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 “Trento” Workshop on Advanced Silicon Radiation Detectors (TREDI2020) on 17 February 2020 in TU Wien (Vienna, Austria).

Overview

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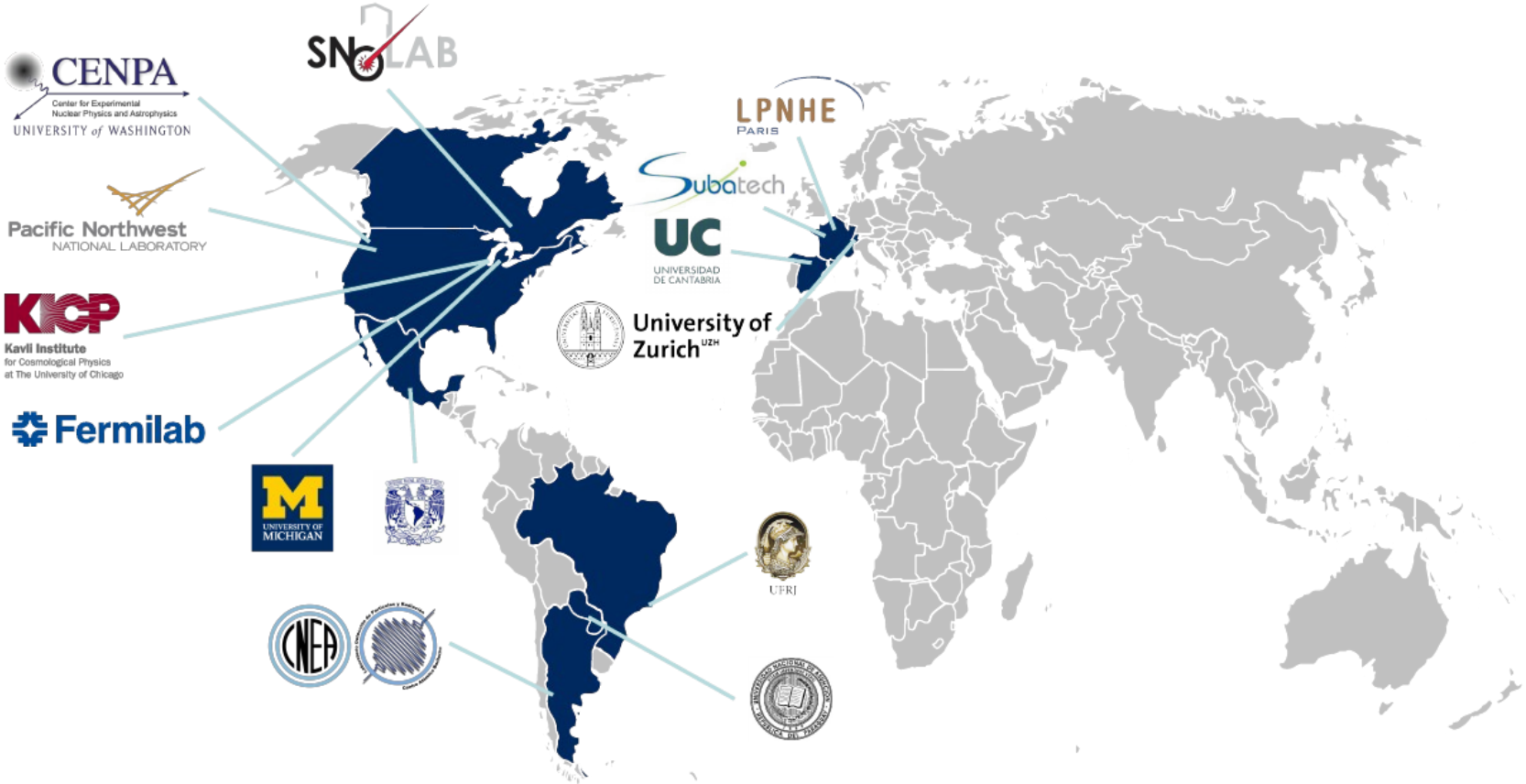
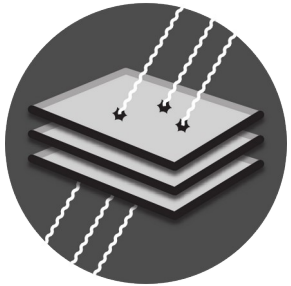
Introduction



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 operating in SNOLAB

DAMIC at SNOLAB

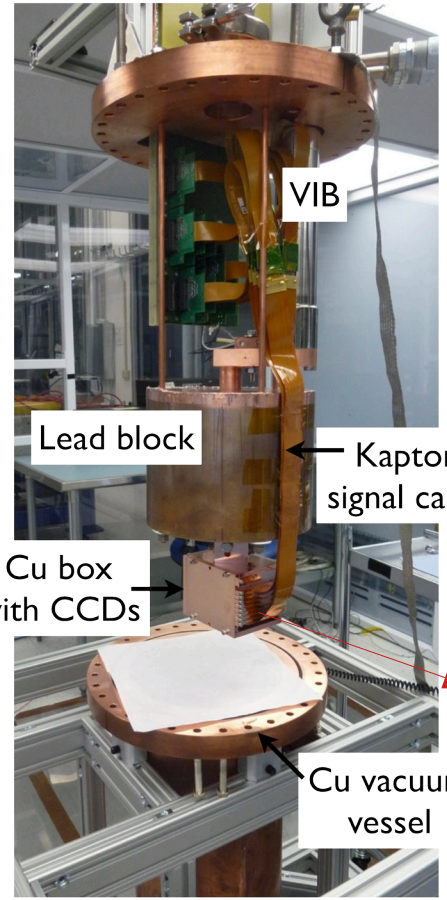
Figures from a)

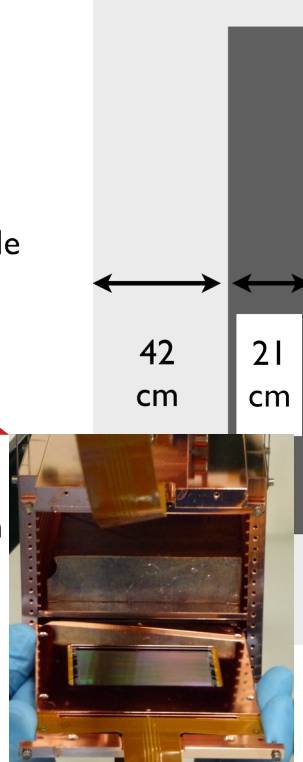
In SNOLAB, we've set up a DAMIC experiment under 2km of rock (~6km w.e.).

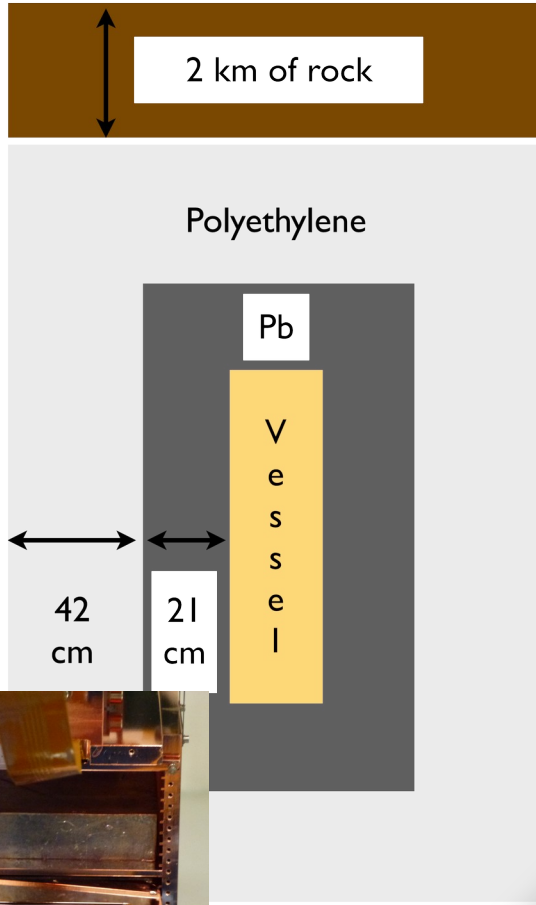
We then shielded the CCDs using Polyethylene, lead and copper.

