Simultaneous detection of boosted dark matter and neutrinos from the semi-annihilation

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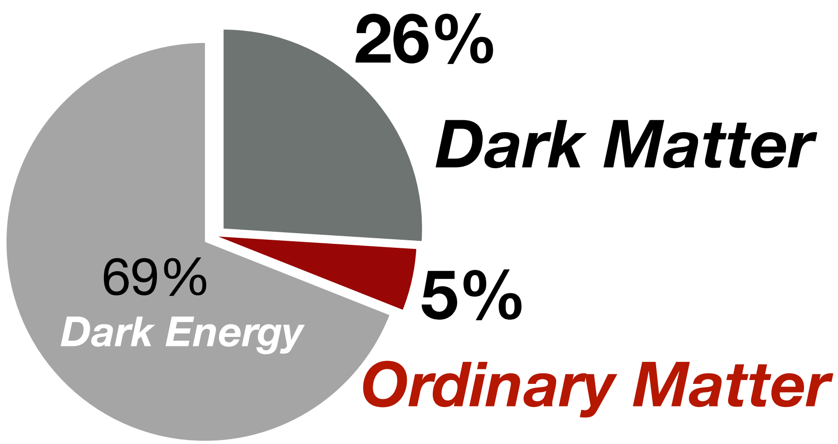
MA, T. Toma, JCAP02 (2024), 033

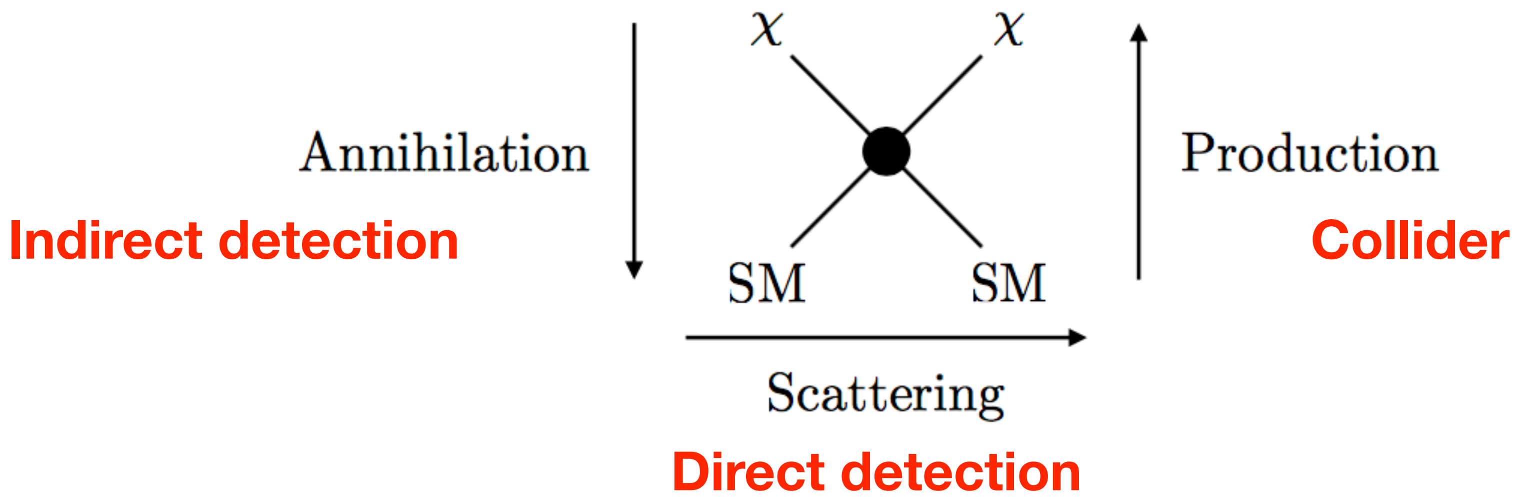
The Dark Side of the Universe
SEPTEMBER 8 - 14, 2024

Introduction

- **Dark mater**



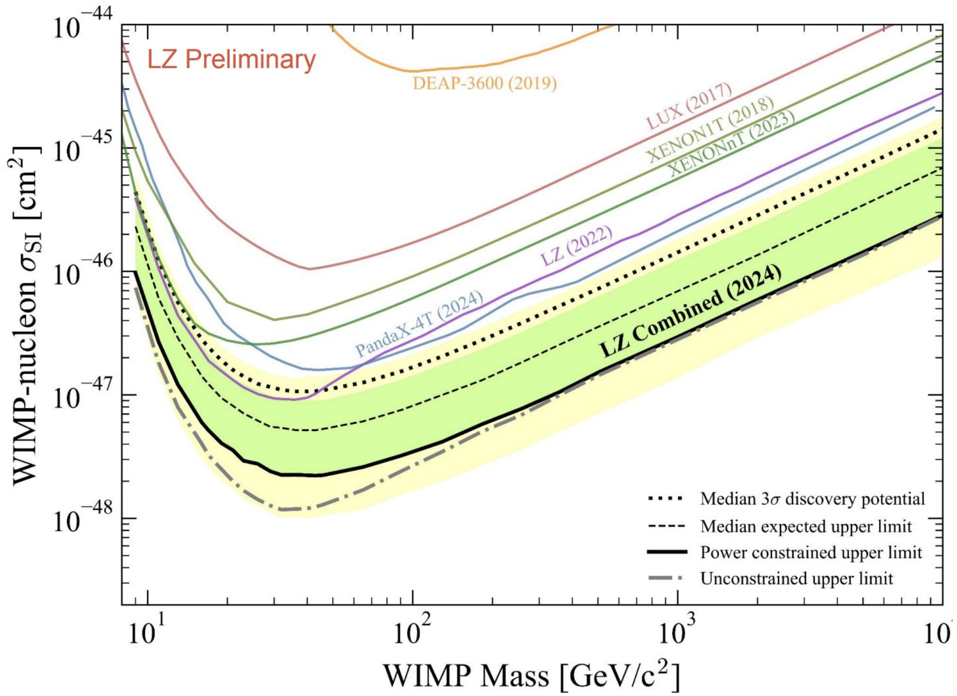
- **DM detections**



Interactions between SM and DM sectors are still unknown.

Introduction

❖ Direct detection



- Severe constraints on the WIMP-nucleon cross section

- Thermal dark matter scenarios :

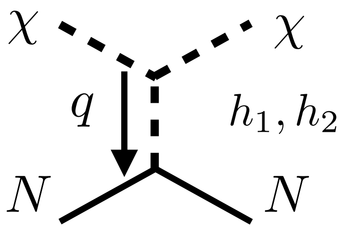
  Some mechanism is required to suppress scatterings between DM and nucleons.

