Distinctive signals of boosted dark matter from semi-annihilations

Takashi Toma

Seminar at DMWG (Online)

Based on arXiv: arXiv:2109.05911 [hep-ph]

Outline

1. Introduction
   - Dark matter (WIMP)
   - Semi-annihilations ($\chi\chi \to \bar{\chi}\phi$)
2. Specific channel ($\chi\chi \to \bar{\chi}\nu$)
   - Signals
   - Detection of boosted dark matter
3. Summary

Dark matter

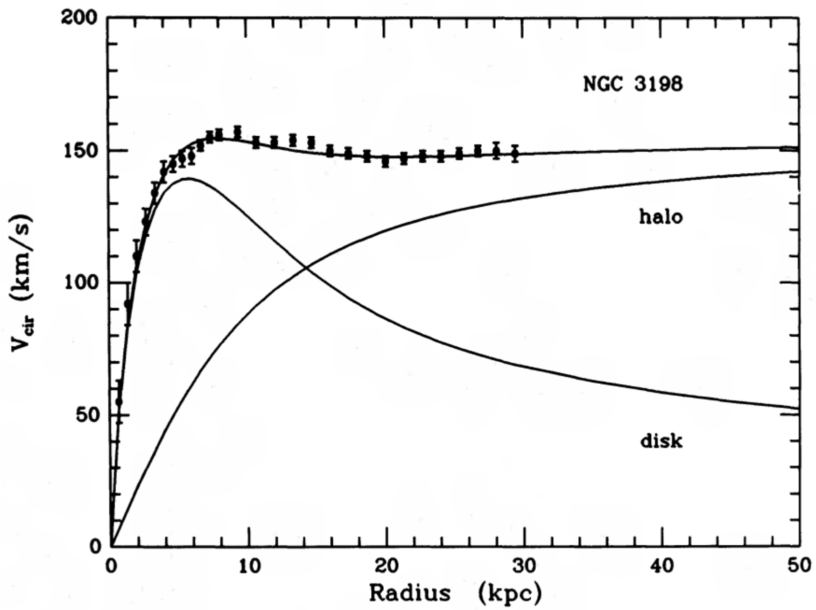
Albada et al. ApJ (1985)

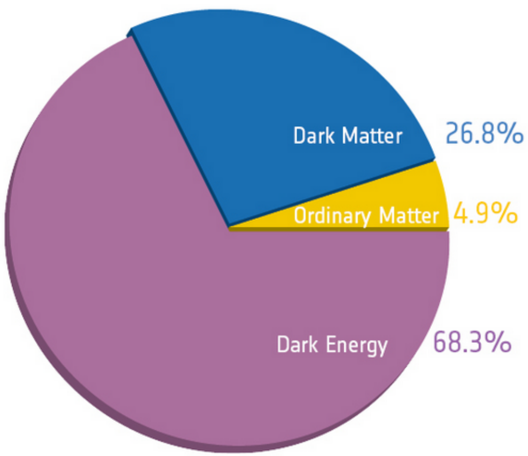
©PLANCK Coll.
©HUBBLESITE
©MPA

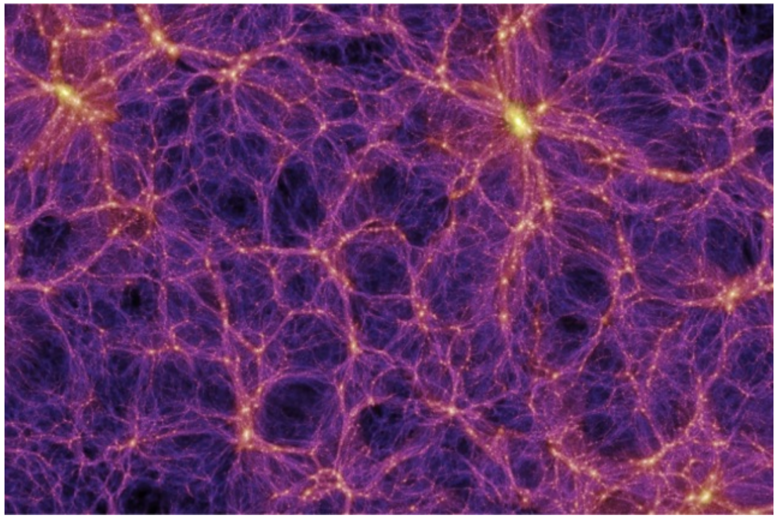
There is a lot of evidence of dark matter.

- Rotation curves of spiral galaxies
- CMB observations
- Gravitational lensing
- Structure formation of the universe
- Collision of bullet cluster

Existence of DM is crucial.





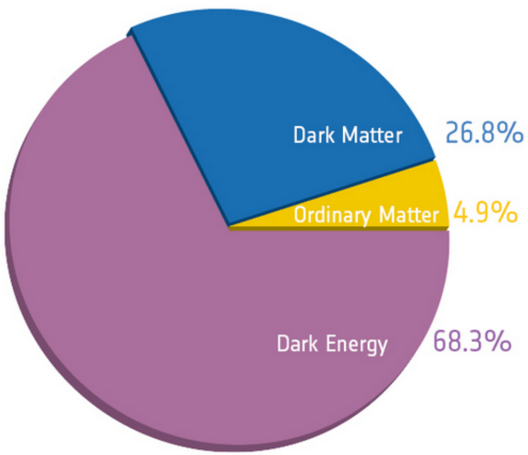


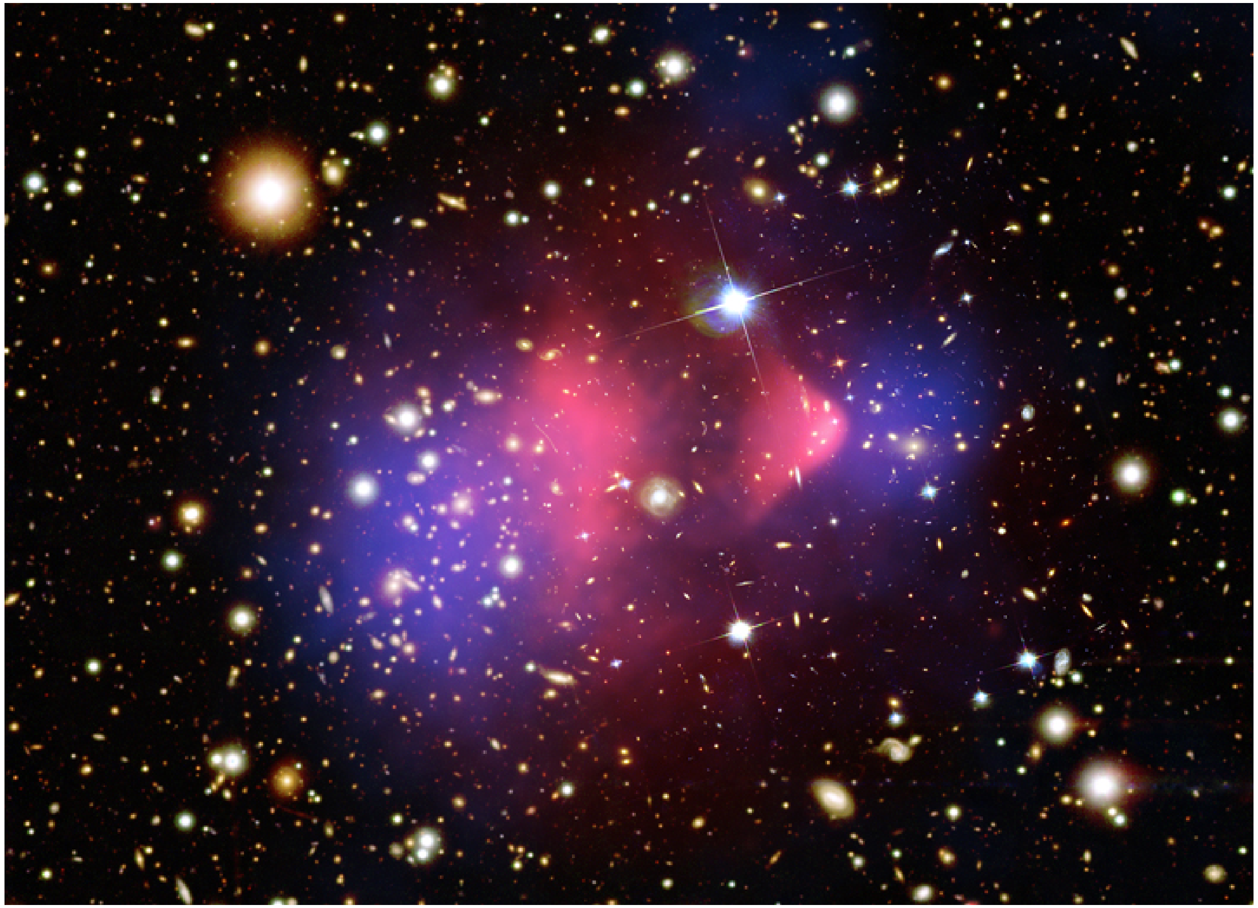
Dark matter

There is a lot of evidence of dark matter.

- Rotation curves of spiral galaxies
- CMB observations
- Gravitational lensing
- Structure formation of the universe
- Collision of bullet cluster

Existence of DM is crucial.



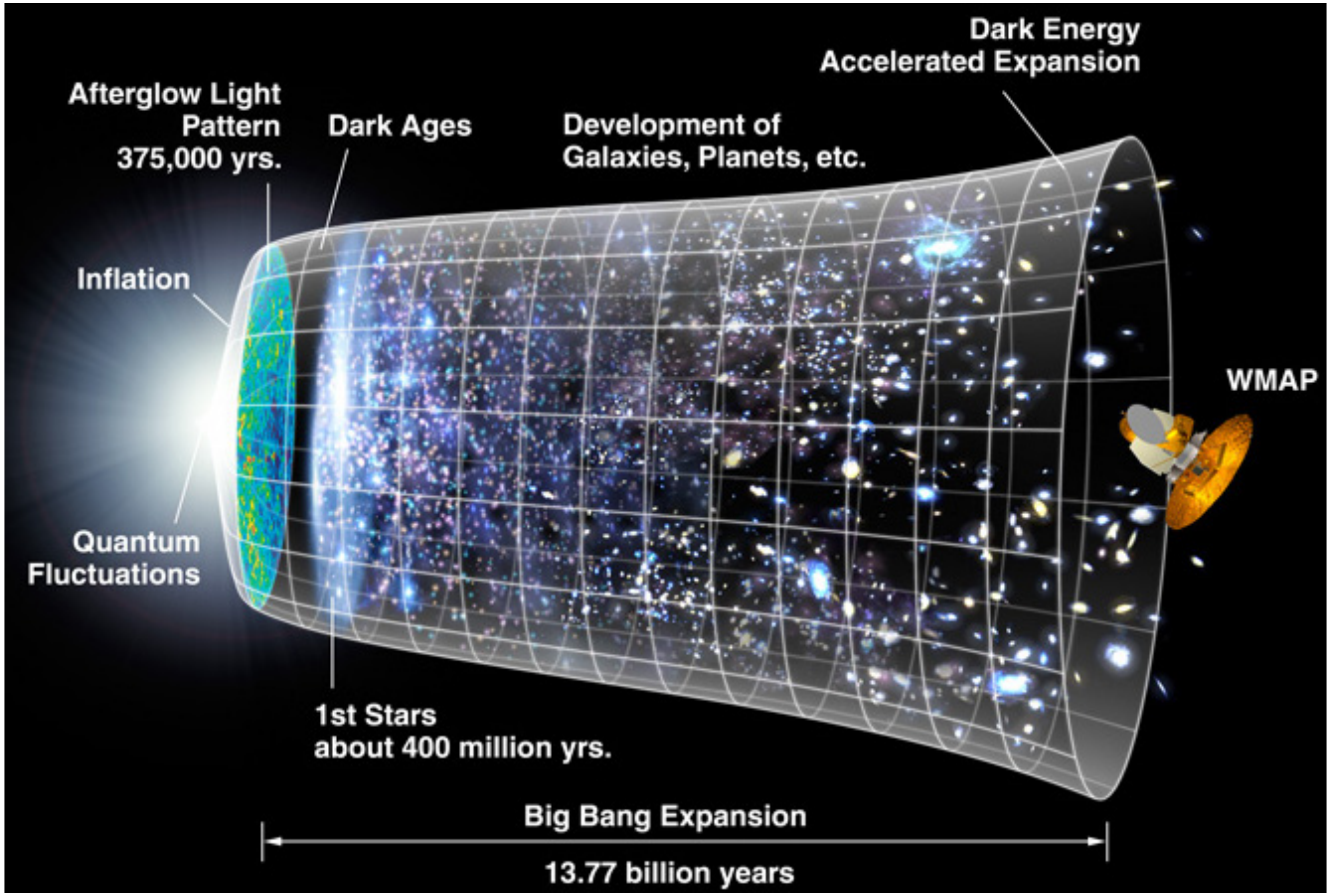


©MPA

Nature of DM

- Stable (at least longer than age of universe)
- Electrically neutral (may have very small charge)
- Occupy 27% of energy density of the universe
- Graviational interaction
- Non-relativistic (cold)

