暗黒物質の半対消滅から生じるシグナル

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阿蘇研究会

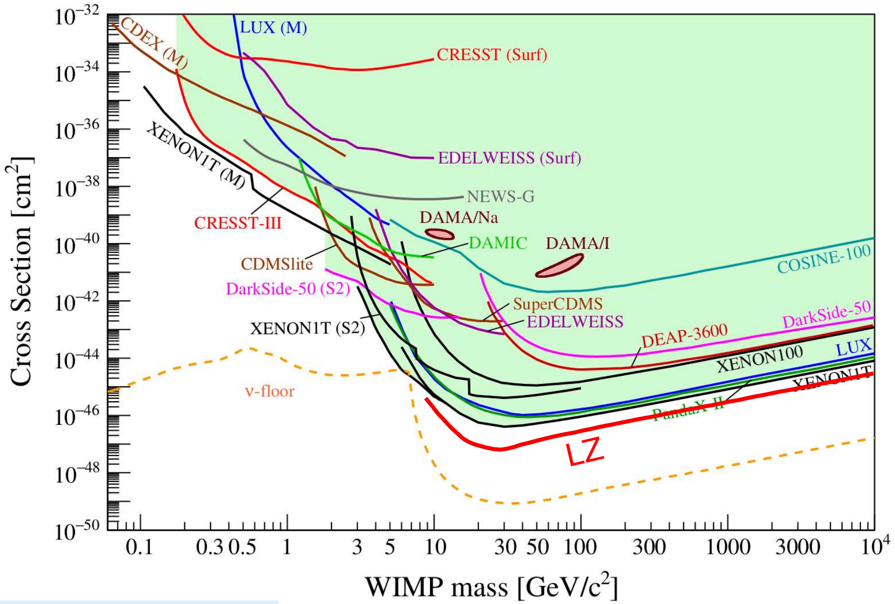
参考文献: Phys.Rev.D 105 (2022) 4, 043007,
arXiv:2309.00395

共同研究者：青木 真由美 氏

要約

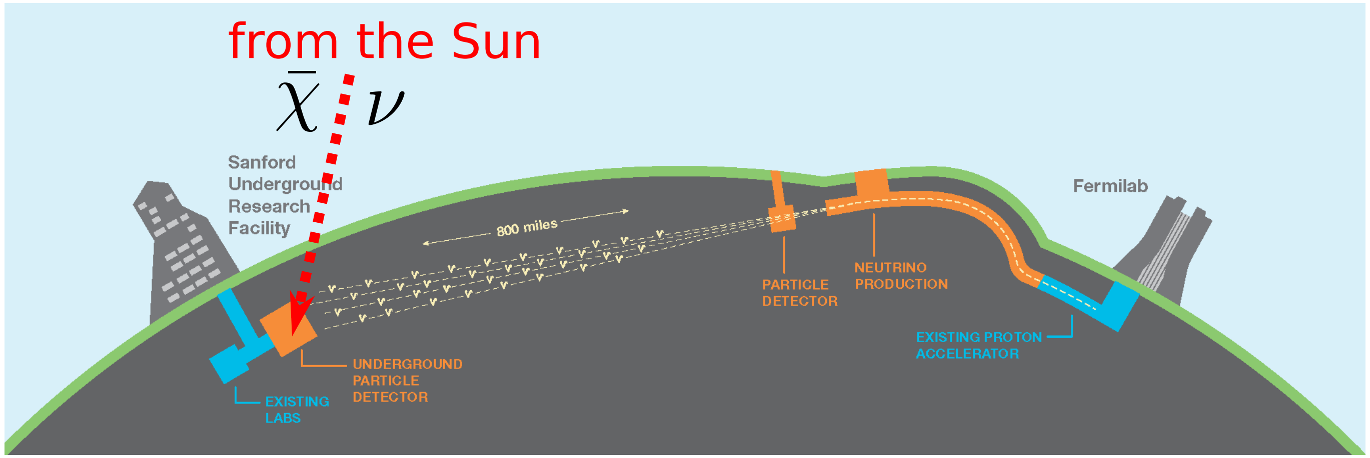
- DM直接検出実験の制限が強い
  $\Rightarrow$ 速度または運動量依存の散乱断面積 (ex. pNG DM)
  $\Rightarrow$ 速度の速いDMが生成
  されれば検出できるかも

参照：日本物理学会誌2023年6月号

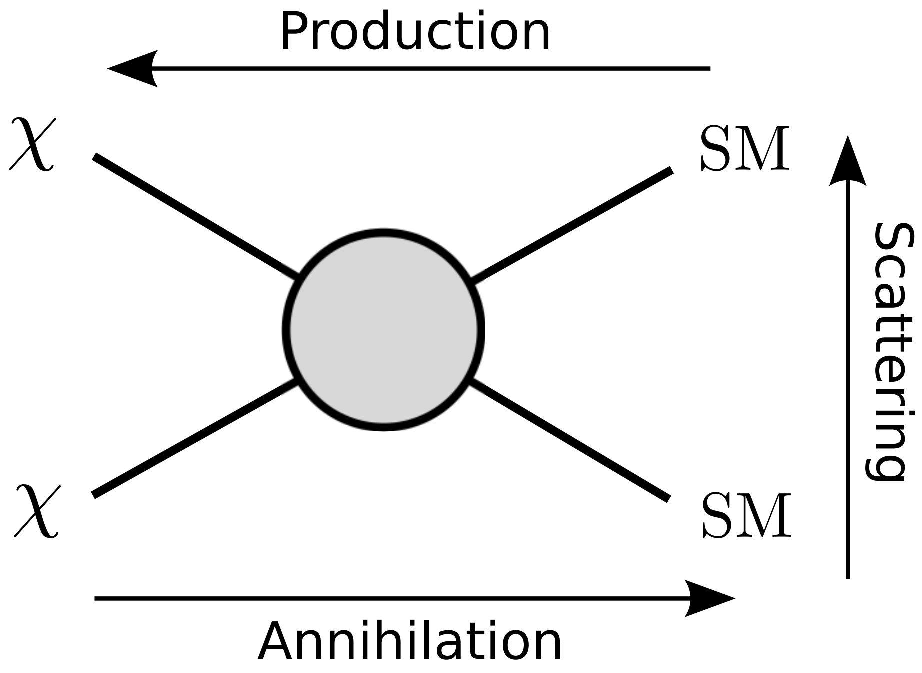


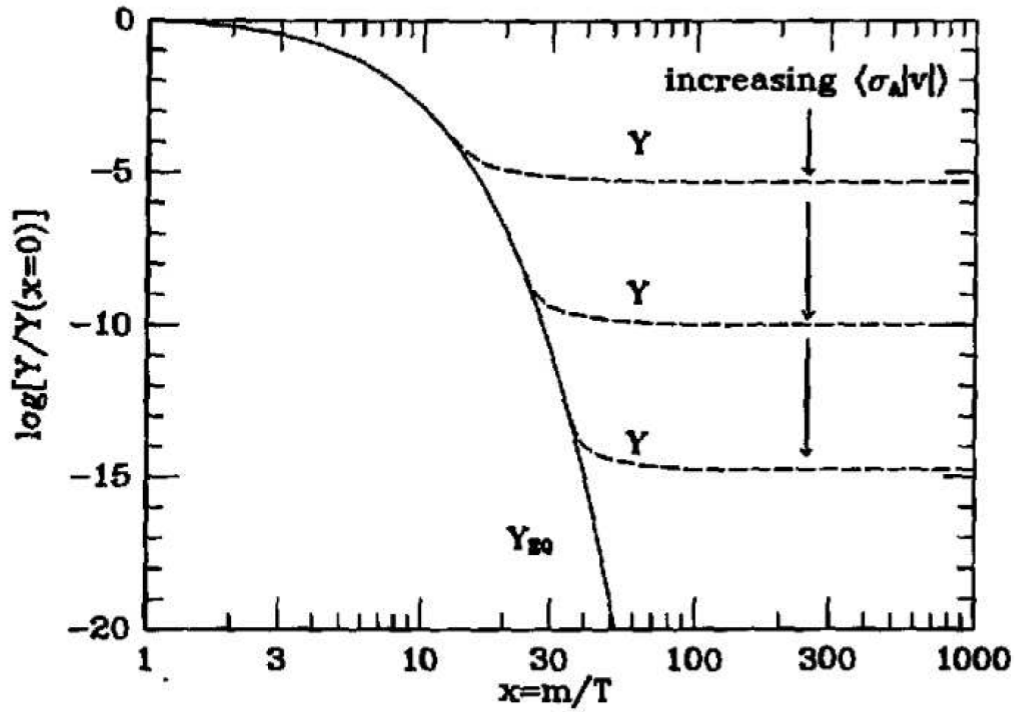
- DM加速機構の一つ
  半対消滅 (semi-annihilation)
  $\chi\chi \to \chi\phi$

- DUNEで検証できるかも



WIMP (Weakly Interacting Massive Particle)

