Experimental Perspectives on Electron Beam Dumps

DND2020 Workshop

Luca Doria (doria@uni-mainz.de)

PRISMA Cluster of Excellence and Institut für Kernphysik
Johannes-Gutenberg Universität Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence
PRISMA+
Precision Physics, Fundamental Interactions and Structure of Matter

Introduction

- (Light) Dark Matter

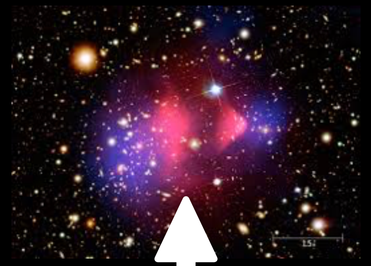
- (Electron) Beam dump experimental concept

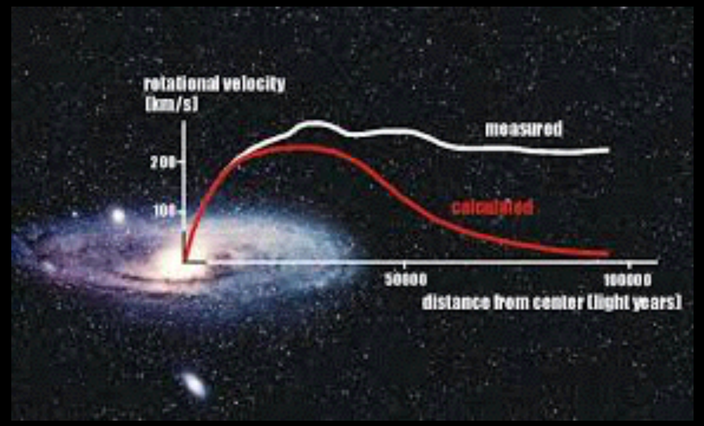
- Running and proposed experiments

- An opportunity for ARIEL ?

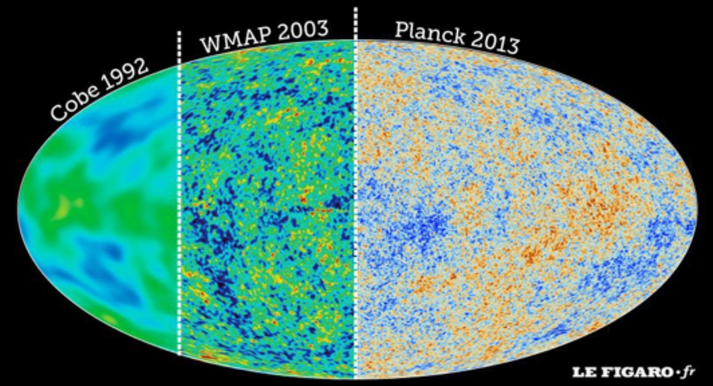
LIGHT DARK MATTER

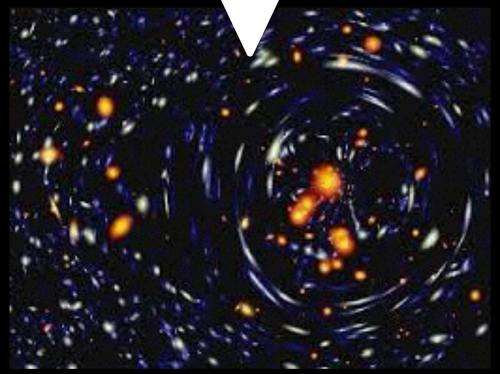
Evidence for Dark Matter





Dark Matter





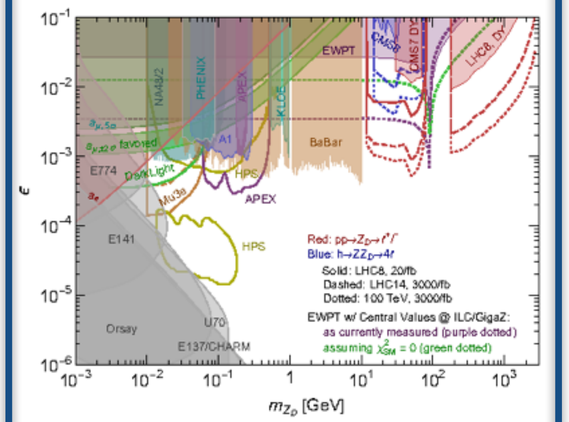
Dark Matter Mass range

eV keV MeV GeV TeV DM Mass

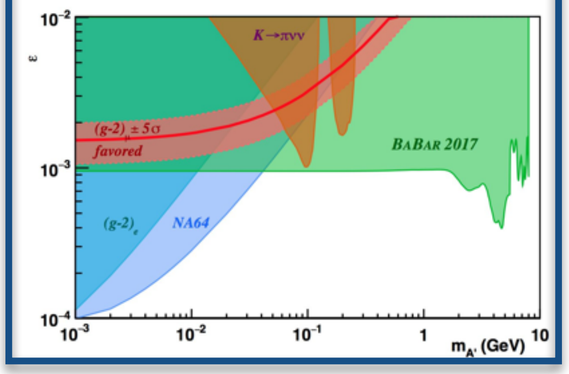
Lee-Weinberg, m>10 GeV

LDM

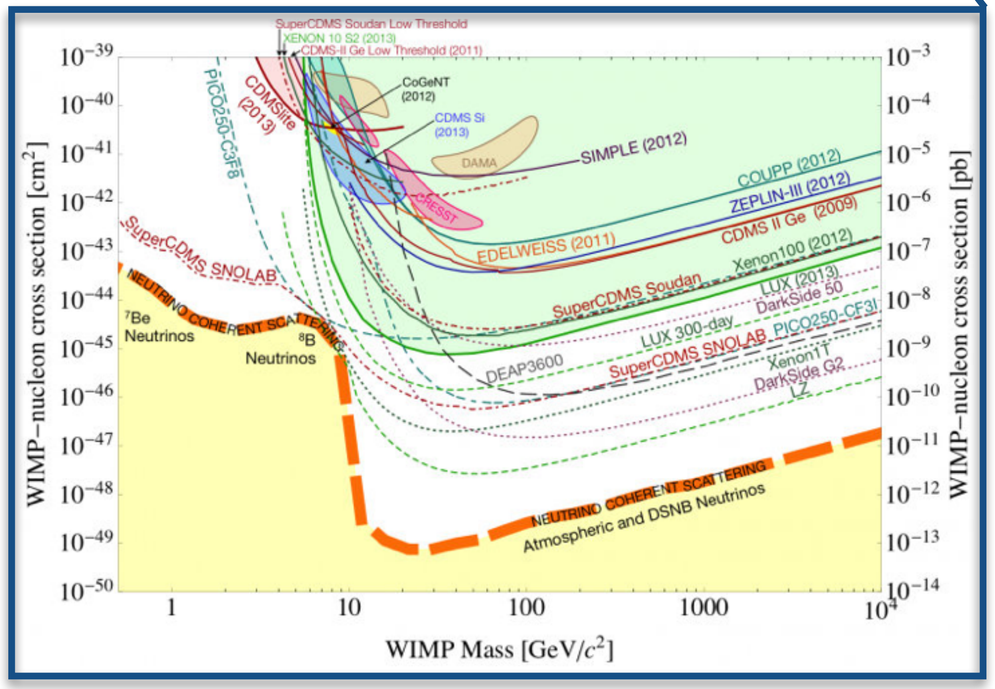
Visible Decays



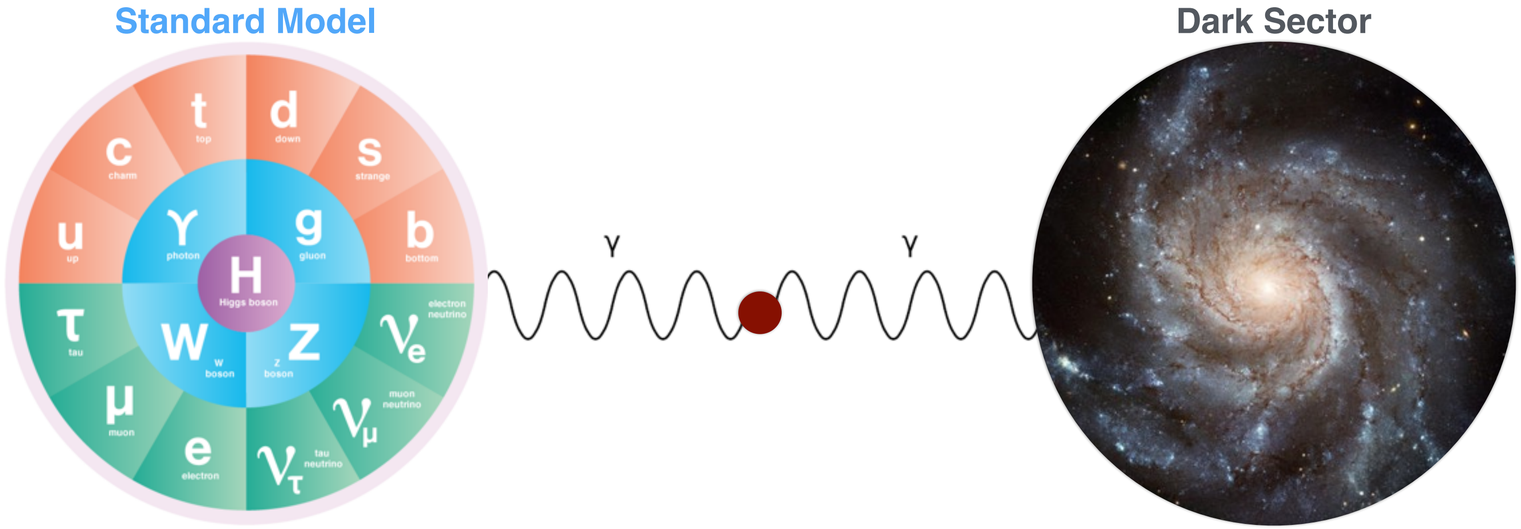
Invisible Decays



WIMPS



The Dark Sector



"Portals"

Vector $\frac{1}{2}\epsilon_Y F_{\mu\nu}F'^{\mu\nu}$

Higgs $\epsilon_h |h|^2 |\phi|^2$ Precision Higgs Physics

Neutrino $\epsilon_\nu h L \psi$ New Neutrino States

Axion $\frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$

Minimal Dark Photon Model

$$\mathcal{L} \sim \bar{\chi}(i\not{D} - m_\chi)\chi + \frac{1}{2}\epsilon_Y F'_{\mu\nu}B_{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu$$

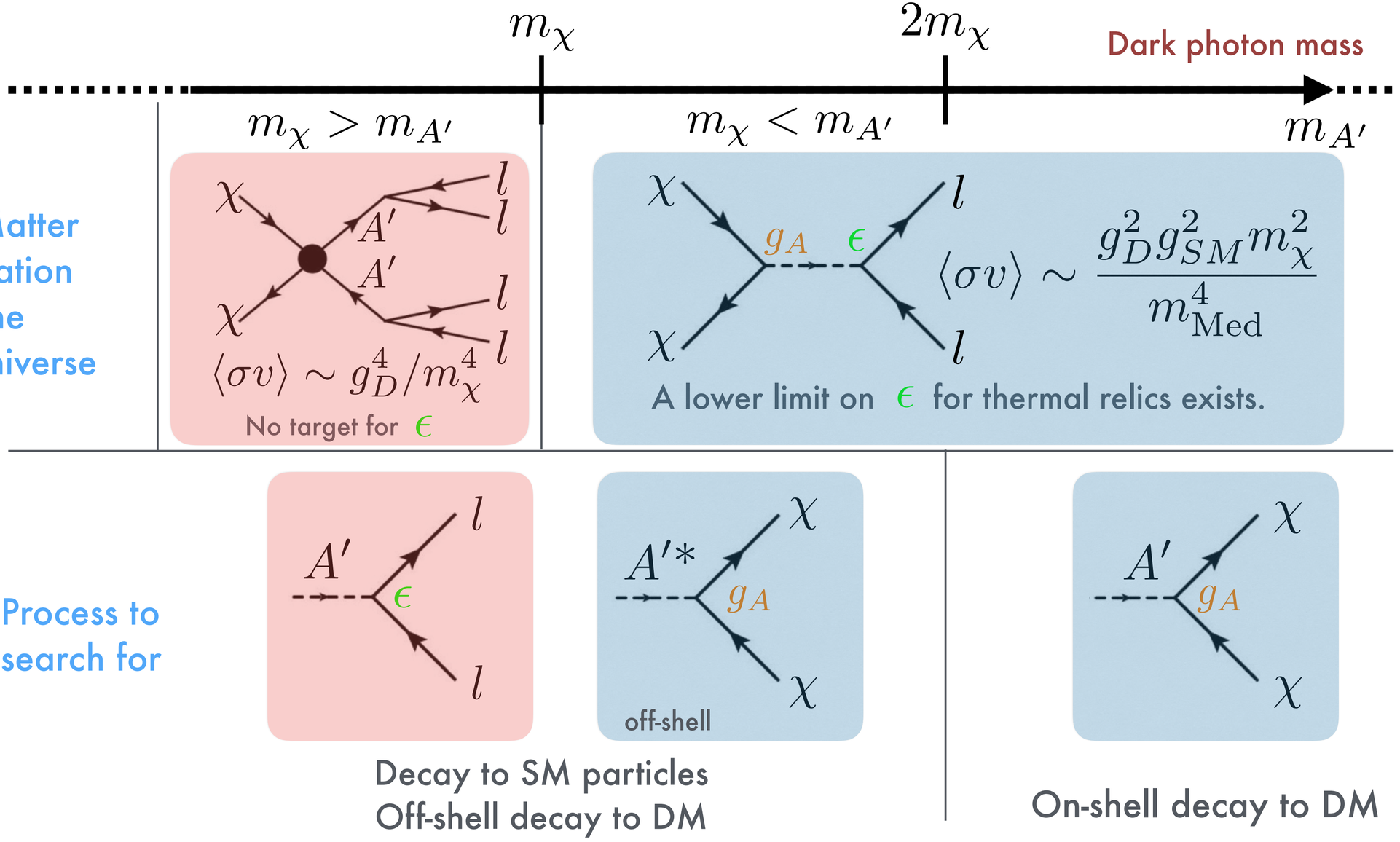
$D_\mu = \partial_\mu + i g_D A'_\mu$ New U(1) massive gauge boson

After EW Symmetry Breaking:

$\epsilon = \epsilon_Y \cos\theta_W \ll 1$ $\quad \frac{1}{2}\epsilon F'_{\mu\nu}F_{\mu\nu}$

