Fermilab

15th Conference on the Intersections of Particle and Nuclear Physics (CIPANP 2025)

Madison Wisconsin June 9-13

# Searching for millicharged particles at accelerator facilities with skipper-CCDs


**Brenda Aurea Cervantes Vergara**

*bcervant@fnal.gov*



U.S. DEPARTMENT of ENERGY

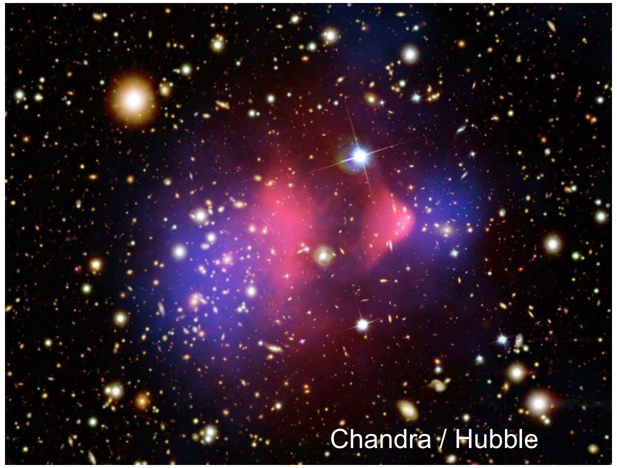
Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

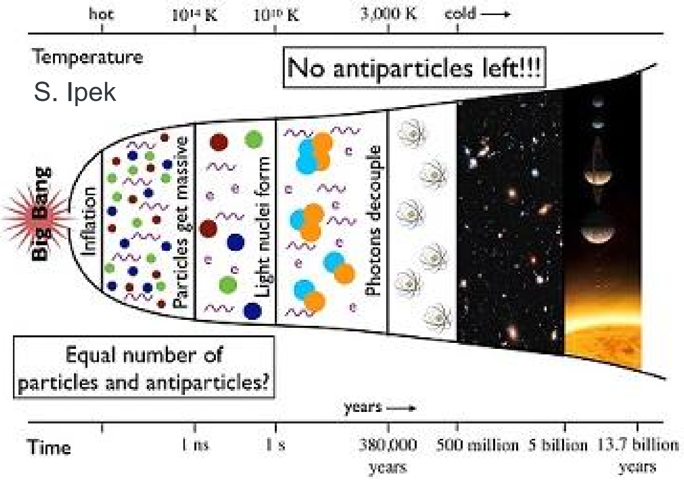

FERMI NATIONAL ACCELERATOR LABORATORY

# The need for new physics

The SM is incomplete. There are many intriguing questions yet to solve:

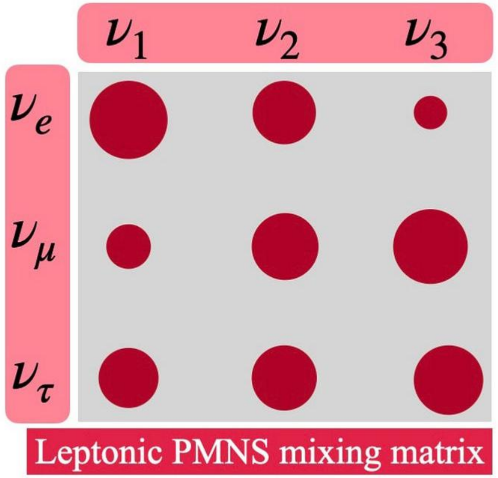
### What is dark matter?

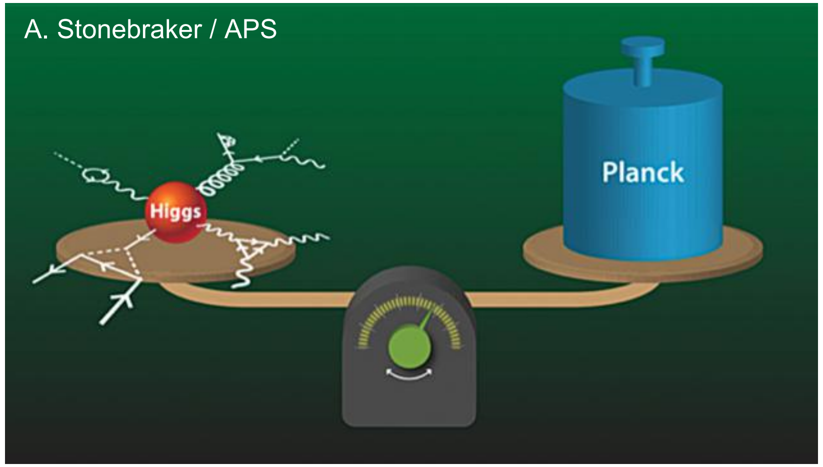



### Why is there more matter than antimatter?

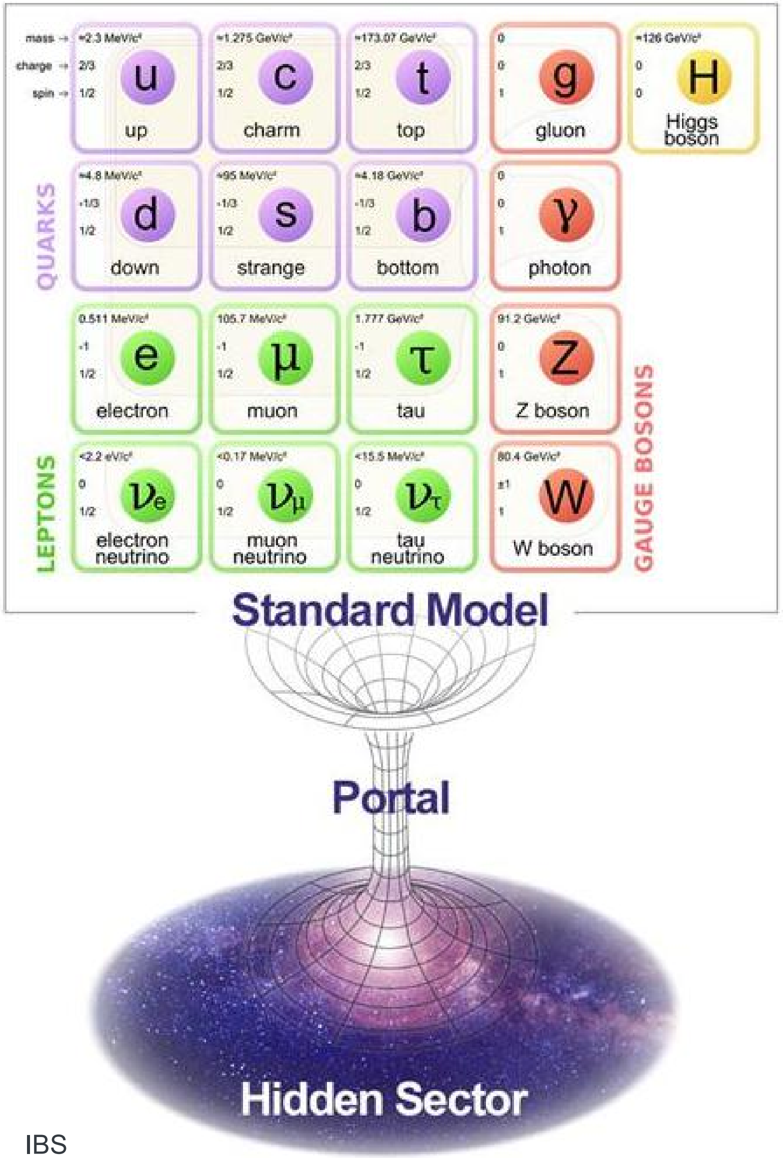
### How do neutrinos get their mass?




### Why is the Higgs so light?

# Dark sector models

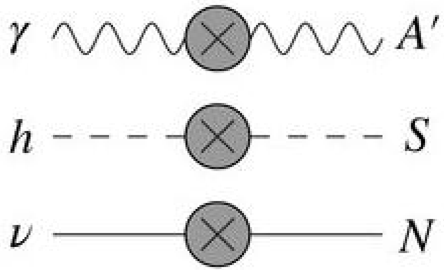



IBS

Appealing framework to address key puzzles, as experiments continue to rule out other explanations.

**Set of new particles and forces, interacting very feebly with the SM through "portals" associated to specific mediators**

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$




Dark photon (vector)

Dark Higgs (scalar)

Dark neutrino (fermion)

Due to their extremelly small couplings, producing dark sector particles at detectable rates requires high-intensity sources, such as **accelerators**.


J. Beacham et al.. Physics Beyond Colliders at CERN: BSM working group report. [10.1088/1361-6471/ab4cd2]
N. Bozorgnia et al.. Dark matter candidates and searches. [10.1139/cjp-2024-0128]

# Millicharged particles: a window to the dark sector

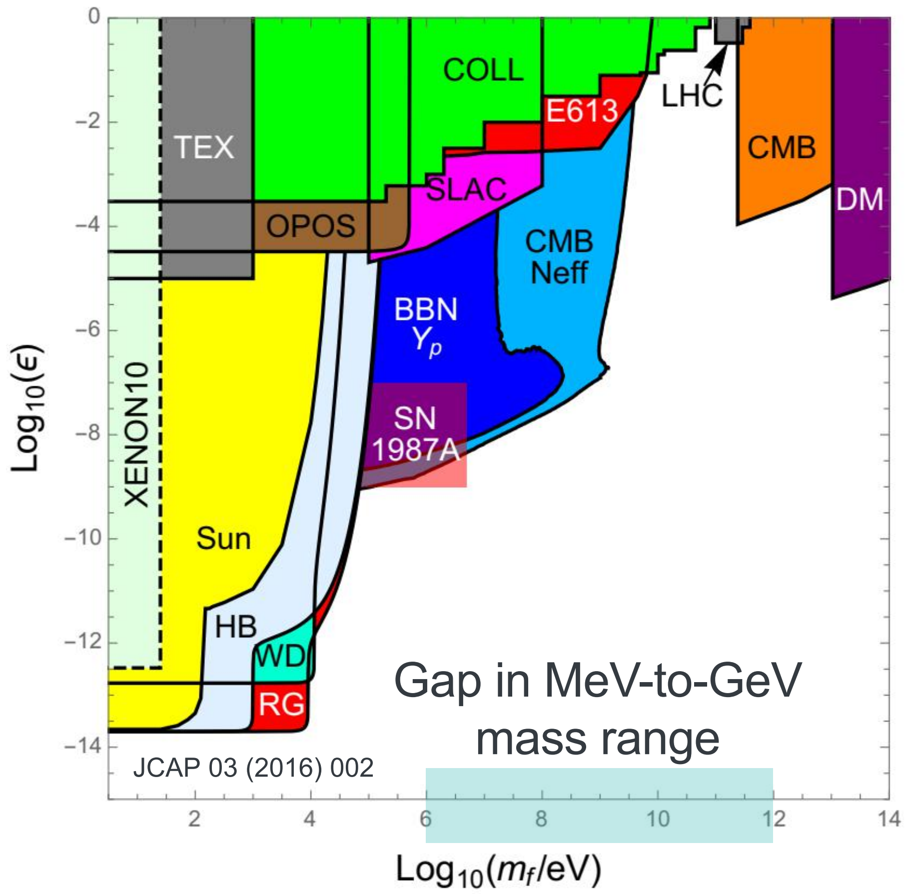
**Hypothetical particles with fractional electric charge**

**mCPs arise naturally in dark sector models**, e.g. as a new fermion, charged under a new massless vector boson that kinetically mixes with the SM photon

If they exist, they:

- Would **test charge quantization**
- Could be **candidates for a fraction of the dark matter**

Extremely feeble electromagnetic interactions with ordinary matter requires ultra-sensitive detectors.