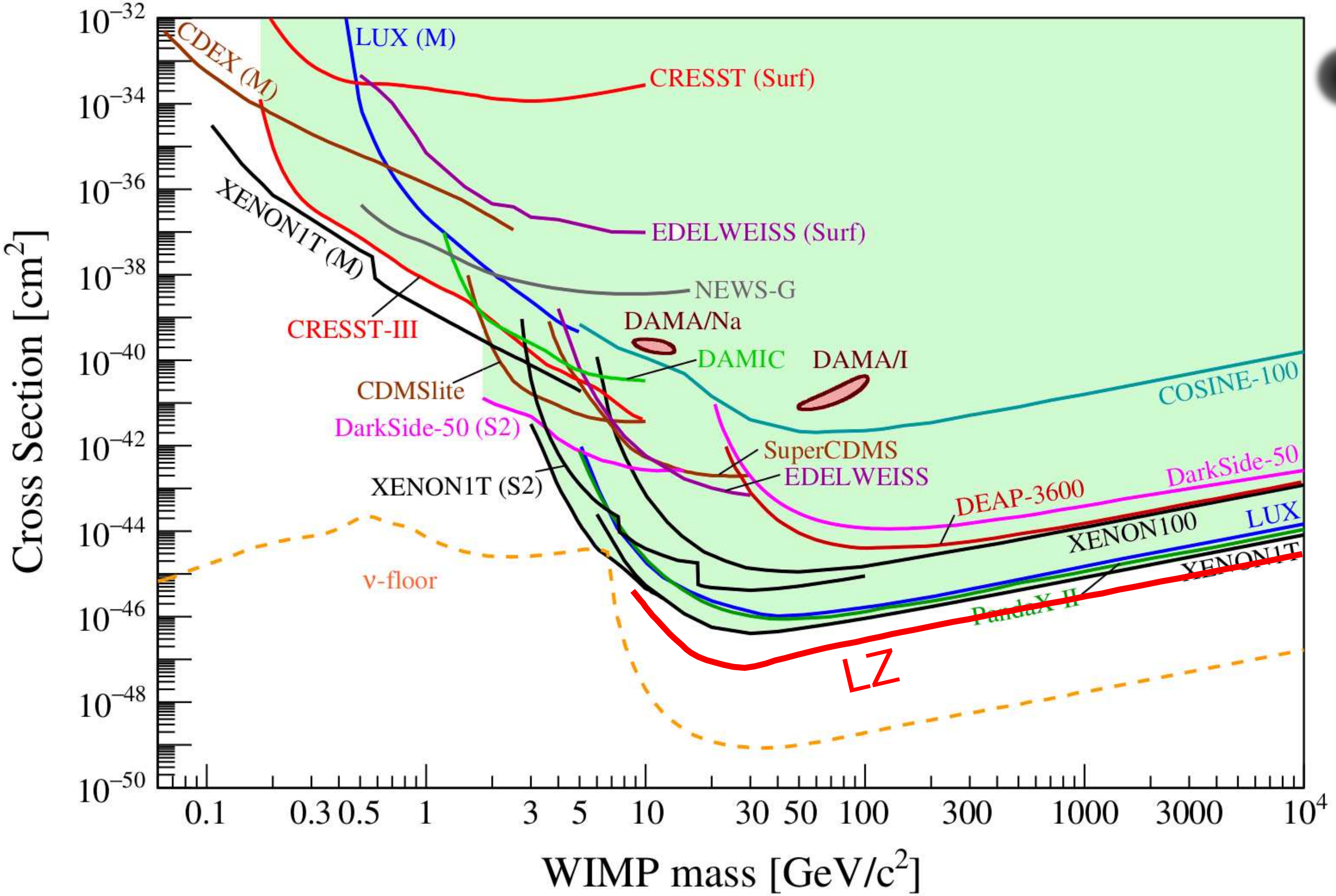


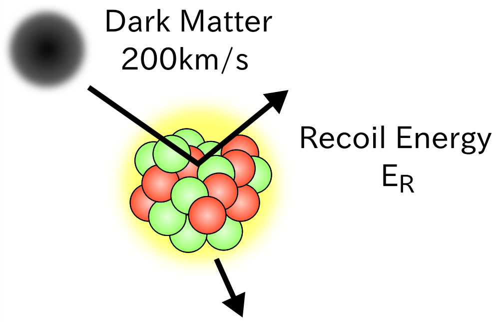


$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right)$$

- 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

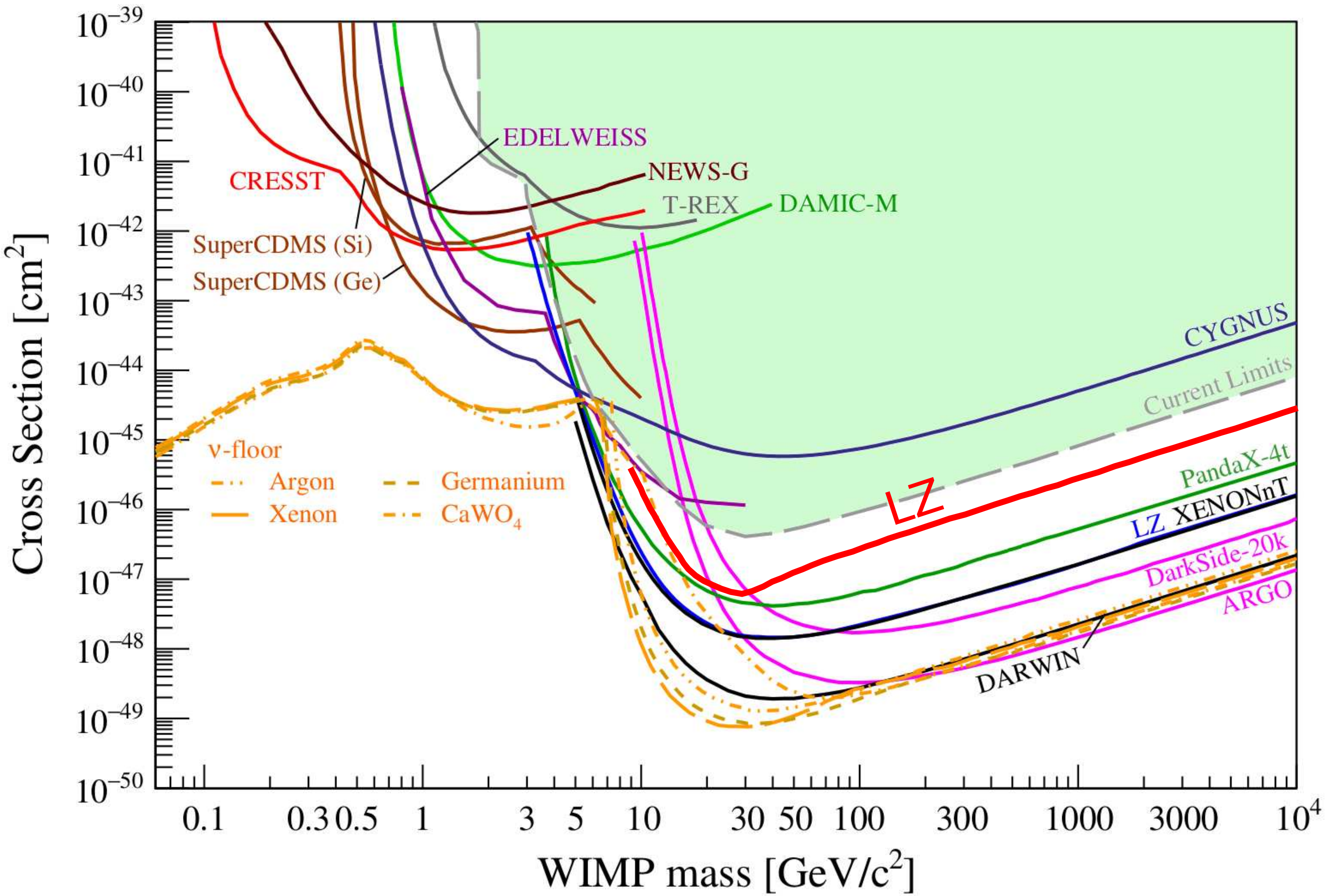




arXiv:2104.07634
LZ arXiv:2207.03764

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

Future sensitivity of direct detection experiments



Billard et al.,
arXiv:2104.07634
LZ arXiv:2207.03764

- Experiments will reach the neutrino floor in 20 years.

Wayout

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

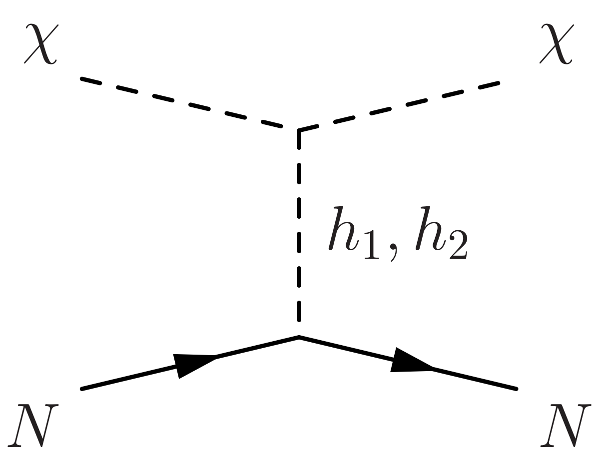
  Ex.1 pNGB DM ($i\mathcal{M} \propto v_\chi^2$)

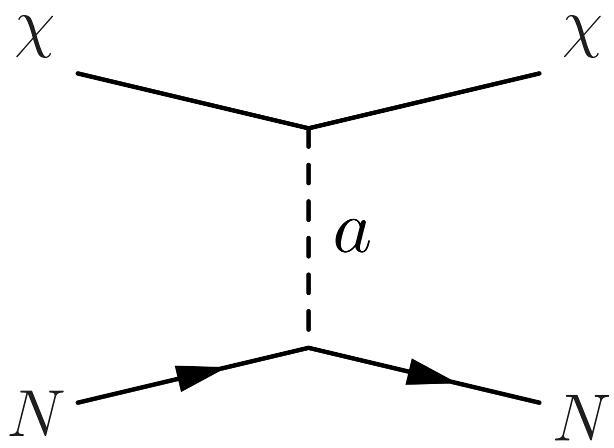
  C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

  Ex.2 Fermion DM with Pseudo-scalar int.

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

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





$\Rightarrow$ These could be detected if boosted.

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

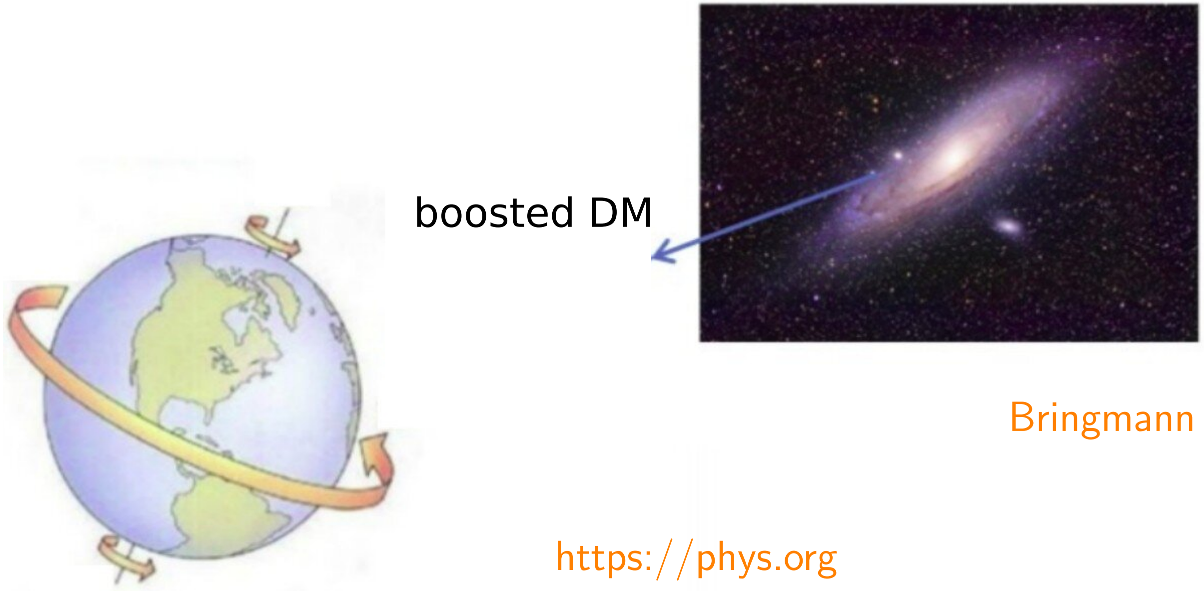
Anapole int.	$\mathcal{L} \supset \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\gamma_5\partial_\nu\chi F^{\mu\nu}$	$\to$	$\sigma \propto v^2$
SP int.	$\mathcal{L} \supset \frac{1}{\Lambda^2}\left(\bar{\chi}\chi\right)\left(\bar{p}\gamma_5 p\right)$	$\to$	$\sigma_{\mathrm{SD}} \propto v^2$
PP int.	$\mathcal{L} \supset \frac{1}{\Lambda^2}\left(\bar{\chi}\gamma_5\chi\right)\left(\bar{p}\gamma_5 p\right)$	$\to$	$\sigma_{\mathrm{SD}} \propto v^4$

Mechanisms to boost DM

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

Other processes to boost DM

- 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

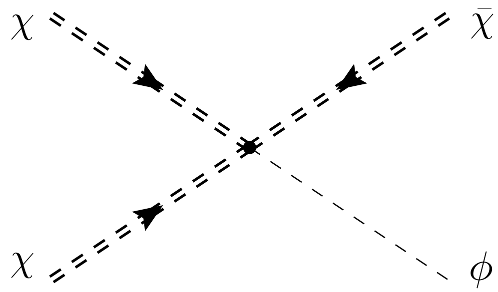


Bringmann and Pospelov, PRL (2019), arXiv:1810.10543

https://phys.org

Semi-annihilations

- $\chi_i \chi_j \to \chi_k \phi$ F. D'Eramo and J. Thaler, JHEP (2010) [arXiv:1003.5912]
  χ_i: DM particles, ϕ: SM or new unstable particle
  One DM particle is in final state.
- Simplest case: $\chi\chi \to \bar{\chi}\phi$
  χ: DM, ϕ: SM particle or new unstable particle



- Simple $\mathbb{Z}_2$ parity does not work to stabilize DM.
  $\Rightarrow$ DM is a non self-conjugate particle.
- Boltzmann equation

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

1st term: normal ann. 2nd term: semi-ann.
Note: normal annihilations also exist.

Example of model building

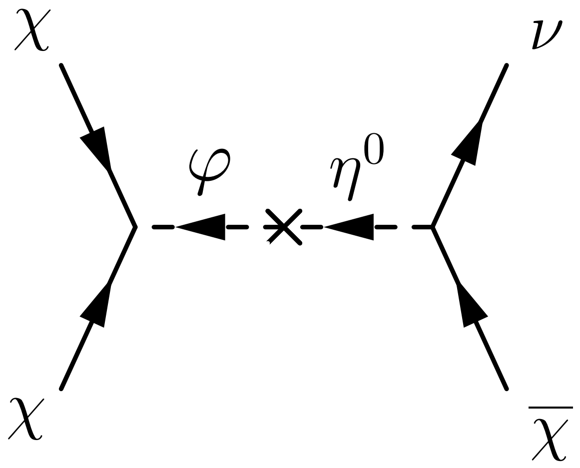
- Semi-annihilation $\chi\chi \to \nu\overline{\chi}$

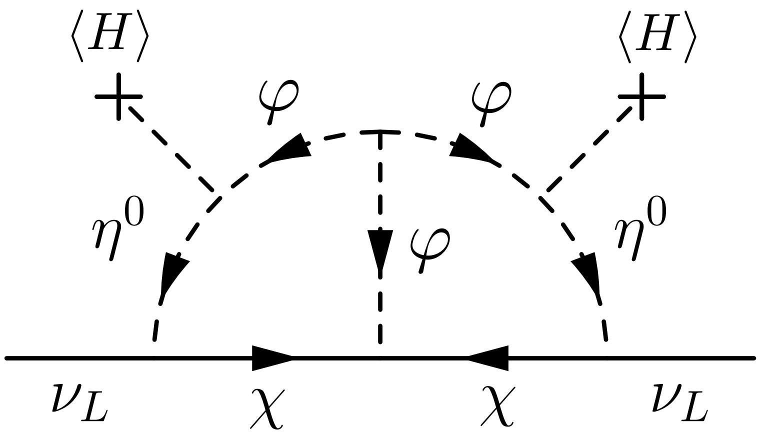
  Ex. $\mathbb{Z}_3$ symmetric model with radiative neutrino masses

  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





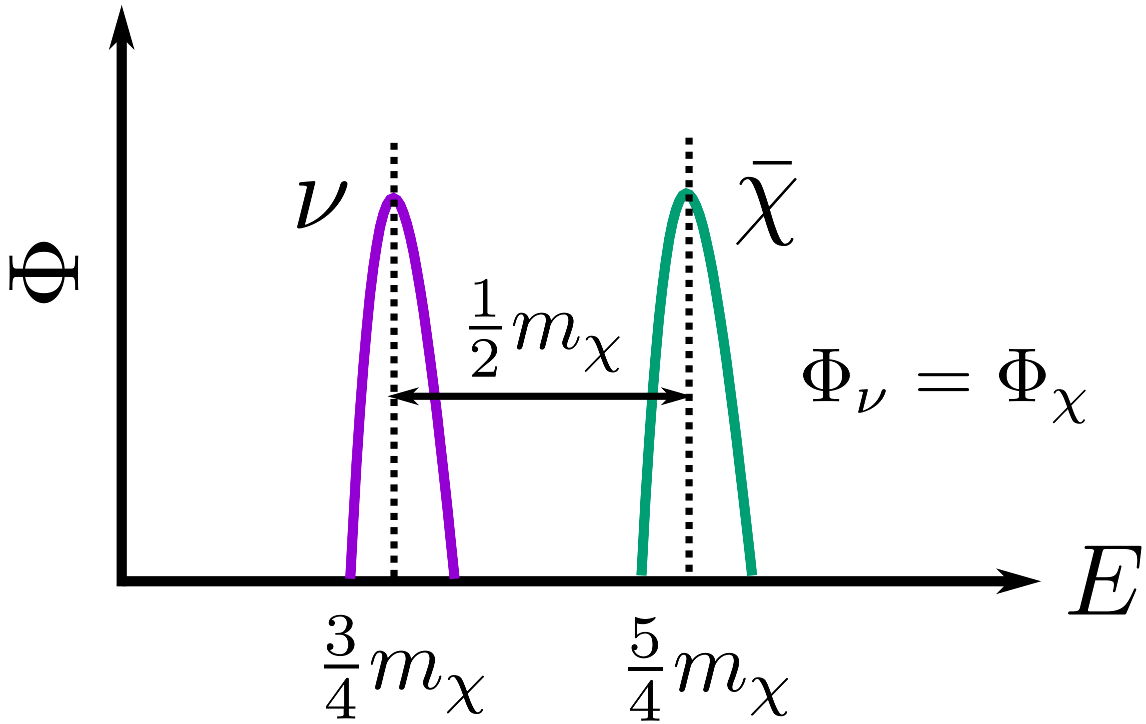
Distinctive signals from semi-annihilations

