Results from the DAMIC-M Low Background Chamber

Sravan Munagavalasa

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THE UNIVERSITY OF CHICAGO

LPNHE PARIS

Background and Motivation

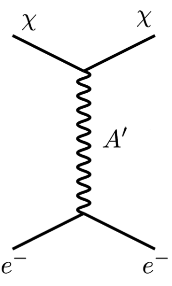
Background

2017: DAMIC at SNOLAB began the search for WIMPs
2021: The DAMIC-M collaboration was formed

- Builds off the expertise of the DAMIC
- Different experiment
- Different detector

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 $A^{'}$

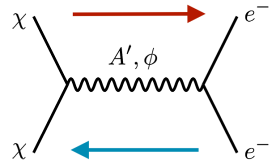
Benchmark Models

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

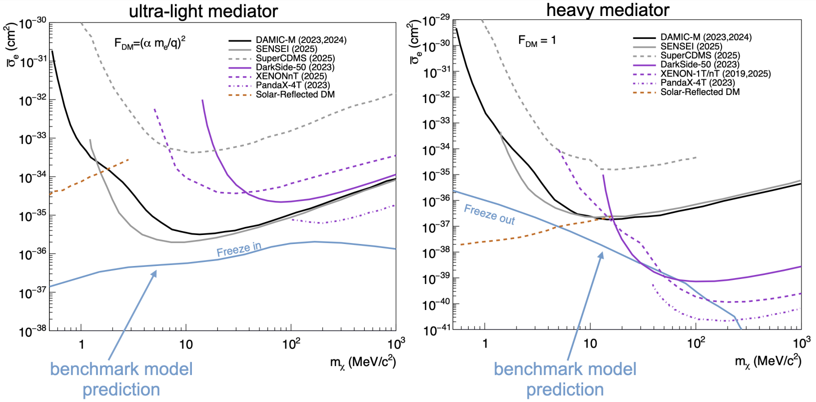
DM and SM in equilibrium in early universe. DM + DM $\to$ SM are more efficient so DM density drops until density is too low for DM to find each other.

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 SM + SM $\to$ DM until density is too low.



Status of Benchmark Models 2024



Detection Stratagies of Hidden-Sector DM

e^- set the typical momentum transfer

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

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

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

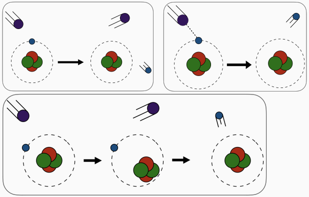
Detector Requirements:

- $\mathcal{O}$(eV) scale ionization threshold
- sub-eV scale resolution
- Low dark current
- low background

DArk Matter In CCDs – Modane

Detect Dark Matter

- MeV-to-GeV scale electronic recoils
- eV-to-keV scale absorption
- MeV-to-GeV scale nuclear recoils

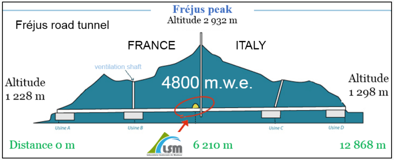


Silicon Skipper-CCDs

- target exposure ∼1 kg yr
- ionization threshold 1.2 eV
- single electron resolution

Laboratoire Souterrain de Modane

- dark current $<100\,e^-/g/d$
- background rate ∼1 dru



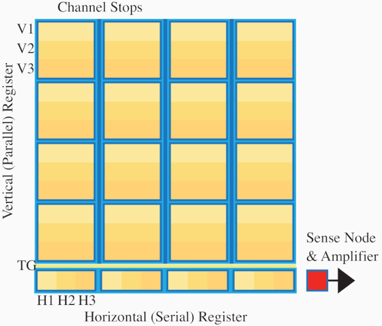
$1\,\text{dru} = 1\,\text{background event/keV/kg/d}$

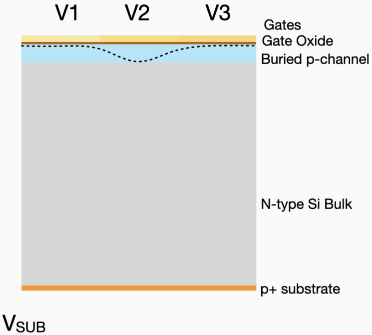
Charge-Coupled Device

Charge Coupled Device

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

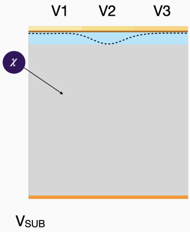
Originally developed at LBNL for astronomy

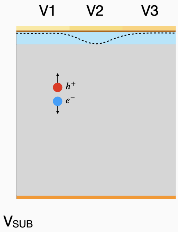


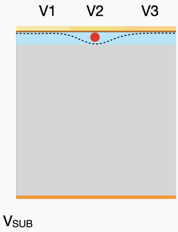


Charge-Coupled Devices

DM interacts with silicon bulk, generating an electron–hole pair
A backside substrate bias creates the electric field across the bulk
h^+ is collected in the potential well under the gate.







