IRN Terascale - IPHC, Strasbourg - 19 May 2025

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

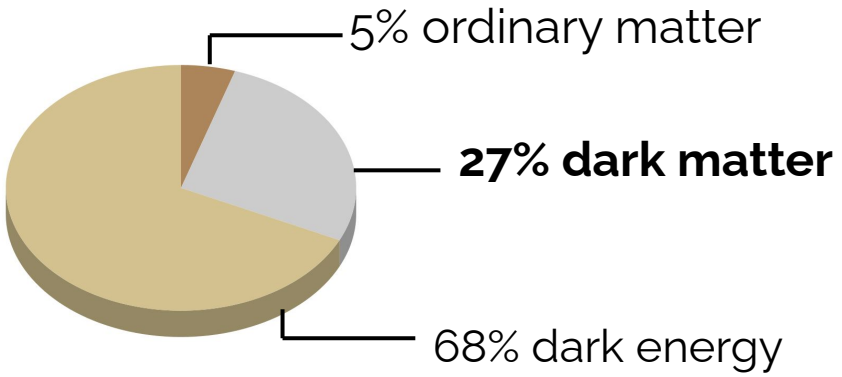
Claudia De Dominicis

Outline

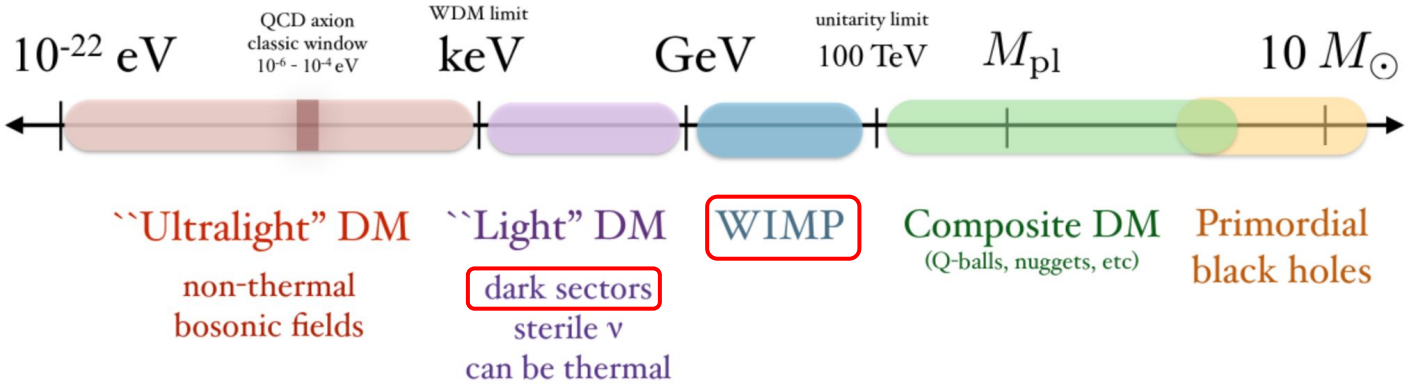
- What is the DARK MATTER?
- How DAMIC-M look for DM?
- Latest DAMIC-M results

What is the DARK MATTER?

