Searching for Millicharged Particles from the eV to GeV mass scale with Skipper-CCDs

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15th International Workshop on the Identification of Dark Matter 2024

July 11th 2024

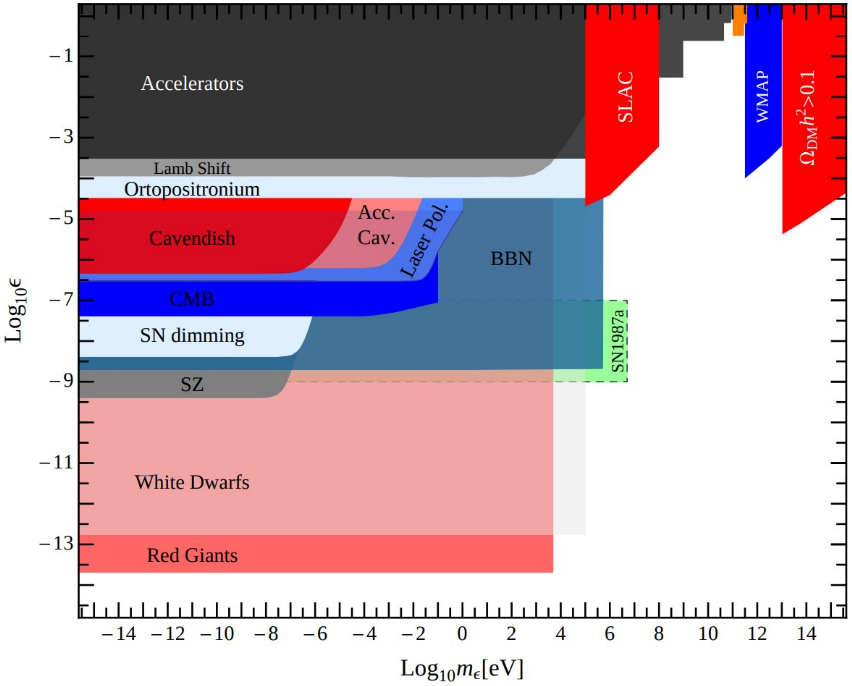
Talk overview

- Why mCP?
- Why Skipper-CCDs?
- Where are the experiments?
- Fixed target: SENSEI result, OSCURA, DarkBeats.
- Reactors: CONNIE/ ATUCHA (vIOLETA)
- LHC: Moskita
- Conclusion

Why mCP? - Current constraints

$$\mathcal{L}_{mCP} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon e B\!\!\!/ + M_{mCP})\chi$$

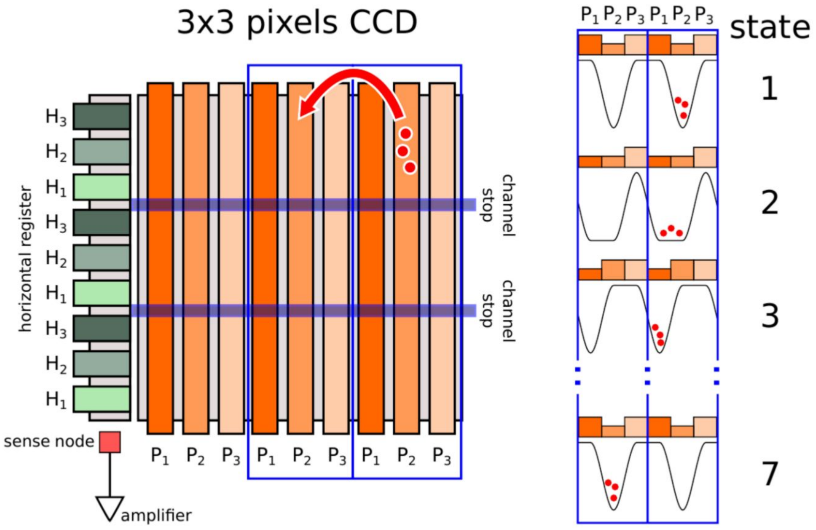
- Simple extension of the SM with deep implications if observed!
- Might be a component of Dark Matter
- Presents itself as a fractionally charged fermion.

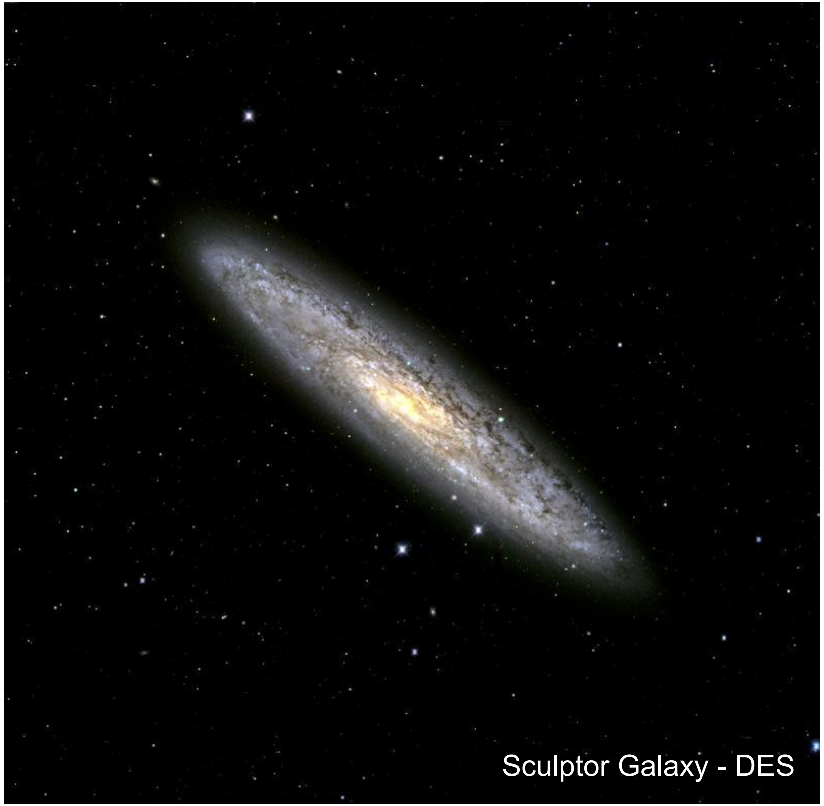


[10.1088/1126-6708/2009/11/027]

B. Holdom, *Two* U(1)′*s and epsilon charge shifts*, *Phys. Lett.*B 166 (1986) 196.
D.E. Brahm and L.J. Hall, U(1)′*dark matter*, *Phys. Rev.*D 41 (1990) 1067

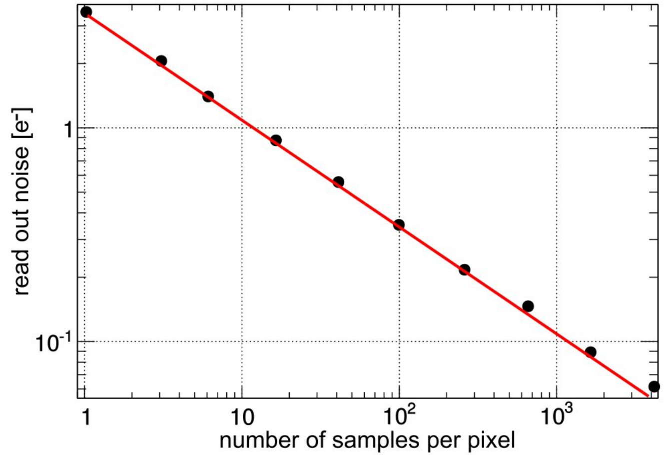
Charged Coupled Devices (CCD) + floating gate amplifier = Skipper-CCD



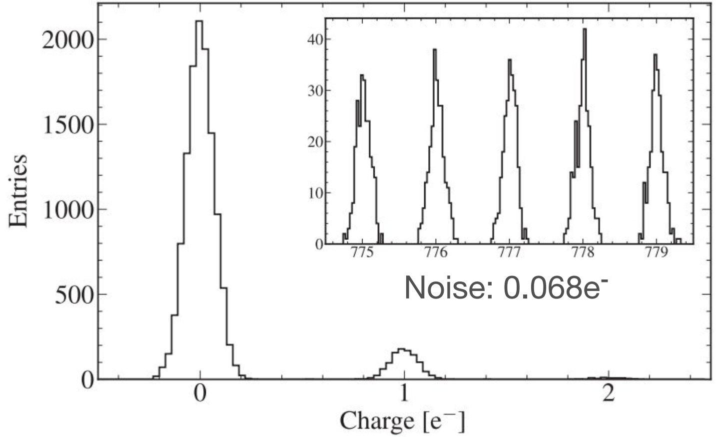

Sculptor Galaxy - DES

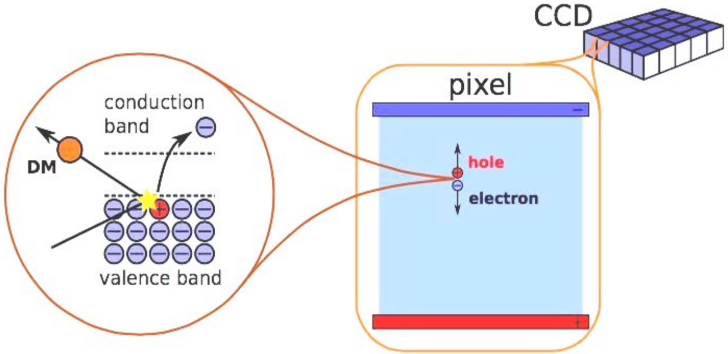
Fermilab

Skipper-CCDs for Dark Matter



$$\sigma = \frac{\sigma_1}{\sqrt{N}}$$





Janesick et al., New advancements in charge-coupled device technology - sub-electron noise and 4096×4096 pixel CCDs.
Moroni et al., Sub-electron readout noise in a Skipper CCD fabricated on high resistivity silicon.
Tiffenberg et al., Single-Electron and Single-Photon Sensitivity with a Silicon Skipper-CCD.

Why Skipper-CCDs?

CCDs w/ Skipper amplification (designed by LBNL):

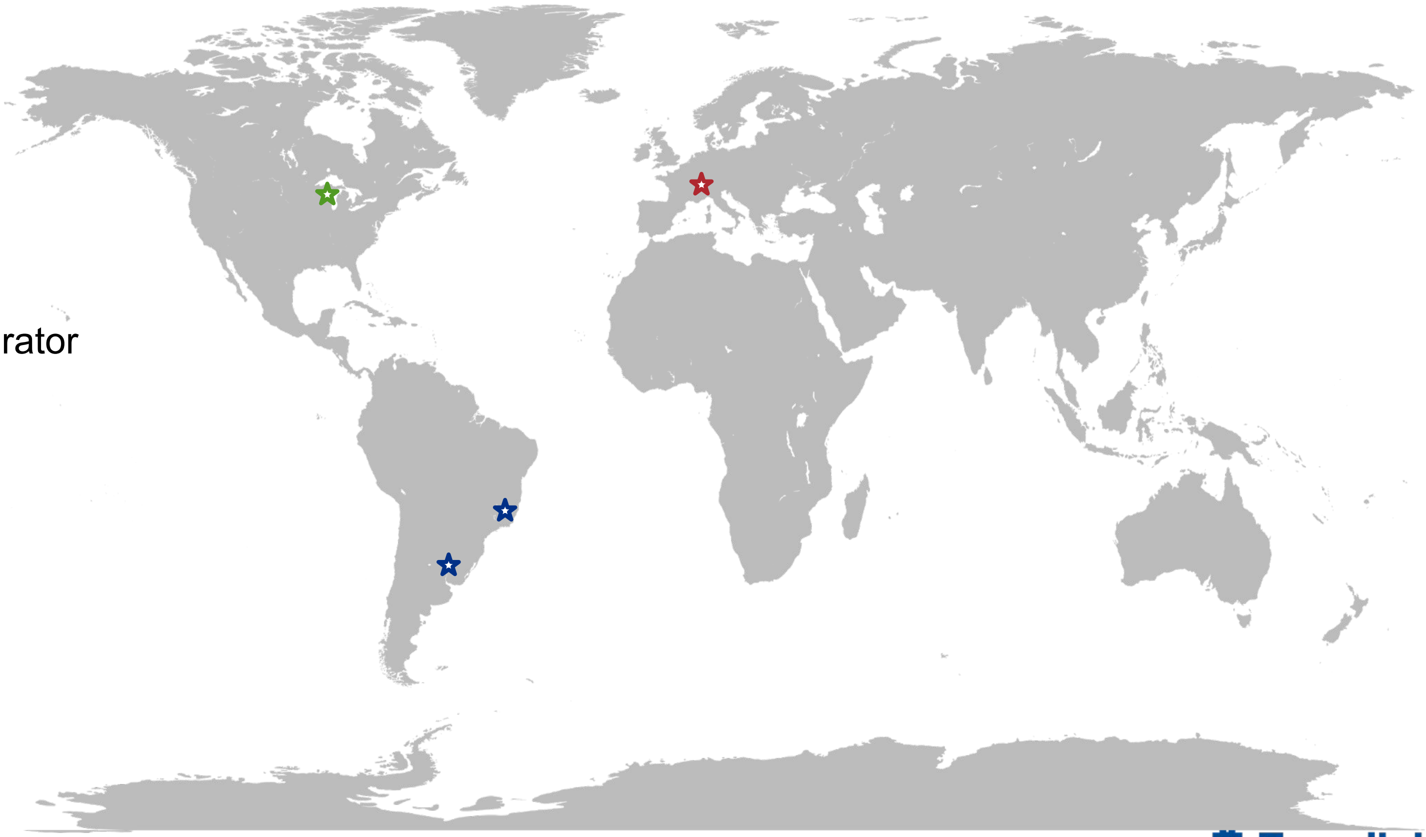
- Energy threshold of Si bandgap (~1.1 eV)
- Low dark current (~10^{-5} e^-/pix/day)
- Sub-electron (~0.1e^-) readout noise

