DAMIC at Modane

Dark Matter in CCDs at Modane (DAMIC-M): a silicon detector apparatus searching for low-energy physics processes.

DAMIC

Steven Juhyung Lee on behalf of DAMIC and DAMIC-M collaborations at 15th Topical Seminar on Innovative Particle and Radiation Detectors (IPRD19) on 15 October 2019 at Siena, Italy

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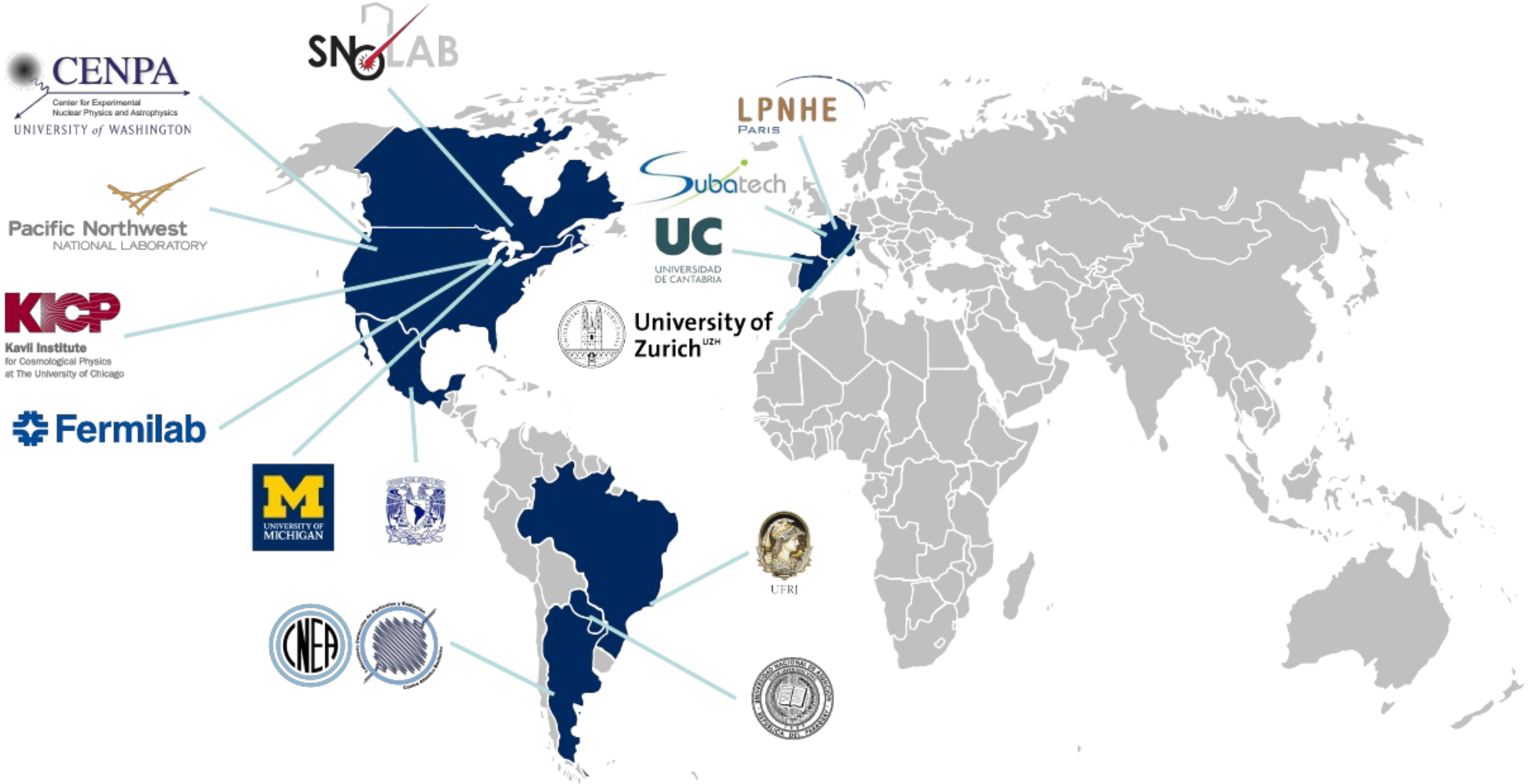
Introduction



The DAMIC and DAMIC-M collaborations are comprised of multiple institutes spread throughout Americas and Europe.

DAMIC

DAMIC stands for DArk Matter In CCDs and the concept is relatively simple.

We use the silicon bulk of the Charge-Coupled Devices (CCDs) as the 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.

Since 2012, DAMIC has been collecting data at SNOLAB

DAMIC at SNOLAB

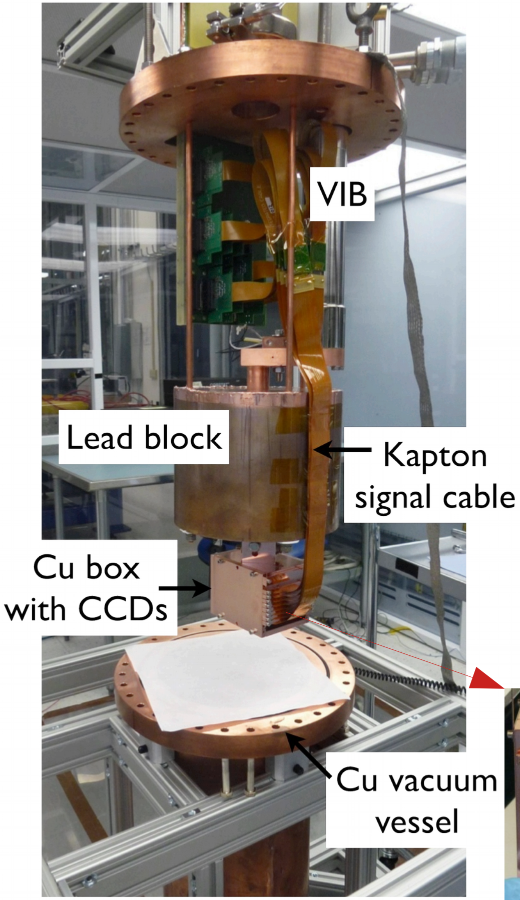
Figures from a)

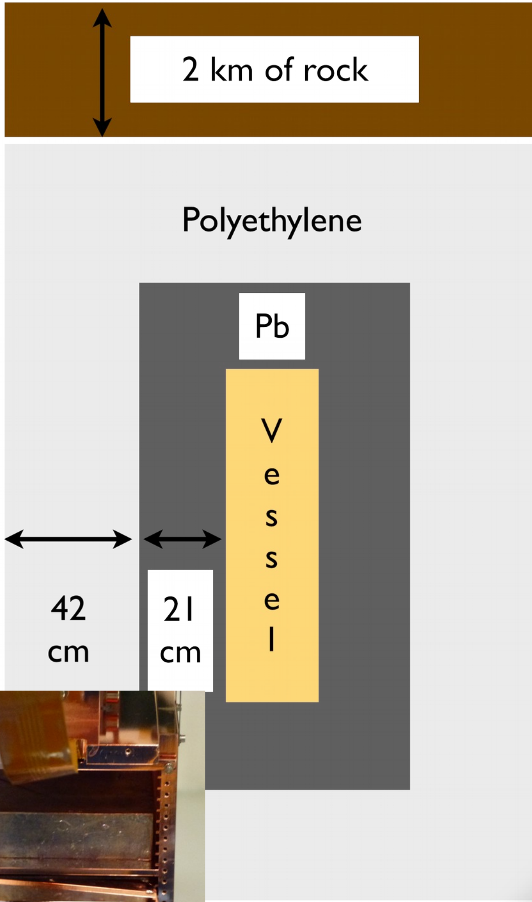
In SNOLAB, we've set up a DAMIC experiment under 2km of rock (~6km w.e.).

