# Dark Matter search in a Beam Dump eXperiment (BDX) @ Jefferson Lab

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**INFN**
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# Outline

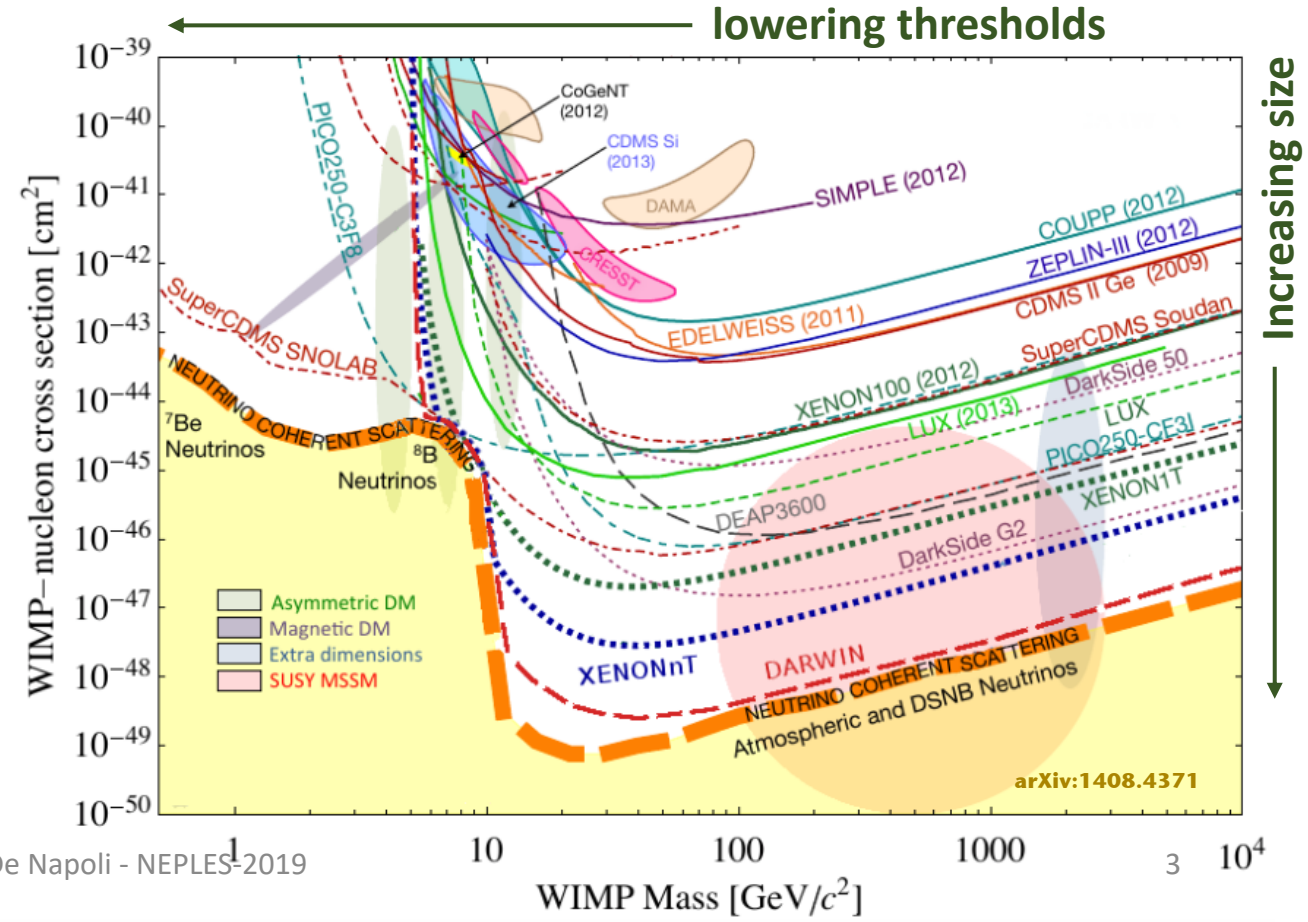
- Physics motivations: “Light” Dark Matter & Dark Photon scenario (a brief introduction!)
- BDX overview
- Signal & Background: simulations and experimental campaigns
- BDX reach
- The BDX(Mini) experiment
- Conclusions

# Light Thermal Dark Matter

- An extensive experimental program based on the WIMPs paradigm is ongoing
- Up today searches for WIMPs haven't seen anything + no new physics at the weak-scale from LHC
- Within next years, will either find WIMPs or rule out most of the accessible parameter space

Negative results call for extending the DM hunting territory to unexplored regions

**Where else to look ?**



# Light Thermal Dark Matter

- Many theoretical suggestions and exp attempts to extend the search to low masses (<1 GeV)
- Up today Beam dump (e-) experiments can provide unprecedented sensitivity to light dark matter and Jefferson Lab can play a significant role in light DM search

Extending the hunting territory to a mass region where (traditional) Direct Detection is (almost) impossible

**LIGHT THERMAL DARK MATTER**

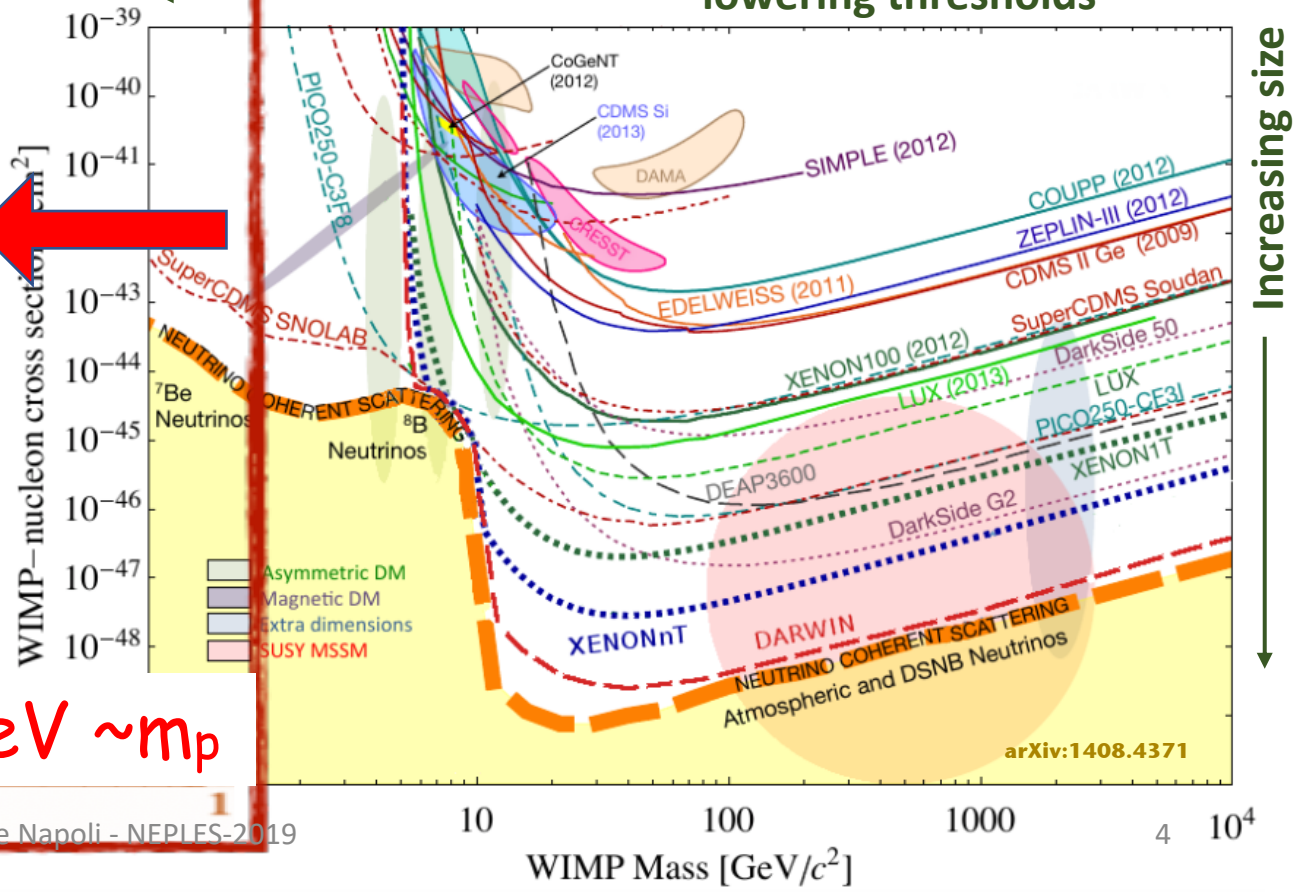
*Light Dark Matter (MeV-GeV) is an attracting DM candidate but* *requires a new Force* *to overcome the Lee-Weinberg limit ($m_\chi$>2 GeV), not overproduce DM and* *achieve the correct thermal relic abundance*

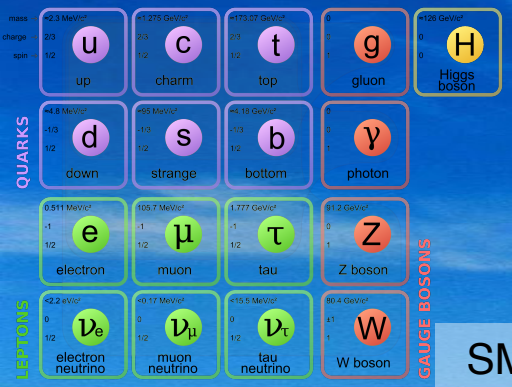
MeV ~$m_e$

GeV ~$m_p$

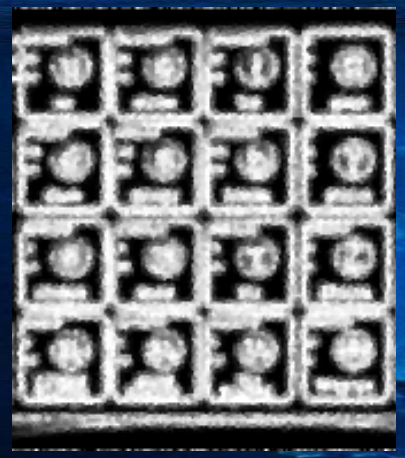

lowering thresholds

Increasing size





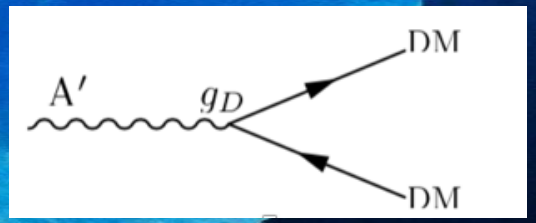

SM partciles make ~5% of the Universe, why should the Dark Matter world (~24%) be any simpler?



# Hidden Sector

## Made by New Particles & New Forces

*LDM particles may interact via a new U(1) light vector mediator Dark/Heavy Photon, A'*



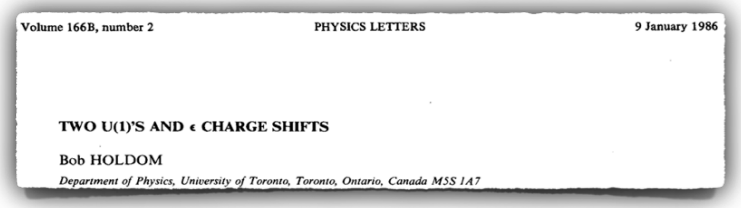

**Hidden Sector comprised of χ's, A's, and other related particles and forces**

**✓ It's *hidden:* particles have no direct SM couplings and the forces don't couple directly to SM charges**

**✓ But it's not invisible!**

# Dark Photon

**IF THERE IS AN ADDITIONAL U(1) SYMMETRY, THE NEW VECTOR BOSON A' KINETICALLY MIXES WITH THE SM PHOTON**


Volume 166B, number 2 PHYSICS LETTERS 9 January 1986

TWO U(1)'S AND ε CHARGE SHIFTS

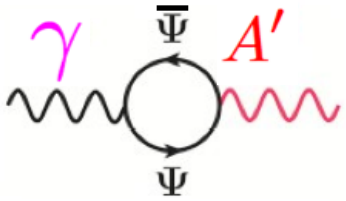
Bob HOLDOM

Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

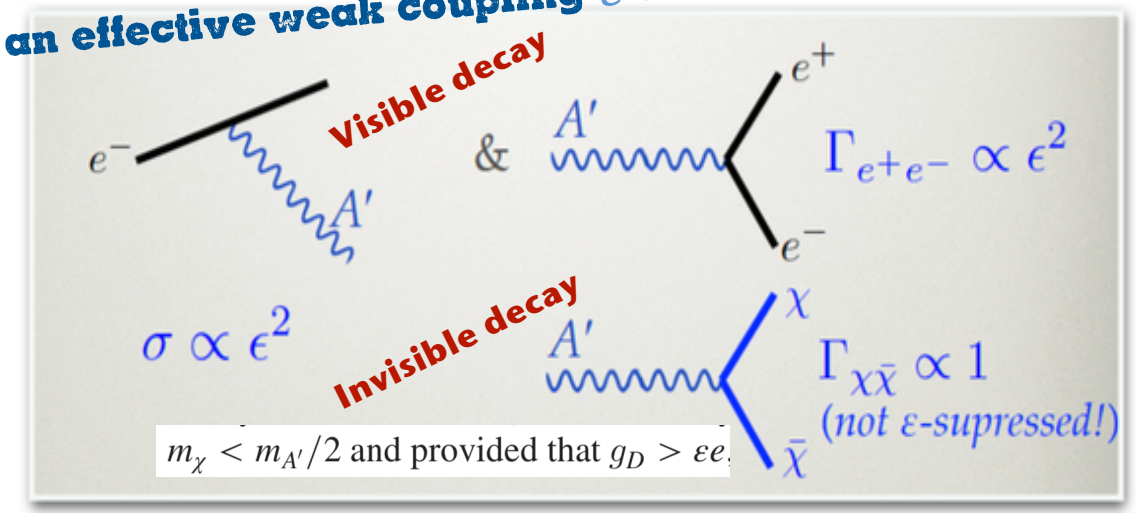
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic mixing"

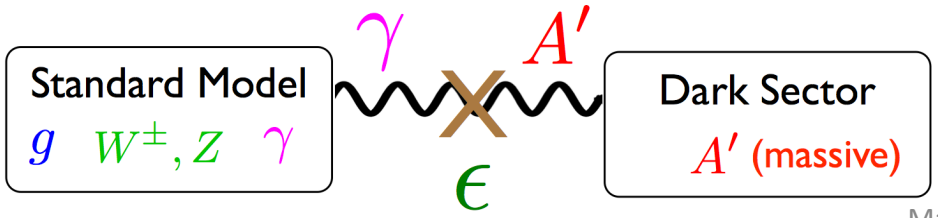
***Loops of heavy particles charged under photon and A'***

