Hunting for Boosted DM

Jong-Chul Park

CHUNGNAM NATIONAL UNIVERSITY

D. Kim, K. Kong, **JCP**, S. Shin, JHEP08 (2018) 155 [arXiv: 1804.07302]

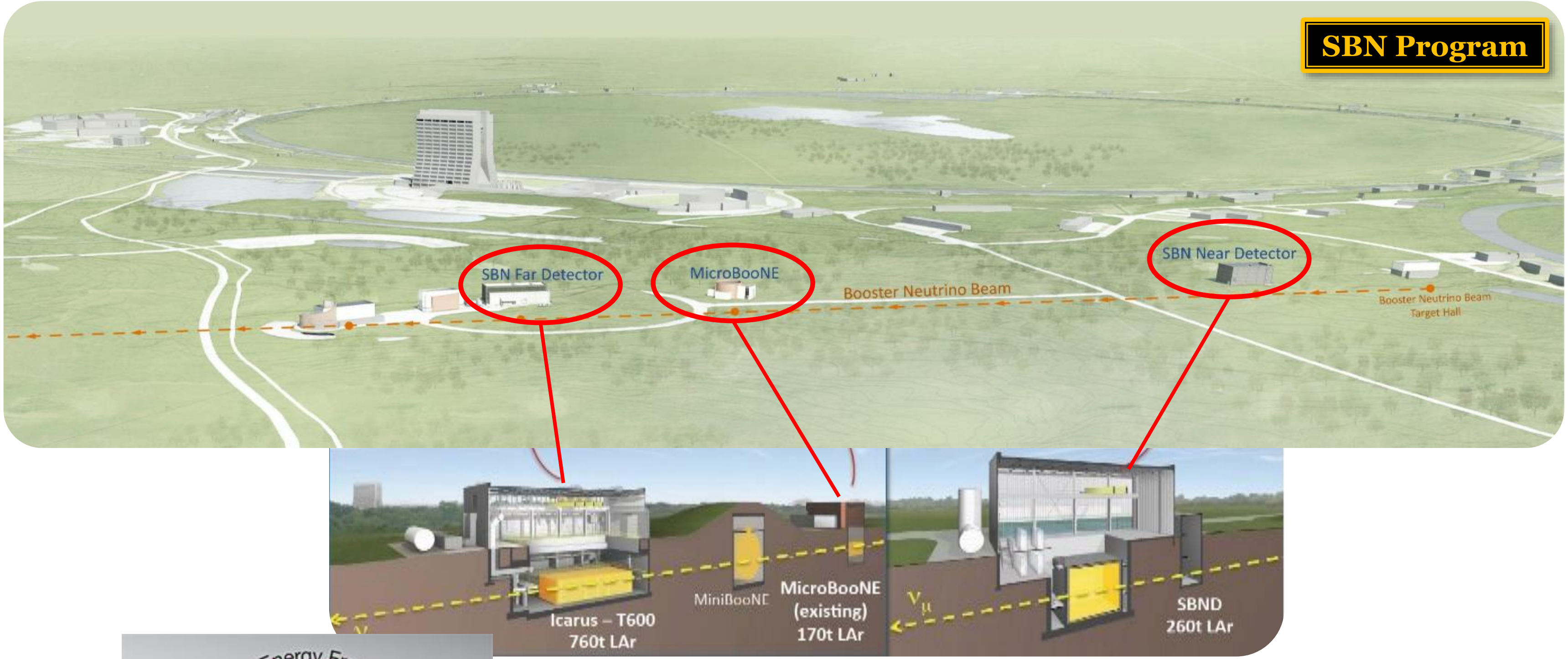
August 28 (2018)

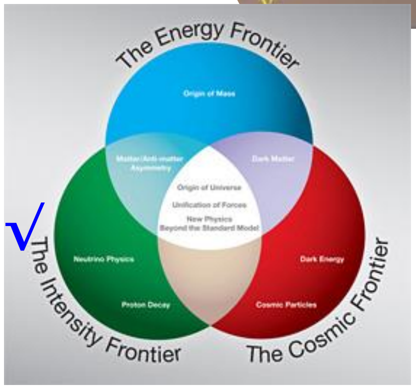
Surface ν Detectors

Physics Motivation?

Surface ν Detectors: SBN

❖ Short-Baseline Neutrino (SBN) Program @ Fermilab

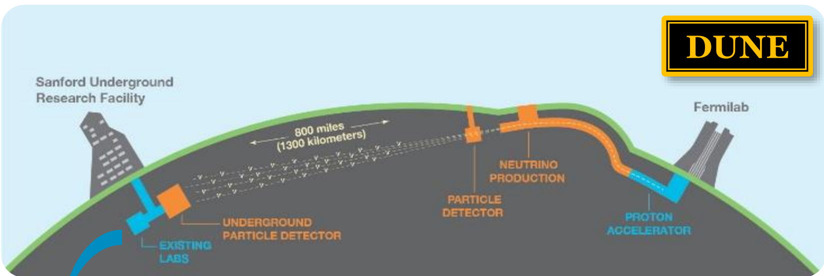


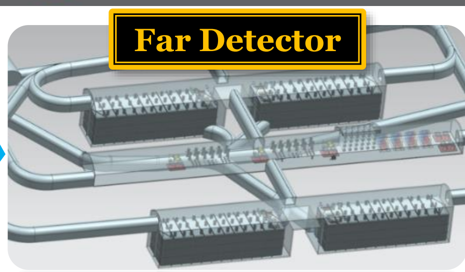


- ✓ Physics @ SBN: *ν* oscillation, sterile *ν*, etc.
- ✓ E spectrum & flavor of *ν*'s produced by the Booster Neutrino Beam
- ✓ Development of the LAr-TPC technology for DUNE

Surface ν Detectors: ProtoDUNE

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



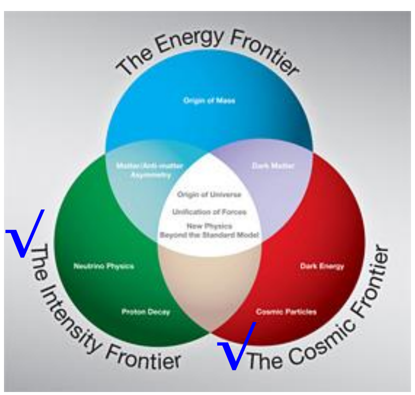


4 ×10 kt → 0.3+0.2 kt

❖ SP: single-phase

❖ DP: dual-phase

✓ Physics @ DUNE: neutrino, BSM, etc.



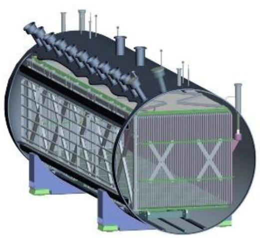
<Originally>

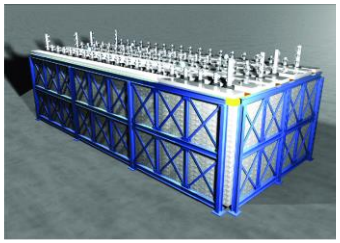
✓ To test the long-term stability & operation

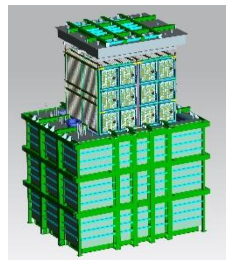
✓ To calibrate beam & cosmic-ray responses

Surface ν Detectors: Features & Status

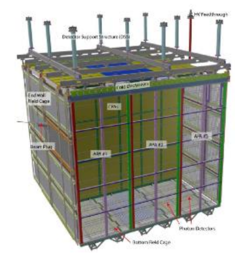
SBN Program

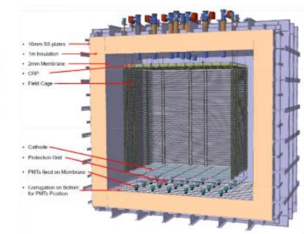






ProtoDUNE





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	~ 0.3	$\sim$ 6 m underground	$\mathcal{O}(10)$	$\mathcal{O}(1^\circ)$
SBND	LArTPC	$4 \times 4 \times 5$	0.112	~ 0.07	$\sim$ 6 m underground	$\mathcal{O}(10)$	$\mathcal{O}(1^\circ)$
ProtoDUNE SP	LArTPC	$3.6 \times 6 \times 7$ ($\times 2$)	~ 0.42	~ 0.3	on the ground	~ 30	$\sim 1^\circ$
ProtoDUNE DP	LArTPC	$6 \times 6 \times 6$	~ 0.3	~ 0.21	on the ground	~ 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 (~2 year)**

Surface ν Detectors

Other Physics Motivation?

Any physics potential with the SBN/ProtoDUNE detectors,

especially BSM physics?

Other Physics Motivati n?

Any physics potenti DUNE detectors,

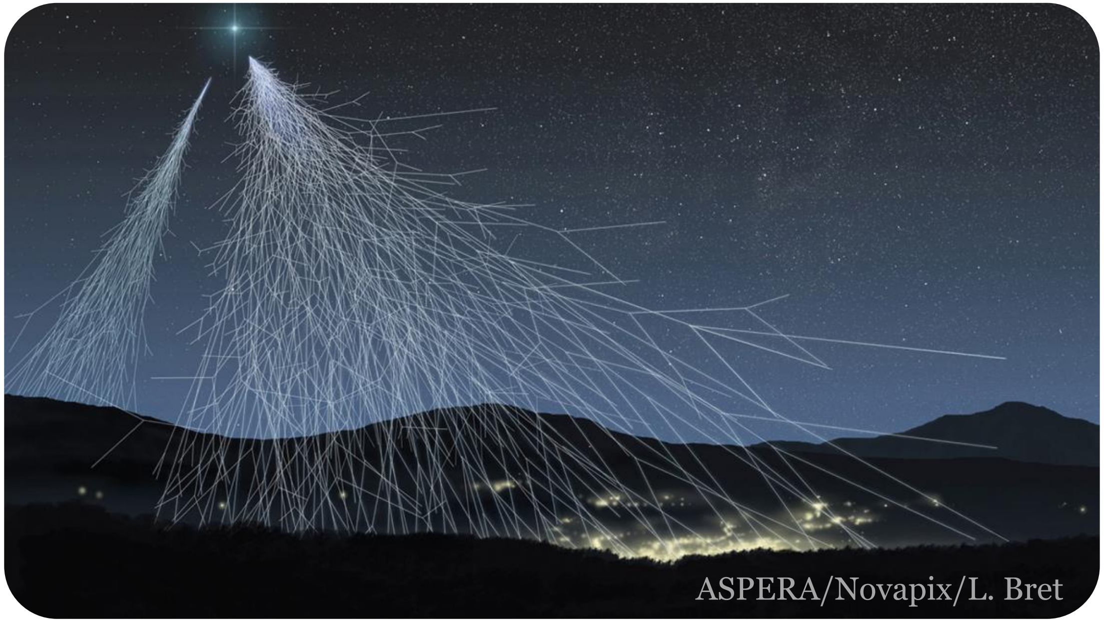
physics?

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.



