Direct Detection of Dark Matter with Mediators at Loop

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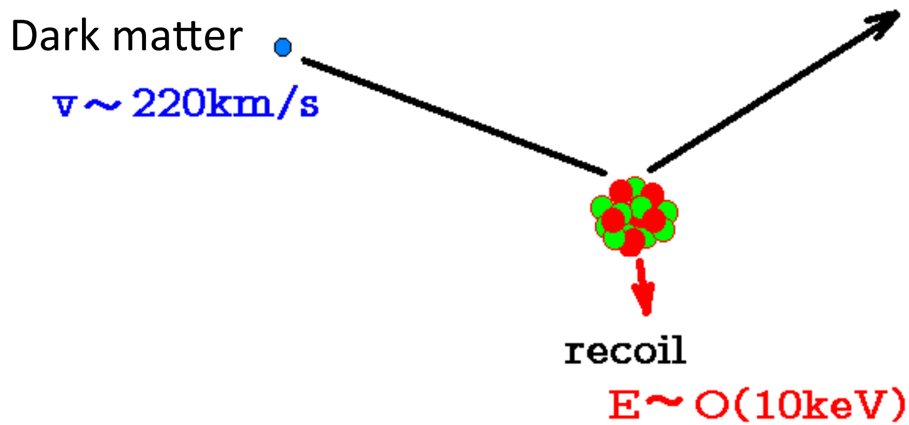
  II-III. Dirac fermion dark matter

III. Conclusion

Dark matter direct detection experiments



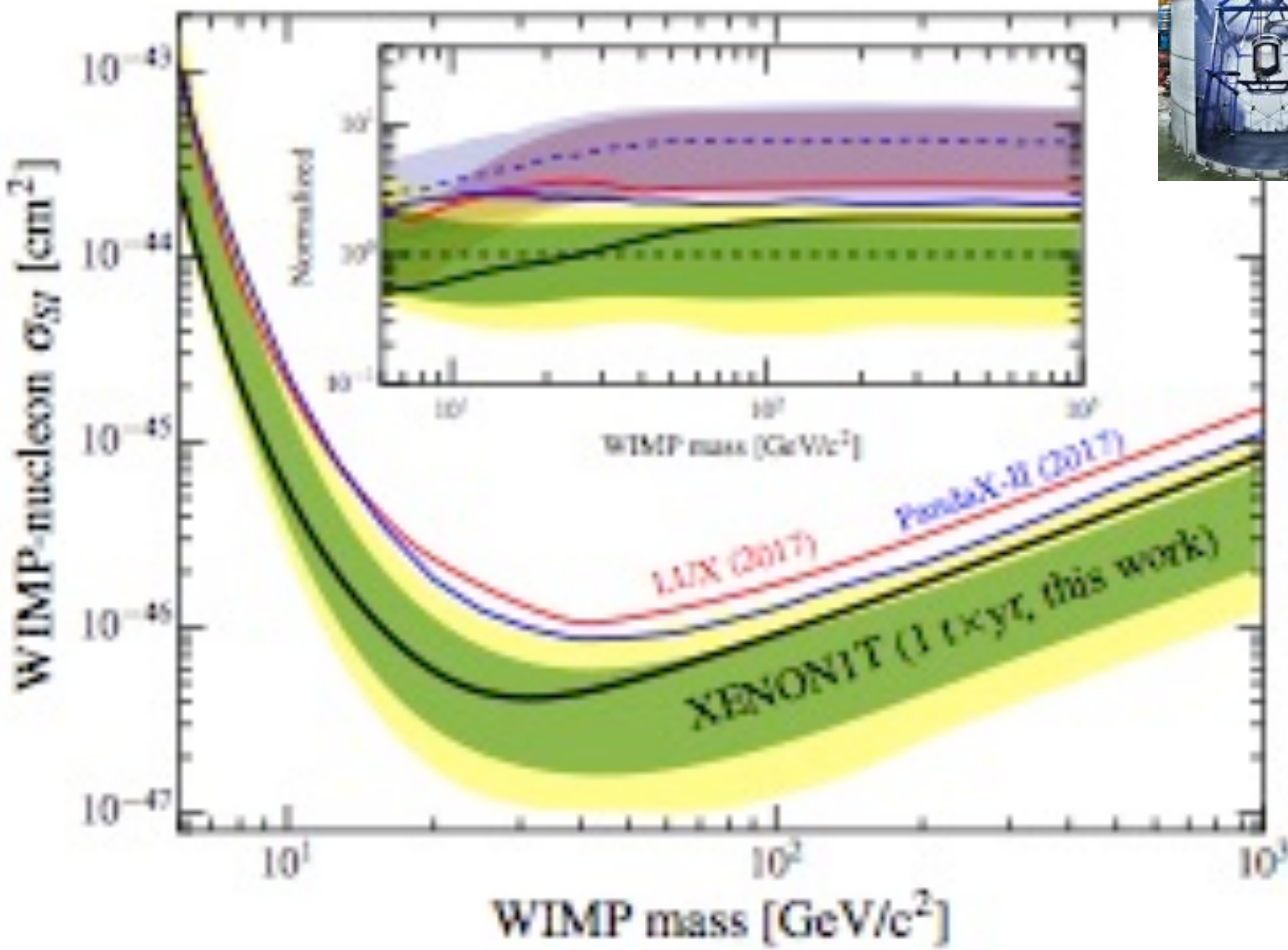
$$\mathcal{L} = \sum_{N=p,n} \underbrace{f_N \overline{\chi^0} \chi^0 \overline{N} N}_{\text{Spin-independent (SI) interaction}} + \underbrace{a_N \overline{\chi^0} \sigma_a \chi^0 \overline{N} \sigma_a N}_{\text{Spin-dependent (SD) interaction}}$$

Elastic scattering cross section with nucleus (m_T: nucleus mass, $n_{p/n}$:# of proton and neutron)

$$\sigma = \frac{4}{\pi} \left(\frac{m_{\tilde{\chi}^0} m_T}{m_{\tilde{\chi}^0} + m_T} \right)^2 \left[\underbrace{(n_p f_p + n_n f_n)^2}_{\text{SI}} + 4 \frac{J+1}{J} \underbrace{(a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2}_{\text{SD}} \right]$$

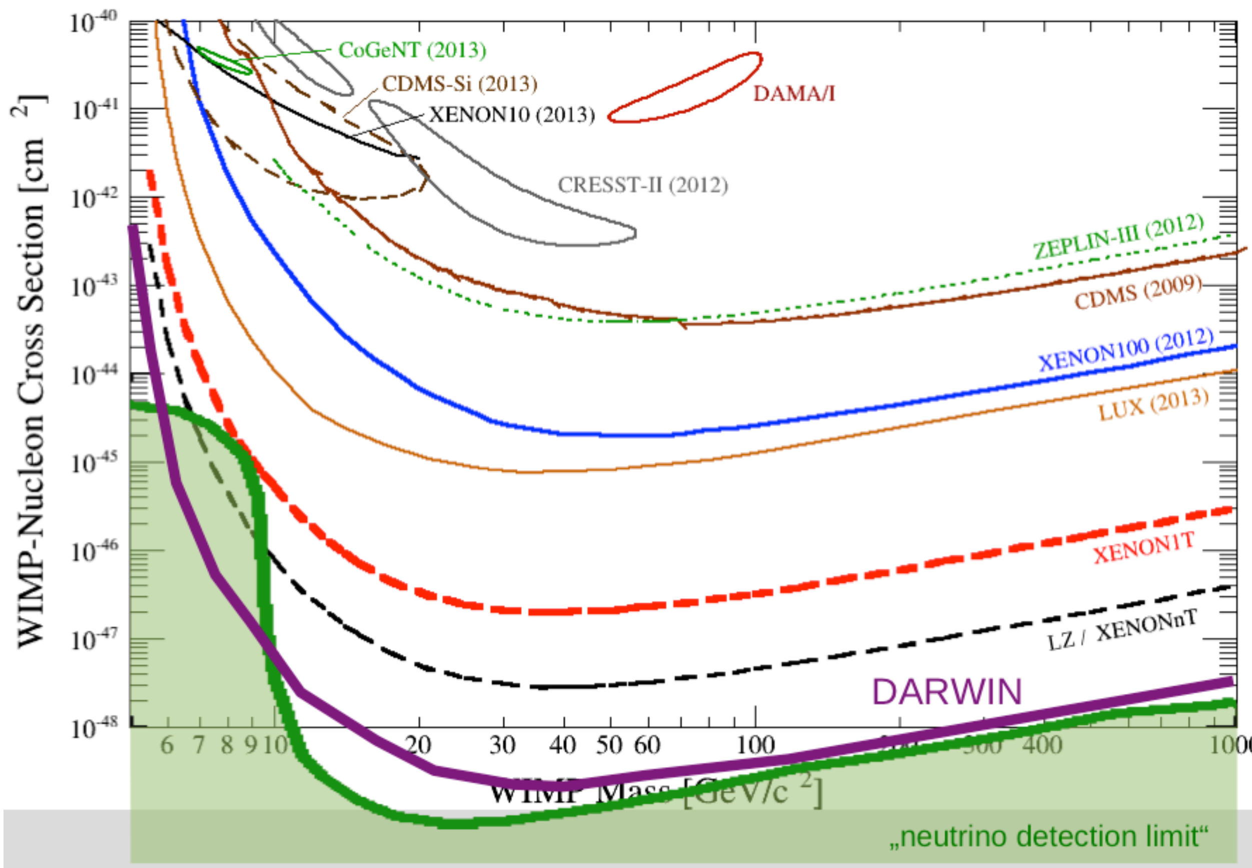
The SI cross section is enhanced for large atomic number nucleus.

Latest results by XENON1T



Future of dark matter direct detection

- XENONnT (2019~), LZ(2020~) : ~20 ton*year
- Darwin (2020+):~200 ton*year



Shumann's talk (Taup2015)

Beyond tree level

The DM couplings with SM fields have been already constrained if it is induced at tree level.

Example) Singlet fermion DM coupled with Higgs boson

$$L_{\rm int} = -f_X \bar{X} X h$$

The coupling is not gauge inv, and it is induced by Singlet-doublet Higgs mixing. The SI scattering cross section is evaluated as

$$\sigma^p_{\rm SI} \simeq 2 \times 10^{-42} {\rm cm}^2 \times f_X^2$$

Thus, $f_X \lesssim 5 \times 10^{-3}$ for $M_{\rm DM} \simeq 30 {\rm GeV}$ from XENON1T.

