GDR DUPHY - 12th June 2025 - Lyon

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

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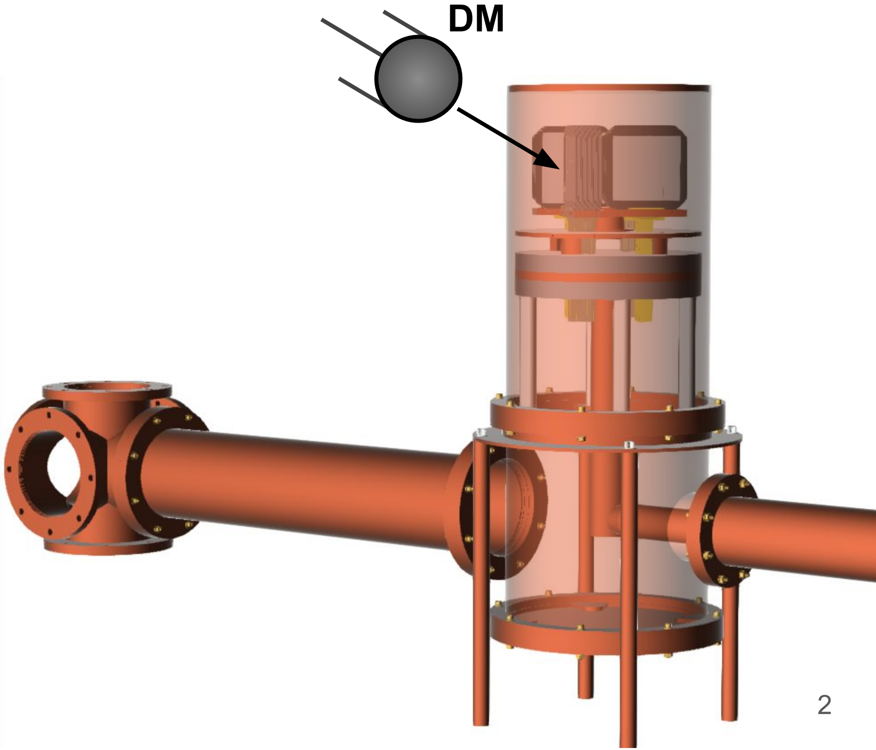
LPNHE PARIS

cnrs

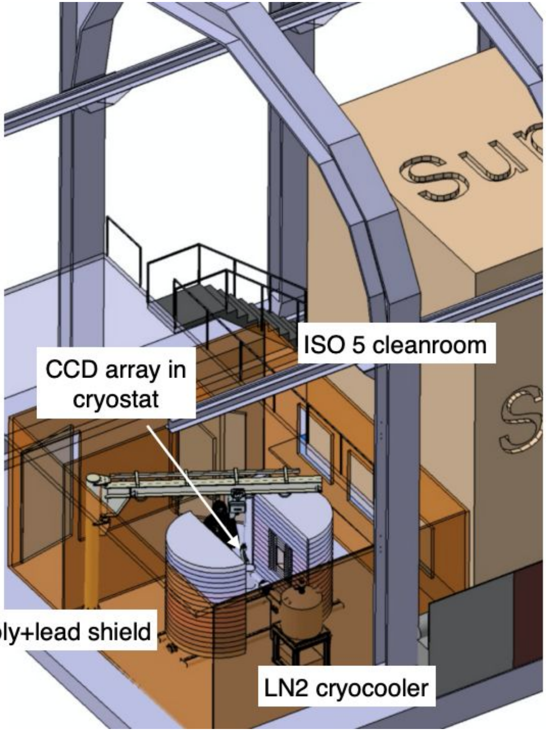
Outline

- The DAMIC-M experiment:
  - Working principle
  - Status of the experiment

- The Low Background Chamber



DArk Matter In CCDs at Modane



DAMIC-M@LSM
(conceptual design)

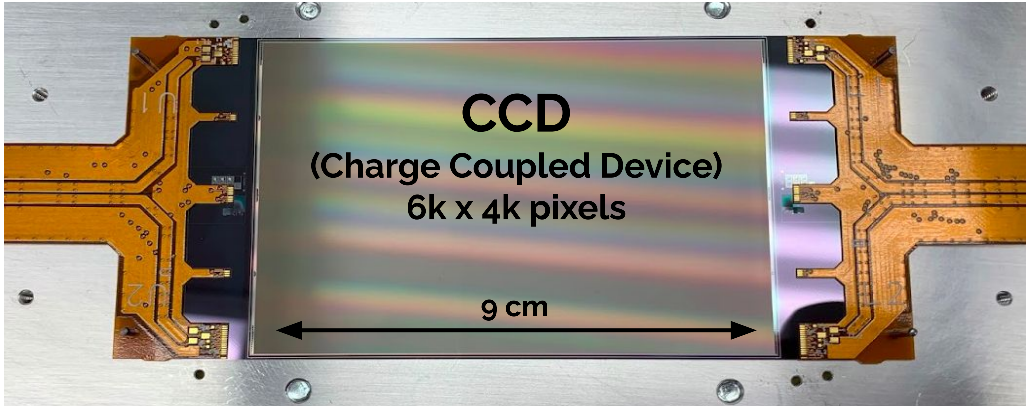
DAMIC experiment
at SNOLAB (Canada)

DAMIC-M experiment
at LSM (Modane, France)

2017 — 2022 — 2025

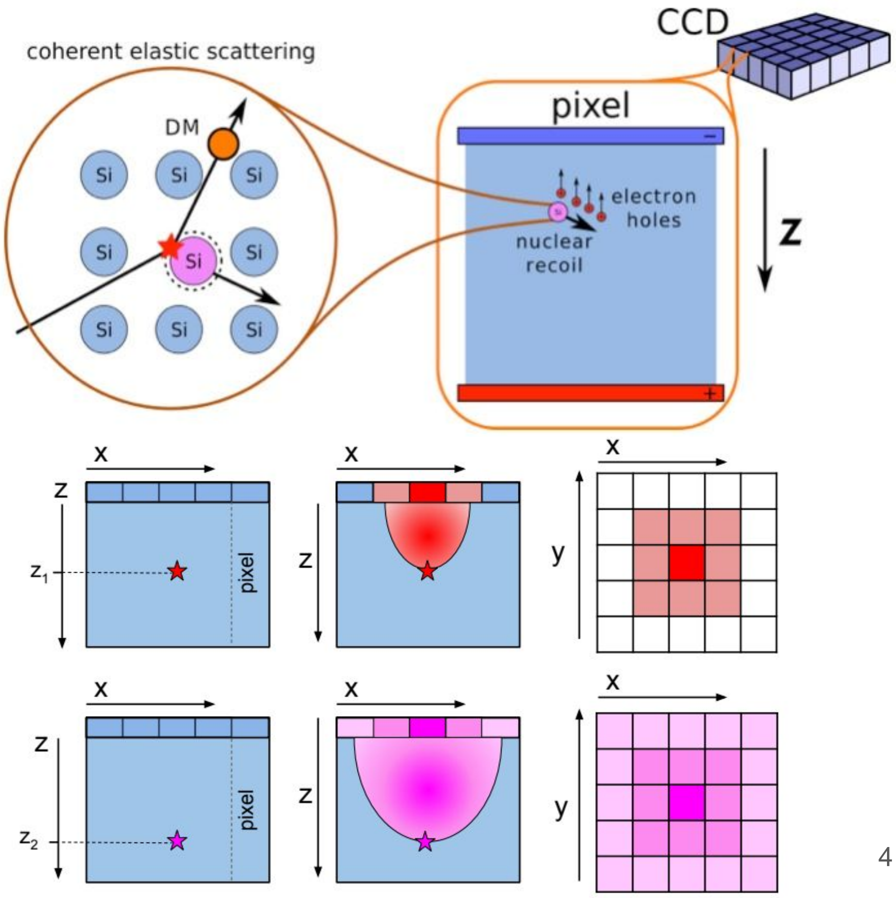
Low Background Chamber
at LSM (Modane, France)