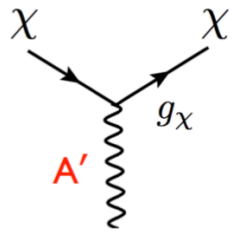


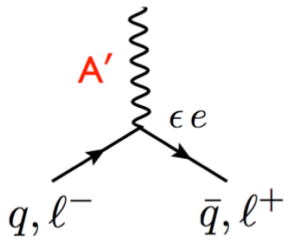

**Mixing induces an effective weak coupling ε·e to electric charge**




*A' acts as a "portal" between the SM and the new sector*



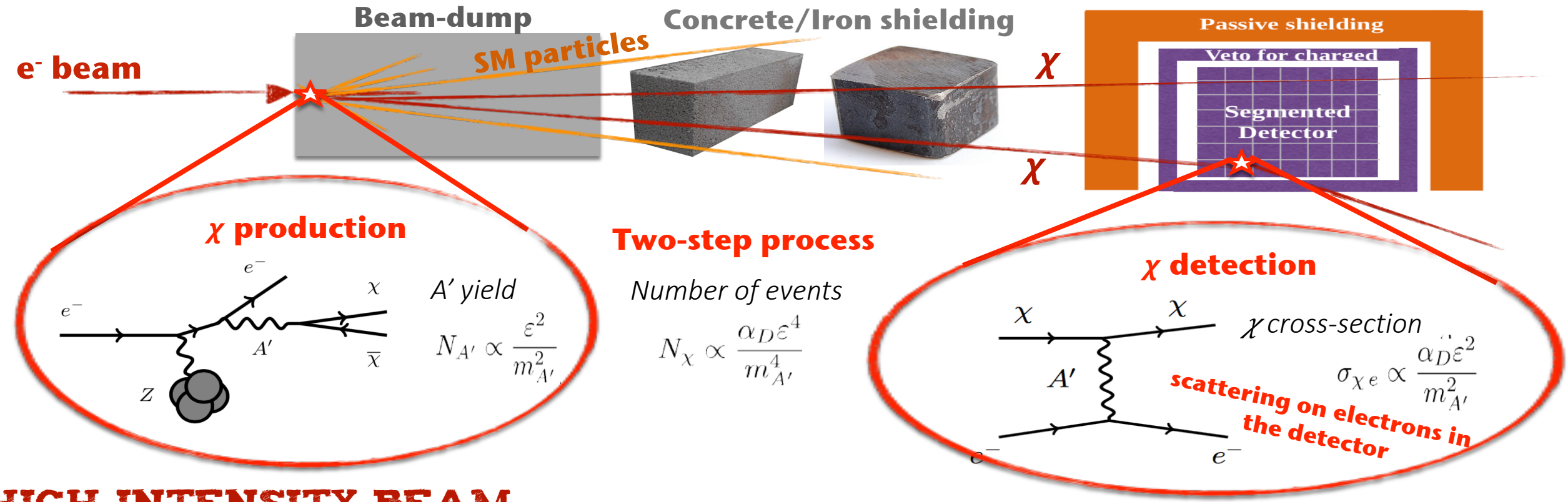




4 parameters: $m_\chi$, $m_{A'}$, ε, $\alpha_D$

$m_\chi$, ~ $m_{A'}$: MeV - GeV

# BDX in a nutshell




## HIGH INTENSITY BEAM

**Sensitivity scales linearly with the total number of EOT**

## O(10) GEV BEAM ENERGY

**High energy helps cross-sections and kinematics**

## HIGH ENERGY DEPOSITION

**χ takes a big fraction of the beam energy-> high energy e- recoil**

## DM SIGNATURE

**Electromagnetic shower in the Ecal with energyes ≳ 300 MeV**

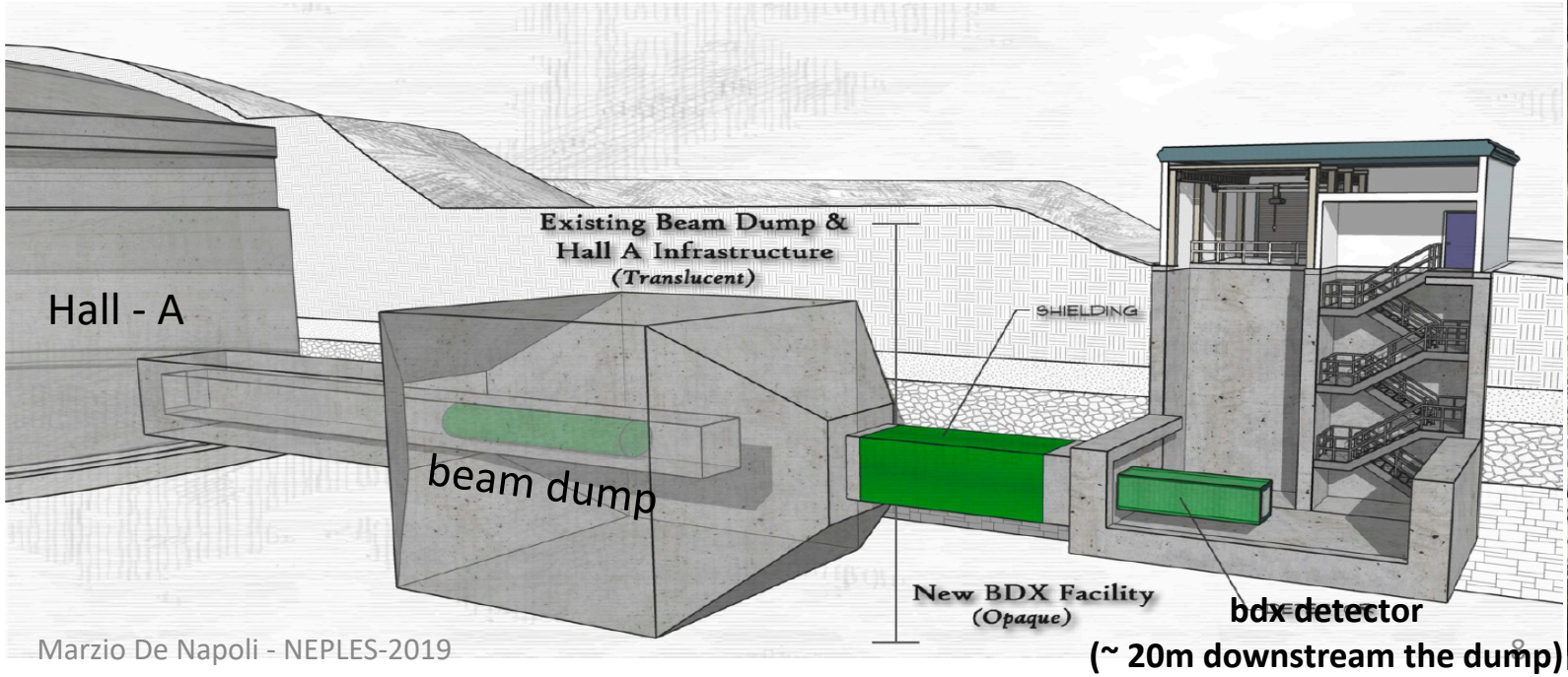
# BDX @ JLAB

**JLAB is the ideal palce to run an electron beam-dump experiment**

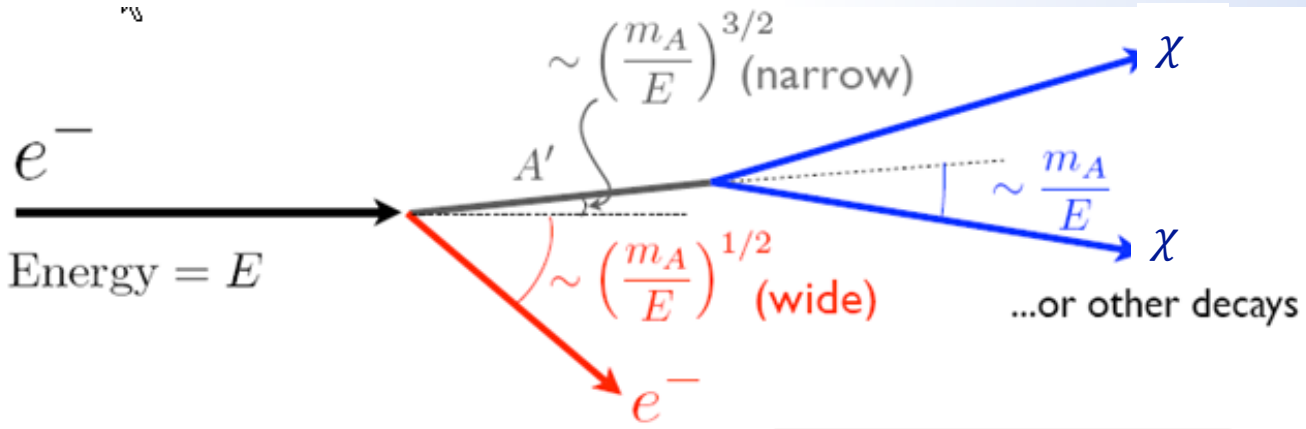
- ✓ $e^-$ beam with energies up to **11GeV**
- ✓ Very **high beam current** up to ~**65 μA**