UNIVERSE
according to the ΛCDM model

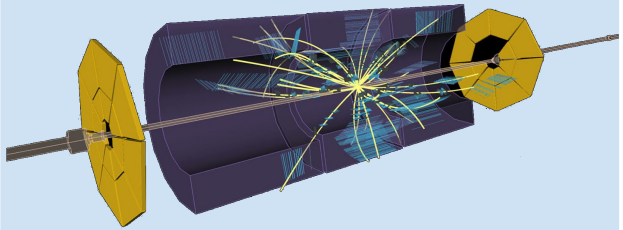


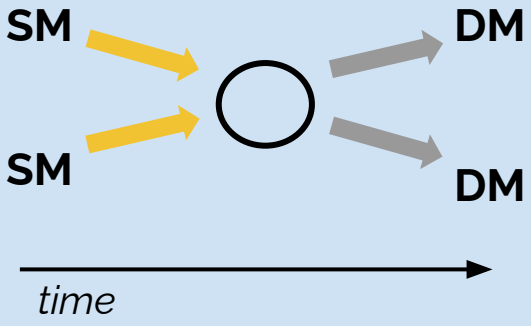
A lot of Dark Matter candidates



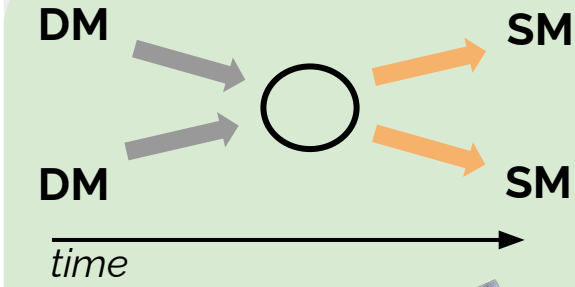
DM detection strategies

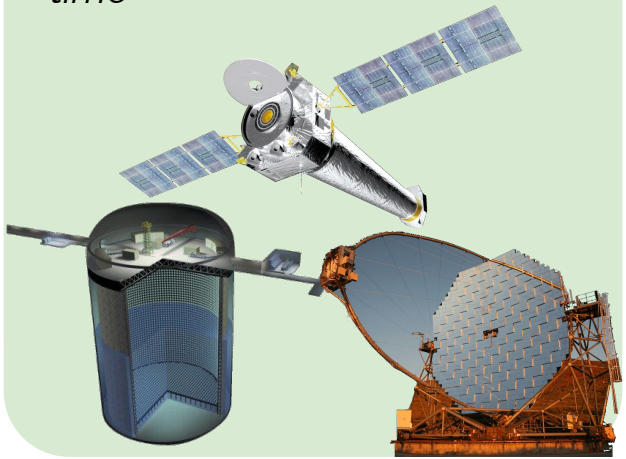
Production at colliders



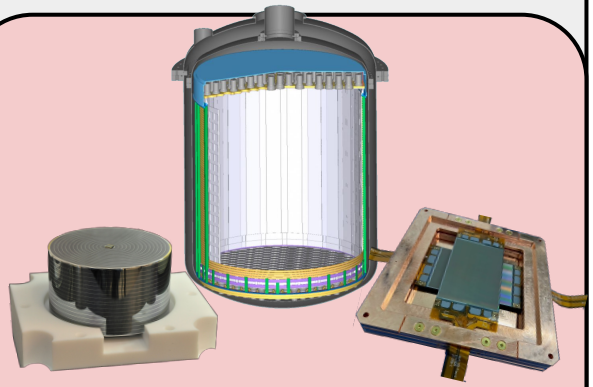


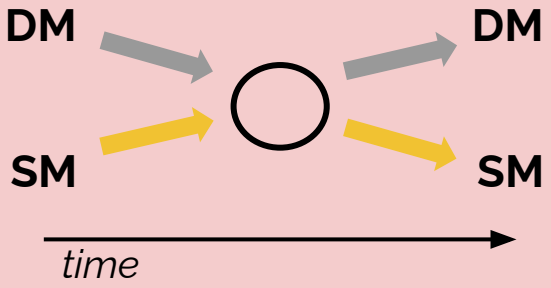
Indirect detection





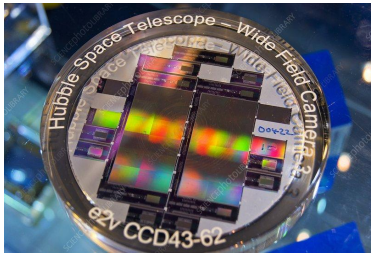
Direct detection

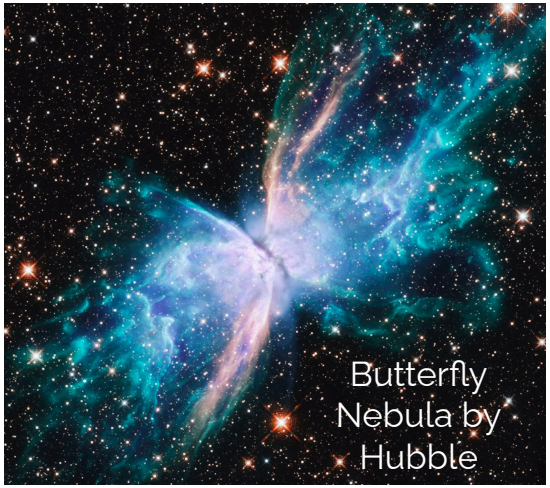




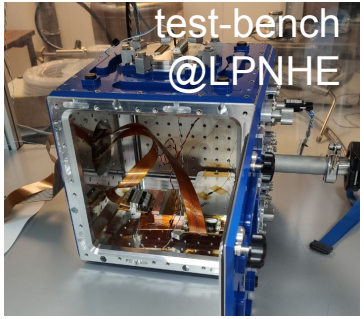
Charge Coupled Devices

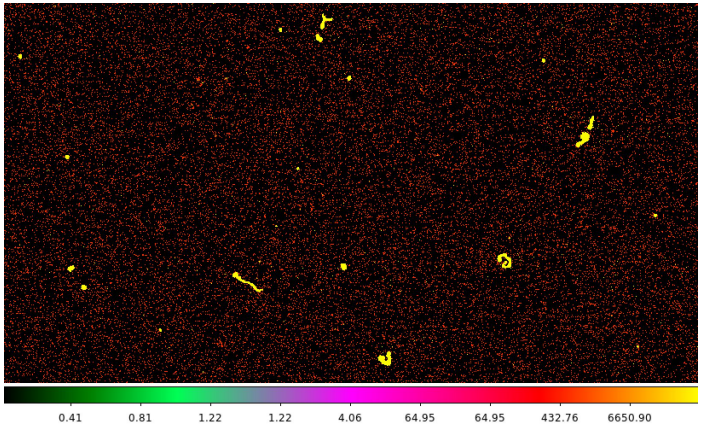
CCD for Astronomy



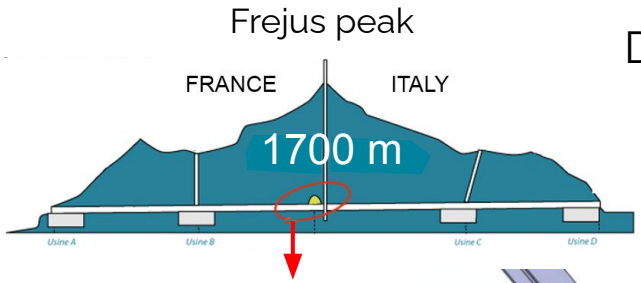


CCD for Particle Detection

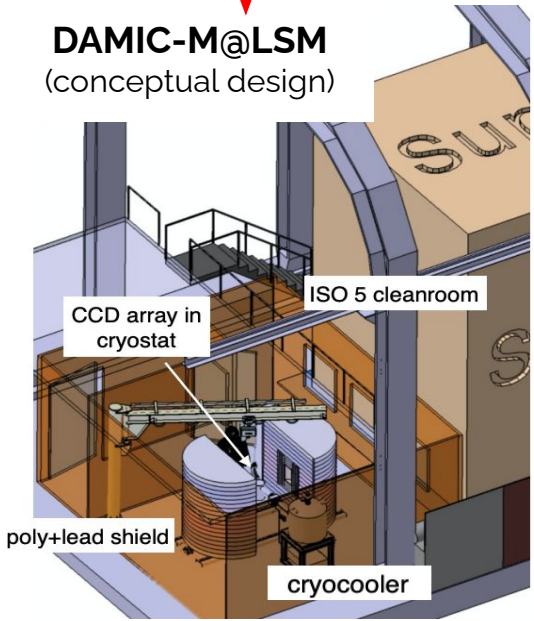




DAMIC-M: Dark Matter in CCD at Modane



DAMIC-M@LSM
(conceptual design)



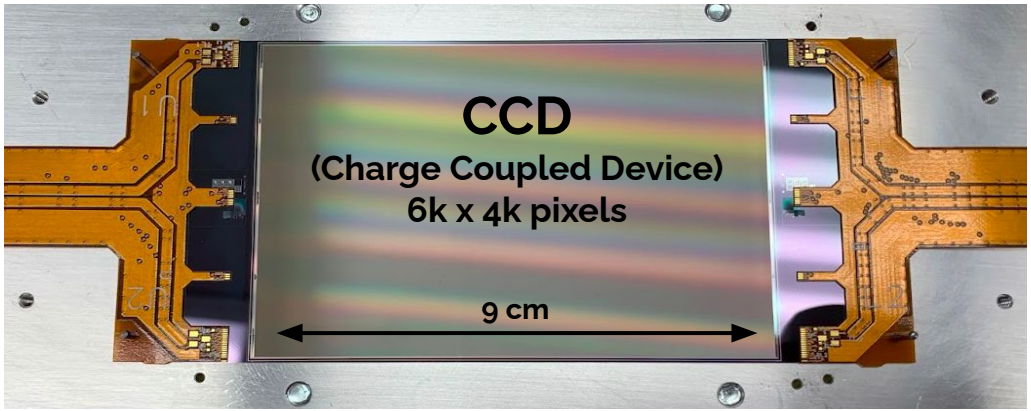
DAMIC experiment
at SNOLAB (Canada)

2017 — 2022 — 2025

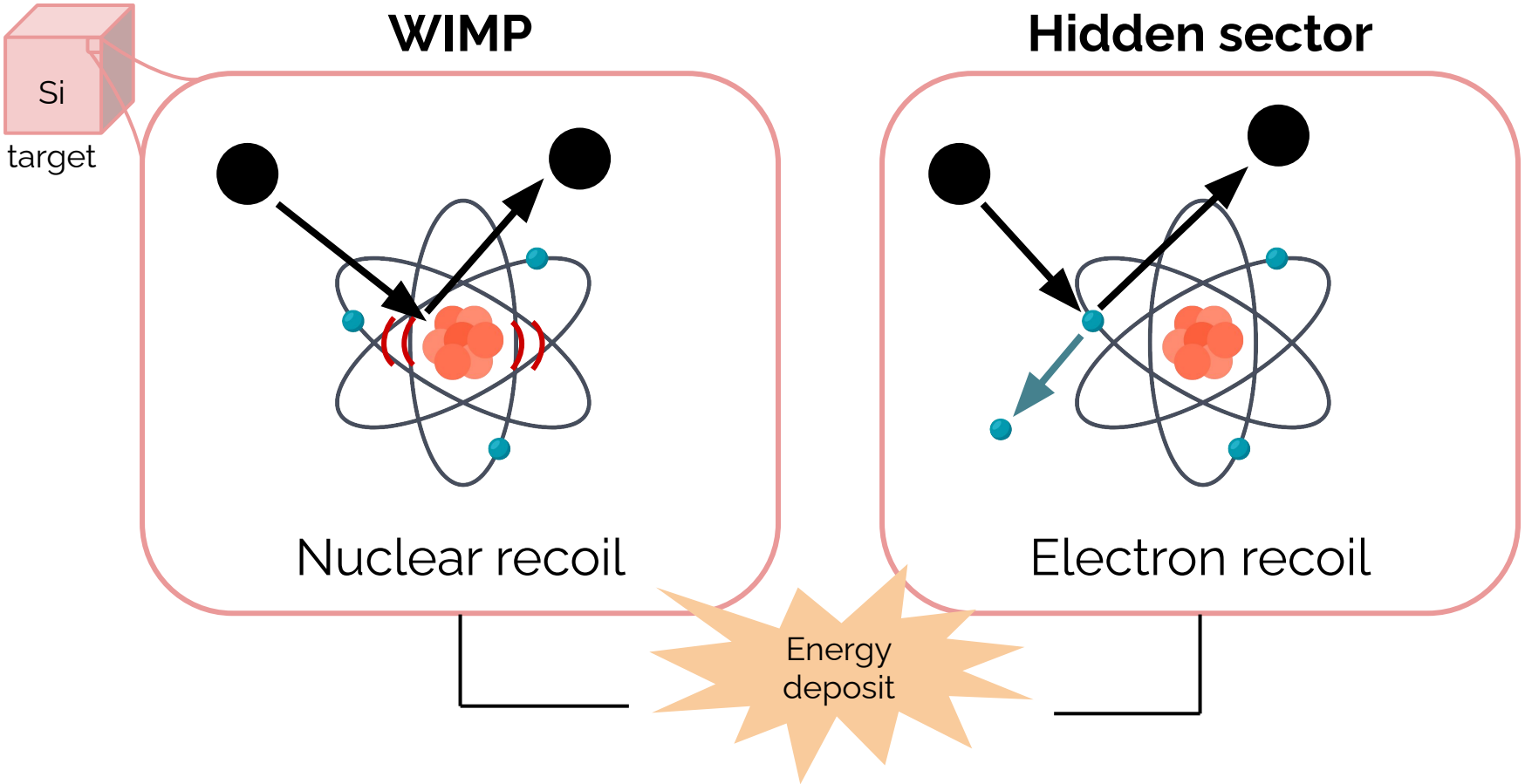
DAMIC-M experiment
at LSM (Modane, France)

Low Background Chamber
at LSM (Modane, France)

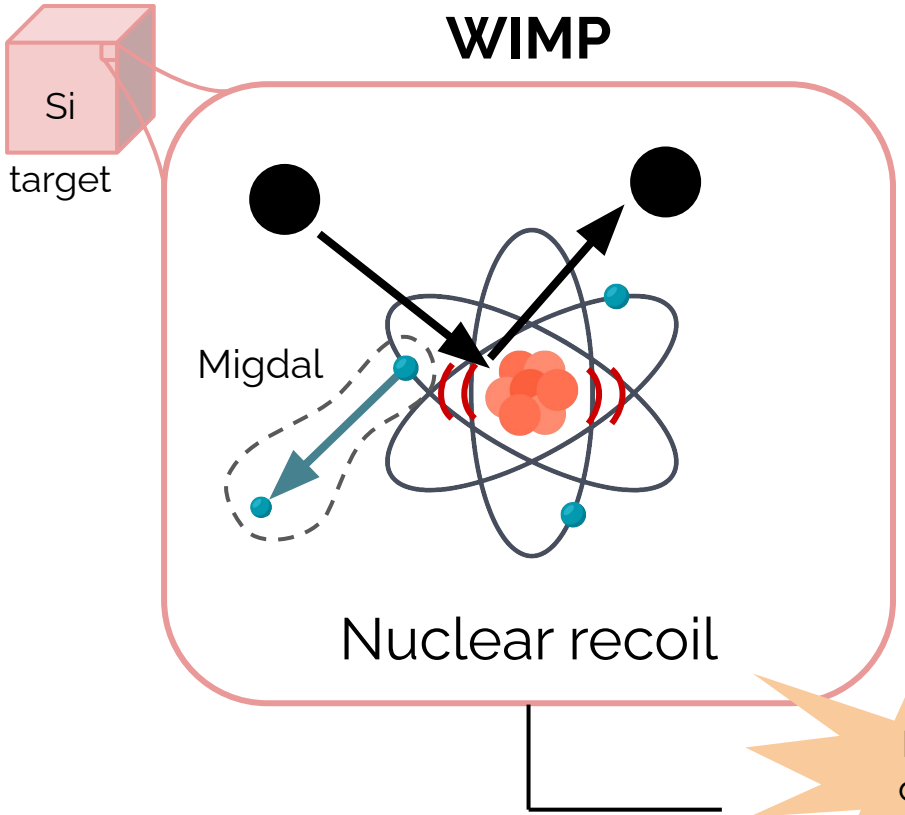
Aim: detect **Light DM** (WIMP, Hidden Sector) signals via interaction with Si nucleus or e- in the bulk of **CCDs**



