# The BDX experiment at Jefferson Laboratory

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On behalf of the BDX collaboration

INFN-Genova

# Outline

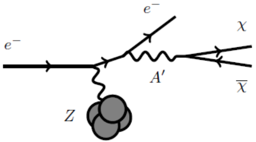
## A fixed target, $e^-$ beam LDM experiment

Beam Dump eXperiment: Light Dark Matter (LDM) direct detection in a $e^-$ beam, fixed-target setup[1]

LDM parameters space:
$M'_A$, $M_\chi$, $\varepsilon$, $\alpha_D$
$M'_A \simeq 10 \div 1000$ MeV
$M_\chi \simeq 1 \div 100$ MeV

### $\chi$ production

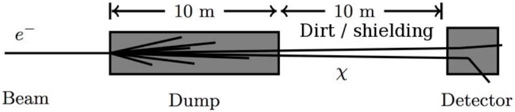
- High-energy, high-intensity $e^-$ beam impinging on a dump
- $\chi$ particles pair-produced radiatively, trough $A'$ emission

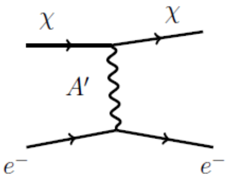



### $\chi$ detection

- Detector placed behind the dump, $\simeq 20m$
- Neutral-current $\chi$ scattering on atomic $e^-$ trough $A'$ exchange,recoil releasing visible energy
- Signal: high-energy EM shower, $E > .3$ GeV

Number of events scales as: $N \propto \frac{\alpha_D \varepsilon^4}{m_A^4}$




[1] For a comprehensive introduction: E. Izaguirre *et al*, Phys. Rev. D 88, 114015

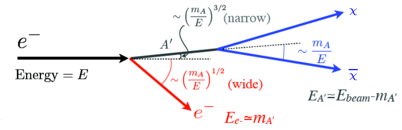
## LDM production and detection

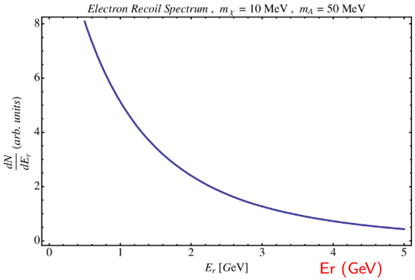
**Production:** Main features follows from thin-target kinematics $*$ $e^-$ energy loss and secondaries emission in the dump

- Thin target kinematics:
  - $A'$ emitted with forward kinematics, $E'_A \simeq E_0$
  - High-energy $\chi$ beam strongly focused along primary beam direction - allowing a compact detector
- $e^-$ in the dump: $e^-$ loses energy by ionization and Bremsstrahlung, $\chi$ kinematics gets broader

**Detection:** $\chi - e^-$ elastic scattering

- $e^-$ recoil: EM shower (O(GeV))
- Background rejection is not critical



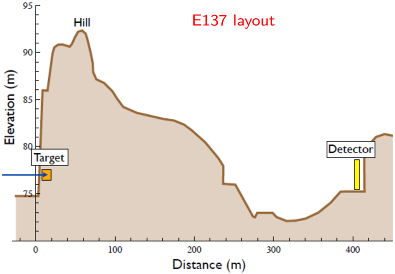
# BDX vs past/current beam-dump experiments

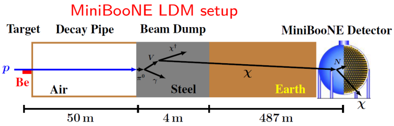
**Past $e^-$ beam-dump experiments (E137):**

- Accumulated charge was limited (E137: O($10^{20}$) EOT)
- LDM results are a re-analysis of old data[2]- the experiment itself was not optimized for this research

**$p$ beam-dump experiments (LSND/MiniBooNE[3]):**

- Higher beam-related backgrounds (hadronic environment) - higher production yield
- Complementarity:
  - Experimental: different beams / different signals
  - Theoretical: leptophilic vs leptophobic models

