DAMIC-M
Status of the CCDs Sensors

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(on behalf of the DAMIC-M Collaboration)

The 26th International Workshop on Vertex Detectors

October 18, 2019

CSIC
Consejo Superior de Investigaciones Científicas

IFCA
Instituto de Física de Cantabria

DAMIC-M

Outline

Scientific framework

- Dark Matter
- Direct Detection

DAMIC Experiment

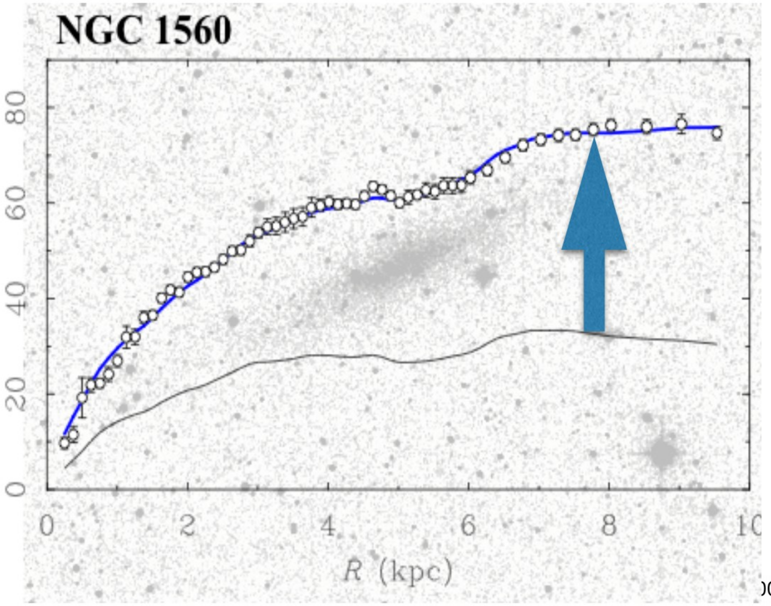
- DAMIC at SNOLAB
- CCDs as Dark Matter Detectors

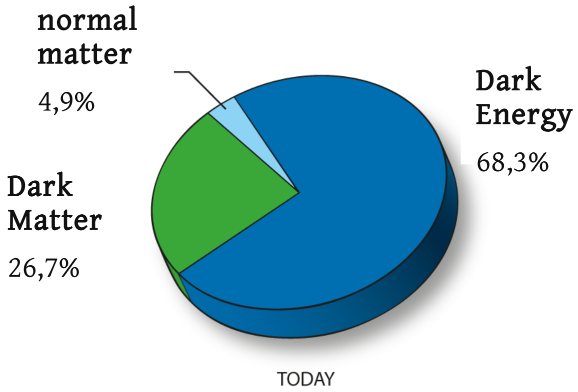
DAMIC-M: DAMIC at Modane

working to achieve single electron resolution and a background level lower than 0.1 dru

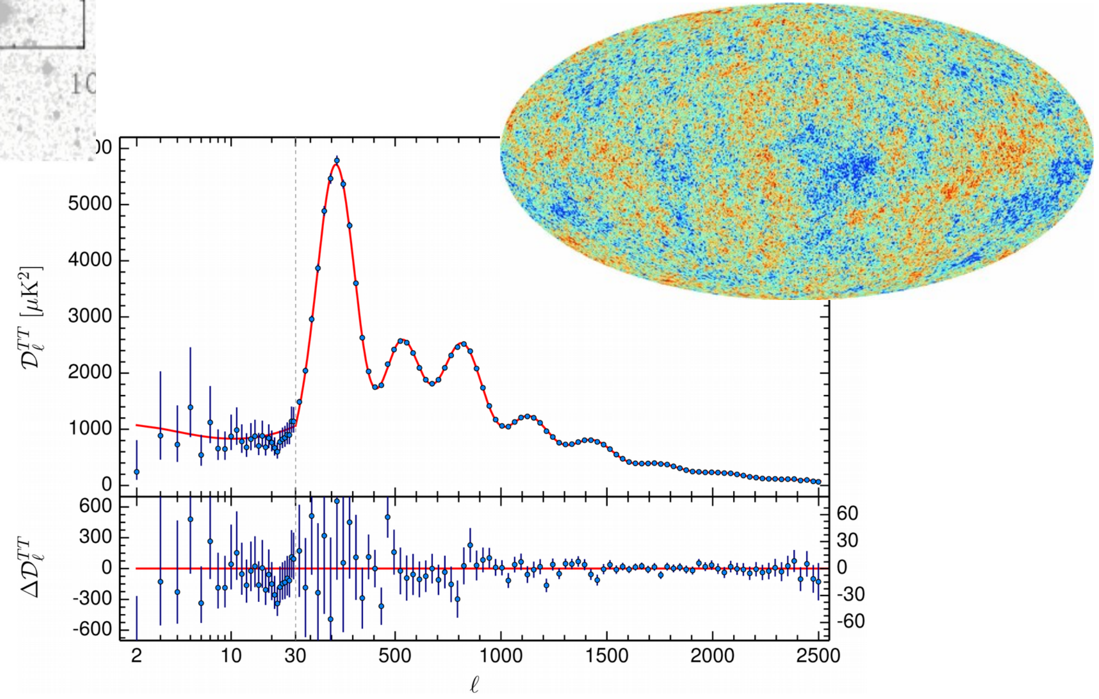
Dark Matter

Begman. et al. MNRAS 249 (1991)





Plank Collaboration, A&A 594, A11 (2016)



Evidence

- Galaxy Rotation
- CMB
- Lensing

Interactions

- Gravity: yes → matter
- EM: no → dark
- other? Maybe?
  – Weakly interacting Massive Particles

DAMIC Experiment

DM Direct Detection

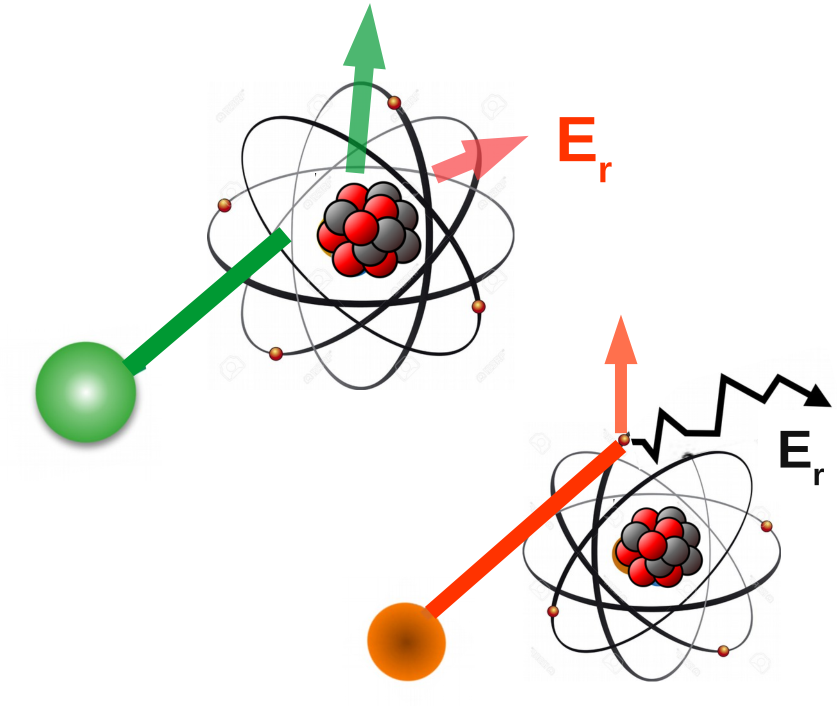
SIGNAL:

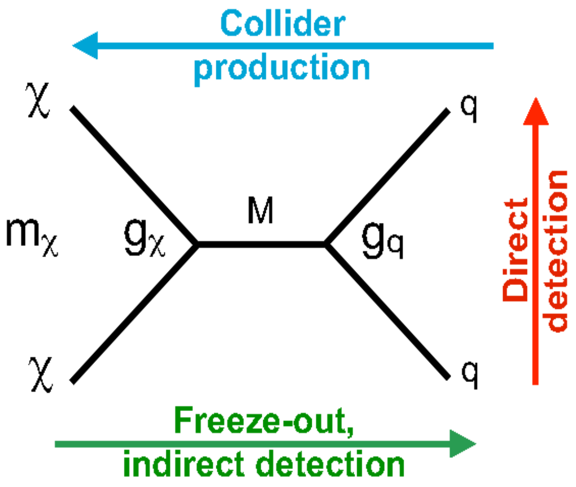
scattering off nuclei

- The standard **WIMP** paradigm
- 1–1000 GeV DM masses
- 1–100 keV recoil energy

scattering off electrons

- As in the case of a **dark photon**
- 1–1000 MeV DM masses
- 1–10 eV recoil energy





The measure of this rare events requires EXTREMELY LOW Backgrounds: electromagnetic radiation, neutrons, alpha particles, neutrinos

cosmic rays and secondary/tertiary particles: **deep underground** laboratories

Radon (^{222}Rn) decays in air: passive shields Pb, polyethylene, …

alpha particles: ^{210}Pb **decays at the detector surfaces**, nuclear recoils from the Rn daughters

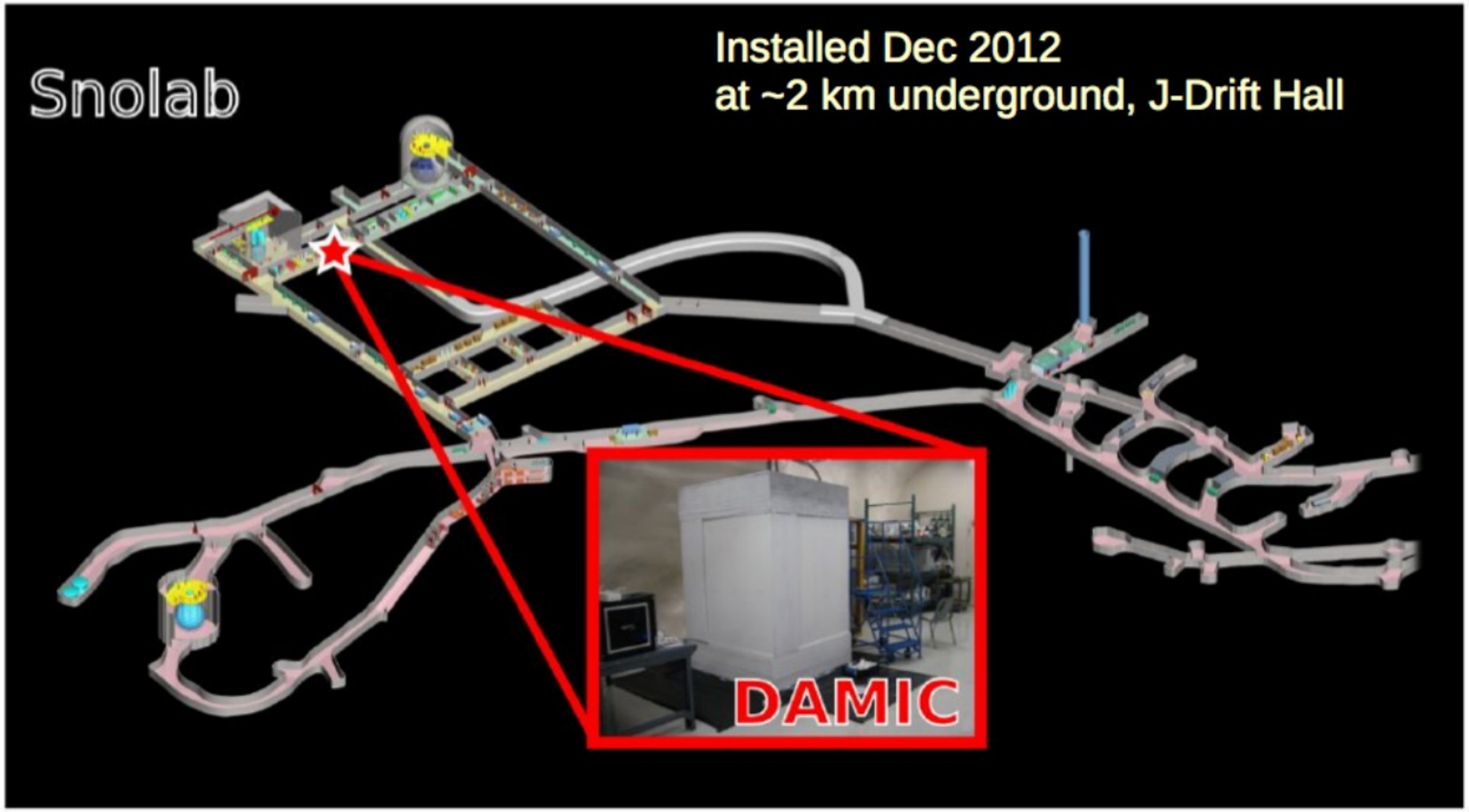
external/internal radioactivity: ^{238}U, ^{238}Th, ^{40}K, ^{60}Co, ^{39}Ar, ^{137}Cs, … decays in the detector materials, target medium, shields

…

DAMIC

at SNOLAB currently taking data

(Vale Creighton Mine located near Sudbury, Ontario, Canada)



DAMIC

DArk Matter In CCDs

In **SNOLAB**, we have set up a DAMIC experiment under 2km of rock (muon flux reduced by ~5 orders of magnitude).

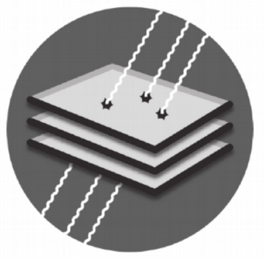
We then **shielded the CCDs** using

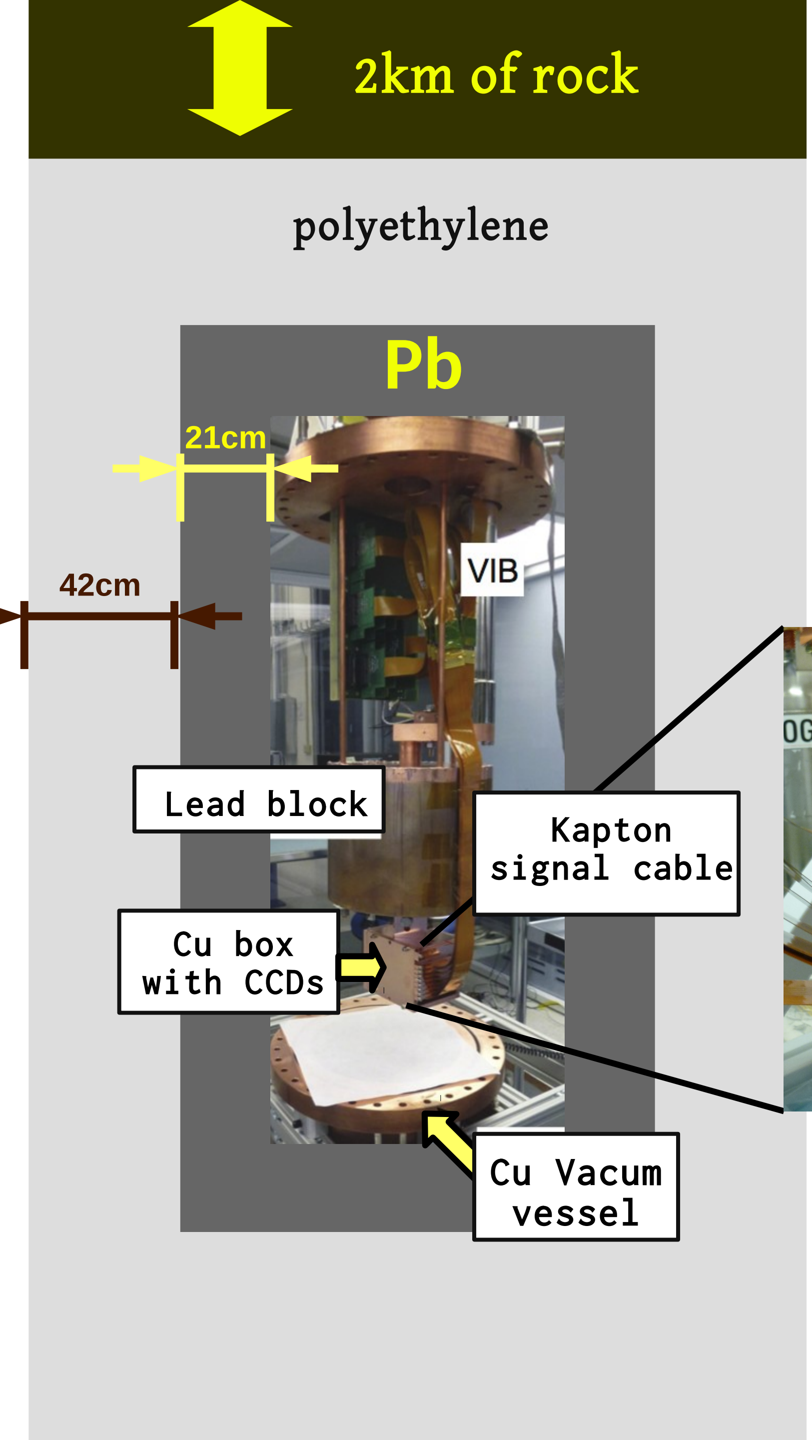
– ancient lead to stop gammas

– **polyethylene layer** (~42cm) **to stop neutrons**

– a layer of low radioactive lead (~21cm) **to stop gammas**

We currently have background reading around ~11,8 dru (events/keV/kg/day).

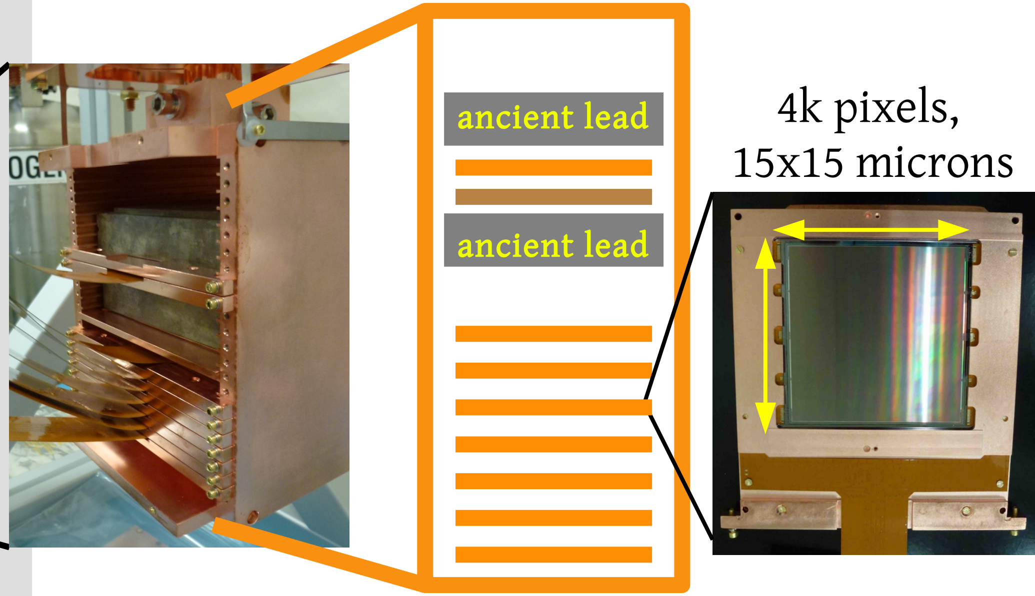




Current detector configuration:

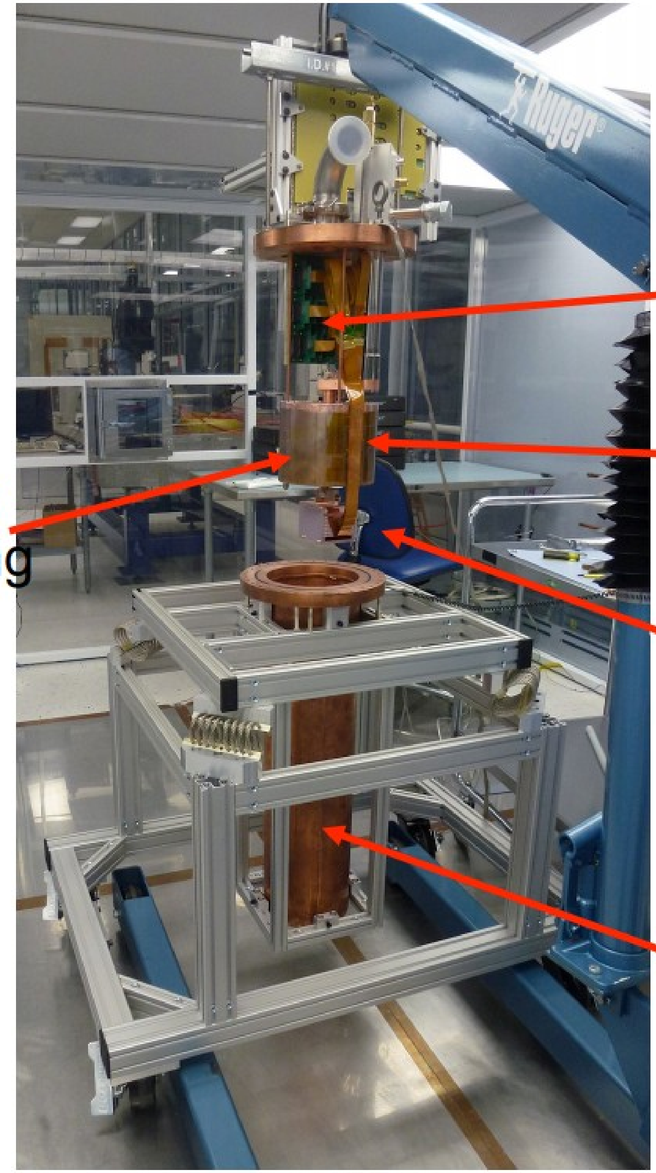
7CCDs in stable data tacking since 2017

1 CCD sandwiched in ancient lead

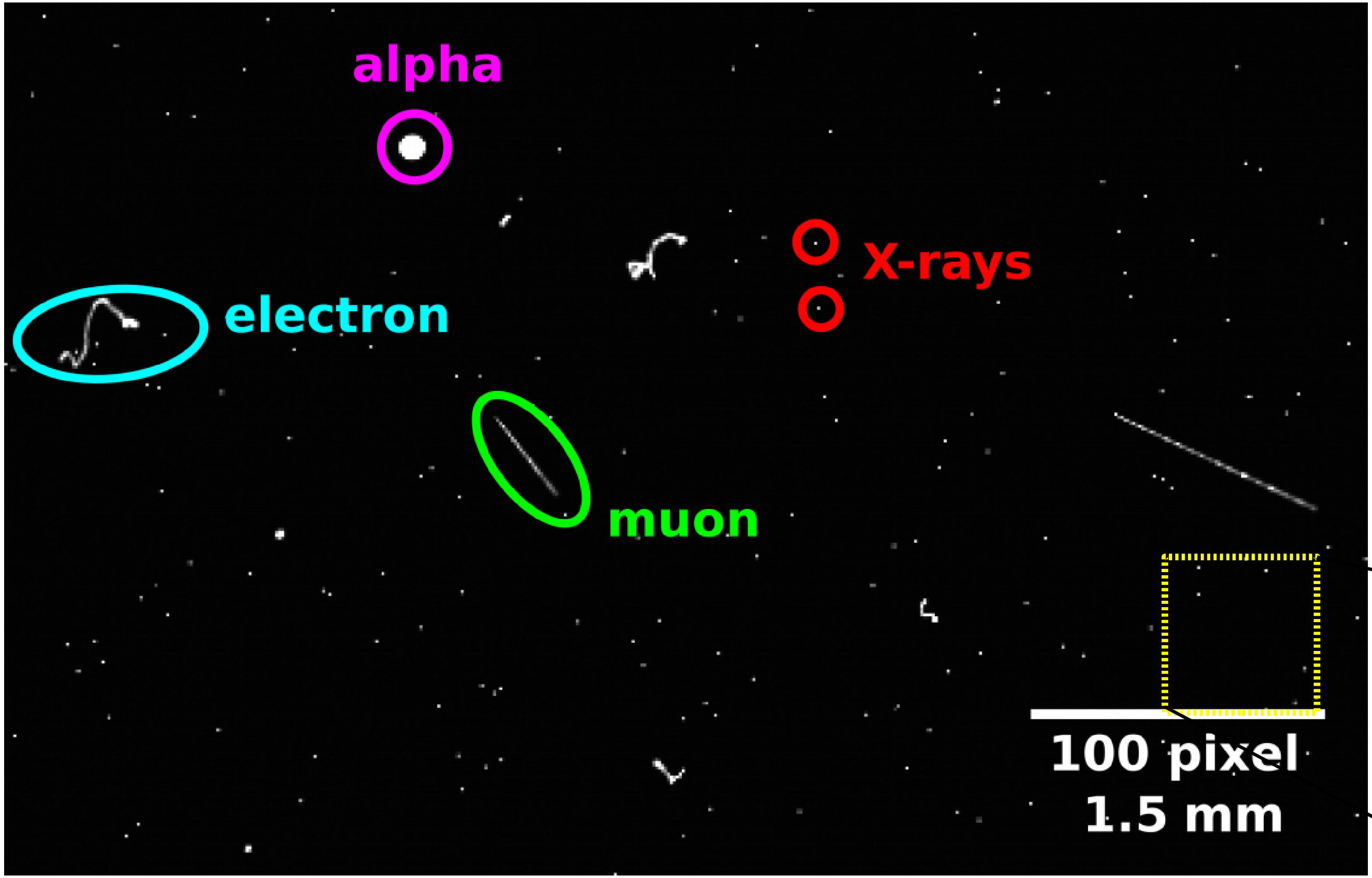


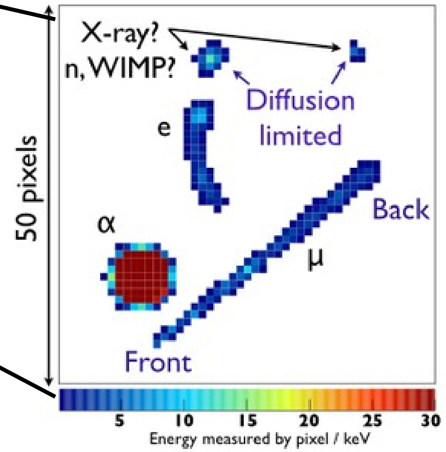
DAMIC


vacuum and cryo lines,electronics
6" lead shielding
20" thick poly shielding

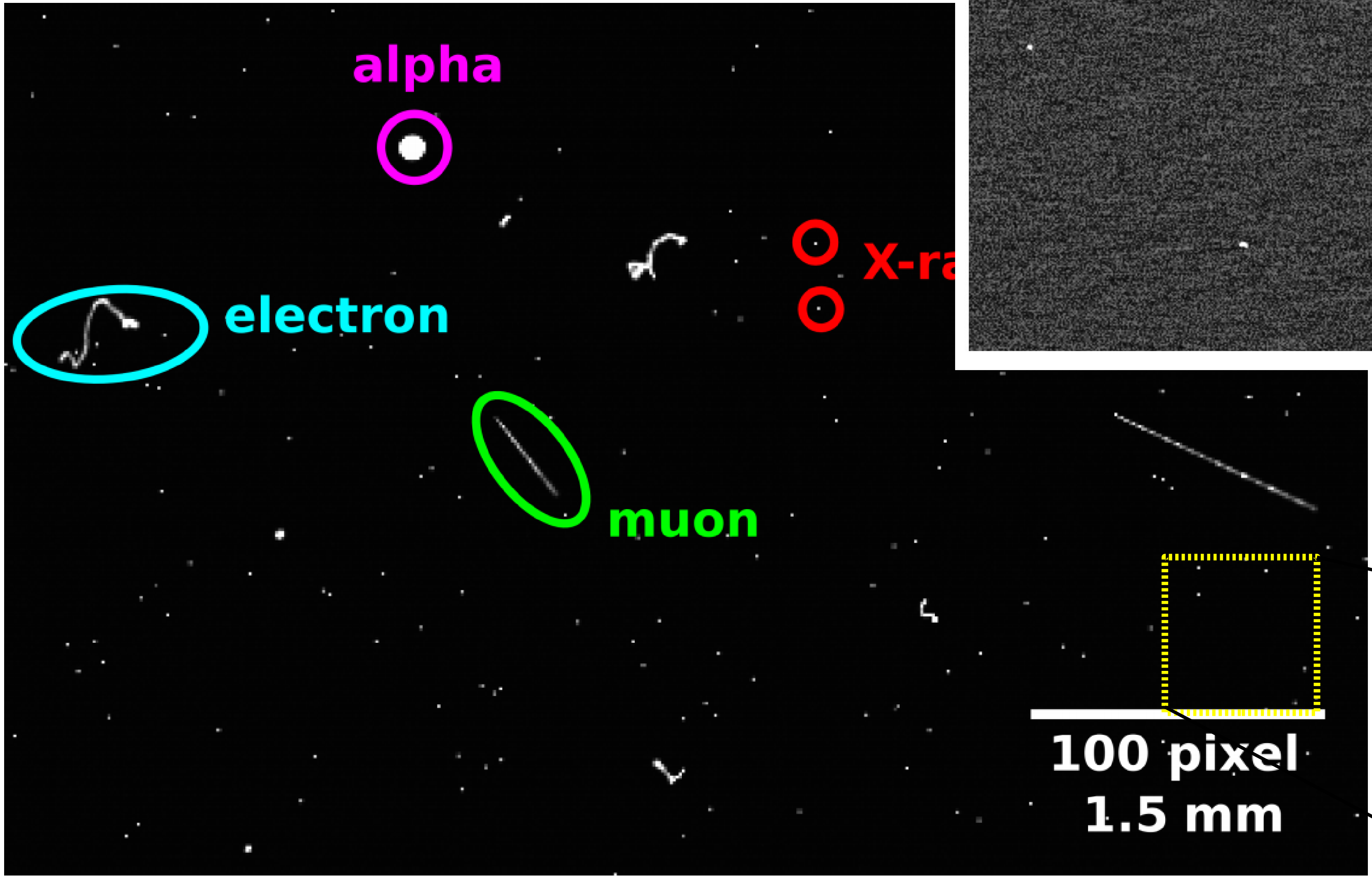

in-vacuum electronics
Kapton cable
Cu box
Cu vessel

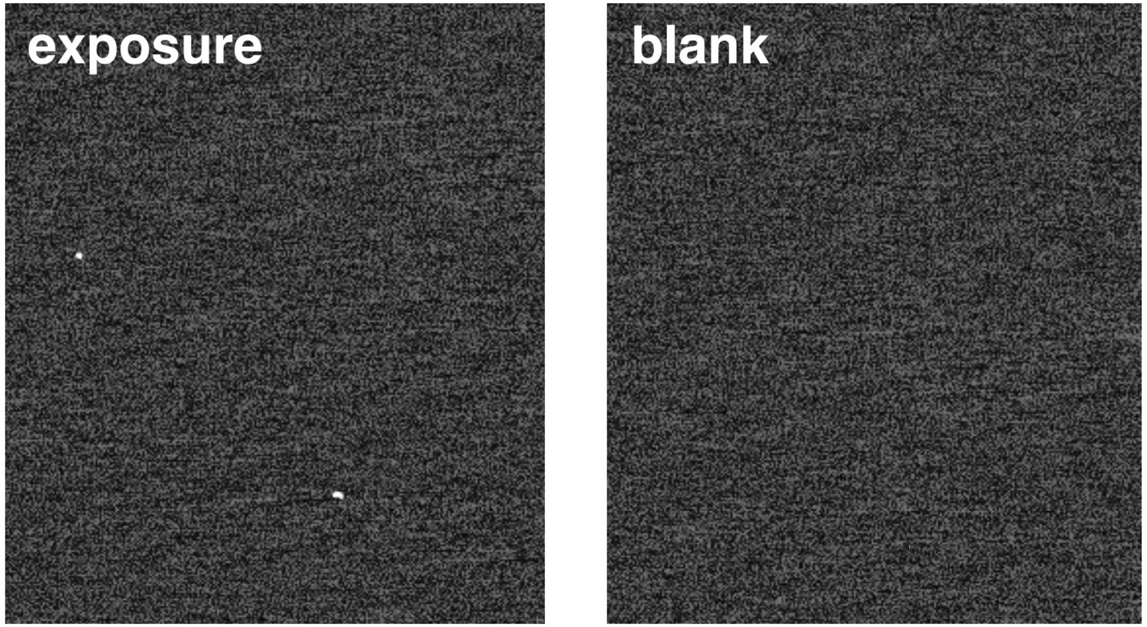
CCDs as Dark Matter Detectors

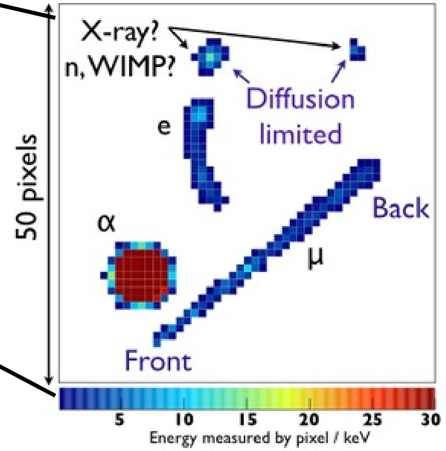




CCDs as Dark Matter

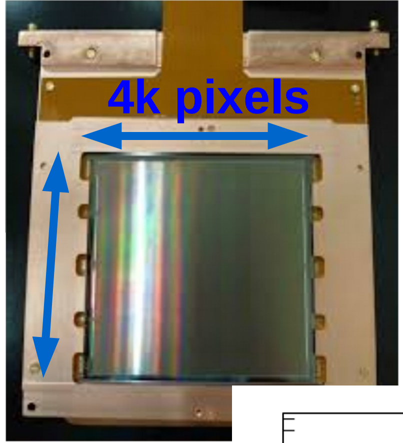






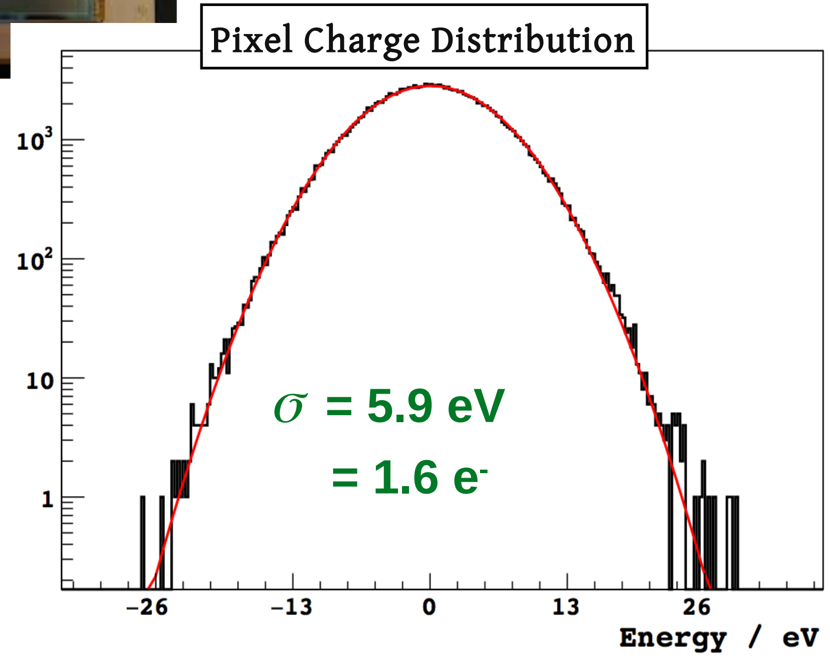
DAMIC at SNOLAB

DArk Matter In CCDs



Performance

- **Conventional 3-phase, triple polysilicon gate CCD, n-type substrate**
- **7 CCDs** in stable data taking since 2017
- **40 g target mass**
  - **16 mega pixels**, each individual pixel is **15 microns square**
  - **675 microns thick**
- **Extremely pure silicon ~10^{11} donors/cm^{-3}**, which leads to **fully depleted operation at** reasonably low values of the applied bias voltage, **~40V**
- Operating temperature of **~140 K (to minimize dark current)**
- **Conventional floating diffusion amplifiers**, and **p-channel MOFSETs** are used **for reset and amplification**
- **Slow readout time, to minimize read noise**



Major Achievements:

- Exquisite spatial resolution: unique background characterization and rejection
- Lowest Dark Current ever measured in a Silicon detector:
  - 5×10^{-22} A/cm^2, <0.001 e/pixel/day (at 140K)
- Resolution of 2e- achieved at SNOLAB
- Best results for DM scattering with masses <5MeV/c^2

DAMIC-M

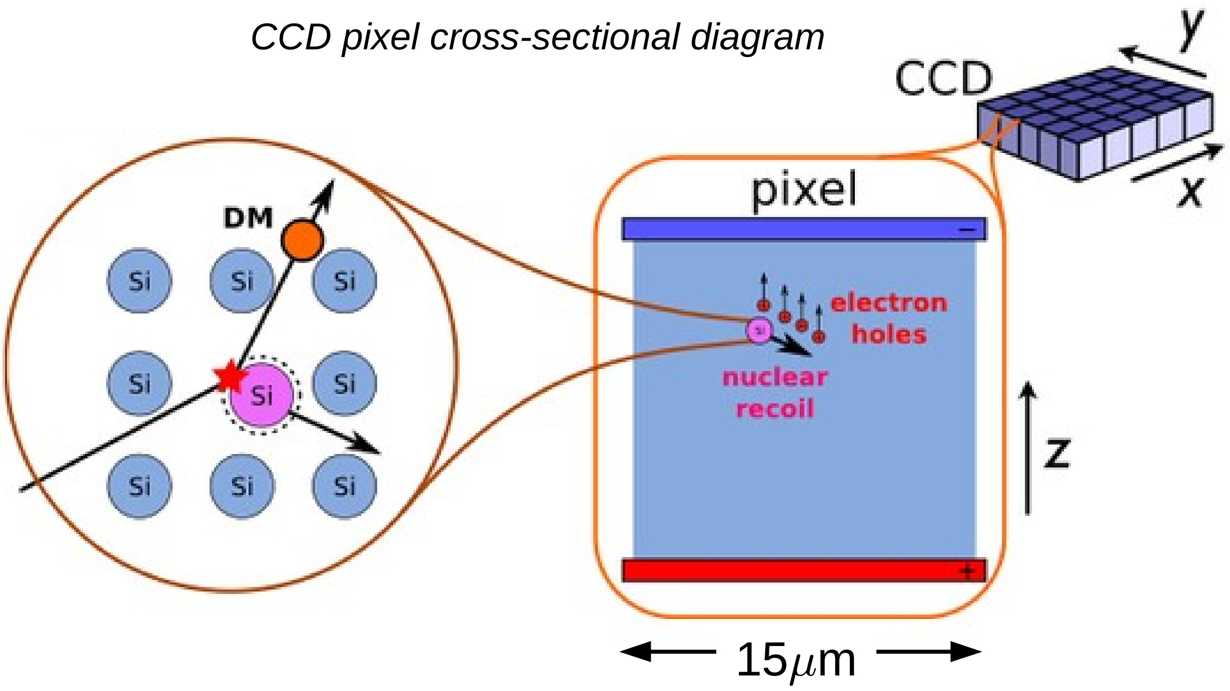
upgrade of DAMIC at Modane

will feature single electron resolution allowing for detection thresholds of 2-3 e-

CCDs as Dark Matter Detectors

The silicon bulk of the CCD is used as target to interact with dark matter candidates. From this interaction we expect charge carriers to form within the bulk and we collect and count the number of carriers in each pixel. It is a direct detection apparatus for dark matter.

CCD pixel cross-sectional diagram



Interaction with silicon produces free charge carries...

- **drifted across fully-depleted region**
  → *very little loss of charge*
- **collected** in **15 micron square pixels**
  → *exceptional position resolution*
- stored until a user-defined **readout time after many hours**
  → *large exposures*

Silicon has lower energy threshold

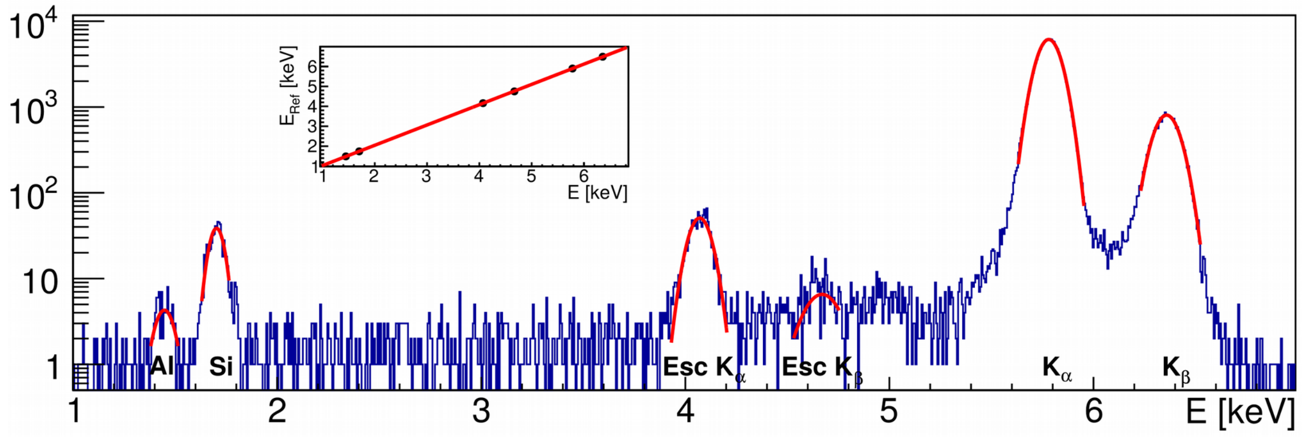
Silicon band-gap: 1.2 eV

Mean energy for 1 e-h pair: 3.8 eV

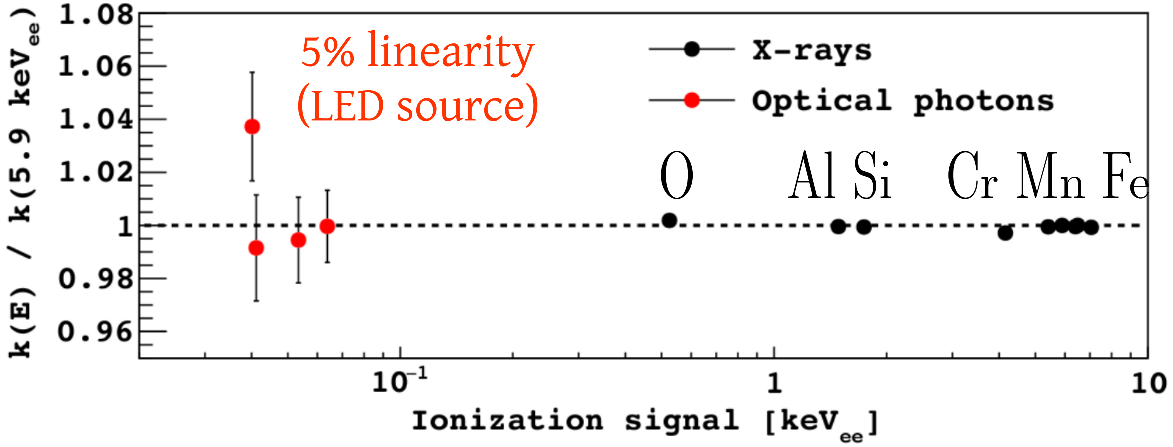
The method of read-out can be optimized to improve read-out noise at the cost of read-out time

