LDMA 2025

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

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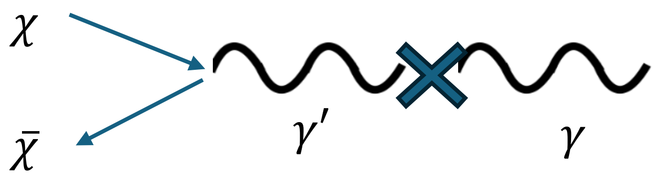
Theoretical Motivation for millicharged particles

Millicharged particle (mCP) (χ) has mass m_χ and charge $Q_\chi = \varepsilon e$.

- mCP are not forbidden by the SM and have not yet been ruled out.
- Charge quantization is not yet fully understood. Some theories include:
  - Grand Unification Theories (GUTs)
  - String theory
- mCP *may* be a dark matter candidate.
- Two common mCP models:



<u>Pure mCP:</u>

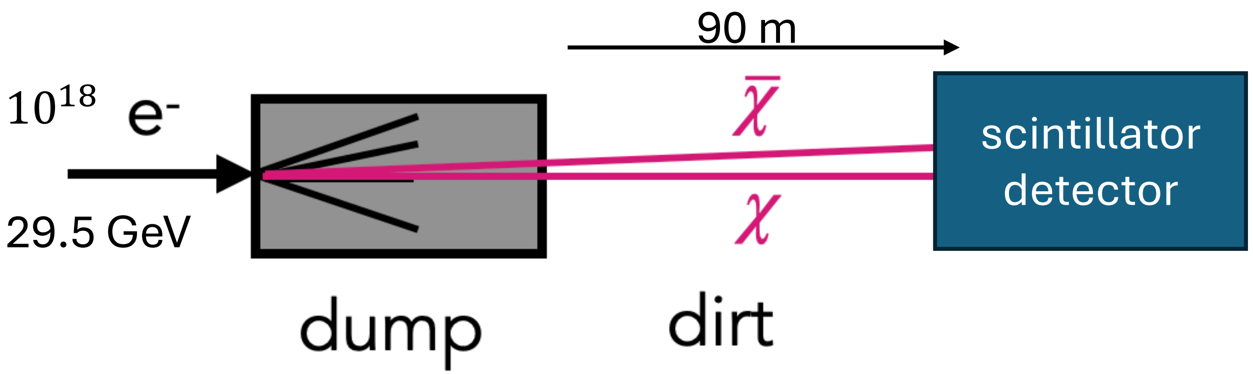
1. No hidden U(1) [dark photon] needed
2. Prediction from String theory
3. Rational or irrational charge, Q_χ
4. No annihilation channel to γ'

<u>Effective mCP:</u>

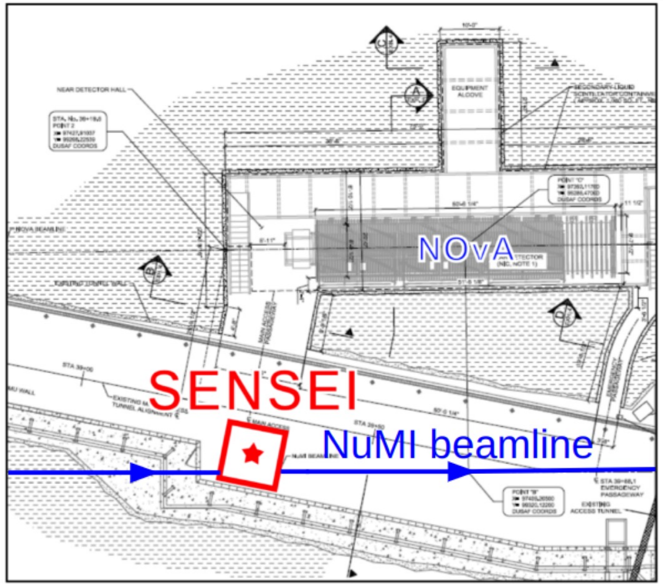
1. Hidden U(1) required
2. Predicted by GUTs
3. Dark photon kinetically mixes with SM photon
4. Annihilation to γ' -> γ ; affects CMB (ΔN_{eff})

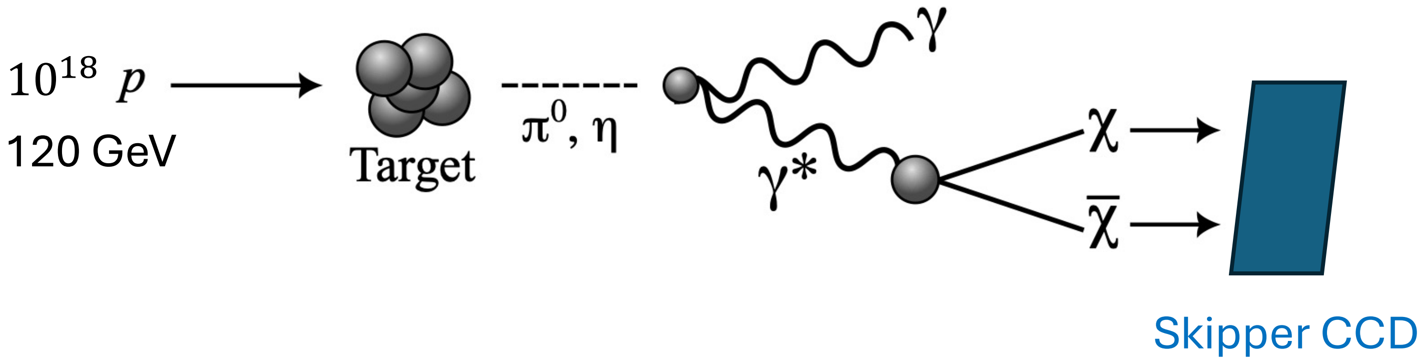
Motivation from previous experimental searches

Electron beam dump: SLAC-mQ



Proton beam dump: SENSEI

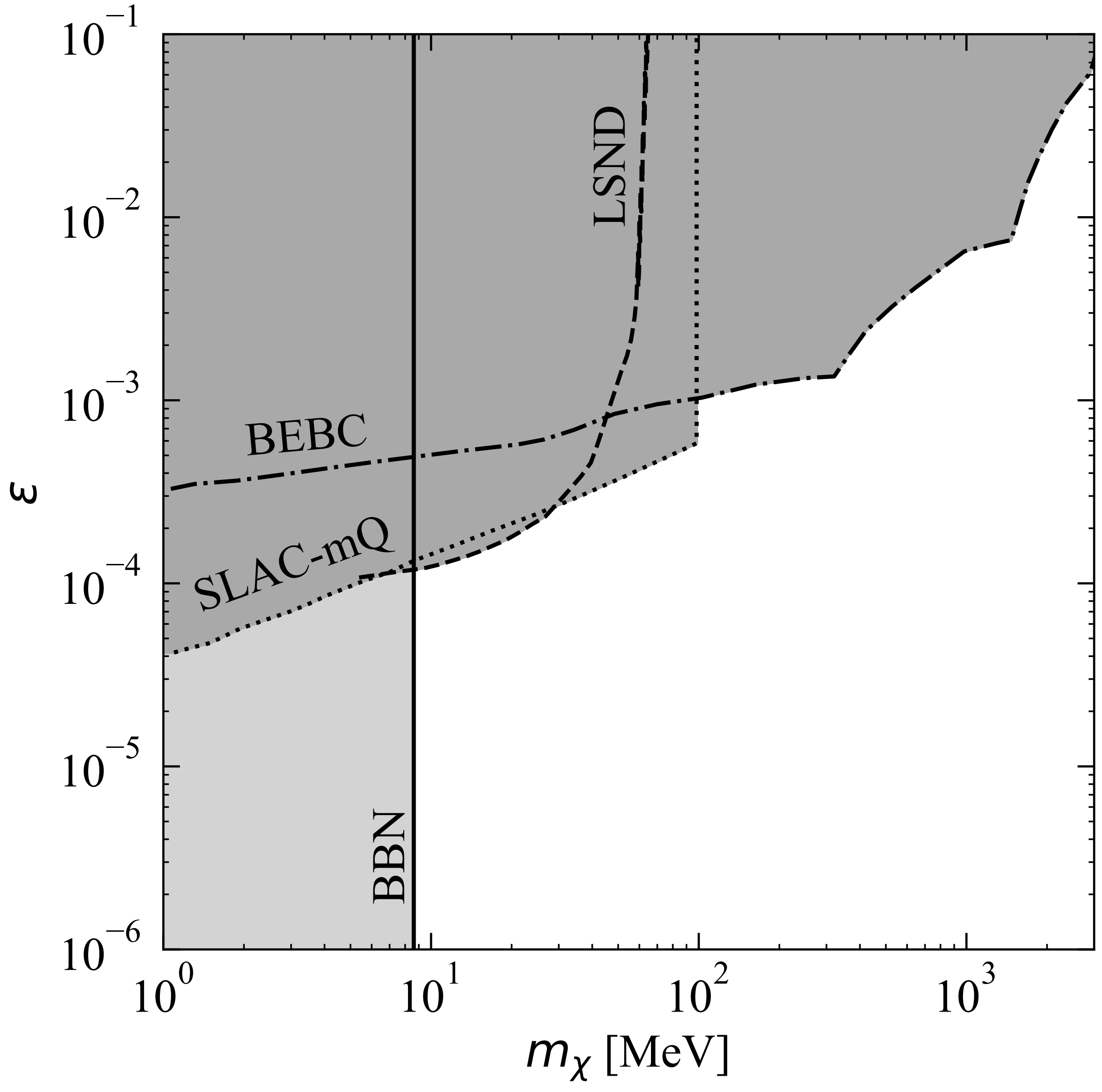




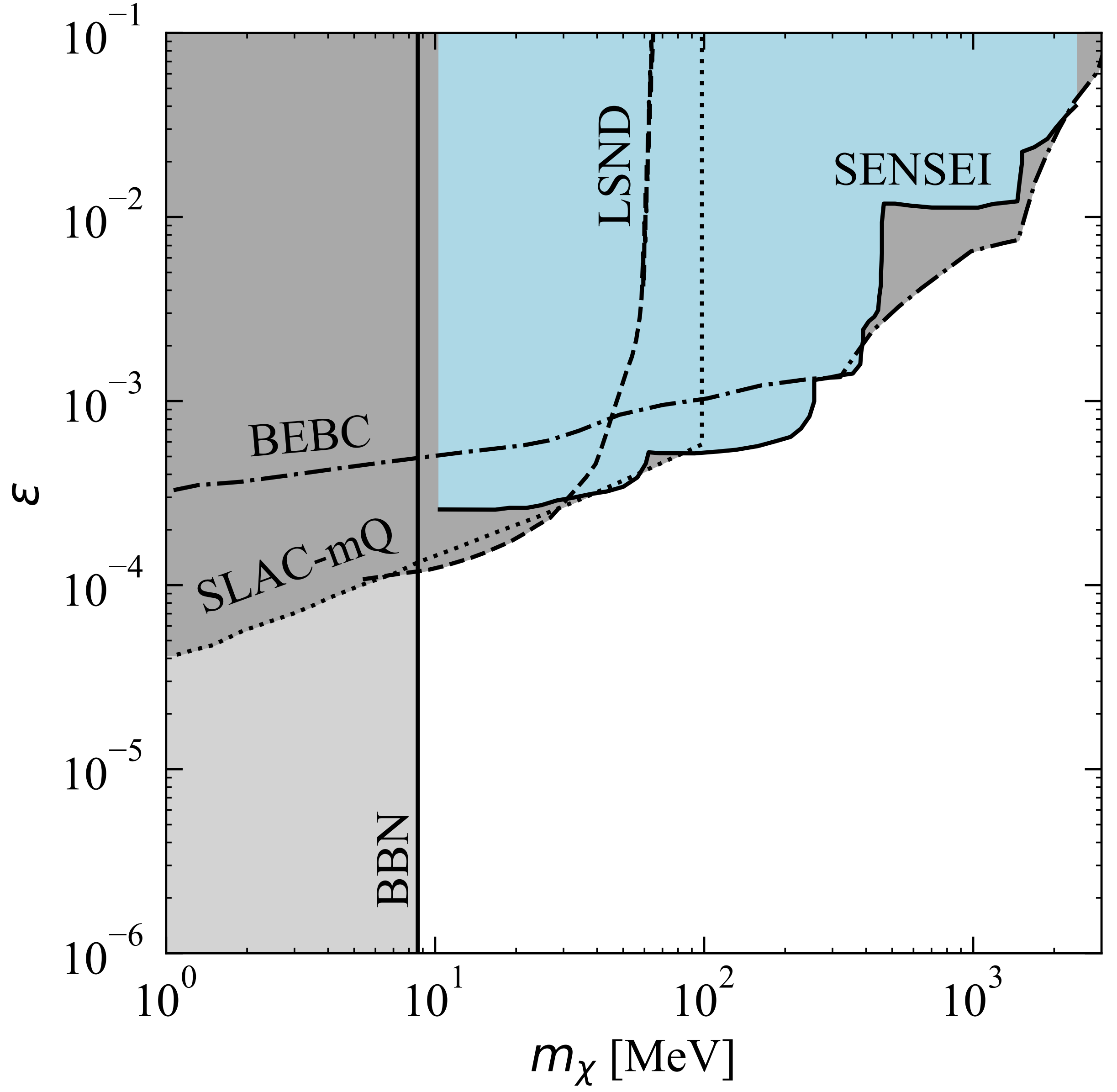
2g Skipper CCD
48 g/days exposure

[2305.04964]

Motivation from previous experimental searches

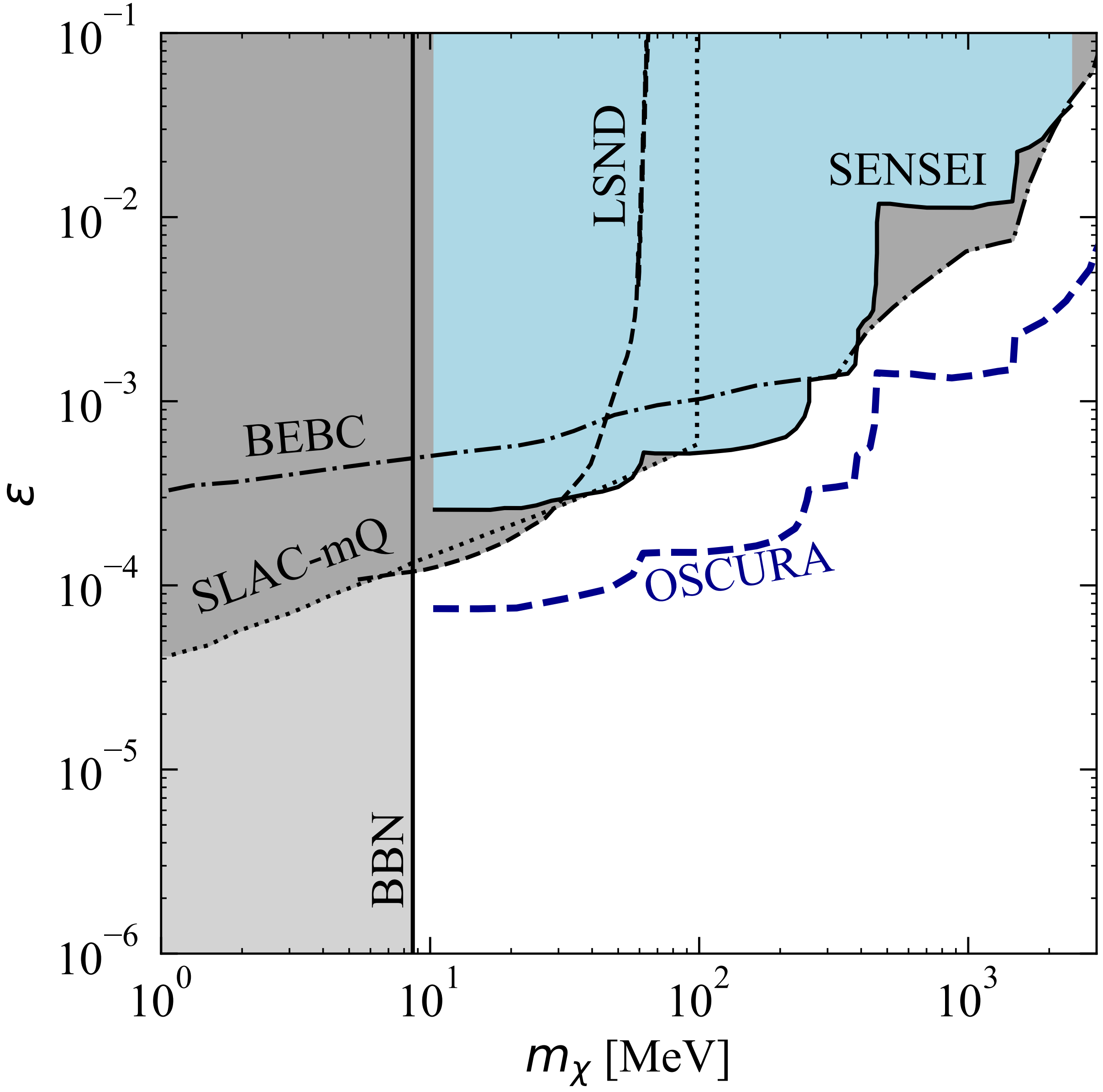


Motivation from previous experimental searches



Motivation from previous experimental searches

Skipper CCDs have become a new and interesting tool to search for mCP at beam dump experiments.