Future experiments may have sensitivities to models where DM are coupled with SM at loop level.

II. Direct detection of dark matter with mediators at loops

II-I. Wino dark matter (JH, N.Nagata, K. Ishiwata , 2015)

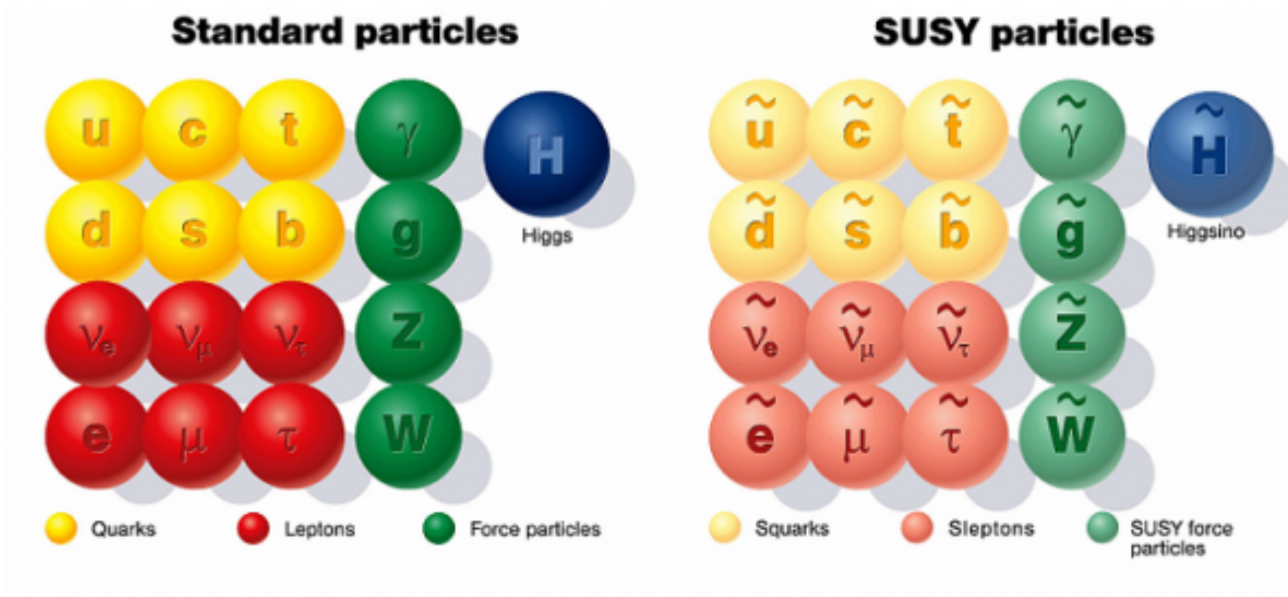
II-II. Peudo scalar mediated singlet fermion dark matter (T. Abe, M. Fujiwara, JH, in preparation)

II-III. Dirac fermion dark matter (JH, N.Nagata, R.Nagai, 2018)

Wino dark matter direct detection

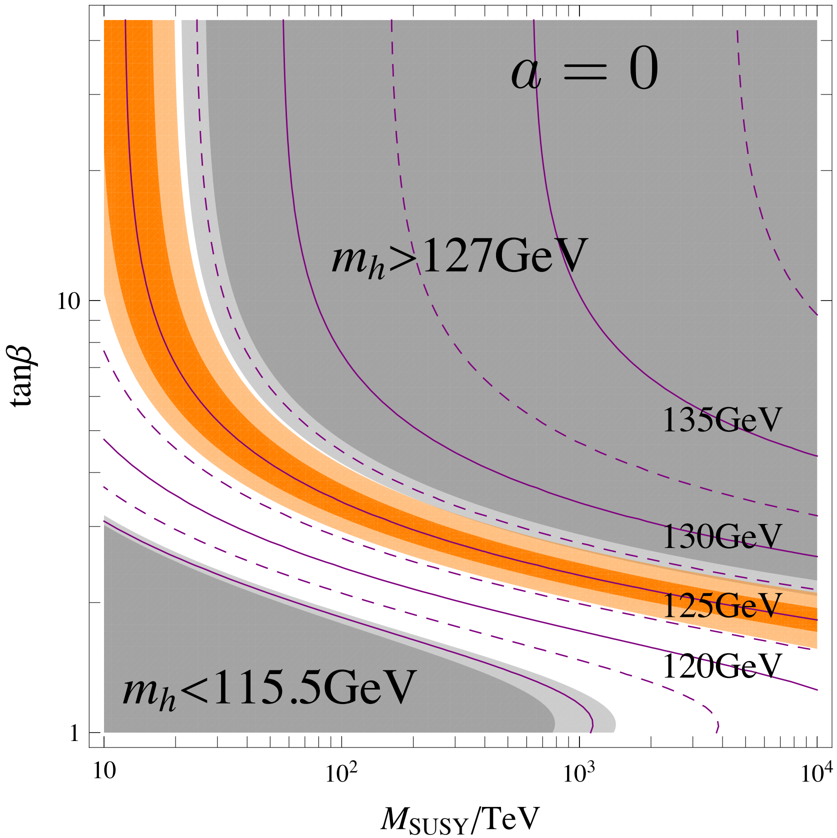
JH, N.Nagata, K. Ishiwata
(2015)

What is wino?



- Superpartner of $SU(2)_L$ gauge bosons in SUSY SM.
- $SU(2)_L$ triplet and $U(1)_Y$ neutral fermion.
- Neutral component of Winos is a candidate of WIMP DM.

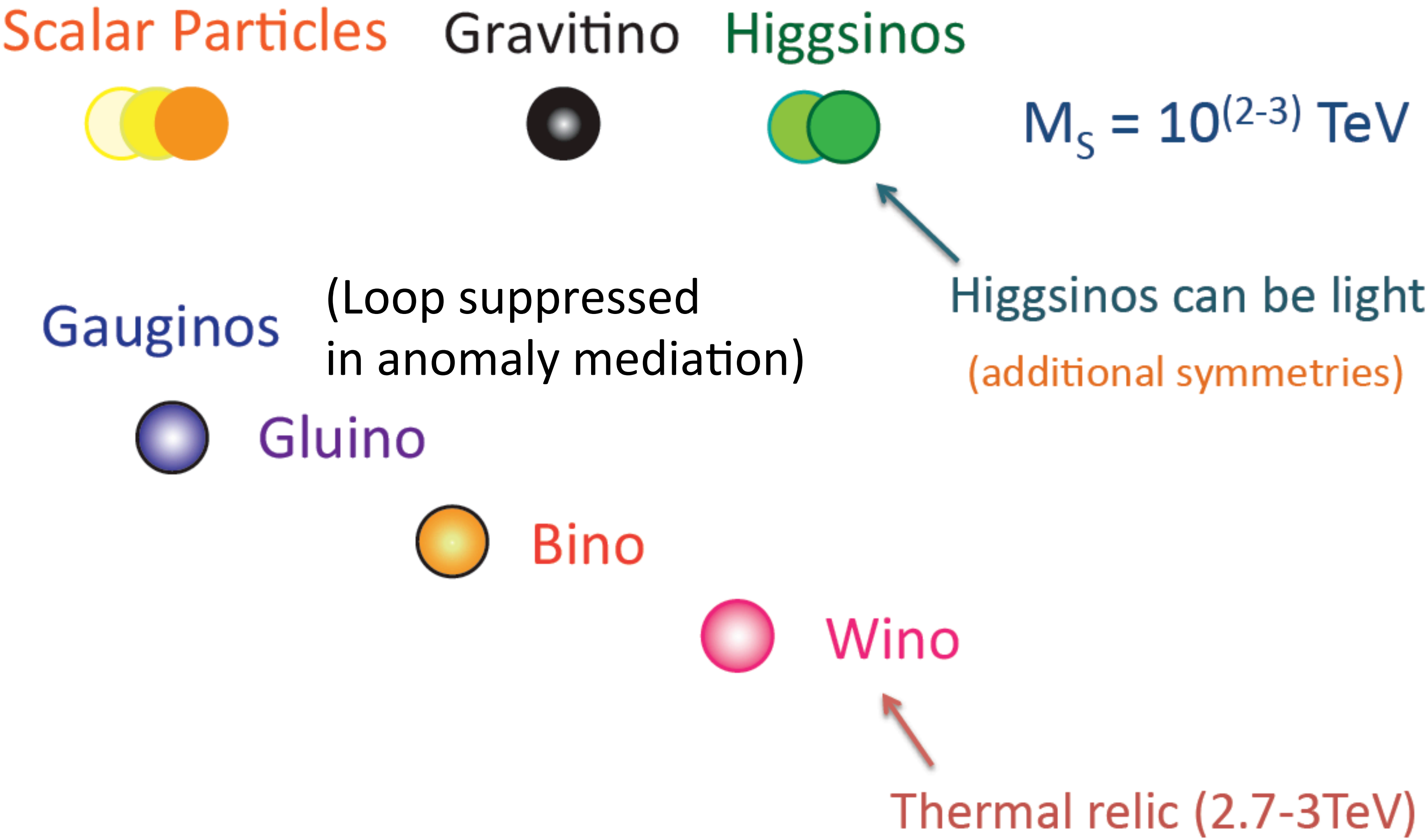
Higgs mass in High-scale SUSY



(Ibe, Matsumoto, Yanagida (12))

For tanβ~2-5, 125 GeV Higgs mass is well-explained in High-scale SUSY (~O($10^{2\text{-}3}$) TeV). This is consistent with various problems in SUSY SM (flavor, CP, gravitino, proton decay…)

