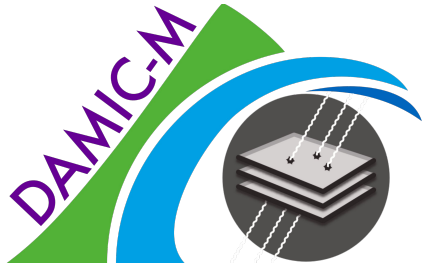
PASCOS 2024 - Quy Nhon (Vietnam)

Shedding Light on Dark Matter: Status and first results of the DAMIC-M experiment

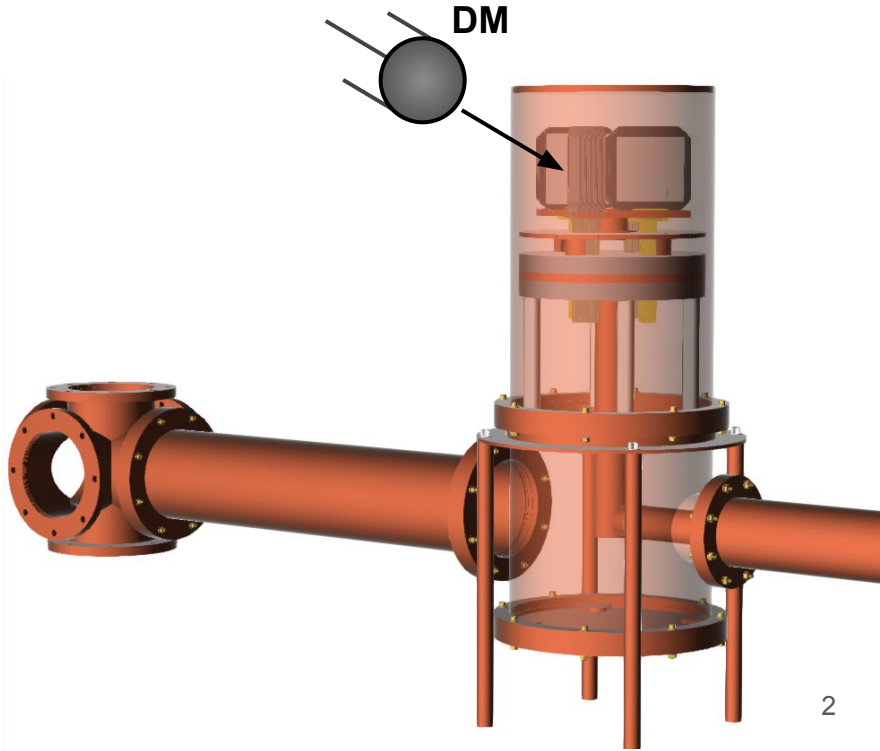
Claudia De Dominicis



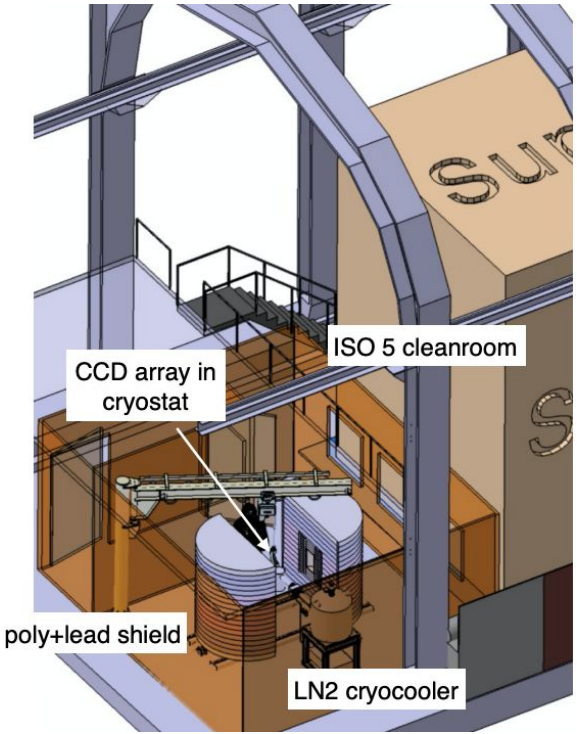
Outline

- The DAMIC-M experiment:
  - CCD operation
  - Physics reach
  - Status of the experiment

- The Low Background Chamber



DArk Matter In CCDs at Modane



DAMIC-M@LSM
(conceptual design)

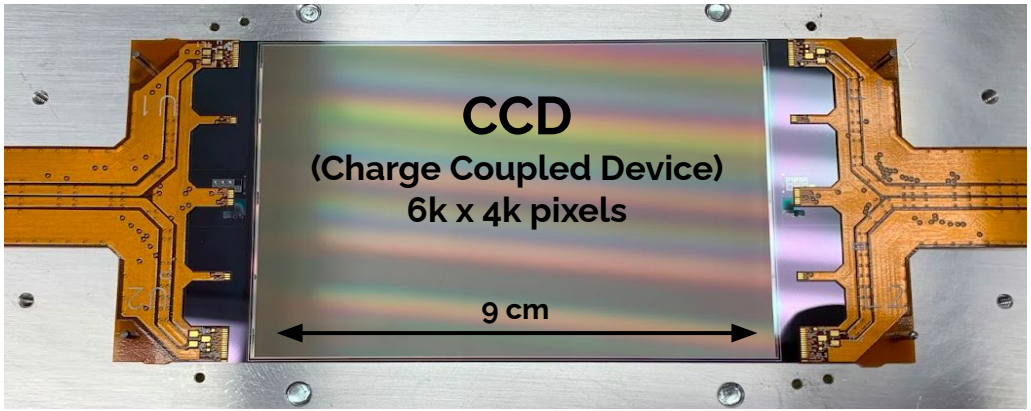
DAMIC experiment
at SNOLAB (Canada)

DAMIC-M experiment
at LSM (Modane, France)

