Probing Millicharged Particles at BDX with Ultralow-Threshold Sensors

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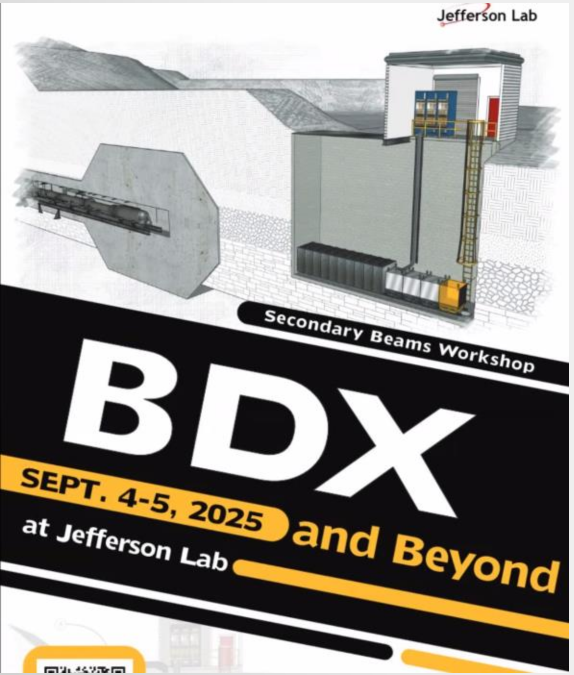
09/04/2025



Letter of Intent to PAC 53
Probing Millicharged Particles at an Electron Beam Dump with Skipper-CCDs at BDX

Marco Battaglieri,[a] Mariangela Bondi,[i] Ana Botti,[b] Brenda A. Cervantes-Vergara,[b] Raffella De Vita,[a,l] Rouven Essig,[d] Juan Estrada,[b] Peiran Li,[e] Zhen Liu,[e] Megan McDuffie,[d,f] Santiago Perez,[g] Dario Rodrigues,[g] Ryan Plestid,[h] Marco Spreafico,[a] Javier Tiffenberg,[b] Hailin Xu[d,f] and the BDX Collaboration

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Probing millicharged particles at an electron beam dump with ultralow-threshold sensors

Rouven Essig,[a] Peiran Li,[b] Zhen Liu,[b] Megan McDuffie,[a,c] Ryan Plestid[d] and Hailin Xu[a,c]

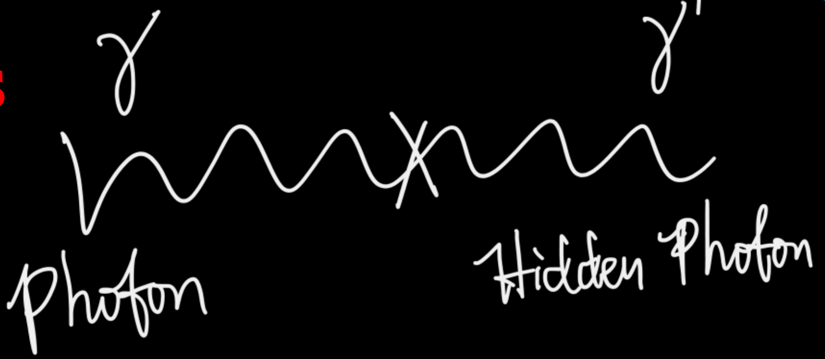
A generic light hidden photon and millicharged particles

