Colloque national Action Dark Energy - 6/7 Nov. 2023

Search for light Dark Matter with the DAMIC & DAMIC-M experiments

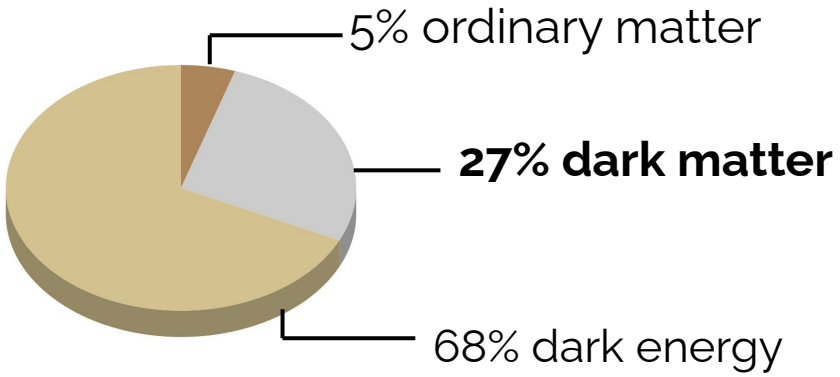
Claudia De Dominicis

Outline

- What is the DARK MATTER?
- What are DAMIC & DAMIC-M?
- DAMIC & DAMIC-M results

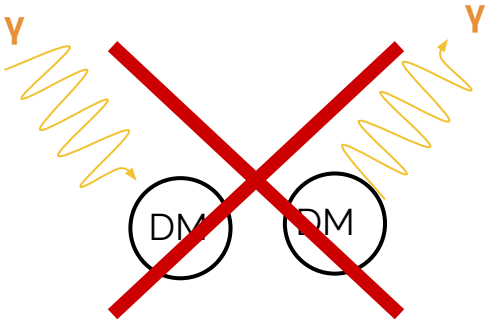
What is the DARK MATTER?

UNIVERSE
according to the ΛCDM model

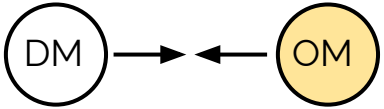


Dark **Matter**

Invisible

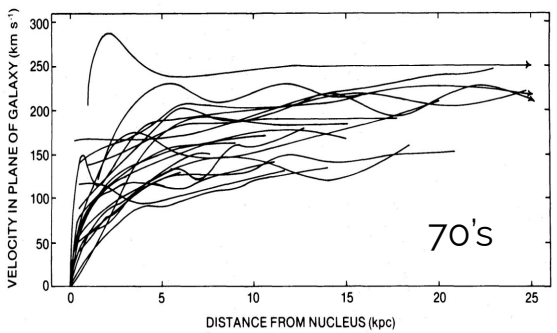


gravitational interaction



Some dark matter evidence

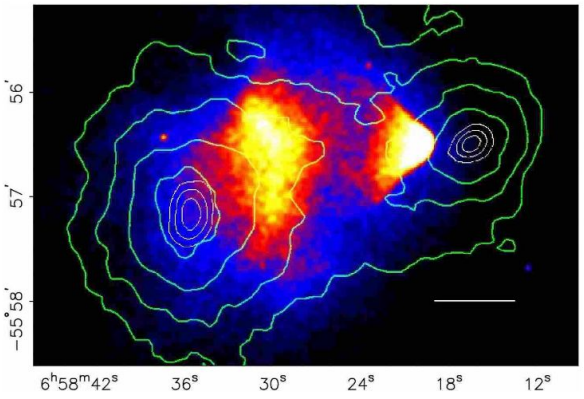
Galaxy rotation curves



Rotation curves for 21 spiral galaxies

V.Rubin et al., doi: 10.1086/158003

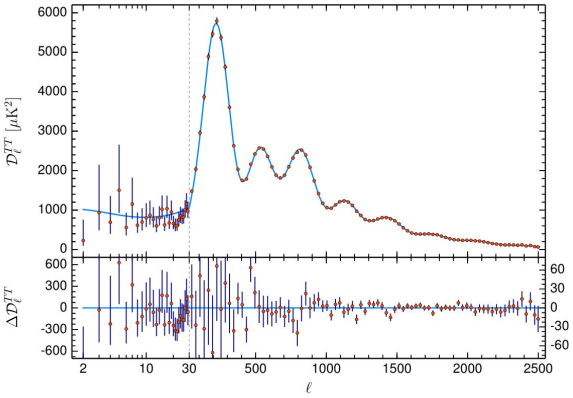
Gravitational lensing



Bullet cluster

D. Clowe et al, doi: 10.1086/508162

Cosmic Microwave Background



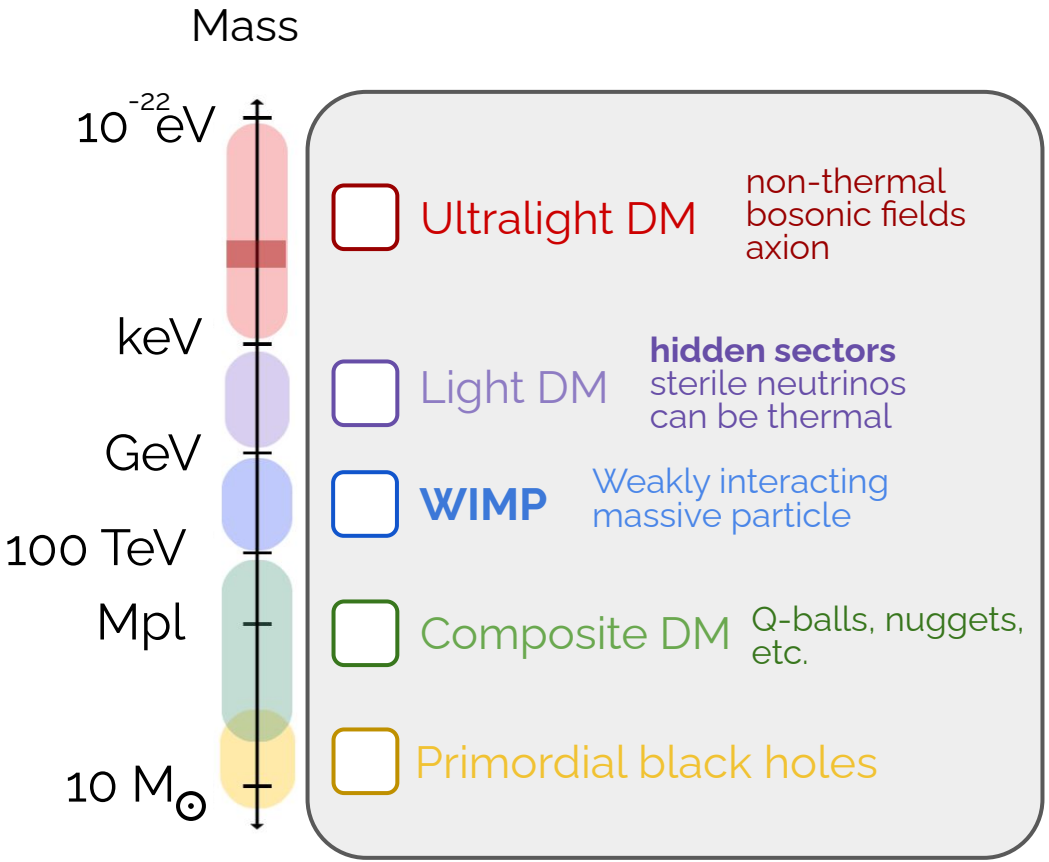
Planck 2018 temperature power spectrum

Planck coll., doi: 10.1051/0004-6361/201833910

Dark matter candidates

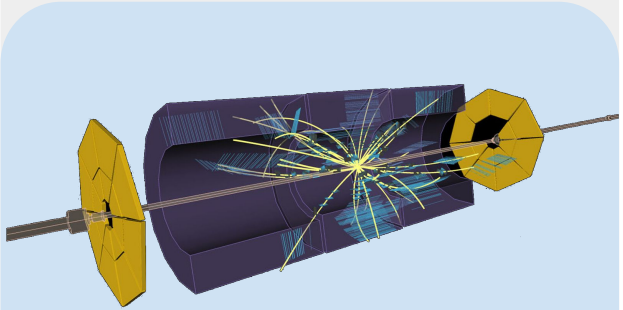
Dark matter features

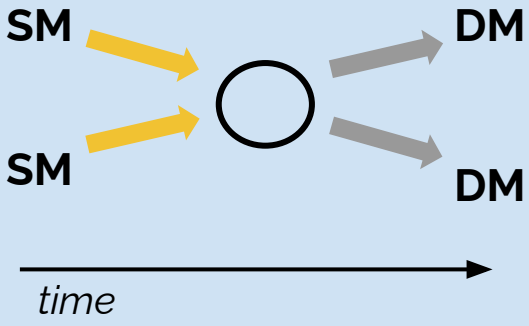
- interactions: gravitational, ???
- cold (or warm)
- collisionless
- stable
  life-time ~ Universe age