Some existing bounds on mCPs from models with a massless dark photon

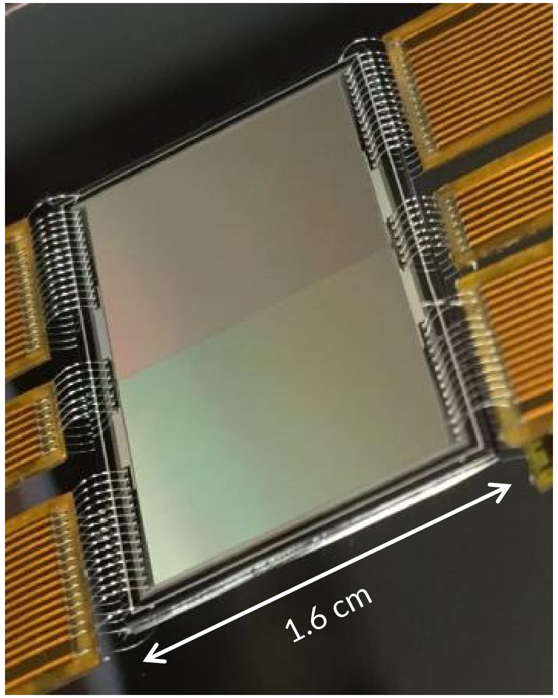

B. Holdom. Two U(1)′s and epsilon charge shifts. [10.1016/0370-2693(86)91377-8]
D. Brahm et al.. U(1)′ dark matter. [10.1103/PhysRevD.41.1067]
M. Fabbrichesi et al.. The dark photon. [10.48550/arXiv.2005.01515]

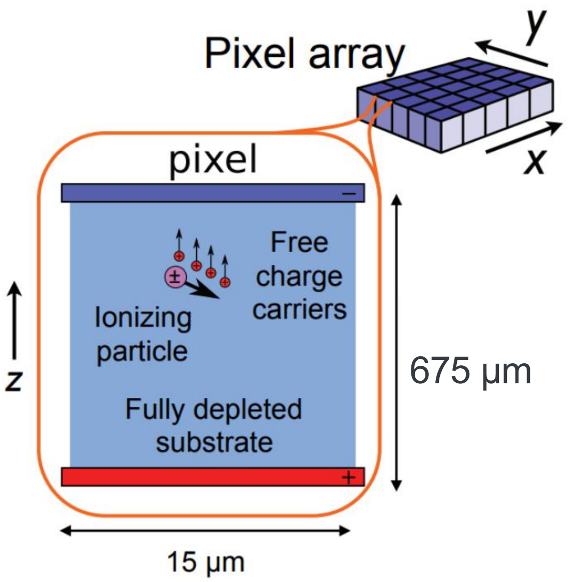
# Skipper-CCDs: electron-counting silicon sensors

Skipper-CCDs are **pixelated ionization sensors**, with a **readout stage that enables multiple measurements of the charge in each pixel.**

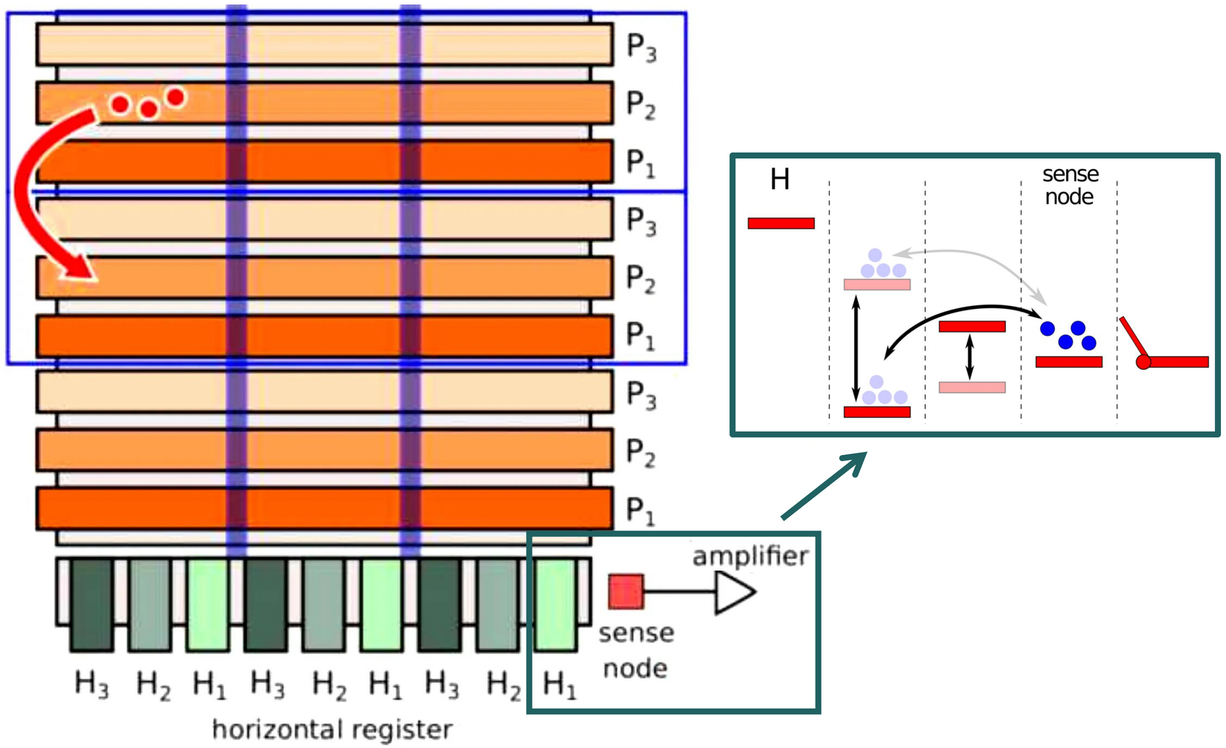
Ionizing radiation produces electron-hole pairs in sensitive region. In silicon, 1 eh pair ≈ 3.75 eV.

Charge is collected near the surface and transferred along the CCD until the readout stage.



