

Probing Benchmark Models of Hidden-Sector Dark Matter with DAMIC-M

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Dark Matter In CCDs – Modane

Detect Dark Matter

MeV-to-GeV scale electron recoils

eV-to-keV scale absorption

MeV-to-GeV scale nuclear recoils

Silicon Skipper-CCDs

ionization threshold 1.2 eV

single electron resolution

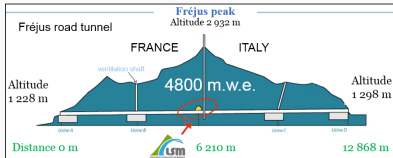
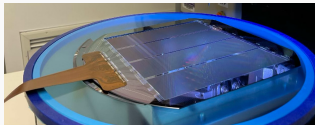
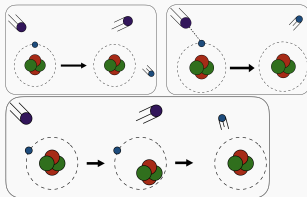
Laboratoire Souterrain de Modane

background rate ~ 1 dru

dark current $< 100 \text{ e}^-/\text{g}/\text{d}$

target exposure 1 kg yr

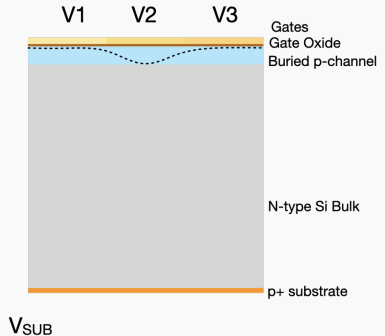
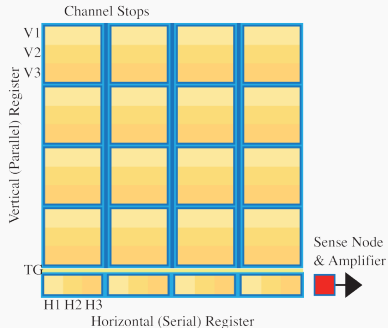
$1 \text{ dru} = 1 \text{ background event}/\text{keV}/\text{kg}/\text{d}$