Specific semi-annihilation process

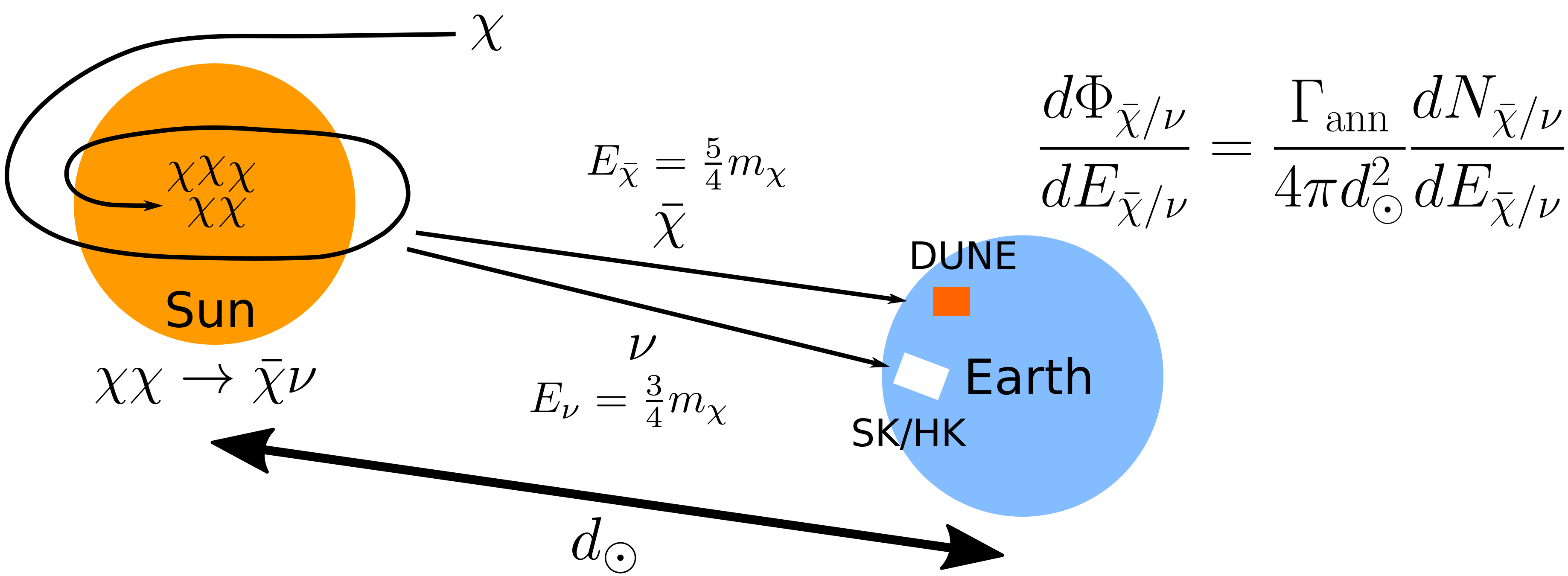
- We focus on $\chi\chi \to \nu\overline{\chi}$.
  - Both final state particles are monochromatic
  - May correlate with generation of small neutrino masses
- Energy of the produced particles

$$E_{\bar{\chi}} = \frac{5}{4} m_\chi \quad (v_\chi = 0.6), \qquad E_\nu = \frac{3}{4} m_\chi$$

- Possible to detect both particles (monochromatic)
  - Energy difference: $\frac{1}{2} m_\chi$
  - Same flux for $\bar{\chi}$ and ν
- If detected, this strongly implies that DM is a Dirac fermion with spin 1/2.

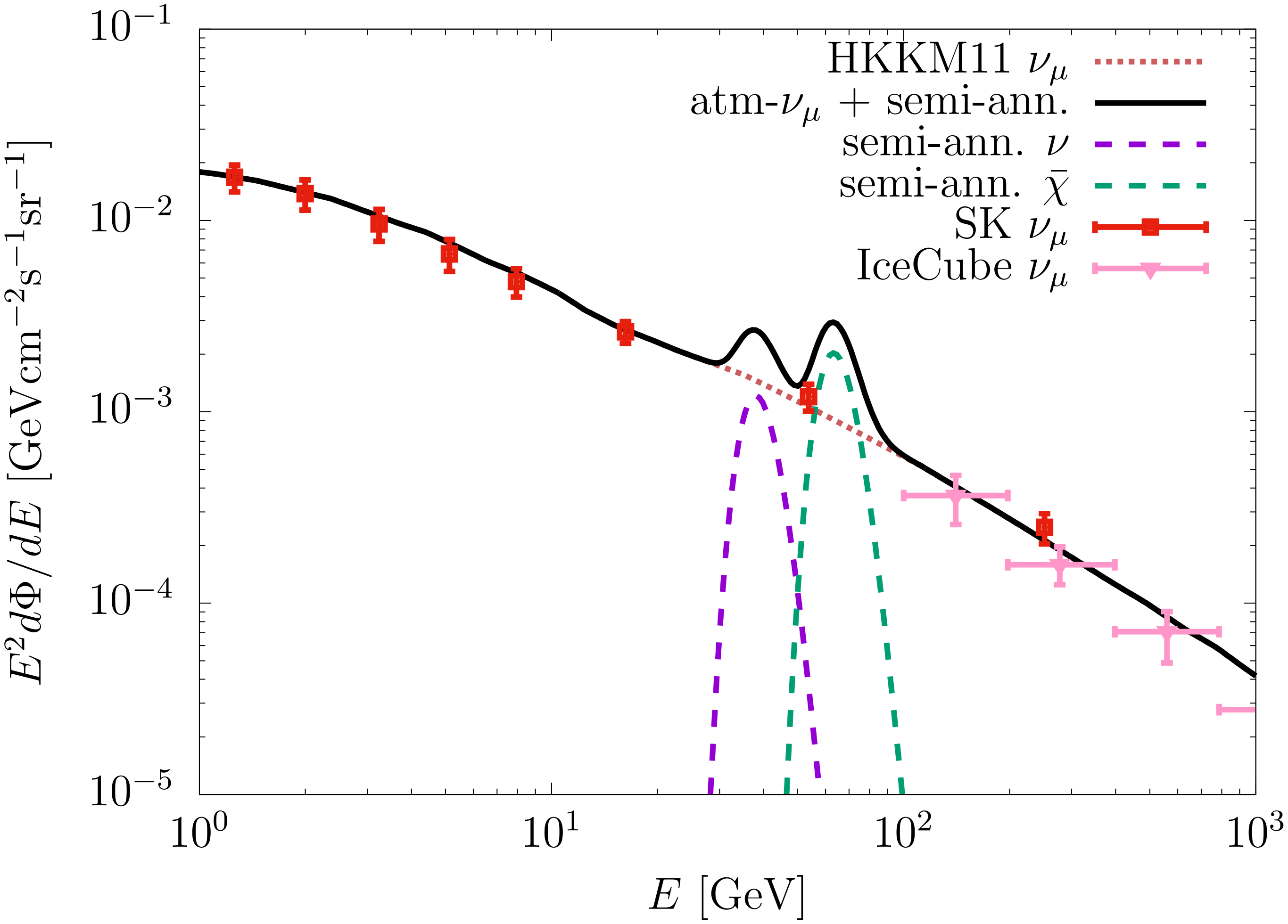


Signals from the Sun

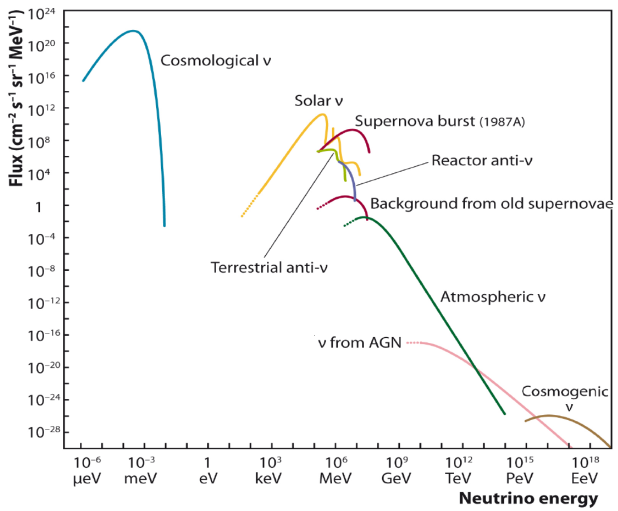


- A number of DM particles are accumulated in the centre of the Sun.
- Semi-annihilation occurs.
- Two kinds of signals can be searched at large volume neutrino detectors (SK, HK, DUNE etc).
- Signals produced at Galactic centre is smaller.

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



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



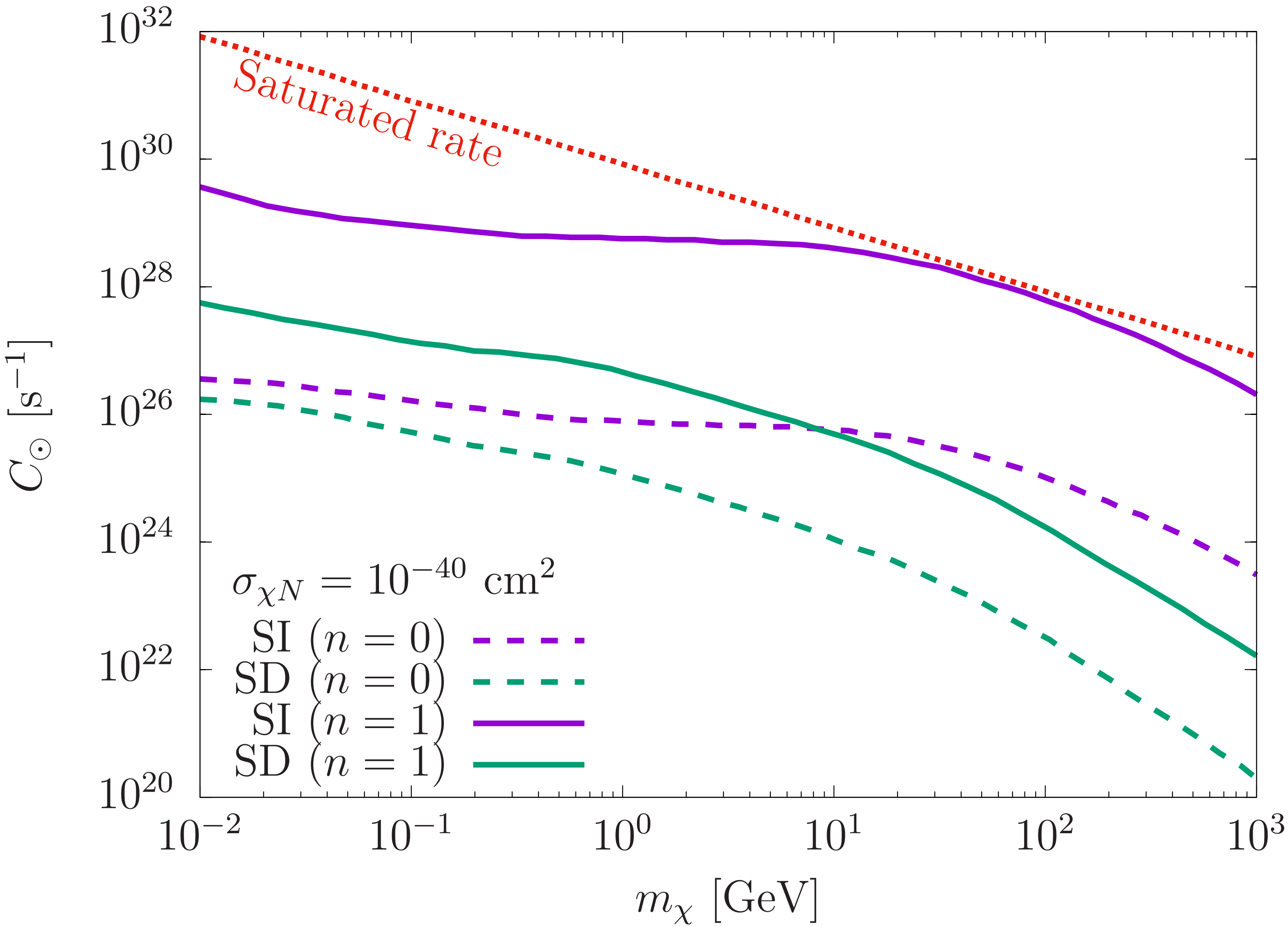
- $m_\chi = 50$ GeV and $\sigma_{\rm SD} = 3 \times 10^{-41}$ cm^2 (non-relativistic)
- $\Delta E/E = 25\%$ is assumed

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

Semi-annihilation at the Sun

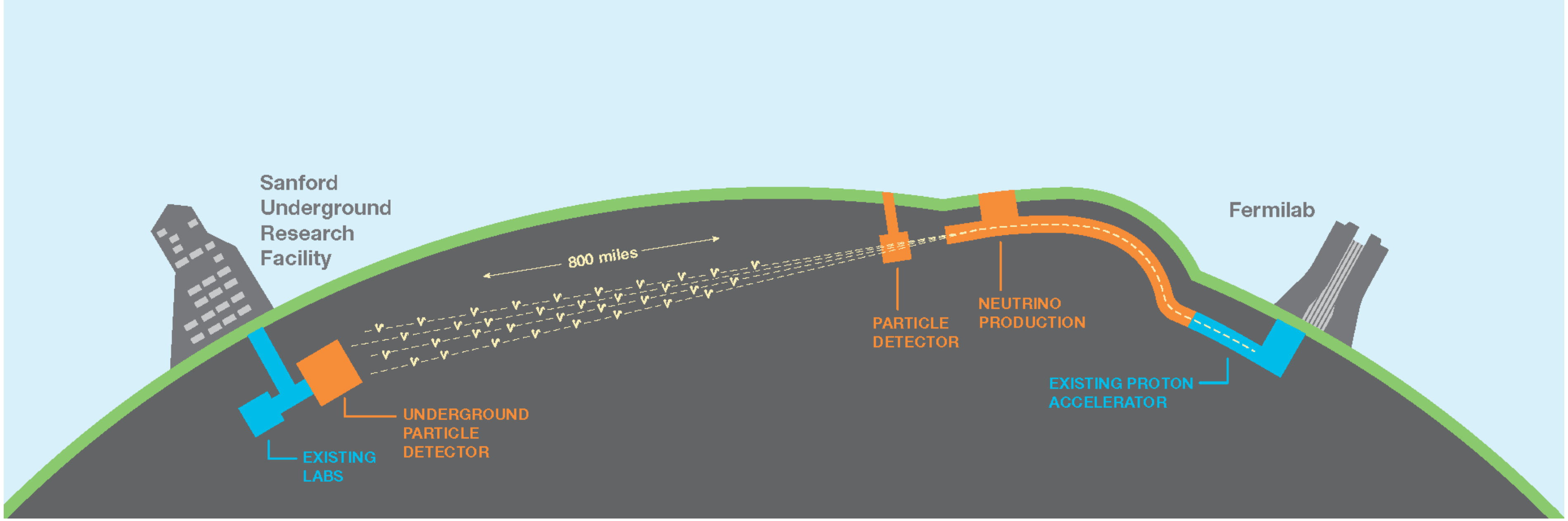
R. Garani et al., JCAP (2014) [arXiv:1702.02768]

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

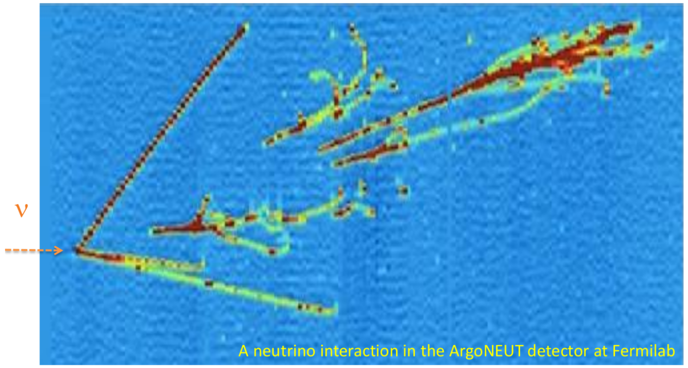


$$\sigma_{\chi N} \sim \sigma_0 (Q^2/Q_0^2)^n$$

DUNE (Deep Underground Neutrino Experiment)

