Winter Hall A Collaboration

Jan 16, 2024, 8:00 AM → Jan 17, 2024, 7:25 PM US/Eastern

ARC 231/233 & Cebaf Center Auditorium (Jefferson Lab)

Arun Tadepalli (Jefferson Lab), Bishnu Pandey (Virginia Military Institute), Carlos Ayerbe Gayoso (Old Dominion University), Mark Jones (Jefferson Lab), Michael Nycz (University of Virginia)

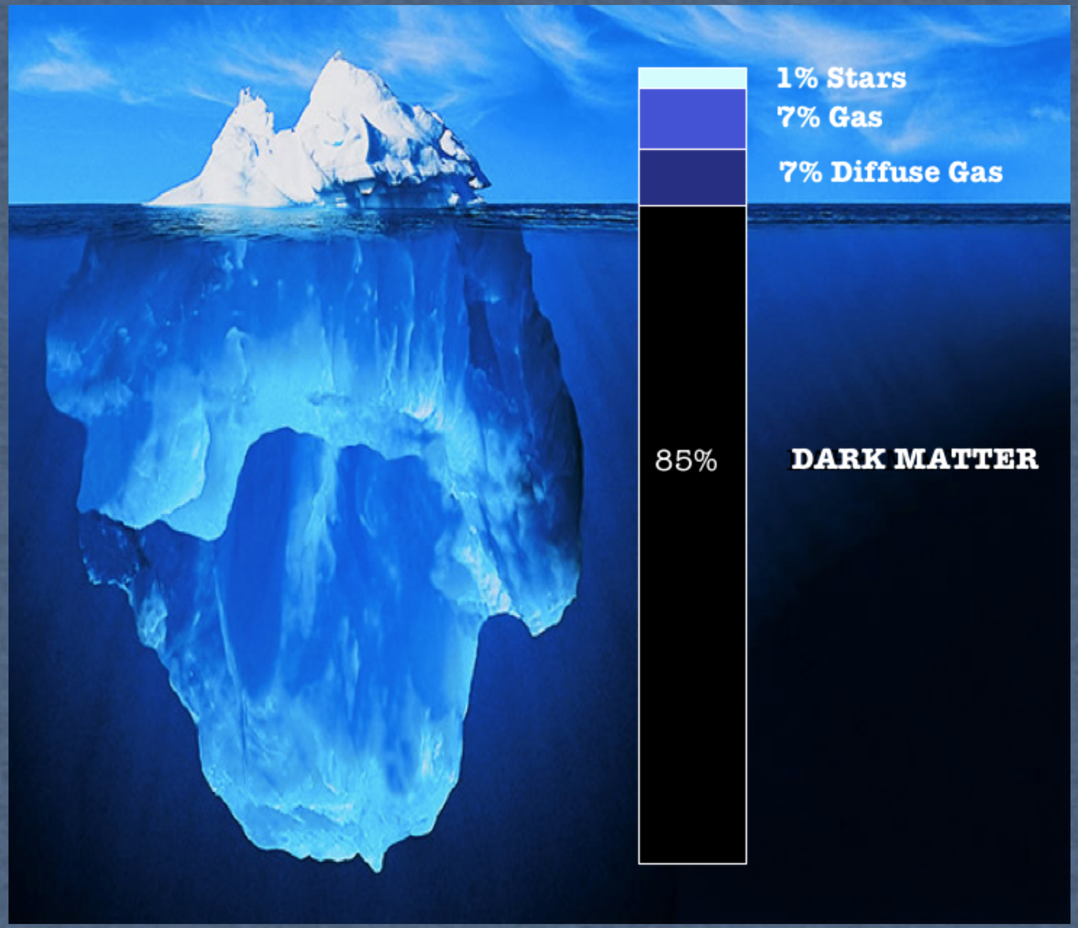
BDX
Dark Matter search in a beam-dump experiment at Jefferson Lab

M.Battaglieri (INFN)
on behalf of the BDX Collaboration

Dark Matter (DM) vs Baryonic Matter (BM)

Compelling astrophysical indications about DM existence

★ How much DM w.r.t. BM?



★ Does DM participate to non-gravitational interactions?
★ Is DM a new particle?

★ Constraint on DM mass and interactions

- should be '*dark*' (no em interaction)
- should weakly interact with SM particles
- should provide the correct relic abundance
- should be compatible with CMB power spectrum

… assuming that the gravity is not modified and DM undergoes to other interactions

★ We can use what we know about standard model particles to build a DM theory

Use the SM as an example: $SM = U(1)_{EM} \times SU(2)_{Weak} \times SU(3)_{Strong}$

Particles, interactions and symmetries

Known particles & new force-carriers

Particles:
quarks, leptons

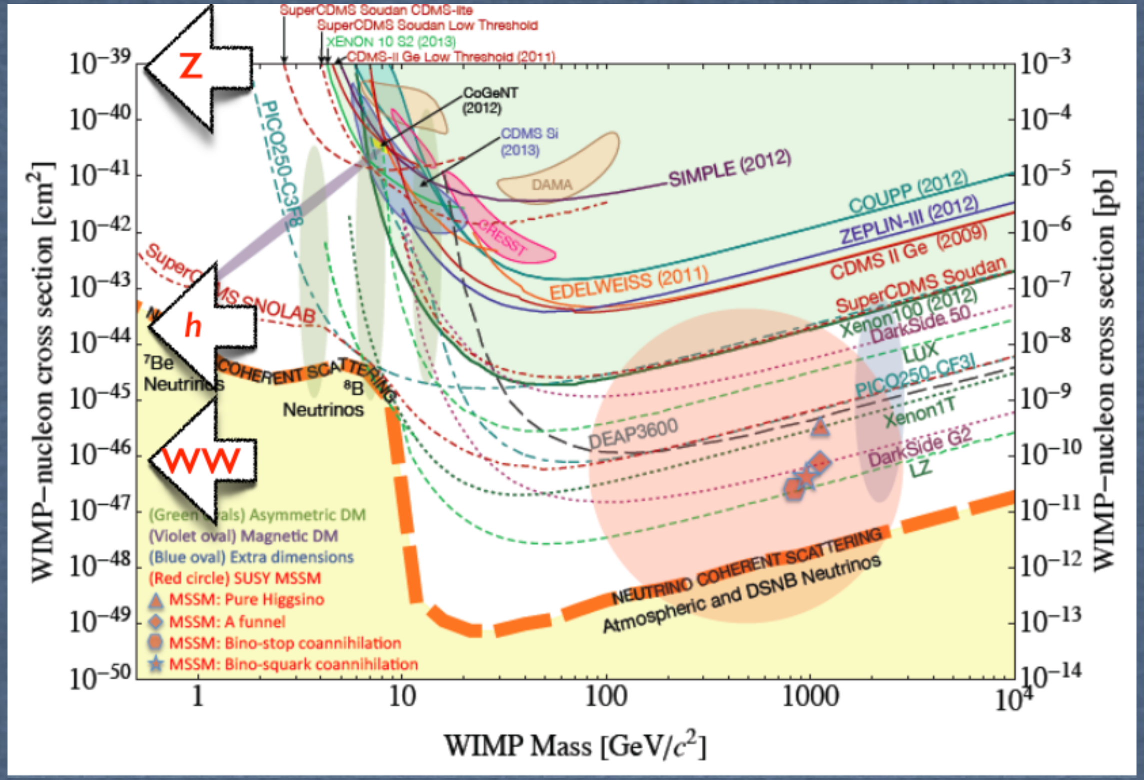
Force-carriers:
gluons, γ, W, Z, graviton (?), Higgs, ...

Two options:

★ New matter interacting trough the same forces
★ New matter interacting through new forces

Exploring the WIMP's option

★ Experimental limits



Slow-moving cosmological weakly interacting massive particles

- DM detection by measuring the (heavy) nucleus recoil
- Constraints on the interaction strength from the DM Direct Detection limits
  - Scattering through Z boson ($\sigma \sim 10^{-39} cm^2$): ruled out
  - Approaching limits for scattering through the Higgs ($\sigma \sim 10^{-45} cm^2$)
  - Close to irreducible neutrino background

✳ No signal observed in Direct Detection

✳ Experiments have (almost) no sensitivity to (light) DM (<1 GeV)

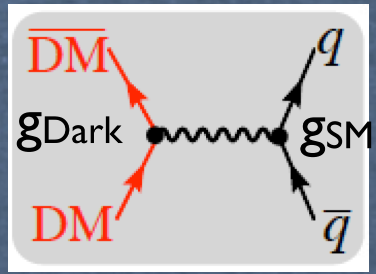
Direct Detection

1 MeV — 1 GeV — Mz — 10 TeV

WIMPs

WIMPs paradigm is not the only option (keeping the DM thermal origin)

