Searching for dark matter annihilation in the Sun with the IceCube Upgrade

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with **Dan Hooper**

Based on 2505.06734
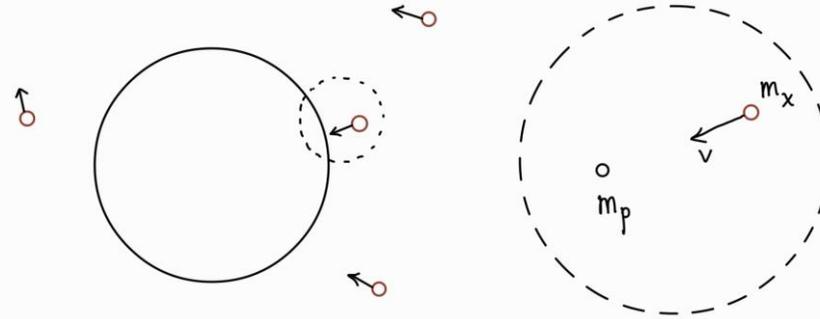
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Image credit: NASA

- A way to search for dark matter is to look for potential products of its annihilation

- We've looked extensively for excesses induced by DM annihilation in:

  - Gamma rays from the Galactic Center, dwarf galaxies
  - Antimatter in the cosmic ray spectrum
  - Neutrinos from the core of the Sun

- Direct detection experiments have placed very stringent constraints, disfavoring many of the simplest models

- We find that IceCube Upgrade will be able to probe beyond these constraints by leveraging an unprecedented sensitivity to DM annihilating in the Sun

- DM could accumulate in the Sun by scattering with nuclei.

- The population of accumulated DM particles evolves by

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} = \Gamma_{\mathrm{cap}} - 2\Gamma_{\mathrm{ann}}.$$

- After a long time, equilibrium can be achieved: $\Gamma_{\mathrm{cap}} = 2\Gamma_{\mathrm{ann}}$.

- Neutrino fluxes could be produced from DM annihilation and escape the Sun.

- The capture rate depends on the DM mass and scattering cross section ($m_\chi \gg m_p$):

$$\Gamma_{\text{cap}} \approx 5 \times 10^{18} \text{ s}^{-1} \times \left(\frac{100 \text{ GeV}}{m_\chi}\right)^2 \left(\frac{\sigma_{\chi p}}{10^{-42} \text{ cm}^2}\right)$$

- The annihilation rate goes like

$$\Gamma_{\text{ann}} \approx \frac{N_\chi^2 \langle \sigma v \rangle}{2 V_{\text{eff}}}$$