Strong candidates:
WIMP, FIMP, SIMP, axion, sterile neutrino, primodial black holes etc $\uparrow$
Revived by recent observations of gravitational waves

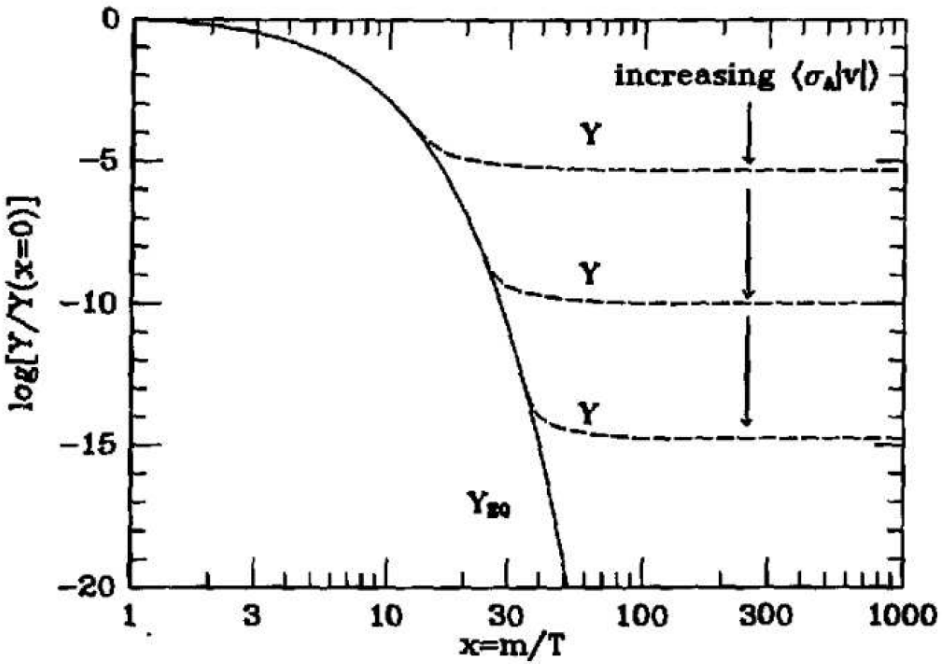


WIMP production

Evolution of DM number density follows the Boltzmann eq.

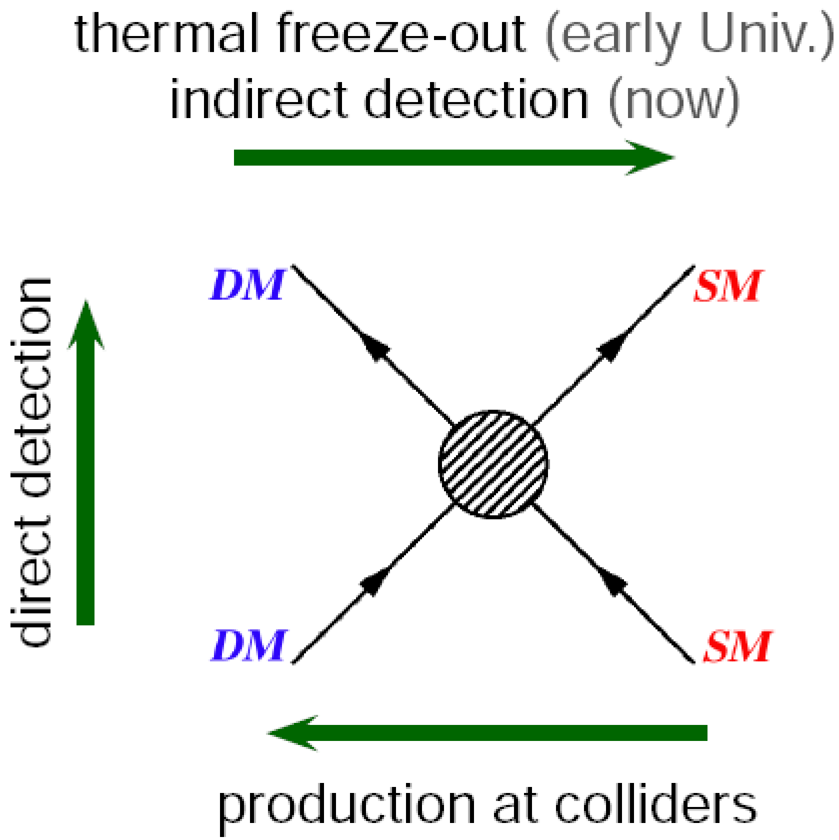
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}2}\right)$$

change variables $t \leftrightarrow x \equiv \frac{m}{T}, \quad n_\chi \leftrightarrow Y \equiv \frac{n_\chi}{s}, \quad \Gamma \equiv \langle\sigma v\rangle\, n_\chi^{\mathrm{eq}},$



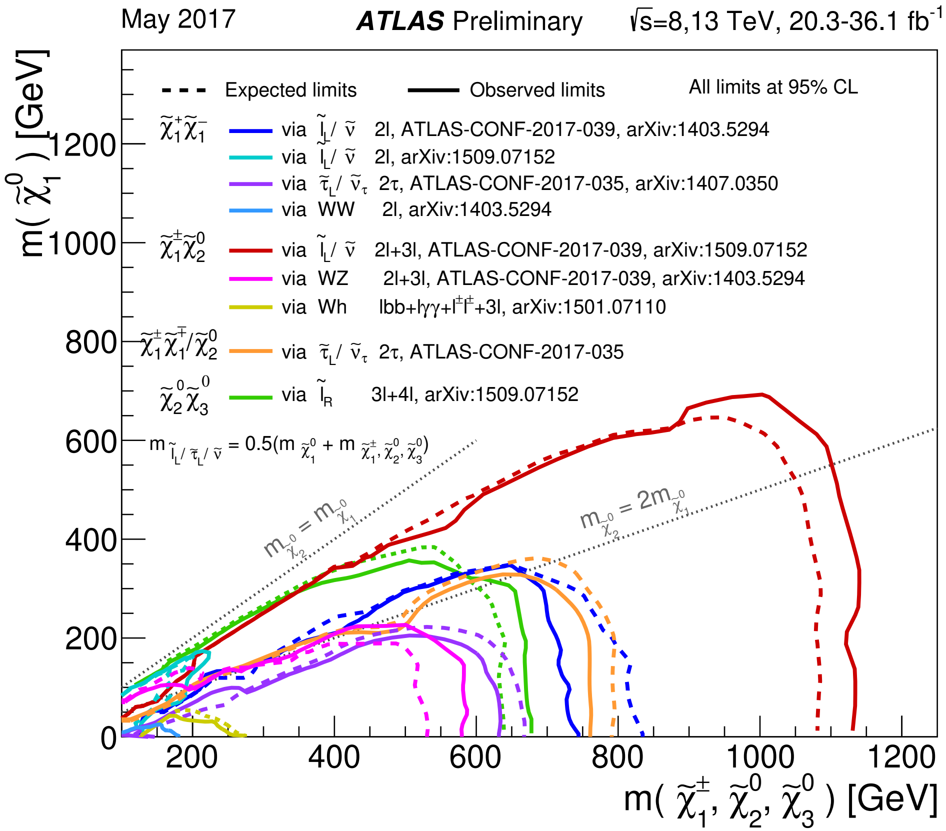
- DM relic is determined by $\langle\sigma v\rangle$.
- σv can be expanded by v.
  $\rightarrow \sigma v = a + bv^2 + \mathcal{O}\left(v^4\right)$
  a: s-wave, b: p-wave
- $\Omega h^2 \sim \frac{10^{-10}\ [\mathrm{GeV}^{-2}]}{\langle\sigma v\rangle} \sim 0.1$
  (Planck Coll.)
  $\rightarrow \langle\sigma v\rangle \sim 10^{-9}\ [\mathrm{GeV}^{-2}]$
  $\approx 10^{-26}\ [\mathrm{cm}^3/\mathrm{s}]$

WIMP search status



Collider search

Summary plot from ATLAS

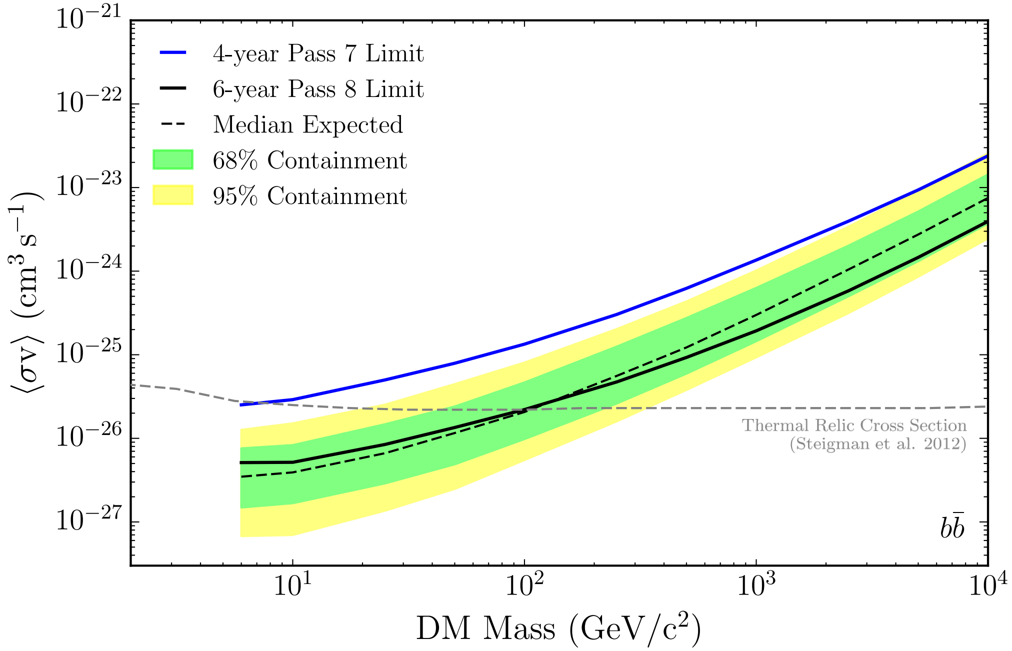


- WIMP DM can experimentally be detectable.
- Collider search: mass degenerate is required.

