Lake Louise Winter Institute


# Dark Matter direct detection with the DAMIC-M experiment

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on behalf of the DAMIC-M collaboration

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CSIC Consejo Superior de Investigaciones Científicas
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# OVERVIEW

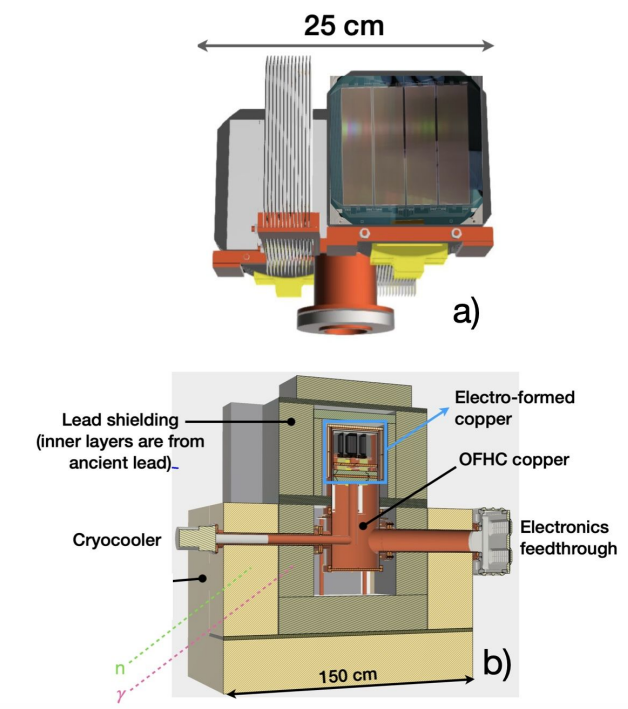
- Dark Matter with CCDs at Modane
  - CCD technology (Skipper CCDs)
  - Targeted dark matter
- Analysis: DM-electron scattering
  - LBC-2024 Science run
    - Pattern Analysis
    - Daily modulation
- Future prospects

- Probing Benchmark Models of Hidden-Sector Dark Matter with DAMIC-M
- Daily Modulation Constraints on Light Dark Matter with DAMIC-M
- A Fast Earth-scattering Formalism for Light Dark Matter with Dark Photon Mediators

# DArk Matter In CCDs at Modane

DAMIC-M is a direct detection DM experiment based on CCDs.

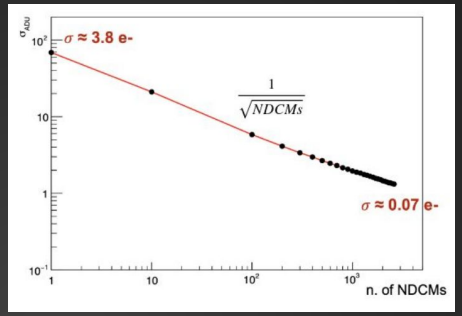
- It is located at the **Laboratoire Souterrain de Modane**.
- Expected to begin construction this year.
- It will have **26 CCD modules** with **4 CCDs** each.
- Will take data for **~2 years**.
- Current data comes from the prototype version, the **Low Background Chamber** (LBC).
  - ➢ Great results with only **8%** of the total target mass!

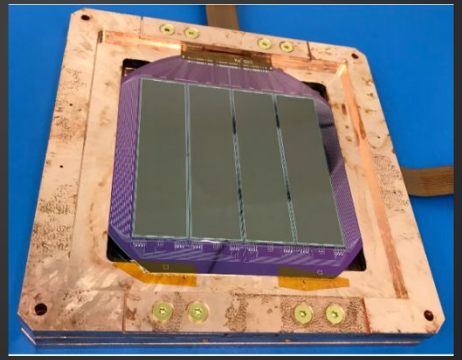


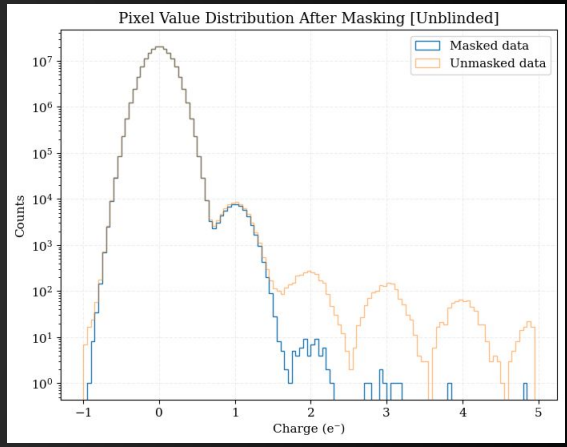
# SKIPPER CCDs

The DAMIC-M detector is based on **Skipper** CCDs.

- The CCD is a charge coupled device made of an **n-type silicon substrate** with a buried **p-channel**.
- DM crossing the depletion region with an average energy of **3.7 eV** creates **electron-hole** pairs through scattering.
- A CCD consists of a pixel array of **6144x1600**, with a volume of **15x15x669 μm³**.
- The **skipper amplifier** allows for non-destructive repetitive charge measurements (NDCM). This increases the resolution allowing for **single electron resolution**.

