Indirect Dark Matter Search

Implication on the IceCube Detector

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NCTS-NTHU Hsinchu/F.G.S Kaohsiung

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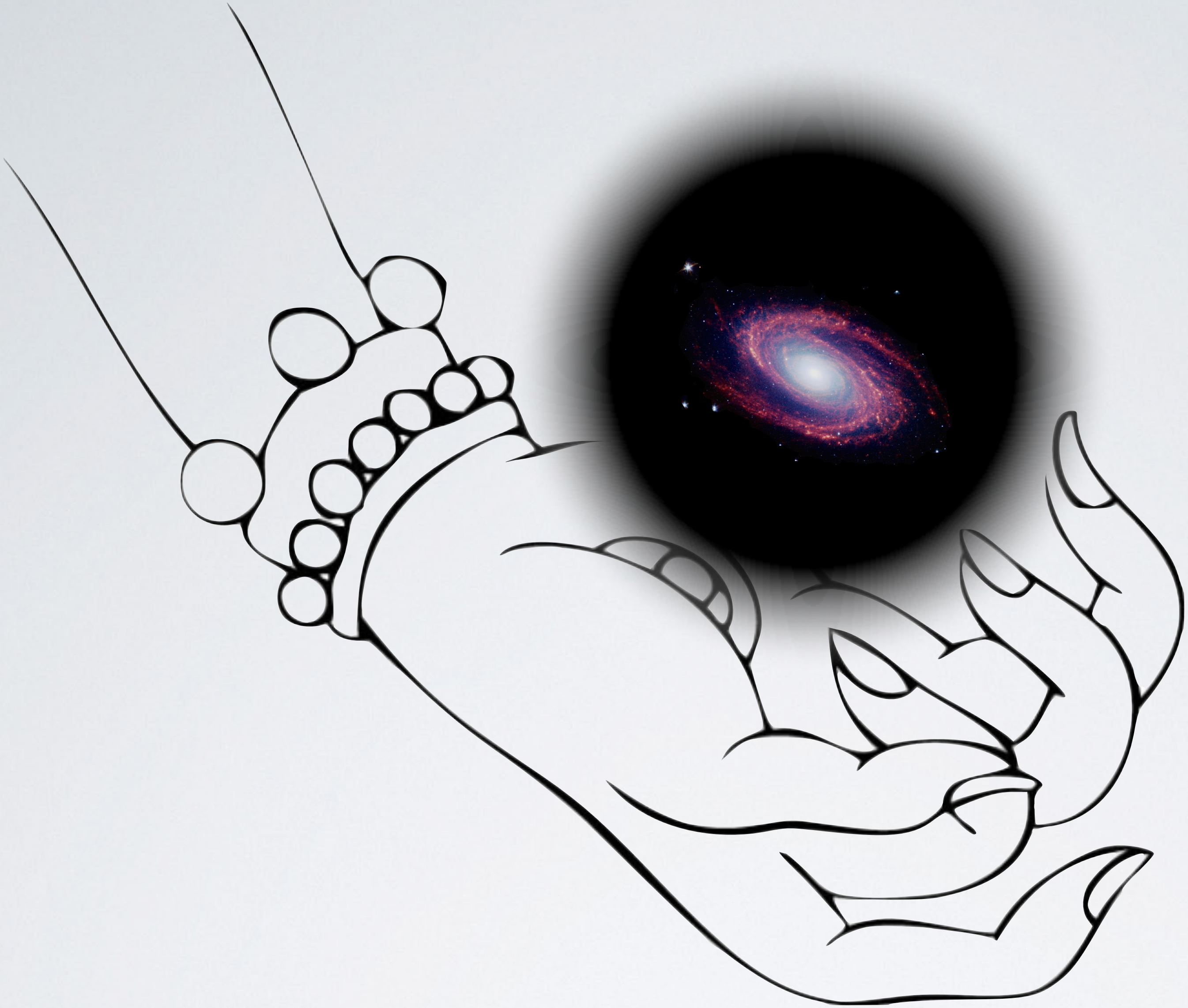
arXiv:1408.5471(2014) (*JCAP Accepted*)

G.-L. Lin, Yen-Hsun Lin and F.-F. Lee
arXiv: 1409.3094(2014)

Outline

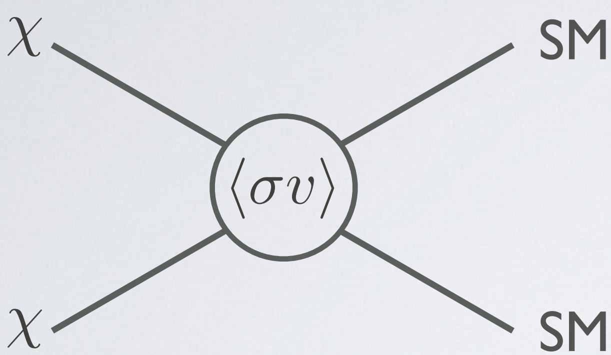
- DM interactions
  - Annihilation
  - Scattering with nucleus
  - ***Scattering among DMs (self-interaction)***
- DM evolving in the Sun/Earth
- Physical implications
- Detection and sensitivity in IceCube/PINGU
- Summary



Dark Matter Interactions

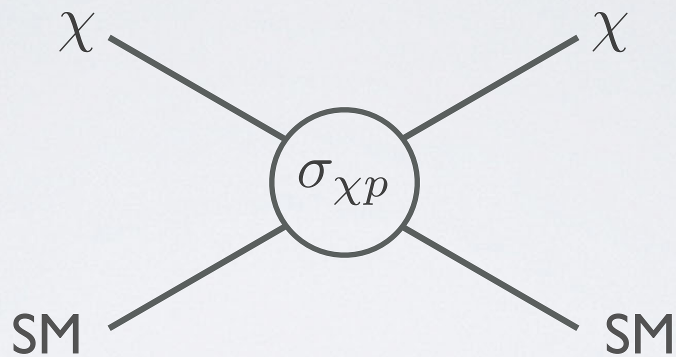
Annihilation, scattering and all that…

Possible interactions



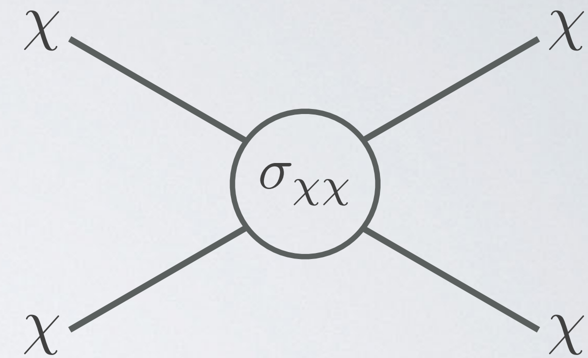
Annihilation

Dark matters annihilate among themselves and Standard Model particles produced in the final state.



Nucleon scattering

Dark matter scatters with nucleon and momentum is transferred between them.



Self-interaction

Dark matter scatters among themselves. Momentum is transferred during the process.