Access to low-mass searches:

- Electron scattering of 1-1000 MeV DM
- Nuclear scattering of 1-1000 MeV DM via Migdal effect
- Absorption of 1-1000 eV DM
- Etc…

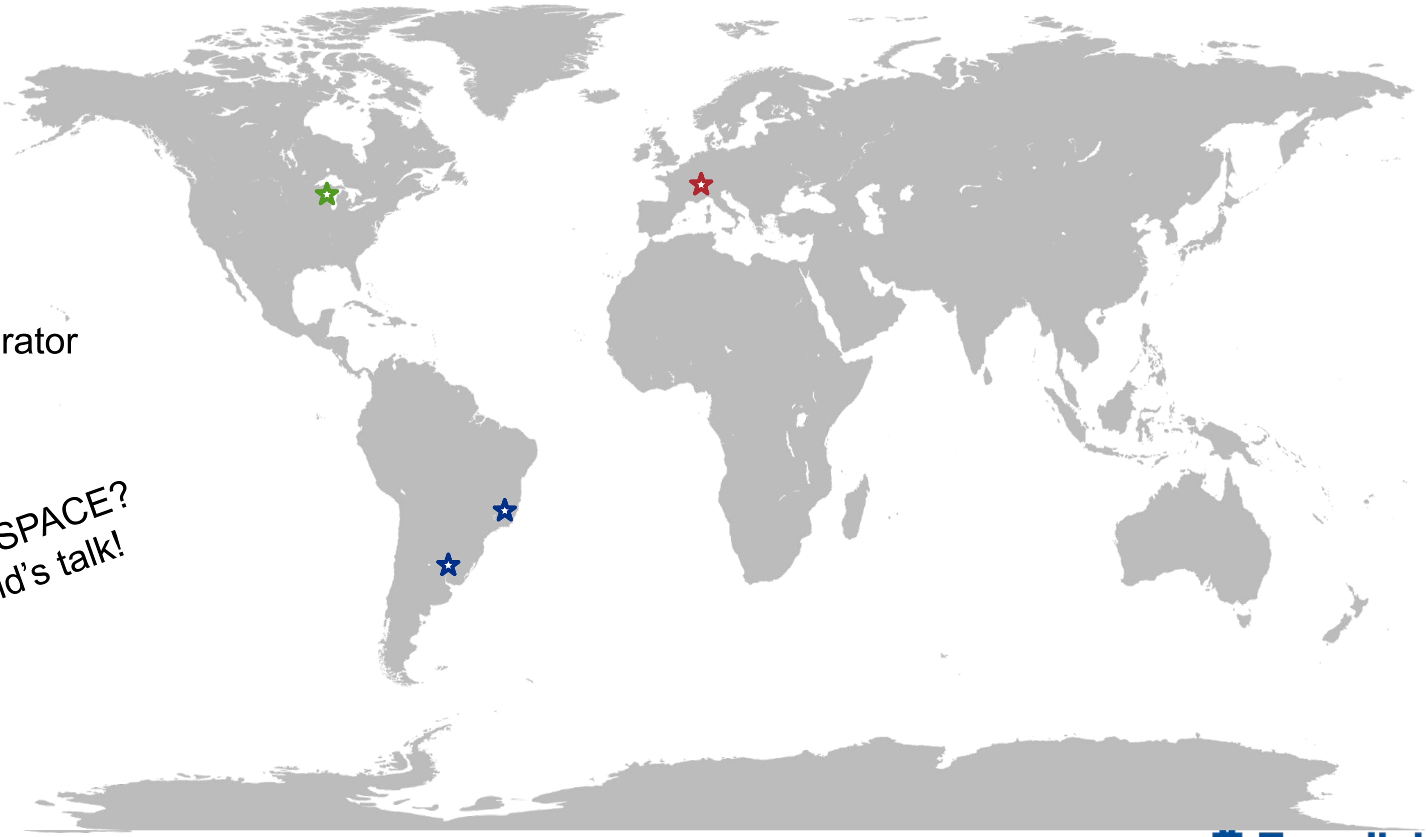
Fermilab

Skipper-CCD millicharged searches know no borders :)



- Fixed target accelerator
- Reactors
- LHC

Skipper-CCD millicharged searches know no borders :)

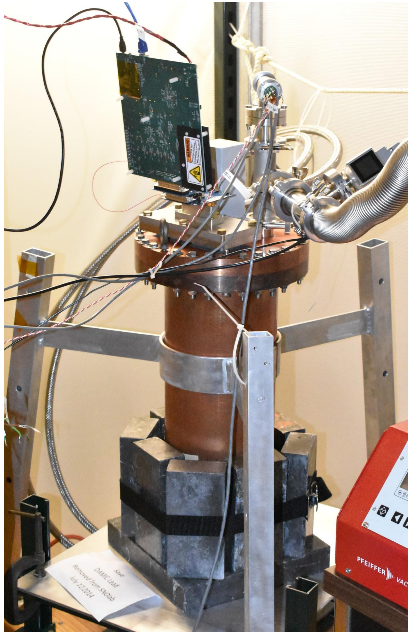


- Fixed target accelerator
- Reactors
- LHC

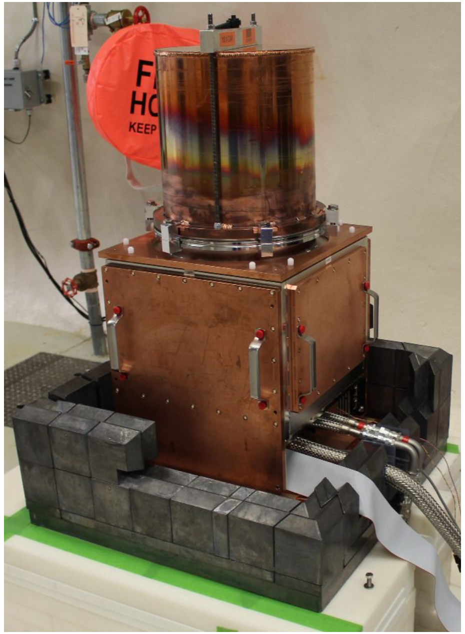
The final frontier: SPACE?
See Nate Saffold's talk!