2017 — 2022 — 2025

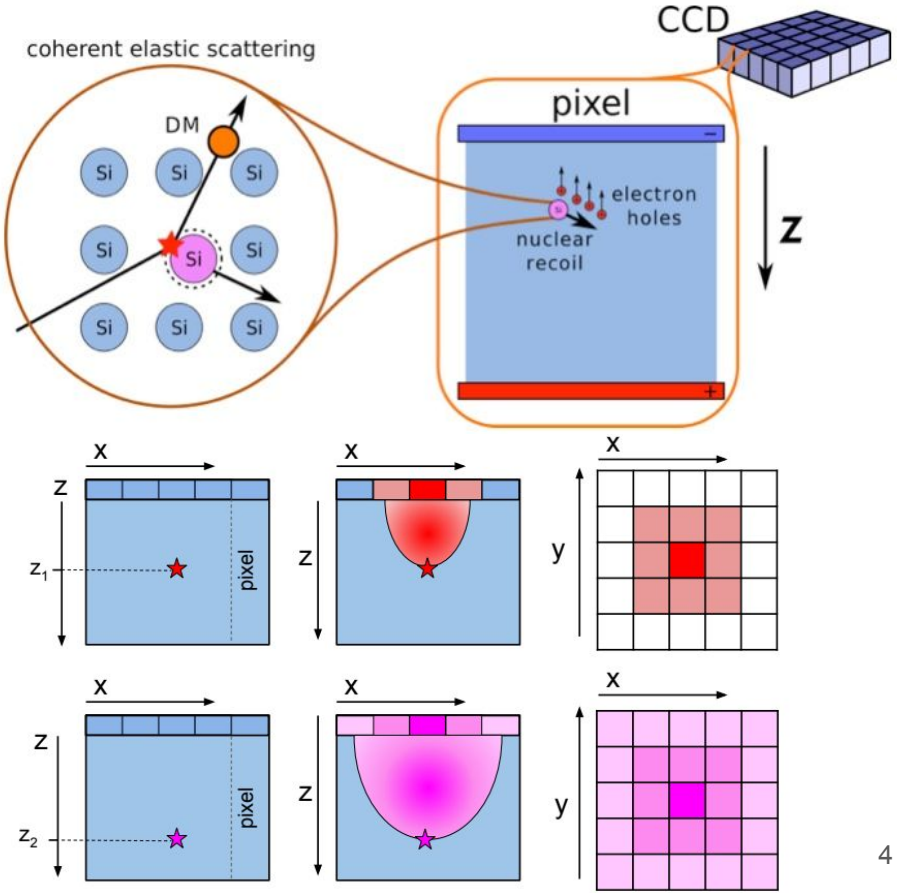
Low Background Chamber
at LSM (Modane, France)