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



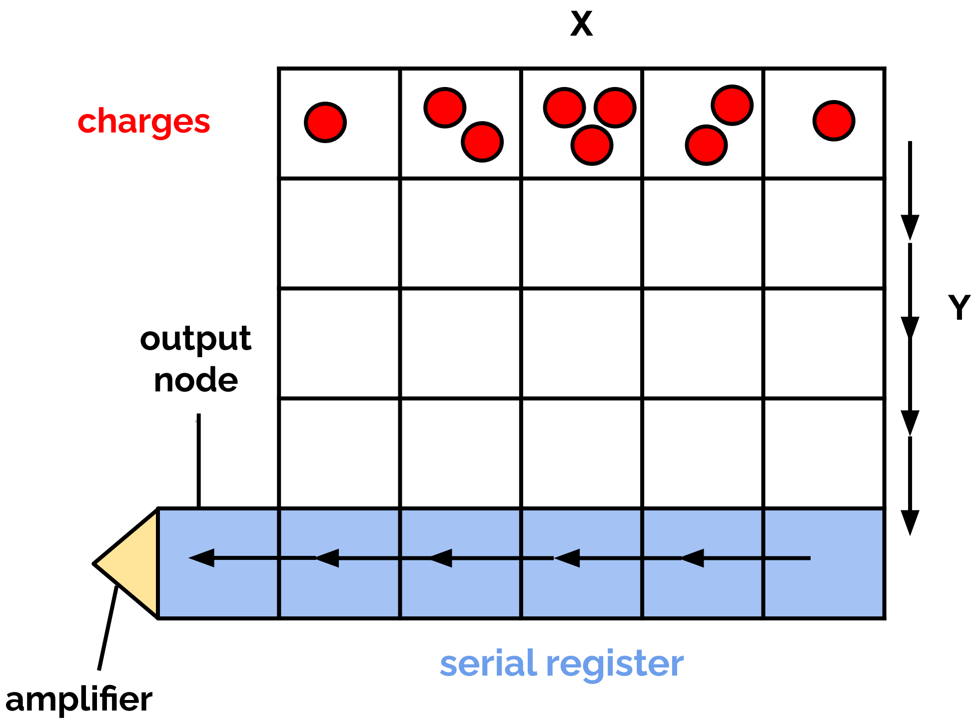
CCDs operation and 3D reconstruction

- CCD: n-type silicon with buried p-channel, thickness = 0.67 mm
- Creation of a depletion region (active volume) in the CCD (full depletion)
- DM interaction causes creation of e-/h pair (3.74 eV required on average) in depletion region
- **3D reconstruction:**
  - z position: diffusion of charges during drift
  - x-y position: Precise spatial resolution (0.015 mm x 0.015 mm pixels)



CCD readout

- charges in a row moved to the following row
- charges in the serial register moved pixels by pixels in X direction
- charges in the output node read by amplifier
- In DAMIC-M: Skipper Amplifier



CCD readout

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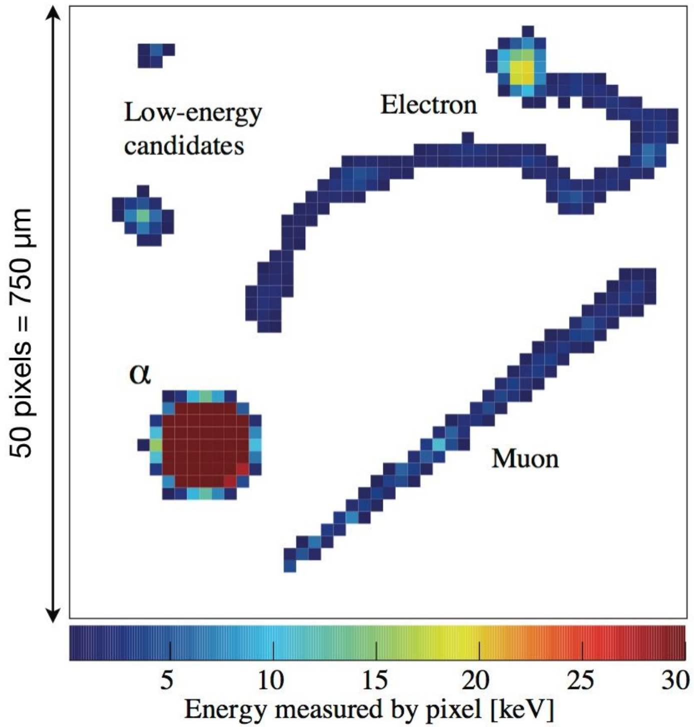
Particles in CCD images

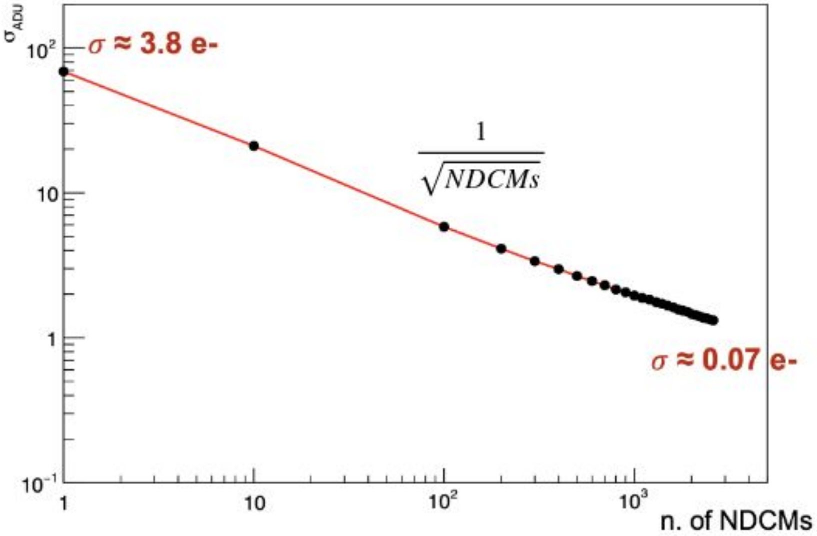


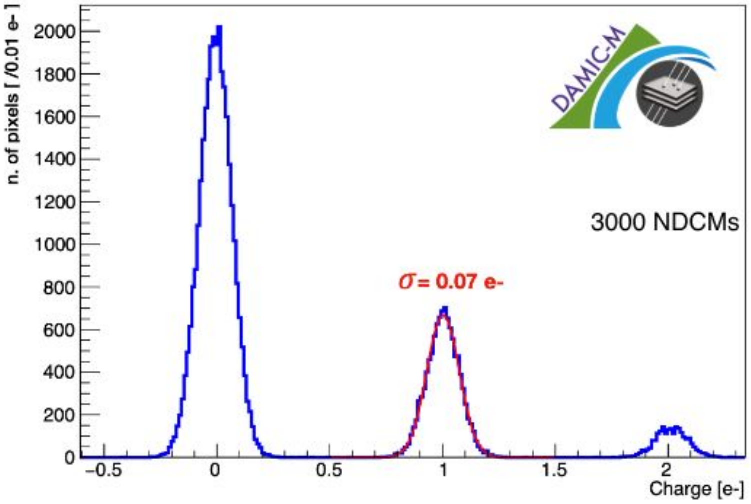
Skipper CCDs for sub-electron resolution

Skips = Non Destructive Repetitive Charge Measurements (NDCMs)

Charges in output node read by amplifier N times

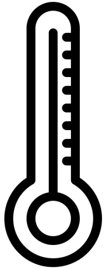
Readout noise decrease by a factor 1/sqrt(N)





Single electron resolution

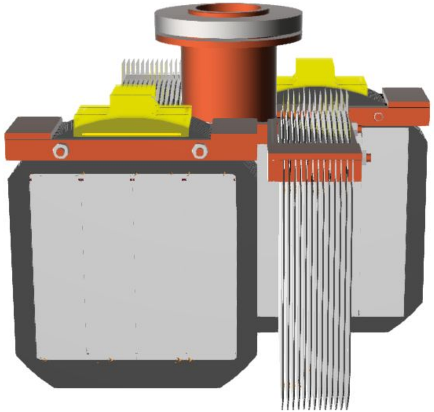
DAMIC-M detector features



~130 K

Temperature

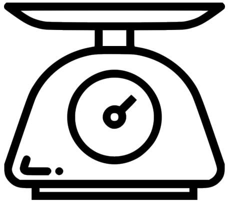
DAMIC-M CCD stack



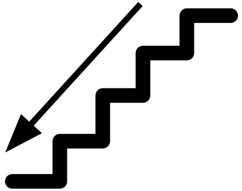
~200 SKIPPER CCDs

6000 pix x 1500 pix

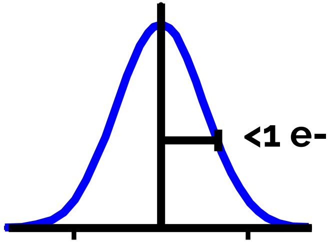
~0.7 kg



Sensitive Mass



Background Level
<= 1 d.r.u



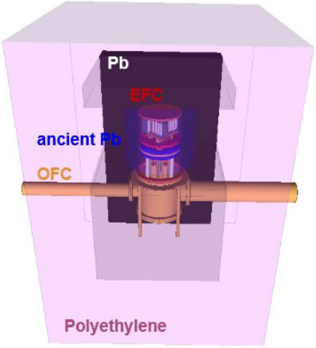
Resolution (readout noise)
~0.1 eV

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

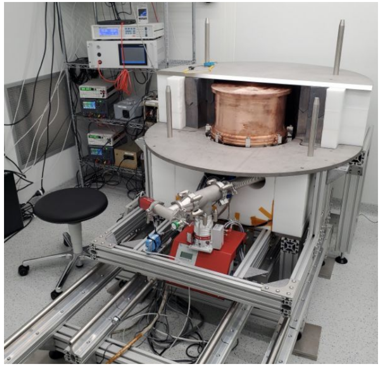
Status of DAMIC-M

- Detector design finalized
- DAMIC-M CCDs tested and packaged (soon to be re-tested at LSM)
- 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

