Boosted Dark Matter & Surface Detectors

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D. Kim, K. Kong, **JCP**, S. Shin [arXiv: 1804.07302]

THE 14TH INTERNATIONAL WORKSHOP ON THE DARK SIDE OF THE UNIVERSE

DSU 2018

25 - 29 June 2018 LAPTh, Annecy, France

LAPTh

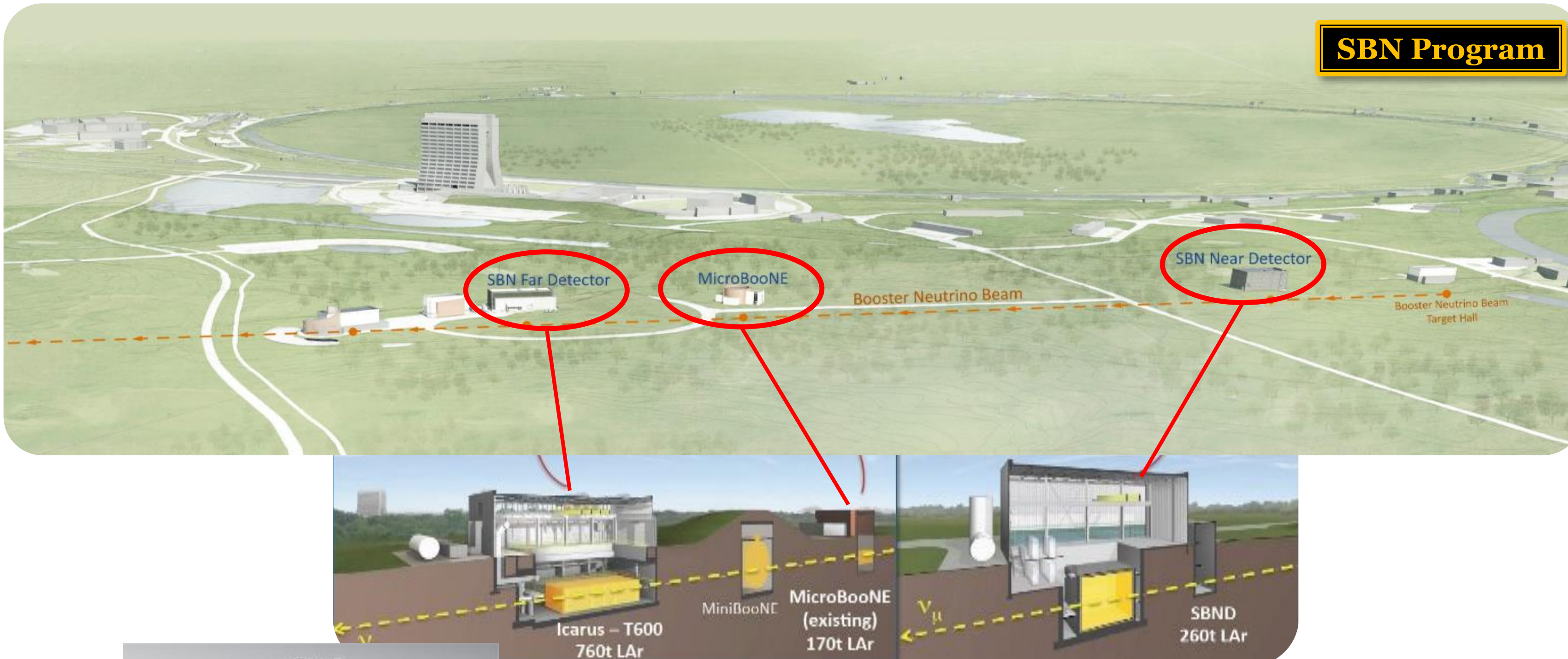
June 28 (2018)

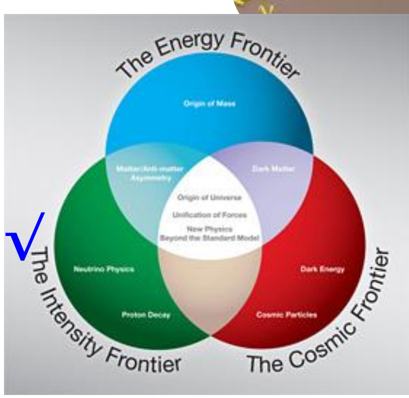
Surface ν Detectors

Physics Motivation?

Surface ν Detectors: SBN

❖ Short-Baseline Neutrino (SBN) Program @ Fermilab

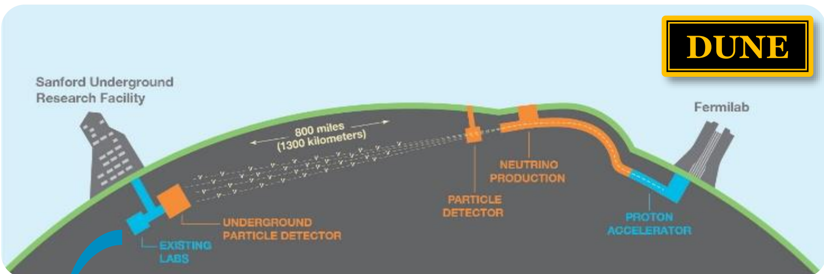




- ✓ Physics @ SBN: ν oscillation, sterile ν, etc.
- ✓ E spectrum & flavor of ν's produced by the Booster Neutrino Beam
- ✓ Development of the LAr-TPC technology for DUNE

Surface ν Detectors: ProtoDUNE

❖ ProtoDUNE: a prototype of the Deep Underground Neutrino Experiment (DUNE) @ CERN



❖ SP: single-phase

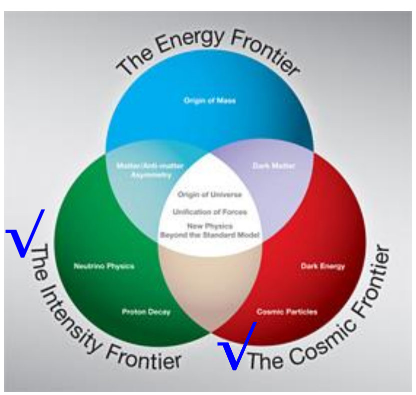
❖ DP: dual-phase

4 ×10 kt

0.3+0.2 kt

<Originally>

✓ Physics @ DUNE: neutrino, BSM, etc.

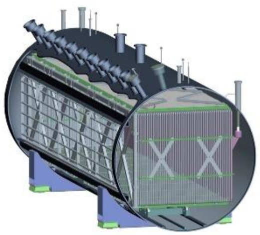


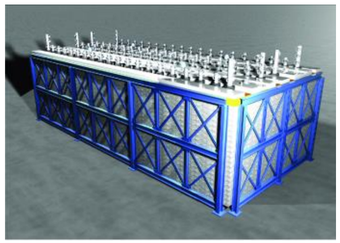
✓ To test the long-term stability & operation

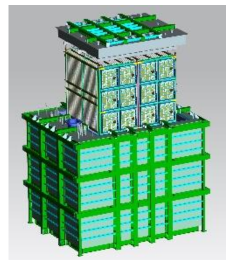
✓ To calibrate beam & cosmic-ray responses

Surface ν Detectors: Status

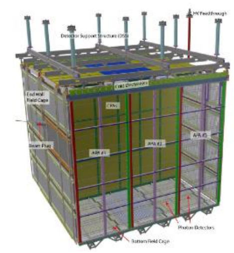
SBN Program

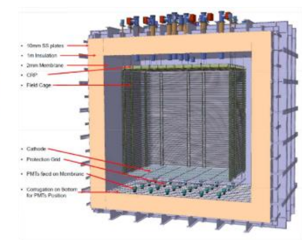






ProtoDUNE





Detector	Target material	Active volume $w \times h \times l$ [m^3]	Active volume mass [kt]	Fiducial volume mass [kt]	Depth	Electron $E_{\rm th}$ [MeV]	Electron $\theta_{\rm res}$
MicroBooNE	LArTPC	$2.56 \times 2.33 \times 10.37$	0.089	0.055	$\sim$ 6 m underground	$\mathcal{O}(10)$	$\mathcal{O}(1^\circ)$
ICARUS	LArTPC	$2.96 \times 3.2 \times 18$ ($\times 2$)	0.476	$\sim$ 0.3	$\sim$ 6 m underground	$\mathcal{O}(10)$	$\mathcal{O}(1^\circ)$
SBND	LArTPC	$4 \times 4 \times 5$	0.112	$\sim$ 0.07	$\sim$ 6 m underground	$\mathcal{O}(10)$	$\mathcal{O}(1^\circ)$
ProtoDUNE SP	LArTPC	$3.6 \times 6 \times 7$ ($\times 2$)	$\sim$ 0.42	$\sim$ 0.3	on the ground	$\sim$ 30	$\sim 1^\circ$
ProtoDUNE DP	LArTPC	$6 \times 6 \times 6$	$\sim$ 0.3	$\sim$ 0.21	on the ground	$\sim$ 30	$\sim 1^\circ$

- ✓ MicroBooNE: on-going since July 2015 (BNB: operational since October 2015)
- ✓ ICARUS: planned to start of operation in 2019
- ✓ SBND: planned to start of operation in 2019/2020
- ✓ ProtoDUNE: operation from September 2018 & now planned to **take cosmic-origin data for new physics searches**

Other Physics Motivation?

Any physics potential with the SBN/ProtoDUNE detectors,

especially BSM physics?

Other Physics Motivati… n?

Any physics potenti … DUNE detectors,

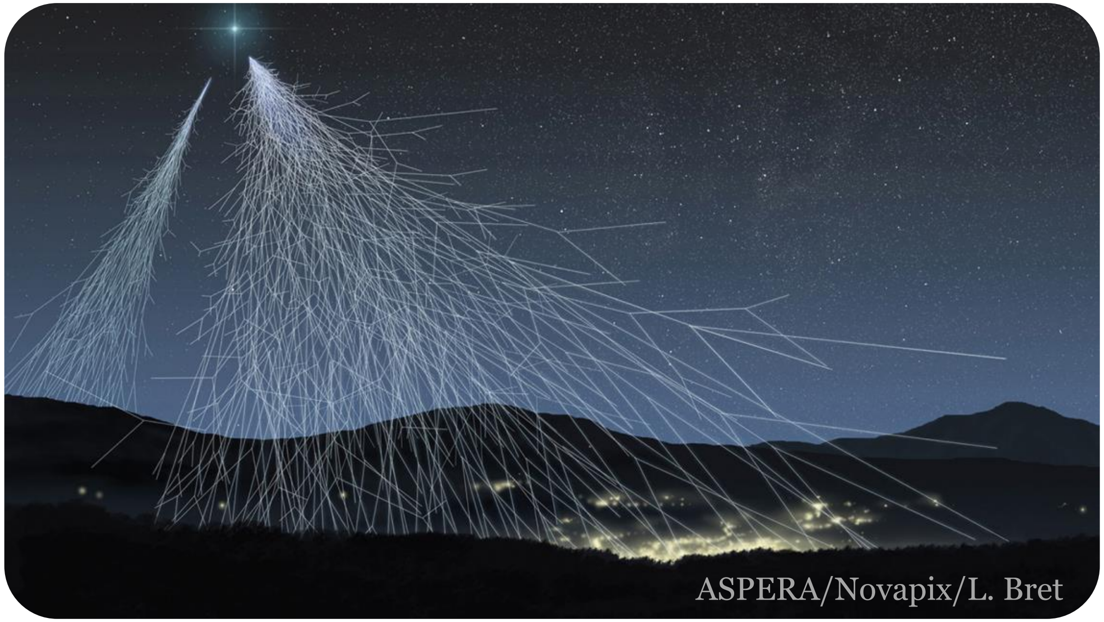
… physics?

Timely & Highly Motivated!

Surface ν Detectors: Common Belief

❖ Huge amount of backgrounds (mainly) due to their location (almost on the ground)

➔ Signal events would get buried inside the huge cosmic backgrounds.