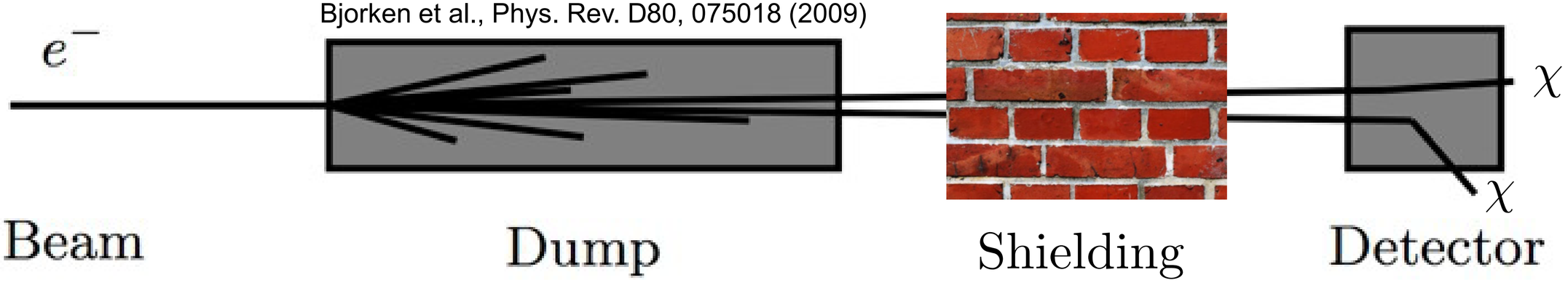
4 parameters: $m_{A'}$ m_χ $\alpha_D = \frac{g_D^2}{4\pi}$ ϵ_Y

Search Strategy vs Mass Hierarchy

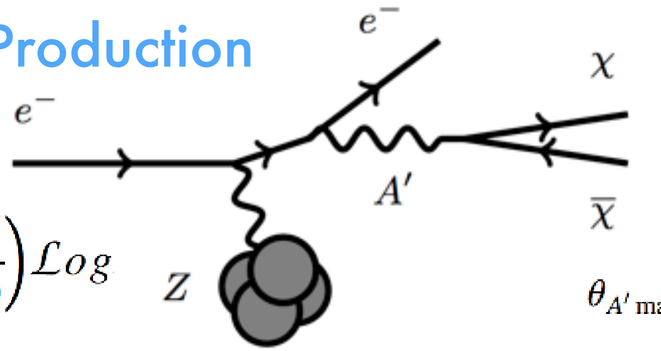


Electron Beam Dump Experiments

Bjorken et al., Phys. Rev. D80, 075018 (2009)



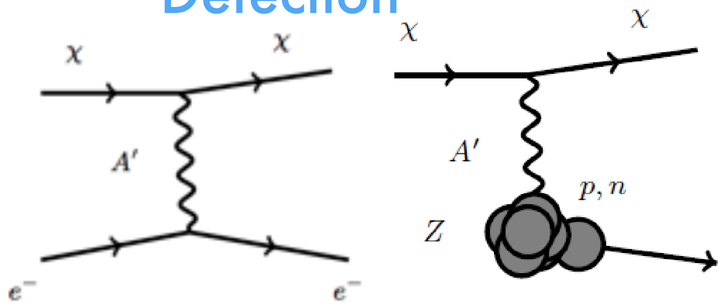
Production



$$\frac{d\sigma}{dx} \approx \frac{8Z^2\alpha^3\epsilon^2 x}{m_{A'}^2}\left(1+\frac{x^2}{3(1-x)}\right)\mathcal{L}og$$

$$\theta_{A'\,\max} \sim \max\left(\frac{\sqrt{m_{A'}m_e}}{E_0}, \frac{m_{A'}^{3/2}}{E_0^{3/2}}\right)$$

Detection



Production Yield

$$Y_{Prod} \sim \epsilon^2/m_A^2$$

Total Yield

$$Y_{TOT} \sim \epsilon^4\alpha_D/m_A^4$$

Detection Yield

$$Y_{Det} \sim \epsilon^2\alpha_D/m_A^2$$

Electron Beam Dump Experiments

- Availability of high-current, CW accelerators

- Parasitic operation

- Complementarity wrt proton beam dumps (meson decays)

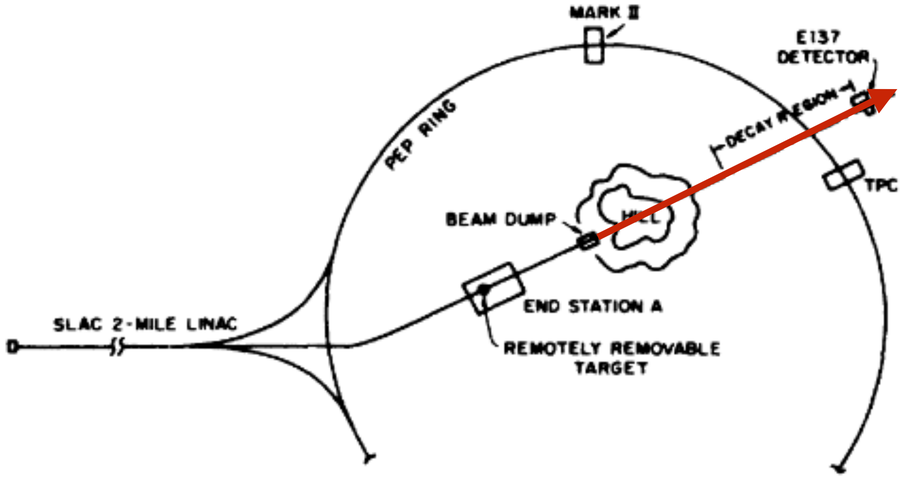
- Lower neutrino background

- Theoretically simpler signal (similar to QED processes)

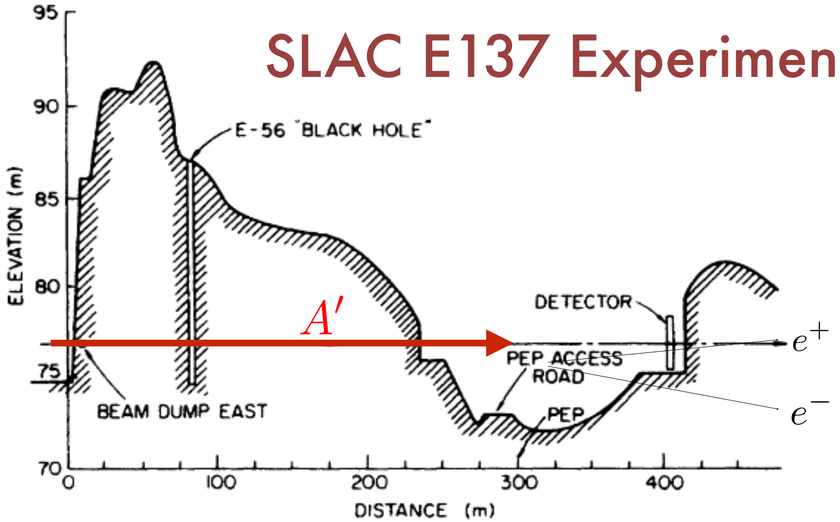
- Double test: DM production (in the BD) AND interaction (in the detector)

EXPERIMENTS

Prehistory of electron BD experiments



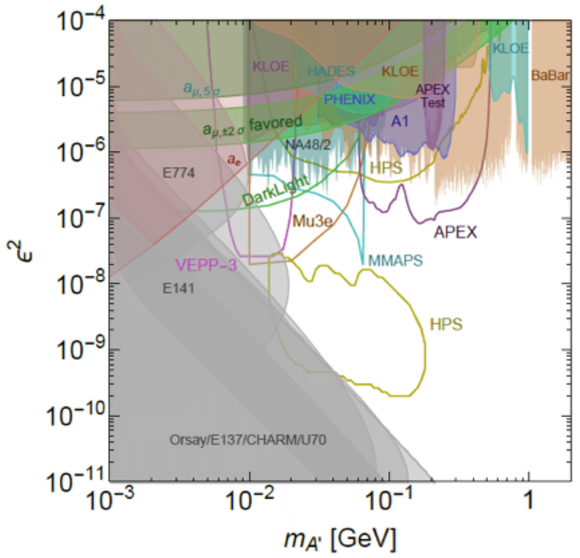
SLAC E137 Experiment



J.D. Bjorken et al. Pays. Rev. D, 38:3375-3386 (1988)

- Beam: 20GeV electrons on Al target
- ~200m decay length (mostly earth shielding)
- Detector: scintillators + wire chambers

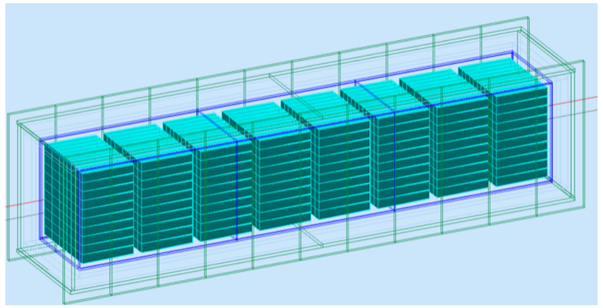
- Other experiments (originally for axion searches):
  - SLAC E141: 9 GeV electrons on W
    E. M. Riordan et al., Phys. Rev. Lett. 59, 755 (1987).
  - Fermilab E774: 275 GeV electrons on W
    A. Bross et al., Phys. Rev. Lett. 67, 2942 (1991).



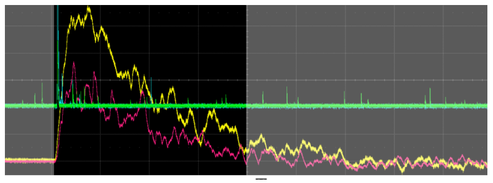
Data reinterpreted theoretically by: Bjorken et al. Phys.Rev.D80:075018 (2009)

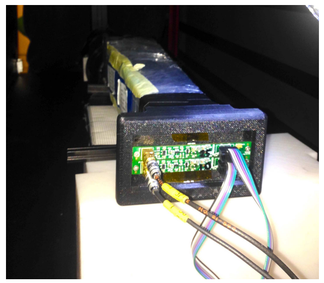
BDX at JLab

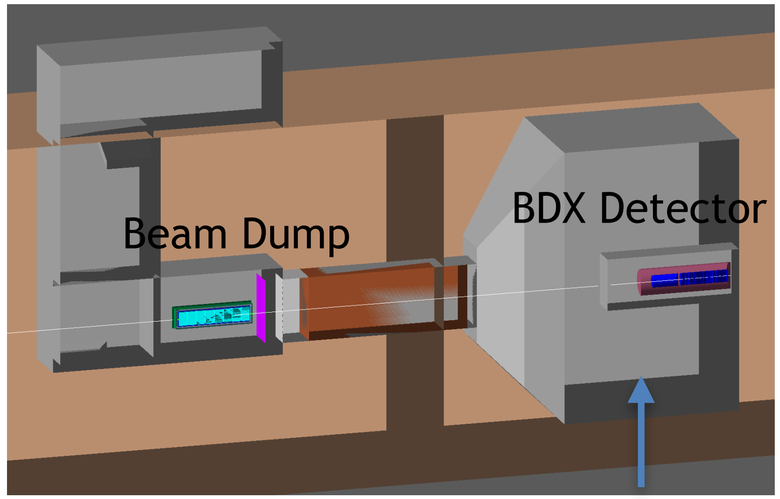
Proposed Detector:
820 CsI(Tl) BaBar EM Cal
Crystals: 32x5x5 cm
8 Modules, 10x10 crystals
SiPM readout
3m length, 0.5x0.5m CS



Detector Prototyping in progress.
Beam/Cosmics tests at INFN-Catania
Background tests at JLAB







New Infrastructure

Beam:
E = 11GeV
I =100uA
10^{22} EOT/yr

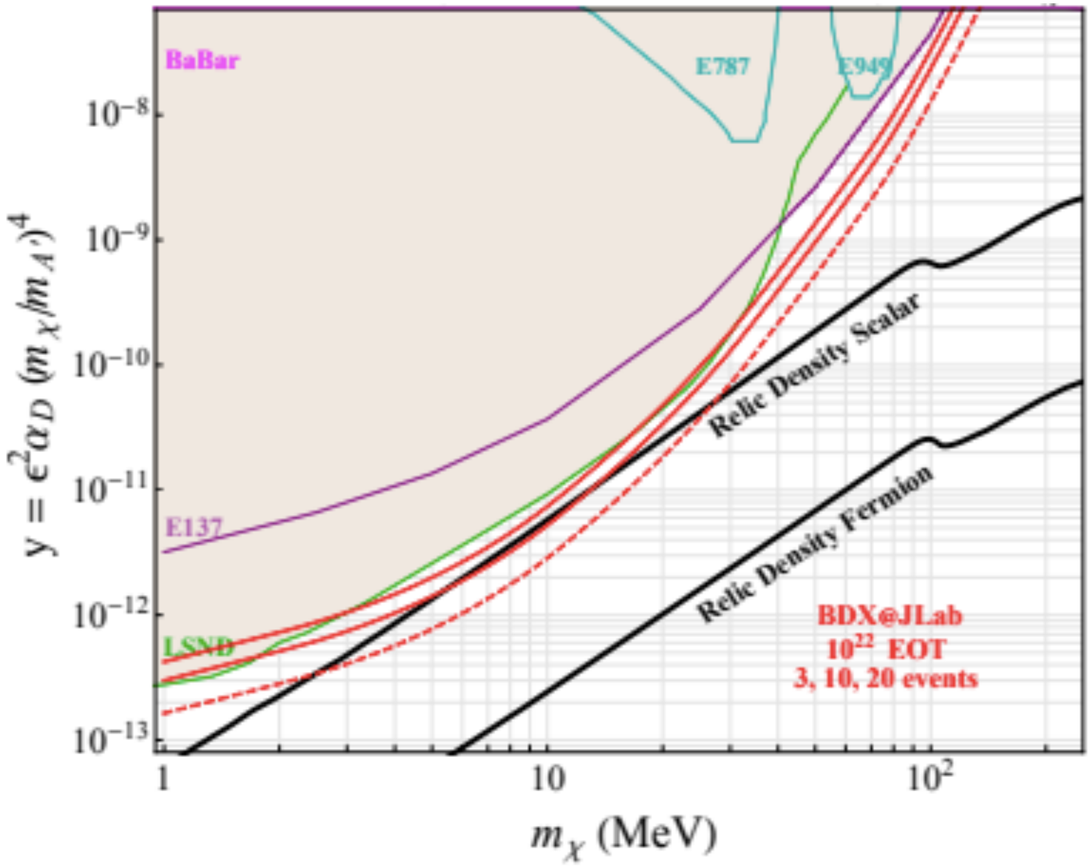
Dark matter search in a Beam-Dump eXperiment (BDX) at Jefferson Lab