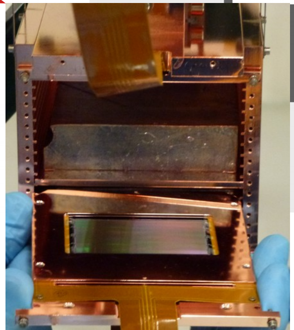
We then shielded the CCDs using Polyethylene, lead and copper.

Some of the CCDs are surrounded by ancient lead for further background reduction.

We currently have background reading around ~11.8 DRU $(Event \cdot keV^{-1} \cdot kgram^{-1} \cdot day^{1})$.







CCDs for DAMIC

The CCDs that we have been using are produced by Lawrence Berkeley National Laboratory (LBNL) and Dalsa. These CCDs are large area, thick, 3-stage high-voltage compatible, p channel in n bulk, fully-depleted back-illuminated scientific grade CCDs.

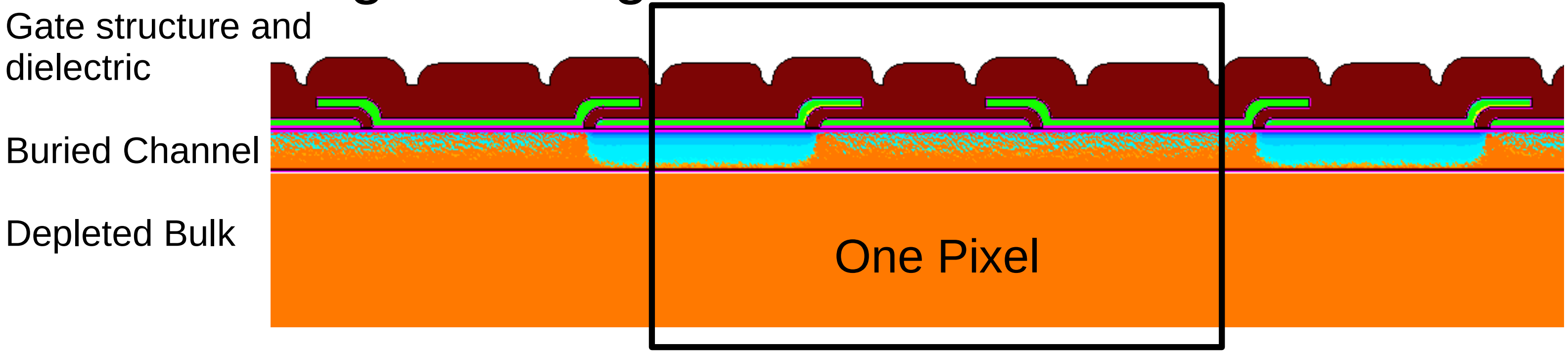
They are 675 microns thick, and each individual pixel is 15x15 microns square, and each CCD has over 16 million pixels and weighing 6.0 grams each.

They are operated in 10^{-7}mbar vacuum, and at 135Kelvin and fully depleted at 40V.

Scientific CCDs

One of the greatest advantages of using scientific CCDs as the particle sensors is the fact that the CCDs were designed originally for computer memory rather than image sensors.

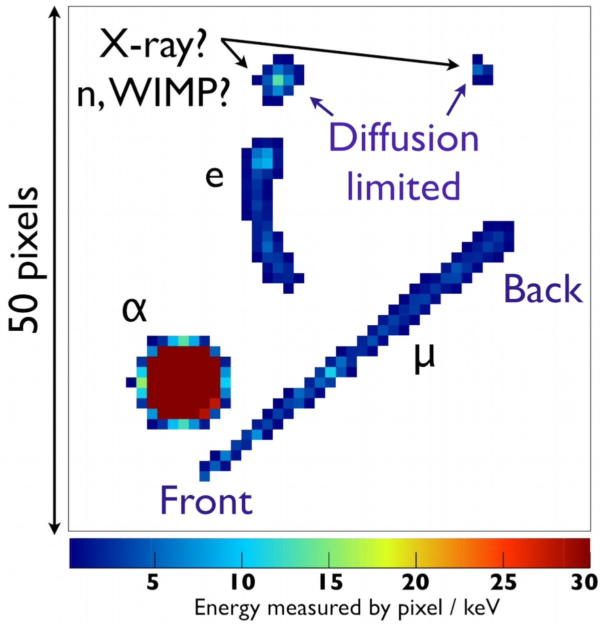
The CCDs operate by collecting charges while fully depleted and read out by sending varying clock voltages to the gate structures to shift the charges through its buried channel until readout.

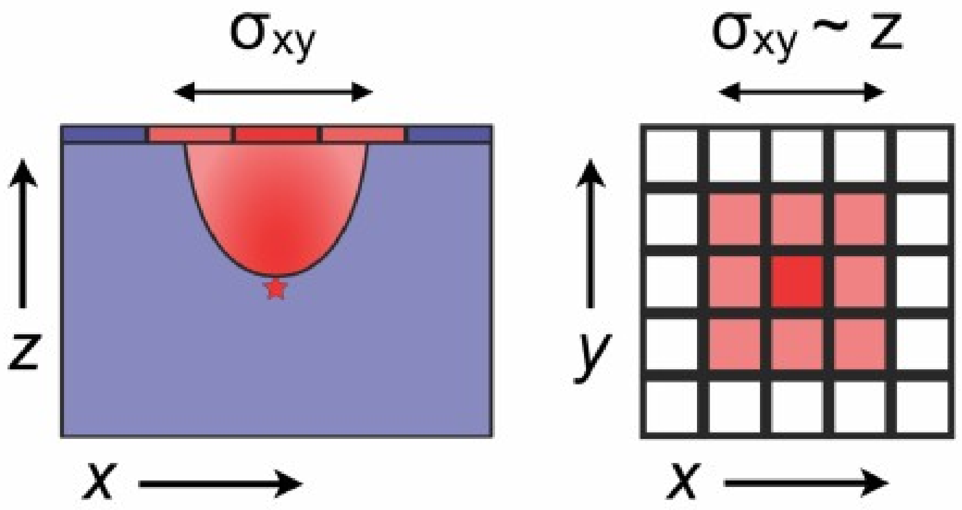


As a result, the leakage current and the readout noise can be controlled using the operating parameters.

Particle tracks in CCDs

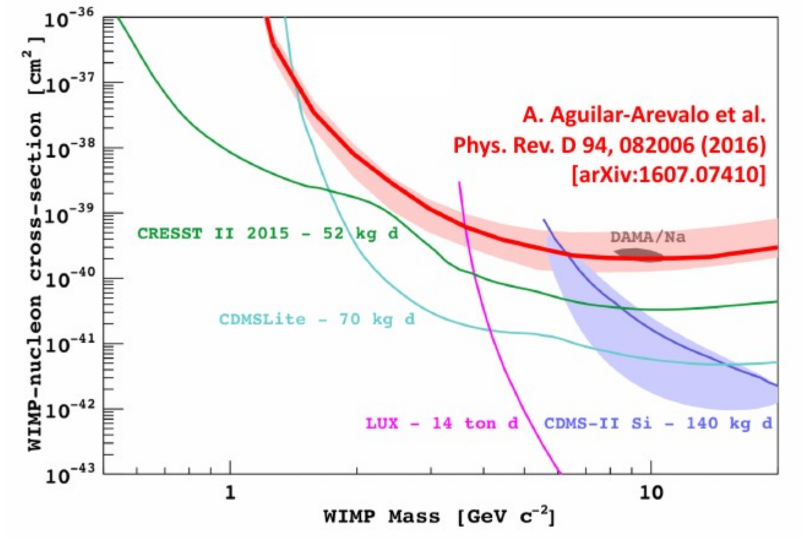
We should note that by modeling the charge carrier diffusion in the device, we can use each individual CCD to reconstruct the particle tracks in 3D.