Effective volume occupied
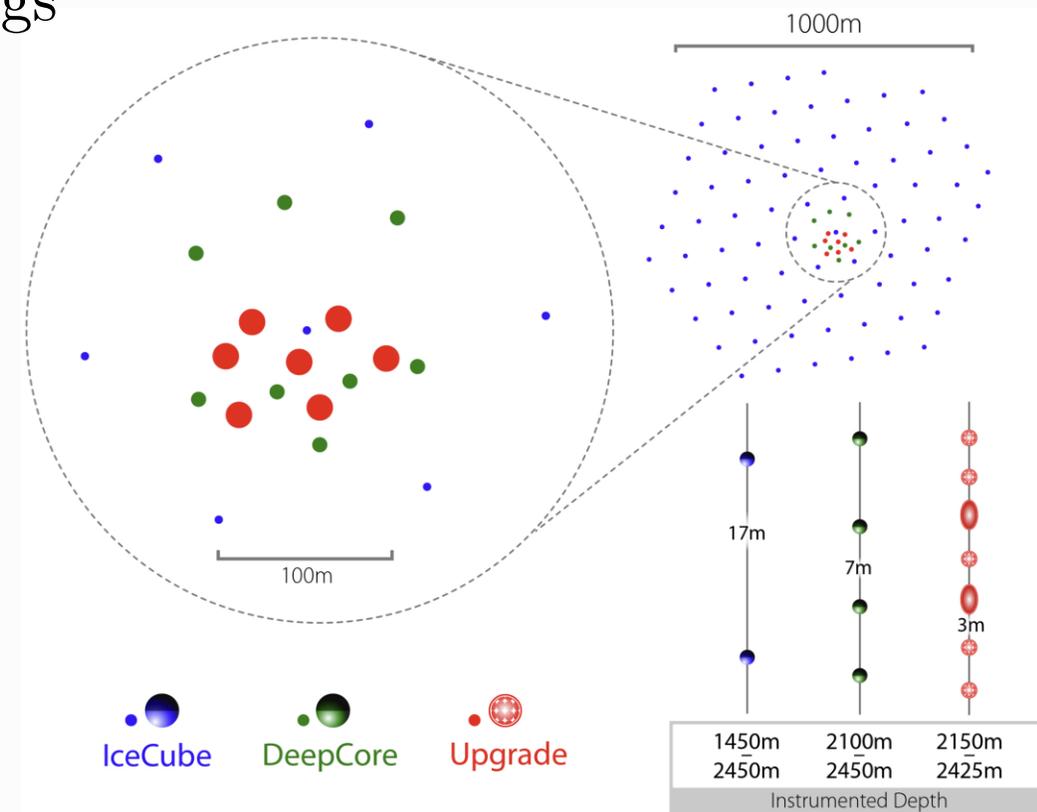by DM particles in the Sun

- It's safe to neglect evaporation for $m_\chi \gtrsim 3$ GeV, for which the timescale of evaporation exceeds the age of the Solar System.

- The IceCube Upgrade consists of seven new strings with ~ 700 optical sensors

- The denser sensor array will allow detection of much lower-energy neutrinos ($\gtrsim 1$ GeV)

- The rate of detected muon tracks depends on the effective volume of the detector, the cross section for neutrino scattering, and the differential flux of neutrinos,

$$\frac{\mathrm{d}\phi_\nu}{\mathrm{d}E_\nu} \propto \frac{\Gamma_{\mathrm{ann}}}{4\pi D^2}$$

The IceCube Collaboration, arXiv:1908.09441

- We then compare the predicted signal to the rate of atmospheric neutrino events and make projections at the 2σ-level for 10 years of data collection.

- Spin-independent vs. spin-dependent couplings:

spin of the nuclear target

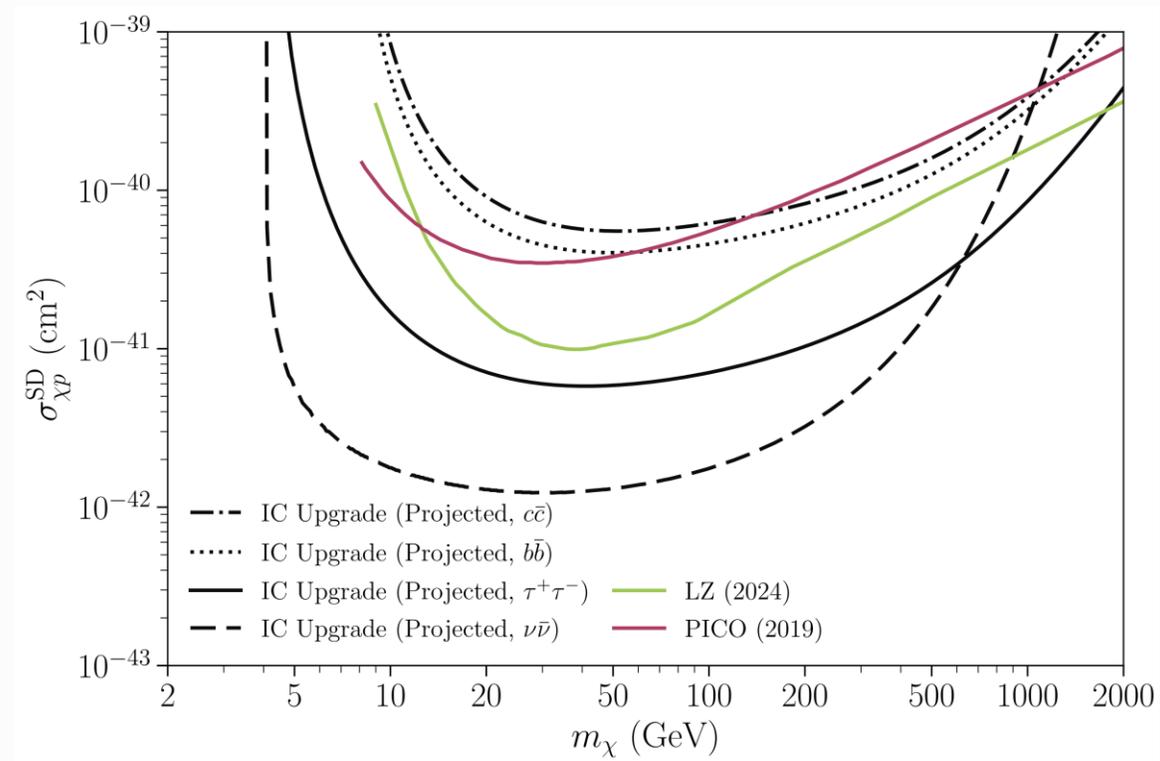$$\sigma_{\chi p}^{\mathrm{SI}} \propto A^2 \qquad\qquad \sigma_{\chi p}^{\mathrm{SD}} \propto J(J+1)$$

nuclear mass number

- For spin-independent couplings between DM and protons in the Sun, we find:

- We'll focus on spin-dependent couplings instead, for which we find:
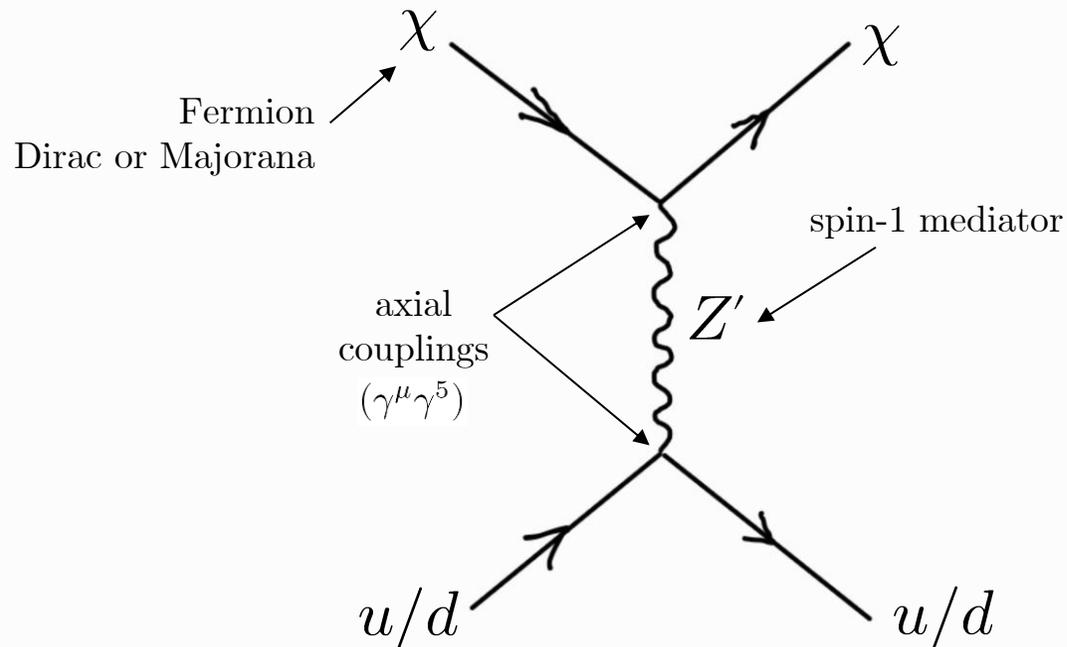