Introduction

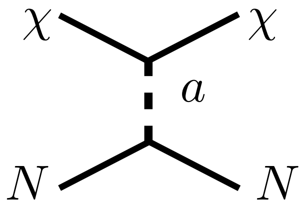
❖ Scattering suppressions:

- **Pseudo-Nambu-Goldstone DM** — Gross, Lebedev, Toma, PRL(2017)
  - SM + $S = (s + i\chi)/\sqrt{2}$
  - The system is invariant under a global U(1), $S \to e^{i\alpha} S$,
    which is broken softly by $\frac{\mu_S'^2}{4} S^2 + h.c.$
  - CP symmetry → χ is DM
  - the direct detection scattering amplitude :

$$i\mathcal{M}_{\chi q \to \chi q} \sim \frac{\sin\theta\cos\theta(m_{h_1}^2 - m_{h_2}^2)}{v_s m_{h_1}^2 m_{h_2}^2} q^2 \underset{q^2 \to 0}{\longrightarrow} 0$$



- **Pseudo-scalar interacting fermionic DM**



The scattering amplitude is suppressed by a small momentum transfer, while the annihilations into SM particles are unsuppressed.

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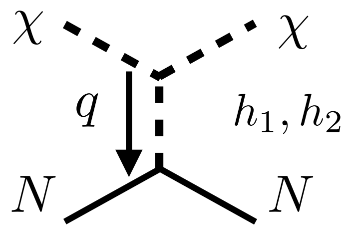

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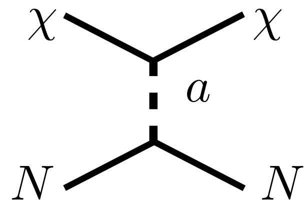

- **The scattering amplitude is suppressed by a small momentum transfer, while the annihilations into SM particles are unsuppressed.**
- One might think that it would be extremely difficult to observe such DM in usual DD experiments.

But we still have chance.

Introduction

- **Boosted dark matter**
  - Boosted mechanism :
    - Scattering with high energy cosmic rays
    - Multi-component dark matter models

      Conversion : $\chi_2\chi_2 \to \chi_1\chi_1$ Semi-annihilation : $\chi_2\chi_3 \to \chi_1\,\mathrm{SM}$

    - Semi-annihilation : $\chi\chi \to \chi\,\mathrm{SM}$

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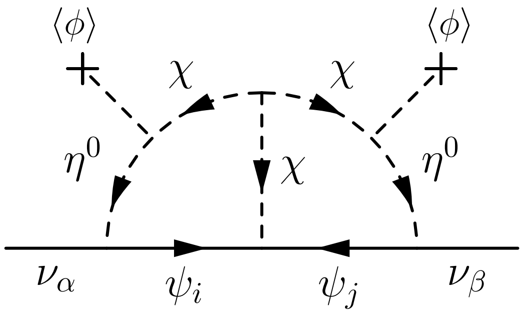
    - Semi-annihilation : $\chi\chi \to \chi\,\mathrm{SM}$

      e.g.) Radiative seesaw model with Z3 sym.

      - SM + Dirac fermions + Inert scalars

	ψ_i	η	χ
$SU(2)$	**1**	**2**	**1**
$U(1)_Y$	0	1/2	0
$\mathbb{Z}_3$	1	1	1
L number	1/3	−2/3	−2/3

Ma, PLB662 (2008)



      - L is softly broken in the scalar potential.
      - Semi-annihilation $\psi\psi \to \nu\overline{\psi}$

MA, Toma, JCAP09 (2014)

Introduction

- We focus on the semi-annihilation :

$$\chi\chi \to \nu\overline{\chi}$$

Simultaneous detection of the BDM and neutrino

at large volume neutrino detectors.

- Super-Kamiokande/Hyper-Kamiokande, IceCube/DeepCore, DUNE

Setup

Setup

- **Semi-annihilation process :** $\chi\chi \to \nu\overline{\chi}$
  - The dark matter must be a Dirac fermion.
  - Assuming non-relativistic DM in the initial state, energies are fixed at

$$E_\nu = 3m_\chi/4, \quad E_\chi = 5m_\chi/4$$

Distinctive signals of the semi-annihilation process

Setup

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Distinctive signals of the semi-annihilation process

  - The CP conjugate process $\overline{\chi\chi} \to \overline{\nu}\chi$ is also allowed.
    But we concentrate only on $\chi\chi \to \nu\overline{\chi}$.

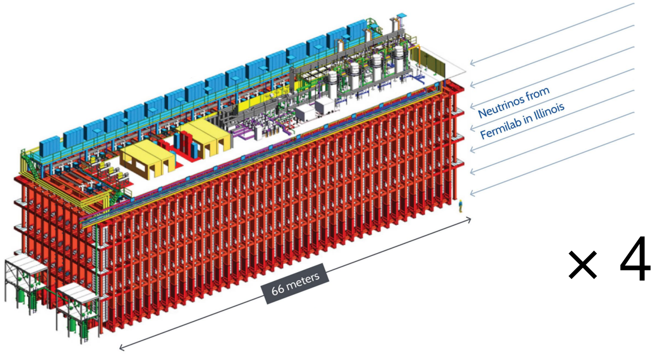
  - The corresponding speed of the BDM : $v_\chi = 0.6$

    Detection at SK/HK and IceCube/DeepCore is difficult.

  - We investigate by using DUNE detector.

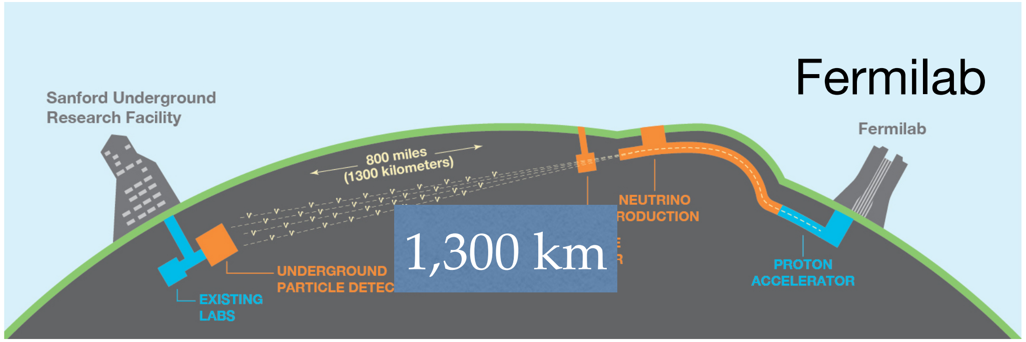
DUNE (Deep Underground Neutrino Experiment)

❖ **DUNE far detector**



× 4

DUNE (Deep Underground Neutrino Experiment)



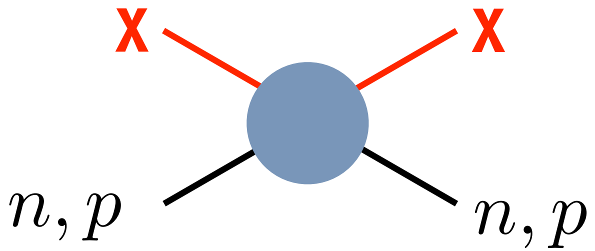
- Liquid Argon Time Projection Chamber detector
- Four modules with a fiducial volume of 10 kilotons each
- Two modules: Physics in 2028 or early 2029

❖ **Our setup:**
- 40 kton liquid argon fiducial volume
- 10 years exposure

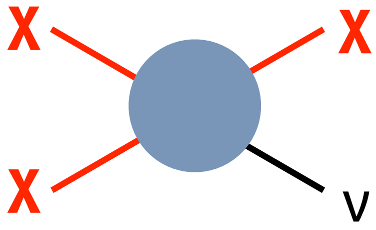
Signal from the Sun

- We consider the BDM and neutrino from the semi-annihilation of captured DM in the Sun.

