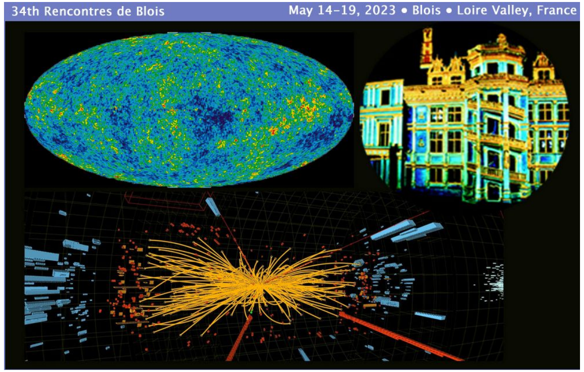

DAMIC-M: Status and First results

Agustin Lantero on Behalf of the DAMIC-M collaboration

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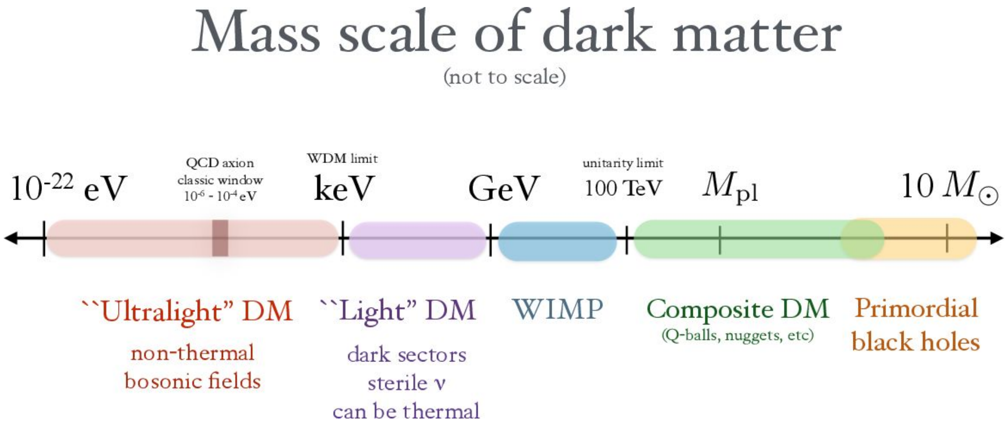
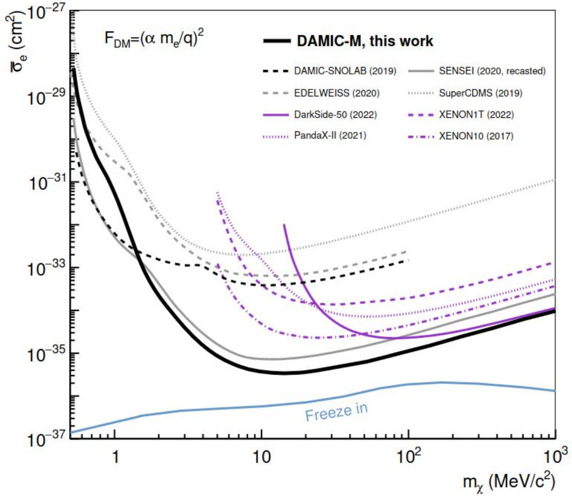
Dark Matter Searches

- **Dark Matter** (DM) existence is an observational evidence.
    - Cold Dark matter $v \sim 10^{-6}$ mc^2.
    - Local density 0.3 GeV $c^{-2}cm^{-3}$.
    - The Standard Model can not predict it's properties.
- The **search of 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.

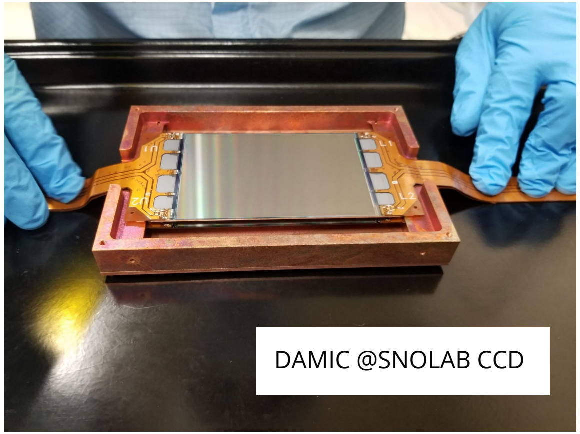


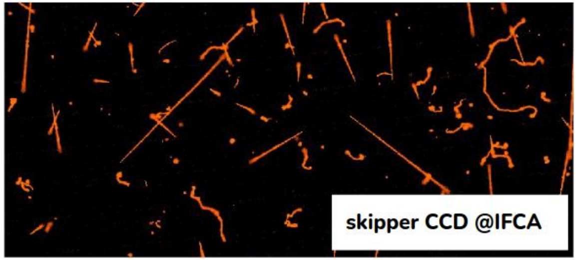
Lin, Tongyan. "TASI lectures on dark matter models and direct detection." *arXiv: High Energy Physics - Phenomenology* (2019): n. pag.



