Using scientific-grade CCDs for the direct detection of dark matter with the DAMIC-M experiment

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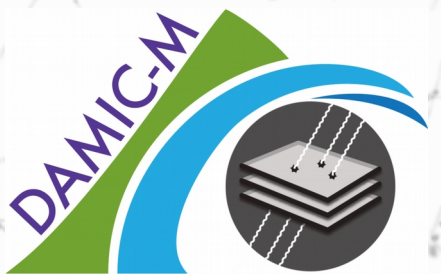
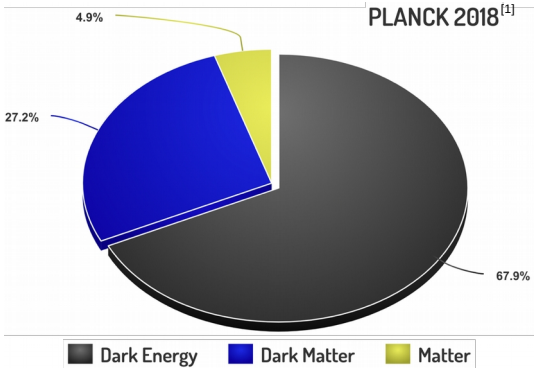
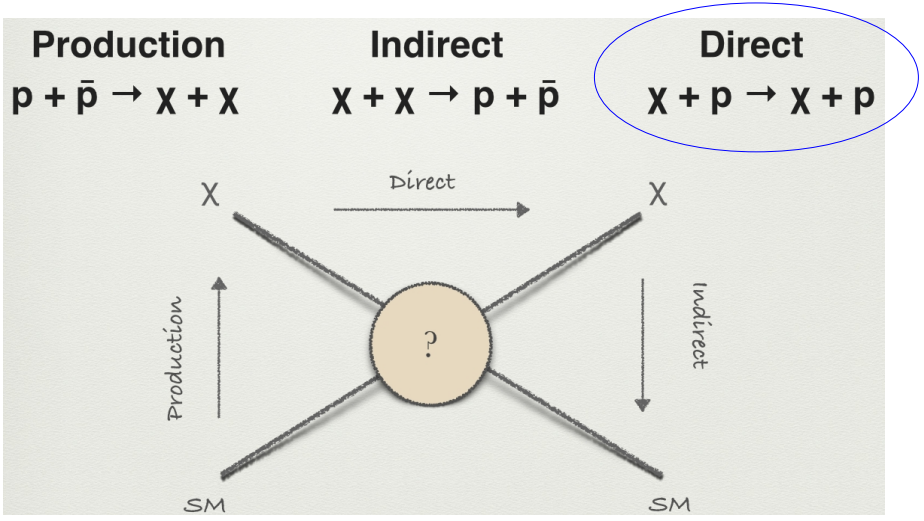


Dark matter introduction

Dark Matter can explain several galactic phenomena, like the rotation speed of the galaxies.

- Must be 5 times more than ordinary matter described by Standard Model
- Not electromagnetically interacting
- Gravitationally interacting like ordinary matter



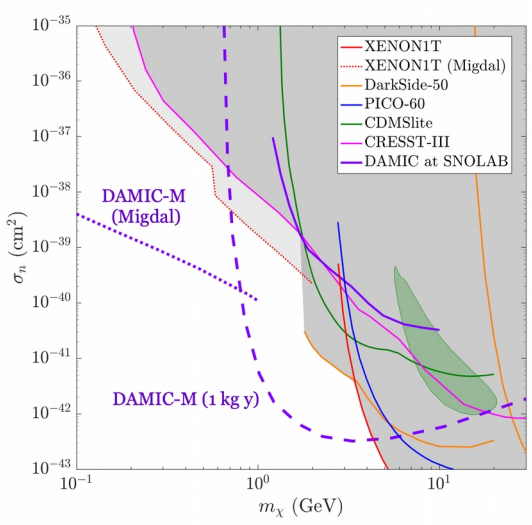


The DAMIC collaboration is dedicated to the dark matter search through its direct interaction with ordinary matter.
Dark matter candidates:

