Boosted Dark Matter (BDM) at DUNE

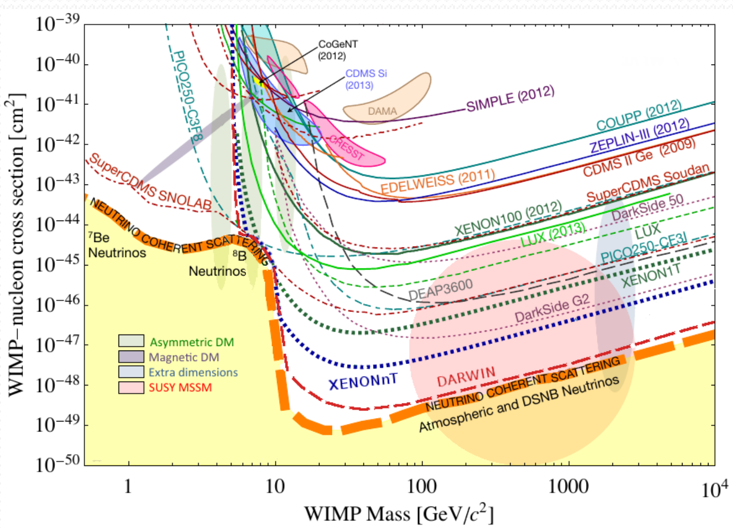
1612.06867, 1712.07126, 1803.03264, 1804.07302, more in progress,
in collaboration with H. Alhazmi, W. Bonivento, A. Chatterjee, A. De Roeck, K. Dienes, G. Giudice, K. Kong, P. Machado, Z. Moghaddam, J.-C. Park, S. Shin, B. Thomas, L. Whitehead, J. Yu

Doojin Kim

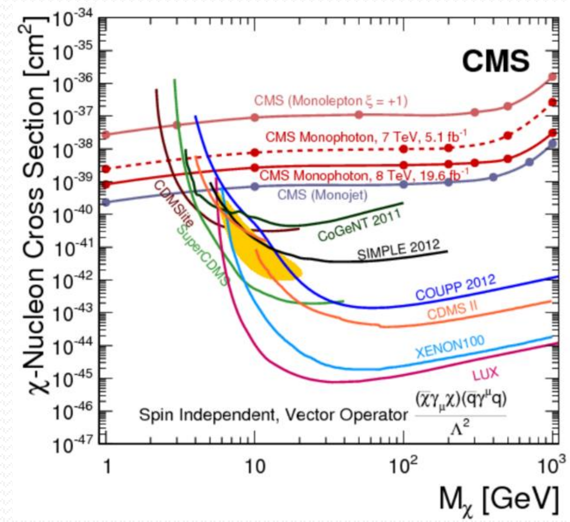
August 14th, 2018

Current Status of DM Searches

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



[P. Cushman, C. Calbiati and D. N. McKinsey, (2013); L. Baudis (2014)]



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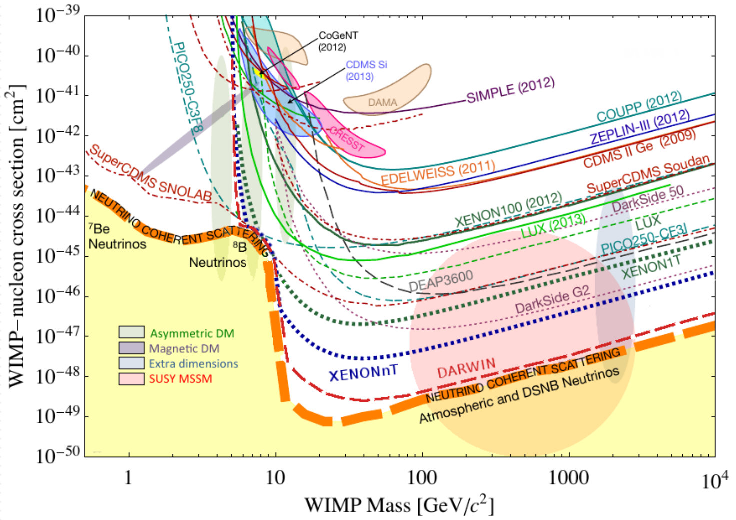

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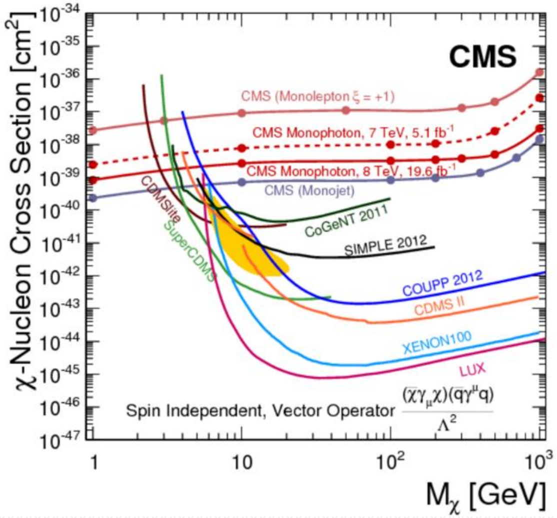

[CMS mono-photon search (2014)]

Time to change our approach?!

Conventional Approach

- Traditional approaches for DM searches:
  - ✓ Weak-scale mass
  - ✓ Weakly-coupled
  - ✓ Minimal dark sector
  - ✓ Elastic scattering
  - ✓ Non-relativistic

Conventional vs. Nonconventional Approach

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- Modified approaches for DM searches:
  - ✓ Other mass scale: e.g., PeV, sub-GeV, MeV, keV, meV, …
  - ✓ Weaker coupling to the SM: e.g., vector portal (dark photon), scalar portal, axion portal, …
  - ✓ "Flavorful" dark sector: e.g., more dark matter species, unstable heavier dark sector states, …
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DM Search Strategies

Scattering \ v_{DM}	Non-relativistic ($v_{DM} \ll c$)
elastic	Direct detection
*in*elastic	inelastic DM (iDM)

Very well-studied

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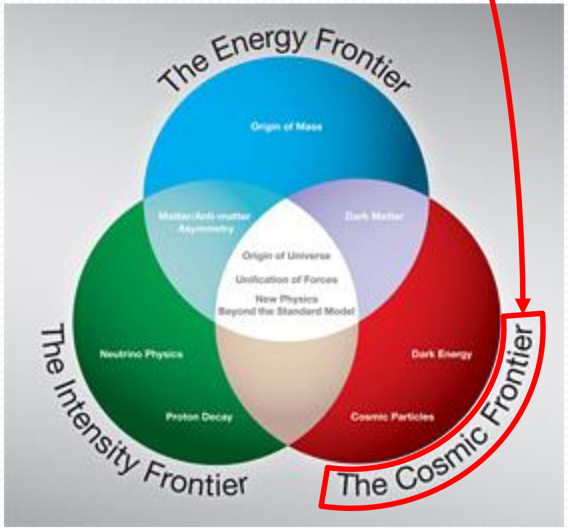
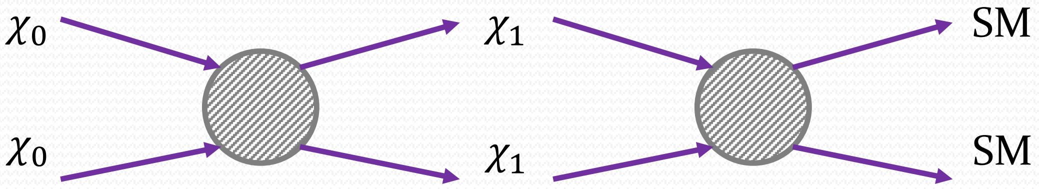


Two-component Boosted DM Scenario

- 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.



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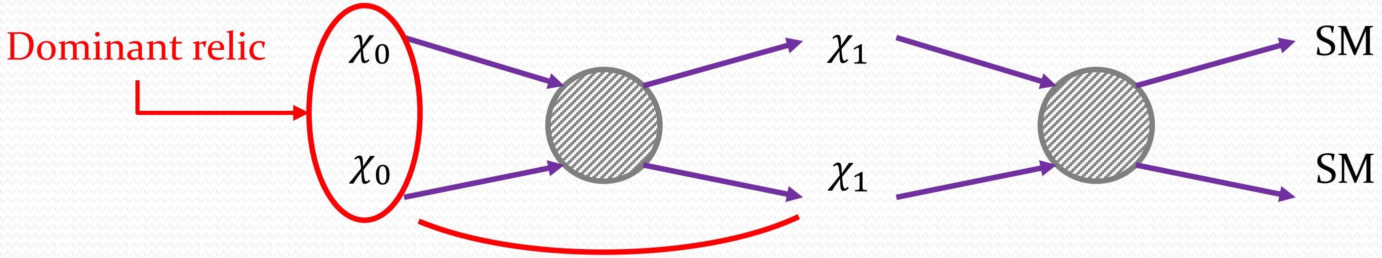

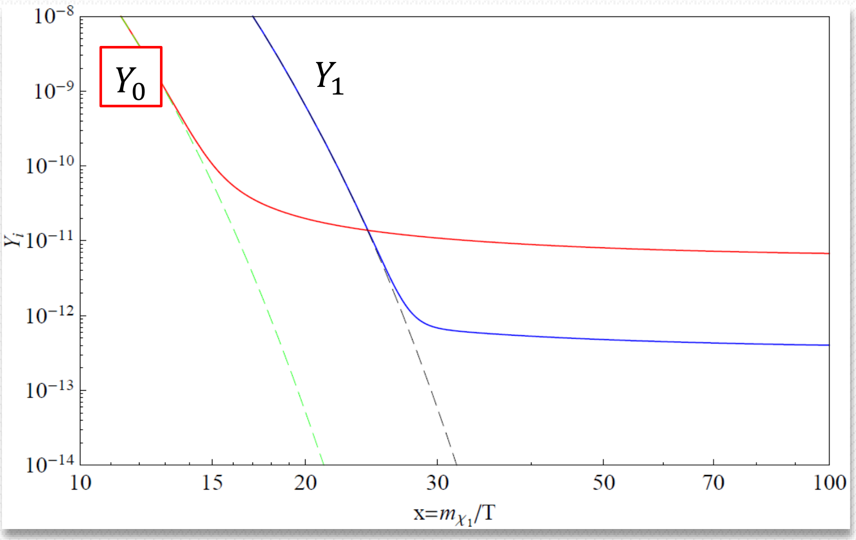

"Assisted" freeze-out mechanism

[Belanger, Park (2011)]

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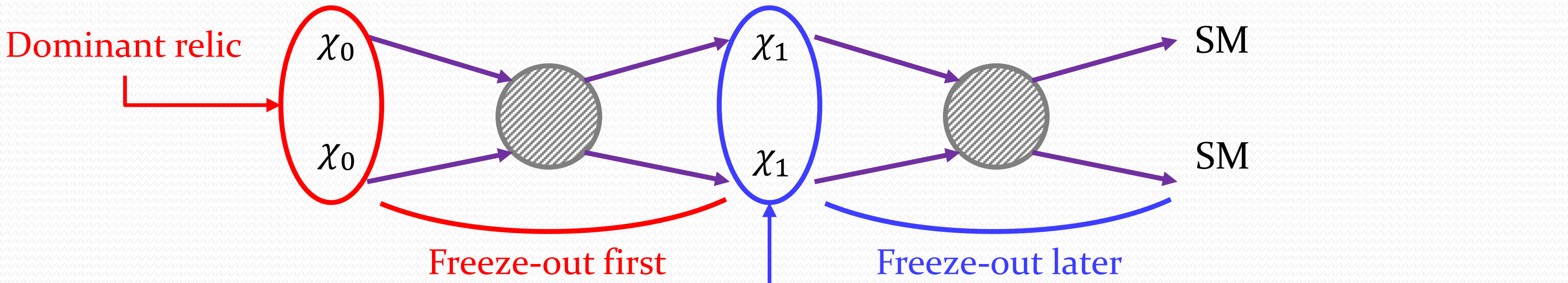

