Boosted Dark Matter Searches via Dark-Strahlung

with Doojin Kim & Seodong Shin [1903.05087]

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Various current/next generation large volume neutrino experiments
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: $E_k \sim O(1 - 1000 \text{ keV})$ → $E_{\text{recoil}} \sim O(1-100 \text{ keV})$
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**What if DM has a relativistic velocity?**

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

- Multi-component model
  \[ m_0 \gg m_1 \]

- Semi-annihilation model
  \[ m_\chi \gg m_\chi \]

- Decaying multi-component DM
  \[ m_\phi \gg m_\chi \]

- Energetic cosmic-ray induced DM
  \[ E_{e^\pm,p^\pm,...} \gg m_\chi \]
Boosted DM Searches

Boosted DM (BDM) models: 
Receiving rising attention as an alternative scenario
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Search for Boosted Dark Matter Interacting with Electrons in Super-Kamiokande

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
Example model: fermionic heavier($\chi_0$)/lighter($\chi_1$) 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**
(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
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
BDM usually behaves like \(\nu\)'s, resulting in signatures which would be invoked by \(\nu\)'s.

- \textbf{A challenging task} to verify that observed events are actually \textit{BDM-induced} or induced by \(\nu\)'s coming from the decay/pair-annihilation of DM.

- \(\nu\)'s do not involve this sort of process, except negligible \(Z/W\)-strahlung.

- \textbf{Additional observations in DS channel} might serve a “milestone” in the field of BDM.

- \textbf{Drawback}: DS production cross-section is smaller than the leading-order (LO) contribution.
Dark-Strahlung vs. Leading-order: X-section

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

- DS events occur more frequently in decreasing \(m_{\text{DM}}\) & \(m_X\) and increasing \(g_X\) & \(E_{\text{DM}}\) as expected in the QED bremsstrahlung.

- \(\sigma_{\text{DS}}/\sigma_{\text{LO}}\) could be even \(O(10 - 20\%)\) with large \(E_{\text{DM}} \sim 0.1 - 1\) TeV.

- For cosmogenic BDM \(E_{\text{DM}} \sim 0.1\) TeV or larger is possible, while for beam-produced DM \(E_{\text{DM}} \lesssim O(10\) GeV\).

- True potential of DS can be assessed with involving BGs.
Dark-Strahlung vs. Leading-order: Run-time

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

- The simple LO process encounters enormous BGs in BDM searches.

- $T_{DS}/T_{LO} = 0.5, 1, \& 2 \Rightarrow$ dashed, solid, & dot-dashed curves, respectively

- $T_{DS}/T_{LO} = 2$ means the DS channel requires twice more time than the LO channel.

- Even under mild BG contamination ($N_{BG}=10^3$) 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 $E_{DM}$).

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

Diagram:
- Dominant relic: $\chi_0$
- Heavy DM
- Freeze-out first

- Light DM
- Freeze-out later

**Thermal relic:** $Y_i = n_i / s$

- $Y_0$
- $Y_1$

**"Assisted Freeze-out"** Mechanism

- Heavier relic $\chi_0$: hard to detect it due to tiny coupling to SM
- Lighter relic $\chi_1$: hard to detect it due to small relic

$\chi_1$: Negligible, Non-relativistic **thermal** relic
Boosted DM (BDM) Models

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

\[ \mathcal{L}_{\text{int}} \ni \left( \frac{\mu_\chi}{2} \right) \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 F_{\mu\nu} + \text{h. c.} \]

- \( \chi_2 \): a heavier (unstable) dark-sector state
- Flavor-conserving \( \rightarrow \) elastic scattering (eBDM)
- Flavor-changing \( \rightarrow \) inelastic scattering (iBDM)

- 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.
  - iBDM-inducing operators: two chiral fermions, two real scalars, dipole moment interactions, etc.

Kim, JCP & Shin, PRL (2017)
Giudice, Kim, JCP, Shin, PLB (2018)
BDM: Production & its Signatures

Benchmark: two-component DM scenario

\( \chi_0 \rightarrow \chi_1 \) becomes boosted \((\gamma_1 = m_0 / m_1)\)

\[ F_{\chi_1} \propto \langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1} m_0^2 \]

elastic scattering (eBDM)  
[Agashe, Cui, Necib, Thaler (2014)]

inelastic scattering (iBDM)  
[D. Kim, JCP, S. Shin (2016)]

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**Issue 2: Avoidable by iBDM Scenario**

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

- **Additional signatures** from the decay of heavier unstable dark-sector state (or excited state) \( \chi_2 \) at the expense of “minimalism” of underlying BDM models.
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.
High E colliders (e.g., LHC): DM productions with $E_{DM} \sim O(0.1 - 1 \text{ TeV})$ 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.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>fully contained electron-like sample</td>
<td>14,053</td>
</tr>
<tr>
<td>fully contained muon-like sample</td>
<td>20,853</td>
</tr>
<tr>
<td>partially contained muon-like sample</td>
<td>6,871</td>
</tr>
</tbody>
</table>

~$40.2/\text{yr/kt}$: may contain multi-track events

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 $E > ~10 \text{ MeV}$.)

$\Rightarrow$ Potential BGs for elastic scattering of BDM (eBDM)

[Super-Kamiokande (2012)]

[DUNE CDR-Vol.2 (2015)]
BDM is incoming ultra-relativistically!

Define "search cone" with the half-opening angle $\theta_c$ 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: $\nu$ 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. \[\text{[P. deNiverville et al, 1609.01770]}\]
- DM typically carries away $E \ll E_{\text{beam}}$:
  - e.g., $E \sim 10 \text{ GeV}$ for $E_{\text{beam}} = 120 \text{ GeV}$.
- More capable of controlling potential backgrounds:
  - e.g., on-/off-target beam data analysis in MiniBooNE \[\text{[MiniBooNE, 1807.06137]}\]

Cosmogenic BDM

- Many mechanisms for producing BDM in the universe allow $E_{\text{DM}} \gtrsim O(100 \text{ GeV})$.
- 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., $\nu$-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
Mostly: neutrino physics $\Rightarrow$ oscillation including CP, supernova neutrino, neutrinos from dark matter, etc.

Next: nucleon (proton) decay

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