Signals of boosted dark matter and neutrinos

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Electroweak Interactions & Unified Theories

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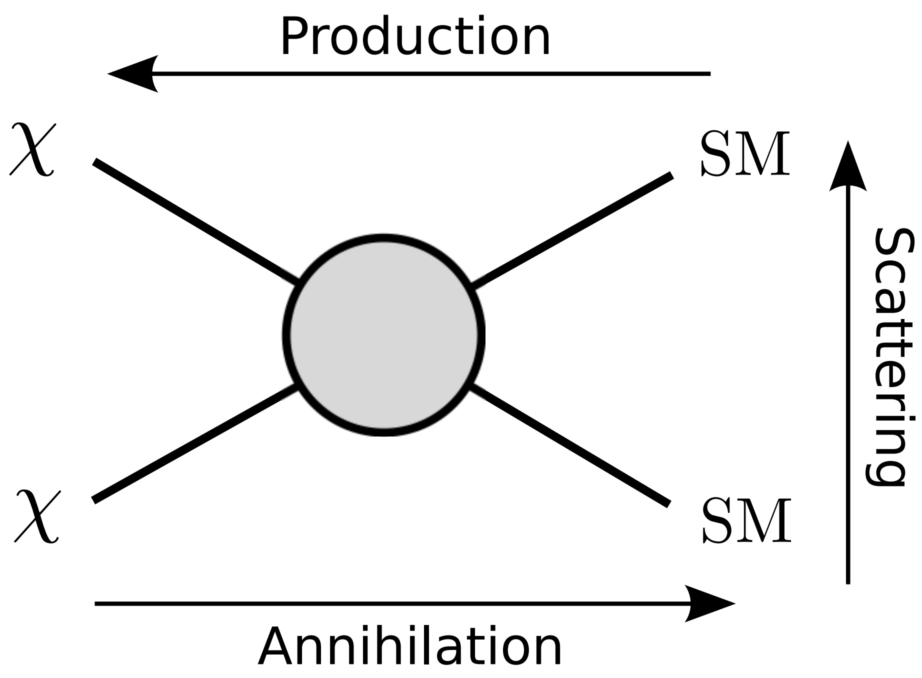
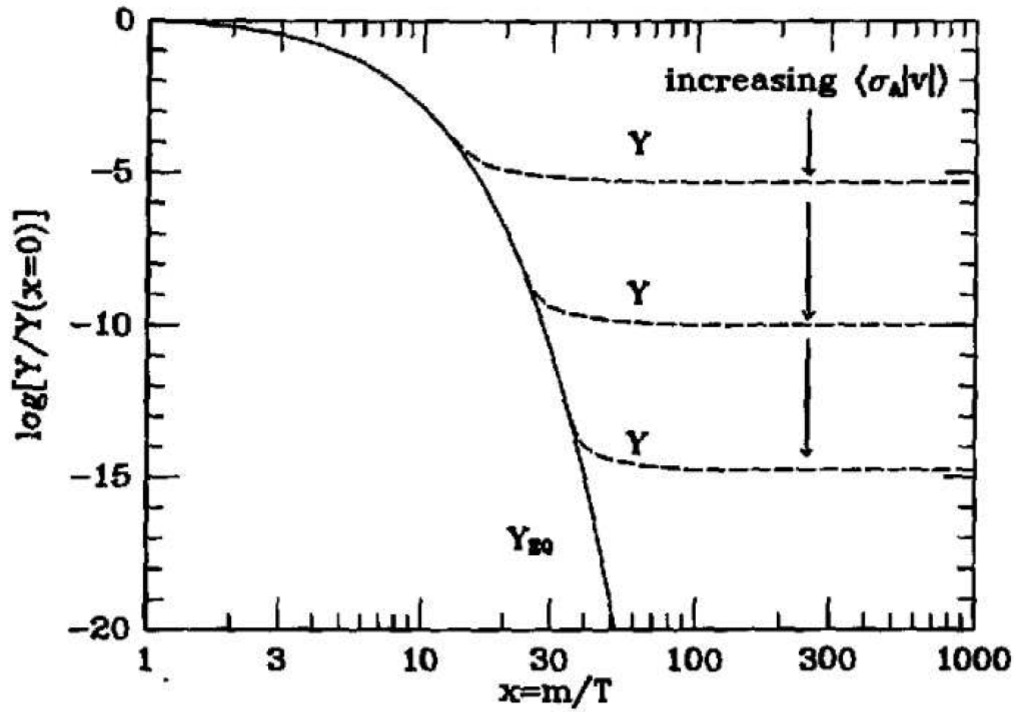
Collaborator: Mayumi Aoki

Thermal dark matter (WIMPs)

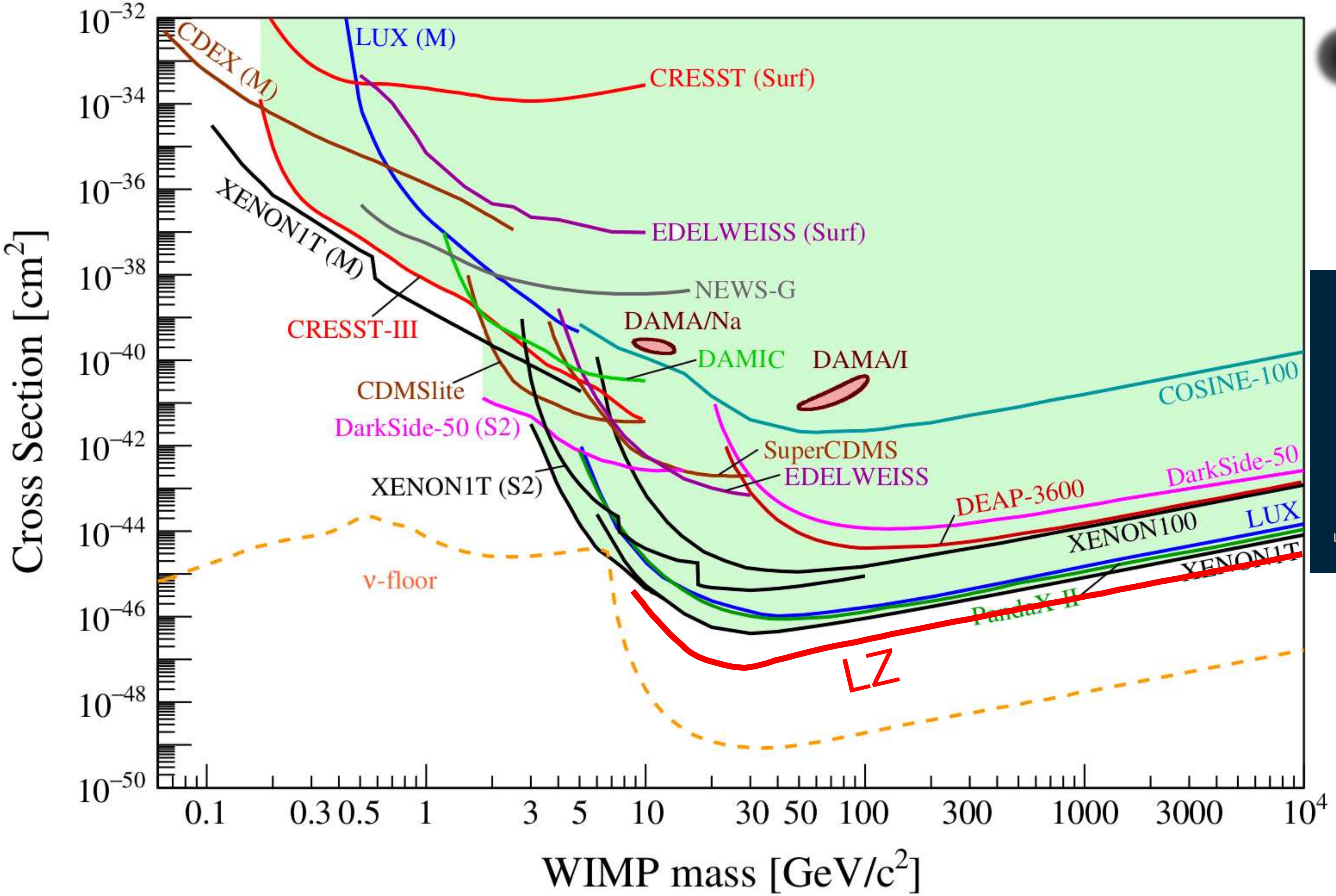


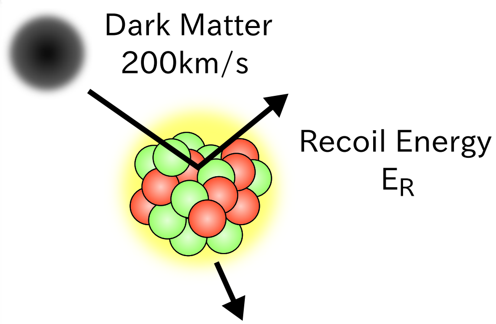


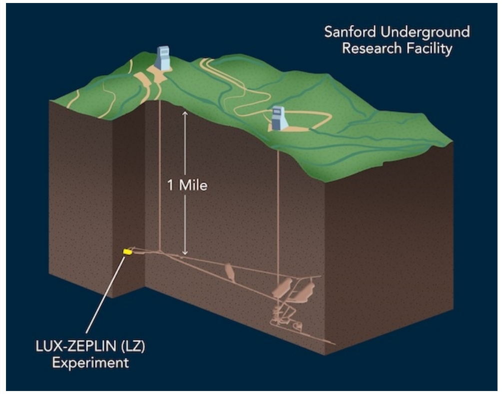
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}2} \right)$$