Charge Coupled Device

High voltage, high-resistivity, fully depleted, p-channel CCD

Originally developed at LBNL for astronomy

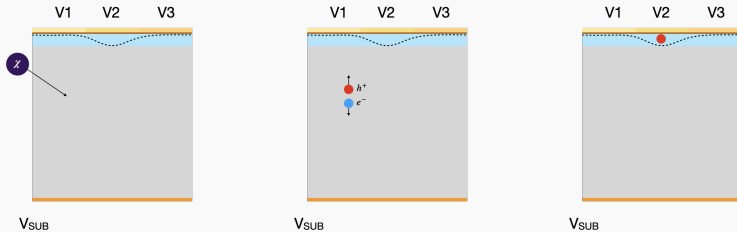


Charge-Coupled Devices

DM interacts with silicon bulk, generating an e^-/h^+ pair

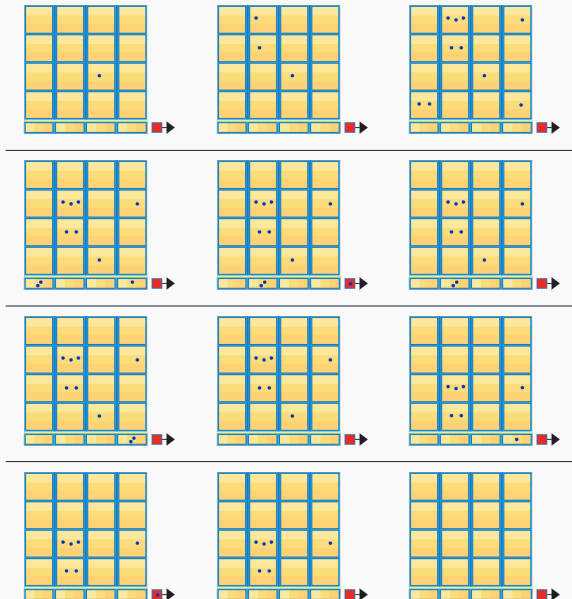
V_{SUB} generates E-field across bulk

h^+ is collected in the potential well under

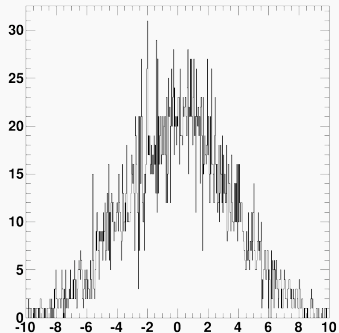
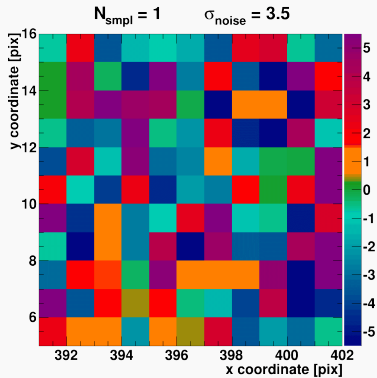


Charge-Coupled Devices

Expose
Vertical
Horizontal
readout

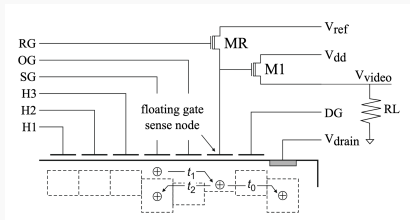


Conventional CCD Noise



Skipper CCD Readout Stage

Non Destructive Charge Measurements Janesick et al. (1990)
Engineered for LBNL CCDs, Tiffenberg et al. (2017)

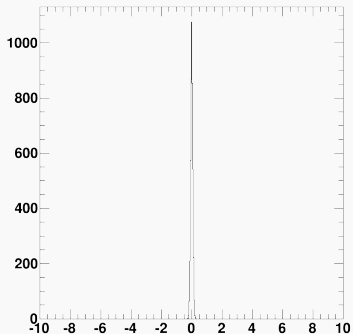
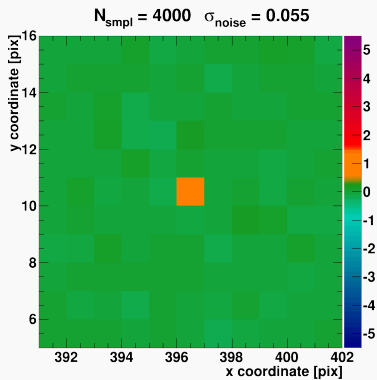


$$\sigma_{NDCM} = \frac{\sigma_1}{\sqrt{NDCM}}$$

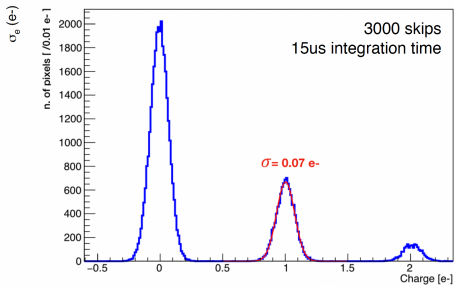
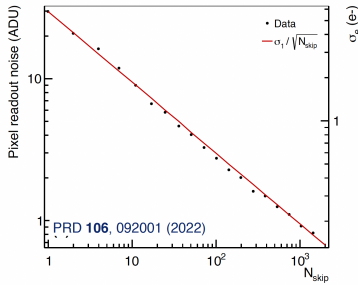
NDCM: Non-Destructive-Charge-Measurement



Noise Reduction



$$1/\sqrt{NDCM}$$



Cosmogenic Activation of Silicon

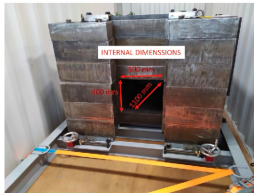
Cosmic rays spallation in **Si** results in tritium (^3H)

$$t_{1/2} \approx 12.23 \text{ yrs}$$

mean β energy 5.7 keV

Minimize Si exposure to few months

Strict shielding protocols for all transports/storage



Complex Logistics:

Europe → Montreal → SNOLAB → Seattle → Modane

DAMIC-M CCD Modules

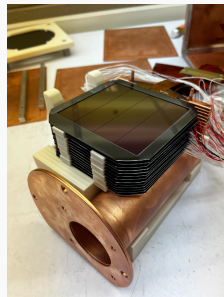
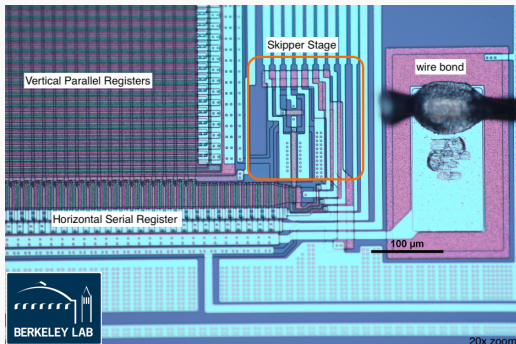
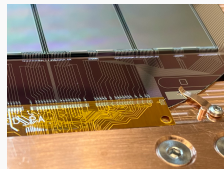
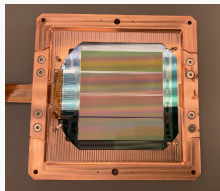
1 Module = 4 Skipper-CCDs

Each Skipper-CCD:

6k x 1.5k pixels

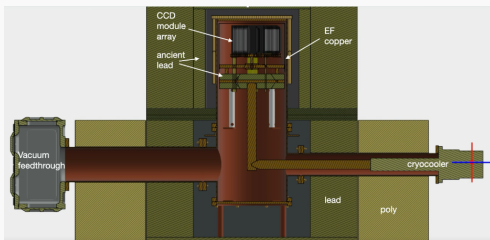
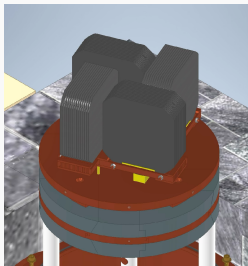
3.3 g target

15 μm x 15 μm x 675 μm



DAMIC-M Experiment

Design driven by the stringent requirements on background

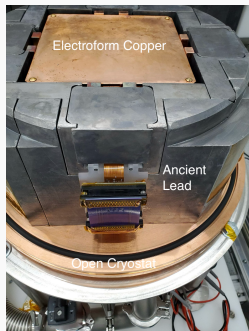


DAMIC-M Prototype: Low Background Chamber

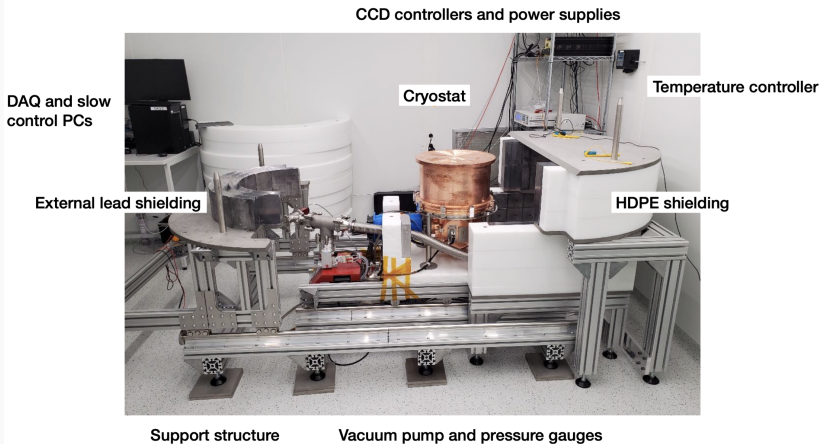
Low Background Chamber

Objectives:

1. Gain working experience at LSM
2. Characterize DAMIC-M components in a low background environment
3. Test subsystems (DAQ, front-end electronics, slow control)
4. First science run results with fraction of exposure of DAMIC-M