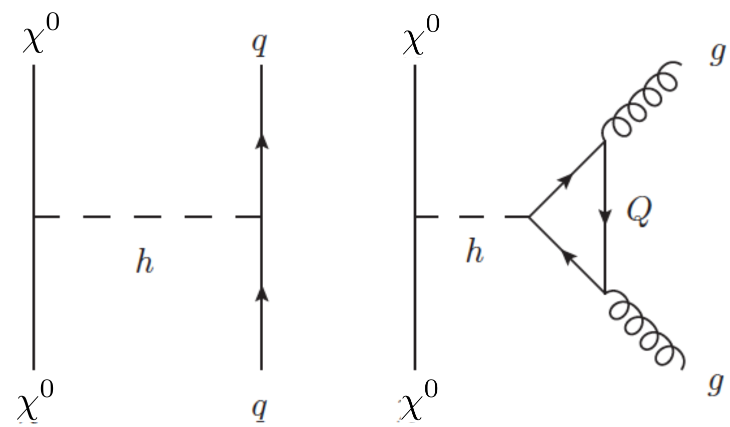
Mass spectrum in High-scale SUSY



J. Hisano, S. Matsumoto, M. Nagai, O. Saito, M. Senami (2006).

Tree-level contribution to SI interaction of wino

Higgsino-Wino mixing induces to tree-level coupling with Higgs boson, though it is suppressed by m_W/μ (μ:Higgsino mass). In the case, loop contributions are dominant.



q : light quarks (u,d,s)

Q: heavy quarks (c,b,t)

Effective SI interaction at parton level

Effective SI interactions of Majorana fermion χ^0 at parton level up to D=7:

$$\mathcal{L}_{\rm eff} = \sum_{i=q,G} C^i_{\rm S}\mathcal{O}^i_{\rm S} + \sum_{i=q,G}(C^i_{{\rm T}_1}\mathcal{O}^i_{{\rm T}_1} + C^i_{{\rm T}_2}\mathcal{O}^i_{{\rm T}_2})$$

- Scalar operators:

$$\mathcal{O}^q_{\rm S} \equiv m_q\bar{\chi}^0\chi^0\bar{q}q \qquad \mathcal{O}^G_{\rm S} \equiv \frac{\alpha_s}{\pi}\bar{\chi}^0\chi^0 G^a_{\mu\nu}G^{a\mu\nu}$$

M : WIMP mass
m_q: quark mass

- Twist-2 operators:

$$\mathcal{O}^i_{{\rm T}_1} \equiv \frac{1}{M}\bar{\chi}^0 i\partial^\mu\gamma^\nu\chi^0\mathcal{O}^i_{\mu\nu} \qquad \mathcal{O}^i_{{\rm T}_2} \equiv \frac{1}{M^2}\bar{\chi}^0(i\partial^\mu)(i\partial^\nu)\chi^0\mathcal{O}^i_{\mu\nu}$$

Twist-2 operators for quarks and gluon:

$$\mathcal{O}^q_{\mu\nu} \equiv \frac{1}{2}\bar{q}i\left(D_\mu\gamma_\nu + D_\nu\gamma_\mu - \frac{1}{2}g_{\mu\nu}\not{D}\right)q \qquad \mathcal{O}^G_{\mu\nu} \equiv G^{a\rho}_\mu G^a_{\nu\rho} - \frac{1}{4}g_{\mu\nu}G^a_{\rho\sigma}G^{a\rho\sigma}$$

Nuclear matrix elements

- Scalar operators :

$$\langle N | m_q \bar{q} q | N \rangle \equiv m_N f_{T_q}^{(N)} \qquad (f_{T_q}^{(N)}\text{: mass fraction})$$

$$\langle N | \frac{\alpha_s}{\pi} G^a_{\mu\nu} G^{a\mu\nu} | N \rangle = m_N \frac{4\alpha_s^2}{\pi \beta(\alpha_s; N_f = 3)} [1 - (1 - \gamma_m) \sum_q f_{Tq}^{(N)}]$$

(From trace anomaly)

1. Mass fractions $f_{T_q}^{(N)}$ come from Lattice QCD outputs.

Proton		Neutron	
$f_{T_u}^{(p)}$	0.019(5)	$f_{T_u}^{(n)}$	0.013(3)
$f_{T_d}^{(p)}$	0.027(6)	$f_{T_d}^{(n)}$	0.040(9)
$f_{T_s}^{(p)}$	0.009(22)	$f_{T_s}^{(n)}$	0.009(22)

2. Matrix elements in our operator definition are $\mathcal{O}(m_N)$. This imply that we have to evaluate one-loop higher diagrams for gluon than those for quarks
3. Quark operator and gluon operator are RG-inv at least at $\mathcal{O}(\alpha_s)$.

Nuclear matrix elements

- Twist-2 operators:

$$\langle N(p)|\mathcal{O}^q_{\mu\nu}|N(p)\rangle = m_N\left(\frac{p_\mu p_\nu}{m_N^2}-\frac{1}{4}g_{\mu\nu}\right)(q^{(N)}(2;\mu)+\bar{q}^{(N)}(2;\mu))$$

$$\langle N(p)|\mathcal{O}^G_{\mu\nu}|N(p)\rangle = -m_N\left(\frac{p_\mu p_\nu}{m_N^2}-\frac{1}{4}g_{\mu\nu}\right)g^{(N)}(2;\mu)$$

The 2nd moments of parton-distribution functions (PDFs)

$$q^{(N)}(2;\mu)=\int_0^1 dx\ x\ q^{(N)}(x,\mu) \qquad g^{(N)}(2;\mu)=\int_0^1 dx\ x\ g^{(N)}(x,\mu)$$

1. The 2nd moments of PDFs at $\mu = m_Z$ comes from CTEQ PDFs.

$g(2)$	$0.464(2)$		
$u(2)$	$0.223(3)$	$\bar{u}(2)$	$0.036(2)$
$d(2)$	$0.118(3)$	$\bar{d}(2)$	$0.037(3)$
$s(2)$	$0.0258(4)$	$\bar{s}(2)$	$0.0258(4)$
$c(2)$	$0.0187(2)$	$\bar{c}(2)$	$0.0187(2)$
$b(2)$	$0.0117(1)$	$\bar{b}(2)$	$0.0117(1)$

2. Matrix elements in our operator definition are $\mathcal{O}(m_N)$.

Strategy to evaluate SI coupling of nucleon

Evaluate the Wilson coefficients at $\mu_W \simeq m_Z$ with Nf=5 active quarks by integrating out heavy particles.

↓

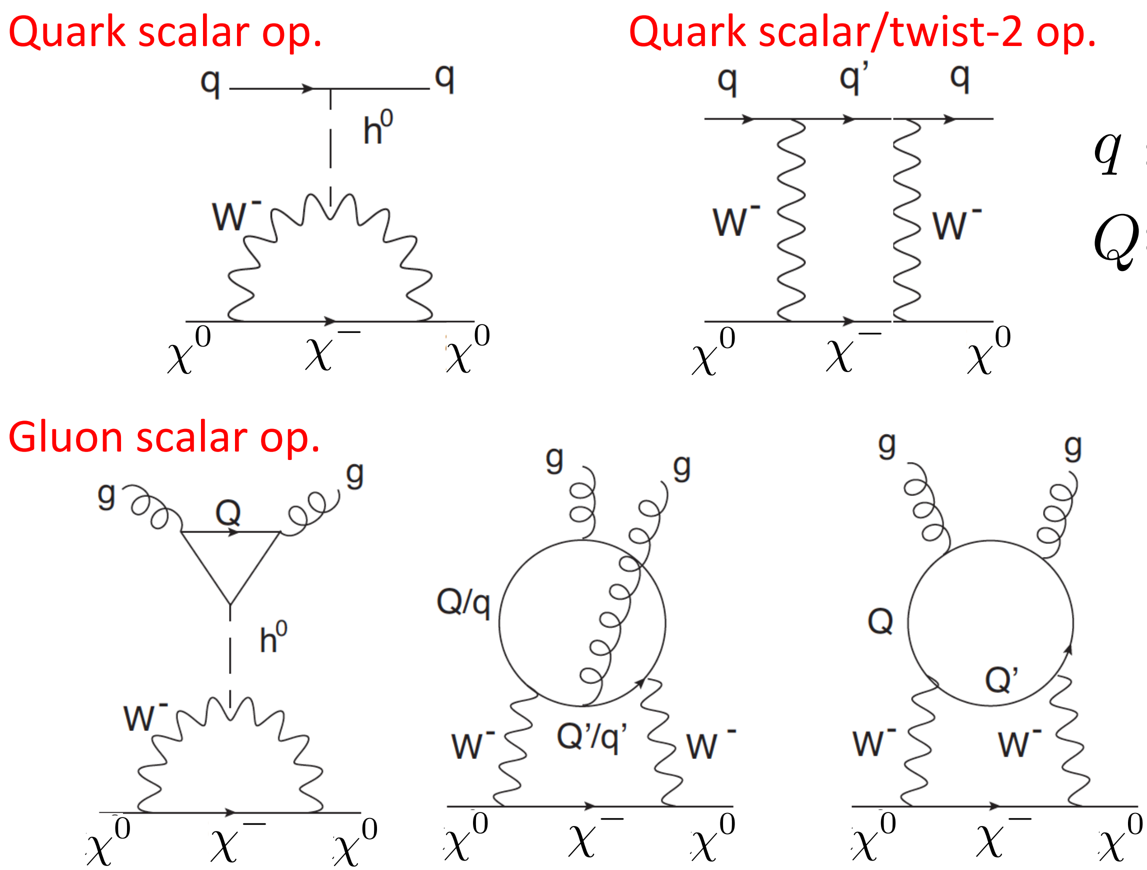
Evolve the the Wilson coefficients down to the scale at which the nucleon matrix elements are evaluated.

↓

Express the SI coupling with nucleon.

Scalar operators and twist-2 operators are not mixed with each other in RG flow so that we can evaluate those contributions to the SI coupling with nucleon separately.

