Signals of boosted dark matter and neutrinos from the semi-annihilation

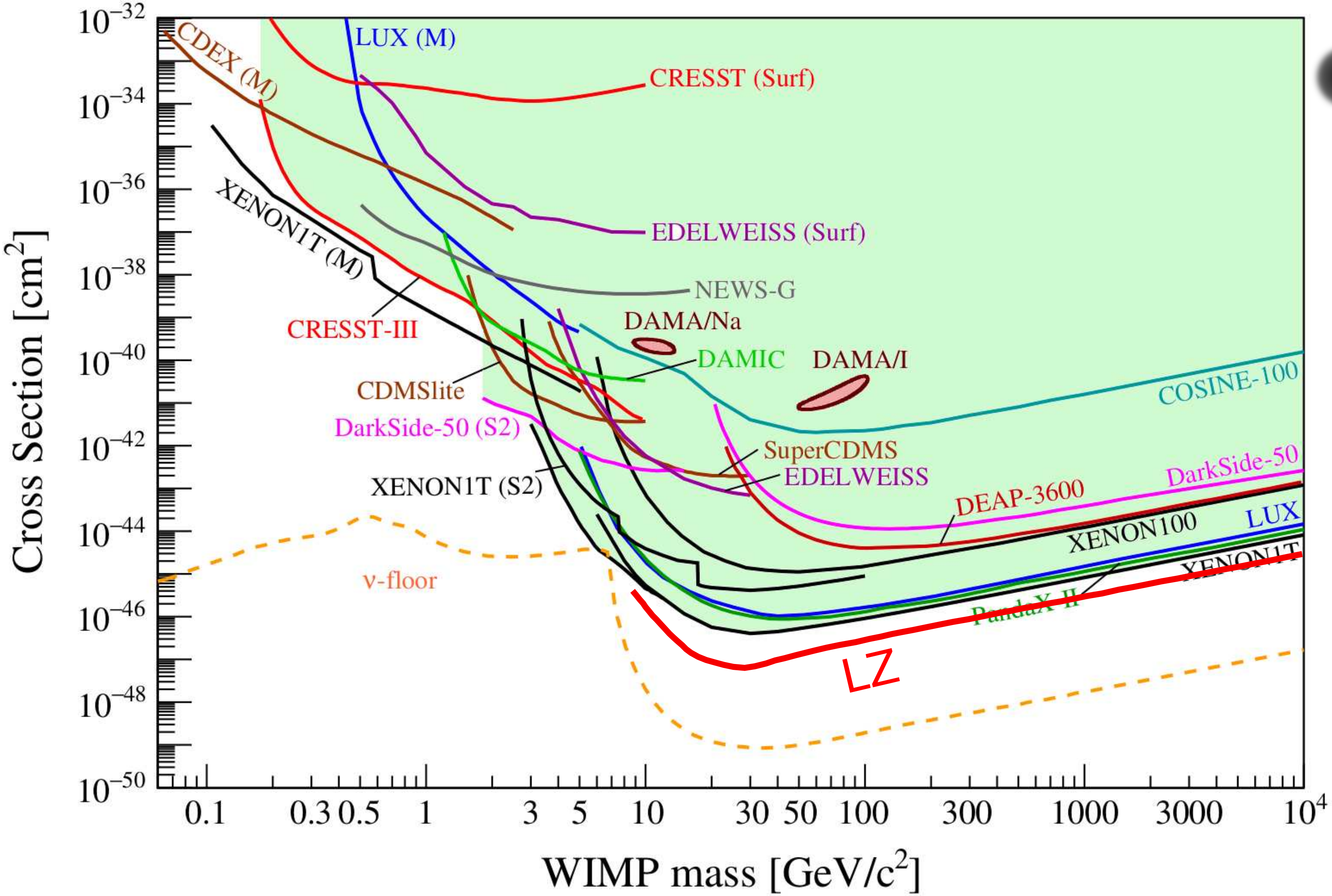
Takashi Toma

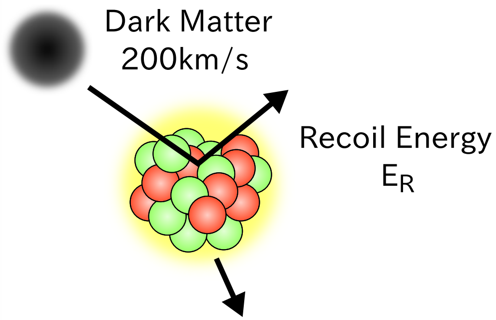
What is dark matter? @ YITP

Based on: Phys.Rev.D 105 (2022) 4, 043007,
JCAP 02 (2024) 033

Collaborator: Mayumi Aoki

Status of direct detection experiments





arXiv:2104.07634
LZ arXiv:2207.03764

- LZ gives the strongest bound above 10 GeV DM mass at present.

Wayout

- v_χ dependent cross section ($v_\chi \sim 10^{-3}$)

  Ex.1 pNG DM ($i\mathcal{M} \propto v_\chi^2$)

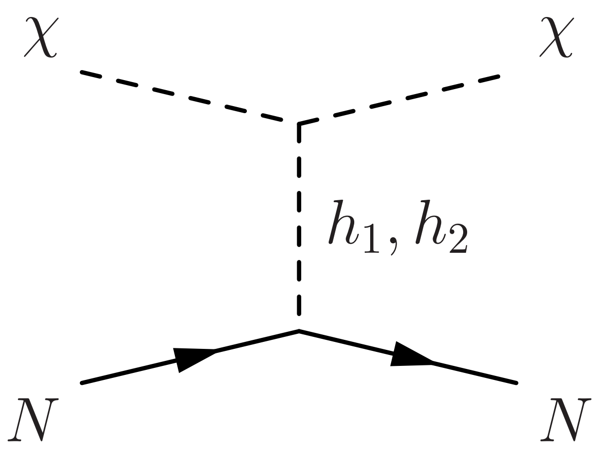
  C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

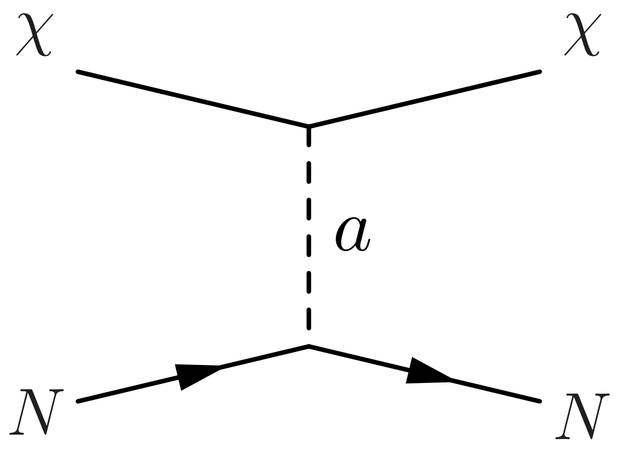
  Ex.2 Fermionic DM with Pseudo-scalar int.

  $$\mathcal{L} = a\overline{\chi}\gamma_5\chi$$

  T. Abe, M. Fujiwara, J. Hisano, JHEP (2019) [arXiv:1810.01039]

- Challenging to explore with standard way of direct detection experiments





$\Rightarrow$ These DM could be searched if boosted.

Semi-annihilation: $\chi\chi \to \overline{\chi}\nu$

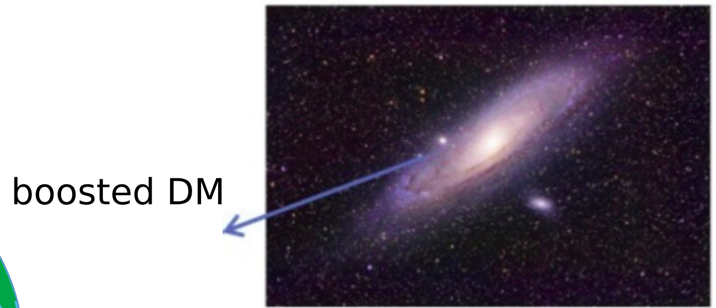
New signal of DM

Mechanisms to boost DM

- Semi-annihilations $\chi\chi \to \overline{\chi}\phi$ $(v_\chi = \mathcal{O}(0.1-1))$
  $\Rightarrow$ Simple and small uncertainties

Other processes to boost DM

- SIMP: $\chi\chi\chi \to \chi\overline{\chi}$
- Decay or annihilations of heavier particles (non-minimal dark sector)
  $\chi_2\chi_2 \to \chi_1\chi_1$ $(m_{\chi_2} \gg m_{\chi_1})$
- Collision with high energy cosmic-rays

