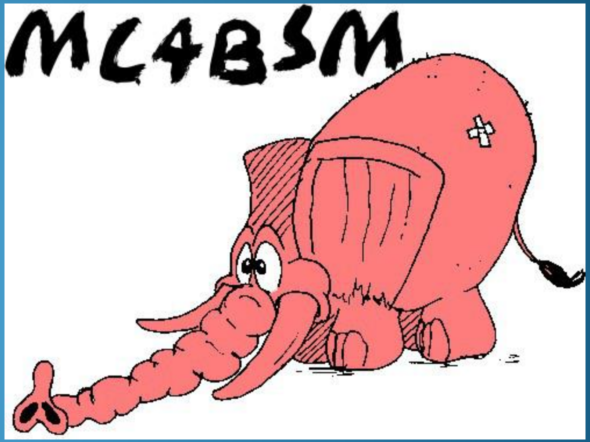
# (In)elastic (Boosted) Dark Matter Searches and Monte Carlo Simulation

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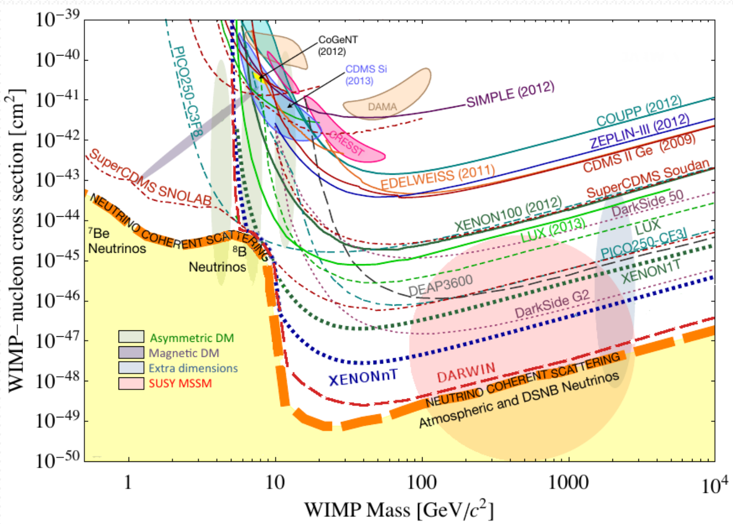
**Monte Carlo Tools for Physics Beyond the Standard Model**

Institute for Particle Physics Phenomenology,

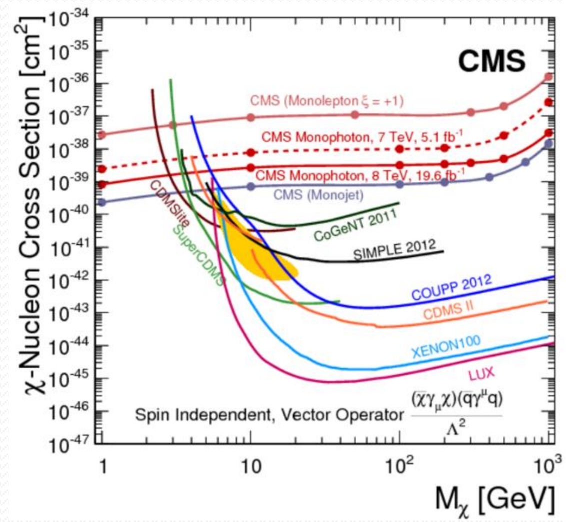
Durham University, United Kingdom, April 18th, 2018

# Current Status of Dark Matter Searches

- **No observation** of DM signatures via non-gravitational interactions while many searches/interpretations designed/performed under WIMP/minimal dark-sector scenarios ⇒ merely excluding more parameter space in dark matter models




[Cushman, Calbiati, McKinsey (2013); Baudis (2014)]




[CMS mono-photon search (2014)]

*Time to change our approach?!*

# Conventional vs. Nonconventional Approaches

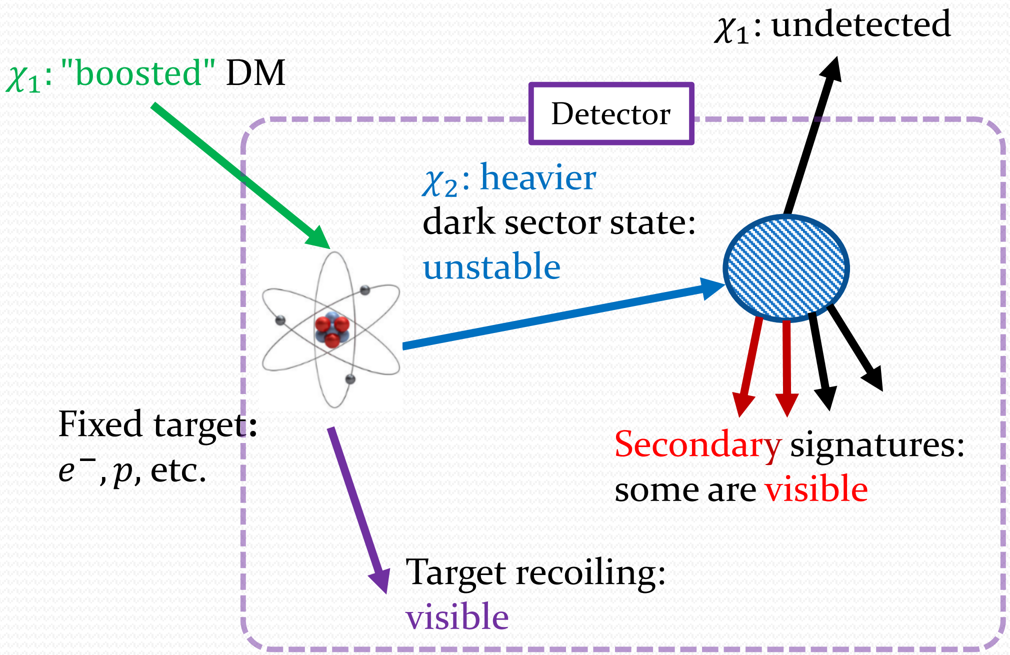
- Conventional/traditional approaches for DM searches;
  - ✓ ~~Weak-scale~~ mass
  - ✓ ~~Weakly~~ coupled
  - ✓ ~~Minimal dark~~ sector
  - ✓ ~~Elastic~~ scattering
  - ✓ ~~Non-relativistic~~

- Nonconventional/modified approaches for DM searches;
  - ✓ Other mass scales, e.g., sub-GeV, MeV, keV, …
  - ✓ Weaker connection to the SM, e.g., vector portal (dark photon), scalar portal, …
  - ✓ "Flavorful" dark sector, e.g., more DM species, unstable heavier dark-sector states, …
  - ✓ Inelastic scattering
  - ✓ Relativistic