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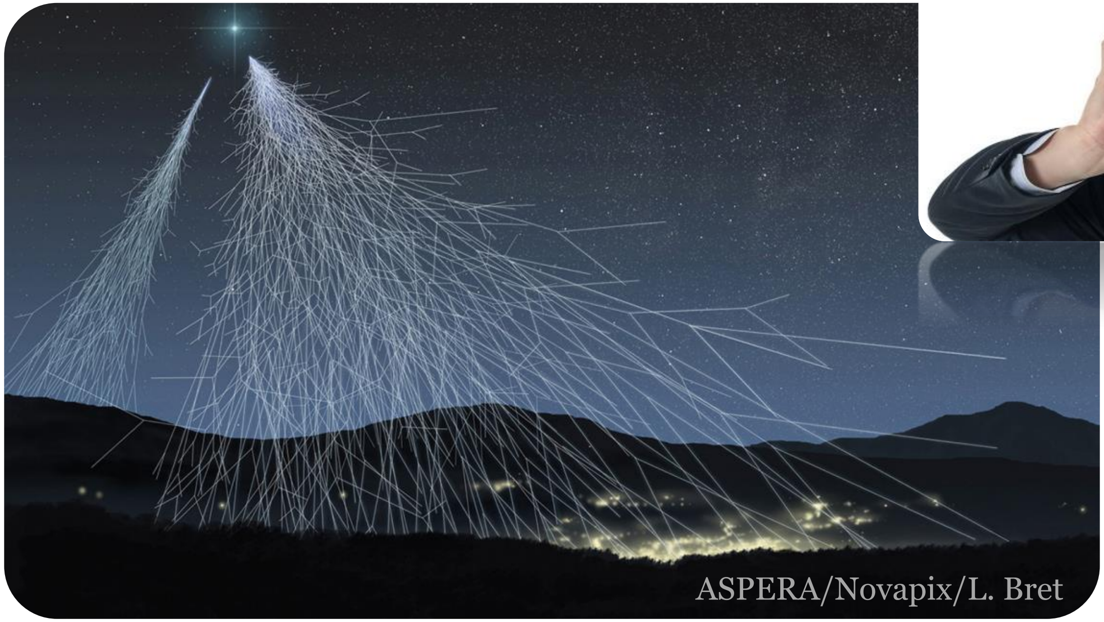
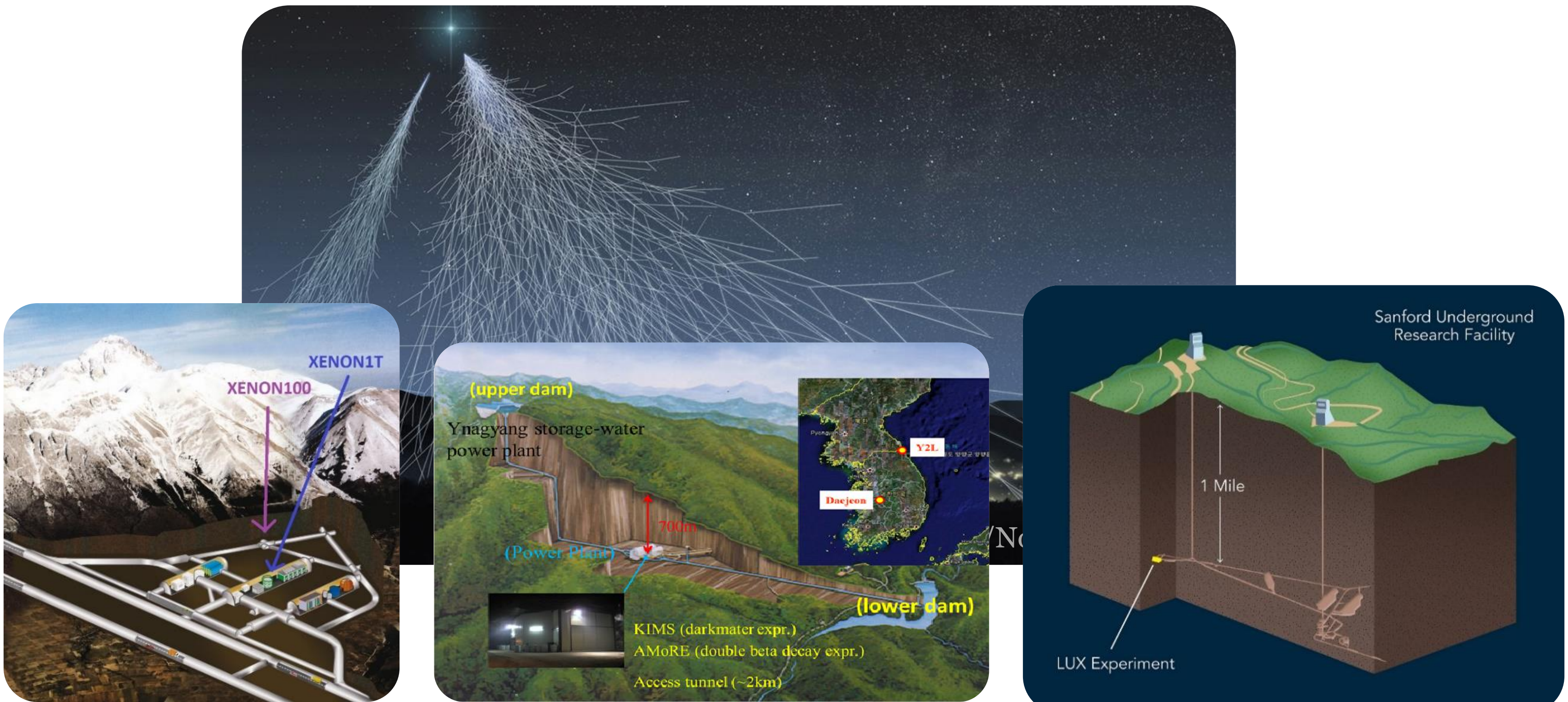


Surface ν Detectors: Common Belief

- 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 Approaches

I. Signals leaving appreciable tracks: the source direction is inferred from the track.

➔ Restricting to events coming through the Earth from the opposite side of the detector location.

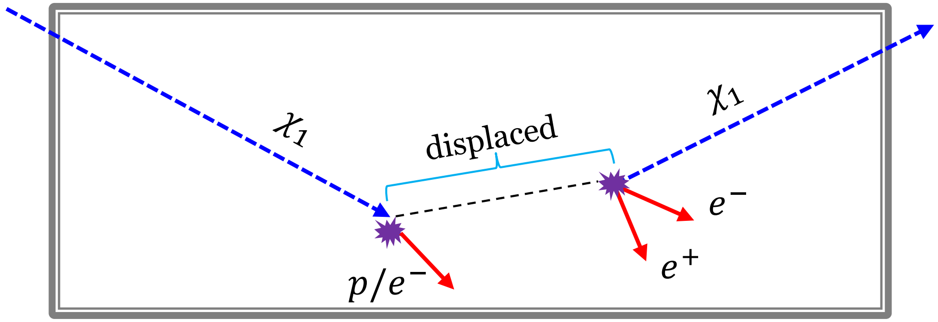
➔ Potential backgrounds in that direction are significantly suppressed while signals are intact. (Similar to up-going ν searches @ SK, IceCube, NOvA, etc)

Kim, Kong, **JCP**, Shin [1804.07302]

II. A signal with many unique features (e.g. *i*BDM): Possible to isolate signal events from cosmic background events efficiently.

(due to good detector performance: positon/angular/energy resolution, etc.)

Chatterjee, **JCP** et al., [1803.03264]



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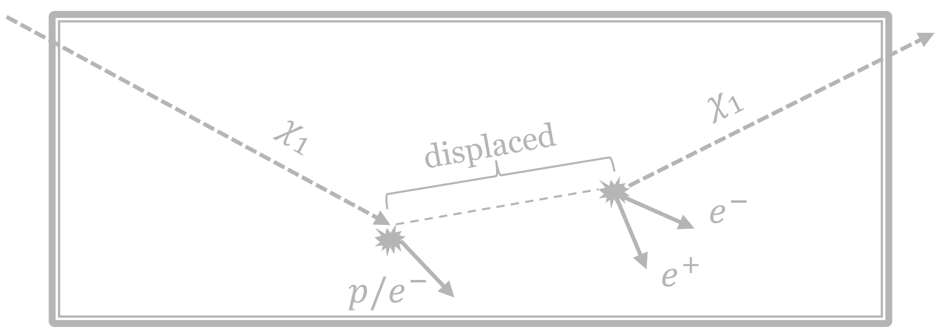


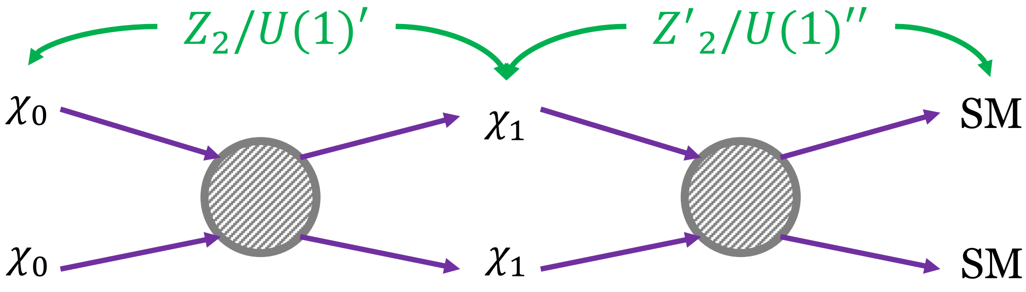
Target Approach

Earth Shielding

(Benchmark: Boosted DM)

Two-component BDM Scenario

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



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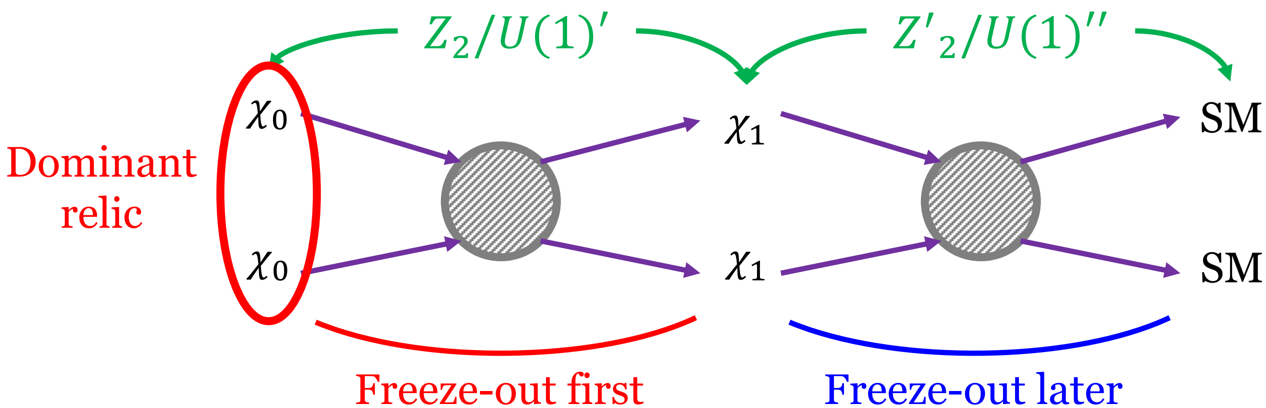