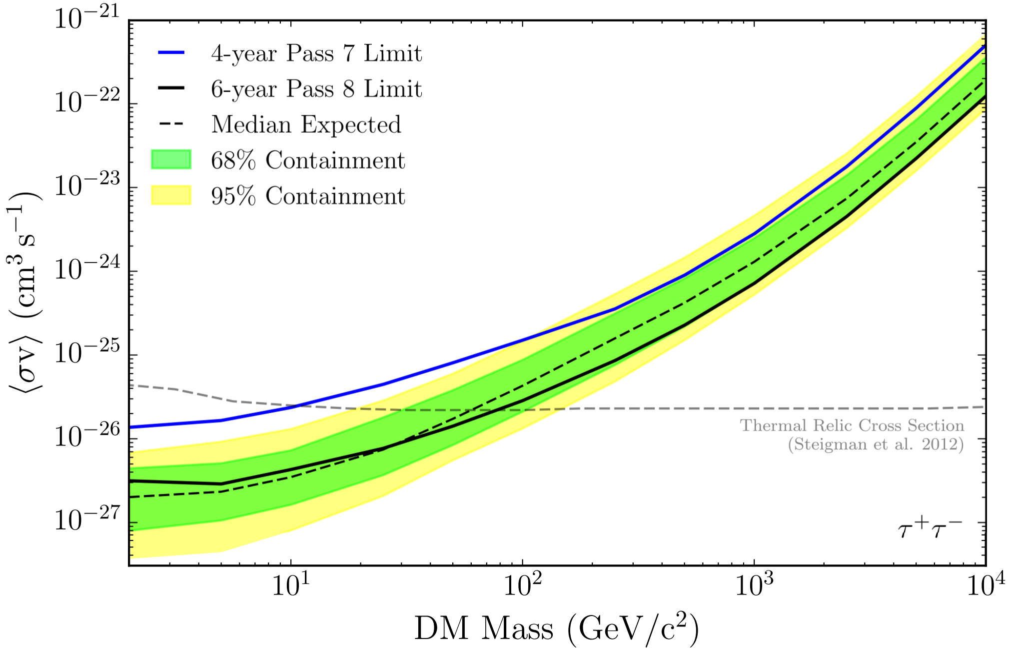
WIMP search status

Indirect detection (Gamma-rays from dSphs)

$\chi\chi \to b\bar{b}$



$\chi\chi \to \tau^+\tau^-$



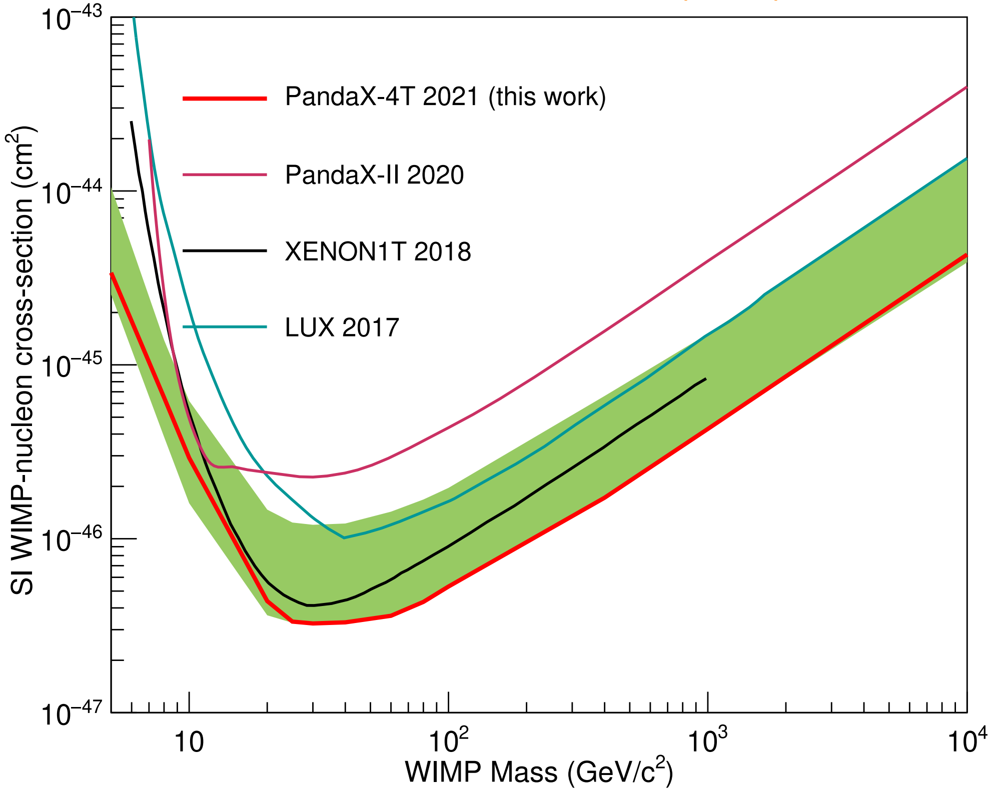
Fermi-LAT, PRL (2015) arxiv:1503.02641

- A lot of gamma-rays are generated if final state particles are charged.
- $m_{\rm DM} \lesssim 100$ GeV is excluded if thermal WIMP scenarios are assumed.
- $\langle\sigma v\rangle \sim 10^{-26}\ {\rm cm}^3/{\rm s}$ for thermal DM

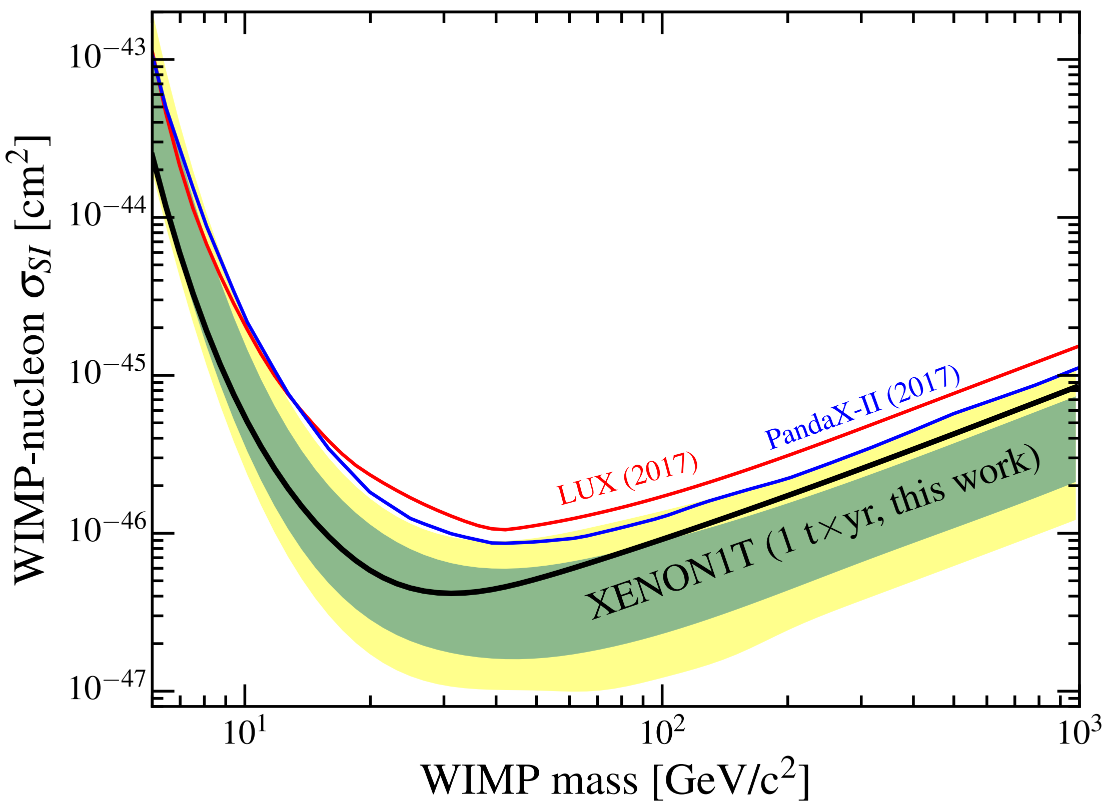
WIMP search status

Direct detection

PandaX-4T (2021) 2107.13438



XENON1T (2020)



- Experimental bounds are stronger and stronger.

Wayout

(1) Interactions between DM and SM are very weak? $\rightarrow$ non-WIMP DM?

(2) Elastic cross section is suppressed by small DM velocity?

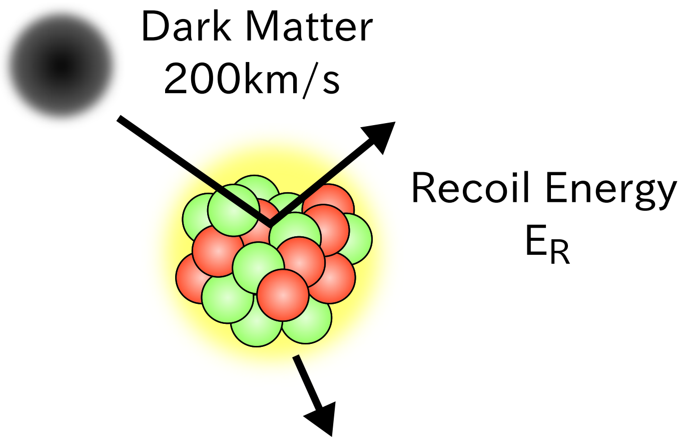
The pNGB DM model

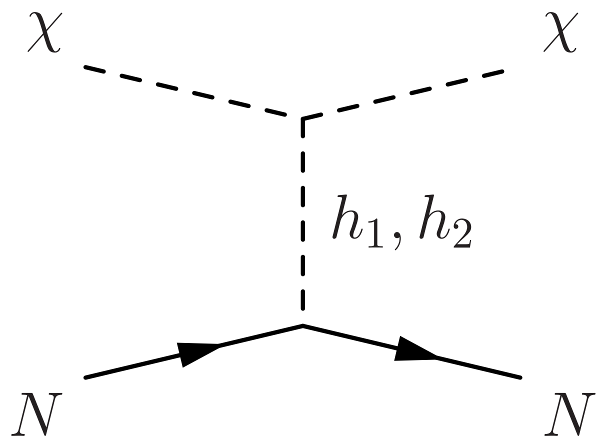
C. Gross, O. Lebedev, TT, PRL (2017) [arXiv:1708.02253]

- Introduce complex scalar field $S = (s + i\chi)/\sqrt{2}$
- Global $U(1)$ symmetry is assumed (invariant under $S \to e^{i\alpha} S$)

$$\mathcal{V} = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4$$

$$- \left(\frac{\mu_S'^2}{4} S^2 + \mathrm{H.c.}\right) \quad \leftarrow \text{soft breaking mass term}$$





- Scattering amplitude cancels between h_1, h_2 mediated diagrams

$$i\mathcal{M} \sim i\left(\frac{m_{h_1}^2}{q^2 - m_{h_1}^2} - \frac{m_{h_2}^2}{q^2 - m_{h_2}^2}\right) \sim i\frac{q^2(m_{h_1}^2 - m_{h_2}^2)}{m_{h_1}^2 m_{h_2}^2} \quad \to \quad 0$$

Summary so far

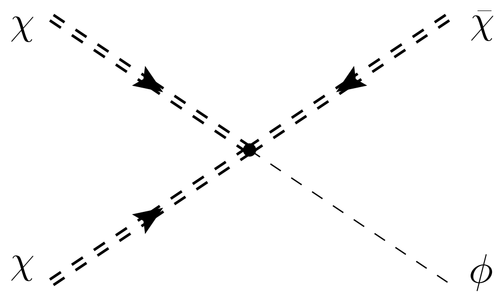
- Direct detection experiments set strong bounds on interactions between DM and SM.
- This implies v_χ dependent elastic cross section: $\sigma \propto v_\chi^n$.
  Ex. pNGB DM
- Elastic scattering can be enhanced if boosted.
  May be detected by experiments.