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



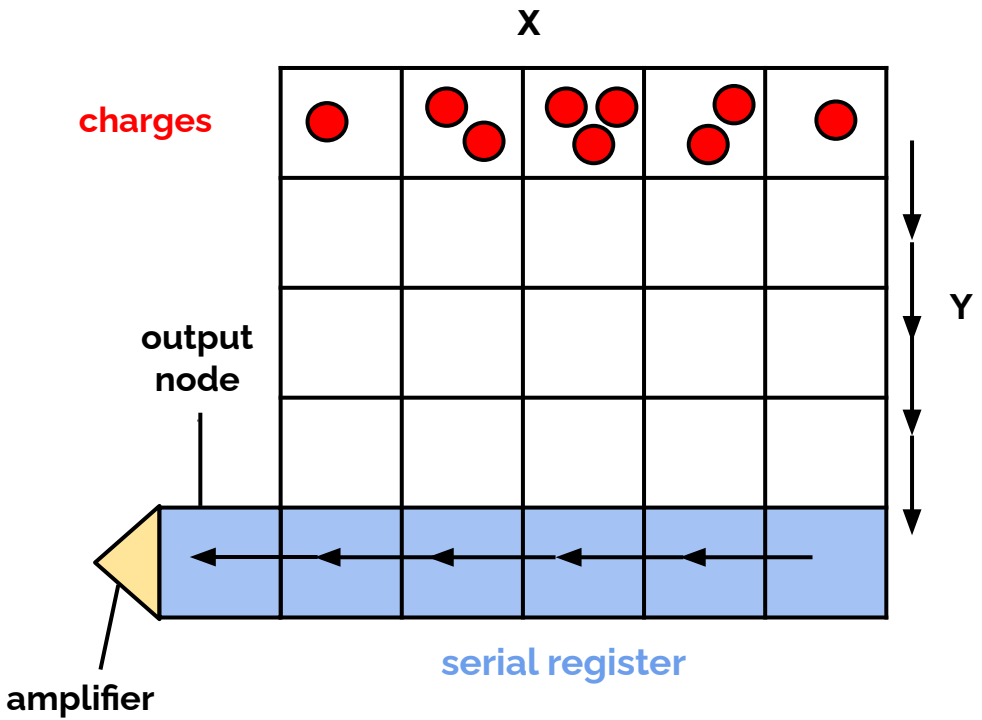
CCDs operation and 3D reconstruction

- 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

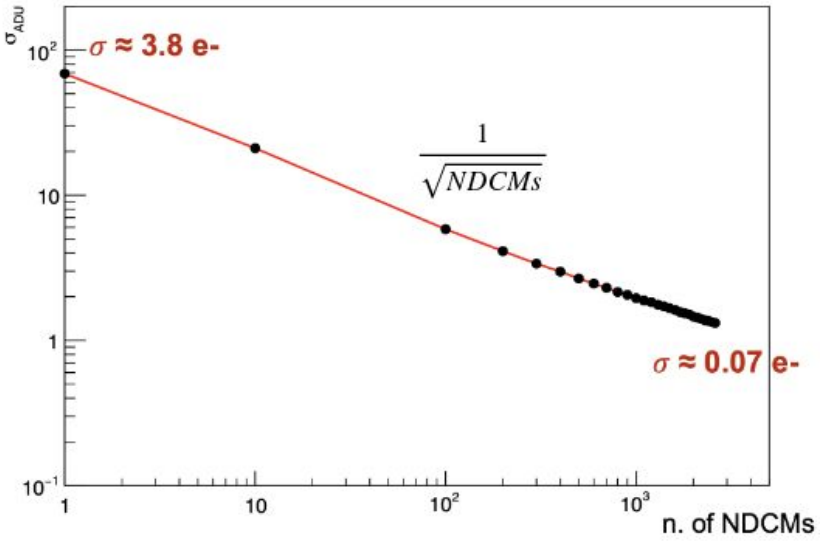


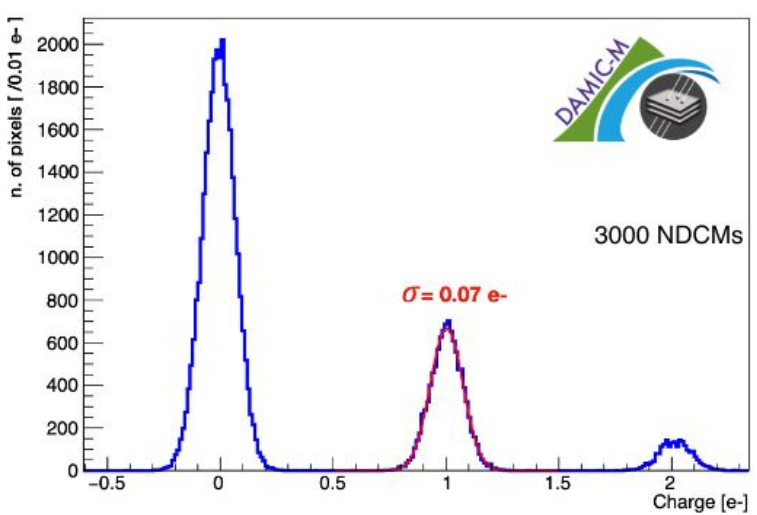
Skipper CCDs for sub-electron resolution

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)

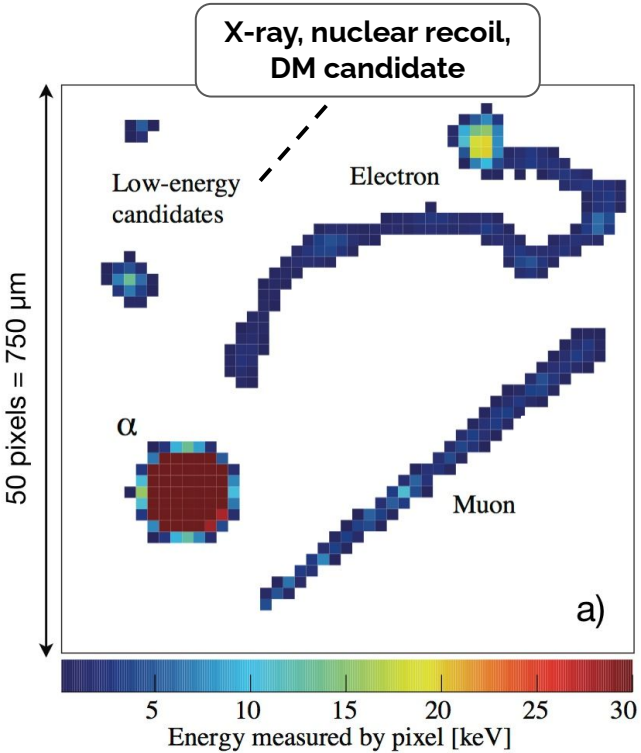




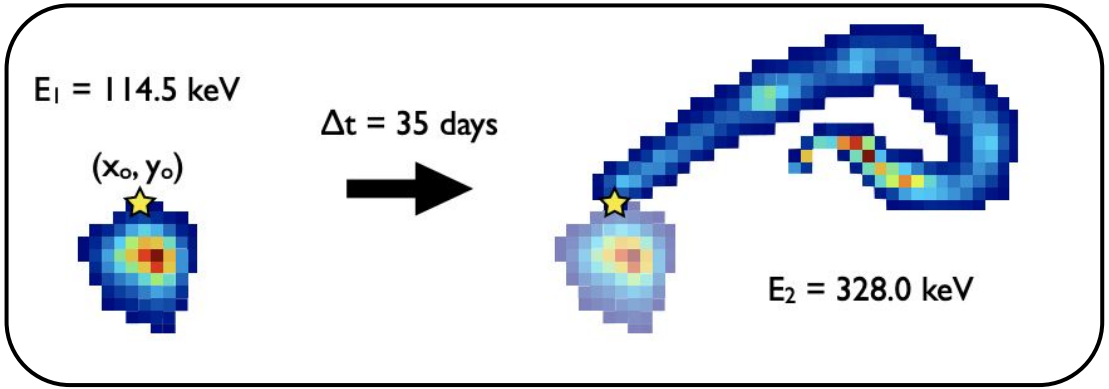
Single electron resolution

Particle identification

Signatures of different ionizing particles in a CCD



Identification of decay chains

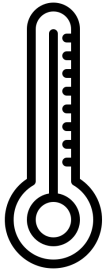


Decay chain of a Si-32 nucleus in the CCD:
[JINST 10 (2015) P08014, JINST 16 (2021) P06019]

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

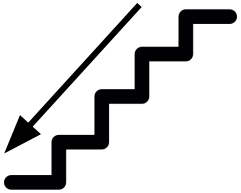
$^{32}\mathrm{P} \rightarrow ^{32}\mathrm{S} + \beta$ with $t_{1/2}$ = 14 d, Q-value = 1.71 MeV