- WIMP is thermalized with SM particles in early universe
- To get $\Omega_\chi h^2 = 0.12$, roughly $\sigma \sim$ 1pb $\sim 10^{-26}\mathrm{cm}^3/\mathrm{s} \sim 10^{-36}\mathrm{cm}^2$
- Almost independent on DM mass
- Mass range: 10 MeV $-$ 100 TeV

Status of direct detection experiments







arXiv:2104.07634
LZ arXiv:2207.03764
SLAC

- 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 ($\sigma \propto v_\chi^4$)

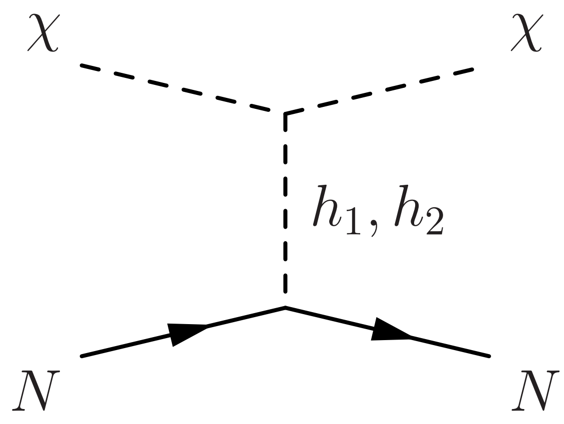
  C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

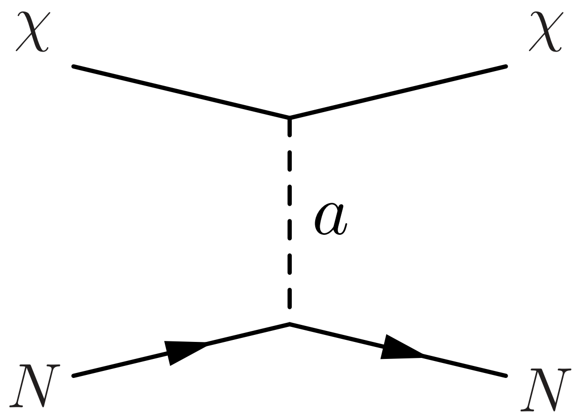
  Ex.2 Fermionic DM with Pseudo-scalar int.

  $$\mathcal{L} = a\overline{\chi}\gamma_5\chi \quad (\sigma \propto v_\chi^2)$$

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

  · Challenging to explore with standard way of direct detection experiments

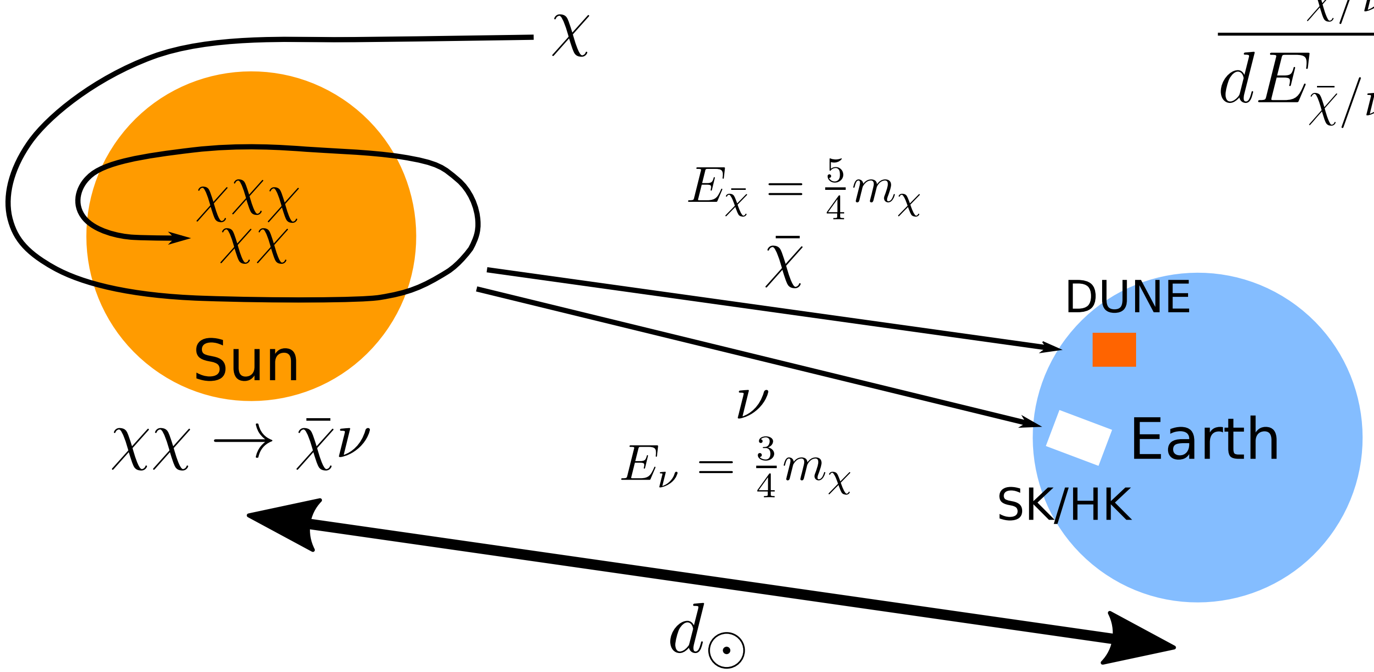




$\Rightarrow$ Could be searched if it is accelerated.

$\Rightarrow$ We consider DM accelerated by semi-annihilaton $\chi\chi \to \overline{\chi}\nu$
Exotic DM signals

Signals from the Sun



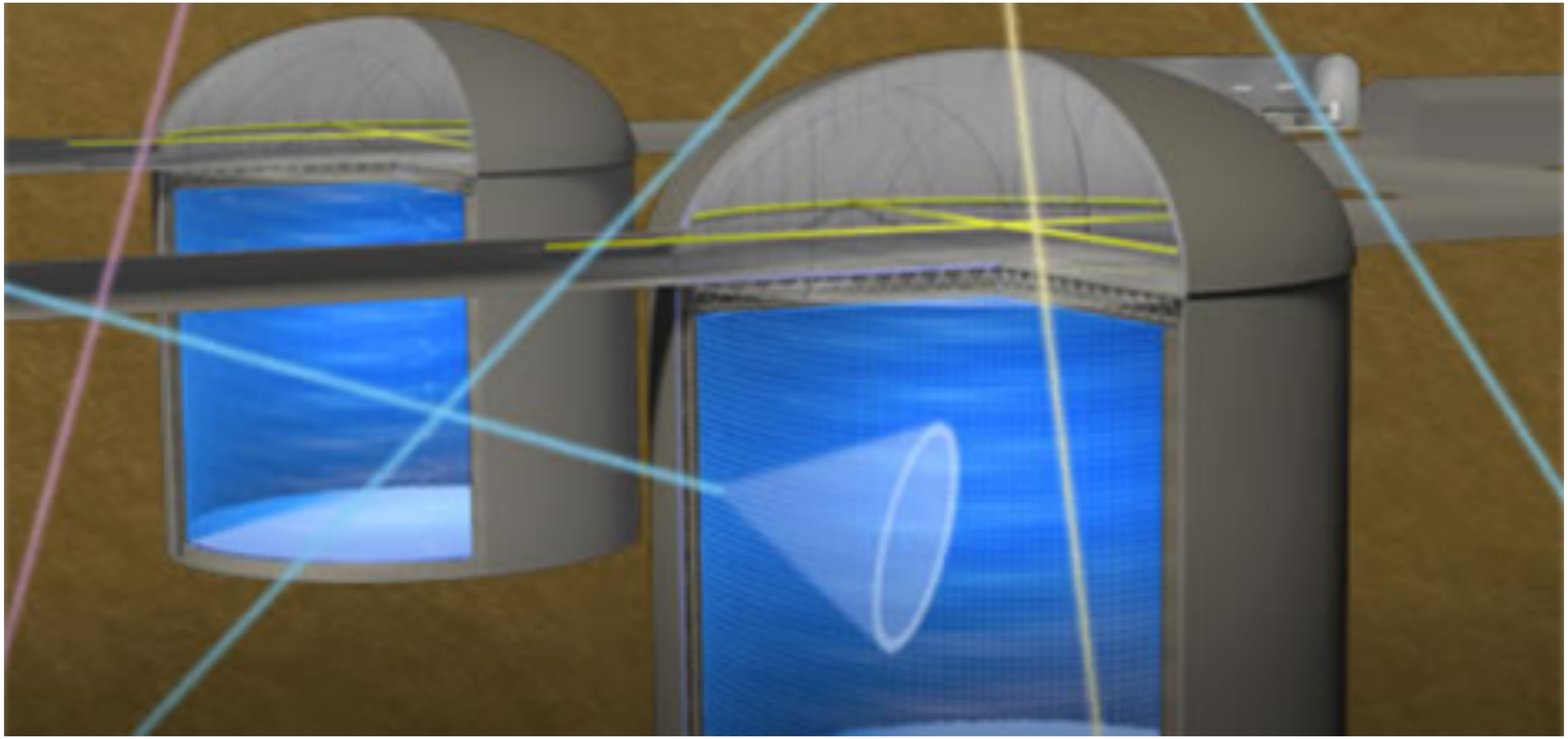
$$\frac{d\Phi_{\bar{\chi}/\nu}}{dE_{\bar{\chi}/\nu}} = \frac{\Gamma_{\rm ann}}{4\pi d_\odot^2}\frac{dN_{\bar{\chi}/\nu}}{dE_{\bar{\chi}/\nu}}$$

- DM particles are accumulated in centre of the Sun.
- Semi-annihilation occurs, and boosted DM and neutrino are produced.
- These can be searched at large volume neutrino detectors (SK, HK, IceCube, DUNE etc).

