Probing the coupling of heavy dark matter to nucleons by detecting neutrino signature from the Earth core

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Outline

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    - Detectors: IceCube & KM3NeT
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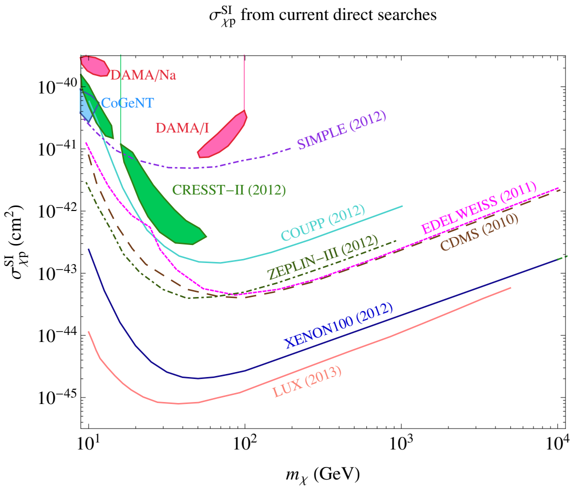
    - *Spin-independent DM-proton cross-sections*
5. Summary

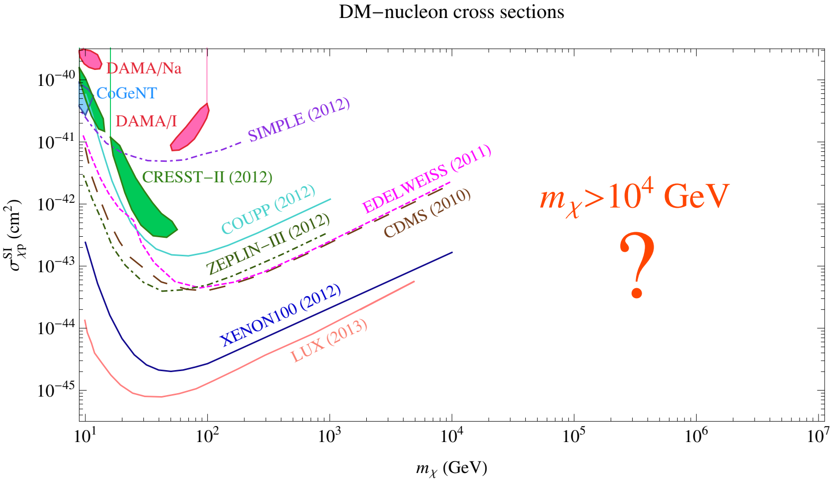
Spin-independent $\sigma_{\chi p}$ from current direct searches

The current direct searches are up to $m_\chi = 10^4$ GeV.



Beyond $m_\chi = 10^4$ GeV...?

What is beyond $m_\chi = 10^4$ GeV?



Motivations

- Current $\sigma_{\chi p}^{\mathrm{SI}}$ limits are up to $m_\chi = 10^4$ GeV only
- What is $\sigma_{\chi p}^{\mathrm{SI}}$ beyond $m_\chi = 10^4$ GeV, the heavy DM region
- Earth is potentially an ideal place to probe this problem:
  - Sensitive to $\langle \sigma v \rangle$ and $\sigma_{\chi p}^{\mathrm{SI}}$ both
  - Galactic DM can probe $\langle \sigma v \rangle$ only
  - νs from DM in the Sun suffer from severe energy attenuation after a few TeVs
- IceCube and KM3NeT may be able to provide answer to this question

Neutrino signals from planet-captured DM

The differential neutrino flux at the detector

$$\frac{d\Phi_\nu}{dE_\nu d\Omega} = \overbrace{\frac{\Gamma_A(m_\chi, \langle\sigma v\rangle, \sigma_{\chi p})}{4\pi R^2}}^{\text{annihilation rate}} \underbrace{\sum_f B_f \left(\frac{dN_\nu}{dE_\nu d\Omega}\right)_f}_{\text{neutrino spectrum at the detector}}$$

with the relation between capture rate[1], Γ_C,

$$\Gamma_A = \frac{\Gamma_C}{2}\tanh^2(t\sqrt{\Gamma_C C_A}) = \frac{\Gamma_C}{2}\tanh^2(t/\tau_\oplus)$$