Loop-level contribution to SI interaction @ LO of α_s

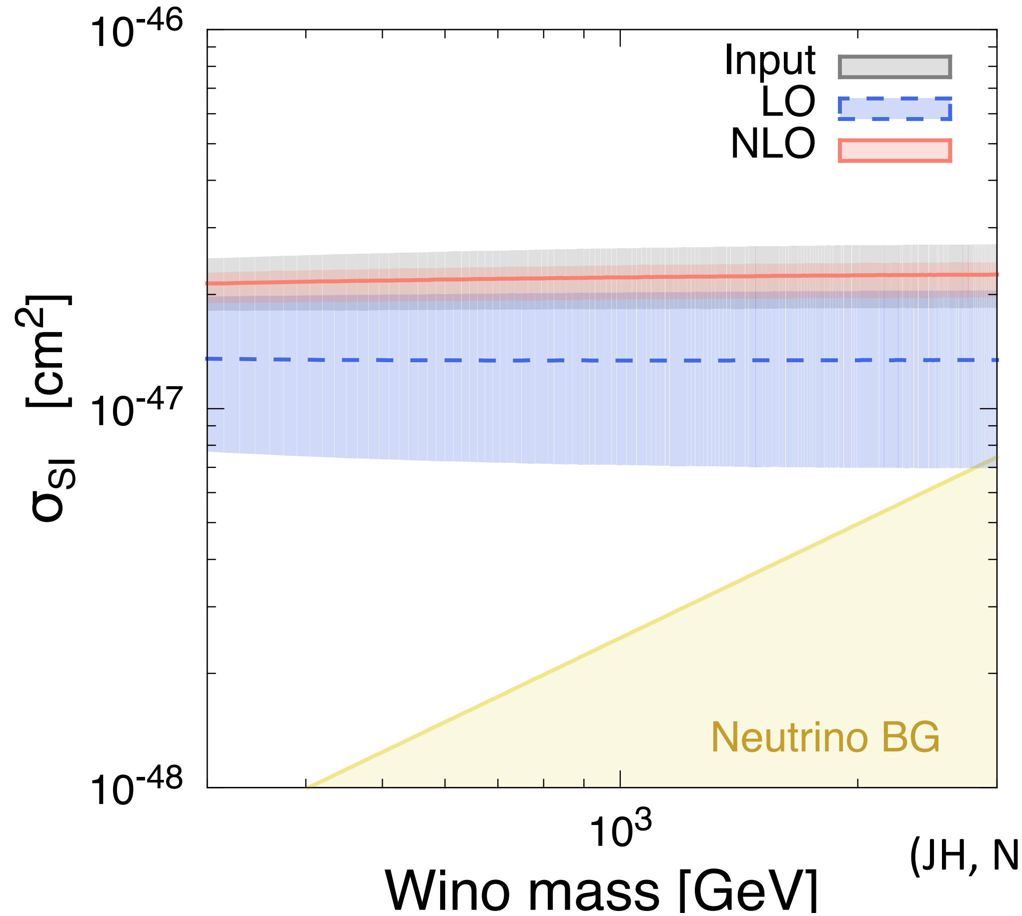


q : light quarks (u,d,s)

Q: heavy quarks (c,b,t)

These contributions are not suppressed by power of of wino mass. When Higgsino mass is much heavier than wino one, loop-level contribution dominates over tree-level one. (JH, Matsumoto, Nojiri, Saito)

SI cross section of wino with nucleon at NLO of α_s

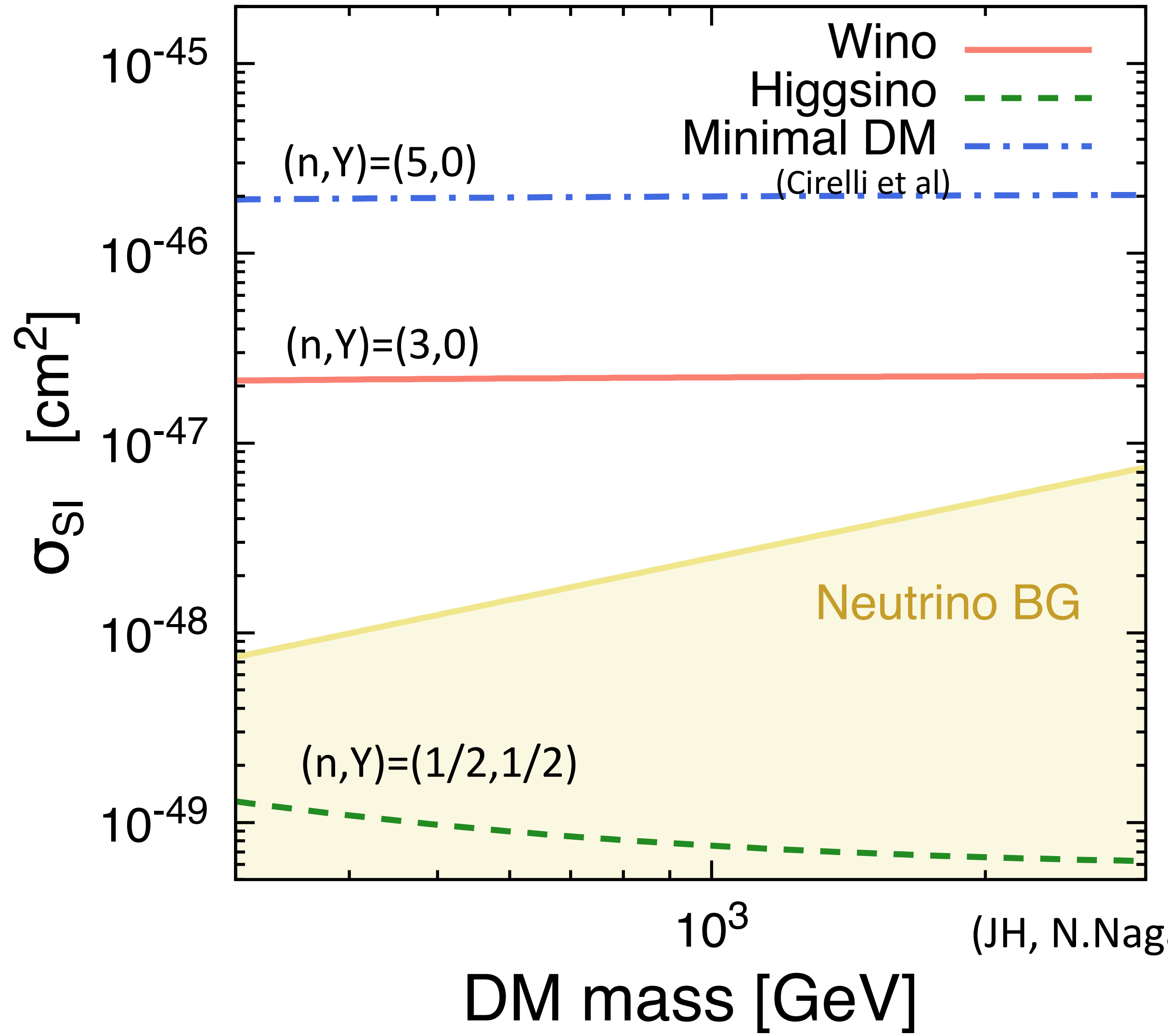


(JH, N.Nagata, K. Ishiwata,2015)

- In a heavy wino mass limit, $\sigma^p_{\rm SI} = 2.3\ {}^{+0.2}_{-0.3}\ {}^{+0.5}_{-0.4} \times 10^{-47}\ {\rm cm}^2$ (first error: higher order, second one: input)
- Thermal wino DM (M~3TeV) has larger cross section than neutrino BG.

Electroweakly-interacting dark matter

Neutral fermions with only weak interactions are DM candidates.



(JH, N.Nagata, K. Ishiwata,2015)

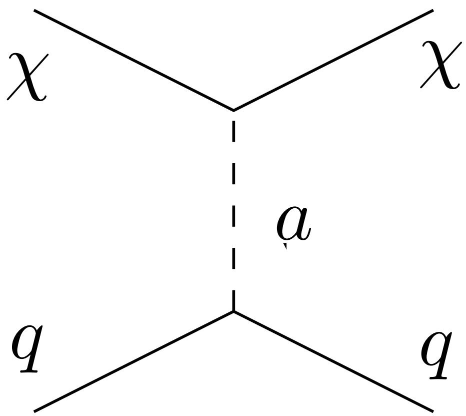
Peudo scalar mediated dark matter direct detection

T. Abe, M. Fujiwara, JH
(in preparation)

Pseudo scalar mediated coupling

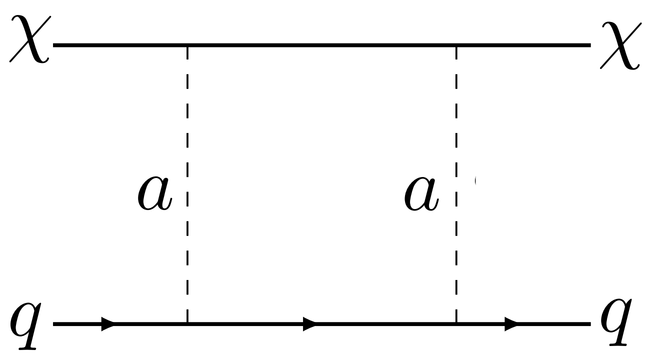
Tree-level scattering is spin-dependent, and suppressed by momentum transfer. The cross section is too small to be observed.

(Escudero et al, 2016)



$$\bar{\chi}\gamma_5\chi\bar{q}\gamma_5 q \Rightarrow (\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q})$$

The loop diagrams can dominate over the tree-level diagrams since they can induce spin-independent scattering. (Arcadi et al, 2017)



Pseudo Scalar Mediator DM Model

Pesude scalar (a_0)+Two-Higgs doublets ($H_{1/2}$) + Majorana fermion (χ)

(Ipek, Mckeen, Neslon, 1214)

$$\mathcal{L} \supset + i\frac{g_\chi}{2} a_0 \bar{\chi}\gamma^5\chi - (V_{\rm THDM} + V_{a_0} + V_{\rm port}) \,,$$

where

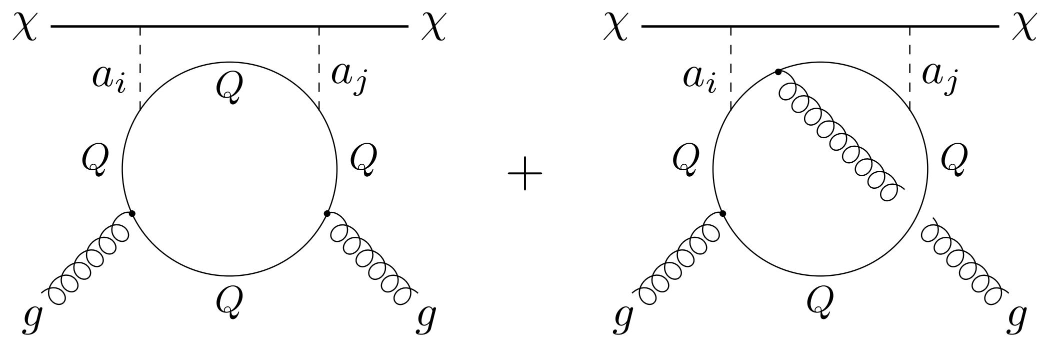
$$V_{\rm port} = \kappa(i a_0 H_1^\dagger H_2 + {\rm h.c.}) + c_1 a_0^2 H_1^\dagger H_1 + c_2 a_0^2 H_2^\dagger H_2.$$

$$\begin{aligned} V_{\rm THDM} =& m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - m_3^2 \left(H_1^\dagger H_2 + {\rm h.c.}\right) \\ &+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ &+ \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + {\rm h.c.}\right], \end{aligned}$$

$$V_{a_0} = \frac{1}{2} m_{a_0}^2 a_0^2 + \frac{\lambda_{a_0}}{4} a_0^4$$

CP symmetry and softly broken Z_4 symmetry are imposed.