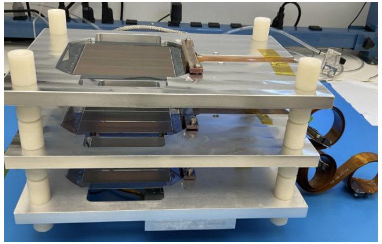
DAMIC-M design



LBC @LSM



DAMIC-M CCD modules @LSM

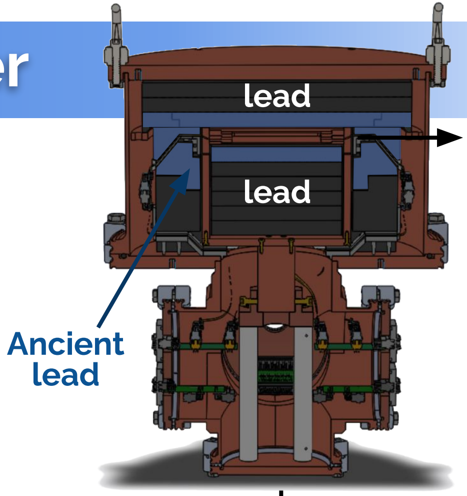


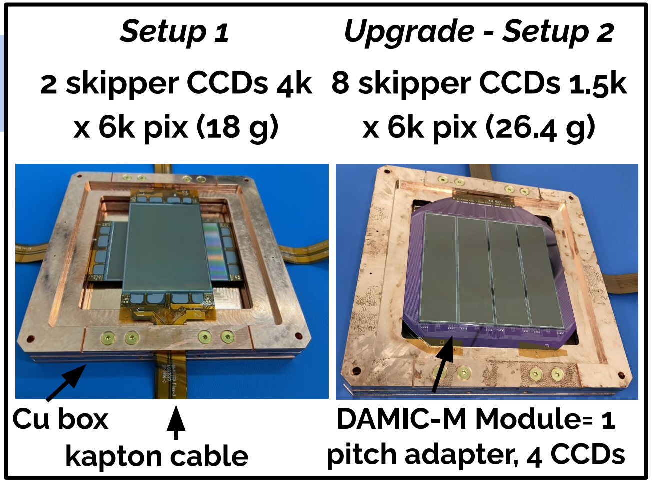
DAMIC-M CCD module packaging @UW

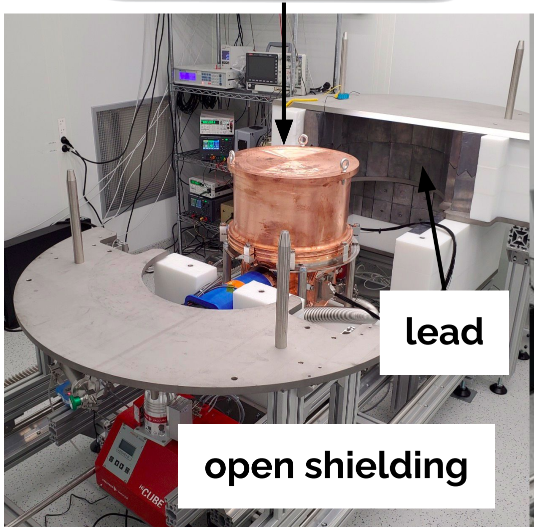
Low Background Chamber

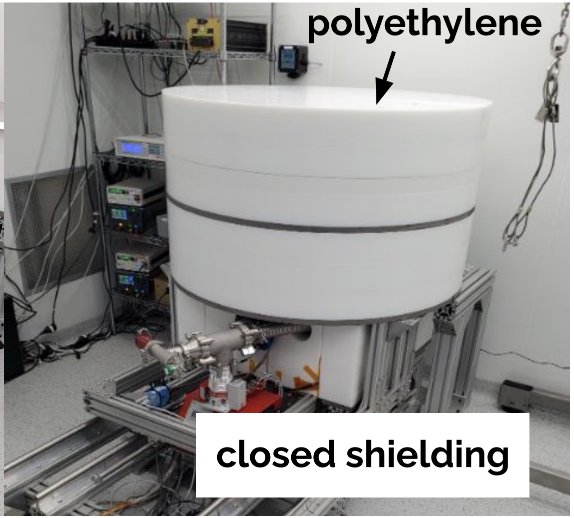
- **Aim:**
  - Demonstrate the ability to control backgrounds for DAMIC-M
  - Integration/operation of DAMIC-M electronics
  - Provide test bench for dark current studies and reduction strategies
  - First dark matter search

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

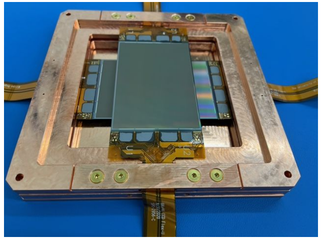








LBC - Data Taking



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

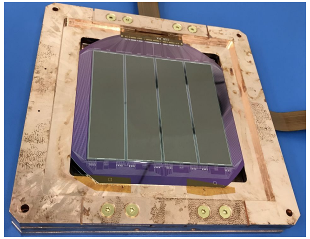
Science run 1: May-Ago 2022

- 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



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
- **Dark current (DC)= 1.2-1.6E-4 e-/pixel/day**
- **Exposure: 1.3 kg-day**

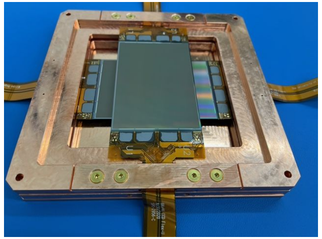
new!

coming soon!

Pattern analysis

Daily modulation analysis of 1e- signal

LBC - Data Taking



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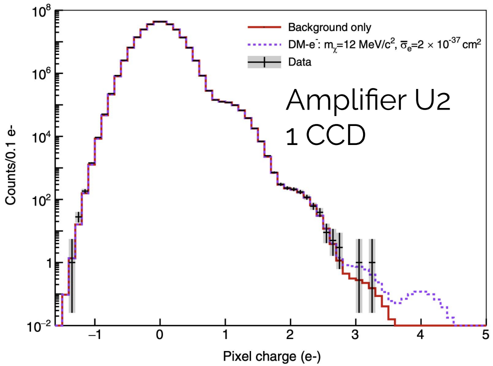
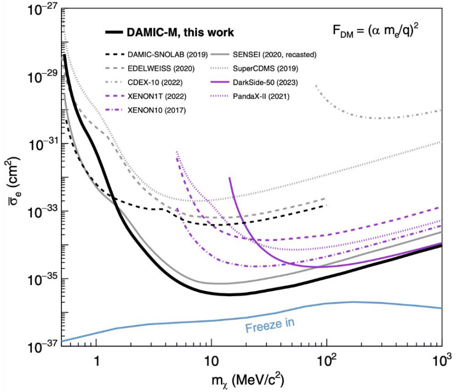
39.97 g-days

Pixel charge distribution (PCD) analysis

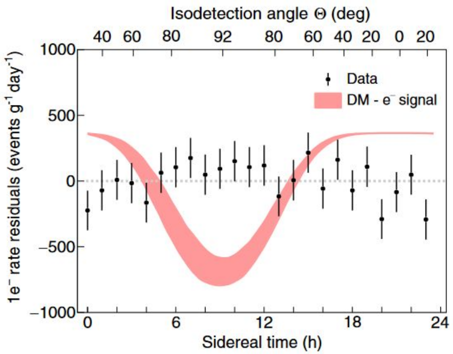
Daily modulation analysis of 1e- signal

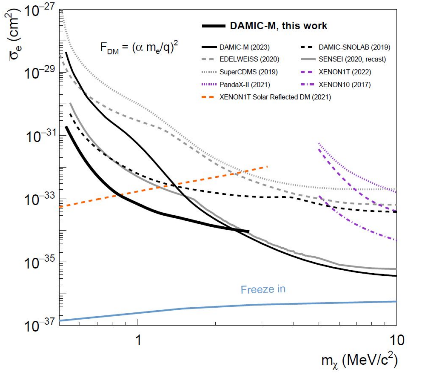
PCD analysis [Phys. Rev. Lett. 130, 171003, 2023]





