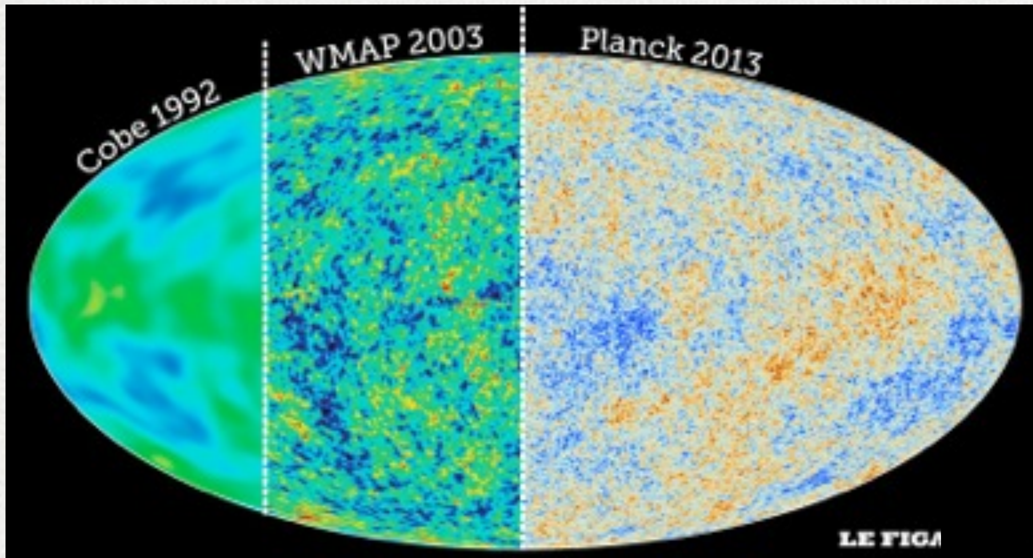
TEST OF DARK MATTER SELF-INTERACTION AND ITS TEMPERATURE IN THE SUN

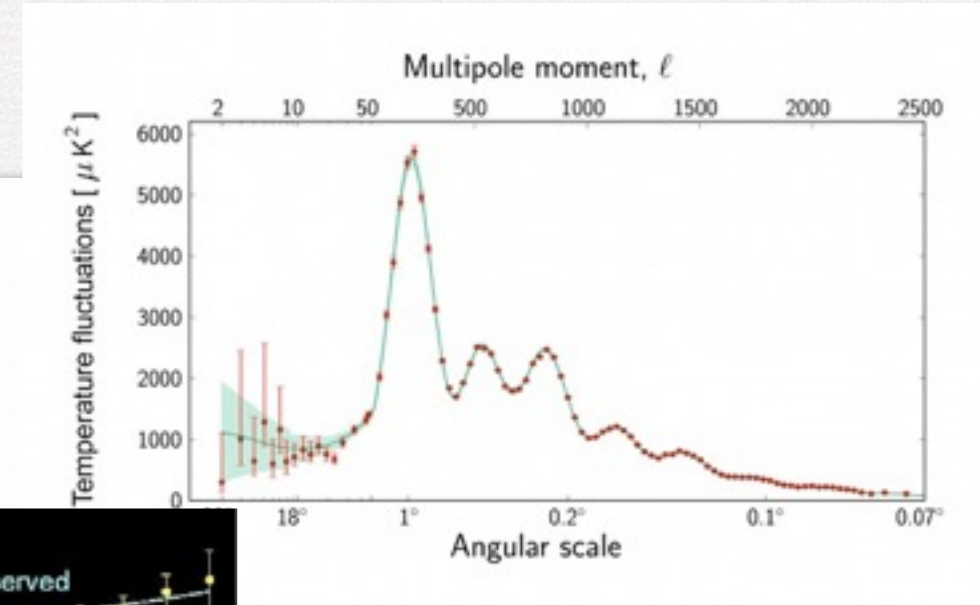
Chian-Shu Chen (Academia Sinica)

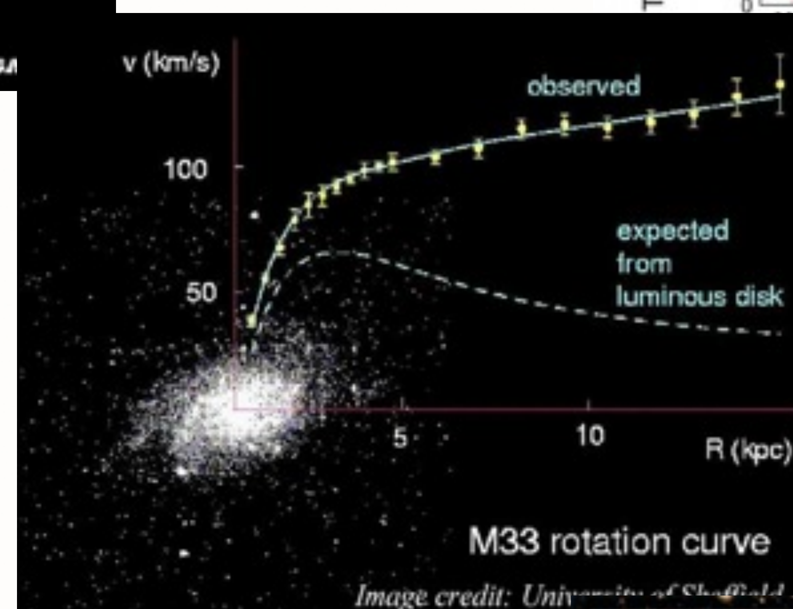
2015/10/27

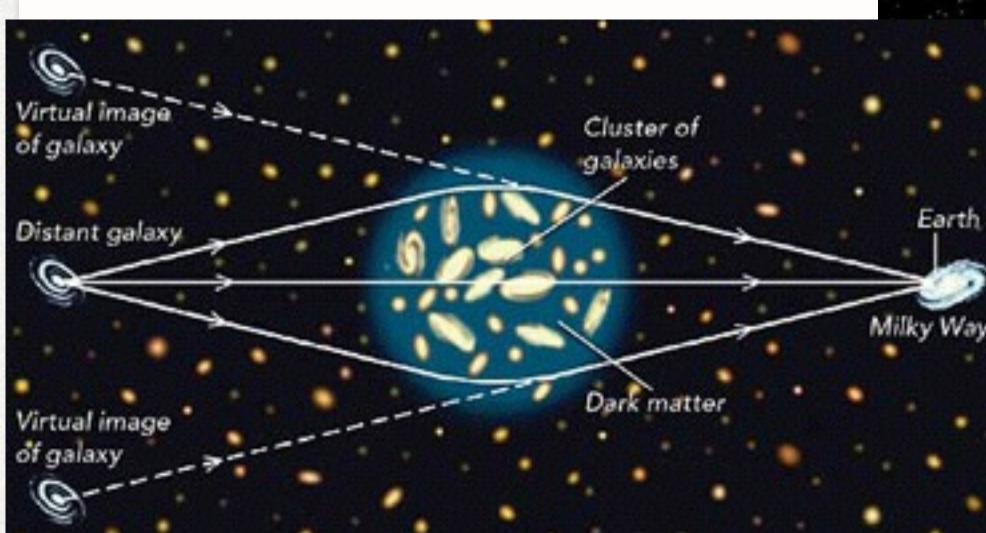
base on 1408.5471(JCAP),1505.03781, and 1508.05263
in collaboration with Guey-Lin Lin and Yen-Hsun Lin

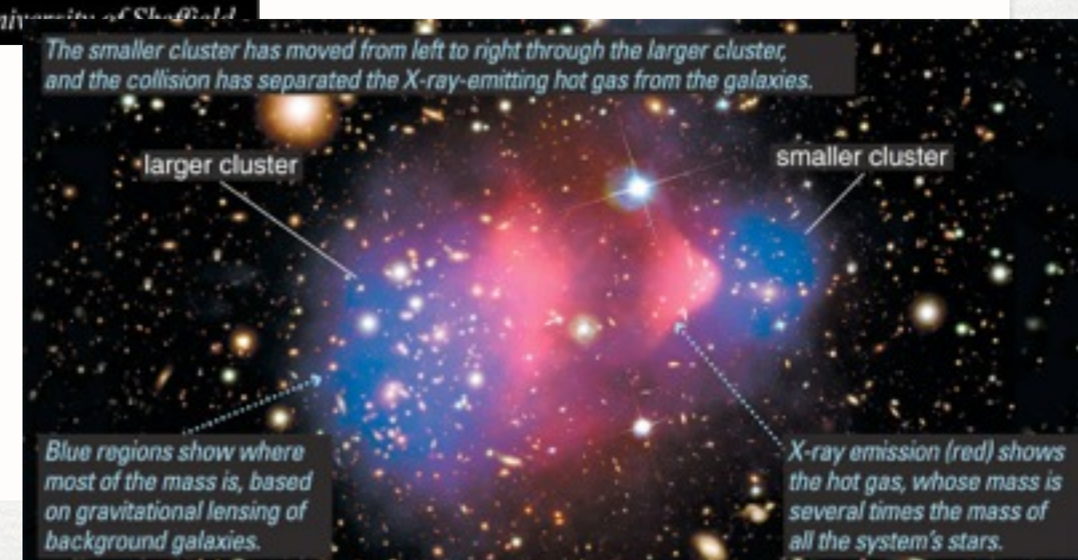
- We have long observed the gravitational pull of "DM" exerts on regular baryonic matter, no conclusive hint of the particle physics governing DM has so far shown up in laboratory exps.





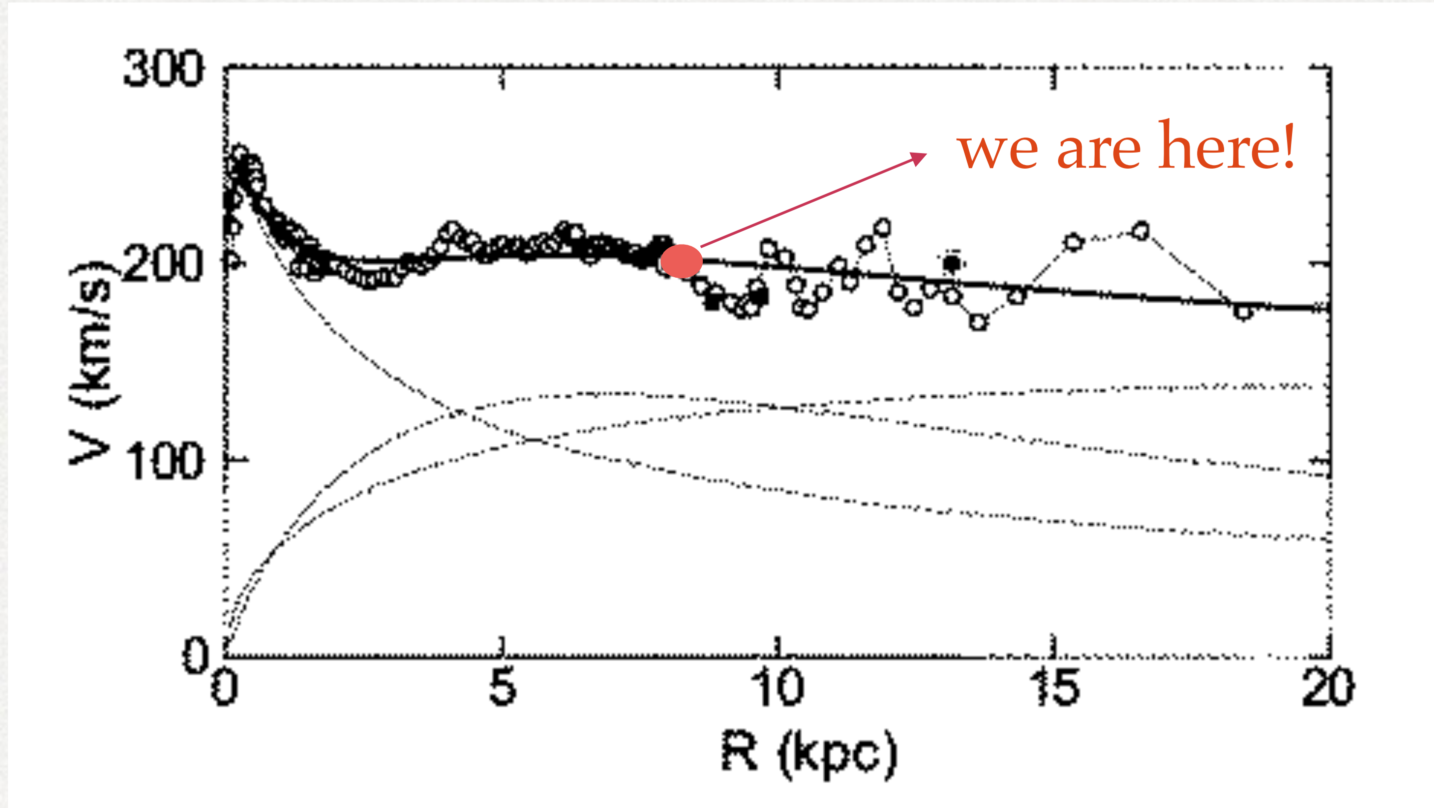




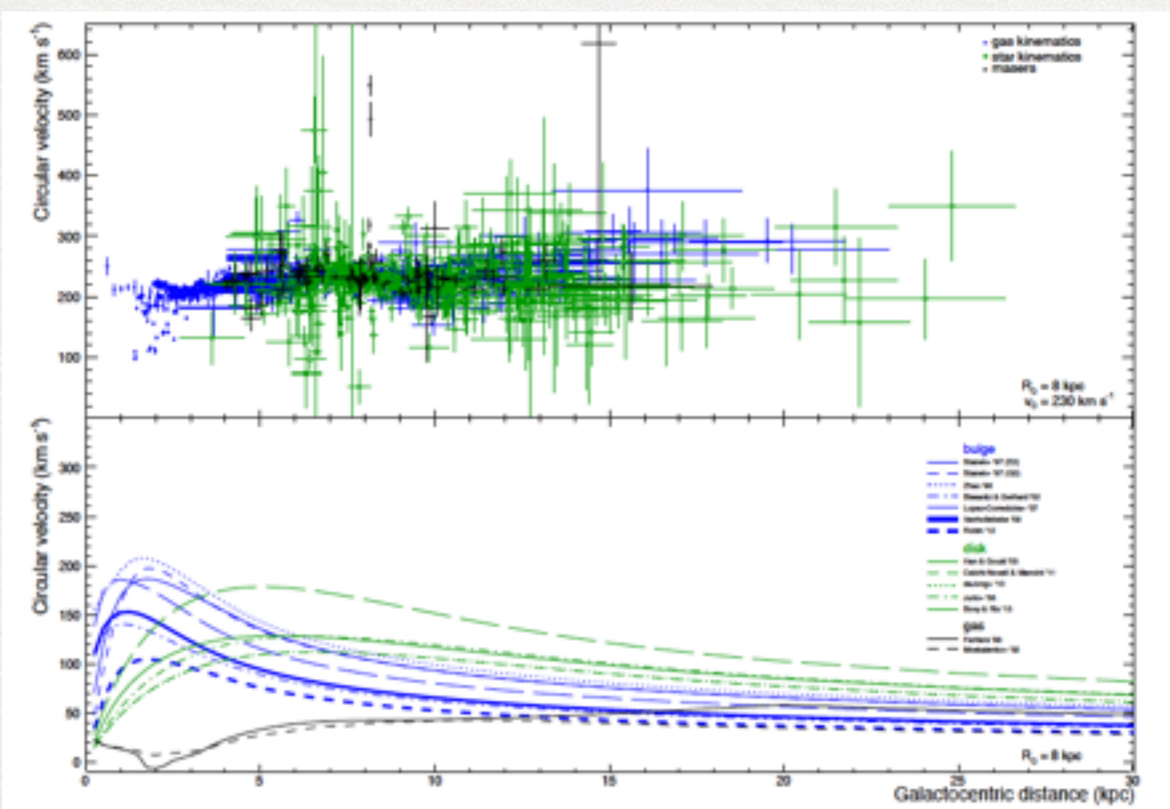


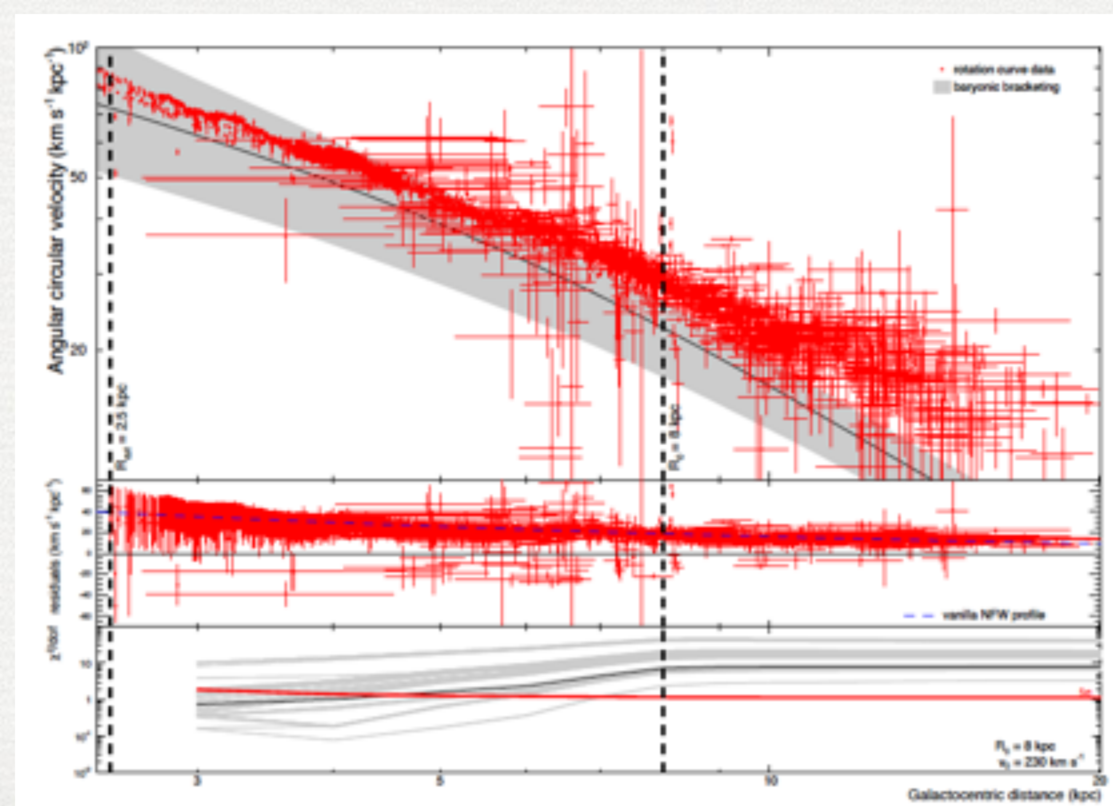
search dark matter particle at our own galaxy

arXiv:1110.4431



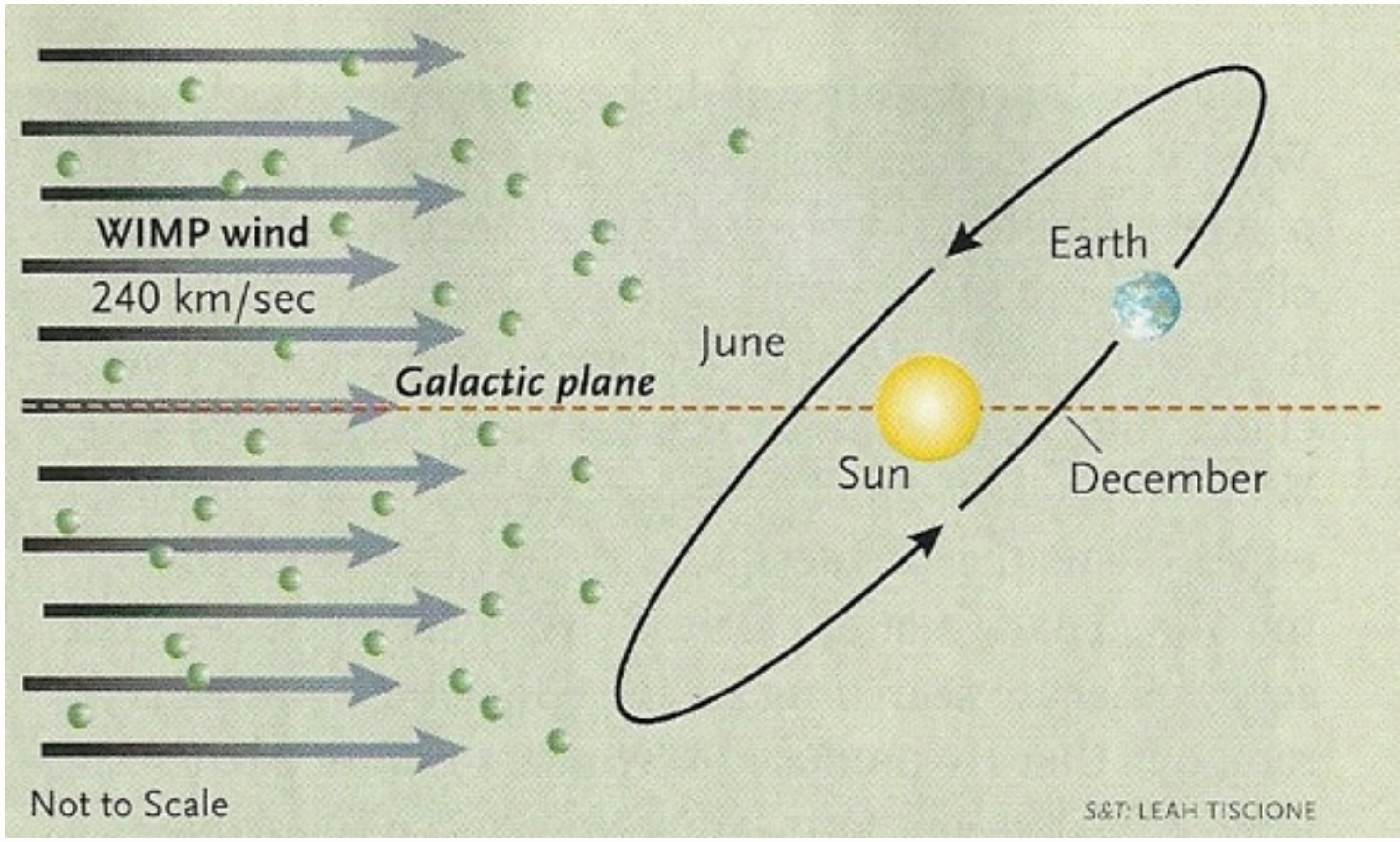
F. Iocco et al (nature physics2015)