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 scientific grade CCDs.

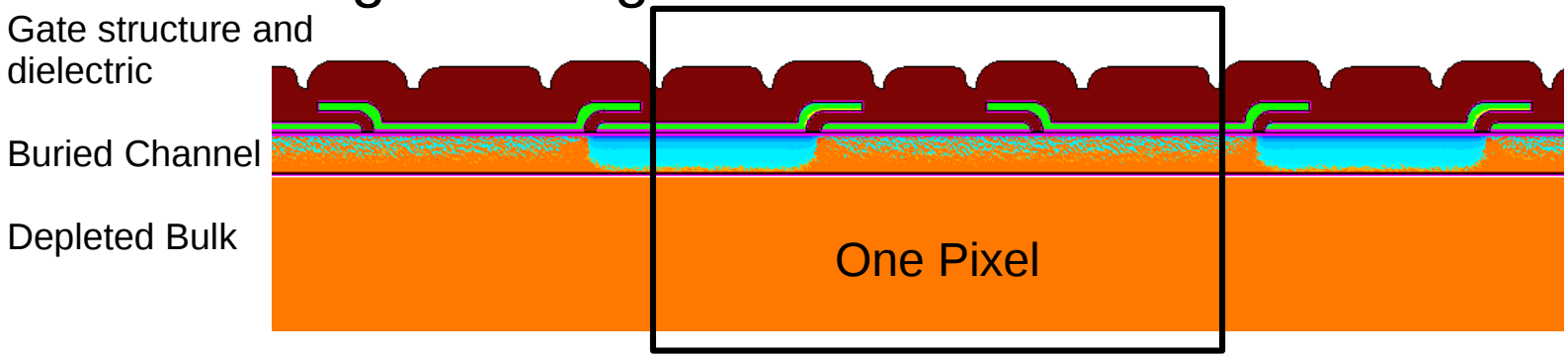
They are 675 microns thick, and each individual pixel is 15x15 microns square, and each CCD has over 16 million pixels and weighing 6.0 grams each.

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.

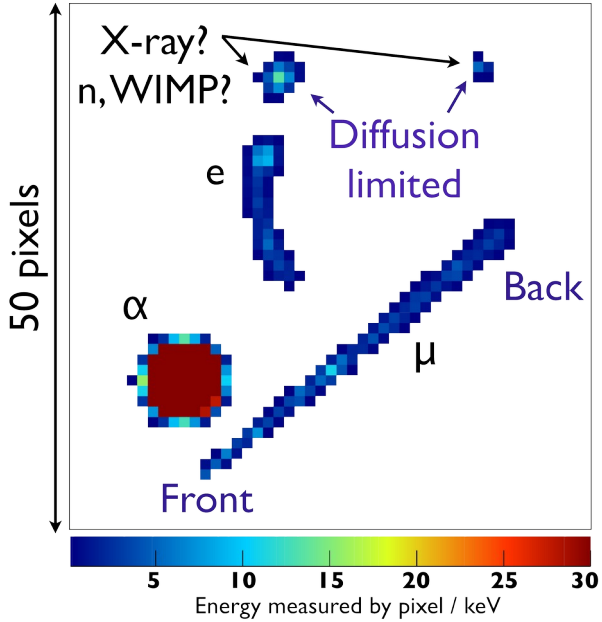
The CCDs operate by collecting charges while fully depleted and read out by sending varying clock voltages to the gate structures to shift the charges through its buried channel until readout.

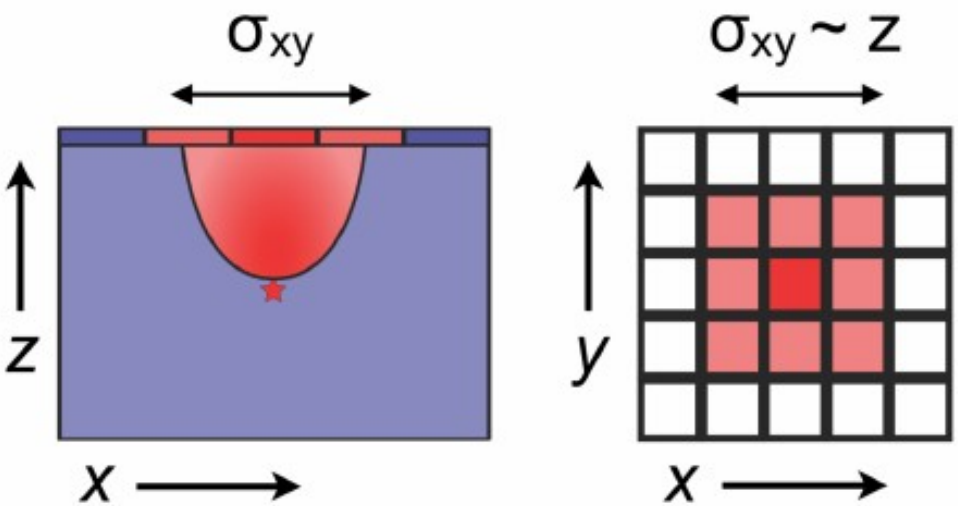


As a result, the leakage current and the readout noise can be controlled using the operating parameters.

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.

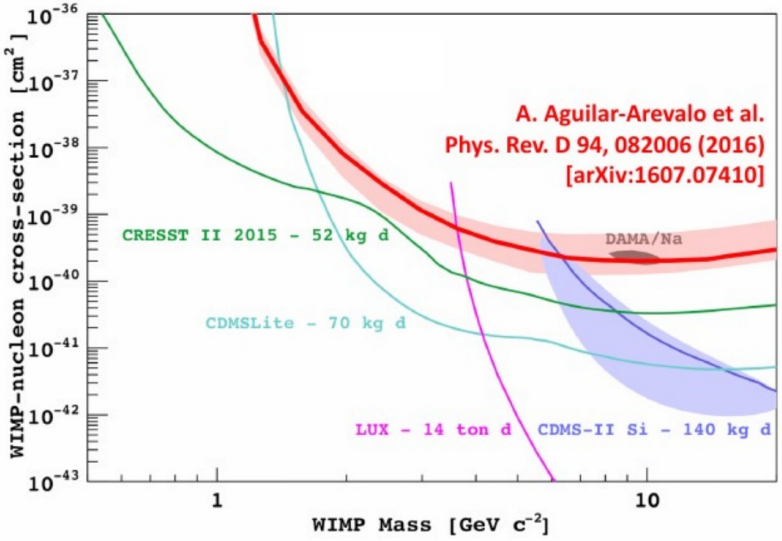


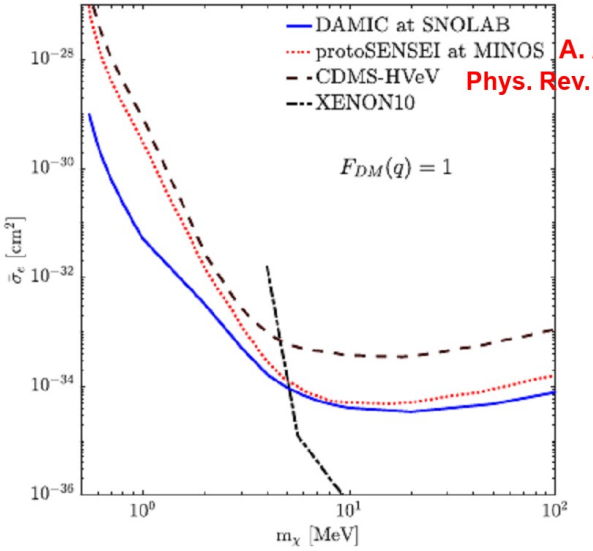


Figures from a)

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. Aguilar-Arevalo et al.
Phys. Rev. Lett. 123, 181802 (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 Sousterrain de Modane (LSM).