$\langle \sigma v \rangle \sim g^2_{Dark}\, g^2_{SM}\, M^2_{DM}/M^4_{mediator}$



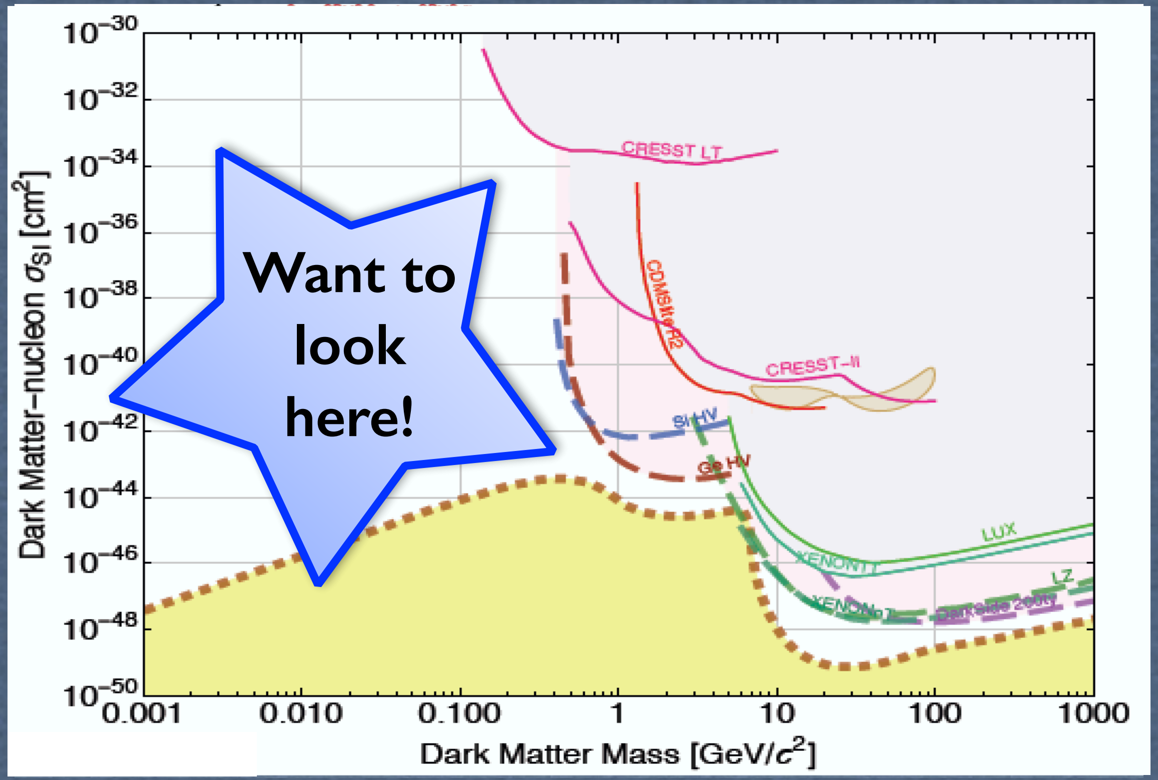
Light Dark Matter

Light Dark Matter (<TeV) naturally introduces light mediators

New interaction

Light Dark Matter

★ Experimental limits



Light Dark Matter with a (almost) weak interaction (new force!)

- Direct Detection is difficult
  - Low mass elastic scattering on heavy nuclei produces small recoil
  - eV-range recoil requires a different detection technology
  - Directionality may help to go behind existing limits at large masses

Accelerators-based DM search

covers an unexplored mass region extending the reach outside the classical DM hunting territory

- **High intensity**
- **Moderate energy**

Light Dark Matter | Direct Detection

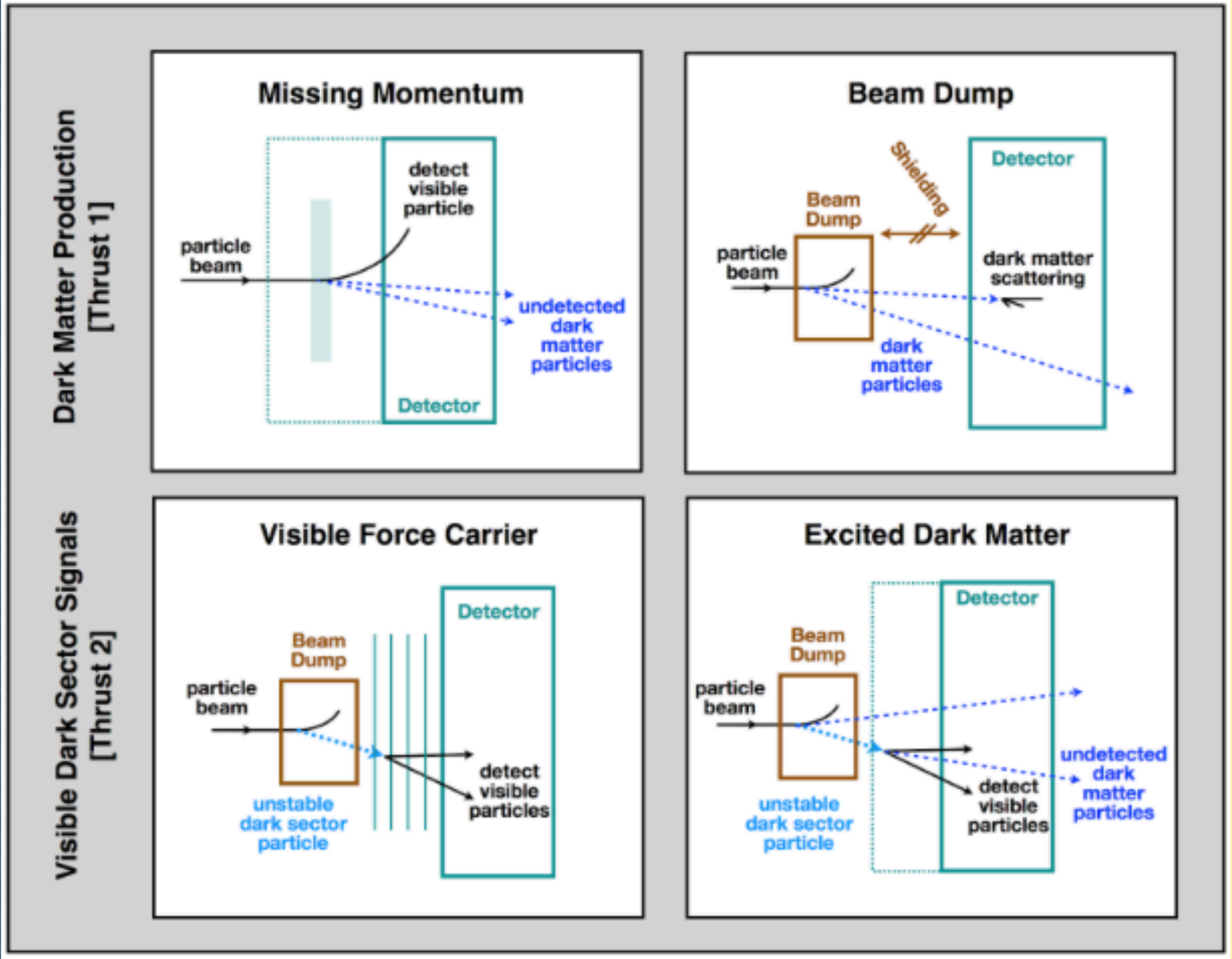
1 MeV | 1 GeV | Mz | 10 TeV

WIMPs

Dark Sector or Hidden Sector (DM not directly charged under SM interactions)

Can be explored at accelerators!

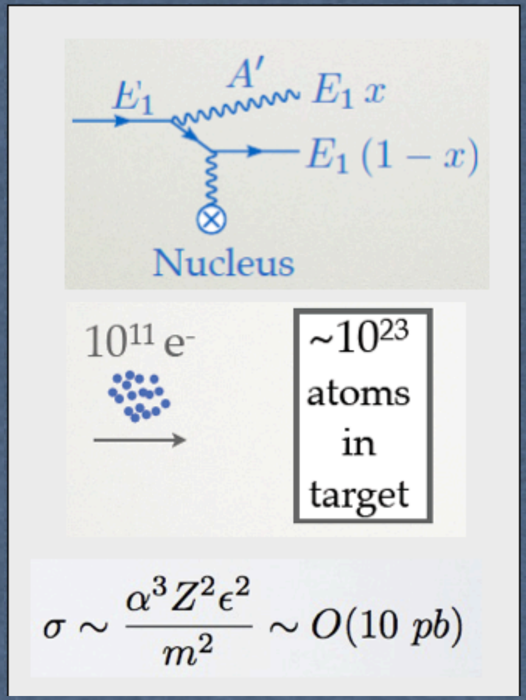
Experimental techniques

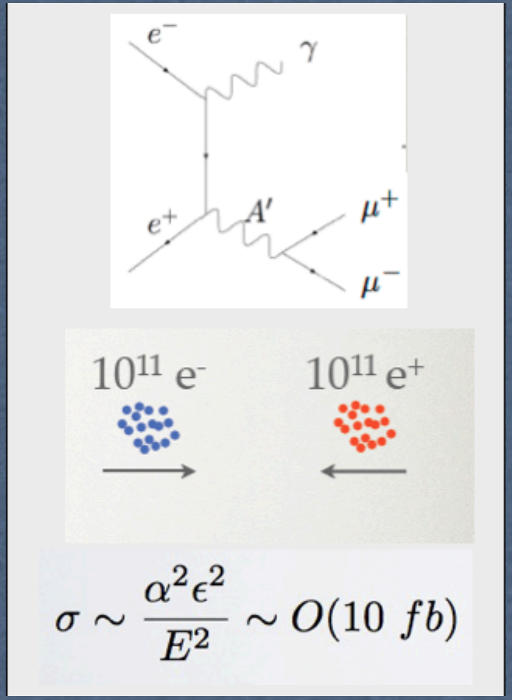


Fixed target vs. collider

Fixed Target | e+e- colliders

Process
Luminosity
Cross-Section





- high backgrounds
- limited A' mass

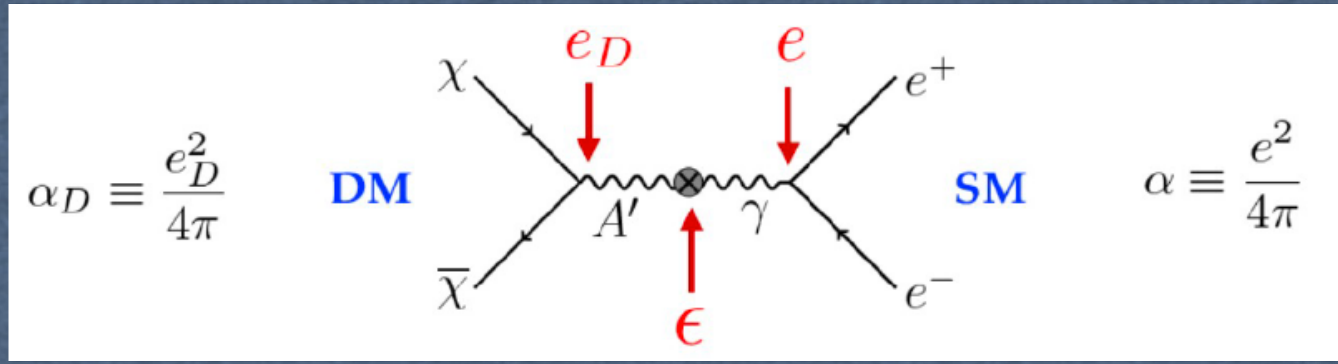
- low backgrounds
- higher A' mass

✳ $1/M_{A'}$ .vs. $1/E_{beam}$
✳ Coherent scattering from Nucleus (~Z^2)

