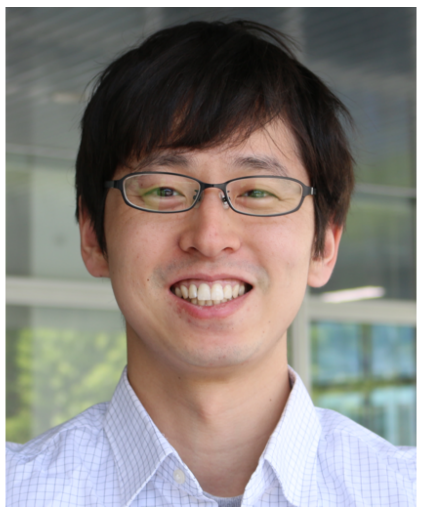
Loop corrections to dark matter direct detection in a pseudoscalar mediator dark matter model



Tomohiro Abe

Institute for Advanced Research,
KMI, Nagoya U.

高等研究院 名古屋大学

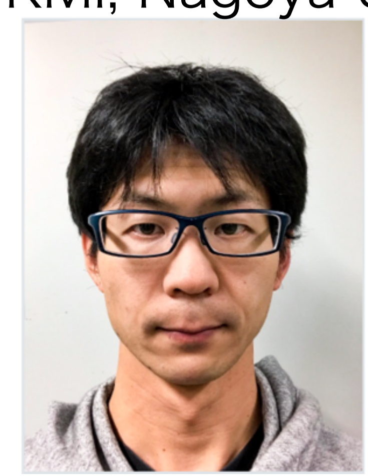
Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

in collaboration with

Junji Hisano
Nagoya U, KMI, Kavli IPMU

Motoko Fujiwara
Nagoya U.

Yutaro Shoji
KMI, Nagoya U.

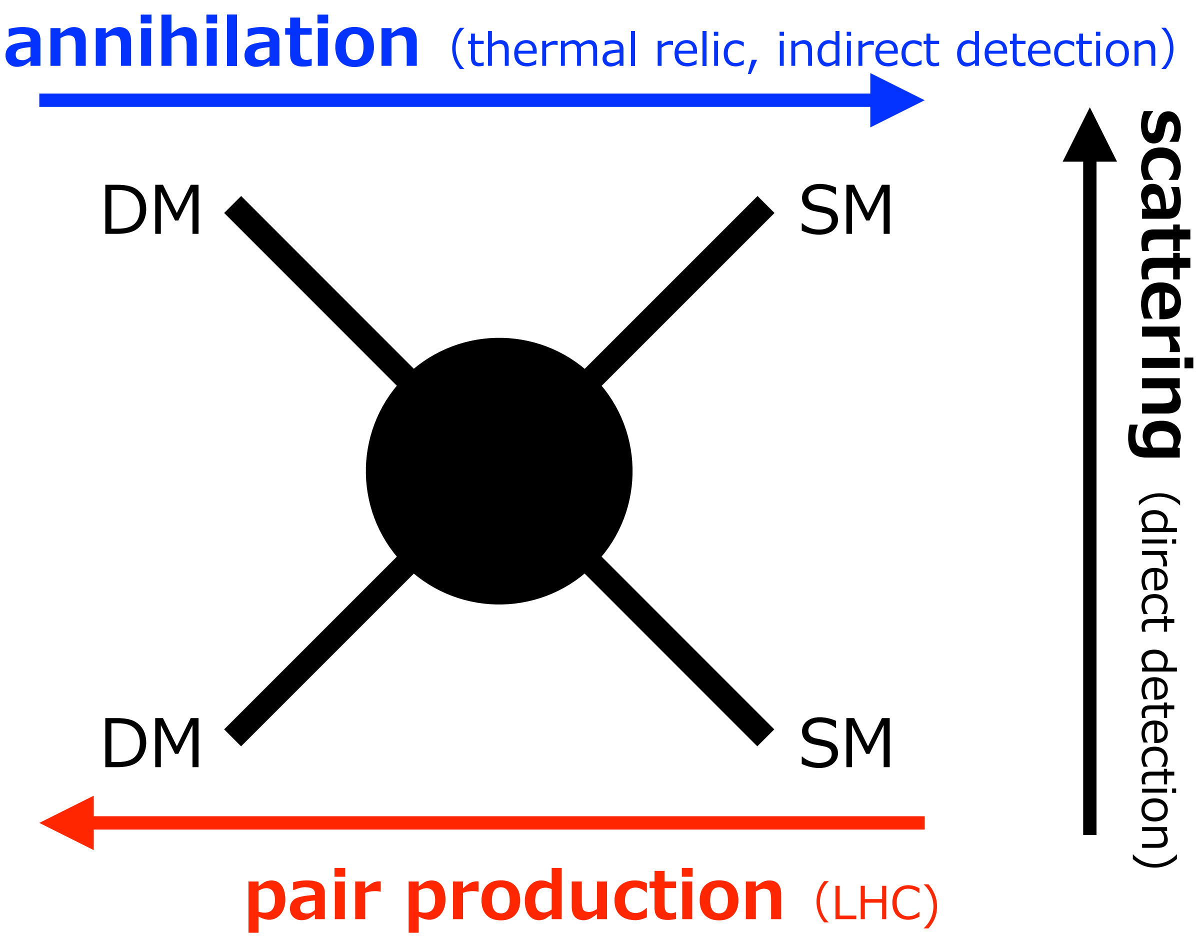


This talk is based on **JHEP 1902 (2019) 028** (arXiv:1810.01039) and an ongoing project

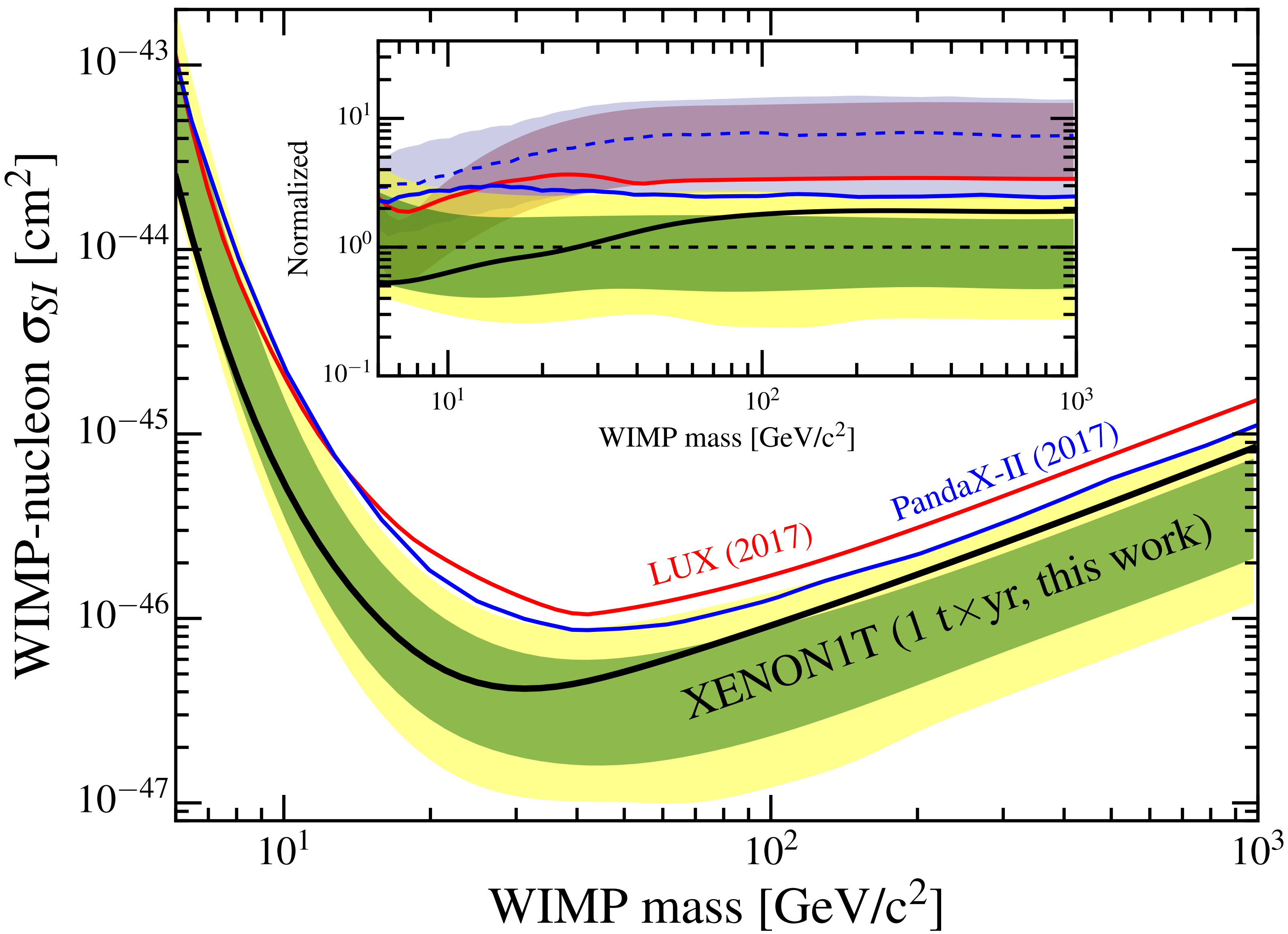
WIMP dark matter

Features of WIMP (Weakly Interacting Massive Particle)