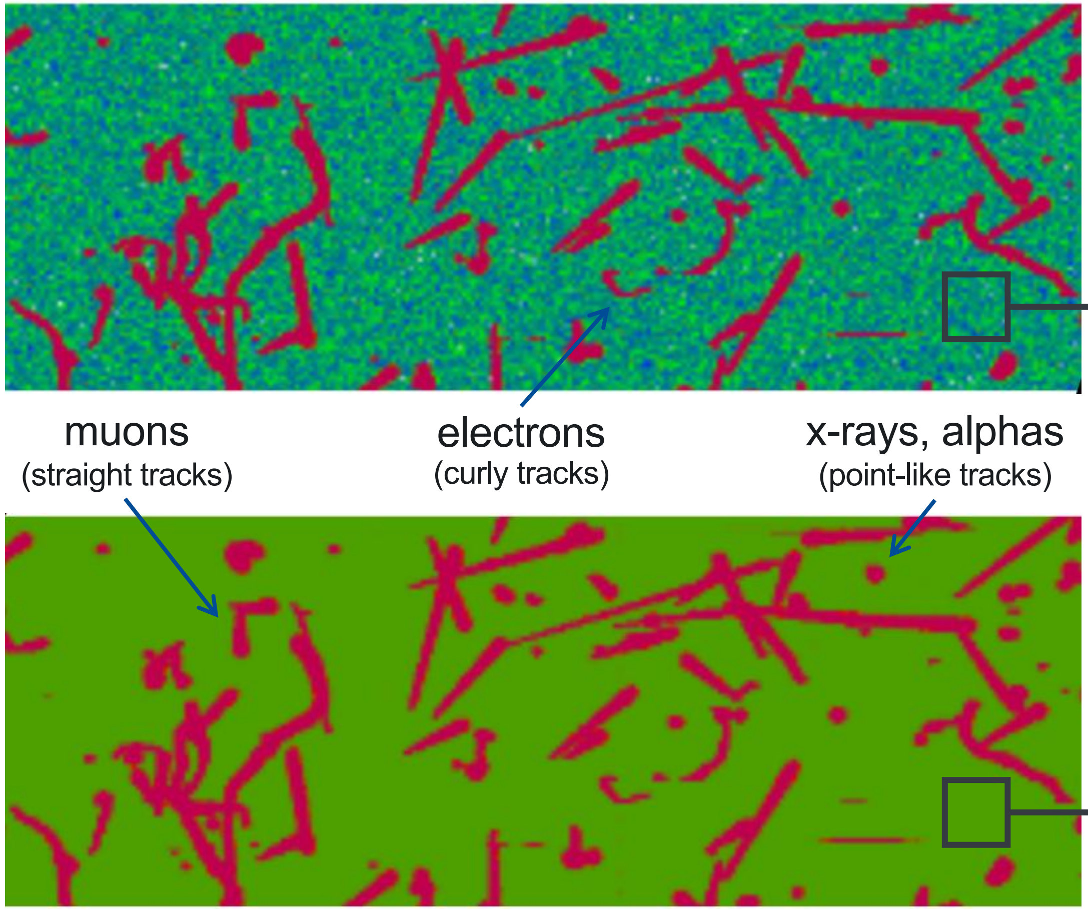



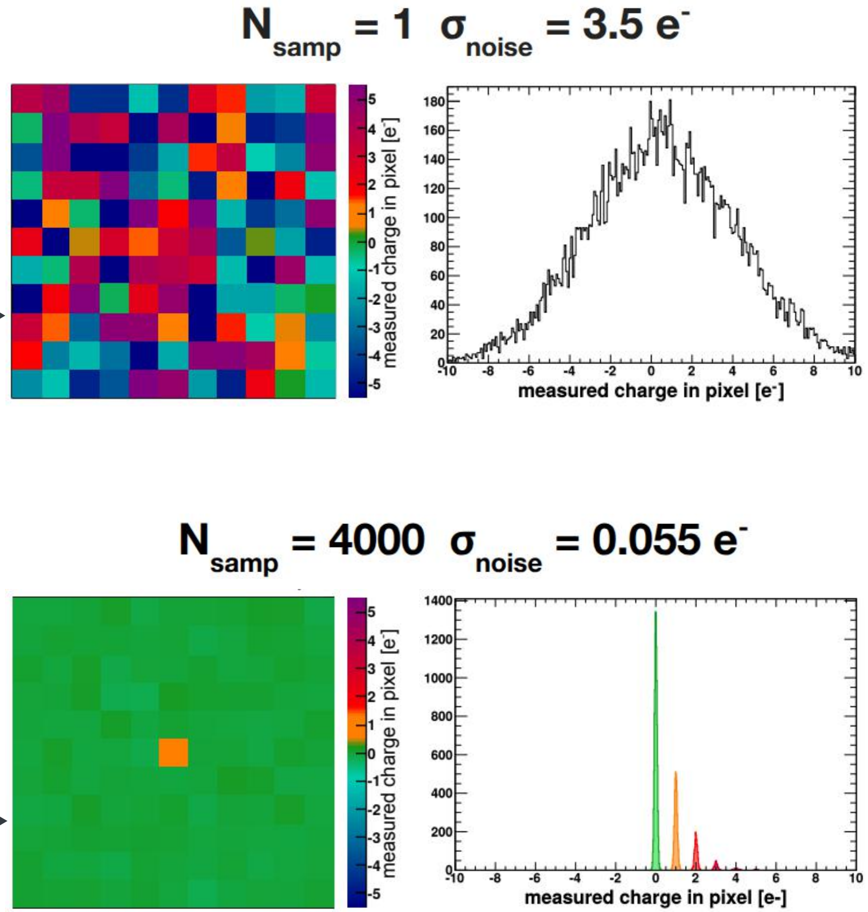

3x3 pixel CCD




J. Janesick et al.. New advancements in charge-coupled device technology: sub-electron noise and 4096×4096 pixel CCDs. [10.1117/12.19452]
G. Fernandez Moroni et al.. Sub-electron readout noise in a Skipper CCD fabricated on high resistivity silicon. [10.1007/s10686-012-9298-x]
J. Tiffenberg et al.. Single-Electron and Single-Photon Sensitivity with a Silicon Skipper-CCD. [10.1103/PhysRevLett.119.131802]

# Skipper-CCDs: electron-counting sensors

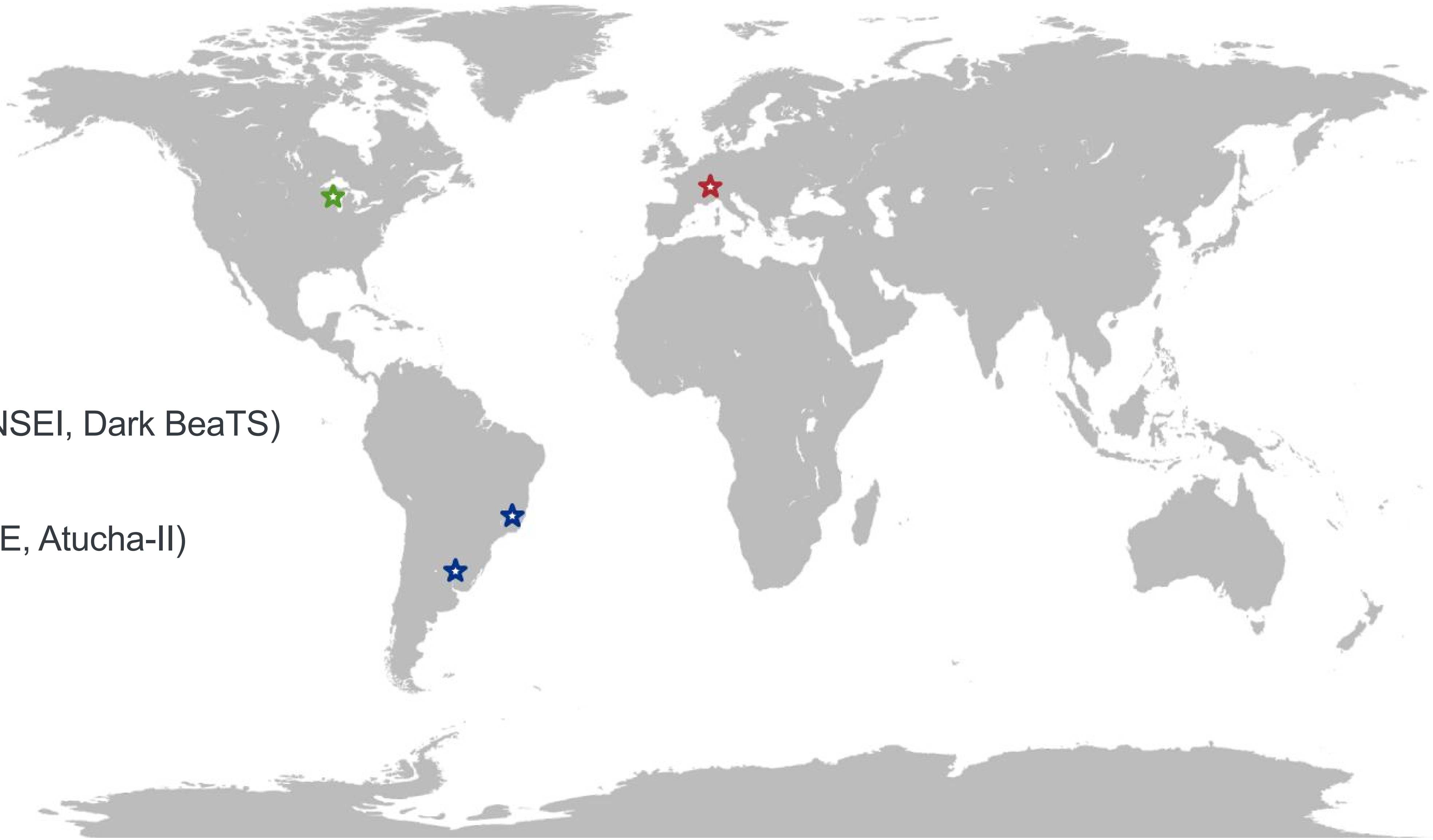



Noise reduction to sub-electron levels enables precise electron counting!

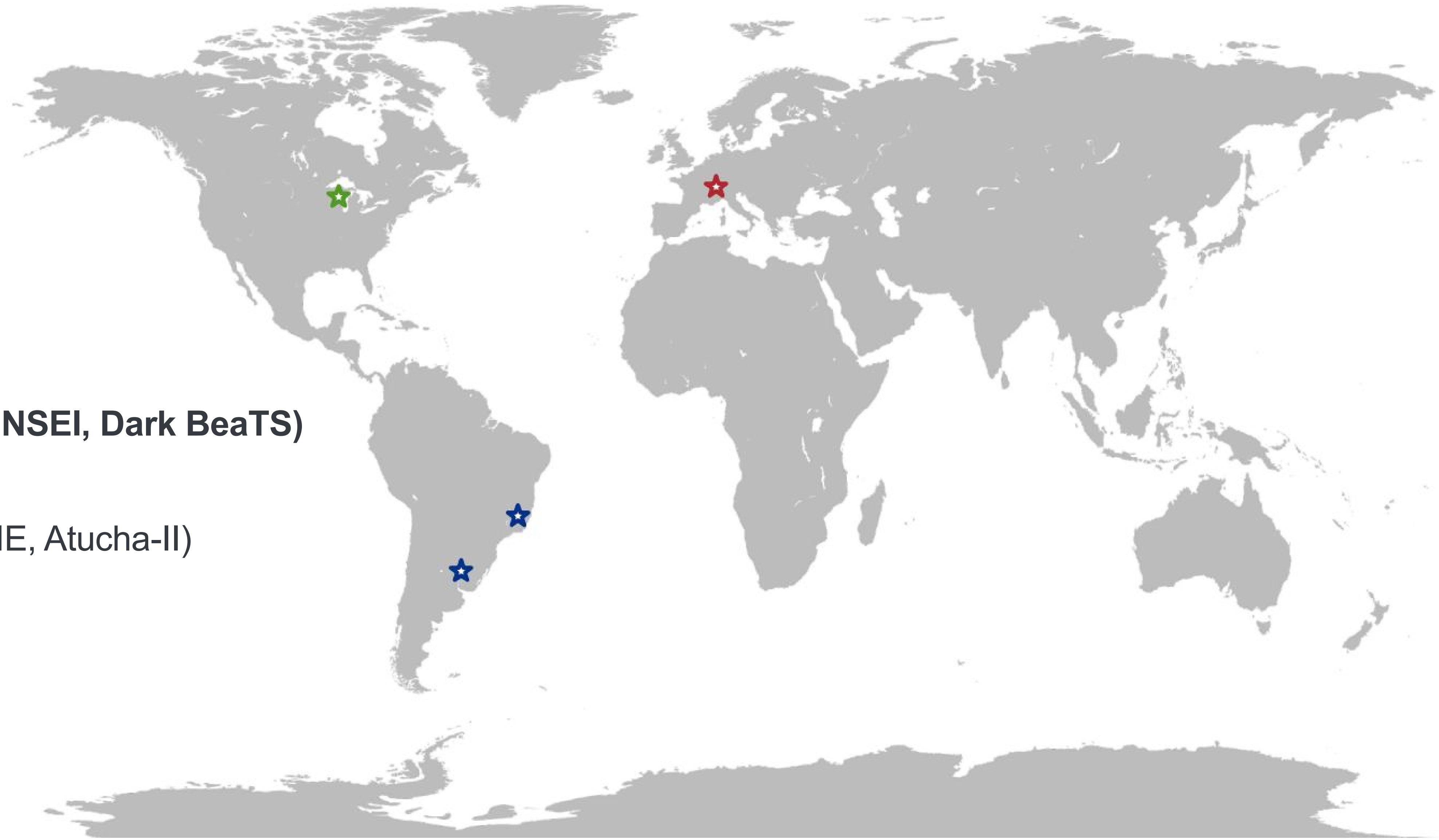
Other advantages: eV energy threshold, low instrumental background ($<10^{-3}$ $e^-$/pix/day), μm-scale spatial resolution. → **Great sensors to search for feeble signals!**

# Skipper-CCDs for mCP searches



- Beam-dump (SENSEI, Dark BeaTS)
- LHC (Moskita)
- Reactors (CONNIE, Atucha-II)

# Skipper-CCDs for mCP searches



**Beam-dump (SENSEI, Dark BeaTS)**

LHC (Moskita)

Reactors (CONNIE, Atucha-II)

