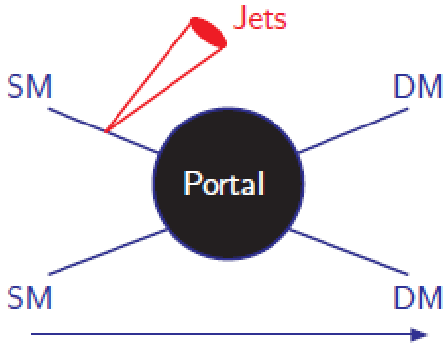


(b) Indirect Detection



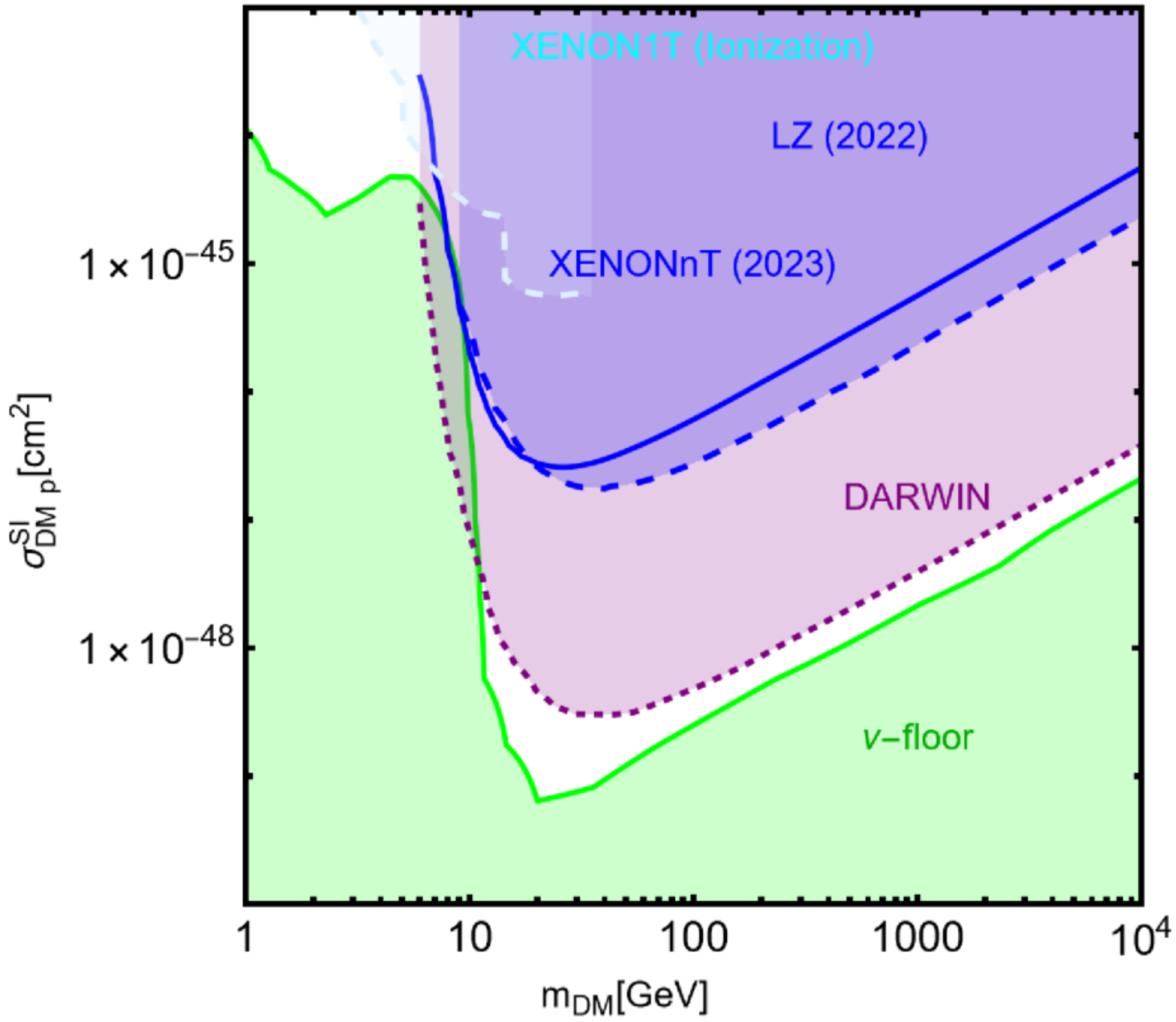
(a) Direct Detection





(c) Collider Detection

Landscape of Direct Detection



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

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

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

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

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

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

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

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

DD of Scalar DM

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

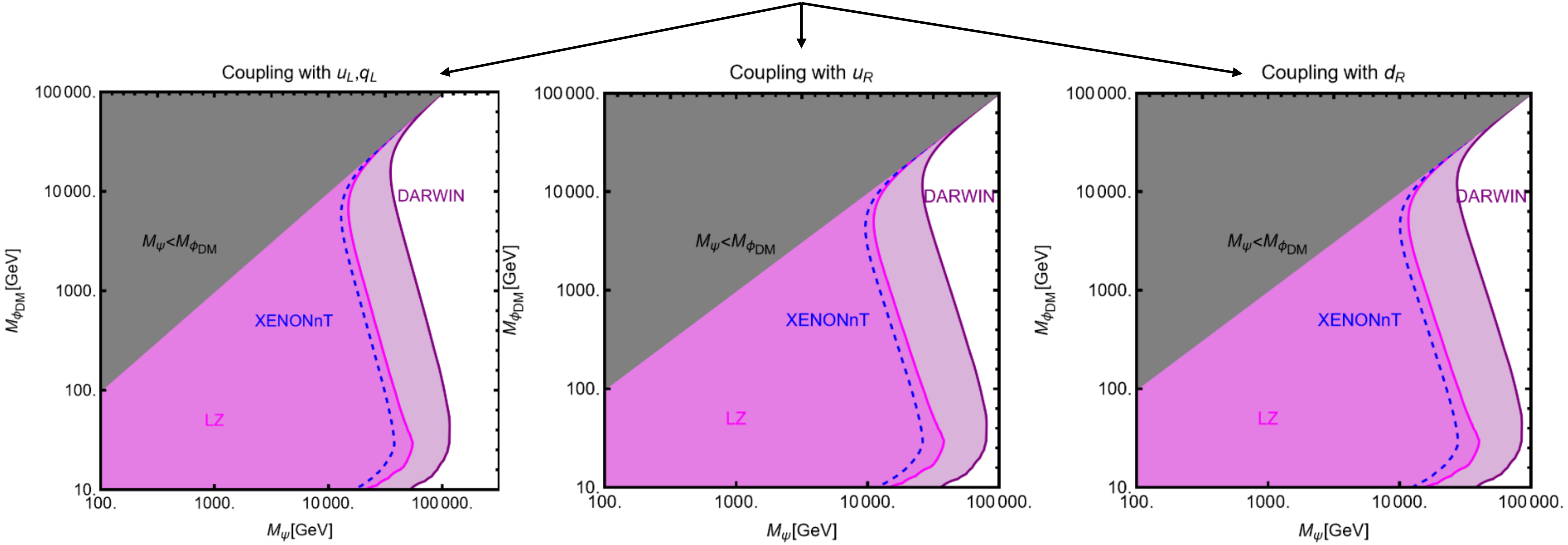
Non-relativistic Limit

Absent for real scalar DM

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

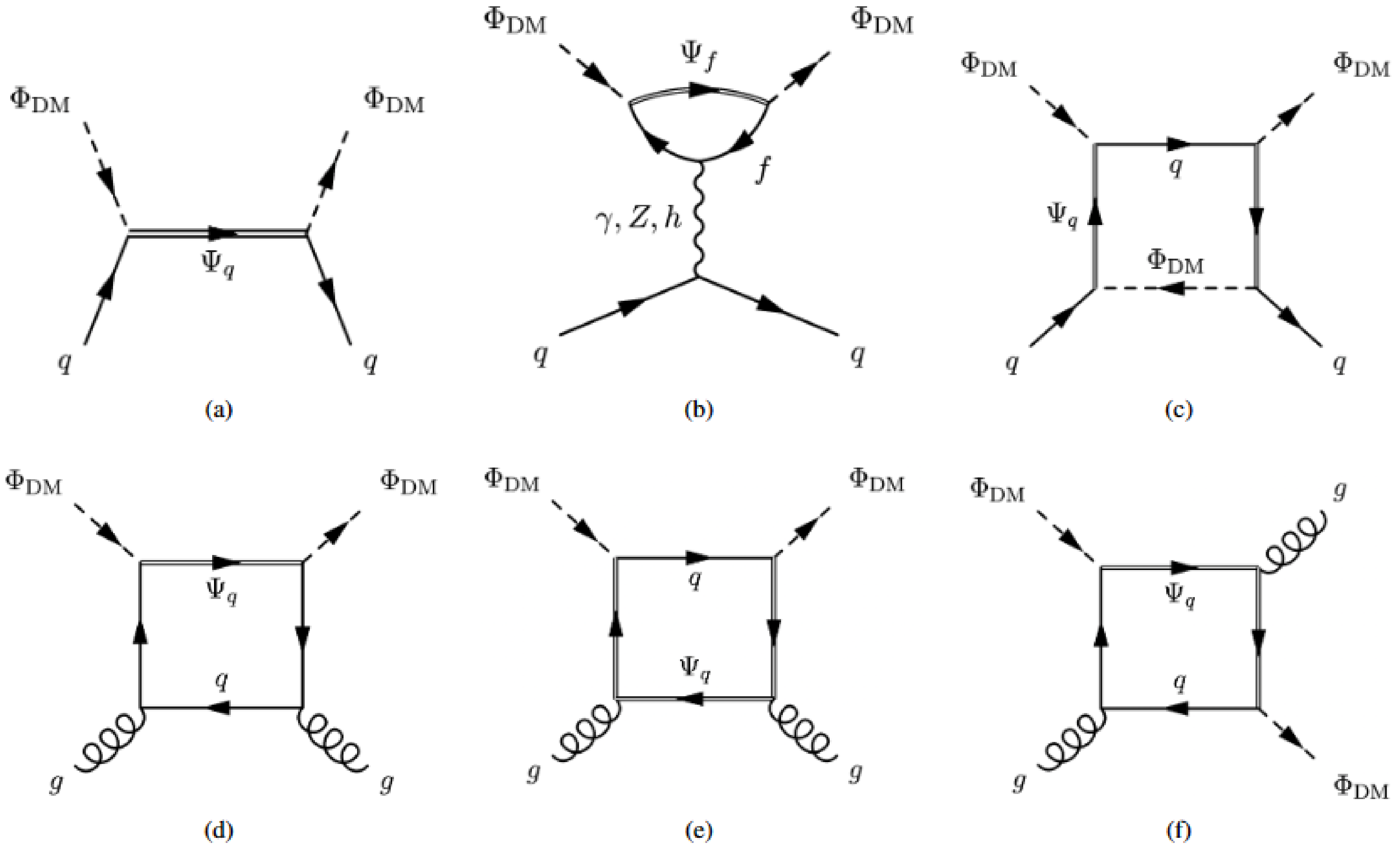
Complex Scalar DM coupled with first generation quarks