- weakly interacting to the SM
- freeze out mechanism
- correlation among various observables
- simple and attractive



Constraints from direct detection



[XENON1T (2018)]

- WIMP models have been severely constrained today
- We need ideas to avoid this strong constraint

Fermionic DM with Pseudo-scalar coupling

If DM has a pseudo-scalar interaction,

$$\mathcal{L} \supset \bar{\psi} i \gamma_5 \psi a \qquad \psi = \text{DM}, \; a = \text{mediator (scalar)}$$

then **we can avoid the constraints from the direct detections while keeping the WIMP scenario**

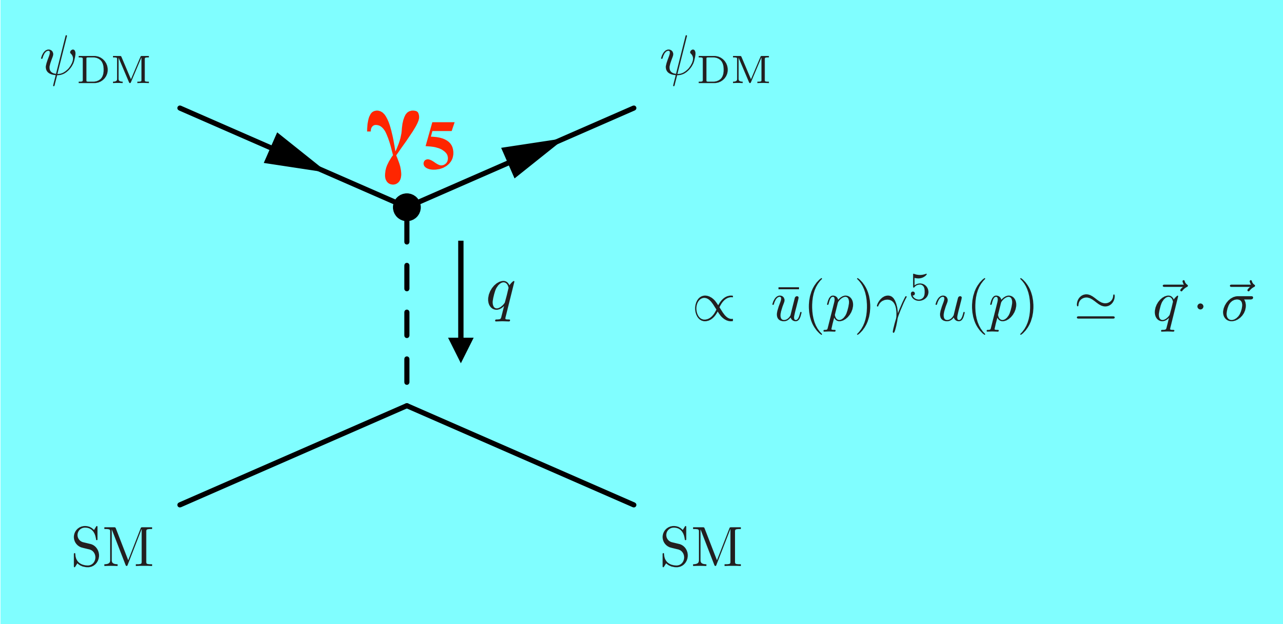
Fermionic DM with Pseudo-scalar coupling

If DM has a pseudo-scalar interaction,

$$\mathcal{L} \supset \bar{\psi} i \gamma_5 \psi a \qquad \psi = \text{DM},\ a = \text{mediator (scalar)}$$

then **we can avoid the constraints from the direct detections while keeping the WIMP scenario**

Suppression in the direct detection



$$\psi = \sum_s \int \frac{d^3p}{(2\pi)^3\sqrt{2E_p}} \left(a_{p,s} u_s(p) e^{-ipx} + b^\dagger_{p,s} v_s(p) e^{ipx}\right)$$

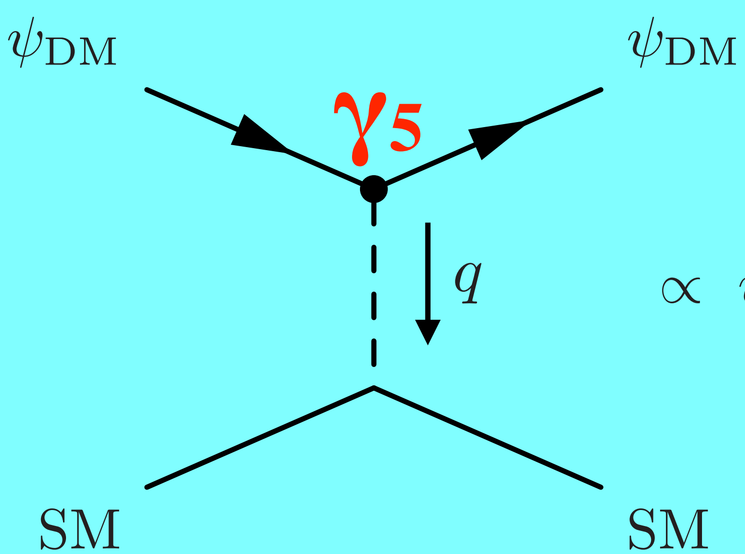
Fermionic DM with Pseudo-scalar coupling

If DM has a pseudo-scalar interaction,

$$\mathcal{L} \supset \bar{\psi} i \gamma_5 \psi a \qquad \psi = \text{DM}, \ a = \text{mediator (scalar)}$$

then **we can avoid the constraints from the direct detections while keeping the WIMP scenario**

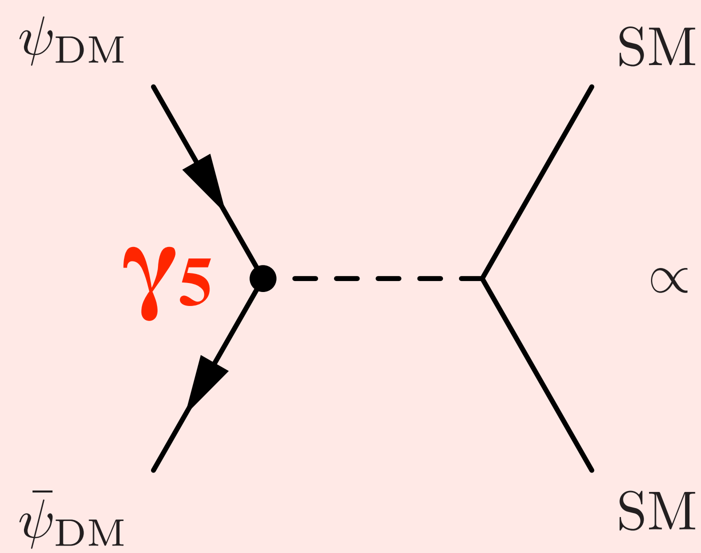
Suppression in the direct detection



$$\propto \ \bar{u}(p)\gamma^5 u(p) \ \simeq \ \vec{q}\cdot\vec{\sigma}$$

$$\psi = \sum_s \int \frac{d^3p}{(2\pi)^3\sqrt{2E_p}} \left(a_{p,s}u_s(p)e^{-ipx} + b^\dagger_{p,s}v_s(p)e^{ipx}\right)$$

Annihilation cross section is not suppressed



$$\propto \ \bar{v}(p)\gamma^5 u(p) \ \simeq \ m_{\rm DM}$$

Two-Higgs-Doublet Model + a

[Ipek et. al (2014)]

DM and scalar sector

		spin	$SU(2)_L$	$U(1)_Y$	Z_2
DM	χ	$1/2$	$\mathbf{1}$	0	-1
CP-odd mediator	a_0	0	$\mathbf{1}$	0	1
two-Higgs doublets	H_1	0	$\mathbf{2}$	$1/2$	1
	H_2	0	$\mathbf{2}$	$1/2$	1

see a white paper for more details [1810.09420]