Surface ν Detectors: Common Belief

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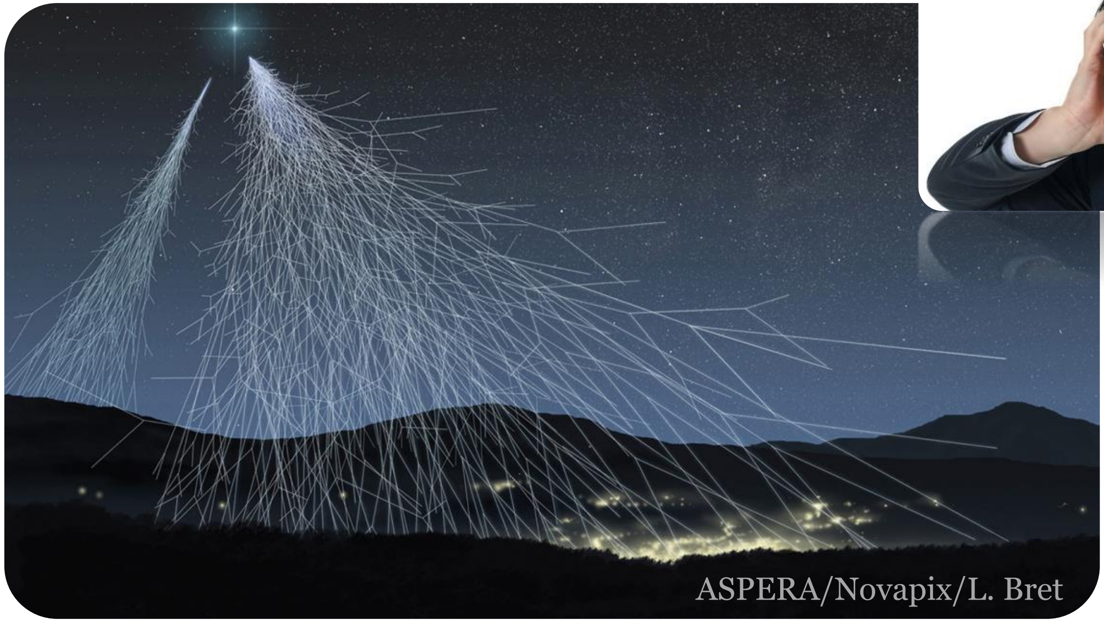
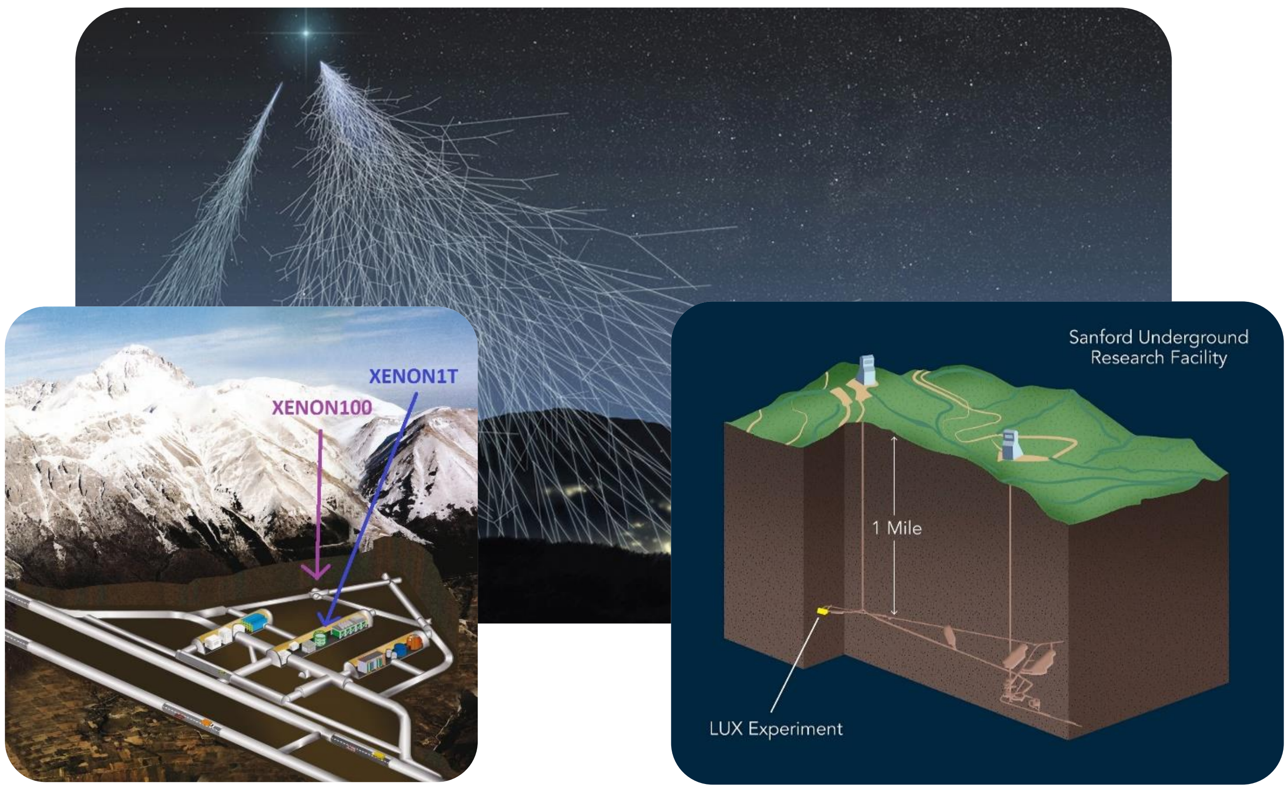
➔ Search for cosmic-origin new physics signal @ surface detectors is hopeless.



Surface ν Detectors: Common Belief

- Huge amount of backgrounds (mainly) due to their location (almost on the ground)
  - ➔ Signal events would get buried inside the huge cosmic backgrounds.
  - ➔ Search for cosmic-origin new physics signal @ surface detectors is hopeless.
  - ➔ Solution: Installing detectors deep under the ground!



Surface ν Detectors: New Approach

- ❖ Signals leaving appreciable tracks: the source direction is inferred from the track. (due to good detector performance: positon/angular/energy resolution, etc.)

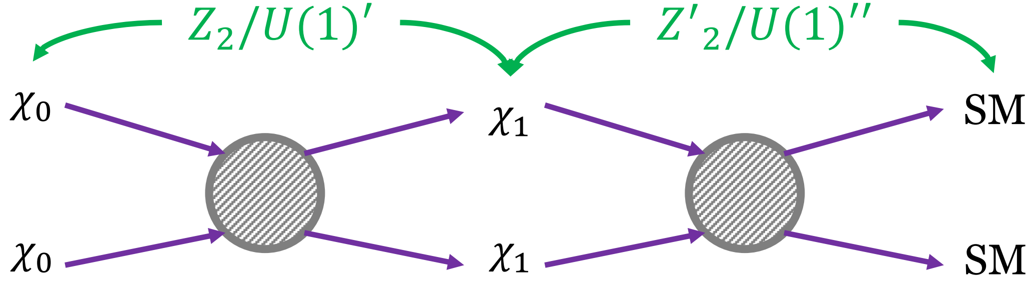
  ➔Restricting to events coming through the Earth from the opposite side of the detector location. (Similar to up-going *ν* searches @ SK, IceCube, NOvA, etc)

  ➔ Potential backgrounds in that direction are significantly suppressed while signals are intact. (→ will be discussed in detail, soon!)

- ❖ A signal with many unique features (e.g. *i*BDM): Possible to reject cosmic background events sufficiently ➔ **See Doojin Kim's talk!**

Two-component BDM Scenario

G. Belanger, **JCP** (2011)



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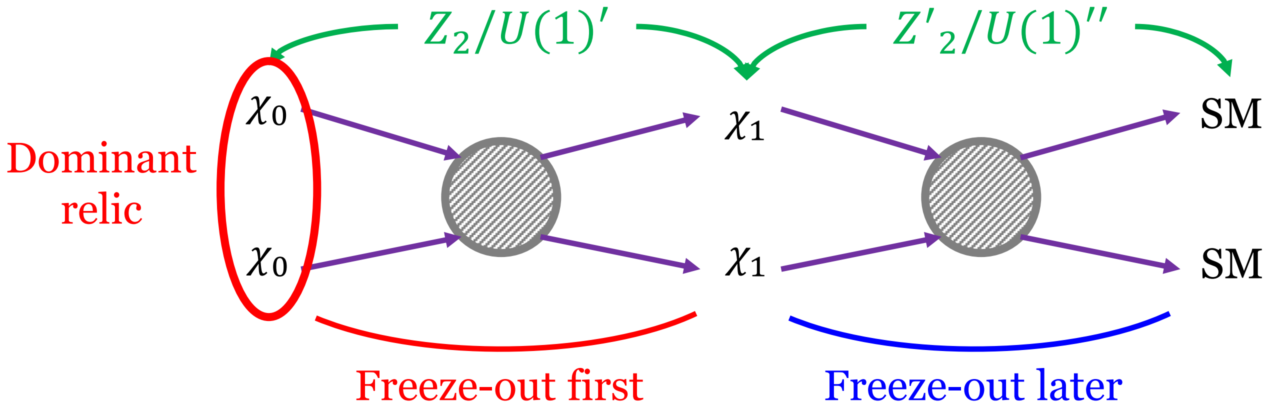

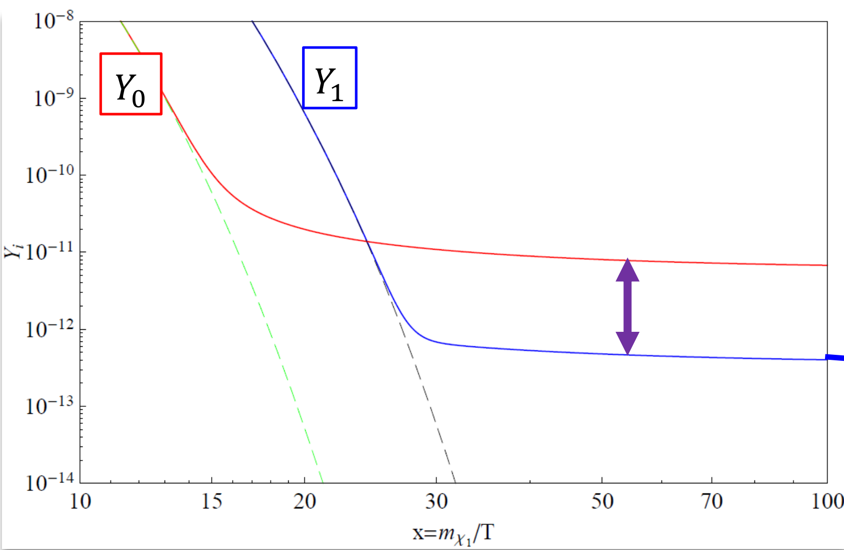

"**<u>Assisted Freeze-out</u>**" Mechanism

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

χ_1: Negligible, Non-relativistic relic

Two-component BDM Scenario

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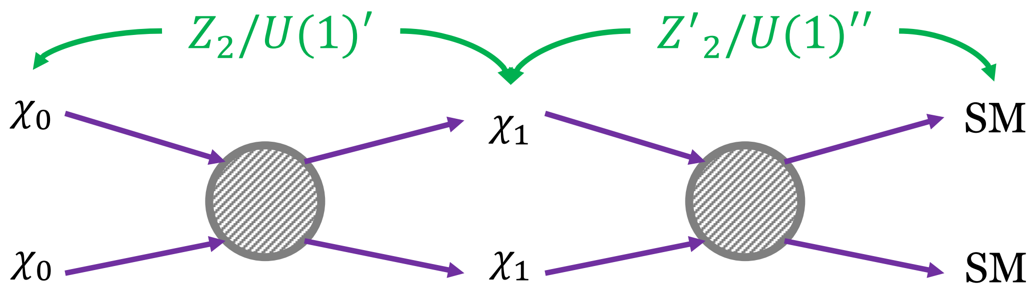
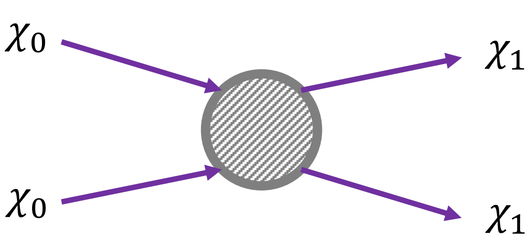


$\chi_0\chi_0 \to \chi_1\chi_1$ (current universe): **Relativistic!!** ($\gamma_1 = m_0/m_1$)

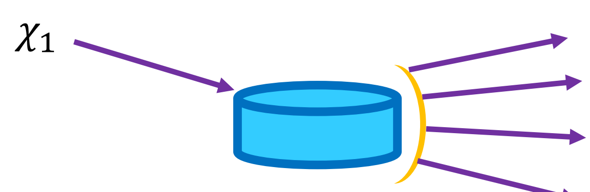
(Note that relic χ_1 is non-relativistic.)



(Galactic Center)

becomes boosted

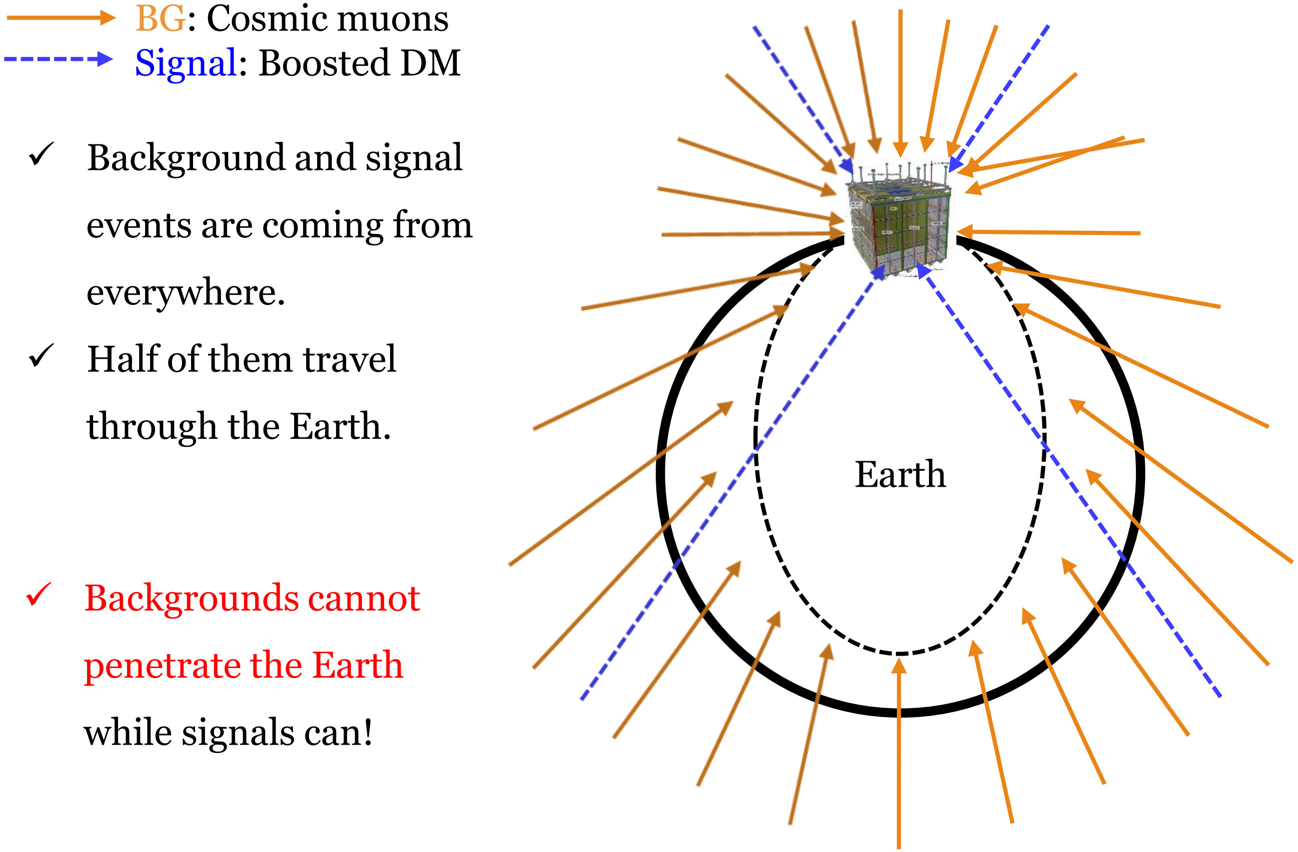
($\gamma_1 = m_0/m_1$)



(Laboratory)

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

Earth Shielding



- ✓ Background and signal events are coming from everywhere.
- ✓ Half of them travel through the Earth.

