GDR DUPHY - 9-11 Octobre 2024 - Lyon (France)

Status and results of the DAMIC-M experiment

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LPNHE PARIS

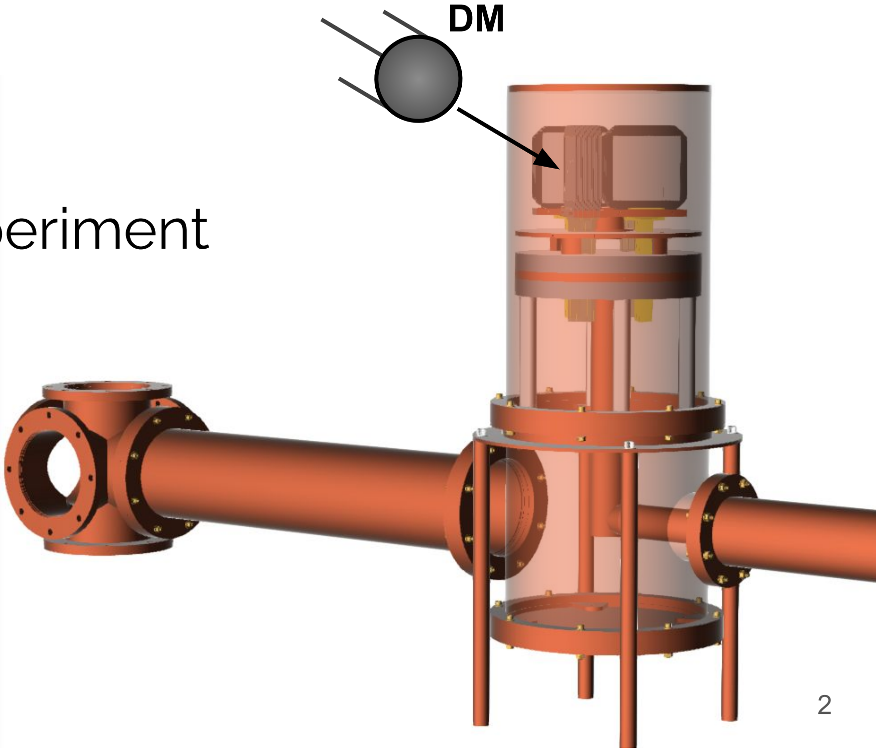
DAMIC-M

cnrs

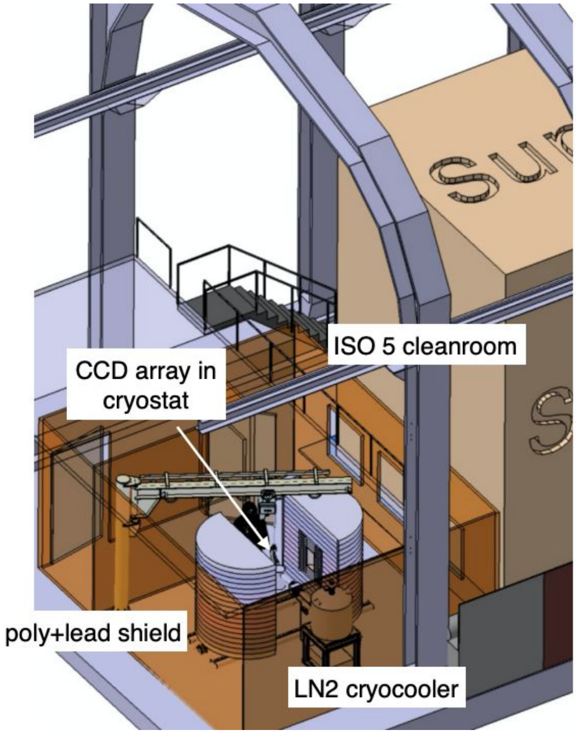
Outline

- The DAMIC-M experiment:
  - Physics reach
  - Status and timeline of the experiment

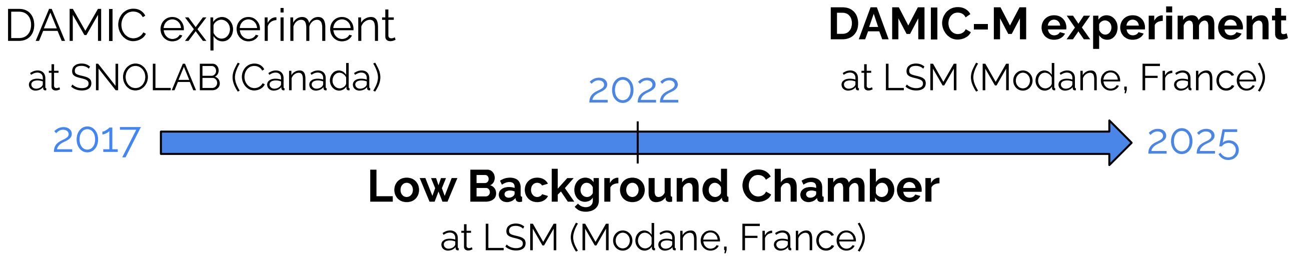
- The Low Background Chamber



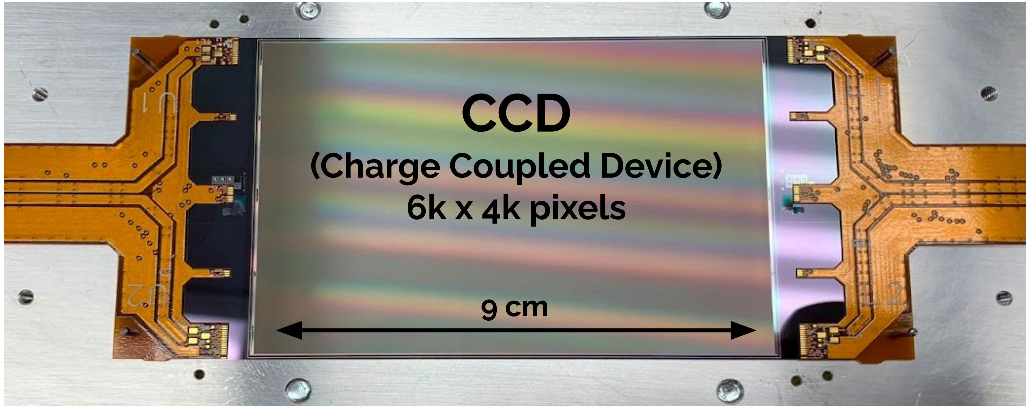
DArk Matter In CCDs at Modane



DAMIC-M@LSM
(conceptual design)



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

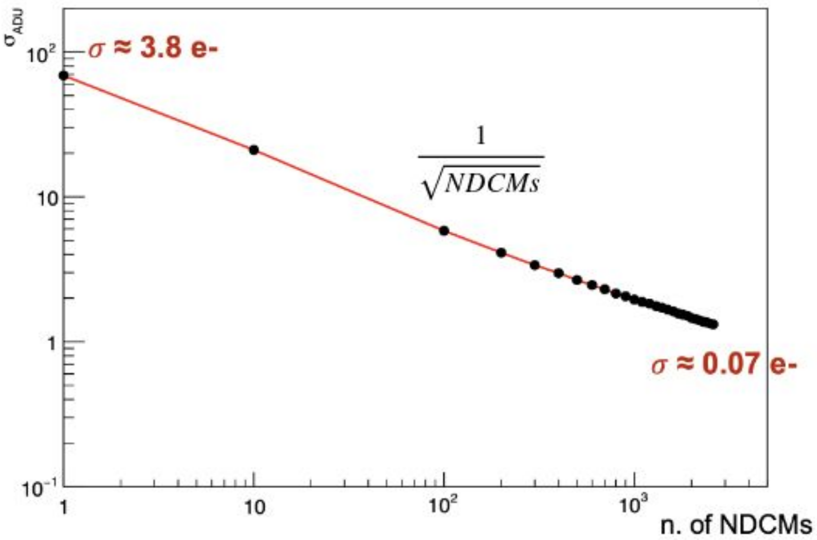


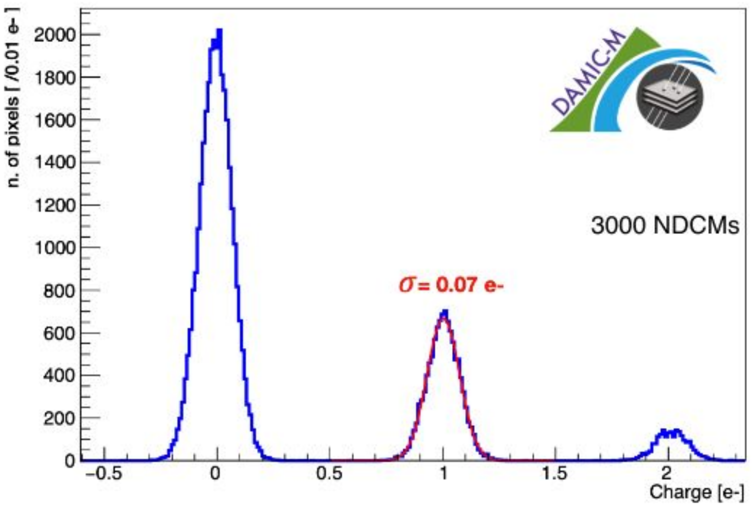
Skipper CCDs for sub-electron resolution