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

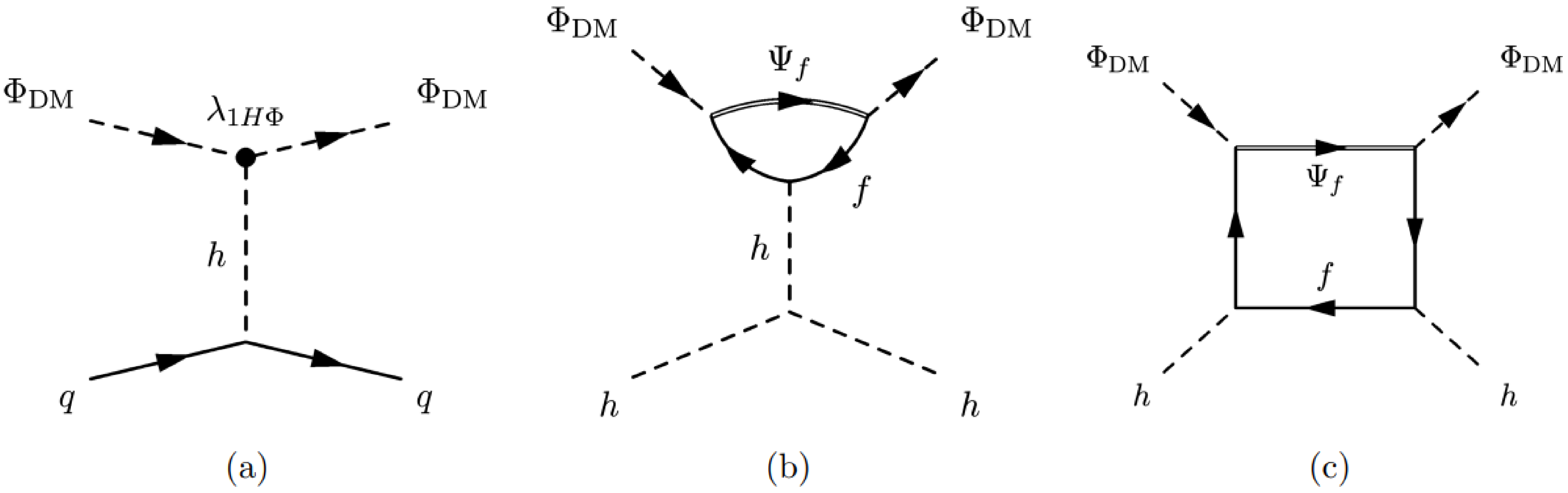


Coupling emerges at tree-level. Substantially excluded by present constraints.

Loop diagrams for coupling with other quark generations.



Radiatively induced Higgs Portal coupling



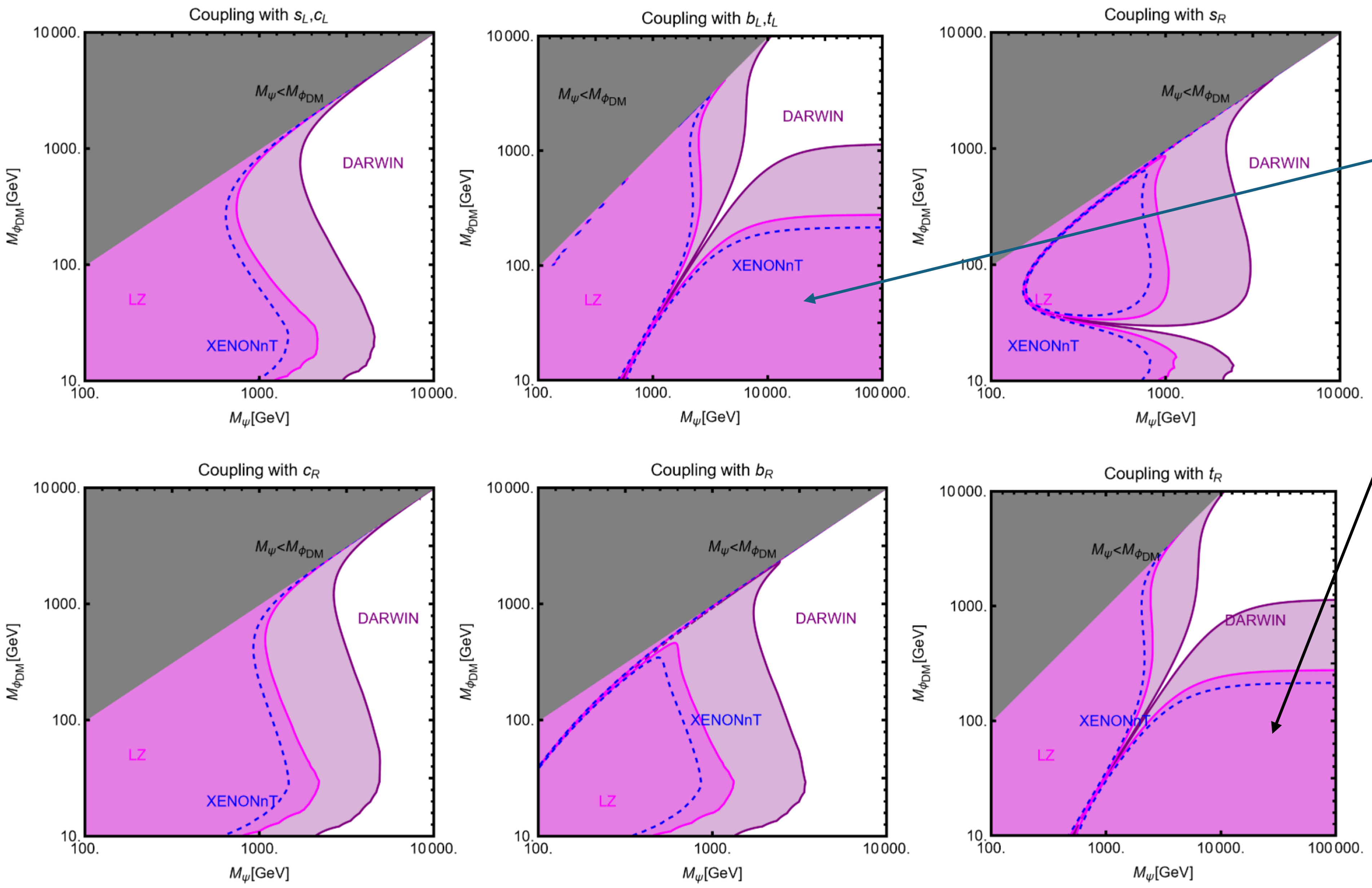
$$d_H^q = \sum_f \frac{g^2 \left|\Gamma_{L,R}^f\right|^2 M_{\psi_f}^2}{32\pi^2 m_H^2 m_W^2} F_H\left(\frac{m_f^2}{M_{\psi_f}^2}, \frac{M_{\phi_{DM}}^2}{M_{\psi_f}^2}\right)$$