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

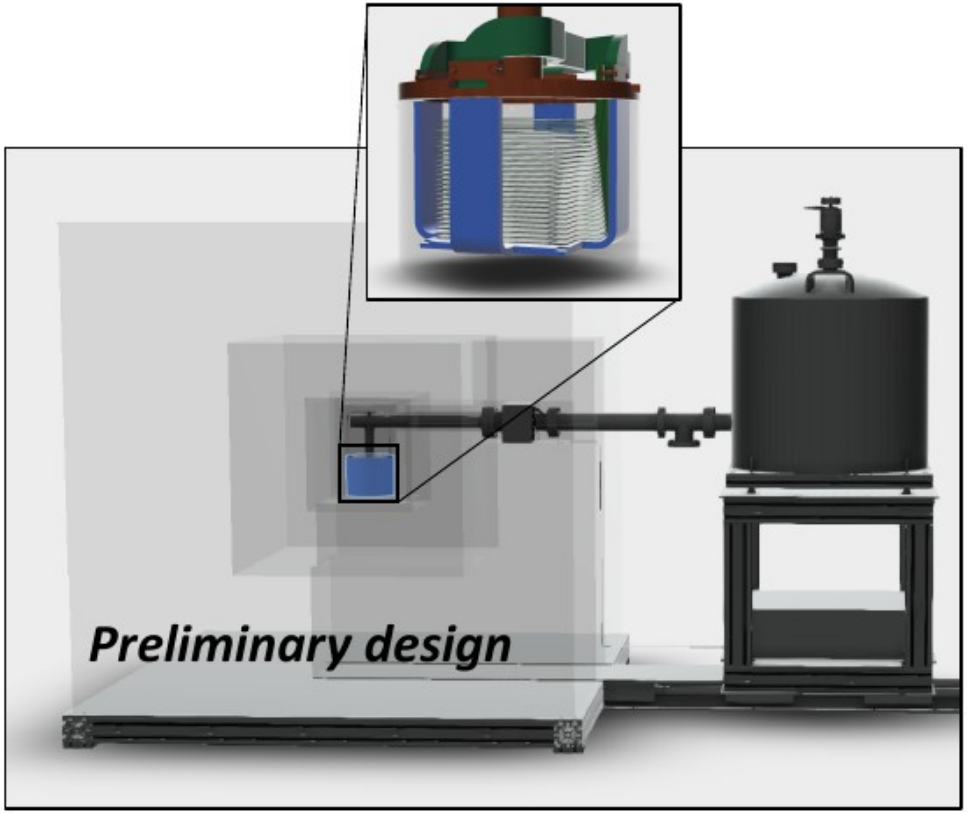
We also intend to lower the background.

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.

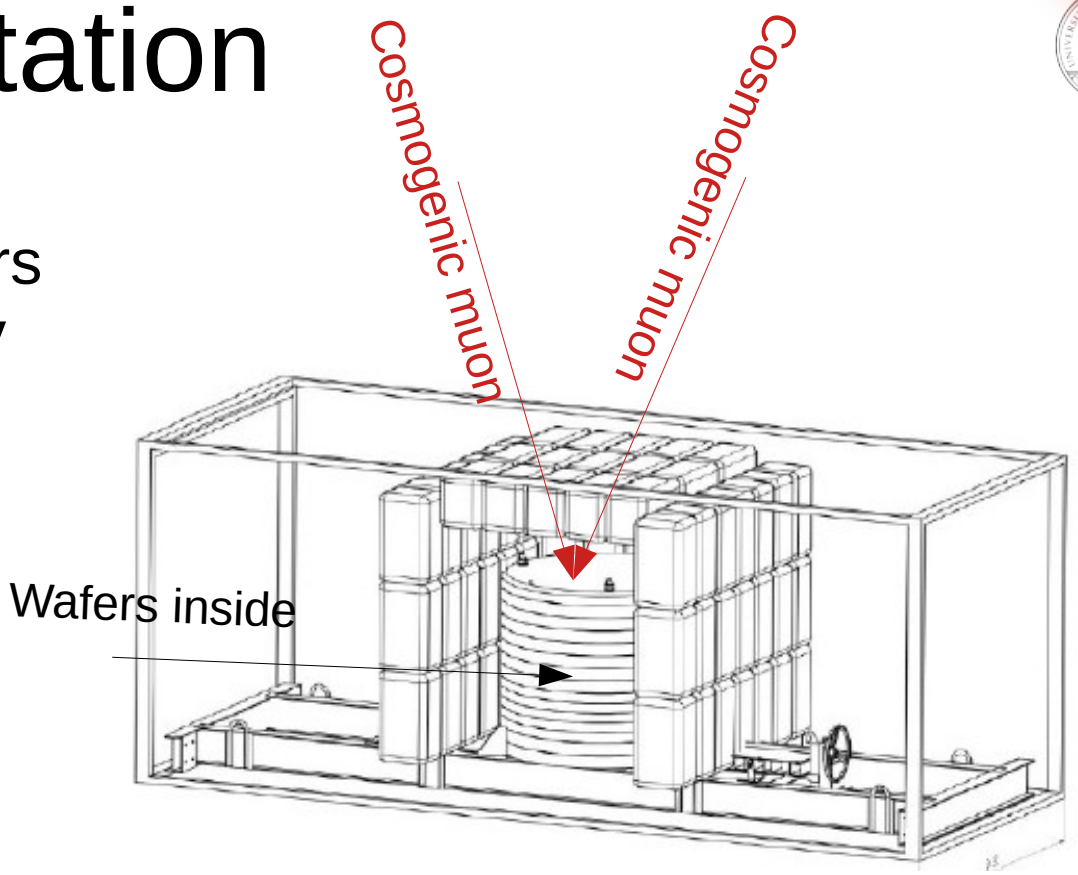
This starts from the CCD production.



CCD Transportation

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

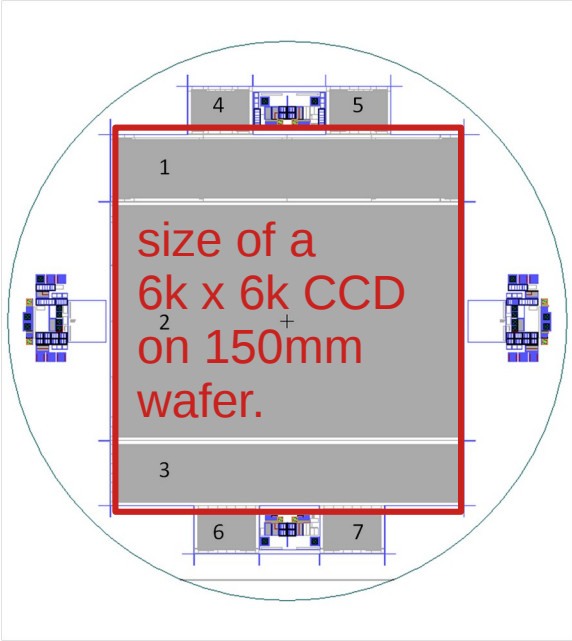
Also to minimize the leakage current, ultra-high resistance (n type >20kOhm) silicon ingots from Topsil will be used.