Calibration and Energy Resolution

- Energy calibration using a O, Al, Si, Cr, Mn, and Fe x-ray lines



very nice linearity response of the CCDs down to 40eV



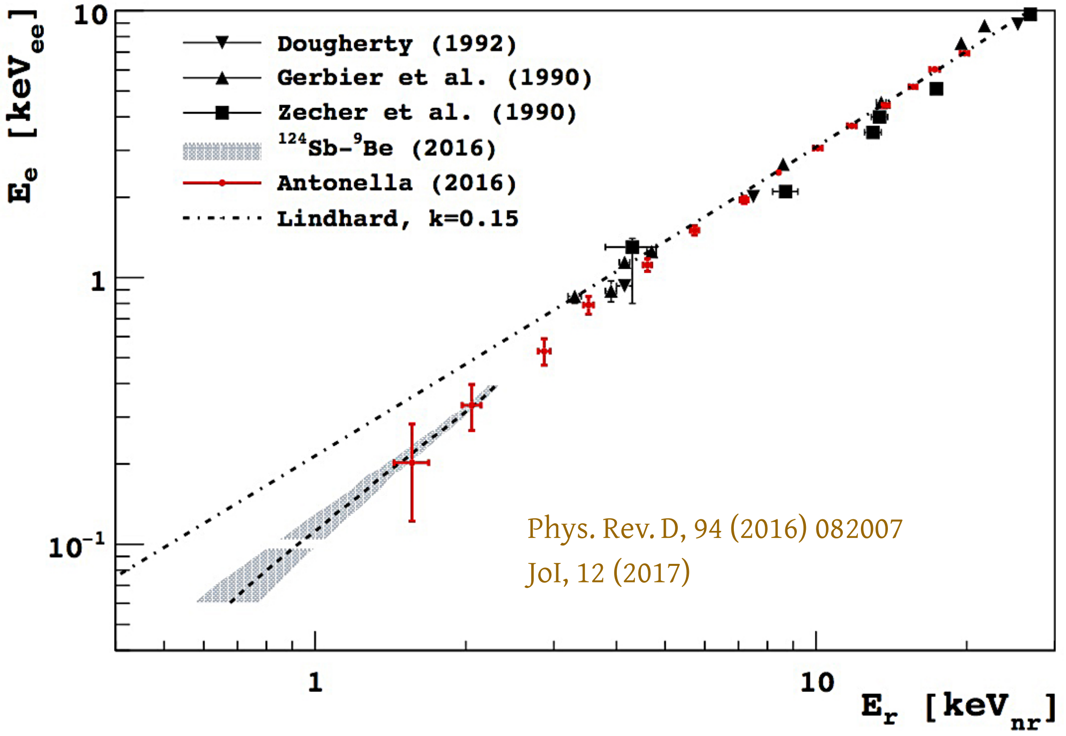
- Amplifiers measure amount of charge in ADU
- Conversion factor k (ke V_{ee}/ADU) calibrated using X-ray emission lines
- k is constant over the energy range we are interested in

Nuclear Recoil Efficiency

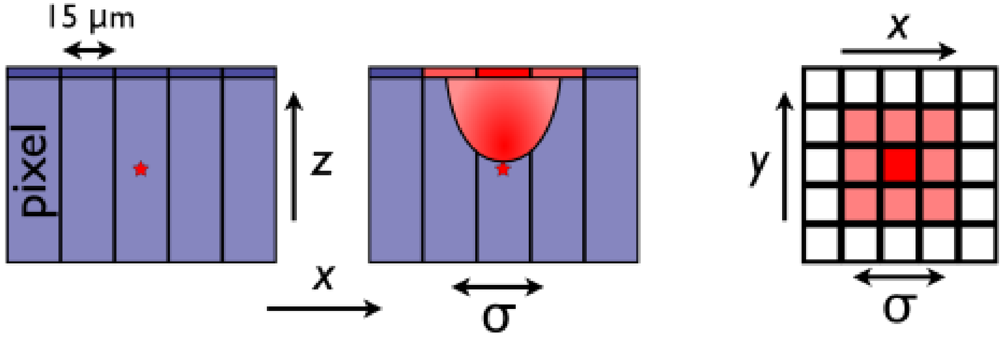
To characterize a potential DM signal is very important to know the relation between the **energy deposited by the recoiling nucleus in the form of ionization E_r** and **the nucleus kinetic energy E_e.**

Calibrations at low energies with low-E neutrons from a ^{124}Sn–^{9}Be photo-neutron source down to 0.7 keV_{nr}.

How to: nucleus from the source (monochromatic neutron flux of 24keV) elastically scatter off silicon nuclei; the subsequent nuclear recoils deposit their kinetic energy in the silicon bulk within 10 nm, producing signals that mimic those expected from WIMP interactions.

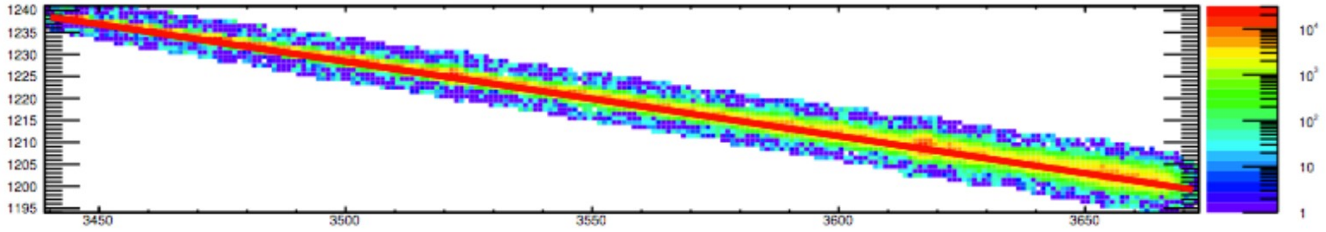


Depth Reconstruction

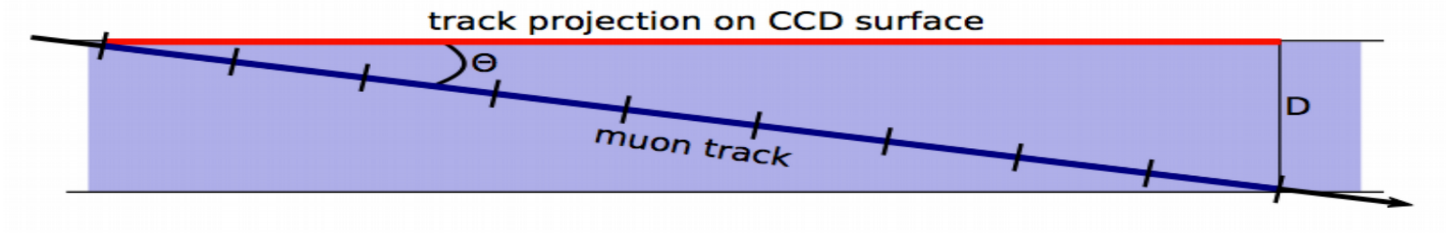


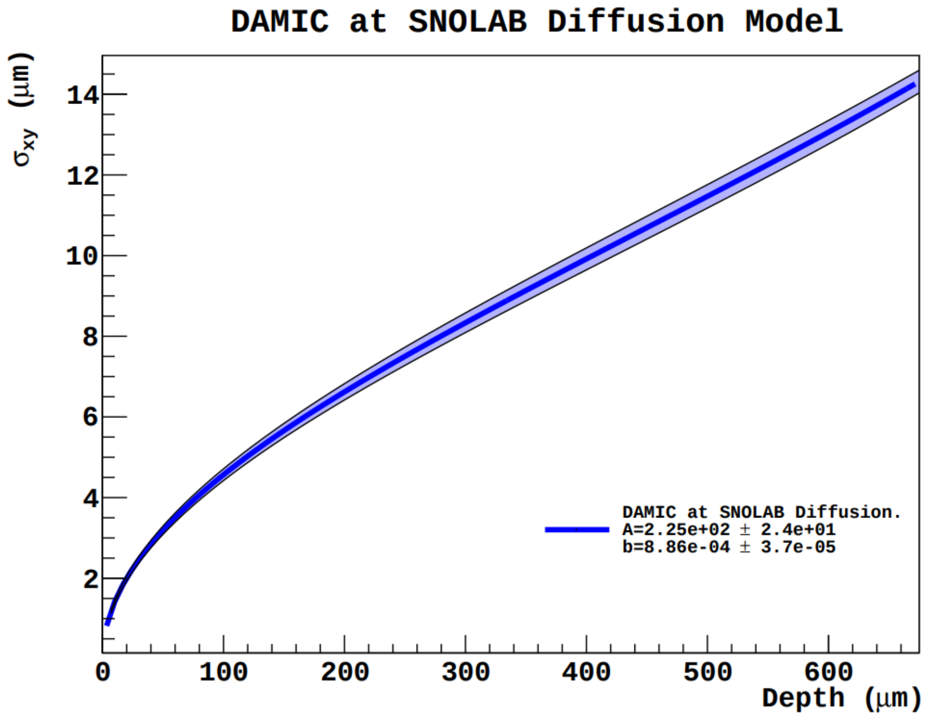
Muons tracks (at ground level) allows measurements of diffusion

Muon track: CCD top view



CCD side view





Diffusion can be measured as a function of the interaction depth

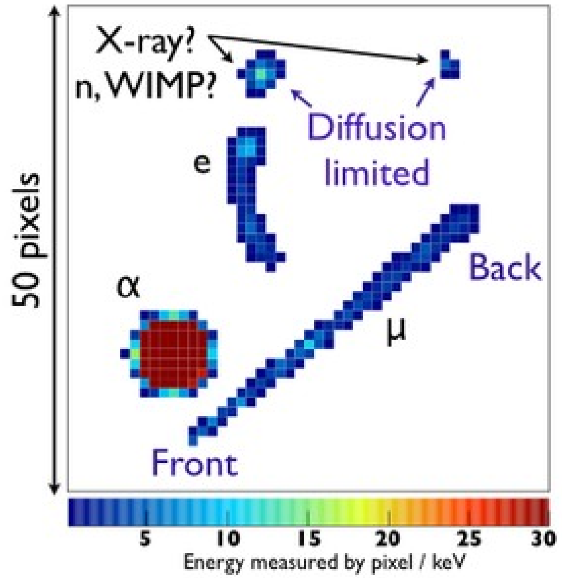
$$\sigma_{xy}(z) = \sqrt{-A \ln(1 - bz)}$$

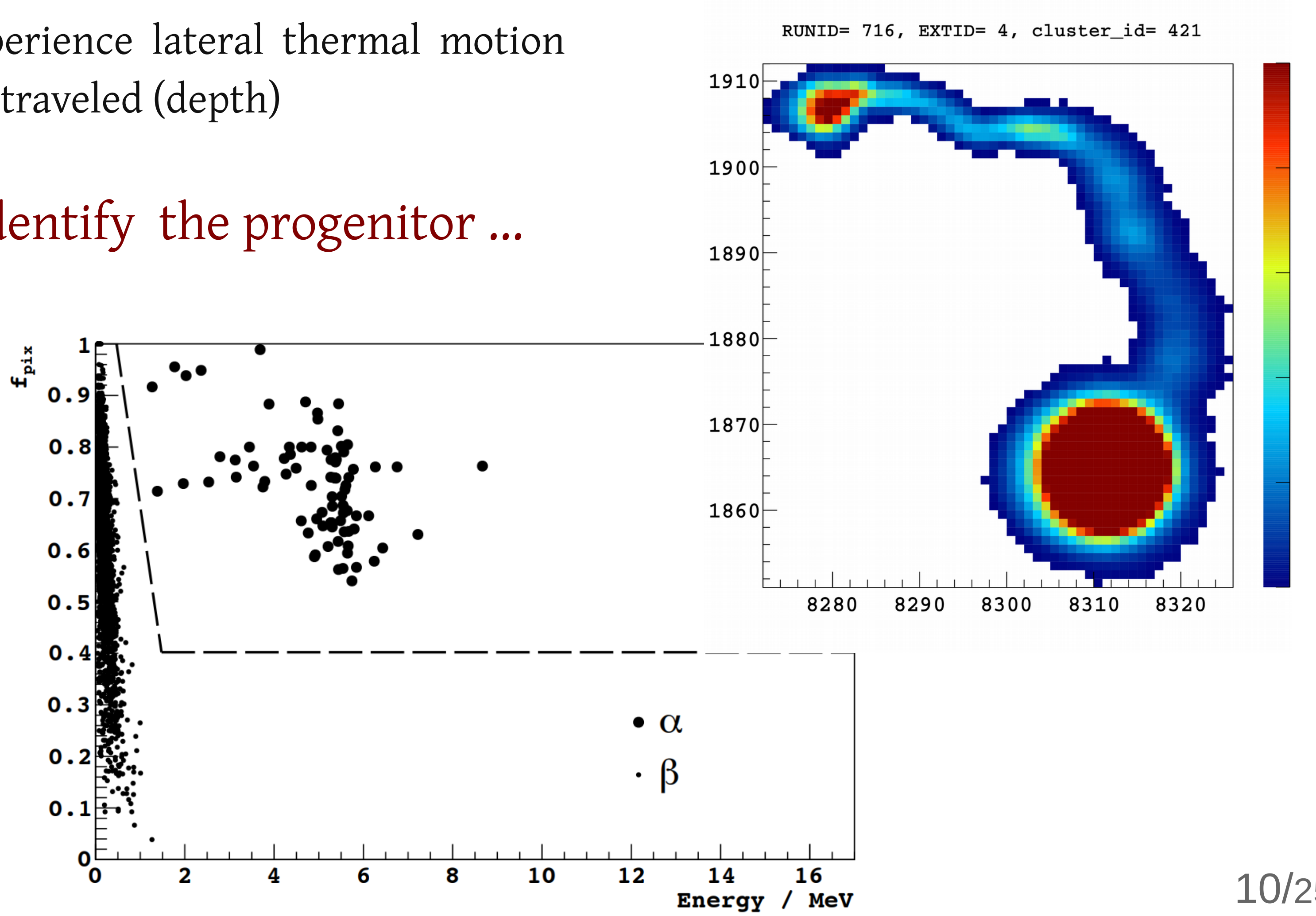
Background Characterization

Particle Identification

As charges drift across the CCD, they experience lateral thermal motion (diffusion) proportional to vertical distance traveled (depth)

Above 1keV, the event profile can identify the progenitor ...





Background Characterization

Background Characterization and Rejection

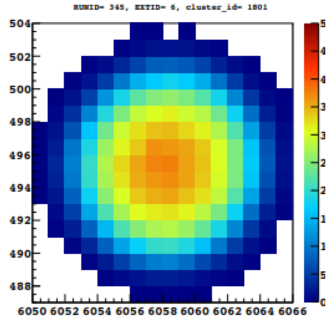
^{210}Pb (from radon) and ^{32}Si (cosmogenic) are backgrounds that are very hard to estimate and must be demonstrated **to be low** (or able to be rejected) **for** any proposed **dark matter search in Si** without electron rejection.

^{210}Pb → (64keV) → ^{210}Bi (5d) → (1.2MeV) → ^{210}Po

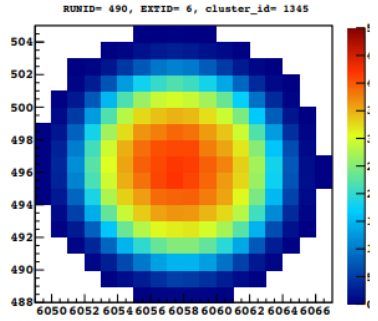
^{32}Si → (0.22MeV) → ^{32}P (14d) → (1.7MeV) → ^{32}S

3 alphas at the same location consistent with a sequence from ^{232}Th

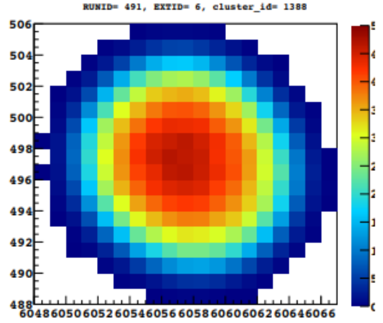
E = 5.4 MeV



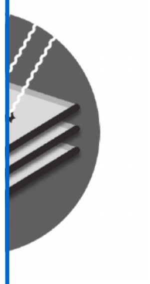
E = 6.8 MeV



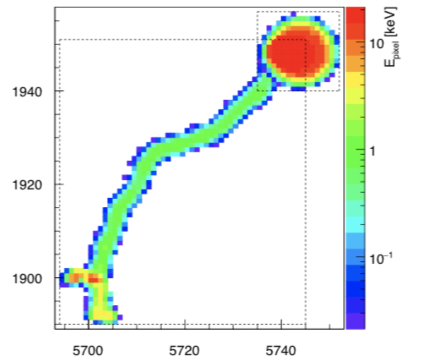
E = 8.8 MeV



1 Δt = 17.8 d 2 Δt = 5.5 h 3

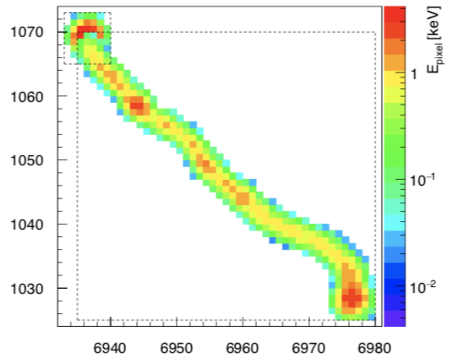


^{210}Pb β_1-α



- $E_{\beta 1}$ = 717 keV
- E_{α} = 3.62 MeV
- Δt = 32.3 d

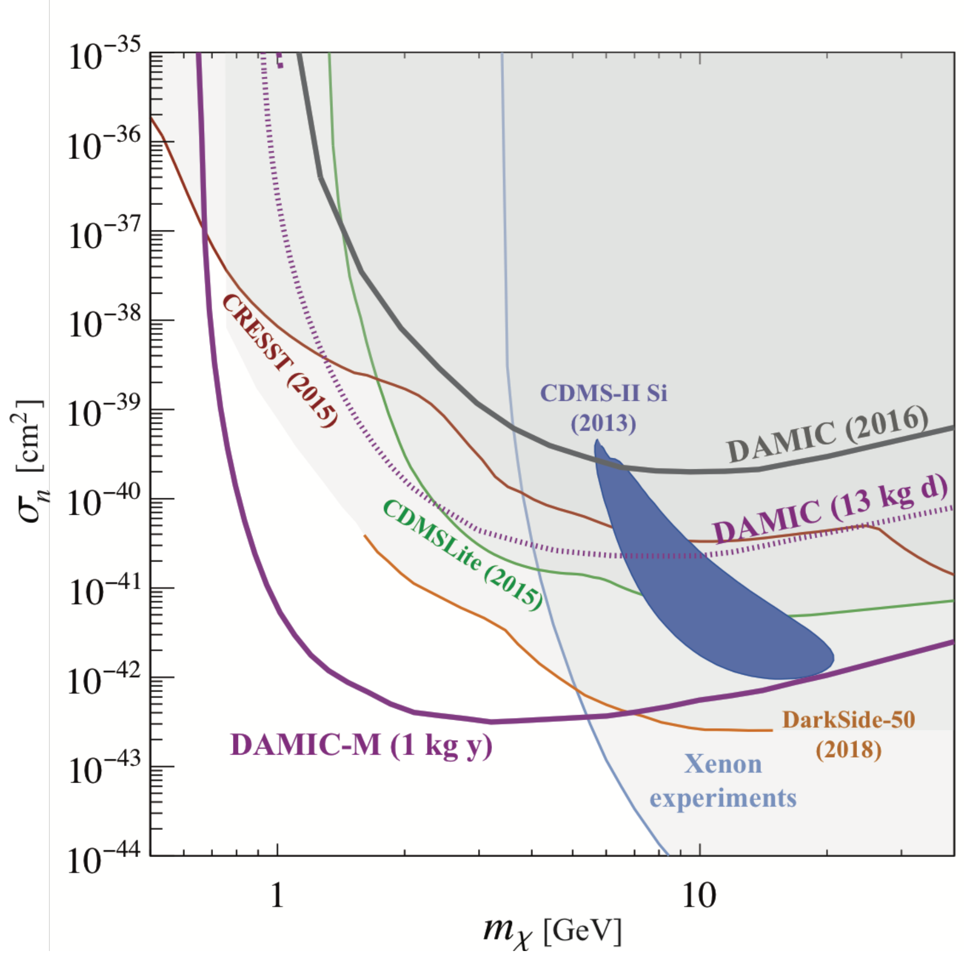
^{32}Si β_1-β_2



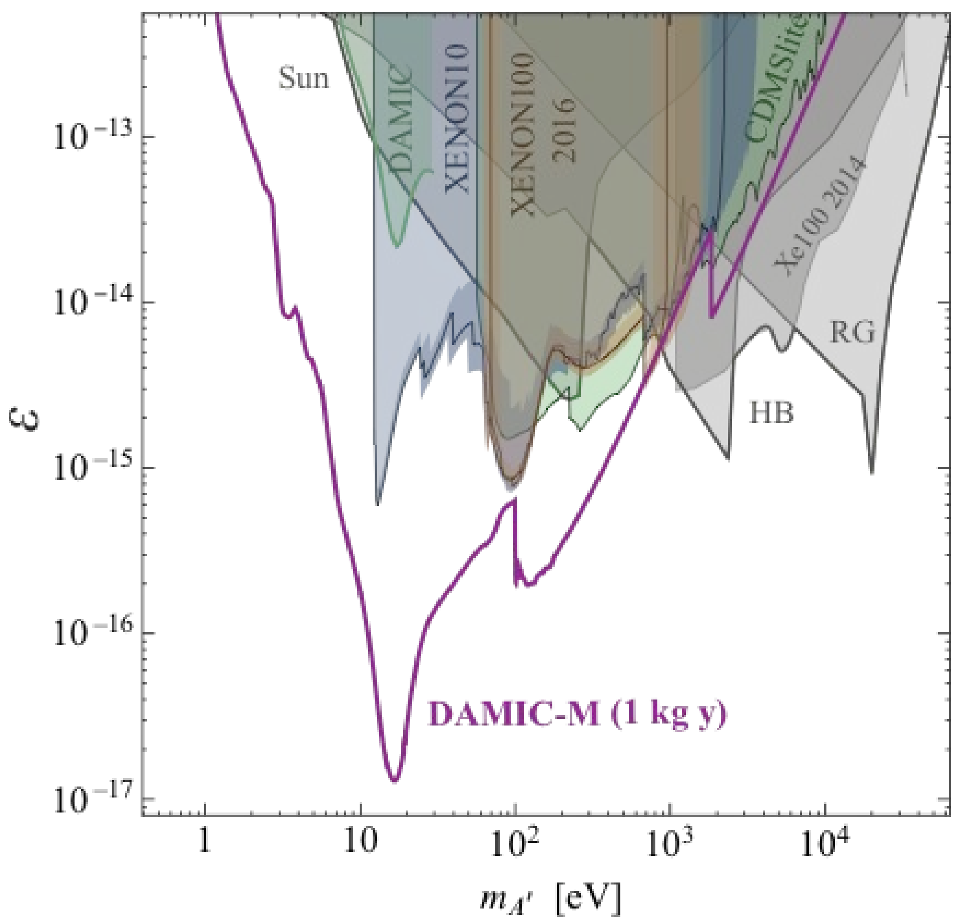
- $E_{\beta 1}$ = 110 keV
- $E_{\beta 2}$ = 361 keV
- Δt = 11.7 d

