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# Neutrino Constrains on Dark Matter Captured in the Sun*

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# Gravitational Capture of Dark Matter

- The Sun moves through a halo of dark matter (DM) that is gravitationally bound to our galaxy.
- A fraction of these incident DM particles interact with solar media, lose kinetic energy, get gravitationally bound to the Sun, and eventually drift to the core.
- The number density of DM in the Sun keeps increasing till an equilibrium between capture and annihilation is achieved.
- If neutrinos are produced in these annihilations, they escape the Sun and can be detected by terrestrial experiments.

Press and Spergel, *Astrophys. J.* 296 (1985) 679-684;
Gould , *Astrophys. J.* 321 (1987) 560;
Griest and Seckel, *Nucl.Phys.B* 283 (1987) 681-705; …

# Neutrino Flux from DM in the Sun

- If DM annihilates to quarks, they hadronize and produce mesons that eventually decay inside Sun, producing neutrinos.
- The neutrinos undergo flavor conversion inside the Sun, in vacuum to Earth, and inside Earth during night.
- The flux of $\nu_\alpha$ at the detector is —

Rate of annihilation of DM in Sun $\Gamma_{\mathrm{A}} \overset{eq}{\to} \Gamma_{\mathrm{cap}}/2$

$$\frac{d\Phi_\alpha}{dE_\nu} = \frac{\Gamma_{\mathrm{A}}}{4\pi d^2} \sum_\beta P_{\alpha\beta} \frac{d\varphi_\beta}{dE_\nu}$$

150 million km

Flavor Conversion

Spectrum of neutrinos
per annihilation

# Relative capture rate for inelastic DM

$$k_{\rm cap} = \Gamma_{\rm cap}(M_\chi, \delta)\,/\,\Gamma_{\rm cap}(M_\chi, 0)\,.$$