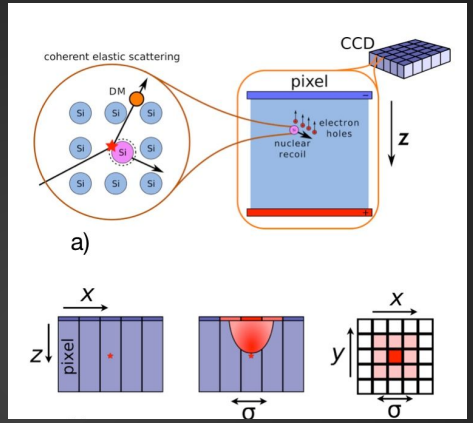


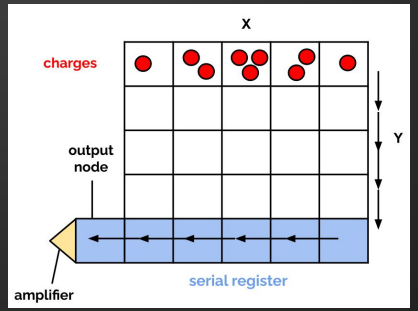





# CCD OPERATION

- Generated charge **drifts** to the top, with the charge undergoing thermal **diffusion** to fall into adjacent pixels.
- The charge is **read-out** on the skipper amplifier:
  - **Vertical** voltage moves charge towards the **serial register**.
  - Charge in the serial register is moved towards the **amplifier** with **horizontal** voltages towards the skipper amplifier
- **Binning** is applied. For this data, a **1x100** binning is applied giving images of size 6144x16.

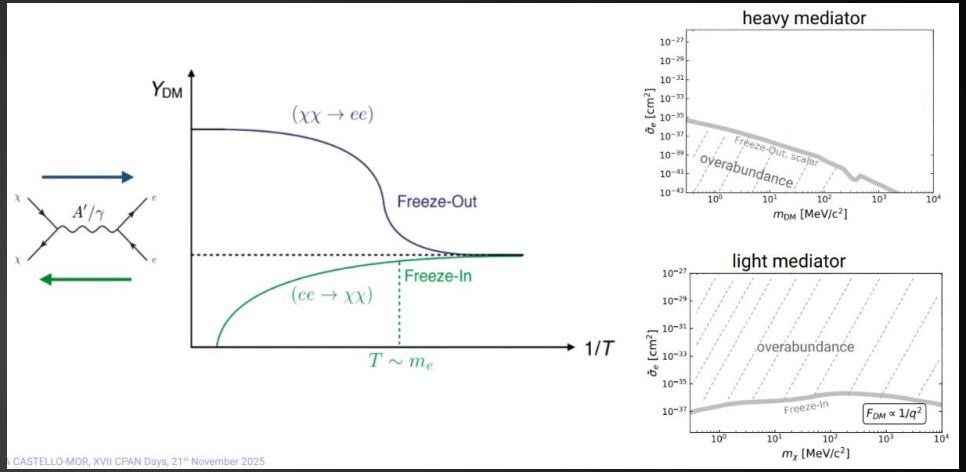


# DARK SECTOR

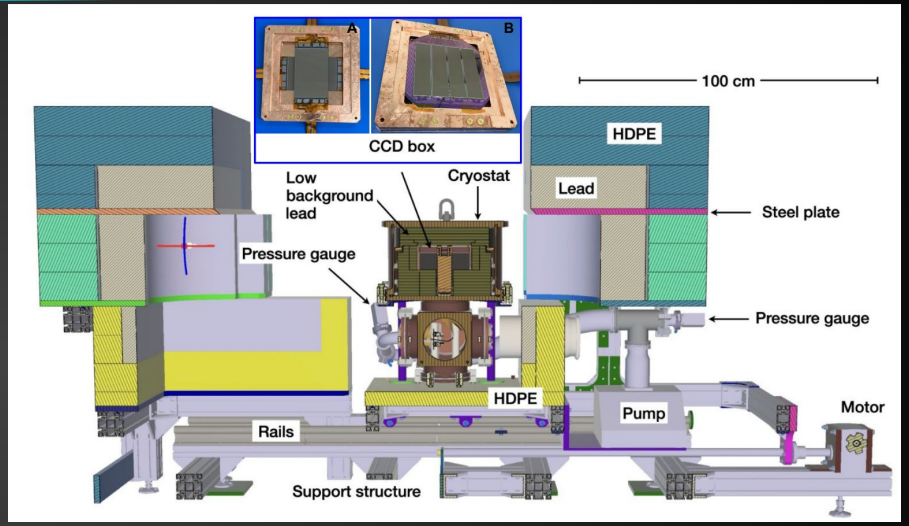
We target dark sector candidates.

- Collection of hypothetical particles that only interact weakly with the SM particles through gravity or other mediators.
- These models can produce the correct abundance of DM.
- Dark photon mediator:
  - Ultra-light mediator: usually associated with the freeze-in mechanism.
  - Heavy mediator: usually associated with the freeze-out mechanism.
- We look for the scattering of these DM particles with the SM particles.