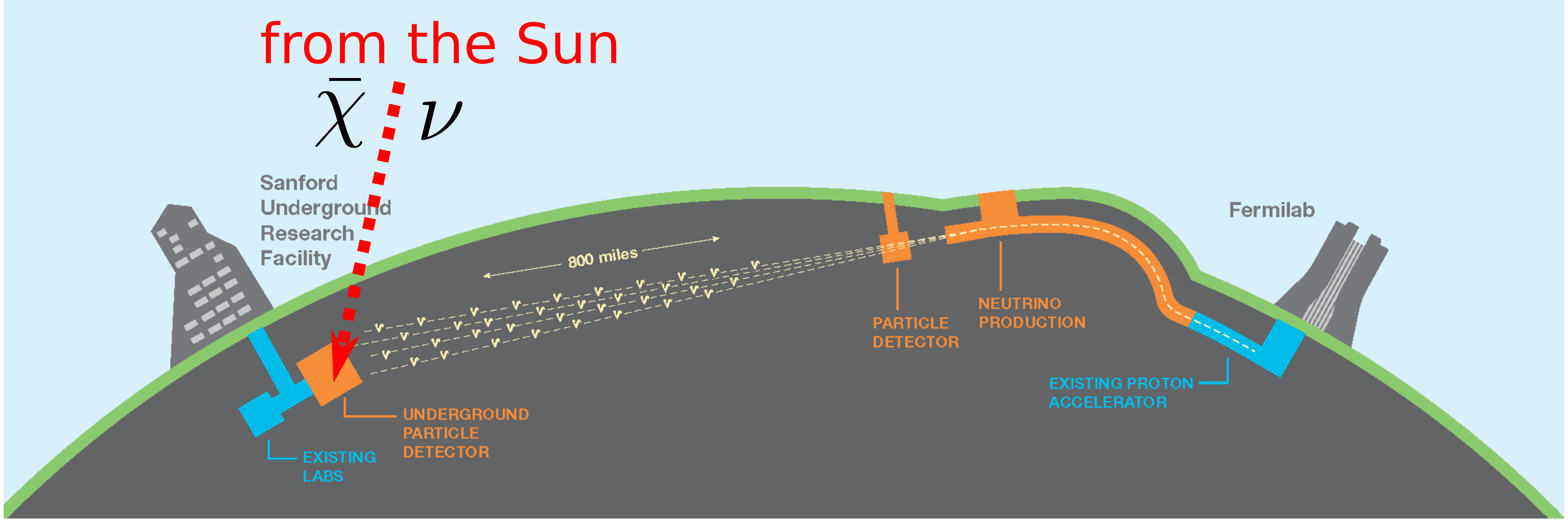


- Two detectors: near and far detectors.
- Massive liquid argon (fiducial volume: 40kt)
- Precise reconstruction of particle's trajectories with LArTPC



DUNE Coll., [arXiv:2002.03005]

DUNE (Deep Underground Neutrino Experiment)



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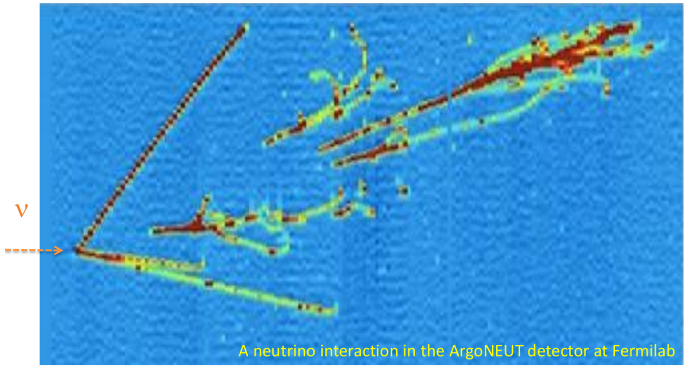

DUNE Coll., [arXiv:2002.03005]

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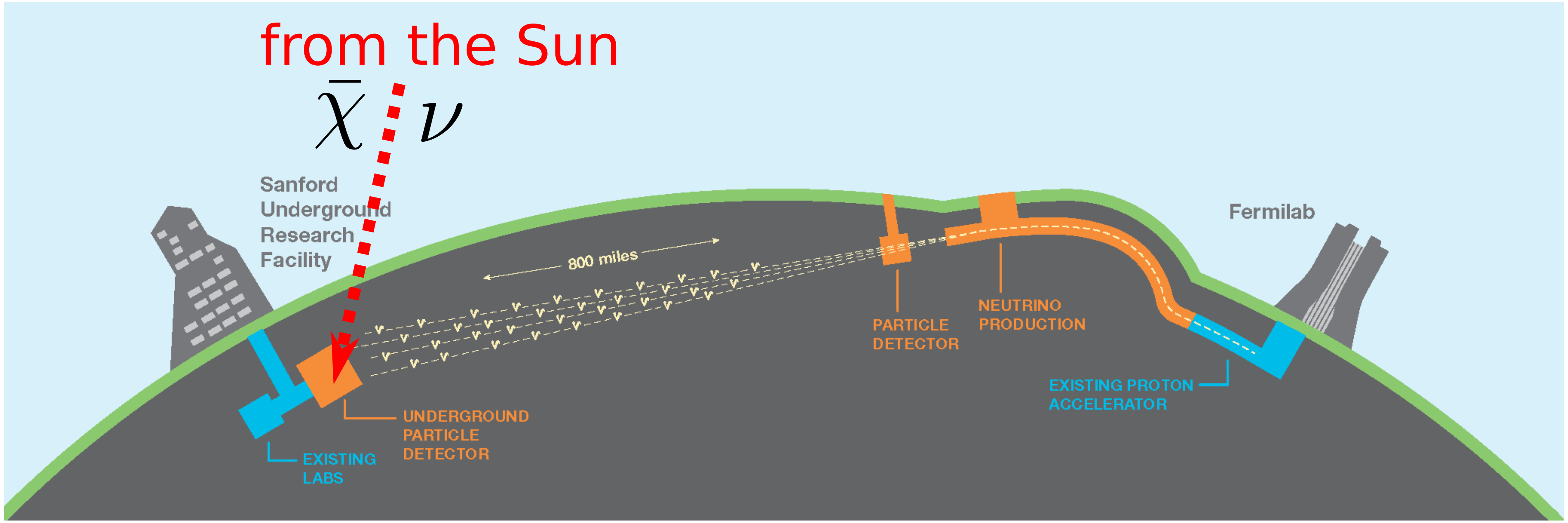
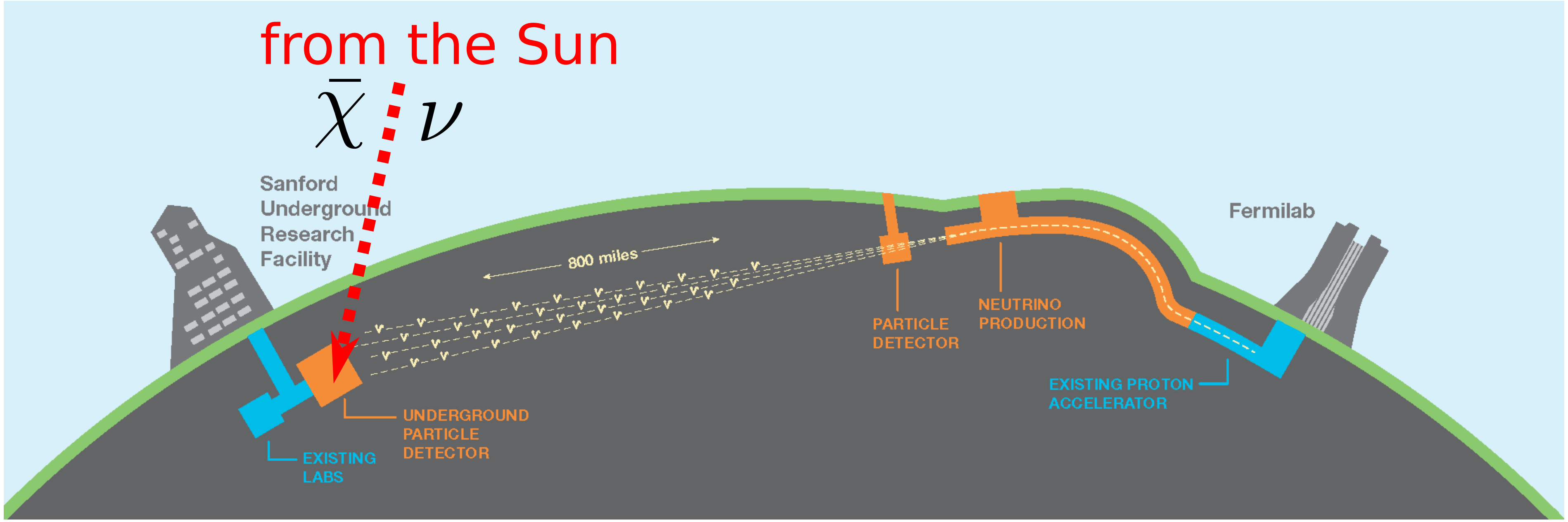


DUNE Coll., [arXiv:2002.03005]

Timeline of far detector modules

- 2025: DUNE physics deta taking with atmospheric neutrinos (fiducial mass 20kt)
- 2026: DUNE physics deta 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: slimed version of DUNE will run
- 2035: DUNE full spec (40kt)
- 2027: Hyper-K