Jungman, Kamionkowski and Griest, Phys.Rept. **267,** 195(1996)
Bertone, Hooper and Silk, Phys.Rept. **405,** 279(2005)

Spergel and Steinhardt, PRL **84,** 3760(2000)

DM scattering with nucleus

- Spin-dependent

$$\sigma_{\chi N}^{\rm SD} = A^2 \left(\frac{m_\chi + m_p}{m_\chi + m_N} \right)^2 \frac{4(J+1)}{3J} \left| \langle S_p \rangle + \langle S_n \rangle \right|^2 \sigma_{\chi p}^{\rm SD}$$

spin expectation value of the nucleus

Divari *et al.*, PRC **61**, 054612(2000)

- Spin-independent

$$\sigma_{\chi N}^{\rm SI} = A^2 \left(\frac{m_\chi + m_p}{m_\chi + m_N} \right)^2 \left[Z + (A - Z) \frac{f_n}{f_p} \right]^2 \sigma_{\chi p}^{\rm SI}$$

≠1 indicates *isospin-violation*

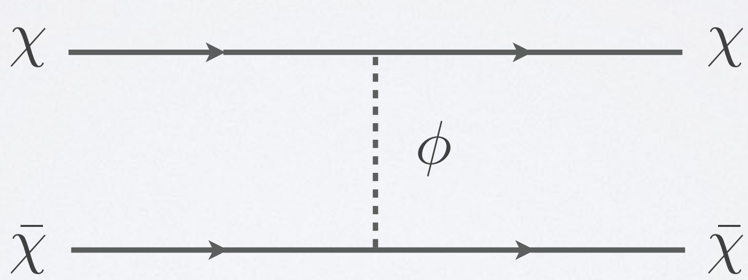
Kurylov and Kamionkowski, PRD **69**, 063503(2004)

DM self-interaction (self-int.)

Buckley and Fox, PRD **81**, 083522(2010)
Fan *et al.*, PRL **110,** 211302(2013)
Feng, Kaplinghat and Yu, PRL **104**, 151301(2010)
Kaplinghat, Tulin and Yu, PRD **89**, 035009(2014)
Loeb and Wiener, PRL **106**, 171302(2011)

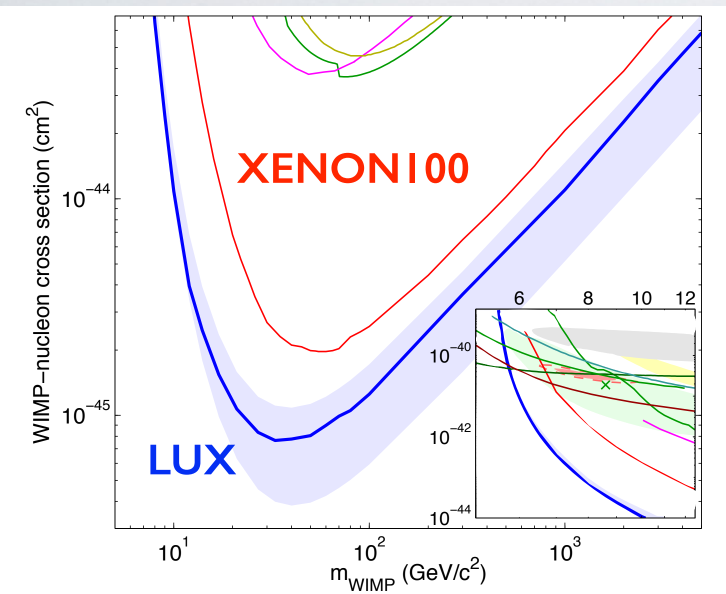
- Many models are on progress
- Commonly described by a Yukawa interaction:

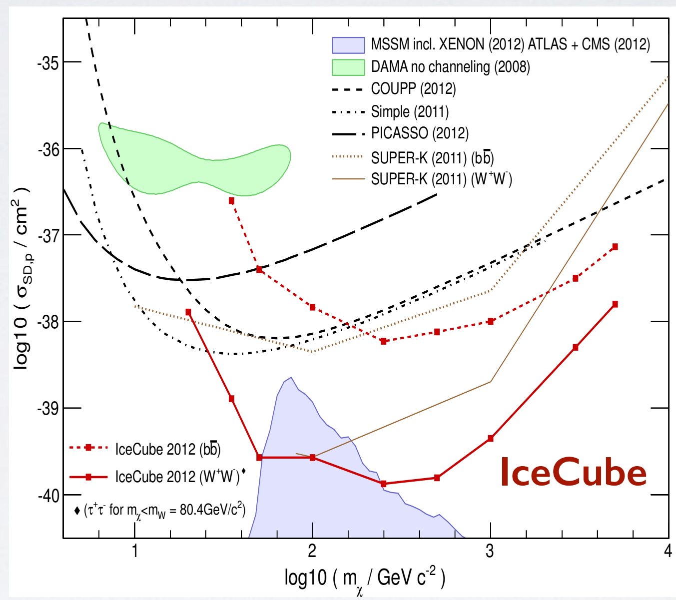
$$\mathcal{L}_{\rm int} = \begin{cases} g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu, & \text{vector mediator} \\ g_\chi \bar{\chi}\chi\phi, & \text{scalar mediator} \end{cases}$$

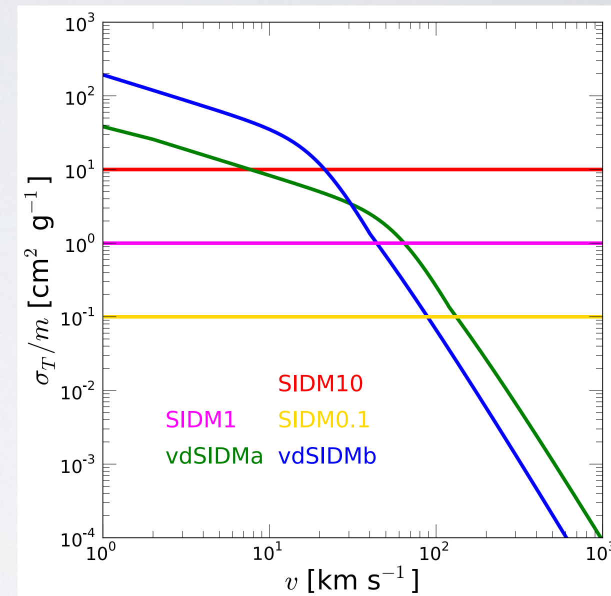


- Here we treat it as a phenomenological parameter $\boldsymbol{\sigma_{\chi\chi}}$, *self-int. scattering cross section*, and discuss the kinematics only

