
# DAMIC-M: Status and First results

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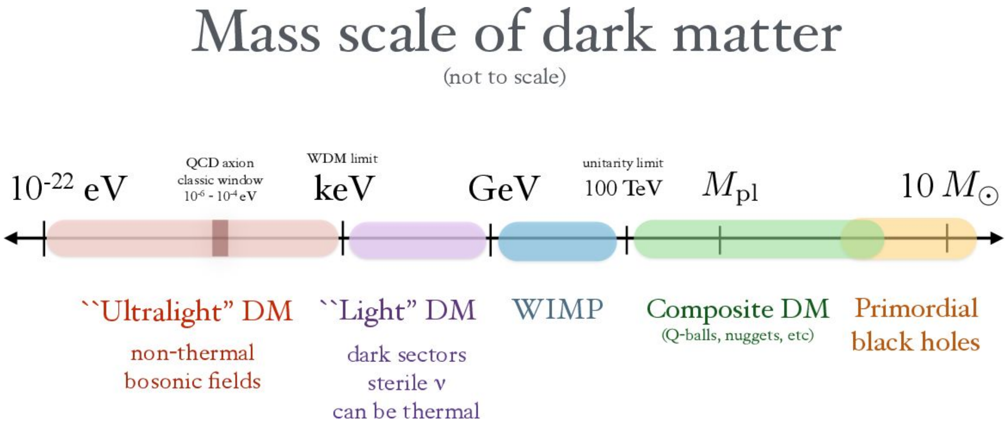
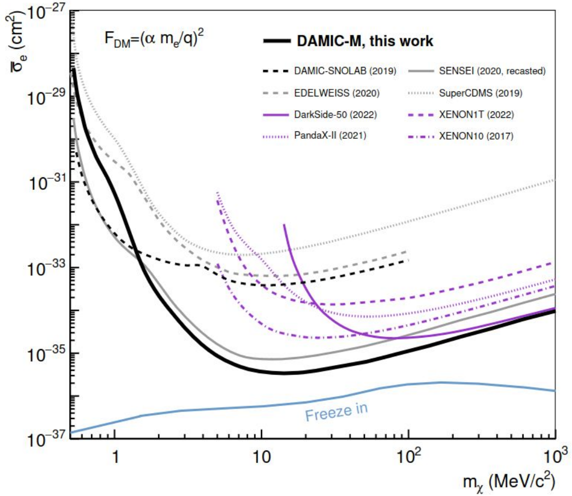
# Dark Matter Searches



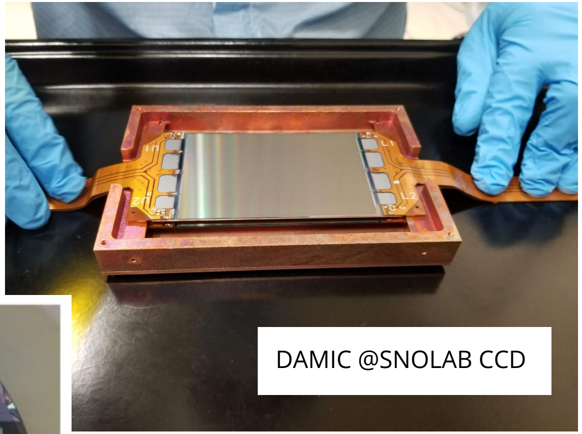

Lin, Tongyan. "TASI lectures on dark matter models and direct detection." *arXiv: High Energy Physics - Phenomenology* (2019): n. pag.

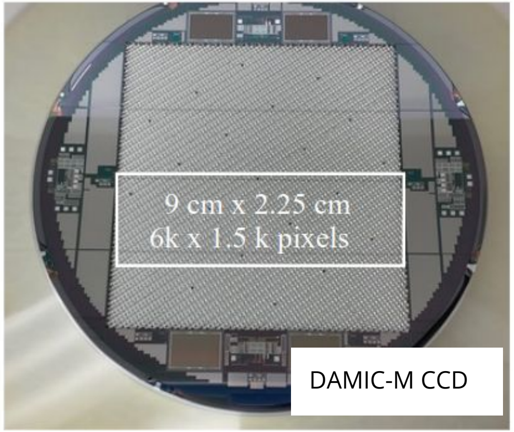
- **Dark Matter** (DM) existence is an observational evidence.
    - Cold Dark matter.
    - Local density 0.3 GeV $c^{-2}cm^{-3}$.
    - The Standard Model can not predict it's properties.
- The **search for sub-GeV** is yet to be explored in the following years with direct searches experiments:
    - Dark Matter scatters with the nucleons and electrons of the detector with low probability.
    - Detectors with low energy thresholds, low environmental backgrounds and large exposures.

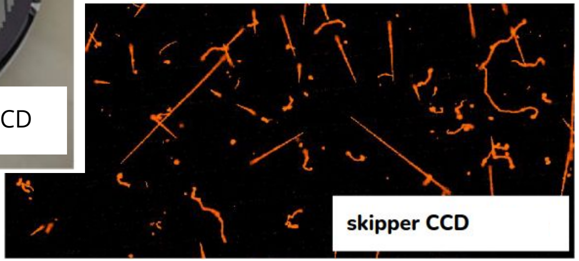


# CCDs for Dark Matter Detection

- **Charged Coupled Devices (CCDs)** are widely used in astrophysics experiments.
- **Features:**
  - Silicon
  - Mono-crystal.
  - n-type.
  - High resistivity (>10,000 Ω cm).
  - Three-phase polysilicon structure to keep and transfer the charge.

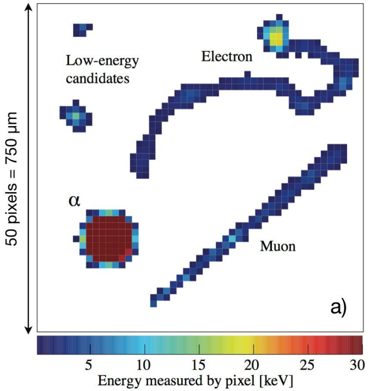


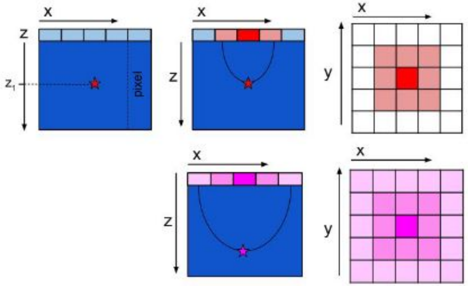



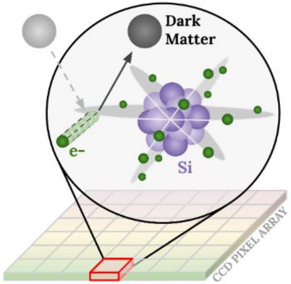



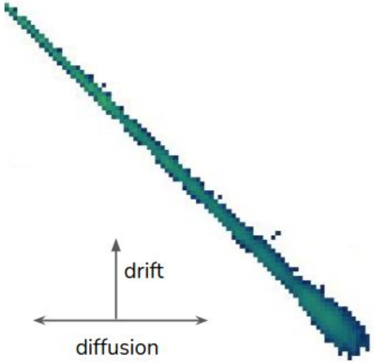
# CCDs for Dark Matter Detection

- Particle interacts with the Silicon nucleus or electrons **generating charge** that is collected in the pixels.
- The charge is **diffused** to the contiguous pixels.
    - The dispersion of the charges will depend on the depth of the interaction.
- The trace of the interacting particle can be **reconstructed**.
    - The shape gives information about the type of particle.
- **High spatial resolution.**