CCDs for Dark Matter Detection

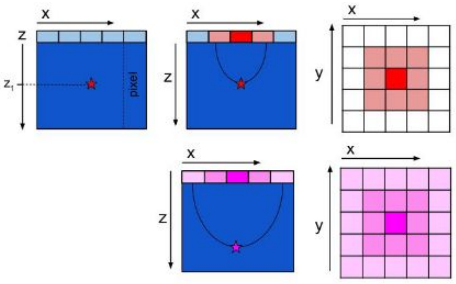
- **Charged Coupled Devices (CCDs)** are widely used in astrophysics experiments.
- **Features:**
    - Silicon
    - Mono-crystal.
    - n-type.
    - High resistivity (>10,000 Ω cm).
    - Three-phase polysilicon structure to keep and transfer the charge.

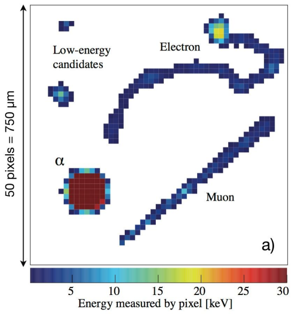


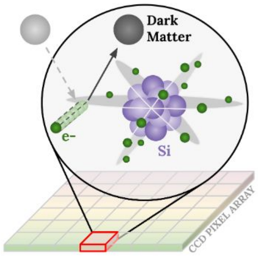


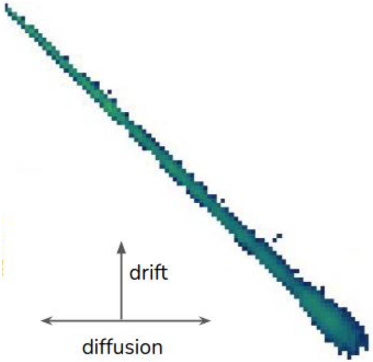
CCDs for Dark Matter detection

- 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.**

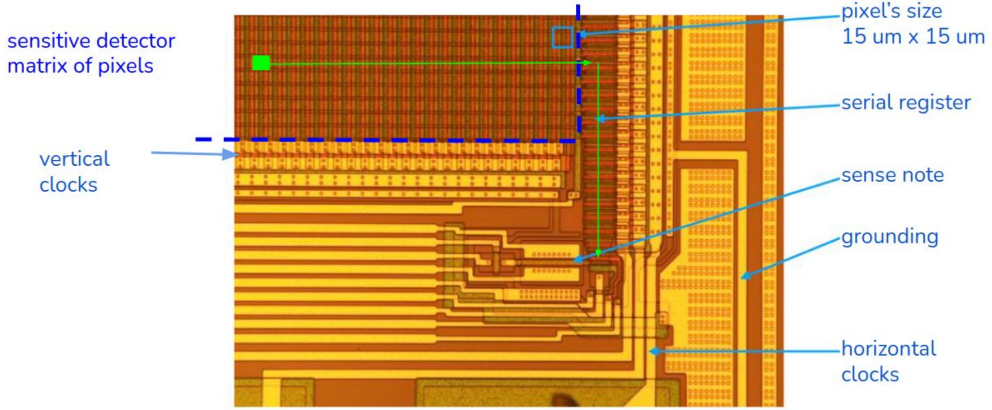




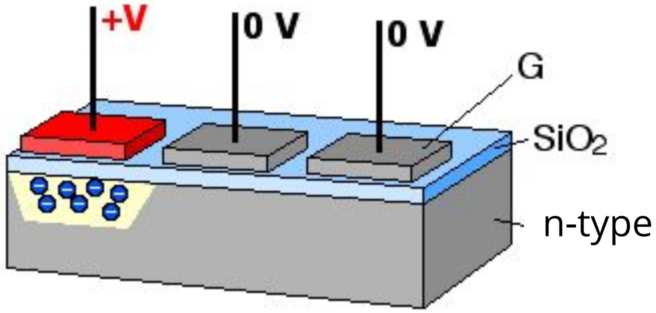