Detection of boosted DM

- Boosted DM ($v_\chi = 0.6$) is difficult to produce Cherenkov radiation.

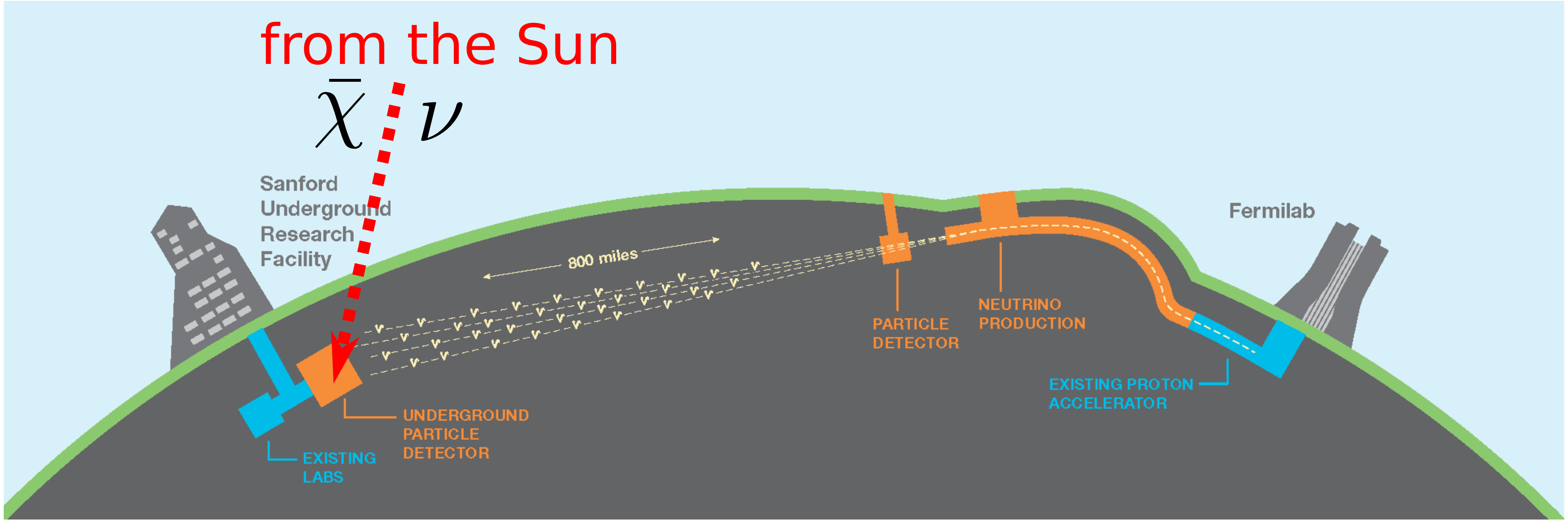
  $v_p > 0.75$ is required to produce Cherenkov radiation.



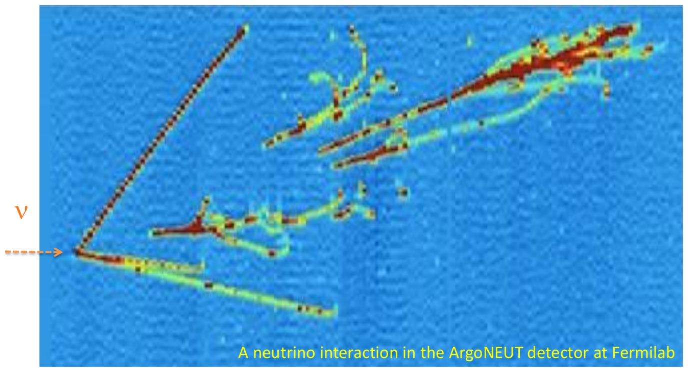
Hyper-Kamiokande Collaboration

$\Rightarrow$ We focus on DUNE.

DUNE (Deep Underground Neutrino Experiment)

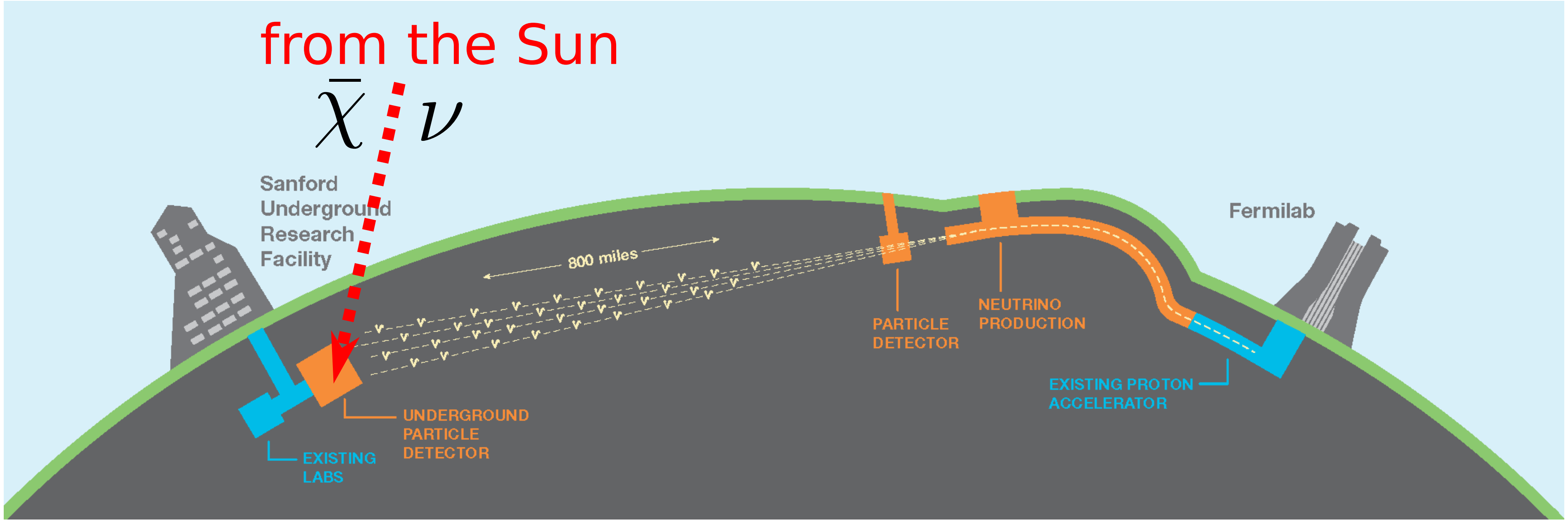


- Two detectors: near and far detectors.
- Massive liquid argon (fiducial volume: 40kt)
- Precise reconstruction of particle's trajectories with LArTPC



DUNE Coll., [arXiv:2002.03005]

DUNE (Deep Underground Neutrino Experiment)



DUNE Coll., [arXiv:2002.03005]

Timeline of far detector modules ⇒ Delayed

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 data taking

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

But boosted DM could be detectable only by DUNE.

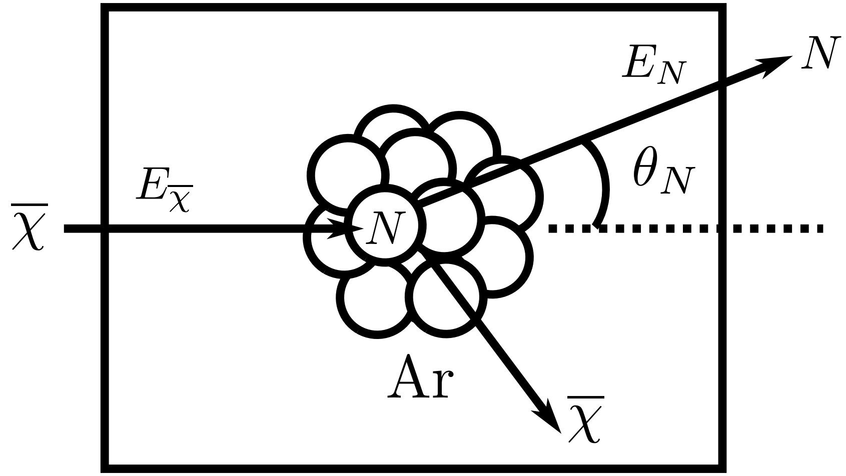
Setup for boosted dark matter

We parametrize the cross section as

$$\frac{d\sigma_{\chi N}}{dQ^2} = \frac{\sigma_0 s}{4m_N^2|\boldsymbol{p}_\chi|^2}\left(\frac{Q^2}{Q_0^2}\right)^n |F(Q^2)|^2$$

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

1. $n = 0$ (constant $\sigma_{\chi N}$)
2. $n = 1$ (Q^2 dependent $\sigma_{\chi N}$)
3. $n = 2$ (Q^4 dependent $\sigma_{\chi N}$)



Energy reconstruction

For boosted DM signal

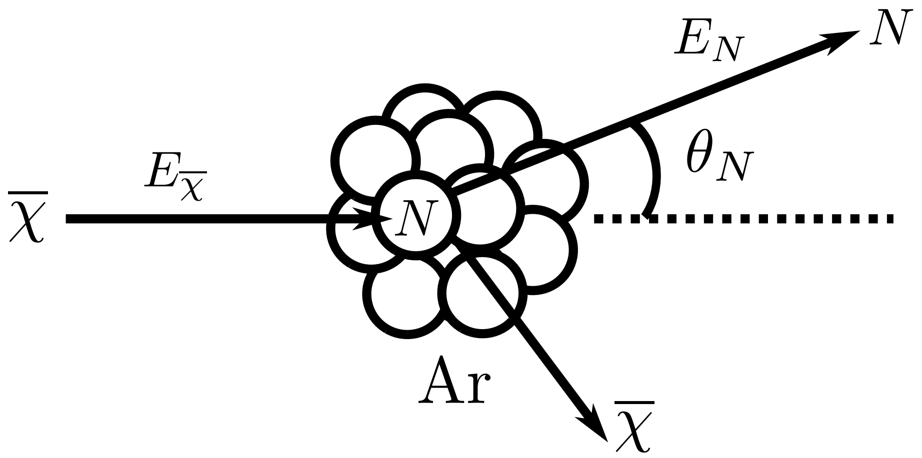
$$\cos\theta_N = \frac{E_\chi + m_N}{|\boldsymbol{p}_\chi|}\sqrt{\frac{E_N - m_N}{E_N + m_N}}$$