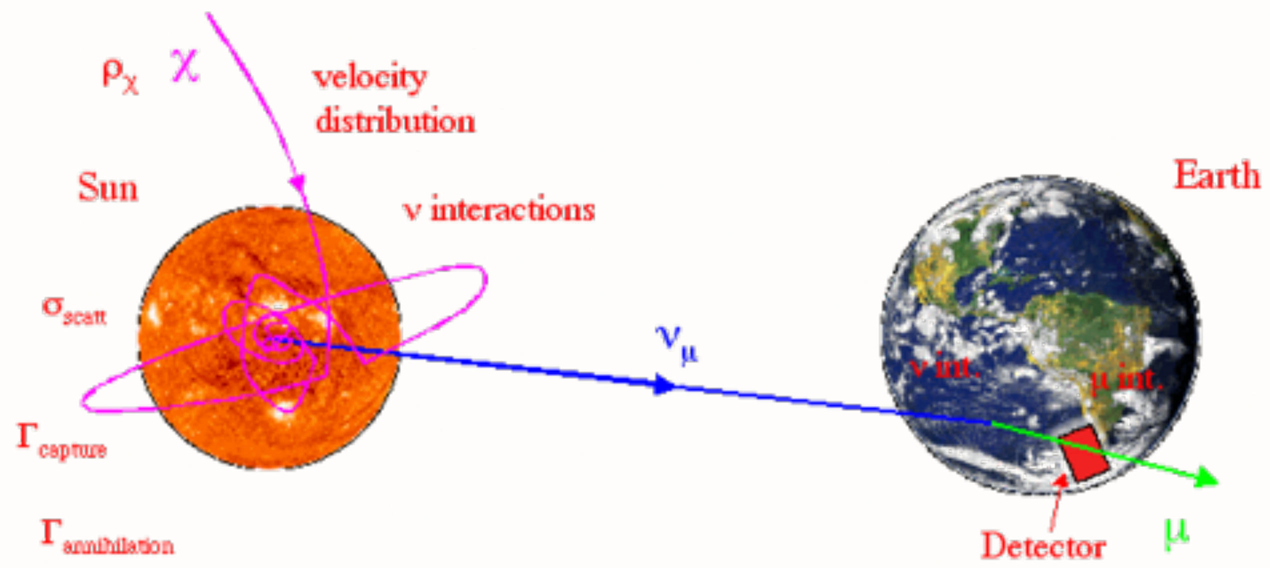


DM is surrounding us of

$\varrho_{DM} \sim 0.3\text{-}0.4\ GeV/cm^3$



If DM interacts with nucleons, this can also happen

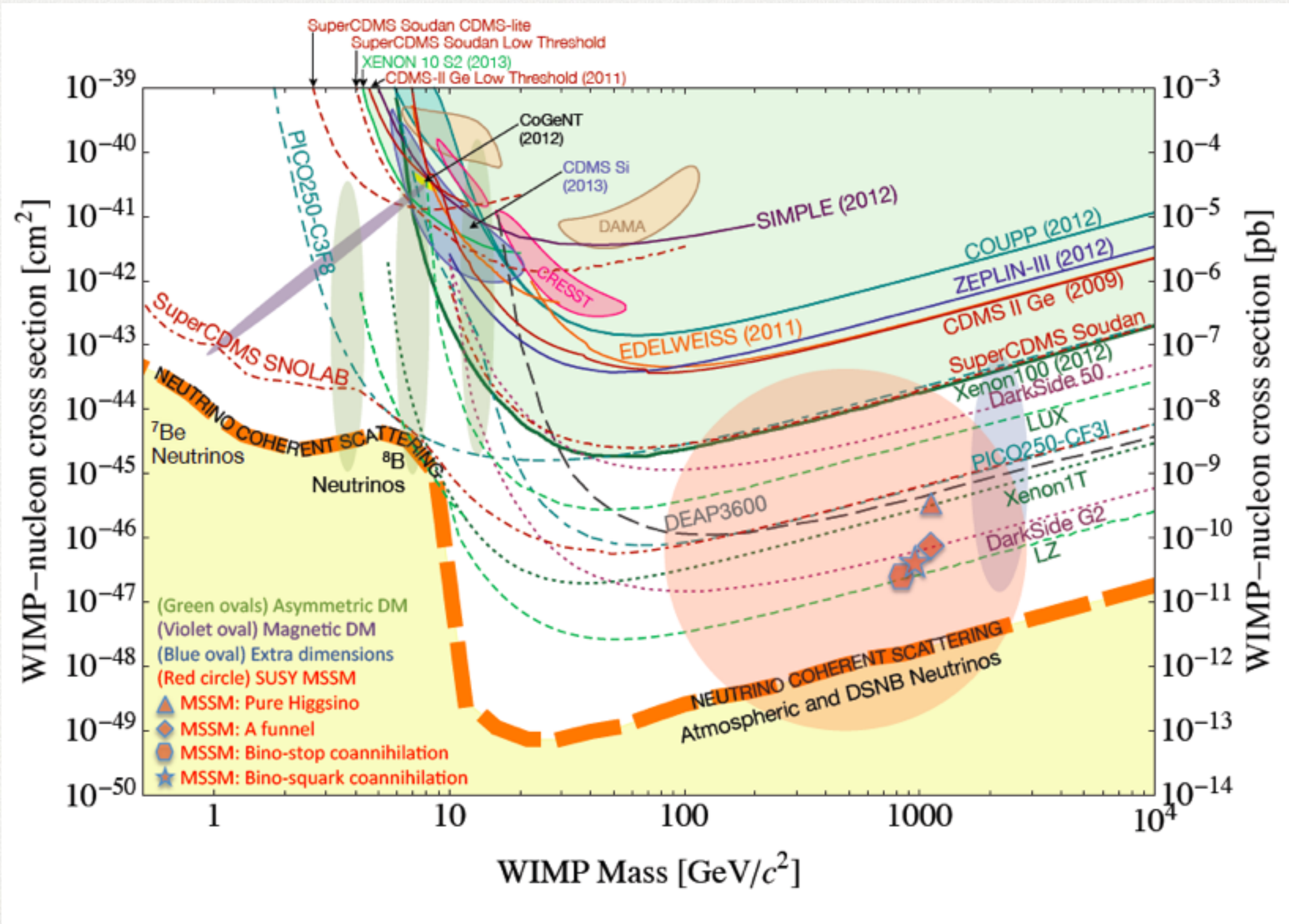


- remarks:
  - The indirect searches of DM in the Sun are tightly linked to direct detection searches, which are sensitive to the cross section for DM scattering off the nucleons of heavy nuclei.

The Sun has an escape velocity, from its surface, of about 618 km/s while the mean-squred velocity of the Galactic DM in the halo is about 270 km/s. Therefore, the gravitational effects of the Sun is significant.

current limits and future expectations

compilation of WIMP-nucleon spin-independent cross section limits



relevant processes of DM in the Sun

- ## Capture and evaporation :

A DM can collide with nuclei and lose energy when it traverse the Sun. If the final velocity of the DM after collision is less than the local escape velocity $v_e(r)$, then it gets gravitationally trapped. However, the captured DM may scatter off energetic nuclei and be ejected, whenever the DM velocity after collision is larger than the local escape velocity.

- ## Annihilation :

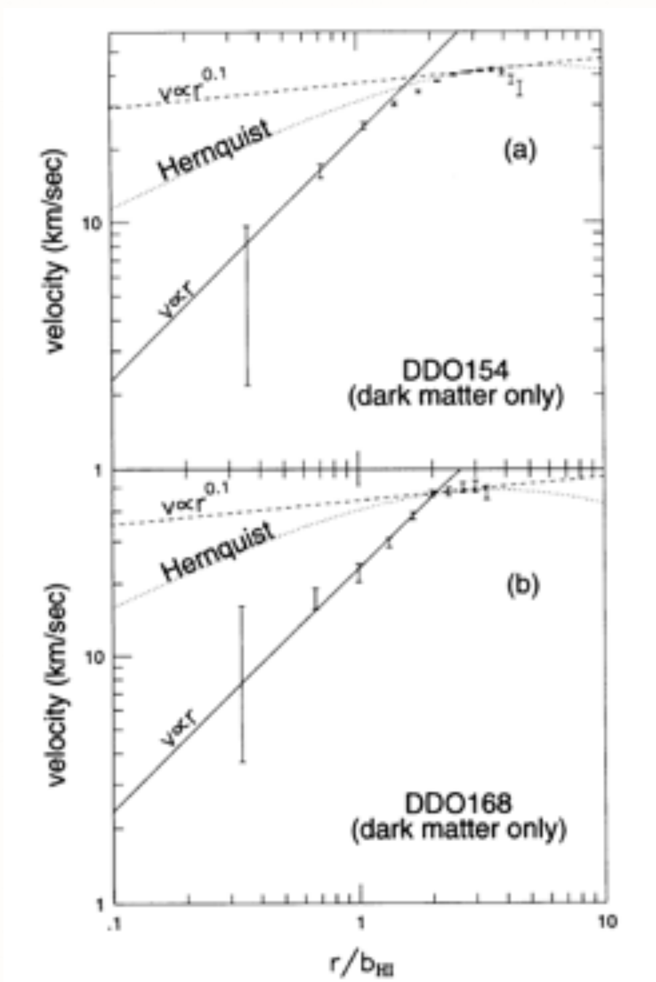
Once DM χ is captured by the Sun, the χ will come to thermal equilibrium and sink into the core. With time, the χ concentration will increase until the density is high enough for $\chi\ \chi$ annihilation to occur. A steady state will be achieved if the time to reach equilibrium is short compare to the age of the object.

Can DM interact with itself ?

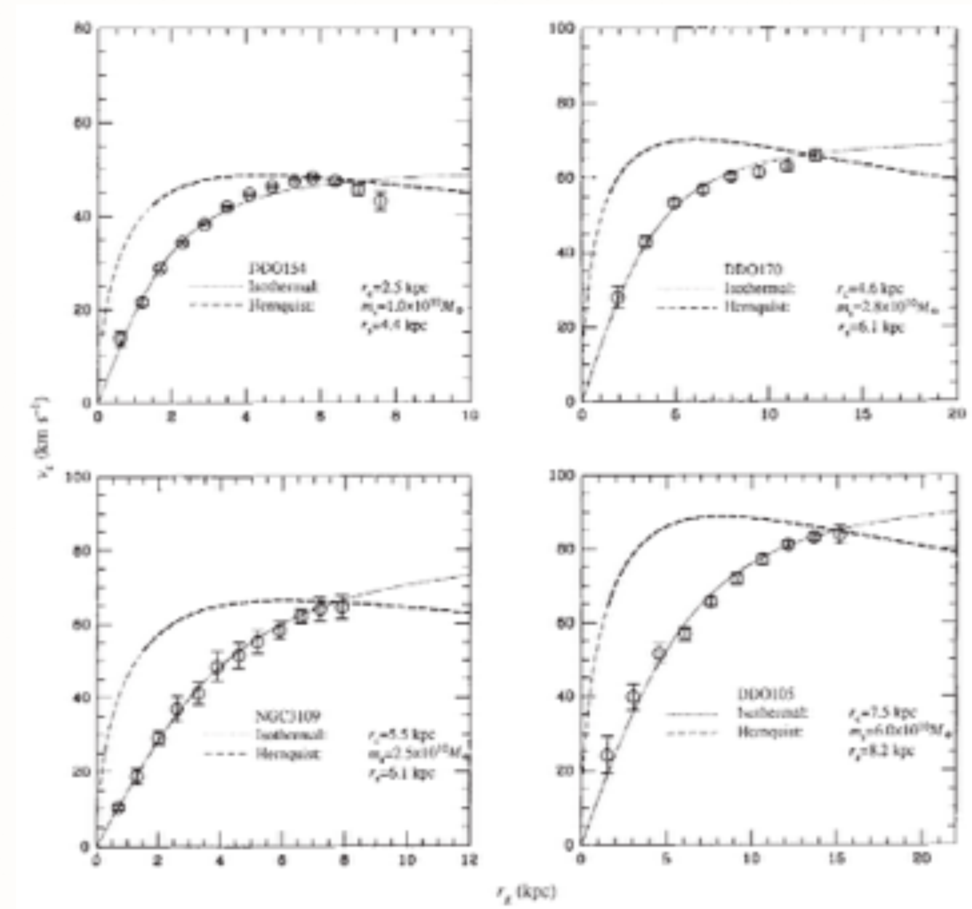
collisionless cold dark matter ?

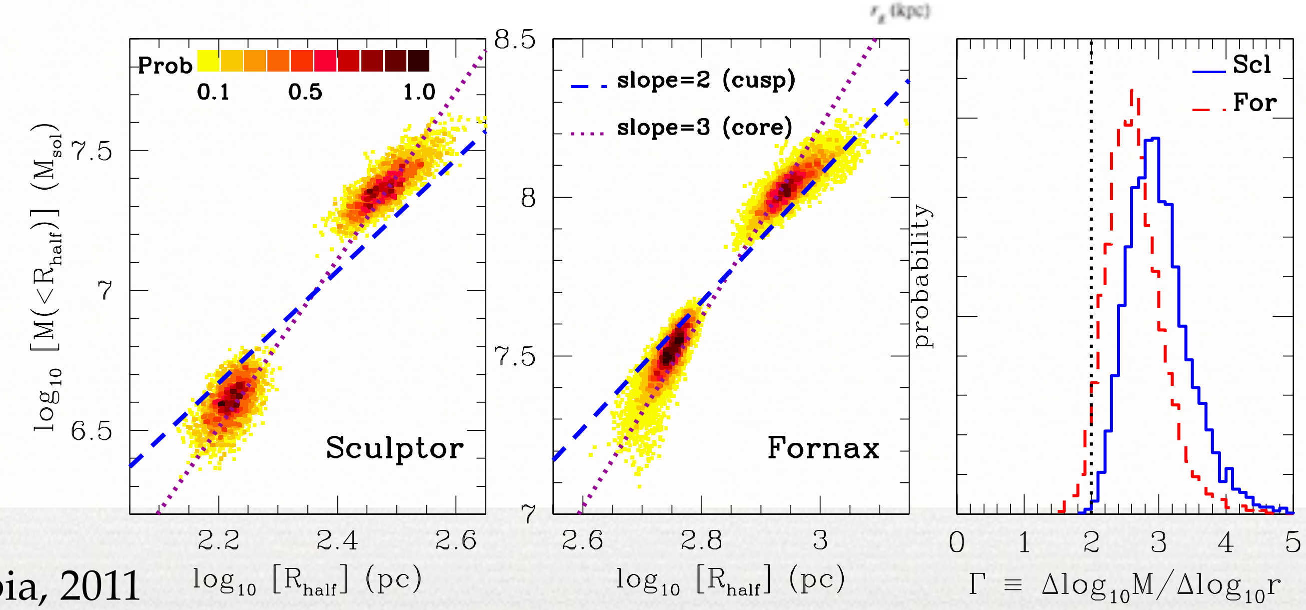
- inconsistencies between N-body simulations and observations

- 1. Cusp and core problem :



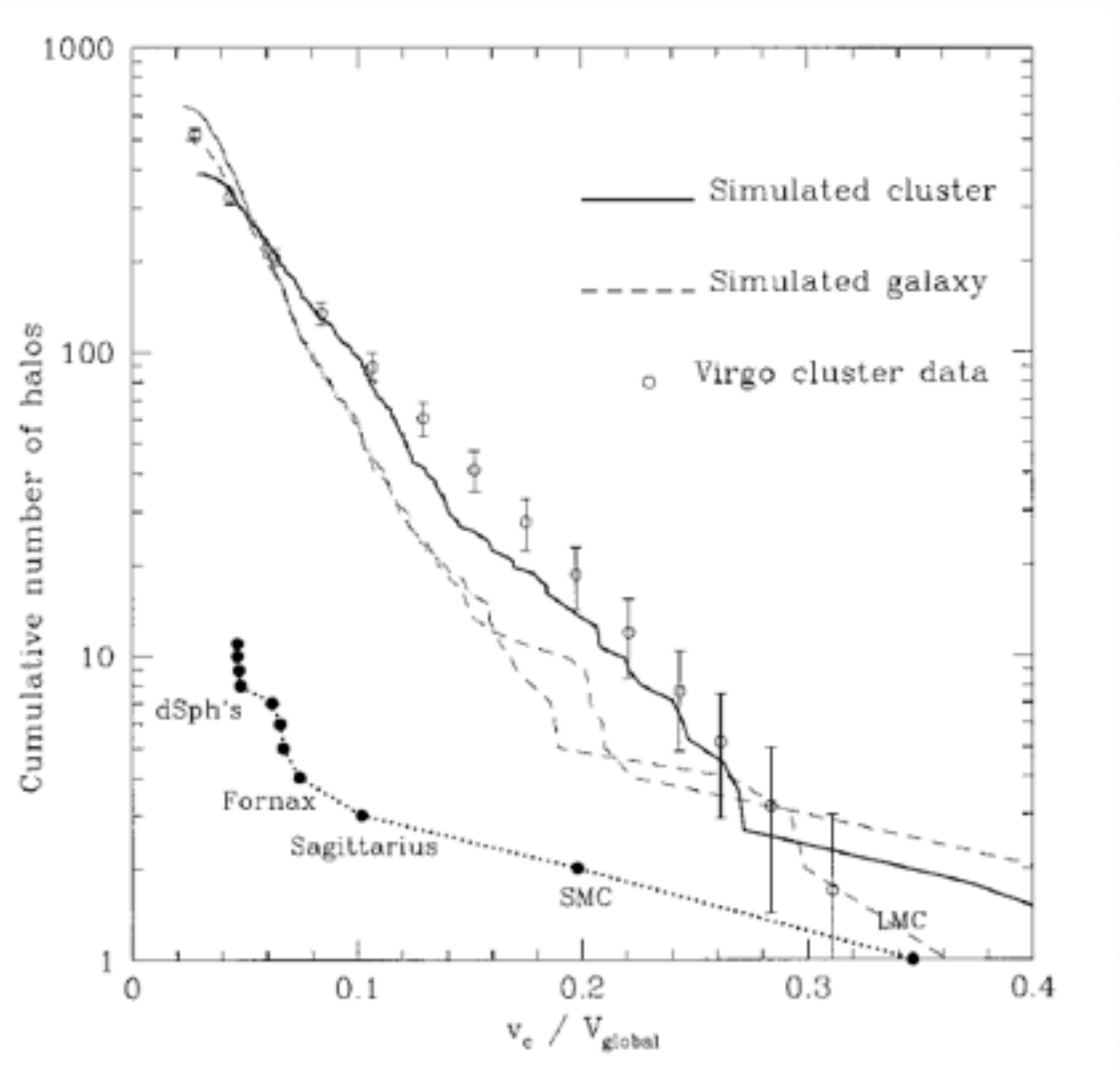
R.A. Flores and J.R. Primack, ASJ(1994)





M.G.Walker and J. Penarrubia, 2011

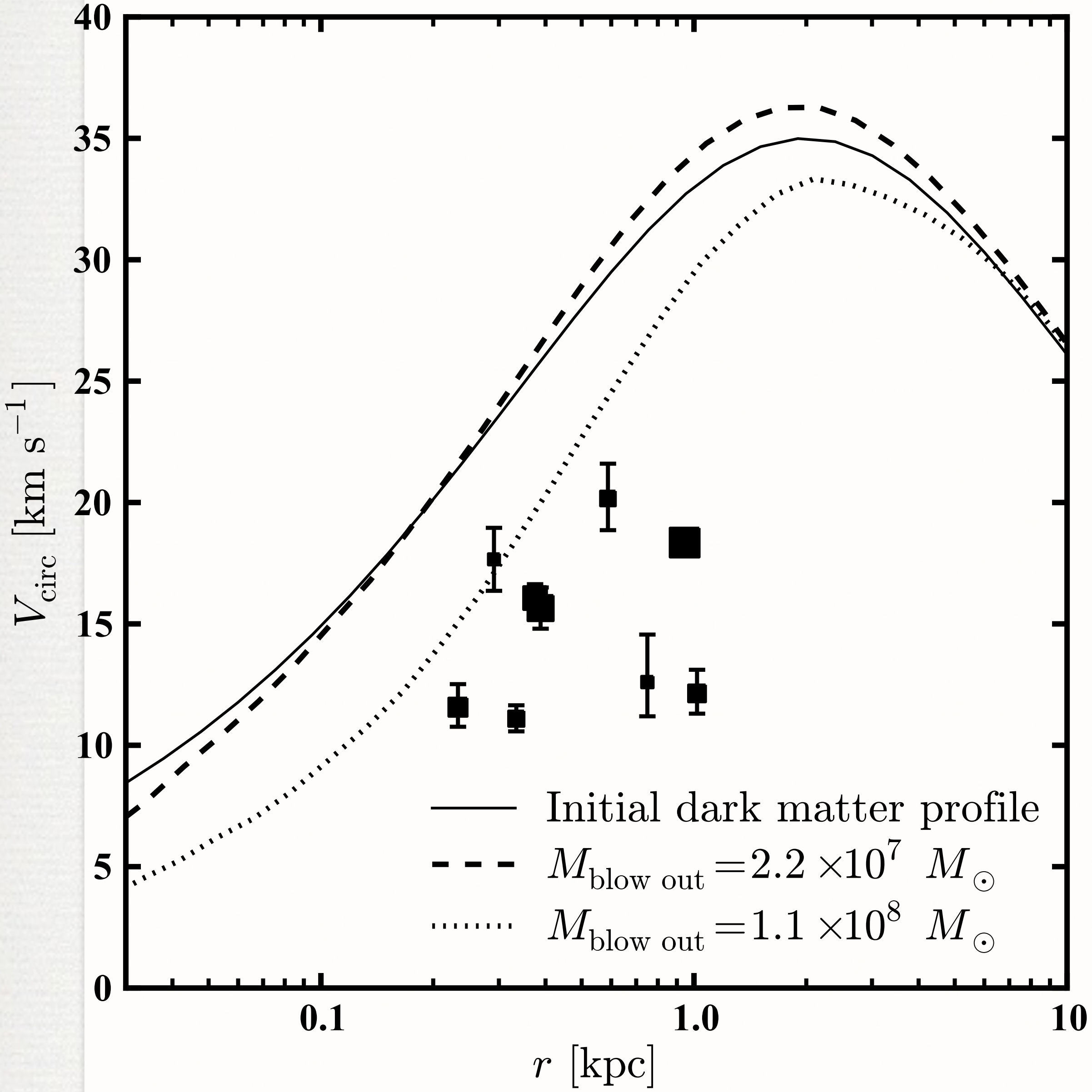
2. Missing satellites

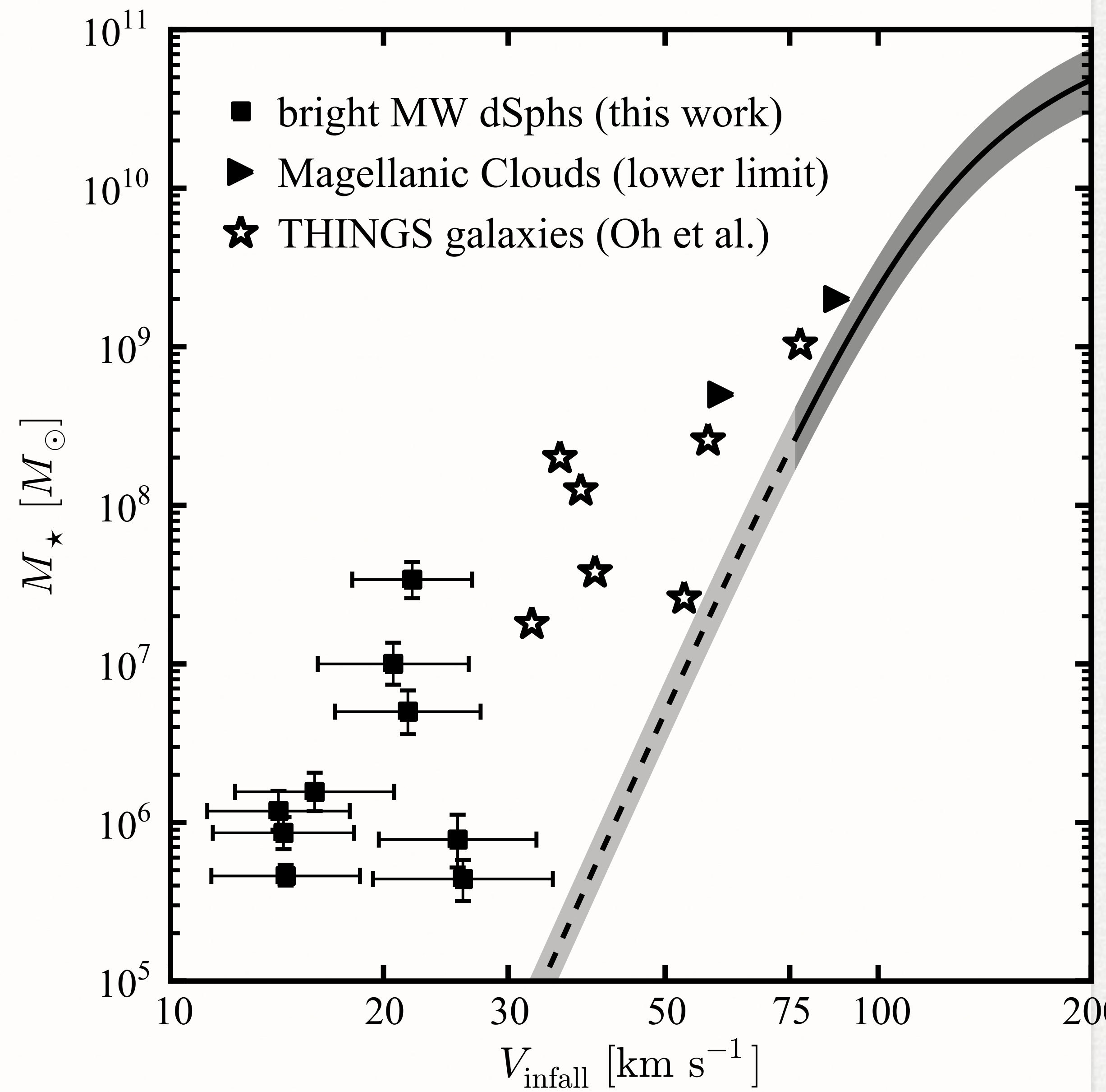


B. Moore, Astro. J. 1999

3. Too big to fail

M. Boylan-Kolchin et al, 2012





Remarks :

However, comparisons to cosmological models tend to be inconclusive for the simple reason : while most cosmological N-body simulations consider only dark matter particles, one observes only baryons.