where $C_A \propto \langle\sigma v\rangle\, m_\chi^{2/3}$ and

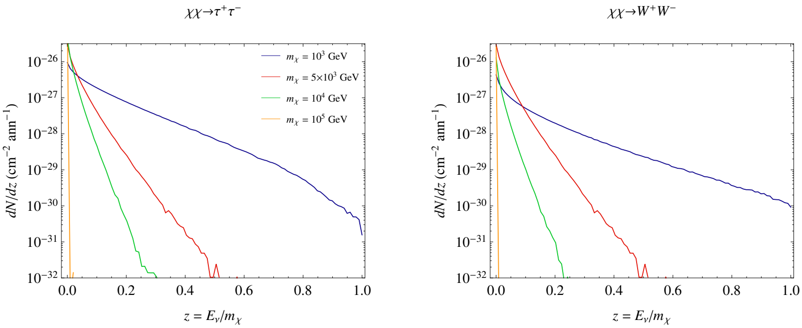
$$\Gamma_C \propto \frac{\rho_0}{\mathrm{GeV\ cm^{-3}}}\frac{\mathrm{km\ s^{-1}}}{\bar{v}}\frac{\mathrm{GeV}}{m_\chi}\frac{\sigma_{\chi p}}{\mathrm{pb}}\sum_A F_A^*(m_\chi).$$

[1] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. **268**, 195 (1996).

Neutrino spectra dN/dE from DM: Sun

This issue has been investigated sometime ago.[2] Here we reproduce some of the results with `WimpSim`.[3] After a few TeVs:

- νs suffer from severe energy attenuation
- ν-spectra strongly depleted



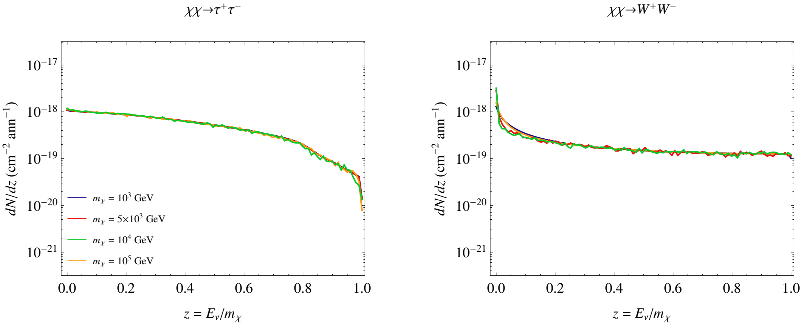
[2] M. Cirelli *et al.*, Nucl. Phys. B **10**, 001 (2007).

[3] J. Edsjö, `http://www.fysik.su.se/~edsjo/wimpsim/`.

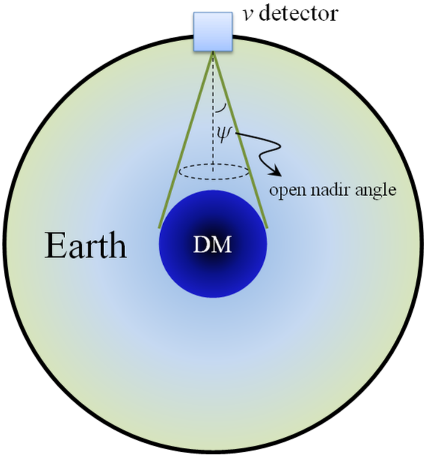
Neutrino spectra dN/dE from DM: Earth

After a few TeVs:

- νs do not suffer from severe energy attenuation
- ν-spectra have no sufficiently depleted



Schematic view of the Earth-captured DM

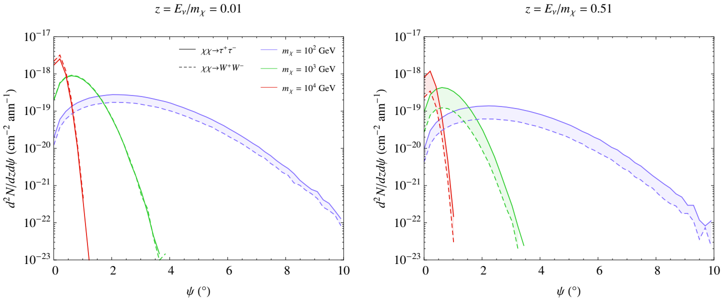


$$V_{\rm eff}(m_\chi) = V_{\rm Earth}\left(\frac{20\ {\rm GeV}}{m_\chi}\right)^{2/3}$$

$$\psi_{\max}(m_\chi) = \sin^{-1}\left(\frac{1}{R_\oplus}\left(\frac{3V_{\rm eff}(m_\chi)}{4\pi}\right)^{1/3}\right)$$