Dark Photon Signatures

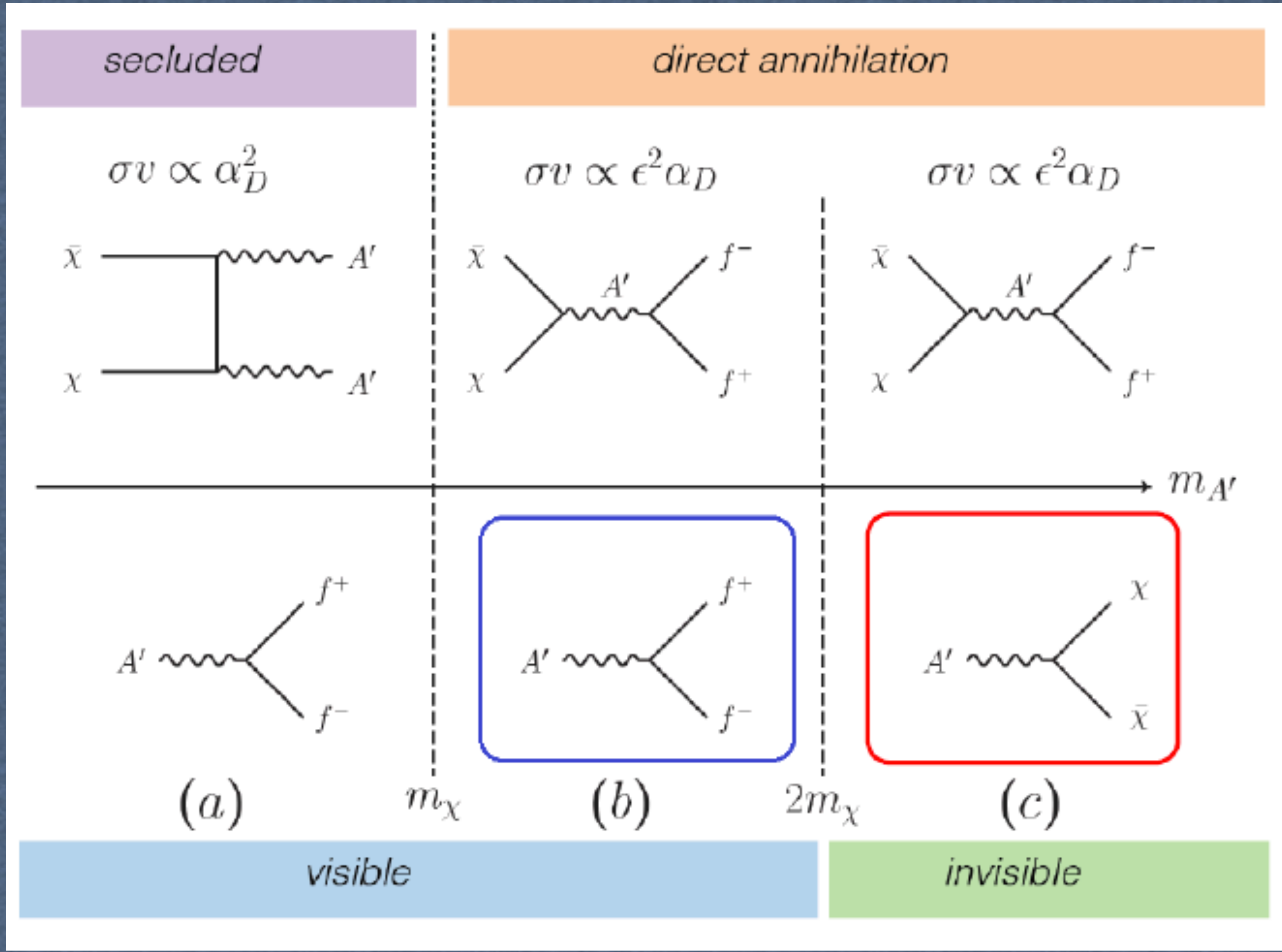
Vector mediated Light Dark Matter

- Vector-Portal: DM-SM interaction mediated by U(1) gauge-boson (dark photon or A') couples to electric charge



A' interaction scenarios

- **Secluded**: no constraints by cosmology for accelerator based experiments. Any ε allowed
- **Visible decay**: final state contains SM particles
- **Invisible decay**: A' decays to Dark Sector invisible particles



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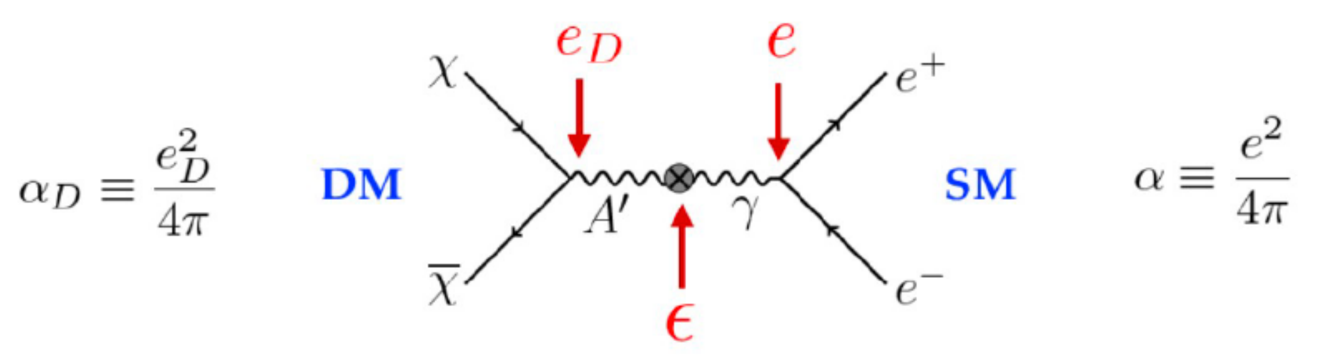

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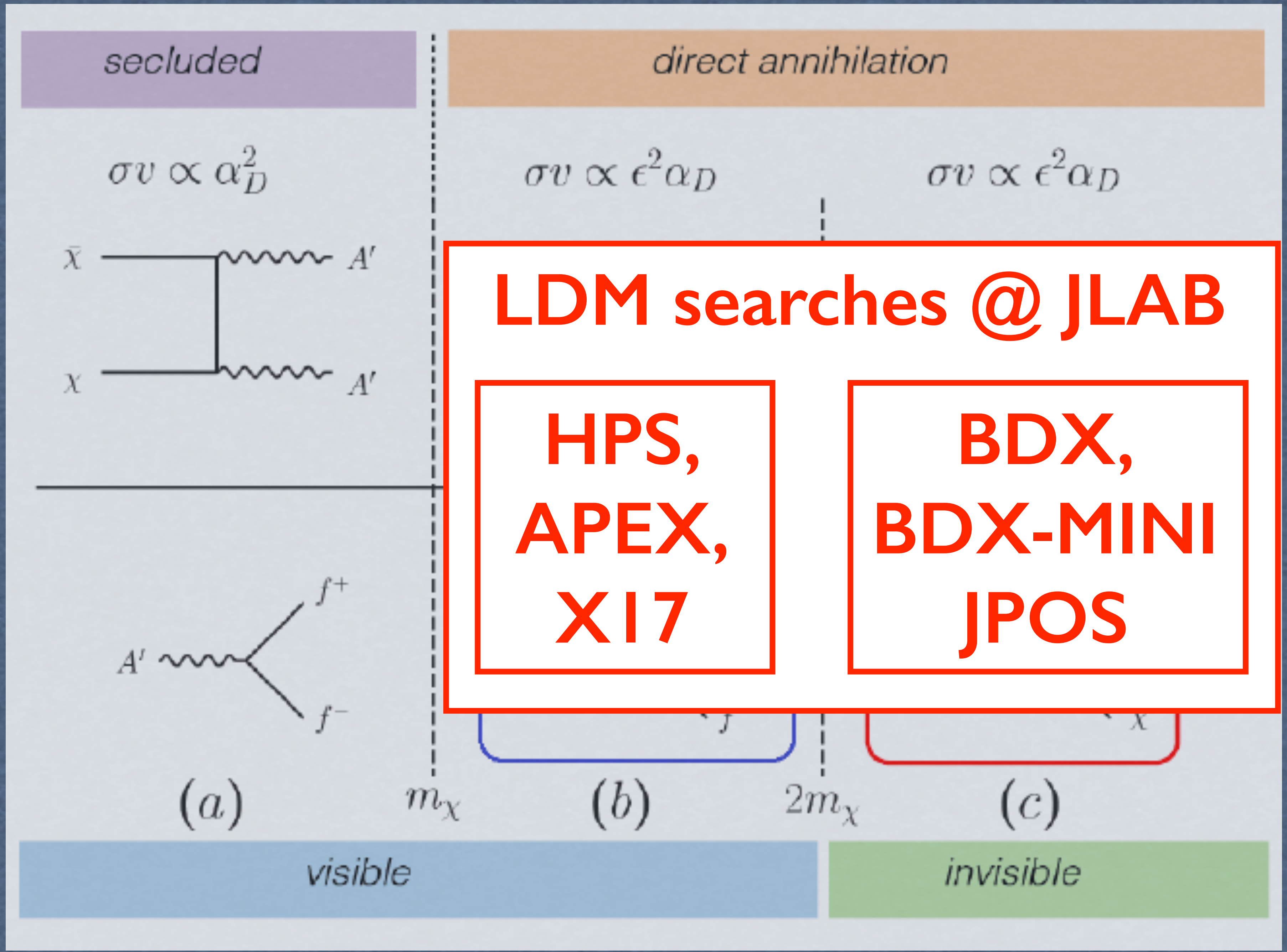
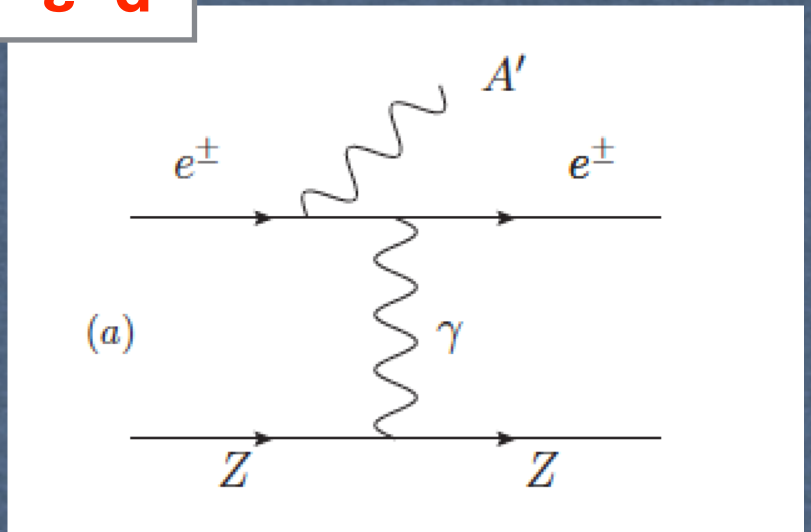