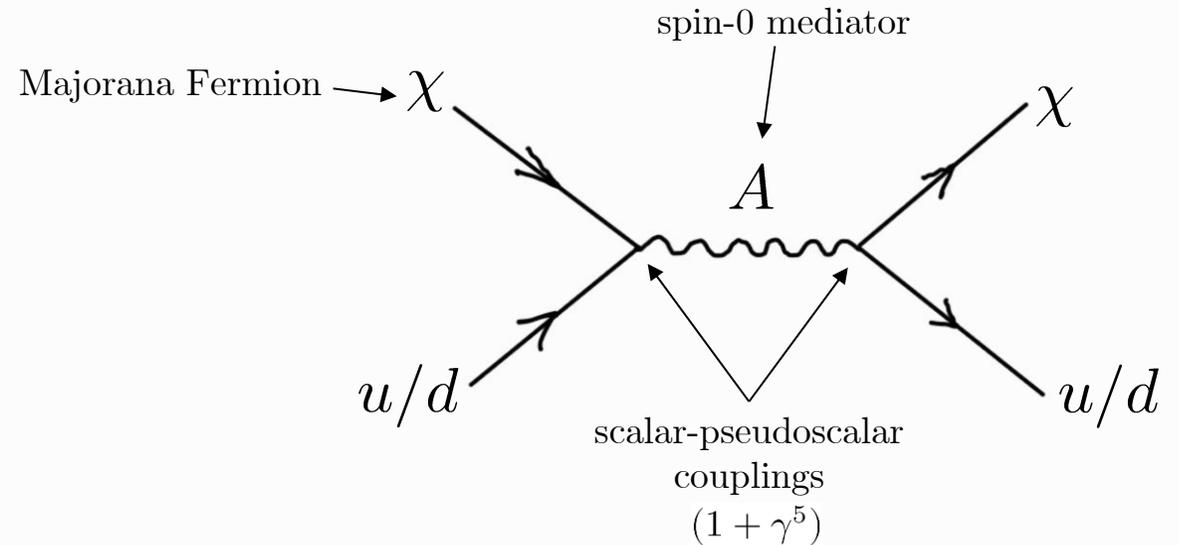- Great performance for models with significant annihilation to $\nu\bar{\nu}$ and $\tau^{+}\tau^{-}$

- The IceCube Upgrade will be able to look for models with

  - Predominant spin-dependent scattering with nucleons

  - No suppression of the scattering cross section at low velocities

- Tree-level options satisfying these requirements are:

Axial models

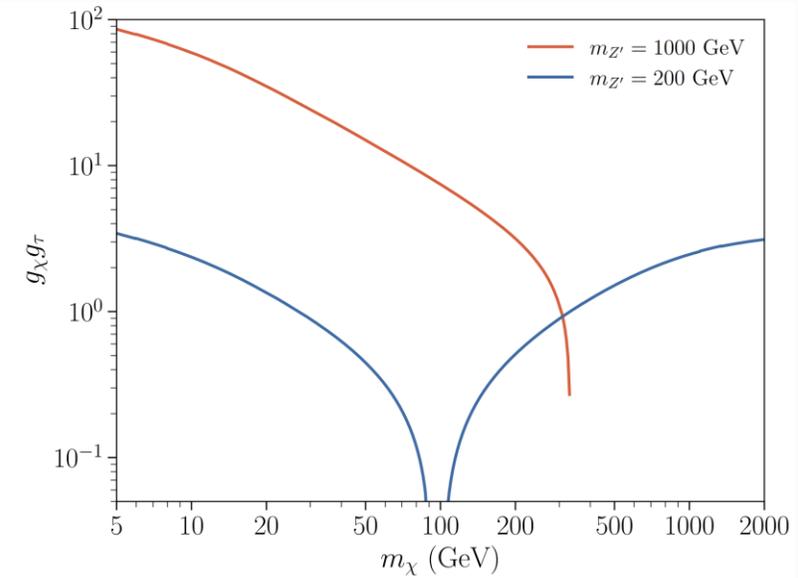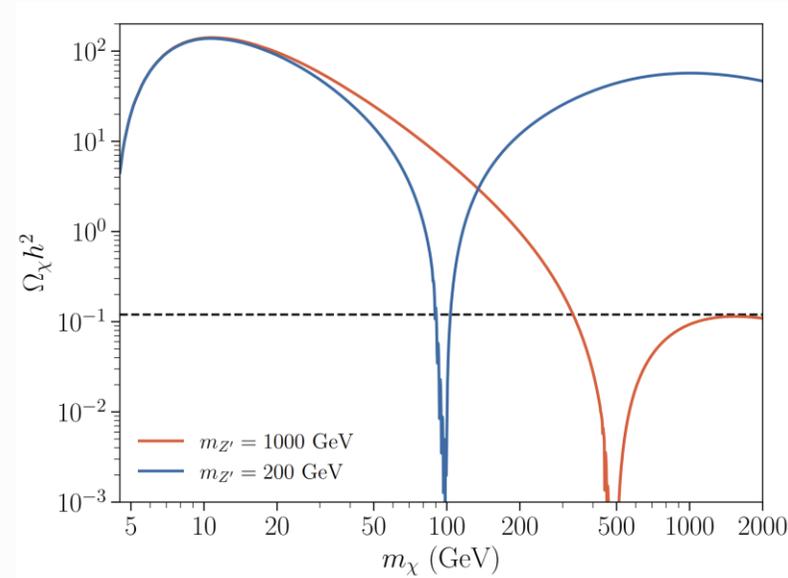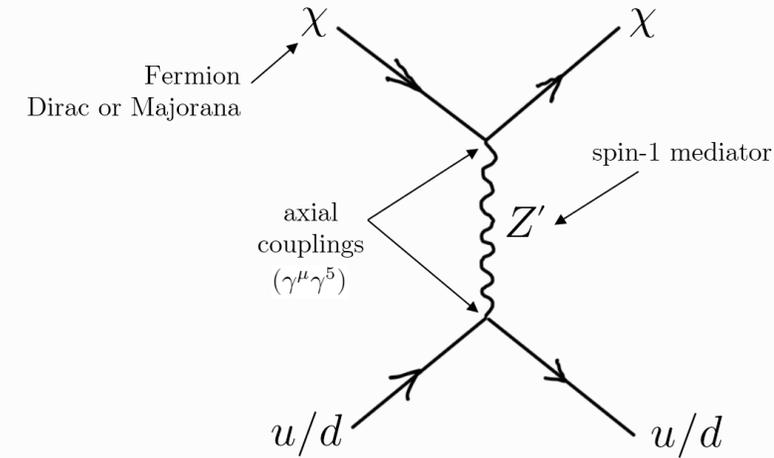Scalar-pseudoscalar models

Axial models:

- The scattering cross section goes like $\sigma_{\chi p} \propto \dfrac{g_\chi^2 g_q^2}{m_{Z'}^4}$

- The right relic abundance can be obtained for various parameter choices:

- Accounting for constraints, for an observable flux of neutrinos we'd need

$$g_{u,d} \sim (0.01 - 0.2) \times (1/g_\chi)(m_{Z'}/300 \text{ GeV})^2$$

Scalar-pseudoscalar models:
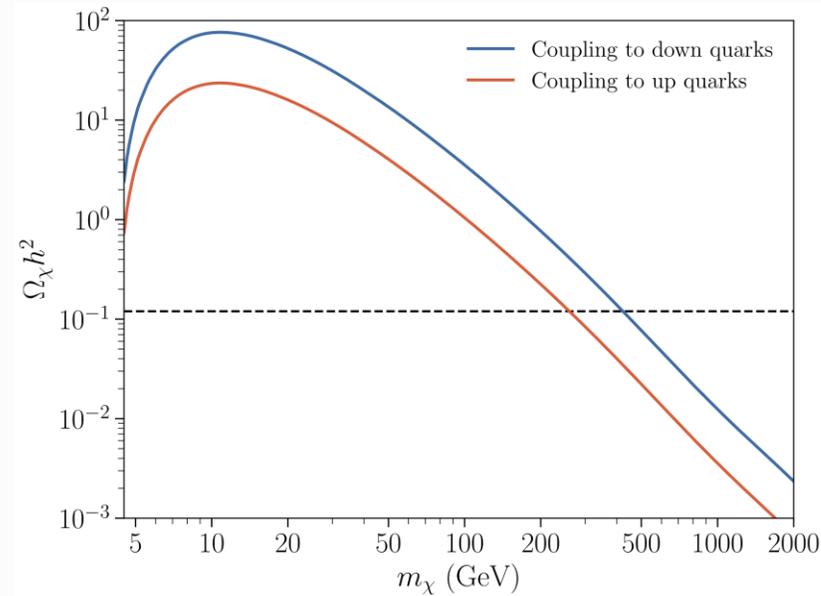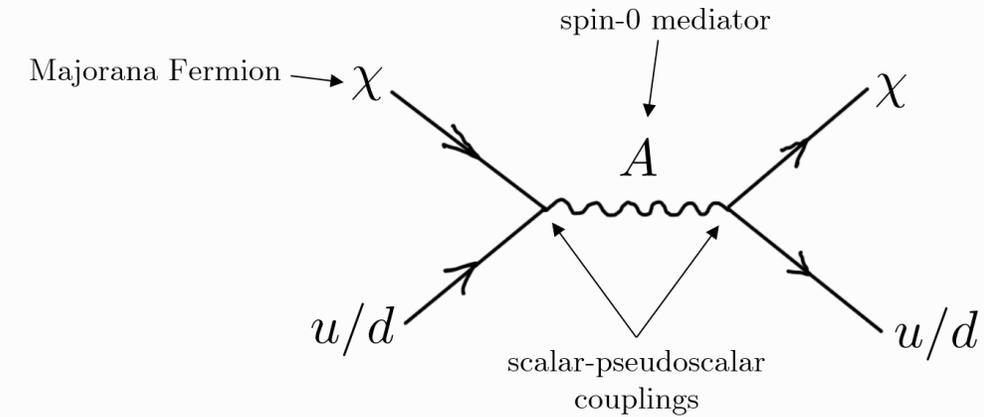
- The scattering cross section goes like $\sigma_{\chi p} \propto \dfrac{\lambda_{\chi q}^4}{m_A^4}$

spin-0 mediator

Majorana Fermion $\rightarrow \chi$

χ

A

u/d

scalar-pseudoscalar couplings

u/d

- The right relic abundance can be obtained for various parameter choices:

- Accounting for constraints, for an observable flux of neutrinos we'd need

$\lambda_{\chi u} \sim 1.5 \times (m_A/3 \text{ TeV})$ or $\lambda_{\chi d} \sim 2.2 \times (m_A/3 \text{ TeV})$

- The IceCube Upgrade will have an unprecedented sensitivity to dark matter particles annihilating in the core of the Sun

- The capabilities brought in by the Upgrade should significantly improve on existing bounds, especially for models in which $\chi\chi \to \tau\bar{\tau}$ or $\chi\chi \to \nu\bar{\nu}$ are significant

- Models where the DM has spin-dependent couplings to nucleons without low-velocity suppression are the most promising targets for the IceCube Upgrade