The BDX Collaboration

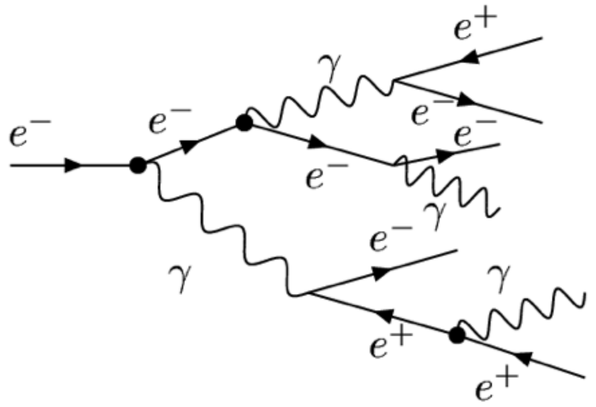
arXiv:1607.01390

BDX at JLab

90% Upper limits

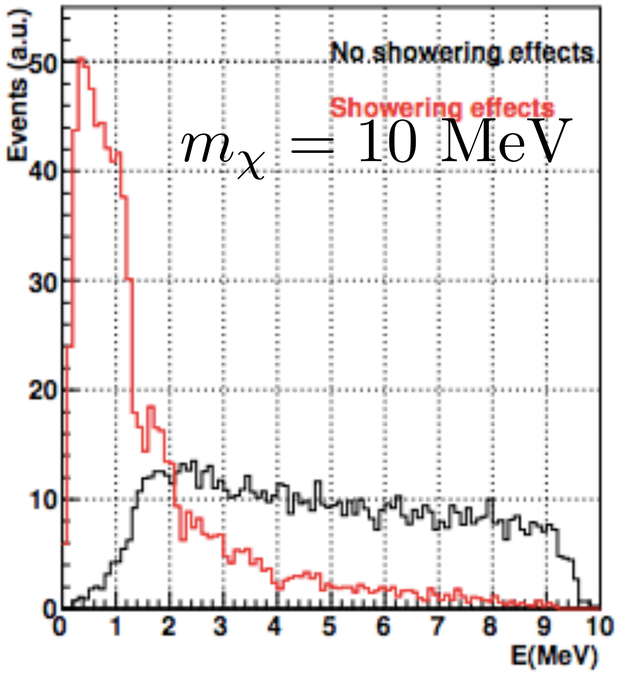


arXiv:1607.01390

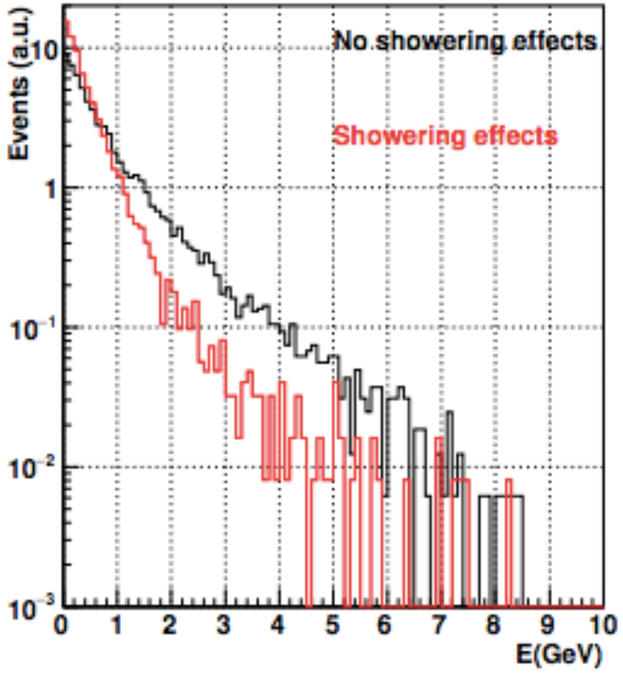


Simulation of showering effects in the beam dump mandatory for assessing the experimental reach.

DM energy

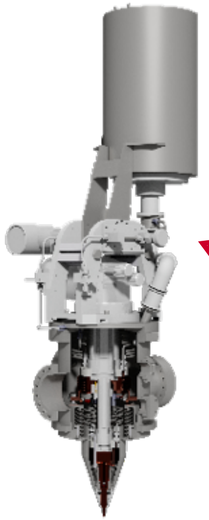


Recoil Electron energy

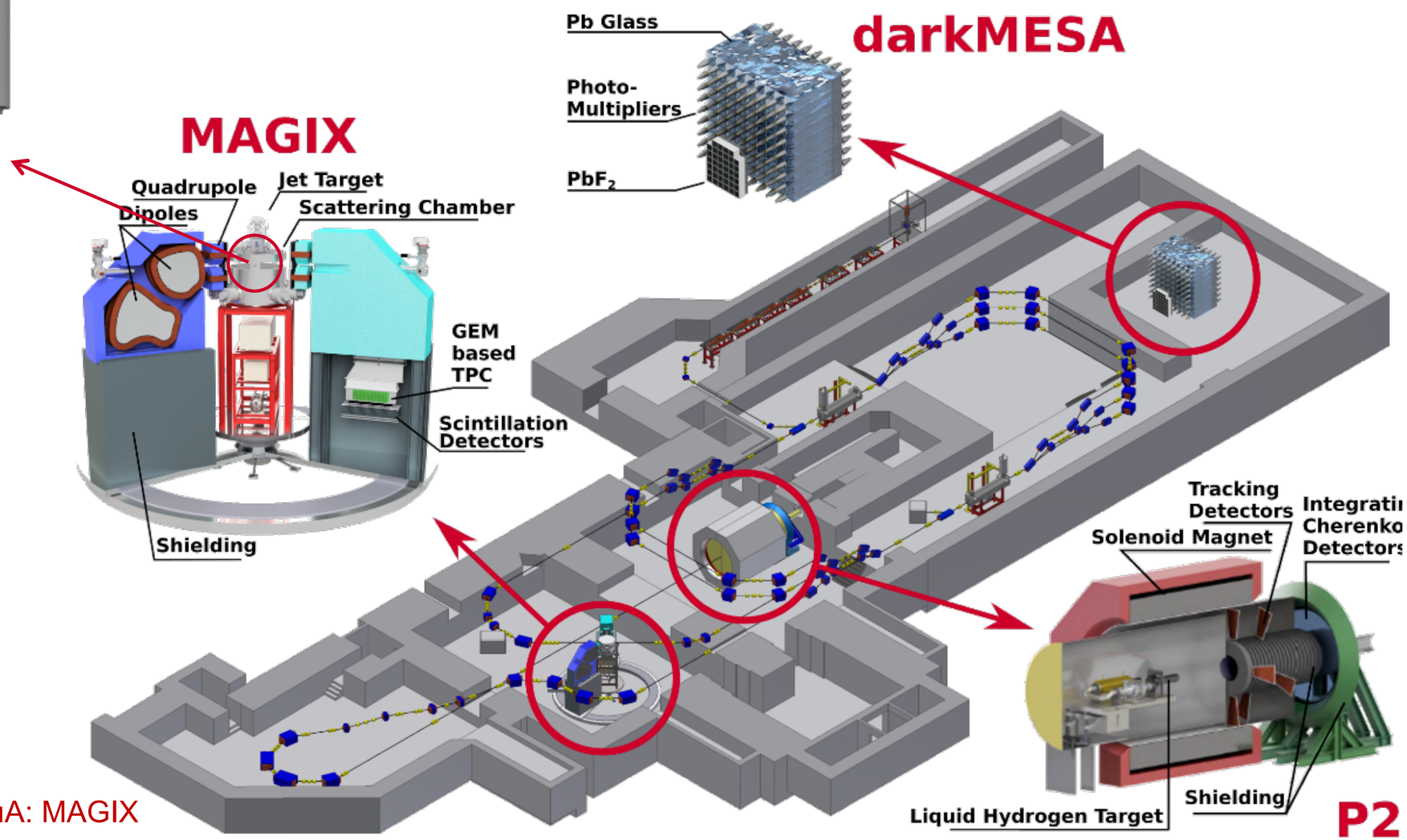


https://www.jlab.org/accel/ops/ops_liaison/BDX/BDX.html

MESA



MESA accelerator
1.3 GHz c.w. beam
Normal conducting injector
2 superconducting cavities
Several recirculations



Two main operation modes

1. ERL mode, polarized, 30–105 MeV, 1000 µA: MAGIX
High beam currents, thin gas-jet targets

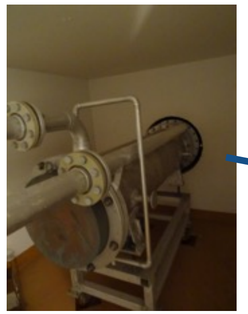
2. EB mode, (un-)polarized, 155 MeV, 150 µA: P2
High stability, thick targets, long runs, high luminosities

(2.) MX-EB mode: (un-)polarized, 30–105 MeV, 10 µA: MAGIX
Early MAGIX measurements, short runs

DarkMESA

Beam Dump

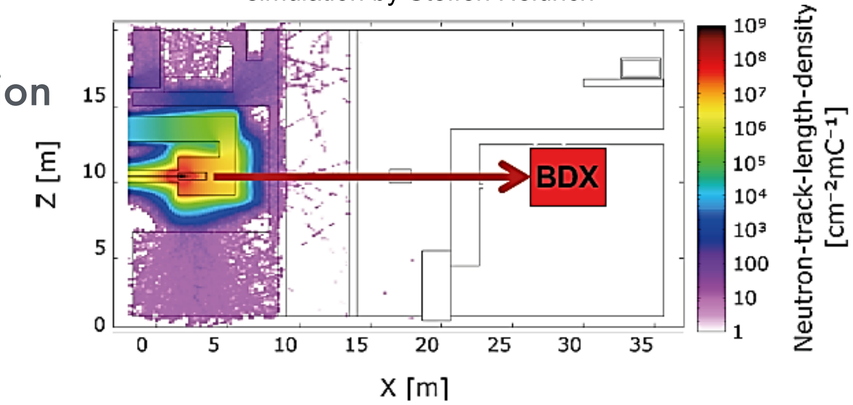
- 20 X_0 Beam Dump
- Material: Aluminum (+ Water)
- Addition of a W plate?
- Energy on Dump: ~135 MeV
- 10^4 h of operation; 10^{22} EOT



Experimental Area

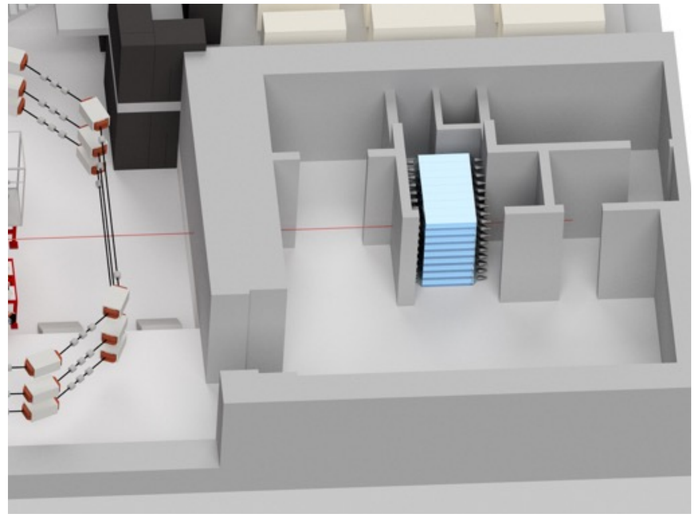
- 70 X_0 (~8m) barite concrete
- ~ no neutrons at detector position
- no beam dump backgrounds
- No neutrinos

simulation by Steffen Heidrich



Detector Concept:

- 81 lead glass blocks
- 30x30x150cm each
- 5'' PMTs or SiPM readout
- Other crystals under study

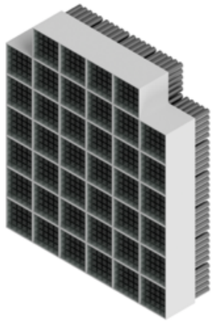


Background Rejection

- Beam on/off
- Comics Veto
- Segmentation

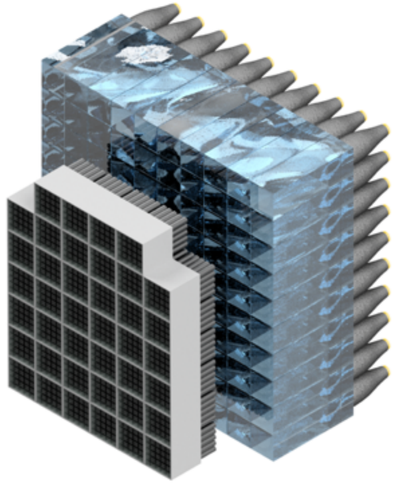
DarkMESA

Phase 1



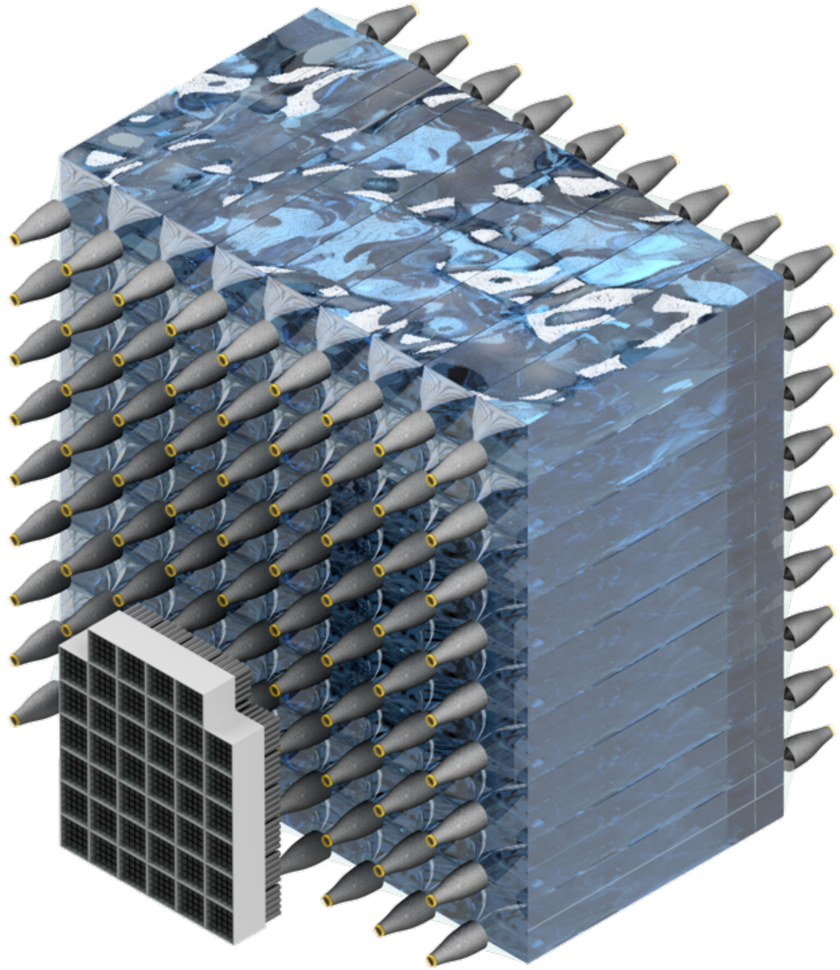
1000 (available!) PbF2 crystals
Volume: 1x1x0.13 m^3
5x5 crystal sub-modules
1200 kg mass