Low Background Chamber



Science Run 2 - October 2024 to January 2025

Upgrades:

DAMIC-M CCD Modules

Electroformed Copper Box

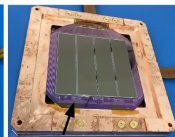
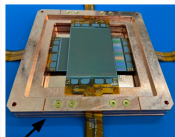
Custom Low Noise Electronics

pixel binning: 1×100 (col $\times$ row)

Achievements:

- $\lambda_{DC} = 400 \text{ e}^-/\text{g}/\text{d}$
- $\sigma_{500} = -0.16 \text{ e}^{-1}$
- 1.3 kg d exposure

2 skipper CCDs 4k x 6k pix (18 g) 8 skipper CCDs 1.5k x 6k pix (26.4 g)



LBC Pattern Selection

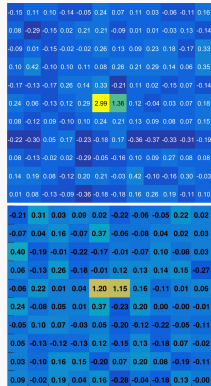
We search for patterns of 2-3 consecutive pixels with charge:

$$\{11\}, \{21\}, \{111\}, \{22\}, \{31\}, \{211\}$$

B_p^{rc} : random coincidences from Poisson dark current

B_p^{rad} : radiogenic backgrounds estimated number of clusters and simulations

No evidence for a signal!!!



	Pattern p					
	$\{11\}$	$\{21\}$	$\{111\}$	$\{31\}$	$\{22\}$	$\{211\}$
D_p	144	0	0	1	0	0
B_p^{rc}	141.4	0.111	0.042	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
B_p^{rad}	0.039	0.039	0.016	0.052	0.011	0.035

Dark Matter Rate in CCD Bulk

$$\frac{dR}{dE_e} \propto \bar{\sigma}_e \int \frac{dq}{q^2} \left[\int_{v > v_{min}} d^3v \frac{f(\mathbf{v})}{v} \right] |F_\chi(q)|^2 |f_{cry}(q, E_e)|^2 |f_{scr}(q, E_e)|^2$$

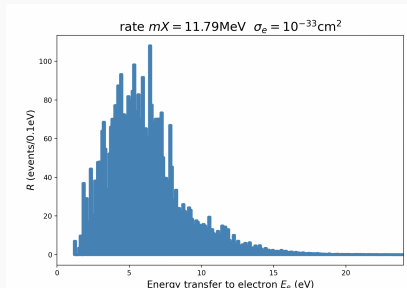
$\bar{\sigma}_e$: DM- e^- Cross section

$f(v)$: DM Halo distribution

F_χ : Dark Matter Form Factor

F_{cry} : Silicon crystal form factor

f_{scr} : Screening form factor

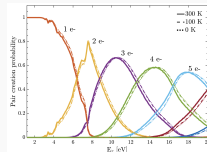


Detector Response

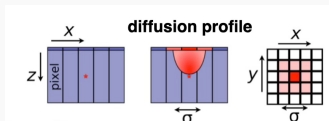
Charge Ionization: Phys. Rev. D 102, 063026 (2020)

$p(q_e | E_e)$: prob. of energy deposition E_e ionizing q_e electrons

$$N_{q_e}(\bar{\sigma}_e, m_\chi) = \int dE_e \frac{dR}{dE_e}(\bar{\sigma}_e, m_\chi) p(q_e | E_e)$$



Diffusion Model: Phys. Rev. D 102, 063026 (2020)



$$\sigma_{xy}^2 = -A \log |1 - b \cdot z_0| \cdot (\alpha + \beta \cdot E_e)^2$$

$P_{q_e \rightarrow p}$: probability of charge multiplicity q_e diffusing into pattern p
from toy Monte-Carlo of diffusion model

Signal Model

Expected number occurrences of pattern $\{p\}$ for a given model

$$S_p(\bar{\sigma}_e, m_\chi) = \sum_{q_e} N_{q_e}(\bar{\sigma}_e, m_\chi) P_{q_e \rightarrow p}$$