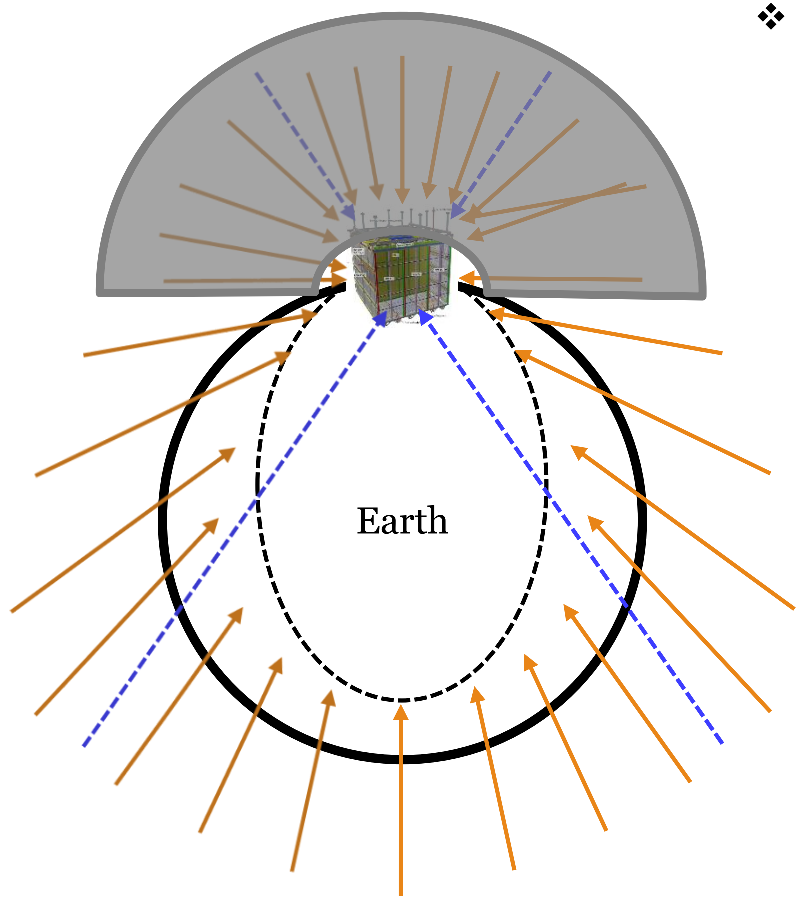
- ✓ Backgrounds cannot penetrate the Earth while signals can!

Earth Shielding

BG: Cosmic muons
Signal: Boosted DM

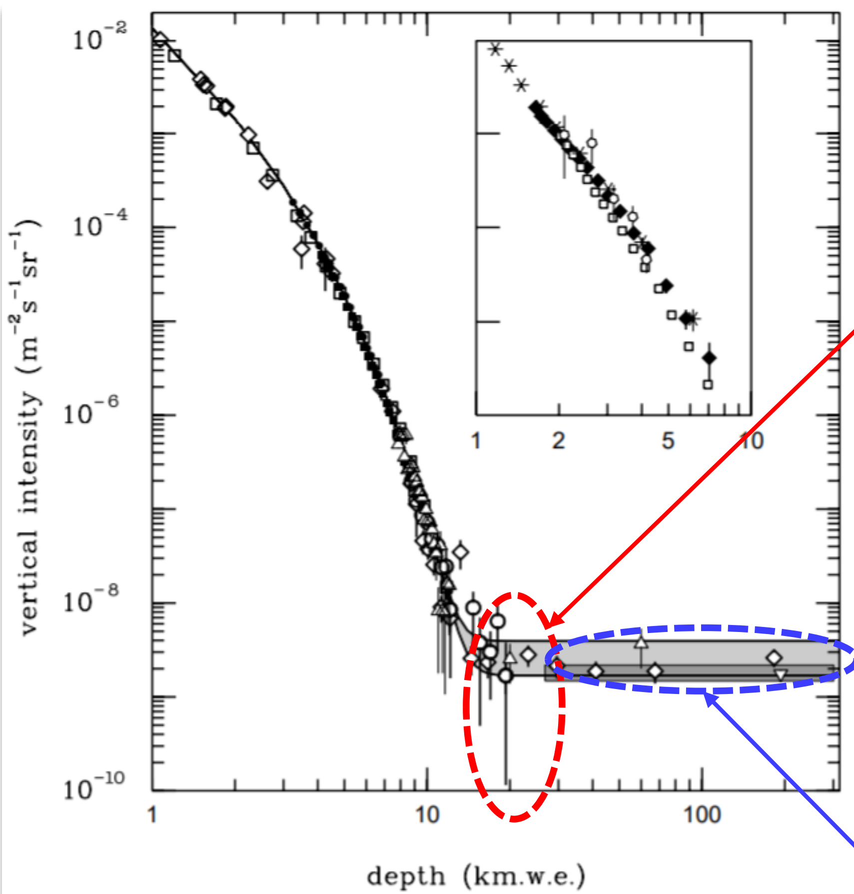
- ✓ Background and signal events are coming from everywhere.
- ✓ Half of them travel through the Earth.

- ✓ Backgrounds cannot penetrate the Earth while signals can!



- ❖ Accept only **events traveling through the Earth** (i.e., coming out of the bottom surface) at the price of half statistics (for a cumulatively isotropic signal);
  direction inferred from recoil track
  ➔ Essentially, **no cosmic-origin BGs** except Atm neutrino BG (cf. observation of upward-muons induced by muon neutrinos created by DM annihilation [NOvA Collaboration, in progress])

Muon Flux inside the Earth



[Particle Data Group (2015)]

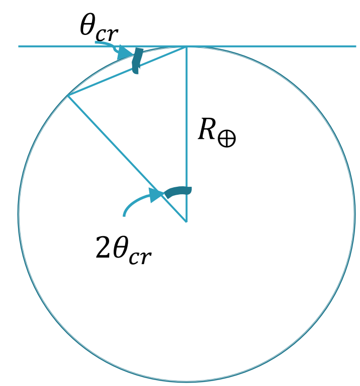
Flattened by neutrino-genic muons

- N_μ at sea level is $\sim 100\ \mathrm{m^{-2}s^{-1}sr^{-1}} = 3 \times 10^9\ \mathrm{m^{-2}yr^{-1}sr^{-1}}$. [Particle Data Group (2015)]
- N_μ at 20 km.w.e. ≈ 7 km below sea level is $\sim 10^{-9}\ \mathrm{m^{-2}s^{-1}sr^{-1}}$, i.e., suppressed by a factor of $\sim 10^{11}$.

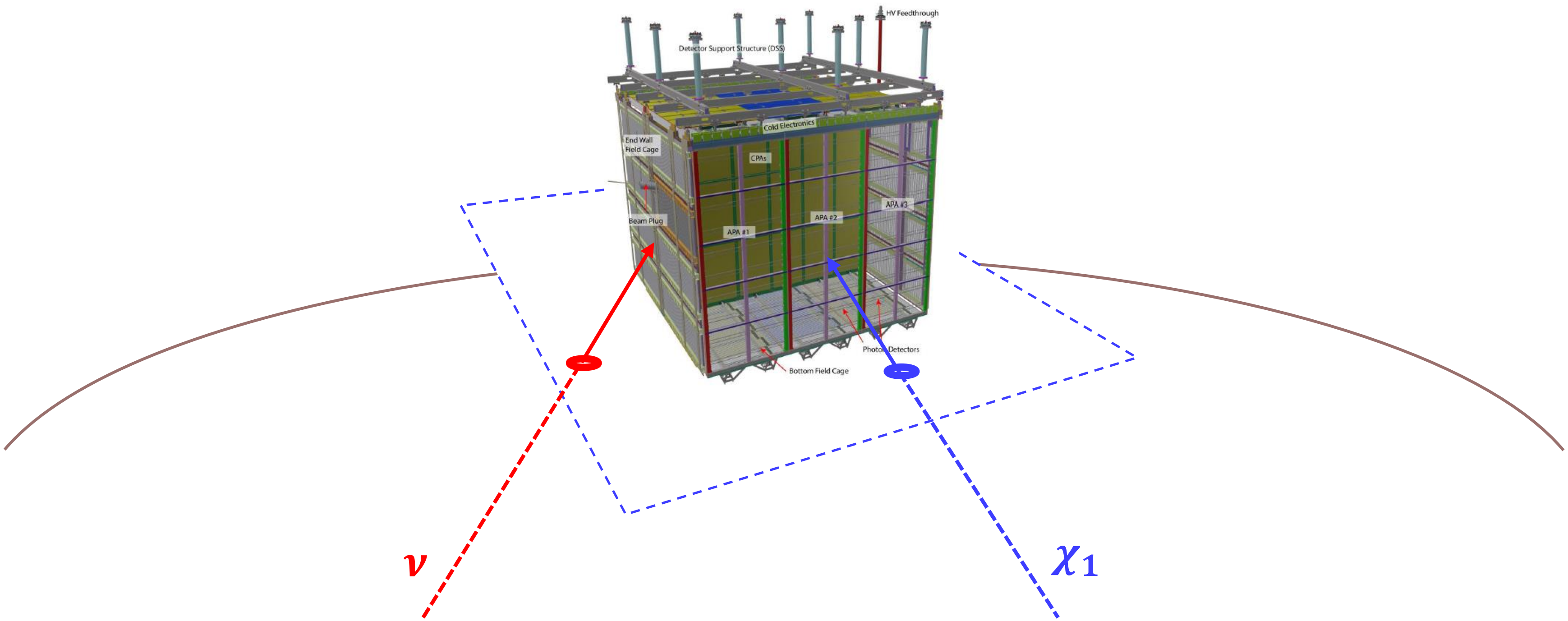
  ➔ (Potential) muon-induced BG is negligible for muons incident at $\theta > \theta_{cr}$.

$$\theta_{cr} \approx \frac{7\ \mathrm{km}}{2R_\oplus} \approx 0.03^\circ$$

Almost horizontal plane



Effective 1yr Data Collection



~D_f 40 neutrino-induced *e*-like, single-track events/yr/kt

$\mathcal{F}_{\chi_1} \sim D_f \, 3 \times (10^1 - 10^6)\text{cm}^{-2}\text{yr}^{-1}$

D

D_f: effectively a certain fraction of day when the Earth Shielding effect can be utilized, with respect to the source core.
(e.g. for Sun: effectively, half year ➔ D_f=1/2)

BDM Detection

❖ Flux of boosted χ_1 around the Earth

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

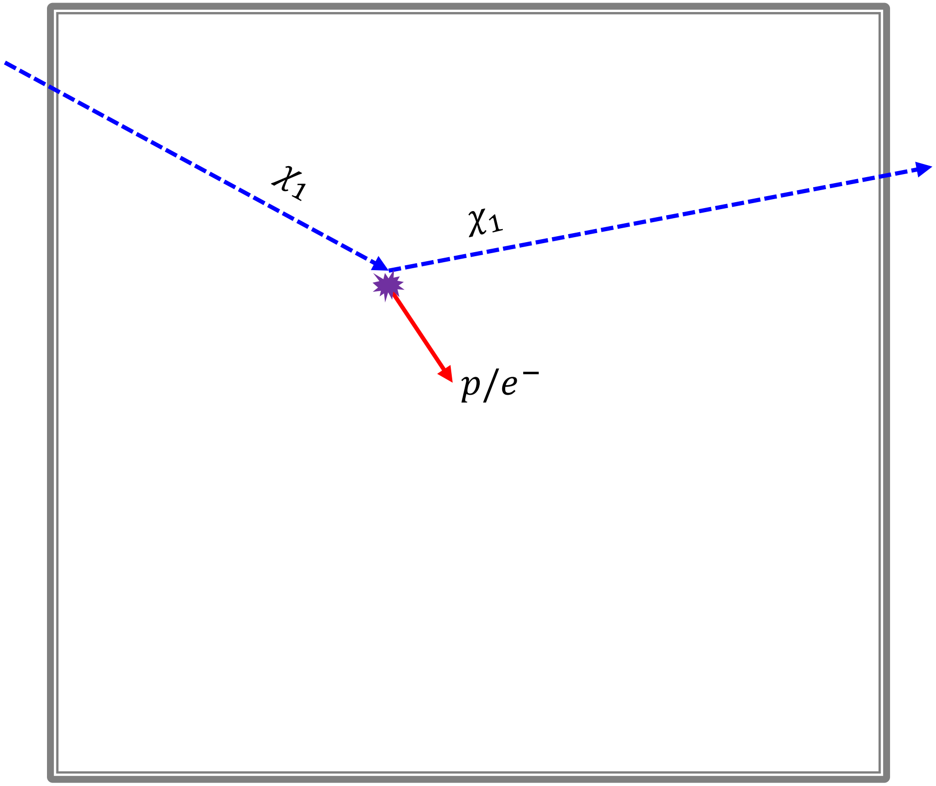
from the number density of DM χ_0, $n_0 = \rho_0 / m_0$

❖ Setting $\langle \sigma v \rangle_{\chi_0 \chi_0 \to \chi_1 \chi_1} \sim 10^{-26}\ \mathrm{cm^3 s^{-1}}$ & assuming NFW DM halo profile,

$\mathcal{F}_{\chi_1} = \mathcal{O}(10^{-1} \sim 10^{-6})\mathrm{cm^{-2} s^{-1}}$ for $m_0 = \sim 30$ MeV to ~10 GeV

- ✓ Not small enough for small-volume (~1 ton) detectors to have signal sensitivity (e.g., conventional WIMP detectors: Xenon1T, LZ, ...)
- ✓ Big enough for sub-kton (e.g. ProtoDUNE, SBN) to observe signal events (better position/angle/vertex resolution & particle identification, lower E_{th} compared to Super-Kamiokande)

Expected Signatures



- Elastic scattering (eBDM): only e/p recoil (ER)

  ➔ single track

- **Tracks** will **pop-up** inside the fiducial volume.
- Focus on e-recoil.
- Straightforwardly applicable to p-recoil

  (up to form factor, DIS, etc.)