Phase 2



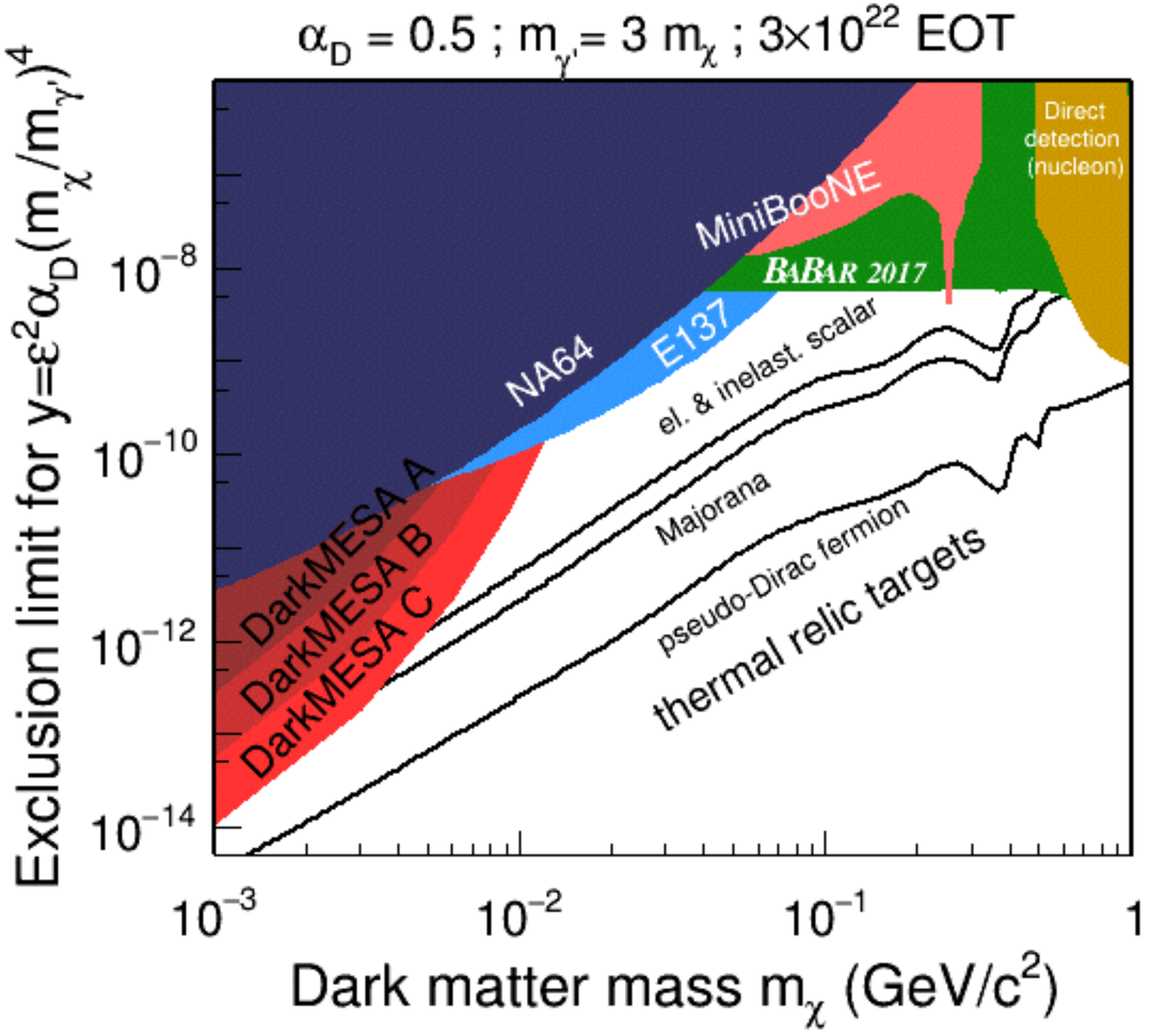
Addition of Pb-Glass blocks
Volume: 1m^3
4100 kg mass

Phase 3



Reach maximum volume: O(10m^3)

DarkMESA

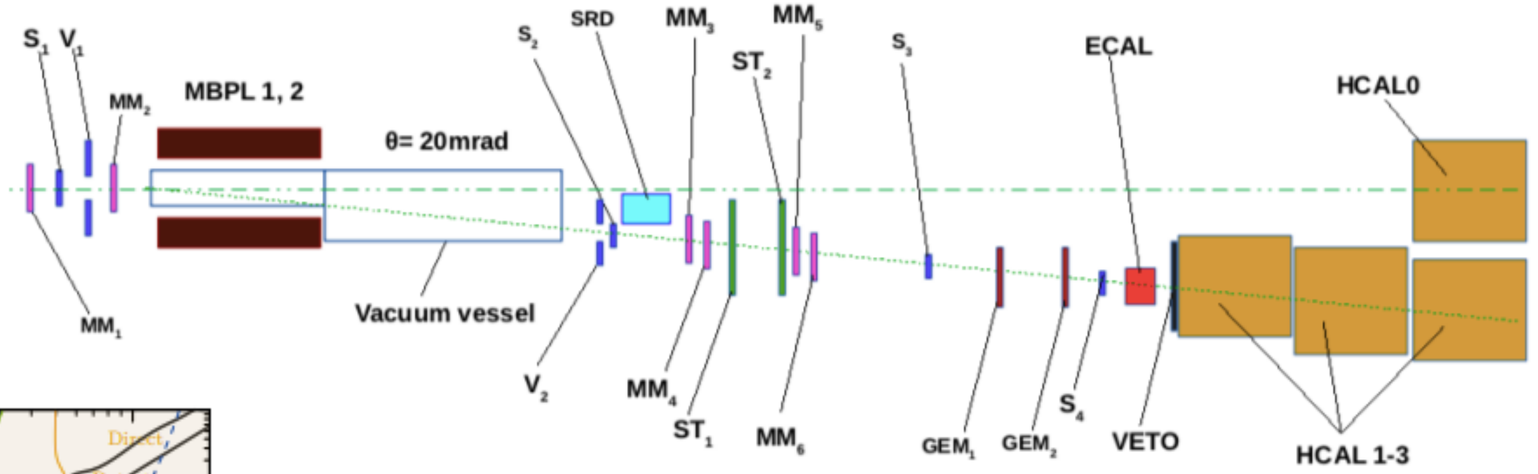


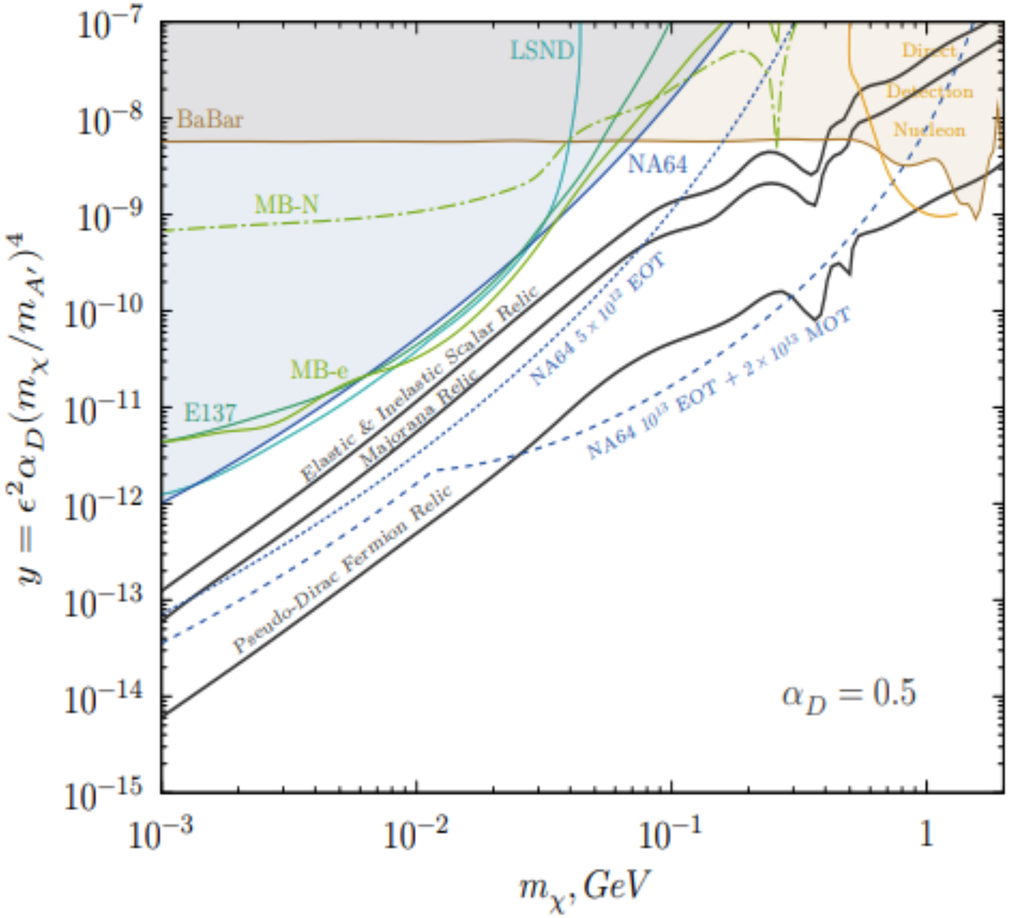
Simulation

- GEANT4
  - Experimental Halls
  - Beam Dump
  - Detector
  - DM/e DM/p interaction

- MadGraph-4
  - Dark Photon Production
  - Input to GEANT4

NA64 at CERN

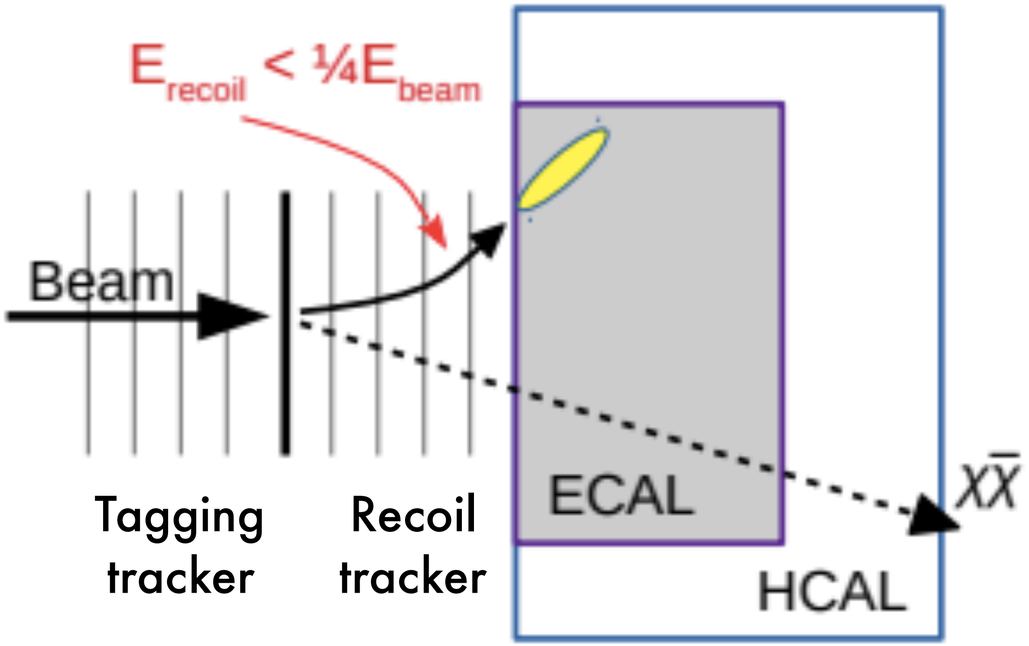




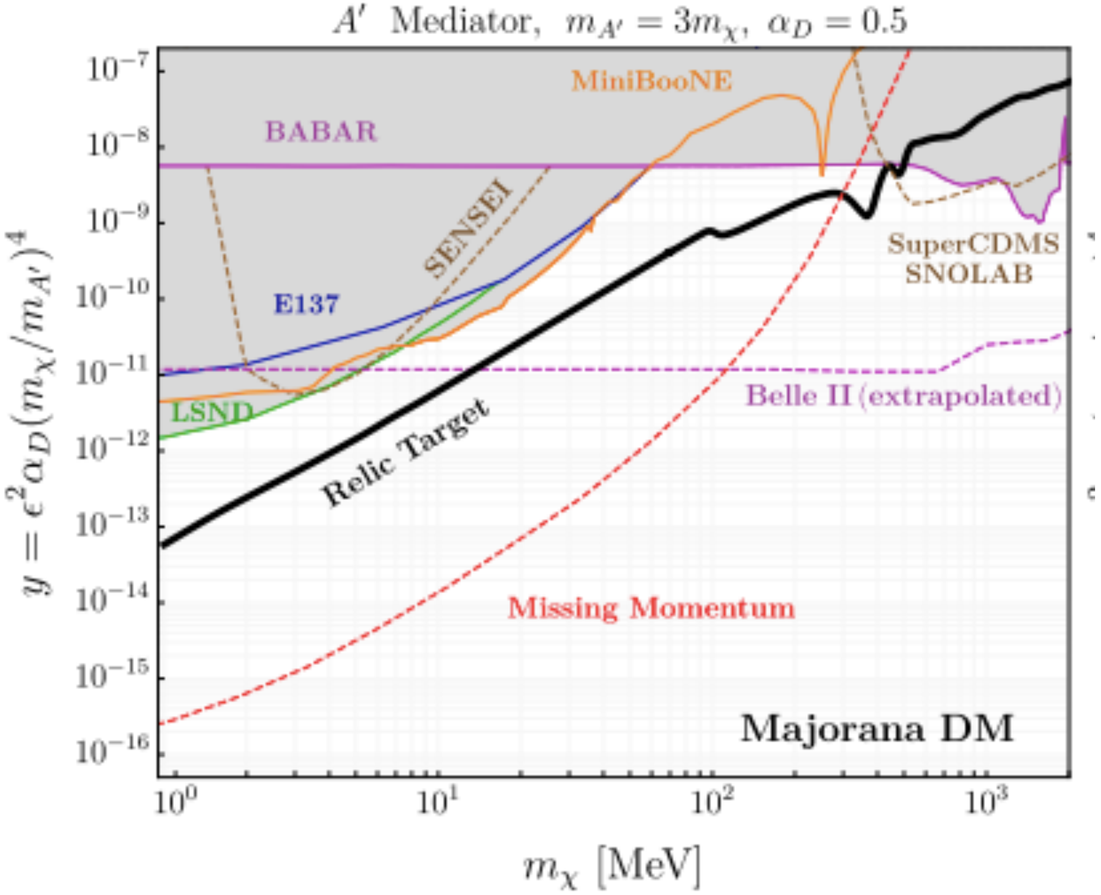
- 100 GeV Electron beam from CERN SPS
- “Active” beam dump
- Missing energy (due to DP production) technique
- Yield ~ ϵ^2

arXiv:1710.00971

LDMX



- Location: TBD (SLAC? CERN? JLab? …)
- Missing momentum technique:
  - Similar to E miss + tracking (angles)
- Tracking from HPS@JLab experience
- Calorimetry from CMS@LHC experience