Experimental constraints







Spin-independent: $\sigma_{\chi p}$

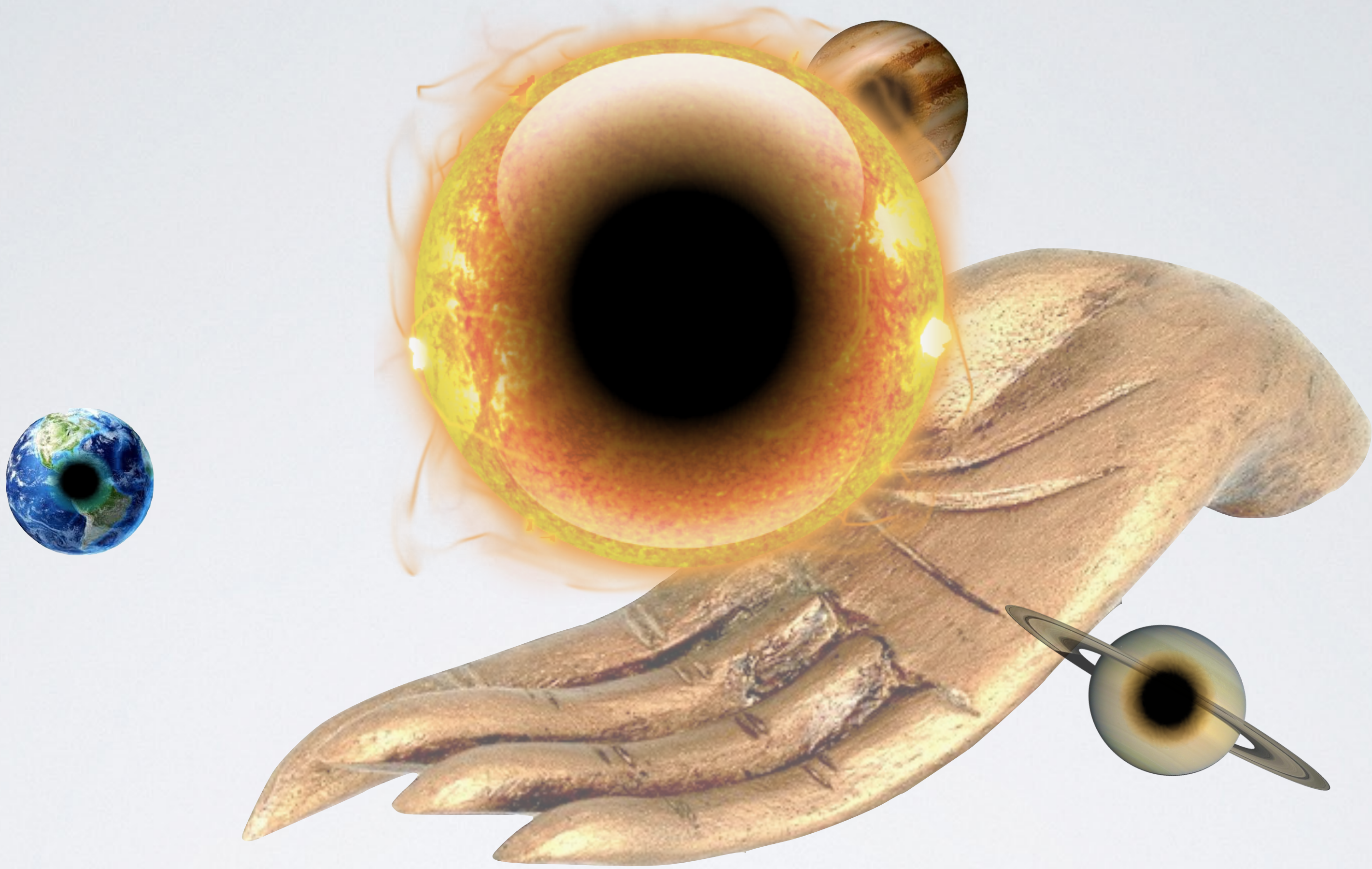
Akerib *et al.* [LUX Collabo.]
PRL **112**, 091303(2014)

Spin-dependent: $\sigma_{\chi p}$

Aartsen *et al.* [IceCube Collabo.]
PRL **110**, 131302(2013)

Self-interaction: $\sigma_{\chi\chi}$

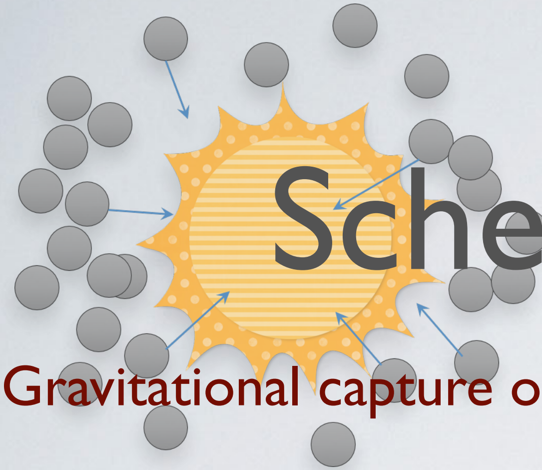
Zavala, Vogelsberger and Walker
Mon.Not.R.Astron.Soc. **431**, L20(2013)

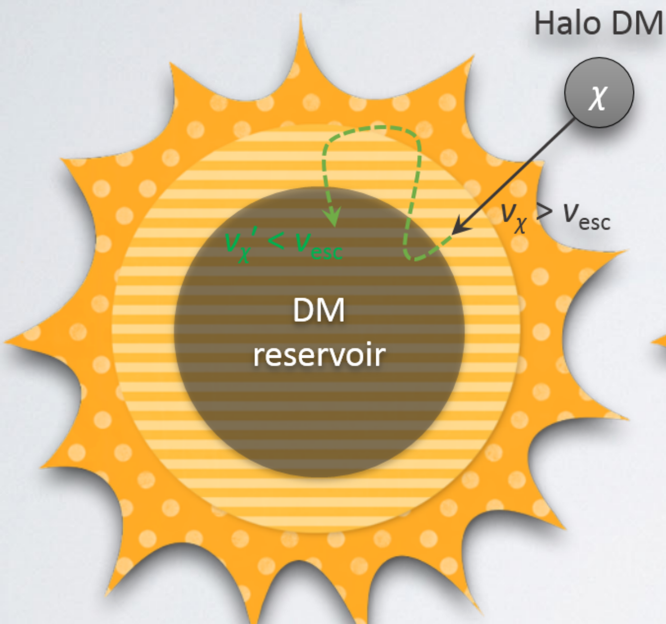


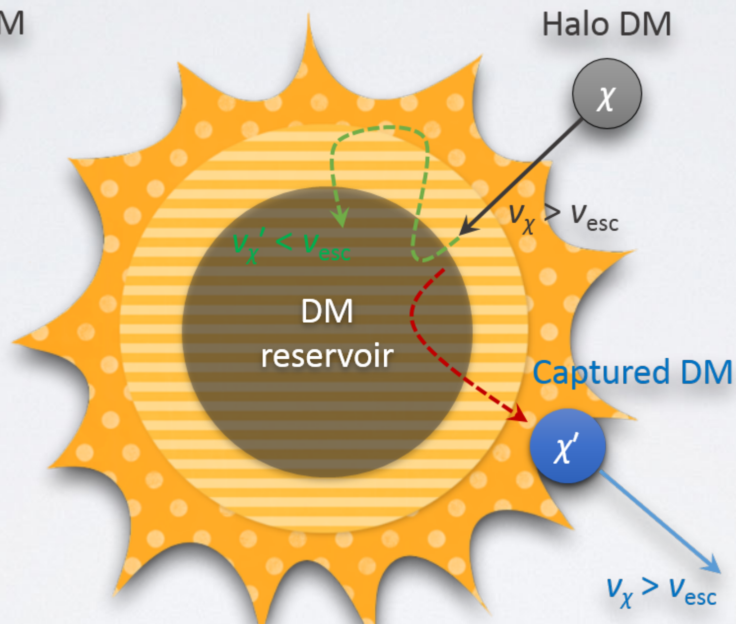
Dark Matter Evolving

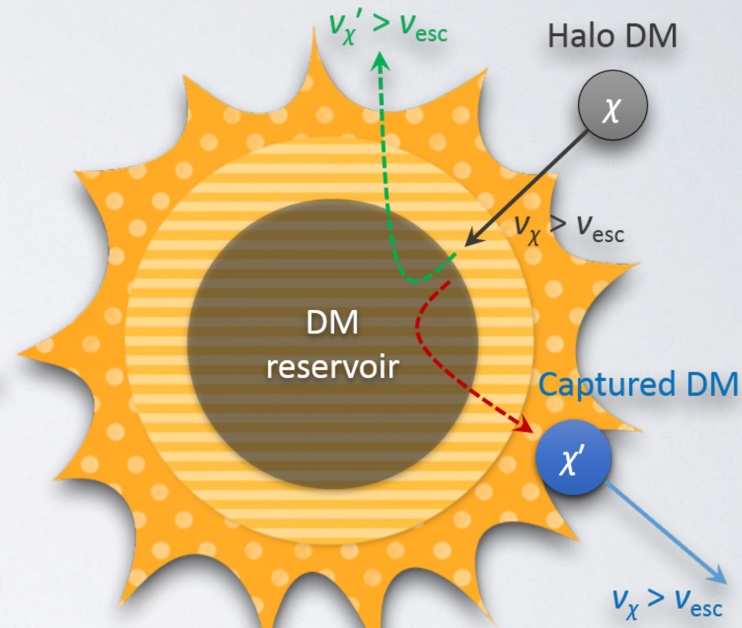
The influence of self-int. to the DM captured by the stars

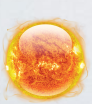
Schematic view of self-int.