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

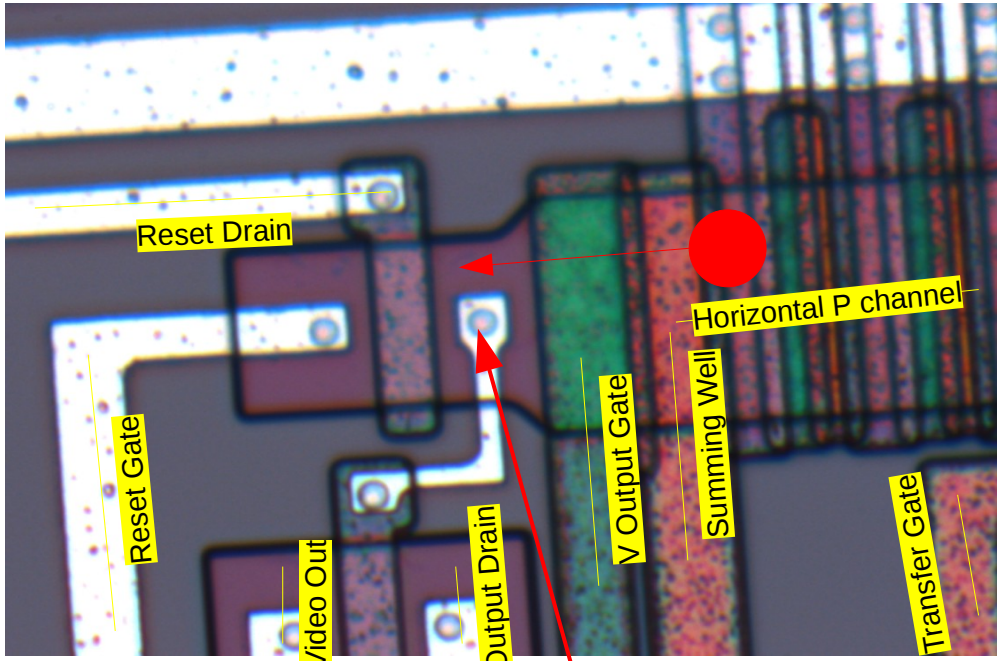
New CCDs

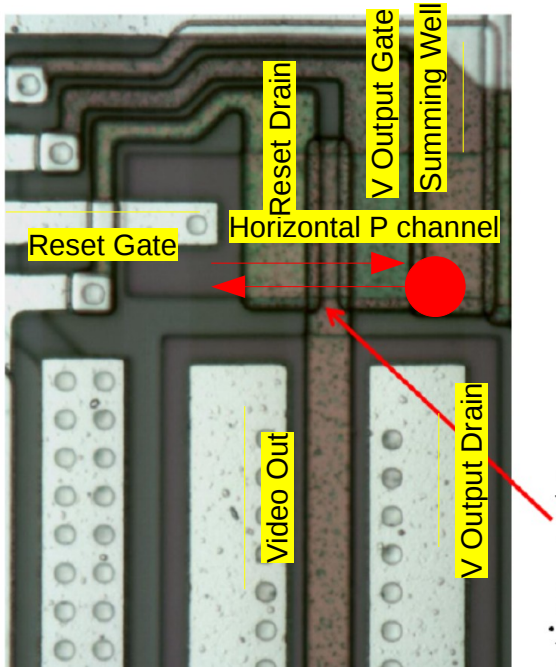
The new CCDs will keep the same pixel structure and size. However there will be over 36 million pixels per device resulting in increased target area and mass.



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.

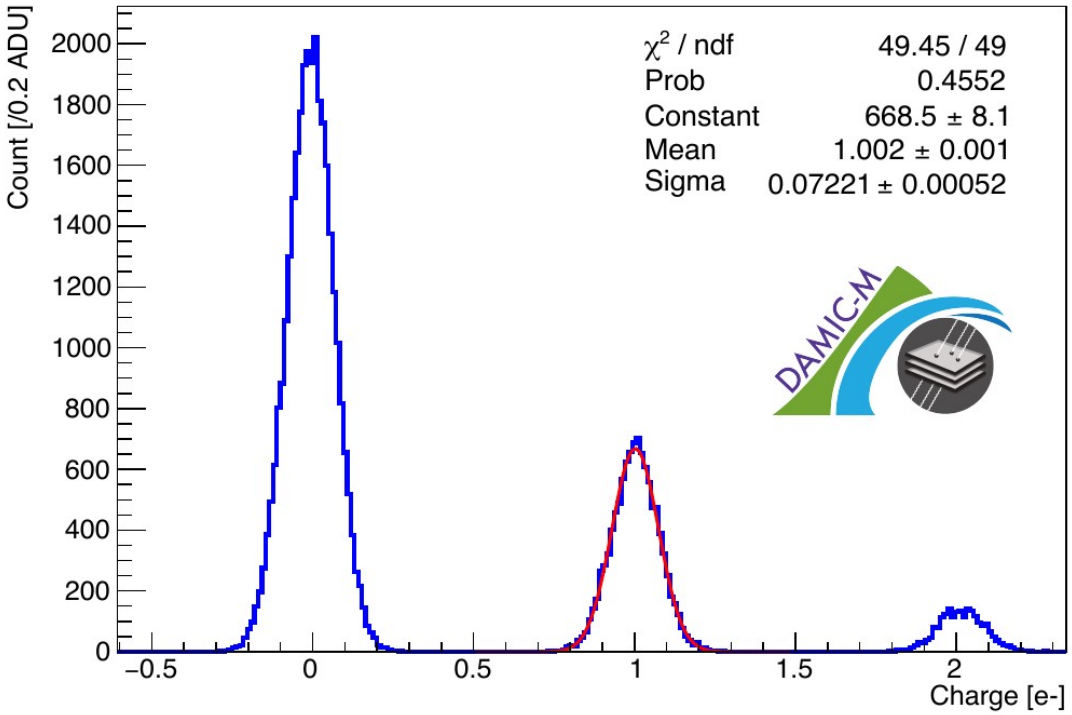
Right figure from d)

Skipper amplifier.

As a result, the charges can be sampled 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).

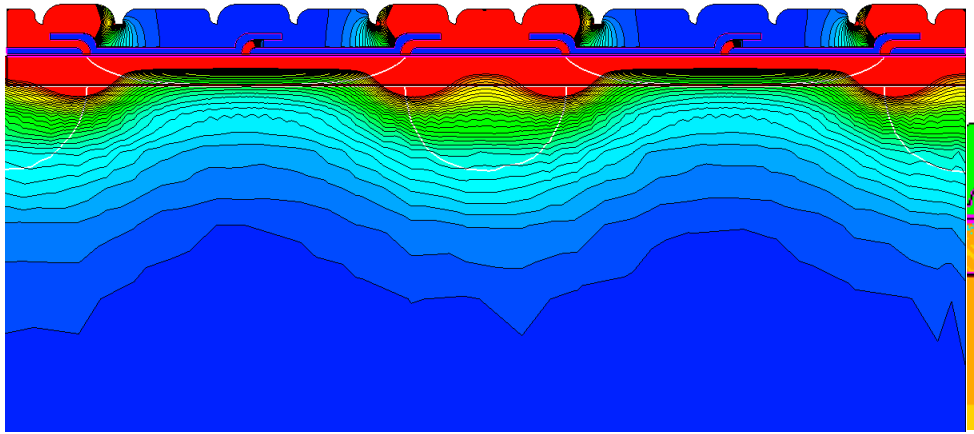
We intend to reach these goals by modeling the CCDs and the whole detector setup using simulations.

