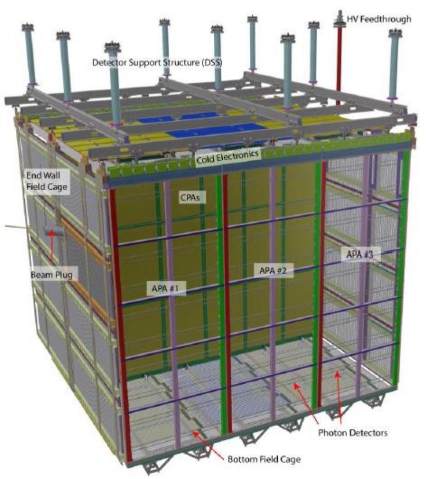
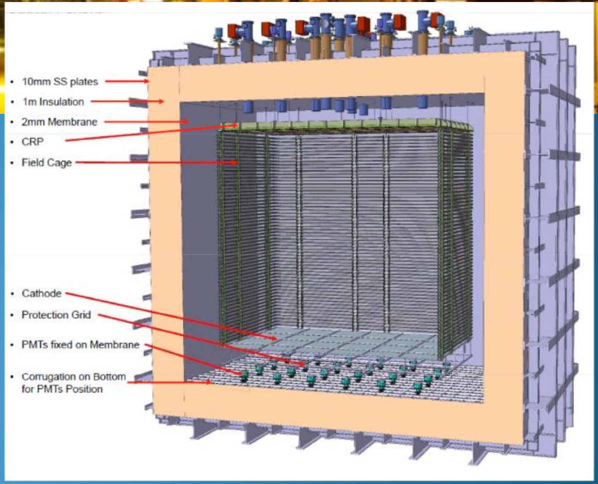
Inelastic Boosted Dark Matter at ProtoDUNE





Doojin Kim

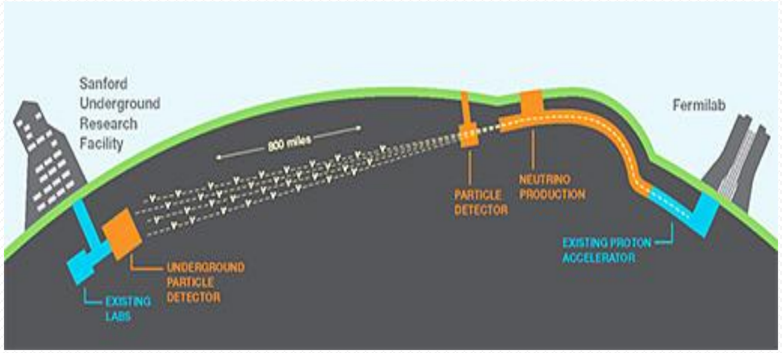
14th International Workshop Dark Side of the Universe, Annecy, France

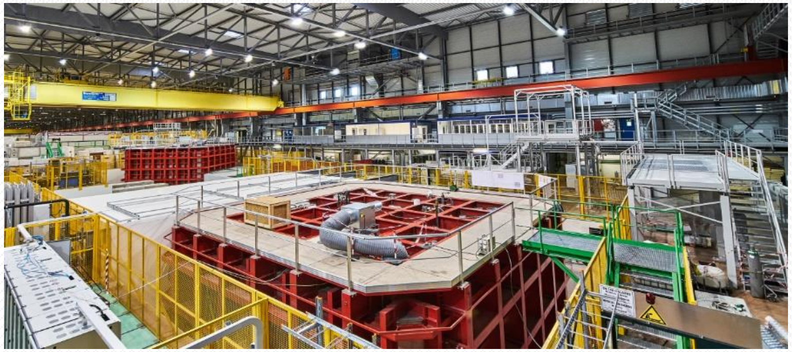
June 28th, 2018

In collaboration with A. Chatterjee, A. De Roeck, Z. Moghaddam, J.-C. Park, S. Shin, L. Whitehead, J. Yu, arXiv:1803.03264

ProtoDUNE as Prototypical Detectors of DUNE

Prototype of DUNE





- ✓ Physics at DUNE: neutrino sector, BSM, etc. (at intensity and cosmic frontiers)

- ✓ Testing long-term stability and operation of Liquid Argon TPC detectors,
- ✓ Acting as an engineering proof-of-principle for scalability (kiloton-scale) ,
- ✓ Calibrating beam response and cosmic-ray response

Physics Motivation at ProtoDUNE?

- Any **potential for physics** (e.g., BSM at cosmic frontier) with ProtoDUNE detectors?

Pros

- ✓ Large (fiducial) volume
- ✓ Equally good detector performance like DUNE (angular/position/energy resolution etc.)

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Cons

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- Nevertheless, can we do interesting physics?

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Pros

- ✓ Large (fiducial) volume
- ✓ Equally good detector performance like DUNE (angular/position/energy resolution etc.)

vs.

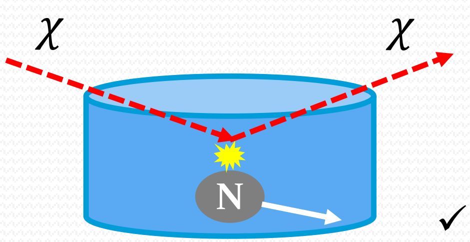
Cons

- ✓ Large amount of backgrounds (due to their location)

- ❑ Nevertheless, can we do interesting physics?
  - ⇒ Focusing on **dark matter physics**.
  - ⇒ Talking about **what we can achieve** at ProtoDUNE.

Non-relativistic Dark Matter Search

❑ (Mostly) focusing on weakly interacting massive particles (WIMPs) search



~~Non~~-relativistic,

in elastic scattering

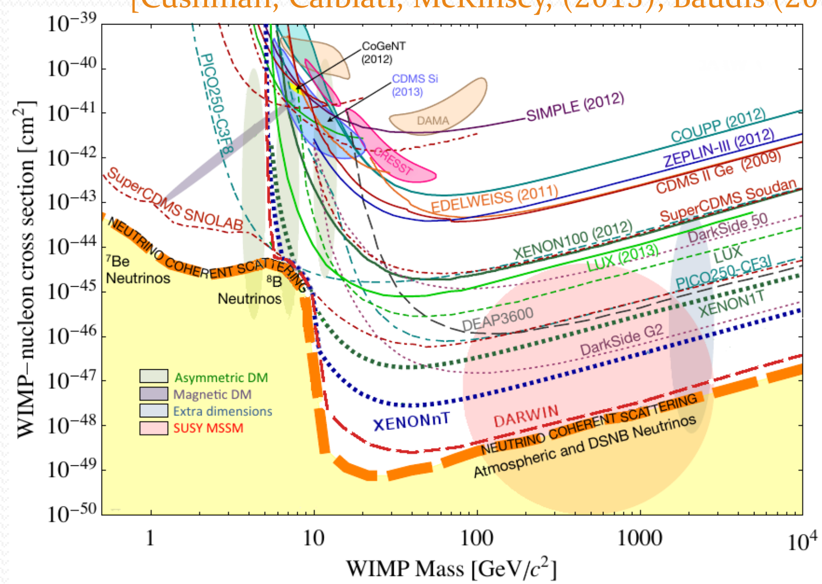
of ~~weak~~ *other* -scale DM

with nuclei *or electron*

✓ $E_{\text{recoil}} \sim 1 - 100$ keV

✓ Detectors designed to be sensitive to this energy scale

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



✓ Null observation of WIMP signals

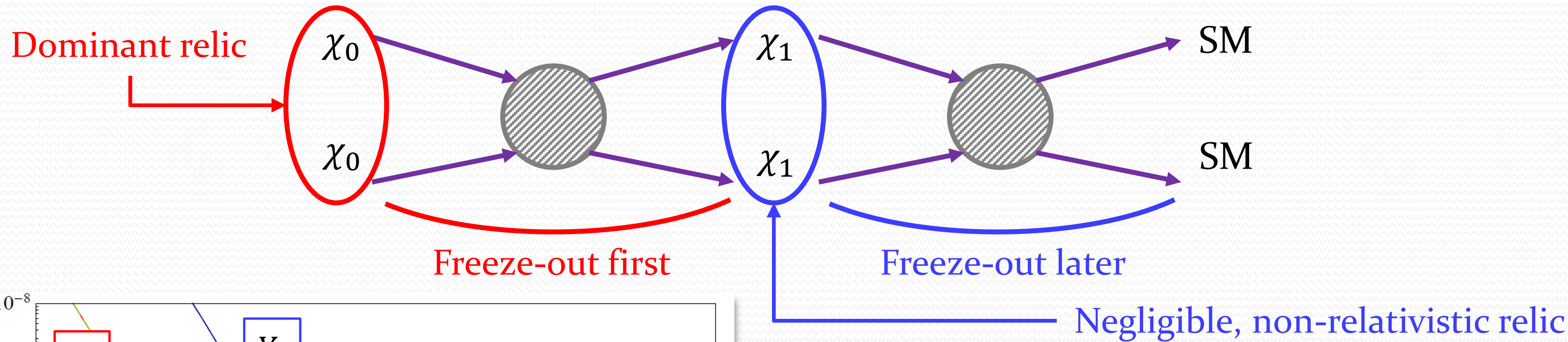
✓ A wide range of parameter space already excluded

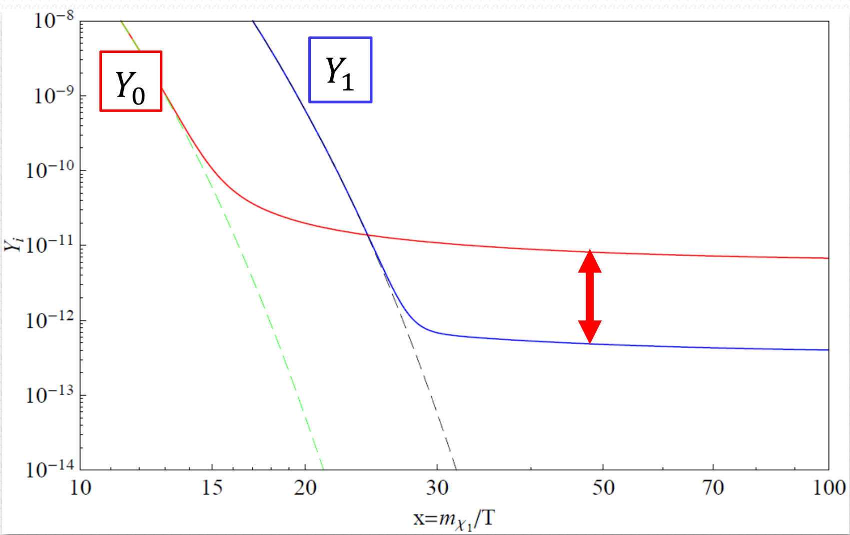
✓ Close to the neutrino "floor"

✓ **Need new ideas!**

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.