DM detection principle



DM detection principle



m_χ = 100 MeV → Enr ≈ eV

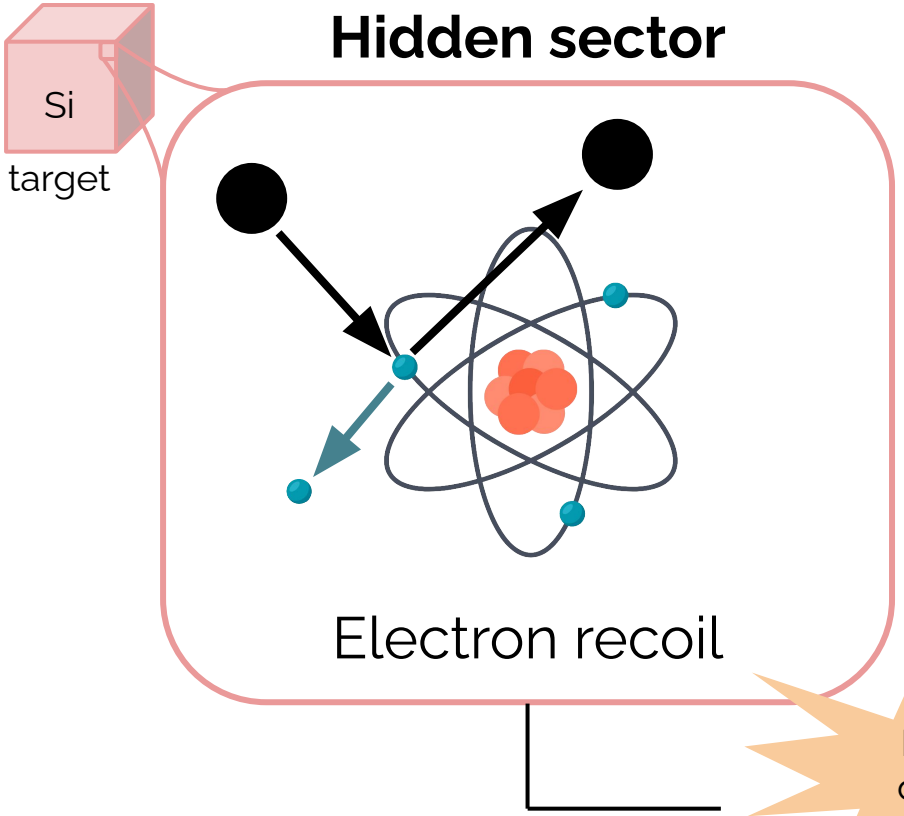
not detectable with current direct detection threshold

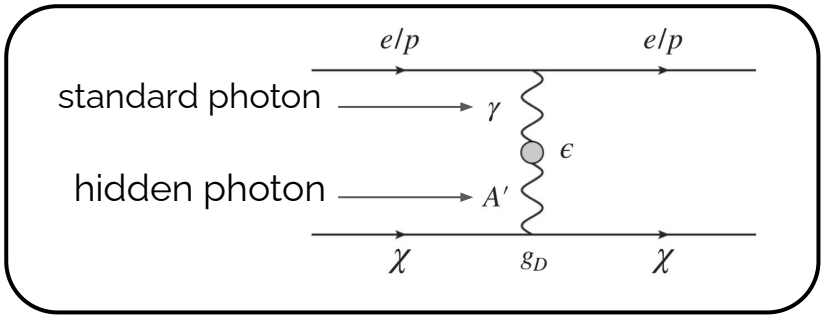
silver lining

Migdal effect*

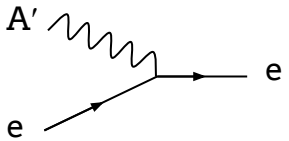
(*) never observed in nuclear scattering

DM detection principle

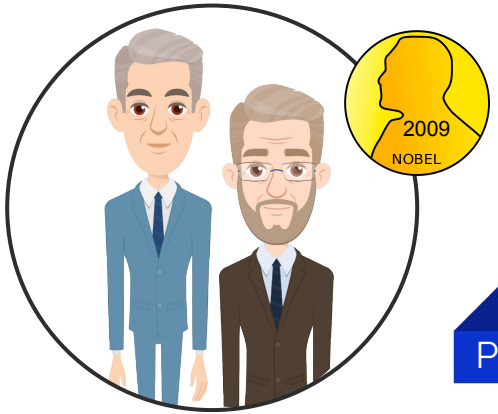




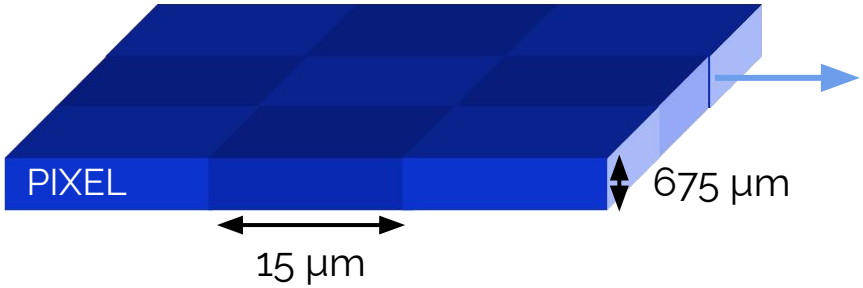
Hidden photon absorption is also possible. DM photon can be DM candidate!

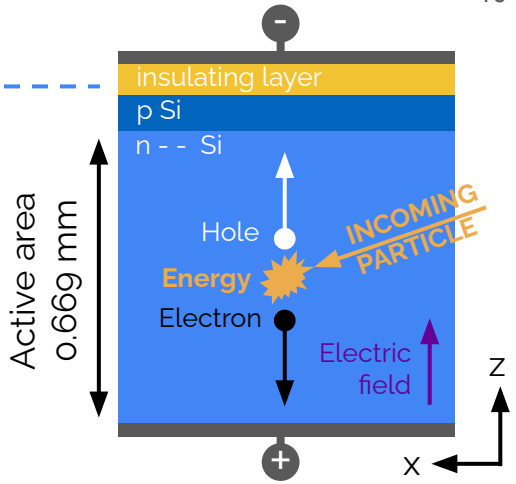


CCD operation



Willard Boyle
George E. Smith



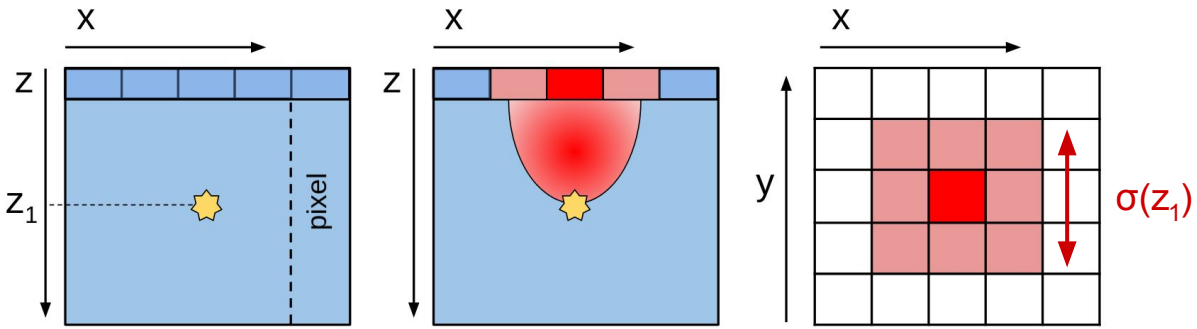


Interaction | Creation e-/h pairs | Diffusion | Hole collection

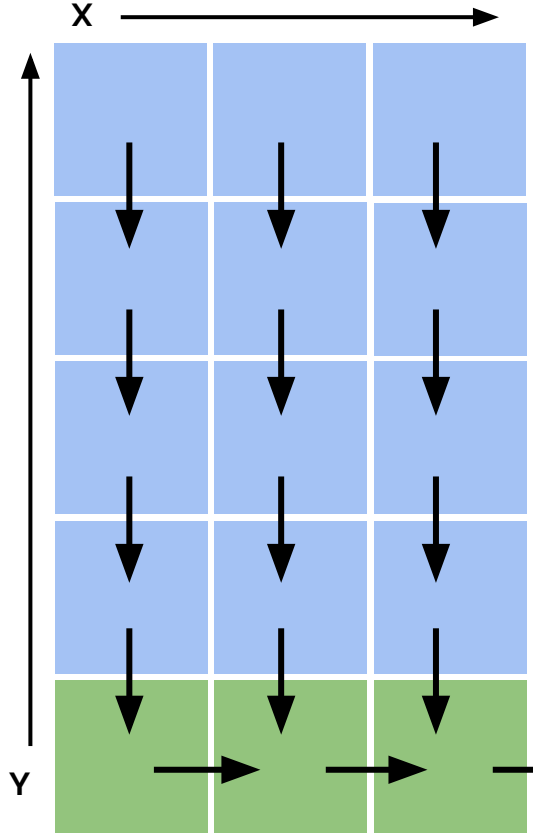
Diffusion

the diffusion spread is positively correlated with the interaction depth

3D reconstruction



CCD readout



DAMIC

STANDARD READOUT

SUMMING WELL

1 TIME

SENSE NODE

AMPLIFIER

Readout noise > 1 e-

DAMIC-M

SKIPPER READOUT

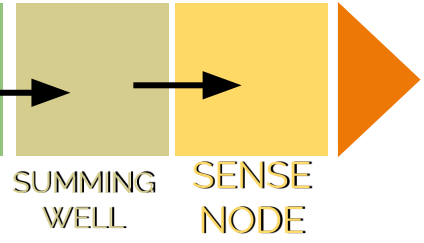
N TIMES

N NDCMs

Non Destructive Charge Measurements

Readout noise reduced by a factor 1/sqrt(N)