$$\frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}$$

Our Electromagnetism

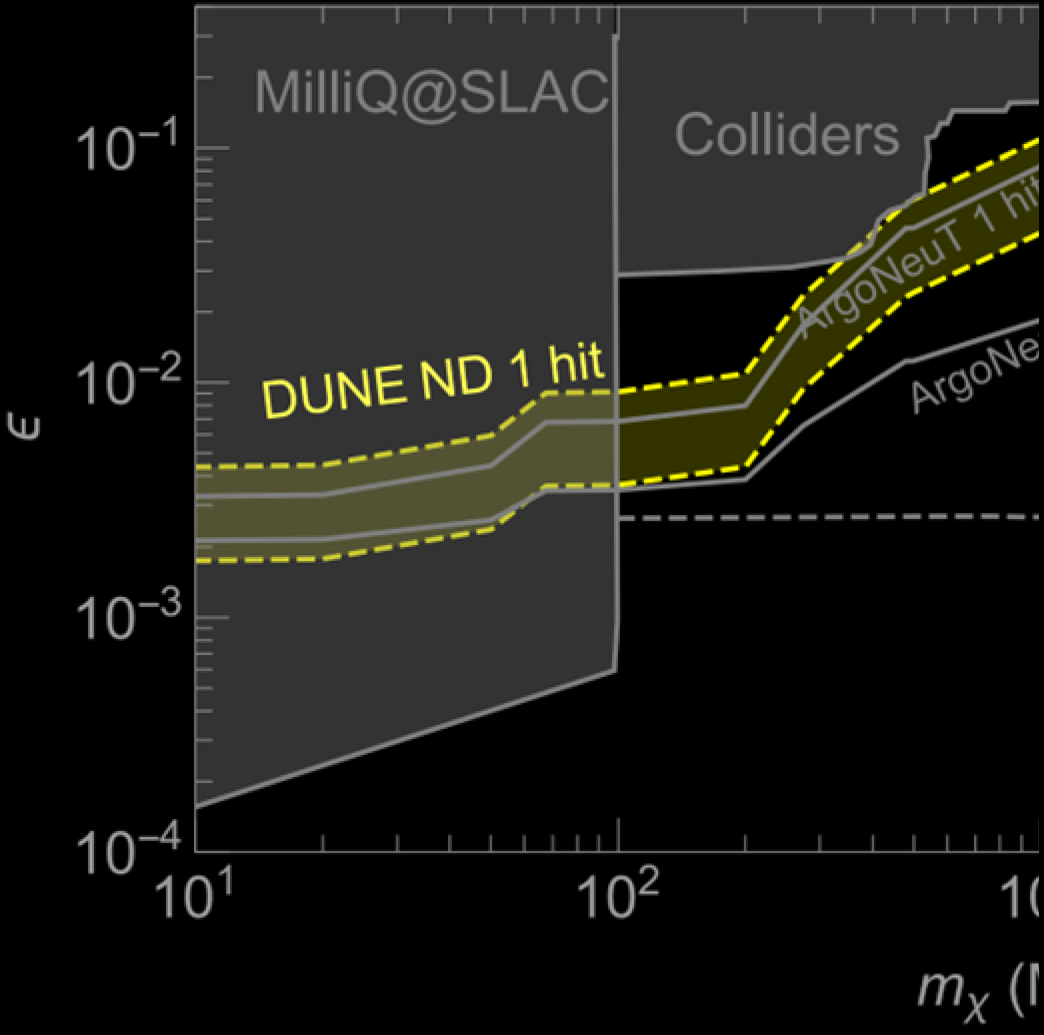
Hidden Electromagnetism

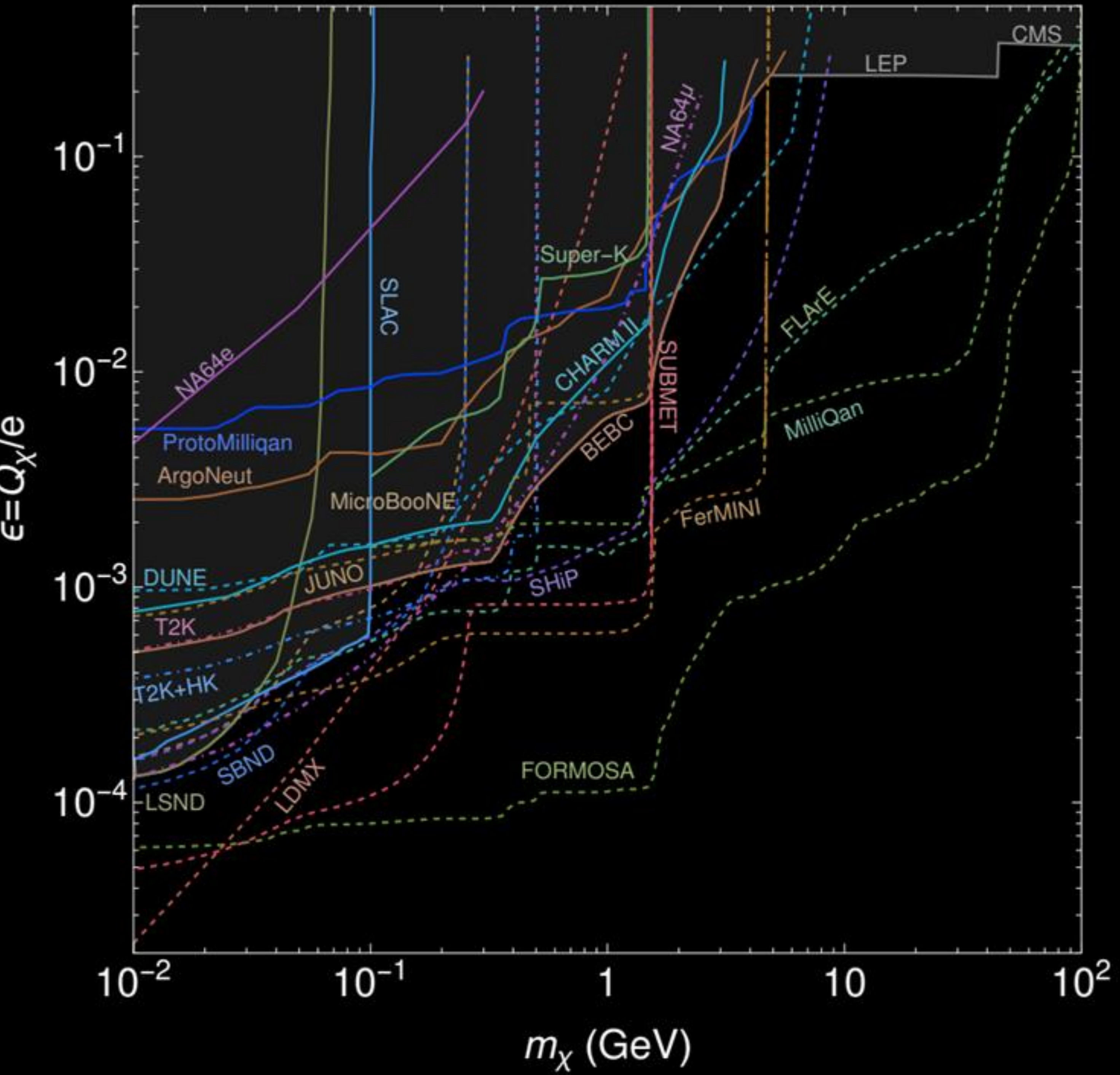
Electron feels the force by our photon



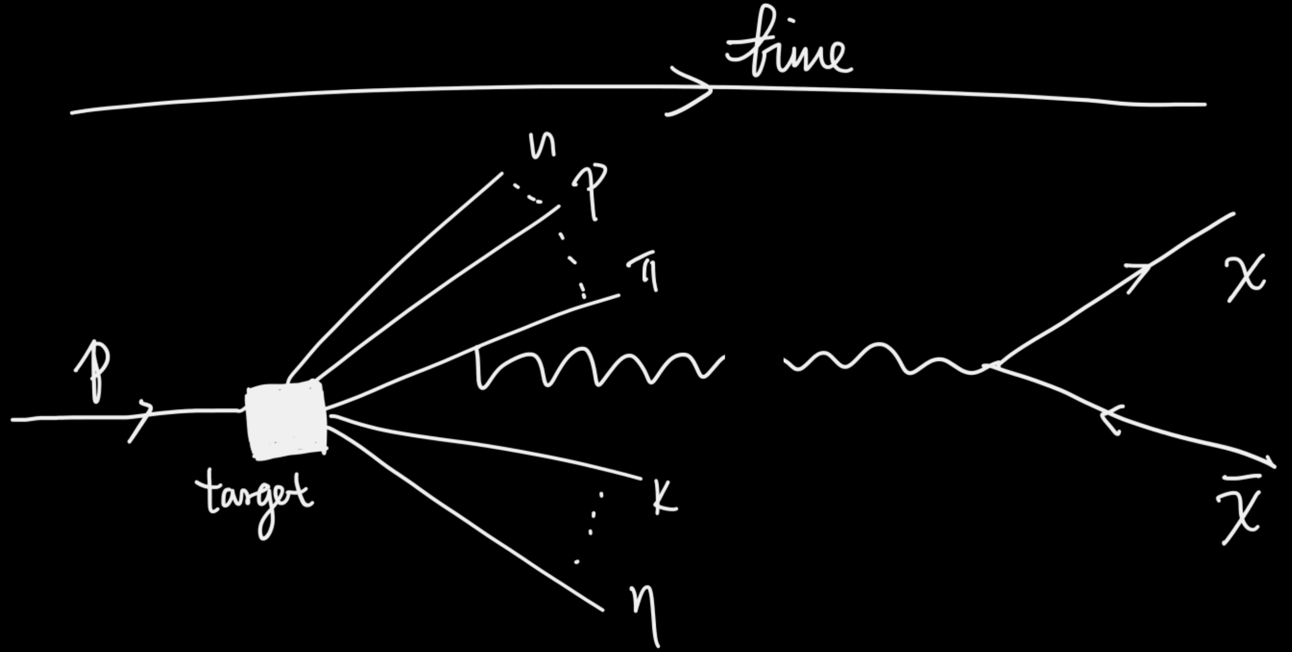
Hidden electron feels the force by hidden photon

Current Status & Futur

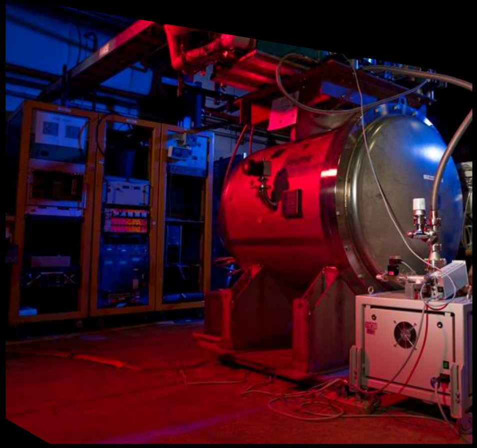


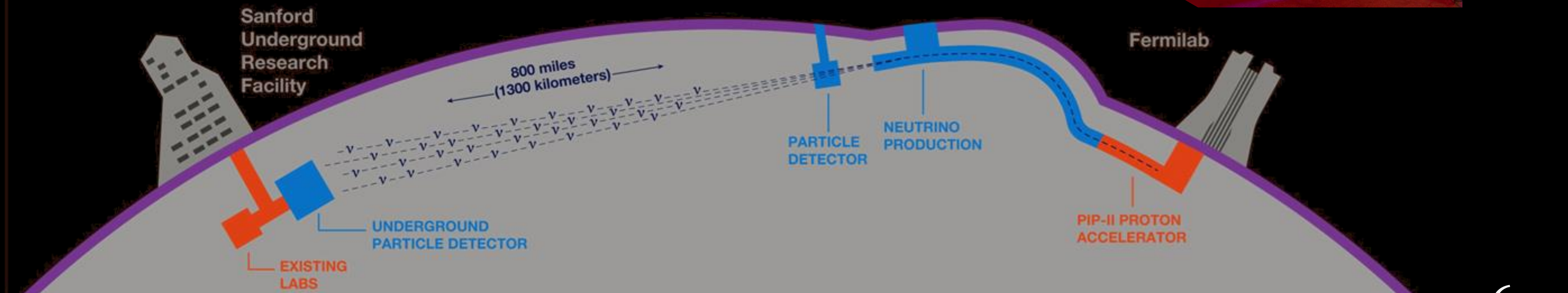


Millicharged Particles at Neutrino Experiments



High beam energy
High beam intensity (10^{20}~10^{23} Proton On Target)

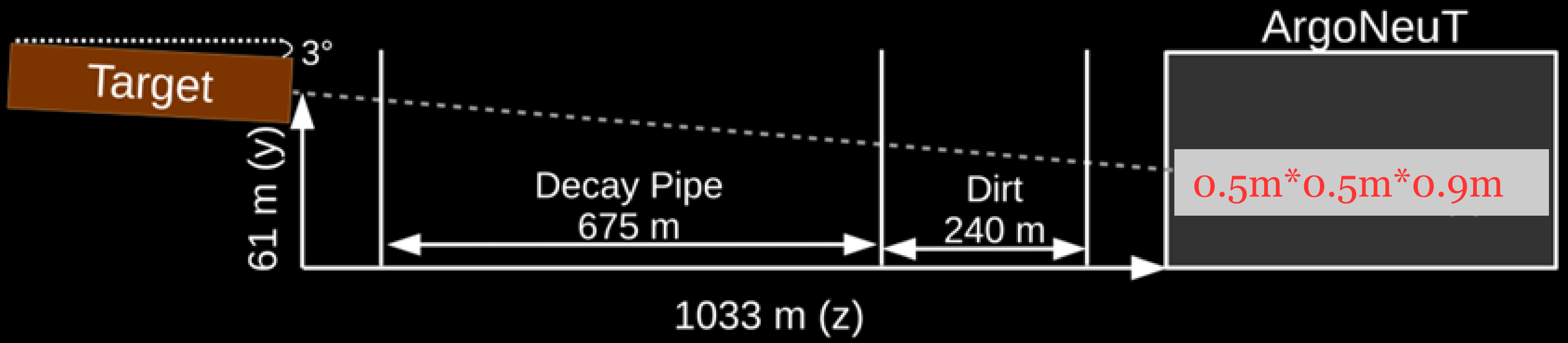




NuMI beam: good source for Millicharged particles

High beam energy
High POT

Typical geometric acceptance: $10^{-5\sim6}$



	π^0	η	η'	ρ	ω	ϕ	J/ψ	DY
#/POT	2.9	3.2×10^{-1}	3.4×10^{-2}	3.7×10^{-1}	3.7×10^{-1}	1.1×10^{-2}	5.4×10^{-7}	$4.7\times10^{-10}\epsilon^2$
$2\times \mathrm{Br}_{X\to\chi\bar{\chi}}(\%)$	$2.3\epsilon^2$	$1.4\epsilon^2$	$0.04\epsilon^2$	$0.009\epsilon^2$	$0.018\epsilon^2$	$0.058\epsilon^2$	$12\epsilon^2$	—
$A_{\rm geo}^{\rm ArgoNeuT}(m_\chi=20\ \mathrm{MeV})$	3.1×10^{-5}	2.1×10^{-5}	1.6×10^{-5}	1.9×10^{-5}	2.0×10^{-5}	9.1×10^{-6}	5.0×10^{-6}	3.2×10^{-6}
$A_{\rm geo}^{\rm ArgoNeuT}(m_\chi=200\ \mathrm{MeV})$	—	5.4×10^{-5}	3.4×10^{-5}	2.3×10^{-5}	2.2×10^{-5}	1.1×10^{-5}	4.6×10^{-6}	3.1×10^{-6}

Detection

Signal scattering probability and mean free path

$$\frac{d\sigma}{dE_r} = \pi\alpha^2\epsilon^2 \frac{2E_\chi^2 m_e + E_r^2 m_e - E_r\left(m_\chi^2 + m_e(2E_\chi + m_e)\right)}{E_r^2(E_\chi^2 - m_\chi^2)m_e^2}$$

$$\left.\frac{d\sigma}{dE_r}\right|_{E_\chi \gg m_\chi, m_e, E_r} \simeq \frac{2\pi\alpha^2\epsilon^2}{E_r^2 m_e}.$$

Dominated by low recoil energy scattering

$$\lambda(E_r^{\min}) \simeq \left(\frac{10^{-2}}{\epsilon}\right)^2 \left(\frac{E_r^{\min}}{1\ \mathrm{MeV}}\right) 1\ \mathrm{km}$$

How to see Millicharged Particles (Again)?