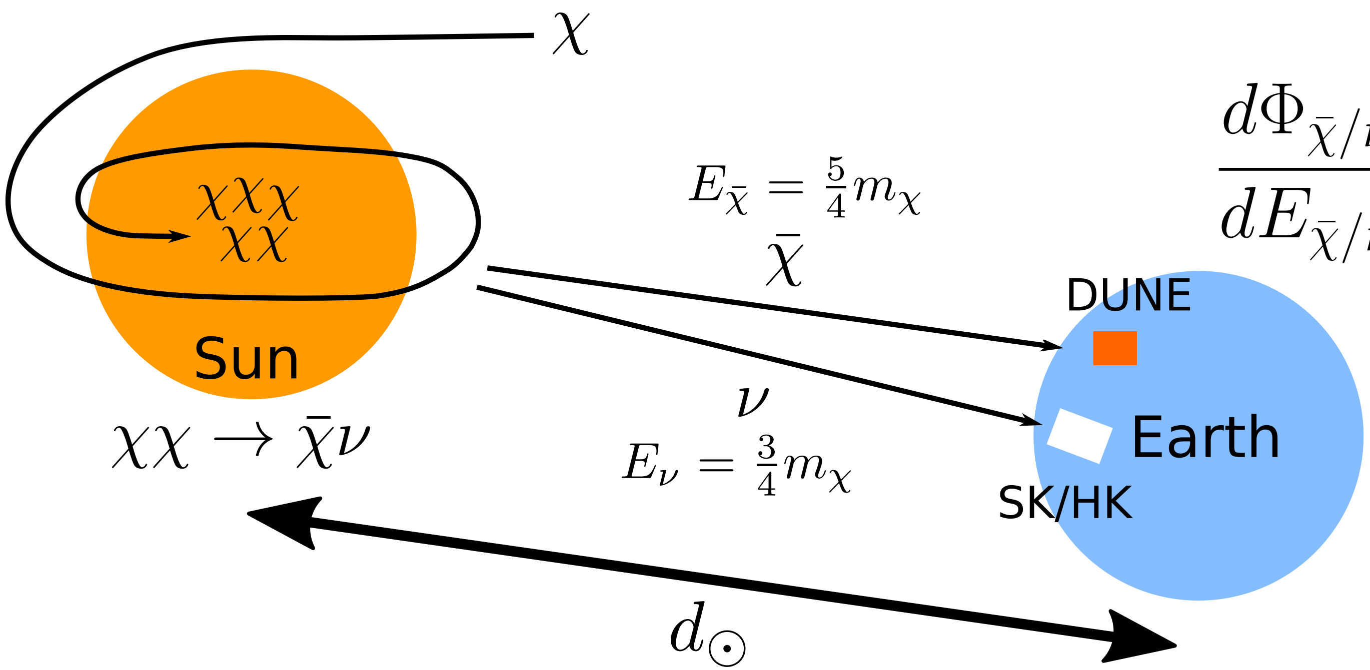


Bringmann and Pospelov, PRL (2019), arXiv:1810.10543

https://phys.org

Boosted dark matter signals from semi-annihilations

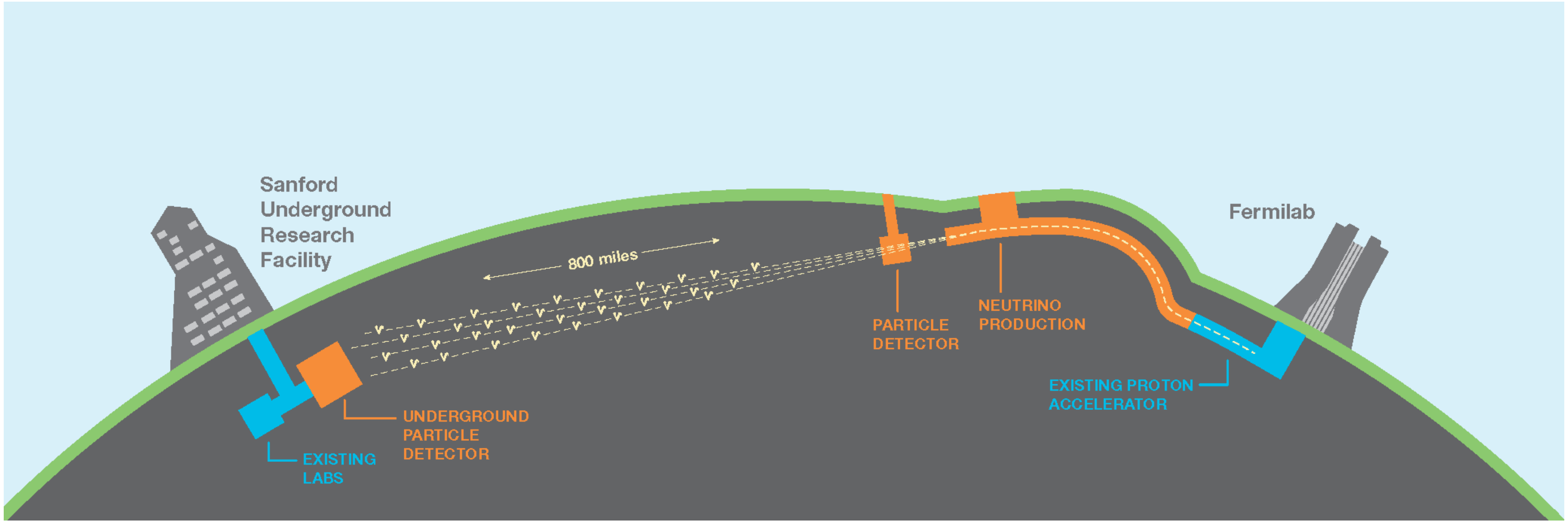
Signals from the Sun



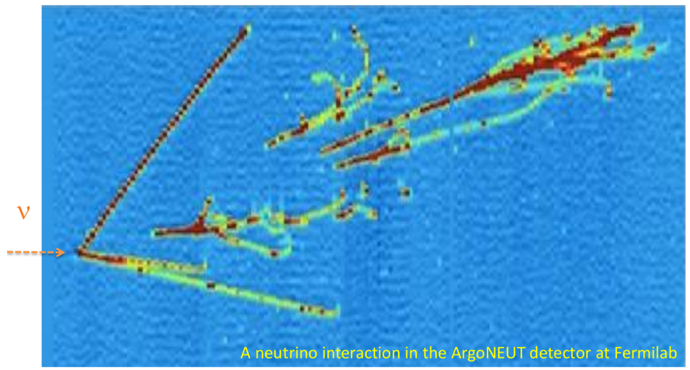
$$\frac{d\Phi_{\bar{\chi}/\nu}}{dE_{\bar{\chi}/\nu}} = \frac{\Gamma_{\rm ann}}{4\pi d_\odot^2}\frac{dN_{\bar{\chi}/\nu}}{dE_{\bar{\chi}/\nu}}$$

- A number of DM particles are accumulated in the centre of the Sun.
- Semi-annihilation occurs.
- Two kinds of signals can be searched at large volume neutrino detectors (SK, HK, DUNE etc).
- Signals from Galactic centre are smaller.

DUNE (Deep Underground Neutrino Experiment)

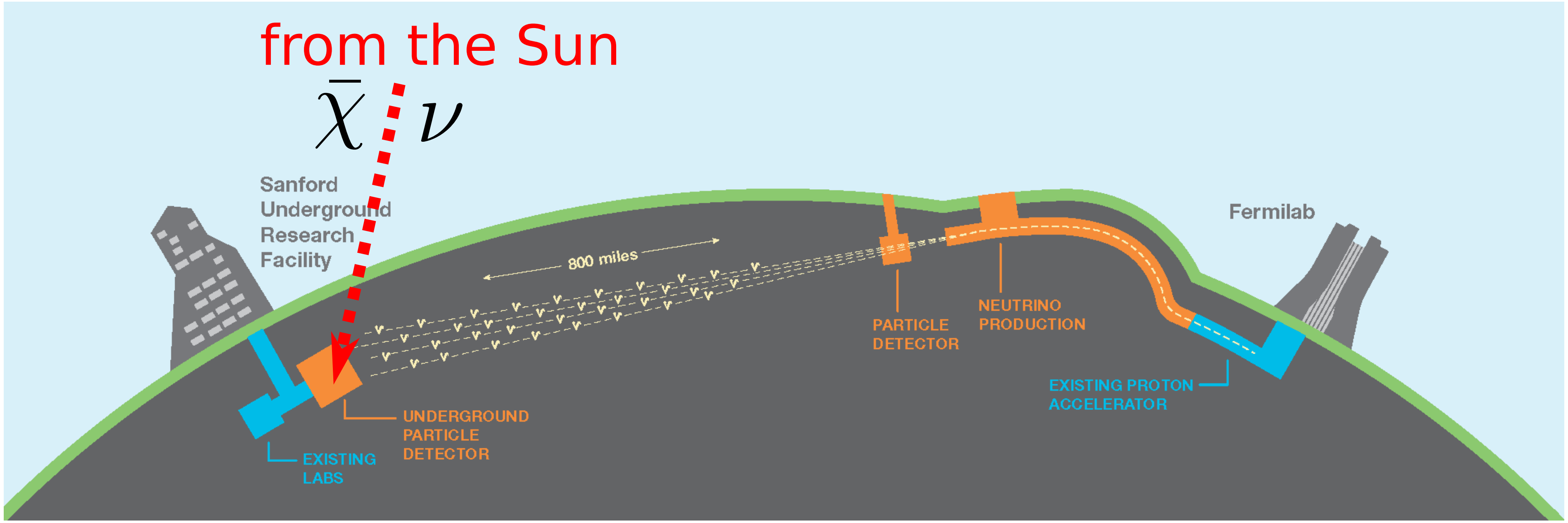


- Two detectors: near and far detectors.
- Massive liquid argon (fiducial volume: 40kt)
- Precise reconstruction of particle's trajectories with LArTPC



DUNE Coll., [arXiv:2002.03005]

DUNE (Deep Underground Neutrino Experiment)



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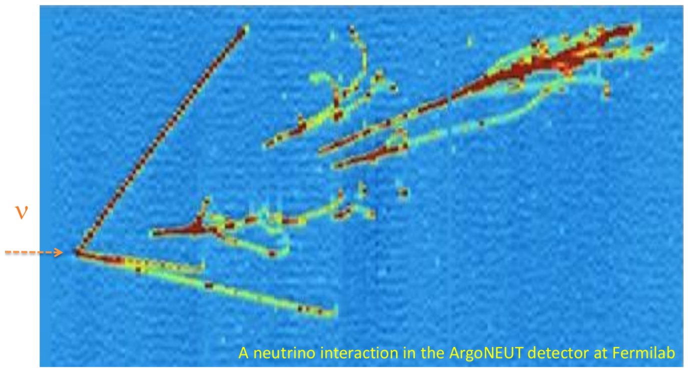