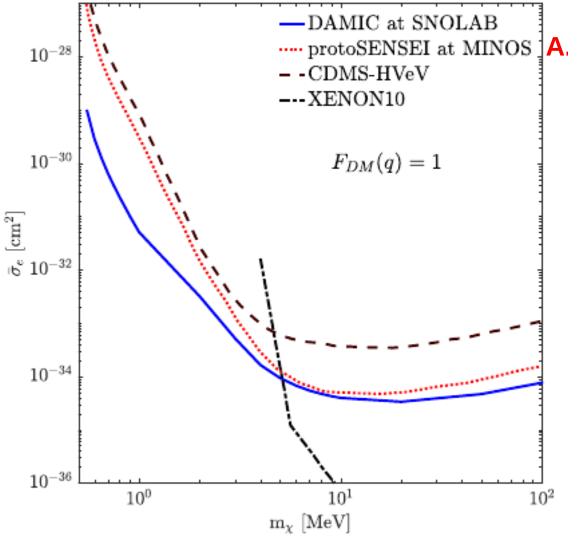




Results from SNOLAB

By optimizing the operating parameters and pixel selection, we were able to observe leakage current down to $2\times10^{-22}\,Acm^{-2}$ and readout noise of 1.6 electrons at our SNOLAB experiment.





A. Augilar-Arevalo et al.
Under review (2019)
[arXiv: 1907.12628]

As of this date, we have been able to use our experiment to set constraints for Weakly Interacting Massive Particles (WIMP) and potential Dark-Matter electron free scattering cross sections.

DAMIC at Modane

We should also note that DAMIC at SNOLAB has been operating for over 6 years. The experiment needs maintenance and most of all upgrades.

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 Sous terrain de Modane (LSM).

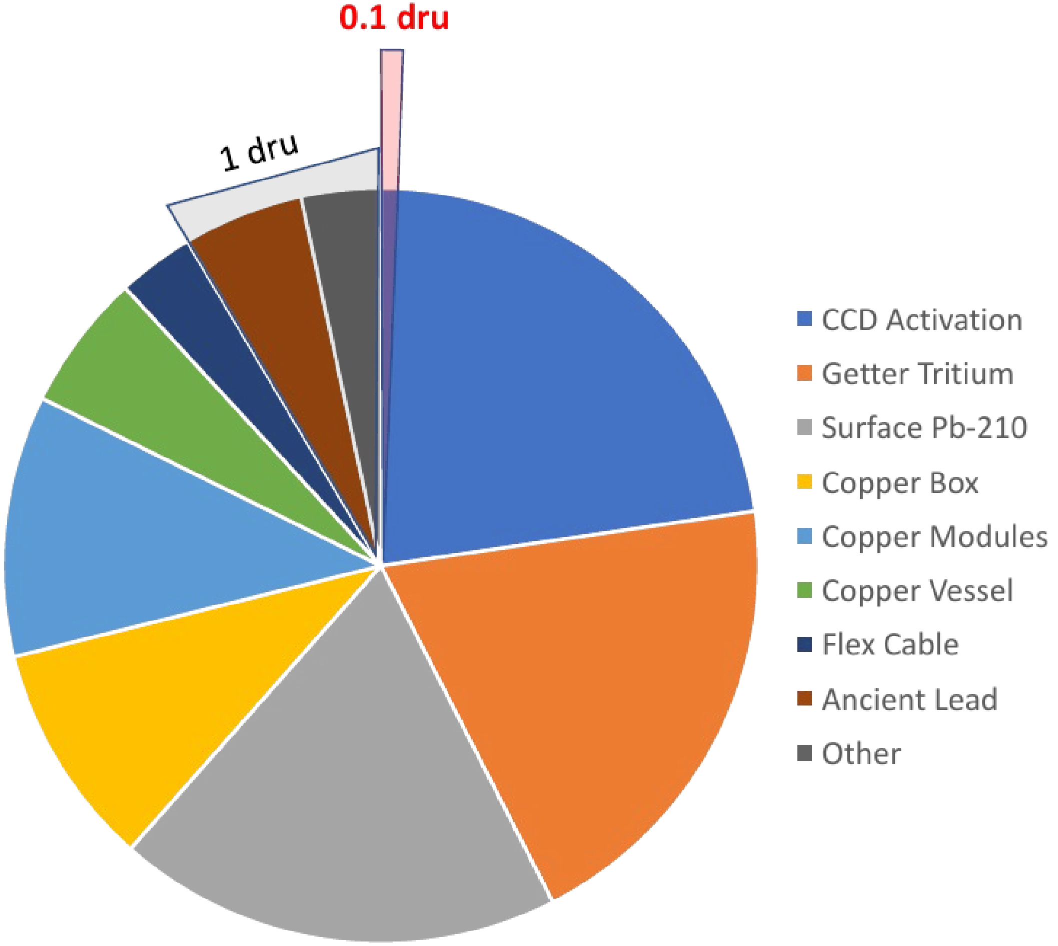
At LSM, we intend to install 50 even larger area LBNL CCDs with skipper amplifiers.

We also intend to lower the background.

Background model from SNOLAB

- **Tritium** – will shield silicon to eliminate activation backgrounds and remove getter hydrogen
- **Pb-210** – will properly clean all surfaces and control exposure to radon
- **Copper** – will electroform 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 expect to contribute > 1 dru
- Working now to better understand the contributions down to 0.1 dru

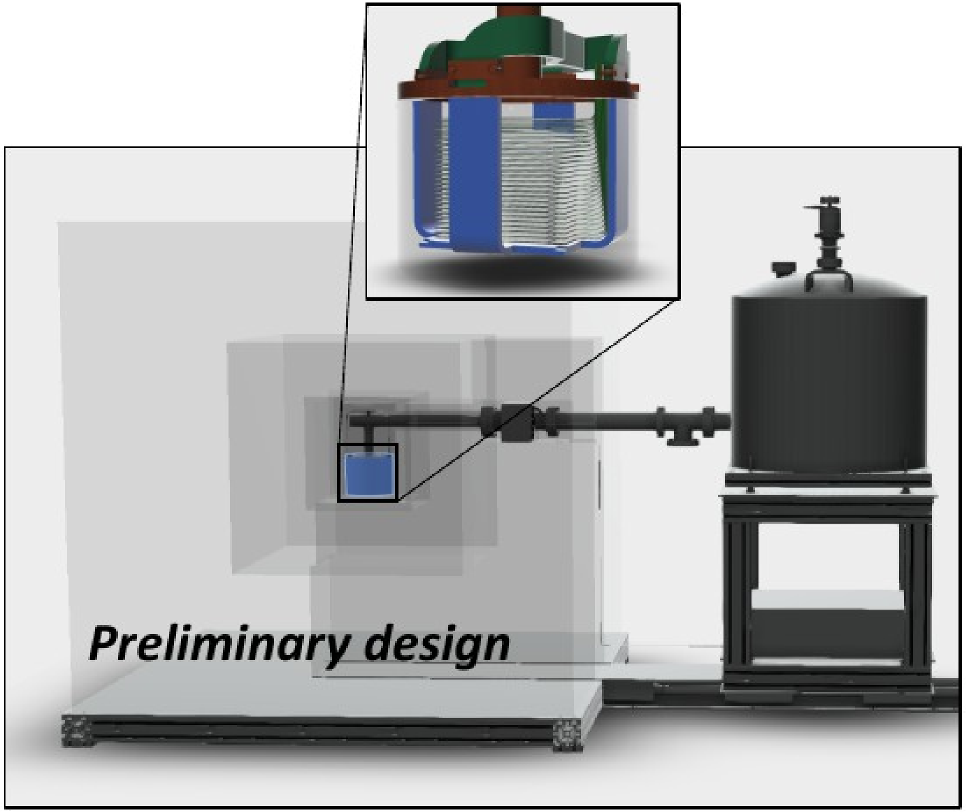


DAMIC-M Preliminary Design

To reach the target background, we will be using a charcoal cryo-pump to minimize contamination once target vacuum has been achieved.