# SENSEI at MINOS: setup

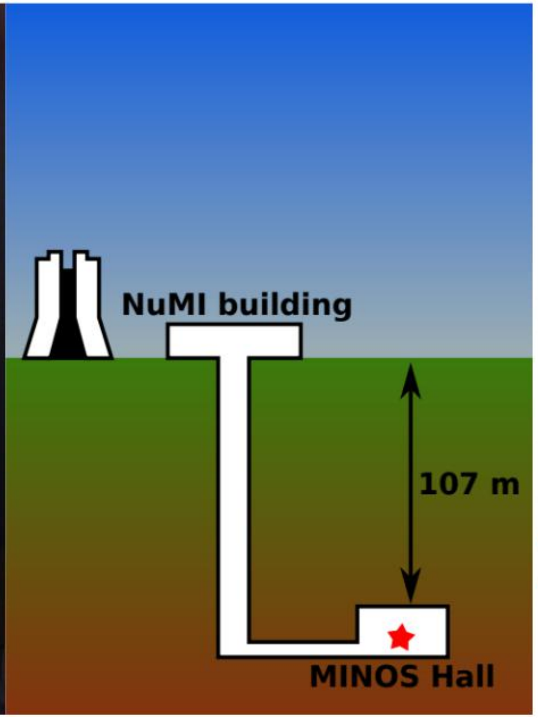
**SENSEI's main scope is to search for light DM with skipper-CCDs.**

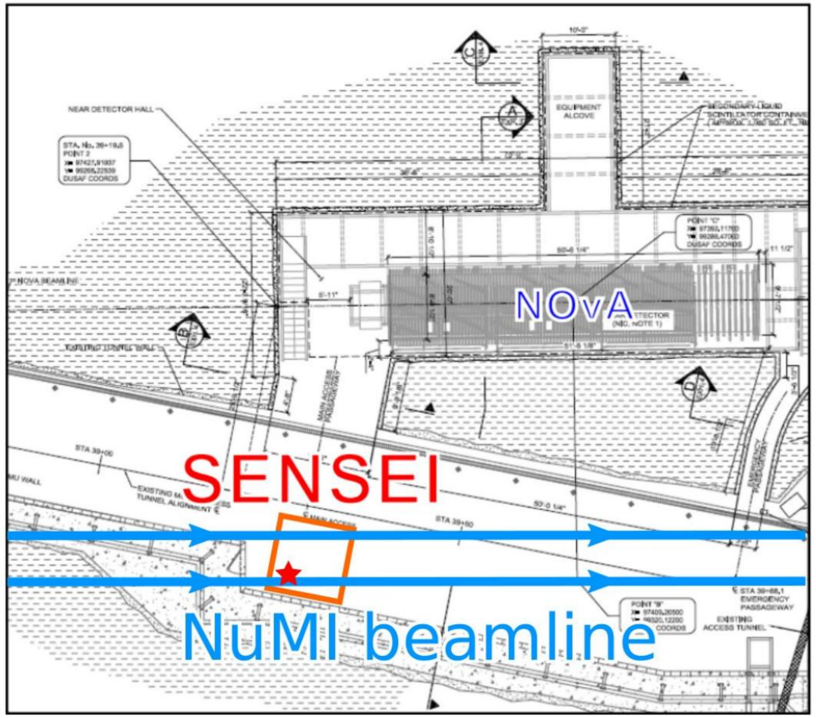
Since 2018, SENSEI has been continuously improving world-leading limits on sub-GeV DM.

Two setups: 1) 2019 - MINOS at Fermilab [PRL 122, 161801; PRL 125, 171802; PRA 17, 014022]

2) 2021 - SNOLAB [PRL 134, 011804; PRL 134, 161002]

**Data collected at MINOS during 2020 was used to search for mCPs from the NuMI beam.**



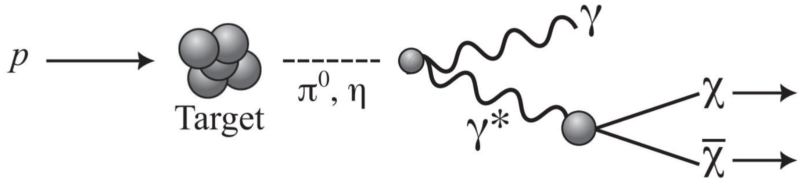
# SENSEI at MINOS: mCP search

PRL 133, 071801 (2024)

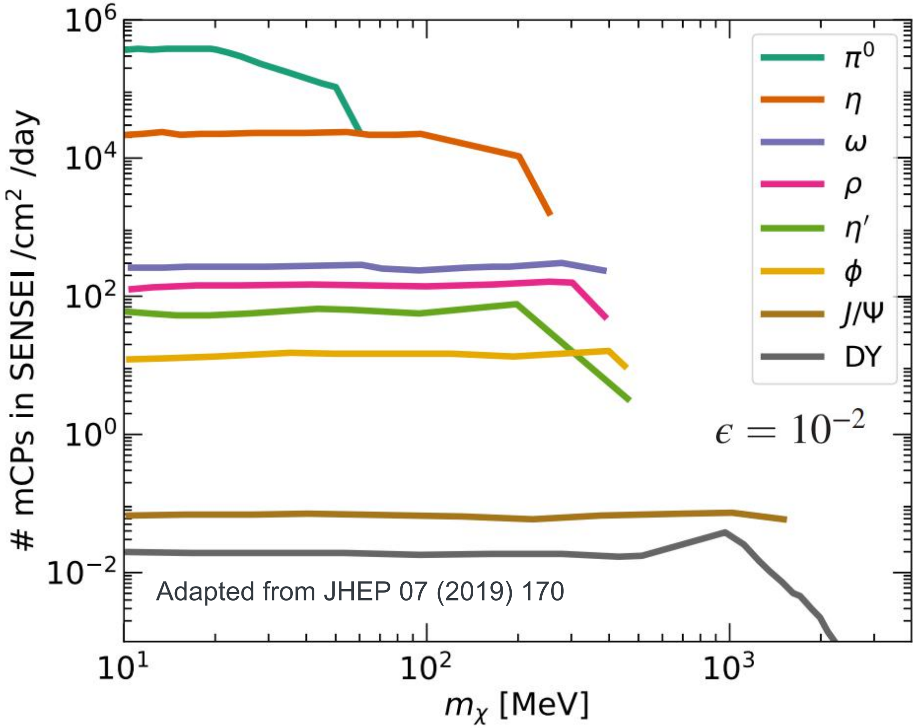
NuMI beam: 120-GeV proton beam striking a graphite target.

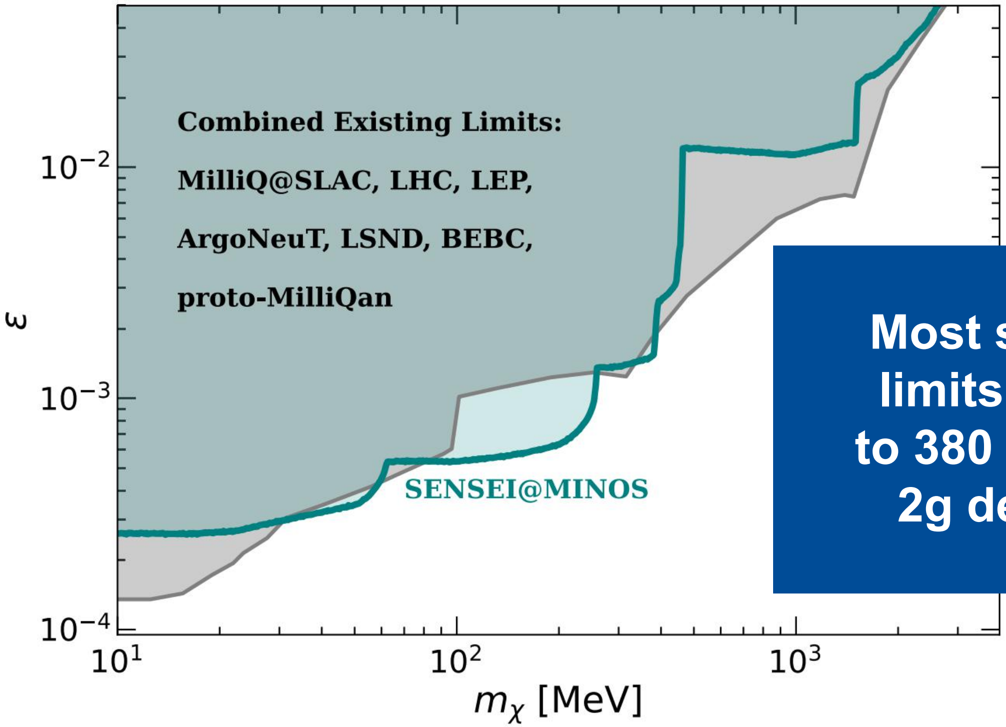
mCPs could be produced collinearly with the beam primarily in meson decays.

Included collective excitation effects [Comm Phys 7, 416 (2024)] and pair-creation probabilities [PRD 102, 063026], 063026] in detection cross-section.




| | $1e^-$ | $2e^-$ | $3e^-$ | $4e^-$ | $5e^-$ | $6e^-$ |
|---|---|---|---|---|---|---|
| Effective Efficiency | 0.069 | 0.105 | 0.325 | 0.327 | 0.331 | 0.338 |
| Exposure [g-day] | 1.38 | 2.09 | 9.03 | 9.10 | 9.23 | 9.39 |
| Observed Events | 1311.7 | 5 | 0 | 0 | 0 | 0 |