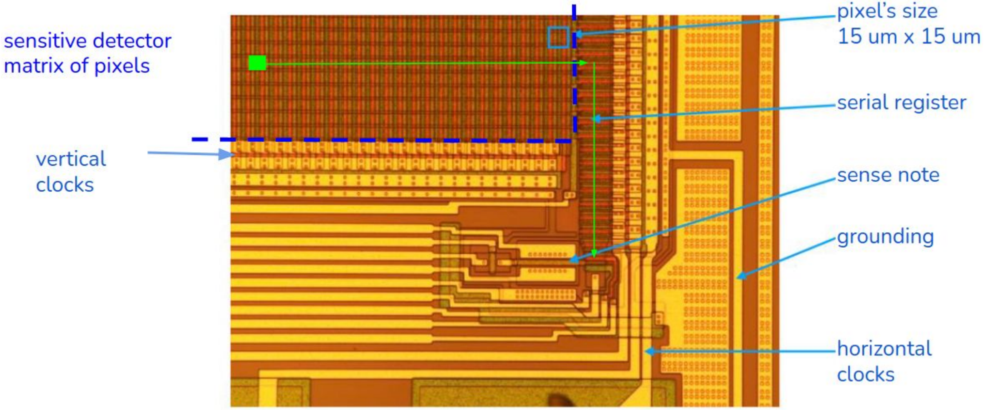


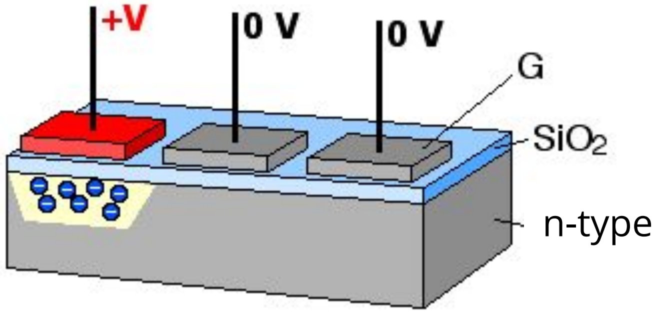



# Charge transfer

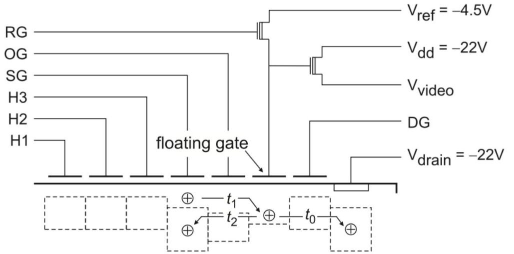


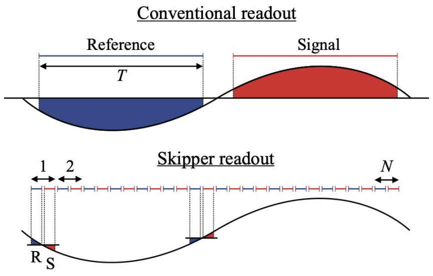

- The pixel **charge is transferred** to the contiguous pixel by changes in the potential voltage of the gate phases.
- An **appropriate clocking** allows to move all the charge through all the pixels until reaching the amplifier.
- **Charge Transfer Inefficiency** (CTI) is quite low.
  - CTI ~ $10^{-6}$ $e^{-}$/transfer.
- **Amplifier** converts charge into voltage.
  - This voltages are converted into **ADC** (Analog to Digital Conversion).

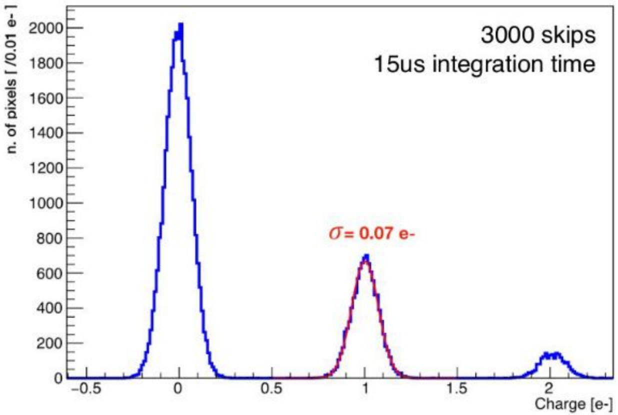


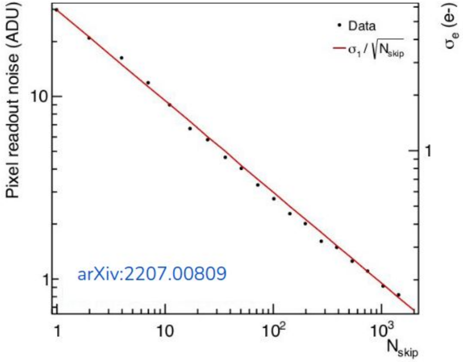
# Skipper readout

- In 2017, the **<u>new Skipper CCDs</u>** demonstrated that a **pixel can be measured *N* uncorrelated times**.
  - Pixel charge is moved back a forward into the sense node and readed multiple times.
  - Reduce the subdominant low frequency amplifier noise *1/f*.
  - **<u>Readout noise reduce by 1/√N.</u>**
  - For large number of skippers **<u>sub-electron readout noise</u>** is reached.