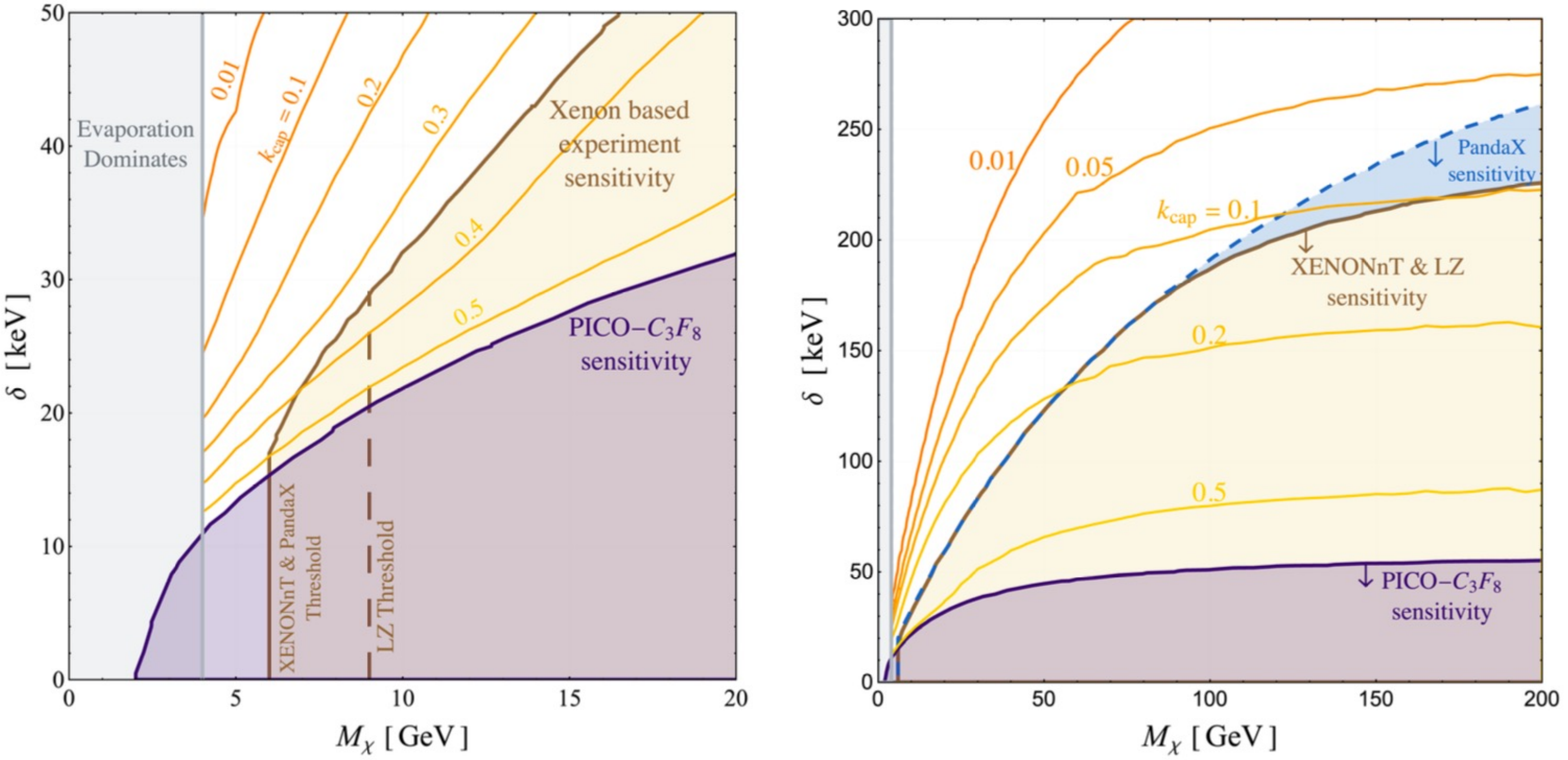


**Figure 2**: The contours for relative capture rate $k_{\rm cap}$ (see Equation (2.8)) are compared with the sensitivity of direct-detection experiments. The figure on the left focuses on the small-mass parameter space. The shaded regions show non-zero relative event rate in direct-detection experiments, $k_{\rm DD} \geq 0$, for PICO-C3F8 (purple), XENON and LZ (cream), and PandaX (blue). The gray shaded region represents the evaporation mass of dark matter, which we fix at 4 GeV for all $\delta \geq 0$. One can see that there is a significant parameter space where direct-detection experiments are not sensitive, but where indirect detection from a significant gravitational capture and annihilation of DM in the Sun is possible.