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

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

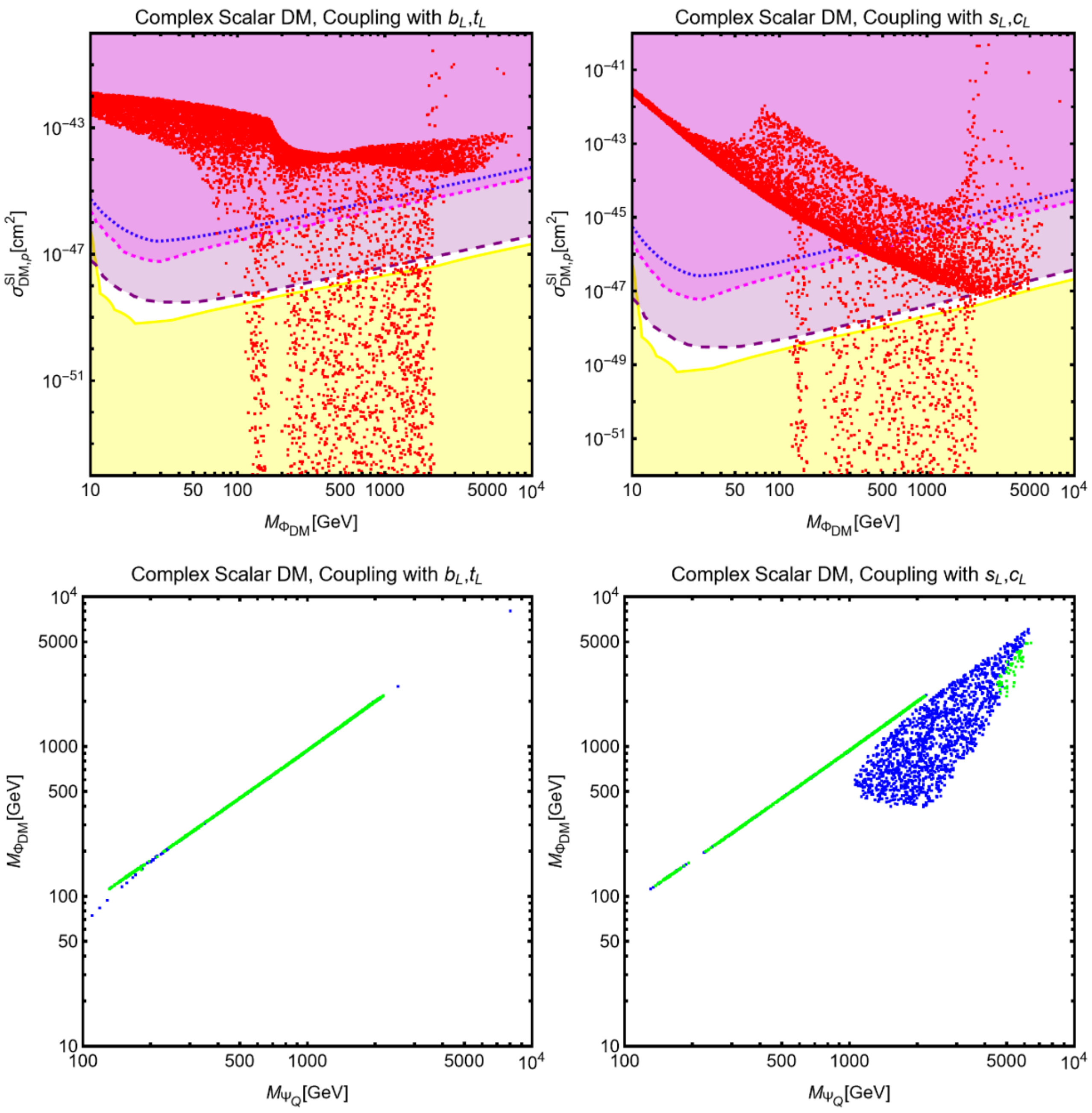
We assume

$$M = M_{\psi_f}$$

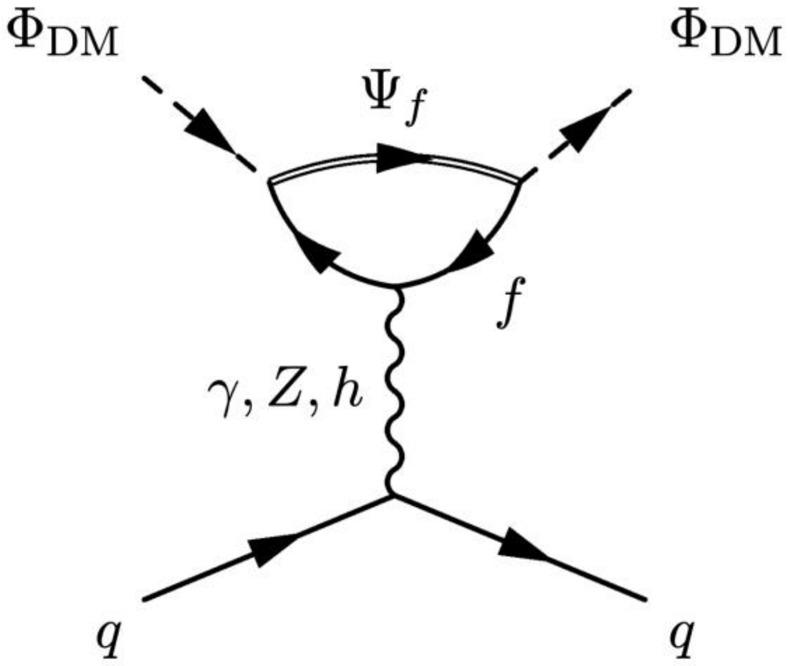


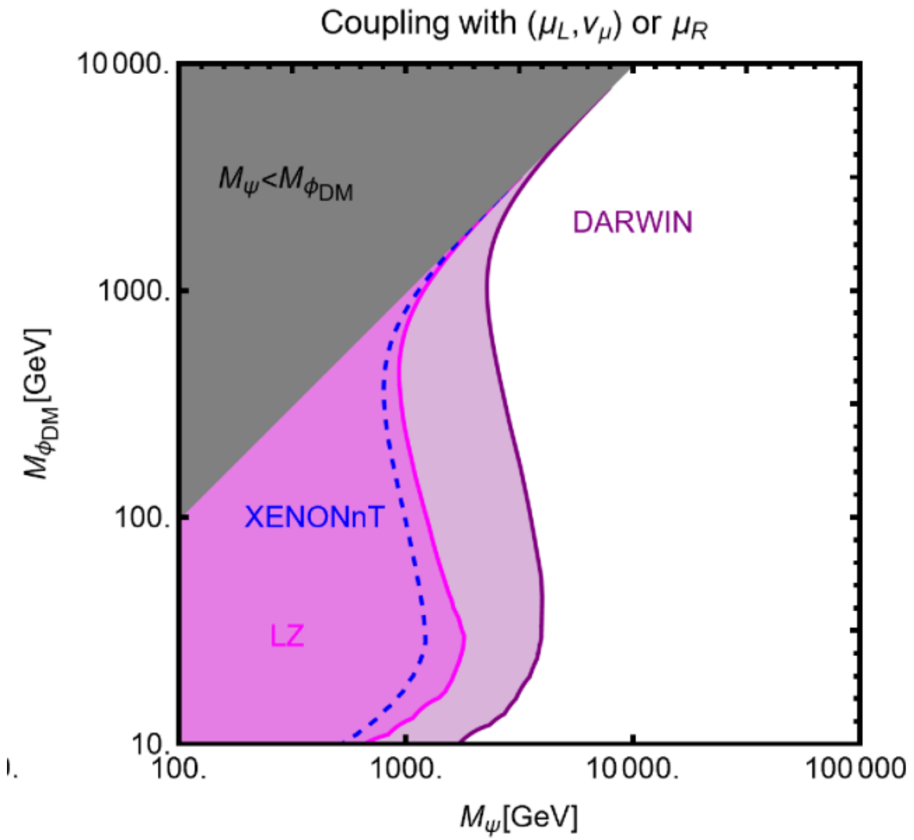
Strong constraints from the radiative Higgs portal

Interplay with the relic density.

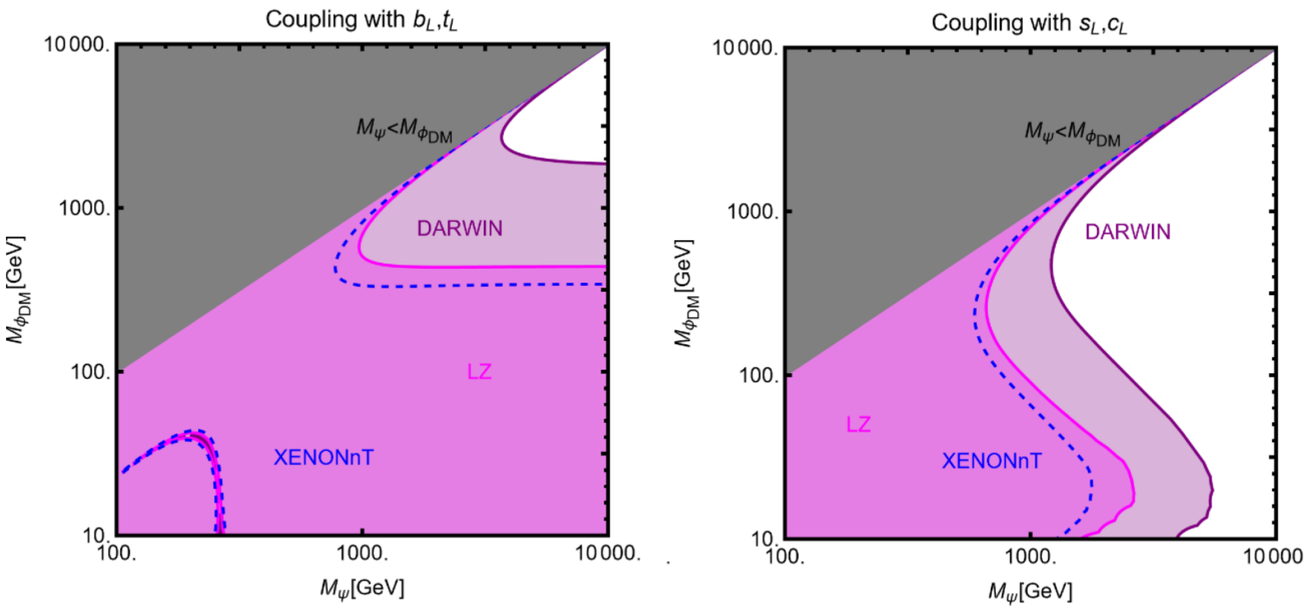


Penguin diagrams present also for couplings with leptons.

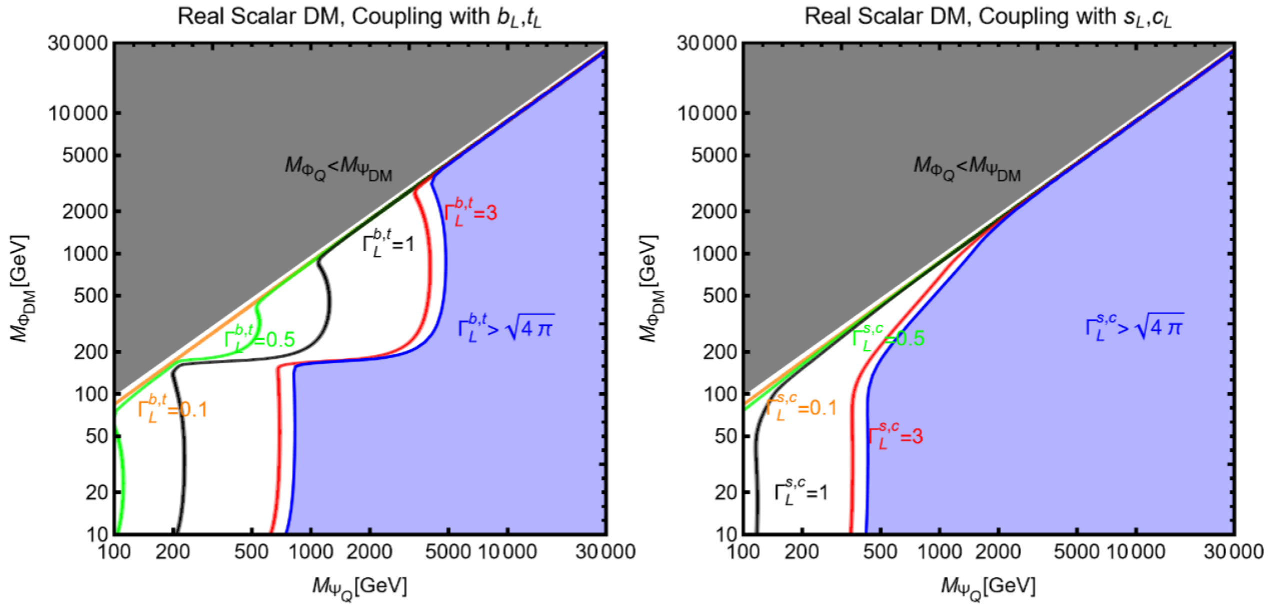




DD present also for leptophilic DM.