Mechanisms to boost DM

- Semi-annihilations $\chi\chi \to \bar{\chi}\phi$
  $\Rightarrow$ Simle and small uncertanties
- Decay or annihilations of heavier particles
- Collision with high energy cosmic-rays

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
- DM cannot be stabilized by $\mathbb{Z}_2$ parity.
  $\Rightarrow$ DM is a non-self-conjugate particle if it is assumed to be stable.
- Boltzmann equation

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

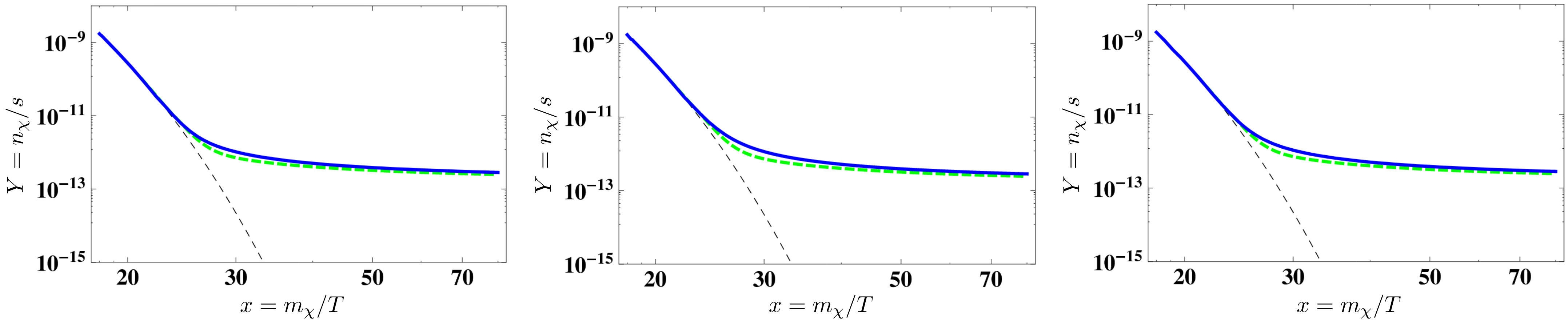
1st term: semi-ann. 2nd term: normal ann.
Note: normal annihilations always exist.

Relic abundance with semi-ann.

- $\chi\chi \to \bar{\chi}\phi$

$$\Omega h^2 \sim 2\frac{1.07\times 10^{-10}}{\langle\sigma_{\chi\bar{\chi}}v\rangle + \langle\sigma_{\chi\chi}v\rangle}, \quad \text{cf } \Omega h^2 \sim \frac{1.07\times 10^{-10}}{\langle\sigma_{\chi\bar{\chi}}v\rangle} \text{ for normal ann.}$$

- does not change much from normal case.
- A bit longer time is needed to reach the freeze-out value Ωh^2.



only $\langle\sigma_{\chi\bar{\chi}}v\rangle$ — only $\langle\sigma_{\chi\chi}v\rangle$ — mixed

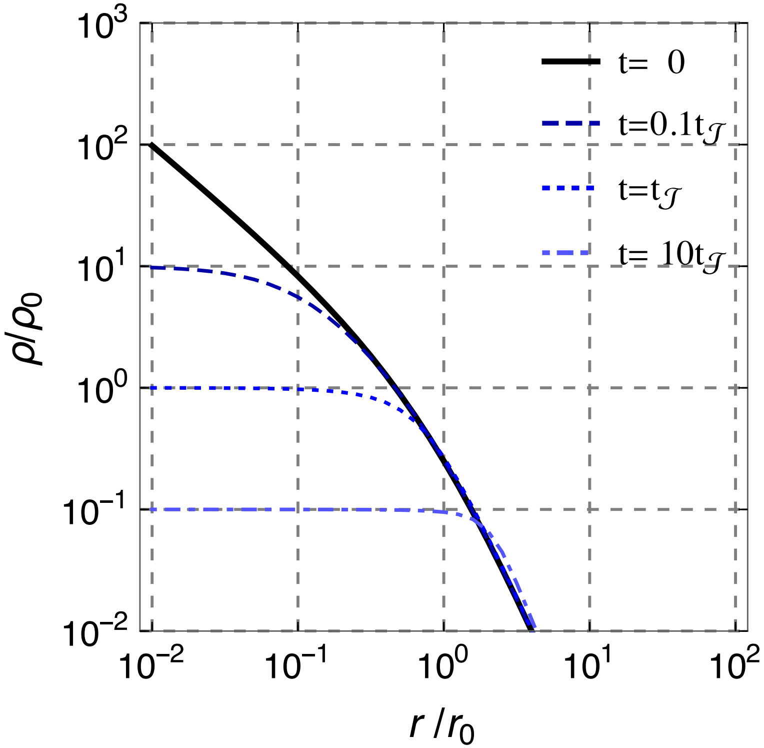
Blue lines: Numerical — Green lines: semi-analytic

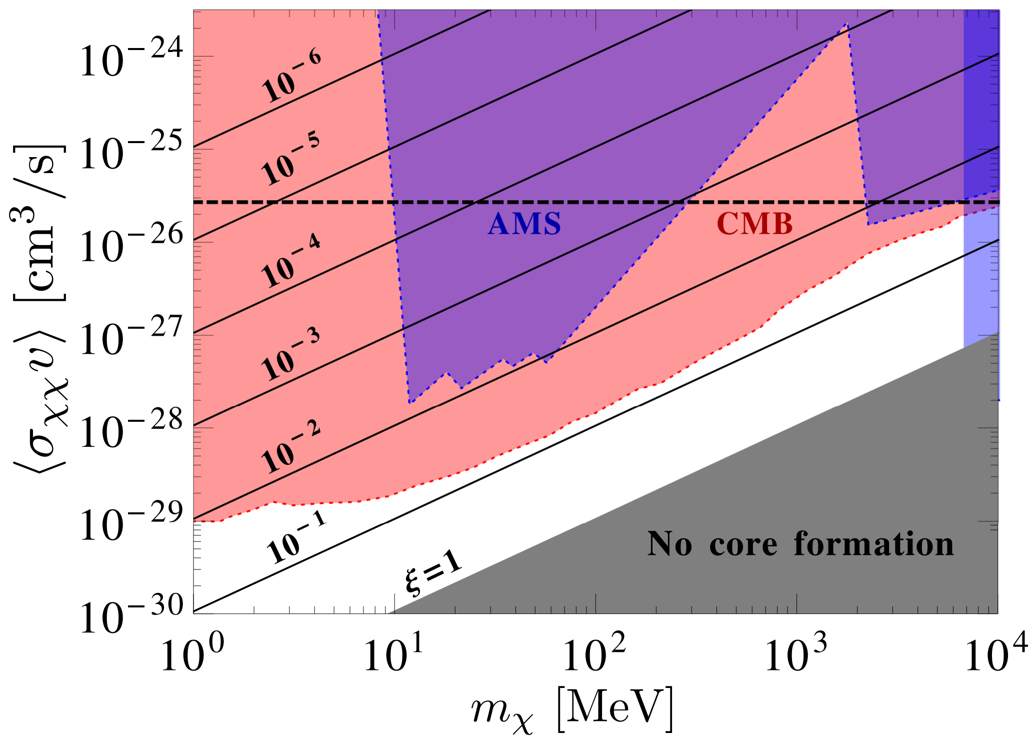
F. D'Eramo and J. Thaler, JHEP (2010) [arXiv:1003.5912]

Core formation via self-heating (implication of semi-ann.)

- Collisionless WIMP ⇒ core vs cusp problem
- semi-ann. $\chi\chi \to \bar{\chi}\phi$ gives a momentum to $\bar{\chi}$ $(E_{\bar{\chi}} \sim 5m_\chi/4)$.
  ⇒ pressure in centre of DM profile
  ⇒ core is formed. X. Chu and C. Garcia-Cely, JCAP (2018) [arXiv:1803.09762]

Energy absorption efficiency: $\xi \sim \frac{r_s}{\lambda} \sim 10^{-3}\left(\frac{r_s}{5\ \mathrm{kpc}}\right)\left(\frac{\rho_\chi}{M_\odot/\mathrm{pc}^3}\right)\left(\frac{\sigma_{\mathrm{self}}/m_\chi}{10^{-3}\ \mathrm{cm}^2/\mathrm{g}}\right)$

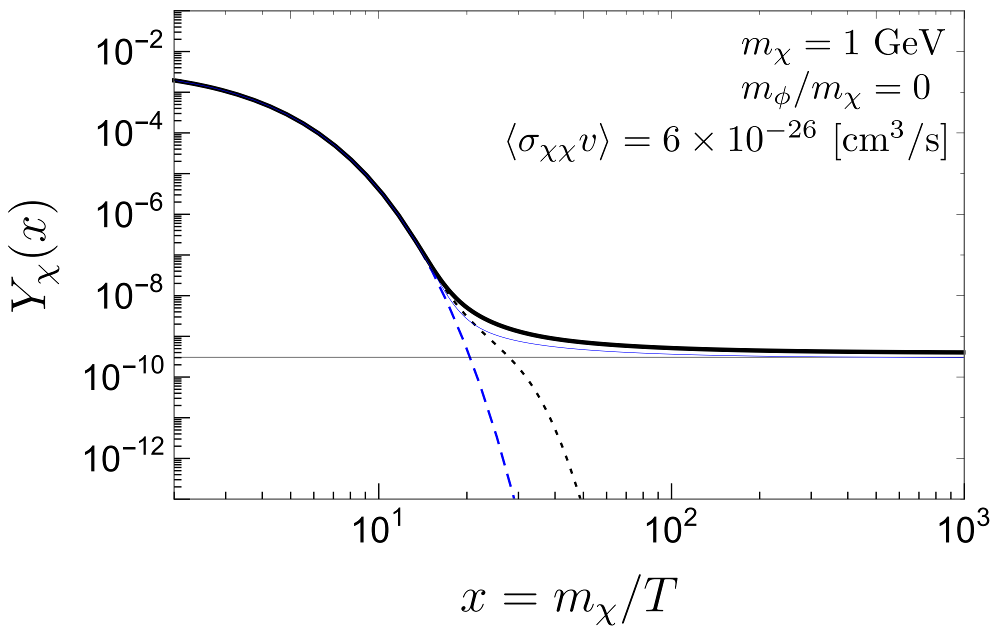


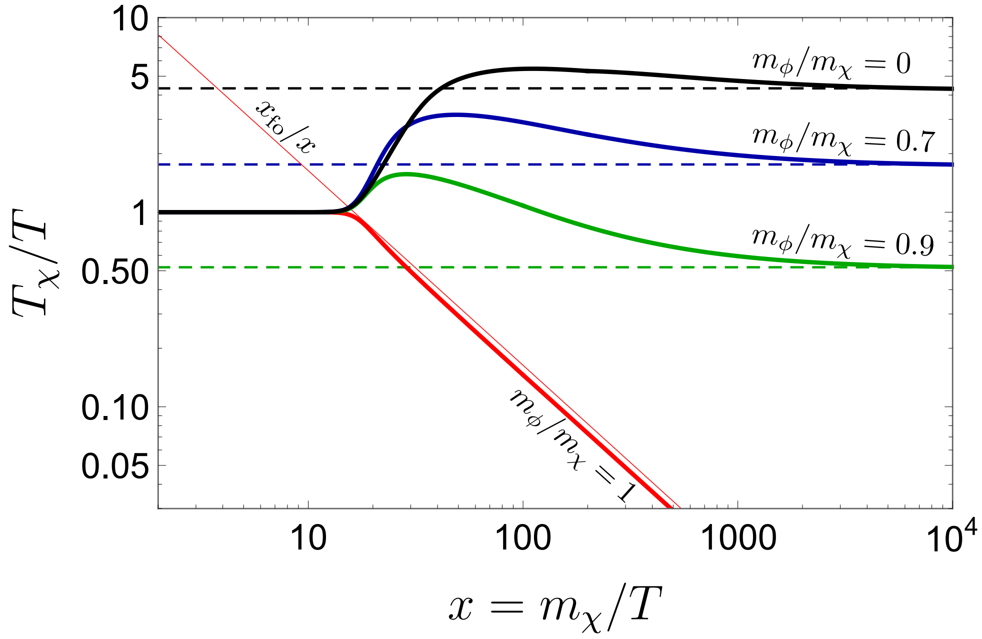


Self-heating via semi-annihilations (implication of semi-ann. 2)