DAMIC-M detector features



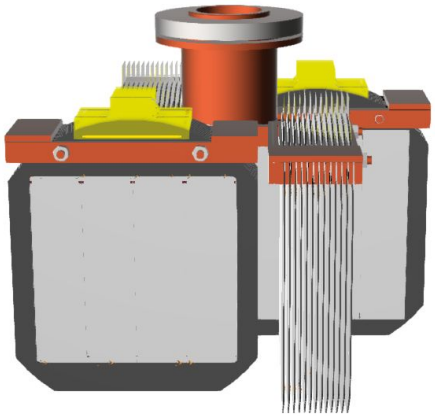
~130 K

Temperature



Background Level
< 1 d.ru

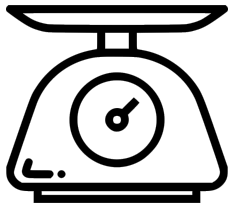
DAMIC-M CCD stack



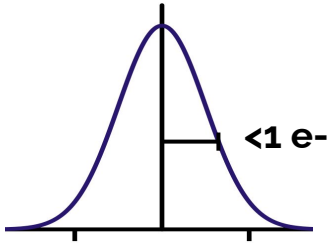
~200 SKIPPER CCDs

6000 pix x 1500 pix

~1 kg



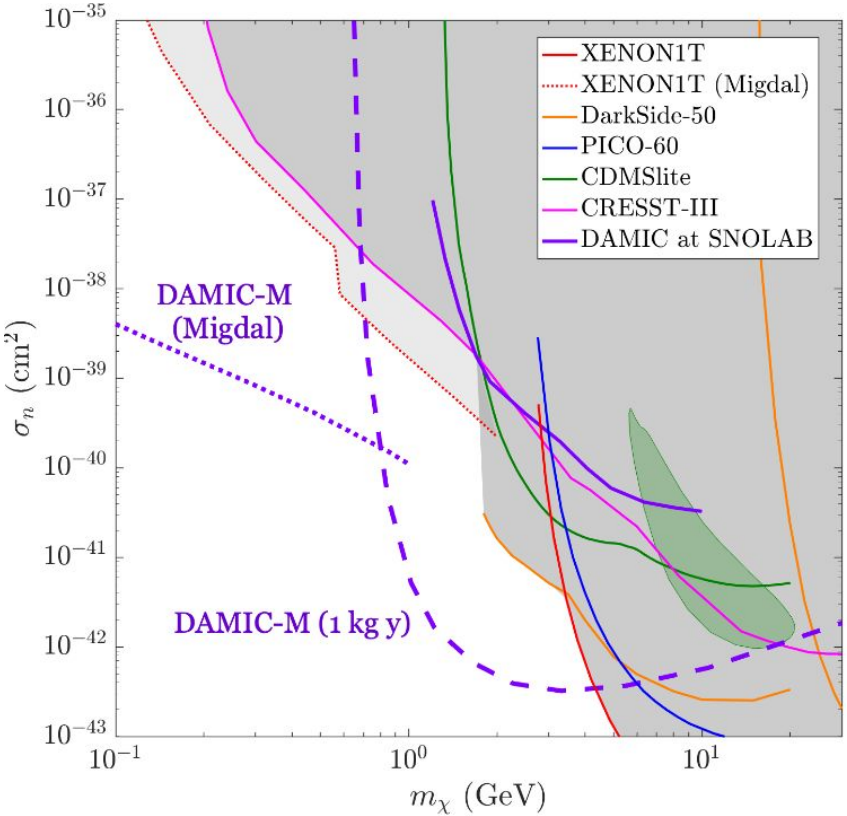
Sensitive Mass

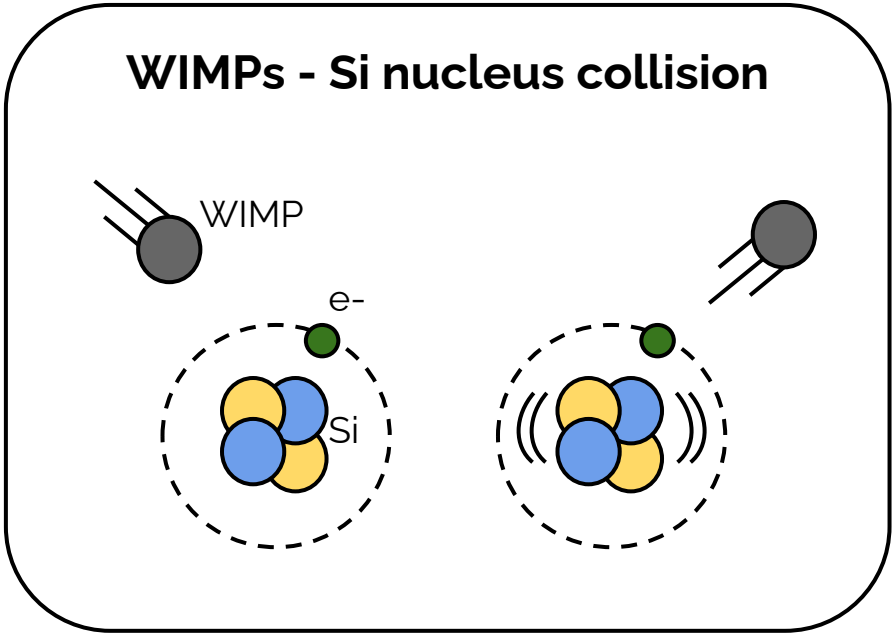


Resolution (readout noise)
~0.1 eV

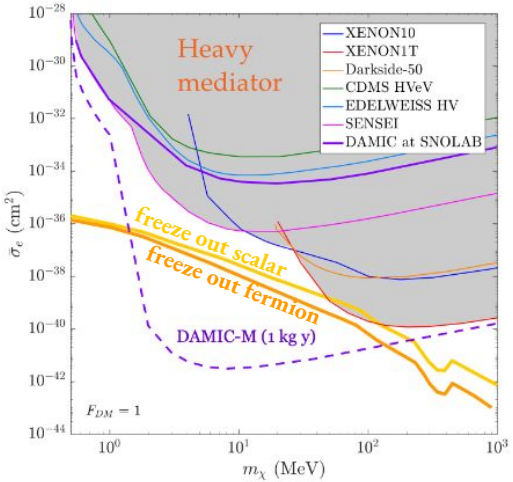
(*) 1 d.r.u = 1 decay/kg/day/keV

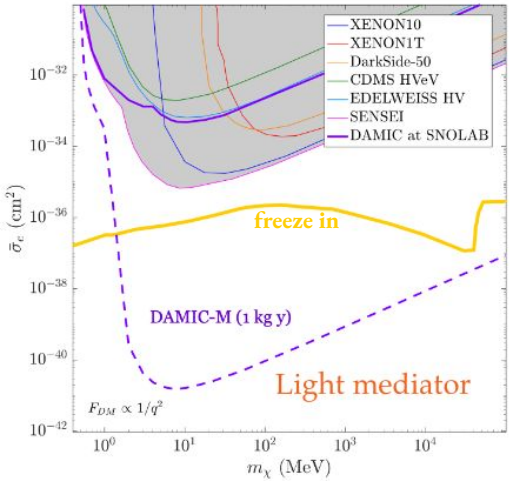
Physics reach - Light WIMPs

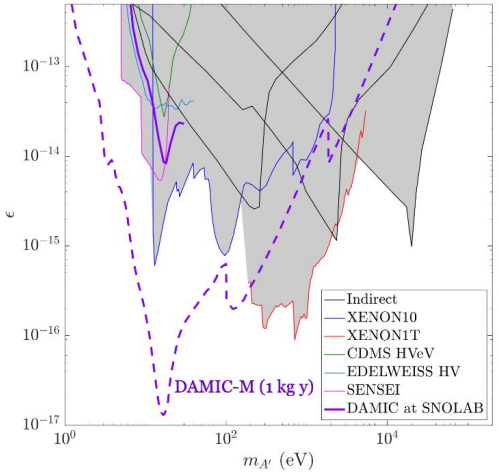




Physics reach - Hidden sector

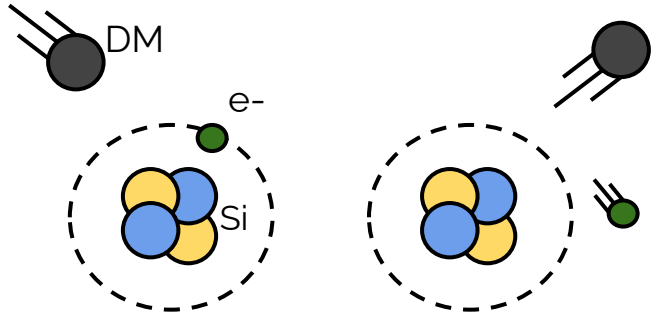






Hidden dark photon

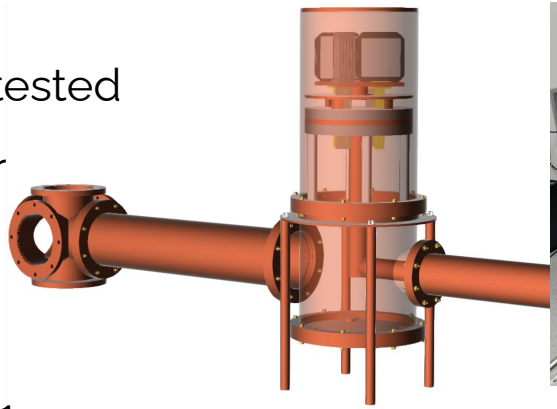
DM - valence e- collision



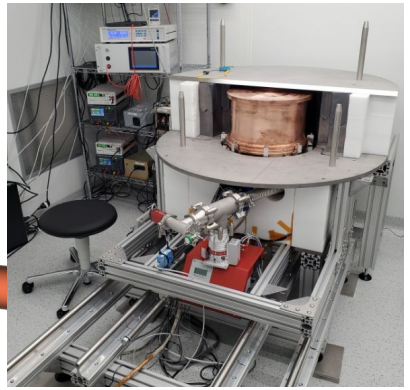
Status of DAMIC-M