Baryons complicate not only the measurement of a dark matter density profile but also its interpretation within the context of the CDM paradigm.

Measurement : the fact that any uncertainty (e.g., stellar mass-to-light ratios) in the baryonic mass profile propagates to the inferred dark matter profile, as the latter is merely the difference between dynamical and baryonic mass profiles.

Interpretation : the possibility that various poorly understood dynamical processes involving baryons might alter the original structure of a dark matter halo.

Dark Matter Self-interaction

- If dark matter interacts with itself, it might solve these small scale problems.

PHYSICAL REVIEW LETTERS

Observational Evidence for Self-Interacting Cold Dark Matter

David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton, New Jersey 08544
(Received 20 September 1999)

Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark matter particles are self-interacting with a large scattering cross section but negligible annihilation or dissipation. In this scenario, astronomical observations may enable us to study dark matter properties that are inaccessible in the laboratory.

- Constraints from Bullet Cluster matter distribution, halo shape, core densities, …….

- analysis based on the kinematics of dwarf spheroidals, DMSI only alleviate small scale structure when

$$0.1\ \mathrm{cm}^2/\mathrm{g} < \sigma_{\chi\chi}/m_\chi < 1.0\ \mathrm{cm}^2/\mathrm{g}$$

- The general DM evolution equation in the Sun is given by

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

$$N_\chi(t) = \frac{C_c \tanh(t/\tau_A)}{\tau_A^{-1} - (C_s - C_e)\tanh(t/\tau_A)/2} \quad \text{for} \quad N_\chi(0) = 0$$

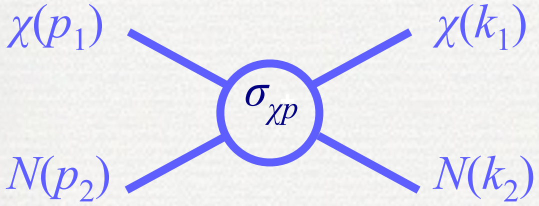
$$\tau_A = \frac{1}{\sqrt{C_c(C_a + C_{se}) + (C_s - C_e)^2/4}}$$

time scale for the DM in the Sun to reach the equilibrium

in the equilibrium state, $\tanh(t/\tau_A) \sim 1$

$$N_{\chi,\mathrm{eq}} = \frac{C_s - C_e}{2(C_a + C_{se})} + \sqrt{\frac{(C_s - C_e)^2}{4(C_a + C_{se})^2} + \frac{C_c}{C_a + C_{se}}}$$

The capture rate can be categorized by the spin-dependent and spin-independent interactions



$$C_c^{\rm SD} \simeq 3.35 \times 10^{24}\ {\rm s}^{-1} \left(\frac{\rho_0}{0.3\ {\rm GeV/cm^3}}\right) \left(\frac{270\ {\rm km/s}}{\bar{v}}\right)^3 \left(\frac{\rm GeV}{m_\chi}\right)^2 \left(\frac{\sigma_{\rm H}^{\rm SD}}{10^{-6}\ {\rm pb}}\right)$$

$$\sigma_i^{\rm SD} = A^2 \left(\frac{m_\chi + m_p}{m_\chi + m_A}\right)^2 \frac{4(J_i+1)}{3J_i} |\langle S_{p,i}\rangle + \langle S_{p,i}\rangle|^2 \sigma_{\chi p}^{\rm SD}$$

or

$$C_c^{\rm SI} \simeq 1.24 \times 10^{24}\ {\rm s}^{-1} \left(\frac{\rho_0}{0.3\ {\rm GeV/cm^3}}\right) \left(\frac{270\ {\rm km/s}}{\bar{v}}\right)^3 \left(\frac{\rm GeV}{m_\chi}\right)^2 \left(\frac{2.6\sigma_{\rm H}^{\rm SI} + 0.175\sigma_{\rm He}^{\rm SI}}{10^{-6}\ {\rm pb}}\right),$$

$$\sigma_i^{\rm SI} = A^2 \left(\frac{m_A}{m_p}\right)^2 \left(\frac{m_\chi + m_p}{m_\chi + m_A}\right)^2 \sigma_{\chi p}^{\rm SI}$$

- The captured DM might collide with the nuclei inside the Sun and be kicked out from the Sun if the final state velocity is larger than the escape velocity. —- evaporation

$$C_e \simeq \frac{8}{\pi^3}\sqrt{\frac{2m_\chi}{\pi T_\chi(\bar{r})}}\frac{v_{\rm esc}^2(0)}{\bar{r}^3}\exp\left(-\frac{m_\chi v_{\rm esc}^2(0)}{2T_\chi(\bar{r})}\right)\Sigma_{\rm evap}$$

evaporation effect can be relevant only for low DM mass ~ O(1) GeV.

$$\phi(r) = \int_0^r \frac{G_N M_\odot(r')}{r'^2}dr'$$ gravitational potential

$$\frac{3}{2}kT(0) = m_\chi \phi(\bar{r})$$

if take the solar core to have a constant density, we have $\bar{r} \approx 0.13 R_{Sun}\sqrt{\frac{m_p}{m_\chi}}$

similarly the annihilation coefficient can be given by :

local gravitational potential:

$$\phi(r) = \int_0^r \frac{G_N M_\odot(r')}{r'^2} dr'$$

$$M_\odot(r) = 4\pi \int_0^r r'^2 \rho_\odot(r') dr'$$

DM number density is determined by solar gravitational potential and scales as

$$n_\chi(r) = n_0 e^{-m_\chi \phi(r)/T_\chi}$$

density at the core

The annihilation coefficient C_a is defined as

$$C_a = \langle \sigma v \rangle_\odot \frac{\int_\odot n_\chi^2(r) d^3 r}{[\int_\odot n_\chi(r) d^3 r]^2} \simeq \frac{\langle \sigma v \rangle V_2}{V_1^2}$$

$$V_j \simeq 6.5 \times 10^{28} \text{ cm}^3 \left(\frac{10 \text{ GeV}}{j m_\chi} \right)^{3/2}$$

the relative velocity average annihilation cross section

The DM self-capture rate

The DM scatters with the DM that have been captured inside the Sun.

$$C_s \propto n_\chi \sigma_{\chi\chi} F(\bar{v}_\chi, v_{\rm esc})$$

$$C_s = \sqrt{\frac{3}{2}} n_\chi \sigma_{\chi\chi} v_{\rm esc}(R_\odot) \frac{v_{\rm esc}(R_\odot)}{\bar{v}} \left\langle \widehat{\phi}_\chi \right\rangle \frac{{\rm erf}(\eta)}{\eta}$$

$$\eta^2 = 3(v_\odot/\bar{v})^2/2$$

$$\left\langle \widehat{\phi}_\chi \right\rangle \simeq 5.1$$

dimensionless average solar potential experienced by the captured DM within the Sun

DM self-interaction induced evaporation C_{se}:

- DM can interact among themselves, DM trapped in the solar core could scatter with other trapped DM and results in the evaporation. This process involves two DM particles just like annihilation. Both processes lead to the DM dissipation in the Sun. While C_{se} does not produce neutrino flux as C_a does.

- The derivation of this term is similar to the nucleon induced evaporation with the parameter replacements

$$m_N \to m_\chi,\ T_N \to T_\chi$$

DM satisfies the Maxwell-Boltzmann distribution

$$f_\odot(w) = \frac{4}{\sqrt{\pi}} \left(\frac{m_\chi}{2T_\chi}\right)^{3/2} n_\chi w^2 \exp\left(-\frac{m_\chi w^2}{2T_\chi}\right)$$

- Take the final state velocity v such that v > w. The DM-DM differential scattering rate with the velocity transition w -> v is

$$R^+(w \to v)dv = \frac{2}{\sqrt{\pi}} n_\chi \sigma_{\chi\chi} \frac{v}{w} e^{-\kappa^2(v^2-w^2)} \chi(\beta_-, \beta_+) dv$$

with $\beta_\pm = \pm\kappa w$ with $\kappa = \sqrt{\frac{m_\chi}{2T_\chi}}$ and $\chi(a,b) \equiv \int_a^b du e^{-u^2} = \frac{\sqrt{\pi}}{2}[\mathrm{erf}(b) - \mathrm{erf}(a)]$

we integrate the scattering rate with v greater than the escape velocity

$$\Omega^+_{v_{\rm esc}}(w) = \int_{v_{\rm esc}}^{\infty} R^+(w \to v')dv' = \frac{2}{\sqrt{\pi}} \frac{n_\chi \sigma_{\chi\chi}}{w} \frac{T_\chi}{m_\chi} \exp\left[\frac{m_\chi(v_{\rm esc}^2 - w^2)}{2T_\chi}\right] \chi(\beta_-, \beta_+)$$

the evaporation rate per unit volume at position r , and we sum up all possible states of the incident DM

$$\frac{dC_{se}}{dV} = \int_0^{v_{\rm esc}} f_\odot(w) \Omega^+_{v_{\rm esc}}(w) dw$$

- again DM number density inside the Sun is given by

$$n_\chi(r) = n_0 \exp\left(-\frac{m_\chi \phi(r)}{T_\chi}\right)$$

$$\frac{dC_{se}}{dV} = \frac{4}{\sqrt{\pi}}\sqrt{\frac{m_\chi}{2T_\chi}}\frac{n_0^2\sigma_{\chi\chi}}{m_\chi}\exp\left[-\frac{2m_\chi\phi(r)}{T_\chi}\right]\exp\left[-\frac{E_{\rm esc}(r)}{T_\chi}\right]\tilde{K}(m_\chi)$$

with

$$\tilde{K}(m_\chi) = \sqrt{\frac{E_{\rm esc}(r)T_\chi}{\pi}}\exp\left[-\frac{E_{\rm esc}(r)}{T_\chi}\right] + \left(E_{\rm esc}(r) - \frac{T_\chi}{2}\right)\operatorname{erf}\left(\sqrt{\frac{E_{\rm esc}(r)}{T_\chi}}\right)$$

$$E_{\rm esc}(r) = \frac{1}{2}m_\chi v_{\rm esc}^2(r)$$

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

- The general DM evolution equation in the Sun is given by

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

$$N_\chi(t) = \frac{C_c \tanh(t/\tau_A)}{\tau_A^{-1} - (C_s - C_e)\tanh(t/\tau_A)/2}$$ for $N_\chi(0) = 0$

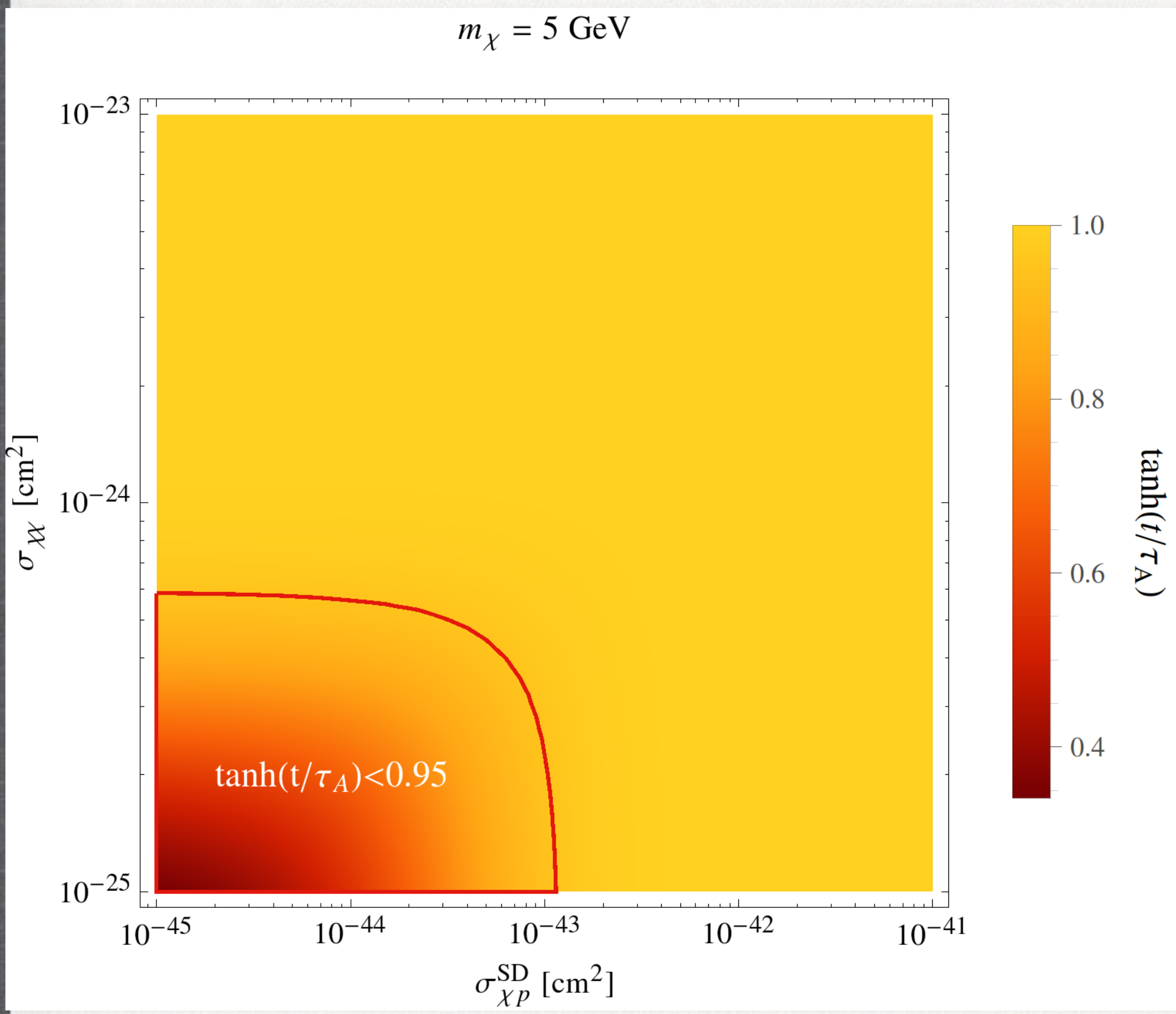
$$\tau_A = \frac{1}{\sqrt{C_c(C_a + C_{se}) + (C_s - C_e)^2/4}}$$

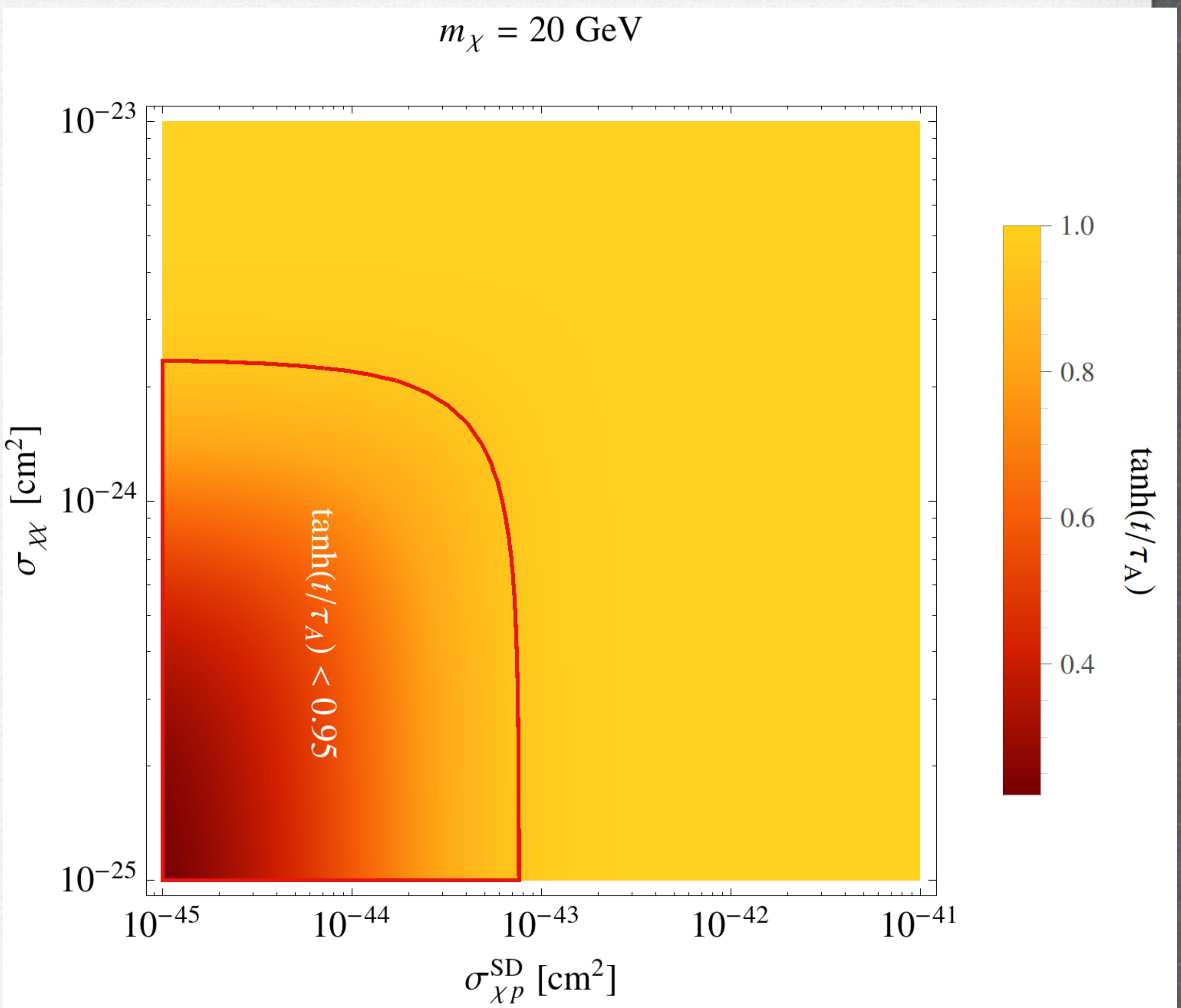
time scale for the DM in the Sun to reach the equilibrium

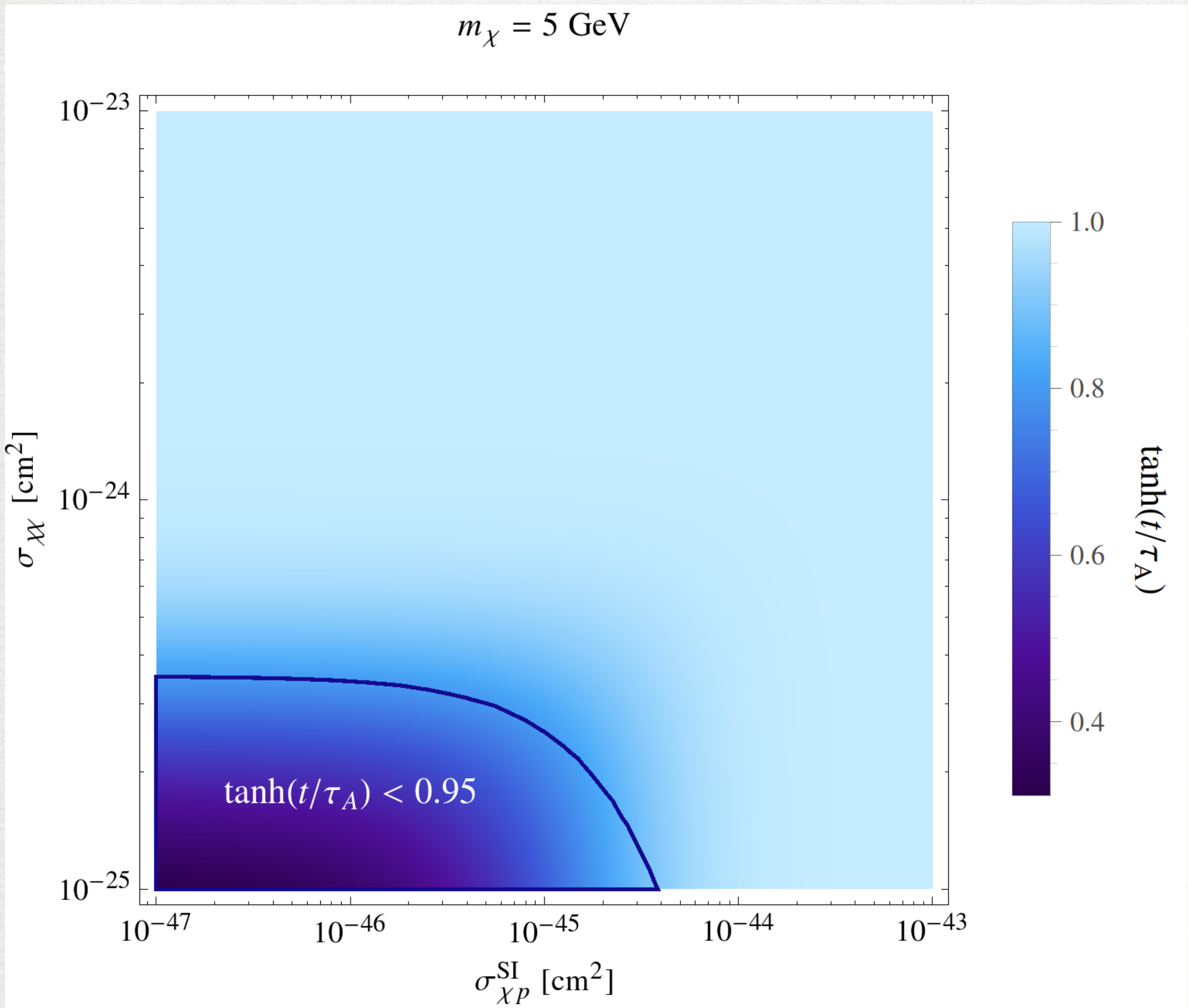
in the equilibrium state, $\tanh(t/\tau_A) \sim 1$

$$N_{\chi,\mathrm{eq}} = \frac{C_s - C_e}{2(C_a + C_{se})} + \sqrt{\frac{(C_s - C_e)^2}{4(C_a + C_{se})^2} + \frac{C_c}{C_a + C_{se}}}$$