Signal scattering probability and mean free path

$$\frac{d\sigma}{dE_r}\bigg|_{E_\chi \gg m_\chi, m_e, E_r} \simeq \frac{2\pi\alpha^2\epsilon^2}{E_r^2 m_e}.$$

$$\lambda(E_r^{\min}) \simeq \left(\frac{10^{-2}}{\epsilon}\right)^2 \left(\frac{E_r^{\min}}{1\ \mathrm{MeV}}\right) 1\ \mathrm{km}$$

Dominated by low recoil energy scattering

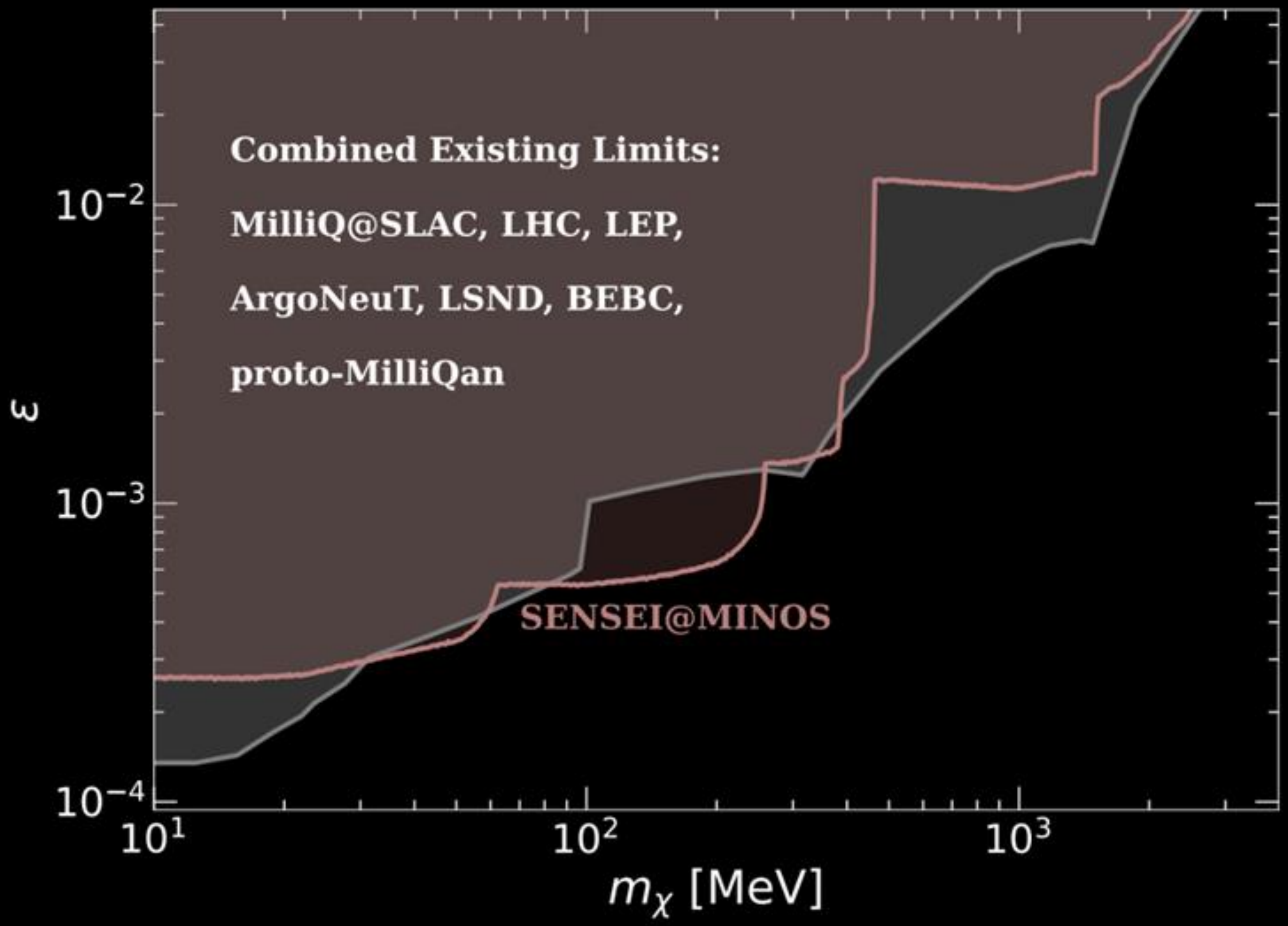
What if we lower the threshold?

Compared to LAr, Skipper CCD increases signal efficiency by 10^5 (1 MeV v.s. 10 eV)

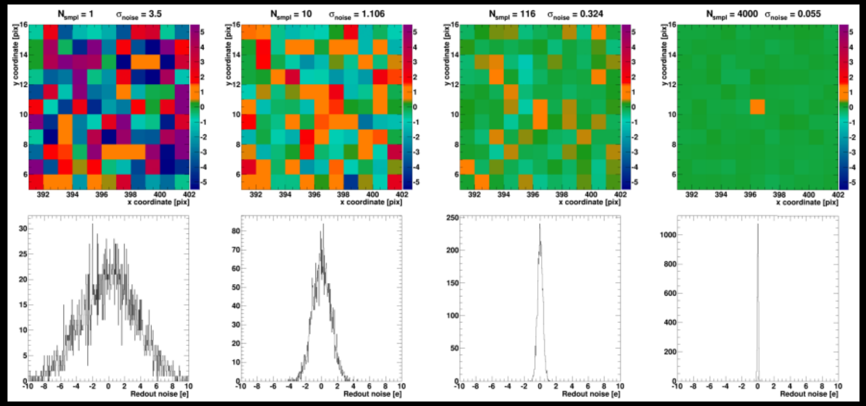
Single Scatter Detection Parametric (1-hit):

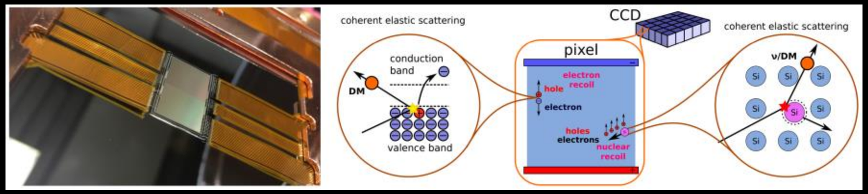
- Detection Rate proportional to Volume
  - SENSEI 3gram is small in volume, about $1/10^5$ compared to ArgoNeuT
- Detection Rate proportional to effective POT
- But Skippers has much lower 1-hit background.

New Results with SENSEI Collaboration (2305.04964)

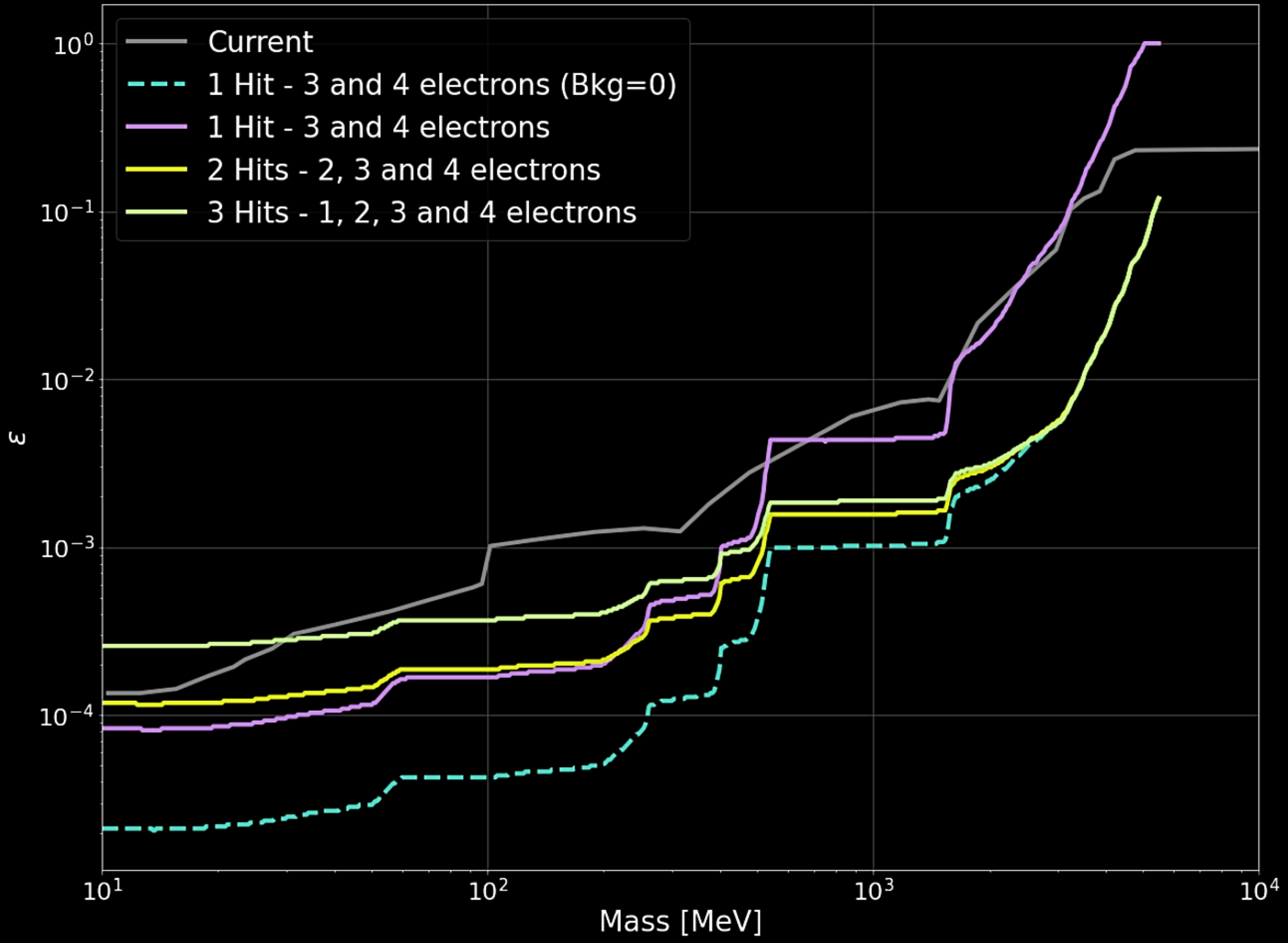


3 gram of detectors with 3 days equivalent of data ($9g \cdot day$ on NUMI beam) already achieving new results.