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).

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

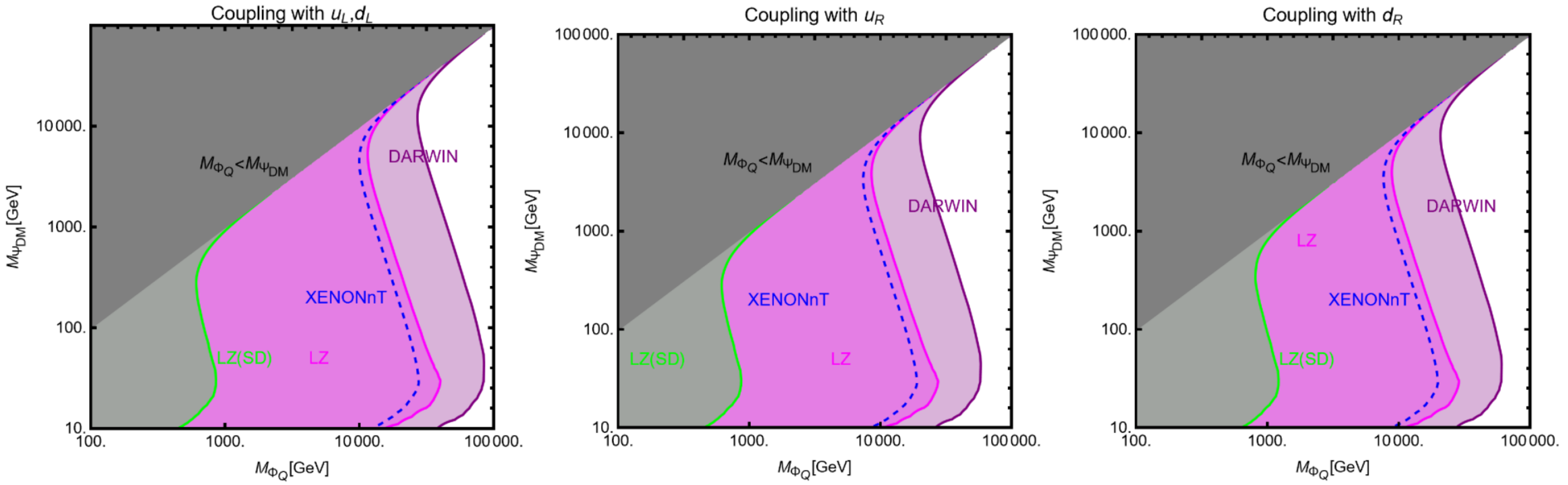
Responsible for SD interactions

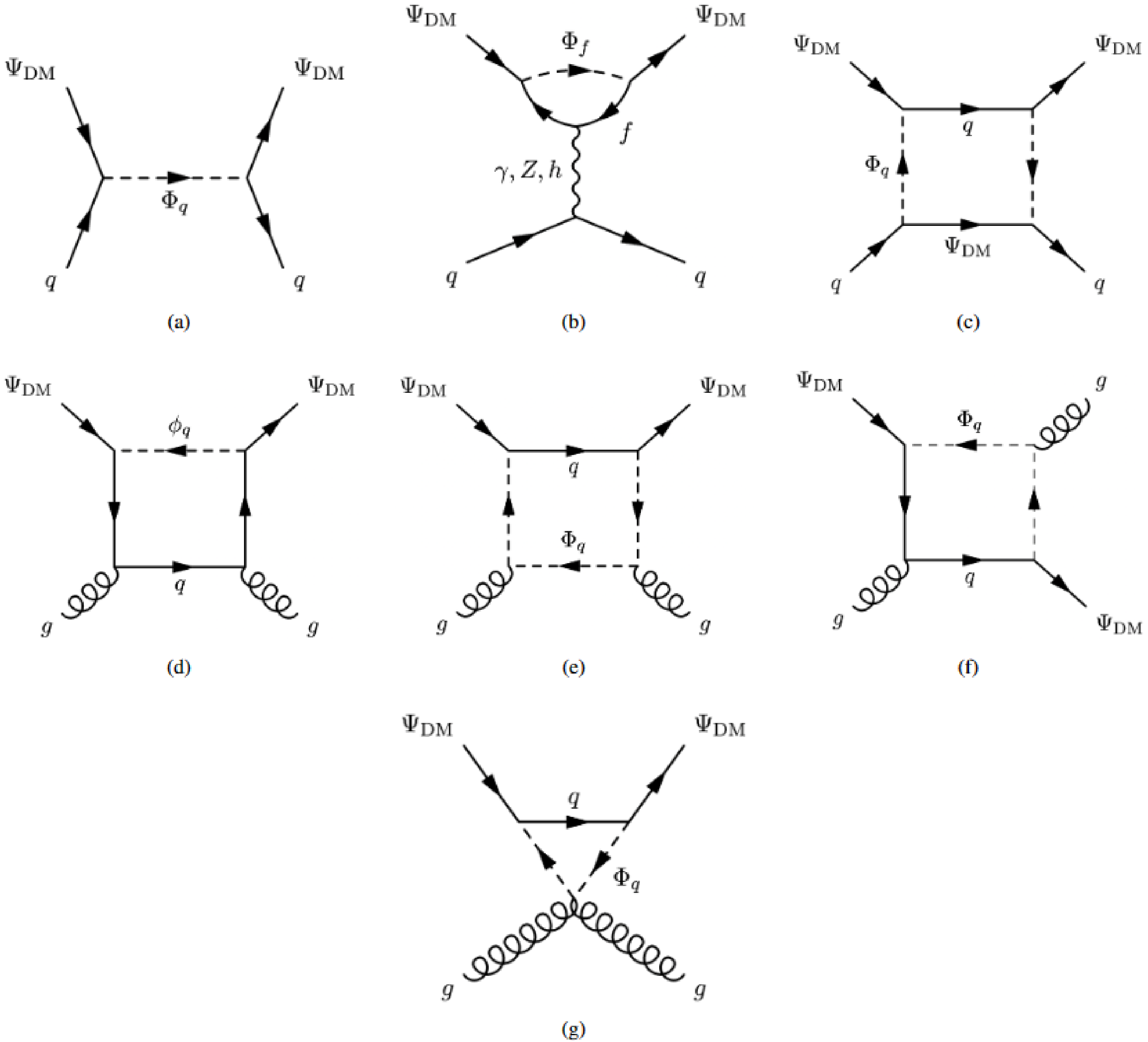
$$L_{eff}^{fermion,q} = \sum_{q=u,d} c^q \bar{\psi}_{DM} \gamma_\mu \psi_{DM} \bar{q} \gamma^\mu q + \sum_{q=u,d,s} \tilde{c}^q \bar{\psi}_{DM} \gamma_\mu \gamma_5 \psi_{DM} \bar{q} \gamma^\mu \gamma_5 q + \sum_{q=u,d,s} d^q m_q \bar{\psi}_{DM} \psi_{DM} \bar{q} q + \sum_{q=c,b,t} d^{g,q} \bar{\psi}_{DM}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

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

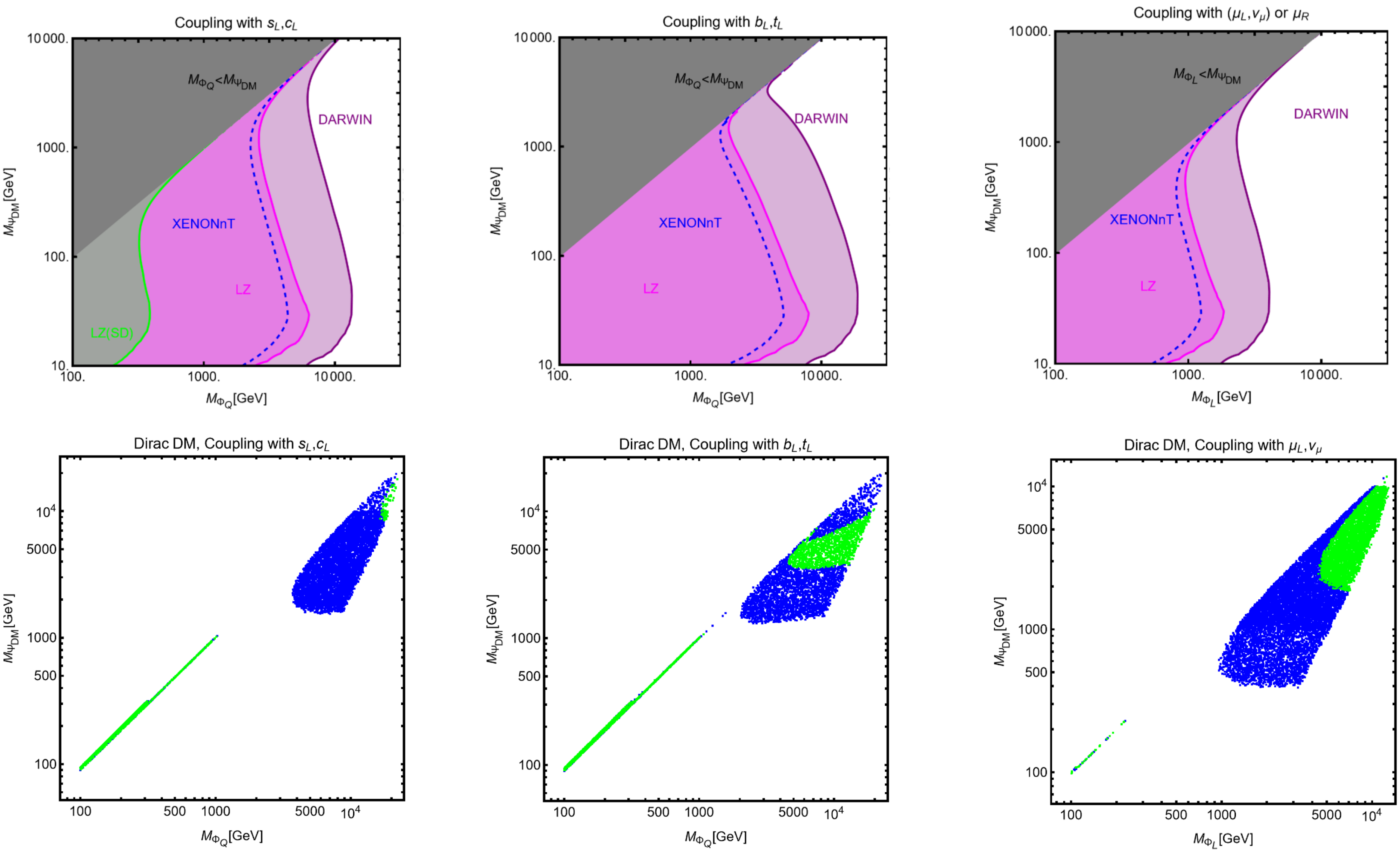
$$+ \sum_{q=c,b,t} \left(g_1^{g,q} \frac{\bar{\psi}_{DM} i\partial^\mu \gamma^\nu \psi_{DM} O_{\mu\nu}^g}{M_{\psi_{DM}}} + g_2^{g,q} \frac{\bar{\psi}_{DM} (i\partial^\mu)(i\partial^\nu) \psi_{DM} O_{\mu\nu}^g}{M_{\psi_{DM}}^2} \right) + \frac{\tilde{b}_\psi}{2} \bar{\psi}_{DM} \sigma^{\mu\nu} \psi_{DM}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