Loop-level contribution to SI interaction



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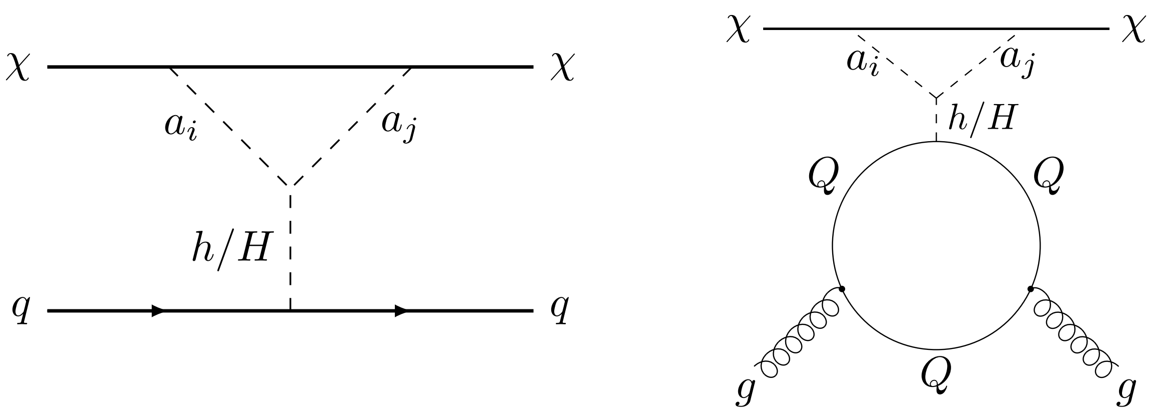
Q: heavy quarks (c,b,t)

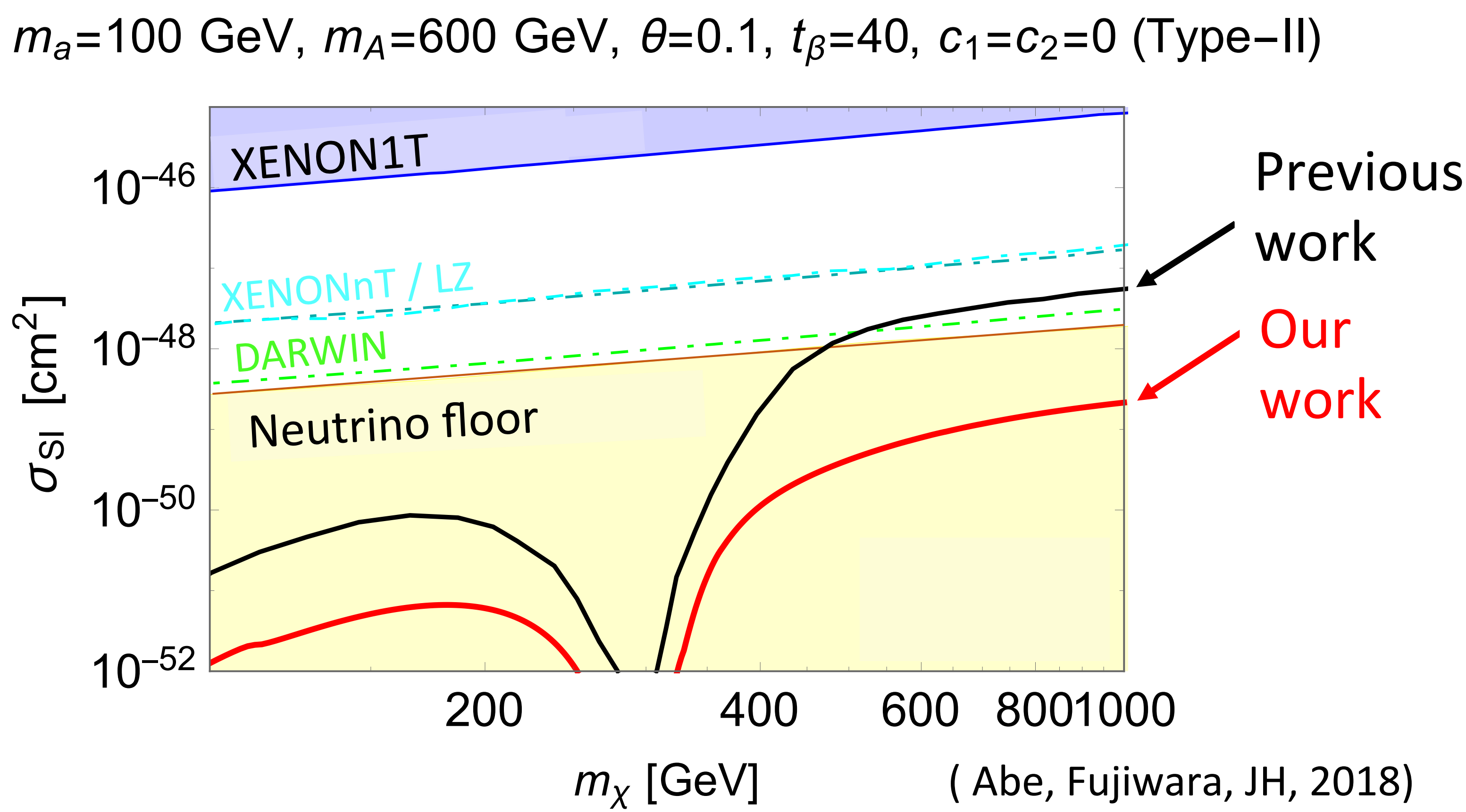


In previous work,

- Gluon contribution at two-loop level are not correctly evaluated.
- Three point vertices (h-a-a) are not included.
- Operator decomposing is not complete, though numerically small.

$$\frac{1}{2}\bar{q}i(\partial_\mu\gamma_\nu + \partial_\nu\gamma_\mu)q = \mathcal{O}^q_{\mu\nu} + \frac{1}{4}g_{\mu\nu}m_q\bar{q}q$$

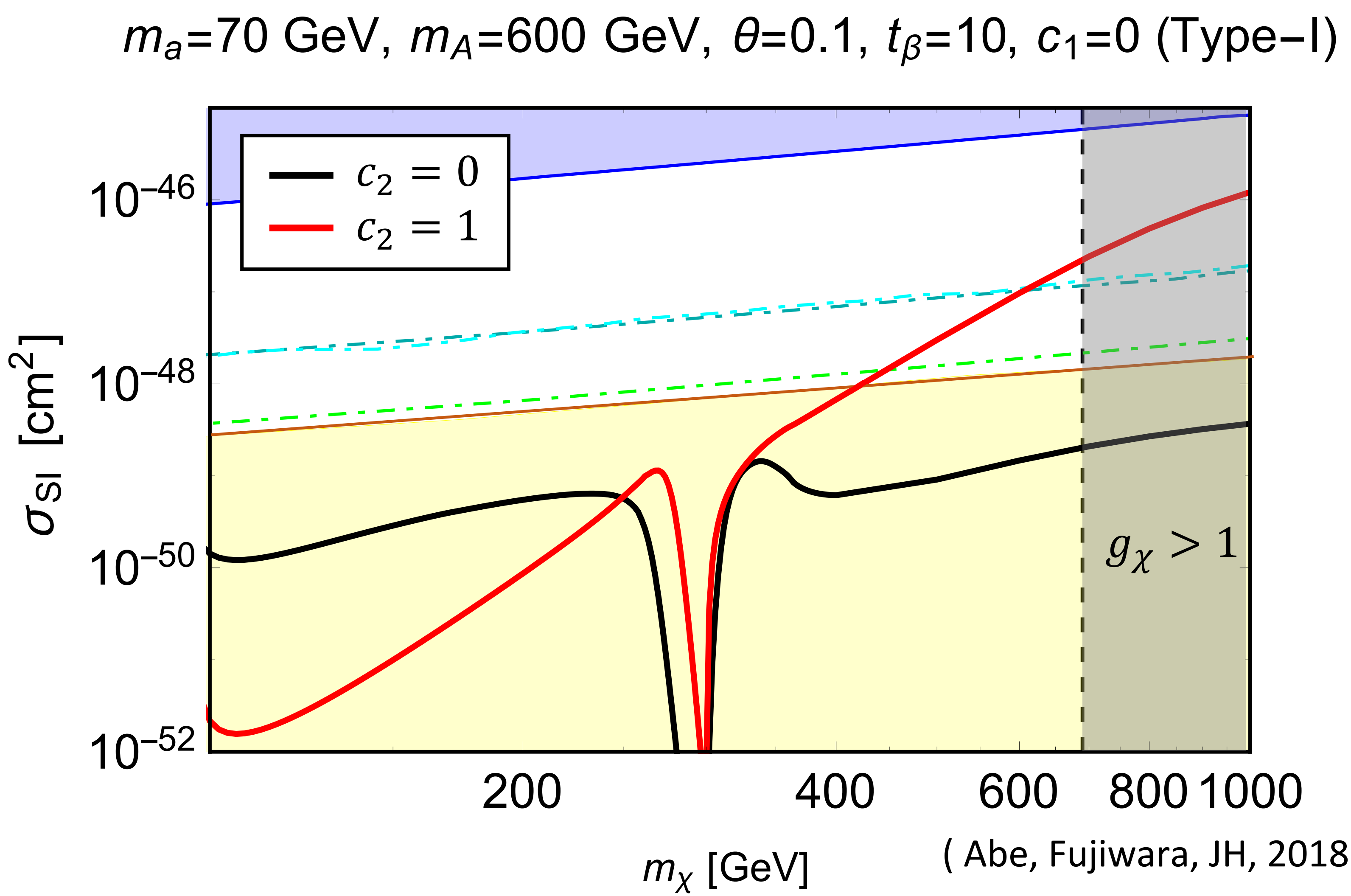
SI cross section is sadly suppressed



(Abe, Fujiwara, JH, 2018)

Here, coupling constant for $+i\frac{g_\chi}{2}a_0\bar{\chi}\gamma^5\chi$ is scaled so that the thermal relic abundance is consistent with observed DM density.