Scientific Reach

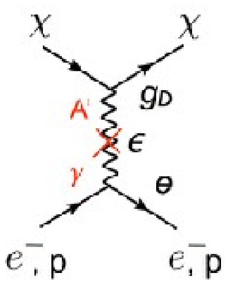
WIMP – nuclear recoil search



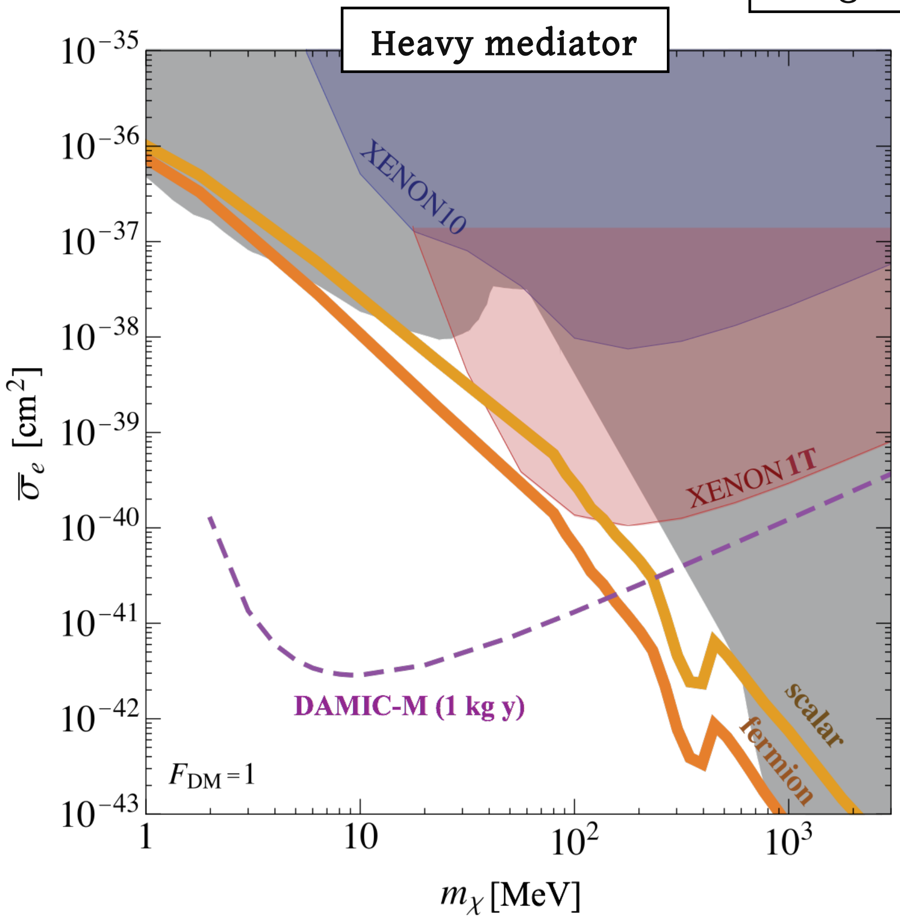
Hidden photon search

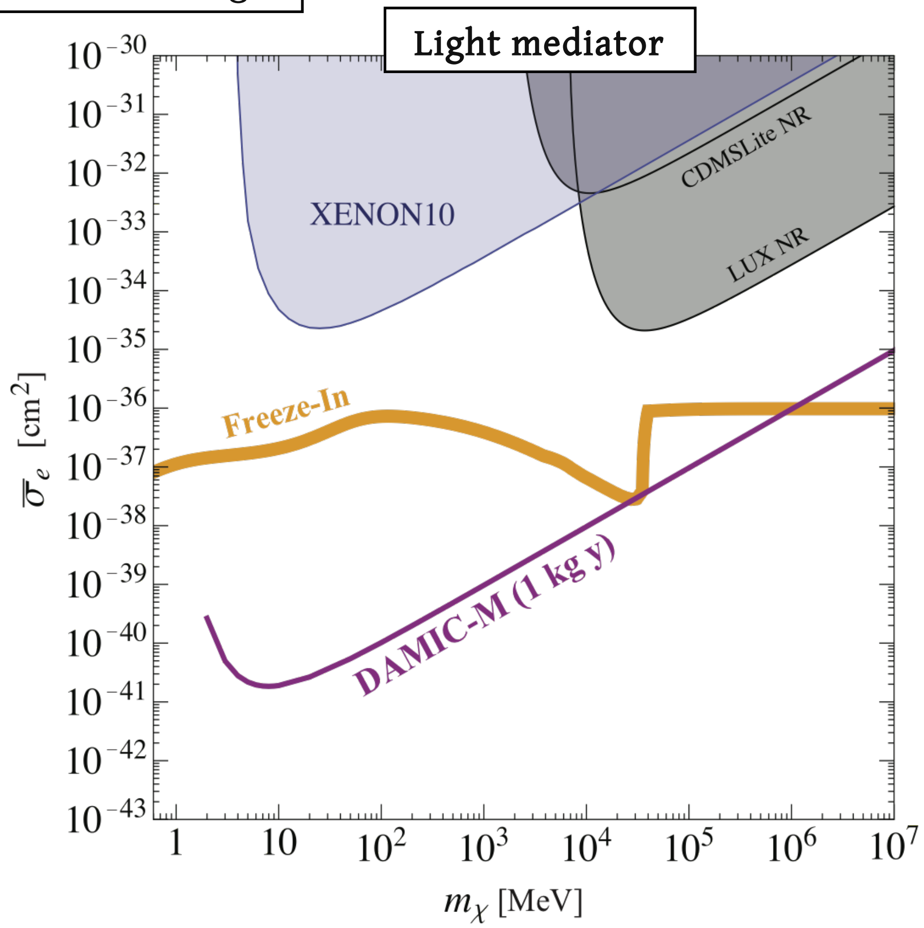


Scientific Reach



Light dark matter – electron scattering





DAMIC-M will be sensitive to light dark matter even if these candidates constitute only a small fraction of the total DM in the universe.

DAMIC-M

DAMIC at Modane (2022)

As of **2018** a **new collaboration called DAMIC at Modane** has been established. The goal of DAMIC-M is to operate a DAMIC experiment at Laboratoire Souterrain de Modane (LSM) with a single electron resolution with a background level of 0.1 dru.

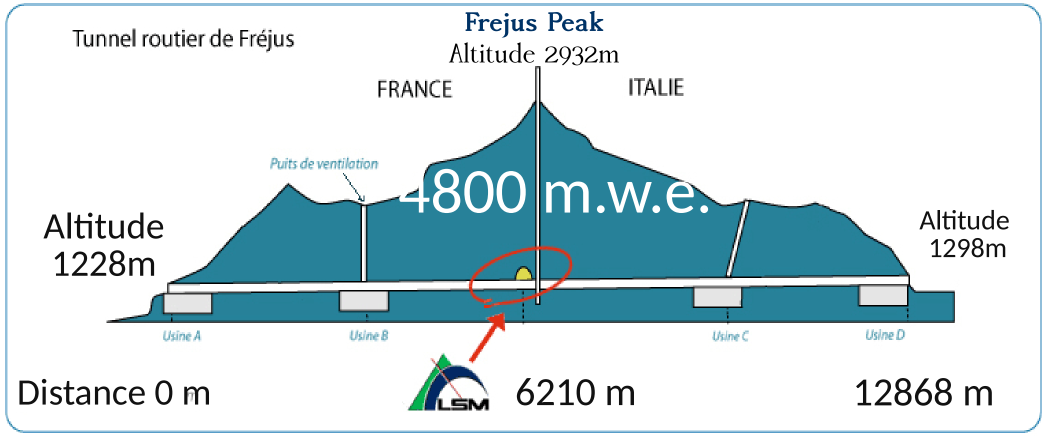
Ongoing R&D for DAMIC-M:

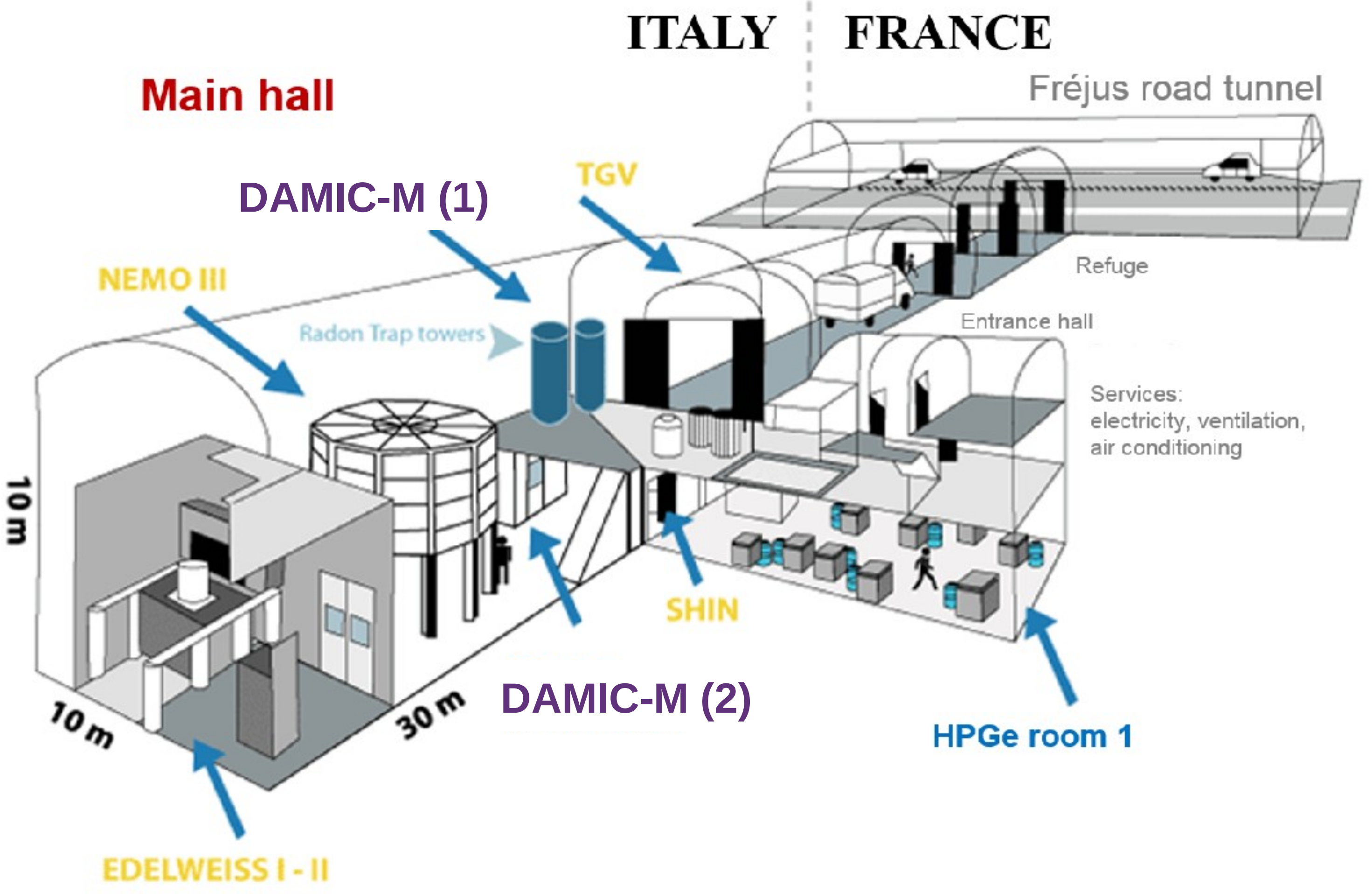
- ✔ To achieve single electron resolution
- ✗ To better characterize the background level, and reduce to 0.1 dru
- ✗ To select the best skipper amplifiers

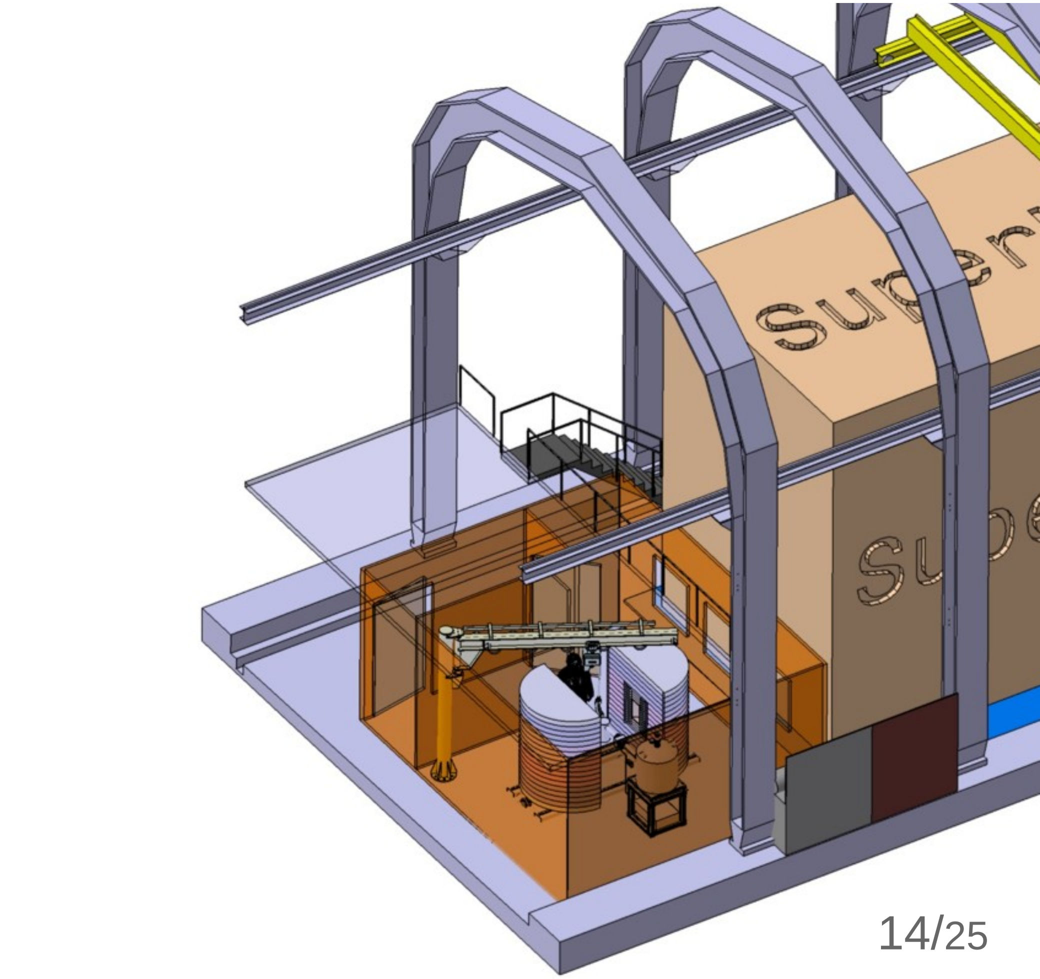
→ to finally go for production

DAMIC-M

Laboratoire Souterrain de Modane



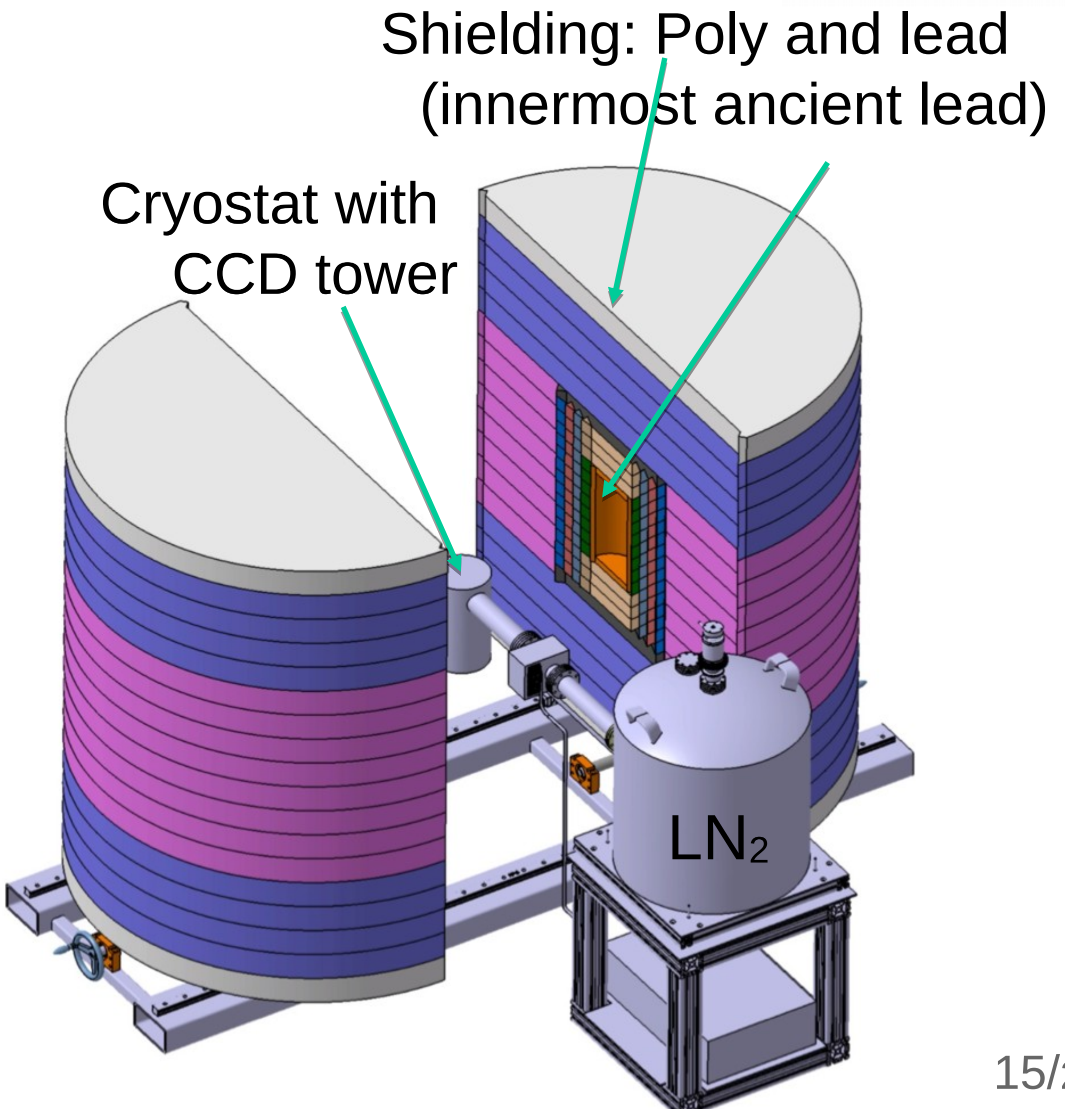




DAMIC-M

CCD Shielding Preliminary Design

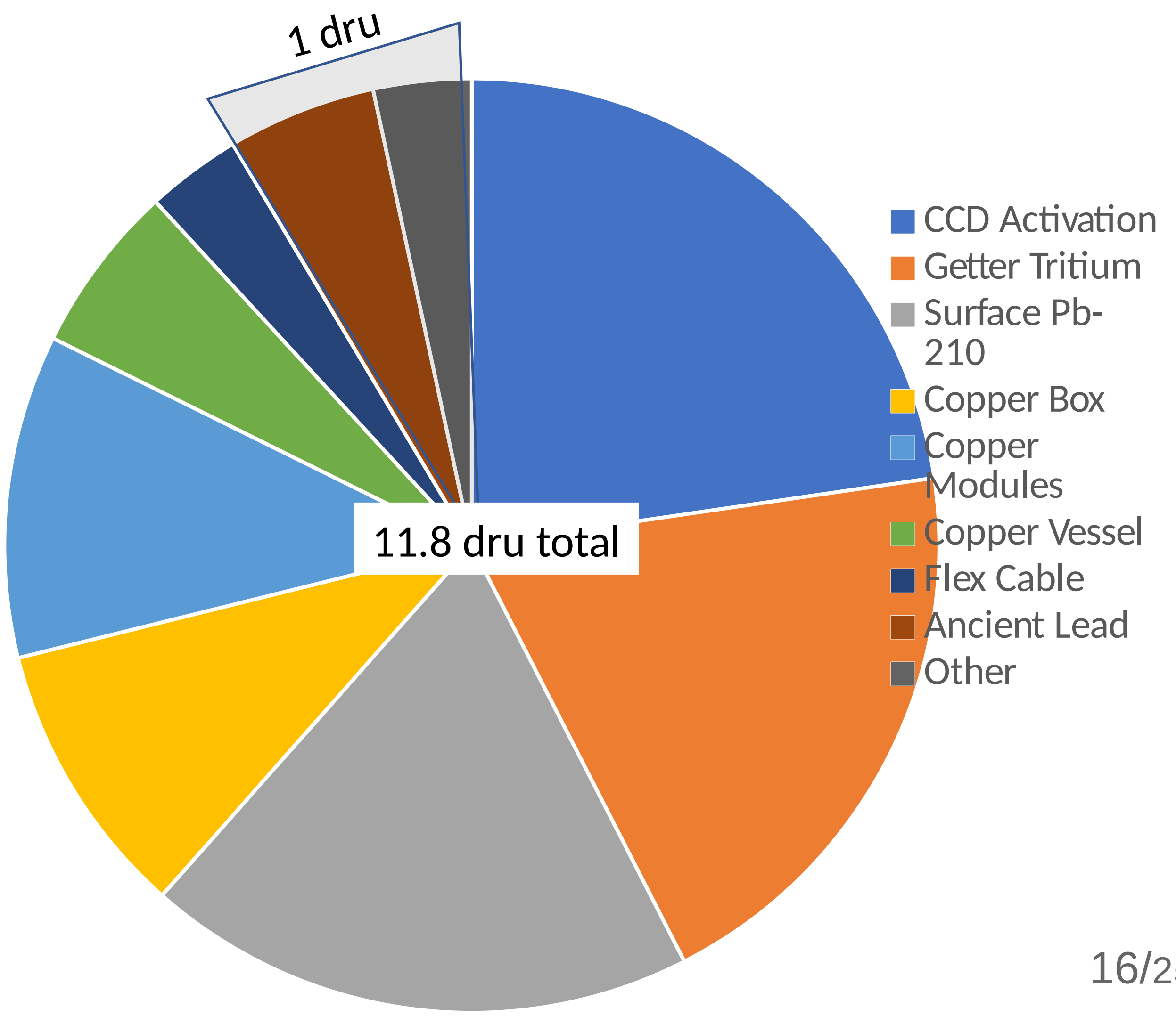
- 50 CCDs (kg-size target mass)
  - Most massive CCDs ever built (>10 g each)
- Single electron resolution with skipper readout (demostrated by Fermilab SENSEI group)
- A fraction of dru (events/kg/keV/day) background
- Classical design (Ge detectors and DAMIC at SNOLAB)
- R&D and design up to 2021
- Construction 2022
- Installation in 2023