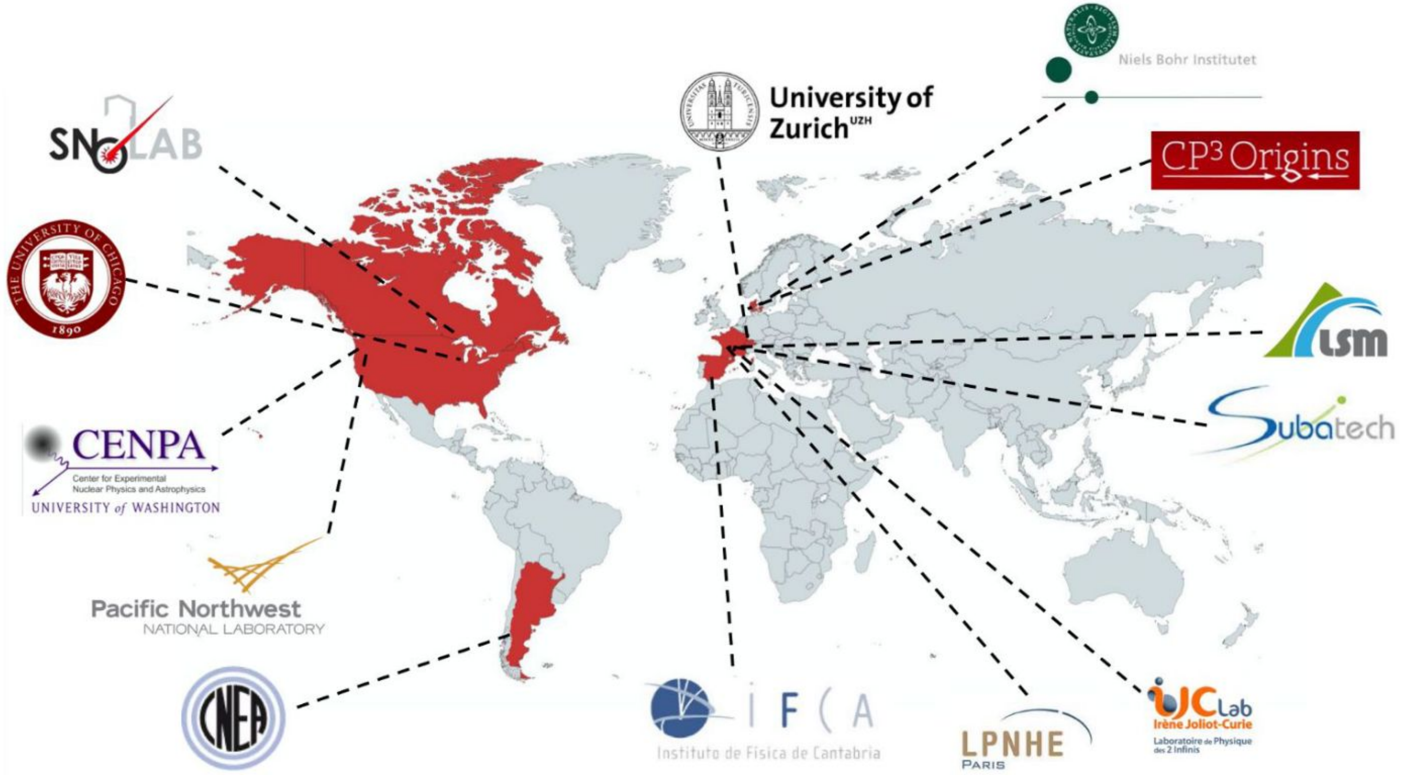


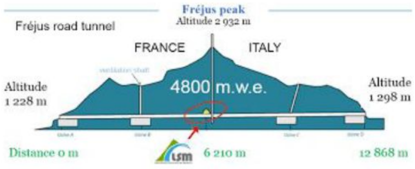



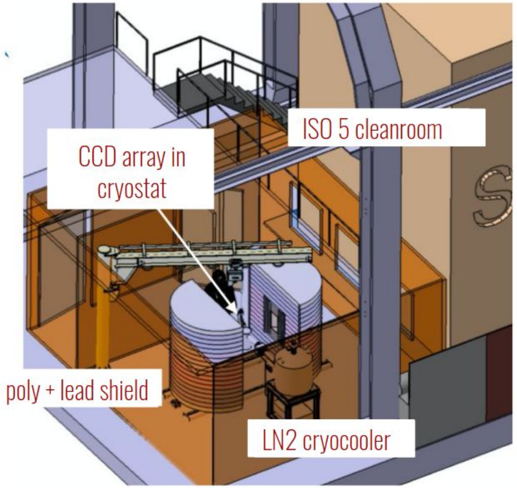
# The DAMIC-M Collaboration



# Dark Matter in CCDs at Modane (DAMIC-M)

- **<u>Laboratoire Souterrain de Modane (LSM).</u>**
  - 4800 water equivalent meters under Fréjus peak.
- **<u>Detector specifications.</u>**
  - 208 skipper CCD arrays.
  - 9 Mpixels, 675 μm thick and $m_{CCD}$~3.5 g.
  - $m_{detector}$~ 700 g.
  - Single electron resolution and self-calibration.
  - Low dark current.
- **<u>Goals.</u>**
  - Few eV threshold.
  - Fraction of dru (events/g/days) background.
  - Nuclear and electron recoils detection in the sub-GeV mass range.