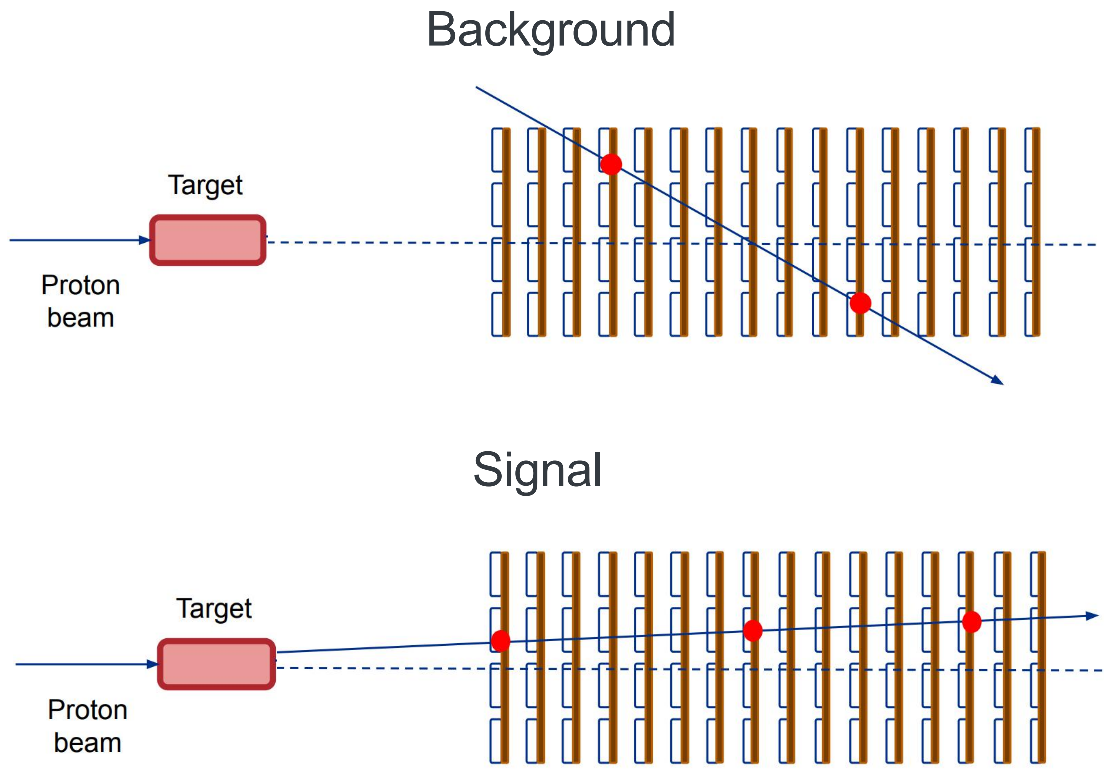

**Most stringent limits from 30 to 380 MeV with 2g detector!**

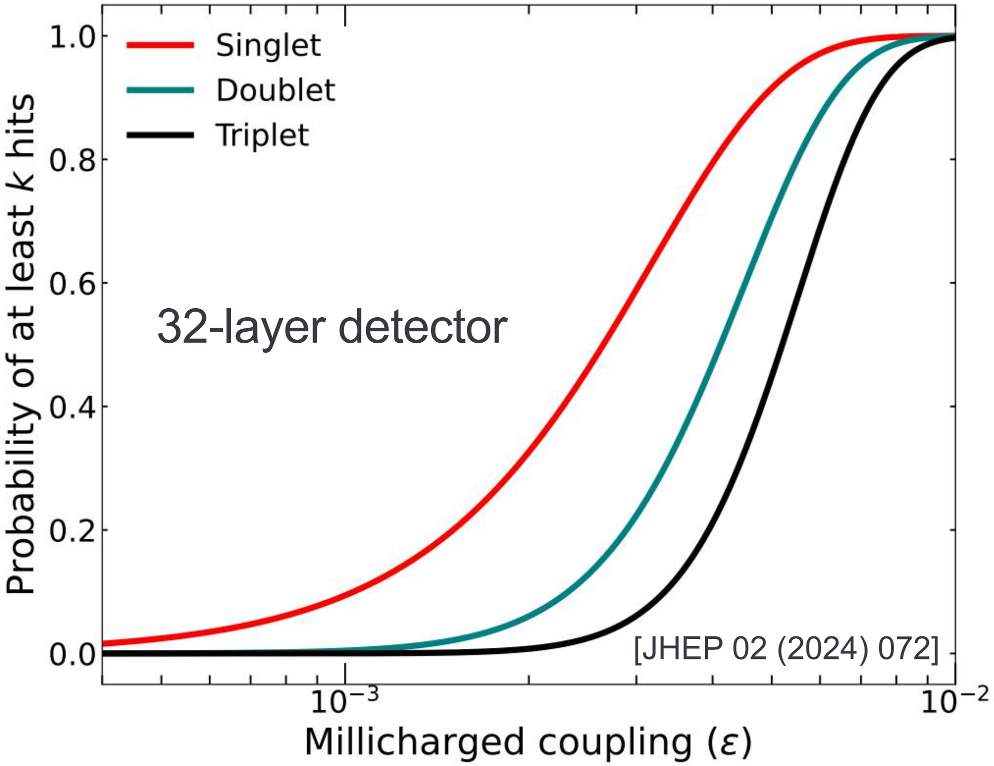
FERMI NATIONAL ACCELERATOR LABORATORY

# Tracking: a way to reduce backgrounds

Skipper-CCDs lack time resolution to reduce beam-unrelated backgrounds.

**Multi-layer detectors could enable background-free mCP searches by tracking multiple interactions**, despite low occurrence probability.



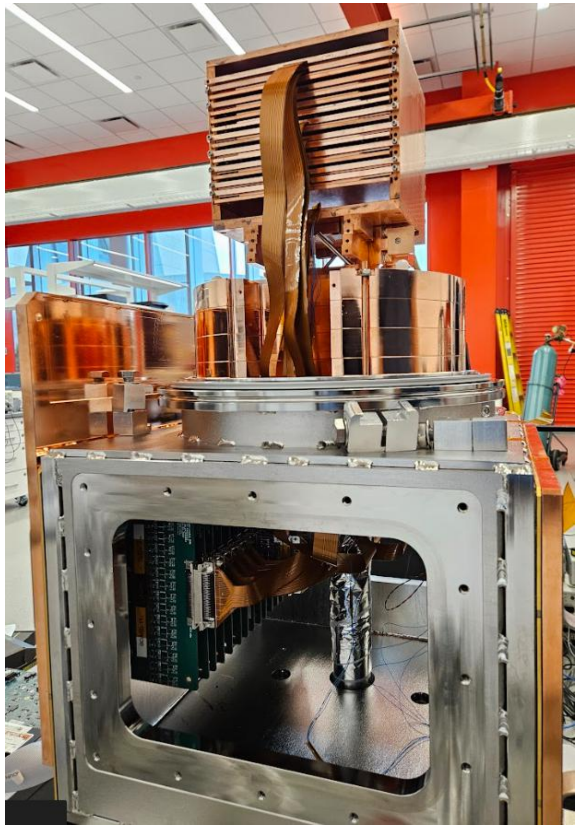

R. Harnik et al.. Millicharged particles in liquid argon neutrino experiments. [10.1007/JHEP07(2019)170]
S. Perez et al.. Searching for millicharged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab. [10.1007/JHEP02(2024)072]

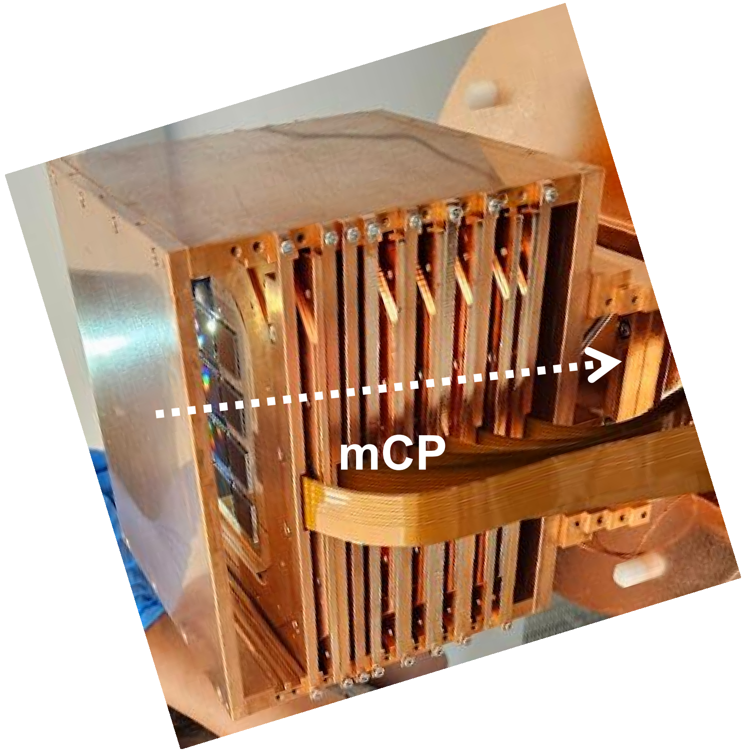
# Dark BeaTS

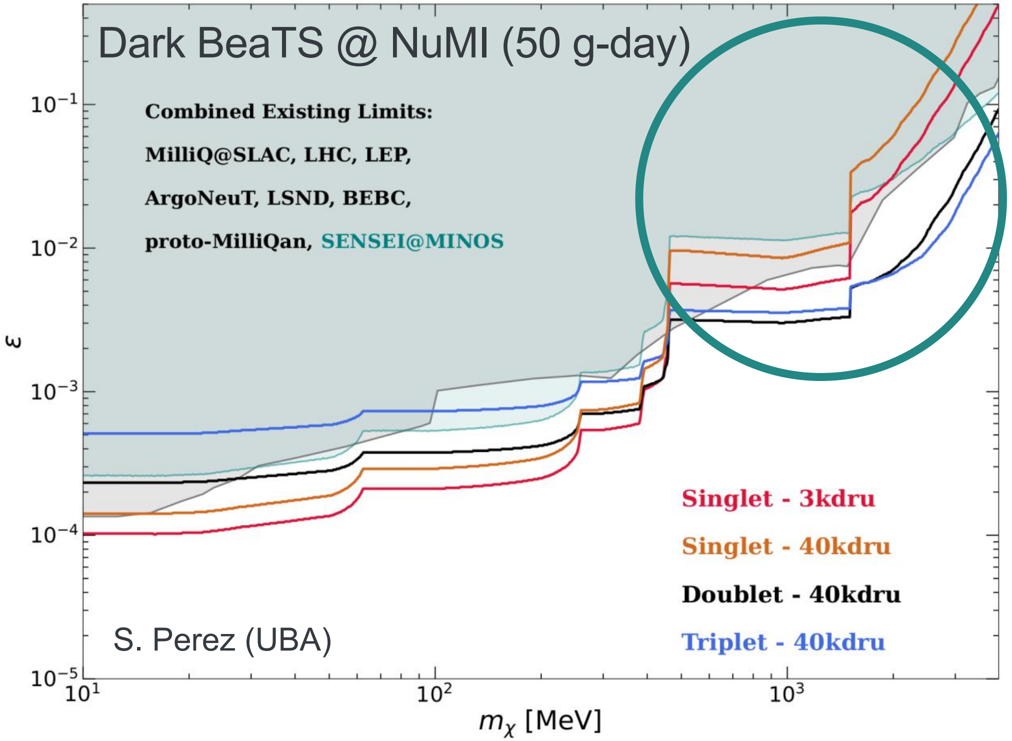
**~100-gram skipper-CCD multi-layer detector to search for mCPs from NuMI.**

FNAL LDRD-funded project. Pathfinder to develop the hardware, software and expertise needed for future dark sector searches at accelerators with skipper-CCDs.

Main goals: 1) Deploy and run Dark BeaTS at MINOS; 2) Advance tracking of low-energy depositions.