- WIMP(s): Weakly Interacting Massive Particle(s)
- Hidden sector candidates

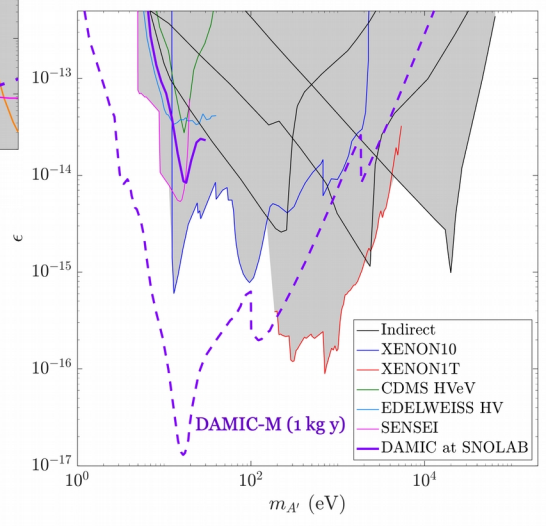
DAMIC-M expected sensitivity

DAMIC-M expected limits for 1 kilogram of target mass exposed exposed for 1 year (1 kg year).

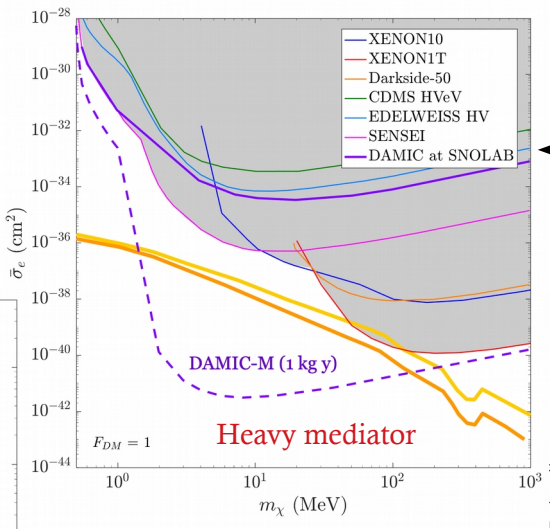


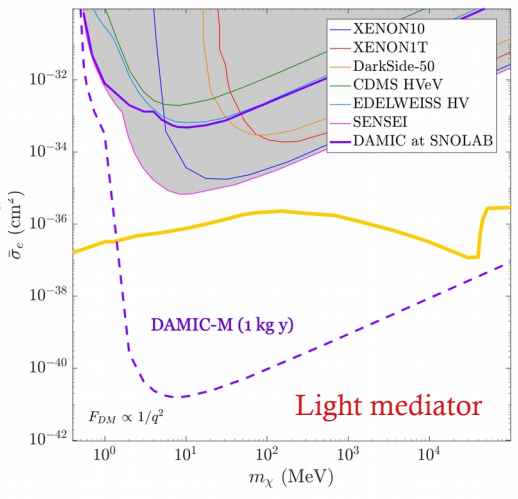
Spin-independent WIMP-nucleon scattering cross section vs DM mass

Kinetic mixing parameter vs $m_{A'}$ assuming that the dark photon constitutes all of the DM