***Inelastic boosted/relativistic DM searches***

# Inelastic "Relativistic"/Boosted Dark Matter

- Generic model framework [DK, Park, Shin (2016)]



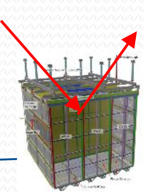

- ✓ Probing heavier dark-sector states
- ✓ Target recoil (like in typical DM direct detection exp.) + secondary visible signatures ⇒ more handles, (relatively) background-free (no secondary signatures in usual backgrounds)
- ✓ Complementary to standard DM direct searches

# Boosted/Relativistic Dark Matter: Cosmic Frontier

- Signals coming from the universe today, nontrivial model building required
  - ✓ Semi-annihilation in e.g., $Z_3$ models [D'Eramo, Thaler (2010)]
  - ✓ Fast-moving DM via induced nucleon decays [Huang, Zhao (2013)]
  - ✓ "Assisted" freeze-out [Belanger, Park (2011)], Two-component DM models [Agashe, Cui, Necib, Thaler (2014)]

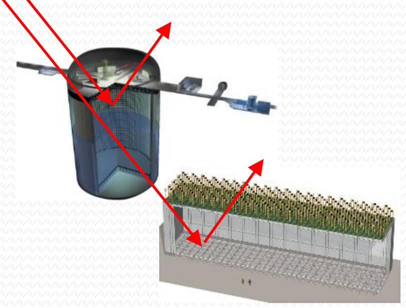
- Incoming flux of boosted DM is typically small.

Surface-based detectors, e.g., ProtoDUNE, SBN Program [Chatterjee, **DK**, et al. (2018); **DK**, Kong, Park, Shin in progress]



Earth surface

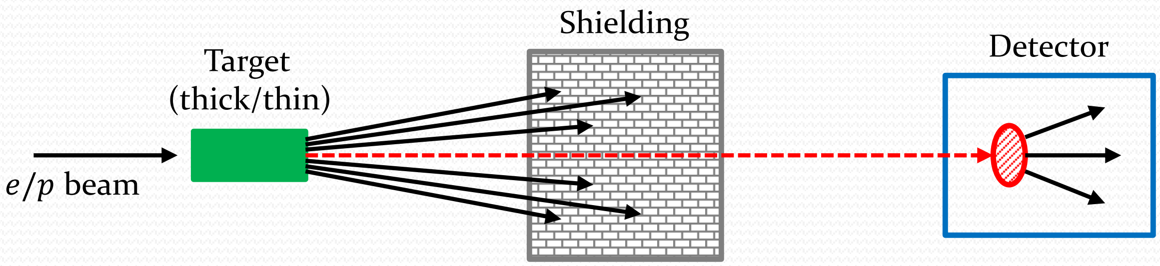
Underground large-volume detectors, e.g., Super/Hyper-K, DUNE [Agashe, Cui, Necib, Thaler (2014); Huang, Zhao (2013); Necib, Moon, Wongjirad, Conrad (2016); Berger, Cui, Zhao (2014); Kong, Mohlabeng, Park (2014); Alhazmi, Kong, Mohlabeng, Park (2016); **DK**, Park, Shin (2016)]



Conventional WIMP detectors (with some model variation), e.g., Xenon, Lux-Zeplin [Giudice, **DK**, Park, Shin (2017)]

# Boosted/Relativistic Dark Matter: Intensity Frontier

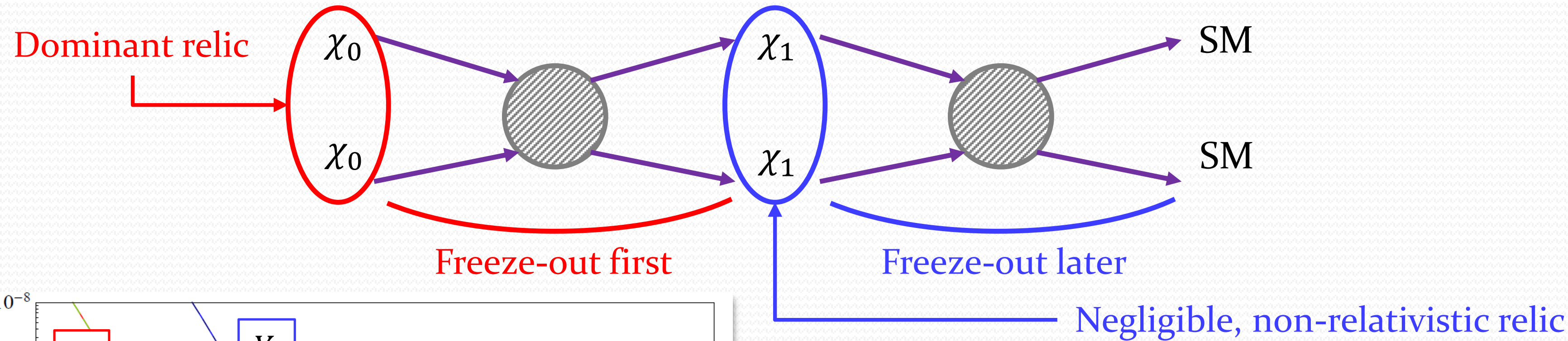
- ❑ Signals coming from colliders, additional model building not always necessary
- ❑ If dark sectors (containing dark matter) are more "weakly" connected to the SM sector, high intensity experiments are also motivated, e.g., fixed target experiments.
  - ✓ BDX, NA64, MicroBooNE, SeaQuest, LDMX, T2HKK, DUNE, SHiP, and many more