**BDX has been approved by JLAB-PAC46 with maximum scientific rate (A)**

proposal arxiv.org/abs/1607.01390



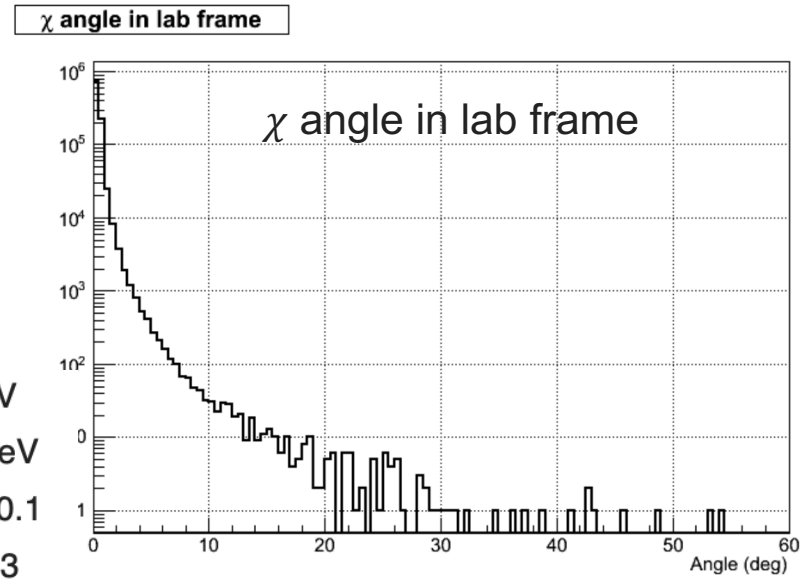

# Kinematics: highly-focused energetic $\chi$ beam

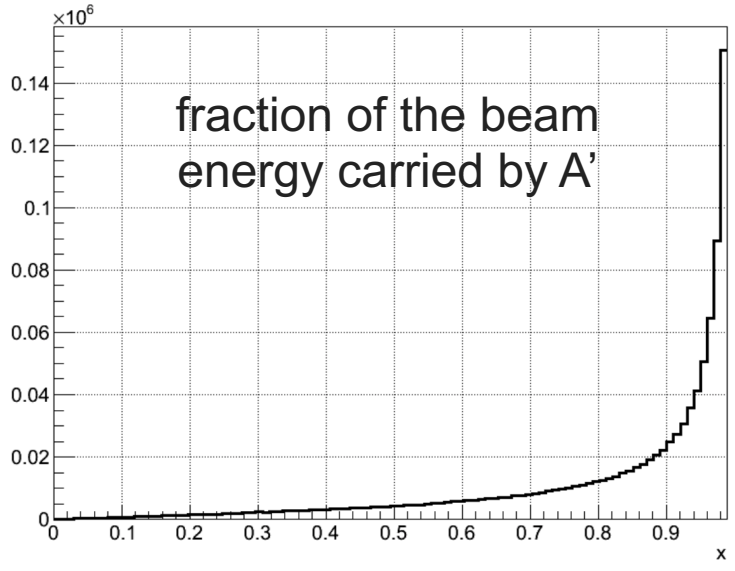


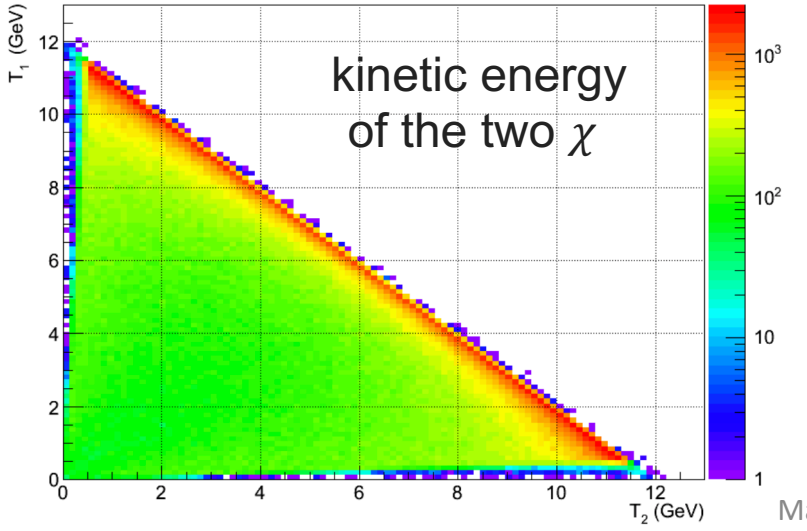

Heavier product (here A') takes most of beam energy

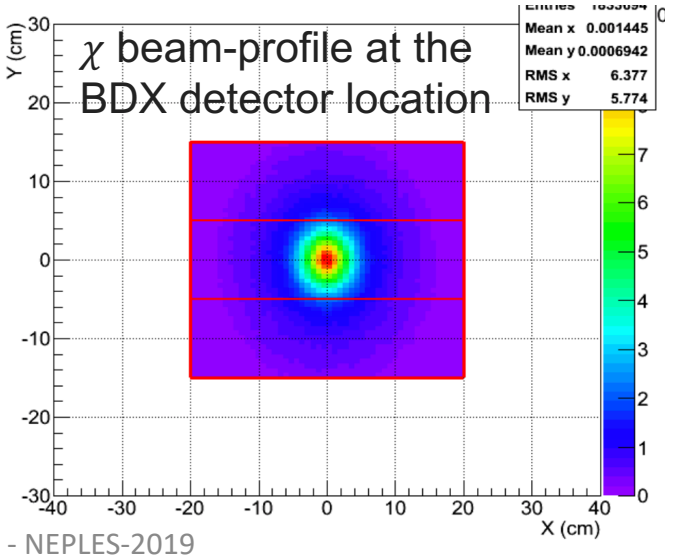
$$E_A \sim E - m_A$$
$$E_e \sim m_A$$

- M_A' = 50 MeV
- M_Chi = 10 MeV
- Alpha_dark = 0.1
- Epsilon = 10^-3

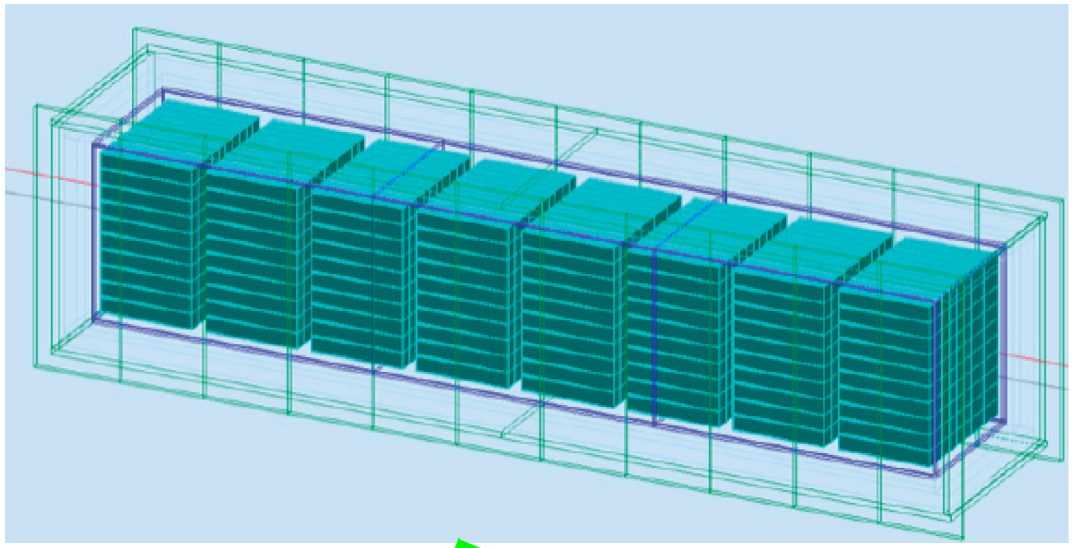


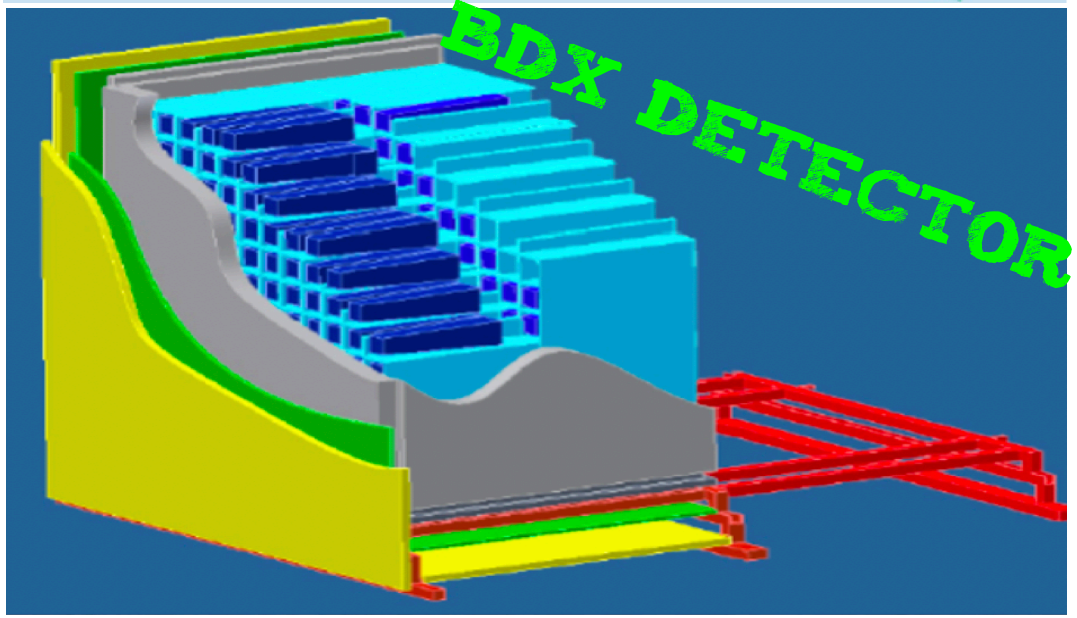



# Experimental setup

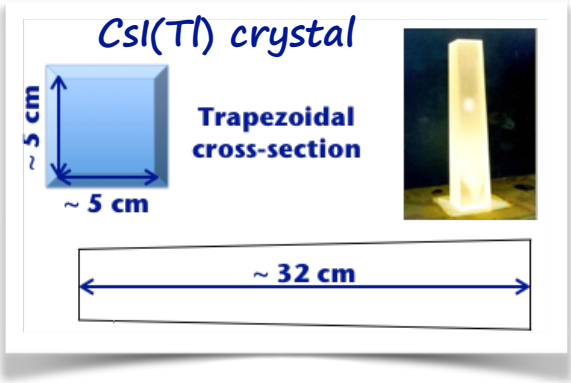





## DM DETECTION

### Modular Electromagnetic Calorimeter

- Size: ~3m long, ~50x50cm$^2$ front face
- 800 CsI(Tl) crystals (from BaBar EMCal)
- 8 Modules, 10x10 crystal each
- 6x6 mm$^2$ SiPM readout
- Internal lead shielding for (partial) shower containment



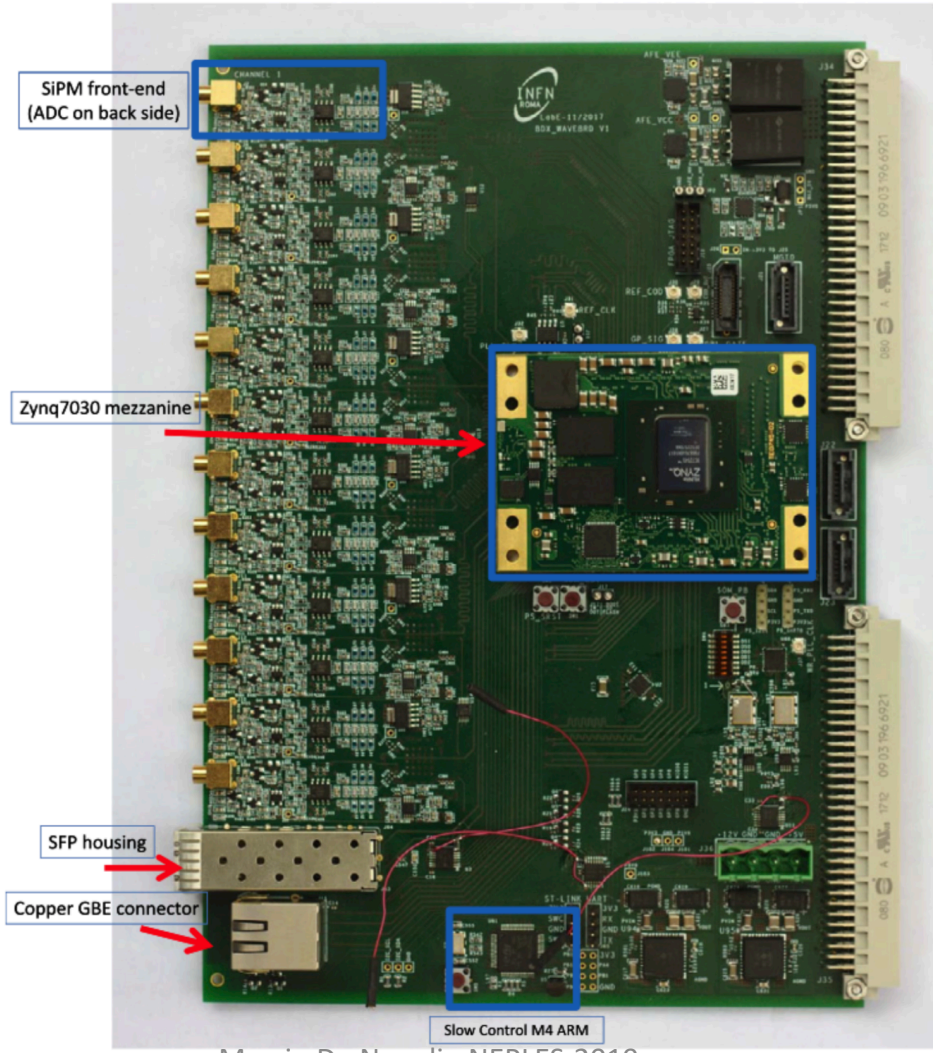

## BACKGROUND REJECTION

### Two active veto layers

- large paddles of 1/2cm thick plastic scintillator
- WLS fibers & scintillators
- SiPM light-readout

# FEE & DAQ

## A multi-channel FEE and digitizer board developed for BDX




- Highly configurable
- FEE included on-board
  - 12 ch individually controlled
  - SiPM connected through coaxial cables and MCX connector
  - dual gain amplifiers
  - bias generated on-board (up to 100V, resolution <50mV)
- Sampling unit
  - resolution 12 or 14 bit
  - sampling frequencies of 65, 125, 160, and 250 MHz
- Timing
  - external clock/time-stamp (GPS)
  - Phase Locked Loop to multiply the input clock and distribute to each ADC and to the FPGA
- Board control
  - commercial FPGA for Data collection and manipulation
  - separated M4 ARM processor for the control of the many ADCs, HV regulators etc
  - Slow control EPICS interface
- VME connection only for power (+5V,+12V) (bus not used) and mechanical support
- Board cost depends on the configuration (range 1.5-3 k€/board)

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 936, 21 August 2019, Pages 286-287

A low cost, high speed, multichannel analog to digital converter board

F. Ameli [a], M. Battaglieri [b], M. Bondì [c], M. Capodiferro [a], A. Celentano [b], T. Chiarusi [d], G. Chiodi [a], M. De Napoli [c], R. Lunadei [a], L. Marsicano [b], P. Musico [b], F. Pratolongo [b], L. Recchia [a], D. Ruggieri [a], L. Stellato [a]

Show more

# FEE & DAQ

## TRIGGERLESS STREAMING READOUT

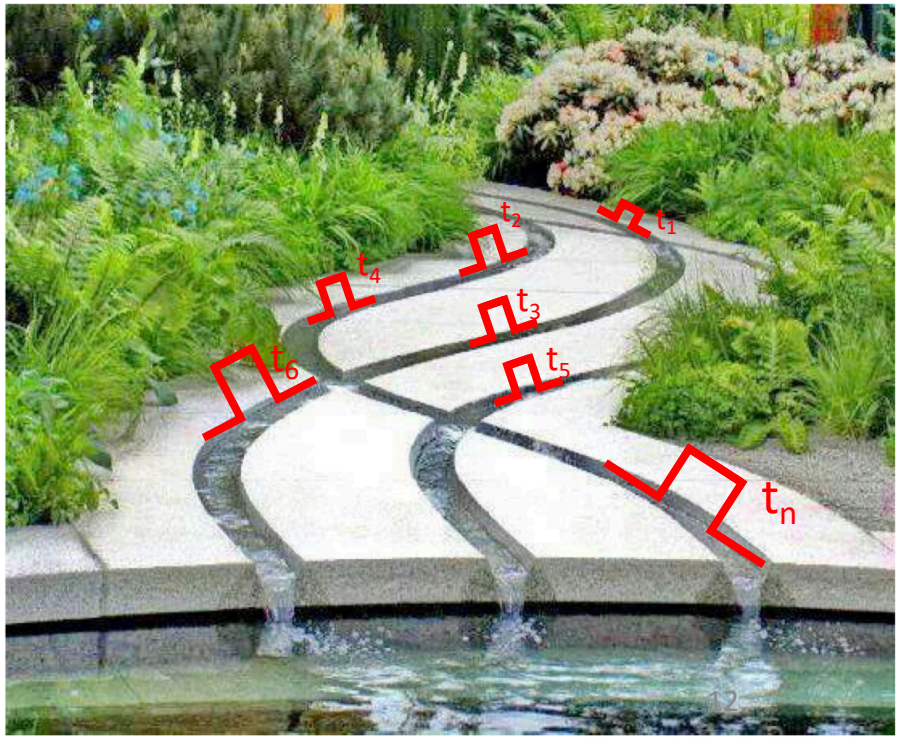
**Raw data from all channels of the detector are continuously read**

- Data flow is controlled at source: validation checks to reject noise and suppress empty channels
- The data then flows unimpeded in parallel channels to local compute resource
- Time-stamp provided by a synchronous common clock distributed to each FEE
- Data is organized in 2D dimensions by channel and time

**advantages**

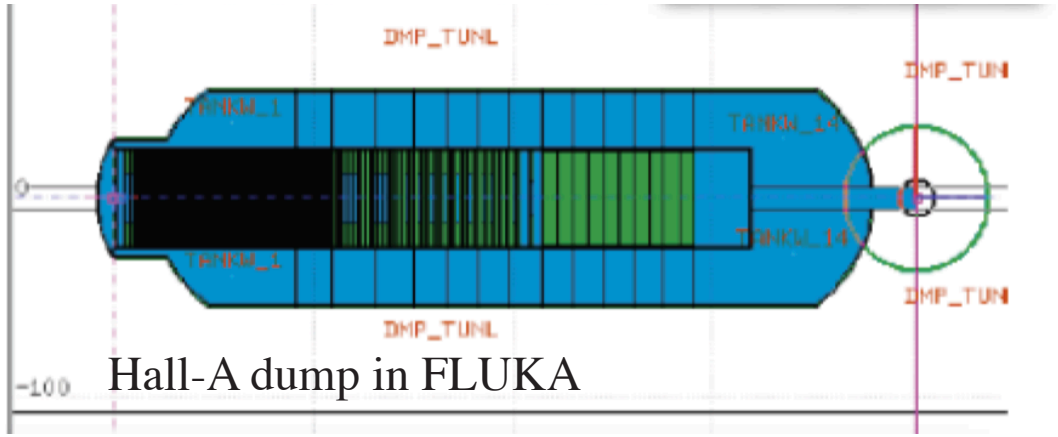
**the lack of a trigger means**

- Potentially useful physics is not discarded
- Readout speed is independent of detector response time
- Different analysis/event selections in parallel on the 2D data structure

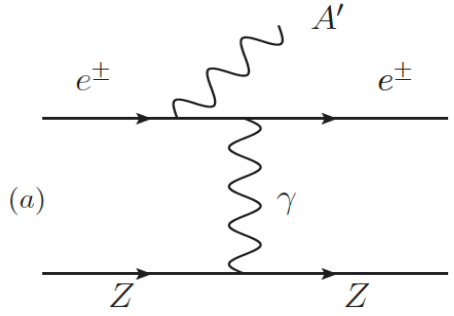


# Signal : $\chi$ production

- Beam-dump modelled as a uniform block of aluminum
- MadGraph4 to generate LDM events produced in $e^-$-Al collisions
- We also considered the development of the e-induced EM shower in the beam-dump, leading to the production of secondary e- and e+, with lower energy
- Sampling of em shower simulated with GEANT4