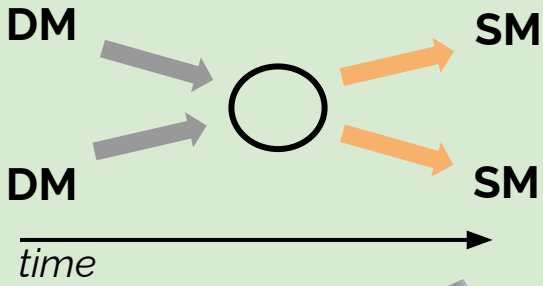
DM detection strategies

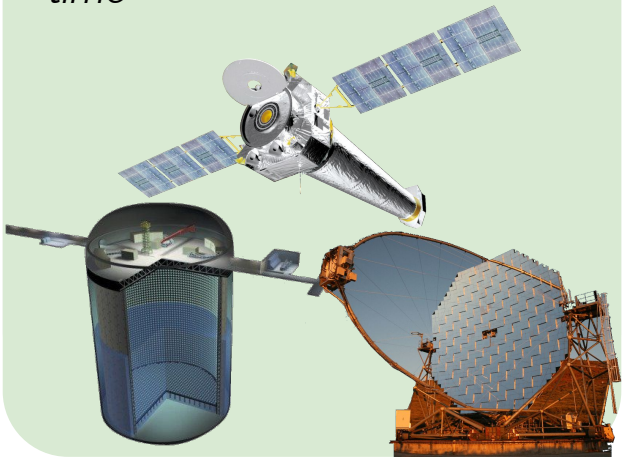
Production at colliders



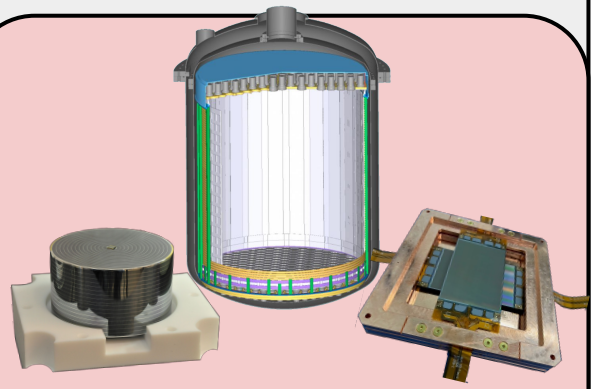


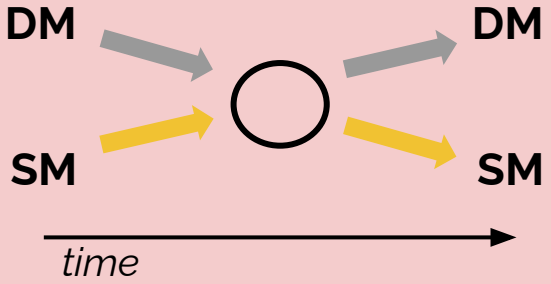
Indirect detection





Direct detection





DAMIC & DAMIC-M: Dark Matter in CCD

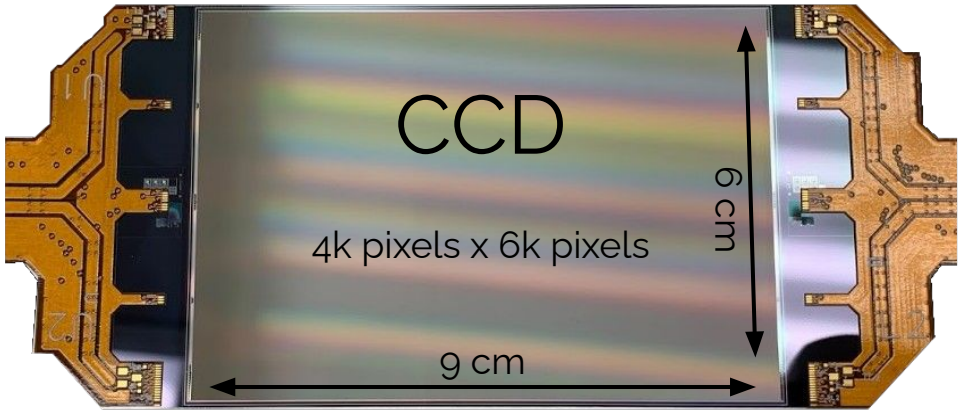
2017 2022 2024

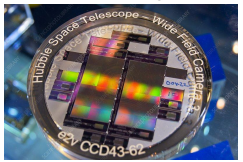
..TIMELINE...

Low Background Chamber LSM Laboratoire Souterrain de Modane

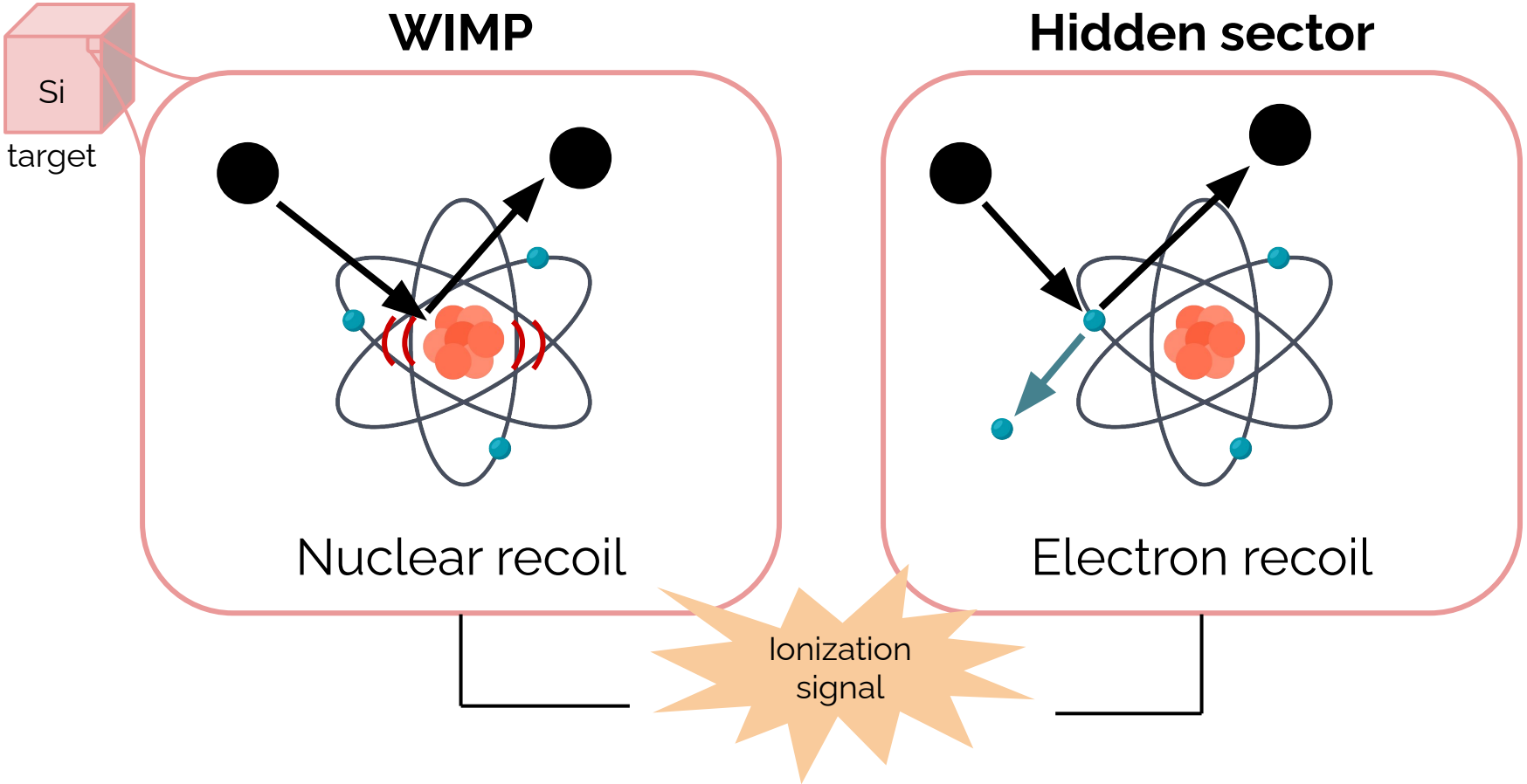
Aim

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



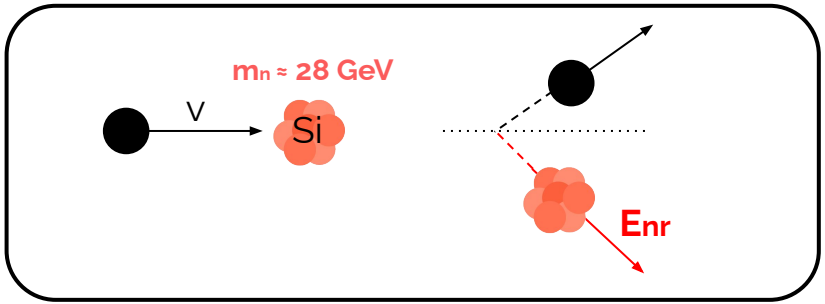


DM detection principle



DM detection principle

WIMP - Nuclear recoil



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

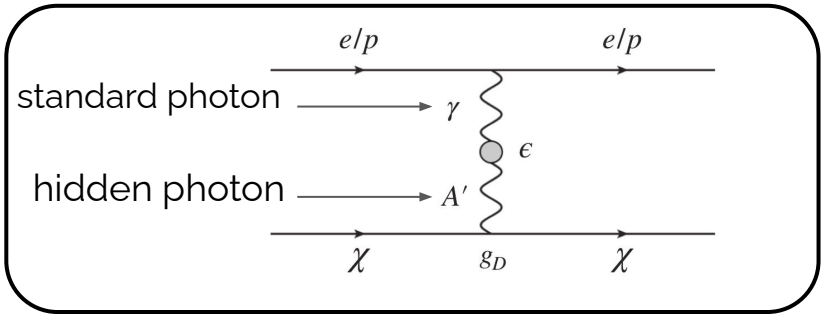
$$\begin{cases} 400\ \text{keV}\left(\frac{m_n}{28\text{GeV}}\right) & m_\chi >> m_n \\ 500\ \text{eV}\left(\frac{m_\chi}{1\text{GeV}}\right)^2\left(\frac{28\text{GeV}}{m_n}\right) & m_\chi << m_n \end{cases}$$