  - **in the Sun**



Capture



Semi-annihilation

- The semi-annihilation and the capture process easily equilibrate when $4 \text{ GeV} < m_\chi$.

Garani, Palomares-Ruiz, JCAP05 (2017)

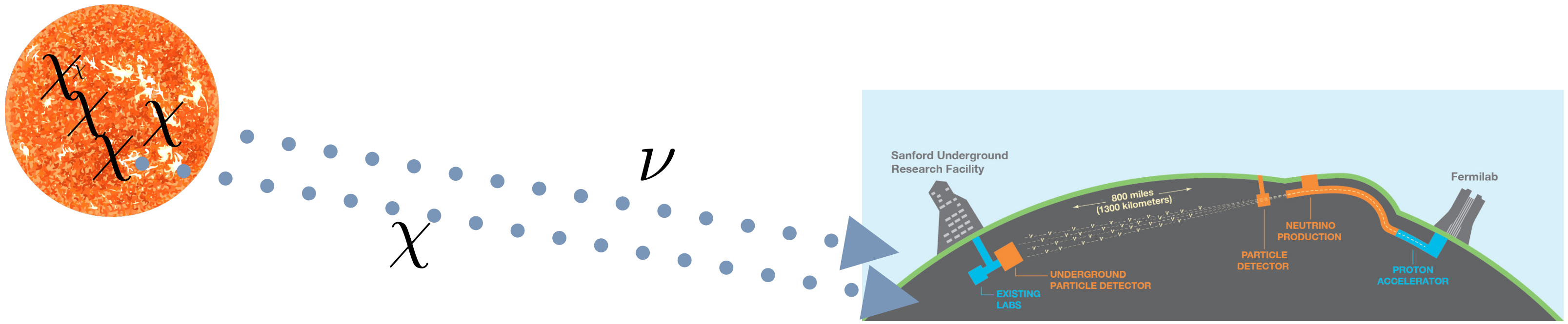
DM annihilation rate : $\Gamma_{\rm ann} = C_\odot/2$ $C_\odot$: Capture rate

- **We concentrate on the dark matter mass range:**

$$4 \text{ GeV} \le m_\chi \le 100 \text{ GeV}$$

Signal from the Sun

❖ **The BDM/neutrino flux :**



$$\frac{d^2\Phi_\chi}{dE_\chi d\Omega} = \frac{\Gamma_{\rm ann}}{4\pi d_\odot^2}\delta\left(E_\chi - \frac{5}{4}m_\chi\right)\delta\left(\Omega - \Omega_\odot\right)$$

$$\frac{d^2\Phi_\nu}{dE_\nu d\Omega} = \frac{\Gamma_{\rm ann}}{4\pi d_\odot^2}\delta\left(E_\nu - \frac{3}{4}m_\chi\right)\delta\left(\Omega - \Omega_\odot\right)$$

$d_\odot$: the distance between Earth and the Sun

$\Omega_\odot$: the Sun's solid angle

$\Gamma_{\rm ann} = C_\odot/2$

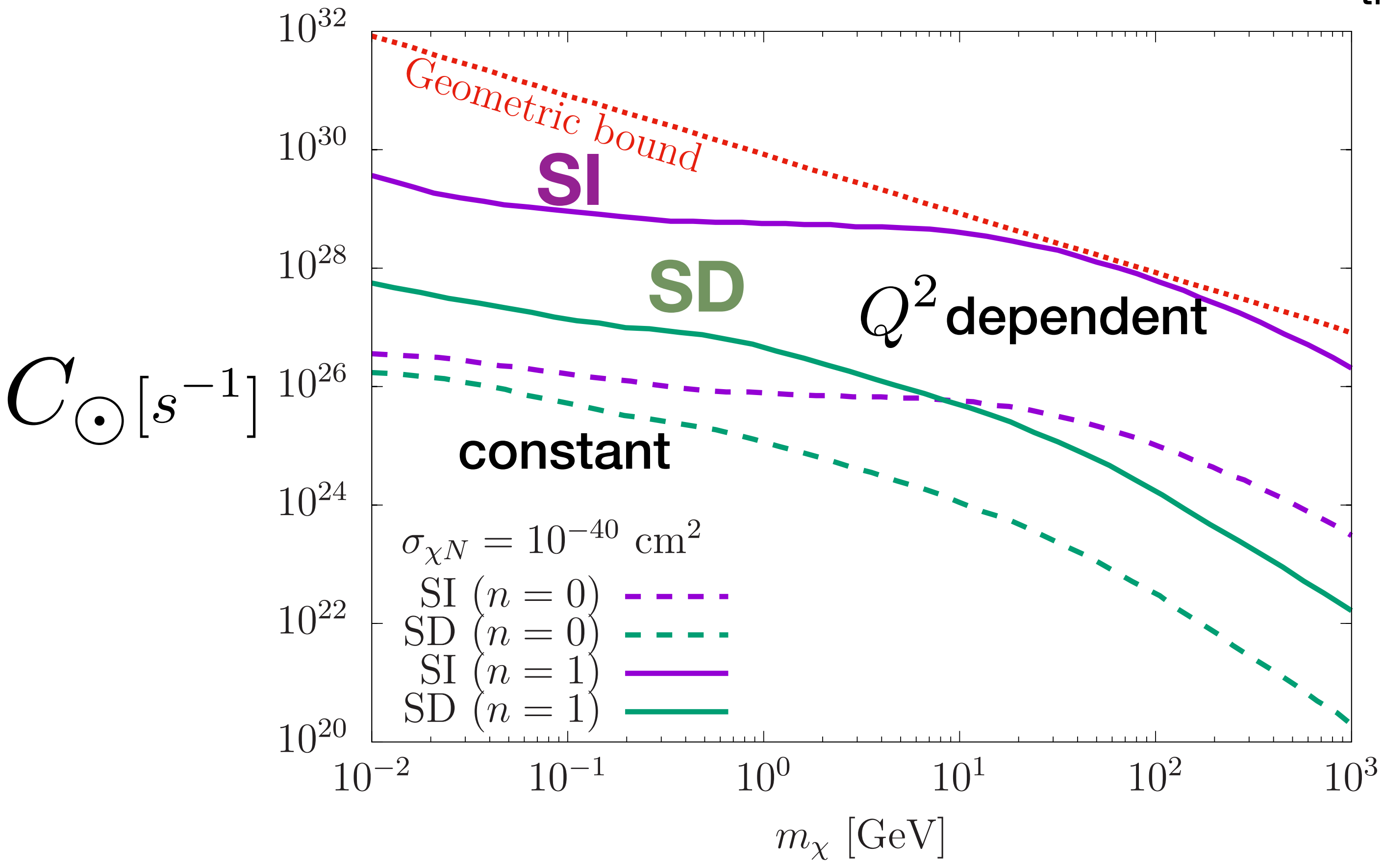
Dark matter capture rate in the Sun

Capture rate for constant and Q^2 dependent cases

Garani, Palomares-Ruiz, JCAP05 (2017)