A'-production in the beam-dump




A'-strahlung in $e^+/e^-$ nucleon scattering

$\sigma \propto \varepsilon^2 \alpha^3$

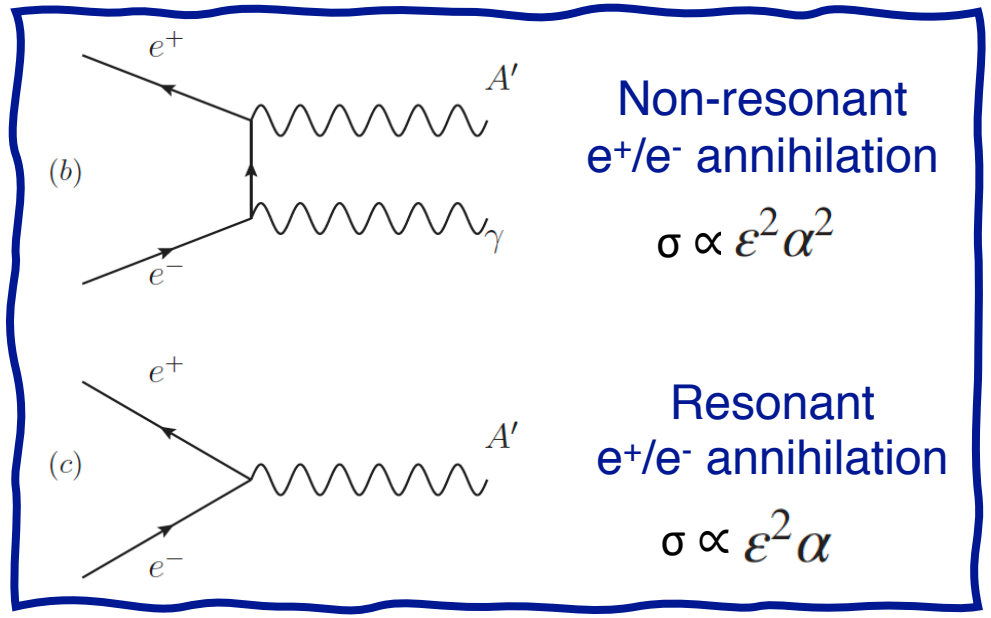
In previous papers describing A' production in electron beam-dump experiments, only the bremsstrahlung-like production by electrons has been included

*Including the EM showering inside the dump is important !*

# Signal : $\chi$ production

$\chi$ yield ← *Including EM showering inside the dump has an impact on* → $\chi$ beam properties

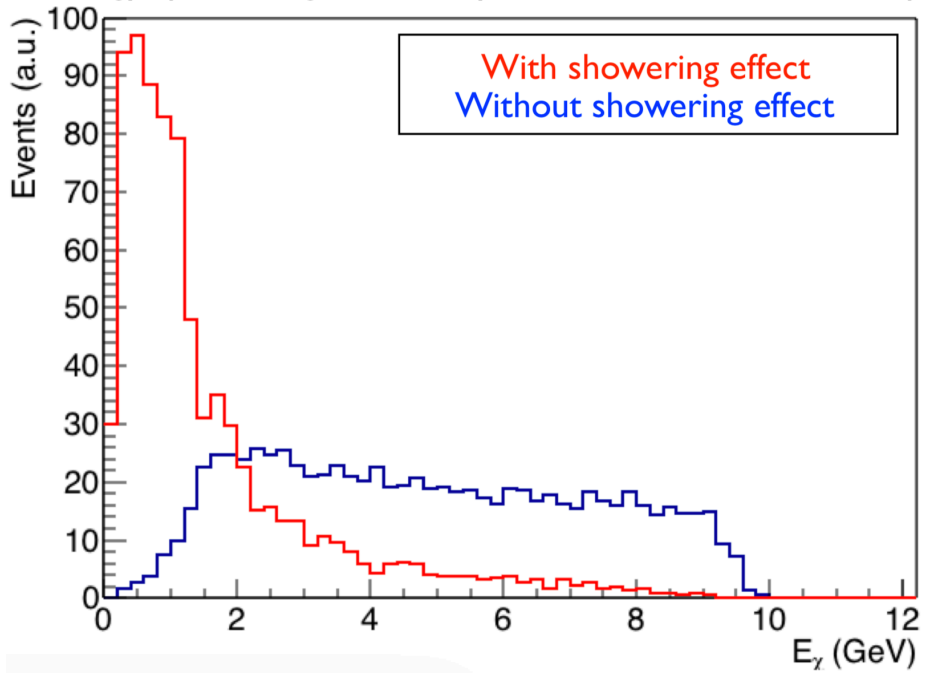
In the positron-rich environment produced by the EM showering contributions from e+ annihilations can be sizable




These mechanisms significantly enhance the reach in certain mass regions and have to be considered for a correct evaluation of the exclusion area in LDM parameter space

**Softer DM E spectrum and defocused DM beam**

X energy spectrum generated by 10 GeV e-beam in the dump



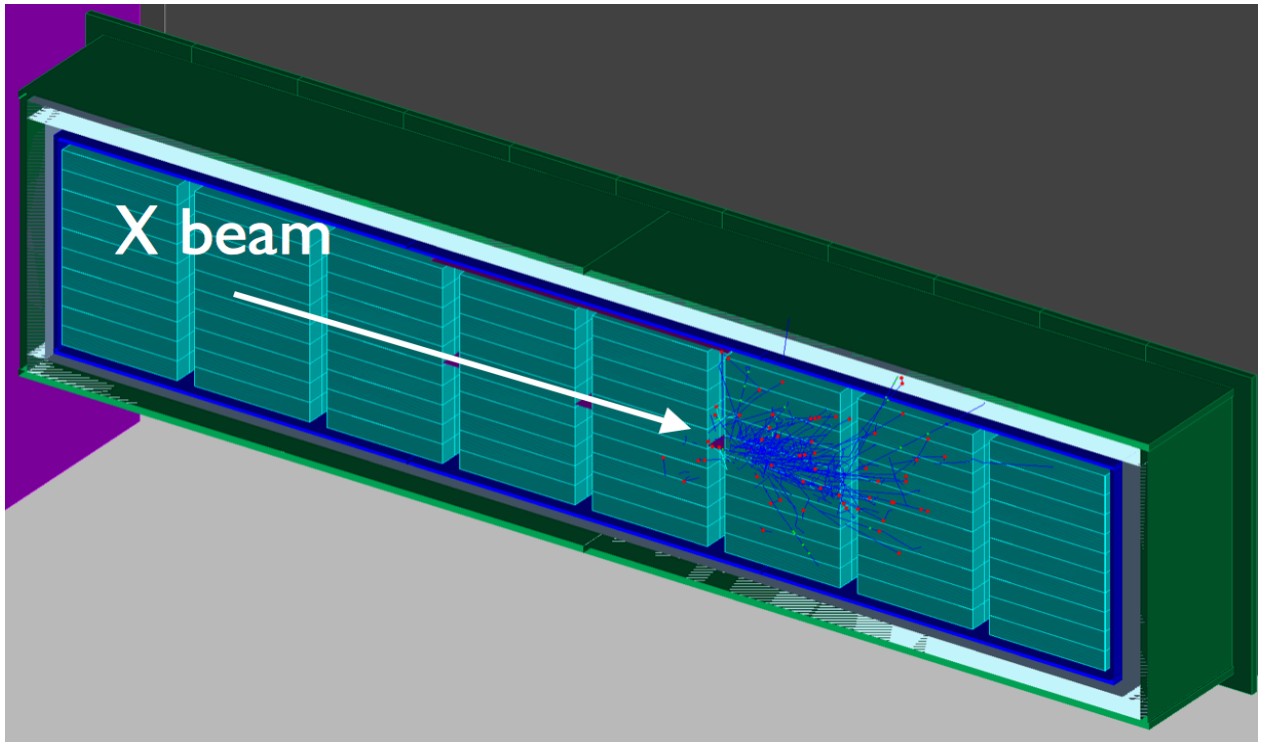

*Novel Way to Search for Light Dark Matter in Lepton Beam-Dump Experiments, L. Marsicano et al, Phys. Rev. Lett. 121, 041802, 2018*

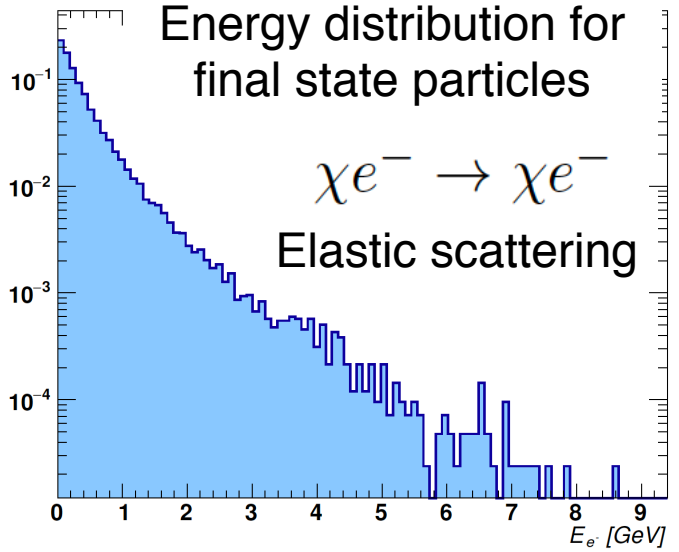
*Dark photon production through positron annihilation in beam-dump experiments L. Marsicano et al., Phys. Rev. D 98, 015031 (2018)*

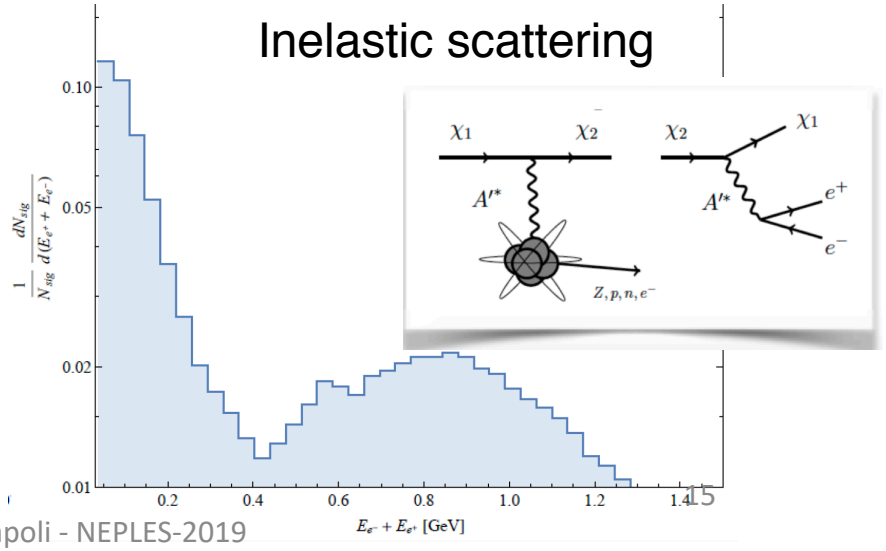
# Signal: $\chi$ detection

- $\chi$ propagated to the detector and elastically scatters off active volume electrons
- Geant4 used to simulate the response of the detector to the scattered electron
- The typical signal in the BDX experiment is an event with large (> 300 MeV) energy deposition in the Ecal, with no activity in the surrounding veto
- Detection efficiency ~10%-40%*