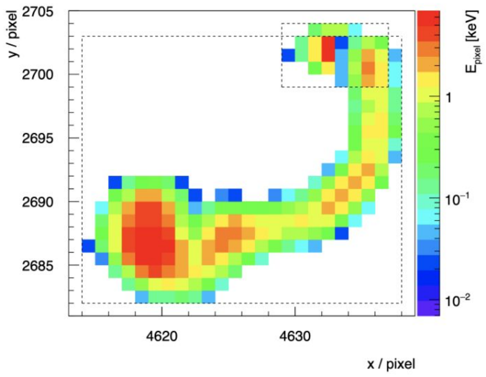


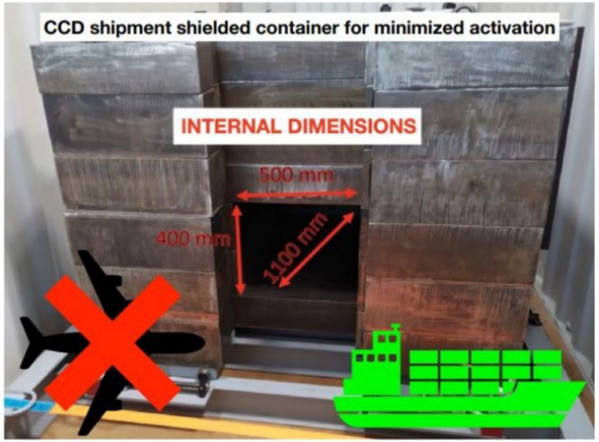



# DAMIC-M: Background Mitigation

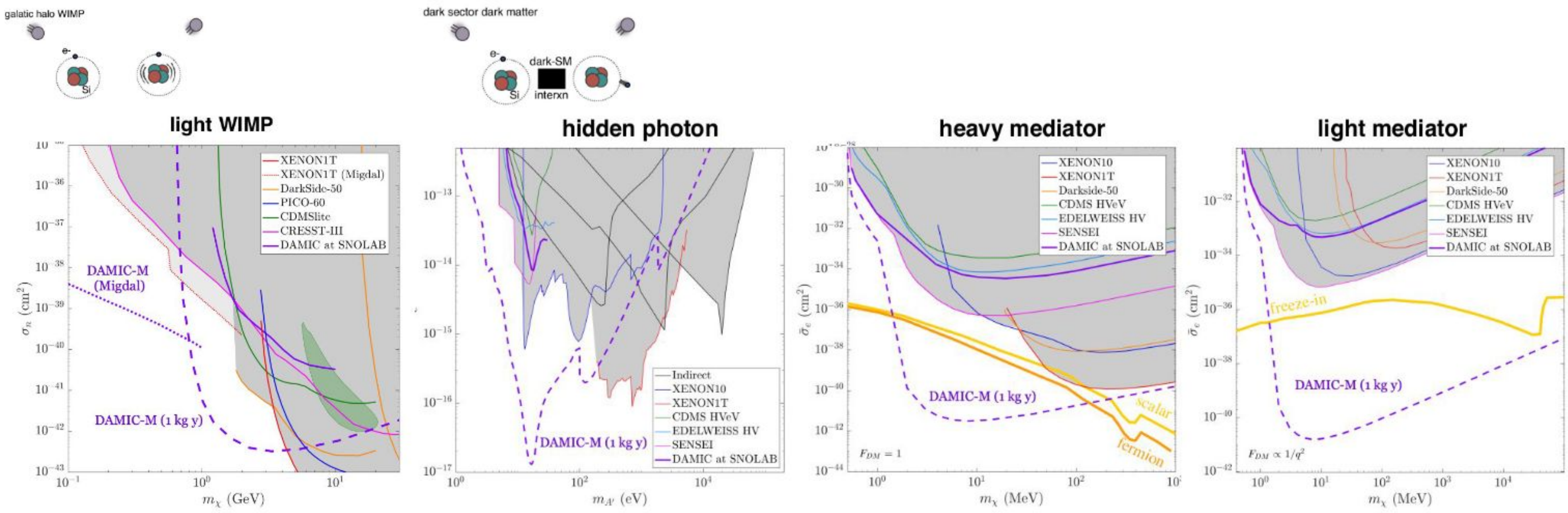
- **Geant4 simulations** of the setup and materials emission.
- **Custom detector response** simulation.
- **Background rejection.**
    - Identify surface events.
    - Spatial correlation in time between clusters.
- **Background control.**
    - Materials developed with cleaning procedures.
    - Underground storage in radon free environments.
    - Electroformed copper pieces (EFC).
    - Ancient Lead.
    - R&D on low background flex cables (PNNL, R. Saldanha LRT2022).

https://iopscience.iop.org/article/10.1088/1748-0221/16/06/P06019



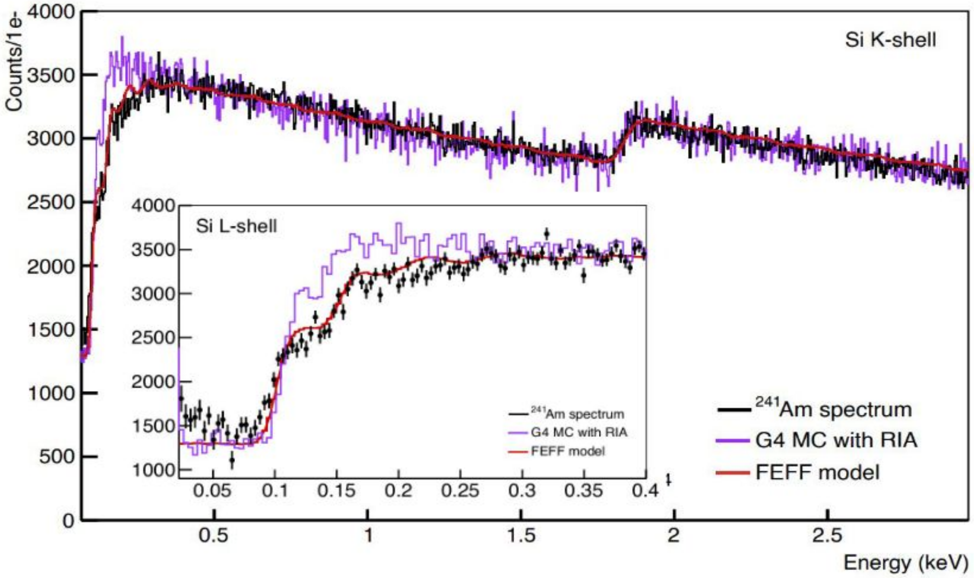



# DAMIC-M: Sensitivity projections



# First results (Chicago TC): Compton Scattering on Silicon

- **First detection** of Compton scattering on Si valence electrons below 100 eV down to 23 eV.
  - Observed scattering on valence $L_1$(150eV) and $L_{2,3}$(99.2eV) shells.
  - Measured at Chicago Test Chamber.

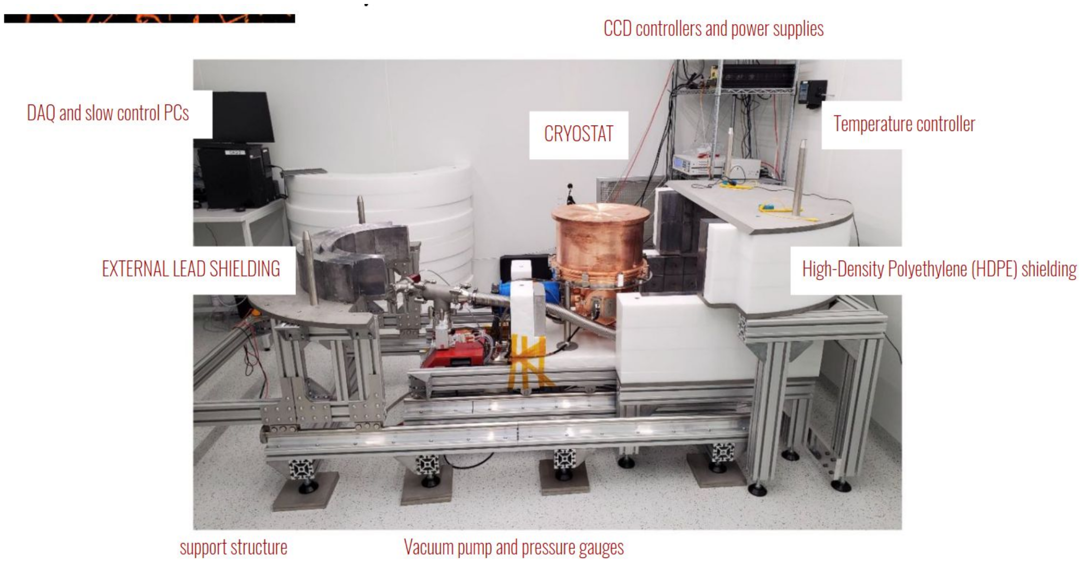



https://doi.org/10.1103/PhysRevD.106.092001

- **Achievements:**
  - **Geant4 MC overestimates** the scattering of the L-Shell.
  - **FEFF model tested to be more accurate** reproducing the L-Shell Compton scattering.
  - **High efficiency and accuracy detection** of energy deposits of a few $e^-$ using **skipper CCDs.**