Skips = Non Destructive Repetitive Charge Measurements (NDCMs)

Charges in output node read by amplifier N times

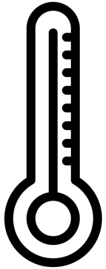
Readout noise decrease by a factor 1/sqrt(N)





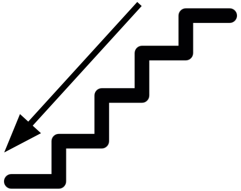
Single electron resolution

DAMIC-M detector features



~130 K

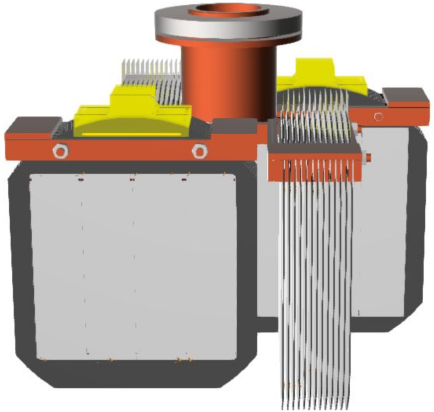
Temperature



1 d.r.u*

Background Level
< 1 d.ru

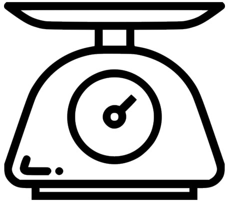
DAMIC-M CCD stack



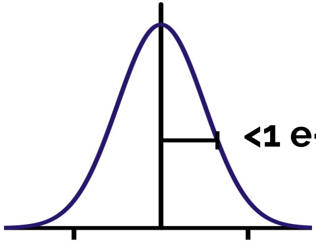
~200 SKIPPER CCDs

6000 pix x 1500 pix

~1 kg



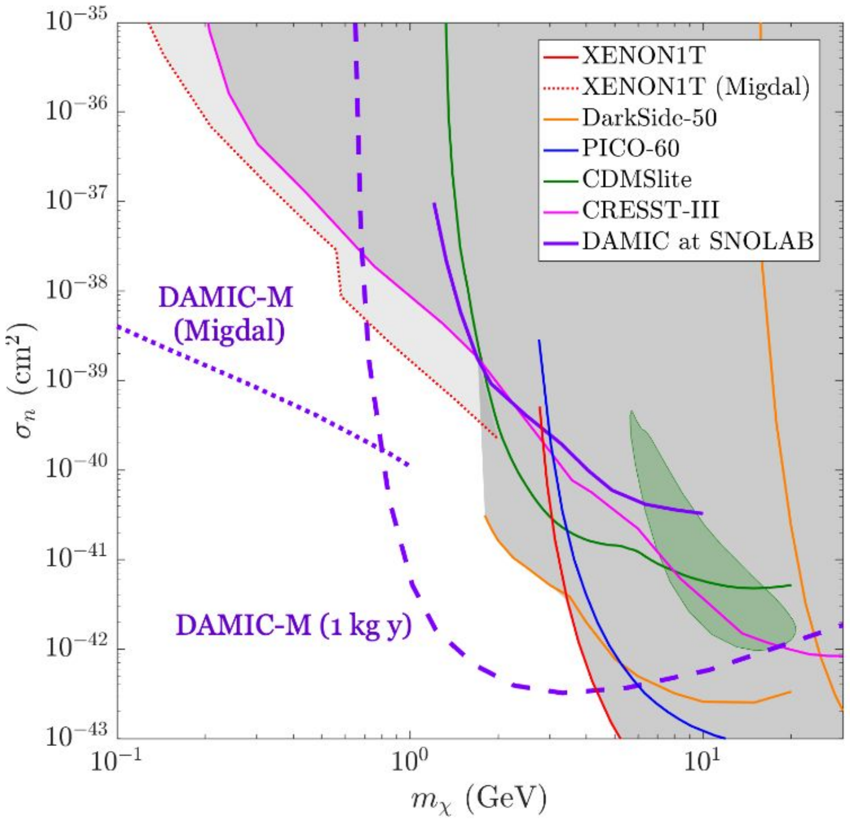
Sensitive Mass



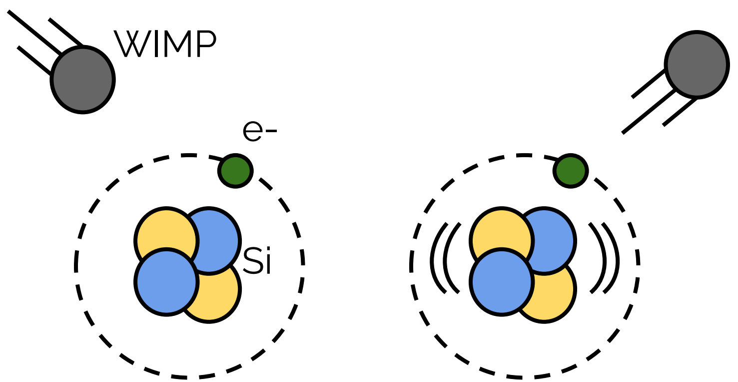
Resolution (readout noise)
~0.1 eV

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

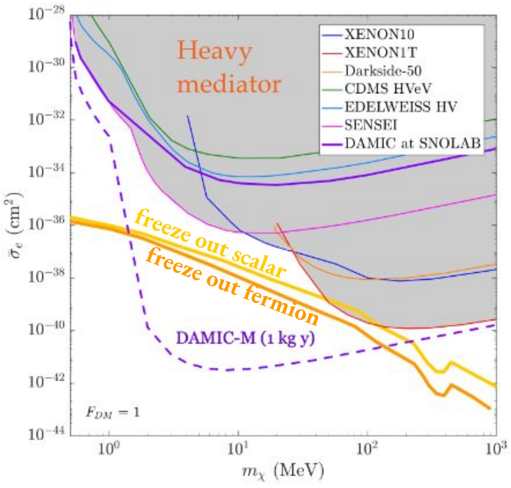
Physics reach - Light WIMPs

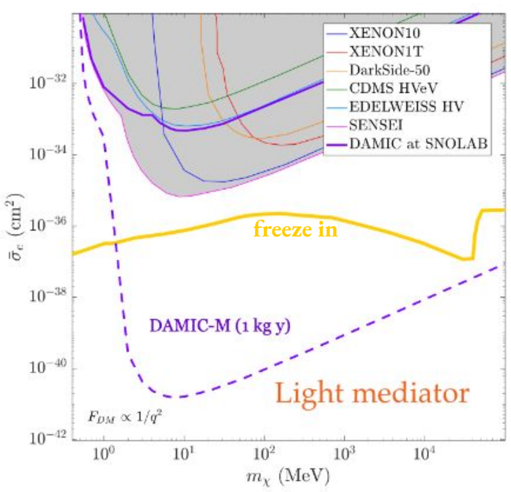


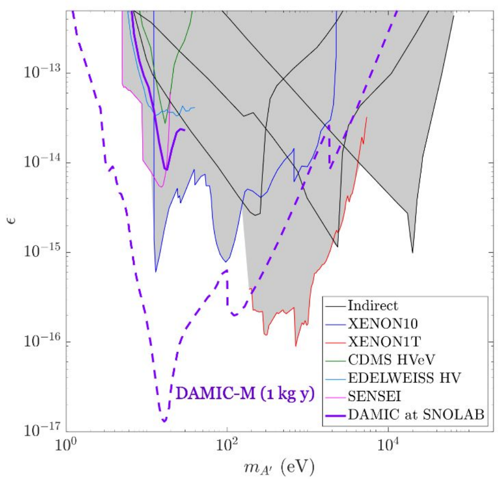
WIMPs - Si nucleus collision



Physics reach - Hidden sector

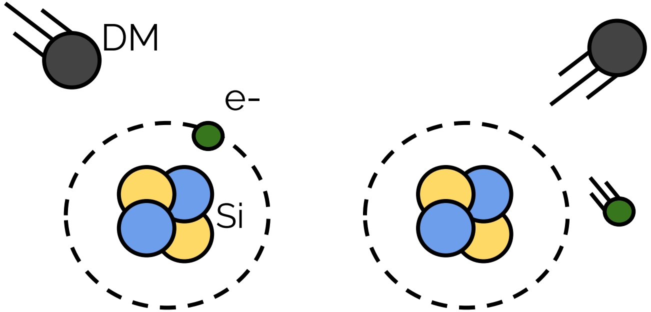






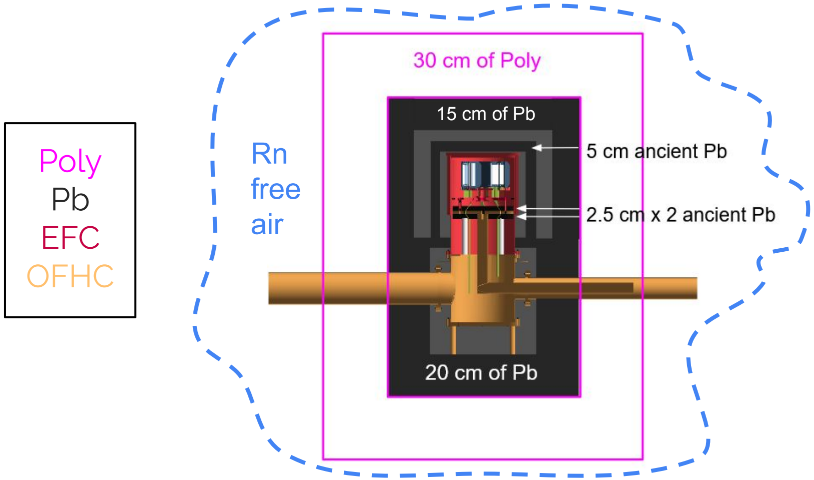
Hidden dark photon

DM - valence e- collision

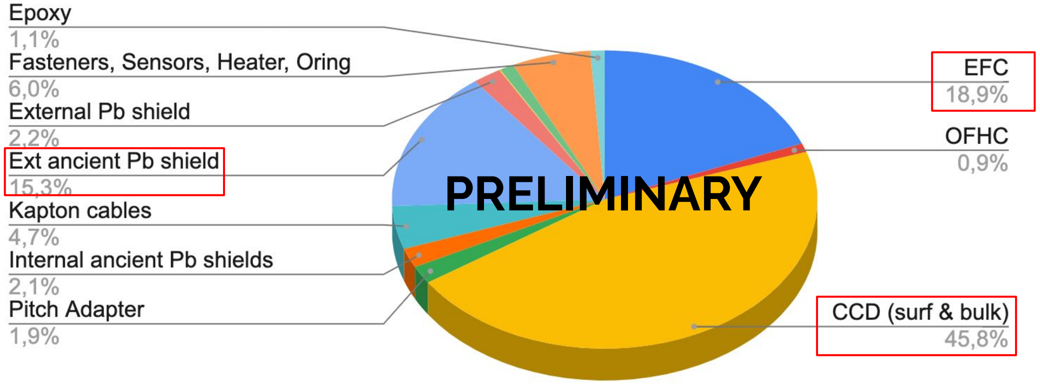


Background estimation for DAMIC-M

Simulations carried out using Geant4 + Python based code to simulate detector response (e.g. pixelation and clusterization). Radioactive isotopes (U/Th chains, K40, cosmogenic) uniformly distributed in the different detector components. The isotopes activities are coming from: LBC or DAMIC@SNOLAB assays, material suppliers, or calculated for cosmogenic isotopes ($T_{exposure}$ = 10 d/3m, $T_{cooling}$= 6m, T_{run}=1y for EFC/OFHC).

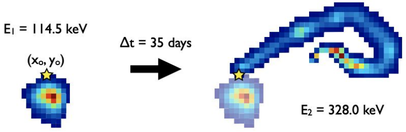


bkg rate = 0.92 d.r.u



Most of contribution to the bkg is coming from: in CCD contaminants (Si32 and Tritium), EFC components (assuming an exposure time to cosmic rays of only 10 days!), External ancient Pb shield!