Daily modulation analysis of 1e- signal





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

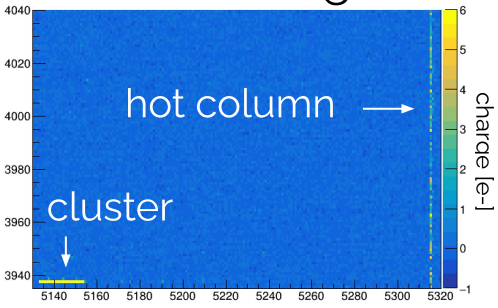
Cleaning procedure:

- 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

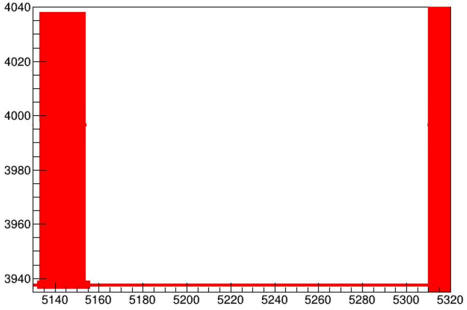
→ **95% of data kept for the analysis**

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

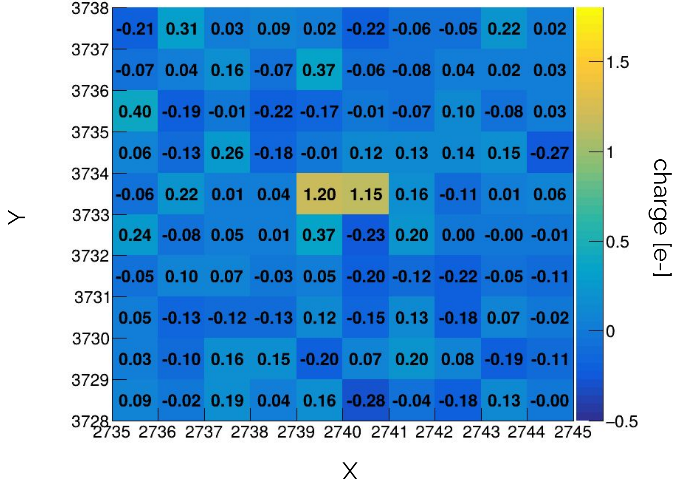
Partial image



Mask



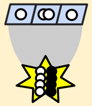
Example {11} pattern



LBC - Pattern analysis

DM | **RADIOACTIVE BKG** | **RANDOM COINCIDENCE SINGLE e- BKG**

Energy deposit ⟶ N e-/h



diffusion

Edep → real pattern

1e- 1e-
2e-

+ single e- bkg

resolution

Prob(Edep→observed patt)

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

rates

1e- 2e- 3e-

random coincidence

accidental pattern

1e- 1e-

resolution

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]

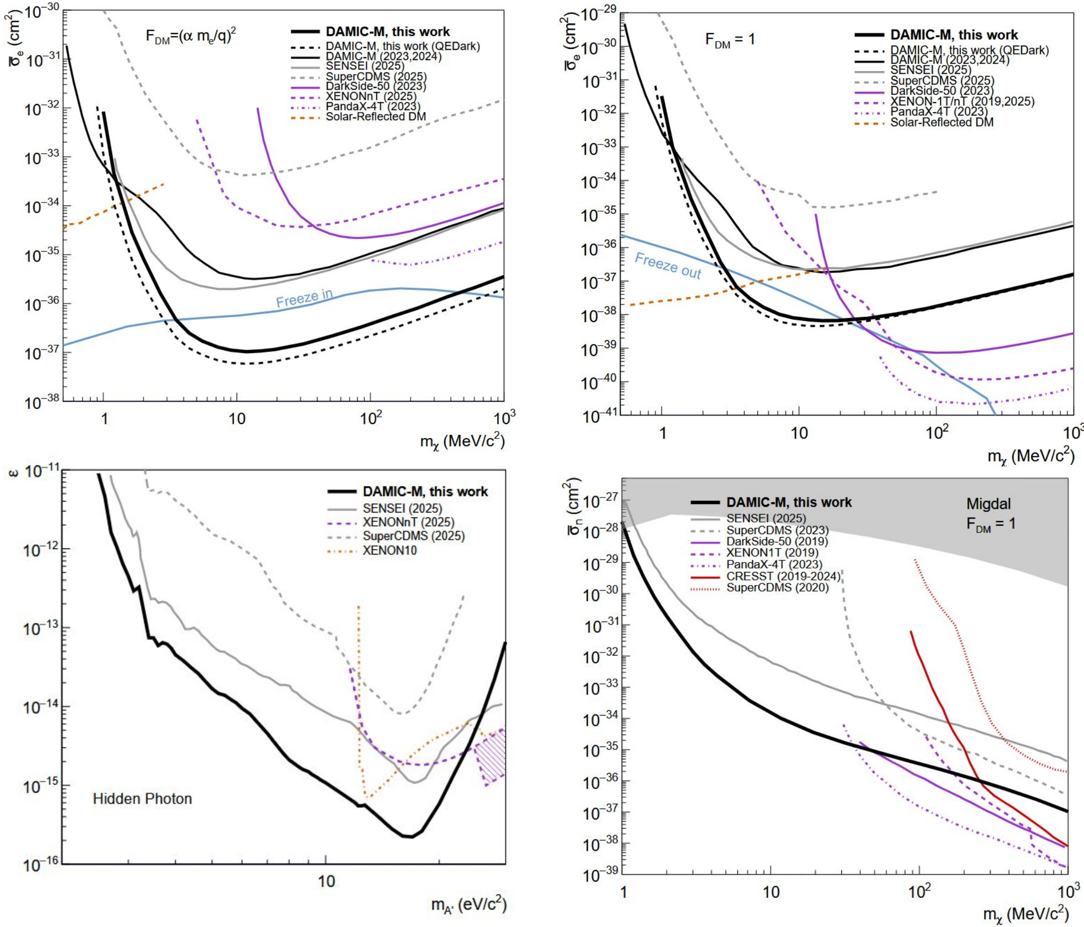
No evidence for a signal

two-sided profile likelihood ratio test statistic

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

90% C.L limit on DM signal

LBC - Pattern analysis



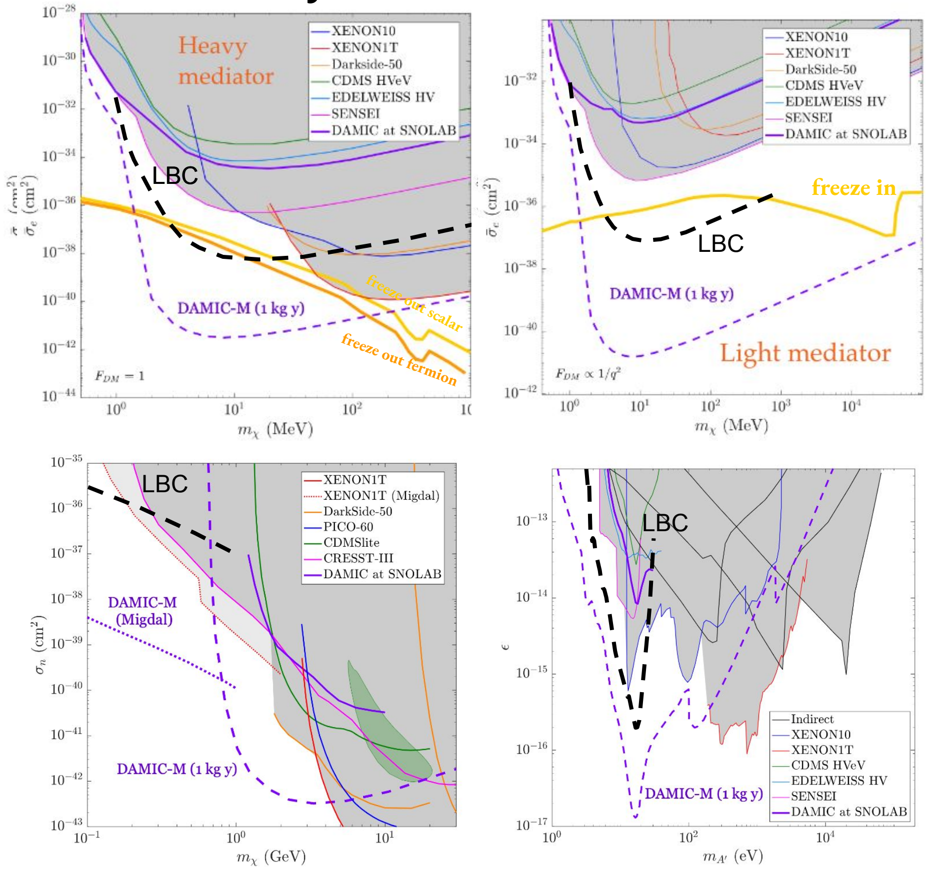
- **Stringent constraints** on DM particles with masses between **0.75 and 1000 MeV** interacting with **electrons** through an **ultra-light or heavy mediator.**
- **Exclusion of benchmark scenarios**, for large ranges of DM masses **below 1 GeV**, where hidden-sector particles are produced as a major 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

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

Stay Tuned for DAMIC-M!