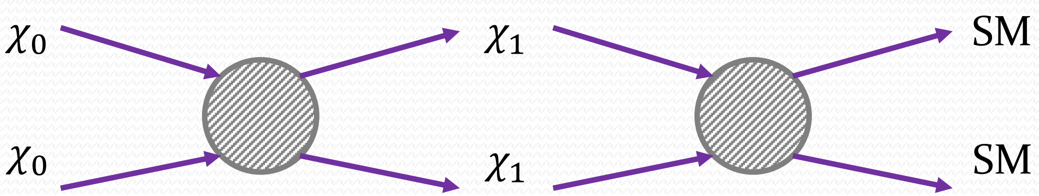
"Assisted" freeze-out mechanism

[Belanger, Park (2011)]

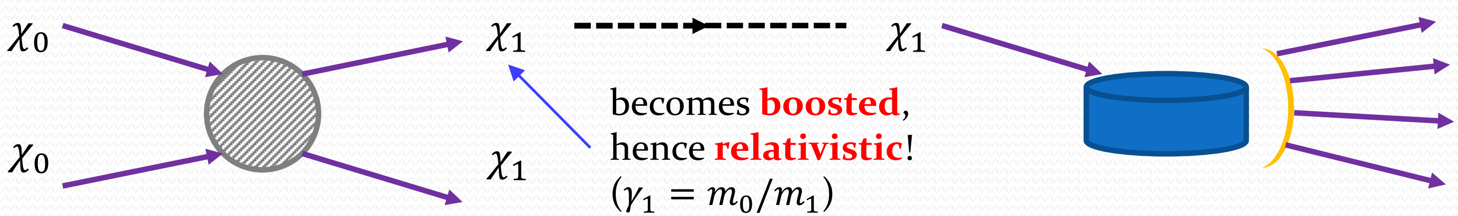
See Jong-Chul Park's talk

“Relativistic” Dark Matter Search

See Jong-Chul Park’s talk



- ✓ Heavier relic χ_0: hard to detect it due to tiny/negligible coupling to SM
- ✓ Lighter relic χ_1: hard to detect it due to small amount



(Galactic Center at **CURRENT** universe) (Laboratory)

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

Flux of Boosted DM

- Flux of boosted χ_1 near the earth [Agashe et al (2014); Belanger, Park (2011)]

$$\begin{aligned}\mathcal{F} &= \frac{1}{2}\cdot\frac{1}{4\pi}\int d\Omega \int_{\rm los} ds \langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}\left(\frac{\rho(s,\theta)}{m_0}\right)^2 \\ &= 1.6\times 10^{-4}\,{\rm cm^{-2}s^{-1}} \qquad (4.3)\\ &\times \left(\frac{\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}}{5\times10^{-26}\,{\rm cm^3s^{-1}}}\right)\times\left(\frac{\rm GeV}{m_0}\right)^2 \\ &\equiv \mathcal{F}^{180^\circ}_{\rm ref}\times\left(\frac{\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}}{5\times10^{-26}\,{\rm cm^3s^{-1}}}\right)\times\left(\frac{\rm GeV}{m_0}\right)^2,\end{aligned}$$

from DM number density

- Setting $\langle\sigma v\rangle_{\chi_0\chi_0\to\chi_1\chi_1}$ to be $\sim 10^{-26}\ {\rm cm^3s^{-1}}$ and assuming NFW DM halo profile, one finds

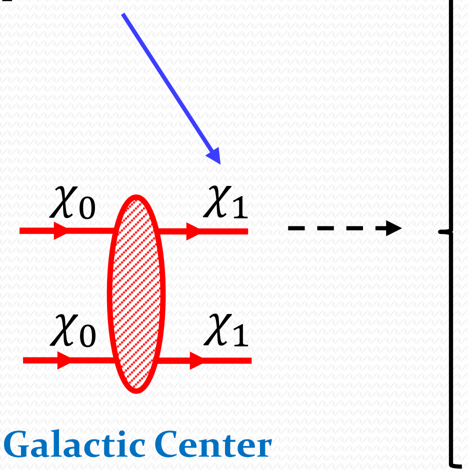
$\mathcal{F}_{\chi_1}$ spans $\sim 10^{-1}$ to $\sim 10^{-5}\ {\rm cm^{-2}s^{-1}}$ for $\mathcal{O}(30\ {\rm MeV})$ to $\mathcal{O}(2\ {\rm GeV})$ mass of χ_0

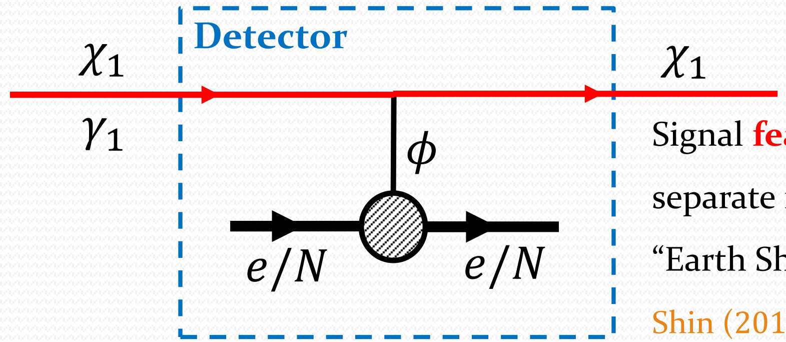
$\Rightarrow$ **Big enough** for kt/sub-kt LArTPC detectors to observe signal events (LArTPC detectors have good position/angle/vertex resolution, low threshold, and great particle identification)

Generic BDM Signal Processes

(a) Elastic scattering (eBDM) (cf. eBDM at DUNE [Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016)])

Our focus here is
$m_0 = E_1 = \sim 30$ MeV $-\sim 2$ GeV





Signal **featureless**, hence hard to separate from potential BGs $\Rightarrow$ "Earth Shielding" [DK, Kong, Park, Shin (2018)] (see Jong-Chul Park's talk)

- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

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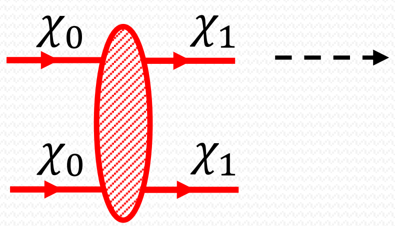
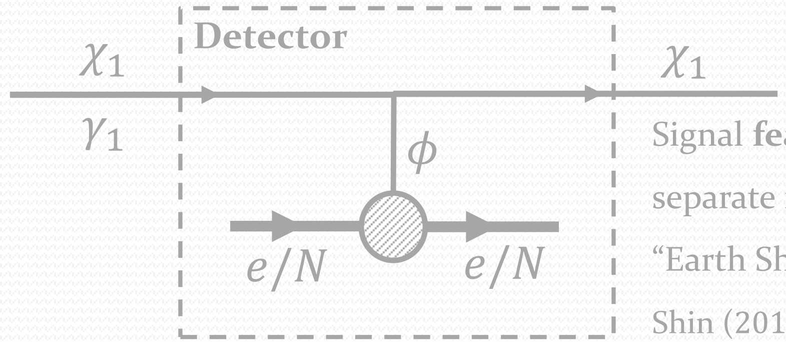


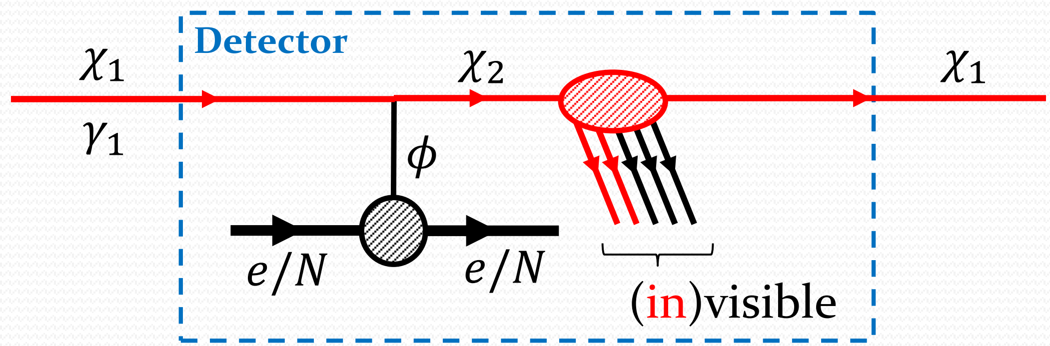
Galactic Center

(a) Elastic scattering (eBDM) (cf. eBDM at DUNE [Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016)])



Signal **featureless**, hence hard to separate from potential BGs $\Rightarrow$ "Earth Shielding" [DK, Kong, Park, Shin (2018)] (see Jong-Chul Park's talk)

(b) Inelastic scattering (iBDM) (cf. iBDM at DUNE [**DK**, Park, Shin (2016)])



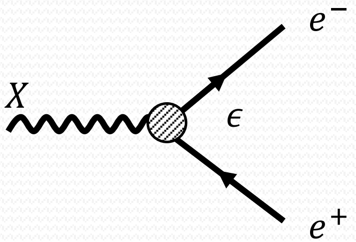
Many signal **features**, helping veto BGs hence using full data

- χ_0: heavier DM
- χ_1: lighter DM
- γ_1: boost factor of χ_1
- χ_2: massive unstable dark-sector state
- ϕ: mediator/portal particle

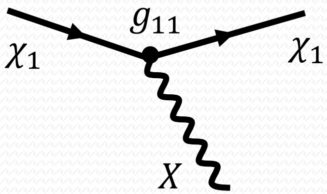
Benchmark Model: Building Blocks

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

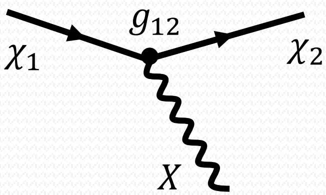
- ❑ Vector portal (e.g., dark gauge boson scenario)



- ❑ Fermionic DM
  - ❖ χ_2: a heavier (unstable) dark-sector state
  - ❖ Flavor-conserving neutral current ⇒ elastic scattering