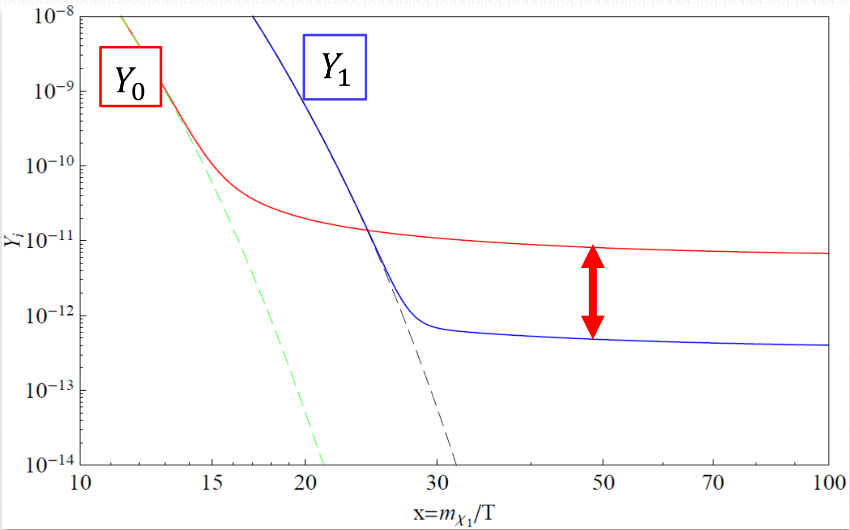



- ❑ Quite a few phenomenological studies/proposals in the context of dark photon decays, elastic/inelastic scattering of DM, etc. [LoSecco et al. (1980); Bjorken, Essig, Schuster, Toro (2009); Batell, Pospelov, Ritz (2009); deNiverville, Pospelov, Ritz (2011); Izaguirre, Krnjaic, Schuster, Toro (2014); Izaguirre, Kahn, Krnjaic, Moschella (2017); Berlin, Gori, Schuster, Toro (2018); Bonivento, **DK**, Park, Shin in progress, and many more]

# Two-component Boosted DM Scenario

- A possible relativistic source: BDM scenario (cosmic frontier), stability of the two DM species ensured by separate symmetries, e.g., $Z_2 \otimes Z_2'$, $U(1) \otimes U(1)'$, etc.

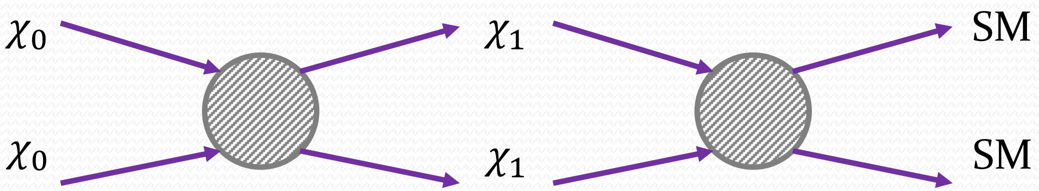


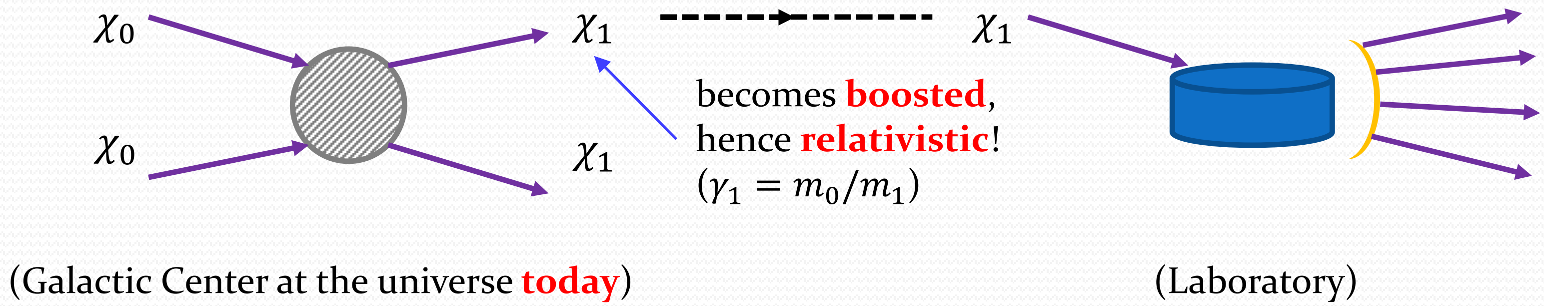

"Assisted" freeze-out mechanism

[Belanger, Park (2011)]

# "Relativistic" Dark Matter Search




- ✓ Heavier relic $\chi_0$: hard to detect it due to tiny/negligible coupling to SM
- ✓ Lighter relic $\chi_1$: hard to detect it due to small amount




[Agashe, Cui, Necib, Thaler (2014)]

# Boosted DM Detection

- Flux of boosted $\chi_1$ near the earth

$$\mathcal{F}_{\chi_1} \propto (\text{interaction strength}) \times (\chi_0 \text{ number})^2$$

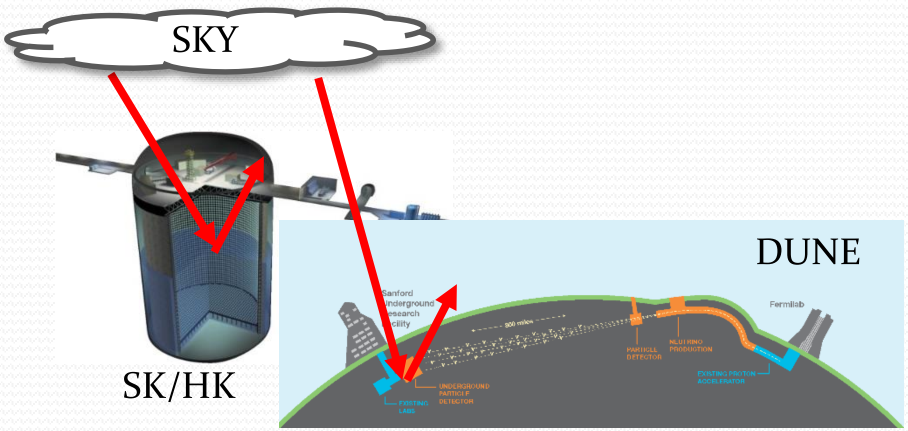
$$\sim 0.8 \times 10^{-7}\text{cm}^{-2}\text{s}^{-1} \left(\frac{\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1}}{10^{-26}\text{cm}^3\text{s}^{-1}}\right)\left(\frac{20\text{ GeV}}{m_0}\right)^2$$

from DM number density

- Setting $\langle \sigma v \rangle_{\chi_0\chi_0 \to \chi_1\chi_1}$ to be $\sim 10^{-26}$ $\text{cm}^3\text{s}^{-1}$ and assuming Navarro-Frenk-White DM halo profile, a standard profile, one finds

$$\mathcal{F}_{\chi_1} \sim 10^{-7}\text{cm}^{-2}\text{s}^{-1}$$ For WIMP mass-range $\chi_0$ [e.g., $\mathcal{O}(20\text{ GeV})$]