A' Production mechanisms - e±

~ ε² α³



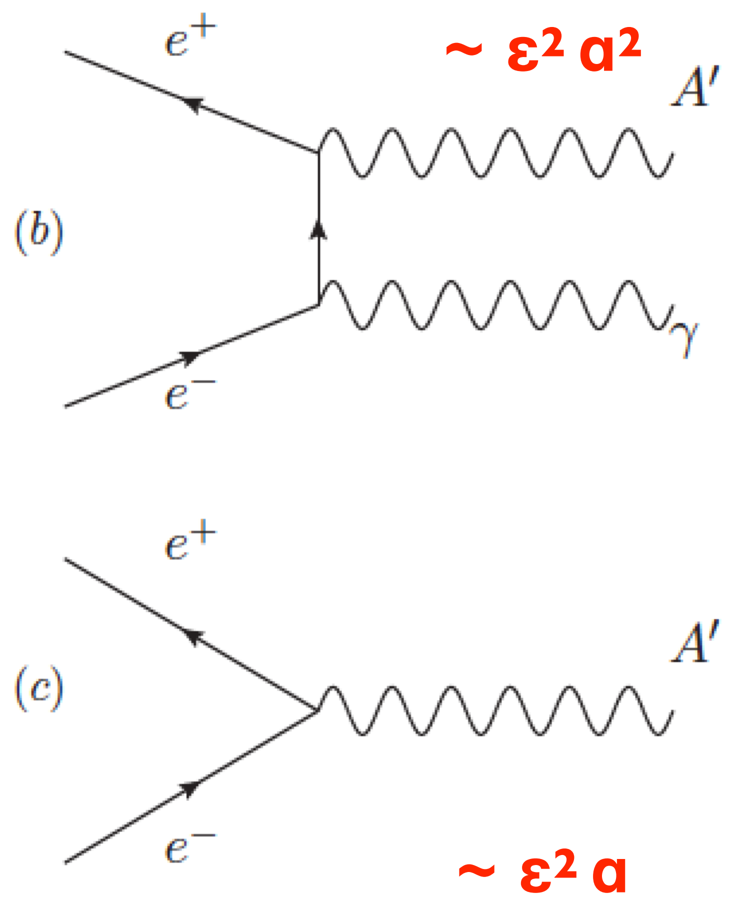
The Weizsacker-Williams approximation (*A'-strahlung*)

- The first tree-level mechanism proposed

L. Marsicano et al. Phys. Rev. Lett., 121(4) 041802, 2018
L. Marsicano et al. Phys. Rev. D, 98 (1) 015031, 2018

A' Production - resonant/non-resonant production

- Specific for positron annihilation
- A beam dump is a copious source of positrons
- Positrons in the EM shower may have any energy in the range of 0 - E_{beam}



- **NON-RESONANT annihilation**
- **RESONANT annihilation**

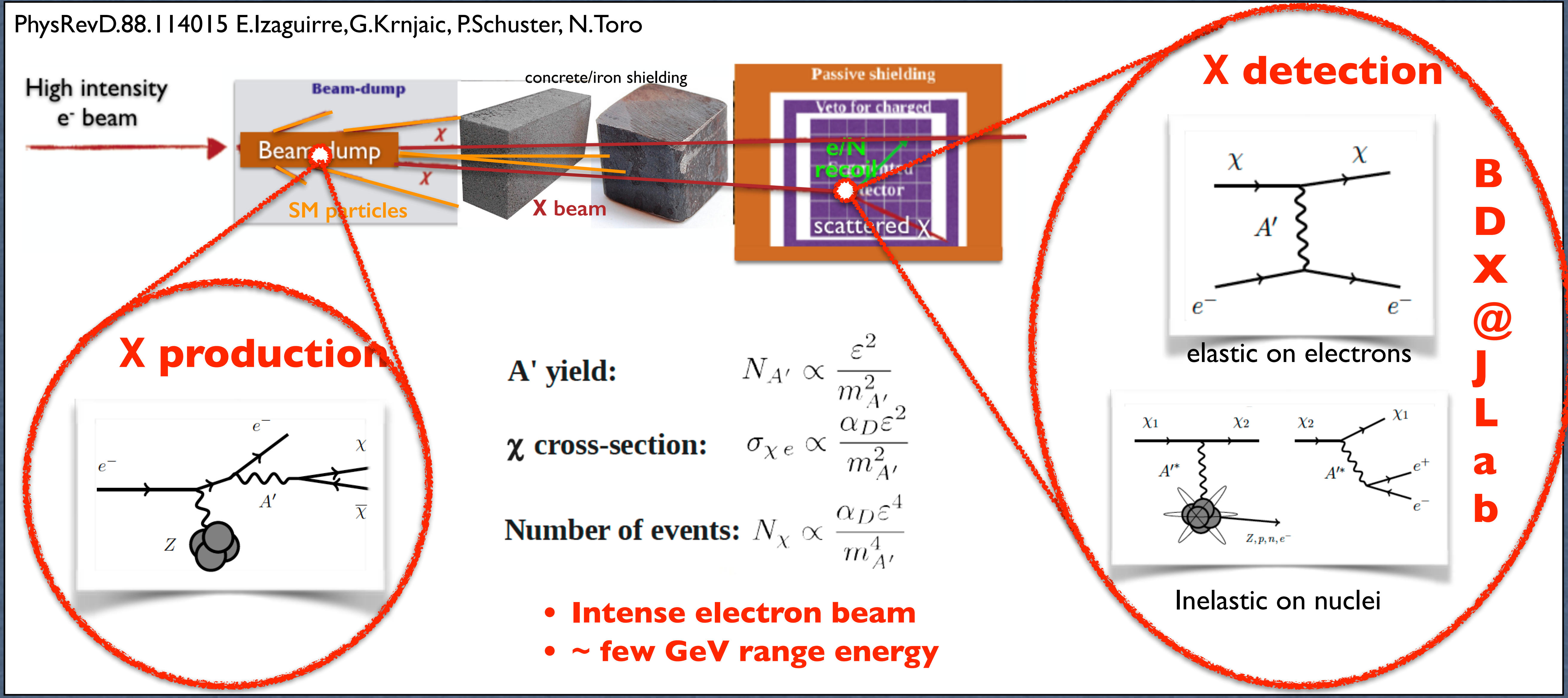
$$\sigma_r = \sigma_{\rm peak} \frac{\Gamma^2_{A'}/4}{(\sqrt{s} - m_{A'})^2 + \Gamma^2_{A'}/4},$$

The BDX experiment

Two step process

I) An electron radiates an A' and the A' promptly decays to a χ (DM) pair

II) The χ (in-)elastically scatters on a e-/nucleon in the detector producing a visible recoil (GeV)



Experimental signature in the detector: **X-electron → EM shower ~GeV energy**

BDX @ JLab

★ JLab Hall-A offers the best condition for the BDX experiment
- A high energy beam: 11 GeV
- The highest available electron beam current: ~65 uA
- The highest integrated charge: 10^{22} EOT (41 weeks)

★ Fully parasitic wrt Hall-A physics program

★ Drilled shaft downstream of Hall-A BD

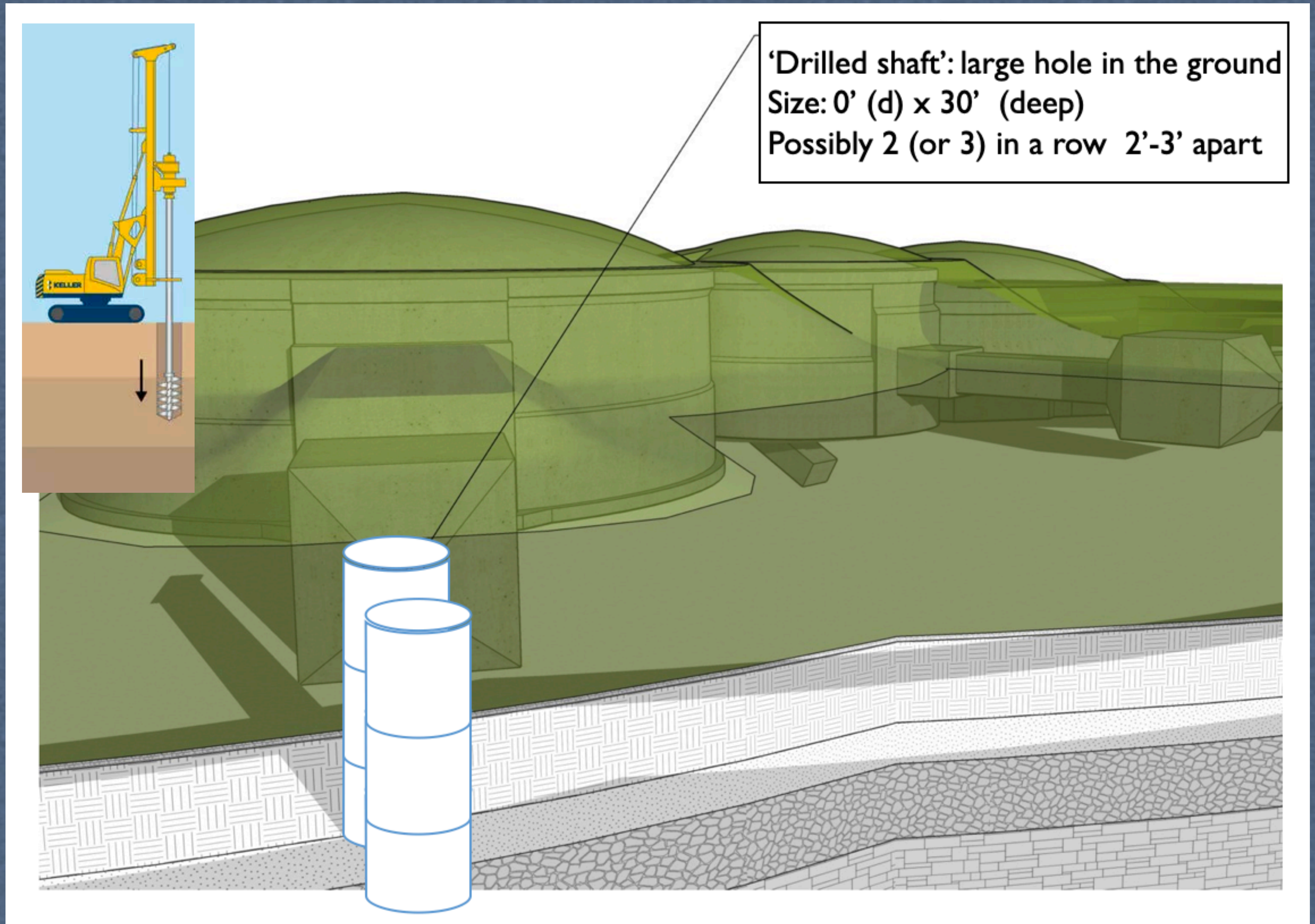
★ Approved by JLab PAC-46 in July 2018 with maximum scientific rate (A) and waiting for scheduling