DM-electron cross section vs m_χ





DAMIC-M overview

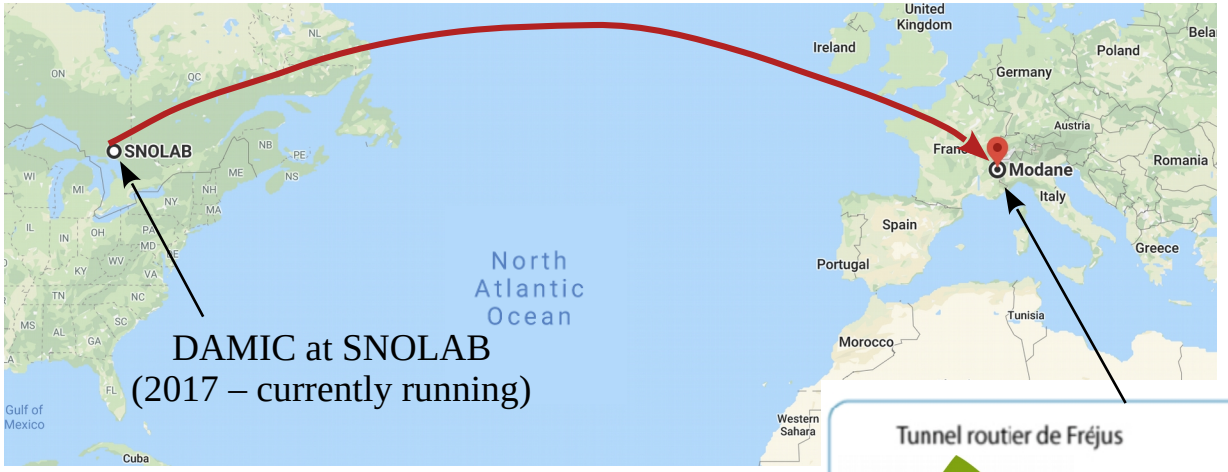
To achieve these limits:

- Very low background (cosmic bg & radioactivity)
- Massive detector
- Very low threshold & Single e resolution

DArk Matter In CCDs at Modane (DAMIC-M)[2]:

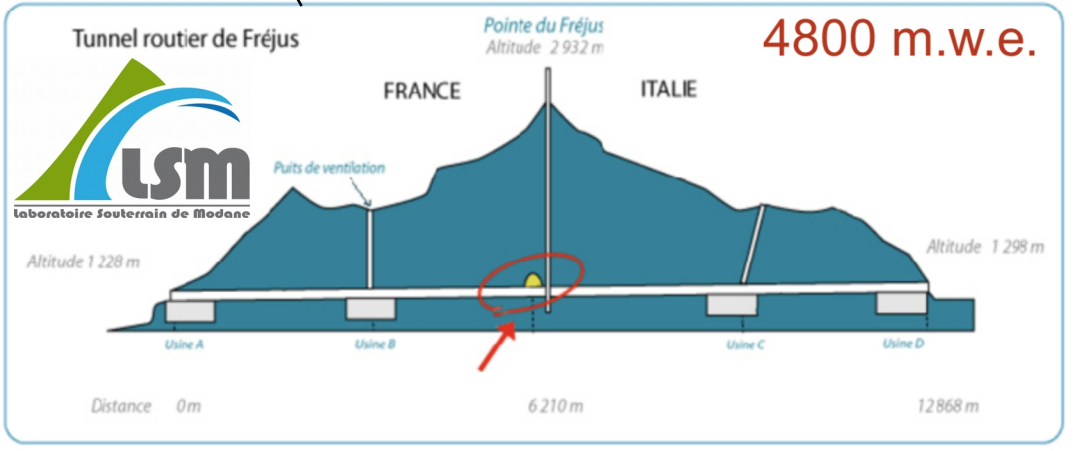
- Placed in Underground Laboratory at Modane
- Radiopure materials for construction & shielding ~0.1 events/(keV kg day) = 0.1 dru
- Scientific grade **C**harge-**C**oupled **D**evices with a total target mass of ~1kg
- CCDs with Skipper readout implementation
- R&D of a novel acquisition system

DAMIC at Modane (DAMIC-M)