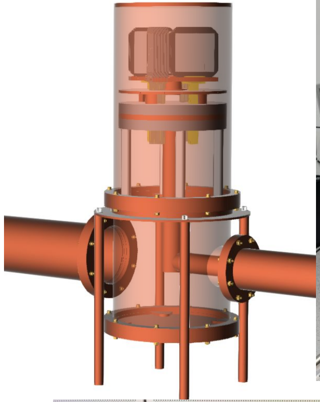
Silver lining: Si32 decay chain events can be excluded with analysis techniques looking for tracks originating in the same point of the pixel array with a given distance in time!



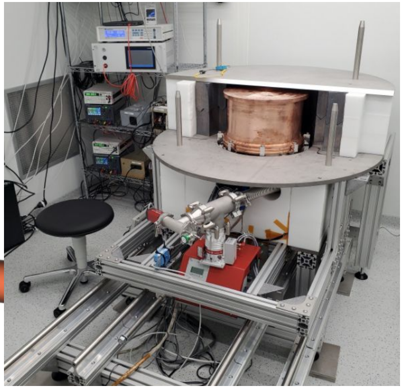
Status of DAMIC-M

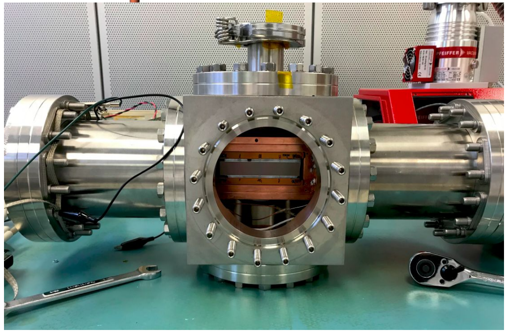
- Detector design finalized
- DAMIC-M CCD testing ongoing, packaging soon
- Electronics designed, under test *(see L. Iddir's talk!)*
- Calibration with radioactive sources:
  - gamma source: Phys. Rev. D 106, 092001
    (see also my last GDR-DUPHY talk here)
  - neutron source: ongoing analysis
- DAMIC-M prototype, Low Background Chamber (LBC), operating at LSM [arXiv:2407.17872]
- Final installation in 2025

Preliminary design DAMIC-M



LBC @LSM

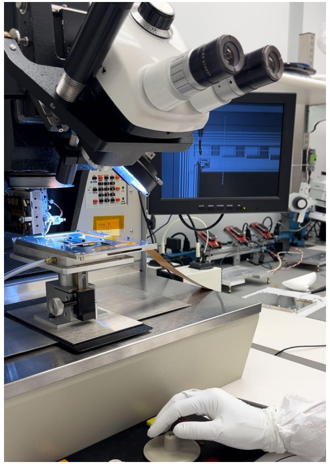




Compton measurement setup @UChicago

Status of DAMIC-M - CCD testing at UW

packaging station



CCD bonding

test chambers

inside the chambers

Current status:

73%

138/188 CCDs tested with 60% yield!

CCD module packaging coming soon

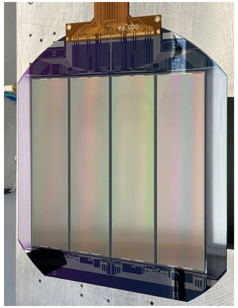
Thanks to M.Traina and A.Chavarria for the beautiful photos

DAMIC-M plan and schedule

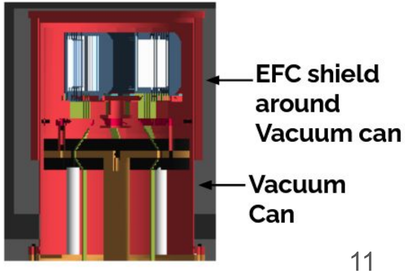
Dec 2024
- CCD modules (1 module = 4 CCDs) arriving at LSM

Feb 2025
- Disassembly of the LBC
- Repairing and cleaning of DAMIC-M clean room

Apr 2025
- DAMIC-M installation
    - 1st Phase:
        - installation of 26 modules (half a CCD array)
        - OFHC vacuum can (instead of EFC) → bkg rate increase = +1.35 d.r.u. Discussion with Canfranc ongoing to produce the EFC vacuum can (more info here about electroforming at CanFranc)
        - no EFC shield around vacuum can to screen ext. Pb shield contribution → bkg rate increase = +0.18 d.r.u
    - 2nd Phase:
        - full array installation
        - EFC vacuum can
        - EFC shield around vacuum can