★ Expected to run in parallel to the Moeller experiment (2026-2029)

★ Presented, discussed, and included in SNOWMASS-21 report (RF6-RF0)

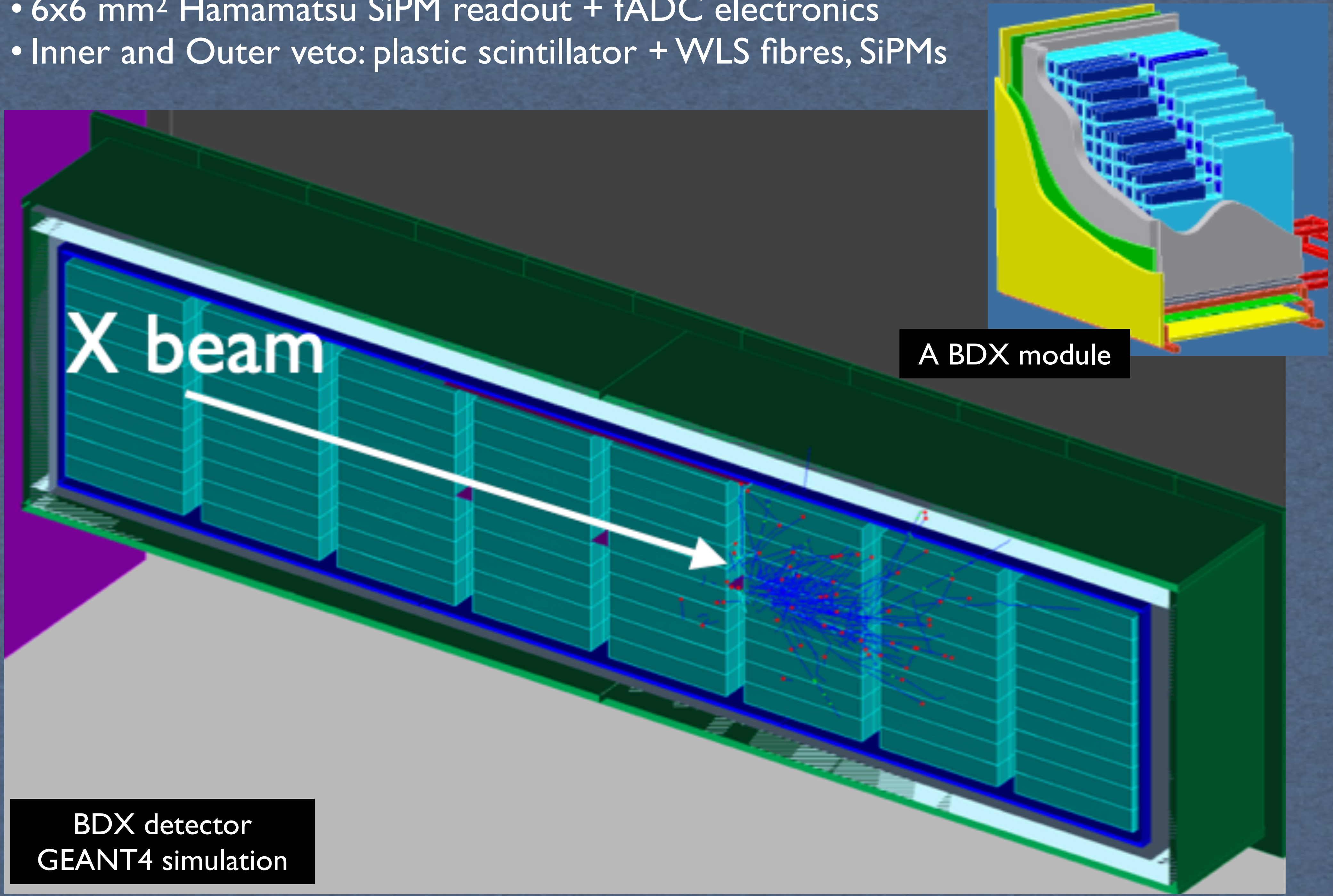
★ BDX would take advantage of the future 11 GeV positron beam and 20+ GeV upgrade

★ BDX Collaboration: more than 100 researchers from 18 institutions (US, Italy, Germany, UK, Korea) signed the BDX proposal



The BDX detector

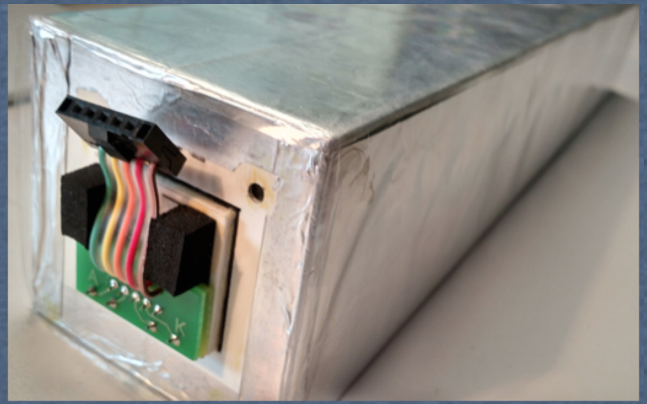
- Modular design
- 8 modules each having 10x10 crystals
- 800 CsI(Tl) crystals
- 6x6 mm^2 Hamamatsu SiPM readout + fADC electronics
- Inner and Outer veto: plastic scintillator + WLS fibres, SiPMs

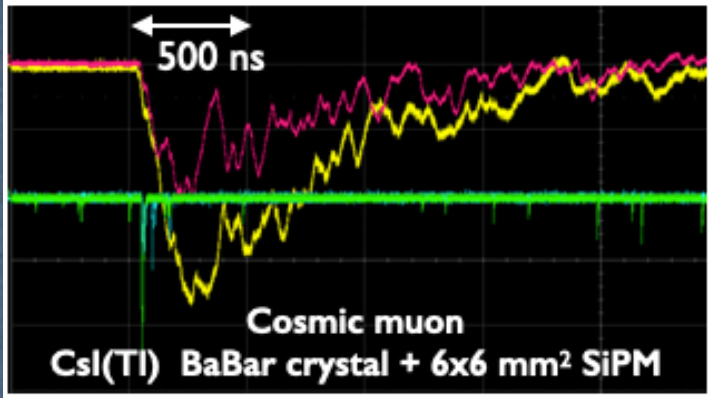


A BDX module

BDX detector
GEANT4 simulation

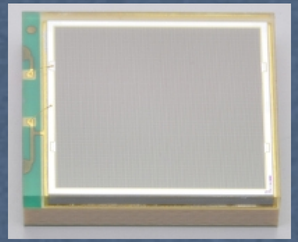
E.M. Calorimeter





Crystals available from BABAR em calorimeter

- Size: (5x5)cm^2 front face, (6x6)cm^2 back face, 30cm length
- 820 crystals available from end cap
- Decay time: fast 900ns, slow 4000ns
- LY= 50k γ/MeV



SiPM readout

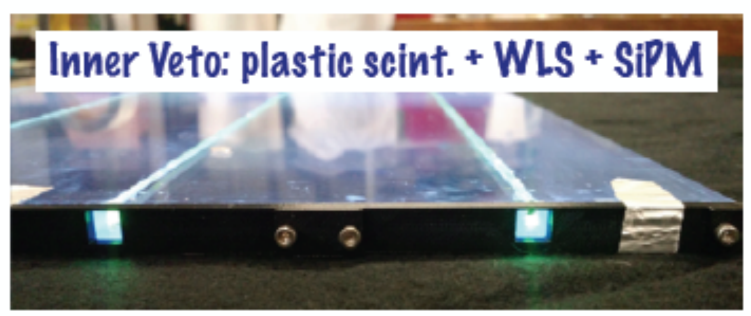
- Size: 6x6 mm^2, 25μm, 57.6k cells, trenched, pde=25%
- SPE capability
- CsI(Tl): 40 pe/MeV
- Time resolution: ~6ns (MIPs)

M.Bondi et al. NIM.A, 867:148–153, 2017

Veto

Inner/Outer veto:

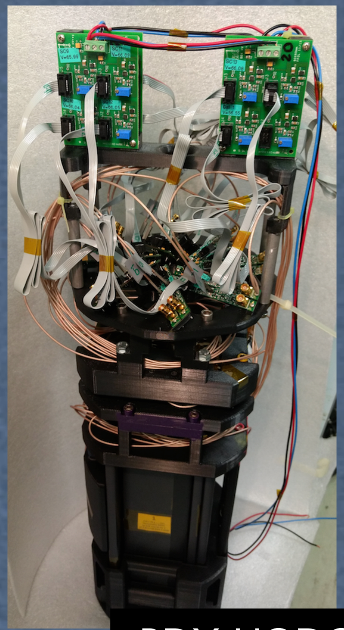
- 1cm (clear) plastic scintillator + WLS fibers
- 3x3 SiPM readout
- LY= 15-50 pe/MIP



Background

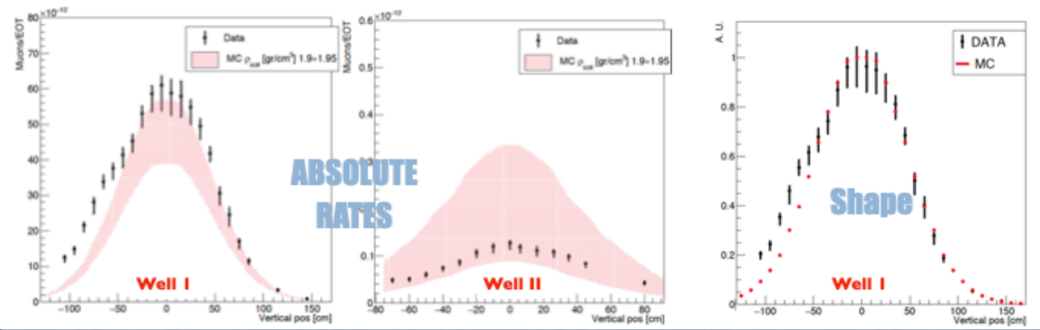
- Beam unrelated: cosmic rays (BDX-PROTO)
- Beam related: n and muons (BDX-HODO)
- High stat simulations (FLUKA and GEANT4) validated with measurements

BD muons bg measurement



BDX-HODO

M.Battaglieri et al. NIM.A, 925:116–122, 2019



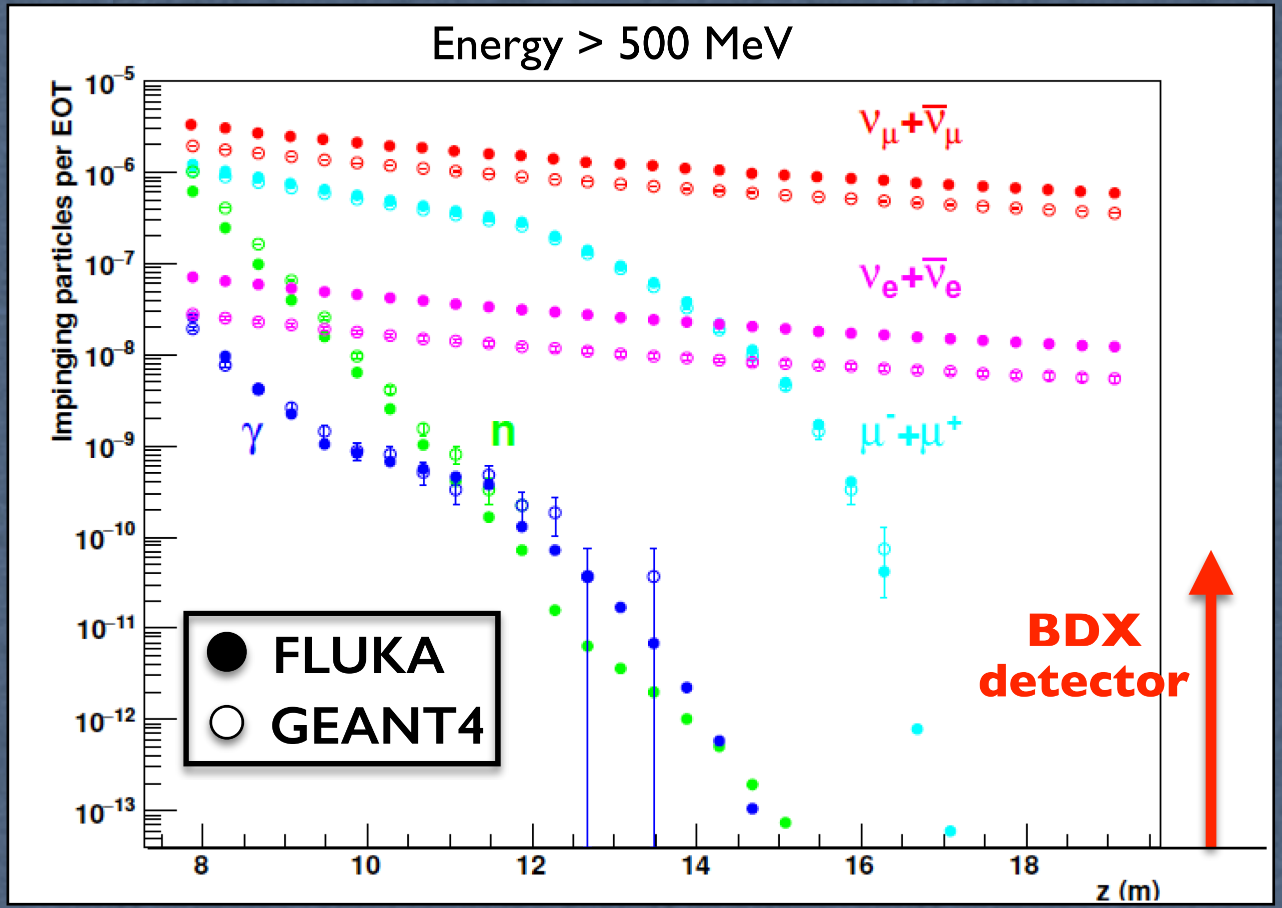
Cosmic muons

- Rate (E_{Thr}~300MeV) < 2 counts
- Conservatively extrapolated from the (lower E) non-0 counts region
- Measured rate scaled to the JLab set-up (x800 crystals)

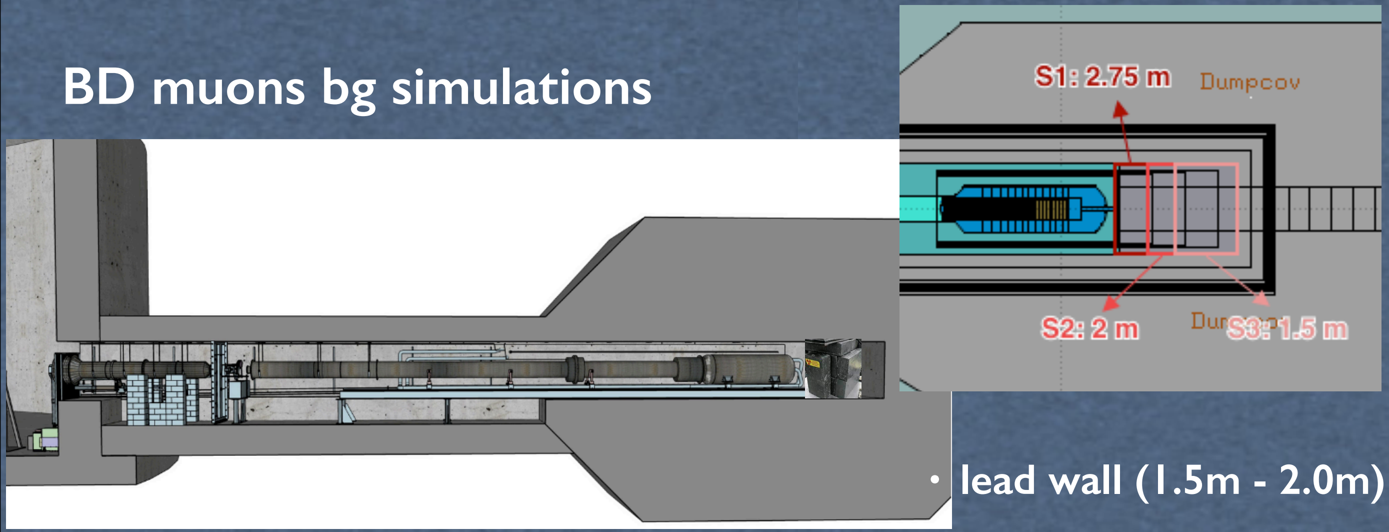
BDX prototype

★ No μ, n and γ with E>100 MeV are found at the detector location

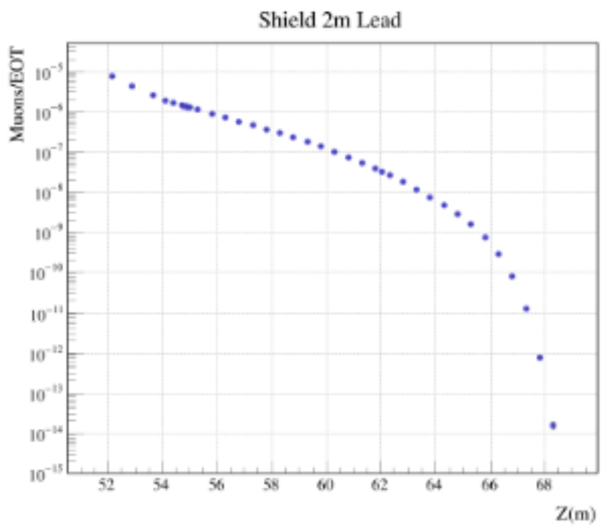
★ Validated by an in-situ measurement using BDX-HODO



BD muons bg simulations



- lead wall (1.5m - 2.0m)



★ **Neutrino**

- $\pi \rightarrow \mu\, \nu_\mu \quad \mu \rightarrow e\, \nu_\mu\, \nu_e$
- Mainly low energy (<60 MeV) from decay at rest
- Some ν produced in HadShower and boosted to BDX detector

Non-negligible contribution by ν CC interaction

$\nu + N \rightarrow X + e^-$

$\nu + e^-$ suppressed

Neutrino *irreducible* bg represents the ultimate limitation for BDX (~10 counts in BDX life time)