*depending on analysis cuts/$m_{A'}$

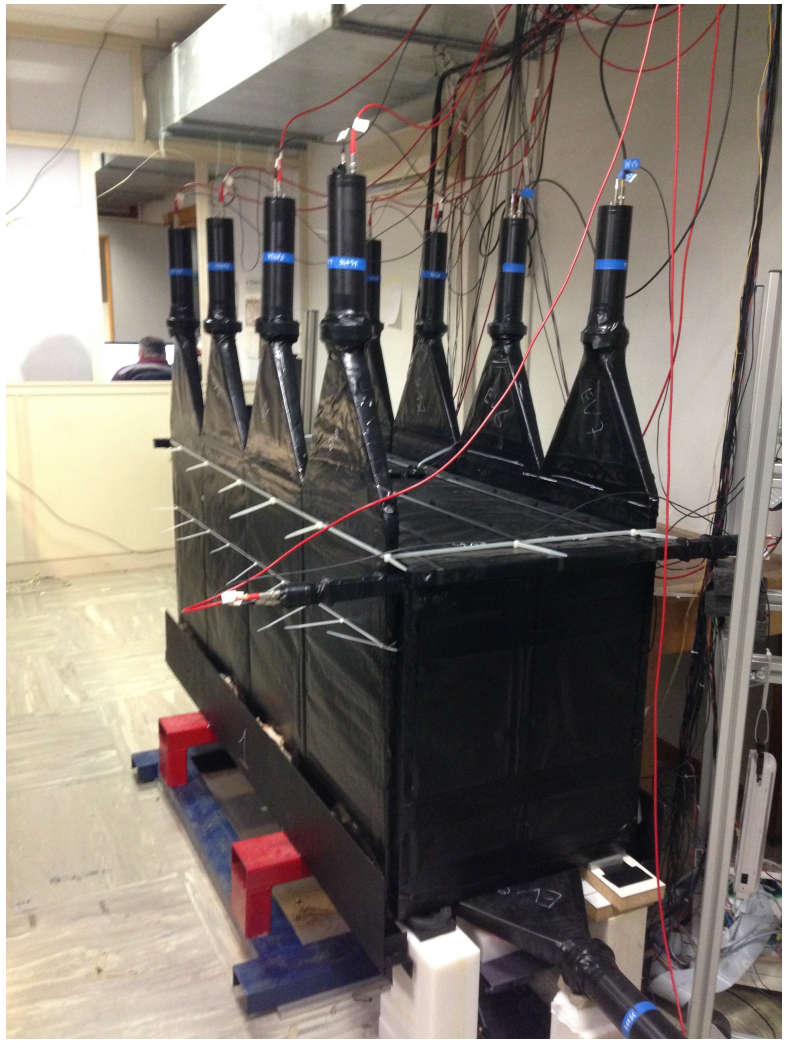


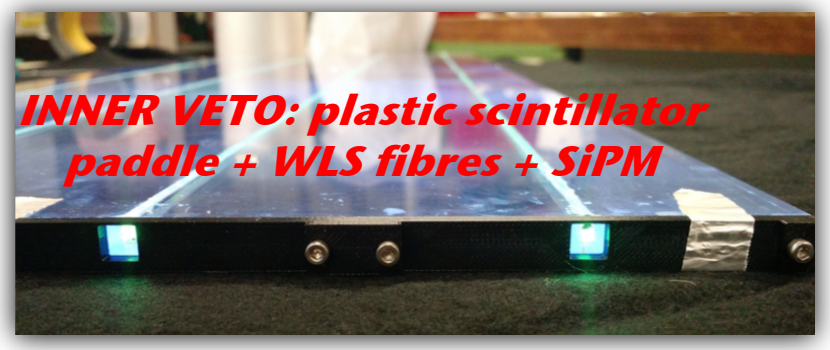



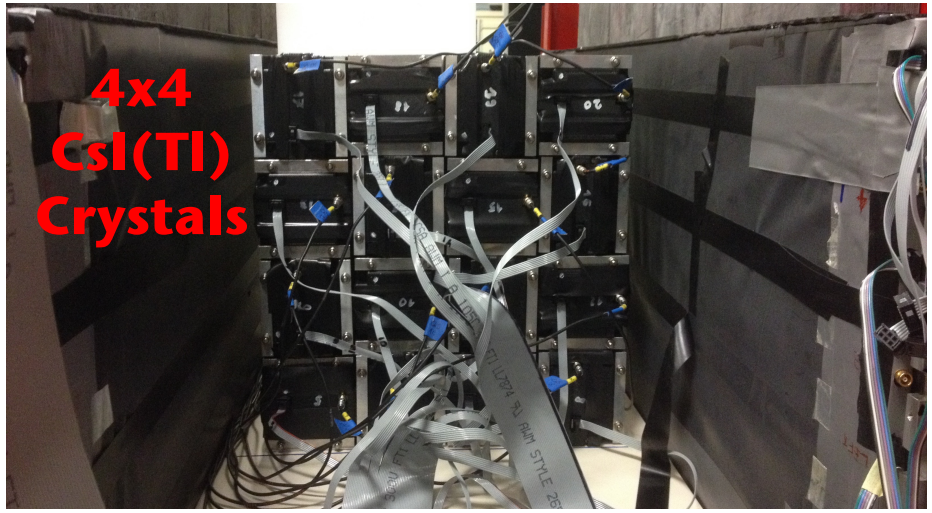



# Cosmogenic Background

## BDX DETECTOR PROTOTYPE



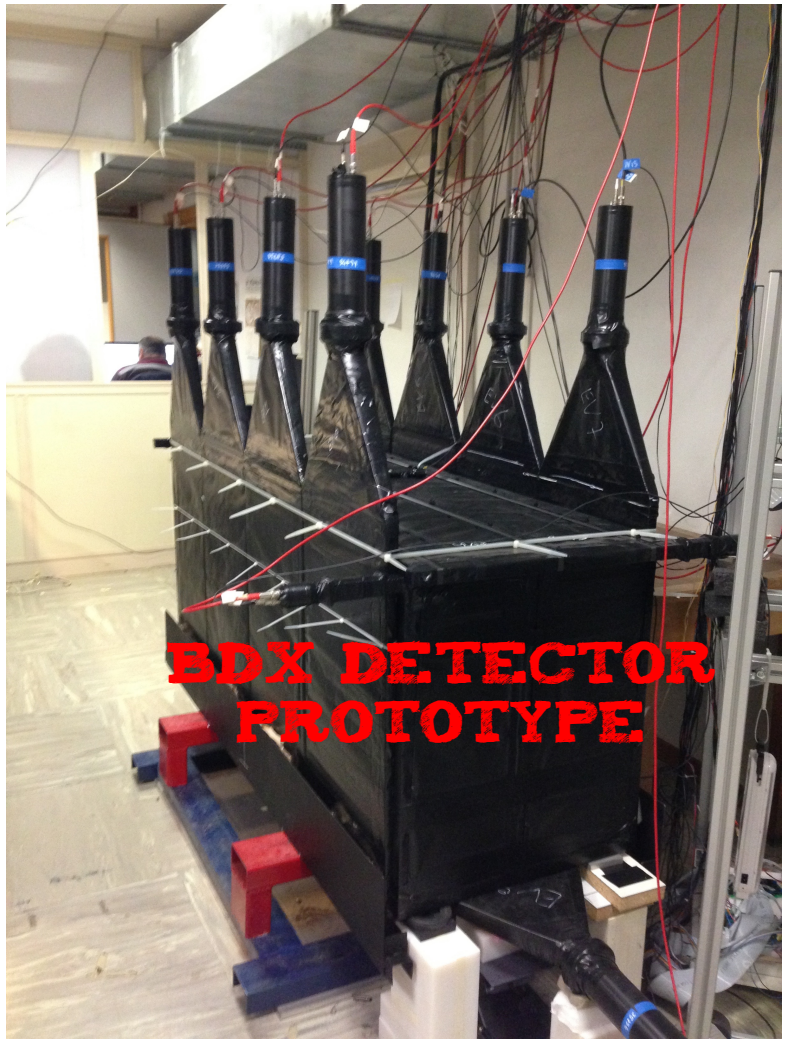


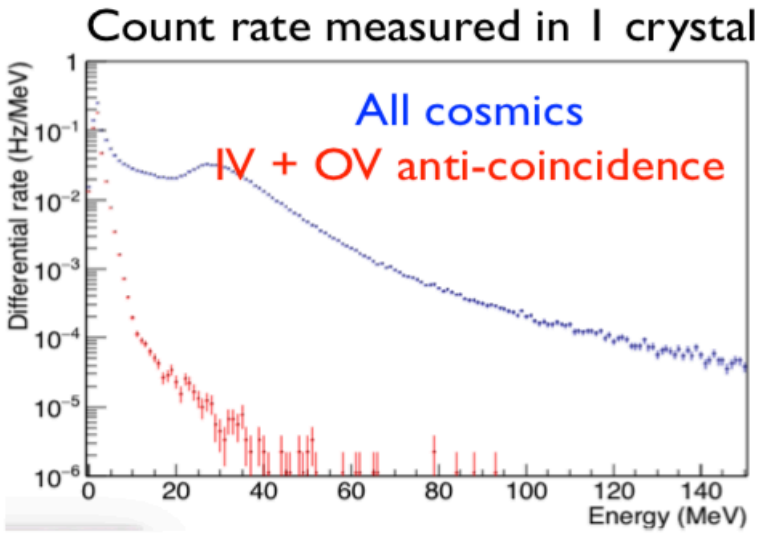



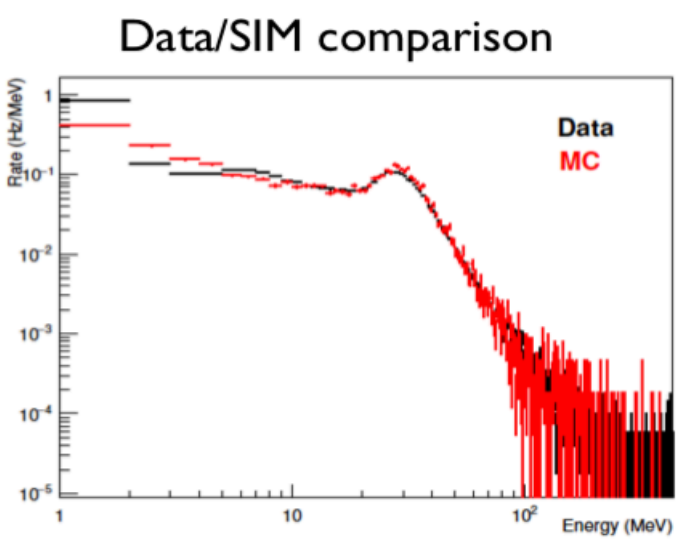

OUTER VETO:
Plastic scint +
Light guide +
PMT /
WLS scint. +
SiPM

# Cosmogenic Background

Cosmic background measured with the BDX detector prototype in Catania and LNS (similar overburden expected at JLab)



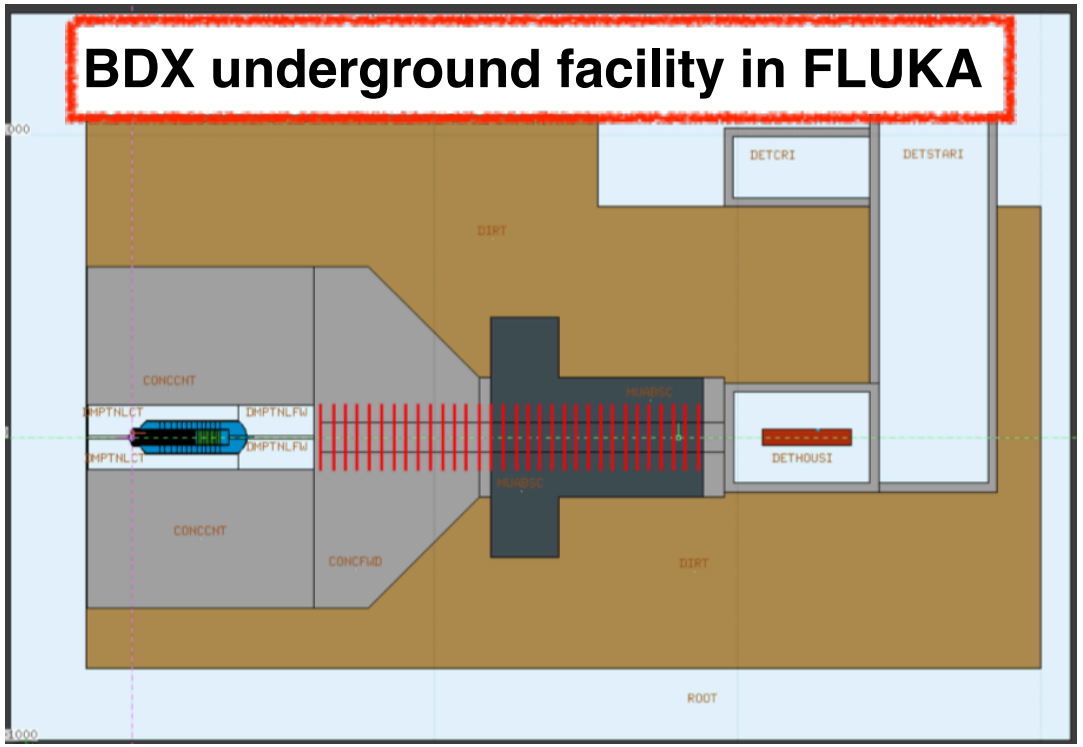




Expected cosmic background counts in the BDX lifetime conservatively projected to the full detector

| Energy Thresold (MeV) | Expected Counts (285 days meas.) |
|---|---|
| 200 | $740 \pm 300$ |
| 250 | $57 \pm 25$ |
| 300 | $4.7 \pm 2.2$ |
| 350 | $0.037 \pm 0.022$ |

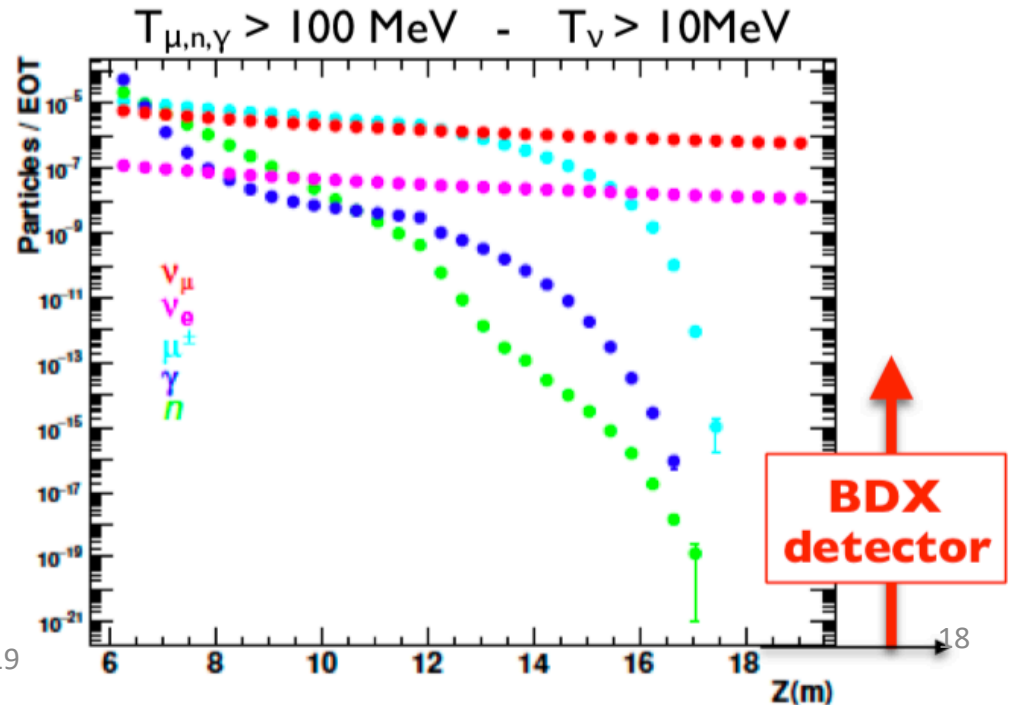
# Beam-related background




- Particles produced in the beam-dump by an 11 GeV electron beam tracked to BDX detector location
- 6.6m iron shield + 2m concrete to stop high energy muons
- different shielding configuration tested

**High statistics** simulations : **~$10^{17}$ EOT equivalent at BDX detector location** (biasing technique)

*All high energy SM particles ranged-out except neutrinos*




★ **No n and γ with E>100 MeV are found at the detector location**
★ **All the μ emitted forward and passing through the shielding are ranged-out**
★ **some μ emitted at a large angle propagate in the dirt and then, after a hard interaction, re-scattering in the detector. They result in a non-zero background rate but they have a kinetic energy lower than 300 MeV**

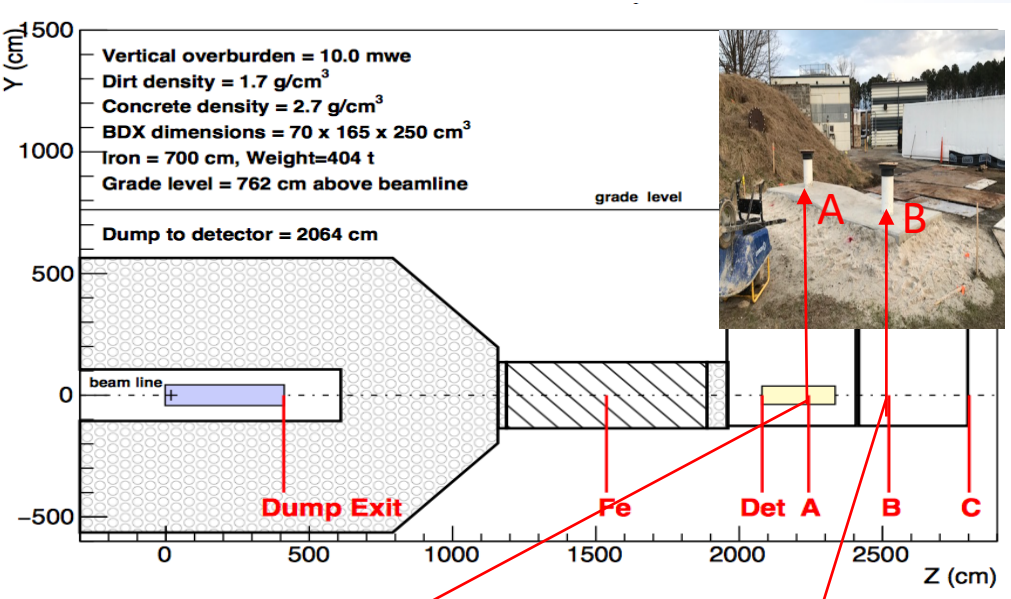
# Background assessment

Contents lists available at ScienceDirect
Nuclear Inst. and Methods in Physics Research, A
journal homepage: www.elsevier.com/locate/nima