A. Kamada et al., PRL (2018) [arXiv:1707.09238]

- Assumption: elastic scattering $\chi\phi \to \chi\phi$ is inefficient.
  $\Rightarrow T_\chi \neq T$





- $T_\chi \propto a^{-1}$ after freeze-out like radiation
- small effect on relic abundance ∼30%

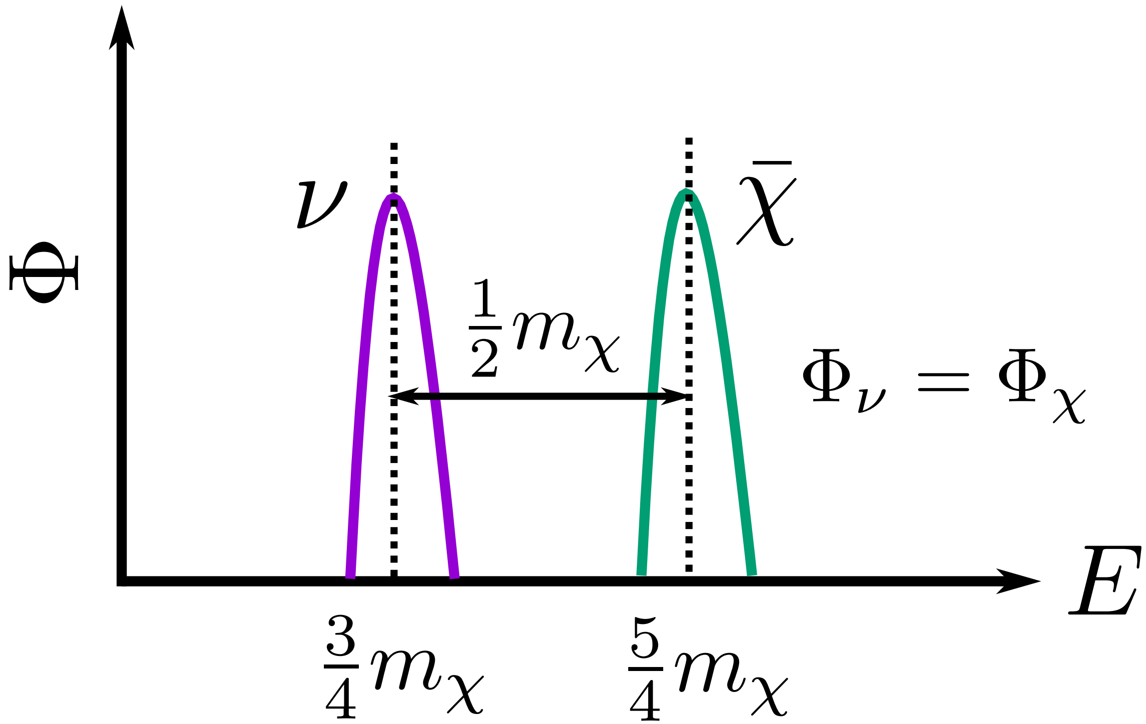
Distinctive signals from semi-annihilations

Specific semi-annihilation

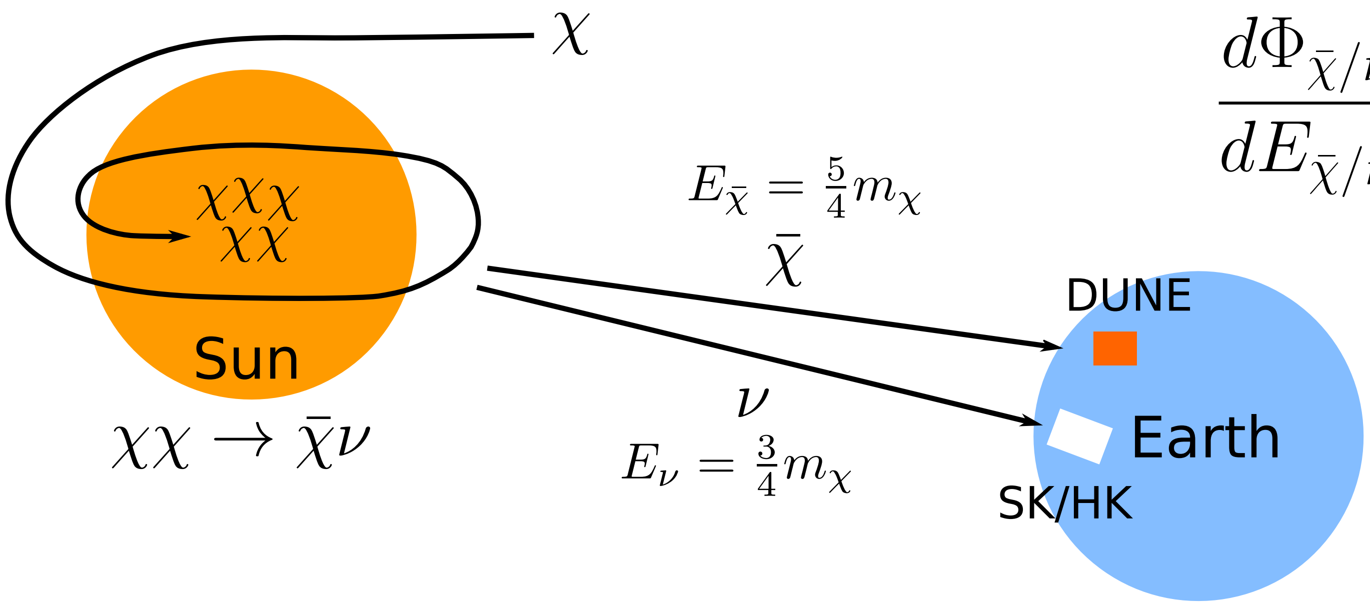
- We focus on $\chi\chi \to \bar{\chi}\nu$.
  - One of native semi-annihilation processes
  - May correlate with generation of small neutrino masses
- Energy of the produced particles

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

- 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



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

- A number of DM particles are accumulated in the centre of the Sun.
- Semi-annihilation occurs.
- Two different signals may be searched at large volume neutrino detectors.
- Signals from Galactic centre $\Rightarrow$ Produced flux is smaller

Semi-annihilation from the Sun

- Number of DM particles accumulated in the Sun

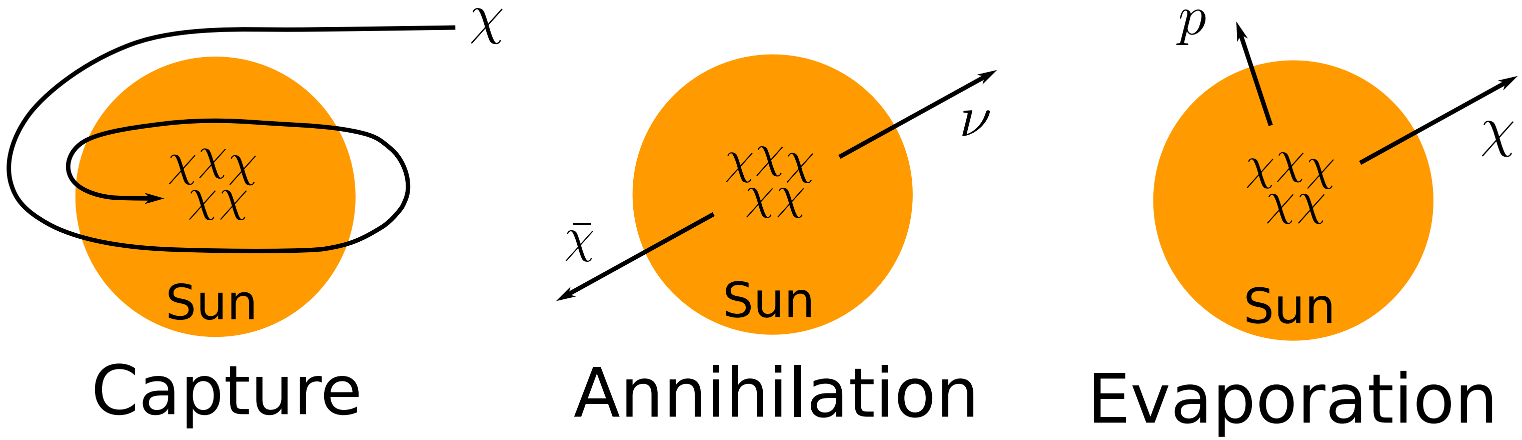
$$\frac{dN_\chi}{dt} = \Gamma_{\rm capt} - 2\Gamma_{\rm ann} - \Gamma_{\rm evap}$$