Potential Backgrounds

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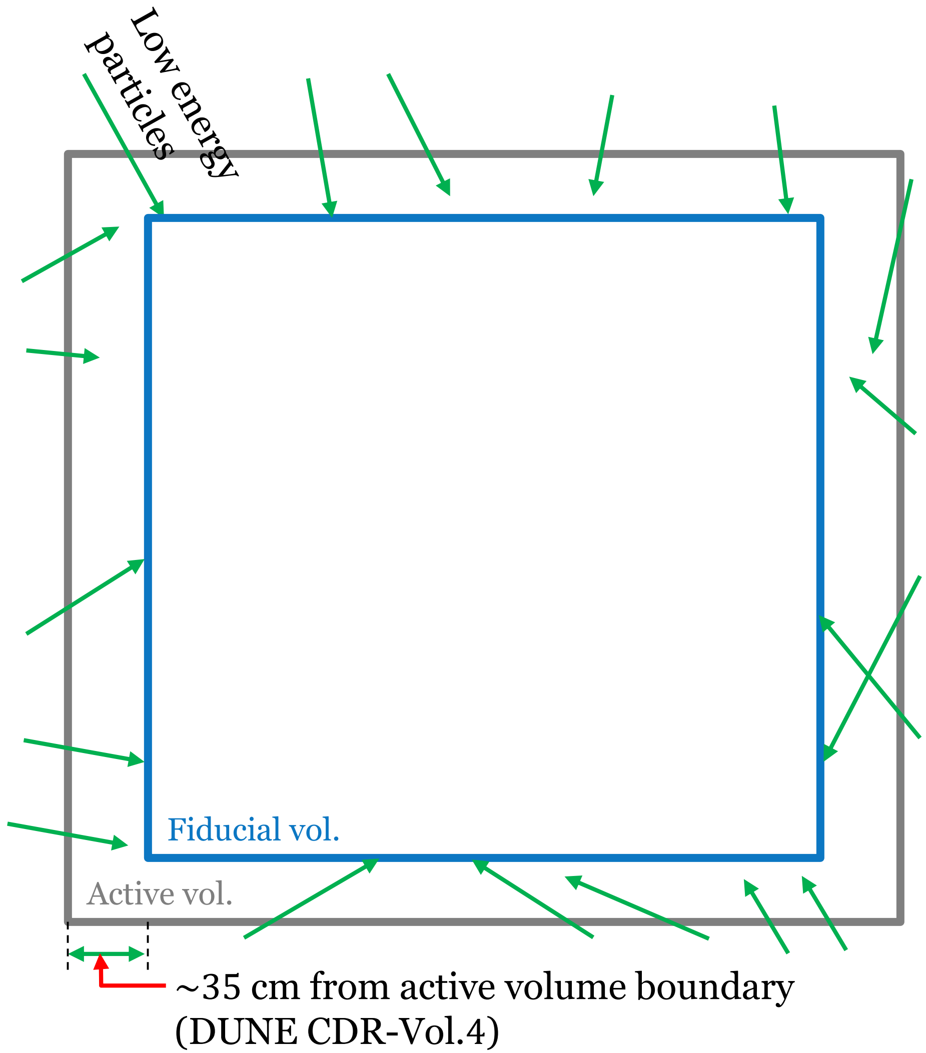
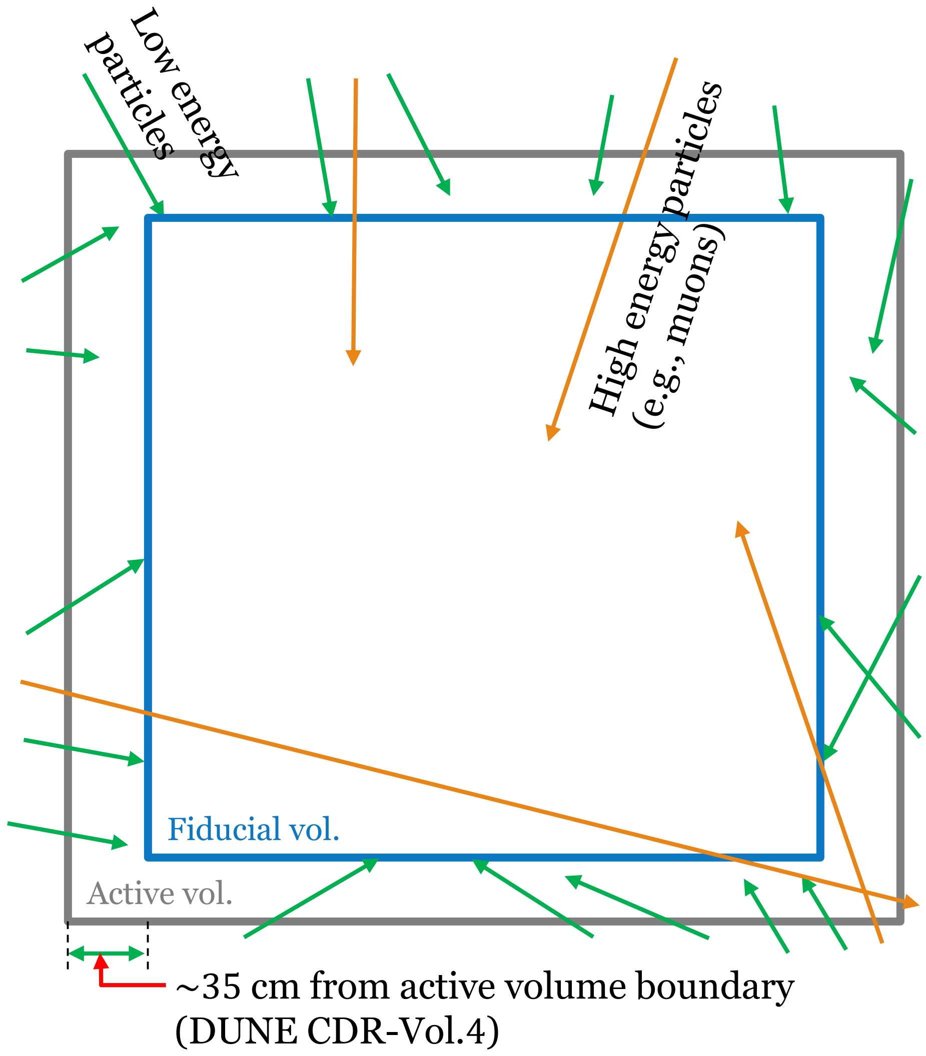


- Low E particles ($\lesssim$ 30 MeV) can be removed/suppressed by taking a fiducial vol. smaller than the active vol. (Fiducial vol.: e.g. ~170 t/300 t for ProtoDUNE DP/SP)

Potential Backgrounds



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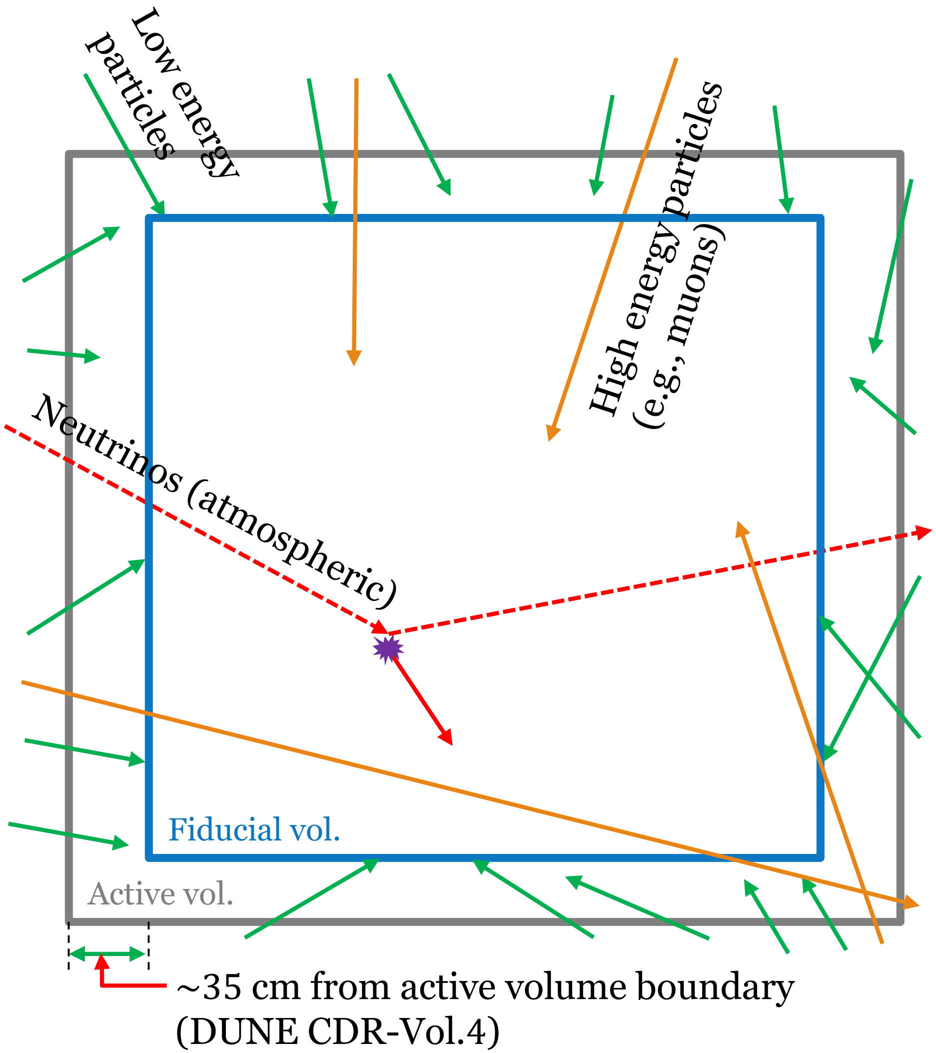
- High E particles (e.g., muon) create tracks incoming outside the fiducial vol., which can be rejected by a trigger and the post-analysis.

  ➔ A large flux is expected for the detectors placed on the ground, e.g., ProtoDUNE, SBN.

Potential Backgrounds



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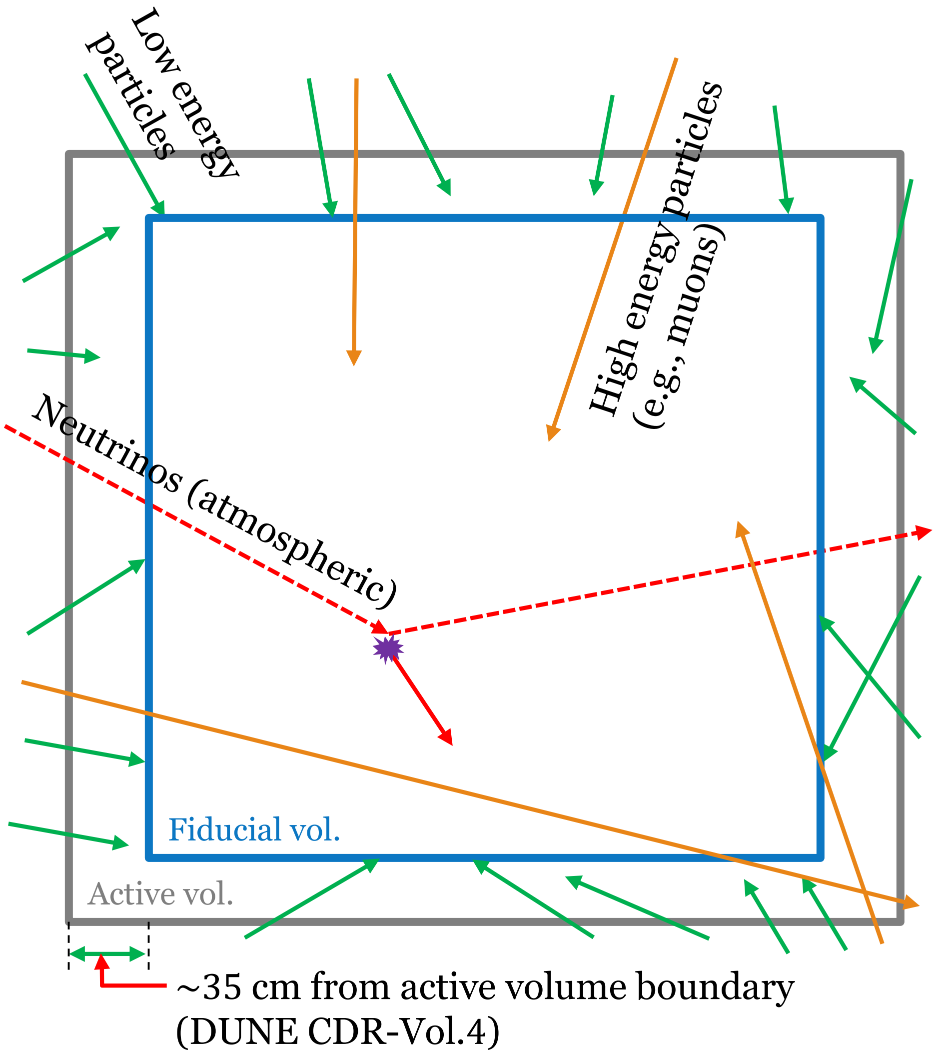
- (Atmospheric) neutrinos are (potentially) irreducible.
  ➔ ~40 single-track *e*-like events/yr/kt

Potential Backgrounds



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Can be rejected by "**Earth Shielding**"
[Kim, Kong, **JCP**, Shin, arXiv: 1804.07302]

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Number of Signal Events

❖ Number of signal events N_{sig} is

$$N_{\text{sig}} = \sigma_\epsilon \cdot D_f \cdot \mathcal{F} \cdot t_{\text{exp}} \cdot N_T$$

- ✓ σ_ϵ: scattering cross section between χ_1 (BDM) and electron (target)
- ✓ D_f: data collection fraction of day
- ✓ $\mathcal{F}$: flux of incoming (boosted) χ_1
- ✓ t_{exp}: exposure time
- ✓ N_e: total number of target electrons

Controllable! (once a detector is determined)

Realistic experimental effects such as cuts, E_{th} are absorbed into σ_ϵ.