Fixed target: SENSEI@MINOS

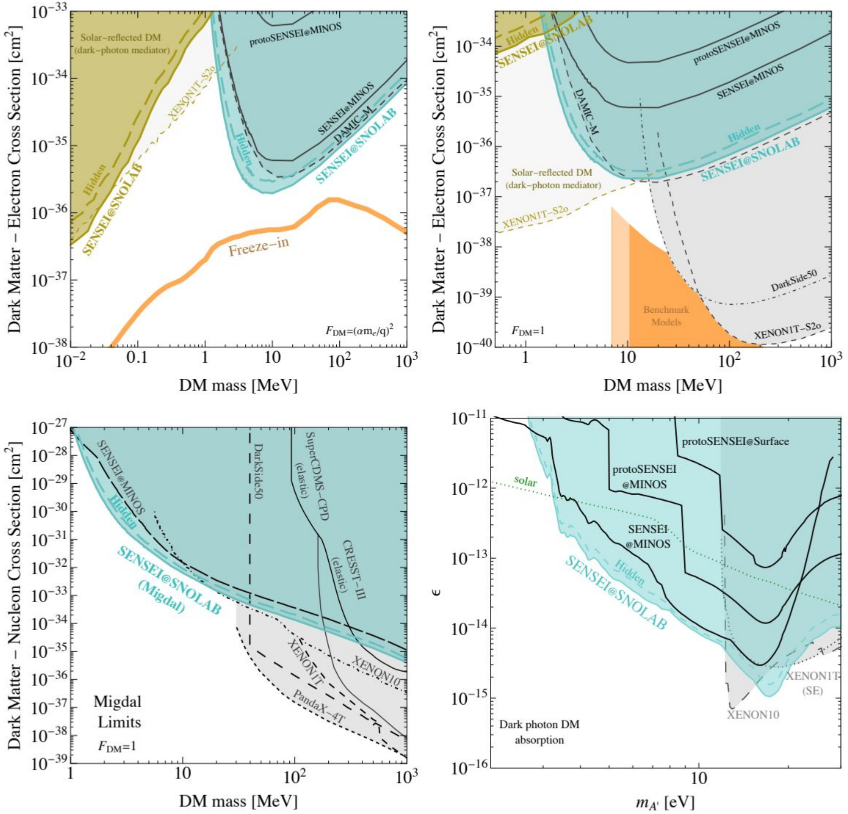
SENSEI@MINOS



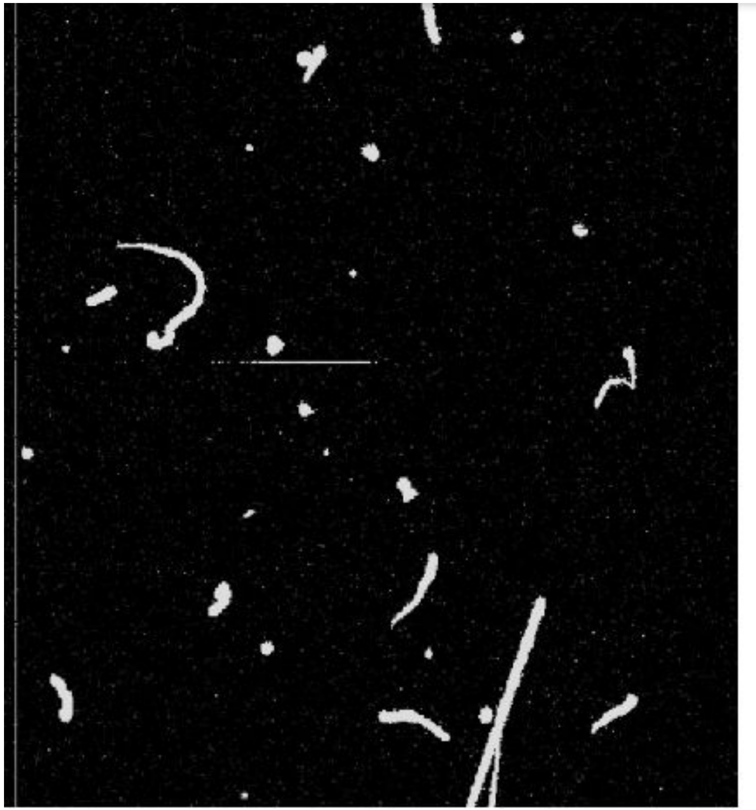
SENSEI@SNOLAB



Fixed target: SENSEI@MINOS

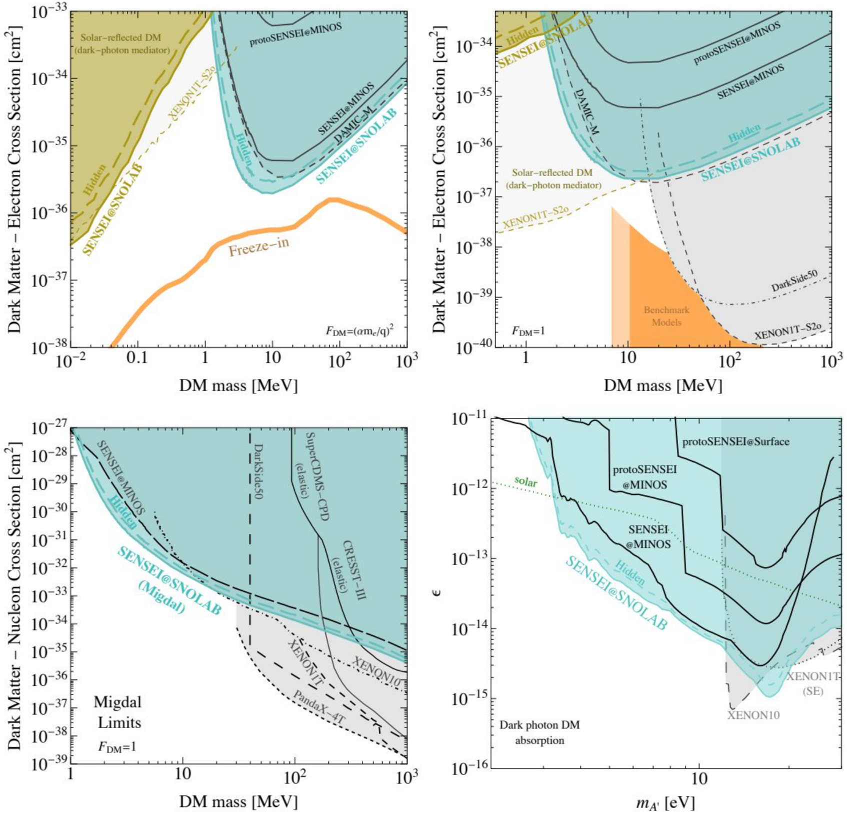


SENSEI constraints for low mass dark matter (Ana Botti's talk wednesday)



Long exposure example from MINOS dataset

Fixed target: SENSEI@MINOS



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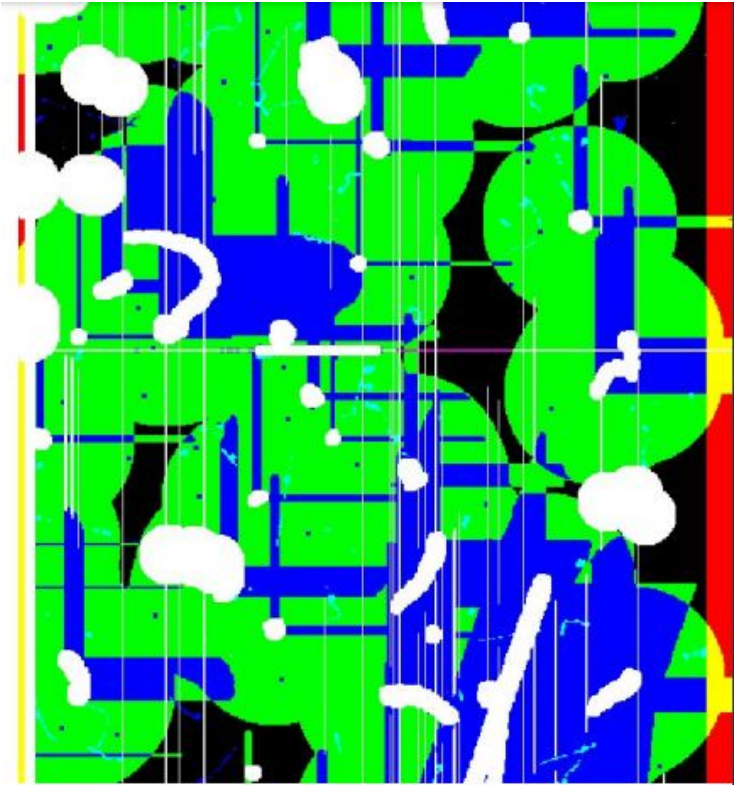
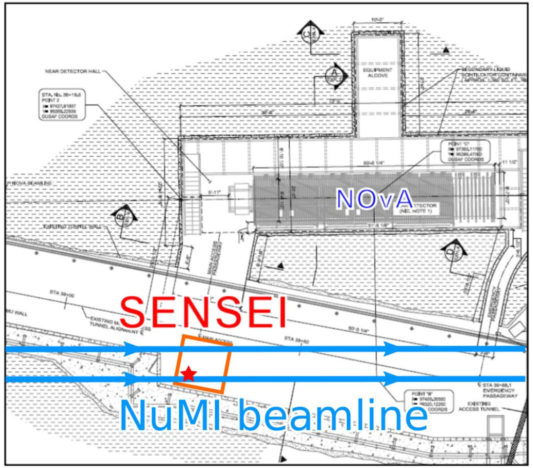
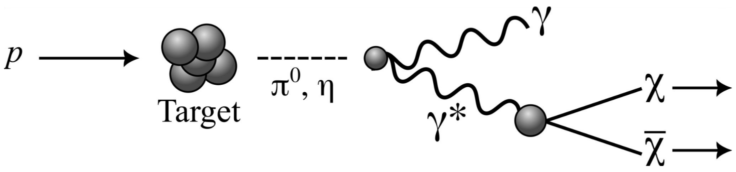


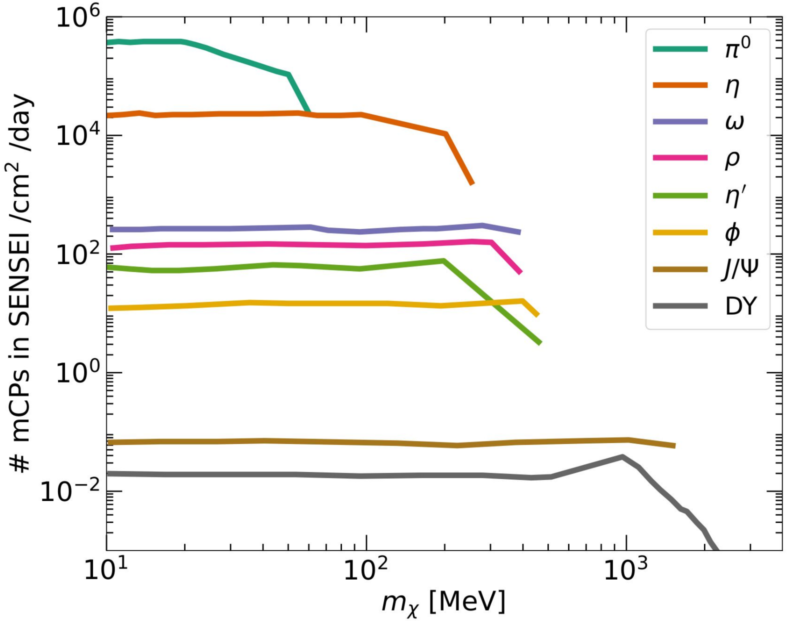
Long exposure example from MINOS dataset

Fixed target: SENSEI@MINOS

Harnik, R., Liu, Z. & Palamara, O. Millicharged particles in liquid argon neutrino experiments. *J. High Energ. Phys.* **2019**, 170 (2019).







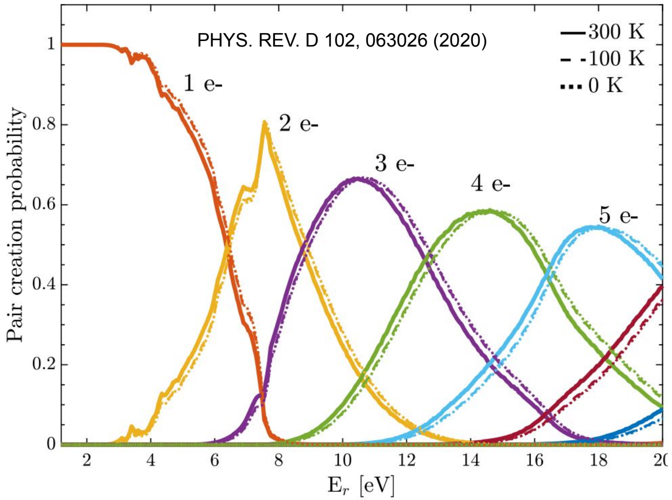
Highly boosted from a 120 GeV proton beam!

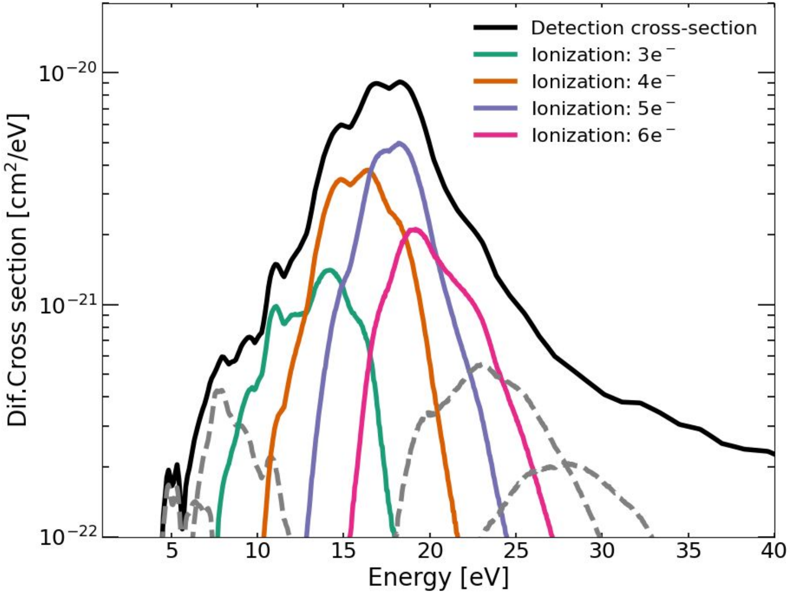
mCP interaction with silicon

From Fermi's energy loss formula, we can model the electron loss function using the DarkELF package

$$\frac{d\sigma}{d\omega} = \frac{8\alpha\varepsilon^2}{n_e\beta^2}\int_0^\infty dk\left\{\frac{1}{k}\mathrm{Im}\left(-\frac{1}{\epsilon(\omega,k)}\right) + k\left(\beta^2 - \frac{\omega^2}{k^2}\right)\mathrm{Im}\left(\frac{1}{-k^2+\epsilon(\omega,k)\omega^2}\right)\right\}$$

e the mCP interacts we take into account the probability of exciting an electron-hole pair in silicon:





Knapen, Simon, Jonathan Kozaczuk, and Tongyan Lin. "PYTHON package for dark matter scattering in dielectric targets." Physical Review D 105.1 (2022): 015014.

Collective excitations and low-energy ionization signatures of relativistic particles in silicon detectors. R. Essig, R. Plestid, and A. Singal. https://arxiv.org/pdf/2403.00123.pdf

Fixed target: SENSEI@MINOS

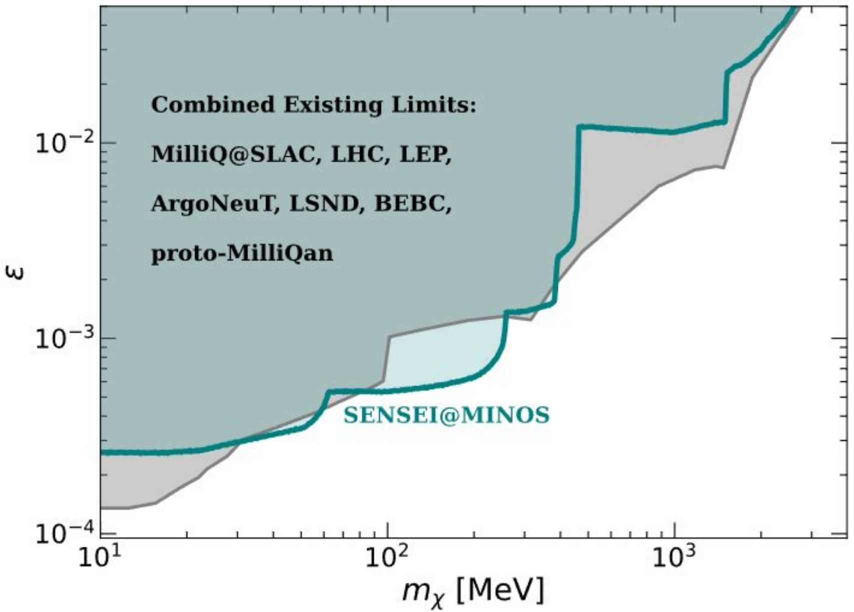
Extended the original 2020 search to 5 and 6 electrons.