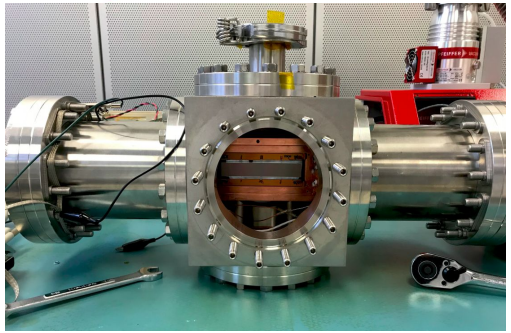
- Detector design almost finalized
- CCDs produced, CCD modules already tested
- CCD packaging and testing this summer
- Electronics designed, under test
- Calibration with radioactive sources:
  - gamma source: Phys. Rev. D 106, 092001
  - neutron source: ongoing analysis
- DAMIC-M prototype, Low Background chamber, operating at LSM
- Final installation in 2025

Preliminary design DAMIC-M



LBC @LSM



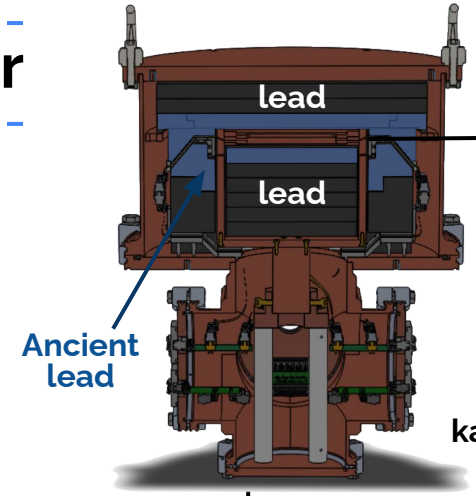


Compton measurement setup @UChicago

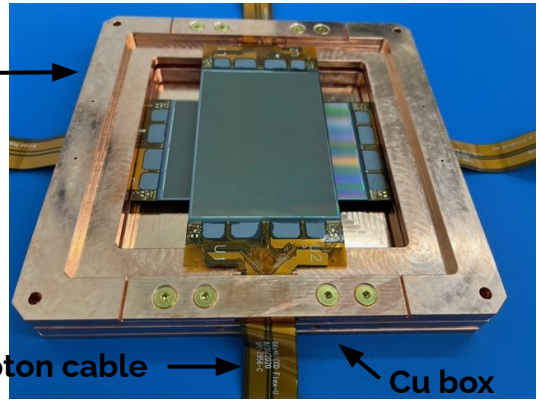
Low Background Chamber

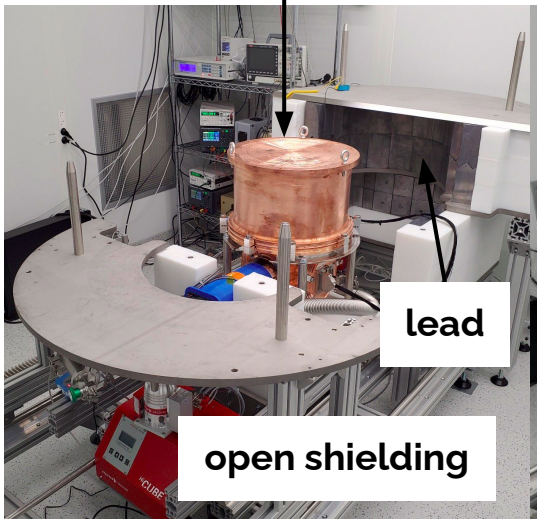
- **Aim:**
  - Demonstrate the ability to control backgrounds for DAMIC-M
  - integration/operation of DAMIC-M electronics
  - Provide test bench for dark current studies and reduction strategies
  - First dark matter search