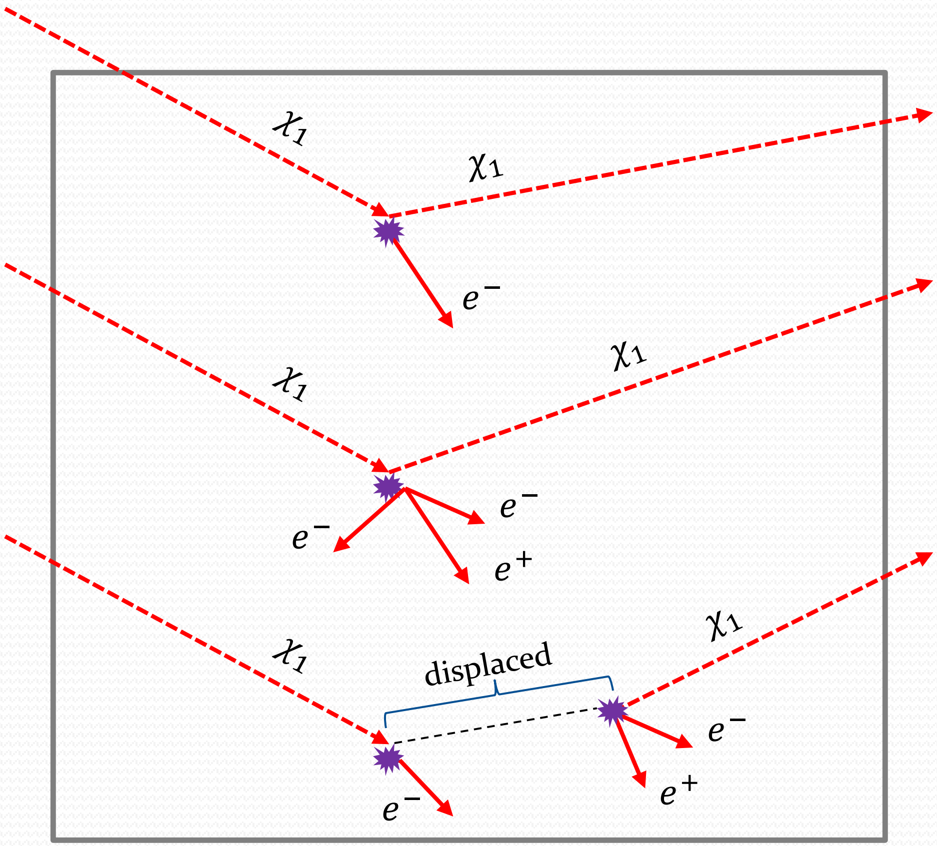
  - ❖ **Flavor-changing neutral current ⇒ inelastic scattering**



Not Only for This Model But for Other Models

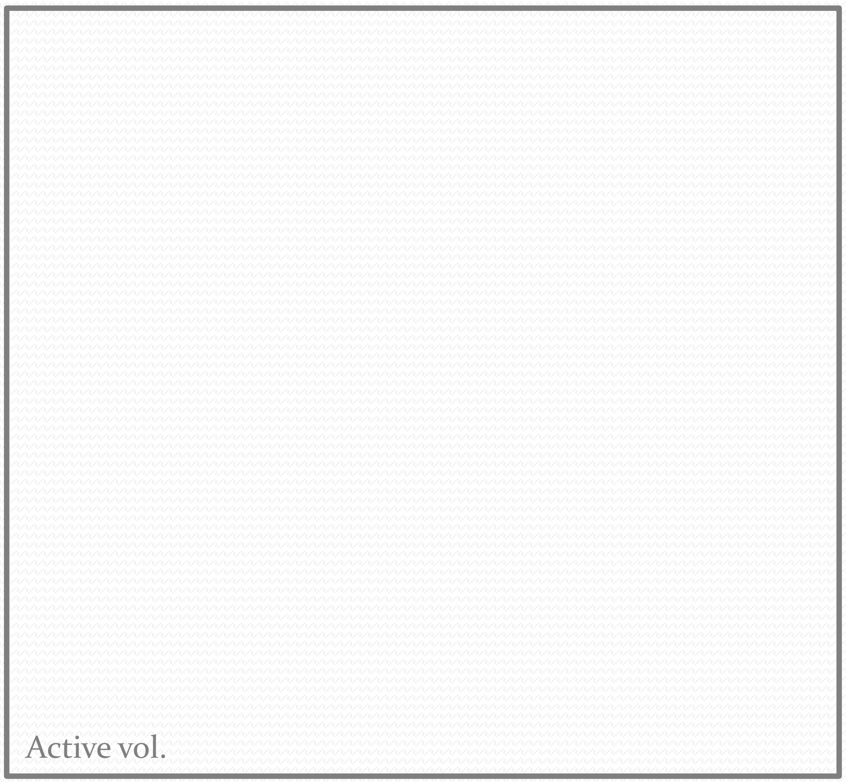
- Not restricted to this model: various models conceiving BDM signatures
  - BDM source: galactic center, solar capture, dwarf galaxies, assisted freeze-out, semi-annihilation, fast-moving DM etc. [Agashe et al. (2014); Berger et al. (2014); Kong et al. (2014); Alhazmi et al. (2016); Super-K (2017); 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.
  - *i*BDM-inducing operator: two chiral fermions, two real scalars, dipole moment interactions, etc. [Tucker-Smith, Weiner (2001); Giudice, **DK**, Park, Shin (2017)]

Expected Signatures with Electron Recoil



- Ordinary elastic scattering: electron recoil (ER) only, i.e., single track
- "Prompt" inelastic scattering: ER + e^+e^- pair (from the decay of on-shell X), i.e., **three tracks**
- "Displaced" inelastic scattering: ER + e^+e^- pair (typically from a three-body decay of χ_2), i.e., again **three tracks**
- Note that **tracks will pop up inside the fiducial volume**.
- Straightforwardly applicable to proton recoil (up to form factor, DIS etc.)

Potential Backgrounds



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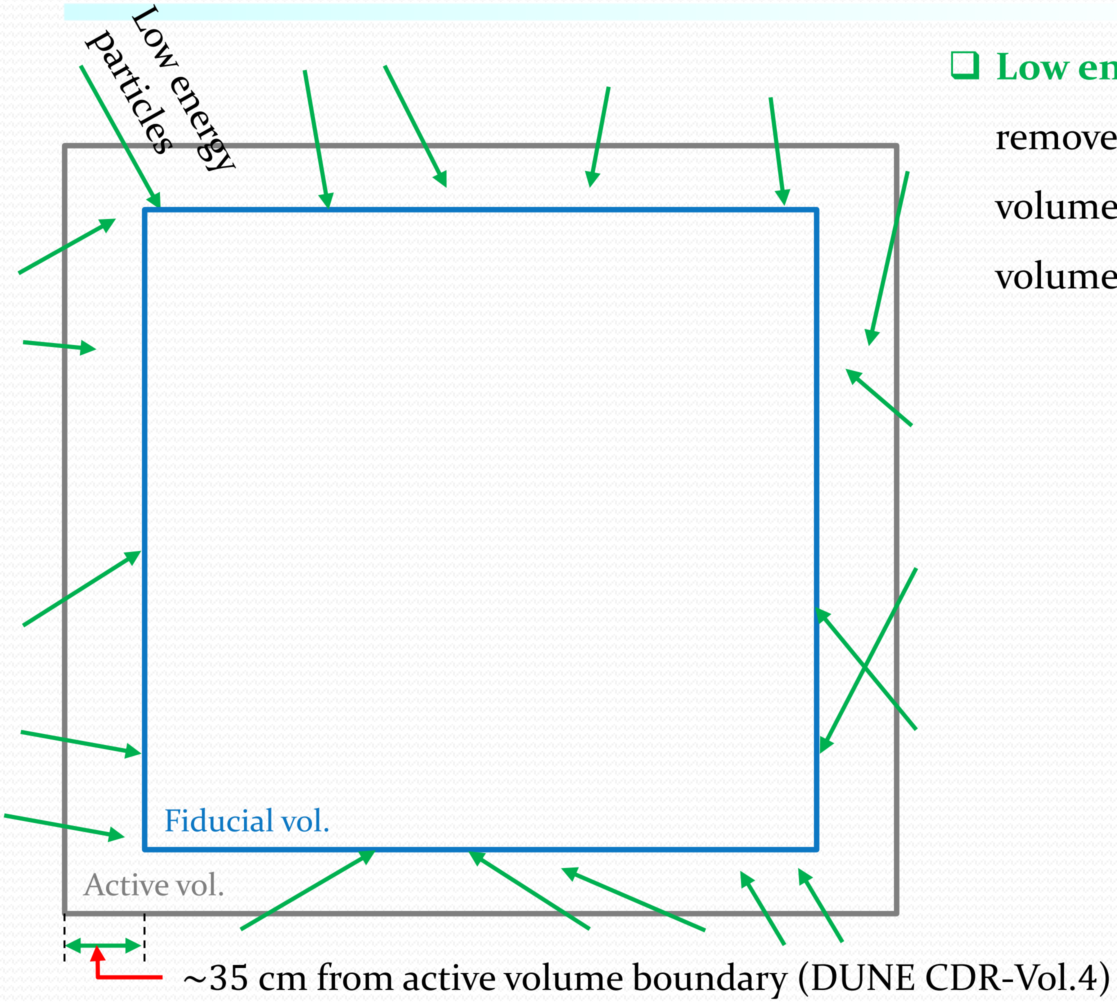

- **Low energy particles** ($\gtrsim$ 30 MeV): can be removed/suppressed by taking a fiducial volume (blue box) smaller than the active volume. (170 t for Dual, 300 t for Single)

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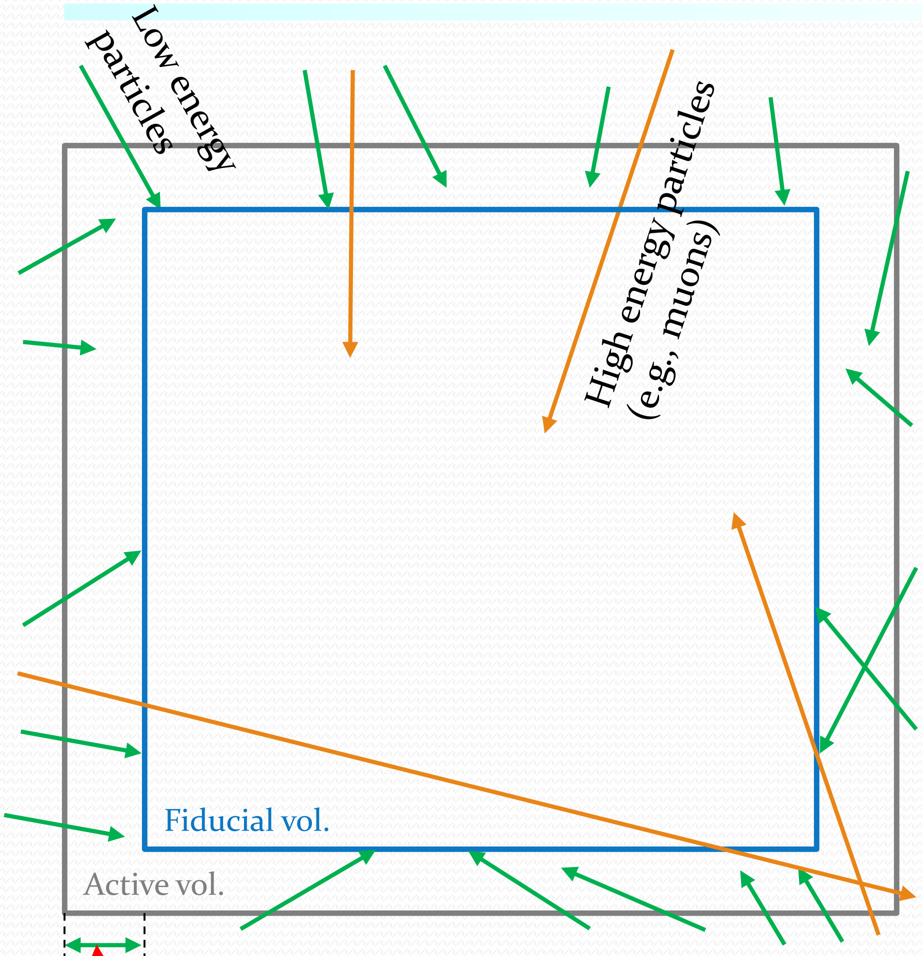