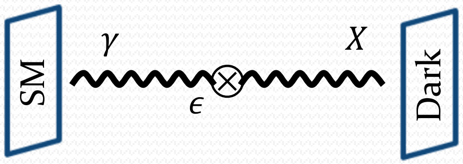
- No sensitivity in conventional dark matter direct detection experiments ⇒ large-volume (neutrino) detectors motivated
  - ✓ Super-/Hyper-Kamiokande (SK/HK)
  - ✓ Deep Underground Neutrino Experiment (DUNE)



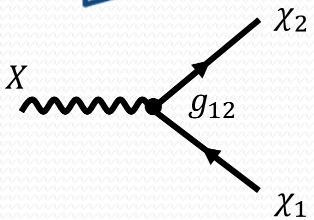
# Benchmark Model

$$\mathcal{L}_{\rm int} \ni -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{11}\bar{\chi}_1 \gamma^\mu \chi_1 X_\mu + g_{12}\bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + \text{h.c.} + (\text{others})$$

- Vector portal (e.g., "dark photon" scenario) [Holdom (1986)]



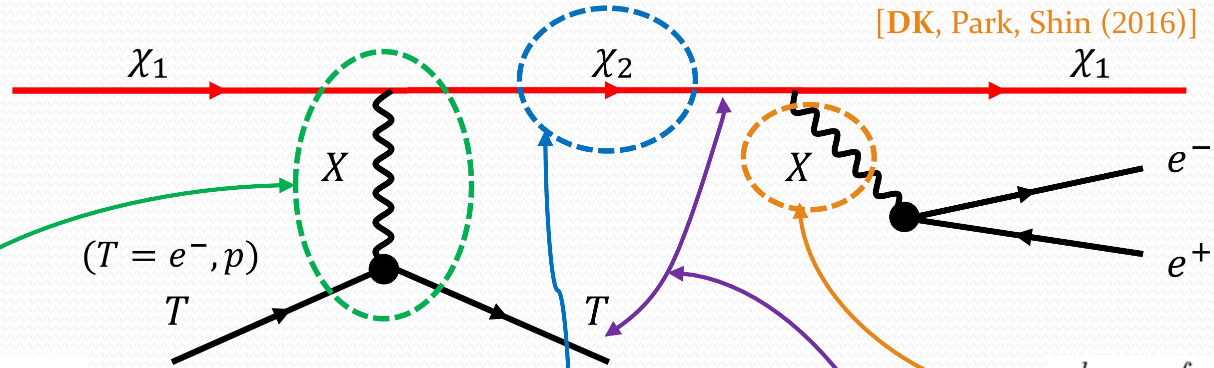

- Fermionic DM
  - $\chi_2$: a heavier (unstable) dark-sector state
  - Flavor-conserving interaction ⇒ elastic scattering (can be **suppressed or even vanishing**)
  - Flavor-changing interaction ⇒ inelastic scattering




- Not restricted to this model: various models conceiving BDM signatures
  - BDM source: galactic center, solar capture, dwarf galaxies, assisted freeze-out, semi-annihilation, fast-moving DM etc. [Agashe et al. (2014); Berger et al. (2015); Kong et al. (2015); Alhazmi et al. (2017); Super-K (2017); Belanger et al. (2011); D'Eramo et al. (2010); Huang et al. (2013)]
  - Portal: vector portal, scalar portal, etc.
  - DM spin: fermionic DM, scalar DM, etc.
  - iBDM-inducing operator: two chiral fermions, two real scalars, dipole moment interactions, etc. [Tucker-Smith, Weiner (2001); Giudice, **DK**, Park, Shin (2017)]

# Inelastic BDM ($i$BDM) at Large-Volume Detectors

[**DK**, Park, Shin (2016)]




$$\frac{d\sigma}{dE_T} = \frac{m_T}{8\pi\lambda(s, m_T^2, m_1^2)}\overline{|\mathcal{M}|}^2$$

$$\overline{|\mathcal{M}|}^2 = \frac{8(\epsilon e g_{12})^2 m_T}{\{2m_T(E_2 - E_1) - m_X^2\}^2} \times \left[\mathcal{M}_0(F_1+\kappa F_2)^2 + \mathcal{M}_1\left\{-(F_1+\kappa F_2)\kappa F_2 + \frac{(\kappa F_2)^2}{4m_T}(E_1 - E_2 + 2m_T)\right\}\right]. \quad (2)$$

($F_1 = 1, F_2 = 0$ for electron)

$$\mathcal{M}_0 = \left[m_T(E_1^2 + E_2^2) - \frac{(\delta m)^2}{2}(E_2 - E_1 + m_T) + m_T^2(E_2 - E_1) + m_1^2 E_2 - m_2^2 E_1\right], \quad (3)$$

$$\mathcal{M}_1 = m_T\left[\left\{(E_1+E_2) - \frac{m_2^2 - m_1^2}{2m_T}\right\}^2 + (E_1 - E_2 + 2m_T)\left\{(E_2 - E_1) - \frac{(\delta m)^2}{2m_T}\right\}\right], \quad (4)$$

$\delta m \equiv m_2 - m_1$

$$m_2 \le \underbrace{\sqrt{m_T^2 + 2E_1 m_T + m_1^2}}_{\equiv s} - m_T\,.$$

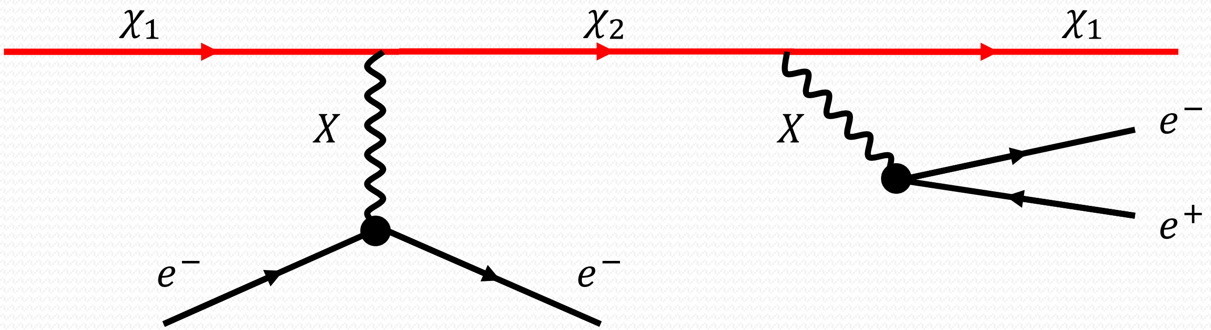
$$\frac{d\sigma}{dE_X} = \int d\gamma_2 \frac{d\sigma}{d\gamma_2}\frac{1}{2E_X^*\sqrt{\gamma_2^2 - 1}}$$

$$\cos\theta = \frac{E_T E_2 + (m_T^2 + m_2^2 - s)/2}{\sqrt{(E_2^2 - m_2^2)(E_T^2 - m_T^2)}}$$

- $\theta$ (roughly) determines angular separation between the primary (target recoil) and the secondary ($e^+e^-$ pair) signals.