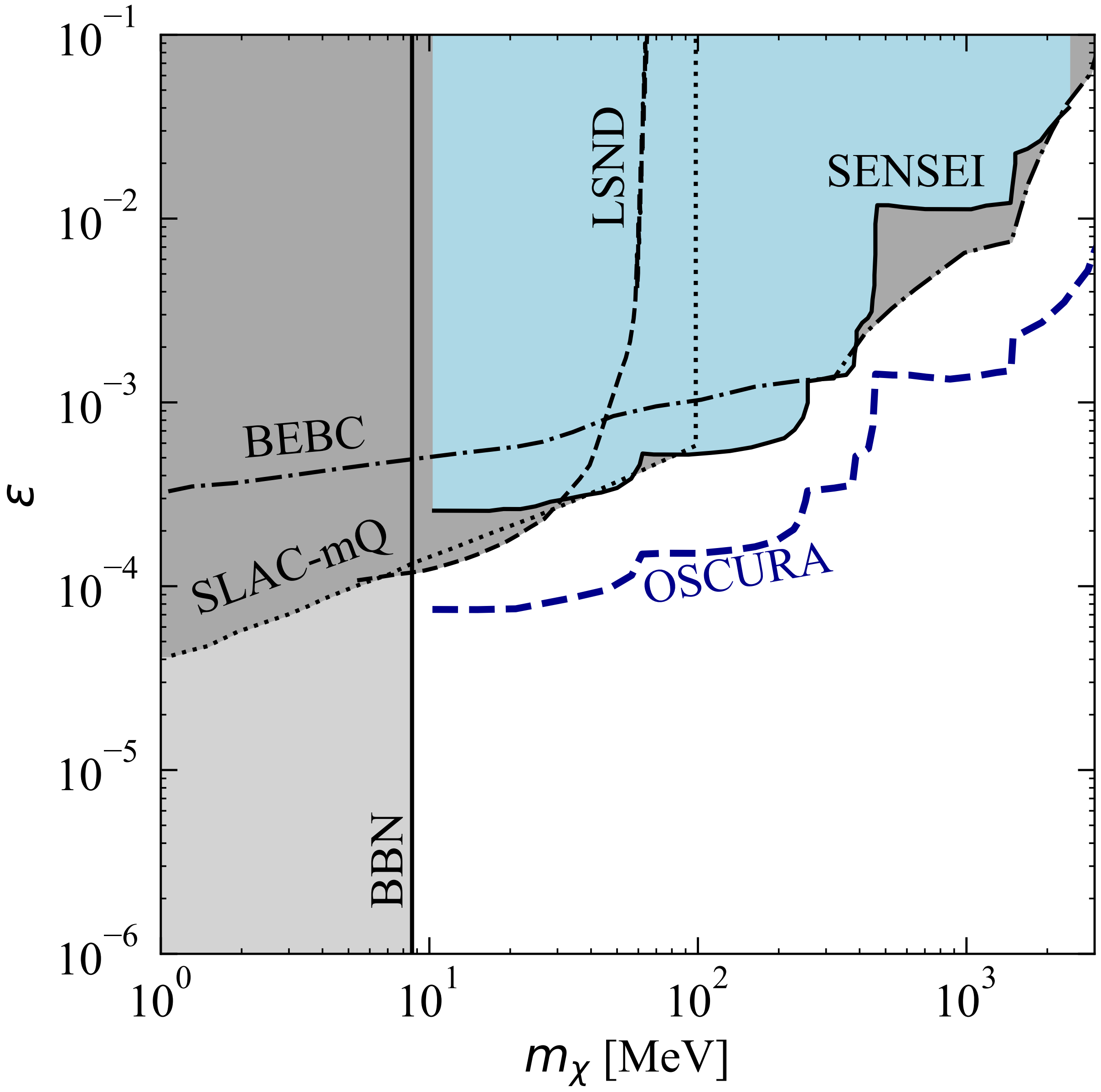


Motivation from previous experimental searches

What if we put a Skipper CCD in front of an electron beam dump with more EOT compared to SLAC?

Can we probe new parameter space? How much?

How difficult/affordable is this to do?



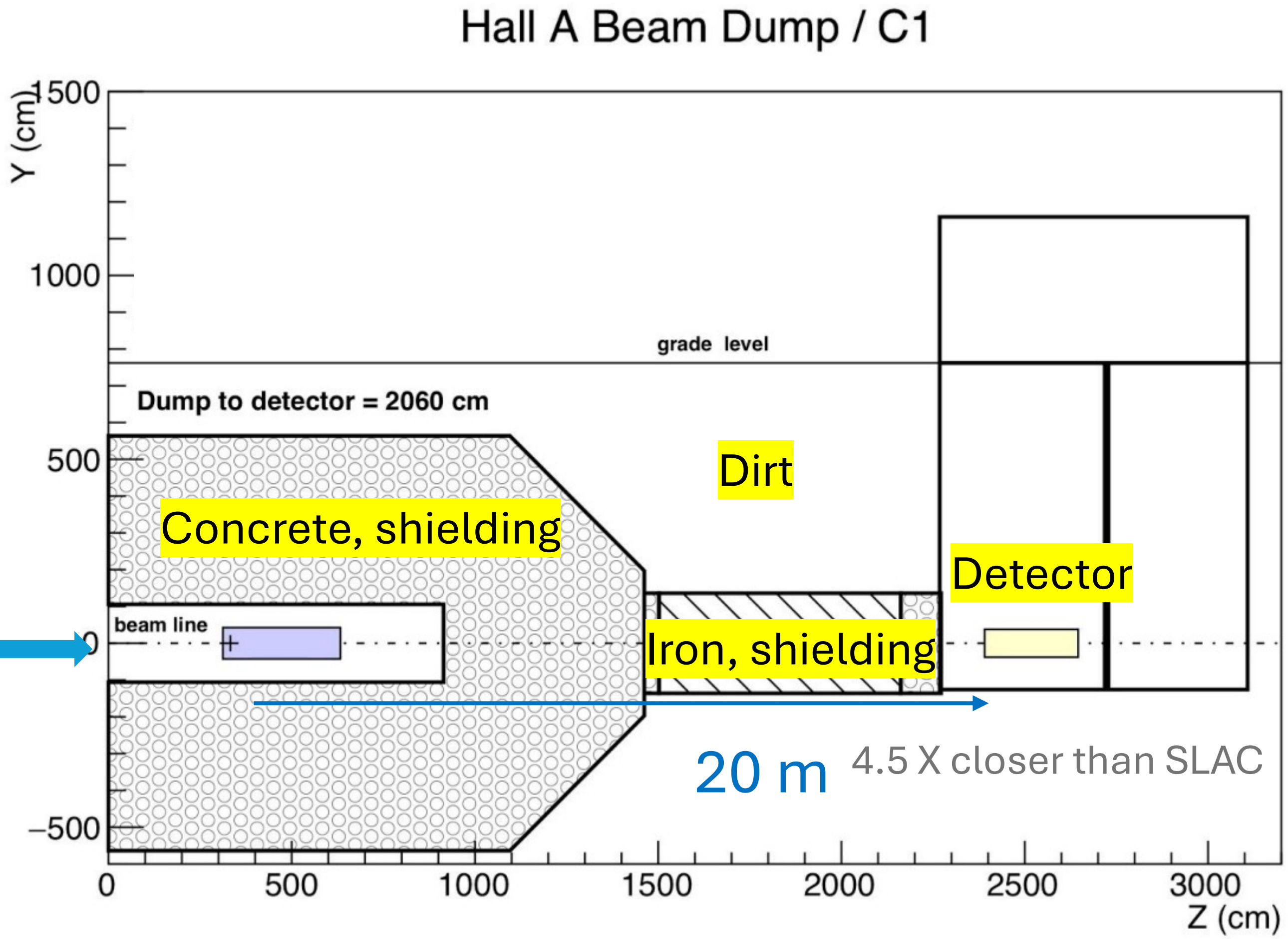
BDX proposal @ JLab : DM search

10^4 more EOT than SLAC

10^{22} EOT

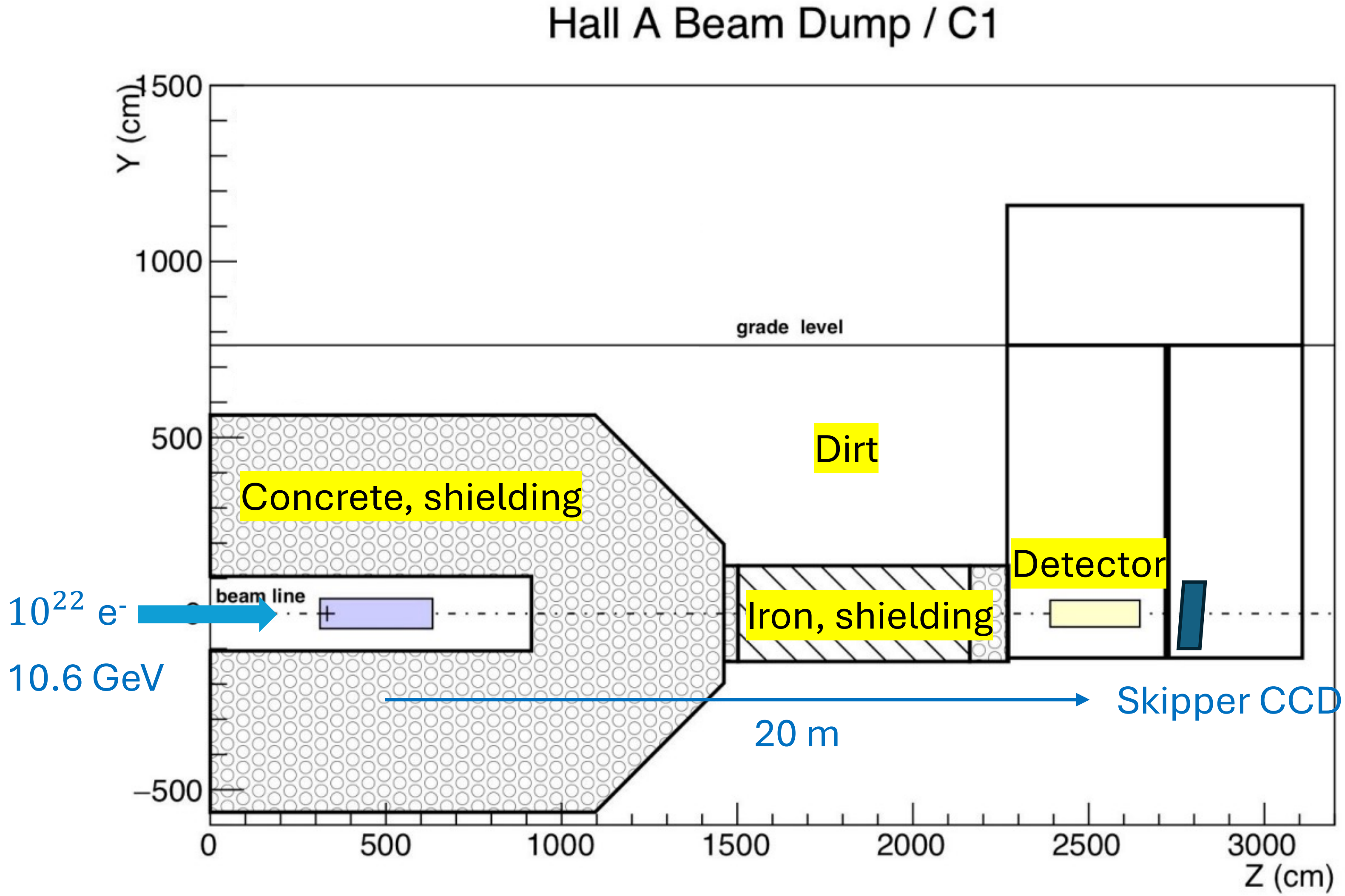
e^-

10.6 GeV



BDX Proposal
Ie. [1910.03532]

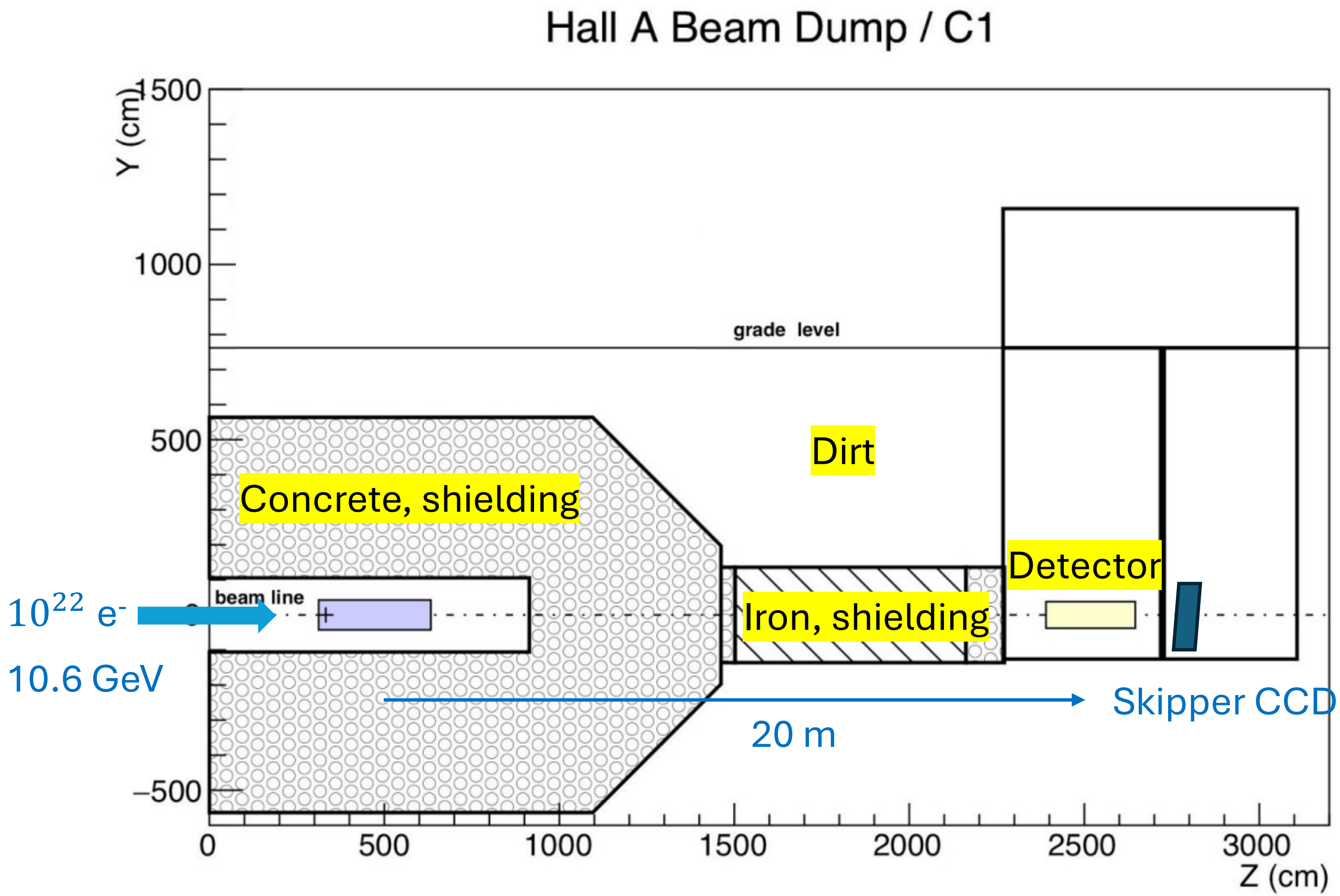
BDX proposal @ JLab + Skipper CCD



Skipper CCDs have demonstrated low background, single electron precision via repeated non-deconstructive read out

2 cm X 10 cm

BDX proposal @ JLab + Skipper CCD



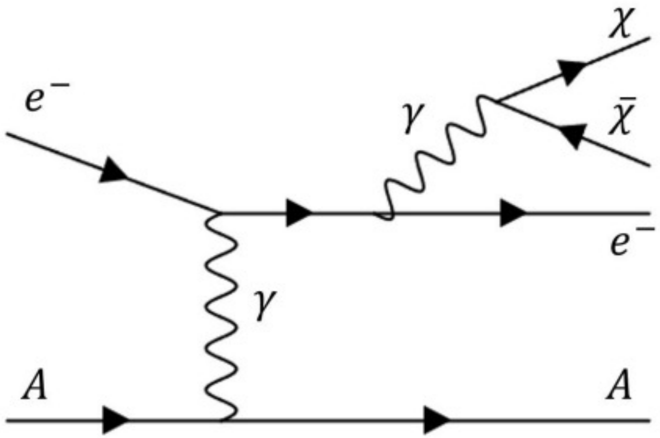
Skipper CCDs have demonstrated low background, single electron precision via repeated non-deconstructive read out

2 cm X 10 cm

How difficult/affordable is this to do?
→ Relatively inexpensive and possible to run parasitic with BDX proposal

mCP production channels at electron beam dumps

Trident



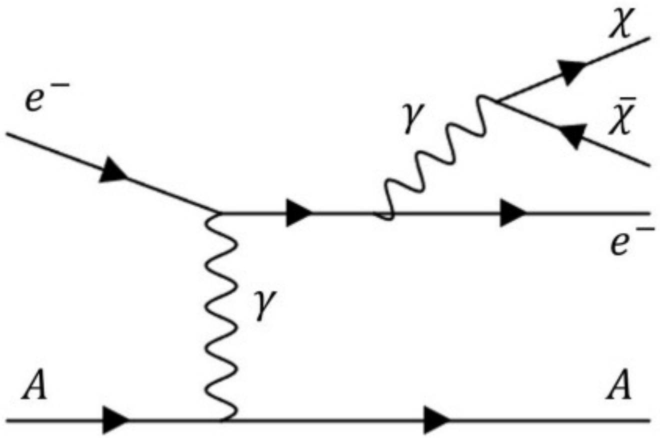
Electron-Positron annihilation

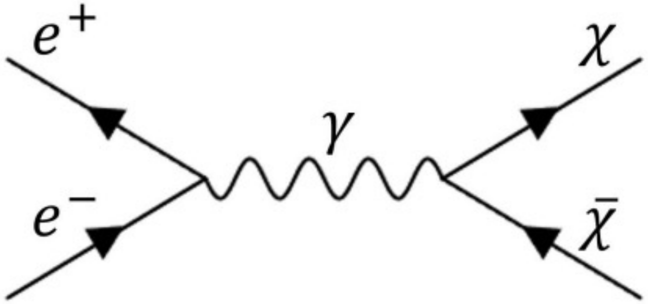
Compton

Vector meson decay

mCP production channels at electron beam dumps: EM cascade of daughter particles (γ, e+, e-)