small mn → low mass WIMPs

m_χ = 100 MeV → Enr ≈ eV

not detectable with current direct detection threshold

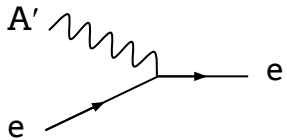
Hidden sector - Electron recoil



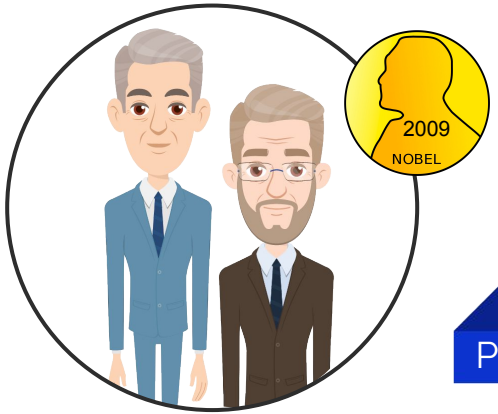
$$\Delta E_e \leq \frac{1}{2}\mu_{\chi N} v^2 \simeq \frac{1}{2}\ \text{eV} \times \left(\frac{m_\chi}{\text{MeV}}\right)$$

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

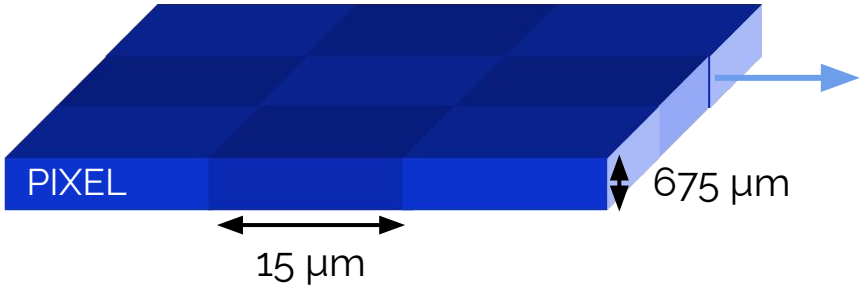
Hidden photon absorption is also possible. DM photon can be DM candidate!