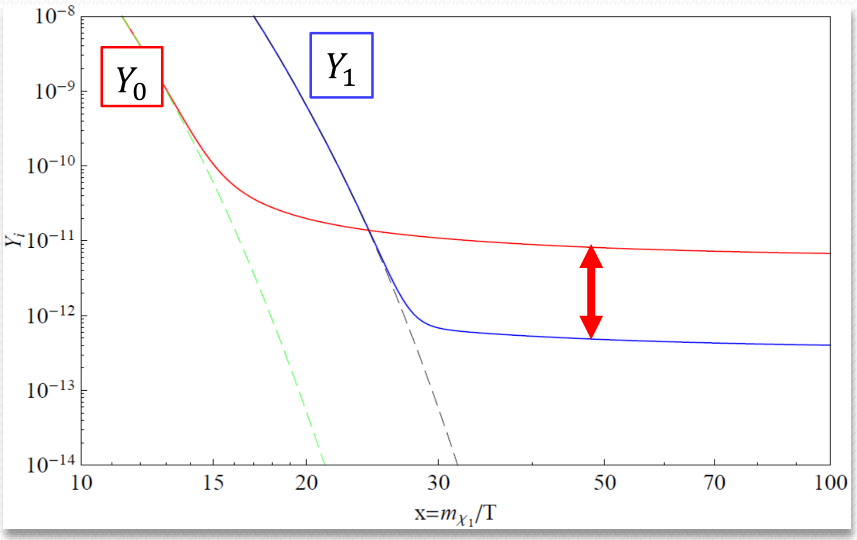

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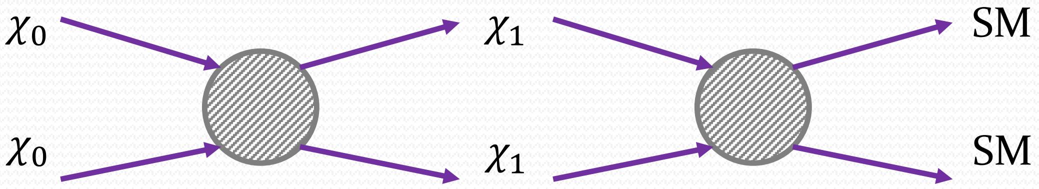
"Relativistic" Dark Matter Search



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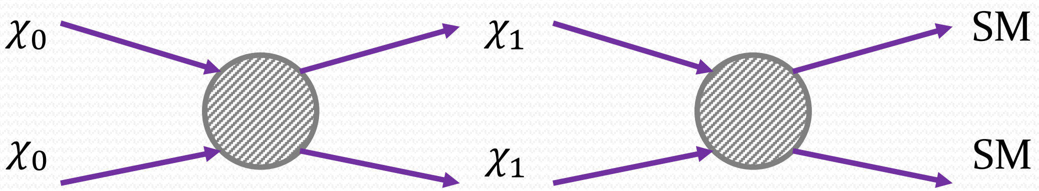

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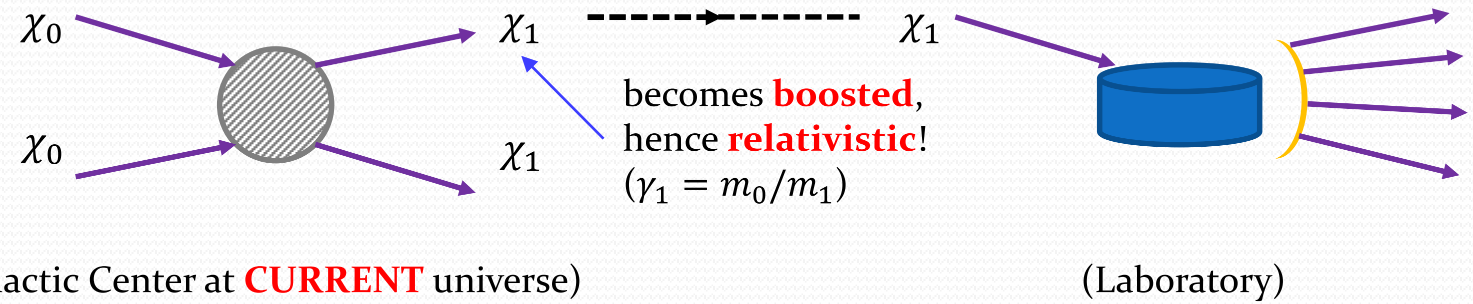

[Agashe, Cui, Necib, Thaler (2014)]

Boosted DM Detection

- Flux of boosted χ_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 $\sim 10^{-26}$ cm^3s^{-1} and assuming Navarro-Frenk-White DM halo profile, a standard profile, one finds

$\mathcal{F}_{\chi_1} \sim 10^{-1}$ to $10^{-7}\text{cm}^{-2}\text{s}^{-1}$ for $\mathcal{O}(30\text{ MeV})$ to $\mathcal{O}(20\text{ GeV})$ mass of χ_0

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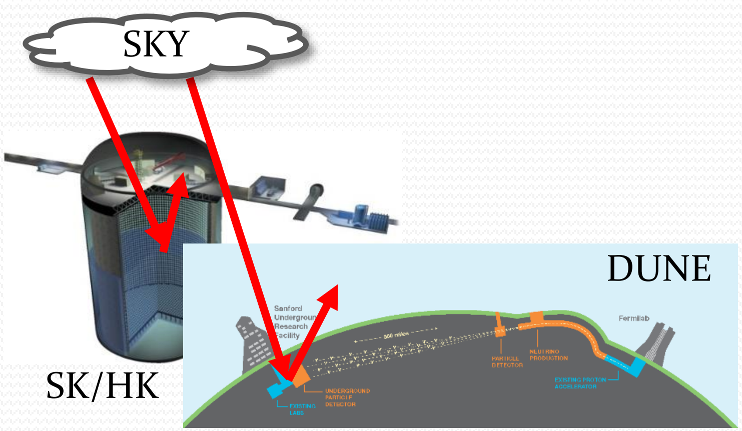
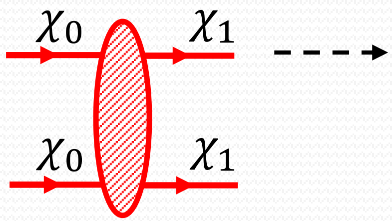
- Too small for small-volume detectors (e.g., conventional WIMP detectors) ⇒ large-volume (neutrino) detectors motivated
  - ✓ Super-/Hyper-Kamiokande (SK/HK)
  - ✓ Deep Underground Neutrino Experiment (DUNE)
  - ✓ ProtoDUNE, ICARUS at SBN, etc.

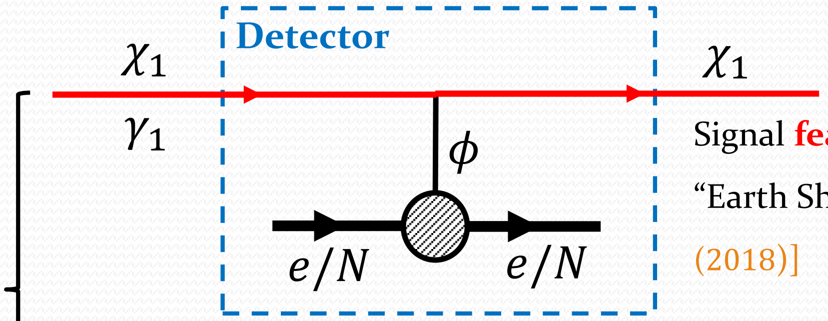


Generic BDM Signal Processes

Galactic Center

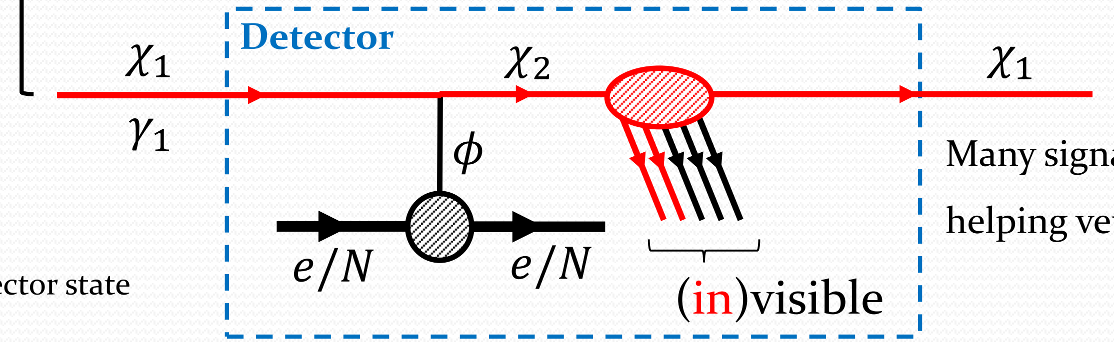


(a) Elastic scattering (eBDM) (cf. eBDM at DUNE [Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016)])



Signal **featureless**, not free from BGs ⇒ "Earth Shielding" [**DK**, Kong, Park, Shin (2018)]

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



Many signal **features**, helping veto BGs

- 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

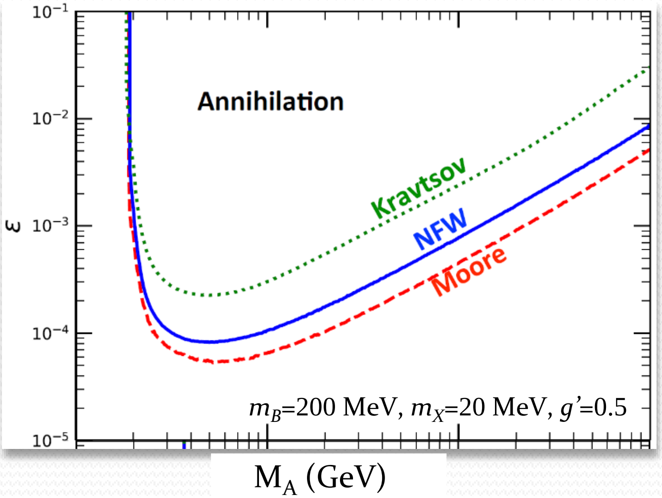
✓ Similar signatures at intensity-frontier exp. [LoSecco et al. (1980); Bjorken, Essig, Schuster, Toro (2009); Batell, Pospelov, Ritz (2009); deNiverville, Pospelov, Ritz (2011); Izaguirre, Krnjaic, Schuster, Toro (2014); Izaguirre, Kahn, Krnjaic, Moschella (2017); Berlin, Gori, Schuster, Toro (2018); Bonivento, **DK**, Park, Shin in progress, and many more]

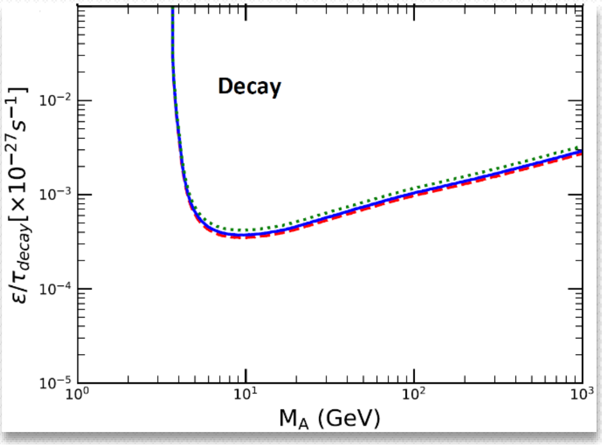
SK Official Results for eBDM Search

Search for Boosted Dark Matter Interacting With Electrons in Super-Kamiokande

(Dated: November 16, 2017)

A search for boosted dark matter using 161.9 kiloton-years of Super-Kamiokande IV data is presented. We search for an excess of elastically scattered electrons above the atmospheric neutrino background, with a visible energy between 100 MeV and 1 TeV, pointing back to the Galactic Center or the Sun. No such excess is observed. Limits on boosted dark matter event rates in multiple angular cones around the Galactic Center and Sun are calculated. Limits are also calculated for a baseline model of boosted dark matter produced from cold dark matter annihilation or decay.