DM angular distribution in the Earth[4]

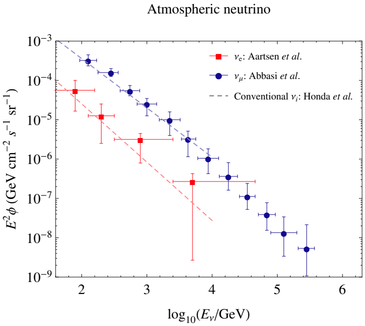
- Most DM signals are concentrating within 1° when $m_\chi > 10^4$ GeV.
- The spectrum for each m_χ has been summed over all neutrino types.



[4] A. Gould, Astrophys. J., **321**, 571 (1987).

Atmospheric background

- Major atmospheric neutrinos: ν_e and ν_μ
- Data points from IceCube[5]; conventional νs[6] are also presented
- Prompt νs are not into account.



[5] M.G. Aartsen *et al.* (IceCube Collaboration), Phys. Rev. Lett. **110**, 151105 (2013); R. Abbasi *et al.* (IceCube Collaboration), Phys. Rev. D **84**, 082001 (2011).

[6] M. Honda *et al.*, Phys. Rev. D **75**, 043006 (2007).

Track and cascade events

The neutrino event rate

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

with two kinds of events:

$$\text{Cascade}: \begin{cases} \nu_e, & \text{N.C. \& C.C.} \\ \nu_\mu, & \text{N.C.} \\ \nu_\tau, & \text{N.C. \& C.C.} \end{cases} \qquad \text{Track: } \nu_\mu, \text{ C.C.}$$

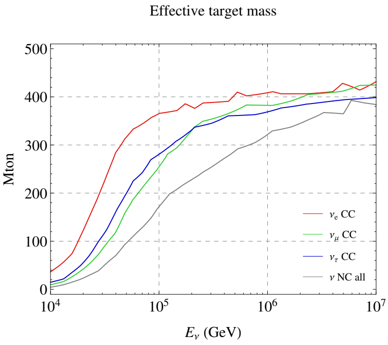
The ν effective areas $A_{\rm eff}$ can be obtained by the effective mass $M_{\rm eff}$ of IceCube[7] via

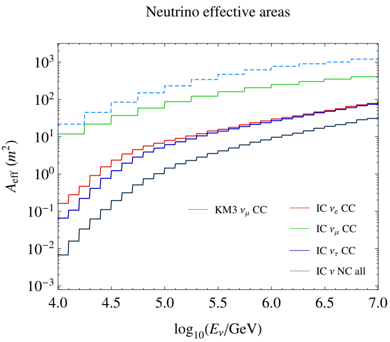
$$A_{\rm eff}(E) \approx \rho V_{\rm eff}(E) N_A \sigma_\nu(E) = M_{\rm eff}(E) N_A \sigma_\nu(E).$$

[7] C. Kopper, Talk @ EPS HEP 2013, Stockholm, Sweden, 18 Jul, 2013.

Effective areas

The ν_μ effective areas of IceCube[8] and KM3NeT[9] are from published papers.



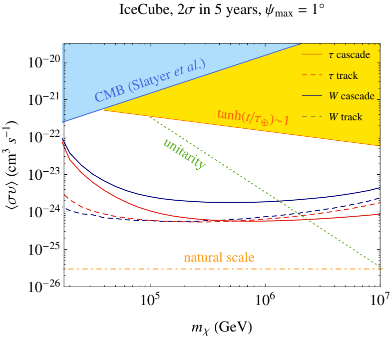


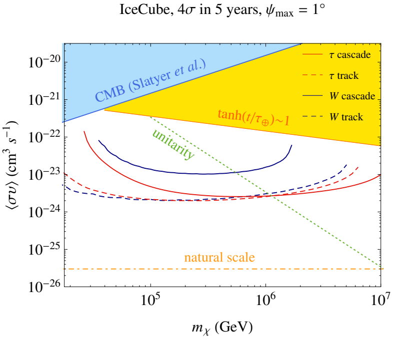
[8] M.G. Aartsen *et al.* (IceCube Collaboration), arXiv:1307.6669 (2013).