	$1e^-$	$2e^-$	$3e^-$	$4e^-$	$5e^-$	$6e^-$
Eff. Efficiency	0.069	0.105	0.325	0.327	0.331	0.338
Exp. [g-day]	1.38	2.09	9.03	9.10	9.23	9.39
Obs. Events	1311.7	5	0	0	0	0

With only 2 grams of silicon!!

Source	Uncertainty [%]	Error on limit [%]
mCP flux	22	6
σ_{int}	5	2
CCI	$\ll$10	2
POT	2	0.5
	Total:	7

Simulated the systematics to assess impact on limit, error falls in the width of the line.

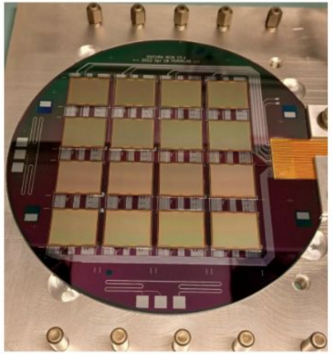


$$N(\varepsilon, m_\chi) = A\Delta T \int \phi(\varepsilon, E_\chi, m_\chi) P(hits \geq 1) dE_\chi$$

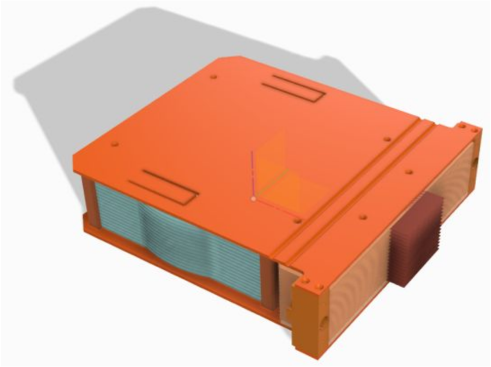
arxiv.org/abs/2305.04964 accepted at PRL

Fixed target: OIT - Oscura Integration test

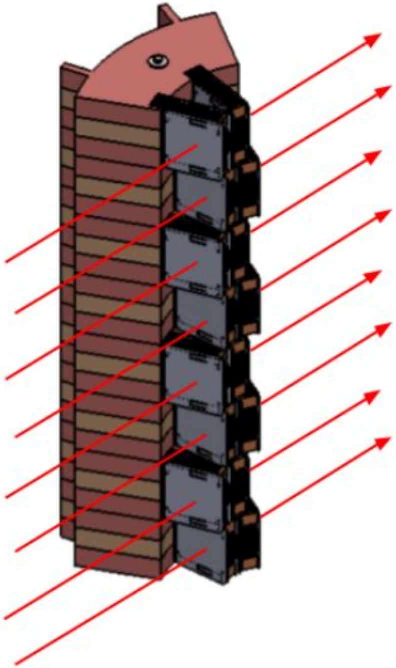
We can build larger skipper arrays thanks to the efforts of OSCURA (see talk by Brenda Cervantes)



1 MCM = 16 SENSORS

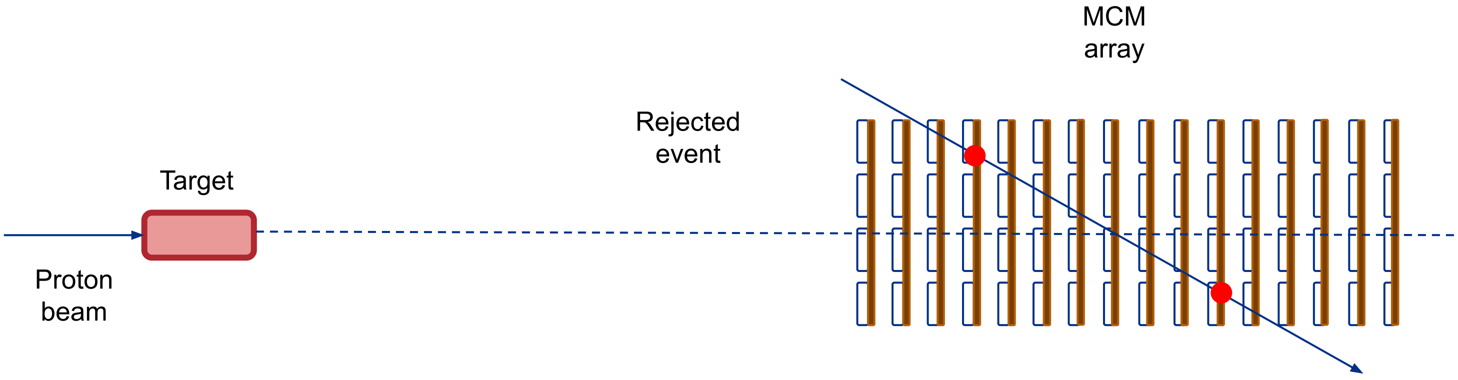


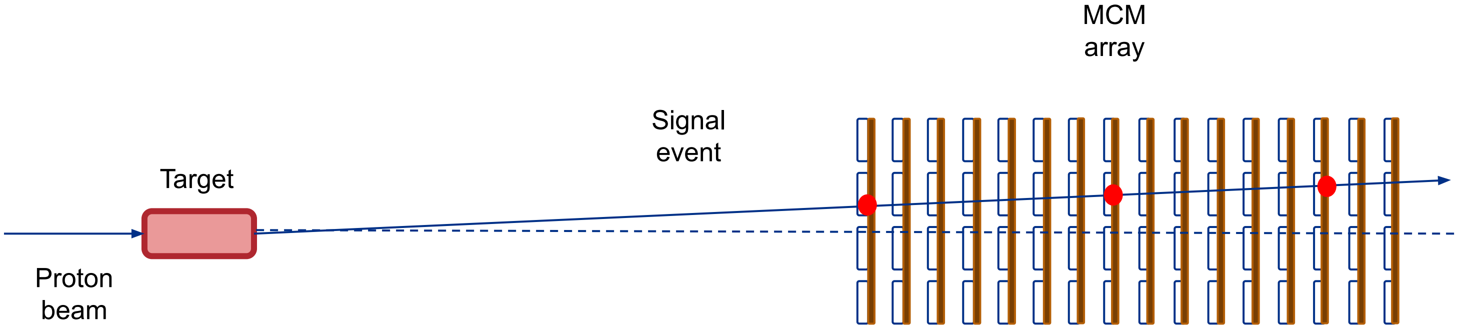
1 SM = 16 MCM



1 Slice= 16 SM

Fixed target: OIT - Oscura Integration test





Harnik, R., Liu, Z. & Palamara, O. Millicharged particles in liquid argon neutrino experiments. *J. High Energ. Phys.* **2019**, 170 (2019).

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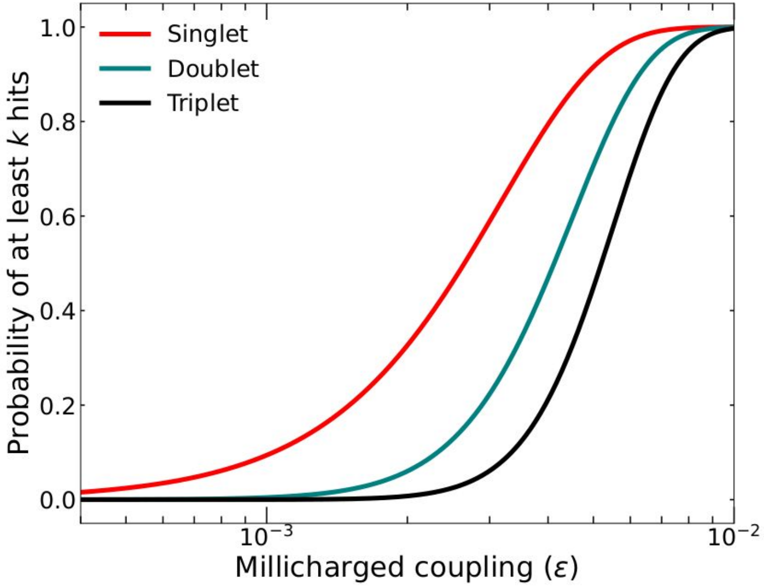
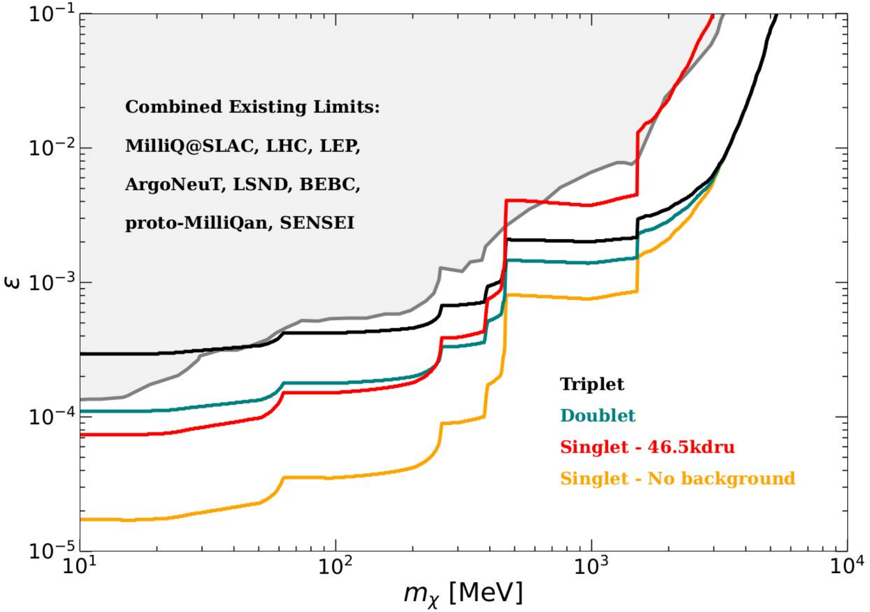


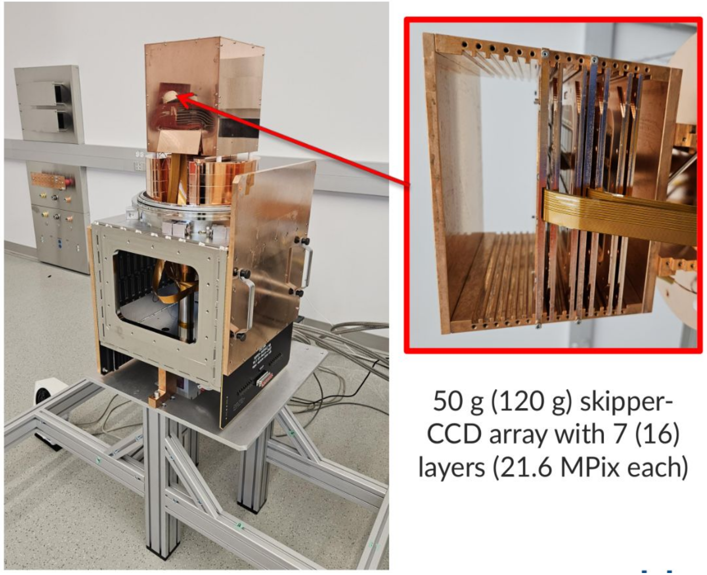


Lower probability to have doublet events but more robust to background - can help for higher masses

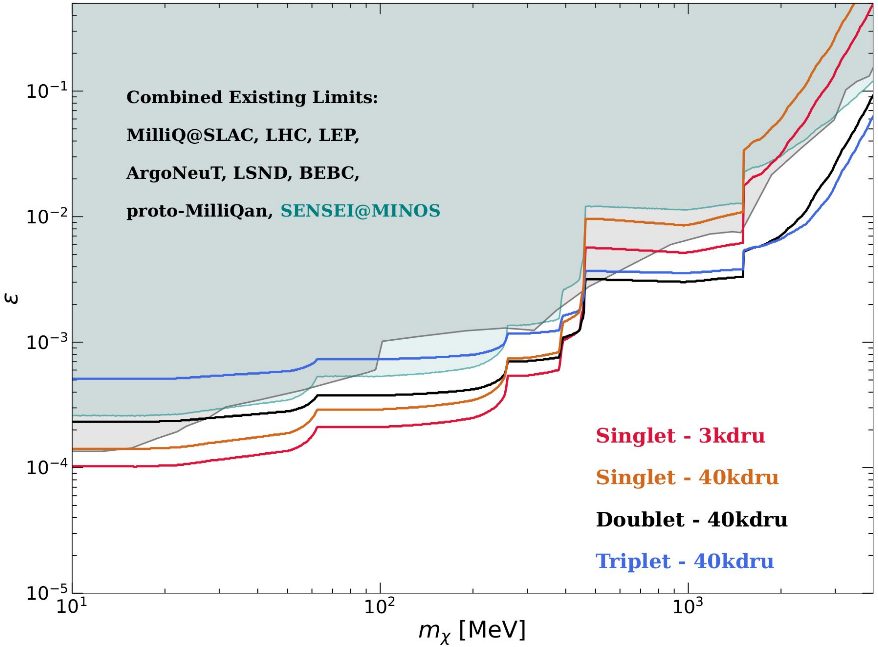
Perez, S., Rodrigues, D., Estrada, J. *et al.* Searching for millicharged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab. *J. High Energ. Phys.* **2024**, 72 (2024).