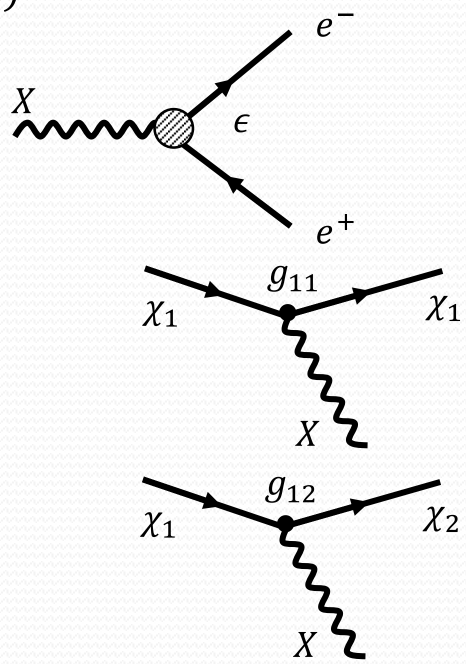




[SK Collaboration, arXiv:1711.05278]

Benchmark Model

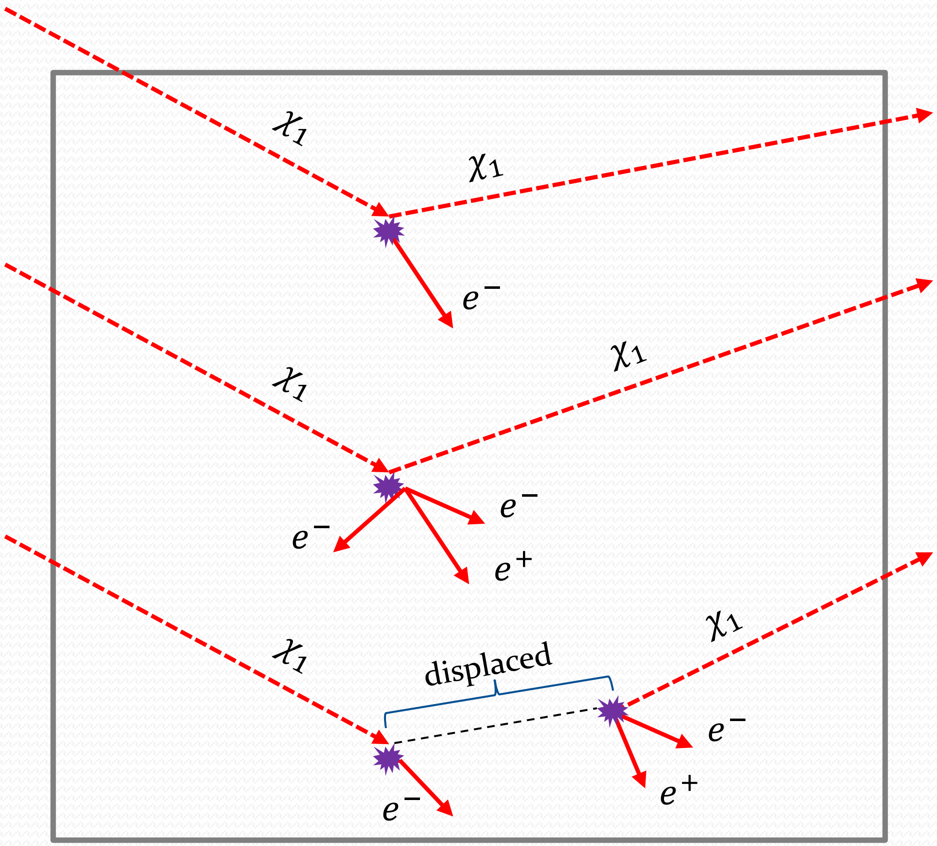
$$\mathcal{L}_{\rm int} \ni -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{11}\bar{\chi}_1 \gamma^\mu \chi_1 X_\mu + g_{12}\bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + \text{h.c.} + (\text{others})$$



- Vector portal (e.g., dark gauge boson scenario) [Holdom (1986)]
- Fermionic DM
  - χ_2: a heavier (unstable) dark-sector state
  - Flavor-conserving neutral current ⇒ elastic scattering (can be suppressed or even vanishing)
  - Flavor-changing neutral current ⇒ inelastic scattering
- Not restricted to this model: various models conceiving BDM signatures
  - BDM source: galactic center, solar capture, dwarf galaxies, etc.
  - 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)]

Expected Signatures with Electron Recoil

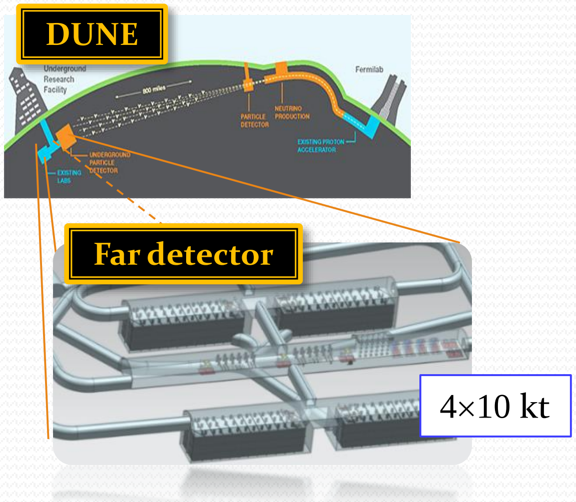


- ❑ Ordinary elastic scattering: electron recoil (ER) only, i.e., single track
- ❑ "Prompt" inelastic scattering: ER + e^+e^- pair (from the decay of on-shell X), i.e., **three tracks**
- ❑ "Displaced" inelastic scattering: ER + e^+e^- pair (typically from a three-body decay of χ_2), i.e., again **three tracks**

- ❑ Note that **tracks will pop up inside the fiducial volume**.
- ❑ Straightforwardly applicable to proton recoil (up to form factor, DIS etc.)

Example search:
*i*BDM@ProtoDUNE (& DUNE)

ProtoDUNE as Prototypical Detectors of DUNE

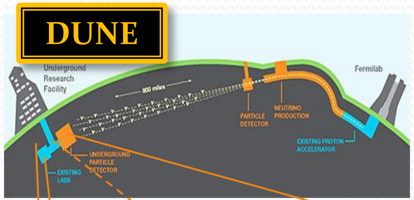


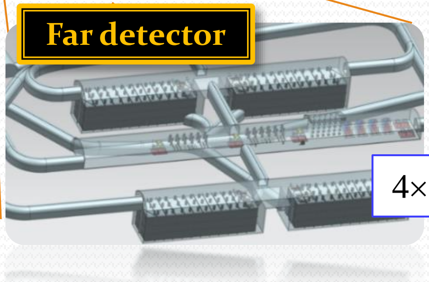
- ✓ Physics at DUNE: neutrino sector, BSM, etc. (at intensity and cosmic frontiers)

ProtoDUNE as Prototypical Detectors of DUNE

❖ SP: single-phase

❖ DP: dual-phase

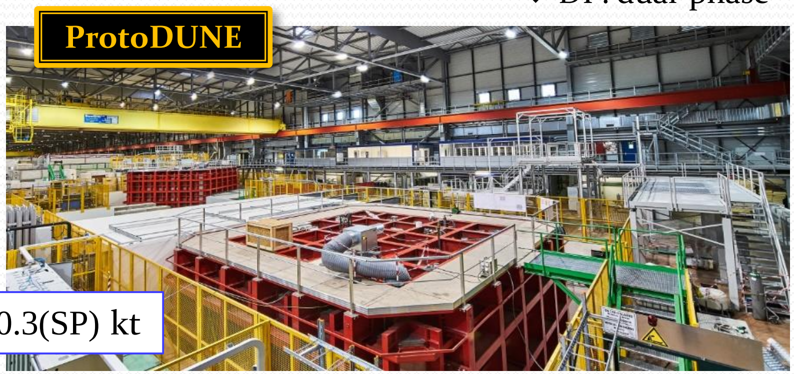




4×10 kt

Prototype of DUNE

0.2(DP)+0.3(SP) kt



<Original purpose>

- ✓ 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

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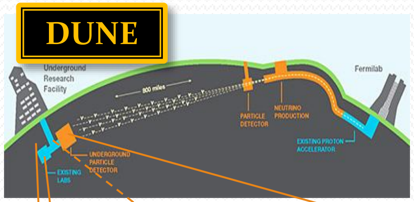

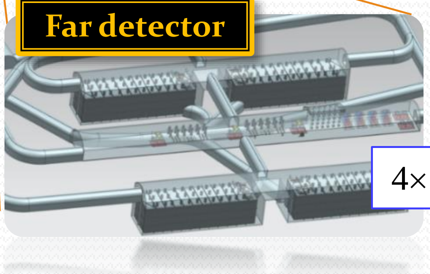

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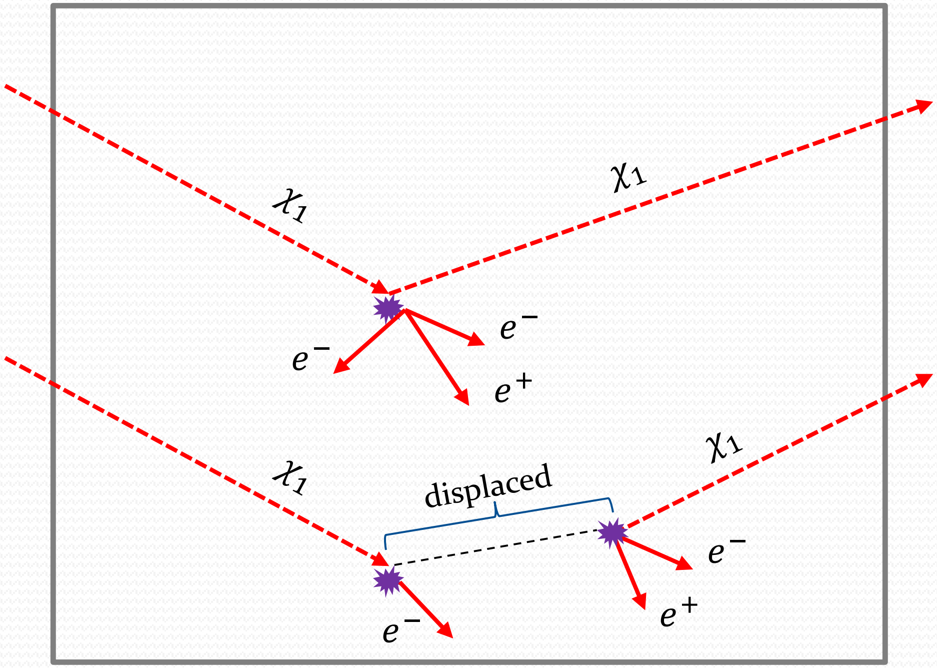
- ✓ Calibrating beam response and cosmic-ray response
- ✓ Now: operation from Sep. 2018 & planned to take cosmic-origin data for new physics searches (~2 years)

Expected *i*BDM Signatures (Reminder)



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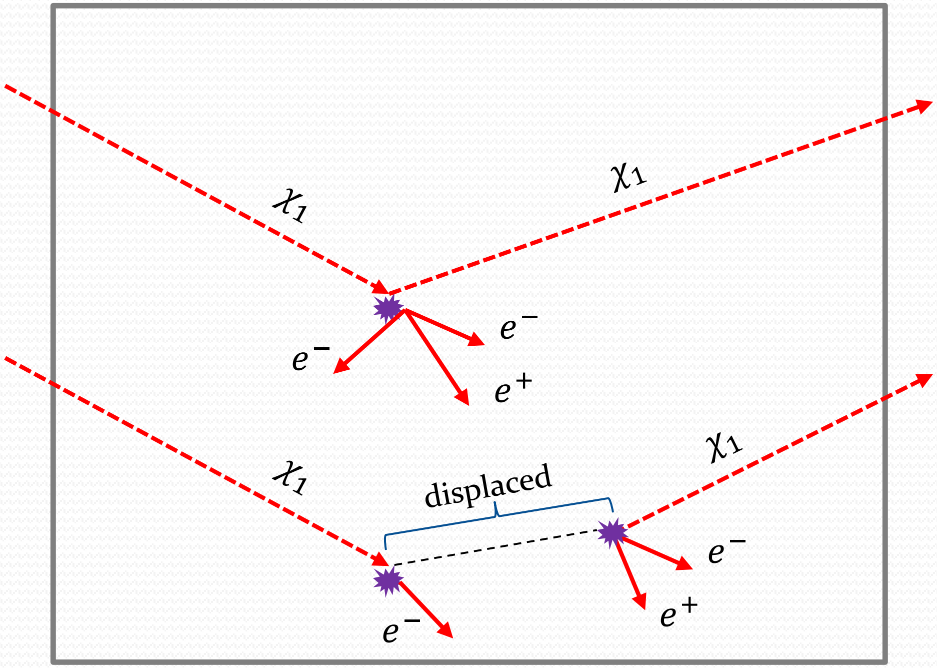

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(Potentially), cosmic-induced BGs (e.g., cosmic muons) challenging ⇒ **negligible due to many criteria**: multi-track in the fiducial volume, correlated displaced vertex, small chance of "sneaking-in" muon, small chance of *e*-looking muons, etc.