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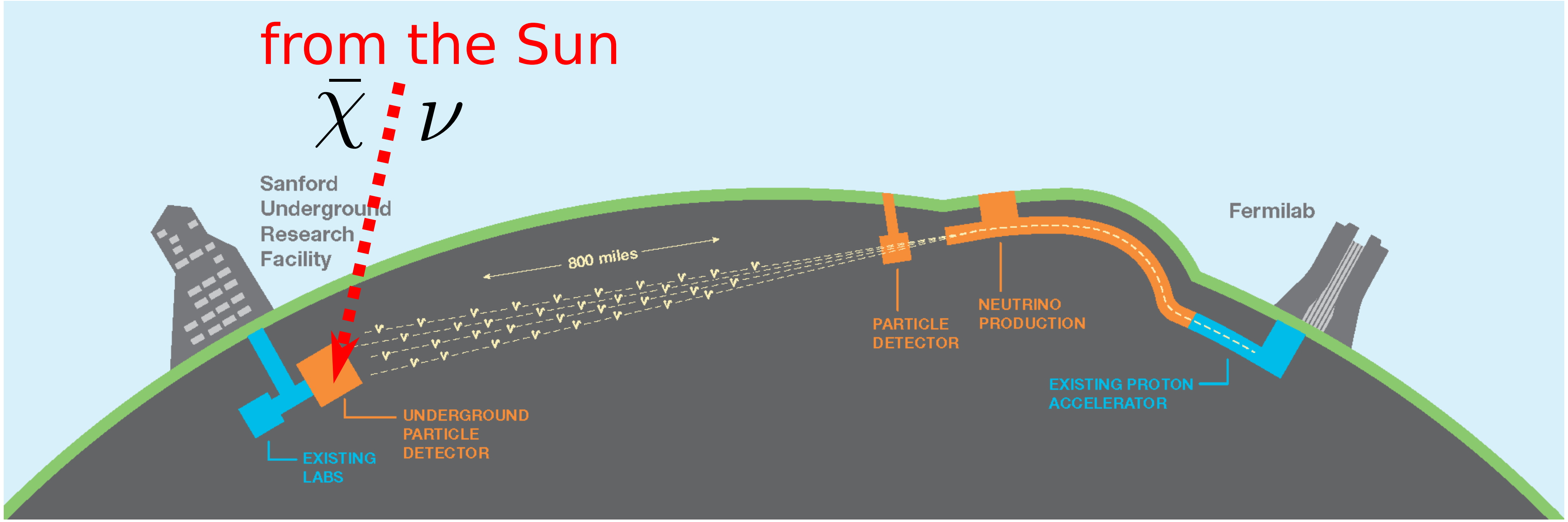
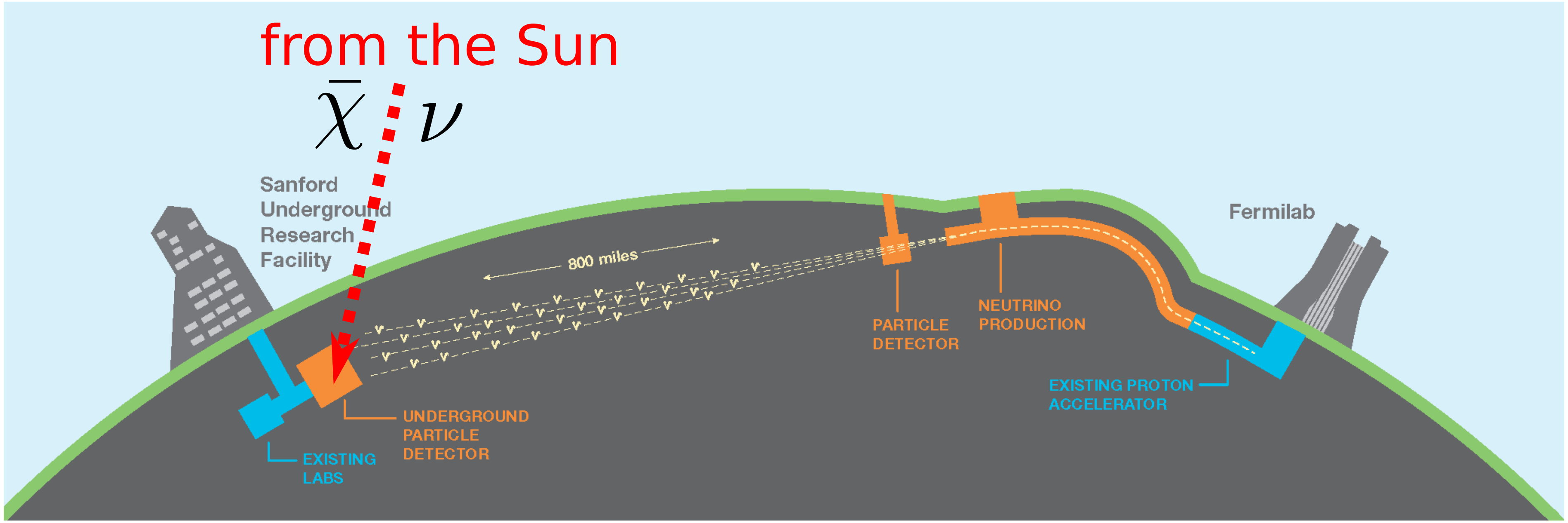


DUNE Coll., [arXiv:2002.03005]

Timeline of far detector modules

- 2025: DUNE physics data taking with atmospheric neutrinos (fiducial mass 20kt)
- 2026: DUNE physics eta taking with beam starts (fiducial mass 20kt)
- 2027: add third fiducial module (20kt + 10kt = 30kt)
- 2029: add fourth fiducial module (30kt + 10kt = 40kt)

DUNE (Deep Underground Neutrino Experiment)



Timeline of far detector modules ⇒ Delayed

DUNE Coll., [arXiv:2002.03005]

More cost is needed than initially expected. (2 billion ⇒ 3 billion dollars)

- 2029: slimmed version of DUNE will run
- 2035: DUNE full spec (40kt)
- 2027: Hyper-K

⇒ DUNE has no advantage for ν mass ordering, CP violation etc.

Simulation tool

- GENIE (neutrino event generator)
  http://www.genie-mc.org/
  - Detailed experimental simulation (DUNE, SK etc) can be done.
  - Boosted DM can also be implemented.