Fixed target: Dark BeaTS - Dark beam Tracking Skipper-CCDs

Dark BeaTS
(Dark Beam Tracker with Skipper-CCDs)

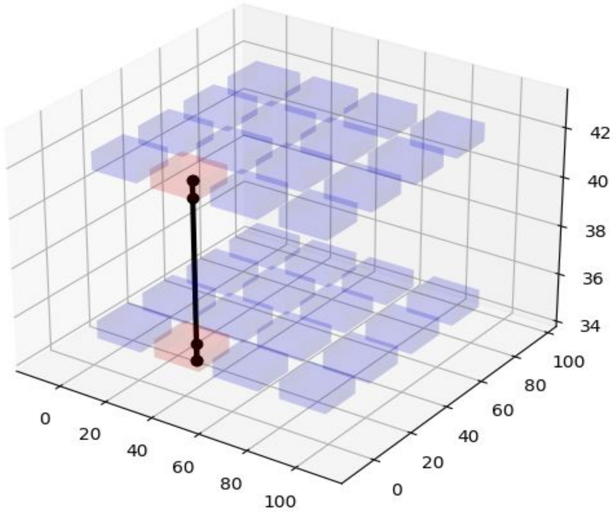


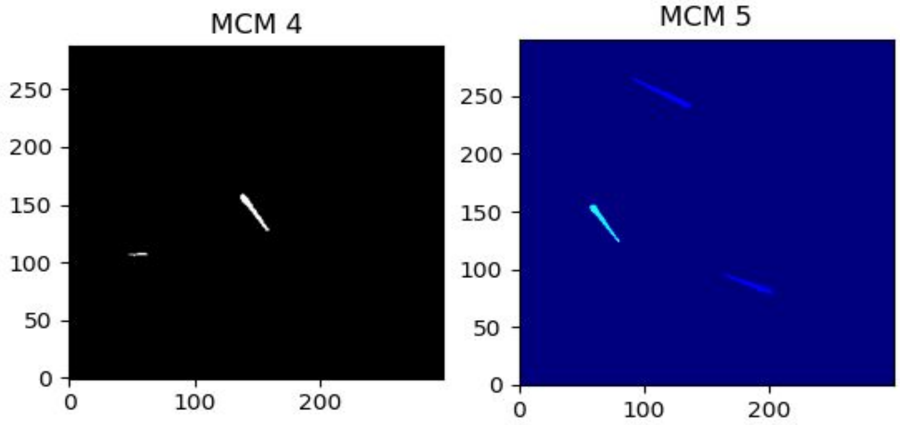
50 g (120 g) skipper-CCD array with 7 (16) layers (21.6 MPix each)



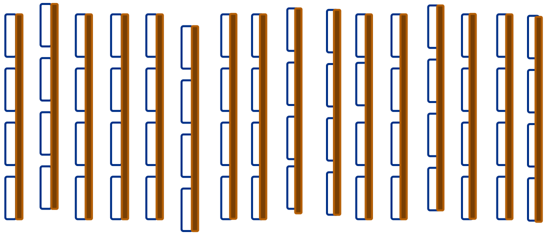
Fixed target: Dark BeaTS - Dark beam Tracking Skipper-CCDs

Demonstrated small scale muon tracking, there is still a lot of work to do to achieve the single-electron tracking capability.





Muons could provide a solid calibration for misalignments



Reactor: CONNIE / ATUCHA

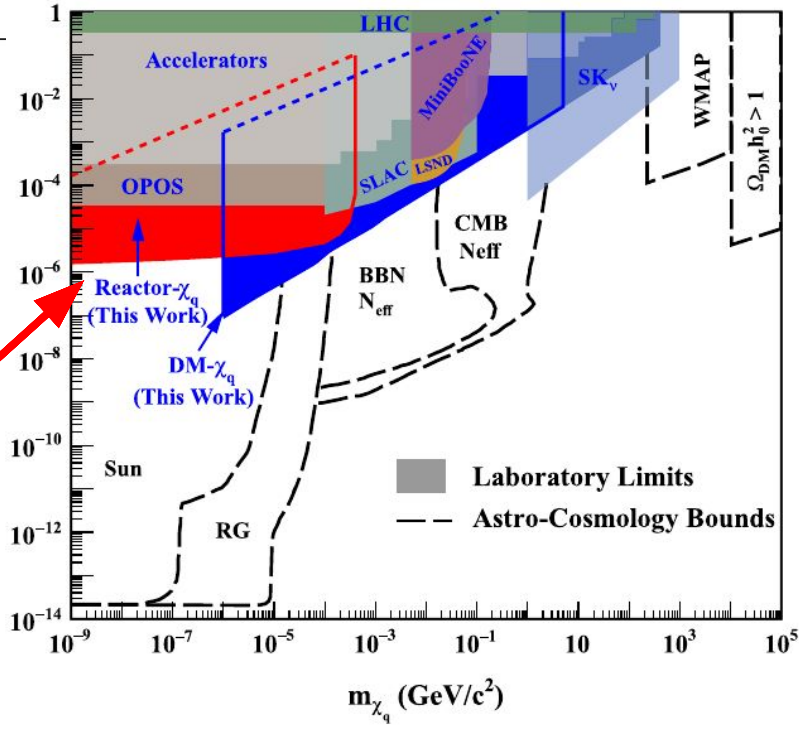
PHYSICAL REVIEW D **99,** 032009 (2019)

Constraints on millicharged particles with low-threshold germanium detectors at Kuo-Sheng Reactor Neutrino Laboratory

L. Singh,[1,2,*] J. W. Chen,[3,4] H. C. Chi,[5] C.-P. Liu,[5] M. K. Pandey,[3] H. T. Wong,[1,†] C. P. Wu,[3] M. Agartioglu,[1,5,6] M. Deniz,[1,6] H. B. Li,[1] S. T. Lin,[1,7] V. Sharma,[1,2] M. K. Singh,[1,2] V. Singh,[2] and Q. Yue[8]

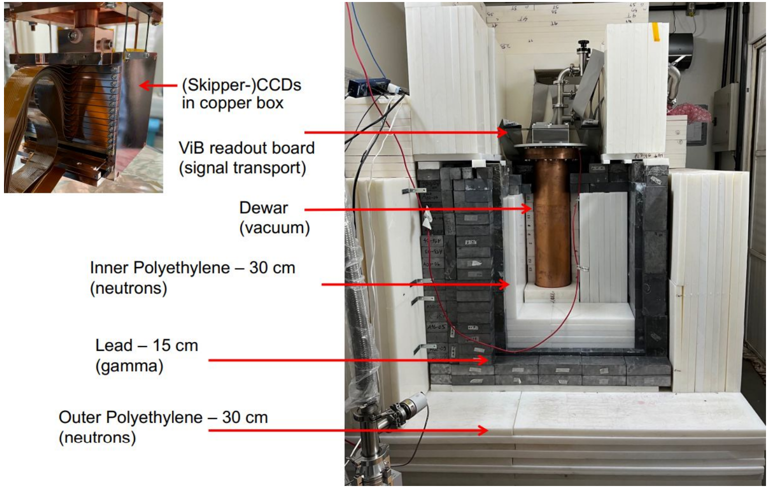
(TEXONO Collaboration)

We based this analysis in the exclusion limit set by TEXONO in 2019 (90% C.L.)



Reactor: CONNIE

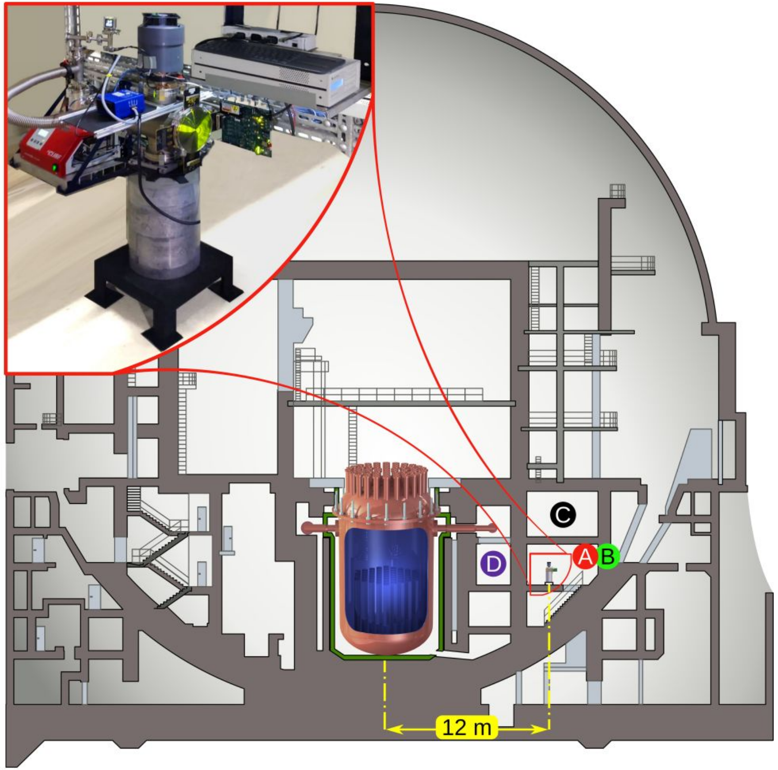
- At around 30 m from the 3.95 GWth Angra 2 reactor.
- Accumulated a lot of data with regular low-noise CCDs, now upgraded to Skipper-CCDs.
- Main focus on neutrino physics
- Now testing OSCURA MCMs.

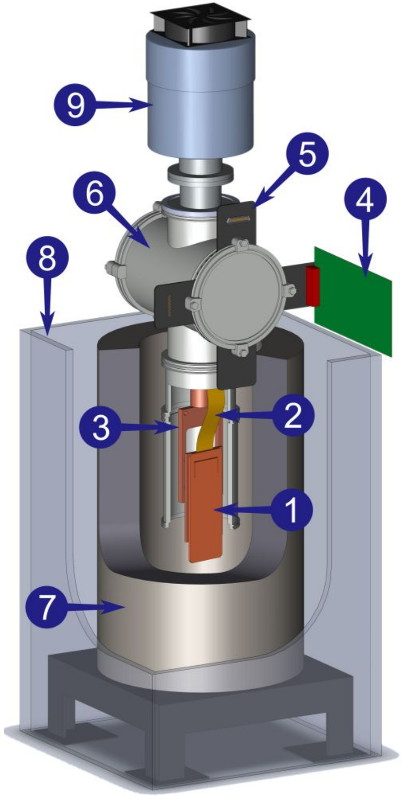


Reactor: ATUCHA-II

- Installed 12 m from the nucleus **inside** the containment dome of the Atucha II 2-GWth reactor.

- Uses skipper-CCD, focus on neutrino physics but ideal to search for BSM physics due to its location.