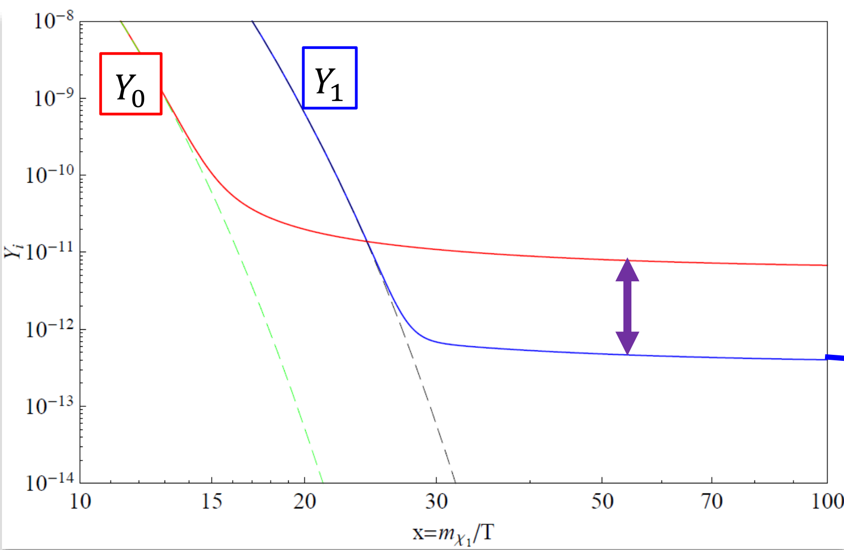

"**<u>Assisted Freeze-out</u>**" Mechanism

- ✓ 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

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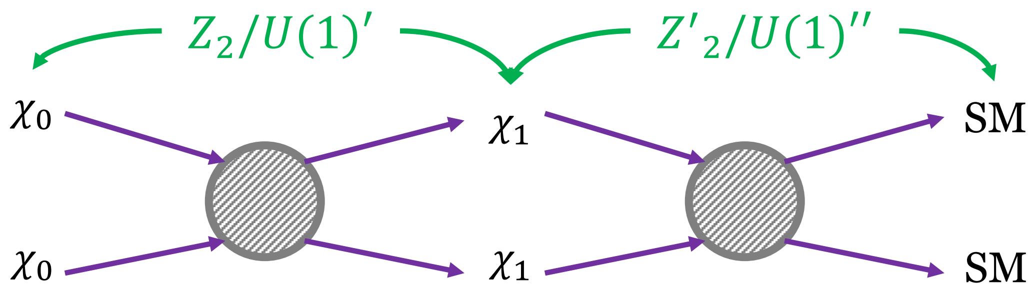
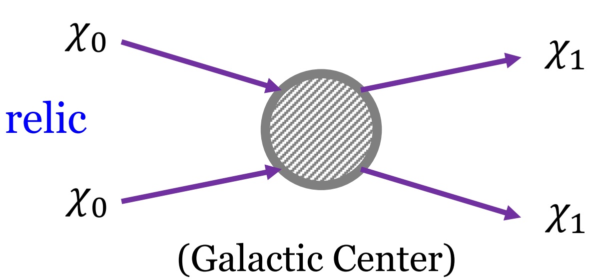


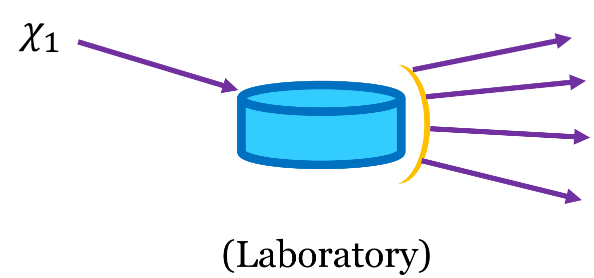
$\chi_0\chi_0 \rightarrow \chi_1\chi_1$ (current universe): **Relativistic!!** ($\gamma_1 = m_0/m_1$)

(Note that relic χ_1 is non-relativistic.)



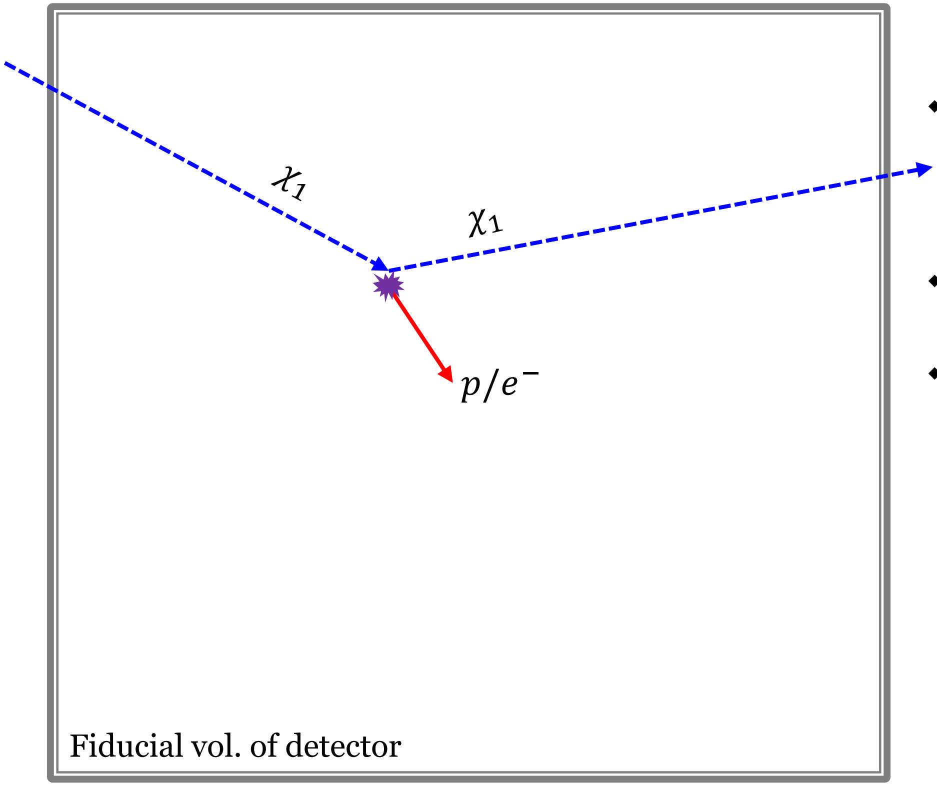
becomes boosted

($\gamma_1 = m_0/m_1$)



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

Expected Signatures



- Ordinary elastic scattering (eBDM): only electron/proton recoil ➔ single track
- Tracks will **pop-up** inside the fiducial volume.
- Focus on e-recoil. But, Straightforwardly applicable to p-recoil (up to form factor, DIS, etc.)

Flux of BDM & its 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, $n_o=\rho_o/m_o$

- 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

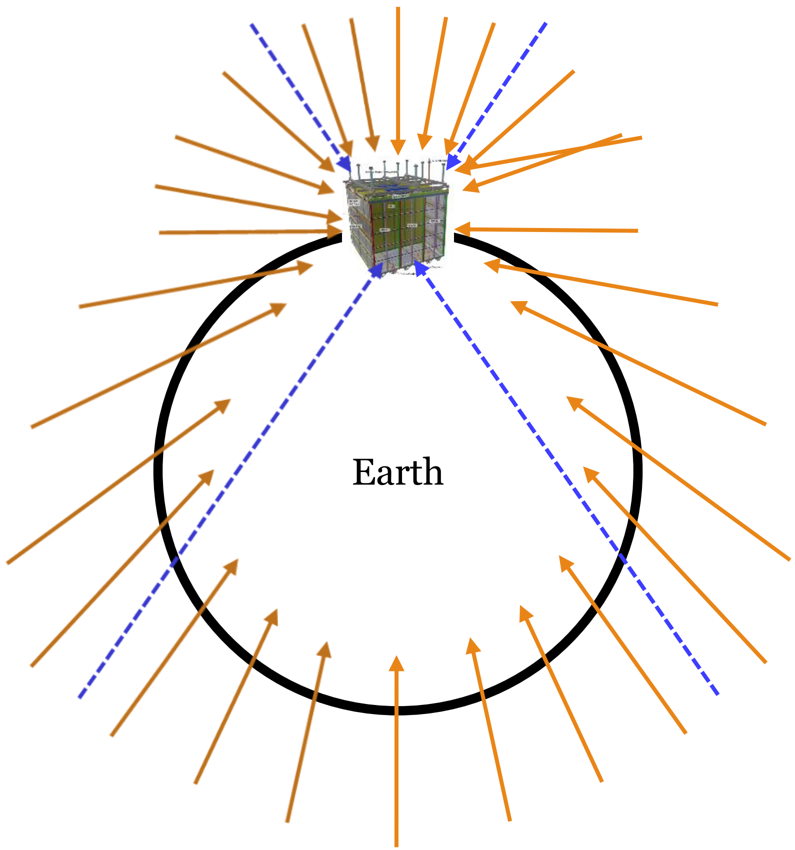
✓ Not small enough for small-volume (~1 ton) detectors to have signal sensitivity (e.g., conventional WIMP detectors: Xenon1T, LZ, COSINE-100(+2 ton LS), …)

✓ 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)

Earth Shielding

BG: Cosmic muons
Signal: Boosted DM

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



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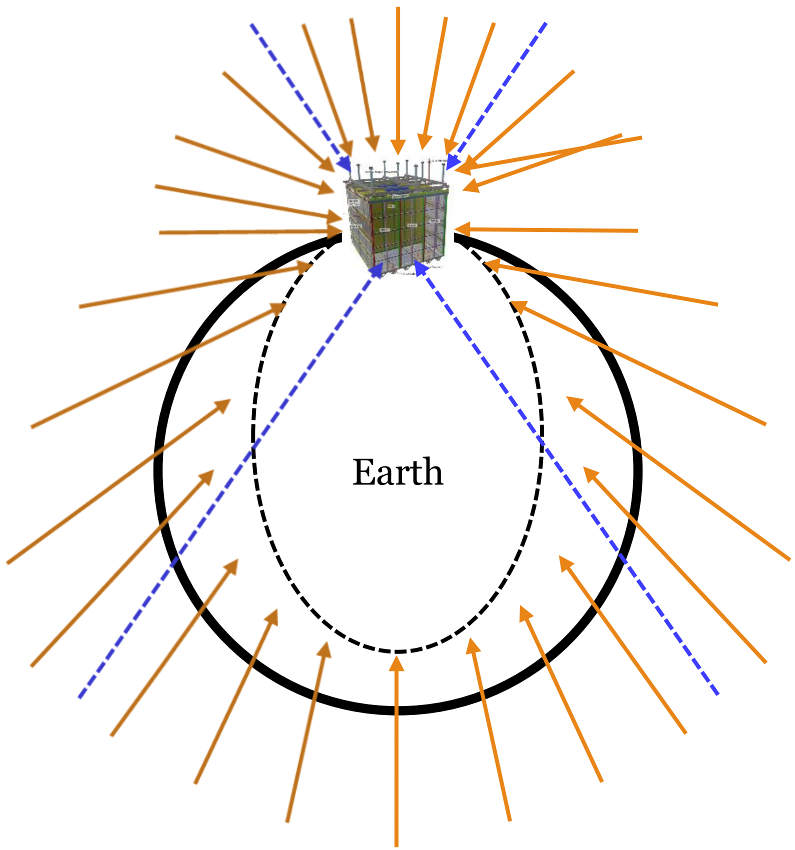

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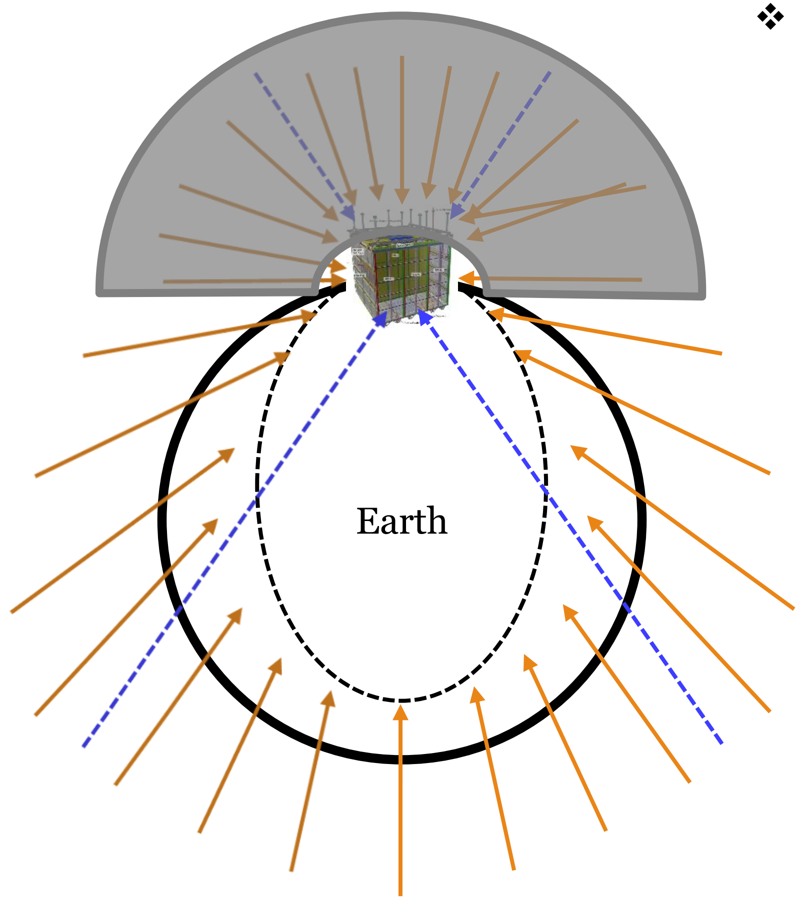
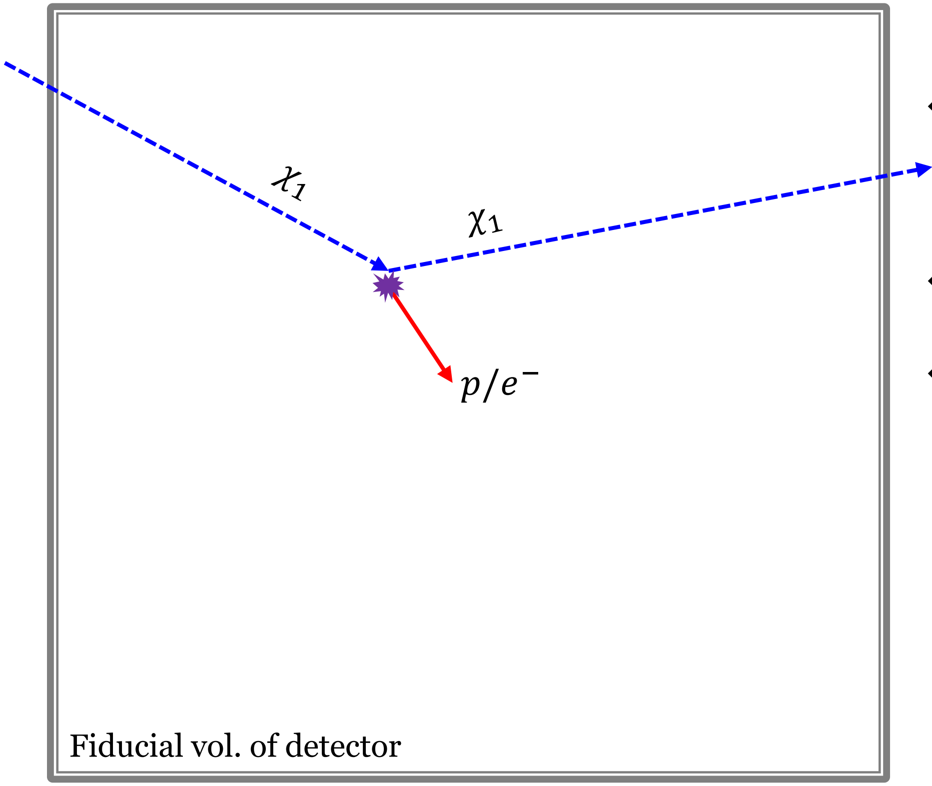


❖ Accept only **events traveling through the Earth** (i.e., coming out of the bottom surface) at the price of half statistics (for a cumulatively isotropic signal);

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])

Expected Signatures (Reminder)



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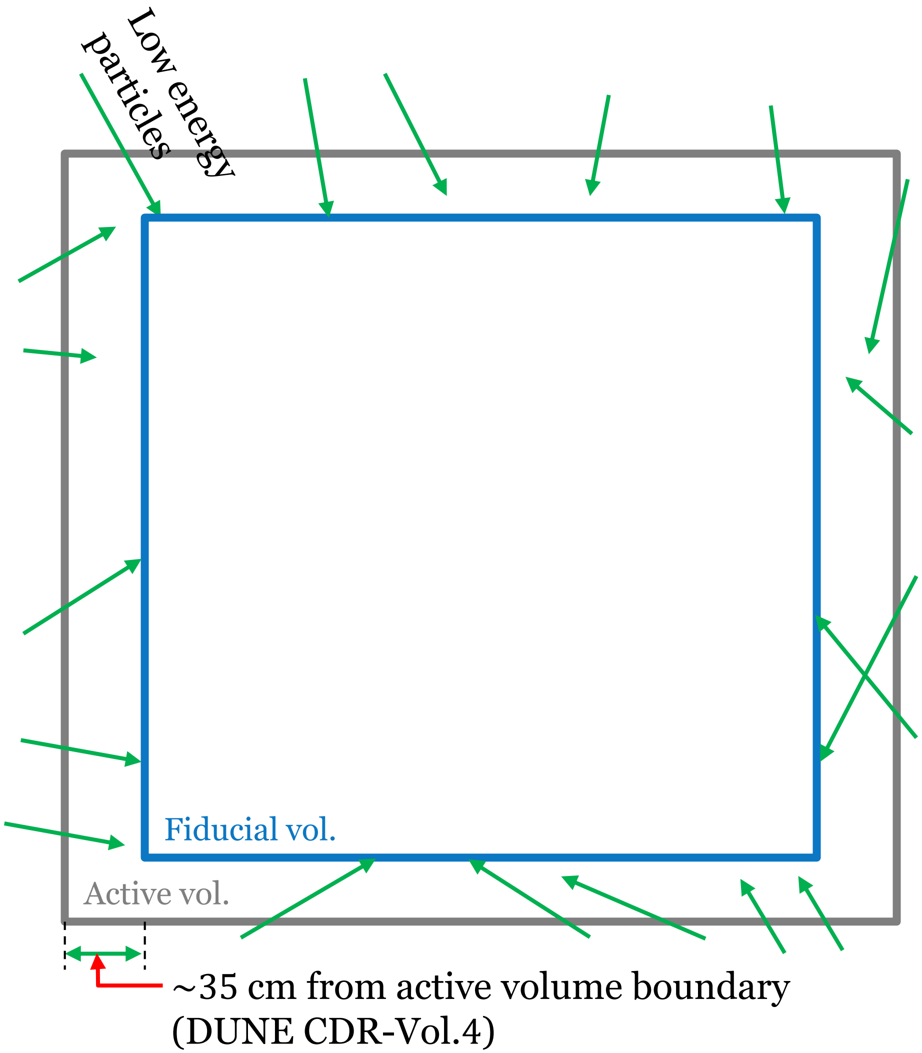

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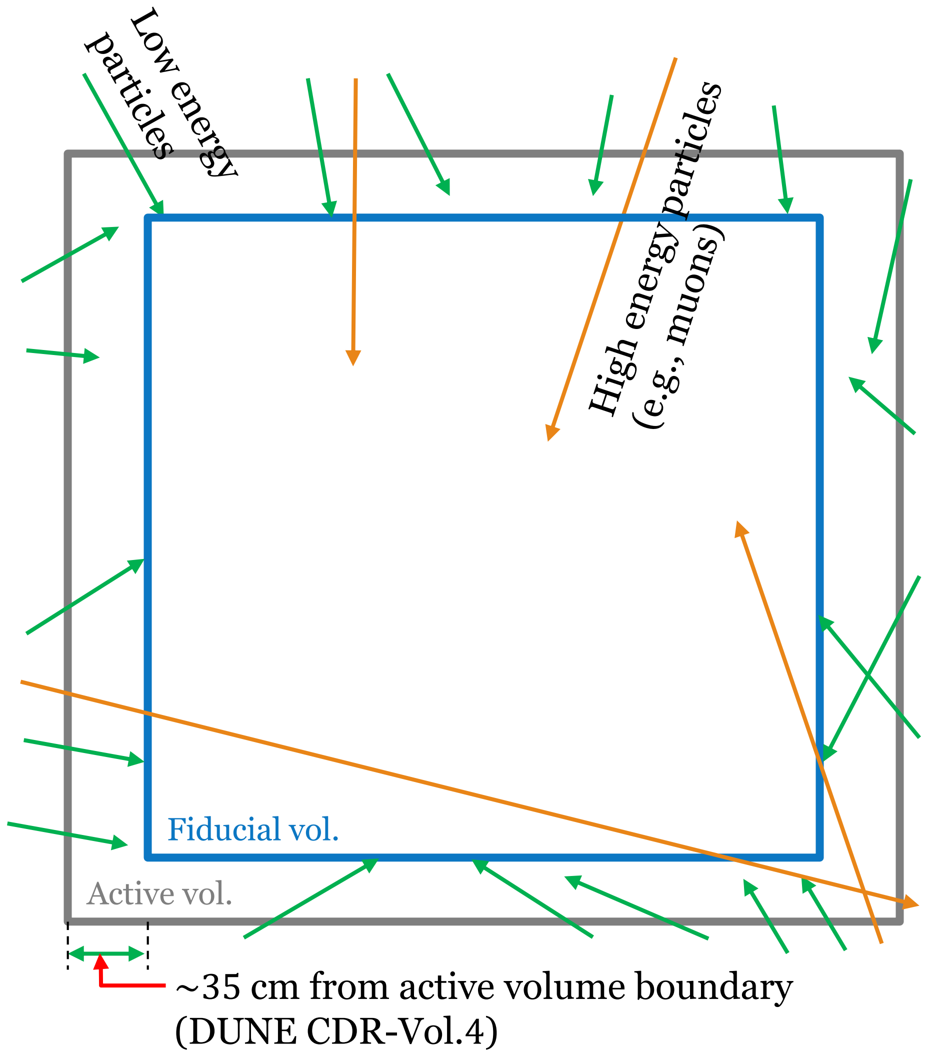

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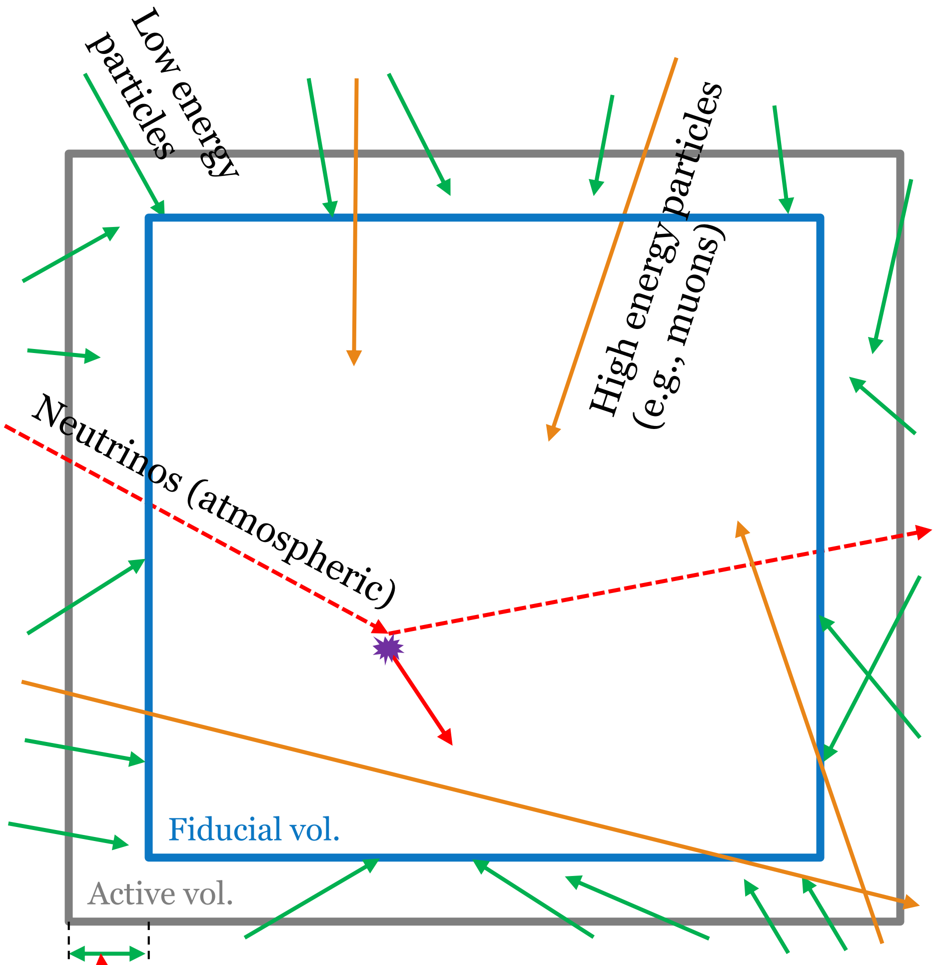

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- (Atmospheric) neutrinos are (potentially) irreducible.
  ➔ ~40 single-track *e*-like events/yr/kt

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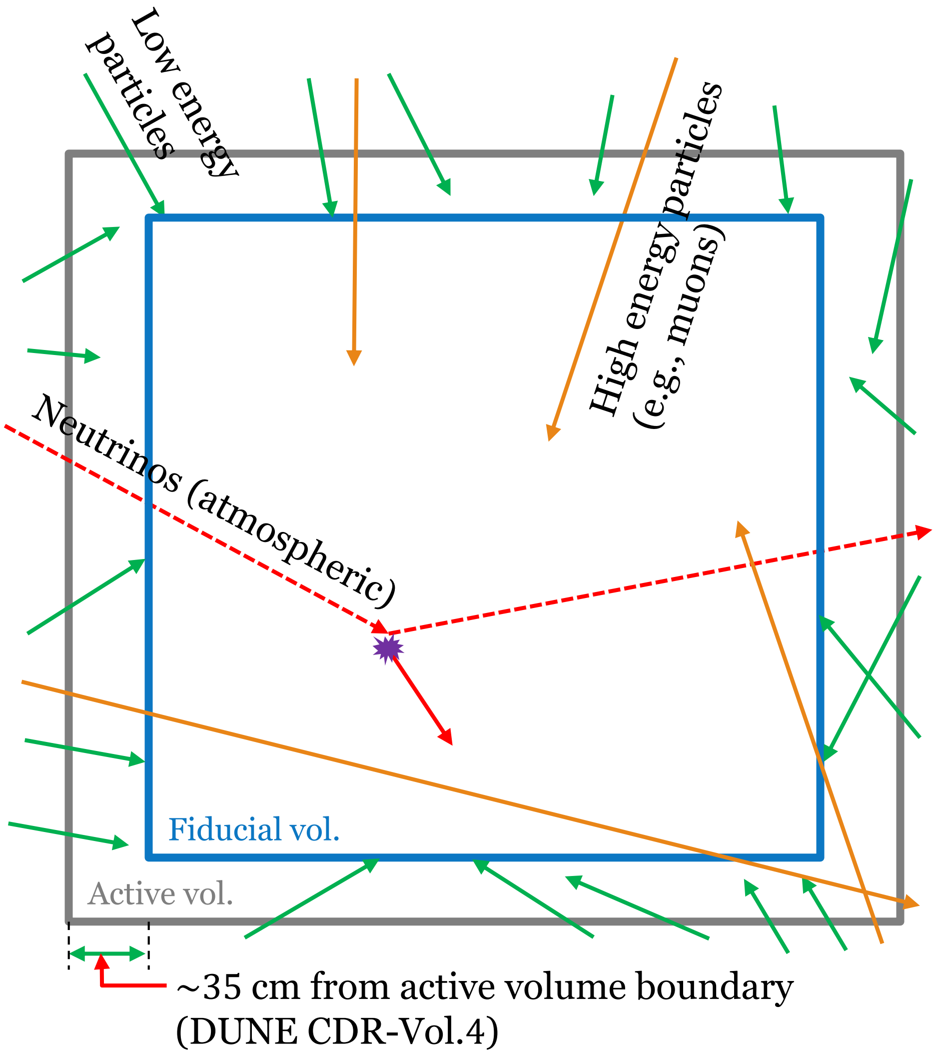

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Can be rejected by "**Earth Shielding**"
[Kim, Kong, **JCP**, Shin, arXiv: 1804.07302]

- **(Atmospheric) neutrinos** are (potentially) irreducible.

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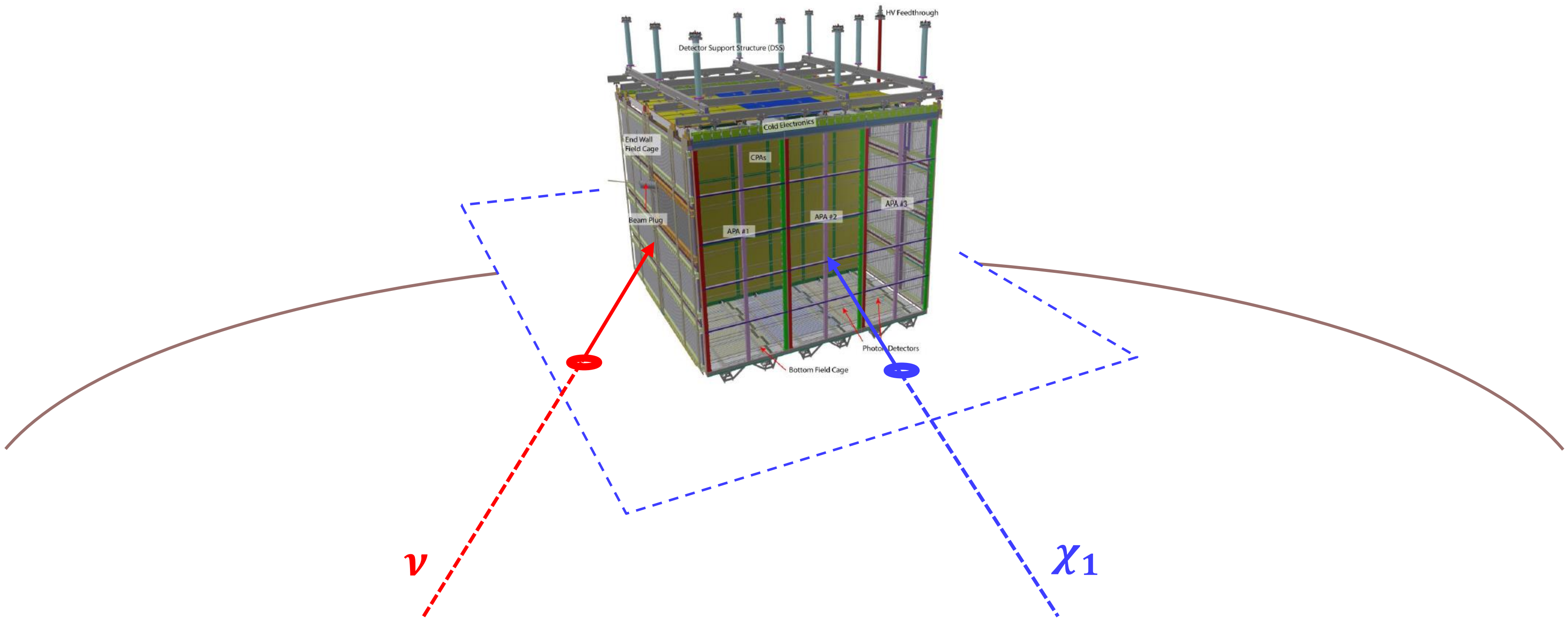
Effective Data Collection for 1yr-Run



$\sim D_f \cdot 40$ neutrino-induced e-like, single-track events/yr/kt

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

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 for one year run ➔ D_f=1/2)

Number of Signal Events

❖ Number of signal events N_{sig} is

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

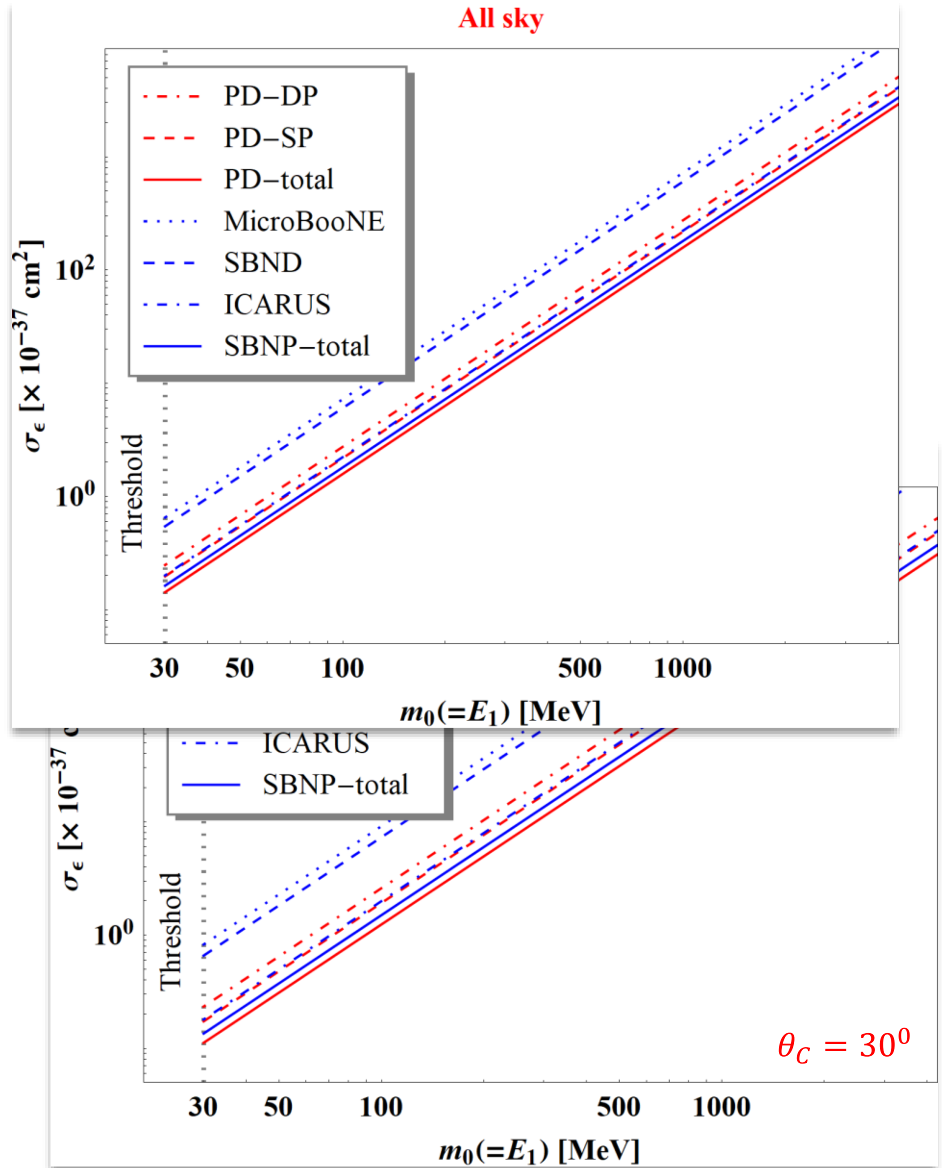
- ✓ σ_ϵ: scattering cross section between χ_1 (BDM) and electron (target)
- ✓ D_f: data collection fraction of day
- ✓ $\mathcal{F}$: flux of incoming (boosted) χ_1
- ✓ t_{exp}: exposure time
- ✓ N_e: total number of target electrons

Controllable! (once a detector is determined)

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

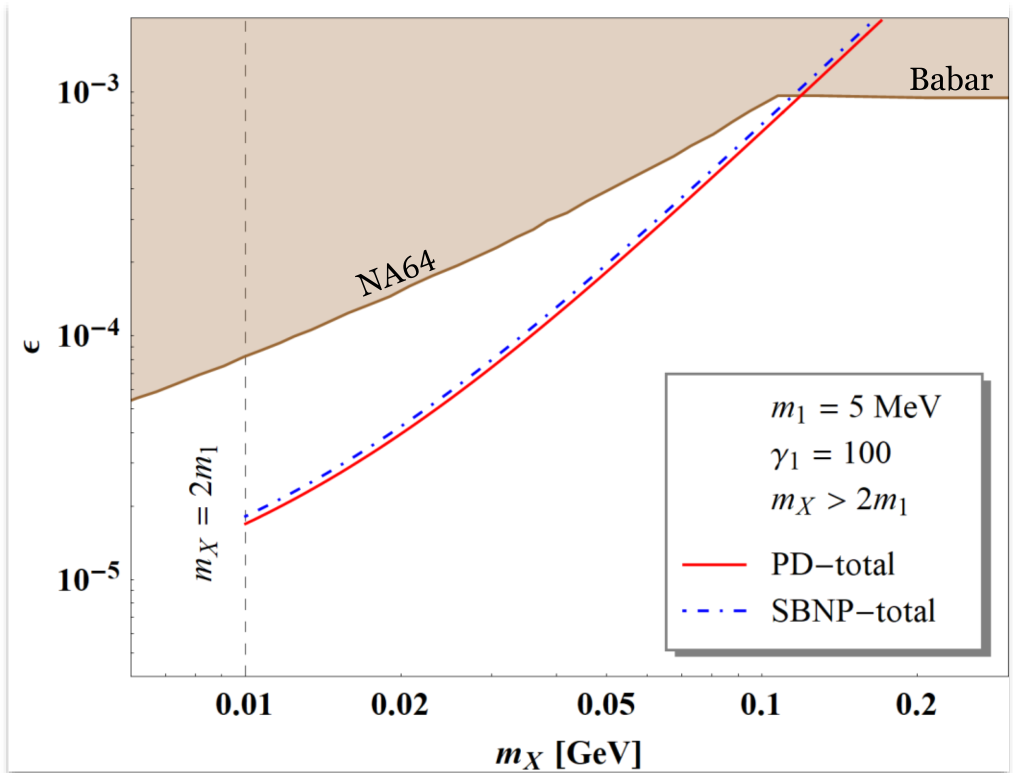
Model-Independent Reach

- 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.



D_f=1/2 is assumed.

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

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

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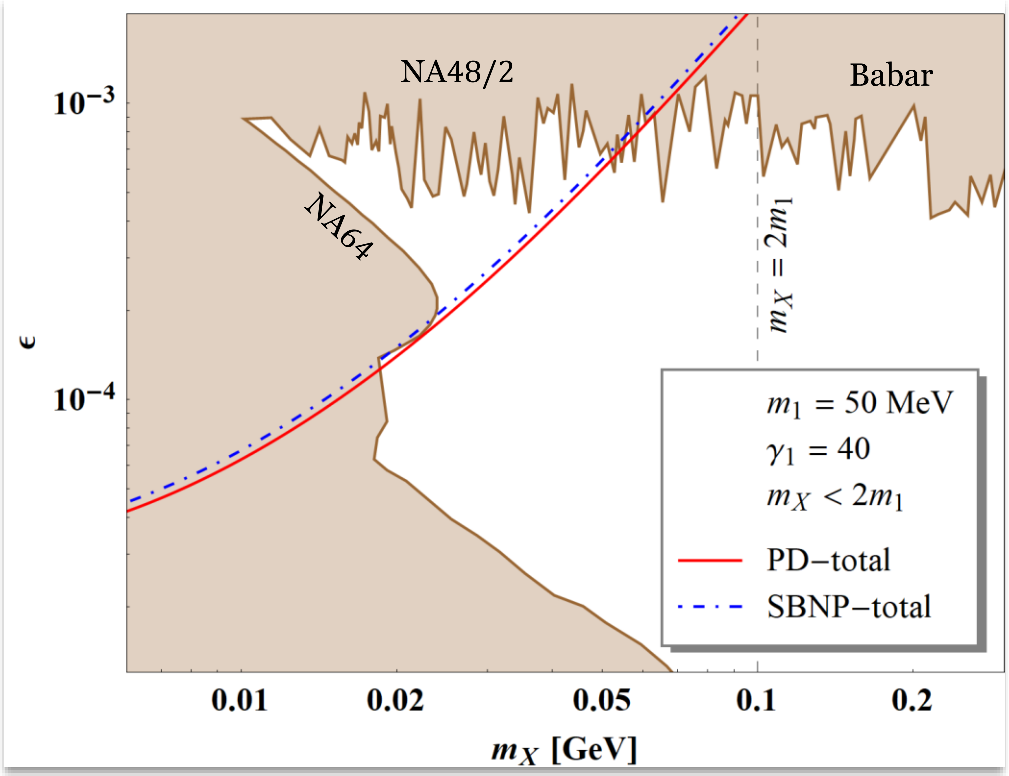

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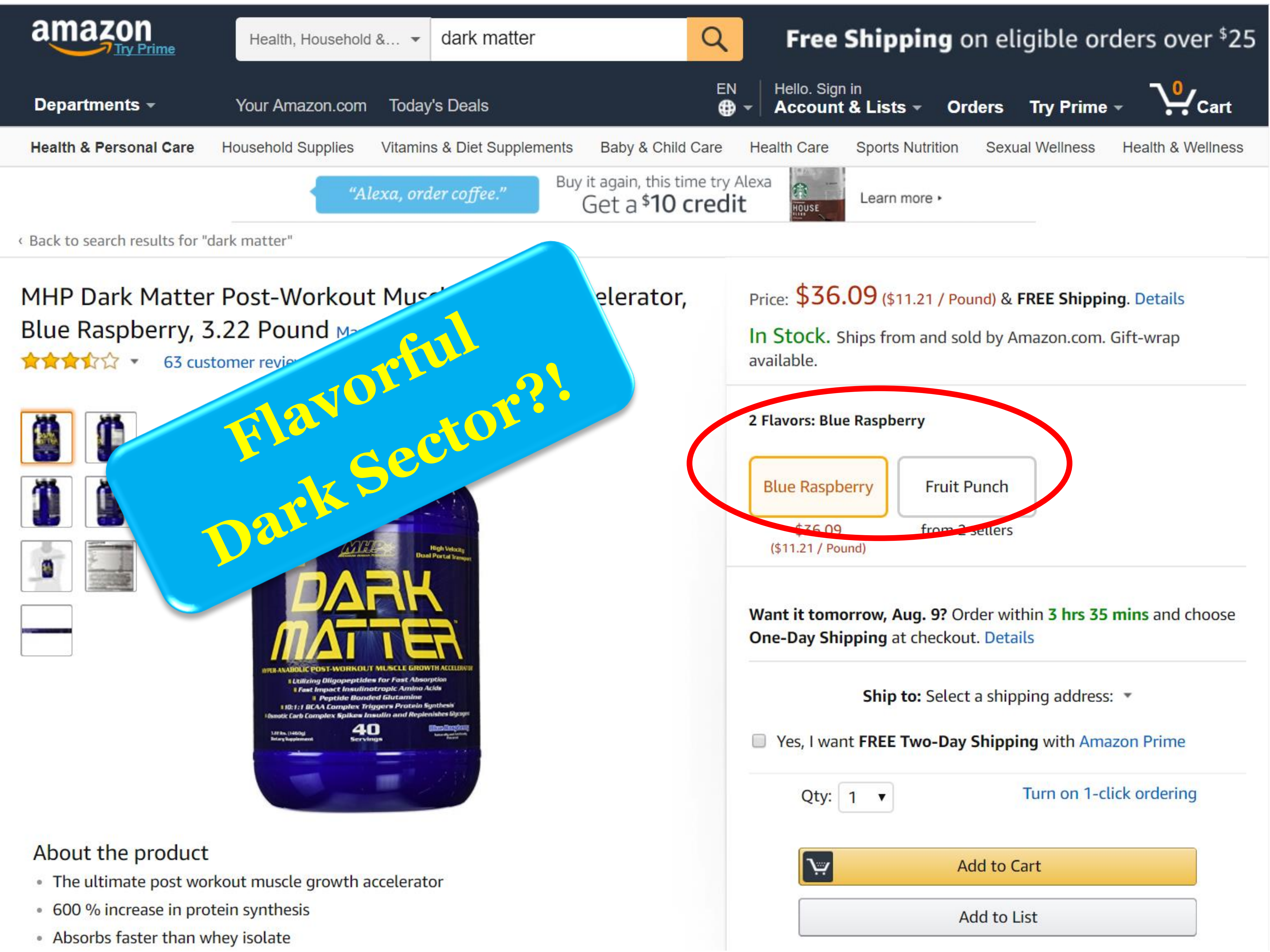
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Baby & Child Care
Health Care
Sports Nutrition
Sexual Wellness
Health & Wellness
"Alexa, order coffee."
Buy it again, this time try Alexa
Get a $10 credit
Learn more ›
‹ Back to search results for "dark matter"
MHP Dark Matter Post-Workout Mus... elerator, Blue Raspberry, 3.22 Pound
63 customer revie...
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Dark Sector?!
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from 2 sellers
Want it tomorrow, Aug. 9? Order within 3 hrs 35 mins and choose One-Day Shipping at checkout. Details
Ship to: Select a shipping address:
Yes, I want FREE Two-Day Shipping with Amazon Prime
Qty: 1
Turn on 1-click ordering
Add to Cart
Add to List
DARK MATTER
40 Servings
About the product
The ultimate post workout muscle growth accelerator
600 % increase in protein synthesis
Absorbs faster than whey isolate

Conclusion

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

Focus of this talk!