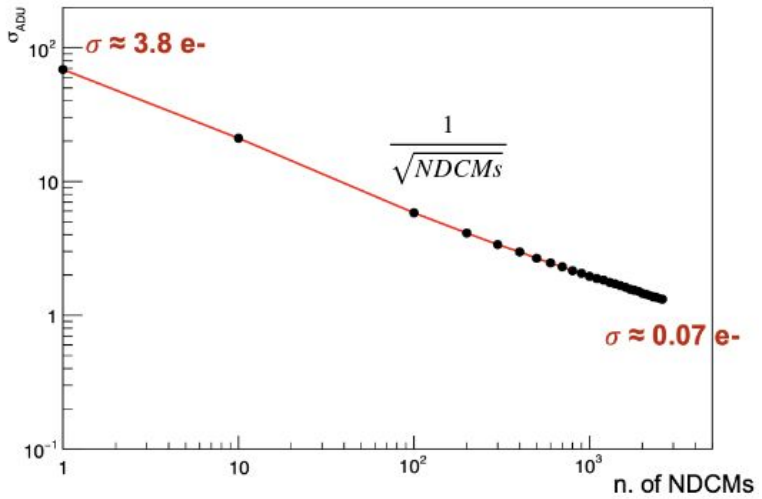
Readout noise < 1 e-



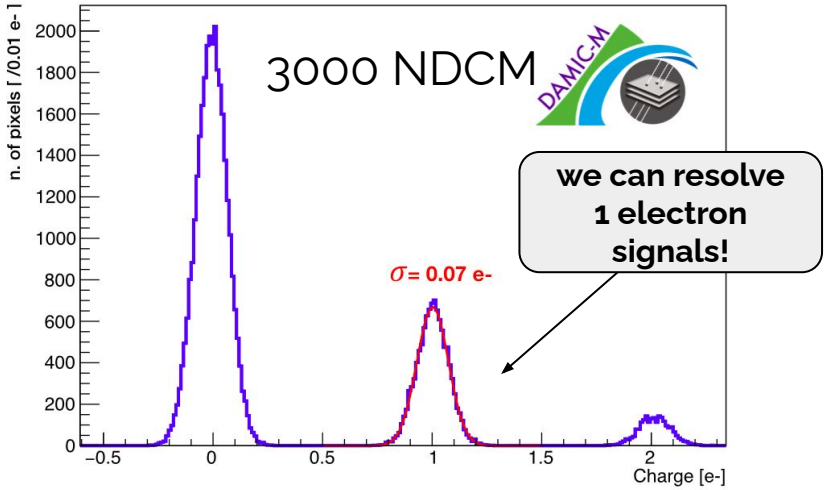
AMPLIFIER

Skipper readout

Readout noise reduced
by a factor 1/sqrt(NDCM)

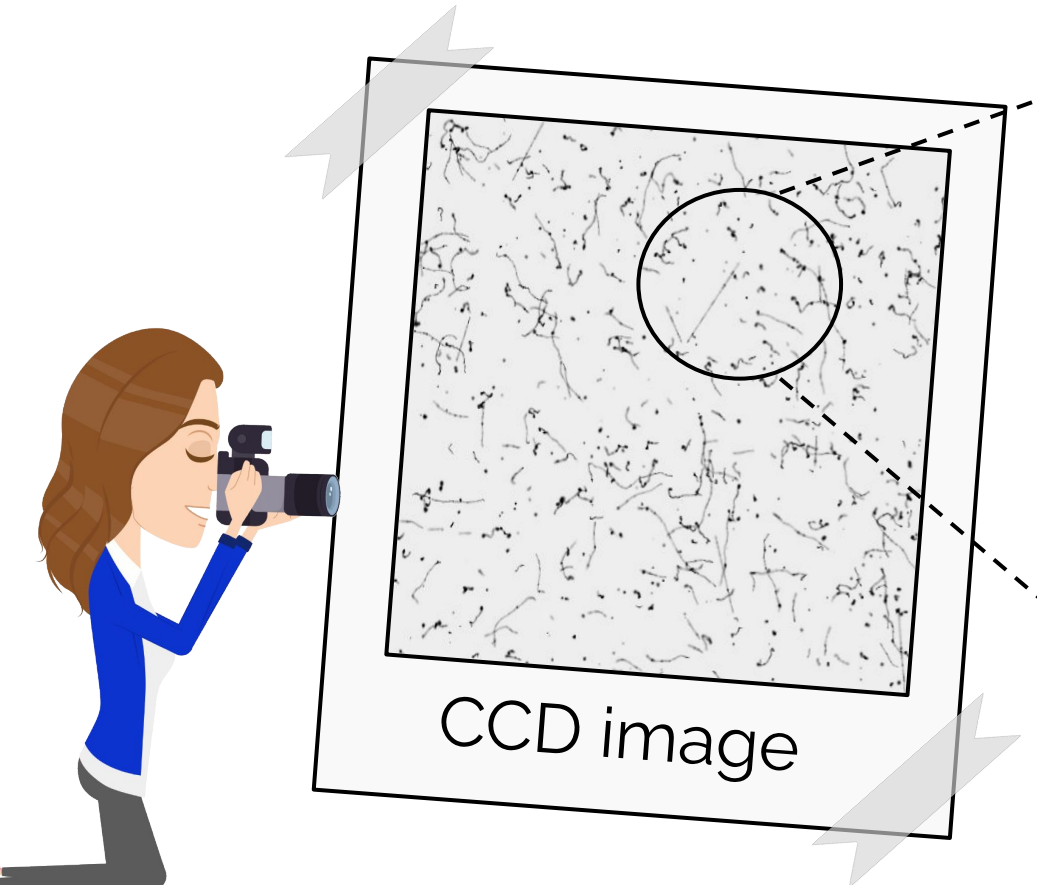


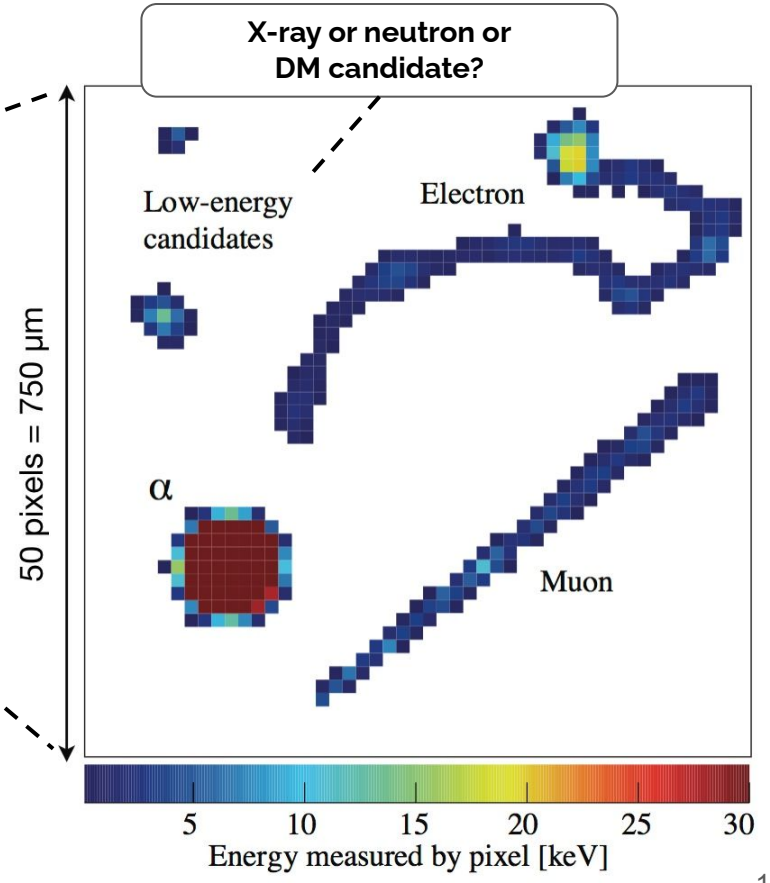
Pixel charge distribution
with SKIPPER amplifiers



[arXiv:1706.00028]