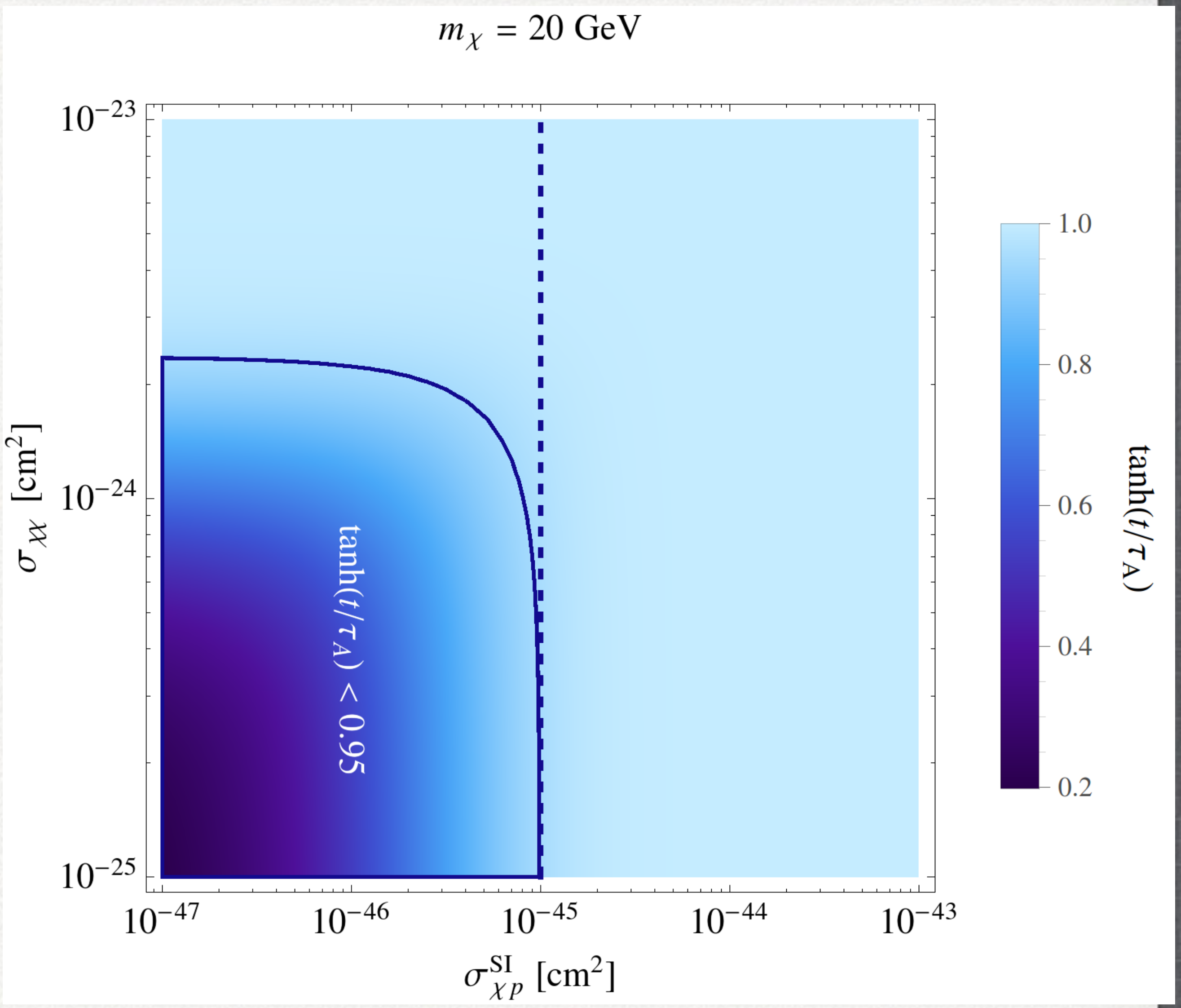
numerical results : parameter space







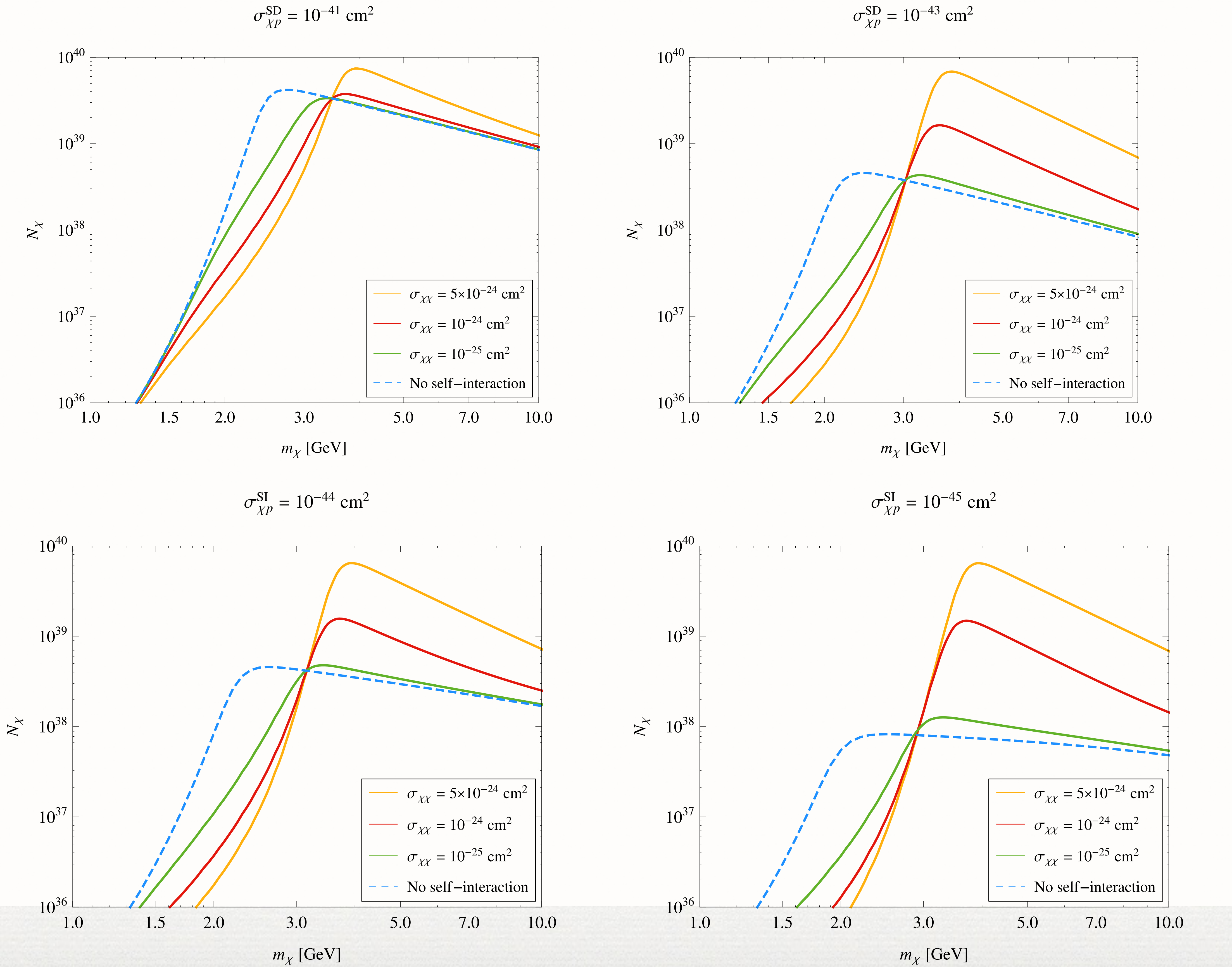
m_χ = 5 GeV
10^{-23}
10^{-24}
10^{-25}
$\sigma_{\chi\chi}$ [cm^2]
10^{-47}
10^{-46}
10^{-45}
10^{-44}
10^{-43}
$\sigma^{SI}_{\chi p}$ [cm^2]
$\tanh(t/\tau_A) < 0.95$
1.0
0.8
0.6
0.4
$\tanh(t/\tau_A)$



m_χ = 20 GeV
10^{-23}
10^{-24}
10^{-25}
$\sigma_{\chi\chi}$ [cm^2]
10^{-47}
10^{-46}
10^{-45}
10^{-44}
10^{-43}
$\sigma^{SI}_{\chi p}$ [cm^2]
$\tanh(t/\tau_A) < 0.95$
1.0
0.8
0.6
0.4
0.2
$\tanh(t/\tau_A)$

- General speaking, the inclusion of DM self-interaction will increase the capture DM number

CSC et al, JCAP2014



we define the dimensionless quantity

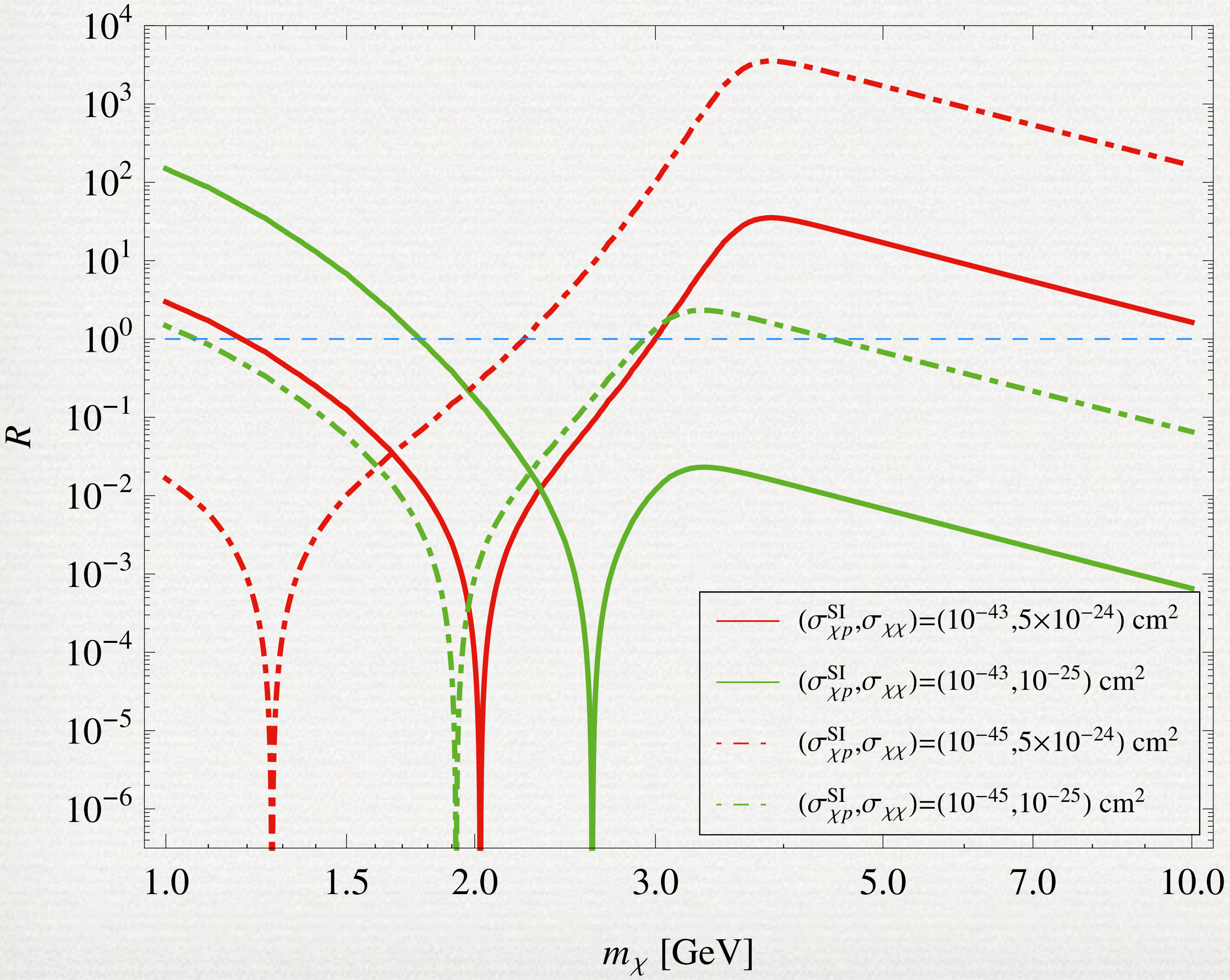
$$R \equiv \frac{(C_s - C_e)^2}{C_c(C_a + C_{se})}$$

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

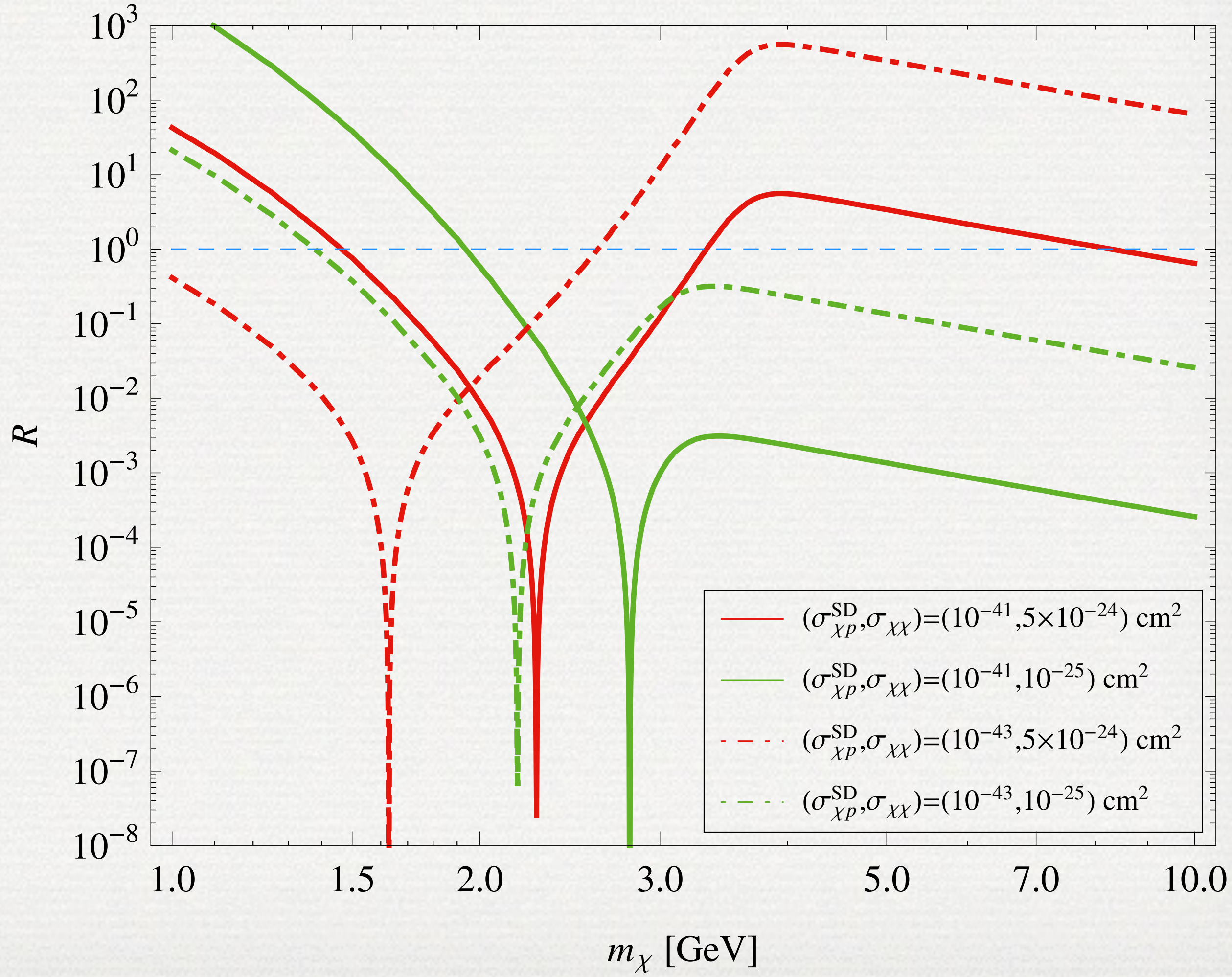
$$\Gamma_A = \frac{1}{2}\frac{C_c C_a}{C_a + C_{se}}\left(\pm\sqrt{\frac{R}{4}} + \sqrt{\frac{R}{4}+1}\right)^2$$

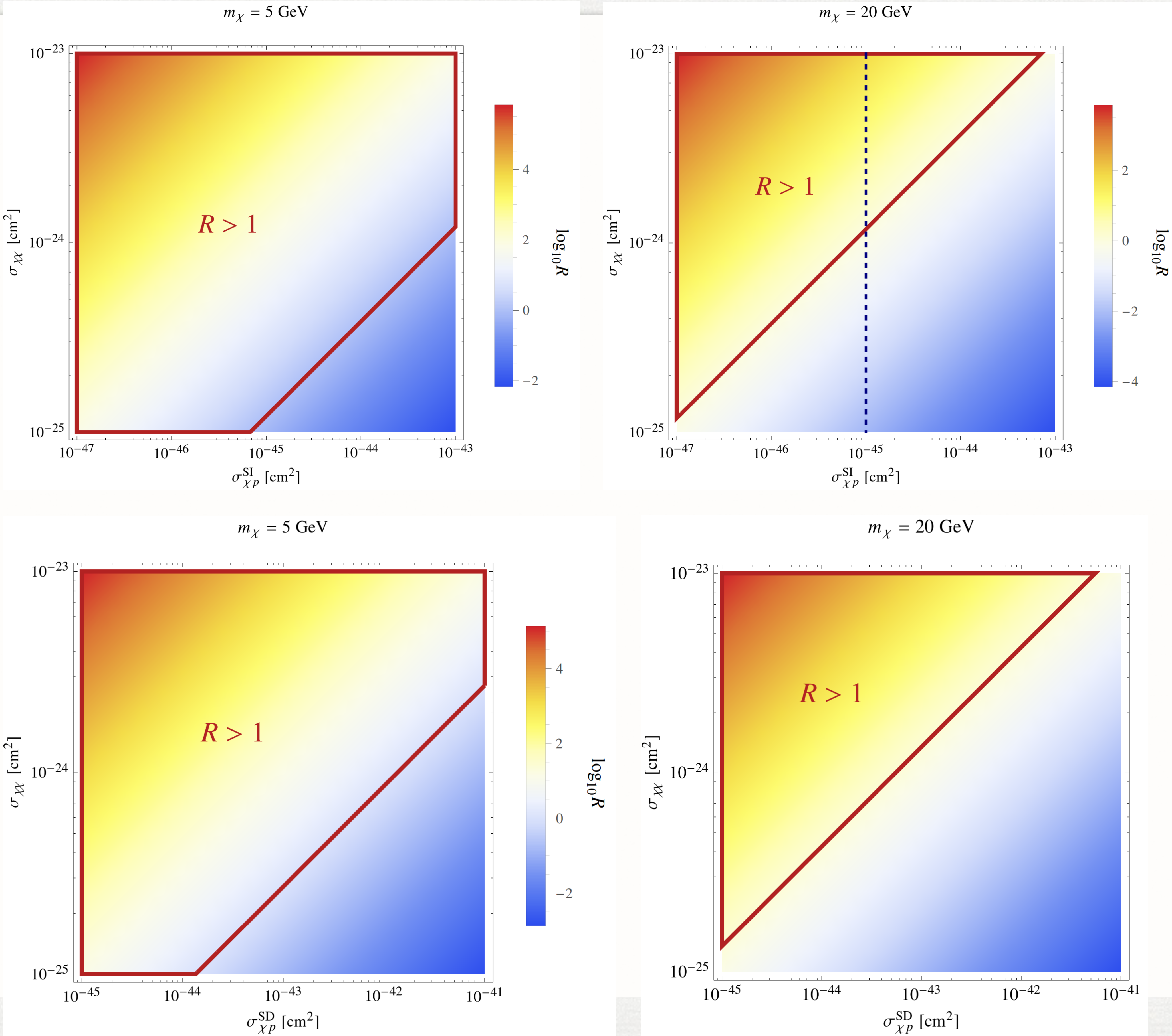
$$\Gamma_A = \frac{C_a}{2} N_\chi^2$$

Spin−independent $\sigma_{\chi p}$



Spin−dependent $\sigma_{\chi p}$





m_χ = 5 GeV
$R > 1$
$\sigma_{\chi\chi}$ [cm^2]
$\sigma_{\chi p}^{SI}$ [cm^2]
$\log_{10}R$
m_χ = 20 GeV
$R > 1$
$\sigma_{\chi\chi}$ [cm^2]
$\sigma_{\chi p}^{SI}$ [cm^2]
$\log_{10}R$
m_χ = 5 GeV
$R > 1$
$\sigma_{\chi\chi}$ [cm^2]
$\sigma_{\chi p}^{SD}$ [cm^2]
$\log_{10}R$
m_χ = 20 GeV
$R > 1$
$\sigma_{\chi\chi}$ [cm^2]
$\sigma_{\chi p}^{SD}$ [cm^2]

IceCube-PINGU is a proposed low-energy infill extension to the IceCube Observatory. PINGU will feature the world's largest effective volume for neutrinos at an energy threshold of a few GeV.

The DM annihilation rate in the Sun's core is given by

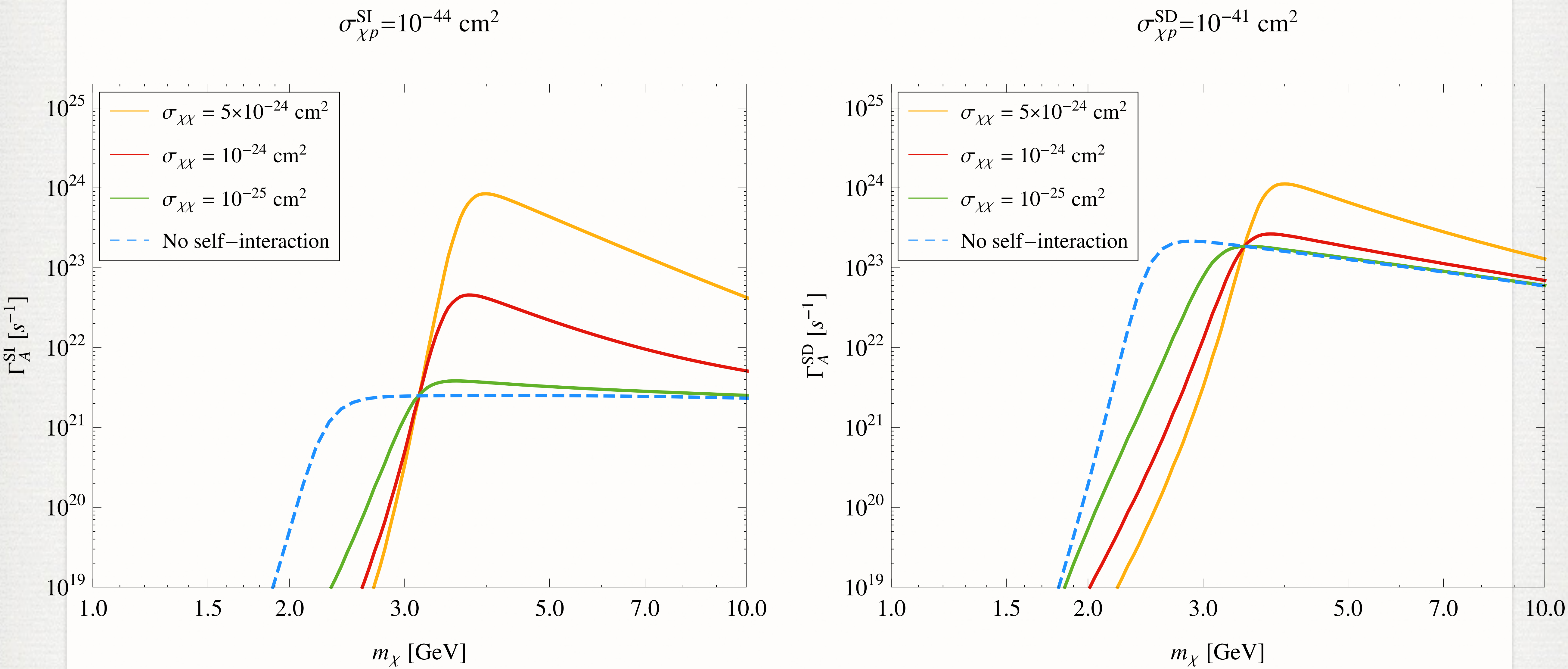
$$\Gamma_A = \frac{C_a}{2} N_{\chi,\mathrm{eq}}^2.$$

The primary DM annihilation spectrum is model dependent, here we consider $\chi\chi$ to $\tau^+\tau^-$ and $\nu\nu$, for neutrino final state productions since the low mass region is our interest.