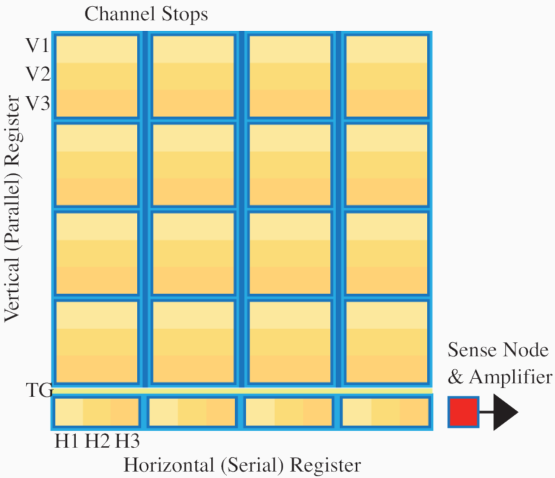
Charge-Coupled Devices

Expose

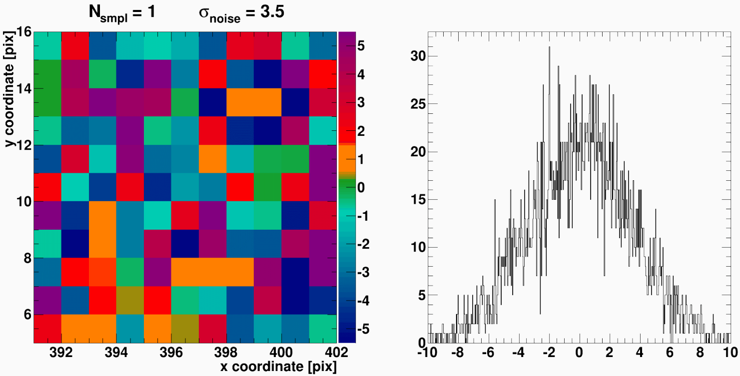
Vertical

Horizontal

readout



Conventional CCD Noise

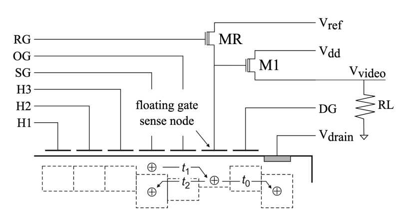


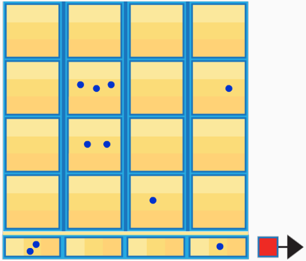
Skipper CCD Readout Stage

Non Desitructive Charge Measurements Janesick et al. (1990)

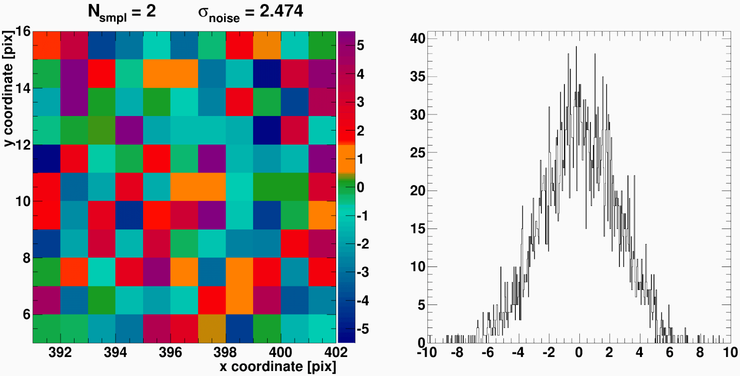
Engineered for LBNL CCDs, Tiffenberg et al. (2017)