~35 cm from active volume boundary (DUNE CDR-Vol.4)

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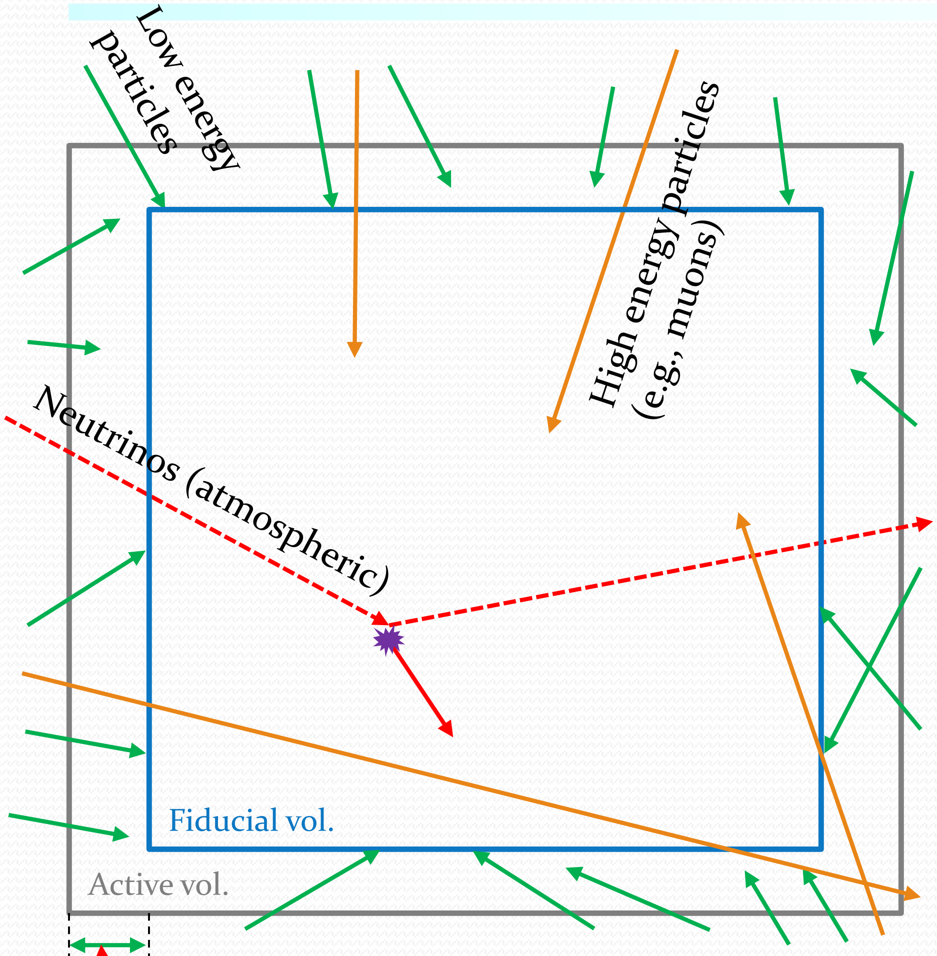

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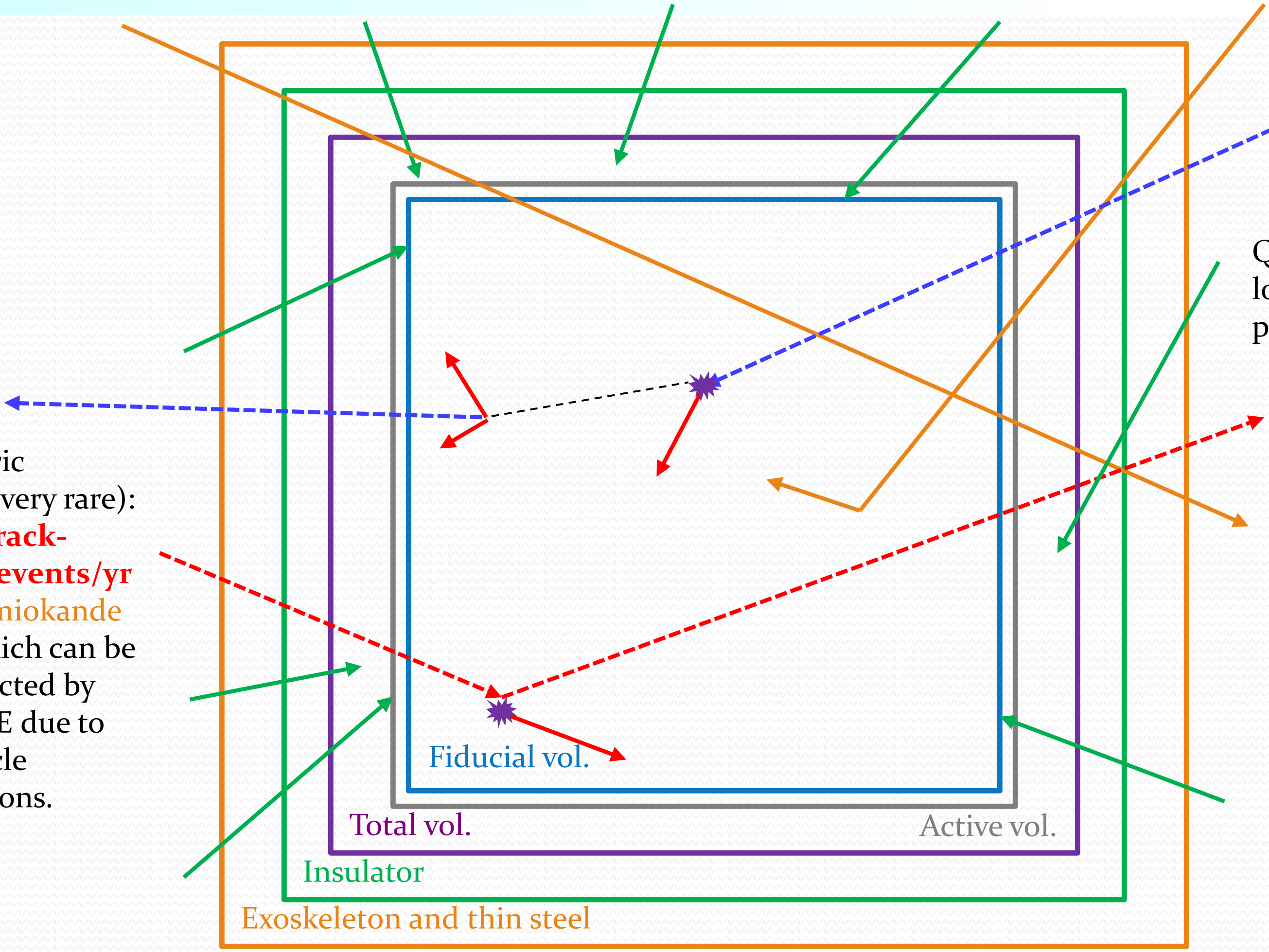
- **(Atmospheric) neutrinos**: (potentially) irreducible for elastic scattering signals, but not for inelastic scattering signals.

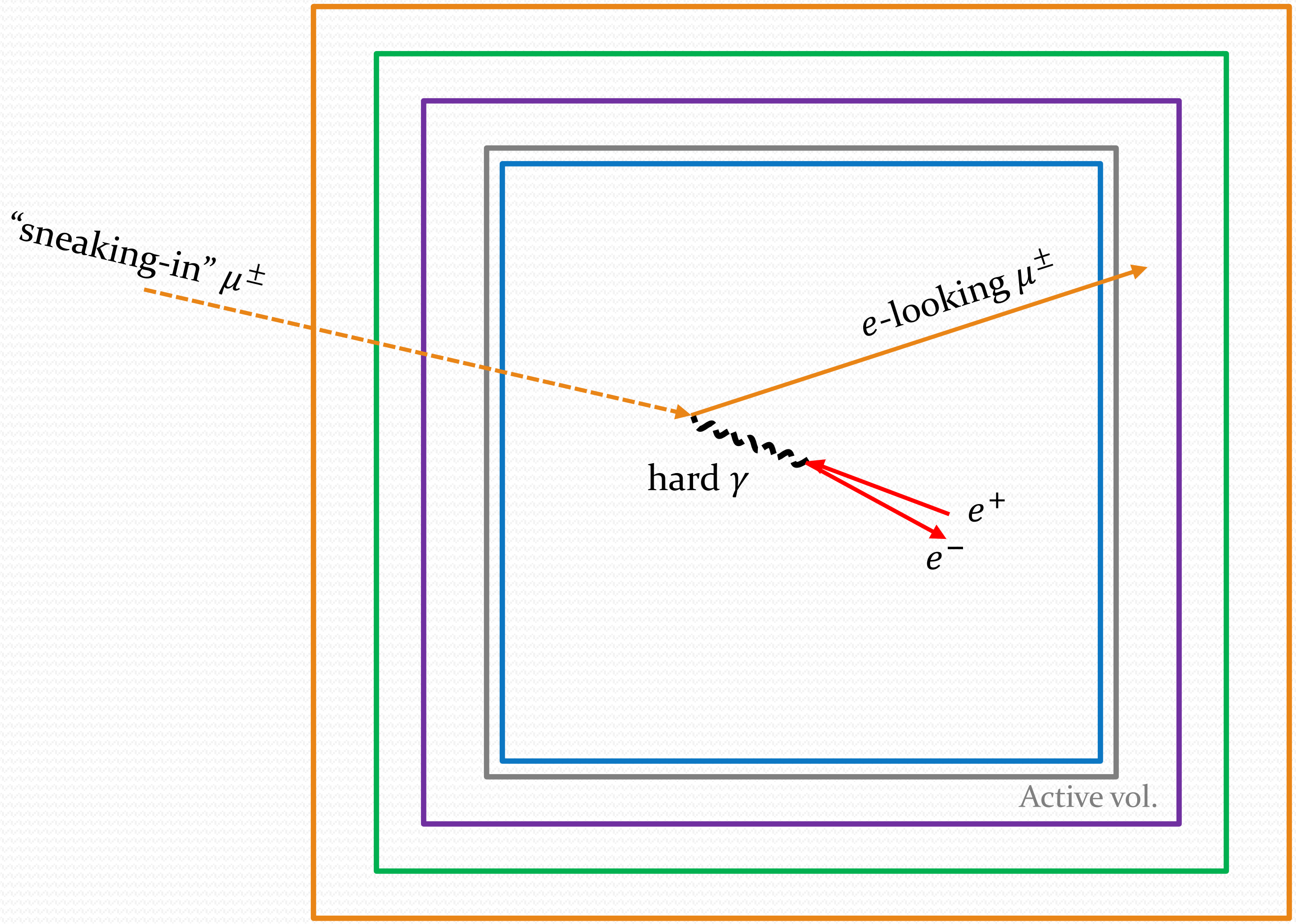
Cosmic Backgrounds: 1ms Snapshot at ProtoDUNE