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) [applies to $t_{\rm exp}$ and N_e]

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

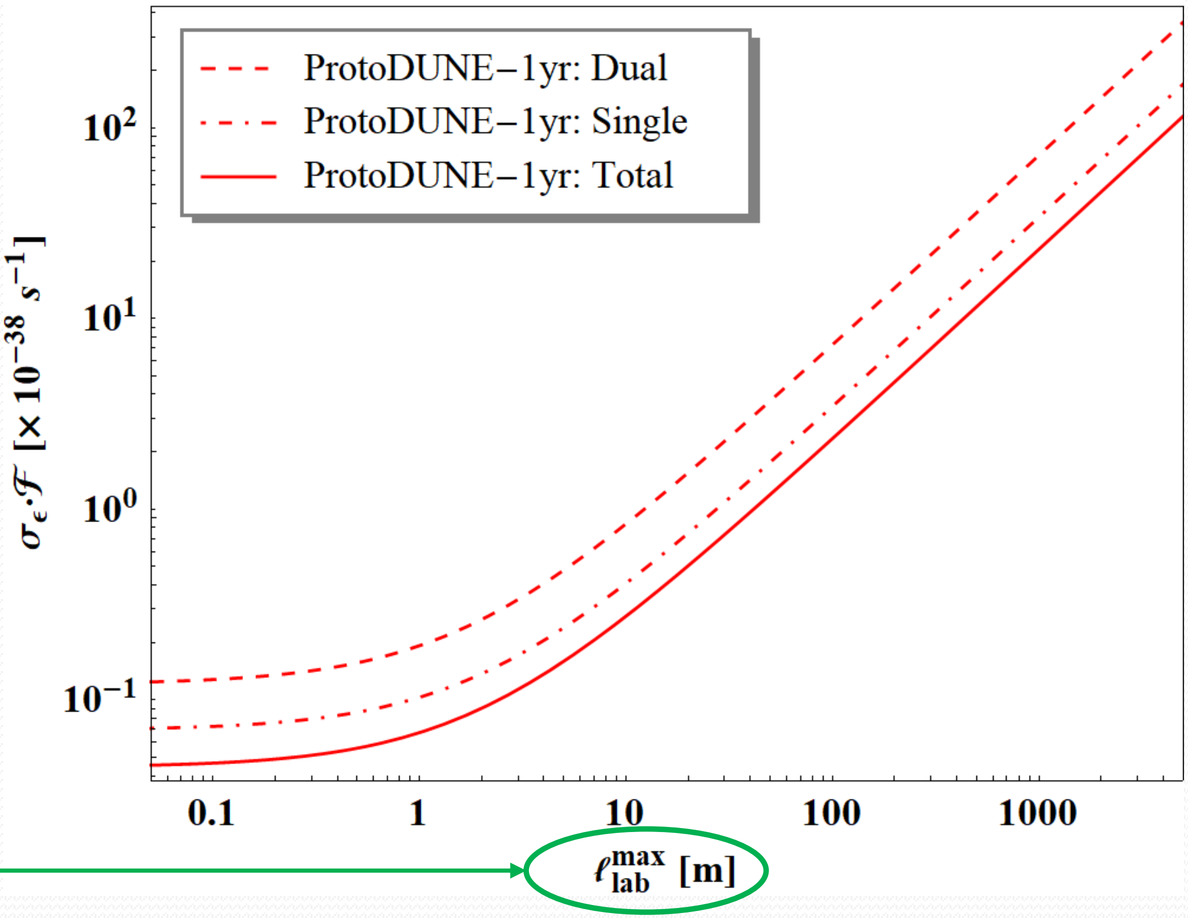
90% C.L. with zero BG

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

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



Model-independent Reach: More Familiar Form

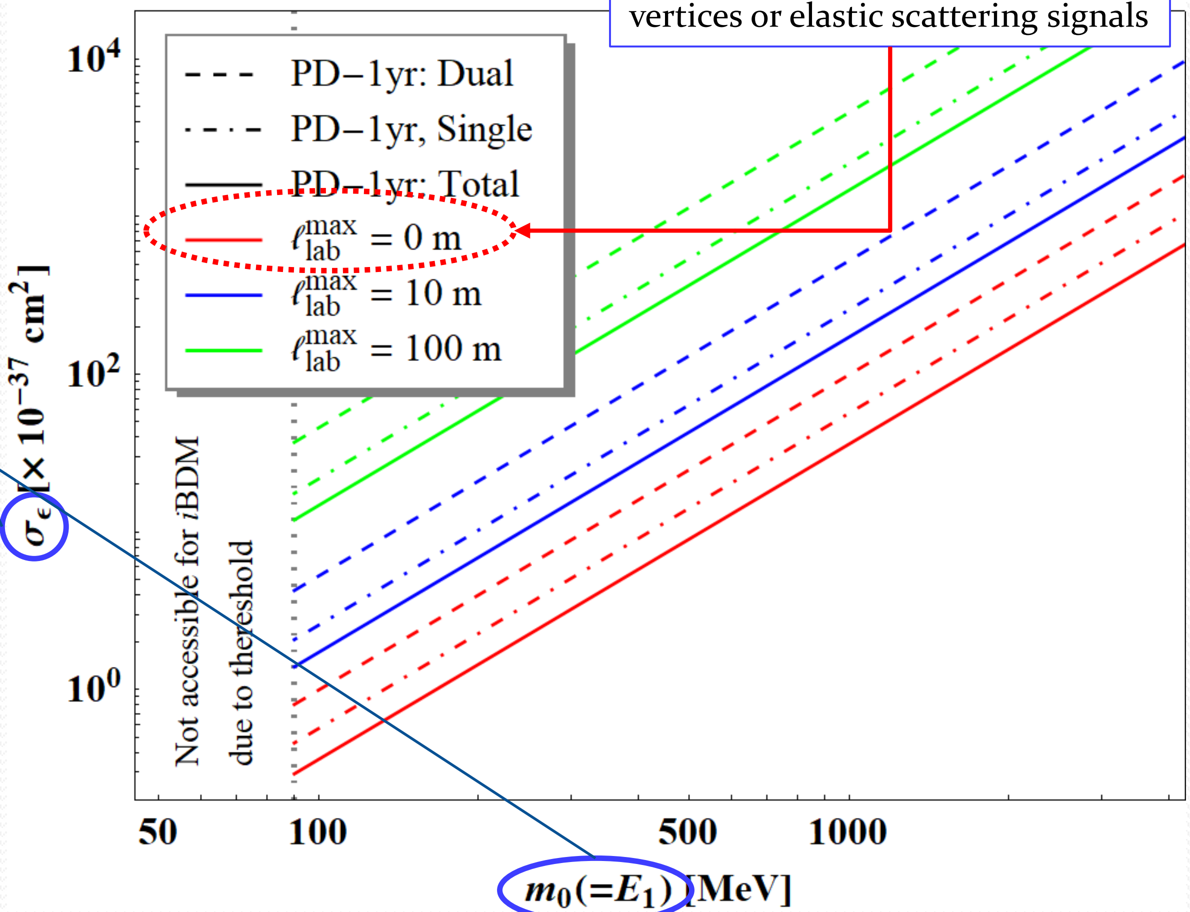
$$\sigma \geq \frac{2.3}{\mathcal{F} \cdot A \cdot t_{\text{exp}} \cdot N_e}$$

$$\mathcal{F} \sim \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \to \chi_1 \chi_1}}{m_0^2}$$

⇒ Experimental sensitivity can be represented by σ_ϵ vs. $E_1 (= m_0 = \gamma_1 m_1)$

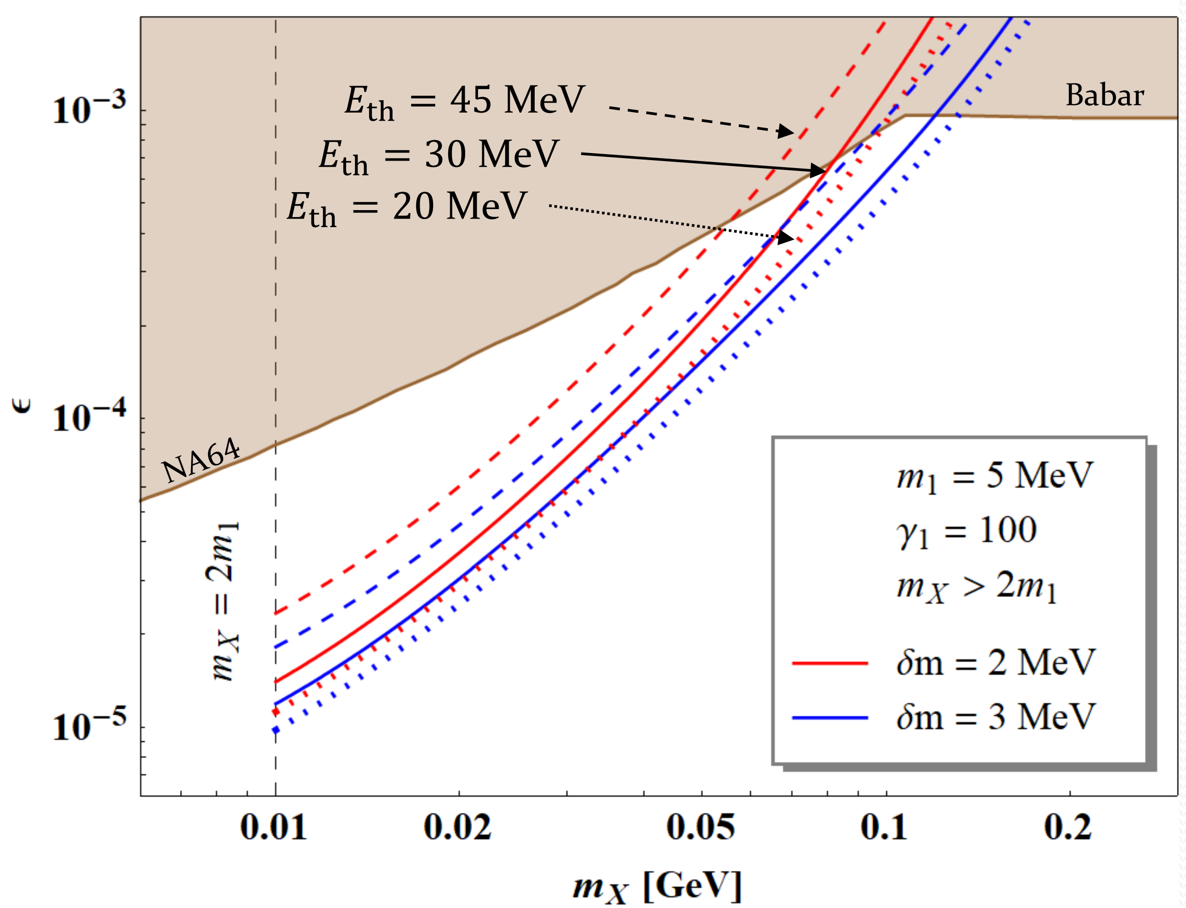
(cf. σ vs. m_{DM} in conventional WIMP searches)

relevant to signals with overlaid vertices or elastic scattering signals



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 $g_{12} = 1$ and vanishing BGs are assumed.
- Three different possible threshold values are studied.