Almost all of components of the DAMIC-M experiment will be carefully assayed for radioimpurity.

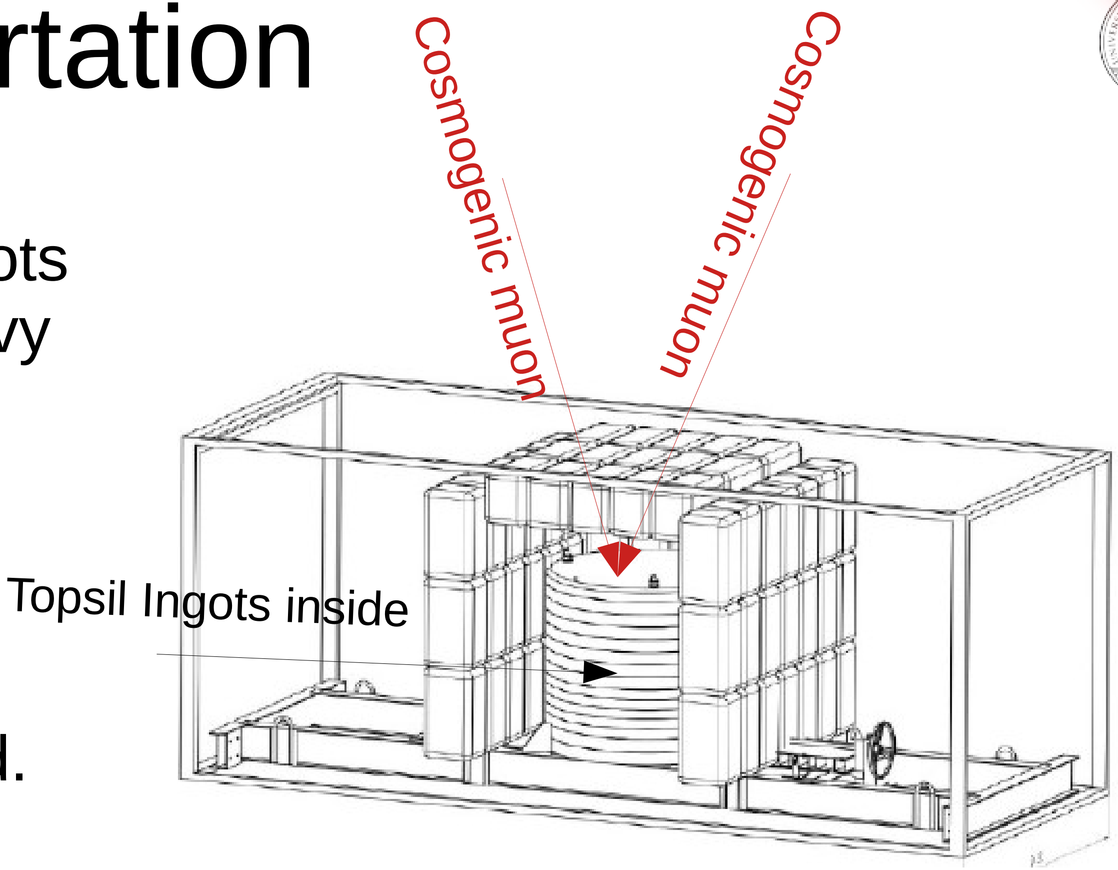
This starts from the CCD production.



CCD Transportation

To minimize the radioimpurity from muon spallation, the ingots will be transported under heavy iron shielding.

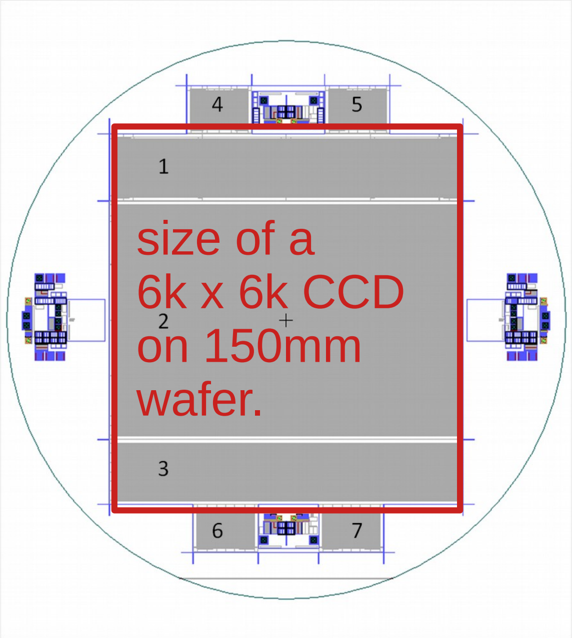
Also to minimize the leakage current, ultra-high resistance (n type >20kOhm) silicon ingots from Topsil will be used.



Once transported to Dalsa/LBNL the CCDs will be produced using clean methods and also under shielding.