with the OSCURA collaboration (2304.08625)



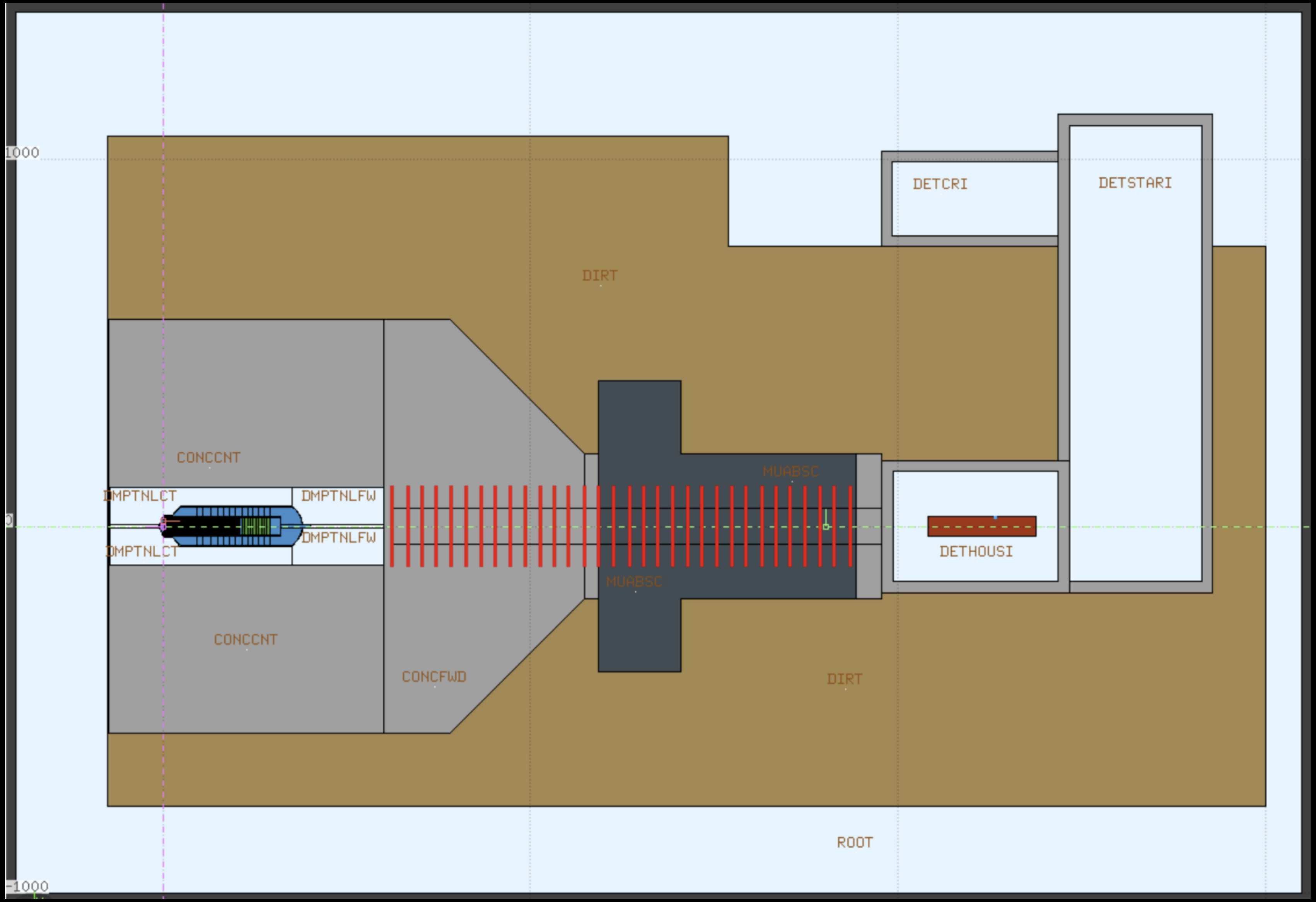
Assuming 1kg skipper CCD for “early science” of OSCURA experiment.

Different background level assumptions:

- Very conservatively assuming a large number of backgrounds;
- Adapting our multi-hit strategy;
- Also shown in dashed the zero-background projections (consistent with my earlier calculation in the previous slide).

Probing Millicharged Particles at an Electron Beam Dump with Ultralow-Threshold Sensors
R. Essig, **P.R. Li**, ZL, **M. McDuffie**, R. Plestid, **H.L. Xu**, 2412.09652

BDX Experiment



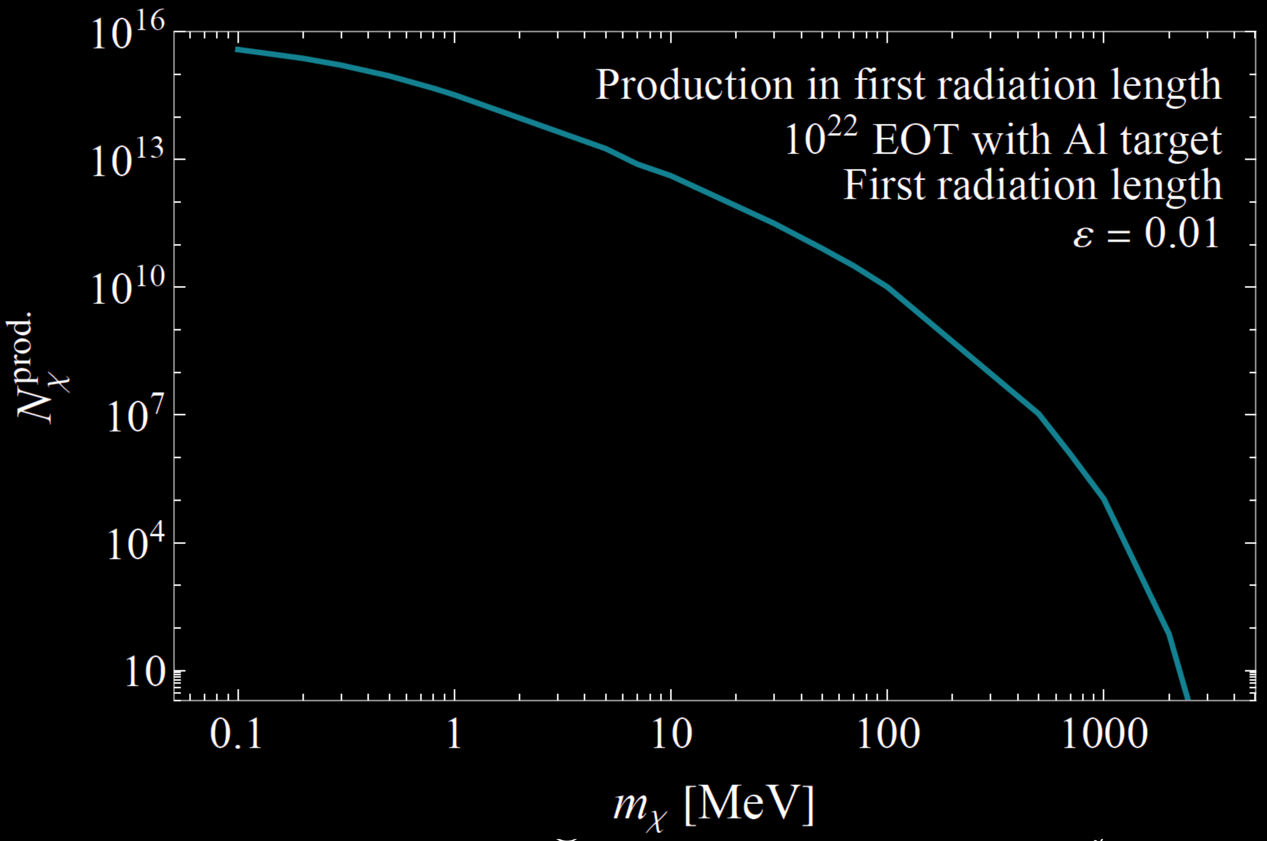
10.6 GeV electron beam with 10^{22} EoT (electron on Target) on 3meter of Al. Jefferson Lab.