Two-Higgs-Doublet Model + a

[Ipek et. al (2014)]

DM and scalar sector

		spin	$SU(2)_L$	$U(1)_Y$	Z_2
DM	χ	$1/2$	$\mathbf{1}$	0	-1
CP-odd mediator	a_0	0	$\mathbf{1}$	0	1
two-Higgs doublets	H_1	0	$\mathbf{2}$	$1/2$	1
	H_2	0	$\mathbf{2}$	$1/2$	1

see a white paper for more details [1810.09420]

Assumptions

- $\langle a_0 \rangle = 0$
- CP invariance in the DM and scalar sectors

Two-Higgs-Doublet Model + a

[Ipek et. al (2014)]

DM and scalar sector

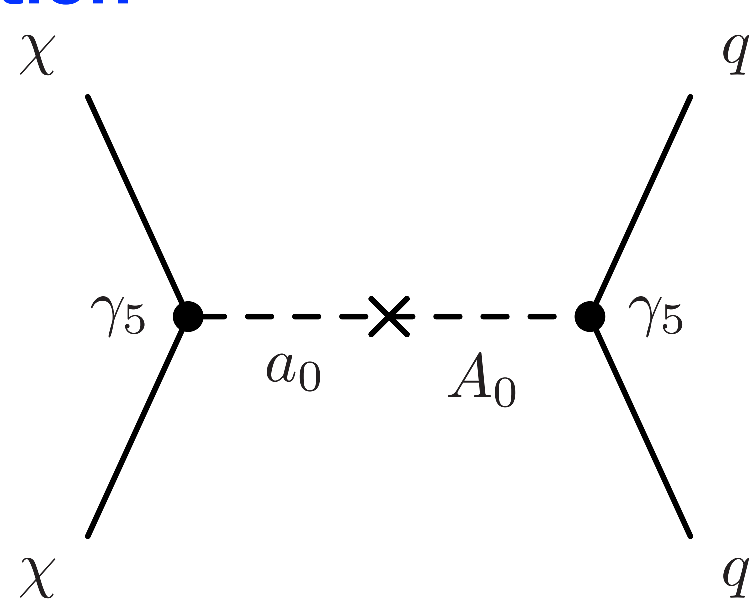
		spin	$SU(2)_L$	$U(1)_Y$	Z_2
DM	χ	$1/2$	$\mathbf{1}$	0	-1
CP-odd mediator	a_0	0	$\mathbf{1}$	0	1
two-Higgs doublets	H_1	0	$\mathbf{2}$	$1/2$	1
	H_2	0	$\mathbf{2}$	$1/2$	1

see a white paper for more details [1810.09420]

Assumptions

- $\langle a_0 \rangle = 0$
- CP invariance in the DM and scalar sectors

Pseudoscalar interaction



Two-Higgs-Doublet Model + a

[Ipek et. al (2014)]

DM and scalar sector

		spin	$SU(2)_L$	$U(1)_Y$	Z_2
DM	χ	$1/2$	**1**	0	-1
CP-odd mediator	a_0	0	**1**	0	1
two-Higgs doublets	H_1	0	**2**	$1/2$	1
	H_2	0	**2**	$1/2$	1

see a white paper for more details [1810.09420]

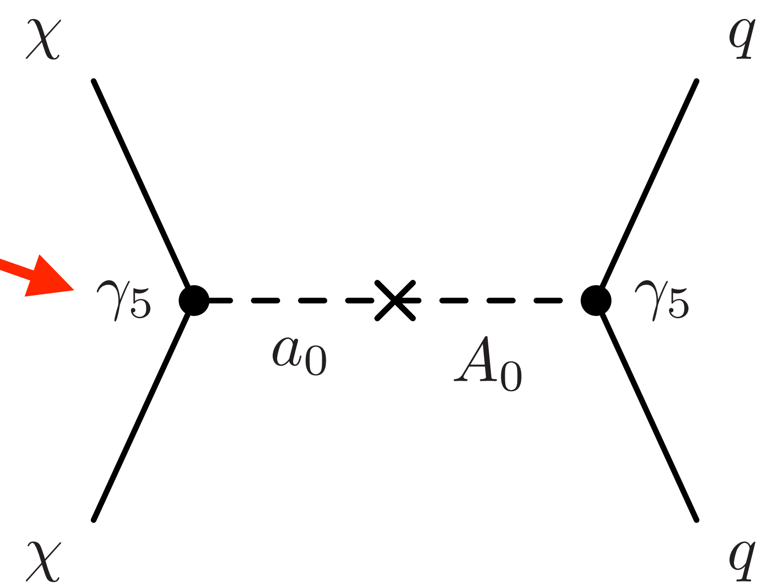
Assumptions

- $\langle a_0 \rangle = 0$
- CP invariance in the DM and scalar sectors

Pseudoscalar interaction

$g_\chi \bar{\chi} i \gamma_5 a_0 \chi$

only pseudo-scalar interaction thanks to CP invariance



Two-Higgs-Doublet Model + a

[Ipek et. al (2014)]

DM and scalar sector

		spin	$SU(2)_L$	$U(1)_Y$	Z_2
DM	χ	$1/2$	$\mathbf{1}$	0	-1
CP-odd mediator	a_0	0	$\mathbf{1}$	0	1
two-Higgs doublets	H_1	0	$\mathbf{2}$	$1/2$	1
	H_2	0	$\mathbf{2}$	$1/2$	1

see a white paper for more details

[1810.09420]

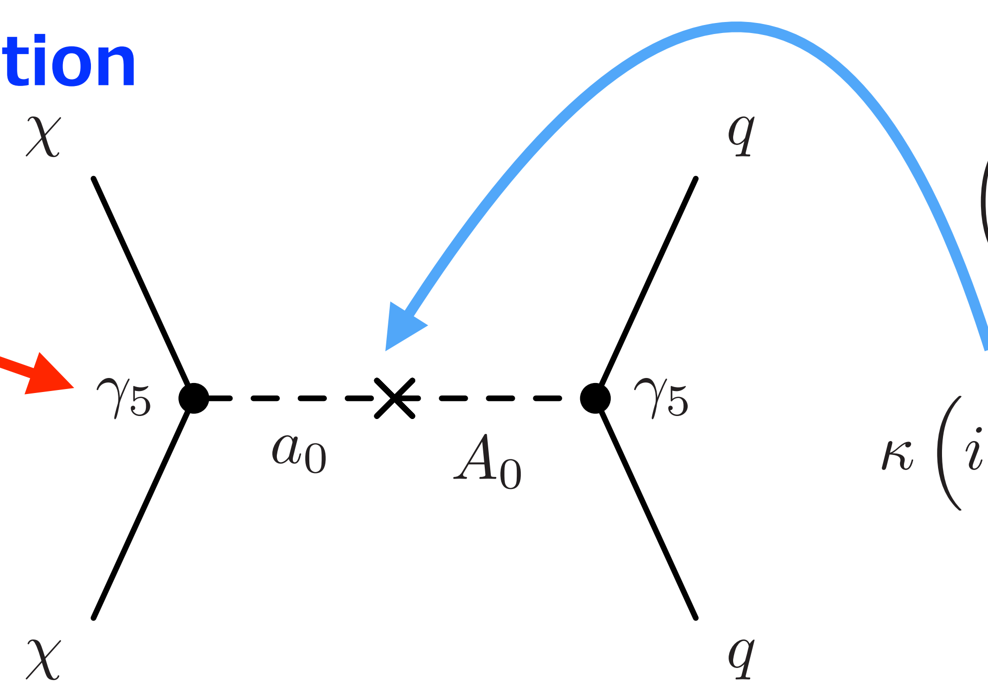
Assumptions

- $\langle a_0 \rangle = 0$
- CP invariance in the DM and scalar sectors

Pseudoscalar interaction

$g_\chi \bar{\chi} i \gamma_5 a_0 \chi$

only pseudo-scalar interaction thanks to CP invariance



mix the two CP-odd states

$$\begin{pmatrix} A \\ a \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A^0 \\ a_0 \end{pmatrix}$$

$$\kappa \left(i a_0 H_1^\dagger H_2 + (h.c.) \right)$$

A model with pseudo-scalar mediator (cont'd)

Lagrangian

$$
\begin{aligned}
\mathcal{L} \supset &+ \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \frac{g_\chi}{2} a_0 \bar{\chi} i\gamma^5 \chi \\
&+ \frac{1}{2}\partial^\mu a_0 \partial_\mu a_0 - \frac{m_{a_0}^2}{2} a_0^2 - \frac{\lambda_a}{4} a_0^4 \\
&- \kappa\left(i a_0 H_1^\dagger H_2 + (h.c.)\right) - c_1 a_0^2 H_1^\dagger H_1 - c_2 a_0^2 H_2^\dagger H_2
\end{aligned}
$$