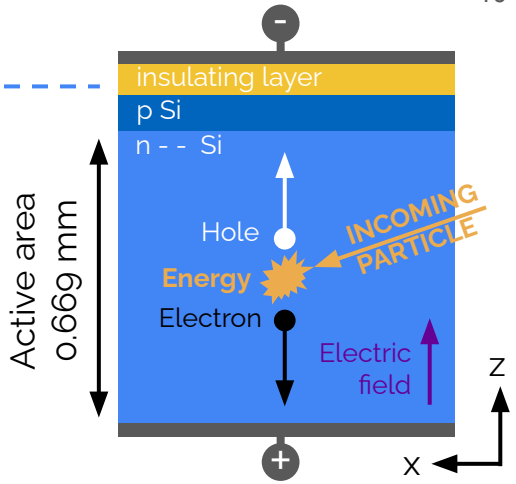


CCD operation



Willard Boyle
George E. Smith



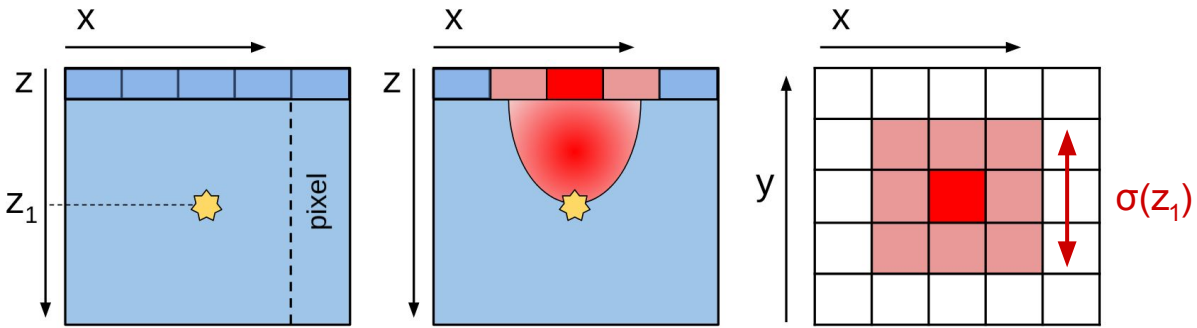


Interaction → Creation e-/h pairs → Diffusion → Hole collection

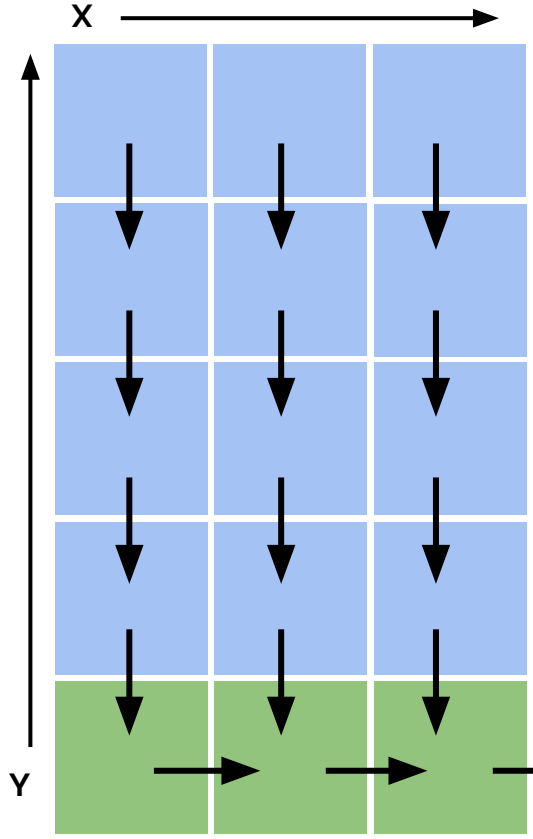
Diffusion

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-

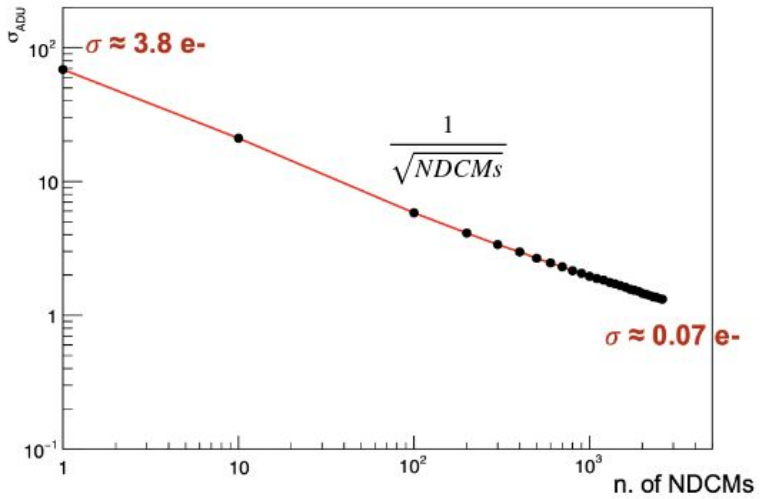
SUMMING WELL

SENSE NODE

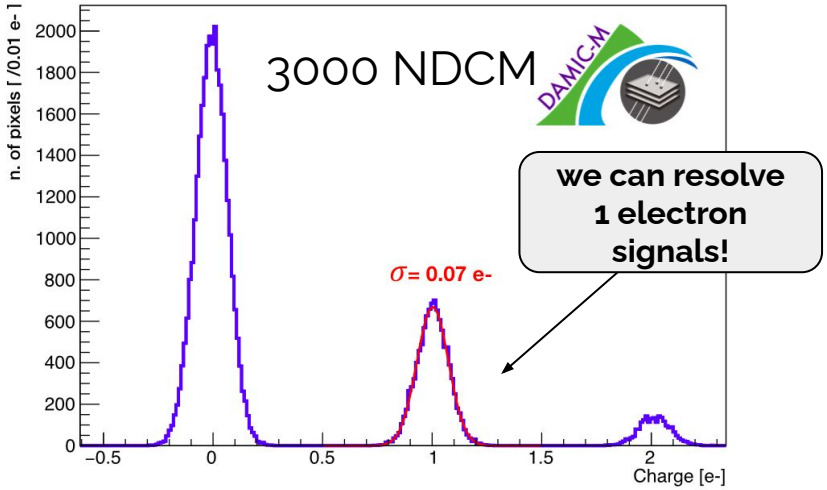
AMPLIFIER

Skipper readout

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

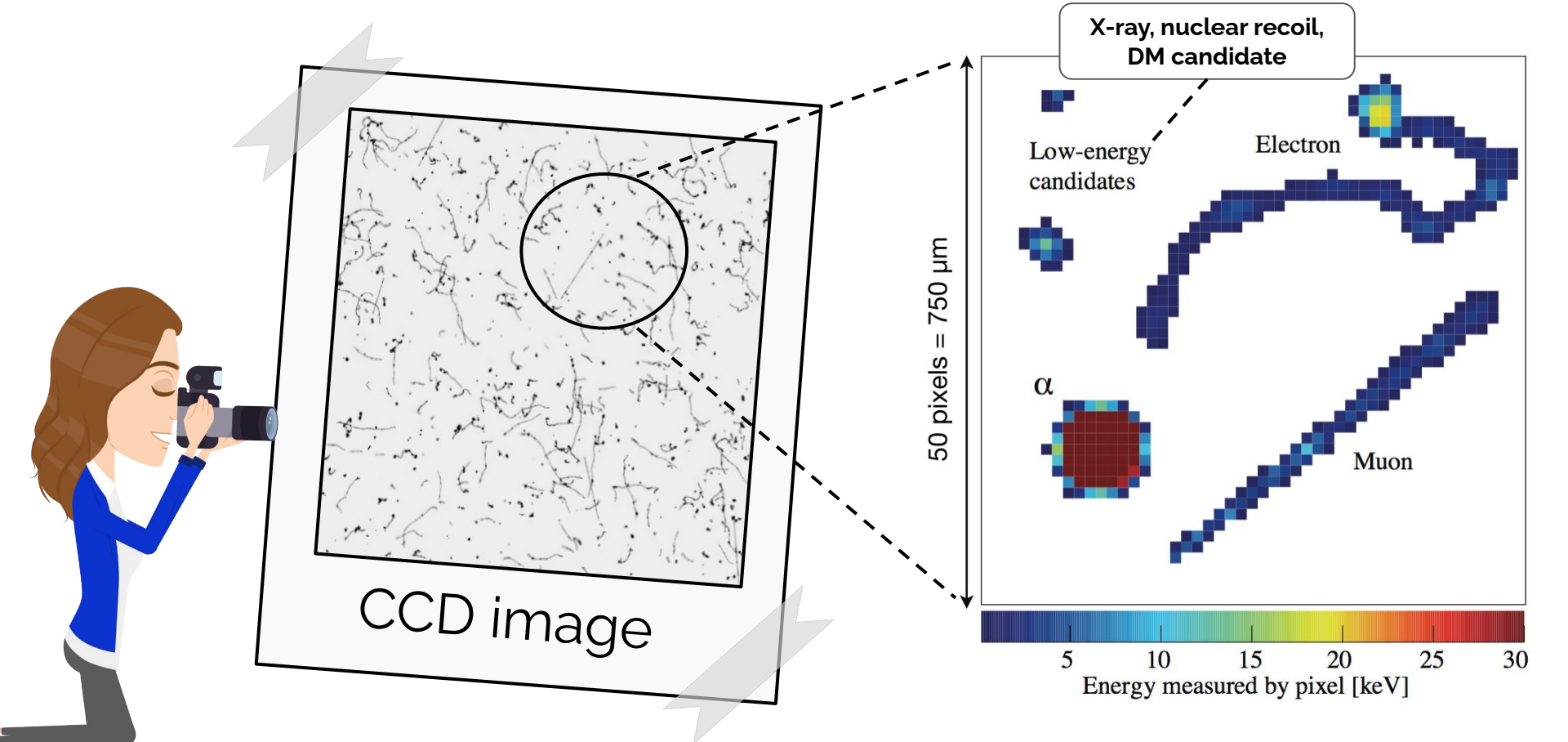


Pixel charge distribution
with SKIPPER amplifiers



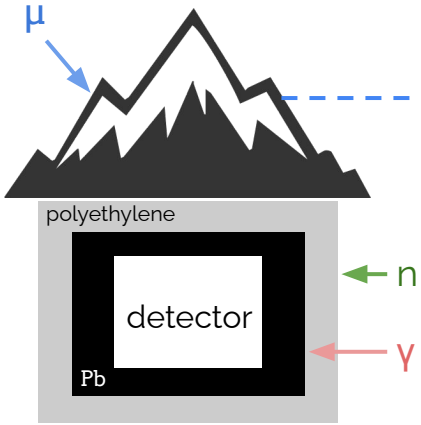
[arXiv:1706.00028]

Photographing particles



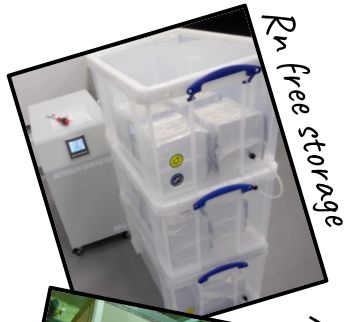
Backgrounds

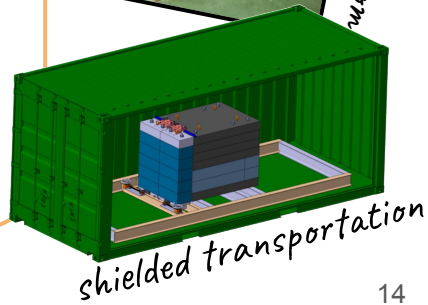
X-ray, n, DM?



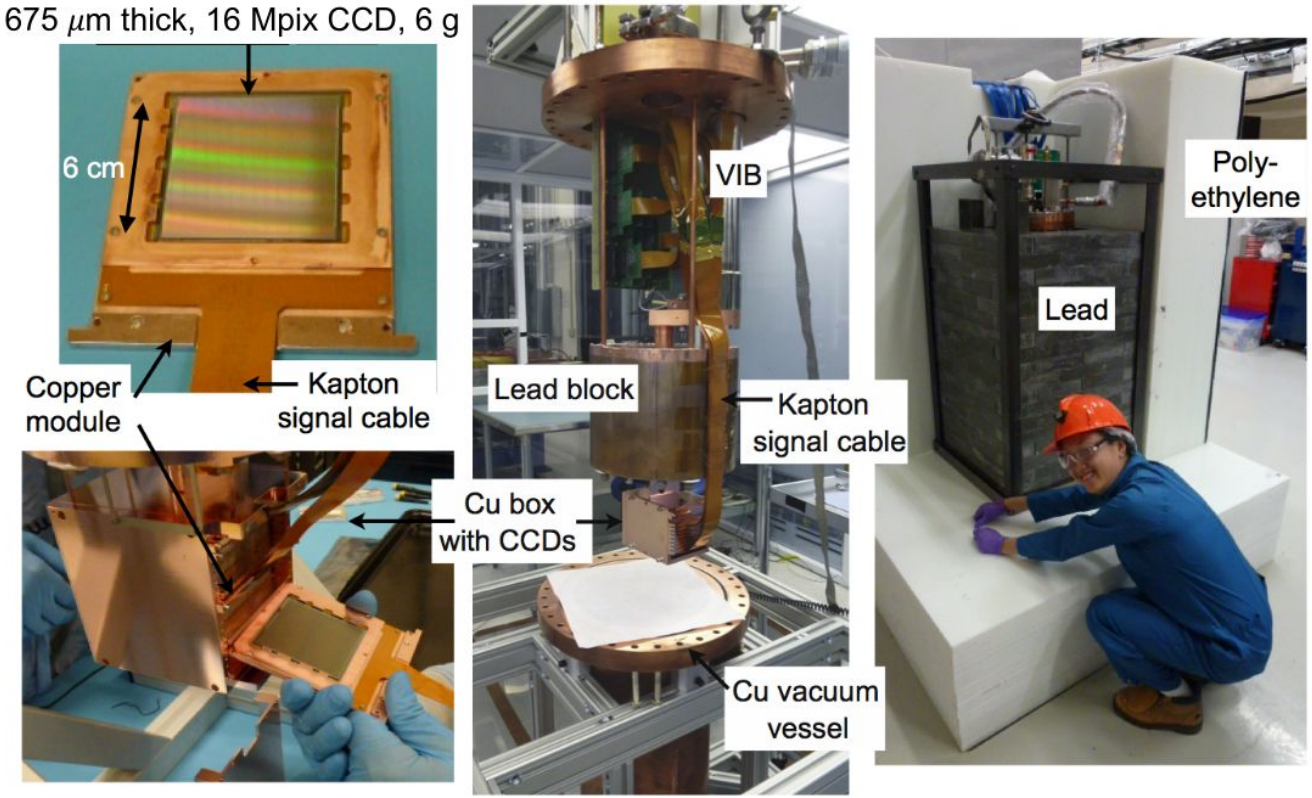
Background source	Solution
cosmic muons	underground laboratory
external neutrons	polyethylene shield
external gammas	Pb shield
internal background U-238, Th-232 chains cosmogenic activation (in Cu and Si) dark current	low background materials limit exposure to air (Rn) cleaning procedures limit exposure to cosmic rays low temperature