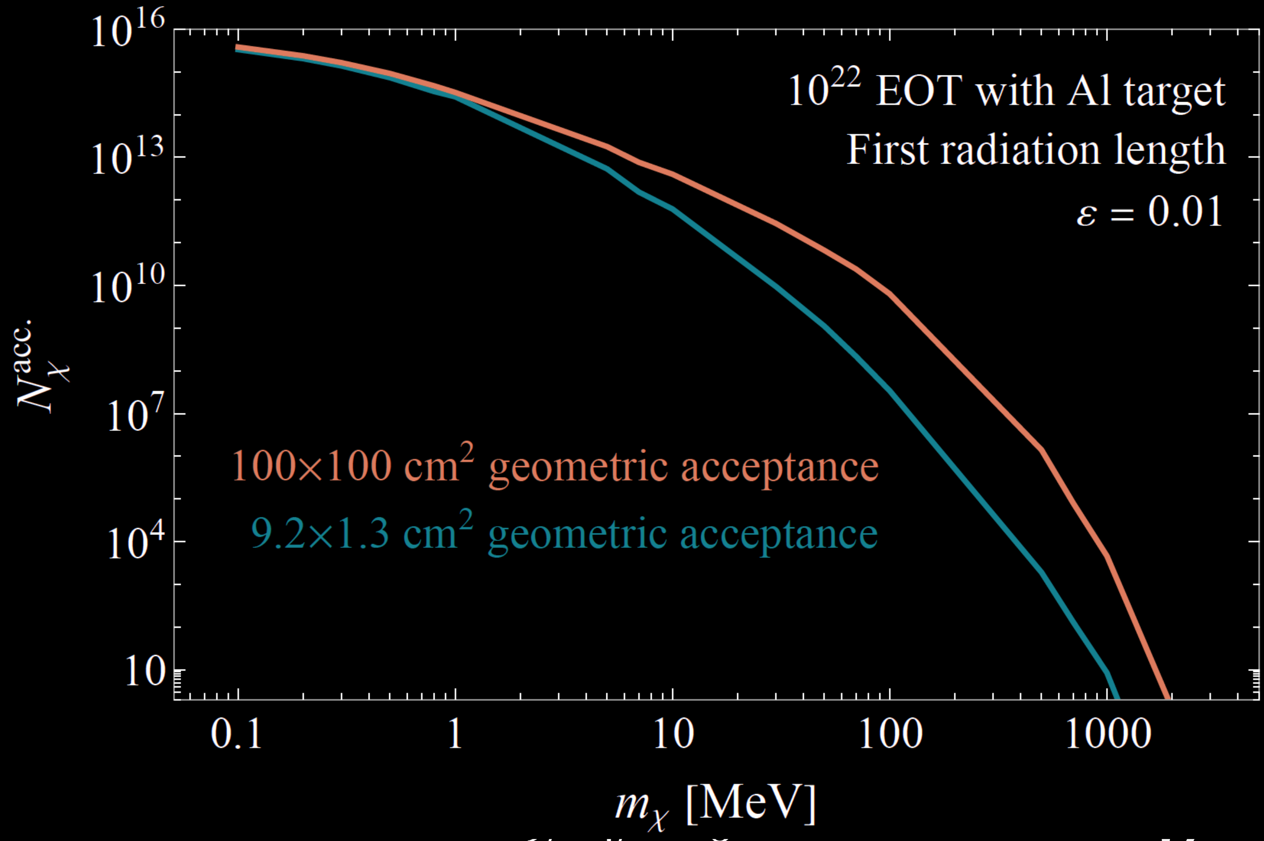
Electron Beamdumps

Probing Millicharged Particles at an Electron Beam Dump with Ultralow-Threshold Sensors

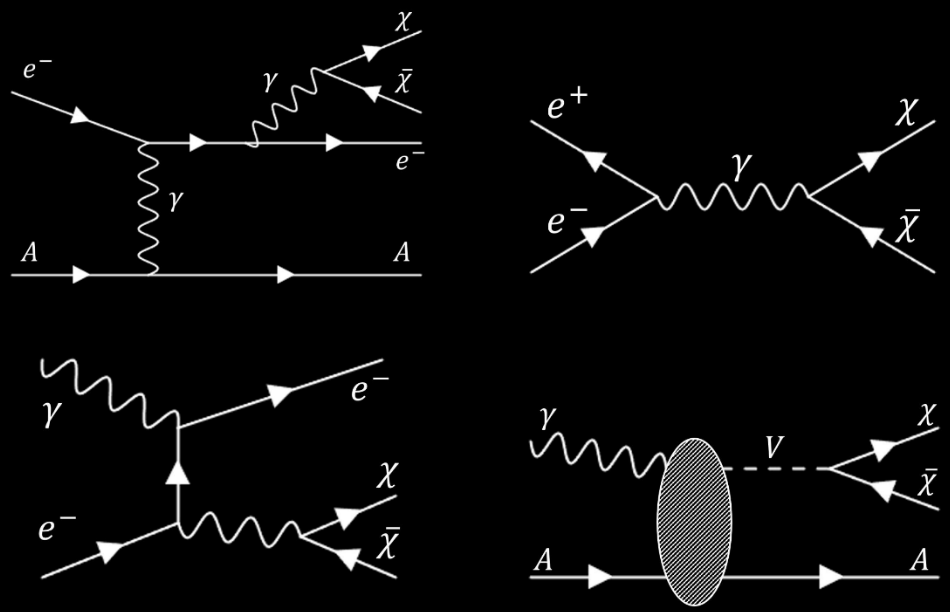
R. Essig, P.R. Li, ZL, M. McDuffie, R. Plestid, H.L. Xu, 2412.09652

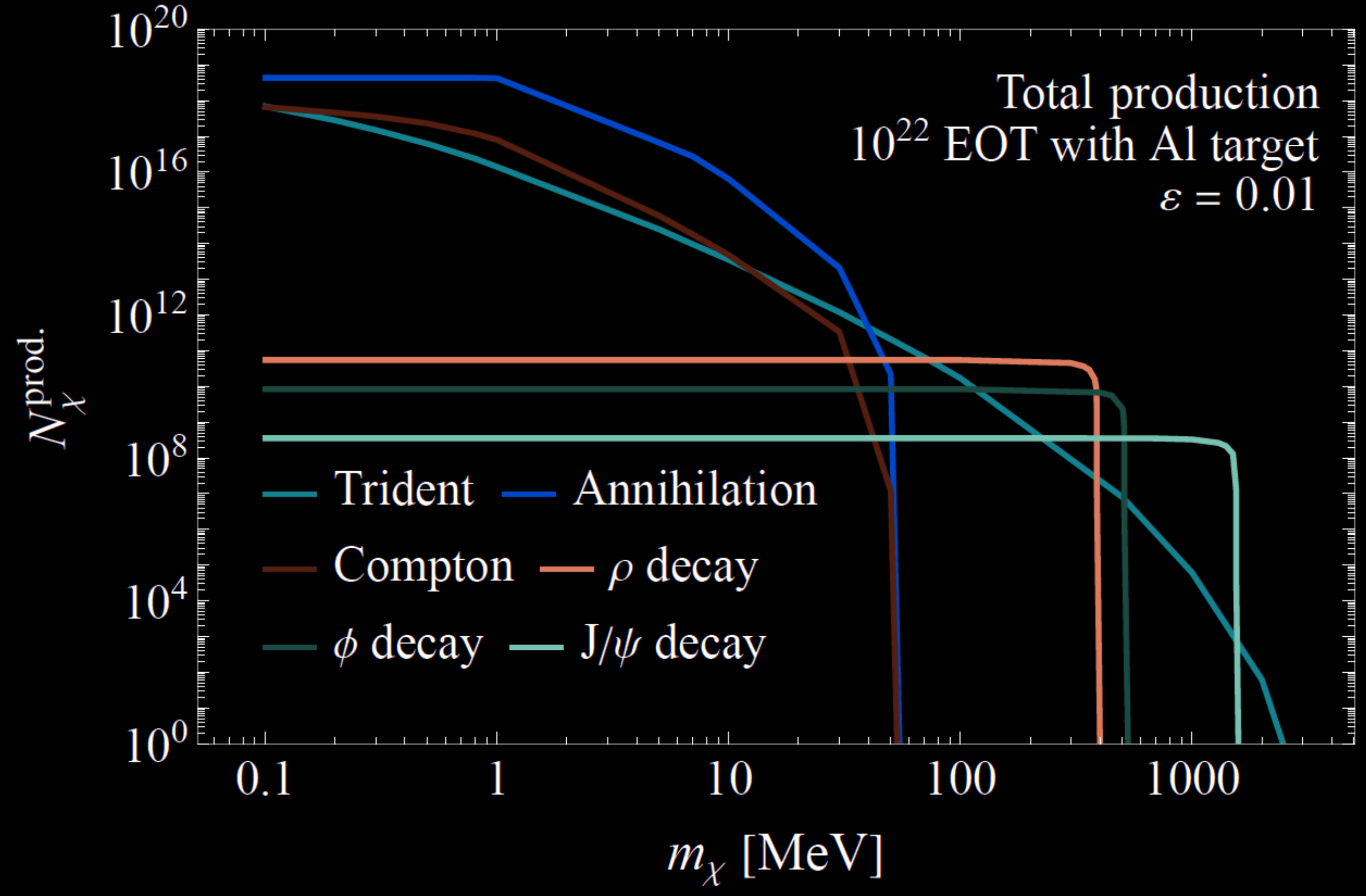
- Production of mCPs in the first radiation length (Many existing searches & projections rely on this)
- Production of mCPs in the electromagnetic cascade