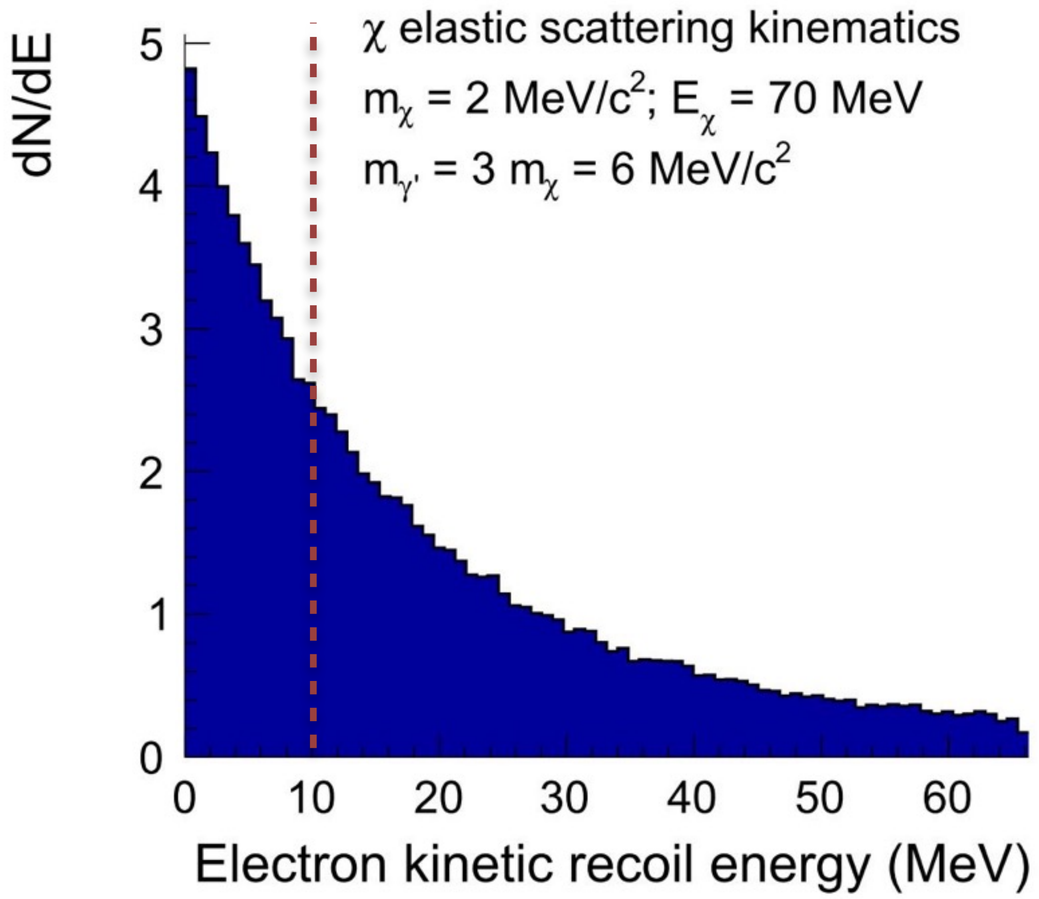


Signal:
- Recoiling electron with E<Ebeamy
- High transverse momentum
- No other activity in the CALs

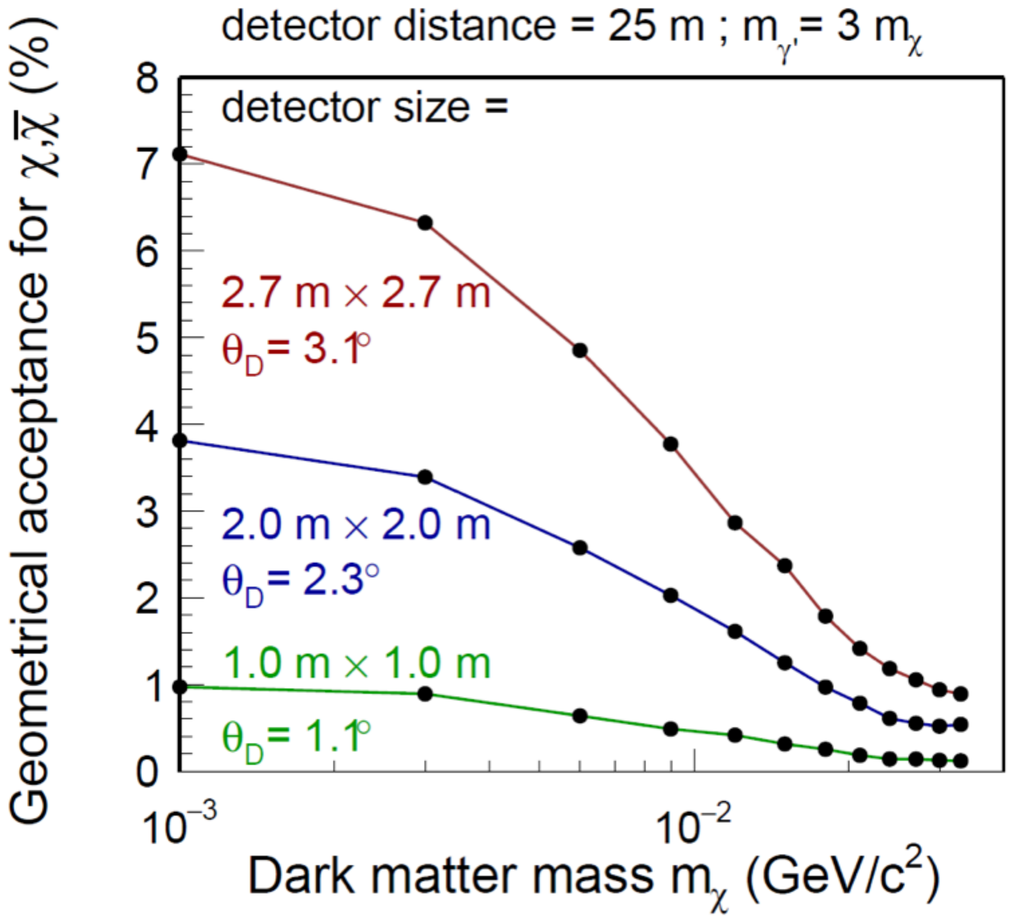
arXiv:1808.05219

SIMULATION AND TESTS (MESA)

Acceptance



~90% acceptance for ~10 MeV th and small masses.

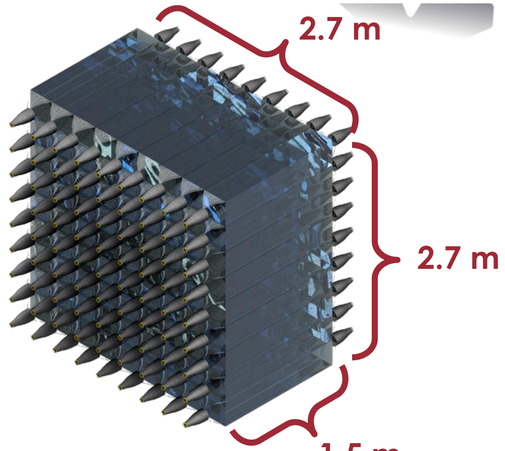


few % geometric acceptance for ~m1 detector at ~25 m from BD.

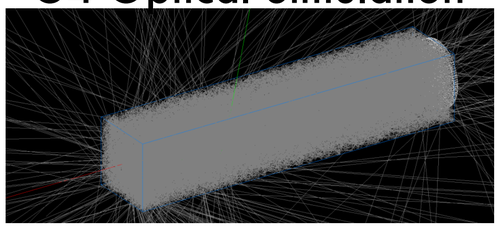
Experience with DarkMESA

1) Lead Glass Blocks –> Cherenkov Calorimeter –> Directionality + no NR
2) Scintillation Crystals
5'' Photomultipliers available (move to SiPMs ?)
Materials available:

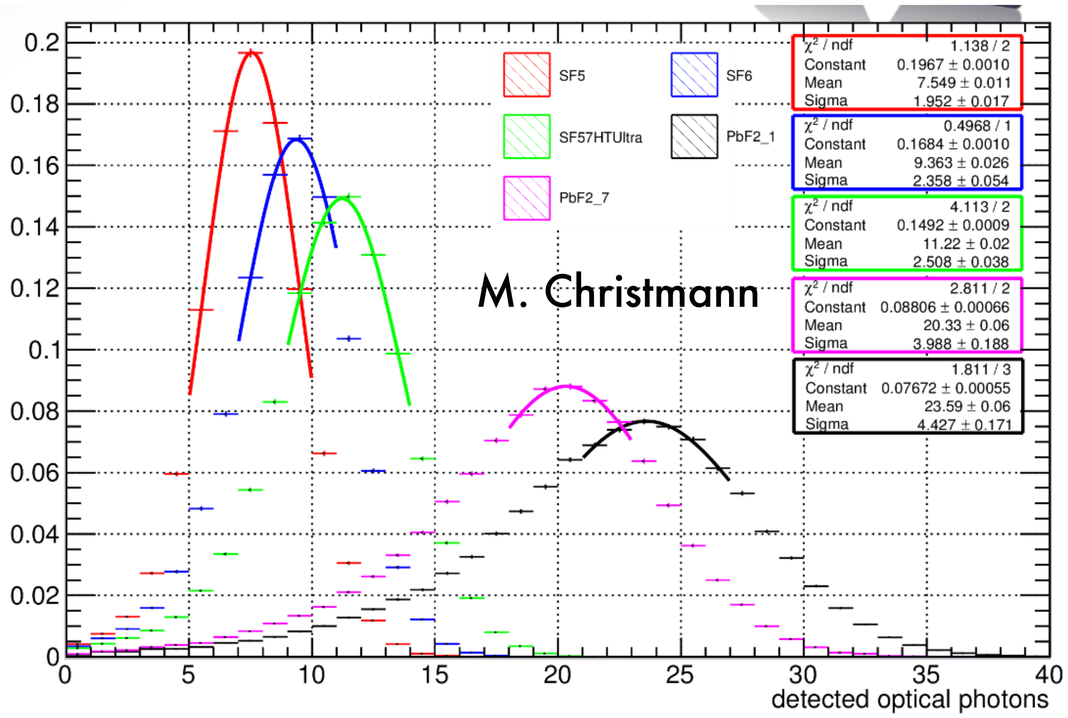
	X [mm]	Y [mm]	Z [mm]	Density [g/cm³]
SF 5	70	55	160	4.07
SF 6	30	55	160	5.18
SF 57 HTultra	40	55 (180)	160	5.51
BGO	21	21	230	7.13
PbF_2 (1)	Frustum of a pyramid		150	7.77
PbF_2 (7)	(30x30 / 26x26)		185.4	7.77



G4 Optical Simulation

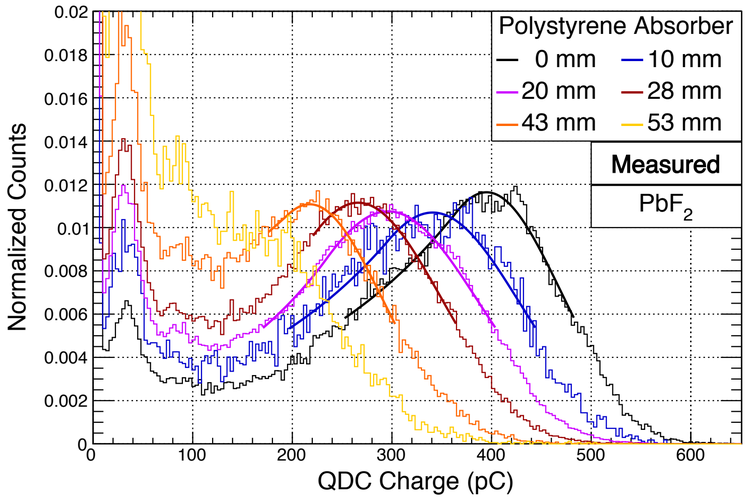


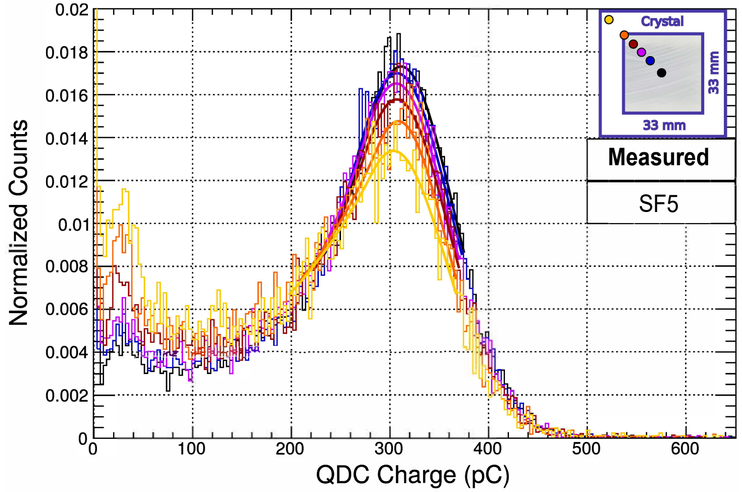
\+ Quantum Efficiency
Refraction Index
Emission spectra