LBC installation, December 2021

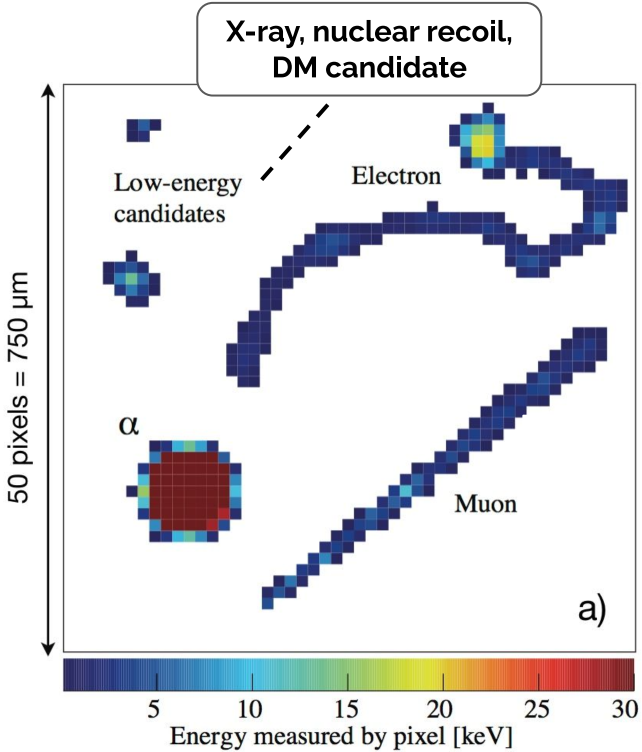
Thank you for the attention !

European Research Council
Established by the European Commission

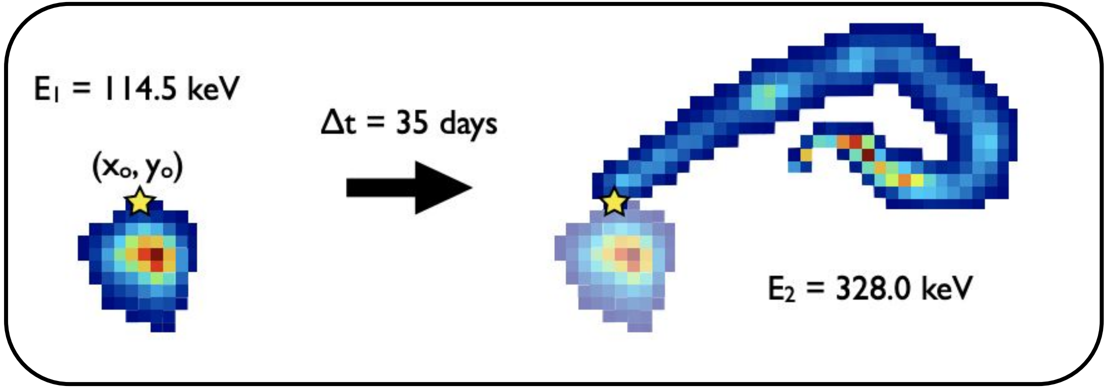
BACKUP

Particle identification

Signatures of different ionizing particles in a CCD



Identification of decay chains



Decay chain of a Si-32 nucleus in the CCD:
[JINST 10 (2015) P08014, JINST 16 (2021) P06019]

$^{32}\mathrm{Si} \rightarrow ^{32}\mathrm{P} + \beta$ with $t_{1/2}$ = 150 y, Q-value = 227 keV

$^{32}\mathrm{P} \rightarrow ^{32}\mathrm{S} + \beta$ with $t_{1/2}$ = 14 d, Q-value = 1.71 MeV

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.

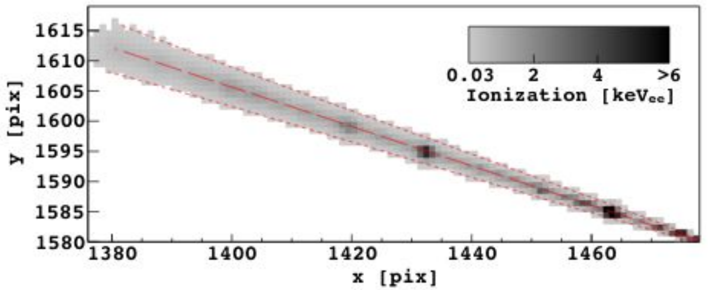
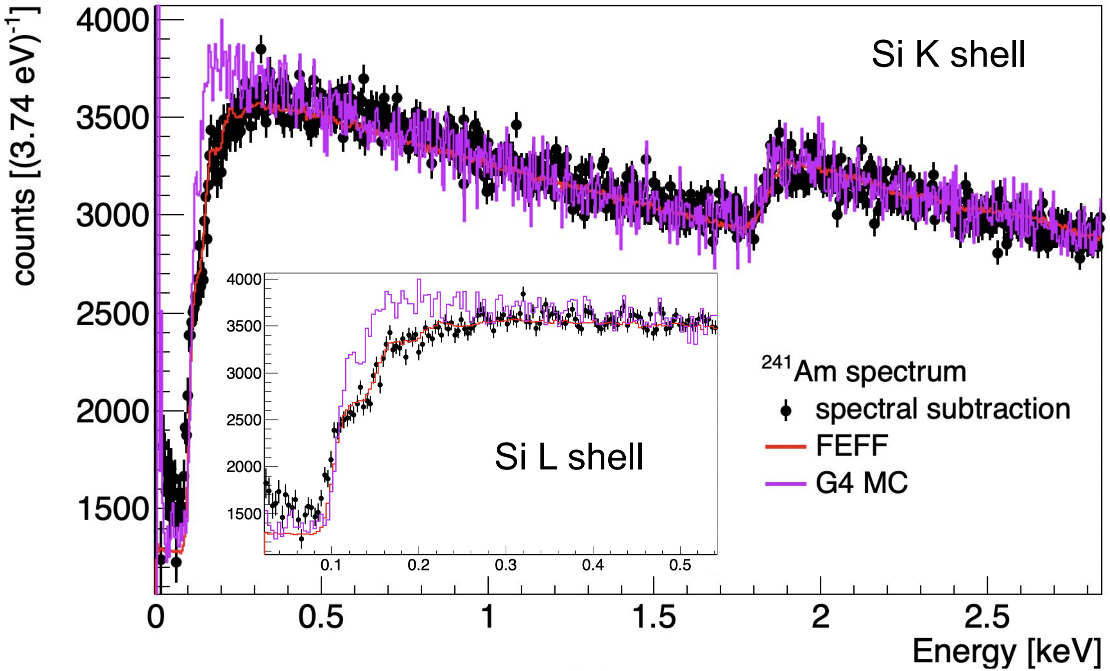


FIG. 4. A MIP observed in cosmic ray background data acquired on the surface. Only pixels whose values are above the noise in the image are colored. The large area of diffusion on the top left corner of the image is where the MIP crosses the back of the CCD. Conversely, the narrow end on the bottom right 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 3 σ 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.)

Compton measurement



Thanks to the skipper CCD resolution, the compton spectrum was measured down to 23 eV and the L-shell steps could be resolved.