A model with pseudo-scalar mediator (cont'd)

Lagrangian

In this talk, g_χ is fixed to obtain the correct relic abundance ($\Omega h^2 = 0.12$)

$$
\begin{aligned}
\mathcal{L} \supset & + \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \frac{g_\chi}{2} a_0 \bar{\chi} i\gamma^5 \chi \\
& + \frac{1}{2}\partial^\mu a_0 \partial_\mu a_0 - \frac{m_{a_0}^2}{2} a_0^2 - \frac{\lambda_a}{4} a_0^4 \\
& - \kappa\left(i a_0 H_1^\dagger H_2 + (h.c.)\right) - c_1 a_0^2 H_1^\dagger H_1 - c_2 a_0^2 H_2^\dagger H_2
\end{aligned}
$$

A model with pseudo-scalar mediator (cont'd)

Lagrangian

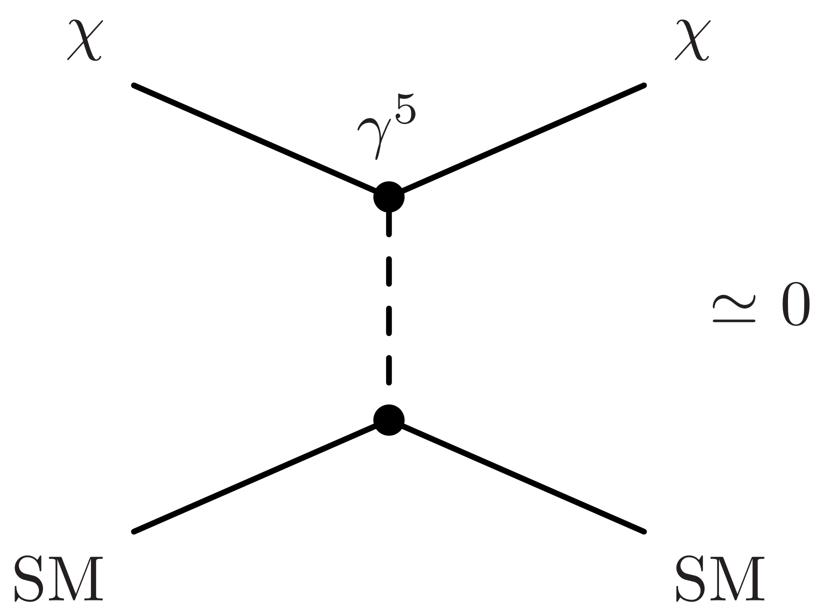
In this talk, g_χ is fixed to obtain the correct relic abundance ($\Omega h^2 = 0.12$)

$$\mathcal{L} \supset + \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \frac{g_\chi}{2} a_0 \bar{\chi} i \gamma^5 \chi$$
$$+ \frac{1}{2}\partial^\mu a_0 \partial_\mu a_0 - \frac{m_{a_0}^2}{2} a_0^2 - \frac{\lambda_a}{4} a_0^4$$
$$- \kappa\left(i a_0 H_1^\dagger H_2 + (h.c.)\right) - c_1 a_0^2 H_1^\dagger H_1 - c_2 a_0^2 H_2^\dagger H_2$$