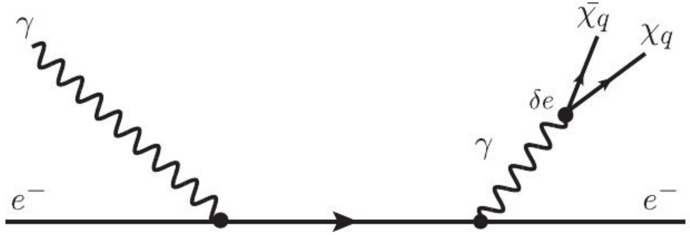
Reactor: CONNIE / ATUCHA

Gamma flux produced by a nuclear reactor

$$\frac{dN_\gamma}{dE_\gamma} = 0.581 \times 10^{18} e^{-1.1 E_\gamma(\mathrm{MeV})} \times \mathrm{Power(MW)}$$

Lepton-pair production formula

$$\frac{d\sigma}{dE_{\chi_q}}(\gamma e \to \chi_q \bar{\chi}_q e) \simeq \frac{4}{3} \frac{\delta^2 \alpha^3}{m_e^2 E_\gamma^3} [(3(E_{\chi_q}^2 + E_{\bar{\chi}_q}^2) + 2E_{\chi_q} E_{\bar{\chi}_q})] \times \log\left(\frac{2E_{\chi_q} E_{\bar{\chi}_q}}{E_\gamma m_{\chi_q}}\right)$$



Fermilab

Reactor: CONNIE / ATUCHA

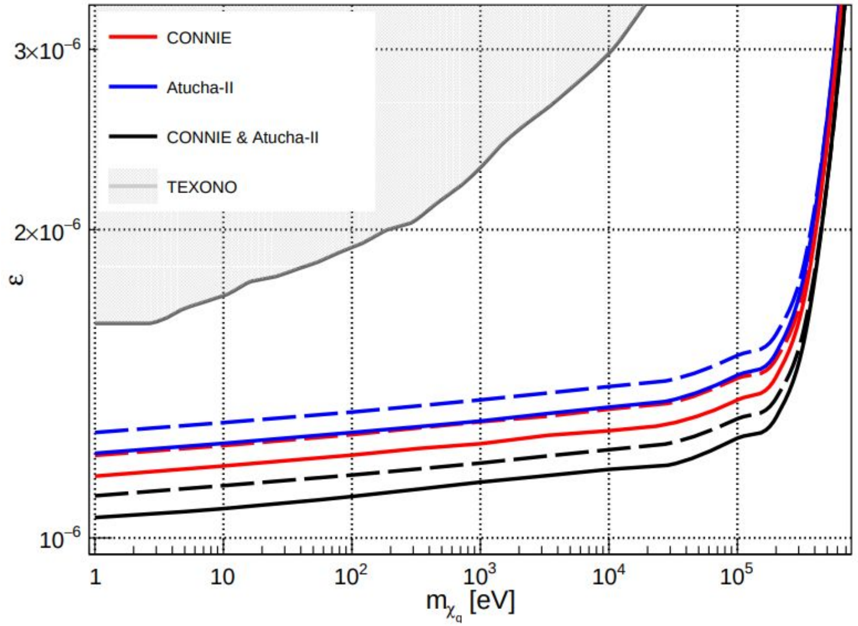
$$\frac{dR}{dT} = \rho_A \int_{E_{\min}}^{E_{\max}} \left[\frac{d\sigma}{dT}\right] \left[\frac{d\phi_{\chi_q}}{dE_{\chi_q}}\right] dE_{\chi_q}$$

Detection

Production

Observable	CONNIE	Atucha-II
Reactor ON exposure [g-day]	14.9	59.4
Reactor OFF exposure [g-day]	3.5	22.6
Energy bin [eV]	15–215	40–240
Reactor ON counts	6	168
Reactor OFF counts	2	71
90% C.L. upper limit on events	6.2	30.9

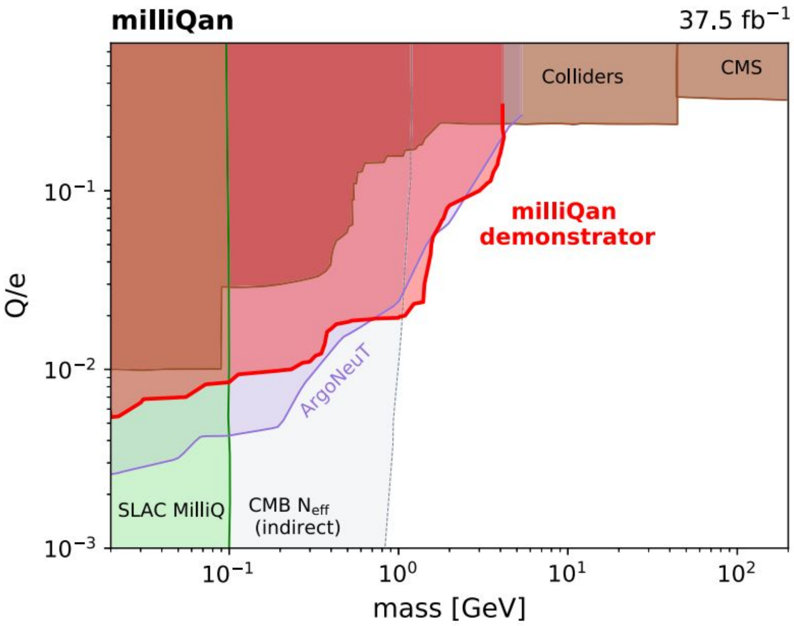
We calculate the 90% C.L for each mass and coupling and combine both reactor experiments

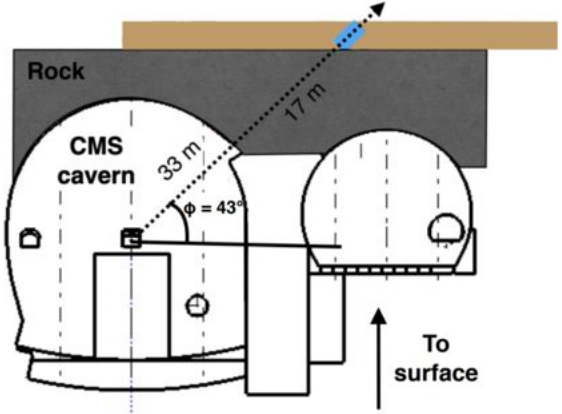


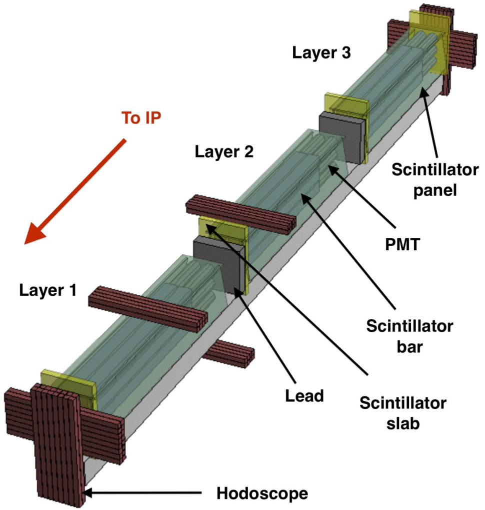
https://arxiv.org/abs/2405.16316

Accelerator: MOSKITA@LHC

The milliQan collaboration identified the CMS service cavern as a good place to search for mCPs during LHC-RUN 3.



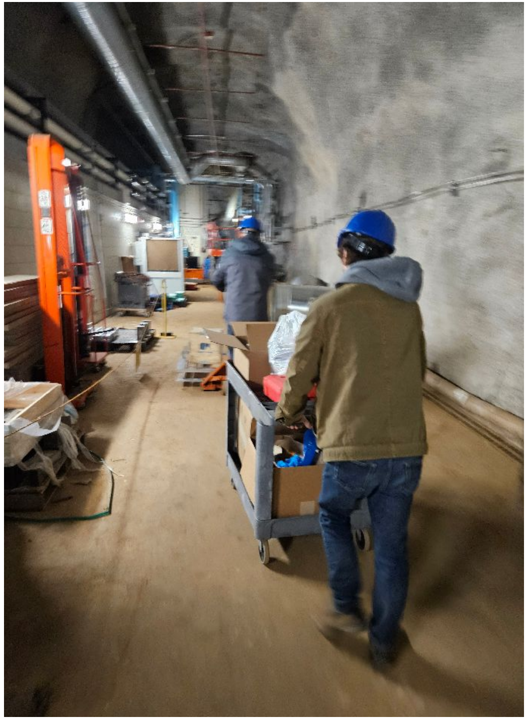




They kindly gave us some space in their lair!!

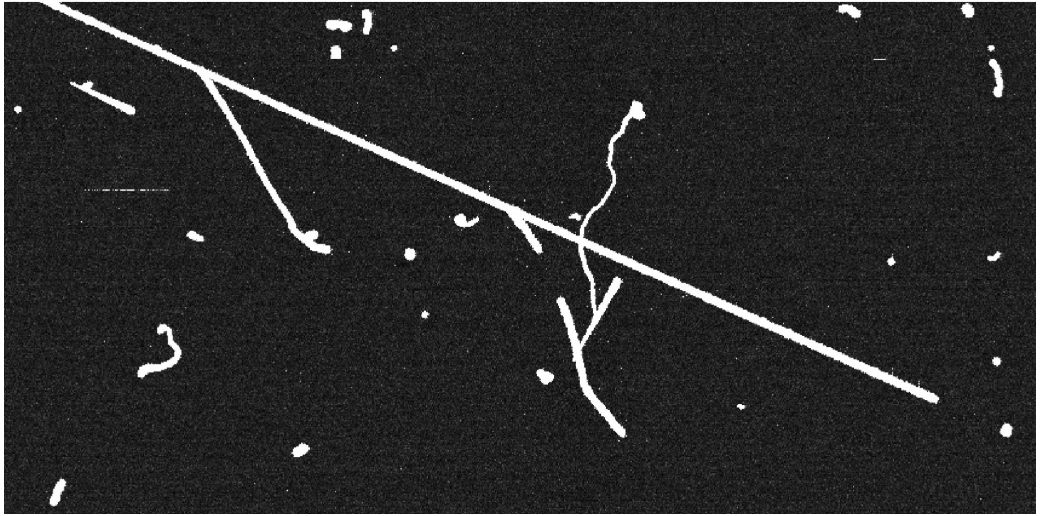
Accelerator: MOSKITA@LHC

Oscura sensor testing setup at FNAL



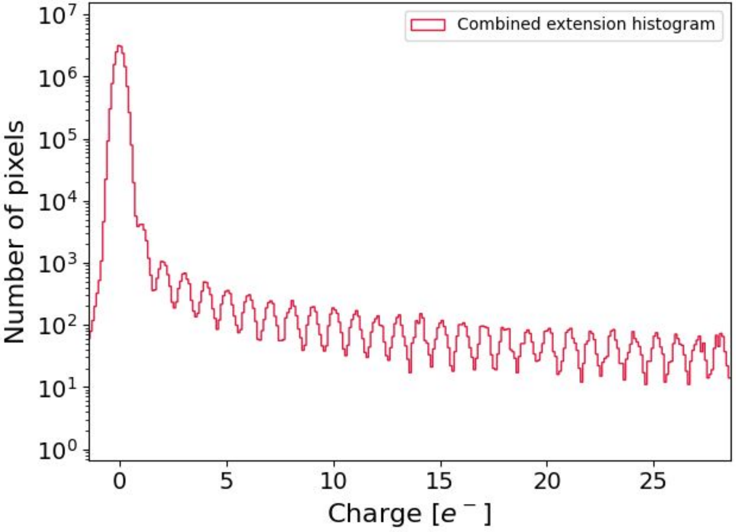
Moved to the CMS service cavern to measure backgrounds

Accelerator: MOSKITA@LHC



Currently taking data with single electron resolution!
Expect results soon!