the Mandelstam variable

$$t = -Q^2$$



reference value : $\sigma_{\chi N} = 10^{-40}\ \mathrm{cm}^2$

Signals from semi-annihilations

Boosted dark matter event

$$\chi\chi \to \nu\overline{\chi}$$

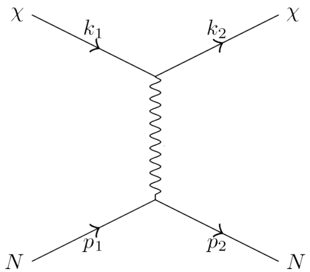
- the number of the BDM signal events at DUNE :

$$N_\chi = N_N T \, \frac{C_\odot}{8\pi d_\odot^2} \sigma_{\chi N} \Big|_{E_\chi = 5m_\chi/4}$$

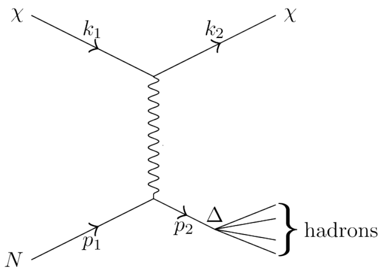
  - the number of nucleons in liquid argon target : $N_N = 2.41 \times 10^{34}$
  - the period of the experiment : $T = 10$ years

- the relevant processes for $\chi N \to \chi N$

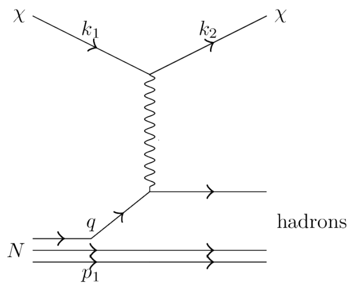
Quasi-Elastic



Resonant



Deep Inelastic



  - The momentum transfer : $Q^2 \lesssim (1.4 \text{ GeV})^2$
  - Quasi-elastic scattering is dominant over the other processes.

Boosted dark matter event

- We parametrize the differential scattering cross section:

$$\frac{d\sigma_{\chi N}}{dQ^2} = \frac{\sigma_0 s}{4m_N^2|\boldsymbol{p}_\chi|^2}\left(\frac{Q^2}{m_N^2 v_0^2}\right)^n |F(Q^2)|^2$$

σ_0 : reference cross section, s : the Mandelstam variable,

$|\boldsymbol{p}_\chi| = 3m_\chi/4$ $v_0 = 220\ \mathrm{km/s}$

Form factor correction: $F(Q^2) = \frac{F(0)}{(1+Q^2/(0.99\ \mathrm{GeV})^2)^2}$

The index *n* represents the order of momentum transfer dependence.

- The total scattering cross section can be obtained by integrating in the range $0 < Q^2 < \lambda(s, m_\chi^2, m_N^2)/s$

$$\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz$$

Neutrino event

$$\chi\chi \to \nu\overline{\chi}$$

- The number of neutrino signal events at DUNE :

$$N_\nu^{\mathrm{CC}} = \frac{N_N T}{3} \sum_\alpha \frac{C_\odot}{8\pi d_\odot^2} \sigma_{\nu_\alpha N}^{\mathrm{CC}} \Big|_{E_{\nu_\alpha} = 3m_\chi/4}$$

  - the neutrinos energy is Ev > 1 GeV.
  - CC deep-inelastic scattering (DIS) interaction is dominant.

$$\nu + N \to \ell + jet$$

Neutrino event

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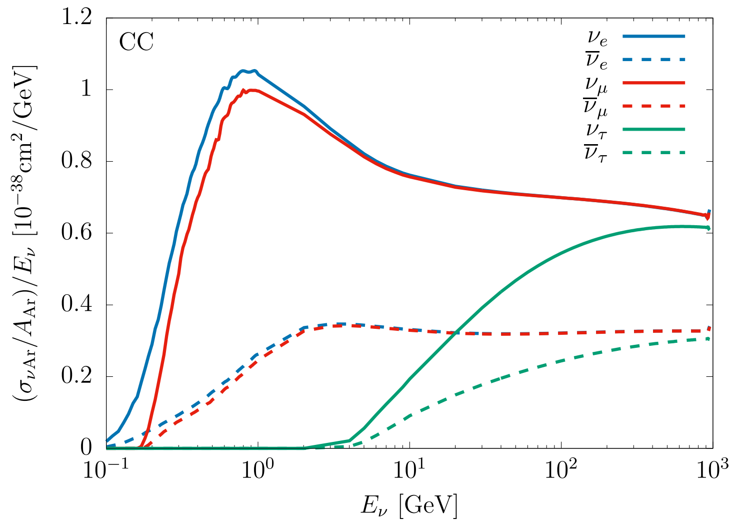


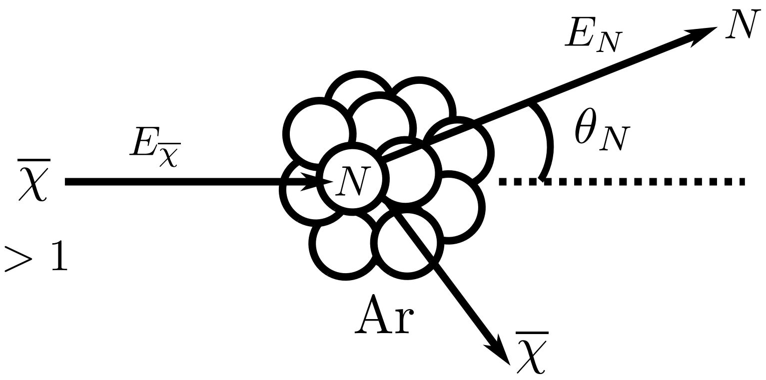
- Evaluation of the cross section :
  - We use the neutrino event generator GINIE to evaluate the cross section.