+ analysis techniques
+ optimization of the design





DAMIC at SNOLAB



Detector: 7 CCDs, 4kx4k pixels, 0.675 mm thick, 6g/CCD

Temperature: ~140 K

Location: SNOLAB (Canada)

Resolution: 1.6 e-

Dark current:
< 0.001 e–/pix/day

Background: ~12 d.r.u*

Operation: 2017-2019, upgrade in 2021

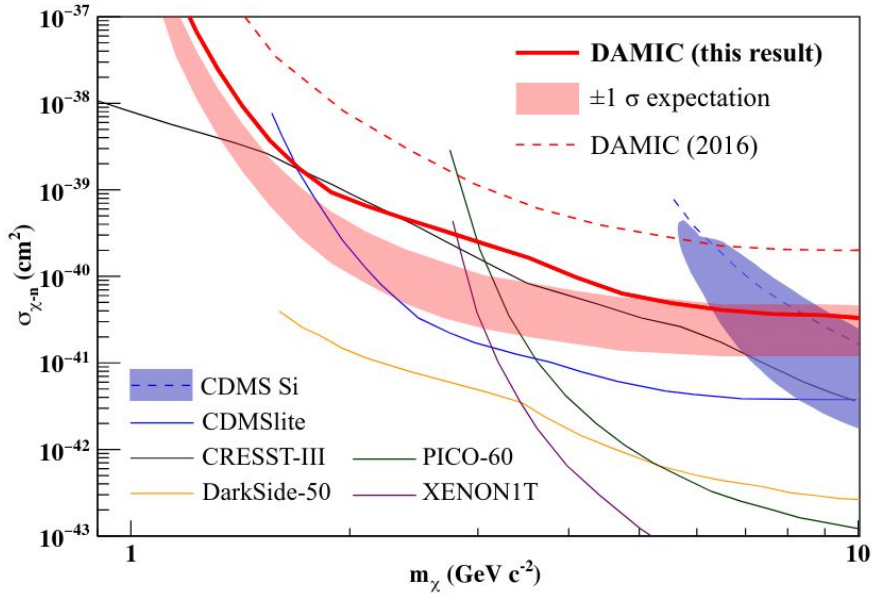
(*) 1 d.r.u = 1 event/kg/day/keV

DAMIC at SNOLAB - WIMP search

Upper limit (90% C.L.) on WIMP-nucleon cross section

Phys. Rev. Lett. 125, 241803 (2020)

exposure: 10.93 kg-days

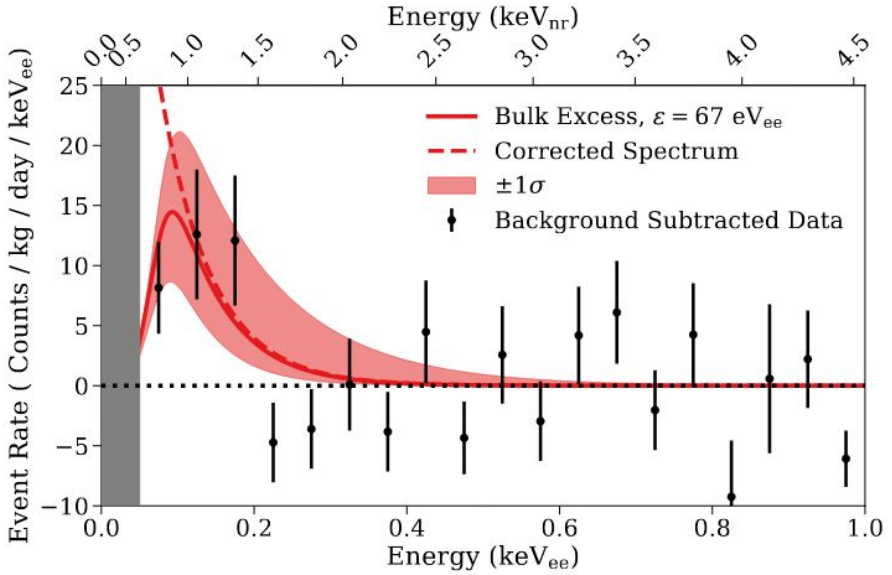


Events excess over background model (3.7 σ):

amplitude s = 17.1 ± 7.6 events and

decay energy ε= 67 ± 37 eVee

Phys. Rev. D 105, 062003 (2022)



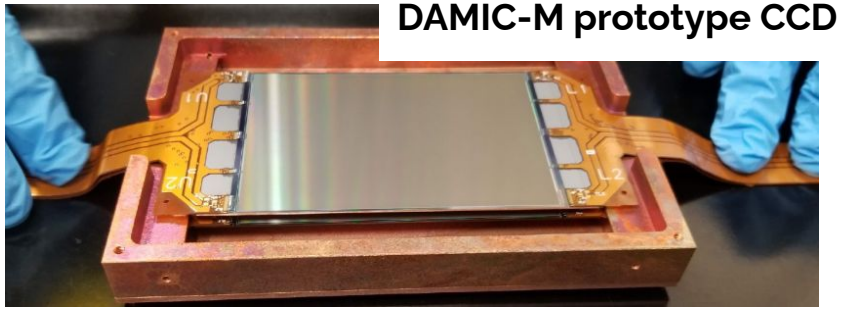
Unknown origin of the excess. Took data with skipper CCDs (DAMIC-M CCDs) to understand it.

DAMIC at SNOLAB - Upgrade

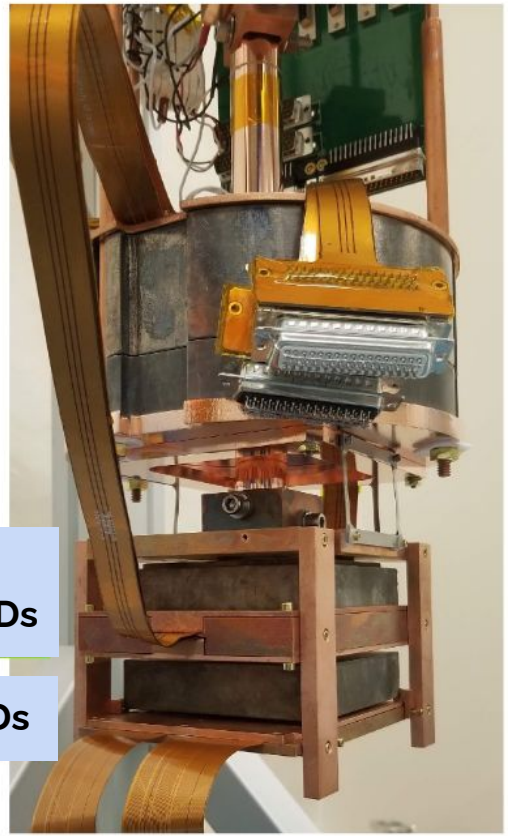
- Aim: investigate event excess found in DAMIC
- Two 24 Mpix DAMIC-M skipper CCDs (18 g Si target) installed in Oct-Nov 2021.
- Detector commissioning completed in early 2022.

Confirmation of the excess of bulk events, with unknown origin.

[arxiv:2306.01717]



DAMIC-M prototype CCD



DAMIC-M prototype CCDs

SENSEI CCDs

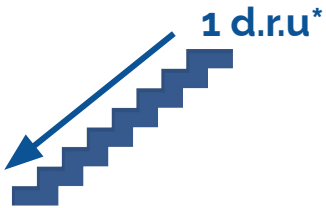
DAMIC-M features

TEMPERATURE

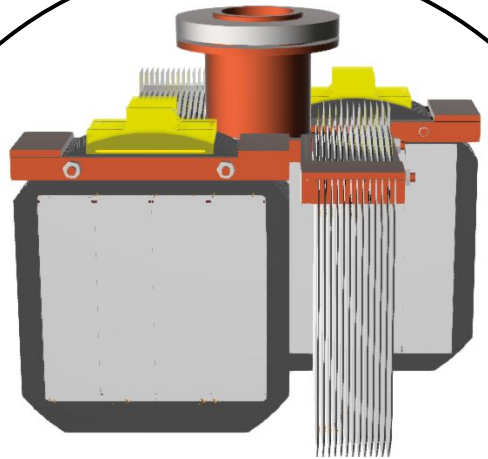
~100 K

-173,1 ˚C

BACKGROUND

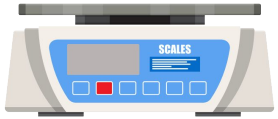


< 1 d.r.u



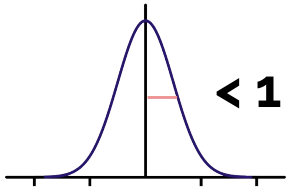
~200 skipper CCDs
1.5k pixels x 6k pixels