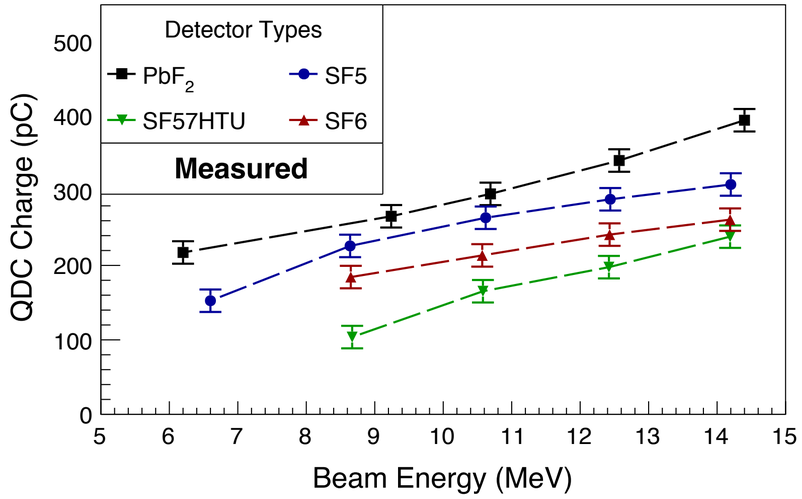


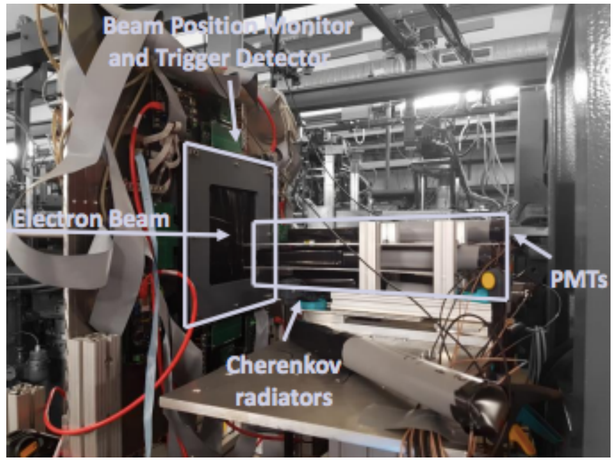
M. Christmann et al.: Nucl.Instr.Meth.A 960 (2020), 163665

Experience with DarkMESA







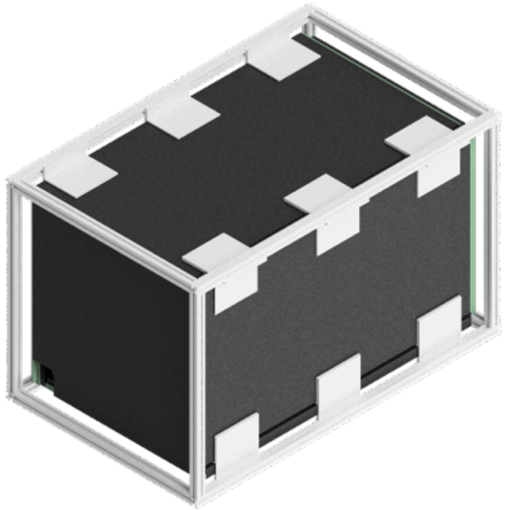


M. Christmann et al.: Nucl.Instr.Meth.A 960 (2020), 163665

Experience with DarkMESA

Prototype:

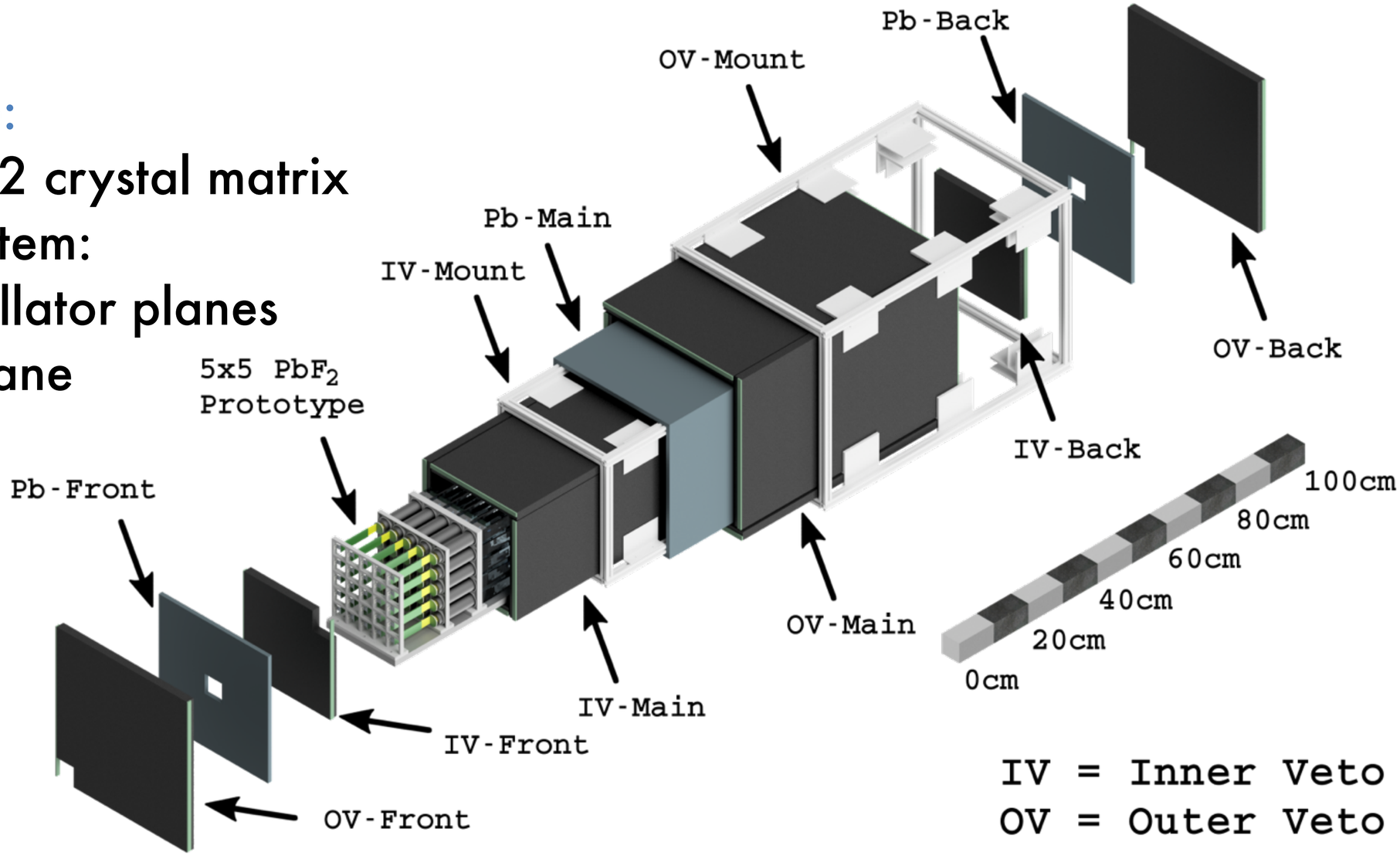
- 5x5 PbF2 crystal matrix
- Veto system:
  2xScintillator planes
  Lead plane



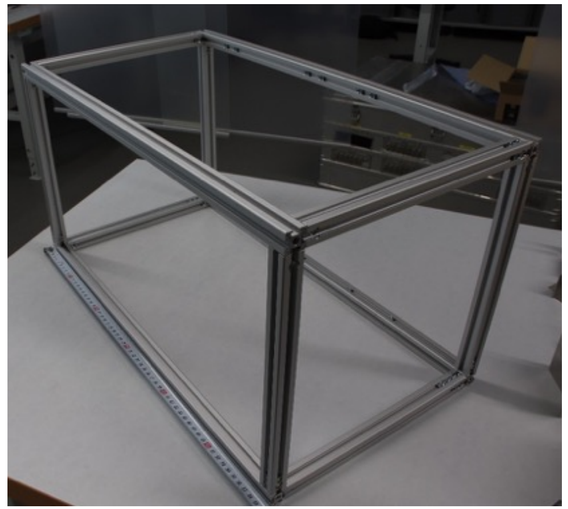
Experience with DarkMESA

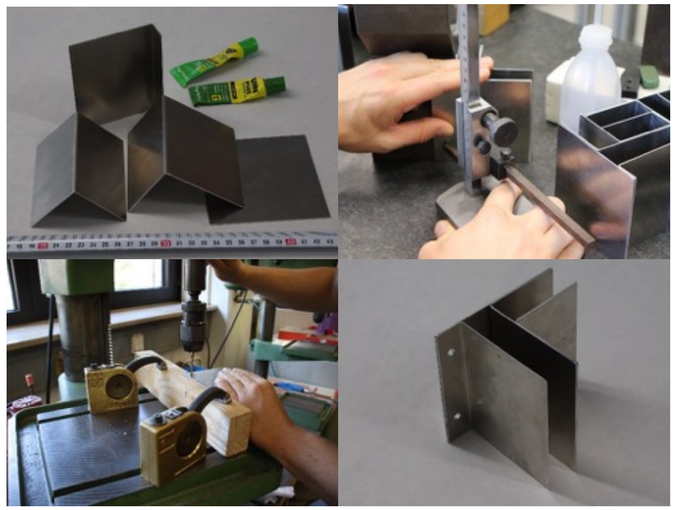
Prototype:

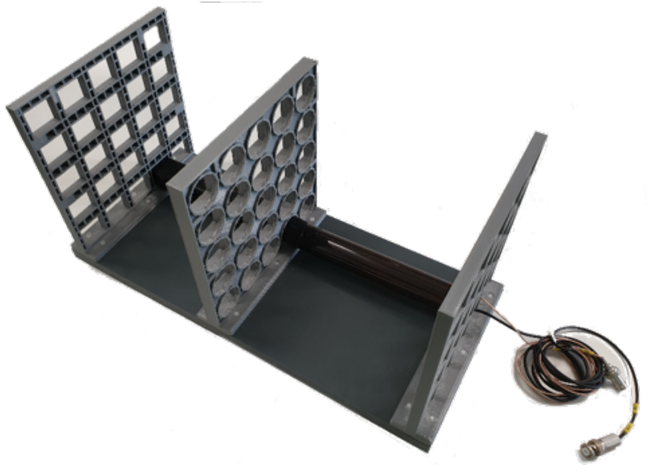
- 5x5 PbF2 crystal matrix
- Veto system:
  2xScintillator planes
  Lead plane