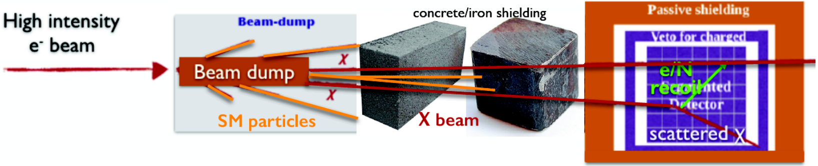



**An optimized $e^-$ beam-dump experiment can explore new territories in the LDM space**

[2] PRL 113, 171802 (2014)
[3] 1702.02688

# BDX experiment layout




**The experiment is designed with two goals:**

## Producing and detecting LDM

- High-intensity $e^-$ beam, $\simeq 10^{22}$ electrons-on-target (EOT)/year
- Medium-high energy, $>$10 GeV
- $\simeq 1\ m^3$ (1-5 tons) detector
- EM-showers detection capability

## Reducing background

- Passive shielding between beam-dump and detector to filter beam-related backgrounds (except $\nu$s)
- Passive shielding and active vetos surrounding the active volume to reduce and identify cosmogenic backgrounds
- Segmented detector for background discrimination based on event topology
- Good time resolution to perform detector-veto coincidence

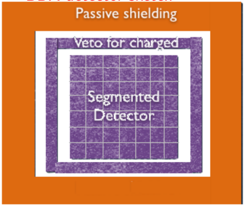
# BDX inner detector

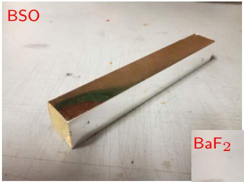
**Active volume requirement:** sensitivity to high-energy EM showers
**Technology:** homogeneus EM calorimeter made with scintillation crystals and SiPM readout

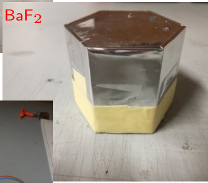
- High crystal density: maximize event yield with compact detector
- Homogeneous solution: minimize dead-spaces and passive materials - critical for background rejection
- Detector segmentation implemented with modular design - each modulus being a matrix of crystals
- SiPM readout: reduce dead spaces between moduli compared to traditional PMT readout, with similar performances (+ self-calibration / low-HV / reliability)
- Time-resolution requirements: O(5 ns), to perform a coincidence with the active-veto system

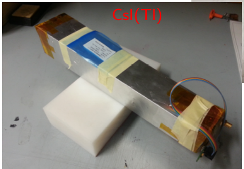
Different options have been considered: BGO, BSO, $BaF_2$, **CsI(Tl)**

BDX detector sketch



# Calorimeter R&D: CsI(Tl)

A dedicated characterization campaign has been performed to measure CsI(Tl) crystal+SiPM properties and verify they are compatible with BDX requirements

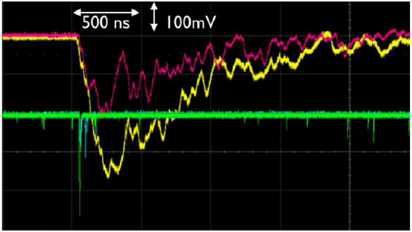
**Setup:**

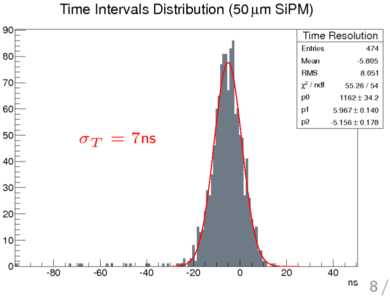
- Cosmics-ray coincidence setup with two plastic scintillator counters read by PMT
- Trigger given by coincidence of two PMTs
- CsI(Tl) crystal with 25-$\mu$m, $6\text{x}6$ mm$^2$ SiPM readout. FEE as foreseen in the final detector (custom trans-impedance amplifier)