MASS



~1 kg

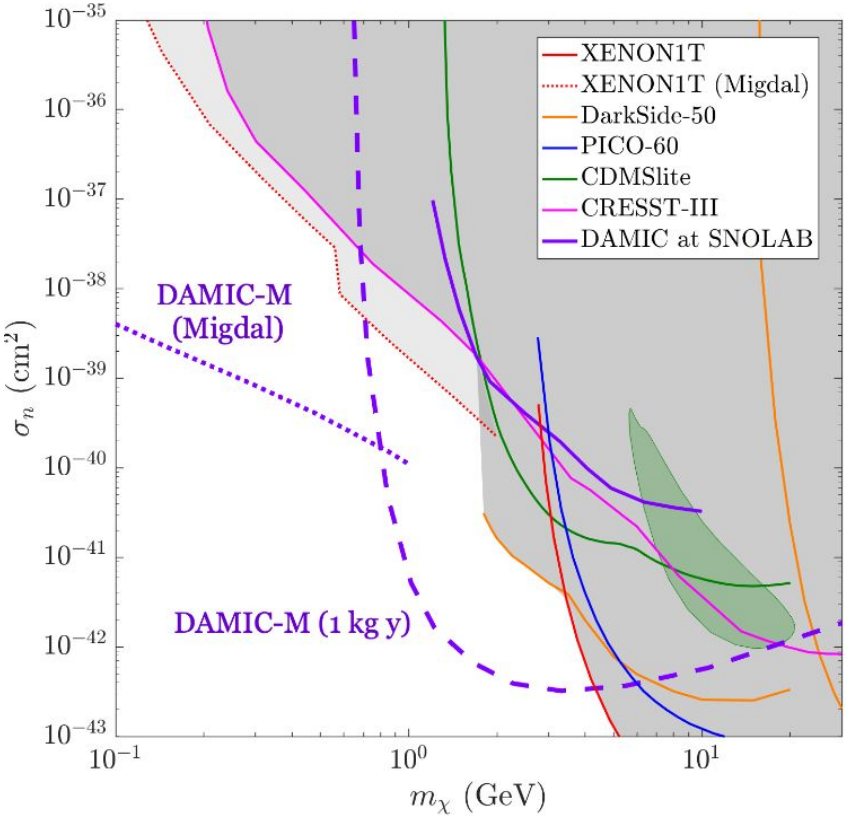
RESOLUTION
readout noise



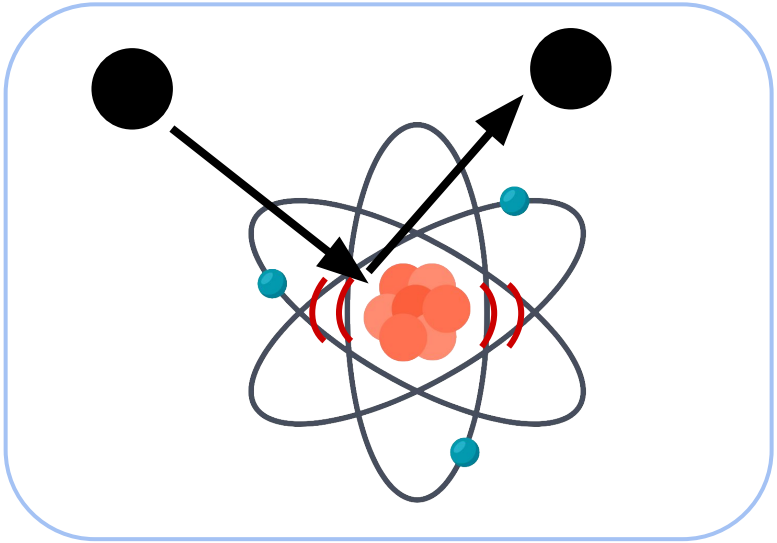
< 1 e-

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

DAMIC-M physics reach

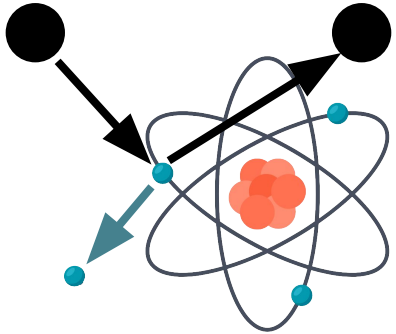


WIMP nuclear scattering

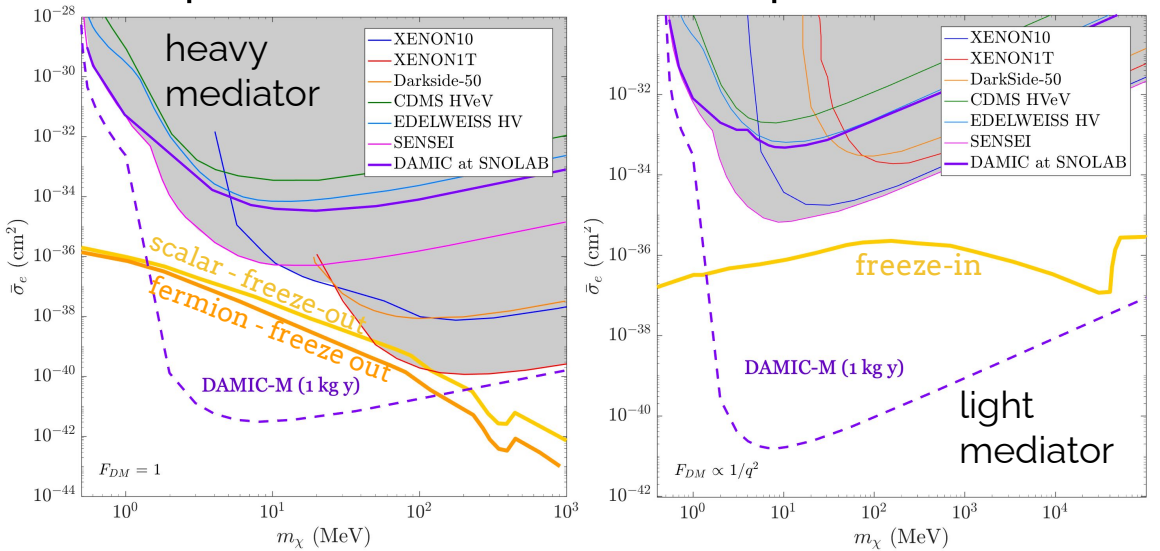


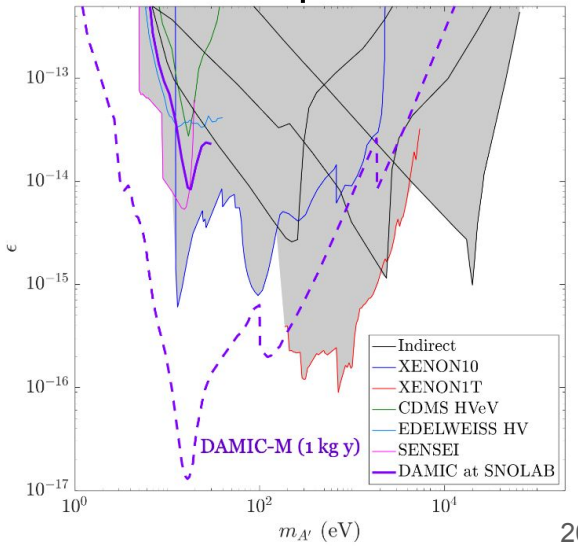
DAMIC-M physics reach

Hidden sector particle electron scattering



Hidden photon absorption

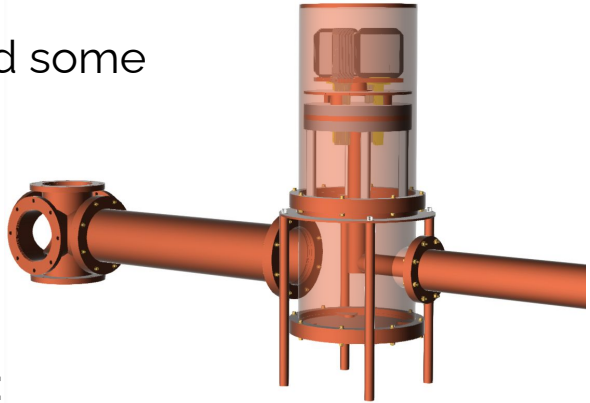




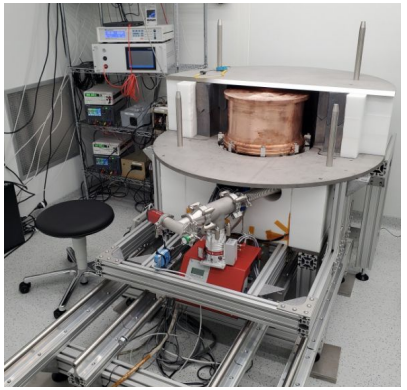
Status of DAMIC-M

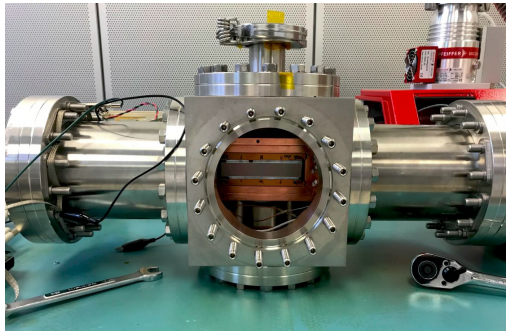
- Detector design almost finalized and some part prototypes are tested
- CCD production ongoing
- Electronics designed, under test
- Calibration with radioactive sources:
  - gamma source: Phys. Rev. D 106, 092001
  - neutron source: ongoing
- Low Background chamber operating at LSM
- Installation in 2024