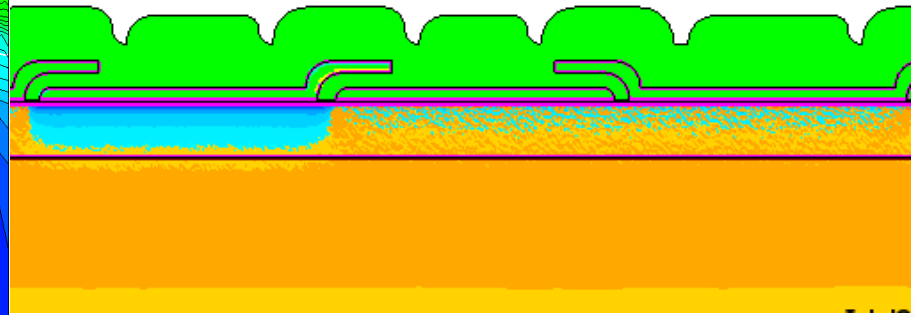
Device simulation

We are using 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.

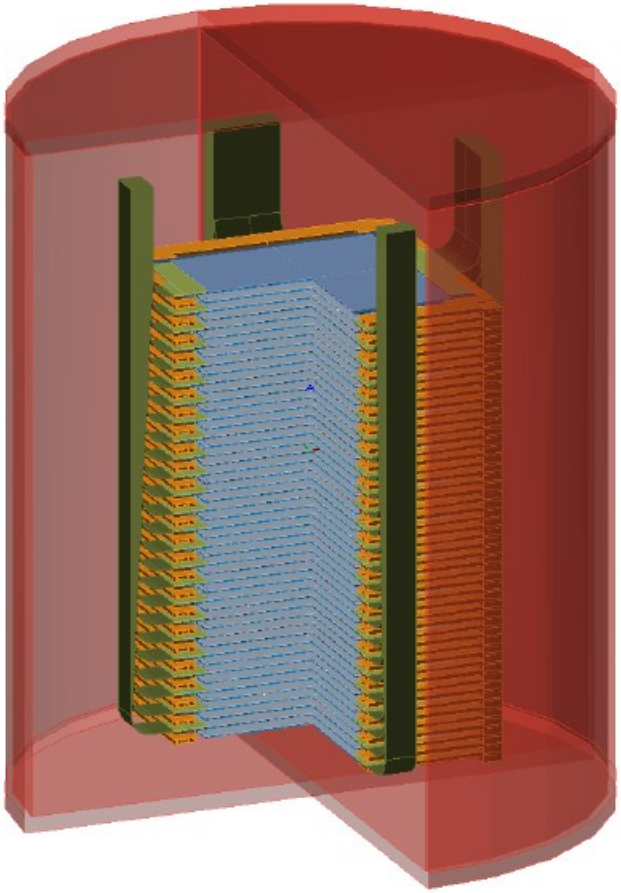


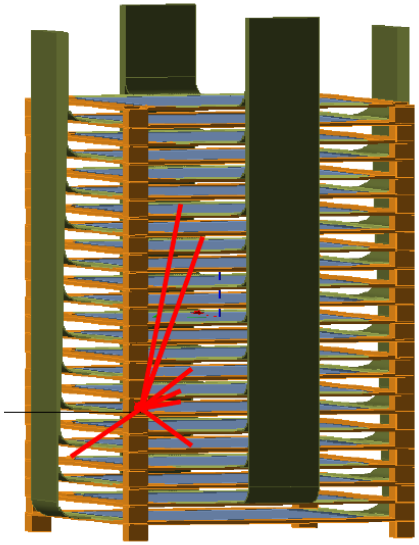


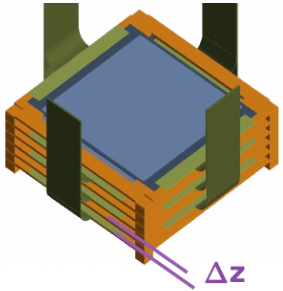
Background simulation

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.

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

DAMIC-M in collaboration with RD50 at CERN has started searching for displacement damage and modeling low energy non ionizing energy loss (NIEL) in silicon. Using the low event rate of DAMIC apparatus, DAMIC-M and RD50 are aiming to model radiation damage induced by a single event.

Thank you for your time.

References

a) Alvaro E. Chavarria et al. "DAMIC at SNOLAB"
13th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2013): Asilomar, California, September 8-13, 2013, DOI:10.1016/j.phpro.2014.12.006 arXiv:1407.0347.

b) Settimo, Mariangela, “The DAMIC experiment at SNOLAB,” in 53rd Rencontres de Moriond on QCD and High Energy Interactions (Moriond QCD 2018) March 17-24, 2018, 2018.

c) A. Aguilar-Arevalo et al. "Constraints on Light Dark Matter Particles Interacting with Electrons from DAMIC at SNOLAB", 2019, arXiv: 1907.12628.

d) C. J. Bebek et al. “CCD Research and Development at Lawrence Berkeley National Laboratory”. SPIE Vol 8453 845305-1, DOI: 10.1117/12.926606.

e) Janesick, James R. “Scientific Charge-Coupled Devices”
SPIE Press, Published in Bellingham, Washington U.S.A
Copyright 2001 The Society of Photo-Optical Instrumentation Engineers