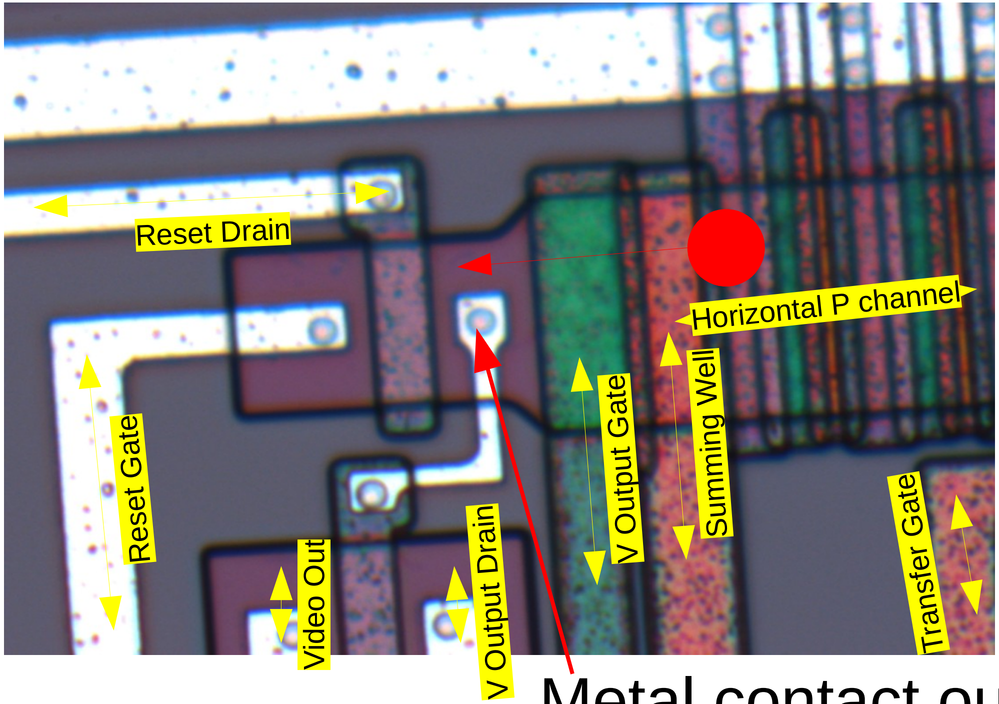
New CCDs

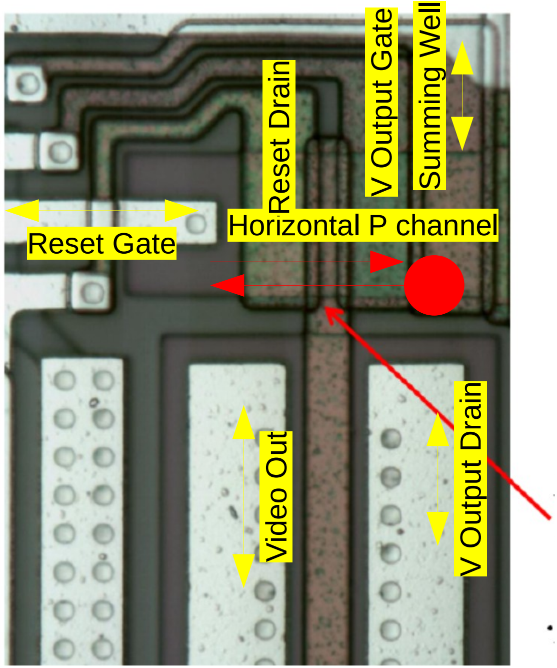
The new CCDs will keep the same pixel structure and size.
However there will be over 36 million pixels per device resulting in increased target area and mass.



These new CCDs will also utilize skipper amplifiers to reduce the readout noise.

Conventional v.s. skipper amp





Metal contact output node

Floating Gate output node

The skipper amplifier utilizes floating gate for the output channel, allowing charges to "skip" past output contact.

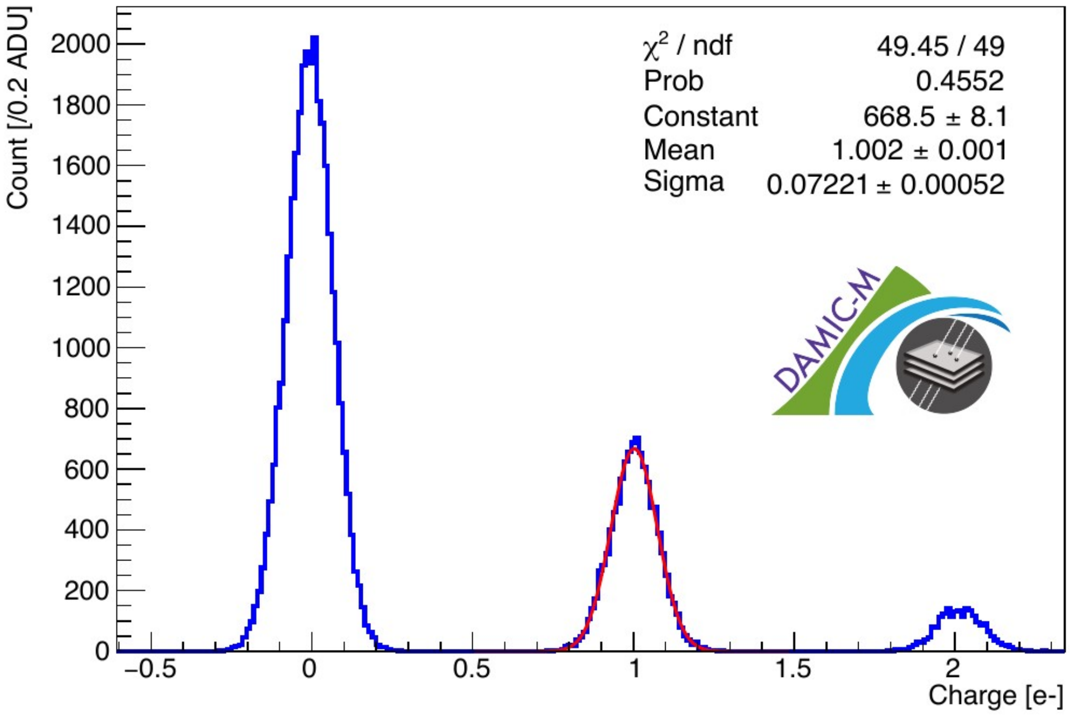
Right figure from d)

Skipper amplifier.

As a result, the charges can be amplified multiple times before being read out.

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

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



Goal of DAMIC-M

The main goal of DAMIC-M is to achieve the highest sensitivity in search for sub-GeV dark matter detection.

To achieve this goal, we aim to operate the CCDs with readout noise less than 0.1 electrons. We also aim to reduce the background to less than to 0.1 DRU (from 11.8 DRU at DAMIC-SNOLAB).

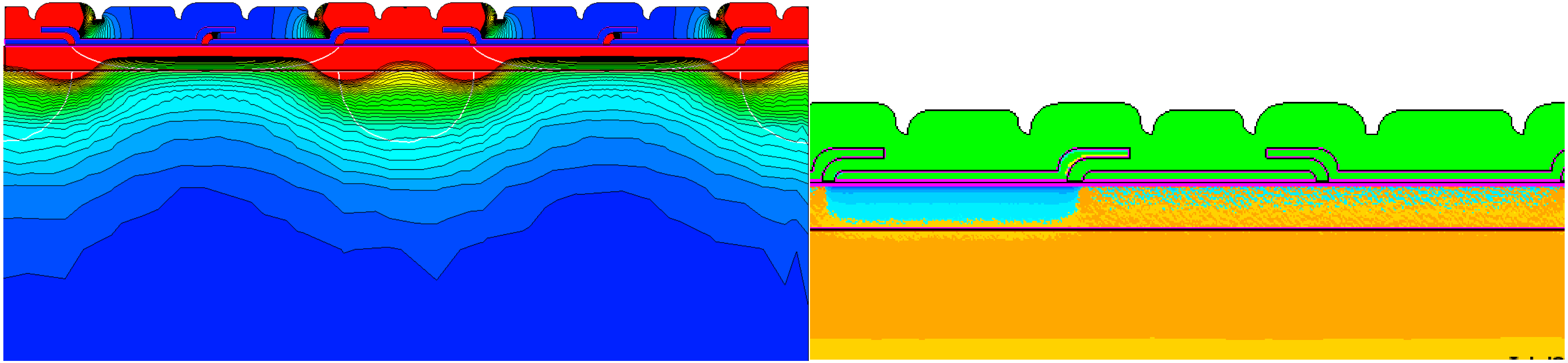
We intend to reach these goals by modeling the CCDs and the whole detector setup using simulations.

Device simulation

Inside the CCD, we will use Synopsys Sentarus TCAD to simulate a small scale CCD.

We will model an accurate behaviour of the charge carriers within the device at different operating conditions.

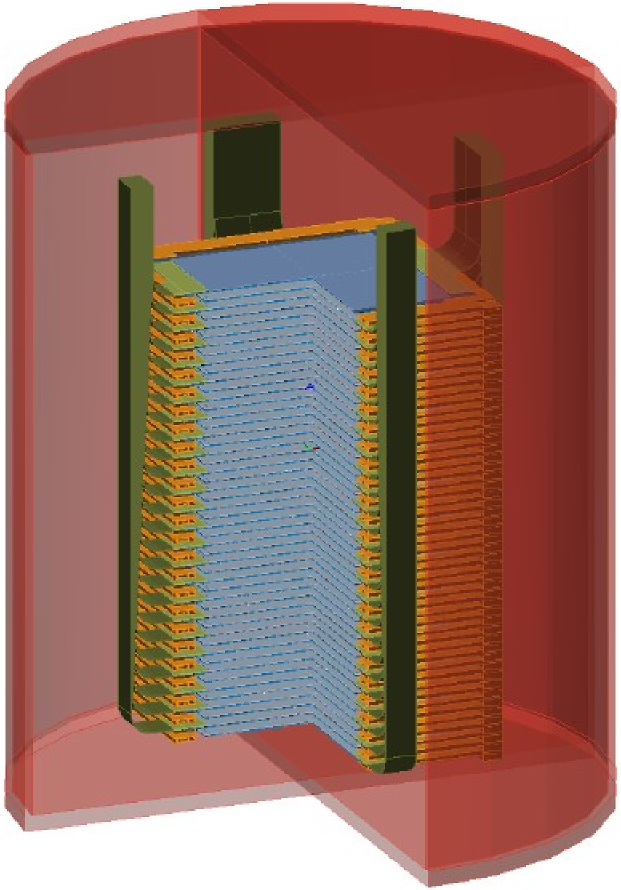
The simulation along side with test setup, the operating parameters will be optimized for signal efficiency.