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

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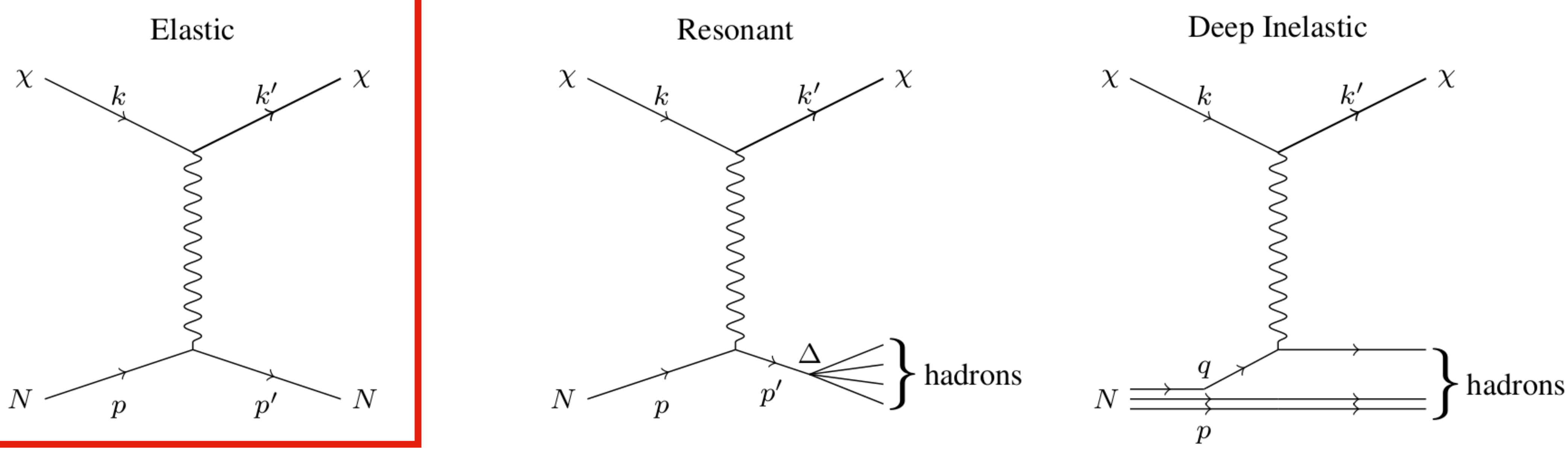
|-----------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                             |
|-----------------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |        m  |
|-----------------------------------------------------------------------------------------------------------------------|
|   0 |        chi_dm |   0 | 2000010000 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 |  37.500 |  62.500 | **1.000 | M = 50.000
|   1 |          Ar40 |   0 | 1000180400 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  37.216 |  37.216 |
|   2 |       neutron |  11 |       2112 |   1 |  -1 |   5 |   5 |   0.156 |  -0.039 |   0.178 |   0.929 | **0.940 | M = 0.897
|   3 |          Ar39 |   2 | 1000180390 |   1 |  -1 |   7 |   7 |  -0.156 |   0.039 |  -0.178 |  36.287 |  36.286 |
|   4 |        chi_dm |   1 | 2000010000 |   0 |  -1 |  -1 |  -1 |   0.530 |   0.110 |  36.892 |  62.140 | **1.000 | M = 50.000 P = (0.014,0.003,1.000)
|   5 |       neutron |  14 |       2112 |   2 |  -1 |   6 |   6 |  -0.374 |  -0.149 |   0.786 |   1.289 |   0.940 | FSI = 3
|   6 |       neutron |   1 |       2112 |   5 |  -1 |  -1 |  -1 |  -0.569 |  -0.091 |   0.611 |   1.261 |   0.940 |
|   7 |      HadrBlob |  15 | 2000000002 |   3 |  -1 |  -1 |  -1 |   0.069 |  -0.015 |  -0.035 |  36.286 | **0.000 | M = 36.286
|   8 |      NucBindE |   1 | 2000000101 |  -1 |  -1 |  -1 |  -1 |  -0.030 |  -0.005 |   0.032 |   0.029 | **0.000 | M = -0.032
|-----------------------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                             |  -0.000 |   0.000 |  -0.000 |   0.000 |               |
|-----------------------------------------------------------------------------------------------------------------------|