# Discovery Potential with *e*-scattering

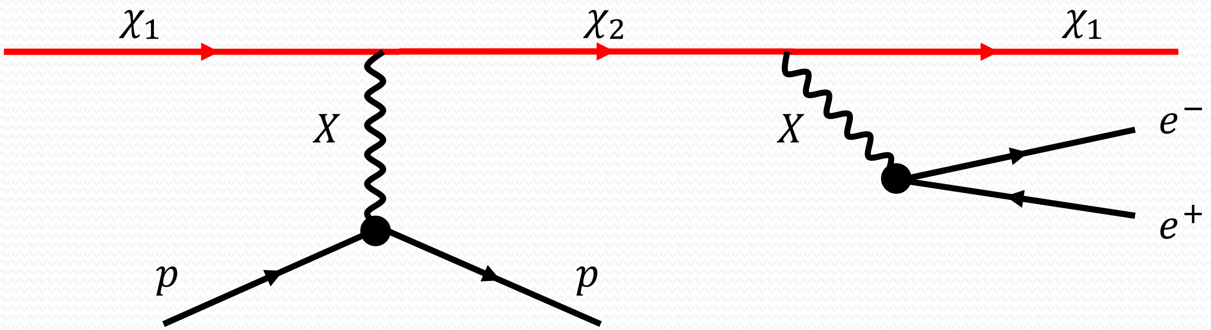
[**DK**, Park, Shin (2016)]




- **GeV/sub-GeV mass** and **sizable boost factor** of dark-sector particles preferred by kinematics
- $e$-scattering preferred ← smaller threshold energy, $e^-$ as a fundamental particle
- $e^+e^-$ from the secondary: **highly collimated** (not separable in most favored parameter region)
- $e^-$ from the primary: collimated, but separable with detectors of good angular resolution
- High chance to observe **two separable charged tracks**

# Discovery Potential with *p*-scattering

[**DK**, Park, Shin (2016)]




- **GeV/sub-GeV mass** and **decent boost factor** of dark-sector particles preferred by kinematics
- (Typically) Larger threshold energy, $p$ could be broken apart, atomic form factor
- $e^+e^-$ from the secondary: **separated**
- $p$ from the primary: **separated** from the secondary particles
- High chance to observe **three separable charged tracks**

# Results

| Exp. | Run time | $e$-ref.1 | $e$-ref.2 | $p$-ref.1 | $p$-ref.2 |
|---|---|---|---|---|---|
| SK | 13.6 yr | 170 | 7.1 | 3500 | 5200 |
| HK | 1 yr | 88 | 3.7 | 1900 | 2800 |
| HK | 13.6 yr | 6.7 | 0.28 | 140 | 210 |
| DUNE | 1 yr | 190 | 9.0 | 150 | 1600 |
| DUNE | 13.6 yr | 14 | 0.69 | 11 | 120 |

TABLE II: Required fluxes in unit of $10^{-7}$ cm$^{-2}$ s$^{-1}$ with which our reference points become sensitive in various experiments.

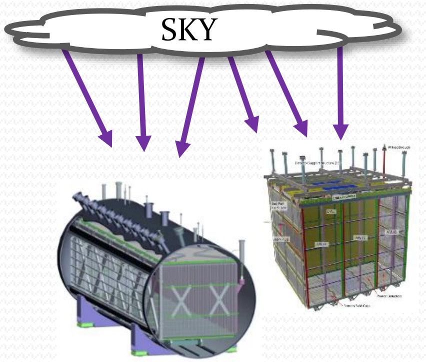
[**DK**, Park, Shin (2016)]

| | $m_1$ | $m_2$ | $m_X$ | $\gamma_1$ |
|---|---|---|---|---|
| $e$-ref1 | 0.4 | 0.5 | 0.06 | 250 |
| $e$-ref2 | 0.1 | 0.14 | 0.03 | 200 |
| $p$-ref1 | 0.4 | 0.9 | 0.2 | 15 |
| $p$-ref2 | 0.1 | 1.0 | 0.5 | 50 |

- $\epsilon^2 = (3 \times 10^{-4})^2$ and $g_{12} = 0.5$ for all reference points
- $\gamma_1$: boost factor of boosted DM $\chi_1$
- "Zero" background assumed
- Every mass in GeV

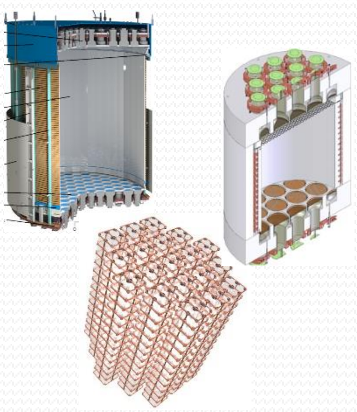
- Recall, in a minimal boosted DM scenario, if flux over the whole sky is $\mathcal{O}(10^{-7})$ cm$^{-2}$s$^{-1}$, it is **promising and achievable**!
- Comparable/better signal sensitivity at DUNE! ⇒ More investigation needed! [De Roeck, **DK**, Moghaddam, Park, Shin, Whitehead, in progress]

# More Applications




- Similar physics opportunities at surface-based detectors, e.g., NO$\nu$A, SBN Program, ProtoDUNE, etc.
- Challenge: enormous cosmic-origin backgrounds (typically from muons)
- Solution
  - ⇒ Many signal features of *i*BDM [Chatterjee, **DK** et al. (2018)]
  - ⇒ "Earth Shielding" for elastic BDM (at the cost of half statistics) [**DK**, Kong, Park, Shin in progress]