- If no DM self-interaction and evaporation, the annihilation rate with an equilibrium N_χ is

$$\Gamma_A = \frac{1}{2} C_a \times \frac{C_c}{C_a} = \frac{C_c}{2}$$

depends only on the capture rate



The neutrino differential flux is

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

The neutrino event rate in the detector from the Sun DM is given by

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

the detector effective area

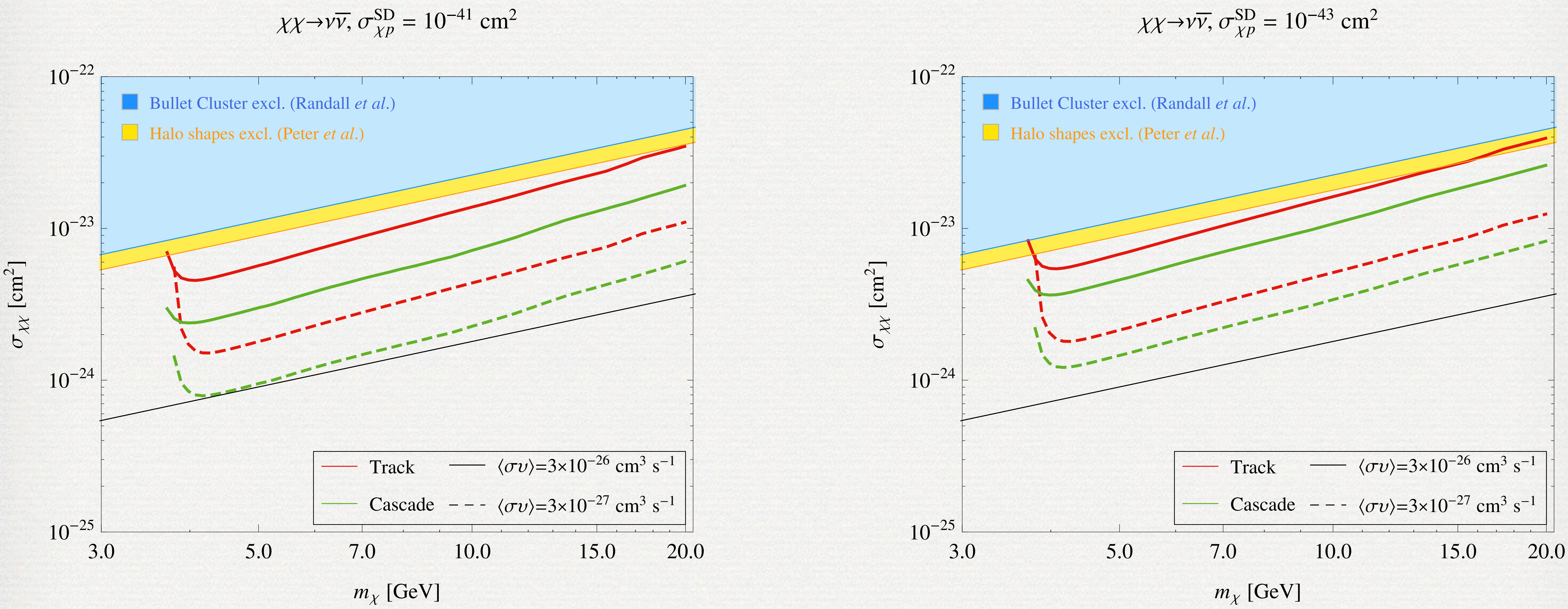
$$A^\nu_{\rm eff}(E_\nu) = \rho_{\rm ice} V_{\rm eff} \frac{N_A}{M_{\rm ice}} (n_p \sigma_{\nu p}(E_\nu) + n_n \sigma_{\nu n}(E_\nu))$$

mass of ice per mole

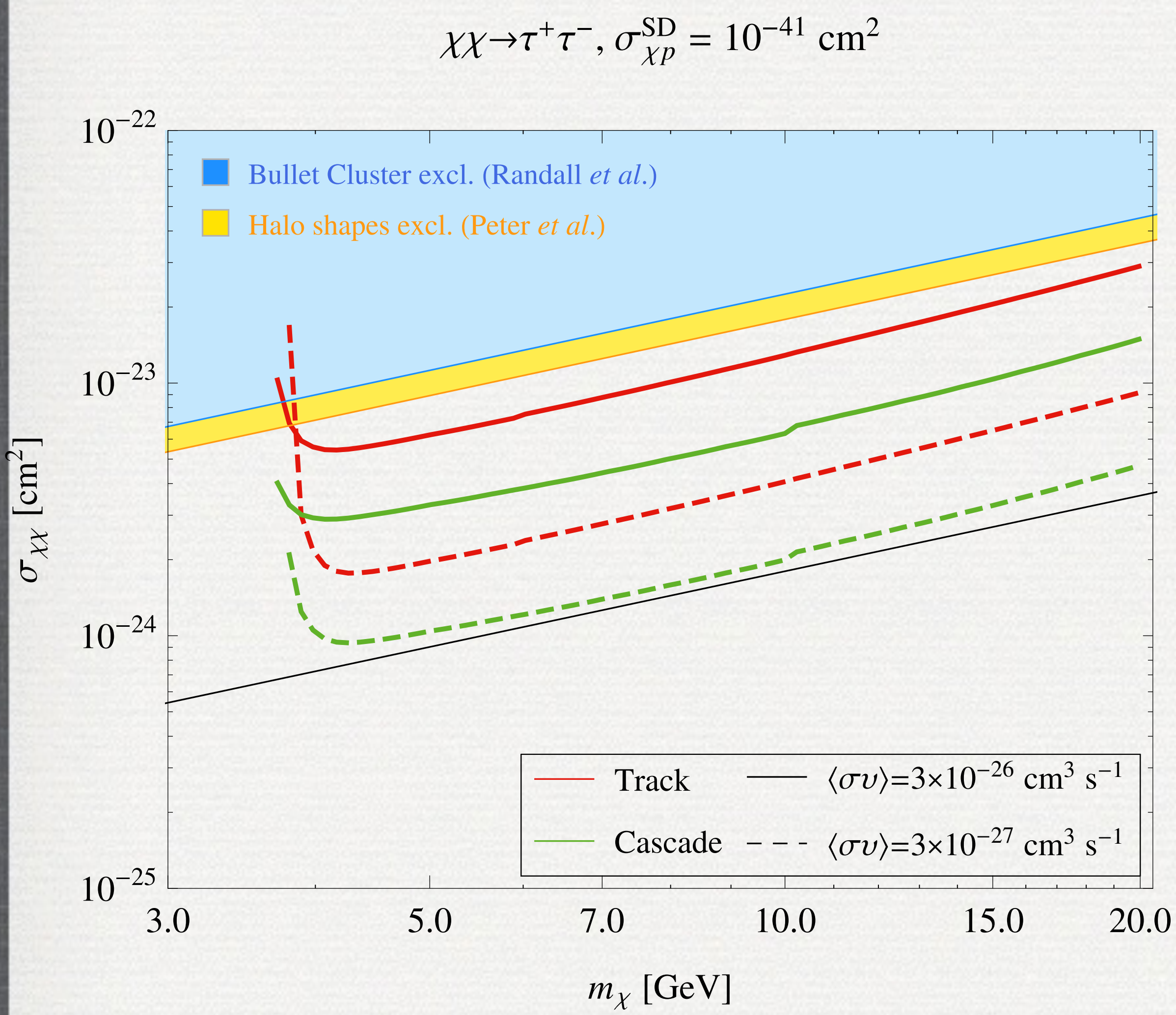
$$\frac{\sigma_{\nu N}(E_\nu)}{E_\nu} = 6.66 \times 10^{-3}\ \mathrm{pb}\cdot\mathrm{GeV}^{-1}$$
$$\frac{\sigma_{\bar\nu N}(E_\nu)}{E_{\bar\nu}} = 3.25 \times 10^{-3}\ \mathrm{pb}\cdot\mathrm{GeV}^{-1}$$

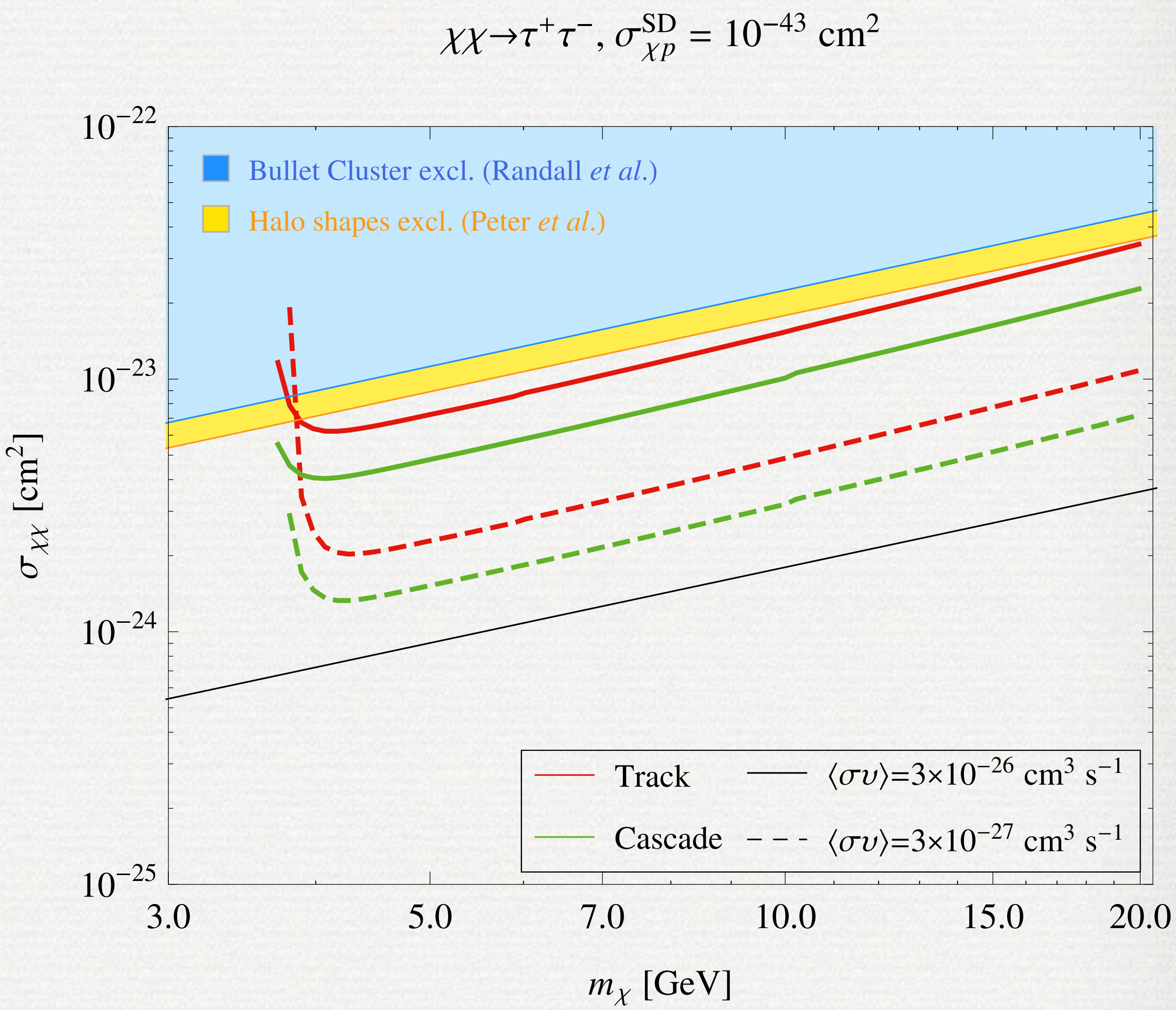
for $1\ \mathrm{GeV} \le E_\nu \le 10\ \mathrm{GeV}$

testability of $\sigma_{\chi\chi}$ for spin-dependent , xx to νν

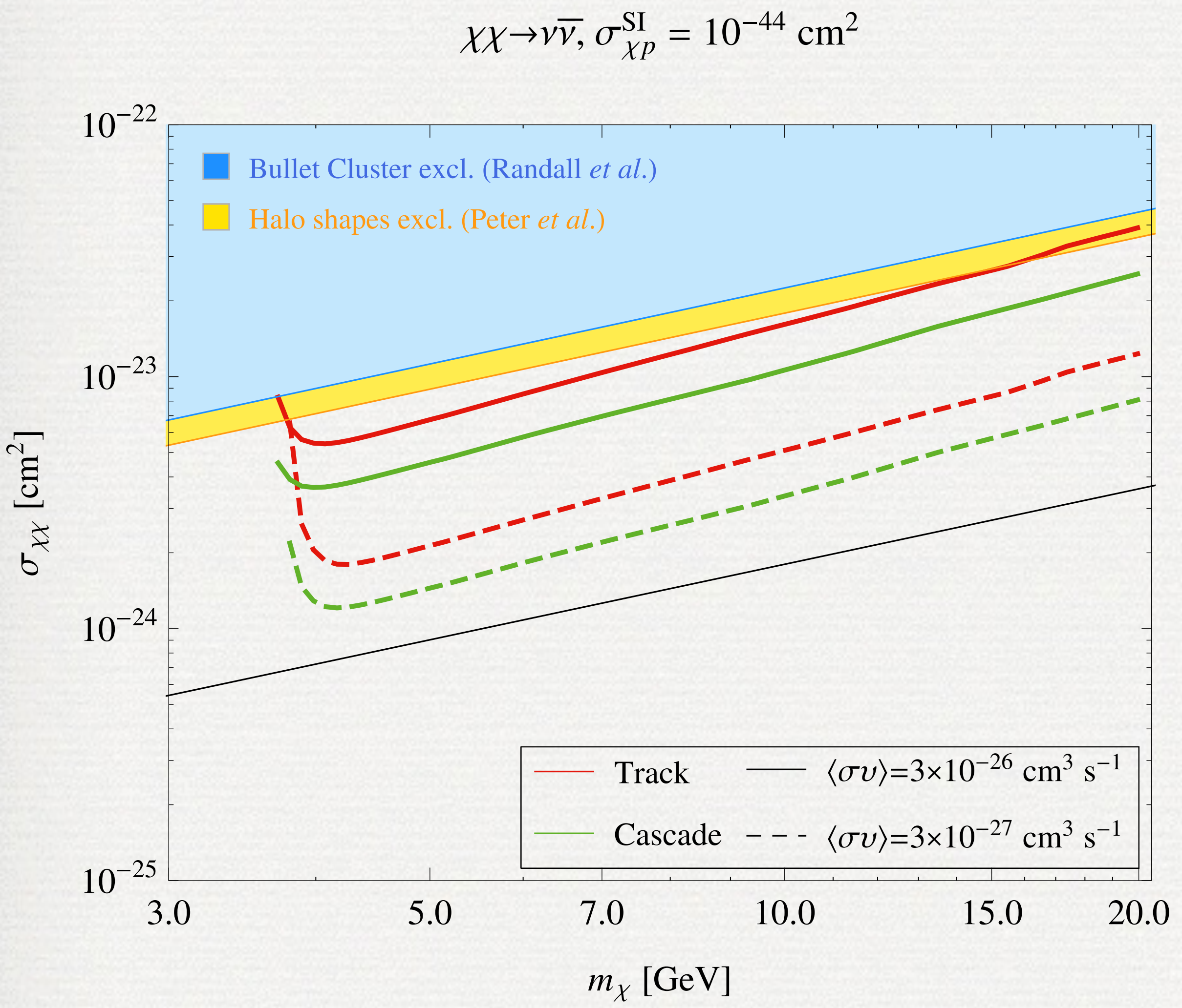


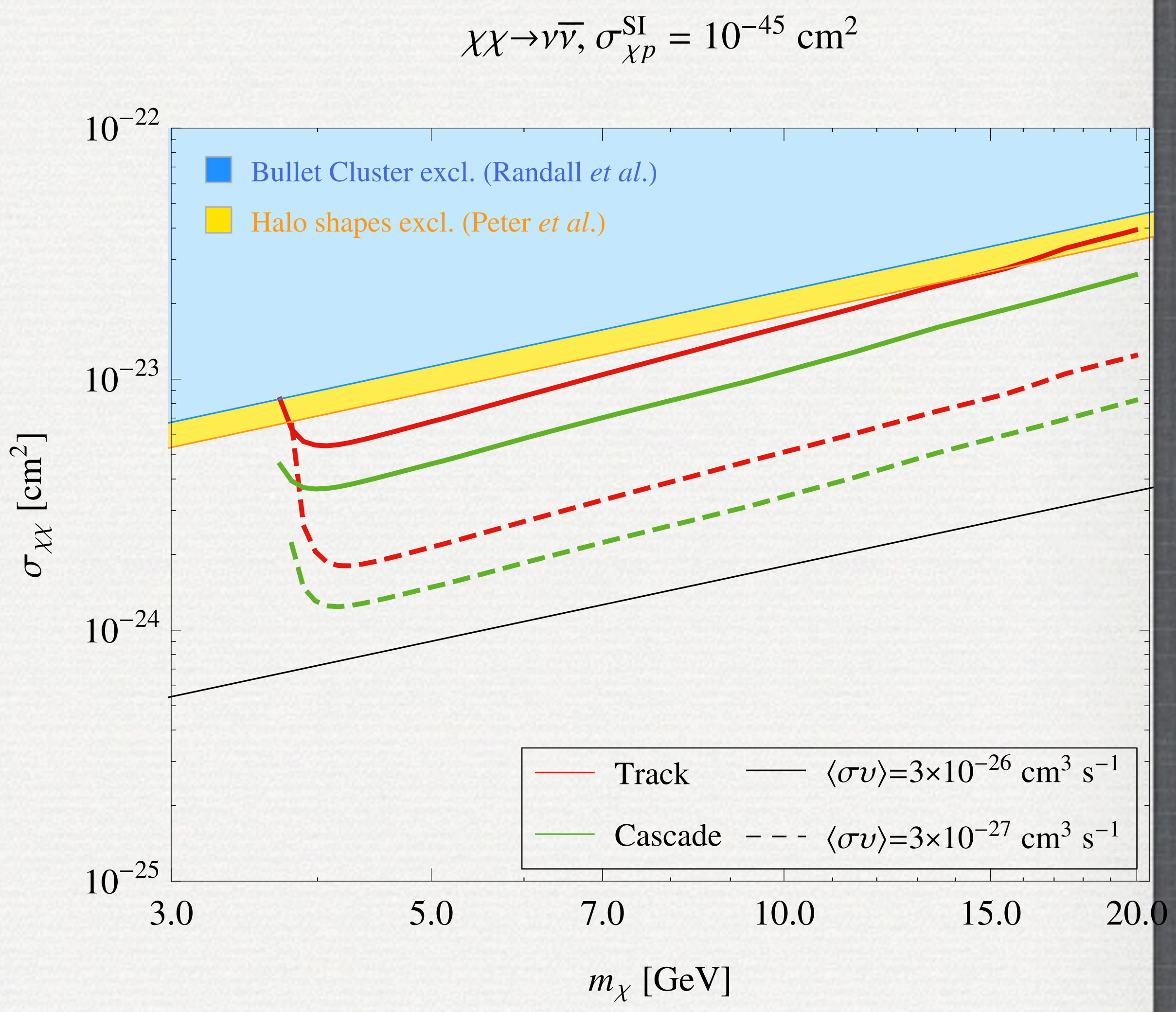
testability of σχχ for spin-dependent , xx to ττ



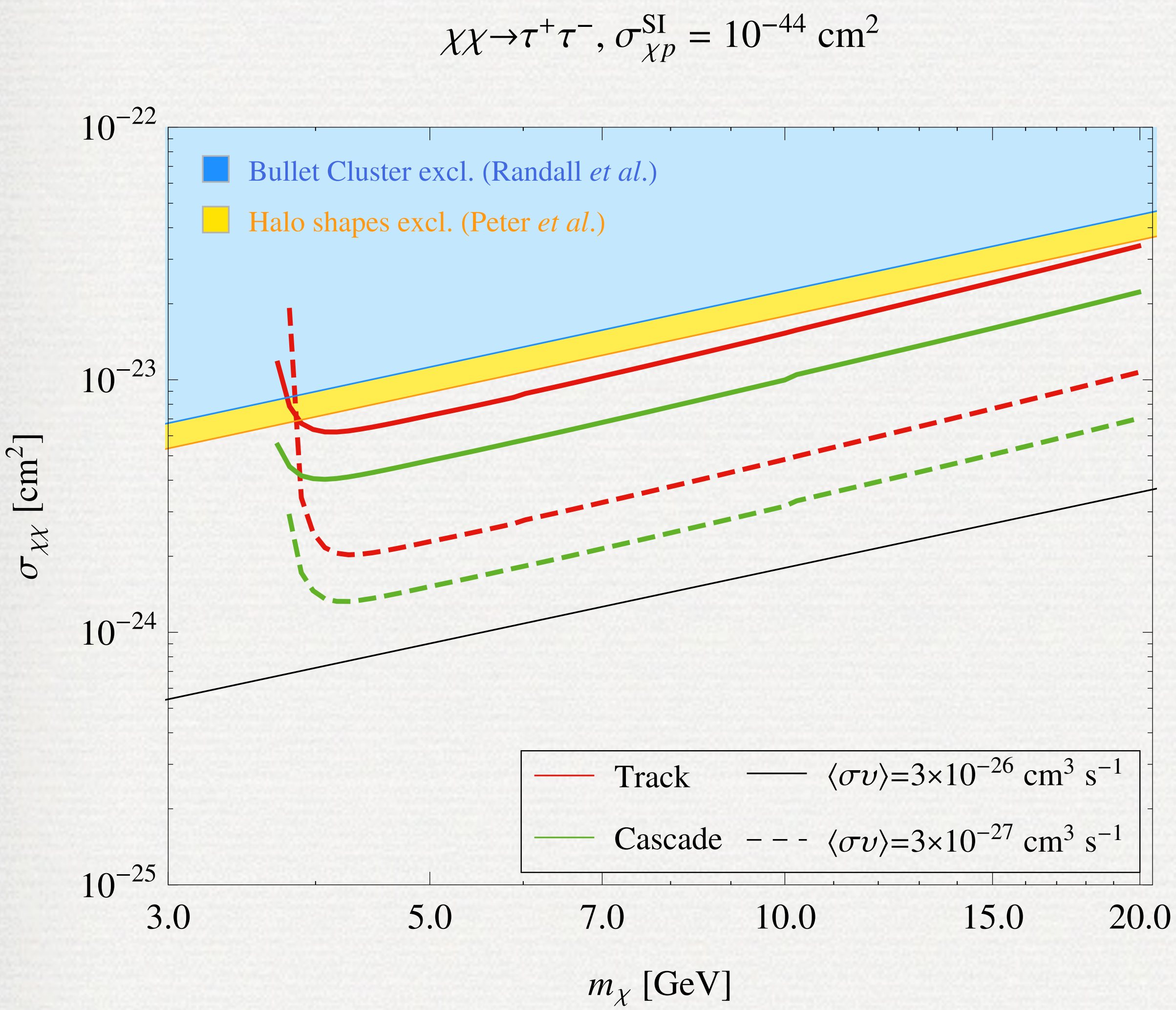


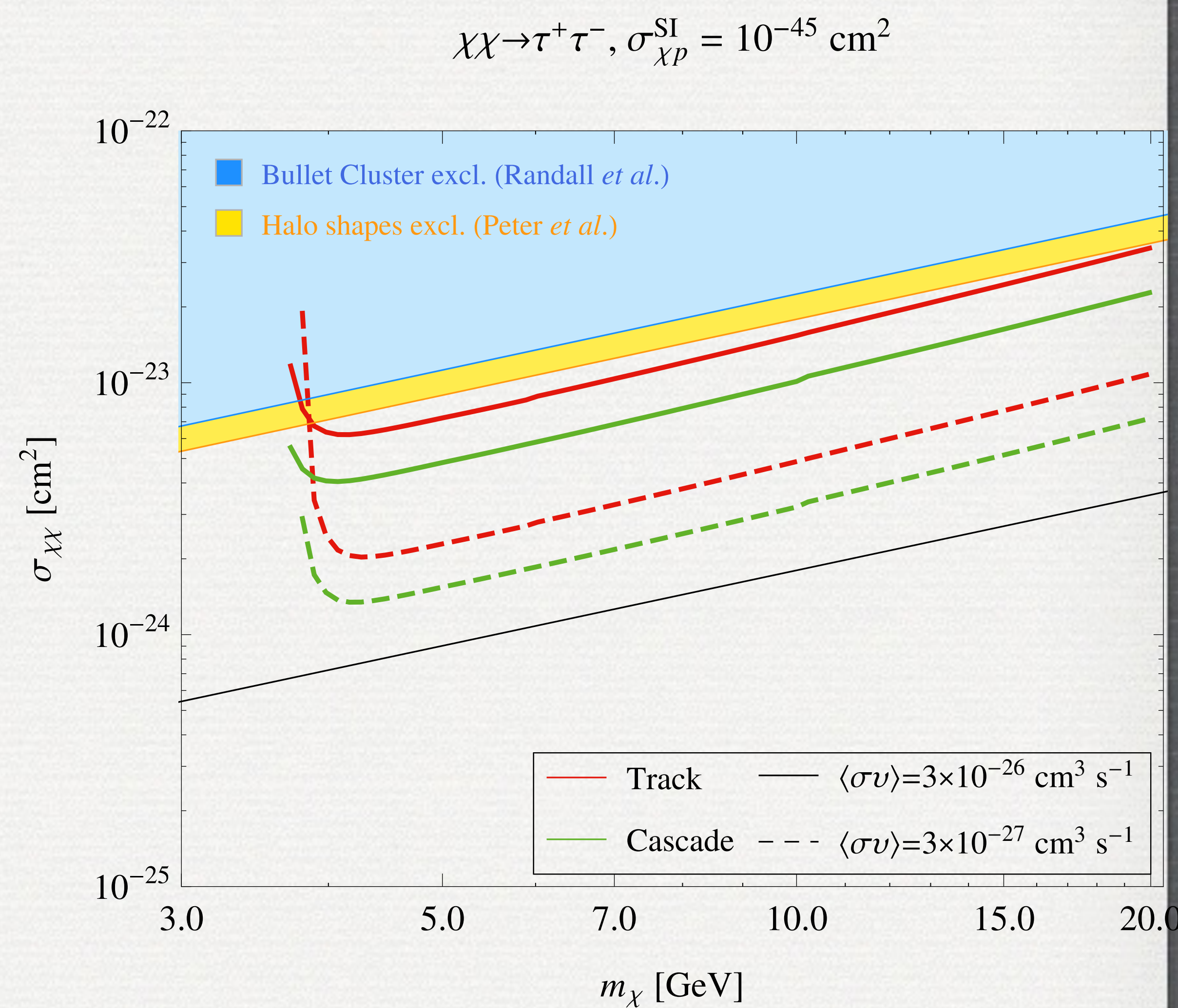
testability of $\sigma_{\chi\chi}$ for spin-independent , xx to νν





testability of $\sigma_{\chi\chi}$ for spin-independent , xx to ττ

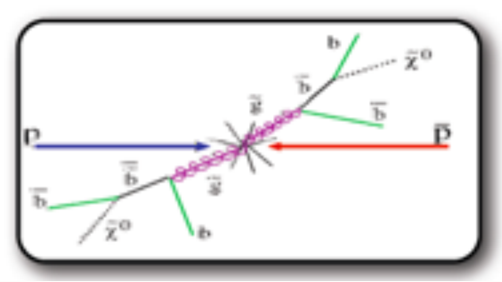


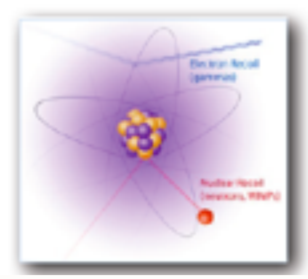


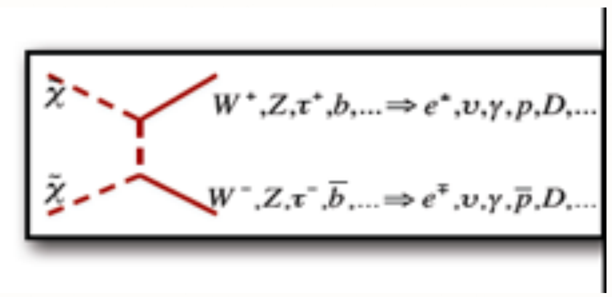
sensitivity to $\sigma_{\chi\chi}$ becomes better for smaller annihilation cross section <σv>.

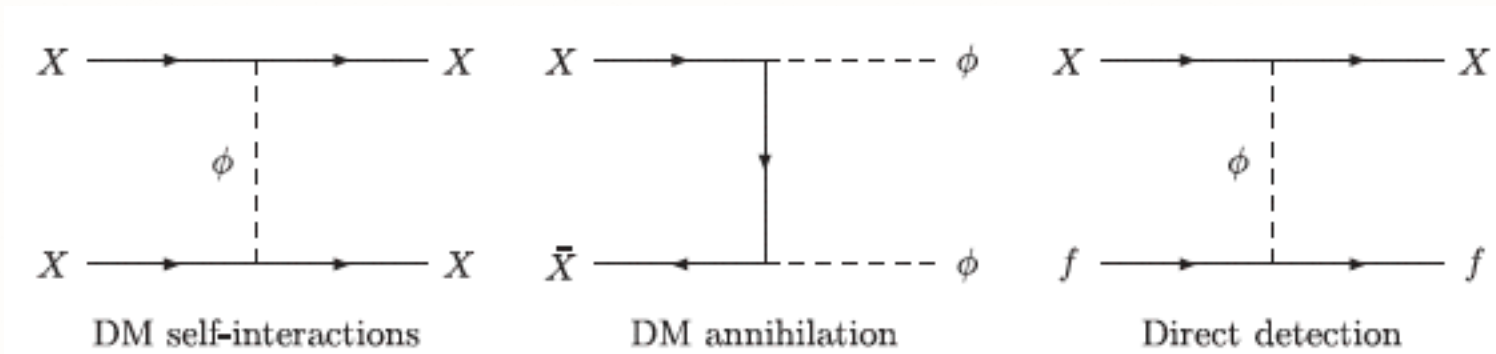
COMPLEMENTARY OF DIRECTION AND INDIRECT SEARCHES

- The accumulation of DM depends on these three processes









- We can show that if DM self-interaction exists, the total captured DM can be less relevant to DM-nuclei cross-section.

- Framework of SIDM

$$\sigma_{\chi\chi} \approx 7.6 \times 10^{-24}\,\mathrm{cm}^2 \left(\frac{\alpha_\chi}{0.01}\right)^2 \left(\frac{m_\phi}{30\,\mathrm{MeV}}\right)^{-4} \left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

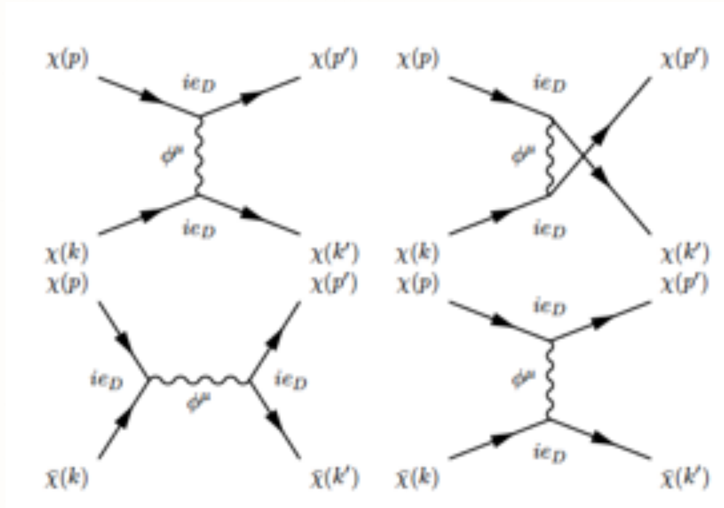
H.B. Yu (PRL2010)

- velocity dependent cross section , dark U(1) force

$$L_{\mathrm{mixing/vector}} = \left(\epsilon_\gamma e J^\mu_{\mathrm{em}} + \epsilon_Z \frac{g_2}{c_W} J^\mu_{\mathrm{NC}}\right) \phi_\mu$$

$$L_{\mathrm{mixing},\,U(1)} = \frac{\varepsilon_\gamma}{2}\phi_{\mu\nu}F^{\mu\nu} + \varepsilon_Z m_Z^2 \phi_\mu Z^\mu$$

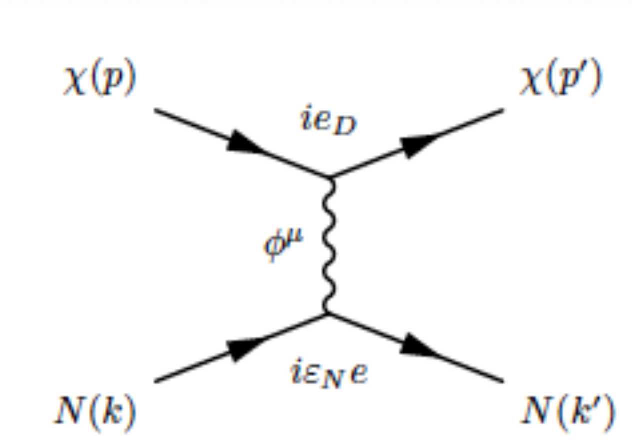
- SIDM cross section



$$\sigma_{\chi\bar{\chi}} \approx 4\pi\alpha_\chi^2 \frac{m_\chi^2}{m_\phi^4}$$

$$\alpha_\chi \equiv e_D^2/(4\pi)$$

- DM-nucleus scattering



$$\sigma_{\chi A} \approx \frac{16\pi\alpha_\chi\alpha_{\rm em}}{m_\phi^4}[\varepsilon_p Z + \varepsilon_n(A-Z)]^2\mu_{\chi A}^2 = \frac{16\pi\alpha_\chi\alpha_{\rm em}}{m_\phi^4}\varepsilon_p^2[Z+\eta(A-Z)]^2\mu_{\chi A}^2$$

$$\mu_{\chi A} \equiv m_\chi m_A/(m_\chi + m_A)$$

- isospin symmetry does not necessarily satisfy & spin-independent cross section dominated

$$\sigma^{SI}_{\chi p} \approx 1.5 \times 10^{-24}\,\mathrm{cm}^2\, \varepsilon_\gamma^2 \left(\frac{\alpha_\chi}{0.01}\right) \left(\frac{m_\phi}{30\,\mathrm{MeV}}\right)^{-4}$$

$$\sigma^{SI}_{\chi n} \approx 5 \times 10^{-25}\,\mathrm{cm}^2\, \varepsilon_Z^2 \left(\frac{\alpha_\chi}{0.01}\right) \left(\frac{m_\phi}{30\,\mathrm{MeV}}\right)^{-4}$$

$$\varepsilon_p = \varepsilon_\gamma + \frac{\varepsilon_Z}{4 s_W c_W}(1 - 4 s_W^2) \approx \varepsilon_\gamma + 0.05\varepsilon_Z$$
$$\varepsilon_n = -\frac{\varepsilon_Z}{4 s_W c_W} \approx -0.6\varepsilon_Z\ .$$

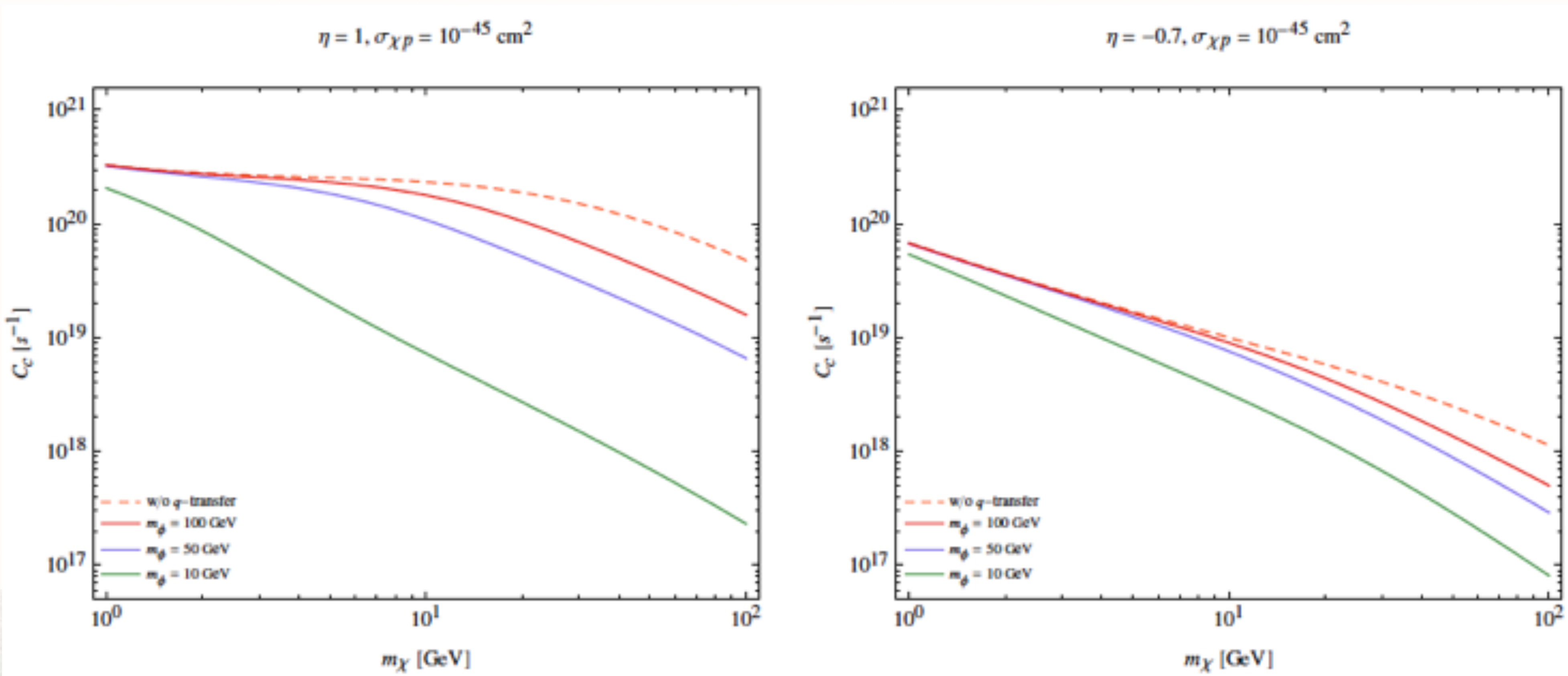
- For a light mediator ϕ at MeV range, $\sigma_{\chi A}$ is sensitive to the momentum transfer

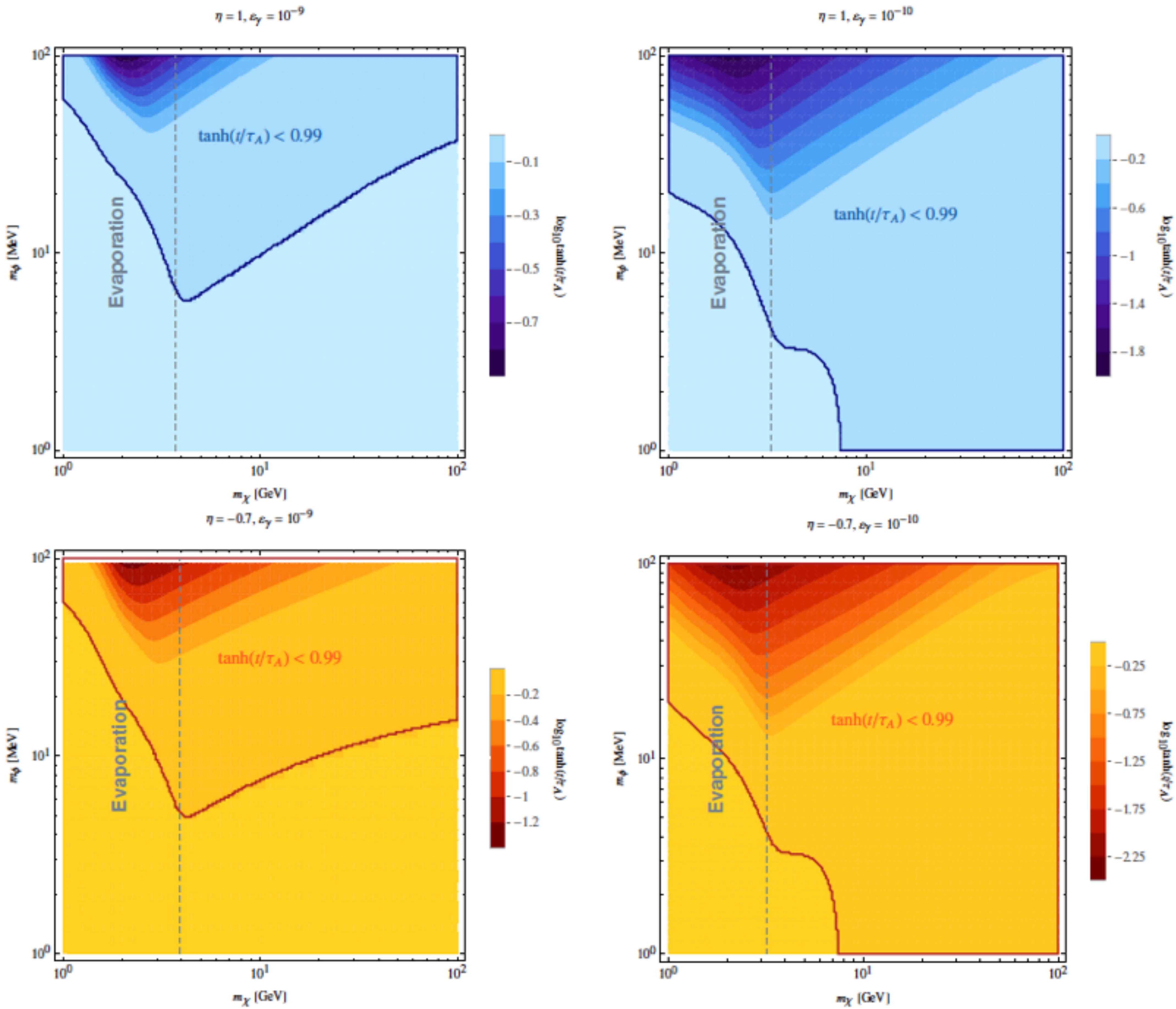
$$\sigma_{\chi A}(\boldsymbol{q}^2) = \frac{m_\phi^4}{(m_\phi^2 + \boldsymbol{q}^2)^2}\sigma^0_{\chi A}$$

$$\boldsymbol{q}^2 = 2m_A E_R$$

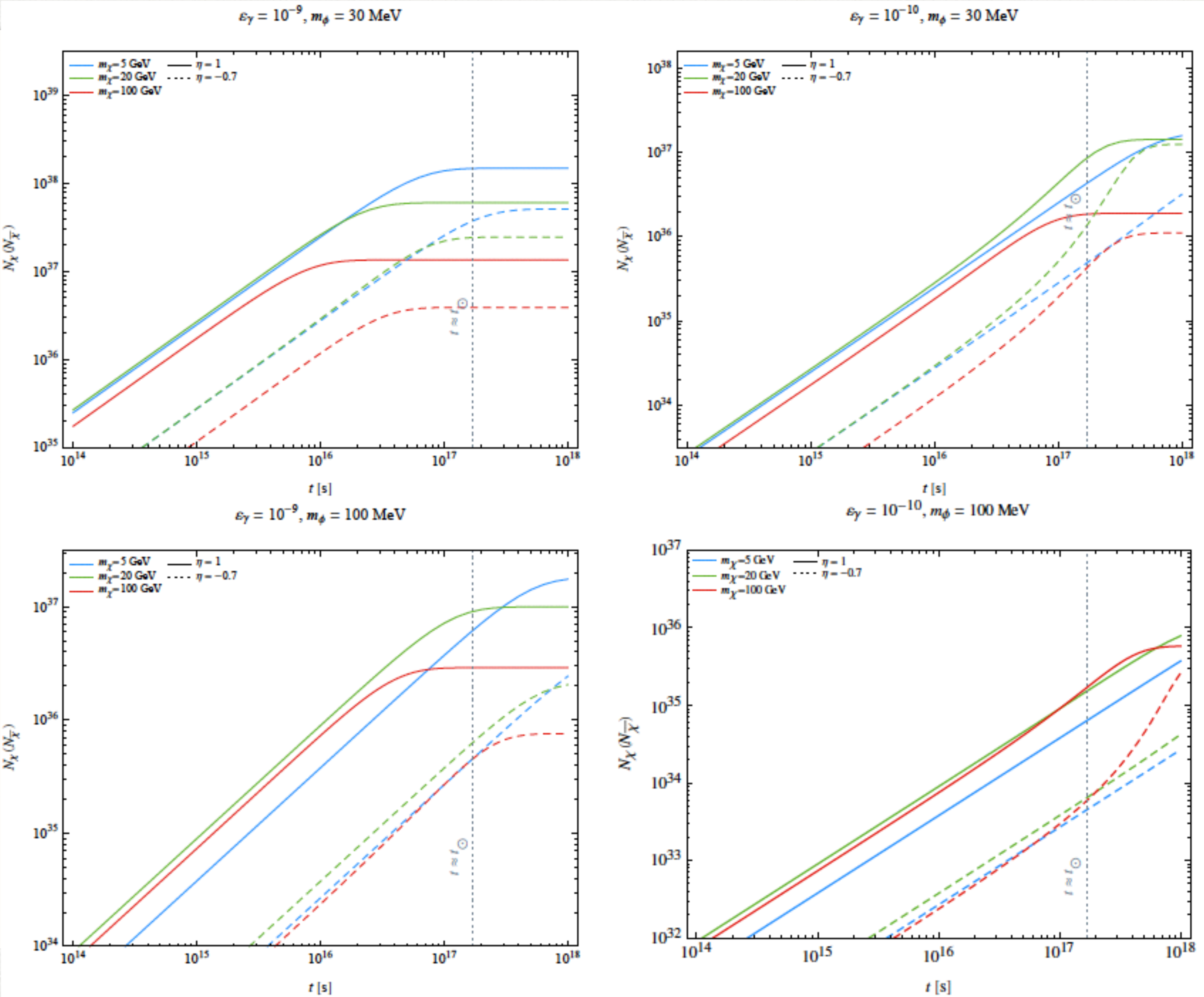
$$C_c \propto \left(\frac{\rho_\chi}{0.15\ \mathrm{GeV/cm^3}}\right)\left(\frac{\mathrm{GeV}}{m_\chi}\right)\left(\frac{270\ \mathrm{km/s}}{v_\chi}\right)\sum_A F_A(m_\chi,\eta)\sigma^0_{\chi A}\frac{m_\phi^4}{(m_\phi^2 + \boldsymbol{q_A}^2)^2}$$

$$C_s(\boldsymbol{q}^2) \propto \left(\frac{\rho_\chi}{0.15\ \mathrm{GeV/cm^3}}\right)\left(\frac{\mathrm{GeV}}{m_\chi}\right)\left(\frac{270\ \mathrm{km/s}}{v_\chi}\right)\sigma^0_{\chi\chi}\langle\hat{\phi}\rangle\frac{\mathrm{erf}(\eta)}{\eta}\frac{m_\phi^4}{(m_\phi^2 + \boldsymbol{q}^2)^2}$$





η = 1, ε_γ = 10^−9
η = 1, ε_γ = 10^−10
η = −0.7, ε_γ = 10^−9
η = −0.7, ε_γ = 10^−10
Evaporation
tanh(t/τ_A) < 0.99
m_φ [MeV]
m_χ [GeV]
log10 tanh(t/τ_A)
−0.1
−0.3
−0.5
−0.7
−0.2
−0.6
−1
−1.4
−1.8
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−0.25
−0.75
−1.25
−1.75
−2.25



$\varepsilon_\gamma = 10^{-9}$, $m_\phi = 30$ MeV
$\varepsilon_\gamma = 10^{-10}$, $m_\phi = 30$ MeV
$\varepsilon_\gamma = 10^{-9}$, $m_\phi = 100$ MeV
$\varepsilon_\gamma = 10^{-10}$, $m_\phi = 100$ MeV
m_χ=5 GeV
m_χ=20 GeV
m_χ=100 GeV
$\eta = 1$
$\eta = -0.7$
N_χ ($N_{\bar{\chi}}$)
t [s]
$t \approx t_\odot$

- complementary test of SIDM model in IceCube-PINGU

$$\chi\bar{\chi} \to \phi\phi \to 4\nu$$

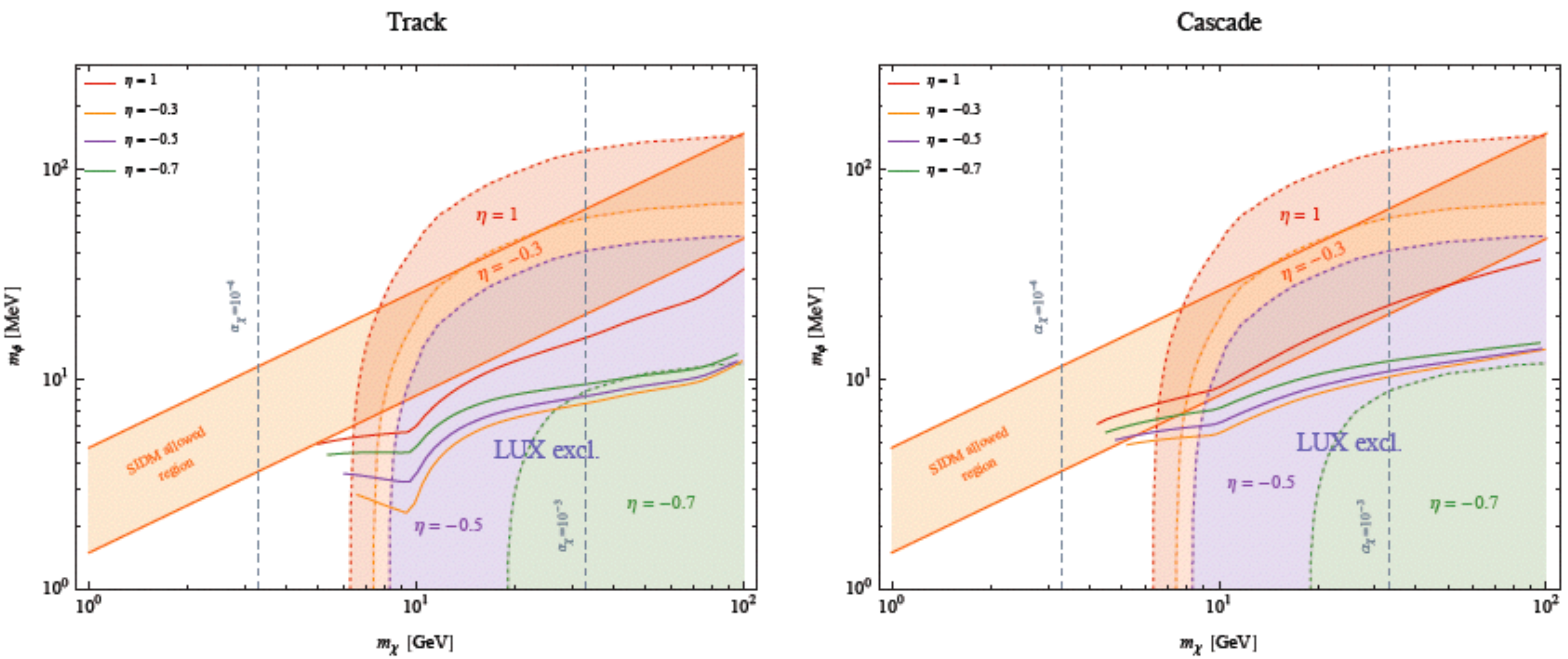
$\mathrm{BR}(\phi \to \nu\bar{\nu}) \approx 75\%, 39\%, 48\%,$ and 67% for $\eta = 1, -0.3, -0.5,$ and -0.7, respectively.

$\tau_\phi \lesssim \mathcal{O}(1)\,\mathrm{s}$ BBN constraint

	Track		Cascade	
$E_{\max}$ [GeV]	N_ν^{atm}	N_ν^{DM}	N_ν^{atm}	N_ν^{DM}
5	7146	76	9874	90
10	10280	91	13775	105
50	21680	132	21803	132
70	23584	138	23111	136
100	26610	146	24363	140

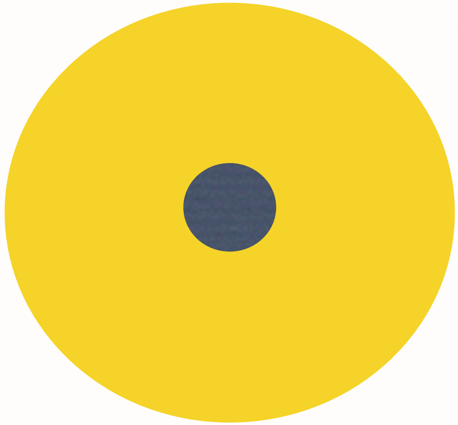
annual signal and background event numbers for reaching 2σ detection significance in 5 years

IceCube-PINGU sensitivities to m_ϕ for different values of η



DM temperature in the Sun

- If the DM-nuclei cross-section is small enough, the heat exchange between DM sphere and the Sun is small. As a result, DM can be treated as an adiabatic system (isolated from the Sun).



- The correct temperature evolution provides modifications to DM signals

DM thermal transport in the Sun

DM thermal system is governed by

1. DM number evolution equation

$$\frac{dN_\chi}{dt} = C_c + C_s N_\chi - C_a N_\chi^2$$

2. the energy transport equation

$$\frac{d\left(N_\chi E_\chi(t)\right)}{dt} = J_c + (J_\chi + J_s) N_\chi - J_a N_\chi^2$$

suppose u is the DM velocity in the halo which is in falling to the spherical shall (with radius r) of the Sun

w is the velocity of infall DM at the shell and the local escape speed on the shell is $v_{esc}(r)$

$$w = \sqrt{u^2 + v_{\text{esc}}^2(r)}$$

To be captured, the DM must loses its energy in a fraction in between

$$\frac{u^2}{w^2} \leq \frac{\Delta E}{E} \leq \frac{4m_X m}{(m_X + m)^2}$$

m is the target mass , it can be the nucleus mass or the DM mass

Assume the energy distribution after the collision is equipartition, the average DM kinetic energy being captured after collision is

$$\bar{E} = \frac{m_\chi}{4}\left(\frac{m_\chi - m_A}{m_\chi + m_A}\right)^2 u^2 + \frac{m_\chi}{2}\frac{(m_\chi^2 + m_A^2)}{(m_\chi + m_A)^2} v_{esc}^2(r)$$

Base on equipartition, the probability that an individual scattering leads to capture is

$$p_{cap} = \frac{v_{esc}^2(r)}{w^2}\left[1 - \frac{u^2}{v_{esc}^2(r)}\frac{(M_x - m)^2}{4M_x m}\right]$$

Therefore, the energy flow per shell volume due to DM-nucleus scattering is

$$\frac{dJ_c}{dV} = \int n_{\mathrm{A}} \sigma_{\chi \mathrm{A}} v_{\mathrm{esc}}^2(r) \frac{f(u)}{u} \times \left[1 - \frac{(m_\chi - m_{\mathrm{A}})^2}{4 m_\chi m_{\mathrm{A}}} \frac{u^2}{v_{\mathrm{esc}}^2(r)}\right] \bar{E} du$$

The DM velocity distribution in the halo, f(u), is assumed to be Maxwell-Boltzmannian

$$f(x) = \sqrt{\frac{6}{\pi}} \frac{\rho_o}{m_\chi \bar{v}} x^2 e^{-x^2} e^{-\eta^2} \frac{\sinh(2x\eta)}{x\eta}$$

$x^2 = 3(u/\bar{v})^2/2$, $\eta^2 = 3(v_\odot/\bar{v})^2/2$

$\bar{v}$ ~ 270 kms^{-1} is the DM dispersion velocity in the halo

$v_\odot$ = 220 kms^{-1} is the relative velocity between the Sun and the MW

- The leading contribution of the total energy flow due to gravitational capture is

$$J_c = \xi \sum_{\rm A} b_{\rm A} \frac{(m_\chi^2 + m_{\rm A}^2)}{(m_\chi + m_{\rm A})^2} \left(\frac{\sigma_{\chi \rm A}}{\rm pb}\right) \langle \phi_{\rm A}^2 \rangle$$

b_A is the number fraction of nucleus, $<\phi_A^2>$ is the average gravitational potential square as a result of nucleus A

$$\xi \equiv \sqrt{\frac{3}{8}} N_\odot \rho_0 \frac{v_{\rm esc}(R_\odot)}{\bar{v}} v_{\rm esc}^3(R_\odot) \frac{\mathrm{erf}(\eta)}{\eta}$$
$$\approx 1.2 \times 10^{23}\,\mathrm{GeV\,s^{-1}} \left(\frac{\rho_0}{0.3\,\mathrm{GeV/cm^3}}\right) \left(\frac{270\,\mathrm{km/s}}{\bar{v}}\right)$$

- Similarly, the energy flow due to self-capture J_S can be derived by setting $m_A \rightarrow m_\chi$ and $n_A \rightarrow n_\chi$ (n_χ is the DM number density in the Sun)

$$J_s \approx \sqrt{\frac{3}{32}} \rho_0 \sigma_{\chi\chi} \frac{\mathrm{erf}(\eta)}{\eta} \frac{v_{\mathrm{esc}}(R_\odot)}{\bar{v}} v_{\mathrm{esc}}^3(R_\odot) \langle \phi_\chi \rangle^2$$

Here I use $\langle \phi_\chi^2 \rangle \approx \langle \phi_\chi \rangle^2$ since DM is concentrated about less than 0.1 solar radius

and $\langle\phi_\chi\rangle = 5.1$ is the average gravitational potential of the DM

- The energy of captured DM could be dissipated due to annihilation. The energy flow due to this process is

$$J_a = \frac{\int 4\pi r^2 n_\chi^2(r) E_\chi(t) dr}{(\int 4\pi r^2 n_\chi(r) dr)^2} \langle \sigma v \rangle$$

<σv> is the thermal-average DM annihilation cross section.

$$J_a(t) \approx 7.5 \times 10^{-65}\,\mathrm{GeV\,s^{-1}} \left(\frac{s m_\chi}{10\,\mathrm{GeV}}\right)^{3/2} \left(\frac{E_\chi(t)}{\mathrm{GeV}}\right)^{-1/2}$$

- Lastly, the captured DMs will continuously exchange energy with the solar nuclei.

$$J_\chi = 8\sqrt{\frac{2}{\pi}}\rho_c m_\chi \frac{k_B(T_\odot - T_\chi)}{(m_\chi + m_{\rm A})^2} \times \sum_{\rm A} f_{\rm A}\sigma_{\chi{\rm A}} \left(\frac{m_{\rm A} k_B T_\chi + m_\chi k_B T_\odot}{m_\chi m_{\rm A}}\right)^{1/2}$$

$\rho_c \approx 110\ \mathrm{g/cm^3}$ is the core density of the Sun, f_A is the mass fraction of nuclei A

Thermal equilibrium conditions

In order to study the temperature evolution of the trapped DM, let's compare the mean collision time between a pair of trapped DMs and that between a trapped DM and nucleus in the Sun.

$$\tau_{\chi\chi}(t) \simeq \frac{V_\odot}{N_\chi(t)\sigma_{\chi\chi}\bar{v}} \quad \text{and} \quad \tau_{\chi\odot} \simeq \frac{V_\odot}{\sum_i N_i \sigma^{\rm SI}_{\chi A_i}\bar{v}}$$

The time scale τ_χ^{eq} for DMs in the Sun to reach thermal equilibrium can be estimated by the condition

$$\tau_\chi^{\rm eq} \simeq \tau_{\chi\chi}(\tau_\chi^{\rm eq})$$

- Consider at early stage and $N_\chi(\tau_\chi^{eq})$ is still far from the maximal value. In this case,

$$N_\chi(\tau_\chi^{\rm eq}) = C_c\tau_\chi^{\rm eq} \text{ for } C_s^2 \gg 4C_cC_a$$

DM self-interaction dominates region

we obtain

$$\tau_\chi^{\rm eq} = \sqrt{V_\odot/C_c\sigma_{\chi\chi}\bar{v}}$$

take $m_\chi = 10$ GeV as benchmark point $\sum_i N_i\sigma_{\chi A_i}^{\rm SI} \simeq 40N_H\sigma_{\chi p}^{\rm SI}$

$$r \equiv \tau_\chi^{\rm eq}/\tau_{\chi\odot} = 40N_H\sigma_{\chi p}^{\rm SI}/\sigma_{\chi\chi}N_\chi(\tau_\chi^{\rm eq})$$

the average mass density of hydrogen in the Sun is 1 g/cm^3 $\Rightarrow$ $N_H = 6\times10^{53}$

$C_c \simeq 5.4\times10^{65}(\sigma_{\chi p}^{\rm SI}/{\rm cm}^2){\rm s}^{-1}$ $\bar{v} \simeq 900$ km/s $r \simeq 10^9\sqrt{\sigma_{\chi p}^{\rm SI}/\sigma_{\chi\chi}}$

- we are interested in the region that

$r < 1$ and $C_s^2/4C_cC_a \equiv 1.9 \times 10^3(\sigma_{\chi\chi}/\sigma_{\chi p}^{SI})(\sigma_{\chi\chi}/\text{cm}^2) \gg 1$

$(\sigma_{\chi p}^{SI}, \sigma_{\chi\chi}) = (10^{-45}\text{cm}^2, 10^{-23}\text{cm}^2)$ (typical values for current constraints)

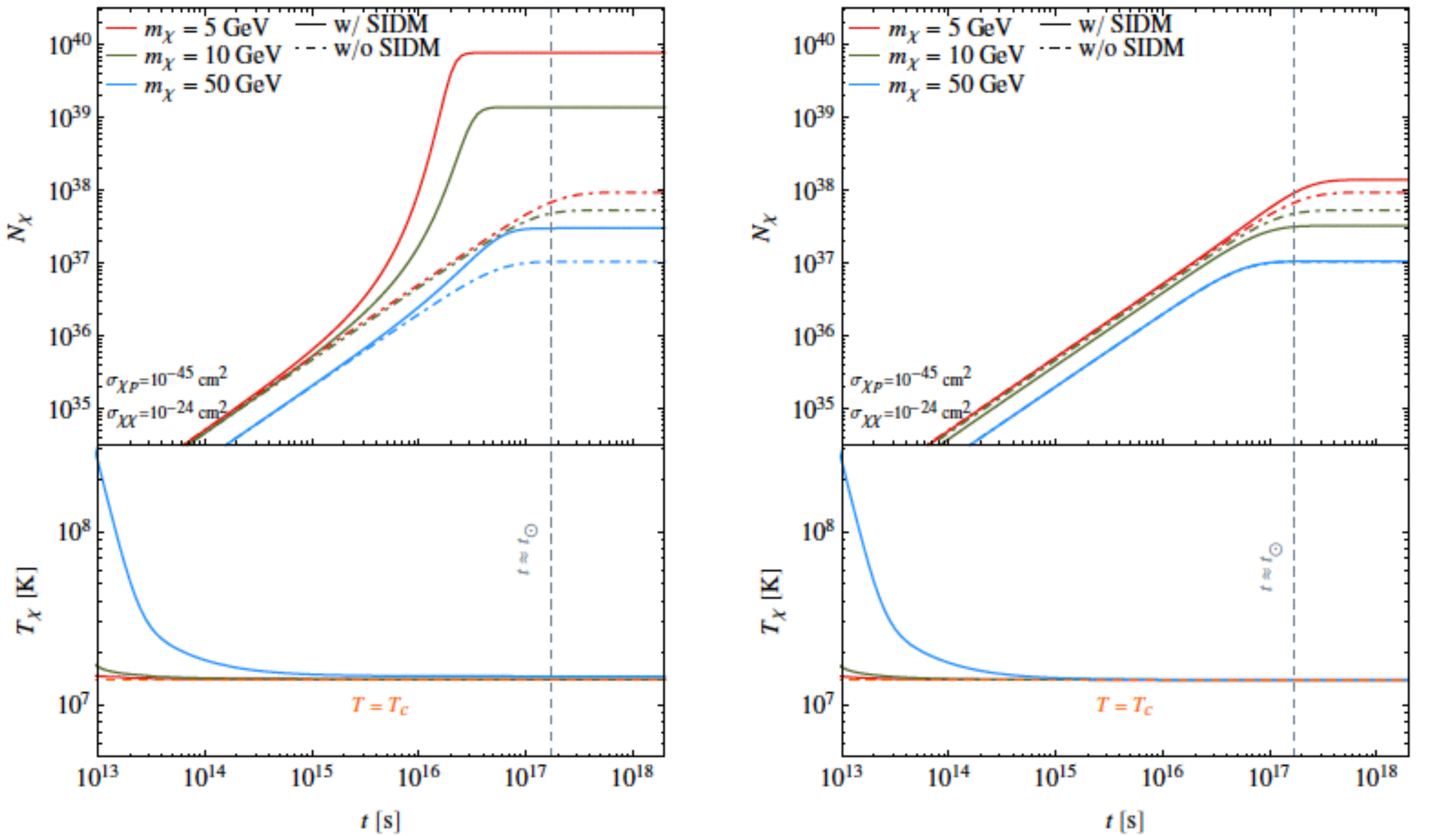
gives $\tau_\chi^{eq} = 4.5\times10^{13}$ s which is much shorter than the age of the Sun 10^{17} s

we justify the thermal equilibrium state of DM

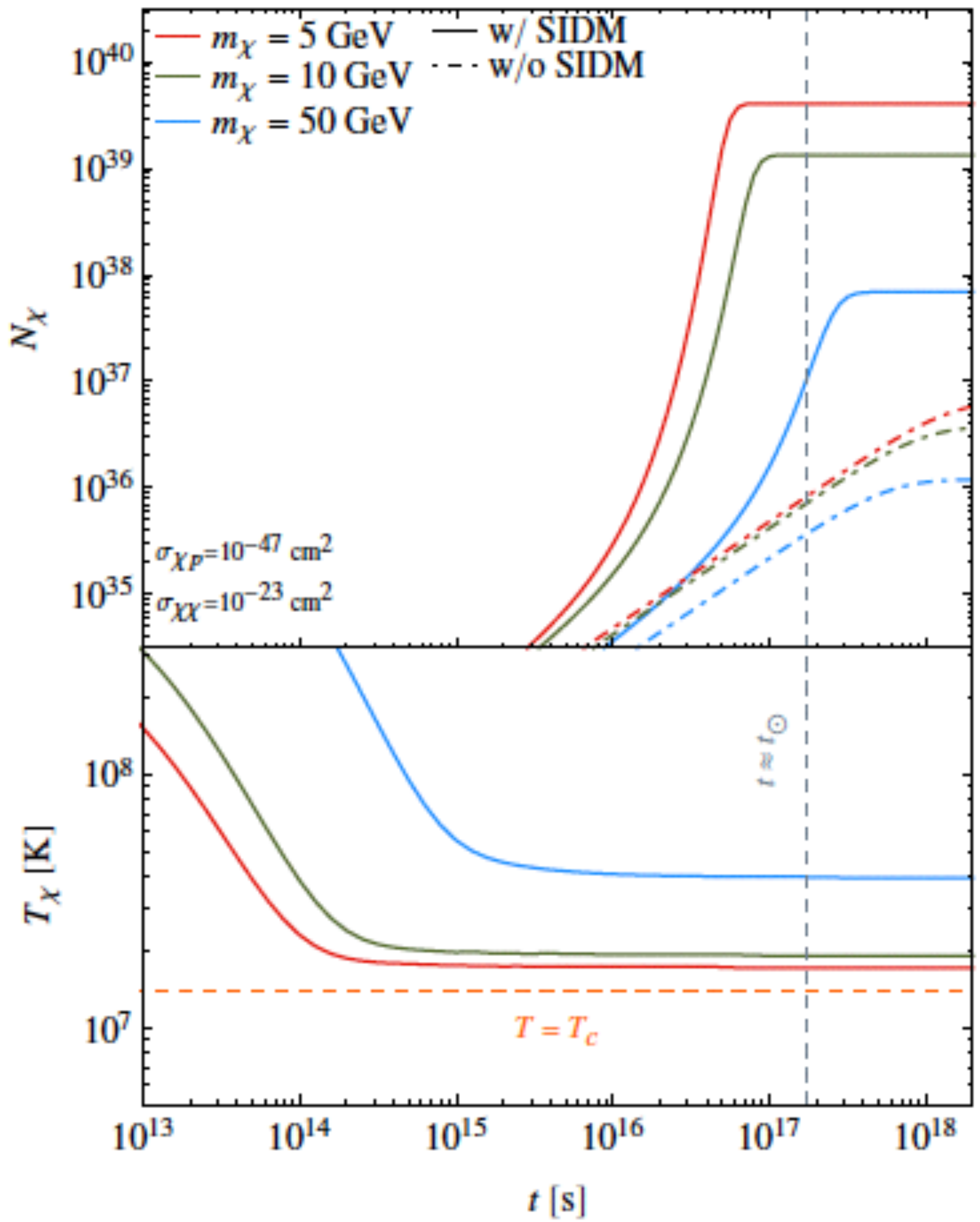
we are able to write $E_\chi(t) = s k_B T_\chi(t)/2$
and put in the equations derived above for $t > 10^{13}$ s

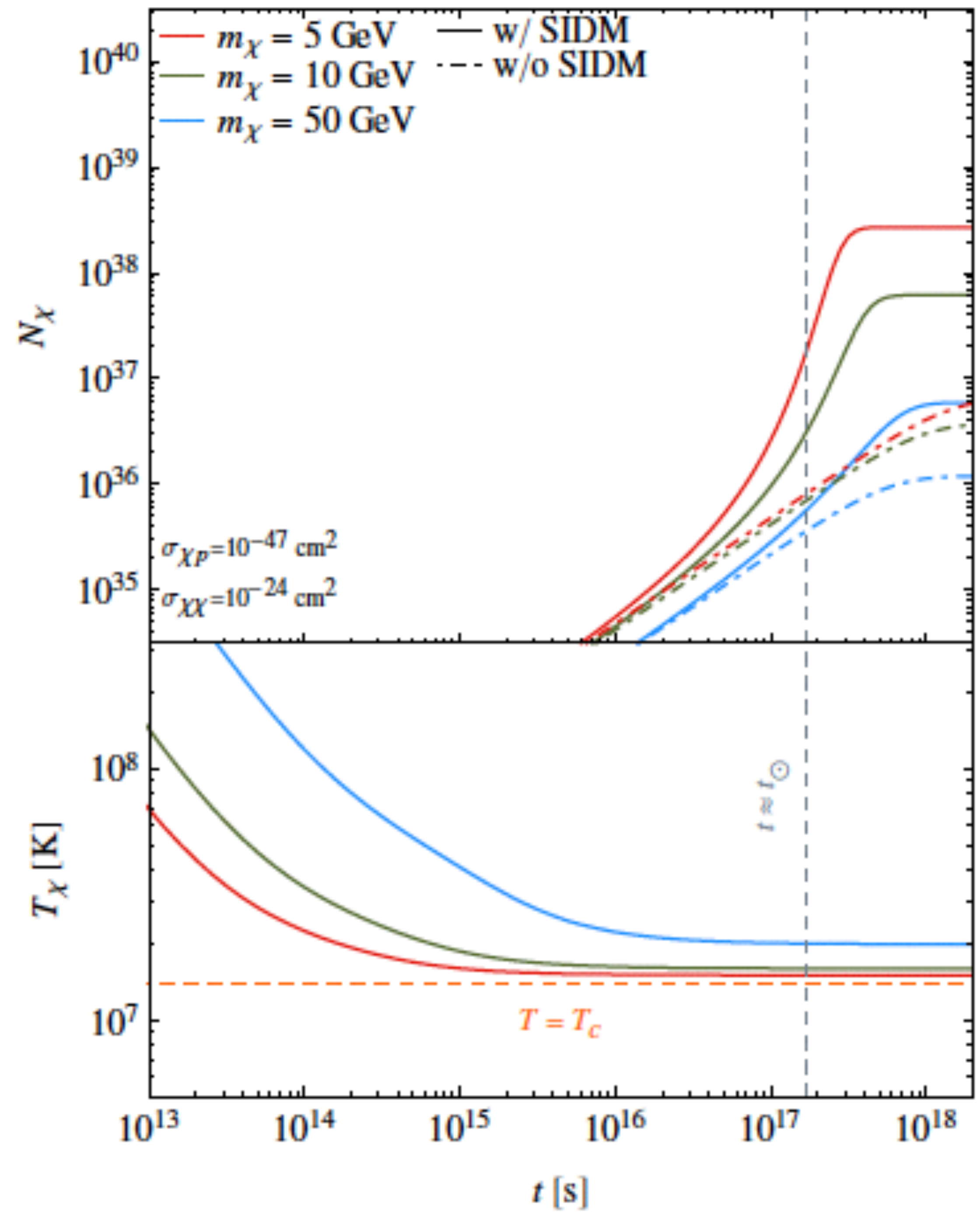
N_χ AND T_χ EVOLUTIONS

- stronger $\sigma_{\chi p}$



- weaker $\sigma_{\chi p}$





some remarks :

- \bar{E} is the DM average kinetic energy before the thermalization, and it is taken as the initial condition for $E_\chi(t)$ at $t = 10^{13}$ s

$$\bar{E} = \frac{m_\chi}{4}\left(\frac{m_\chi - m_A}{m_\chi + m_A}\right)^2 u^2 + \frac{m_\chi}{2}\frac{(m_\chi^2 + m_A^2)}{(m_\chi + m_A)^2} v_{esc}^2(r)$$

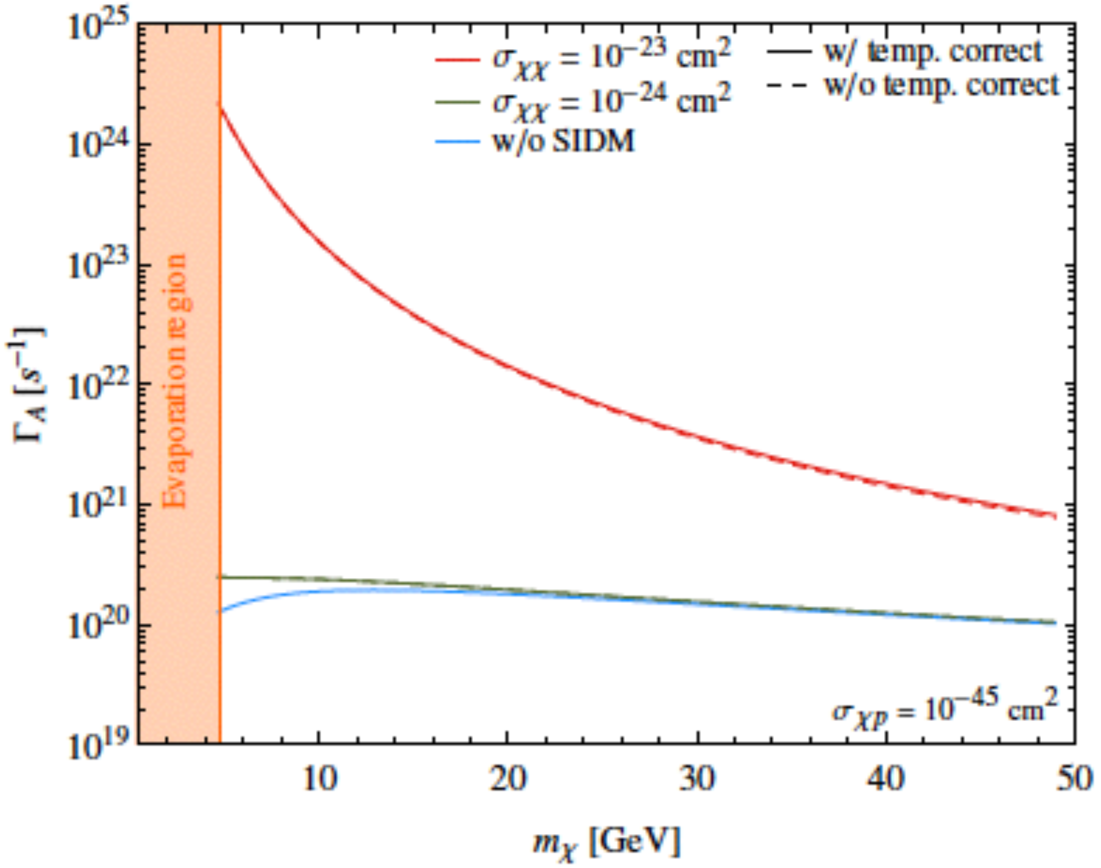
- When DMs reach to the thermal equilibrium, they are populated more closely to the solar core. Hence one expects $E_\chi(t_0) > $ \bar{E}.

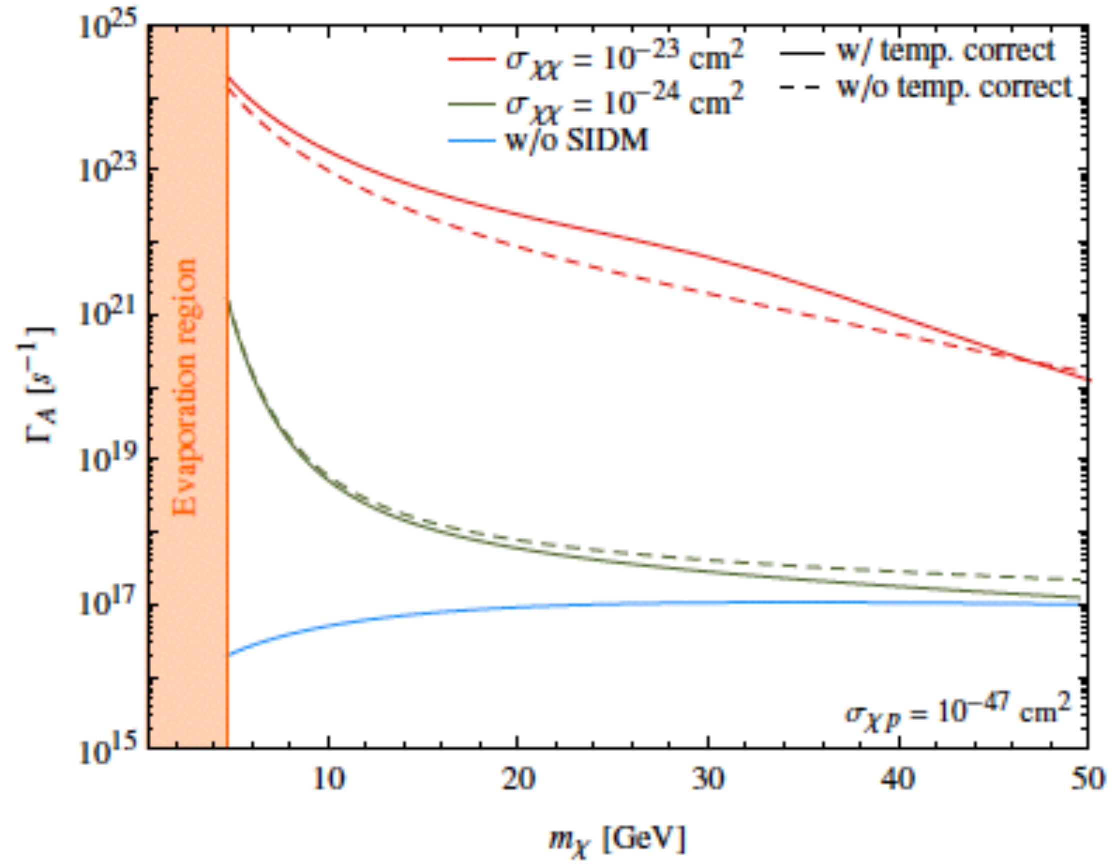
- J_a does not affect the DM temperature. J_c and C_c are constants, as N_χ accumulates they become negligible. We have

$$\frac{dE_\chi(t)}{dt} \approx J_\chi + J_s - C_s E_\chi(t)$$

This eq. approaches zero when the system is balanced. Hence the final T_χ depends on m_χ , $\sigma_{\chi p}$ and $\sigma_{\chi\chi}$, does not depend on the initial condition

annihilation rate with temperature correction





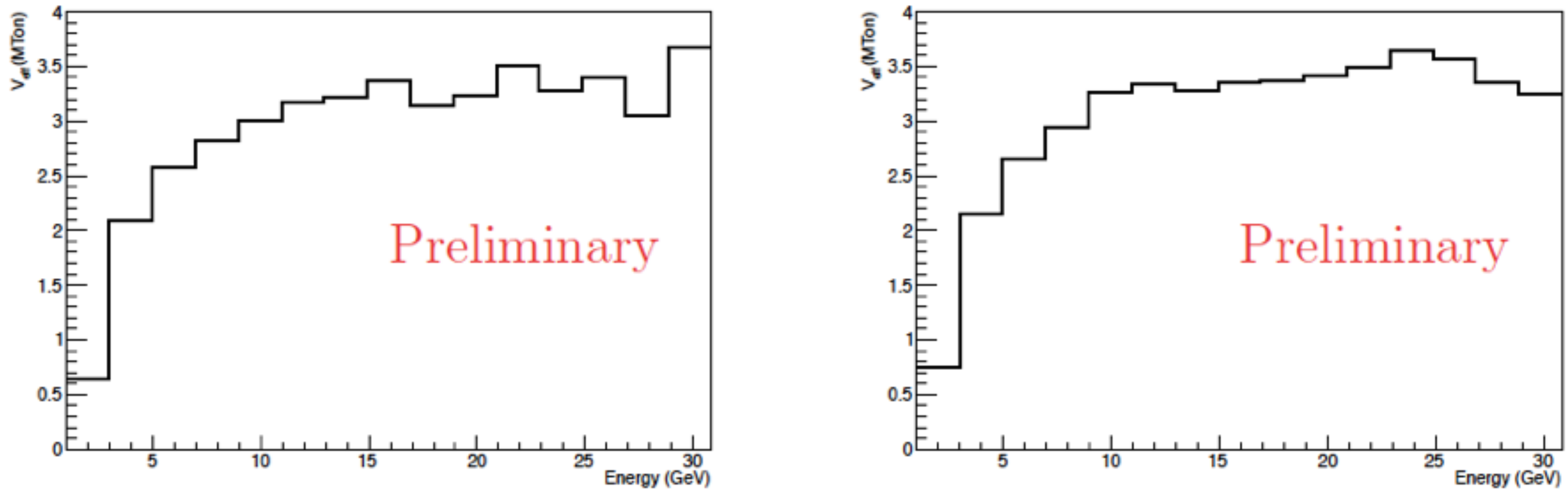
CONCLUSION

- We solve the general DM evolution equation with C_s and C_e inside the Sun.
- DM self-interaction is significant in m_χ ~ GeV scales.
- DM self-interaction will enhance the trapped DM number density and lower the critical mass.
- DM self-interaction help the reach of equilibrium state quicker.
- DM self-interaction is testable in IceCube-PINGU.
- Complementary (direct and indirect detections) test of SIDM models is studied, in particular, for the isospin violation regions and low DM mass regions
- Temperature evolution of DM is resolved and it corrected annihilation rate is given. The derivations are quit general, one can apply to any halo systems and celestial objects if the distributions are known.

Thank you for your attention !

effective volume for both track and cascade signals

arXiv:1401.2046



(a) $V_{eff}(\nu_\mu)$ (b) $V_{eff}(\nu_e)$

baseline 40 string configuration

efficiencies for MultiNest reconstruction of neutrinos

Flavor (Interaction)	N_{reco}/N_{total}
ν_e(CC)	$90.1 \pm 0.5\%$
ν_μ(CC)	$93.1 \pm 0.6\%$
ν_τ(CC)	$99.0 \pm 1.0\%$
ν(NC)	$87.2 \pm 1.7\%$

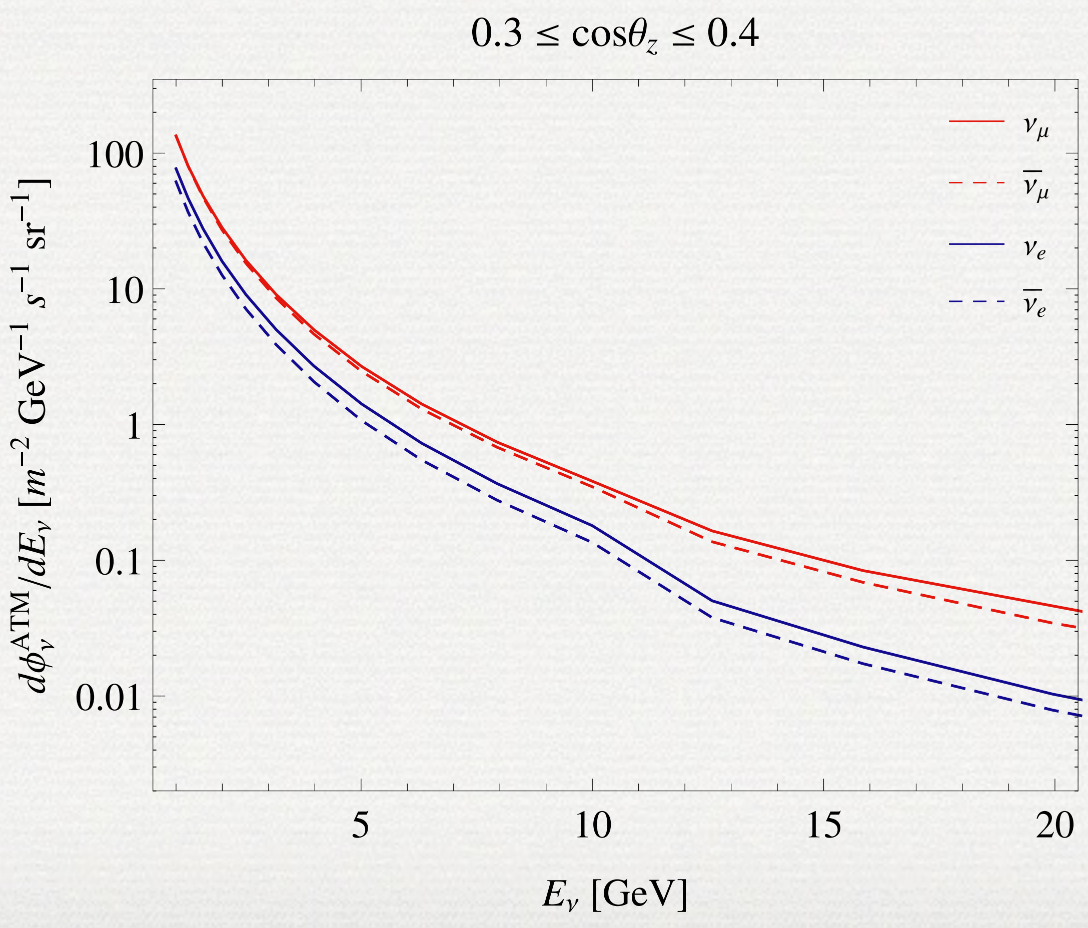
we consider 2σ detection significance in 5 years

$$\frac{N_\nu}{\sqrt{N_\nu + N_{\rm atm}}} = 2.0$$

the atmospheric neutrino backgrounds

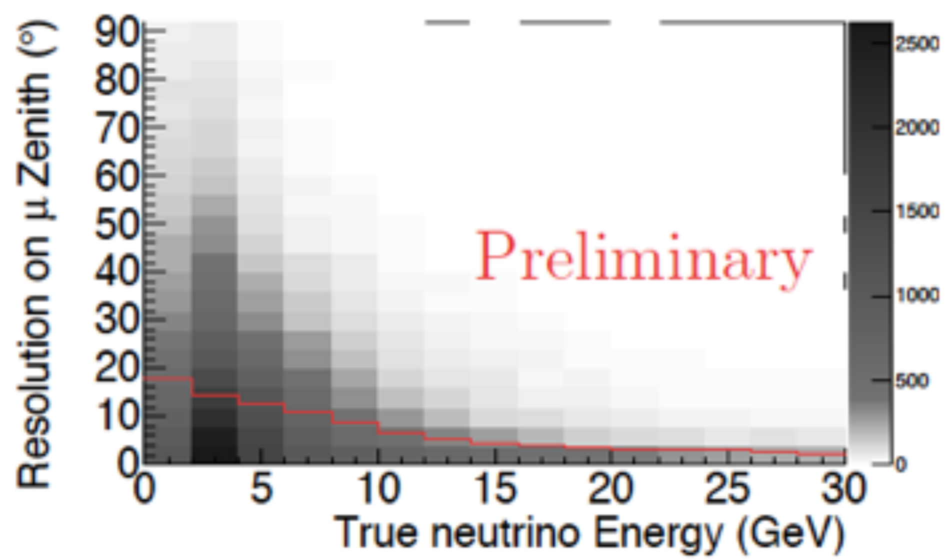
$$N_{\rm atm} = \int_{E_{\rm th}}^{\infty} \frac{d\Phi_{\nu,{\rm atm}}}{dE_\nu d\Omega} A^\nu_{\rm eff}(E_\nu) dE_\nu d\Omega$$

ATM fluxes, Honda *et al.*

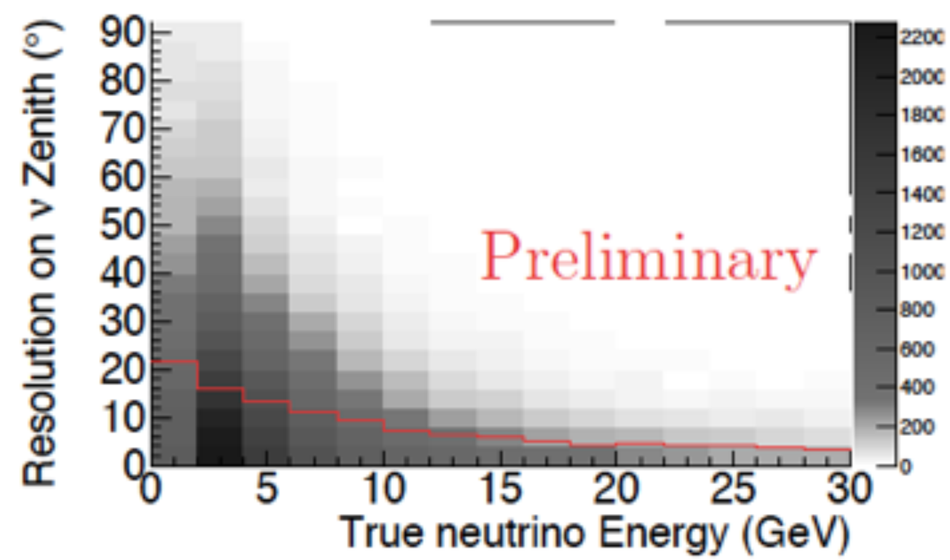


The Sun is roughly 23° above the horizon, $\cos\theta_z \sim 0.39$, in Antarctica during the daylight, that is why we take the atmospheric neutrino flux within $0.3 < \cos\theta_z < 0.4$

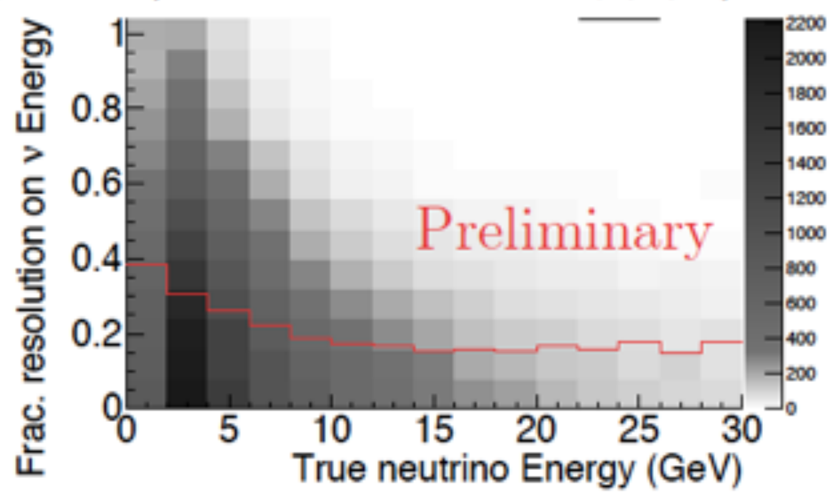
It is across about 6 ~ 7 degrees which roughly fits the angular resolution of IceCube-PINGU in the relevant range



(a) $|\theta_{\mu,\mathrm{true}} - \theta_{\mu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.



(b) $|\theta_{\nu,\mathrm{true}} - \theta_{\nu,\mathrm{reco}}|$ vs. $E_{\nu,\mathrm{true}}$.



(c) $|E_{\nu,\mathrm{reco}} - E_{\nu,\mathrm{true}}|/E_{\nu,\mathrm{true}}$ vs. $E_{\nu,\mathrm{true}}$.

The IceCube-PINGU detector at $E_\nu = 5$ GeV is roughly 10^0. We consider neutrino events arriving from the solid angle range surrounding the Sun with 10 degrees.

arXiv:1401.2046