|       Vertex:         chi_dm @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =    0.000000e+00 s)   |
|-----------------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                                      none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:     NO |   Accepted:    YES                         |
|-----------------------------------------------------------------------------------------------------------------------|
| sig(Ev) =       4.88517e-38 cm^2  | dsig(Q2;E)/dQ2 =          1.73521e-39 cm^2/GeV^2 | Weight =          1.00000 |
|-----------------------------------------------------------------------------------------------------------------------|
```

Setup for boosted dark matter



arXiv: 1912.05558, J. Berger et al.

- There are 3 processes.
- (Quasi)-elastic scattering is dominant for our case $(\chi\chi \to \nu\overline{\chi})$
  $0 \leq Q^2 \lesssim \frac{9}{4}m_N^2 \approx (2\ \mathrm{GeV})^2$

Setup for boosted dark matter

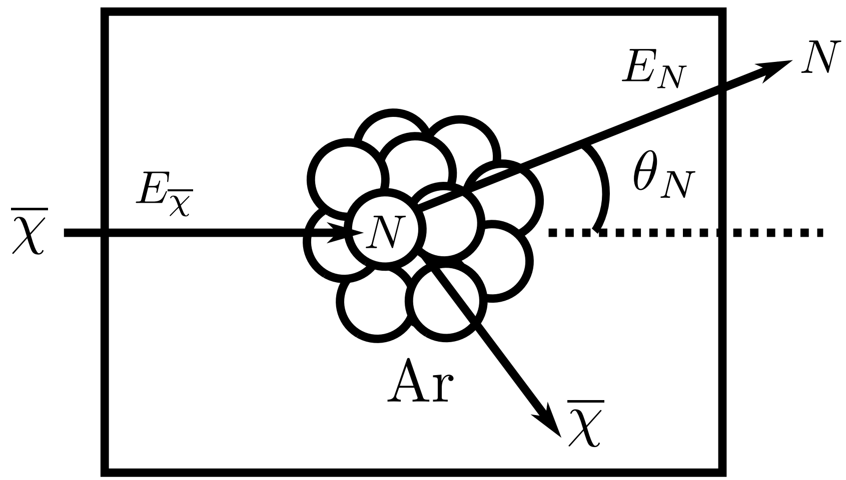
We parametrize the cross section as

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

- $F(Q^2) = \dfrac{1}{(1+Q^2/M_A^2)^2}$
- Parameters: $|\boldsymbol{p}_\chi| = \frac{5}{4}m_\chi$ and σ_0 (reference cross section)

We consider three cases.

1. $n = 0$ (constant)
2. $n = 1$ (Q^2 dependent)
3. $n = 2$ (Q^4 dependent)



Energy reconstruction

Boosted DM signal

- For elastic scattering $\chi N \to \chi N$, energy and angle are kinematically fixed.

$$\cos\theta_N = \frac{E_\chi + m_N}{|\boldsymbol{p}_\chi|}\sqrt{\frac{E_N - m_N}{E_N + m_N}}$$

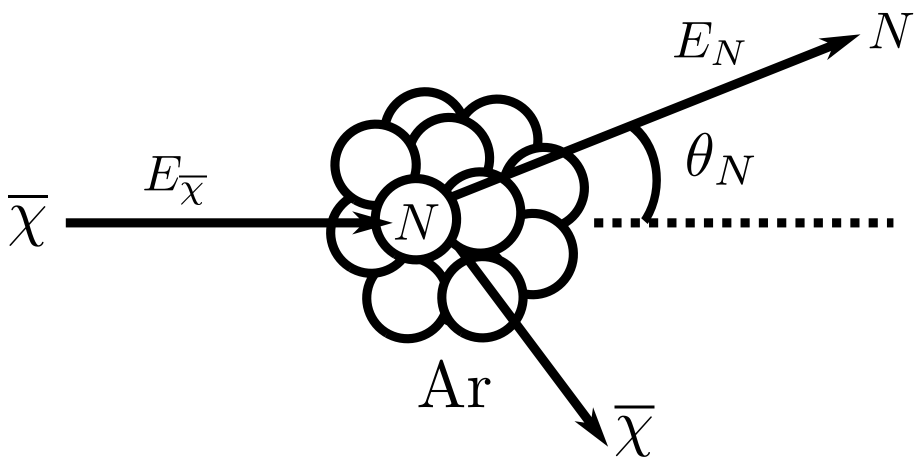
- DM energy can be reconstructed from observed values θ_N and E_N

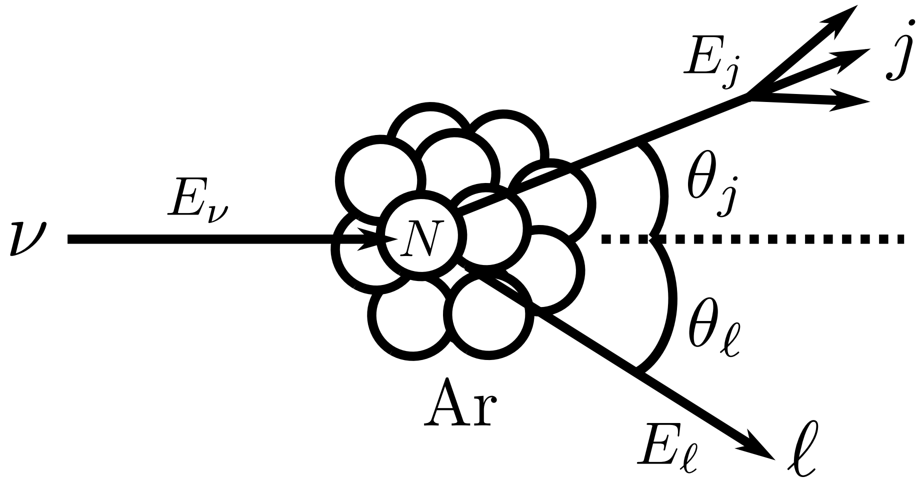
Neutrino signal

arXiv: 1903.04175, C. Rott et al.