Charge transfer

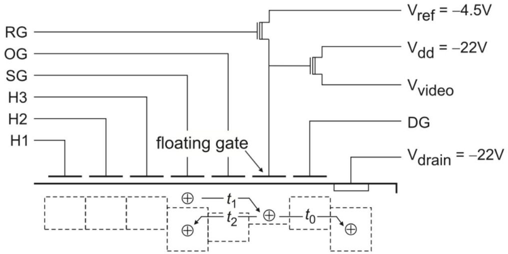


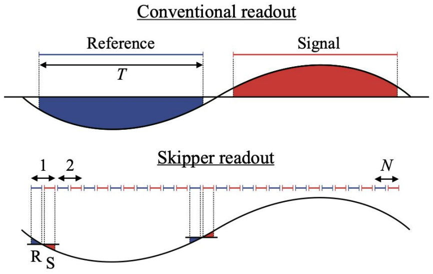
- The pixel **charge is transferred** to the contiguous pixel by changes in the potential voltage of the gate phases.
- An **appropriate clocking** allows to move all the charge through all the pixels until reaching the amplifier.
- **Charge Transfer Inefficiency** (CTI) is quite low.
  - CTI ~ 10^{-6}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

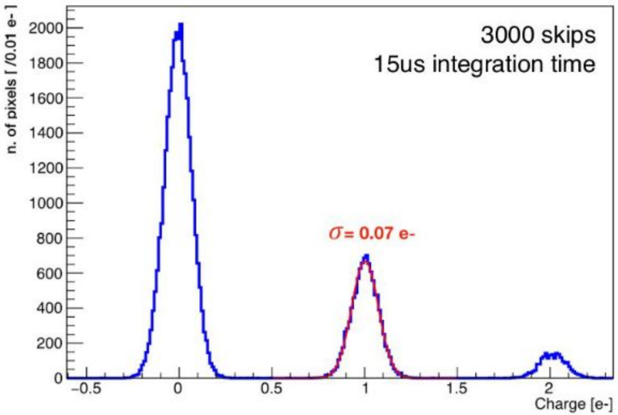


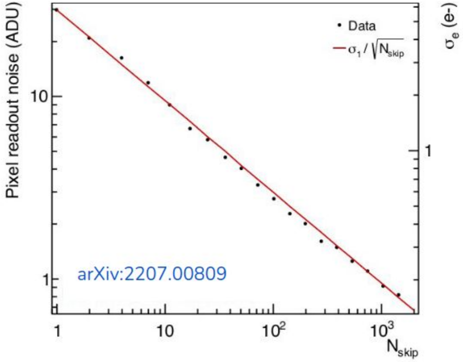
Skipper readout

- 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.