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



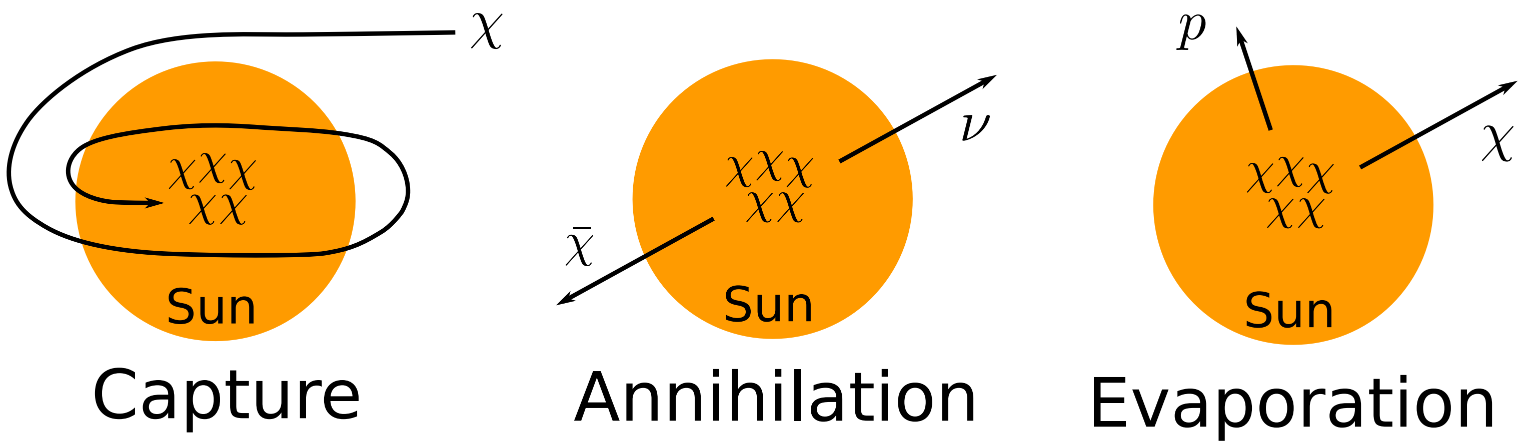
Semi-annihilation from the Sun

- Number of DM particles accumulated in the Sun

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

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

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



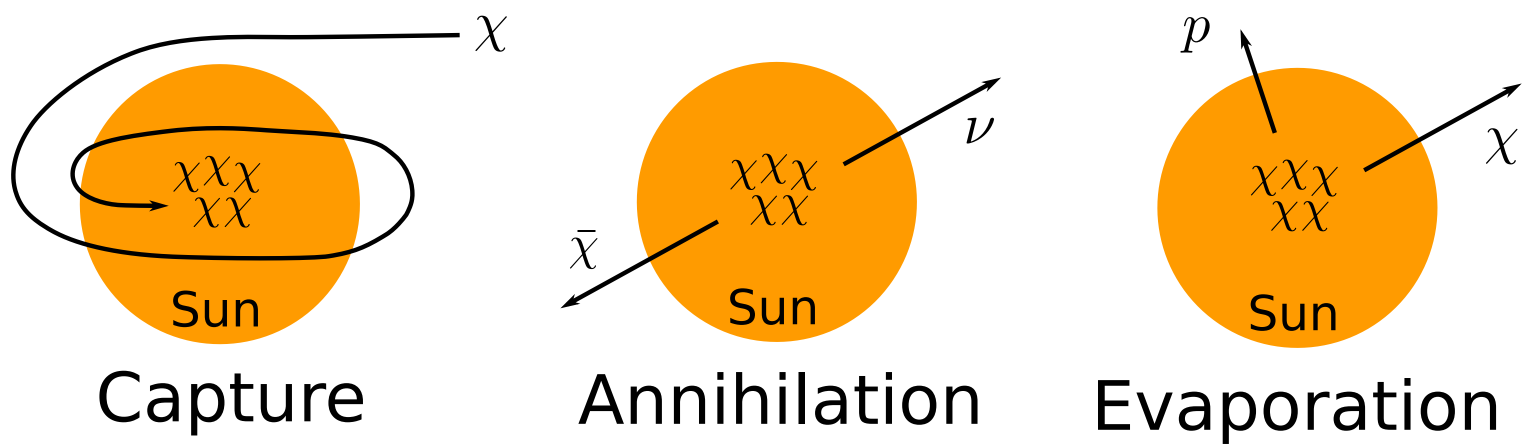
Semi-annihilation from the Sun

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

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

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

- Equilibrium can easily be reached.



Semi-annihilation from the Sun

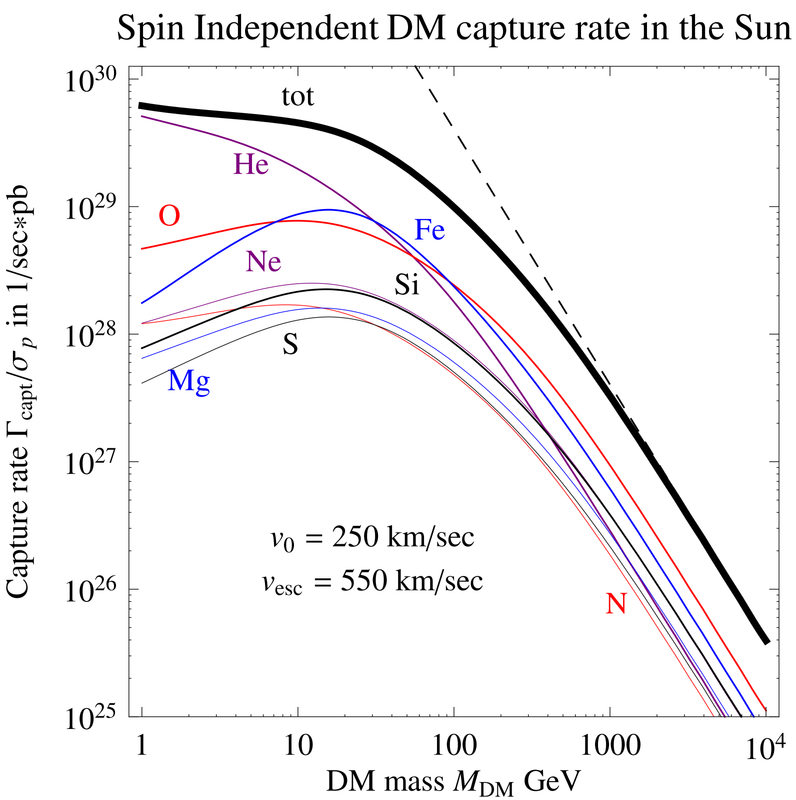
P. Baratella et al., JCAP (2014) [arXiv:1312.6408]

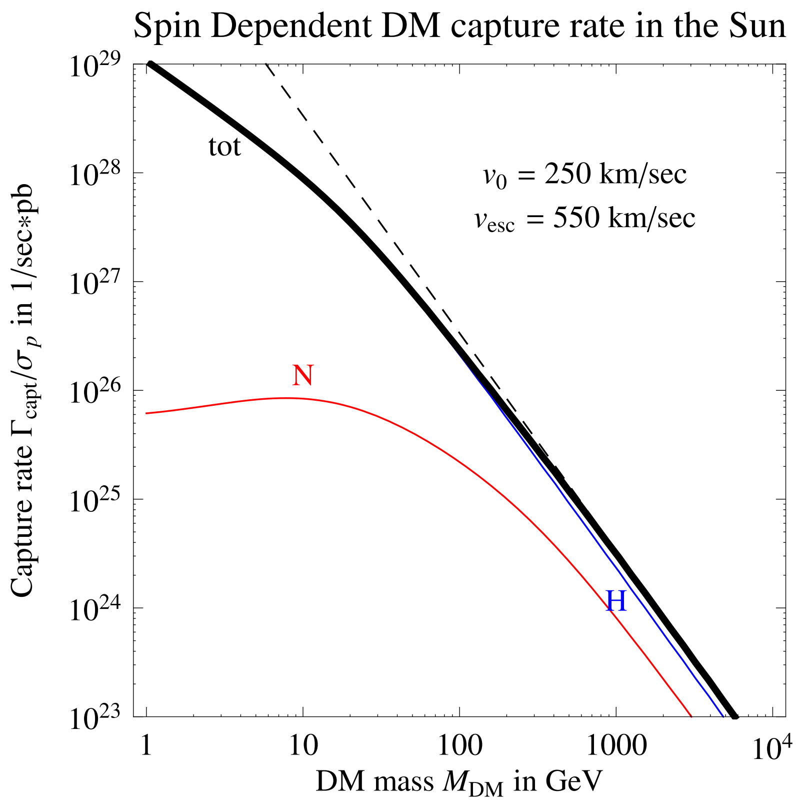
- Capture rate without v depndence

$$\Gamma_{\rm capt} \approx 2.0 \times 10^{20}\ {\rm s}^{-1} \left(\frac{\sigma_{\rm SD}}{10^{-42}\ {\rm cm}^2}\right)\left(\frac{100\ {\rm GeV}}{m_\chi}\right)^2$$

Capture rate with v^2 dependence

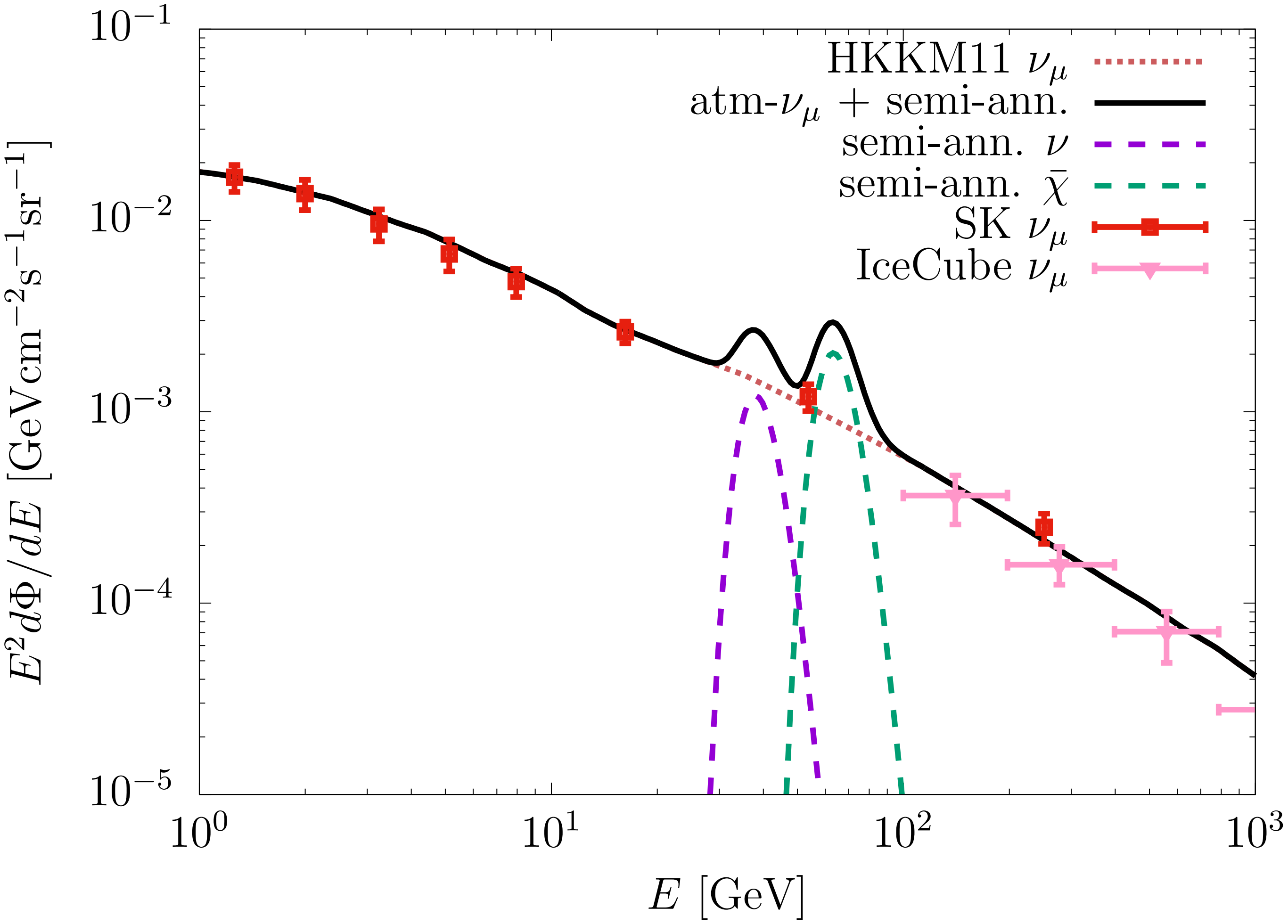
$$\Gamma_{\rm capt} \approx 5.1 \times 10^{21}\ {\rm s}^{-1} \left(\frac{\sigma_{\rm SD}}{10^{-42}\ {\rm cm}^2}\right)\left(\frac{100\ {\rm GeV}}{m_\chi}\right)^2$$