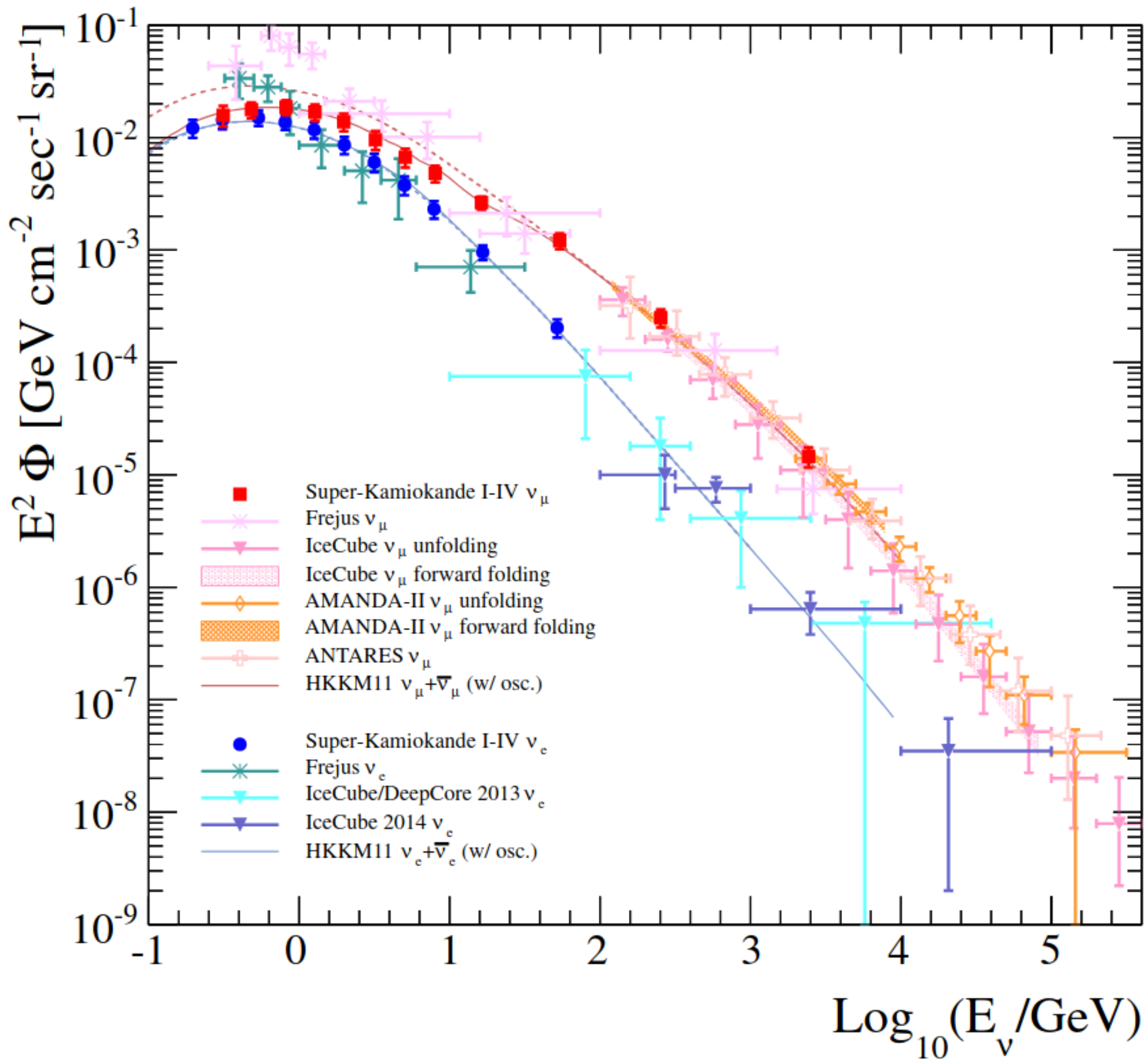
- $\nu + N \to e^- / \mu^- +$ jet

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





Background (atmospheric neutrinos)



$$N_{\mathrm{atm}\,\nu} = N_N T \int \sigma_{\nu N} \frac{d^2\Phi_\nu^{\mathrm{atm}}}{dE_\nu d\Omega} dE_\nu d\Omega$$

Expected number of bkg events in 10 years

994 via NC int. for χ signal ($\nu_{\mathrm{atm}} + N \to \nu_{\mathrm{atm}} + N$)

2070 via CC int. for ν signal ($\nu_{\mathrm{atm}} + N \to e/\mu + j$)

http://www-rccn.icrr.u-tokyo.ac.jp/mhonda/public/

- We use ν_{atm} HAKKM flux at Homestake (close to DUNE detector).

Results

Results

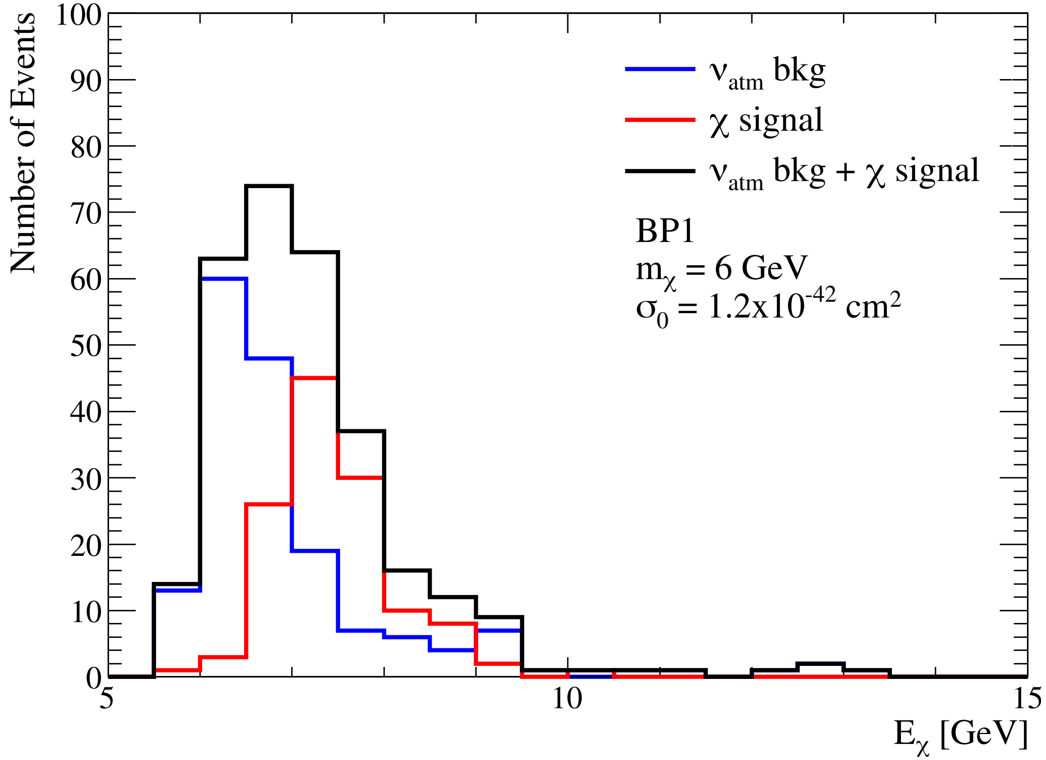
Benchmark parameter sets

	model	m_χ [GeV]	σ_0 [cm^2]	# of ν events	# of χ events
BP1	SD ($n = 1$)	6	1.2×10^{-42}	$N^{\rm CC}_{{\rm atm}\,\nu} = 54/2070$ $N^{\rm CC}_{\nu} = 18/47$	$N^{\rm NC}_{{\rm atm}\,\nu} = 98/994$ $N_\chi = 113/372$
BP2	SD ($n = 2$)	30	5.0×10^{-46}	$N^{\rm CC}_{{\rm atm}\,\nu} = 1/2070$ $N^{\rm CC}_{\nu} = 0/0$	$N^{\rm NC}_{{\rm atm}\,\nu} = 18/994$ $N_\chi = 405/2117$

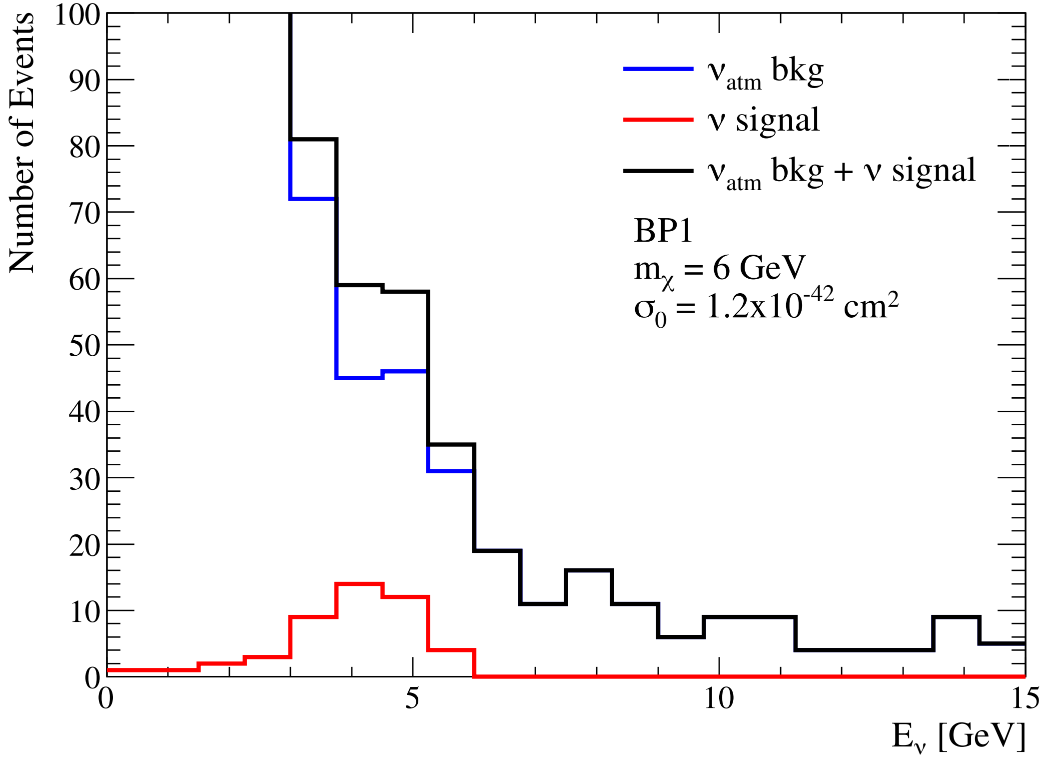
- Assumption: 40kton liquid argon, 10 years exposure
- 4th and 5th columns: Observed events / Expected events (selected by detector threshold and resolutions)
- A large number of BDM signal events for BP2

Energy reconstruction for BP1

Boosted DM signal



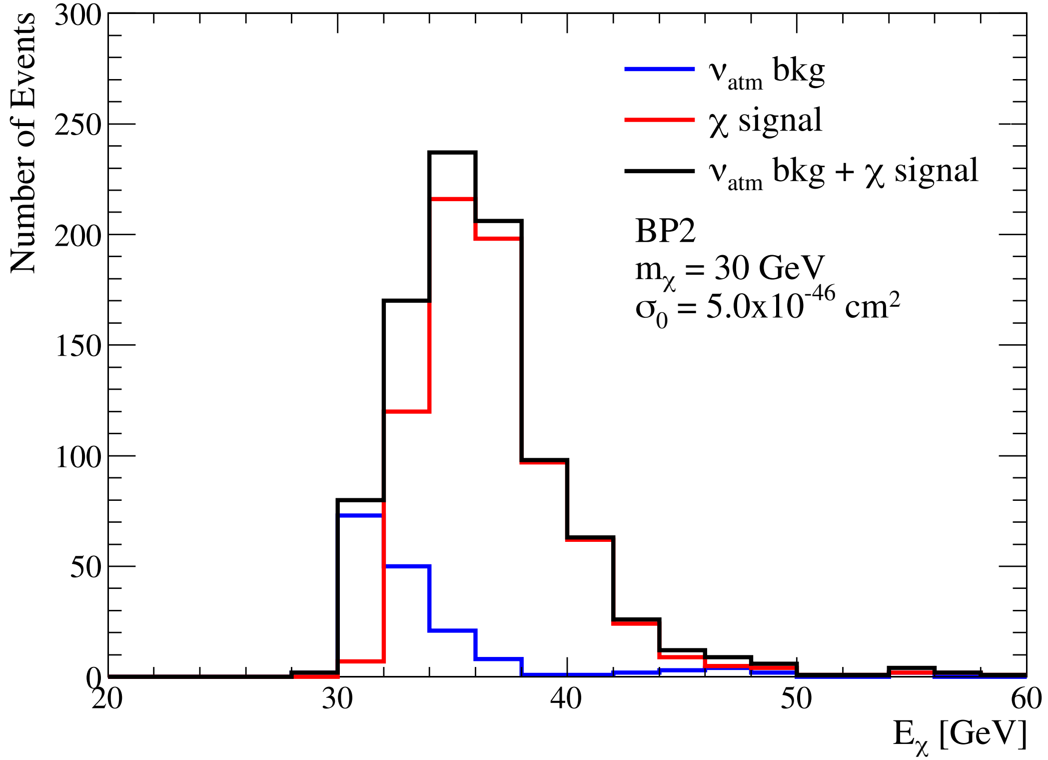
Neutrino signal



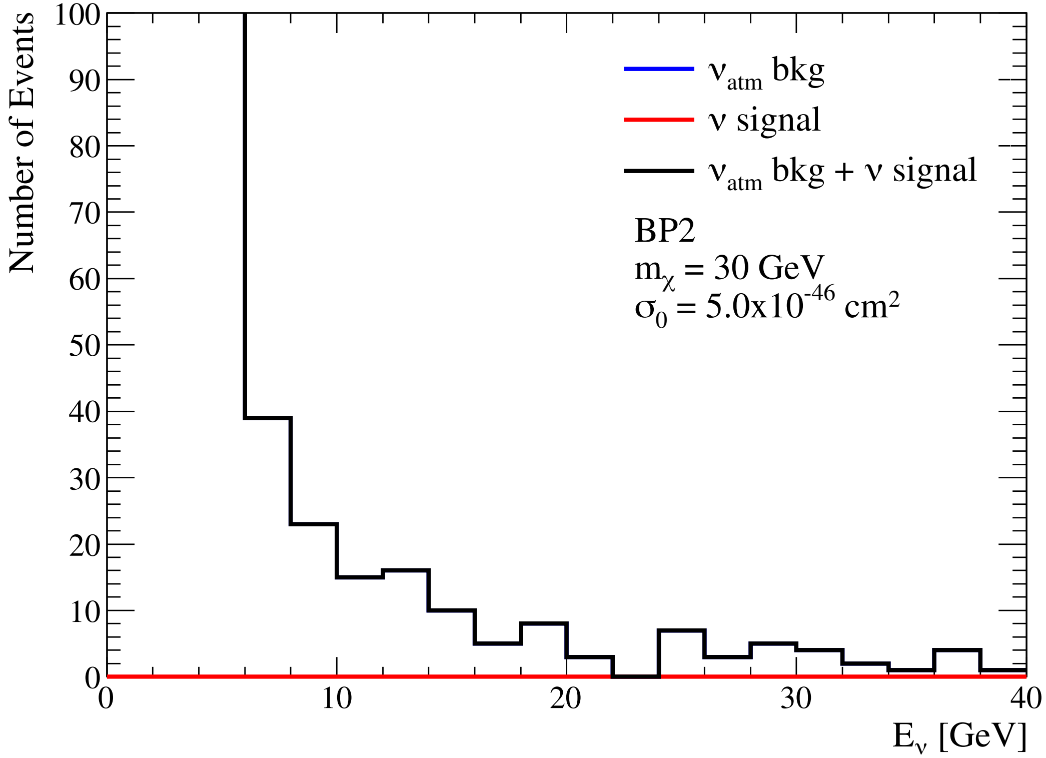
- $E_\chi = 7.5$ GeV and $E_\nu = 4.5$ GeV
- A large number of atmospheric neutrino bkg at low energy

Energy reconstruction for BP2

Boosted DM signal



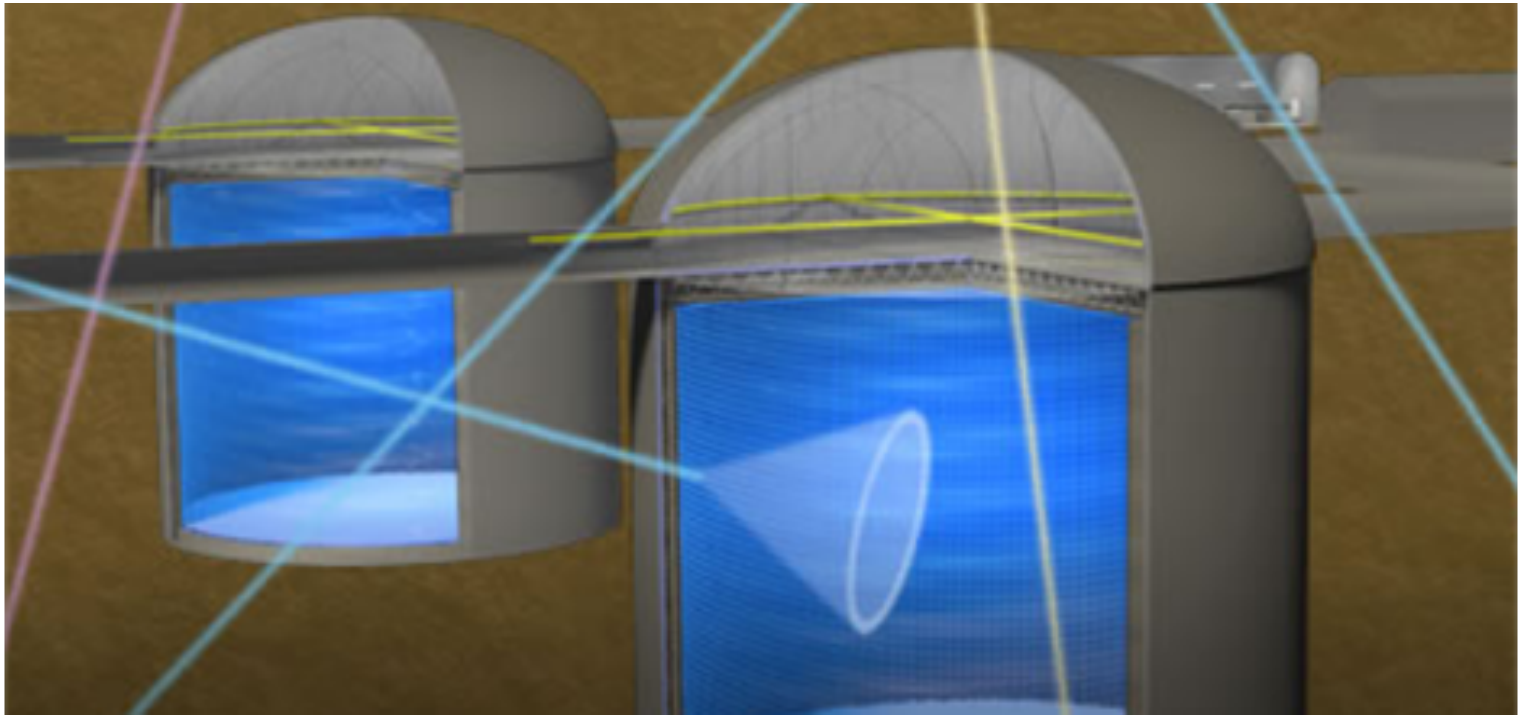
Neutrino signal



- $E_\chi = 37.5$ GeV and $E_\nu = 22.5$ GeV
- A large number of BDM events (left) due to $d\sigma_{\chi N}/dQ^2 \propto Q^4$