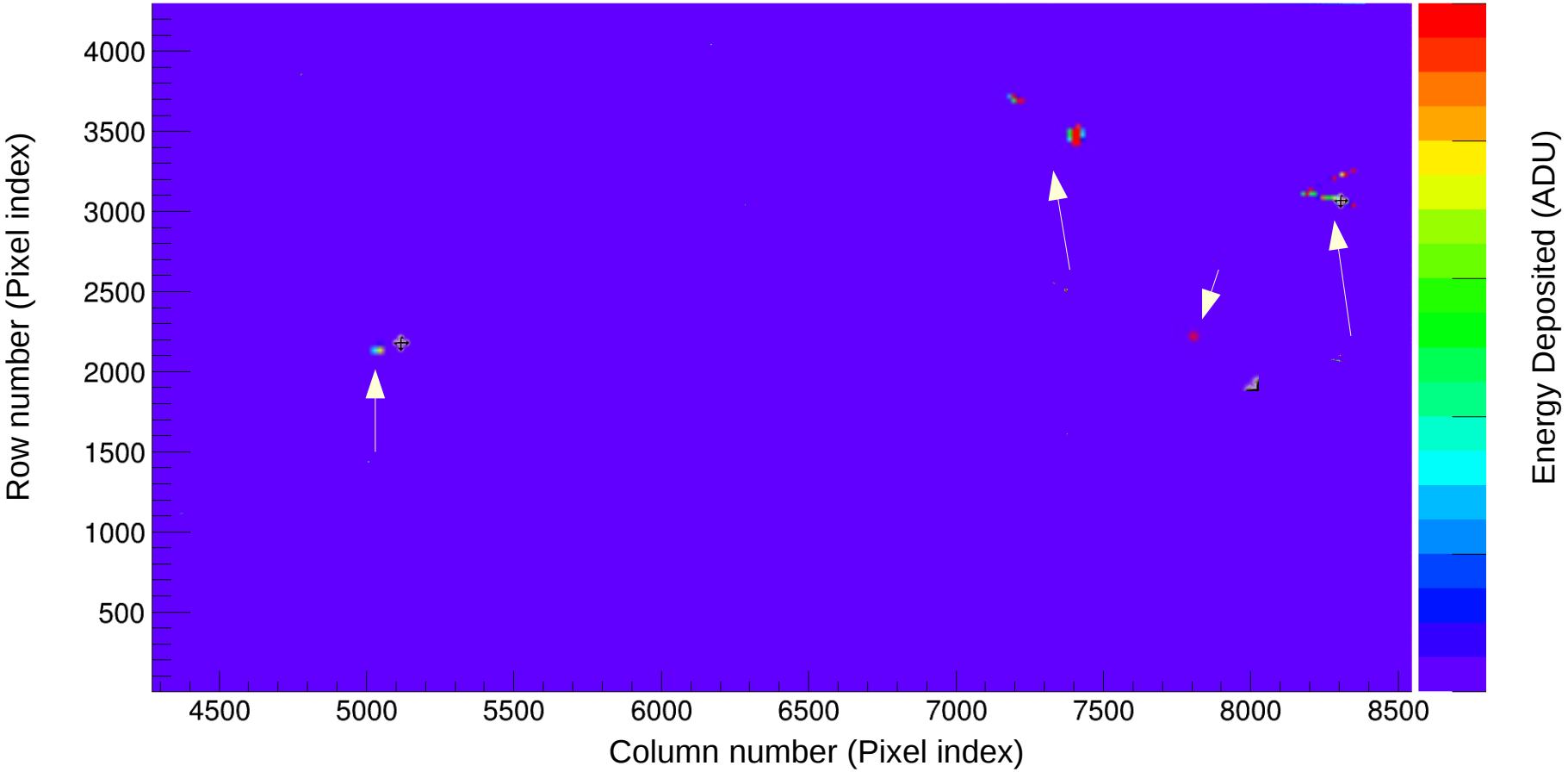
f) C.J. Bebek et al “Status of the CCD development for the Dark Energy Spectroscopic Instrument”
2017 IOP Publishing Ltd. and Sissa Medialab srl, DOI: 10.1088/1748-0221/12/04/C0418

g) S.E. Holland “High-voltage-compatible, fully depleted CCDs”
05-15-2006 Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720

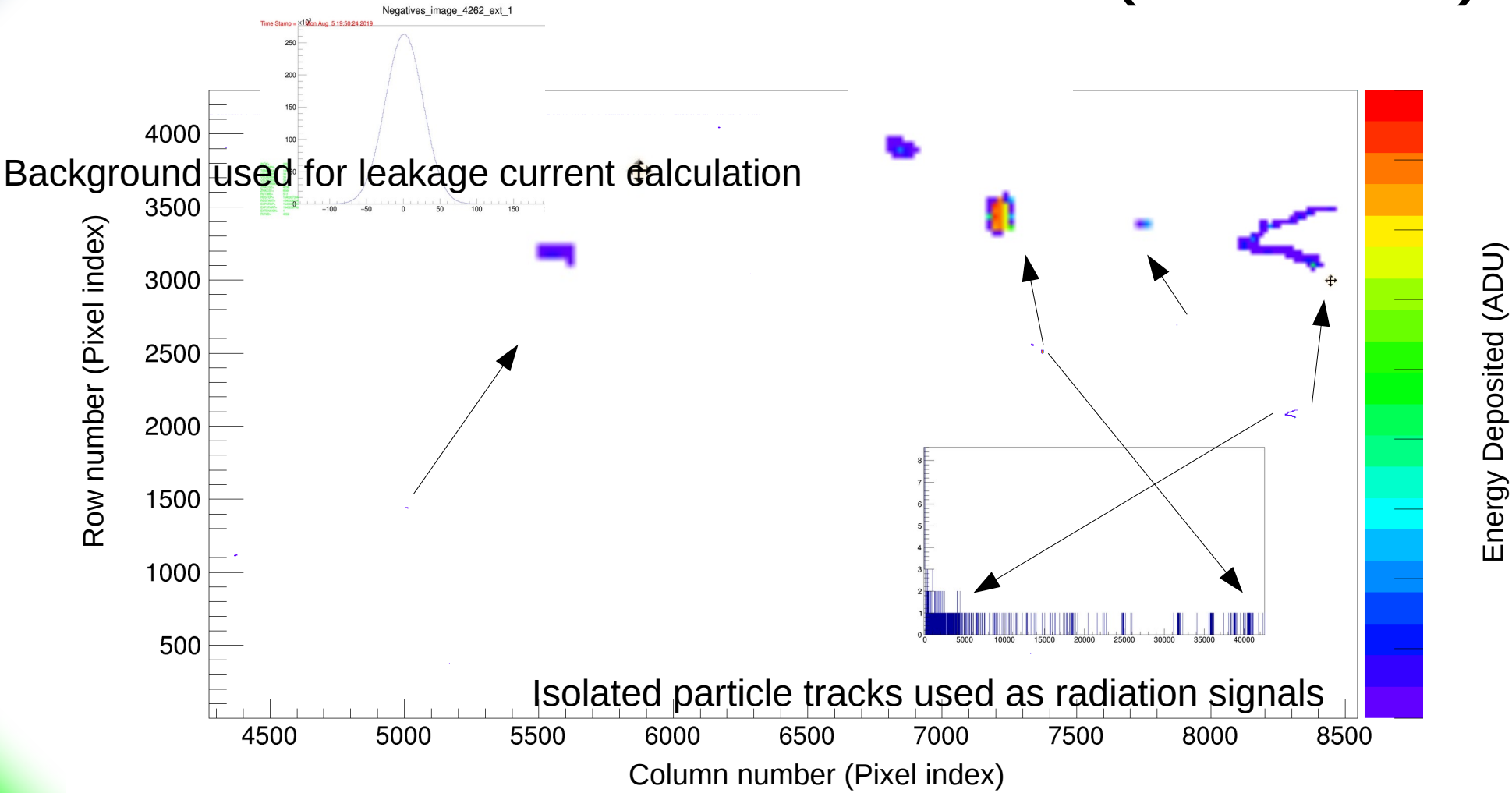
h) S.E. Holland et al “Physics of fully depleted CCDs”
2014 IOP Publishing Ltd. and Sissa Medialab srl, DOI:10.1088/1748-0221/9/03/X0357

i) A. Aguilar-Arevalo et al. "Measurement of radioactive contamination in the high-resistivity silicon CCDs of the DAMIC experiment" 9 Jul 2015, arXiv:1506.02562v2

Particle tracks in CCDs (Raw)



Particle tracks in CCDs (Isolated)



Defects And Matter In CCDs

Some members of the DAMIC-M and RD50 collaborations have been searching for displacement damage using DAMIC-SNOLAB CCDs.