# 2024 SCIENCE RUN

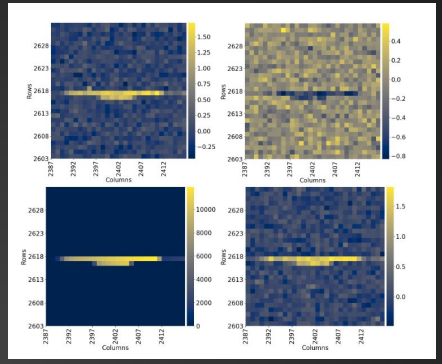
- Data were taken by the **LBC**, from October 2024 to January 2025.
  - It features a total of **6 skipper CCDs** (2 modules).
  - Lead and polyethylene shielding for a **background rate** of **~15 d.r.u** (small opening on the shield).
  - 1 skipper amplifier per CCD.
  - A **resolution** of **0.16 $e^-$.**
  - **Dark current** is around **1.2-1.6 e-4 $e^-$/pixel/day.**
  - Total **exposure** of **1250 g-day.**

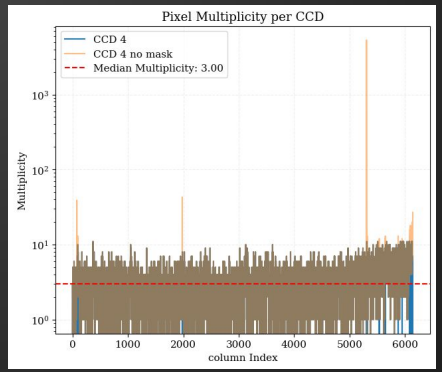


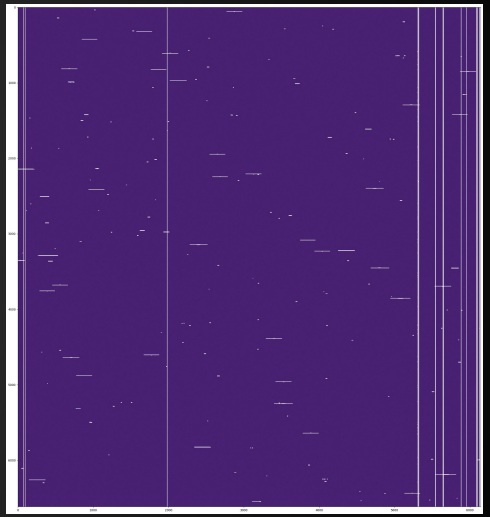
# DATA SELECTION

The two analyses performed have the same dataset. The selection criteria are defined to optimize the pattern analysis.

- We select **horizontal clusters** that are isolated.
- Different masks are applied:
  - **Columns** with abnormally high **charge multiplicity.**
  - Clusters with higher than **5 $e^-$**.
  - **Crosstalk** effects between CCDs of the same module.
  - Pixels with **high variance** in the **NDCM**.
  - **Charge transfer inefficiency** for pixels with charge higher than **100 $e^-$**.
- **95%** of data are kept for the analysis!



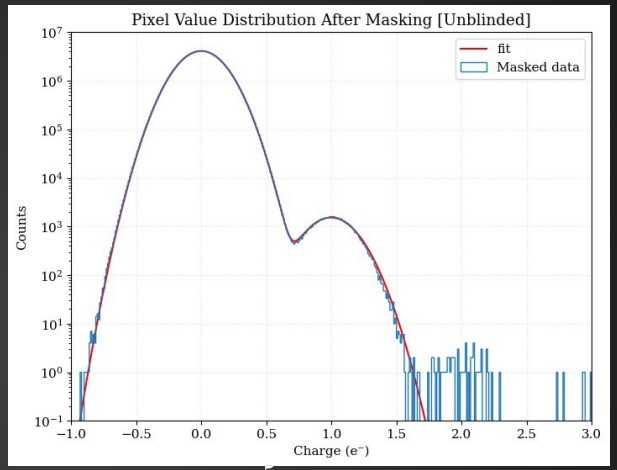
# PATTERN ANALYSIS

Our data shows an **excess** of **2** and **3 e⁻** events. This background limits our analyses.

- The excess can come from different sources:
  - **Radiogenic** background
  - **Unknown** source of background
  - **Dark Matter** signal

We know the radiogenic background and the DM signal are subjected to **diffusion**.

- Having an excess in the 2 e⁻ peak means having an excess in the produced patterns from these events.
- 2 e⁻ events are diffused into {11} patterns **90%** of the time.




$$Expected 2e^- : 0.287$$
$$Observed 2e^- : 60$$

$$x_0 = 7.49 \cdot 10^{-5}, A_0 = 4.10 \cdot 10^6, \sigma = 0.158$$
$$x_1 = 9.97 \cdot 10^{-1}, A_1 = 1.54 \cdot 10^3, \sigma = 0.165$$

# PATTERN DATASET

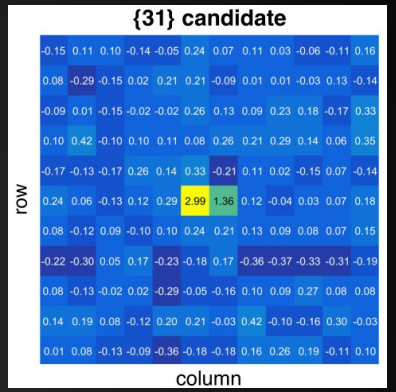
The pattern analysis is done on 6 different patterns that can be found in the images.