Model-Independent Reach

❖ More familiar parameterization is possible with the below modification.

$$\sigma_\epsilon \mathcal{F} \geq \frac{N^{90}}{D_f\, t_{\rm exp}\, N_T}$$

90% C.L.

Detector	N^{90}		$N_{\rm BG}$	
	All sky	30°	All sky	30°
ProtoDUNE-DP	4.86	2.67	4.22	0.28
ProtoDUNE-SP	5.50	2.79	6.02	0.40
ProtoDUNE-total	6.69	3.04	10.24	0.69
MicroBooNE	3.34	2.42	1.10	0.074
SBND	3.54	2.44	1.14	0.094
ICARUS	5.50	2.79	6.02	0.40
SBN Program-total	6.24	2.94	8.53	0.57

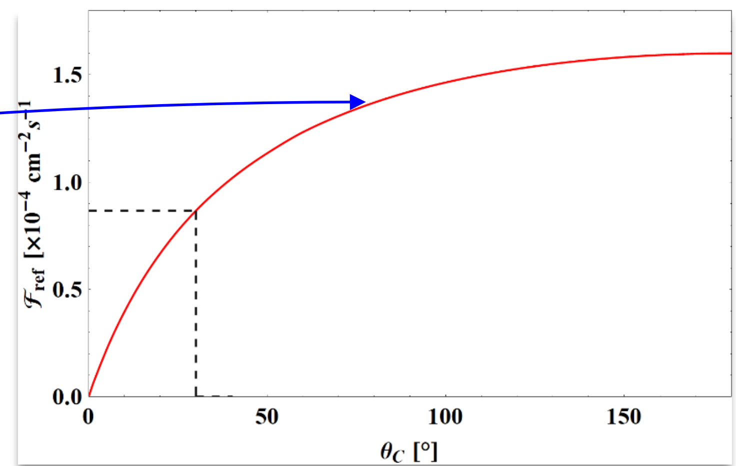
D_f=1/2 is assumed.

$$\mathcal{F} = \frac{1}{2}\cdot\frac{1}{4\pi}\int d\Omega \int_{\rm los} ds \langle\sigma v\rangle_{\chi_0\overline{\chi}_0\to\chi_1\overline{\chi}_1}\left(\frac{\rho(s,\theta)}{m_0}\right)^2$$

$$= 1.6\times10^{-4}\,{\rm cm^{-2}s^{-1}} \times \left(\frac{\langle\sigma v\rangle_{\chi_0\overline{\chi}_0\to\chi_1\overline{\chi}_1}}{5\times10^{-26}\,{\rm cm^3s^{-1}}}\right)\times\left(\frac{\rm GeV}{m_0}\right)^2$$

$$\equiv \mathcal{F}_{\rm ref}^{180^\circ} \times \left(\frac{\langle\sigma v\rangle_{\chi_0\overline{\chi}_0\to\chi_1\overline{\chi}_1}}{5\times10^{-26}\,{\rm cm^3s^{-1}}}\right)\times\left(\frac{\rm GeV}{m_0}\right)^2$$

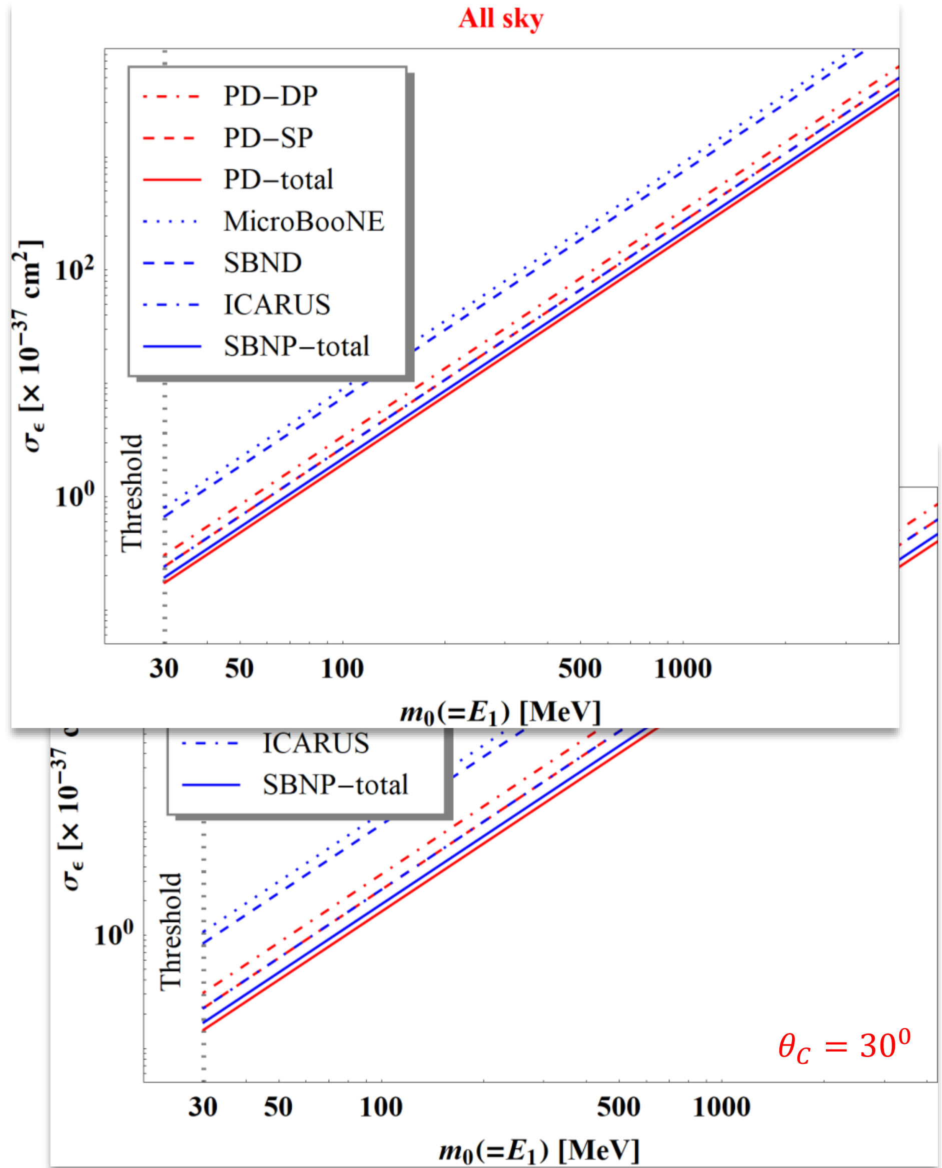
$$\sigma_\epsilon \geq \frac{N^{90}}{D_f\, t_{\rm exp}\, N_T \mathcal{F}_{\rm ref}^{\theta_C}}\left(\frac{5\times10^{-26}\,{\rm cm^3s^{-1}}}{\langle\sigma v\rangle_{\chi_0\overline{\chi}_0\to\chi_1\overline{\chi}_1}}\right)\left(\frac{m_0}{\rm GeV}\right)^2$$



σ_ϵ vs. m_0 (just like σ vs. $m_{\rm DM}$ in conventional WIMP searches)

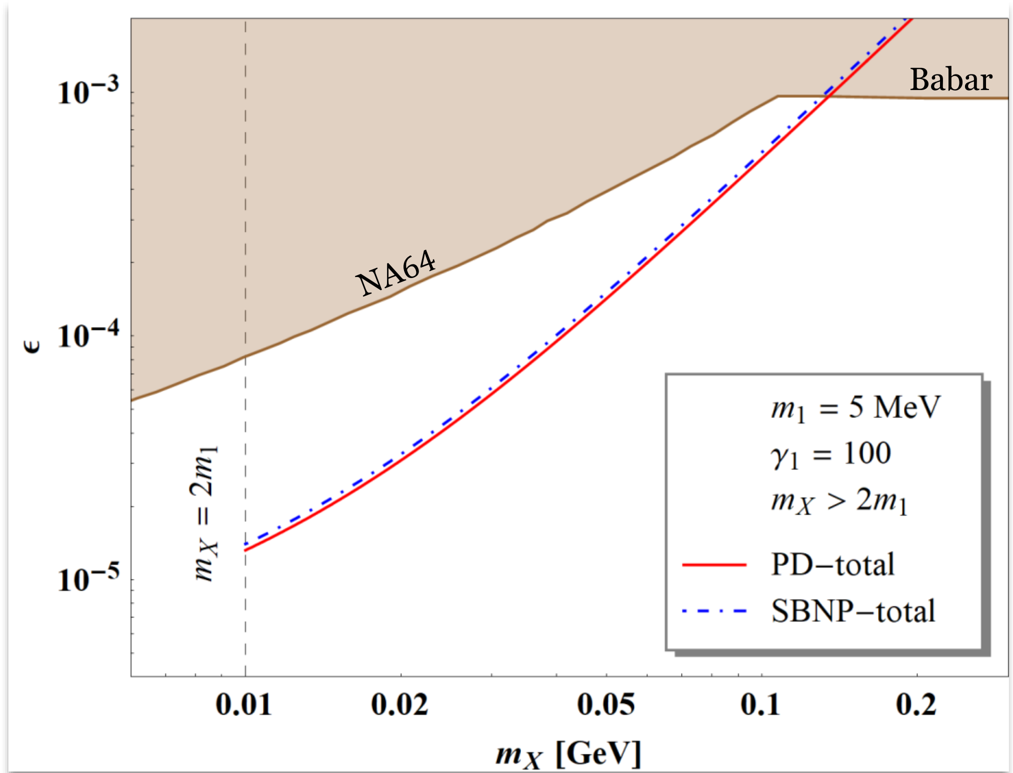
Model-Independent Reach

- ❖ 1-year exposure: effectively half-year data collection ($D_f = 1/2$) is assumed.
- ❖ The limits from all-sky data: DM halo model-independent (up to total flux) and obtained w/o any particular model assumption to describe the interaction between SM particles & BDM.
- ❖ Angular cuts improve the experimental sensitivities at the cost of DM halo model-dependence (optimal θ_C values differ detector-by-detector & run time).



Dark X Parameter Space: Invisible X Decay

- Mass spectra: dark photon decays into DM pairs, i.e., $m_X > 2m_1$
- 1-year data collection from the entire sky and $g_{11} = 1$ are assumed.
- A wide range of unexplored parameter space can be probed even with surface-based detectors.