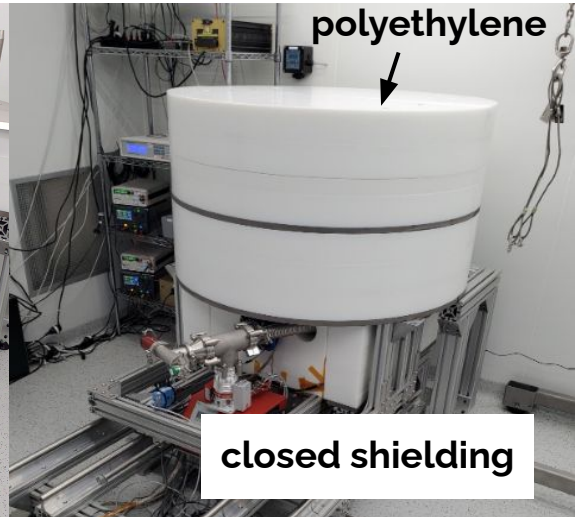
- **Achievements:**
  - Installed at LSM at the end of 2021
  - **First results for hidden sector candidates**
  - Upgrade electro-formed Cu and with DAMIC-M modules (2 modules, 8 CCDs 1,5k x 6k)



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





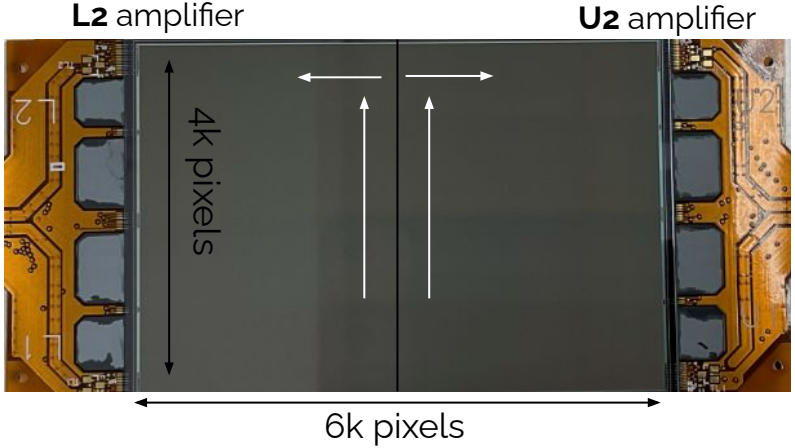


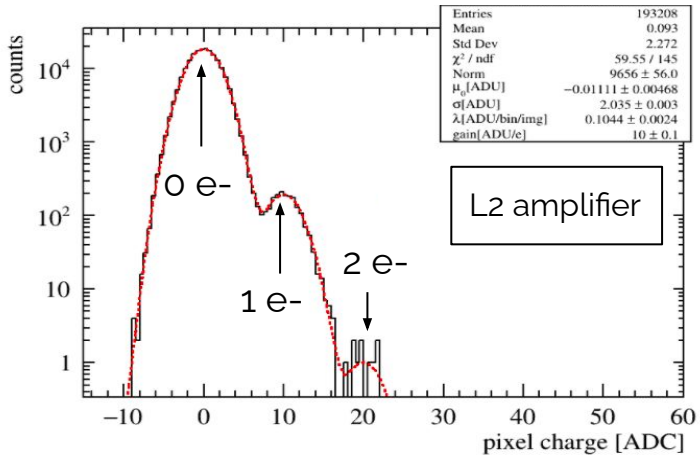
LBC - Data Taking

- Commissioning Run: Feb-May 2022

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

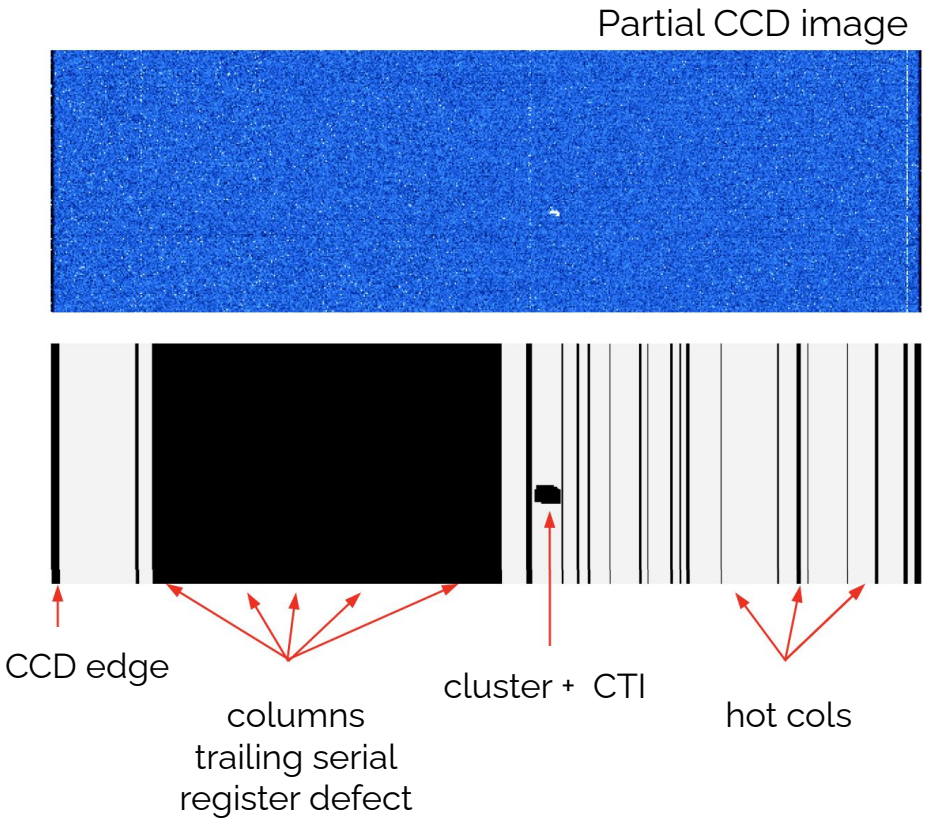
- **Science run: May-Ago 2022**
  - Read out with 2 amplifiers per CCD
  - Binning: 10 pix x 10 pix
  - Temperature: ~110 K
  - Background rate: ~12.5 d.r.u
  - Resolution = 0.2e- (< 1eV) at 650 skips
  - Dark current = 4.5E-3 e-/pixel/day
  - Exposure: 85.2 gr-day