c_1 and c_2 play important role in the followings

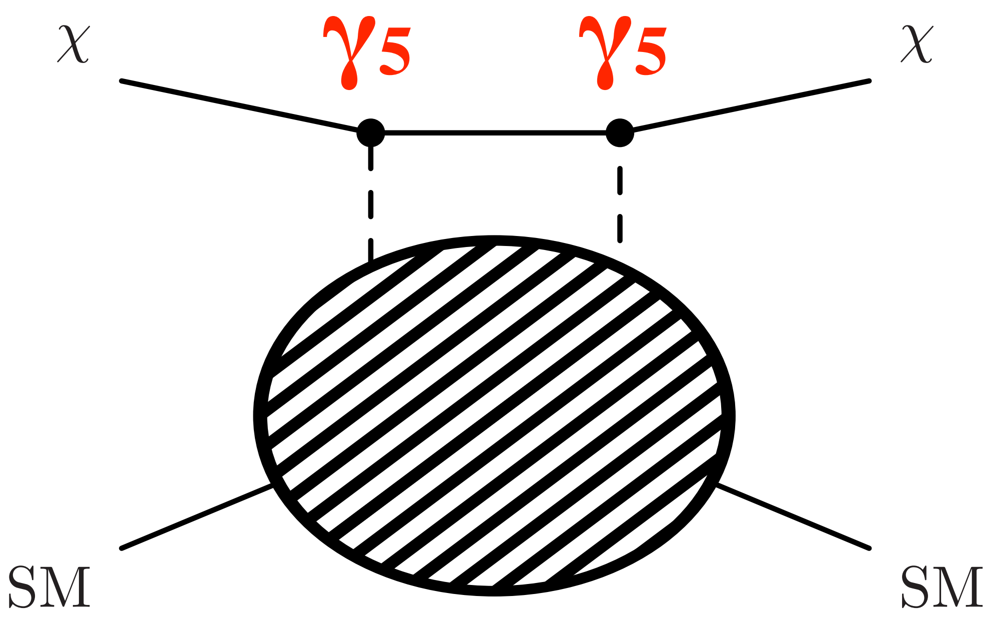
Loop diagrams are essential for σ_{SI}

$\sigma_{SI} = 0$ at the tree level



$$(\bar{\chi}\gamma^5\chi)\mathcal{O}_{\rm SM}$$

$\sigma_{SI} > 0$ at the loop level

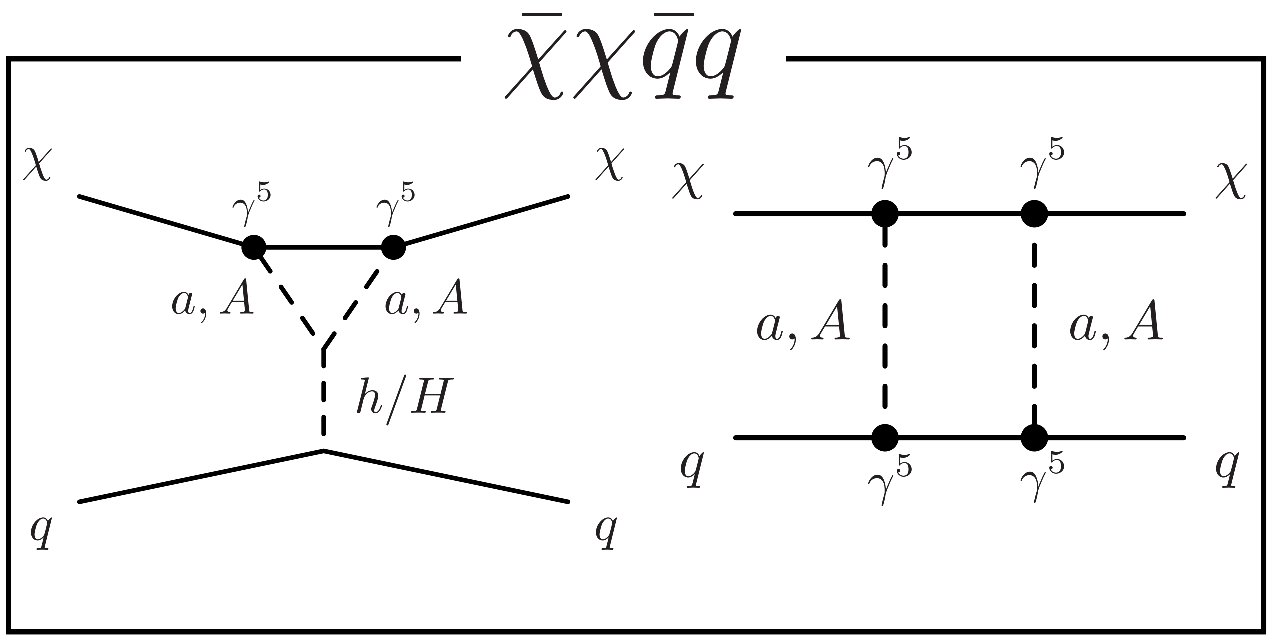


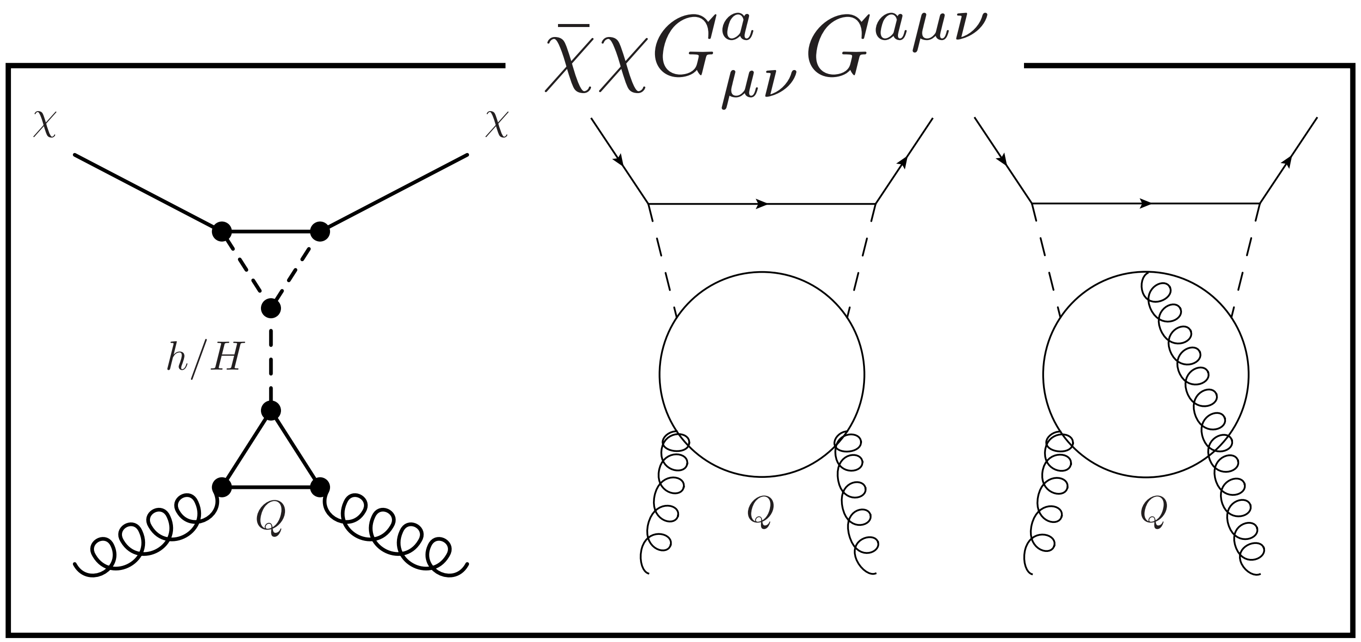
$$(\bar{\chi}\chi)\mathcal{O}_{\rm SM}$$

$(\gamma_5)^2 = 1$

loop correction is essential if models predict $\sigma_{SI} = 0$ at the tree level!

loop diagrams



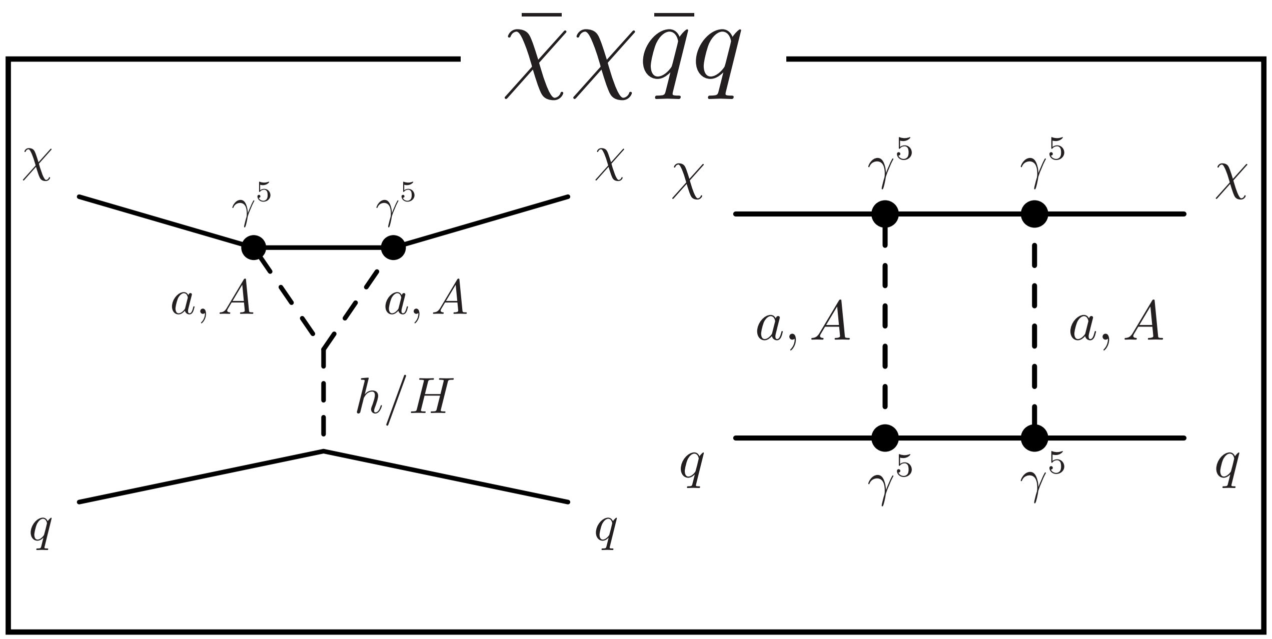


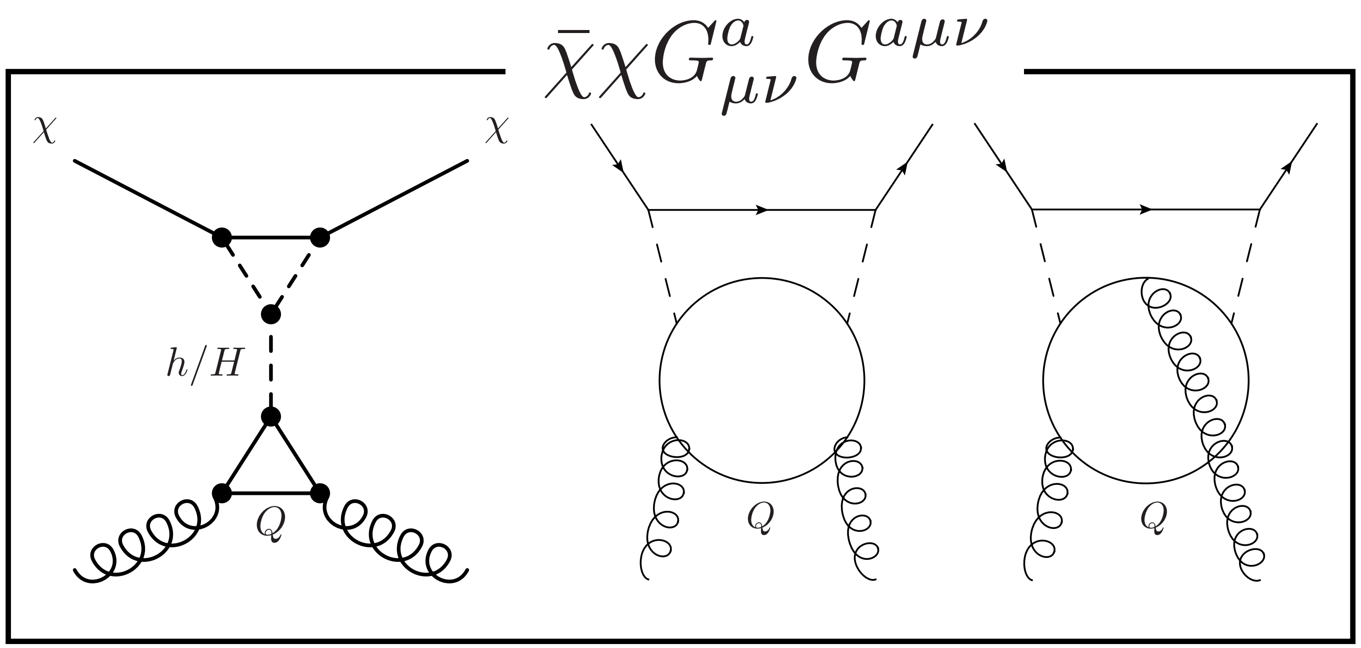
$Q = t, b, c$ (heavy quarks)

Some diagrams were calculated, but not all the diagrams

We calculate all the relevant diagrams [TA Fujiwara Hisano (2019)]

loop diagrams





$Q = t, b, c$ (heavy quarks)