**Results:**

- Light-yield with SiPM readout : $\simeq 1$ phe / MeV / mm$^2$ (1 $\mu$s integration window)
- Time resolution @ 30 MeV: $\sigma_T = 7$ ns

Results were later confirmed with measurements from BDX detector prototype:
**CsI(Tl)+SiPM readout is the optimal choice for the BDX experiment**



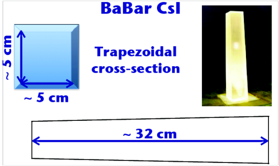



## BDX calorimeter

BDX detector: state-of-the-art EM calorimeter, CsI(Tl) crystals with SiPM-based readout.
Possibility to re-use existing BaBar CsI(Tl) crystals (informal agreement already discussed)

Detector design:

- $\simeq$ 800 CsI(Tl) crystals, total interaction volume $\simeq 0.5 m^3$
- Modular detector: change front-face dimesions and total lenght by re-arranging crystals

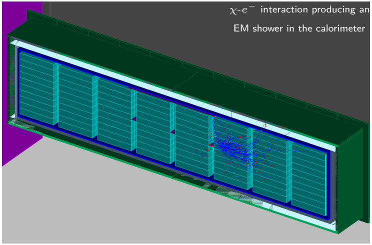



Arrangement:

- 1 module: 10x10 crystals, 30-cm long. Front face: 50x50 cm$^2$
- 8 modules: interaction length 2.6 m

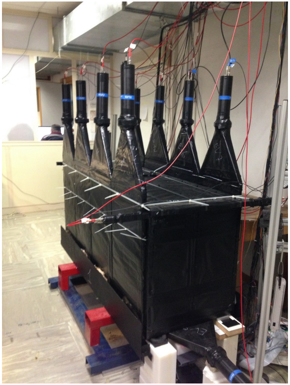
Signal:

- EM-shower, $E_{thr} \simeq 300$ MeV, anti-coincidence with IV and OV
- Efficiency (conservative): O($10\%$) - refined cuts on EM shower directionality can improve this



# BDX active veto

**Active veto requirements:** high efficiency for charged particles detection, hermeticity, compactness
**Technology:** two layers of plastic scintillator counters, made of different paddles, each read by WLS fibers + SiPMs (IV) / PMTs (OV).
5-cm lead vault between two layers to shield photons



**R&D:**

- Veto efficiency for charged particles measured with cosmics-ray setup, in different positions: $\bar{\varepsilon} > 99\%$
- On-going effort to replace light guides by slim wavelength-shifting plastics to reduce dead spaces and simplify mechanical supports

# BDX: experiment facility

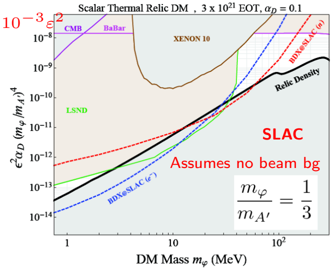
Different $e^-$ facilities have been investigated. Requirements: high-energy (beam focusing and larger parameters space coverage), high-EOT

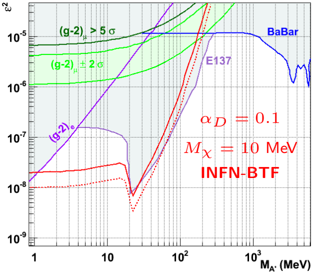
**SLAC - LCLS2**

- $E_e = 4$ (8) GeV, $\simeq 3 \cdot 10^{21}$ EOT/y
- Pulsed beam 1 MHz: reduced cosmogenic bg
- Infrastructure costs limited
- Possible bg from X-ray beam-line
- Time-line: $\simeq$ 2020