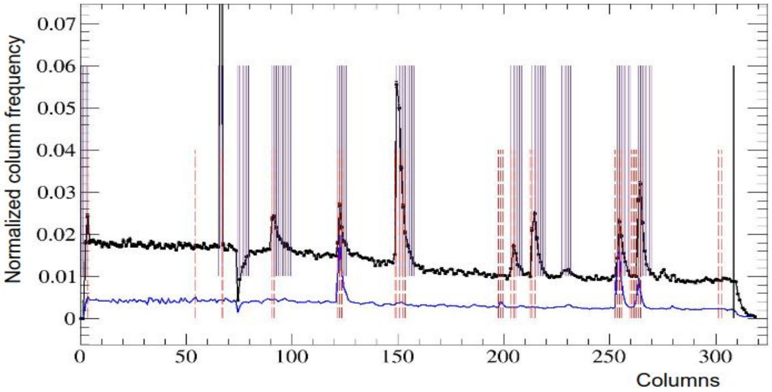
# Low Background Chamber (LBC)

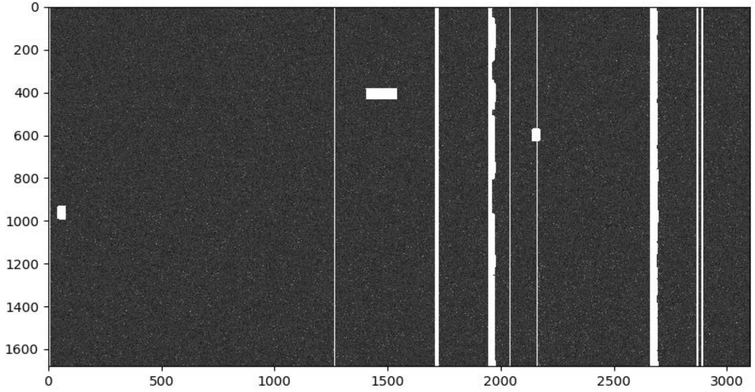
- **DAMIC-M prototype at LSM.**
- **<u>Objectives:</u>**
  - Gain experience at LSM.
  - Characterize DAMIC-M background components.
  - Test of subsystems:
    - CCD controller and electronics.
    - Slow control.
    - DAQ.
      - Data transfer and storage.
    - DQM.
  - Science results with small detector (2CCDs).



# LBC: Data processing

- **<u>Image selection.</u>**
  - Exclude large dark current images.
- **<u>Pedestal subtraction.</u>**
  - Subtract pedestal introduced by the readout amplifier.
- **<u>Cluster reconstruction.</u>**
  - Finding groups of charged pixels.
- **<u>Masking.</u>**
  - Remove clusters + CTI.
    - 10% pixels masked in commission runs.
    - 1% pixels masked in science run.
  - Amplifier cross talk evaluation.
  - Search for hot columns and defects.
    - Remove high charged columns.



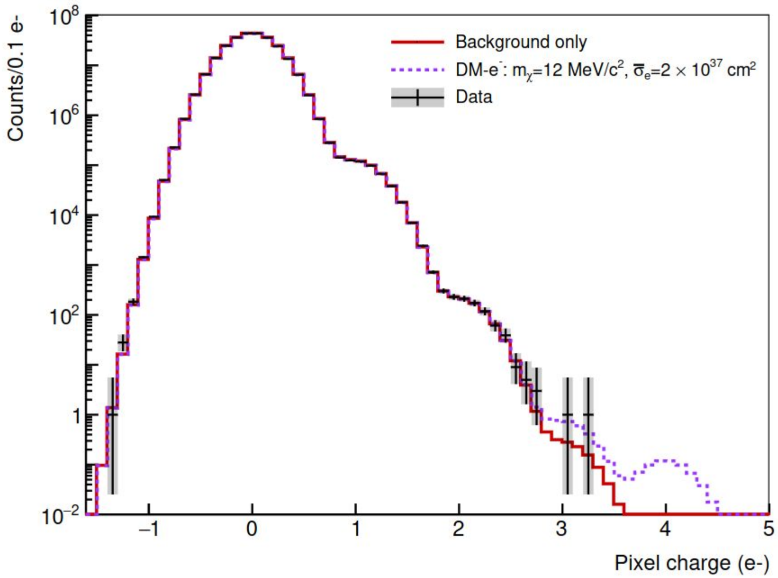



# Dark Matter-e$^-$ analysis: PCD

- DM interacts with the e- of the silicon crystal lattice.
  - Rate of events calculated with **QEDark** (arXiv:1509.01598).
- Detector response simulated with a **custom diffusion model for the LBC CCDs**.
  - eV to e- conversion with low ionization yield (PRD 102,063026 (2020)).
  - This model gives the pixel distribution of electrons produced in the interaction.
- The resulting **pixel charge distribution** (PCD) is a convolution of:
  - **Poissonian background.**
    - Describes the dark current.
  - **Gaussian readout noise.**
    - Pedestal, readout noise and gain.
  - **Expected signal rate.**
- A **likelihood** fit to data is performed with this model for that masses.

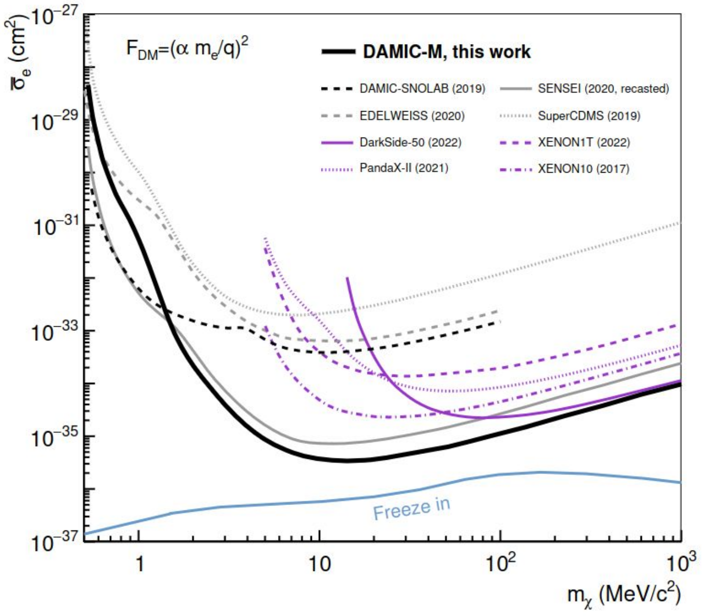
Pixel Charge Distribution PDF:

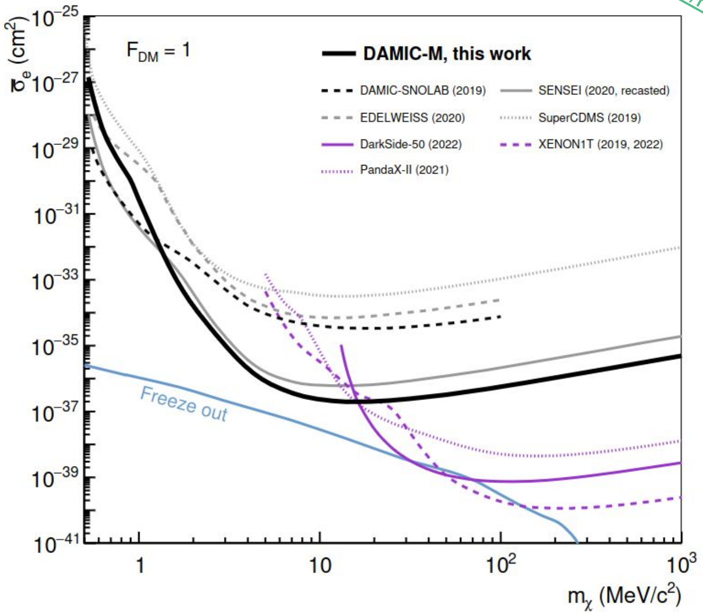
$$p(q) = N\sum_{n_{tot}=0}^{\infty}\left(\left[\sum_{j=0}^{n_{tot}} S(j|\sigma_e, m_\chi) Pois(n_{tot}-j|\lambda_{tot})\right] Gaus(q|\Omega[n_{tot}+\mu_0], \Omega\sigma_{read})\right)$$



# Dark Matter-e⁻ analysis: Upper Limits

https://doi.org/10.1103/PhysRevLett.130.171003

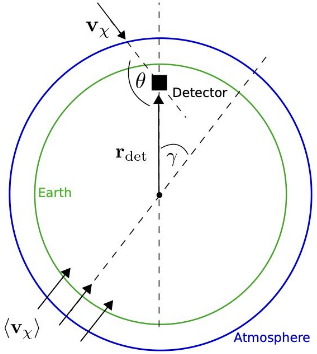


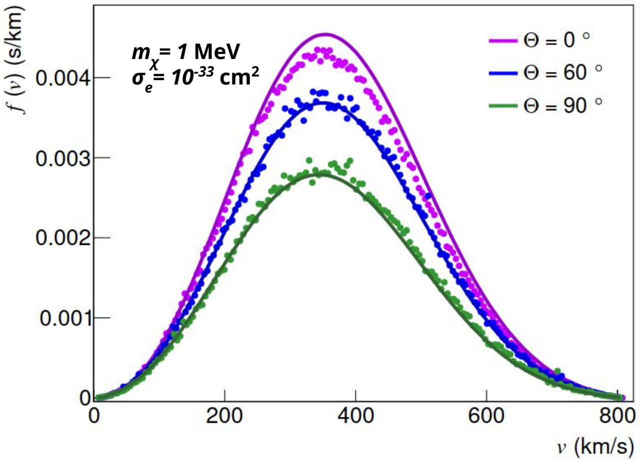




- An **upper limit with 90%CL** is set for the cross section at different DM mass.
- **World leading limit in the region [2,1000] MeV.**
  - DM daily modulation can improve the current limits in the < 2 MeV region (to be included).

# Daily Modulation search: Model

- **DM has an average direction set by the rotation of the Solar system around the Galactic center.**
  - For large enough cross sections DM will interact with the different atoms forming the layers of the Earth.
- **DM flux at the detector would change throughout the day due to the Earth screening.**
  - The angle between the DM flux and the detector (γ) will change according to the rotation of the Earth.
  - Thus the DM velocity distribution will change with a period of ~23.92 hours.
- **DAMIC-M expected background should be uniform with time.**
  - The non-observance of periodicity in the signal will improve the upper limits set for the 1e- (**to be included**).
- **Developing a semi-analytical model to describe the daily modulation for light DM.**
  - Upgrading the Verne code for heavy particles (arXiv:1712.04901).
    - Particles masses ~MeV.
    - Dark Photon mediator and screening effects model.
    - Straight line trajectories.
    - Scattered and reflected components.
  - Comparing with the DaMaSCUS Montecarlo approach (arXiv:1706.02249)

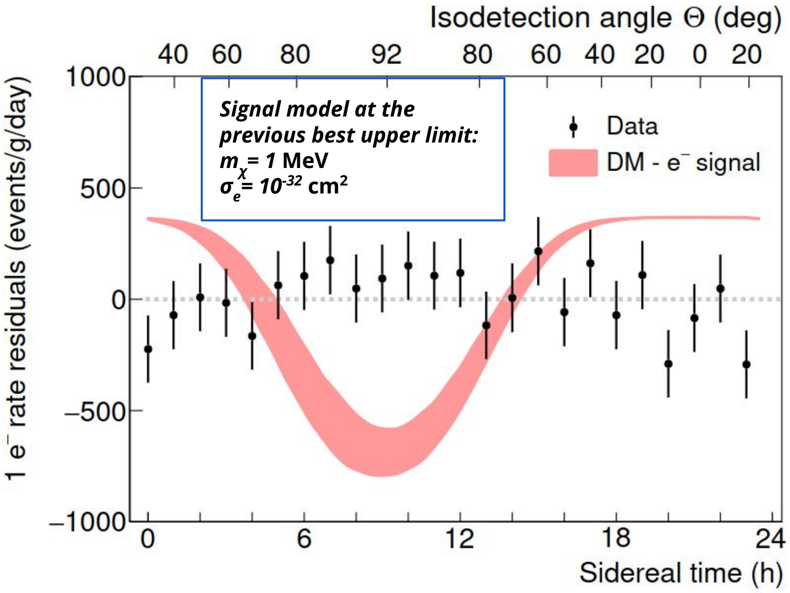



$$\frac{dR}{dE_e} \propto \bar{\sigma}_e \int \frac{dq}{q^2} \left[ \int \frac{f(\mathbf{v},t)}{\mathrm{v}} \, d^3\mathrm{v} \right] |F_{\rm DM}(q)|^2 \, |f_c(q,E_e)|^2$$