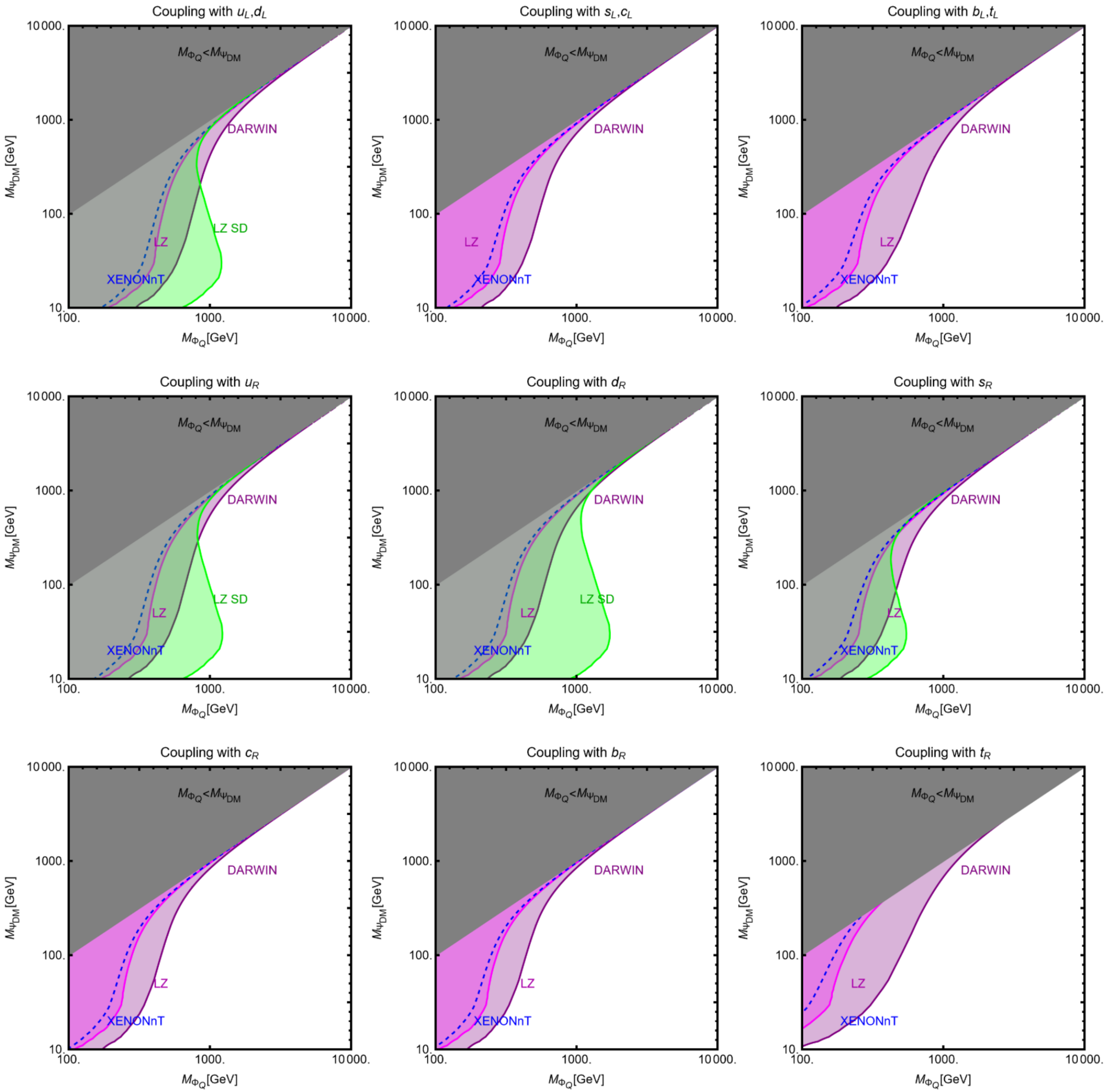
Couplings with first generations strongly constrained also for Dirac Dark Matter



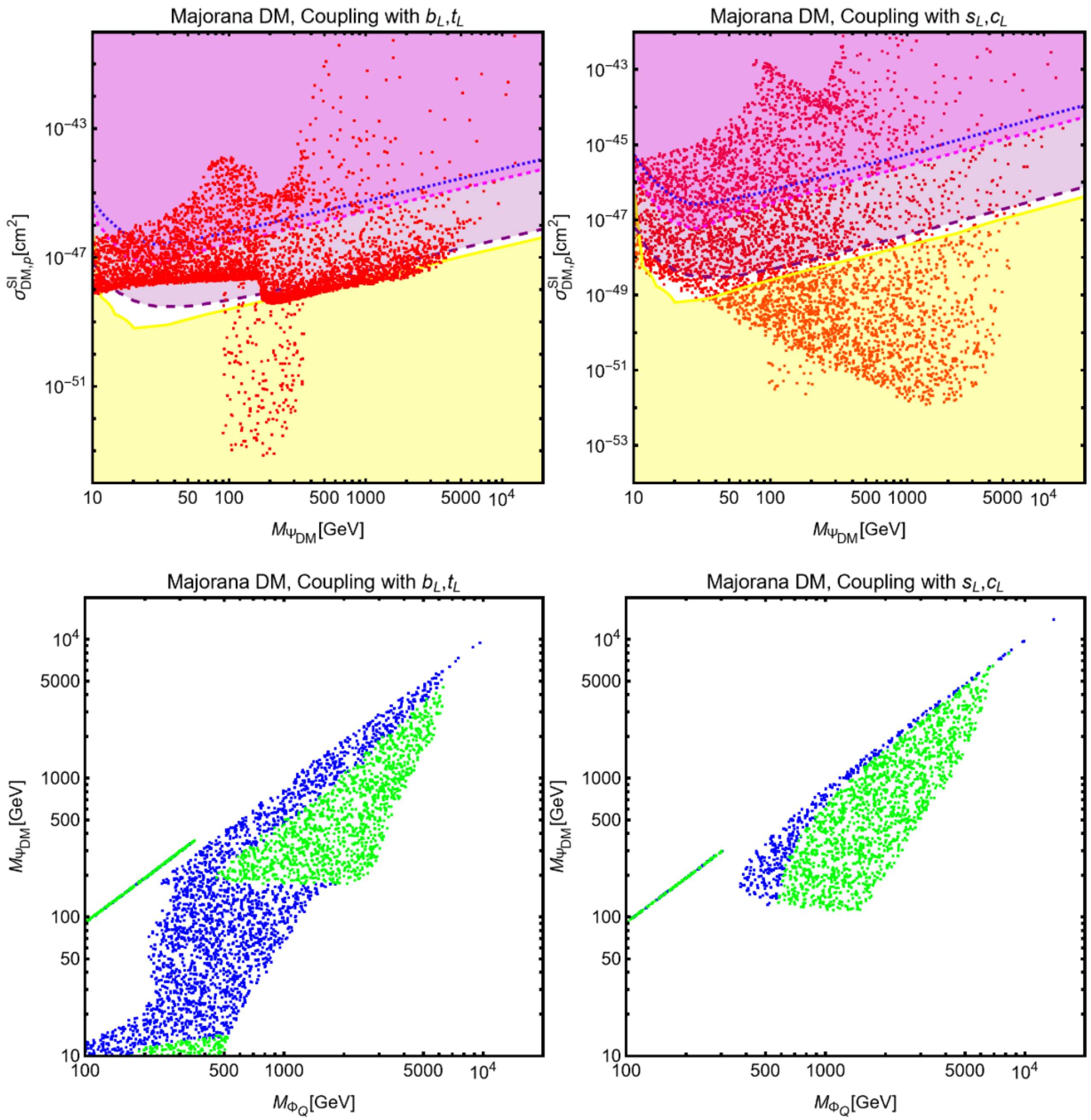


Loop diagrams for couplings with second/third generation of quarks (and leptons).
No radiative portal induced for fermionic DM.


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

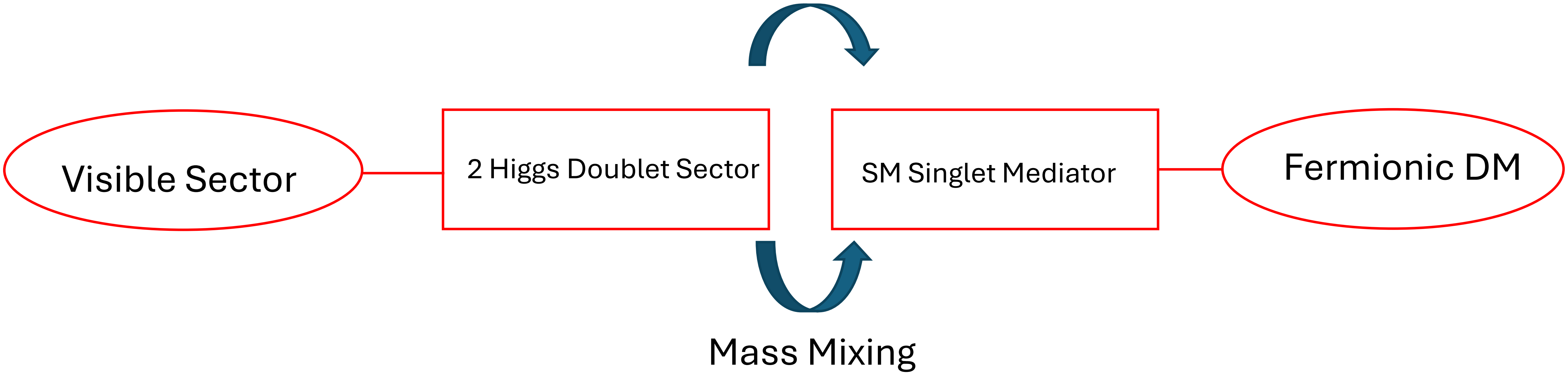


Operators associated to tree-level interactions and penguin diagrams are absent for Majorana DM.