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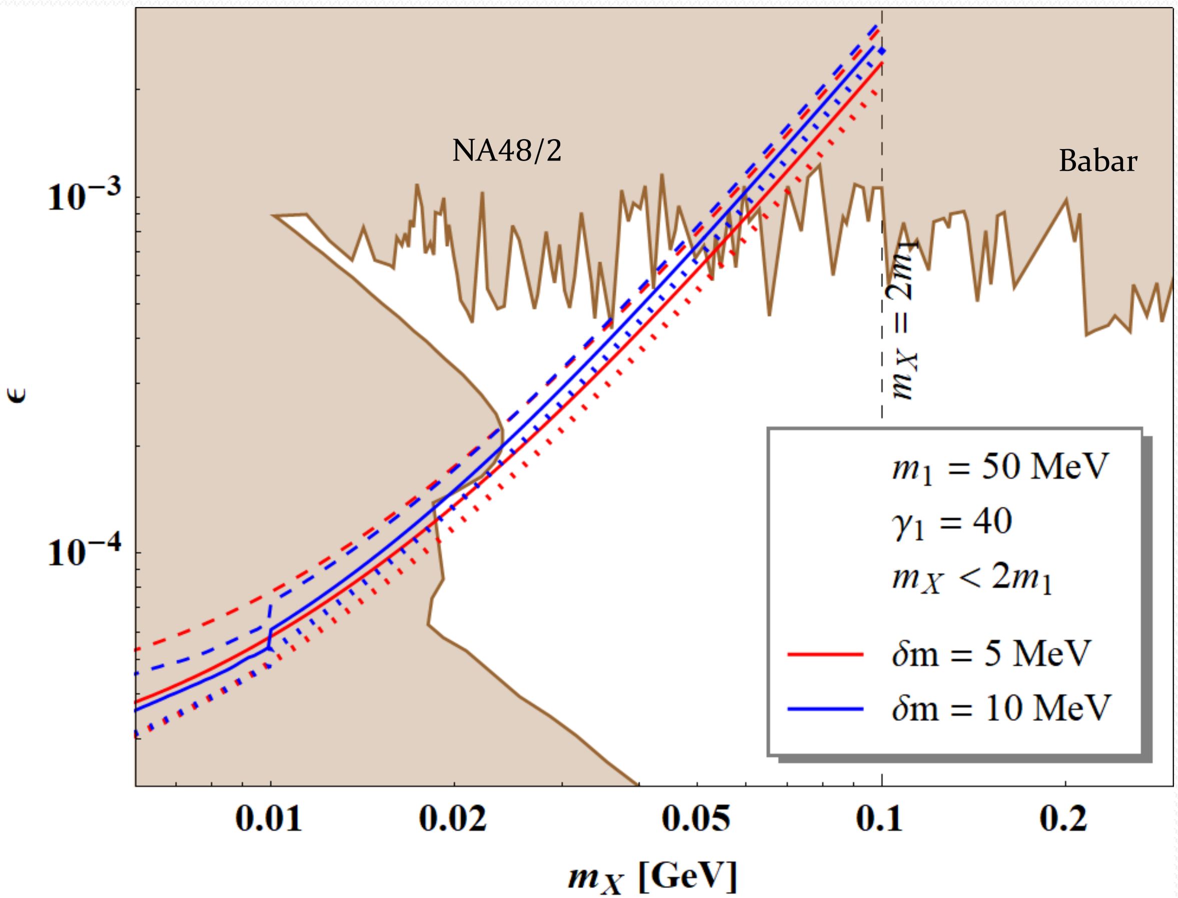

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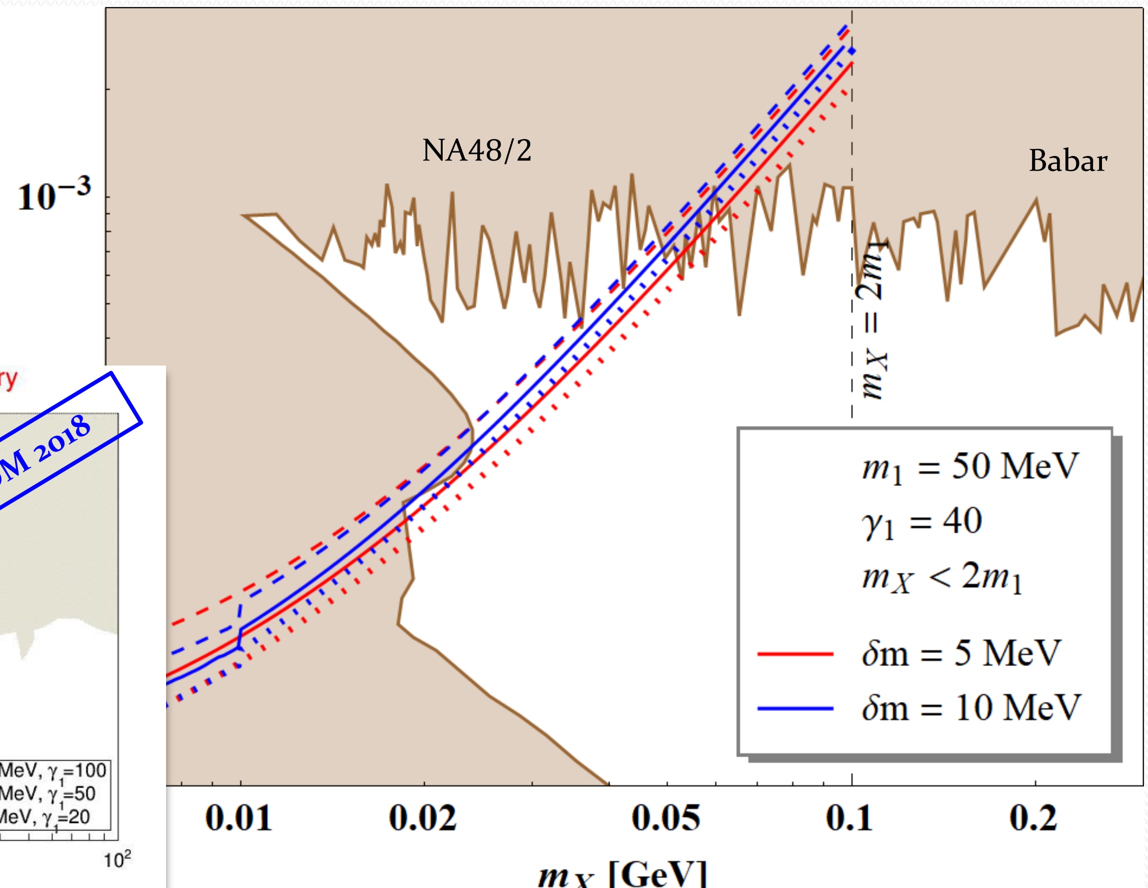
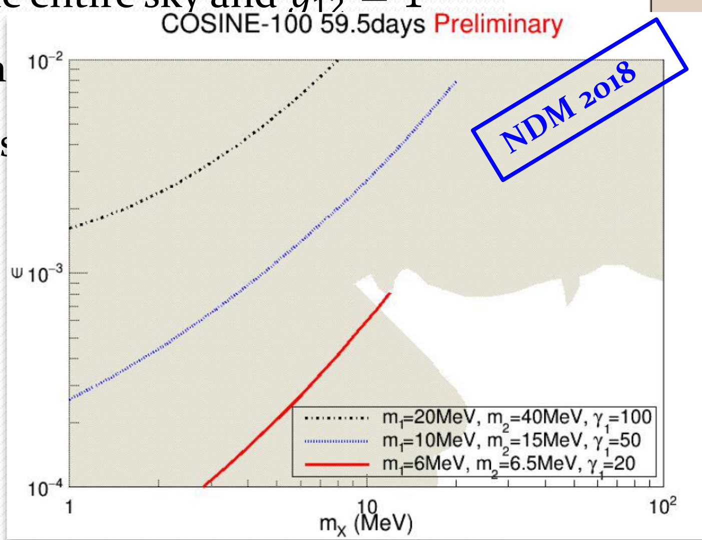
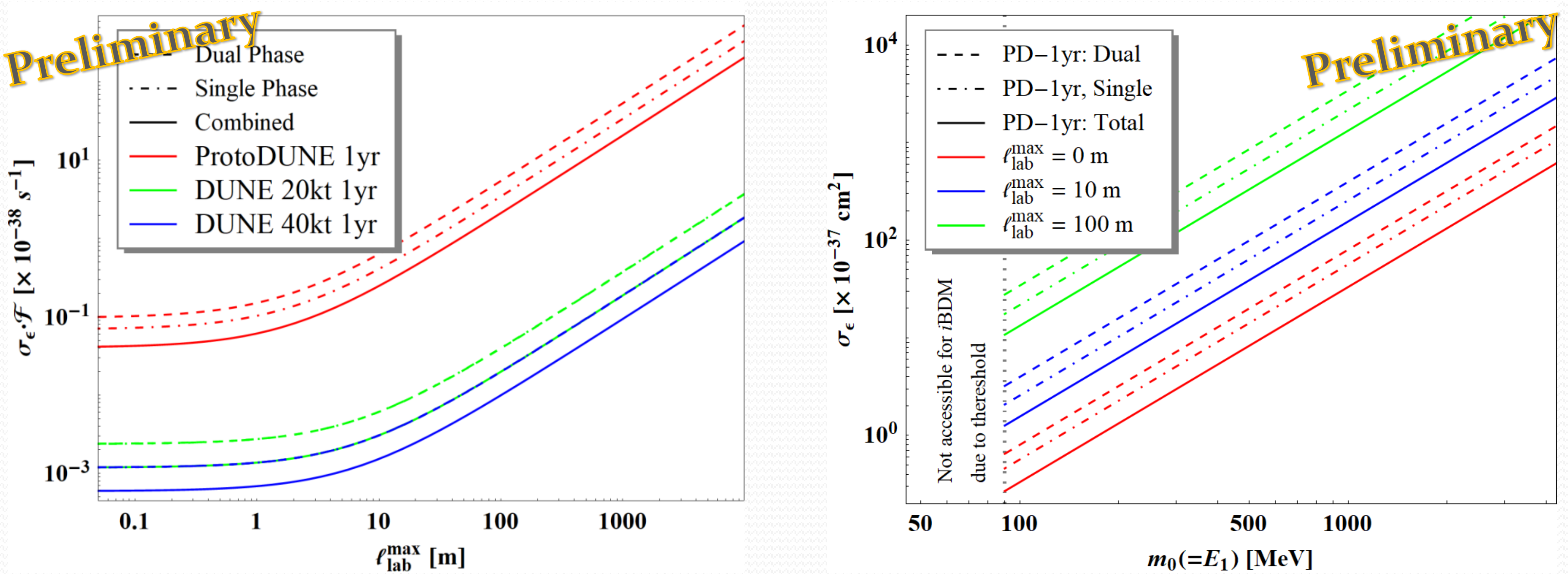