⇒ No advantage of DUNE 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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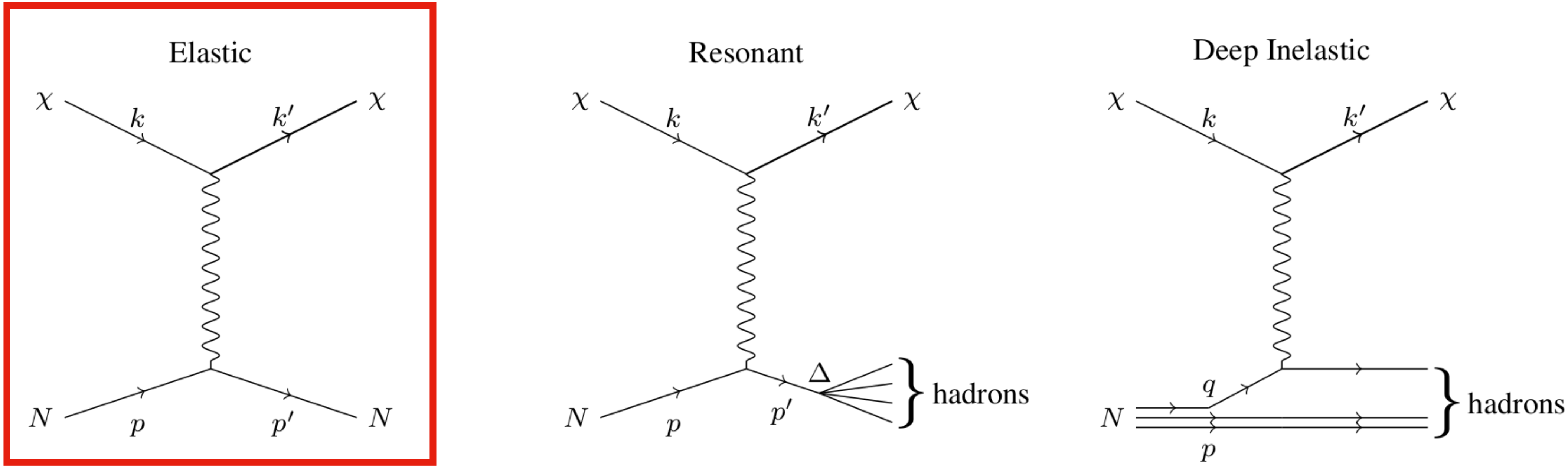
|---------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                     |
|---------------------------------------------------------------------------------------------------------------|
| 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 |
|---------------------------------------------------------------------------------------------------------------|
```

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
  cf: 3° at SK and HK, 30° at IceCube
- These are taken into account in simulation.

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 consider the following cross section (parametrization)

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

- Parameters: $|\boldsymbol{p}_\chi| = \frac{5}{4}m_\chi$ and σ_0 (reference cross section)

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

Setup for boosted dark matter

Number of 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: $N_N = 2.41 \times 10^{34}$

  Exposure time: $T = 10$ yr

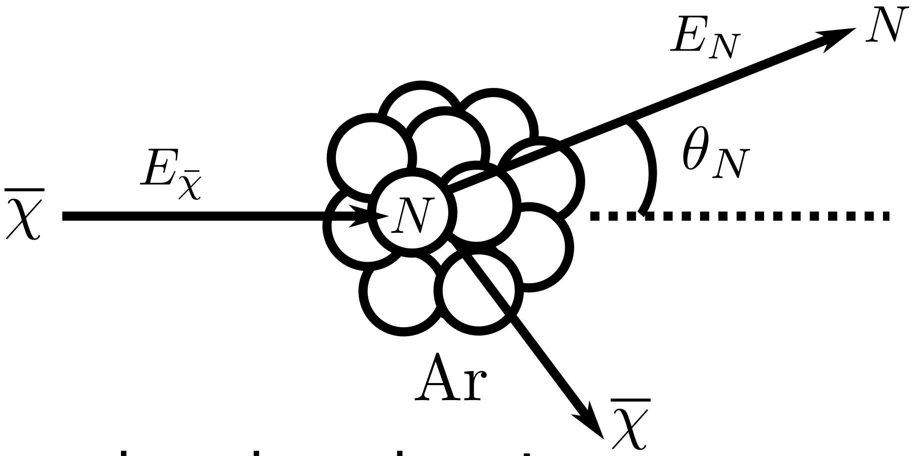
  DM flux: $\frac{d^2\Phi_\chi}{dE_\chi d\Omega} = \frac{\Gamma_{\rm ann}}{4\pi d_\odot^2}\sigma_{\chi N}\Big|_{E_\chi = 5m_\chi/4} = \frac{C_\odot}{8\pi d_\odot^2}\sigma_{\chi N}\Big|_{E_\chi = 5m_\chi/4}$

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

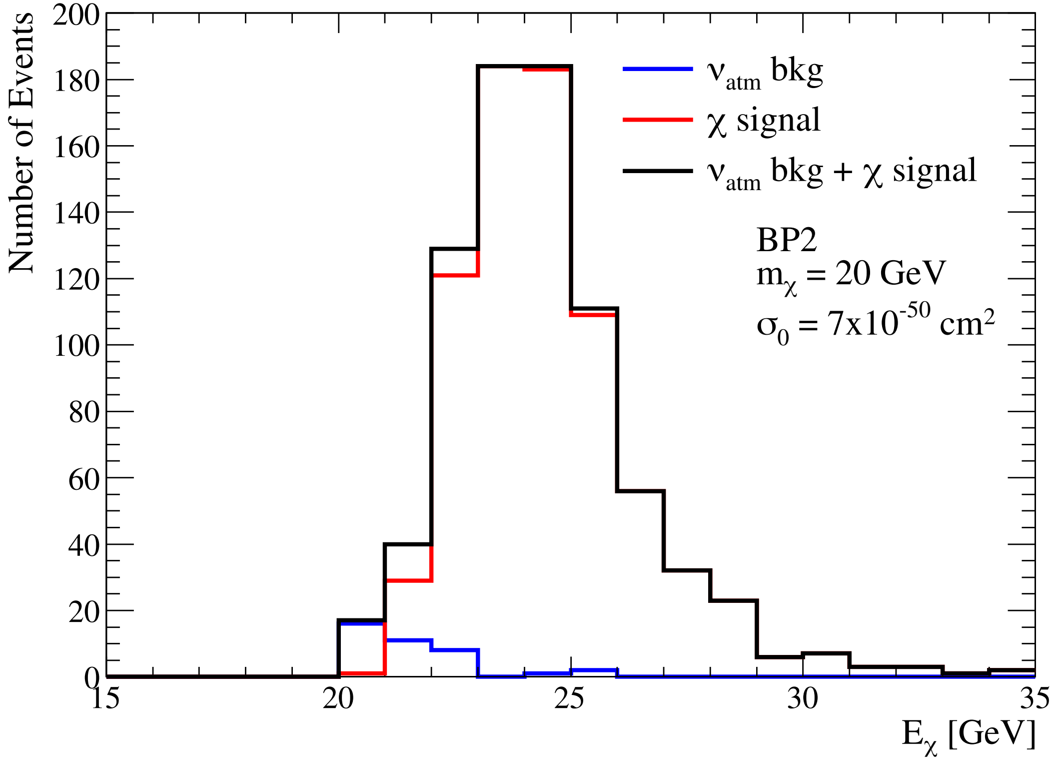
Boosted dark matter signal (energy resonctruction)

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

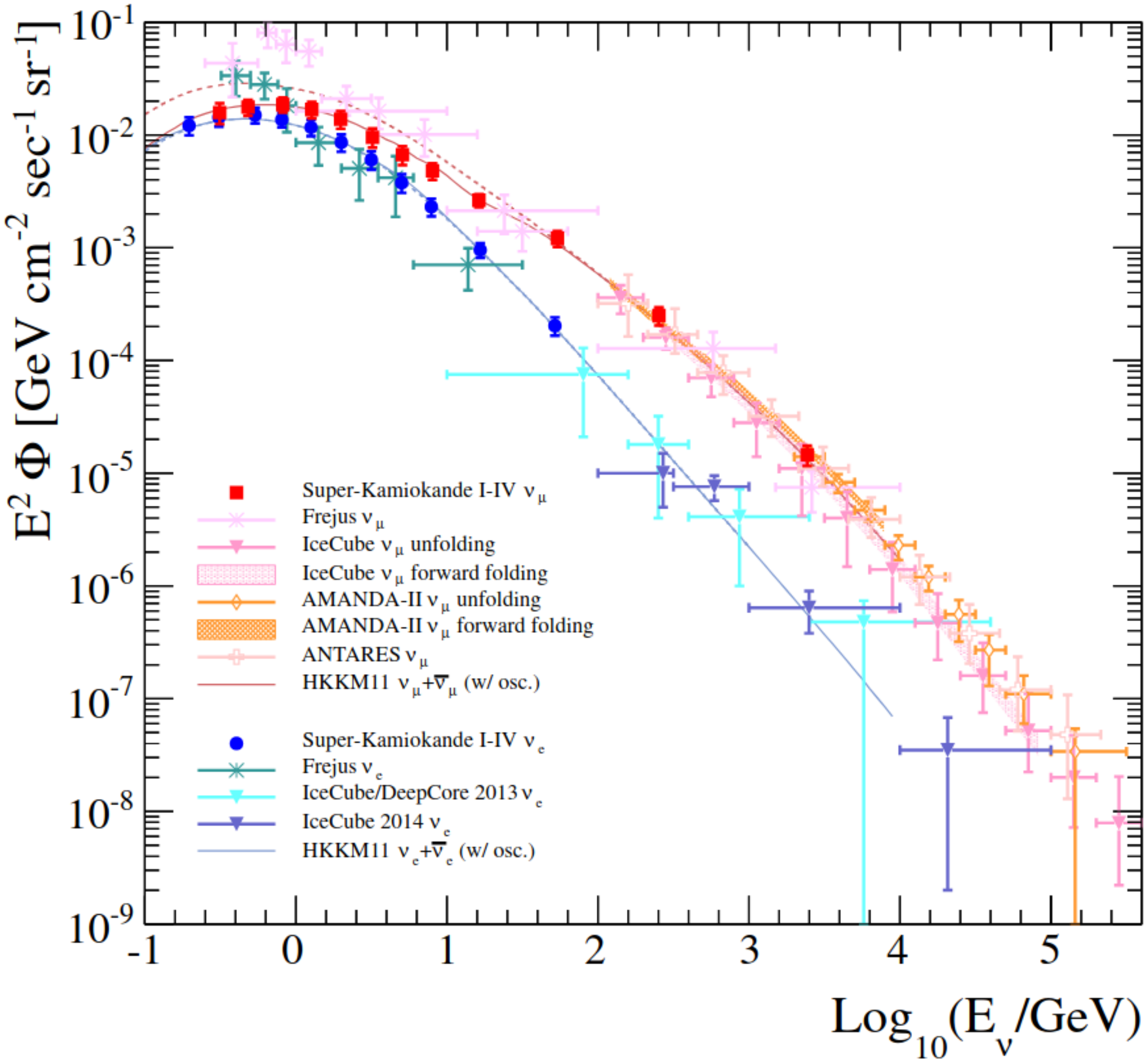
- $\cos\theta_N = \dfrac{E_\chi + m_N}{|\boldsymbol{p}_\chi|}\sqrt{\dfrac{E_N - m_N}{E_N + m_N}}$
- Energy reconstruction from observed θ_N and E_N



ex. benchmark point
$n = 2$
$m_\chi = 20$ GeV,