Data vs Models:

- **agreement in the K-shell region with Relativistic Impulse Approximation**
- **disagreement at L shell with RIA:**
  - softening of the spectrum below 250 eV is observed
  - confirmation of the previous DAMIC measurement [Phys. Rev. D 96, 042002 (2017)]
  - Better agreement with FEFF code

Geant4:
full Geant4 (with RIA) simulation of the experiment + custom detector response simulation

FEFF:
ab initio calculation (full quantum treatment) + detector resolution

LBC - PCD analysis, data selection

- **Image selection**: exclude images with outlier dark current

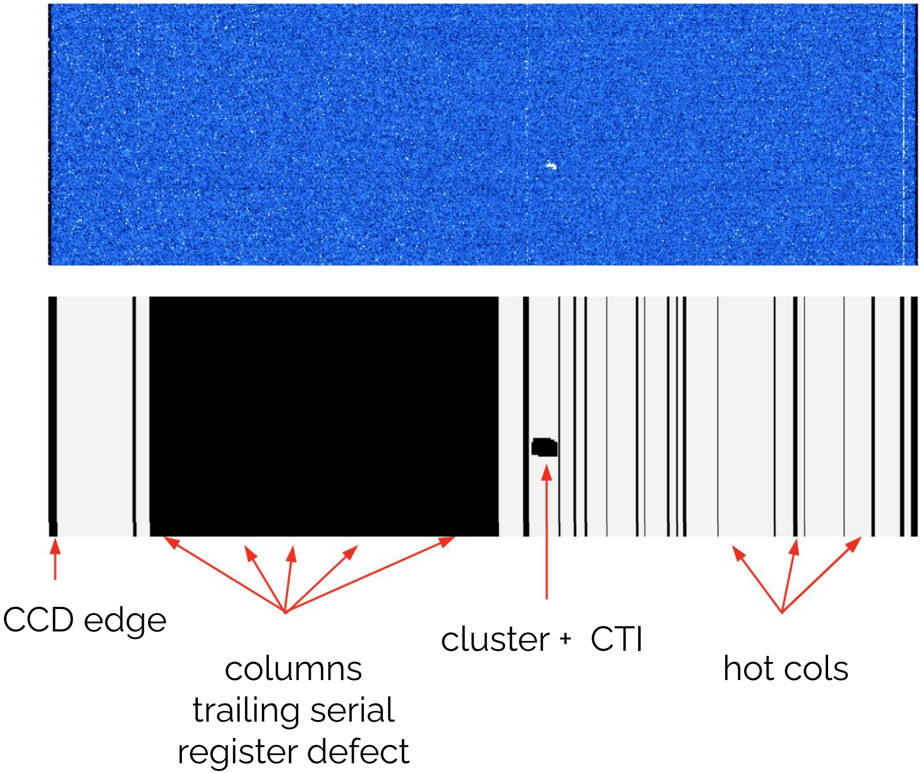
- **Cluster reconstruction**: adjacent pixels with charge > (3 x resolution) and at least 1 pixel ≥ 2e−

- **Cluster + CTI mask**: mask clusters with charge > 7e− + 10 trailing pixels in horizontal and vertical directions to account for Charge Transfer Inefficiencies

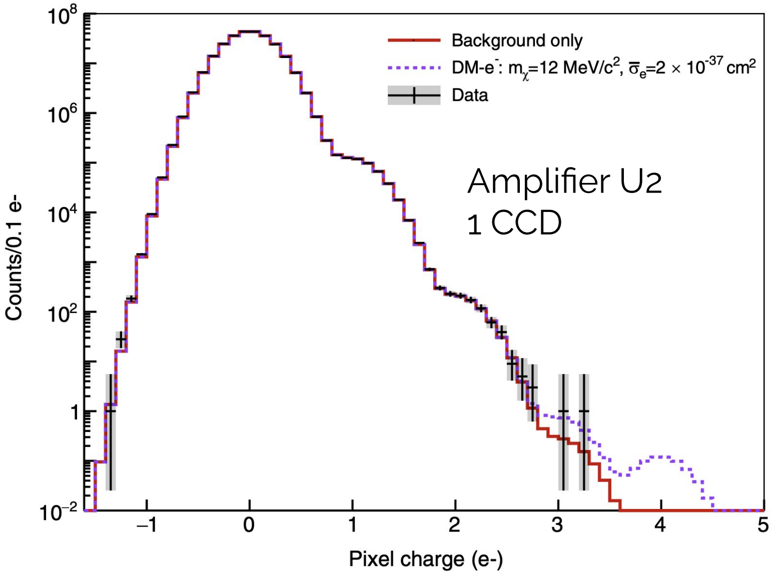
- **Defect mask**:
  - Columns with excess of 1e- pixels (1e- rate vs column number)
  - High-charge pixels appearing in multiple 3-hour exposures
  - Columns with deficit of 1e- pixels (indication of serial register defect); mask all trailing columns

- **Edge mask**: Five-pixel window surrounding image

Partial CCD image



LBC - PCD analysis



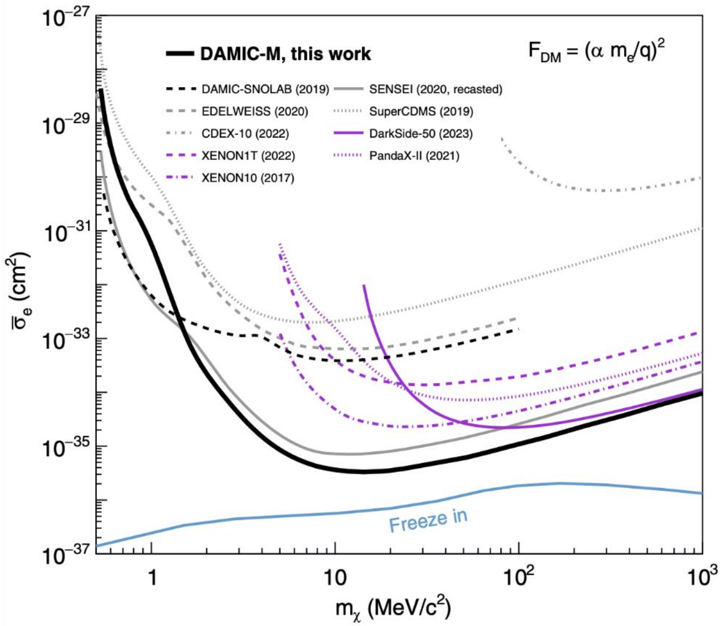
- **Measure the pixel charge distribution (PCD)** per amplifier per CCD after cleaning
- **DM signal generation**:
  - QEdark to generate differential rate of DM signal with halo parameters from PhystatDM (arXiv: 2105.00599 (2021))
  - apply detector response: eV to e- conversion with low energy ionization yield (PRD 102, 063026 (2020)) and diffusion model using parameters measured with LBC CCD
- **Fit whole PCD** and perform **binned joint likelihood minimization** to set 90% C.L. upper limits in cross section-DM mass parameter space:

$$F(p|m_\chi,\bar{\sigma}_e,\epsilon_i,\lambda_i,\sigma_{\rm res}) = \sum_{i=0}^{N_{\rm pix}} N_{\rm im} \sum_{n_q=0}^{\infty} \left[\sum_{j=0}^{n_q} S(j|m_\chi,\bar{\sigma}_e,\epsilon_i) {\rm Pois}(n_q - j|\lambda_i - \lambda_{S,i}) \right] {\rm Gaus}(p|n_q,\sigma_{\rm res}).$$

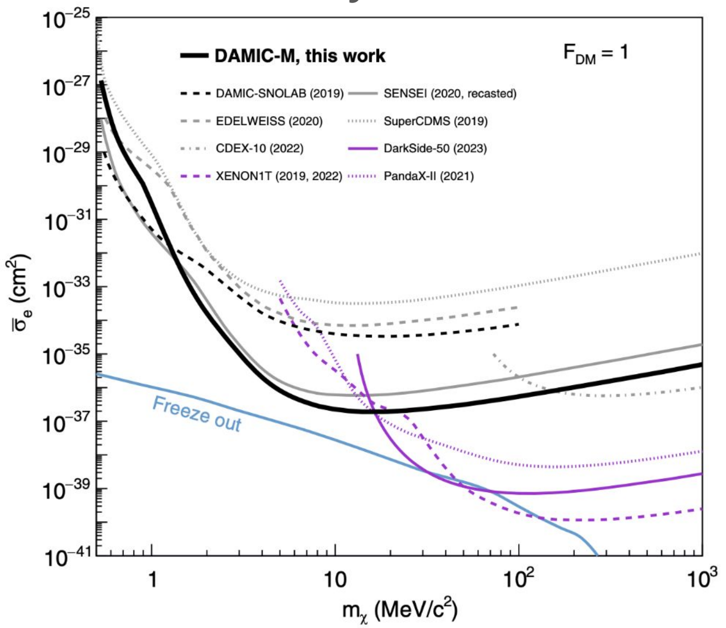
signal — dark current (estimated pixel by pixel) — readout noise

LBC - PCD analysis, 90% CL upper limits

Ultralight mediator



Heavy mediator



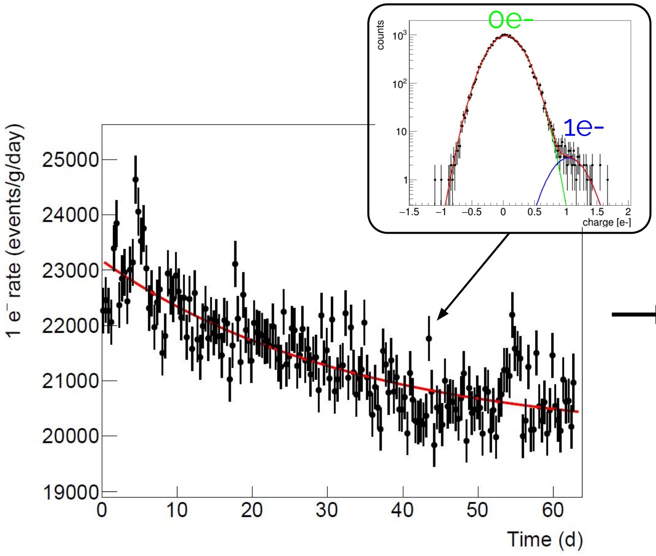
World leading exclusion limits on DM-electron interactions in the mass ranges [1.6-1000 MeV] and [1.5-15.1 MeV] for ultralight and heavy mediator interactions