**Frascati BTF**

- $E_e = 1.25$ GeV (upgrade), $\simeq 3 \cdot 10^{20}$ EOT/y
- Pulsed beam 50 Hz: no cosmogenic bg
- Minimal infrastructure cost
- 2-3 years from now



# BDX: experiment facility

**Mainz (MESA)**

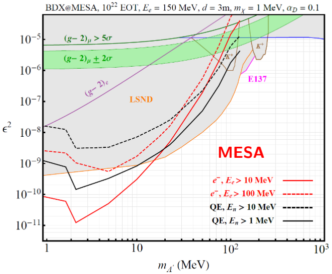
- $E_e = 0.15$ GeV, $\simeq 10^{22} - 10^{23}$ EOT/y
- $E_e < E_\pi$, almost no beam-related backgrounds
- CW beam (3 ns)
- Machine commissioning: 2020

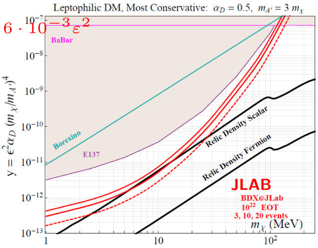
**Mainz (MAMI)**

- $E_e = 1.6$ GeV, $\simeq 10^{21}$ EOT/y
- Non-trivial logistic to place detector after existing A1 beam-dump

**JLab**

- $E_e = 11$ GeV, $\simeq 10^{22}$ EOT/y
- CW beam (4 ns)
- Requires new experimental hall behind Hall-A beam-dump
- Beam is available, beam-time already approved (Moller experiment)



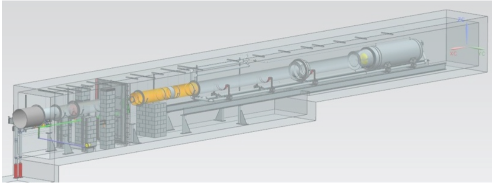

**JLab is the leading option for the BDX experiment**

# JLab facility

Beam Dump eXperiment at Jefferson Laboratory behind Hall-A beam-dump

- Already-approved experiments with more than $10^{22}$, 11 GeV EOT (Moller, PVDIS)
- Detailed description of dump geometry and materials avaialable and implemented in simulations
- Verified compatibility with the planned experiments (Moller setup: beam rastering and target-lenght effects are negligible)
- Detailed estimate of costs / time scale of new experimental hall construction behind Hall-A beam dump


Hall-A beam-dump: Aluminum plates immersed in water for cooling.



# BDX detector prototype

A small-scale protoype of the BDX detector was constructed and installed at INFN-CT (and later moved to INFN-LNS)

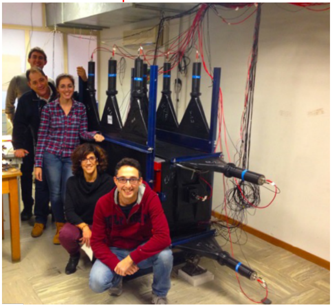
**Goals:**

- Validate the full BDX design and technical choices
- Measure cosmogenic background in a configuration similar to the final detector setup
- Project results to the full BDX-detector and obtain background rate estimate
- Validate MC

**Prototype setup:**

- 1 CsI(Tl) crystal (BaBar endcap), 2 x SiPM readout (25 $\mu$m, 50 $\mu$m)
    - Currently upgraded to 4x4 matrix of CsI(Tl) crystals
- Inner-veto layer: plastic scintillator + WLS-fibers/SiPM readout
- 5-cm lead layer
- External-veto layer: plastic scintillator + PMT readout