Result from data

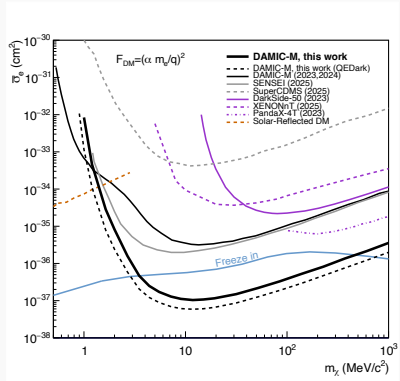
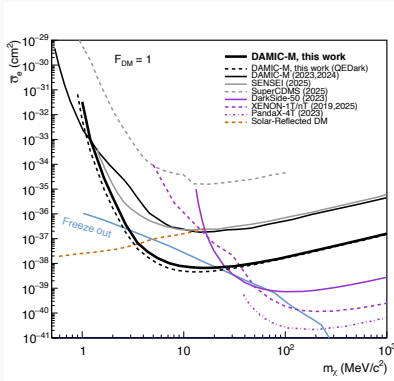
	Pattern p					
	$\{11\}$	$\{21\}$	$\{111\}$	$\{31\}$	$\{22\}$	$\{211\}$
D_p	144	0	0	1	0	0
B_p^{rc}	141.4	0.111	0.042	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
B_p^{rad}	0.039	0.039	0.016	0.052	0.011	0.035

Likelihood function

$$\mathcal{L}(\bar{\sigma}_e, \theta) = \prod_{p \in \text{patterns}} \frac{(S_p(\bar{\sigma}_e) + B_p^{rc} + \theta B_p^{rad})^{D_p} e^{-(S_p(\bar{\sigma}_e) + B_p^{rc} + \theta B_p^{rad})}}{D_p!}$$

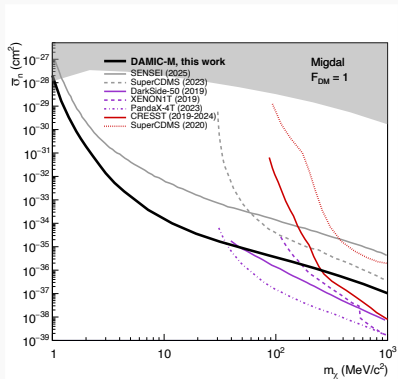
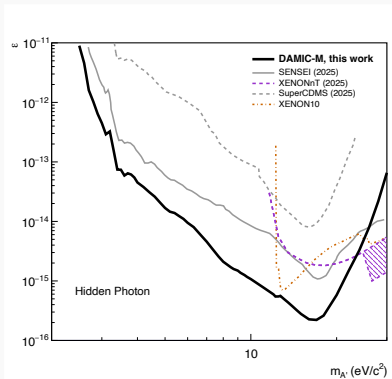
The background-only null hypothesis has $p_0 = 0.24$ (0.10), so we place limits using the profile likelihood ratio test statistics

Dark Matter Electron scattering Exclusion Limits



DAMIC-M probes benchmark hidden-sector dark-matter models!!!

Hidden Photon and Migdal Exclusion Limits



DAMIC-M Collaboration



Backup Slides

Radio Purity of Copper

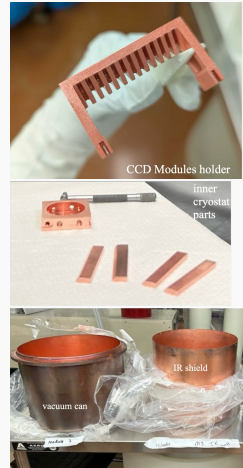
Cu is the material closest to the CCDs
Cosmogenic activation creates various
isotopes of Co

We use **Electroformed Cu** produced and
machined underground at SURF.

Exposure is limited to few weeks.