- We consider patterns of 2 and 3 adjacent pixels and their permutations: **{11,21,111,31,22,211}**

Those patterns can appear in the CCD from 3 main sources:

- **Radioactive background**: Energy deposits of cosmic particles and radioactive decays, that diffuse.
- Random coincidence events: **Dark current** events that occur adjacent.
- **Dark Matter signals**: Energy deposits and diffusion

| | Pattern $p$ | | |
|---|---|---|---|
| | $\{11\}$ | $\{21\}$ | $\{111\}$ |
| $D_p$ | 144 | 0 | 0 |
| $B_p^{\mathrm{rc}}$ | 141.4 | 0.111 | 0.042 |
| $B_p^{\mathrm{rad}}$ | 0.039 | 0.039 | 0.016 |
| | $\{31\}$ | $\{22\}$ | $\{211\}$ |
| $D_p$ | 1 | 0 | 0 |
| $B_p^{\mathrm{rc}}$ | 0.019 | $2.5 \cdot 10^{-5}$ | $5.8 \cdot 10^{-5}$ |
| $B_p^{\mathrm{rad}}$ | 0.052 | 0.011 | 0.035 |



# PATTERN ANALYSIS: Background

Two backgrounds:

- Random coincidence background:
  - **Dark current** events that occur in adjacent pixels.
  - Product of **poisson probabilities**:

$$B^{rc}_{ijk} = P(i)P(j)P(k) \cdot \epsilon_{ijk} + Missidentified$$

- Radioactive background:
  - Model through **Geant4** simulations
  - Added a nuisance parameter to consider uncertainties in the calculation.

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|---|---|---|---|
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| $D_p$ | 144 | 0 | 0 |
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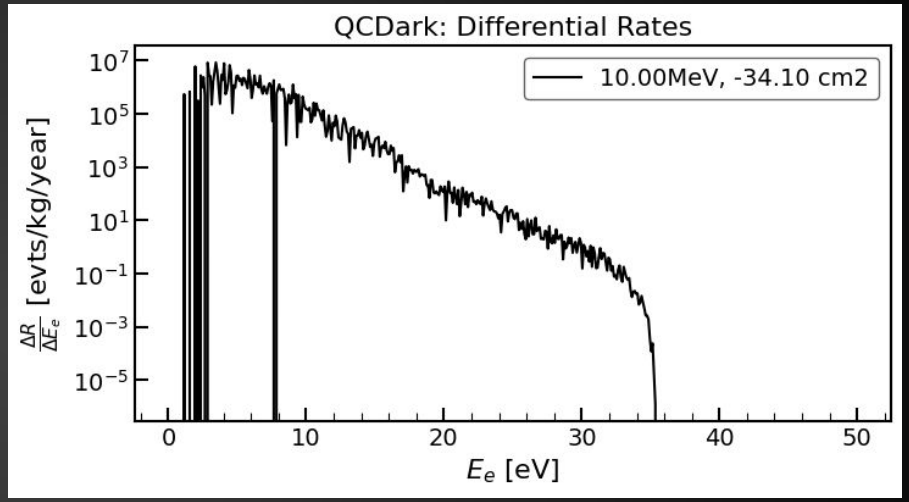
$$B = B_p^{rc} + \theta B_p^{rad}$$

# DARK MATTER SIGNAL

To compute the DM signal we use **QCDark**.

- **Dark matter flux**, integrated over the velocity distribution.
- **DM form factor**: tells if it is an ultralight mediator or a heavy mediator.
- **Crystal form factor**: electronic response of the material.
- **Screening factor**: considers the electrostatic in-medium effects.




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

QCDark

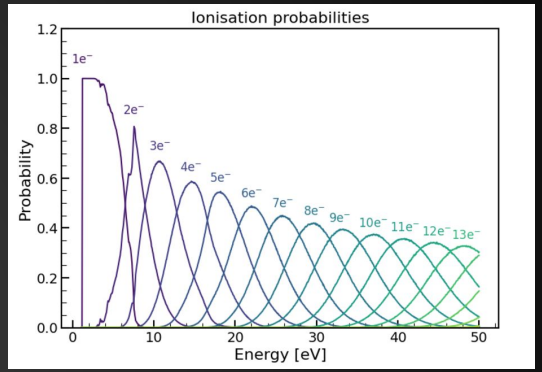
# DARK MATTER SIGNAL

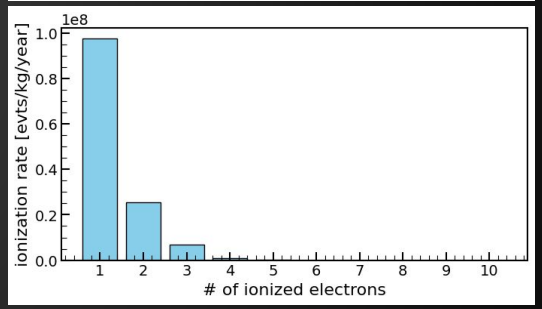
Differential rate is converted into pattern rate through:

- **Ionization probabilities**: events of a certain number of electrons.
- **Pattern efficiencies**: Obtain via Monte Carlo simulations of the diffusion process in the CCD.

$$S^i(p|\mathbf{s},t_i) \propto \sum_{n_q} \mathcal{P}(p|n_q) \int \frac{dR}{dE_e} \mathcal{P}_{eh}(n_q|E_e)\, dE_e$$