[9] U.F. Katz (for the KM3NeT Consortium), Nucl. Instrum. Methods Phys. Res. A **626**, S57 (2011).

Constraints on $\langle\sigma v\rangle$: IceCube

Reaching 2σ and 4σ in 5-year observations. $\psi_{\rm max} = 1^\circ$.





Constraints on $\langle \sigma v \rangle$ from unitarity and CMB

- The unitarity bound in the low-velocity limit[10]

$$\langle \sigma v \rangle_{\rm uni} \leq 1.5 \times 10^{-13}\ \mathrm{cm}^3\ \mathrm{s}^{-1} \left(\frac{\mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{300\ \mathrm{km\ s}^{-1}}{v}\right)$$

- Bound from CMB observation[11]

$$\langle \sigma v \rangle_{\rm CMB} < \frac{3.6 \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{f} \left(\frac{m_\chi}{\mathrm{GeV}}\right)$$

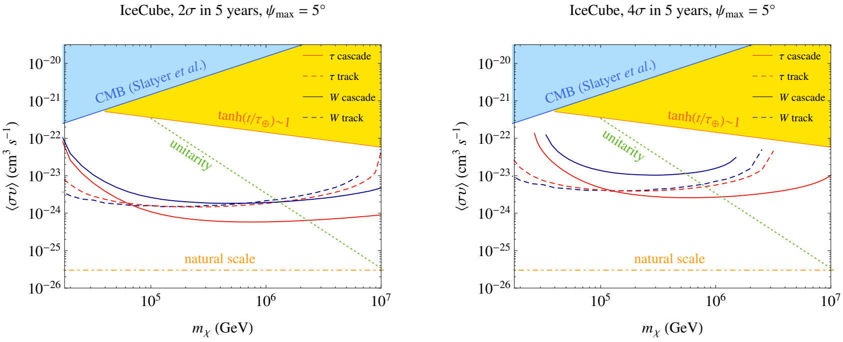
- Beyon $m_\chi > 10^4$ GeV, we extrapolated the XENON100 $\sigma_{\chi p}^{\rm SI}$ limit as our reference

[10] J.F. Beacom, N.F. Bell and G.D. Mack, Phys. Rev. Lett. **99**, 231301 (2007).

[11] T.R. Slatyer, N. Padmanabhan and D.P. Finkbeiner, Phys. Rev. D **80**, 043526 (2009).

Constraints on $\langle\sigma v\rangle$: IceCube

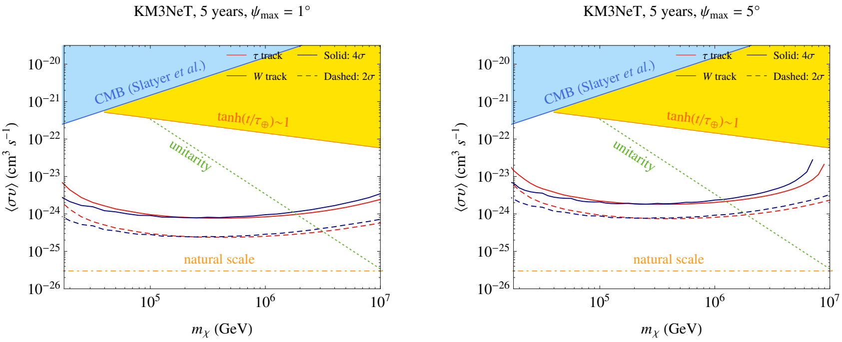
Reaching 2σ and 4σ in 5-year observations. $\psi_{\max} = 5^\circ$.[12]



[12] R. Auer, Nucl. Instrum. Methods Phys. Res. A **602**, 84 (2009).

Constraints on $\langle\sigma v\rangle$: KM3NeT

Reaching 2σ and 4σ in 5-year observations with $\psi_{\max} = 1^\circ$ and 5°.