Measurements of the muon flux produced by 10.6 GeV electrons in a beam dump

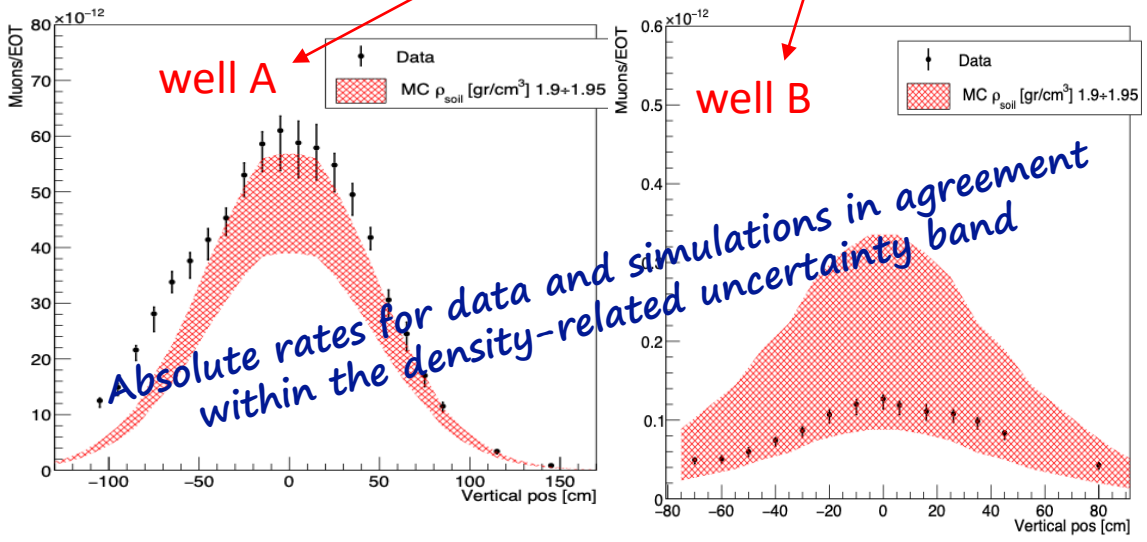
M. Battaglieri[b], M. Bondí[a,*], A. Celentano[b], M. De Napoli[a], R. De Vita[b], S. Fegan[e], L. Marsicano[b,c], G. Ottonello[b], F. Parodi[b], N. Randazzo[a], E.S. Smith[d], T. Whitlatch[d]

## Measuring the flux of μ produced in the Hall-A beam-dump at the BDX location



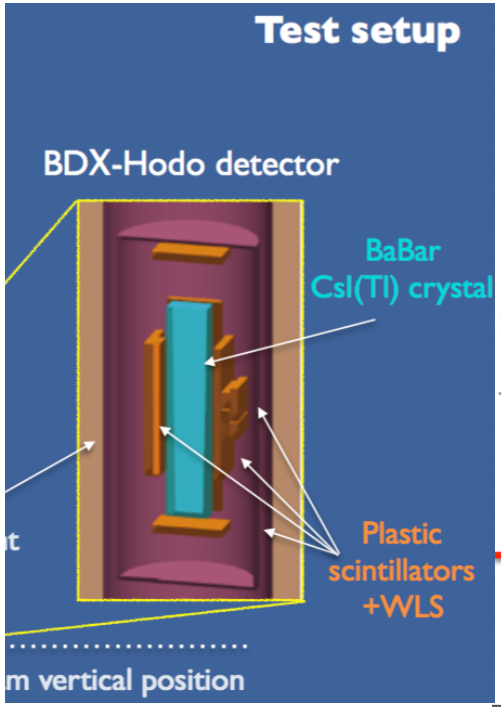


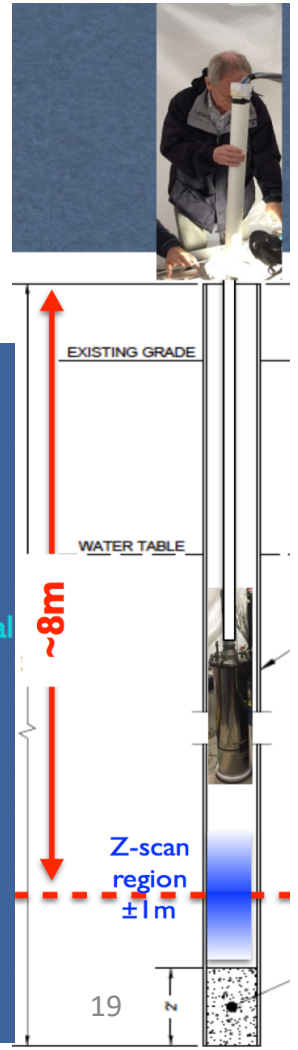





Absolute rates for data and simulations in agreement within the density-related uncertainty band

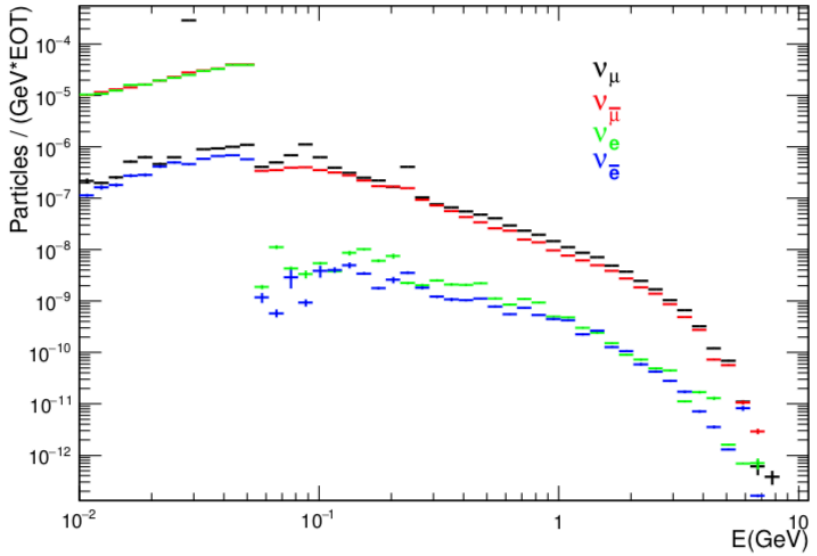
**Hall-A beam parameters:**
- $I_{Beam}$ ~ 22 uA
- $E_{Beam}$ = 10.6 GeV

# Beam-related neutrino background

- Produced in muon decays and hadronic showers (pion decay)
  $\pi \Rightarrow \mu + \nu_\mu$ , $\mu \Rightarrow e + \nu_\mu + \nu_e$
- The majority come from π and μ decay at rest but a non negligible fraction, due to in-flight π decay, experience a significant boost to several GeV



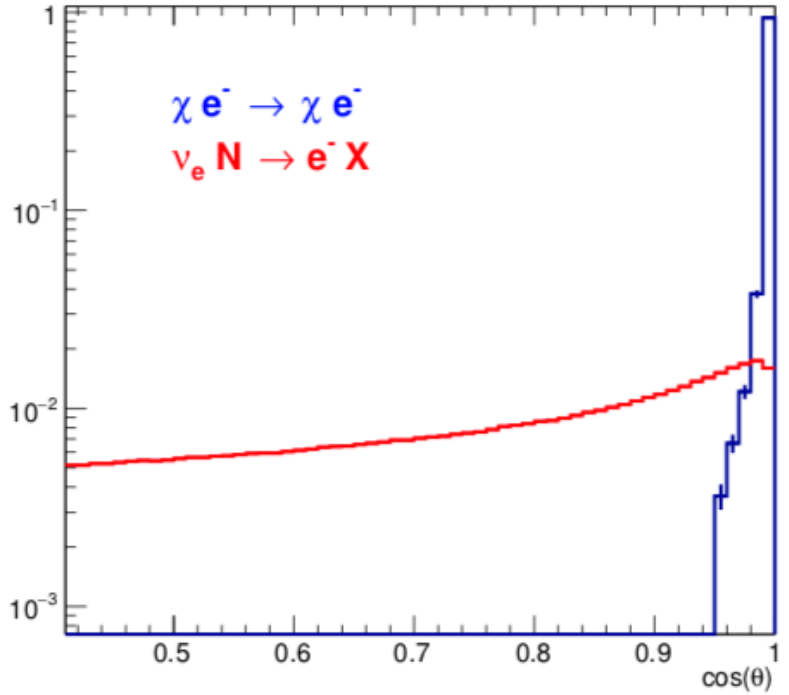

- High energy ν interacting with BDX detector by elastic and inelastic scattering may result in a significant energy deposition -O(300) MeV- that may mimic an EM shower produced by the χ-atomic electron interaction

***Charged Current: $\nu_e + N \Rightarrow X + e$***

**Different kinematics for signal and bg**

$X_{DM} + e^- \rightarrow X_{DM} + e^-$ forward peaked

$\nu_{e^-} + N \rightarrow X + e^-$ spread over all angles




- ★ **BDX only limited by the ν irreducible bg**
- ★ **Expected beam-related bg counts ~5 events (after analysis cuts)**

# BDX reach

Analysis cuts:
- Eseed>350 MeV
- R*<0.6

→ Number of expected background events is B~5 (all due to neutrinos)

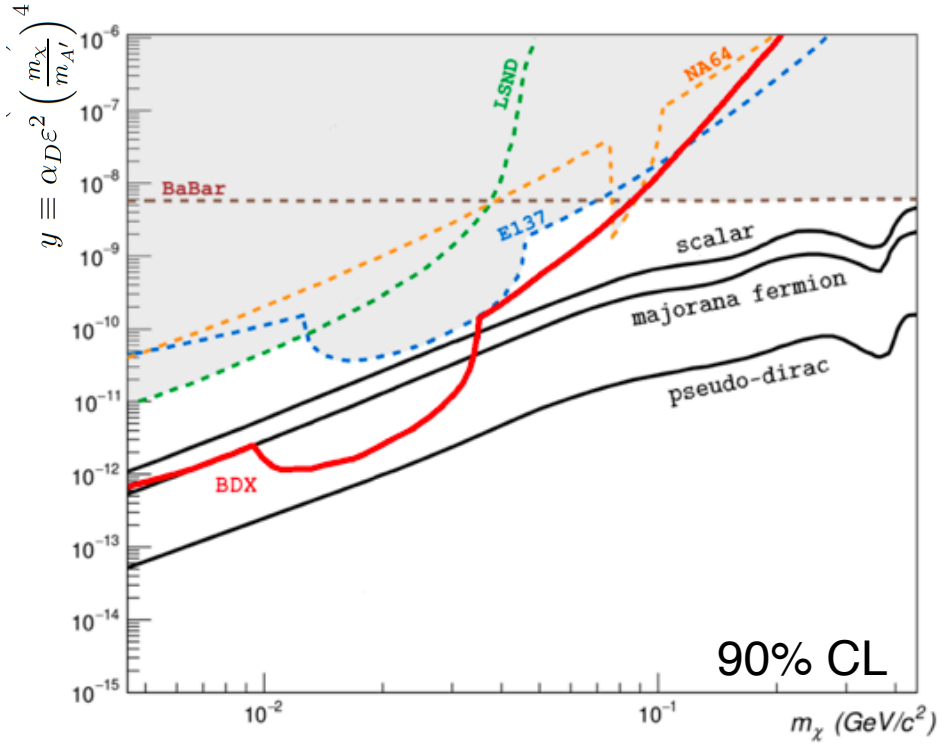
→ which corresponds to a sensitivity of 6 signal events

$$N(\varepsilon_{min}, m_\chi) = 2.3 + 1.5\sqrt{B},$$

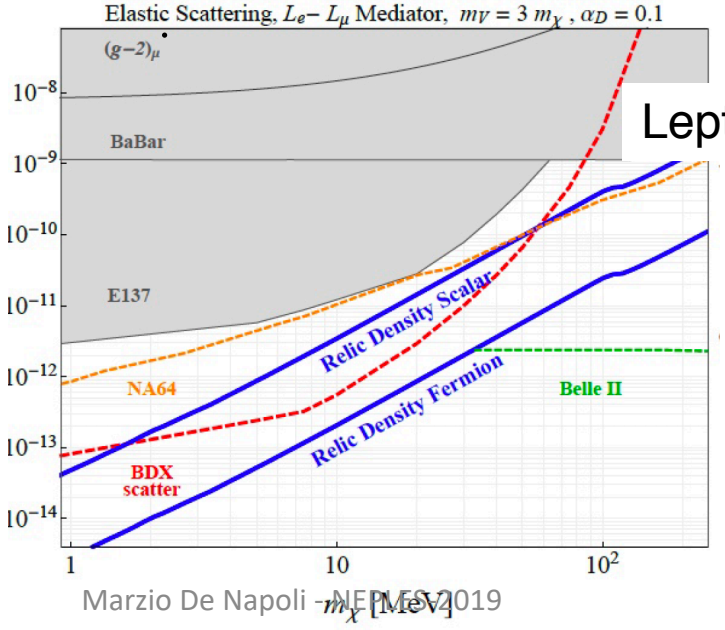
~$10^{22}$ EOT in about 1 year of run
10GeV , 65 uA
No cosmogenic background
O(5) neutrinos background

*Shower transverse dimension: indicating the shower deviation from beam direction