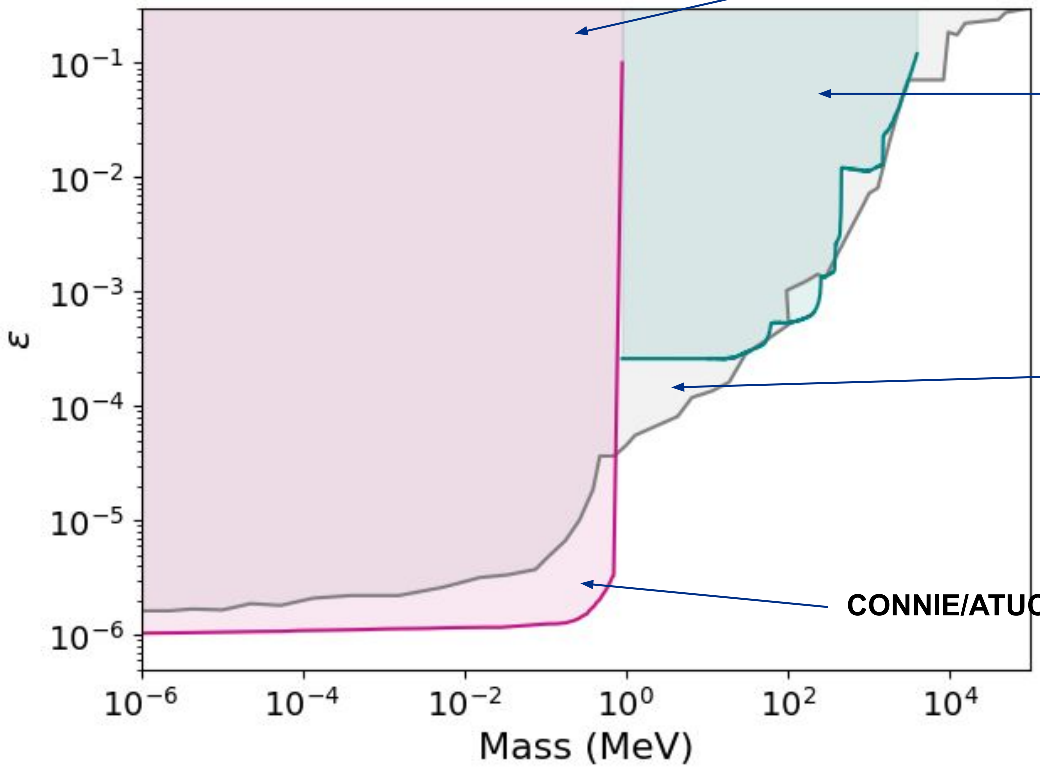
Accelerator: MOSKITA@LHC



Currently taking data with single electron resolution!
Expect results soon!

Skippers: All laboratory limits - preliminary plot

This zone is not excluded by our experiment due to mCP losses at higher coupling.



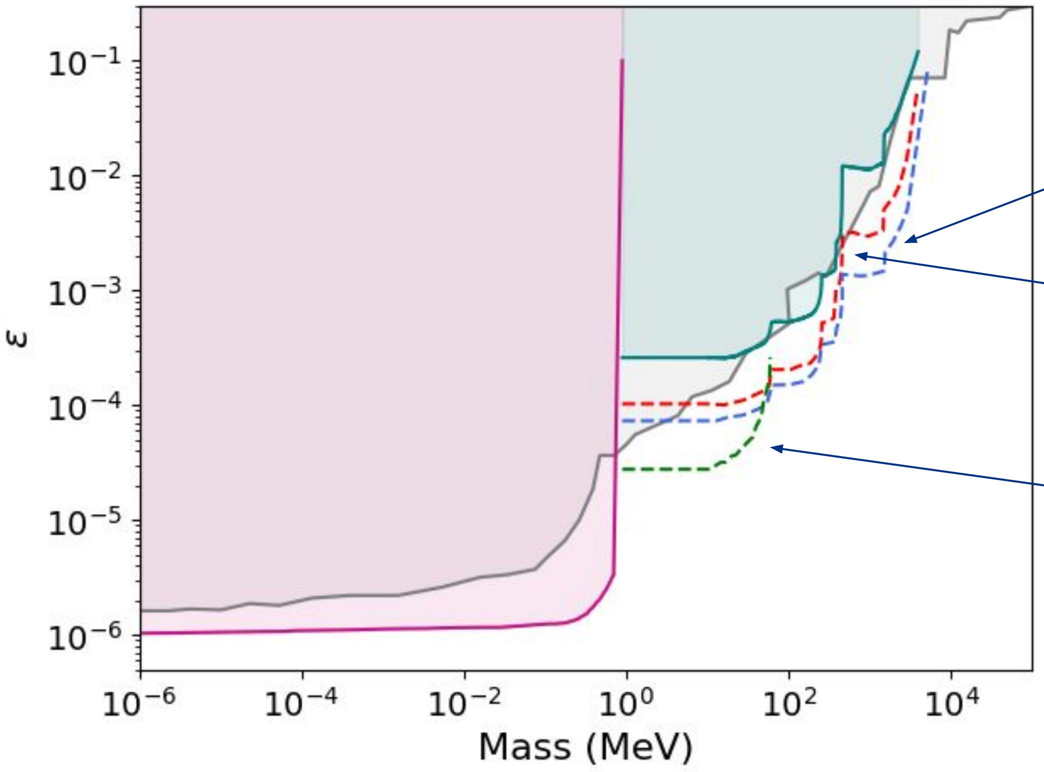
SENSEI result

Current constraints containing: TEXONO, Milliq@SLAC, LHC, LEP, ArgoNeuT, LSND BEBC, proto-MilliQan

CONNIE/ATUCHA-II result

Fermilab

Skippers: Laboratory limits next steps - preliminary plot



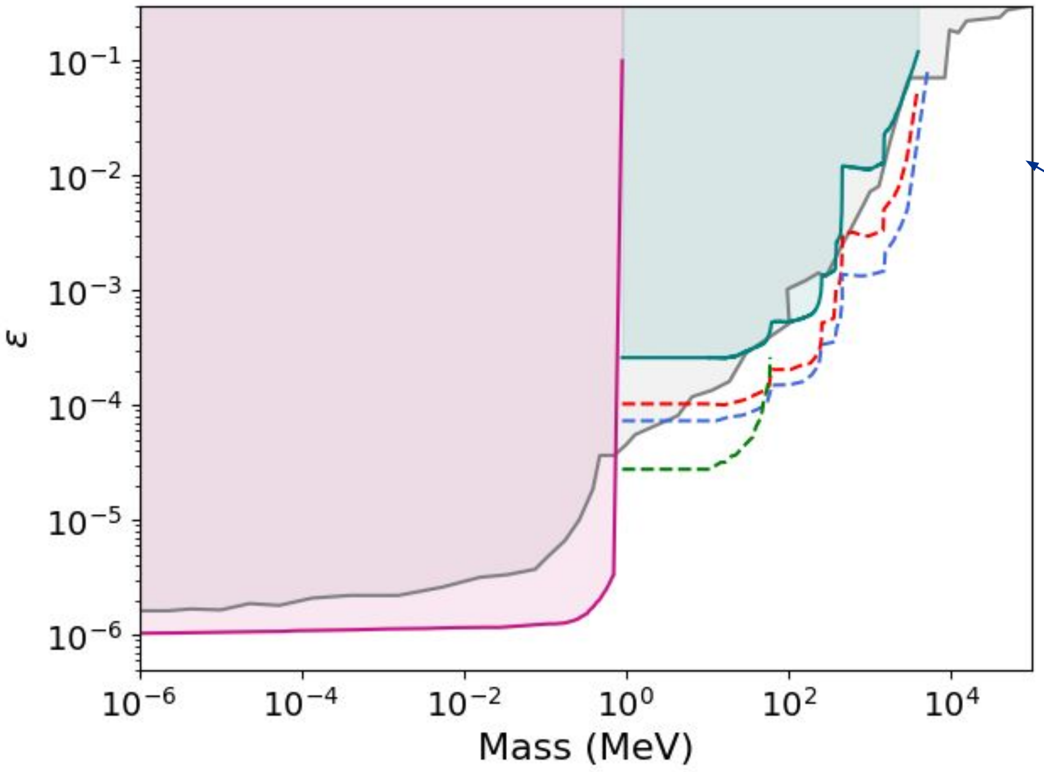
Oscura Integration Test - 1kg - 46.5 kdru

DarkBeats@NUMIbeamline - 50gr/day - 3 kdru

Skipper@PIP-II - 1kg/year - 10 kdru

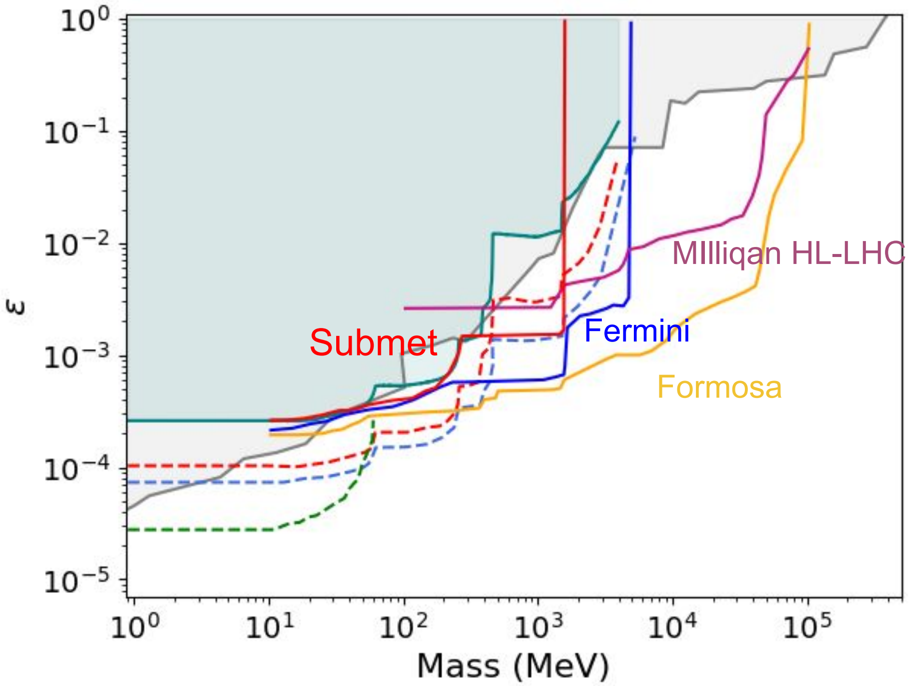
Aguilar-Arevalo, A. A., et al. "Physics Opportunities at a Beam Dump Facility at PIP-II at Fermilab and Beyond." *arXiv preprint arXiv:2311.09915* (2023).

Skippers: All laboratory limits - preliminary plot



Since this region is not limited by detection efficiency experiments like FORMOSA@FPF -LHC and MilliQan are more sensitive.

Skippers: All laboratory limits - preliminary plot



Conclusions

- Skipper-CCDs continue to be very promising for detecting low-energy processes
- The mCP’s mass and charge parameter space can be greatly constrained by Skipper-CCD based experiments to investigate the mystery of charge quantization.
- Several experiments are taking place and new ones are coming which search for mCPs in different locations/sources and strategies.
- Reactor Skipper-CCD collaborations working together improved the laboratory constraint of low mass (eV-MeV) mCPs.
- Fixed target experiments can demonstrate single-electron tracking and place constraints in the MeV mass range of mCPs. Which are masses similar to the standard model particles
- Accelerators experiments (LHC) can extend the search to the GeV mass mCP and also take advantage of tracking. New results coming in the next months!