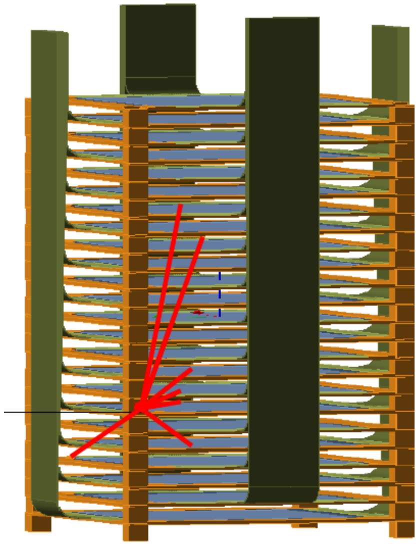


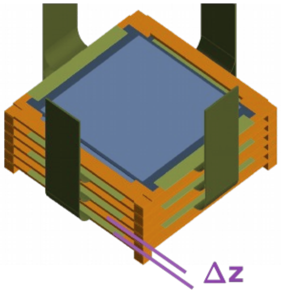
Background simulation

From outside of the CCDs, using the radioimpurity measurements taken during the assaying processes and detector design, GEANT4 will be used to model the background level of DAMIC-M.

We will optimize the design of DAMIC-M using these simulations.







Conclusion

DAMIC-SNOLAB is currently undergoing maintenance/upgrade.

DAMIC-M, in collaboration with RD-50 at CERN has started searching for displacement damage and modeling low energy non ionizing energy loss (NIEL) in silicon.

The DAMIC-M collaboration has been CERN recognized as of 2019.

A prototype of DAMIC-M will be installed within 2020.

Thank you for your time.

References

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e) Janesick, James R. “Scientific Charge-Coupled Devices”
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g) S.E. Holland “High-voltage-compatible, fully depleted CCDs”
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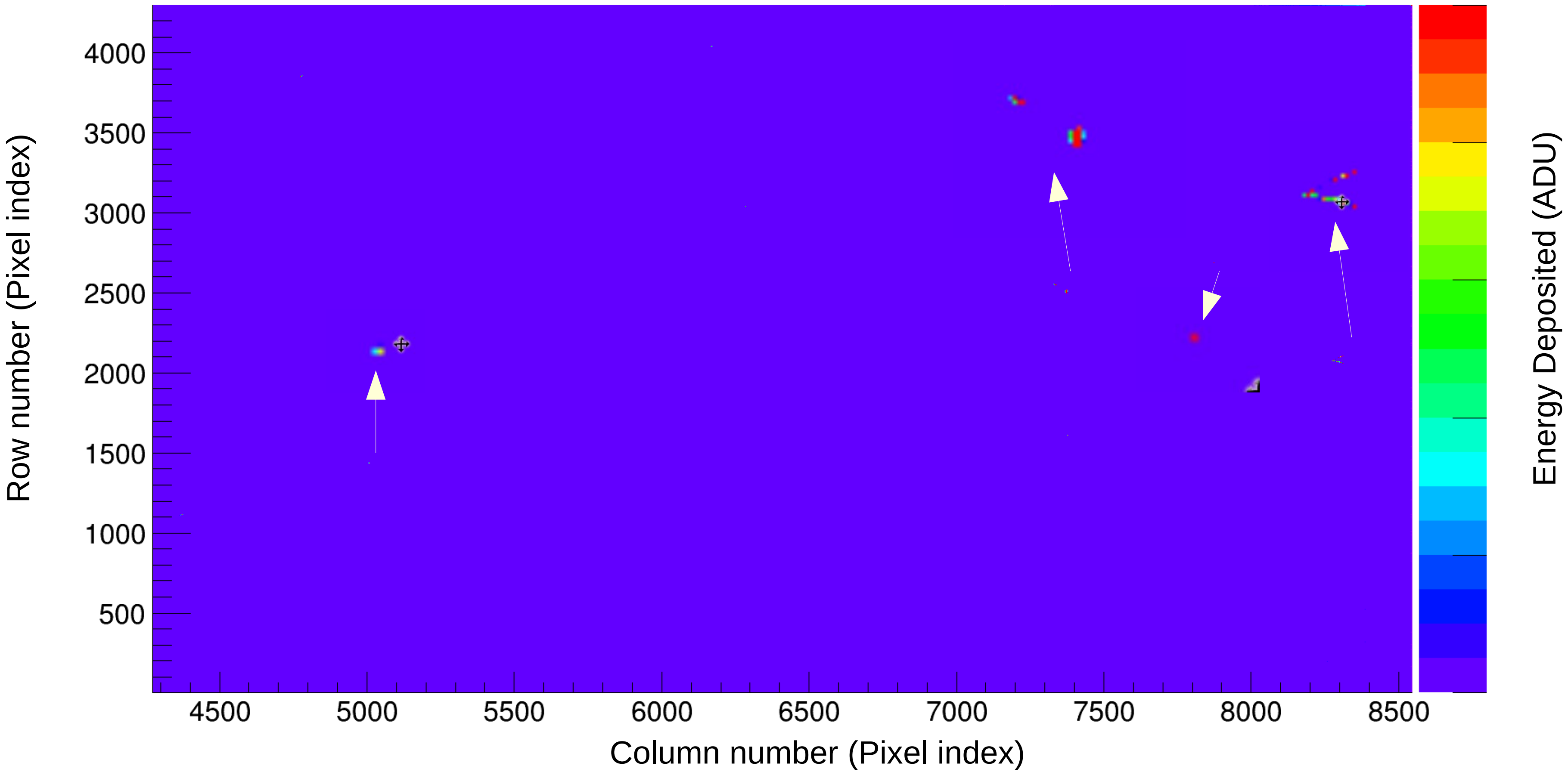
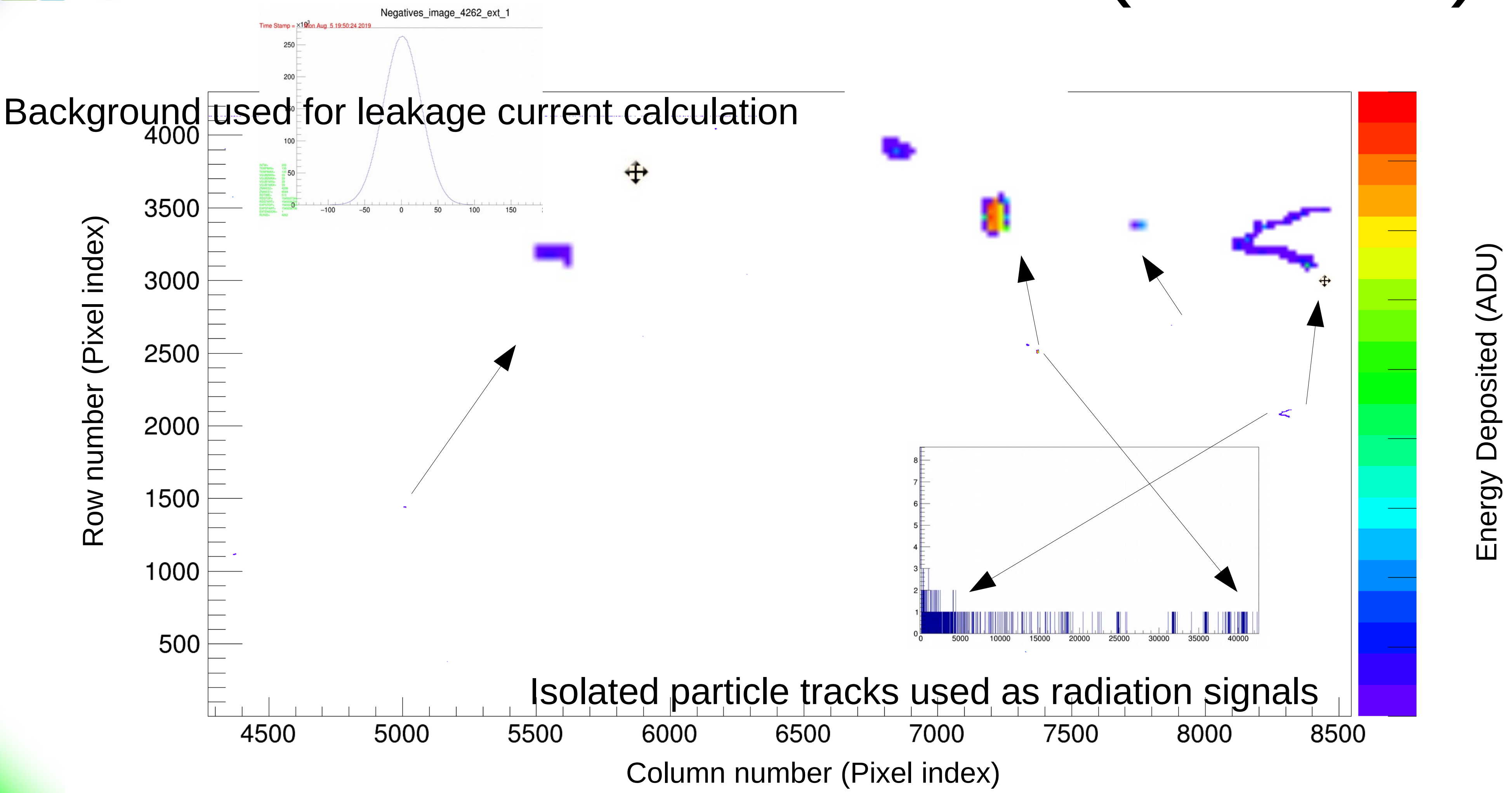
h) S.E. Holland et al “Physics of fully depleted CCDs”
2014 IOP Publishing Ltd. and Sissa Medialab srl, DOI:10.1088/1748-0221/9/03/X0357