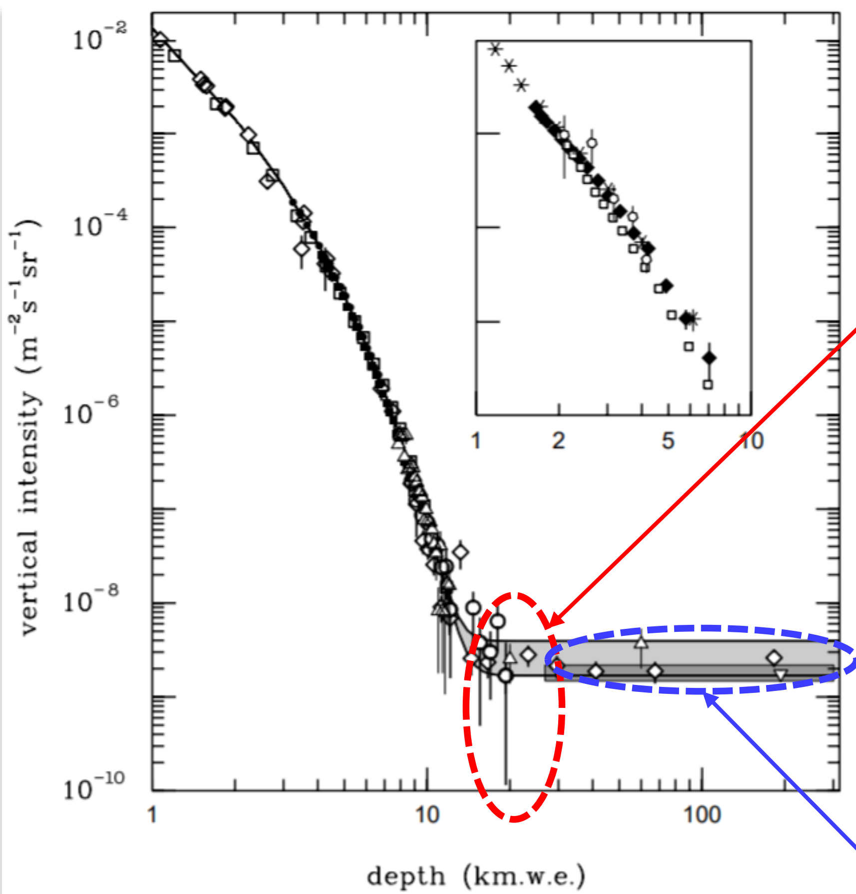
- (light) BDM search is promising & provides a new direction to study DM phenomenology.
- Huge cosmic-ray BG can be **well controlled** with the "**Earth Shielding**" effect.
- **Surface detectors** possesses excellent sensitivities to a wide range of (light) BDM

  ➔ 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

Muon Flux inside the Earth



[Particle Data Group (2015)]

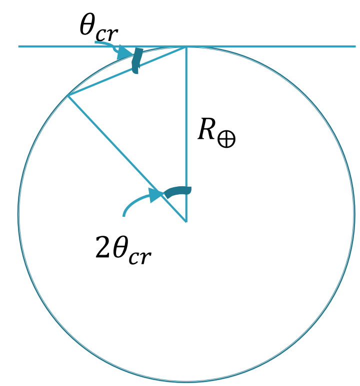
Flattened by neutrino-genic muons

- 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 $\sim 10^{11}$.

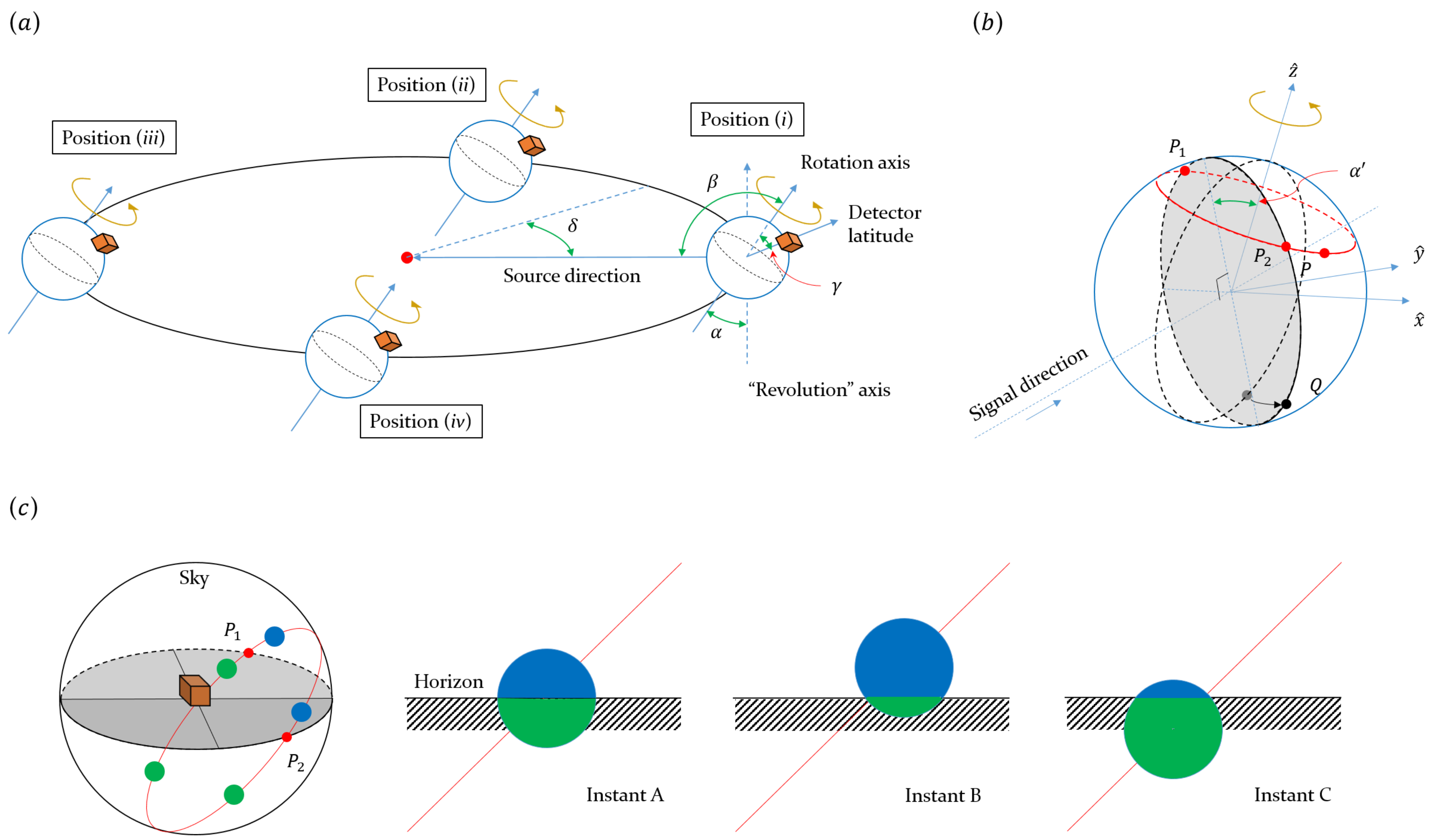
➔ (Potential) muon-induced BG is negligible for muons incident at $\theta > \theta_{cr}$.

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

Almost horizontal plane



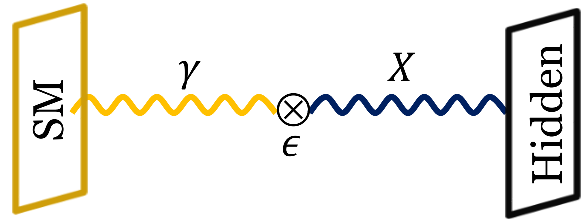
Effect of Earth's Rotation



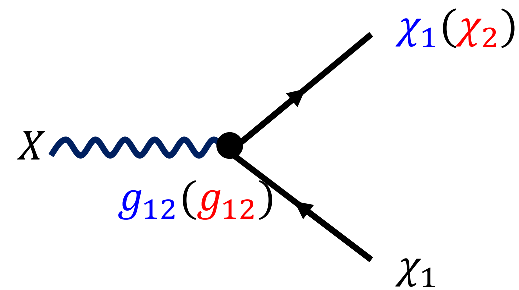
Benchmark Model

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

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)
  - ✓ Flavor-changing ➔ inelastic scattering (*i*BDM)



- 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.

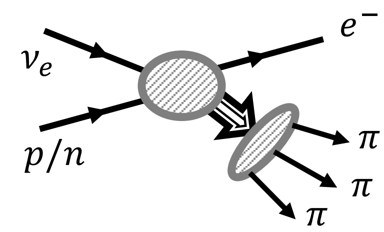
Potential BGs: Neutrinos

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)]

~**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.)

⇒ Potential BGs for elastic scattering signal (eBDM) events

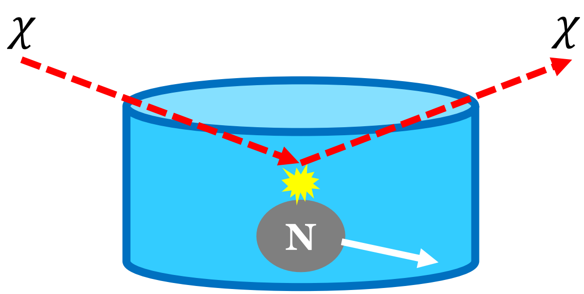
Multi-track candidates: **5.2** /yr/kt

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

⇒ Very likely to be background-free for inelastic scattering signal (*i*BDM) events

Typical DM Direct Search

❖ (Mainly) focusing on "*Non*-relativistic" weakly interacting massive particles (WIMPs) search



[Goodman, Witten (1985)]

(*in*)Elastic scattering of

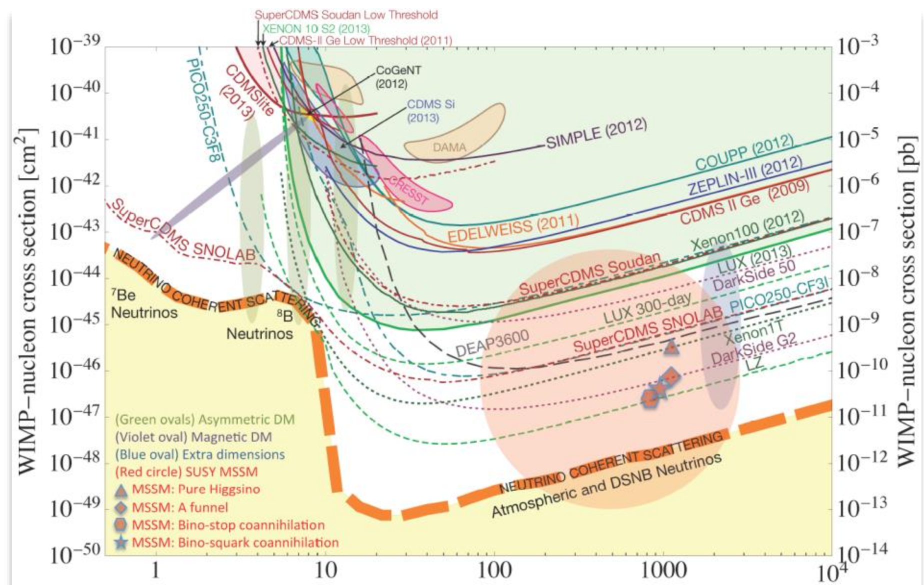
- ✓ ~~Non~~-relativistic
- ✓ *Other* ~~Weak~~-scale DM
- ✓ with nuclei *or electron*

✓ $E_{\text{recoil}} \sim mv^2$

$\sim 1 - 100$ keV

$(v/c \sim 10^{-3})$

✓ Detectors designed to be sensitive to this E range

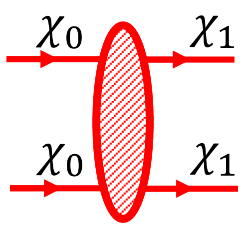


LZ-TDR (2017)

- ✓ No solid observation of WIMP signals
- ✓ A wide parameter respace already excluded
- ✓ Close to the neutrino "floor"
- ✓ Need new ideas!

