Inelastic Boosted Dark Matter

Seodong Shin

1612.06867, 1712.07126, 1803.03264, 1804.07302, 1903.05087, 1908.xxxxx

Gian F. Giudice, Doojin Kim, Kyoungchul Kong, Pedro A. N. Machado, Jong-Chul Park

DUNE experimentalists: Chatterjee, De Roeck, Moghaddam, Whitehead, Yu
Not simple dark sector

“WIMP may be an oversimplification of dark sector.”

- Multi-component? dark p or e or $\nu$?
- Relativistically moving? dark e or $\nu$?
- Dark gauge symmetry? U(1), SU(2), SU(3)?
- Different flavor? dark e, $\mu$?

See also lectures by Hitoshi, Tongyan
Multi-component Boosted DM (BDM)

\[ \chi_0: \text{heavy, } \chi_1: \text{light} \]

Agashe, Cui, Necib, Thaler, 1405.7370
Multi-component Boosted DM (BDM)

Most of the relic

χ₀: heavy, χ₁: light

U(1)/Z₂

U(1)'/Z₂

SM

SM

Freeze out first

Agashe, Cui, Necib, Thaler, 1405.7370
Multi-component Boosted DM (BDM)

χ₀: heavy, χ₁: light

Most of the relic

Freeze out first

Freeze out later

Assisted freeze-out mechanism

non-relativistic relic χ₁ (negligible)

Y₀ ≫ Y₁

Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370
Multi-component BDM

- $\chi_0$: gravitationally WIMP accumulated (GC, Sun, dSphs)

- $\chi_0 \chi_0 \rightarrow \chi_1 \chi_1$ (current universe) relativistic

※ relic $\chi_1$ is non-relativistic
Multi-component BDM

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  ※ relic $\chi_1$ is non-relativistic

Observe $\chi_1$ scattering off target with $E_1 > E_{th}$
(indirect detection of $\chi_0$)
Multi-component BDM

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  ※ relic $\chi_1$ is non-relativistic

Observe $\chi_1$ scattering off target with $E_1 > E_{th}$

(indirect detection of $\chi_0$)

 Flux of $\chi_1 \simeq 1.6 \times 10^{-8} \text{ cm}^{-2}\text{s}^{-1} \times \left( \frac{\langle \sigma v \rangle_{0 \rightarrow 1}}{5 \times 10^{-26} \text{ cm}^3\text{s}^{-1}} \right) \times \left( \frac{100 \text{ GeV}}{m_0} \right)^2$

Assume: NFW

Fixed $\sim 1$ if s-channel annihilation dominates

10,000 times smaller than the flux of atmospheric neutrino
Huge detector if $m_{\chi_0} \gtrapprox O(10 \text{ GeV})$

Flux: small & Energy of $\chi_1$: large $\rightarrow$ Large volume $\nu$ experiments
Huge detector if $m_{\chi_0} \approx O(10 \text{ GeV})$

Flux: small & Energy of $\chi^1$: large $\rightarrow$ Large volume $\nu$ experiments

Subtraction of major background ($\nu$)

Important for all cosmogenic BSM signals
Huge detector if $m_{\chi_0} \gtrsim O(10 \text{ GeV})$

Flux: small & Energy of $\chi^1$: large  $\rightarrow$  Large volume $\nu$ experiments

Subtraction of major background ($\nu$)

Important for all cosmogenic BSM signals

- Directional information: e.g., GC, Sun, dSphs
- Signal with unique feature

Open up novel possibilities of BDM search in many experiments
Inelastic BDM (iBDM)

\( \chi_0 \): heavy DM
\( \chi_1 \): light BDM
\( \chi_2 \): excited state

Kim, Park, SS, PRL 119, 161801 (2017)
Giudice, Kim, Park, SS, PLB 780, 543 (2018)
Inelastic BDM (iBDM)

$\chi_0$: heavy DM

$\chi_1$: light BDM

$\chi_2$: excited state

Assume a contact interaction (no details discussed)

(a) Elastic scattering (eBDM)

(b) Inelastic scattering (iBDM)

Kim, Park, SS, PRL 119, 161801 (2017)

Giudice, Kim, Park, SS, PLB 780, 543 (2018)
Inelastic BDM (iBDM)

\( \chi_0 \): heavy DM
\( \chi_1 \): light BDM
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Follow the structure of inelastic DM e.g., pseudo-Dirac fermion, dark photon

(a) Elastic scattering (eBDM)

(b) Inelastic scattering (iBDM)

Kim, Park, **SS**, PRL 119, 161801 (2017)

Giudice, Kim, Park, **SS**, PLB 780, 543 (2018)
Signals inside a fiducial volume

- Tracks pop-up inside fiducial volume
- Track observation & time correlation can reject bkg.

**Fiducial volume**

**Primary signature**
- (quasi-elastic) e-scattering
- (quasi-elastic) p-scattering
- DIS

**iBDM**

- \( \chi_1 \): light BDM
- \( \chi_2 \): excited state
New method in eBDM search: darkstrahlung

Kim, Park, SS, 1903.05087

eBDM: elastically scattering BDM

• Different from \( \nu \rightarrow \nu \nu \)

• NLO but \( \text{O}(10-20\%) \) of LO possible (impossible for beam produced DM)

• Efficient for large \( N_{BG} \) (cosmogenic BSM signal)

\( \chi^1 \): light BDM
Signal probe

- DUNE: Search for both iBDM & eBDM

De Roeck, Kim, Moghaddam, Park, SS, Whitehead, work in progress
Smaller size detectors are good enough if $m_{\chi_0} \lesssim O(1 \text{ GeV})$

$$\text{Flux of } \chi_1 \approx 1.6 \times 10^{-8} \text{ cm}^{-2}\text{s}^{-1} \times \left( \frac{\langle \sigma v \rangle_{0\rightarrow 1}}{5 \times 10^{-26} \text{ cm}^3\text{s}^{-1}} \right) \times \left( \frac{100 \text{ GeV}}{m_0} \right)^2$$

Assume: NFW
**Signal probe**

- **DUNE**: Search for both iBDM & eBDM  
  De Roeck, Kim, Moghaddam, Park, SS, Whitehead, work in progress

- **Moderate volume surface-based neutrino experiments**:  
  Short-baseline neutrino program, ProtoDUNE  
  Kim, Kong, Park, SS, 1804.07302

  Chatterjee, De Roeck, Kim, Moghaddam, Park, SS, Whitehead, Yu, 1803.03264

First idea searching for NP at ProtoDUNE. Proposal submitted to take 3 yr comic data.
Signal probe

- **DUNE**: Search for both iBDM & eBDM  
  De Roeck, Kim, Moghaddam, Park, SS, Whitehead, work in progress
  
- **Moderate volume surface-based neutrino experiments**:  
  Short-baseline neutrino program, ProtoDUNE

- **Ton-scale DM direct detection experiments**:  
  XENON1T, DarkSide-20k, COSINE-100

  **First iBDM search result**  
  PRL 2019

  106kg array of 8 ultra-pure NaI(Tl) crystals  
  surrounded by 2200L of liquid scintillator (~ 2 ton)

  Observed: 21 events, Background expected: 16.4 ± 2.1
Complementary searches

Large volume $\nu$ experiments (underground)

- Signal observation
- Background subtraction

Early discovery & less $\nu$ background

Better resolution ($E_{\text{th}}$, angle)
Sensitive for smaller $E_1 = m_0$

Moderate volume surface $\nu$ experiments

Ton scale DM direct detection experiments (underground)
Applications of dark sector structure

- Positron excess (TeV)  
  Kim, Park, SS, 1702.02944

- High Energy cosmic-ray signals: IceCube (PeV), ANITA (EeV)  
  Heurtier, Kim, Park, SS, 1905.13223

- Light DM searches in fixed target experiments: e.g, \( \nu \)-experiments  
  Heurtier, Kim, Park, Park, SS, in progress

Subtraction of major background (\( \nu \))?
Applications of dark sector structure

- Positron excess (TeV) Kim, Park, SS, 1702.02944
  Heurtier, Kim, Park, SS, 1905.13223
- High Energy cosmic-ray signals: IceCube (PeV), ANITA (EeV)
  Heurtier, Kim, Park, Park, SS, in progress
- Light DM searches in fixed target experiments: e.g, ν-experiments

Arrival time to detectors & Recoil energy

Dutta, Kim, Liao, Park, SS, Strigari, 1906.10745 & in progress

Subtraction of major background (ν)?
Applications of dark sector structure

• Positron excess (TeV) Kim, Park, SS, 1702.02944

Heurtier, Kim, Park, SS, 1905.13223

• High Energy cosmic-ray signals: IceCube (PeV), ANITA (EeV)

Heurtier, Kim, Park, Park, SS, in progress

• Light DM searches in fixed target experiments: e.g, $\nu$-experiments

Arrival time to detectors & Recoil energy

Dutta, Kim, Liao, Park, SS, Strigari, 1906.10745 & in progress

$$\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow \nu_\mu e^+ \bar{\nu}_\mu \nu_e$$

prompt delayed
Applications of dark sector structure

- Positron excess (TeV) Kim, Park, SS, 1702.02944

- High Energy cosmic-ray signals: IceCube (PeV), ANITA (EeV)

- Light DM searches in fixed target experiments: e.g, $\nu$-experiments

\[ \pi^- + p \rightarrow X + n \]

\[ X \rightarrow \chi \bar{\chi} \]

Arrival time to detectors & Recoil energy

Dutta, Kim, Liao, Park, SS, Strigari, 1906.10745 & in progress
Applications of dark sector structure

• Positron excess (TeV)  
  Kim, Park, **SS**, 1702.02944

• High Energy cosmic-ray signals: IceCube (PeV), ANITA (EeV) 
  Heurtier, Kim, Park, **SS**, 1905.13223
  Heurtier, Kim, Park, Park, **SS**, in progress

• Light DM searches in fixed target experiments: e.g, \( \nu \)-experiments

\[
\pi^- + p \rightarrow X + n \\
X \rightarrow \chi\bar{\chi}
\]

Arrival time to detectors & Recoil energy

Dutta, Kim, Liao, Park, **SS**, Strigari, 1906.10745 & in progress

**3σ (2.4σ) statistical deviation** for Rn = 5.5fm (4.7fm)

**COHERENT, 2018 CsI data**
Conclusions

• BDM (iBDM & eBDM) is a candidate of Dark World beyond WIMP
  New DM search strategies required!

• Unique signal feature helps to reject $\nu$ background:
  i) iBDM
  ii) Darkstrahlung for eBDM

• Complementary searches in various experiments
Backup: other energetic DM scenarios

• Semi-annihilation model  
  D'Eramo, Thaler, 1003.5912

• 3 → 2 model  
  Carlson, Machaceck, Hall, Astrophys J. (1992)
  Hochberg, Kuflik, Volansky, Wacker, 1402.5143

• Decaying multi-component DM  
  Bhattacharya et al., 1407.3280
  Kopp, Liu, Wang, 1503.02669

• High velocity (semi-relativistic) DM

  Anti-DM from DM-induced nucleon decay in the Sun  
  Huang, Zhao, 1312.0011

Ultra High Energetic Cosmic-Ray induced DM

  Bringmann, Pospelov, 1810.10543
  Cappiello, Ng, Beacom, 1810.07705
  Cappiello, Beacom, 1906.11283

  Ema, Sala, Sato, 1811.00520
  Yin, 1809.08610
Backup: Sensitivities at DUNE vs HK

- DUNE preferred parameter region over HK although the size is 1/10 (lower $E_{th}$, better resolution)
- Difference is huge for p-scattering

$$m_X > 2m_1 \quad \chi_2 \rightarrow X^* \chi_1 \rightarrow e^+ e^- \chi_1$$

$$m_X < 2m_1 \quad \chi_2 \rightarrow X^{(*)} \chi_1 \rightarrow e^+ e^- \chi_1$$

Kim, Machado, Park, SS, To appear soon
Backup: cosmic-ray background

e.g., primary: e-scattering, secondary e$^+$ e$^-$

Fiducial volume  cosmic $\mu$ events (> 400 MeV) $\approx$ 94/m$^2$/s/sr at sea level

- Dominant background: sneaking-in muon (rare events but many cosmic-muons)
- Assume the unknown probability $\sim$ 0.6%

4x10$^{11}$/yr/detector

ProtoDUNE

SP: 300 t
DP: 210 t

$\frac{\alpha}{\pi}$ $\sim$ 0.2%
+ a track pops-up here with $E > E_{th}$ and with unclear kink feature

$\frac{e^+}{e^-} \sim 0.1$

$\frac{e^+}{e^-} \sim 1$

Chatterjee, De Roeck, Kim, Moghaddam, Park, SS, Whitehead, Yu, 1803.03264 (PRD 98, 075027)
Backup: cosmic-ray background

e.g., primary: e-scattering, secondary e⁺ e⁻

Fiducial volume cosmic μ events (> 400 MeV) ≈ 94/m²/s/sr at sea level

- Dominant background: sneaking-in muon (rare events but many cosmic-muons)
- Assume the unknown probability ~ 0.6%
- Pattern analysis by machine learning will decrease further (N_{bkg}: negligible)

4×10^{11}/yr/detector

ProtoDUNE

SP: 300 t
DP: 210 t

2×10^{-8} < 100
6×10^{-3} in total detectors

Chatterjee, De Roeck, Kim, Moghaddam, Park, SS, Whitehead, Yu, 1803.03264 (PRD 98, 075027)
Backup: Earth shielding

Kim, Kong, Park, SS, 1804.07302

Collect upward-going signal only when the source is at the opposite side

From the sun: half
From the GC:
SBNP: 0.66, ProtoDUNE: 0.69

$\chi^0 \chi^0 \rightarrow \chi^1 \chi^1$
Backup: COSINE-100 result

COSINE-100, 1811.09344

Based on theoretical study
Giudice, Kim, Park, SS, 1712.07126

106kg array of 8 ultra-pure NaI(Tl) crystals immersed in an active veto detector

2200L of liquid scintillator (~2 ton)

Observed: 21 events, Background expected: 16.4 ± 2.1
Backup: sensitivity

\[ N_{\text{sig}} = \sigma \cdot F \cdot A \cdot t_{\text{exp}} \cdot N_T \]

- \( \sigma \): scattering cross section between \( \chi_1 \) and (target) electron
- \( F \): flux of incoming (boosted) \( \chi_1 \)
- \( A \): acceptance  (detector geometry, only for iBDM)
- \( t_{\text{exp}} \): exposure time
- \( N_T \): total number of target  
  (e,p,n)  ) Fixed for a given experiment
Backup: sensitivity

\[ N_{\text{sig}} = \alpha \cdot F \cdot A \cdot t_{\text{exp}} \cdot N_T \]

- \( \alpha \): scattering cross section between \( \chi_1 \) and (target) electron
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- \( t_{\text{exp}} \): exposure time
- \( N_T \): total number of target \((e,p,n)\) (Fixed for a given experiment)

Both primary and secondary inside the fiducial volume

- Function of decay length of \( \chi_2 \) (event generation assuming cumulatively isotopic flux of \( \chi_1 \))
- Conservatively, we calculate the maximum mean decay length in the laboratory frame for each parameter set
Backup: sensitivity

\[ N_{\text{sig}} = \sigma_f \cdot F \cdot A \cdot t_{\text{exp}} \cdot N_T \]

- \( \sigma_f \): scattering cross section between \( \chi_1 \) and (target) electron
- \( F \): flux of incoming (boosted) \( \chi_1 \)
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Both primary and secondary inside the fiducial volume

- Function of decay length of \( \chi_2 \) (event generation assuming cumulatively isotopic flux of \( \chi_1 \))
- Conservatively, we calculate the maximum mean decay length in the laboratory frame for each parameter set

with signal efficiency
Backup: model independent sensitivity

\[
\sigma_e \cdot \mathcal{F} \geq \frac{2.3}{A(t_{\text{lab}}^{\text{max}}) \cdot t_{\text{exp}} \cdot N_T}
\]

zero-background assumption

(90% C.L.)

e.g., ProtoDUNE (worst case)

\[N_{bkg} = 100, N^{90} = 17.8\]
(Almost) Model independent sensitivity

\[ \sigma_\epsilon \cdot F \geq \frac{2.3}{A(\bar{E}_{\text{lab}}^{\text{max}}) \cdot t_{\text{exp}} \cdot N_T} \]

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

Fix (then use NFW)

\[ \langle \sigma v \rangle_{\chi_0 \chi_0 \rightarrow \chi_1 \chi_1} = 5 \times 10^{-26} \text{ cm}^3 \text{s}^{-1} \]

\[ N_{\text{bkg}} = 100, N^{90} = 17.8 \]

e.g., ProtoDUNE (worst case)

\[ m_0(=E_1) [\text{MeV}] \]

\[ \sigma_\epsilon [\times 10^{-37} \text{ cm}^2] \]

Graph showing sensitivity limits with various lines representing different scenarios and experimental conditions.
(Almost ) Model independent sensitivity

$$\sigma_\epsilon \cdot F \geq \frac{2.3}{A(\tilde{\ell}_{\text{lab}}^{\text{max}}) \cdot t_{\text{exp}} \cdot N_T}$$

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

Fix (then use NFW)

$$\langle \sigma v \rangle_{\chi_0\chi_0 \rightarrow \chi_1\chi_1} = 5 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$$

$$n_{\text{bkg}} = 100, \quad N^{90} = 17.8$$

e.g., ProtoDUNE (worst case)

Information of energy and flux
(In)direct dark matter detection?

Cone search: 8 cones from 5° to 40° around GC
→ No clusters visible

Limit for $m_{\chi} = 20$ MeV

SK preliminary
$0.1 \text{ GeV} < p_e < 1 \text{ TeV}$

$\theta_e^{th}$ with angular resolution $\theta$

$|m_1| = 200 \text{ MeV}, m_x = 20 \text{ MeV}, g_{11} = 0.5$

SK, 1711.05278

GC & Sun

90% bound
Backup: Darkstrahlung topology

Altmannshofer, Gori, Pospelov, Yavin, 1406.2332

de Gouvea, Fox, Harnik, Kelly, Zhang, 1809.06388

Gupta, Primulando, Saraswat, 1504.01385

Kim, Lee, Park, Zhang, 1612.02850
Backup: Higher Energy?

Heurtier, Kim, Park, **SS**, 1905.13223