

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

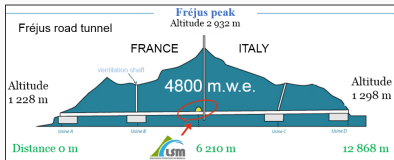
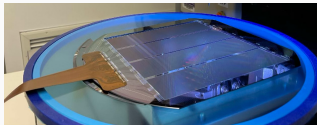
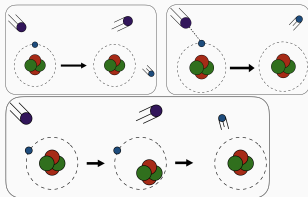
Laboratoire Souterrain de Modane

background rate ~ 1 dru

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

target exposure 1 kg yr

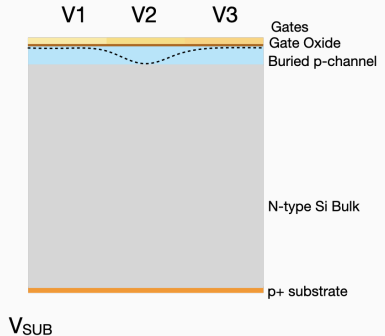
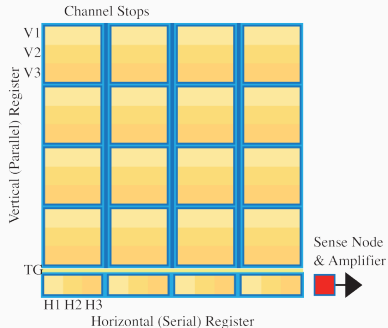
$1 \text{ dru} = 1 \text{ background event/keV/kg/d}$



Charge Coupled Device

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

Originally developed at LBNL for astronomy

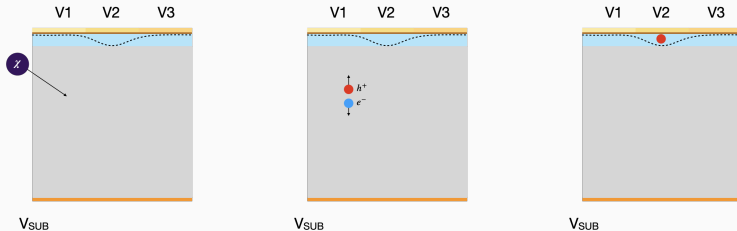


Charge-Coupled Devices

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

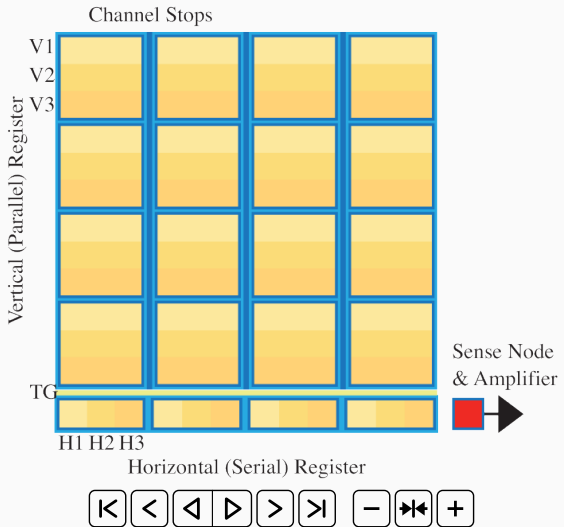
V_{SUB} generates E-field across bulk

h^+ is collected in the potential well under

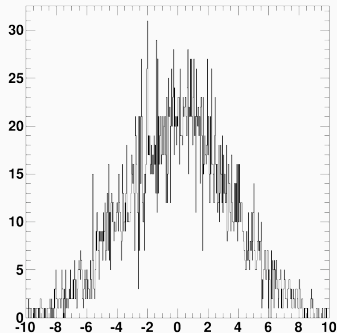
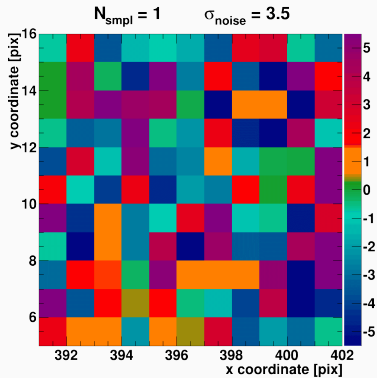