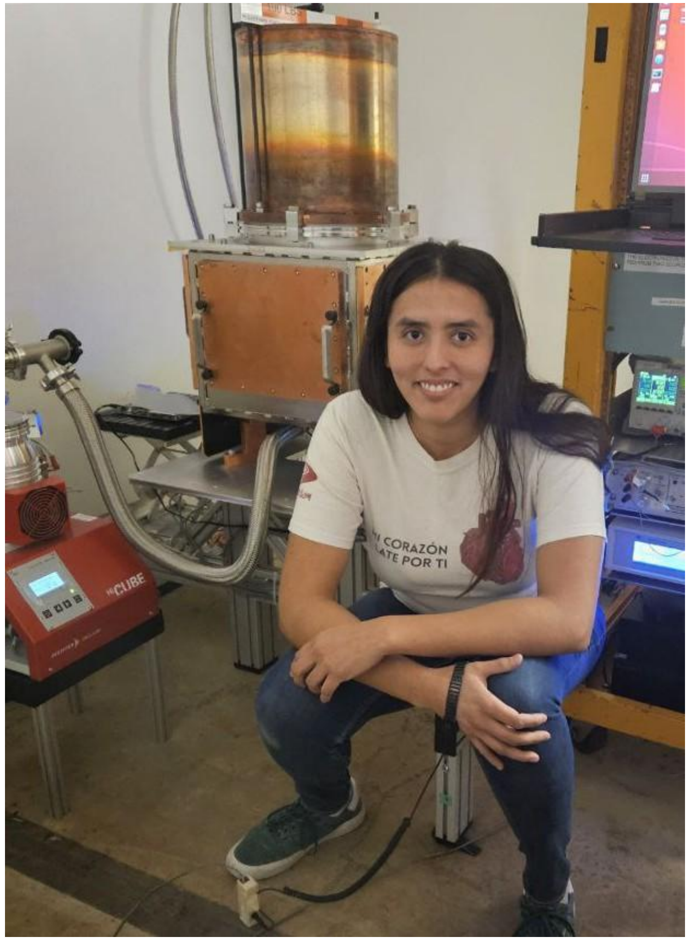



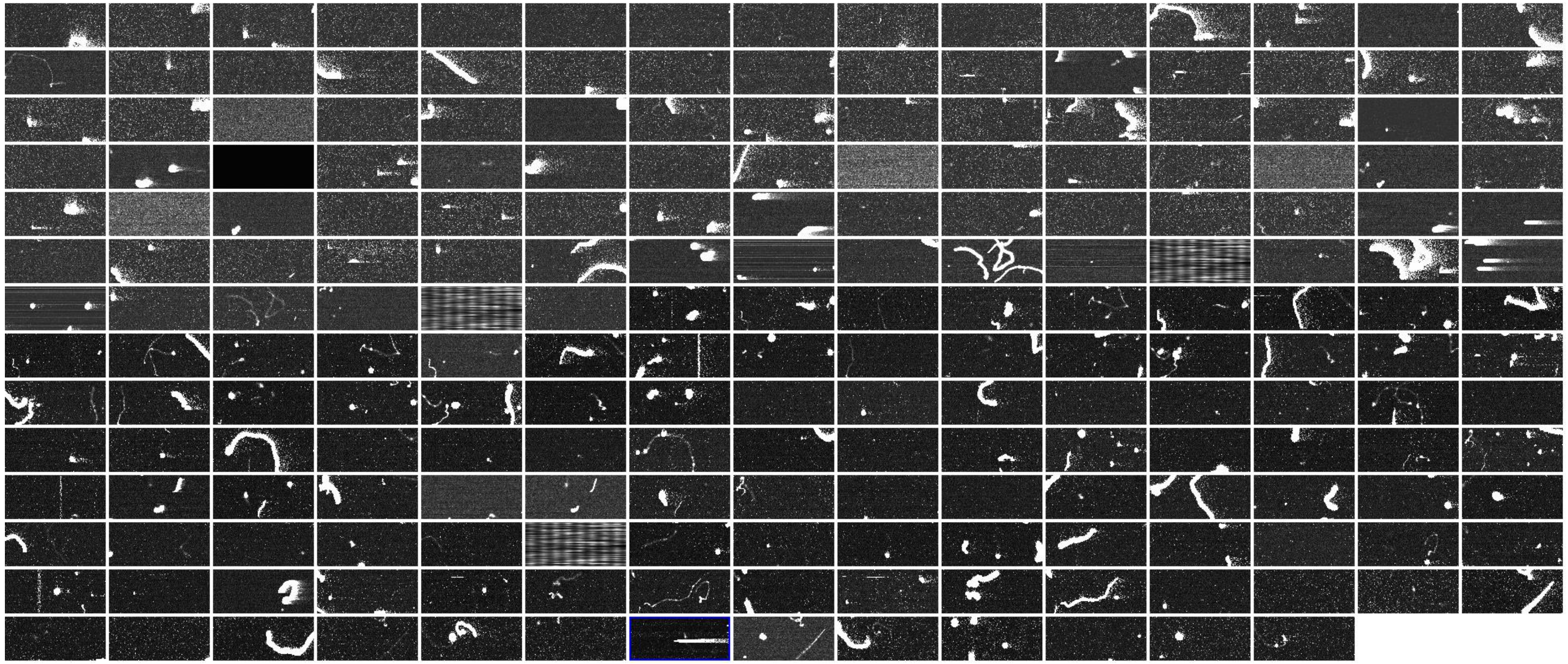

Tracking enhances sensitivity at GeV masses!

# Dark BeaTS at MINOS

## The largest skipper-CCD detector is now taking data at MINOS!

Commissioning started last February with a 13-layer detector (~200 skipper-CCDs). Most of them are working with single-electron resolution!



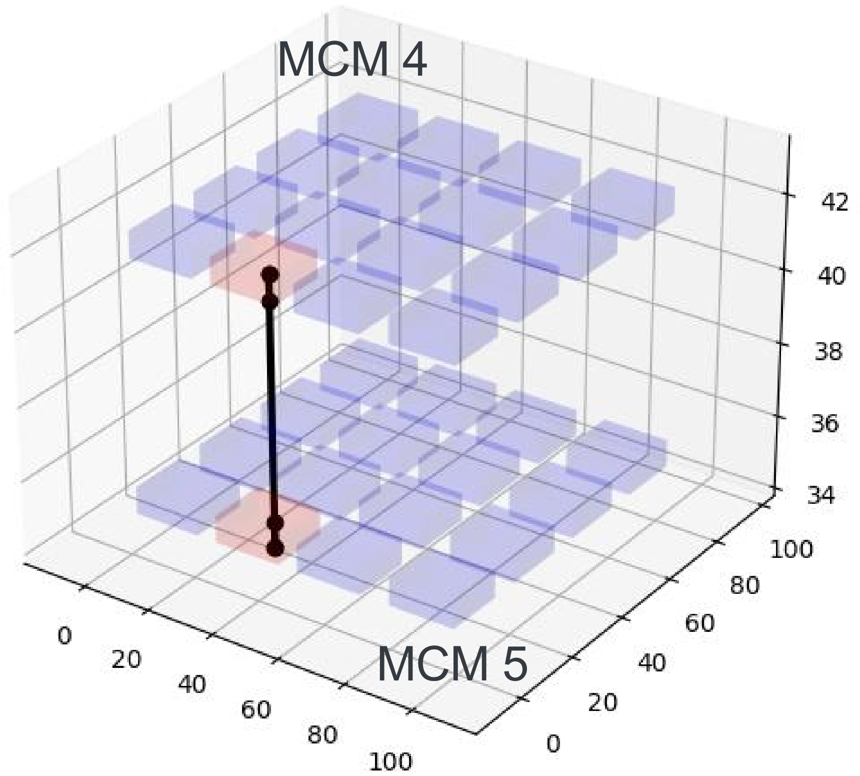
Once optimal parameters are defined, run and collect data (hopefully with NuMI ON in 2026). In parallel, advance tracking.

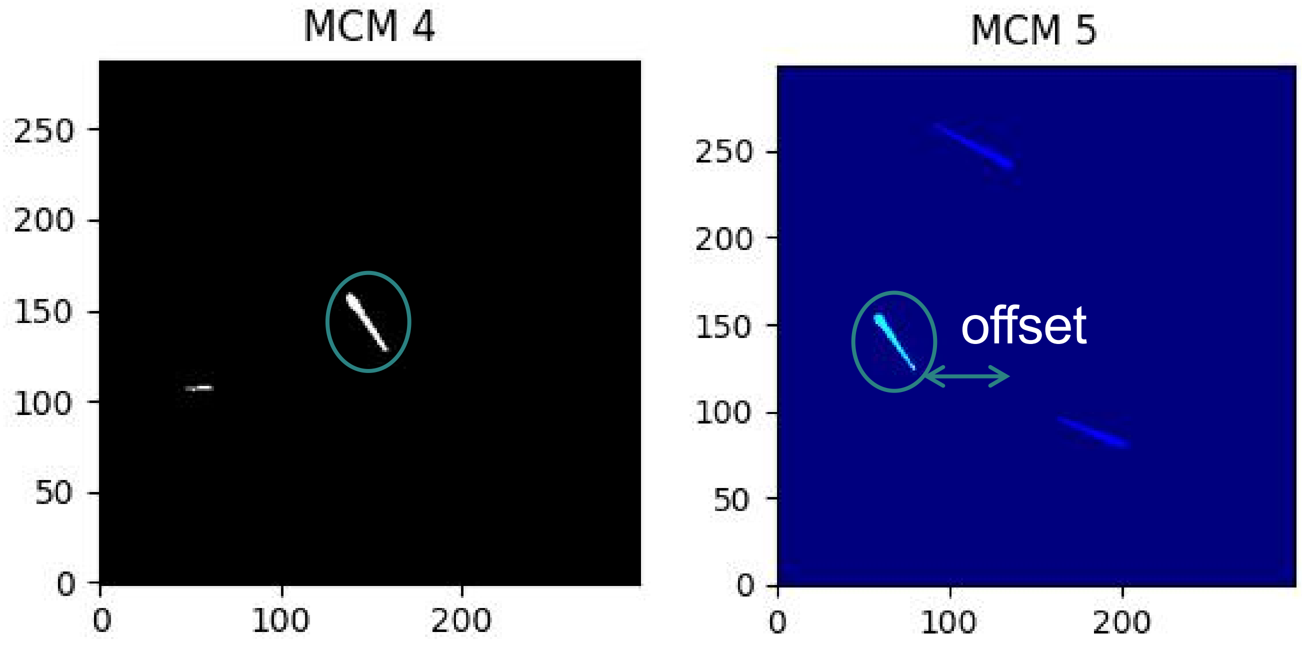
# Dark BeaTS: challenges with tracking

Tracking is challenging with current hardware. **New packaging and precise module assembly are needed to reduce degrees of freedom.**