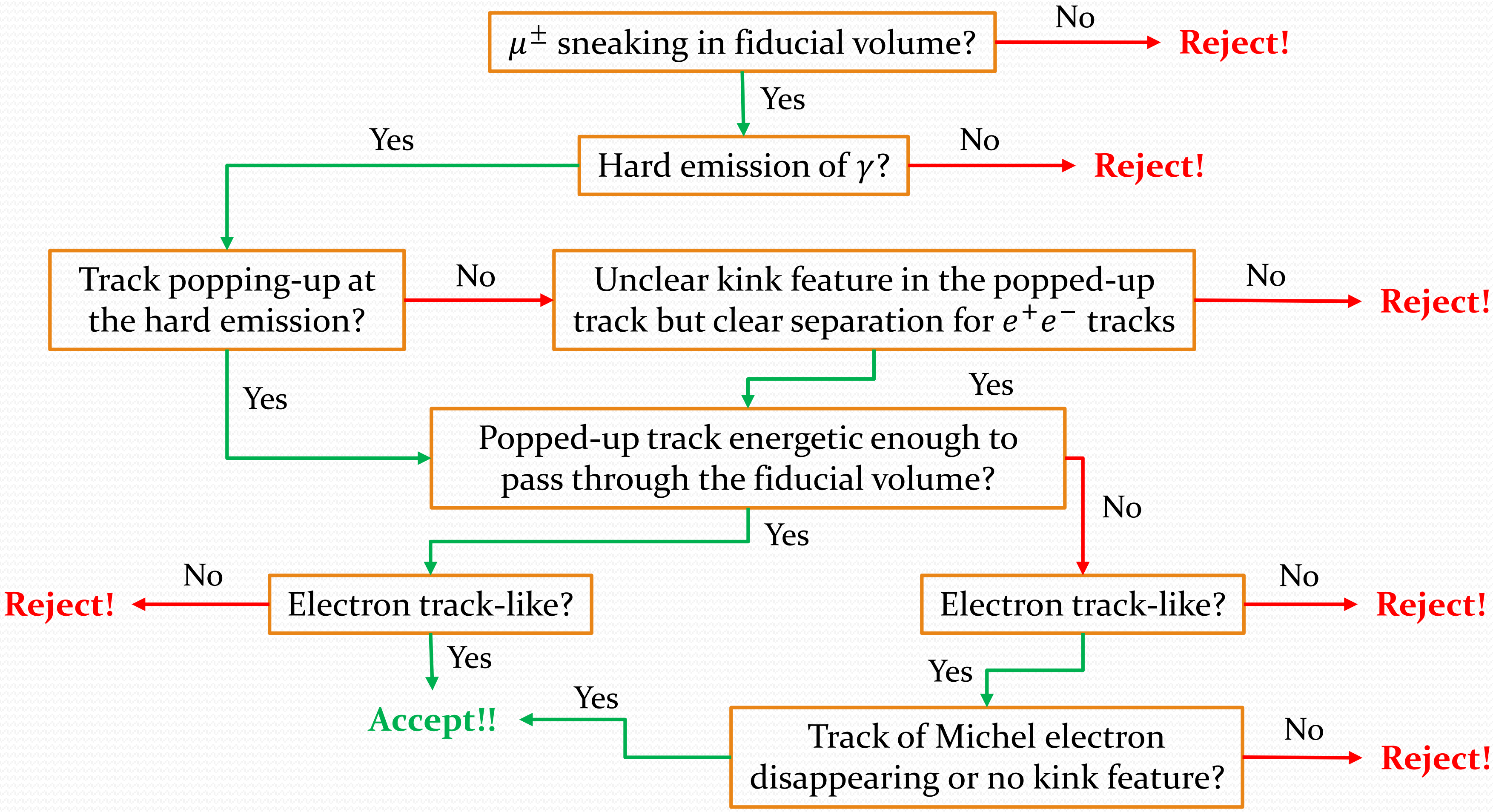
Atmospheric neutrinos (very rare): **~5 multitrack-involving events/yr** [Super-Kamiokande (2012)] which can be readily rejected by ProtoDUNE due to good particle identifications.

A humongous number of muons: $\mathbf{10-20\ /ms \approx}$ $\mathbf{\sim 4\times 10^{11}\ /yr}$ [Particle Data Group (2015)] which may give BG events due to particle mis-identification, mis-measurement etc.

Case Study I



Conditions to Mimic an *i*BDM Signal



“Sneaking-in” Muons

- μ reconstruction efficiency for a small muon counter-tagged muon event [MicroBooNE Collaboration, MICROBOONE-NOTE-1010-PUB]

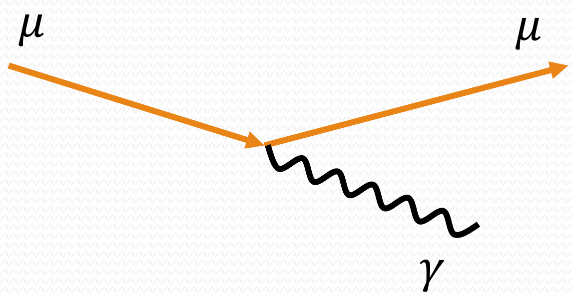
  $\Rightarrow$ 0.09% missed with 2016 data (lower with 2017 data, not public yet)

- “Conservative” estimate for the “sneaking-in” muon probability.

$$\mathbf{10^{-3}}\ (> \mathbf{0.09\%})$$

(Caveat: ProtoDUNE has no cosmic muon counter at the moment.)

Hard Emission of a Photon

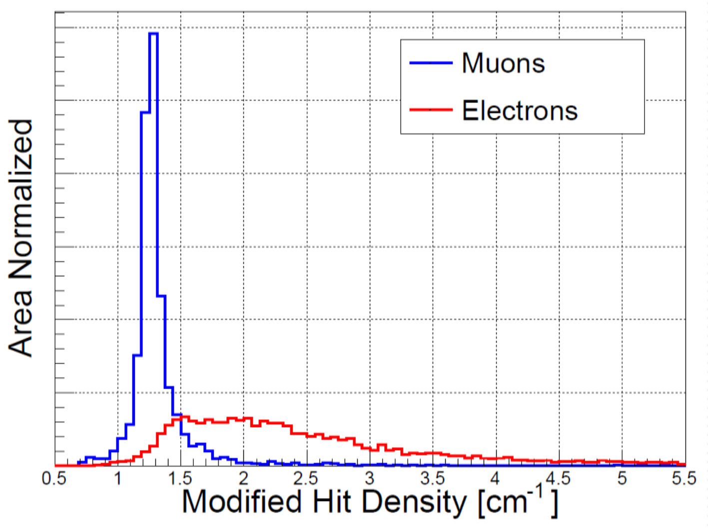


$$\sim \frac{\alpha}{\pi} \approx 2 \times 10^{-3}$$

Phase-space suppression factor

Electron-faking Muon

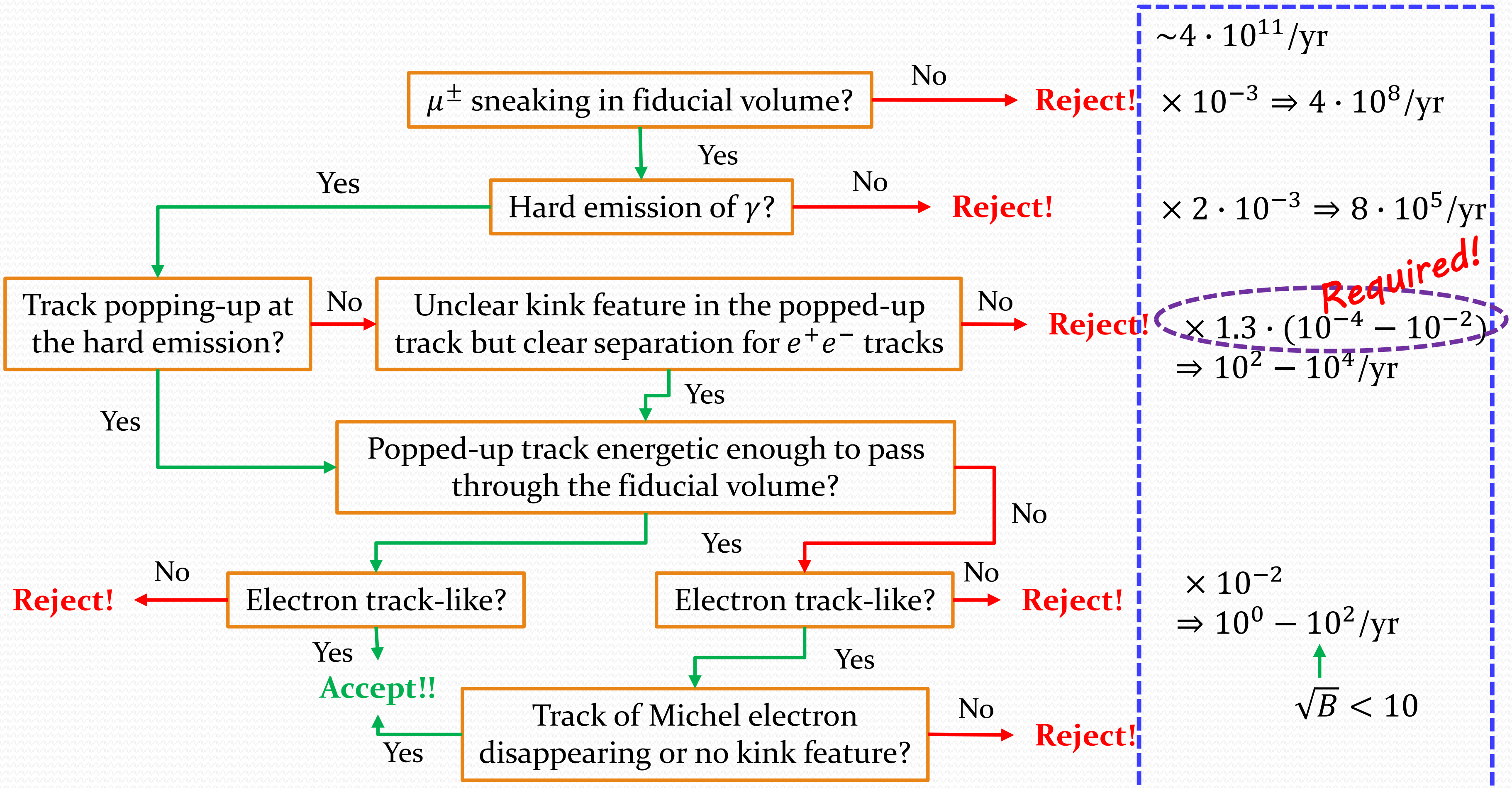
- All known studies simply reporting a negligible rate of muons misidentified as electrons, but how negligible?
- A hint from an example study [ArgoNeuT Collaboration, "First Observation of Low Energy Electron Neutrinos in a Liquid Argon Time Projection Chamber", arXiv:1610.04102]