BDX sensitivity

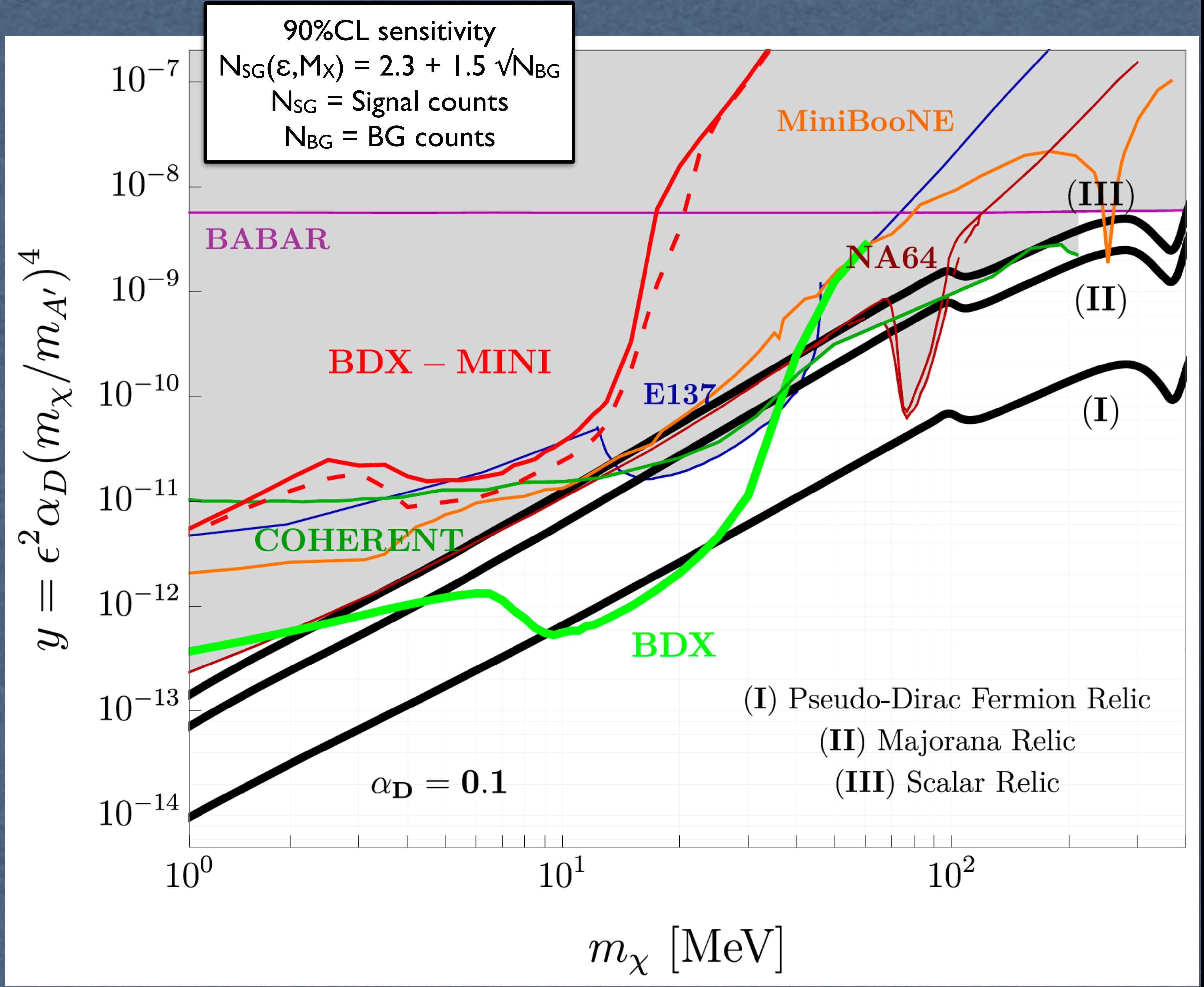
Beam time request (parasitic to Hall-A ops)

- 10^{22} EOT (65 uA for 285 days)
- BDX can run parasitically with any Hall-A E_{beam}>10 GeV experiments (e.g. Moeller)

Beam-related background	
Energy threshold	N_ν (285 days)
300 MeV	~10 counts

Cosmic background	
Energy threshold	$\sqrt{Bg}$ (285 days)
300 MeV	<2 counts

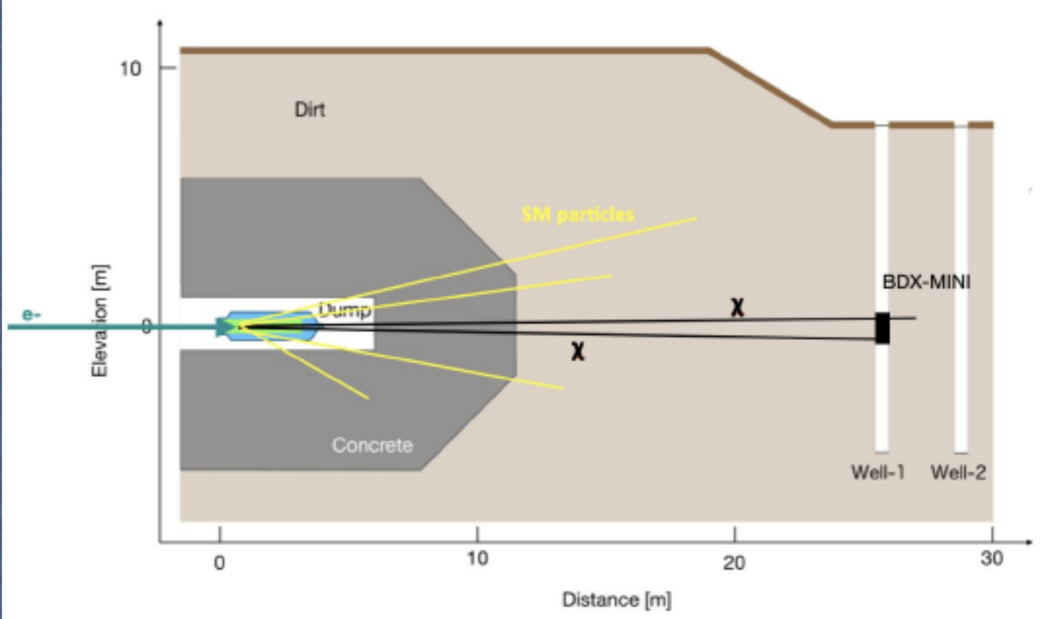
- Calculation includes resonant positron annihilation
- Sensitivity to inelastic LDM is not shown



The sensitivity of BDX exceeds more than 10x the existing limits on LDM production
Such tight exclusions will set limits on LDM mechanisms or render an important null result

BDX-MINI @JLab

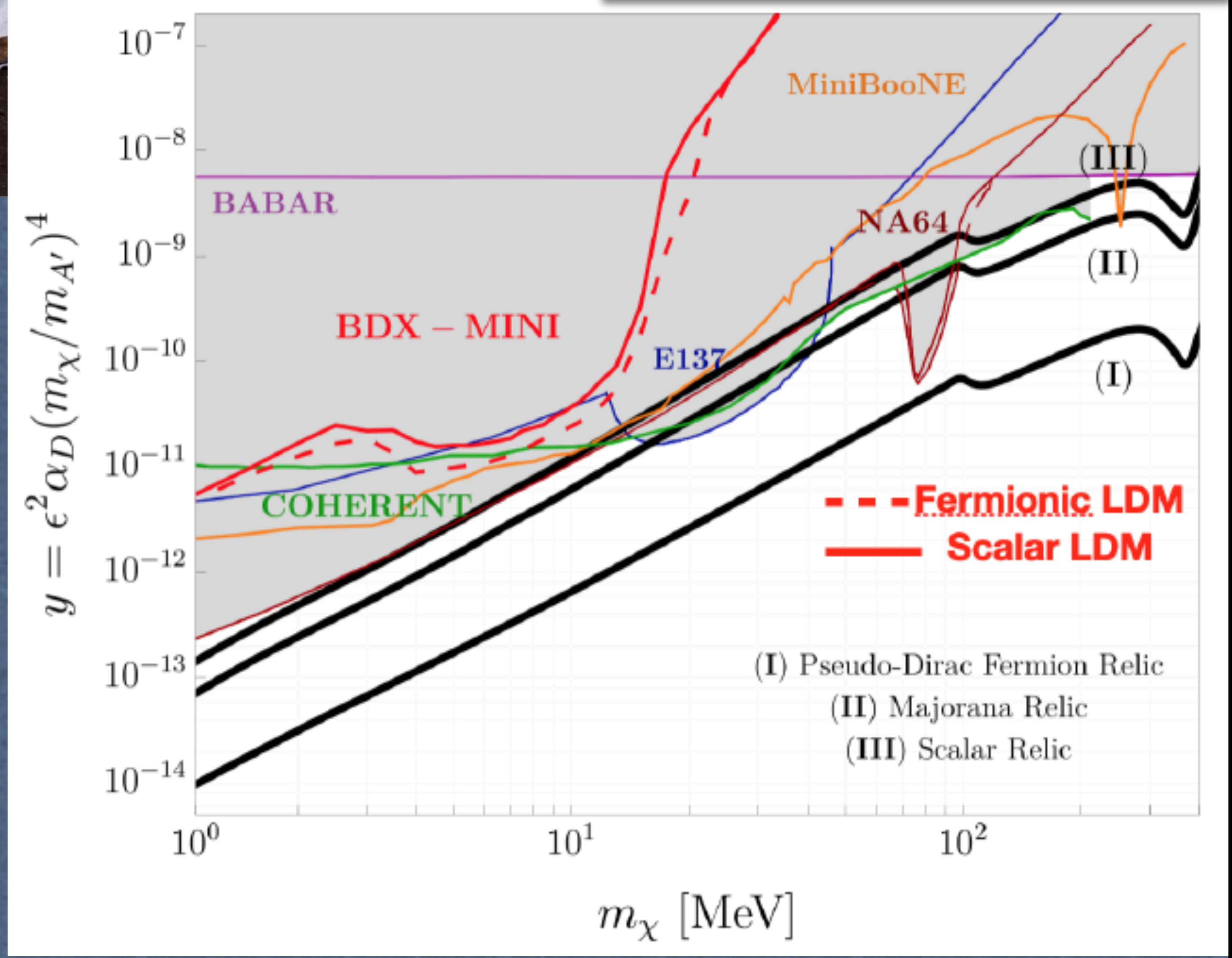
BDX-MINI: pilot experiment to prove the validity and feasibility of the BDX experiment



- Installed in March 2019
- Run form Dec 2019 to Aug 2020
- Collected 4e21 EOT (40% BDX!) in ~4 months (+ cosmics)
- Good detector performance with high duty factor

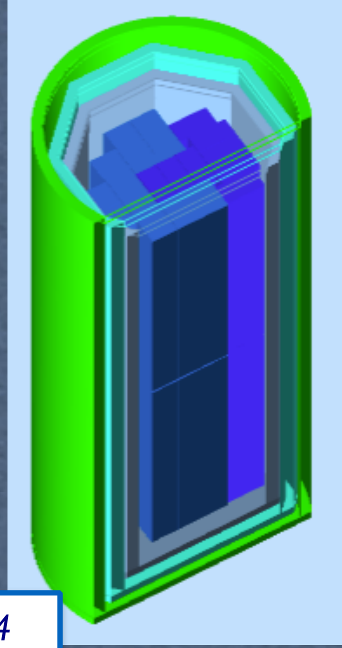
- Two wells dug for bg muon tests
- E_{beam}=2.2 GeV, no muons
- Limited reach but first physics result!

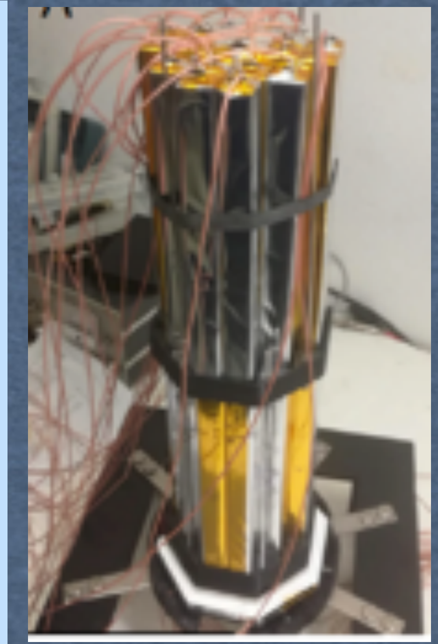
M.Battaglieri et al. _Phys. Rev. D 106, 072011

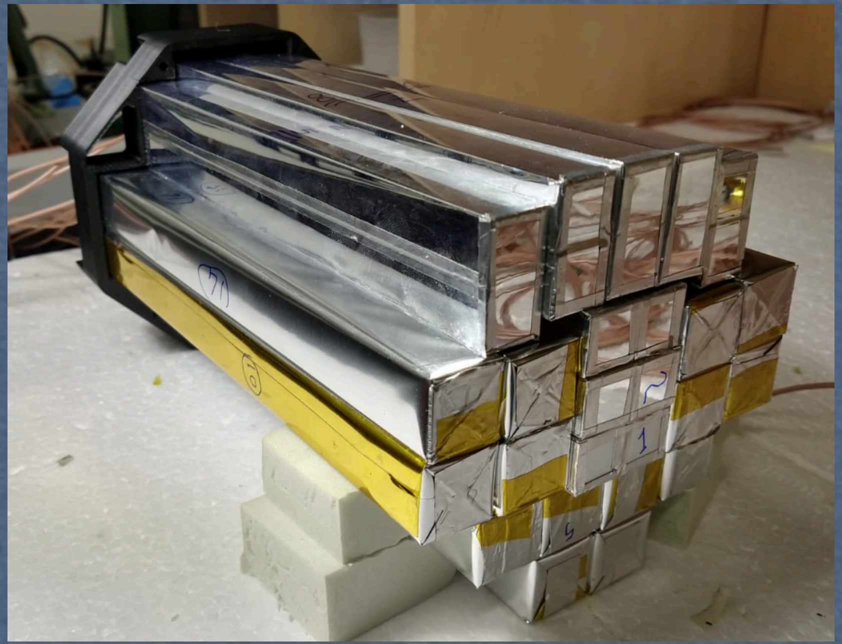


- 44 PbWO4 PANDA/FT-Cal crystals (~1% BDX active volume)
- 6x6 mm2 SiPM readout
- 2 active plastic scintillator vetos: cylindrical and octagonal (8 sipm each) + 2x lids + Passive W shielding

M.Battaglieri et al. EPJC (2021) 81: 164







- Data-taking completed, analysis completed
- Results provide exclusion limits similar to the best existing experimnts (E137, NA64, BaBar, …)

LDM searches status

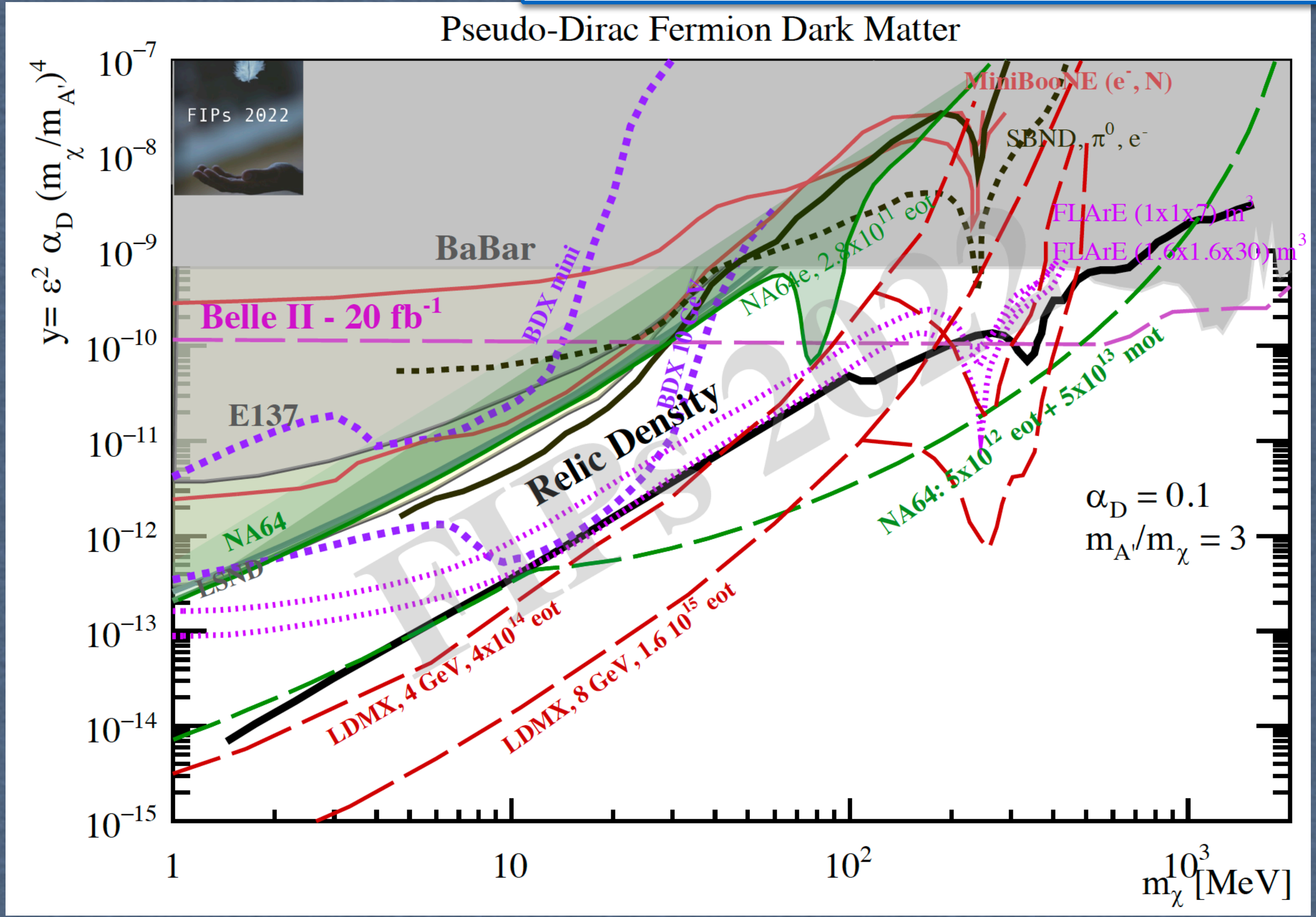
L.G. Krnjaic et al. Snowmass 2021 Rare & Precision Frontier (RF6): 7 2022
C. Antel et al. Feebly interacting particles: Fips 2022 workshop report, 2023

- CERN-FIPs workshop report, (SNOWMASS22) shows that BDX offers great potential for discovering LDM (or disproving it, in a large area of parameter space)

- Several experiments planned/proposed (LHC, SLAC, Mainz, FNAL, KEK, PSI, LPARC) with a variety of beams (proton, leptons, photons), energies (from 150 MeV to 14 TeV) and experimental techniques (visible, invisible, recoil, ..) with a timeline that reaches ~2042

- BDX has the unique opportunity to be one of the first (significant) experiments to set limits and verify/falsify viable theoretical scenarios (relic LDM, inelastic DM, …)

- Over the last 5 years, NA64 has pushed the exclusion limit slightly down (it is scheduled to run more!)



Conclusions

- ✳ The existence of Dark Matter is a compelling reason to investigate new forces and matter over a broad range of mass
- ✳ Accelerator-based (Light)DM search provides a unique feature of distinguishing DM signal from any other cosmic anomalies or effects
- ✳ An extensive program to explore the Dark Sector making use of the high-intensity ~11GeV electron beam available at Jefferson Lab is in full swing
- ✳ Discovery or decisive tests of the simplest scenarios will possible in the next 5-10 years!
- ✳ BDX is an optimised beam-dump experiment ready to run at Jefferson lab
- ✳ The BDX concept has been tested with several prototypes and dedicated measurement campaigns
- ✳ The BDX-MINI successful pilot run has demonstrated the potential of the BDX (technique and physics reach)
- ✳ Collecting 10^{22} EOT in 285 days of parasitic running (in parallel to Moeller?) at 11 GeV, the BDX experiment would be >10 times more sensitive than previous experiments