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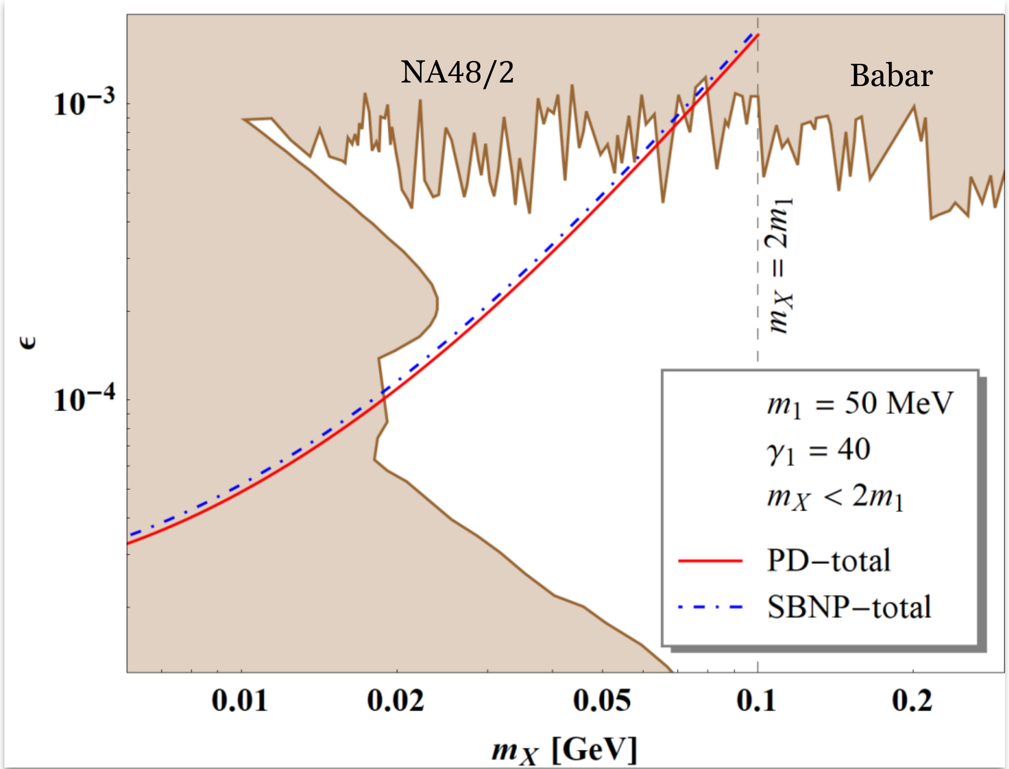
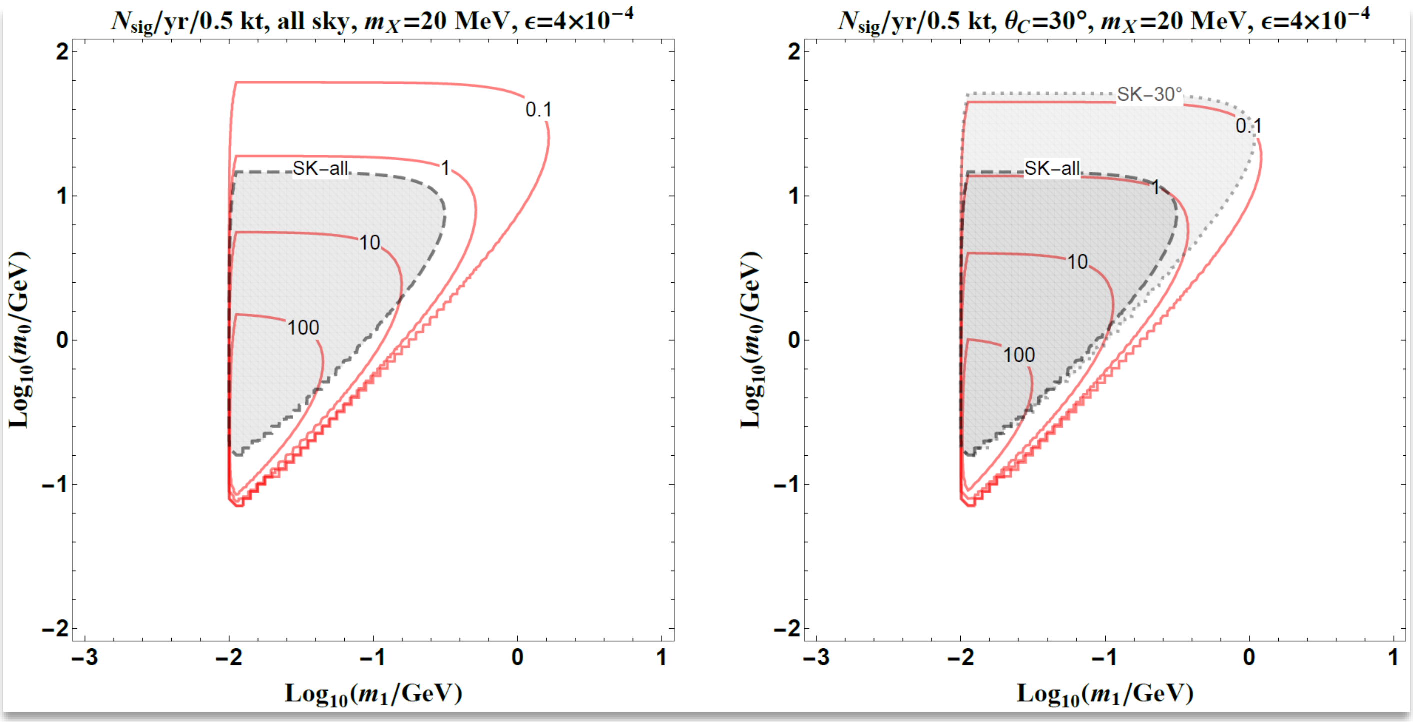


D_f=1/2 is assumed.

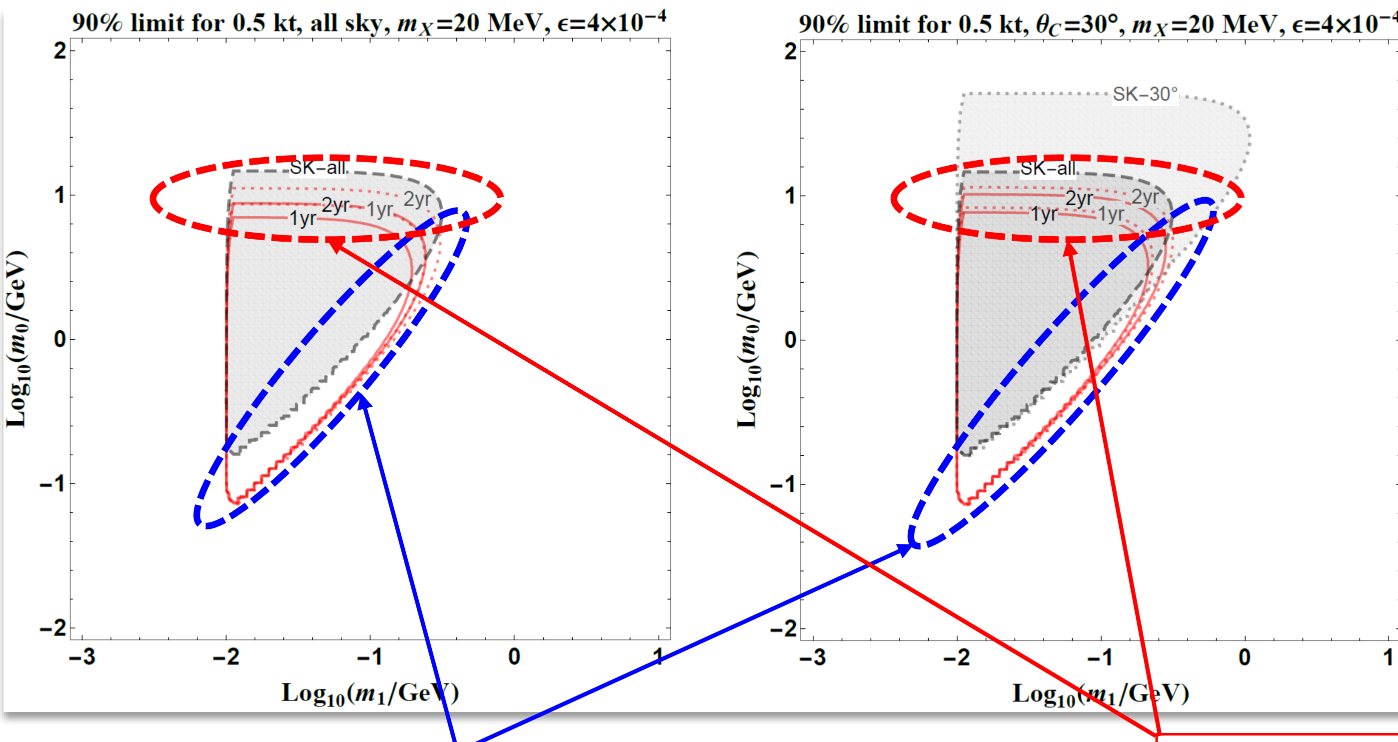
Expected Signal Rate

- A 0.5 kt-$V_{\rm fid}$ detector and $2m_1 > m_X$ (i.e., visibly-decaying X) and $g_{11} = 1$ are assumed.
- Results with 1-year (effectively ½-year assumed) exposure.



Expected Experimental Reach

- A 0.5 kt-$V_{\rm fid}$ detector and $2m_1 > m_X$ (i.e., visibly-decaying X) and $g_{11} = 1$ are assumed.
- Results with 1-year & 2-year (effectively ½-year & 1 year assumed) exposures.



Full ProtoDUNE/SBN can cover the parameter space uncovered by SK!
(especially, the region where the relevant recoil E is lower than ~100 MeV.)

The analysis with **an angle cut** allows to probe more parameter space, as expected.

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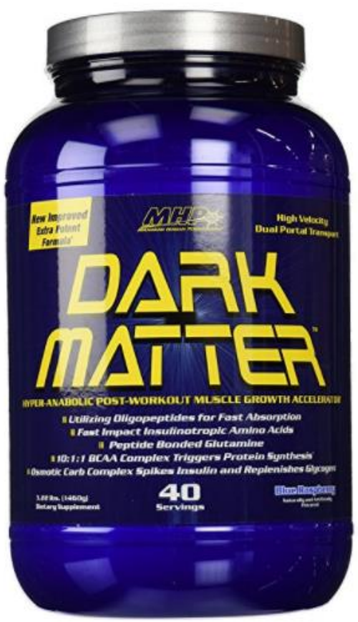

About the product

- The ultimate post workout muscle growth accelerator
- 600 % increase in protein synthesis
- Absorbs faster than whey isolate

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In Stock. Ships from and sold by Amazon.com. Gift-wrap available.

2 Flavors: Blue Raspberry

Blue Raspberry	Fruit Punch
$36.09 ($11.21 / Pound)	from 2 sellers

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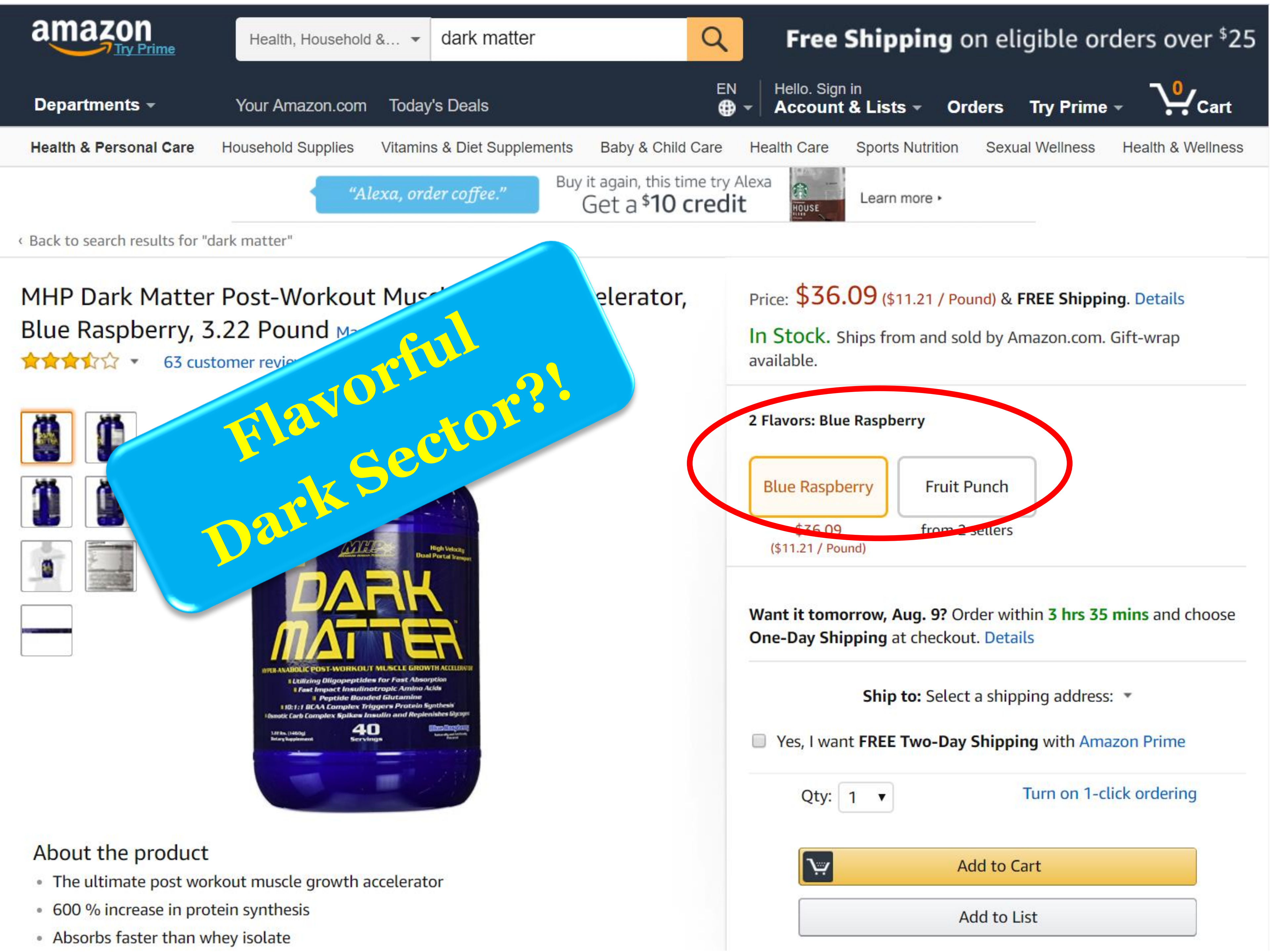
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About the product
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Conclusion

Scattering \ v_{DM}	***non*-relativistic** **($v_{DM} \ll c$)**	**relativistic** **($v_{DM} \sim c$)**
elastic	Direct detection	Boosted DM (eBDM)
***i*nelastic**	inelastic DM (*i*DM)	inelastic BDM (*i*BDM)

Focus of this talk! (Boosted DM (eBDM))