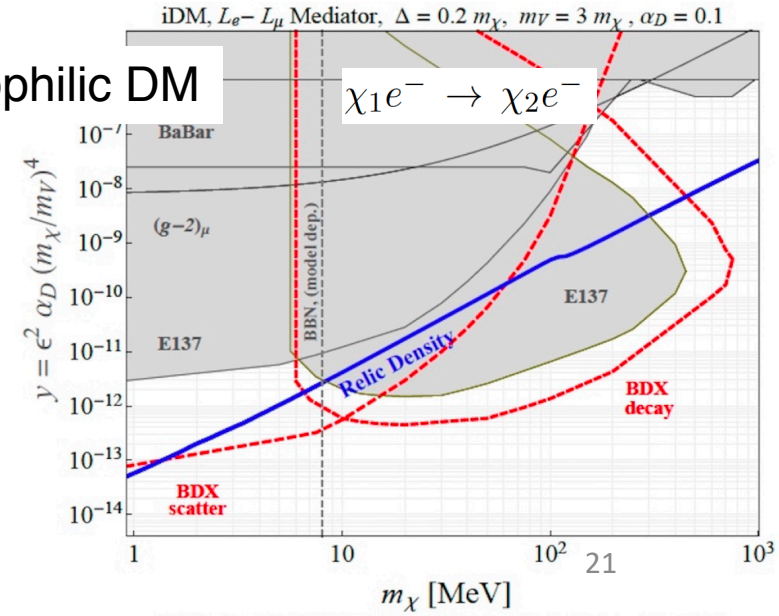
**BDX SENSITIVITY MORE THAN AN ORDER OF MAGNITUDE BETTER THAN EXISTING LIMITS**




**CAN EXCLUDE THERMAL SCENARIO IN A WIDE MASS RANGE**



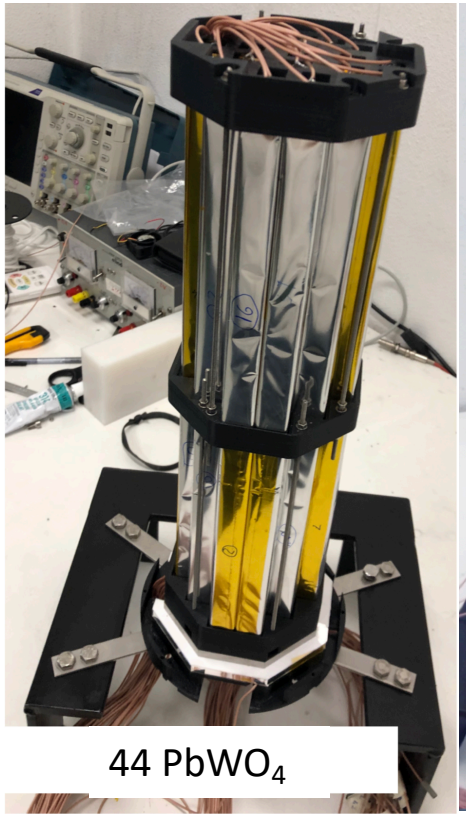

Leptophilic DM

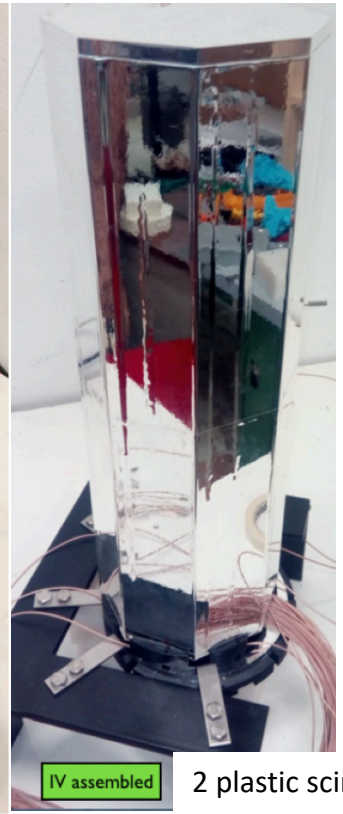


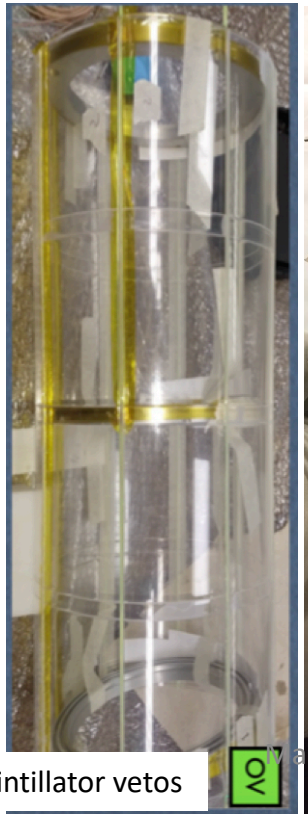
# BDX-MINI

- ✓ A proof of principle experiment (BDX-MINI) has recently started at JLAB
- ✓ BDX – Mini detector placed ~25 m from Hall-A dump
- ✓ Present unshielded configuration. No beam-related bck due to the low e-beam energy (2.2 GeV)

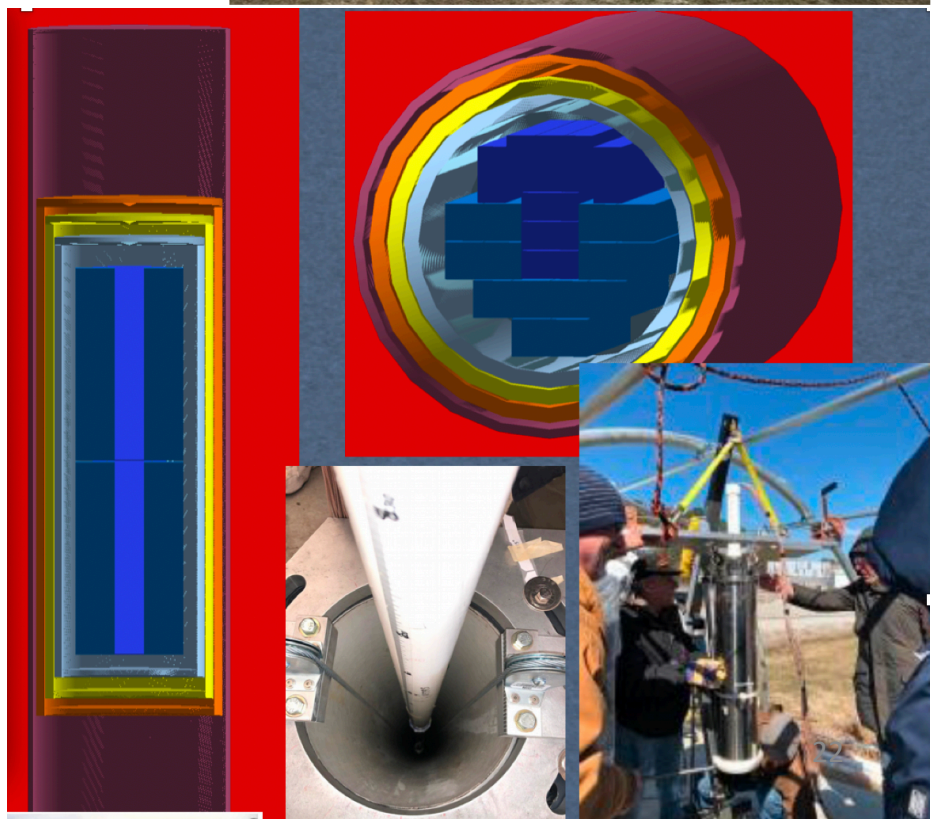

## BDX-MINI DETECTOR


44 $PbWO_4$



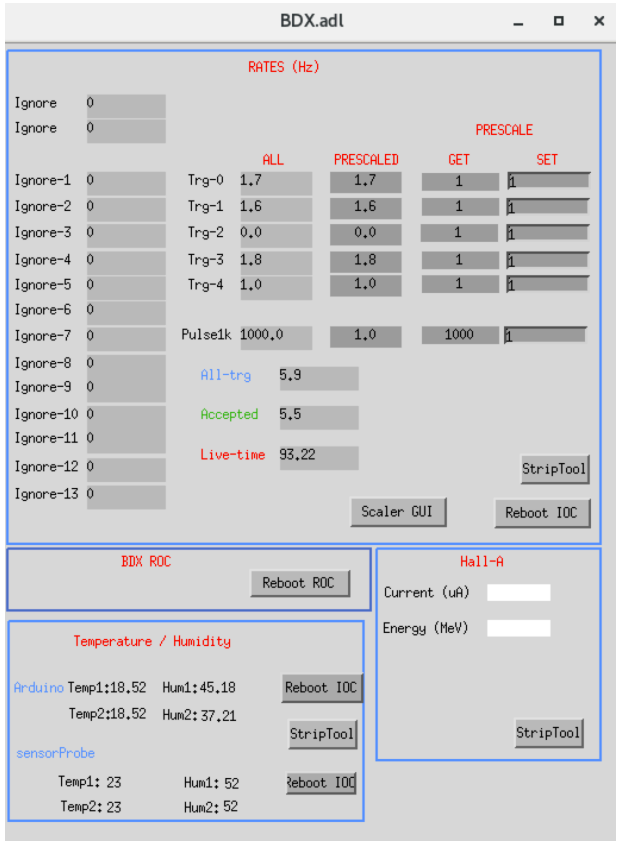



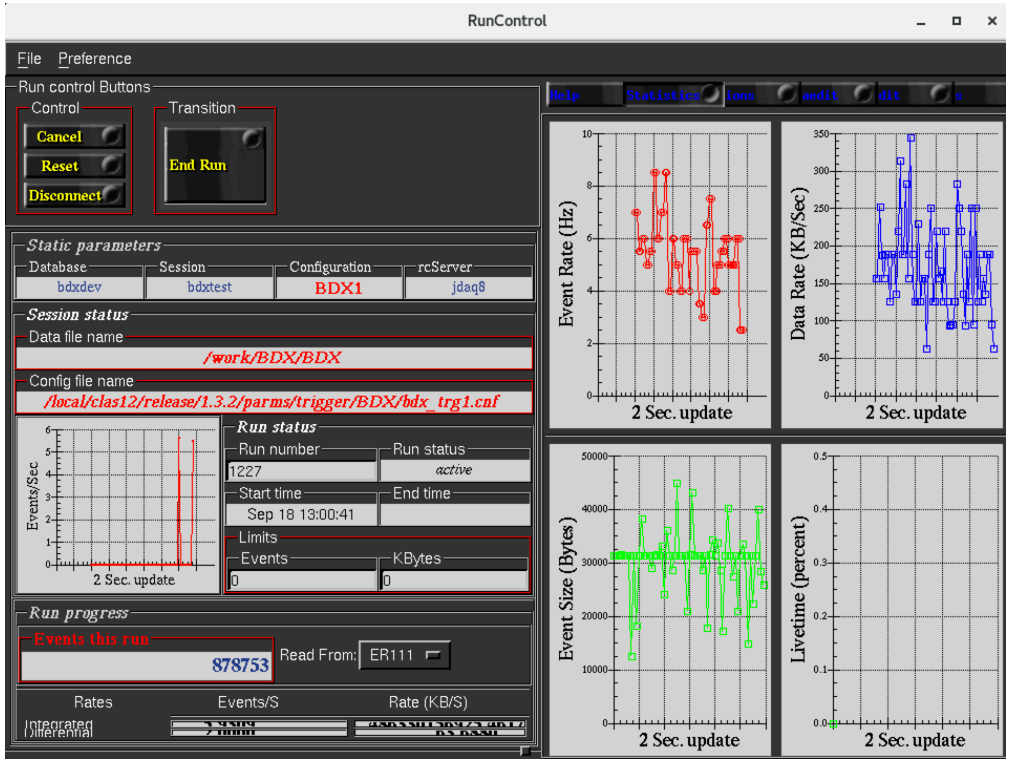
2 plastic scintillator vetos



# BDX-MINI

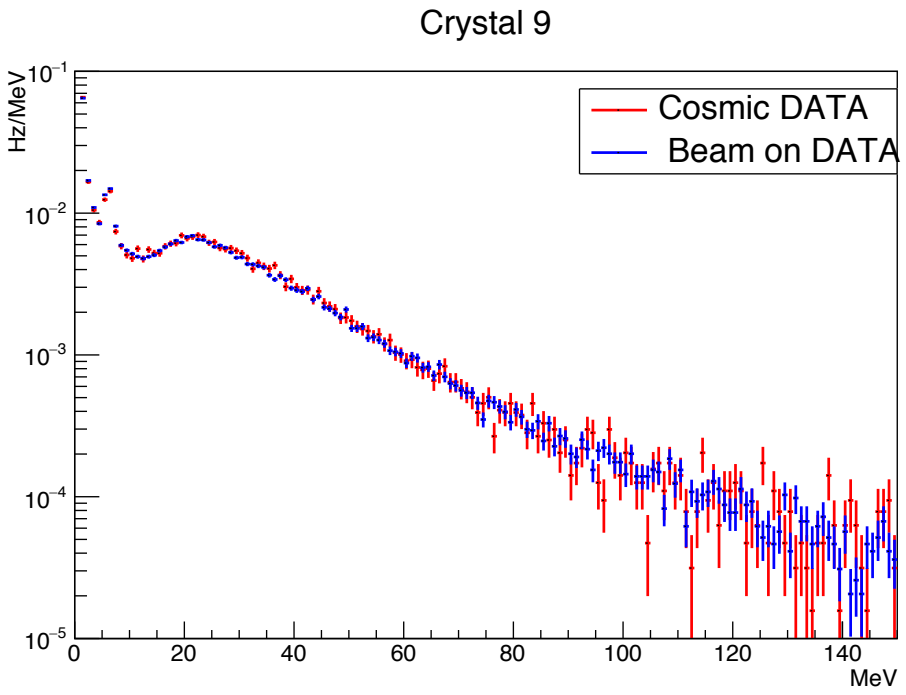
- ✓ The detector has been commissioned this spring during a 1.1GeV beam in Hall-A
- ✓ Cosmic data taking is ongoing

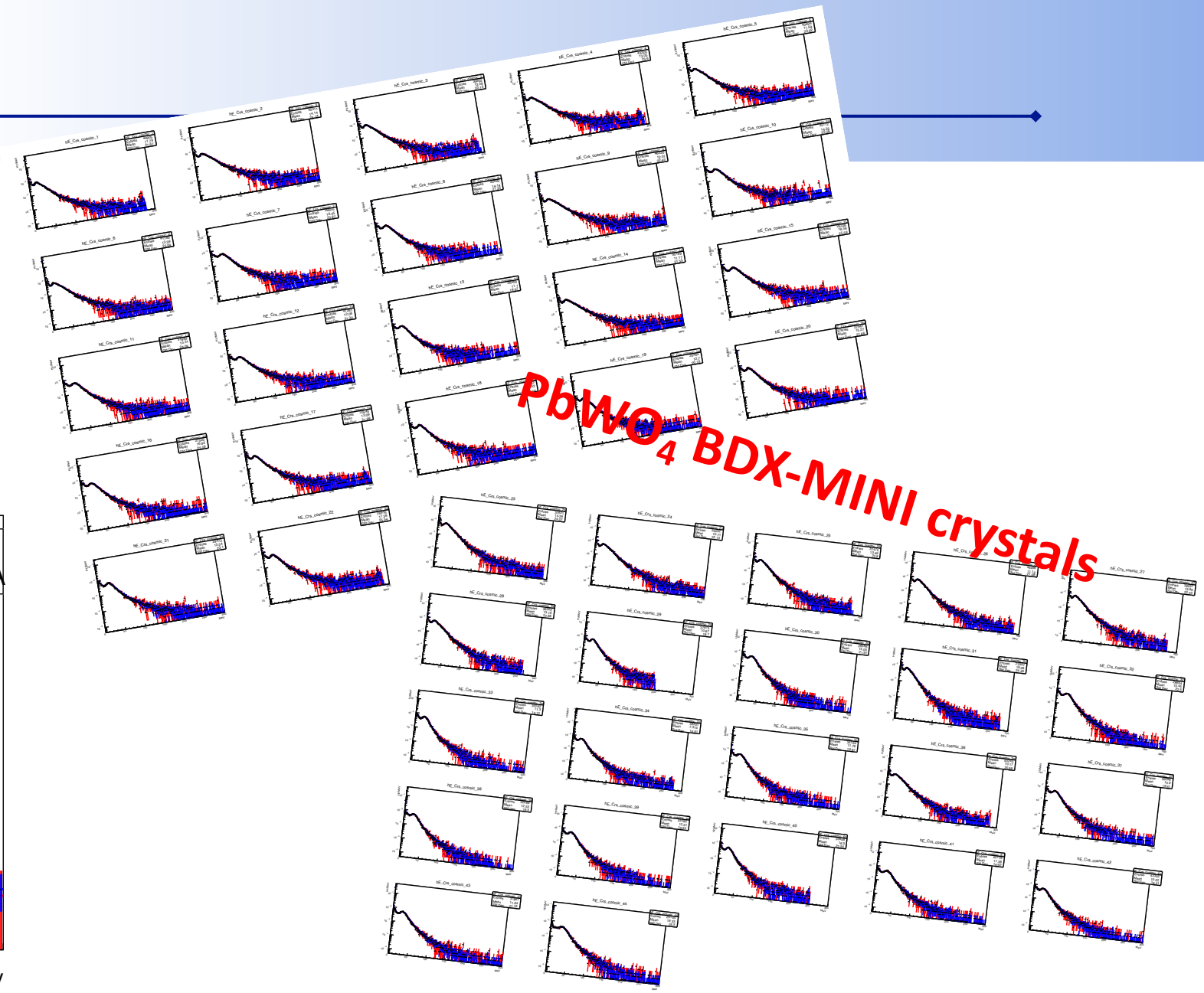


# BDX-MINI

- ✓ Detailed MC simulations for comiscs and $\chi$ particles have been done
- ✓ Calibrations & efficiency studies just started

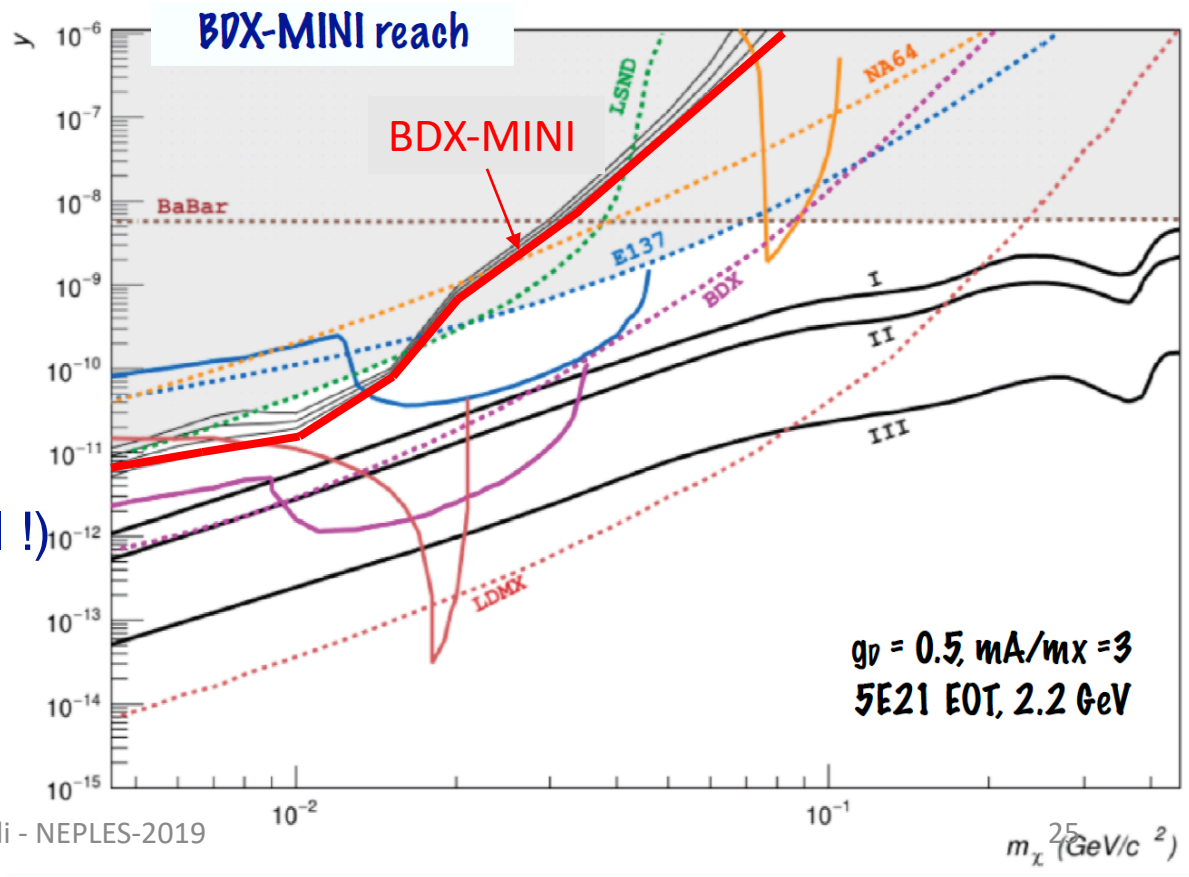


# BDX-MINI

*BDX-MINI is the first dedicated new-generation e- beam-dump experiment whose physics reach should almost cover a kinematic region measured by summing up old not-optimized experiments*

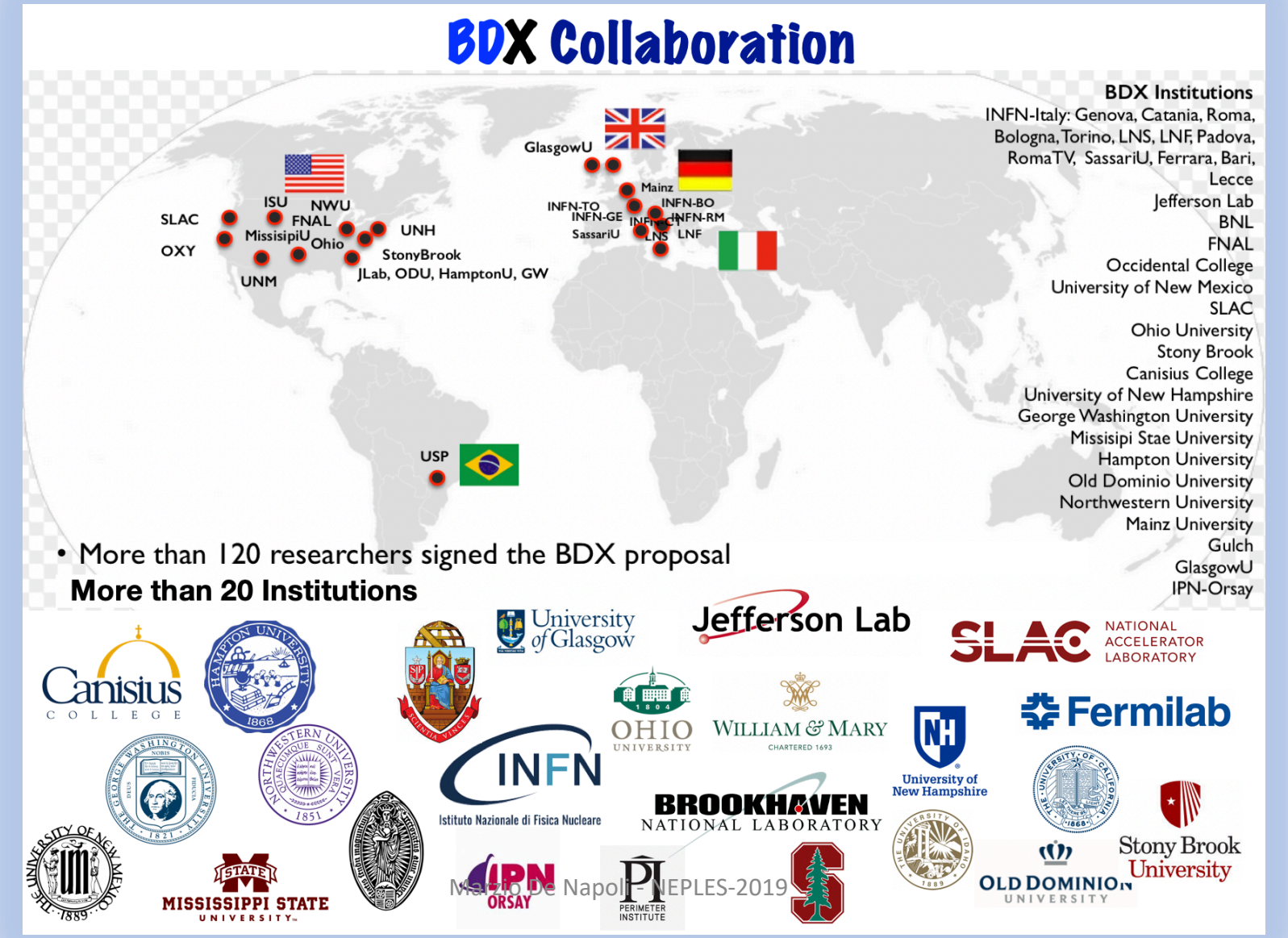
- Beam energy 2.2 GeV
- Beam current ~150 μA
- Two experimental campaigns planned:
  1) ~1.5 month starting from November this year
  2) ~1 month February 2020
- The goal is to collect a total number of $5*10^{21}$ EOT (not so different from the real BDX experiment goal !)



# Conclusions

- Hidden Sector Dark Matter is part of the thermal relic paradigm. It has testable predictions and clear targets that can be probed by experiments at accelerators
- BDX@JLAB is the first new-generation dedicated electron-beam dump experiment to search for LDM
- In about 1year of measurements BDX can extend existing limits up to one order of magnitude and exclude some LDM scenario
- BDX has been approved by JLAB-PAC46 with the maximum scientific rate
- DOE funding opportunity - FOA Dark Matter New Initiatives (May 30)
  - Only design and experimental work plan (no construction !)
  - Selected projects will access to funds for construction (up to $10;-$15M) in 2021
  - Results announced in FY19 (expected)
    - BDX – total request $1.15M, total time 20 months
      - Design of the new Hall
      - Shielding optimization
      - Detector integration
- The pilot BDX-Mini experiment is installed at JLab and is expected to take beam-on data fall this year and at the beginning of 2020. Stay tuned !

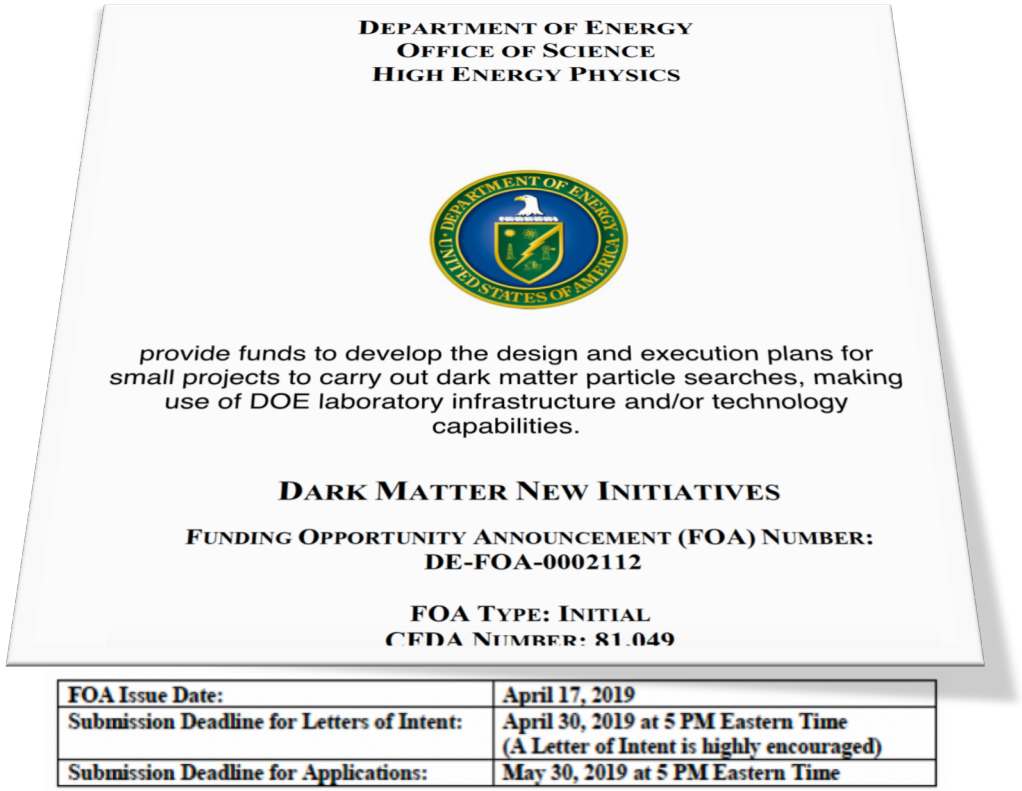
# BDX Collaboration



# DOE funding opportunity (FOA)

FOA Dark Matter New Initiatives :

- Only design and experimental work plan (no construction !)
- Up to $2M, in 1y-2y
- Selected projects will access to funds for construction (up to $10;-$15M) in 2021
- Results announced in FY19 (expected)



DEPARTMENT OF ENERGY
OFFICE OF SCIENCE
HIGH ENERGY PHYSICS

*provide funds to develop the design and execution plans for small projects to carry out dark matter particle searches, making use of DOE laboratory infrastructure and/or technology capabilities.*

**DARK MATTER NEW INITIATIVES**

**FUNDING OPPORTUNITY ANNOUNCEMENT (FOA) NUMBER:**
**DE-FOA-0002112**

**FOA TYPE: INITIAL**
**CFDA NUMBER: 81.049**

| | |
|---|---|
| **FOA Issue Date:** | **April 17, 2019** |
| **Submission Deadline for Letters of Intent:** | **April 30, 2019 at 5 PM Eastern Time (A Letter of Intent is highly encouraged)** |
| **Submission Deadline for Applications:** | **May 30, 2019 at 5 PM Eastern Time** |

**Proposal for Program Announcement Number LAB 19-2112**

## Design and execution plans of Beam-Dump eXperiment (BDX) at Jefferson Lab

### 1 Cover Page

Title of Proposal:
**Design and execution plans of Beam-Dump eXperiment (BDX) at Jefferson Lab**

Applicant Institution:
**Thomas Jefferson National Accelerator Facility**
*12000 Jefferson Ave, Newport News, VA 23606*

Principal Investigator:
**Elton S. Smith**
*JLab Senior Staff Scientist*
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**Deborah Dowd**
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DOE National Laboratory Program Announcement Number:
**LAB 19-02112**

DOE/SC Program Office
**High Energy Physics (HEP)**

DOE/SC Program Office Technical Contact
**Dr. Kathleen Turner**

PAMS Letter of Intent
**LOI-0000025692**

Research Track
**Track #1**

PRD area
**PRD #1: Create and detect dark matter particles and associated forces below the proton mass, leveraging DOE accelerators that produce beams of energetic particles.**

- Design of the new Hall
- Shielding optimization
- Detector integration

- Total request $1.15M
- Total time: 20 months