# Daily Modulation search: Analysis

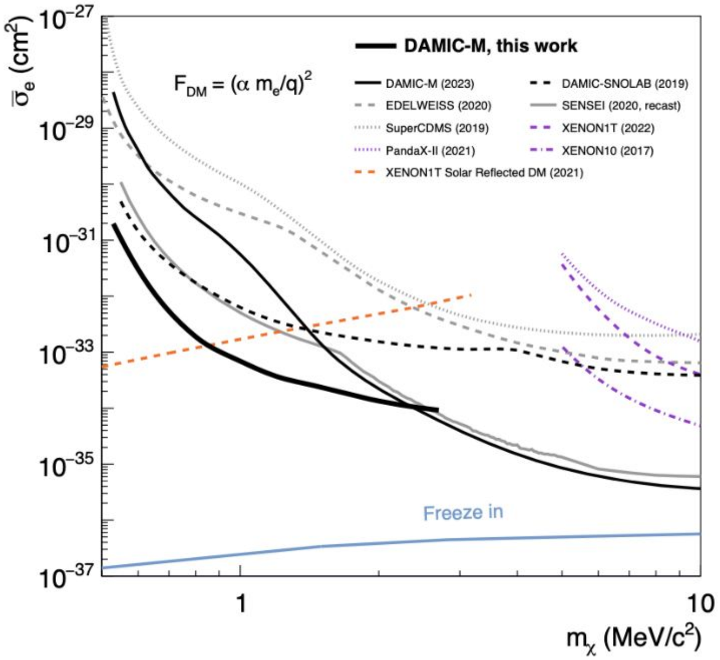
- A **likelihood** fit to data is performed using ***F($t_i$|θ)*** for the mass parameter space.
  - A time-dependent signal + background model is used.
- The fit finds no preference for signal at any mass.
- The correspondent exclusion limits are obtained with a 90% C.L.

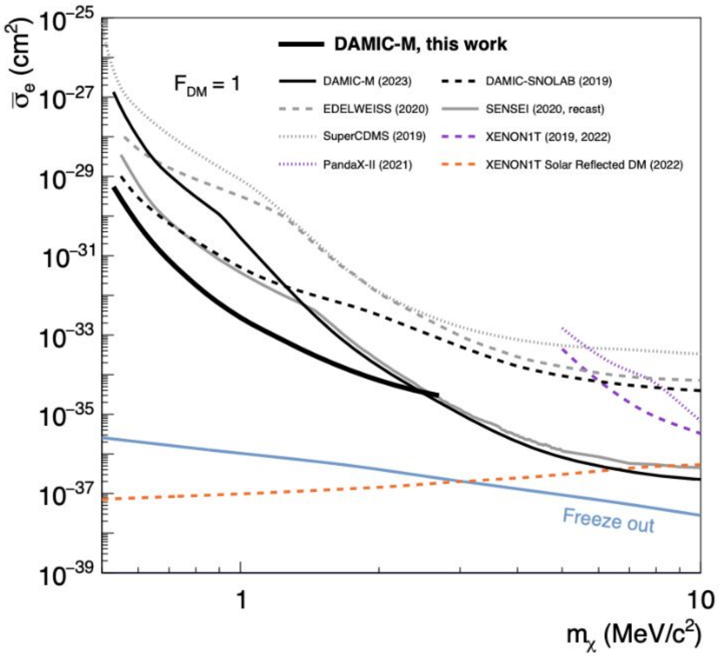



$$F(t_i|\theta) = \frac{1}{t_{\text{exp}} m_{\text{pix}}} \sum_{j=0}^{1} \text{Pois}(1-j|\lambda(t_i)) S(j|m_\chi, \bar{\sigma}_e, t_i)$$