Still we have a chance in future.



(Abe, Fujiwara, JH, 2018)

$$V_{\rm port} = \kappa(ia_0 H_1^\dagger H_2 + \text{h.c.}) + c_1 a_0^2 H_1^\dagger H_1 + c_2 a_0^2 H_2^\dagger H_2.$$

Dirac fermion dark matter direct detection

JH, N. Nagata, R. Nagai
(2018)

Dirac fermion dark matter

- If Dirac fermion has one-zero hypercharge, Y, SI cross section with neutron is about Y^2 times $10^{-39}cm^2$. The mass must be larger than ~10^5 TeV if they are DM.

- If the Dirac fermion is gauge singlet and coupled with SM particles at loop level, it is still a viable DM candidate as will be shown.

- The thermal relic abundance is suppressed by s-wave annihilation so that the DM mass is favored to be heaver . (Good for null results @ LHC)

- The stability comes from global $U(1)_D$. The asymmetric dark matter is one of the motivation for the Dirac fermion DM.

SI cross section

Effective coupling of Dirac fermion DM:

1) Contact interactions,

$$\mathcal{L}_{\text{eff}-N} = f_V^{(N)}\overline{\chi}\gamma^\mu\chi\overline{N}\gamma_\mu N + f_S^{(N)}\overline{\chi}\chi\overline{N}N \ ,$$

2) EM interactions,

$$\mathcal{L}_{\text{eff}-\gamma} = \frac{1}{2}C_M^\gamma\overline{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} - \frac{i}{2}C_E^\gamma\overline{\chi}\sigma^{\mu\nu}\gamma_5\chi F_{\mu\nu} + C_R^\gamma\overline{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}$$

The differential SI cross section with nuclei (E_R :recoil energy)

$$\frac{d\sigma_{\chi T}}{dE_R} = F_c^2(E_R)\Bigg[\frac{Z^2e^2}{4\pi}\left(\frac{1}{E_R} - \frac{1}{E_R^{\max}(v_{\text{rel}}^2)}\right)(C_M^\gamma)^2 + \frac{Z^2e^2}{4\pi v_{\text{rel}}^2}\frac{1}{E_R}(C_E^\gamma)^2$$
$$+ \frac{m_T}{2\pi v_{\text{rel}}^2}\left|Z\left(f_S^{(p)} + f_V^{(p)} - eC_R^\gamma - \frac{e}{2m_\chi}C_M^\gamma\right) + (A-Z)\left(f_S^{(n)} + f_V^{(n)}\right)\right|^2\Bigg]$$

Here, $E_R^{\max}(v_{\text{rel}}^2) = 2m_\chi^2 m_T v_{\text{rel}}^2/(m_\chi + m_T)^2$ is maximum recoil energy for fixed relative velocity (v_{rel}). MDM or EDM contribution may be dominant, and accidental cancel with various terms does not occurs.

(Banks et al, 10)

Models

- Global $U(1)_D$ is introduced.
- Mediators have the same gauge quantum numbers as in those in SM so that they can transit to SM fields.
- Mediator fermions are $U(1)_D$ neutral while scalars are charged.

	Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_D$
DM	ξ_χ	$1/2$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$
	η_χ	$1/2$	$\mathbf{1}$	$\mathbf{1}$	0	-1
Model 1	ξ_Q	$1/2$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	0
	η_Q	$1/2$	$\overline{\mathbf{3}}$	$\mathbf{2}$	$-\frac{1}{6}$	0
	$\widetilde{Q}$	0	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$+1$
	$\xi_{\bar{u}}$	$1/2$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	0
	$\eta_{\bar{u}}$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	0
	$\widetilde{\bar{u}}$	0	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	-1
	$\xi_{\bar{d}}$	$1/2$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	0
	$\eta_{\bar{d}}$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	0
	$\widetilde{\bar{d}}$	0	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	-1
Model 2	ξ_L	$1/2$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	0
	η_L	$1/2$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0
	$\widetilde{L}$	0	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$+1$
	$\xi_{\bar{e}}$	$1/2$	$\mathbf{1}$	$\mathbf{1}$	1	0
	$\eta_{\bar{e}}$	$1/2$	$\mathbf{1}$	$\mathbf{1}$	-1	0
	$\widetilde{\bar{e}}$	0	$\mathbf{1}$	$\mathbf{1}$	1	-1

Interactions

- DM-mediator interactions

$$\mathcal{L}_{\chi f\tilde{f}} = a_Q\,\xi_\chi\xi_Q\widetilde{Q}^* + b_Q\,\eta_\chi\eta_Q\widetilde{Q} + a_{\bar{u}}\,\xi_\chi\eta_{\bar{u}}\widetilde{\bar{u}} + b_{\bar{u}}\,\eta_\chi\xi_{\bar{u}}\widetilde{\bar{u}}^* + a_{\bar{d}}\,\xi_\chi\eta_{\bar{d}}\widetilde{\bar{d}} + b_{\bar{d}}\,\eta_\chi\xi_{\bar{d}}\widetilde{\bar{d}}^*$$
$$+ a_L\,\xi_\chi\xi_L\widetilde{L}^* + b_L\,\eta_\chi\eta_L\widetilde{L} + a_{\bar{e}}\,\xi_\chi\eta_{\bar{e}}\widetilde{\bar{e}} + b_{\bar{e}}\,\eta_\chi\xi_{\bar{e}}\widetilde{\bar{e}}^* + \mathrm{h.c.}\ .$$

- Mediator-Higgs interactions

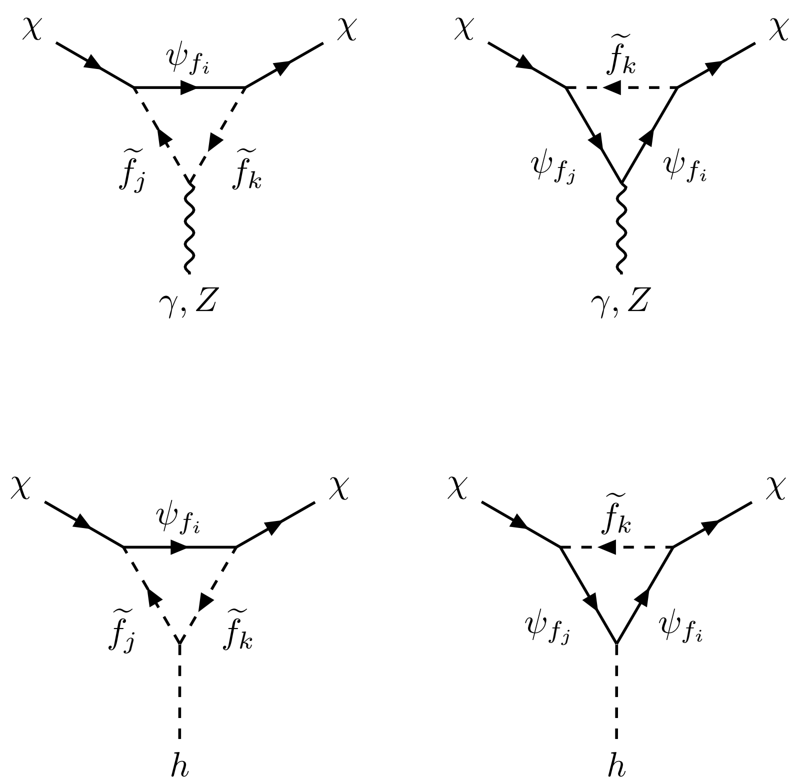
$$\begin{aligned}\mathcal{L}_{\mathrm{Yukawa}} = &- \kappa_{\bar{u}}\xi_{\bar{u}}\epsilon_{\alpha\beta}(\xi_Q)_\alpha(H)_\beta - \kappa'_{\bar{u}}\eta_{\bar{u}}(\eta_Q)^\alpha(\widetilde{H})_\alpha \\ &- \kappa_{\bar{d}}\xi_{\bar{d}}(\xi_Q)_\alpha(H^\dagger)^\alpha - \kappa'_{\bar{d}}\eta_{\bar{d}}(\eta_Q)^\alpha(H)_\alpha \\ &- \kappa_{\bar{e}}\xi_{\bar{e}}(\xi_L)_\alpha(H^\dagger)^\alpha - \kappa'_{\bar{e}}\eta_{\bar{e}}(\eta_L)^\alpha(H)_\alpha + \mathrm{h.c.}\end{aligned}$$

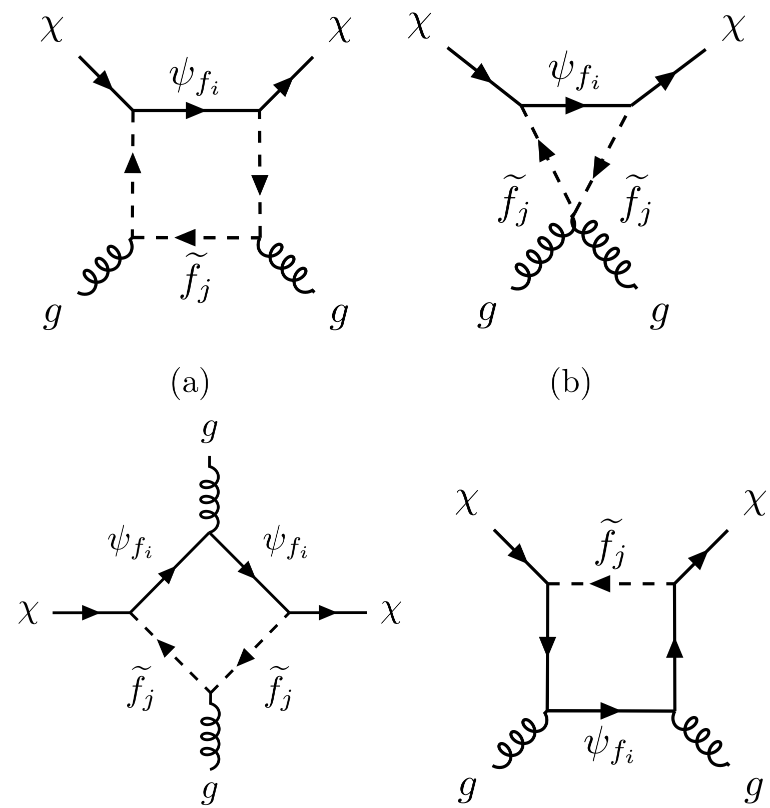
$$\mathcal{L}_{\mathrm{tri}} = -A_{\bar{u}}\widetilde{\bar{u}}\epsilon_{\alpha\beta}(\widetilde{Q})_\alpha(H)_\beta - A_{\bar{d}}\widetilde{\bar{d}}(\widetilde{Q})_\alpha(H^\dagger)^\alpha - A_{\bar{e}}\widetilde{\bar{e}}(\widetilde{L})_\alpha(H^\dagger)^\alpha + \mathrm{h.c.}\ .$$

$$\mathcal{L}_{\mathrm{quart}} = -\sum_f \lambda_f|\widetilde{f}|^2|H|^2 - \lambda'_Q\widetilde{Q}^\dagger\tau_a\widetilde{Q}H^\dagger\tau_a H - \lambda'_L\widetilde{L}^\dagger\tau_a\widetilde{L}H^\dagger\tau_a H + \ldots$$

Coupling constants a and b are complex, and relative phases contribute to DM EDM.