DAMIC-M

Background model from SNOLAB

- 20% of background comes from ^{3}H production from silicon activation
- 20% of background comes from tritium in the getter
- 20% of background comes from ^{210}Pb
- 20% of background comes from OFC copper
- ...remaining 20% comes from a mixed bag of detector materials (mostly kapton cabling)



DAMIC-M

Challenging goal: 0.1 dru

✔ **Tritium** – will **shield silicon** to eliminate activation backgrounds and remove getter hydrogen

✔ **Surface ^{210}Pb** – will properly **clean all surfaces** and control exposure to radon

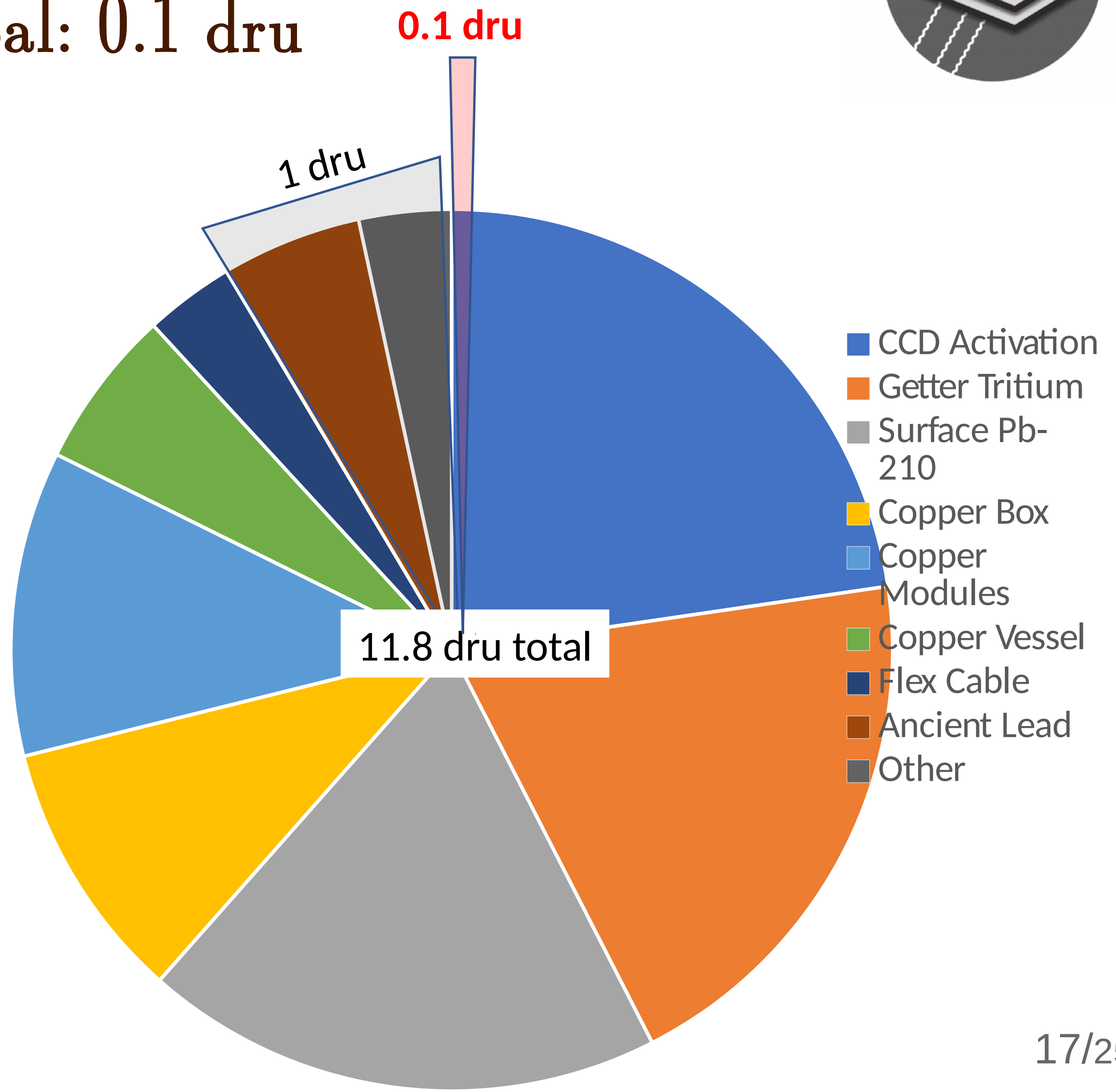
✔ **Copper** – will **electrofrom** all **components near CCD** and **shield from activation**

✗ **Cable** – extensive research ongoing into clean cable and connector options

✗ **Other (<1 dru)** – need to better measure component activities (ongoing)

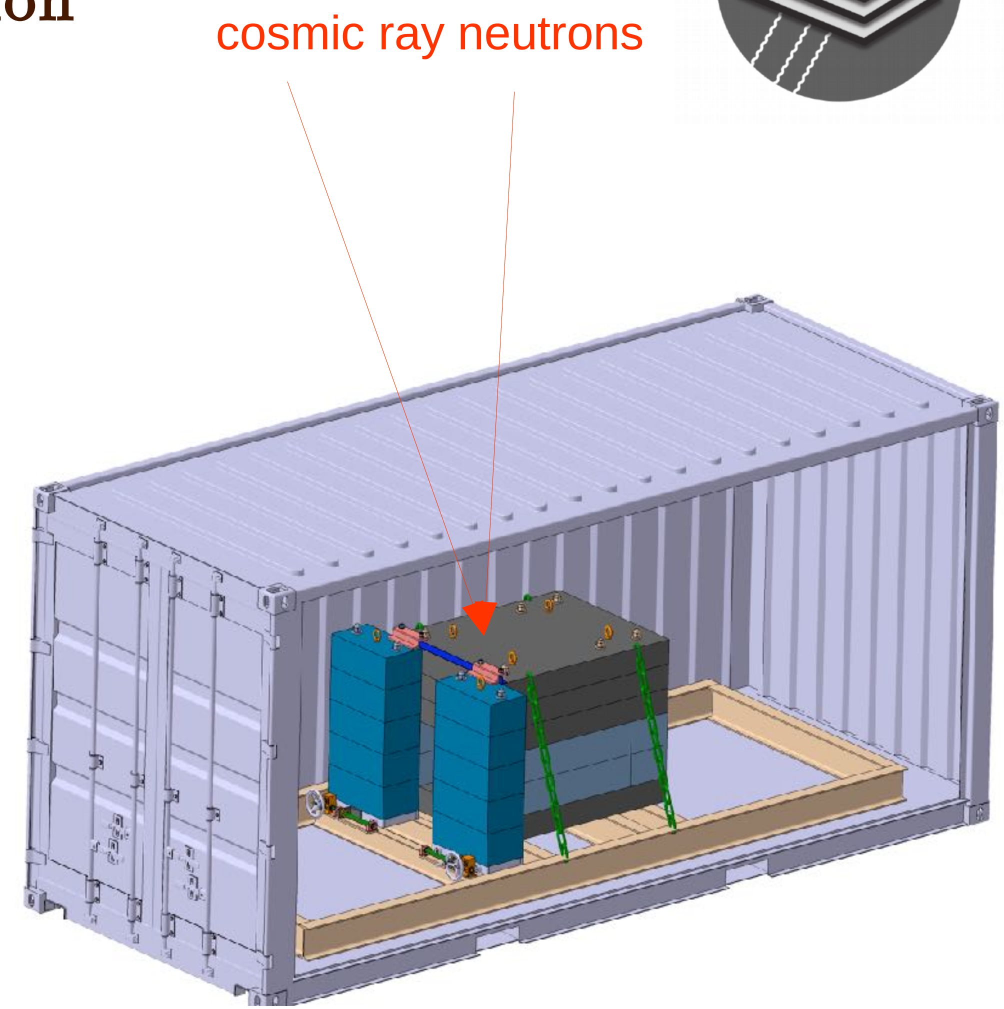
Removes ALL known backgrounds that we expected to contribute > 1 dru.

→ Working now to better understand the contributions down to 0.1 dru



DAMIC-M

CCD Transportation



CCDs are fabricated by Teledyne DALSA in Canada.

The wafers and CCDs will be shipped by sea in a custom-made shielded container.

To minimize the radioimpurity from muon spallation, all (inclyding electroformed cooper) will be transported under a heavy iron shielding cavity.

This shielding reduces tritium cosmogenic activation by a factor ~25.

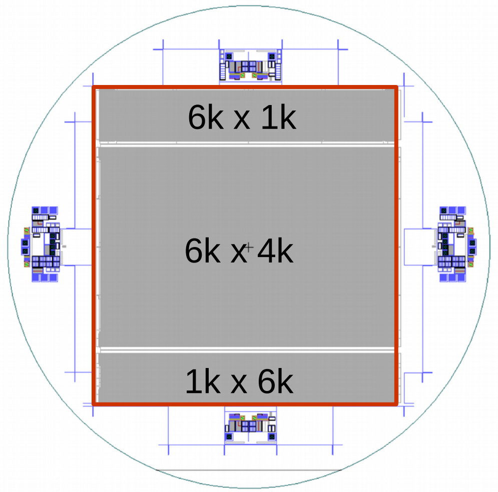
(8–10 days transatlantic journey)

DAMIC-M

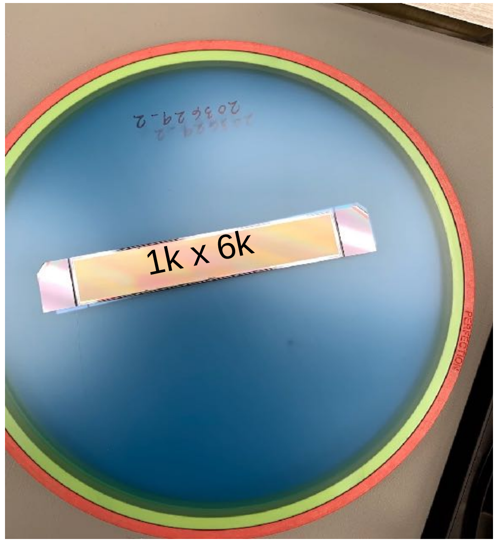
CCD prototype

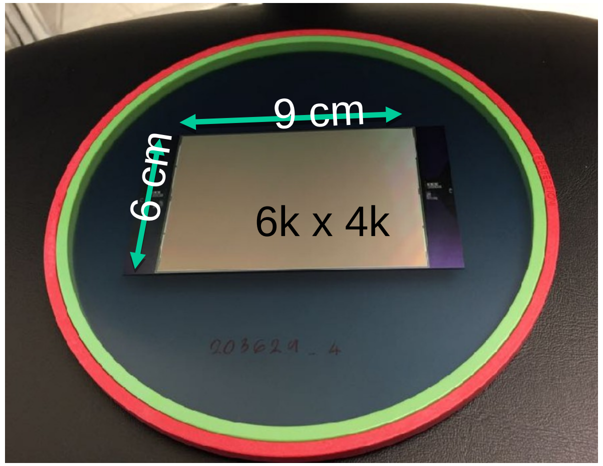
Designed by S. Holland (LBNL), fabricated by Teledyne DALSA

Three CCDs per 6” wafer to test different skipper readout amplifier design.



6k x 6k CCD on 150 mm wafer
675 μm thick



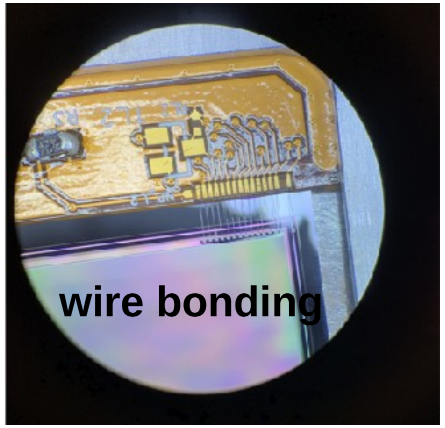


DAMIC-M

CCD Packaging

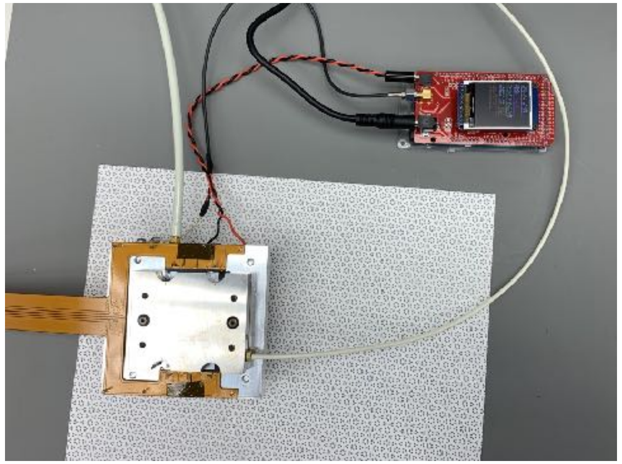
1k x 6k DAMIC-M prototype CCDs

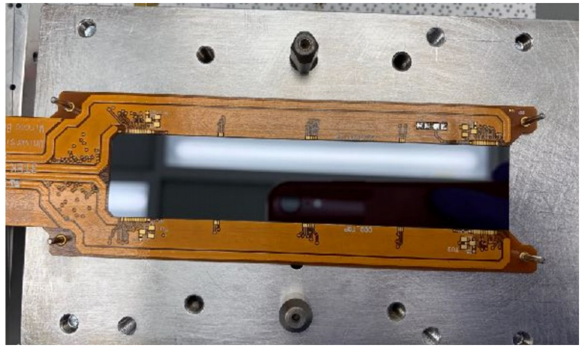
Improvement of packaging procedures originally developed for DAMIC at SNOLAB, notably by reducing the curing (and potential exposure of CCDs to radon) from a day to few hours



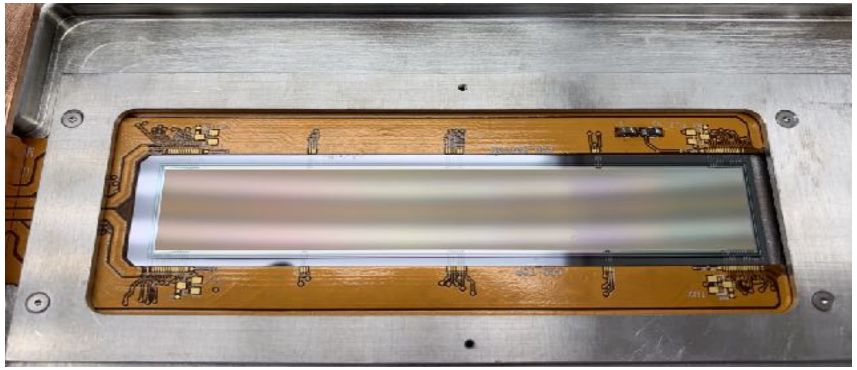
kapton flex cable

temperature controlled curing





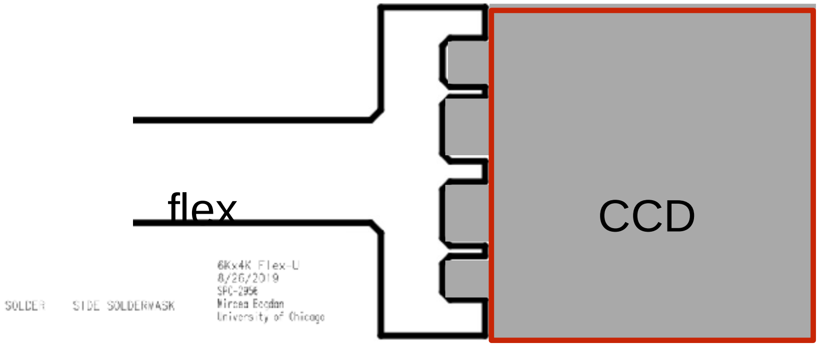
glueing flex on a silicon substrate



glueing CCD on a silicon substrate

DAMIC-M

Low-Background Cables



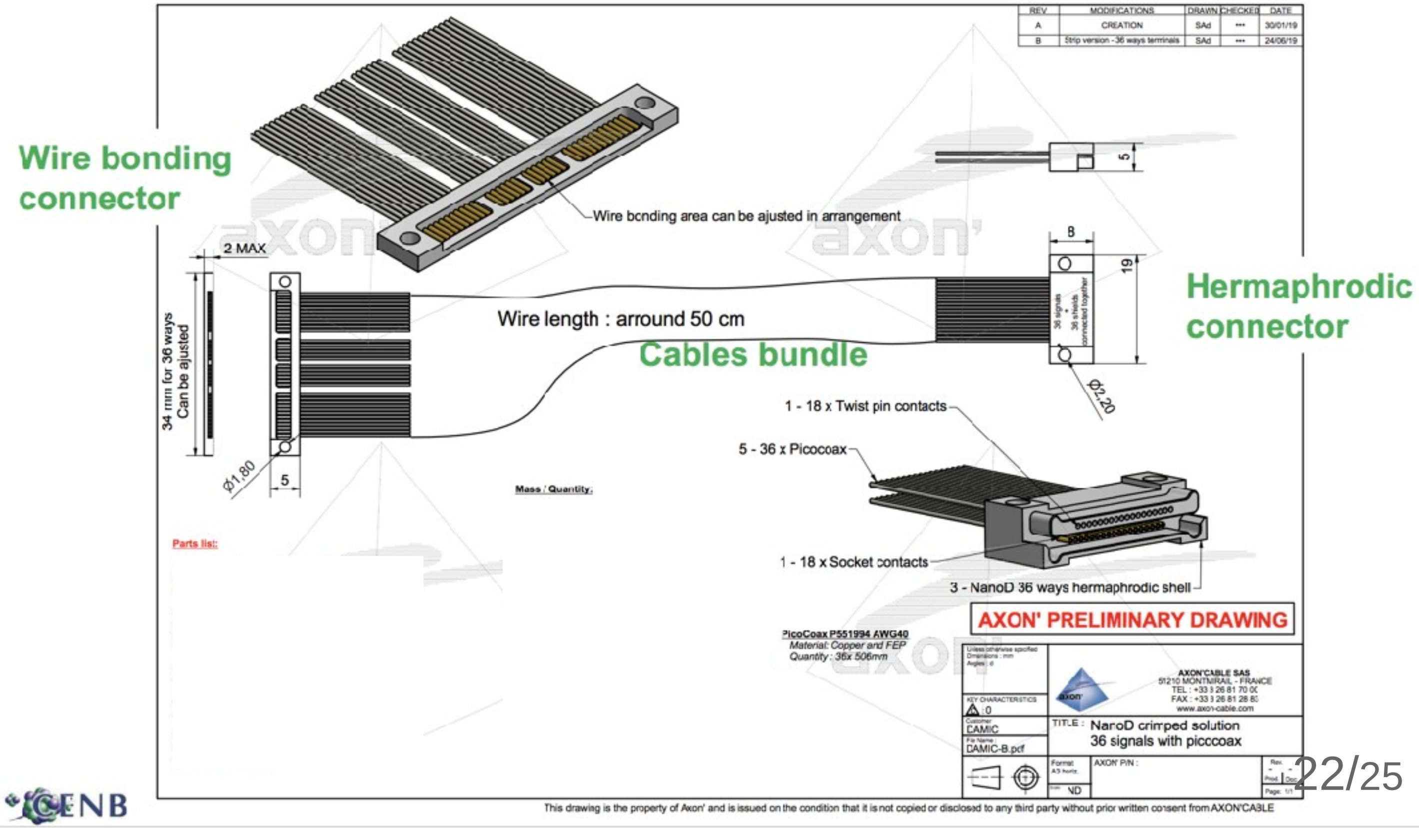
Flex cable R&D

Minimize mass close to CCD

Develop clean fabrication procedures for multilayer flex (PNNL)

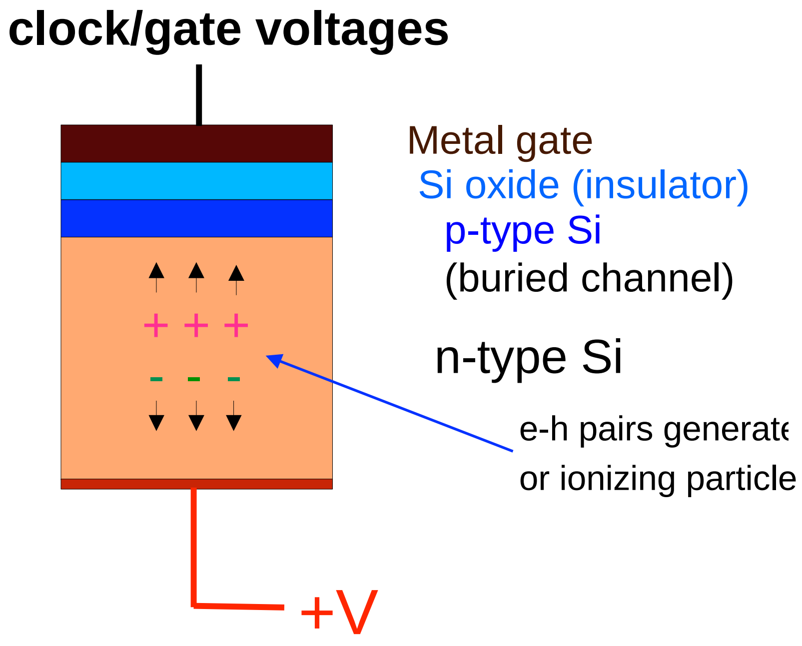
We are also pursuing with **AXON** a solution employing picocoaxial cables (low-background demonstrated by MAJORANA).