Logistics:

SURF (South Dakota) → Modane



Ancient Lead



Standard lead has traces of ^{210}Pb

$$t_{1/2} = 22 \text{ yrs}$$

beta decay produces bremsstrahlung

Ancient Roman lead close to the CCD

Most of ^{210}Pb

From sunken ship

Très faible activité further away

Polyethylene shielding to stop neutrons



Data Cleaning Procedure

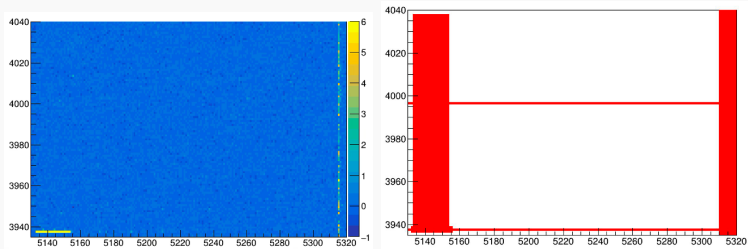
Masked:

hot regions of CCDs (excess pixels with charge $\geq 1 e^-$)

mask **clusters** of charged pixels $> 5 e^-$

Correlated pixels of cross talk between CCDs

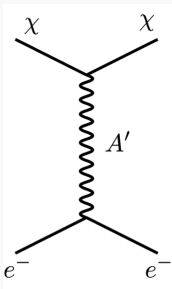
Pixels with high variance in NDCM measurements



95% of data kept for the analysis!!!

Motivation

New forces and mediators below the weak scale have been proposed to mediate interactions with sub-GeV.



This hidden sector is linked to the standard model through kinematic mixing.

Most minimal scenario is the dark photon mediator A'

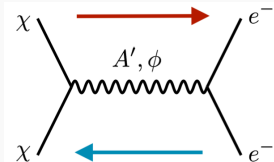
Benchmark Models

Heavy mediator ($m_\chi < m_{A'}$): **thermal freeze-out**

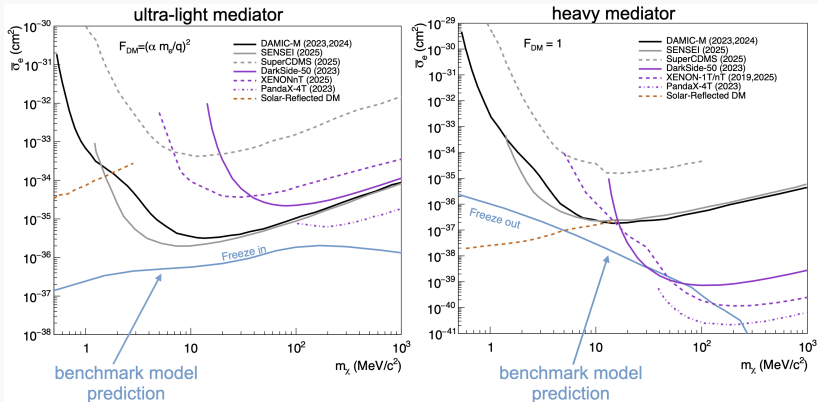
DM and SM in equilibrium in early universe. $\text{DM} + \text{DM} \rightarrow \text{SM}$ are more efficient so DM density drops until density is too low for DM to find each other.

Ultra-light mediator ($m_\chi \gg m_{A'}$): **thermal freeze-in**

DM interactions were not efficient so never in thermal equilibrium. DM abundance builds up as $\text{SM} + \text{SM} \rightarrow \text{DM}$ until density is too low.



Status of Benchmark Models 2024



Detection Strategies of Hidden-Sector DM

e^- set the typical momentum transfer

$$v_e \sim \alpha \gg v_\chi \sim 10^{-3}$$

$$q_{\text{typ}} \simeq \mu_{\chi e} v_{\text{rel}} \sim \alpha m_e \sim 4 \text{ keV}$$

$$E_e \simeq q_{\text{type}} v_\chi \simeq \mathcal{O}(\text{eV})$$

Detector Requirements:

$\mathcal{O}(\text{eV})$ scale ionization threshold

sub-eV scale resolution

Low dark current

low background

LBC Image: What do you see?