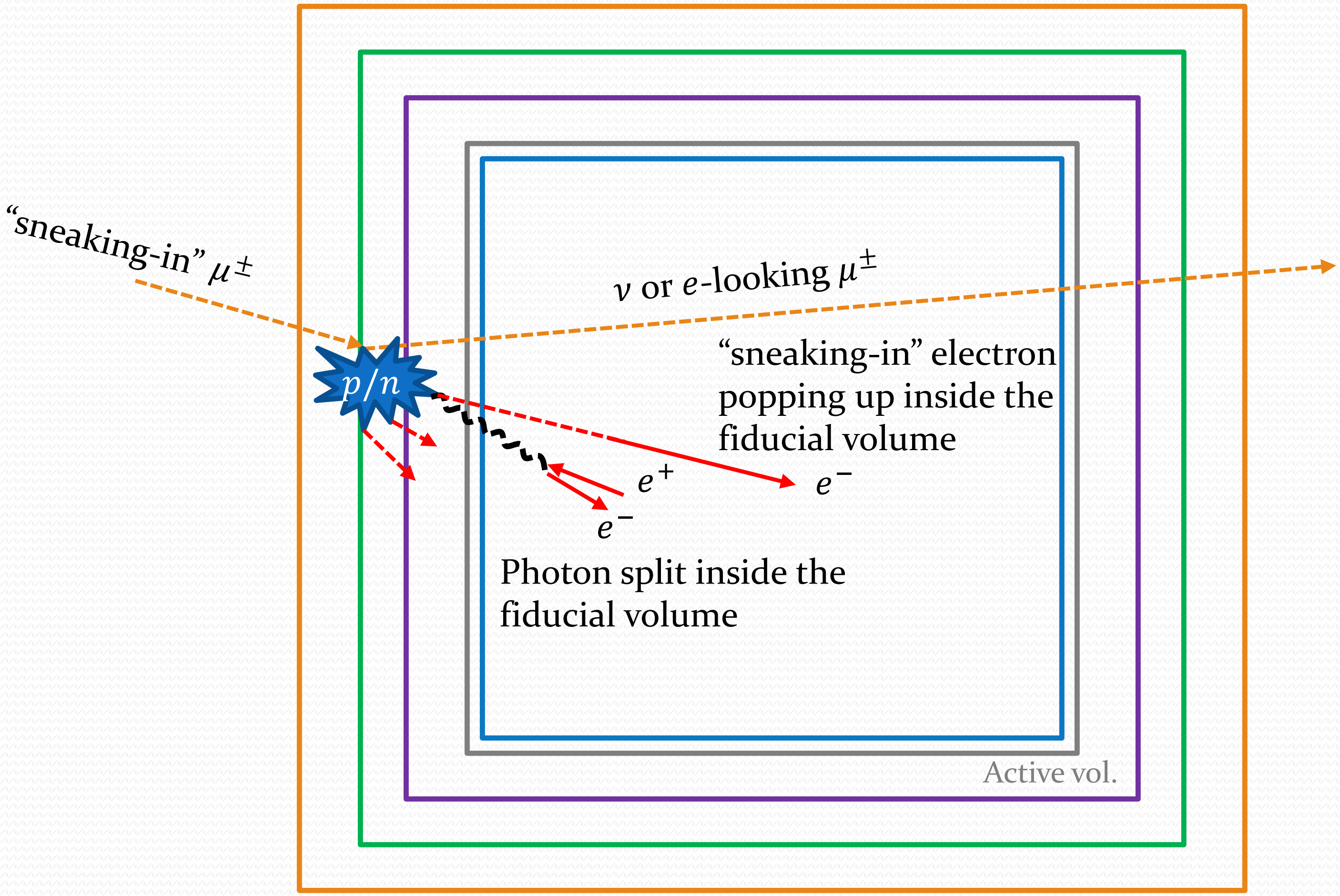
If cut here, ~8% of the fake

- This is too large to be true, because
  - Other criteria discriminate more,
  - ~7% contamination from γ sample (i.e., e vs. γ) is reported, whereas e vs. μ is simply stated negligible.
- Nevertheless, a very conservative estimate of fake probability is $\mathbf{10^{-2}}$

Case Study I: Overall Survival Rate



Case Study II



Case Study II: Overall Survival Rate

1) Deep inelastic scattering with a p/n

$N_{\text{event}} \sim$ (DIS cross section) $\times$ (muon flux) $\times$ (1 year) $\times$ (number of nucleons inside the passive volume) $\sim 2 \times 10^5\ \text{yr}^{-1}$

2) Photon split inside the fiducial volume after traveling more than ~35 cm in Liquid Ar

3) Electron "sneaks in" and pops up inside the fiducial volume

4) Incoming muon not leaving a visible track inside the active volume

$\sim 10^{11}/\text{yr}$

$\sim 2 \times 10^5/\text{yr}$

$\times\ 5 \cdot 10^{-3} \Rightarrow 10^3/\text{yr}$

$\times\ 10^{-3} \Rightarrow 1/\text{yr}$

Indeed, should be smaller than muon "sneak-in" probability

Model-independent Reach

- **Non-trivial** to find appropriate parameterizations for providing **model-independent reaches** due to many parameters involved in the model
- Number of signal events $N_{\rm sig}$ is

$$N_{\rm sig} = \sigma_\epsilon \cdot \mathcal{F} \cdot A \cdot t_{\rm exp} \cdot N_e$$

  - σ_ϵ: scattering cross section between χ_1 and (target) electron
  - $\mathcal{F}$: flux of incoming (boosted) χ_1
  - A: acceptance
  - $t_{\rm exp}$: exposure time
  - N_e: total # of target electrons

Controllable! (once a detector is determined)

Here we factored out the acceptance related to distance between the primary (ER) and the secondary vertices, other factors like cuts, energy threshold, etc are absorbed into σ_ϵ.

Model-independent Reach: Prospect

90% C.L. with

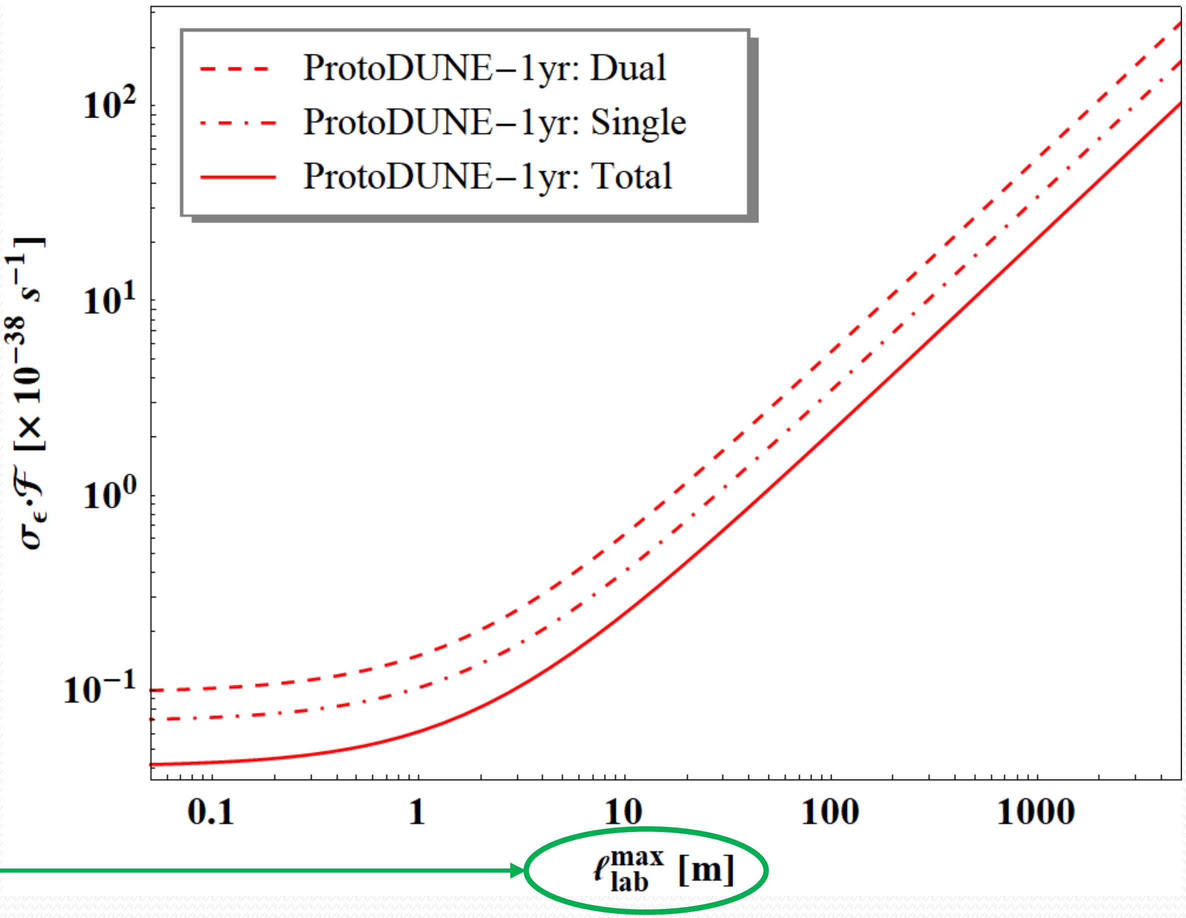
zero BG

$$\sigma_\epsilon \cdot \mathcal{F} \geq \frac{2.3}{A(\ell_{\rm lab}) \cdot t_{\rm exp} \cdot N_e}$$