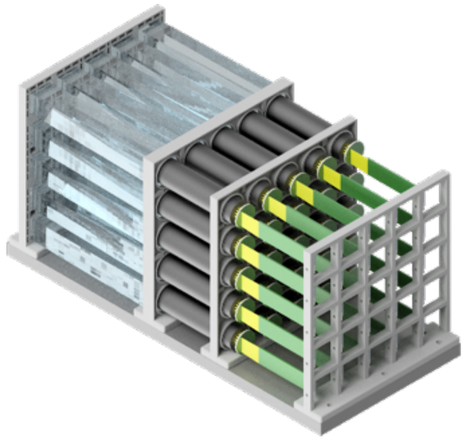


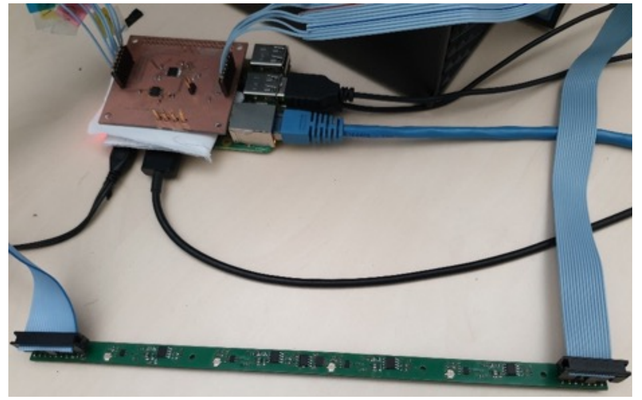
Experience with DarkMESA







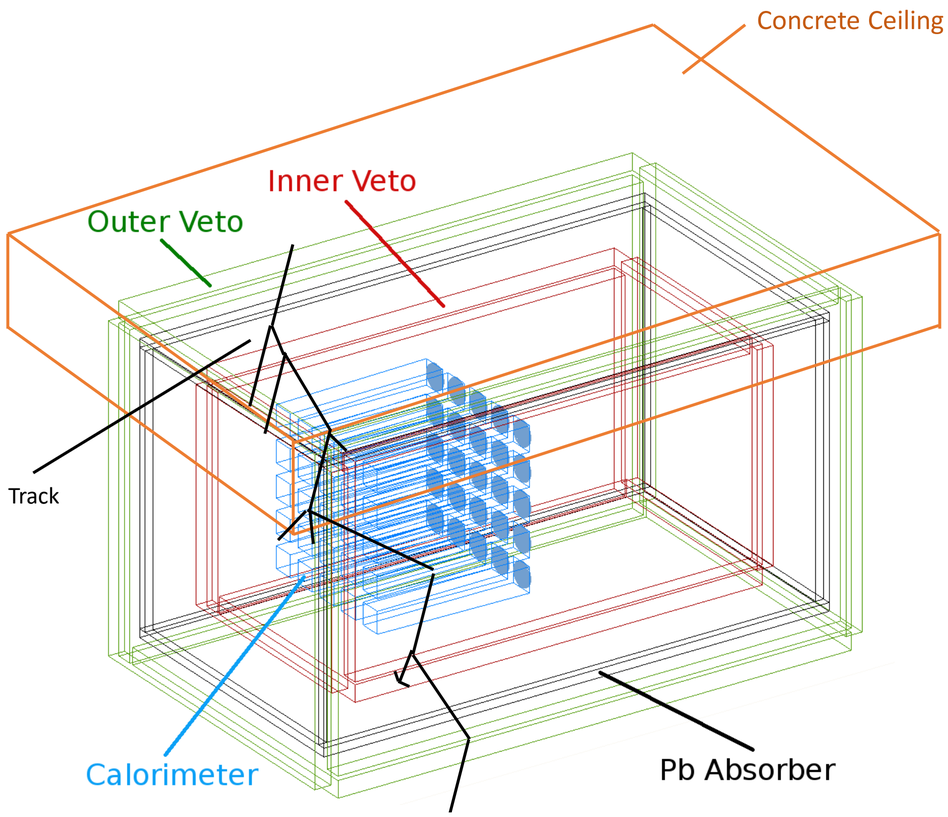


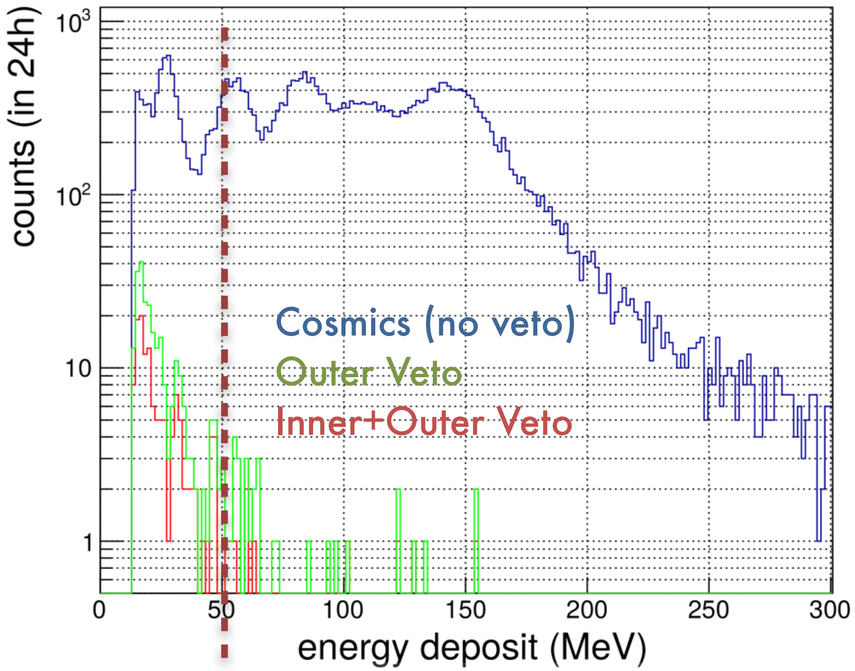


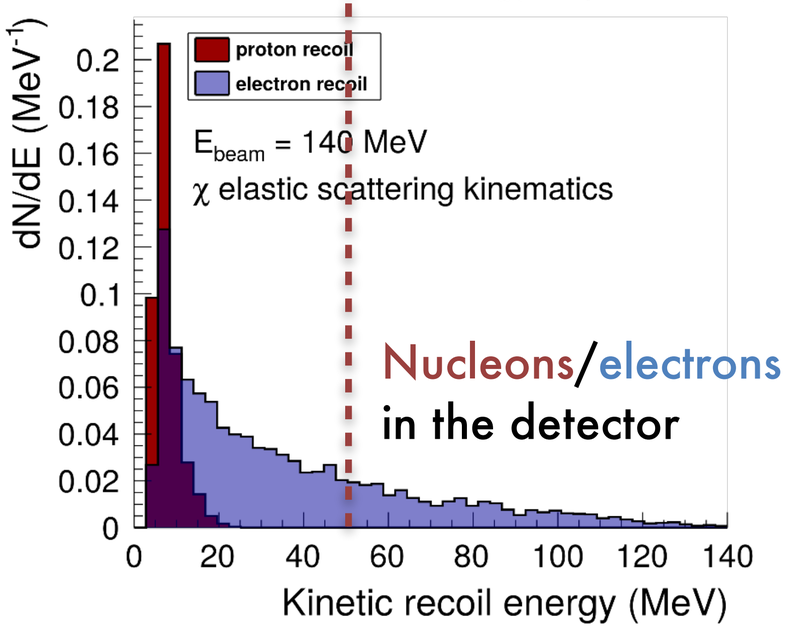
Scintillator planes coupled with SenseL SiMs through dedicated cards with amplifiers.

Experience with DarkMESA

Full simulation of the prototype



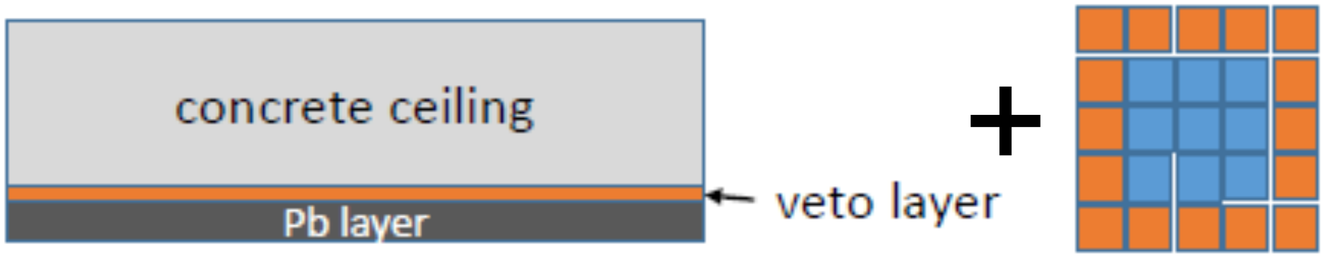




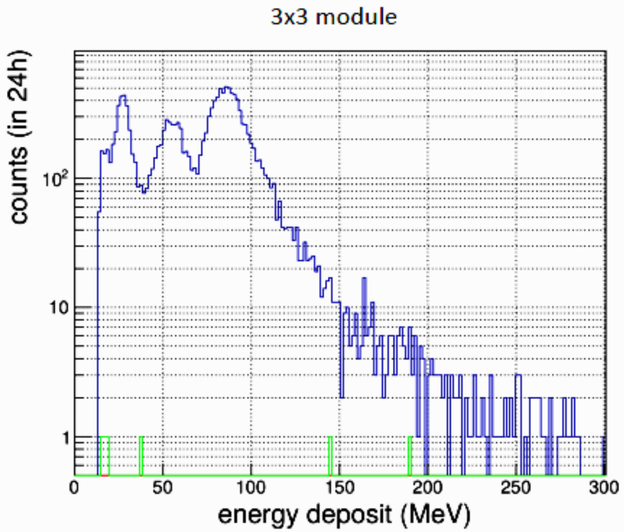
Simulation by M. Christmann

Experience with DarkMESA

Additional Pb-Scint Layer



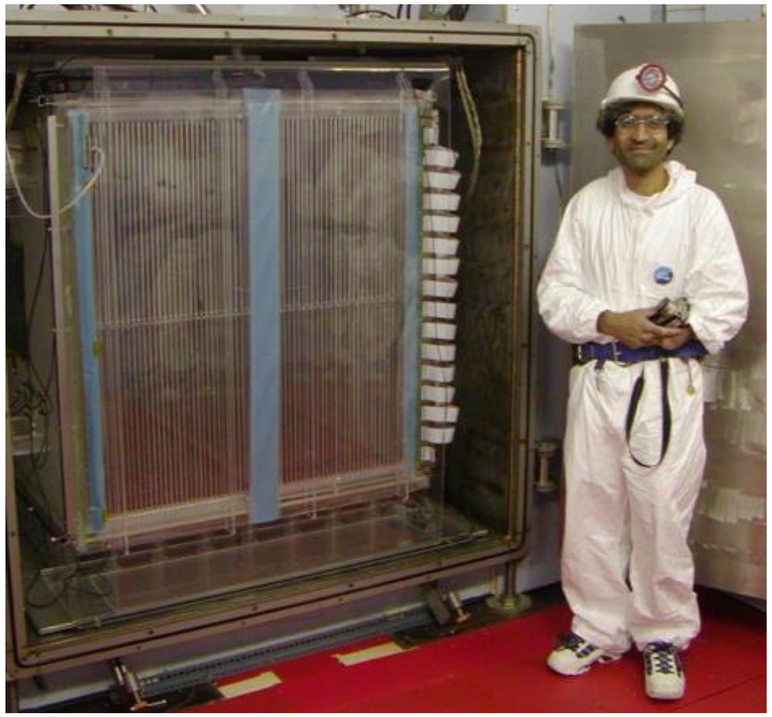
→ only 3x3 crystals as DM detector



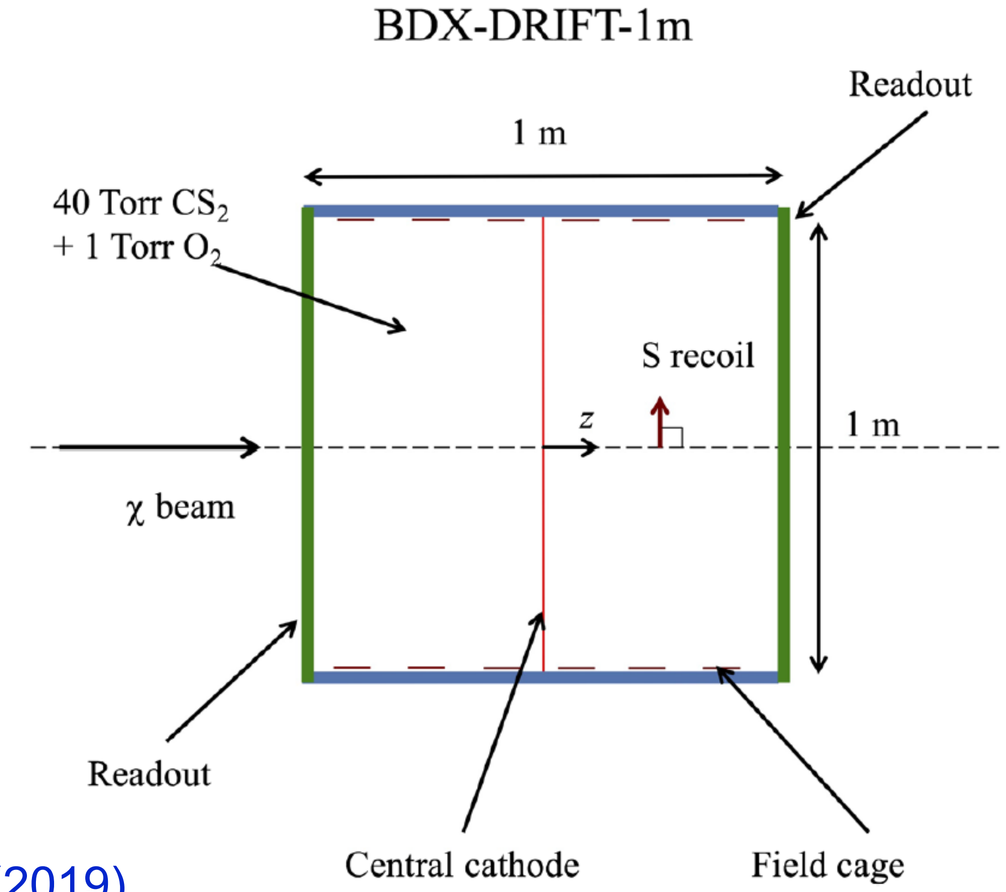
0 counts in 1 day after veto ON.

Simulation by M. Christmann

The DRIFT Option



D. Snowden-Ifft et al., Phys. Rev. D 99 (2019)



Collaboration with

- Lamar University
- Occidental College
- Canisius College

DRIFT: a low pressure negative ion time projection chamber, operated successfully for many years but not used for LDM searches

The ARIEL Case

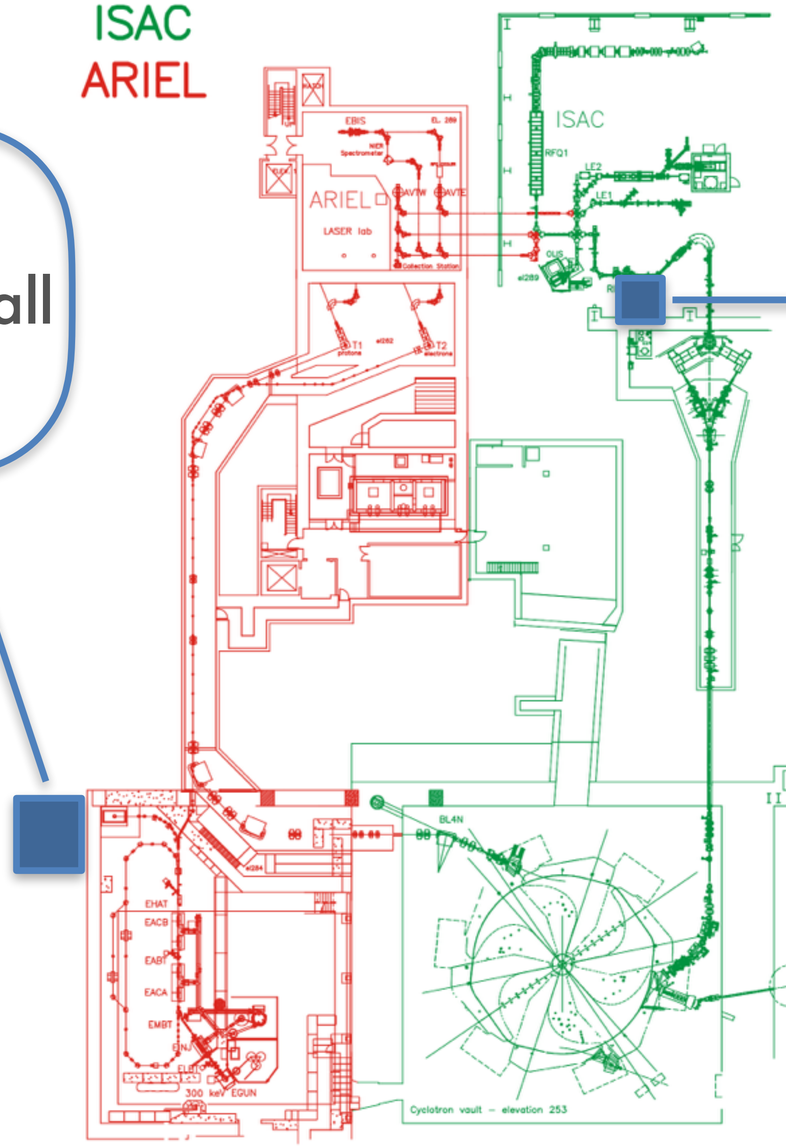
- Where to locate the experiment?
- Sensitivity?
- Integration into the existing infrastructure?
- Detector technology?