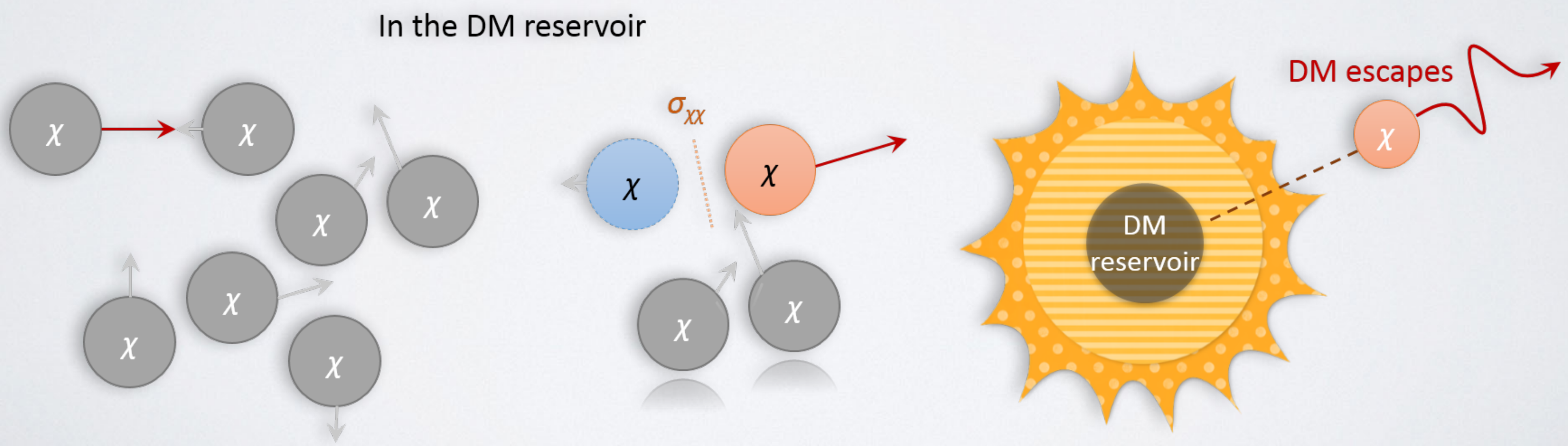
	Enhancement	***No change***	***Reduction***
	Self-captured	Self-ejected: only one	Self-ejected: both
	**Dominant**	**Irrelevant**	**Irrelevant**
	**Irrelevant**	**Irrelevant**	**Dominant**

Zentner, PRD **80**, 063501 (2009)

Disadvantage of self-int.

- DM in the reservoir scatters with other as well
- Such scattering may leads to the ejection of captured DM
- It is described as ***self-int. induced evaporation***

Chen *et al.*, 1408.5471(2014)
Accepted by JCAP



Self-int. induced evaporation

Chen *et al.*, 1408.5471(2014)
Accepted by JCAP

- Such interaction contributes to the ***reduction*** of DM number in the Sun
- It makes evaporation to occur earlier
- The rate, C_{se}, is given by:

$$C_{se} = \frac{\int \frac{dC_{se}}{dV} d^3r}{\left(\int_\odot n_\chi(r) d^3r\right)^2}$$

General DM evolution equation

Chen *et al.*,1408.5471(2014)
Accepted by JCAP

- The general DM evolution equation:

$$\frac{dN_\chi(t)}{dt} = C_c - (C_e + C_{se} - C_s)N_\chi(t) - C_a N_\chi^2(t)$$

- With the solution

$$N_\chi(t) = \frac{C_c \tanh(t/\tau_A)}{\tau_A^{-1} - (C_s - C_e)\tanh(t/\tau_A)/2}$$

- And the equilibrium time-scale

$$\tau_A = \frac{1}{\sqrt{C_c(C_a + C_{se}) + (C_s - C_e)^2/4}}$$

How N_χ evolves?

- By equilibrium state we mean **tanh(*t*/τ_A)⟶1**, thus

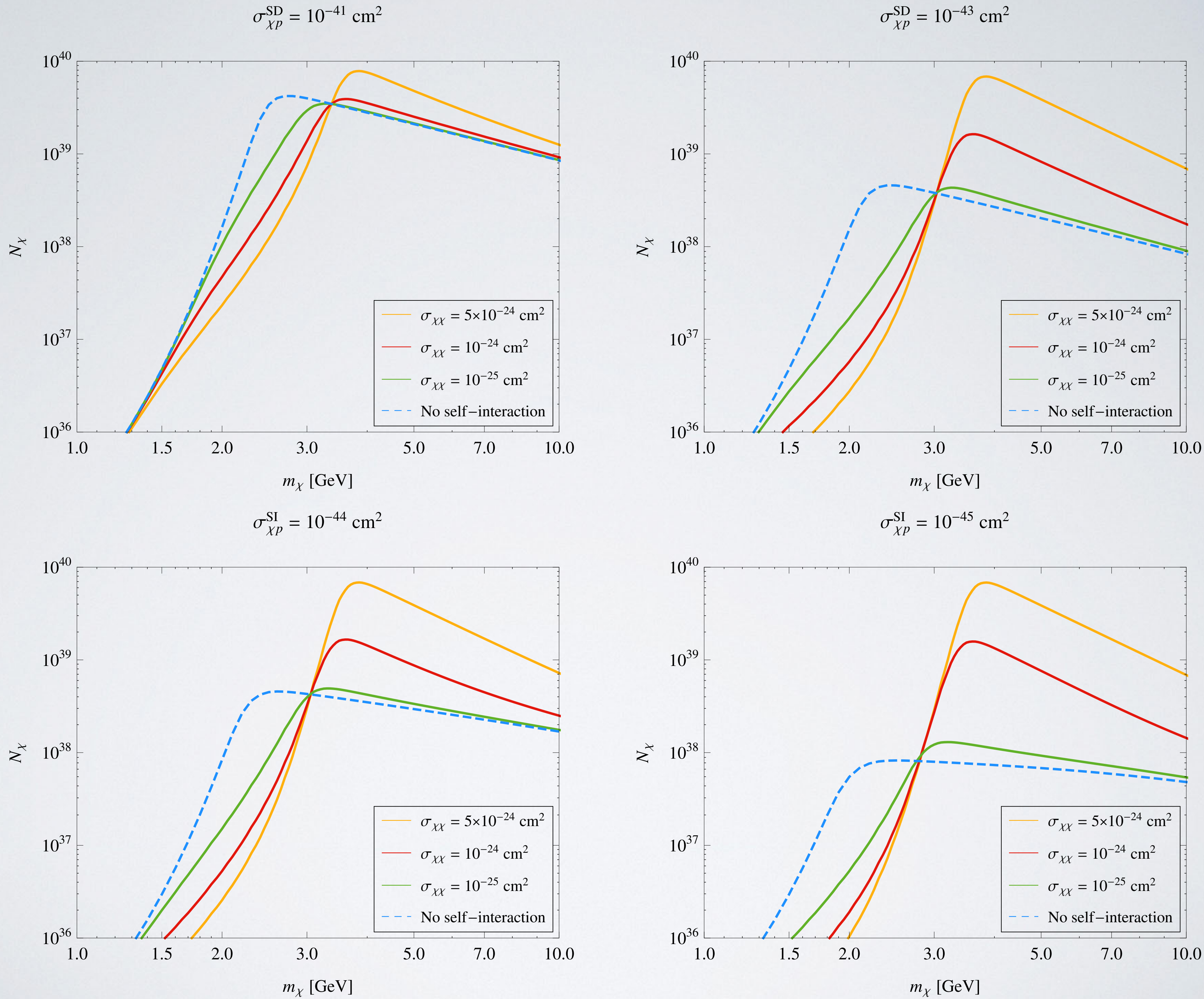
$$N_{\chi,\mathrm{eq}} = \sqrt{\frac{C_c}{C_a + C_{se}}}\left(\pm\sqrt{\frac{R}{4}} + \sqrt{\frac{R}{4}+1}\right)$$