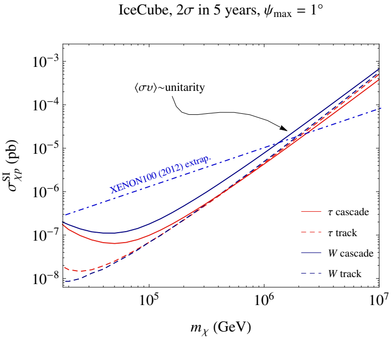
Constraints on $\sigma_{\chi p}^{\mathrm{SI}}$

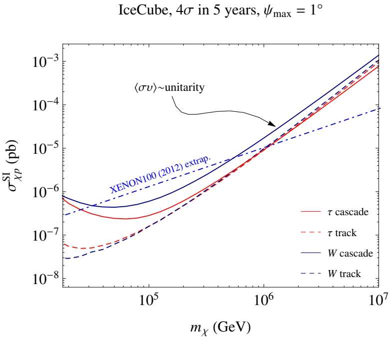
To constrain $\sigma_{\chi p}^{\mathrm{SI}}$, we consider two scenarios for $\langle \sigma v \rangle$:

- Optimistic one: $\langle \sigma v \rangle \sim$unitarity
- Natural scale: $\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$.

Constraints on $\sigma_{\chi p}^{\rm SI}$: IceCube with unitarity

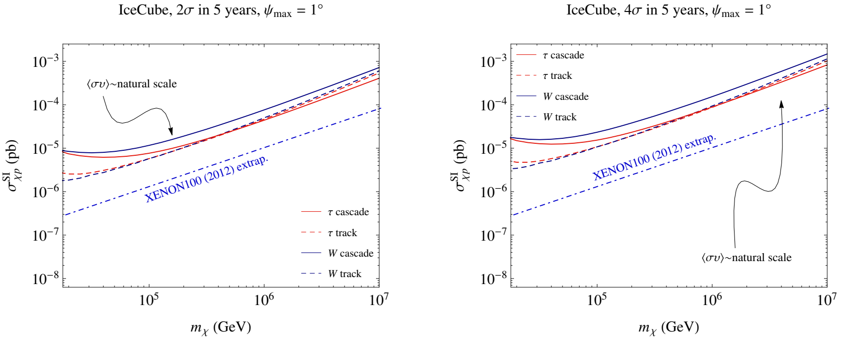
Reaching 2σ and 4σ in 5-year observations. $\psi_{\rm max} = 1°$.





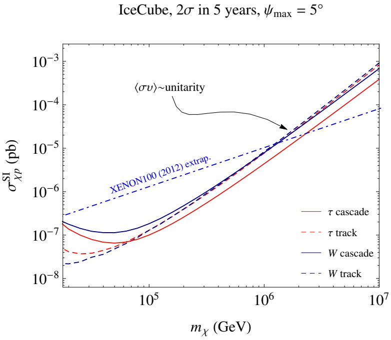
Constraints on $\sigma_{\chi p}^{\rm SI}$: IceCube with natural scale

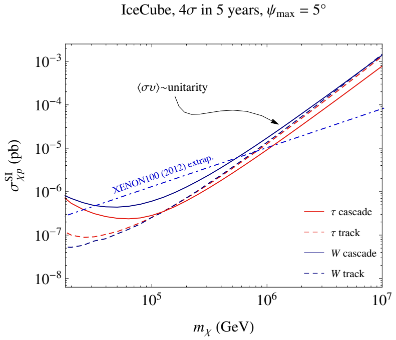
Reaching 2σ and 4σ in 5-year observations. $\psi_{\rm max} = 1^\circ$.