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

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

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

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

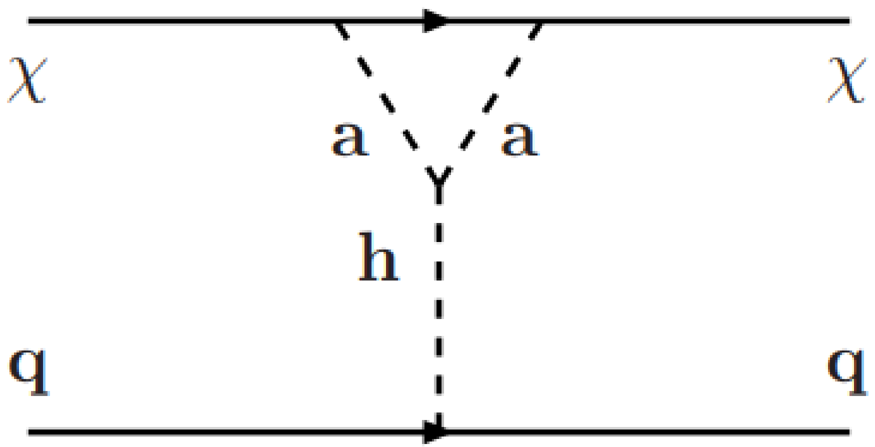
$$g_{aff} = sin\theta\, g_{A^0ff}$$

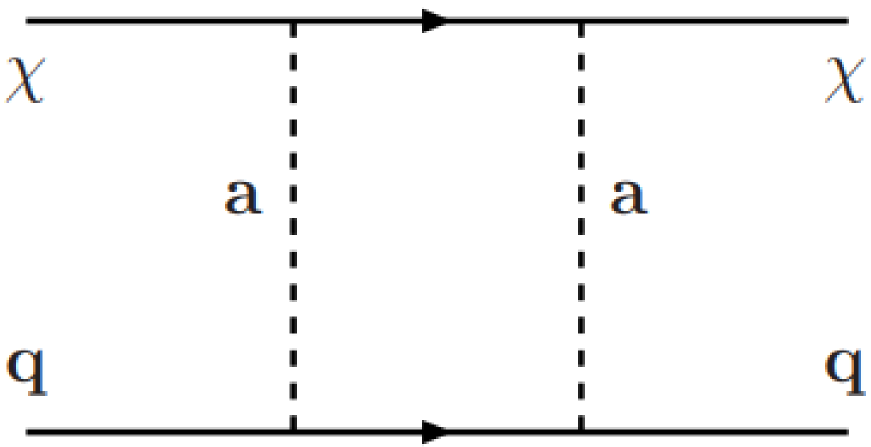
	Type I	Type II	Type X	Type Y
g_{htt}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$
g_{hbb}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to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

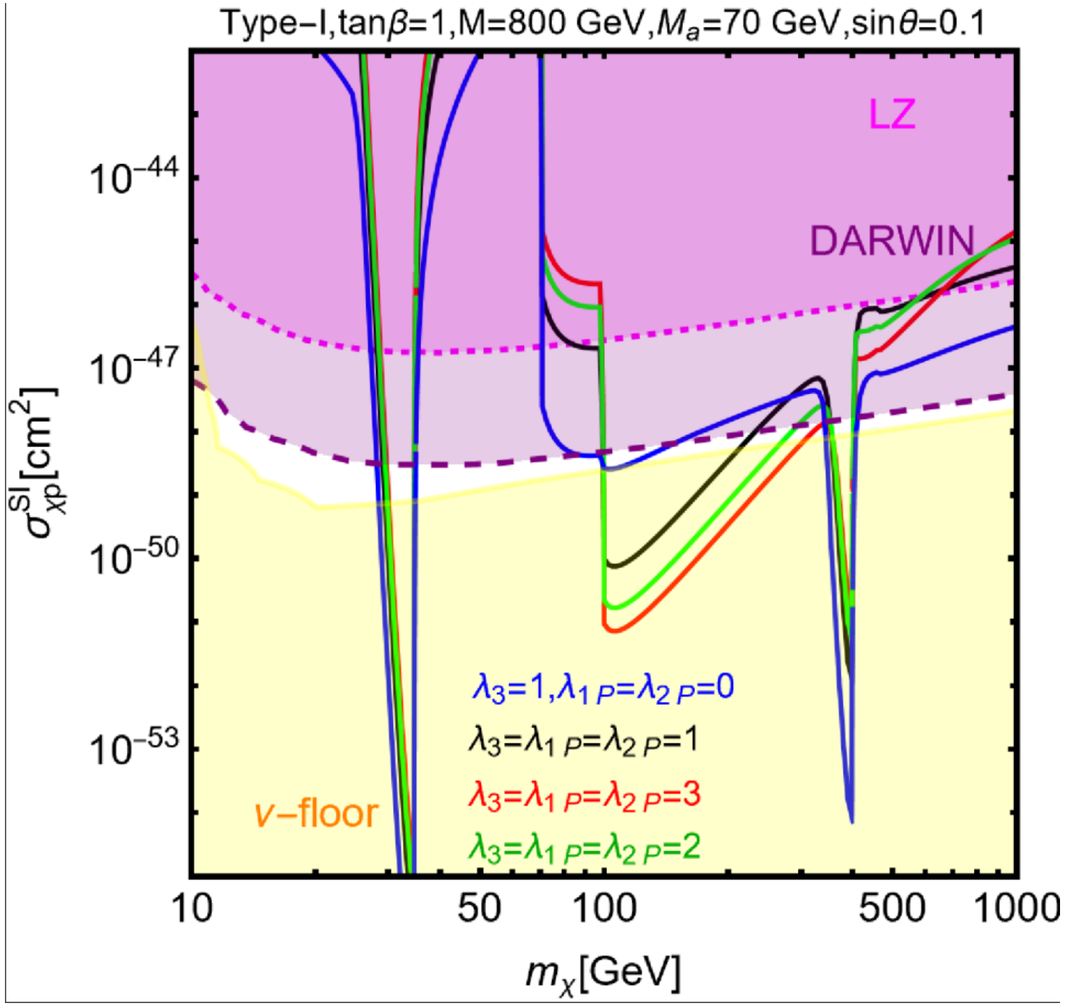
At tree level:

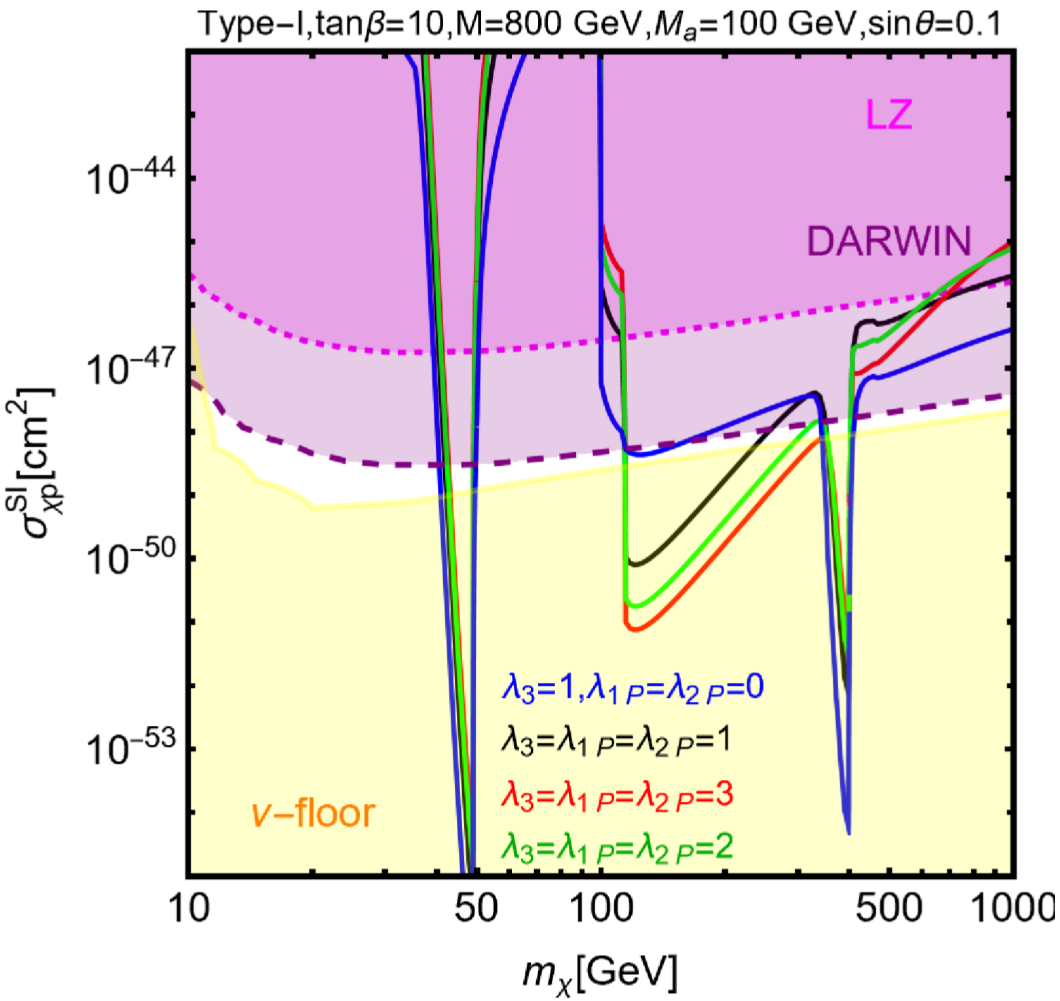
$$\bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{f}\gamma_{\mu}\gamma_5 f \longrightarrow (\sigma_N\cdot\vec{q})(\sigma_\chi\cdot\vec{q}) \longrightarrow \frac{d\sigma}{dE_R}=\frac{g_\chi^2}{128\pi}\frac{q^4}{m_a^4}\frac{m_T^2}{m_\chi m_N}\frac{1}{v_E^2}\sum_{N.N'=p,n} g_N g_{N'} F_{\Sigma''}^{NN'}(q^2)$$