- *R* determines self-int. is important or not:

$$R \equiv \frac{(C_s - C_e)^2}{C_c(C_a + C_{se})} \rightarrow \begin{cases} > 1, & \textbf{important} \\ < 1, & \textbf{irrelevant} \end{cases}$$

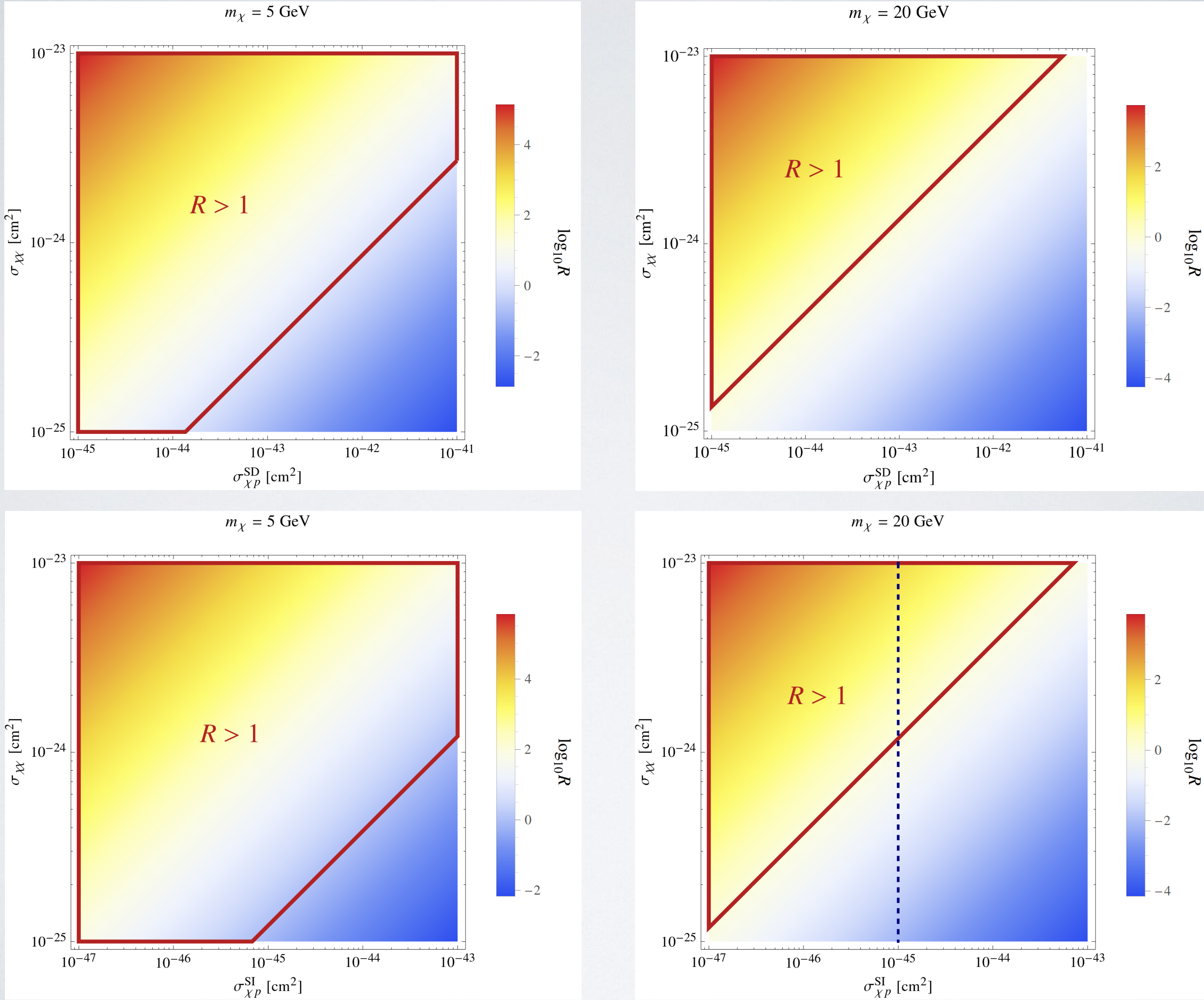
Spin-dependent

Spin-independent



Spin-dependent

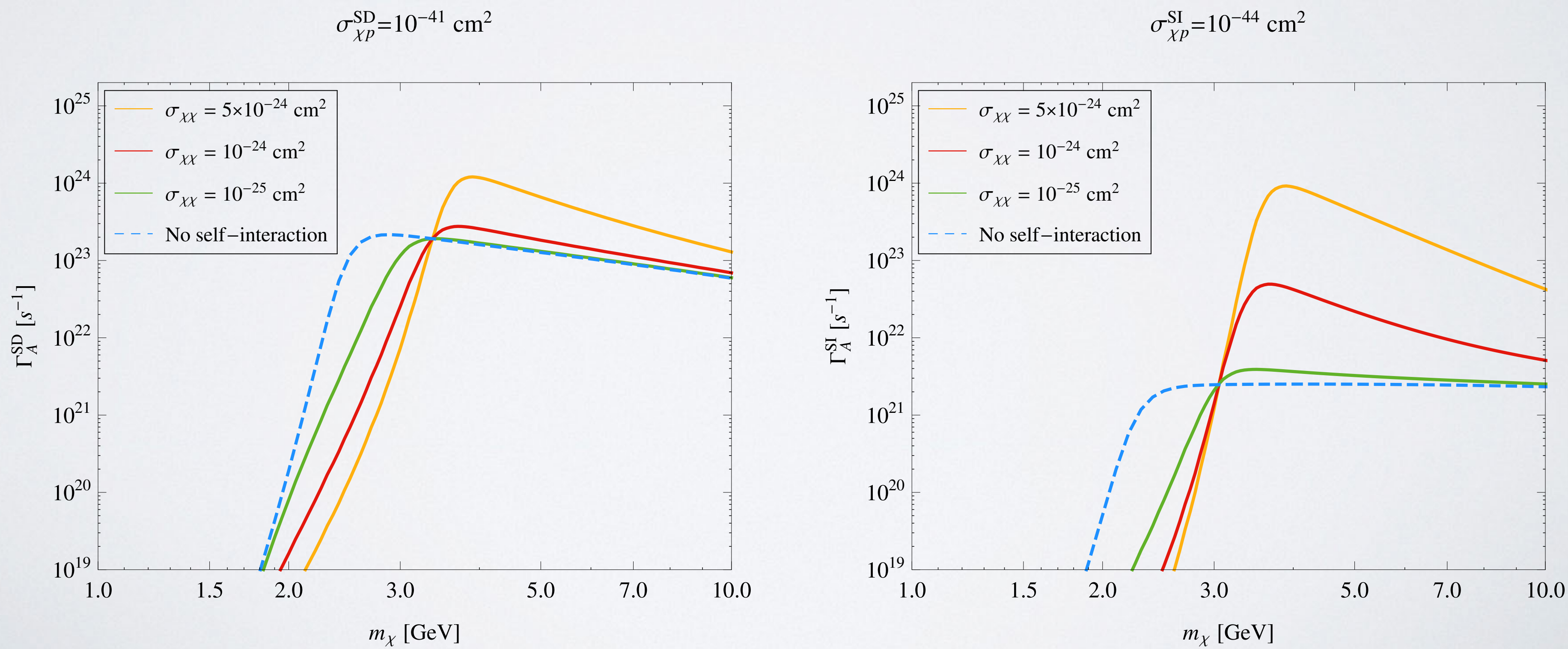
Spin-independent



Annihilation rate of the Sun

- The total annihilation is

$$\Gamma_A = \frac{1}{2} C_a N_\chi^2$$



Glimmer in the Dark

Detecting possible neutrino signal from DM annihilation

Buddha image (water color) from hphucnguyen.deviantart.com

Neutrino as the messenger

- The neutrino flux from DM annihilation

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \frac{\Gamma_A}{4\pi R_\odot^2} P_{\nu_{j\to i}}(E_\nu) \sum_f B_f \left(\frac{dN_{\nu_j}}{dE_{\nu_j}}\right)_f$$