Some diagrams were calculated, but not all the diagrams

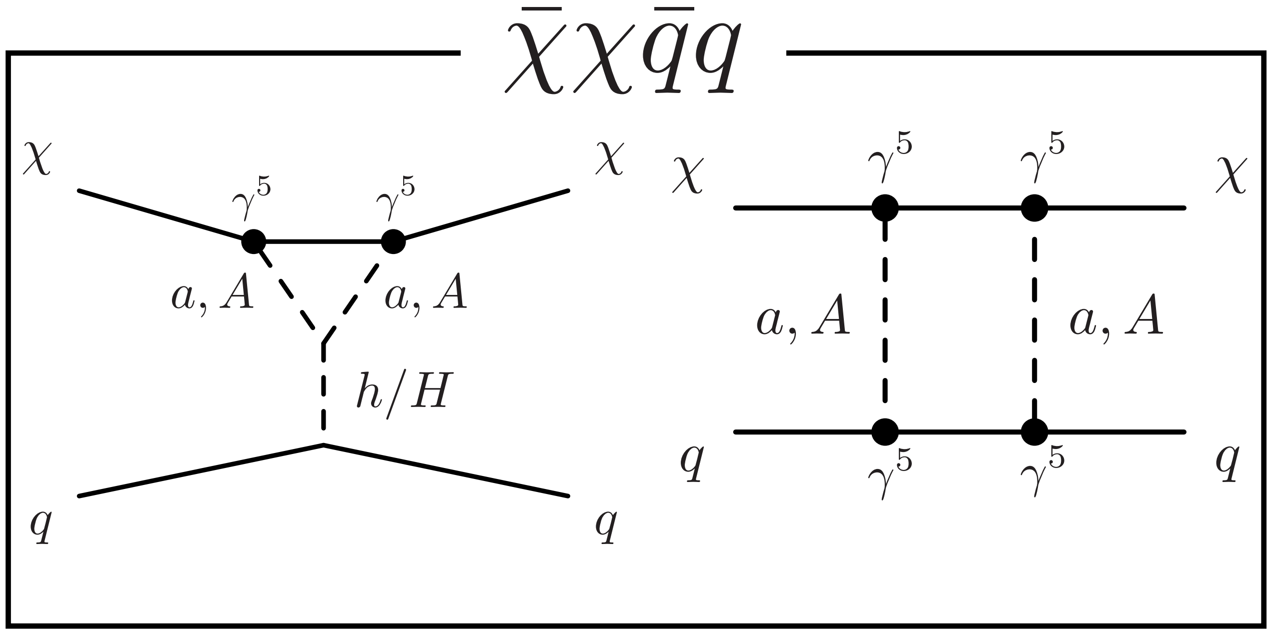
We calculate all the relevant diagrams **[TA Fujiwara Hisano (2019)]**

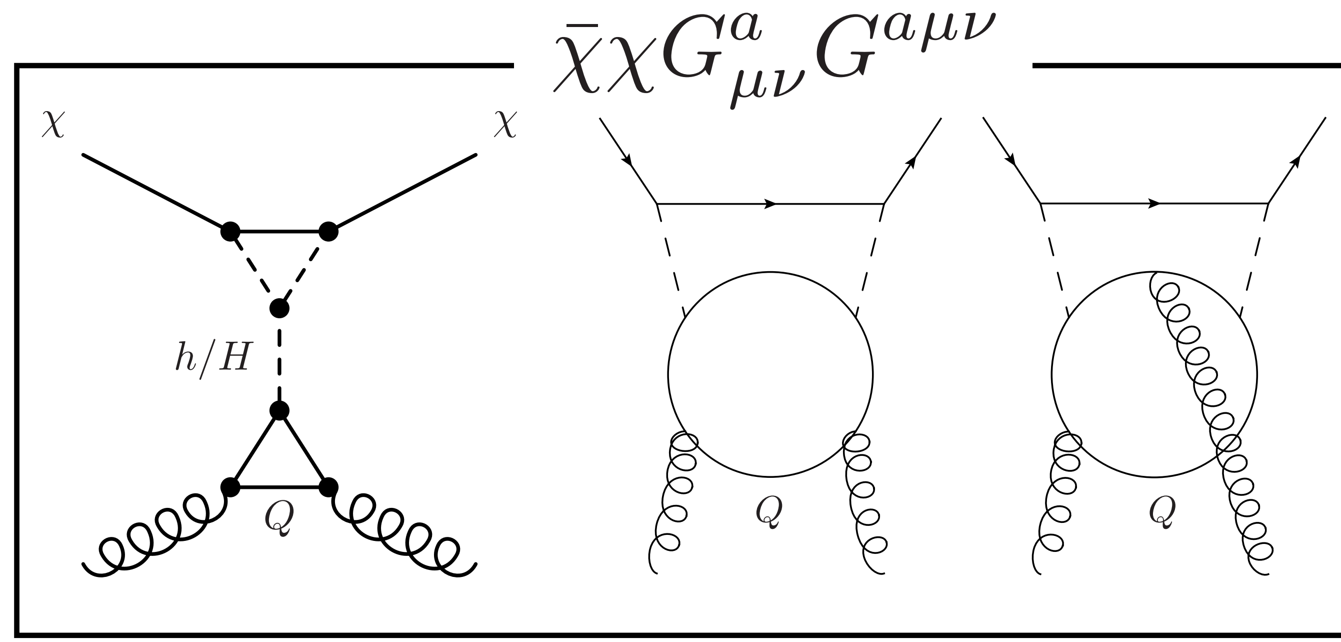
- 1-loop diagrams were calculated in the literatures [Ipek+ ('14), Arcadi+ ('18), Bell+ ('18), ⋯]
    - ⋆ but the following terms were ignored

$$c_1 a_0^2 H_1^\dagger H_1 + c_2 a_0^2 H_2^\dagger H_2$$

    - ⋆ we find they are important **[TA Fujiwara Hisano (2019)]**

loop diagrams





$Q = t, b, c$ (heavy quarks)

Some diagrams were calculated, but not all the diagrams

We calculate all the relevant diagrams **[TA Fujiwara Hisano (2019)]**

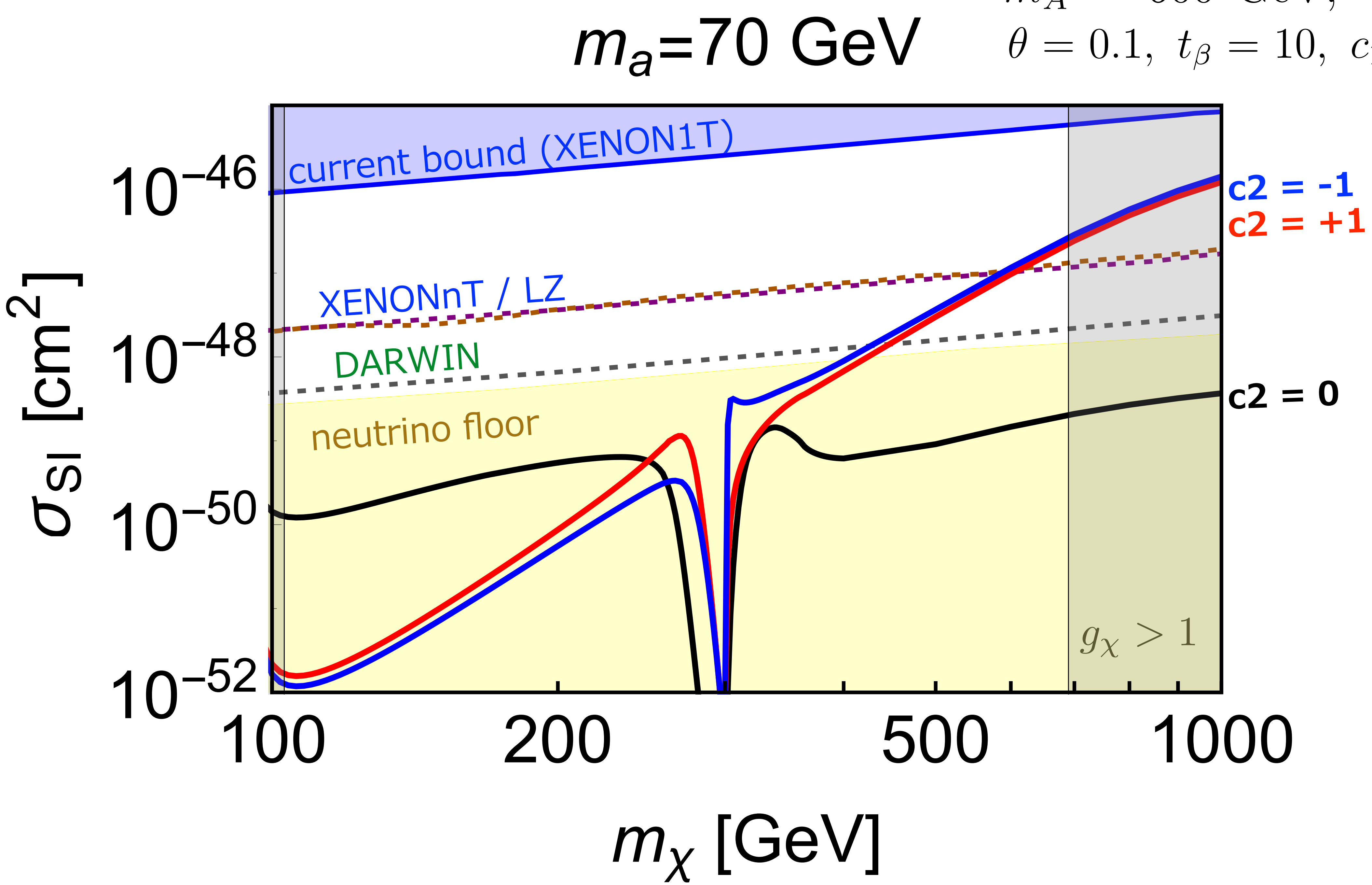
- 1-loop diagrams were calculated in the literatures [Ipek+ ('14), Arcadi+ ('18), Bell+ ('18), ⋯]
  - ⋆ but the following terms were ignored
  $$c_1 a_0^2 H_1^\dagger H_1 + c_2 a_0^2 H_2^\dagger H_2$$
  - ⋆ we find they are important **[TA Fujiwara Hisano (2019)]**