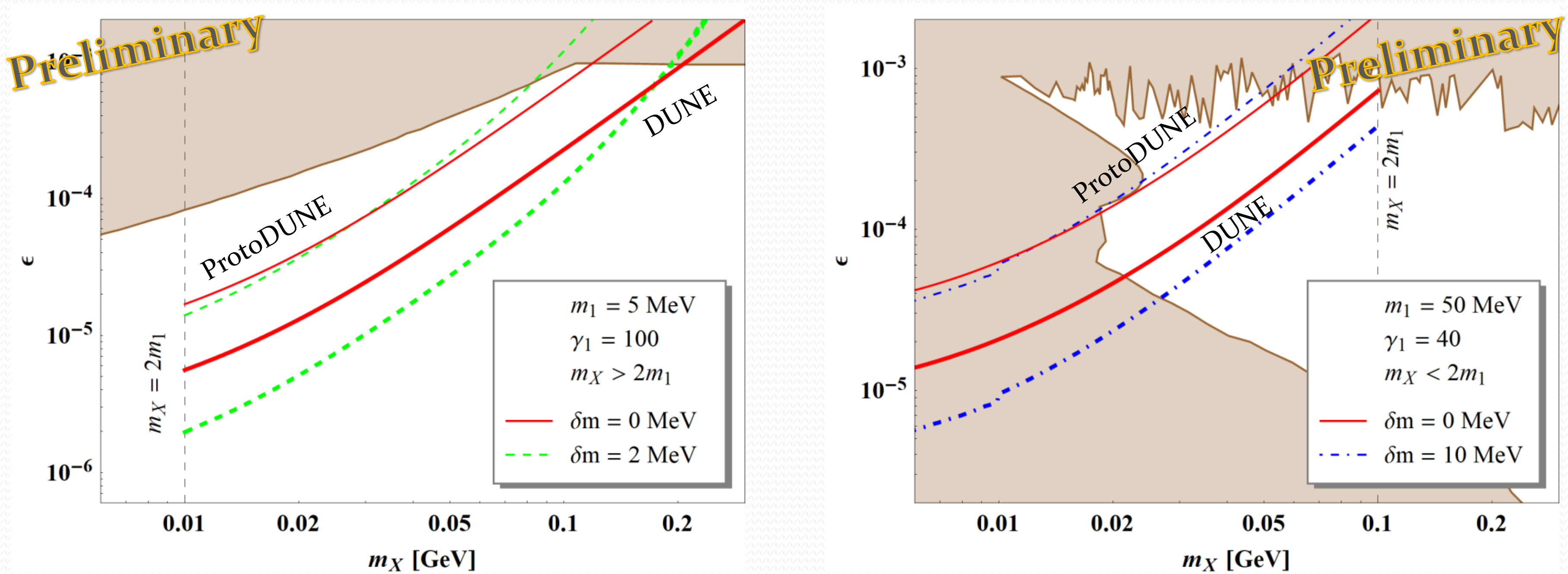


*i*BDM and eBDM Prospects at DUNE



- Comparison between ProtoDUNE 1-year vs. DUNE 10 kt + 10 kt, DUNE 20 kt + 20 kt 1-year with all-sky data for *i*BDM (left panel) and eBDM (right panel) signatures
- The limit for *i*BDM (eBDM) becomes lower by ~2 (~1) orders of magnitude at DUNE due to background-free analysis (large neutrino-induced background). ← Improvement by $V_{\rm Detector}$ for *i*BDM vs. $\sqrt{V_{\rm Detector}}$ for eBDM.

Probing Dark Photon Parameter Space



- Comparison between ProtoDUNE 1-year vs. DUNE 10 kt + 10 kt 1-year with all-sky data for invisible X decay (left panel) and visible X decay (right panel)
- *i*BDM achieves a wider coverage due to (almost) background-free analysis. ⇒ Searches for eBDM from point-like sources (e.g., Sun) are highly motivated as they also allow (almost) zero-background searches.

Conclusions and Outlook

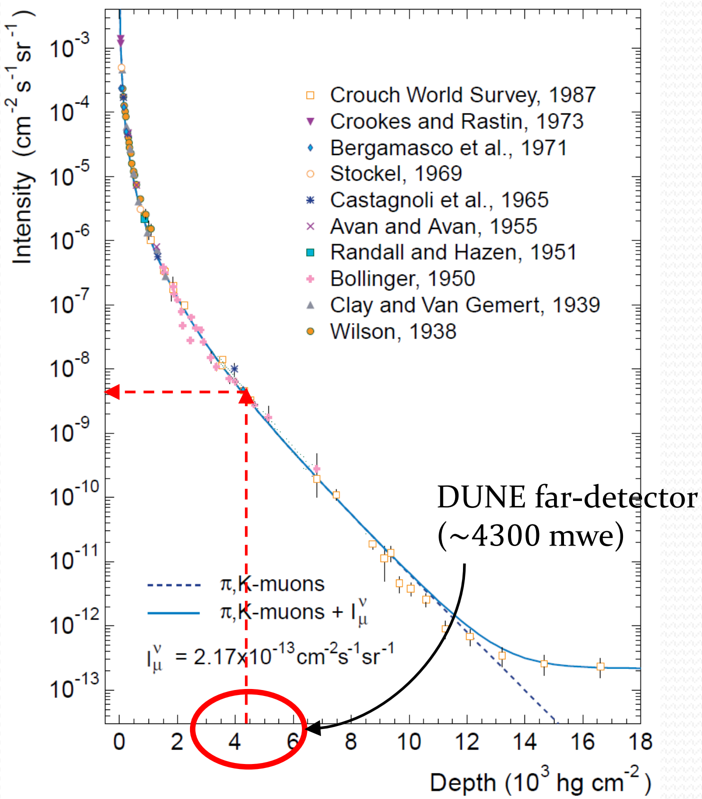
Scattering \ v_{DM}	Non-relativistic ($v_{DM} \ll c$)	Relativistic ($v_{DM} \sim c$)
elastic	Direct detection	**Boosted DM (eBDM)**
*in*elastic	inelastic DM (iDM)	**inelastic BDM (*i*BDM)**

- ❑ The boosted (light) DM search is **promising** and provides a **new direction** to study DM phenomenology.
- ❑ Theoretical/phenomenological studies have been actively conducted and in progress.
- ❑ These ideas can be tested in various **ongoing/projected experiments**.
  - ✓ Experimental studies have already begun, e.g. SK, COSINE-100, ProtoDUNE, ICARUS – Gran Sasso, …

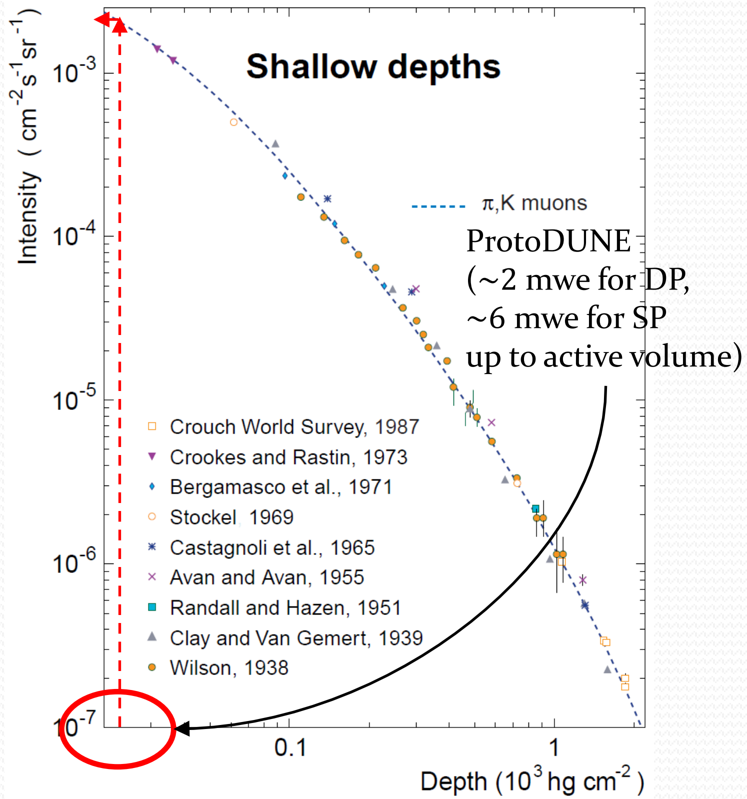
thank you !

Back-up

Potential Backgrounds: High Energy Muons



[Bugaev et al. (1998)]



❑ Expecting $\sim 10^6$ more muon flux at ProtoDUNE than that at the DUNE far-detector.

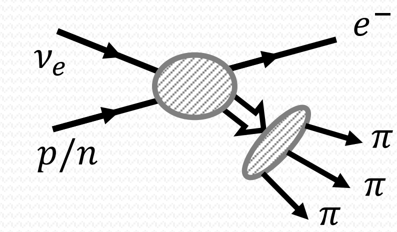
Potential Backgrounds: Neutrinos

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)]

$\sim$**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 > \sim$10 MeV.)

$\Rightarrow$ Potential background for elastic scattering signal events

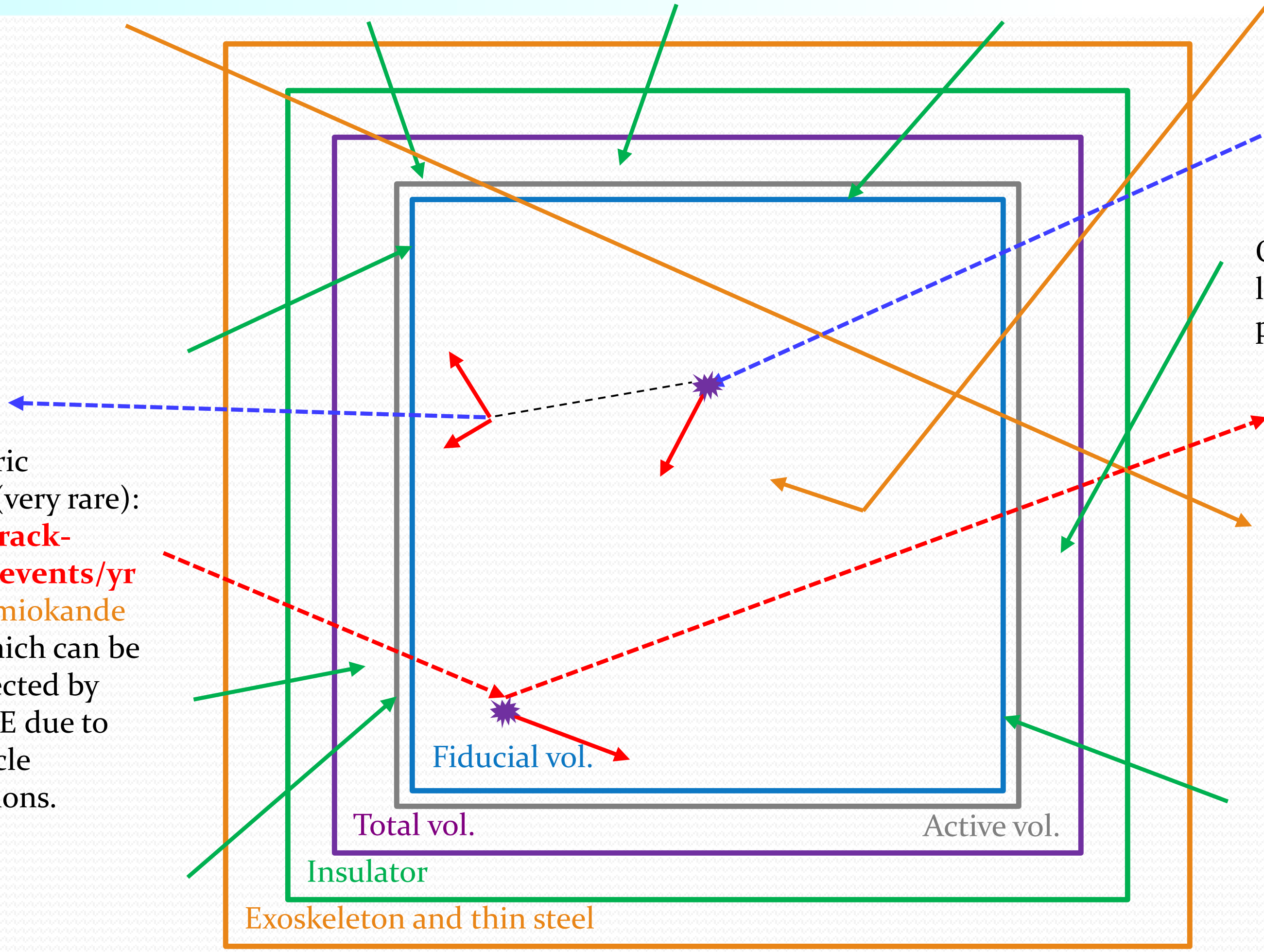
Multi-track candidates: **5.2** /yr/kt

$\Rightarrow$ Most extra tracks come from mesons which can be identified at ProtoDUNE.