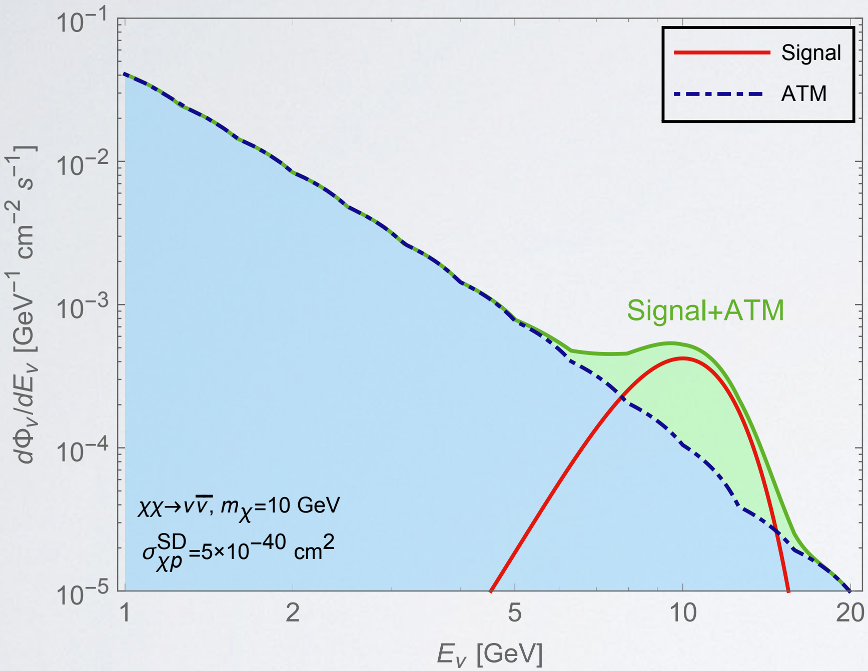
- The event rate, $N_\nu(m_\chi)$:

$$N_\nu(m_\chi) = \int_{E_{\rm thr}}^{m_\chi} \frac{d\Phi_\nu}{dE_\nu} A_{\rm eff}(E_\nu) dE_\nu$$

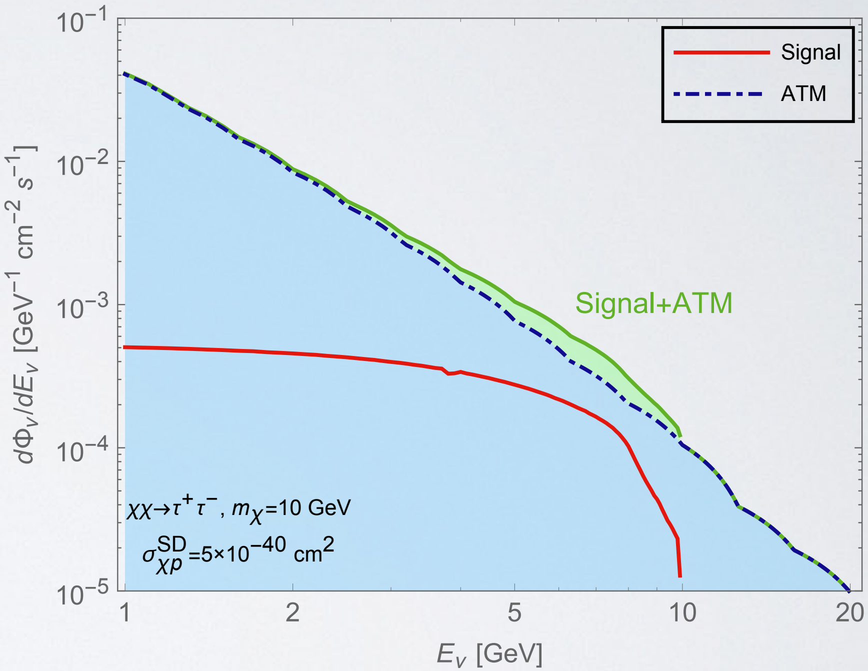
- $A_{\rm eff}$ is the detector effective area

Aartsen *et al.* [IceCube Collabo.], Science **342**, No. 6161, 124852(2013)
Aartsen *et al.* [IceCube Collabo.], 1401.2046(2014)