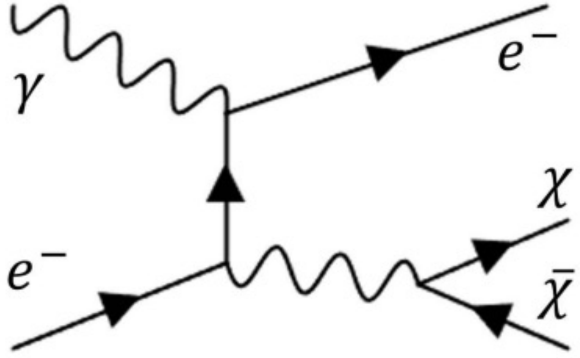
Trident

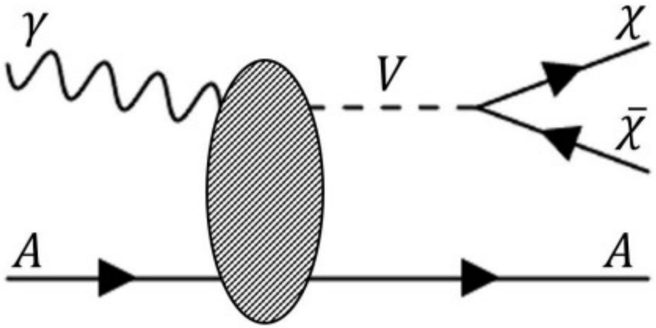




Electron-Positron annihilation

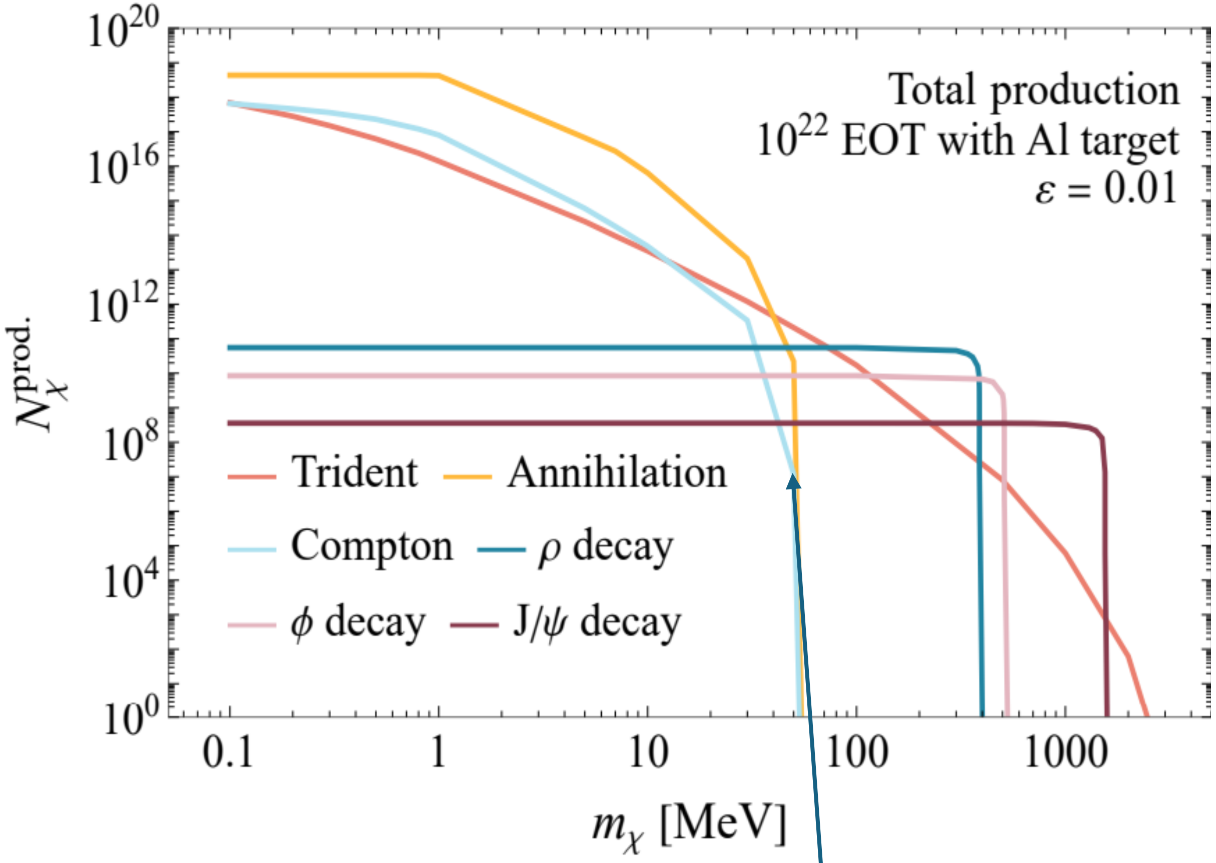
Compton

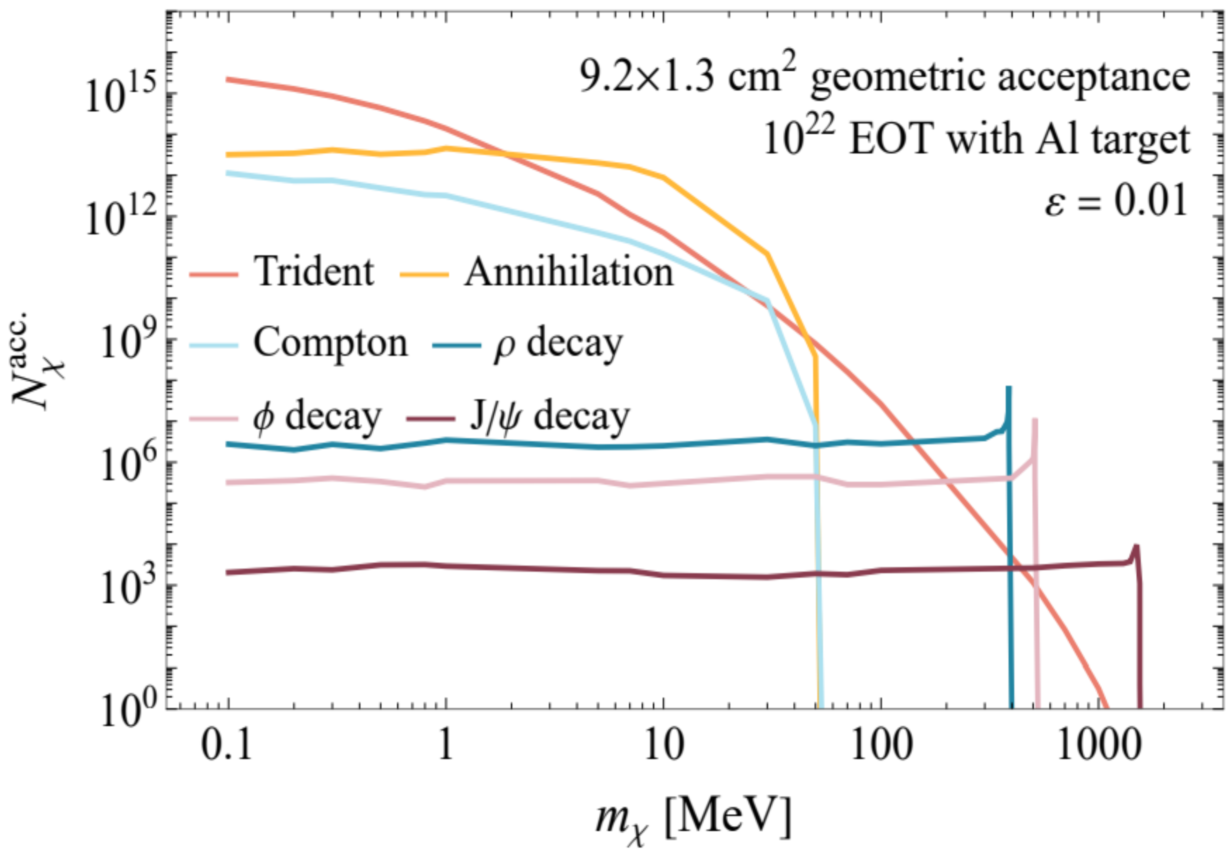




Vector meson decay

mCP production and geometric acceptance

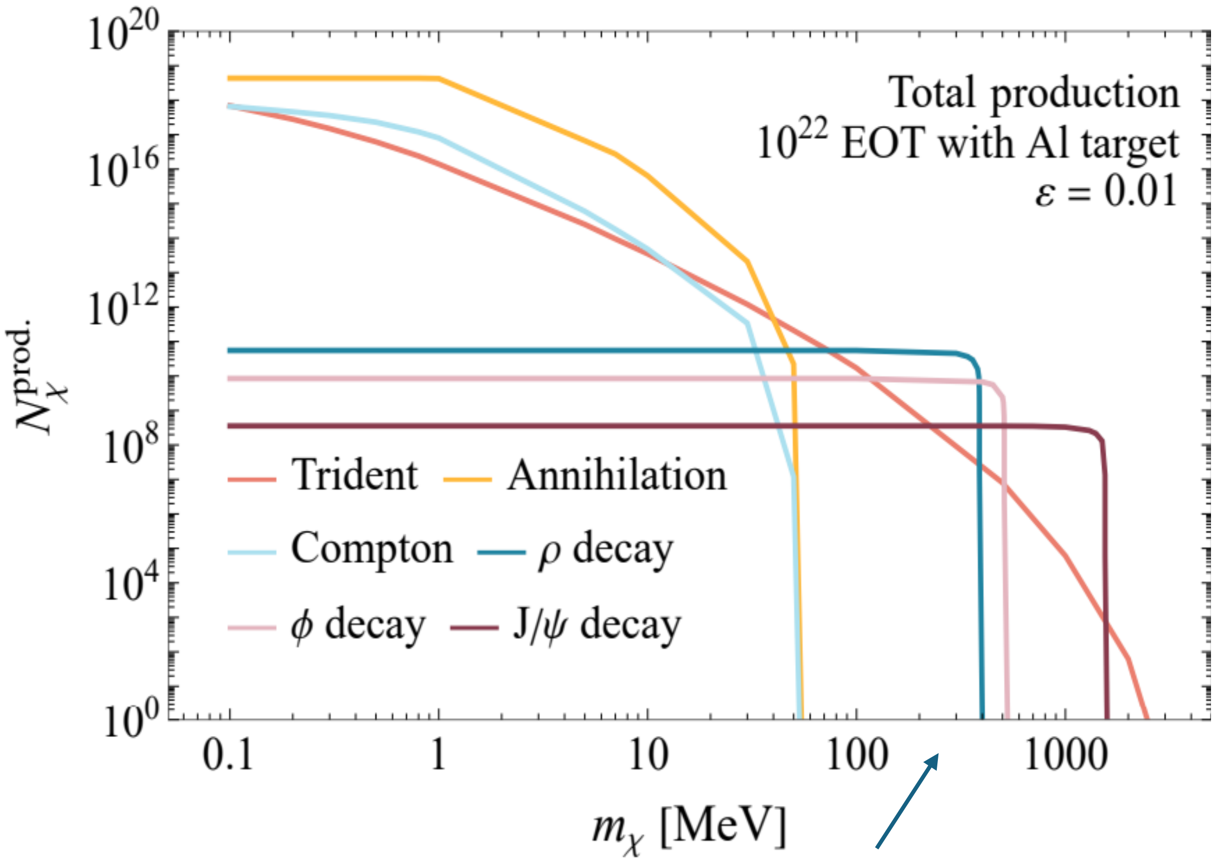


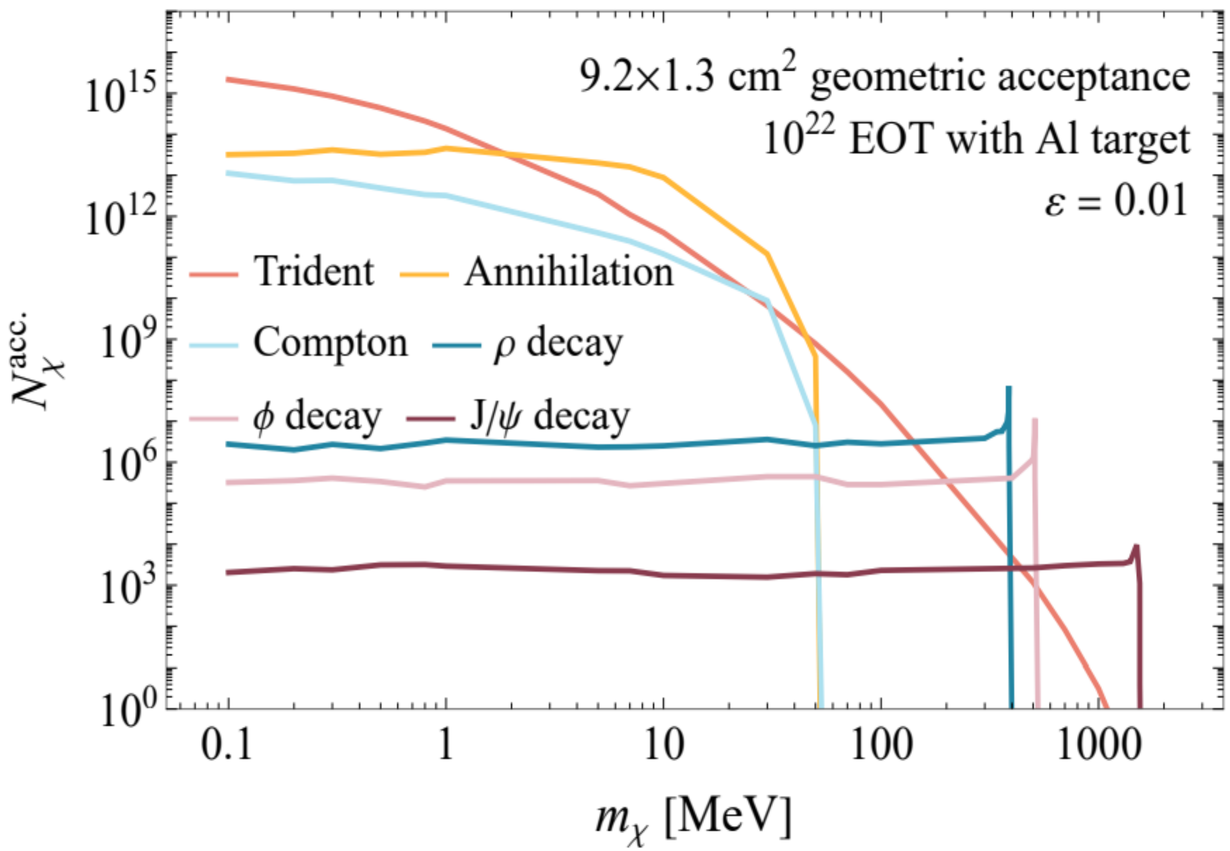


Kinematic Threshold ~50 MeV

Condition: $4m_\chi^2 \sim s = 2meEe + m_e^2$

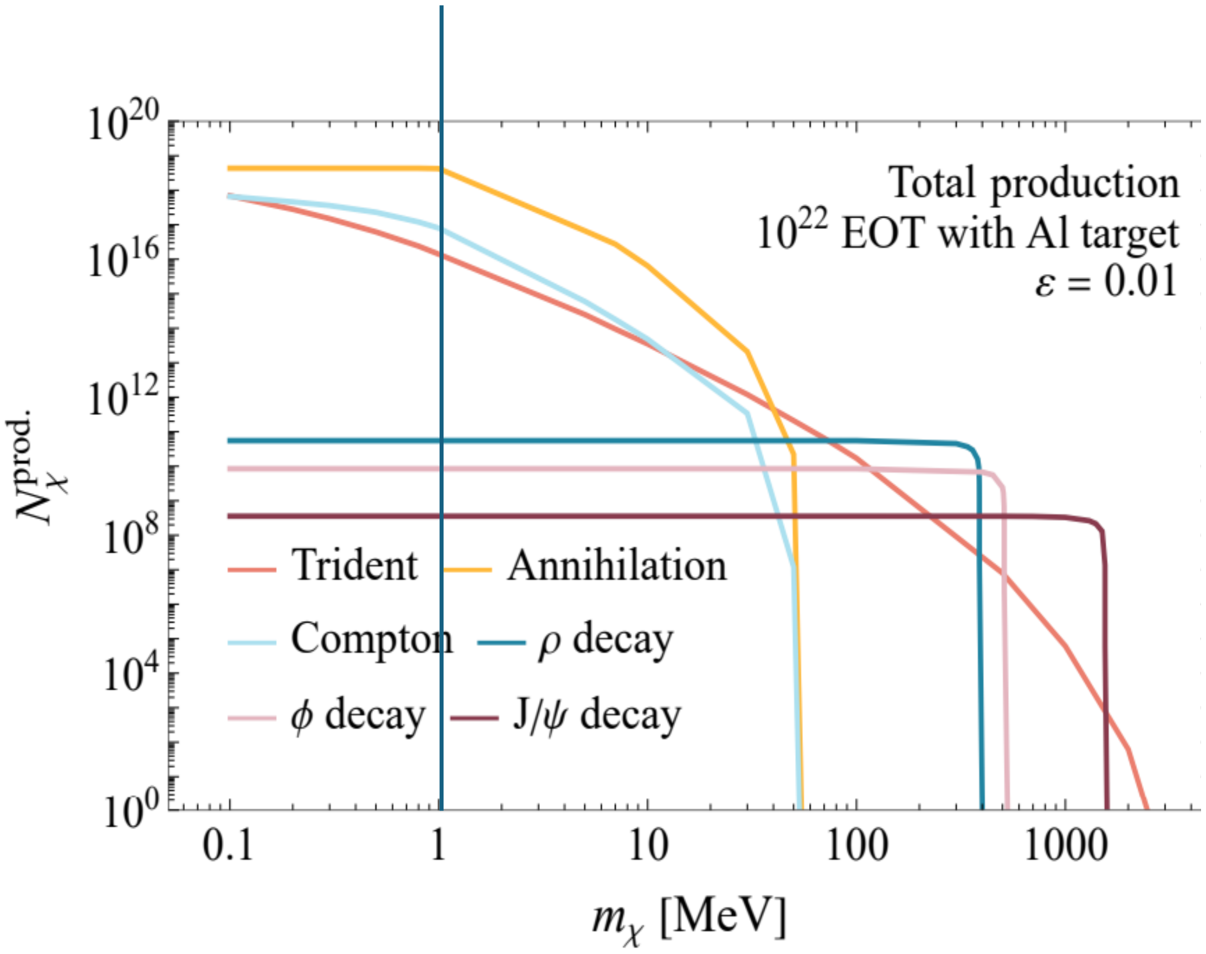
mCP production and geometric acceptance

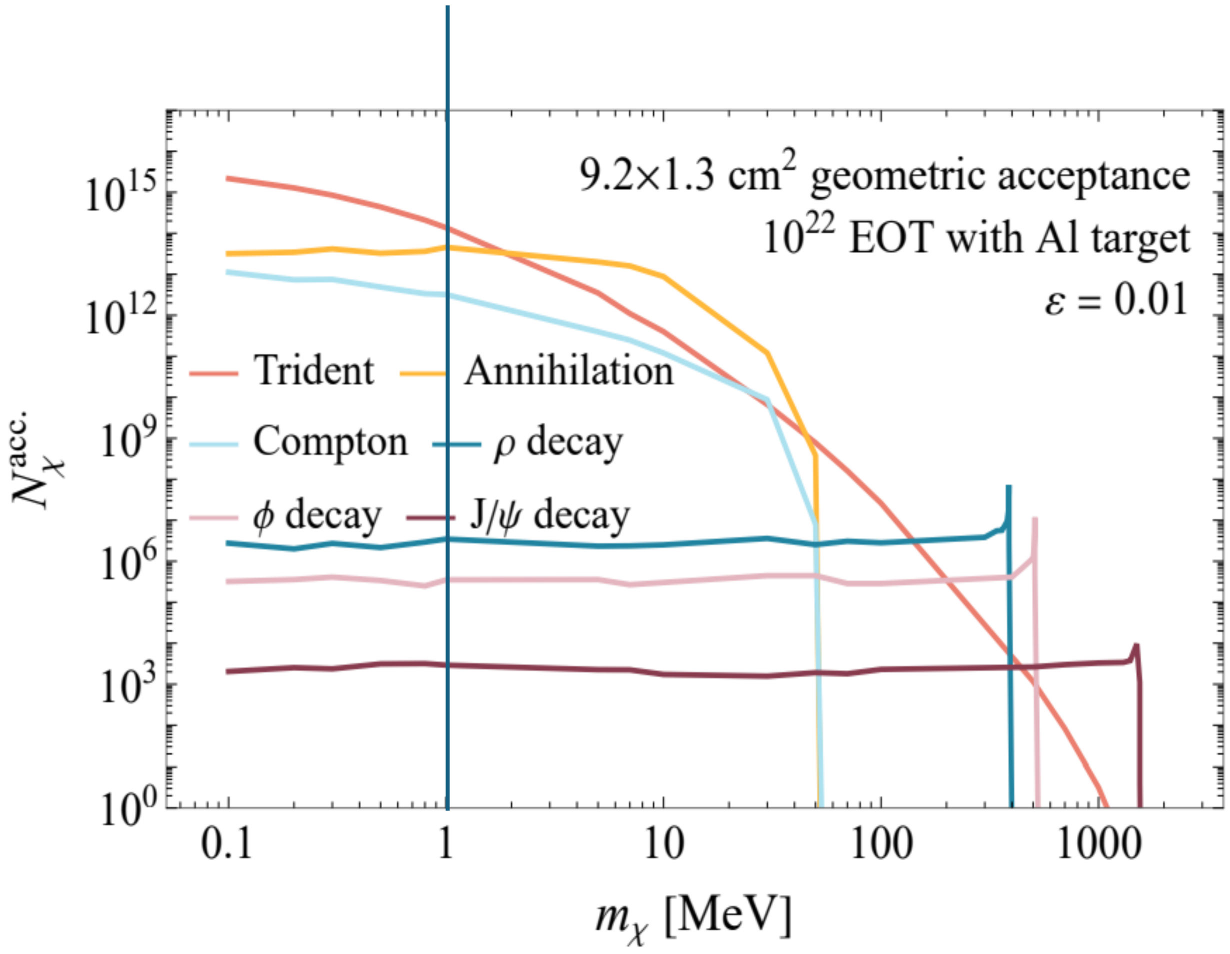




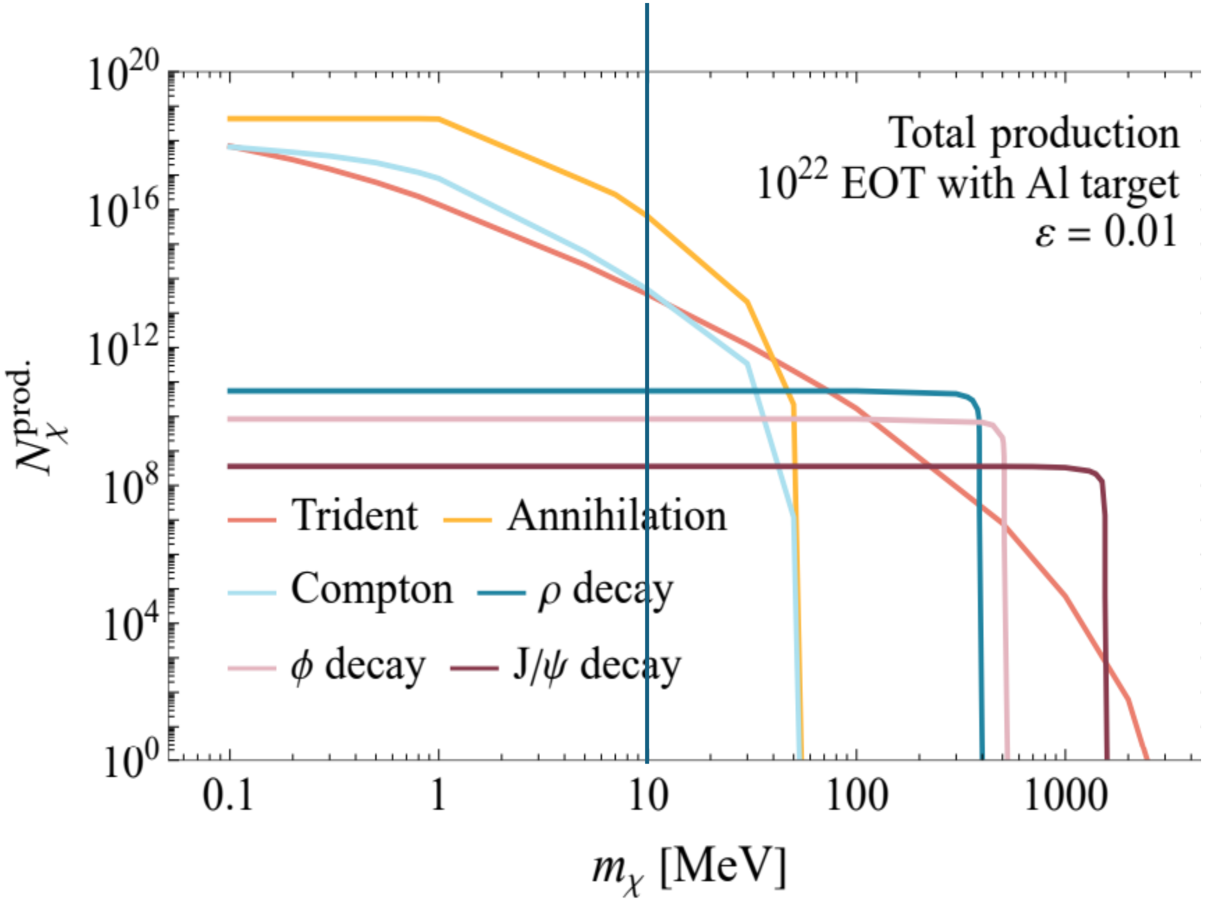
Kinematic Threshold
@ $m_\chi = 0.5\, m_V$