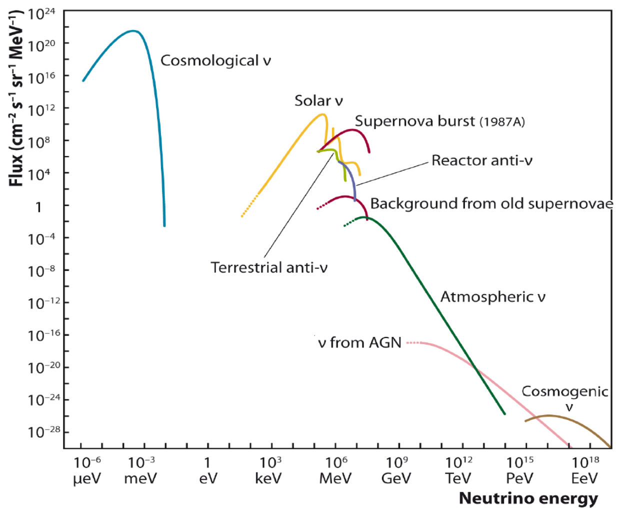


Signals of boosted dark matter and neutrino

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



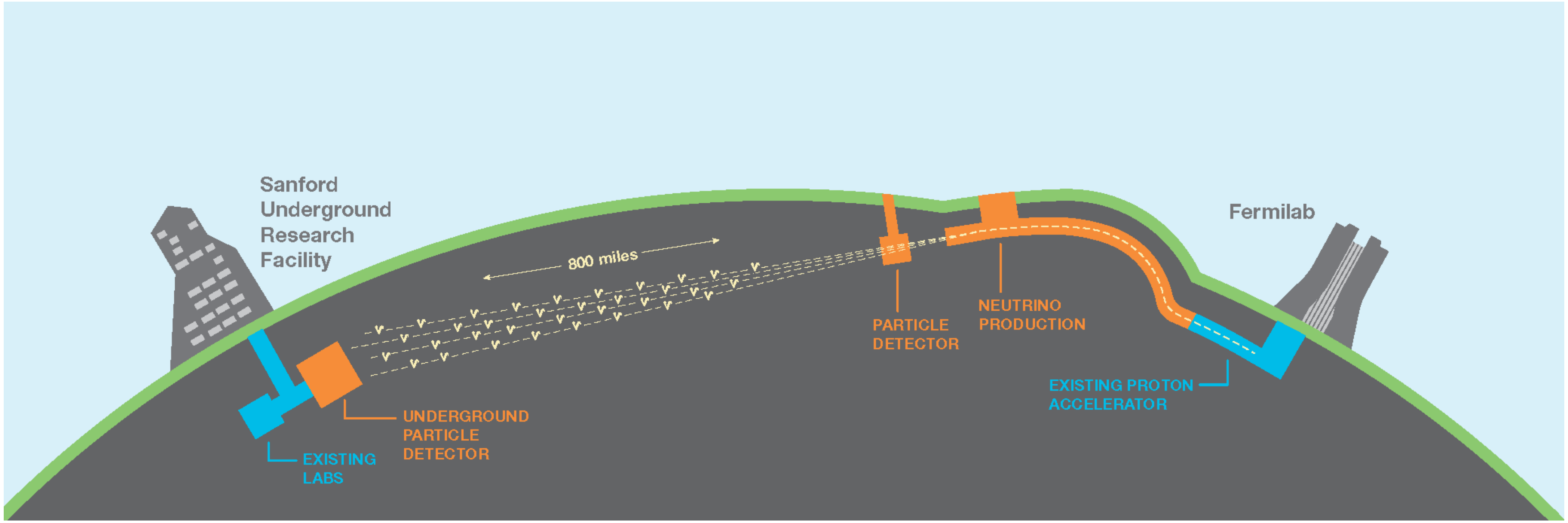
- $$E_{\bar{\chi}} = \frac{5}{4} m_\chi$$
  $$E_\nu = \frac{3}{4} m_\chi$$
  $$\Delta E = \frac{1}{2} m_\chi$$



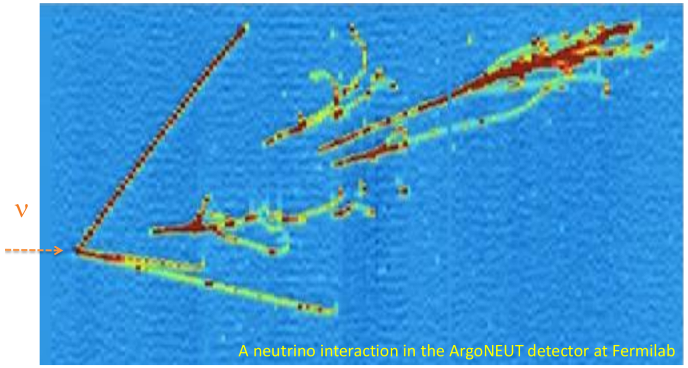
- $m_\chi = 50$ GeV and $\sigma_{SD} = 3 \times 10^{-41}$ cm^2 (non-relativistic)
- $\Delta E/E = 25\%$ is assumed

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

DUNE (Deep Underground Neutrino Experiment)

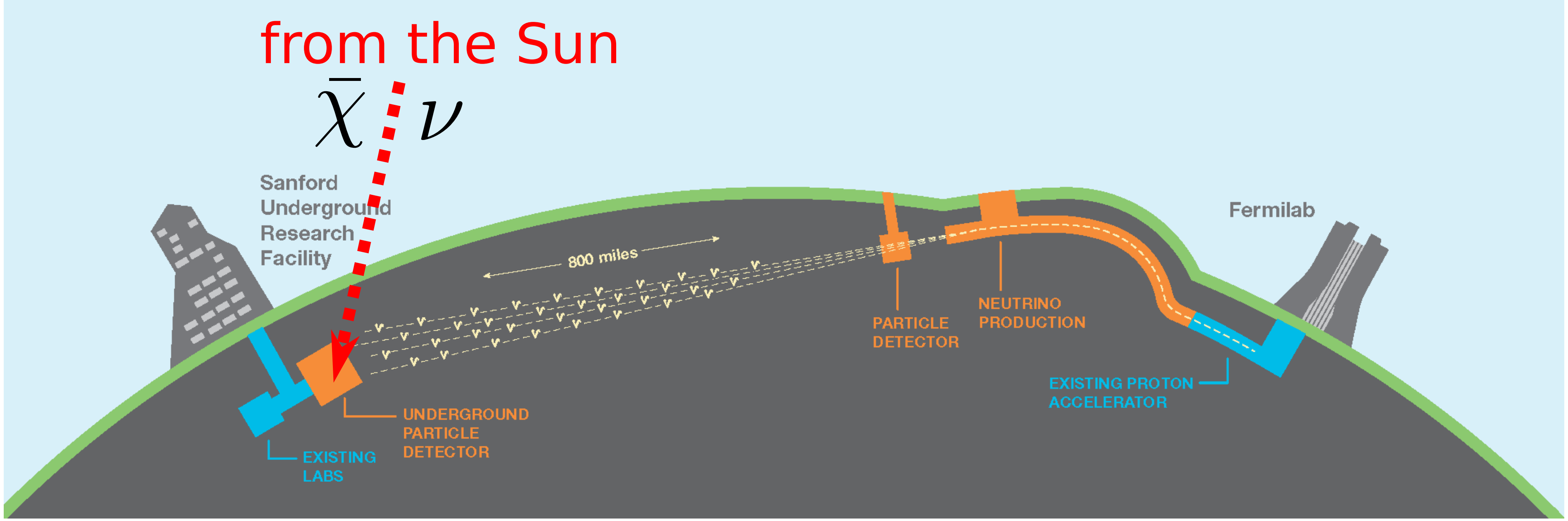


- Two detectors: near and far detectors.
- Massive liquid argon (fiducial volume: 40kt)
- Precise reconstruction of particle's trajectories with LArTPC

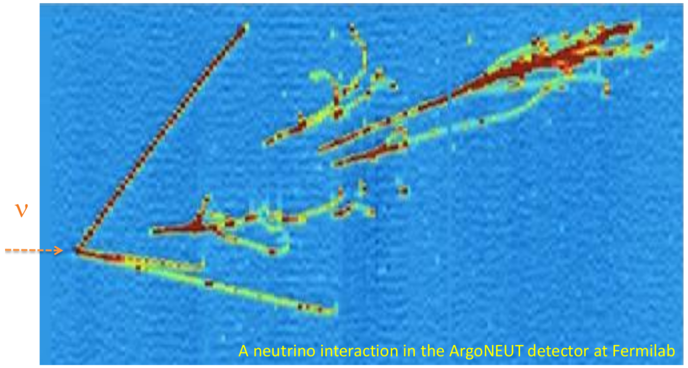


DUNE Coll., [arXiv:2002.03005]

DUNE (Deep Underground Neutrino Experiment)

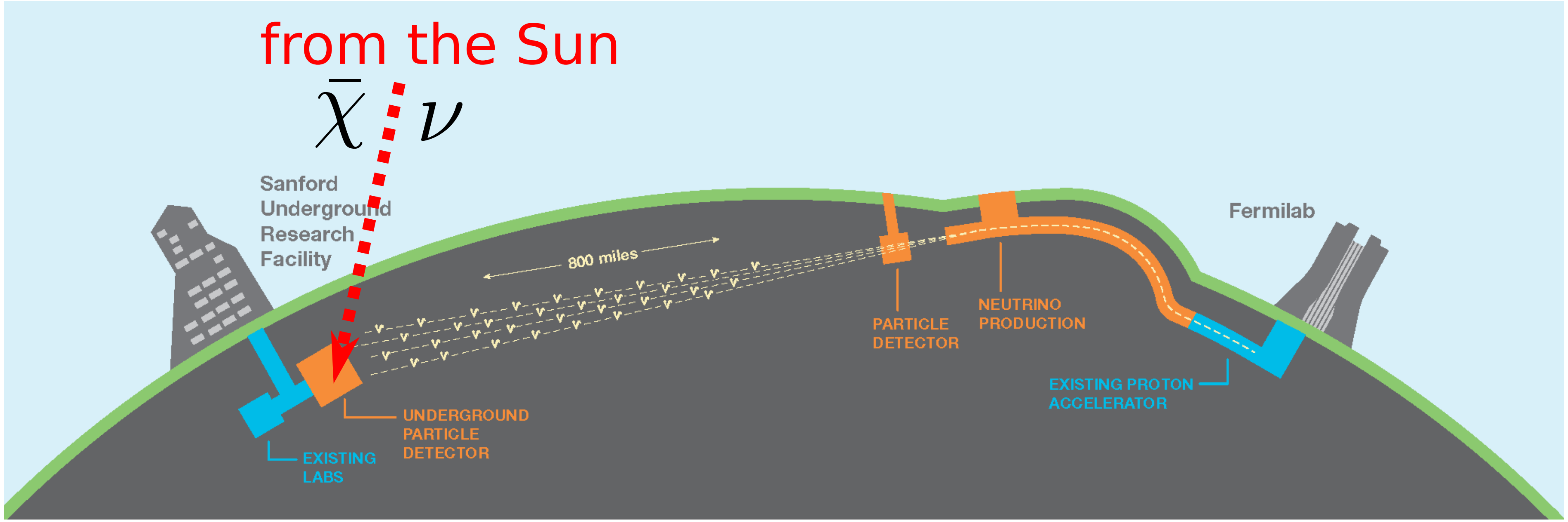


- Two detectors: near and far detectors.
- Massive liquid argon (fiducial volume: 40kt)
- Precise reconstruction of particle's trajectories with LArTPC



DUNE Coll., [arXiv:2002.03005]

DUNE (Deep Underground Neutrino Experiment)



DUNE Coll., [arXiv:2002.03005]