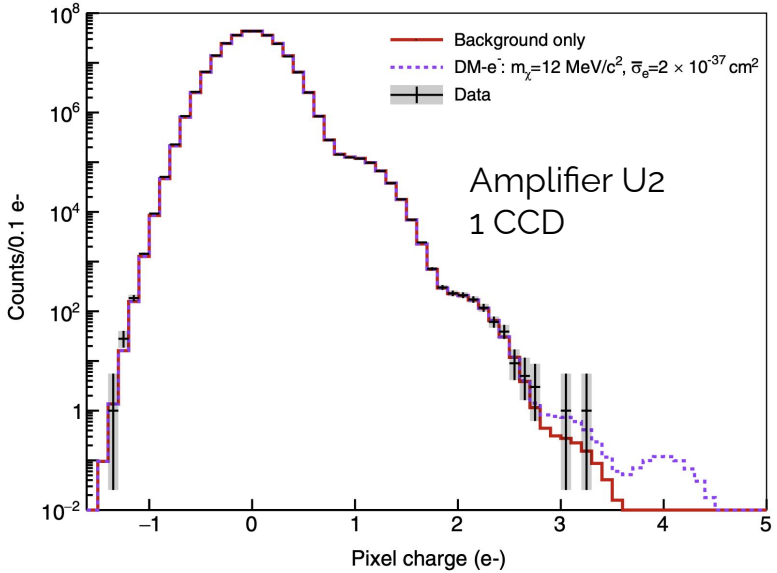


LBC - Data Selection

- **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



LBC - Dark matter-electron limit setting



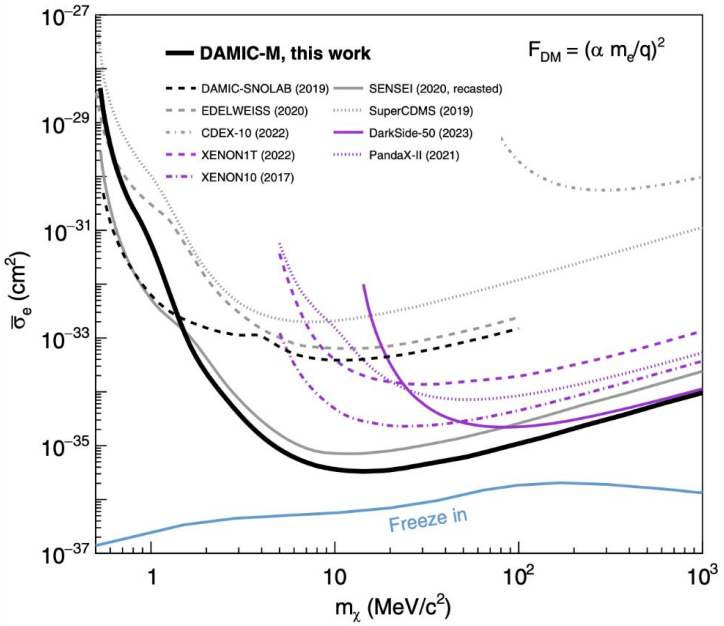
- **Measure the pixel charge distribution (PCD)** per amplifier per CCD
- **DM signal generation**:
  - QEdark to generate differential rate of DM signal with halo parameters from PhystatDM (arXiv: 2105.00599 (2021))
  - apply detector response: eV to e- conversion with low energy ionization yield (PRD 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:

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

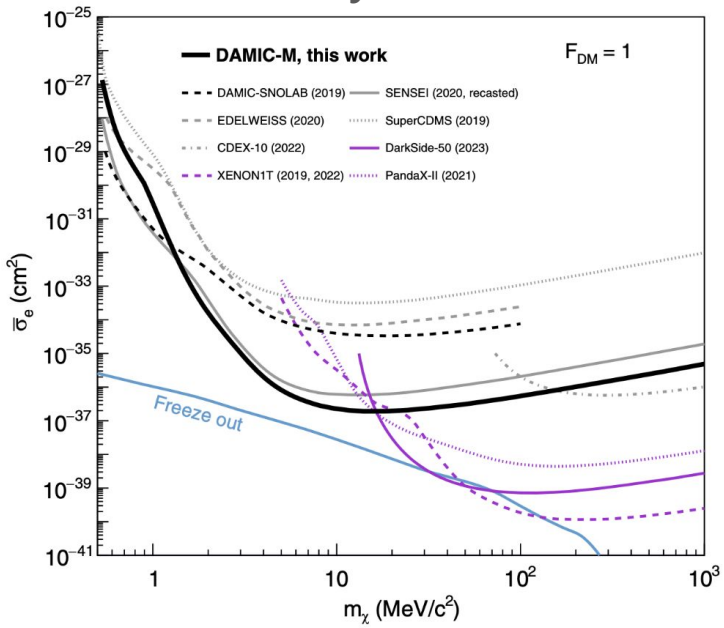
signal — dark current (estimated pixel by pixel) — readout noise

LBC - 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]

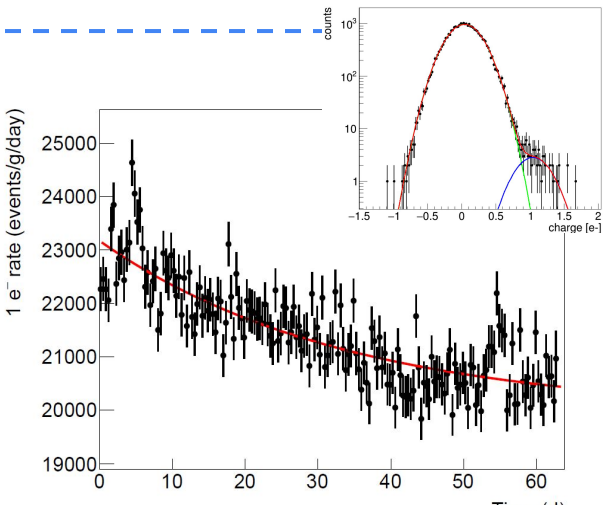
LBC - Daily modulation analysis

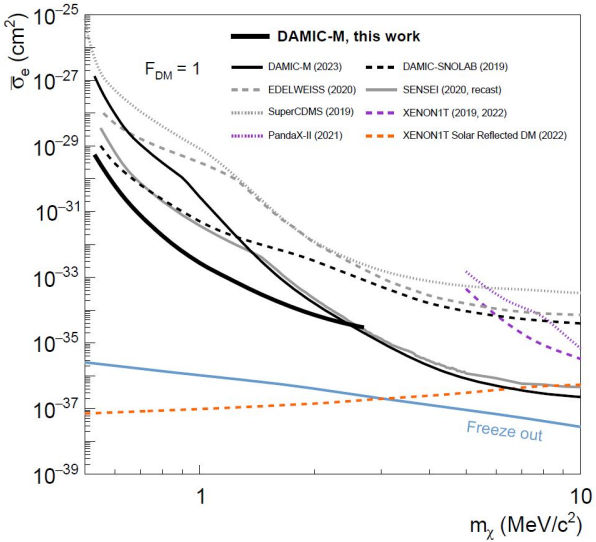
Daily modulation analysis with LBC [Phys. Rev. Lett. 132, 101006, 2024]