Photographing particles



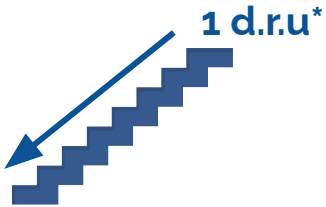


DAMIC-M features

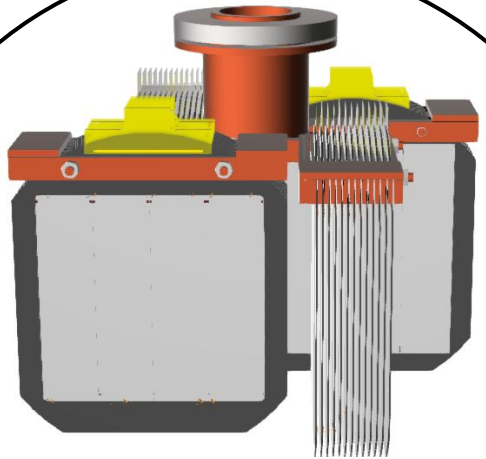
TEMPERATURE

~130 K

BACKGROUND

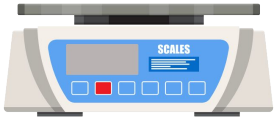


<= 1 d.r.u



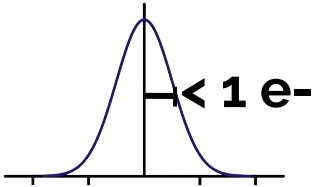
~200 skipper CCDs
1.5k pixels x 6k pixels

MASS



~0.7 kg

RESOLUTION
readout noise

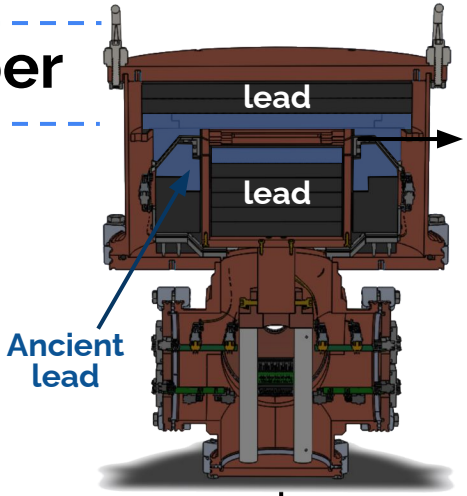


(*) 1 d.r.u = 1 event/kg/day/keV

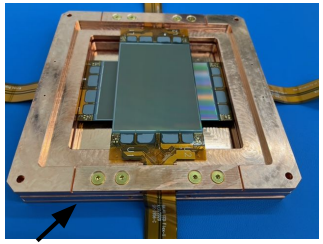
Low Background Chamber

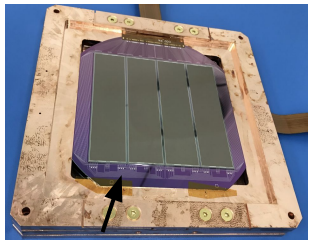
- **Aim:**
  - Demonstrate the ability to control backgrounds for DAMIC-M
  - Integration/operation of DAMIC-M electronics
  - Provide test bench for dark current studies and reduction strategies
  - First dark matter search

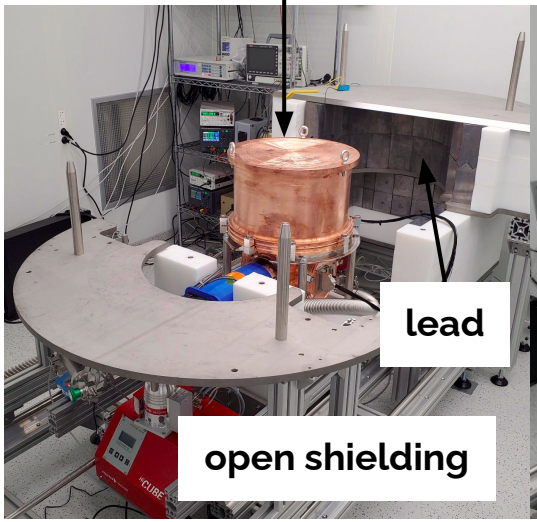
- **Achievements:**
  - Installed at LSM at the end of 2021
  - Results for DM search
  - Upgrades for lower background, lower electronic noise and lower dark current

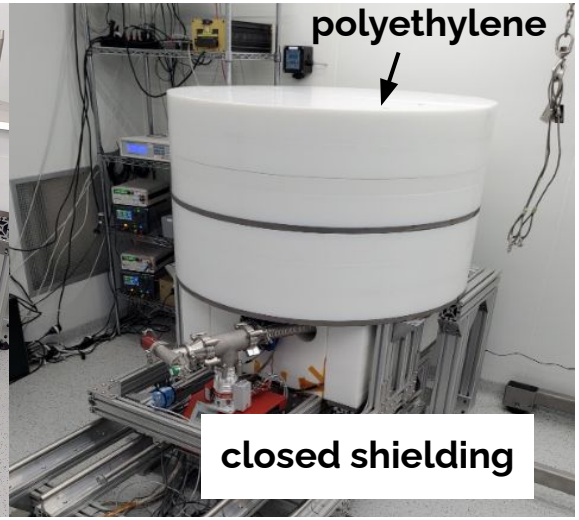


Setup 1	*Upgrade - Setup 2*
2 skipper CCDs 4k x 6k pix (18 g)	8 skipper CCDs 1.5k x 6k pix (26.4 g)

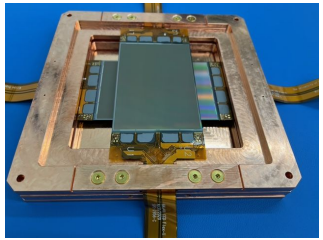








LBC - Data Taking



Setup 1
2 skipper CCDs
4k x 6k pix (18 g)

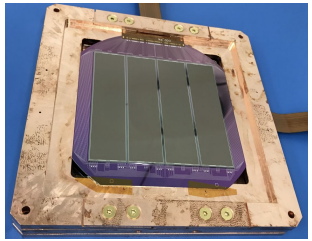
Science run 1: May-Ago 2022

- Read out with 2 amplifiers per CCD
- Binning: 10 pix x 10 pix
- Temperature: ~110 K
- Background rate: ~12.5 d.r.u
- **Commercial electronics**
- Resolution = 0.2e- (< 1eV) at 650 skips (NDCMs)
- **Dark Current (DC) = 4.5E-3 e-/pixel/day**
- **Exposure: 85.2 gr-day**

39.97 g-days

Pixel charge distribution analysis
[Phys. Rev. Lett. 130, 171003, 2023]

Daily modulation analysis of 1e- signal
[Phys. Rev. Lett. 132, 101006, 2024]



Upgrade - Setup 2
8 skipper CCDs
1.5k x 6k pix (26.4 g)

Science run 2: Oct 2024 -Jan 2025

- Read out with 1 amplifier per CCD
- Binning: 1 pix x 100 pix (hor x vert)
- Temperature: ~130 K
- Background rate: ~7 d.r.u + open shield
- **Custom made DAMIC-M electronics**
- Resolution = 0.16e- (< 1eV) at 500 skips (NDCMs)
- **Dark current (DC)= 1.2-1.6E-4 e-/pixel/day**
- **Exposure: 1.3 kg-day**

new!

coming soon!

Pattern analysis

Daily modulation analysis of 1e- signal

LBC - Pattern analysis [arXiv:2503.14617]

Two data sets:

- **1 unblind**, D1 (~7 d): to determine masking and data selection procedure
- **1 blind**, D2 (~77 d): for DM search

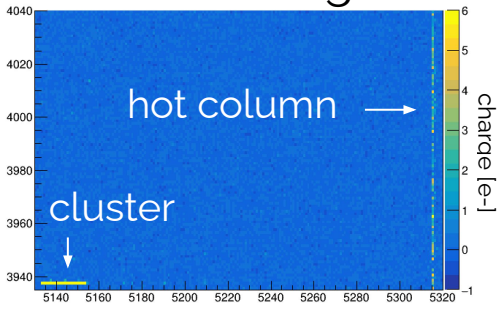
Cleaning procedure:

- mask **hot regions** in CCDs (excess on the N. pixels with charge >=1e-)
- mask **clusters** of charged pixels (Ecluster>=6e-) and cross talk effects in CCDs of the same module
- mask **charge-correlated pixels** in CCDs of the same module & mask pixels with **high variance** in skipper NDCM

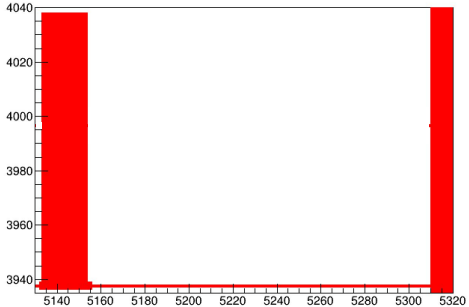
→ **95% of data kept for the analysis**

Pattern selection: permutation of 2 or 3 horizontally adjacent pixels with charge 1e-, 2e-,3e-: {11}, {21}, {111}, {31}, {22}, {211}