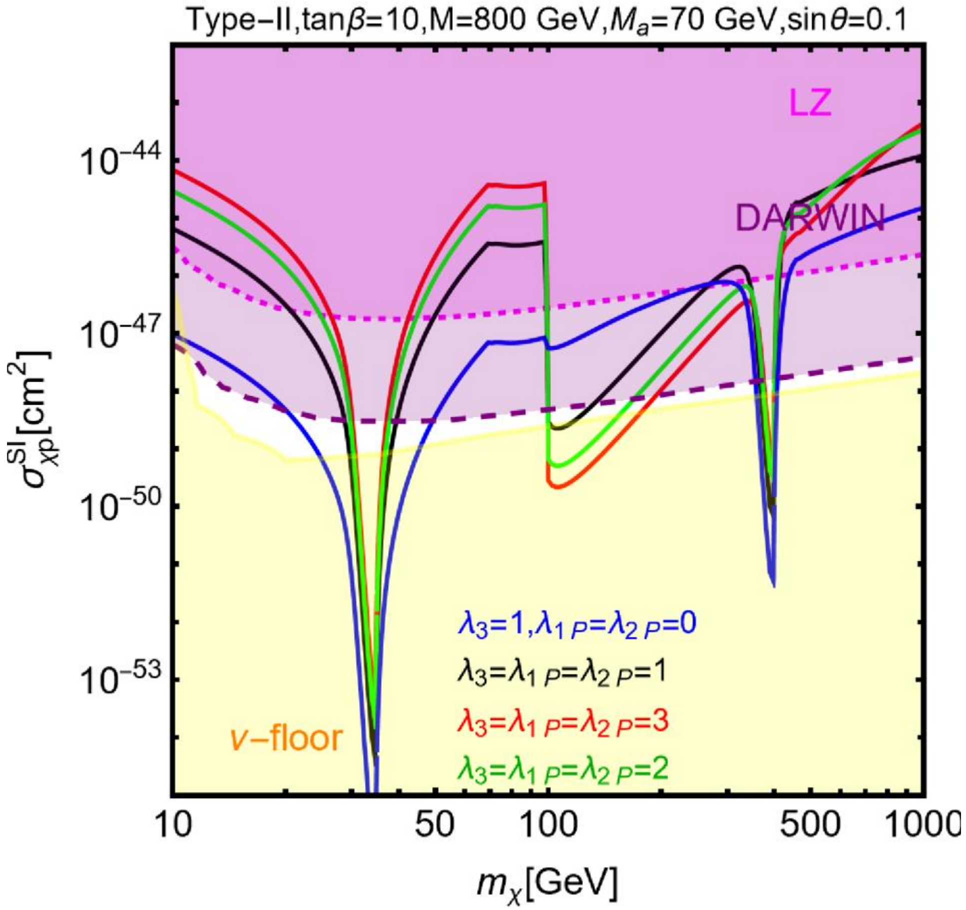
SI Cross section at loop level

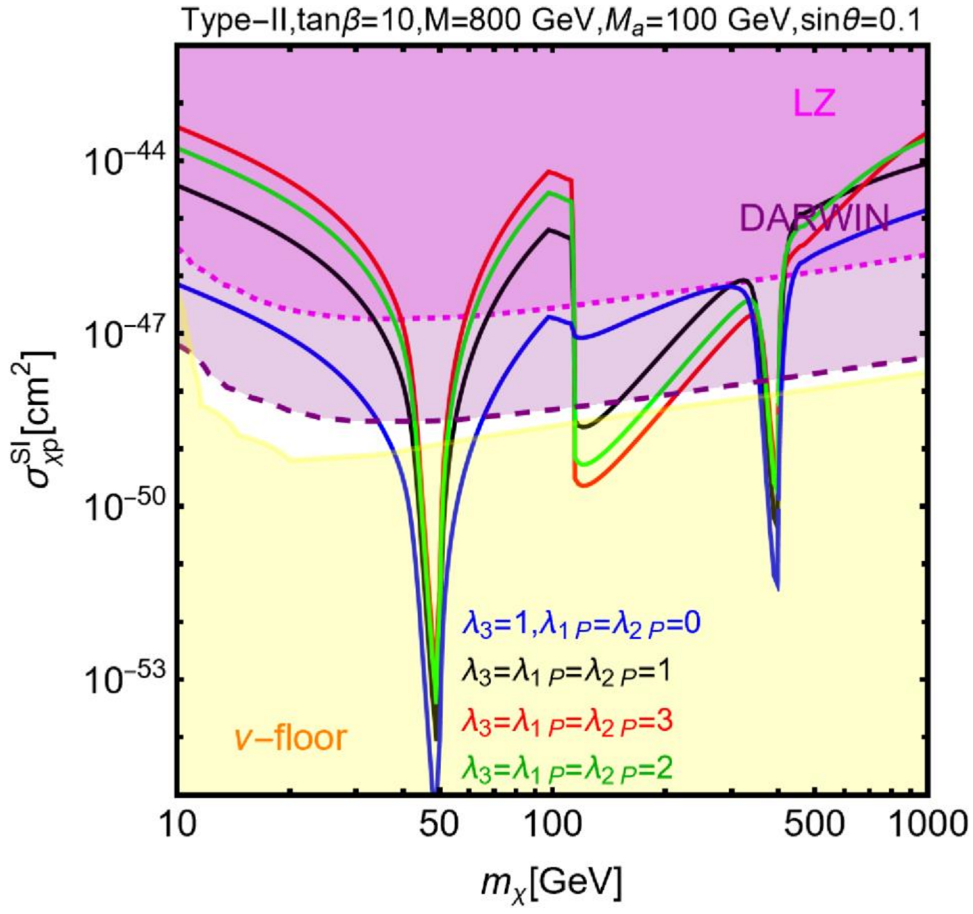


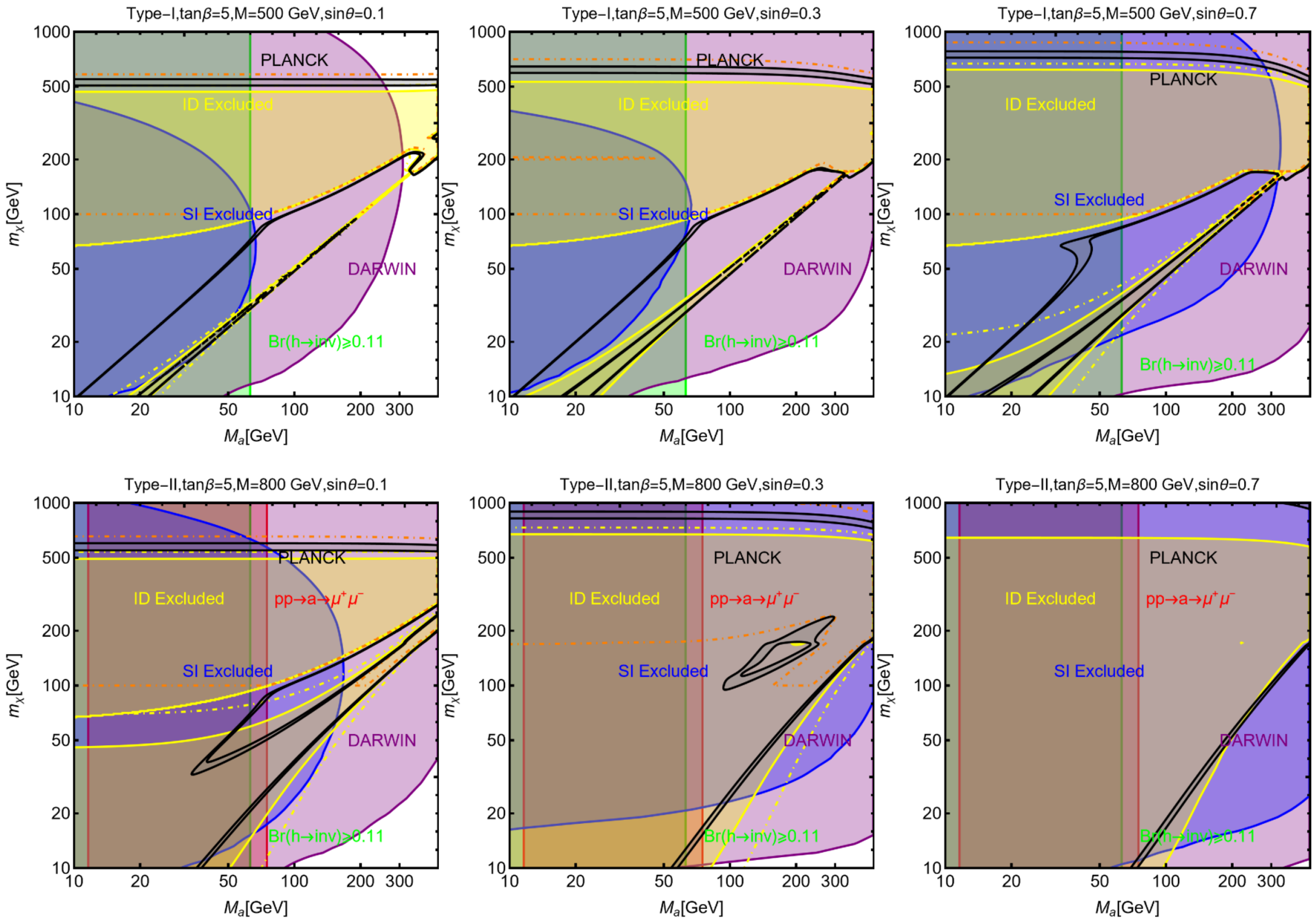


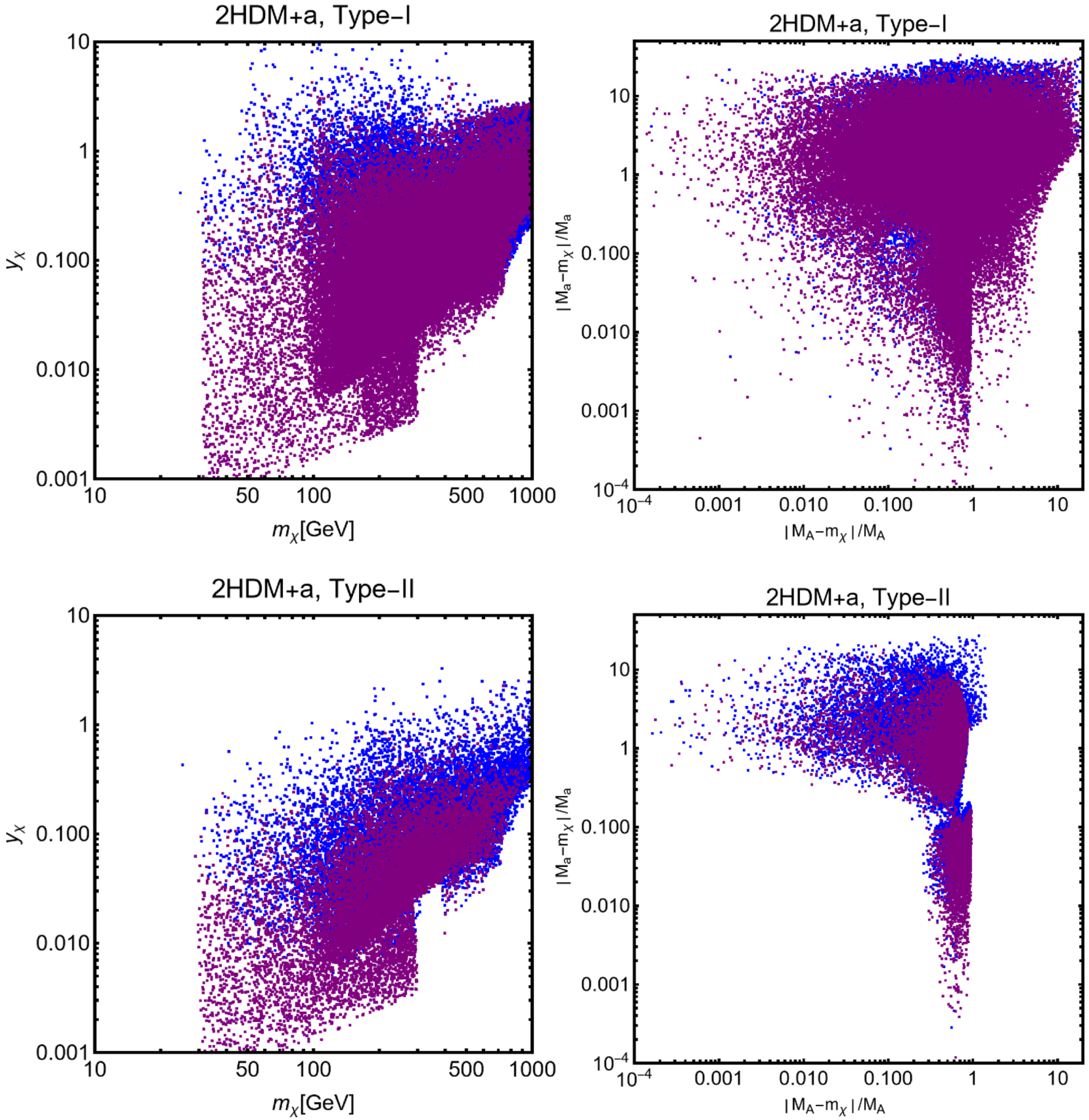

Type−I,tanβ=1,M=800 GeV,M_a=70 GeV,sinθ=0.1
LZ
DARWIN
10^{-44}
10^{-47}
10^{-50}
10^{-53}
$\sigma_{\chi p}^{SI}$[cm^2]
ν−floor
$\lambda_3=1,\lambda_{1P}=\lambda_{2P}=0$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=1$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=3$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=2$
10
50
100
500
1000
m_χ[GeV]


Type−I,tanβ=10,M=800 GeV,M_a=100 GeV,sinθ=0.1
LZ
DARWIN
10^{-44}
10^{-47}
10^{-50}
10^{-53}
$\sigma_{\chi p}^{SI}$[cm^2]
ν−floor
$\lambda_3=1,\lambda_{1P}=\lambda_{2P}=0$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=1$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=3$
$\lambda_3=\lambda_{1P}=\lambda_{2P}=2$
10
50
100
500
1000
m_χ[GeV]


Type−II,tanβ=10,M=800 GeV,M_a=70 GeV,sinθ=0.1
LZ
DARWIN
$\sigma^{SI}_{\chi p}$[cm^2]
10^{-44}
10^{-47}
10^{-50}
10^{-53}
λ_3=1,λ_{1P}=λ_{2P}=0
λ_3=λ_{1P}=λ_{2P}=1
λ_3=λ_{1P}=λ_{2P}=3
λ_3=λ_{1P}=λ_{2P}=2
ν−floor
10
50
100
500
1000
m_χ[GeV]


Type−II,tanβ=10,M=800 GeV,M_a=100 GeV,sinθ=0.1
LZ
DARWIN
$\sigma^{SI}_{\chi p}$[cm^2]