See Doojin Kim's talk! (inelastic BDM (*i*BDM))

- (light) BDM search is promising & provides a new direction to study DM phenomenology.
- Huge cosmic-ray background can be well controlled with the "**Earth Shielding**" effect.
- **Surface detectors** possesses excellent sensitivities to a wide range of (light) BDM

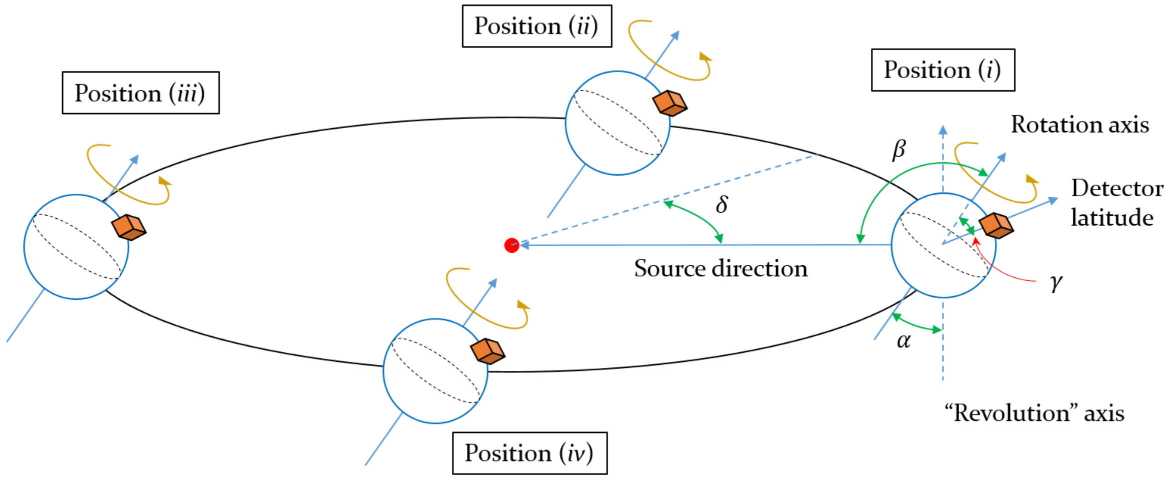
  ➔ allows a deeper understanding in **non-minimal dark sector** physics.
- **Surface detectors** can provide alternative avenue to probe dark photon parameter space.

Thank you

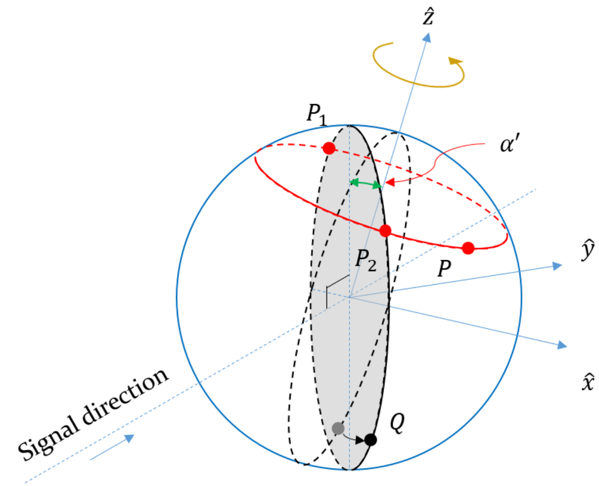
Back-Up

Effect of Earth's Rotation

(a)



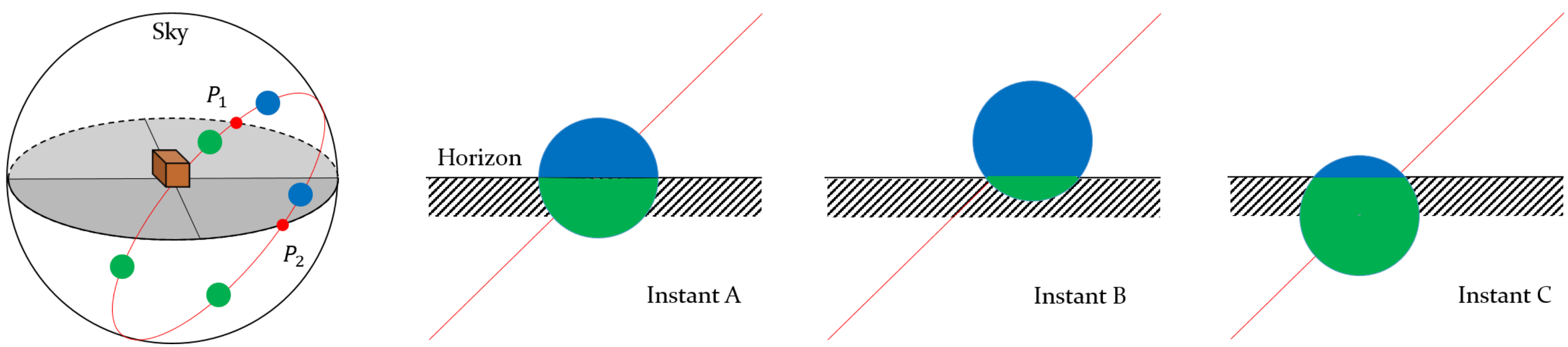
(b)



D_f=1/2 for the Sun / ~0.65 for the GC

@ CERN/Fermilab for the GC.

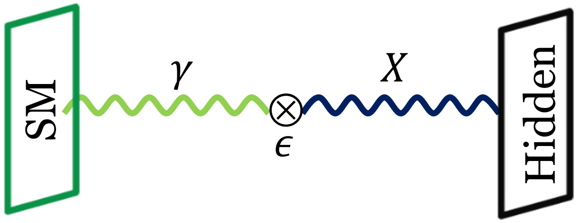
(c)



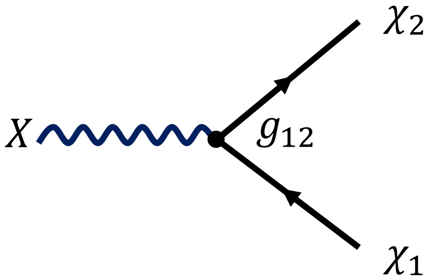
Benchmark Model

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

Based on
Assisted FO set-up
[Belanger, **JCP** (2011)]



- Vector portal (kinetic mixing) [Holdom (1986)]
- Fermionic DM
  - ✓ χ_2: a heavier (unstable) dark-sector state
  - ✓ Flavor-conserving ➔ elastic scattering (eBDM: This talk)
  - ✓ Flavor-changing ➔ inelastic scattering (*i*BDM: Doojin Kim's talk)



- Various models conceiving BDM signatures
  - ✓ BDM source: GC, Sun (capture), dwarf galaxies/assisted freeze-out, semi-annihilation, decaying, etc.
  - ✓ Portal: vector portal, scalar portal, etc.
  - ✓ DM spin: fermionic DM, scalar DM, etc.
  - ✓ iBDM-inducing operators: two chiral fermions, two real scalars, dipole moment interactions, etc.

Detection of BDM

❖ Flux of boosted χ_1 near the earth

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

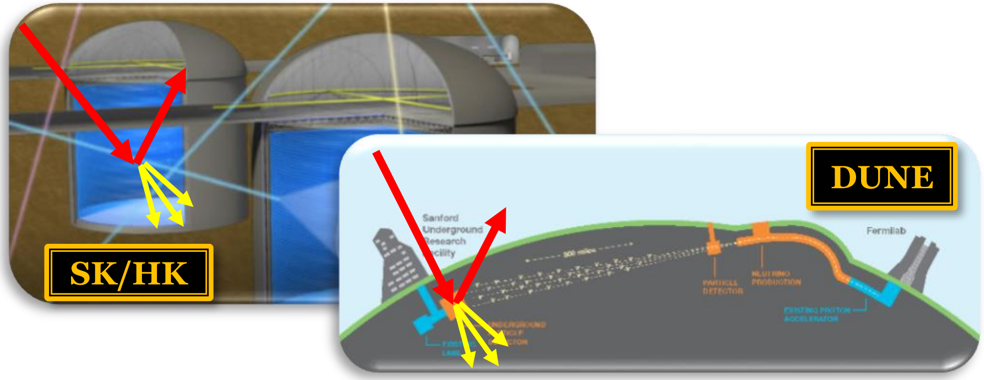
from the number density of DM χ_0, $n_0 = \rho_0 / m_0$

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

one can obtain $\mathcal{F}_{\chi_1} \sim 10^{-6\sim8} \mathrm{cm^{-2} s^{-1}}$ for χ_0 of weak-scale mass, $m_0 \sim$O(10-100 GeV).

❖ Low flux ➔ No sensitivity in conventional DM direct detection experiments

➔ Large volume (neutrino) detectors motivated: Super-/Hyper-K, DUNE, …



❖ Sources

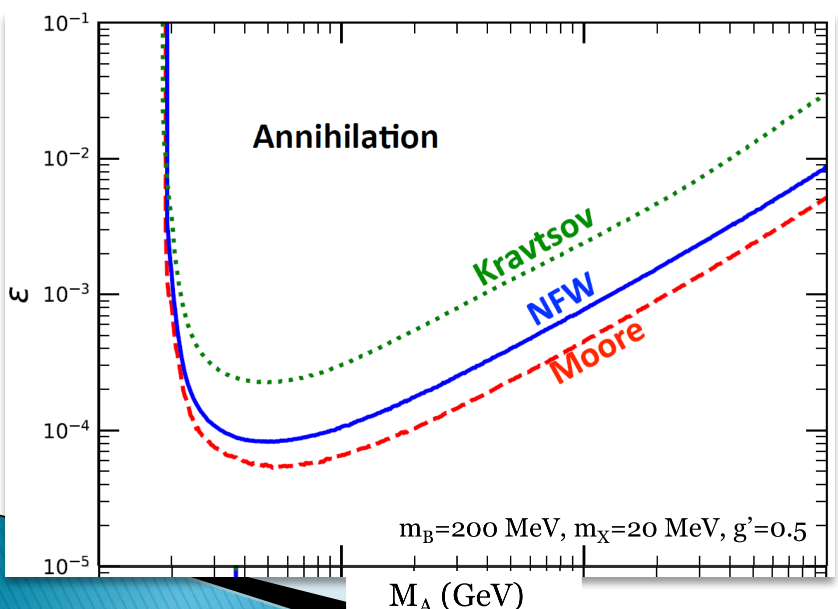
- ✓ GC: Agashe et al. (2014); Necib et al. (2016); Alhazmi, Kong, Mohlabeng, **JCP** (2016); etc.
- ✓ Sun: Berger et al. (2014); Kong, Mohlabeng, **JCP** (2014); Alhazmi, Kong, Mohlabeng, **JCP** (2016); etc.
- ✓ Dwarf galaxies: Necib et al (2016)

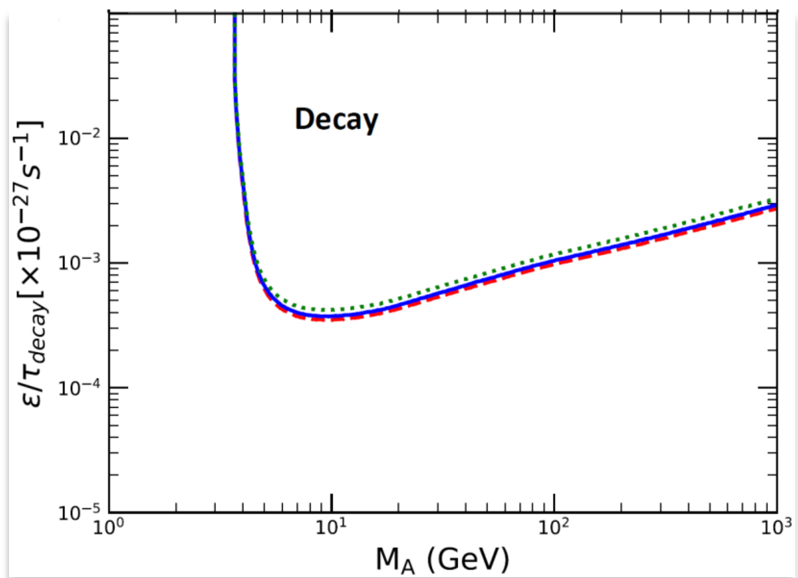
SK Official Results for BDM Search

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

(Dated: November 16, 2017)

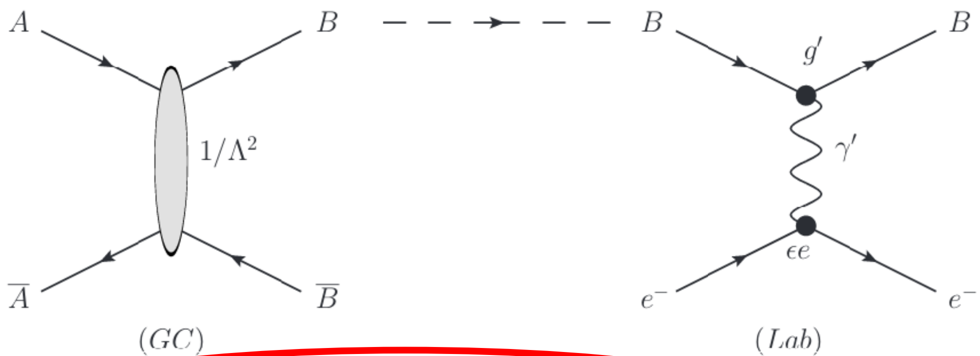
A search for boosted dark matter using 161.9 kiloton-years of Super-Kamiokande IV data is presented. We search for an excess of elastically scattered electrons above the atmospheric neutrino background, with a visible energy between 100 MeV and 1 TeV, pointing back to the Galactic Center or the Sun. 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.