Expected neutrino spectra



$$\chi\chi \to \nu\bar{\nu}$$

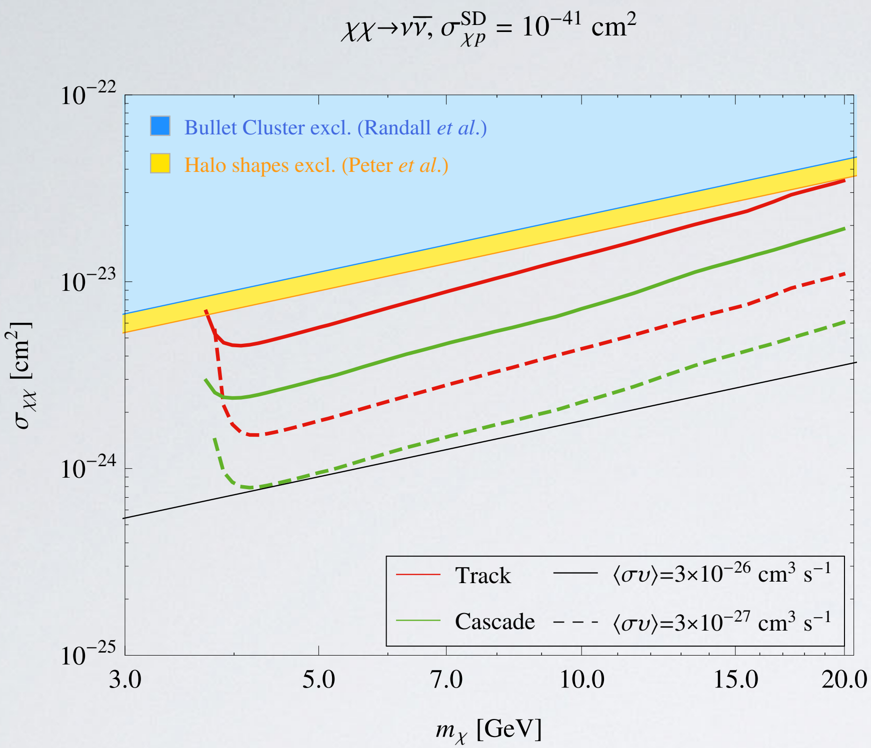


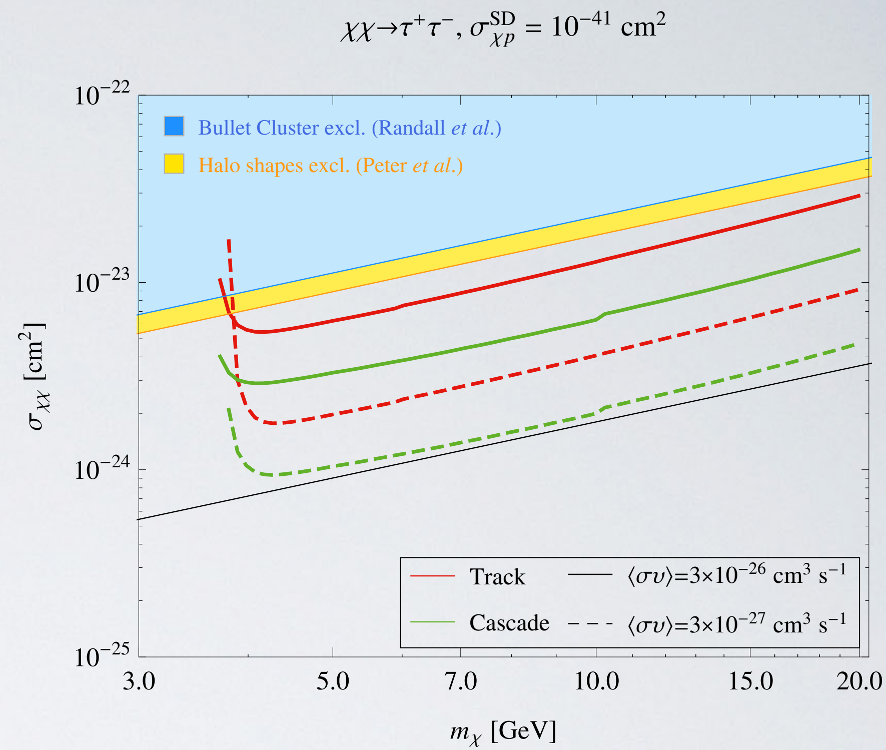
$$\chi\chi \to \tau^+\tau^-$$

$\sigma_{\chi\chi}$ sensitivity: 5-yr 2σ

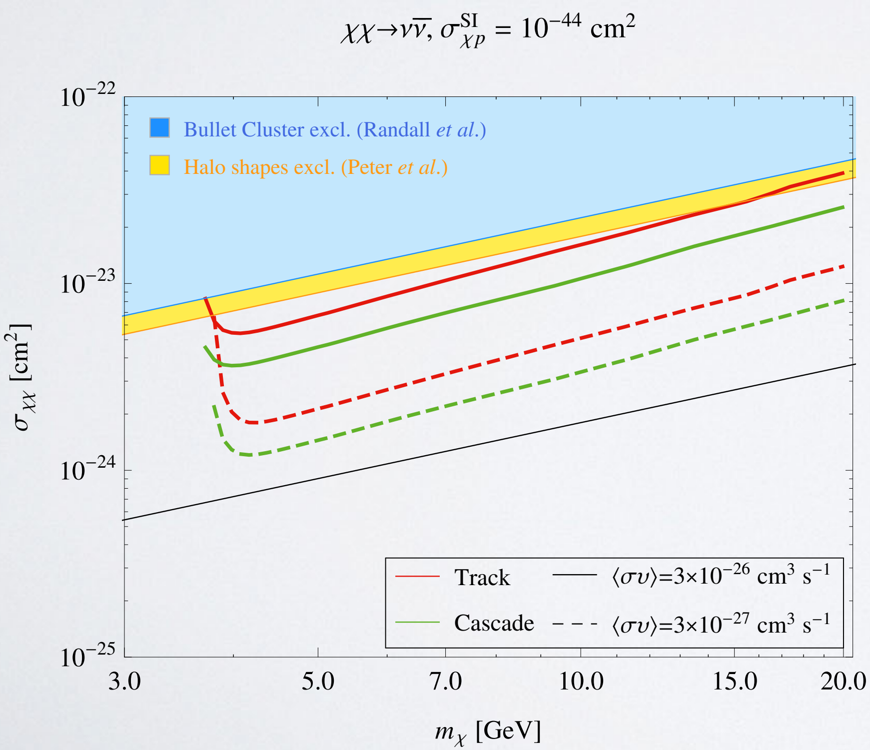
- Examining self-int. using the solar DM by PINGU
- Testing channels: τ and ν, due to less suffering from attenuation
- Two $\langle\sigma v\rangle$ scenarios: 3×10^{-26} and 3×10^{-27} $cm^3\ s^{-1}$
- DM mass range are chosen to cover the sensitivity of PING