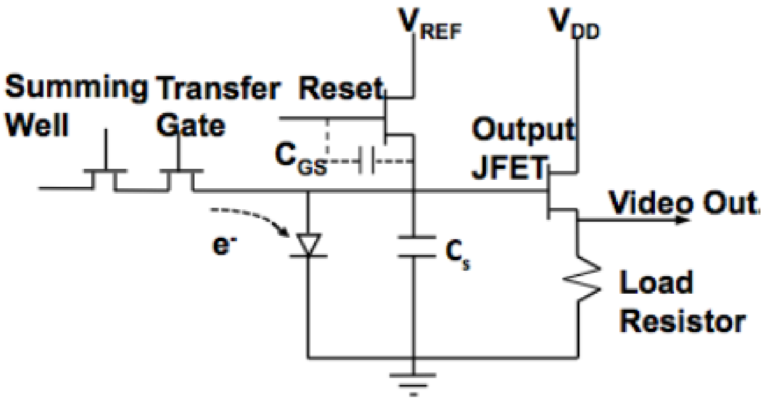
Both would fulfill our requirements for cables radio purity



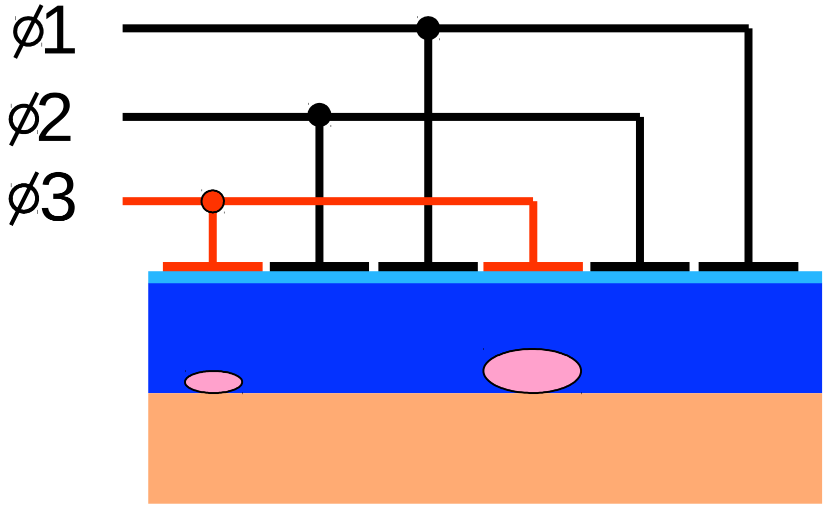
DAMIC-M

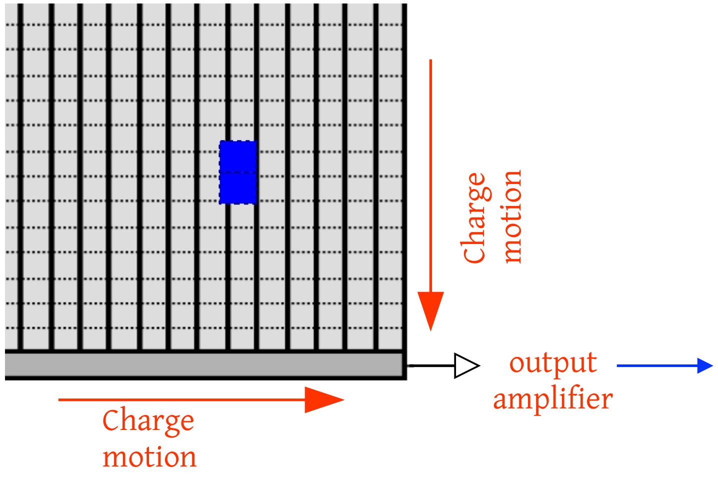
Charge Coupled Device



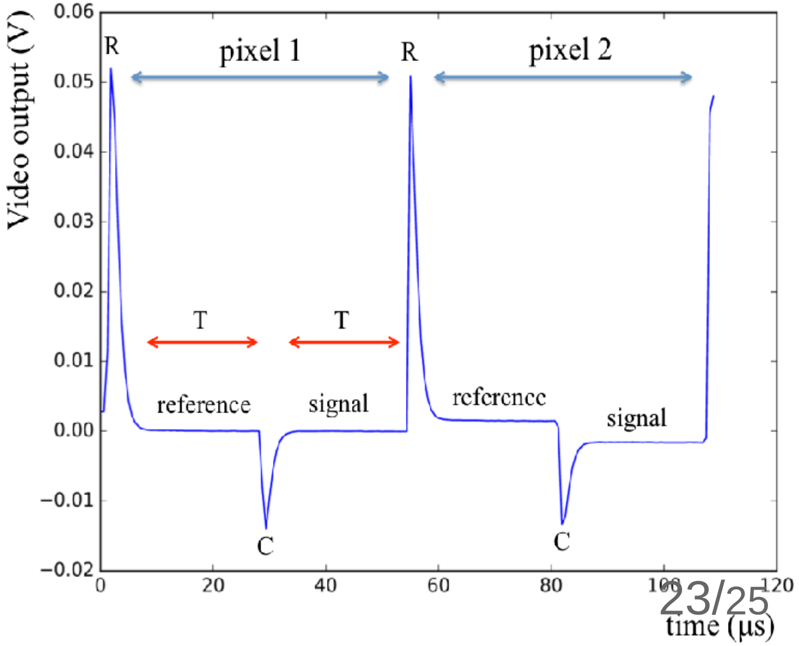


Charge Transfer
through the CCD



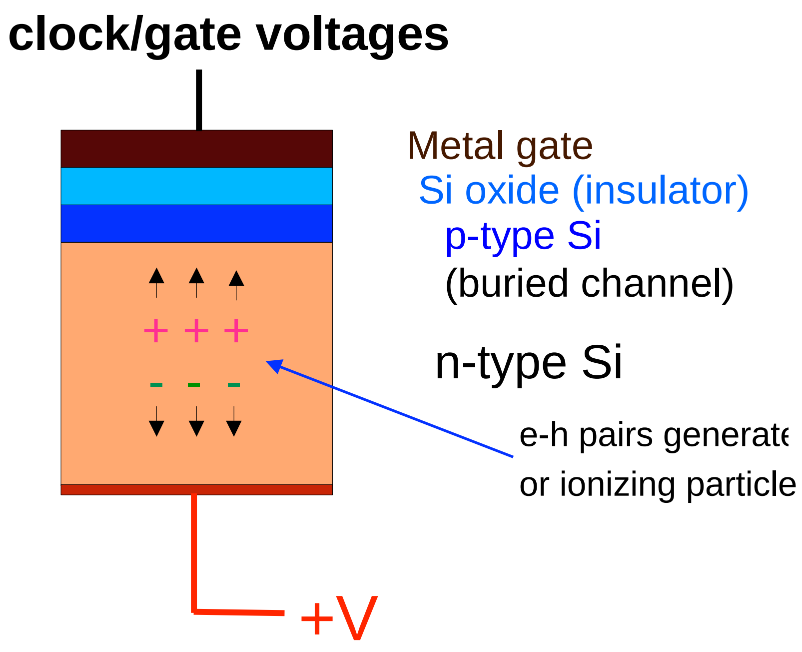


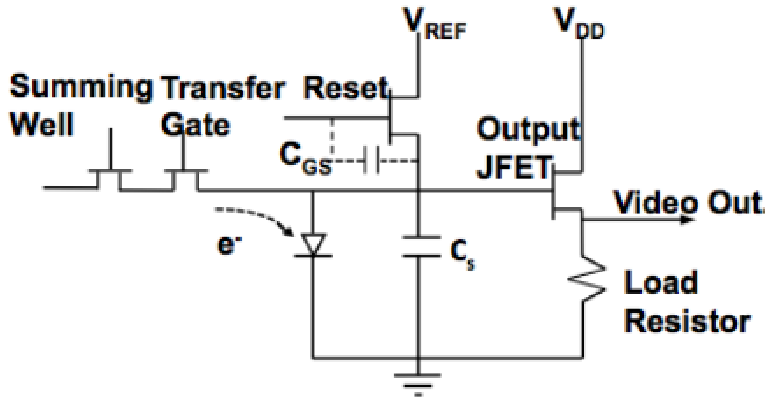
Correlated Double Sampling



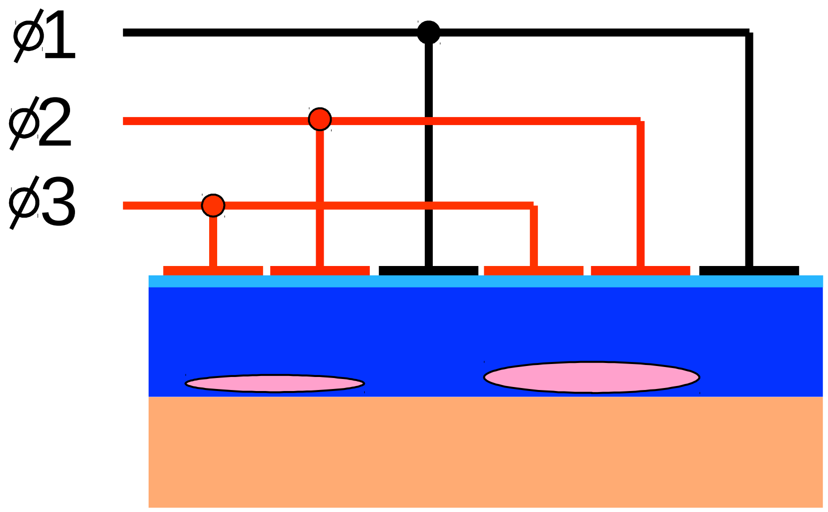
DAMIC-M

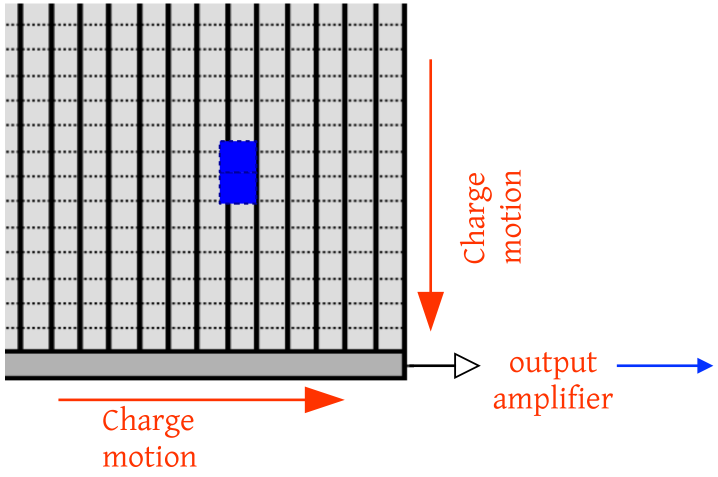
Charge Coupled Device



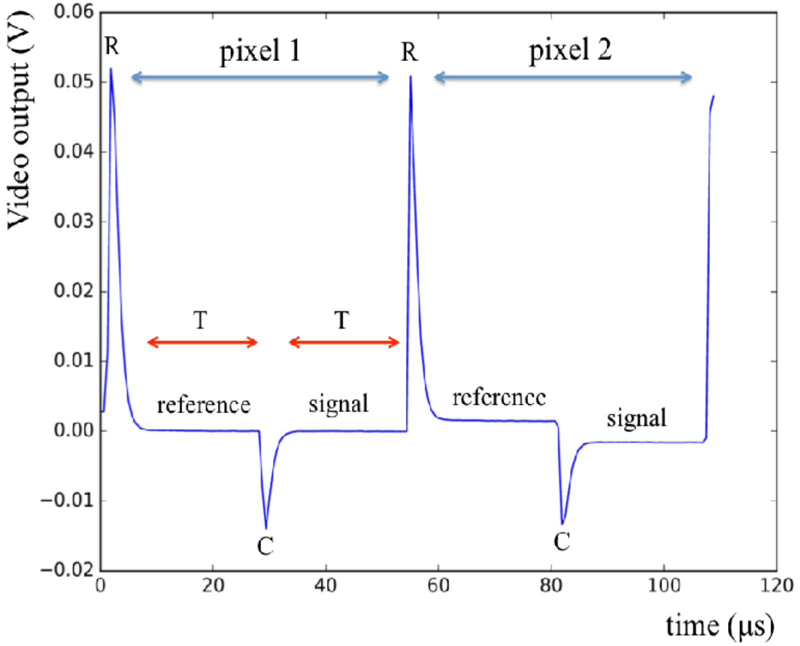


Charge Transfer through the CCD



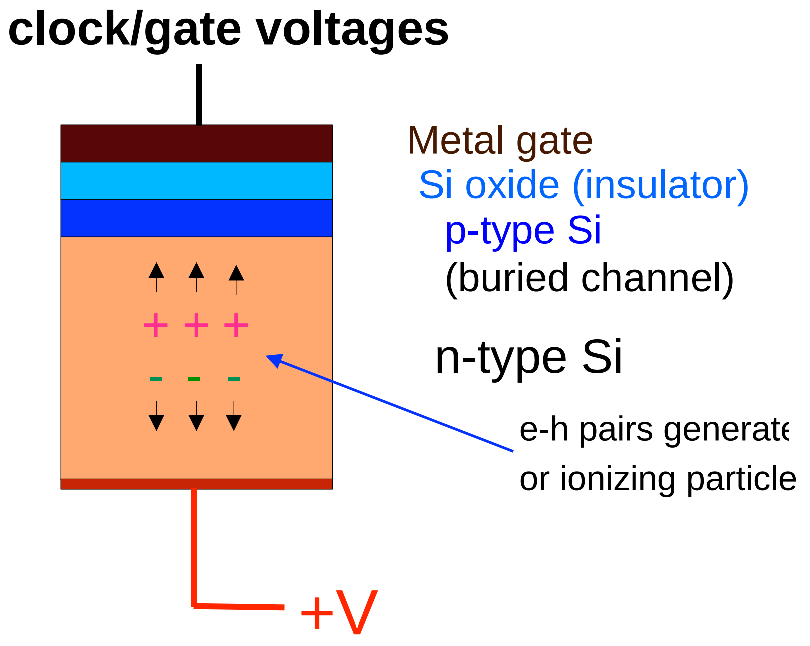


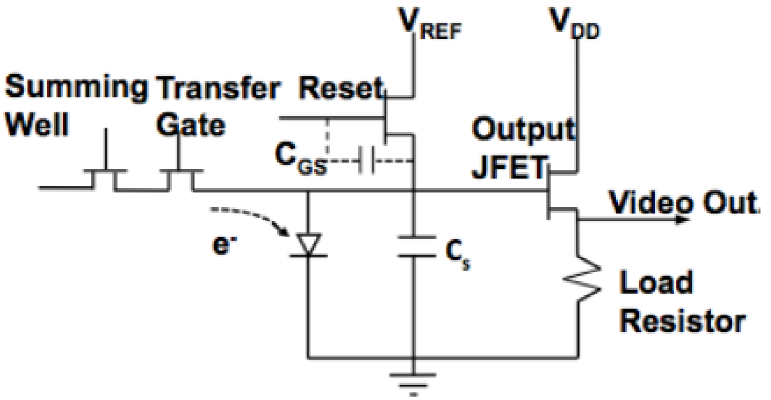
Correlated Double Sampling



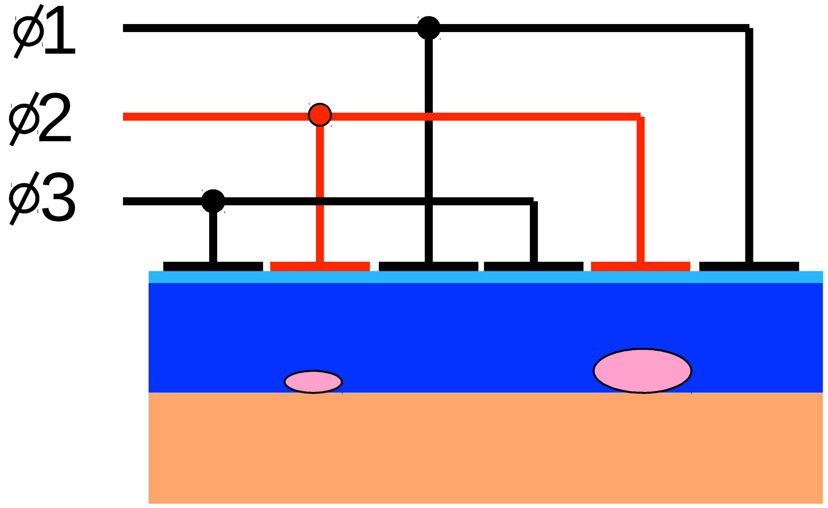
DAMIC-M

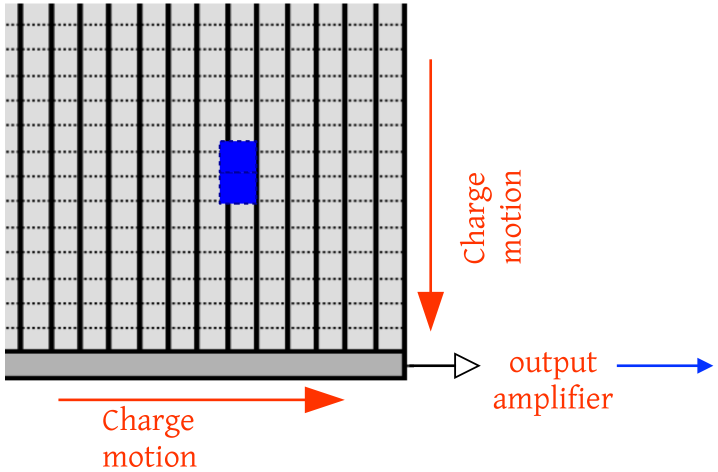
Charge Coupled Device

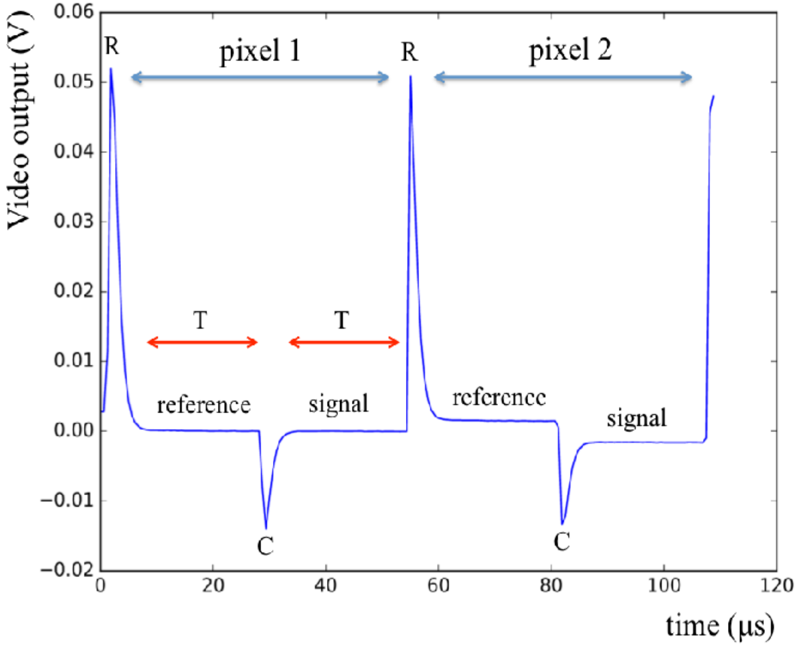




Charge Transfer through the CCD

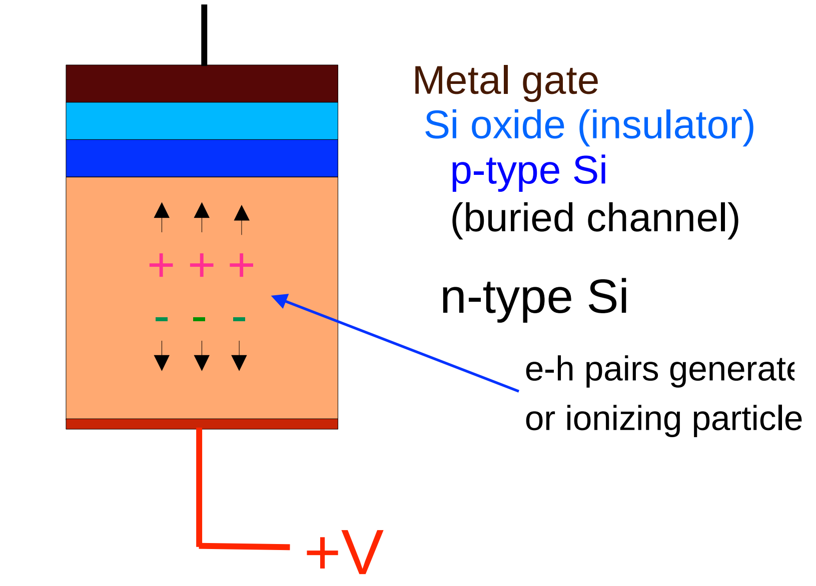


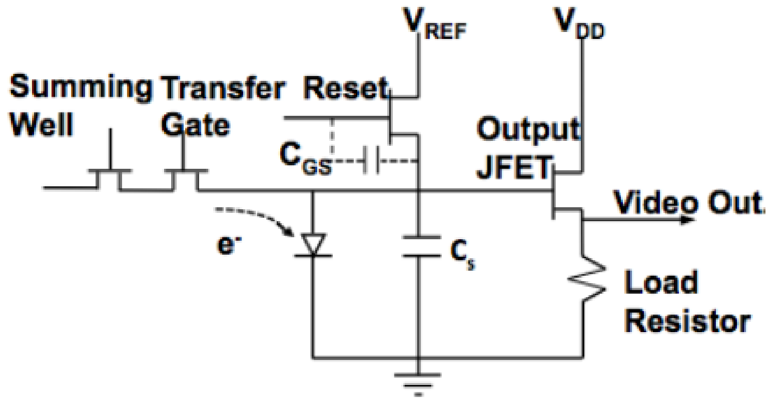




DAMIC-M

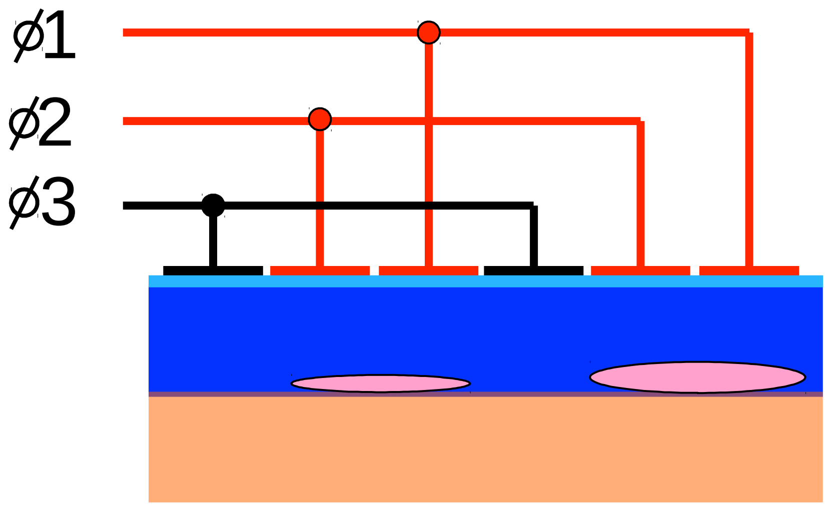
Charge Coupled Device

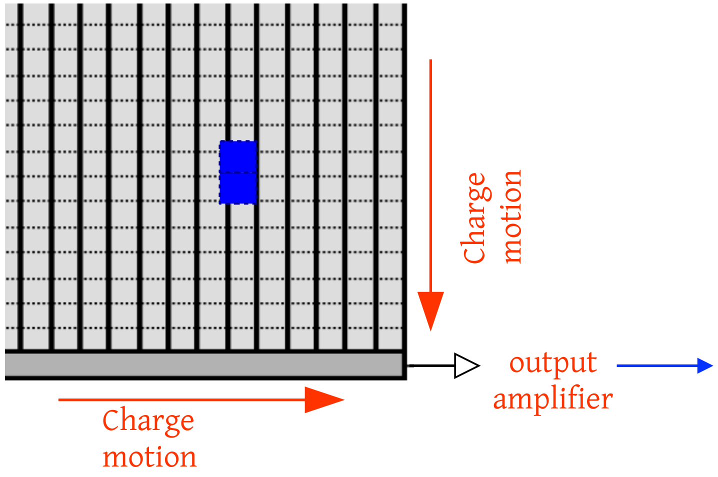




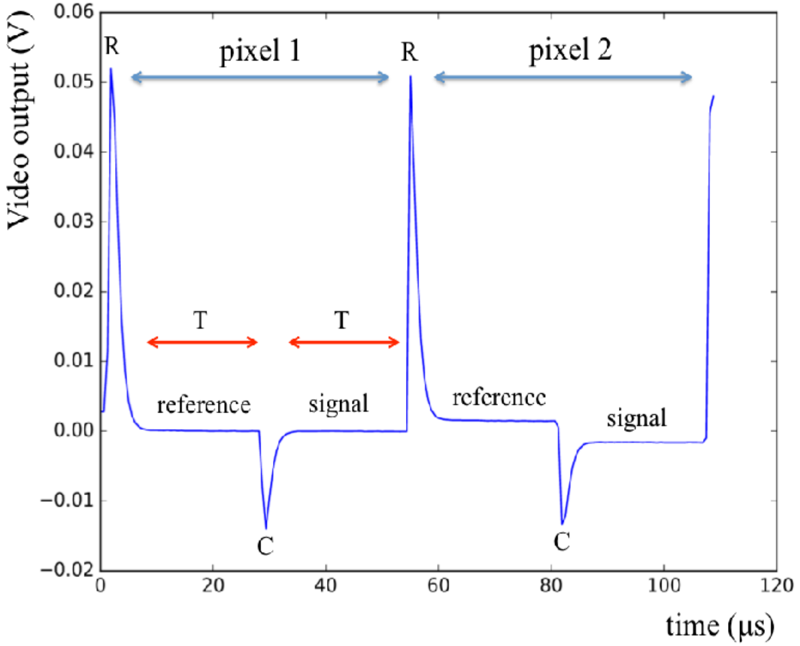
Charge Transfer

through the CCD



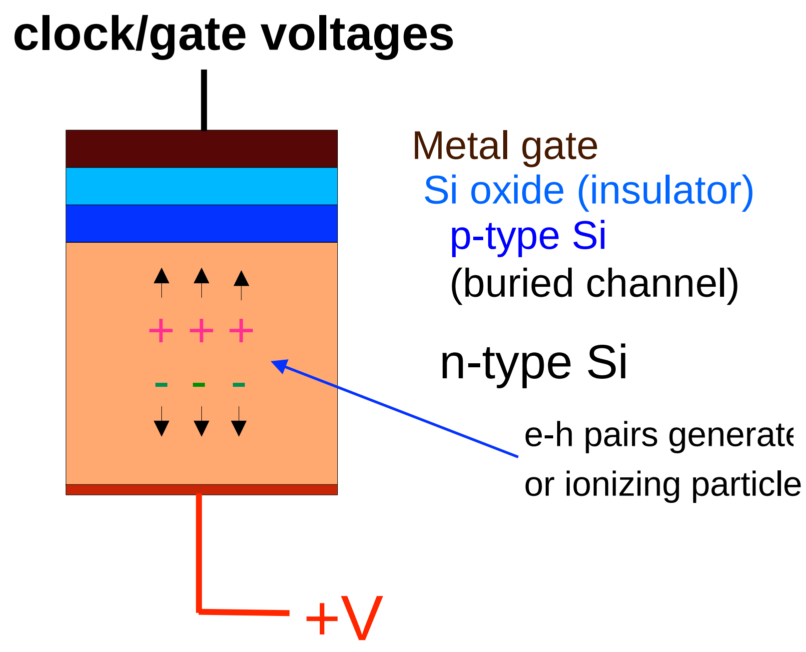