Particle tracks in CCDs (Raw)



Particle tracks in CCDs (Isolated)



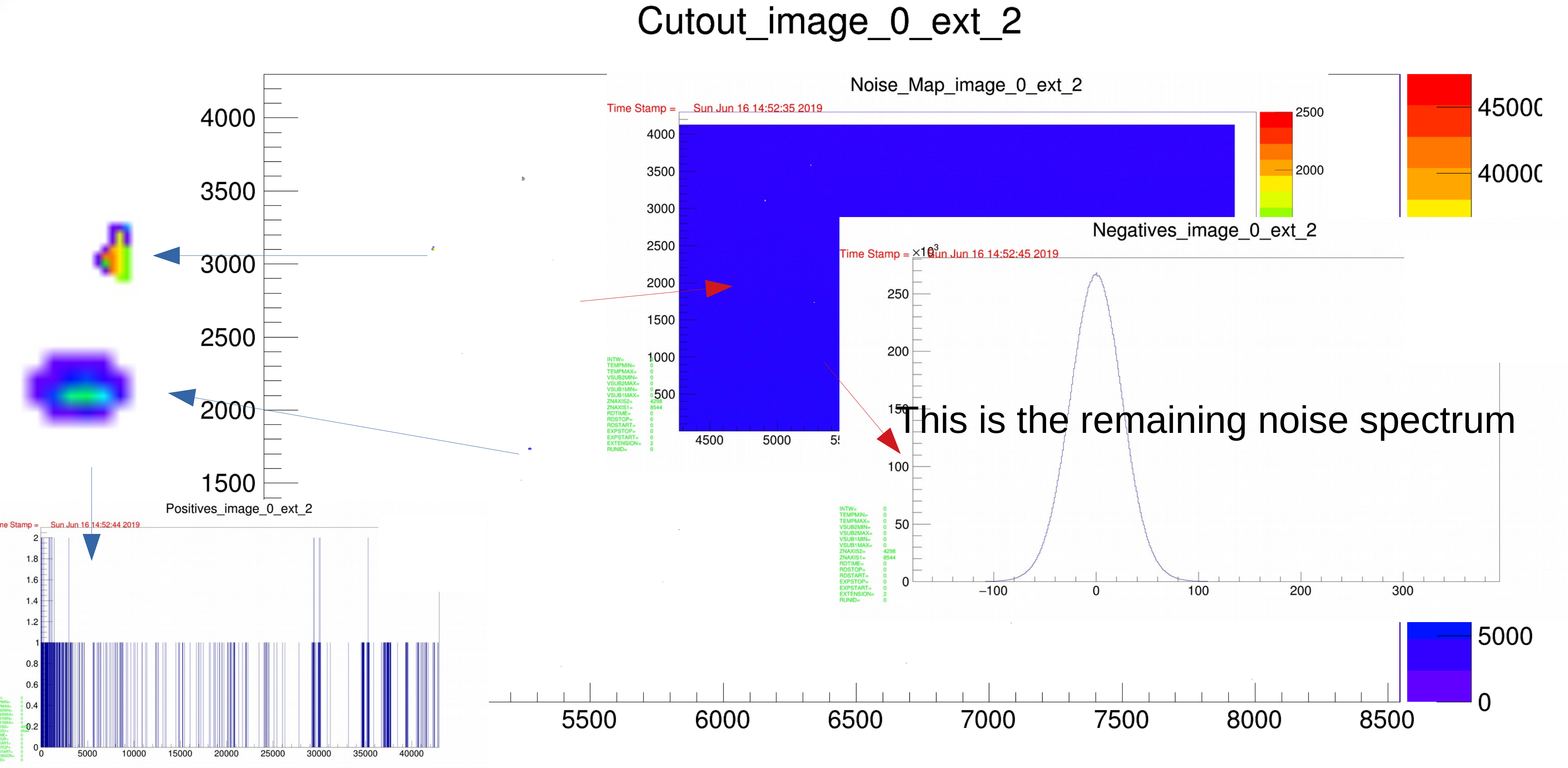
NIEL in CCDs

As the search for dark matter candidates involve searching for electrically neutral particles, DAMIC-M in collaboration with RD-50 at CERN is also modeling the non-ionizing energy loss in silicon (NIEL).

Since the CCDs used for DAMIC have ultra-low leakage current, and readout noise We hope to also model NIEL and IEL at a very accurate scale.

We are also studying the effects of displacement damage at low intensities and energy by simulating the effects using TCAD by embedding displaced atoms in different parts of the bulk.

NIEL in CCDs



This is the signal spectrum

CCD operation

At full depletion, each individual pixel within CCD collects all extra charge carriers in the closest pixel dielectric.

This is done by forming a potential well in the collection region.

During a read-out operation, the leading adjacent gate potential is lowered, and following adjacent gate potential is held high allowing carriers to move through the channel.