Charge-Coupled Devices

Expose
Vertical
Horizontal
readout

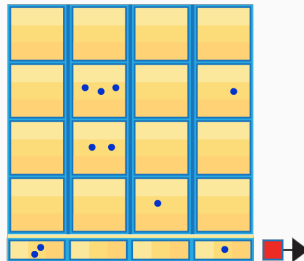
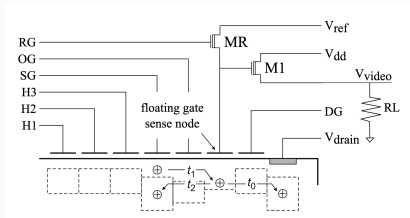


Conventional CCD Noise

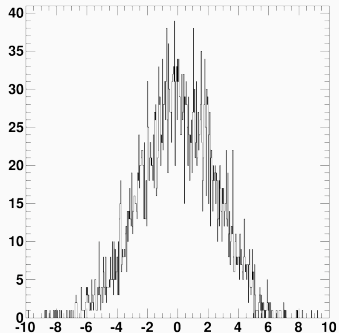
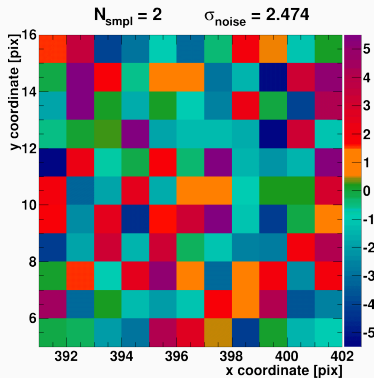


Skipper CCD Readout Stage

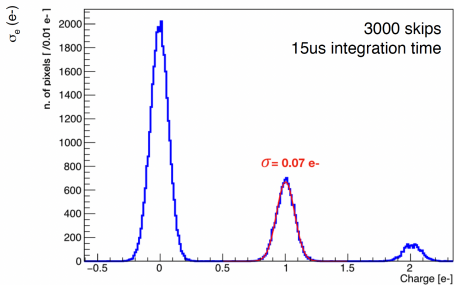
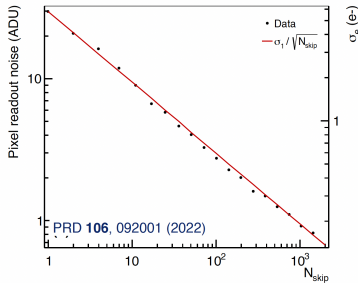
Non Destructive Charge Measurements Janesick et al. (1990)
Engineered for LBNL CCDs, Tiffenberg et al. (2017)



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

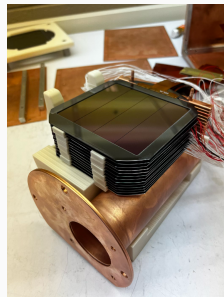
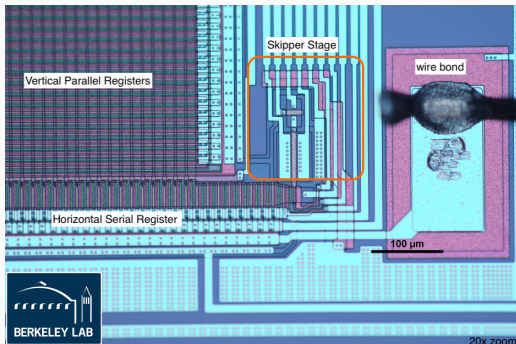
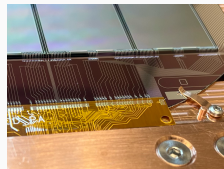
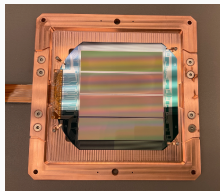
1 Module = 4 Skipper-CCDs

Each Skipper-CCD:

6k x 1.5k pixels

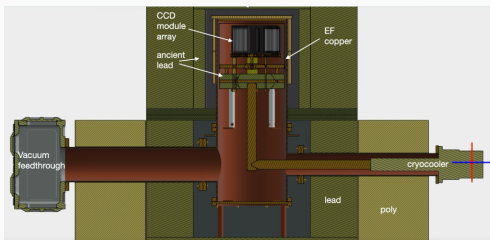
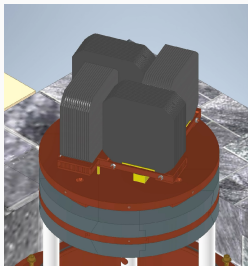
3.3 g target