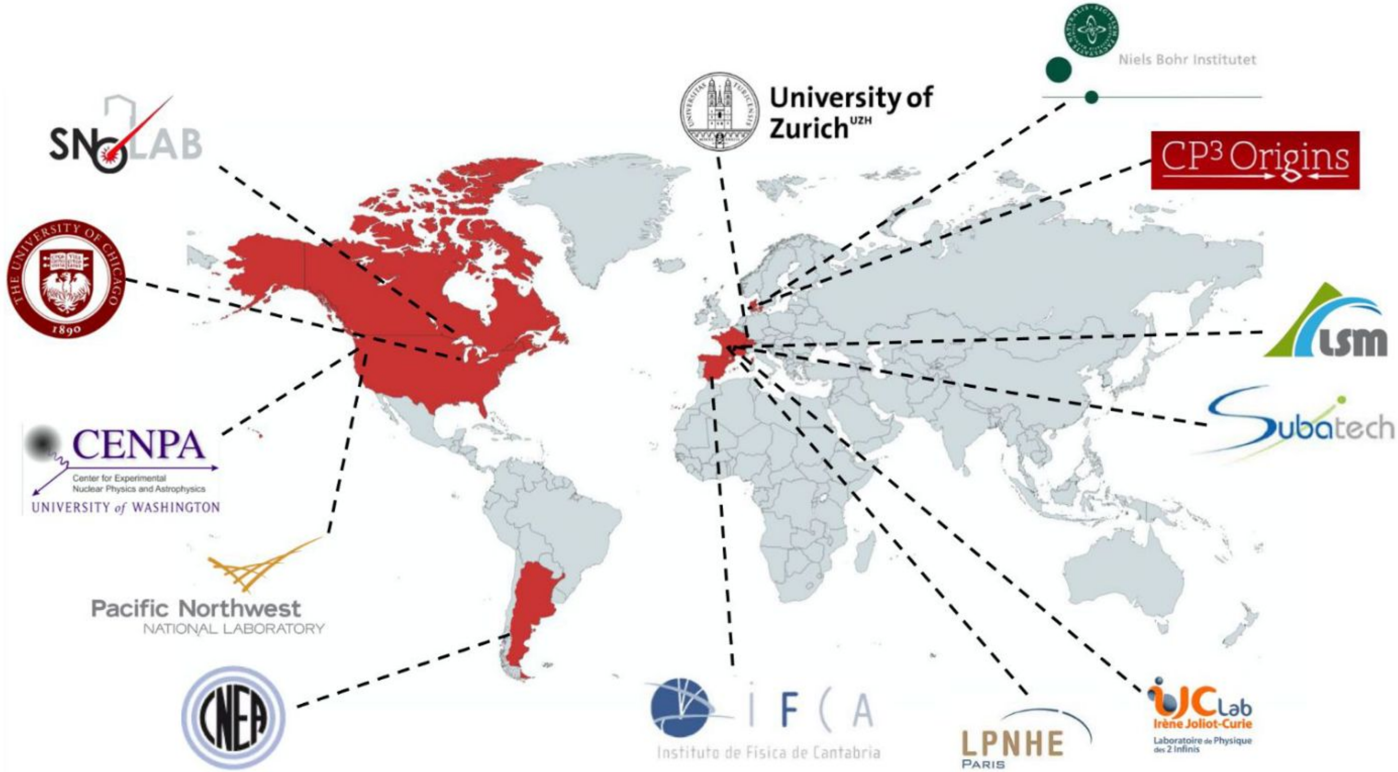






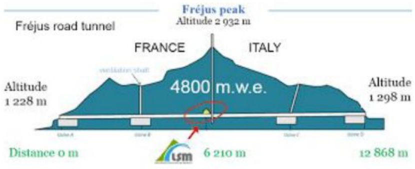


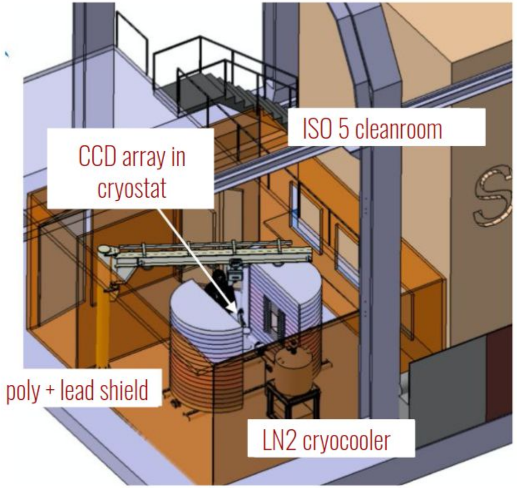
The DAMIC-M Collaboration



Dark Matter in CCDs at Modane (DAMIC-M)

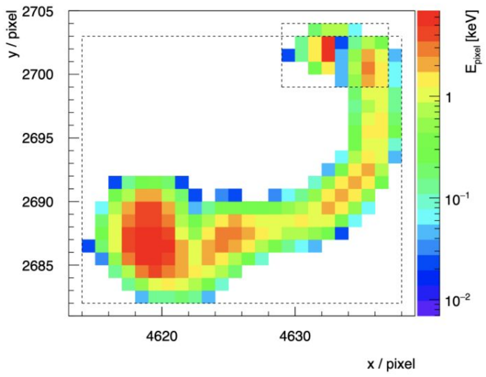
- **Laboratoire Souterrain de Modane (LSM).**
  - 4800 water equivalent meters under Fréjus peak.
- **Detector specifications.**
  - 208 skipper CCD arrays.
  - 9 Mpixels, 675 μm thick and m_{CCD}~3.5 g.
  - $m_{detector}$~ 1kg.
  - Single electron resolution and self-calibration.
  - Low dark current.
- **Goals.**
  - Few eV threshold.
  - Fraction of dru background.
  - Nuclear and electron recoils detection in the sub-GeV mass range.