# Neutrino Flux from DM Annihilation in the Sun

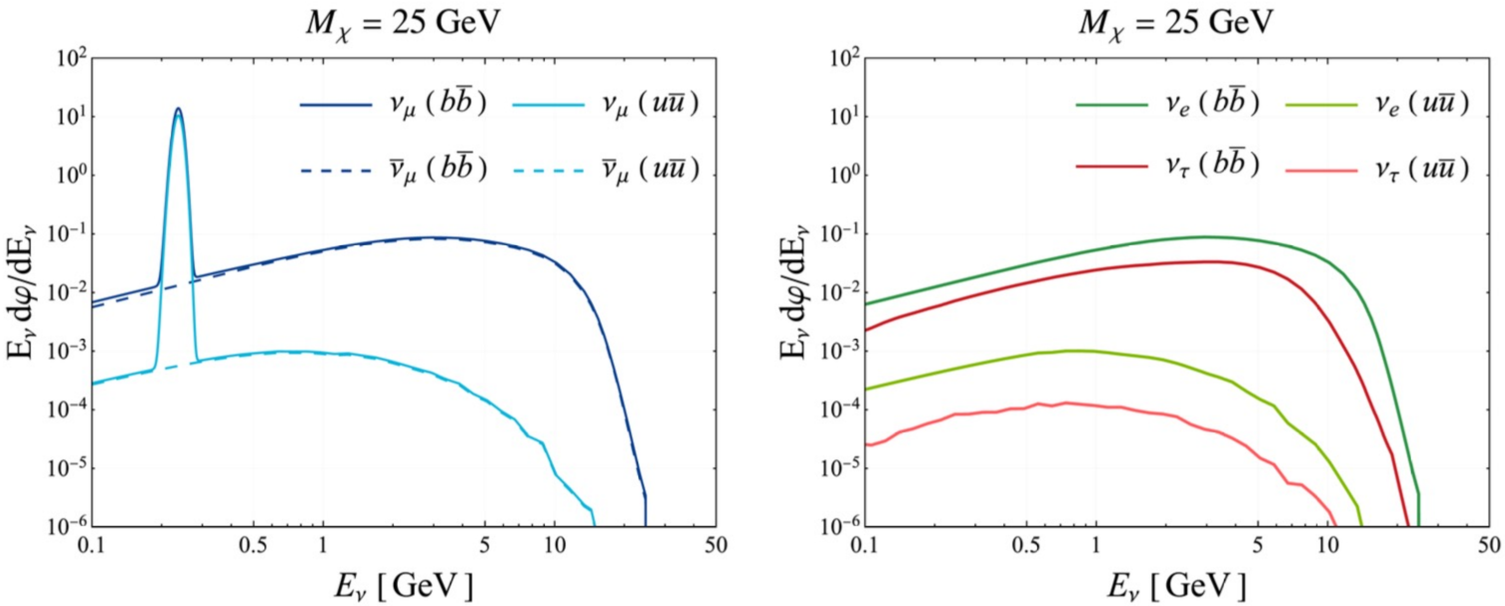


**Figure 3**: *Left:* The energy-scaled spectrum of muon neutrinos and anti-neutrinos per DM annihilation ($E_\nu\, d\varphi_\beta/dE_\nu$) in the Sun is shown for a benchmark DM mass of 25 GeV and for two annihilation channels - '$b\bar{b}$' (blue) and '$u\bar{u}$' (light blue). The neutrino (anti-neutrino) spectrum is shown with solid (dashed) curve. The *spike* in the $\nu_\mu$ spectrum is due to primary and secondary $K^+$ that decay-at-rest (KDAR) in the Sun. For illustration, we represent the mono-energetic feature with a Gaussian of width 10 MeV which is the typical energy resolution of a LArTPC detector at these energies. *Right:* The energy-scaled spectrum of non-muon flavors is shown. The spectrum of anti-neutrinos is same as neutrinos. *Both:* The broad feature from $E_\nu = 500$ MeV to $E_\nu = M_\chi$ in all neutrino spectra, called the *shoulder*, is significant only for the heavy-quark channel. There are additional features in the neutrino spectra at below 250 MeV, notably from three-body decays of kaons, which are not shown here.

Proposed detection of the KDAR with DUNE (C. Rott et al. JCAP 11 (2015); DUNE Collaboration, JCAP 10 (2021) 065

We use PPPC4DMnu to calculate neutrino flux and DM annihilation rate (Baratella et al. JCAP 03 (2014) 053

# Neutrino Flux at the Detector after Flavor Conversion

$$\frac{d\Phi_\alpha^{\mathrm{D}}}{dE_\nu} = \frac{d\Phi_e^{\mathrm{E}}}{dE_\nu} \times \langle P_{e\alpha}^{ED} \rangle + \frac{d\Phi_\mu^{\mathrm{E}}}{dE_\nu} \times \langle P_{\mu\alpha}^{ED} \rangle + \frac{d\Phi_\tau^{\mathrm{E}}}{dE_\nu} \times \langle P_{\tau\alpha}^{ED} \rangle$$

where $\langle P_{\alpha\beta} \rangle$ represents the conversion probabilities averaged over the zenith angles of

the Sun.