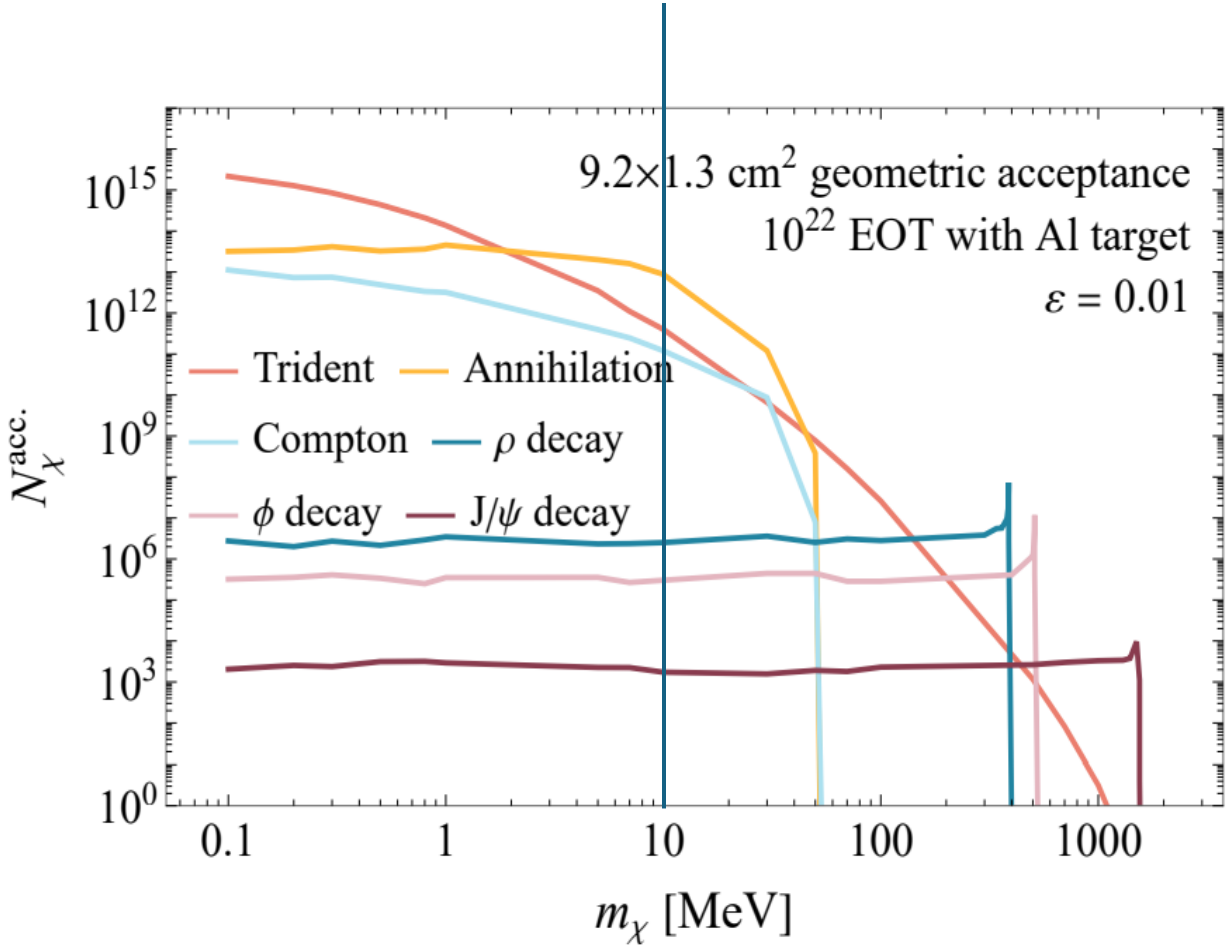
mCP production and geometric acceptance



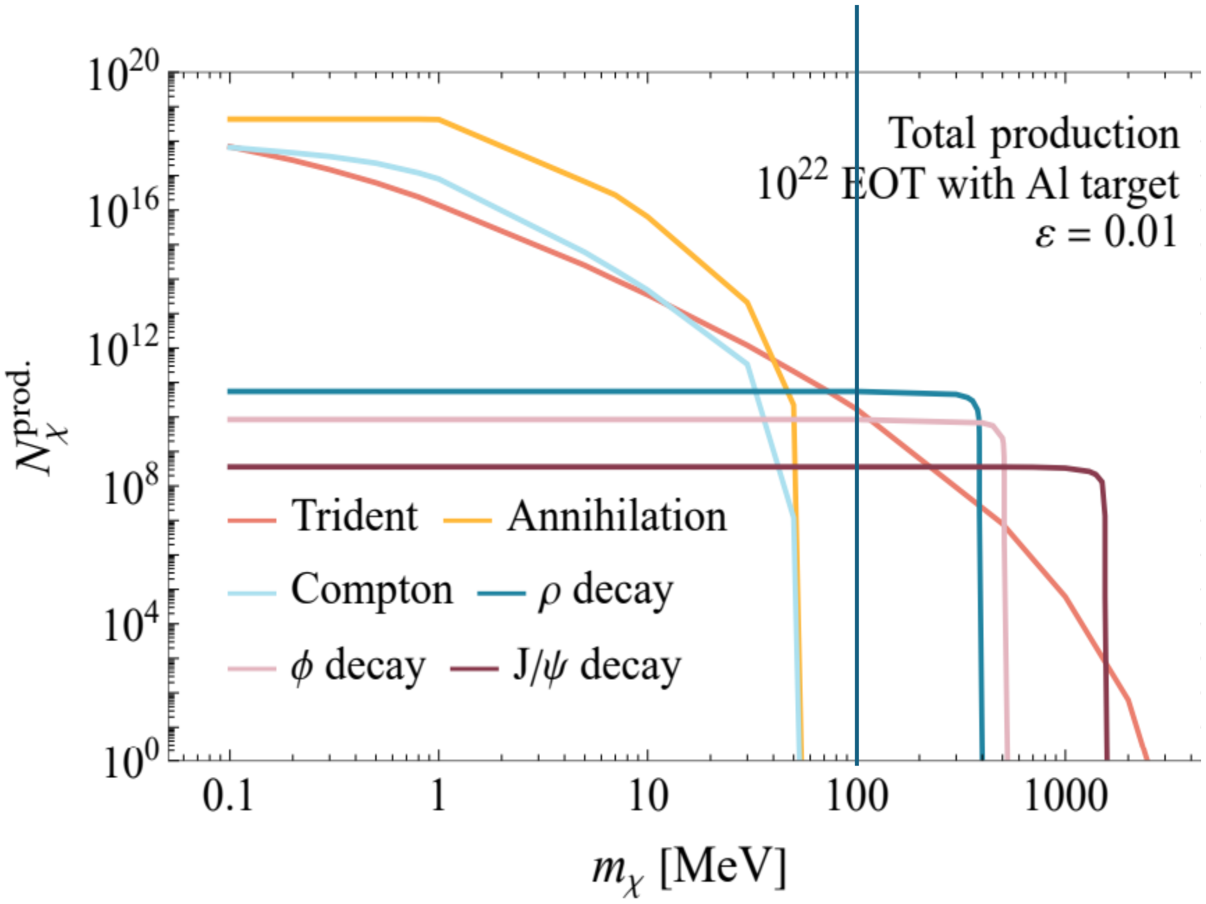


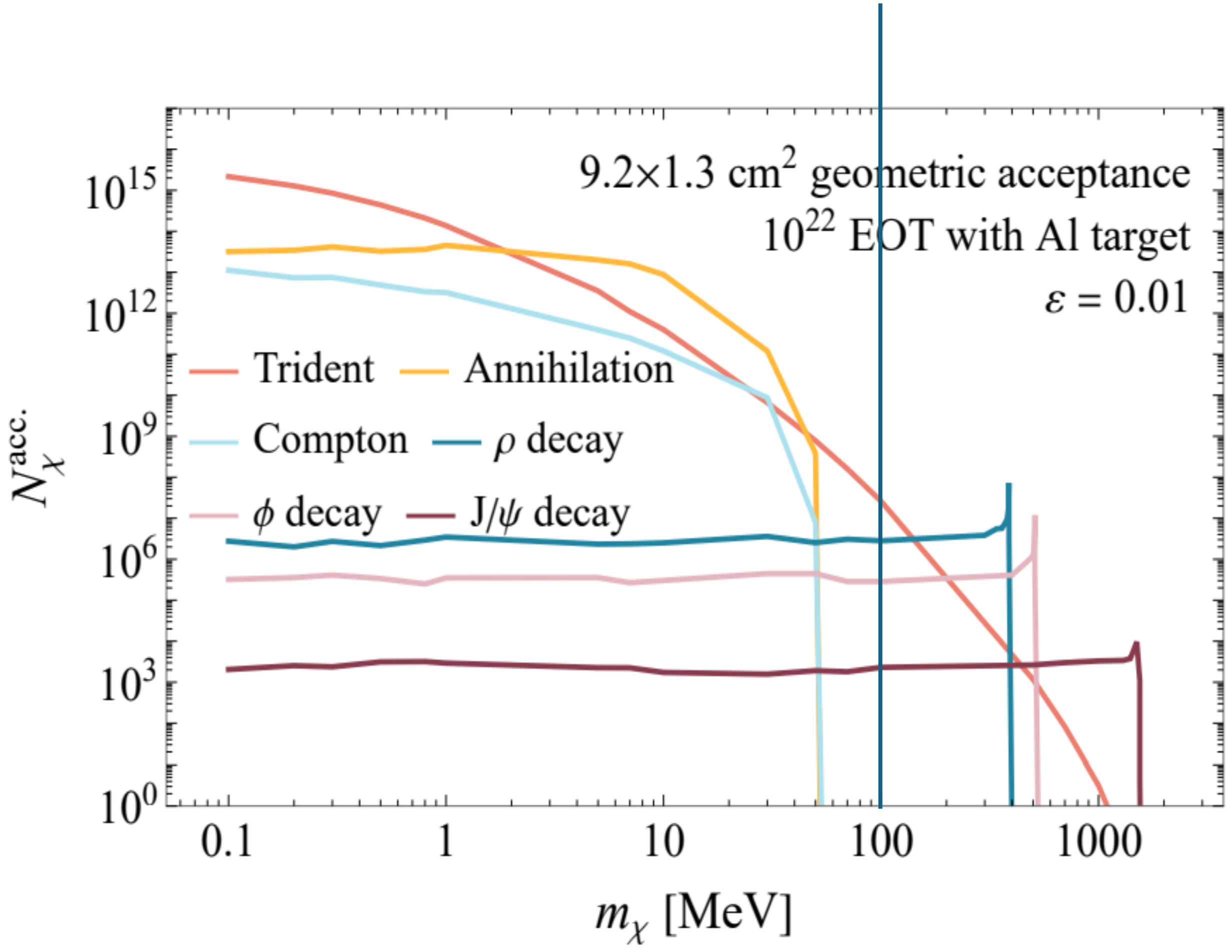
mCP production and geometric acceptance



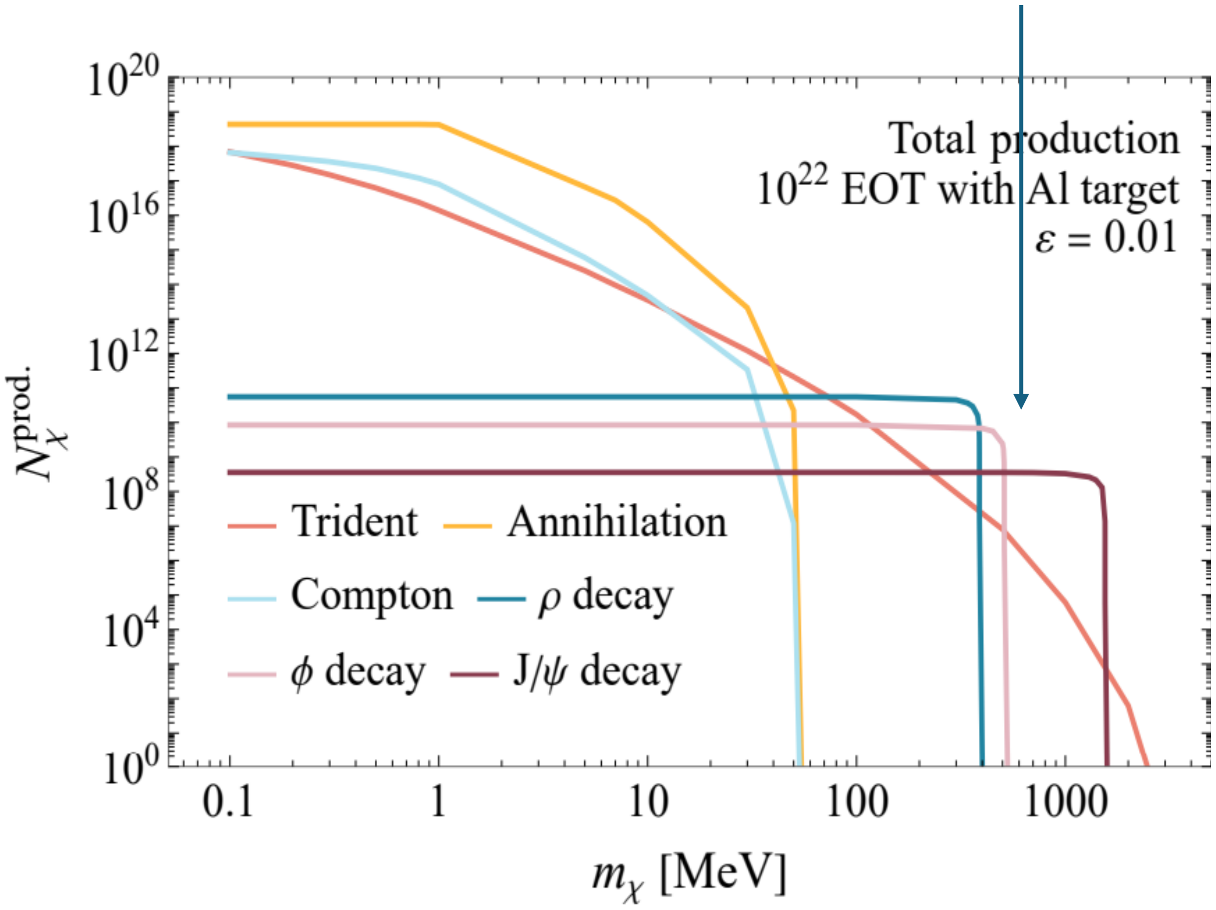


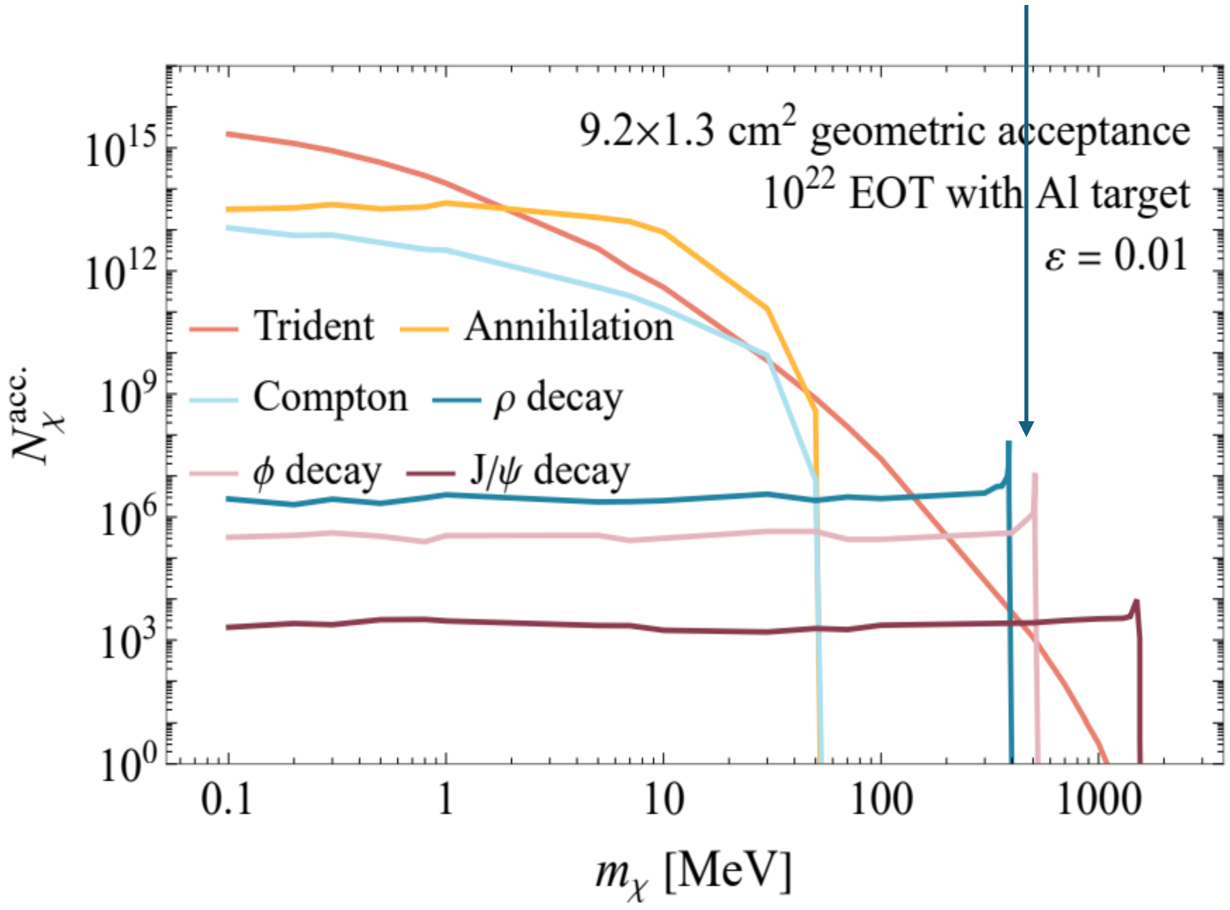
mCP production and geometric acceptance





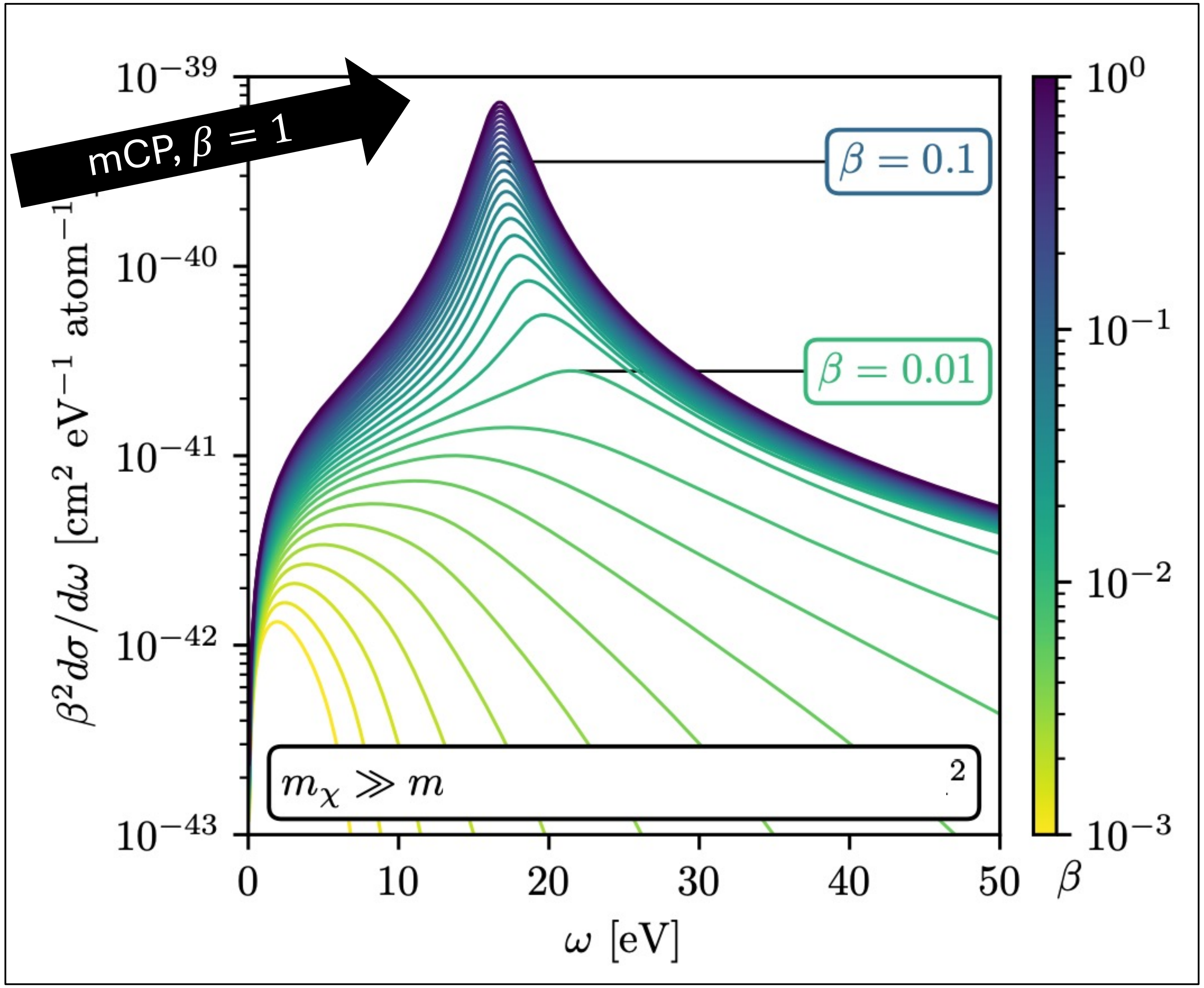
mCP production and geometric acceptance





mCP detection with Skipper CCDs: Signal Prediction

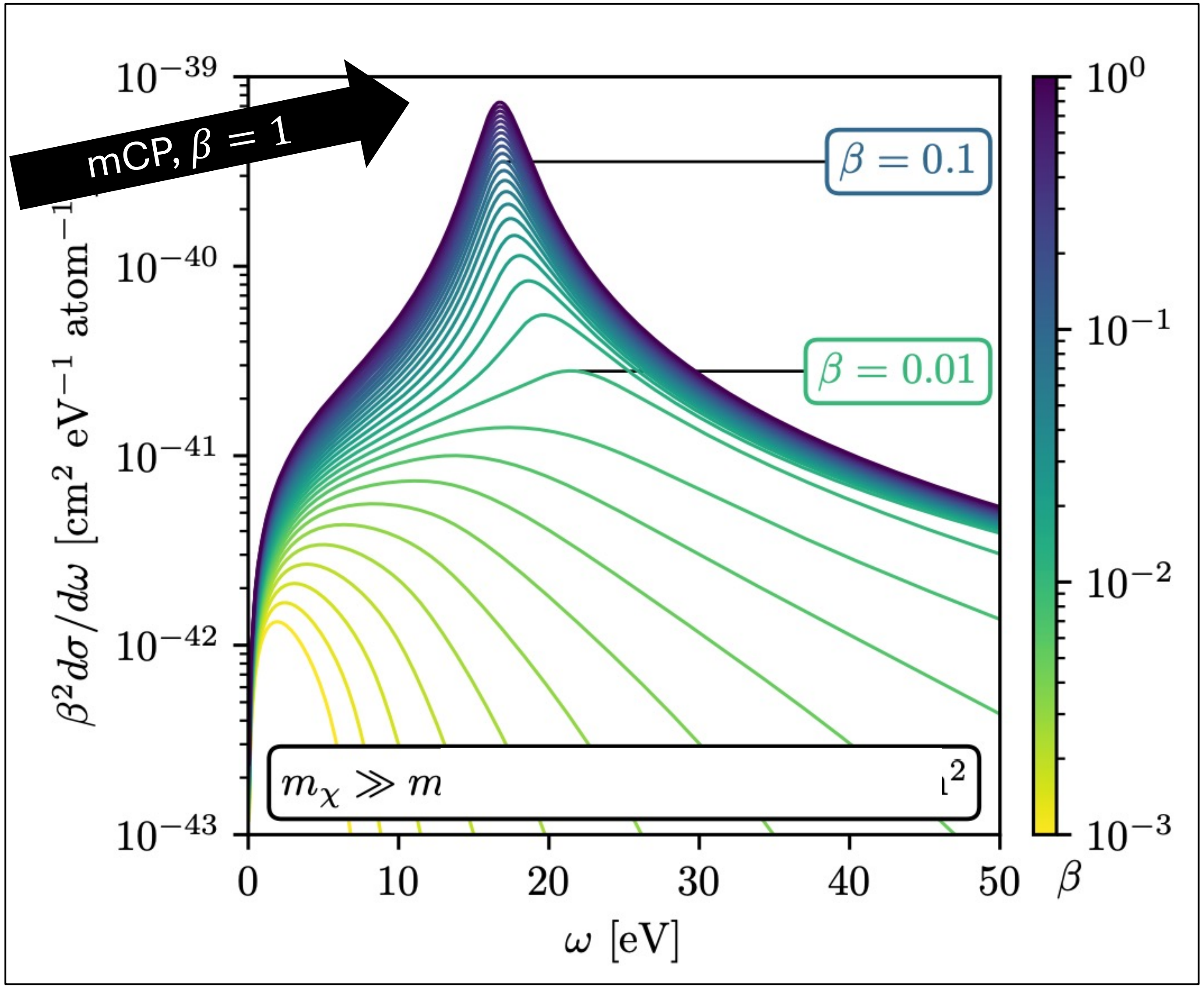
$$\frac{d\sigma}{d\omega}(\varepsilon) \propto \int dk\, \frac{1}{k} \underbrace{Im\left(\frac{-1}{\epsilon(\omega,k)}\right)}_{\text{Electron Loss Function (ELF)}} \propto \varepsilon^2$$



mCP detection with Skipper CCDs: Signal Prediction

$$\frac{d\sigma}{d\omega}(\varepsilon) \propto \int dk\,\frac{1}{k} Im\left(\frac{-1}{\epsilon(\omega,k)}\right) \propto \varepsilon^2$$

- Dominant signal ~ 18 eV
- Higher threshold detectors miss enhancement from collective excitations
- Better rejection of background without loss of signal.
- SENSEI has demonstrated background-free searches in this signal region.