Diagrams for SI scattering

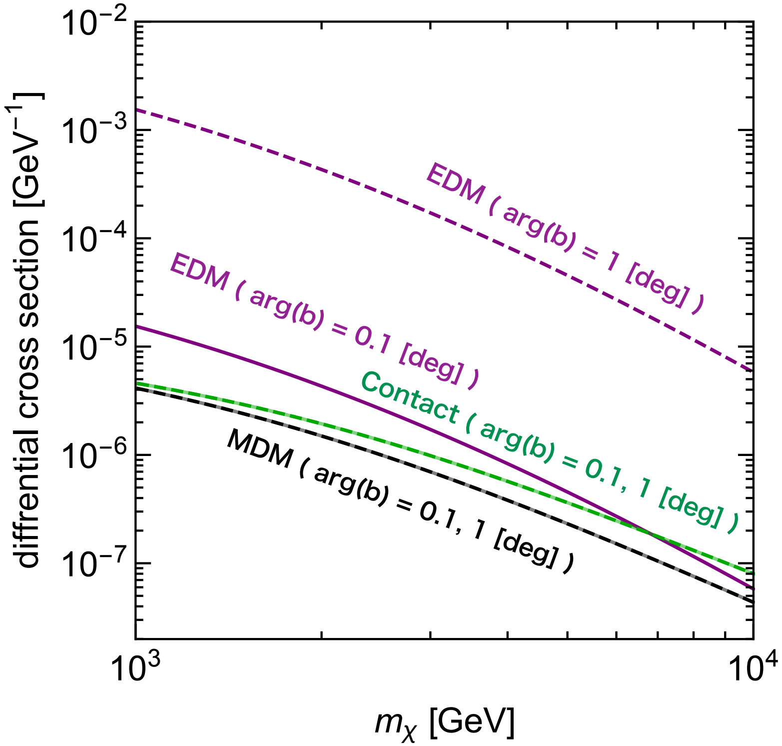




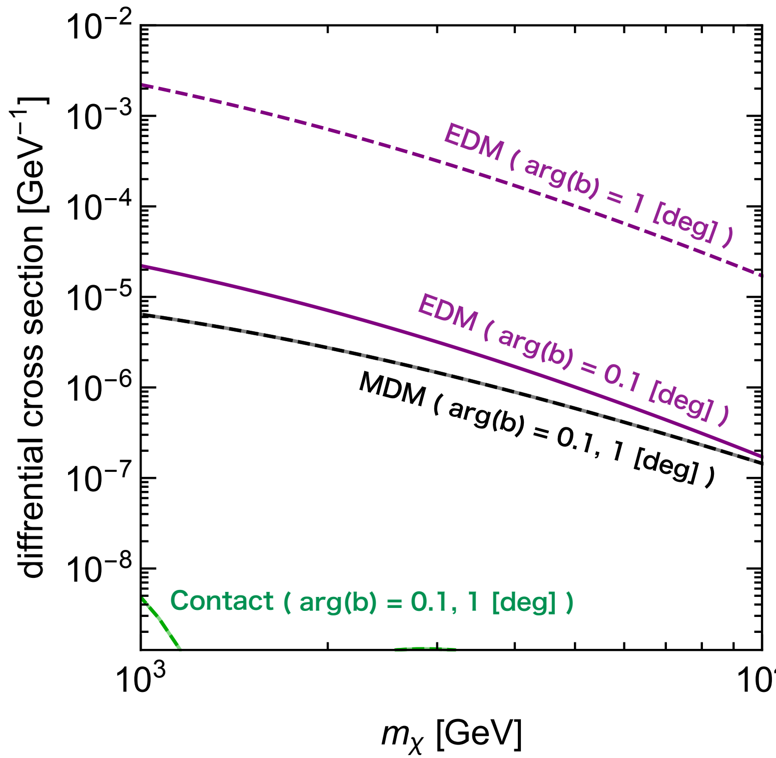
Differential cross section (^{131}Xe)

(JH, N. Nagata, R. Nagai)

Model 1



Model 2

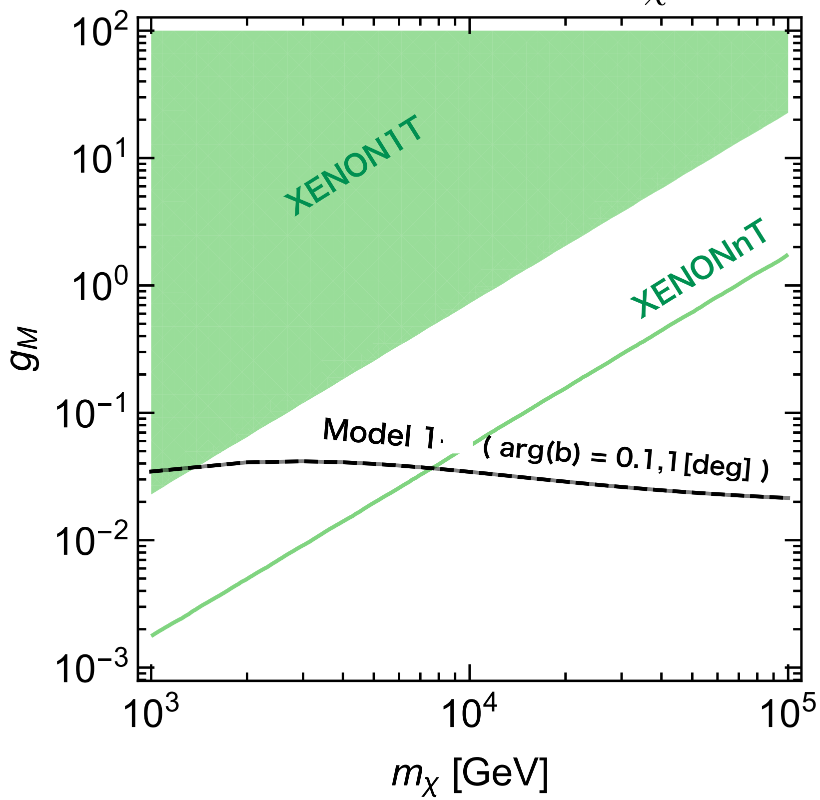


$E_R = 30$ keV, $v_{\rm rel} = 232$ km/s, $Z = 54$, $A = 131$, and $m_T \simeq 122$ GeV (for ^{131}Xe)
$a = |b| = 1$, $\lambda'_Q = \lambda'_L = 0$, $\lambda_f = \kappa_{\bar{f}} = \kappa'_{\bar{f}} = 0.5$,
$\mu_Q = \mu_L = 800$ GeV, $\mu_{\bar{u}} = 750$ GeV, $\mu_{\bar{d}} = \mu_{\bar{e}} = 700$ GeV, while $\widetilde{m}_Q = \widetilde{m}_L = 1.2M$,
$\widetilde{m}_{\bar{u}} = 1.1M$, $\widetilde{m}_{\bar{d}} = \widetilde{m}_{\bar{e}} = M$, and $A_{\bar{f}} = 2M$

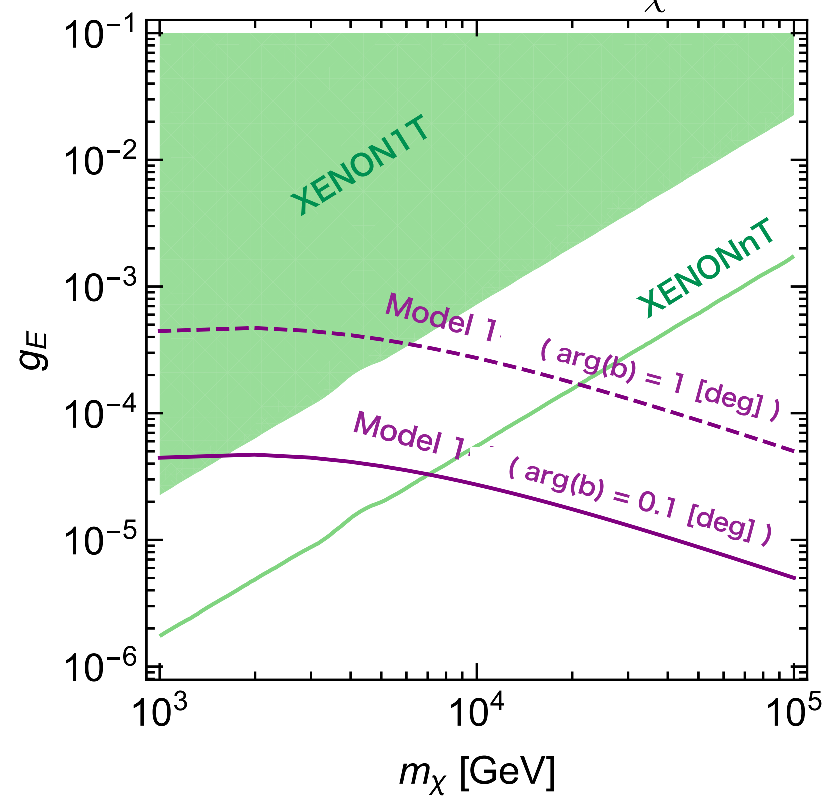
Constraints on MDM and EDM of Dirac fermion DM

(JH, N. Nagata, R. Nagai)