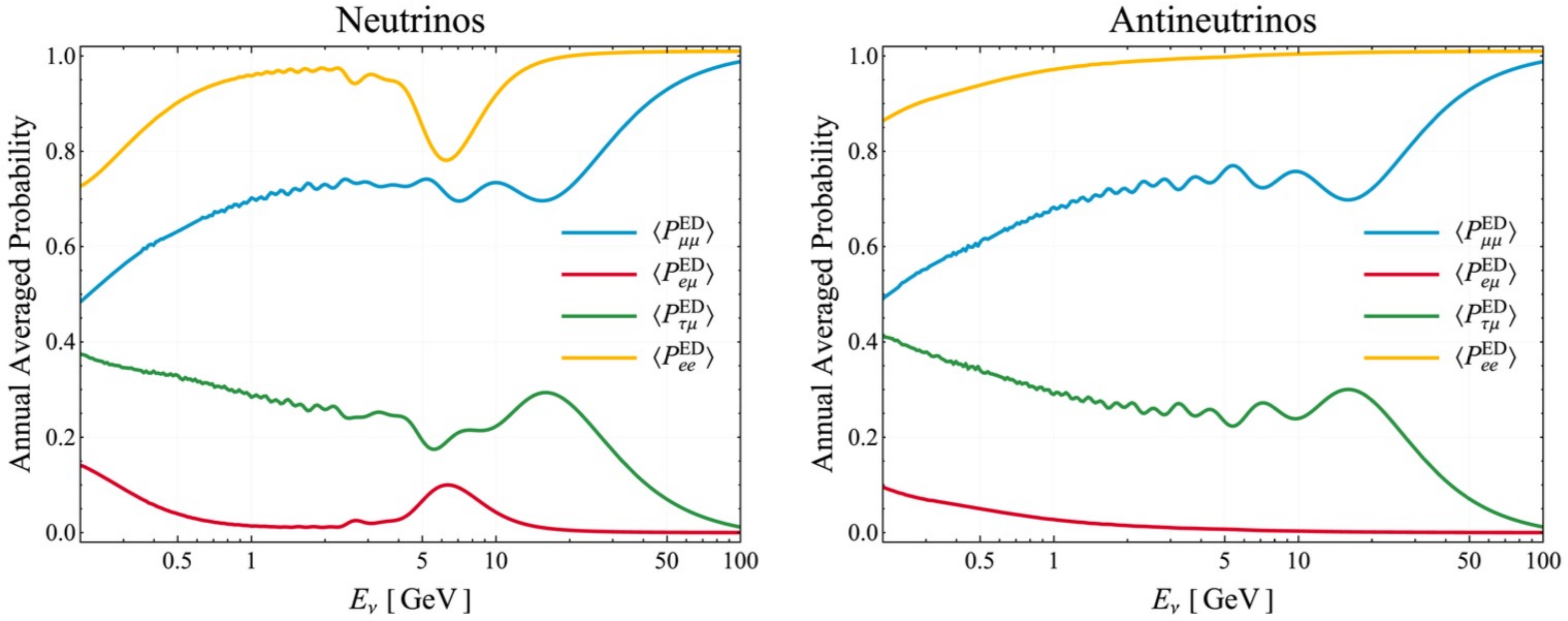
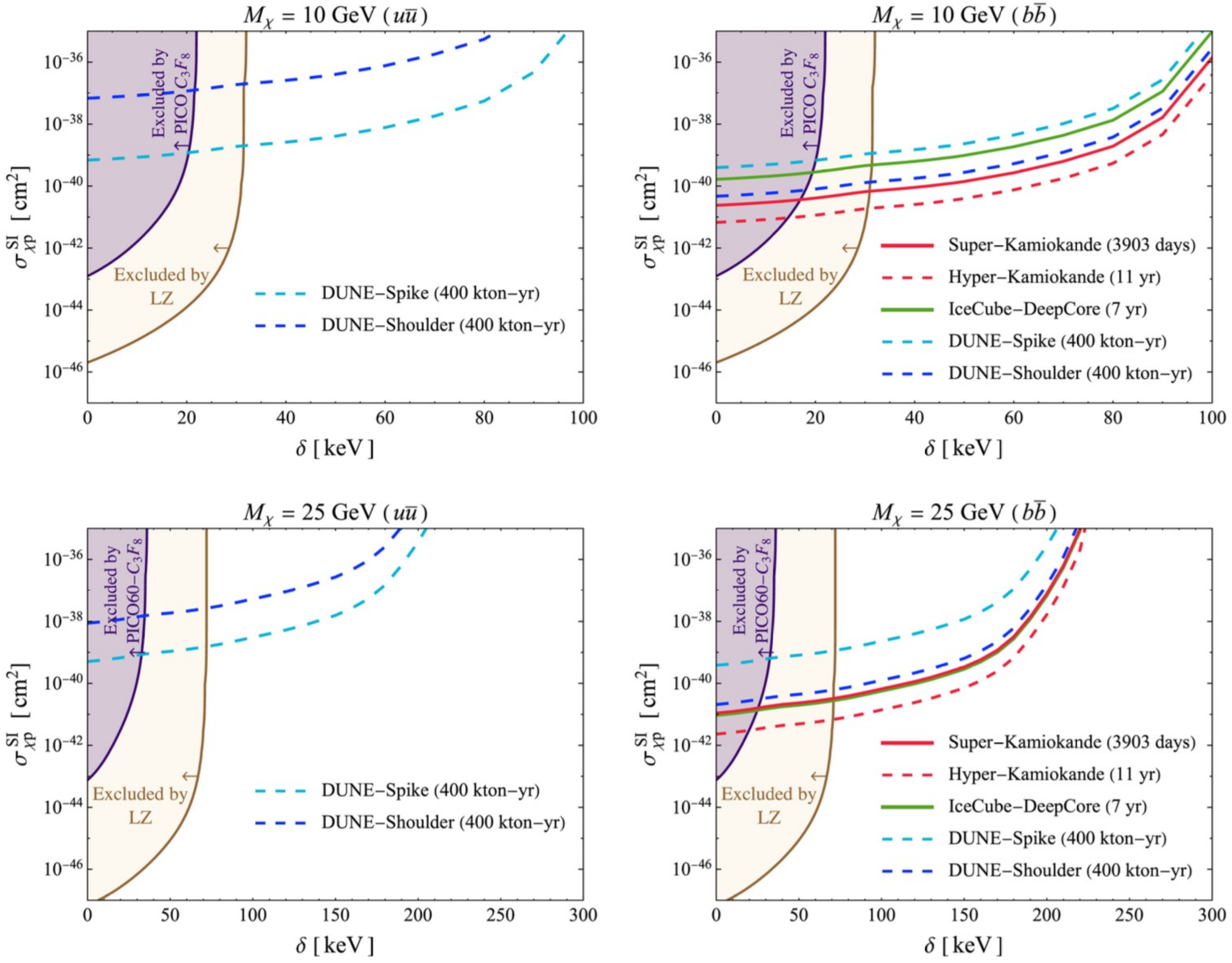