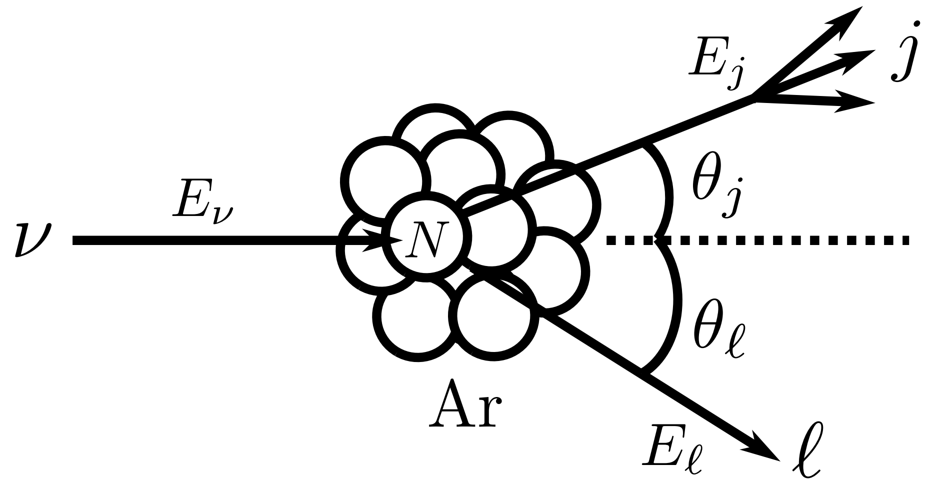
- Elastic scatering is dominant.
  $\Rightarrow$ Energy and angle are kinematically fixed.
- DM energy can be reconstructed from observed values θ_N and E_N

For neutrino signal arXiv: 1903.04175, C. Rott et al.

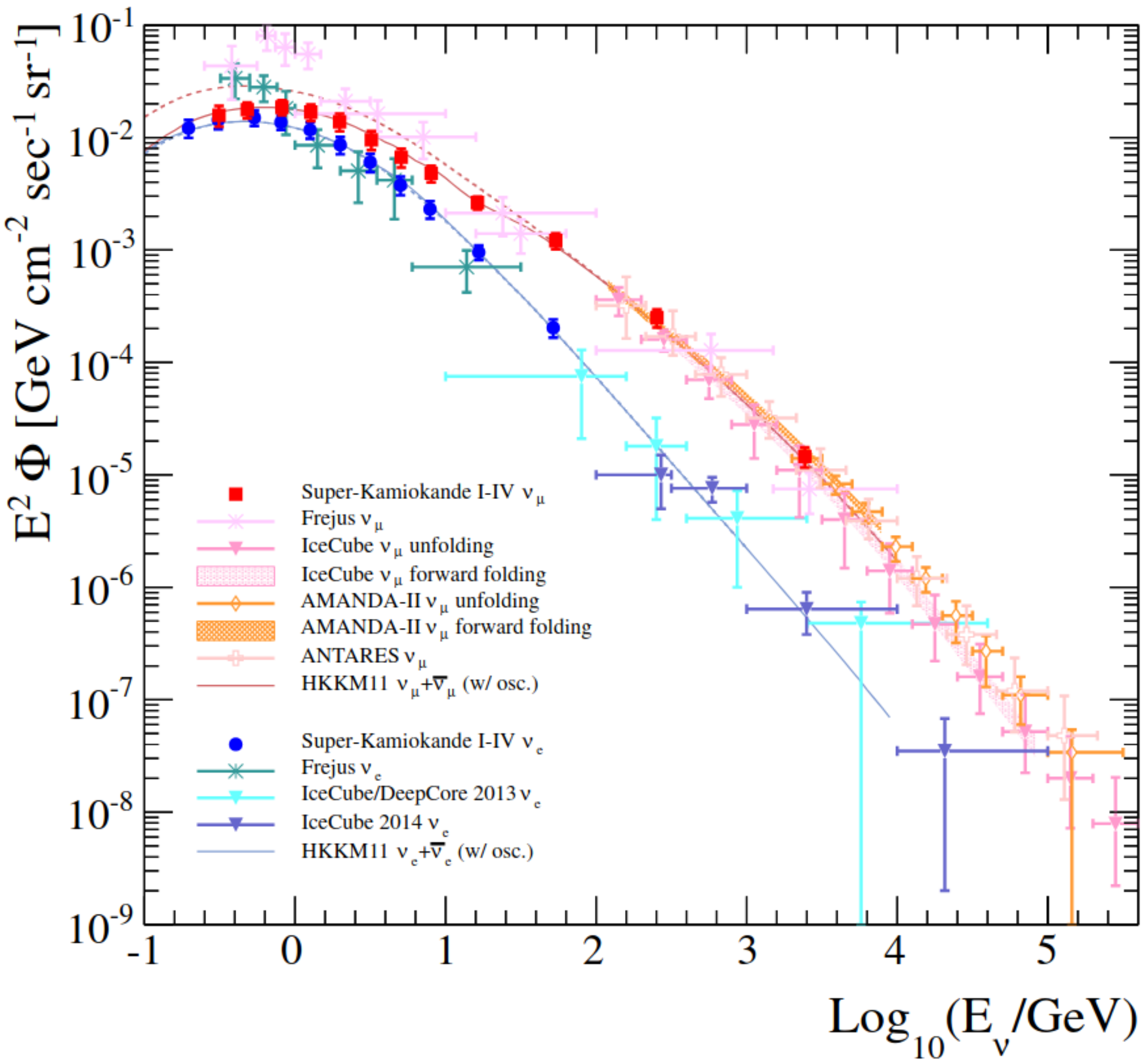
- $\nu + N \to e^-/\mu^- +$ jet

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





Background (atmospheric neutrinos)