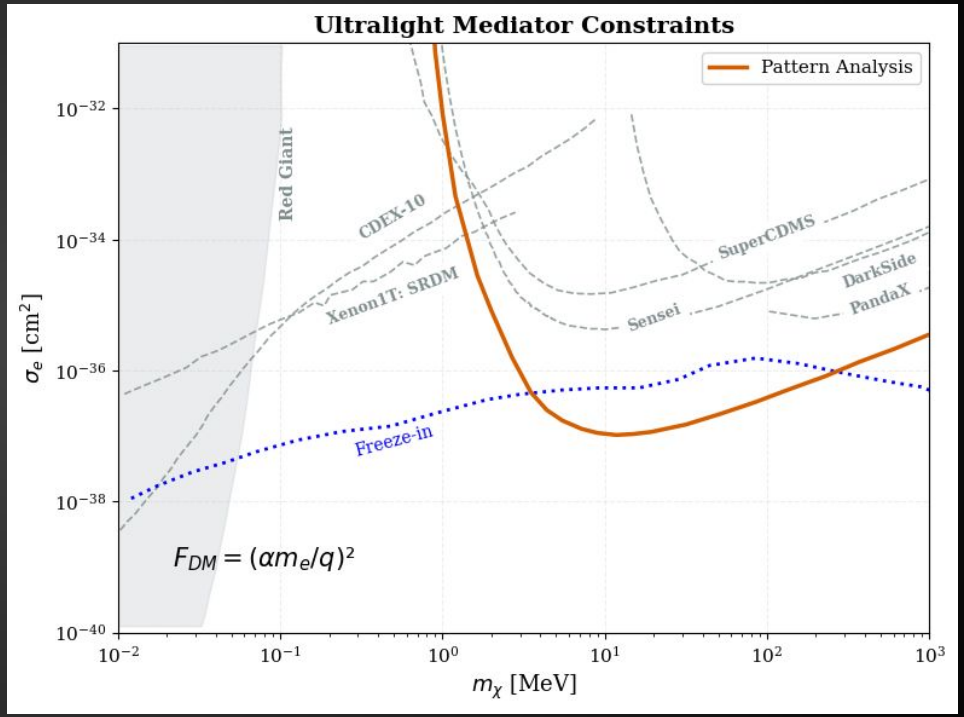
$$\sigma_{xy} = \sqrt{-803.25 \cdot log[1 - 6.5 \cdot 10^{-3} \cdot z]}\ \mu m$$



# PATTERN ANALYSIS: Upper limits

- Stringent constraints on DM particles with masses between **0.75 and 1000 MeV** interacting with electrons.
- **Exclusion of benchmark scenarios**, for large ranges of DM masses below 1 GeV, where hidden-sector particles are produced as a major component of DM in the Universe through the **freeze-in** mechanism.
- This analysis doesn't consider the 1 $e^-$ peak. The search for DM in that dataset is done with the **Daily Modulation**.



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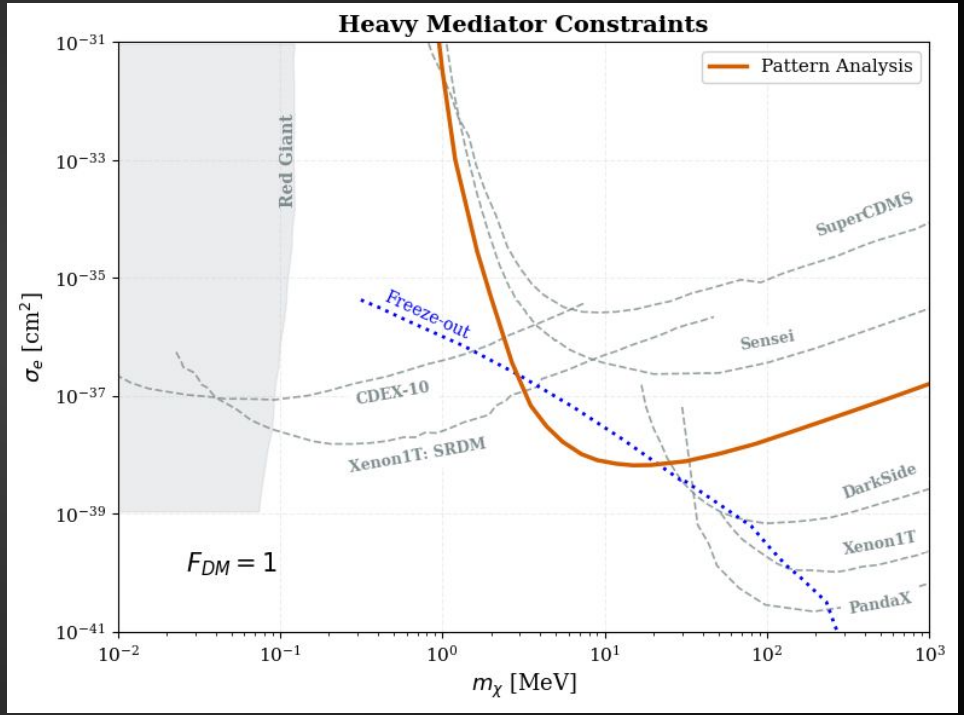
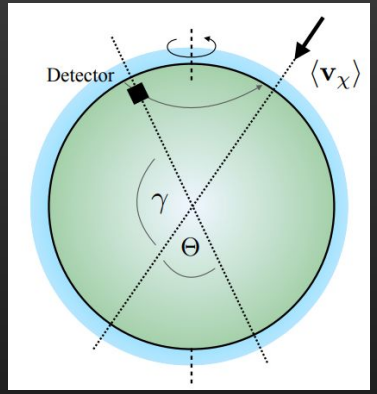
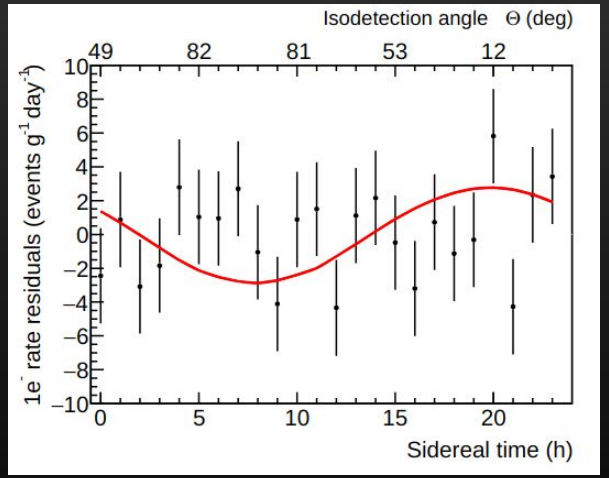