$$\sigma_{NDCM} = \frac{\sigma_1}{\sqrt{\text{NDCM}}} \tag{1}$$

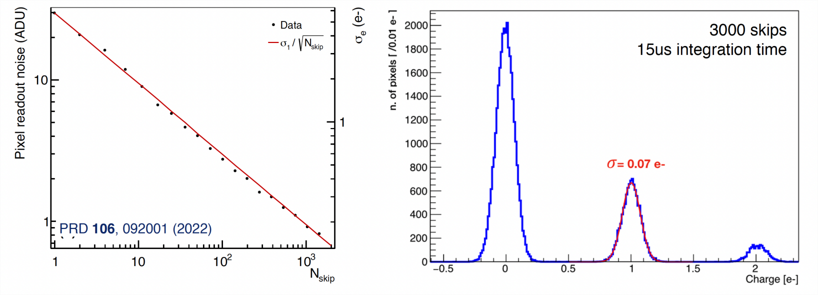




Noise Reduction



$1/\sqrt{NDCM}$



Pixel readout noise (ADU)
σe (e-)
Data
σ1 / √Nskip
PRD 106, 092001 (2022)
Nskip
n. of pixels [/0.01 e-]
3000 skips
15us integration time
σ= 0.07 e-
Charge [e-]

DAMIC-M CCD Module

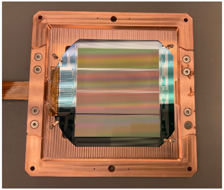
CCD:

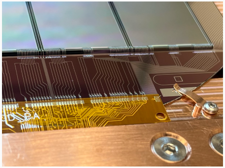
6k x 1.5k pixels

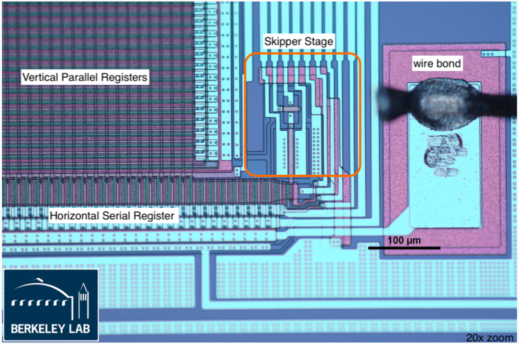
3.3 g targe

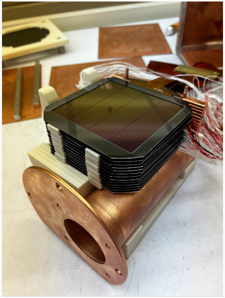
15 µm x 15 µm x 675 µm

4 CCDs per Module



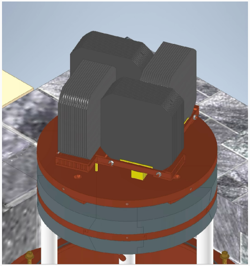


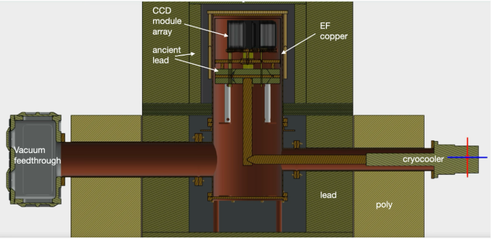




Background Mitigation

Design driven by the stringent requirements on background





Cosmogenic Activation of Silicon

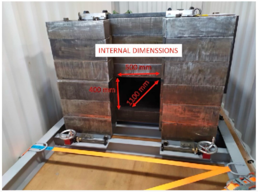
Cosmic rays spallation in **Si** results in tritium (^{3}H)

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

mean β energy $5.7\,\text{keV}$

Minimize Si exposure to few months

Strict shielding protocols for all transports/storage



Complex Logistics:

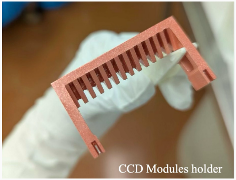
Europe $\rightarrow$ Montreal $\rightarrow$ SNOLAB $\rightarrow$ Seattle $\rightarrow$ Modane

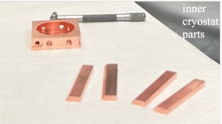
Cu is the material closest to the CCDs
Cosmogenic activation creates various isotopes of Co

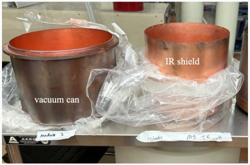
We use **Electroformed Cu** produced and machined underground at SURF.
Exposure is limited to few weeks.