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

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

Expected number of bkg events in 10 years with 40kton LAr

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

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

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

Results

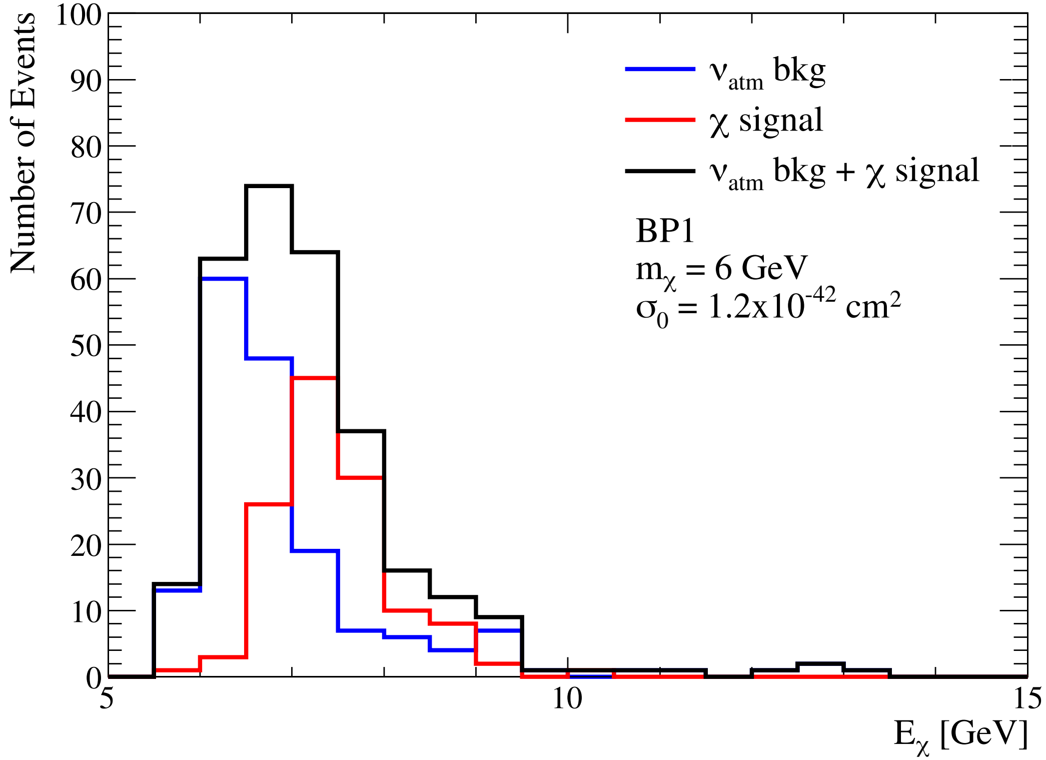
Benchmark parameter sets

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

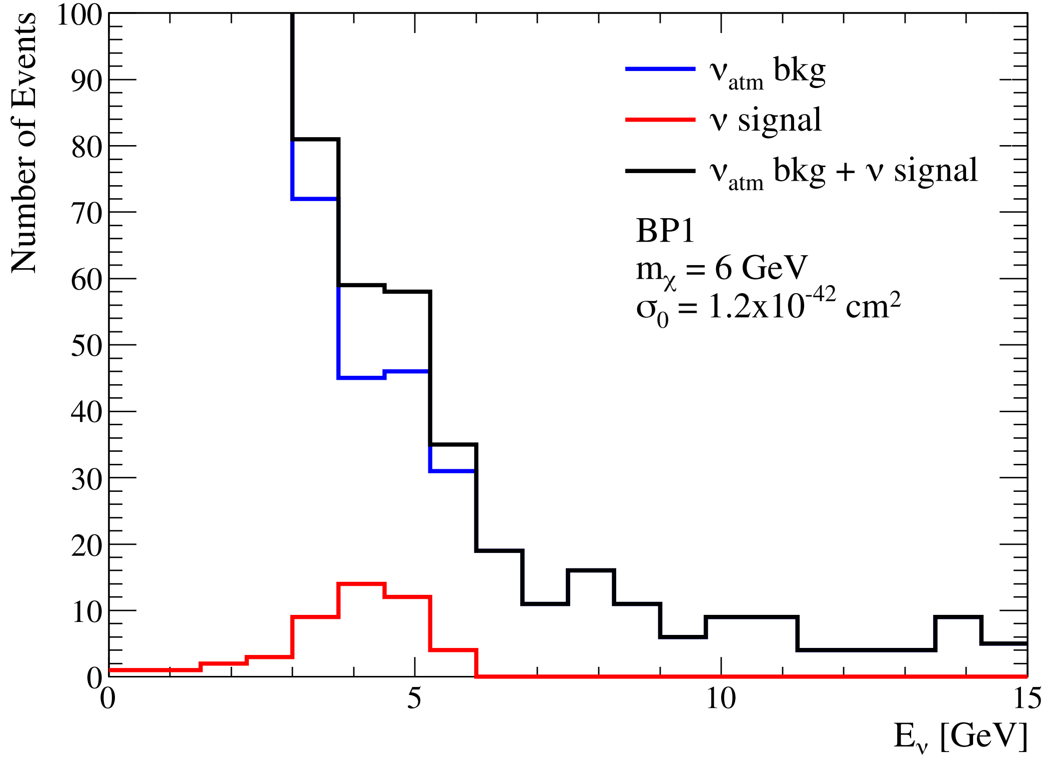
- Assumption: $V=$ 40kton liquid argon, $T=$ 10 years exposure
- We use GENIE (neutrino event generator).
- 4th and 5th columns: Expected events / Total events
  (detector threshold and resolutions)
- Large number of BDM signal events N_χ for BP2 ($n=2$)

Energy reconstruction for BP1

Boosted DM signal



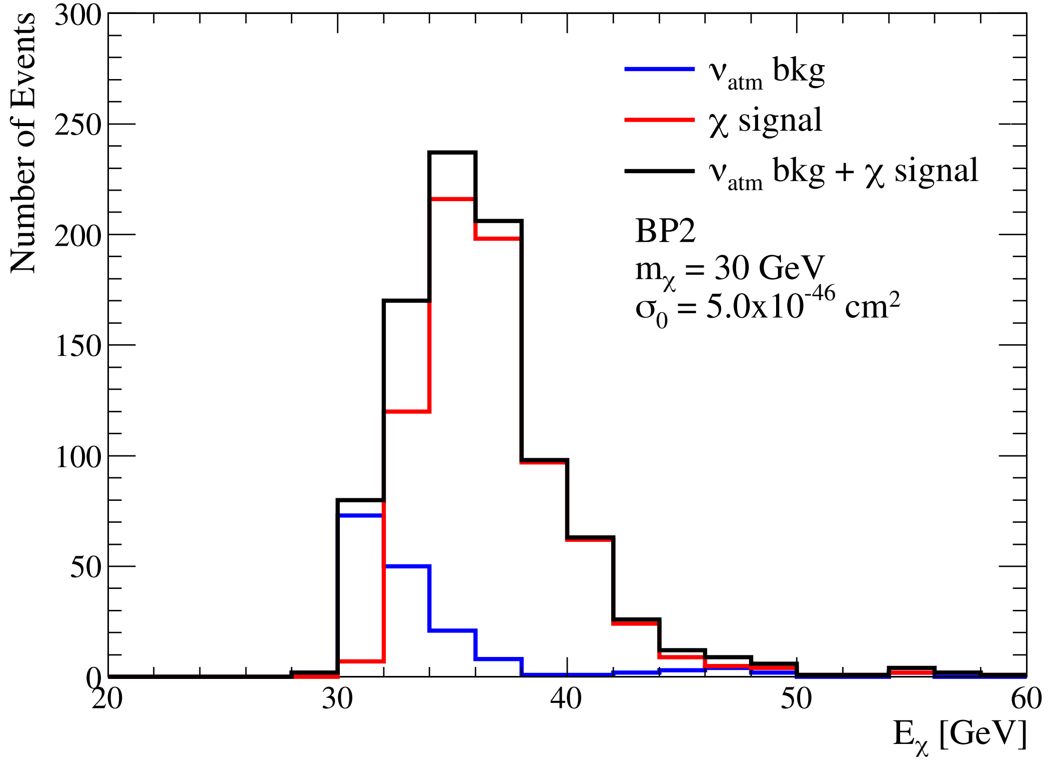
Neutrino signal



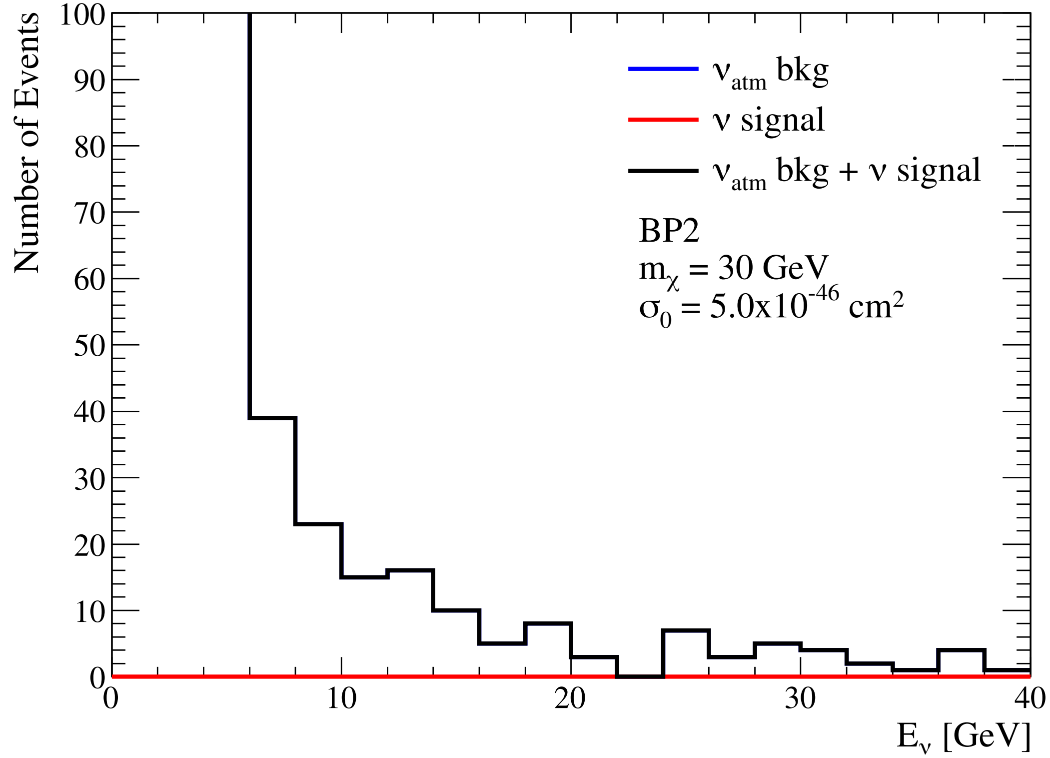
- $E_\chi = 7.5$ GeV and $E_\nu = 4.5$ GeV
- Large number of atmospheric neutrino bkg at low energy