Surface

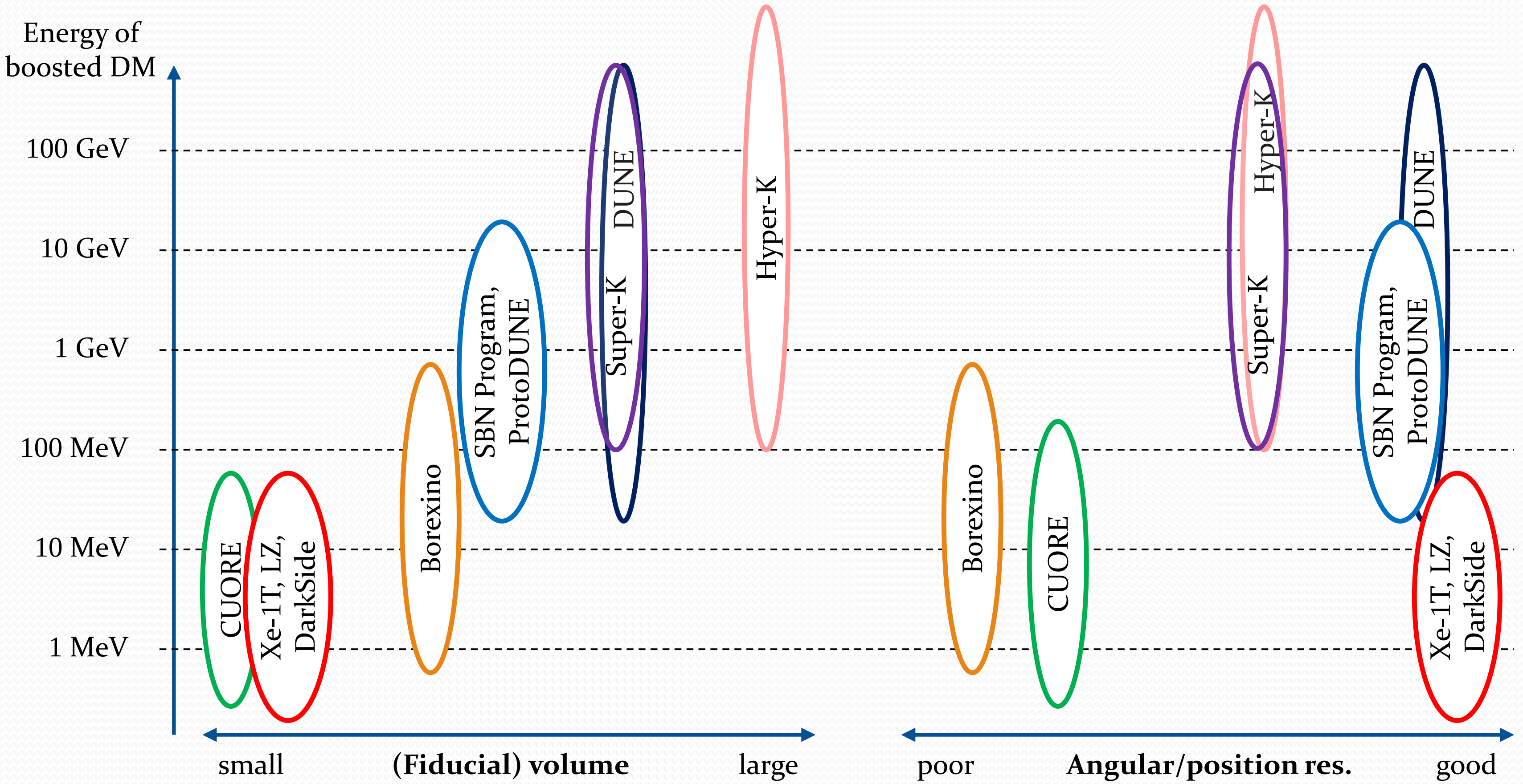


- Similar physics opportunities at conventional WIMP detectors or (small-volume) neutrino detectors, e.g., Xenon, DarkSide, CUORE, etc.
- Challenge: "small" volume w.r.t the flux of boosted DM
- Solution: model modification to increase the flux

$$\mathcal{F}_{\chi_1} \propto m_0^{-2}$$

  - ⇒ Good resolution, sensitivity to low-energy (MeV-range) signals
  - ⇒ Phenomenological study at WIMP detectors with their detector specifics considered [Giudice, **DK**, Park, Shin (2017)]

# (In)elastic BDM Searches in Various Experiments




Detectors are **complementary** to one another rather than superior to the others!

# Event Simulation for Cosmic-frontier Searches

Boosted/relativistic DM injection → Parton-level Calculation → Event Generation → Detector Response

**Boosted/relativistic DM injection**

- ❖ (Usually) boosted DM comes with a fixed boost factor

**Parton-level Calculation**

- Phase-space gen.
- Standard parton-level calculators

**Event Generation**

- Standard event generators
- GENIE

**Detector Response**

- LArSoft
- GEANT4

- ❑ Electron scattering: good enough with standard parton-level calculators (or even phase-space generator) to describe leading behaviors of BDM-initiated events
- ❑ Proton scattering: several effects even before detector responses, e.g., atomic form factor, deep inelastic scattering (DIS of *i*BDM [**DK**, Machado, Park, Shin, in progress]), Δ-resonances regime, nucleon effects etc.
- ❑ GENIE (see also Berger's talk for more details)
  - ✓ The above-mentioned effects are fully considered.
  - ✓ Resonance model in [Rein, Sehgal (1981)] (inputs from lattice QCD needed?)
  - ✓ Elastic BDM has been implemented, *i*BDM is being implemented.

# Event Simulation for Intensity-frontier Searches

Boosted/relativistic DM injection → Parton-level Calculation → Event Generation → Detector Response