# DAILY MODULATION

For this analysis we exploit the characteristic signal of the DM that interacts with the Earth before reaching the detector.

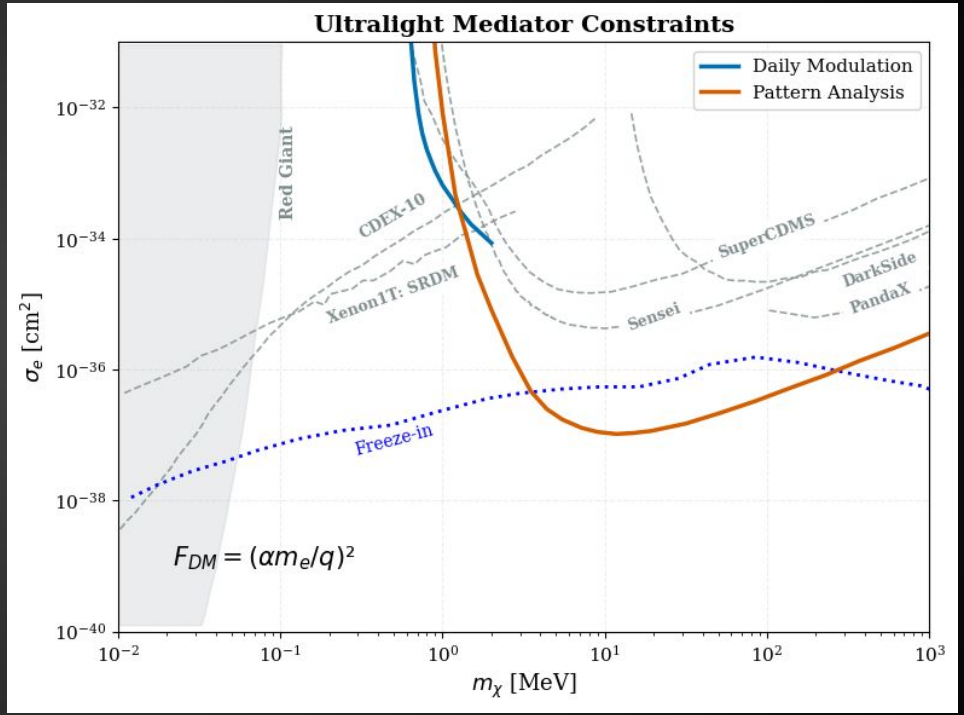
- Depending on the time of the day, the distance that the DM must traverse in order to reach the detector varies. This gives a Daily modulated signal.
- Easy discrimination of a modulated signal over a non-modulated background.
- The flux is computed through simulations of the scattering inside the Earth.



# DAILY MODULATION: Upper limit

- We improve the previous limit below 1.5 MeV.
- The sensitivity is lost below 0.53 MeV.
  - ➢ Halo DM is not energetic enough to create a signal in the CCD.
- This analysis does not scale with the exposure, because it requires 2 interactions (with Earth and the CCD). The Earth becomes transparent for low cross sections.
- Solar Reflected Dark Matter will extend the sensitivity to even lower masses.