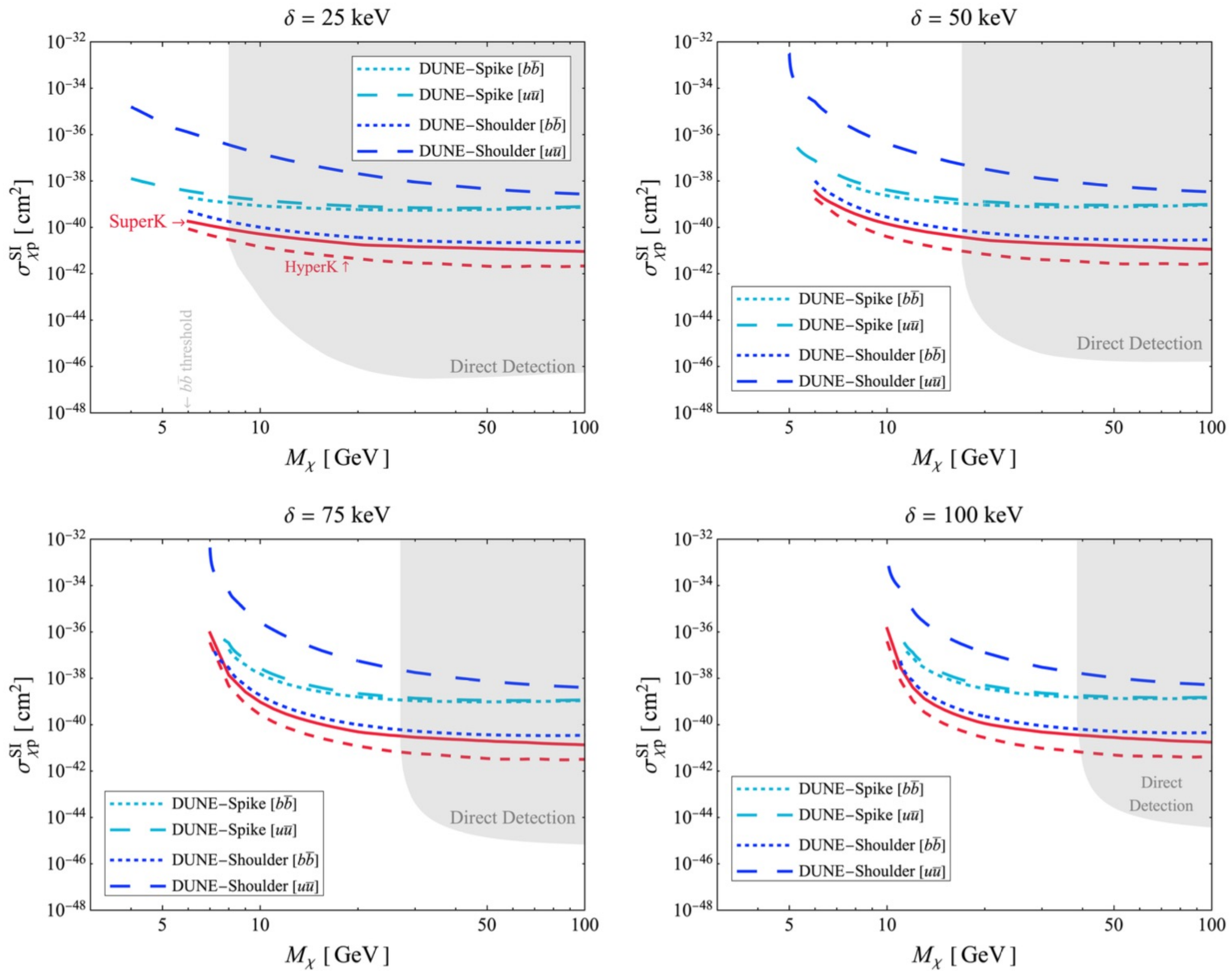