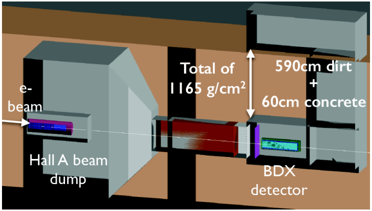
BDX-proto at INFN-CT



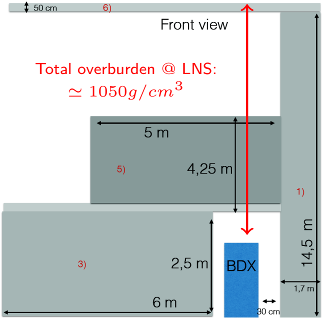
# Cosmogenic backgrounds

- Cosmic background measured with the BDX prototype at INFN-CT and at INFN-LNS, with similar overburden as expected at JLab
- Geant4 simulations (GEMC framework) in very good agreement with data
- The majority of cosmic muons are detected and rejected by the two veto detectors, while cosmic neutrons are shielded by the overburden
- Measured anti-coincidence rate ($E_{thr} \simeq 300$ MeV) $<$ 2 counts: results obtained by conservatively extrapolating from the lower-E, non-zero counts region, projecting to the JLab setup (800 crystals)

| Threshold | Projected counts |
|---|---|
| 250 MeV | $(57 \pm 25)$ |
| 300 MeV | $(4.7 \pm 2.2)$ |
| 350 MeV | $(0.037 \pm 0.022)$ |




LNS BDX test-setup



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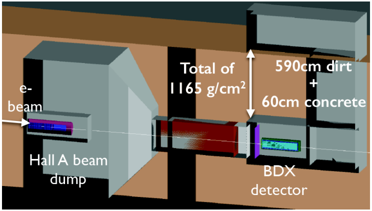
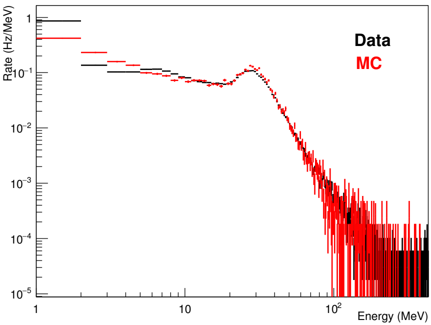



Crystal energy deposition



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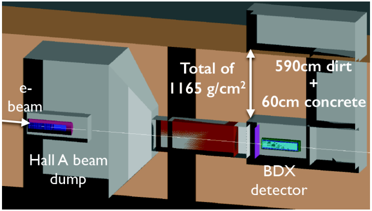


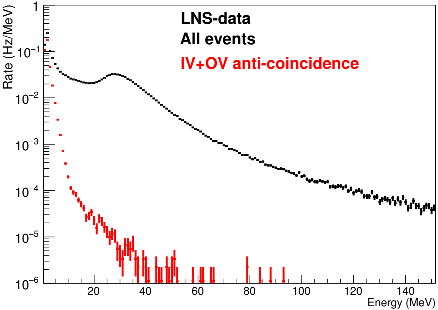

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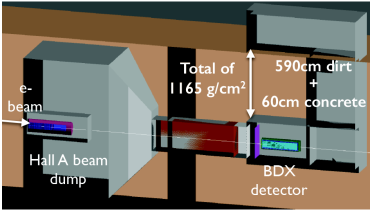
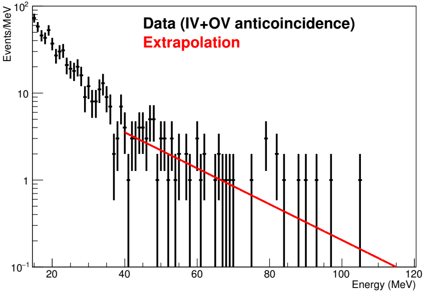