- No neutrino signal due to small cross section (right)

Accompanied neutrinos

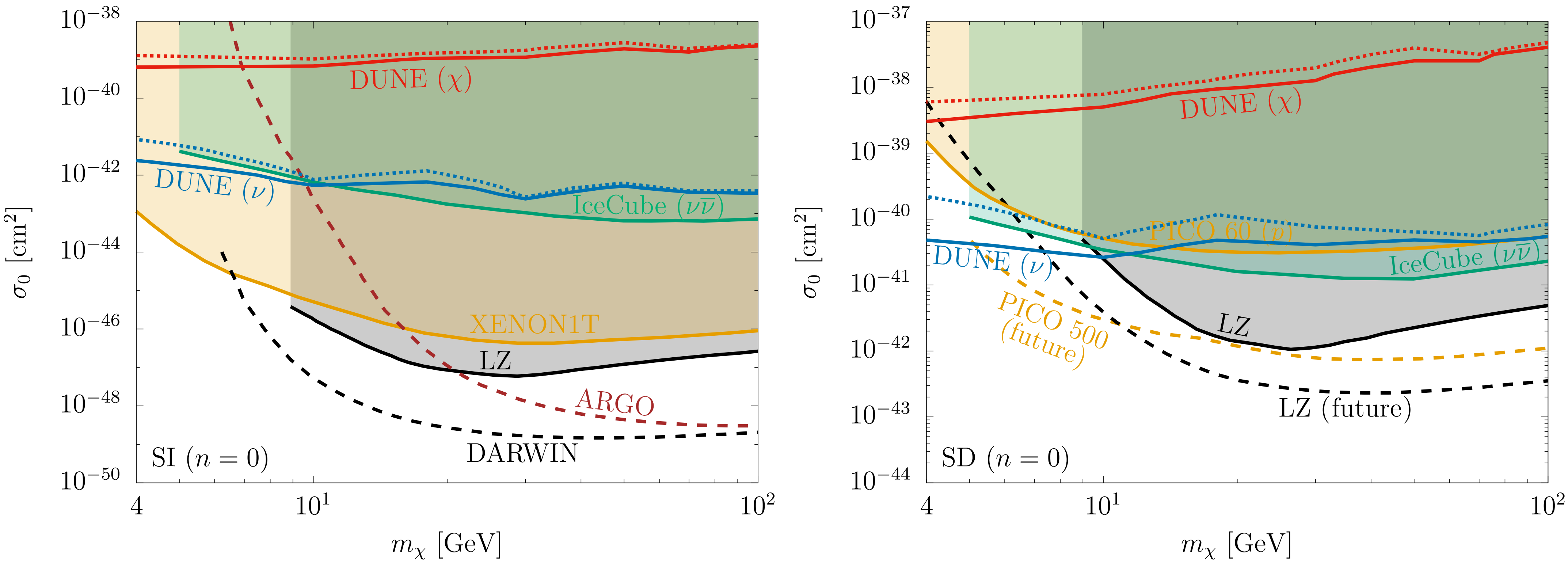
- Even if DUNE has no sensitivity for ν, it can be searched by SK/HK and IceCube etc.



Hyper-Kamiokande Collaboration

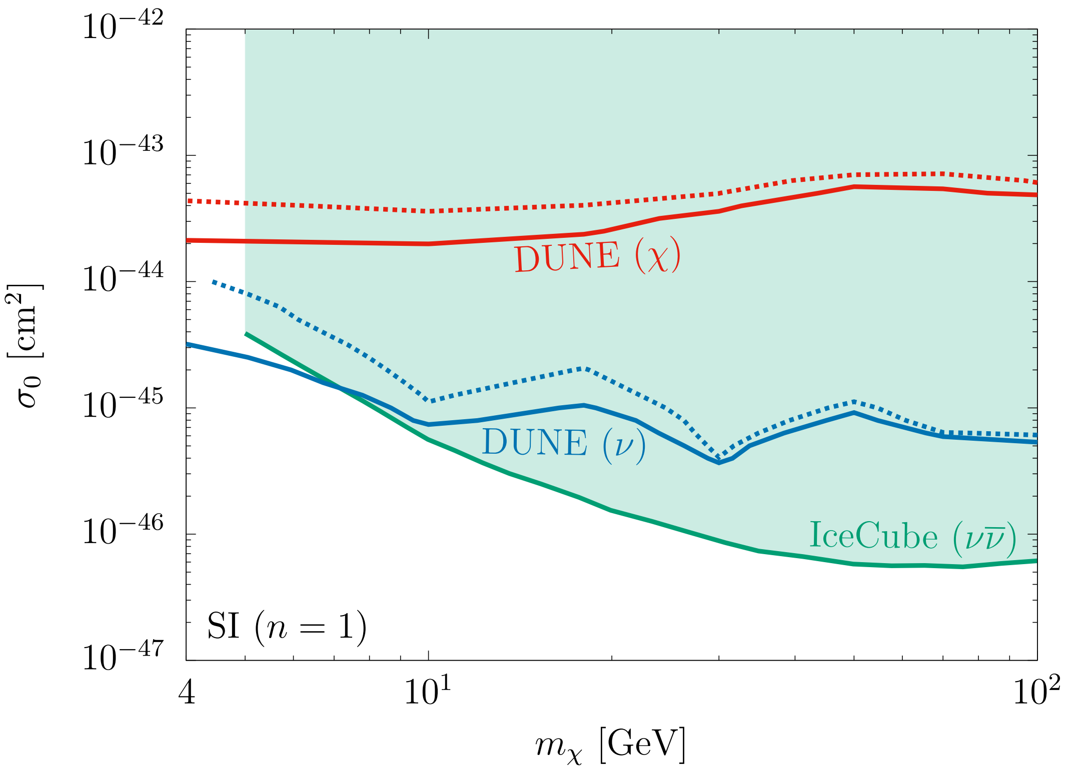
- The boosted DM ($v_\chi = 0.6$) is difficult to produce Cherenkov light. $v_p > 0.75$ is required to produce Cherenkov radiation.

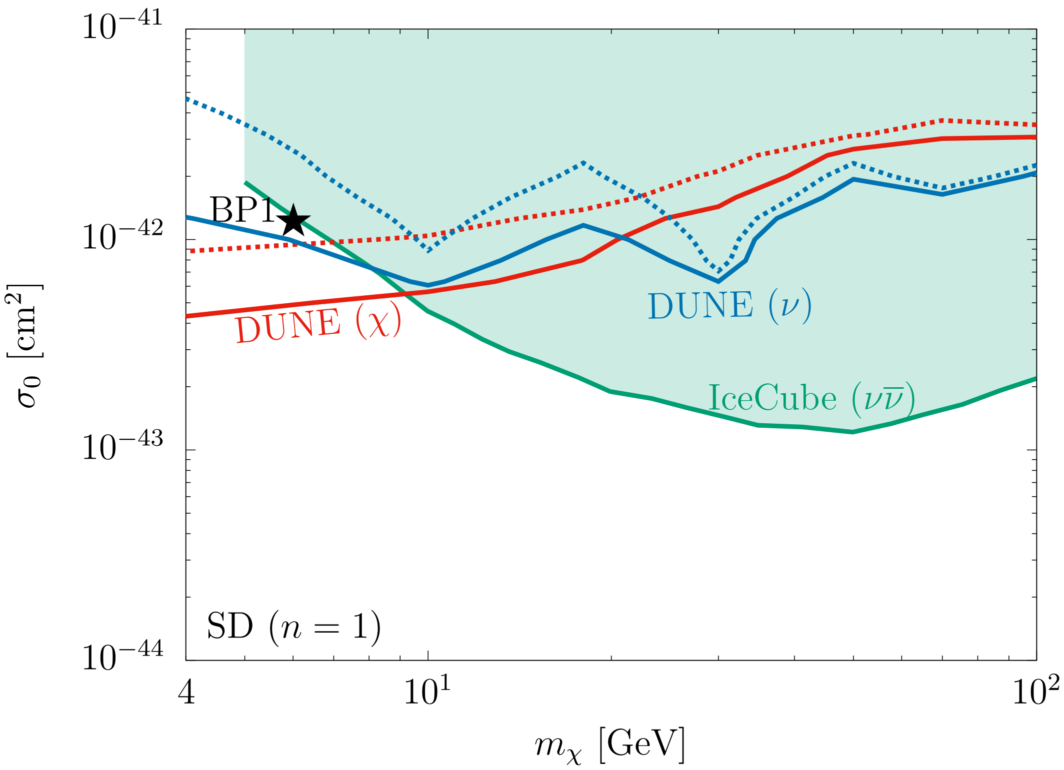
Parameter space 1



- DUNE sensitivity for constant $\sigma_{\chi N}$ $(n = 0)$
- Significance: $\mathcal{S} = \dfrac{N_{\rm sig}}{\sqrt{N_{\rm bkg} + N_{\rm sig} + \delta_{\rm syst}^2}}$, $\delta_{\rm syst}$: 0% (solid lines)
  20% (dotted lines)
- Completely excluded by direct detection experiments as expected.

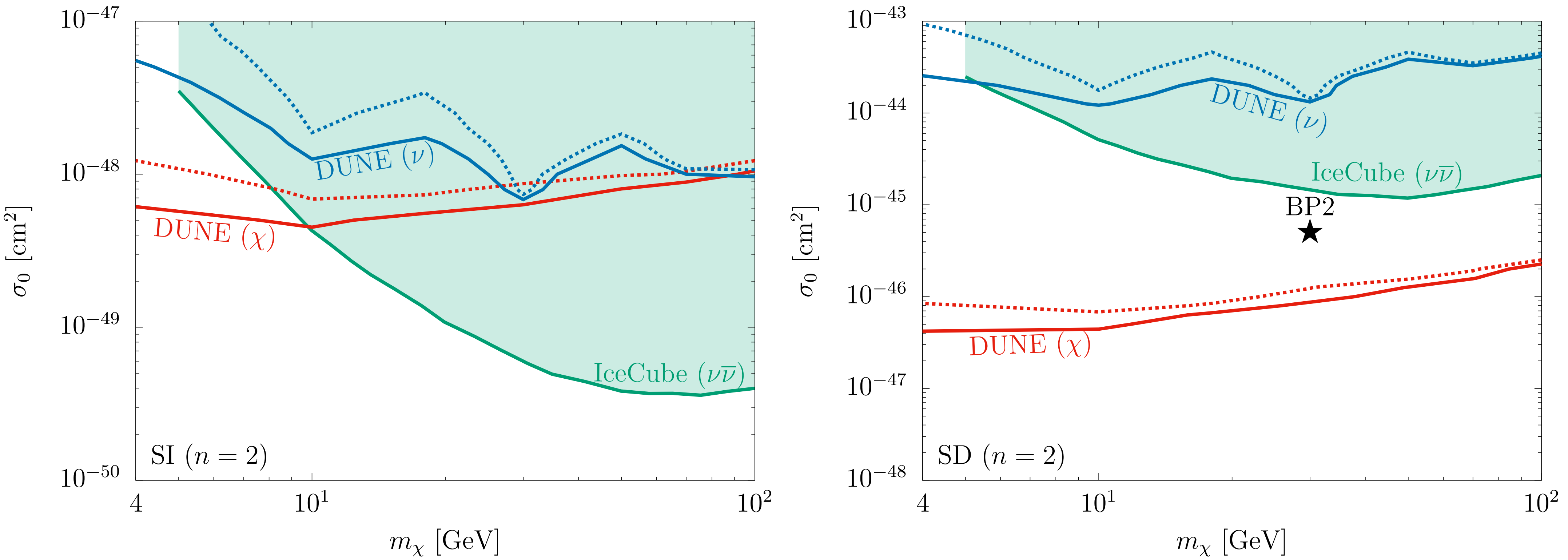
Parameter space 2





- DUNE sensitivity for Q^2 dependent $\sigma_{\chi N}$ $(n = 1)$
- No substantial direct detection constraints.
- Sensitivities can be comparable if DM mass is lower than 10 GeV.

Parameter space 3



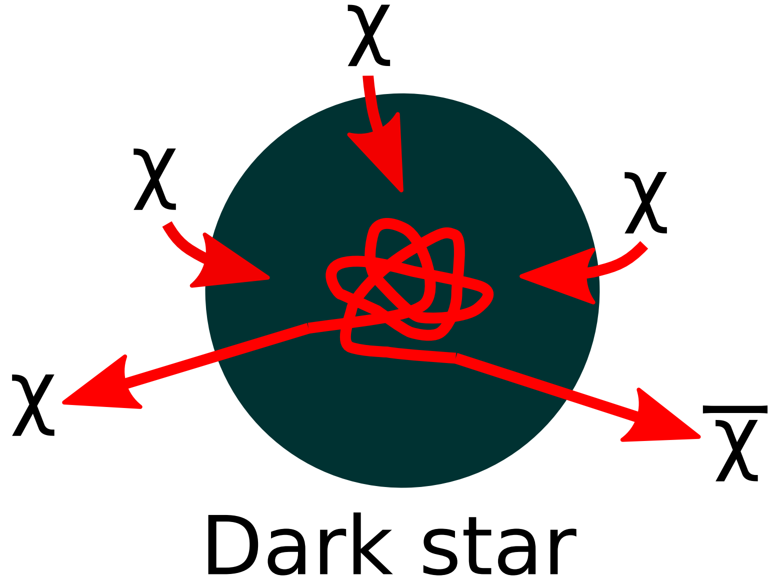
- DUNE sensitivity for Q^4 dependent $\sigma_{\chi N}$ $(n = 2)$
- Much higher sensitivity for BDM
- But neutrinos cannot be observed at the same time
  $\Rightarrow$ combining with Hyper-Kamiokande?

Summary

1. Direct detection experiments impose the strong bound on (minimal) thermal dark matter scenarios.
2. Non-minimal extension of dark sector may induce semi-annihilations.
3. $\chi\chi \to \nu\bar{\chi}$ induces interesting signals, which can be searched by DUNE, or combination of DUNE and SK/HK/IceCube.
4. Q^2 (or v_χ^2) dependent cross sections are needed for BDM detection.

Future works

- Application to new annihilation processes such as SIMP
  - $\displaystyle \frac{dn}{dt} + 3Hn = -\langle \sigma_{3\to 2} v^2 \rangle \left(n^3 - n^2 n_{\rm eq} \right)$