Calculable

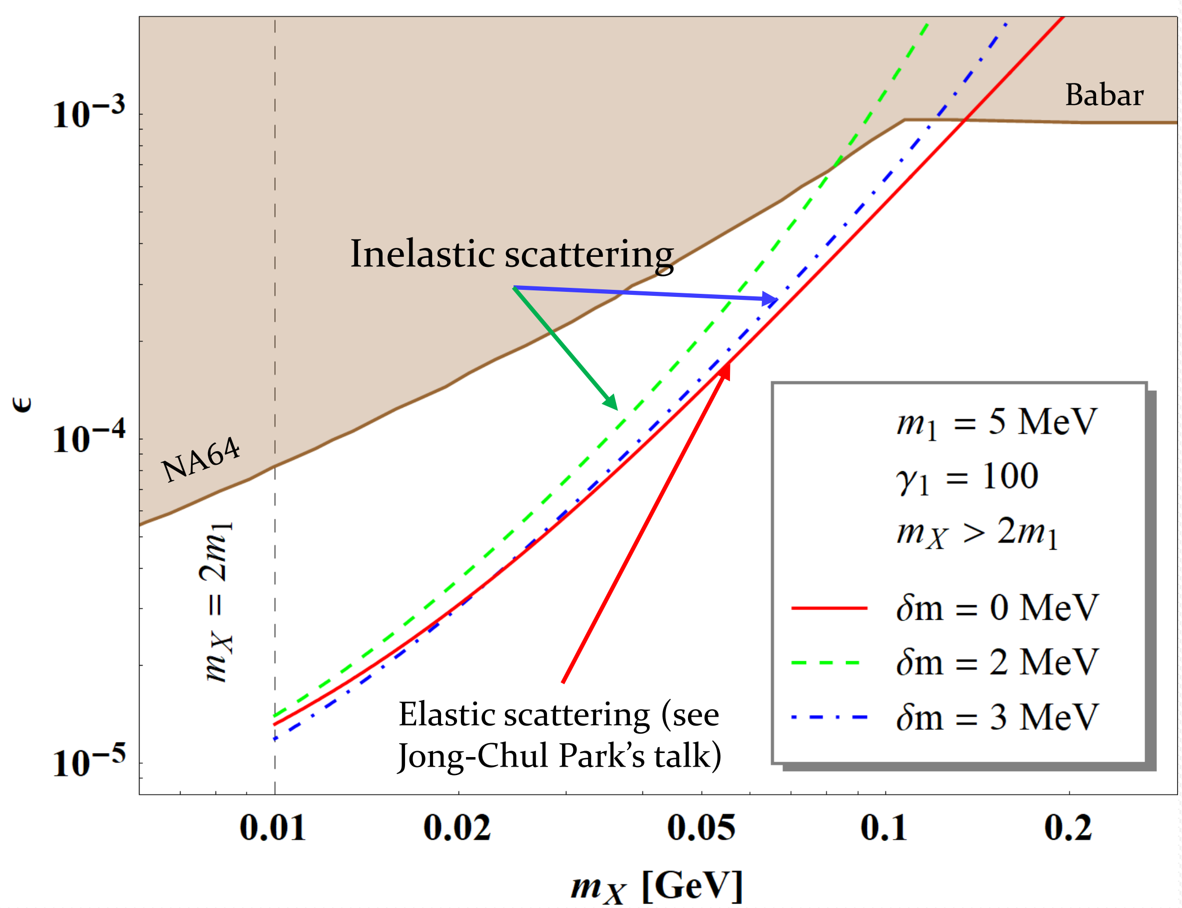
Evaluated under the assumption of cumulatively isotropic χ_1 flux

$\ell_{\rm lab}$ different event-by-event, so taking $\ell_{\rm lab}^{\rm max}$ for more conservative limit



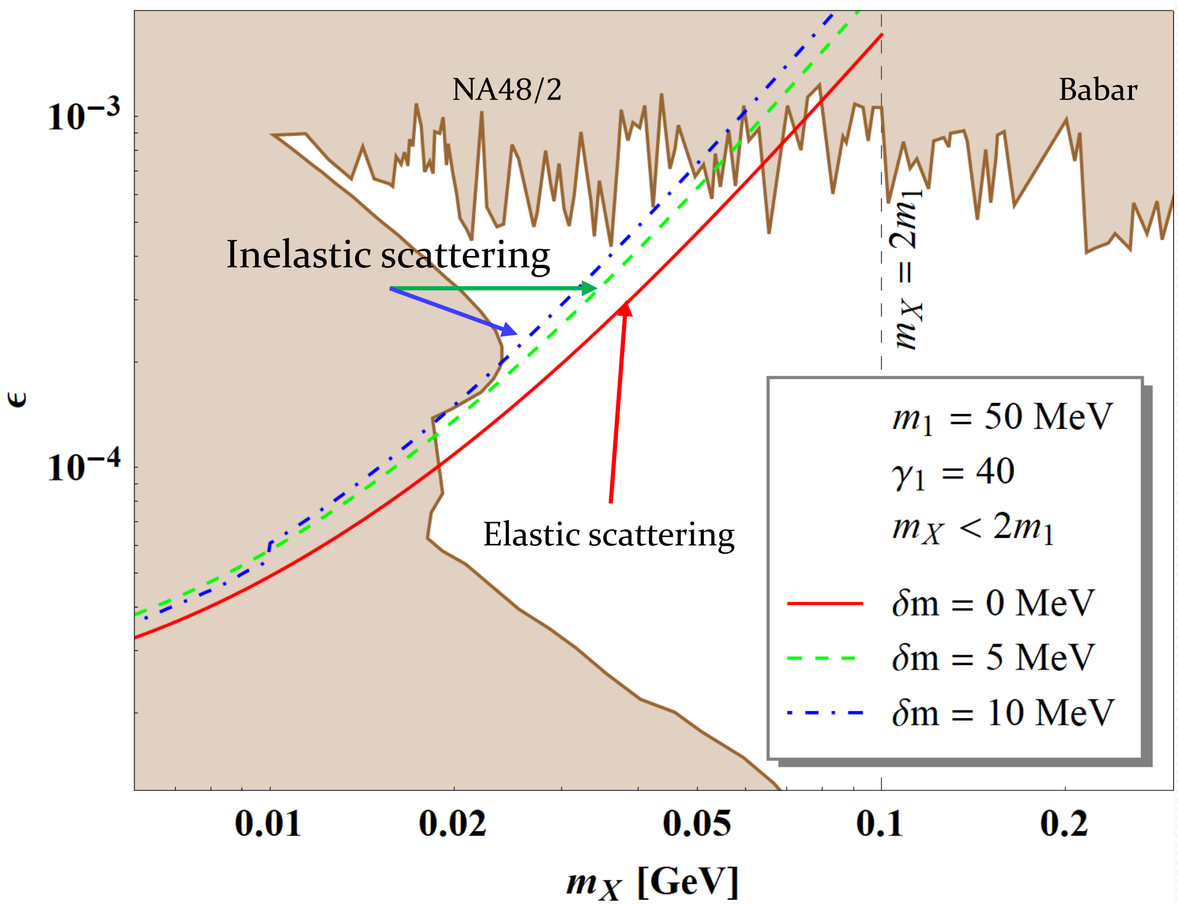
Dark Photon Parameter Space: Invisible X Decay

- ❑ Case study 1: mass spectra for which dark photon decays into DM pairs, i.e., $m_X > 2m_1$
- ❑ 1-year data collection from the entire sky and $g_{11} = g_{12} = 1$ are assumed.
- ❑ Elastic and inelastic scattering channels are complementary to each other.



Dark Photon Parameter Space: Visible X decay

- Case study 2: mass spectra for which dark photon decays into lepton pairs, i.e., $m_X < 2m_1$
- 1-year data collection from the entire sky and $g_{11} = g_{12} = 1$ are assumed.
- Inelastic scattering channel allows us to explore comparable parameter space (for the chosen benchmark point).



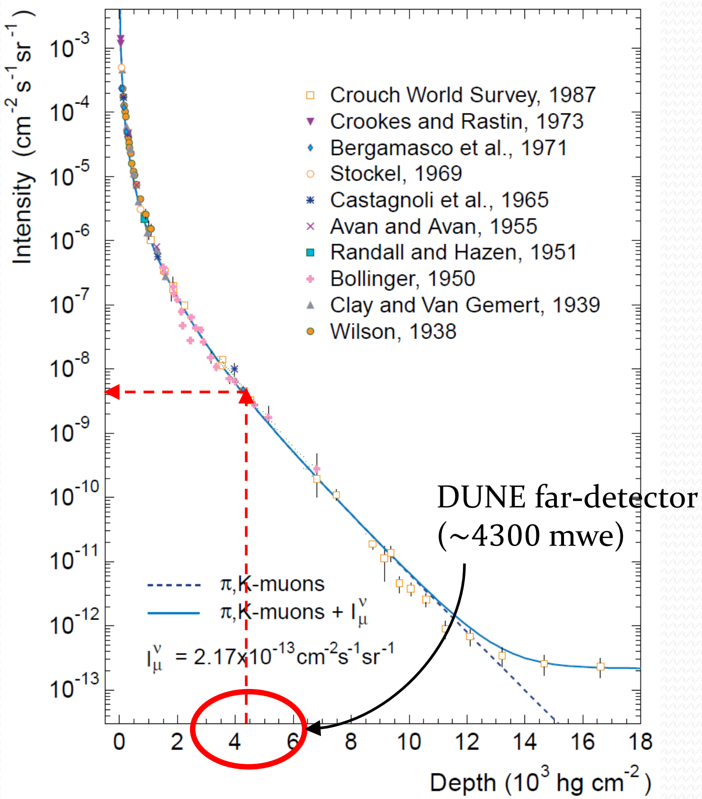
Conclusions and Outlook

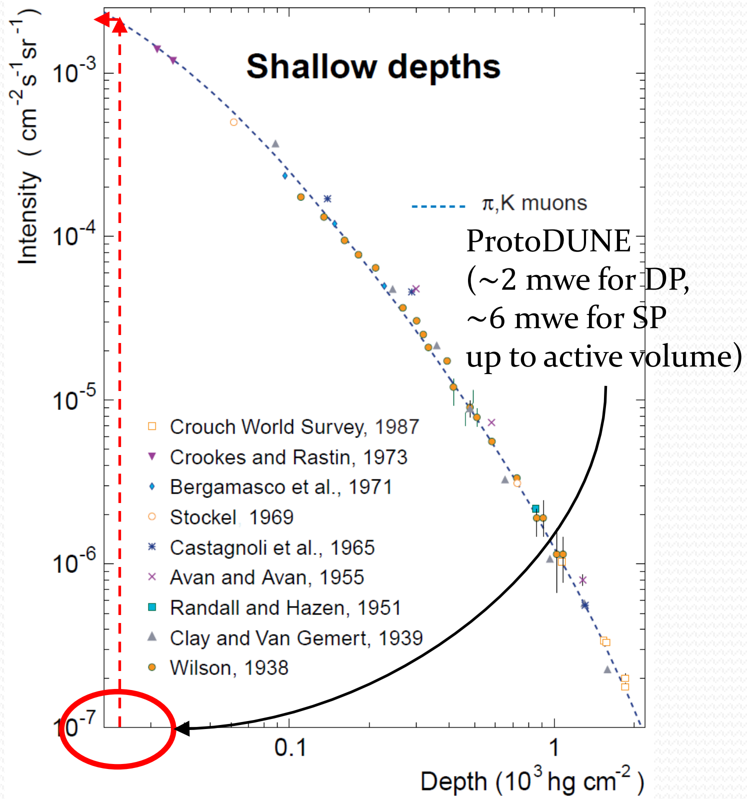
Scattering \ v_{DM}	Non-relativistic ($v_{DM} \ll c$)	Relativistic ($v_{DM} \sim c$)
elastic	Direct detection	Boosted DM (eBDM)
*in*elastic	inelastic DM (iDM)	**inelastic BDM (*i*BDM)**