Boosted dark matter event reconstruction

- **Energy reconstruction**

$$E_\chi = m_N \frac{1 + \alpha \cos\theta_N \sqrt{1 - \beta + \alpha^2 \beta \cos^2\theta_N}}{-1 + \alpha^2 \cos^2\theta_N}$$

$\alpha = \sqrt{(E_N + m_N)/(E_N - m_N)} > 1$ $\beta = m_\chi^2/m_N^2 > 1$



- **the detector information**

DUNE collaboration, arXiv:1512.06148

	Detector threshold	Energy/momentum resolution	Angular resolution
$\mu^\pm$	30 MeV	5 %	1°
$\pi^\pm$	100 MeV	5 %	1°
$e^\pm/\gamma$	30 MeV	$2 + 15/\sqrt{E/\text{GeV}}$ %	1°
p	50 MeV	$\lvert\boldsymbol{p}\rvert < 400$ MeV: 10 % $\lvert\boldsymbol{p}\rvert > 400$ MeV: $5 + 30/\sqrt{E/\text{GeV}}$ %	5°
n	50 MeV	$40/\sqrt{E/\text{GeV}}$ %	5°

Boosted dark matter event reconstruction

❖ Energy reconstruction

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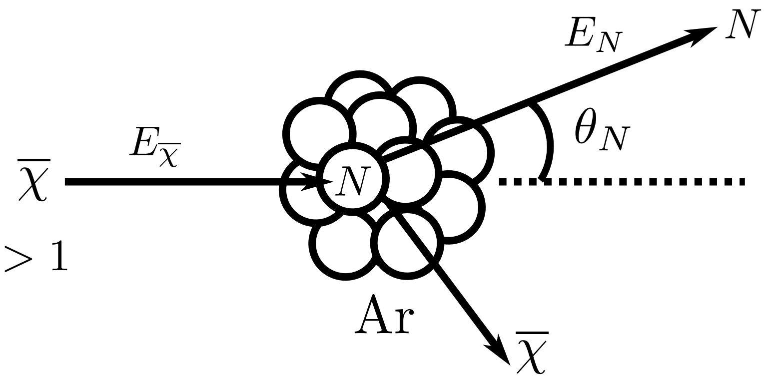

❖ Observed event

- The events below the threshold are discarded.
- The reconstructed BDM energy is smeared by the nucleons in the final state.
- We regard the event is observed only if the reconstructed energy after smearing is within the 2σ energy resolution.

❖ the detector information

DUNE collaboration, arXiv:1512.06148

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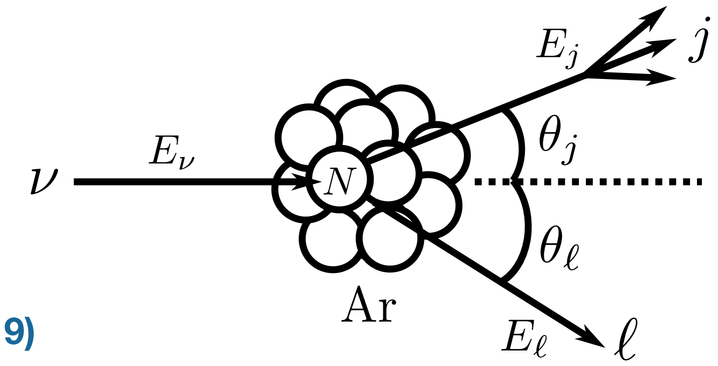
Neutrino event reconstruction

❖ **Energy reconstruction**

$$E_\nu = \frac{1}{2}\frac{\sin\theta_j\,(1+\cos\theta_\ell)+\sin\theta_\ell\,(1+\cos\theta_j)}{\sin\theta_j}E_\ell$$



Rott et.al., JCAP 07 (2019)

- The angles are expected to be very small.
- The reconstructed neutrino energy is smeared with the energy resolution.

❖ **the detector information**

DUNE collaboration, arXiv:1512.06148

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Benchmark point

Benchmark Point

Q^2 dependent case

DUNE 40kt 10years

	model	m_χ [GeV]	σ_0 [cm^2]	# of χ events	# of ν events
BP1	SD ($n = 1$)	6	1.2×10^{-42}	$N^{\rm NC}_{{\rm atm}\,\nu} = 98/994$ $N_\chi = 113/372$	$N^{\rm CC}_{{\rm atm}\,\nu} = 54/2070$ $N^{\rm CC}_\nu = 18/47$

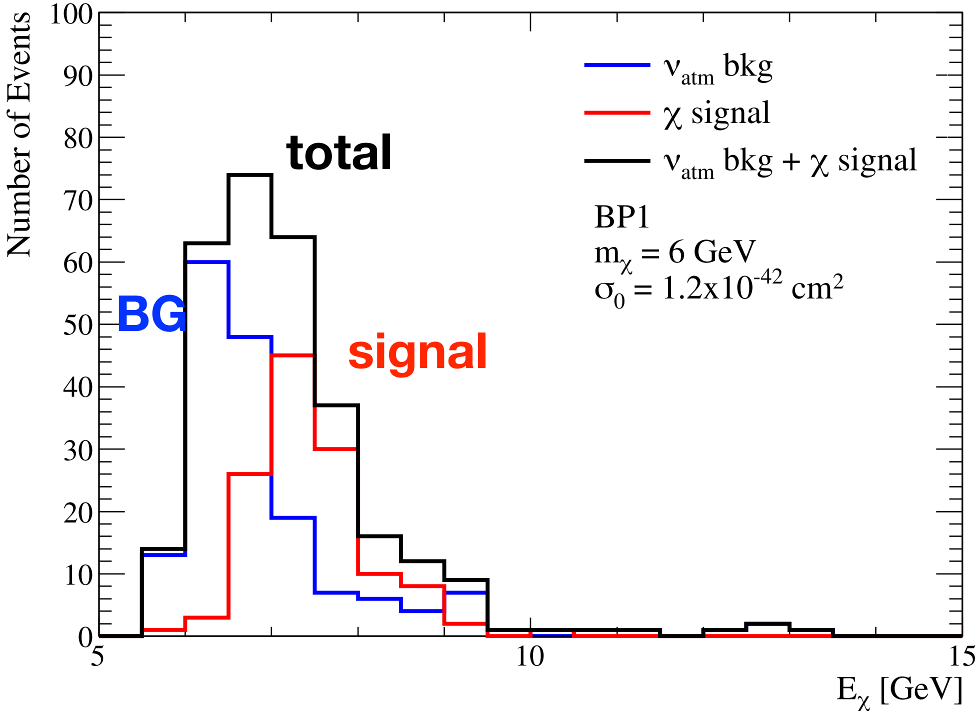
observed / expected

$$\frac{d\sigma_{\chi N}}{dQ^2} = \frac{\sigma_0 s}{4m_N^2|\boldsymbol{p}_\chi|^2}\left(\frac{Q^2}{m_N^2 v_0^2}\right)^n |F(Q^2)|^2$$