Logistics:

SURF (South Dakota) → Modane







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

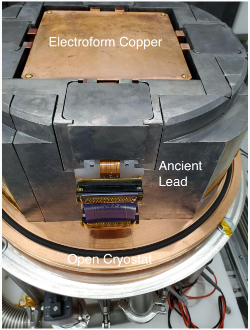
Polyethylene shielding to stop neutrons

Low Background Chamber

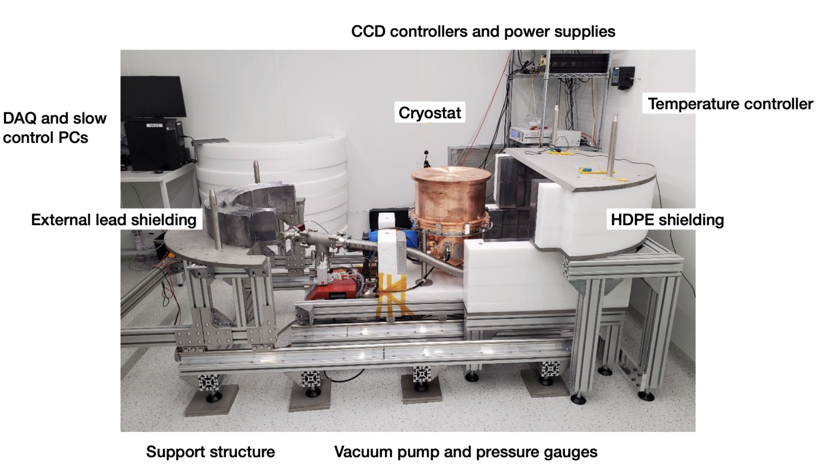
Low Background Chamber

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

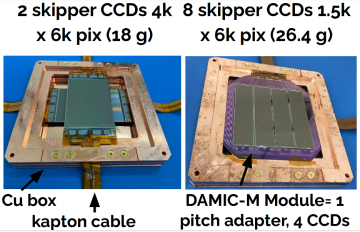
Electroformed Copper Box

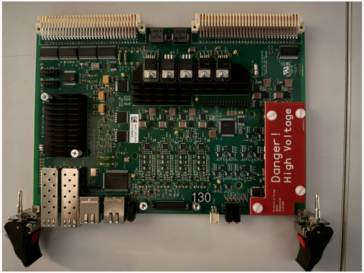
Custom Low Noise Electronics

pixel binning: 1 x 100 (col x row)

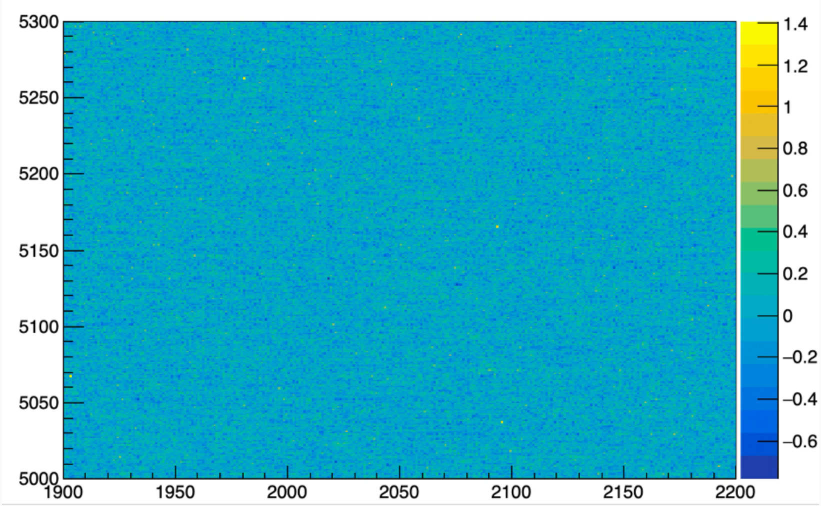
Improvements:

- $\lambda_{DC} = 1\,\mathrm{e}^-/\mathrm{pix/d}\ (400\,\mathrm{e}^-/\mathrm{g/d})$
- $\sigma_{500} = -0.16\,\mathrm{e}^{-1}(0.6\,\mathrm{eV})$
- $1.3\,\mathrm{kg\,d}$ exposure (previous $85\,\mathrm{g\,d}$)





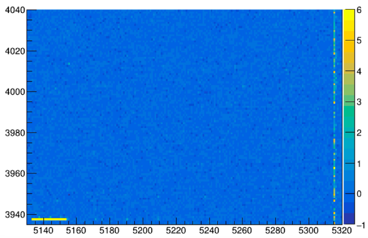
LBC Image: What do you see?

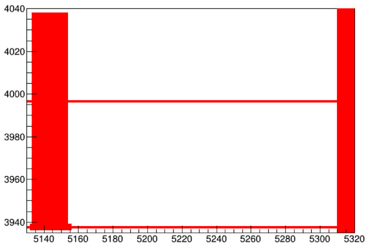


Data Cleaning Procedure

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!!!