# Daily Modulation search: Upper Limits

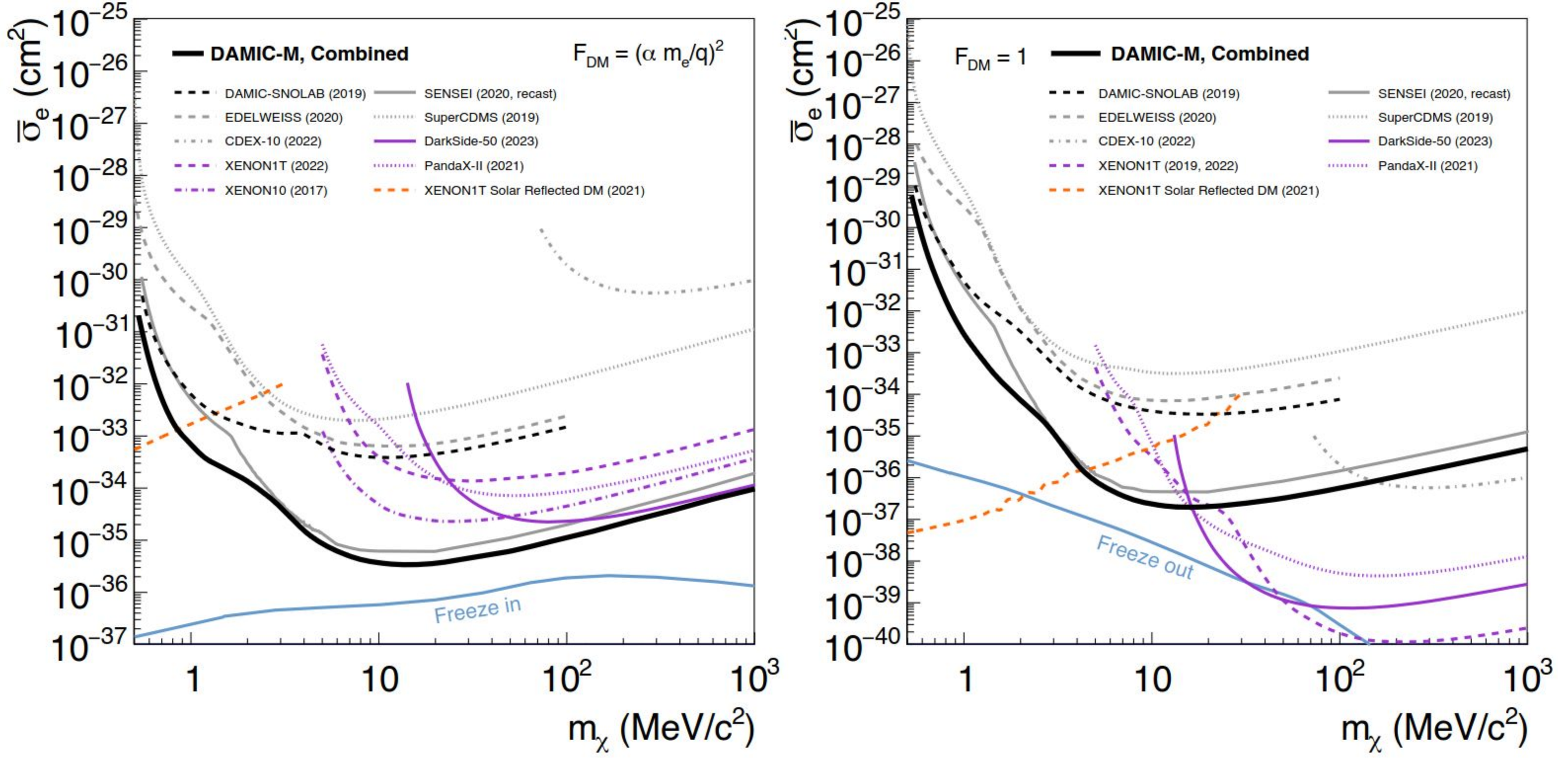
arXiv:2307.07251v1




**This analysis improved by ~2 order of magnitudes our previous PRL limits below 3 MeV.**

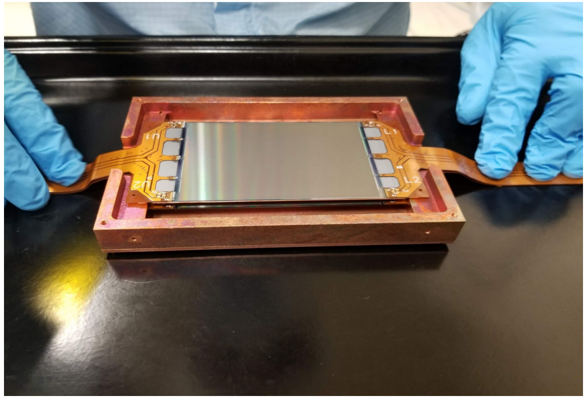
# Dark Matter-e$^-$ full search: Combined Results



# Summary

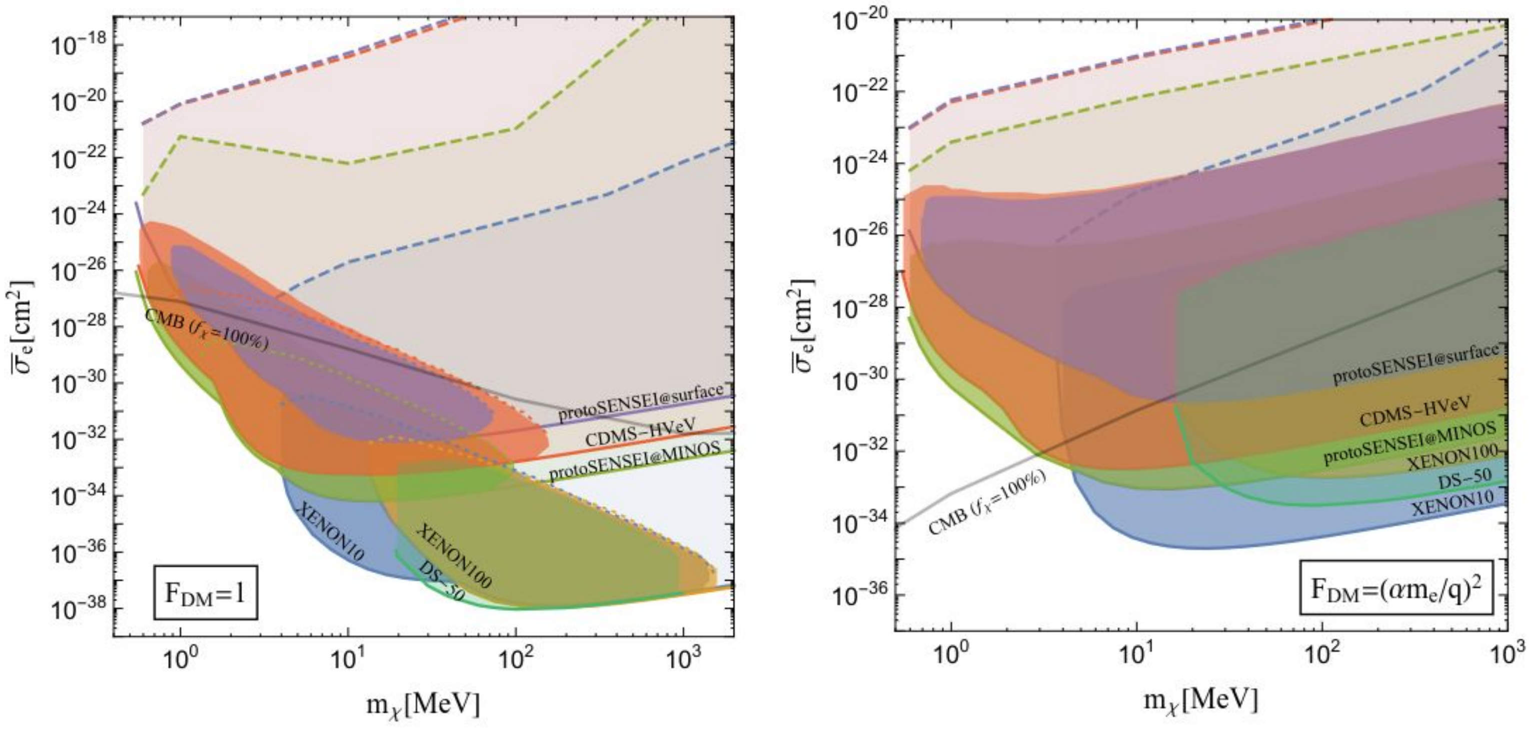
- LBC installed and operational at LSM.
- Scientific data taken under low background conditions and optimised readout noise.
- World leading DM-e scattering limits with 85.2 gr-days exposure.
- DAMIC-M aim to reach 1 kg-years exposure with skipper CCDs and a fraction of dru.
- The experiment will start in 2024.

# Thank you for your attention!

# Daily Modulation constraints CMB

https://arxiv.org/pdf/1905.06348.pdf



# LBC Timeline

| 2021 | | 2022 | | | | 2023 | |
|---|---|---|---|---|---|---|---|
| Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 |
| LBC Installation | | Commissioning the detector<br>• Assembly of the full external shield<br>• Installation of the second electronics | Two low dark current science runs | • Installation of electro-formed copper (EFC) lids<br>• improvement of light tightness | Background runs with EFC lids | • Installation of automatic moving structure for the external shield<br>• Installation of CCD modules. | Commissioning CCD modules |

# LBC data sets

- **<u>Internal shield  (Feb-May 2022).</u>**
  - **Commissioning runs.**
    - Verify performance of detector.
    - Optimize CCD parameters.
    - 300 dru.
    - Dark current reduction with thermal cycles.
- **<u>Internal + External shield (May 2022 - Sept 2022).</u>**
  - **Science runs.**
    - 10 dru.
    - 0.2e- readout noise with 650 skippers.
    - Dark Current = $3 \cdot 10^{-3}$ e-/pix/day.
    - DM-electron analysis with 115 g·day.