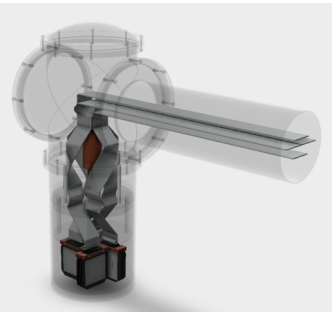


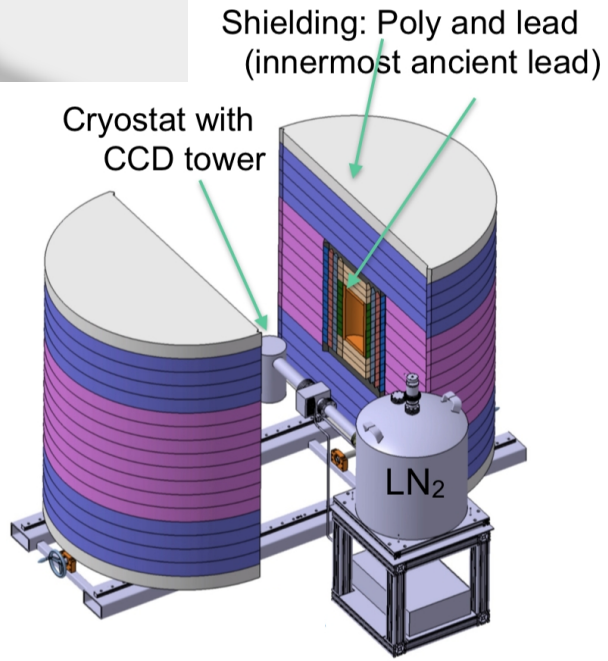
DAMIC-M will be installed in the Modane Underground Laboratory (LSM).

- ~2km of rock to stop cosmic background
- Radon-controlled air supply



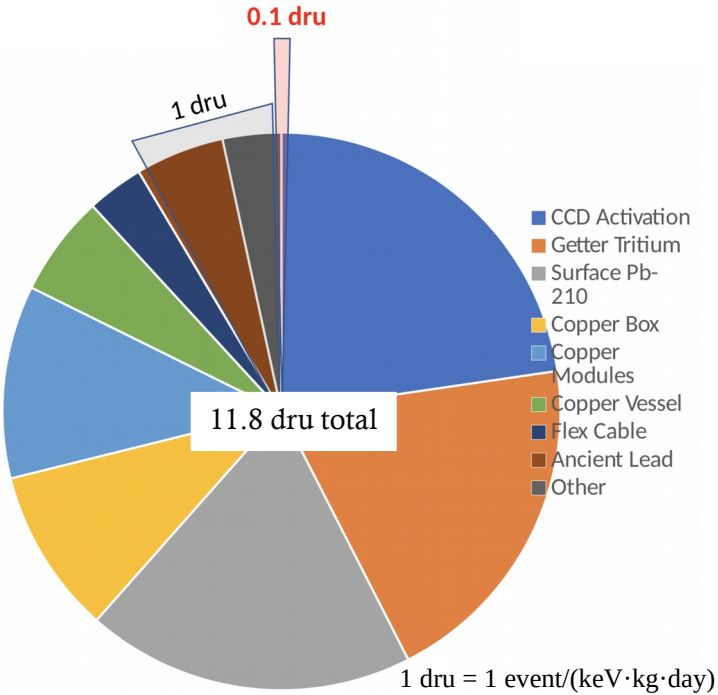
Shielding and Background





DAMIC at SNOLAB background = 11.8 dru

DAMIC-M background goal = a fraction of 1 dru



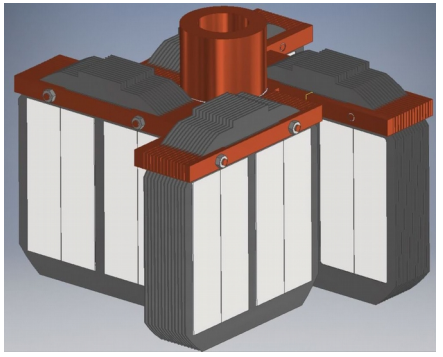
Major improvements for background mitigation:

- Protect the raw materials for the CCD from activation
- Completely remove the gettering layer
- Use of electroformed copper

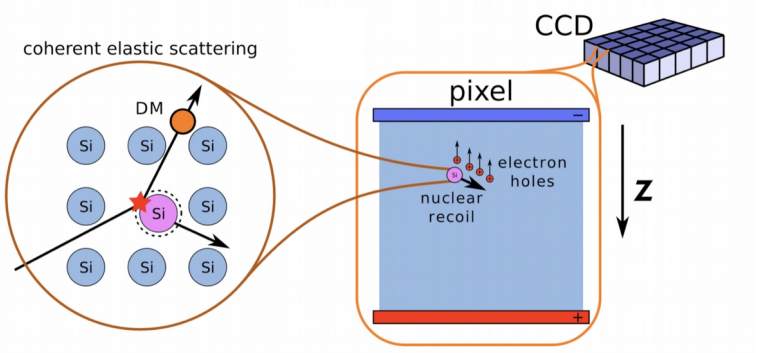
DAMIC-M CCDs

Scientific-grade Charge Coupled Devices (CCDs):