- We found two candidate model classes that are currently consistent with constraints that could produce fluxes observable by the Upgrade
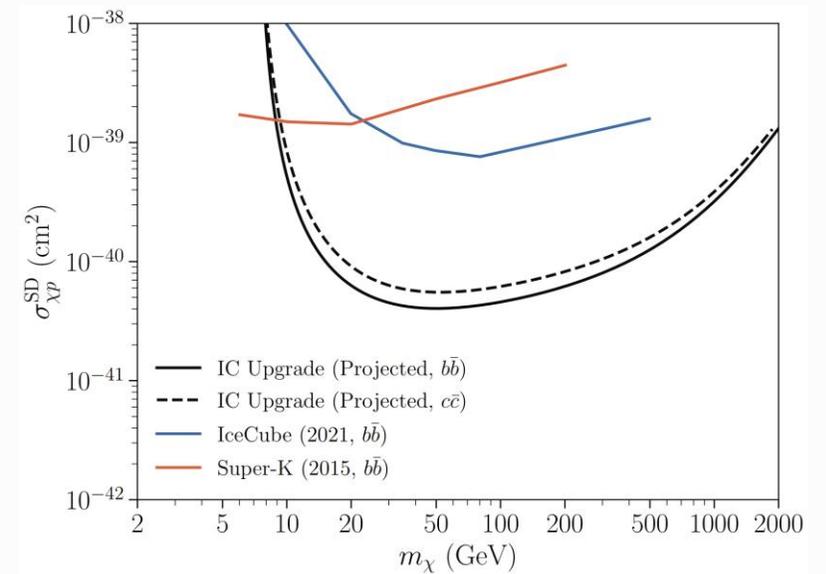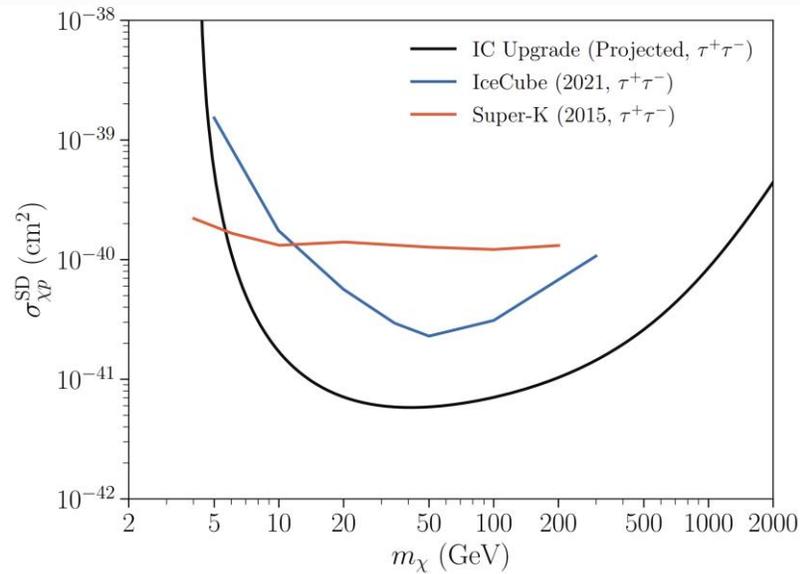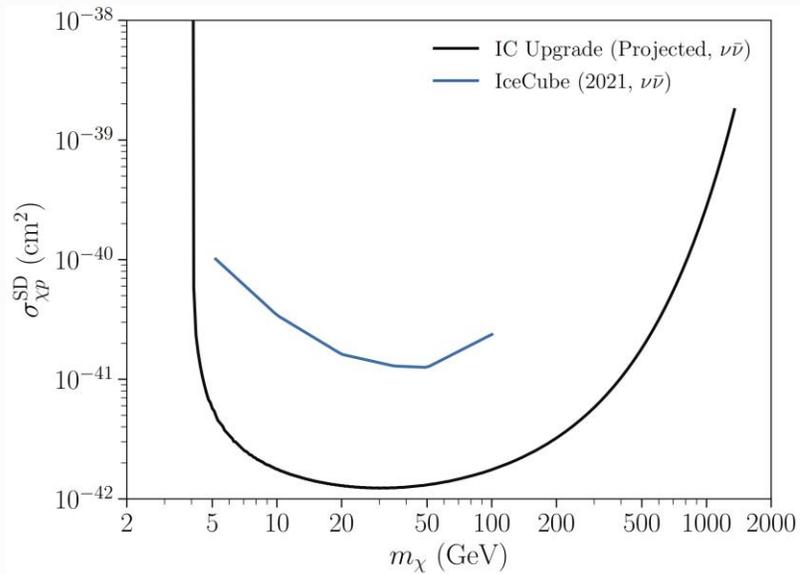
- Formulas used to find projections