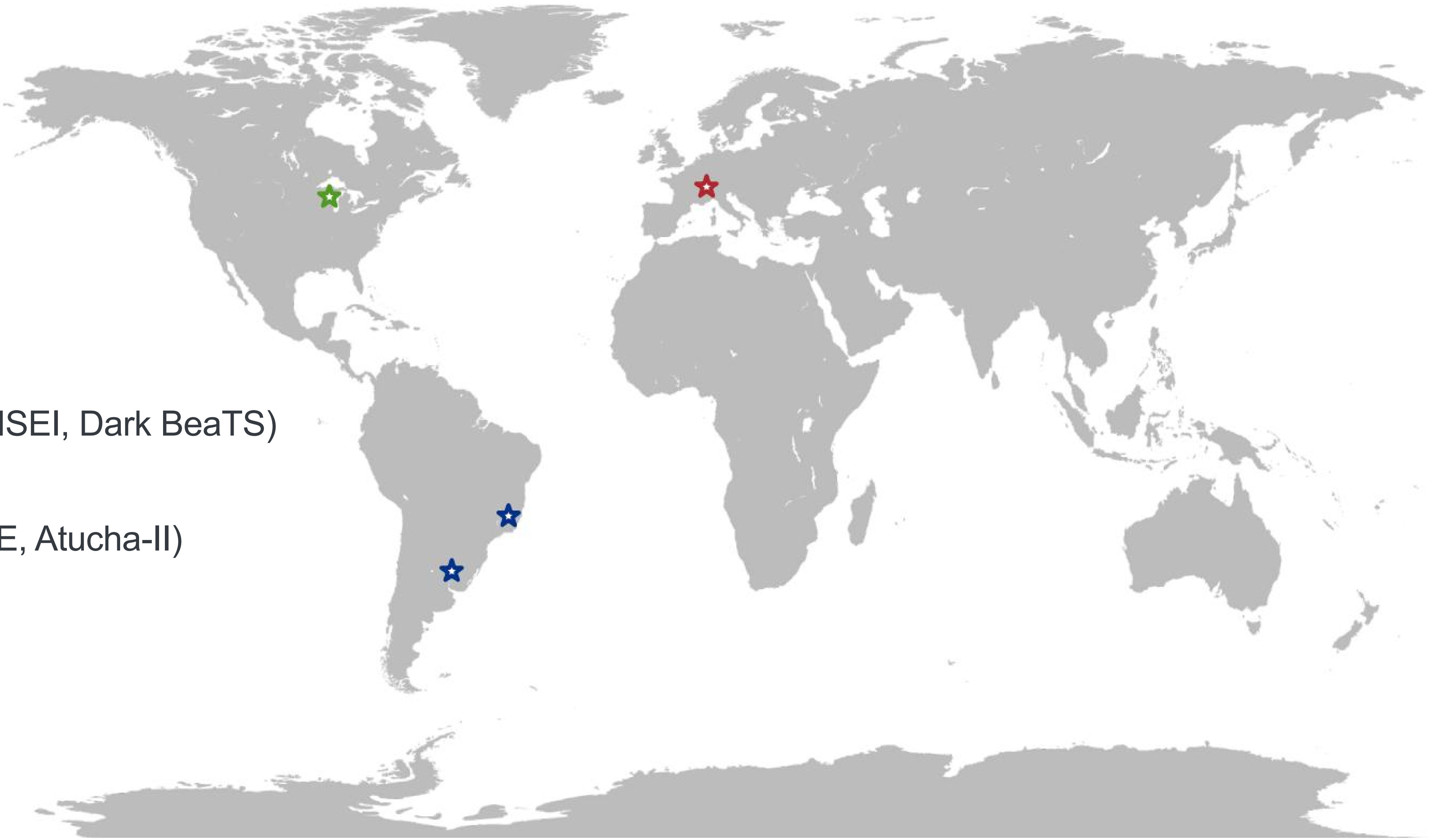
Other ideas: Optical measurements to determine sensor misalignment during module assembly.
In-situ alignment to correct for disalignment during thermal cycles.

Demonstrated muon tracking with surface data. Effort needed to track low-energy depositions.



# Skipper-CCDs for mCP searches



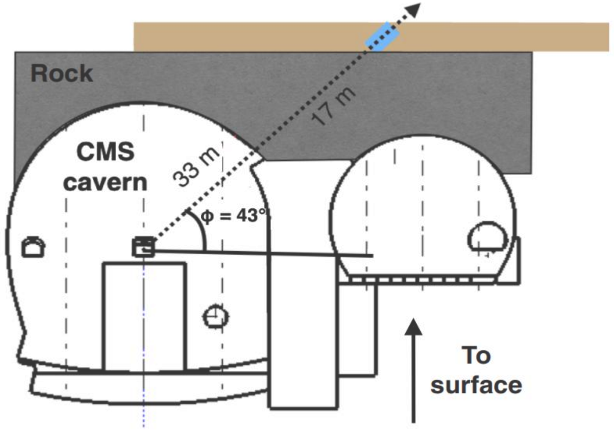
- Beam-dump (SENSEI, Dark BeaTS)
- **LHC (Moskita)**
- Reactors (CONNIE, Atucha-II)

# Moskita at LHC

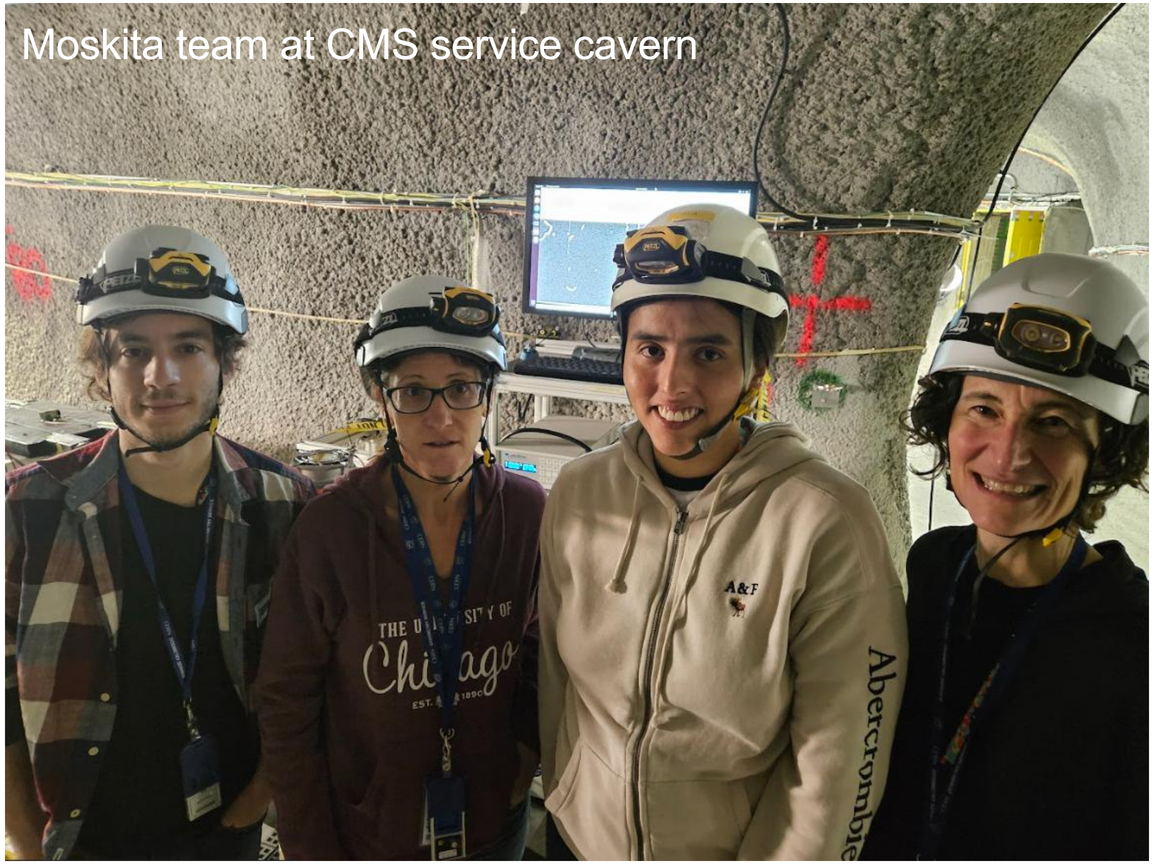
**TeV collisions at LHC enable exploring mCPs in the GeV-mass range.**

The milliQAN collaboration identified the CMS service cavern as a good place to search for mCPs.

In March 2024 we deployed Moskita next to milliQAN. Goal: measure the low-energy background and assess feasibility and science reach of a larger skipper-CCD detector.




2-gram skipper-CCD, as the one in SENSEI at MINOS setup!



Moskita team at CMS service cavern

# Moskita at LHC

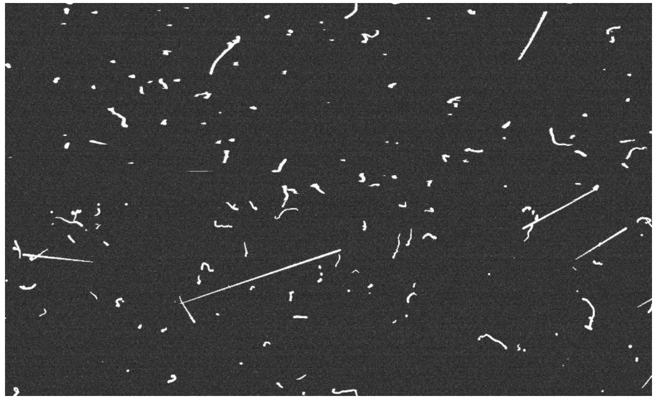
Last year **we ran stable and collected data in periods with and without collisions.**

6 runs in total: 1-4 and 6 (proton-proton period); 5 and 6 (ion-ion period)

Exposure before efficiency: 39.32 g-day (proton-proton period); 9.45 g-day (ion-ion period)

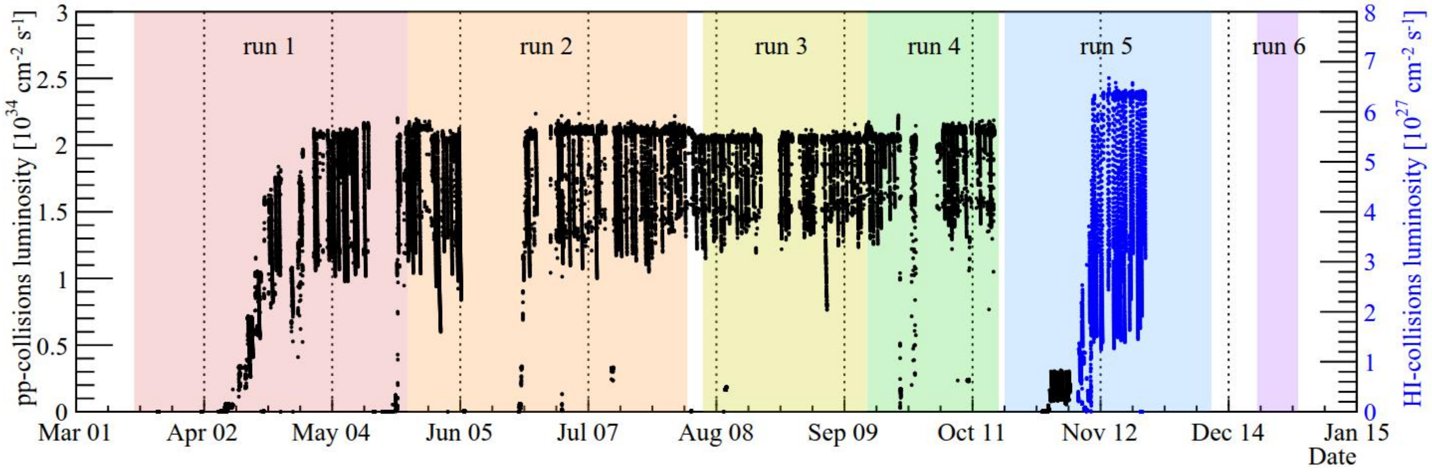
Data analysis is almost complete! Expect publication soon!