Constraints on $\sigma_{\chi p}^{\mathrm{SI}}$: IceCube with unitarity

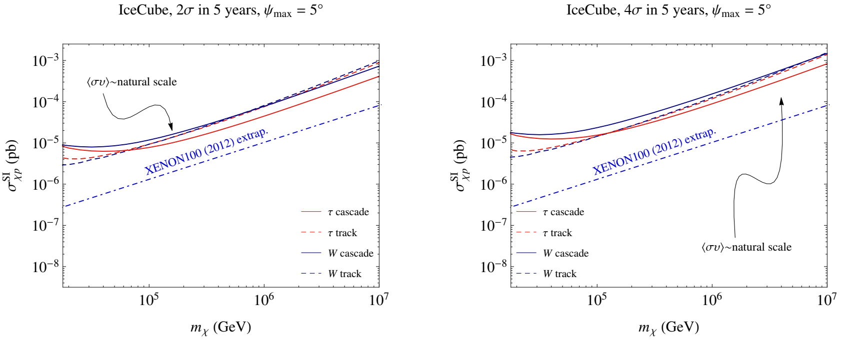
Reaching 2σ and 4σ in 5-year observations. $\psi_{\max} = 5^\circ$.





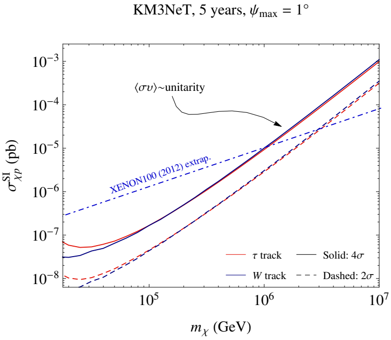
Constraints on $\sigma_{\chi p}^{\rm SI}$: IceCube with natural scale

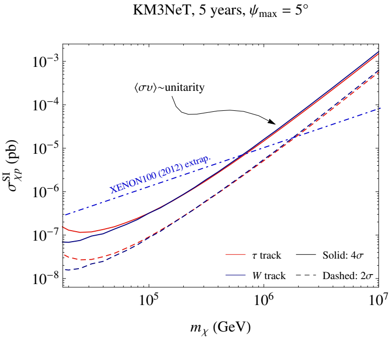
Reaching 2σ and 4σ in 5-year observations. $\psi_{\rm max} = 5^\circ$.



Constraints on $\sigma_{\chi p}^{\mathrm{SI}}$: KM3NeT with unitarity

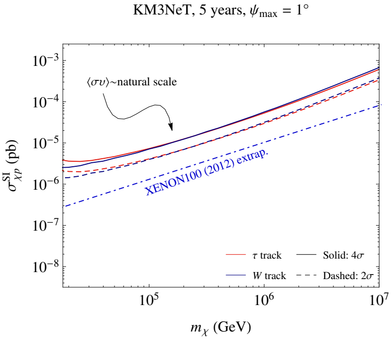
Reaching 2σ and 4σ in 5-year observations with $\psi_{\max} = 1^\circ$ and 5°.

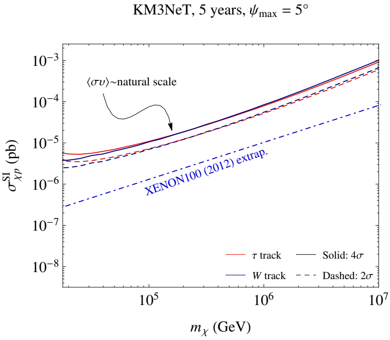




Constraints on $\sigma_{\chi p}^{\mathrm{SI}}$: KM3NeT with natural scale

Reaching 2σ and 4σ in 5-year observations with $\psi_{\max} = 1^\circ$ and 5°.





Summary

- Earth indeed is an ideal place to probe $\langle\sigma v\rangle$ and $\sigma^{\rm SI}_{\chi p}$ in heavy DM region
- Suppressed atmospheric background
- Taking XENON100 extrapolation in heavy DM region as our input:
  - When $m_\chi \lesssim 10^5$ GeV, $\langle\sigma v\rangle$ constraints from $\chi\chi \to \tau^+\tau^-$ and $\chi\chi \to W^+W^-$ tracks have the most stringent limit in IceCube
  - Beyond $m_\chi \gtrsim 10^5$ GeV, $\chi\chi \to \tau^+\tau^-$ cascade is the most stringently constraint in IceCube
  - The constraint obtained from $\chi\chi \to \tau^+\tau^-$ is comparable to the constraint obtained from $\chi\chi \to W^+W^-$ with KM3NeT designed sensitivity
- With unitarity bound and natural scale implemented in $\langle\sigma v\rangle$, it is possible to obtain optimistic and conservative limits for $\sigma^{\rm SI}_{\chi p}$ with given detector sensitivity.