Preliminary design DAMIC-M



LBC @LSM



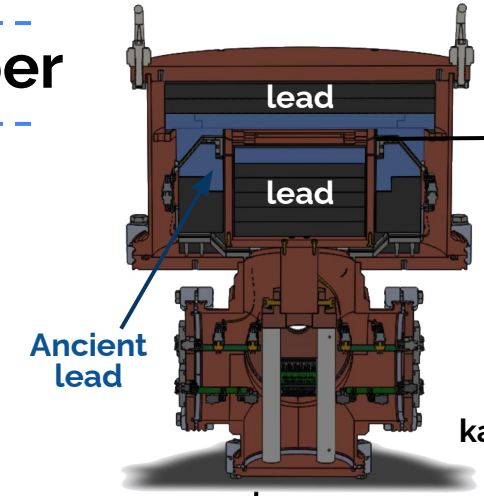


Compton measurement setup @UChicago

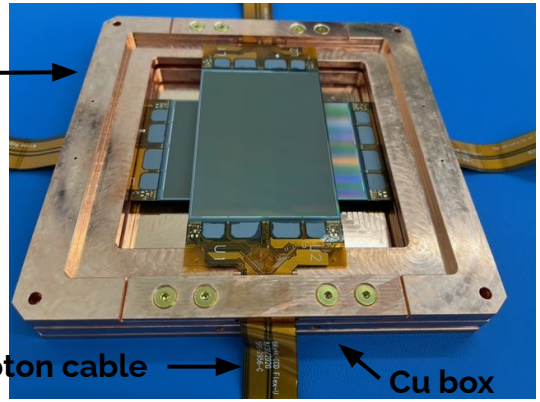
Low Background Chamber

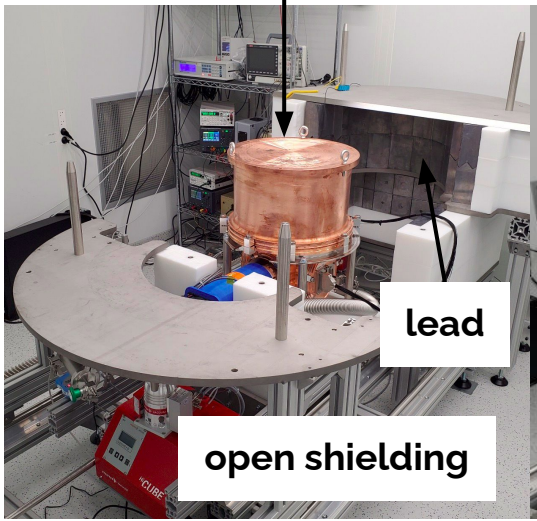
- **Aim:**
  - Demonstrate the ability to control backgrounds for DAMIC-M
  - integration/operation of DAMIC-M electronics
  - Provide test bench for dark current studies and reduction strategies
  - First dark matter search

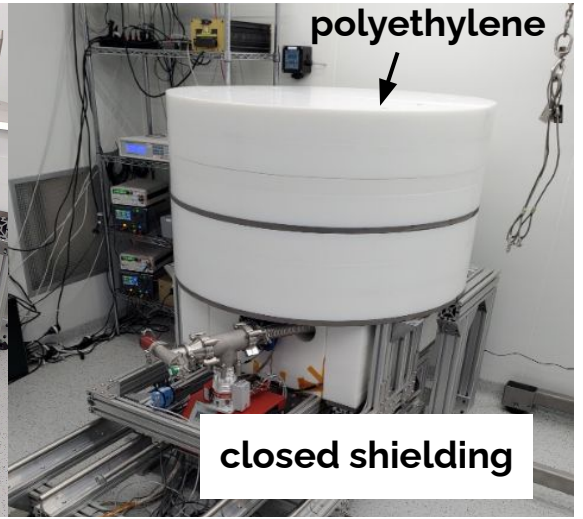
- **Achievements:**
  - Installed at LSM at the end of 2021
  - **First results for hidden sector candidates with an exposure of 85.2 gr-day**
  - Upgrade with DAMIC-M modules: 2 modules = 8 CCDs (1,5k x 6k)