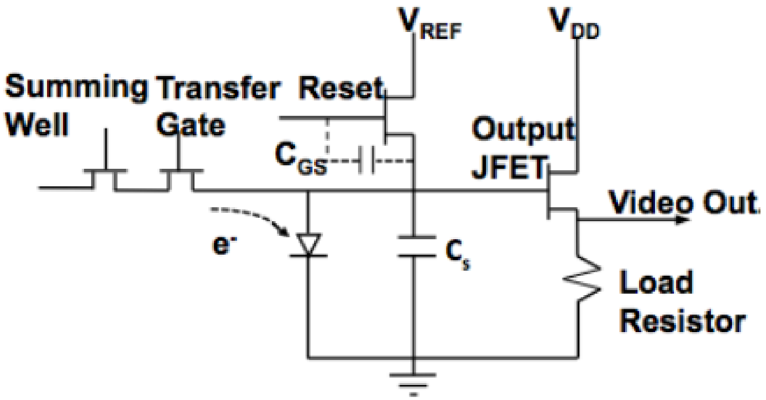
Correlated Double Sampling



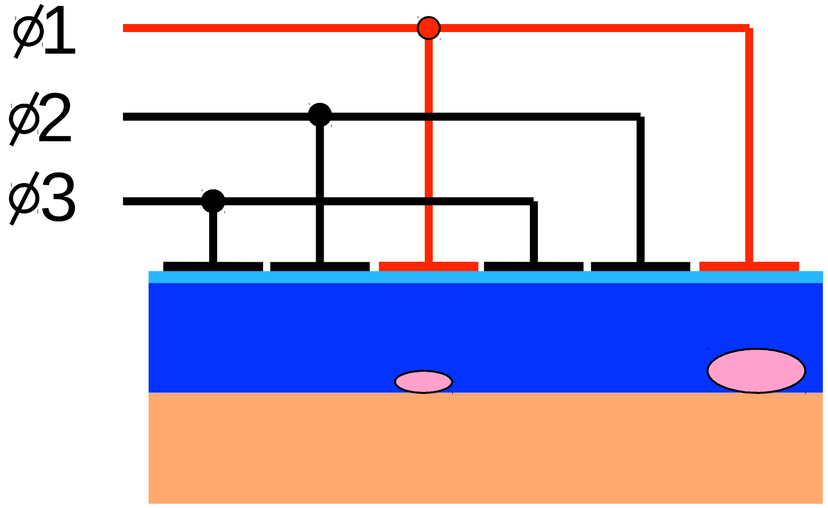
DAMIC-M

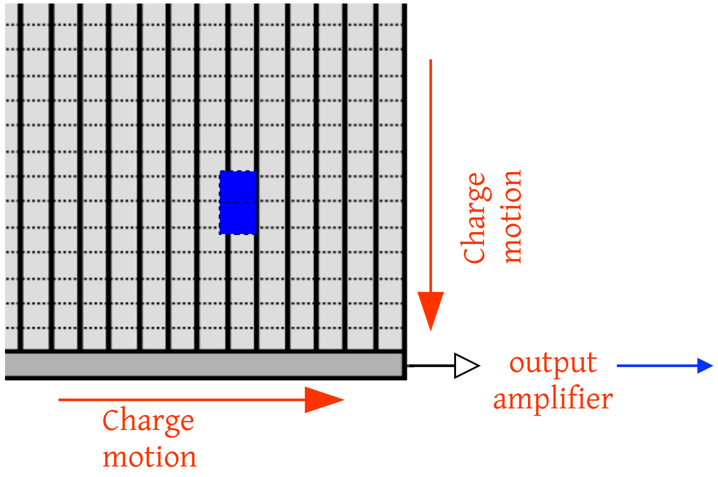
Charge Coupled Device



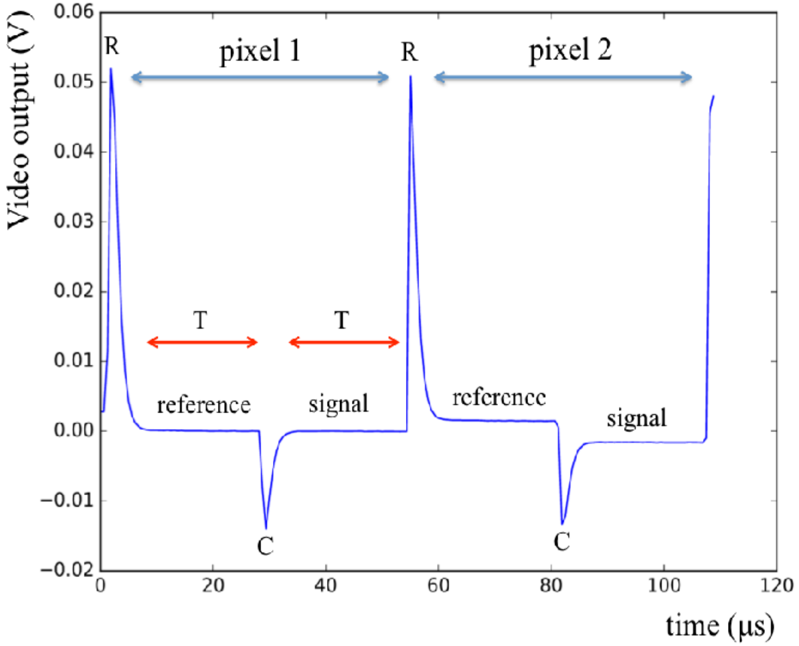


Charge Transfer
through the CCD





Correlated Double Sampling



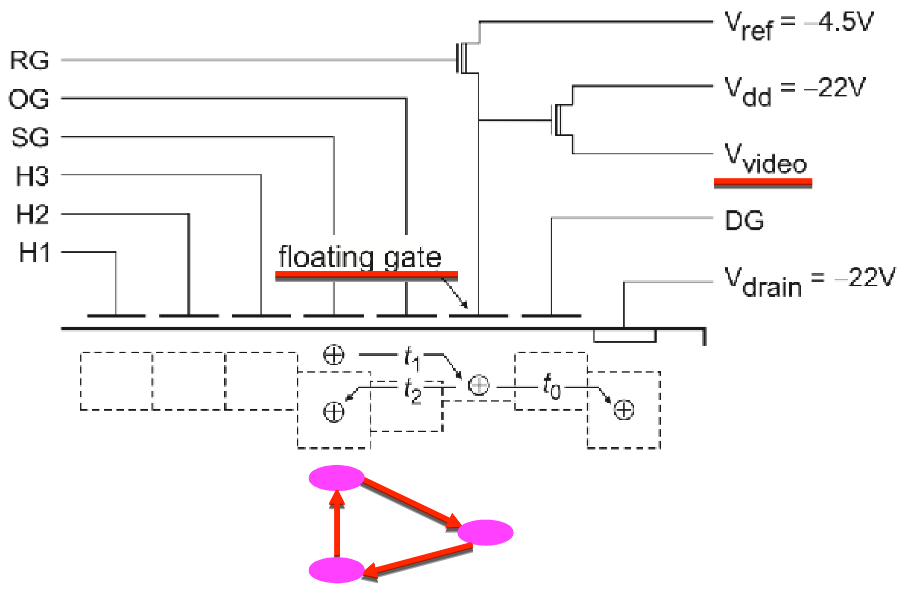
DAMIC-M

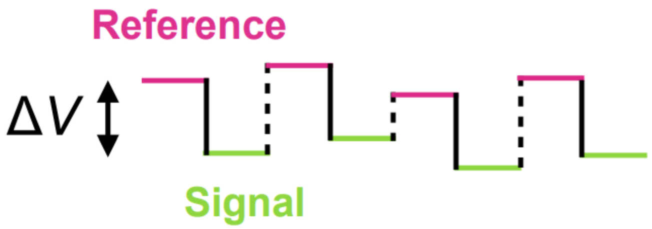
Skipper amplifier

The skipper amplifier utilizes floating gate for the output channel, since the FG is **surrounded by highly resistive material**, the charge contained in it **remains unchanged for long periods of time**.

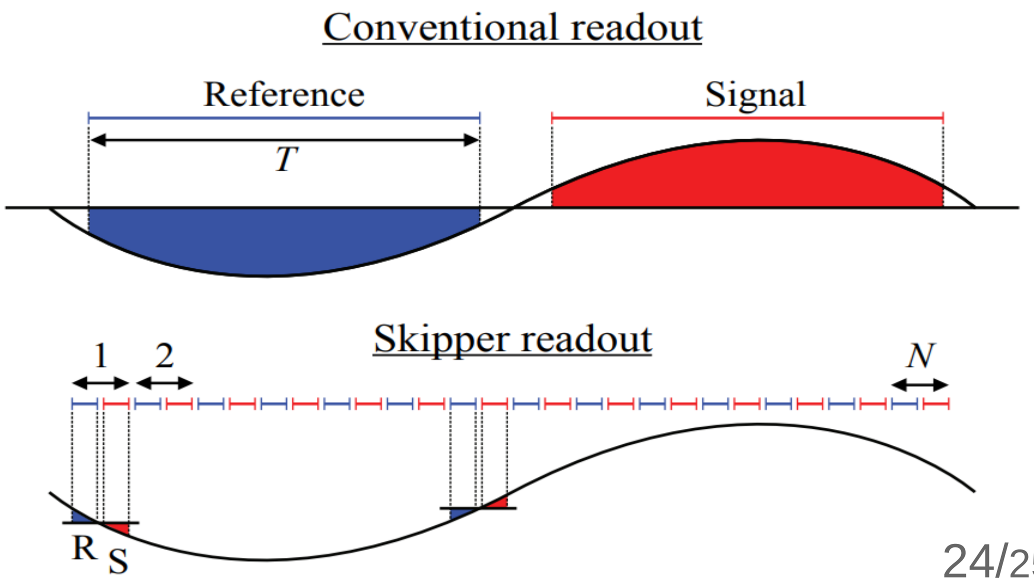
Noise dominated by the 1/f low frequency noise of the output amplifier.

Non-destructive ΔV (charge) measurement (NDCM)!

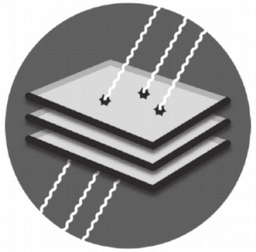




Effect on low frequency noise



DAMIC-M



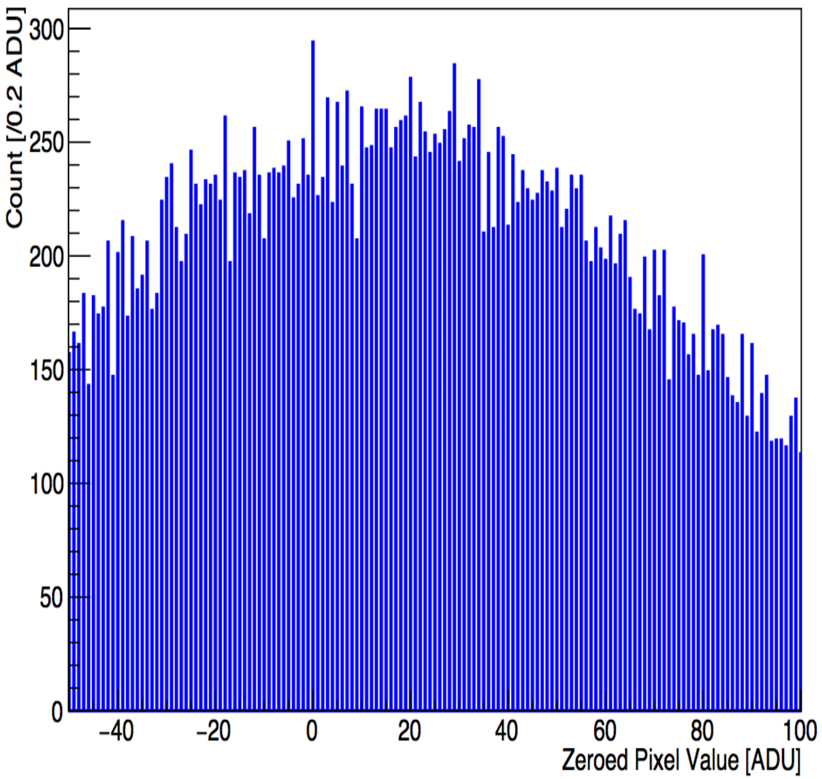
Skipper amplifier

The skipper amplifier utilizes floating gate for the output channel, since the FG is **surrounded by highly resistive material**, the charge contained in it **remains unchanged for long periods of time**.

Noise dominated by the 1/f low frequency noise of the output amplifier.

Non-destructive ΔV (charge) measurement (NDCM)!