**Figure 4**: The flavor conversion probabilities, averaged over the position of the Sun over a period of one year at the proposed location of DUNE far-detector, are shown for neutrinos (left) and antineutrinos (right) as functions of energy.

# The Exclusion Limits from Direct-detection Experiments and Projected Limits for DUNE and Super(Hyper)K



# Neutrino Experiments Exclusion Parameter Space



We use WimPyDD to calculate event rates for direct detection of elastic and inelastic dark matter (I. Jeong et. al. Comput. Phys. Commun. 276 (2022))

We use NuWro to simulate neutrino interactions with Argone

|  |  | $\nu_e$ |  |  | $\nu_\mu$ |  |  |
|---|---|---|---|---|---|---|---|
|  |  | $E_\nu$ | $\theta_\nu$ | Ref. | $E_\nu$ | $\theta_\nu$ | Ref. |
| Spike (QEL) | SuperK | ✓ | ✗ | [25, 26] | ✓ | ✗ | – |
|  | IceCube | ✗ | ✗ | – | ✗ | ✗ | – |
|  | DUNE | ✓ | ✓ | [25, 26] | ✓ | ✓ | [26],[28]* |
| Shoulder (DIS) | SuperK | ✓ | ✓ | [8]* # | ✓ | ✓ | [6–8]* |
|  | IceCube | ✓ | ✗ | – | ✓ | ✓ | [11, 12]* |
|  | DUNE | ✓ | ✓ | [29] | ✓ | ✓ | This Work |

**Table 1**: We provide a bird's eye view of the capabilities of the neutrino experiments to detect the spike and shoulder neutrinos from the dark matter annihilation in the Sun. The spike neutrinos undergo quasi-elastic like (QEL) scattering and the shoulder neutrinos mostly undergo deep-inelastic scattering (DIS). We show the ability (inability) of the detectors to *reasonably* reconstruct the incident neutrino energy and direction with a ✓ (✗). Note that for the shoulder, sensitivity is same for neutrinos

# Conclusion

- Annihilation of the captured dark matter in the Sun results in a novel neutrino flux on Earth
- In case of hadrophilic dark matter, i.e. dark matter couples to both heavy-quarks and light-quarks in DM annihilation in the Sun, and in this case

Neutrino spectrum has two components: a spike at ~236 MeV from kaon decay-at-rest and a broad-spectrum shoulder from prompt decays of mesons

- For inelastic dark matter, we find the parameter space which cannot be probed with direct detection experiments, but can be probed with neutrino experiments

- We find that current limits on elastic DM from SuperK and IceCube from upward-going muons, when converted to inelastic DM case, rule out a large part of the parameter space for inelastic dark matter
- We predict the parameter space for inelastic DM that will be probed by HyperK
- For DM coupling to light quarks, only the spike events are detectable and DUNE excels due to its better performance at low energy and will probe currently unexplored parts of the inelastic DM parameter space.
- We evaluate the sensitivity of DUNE from contained GeV-scale tracks originating from the shoulder muon neutrinos