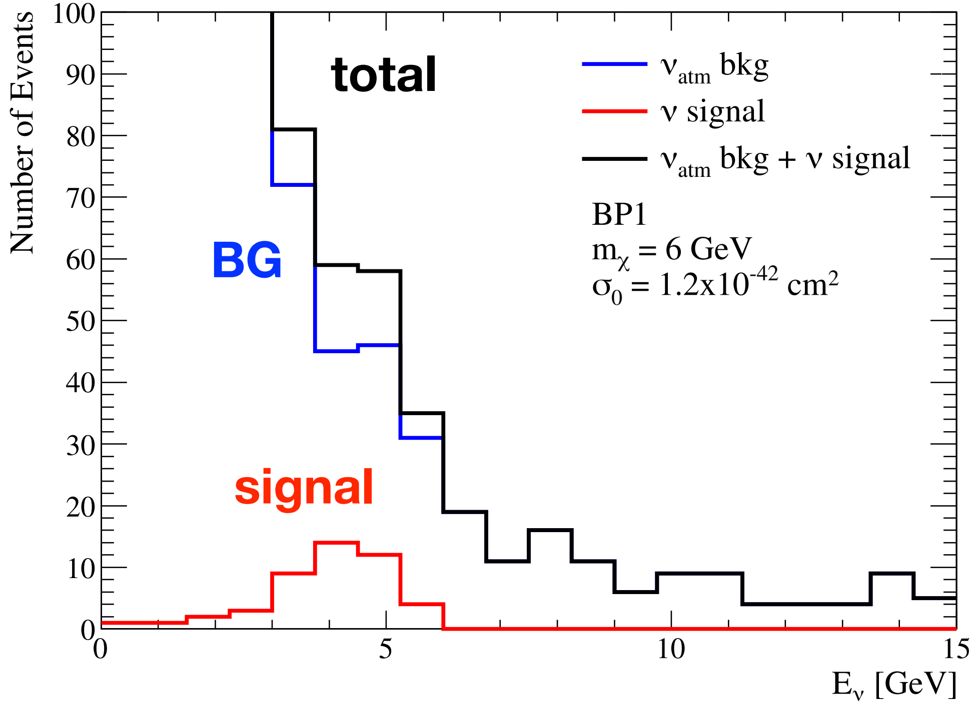
Event reconstruction

- Benchmark Point
  - Q^2 dependent case

Reconstructed **BDM** energy distribution



Reconstructed **neutrino** energy distribution



The true energies : $E_\chi = 7.5$ GeV $\quad E_\nu = 4.5$ GeV

- **These true energies are reconstructed well with a dispersion.**

Parameter search

- We search for the parameter space testable by DUNE in (m_χ, σ_0) plane.

  - the signal significance :

$$\mathcal{S}_\nu = \frac{N_\nu^{\rm CC}}{\sqrt{N_{{\rm atm}\,\nu}^{\rm CC} + N_\nu^{\rm CC} + \delta_\nu^2}}$$

$$\mathcal{S}_\chi = \frac{N_\chi}{\sqrt{N_{{\rm atm}\,\nu}^{\rm NC} + N_\chi + \delta_\chi^2}}$$

  - the systematic uncertainties :

$$\delta_\nu = \left(N_{{\rm atm}\,\nu}^{\rm CC} + N_\nu^{\rm CC}\right)\epsilon_\nu$$

$$\delta_\chi = \left(N_{{\rm atm}\,\nu}^{\rm NC} + N_\chi\right)\epsilon_\chi$$

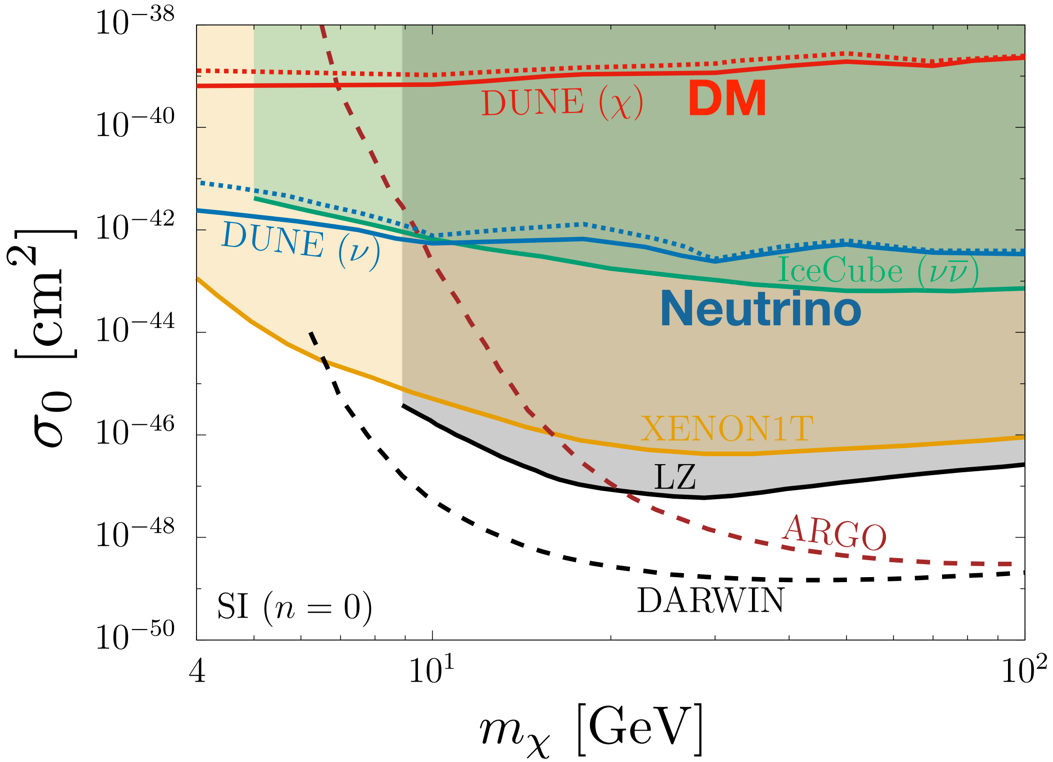
  - We take the two values: $\epsilon_\nu = \epsilon_\chi = 0,\ 0.2$ Kelly et al, JHEP 05 (2022)