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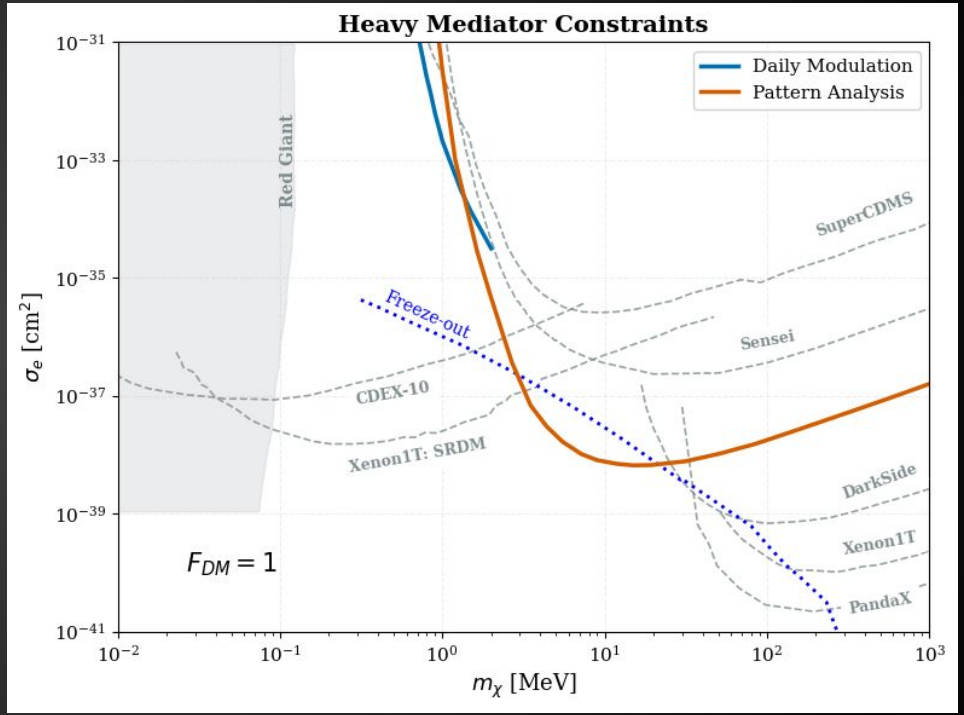
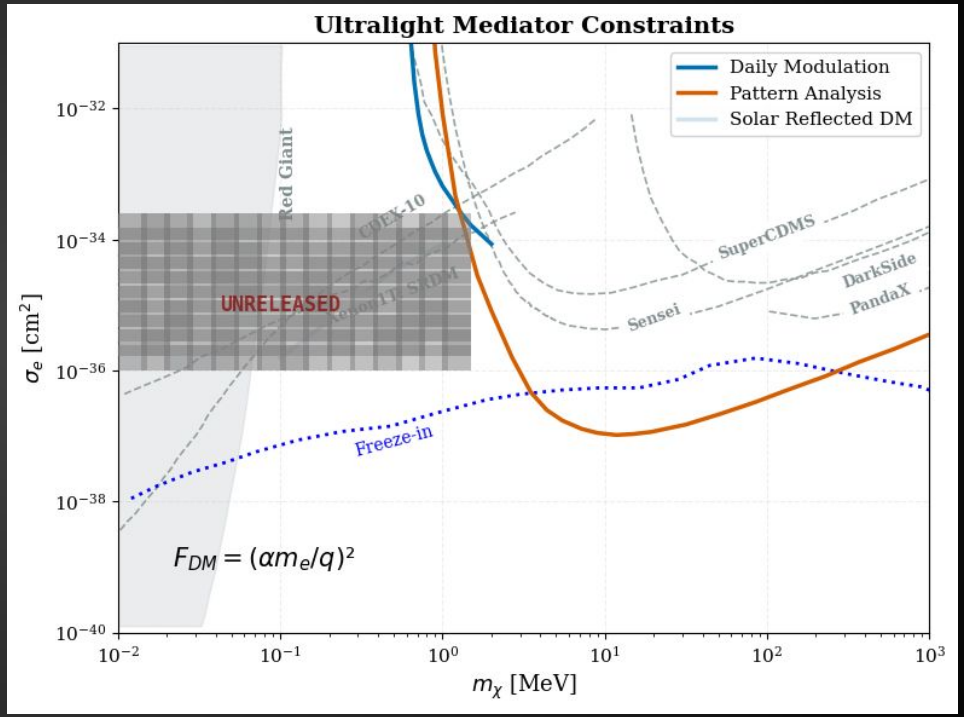


# DAMIC-M'S BRIGHT FUTURE

- New Solar reflected dark matter analysis expected soon!
- DAMIC-M aims for 1 kg-year exposure.
  - Above 1 MeV it will continue exploring freeze-in scenarios.
  - Daily modulation will be less competitive.
  - SRDM will approach freeze-in.