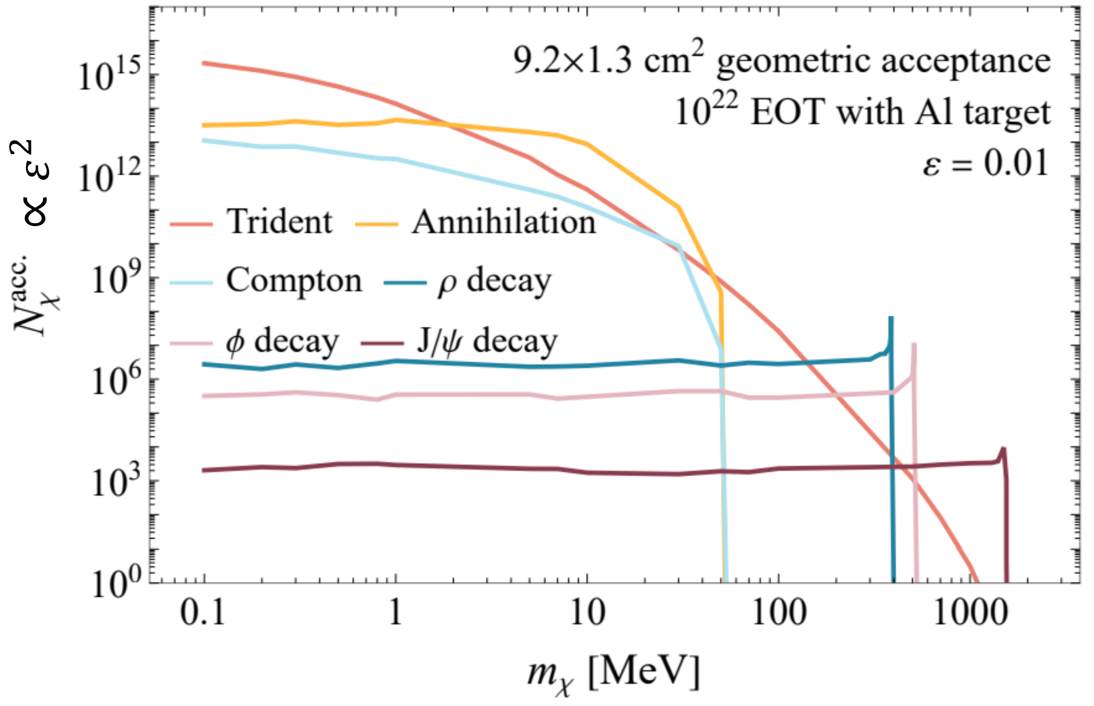


Expected number of signal events

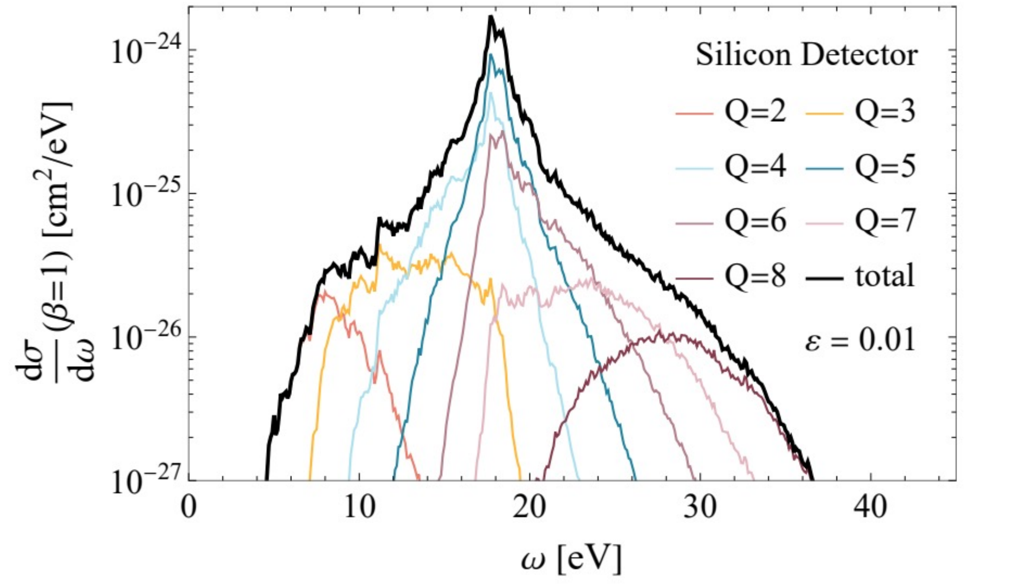
Detector efficiency ~0.20

Detector width
and electron number density

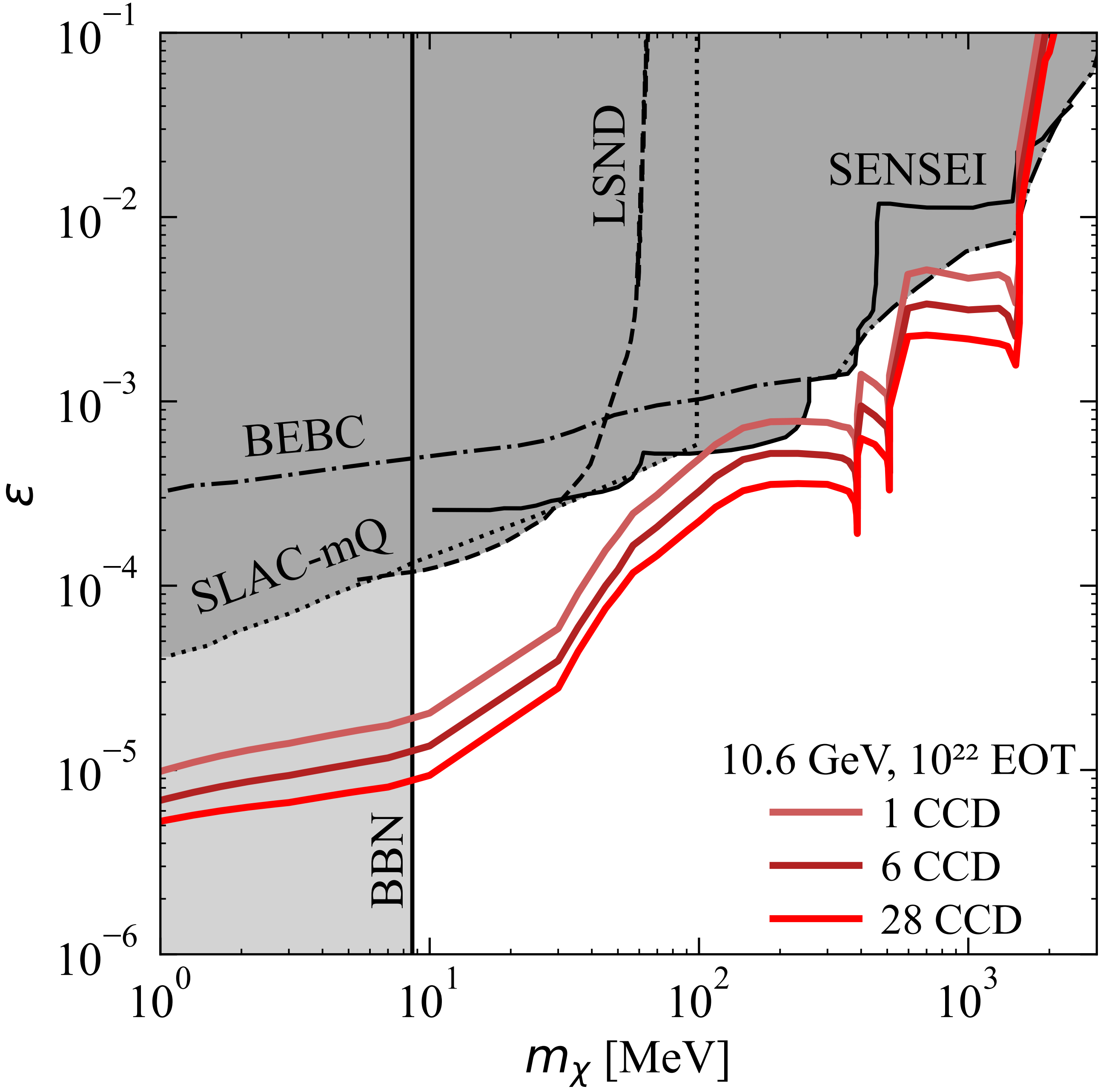
$$N_{\text{detected}}(\varepsilon, m_\chi) = \epsilon_{\text{exp.}} \times N_\chi^{\text{acc.}}(\varepsilon, m_\chi) \times (n_e L) \times \sum_{Q=3}^{7} \sigma_Q(\varepsilon)\,,$$



$$\sigma_Q(\varepsilon) \propto \int d\omega\, P_Q \times \int dk\, \frac{1}{k}\, Im\left(\frac{-1}{\epsilon(\omega,k)}\right) \propto \varepsilon^2$$

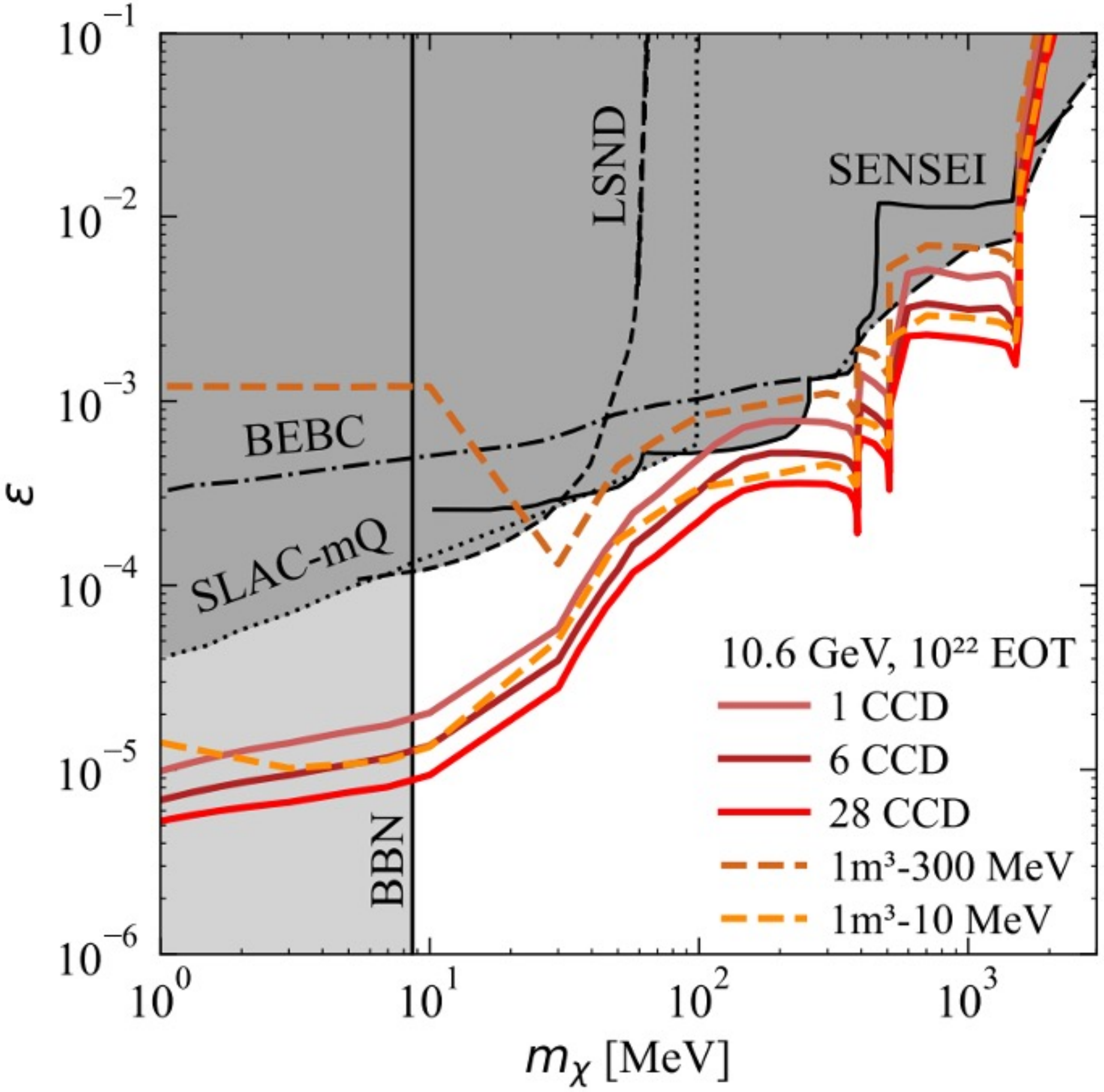


One (2g) Skipper-CCD exceeds sensitivity of existing experiments



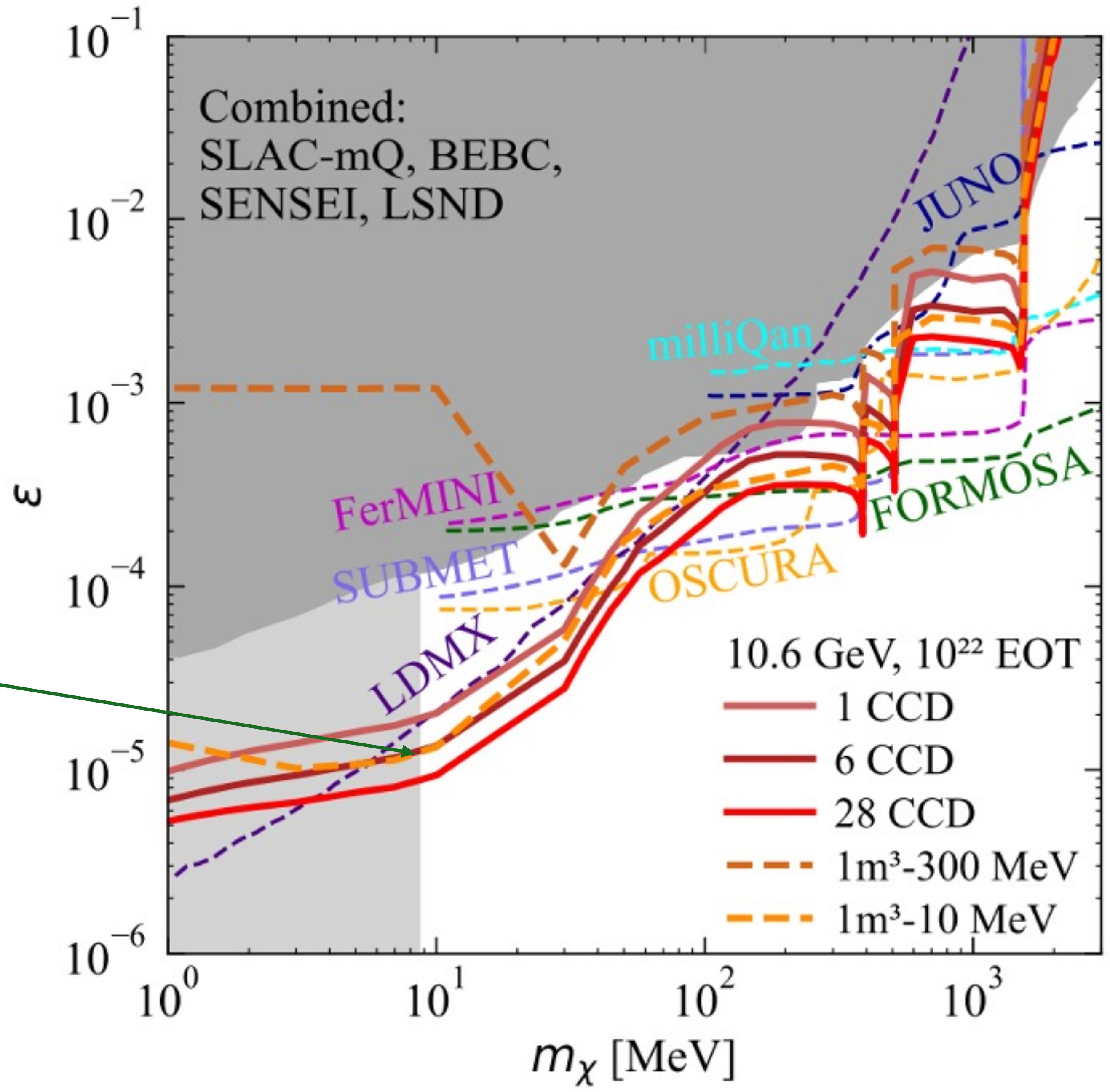
One (2g) Skipper-CCD exceeds sensitivity of existing experiments

… and performs better than a hypothetical $1m^3$ BDX-like detector with threshold energy 300 MeV



Skipper-CCDs are competitive with other proposed experiments

... and world leading at low masses



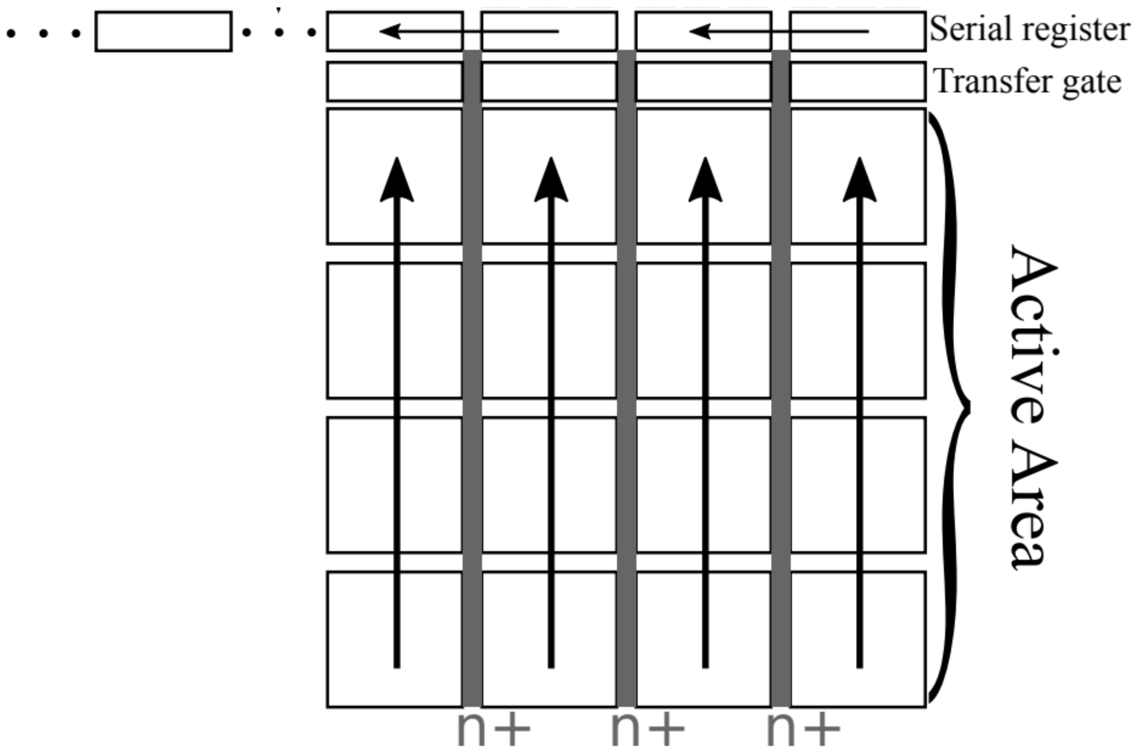
Summary

- Millicharged particles are theoretically motivated as a natural extension to the SM.
- mCP are a possible DM candidate (although do not have to be).
- We properly calculate the mCP production rates in all channels relevant at an electron beam dump.
- Including a Skipper-CCD detector near the proposed BDX detector seems possible and relatively inexpensive.
- We can probe new mCP parameter space at JLab with *ONE* Skipper-CCD.