Parameter space testable by DUNE

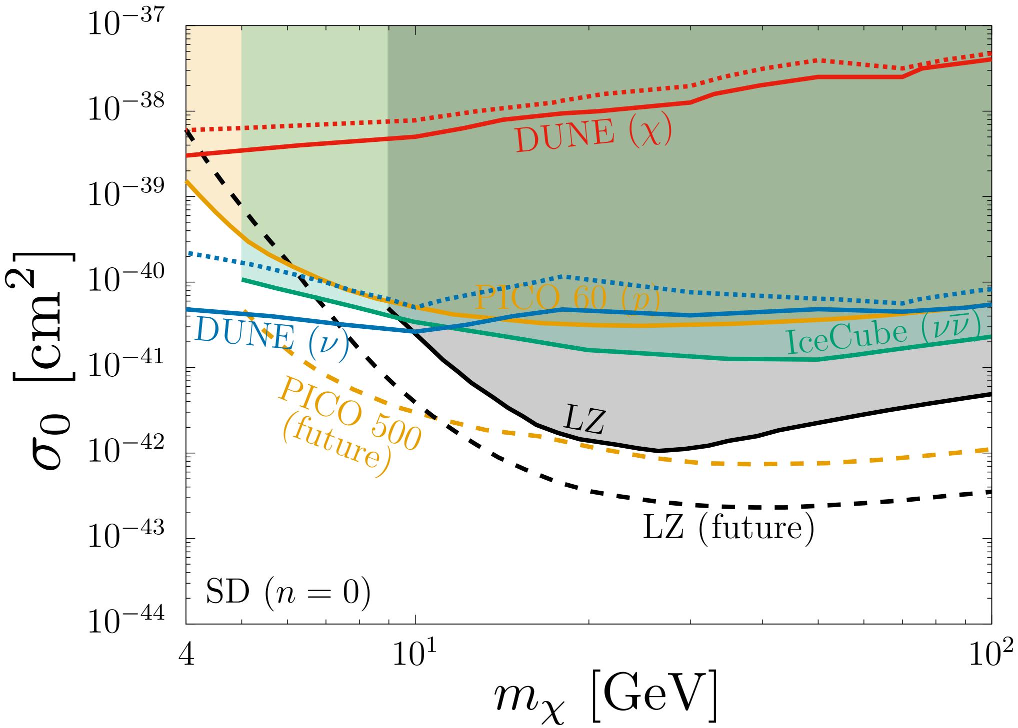
- constant case (n=0)

  - **DUNE sensitivity at 2σ**

SI



SD

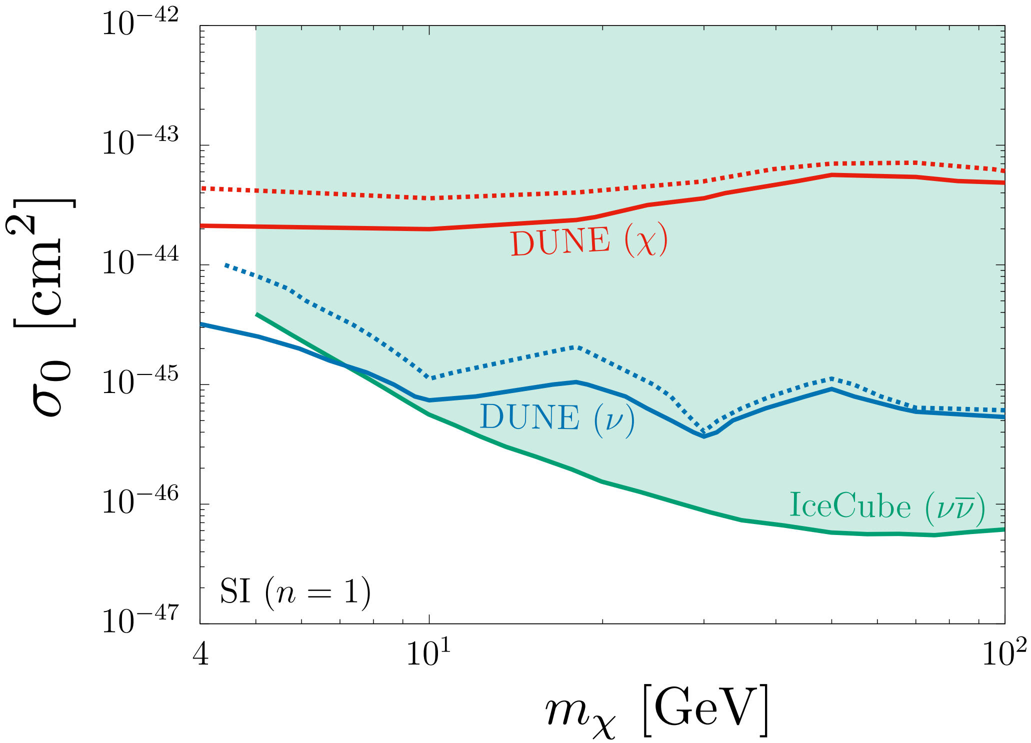


- All the parameter space for the DM which can be searched by DUNE is completely excluded as expected.

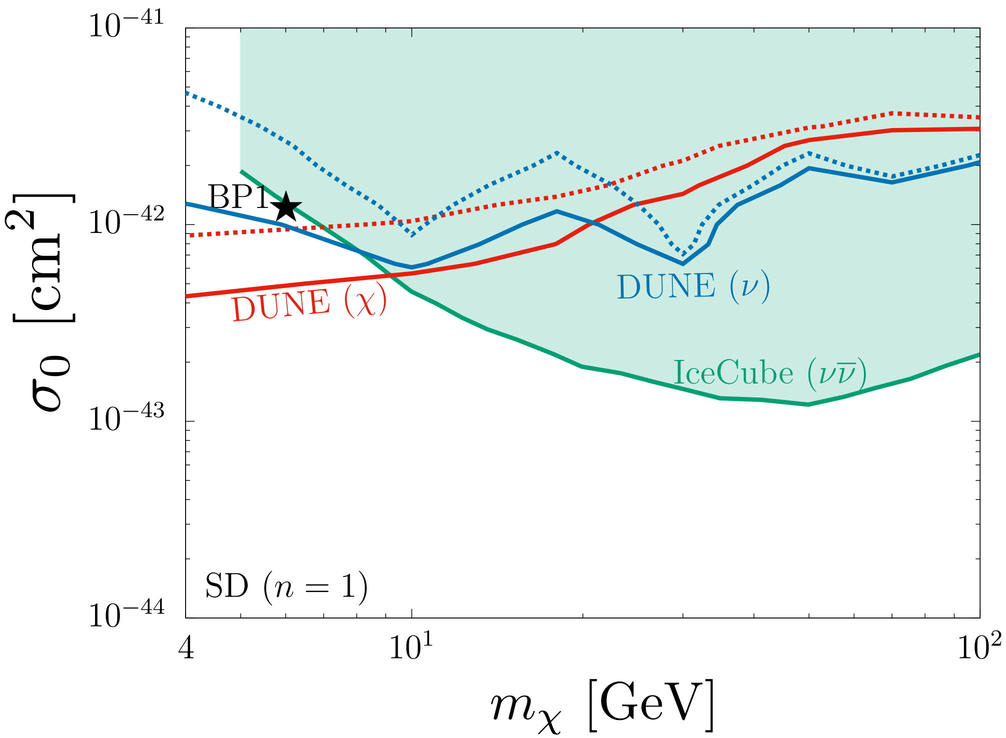
Parameter space testable by DUNE

❖ Q² dependent case (n=1)