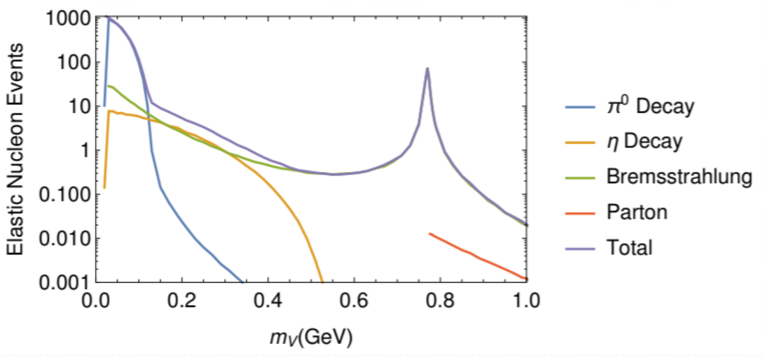
Ex) vector portal

- ❖ Meson ($\pi/\eta$) decays
- ❖ Bremsstrahlung
- ❖ Drell-Yan

- Phase-space gen.
- Standard parton-level calculators

- Standard event generators
- GENIE

- LArSoft
- GEANT4



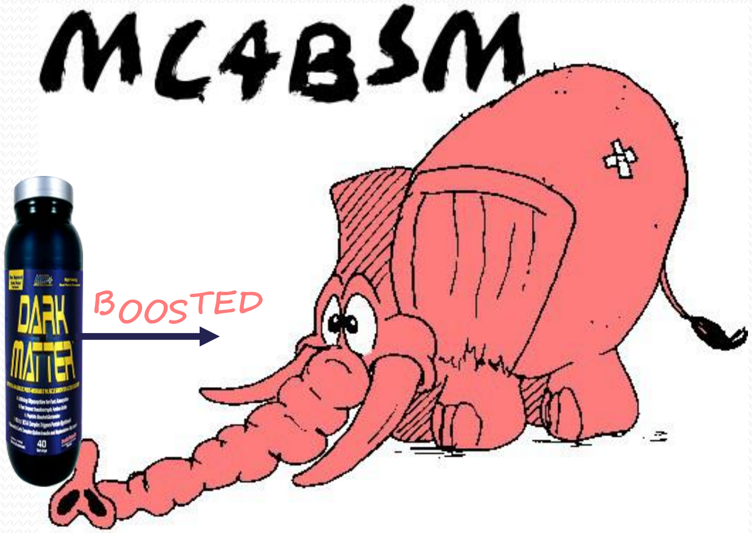

[deNiverville, Chen, Pospelov, Ritz (2017)]

- ❑ BdNMC [deNiverville (2017)],
  - ✓ All production mechanisms are considered.
  - ✓ Target and detector characteristics can be set.
  - ✓ Pre-simulated data is used.

- ❑ Fixed target experiments with the latest MadGraph

# Conclusions

- Boosted/relativistic dark matter searches at the cosmic/intensity frontier are **promising**.
- They may provide an **alternative avenue** to explore dark sector physics (including dark matter).




- Theoretical/phenomenological studies have been **actively** conducted and in progress.
- There are **many ongoing/projected experiments** in which they can be tested/probed.

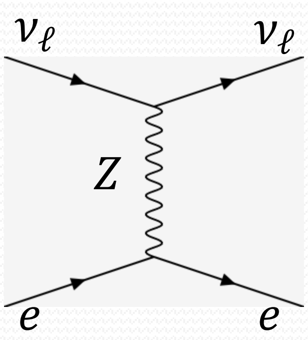
- Many existing MC tools can be utilized for boosted/relativistic DM physics, and an **increasing amount of effort** to develop dedicated MC tools has been made.
- More **active interactions with MC-tool community** are highly expected/encouraged!

# Thank you!

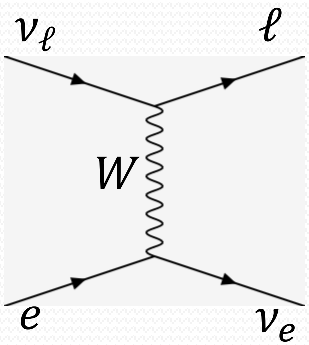
# Background Considerations

## Potential sources

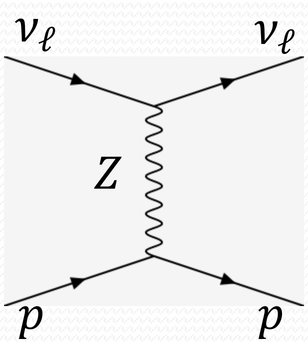
- Cherenkov radiation (CR) by electron/muon is distinguished from that by proton.
- Electron-preferred scenarios:



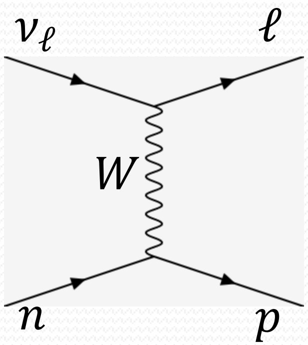

: CR by an N.C.
electron




: CR by a C.C.
electron/muon/tau




: CR by an N.C.
proton unless broken

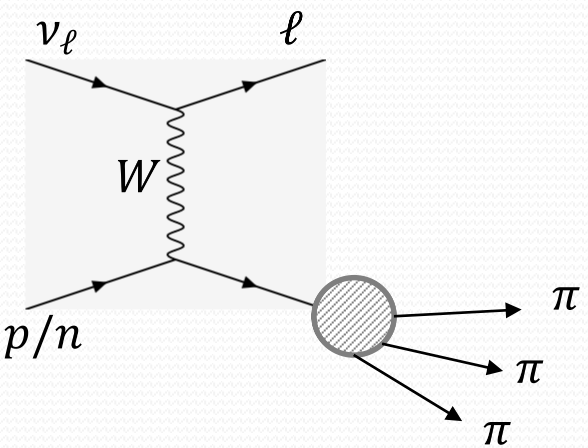



: CR by at least, a C.C.
proton unless broken

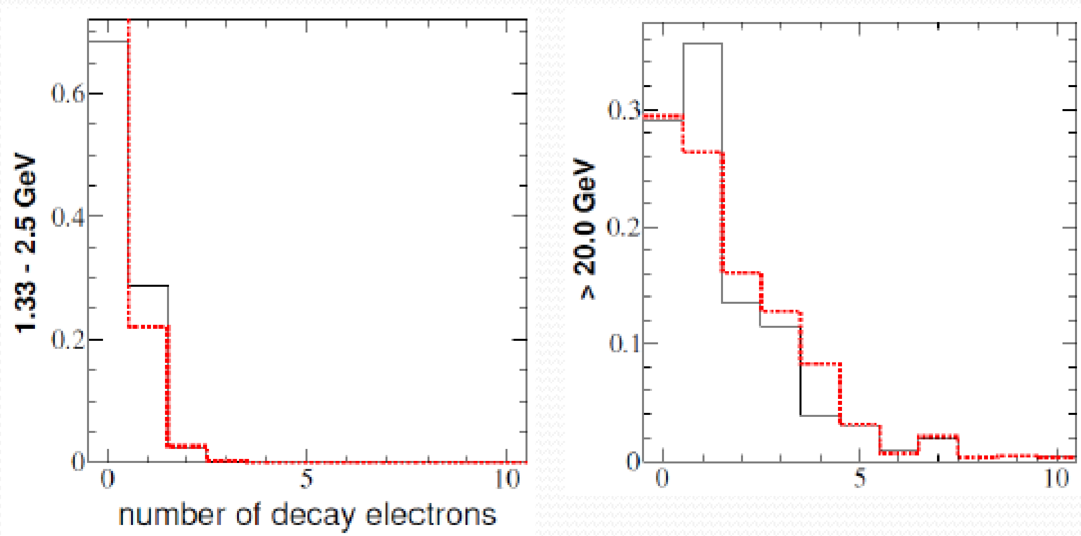
- Proton-preferred scenarios: opening angles among recoil proton, decayed electrons are large enough to resolve