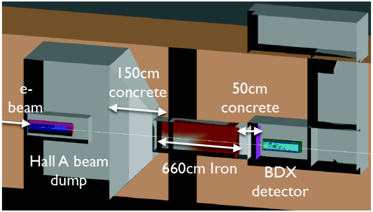



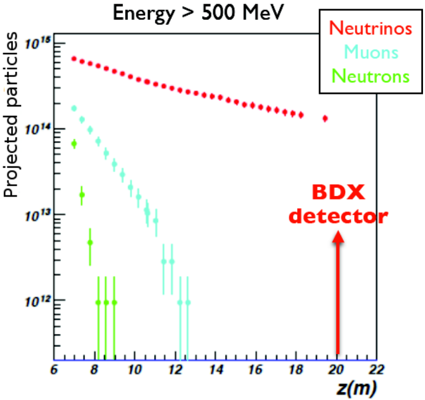

**Cosmogenic background is negligible** with high-energy threshold. It will be measured on-site when beam is off

## Beam-related backgrounds

Beam-related backgrounds estimated trough MC simulations (Geant4/Fluka) Challenge: very high EOT. Solutions:

- Sample non-zero flux as a function of depth and propagate to detector location (G4)
- Use biasing (Fluka)



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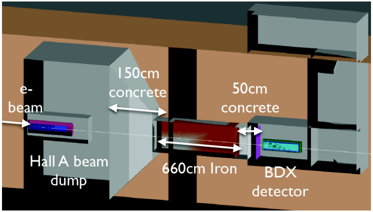
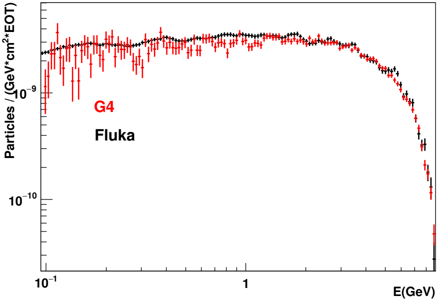



## Muons

- High-energy muon production in the dump dominated by the $\gamma \to \mu^+\mu^-$ process
  - Very good consistency between G4 and Fluka for $\mu$ production in the dump
  - On-site measurement of muons after the Hall-A beam dump is foreseen (see next slide)
- 6.6m iron shield (+2 m concrete) enough to range-out high energy muons: no particles at the detector location



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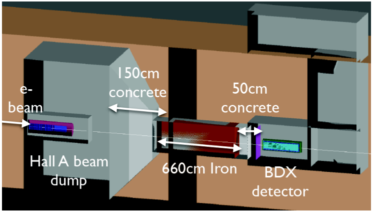
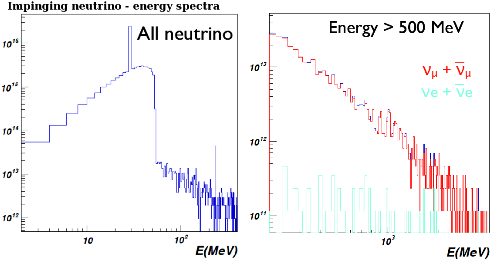
**Neutrinos:** only particles reaching the detector

- Spectrum mainly at low-energy, dominated by $\mu^+$ decay / $\mu^-$ capture on nuclei
- High-energy part from in-flight decays and prompt production processes




Possible background contribution from $\nu_e$ interacting via CC in the detector, producing a high-energy $e^\pm$ resulting in a EM shower

**Neutrino irreducible background** is the ultimate limitation for BDX.

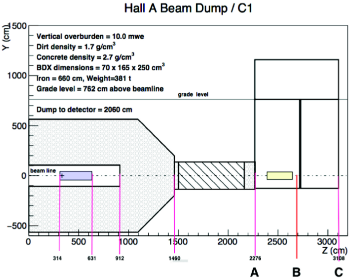
Preliminary estimate ($E_{thr} = 300$ MeV): $N_{\nu_e+\bar{\nu}_e} = 10$ counts for $10^{22}$ EOT

# Beam-related $\mu$: on-site measurement

**Measurement campaign** to characterize the flux of high-energy $\mu$ produced in the Hall-A beam dump. Goal: validate MC for forward particles production with an absolute normalization point