- 2-loop diagrams were "estimated" in the literature [Arcadi+ ('18)]
  - ⋆ but not "calculated"
  - ⋆ we find their estimation is not so accurate **[TA Fujiwara Hisano (2019)]**

σ_{SI} is large if C2 ≠ 0

$$c_1 a_0^2 H_1^\dagger H_1 + c_2 a_0^2 H_2^\dagger H_2$$

$$m_A = 600 \text{ GeV}, \quad \theta = 0.1, \ t_\beta = 10, \ c_1 = 0$$



c2 is important to make σ_{SI} larger than neutrino floor

large c_2 vs scalar potential

large c_2 is

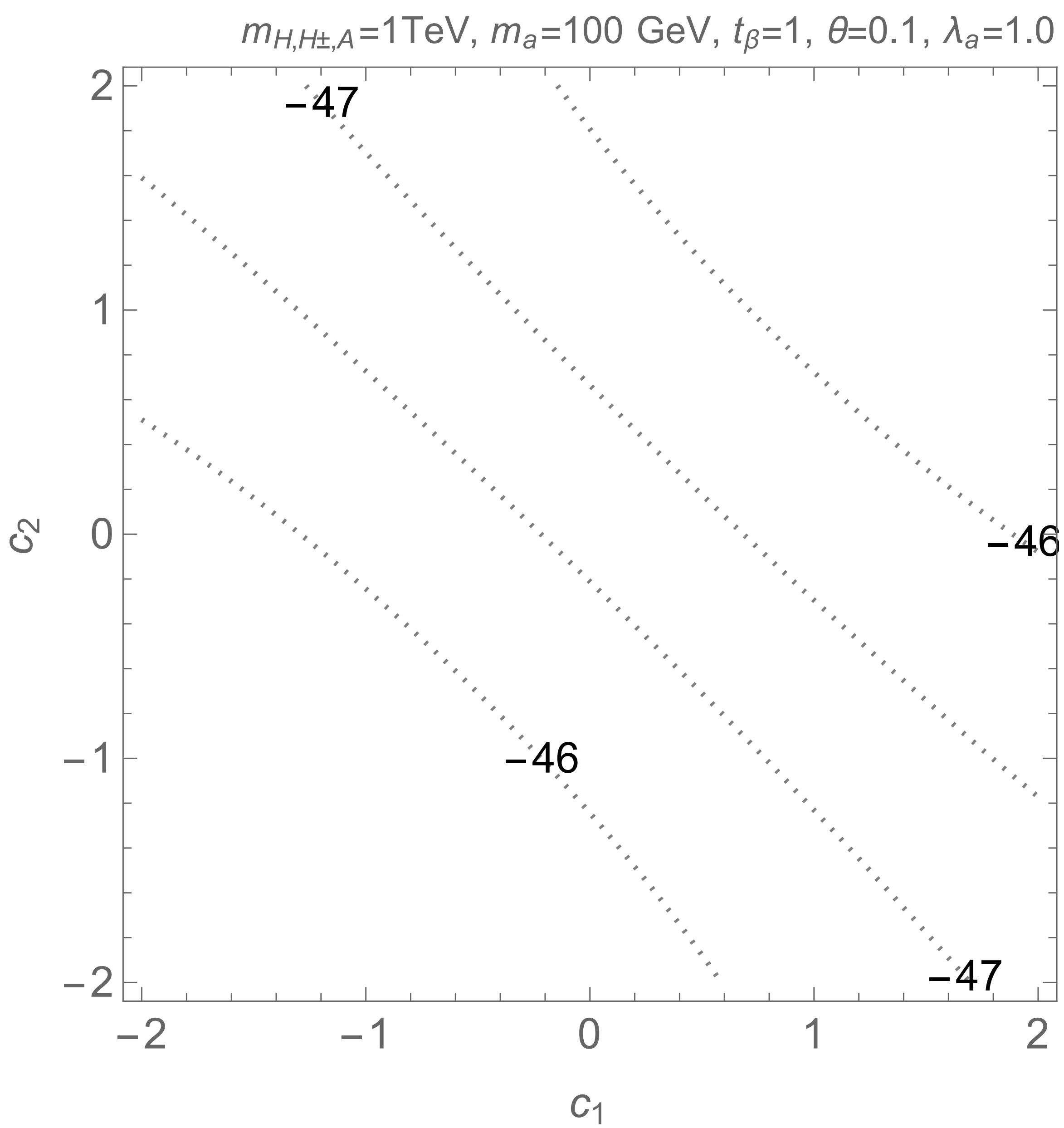
- good to make $\sigma_{\rm SI}$ large enough to test this model
- might be dangerous for the Higgs potential

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

We are trying to find upper/lower bounds on c_1 and c_2 from

- conditions for the potential bounded from below
- conditions for the Electroweak vacuum as the global minimum
- perturbative unitarity bound
- $\cdots$

large C2 vs scalar potential



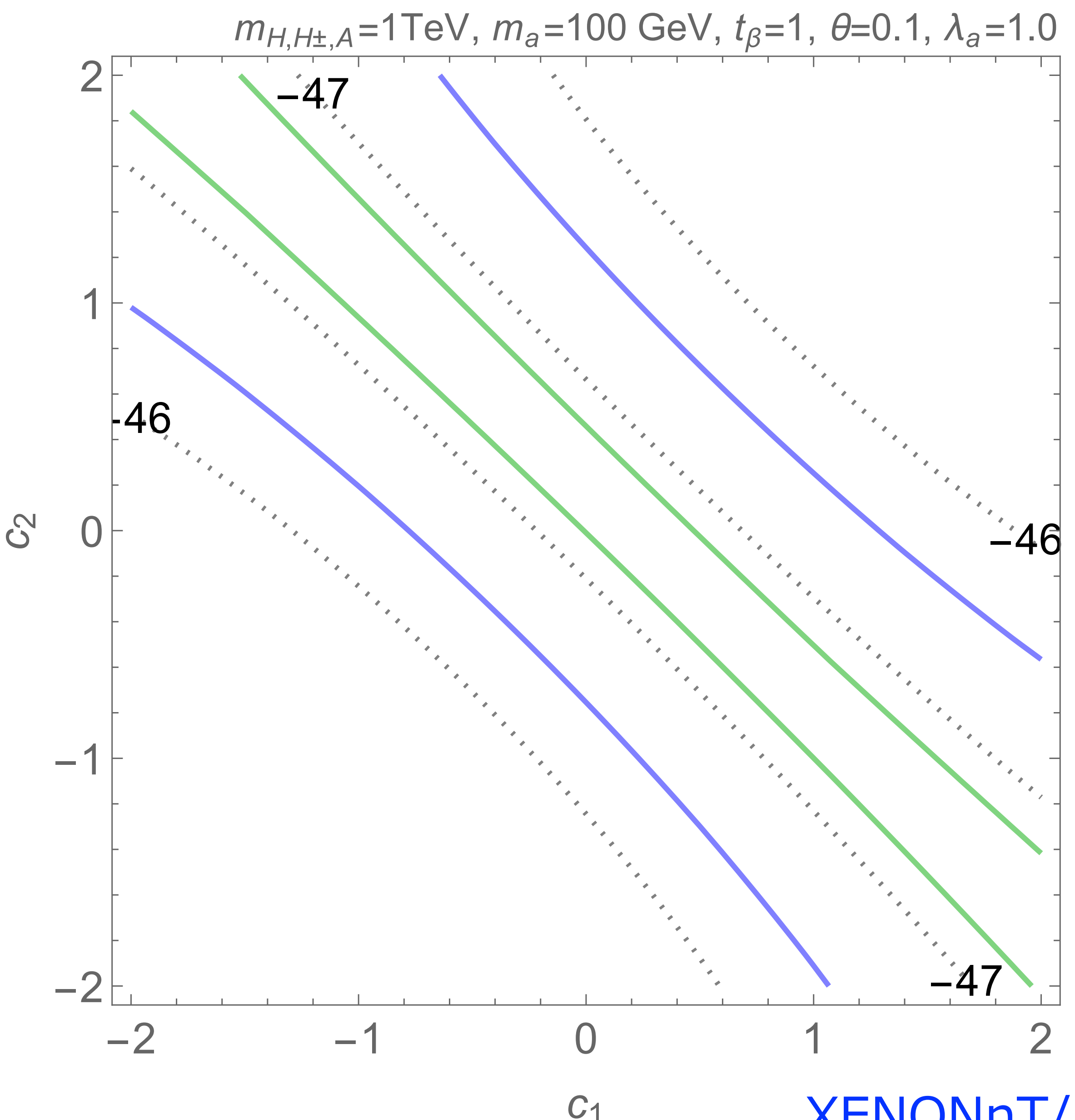
Contours for $\text{Log}_{10}[\sigma_{SI}/\text{cm}^2]$