$\sigma_0 = 7 \times 10^{-50}$ cm^2



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

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

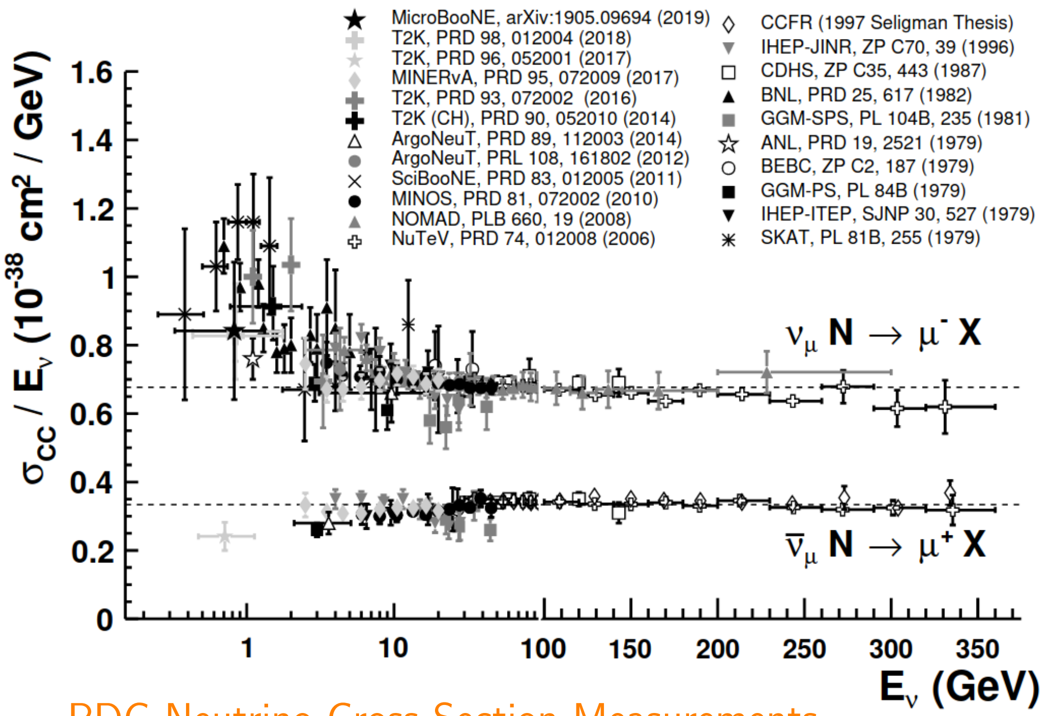
510 via CC int. for ν signal $(\nu_{\mathrm{atm}} + N \to e/\mu + j)$

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

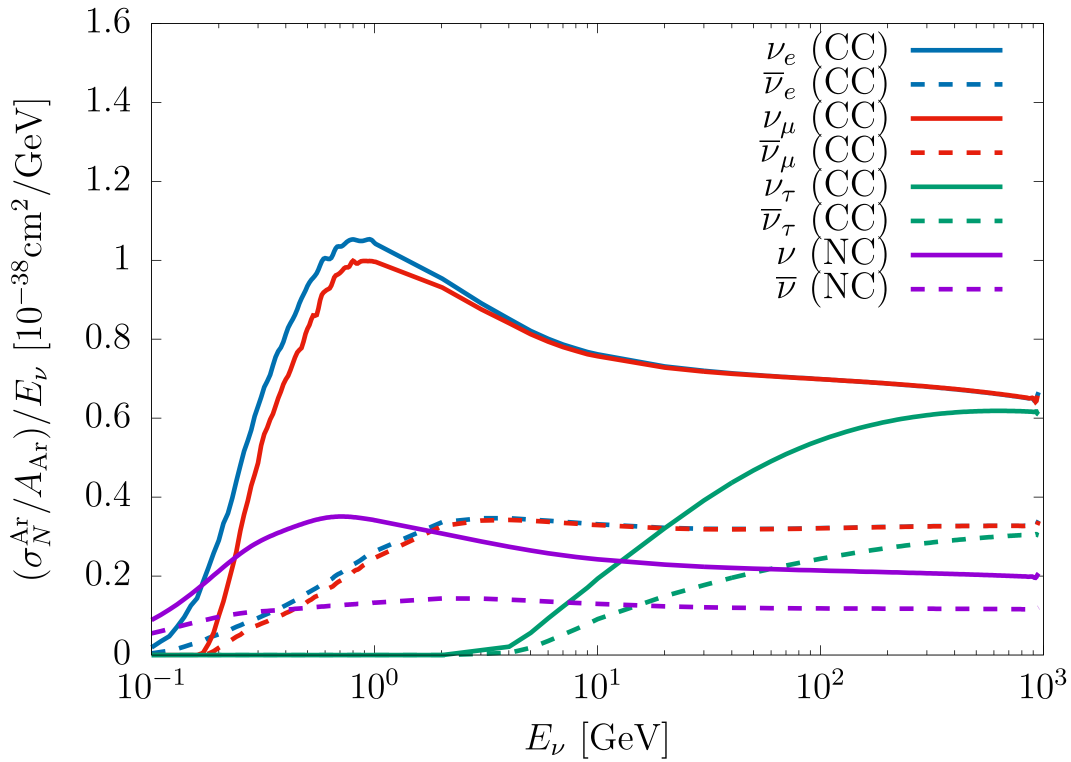
- We use ν_{atm} HAKKM flux at Homestake (close to DUNE detector).

Neutrino cross section

- Default implementation in GENIE



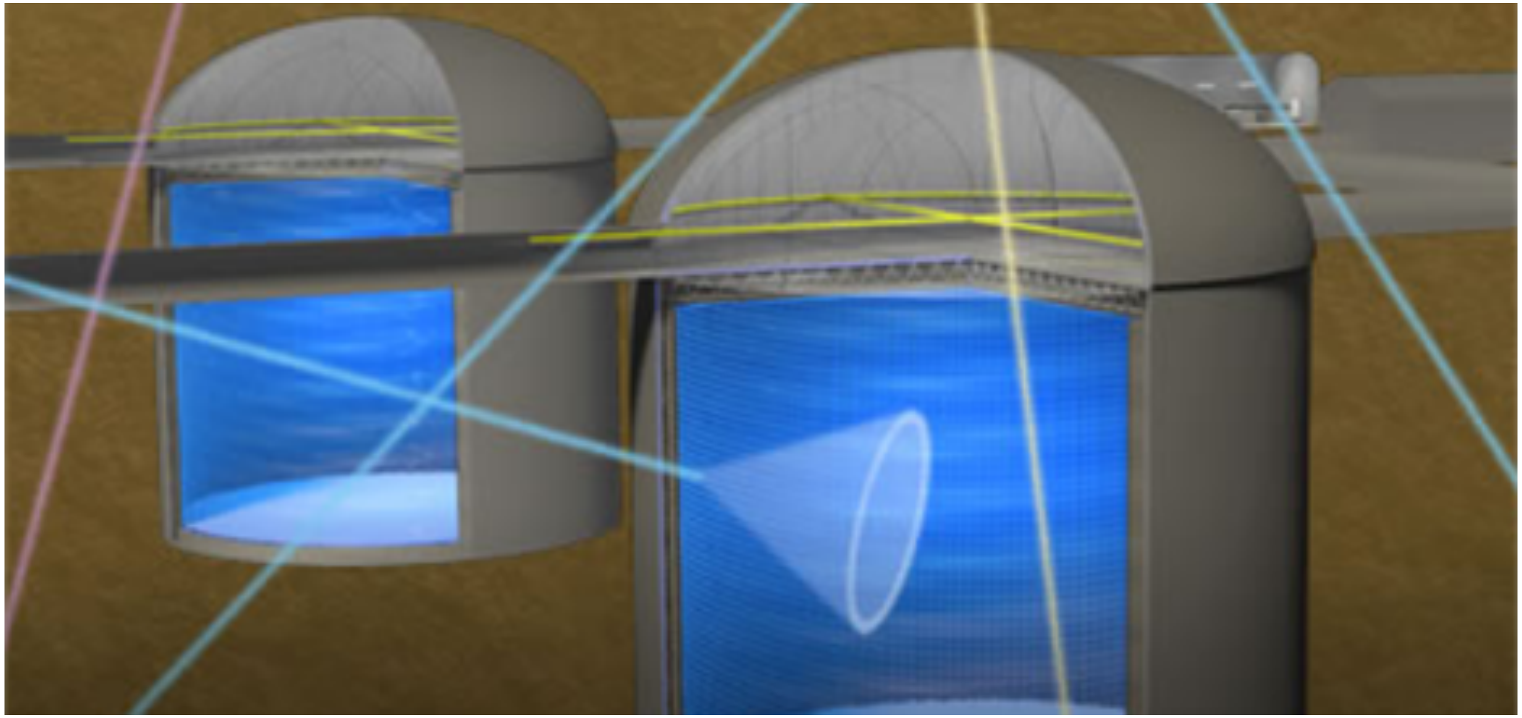
PDG Neutrino Cross Section Measurements



- In the energy range from MeV to $\mathcal{O}(100)$ GeV, many physical processes (non-perturbative QCD, nuclear models, hadronization etc) are important.

Accompanied neutrinos

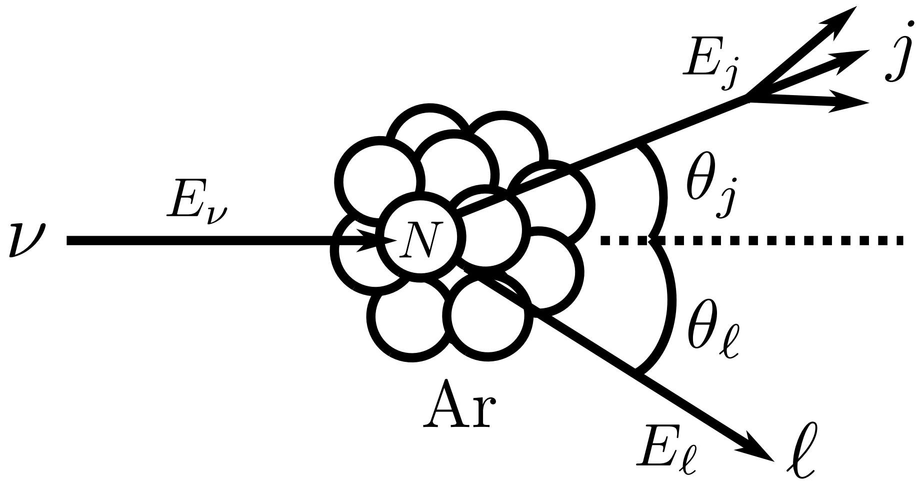
- Accompanied neutrinos can also be searched by DUNE, SK/HK and IceCube etc.

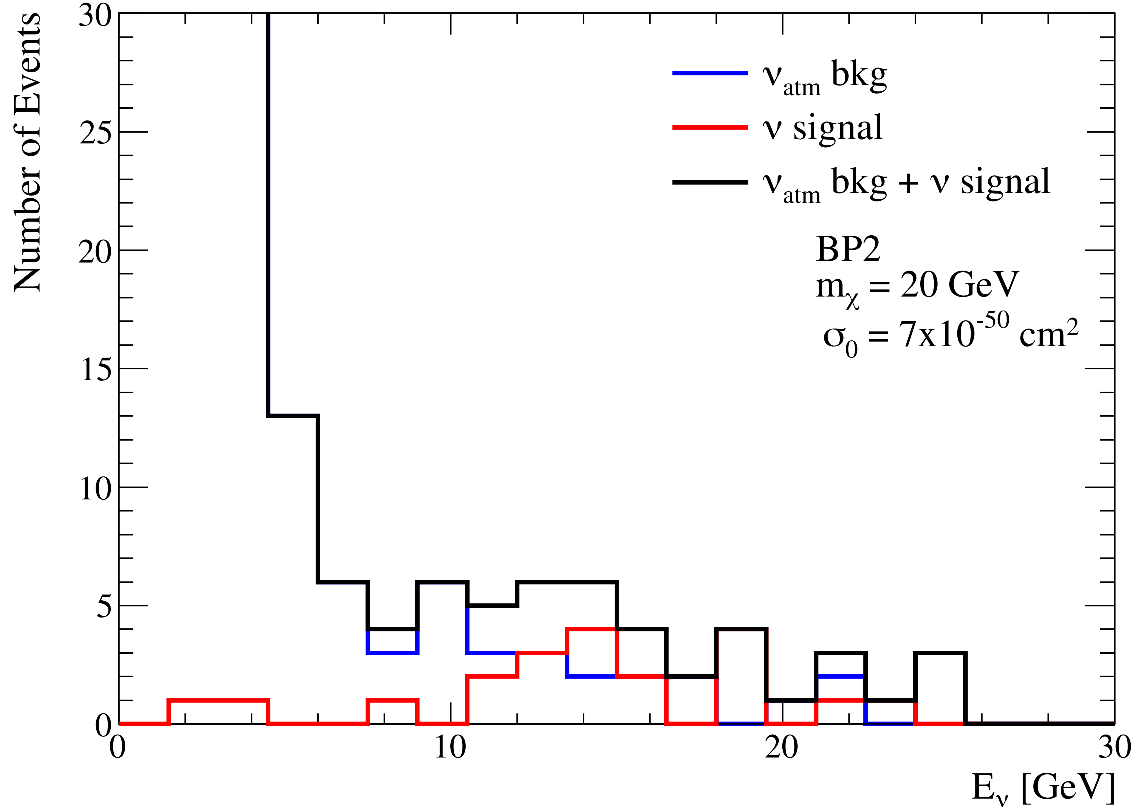


Hyper-Kamiokande Collaboration

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

Neutrino energy reconstruction arXiv: 1903.04175, C. Rott et al.





- $\nu + N \to e^-/\mu^- +$ jet
- $E_\nu = \dfrac{1}{2}\dfrac{\sin\theta_j\,(1+\cos\theta_\ell)+\sin\theta_\ell\,(1+\cos\theta_j)}{\sin\theta_j}E_\ell$
- Benchmark point: $n = 2, \quad m_\chi = 20$ GeV, $\quad \sigma_0 = 7\times 10^{-50}$ cm^2

Results

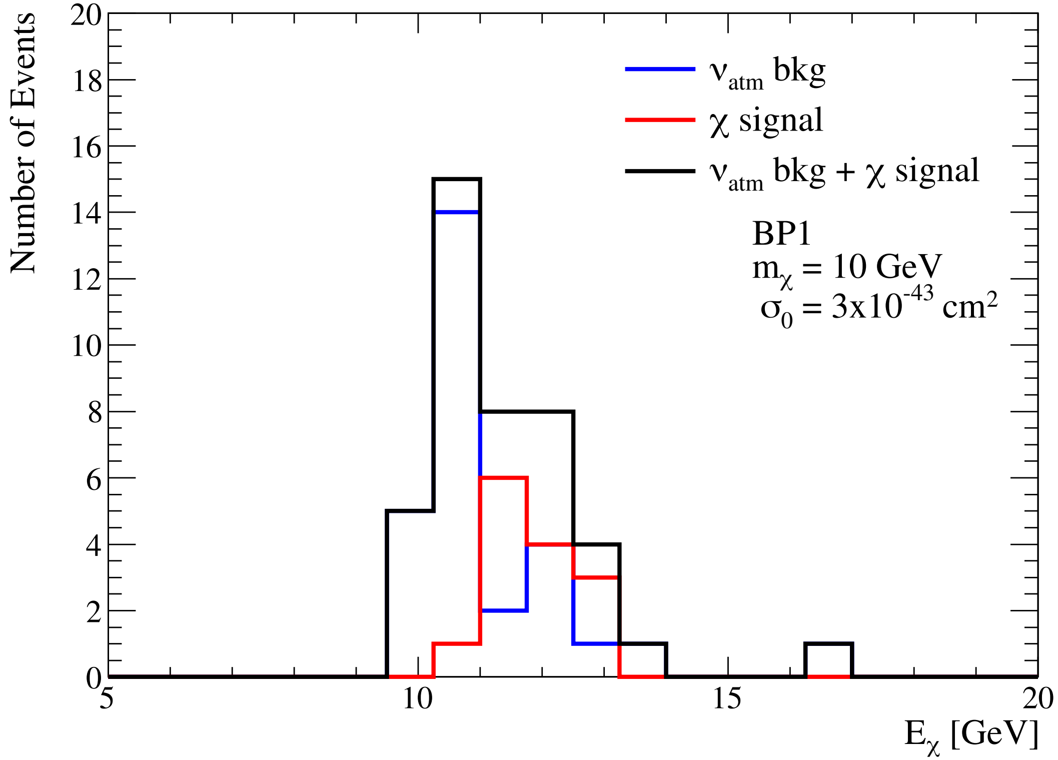
Results

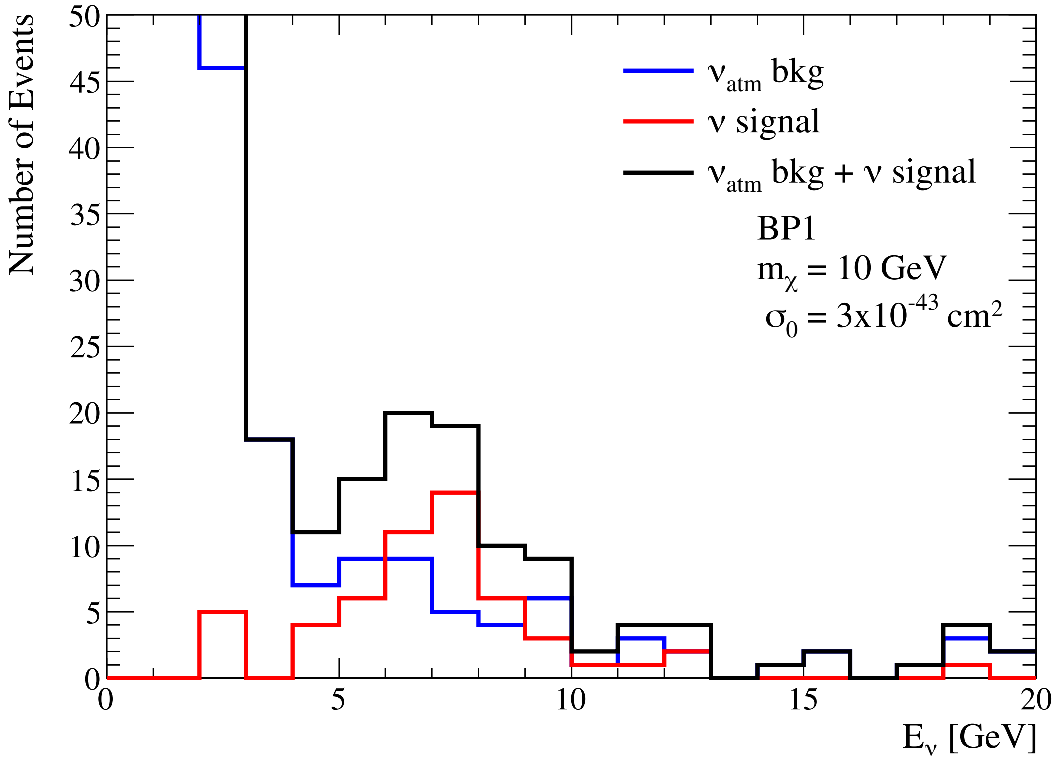
Benchmark parameter sets

	model	m_χ [GeV]	σ_0 [cm^2]	# of ν events	# of χ events
BP1	SD ($n=1$)	10	3.0×10^{-43}	$N^{\rm CC}_{\rm atm\,\nu} = 510/510$ $N^{\rm CC}_{\nu} = 56/56$	$N^{\rm NC}_{\rm atm\,\nu} = 35/245$ $N_\chi = 14/40$
BP2	SI ($n=2$)	20	7.0×10^{-50}	$N^{\rm CC}_{\rm atm\,\nu} = 510/510$ $N^{\rm CC}_{\nu} = 20/20$	$N^{\rm NC}_{\rm atm\,\nu} = 46/245$ $N_\chi = 774/2396$

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