Thanks to all our collaborators and people who made this possible :D

And thank you for listening …

Backup slides!

mCP interaction with silicon

$$\frac{d\sigma_R}{dE} = \underbrace{z^2 \frac{2k_R}{\beta^2}\left(\frac{1-\beta^2 E/E_{max}}{E^2}\right)}$$

$$ze \rightarrow \epsilon e$$

$$\frac{d\sigma_{mcp}}{dE} = \epsilon^2 \frac{d\sigma_R}{dE} \longrightarrow \frac{d\sigma_{mcp}}{dE} = \epsilon^2 |F(E)|^2 \frac{d\sigma_R}{dE}$$

Modeling the Form Factor with the Photo Absorption Ionization model:

$$\frac{d\sigma_{PAI}}{dE} = \frac{\alpha}{\beta^2\pi}\frac{\sigma_\gamma(E)}{EZ} ln[(1-\beta^2\epsilon_1)^2+\beta^4\epsilon_2^2]^{-1/2} + \frac{\alpha}{\beta^2\pi}\frac{1}{N_e\hbar c}\left(\beta^2 - \frac{\epsilon_1}{|\epsilon|^2}\right)\Theta + \frac{\alpha}{\beta^2\pi}\frac{\sigma_\gamma(E)}{EZ} ln\left(\frac{2mc^2\beta^2}{E}\right) + \frac{\alpha}{\beta^2\pi}\frac{1}{E^2}\int_0^E \frac{\sigma_\gamma(E')}{Z}dE'$$

$$\frac{d\sigma_{mcp}}{dE} = \epsilon^2 \frac{d\sigma_{PAI}}{dE}$$

But at low energies, $\sigma_\gamma(E)$ is a bad proxy for relativistic scattering of charged particles

Secondary photons from the reactor

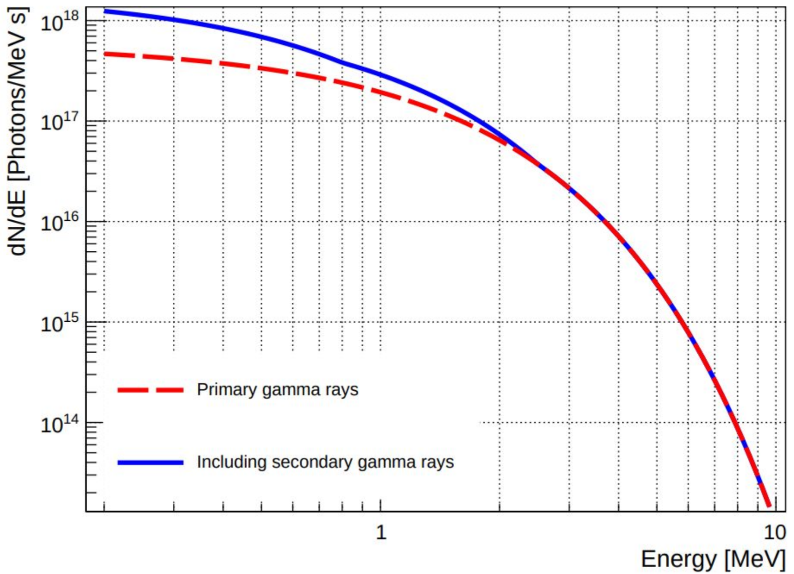
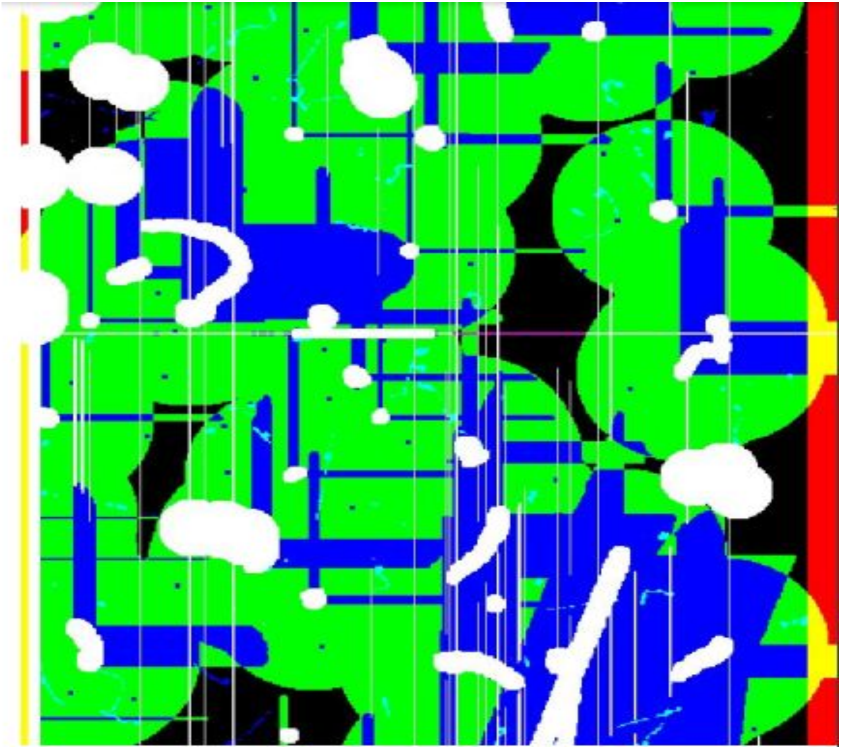


FIG. 3. Photon flux produced in the nuclear reactor. The red dashed line is derived from Eq. 1, considering primary γ-rays only. The blue solid line is obtained from a GEANT4 simulation, taking into account secondary photon production.

Identifying types of events / data processing

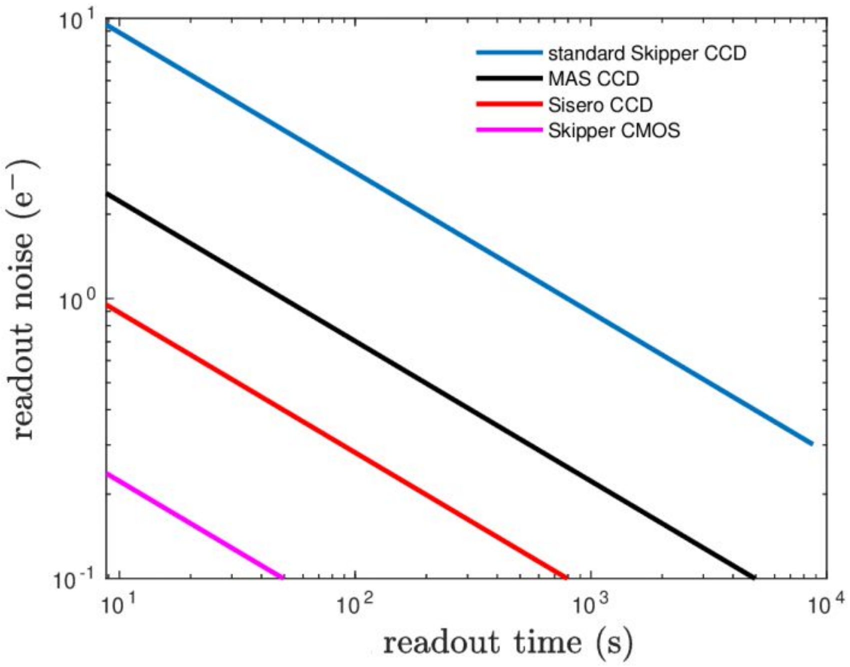
Some of the different pixel masks:

- High energy event mask (White)
- Halo mask (Green)
- Bleed mask (Blue)
- Bad pixel/ Column (White)
- Edge mask (Red)
- Crosstalk (cryan)
- Serial register hit (magenta)

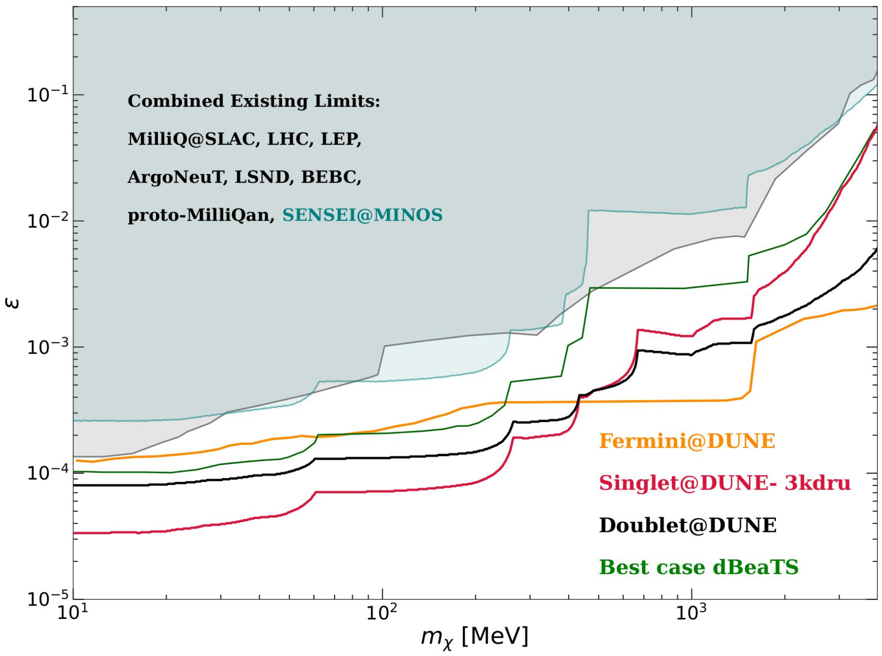


Only the black pixels are taken into account in data analysis

Other things possible with Darkbeats!



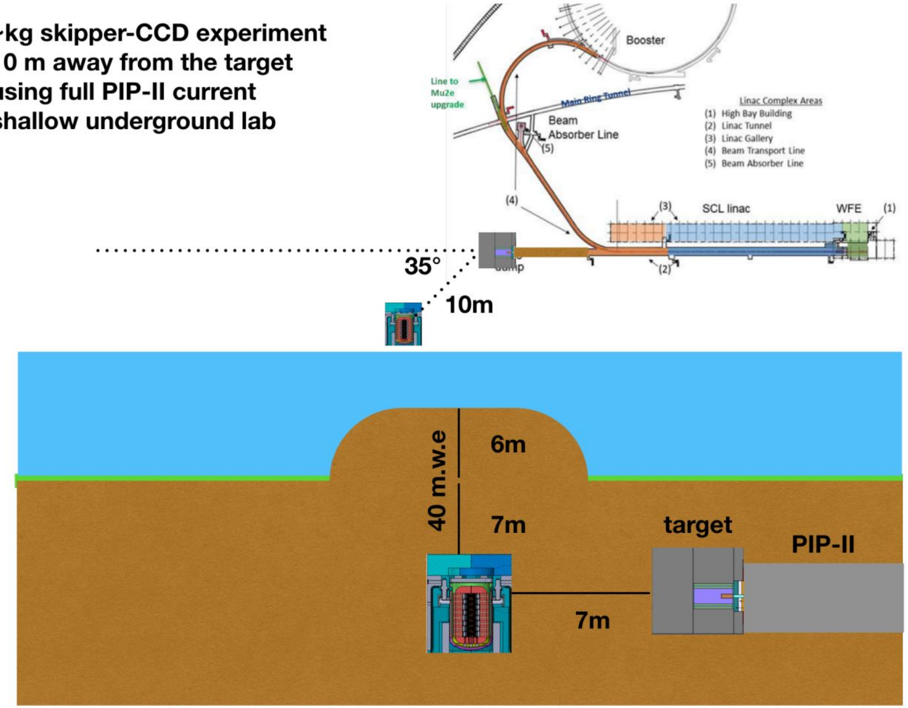
Test faster technologies

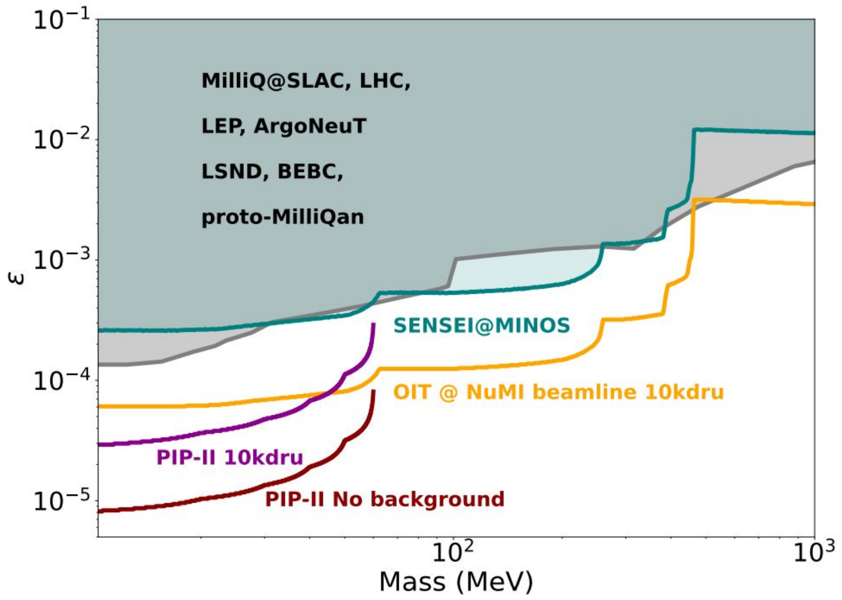


Maybe Install at DUNE's future beamline?

Skipper@PIP-II

- ~kg skipper-CCD experiment
- 10 m away from the target
- using full PIP-II current
- shallow underground lab





Diffusion efficiency

Sample random uniform in x, y and z in micrometers …

$$G(x,y) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

With $\sigma(z) = \sqrt{-A \ln|1 - bz|}$

$$A = 218.715 \mu m$$

$$b = 1.015 \times 10^{-3} \mu m^2$$