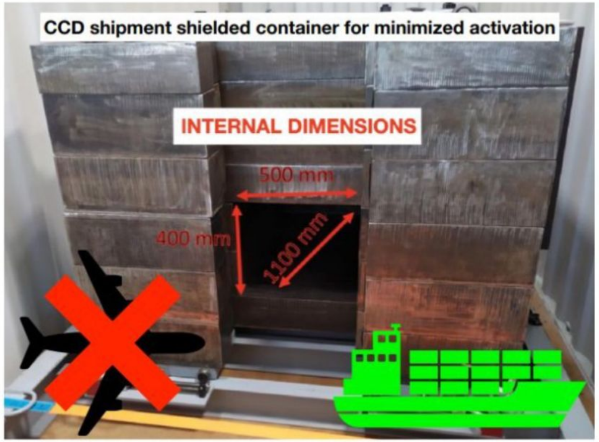


DAMIC-M: Background

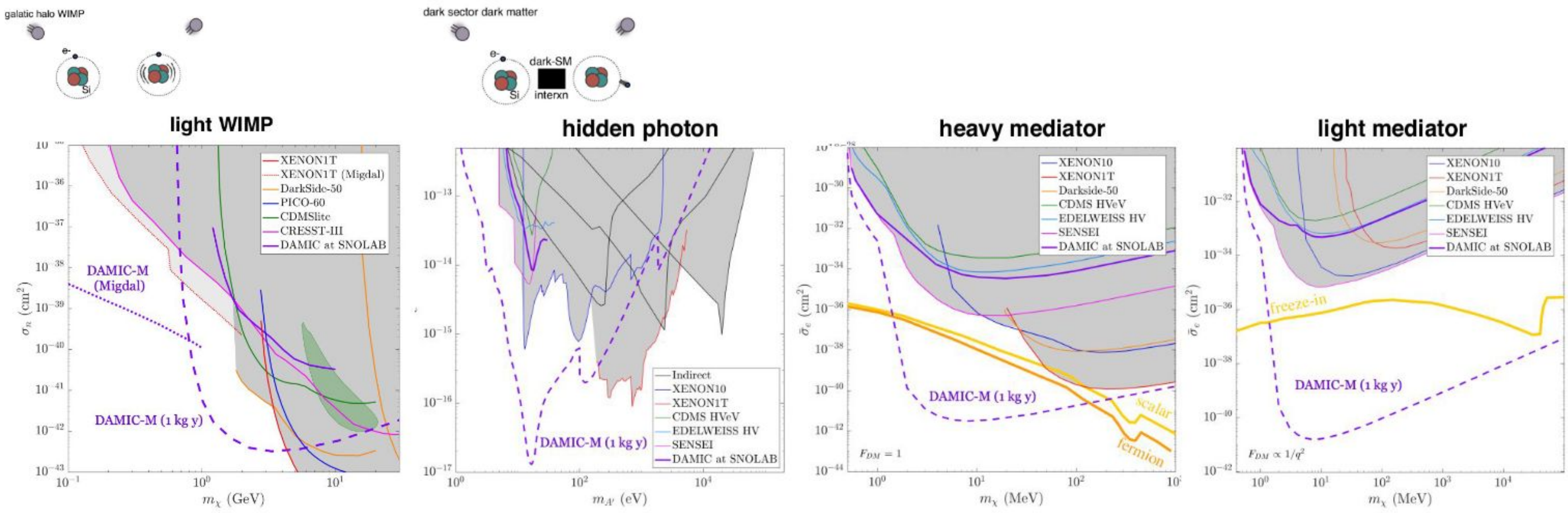
https://iopscience.iop.org/article/10.1088/1748-0221/16/06/P06019



- **Geant4 simulations** of the setup and materials emission.
- **Custom detector response** simulation.
- **Background rejection.**
    - Identify surface events.
    - Spatial correlation in time between clusters.
- <u>**Background control.**</u>
    - 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).



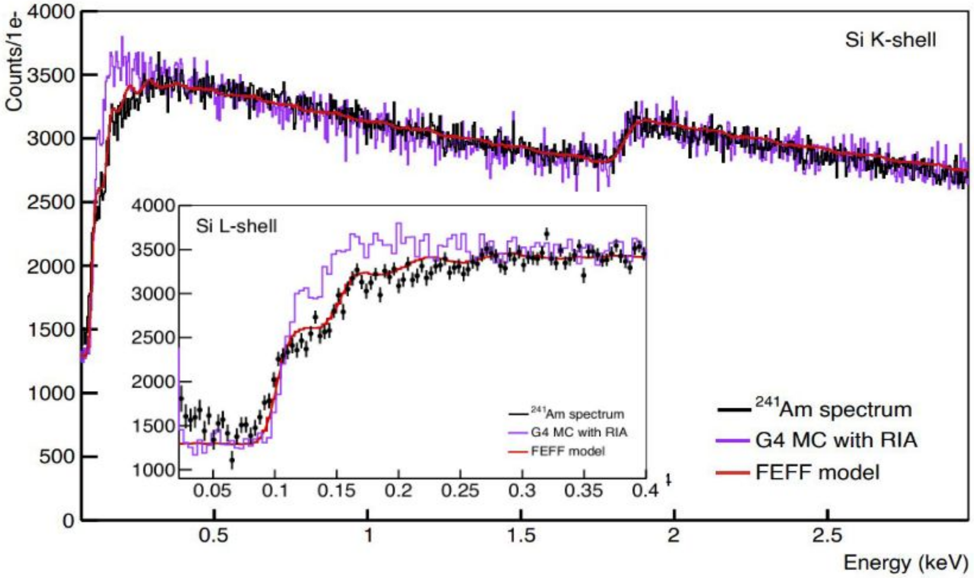
DAMIC-M: Sensitivity projections



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.