| Run | Date start | Date end | No. of images |
|---|---|---|---|
| 1 | Mar 15 | May 22 | 462 |
| 2 | May 22 | Jul 31 | 500 |
| 3 | Aug 04 | Sep 14 | 293 |
| 4 | Sep 14 | Oct 17 | 159 |
| 5 | Oct 19 | Dec 09 | 236 |
| 6 | Dec 21 | Dec 31 | 50 |



| Bin $[e^-]$ | Observed events | |
|---|---|---|
| | Proton-proton | Ion-ion |
| 2 | 327 | 85 |
| 3 | 17 | 6 |
| 4 | 1 | 0 |
| 5 | 2 | 2 |
| 6 | 0 | 0 |
| 7 | 1 | 2 |
| 8 | 2 | 0 |
| 9 | 0 | 0 |
| 10 | 1 | 0 |
| 11-20 | 9 | 6 |

PRELIMINARY



# Conclusions

- Skipper-CCDs remain a promising technology for detecting feeble interactions.
- Accelerator-based skipper-CCD experiments are competitive in probing the MeV-to-GeV mCP parameter space.
- Tracking multiple interactions is being explored to suppress beam-unrelated backgrounds.
- Dark BeaTS and Moskita are paving the way for future dark sector searches at accelerators with skipper-CCDs.

**Stay tuned for new results!**

**Thank you!**

Fermilab

Fermi FORWARD

U.S. DEPARTMENT of ENERGY

FERMI NATIONAL ACCELERATOR LABORATORY

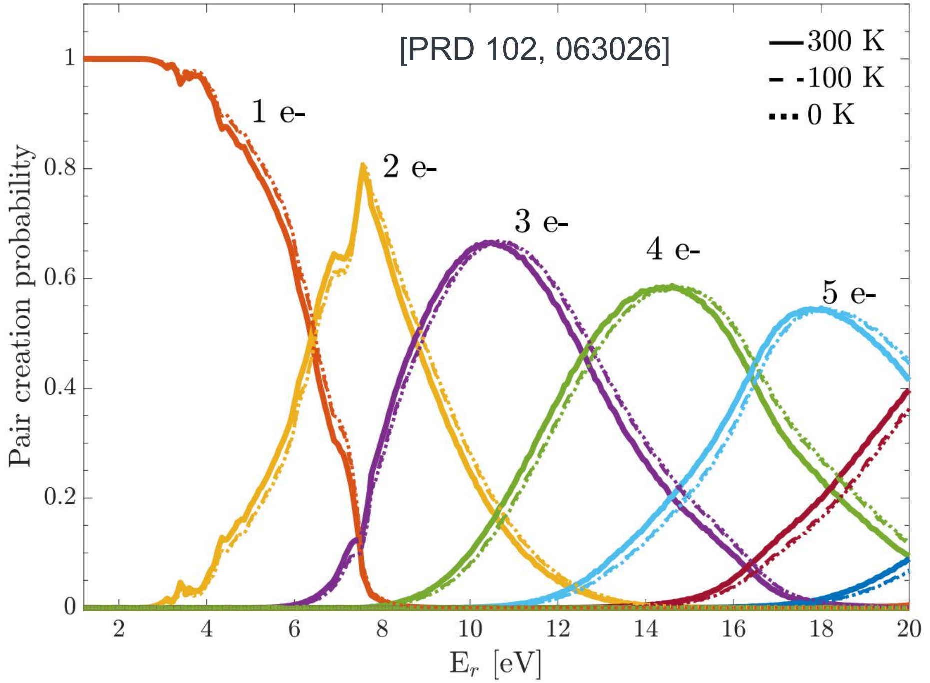
# Relativistic mCPs interaction in silicon <50 eV

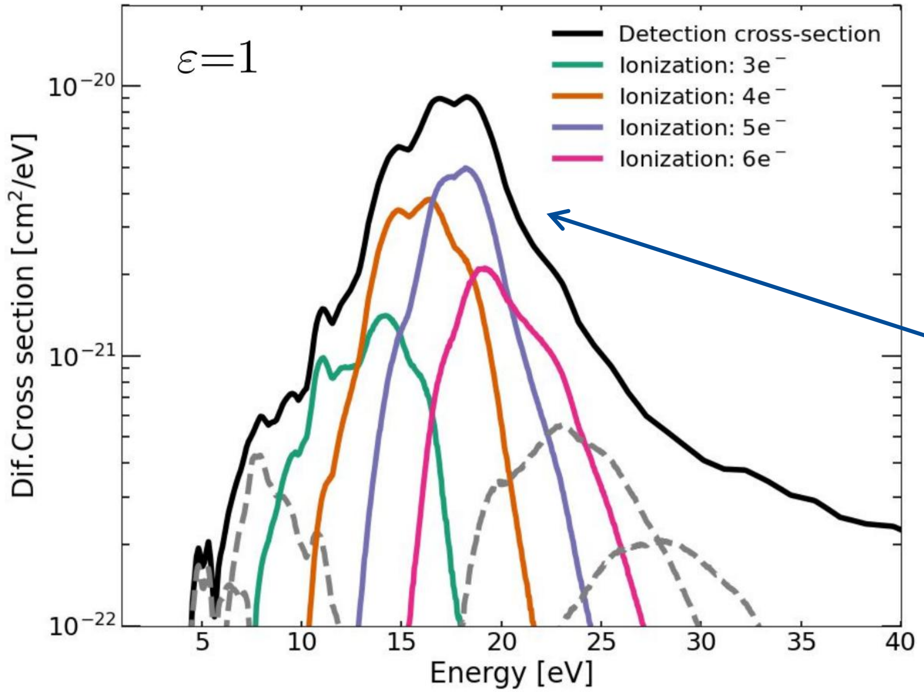
**Beam-produced mCPs can efficiently excite collective electron oscillations.** [Comm Phys 7, 416 (2024)]

Considered Fermi's theory of energy loss that accounts for bulk material properties in a complex dielectric function, taken from DarkELF [PRD 105, 015014]:

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

The detection cross-section accounts for the pair-creation probabilities.



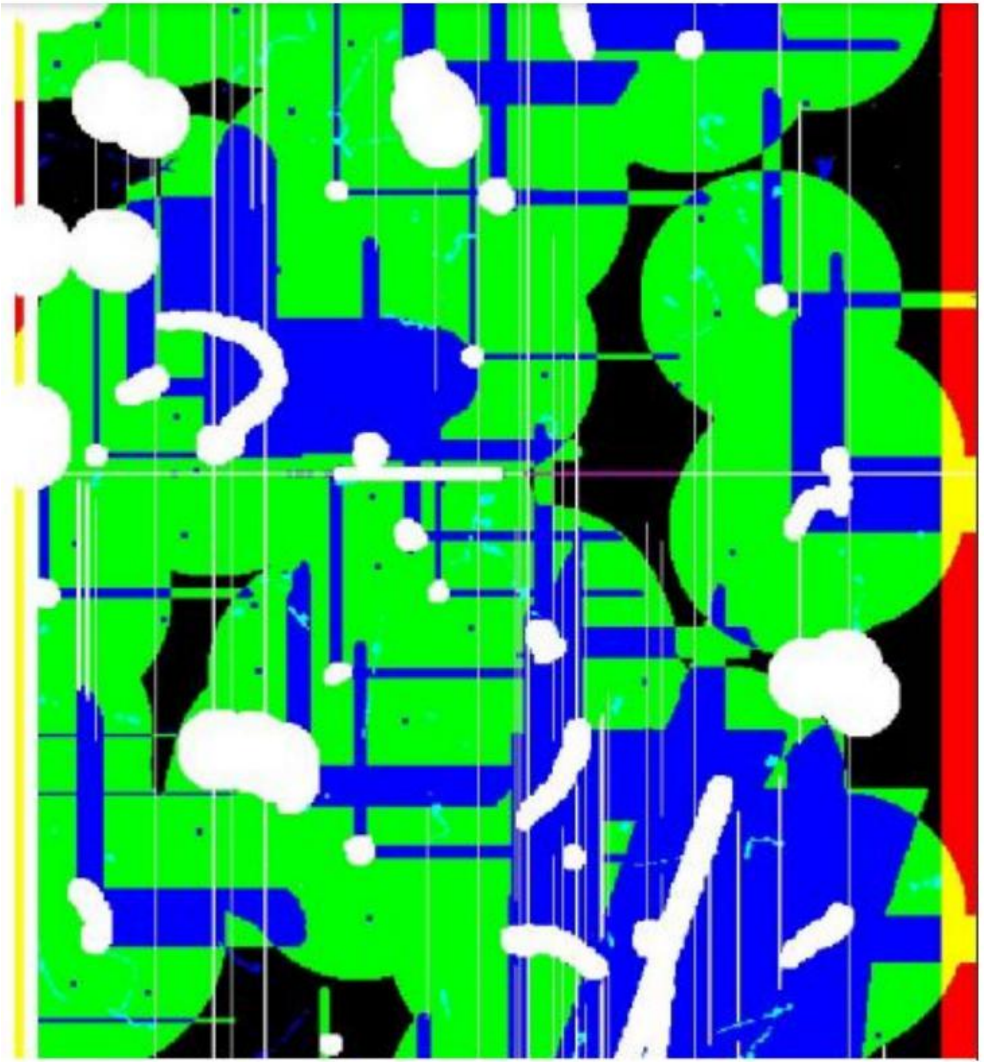

Peak from bulk plasmon resonance enhances signal in background-free region

# Masking

We use masks to exclude events from known sources:

- Border mask (red)
- Hot-column mas (white)
- Serial-register-event mask (magenta)
- Crosstalk mask (cryan)
- High-energy-event mask (white)
- Bleeding-zone mask (blue)
- Halo mask (green)

Only the unmasked pixels are considered to build the low-energy spectrum.



FERMI NATIONAL ACCELERATOR LABORATORY