15 μm x 15 μm x 675 μm



DAMIC-M Experiment

Design driven by the stringent requirements on background

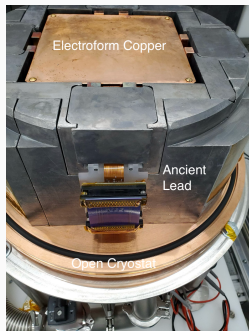


DAMIC-M Prototype: Low Background Chamber

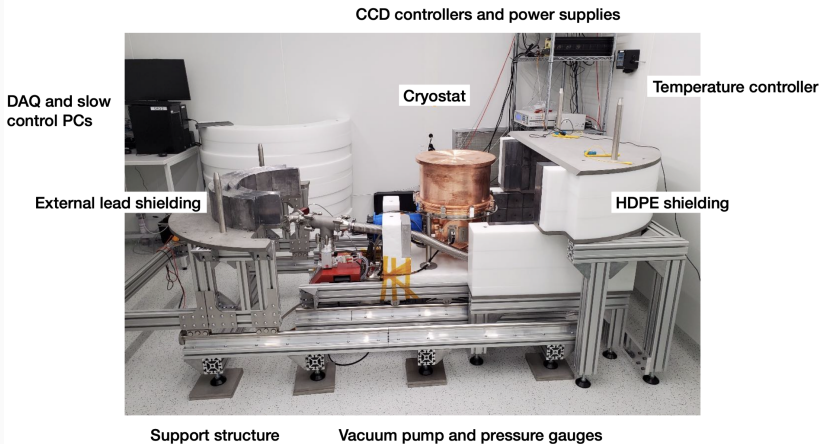
Low Background Chamber

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

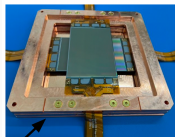
Custom Low Noise Electronics

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

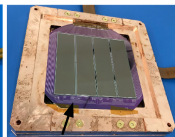
Achievements:

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



Cu box
↑
kapton cable



DAMIC-M Module= 1
pitch adapter, 4 CCDs



LBC Pattern Selection

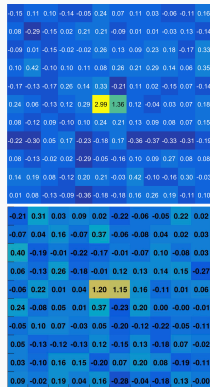
We search for patterns of 2-3 consecutive pixels with charge:

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

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

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

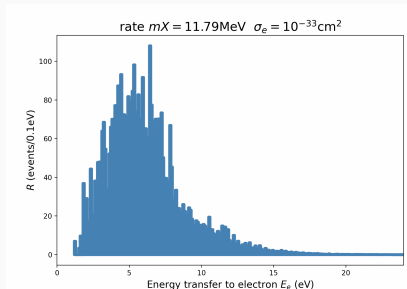
$\bar{\sigma}_e$: DM- e^- Cross section

$f(v)$: DM Halo distribution

F_χ : Dark Matter Form Factor

F_{cry} : Silicon crystal form factor

f_{scr} : Screening form factor

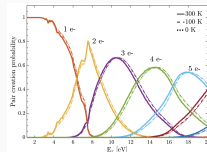


Detector Response

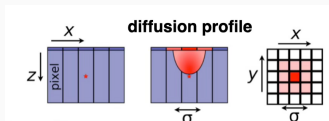
Charge Ionization: Phys. Rev. D 102, 063026 (2020)

$p(q_e | E_e)$: 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

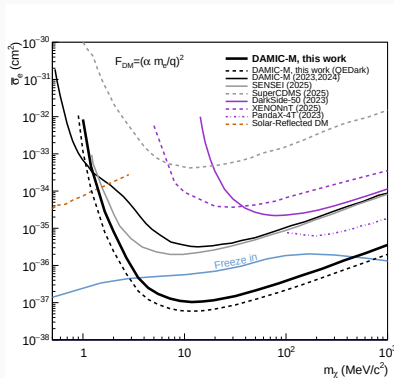
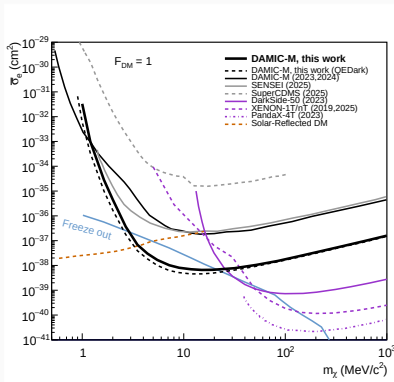
	Pattern p					
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D_p	144	0	0	1	0	0
B_p^{rc}	141.4	0.111	0.042	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
B_p^{rad}	0.039	0.039	0.016	0.052	0.011	0.035

