Boosted Dark Matter Searches via Dark-Strahlung

with Doojin Kim & Seodong Shin [1903.05087]

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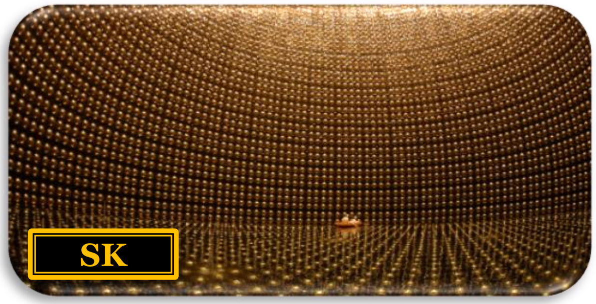
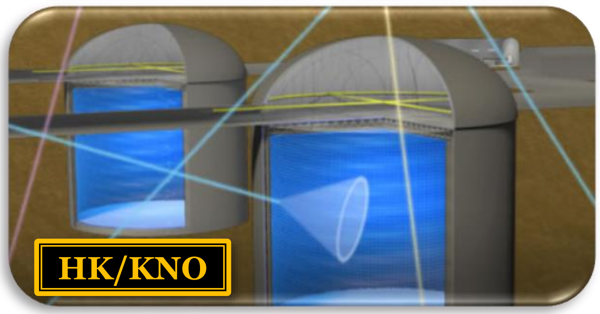
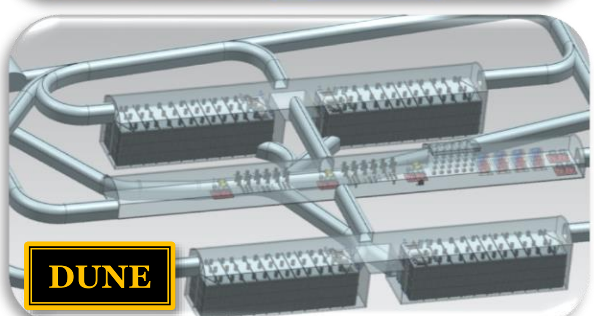
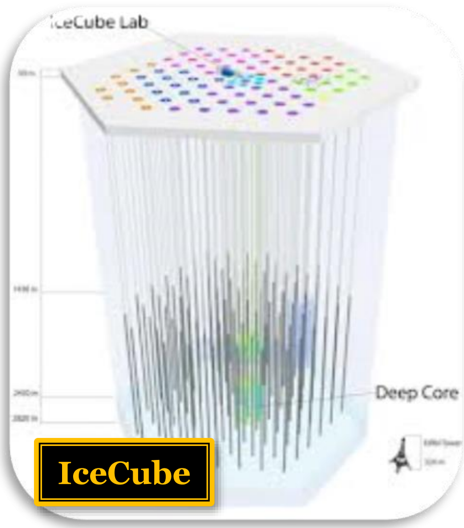
Large Volume ν Experiments

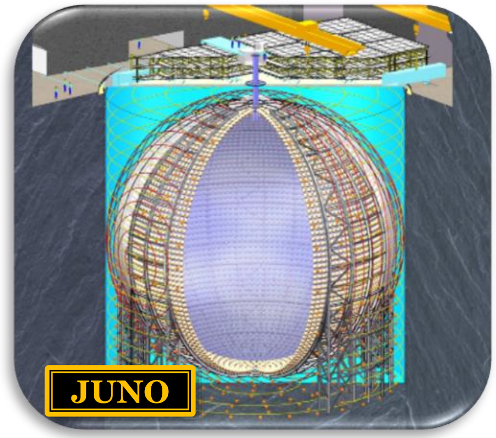
❖ Various current/next generation large volume neutrino experiments











Purposes?

Large Volume ν Experiments: Signals

- Essentially, neutrino experiments have been designed to detect rare EM signals induced by energetic neutrinos ≈ energetic neutral(≈weakly interacting) particles
- Therefore, they can be utilized to search for any energetic neutral new particles.

  ➔ Dark matter (DM) is a good candidate except its low kinetic energy!
- Non-relativistic ($v/c \sim 10^{-3}$) weak-scale DM: E_k ~ O(1 - 1000 keV) ➔ E_{recoil} ~ O(1-100 keV)

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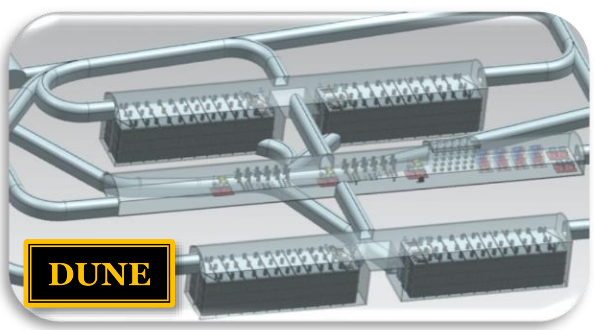
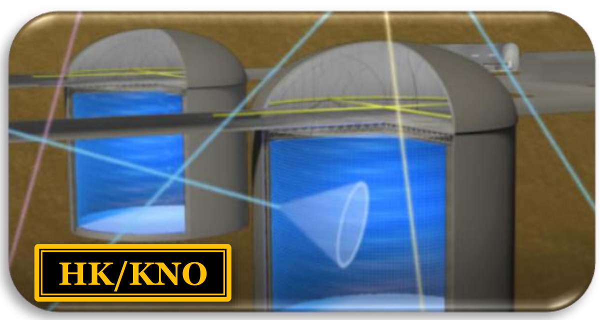
What if DM has a relativistic velocity?

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

- Energetic DM coming from the universe with $E > E_{th}$ (~100 keV or larger) of ν-detectors ➔ detectable in ν-detectors!!



E_{th} ~ O (10 MeV)



E_{th} ~ 5 MeV

Energetic/Boosted Dark Matter (DM)

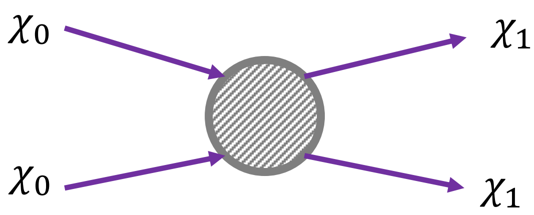
Energetic DM coming from the universe

❖ Various scenarios: requirements ➔ right DM relic abundance & DM boosting mechanism

- ✓ Multi-component model: [Belanger & **JCP**, 1112.4491; Kong, Mohlabeng, **JCP**, 1411.6632; Kim, **JCP**, Shin, 1702.02944; Aoki & Toma, 1806.09154; more]
- ✓ Semi-annihilation model: [D'Eramo & Thaler, 1003.5912]
- ✓ Decaying multi-component DM: [Bhattacharya et al., 1407.3280; Kopp, Liu, Wang, 1503.02669; Cline et al., 1904.13396; Heurtier, Kim, **JCP**, Shin, 1905.13223; Kim; more]
- ✓ High velocity (semi-relativistic) DM
  - Anti-DM from DM-induced nucleon decay in the Sun: [Huang & Zhao, 1312.0011]
  - Energetic cosmic-ray induced DM: [Yin, 1809.08610; Bringmann & Pospelov, 1810.10543; Ema, Sala, Sato, 1811.00520]
- ✓ More ideas~

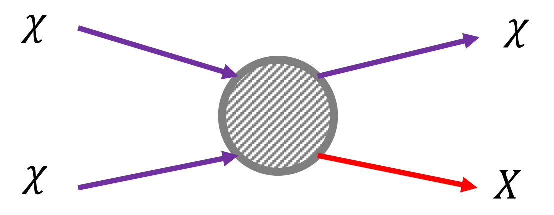
Energetic/Boosted Dark Matter (DM)

Energetic DM coming from the universe



✓ Multi-component model

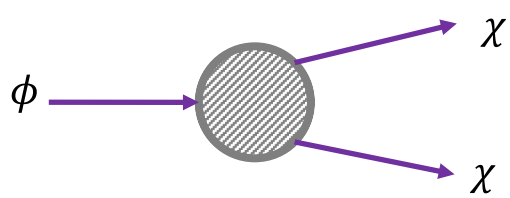
$m_0 \gg m_1$



✓ Semi-annihilation model

$m_\chi \gg m_X$

Large E_k^{DM} due to **mass gap** or **E_k^{CR} transfer**



✓ Decaying multi-component DM

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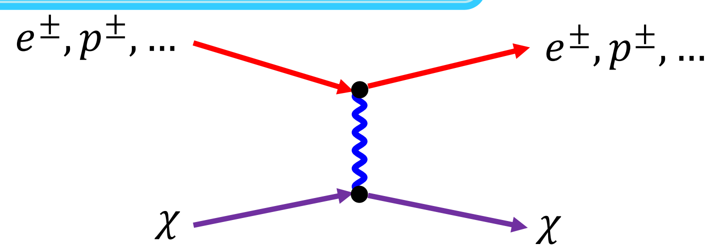