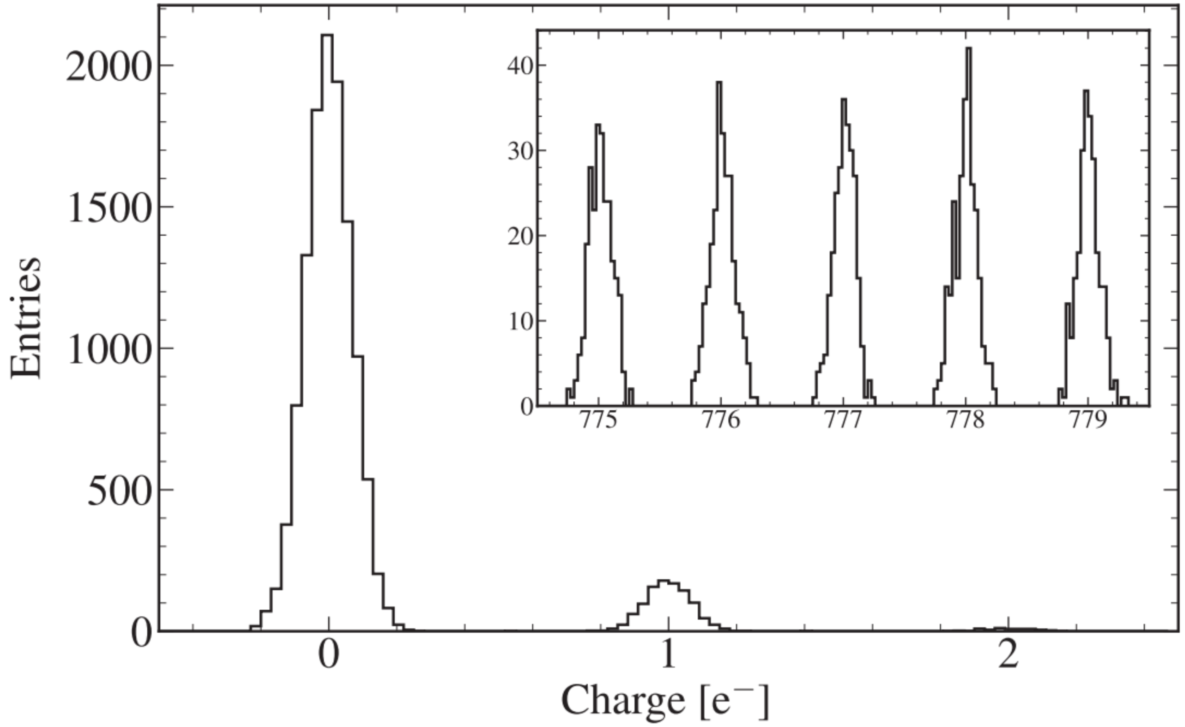
Backup Slides

Single electron sensitivity with Skipper CCDs

Non-deconstructive read-out



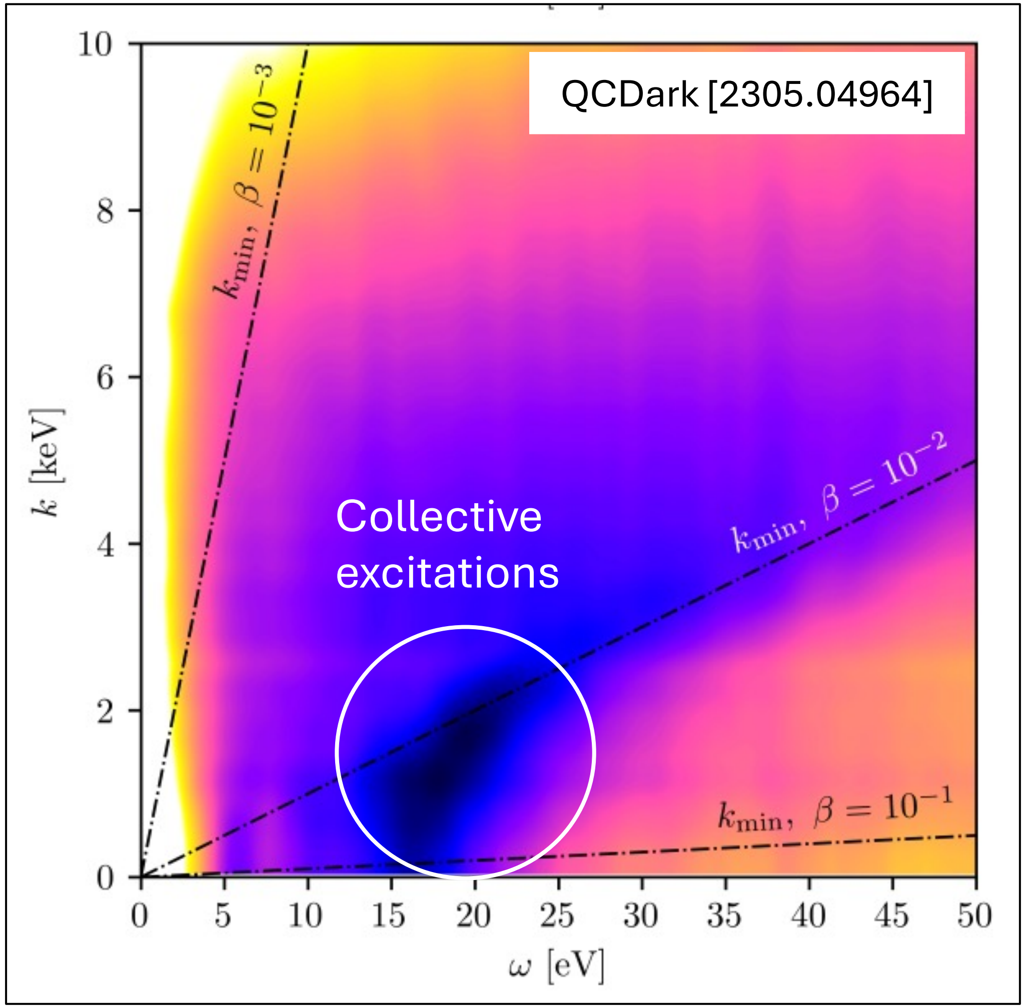
[2106.08347]



[1706.00028]

mCP detection with Skipper CCDs

[2403.00123]

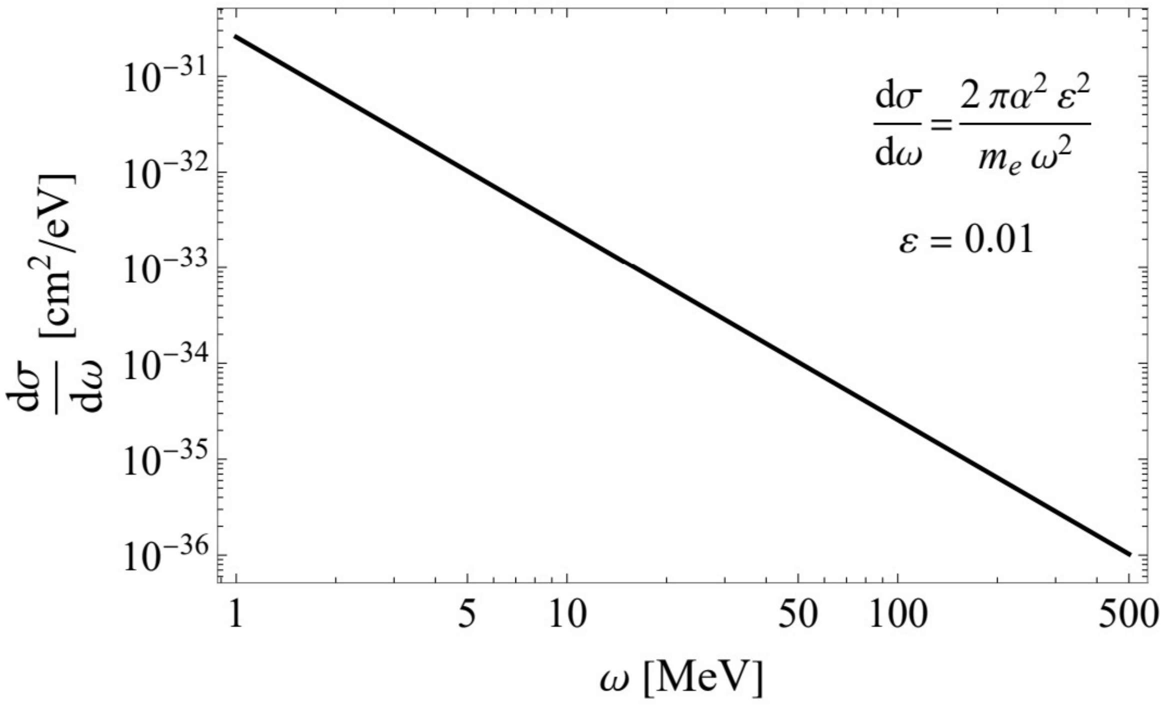


$Im\left(\frac{-1}{\epsilon(\omega, k)}\right)$: Electron Loss Function (ELF)

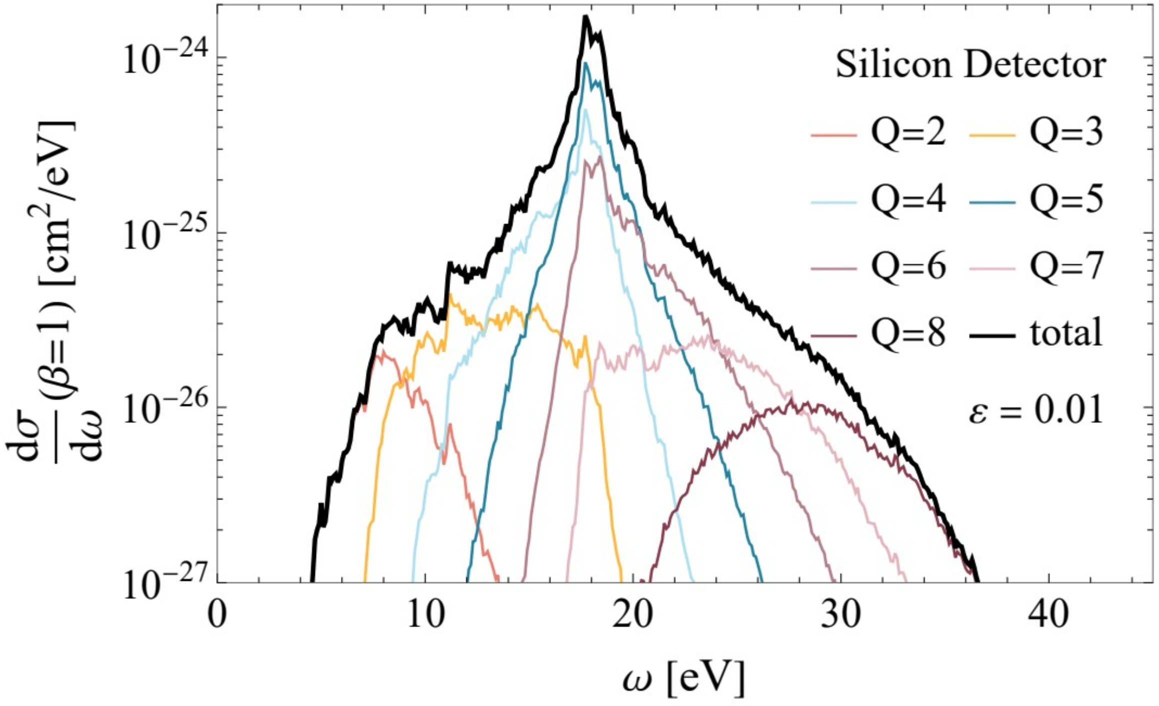
Dielectric Function, calculated by DFT

Higher threshold detectors miss enhancement from collective excitations

Csi (BDX proposed)



Skipper-CCDs



Backgrounds

- Interesting backgrounds to consider:
  1. beam-induced neutrons, gammas, and muons
  2. cosmic rays
  3. pile up from single-electron events
- Each is handled differently
- High energy events are masked. This lowers the effective area of the detector. We estimate a detector efficiency of 20%, loosely motivated by SENSEI.
- Low energy events (ie. 1 electron excitations) are not considered.
- Beam induced neutrons with energy O(100 keV) could reproduce mCP signal.
  - We find that these backgrounds are minimal (< 1 for 10^{22} EOT), with sufficiently shielding (concrete and iron) after the dump.
- Background analysis should be done carefully, given a defined experimental set up.

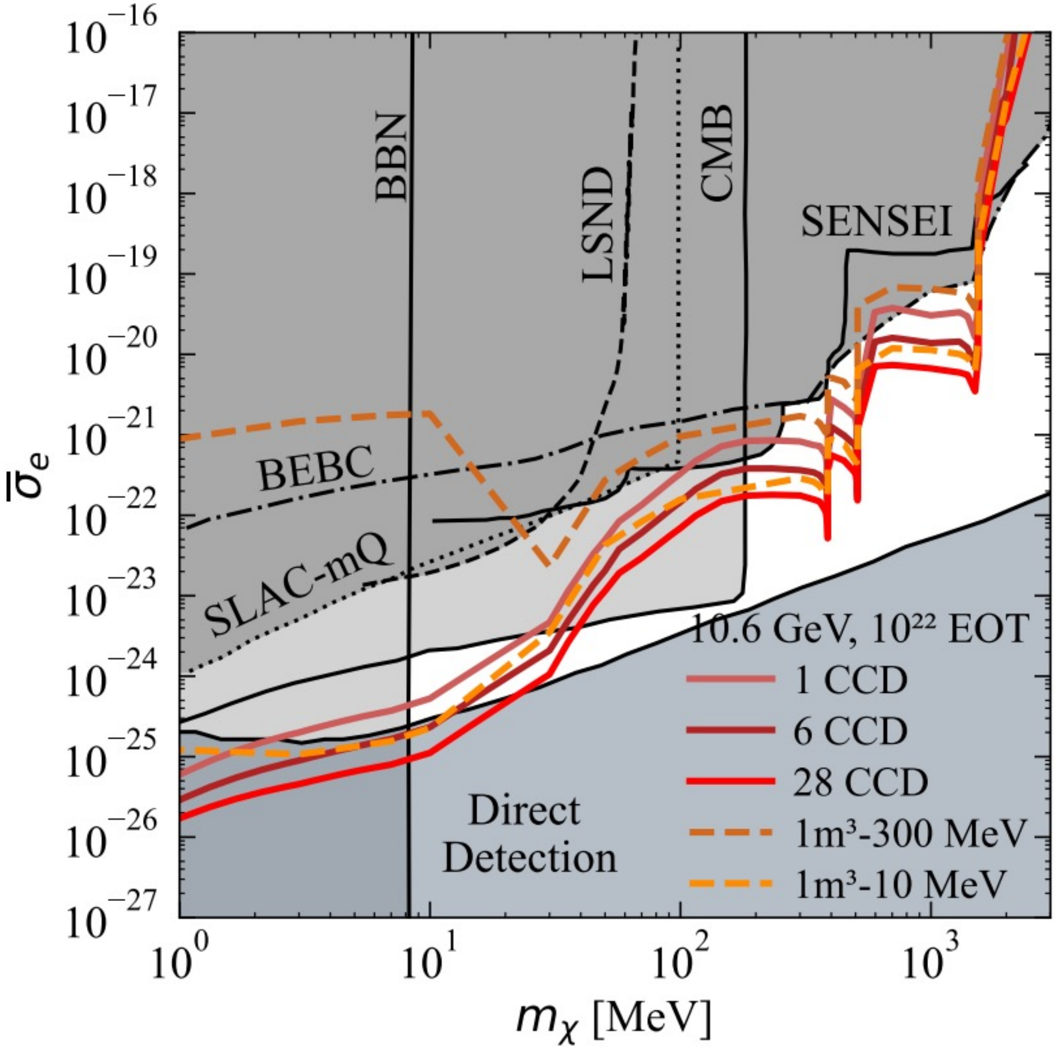
Dark matter interacting with an ultralight dark photon

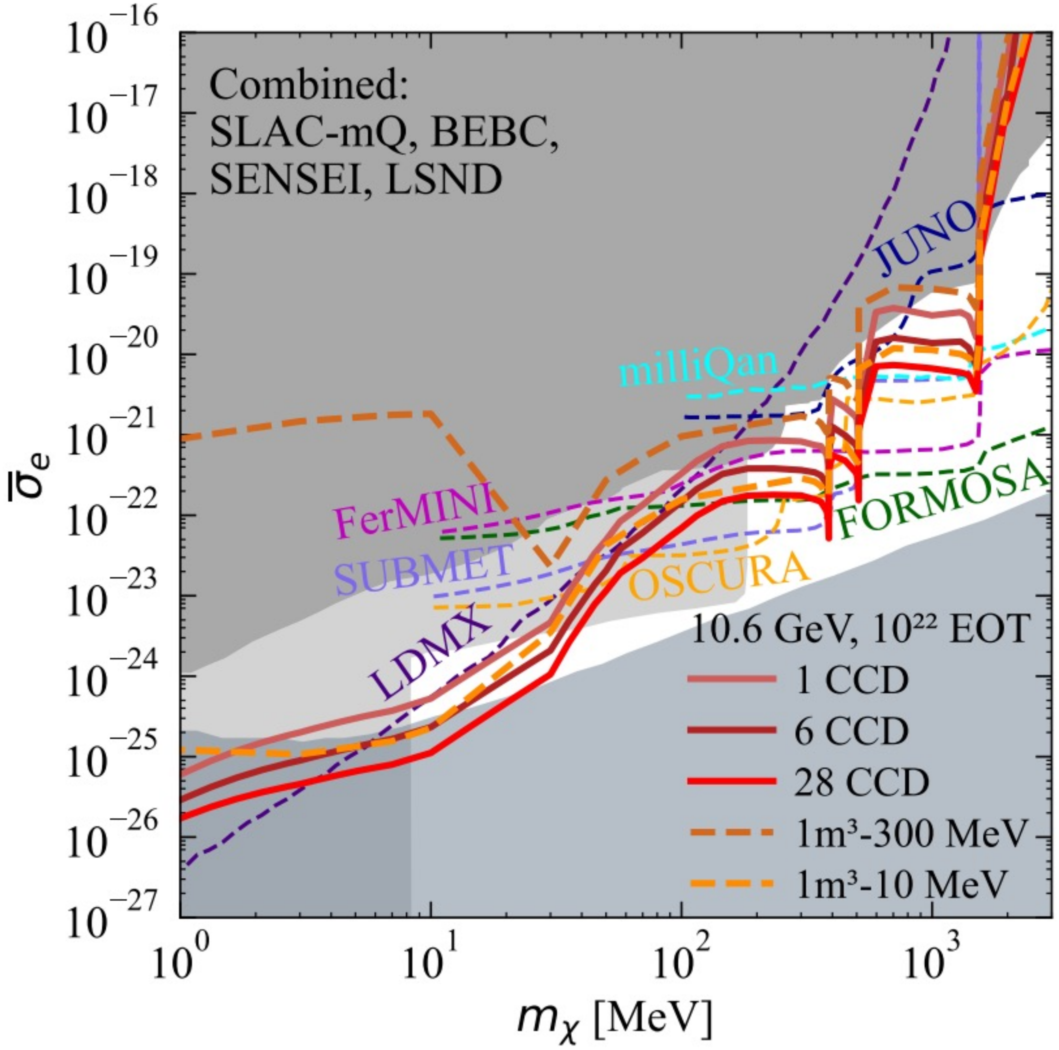
$$\mathcal{L} \supset -\frac{1}{4}\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu} + \frac{1}{2}m_{\mathcal{A}}^2\mathcal{A}_\mu\mathcal{A}^\mu - \frac{\kappa}{2}F_{\mu\nu}\mathcal{F}^{\mu\nu} - g_D\mathcal{A}_\mu\bar{\chi}\gamma^\mu\chi$$

- Ultralight ($m_{\gamma'} \ll 1\ eV$) dark photon kinetically mixes with SM photon.
- After EWSB χ becomes an effective mCP with coupling to SM photon current.
- Effective coupling $Q_\chi = \varepsilon e$, with $\varepsilon = \kappa g_D$.
- We define a reference cross section $\overline{\sigma_e} = \frac{16\,\pi\alpha^2\varepsilon^2\mu_{\chi e}^2}{(\alpha m e)^4}$, which direct detection experiments can constrain.