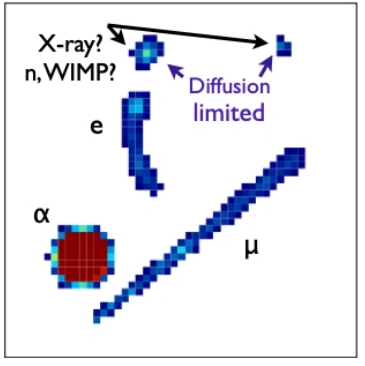
- A CCD is a pixel detector made of silicon
- Each frame composed out of 4 individual 1.5k x 6k pixel CCDs
- ~20g of pure n-type silicon per frame (~10cm x 10cm)
- Great spacial resolution with a pixel area of 15μm x 15μm and 675μm thick
- 3D reconstruction of the interaction point using the charge packet diffusion
- Rejection of inner-silicon background as radioactive decay chains



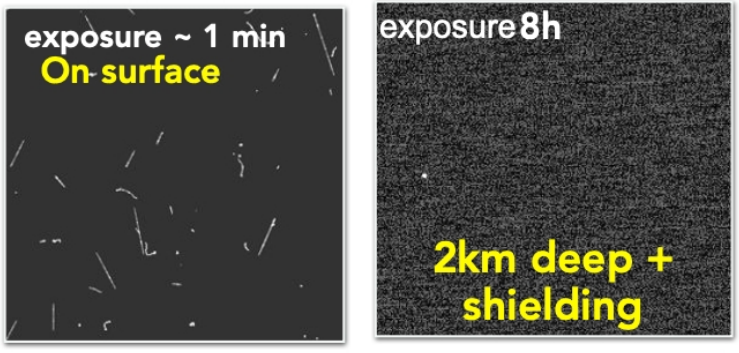
Concept design for the placement of ~50 CCDs for DAMIC-M



Dark matter interaction with silicon atoms creating electron-hole pairs

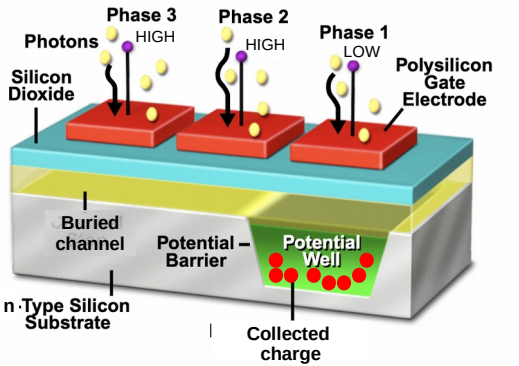


Particle track identification



Real CCD images for given exposure times and locations

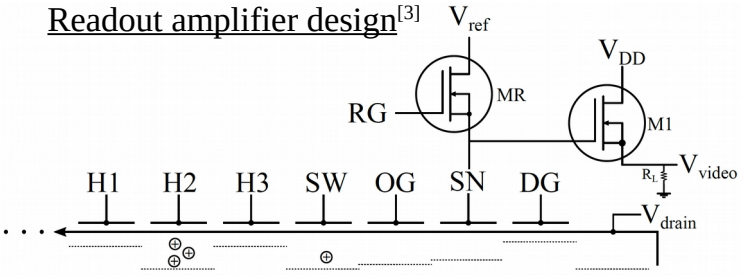
CCD Operation



CCD single pixel structure

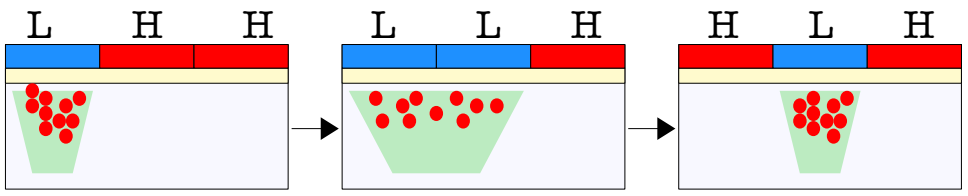
- In n-type Si, the collected charge is holes
- Charge collection at lowest potential
- Apply substrate voltage → full depletion
- **Dark current**: thermally generated charge in the bulk of the silicon