Likelihood function

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

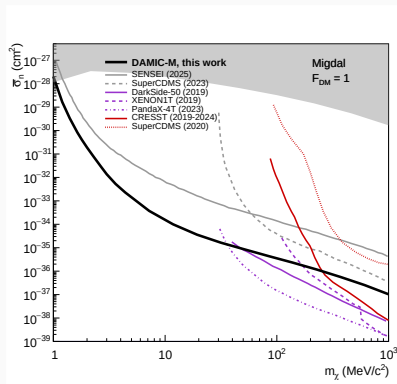
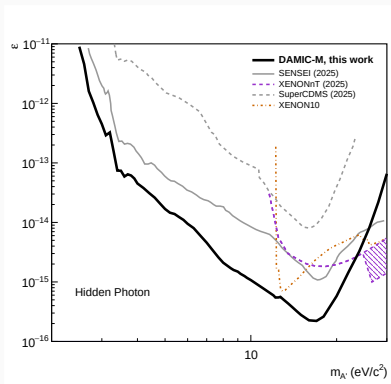
The background-only null hypothesis has $p_0 = 0.24$ (0.10), so we place limits using the profile likelihood ratio test statistics

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

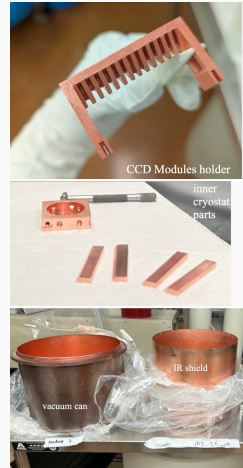
Cu is the material closest to the CCDs
Cosmogenic activation creates various
isotopes of Co

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

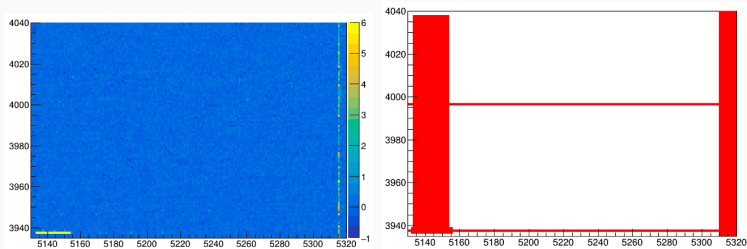
Masked:

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

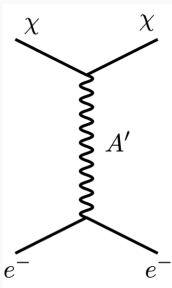
Pixels with high variance in NDCM measurements



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'

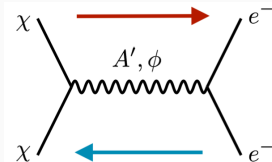
Benchmark Models

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

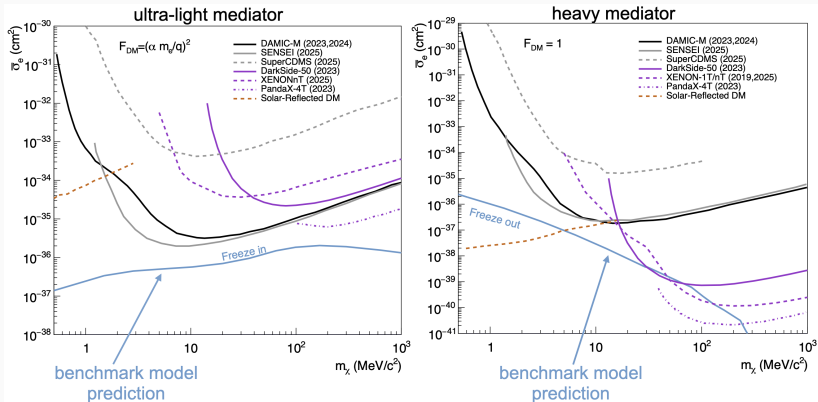
DM and SM in equilibrium in early universe. $\text{DM} + \text{DM} \rightarrow \text{SM}$ are more efficient so DM density drops until density is too low for DM to find each other.

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?