**Setup:**

- Drill hole behind beam-dump at foreseen BDX detector location
- Insert a CsI(Tl) crystal surronded by plastic scintillator counters, matching the beam height. Plastic counters are segmented to provide directional information
- Measure $\mu$ flux when 11-GeV beam is on

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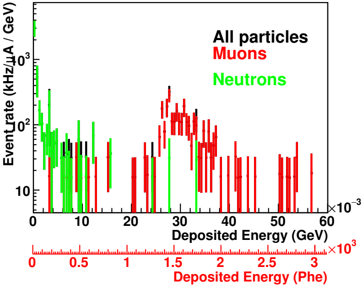
**Status:**

- Detailed MC study performed and discussed with JLab management (BDX-Note 2017-001)
- Detector design completed and materials procured
- Test planned in fall 2017 / spring 2018
  - Time-scale: O(5 months) administrative / civil work, 1-week measurement
  - Budgetary estimate: 40k$


Current dump configuration - no shielding!

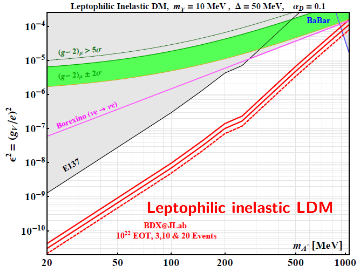


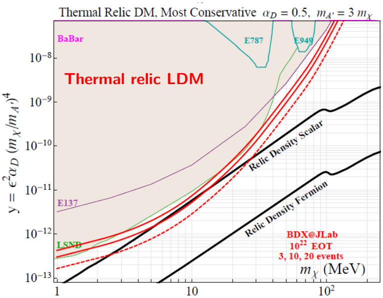
# BDX@JLab: reach

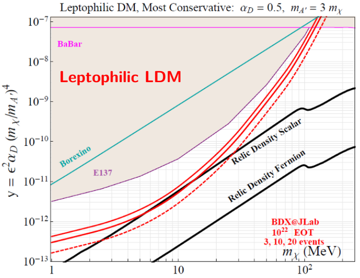
BDX is an optimized beam-dump experiment that can be conclusive for some Light Dark Matter scenarios. Obtained results will guide future second-generation experiments

**The BDX sensitivity for different LDM models has been evaluated - $10^{22}$ EOT:**

- Thermal relic LDM
- Leptophilic LDM
- Leptophilic inelastic LDM



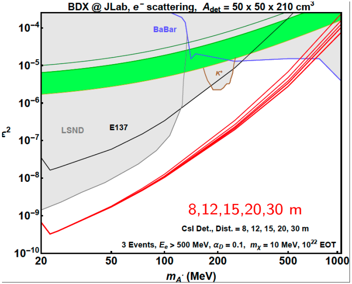



## Systematic studies

A detailed study of the experimental setup - starting from the current configuration - has been performed to evaluate the most promising configuration. Sensitivity for fermionic LDM used to evaluate stability with respect to experimental variables.

Results:

- Very weak dependence on the dump-detector distance
- No sizeable effect by varying the detector footprint (with fixed active volume)
- No sizeable effect by varying the electron energy threshold: 500 MeV vs 50 MeV



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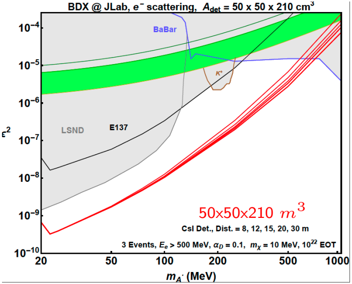