- σ_{SI} becomes large for large c_1 or c_2
- m_{DM} = 1.5 TeV
- Ωh^2 = 0.12 by choosing g_χ
- $\sigma_{SI} < 4.4 \times 10^{-46}$ cm^2 in the plain
- $\sigma_{SI} < 1.4 \times 10^{-45}$ cm^2 (Xenon1T)

[Preliminary]

[TA Fujiwara Hisano Shoji (on-going)]

large C2 vs scalar potential



XENONnT/LZ prospect

neutrino floor

neutrino floor

XENONnT/LZ prospect

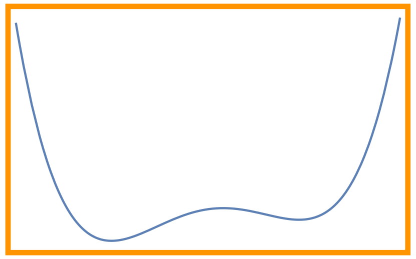
Contours for $\mathrm{Log}_{10}[\sigma_{SI}/\mathrm{cm}^2]$

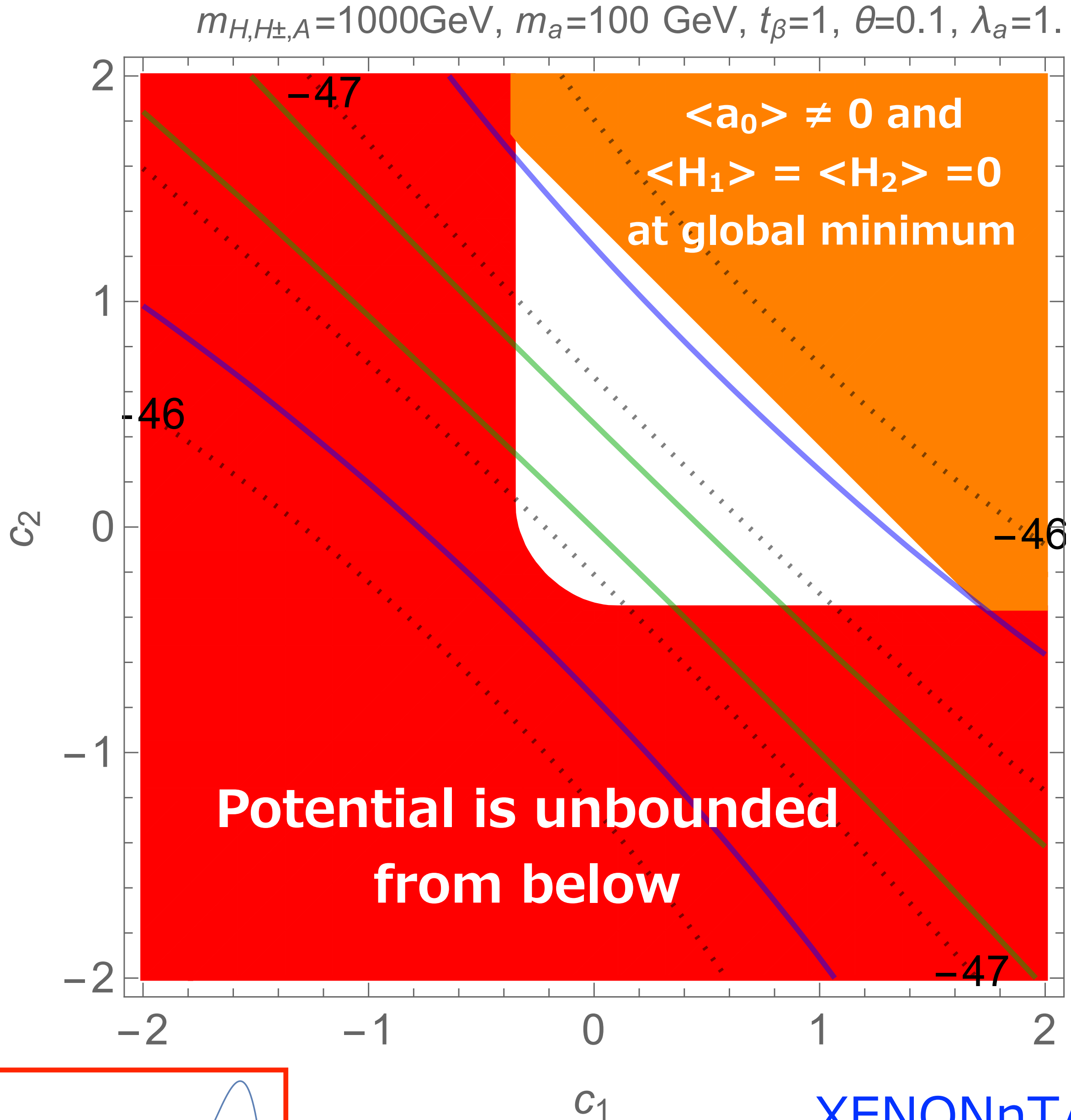
- σ_{SI} becomes large for large c_1 or c_2
- m_{DM} = 1.5 TeV
- Ωh^2 = 0.12 by choosing g_χ
- $\sigma_{SI} < 4.4 \times 10^{-46}$ cm^2 in the plain
- $\sigma_{SI} < 1.4 \times 10^{-45}$ cm^2 (Xenon1T)

[Preliminary]

[TA Fujiwara Hisano Shoji (ongoing)]

large C2 vs scalar potential





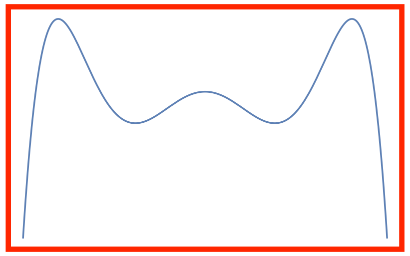
Contours for $\text{Log}_{10}[\sigma_{SI}/\text{cm}^2]$

- σ_{SI} becomes large for large c_1 or c_2
- m_{DM} = 1.5 TeV
- Ωh^2 = 0.12 by choosing g_X
- $\sigma_{SI} < 4.4 \times 10^{-46}$ cm^2 in the plain
- $\sigma_{SI} < 1.4 \times 10^{-45}$ cm^2 (Xenon1T)

XENONnT/LZ prospect

neutrino floor

neutrino floor



XENONnT/LZ prospect

[Preliminary]

Summary

two-Higgs doublet model + fermion DM + a_0

- freeze-out mechanism works
- σ_{SI} is suppressed at the tree level
- loop calculation is needed

We complete loop calculations

- the effect of quartic couplings (c_1 and c_2) are important

$$c_1 a_0^2 H_1^\dagger H_1 + c_2 a_0^2 H_2^\dagger H_2$$

We are trying to find upper/lower bounds on c_1 and c_2

- large c1 and c2 make σ_{SI} large
- too large c1 and c2 predicts electroweak symmetry is not broken at the global minimum
- potential is unbounded if c1 and c2 are negative