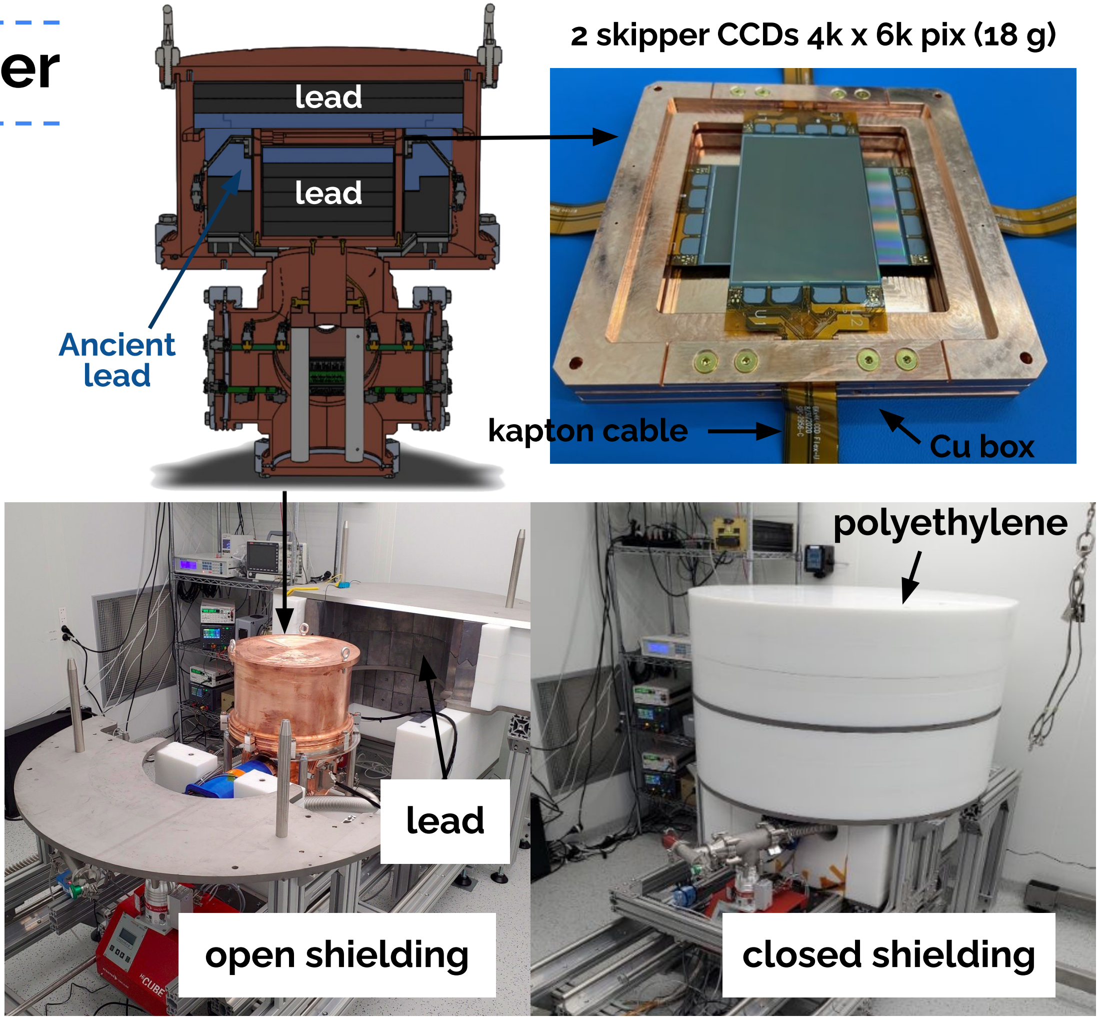
DAMIC-M MODULE



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
  - **First results for hidden sector candidates**
  - Upgrades for lower background, lower electronic noise and lower dark current

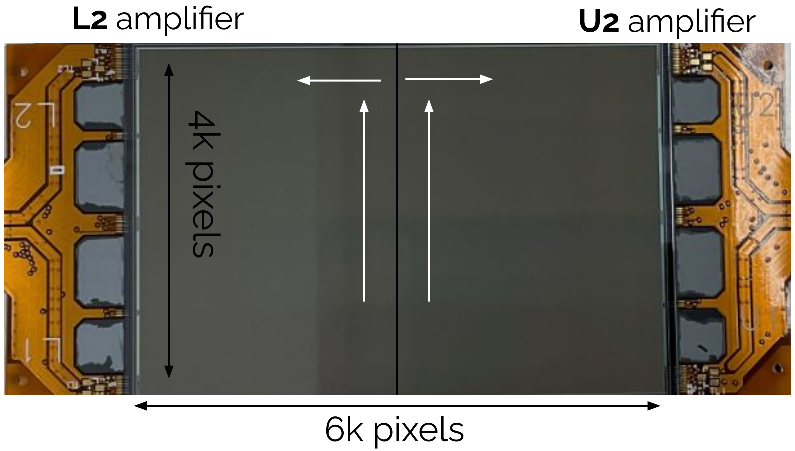


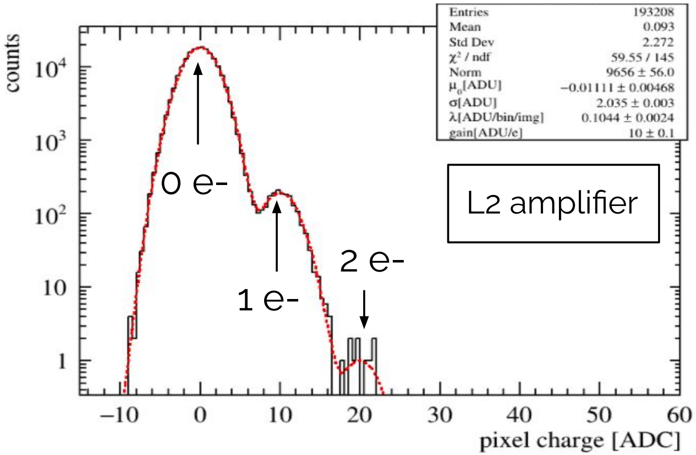
LBC - Data Taking

- Commissioning Run: Feb-May 2022

  optimization of the operating parameters for charge transfer efficiency, resolution, and dark current

- **Science run: 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
  - Resolution = 0.2e- (< 1eV) at 650 skips
  - Dark current = 4.5E-3 e-/pixel/day
  - Exposure: 85.2 gr-day