$$\frac{d\phi_{\nu_\mu}}{dE_{\nu_\mu}} = \frac{1}{3}\frac{\Gamma_{\text{ann}}}{4\pi D^2}\left(\frac{dN_{\nu_e}}{dE_{\nu_e}} + \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} + \frac{dN_{\nu_\tau}}{dE_{\nu_\tau}}\right)_{\text{Inj}}$$

$$\frac{d\phi_{\bar{\nu}_\mu}}{dE_{\bar{\nu}_\mu}} = \frac{1}{2}\frac{\Gamma_{\text{ann}}}{4\pi D^2}\left(\frac{dN_{\bar{\nu}_\mu}}{dE_{\bar{\nu}_\mu}} + \frac{dN_{\bar{\nu}_\tau}}{dE_{\bar{\nu}_\tau}}\right)_{\text{Inj}},$$

$$R_\mu \approx N_A \int\int \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}}(E_{\nu_\mu})\frac{d\sigma_\nu}{dy}(E_{\nu_\mu}, y)\, D_\mu(E_\mu)\, A_{\mu,\text{eff}}\, dE_{\nu_\mu}\, dy$$

$$+ N_A \int\int \frac{dN_{\bar{\nu}_\mu}}{dE_{\bar{\nu}_\mu}}(E_{\bar{\nu}_\mu})\frac{d\sigma_{\bar{\nu}}}{dy}(E_{\bar{\nu}_\mu}, y)\, D_\mu(E_\mu)\, A_{\mu,\text{eff}}\, dE_{\nu_\mu}\, dy,$$

- Constraints on spin-dependent DM-proton couplings

- Potential models one could choose from for fermion DM at the tree level for s-channel interactions:

DM bilinear	SM fermion bilinear			
fermion DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2,\ \sigma_{\mathrm{SI}} \sim 1$	$\sigma v \sim v^2,\ \sigma_{\mathrm{SD}} \sim q^2$	$-$	$-$
$\bar{\chi}\gamma^5\chi$	$\sigma v \sim 1,\ \sigma_{\mathrm{SI}} \sim q^2$	$\sigma v \sim 1,\ \sigma_{\mathrm{SD}} \sim q^4$	$-$	$-$
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	$-$	$-$	$\sigma v \sim 1,\ \sigma_{\mathrm{SI}} \sim 1$	$\sigma v \sim 1,\ \sigma_{\mathrm{SD}} \sim v_\perp^2$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	$-$	$-$	$\sigma v \sim v^2,\ \sigma_{\mathrm{SI}} \sim v_\perp^2$	$\sigma v \sim 1,\ \sigma_{\mathrm{SD}} \sim 1$

- The axial-axial case is the only one that isn't suppressed at low velocities.

- For t-channel interactions, only the Majorana scalar-pseudo scalar case works because it's the only one that Fierz-transforms to the above s-channel case.

- Constraints from Planck and ACT on the axial-axial models we considered: