# The BDX experiment at JLab

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On behalf of BDX collaboration

09 - 04 - 2025

1. Dark Matter
   - Light Dark Matter
   - Inelastic Dark Matter
   - Muon-philic Dark Scalar
2. BDX
   - Experimental setup
   - Physics reach
3. BDX-MINI
   - Experimental setup
   - Results
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# Dark Matter Problem

Astrophysical observations suggest existence of DM

$\rightarrow$ Information only from gravitational interaction

$\Rightarrow$ No clue on DM nature

Common assumption: **thermal origin of DM**

$\rightarrow$ DM we see comes from an epoch of thermodynamical equilibrium with SM

$\rightarrow$ constrain on available mass range

$\rightarrow$ strong constraint on viable DM $\rightarrow$ SM interaction

Thermal DM

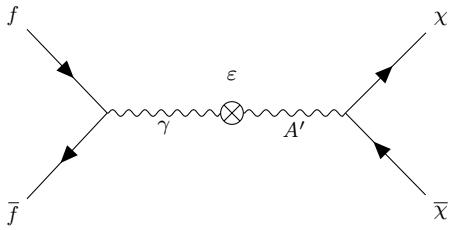
# Light Dark Matter - Dark Photon model

Simplest possibility: "*vector portal*"

$\rightarrow$ $U(1)$ gauge boson (**dark photon**) coupling to electric charge

$$\mathcal{L}_{LDM} \sim g_D A'_\mu J^\mu_\chi + \varepsilon e A'_\mu J^\mu_{EM} + [...]$$

Annihilation in SM:




Model parameters:

- Dark Photon mass $m_{A'}$, coupling to SM $\varepsilon$
- Dark Matter mass $m_\chi$, coupling to DM $g_D$ ($\alpha_D \equiv g_D^2/4\pi$)

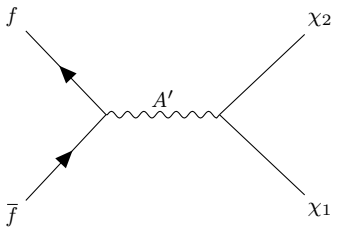
$$y \equiv \frac{g_D^2 \epsilon^2 e^2}{4\pi} \left(\frac{m_\chi}{m_{A'}}\right)^4 \sim \langle \sigma v \rangle_{relic} m_\chi^2$$

arXiv:1607.01390

# Light Dark Matter - Inelastic Dark Matter

Dark Sector may be composed of two states with different mass

$\rightarrow$ Stable low mass state $\chi_1$ and unstable high mass state $\chi_2$




Same parameter $y \equiv \frac{g_D^2 \epsilon^2 e^2}{4\pi} \left(\frac{m_\chi}{m_{A'}}\right)^4 \sim \langle \sigma v \rangle_{relic} m_\chi^2$ can be used to probe this model

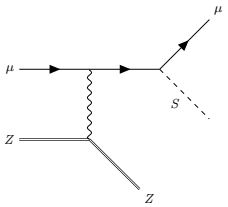
M. Battaglieri et al., arXiv:1910.03532

# Light Dark Matter - Muonphilic Dark Scalar

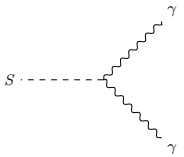
Dark Sector could explain SM anomalies, for example muon $(g-2)_\mu$ anomaly

$\rightarrow$ Simplest possibility: Dark Scalar coupled only to muons

Dark Scalar Production




DS decay




Model parameters:

- Dark Scalar mass $m_S$
- DS-muon coupling $g_\mu$

C. Cesarotti et al., Phys.Rev.D 110 (2024) 5, 055032

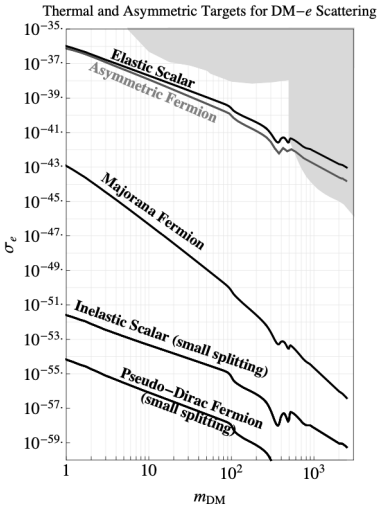
# Light Dark Matter

Direct detection not suited for sub-GeV DM searches:

- DD experiments optimized for $m_\chi >$ GeV
  - $\rightarrow$ $E_R \propto m_\chi^2 / m_N$
  - $\Rightarrow$ very low recoil energy

- LDM-SM interaction cross section depends on impinging particle velocity
  - $\rightarrow$ DD sensitivity strongly model-dependent

- Inelastic DM almost impossible to probe
  - Upscattering kinematically forbidden



# Light Dark Matter

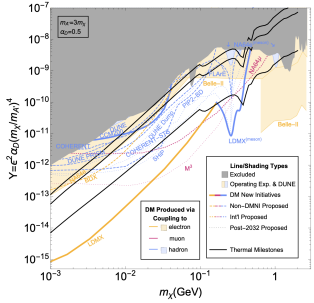
## LDM at accelerators

Accelerator based experiments at the *intensity frontier* uniquely suited to search for LDM:

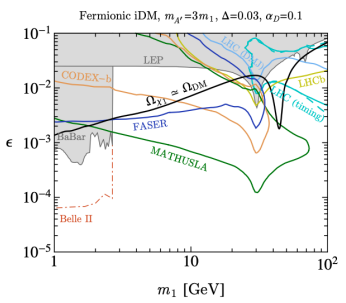
→ High intensity ⇒ increased possibility of DM production

→ Production of relativistic DM ⇒ testing different models

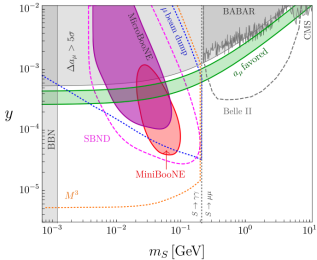
### Light Dark Matter




### Inelastic Light Dark Matter

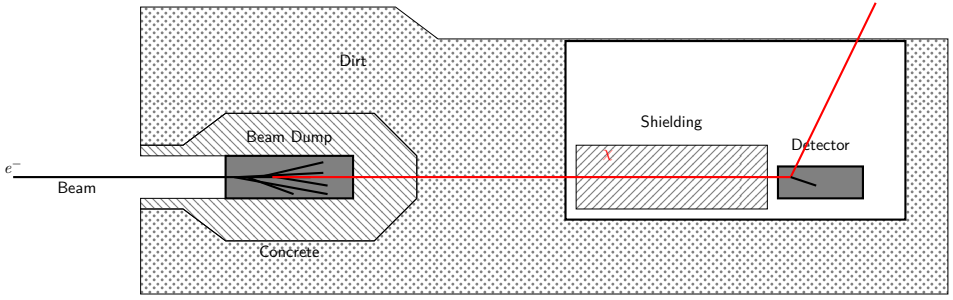



### Muonphilic Dark Scalar



# Beam Dump experiments

**Beam dump experiments**: direct detection of LDM produced by beam impinging on fixed target (beam dump)[1]




$\chi$ production

- $e^-$ beam impinging on target
- $\chi$ from decay of $A'$ produced in the dump

$\chi$ interaction

- $\chi$ propagate through shielding
- $\chi$ scattering through $A'$ exchange

[1] Izaguirre et al., Phys. Rev. D 88, 114015
arXiv:1607.01390

# Beam Dump experiments

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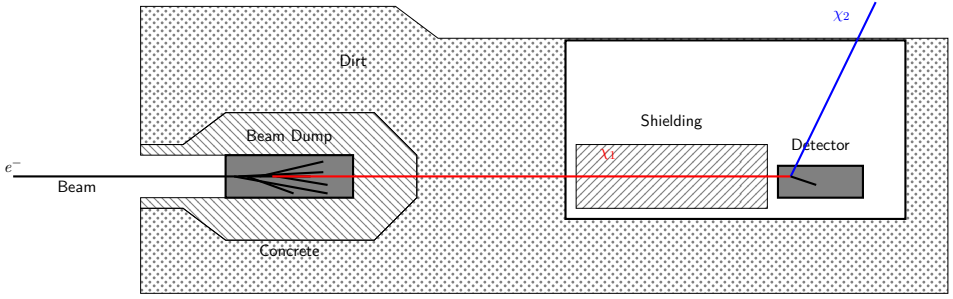


$\chi_{1,2}$ production

- $e^-$ beam impinging on target
- $\chi_1\chi_2$ from decay of $A'$ produced in the dump

$\chi_{1,2}$ interaction

- $\chi_1$ scattering through $A'$ exchange
- $\chi_2$ decay in $\chi_1$ and $e^+e^-$

M. Battaglieri et al., arXiv:1910.03532

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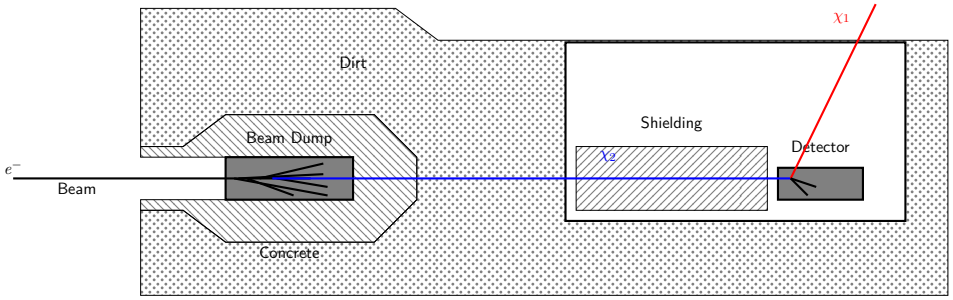


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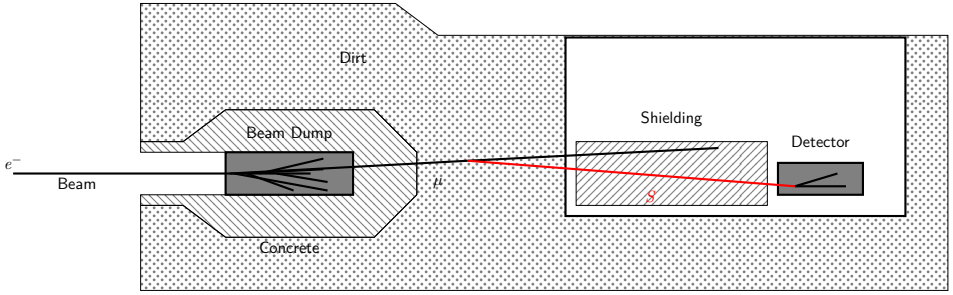
# Beam Dump experiments

**Beam dump experiments**: direct detection of LDM produced by beam impinging on fixed target (beam dump)[2]




DS production

- Secondary $\mu$ cross different materials
- DS production from $\mu$ scattering

DS decay

- DS propagate over large distance
- DS decay identified as two high energy $\gamma$s

[2] Phys.Rev.D 110 (2024) 5, 055032
L. Marsicano et al., Phys.Rev.D 98 (2018) 11, 115022

# BDX

## BDX

**JLab experiment** approved by PAC46

- Run time: 2026-2029
- Fully optimized for LDM searches

JLAB offers the best condition for BDX:

- Medium high energy beam (11 GeV)
- High electron beam current (65 $\mu$A)
- Fully parasitic wrt Hall-A physic program (Moeller)

New facility to be built in front of Hall-A beam dump:

- new underground ($\sim 8$ m) hall
- 25 m downstream of Hall-A beam dump
- passive shielding ($\sim 7$ m steel) to reduce beam related background


arXiv:1607.01390

# BDX - Detector

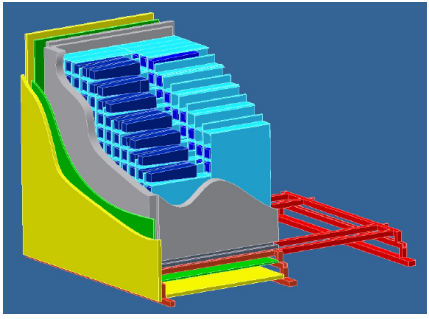
## Detector design

**Electromagnetic calorimeter**:

- homogeneous 3 tons ECal

**Veto system**:

- hermetic multi layer veto
- 2 layer of plastic scintillator counters
- 5 cm lead vault between veto and calorimeter



Modular detector arrangement:

- ECal (BGO, $PbWO_4$)
- Multi-layer veto

$\rightarrow$ total: 3 modules (1 BGO, 2 $PbWO_4$)

Signal detection:

- EM shower ($\gtrsim$ 100 MeV) and no corresponding activity in the active veto

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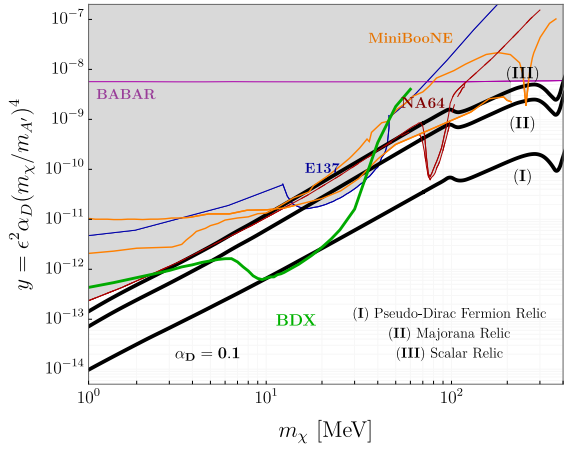
arXiv:1607.01390

# BDX - Reach

Thanks to CEBAF high luminosity and an optimized detector layout, BDX will be able to explore different LDM models

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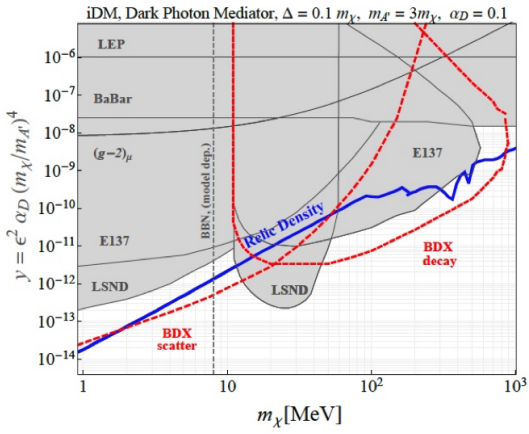


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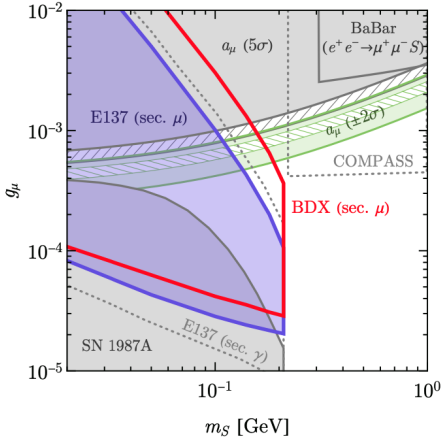
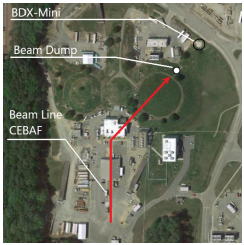


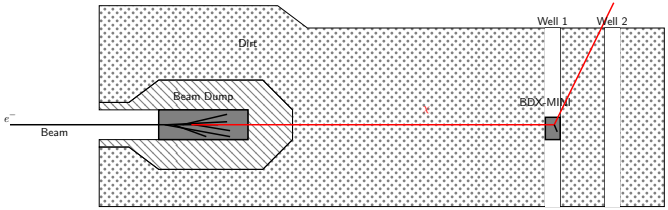

arXiv:1607.01390, arXiv:1910.03532, Phys.Rev.D 98 (2018) 11, 115022

# BDX-MINI - Experimental Setup

Pilot version of BDX:

- detector placed $\sim$ 25 m downstream of beam dump
- 2.56 GeV $e^-$ beam
- current up to $150\ \mu$A
- measurement alternating beam on and beam off data (beam on time $\sim$ 50 %)
  - $\rightarrow$ Cosmogenic background studied with beam-off data
- accumulated $2.54 \times 10^{21}$ EOT



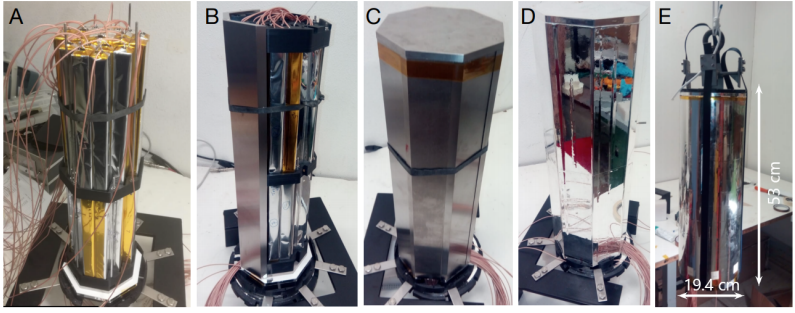




M. Battaglieri et al., Eur.Phys.J.C 81 (2021) 2, 164

# BDX-MINI - Detector

**Electromagnetic calorimeter** (ECal):

- 44 $PbWO_4$ crystals ($4 \times 10^{-3}$ m$^3$ active volume)
- SiPM readout




M. Battaglieri et al., Eur.Phys.J.C 81 (2021) 2, 164

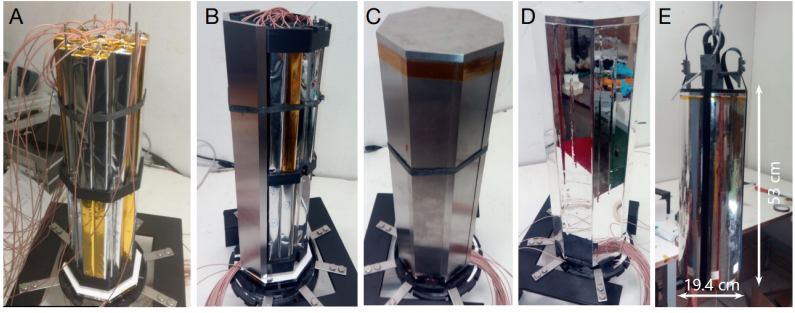
# BDX-MINI - Detector

**Electromagnetic calorimeter** (ECal):

- 44 $PbWO_4$ crystals ($4 \times 10^{-3}$ m$^3$ active volume)
- SiPM readout

**Veto system**

- Active veto:
- Octagonal (IV) plastic scintillator
- Cylindrical (OV) plastic scintilaltor
- Passive tungsten shielding




M. Battaglieri et al., Eur.Phys.J.C 81 (2021) 2, 164

# BDX-MINI - Results

BDX-MINI analysis fully optimized for DM searches

- Cosmic background studied using beam-off data
- Signal cut optimized using beam-off data and signal MC simulation

**Experimental results**

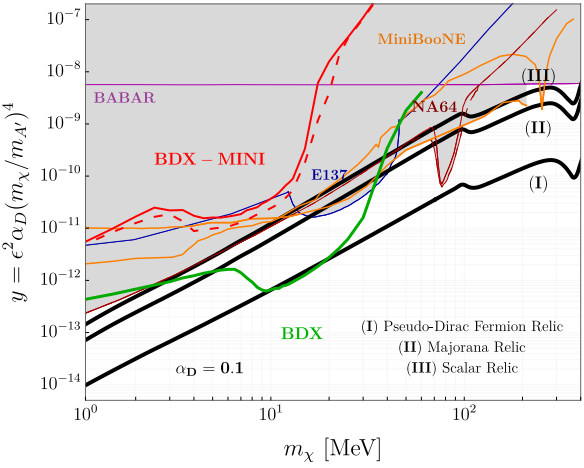
Yields (for $N_{EOT} = 2.54 \cdot 10^{21}$)

- $N_{on} = 3623$
- $N_{off} = 3822$ ($\tau = 1.054$)

No excess is observed

→ evaluated $90\%$ exclusion limit in the LDM parameter space

→ results comparable with flagship experiments




M. Battaglieri et al., Phys.Rev.D 106 (2022) 7, 072011

# Outlook

- Dark matter in the MeV-to-GeV range is largely unexplored
- **BDX**: search for Dark Sector particles in the MeV-GeV mass range
  - Technique viable to probe different DM candidates
  - JLab provides unique opportunities to probe different models
- **BDX-MINI**: pilot version of BDX
  - First modern beam dump experiment searching for Light Dark Matter
  - Detector optimized for LDM searches
  - Analysis aimed to LDM detection
  - Evaluated exclusion limit $\rightarrow$ competitive to flagship experiments
- Beam dump experiment with $e$ beam highly sensitive to Light Dark Matter in the MeV-GeV range

  $\rightarrow$ Sensitivity to large variety of models

  $\rightarrow$ BDX-MINI remarkable results demonstrate that BDX is a mature, ready-to-run experiment (after the construction of a new underground experimental hall)