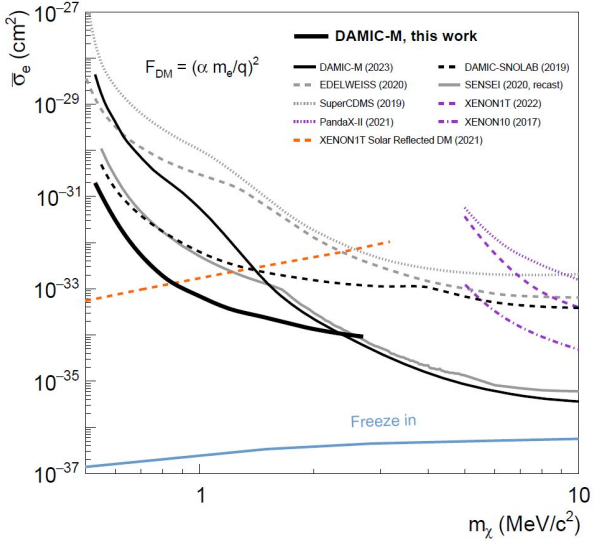
- **time-dependent** analysis to look for a daily modulated DM signal above an un-modulated background (39.97 g-days). DM expected to be modulated over a sidereal day due their interactions in the Earth

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

- Current **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



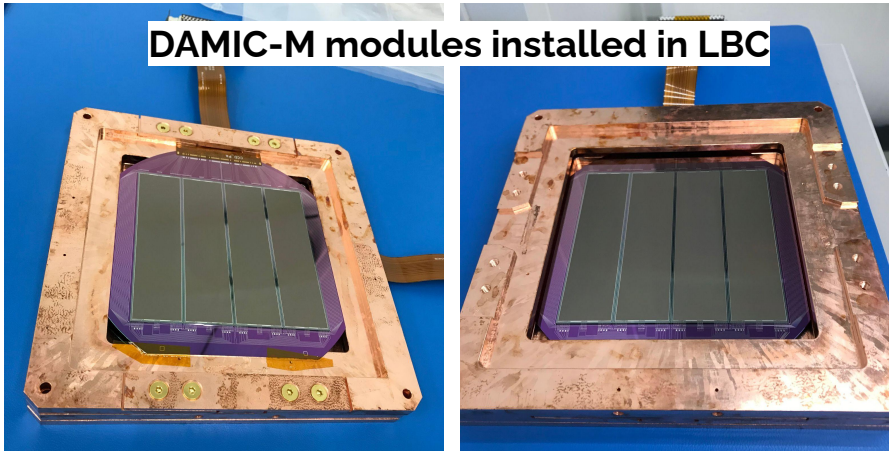


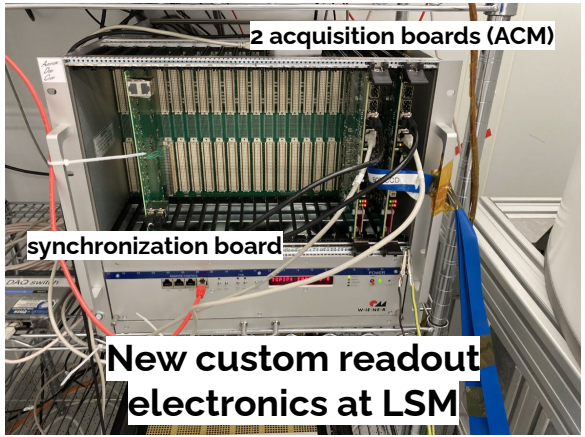


LBC - Current status

Current status:

- 2 DAMIC-M modules installed in LBC: 8 6k x 1.5k skipper CCDs
- Lower dark current: 3 times lower
- Lower background (~7 d.r.u):
  - Cleaner CCDs (shorter surface exposure)
  - More electroformed copper parts (EFCu box lids)
- Custom readout electronics installed for lower noise with fewer Nskips

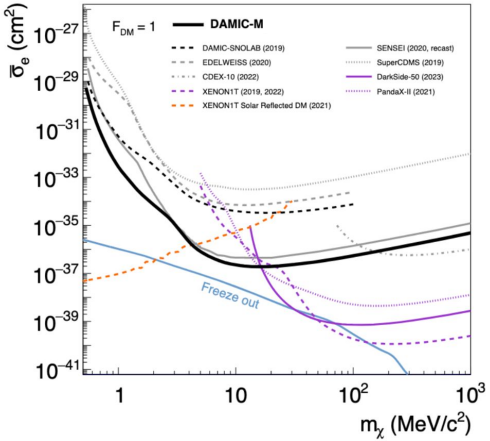


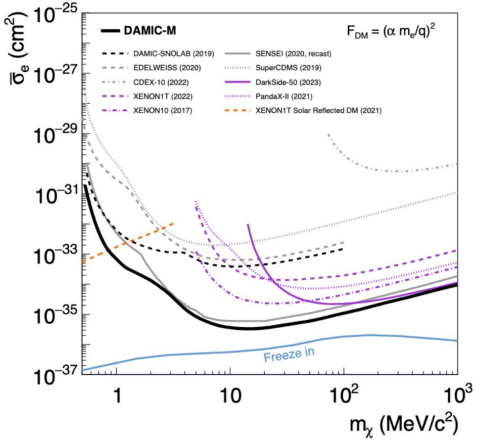


Conclusions

- **On our way towards DAMIC-M**
  - CCDs fabricated, being packaged and tested this summer
  - Calibration measurements:
    - Compton scattering measurement: Phys. Rev. D 106, 092001
    - Photo-nuclear scattering measurement: analysis ongoing
  - Design optimization and finalization
  - Electronics being tested

- **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
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