MDM ($C_M^\gamma \equiv \dfrac{eg_M}{4m_\chi}$)



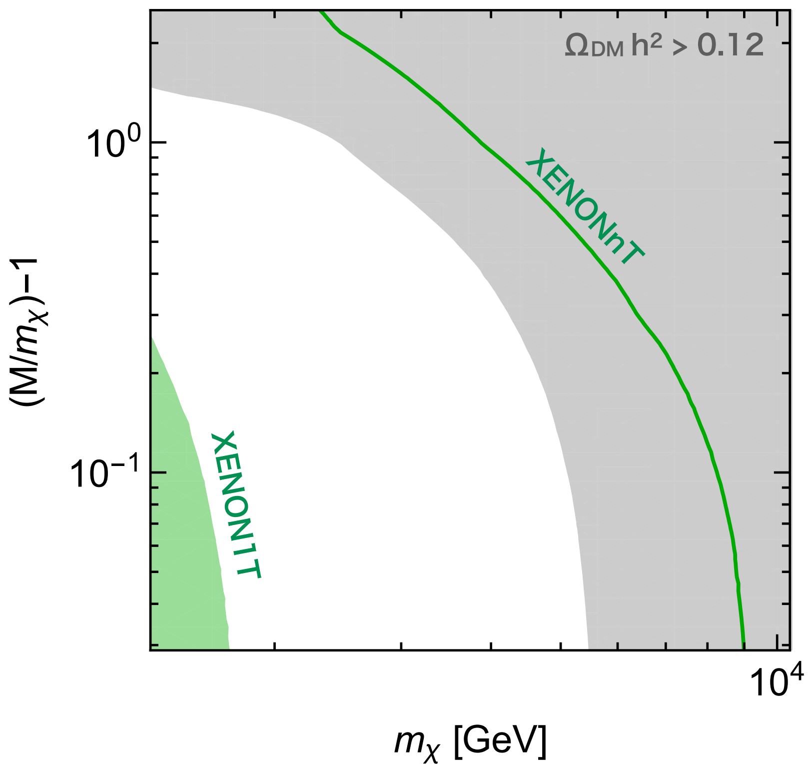
EDM ($C_E^\gamma \equiv \dfrac{eg_E}{4m_\chi}$)



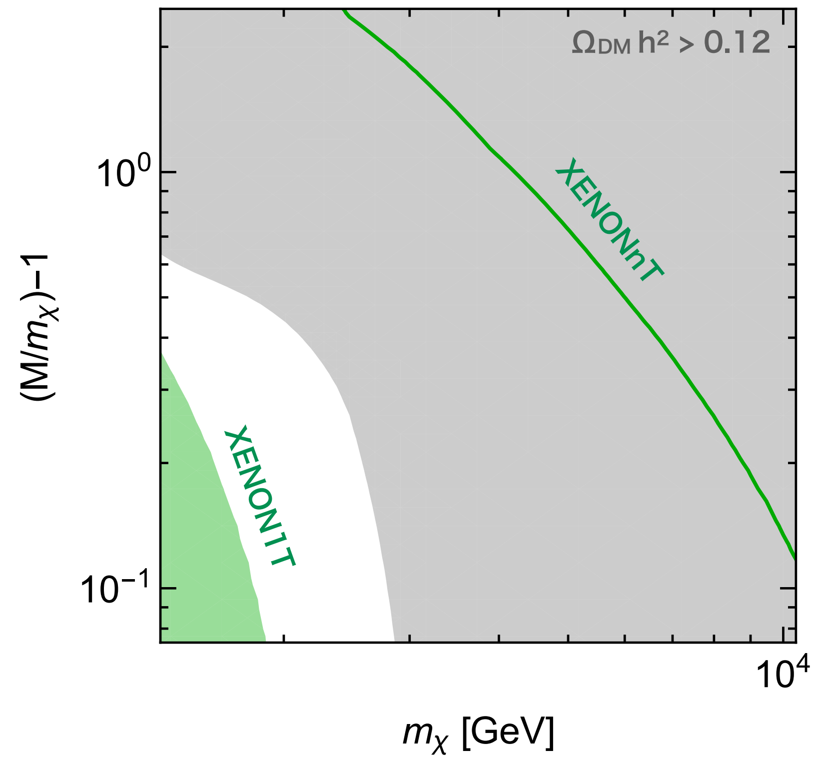
XENON1T constraint (CP conserving)

(JH, N. Nagata, R. Nagai)

Model 1



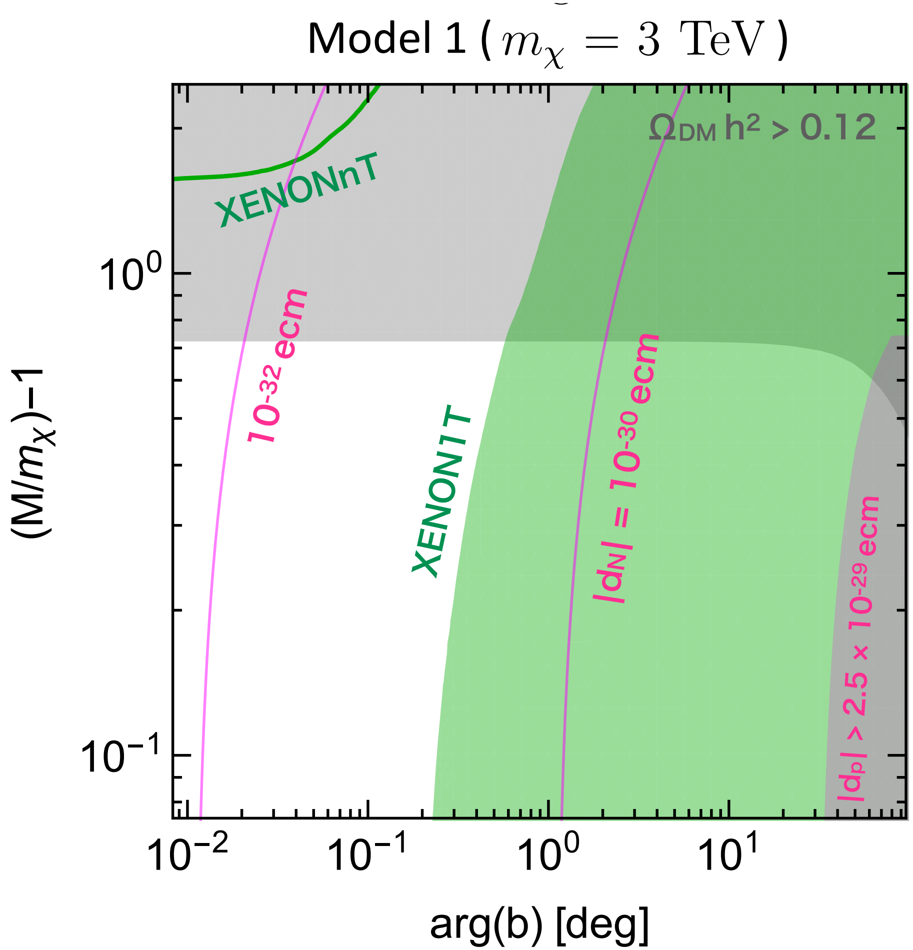
Model 2

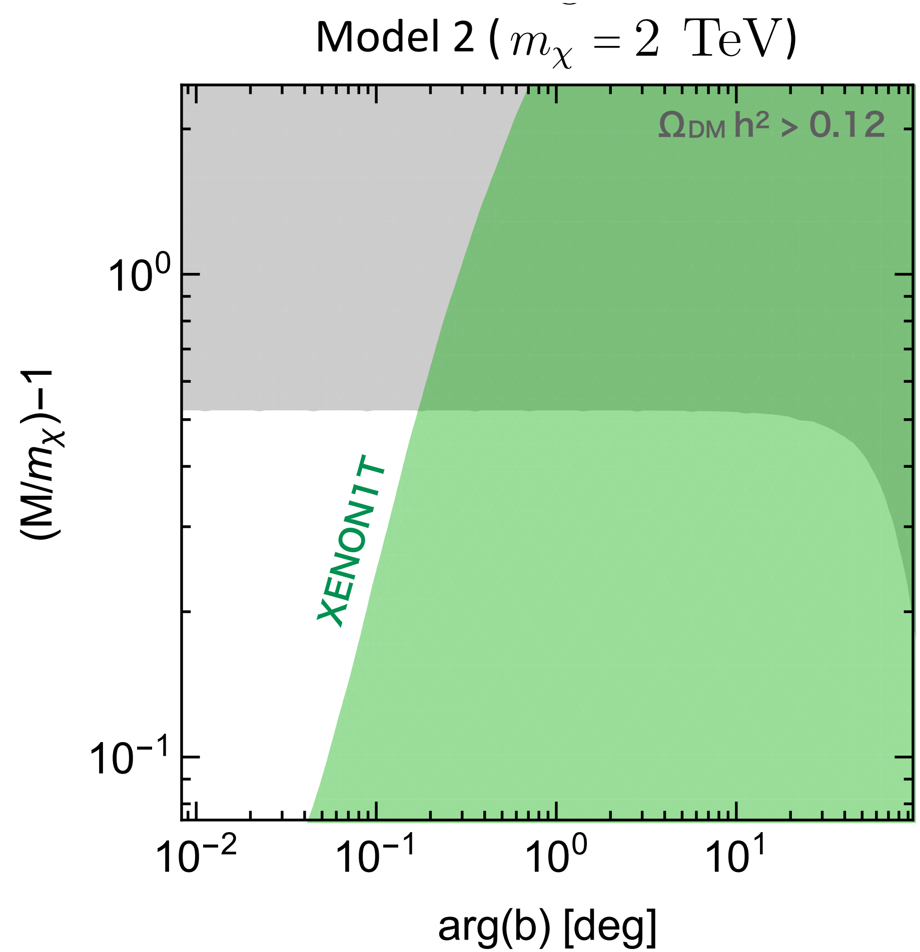


Dirac fermion dark matter is still viable, though it can be severely tested at XENONnT.

XENON1T constraint (CP violating)

(JH, N. Nagata, R. Nagai)





Summary of this talk

Dark matter is a window to BSM. Improvements of direct detection experiments using noble liquid are quite impressive now. Future experiments are sensitive to models in which DM is coupled with SM fields at loop level. We discussed about such three models,

- Wino dark matter
- Peudo scalar mediated (singlet fermion) dark matter
- Dirac fermion dark matter