Energy reconstruction for BP2

Boosted DM signal

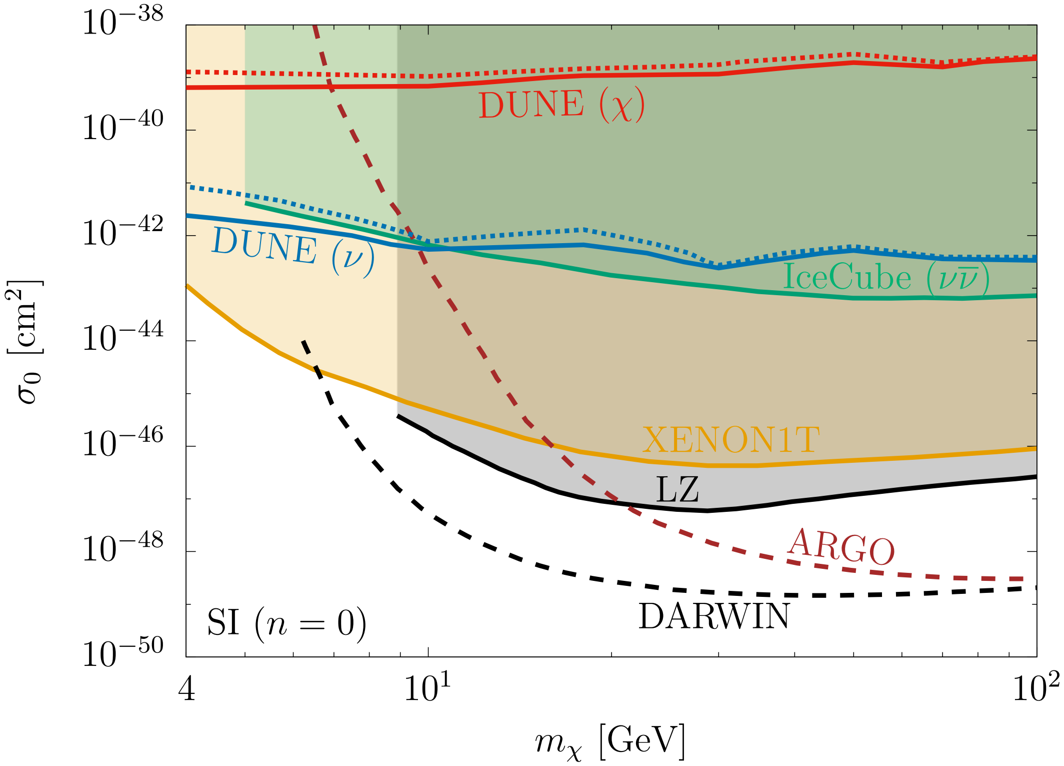


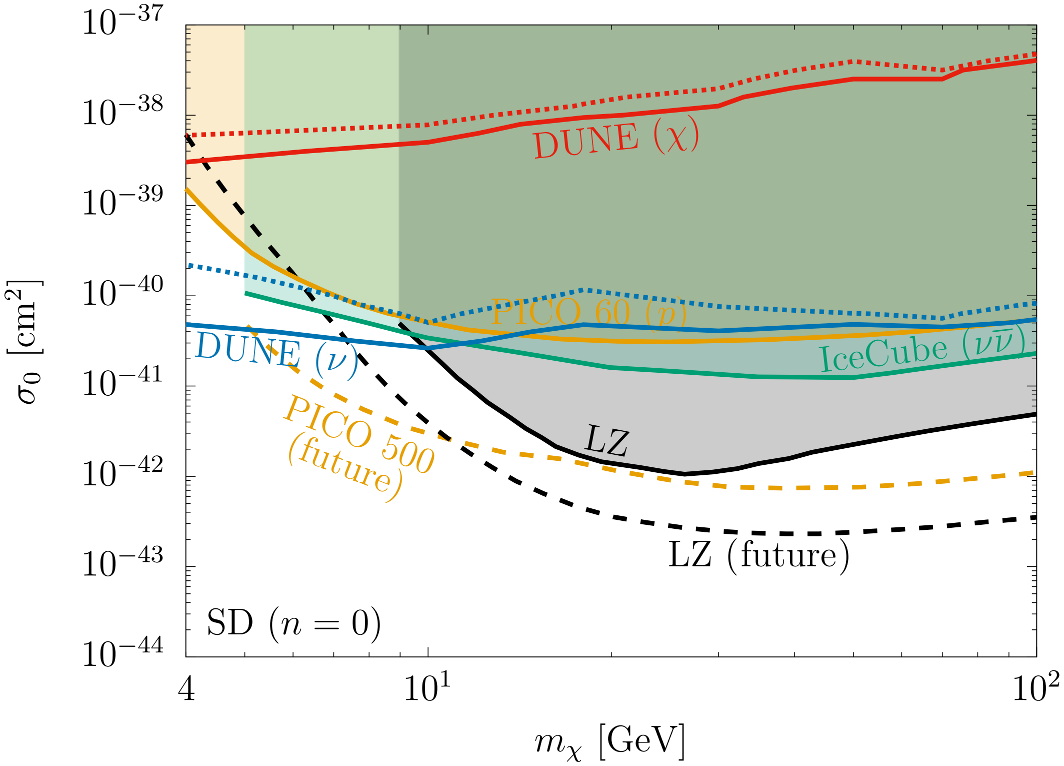
Neutrino signal



- $E_\chi = 37.5$ GeV and $E_\nu = 22.5$ GeV
- 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)

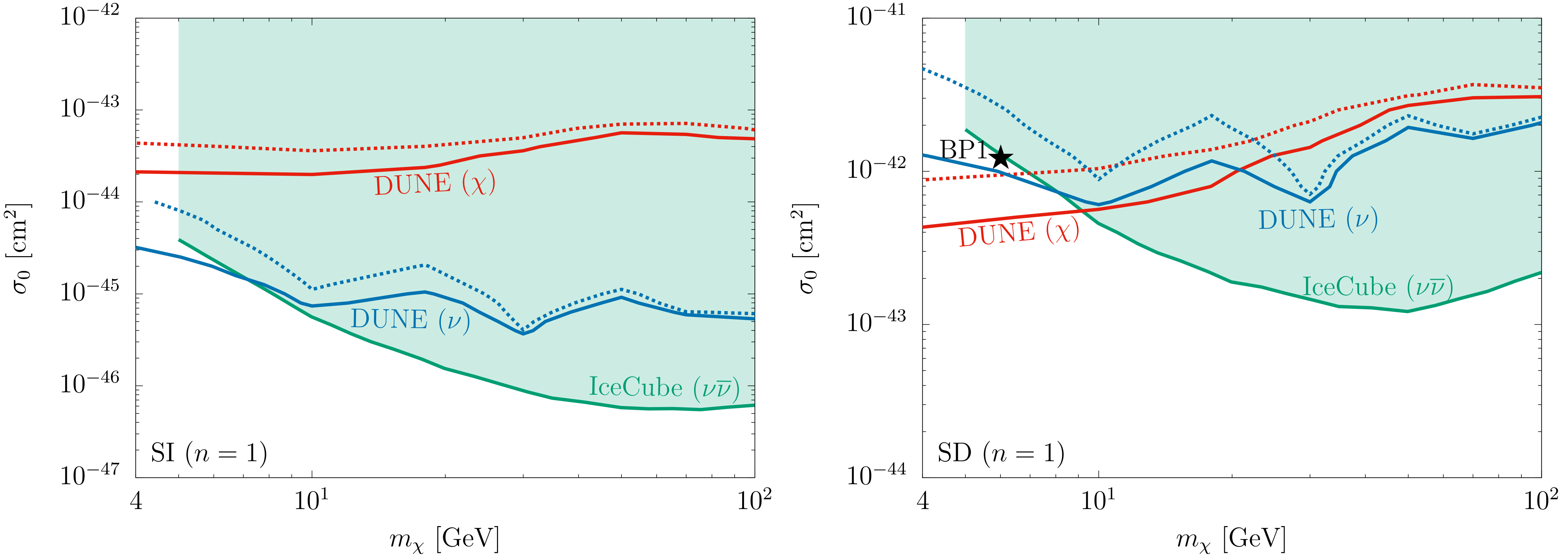
Parameter space ($n = 0$)





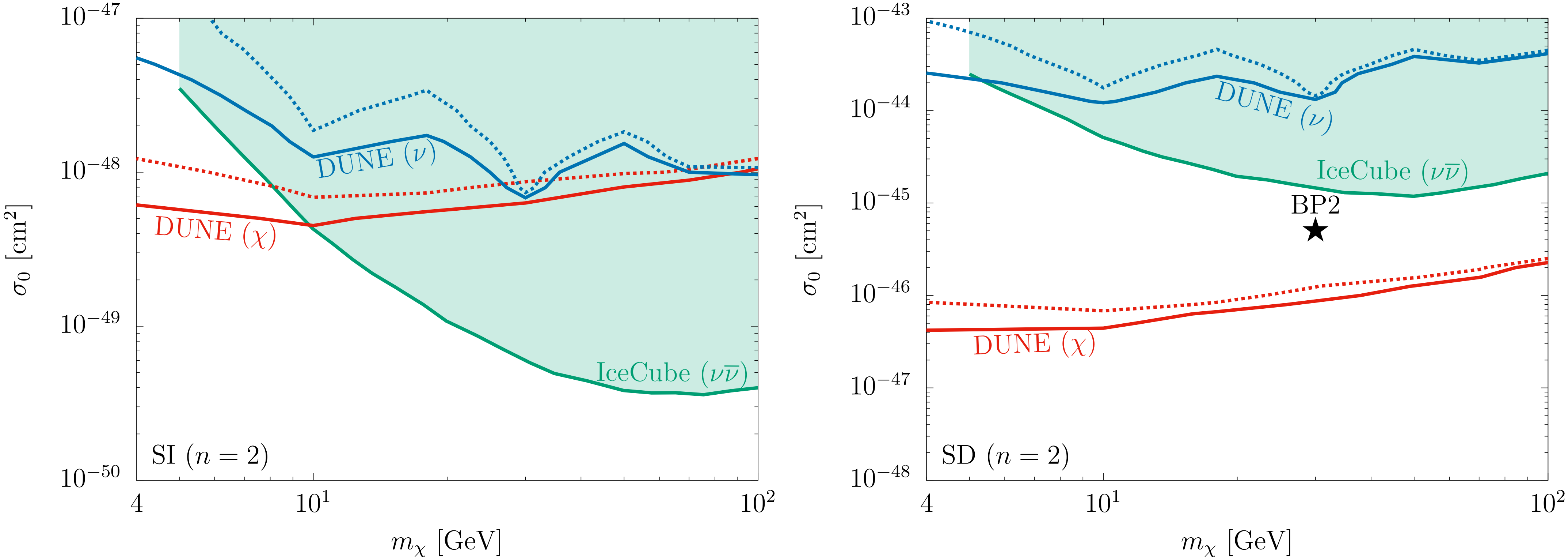
- Significance: $\mathcal{S} = \dfrac{N_{\rm sig}}{\sqrt{N_{\rm bkg} + N_{\rm sig} + \delta_{\rm syst}^2}}$, $\quad \delta_{\rm syst}$: 0% (solid lines)
  20% (dotted lines)
- Completely excluded by direct detection experiments as expected.

Parameter space ($n = 1$)



- No substantial direct detection constraints.
- Sensitivities can be comparable if DM mass is lower than 10 GeV.

Parameter space ($n = 2$)



- Much higher sensitivity for boosted DM (right)
  But large hierarchy with neutrino sensitivity
- Neutrinos cannot be observed at the same time at DUNE
  $\Rightarrow$ combining with Hyper-Kamiokande?