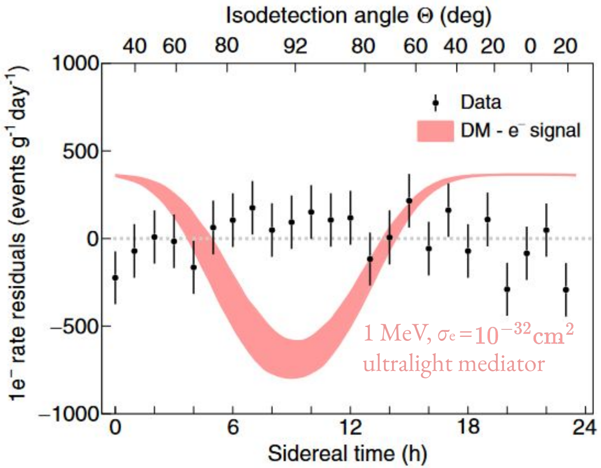
[Phys. Rev. Lett. 130, 171003, 2023]

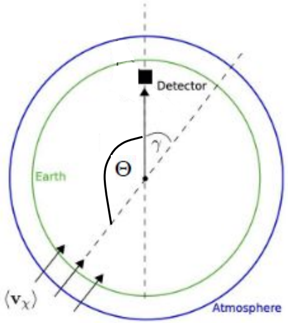
LBC - Daily modulation analysis

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





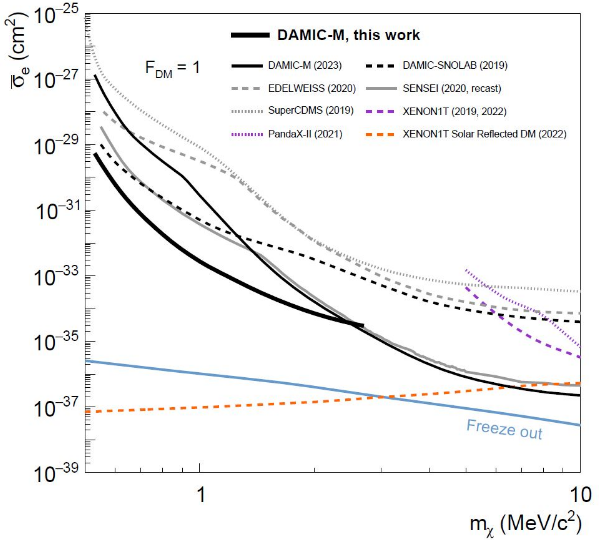


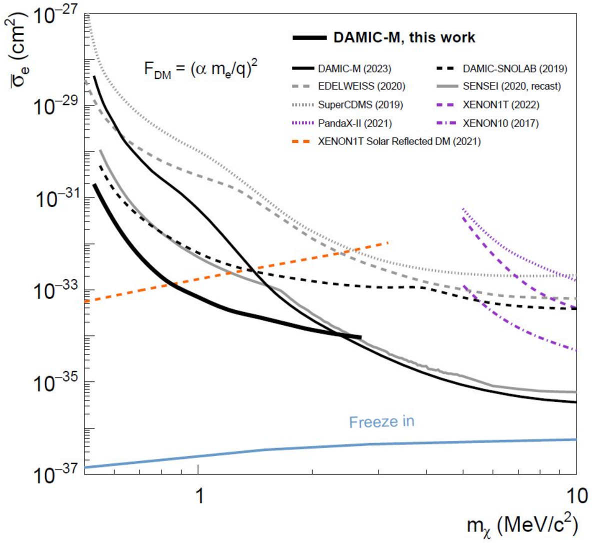
DM signal simulated with the VERNE code

LBC - Daily modulation analysis

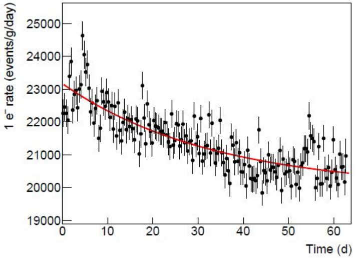
Daily modulation analysis with LBC [Phys. Rev. Lett. 132, 101006, 2024]

- Daily modulation analysis **improves up to ~2 orders of magnitude the previous DAMIC-M limits**, **with the <u>same data set</u>!**
- **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



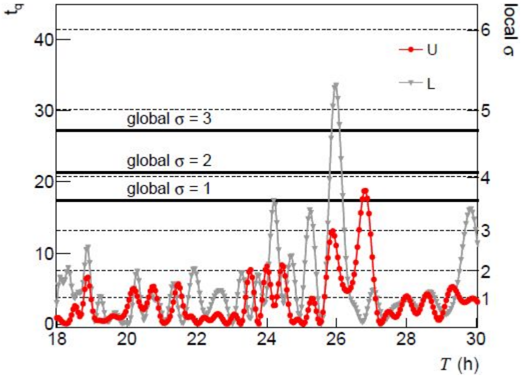


LBC - Daily modulation analysis



63 days from June 8th 2022

Model Independent

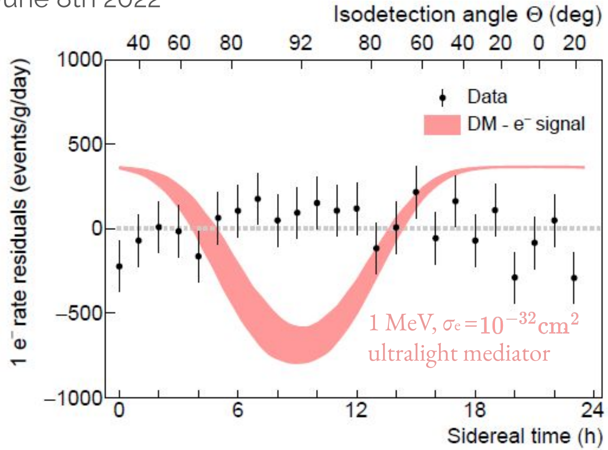


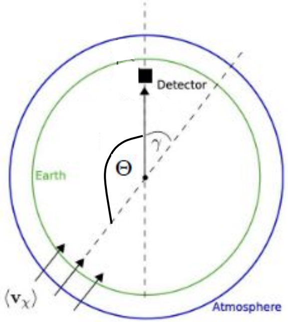
$$F(t) = Be^{-t/\tau} + C + A\cos((2\pi(t-\phi)/T)$$

$$\mathcal{L}(\theta) = \prod_{i=1}^{N_{\mathrm{im}}} \frac{1}{\sqrt{2\pi}\sigma_{R_1}^i} \exp\left\{-\frac{1}{2}\left(\frac{R_1^i - F(t_i|\theta)}{\sigma_{R_1}^i}\right)^2\right\}$$

$$t_q = -2\ln\left(\mathcal{L}_{H_0}/\mathcal{L}_{H_1}\right)$$

Model Dependent



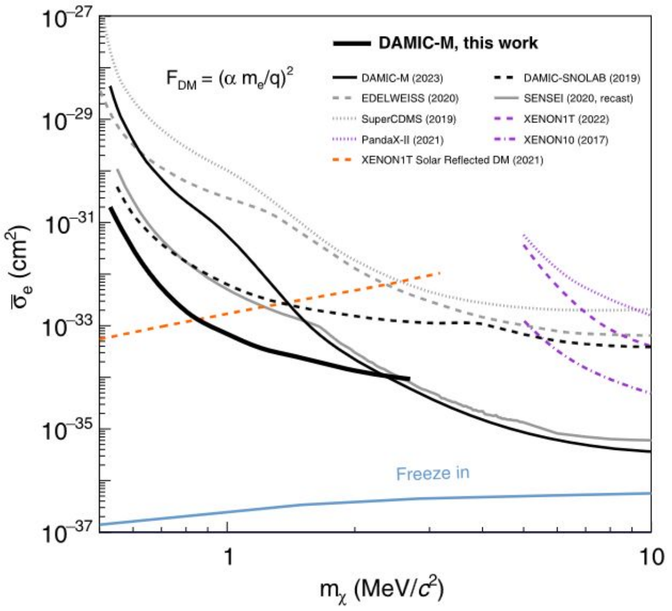


$$\frac{\mathrm{d}R}{\mathrm{d}E_e} \propto \bar{\sigma}_e \int \frac{\mathrm{d}q}{q^2}\left[\int \frac{f(\mathrm{v},t)}{\mathrm{v}}\,\mathrm{d}^3\mathrm{v}\right] |F_{\mathrm{DM}}(q)|^2\, |f_c(q,E_e)|^2$$