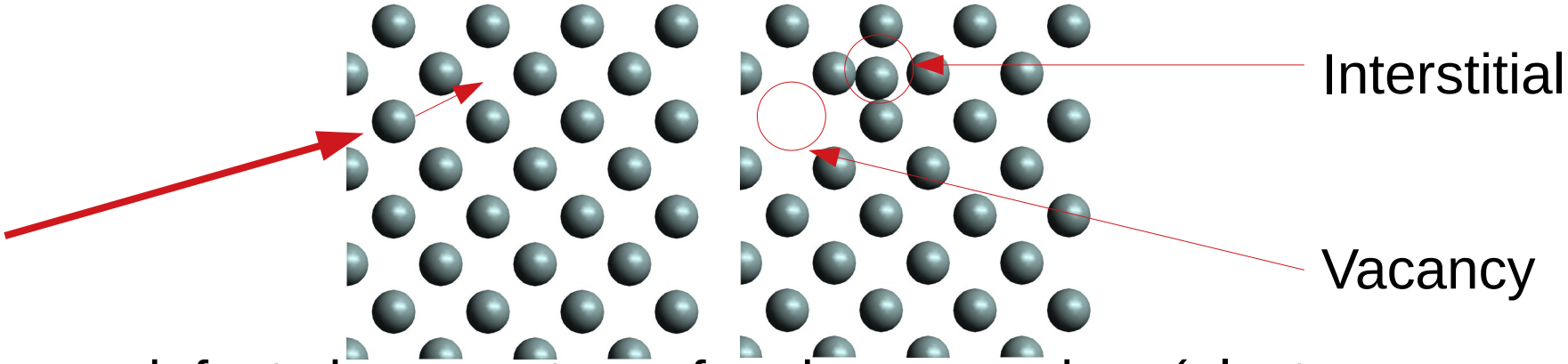
Taking advantage of the fact that DAMIC-SNOLAB has taken data in a very dark, low event count environment, observing and isolating single events are very easy.

Some of these events lead to stable defects which can be thermally stimulated. High temperature TSC and DLTS (above 100K) can be performed to study the characteristics of these stable defects.

In addition, it is worth noting that these are defects resulting from single events. We are hoping to model radiation damage resulting from down to one single event.

Displacement damage

Some of the single events are energetic enough to cause displacement damage. As some of the lattice atoms are moved from their position, they produce interstitial defects and leaving behind vacancy defects. These pairs are called a Frenkel pairs.

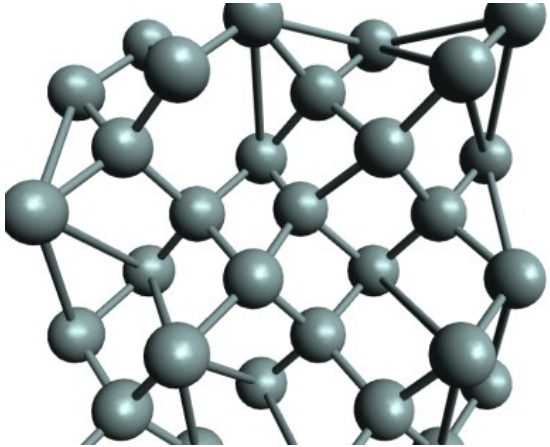


These defects become traps for charge carriers (electrons or holes), as they create new energy states in the forbidden zones of the local lattice bandgap.

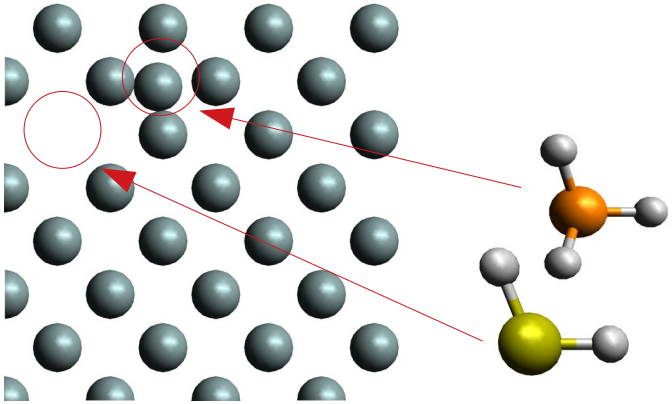
Figure generated using Avogadro 1.2.0

Secondary defects

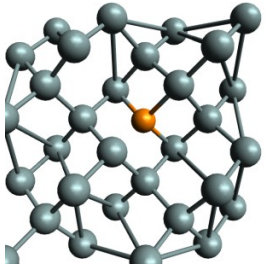
These Frenkel pairs are relatively mobile, and have high chances of mixing together to form stable lattice structures. However as the silicon bulks have large concentration of impurities such as oxygen and hydrogen. the vacancy defects can be filled with impurities and interstitial defects can form in to clusters of impurities forming a complex defect.



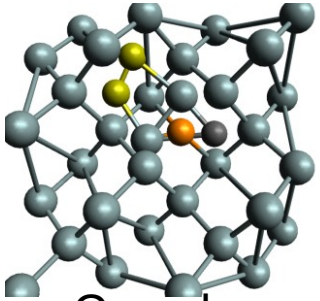
"Pure Si Tetrahedral bond lattice"



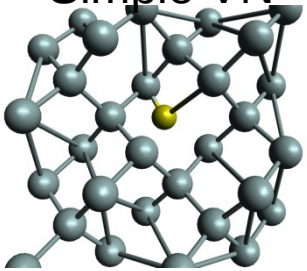
Frenkel pair in lattice (bonds hidden)



Simple VN



Complex IOOCVN



Simple VO

Figure generated using Avogadro 1.2.0

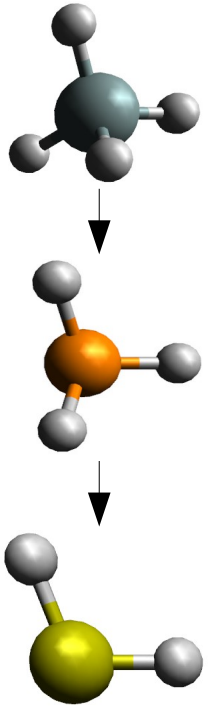
Radioactive lattice atoms

Within DAMIC-SNOLAB, we observed some events which are resulting from the decay chain of Si-32 to P-32 then to S-32.