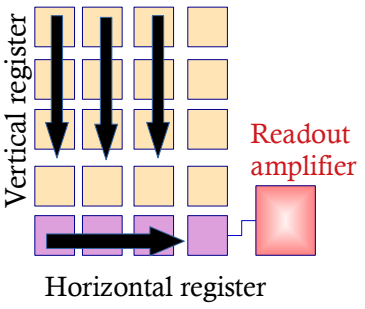
Readout amplifier design[3]

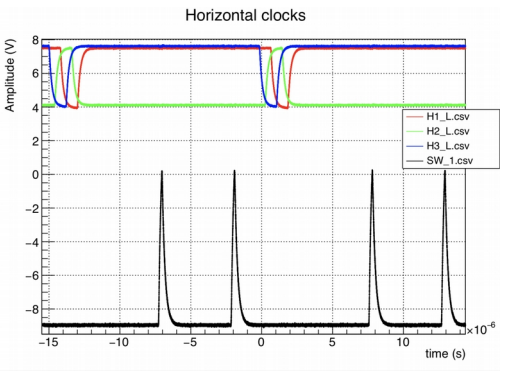


Charge Transfer

- Move the charge by alternating the voltage of the electrodes (phases) from pixel to pixel and then to the readout amplifier







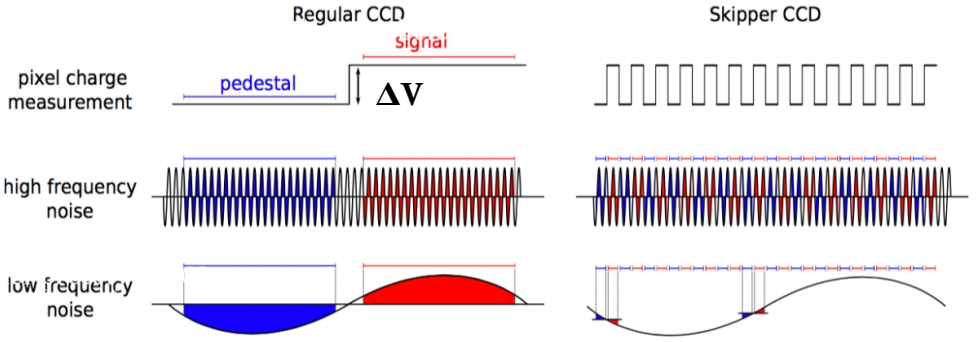
Example of CCD clocks

- **Clock induced noise**: lose or gain charge if the clocks are not well optimized