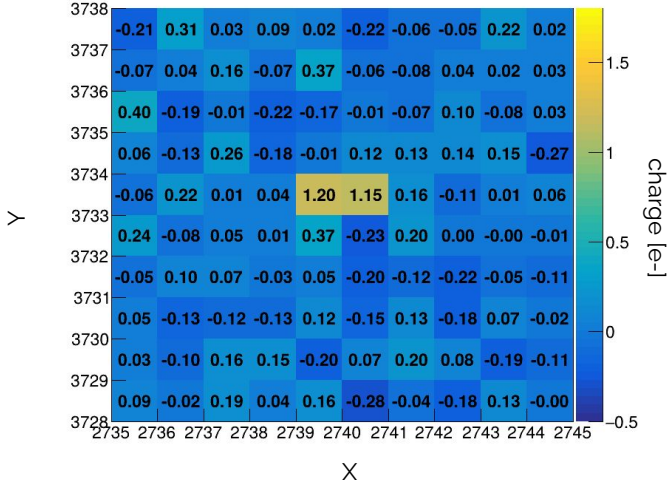
Partial image



Mask



Example {11} pattern



LBC - Pattern analysis [arXiv:2503.14617]

DM **RADIOACTIVE BKG**

Energy deposit → N e-/h

diffusion

Edep → real pattern

1e- 2e- 1e-

+ single e- bkg

resolution

RANDOM COINCIDENCE SINGLE e- BKG

rates

1e- 2e- 3e-

random coincidence

accidental pattern

1e- 1e-

resolution

Prob(Edep→observed patt)

Prob(2,3,4,5 e-→obs patt) = 38,65, 79, 86 %

pattern selection

PATTERN (D_p)

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

Results in D2

1 event over 0.325 expected in [2e-,5e-]

$$\mathcal{L}(\mu,\theta) = \prod_p \frac{(S_p(\mu)+B_p^{rc}+\theta B_p^{rad})^{D_p} e^{-(S_p(\mu)+B_p^{rc}+\theta B_p^{rad})}}{D_p!}$$

$$\prod_p \frac{(\theta\tau_p B_p^{rad})^{N_{rad}} e^{-(\theta\tau_p B_p^{rad})}}{N_{rad}!}$$ ← control region [2.5,7.5 keV]

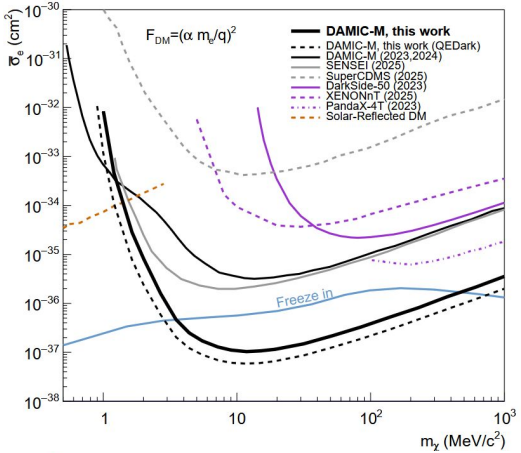
No evidence for a signal

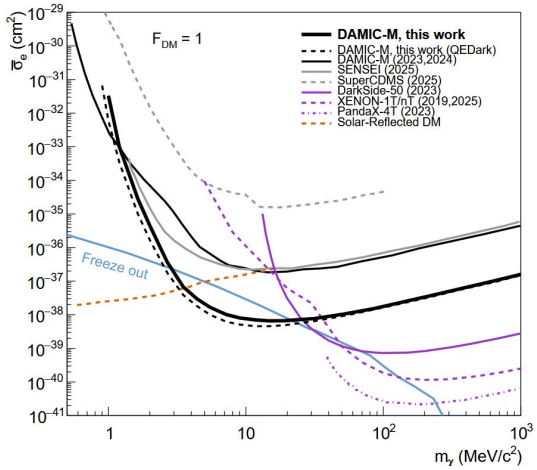
two-sided profile likelihood ratio test statistic

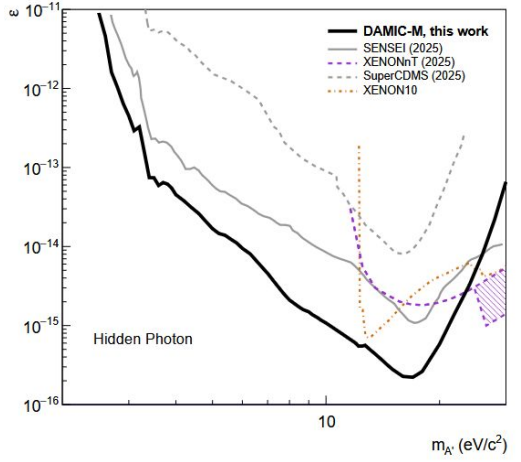
$$\tilde{t}_\mu = -2\log\lambda(\mu)$$

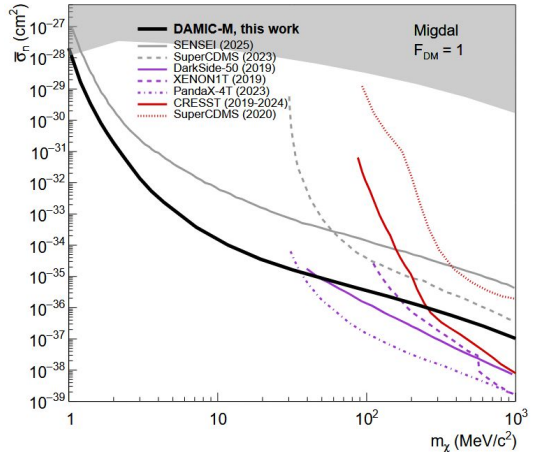
90% C.L limit on DM signal

LBC - Pattern analysis [arXiv:2503.14617]









- **Stringent constraints** on DM particles with masses between **0.75 and 1000 MeV** interacting with **electrons** through an **ultra-light or heavy mediator.**

- **Exclusion of benchmark scenarios**, for large ranges of DM masses **below 1 GeV**, where hidden-sector particles are produced as a major component of DM in the Universe through the **freeze-in or freeze-out** mechanisms.

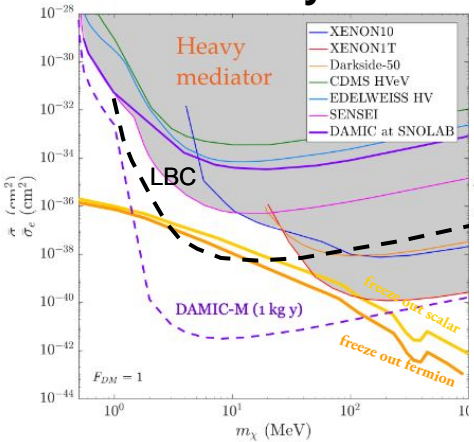
- **Stringent constraints on absorption** of a relic **hidden photon** and DM scattering off nuclei through the **Migdal effect.**

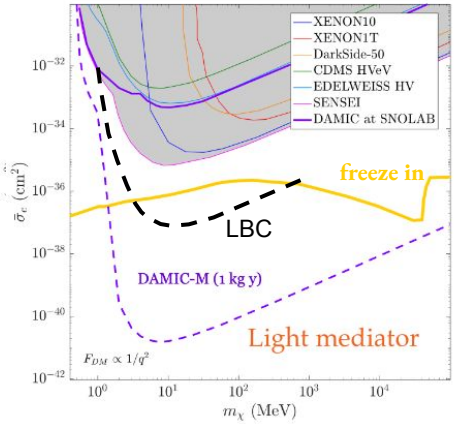
Conclusions

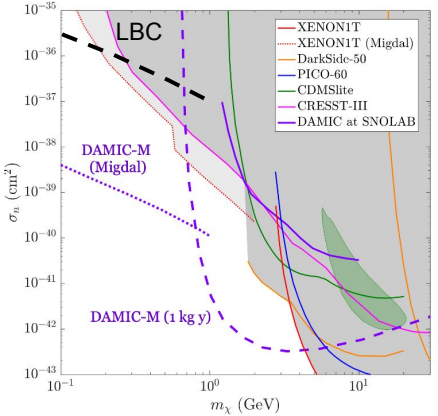
- **On our way towards DAMIC-M**
  - CCDs packaged
  - Design finalized
  - Custom readout electronics ready and successfully tested
  - Dark current lower than before by more than 1 order of magnitude
  - Installation this year!

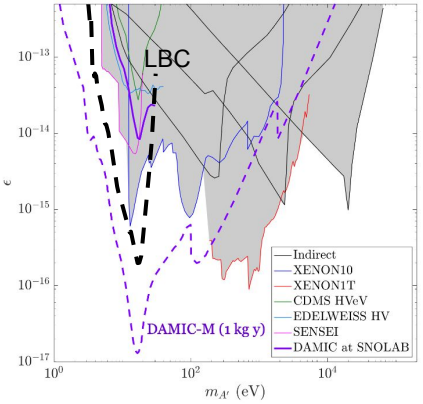
- **Low Background Chamber**
  - World leading exclusion limits on DM-electron interactions, exclusion of benchmark scenarios
  - Displaced to leave the floor to DAMIC-M…

Stay Tuned for DAMIC-M!









Postcard from LSM

LBC installation, December 2021

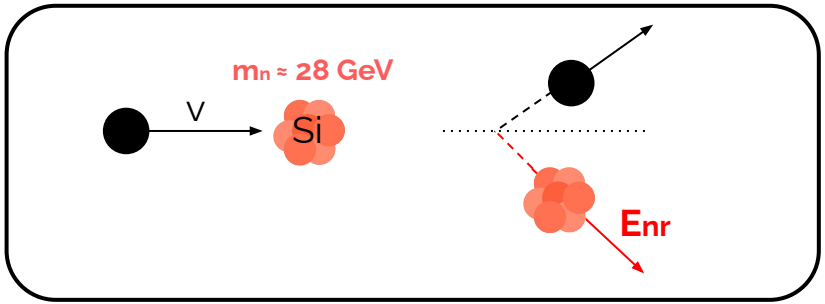
Thank you for the attention !