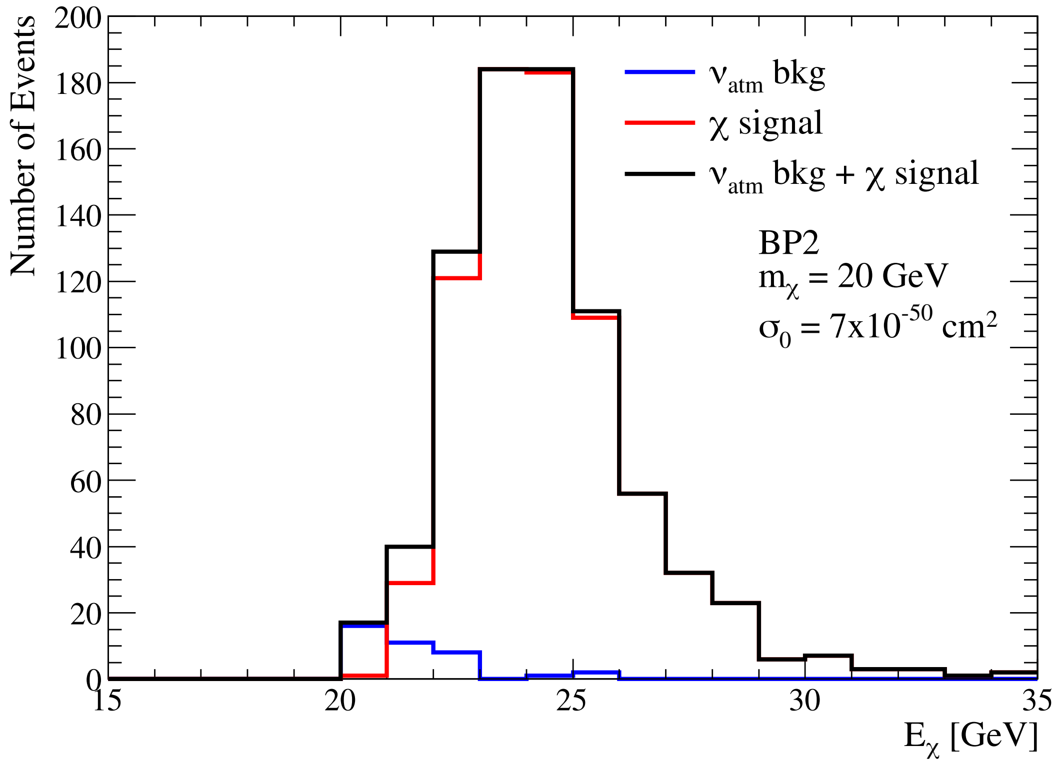
Energy distribution 1

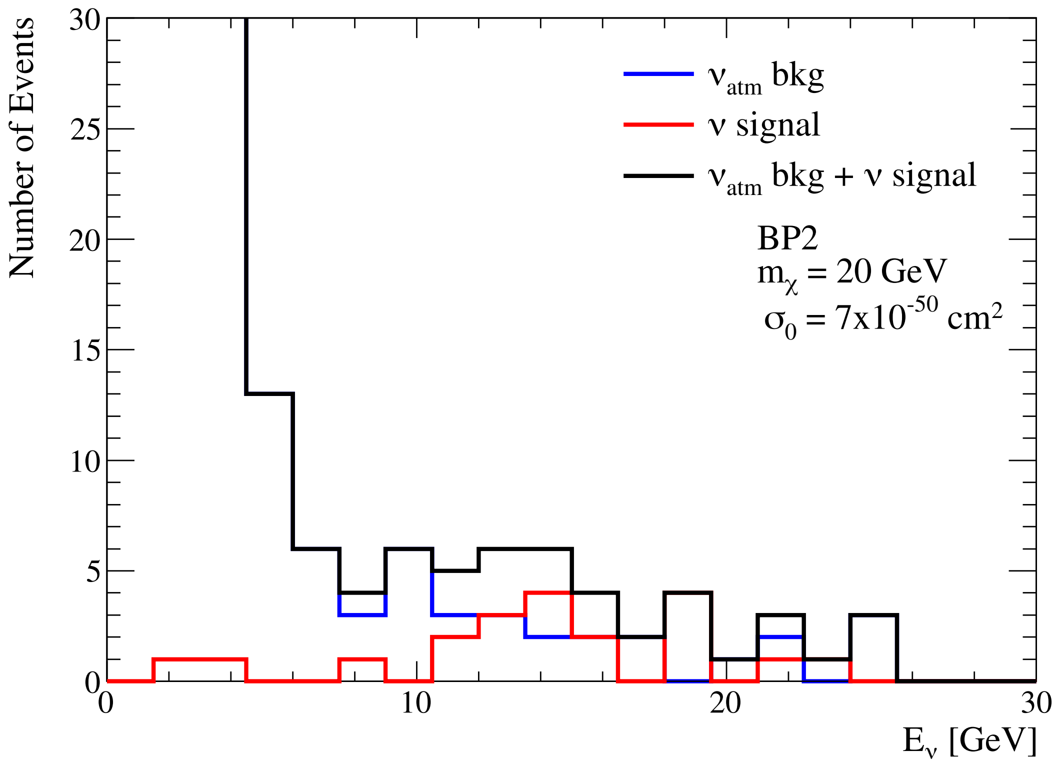




- Energy reconstruction for BP1
- Atmospheric neutrino bkg at low energy

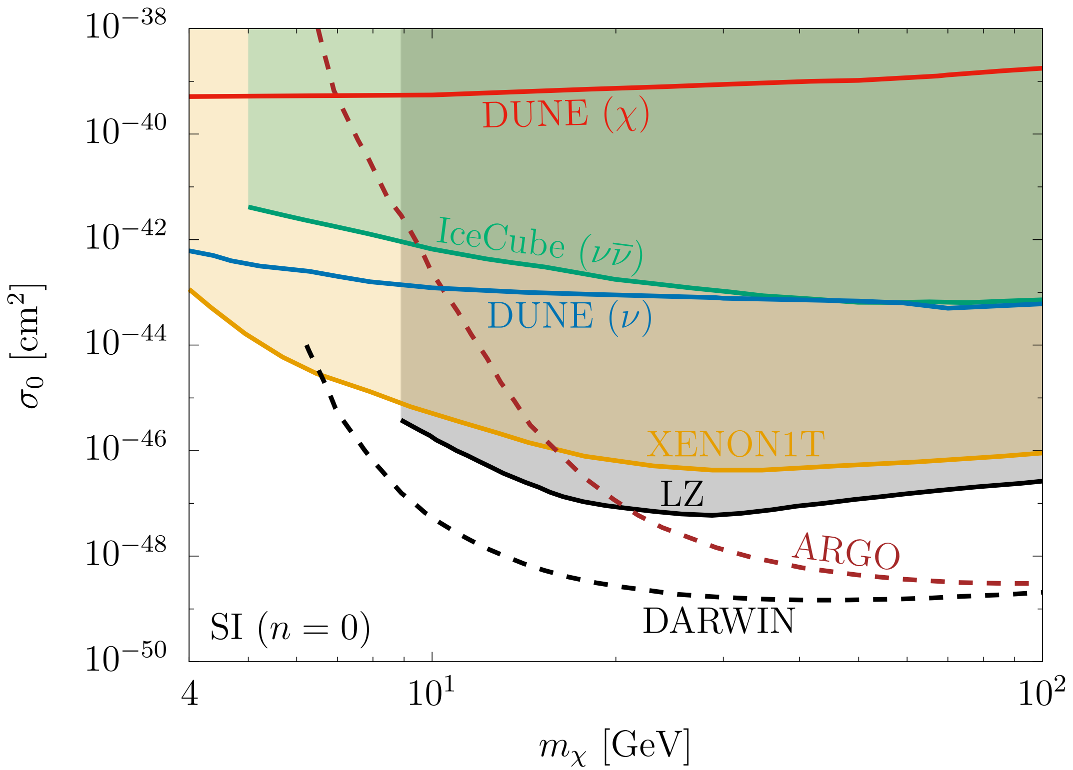
Energy distribution 2

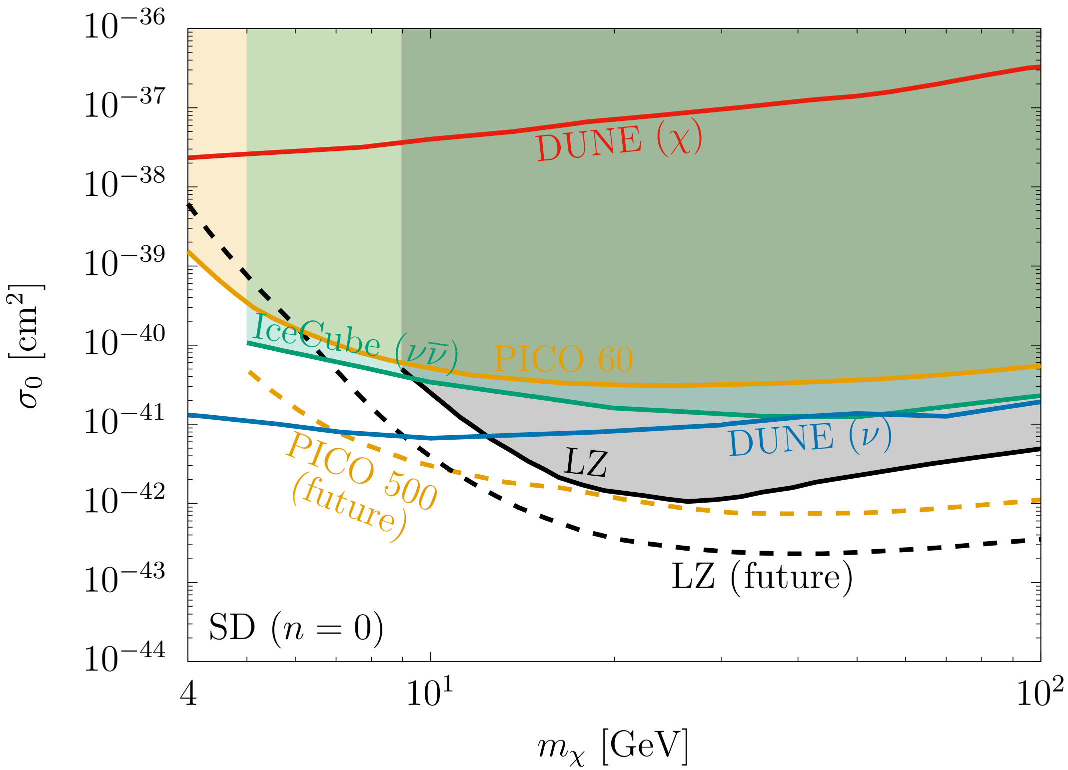




- Energy reconstruction for BP2
- Atmospheric neutrino bkg at low energy
- A large number of BDM events on the left plot

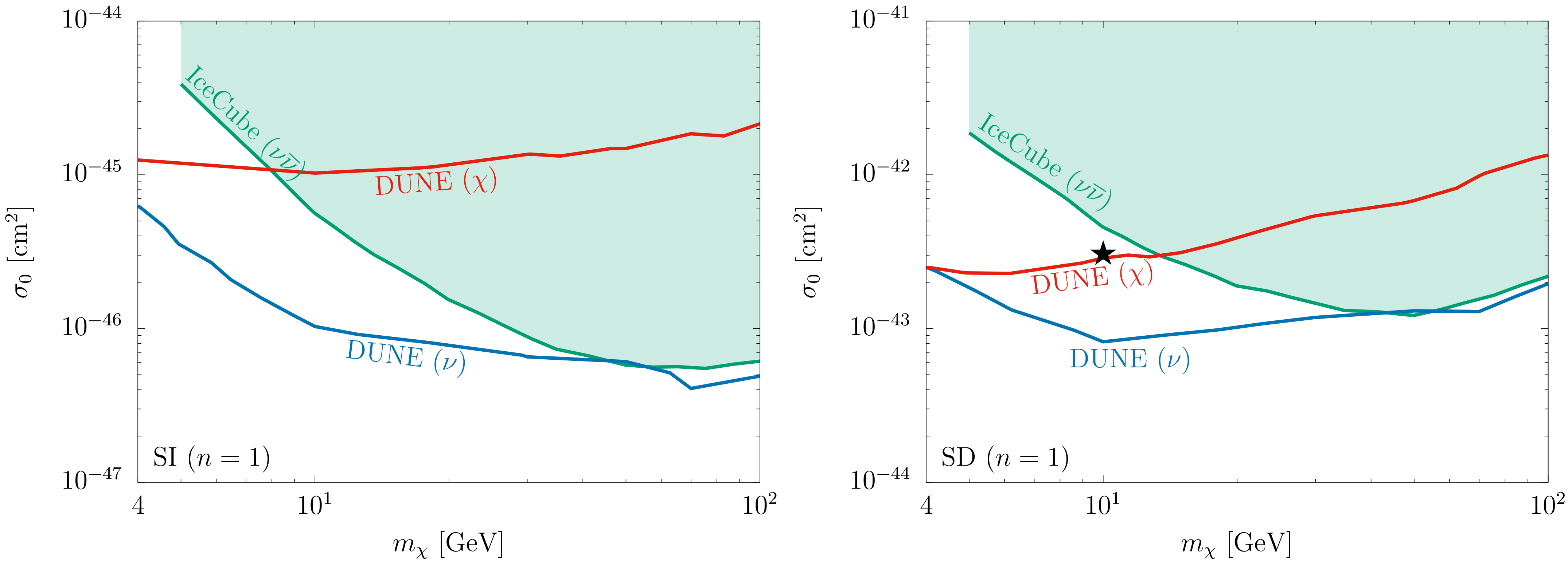
Parameter space 1





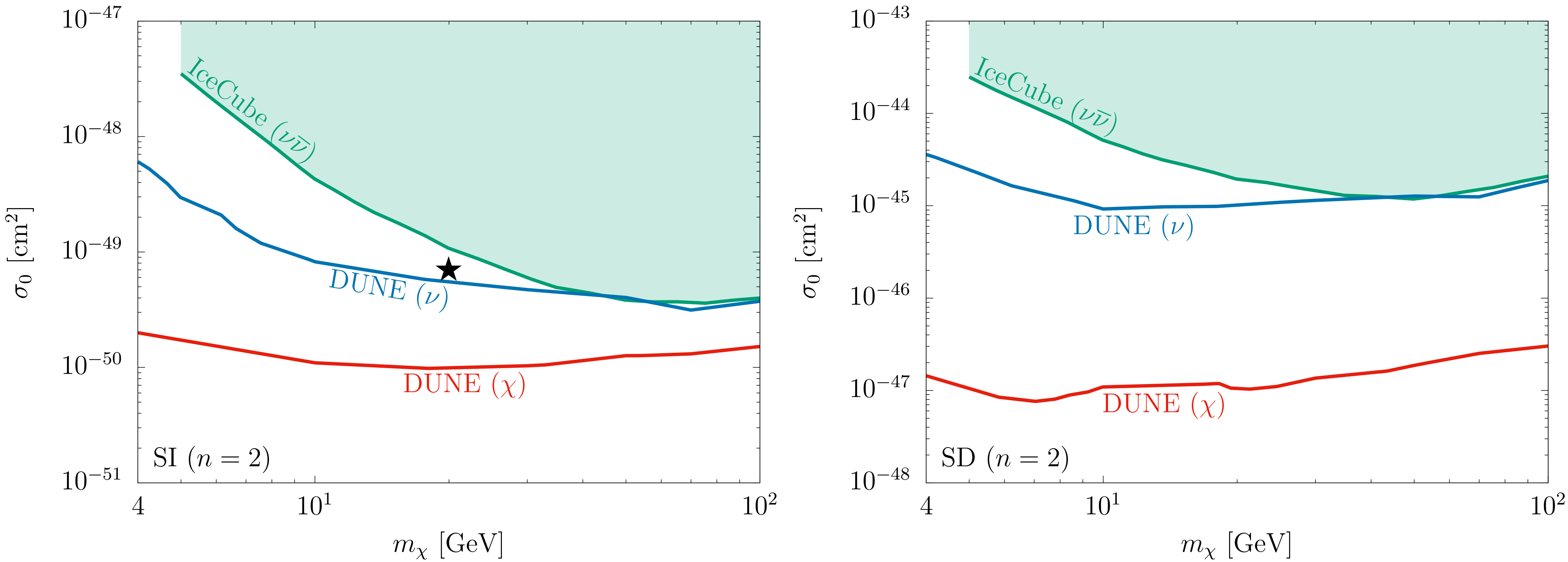
- DUNE sensitivity for constant $\sigma_{\chi N}$ $(n = 0)$
- Significance: $\mathcal{S} = \dfrac{N_{\rm sig}}{\sqrt{N_{\rm bkg} + N_{\rm sig}}}$
- Completely excluded by direct detection experiments as expected.

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.

Parameter space 3



- DUNE sensitivity for Q^4 dependent $\sigma_{\chi N}$ $(n = 2)$
- Sensitivity for BDM can be much higher.

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. $\chi\chi \to \bar{\chi}\nu$ induces distinctive signals, which can be searched by DUNE, but not by SK/HK and IceCube.
4. Q^2 (or v_χ^2) suppressed cross sections are needed for BDM detection.

Future works

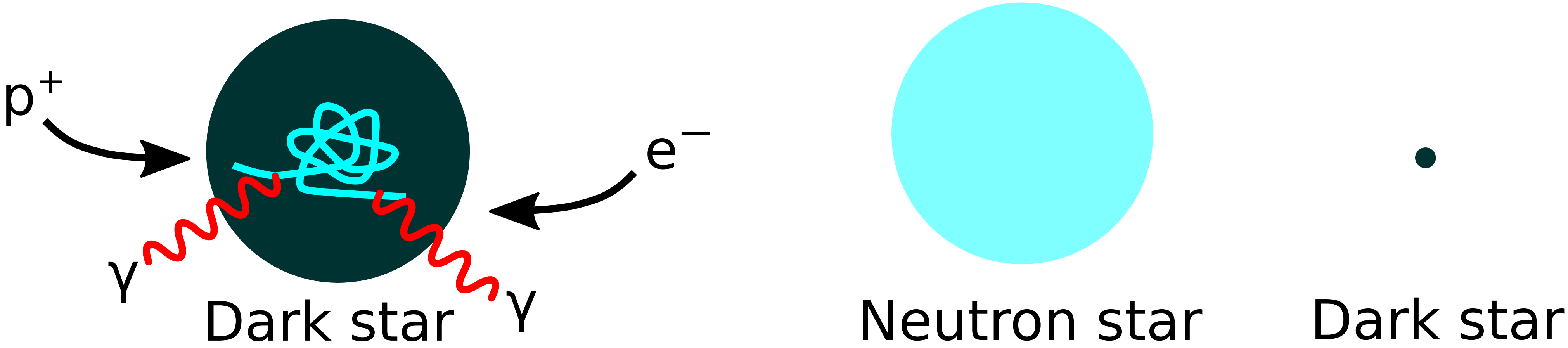
1. Concrete model building
2. Application to multi-component DM, 3→2 or 4→2 processes
   Dark matter paricles are boosted: $E_\chi = \frac{3}{2}m_\chi$, or $2m_\chi$

Future works 2

- Consider very dense compact object (dark star)

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

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



  cf: neutron stars: $M \sim M_\odot$, r ~20km

  $M \sim 0.1 M_\odot$, r ~1km

- This can be signal of boosted dark matter from 3→2 or 4→2 processes, or maybe from semi-ann. too.

Backup

Semi-annihilation at the Sun

- Number of DM particles accumulated in the Sun