10^{-44}
10^{-47}
10^{-50}
10^{-53}
λ_3=1,λ_{1P}=λ_{2P}=0
λ_3=λ_{1P}=λ_{2P}=1
λ_3=λ_{1P}=λ_{2P}=3
λ_3=λ_{1P}=λ_{2P}=2
ν−floor
10
50
100
500
1000
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]


2HDM+a, Type−I
y_χ
0.001
0.010
0.100
1
10
10
50
100
500
1000
m_χ[GeV]
2HDM+a, Type−I
$|M_a - m_\chi|/M_a$
10^{-4}
0.001
0.010
0.100
1
10
$|M_A - m_\chi|/M_A$
2HDM+a, Type−II
y_χ
m_χ[GeV]
2HDM+a, Type−II
$|M_a - m_\chi|/M_a$
$|M_A - m_\chi|/M_A$

Conclusions

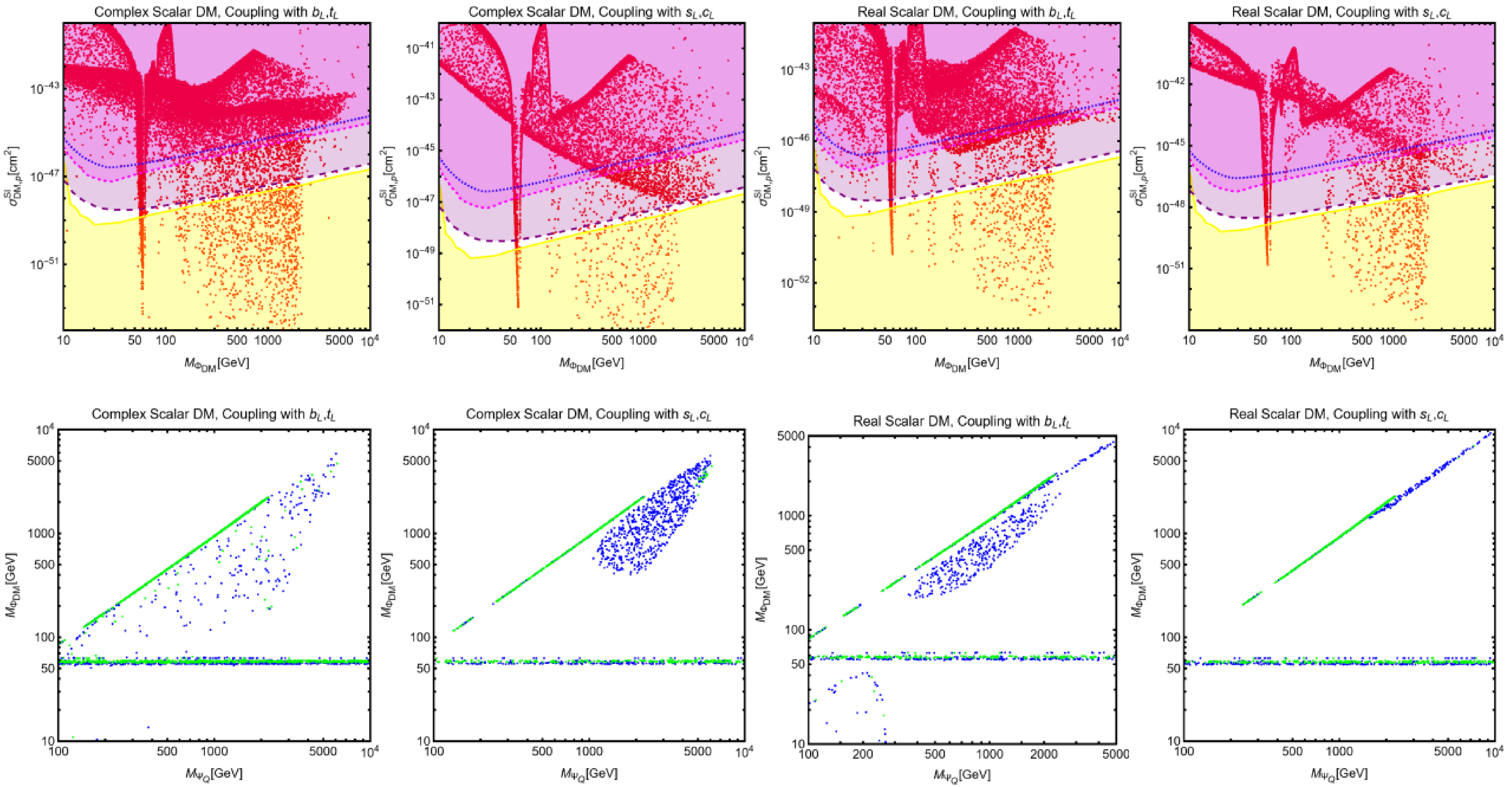
Dark Matter Direct Detection facilities have unprecedented capabilities of testing WIMP models.

Models with loop-induced DD interactions are a very interesting target for current and next generation experiments.

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

Back up

Including a non zero portal coupling...



Complex Scalar DM, Coupling with b_L, t_L
Complex Scalar DM, Coupling with s_L, c_L
Real Scalar DM, Coupling with b_L, t_L
Real Scalar DM, Coupling with s_L, c_L
$\sigma^{SI}_{DM,p}$[cm^2]
$M_{\Phi_{DM}}$[GeV]
Complex Scalar DM, Coupling with b_L, t_L
Complex Scalar DM, Coupling with s_L, c_L
Real Scalar DM, Coupling with b_L, t_L
Real Scalar DM, Coupling with s_L, c_L
$M_{\Phi_{DM}}$[GeV]
M_{Ψ_Q}[GeV]