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

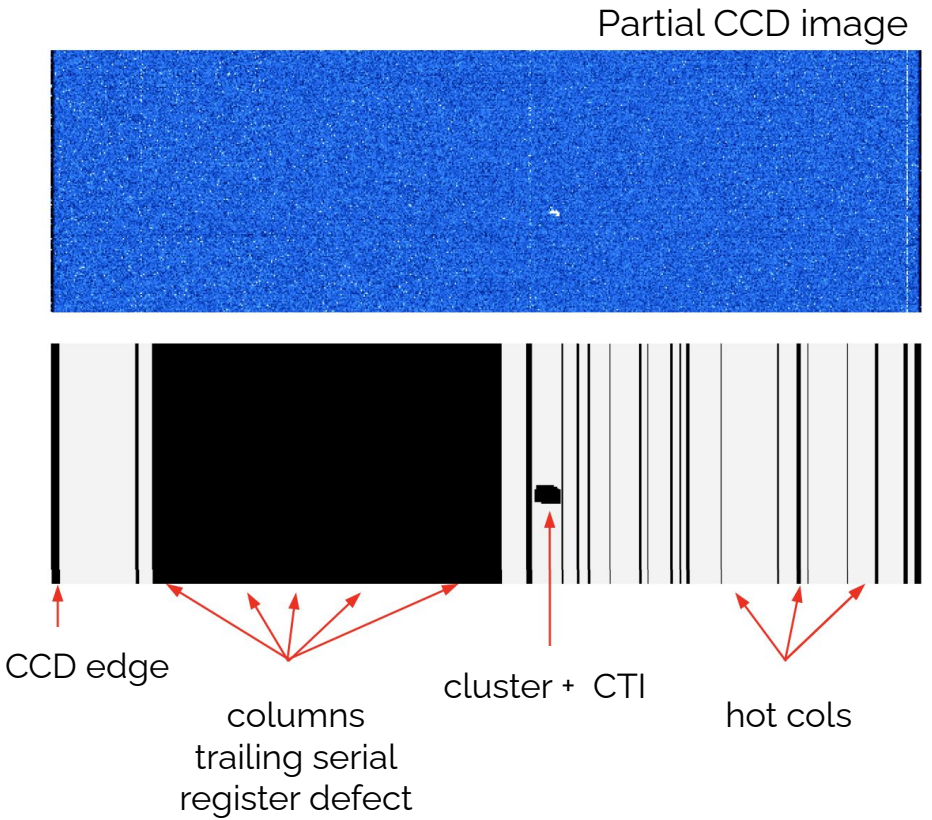




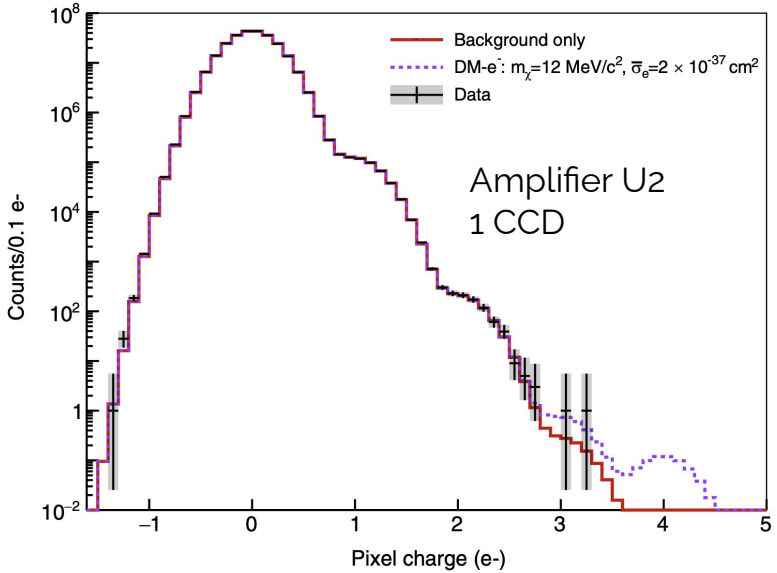


LBC - Data Selection

- **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

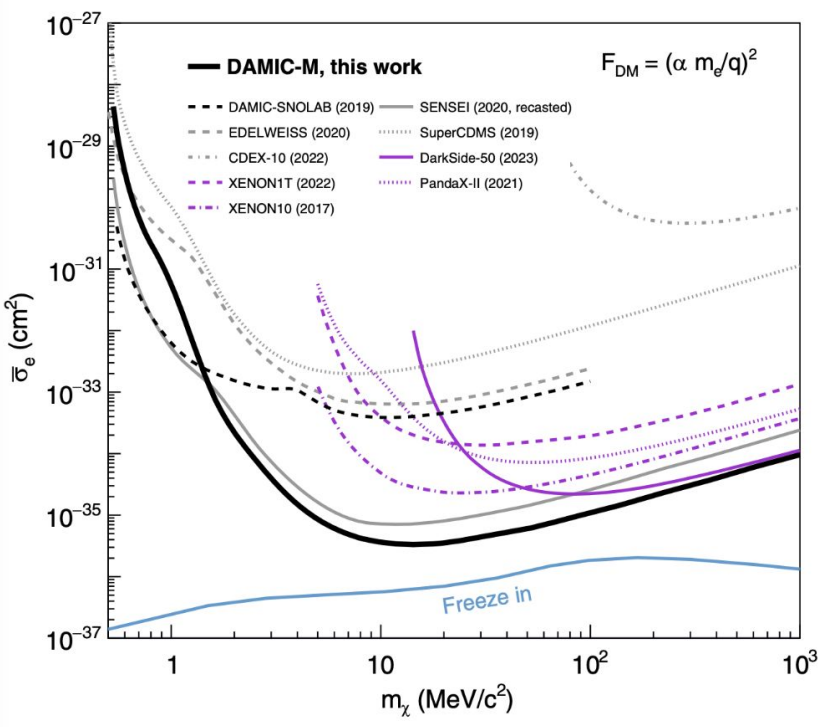


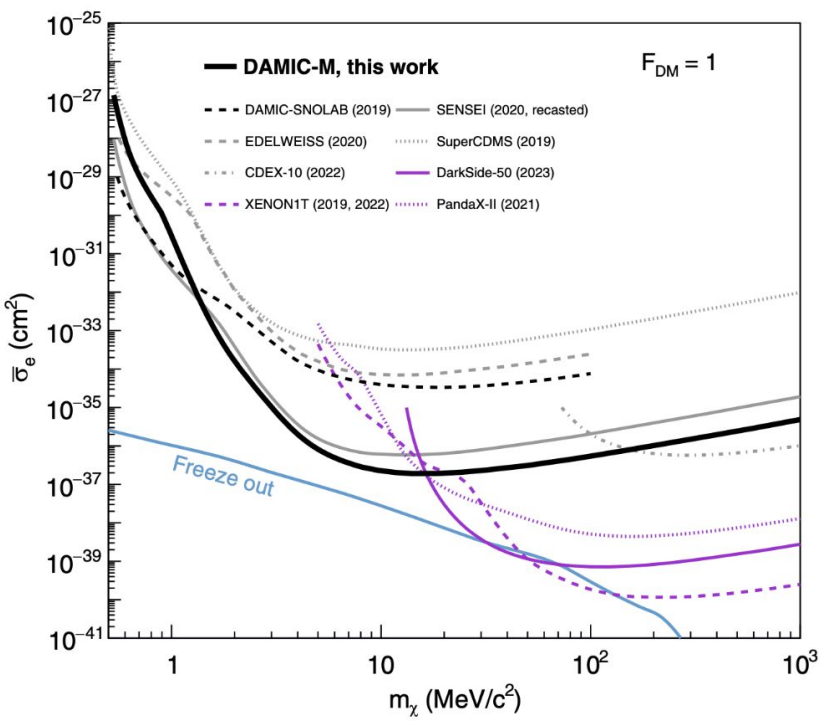
- **Measure single pixel charge distribution (PCD)** per amplifier per CCD
- **DM signal generation**:
  - QEdark to generate differential rate of DM signal with halo parameters from PhystatDM (arXiv: 2105.00599 (2021))
  - apply detector response: : eV to e- conversion with low energy ionization yield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





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

LBC - 90% CL upper limits results

You can find our paper among PRL editors' suggestions!!!!

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- [x] ALL

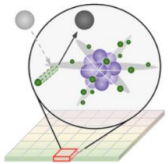
Editors' Suggestion

PDF HTML

First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons

I. Arnquist *et al.* (DAMIC-M Collaboration)

Phys. Rev. Lett. **130**, 171003 (2023) – Published 28 April 2023

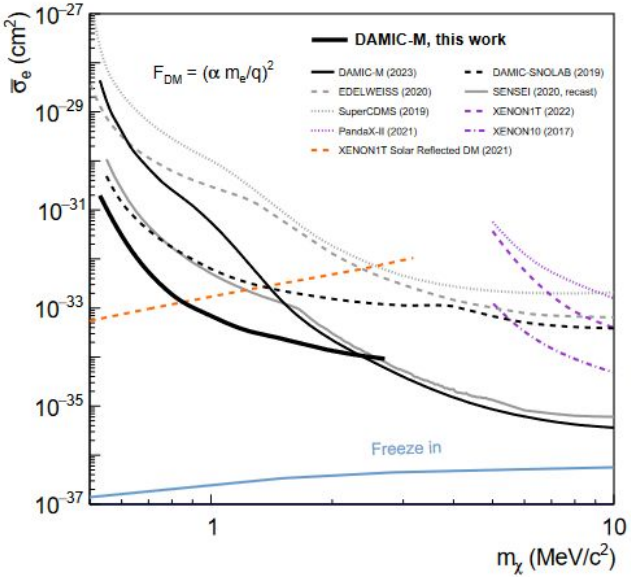


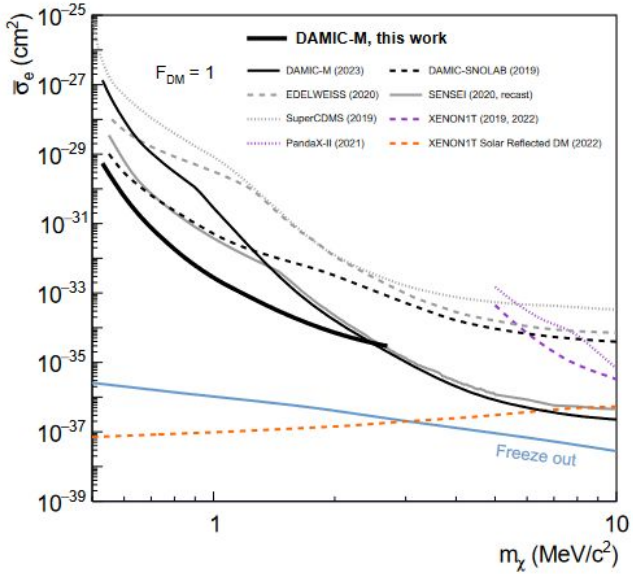
World-leading constraints are placed on electron interactions with dark matter in the MeV to GeV range by the first underground operation of a new CCD detector.

Show Abstract +

LBC - Daily modulation 90% CL upper limits results

We performed a time-dependent analysis to look for a daily modulated DM signal above a time-independent background. DM expected to be modulated over a sidereal day due their interactions in the Earth





Arxiv: 2307.07251

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] MeVan d [0.53, 15.1] MeV for ultralight and hevy mediator interactions

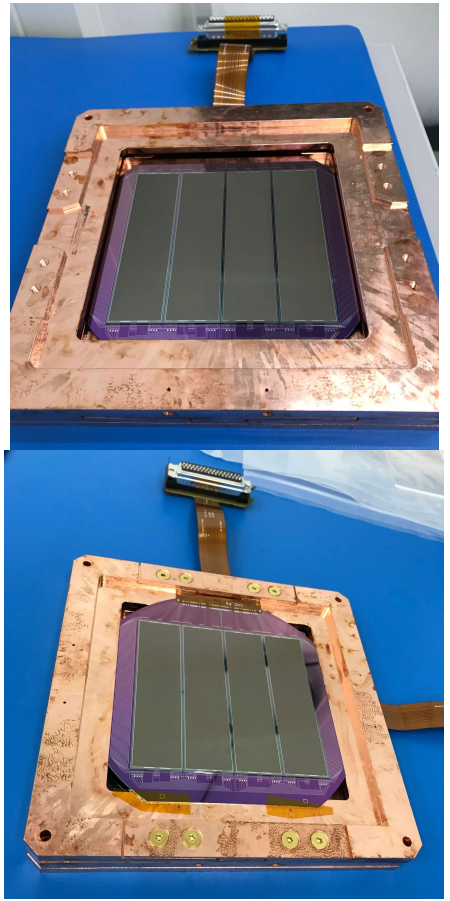
LBC - Current status and next steps

Current status:

- 2 DAMIC-M modules installed in LBC: 8 6k x 1.5k skipper CCDs
- Commissioning phase: optimization of parameters, study of CCD performances and noise
- Lower dark current: 3 times lower
- Lower background (to be measured):
  - Cleaner CCDs (shorter surface exposure)
  - More electroformed copper parts (EFCu box lids)
  - Lower background cables

Next steps:

- Improve sub-electron resolution: Custom readout electronics for lower noise with fewer Nskips



DAMIC-M modules installed in LBC

Postcard from LSM

LBC installation, December 2021

Thank you for the attention !

European Research Council
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