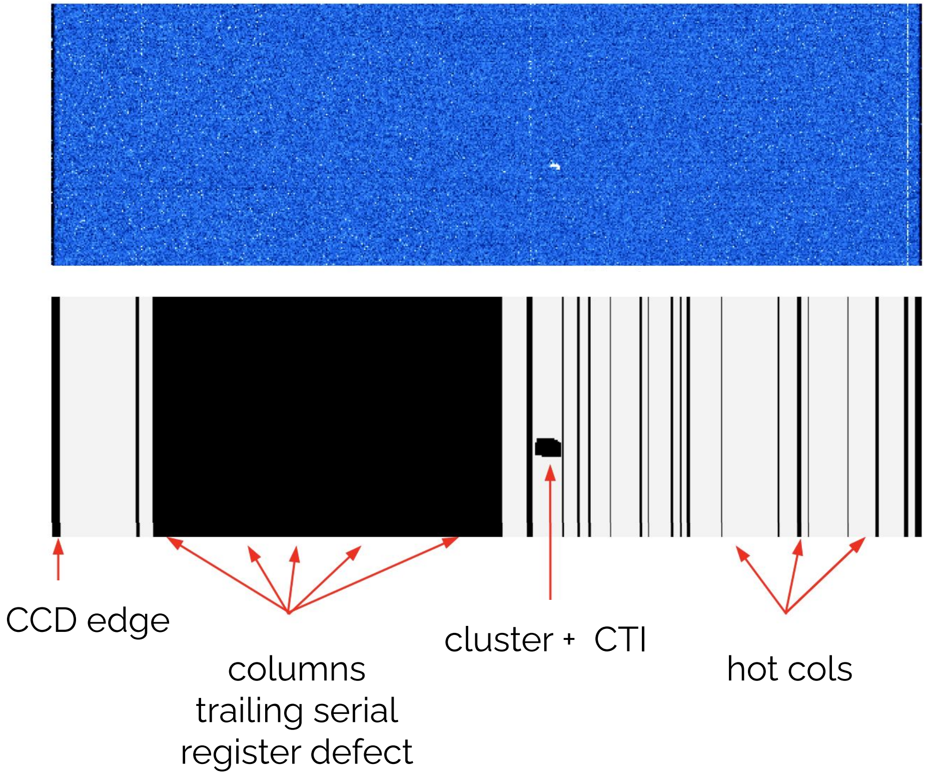




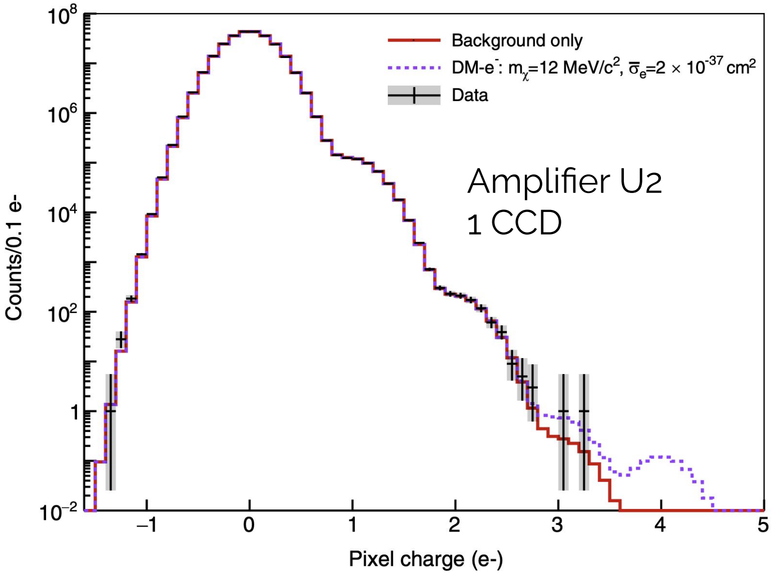
LBC - Data Selection

- **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 - Dark matter-electron limit setting



- **Measure the pixel charge distribution (PCD)** per amplifier per CCD

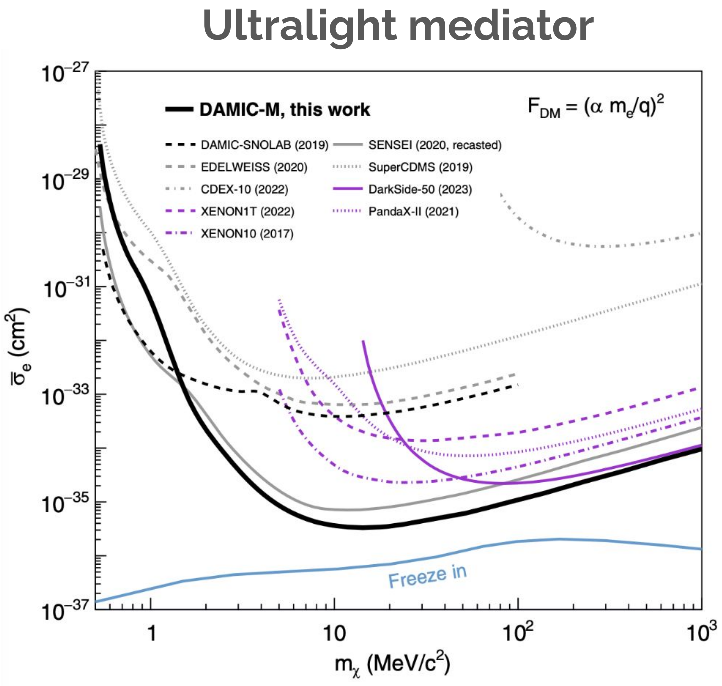
- **DM signal generation**:
  - QEdark to generate differential rate of DM signal with halo parameters from PhystatDM (arXiv: 2105.00599 (2021))
  - apply detector response: eV to e- conversion with low energy ionization yield (PRD 102, 063026 (2020)) and diffusion model using parameters measured with LBC CCD

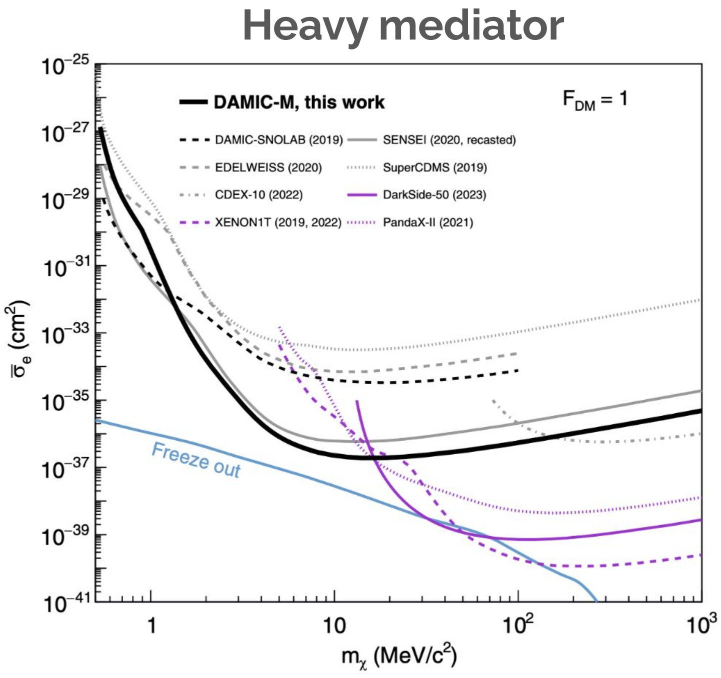
- **Fit whole PCD** and perform **binned joint likelihood minimization** to set 90% C.L. upper limits in cross section-DM mass parameter space:

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

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

LBC - 90% CL upper limits

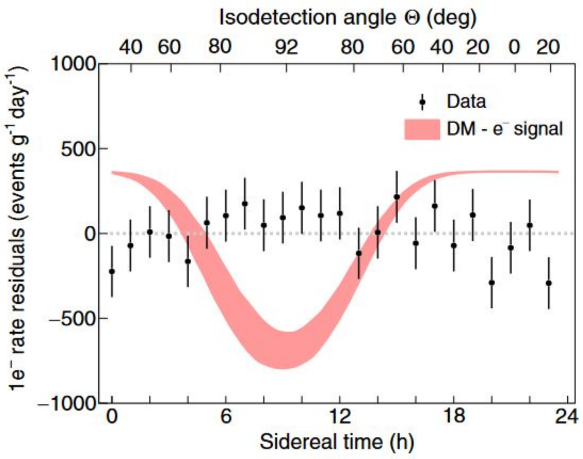




World leading exclusion limits on DM-electron interactions in the mass ranges [1.6-1000 MeV] and [1.5-15.1 MeV] for ultralight and heavy mediator interactions

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

LBC - Daily modulation analysis

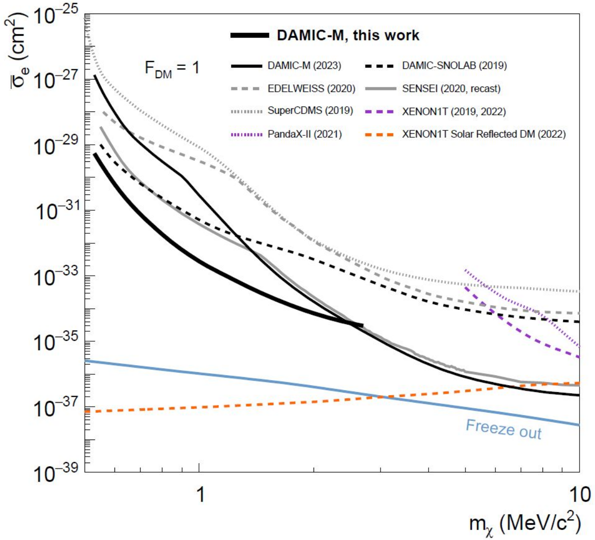


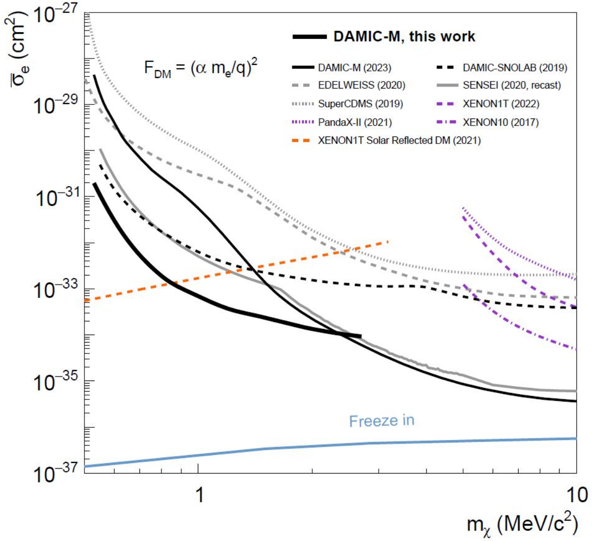
Daily modulation analysis with LBC [Phys. Rev. Lett. 132, 101006, 2024]