SI



SD

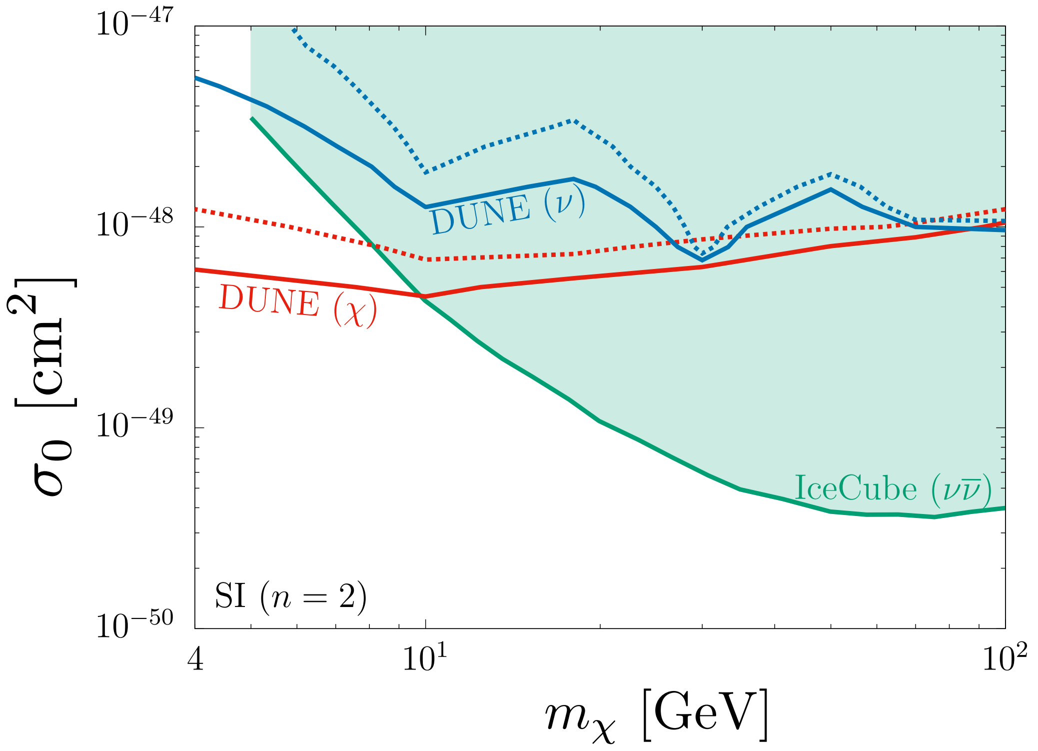


- SD: DUNE can test both signals simultaneously for $m_\chi \lesssim 8$ GeV.

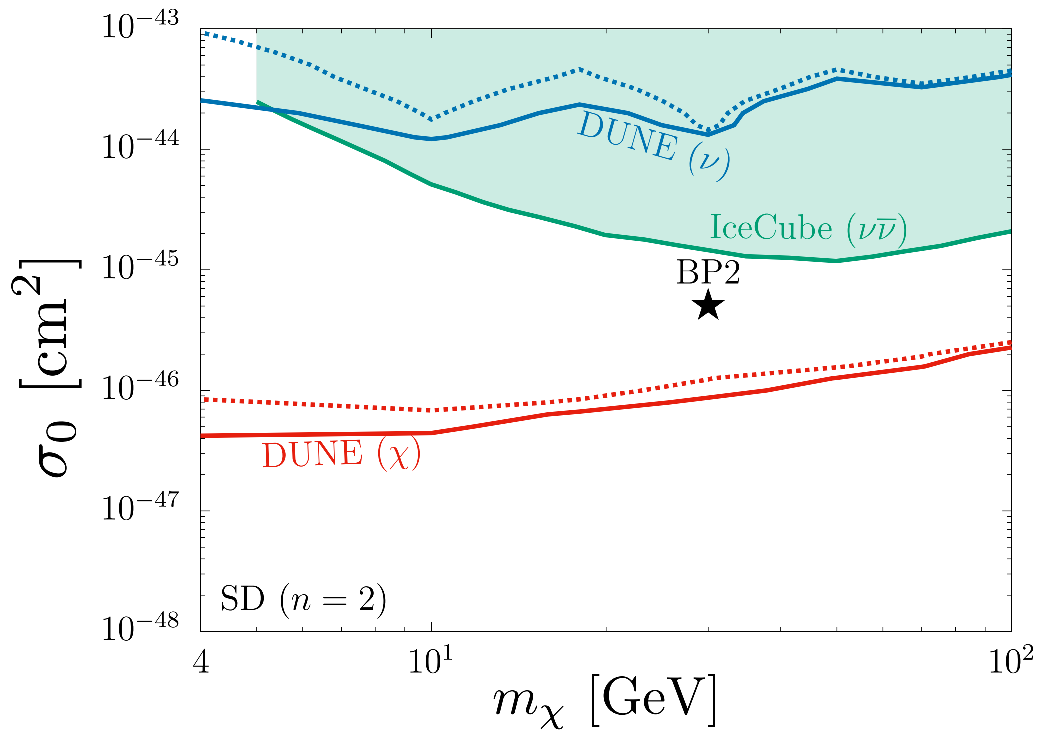
Parameter space testable by DUNE

❖ Q^4 dependent cases (n=2)

SI



SD



Summary

- No dark matter signal in direct detection experiments may indicate that the scattering cross section is suppressed by a small momentum transfer.

- One can explore such DM scenarios if the DM is boosted.

- We considered the dark matter semi-annihilation process

$$\chi\chi \to \nu\overline{\chi}$$

  and search for simultaneous detection of boosted dark matter and neutrino from the Sun.

- We found that the simultaneous detection at DUNE or a combination of DUNE and the other neutrino experiments is possible in some parameter space.

Backup

Models

- Q^2 **dependent models :**

$$\mathcal{L}_{SP} = -y_\chi^S \varphi \overline{\chi}\chi - y_q^P \varphi \overline{q}\gamma_5 q,$$

$$\mathcal{L}_{PS} = -y_\chi^P \varphi \overline{\chi}\gamma_5\chi - y_q^S \varphi \overline{q} q,$$

$$\mathcal{L}_{\rm ana} = a_\chi \overline{\chi}\gamma_\mu\gamma_5\partial_\nu\chi F^{\mu\nu} - eA_\mu \overline{q}\gamma^\mu q,$$

- Q^4 **dependent model :**

$$\mathcal{L}_{PP} = -y_\chi^P \varphi \overline{\chi}\gamma_5\chi - y_q^P \varphi \overline{q}\gamma_5 q$$

BP1 and BP2

Q^2 dependent case

	model	m_χ [GeV]	σ_0 [cm^2]	# of ν events	# of χ events
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Q^4 dependent case

	model	m_χ [GeV]	σ_0 [cm^2]	# of ν events	# of χ events
BP2	SD $(n = 2)$	30	5.0×10^{-46}	$N^{\rm CC}_{{\rm atm}\,\nu} = 1/2070$ $N^{\rm CC}_{\nu} = 0/0$	$N^{\rm NC}_{{\rm atm}\,\nu} = 18/994$ $N_\chi = 405/2117$