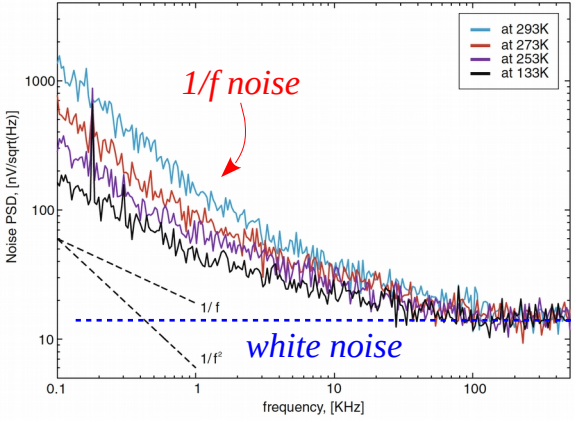
New electronics: 4CABAC board

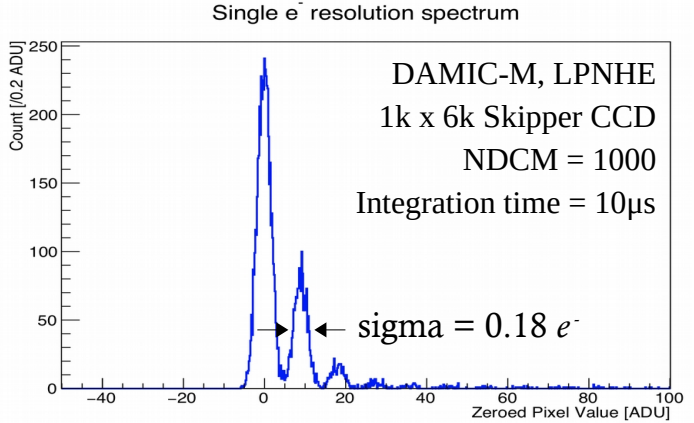
Skipper readout – sub-e^- resolution

- **Regular** CCD: single skip integration time *O*(**10µs**)
  - → high frequency white noise is eliminated
  - → limited by low frequency noise (1/f noise)
- **Skipper** CCD[]: single skip integration time *O*(**1µs**)
  - → **multiple measurements of the pixel charge**
  - → low frequency noise eliminated
  - → single fast measurement of lower resolution



- Output noise decreases as 1/√NDCM (Non-Destructive Charge Measurements), reaching sub-e^- resolution





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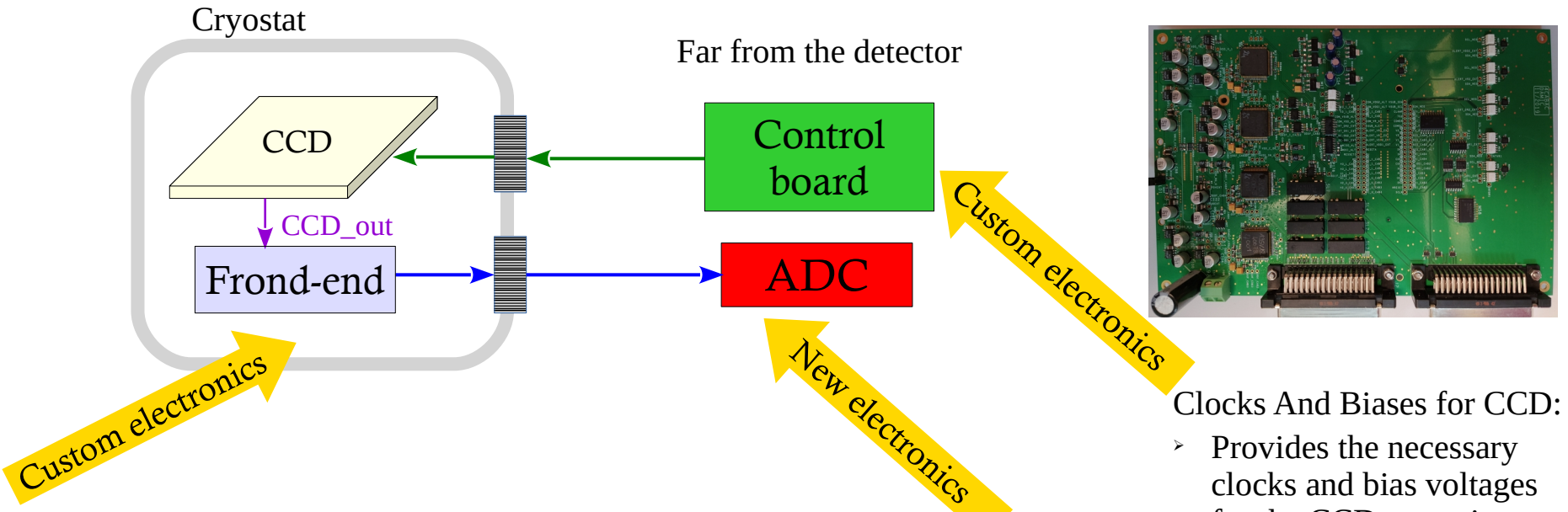
New acquisition system