- **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 their interactions in the Earth

- 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





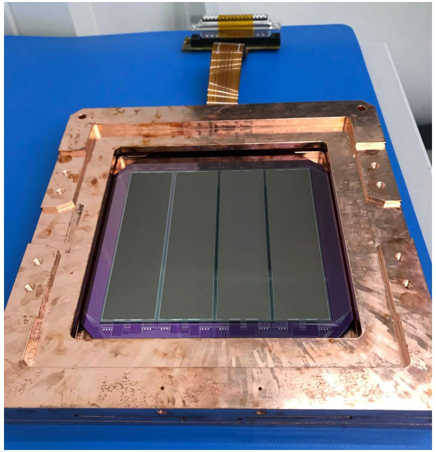
LBC - Current status

Current status:

- 2 DAMIC-M modules installed in LBC: 8 6k x 1.5k skipper CCDs
- Lower background (~7 d.r.u):
  - Cleaner CCDs (shorter surface exposure)
  - More electroformed copper parts (EFCu box lids)
- Study of CCD background content, e.g., Si32, surface Pb210, ongoing (CCDs are made with same Si of final DAMIC-M CCDs!)

Here our LBC technical paper!

DAMIC-M modules installed in LBC

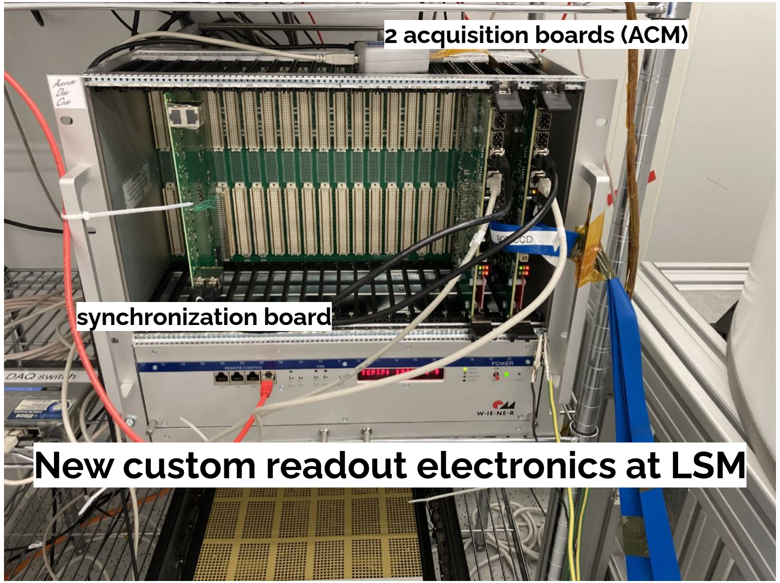


LBC - Current status

Current status:

- Custom readout electronics installed for lower noise with fewer Nskips *(see L. Iddir's talk)*

- Dark current lower by more than 1 order of magnitude!
  - improved light tightening
  - improved clock shaping

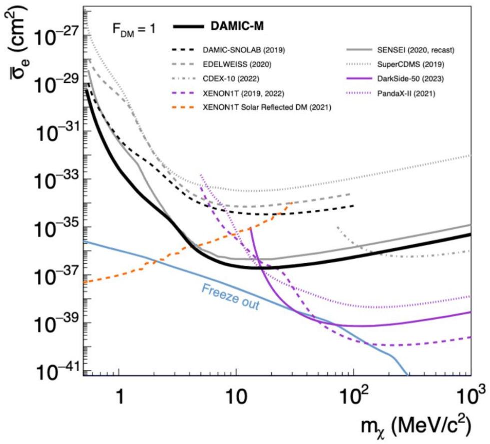


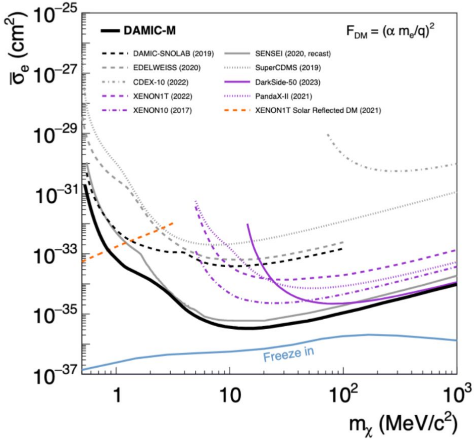
Here our LBC technical paper!

Conclusions

- **On our way towards DAMIC-M**
  - CCDs being tested now! DAMIC-M modules ready by the end of December 2024!
  - Calibration measurements:
    - Compton scattering measurement: [Phys. Rev. D 106, 092001]
    - Photo-nuclear scattering measurement: analysis ongoing
  - Design finalized
  - Custom readout electronics installed and operating at the LBC (lower readout noise for fewer skips)
  - Dark current lower than before by more than 1 order of magnitude!

- **Low Background Chamber**
  - World leading exclusion limits on DM-electron interactions in the mass ranges [0.53, 1000] and [0.53, 15.1] MeV for ultralight and heavy mediator interactions





LBC installation, December 2021

Thank you for the attention !

European Research Council
Established by the European Commission

BACKUP

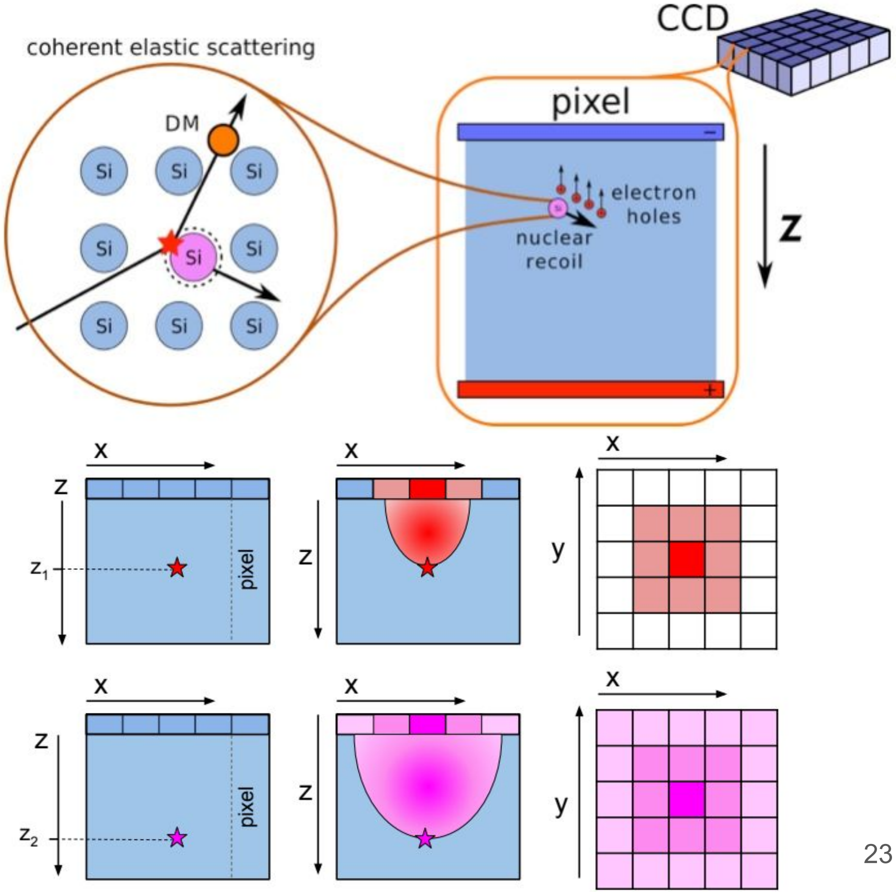
CCDs operation and 3D reconstruction

- CCD: n-type silicon with buried p-channel, thickness = 0.67 mm

- Creation of a depletion region (active volume) in the CCD (full depletion)