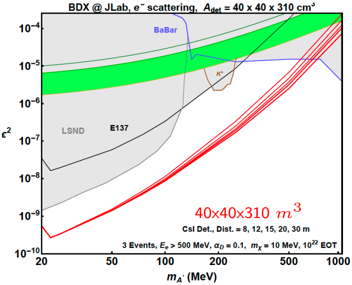

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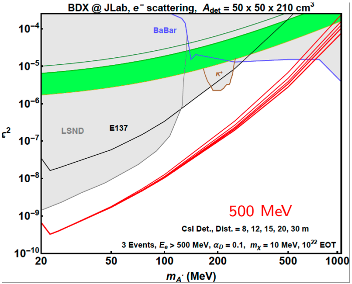
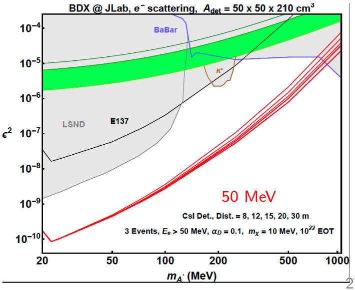
The BDX experimental configuration has been fully defined and proved to be optimized for the experiment



# BDX current status

## BDX status:

- R&D activity ongoing from 2014 - LOI presente to PAC42, with strong positive feedback
- Full proposal presented to JLab PAC44, **approved** - conditionally to MC benchmarking with on-site measurements, and to detector optimization
- On-site $\mu$ measurement foreseen fall 2017 / spring 2018
- Detector optimization in progress with results from MC simulations - validated trough BDX prototype data: plan to give an update to PAC45

## Collaboration:

- BDX proposal signed by more than 100 researchers
- Core group working on key aspects: physics, detector, simulations
- Connection with groups involved in similar activities at SLAC, CERN, Mainz and LNF

Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

*The BDX Collaboration*

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*Occidental College, Los Angeles, California 90041, USA*

*Contact Person, email: Marco.Battaglieri@ge.infn.it
†Spokesperson

**From PAC44 report:** The committee is excited about the physics case, and encourages the BDX collaboration to optimize their experiment in accordance with the many comments received from the TAC and the PAC.

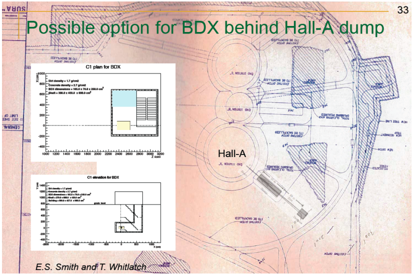
# BDX foreseen activities

## Detector

- Technology selected and design defined. Active volume: CsI(Tl) calorimeter with SiPM readout. Active veto: plastic scintillator + SiPM / PMT readout
- $\simeq$ 1-year time-scale to assembly detector: refurbish 800 BaBar crystals, mount calorimeter, mount active-veto
- $\simeq 1.5M\$$ total cost for full BDX detector construction

## Civil construction

- Detailed costs / time-scale evaluation in collaboration with JLab facility office: $\simeq 1.5M\$$, $\simeq$ 2-years time-scale for construction




Within 2 years (detector assembly + civil work), BDX can be ready to run at JLab, to explore unknown territories in the LDM space, and to provide directions for future activities in this field

## Conclusions

- Dark matter in the MeV-to-GeV range is largely unexplored.
- **Beam Dump eXperiment** at JLab: search for Dark sector particles in the $1 \div 1000$ MeV mass range.
  - High intensity ($\simeq 10^{22}$ EOT/year), high energy (11 GeV) $e^-$ beam
  - Detector: $\simeq 800$ CsI(Tl) calorimeter + 2-layers active veto + shielding. Reuse BaBar crystals with improved SiPM readout
- BDX can be ready to run within $\simeq$ 2 years, and will explore unknown territories in the LDM space
- Current experiment status:
  - Full proposal submitted to JLab PAC 44 - **conditionally approved**
  - On-site background measurements and detector optimization to fulfill PAC requests: update to PAC 45

BDX can produce important physics results, exploring unknown territories in the LDM space, and providing directions for future activities in this field

Backup slides

# $\chi$ kinematics in the beam-dump