Summary

1. Direct detection experiments impose the strong bound on (minimal) thermal DM models.
2. v suppressed cross section naturally evades the bound.
3. Such kind of DM can be searched if it is boosted somehow.
4. $\chi\chi \to \nu\overline{\chi}$ induces two distinctive signals, which can be searched by DUNE, or combining DUNE and SK/HK/IceCube.

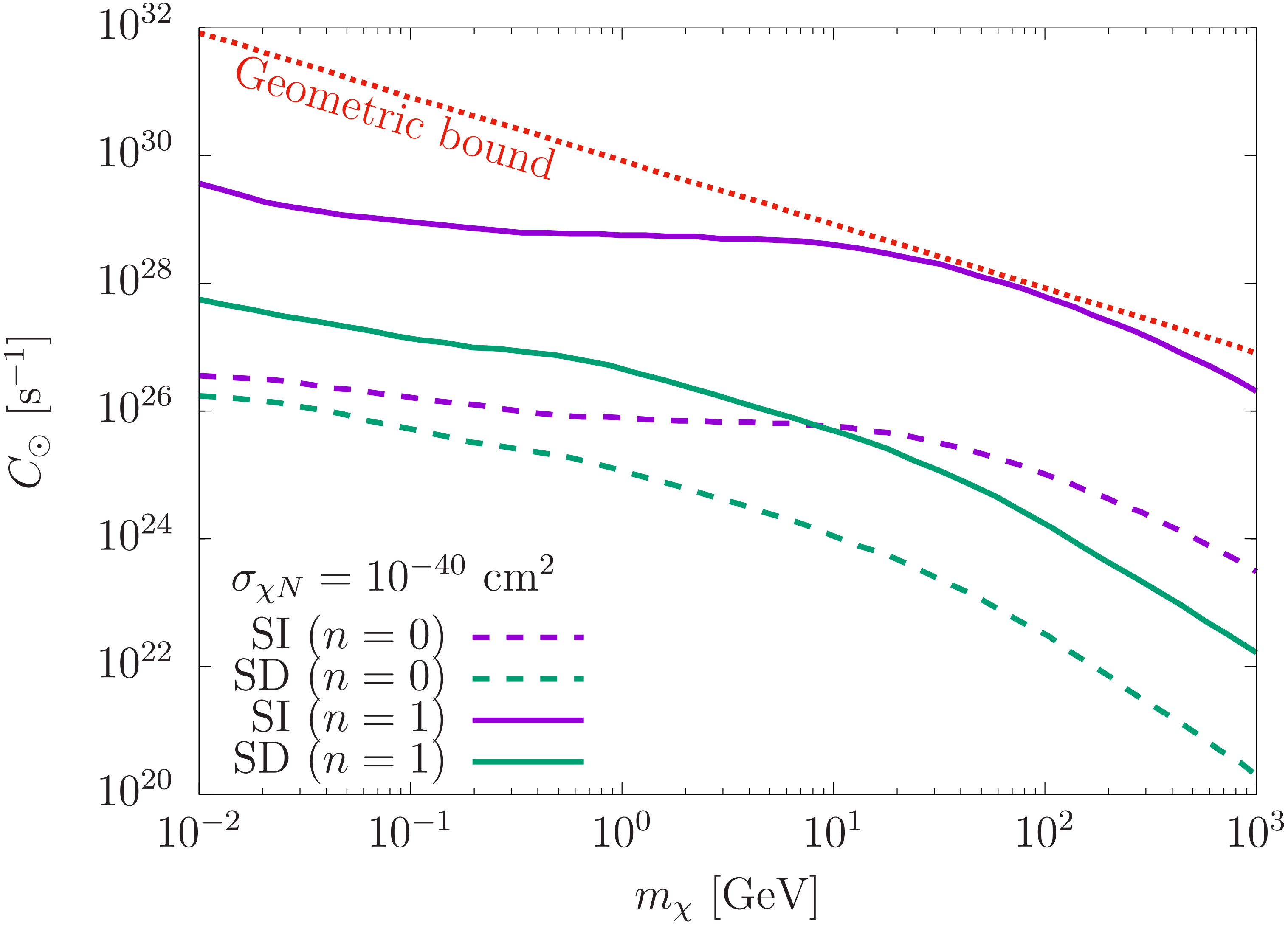
Backup

DM annihilation rate at the Sun

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

- Capture rate for $n = 0, 1$ cases

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



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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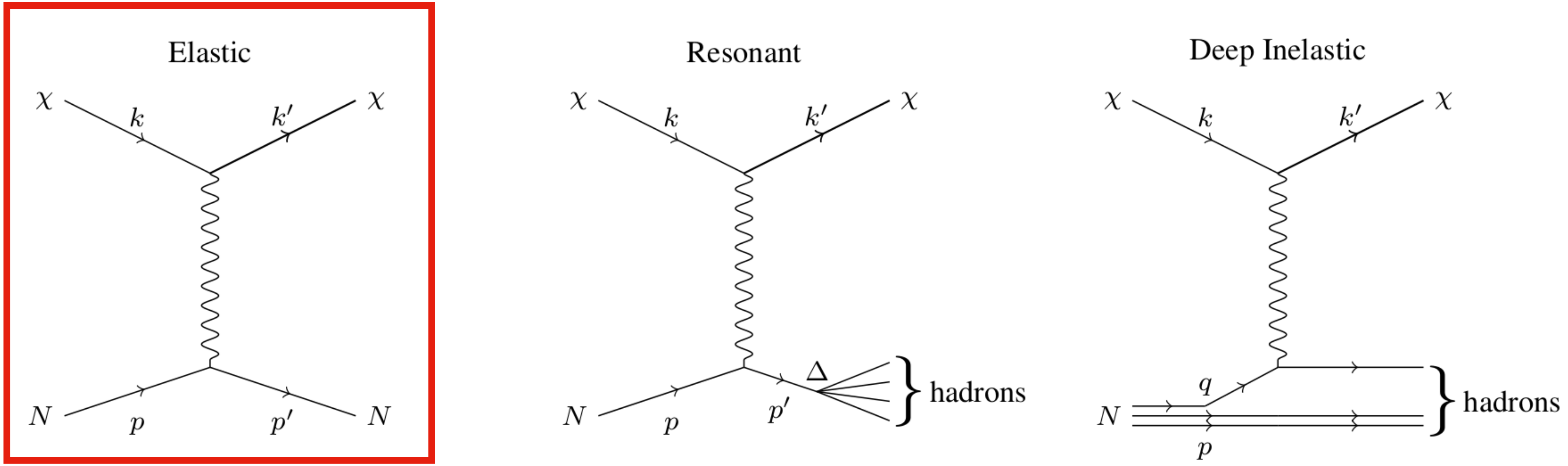
|------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                        |
|------------------------------------------------------------------------------------------------------------------|
| 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 GeV)^2

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

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

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	$2 + 15/\sqrt{E/\text{GeV}}$ %	1°
p	50 MeV	$\boldsymbol{p} < 400$ MeV: 10 % $\boldsymbol{p} > 400$ MeV: $5 + 30/\sqrt{E/\text{GeV}}$ %	5°
n	50 MeV	$40/\sqrt{E/\text{GeV}}$ %	5°

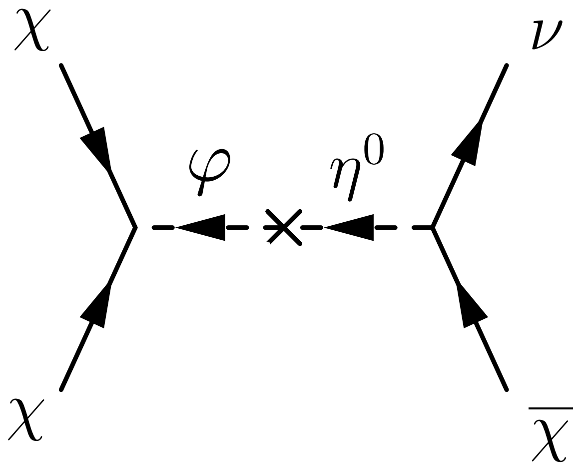
- Precise angular resolution (DUNE)
  cf: 3° at SK and HK, 30° at IceCube
- These are taken into account in event selection.

