Search for Boosted DM @ Surface Detectors

Jong-Chul Park

CNU 충남대학교 CHUNGNAM NATIONAL UNIVERSITY

A. Chetterjee, A. De Roeck, D. Kim, Z. Moghaddam, **JCP**, S. Shin, L. Whitehead, J. Yu [arXiv: 1803.03264]

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

NDM 2018

6th Symposium on Neutrinos and Dark Matter in Nuclear Physics 2018

2018. 6. 29 (Fri) – 7. 4 (Wed) | IBS HQ, Daejeon, Korea

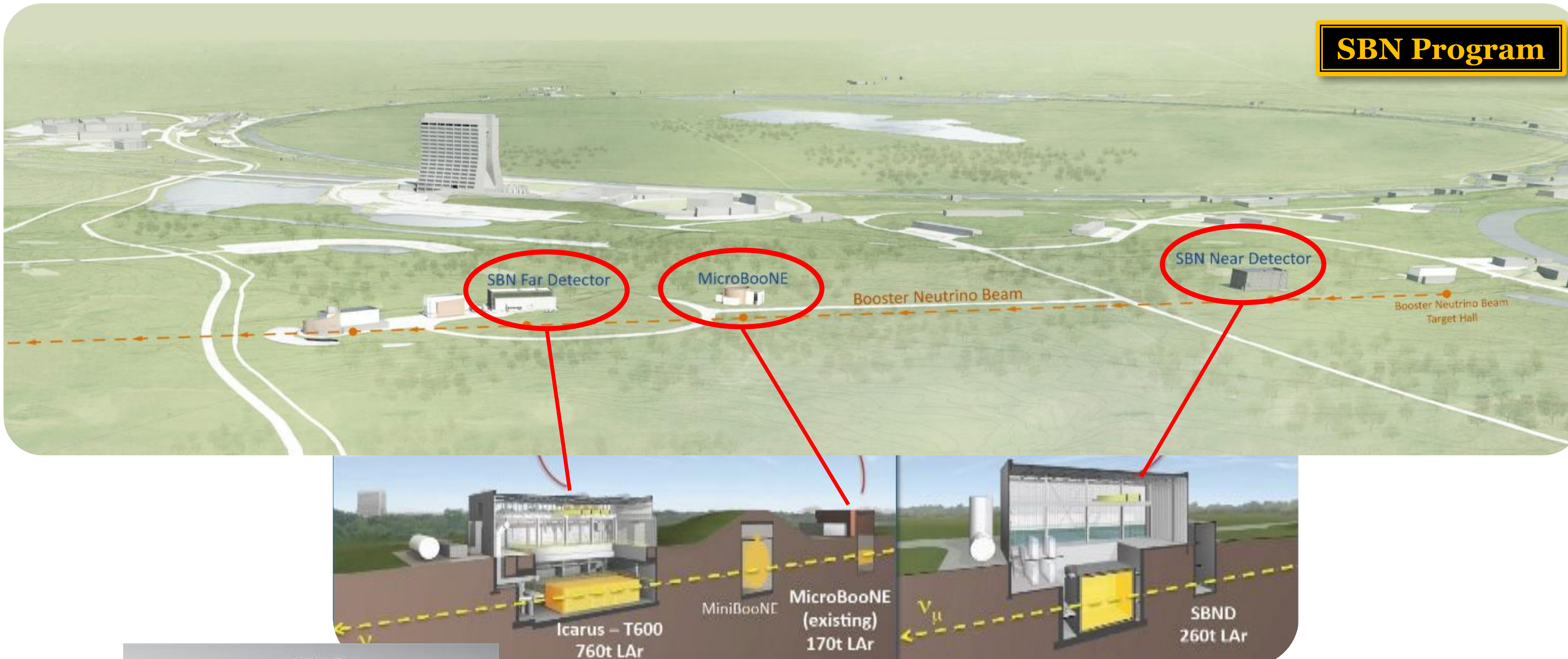
July 03 (2018)

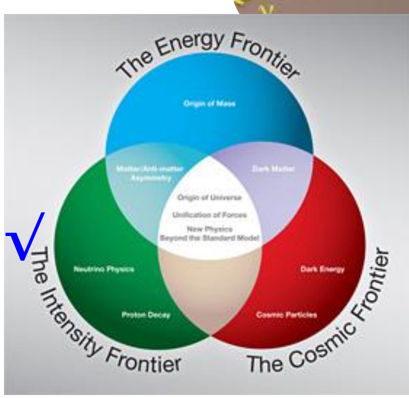
Surface ν Detectors

Physics Motivation?

Surface ν Detectors: SBN

❖ Short-Baseline Neutrino (SBN) Program @ Fermilab

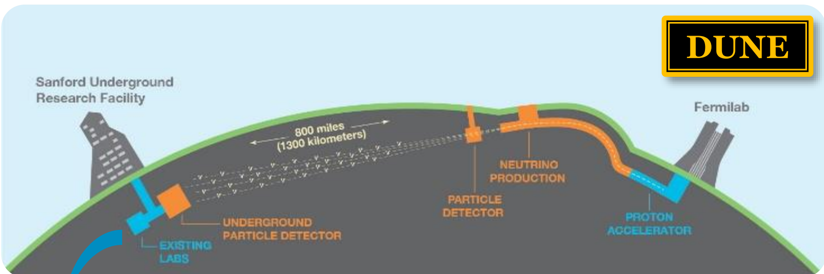


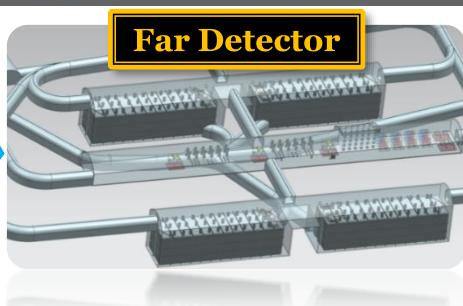


- ✓ Physics @ SBN: *ν* oscillation, sterile *ν*, etc.
- ✓ E spectrum & flavor of *ν*'s produced by the Booster Neutrino Beam
- ✓ Development of the LAr-TPC technology for DUNE

Surface ν Detectors: ProtoDUNE

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





4 ×10 kt

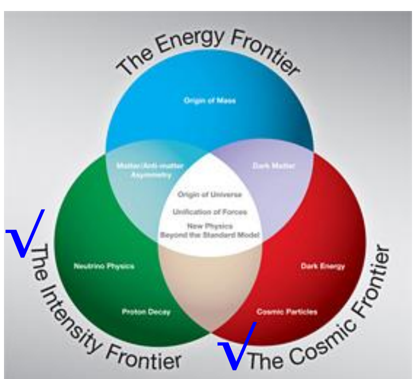
0.3+0.2 kt

❖ SP: single-phase

❖ DP: dual-phase

<Originally>

✓ Physics @ DUNE: neutrino, BSM, etc.

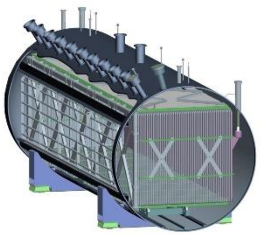


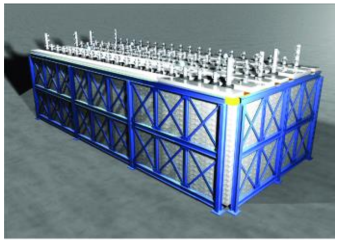
✓ To test the long-term stability & operation

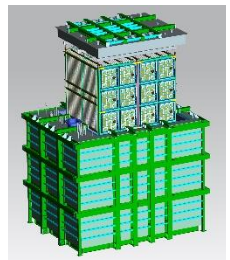
✓ To calibrate beam & cosmic-ray responses

Surface ν Detectors: Status

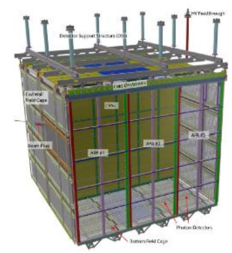
SBN Program

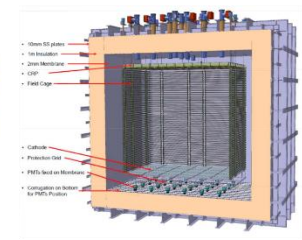






ProtoDUNE





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	~ 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)**

Other Physics Motivation?

Any physics potential with the SBN/ProtoDUNE detectors,

especially BSM physics?

Surface ν Detectors

Other Physics Motivati… …n?

Any physics potenti… …oDUNE detectors,

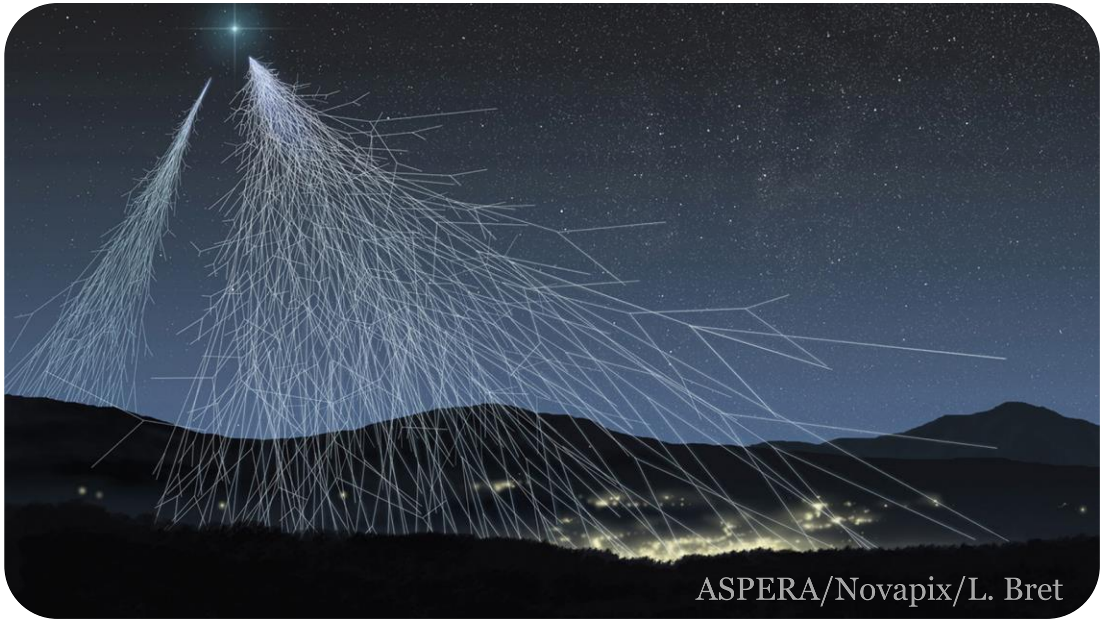
…r physics?

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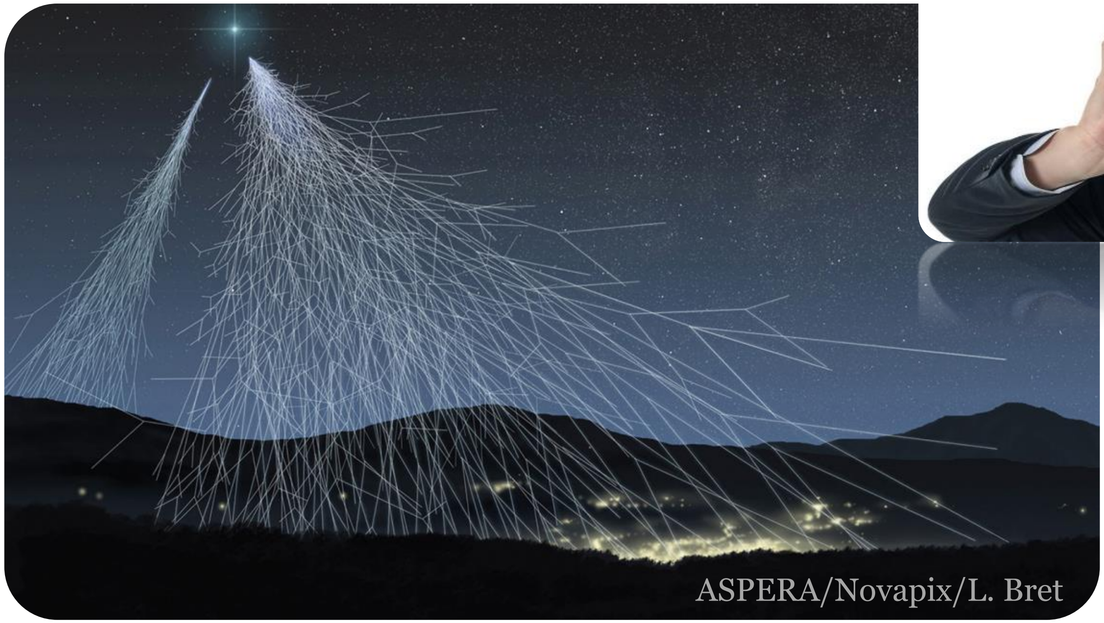
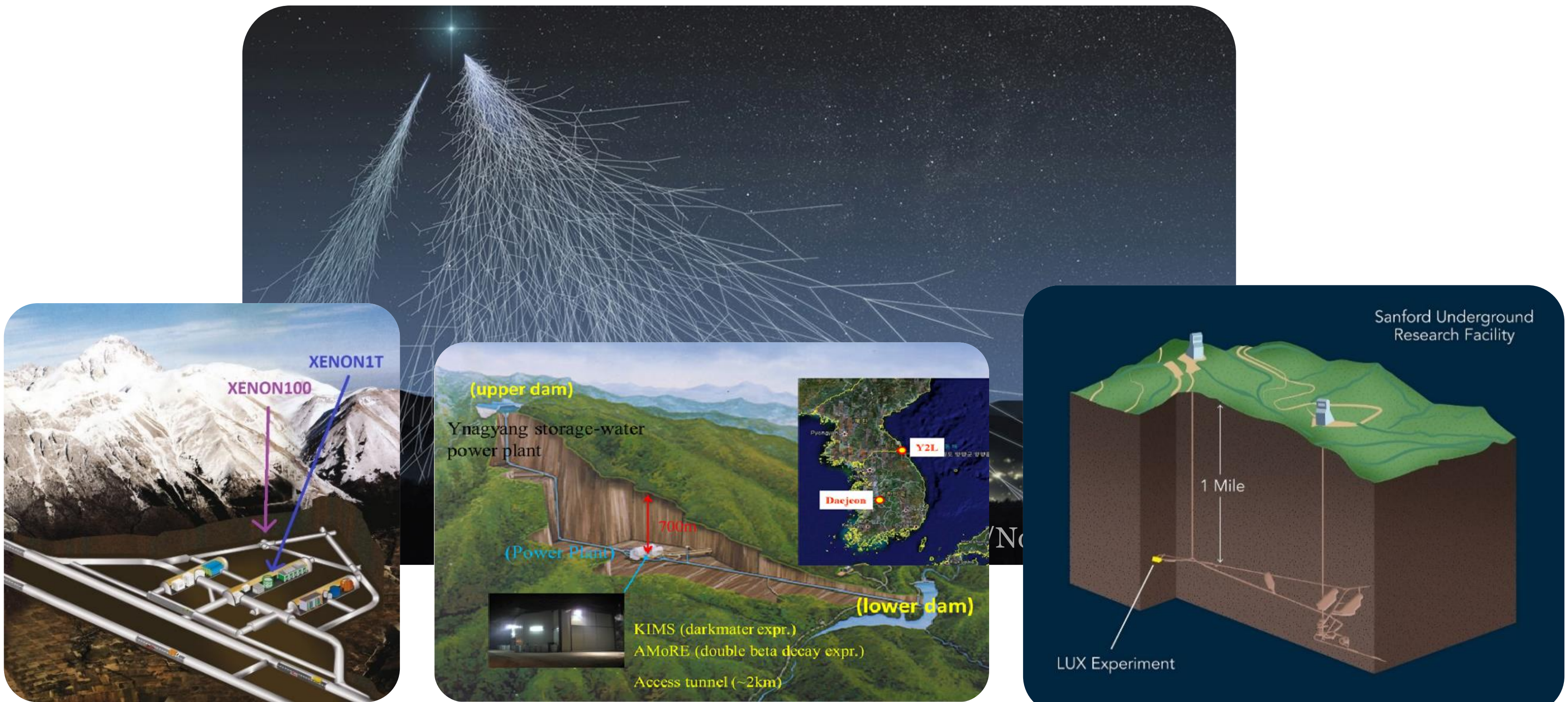


Surface ν Detectors: Common Belief

- 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. (Similar to up-going ν searches @ SK, IceCube, NOvA, etc)

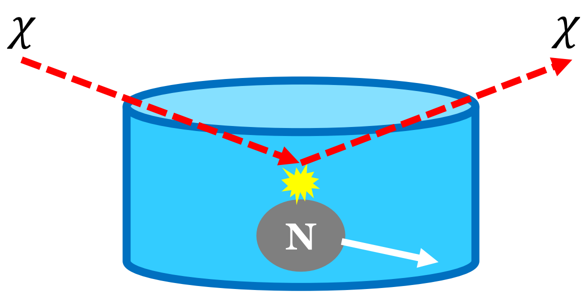
➔ Potential backgrounds in that direction are significantly suppressed while signals are intact.

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.)

Typical DM Direct Search

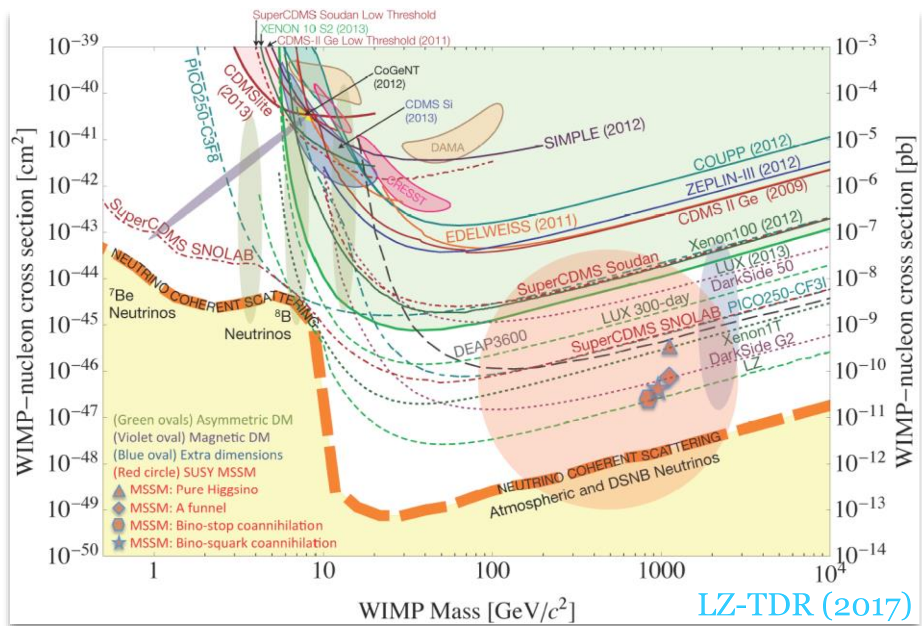
❖ (Mainly) focusing on "*Non*-relativistic" weakly interacting massive particles (WIMPs) search



[Goodman, Witten (1985)]

- ✓ Elastic scattering of
- ✓ Non-relativistic
- ✓ Weak-scale DM
- ✓ with nuclei

- ✓ $E_{recoil} \sim mv^2$
  $\sim 1 - 100$ 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!

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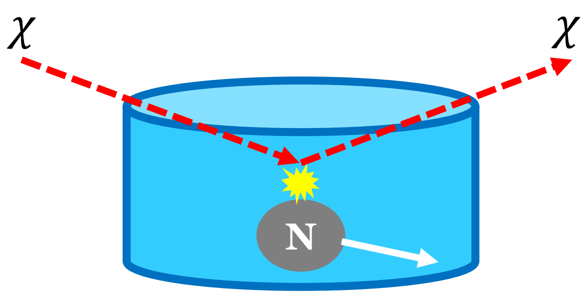

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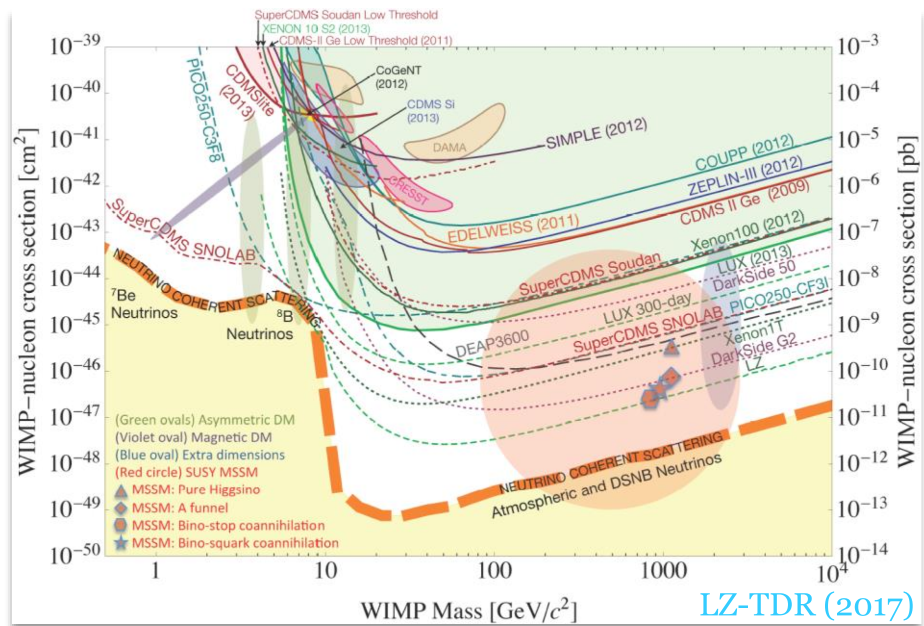
(in)Elastic scattering of
- ✓ ~~Non~~-relativistic
- ✓ Other ~~Weak~~-scale DM
- ✓ with nuclei or electron



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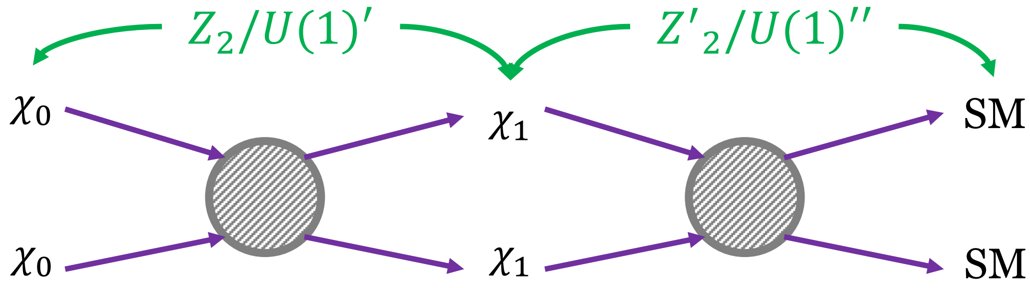
Two-component BDM Scenario

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



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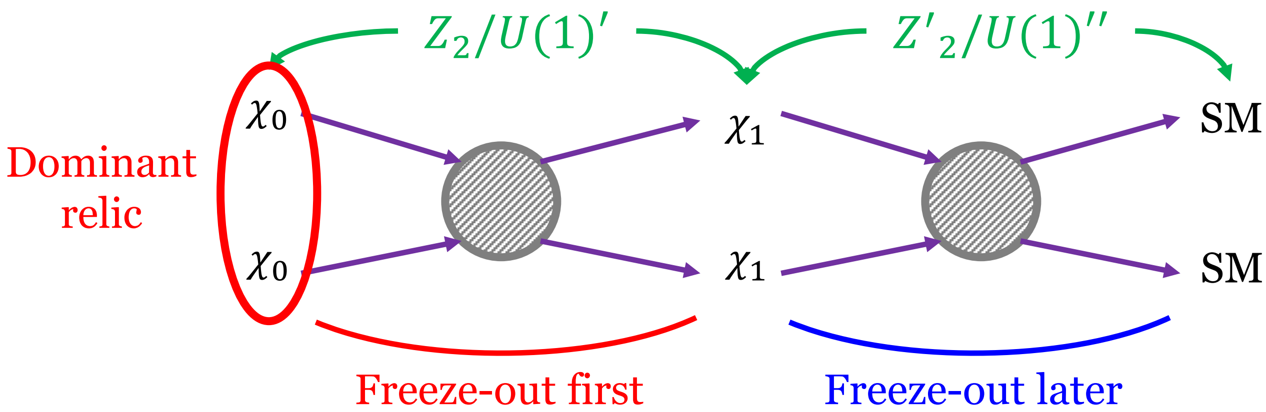
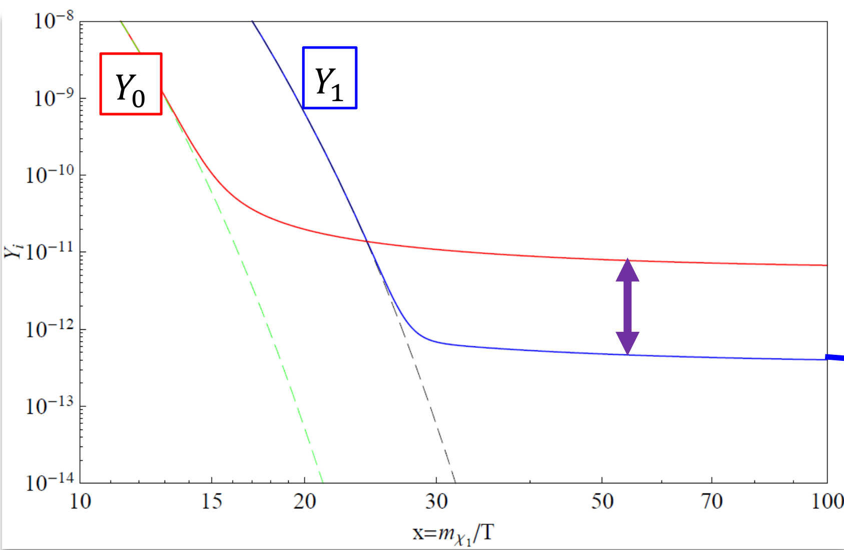


“**Assisted Freeze-out**” Mechanism



✓ 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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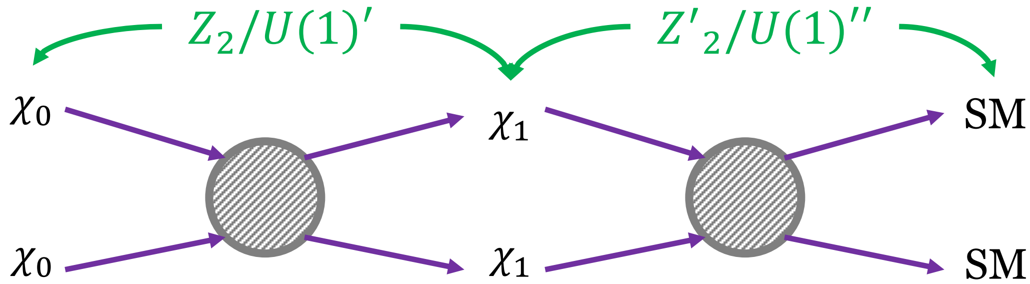
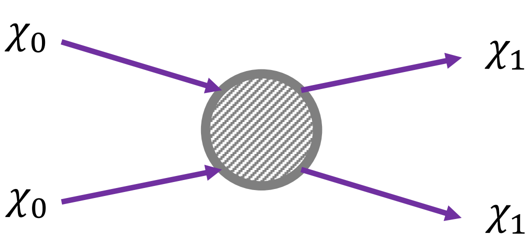


$\chi_0\chi_0 \to \chi_1\chi_1$ (current universe): **Relativistic!!** ($\gamma_1 = m_0/m_1$)

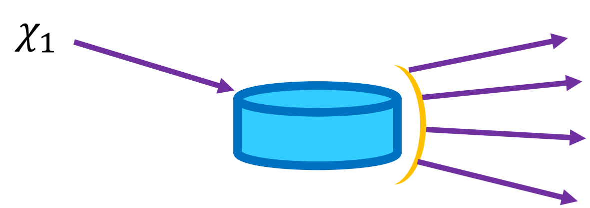
(Note that relic χ_1 is non-relativistic.)



(Galactic Center)

becomes boosted

($\gamma_1 = m_0/m_1$)

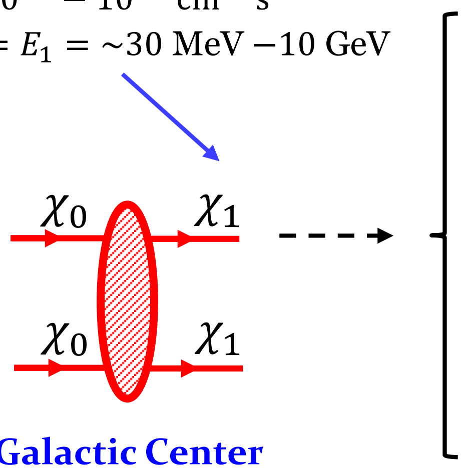


(Laboratory)

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

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



- 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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(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])

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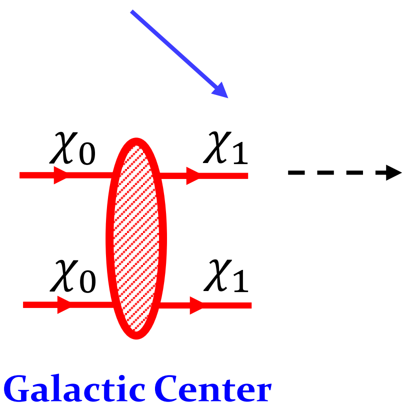

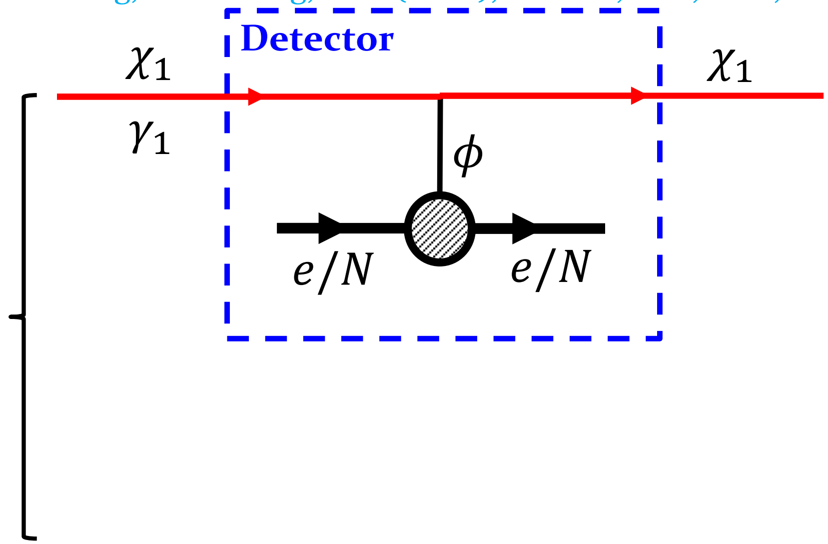

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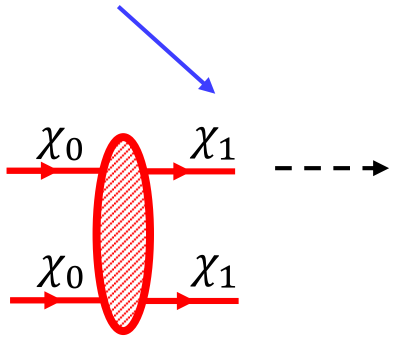

Galactic Center

(a) Elastic scattering (**eBDM**) (cf. eBDM at HK/DUNE/PINGU/Xenon1T/…
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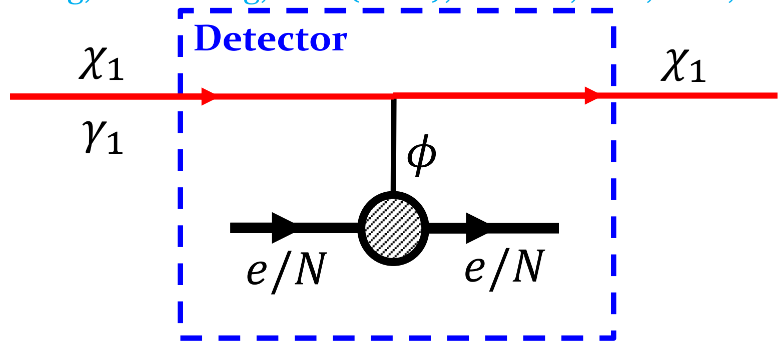

(b) Inelastic scattering (***i*BDM**) (cf. *i*BDM at HK/DUNE/Xenon1T/…
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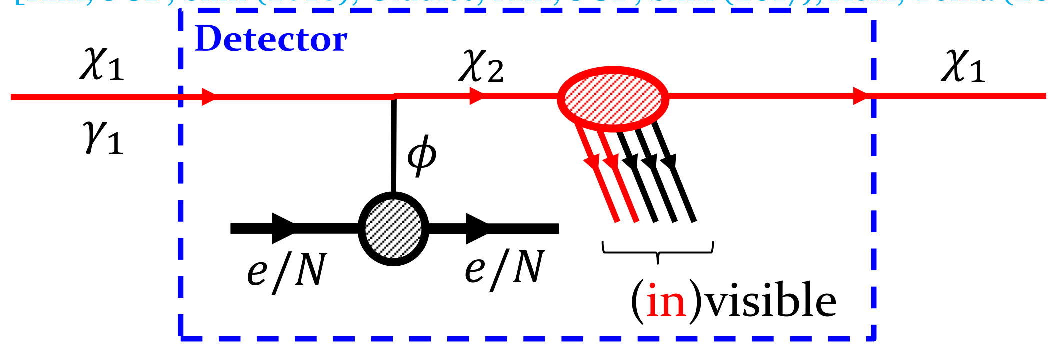

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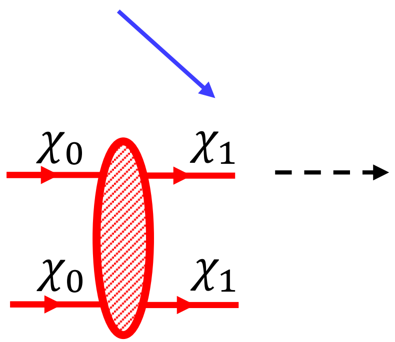

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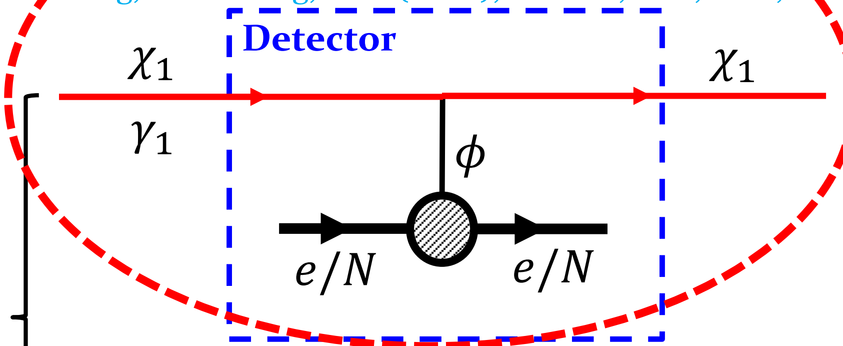

Approach I
(Kim, Kong, **JCP** & Shin, [arXiv:1804.07302])

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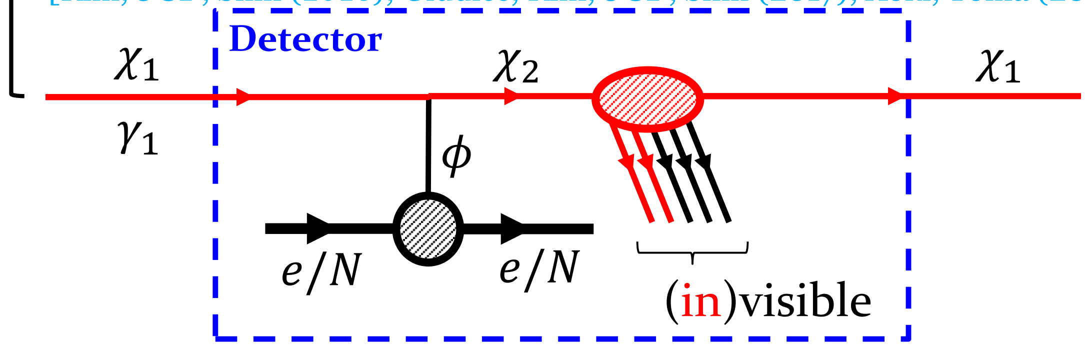

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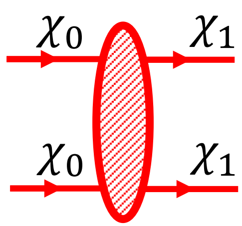

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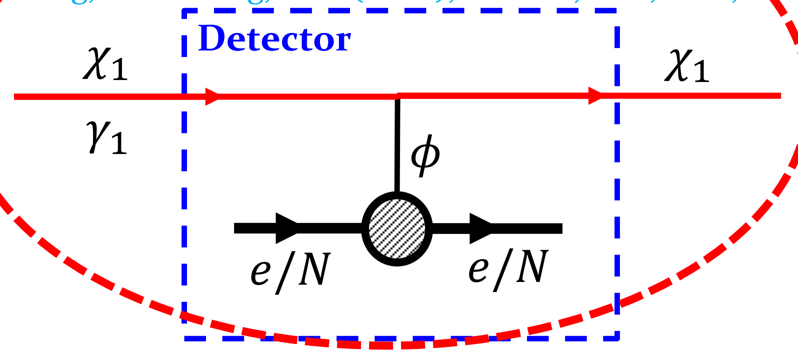

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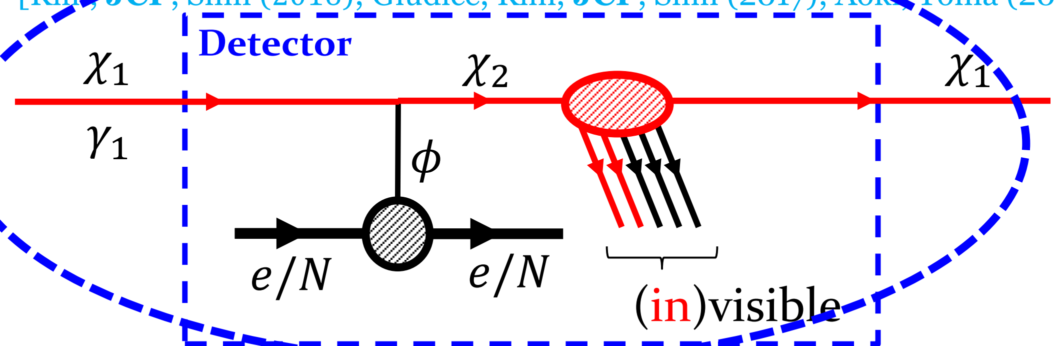

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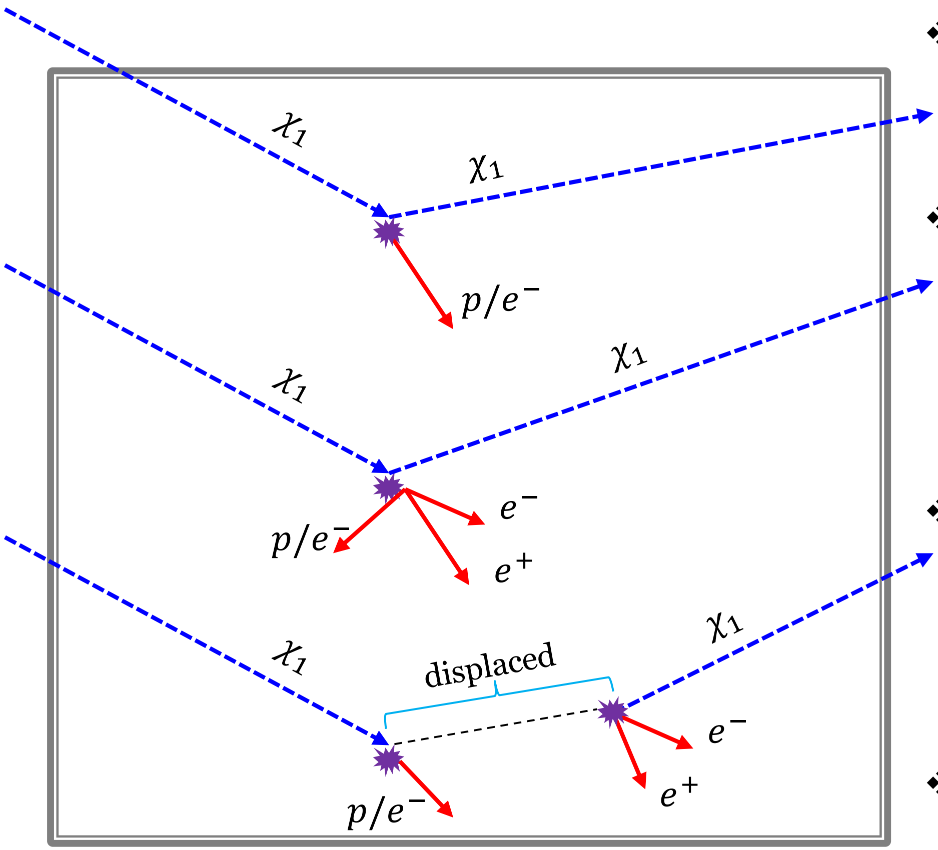
Approach II
(in collaboration with Chatterjee et al., [arXiv:1803.03264])

Expected Signatures



- Ordinary elastic scattering (eBDM): only e/p-recoil (ER/PR) ➔ single track
- "Prompt" inelastic scattering (*i*BDM): ER/PR+e^+e^- pair (from the decay of on-shell X: $m_2 > m_1 + m_X$) ➔ three tracks
- "Displaced" inelastic scattering (*i*BDM): ER/PR+e^+e^- pair (typically from a three-body decay of χ_2) ➔ three tracks
- **Tracks** will **pop-up** inside the fiducial volume.
- Focus on ER. But, Straightforwardly applicable to PR (up to form factor, DIS, etc.)

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

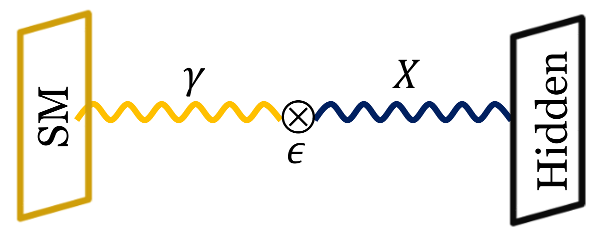
✓ Not small enough for small-volume (~1 ton) detectors to have signal sensitivity (e.g., conventional WIMP detectors: Xenon1T, LZ, COSINE-100(+2 ton LS), ...)

✓ 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)

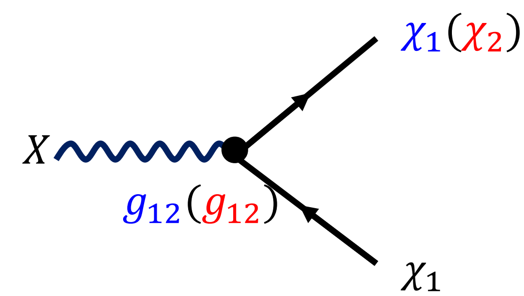
Benchmark Model

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

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.

Approach I

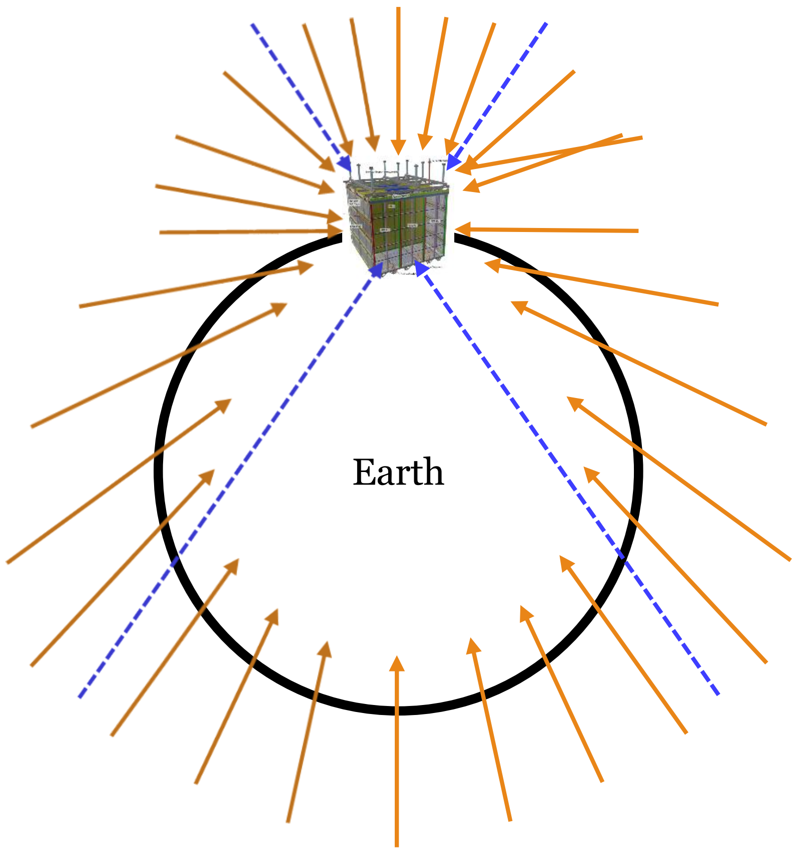
Earth Shielding

(Benchmark: eBDM)

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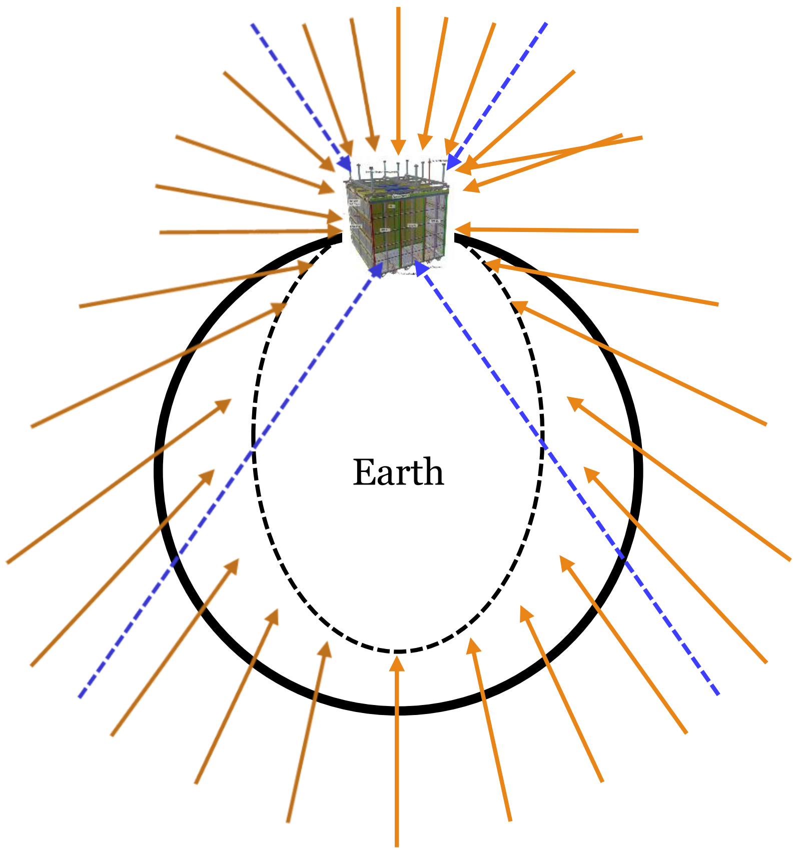
- ✓ Background and signal events are coming from everywhere.
- ✓ Half of them travel through the Earth.

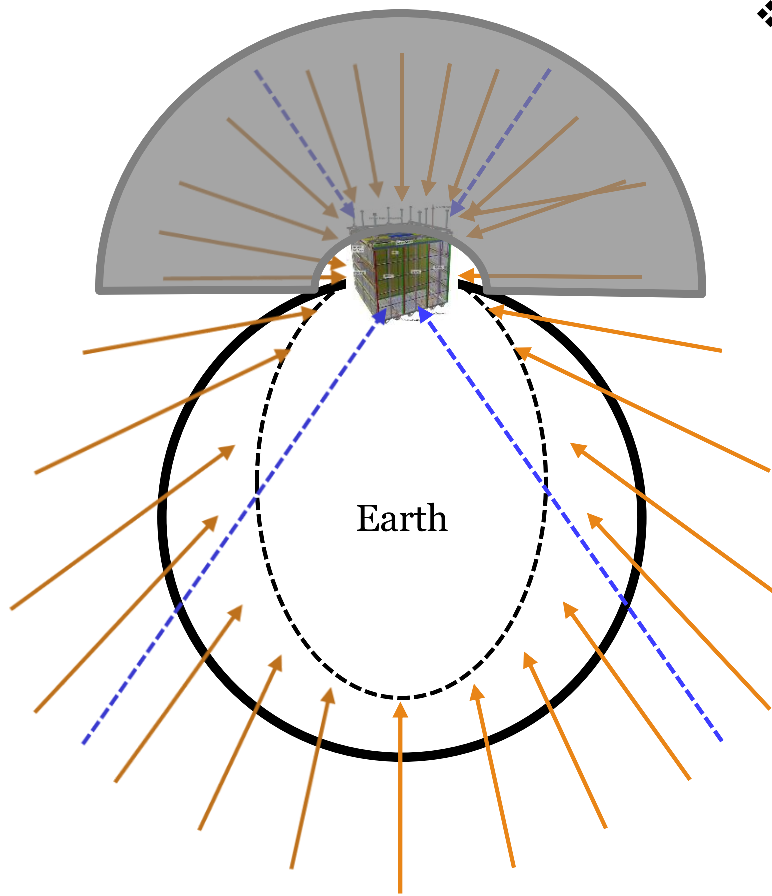
- ✓ Backgrounds cannot penetrate the Earth while signals can!



Earth Shielding

BG: Cosmic muons
Signal: Boosted DM

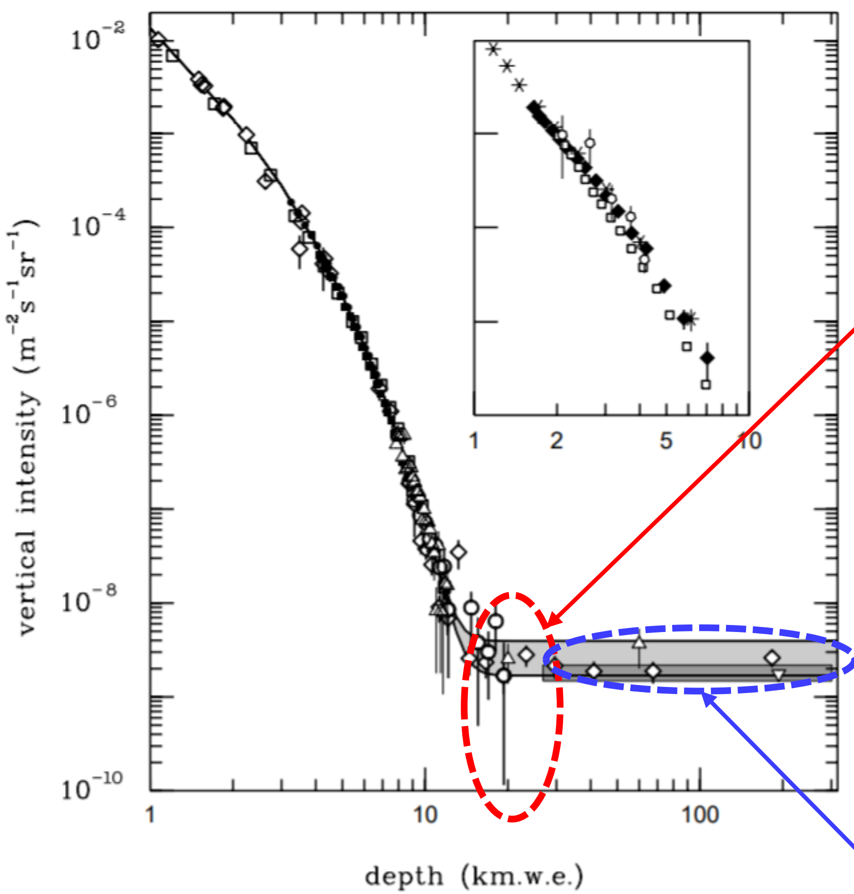
- ✓ Background and signal events are coming from everywhere.
- ✓ Half of them travel through the Earth.
- ✓ Backgrounds cannot penetrate the Earth while signals can!



❖ 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)]

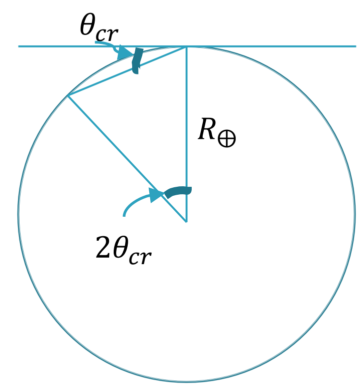
Flattened by neutrino-genic muons

- 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 $\sim 10^{11}$.

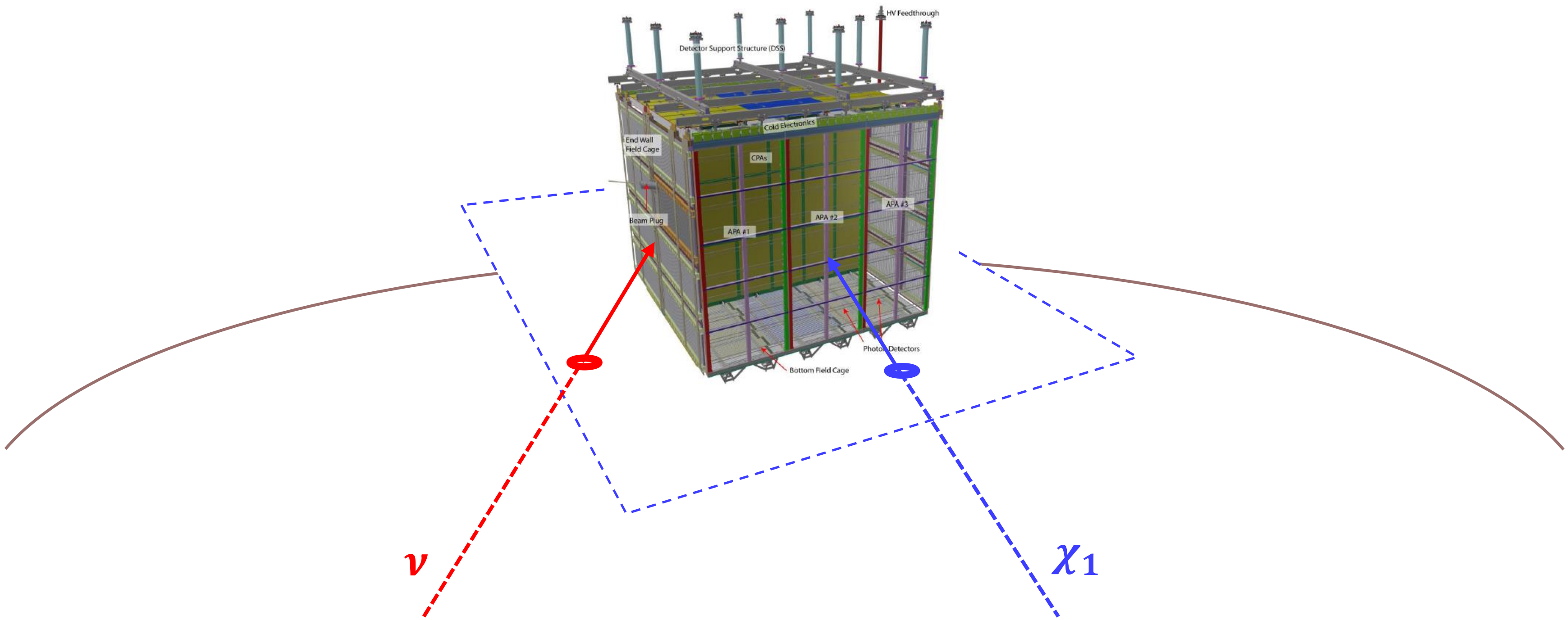
  ➔ (Potential) muon-induced BG is negligible for muons incident at $\theta > \theta_{cr}$.

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

Almost horizontal plane



Effective 1yr Data Collection

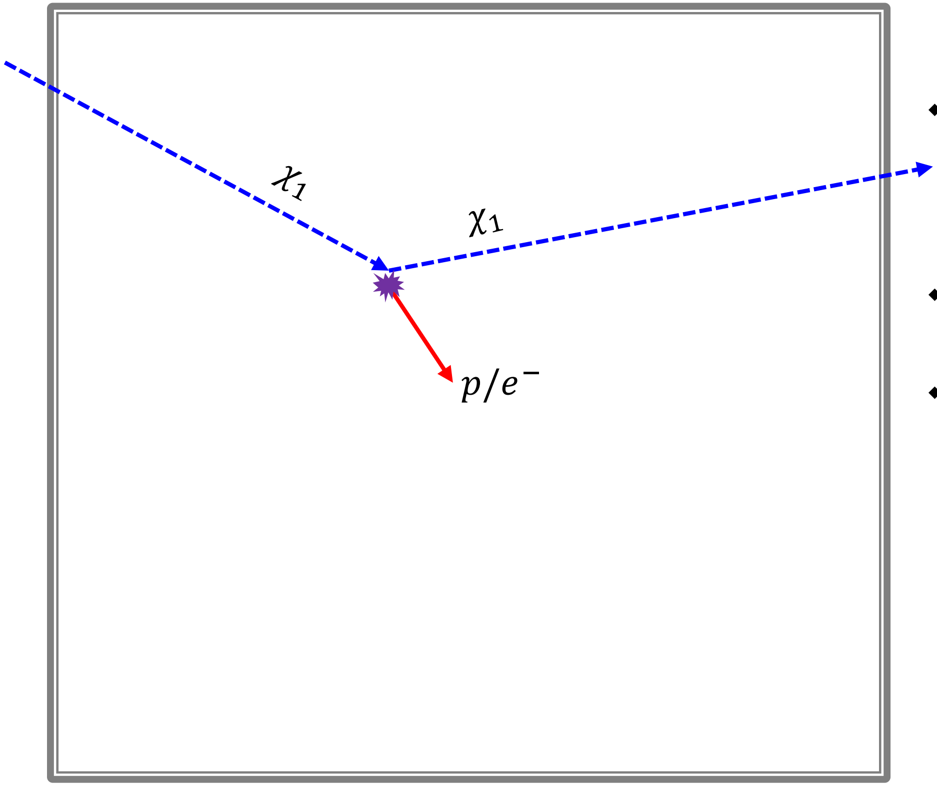


~D_f 40 neutrino-induced *e*-like, single-track events/yr/kt

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

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 ➔ D_f=1/2)

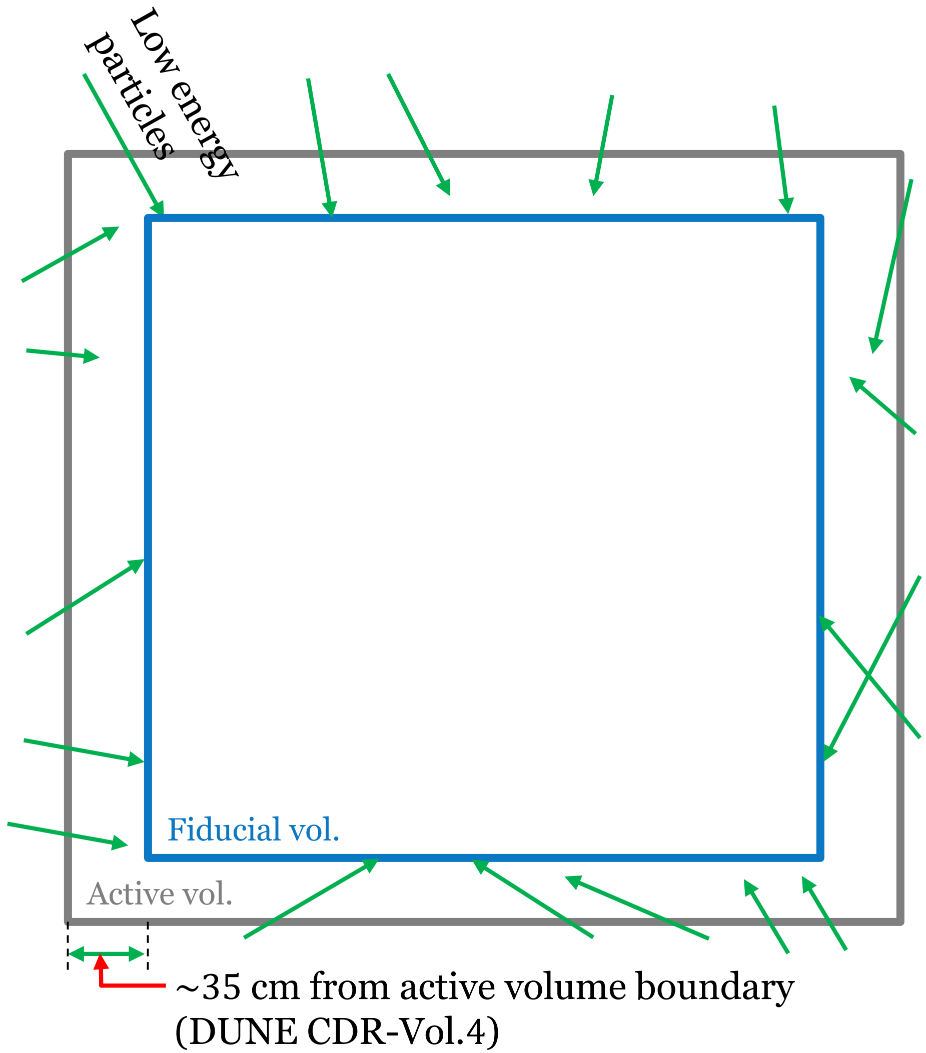
Expected Signatures (Reminder)



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

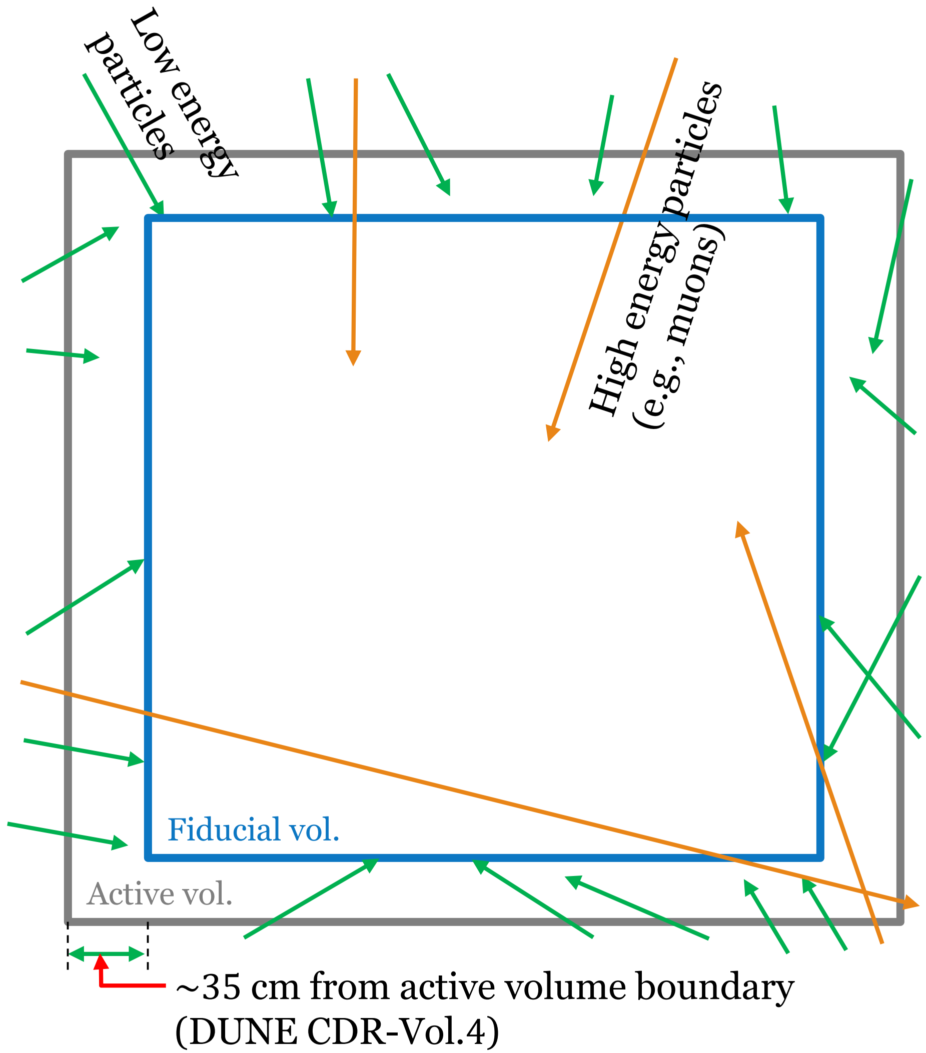
Potential Backgrounds

Potential Backgrounds



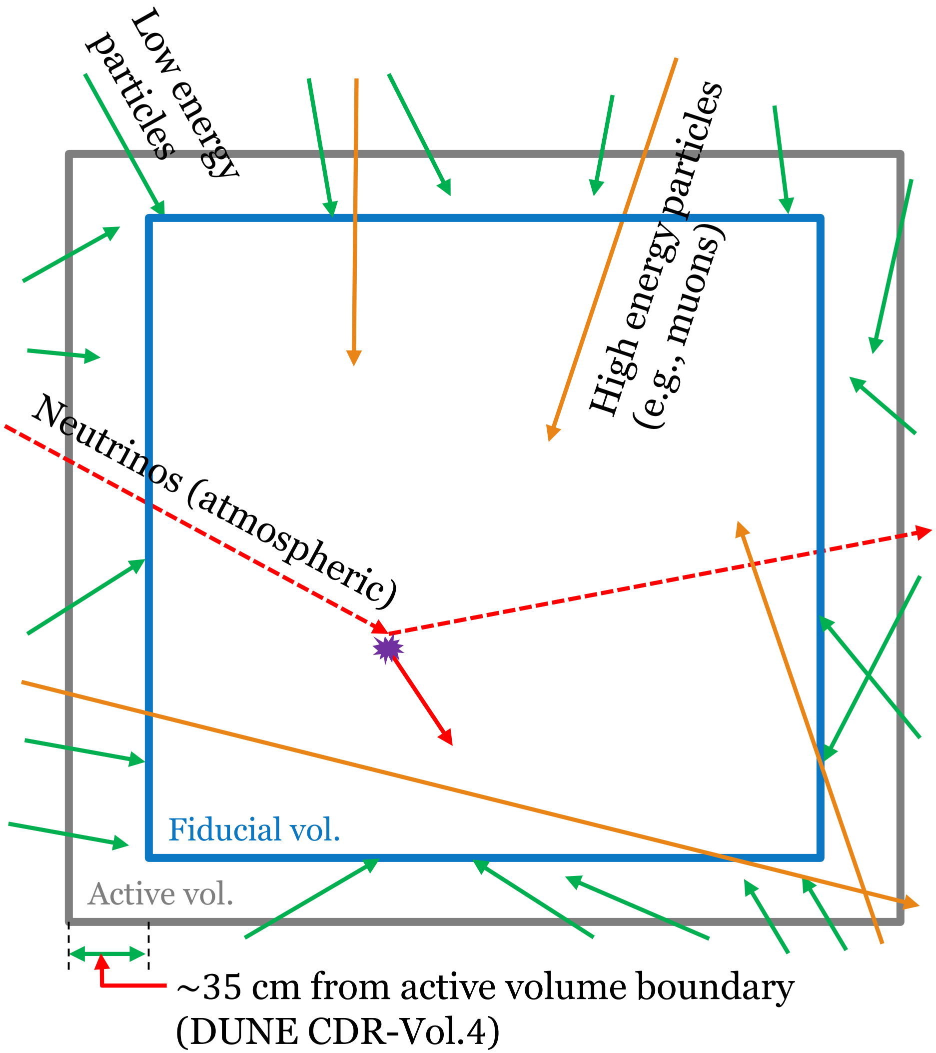
- Low E particles ($\lesssim$ 30 MeV) can be removed/suppressed by taking a fiducial vol. smaller than the active vol. (Fiducial vol.: e.g. ~170 t/300 t for ProtoDUNE DP/SP)

Potential Backgrounds



- Low E particles (≲ 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)
- 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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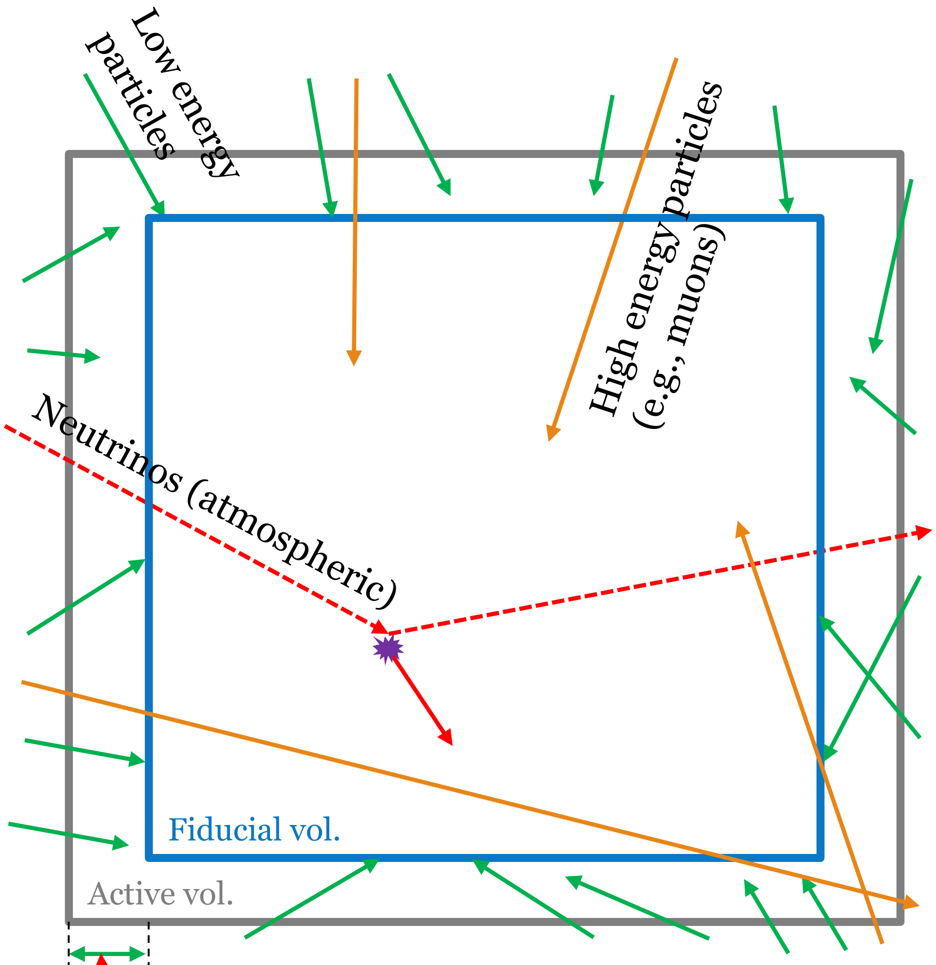
  ➔ A large flux is expected for the detectors placed on the ground, e.g., ProtoDUNE, SBN.
- (Atmospheric) neutrinos are (potentially) irreducible.

  ➔ ~40 single-track *e*-like events/yr/kt

Potential Backgrounds



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

- ❖ Low E particles (≲ 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)
- ❖ 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.

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

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

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.

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

N^{90} ← 90% C.L.

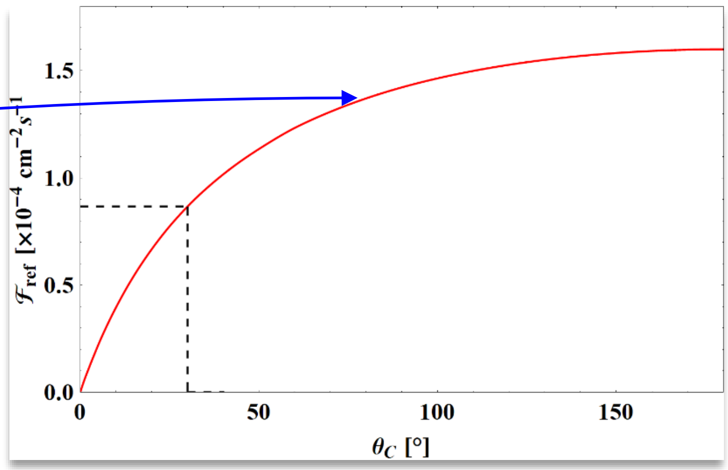
Detector	N^{90}		$N_{\rm BG}$	
	All sky	30°	All sky	30°
ProtoDUNE-DP	4.86	2.67	4.22	0.28
ProtoDUNE-SP	5.50	2.79	6.02	0.40
ProtoDUNE-total	6.69	3.04	10.24	0.69
MicroBooNE	3.34	2.42	1.10	0.074
SBND	3.54	2.44	1.14	0.094
ICARUS	5.50	2.79	6.02	0.40
SBN Program-total	6.24	2.94	8.53	0.57

D_f=1/2 is assumed.

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

$$= 1.6\times 10^{-4}\,{\rm cm^{-2}s^{-1}} \times \left(\frac{\langle\sigma v\rangle_{\chi_0\overline{\chi}_0\to\chi_1\overline{\chi}_1}}{5\times 10^{-26}\,{\rm cm^3s^{-1}}}\right)\times\left(\frac{\rm GeV}{m_0}\right)^2$$

$$\equiv \mathcal{F}_{\rm ref}^{180^\circ} \times \left(\frac{\langle\sigma v\rangle_{\chi_0\overline{\chi}_0\to\chi_1\overline{\chi}_1}}{5\times 10^{-26}\,{\rm cm^3s^{-1}}}\right)\times\left(\frac{\rm GeV}{m_0}\right)^2$$

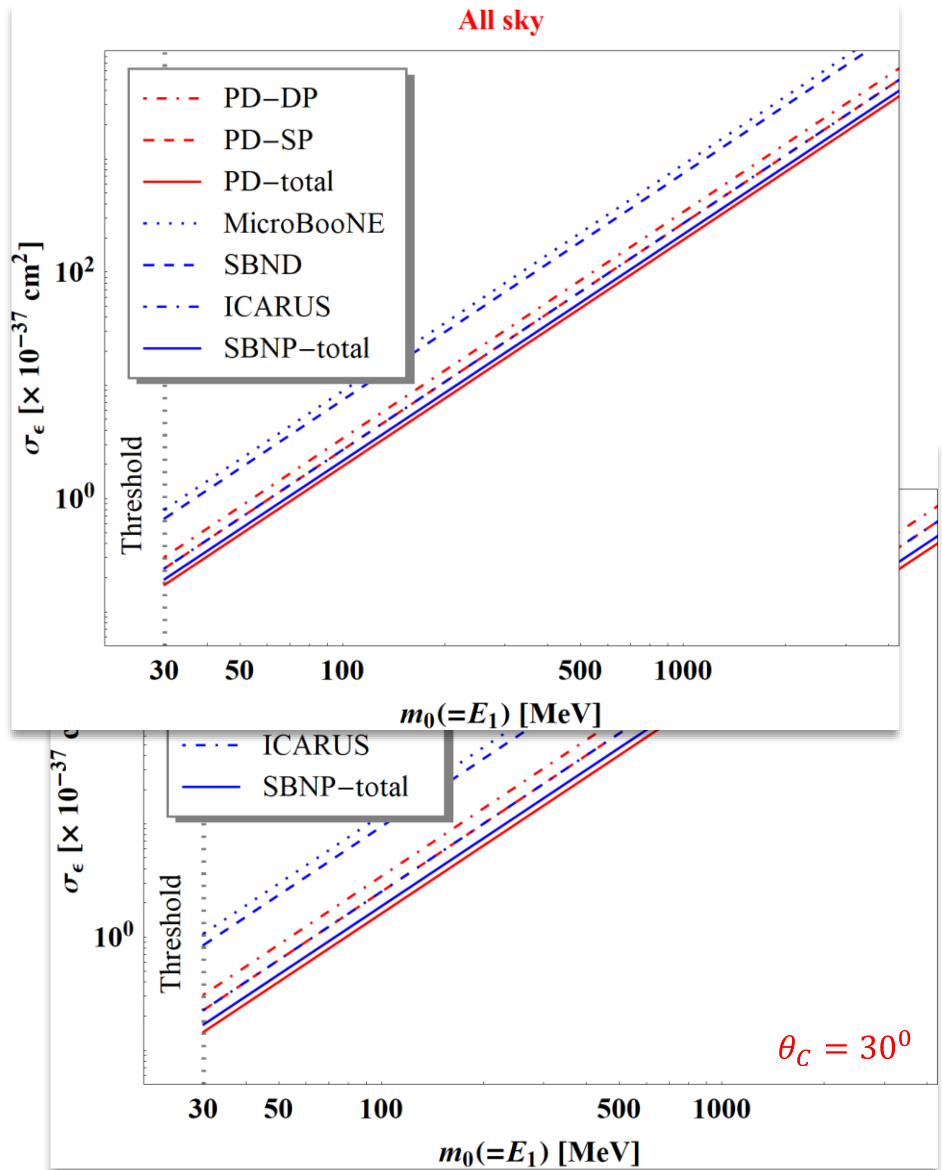


$$\sigma_\epsilon \geq \frac{N^{90}}{D_f\, t_{\rm exp}\, N_T \mathcal{F}_{\rm ref}^{\theta_C}}\left(\frac{5\times 10^{-26}\,{\rm cm^3s^{-1}}}{\langle\sigma v\rangle_{\chi_0\overline{\chi}_0\to\chi_1\overline{\chi}_1}}\right)\left(\frac{m_0}{\rm GeV}\right)^2$$

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

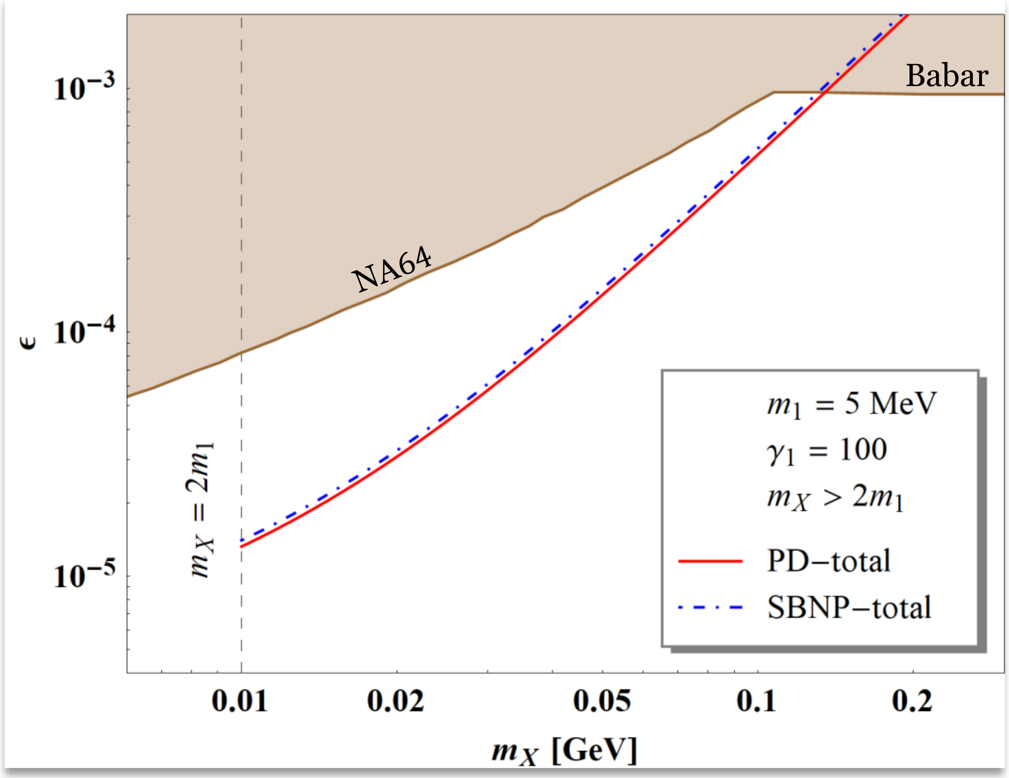
Model-Independent Reach

- 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.



D_f=1/2 is assumed.

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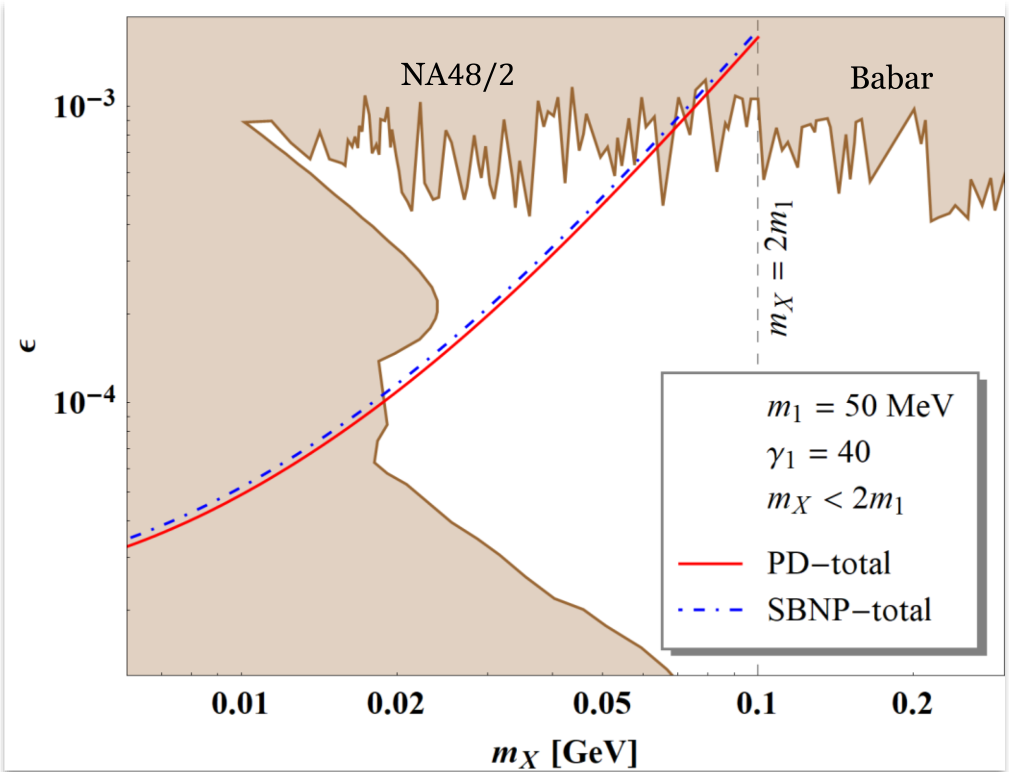
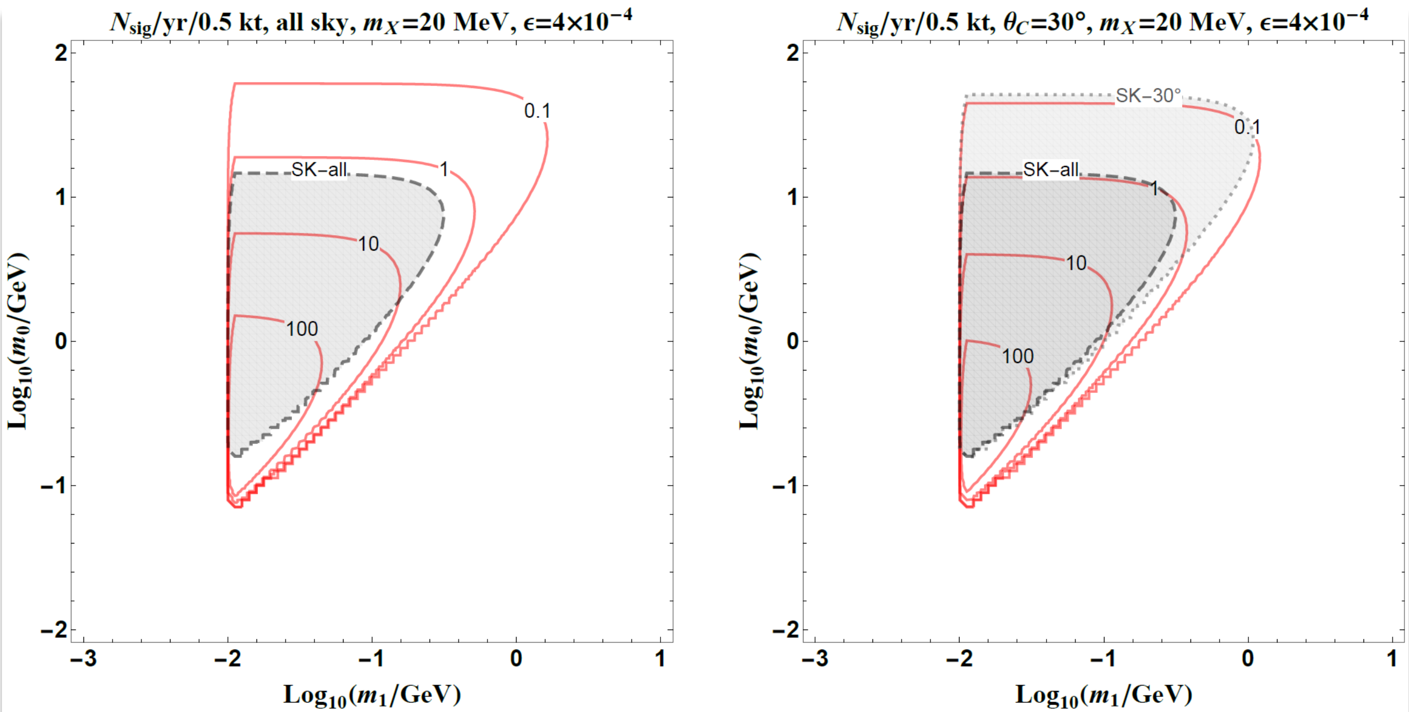


D_f=1/2 is assumed.

Expected Signal Rate

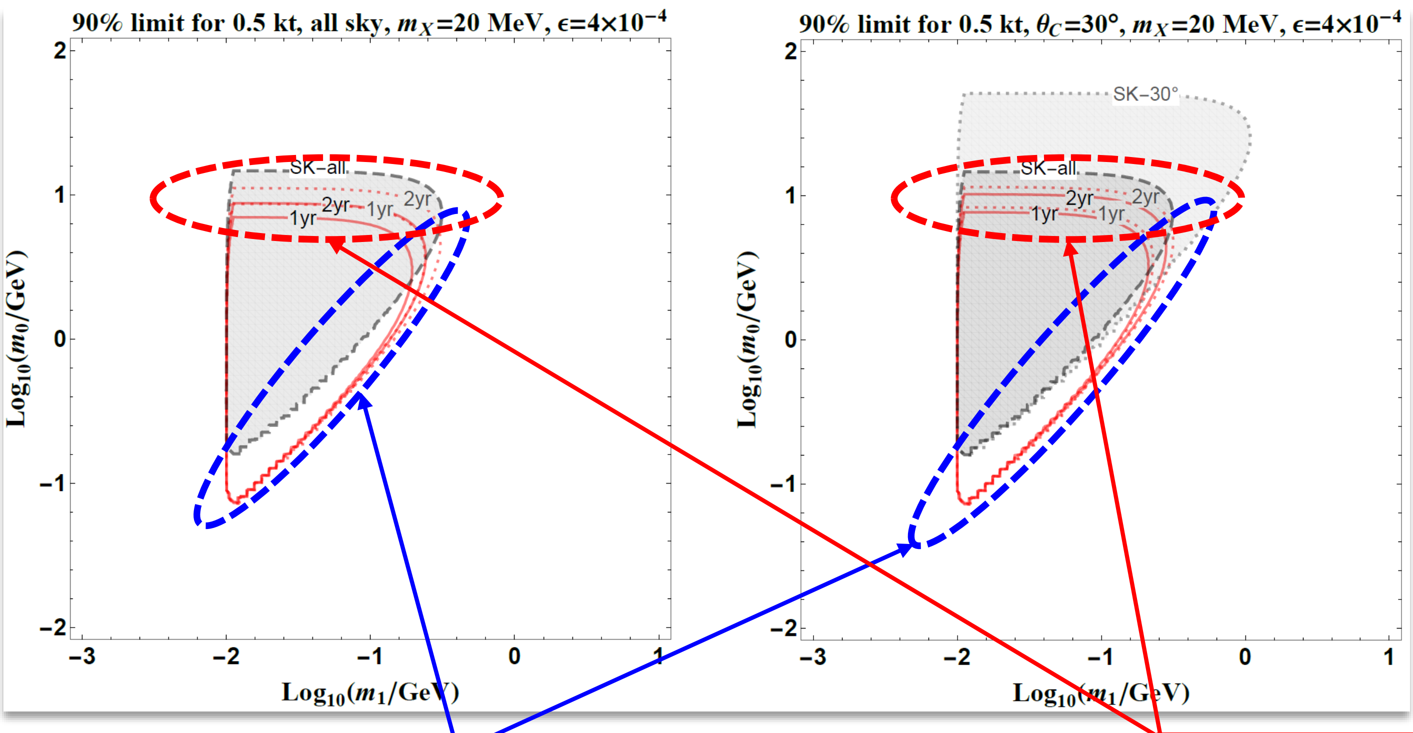
❖ A 0.5 kt-V_{fid} detector and $2m_1 > m_X$ (i.e., visibly-decaying X) and $g_{11} = 1$ are assumed.

❖ Results with 1-year (effectively ½-year assumed) exposure.



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.)

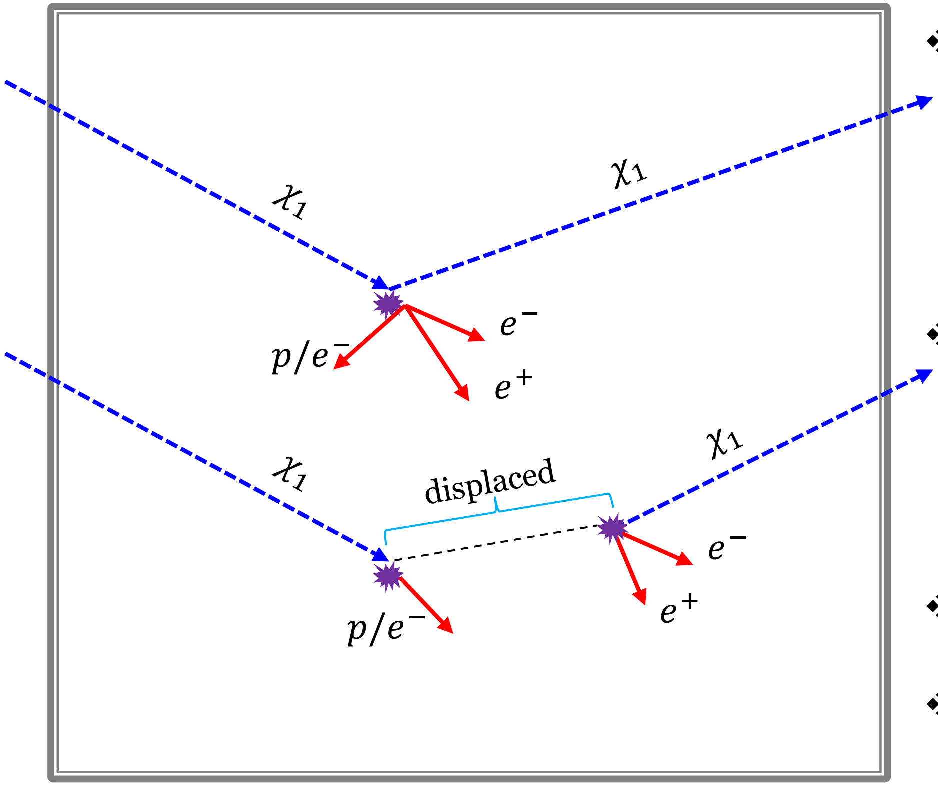
The analysis with **an angle cut** allows to probe more parameter space, as expected.

Approach II

Fruitful Features

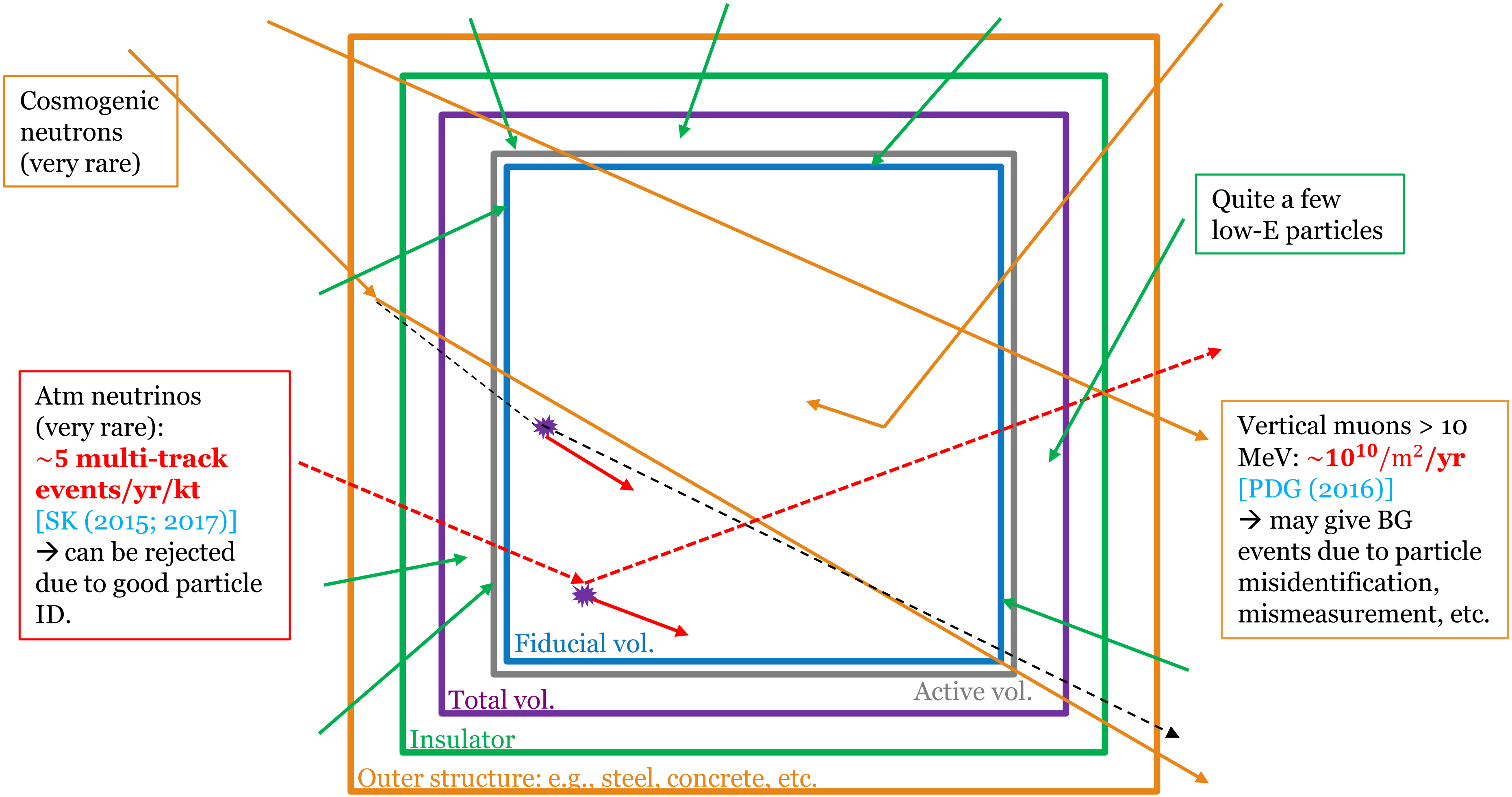
(Benchmark: *i*BDM)

Expected Signatures (Reminder)

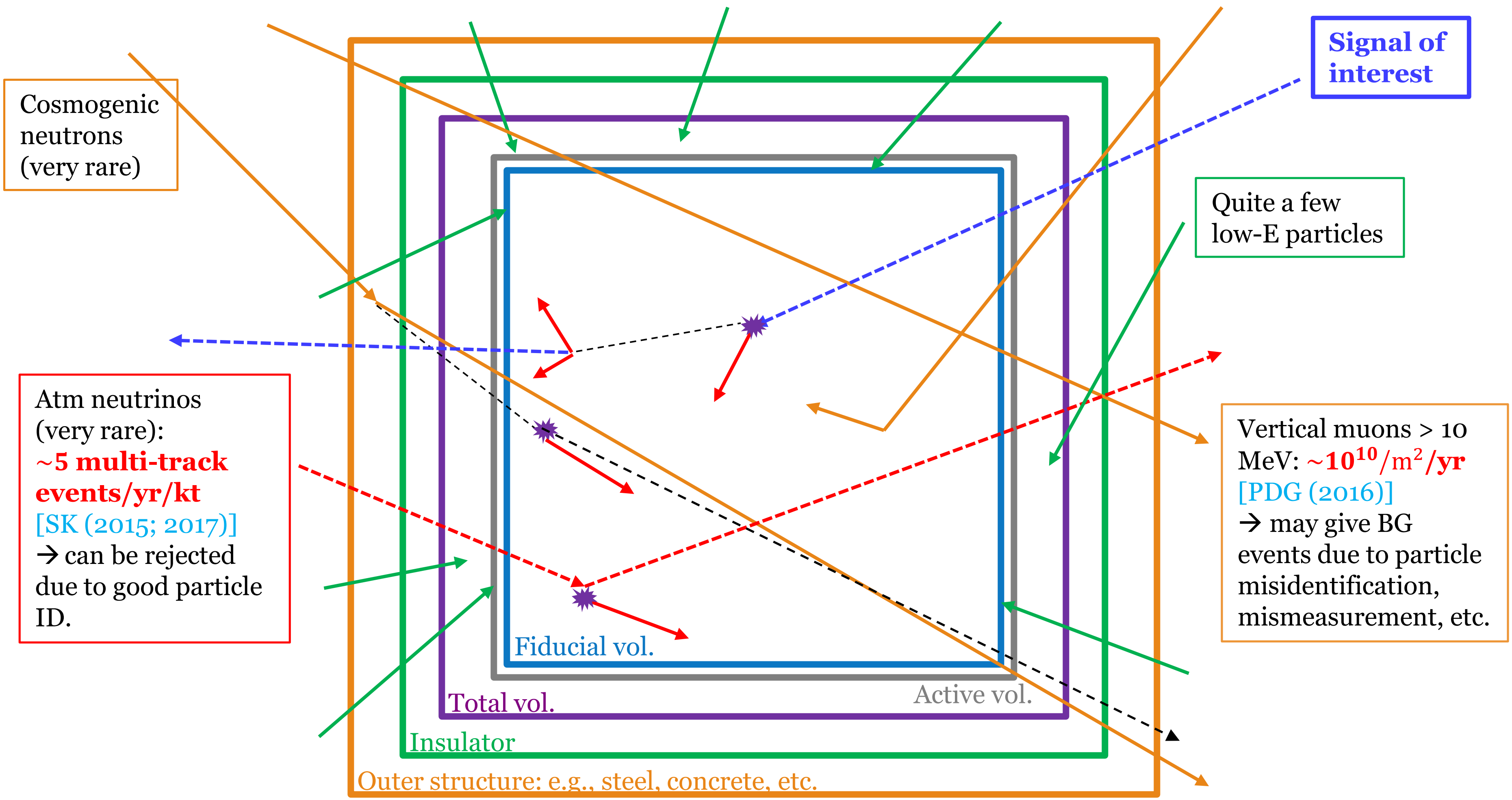


- "Prompt" inelastic scattering (*i*BDM): ER/PR+e^+e^- pair (from the decay of on-shell X: $m_2 > m_1 + m_X$) ➔ three tracks
- "Displaced" inelastic scattering (*i*BDM): ER/PR+e^+e^- pair (typically from a three-body decay of χ_2) ➔ three tracks
- **Tracks** will **pop-up** inside the fiducial volume.
- Focus on ER. But, Straightforwardly applicable to PR (up to form factor, DIS, etc.)

Cosmic-origin BGs

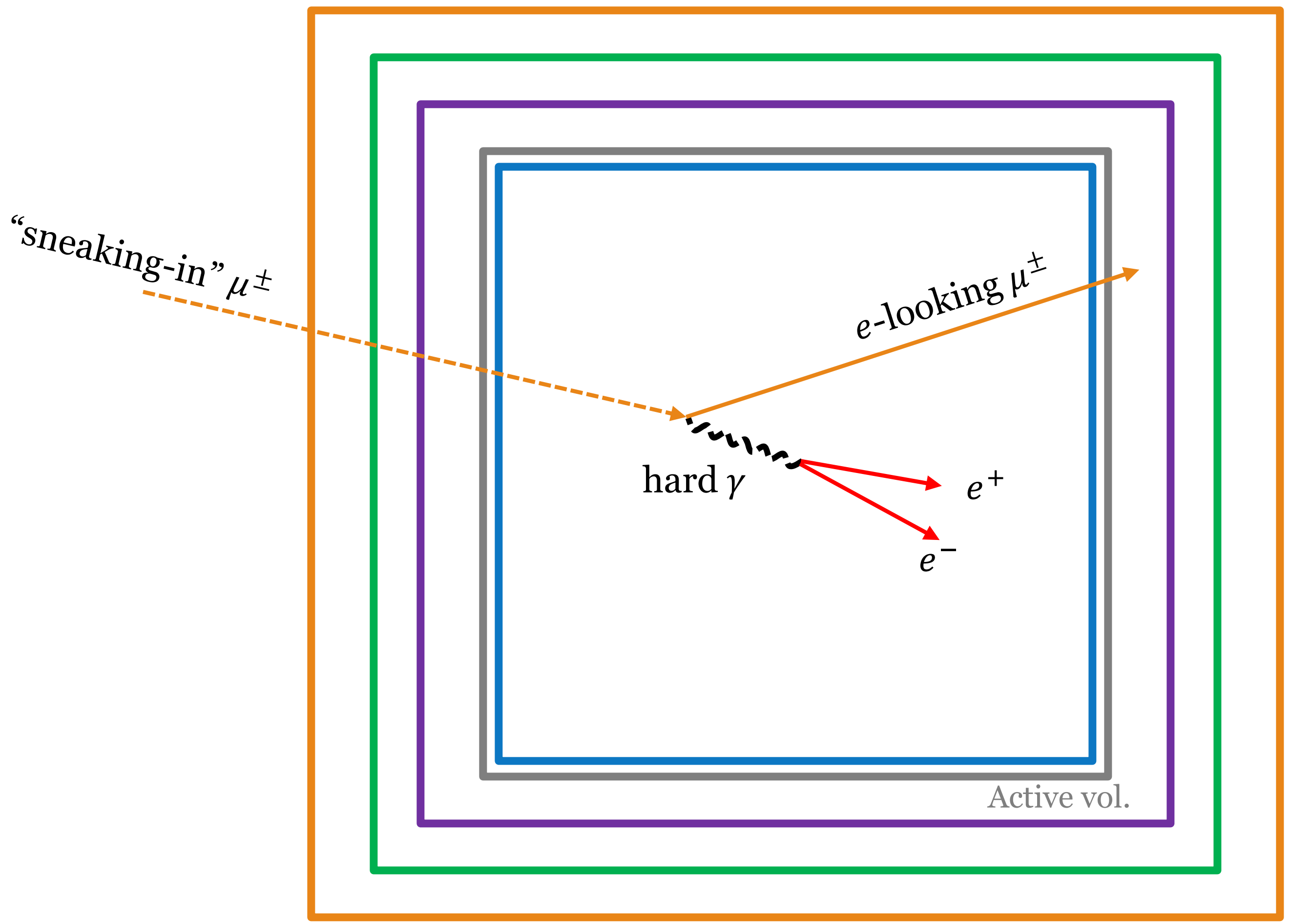


Cosmic-origin BGs vs iBDM Signal

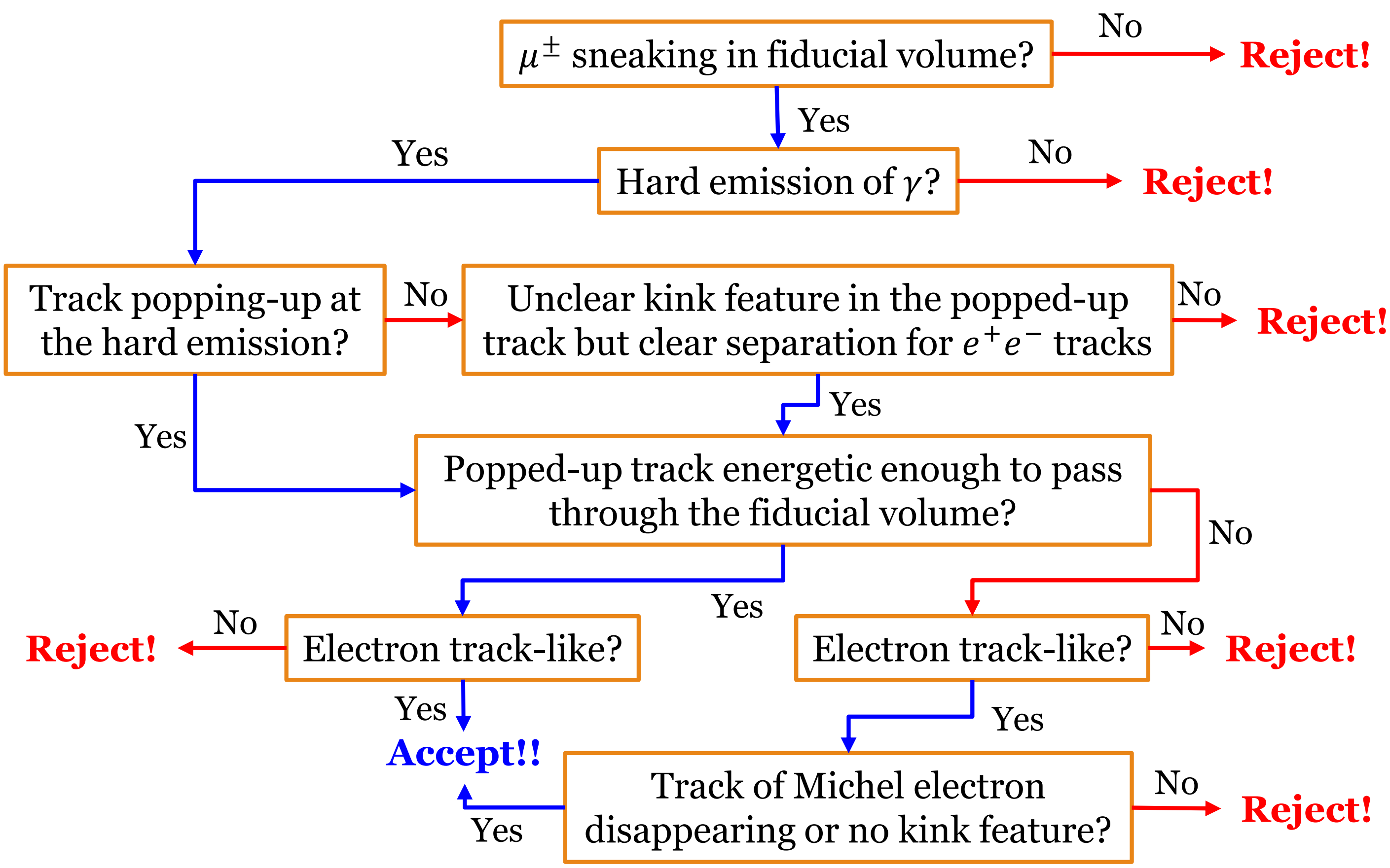


Fake Signals by Mismeasurements?

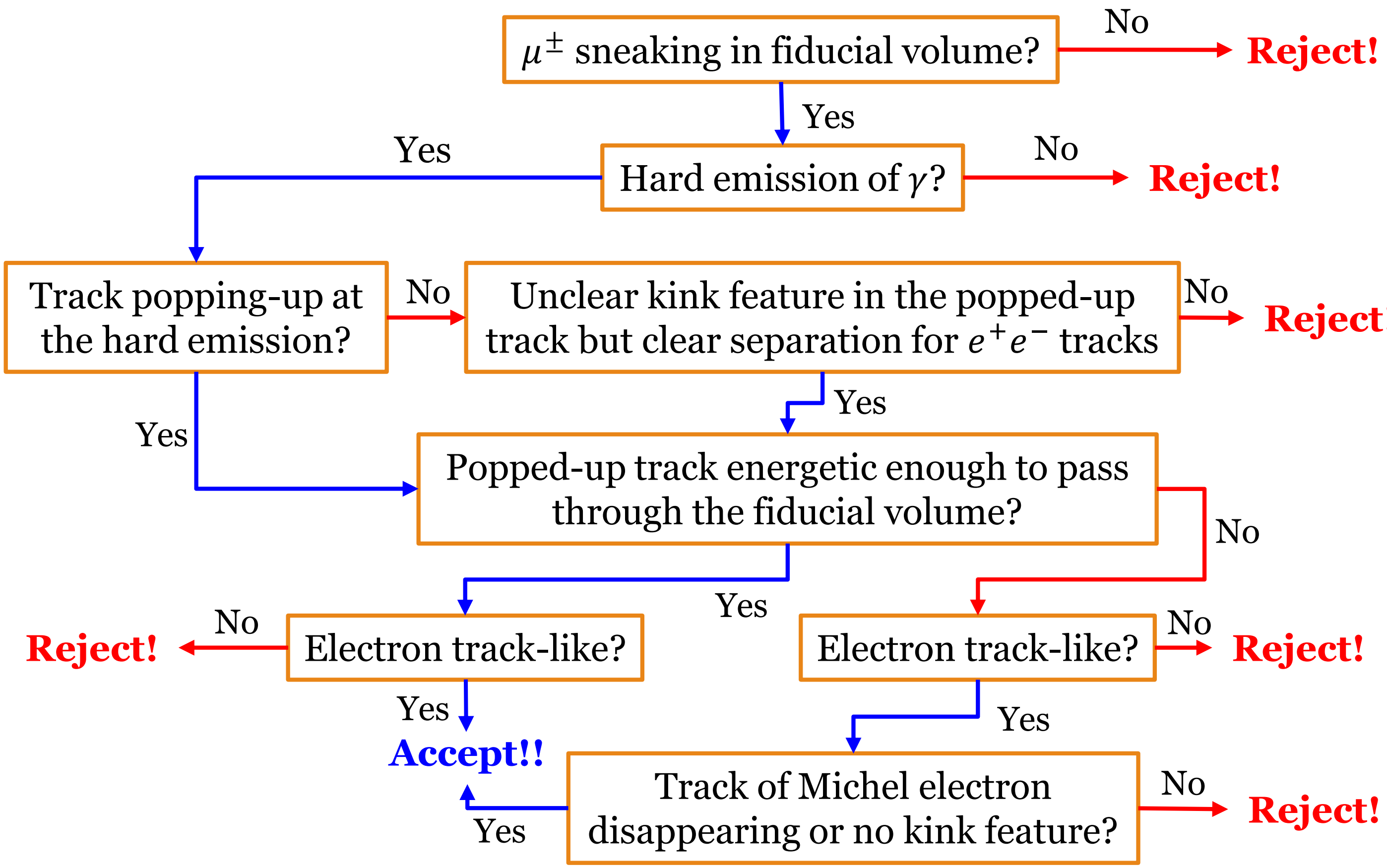
❖ The rate of fake *i*BDM signals by mismeasurements may not be negligible due to enormous high-energetic cosmic background. (e.g., as shown below)



Conditions to Mimic an *i*BDM Signal



Conditions to Mimic an *i*BDM Signal



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

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

[MicroBooNE (2016)]

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

Required!

$\times 1.3 \cdot (10^{-4} - 10^{-2})$

$\Rightarrow 10^{2} - 10^{4}/\text{yr}$

< 1: not considered!

[ArgoNeuT (2017)]

$\times (< 10^{-2})$

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

$\sqrt{B} < 10$

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 (BDM) and electron (target)
- ✓ $\mathcal{F}$: flux of incoming (boosted) χ_1
- ✓ A: acceptance
- ✓ $t_{\rm exp}$: exposure time
- ✓ N_e: total number of target electrons

Controllable! (once a detector is determined)

We factored out the acceptance related to the distance between the primary (ER) & the seco ndary vertices, other factors such as cuts, $E_{\rm th}$ are absorbed into σ_ϵ.

Model-independent Reach: Displaced Vertex

❖ Acceptance determined by the distance between the primary & the secondary vertices

➔ (relatively) conservative limit to require two correlated vertices in the fiducial volumes (also to be distinguished from elastic scattering)

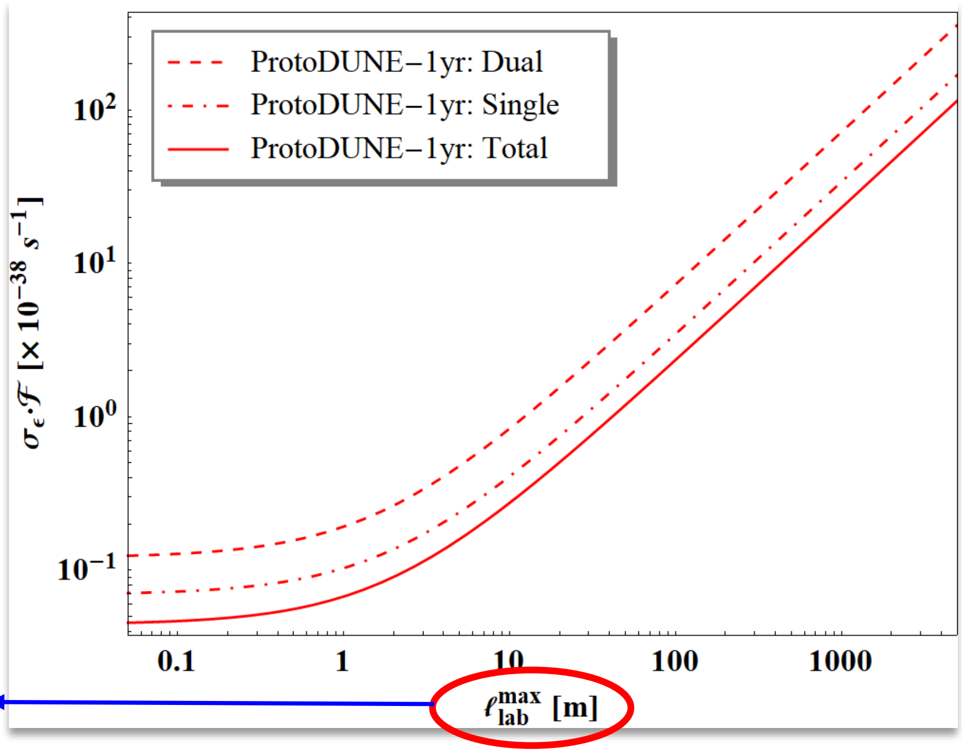
90% C.L. with zero background

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

Evaluated for each detector

Calculable given a detector

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



Model-independent Reach: Familiar Form

❖ More familiar parameterization is possible with the below modification.

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

set to be $5 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$

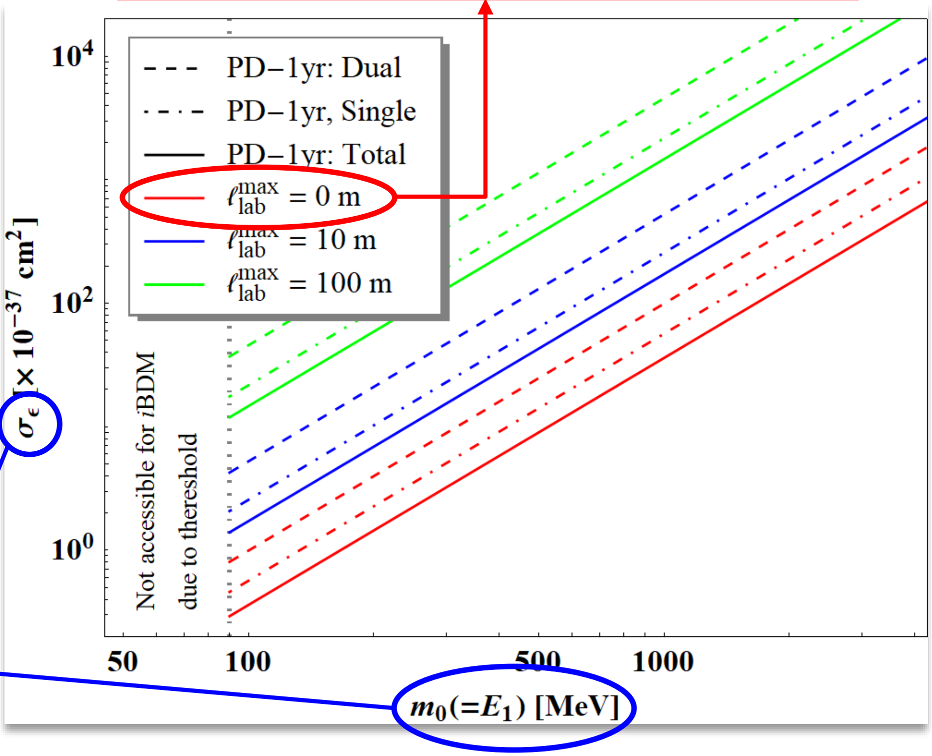
$$\mathcal{F} \sim \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \to \chi_1 \chi_1}}{m_0^2}$$

Relevant to signals with overlaid vertices or elastic scattering signals

❖ Then having

$$\sigma_\epsilon \text{ vs. } m_0 (= E_1 = \gamma_1 m_1)$$

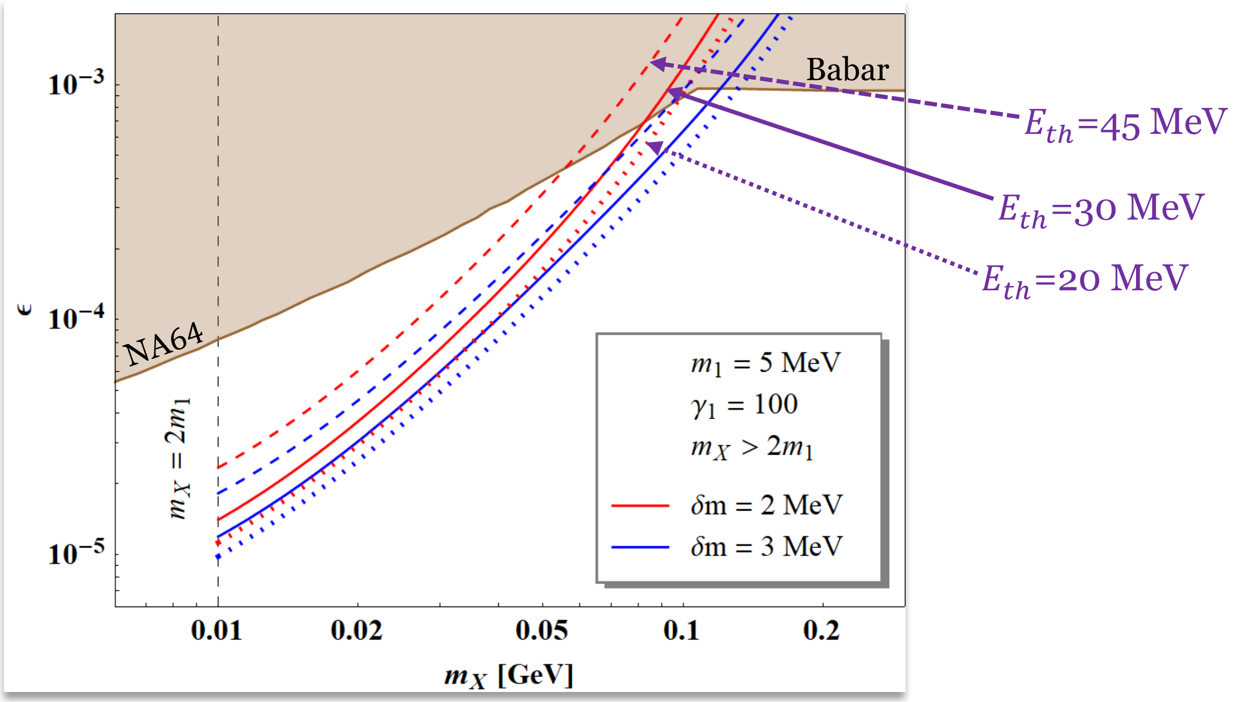
cf. σ vs. $m_{\rm DM}$ in conventional WIMP searches



Experimental sensitivity can be represented by σ_ϵ vs. $m_0(= E_1)$.

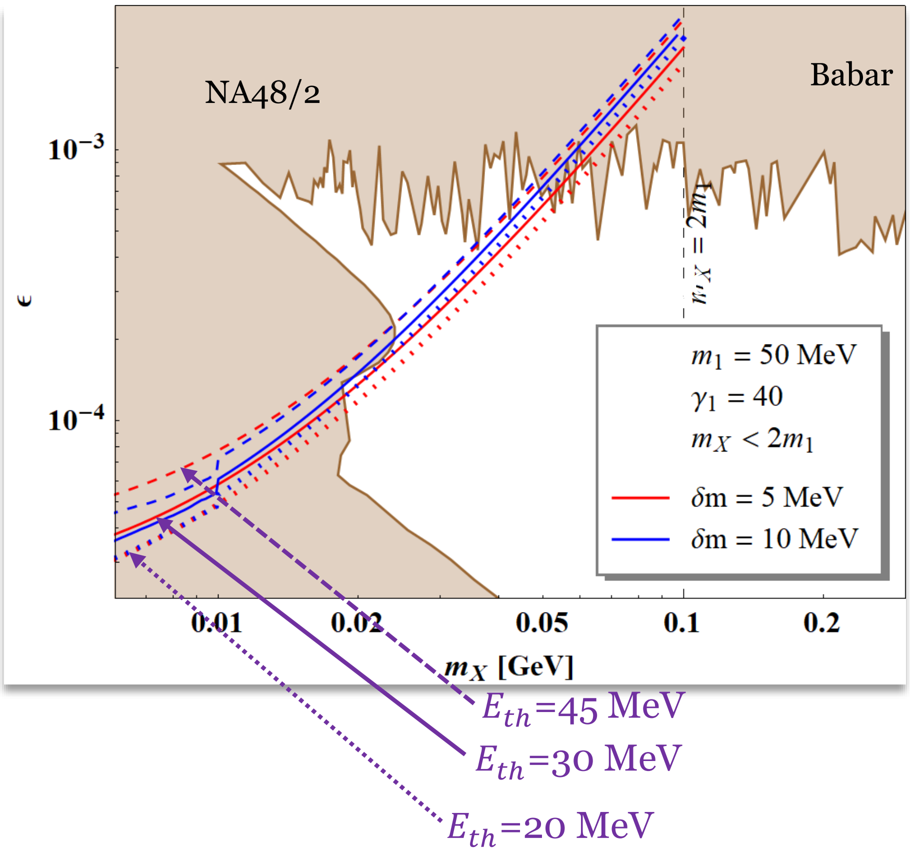
Dark X Parameter Space: Invisible X Decay

❖ Dark X invisibly decays into DM pairs ($m_X > 2m_1$)



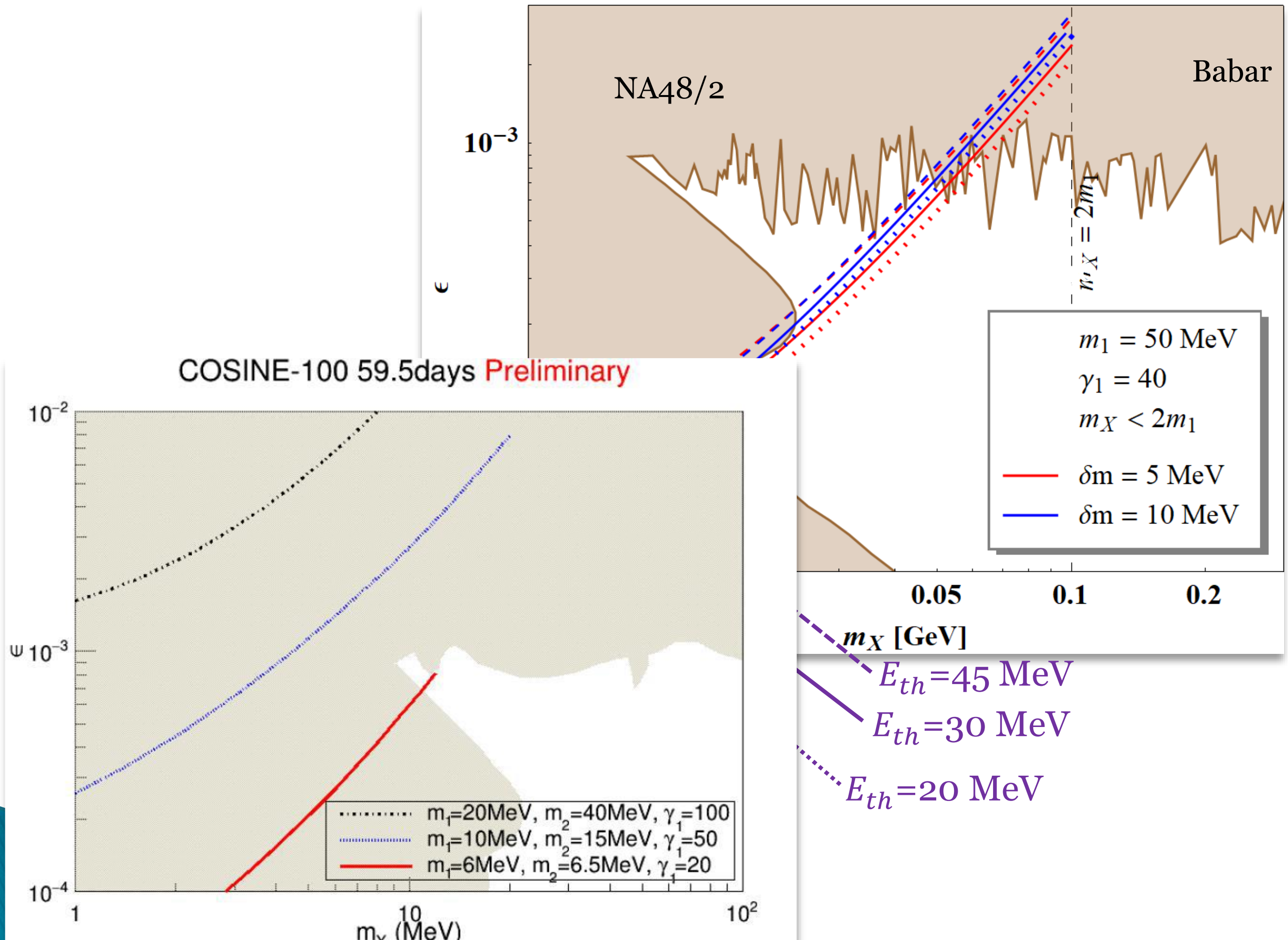
Dark X Parameter Space: Visible *X* Decay

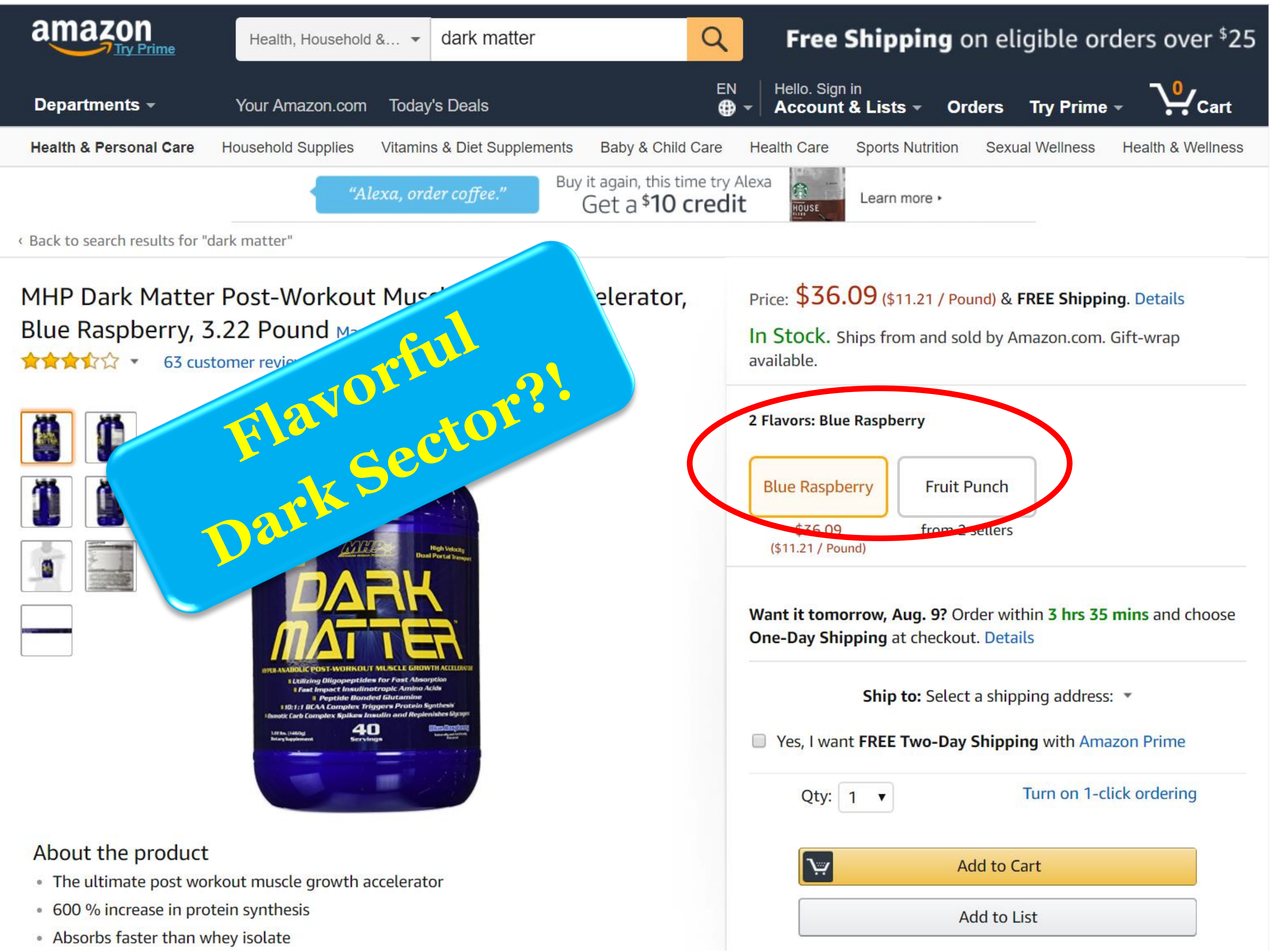
- Dark *X* decays into SM pairs, i.e. e^+e^- ($m_X < 2m_1$)



Dark X Parameter Space: Visible X Decay

❖ Dark X decays into SM pairs, i.e. e^+e^- ($m_X < 2m_1$)




amazon
Try Prime
Health, Household &...
dark matter
Free Shipping on eligible orders over $25
Departments
Your Amazon.com
Today's Deals
EN
Hello. Sign in
Account & Lists
Orders
Try Prime
0
Cart
Health & Personal Care
Household Supplies
Vitamins & Diet Supplements
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 revi…
Flavorful
Dark Sector?!
DARK MATTER
40 Servings
Price: $36.09 ($11.21 / Pound) & FREE Shipping. Details
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
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
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)
***i*nelastic**	inelastic DM (*i*DM)	inelastic BDM (*i*BDM)

→ **Focus I of this talk!** (Boosted DM (eBDM))

→ **Focus II of this talk!** (inelastic BDM (*i*BDM))

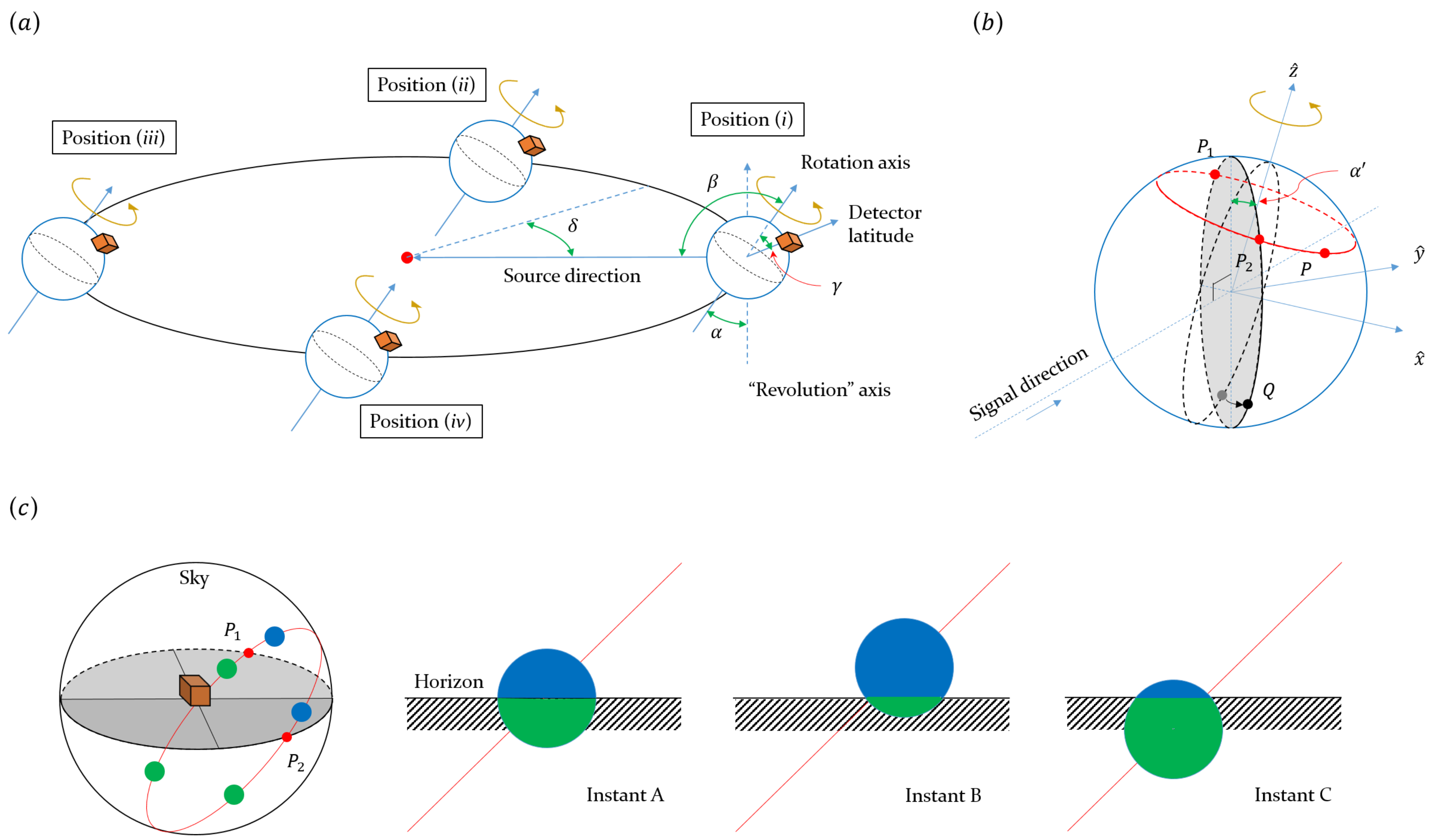
- (light) BDM search is promising & provides a new direction to study DM phenomenology.
- Huge cosmic-ray BG can be **well controlled** with the "**Earth Shielding**" effect and/or **unique/fruitful signal signatures (*i*BDM)**.
- **Surface detectors** possesses excellent sensitivities to a wide range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

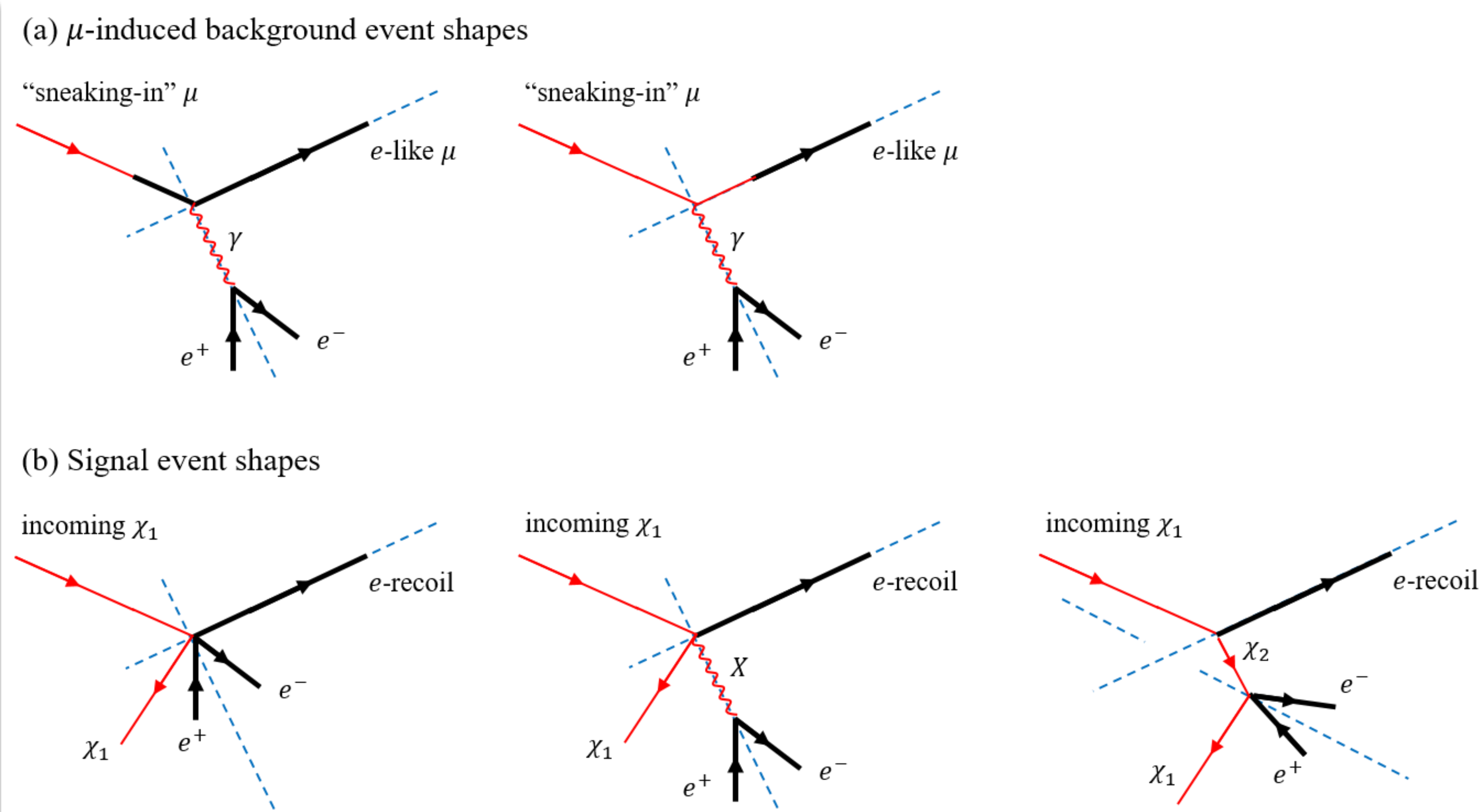
Thank you

Back-Up

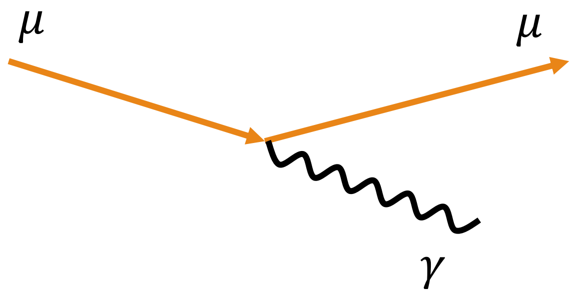
Effect of Earth's Rotation



Possible Event Shapes (*i*BDM)



Hard Emission of a Photon



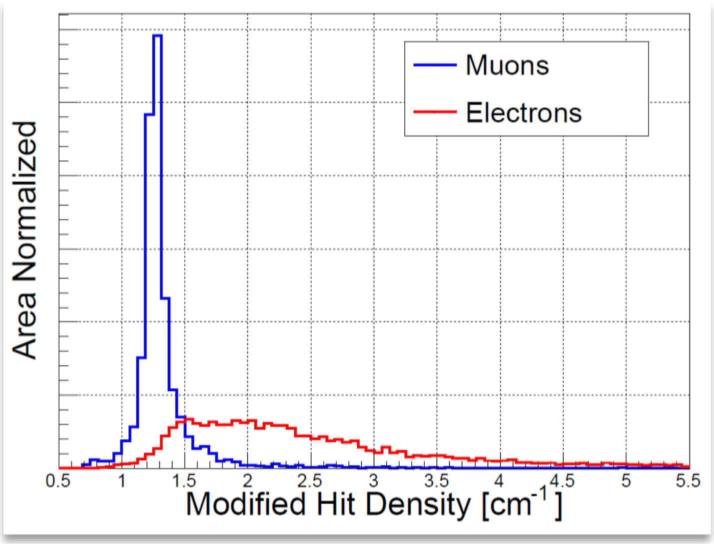
$$\sim \frac{\alpha}{\pi} \approx 2 \times 10^{-3}$$

Phase-space suppression factor

Electron-Faking Muon

- All known studies simply report that a negligible rate of muons are misidentified as electrons. But "How Negligible?"

- A hint from an example study: [ArgoNeut, arXiv:1610.04102]c



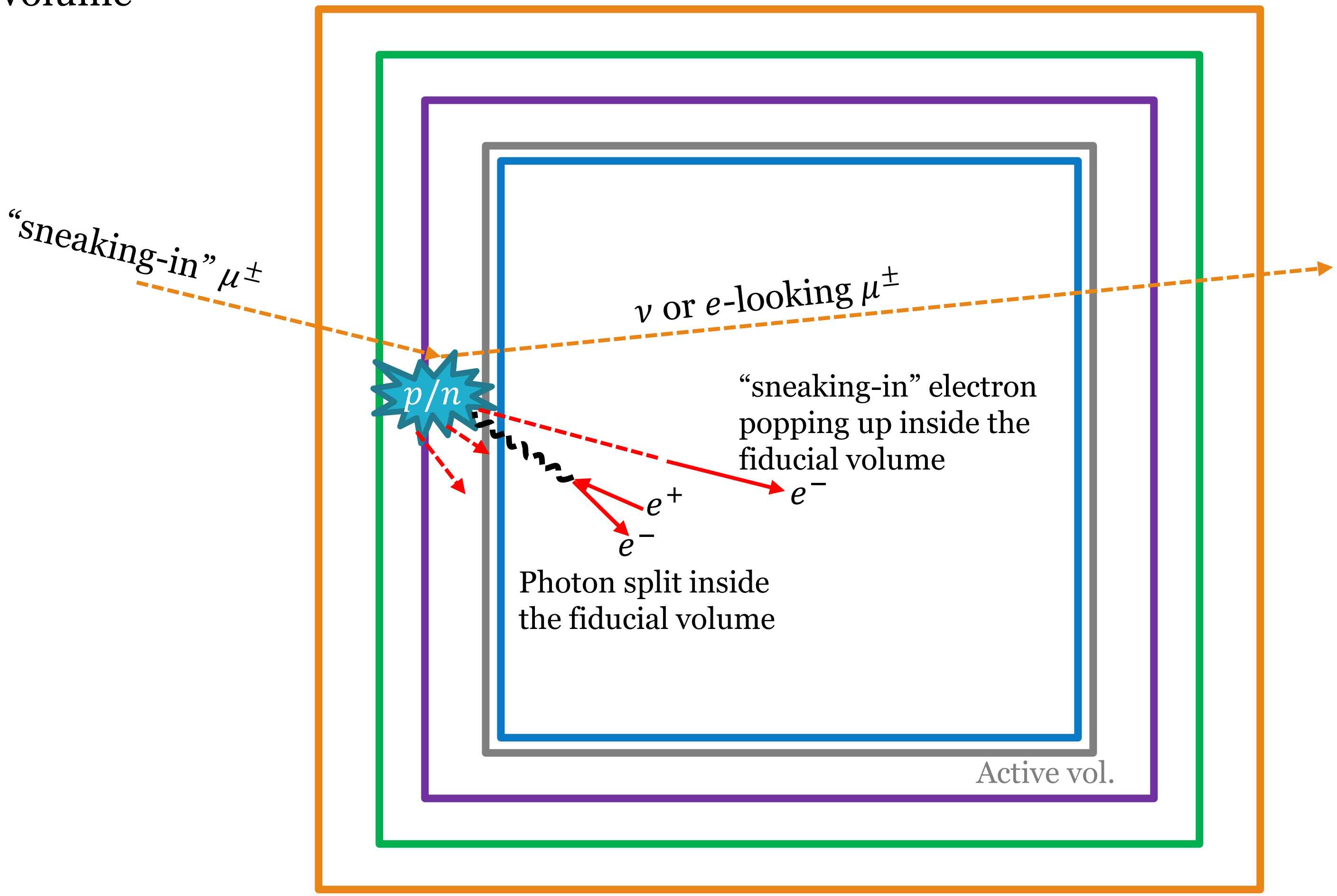
If cut here, ~8% of the fake rate

- 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 rate is $\mathbf{10^{-2}}$.

Fake Signals by Mismeasurements?

❖ Deep inelastic scattering (DIS) of energetic cosmic-muon with a nucleon within the passive volume



Conditions to Mimic an iBDM Signal

0. Muon flux above 5 GeV
1. DIS with a nucleon (p/n)

   $N_{\text{event}} \sim$ (DIS cross section) × (muon flux) × (1 year)

   × (number of nucleons inside the passive volume)

   $\sim 2 \cdot 10^5/\text{yr}$
2. Photon split inside the fiducial volume after traveling more than ~35 cm in Liquid Ar
3. Electron "sneak-in" and pops up inside the fiducial volume
4. Incoming muon not leaving a visible track inside the active volume

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

↓

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

[ArgoNeuT (2017)]

$\times (< 5 \cdot 10^{-3})$

$\Rightarrow < 10^3/\text{yr}$

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

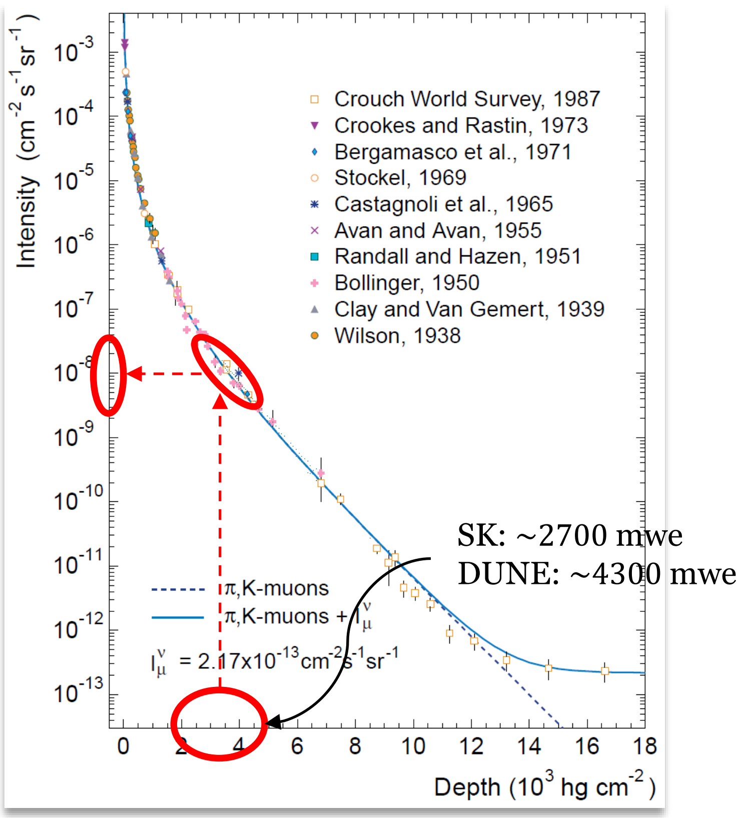
[MicroBooNE (2016)]

$\times (\ll 1)$

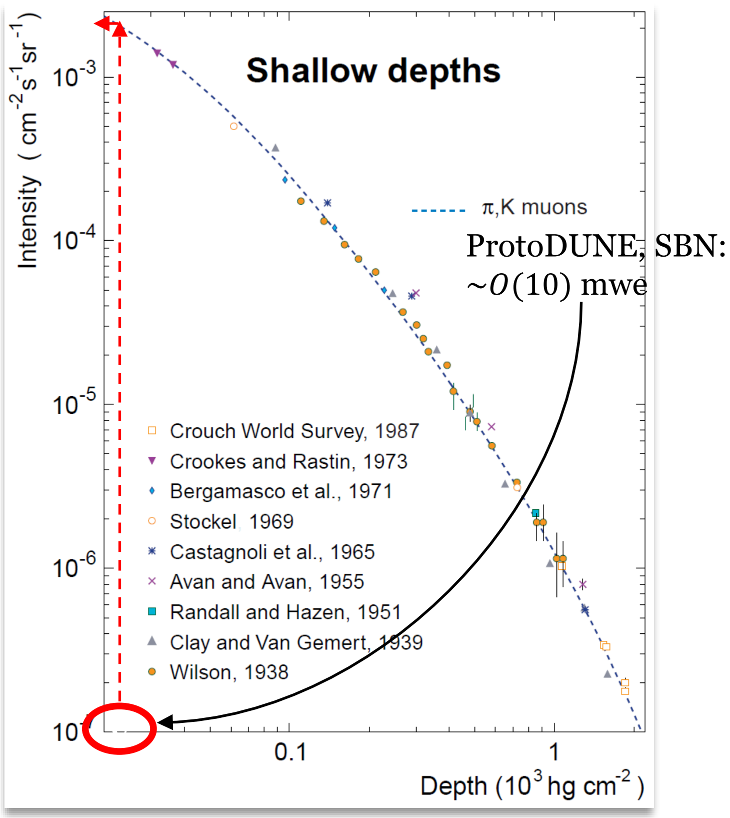
$\Rightarrow$ **$\ll$ 1/yr**

Potential BGs: High E Muons

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



[Bugaev et al. (1998)]



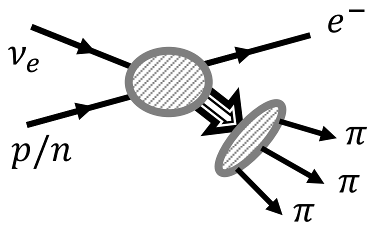
Potential BGs: Neutrinos

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

Detection of BDM

❖ Flux of boosted χ_1 near the earth

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

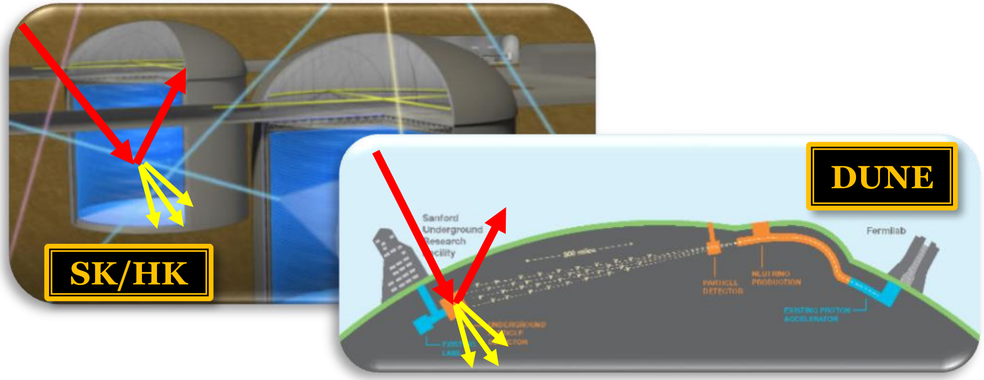
from the number density of DM χ_0, $n_0 = \rho_0 / m_0$

❖ 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 $\mathcal{F}_{\chi_1} \sim 10^{-6\sim 8} \mathrm{cm^{-2} s^{-1}}$ for χ_0 of weak-scale mass, m_0~O(10-100 GeV).

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

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



❖ Sources

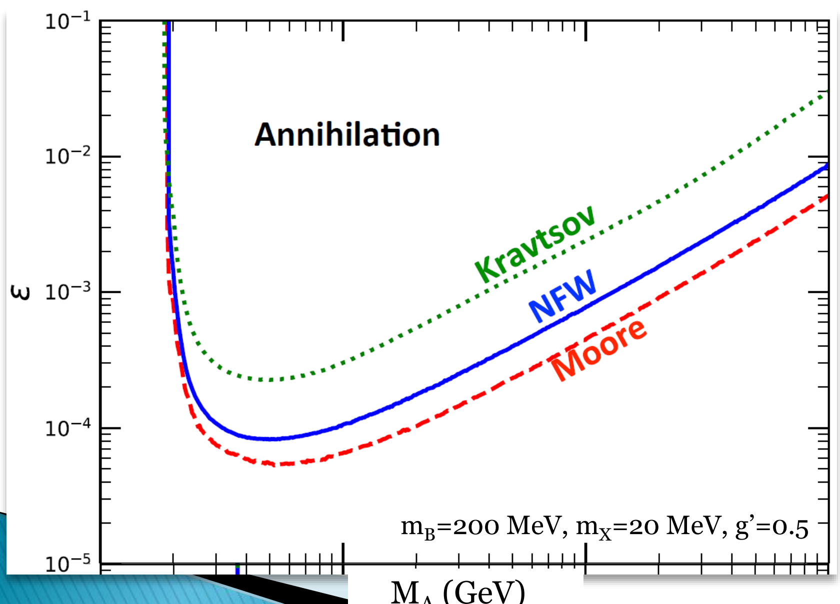
- ✓ GC: Agashe et al. (2014); Necib et al. (2016); Alhazmi, Kong, Mohlabeng, **JCP** (2016); etc.
- ✓ Sun: Berger et al. (2014); Kong, Mohlabeng, **JCP** (2014); Alhazmi, Kong, Mohlabeng, **JCP** (2016); etc.
- ✓ Dwarf galaxies: Necib et al (2016)

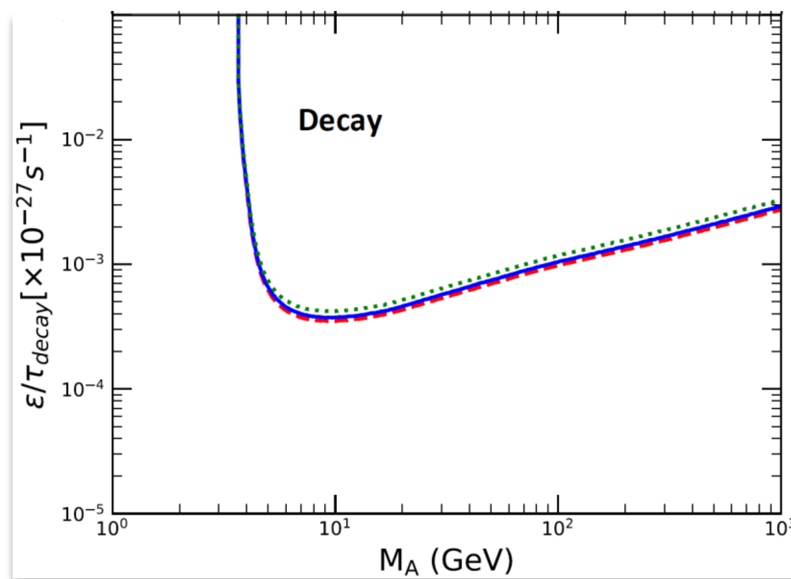
SK Official Results for BDM Search

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

(Dated: November 16, 2017)

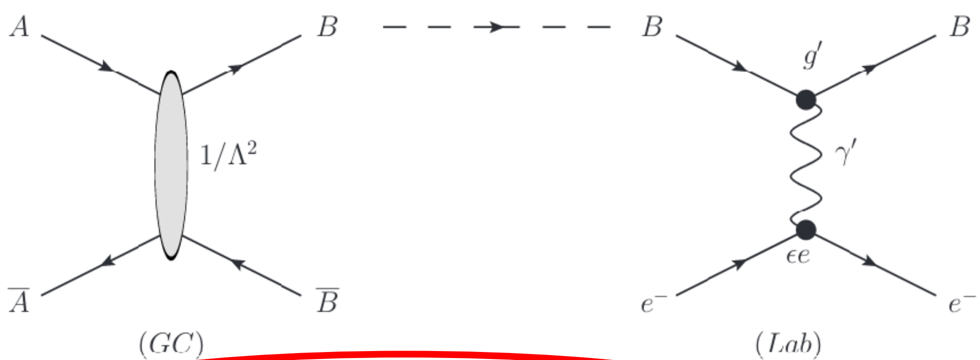
A search for boosted dark matter using 161.9 kiloton-years of Super-Kamiokande IV data is presented. We search for an excess of elastically scattered electrons above the atmospheric neutrino background, with a visible energy between 100 MeV and 1 TeV, pointing back to the Galactic Center or the Sun.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

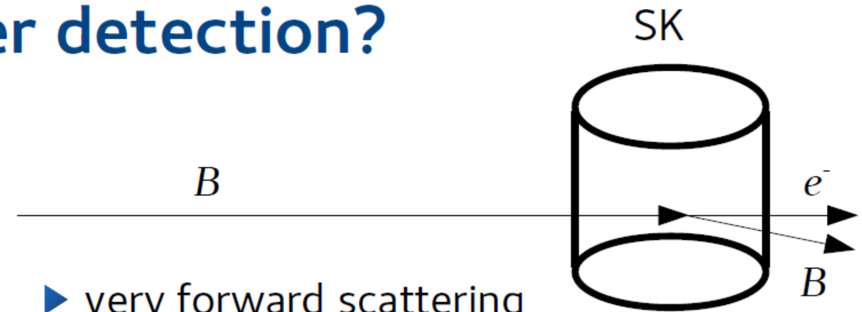




[SK Collaboration, arXiv:1711.05278]

(In)direct dark matter detection?

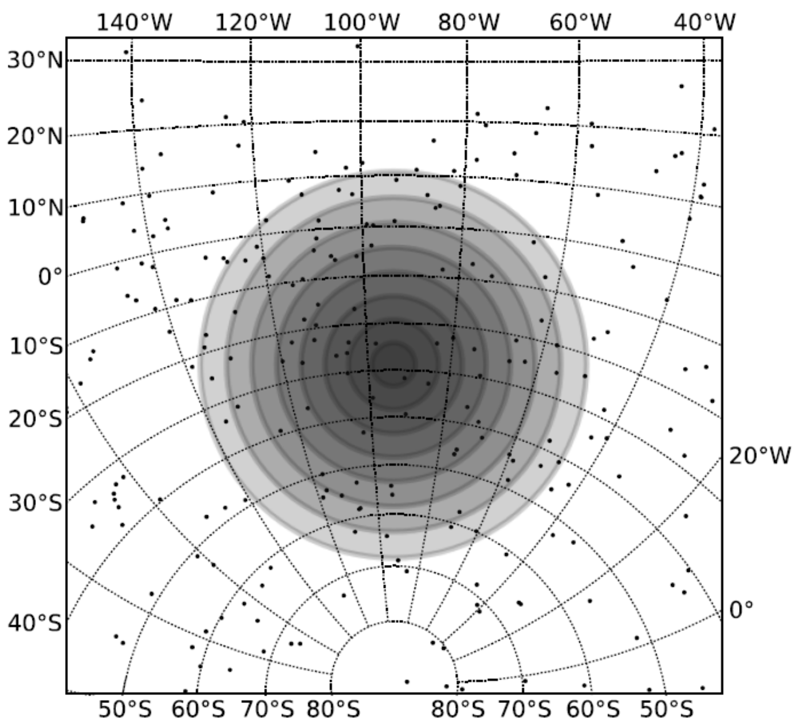




- very forward scattering
- electromagnetic shower
- no hadrons → no decay e, no neutrons

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

→ **No clusters visible**



Limit for m_{γ}'=20 MeV