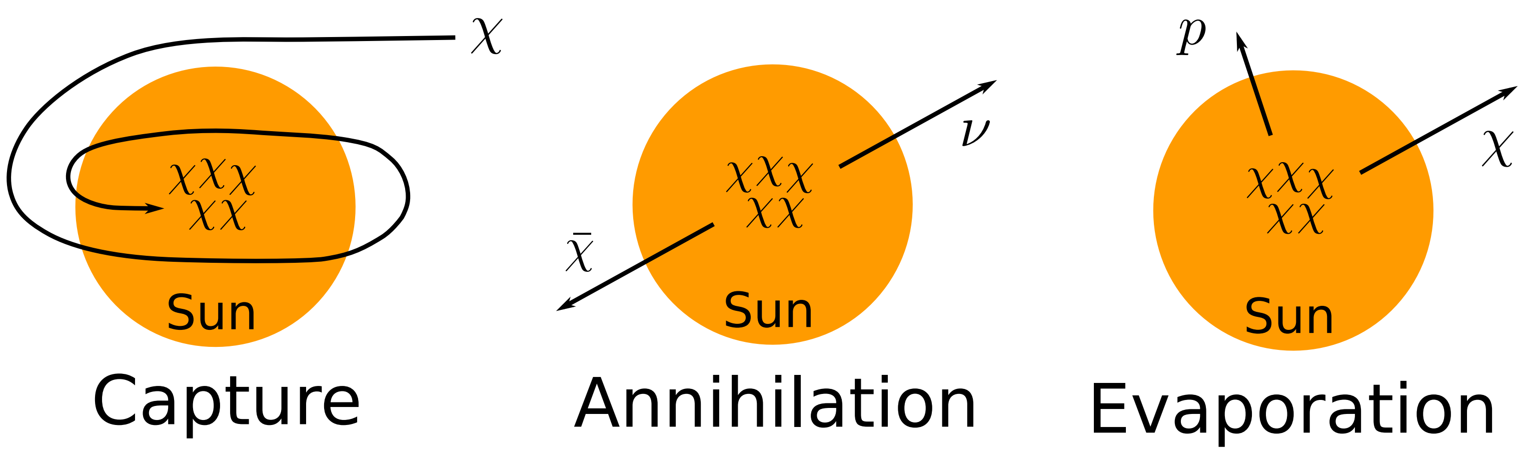
$$\frac{dN_\chi}{dt} = \Gamma_{\rm capt} - 2\Gamma_{\rm ann} - \Gamma_{\rm evap}$$

- Capture rate

$$\Gamma_{\rm capt} = \frac{\rho_\odot}{m_\chi}\sum_i \sigma_i \int_0^{R_\odot} dr 4\pi r^2 n_i(r) \int_0^\infty dv 4\pi v^2 f_\odot(v) \frac{v^2+v_{\rm esc}^2}{v} P(v, v_{\rm esc})$$

where i = all the elements in the Sun

For $m_\chi \gg m_i$, $\Gamma_{\rm capt} \approx \frac{\rho_\odot}{m_\chi^2} 4\pi f_\odot(0) \sum_i m_i \sigma_i I_i \quad \left(I_i \sim \int_0^{R_\odot} dr 4\pi r^2 n_i(r) v_{\rm esc}^4 \right)$



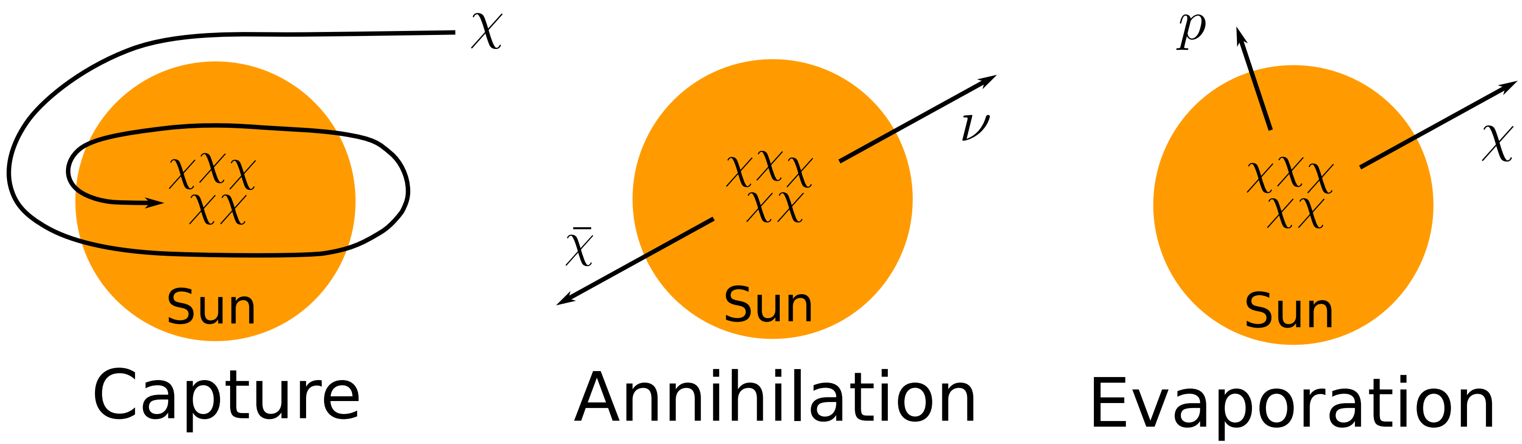
Semi-annihilation at the Sun

- Number of DM particles accumulated in the Sun

$$\frac{dN_\chi}{dt} = \Gamma_{\rm capt} - 2\Gamma_{\rm ann} - \Gamma_{\rm evap}$$

- Annihilation rate: $\Gamma_{\rm ann} = \dfrac{C_{\rm ann}}{2} N_\chi^2$

where $C_{\rm ann} = \left(\dfrac{\langle \sigma_{\chi\chi} v\rangle}{10^{-9}\ {\rm GeV}^{-2}}\right)\left(\dfrac{m_\chi}{100\ {\rm GeV}}\right)^{3/2} 1.7\times 10^{-54}\ {\rm s}^{-1}$



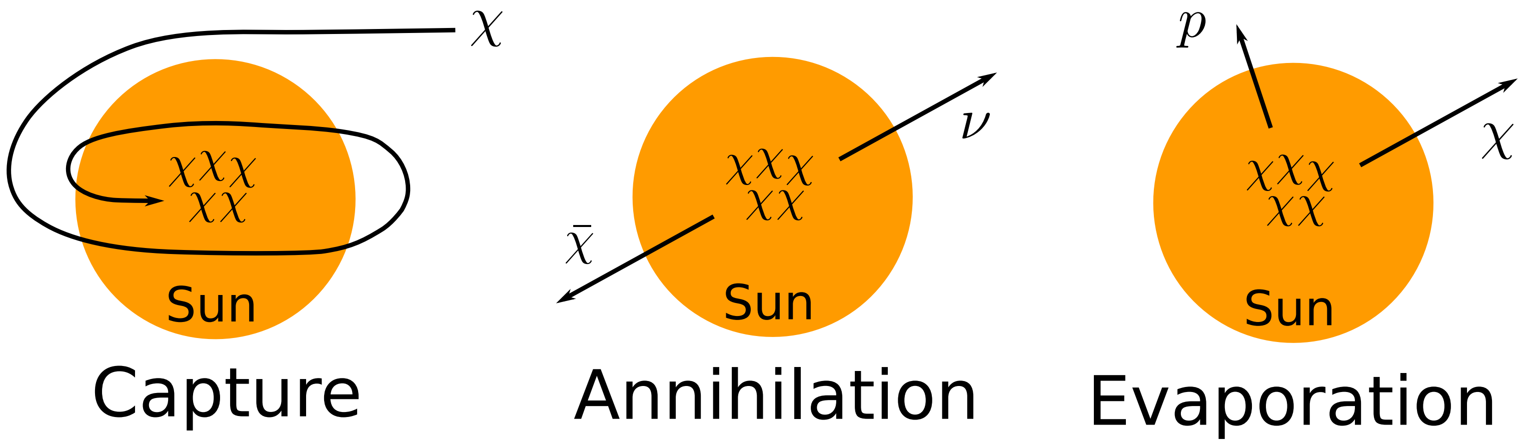
Semi-annihilation at the Sun

- Evaporation rate: Some DM particles scatter with nuclei in the Sun and get enough energy to escape from the Sun.
- Neglecting $\Gamma_{\rm evap}$ ($m_\chi \gtrsim$ 4 GeV), the solution is

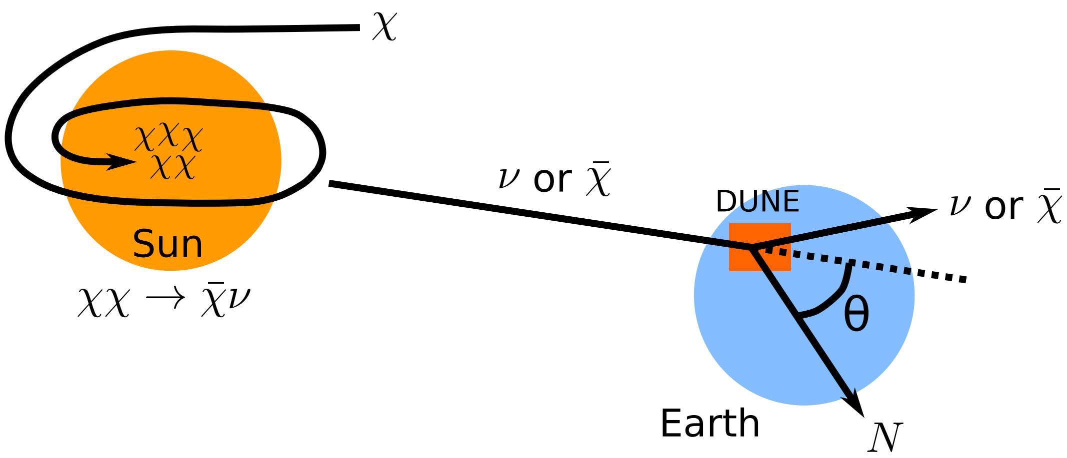
$$\Gamma_{\rm ann} = \frac{\Gamma_{\rm capt}}{2} \tanh^2\left(\frac{t}{\tau}\right) \overset{t \gg \tau}{\longrightarrow} \frac{\Gamma_{\rm capt}}{2}$$

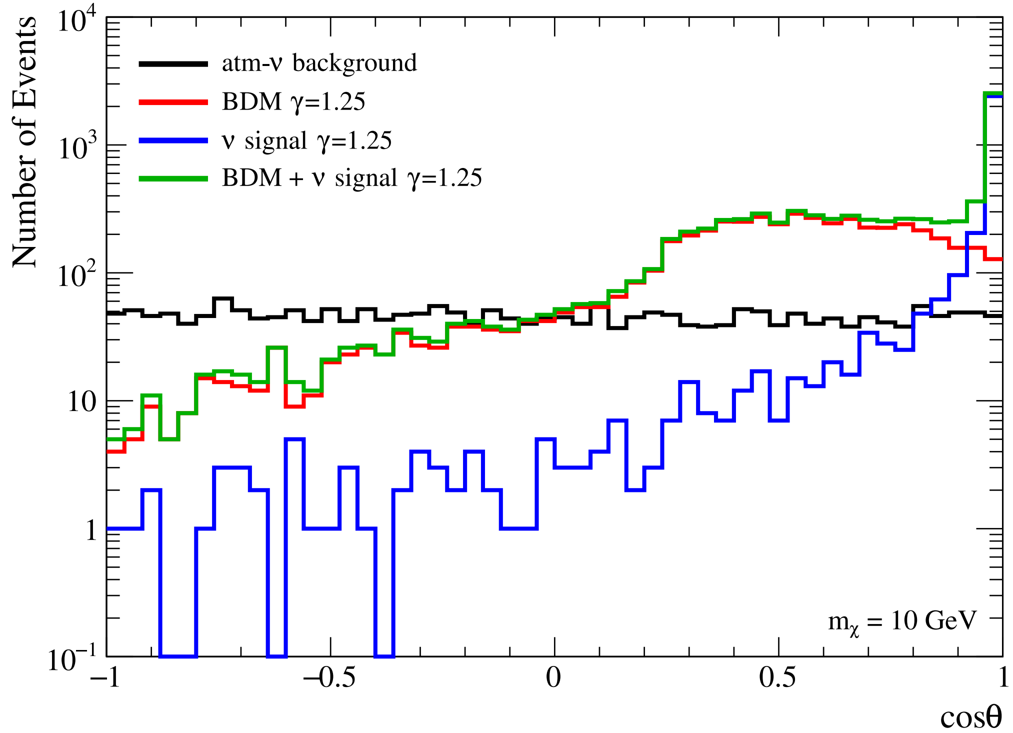
where $\tau = (\Gamma_{\rm capt} C_{\rm ann})^{-1/2}$, Age of the Sun $t \sim$ 4.5 Gyr

- Equilibrium can easily be reached.



Angular distribution





- Atmospheric neutrinos (black line) are uniform.
- Easy to distinguish the signals and $\nu_{\rm atm}$ background.
- But we need to distinguish two signals.