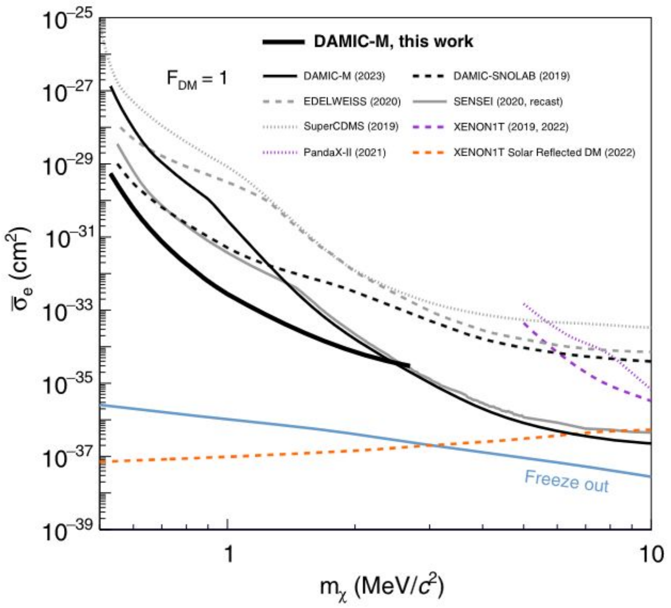
$$F(t_i|\theta) = \frac{1}{t_{\mathrm{exp}} m_{\mathrm{pix}}} \sum_{j=0}^{1} \mathrm{Pois}(1-j|\lambda(t_i)) S(j|m_\chi, \bar{\sigma}_e, t_i)$$

LBC -daily mod analysis, 90% CL upper limits

Ultralight mediator



Heavy mediator



[Phys. Rev. Lett. 132, 101006, 2024]

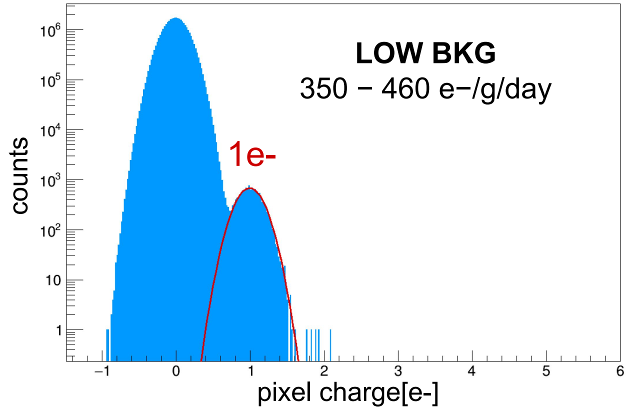
LBC - Pattern analysis [arXiv:2503.14617]

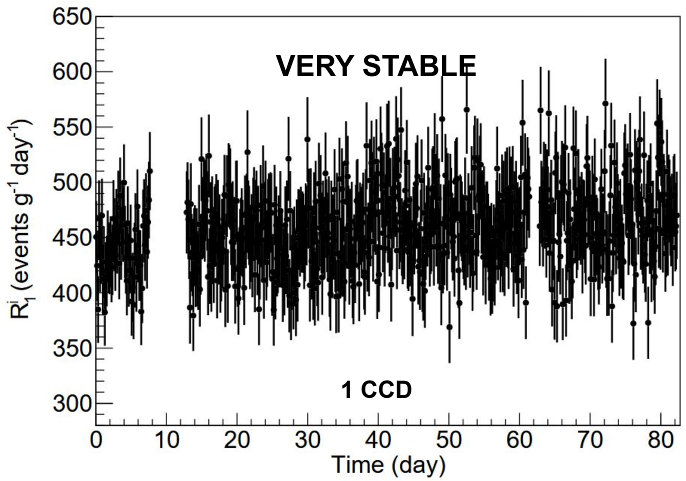
An excess of high-multiplicity isolated pixels is observed in D1 and D2 data sets wrt expectation from Poissonian single
e− rate

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

LBC - Pattern analysis



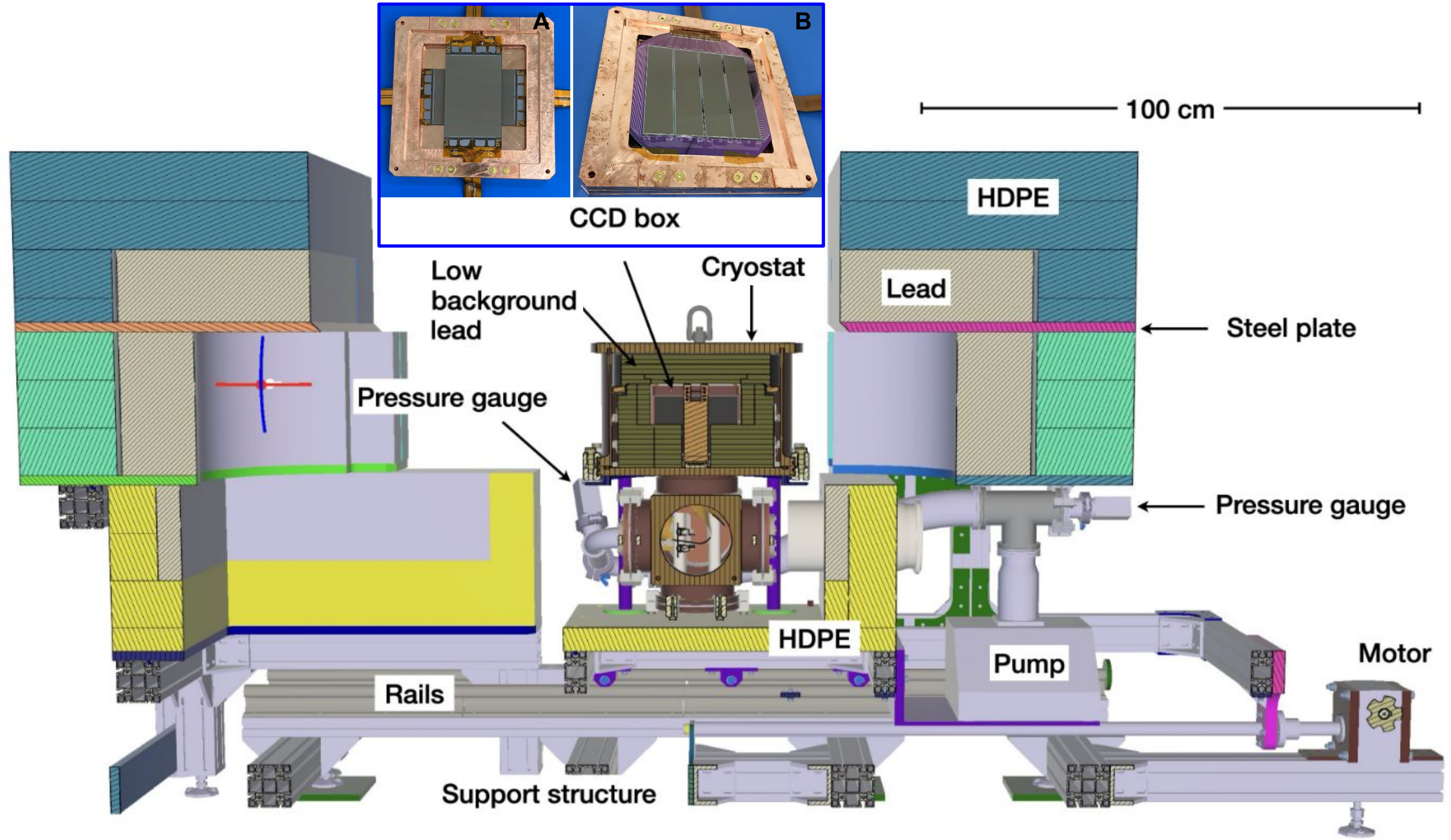


Results

- DM detection window: [2e-,5e-]
- **extremely stable detector**
- **low background**:dark current, infrared light, radioactivity
- high quality of data:
  - **high efficiency in data selection** (95% of the exposure kept)
  - for 2>Edep>5e- → 1 event/73 days
- **No excess of events over background expectation!**

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

0.10	0.11	0.08	0.26	0.21	0.29
0.26	0.14	0.33	-0.21	0.11	0.02
0.12	0.29	2.99	1.36	0.12	-0.04
-0.10	0.10	0.24	0.21	0.13	0.09
0.17	-0.23	-0.18	0.17	-0.36	-0.37


A
B
CCD box
100 cm
HDPE
Lead
Steel plate
Low
background
lead
Cryostat
Pressure gauge
Pressure gauge
HDPE
Pump
Motor
Rails
Support structure