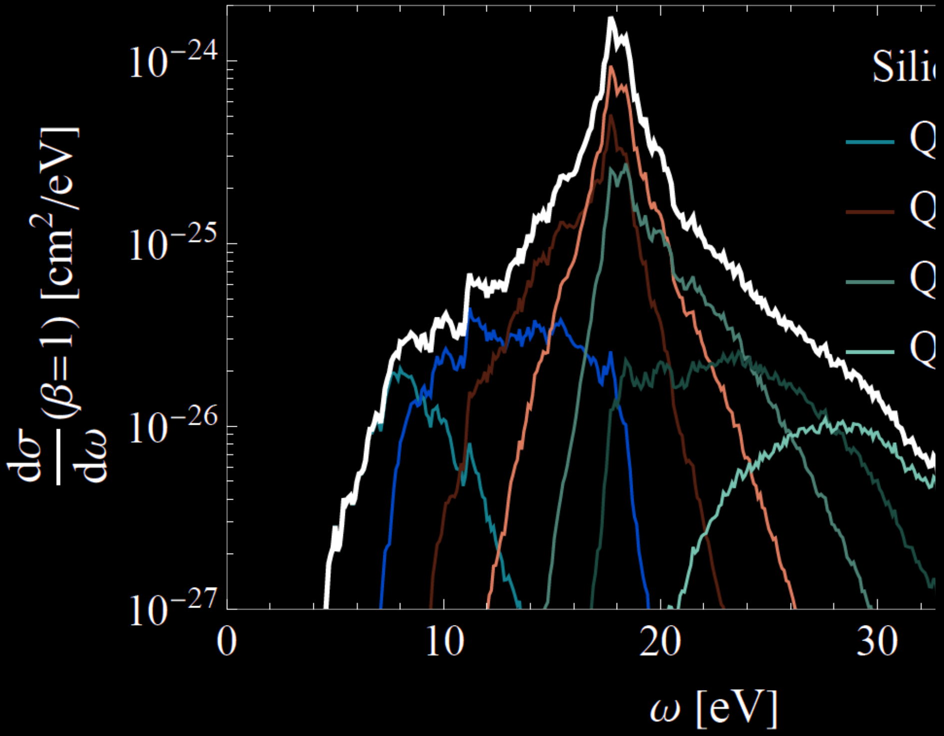


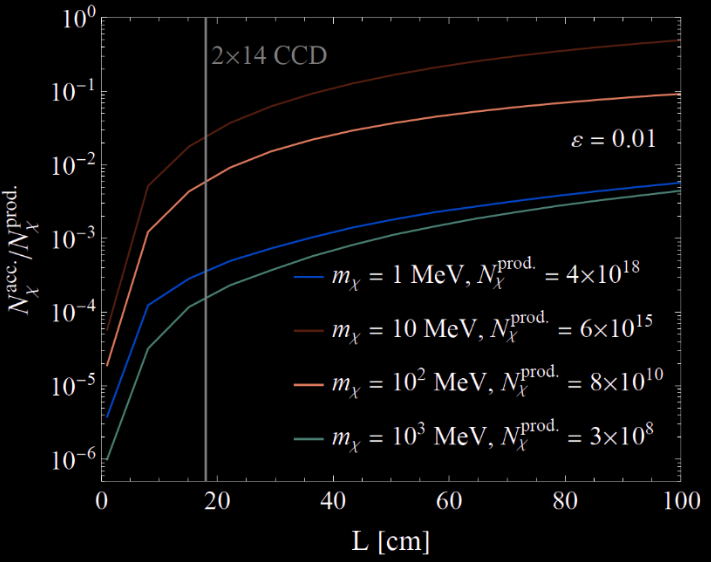
EW Shower Effects

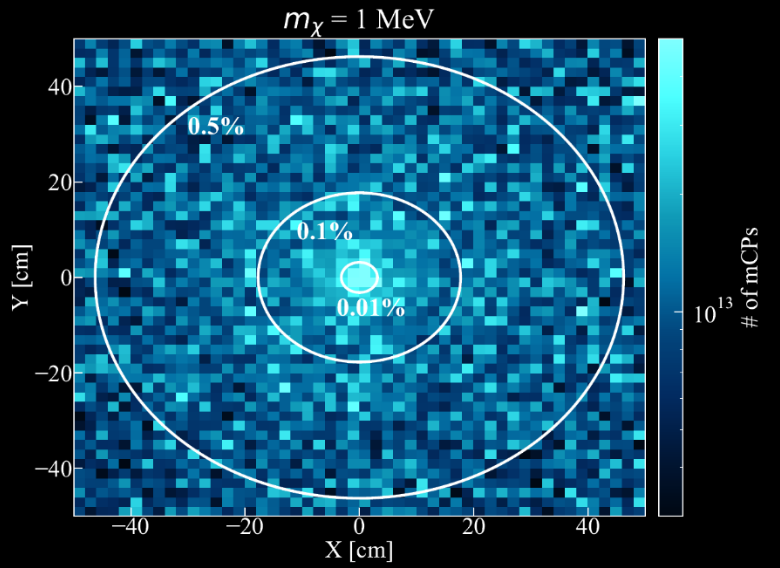


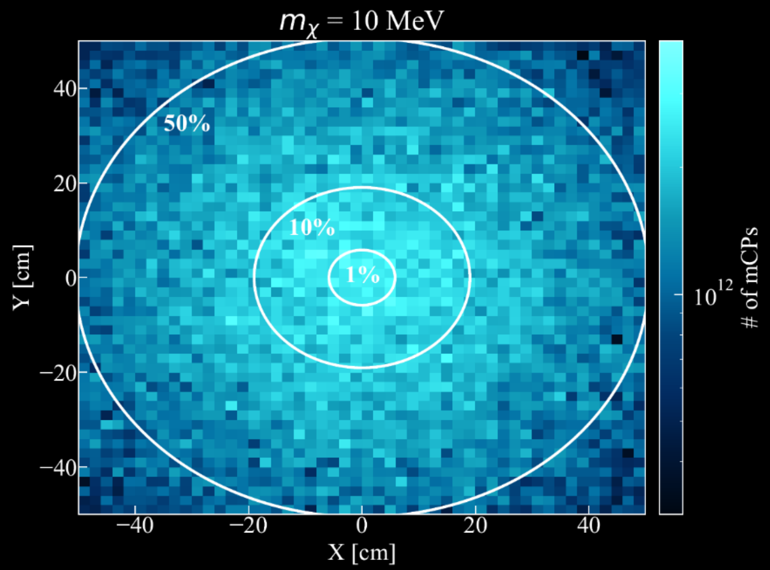


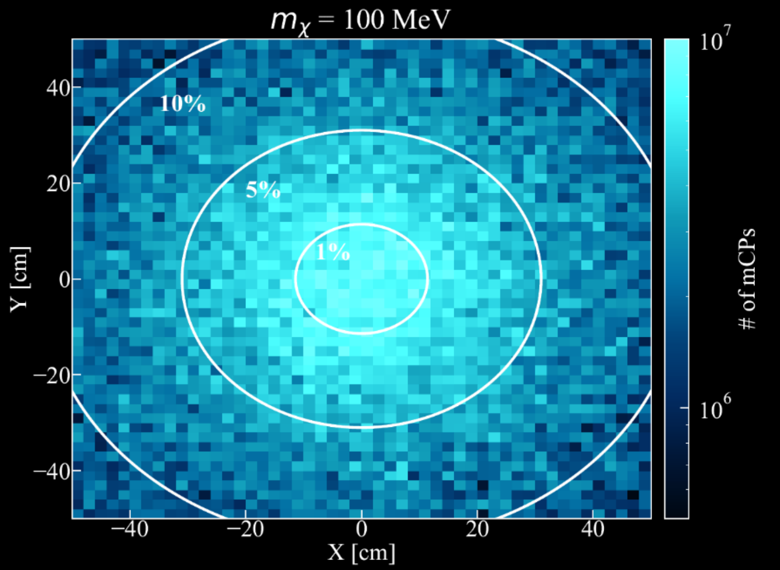
Skipper Responses & Geometric Effects



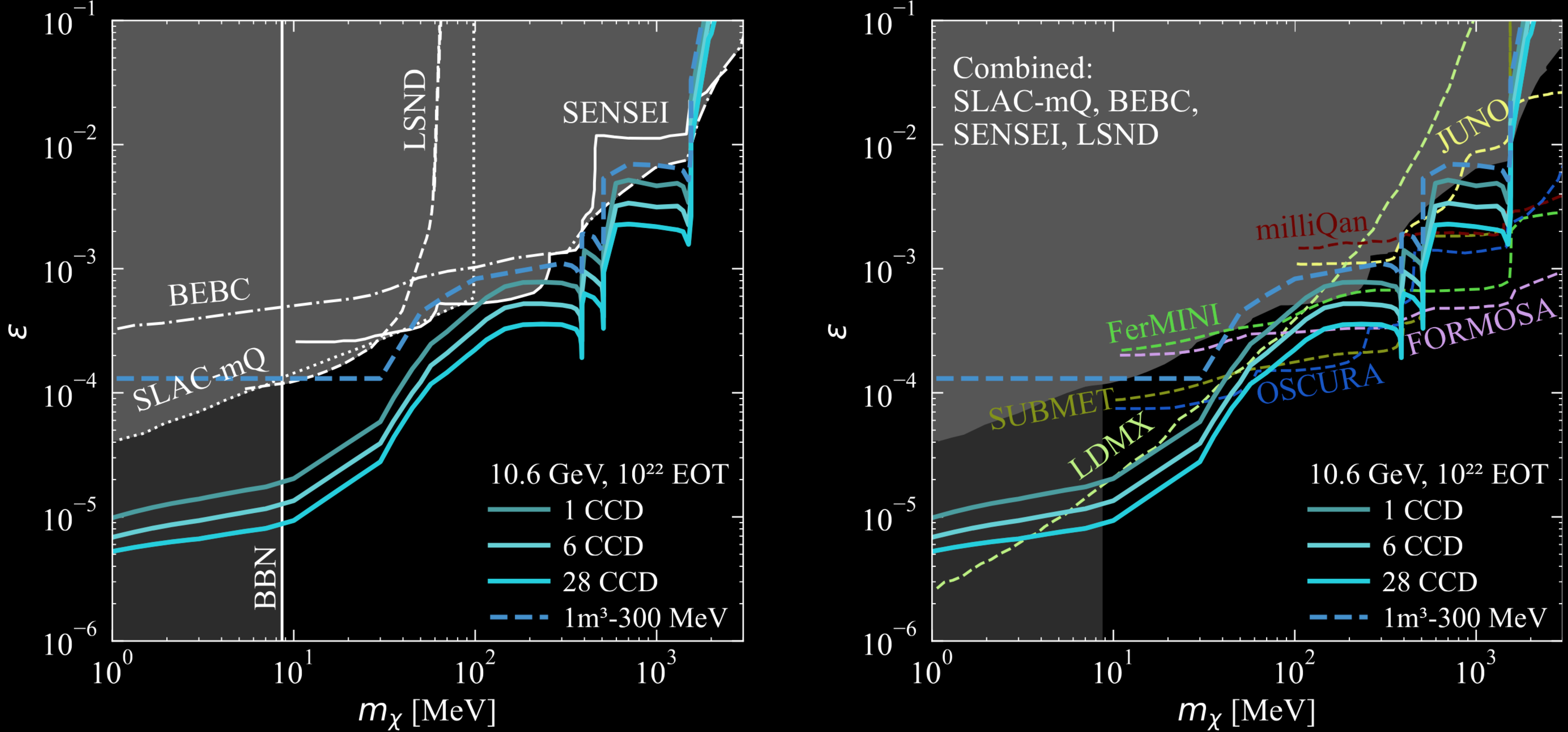


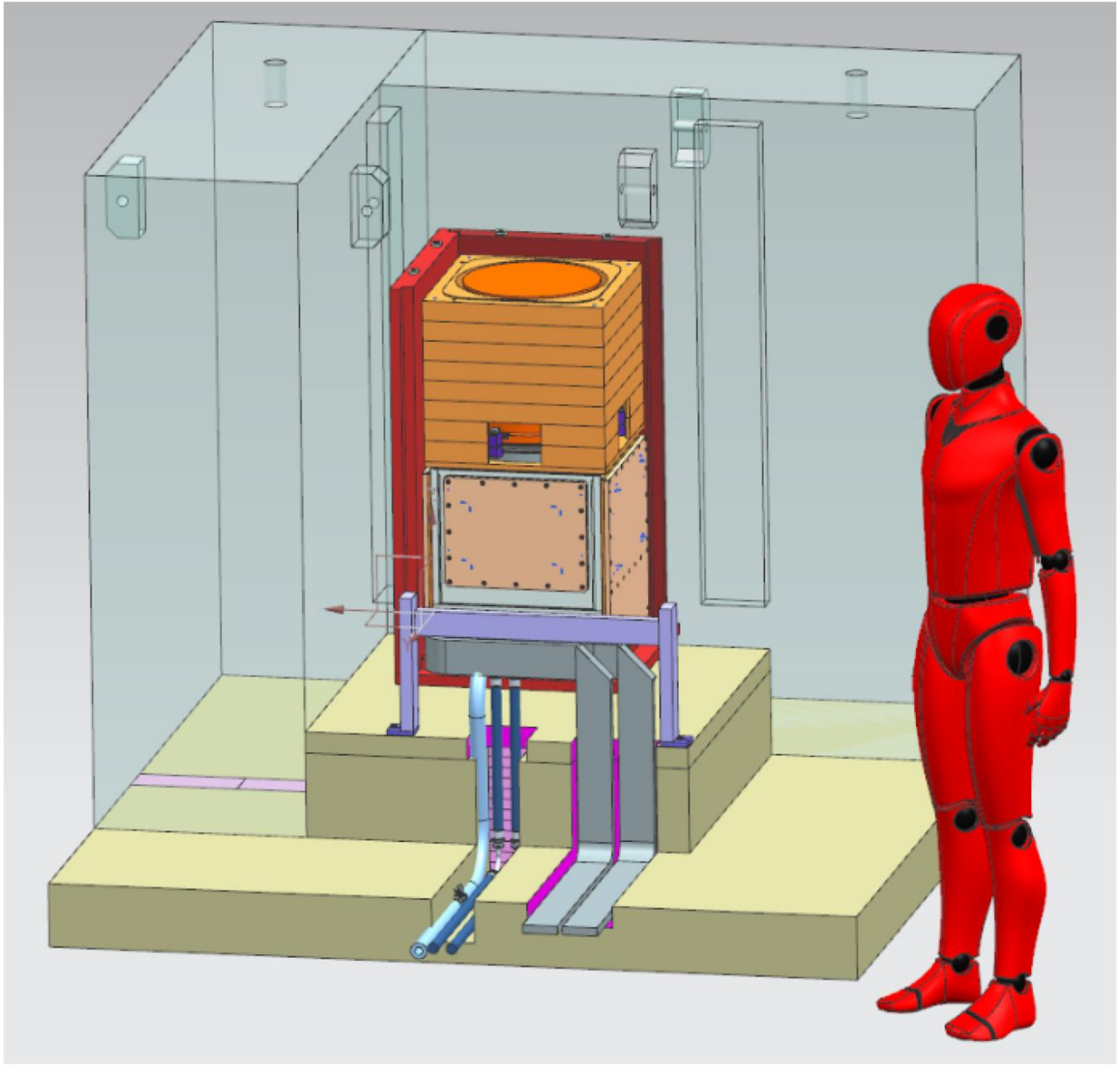


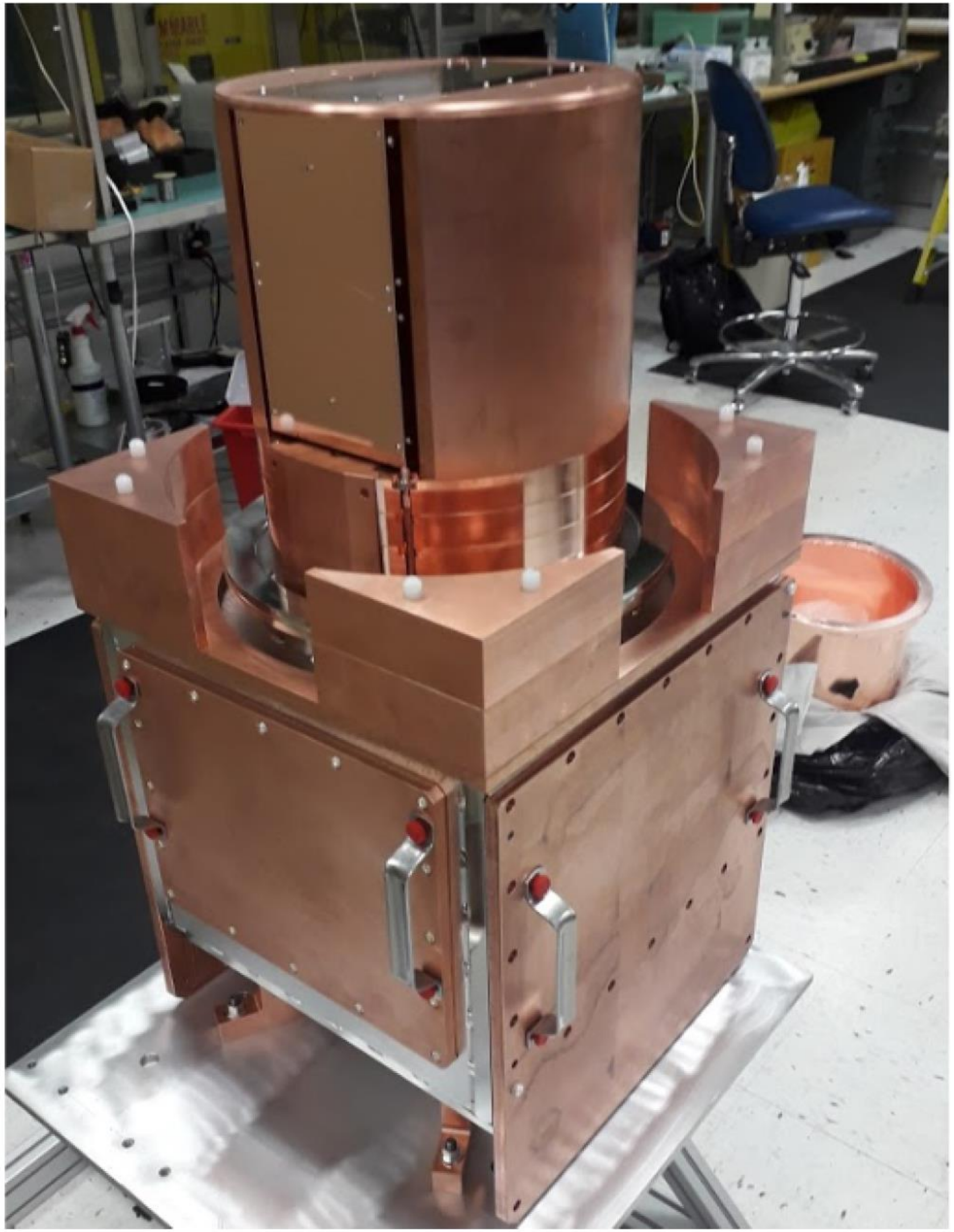




Projections