Skipper Charge Resolution



1 Non Destructive Charge Measurement

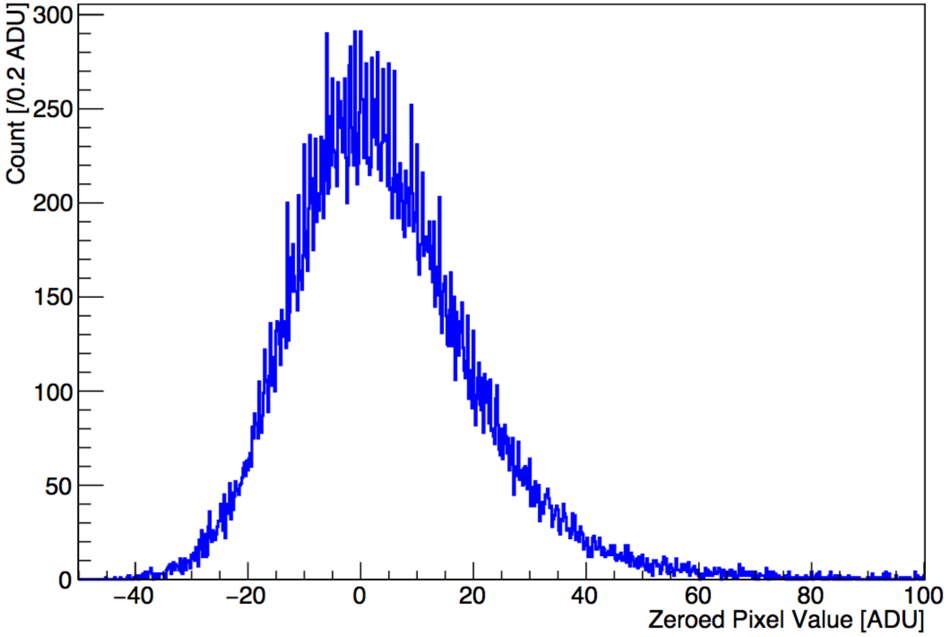
Skipper amplifier

The skipper amplifier utilizes floating gate for the output channel, since the FG is **surrounded by highly resistive material**, the charge contained in it **remains unchanged for long periods of time**.

Noise dominated by the 1/f low frequency noise of the output amplifier.

Non-destructive ΔV (charge) measurement (NDCM)!

Skipper Charge Resolution



25 Non Destructive Charge Measurement

DAMIC-M

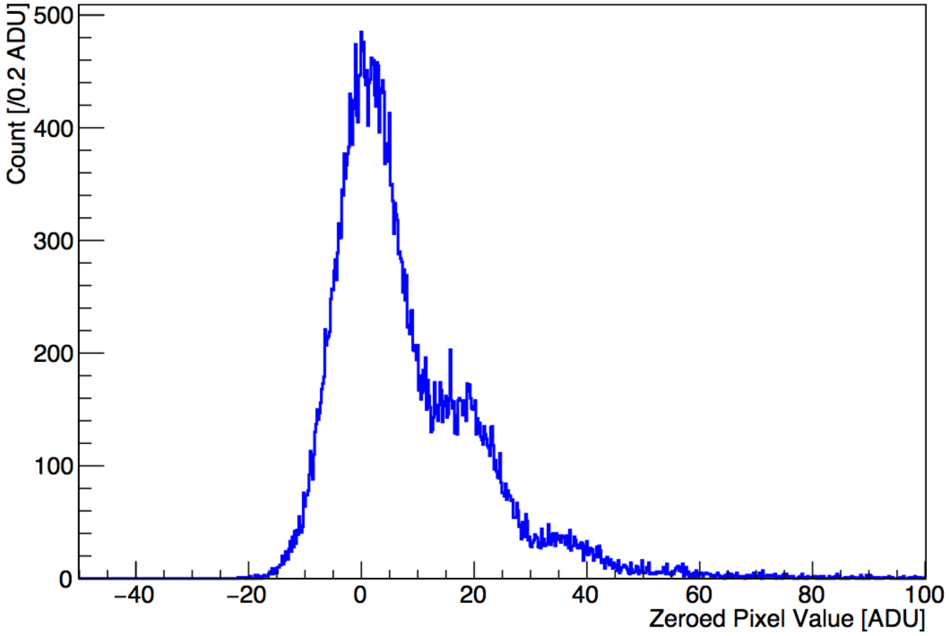
Skipper amplifier

The skipper amplifier utilizes floating gate for the output channel, since the FG is **surrounded by highly resistive material**, the charge contained in it **remains unchanged for long periods of time**.

Noise dominated by the 1/f low frequency noise of the output amplifier.

Non-destructive ΔV (charge) measurement (NDCM)!

Skipper Charge Resolution



100 Non Destructive Charge Measurement

DAMIC-M

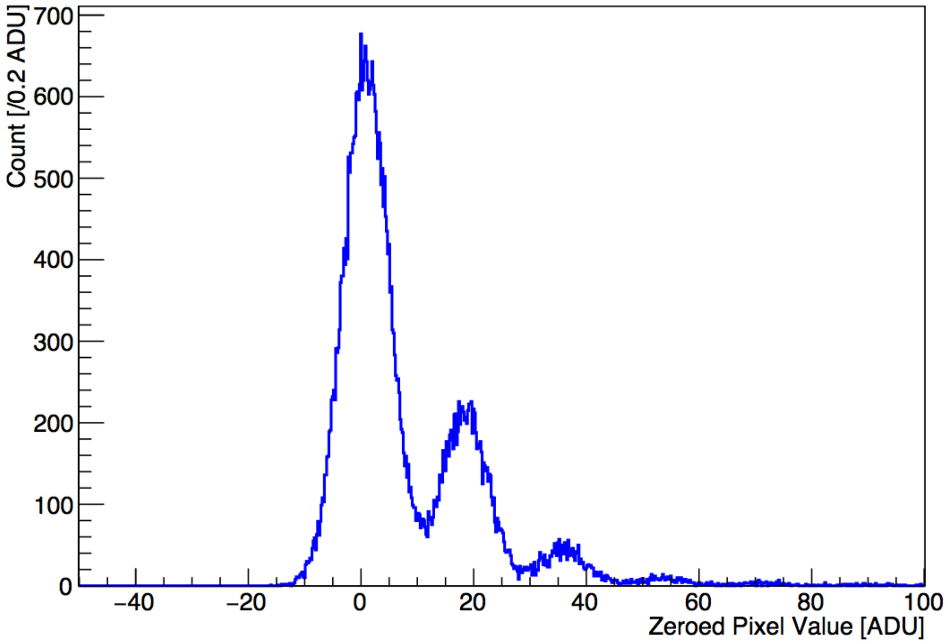
Skipper amplifier

The skipper amplifier utilizes floating gate for the output channel, since the FG is **surrounded by highly resistive material**, the charge contained in it **remains unchanged for long periods of time**.

Noise dominated by the 1/f low frequency noise of the output amplifier.

Non-destructive ΔV (charge) measurement (NDCM)!

Skipper Charge Resolution



200 Non Destructive Charge Measurement

DAMIC-M

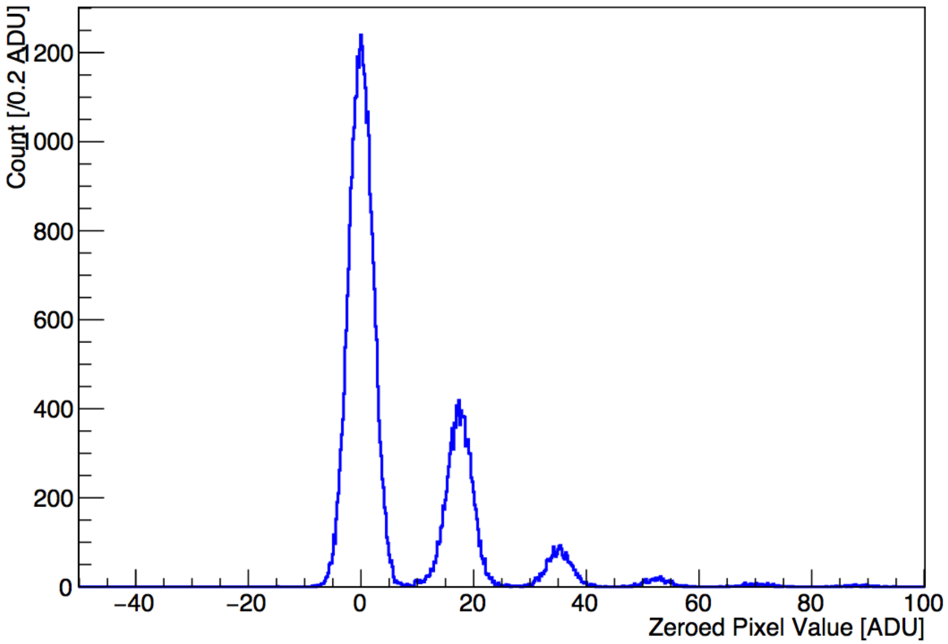
Skipper amplifier

The skipper amplifier utilizes floating gate for the output channel, since the FG is **surrounded by highly resistive material**, the charge contained in it **remains unchanged for long periods of time**.

Noise dominated by the 1/f low frequency noise of the output amplifier.

Non-destructive ΔV (charge) measurement (NDCM)!

Skipper Charge Resolution



800 Non Destructive Charge Measurement

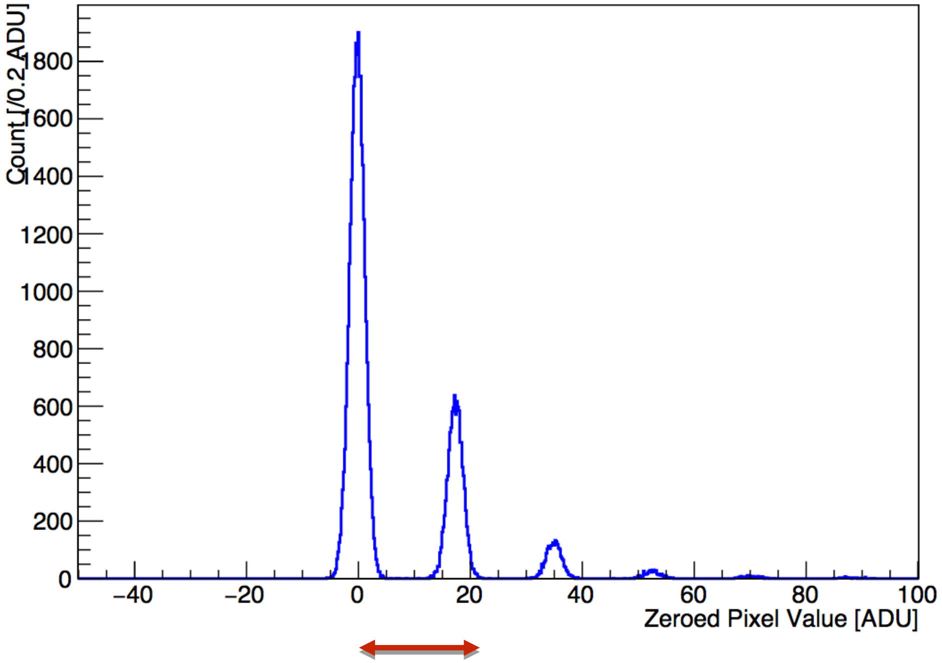
Skipper amplifier

The skipper amplifier utilizes floating gate for the output channel, since the FG is **surrounded by highly resistive material**, the charge contained in it **remains unchanged for long periods of time**.

Noise dominated by the 1/f low frequency noise of the output amplifier.

Non-destructive ΔV (charge) measurement (NDCM)!

Skipper Charge Resolution



1 e- = 17.3 ADU

Direct calibration of ADU to charge (^{57}Co)

2500 Non Destructive Charge Measurement

DAMIC-M

Skipper amplifier

The skipper amplifier utilizes floating gate for the output channel, since the FG is **surrounded by highly resistive material**, the charge contained in it **remains unchanged for long periods of time**.

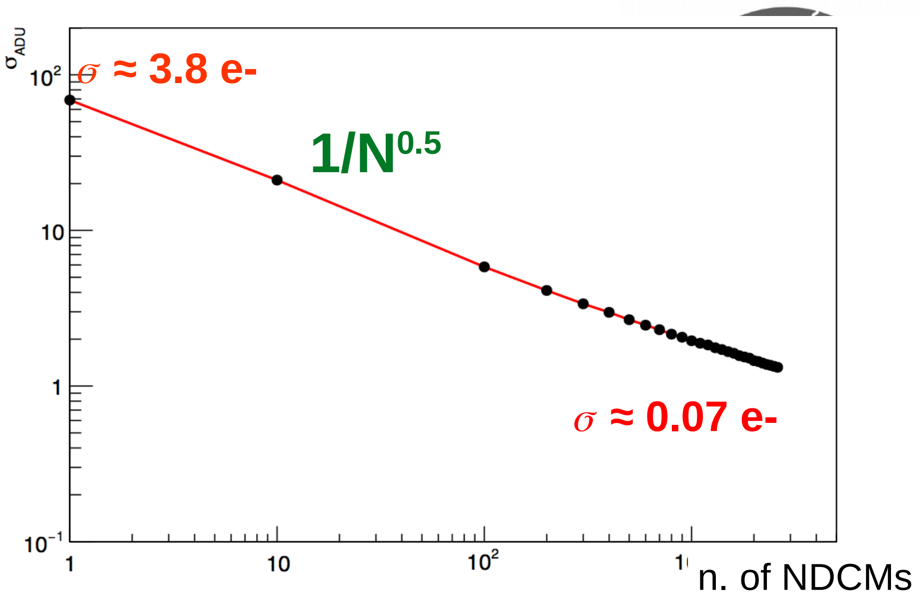
Noise dominated by the 1/f low frequency noise of the output amplifier.

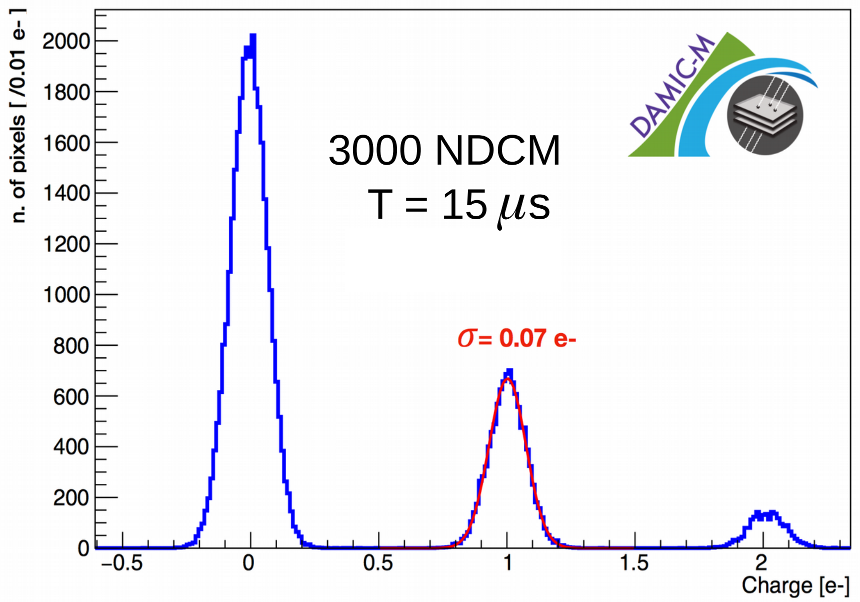
Non-destructive ΔV (charge) measurement (NDCM)!

As a result, **the charge is measured multiple times before being read out.**

As a result, **we can readout the pixels with sub-electron level noise**.

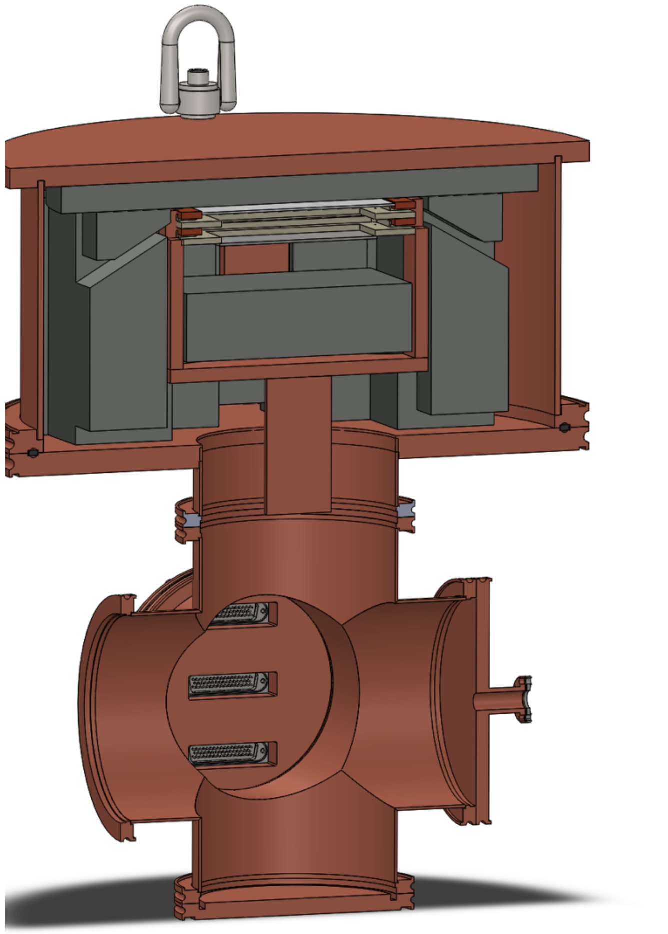
At this time, we were able to achieve **readout noise of 0.07 electron using a smaller prototype CCDs**.





DAMIC-M

Low Background Chamber



A low-background chamber (background level ~ dru) is in preparation.

Main objective:

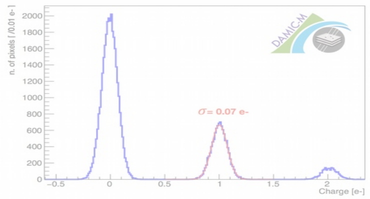
- Characterization of DAMIC-M CCDs in low-background environment: dark current, ^{32}Si rate, ^{210}Pb surface background, and CCD packaging
- First science results with a few CCDs

Installation at LSM beginning of 2020

Summary

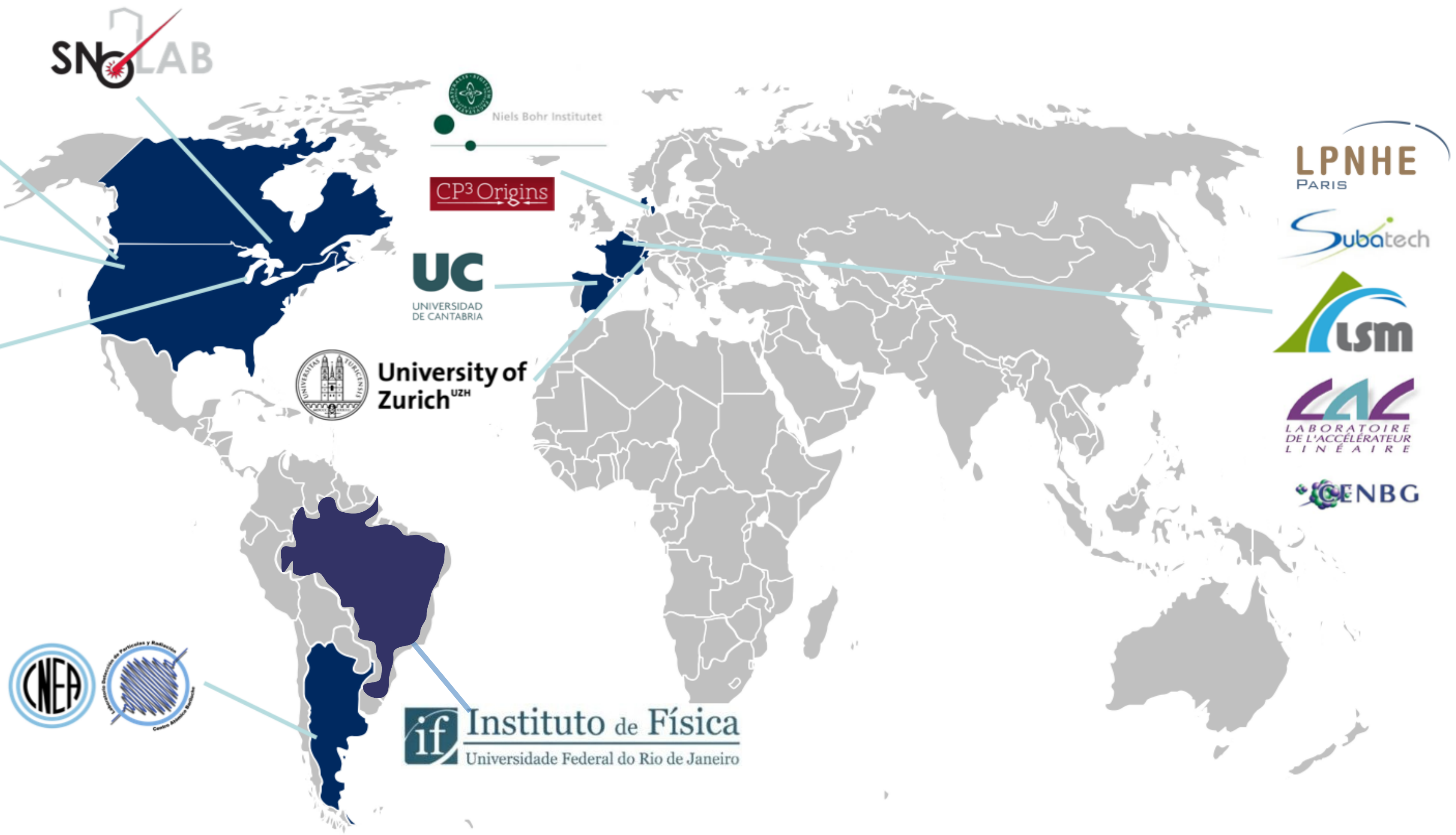
- Silicon detectors are the most sensitive to ionizing particles
- They are microfabricated pixelated sensors, excellent for background characterizations
- All these, have been already demonstrated by DAMIC at SNOLAB: **CCDs** are an **excellent** technology **for dark matter direct detection**.
- Repetitive, uncorrelated measurements of the pixel charges allow for single charge resolution
- Ionizing backgrounds must be really low to search for dark matter, and it is possible to reach it with DAMIC-M

All make DAMIC-M a really competitive detector for dark matter direct detection.



DAMIC-M Collaboration

74 members from 15 different institutions



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SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

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Established by the European Commission

NSF The National Science Foundation

Thanks!