Timeline of far detector modules

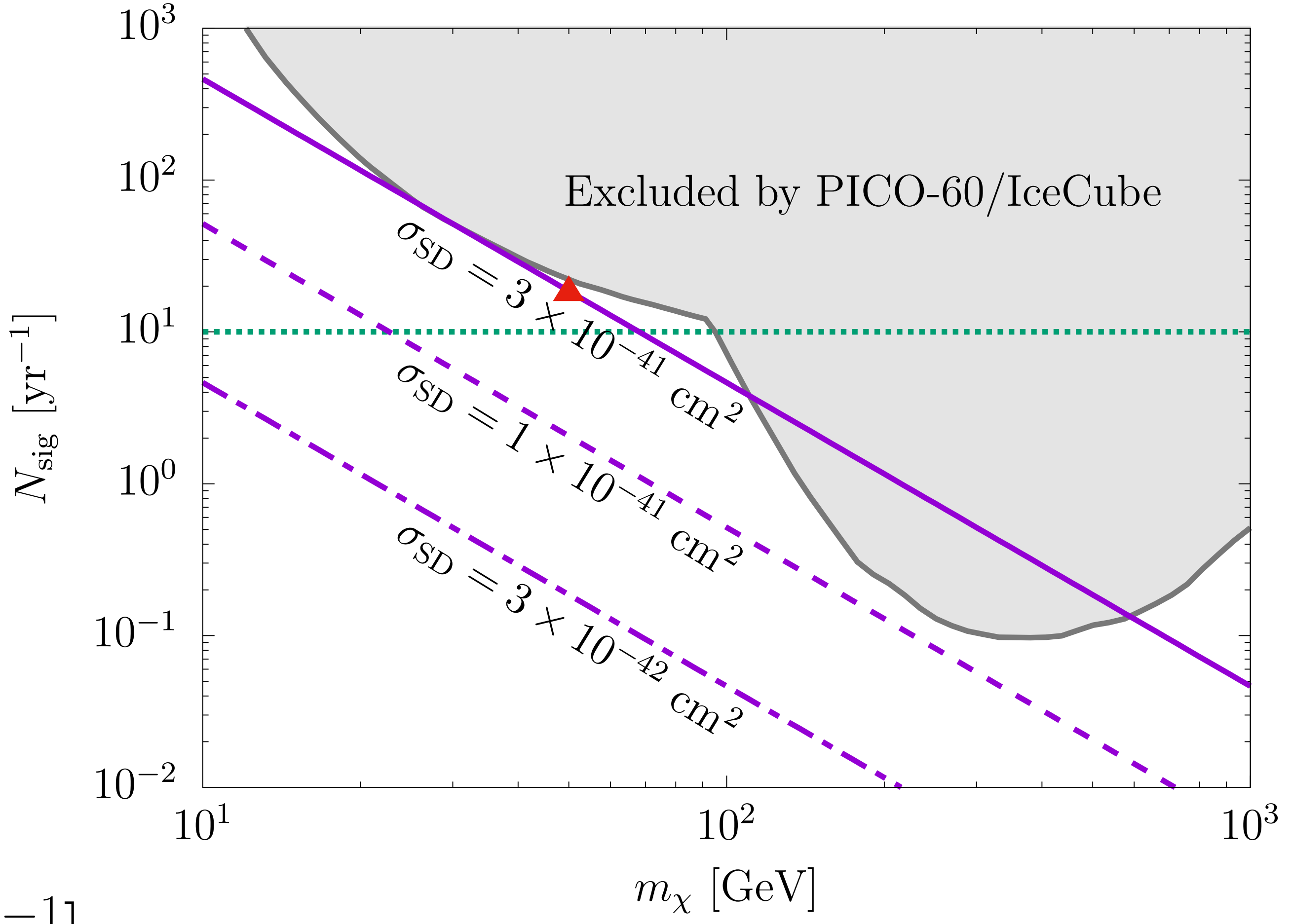
- 2025: DUNE physics deta taking with atmospheric neutrinos (fiducial mass 20kt)
- 2026: DUNE physics deta taking with beam starts (fiducial mass 20kt)
- 2027: add third fiducial module (20kt + 10kt = 30kt)
- 2029: add fourth fiducial module (30kt + 10kt = 40kt)

Expected number of signal events at DUNE

$$N_{\rm sig} = t_{\rm exp}\ N_p\ \Phi_{\bar\chi}\ \tilde\sigma_{\rm SD}$$

- Number of protons
  $N_p \sim 10^{34}$ (LAr 40kt)
- Scattering cross section
  $\bar\chi p \to \bar\chi p$ (Boosted DM)

  Naive estimate:
  $\tilde\sigma_{\rm SD} \sim \sigma_{\rm SD}(0.6/10^{-3})^2$
  $= 3.6 \times 10^5 \sigma_{\rm SD}$



- Benchmark: $N_{\rm sig} > 10$ [yr^{-1}]
- $N_{\rm sig} \gtrsim \mathcal{O}(10)$ if $m_\chi \lesssim 100$ GeV

Energy spectrum

- Energy of scattered proton E_p is kinematically determined.

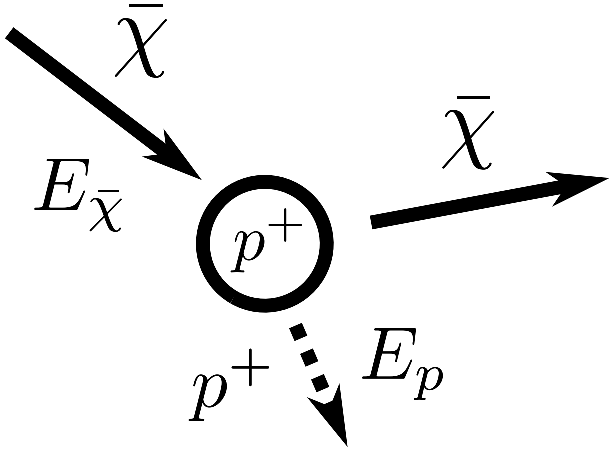
$$m_p \leq E_p \leq m_p \frac{(E_{\bar{\chi}} + m_p)^2 + E_{\bar{\chi}}^2 - m_\chi^2}{(E_{\bar{\chi}} + m_p)^2 - E_{\bar{\chi}}^2 + m_\chi^2}$$

Since $E_{\bar{\chi}} = \frac{5}{4} m_\chi \quad \Rightarrow \quad m_p \leq E_p \lesssim \frac{17}{8} m_p$

Maximum energy is almost independent of m_χ if $m_\chi \gtrsim 10\ \mathrm{GeV}$

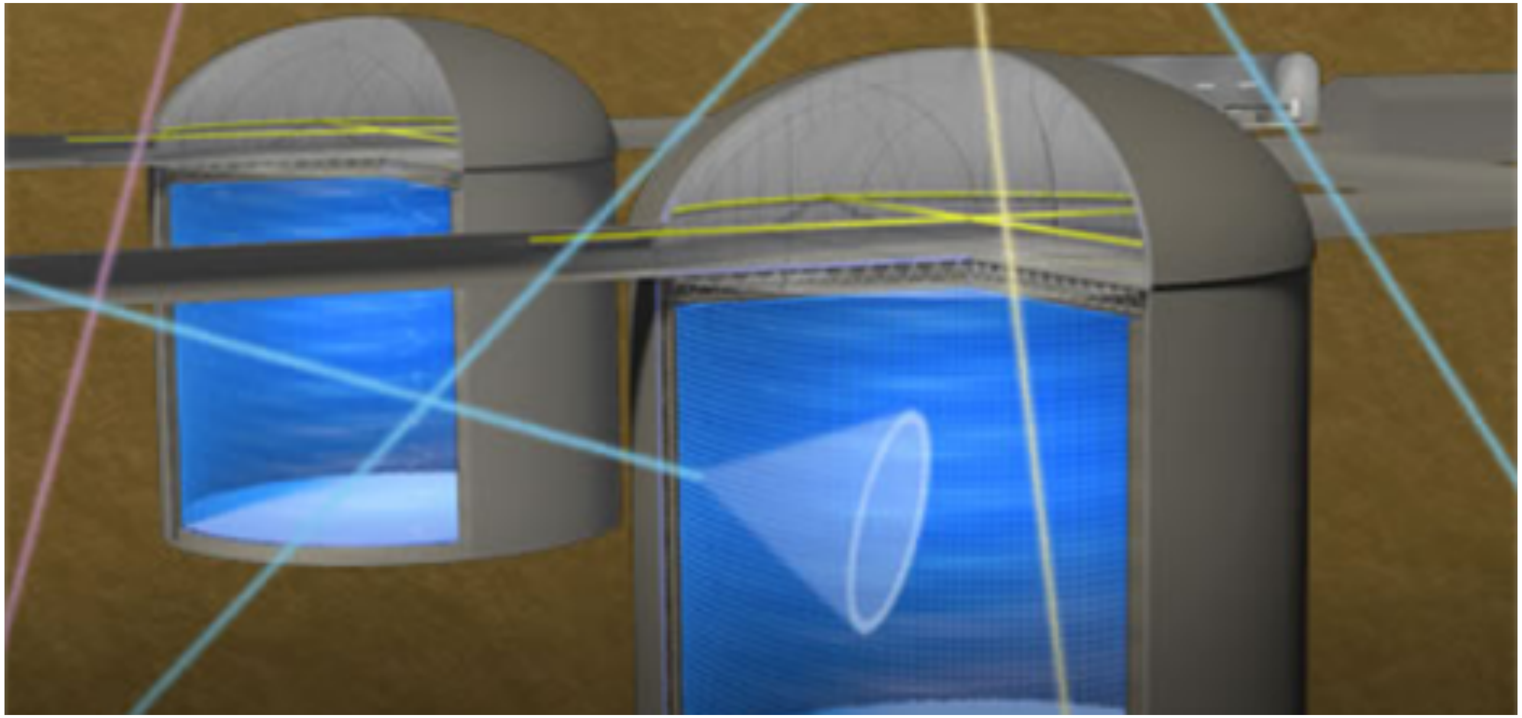
- Whole energy spectrum can identify DM mass ⇒ model dependent

- m_χ can be seen if $m_\chi \lesssim 10\ \mathrm{GeV}$
but one should care about
gamma-ray constraint from $\chi\bar{\chi} \to q\bar{q}$



Neutrino

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



Hyper-Kamiokande Collaboration

- For boosted DM, difficult to emit Cherenkov light ($v_p^{\max} = 0.88c$)
  $v_p > 0.75c$ is required so that Cherenkov radiation is emitted.

Model building

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

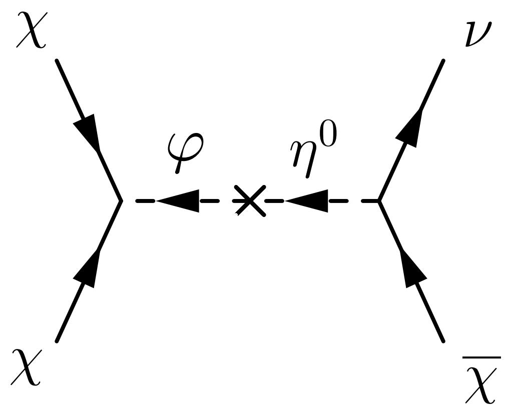
$$\text{Anapole int.} \quad \mathcal{L} \supset \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\gamma_5\partial_\nu\chi F^{\mu\nu} \quad \to \quad \sigma_{\rm SD},\ \sigma_{\rm SI} \propto v^2$$

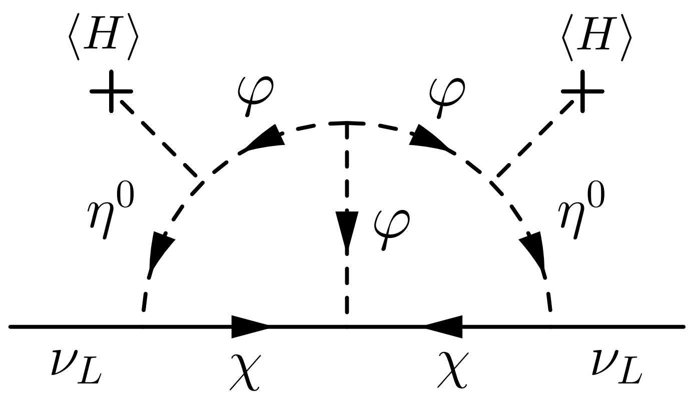
$$\text{SP int.} \quad \mathcal{L} \supset \frac{1}{\Lambda^2}\left(\bar{\chi}\chi\right)\left(\bar{p}\gamma_5 p\right) \quad \to \quad \sigma_{\rm SD} \propto v^2$$

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

- Semi-annihilation $\chi\chi \to \bar{\chi}\nu$
  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
$SU(2)$	**1**	**1**	**2**	**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





Summary

1. Semi-annihilation $\chi\chi \to \bar{\chi}\nu$ induces a characteristic signals.
2. These signals can be searched by large volume neutrino detectors.
3. Rough estimation has been done.

Future works

1. Detailed simulations with `GENIE`
2. Construct concrete models
   - velocity-dependent cross section
   - semi-annihilation $\chi\chi \to \bar{\chi}\nu$
   - model dependent constraints