European Research Council
Established by the European Commission

BACKUP

DM detection principle

WIMP - Nuclear recoil



$E_{nr} \approx 2\,(v\,\mu_n)^2 / m_n$

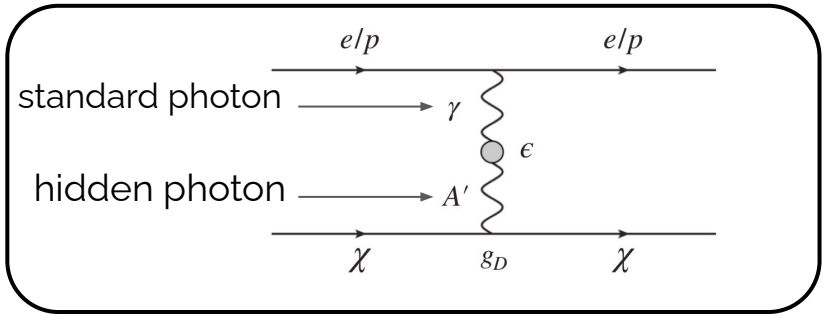
$$\begin{cases} 400\ \text{keV}\left(\frac{m_n}{28\text{GeV}}\right) & m_\chi >> m_n \\ 500\ \text{eV}\left(\frac{m_\chi}{1\text{GeV}}\right)^2\left(\frac{28\text{GeV}}{m_n}\right) & m_\chi << m_n \end{cases}$$

small m_n → low mass WIMPs

m_χ = 100 MeV → Enr ≈ eV

not detectable with current direct detection threshold

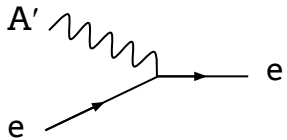
Hidden sector - Electron recoil



$$\Delta E_e \leq \frac{1}{2}\mu_{\chi N} v^2 \simeq \frac{1}{2}\ \text{eV} \times \left(\frac{m_\chi}{\text{MeV}}\right)$$

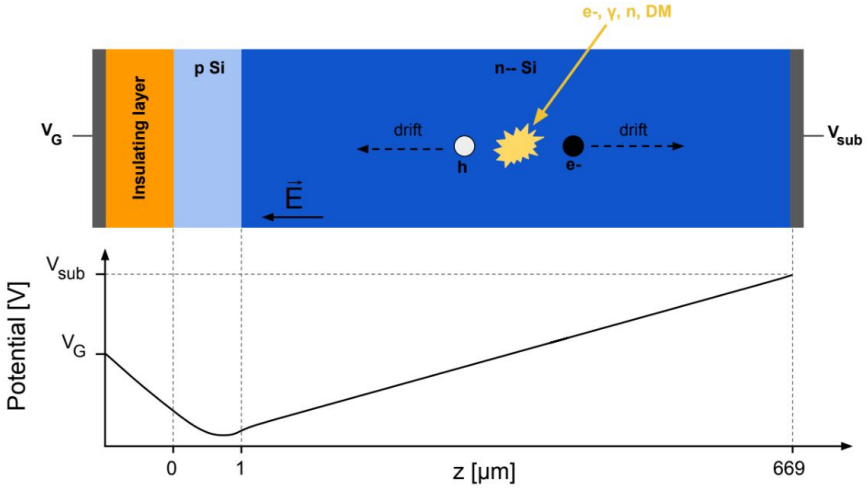
O(eV) Si band gap → Hidden sector mass O(MeV)

Hidden photon absorption is also possible. DM photon can be DM candidate!

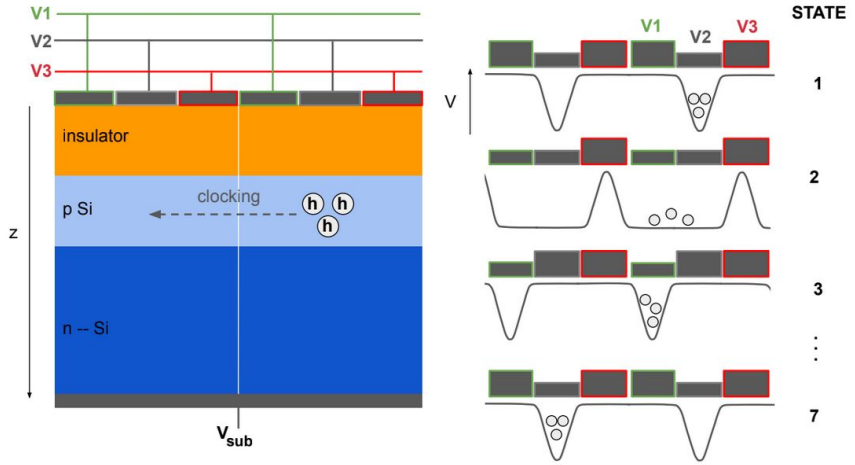


CCD structure and operation

Charge collection



Charge transfer



Diffusion and z reconstruction

$$\sigma_{xy}^2 = -A \ln |1 - bz|.$$

$$A = \frac{\epsilon}{\rho_n} \frac{2k_B T}{e},$$

$$b = \left(\frac{\epsilon}{\rho_n} \frac{V_b}{z_D} + \frac{z_D}{2} \right)^{-1}$$

ϵ permittivity of silicon,
ρ_n : donor charge density in the substrate
k_B: Boltzmann's constant
T: operating temperature (120 K in DAMIC)
e: electron's charge
V_b: bias applied across the substrate (40V in DAMIC)
z_D: thickness of the device

IN DAMIC: σ_{max}=(21±1)μm≈1.4 pix.

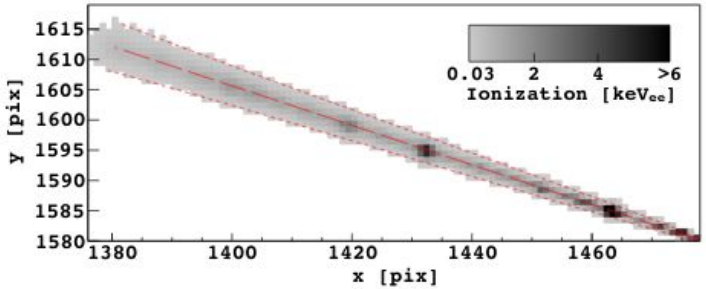


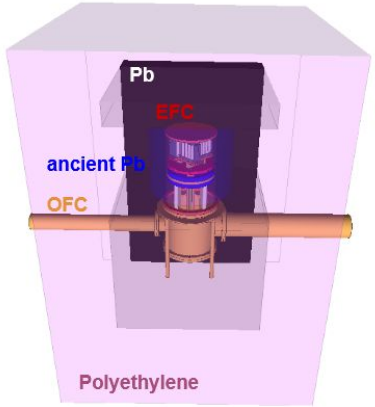
FIG. 4. A MIP observed in cosmic ray background data acquired on the surface. Only pixels whose values are above the noise in the image are colored. The large area of diffusion on the top left corner of the image is where the MIP crosses the back of the CCD. Conversely, the narrow end on the bottom right corner is where the MIP crosses the front of the device. The reconstructed track is shown by the long-dashed line. The short-dashed lines show the 3σ band of the charge distribution according to the best-fit diffusion model.

Search for low-mass WIMPs in a 0.6 kg day exposure of the DAMIC experiment at SNOLAB;
Phys. Rev. D 94, 082006 (2016)
DAMIC Collaboration (A. Aguilar-Arevalo et al.)

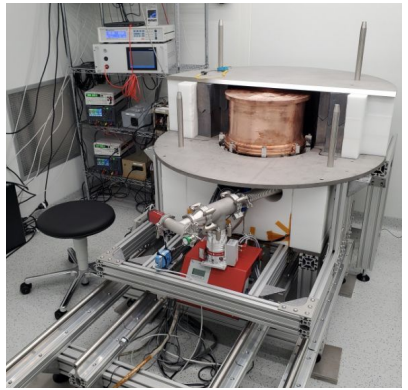
Status of DAMIC-M

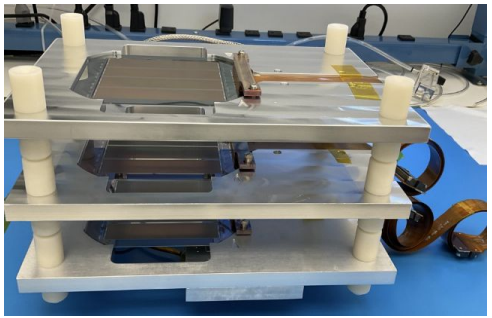
- Detector design finalized
- DAMIC-M CCDs tested and packaged
- Electronics designed, successfully tested
- Calibration with radioactive sources:
  - gamma source: Phys. Rev. D 106, 092001
  - neutron source: 10.6082/uchicago.13992
- DAMIC-M prototype, Low Background Chamber (LBC), operating at LSM since 2022 [JINST 19 T11010]
- Disassembly of LBC: Feb-Mar 2025
- DAMIC-M installation: second half of 2025