✓ Energetic cosmic-ray induced DM

$E_{e^\pm, p^\pm, \ldots} \gg m_\chi$

Boosted DM Searches

Boosted DM (BDM) models:
Receiving rising attention as an alternative scenario

Boosted DM Searches @ SK/COSINE-100

Boosted DM (BDM) models:
Receiving rising attention as an alternative scenario

PHYSICAL REVIEW LETTERS **120,** 221301 (2018)

Editors' Suggestion

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

PHYSICAL REVIEW LETTERS **122,** 131802 (2019)

Editors' Suggestion

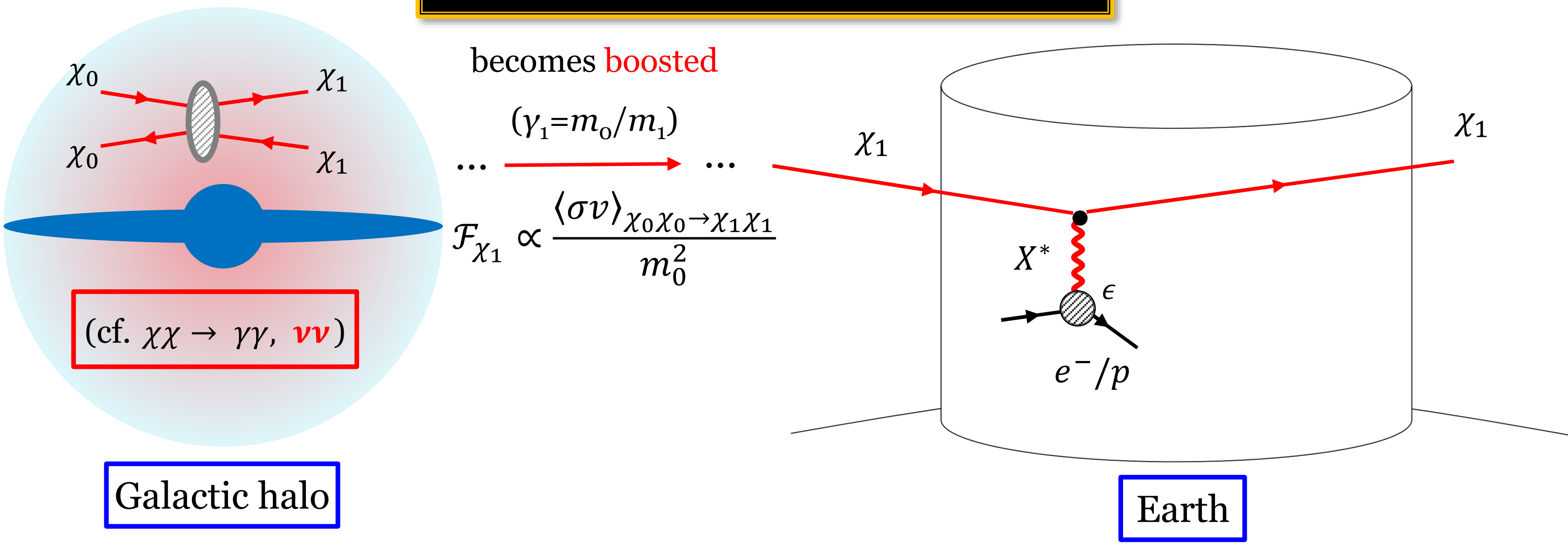
First Direct Search for Inelastic Boosted Dark Matter with COSINE-100

- ✓ Not restricted to primary physics goals
- ✓ Opened to other (unplanned) physics opportunities

Key Features & Issues

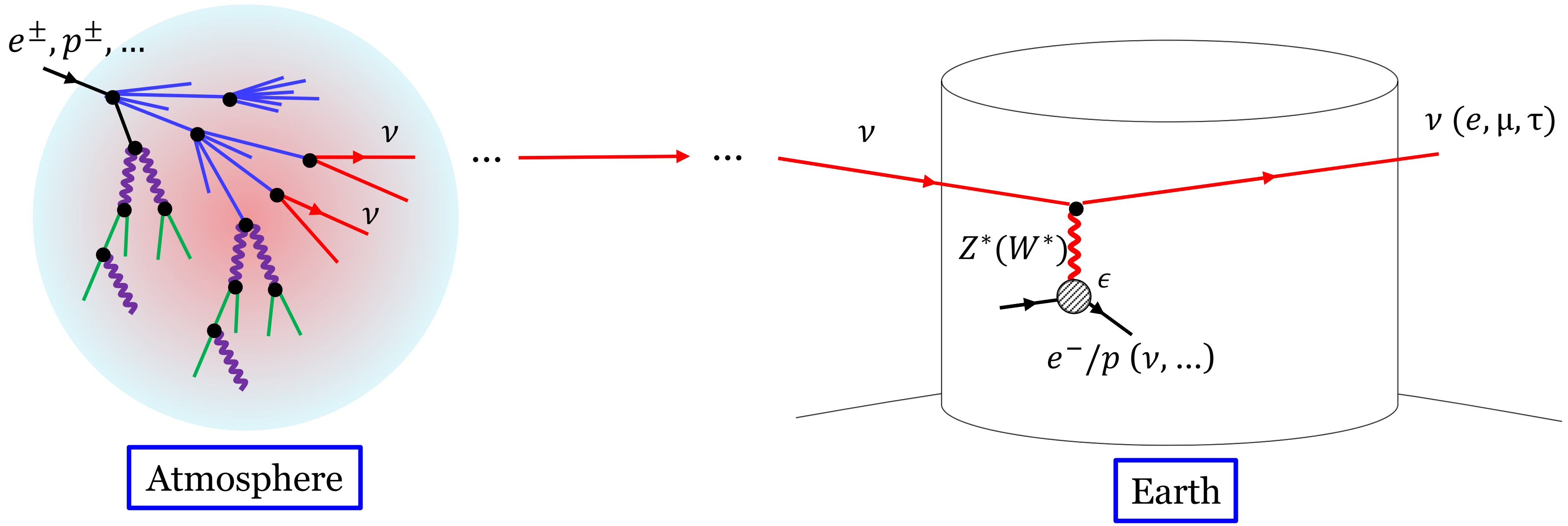
Minimal Two-component Scenario

Benchmark: two-component DM scenario



- Example model: fermionic heavier(χ_0)/lighter(χ_1) DM + dark gauge boson(X)
- Electron & proton(even DIS) scattering channels are available. ➔ Energetic recoil

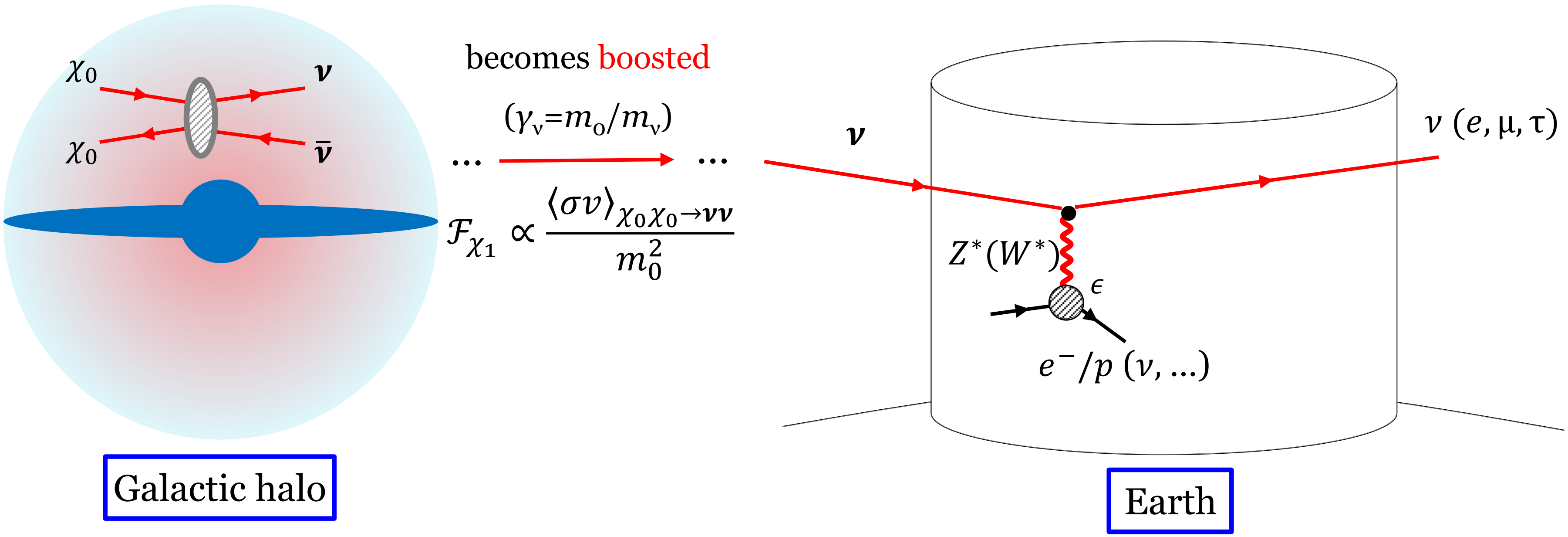
Issue 1: Backgrounds



❖ Irreducible backgrounds: atmospheric-neutrino-induced events

❖ Neutral- & charged-current (even DIS) scattering channels are available. ➔ Energetic recoil