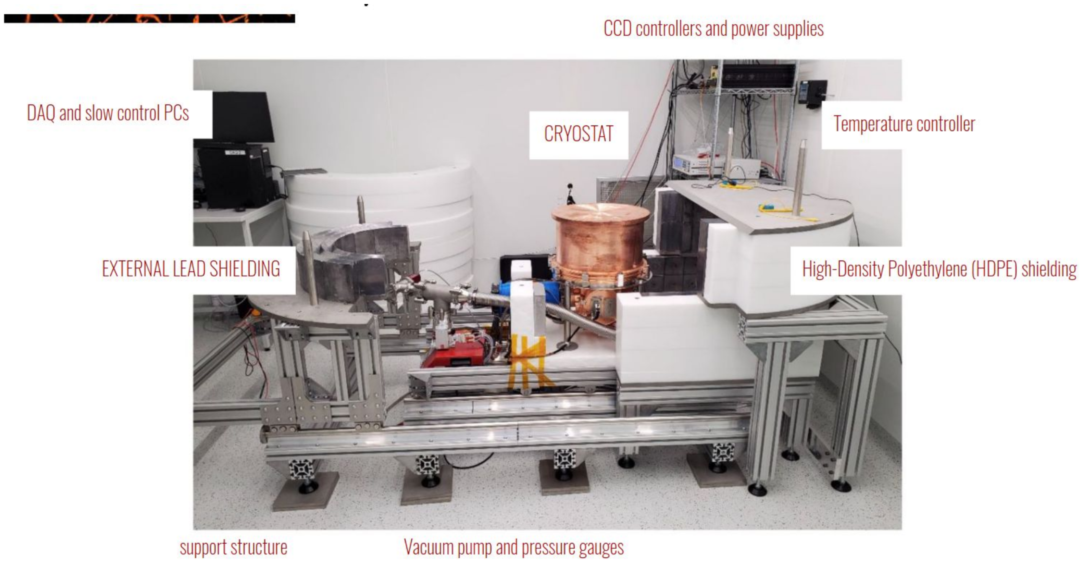
- **Achievements:**
  - **Geant4 MC overestimates** the scattering of the L-Shell.
  - **FEFF model tested to be more accurate** reproducing the L-Shell Compton scattering.
  - **High efficiency and accuracy detection** of energy deposits of a few e^- using **skipper CCDs.**



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

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).

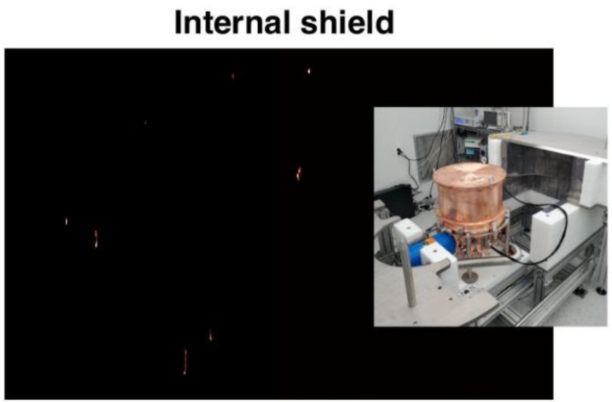


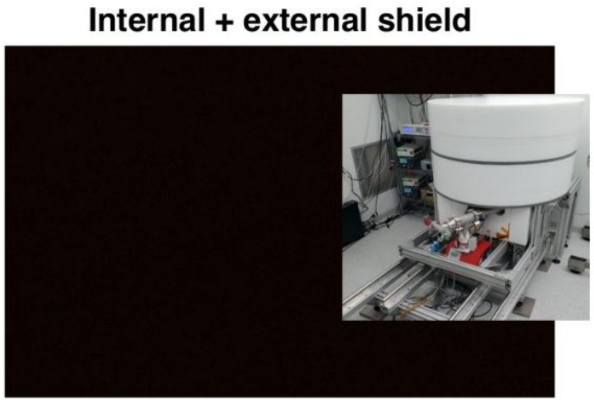
LBC Timeline

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

LBC data sets

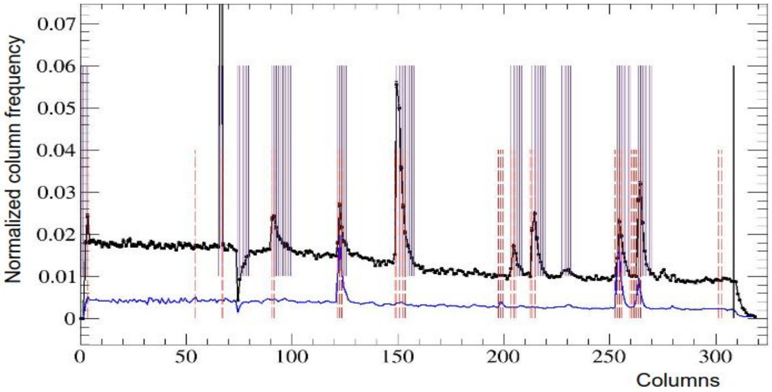
- **<u>Internal shield (Feb-May 2022).</u>**
  - **Commissioning runs.**
    - Verify performance of detector.
    - Optimize CCD parameters.
    - 300 dru.
    - Dark current reduction with thermal cycles.
- **<u>Internal + External shield (May 2022 - Sept 2022).</u>**
  - **Science runs.**
    - 10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