$\Rightarrow$ Very likely to be background-free for inelastic scattering signal events

Cosmic Backgrounds: 1ms Snapshot at ProtoDUNE

Signal of interest

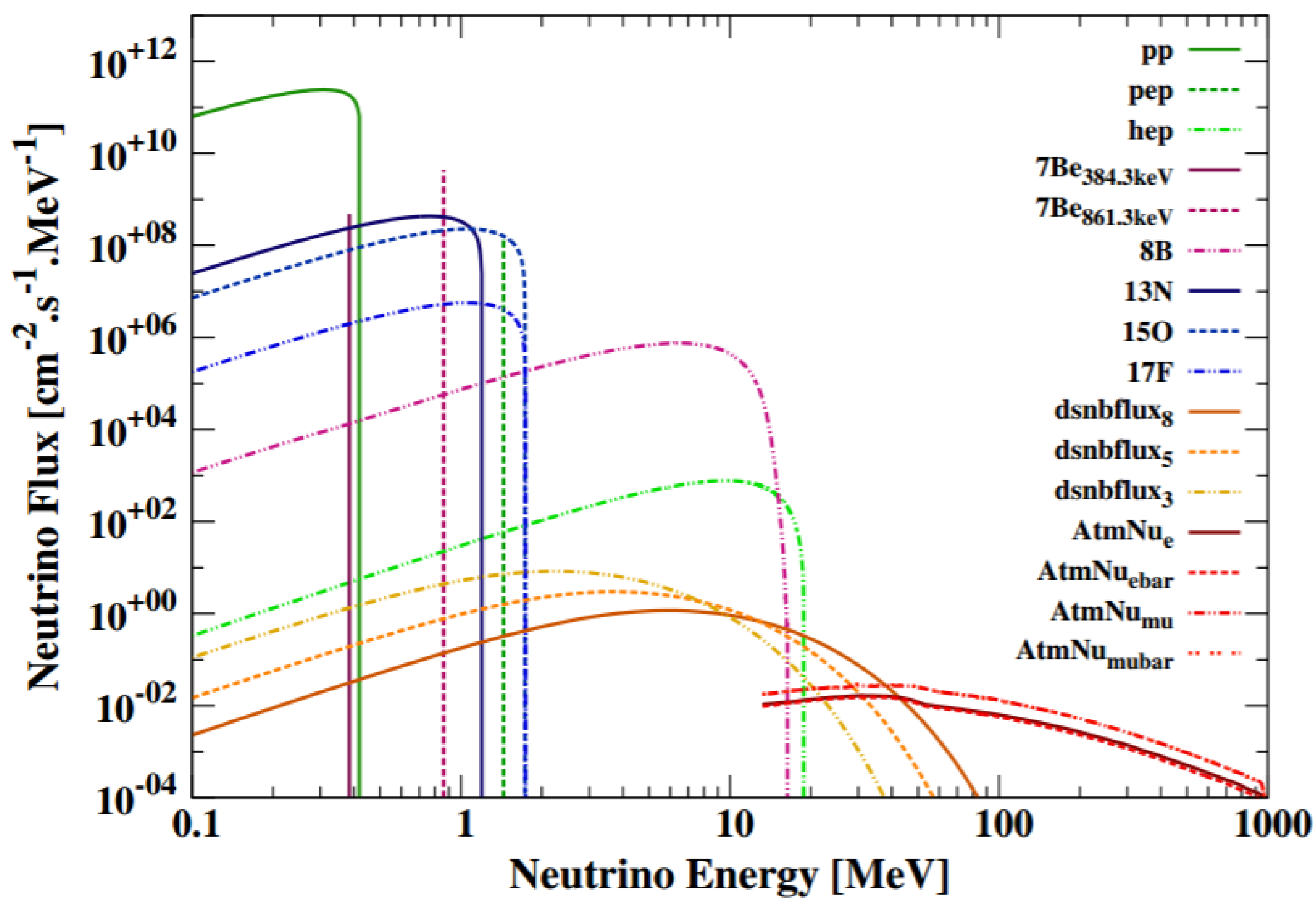


Quite a few low-energy particles

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.

Neutrino Fluxes



[Ruppin et al., (2014)]

eBDM Search at Super-K

[Super-K Collaboration, (2017)]

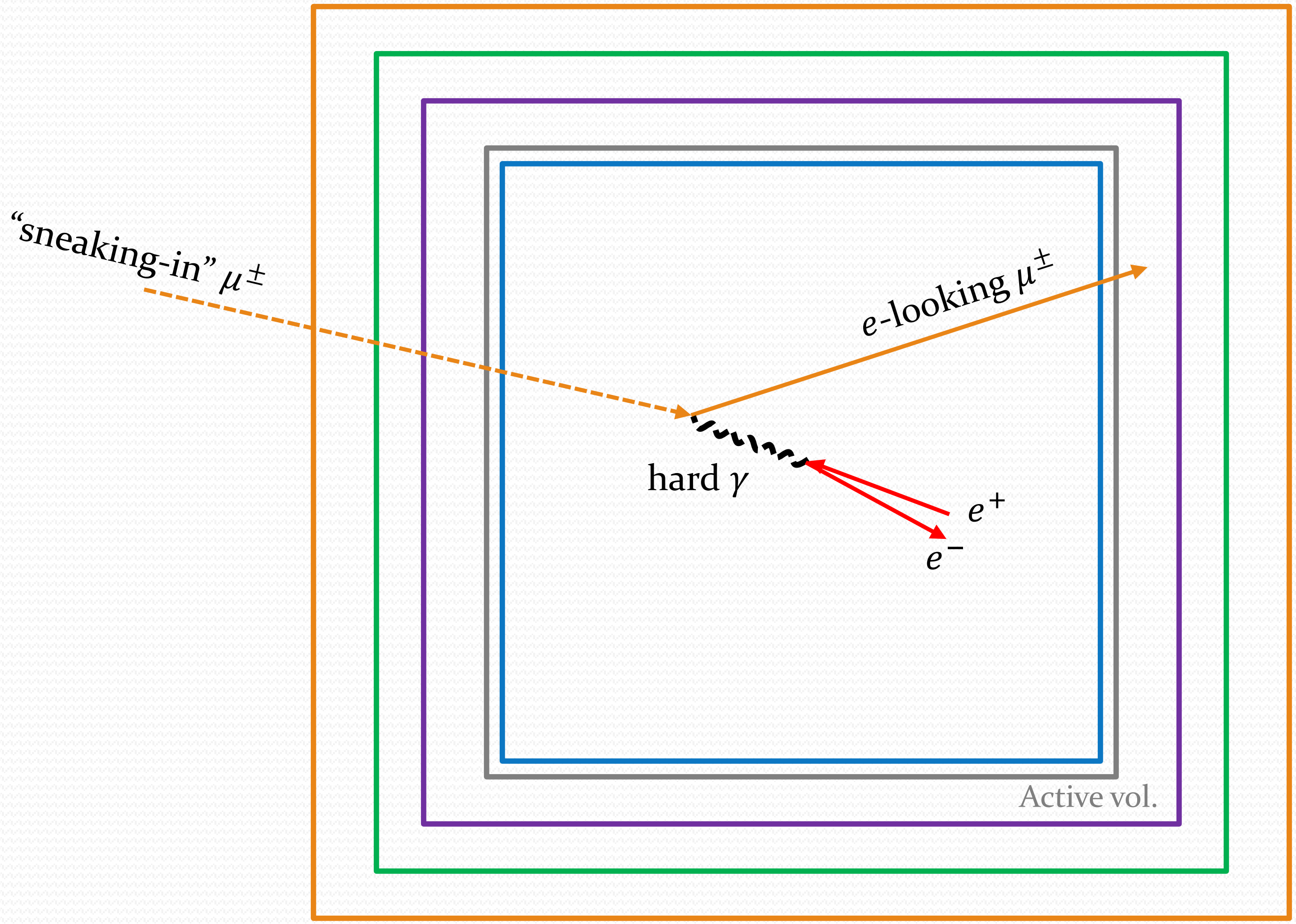
	100 MeV$< E_{vis} <$ 1.33 GeV			1.33 GeV $< E_{vis} <$ 20 GeV			$E_{vis} >$ 20 GeV		
	Data	ν-MC	ϵ_{sig}(0.5 GeV)	Data	ν-MC	ϵ_{sig}(5 GeV)	Data	ν-MC	ϵ_{sig}(50 GeV)
FCFV	15206	14858.1	97.7%	4908	5111.1	93.8%	97	107.5	84.9%
& single ring	11367	10997.4	95.8%	2868	3162.8	93.3%	53	68.2	82.2%
& e-like	5655	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.

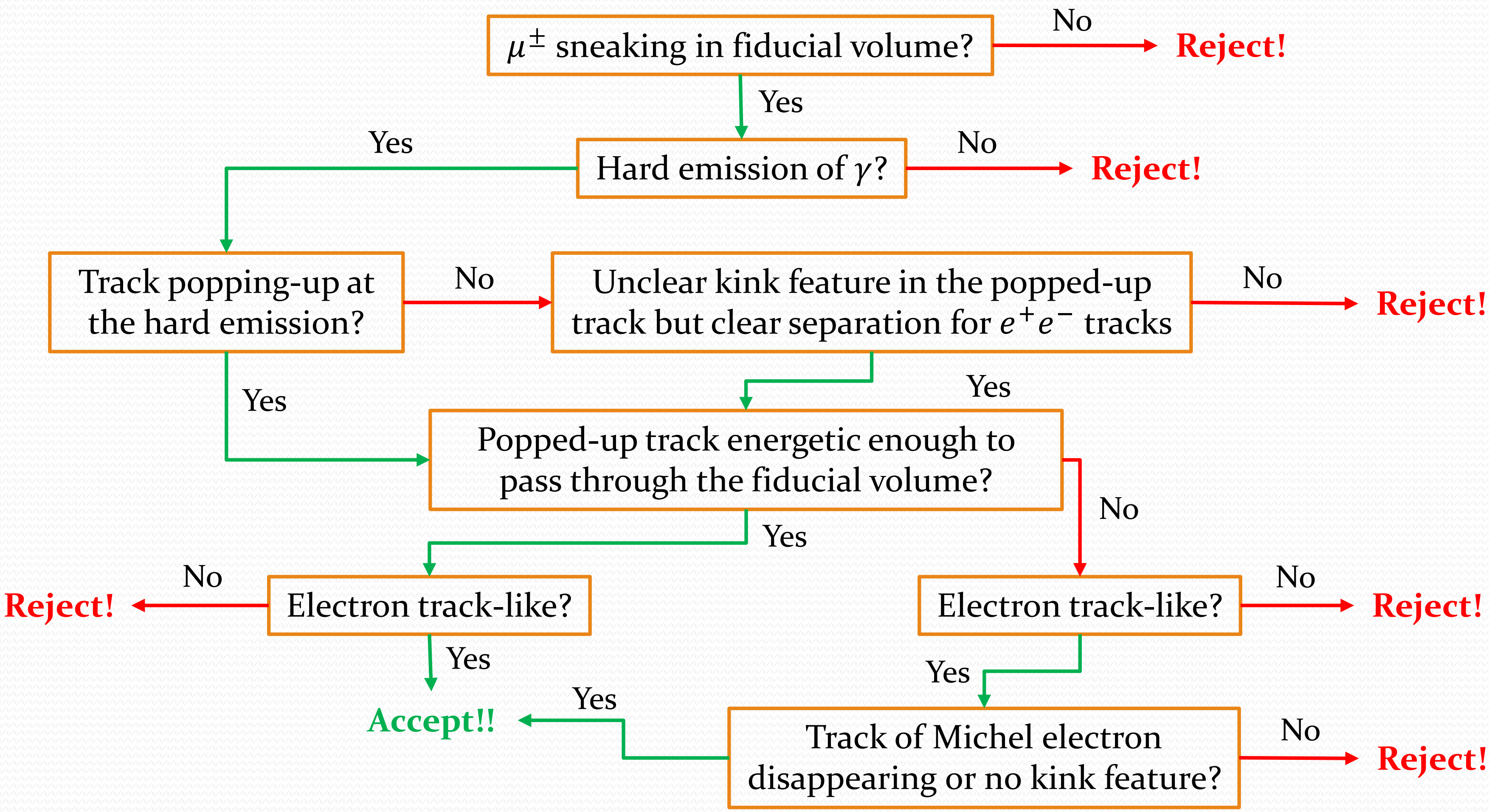
High threshold energy

Single-ring-like objects only

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]