Issue 2: Distinction from ν Scenario



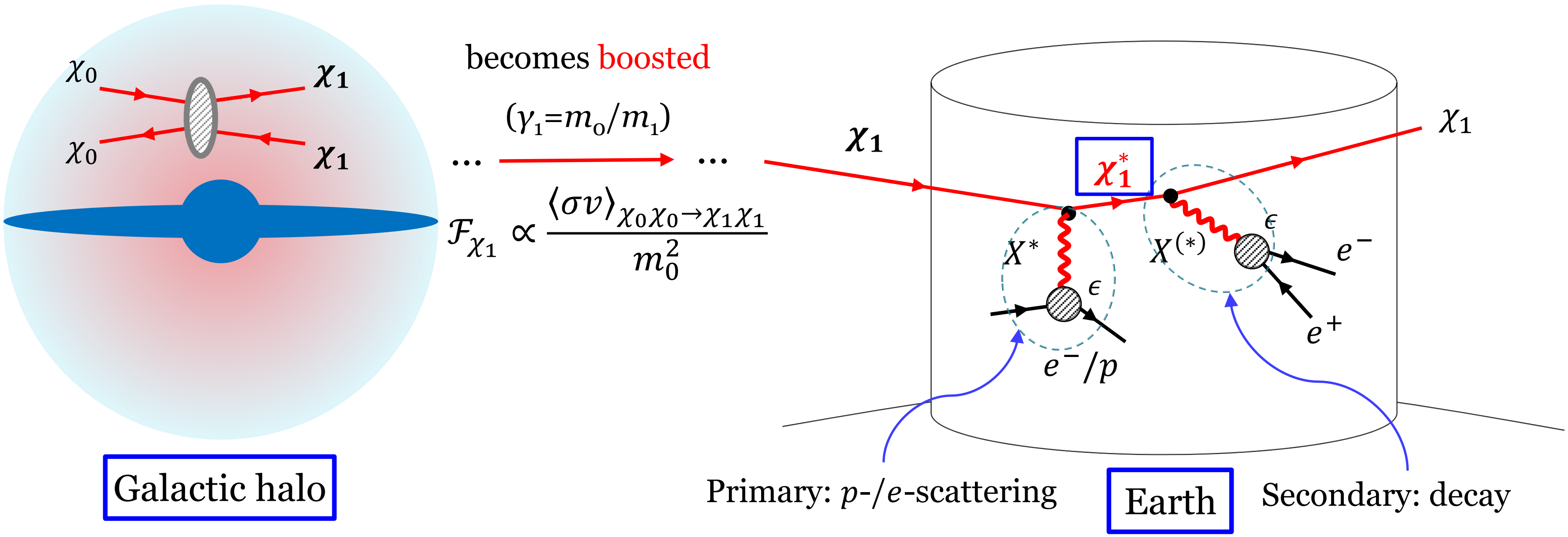
❖ (Light) BDM behaves like a neutrino.

❖ Signature-wise, it is challenging to distinguish the BDM scenario from the neutrino one.

Solution to the Issues:

Basically DM vs ν

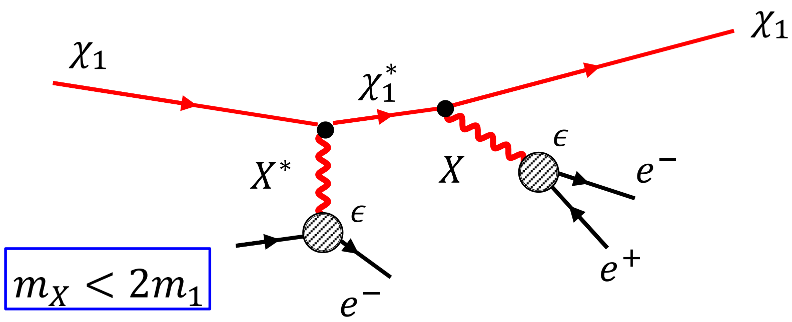
Issues: Avoidable by Subleading Process



❖ Distinctive signatures may arise (even under the minimal setup), once higher-order corrections are taken into account.

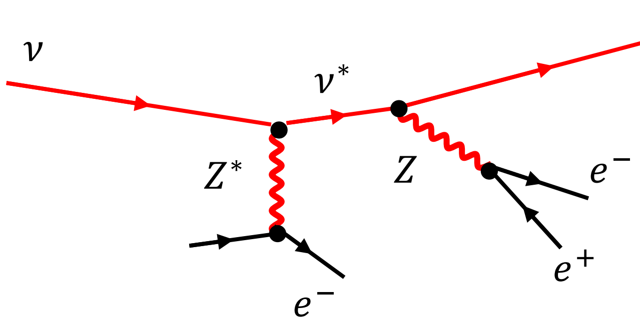
❖ A new BDM search strategy utilizing initial-/final-state dark gauge-boson radiation, i.e. "**Dark-Strahlung** (DS)" from cosmogenic BDM

New BDM Search Strategy via Dark-Strahlung



BDM: e scattering with dark radiation

VS



ν: Z radiation

- ✓ BDM usually behaves like ν's, resulting in signatures which would be invoked by ν's.

  ➔ A challenging task to verify that observed events are actually BDM-induced or induced by ν's coming from the decay/pair-annihilation of DM.

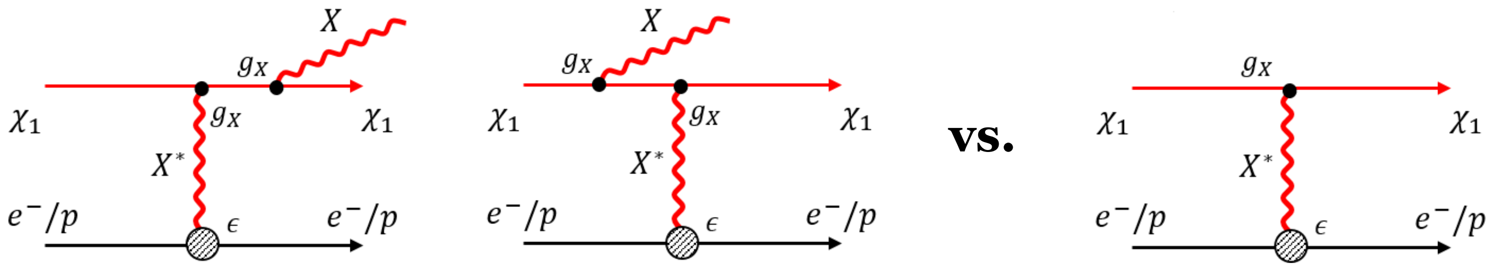
- ✓ ν's do not involve this sort of process, except negligible Z/W-strahlung.

  ➔ Additional observations in DS channel might serve a "milestone" in the field of BDM.

- ✓ Drawback: DS production cross-section is smaller than the leading-order (LO) contribution.

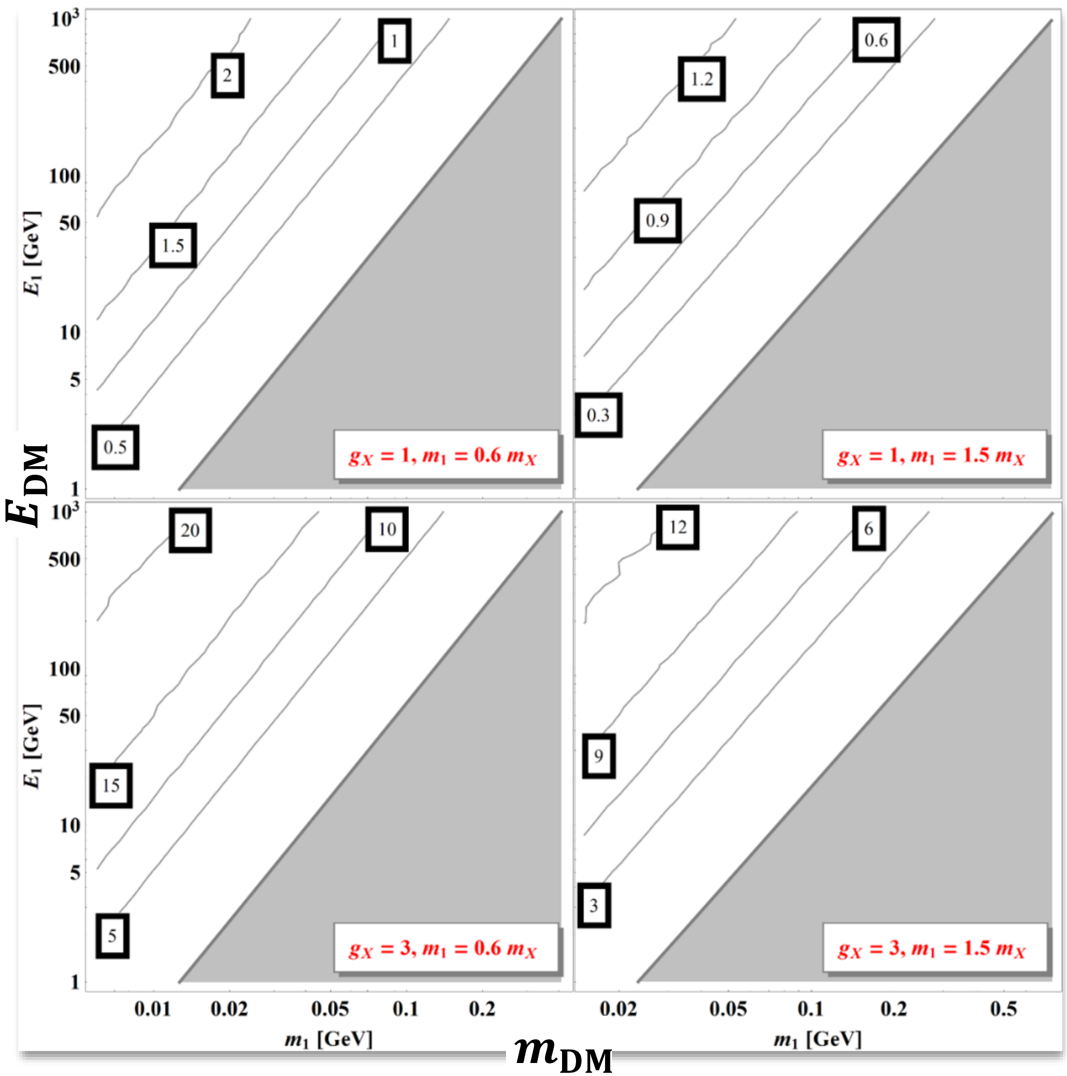
Dark-Strahlung vs. Leading-order: X-section

❖ $\sigma_{\mathrm{DS}}/\sigma_{\mathrm{LO}}[\%]$ ($\chi_1 e^- \to \chi_1 e^- + X$ vs. $\chi_1 e^- \to \chi_1 e^-$) in the $m_{\mathrm{DM}} - E_{\mathrm{DM}}$ plane



Dark-Strahlung vs. Leading-order: X-section

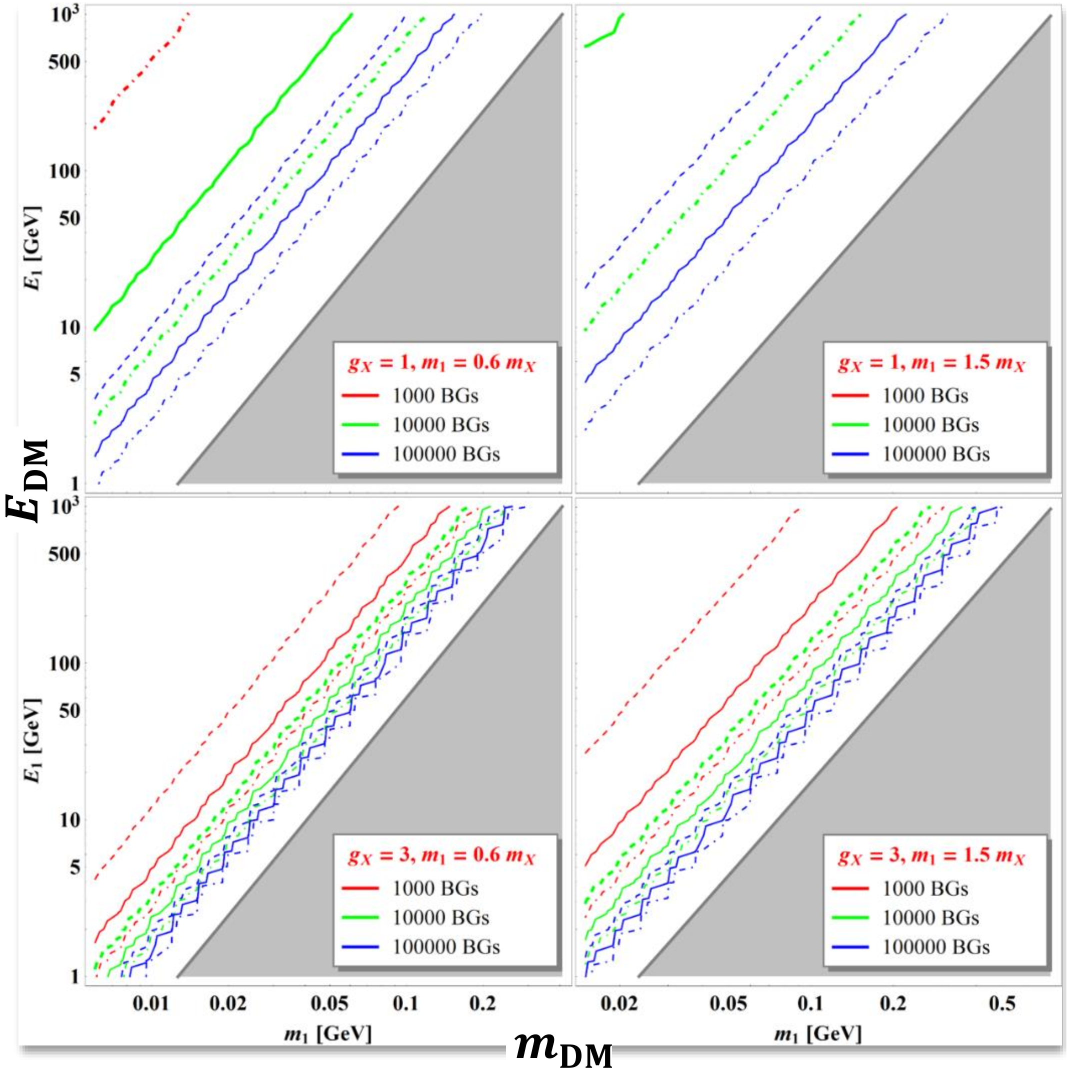
❖ $\sigma_{\rm DS}/\sigma_{\rm LO}[\%]$ ($\chi_1 e^- \to \chi_1 e^- + X$ vs. $\chi_1 e^- \to \chi_1 e^-$) in the $m_{\rm DM} - E_{\rm DM}$ plane



- ✓ DS events occurs more frequently in decreasing $m_{\rm DM}$ & m_X and increasing g_X & $E_{\rm DM}$ as expected in the QED bremsstrahlung.
- ✓ $\sigma_{\rm DS}/\sigma_{\rm LO}$ could be even $O(10-20\%)$ with large $E_{\rm DM}$~0.1 – 1 TeV.
- ✓ For cosmogenic BDM $E_{\rm DM}$~0.1 TeV or larger is possible, while for beam-produced DM $E_{\rm DM} \lesssim O$(10 GeV) .
- ✓ True potential of DS can be assessed with involving BGs.

Dark-Strahlung vs. Leading-order: Run-time

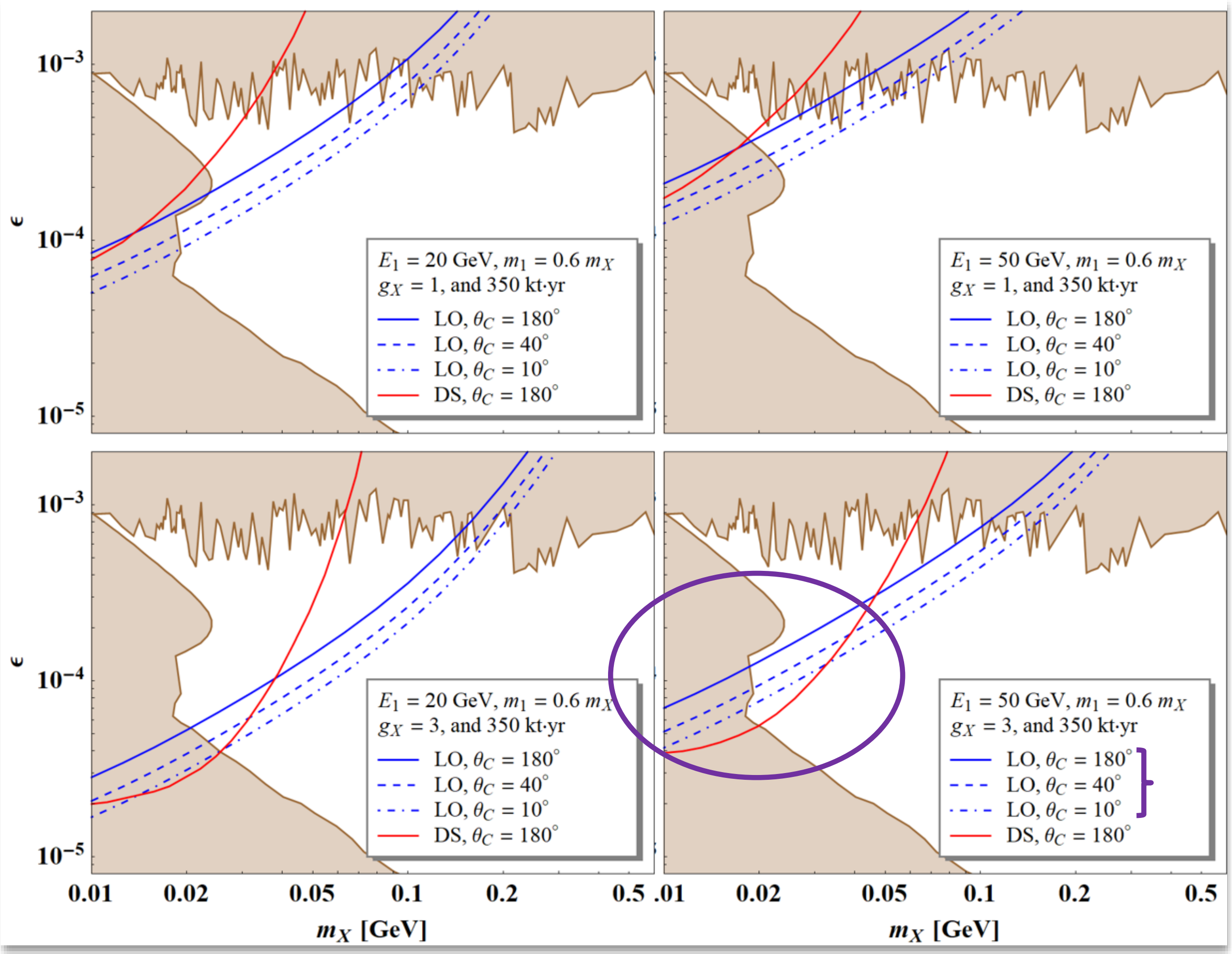
❖ $T_{\rm DS}/T_{\rm LO}$ (Ratios of required run-time) to achieve 90% C.L. in the $m_{\rm DM} - E_{\rm DM}$ plane



- ✓ The simple LO process encounters enormous BGs in BDM searches.
- ✓ $T_{\rm DS}/T_{\rm LO}$=0.5, 1, & 2 ➔ dashed, solid, & dot-dashed curves, respectively
- ✓ $T_{\rm DS}/T_{\rm LO} = 2$ means the DS channel requires twice more time than the LO channel.
- ✓ Even under mild BG contamination ($N_{\rm BG}=10^3$) in the LO, the DS channel remains rather competitive in a wide range of parameter space.

Experimental Sensitivities of DUNE: Dark-X

❖ Experimental sensitivities of DUNE (90% C.L.) in the $m_X - \epsilon$ plane



✓ Major BG to the LO: based on a DUNE study [1512.06148]

✓ The DS channel is at least *complementary* to the LO.

✓ DS allows us to explore a wider parameter regions towards small m_X, large g_X (& larger $E_{\rm DM}$).

DUNE cuts

1) $E_{e^\pm}$ >30 MeV, 2) $\Delta\theta_{e-e^\pm} > 1^\circ$, 3) Scattering & X-decay vertices take place inside the detector.

Conclusion

- Rising interest in extended dark sector scenarios, especially Energetic DM
- A new search channel for the cosmogenic BDM utilizing ***Dark-Strahlung*** (DS)

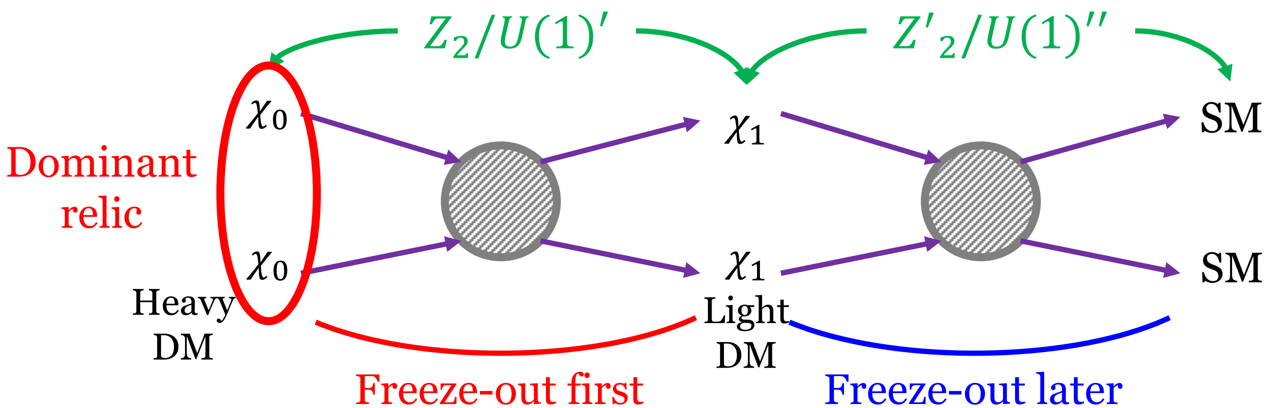
  ➔ The uniqueness of signature renders the search essentially background-free.
- The **observation of DS** can be important evidence to **refute the hypothesis** that the **signals would be induced by ν's** originating from the decay/pair-annihilation of halo dark-matter.
- The DS channel can be complementary to or even surpassing the corresponding leading-order one.

Thank you

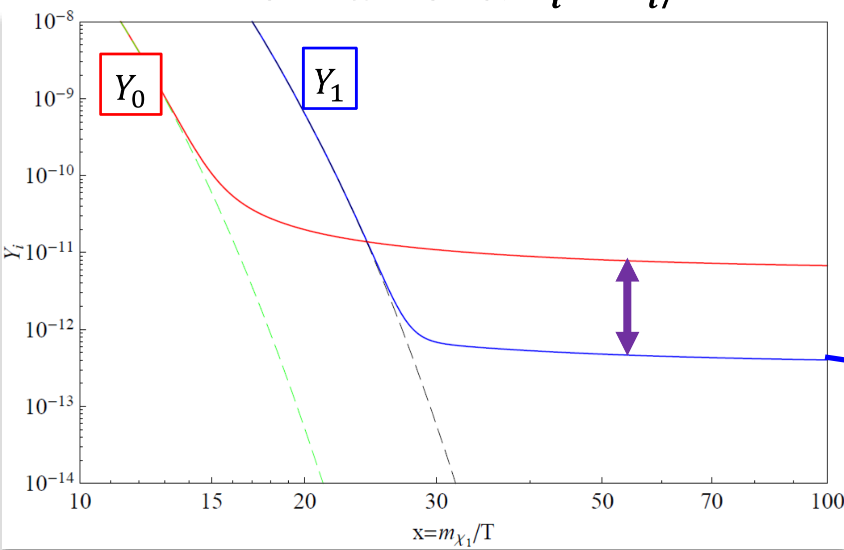
Back-Up

Two-component Scenario

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



Thermal relic: $Y_i = n_i/s$



"**<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

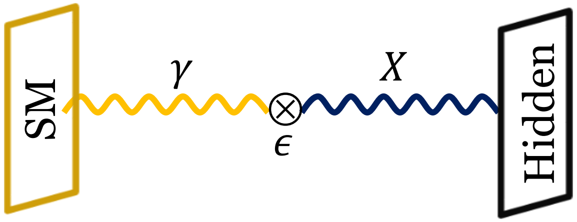
χ_1: Negligible, Non-relativistic **thermal** relic

Boosted DM (BDM) Models

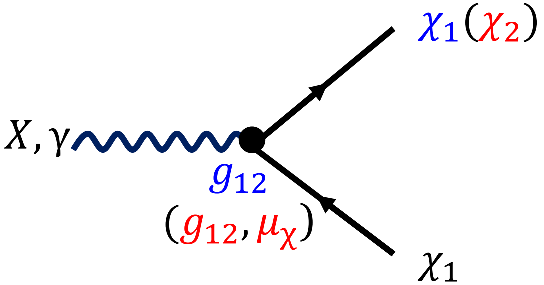
Kim, **JCP** & Shin, PRL (2017)
Giudice, Kim, **JCP**, Shin, PLB (2018)

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

$$\mathcal{L}_{\rm int} \ni (\mu_\chi/2)\bar{\chi}_2\sigma^{\mu\nu}\chi_1 F_{\mu\nu} + h.c.$$



- ✓ χ_2: a heavier (unstable) dark-sector state
- ✓ Flavor-conserving ➔ elastic scattering (eBDM)
- ✓ Flavor-changing ➔ inelastic scattering (*i*BDM)

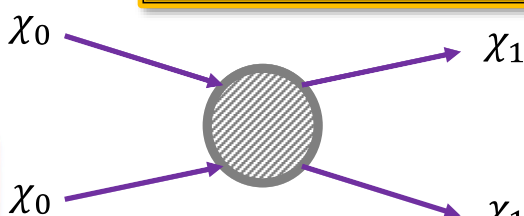


❖ Various models conceiving BDM signatures

- ✓ Source: GC, Sun (capture), dwarf galaxies, etc.
- ✓ Mechanism: assisted freeze-out, semi-annihilation, decaying, cosmic-ray induced DM, etc.
- ✓ Portal: vector portal, scalar portal, etc.
- ✓ DM spin: fermionic DM, scalar DM, etc.
- ✓ *i*BDM-inducing operators: two chiral fermions, two real scalars, dipole moment interactions, etc.

BDM: Production & its Signatures

Benchmark: two-component DM scenario

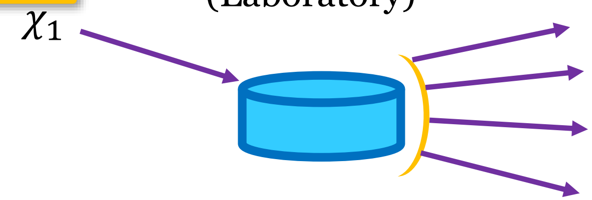


(cf. $\chi\chi \rightarrow \gamma\gamma,\ \boldsymbol{\nu\nu}$)

becomes boosted

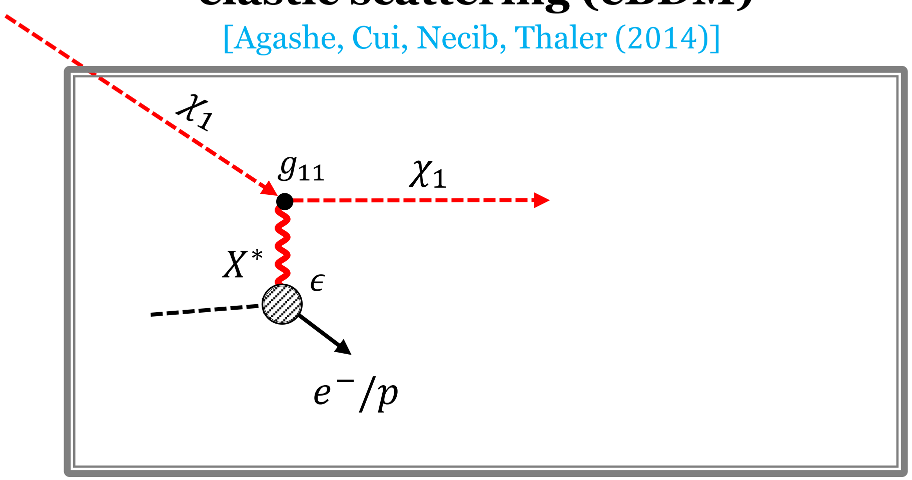
$(\gamma_1 = m_0/m_1)$

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



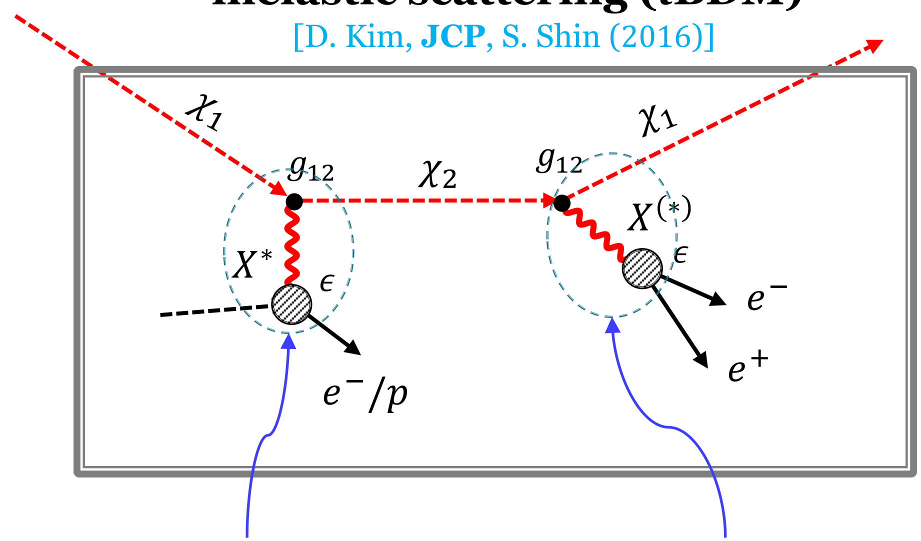
elastic scattering (eBDM)

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



inelastic scattering (*i*BDM)

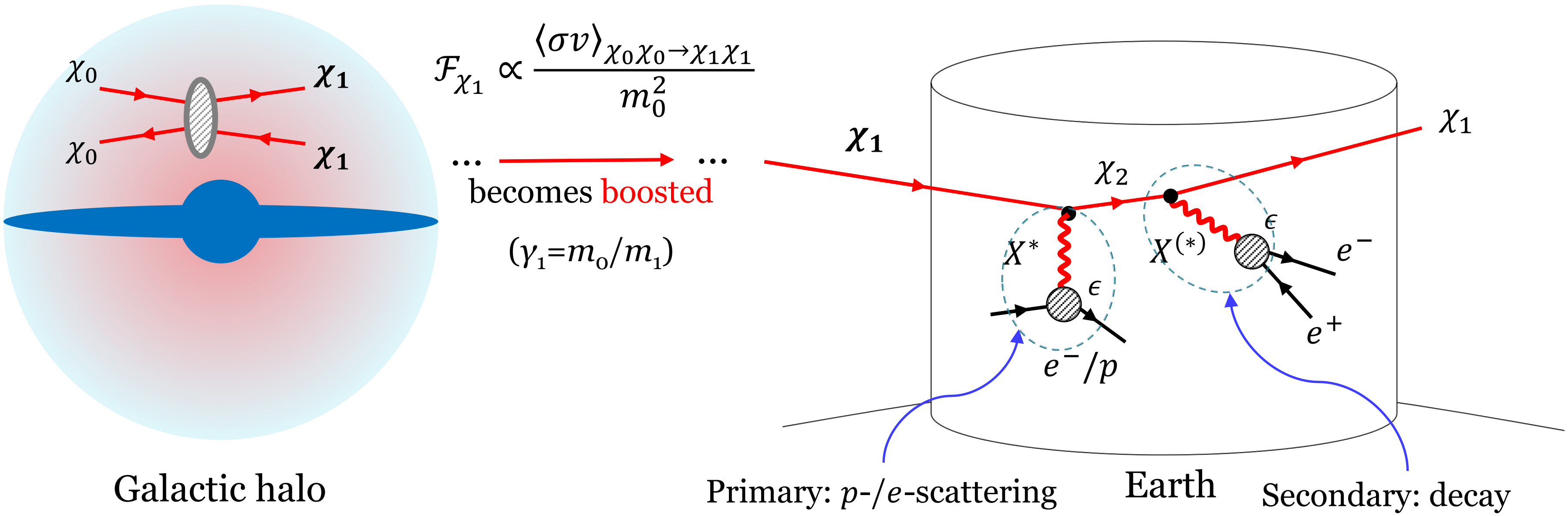
[D. Kim, **JCP**, S. Shin (2016)]



p- or e-scattering (primary)

Decay (secondary)

Issue 2: Avoidable by *i*BDM Scenario



❖ *i*BDM=inelastic BDM: inelastic DM+BDM [Kim, **JCP** & Shin, PRL (2017)]

❖ Additional signatures from the decay of heavier unstable dark-sector state (or excited state) χ_2 at the expense of "minimalism" of underlying BDM models.

Dark Gauge Boson Radiation

❖ A dark gauge boson can radiate from SM fermions and/or dark-sector matter particles just like the ordinary QED bremsstrahlung.

✓ *A'*-strahlung: a dark gauge boson radiation of electron in beam-dump experiments

➔ suppressed by the kinetic mixing [Bjorken, Essig, Schuster, Toro (2014)]

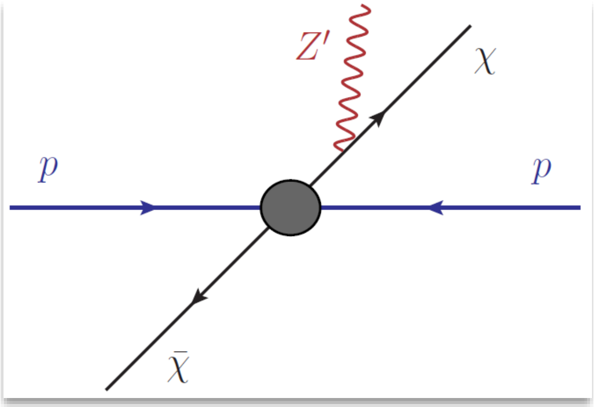
✓ Dark trident: beam-produced DM scatters off a target nucleus, emitting a dark gauge boson which subsequently disintegrates to a e+ & e- pair.

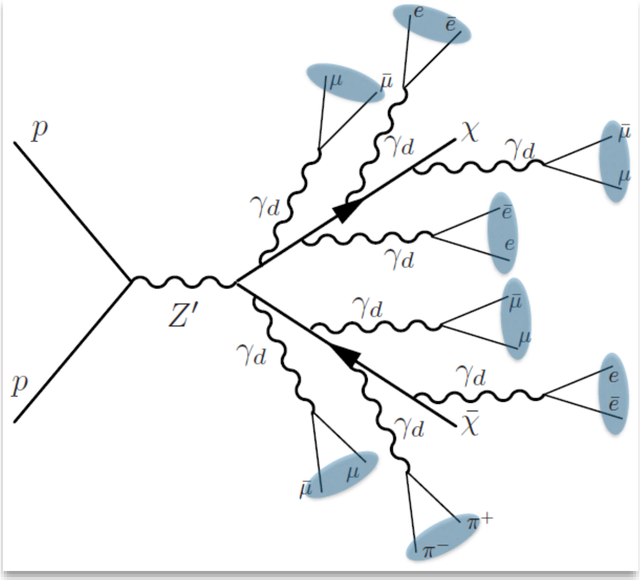
➔ similar to that of the ordinary neutrino trident [Gouva, Fox, Harnik, Kelly, Zhang (2018)]

✓ Related phenomenology was also studied at the LHC but no DM scattering.

[Gupta, Primulando, Saraswat (2015),
Bai, Bourbeau, Lin (2015),
Kim, Lee, Park, Zhang (2016)]

Dark-Strahlung at High E Colliders





- ✓ High E colliders (e.g., LHC): DM productions with $E_{\rm DM} \sim O$(0.1 - 1 TeV) is possible.
- ✓ LHC searches for a dilepton resonance/a mono-Z' jet + missing E_T induced by the DS process have been suggested.
- ✓ Even dark showering may be available at the LHC.
- ✓ No primary DM scattering signals. Only secondary decay signals from emitted X's.

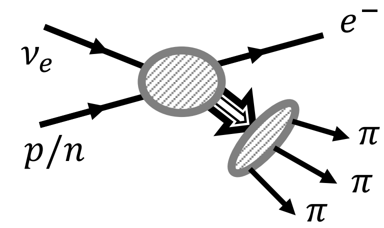
Issue 1: Backgrounds

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

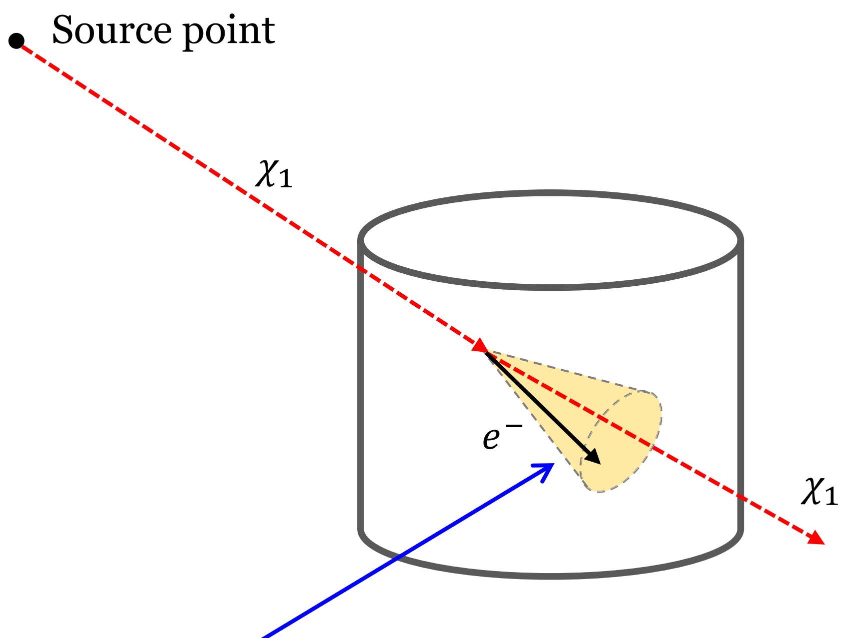
[Super-Kamiokande (2012)]

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

⇒ Potential BGs for elastic scattering of BDM (eBDM)

Issue 1: Backgrounds ➔ Angular Cut

❖ BDM is incoming ultra-relativistically!



Define "search cone" with the half-opening angle θ_C to reduce backgrounds in the LO channel.

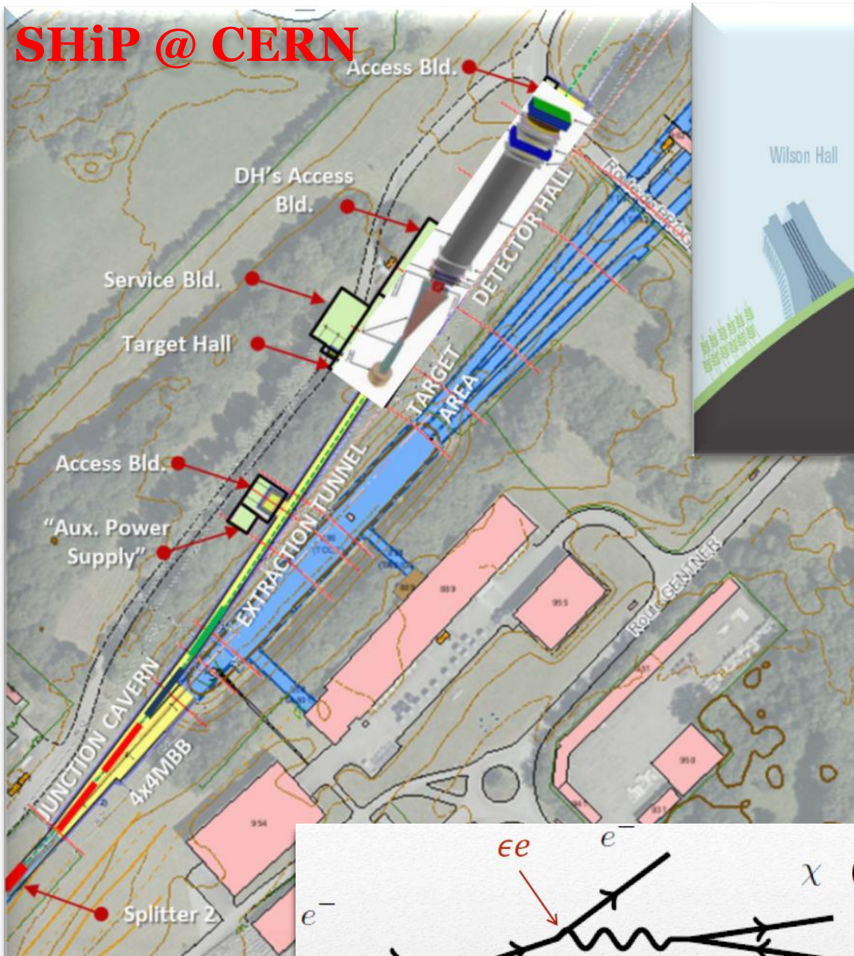
- ✓ Final-state particle move very forward & the scattering angle of the recoil electron is typically less than $\sim 6^\circ$ at $E_{\text{recoil}} = 100$ MeV (minor model dependence)

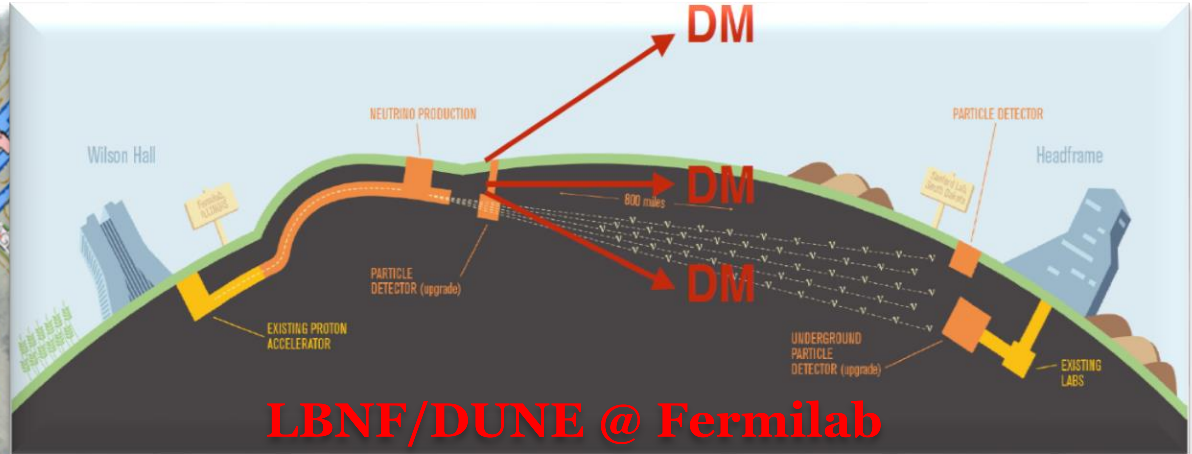
  ➔ directionality measurable.

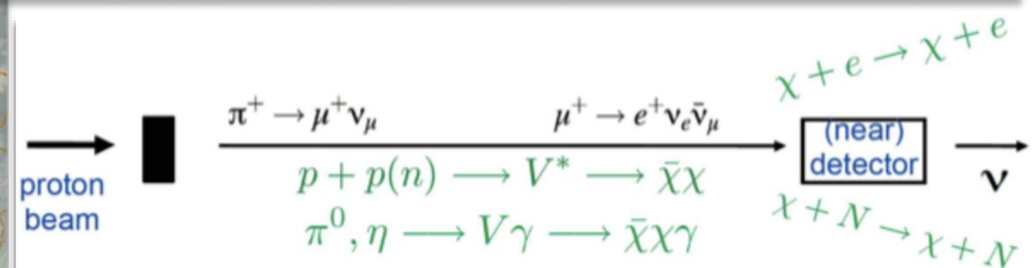
- ✓ Good angular resolution allows to isolate source regions, especially very good for point-like sources such as the Sun & dwarf galaxies.

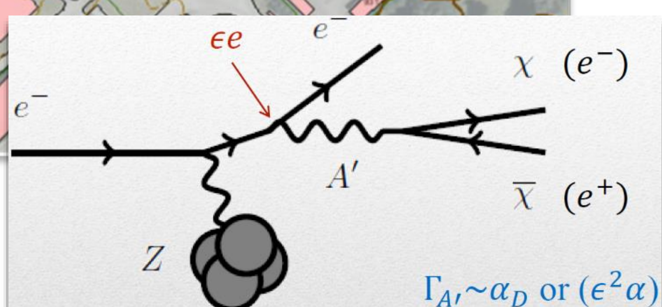
- ✓ GC: too narrow cone ($< \sim 10^\circ$) ➔ loose too many BDM signal events!

Energetic DM @ Fixed Target Exps.









- p/e beam dump ➔ Z', DM production
- Original purpose: ν production (not all)
- Exps.: JSNS²/T2HK(J-PARC), NOVA/MicroBooNE/DUNE(Fermilab), PEX/HPS/DarkLight/BDX (J-Lab), SHiP(CERN), COHERENT(Oak Ridge)

Energetic DM: Beam vs. Cosmic BDM

Beam-produced DM

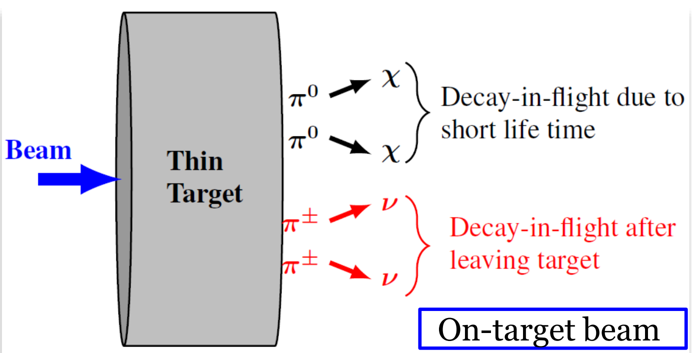
✓ The beam E is distributed to all produced particles. [P. deNiverville et al, 1609.01770]

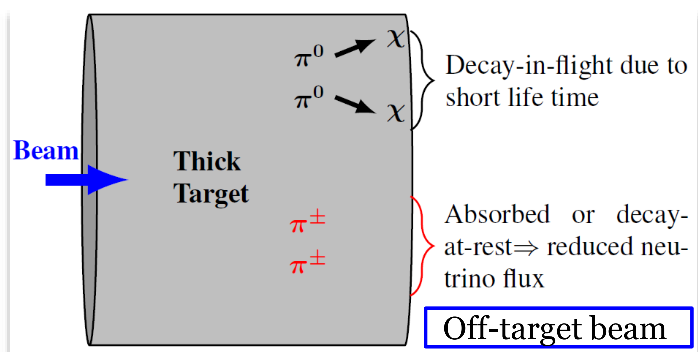
➔ DM typically carries away $E \ll E_{\rm beam}$:

e.g., E ~10 GeV for $E_{\rm beam}$=120 GeV.

✓ More capable of controlling potential backgrounds:

e.g., on-/off-target beam data analysis in MiniBooNE [MiniBooNE, 1807.06137]





Cosmogenic BDM

✓ Many mechanisms for producing BDM in the universe allow $E_{\rm DM} \gtrsim O(100\ {\rm GeV})$.

➔ The DS contributions can be $\gtrsim O(10\%)$ in such high-E realm.

✓ Cosmic-frontier searches are easily plagued by cosmic-ray-induced BGs:

e.g., ν-induced (especially, surface detectors) not well under control & huge

Conventional vs. Nonconventional

❖ Traditional approaches for DM searches:

- ✓ ~~Weak-scale mass~~
- ✓ ~~Weakly coupled~~
- ✓ ~~Minimal dark sector~~
- ✓ ~~Elastic scattering~~
- ✓ ~~Non-relativistic~~

❖ Modified approaches for DM searches:

- ✓ Other mass scale: e.g. PeV, sub-GeV, MeV, keV, meV, …
- ✓ Various couplings to the SM: e.g. vector portal (dark photon), scalar portal, axion portal, …
- ✓ "Flavorful" dark sector: e.g. more DM species, unstable heavier dark-sector states, …
- ✓ Inelastic scattering
- ✓ Relativistic

Large Volume ν Experiments: Purposes

[HK-TDR (2018)]

Other Opportunities?

- Mostly: neutrino physics ➔ oscillation including CP, supernova neutrino, neutrinos from dark matter, etc.
- Next: nucleon (proton) decay

- Such experiments require **big money** ($\gtrsim$O(\$10^8)) **& man power** (O($10^2 - 10^3$))