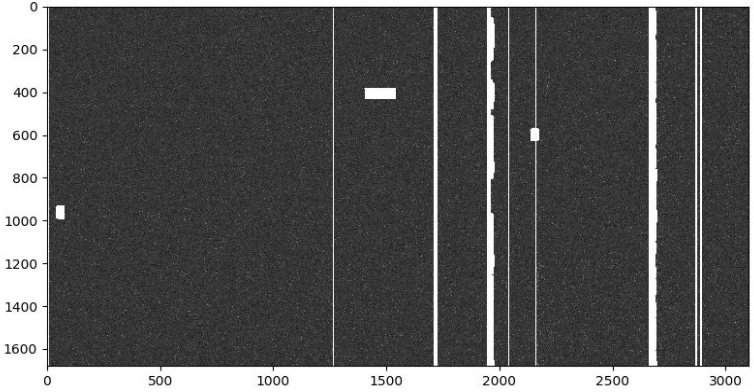




LBC: Data processing

- **Image selection.**
  - Exclude large dark current images.
- **Pedestal subtraction.**
  - Subtract pedestal introduced by the readout amplifier.
- **Cluster reconstruction.**
  - Finding groups of charged pixels.
- **Masking.**
  - 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.



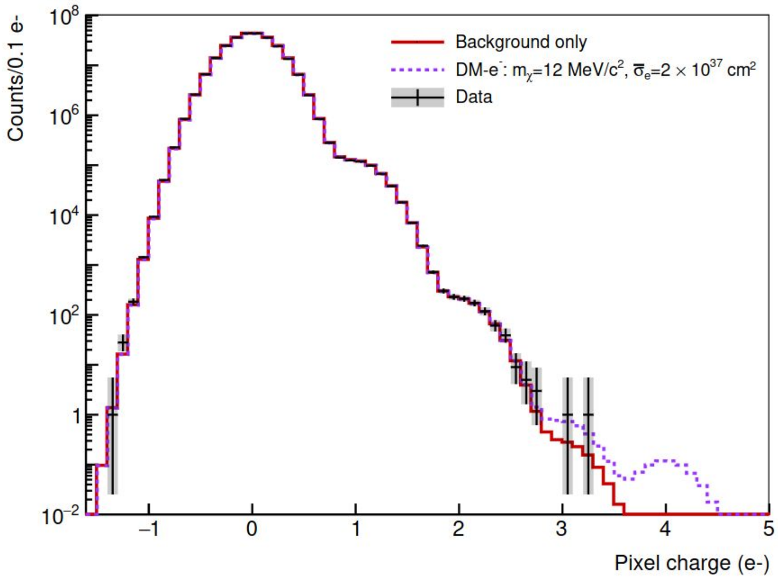


Dark Matter-e⁻ analysis: PCD

- 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.

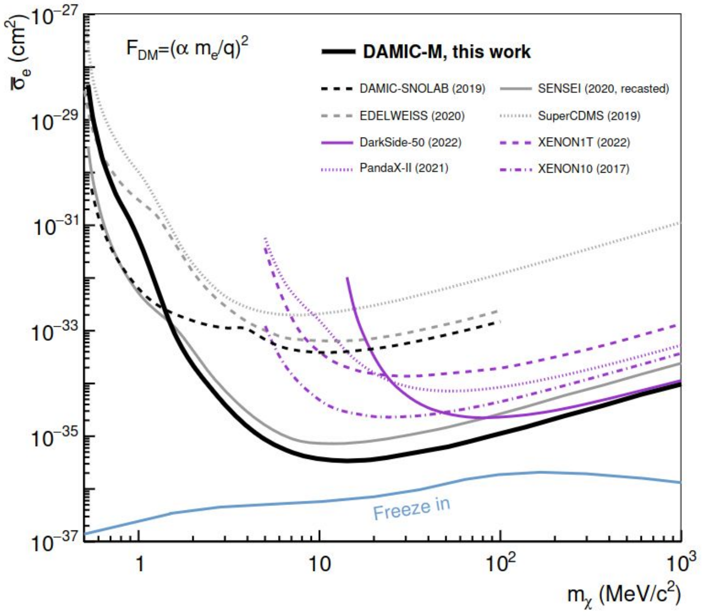
Pixel Charge Distribution PDF:

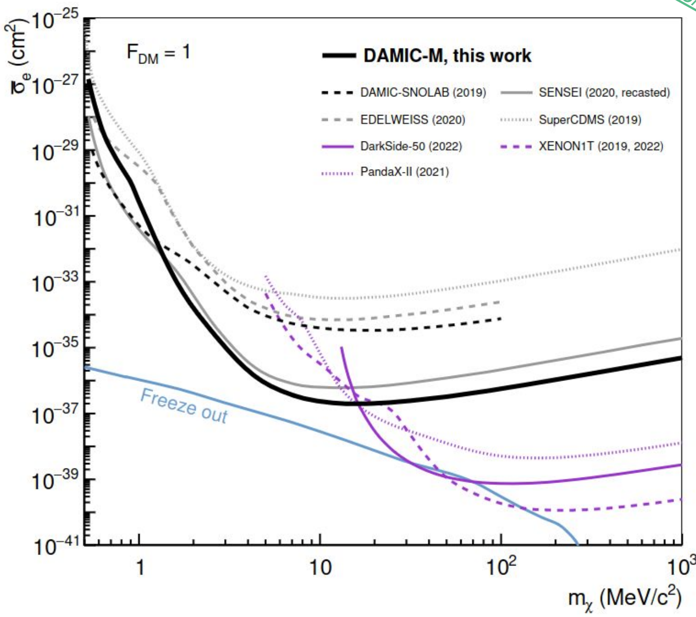
$$p(q) = N \sum_{n_{tot}=0}^{\infty} \left(\left[\sum_{j=0}^{n_{tot}} S(j|\sigma_e, m_\chi) Pois(n_{tot} - j|\lambda_{tot}) \right] Gaus(q|\Omega[n_{tot} + \mu_0], \Omega\sigma_{read}) \right)$$



Dark Matter-e^- analysis: Upper Limits

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

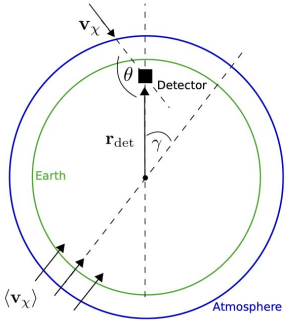


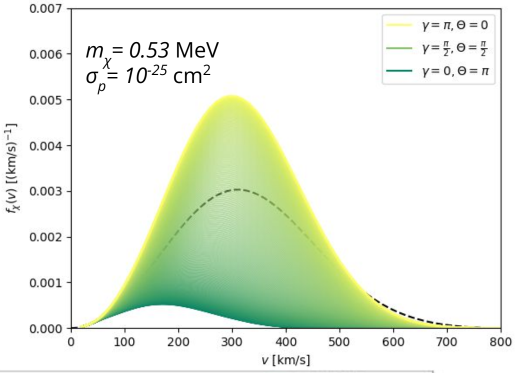


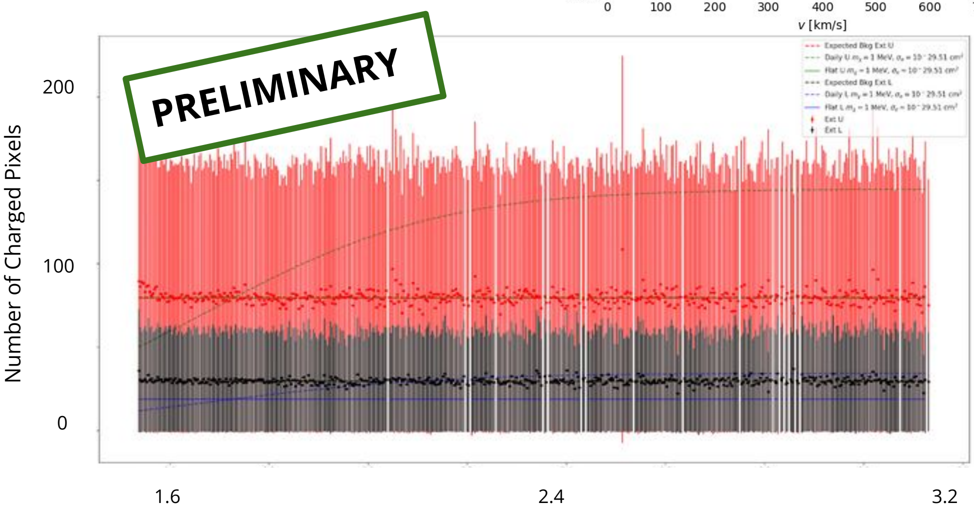
- An **upper limit with 90%CL** is set for the cross section at different DM mass.
- **World leading limit in the region [2,1000] MeV.**
  - DM daily modulation can improve the current limits in the < 2 MeV region (to be included).

Dark Matter-e⁻ analysis: Daily Modulation

- **DM has an average direction set by the galaxy rotation.**
  - 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)







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!