Boosted DM (BDM) Signatures

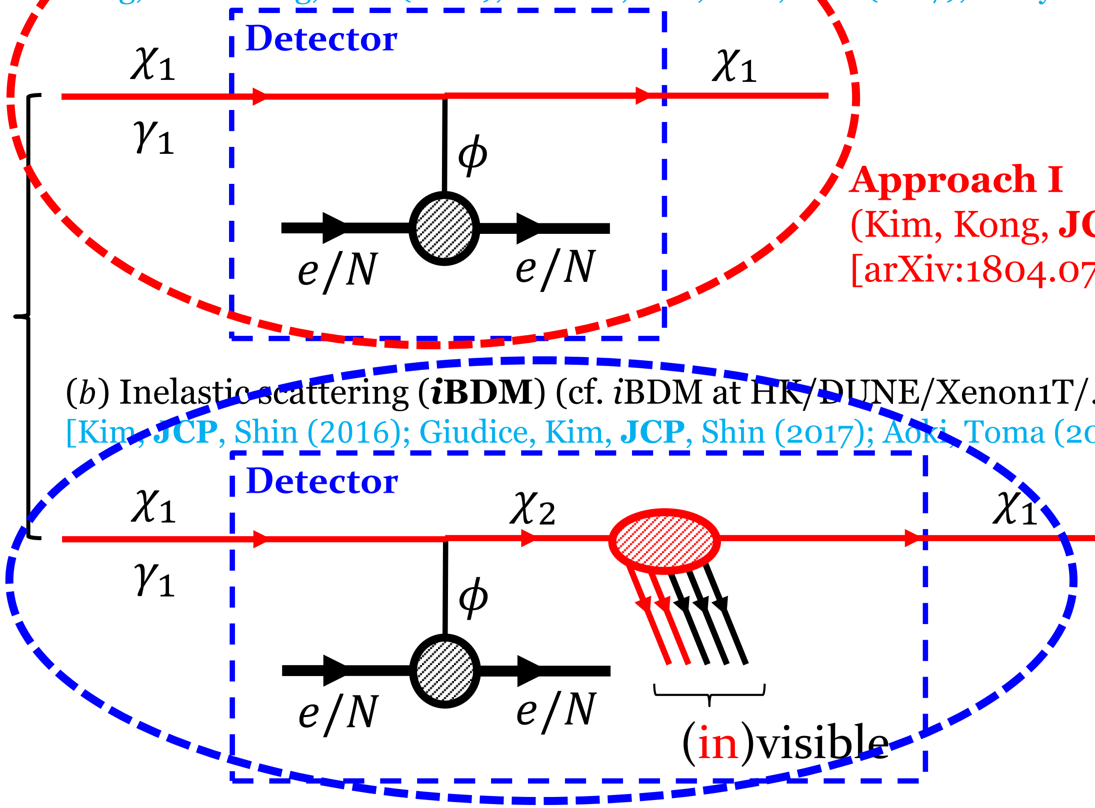
$\mathcal{F}_{\chi_1} = \sim 10^{-1} - 10^{-6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
with $m_0 = E_1 = \sim 30$ MeV -10 GeV



Galactic Center

(a) Elastic scattering (**eBDM**) (cf. eBDM at HK/DUNE/PINGU/Xenon1T/…
[Agashe et al. (2014); Kong, Mohlabeng, **JCP** (2014); Necib et al. (2016); Alhazmi, Kong, Mohlabeng, **JCP** (2016); Giudice, Kim, **JCP**, Shin (2017); many more])

(b) Inelastic scattering (***i*BDM**) (cf. *i*BDM at HK/DUNE/Xenon1T/…
[Kim, **JCP**, Shin (2016); Giudice, Kim, **JCP**, Shin (2017); Aoki, Toma (2018)])



Approach I
(Kim, Kong, **JCP** & Shin, [arXiv:1804.07302])

Approach II
(in collaboration with Chatterjee et al., [arXiv:1803.03264])

- 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

Model-Independent Reach

❖ More familiar parameterization is possible with the below modification.

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

N^{90}: 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

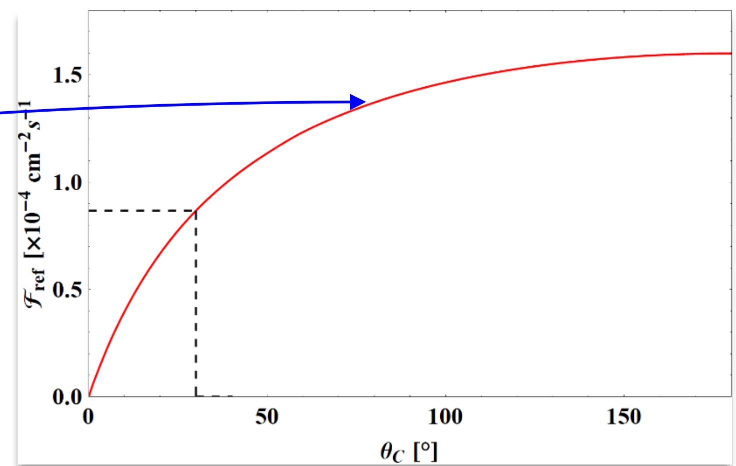
D_f=1/2 is assumed.

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

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

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

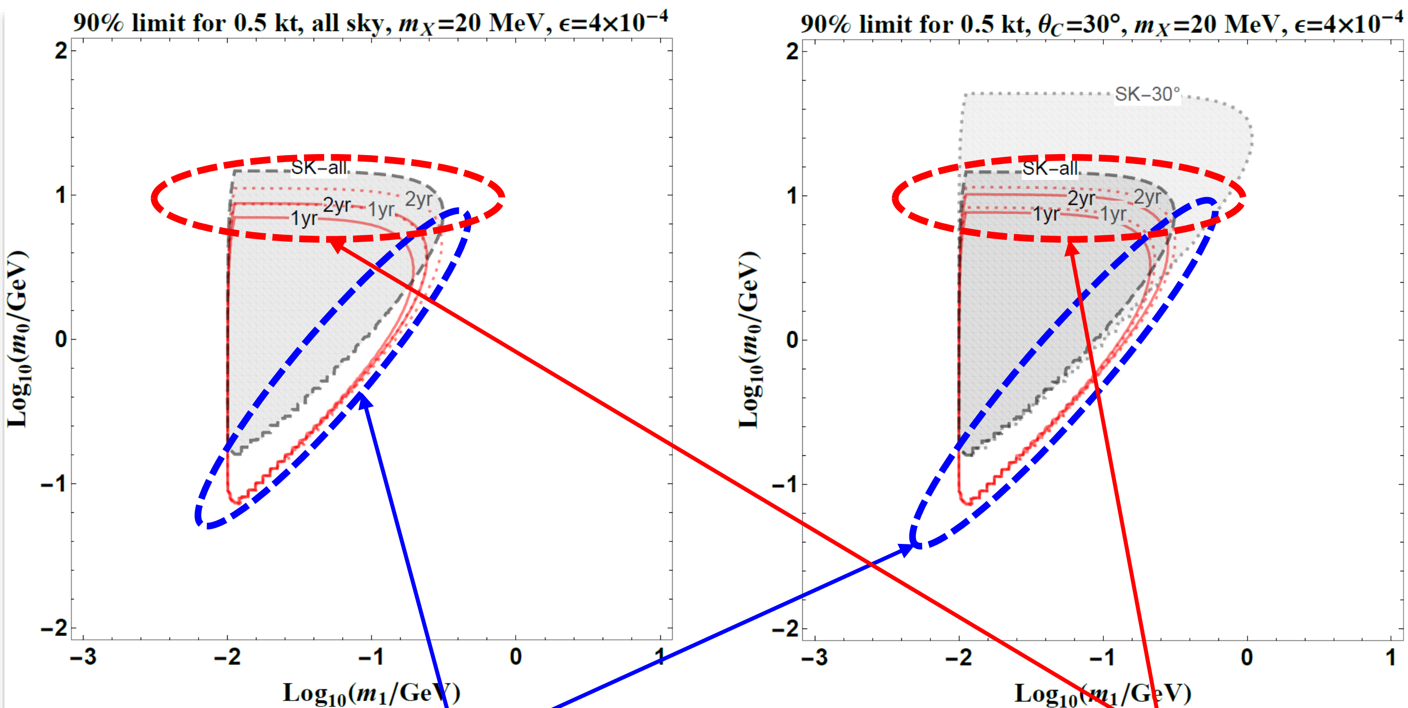
$$\sigma_\epsilon \geq \frac{N^{90}}{D_f\, t_{\rm exp}\, N_T \mathcal{F}_{\rm ref}^{\theta_C}}\left(\frac{5\times10^{-26}\,{\rm cm}^3{\rm s}^{-1}}{\langle\sigma v\rangle_{\chi_0\bar{\chi}_0\to\chi_1\bar{\chi}_1}}\right)\left(\frac{m_0}{\rm GeV}\right)^2$$



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

Expected Experimental Reach

- A 0.5 kt-V_{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.

Detection of BDM

❖ Flux of boosted χ_1 near the earth

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

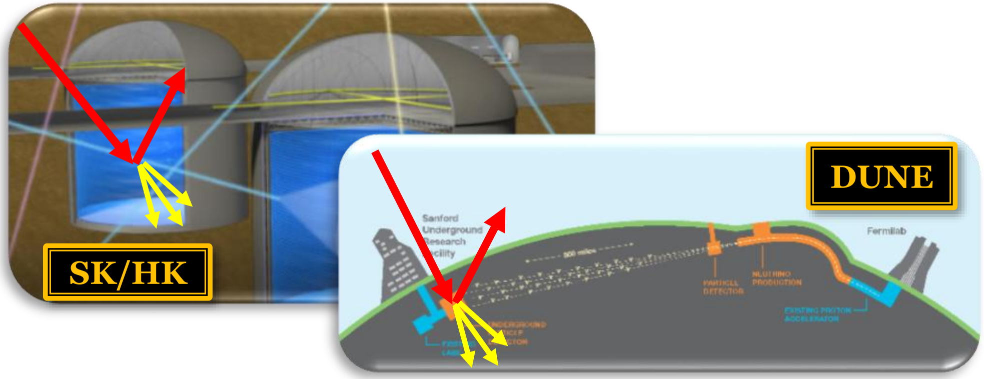
from the number density of DM χ_0, $n_o = \rho_o / m_o$

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

one can obtain $\mathcal{F}_{\chi_1} \sim 10^{-6\sim 8} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ 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: SK/HK, DUNE, IceCube, …



❖ 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)