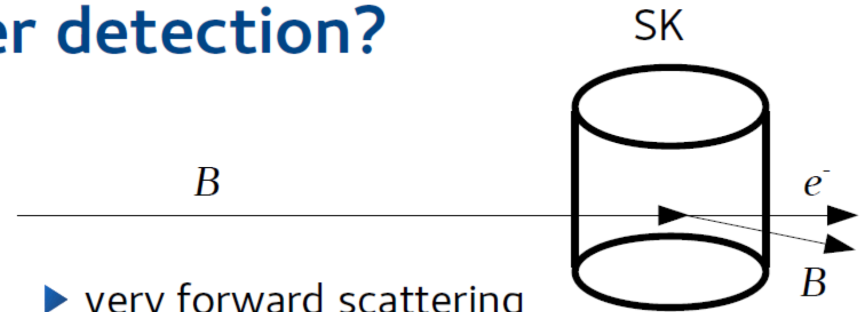




[SK Collaboration, arXiv:1711.05278]

(In)direct dark matter detection?

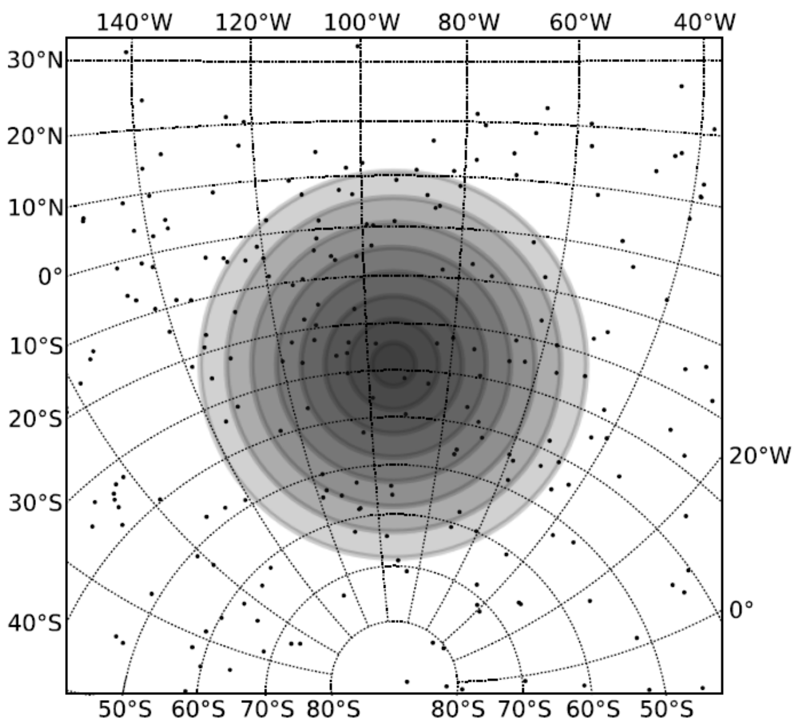




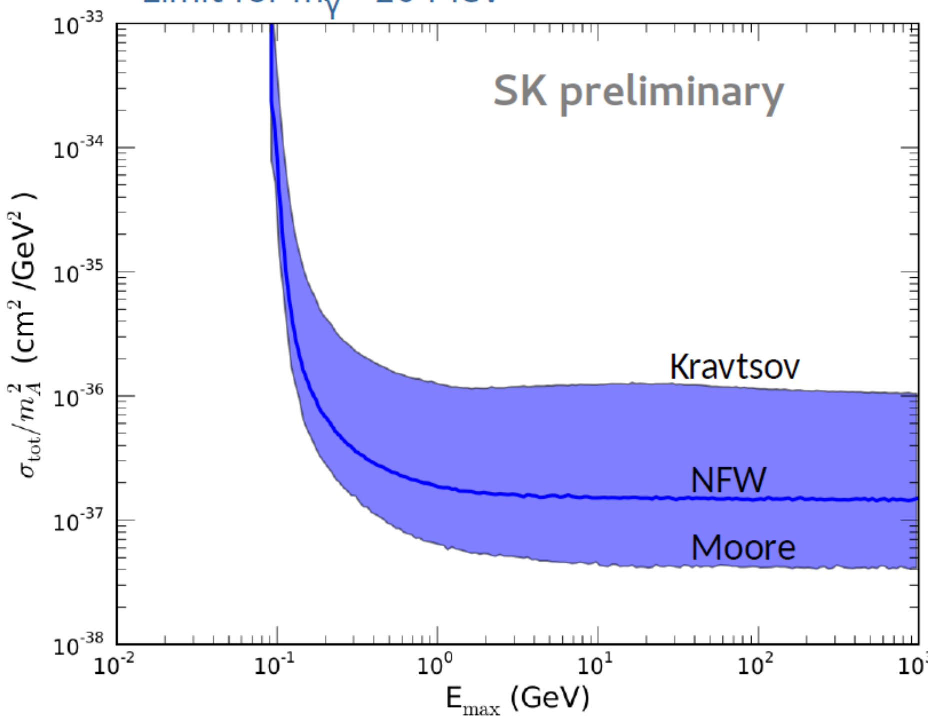
- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

Cone search: 8 cones from 5° to 40° around GC

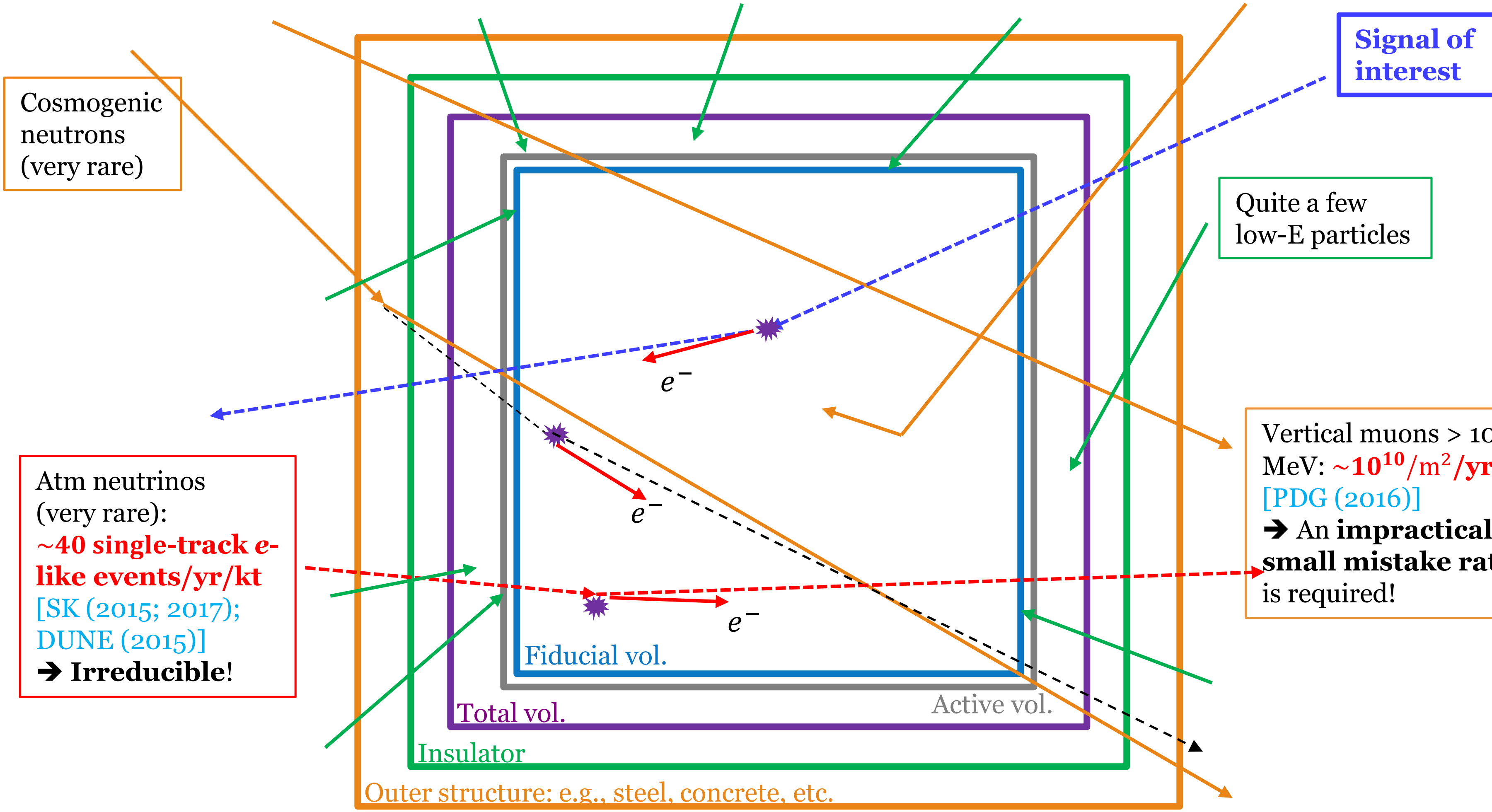
→ **No clusters visible**



Limit for m_{γ}'=20 MeV



Cosmic-origin BGs vs eBDM Signal

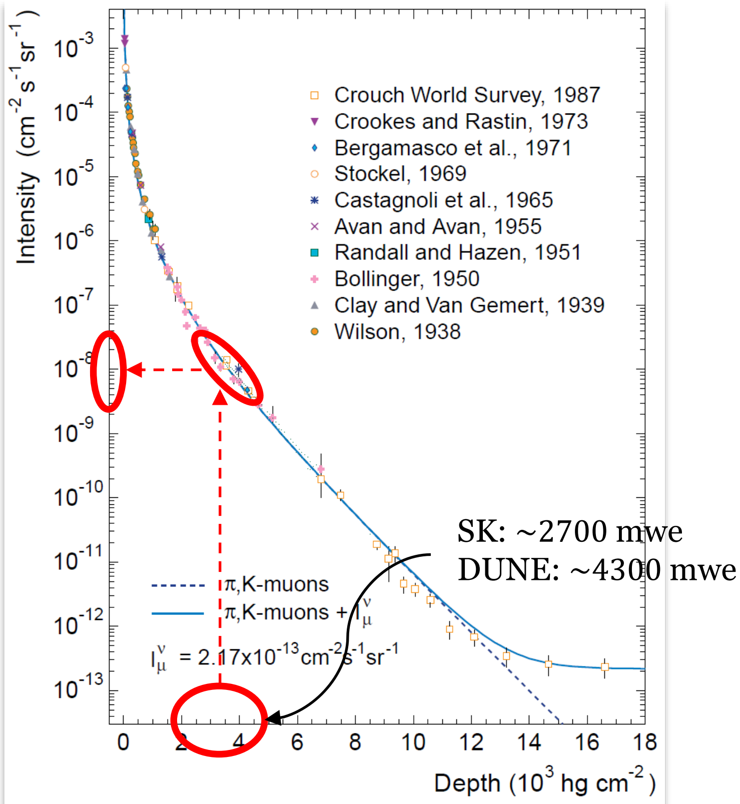


Atm neutrinos (very rare): **~40 single-track *e*-like events/yr/kt** [SK (2015; 2017); DUNE (2015)]
➔ **Irreducible!**

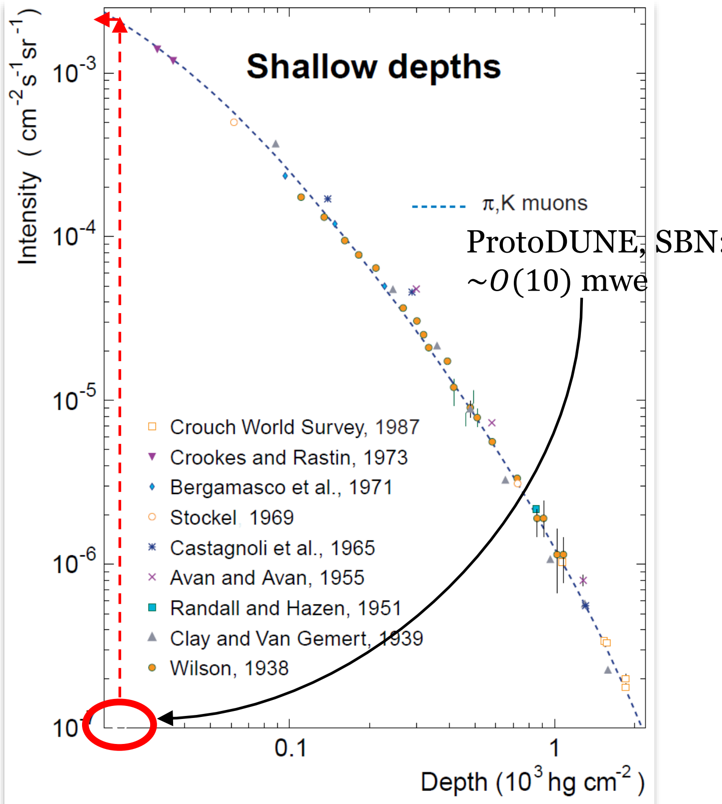
Vertical muons > 10 MeV: **~10^{10}/m^2/yr** [PDG (2016)]
➔ An **impractically small mistake rate** is required!

Potential BGs: High E Muons

❖ Expecting ~10^{5-6} more muon flux at ProtoDUNE/SBN than that at SK/DUNE.



[Bugaev et al. (1998)]



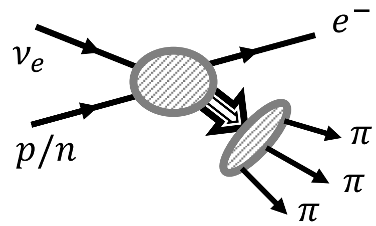
Potential BGs: Neutrinos

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 BGs for elastic scattering signal (eBDM) events

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

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

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