# Background Considerations

## More challenging cases: broken nuclei




$$\pi^+ \to \mu^+\nu \to e^+\nu\nu\nu$$

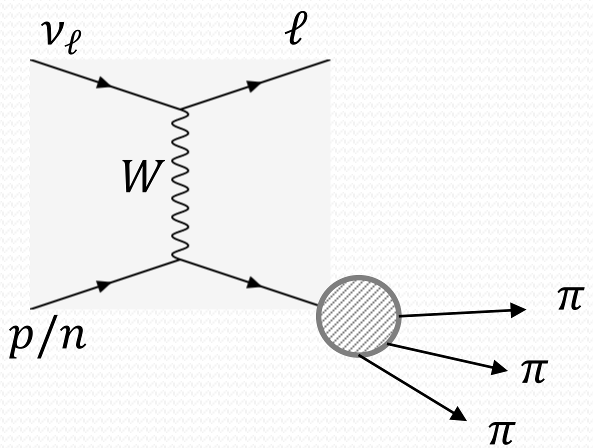



Super-K (2012)

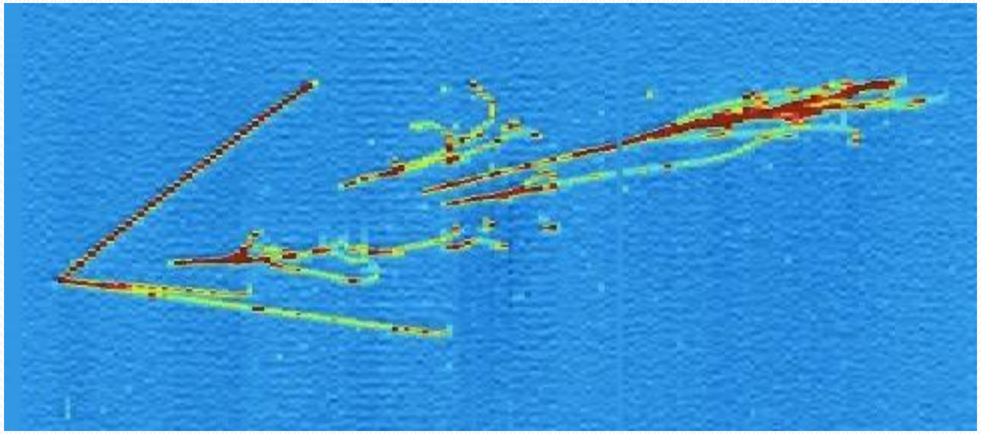
- ❑ Similar expectations for neutral currents
- ❑ (Dedicated study in progress)

# Background Considerations

## More challenging cases: broken nuclei



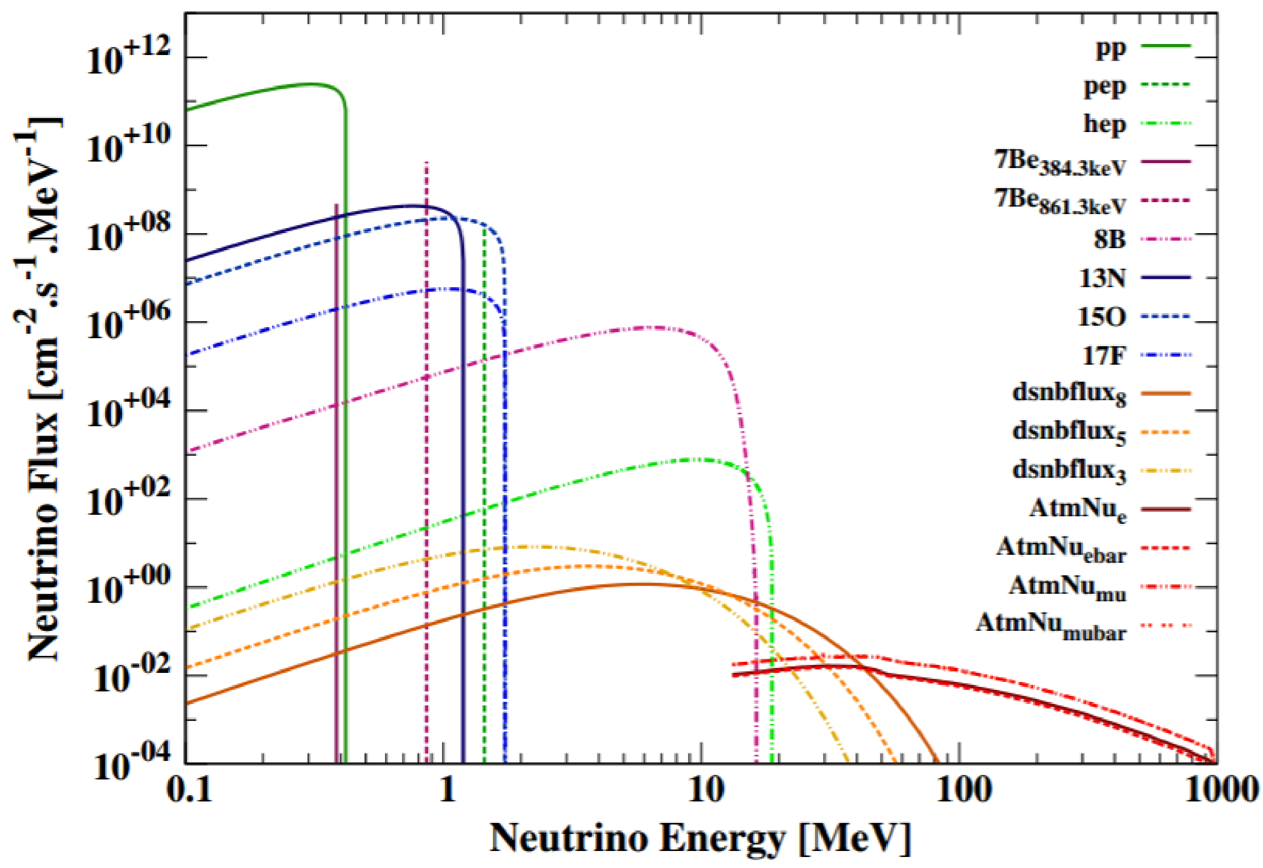

e.g. $\pi^+ \to \mu^+\nu \to e^+\nu\nu\nu$



Particle tracks created by a neutrino interaction in liquid argon in the ArgoNeuT

- ❑ Expecting again that **(quality) track-based particle identification** allows us to distinguish multi-track background events from signal ones
- ❑ A dedicated study is needed

# Flux of Neutrino




[Ruppin et al., (2014)]