- The boosted (light) DM search is **promising** and provides a **new direction** to study DM phenomenology.
- Potential (scary?) **cosmic-ray background** can be well **under control**.
- **ProtoDUNE** possesses **excellent sensitivities** to a wide range of (light) boosted DM, hence allows a **deeper understanding** in non-minimal dark sector physics.
- **ProtoDUNE** can provide an **alternative avenue** to probe dark photon parameter space.
- Physics at ProtoDUNE can provide a **valuable physics input** and potentially a **realistic guideline** for new physics searches at DUNE.
- The same opportunity is available at SBN detectors, e.g., ICARUS.

Back-up

Potential Backgrounds: High Energy Muons





[Bugaev et al. (1998)]

- Expecting ~10^6 more muon flux at ProtoDUNE than that at the DUNE far-detector.

Potential Backgrounds: High Energy Muons

- More quantitatively, the integral intensity of vertical muons above 1 GeV at sea level is ~70 /m^2/s/sr [De Pascale et al, (1993)]
  1) Single phase detector: muons below 1 GeV cannot reach the active volume (~2 MeV/cm × ~6 mwe ≈ 1.2 GeV). ⇒ **~3.5 muons/ms/sr**
  2) Dual phase detector: muons below 1 GeV can reach the active volume (~2 MeV/cm × ~2 mwe ≈ 0.4 GeV). Muon energy spectrum below 1 GeV is almost flat, so muons at sea level in-between 500 MeV and 1 GeV is estimated to be ~10 /m^2/s/sr. ⇒ **~3 muons/ms/sr**

- Expecting that these numbers of muon events can be well **under control** by a (sensible) trigger and/or (dedicated) data analyses.
- However, a possible source is the **cosmogenic neutron** which would give a fake signal. ⇒ The easiest solution is to give up the elastic proton-scattering signal or to take a smaller fiducial volume.

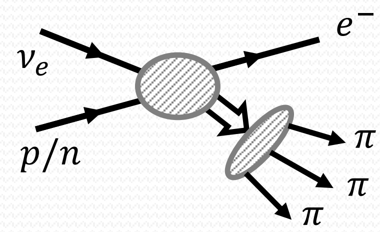
Potential Backgrounds: Neutrinos

Table 4.3: Atmospheric neutrino event rates including oscillations in 350 kt · year with a LArTPC, fully or partially contained in the detector fiducial volume.

Sample	Event Rate
fully contained electron-like sample	14,053
fully contained muon-like sample	20,853
partially contained muon-like sample	6,871

[DUNE CDR-Vol.2 (2015)]

~**40.2**/yr/kt: may contain multi-track events



	SK-I		SK-II		SK-III		SK-IV	
	Data	MC	Data	MC	Data	MC	Data	MC
FC sub-GeV single-ring e-like								
0-decay	2992	2705.4	1573	1445.4	1092	945.3	2098	1934.9
1-decay	301	248.1	172	138.9	118	85.3	243	198.4
π^0-like	176	160.0	111	96.3	58	53.8	116	96.2
μ-like								
0-decay	1025	893.7	561	501.9	336	311.8	405	366.3
1-decay	2012	1883.0	1037	1006.7	742	664.1	1833	1654.1
2-decay	147	130.4	86	71.3	61	46.6	174	132.2
2-ring π^0-like	524	492.8	266	259.8	182	172.2	380	355.9
FC multi-GeV single-ring								
ν_e-like	191	152.8	79	78.4	68	54.9	156	135.9
$\overline{\nu}_e$-like	665	656.2	317	349.5	206	231.6	423	432.8
μ-like	712	775.3	400	415.7	238	266.4	420	554.8
multi-ring								
ν_e-like	216	224.7	143	121.9	65	81.8	175	161.9
$\overline{\nu}_e$-like	227	219.7	134	121.1	80	72.4	212	179.1
μ-like	603	640.1	337	337.0	228	231.4	479	499.0

[Super-Kamiokande (2012)]

Single-track candidates: **32.4** + **8.8** = **41.2** /yr/kt, while total e-like events are 49.9 /yr/kt. (Note that SK takes e-like events with E > ~10 MeV.)

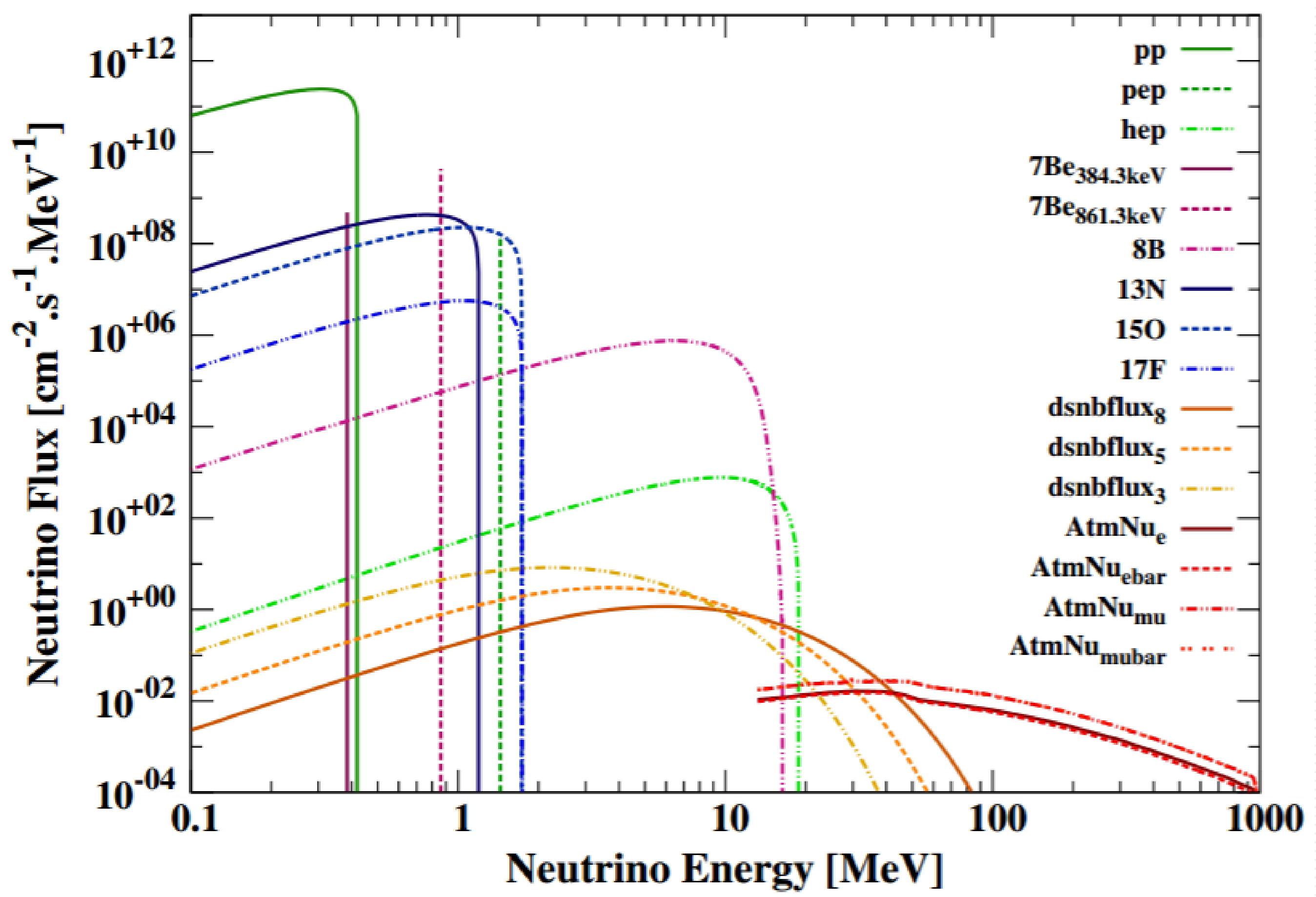
⇒ Potential background for elastic scattering signal events

Multi-track candidates: **5.2** /yr/kt

⇒ Most extra tracks come from mesons which can be identified at ProtoDUNE.

⇒ Very likely to be background-free for inelastic scattering signal events

Neutrino Fluxes



[Ruppin et al., (2014)]

eBDM Search at Super-K

[Super-K Collaboration, (2017)]

	100 MeV< E_{vis} < 1.33 GeV			1.33 GeV < E_{vis} < 20 GeV			E_{vis} > 20 GeV		
	Data	ν-MC	ϵ_{sig}(0.5 GeV)	Data	ν-MC	ϵ_{sig}(5 GeV)	Data	ν-MC	ϵ_{sig}(50 GeV)
FCFV	15206	14858.1	97.7%	4908	5111.1	93.8%	97	107.5	84.9%
& single ring	11367	10997.4	95.8%	2868	3162.8	93.3%	53	68.2	82.2%
& e-like	5655	5571.5	95.7%	1514	1644.4	93.0%	53	68.1	82.2%
& 0 decay-e	5176	5123.6	94.7%	1134	1266.0	93.0%	17	20.0	82.2%
& 0 neutrons	4132	4076.3	93.0%	683	801.5	91.3%	4	5.9	80.7%

TABLE I. Number of events over the entire sky passing each cut in 2628.1 days of SK4 data, simulated ν-MC background expectation, and signal efficiency at representative energy after each cut.

High threshold energy

Single-ring-like objects only