Skipper amplification

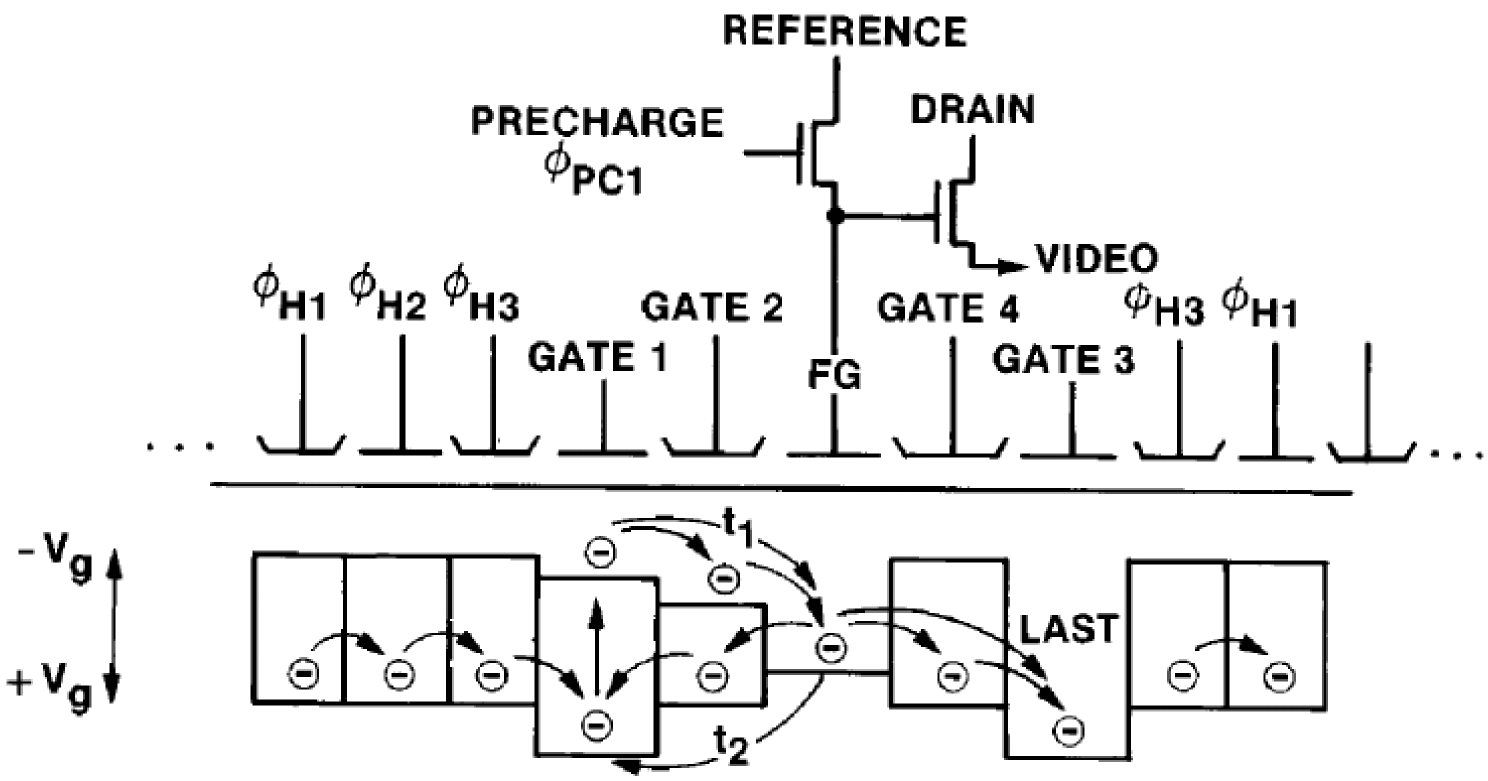


Figure from e)

CCD operation

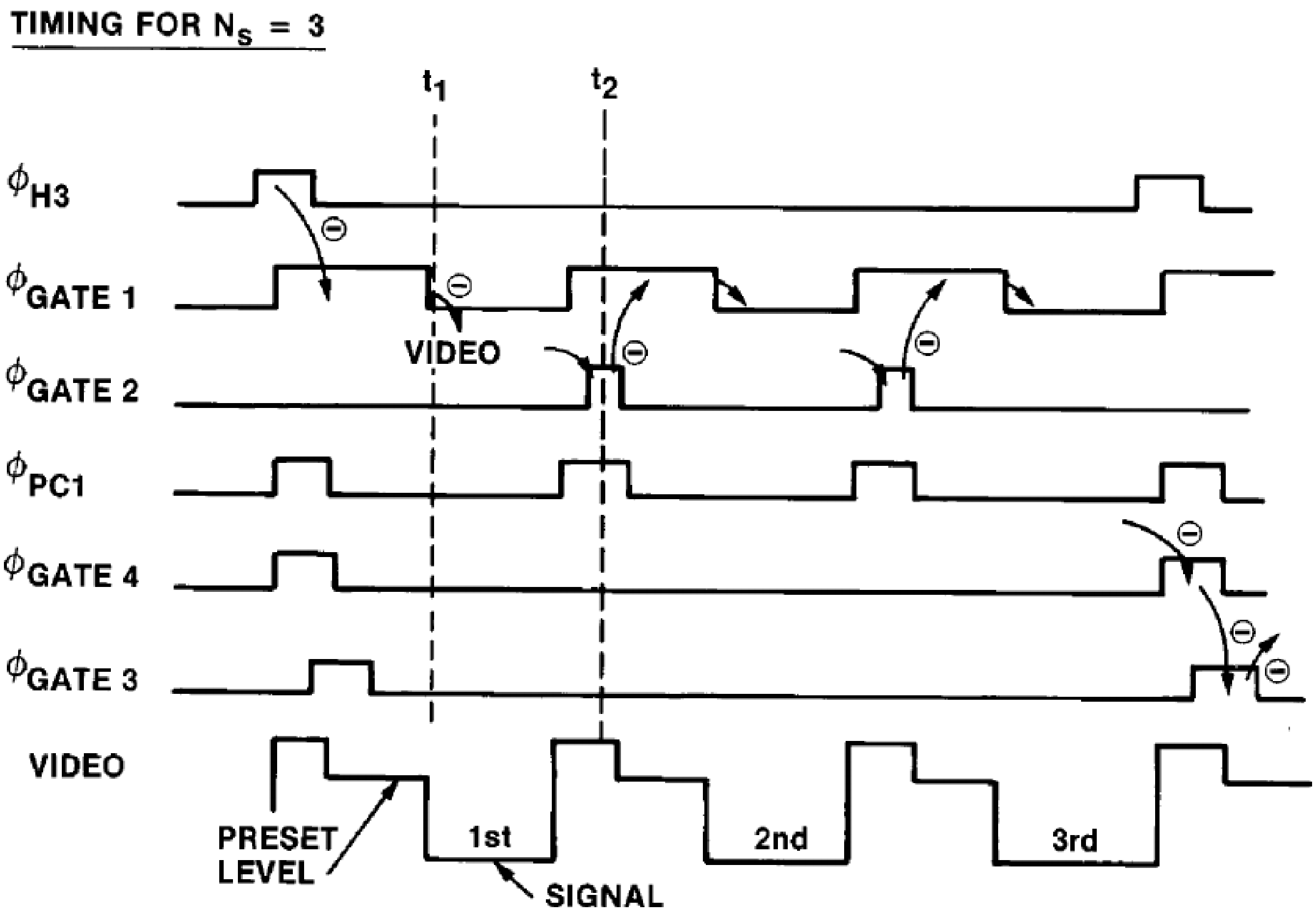


Figure from e)

DAMIC in SNOLAB