DAMIC-M design



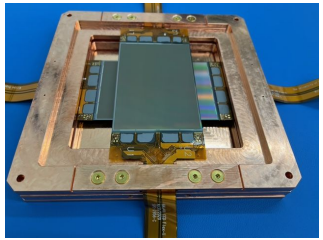
LBC @LSM





DAMIC-M CCD module packaging @UW

LBC - Data Taking



Setup 1
2 skipper CCDs
4k x 6k pix (18 g)

Science run 1: May-Ago 2022

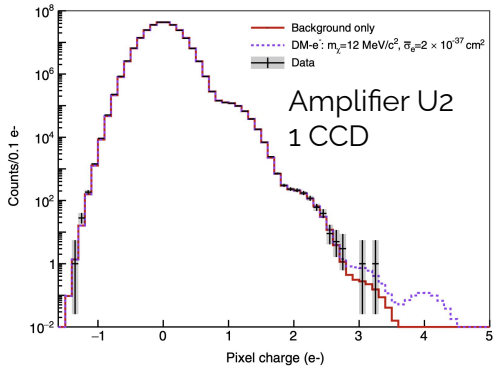
- Read out with 2 amplifiers per CCD
- Binning: 10 pix x 10 pix
- Temperature: ~110 K
- Background rate: ~12.5 d.r.u
- **Commercial electronics**
- Resolution = 0.2e- (< 1eV) at 650 skips
- **Dark Current (DC) = 4.5E-3 e-/pixel/day**
- Exposure: 85.2 gr-day

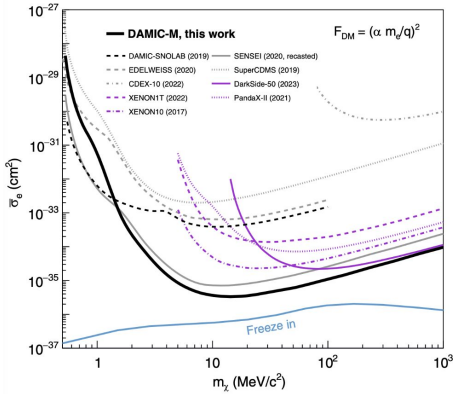
39.97 g-days

Pixel charge distribution (PCD) analysis

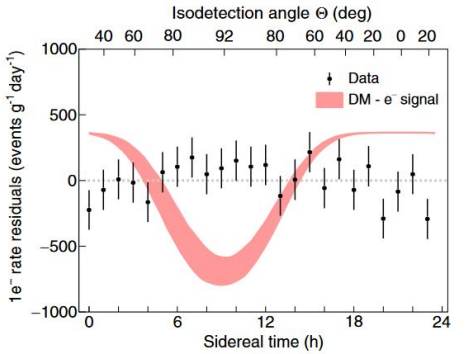
Daily modulation analysis of 1e- signal

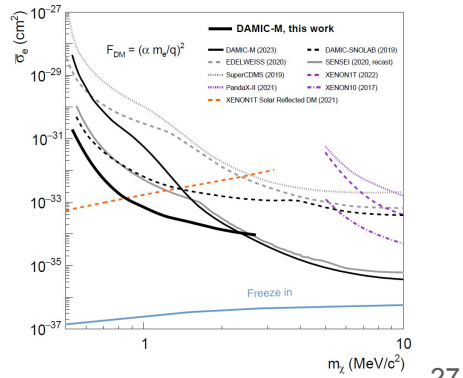
PCD analysis [Phys. Rev. Lett. 130, 171003, 2023]





Daily modulation analysis of 1e- signal [Phys. Rev. Lett. 132, 101006, 2024]

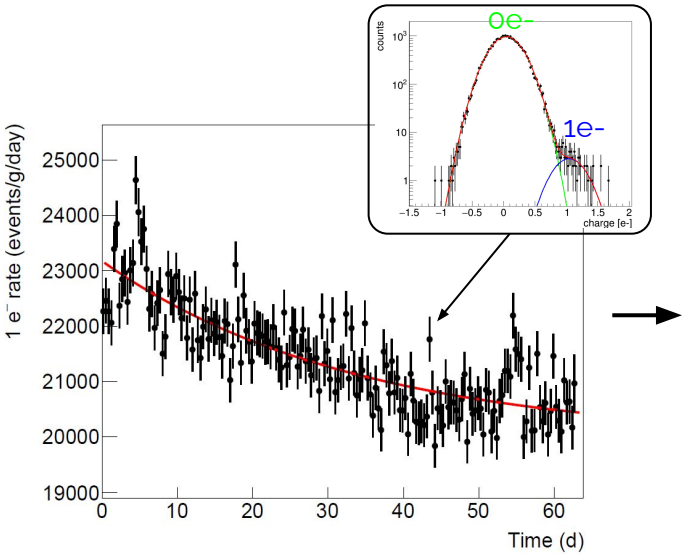


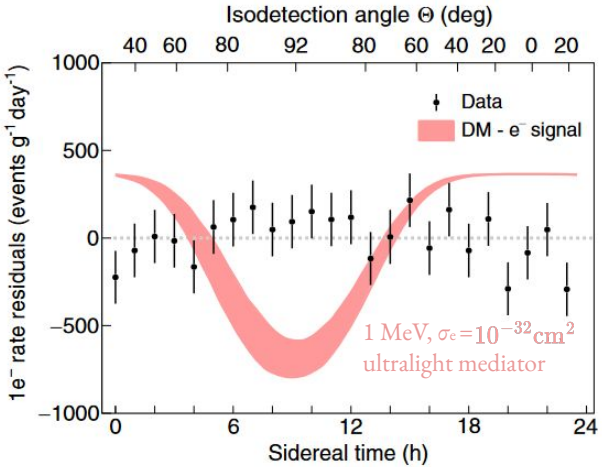


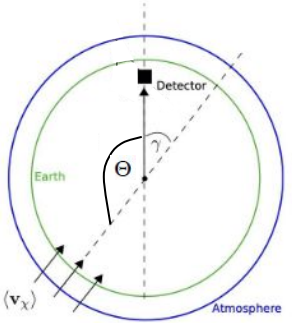
LBC - Data Taking: Daily modulation

Daily modulation analysis with LBC [Phys. Rev. Lett. 132, 101006, 2024]

- **time-dependent** analysis to look for a **daily modulated DM signal above an un-modulated background** (39.97 g-days). DM expected to be modulated over a sidereal day due to its interactions in the Earth





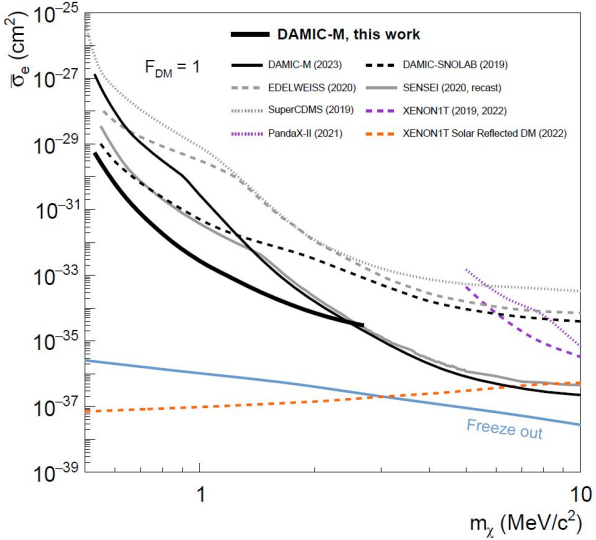


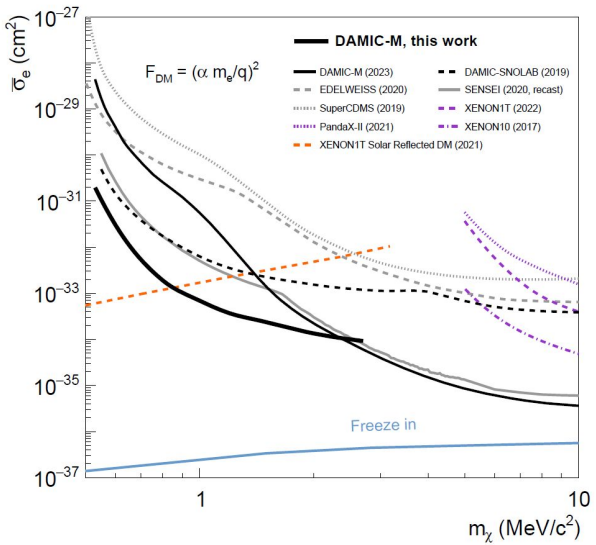
DM signal simulated with the VERNE code

LBC - Data Taking: Daily modulation

Daily modulation analysis with LBC [Phys. Rev. Lett. 132, 101006, 2024]

- Daily modulation analysis **improves up to ~2 orders of magnitude the previous DAMIC-M limits**, **with the same data set!**
- **Best constraints** from searches for a non-relativistic flux of DM particles incident on Earth, for the mass ranges [0.53, 1000] MeV and [0.53, 15.1] MeV for ultralight and heavy mediator interactions





LBC - Pattern analysis [arXiv:2503.14617]

An excess of high-multiplicity isolated pixels is observed in D1 and D2 data sets wrt expectation from Poissonian single
e– rate

Unknown origin but NOT DM. Maybe related to serial register or readout stage.

	Isolated pixels		
	2e-	**3e-**	**4e-**
observed	184	17	1
expected (from poissonian single 1e- rate)	70.2	7E-3	3E-7