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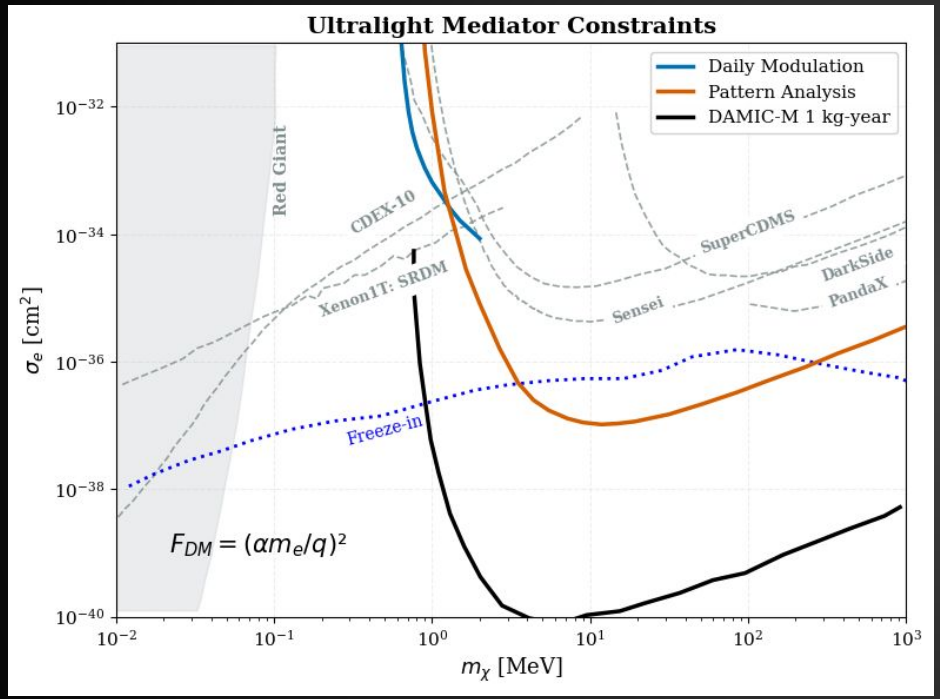
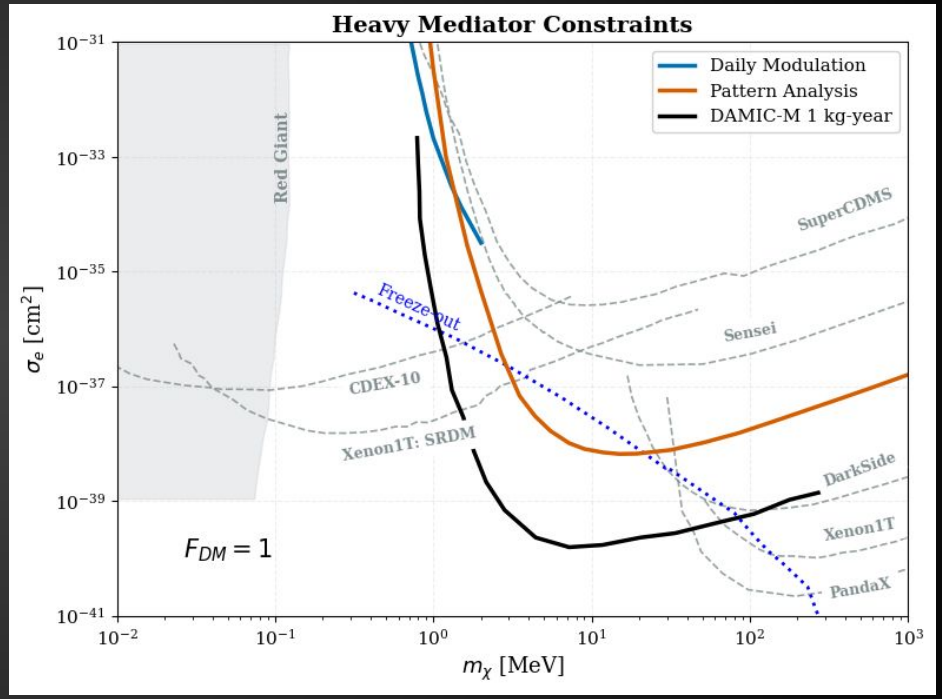


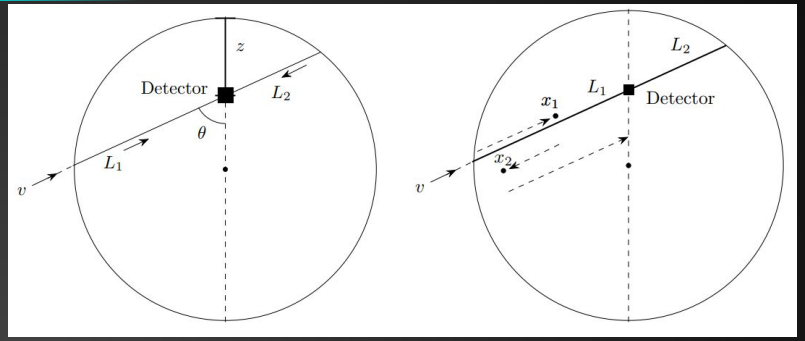
# THANK YOU FOR YOUR ATTENTION

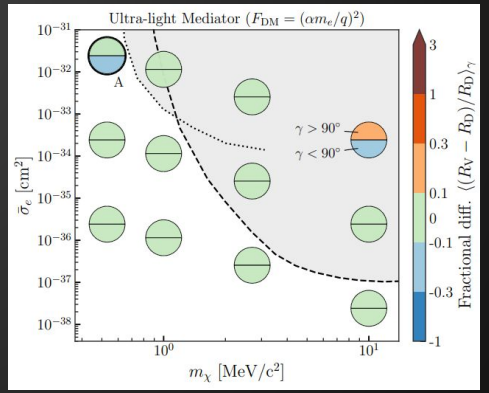
# BACK UP SLIDES

# DAILY MODULATION

Simulations are done with the Verne 2.1 code instead of the full 3D Monte Carlo approach in DaMaSCUS.

- **Verne** only considers scatters in a straight line with the possibility of reflection.
- Only considers up to **two scatter**s.
- This **semi-analytical** approach reduces the computation time significantly.
- These results agree within **10%** with the DaMaSCUS results.




Verne 2.1
DaMaSCUS