LBC Pattern Selection

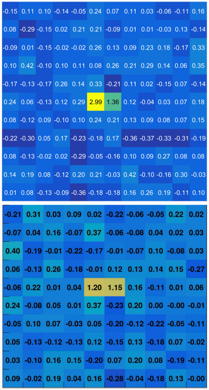
We search for patters of 2-3 consecutive pixels with charge:

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

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

Analysis

Dark Matter Rate in CCD Bulk

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

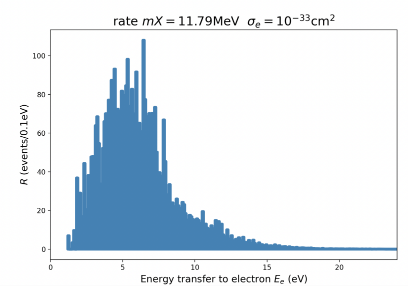
$\bar{\sigma}_e$: DM-e$^-$ Cross section

$f(v)$: DM Halo distribution

F_χ: Dark Matter Form Factor

$F_{\rm cry}$: Silicon crystal form factor

$f_{\rm scr}$: Screening form factor

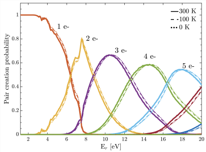


Detector Response

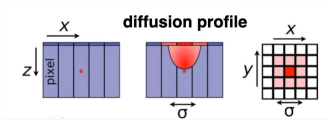
Charge Ionization: Phys. Rev. D 102, 063026 (2020)

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

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



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



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

$P_{q_e \to p}$: 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

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

Result from data

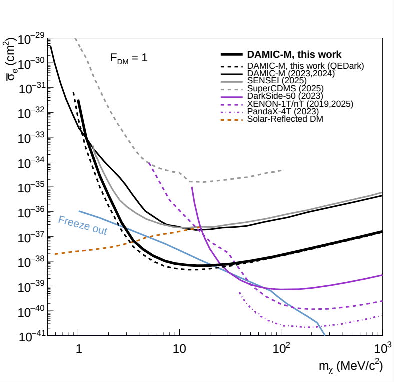
	Pattern p					
	$\{11\}$	$\{21\}$	$\{111\}$	$\{31\}$	$\{22\}$	$\{211\}$
D_p	144	0	0	1	0	0
B_p^{rc}	141.4	0.111	0.042	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
B_p^{rad}	0.039	0.039	0.016	0.052	0.011	0.035

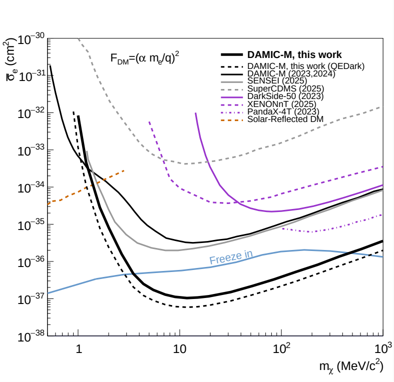
Likelihood function

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

The background-only null hypothesis has p0 $=$ 0.24 (0.10), so we place limits using the profile likelihood ratio test statistics

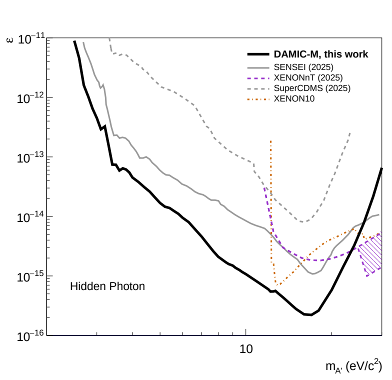
Dark Matter Electron scattering Exclusion Limits

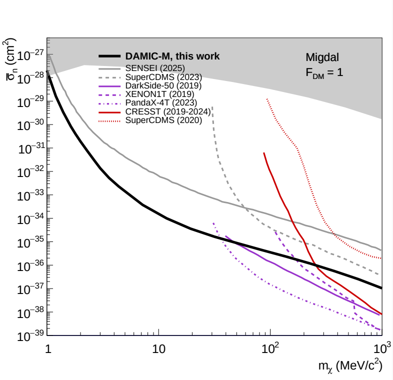




DAMIC-M probes benchmark hidden-sector dark-matter models!!!

Hidden Photon and Migdal Exclusion Limits





DAMIC-M Collaboration