CCD ReadOut Chip

- Low noise frond-end chip
- Amplifies the output of the CCD to improve the Signal-to-Noise Ratio
- Minimizes any introduced noise until the ADC

ADC: **A**nalog to **D**igital **C**onverter

- 18-bit resolution
- 15MHz sampling frequency

Clocks And Biases for CCD:

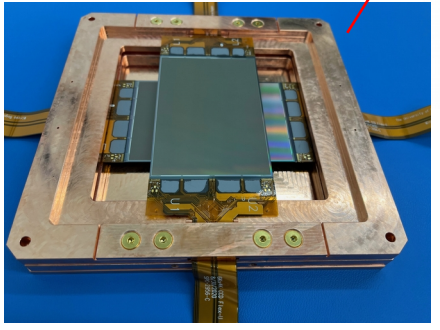
- Provides the necessary clocks and bias voltages for the CCD operation
- Performs the sequencing of the clocks

Low Background Chamber

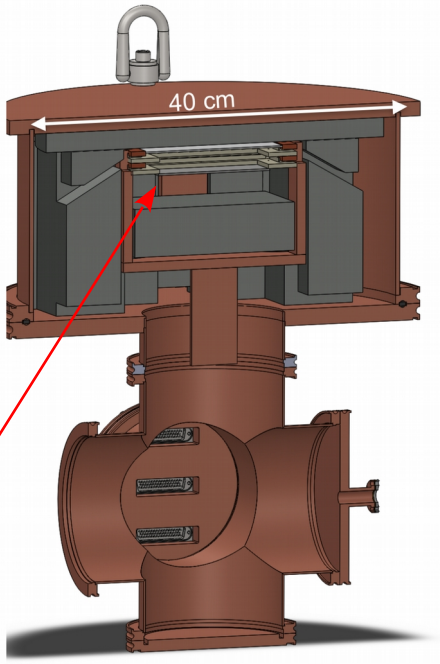
Low Background Chamber (LBC): A smaller test detector with 2x CCDs (~18 g) at LSM. Already installed and operating for tests and scientific runs.

Objectives:

- Characterization of the new CCDs for DAMIC-M.
- Measurements of background at LSM and the activation of the CCDs.
- Test the new electronics and the overall acquisition system.
- First DAMIC-M scientific results.



The 2-CCD package inside the LBC

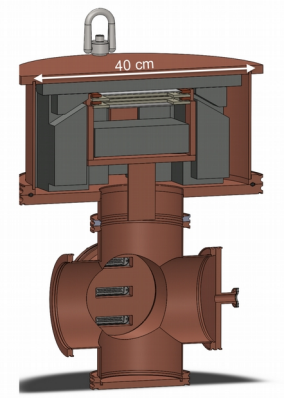


Cross section of the LBS design

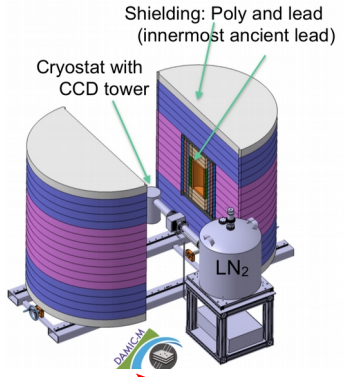
Timeline

Activities:

- Background studies
- Large CCD packaging
- R&D of the new electronics
- Production of the sequencer for the CCD operation
- Operate the CCD with the new acquisition system



Low Background Chamber (LBC)
Installation is complete. Testing and scientific runs on the way.



Installation of DAMIC-M

February 2022 (today)

in 2023

… *STAY TUNED*

References :
[1] *Planck 2018 results. I. Overview and the cosmological legacy of Planck*, Plank Collaboration, 2018
[2] *DAMIC-M Experiment: Thick, Silicon CCDs to search for Light Dark Matter*, N. Castello-Mor for the DAMIC-M Collaboration, 2020
[3] *SENSEI: Characterization of Single-Electron Events Using a Skipper-CCD*, SENSEI Collaboration, 2022