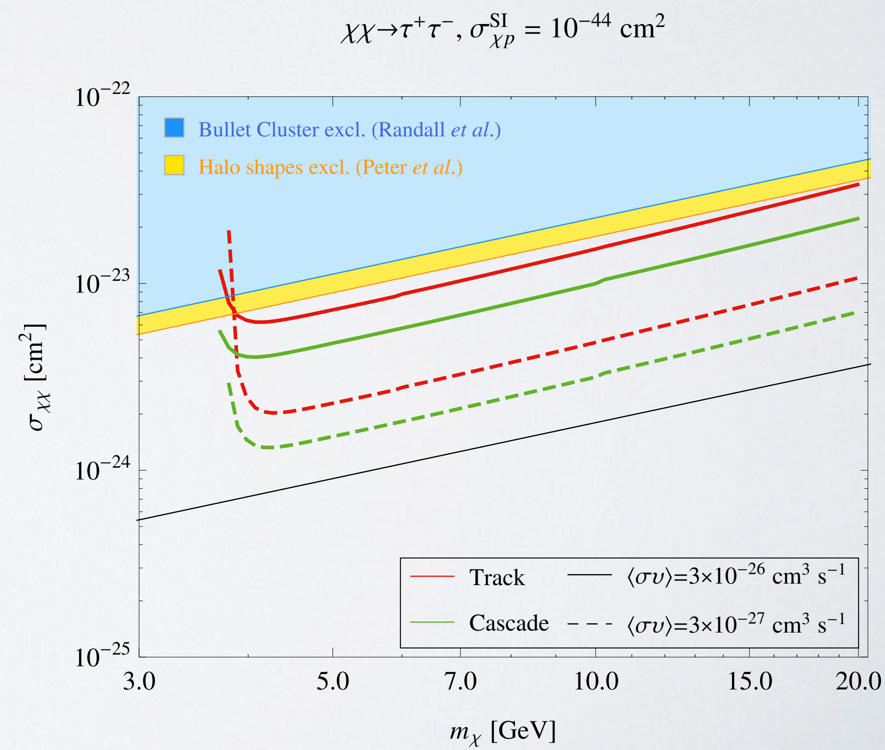
Spin-dependent





Spin-independent





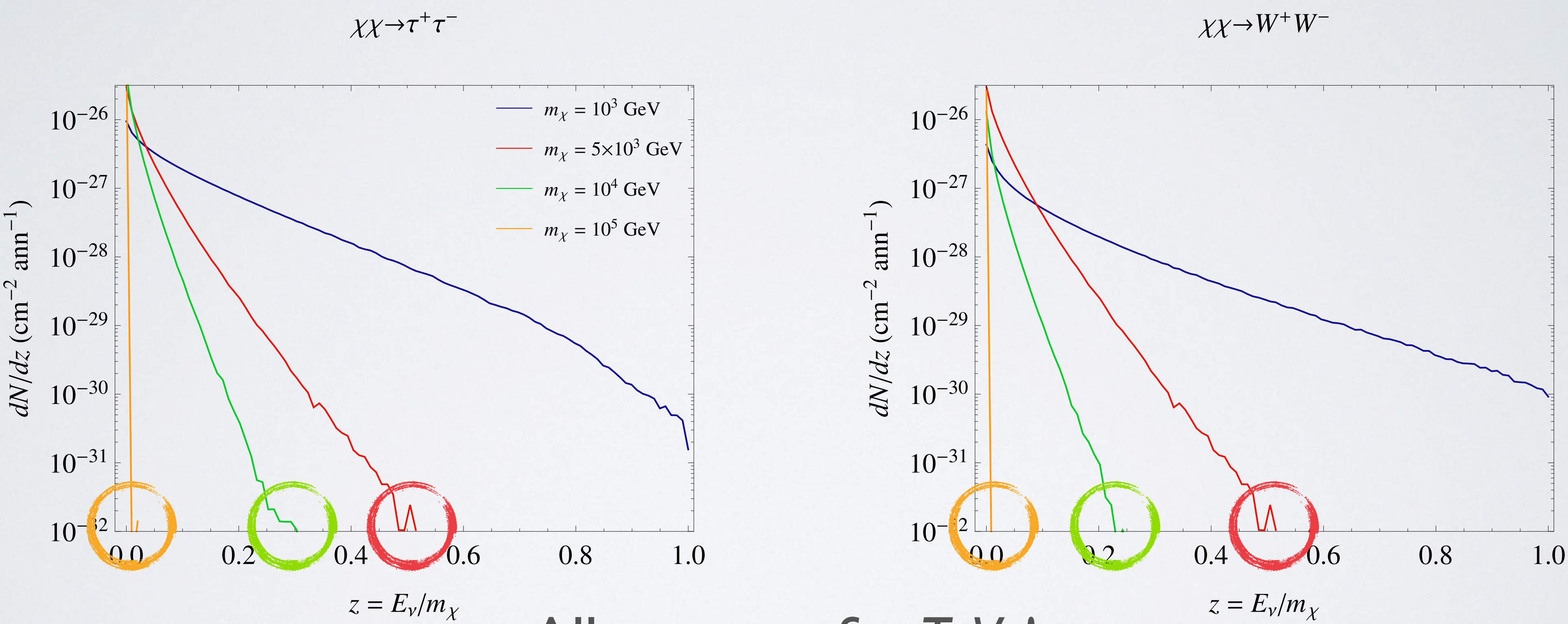
How about Earth?

Lin, Lin and Lee, 1409.3094(2014)

- DM particle is ***easier to escape*** due to weak gravitational binding⟶No good to test GeV DM
- Self-int. will lead to the ***ejection*** of DM in the Earth
- Self-int. is ***insignificant*** at higher mass, $m_\chi \gg$ GeV
- If DM is ***very heavy***, these troubles no longer exist
- No experimental constraint on $m_\chi > 10$ TeV
- Higher energy neutrino suffers from severe ***energy attenuation*** during the propagation in the Sun
- Ideal place to test ***isospin-violation*** with ***heavy DM***

Neutrino attenuation in the Sun

Cirelli *et al.*,Nucl.Phys.B **727**, 99(2005)
Y.-H. Lin, talk @ CosPA2013 & PASCOS2013



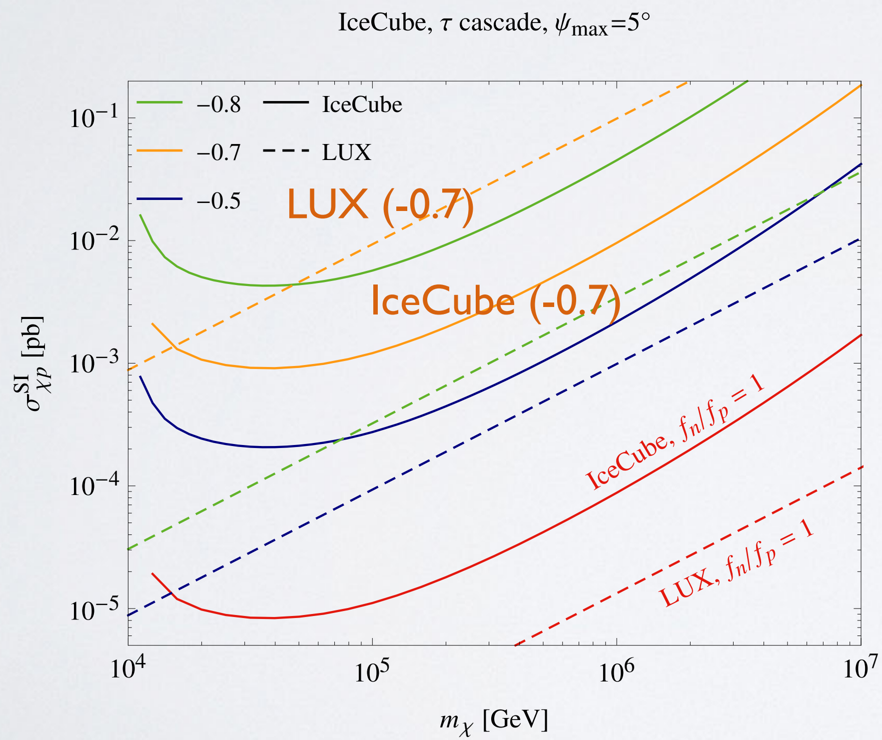
All *stop* at a *few TeVs*!

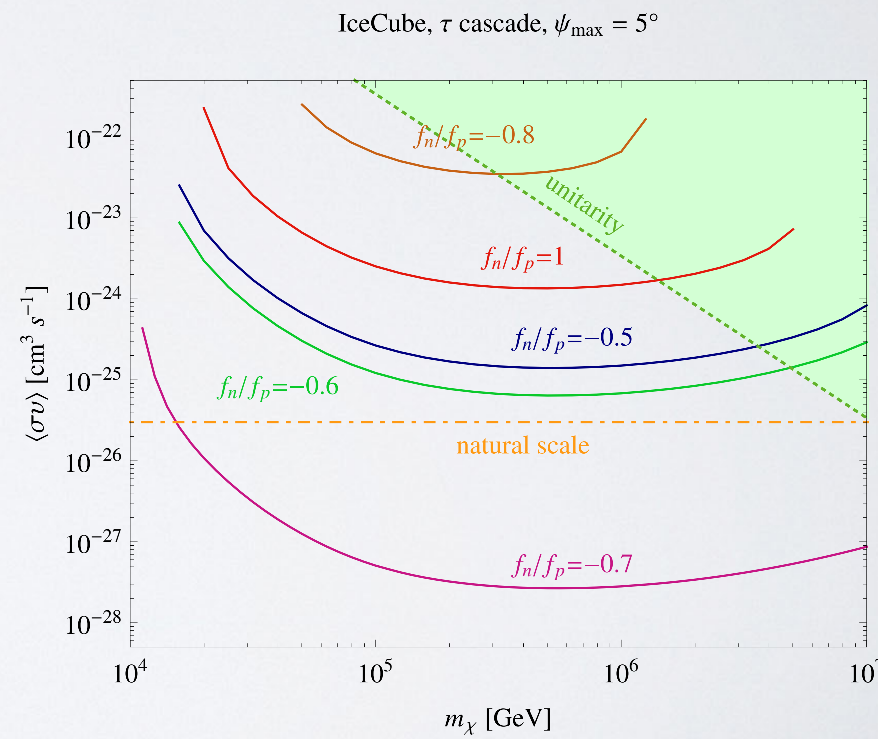
The neutrino carries energy greater than a few TeV cannot escape the Sun!
The spectrum is severely distorted. All primary DM information is lost!

$\sigma_{\chi p}$ and $\langle \sigma v \rangle$ sensitivities

Lin, Lin and Lee, 1409.3094(2014)

- Examining isospin-violation, using Earth DM and IceCube





Epilogue

To summarize so far…

Summary

- To the Sun:
  - Self-int. can be examined by PINGU in the foreseeable future
  - Self-int. plays a significant role when $m_\chi \sim$ GeV
  - When m_χ is sufficient light, the self-int. induced evaporation contributes as well⟶*firstly investigated* by us to our knowledge
- To the Earth:
  - An ideal place probing $m_\chi \gg$ GeV
  - Less neutrino energy attenuation than the Sun
  - Isospin-violation can be tested