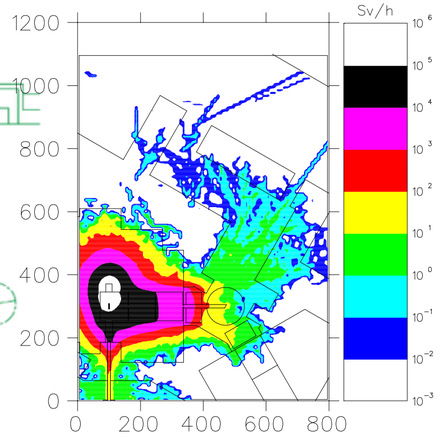
The ARIEL Case

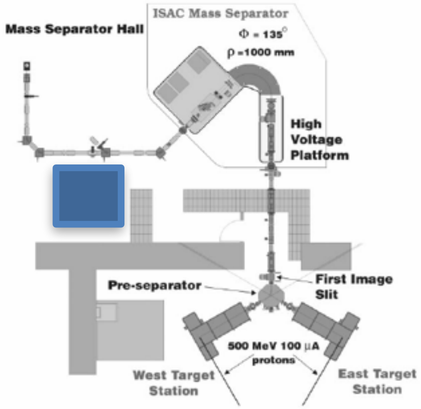
ISAC
ARIEL

Option 2
- Beam-dump in ARIEL Hall
- Distance: ~3m

Option 1
- ARIEL targets + Separator room.
- Parasitic operation possible.
- Backgrounds from ISAC targets?
- Enough space?
- Distance ~ 20m



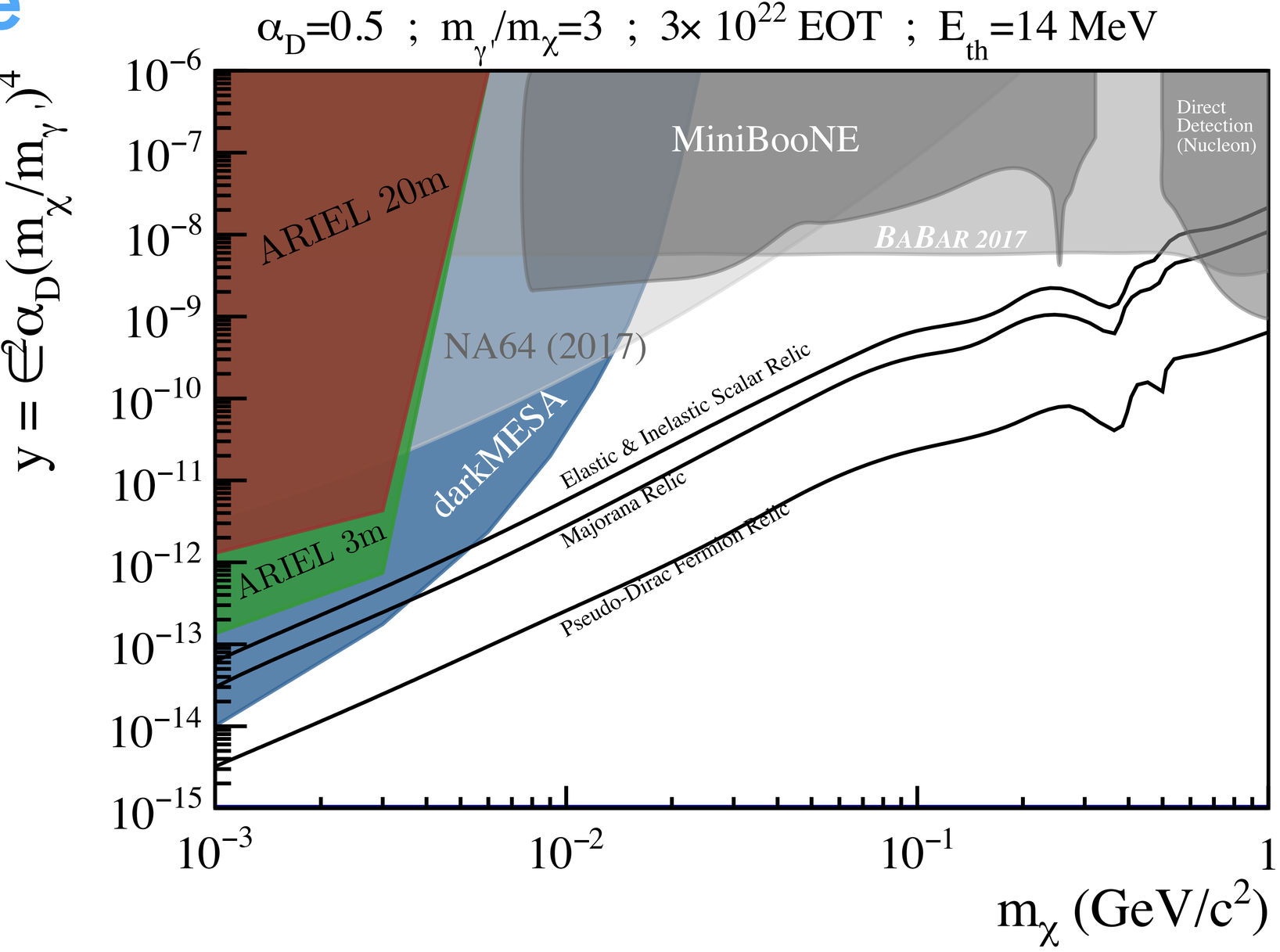




The ARIEL Case

Beam
- E= 30MeV
- 10000 h/year
- 3×10^{23} EOT

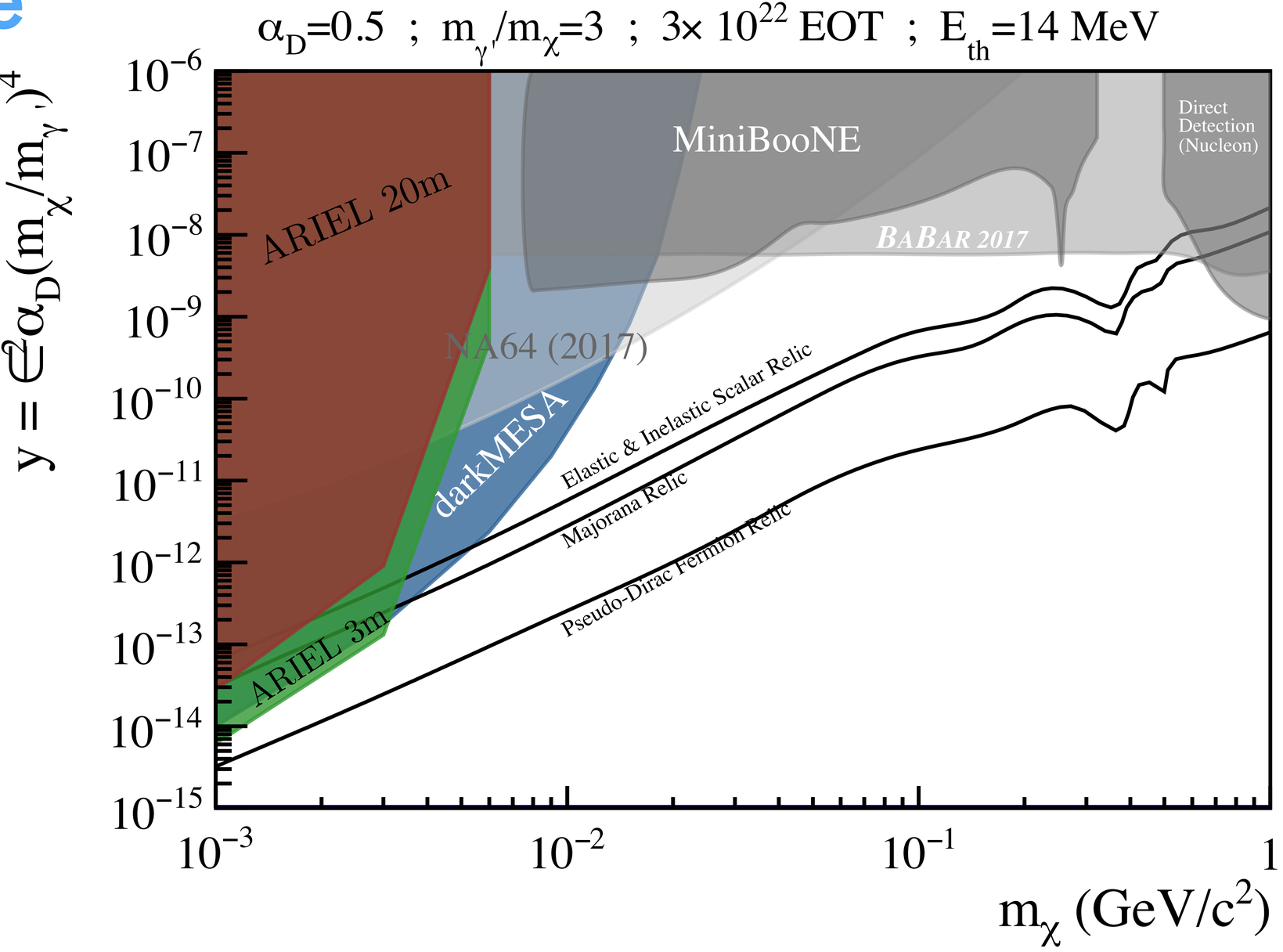
Detector
- 3x3x3 m
- 3m OR 20m distance
- 14 MeV threshold



The ARIEL Case

Beam
- E= 50MeV
- 10000 h/year
- 3×10^{23} EOT

Detector
- 3x3x3 m
- 3m OR 20m distance
- 14 MeV threshold



Summary of Strengths and Challenges

Beam Properties:

High power BD (~100kW expected, more w/o ISOL target..500kW?) , bremsstrahlung on Au (+Al)
Low beam energy (30 MeV —> 50 MeV?)
Have to stay close to BD for good acceptance -> backgrounds?
Advantage: no muon/neutrino background

Detector:

Calorimeter / Noble liquid detector / Gas TPC … ?
Low DM masses —> Low threshold -> BKGs again (environment, BD, low-E neutrals)
Veto system: cosmics, low energy neutrons and photons
Timing? Challenging with CW beam (need sub-ns resolution) —> dedicated bunched beam?

Further studies:

Complex logistics: where to place the detector (separator room, new cave, new beamline, …)?
Enough space in the separator room?
Radiation levels low enough?

Summary

- LDM is a quite generic possibility. Many models on the market: experiments needed!

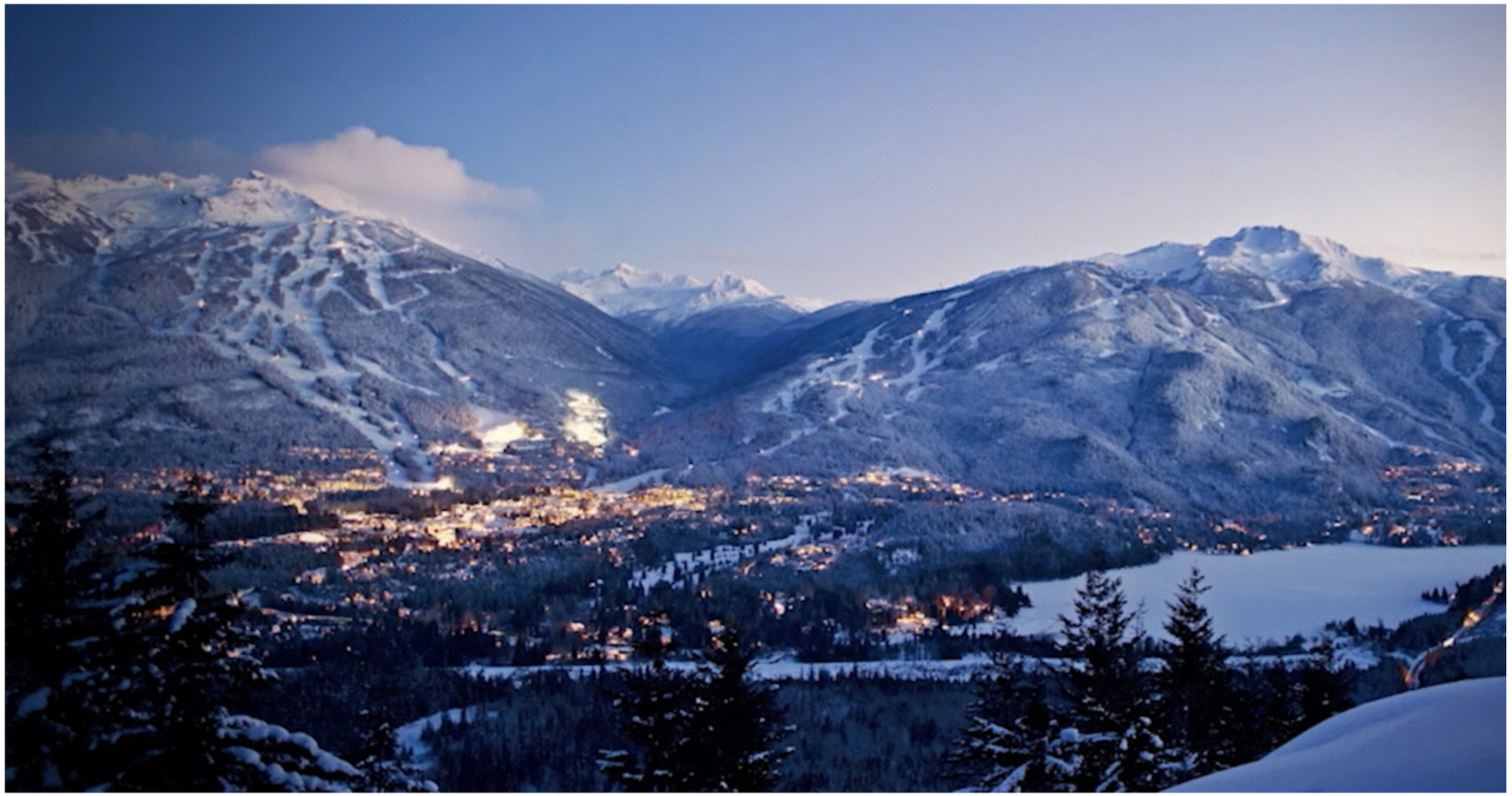
- With a rapidly “heavy” DM window closing, “light” DM searches are gaining a lot of interest.

- Dark sector experiments discussed at major labs equipped with electron machines:
SLAC, Cornell, DESY, ELSA, MAMI/MESA, Frascati, KEK, … Lot of competition.

- BD-type experiments have the potential to explore unique parameter regions at low masses.

- An opportunity for the TRIUMF beams (protons could also be an option…?)

- Realistic full simulation study needed: beam dump + detector technology



Thank you very much!