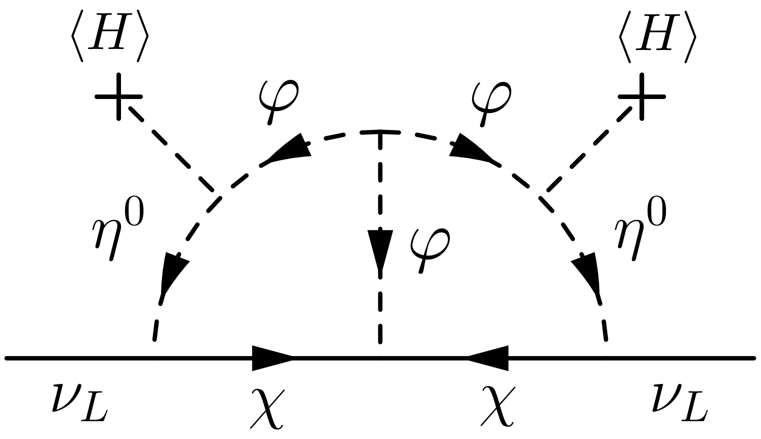
Example of model building

- 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





Example of model building

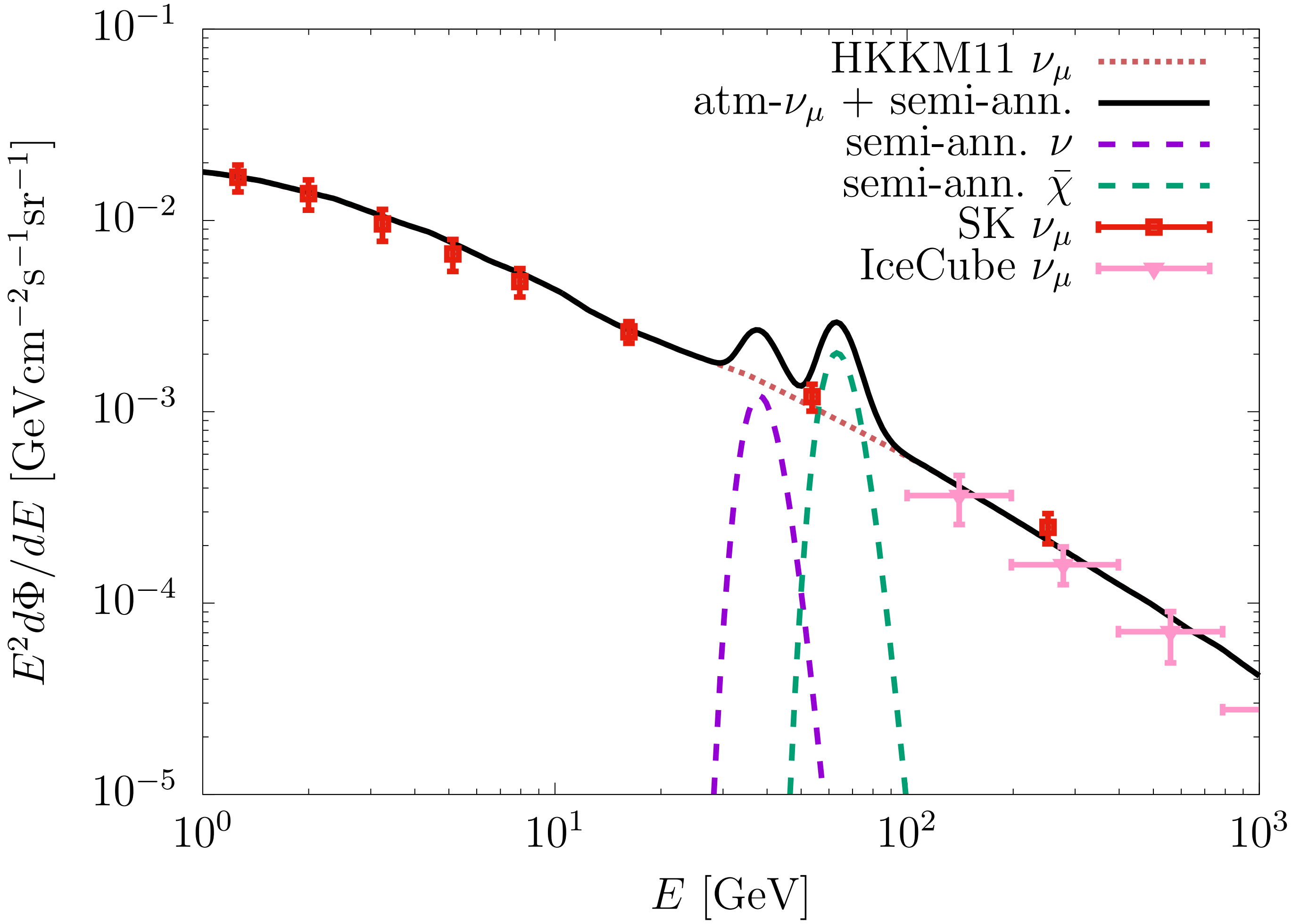
Velocity-dependent scattering $\chi N \to \chi N$

$$\text{Anapole int.} \quad \mathcal{L} \supset \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\gamma_5\partial_\nu\chi F^{\mu\nu} \quad \to \quad \sigma \propto v^2$$

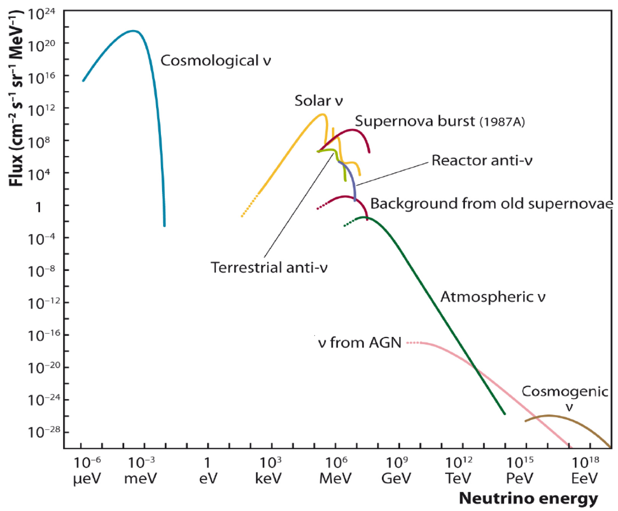
$$\text{SP int.} \quad \mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{\chi}\chi)\left(\bar{N}\gamma_5 N\right) \quad \to \quad \sigma_{\mathrm{SD}} \propto v^2$$

$$\text{PP int.} \quad \mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{\chi}\gamma_5\chi)\left(\bar{N}\gamma_5 N\right) \quad \to \quad \sigma_{\mathrm{SD}} \propto v^4$$

$\nu + \bar{\chi}$ flux if it is nicely reconstructed



- $E_{\bar{\chi}} = \frac{5}{4} m_\chi$
  $E_\nu = \frac{3}{4} m_\chi$
  $\Delta E = \frac{1}{2} m_\chi$



- $m_\chi = 50$ GeV and $\sigma_{\rm SD} = 3 \times 10^{-41}$ cm^2 (non-relativistic)
- $\Delta E/E = 25\%$ is assumed

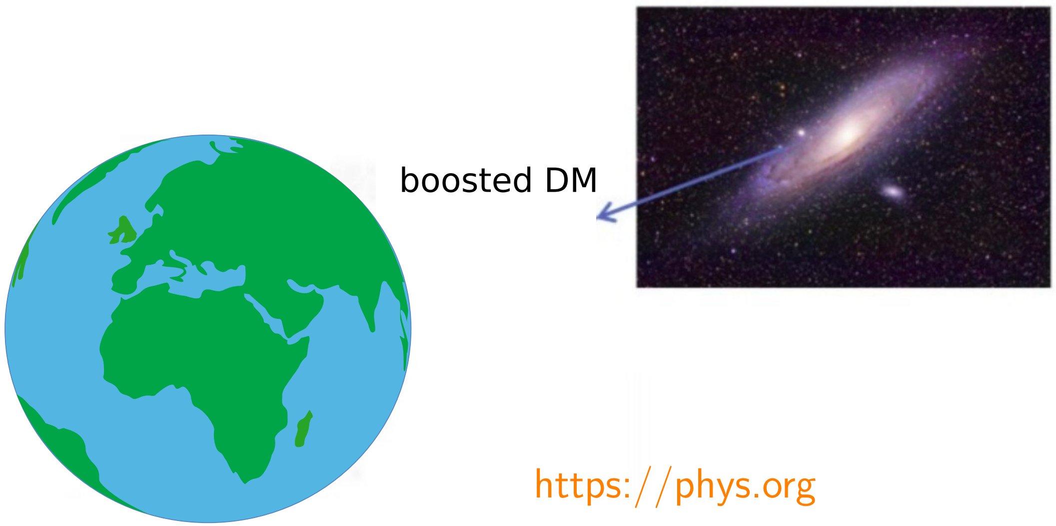
U. Katz and C. Spiering, Prog. Part. Nulc. Phys. (2012) [arXiv:1111.0507]

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

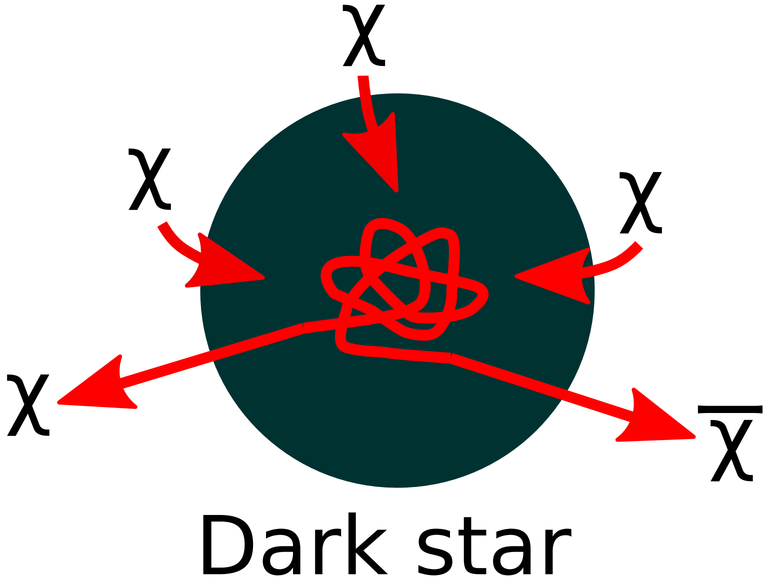
- SIMP: $\chi\chi\chi \to \chi\overline{\chi}$
- Decay or annihilations of heavier particles (non-minimal dark sector)
  $\chi_2\chi_2 \to \chi_1\chi_1$ $(m_{\chi_2} \gg m_{\chi_1})$
- Collision with high energy cosmic-rays
  Bringmann and Pospelov
  PRL (2019), arXiv:1810.10543
- Vacuum decay
  J. Cline, M. Puel, TT, Q. Wang
  arXiv:2308.01333, 2308.12989



https://phys.org

Future works

- Application to new annihilation processes such as SIMP
  - $\dfrac{dn}{dt} + 3Hn = -\langle \sigma_{3\to 2} v^2 \rangle \left(n^3 - n^2 n_{\rm eq} \right)$
  - 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