Good at Excluding. Are we good discovering?

I think so:

- For 1-hit searches: one can test if the excess events follow (this requires a reasonable modeling of backgrounds) the expected behavior:

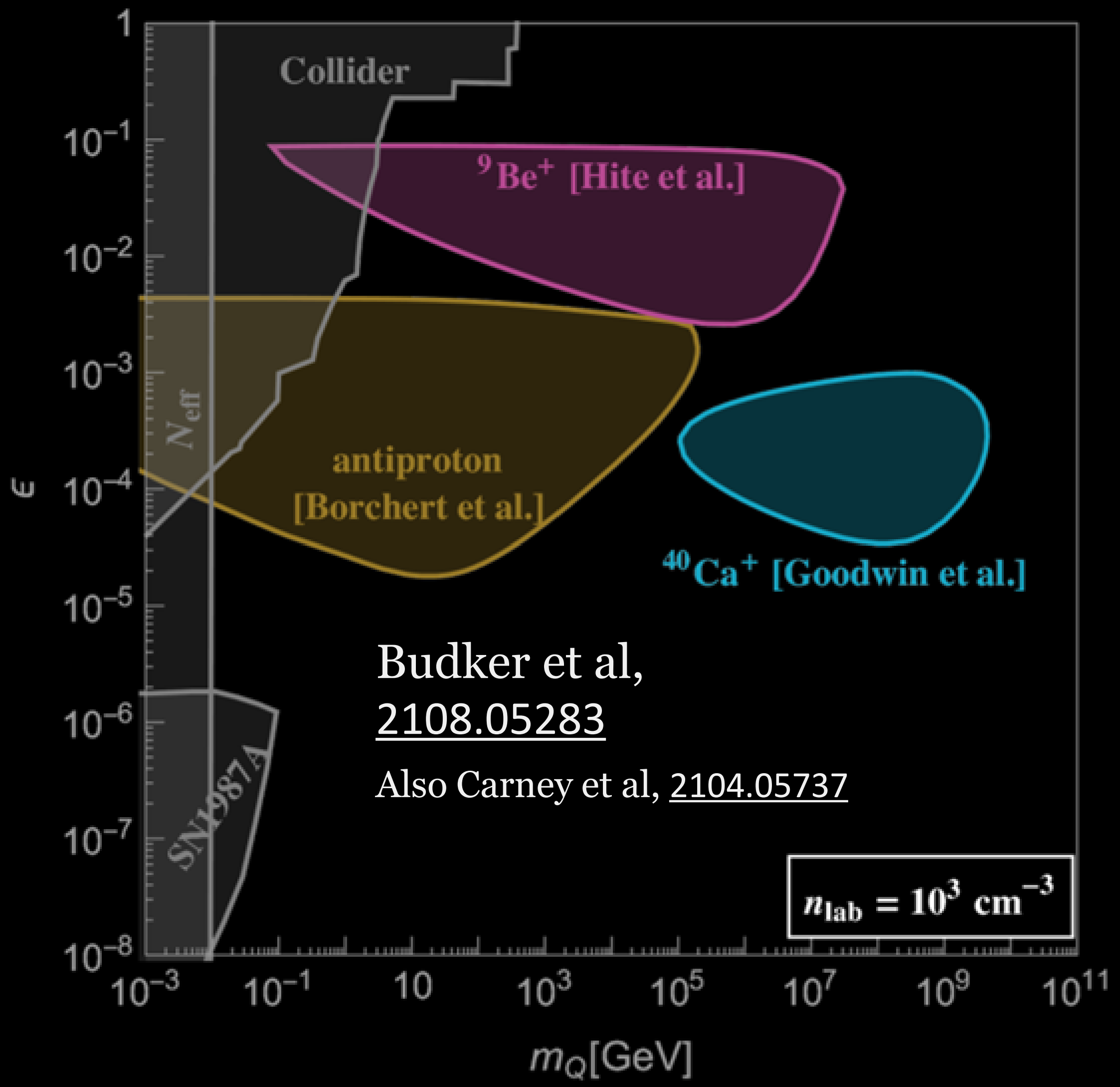
$$\frac{d\sigma}{dE_r} = \pi\alpha^2\epsilon^2 \frac{2E_\chi^2 m_e + E_r^2 m_e - E_r\left(m_\chi^2 + m_e(2E_\chi + m_e)\right)}{E_r^2(E_\chi^2 - m_\chi^2)m_e^2}$$