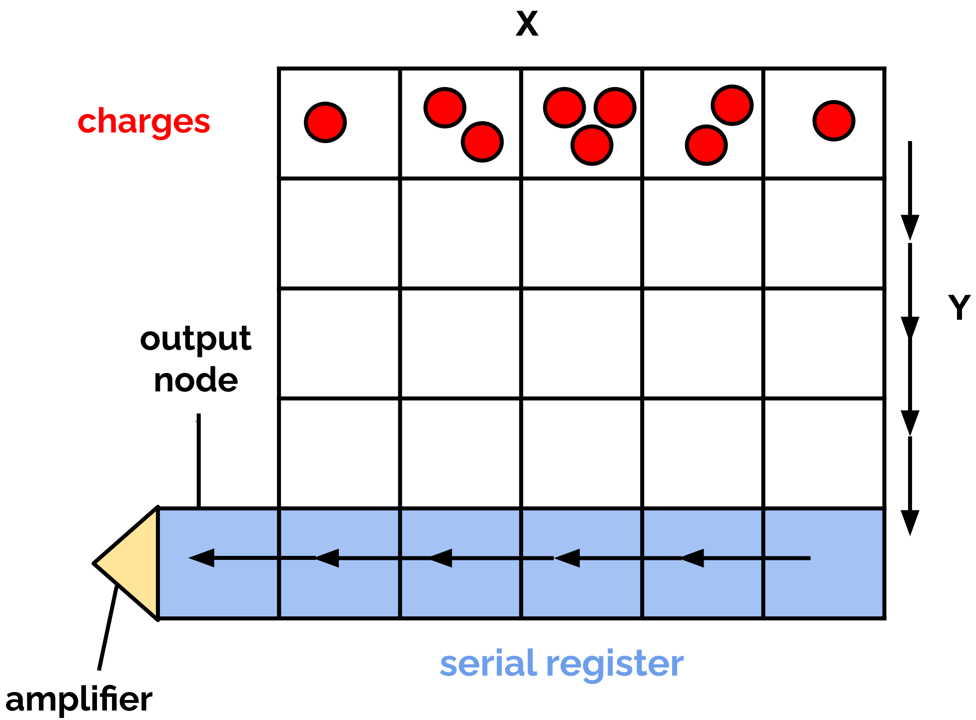
- DM interaction causes creation of e-/h pair (3.74 eV required on average) in depletion region

- **3D reconstruction:**
  - z position: diffusion of charges during drift
  - x-y position: Precise spatial resolution (0.015 mm x 0.015 mm pixels)



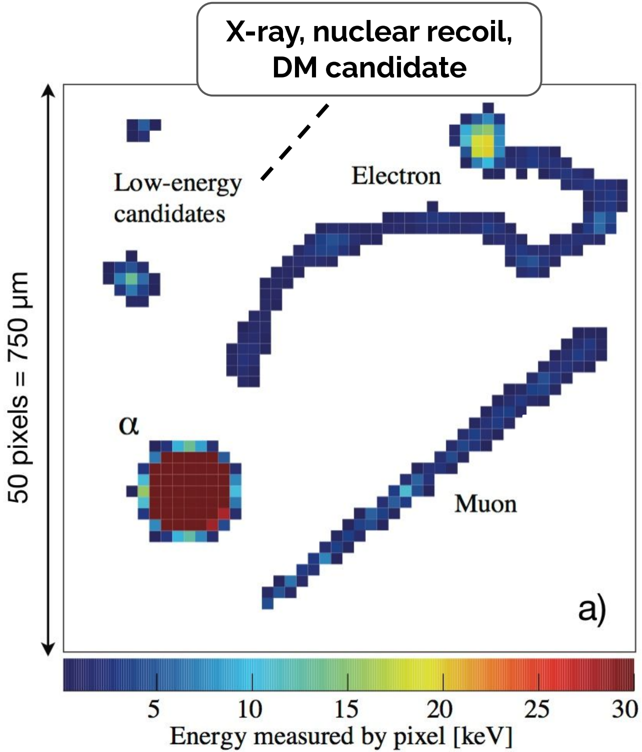
CCD readout

- 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

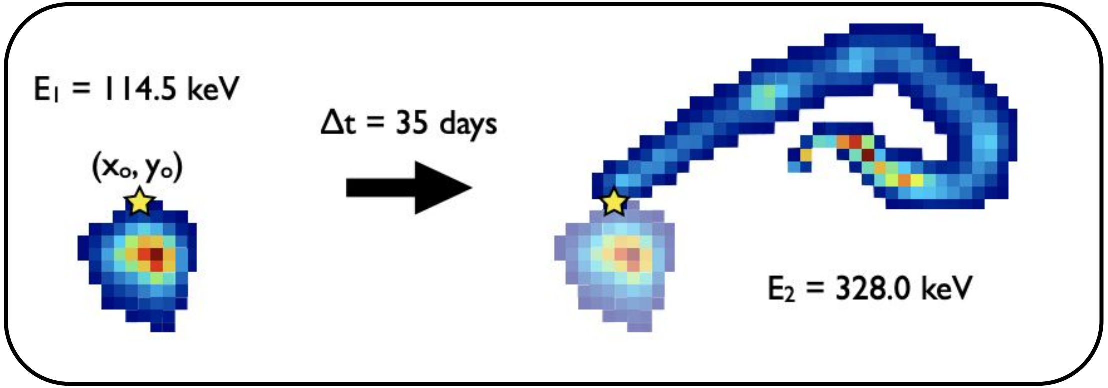


Particle identification

Signatures of different ionizing particles in a CCD



Identification of decay chains

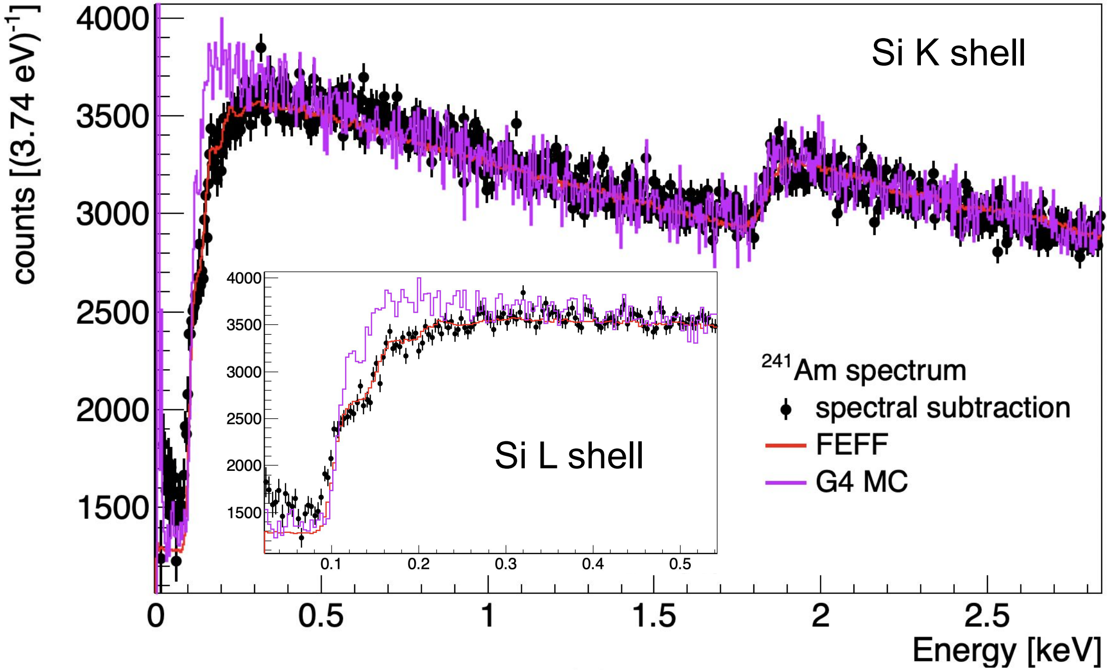


Decay chain of a Si-32 nucleus in the CCD:
[JINST 10 (2015) P08014, JINST 16 (2021) P06019]

$^{32}\mathrm{Si} \rightarrow ^{32}\mathrm{P} + \beta$ 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

Compton measurement



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

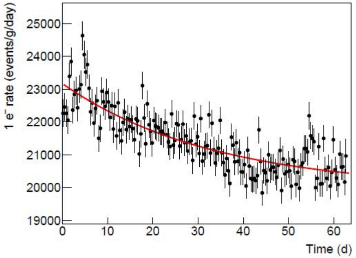
FEFF:
ab initio calculation (full quantum treatment) + detector resolution

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:

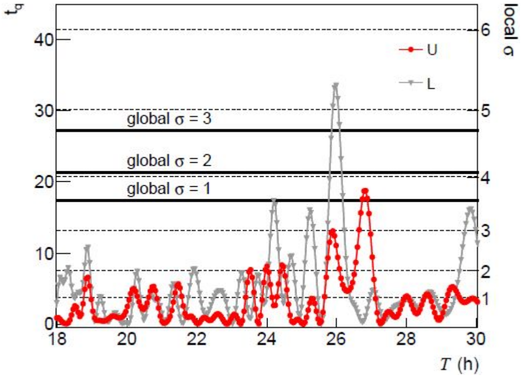
- **agreement in the K-shell region with Relativistic Impulse Approximation**
- **disagreement at L shell with RIA:**
  - softening of the spectrum below 250 eV is observed
  - confirmation of the previous DAMIC measurement [Phys. Rev. D 96, 042002 (2017)]
  - Better agreement with FEFF code