  - Typical mass scale: MeV $\sim$ GeV
  - Boosted DM signals from $\chi\chi\chi \to \chi\overline{\chi}$
  - can be a smoking gun signature of SIMP



- Need to consider very dense compact objects (dark star)

B. Kamenetskaia, A. Brenner, A. Ibarra and C. Kouvaris, arXiv:2211.05845

$\Rightarrow$ enhancement of point source of boosted dark matter

$M \sim 0.1 M_\odot$, r ∼1km

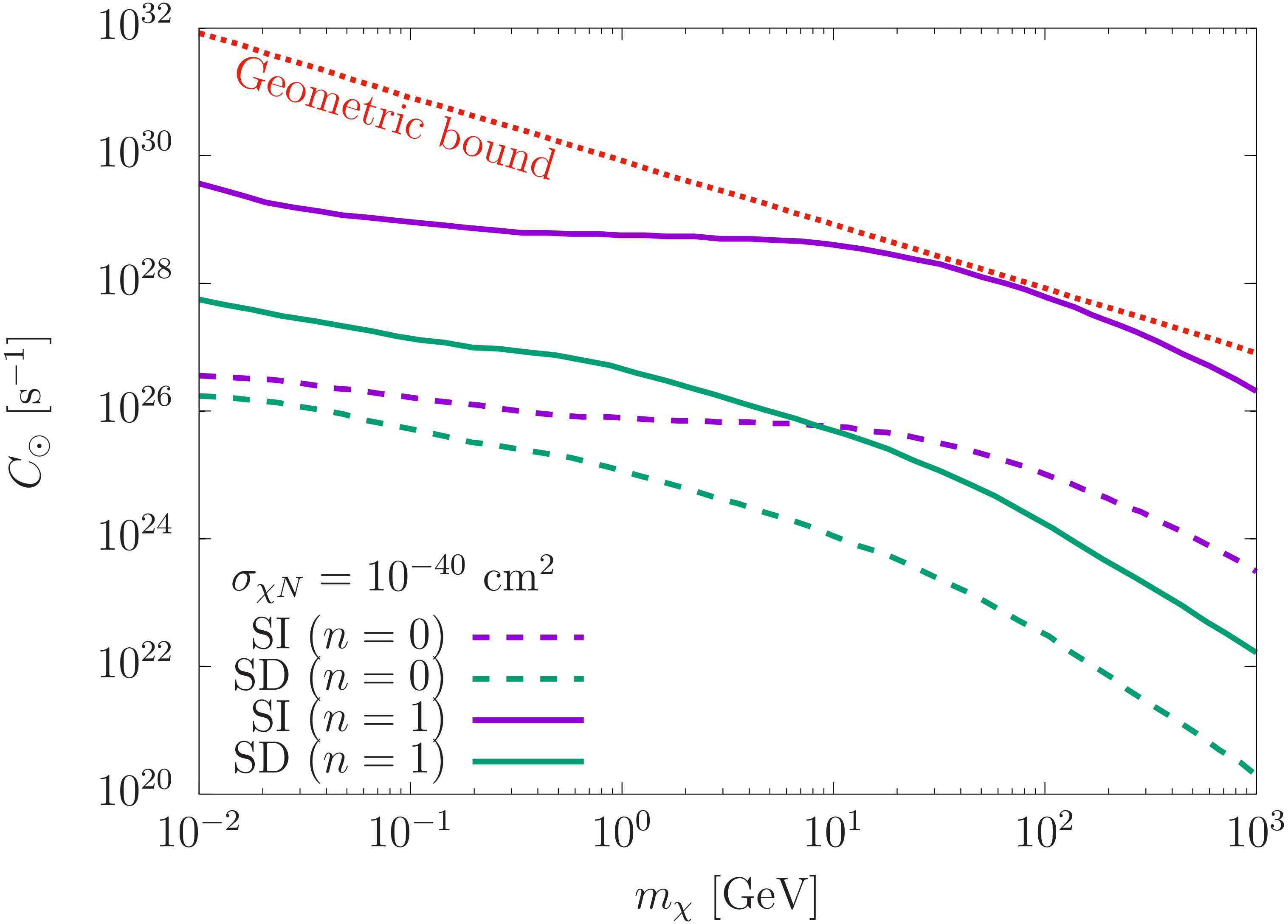
Backup

Semi-annihilation at the Sun

R. Garani et al., JCAP (2014) [arXiv:1702.02768]

- Capture rate for const. and Q^2 (momentum transfer) dependent cases ($\Gamma_{\rm ann} = C_\odot/2$)

$$\sigma_{\chi N} \sim \sigma_0 (Q^2/Q_0^2)^n$$



Threshold and resolution for DUNE

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

- Precise angular resolution (DUNE)
  cf: 3° at SK and HK, 30° at IceCube
- These are taken into account in event selection.

Setup for boosted dark matter

Number of expected signal events ($\overline{\chi} + N \to \overline{\chi} + N$)

- $N_\chi = N_N T \int \sigma_{\chi N} \frac{d^2\Phi_\chi}{dE_\chi d\Omega} dE_\chi d\Omega$
- Number of nucleons: $N_N = 2.41 \times 10^{34}$ (40kt fiducial volume)

  Exposure time: $T = 10$ yr

  DM flux: $\frac{d^2\Phi_\chi}{dE_\chi d\Omega} = \frac{\Gamma_{\rm ann}}{4\pi d_\odot^2} \sigma_{\chi N} \Big|_{E_\chi = 5m_\chi/4} = \frac{C_\odot}{8\pi d_\odot^2} \sigma_{\chi N} \Big|_{E_\chi = 5m_\chi/4}$

  Distance between the Sun and Earth: $d_\odot = 1.5 \times 10^{13}$ cm

Example of model building

- Semi-annihilation $\chi\chi \to \nu\overline{\chi}$

  Ex. $\mathbb{Z}_3$ symmetric model with radiative neutrino masses

  M. Aoki and TT, JCAP (2014) [arXiv:1405.5870]

	χ_L	χ_R	η	φ
$SU(2)$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	0	0	$1/2$	0
$\mathbb{Z}_3$	1	1	1	1
L number	$1/3$	$1/3$	$-2/3$	$-2/3$

New particles