- For double hit searches in LArTPC: one can additionally check the mean distance distribution between the hits
- This is not true for some other mCP searches

Fast developing frontier:

Beyond beam production, we can have:

- Atmospheric production of MCPs
- Local (and collected) abundance of MCP (a fraction of) DM, enabling new searches such as using ion-trap heating or cavity-like experiment
- MCP production prediction improvement (for all beam sourced MCPs)



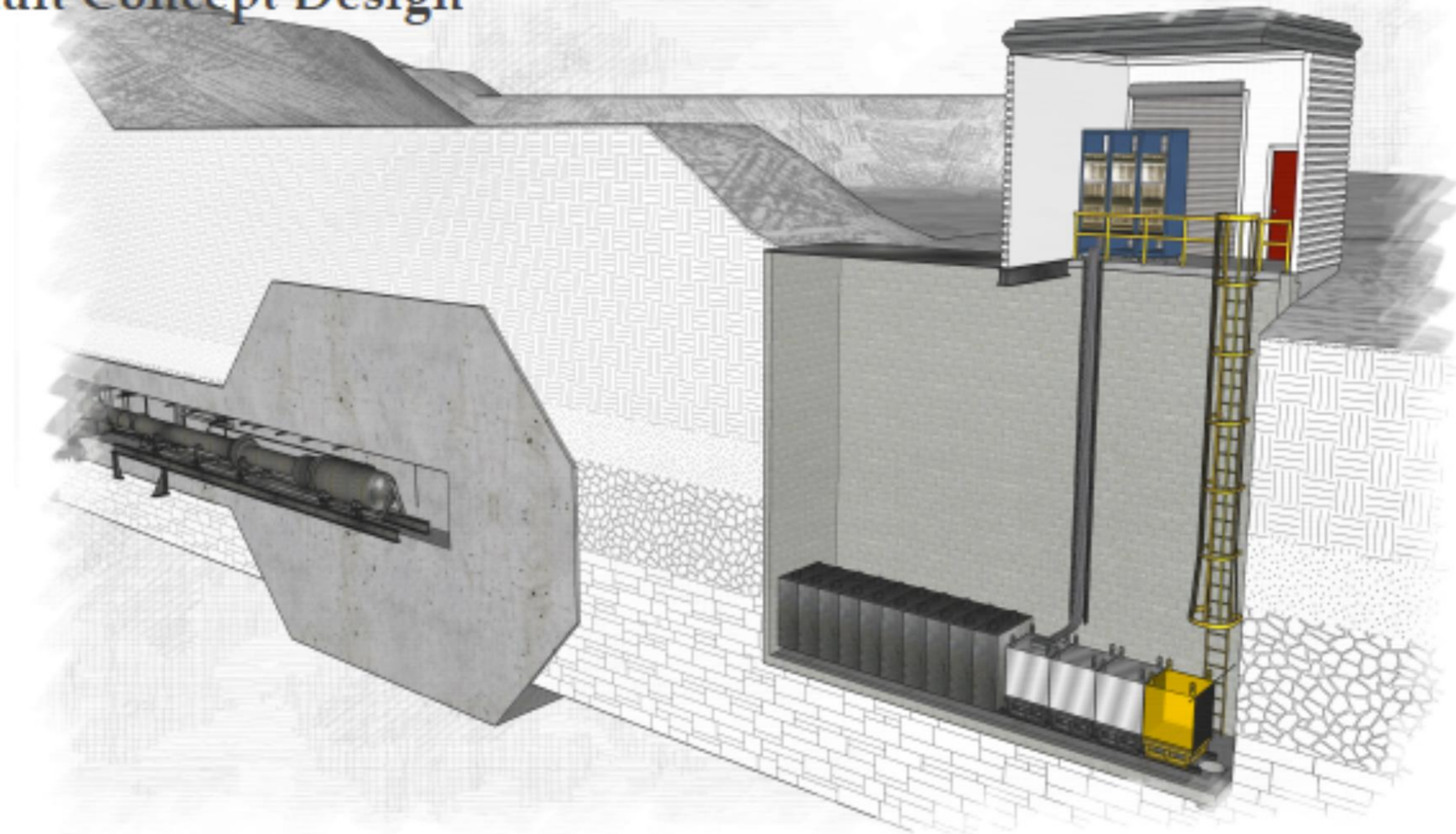
Budker et al, 2108.05283

Also Carney et al, 2104.05737

Summary

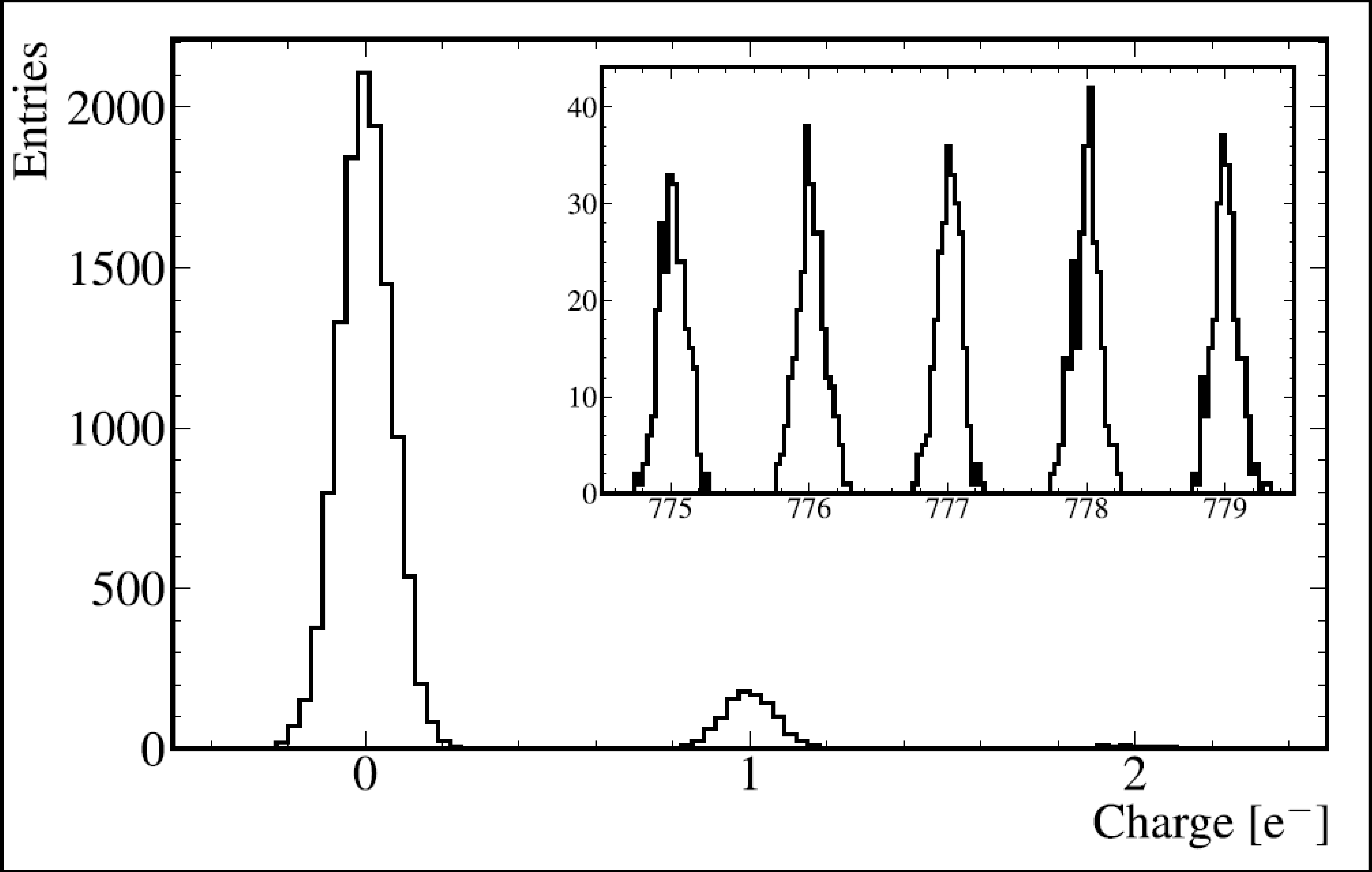
- Exciting opportunity
- Exciting work ahead

Beam Dump Experiment (BDX)
Vault Concept Design



Power consumption

Subsystem	Component	Power Consumption
Vacuum System	Turbo pump + backing pump	100–300 W
Cryogenic Cooling	Cryocooler	300–600 W
Readout Electronics	Controller + digitizers	50–150 W
Computing	Control + local storage	200-300 W


Entries
2000
1500
1000
500
0
0
1
2
Charge [e⁻]
40
30
20
10
0
775
776
777
778
779

$$\frac{d\sigma}{d\omega}(\omega,\varepsilon) = \frac{2\alpha\varepsilon^2}{n_e\pi\beta^2}\int dk \left\{ \frac{1}{k}\mathrm{Im}\left(\frac{-1}{\epsilon(\omega,k)}\right) + k\left(\beta^2 - \frac{\omega^2}{k^2}\right)\mathrm{Im}\left(\frac{1}{-k^2+\epsilon(\omega,k)\omega^2}\right)\right\}$$