LBC - Daily modulation analysis



63 days from June 8th 2022

Model Independent

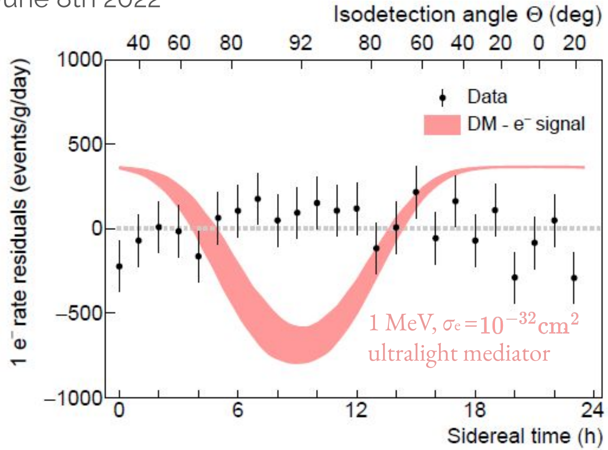


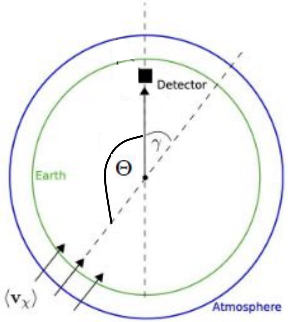
$$F(t) = Be^{-t/\tau} + C + A\cos((2\pi(t-\phi)/T)$$

$$\mathcal{L}(\theta) = \prod_{i=1}^{N_{\rm im}} \frac{1}{\sqrt{2\pi}\sigma^i_{R_1}} \exp\left\{-\frac{1}{2}\left(\frac{R^i_1 - F(t_i|\theta)}{\sigma^i_{R_1}}\right)^2\right\}$$

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

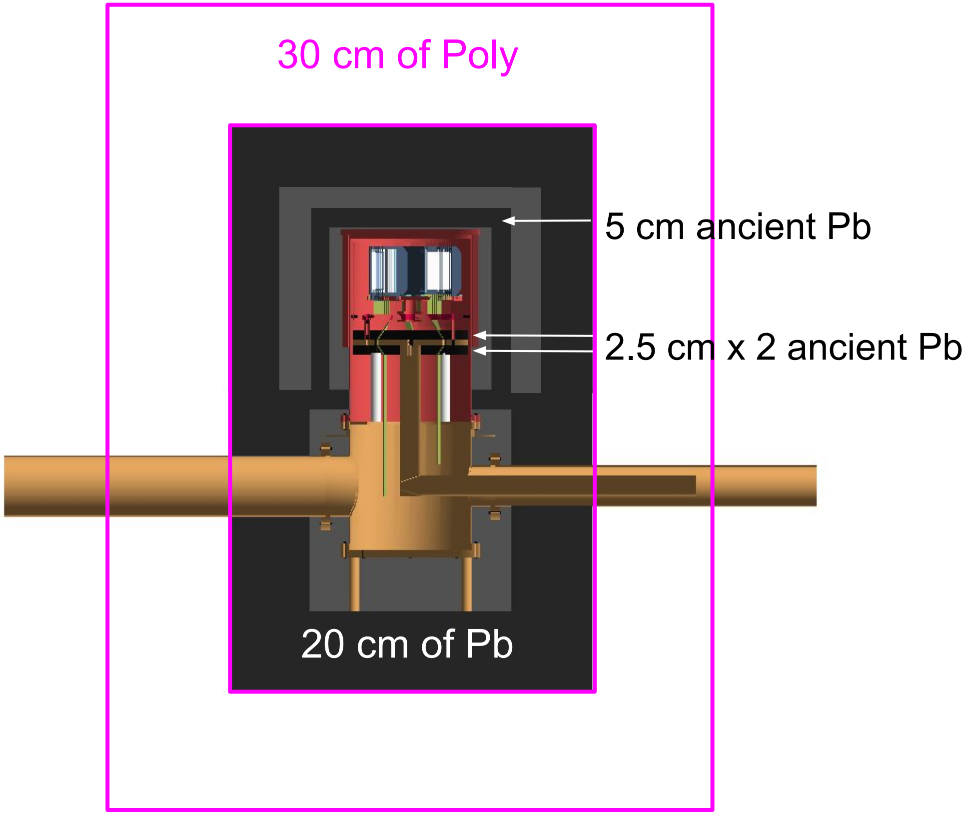
Model Dependent

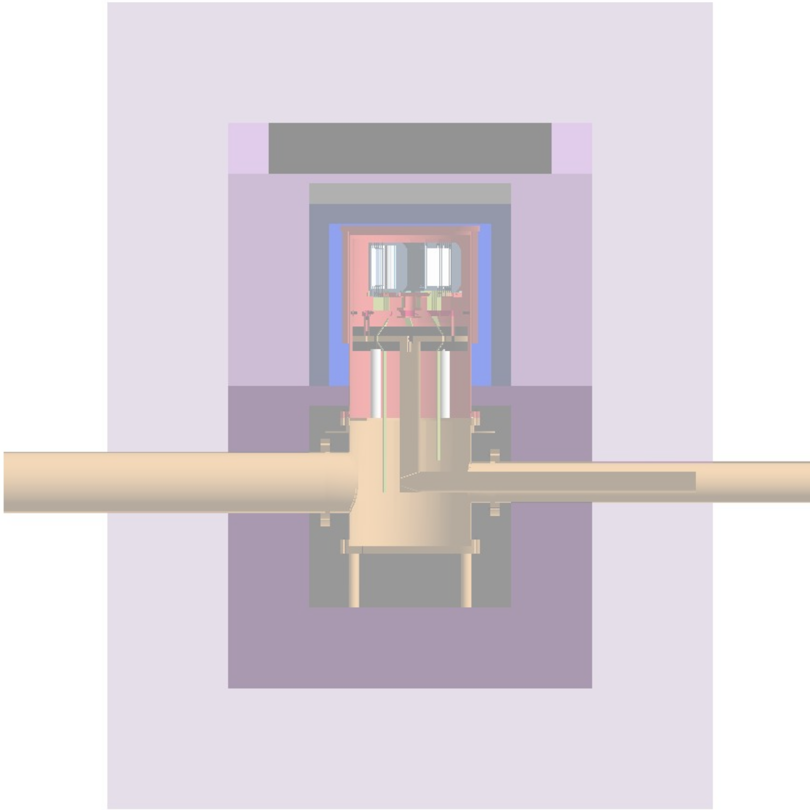


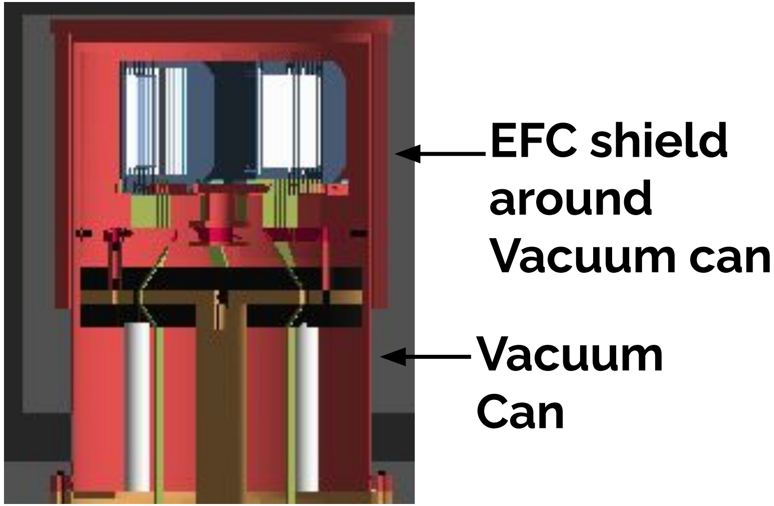


$$\frac{dR}{dE_e} \propto \bar{\sigma}_e \int \frac{dq}{q^2}\left[\int \frac{f(\mathrm{v},t)}{\mathrm{v}} d^3\mathrm{v}\right] |F_{\rm DM}(q)|^2 \, |f_c(q,E_e)|^2$$

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


30 cm of Poly
5 cm ancient Pb
2.5 cm x 2 ancient Pb
20 cm of Pb




EFC shield around Vacuum can
Vacuum Can