- Note 1: if DM is pure mCP *or* effective mCP with massless γ', then no direct detection bounds. These mCP can not penetrate the solar wind to interact with terrestrial detector.
- Note 2: if $g_D{\sim}1.0$ then strong CMB constraints (easily overproduce γ) for $f_\chi > 0.4\%$.

Dark matter interacting with an ultralight dark photon





Comparison with other experiments

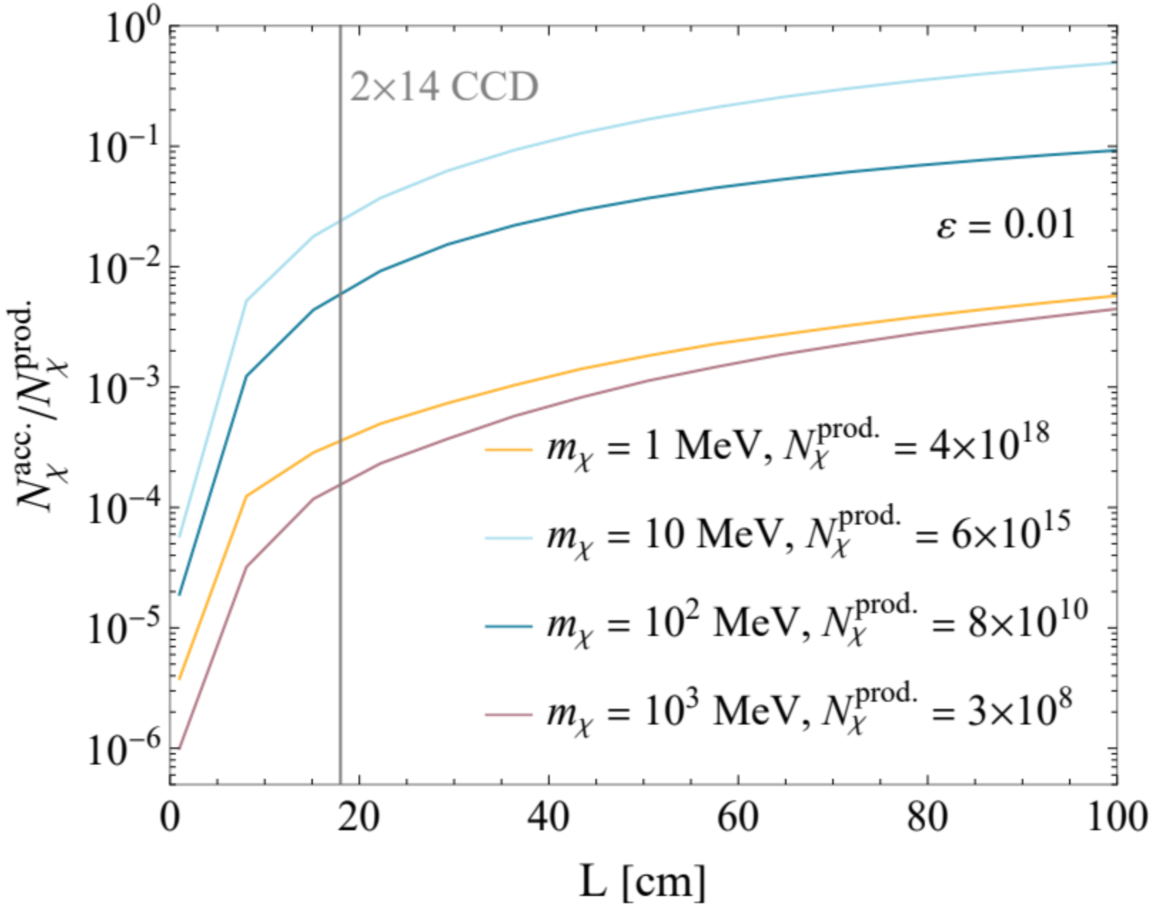
- SLAC-mQ (1990s): electron beam, more energy, larger detector, farther away
- Liquid Scintillator Neutrino Detector (LSND) (1990s): electron beam dump
- BEBC (1970s-80s): proton beam dump + Bubble Chamber detector
- SENSEI (with NUMI beam): proton beam, higher energy, lower POT

Comparison with other proposed experiments

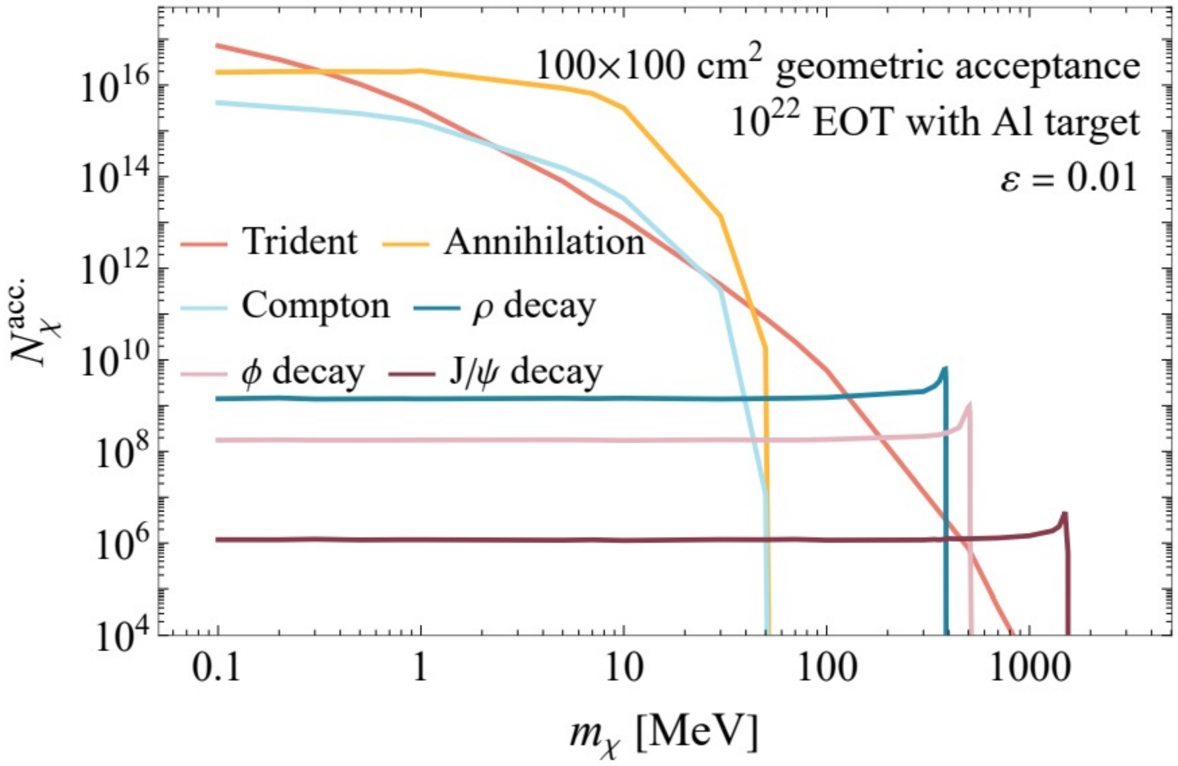
- SUBMET: proton beam @ J-PARC, currently taking data.
- milliQan: proton beam @ CERN, demonstrator already produced results.
- FerMINI: milliQan-like detector with NUMI beam
- FORMOSA: milliQan-like detector @ LHC
- OSCURA: skippers at NUMI beam, same as SENSEI but 500x larger detector
- Nominal BDX design: larger detector, larger threshold energies
- LDMX: electron beam, missing momentum search @ SLAC
- JUNO: mcp produced from cosmic ray showers

Geometric acceptance for other designs

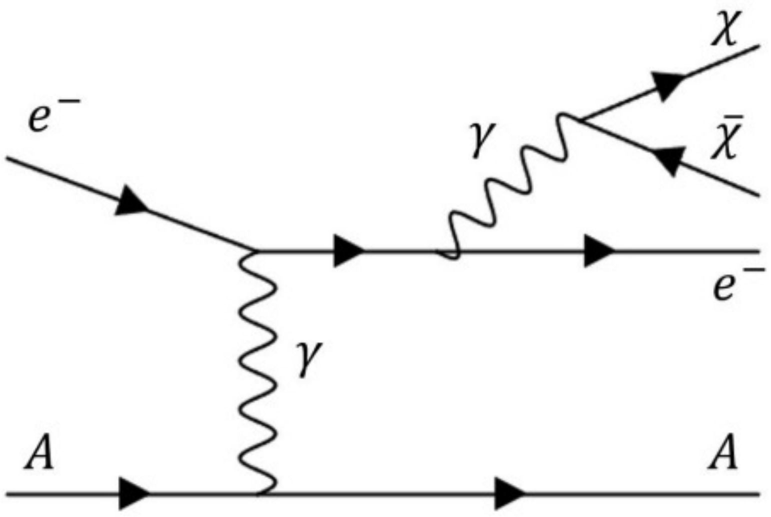
Geometric Acceptance for a $L\times L$ skipper CCD detector



BDX-like Detector



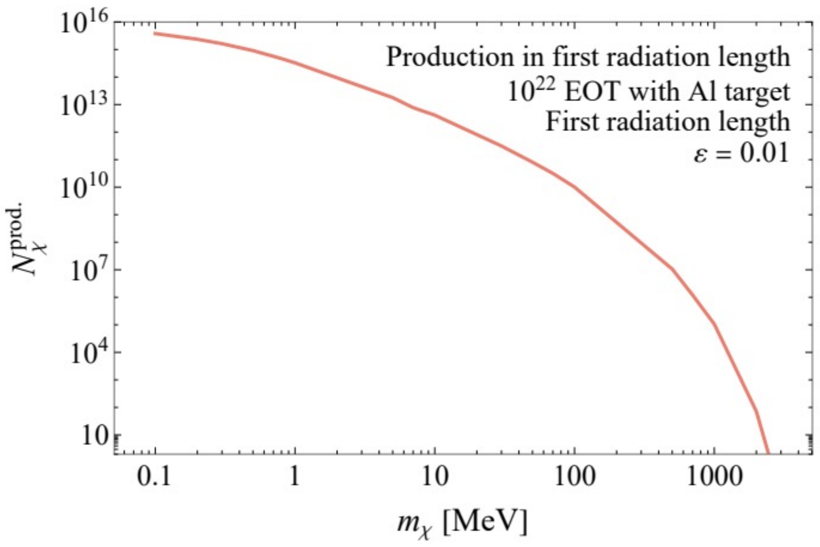
Trident Process

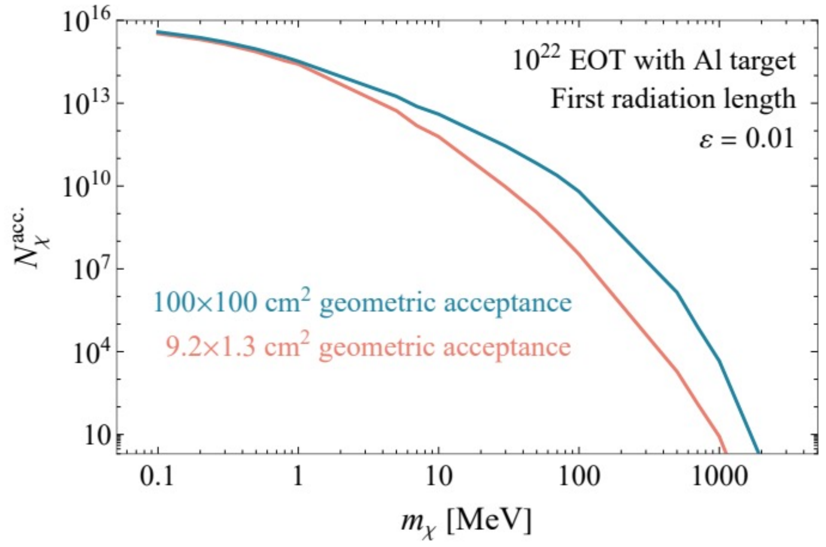


In the first radiation length approximation
Trident process dominates.

$$N_\chi^{\text{prod.}} = 2 \cdot N_{\text{EOT}} \cdot \frac{\rho \cdot N_A}{M_{\text{atom}}} \cdot X_0 \cdot \sigma_{\text{prod.}} ,$$

Secondary e+/e- trident: $N_\chi^{prod.} \propto N_{EOT}\, \lambda_{MFP}\, \sigma(E_e)$





Millicharged particle production at electron beam dumps: beyond the first radiation length

Trident: $N_\chi^{prod.} \propto N_{EOT}\, X_0\, \sigma_{Trident}$ $\longrightarrow$ $N_\chi^{prod.} \propto N_{EOT}\, \lambda_{MFP}\, \sigma(E_e)$

(in 1st Rad. Length)

Electron-Positron annihilation: $\sigma_{annih.} \sim \frac{1}{s}\ (m_\chi < 10\ MeV)$,

$\sim 0\ (m_\chi > 50\ MeV)$, kinematic threshold

Compton: $\sigma_{compt.} \sim \frac{\alpha}{2\pi} \ln\left(\frac{s}{m_e^2}\right) \sigma_{annih.}$, always suppressed compared to annihilation.

Vector Meson: See other slide

Annihilation Production

$$\sigma_{\text{anni.}} = \frac{4\pi\alpha^2\varepsilon^2}{3}\frac{(s+2m_e^2)}{s^3\sqrt{s-4m_e^2}}\left(s+2m_\chi^2\right)\sqrt{s-4m_\chi^2}\,,$$

- Annihilation of positrons with atomic electrons
- $s = 2m_eE + m_e^2$, center-of-mass-energy squared
- Mcp produced at smaller angles. Boost of the mcp is the photon propagator momentum = incident positron with momentum, p_z

Compton Production

$$\sigma_{\text{Comp.}} = \frac{\alpha}{2\pi}\ln\left(\frac{s}{m_e^2}\right)\int_{x_{\min}}^{1}\mathrm{d}x\; P_{\gamma\to ee}(x)\sigma_{\text{anni.}}(xs)\,,$$

- Same kinematic threshold as annihilation
- ~ 10^2 suppression compared to annihilation

Vector Meson decay

In the complete screening approximation (appropriate for $E_e \simeq 10$ GeV), the number of photons produced per radiation length per energy interval $\mathrm{d}E_\gamma$ is given by [60]

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \simeq \frac{N_{\mathrm{EOT}}}{E_\gamma}\left[\frac{4}{3}\left(1-\frac{E_\gamma}{E_e}\right)^2+\left(\frac{E_\gamma}{E_e}\right)^2\right]. \tag{2.3}$$

We multiply this expression by the probability for a photon to produce a ρ meson instead of converting into a e^+e^- pair. When considering coherent production, $E_\rho \simeq E_\gamma$, and so we have

$$\frac{\mathrm{d}N_\rho}{\mathrm{d}E_\gamma} = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \times \frac{\sigma_{\mathrm{coh.}}(E_\gamma)}{\sigma_{\mathrm{pair}}(E_\gamma)}.$$

$$\sigma_{\mathrm{coh.}}(E_\gamma) = A f_{\mathrm{coh.}} \times \sigma_{\gamma p \to \rho p}(E_\gamma)$$

Given a sample of ρ and ϕ mesons, we simulate their two-body decays into $\chi\bar{\chi}$ in the rest frame and boost the mCPs to the lab frame in order to get the total flux within the detector geometric acceptance

$$\frac{\mathrm{d}N_{\gamma\to J/\psi}}{\mathrm{d}E_\gamma} = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\frac{A \times \sigma_{J/\psi}(E_\gamma)}{\sigma_{\mathrm{pair}}(E_\gamma)},$$

MCP detection with Skipper CCDs: Signal Prediction

Differential cross section for relativistic particle with charge $q = \varepsilon e$ interacting with silicon, per e- (in material) [cm^2/eV]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\omega}(\omega, \varepsilon) = \frac{2\alpha\varepsilon^2}{n_e \pi \beta^2} \int_{k_{\min}}^{k_{\max}} dk \left\{ \frac{1}{k} \mathrm{Im}\left(\frac{-1}{\epsilon(\omega, k)} \right) + \text{Small Relativistic Correction} \right\},$$

n_e = Number density of valance electrons in detector.
$\beta \approx 1$ detector is located to only accept forward scattering.
$\varepsilon(\omega, k)$: dielectric function, function of ionization energy (ω) and electron momentum transferred from mcp (k).
Calculated with QCDark code (Density Functional Theory)
Im(-1/ $\varepsilon(\omega, k)$) : electron loss function (ELF), describes the electron transitions due to a perturbation

$k_{\min} = \omega/\beta$ (limited by kinematics) ; $k_{\max} = 2|\vec{p}| - k_{\min} \to \infty$ (interaction is negligible after fermi momentum ~ 5 keV)

For ionization energy $\omega \sim 15 - 20$eV and $\beta > 0.1$, the mcp can excite collective excitations (access plasmon peak).

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