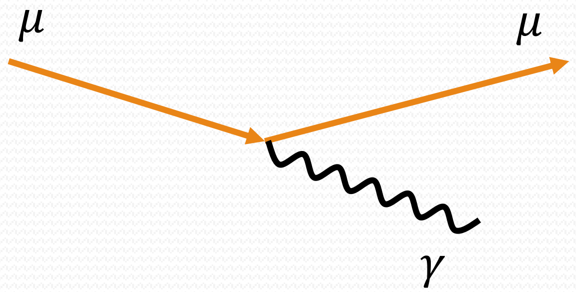
  $\Rightarrow$ 0.09% missed with 2016 data (lower with 2017 data, not public yet)

- "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

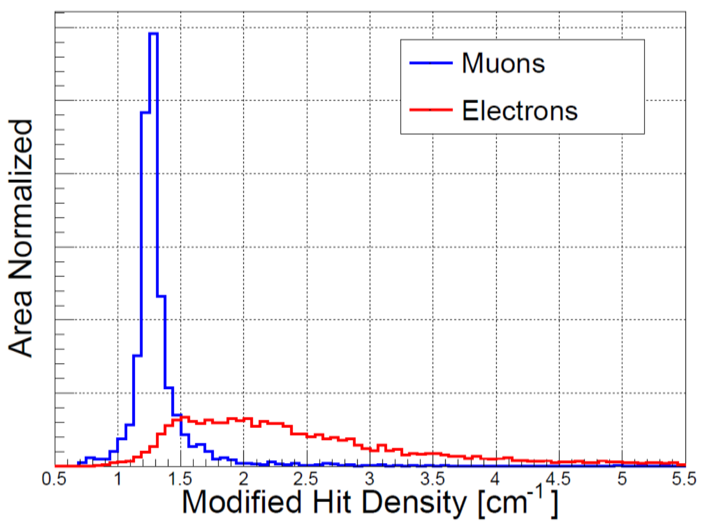


$$\sim \frac{\alpha}{\pi} \approx 2 \times 10^{-3}$$

Phase-space suppression factor

Electron-faking Muon

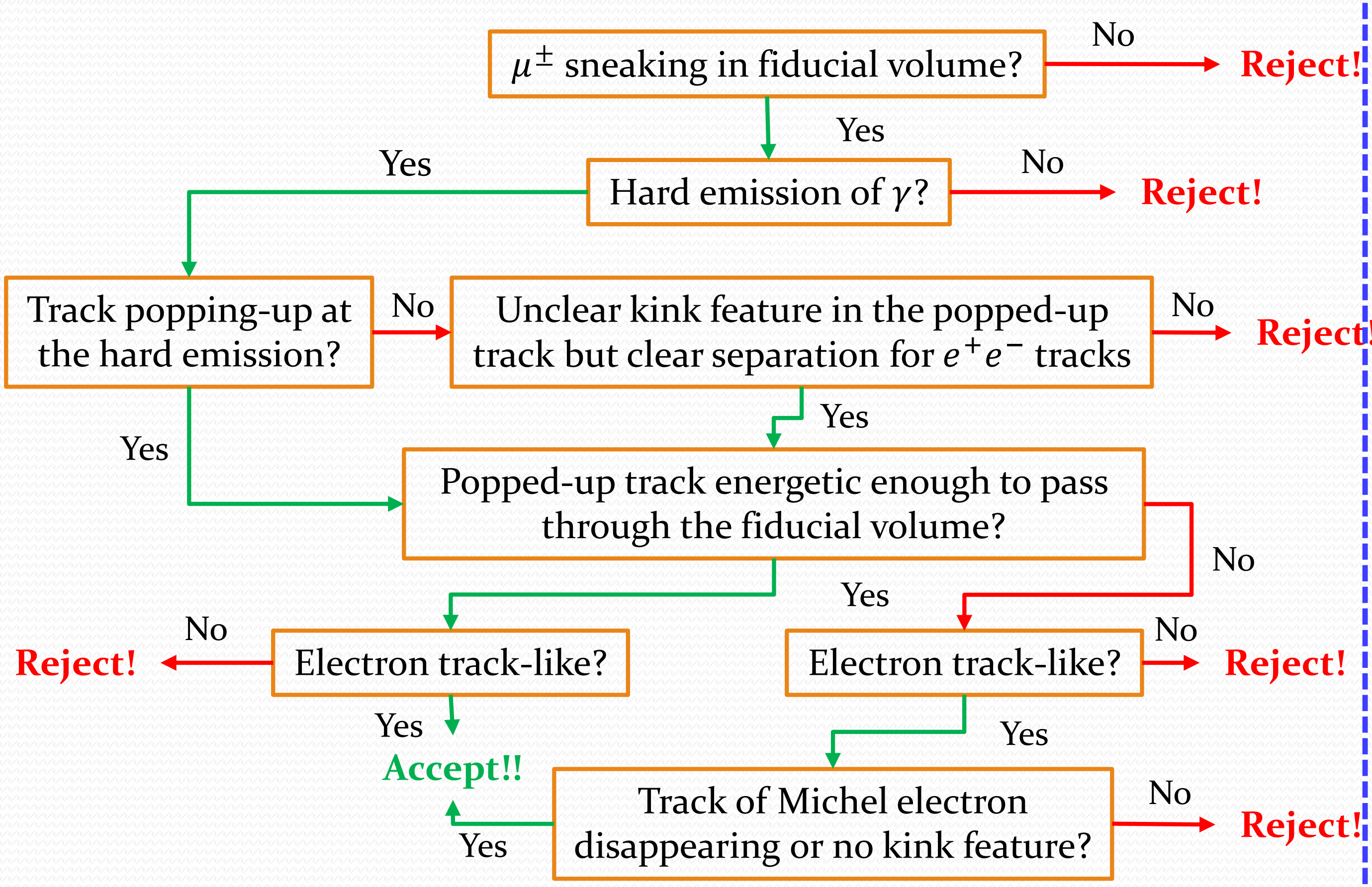
- All known studies simply reporting a negligible rate of muons misidentified as electrons, but how negligible?
- A hint from an example study [ArgoNeuT Collaboration, "First Observation of Low Energy Electron Neutrinos in a Liquid Argon Time Projection Chamber", arXiv:1610.04102]



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



$\sim 4 \cdot 10^{11}/\text{yr}$

$\times\, 10^{-3} \Rightarrow 4 \cdot 10^{8}/\text{yr}$

$\times\, 2 \cdot 10^{-3} \Rightarrow 8 \cdot 10^{5}/\text{yr}$

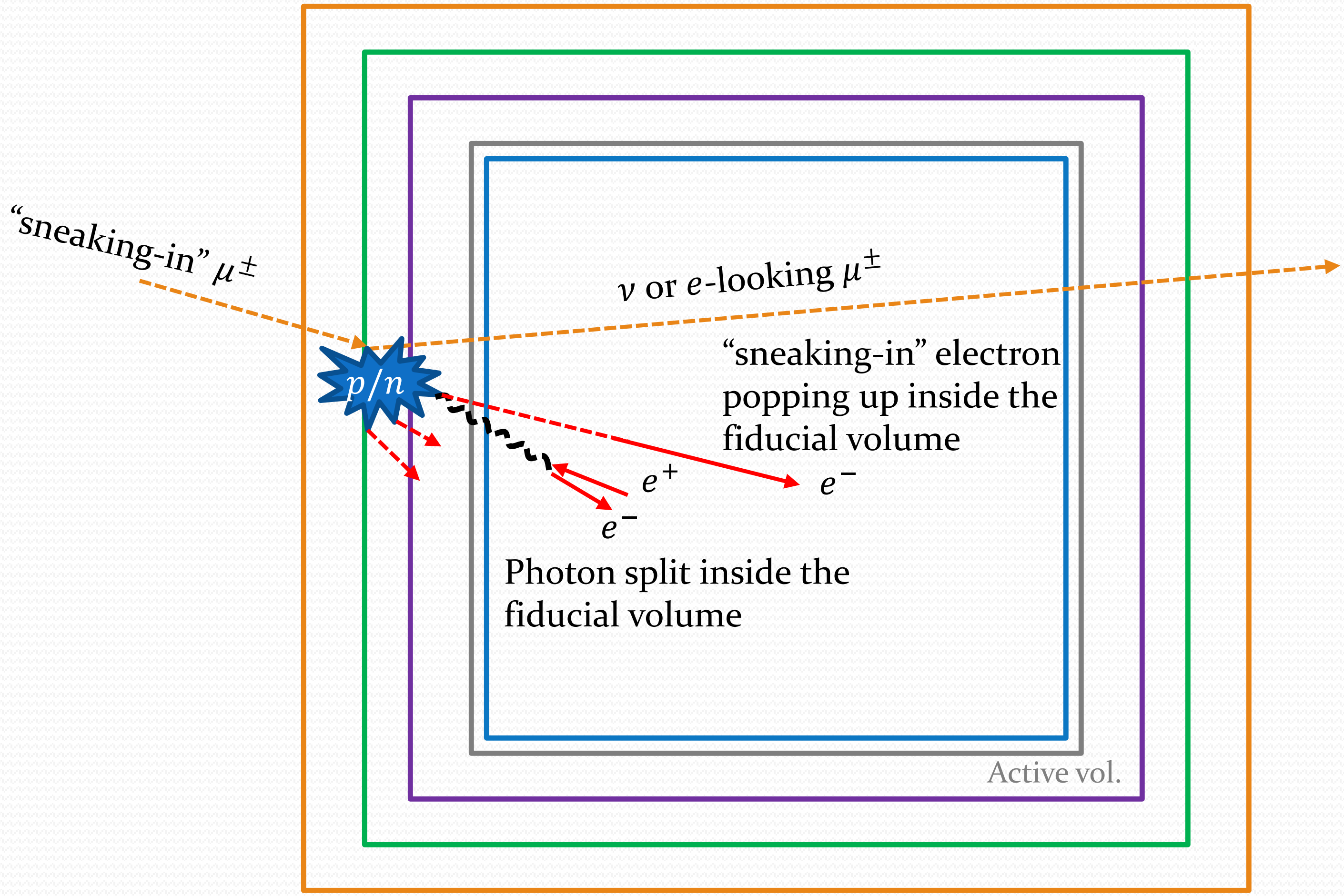
Required!

$\times\, 1.3 \cdot (10^{-4} - 10^{-2})$
$\Rightarrow 10^{2} - 10^{4}/\text{yr}$

$\times\, 10^{-2}$
$\Rightarrow 10^{0} - 10^{2}/\text{yr}$

$\sqrt{B} < 10$

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