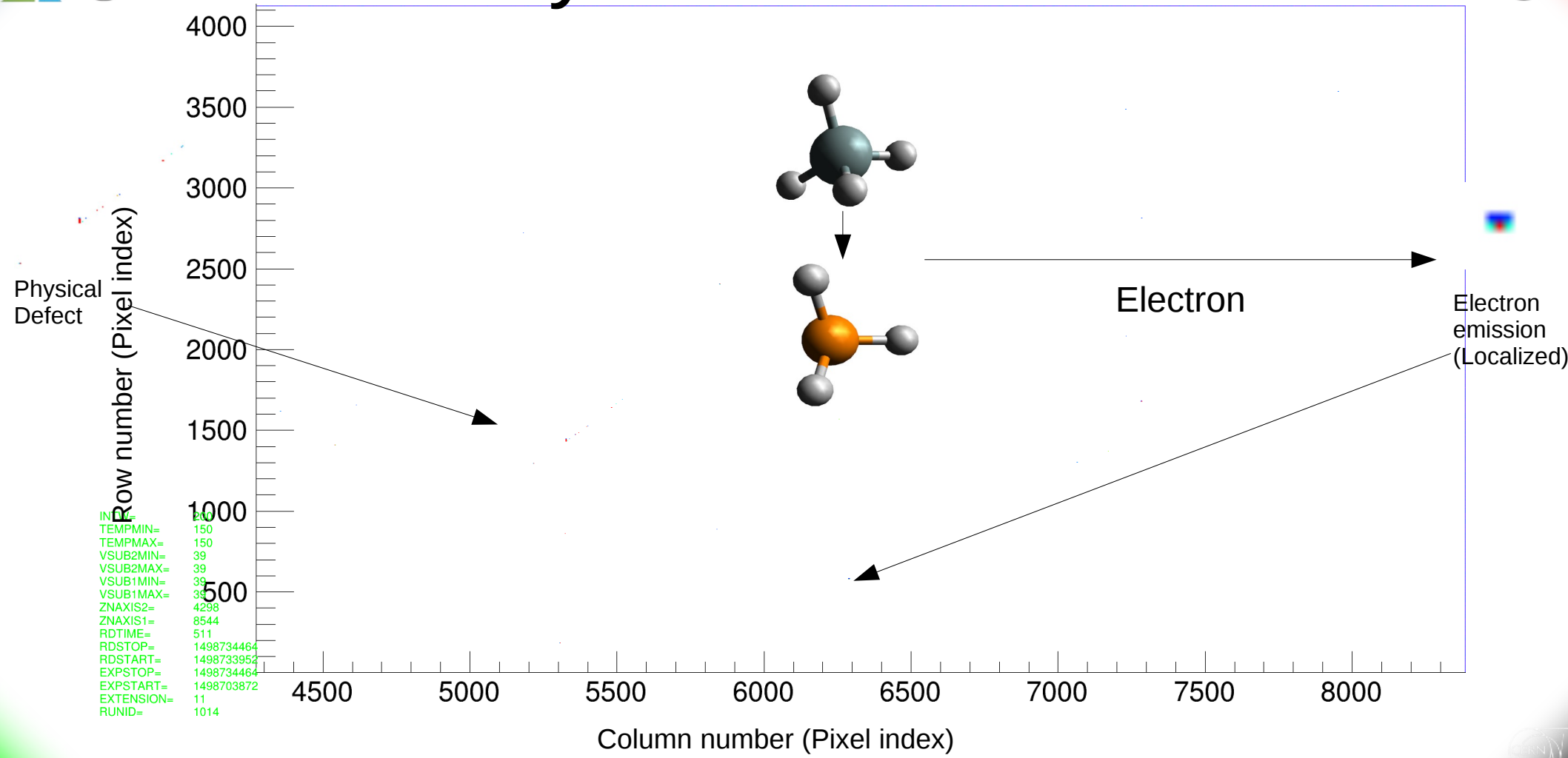
This is particularly interesting because silicon-32 has 4 valence electrons and decays into Phosphorous-32 (HL=153 years). Resulting decay ejects an electron at 69.55keV.

Phosphorous-32 decays into stable Sulfur-32 (HL=14.3 days). Resulting decay ejects an electron at 695.03keV.

We should note that displacement threshold for Sulfur and Phosphorous should be much lower than for Silicon (25eV).



Si-32 decay


Physical Defect
Electron
Electron emission (Localized)
Row number (Pixel index)
Column number (Pixel index)
4000
3500
3000
2500
2000
1500
1000
500
4500
5000
5500
6000
6500
7000
7500
8000
TEMPMIN= 150
TEMPMAX= 150
VSUB2MIN= 39
VSUB2MAX= 39
VSUB1MIN= 39
VSUB1MAX= 39
ZNAXIS2= 4298
ZNAXIS1= 8544
RDTIME= 511
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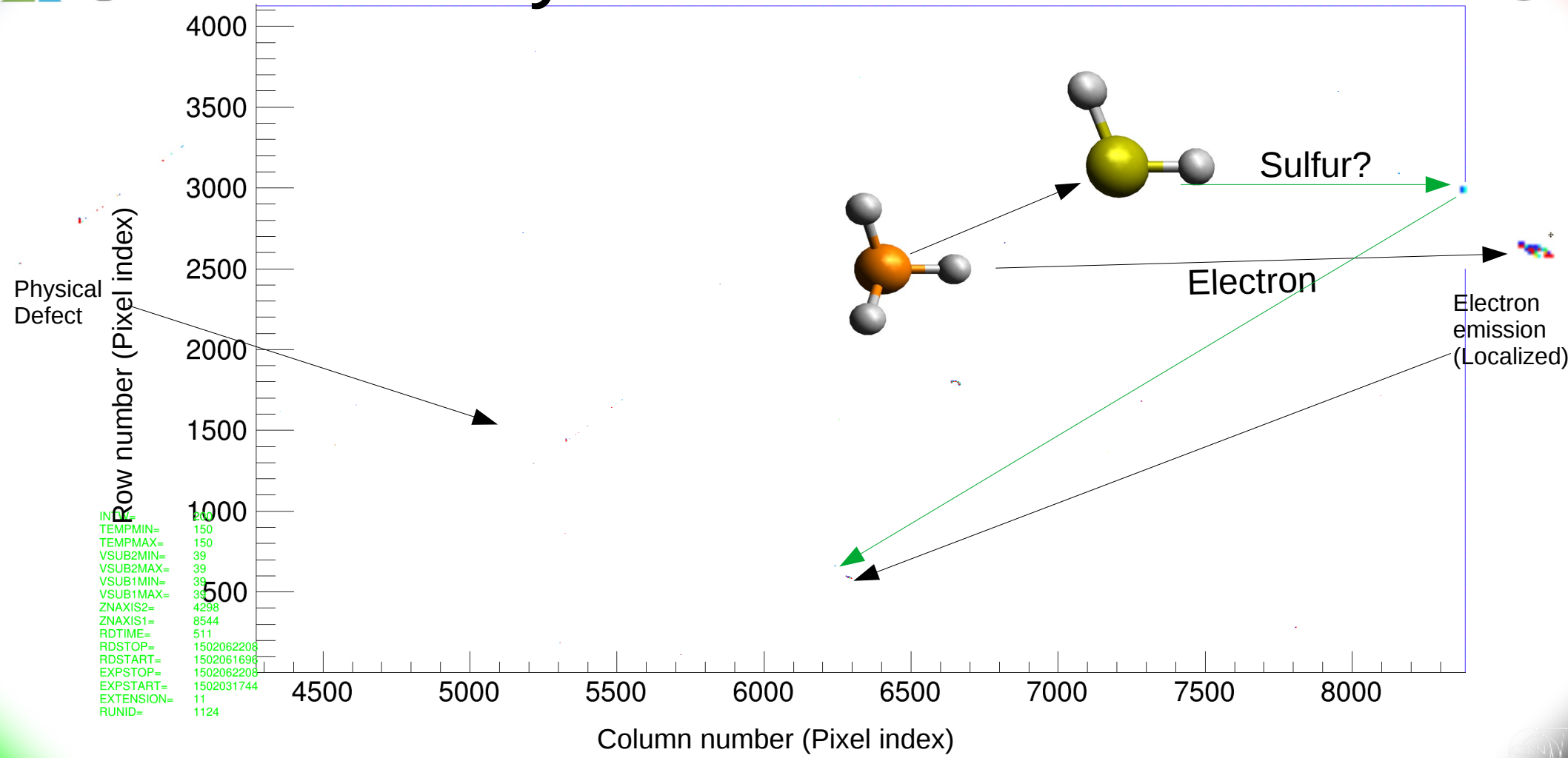
EXPSTART= 1498703872
EXTENSION= 11
RUNID= 1014

P-32 decay


Sulfur?
Electron
Physical Defect
Electron emission (Localized)
Row number (Pixel index)
Column number (Pixel index)
4000
3500
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6000
6500
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TEMPMAX= 150
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VSUB2MAX= 39
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VSUB1MAX= 39
ZNAXIS2= 4298
ZNAXIS1= 8544
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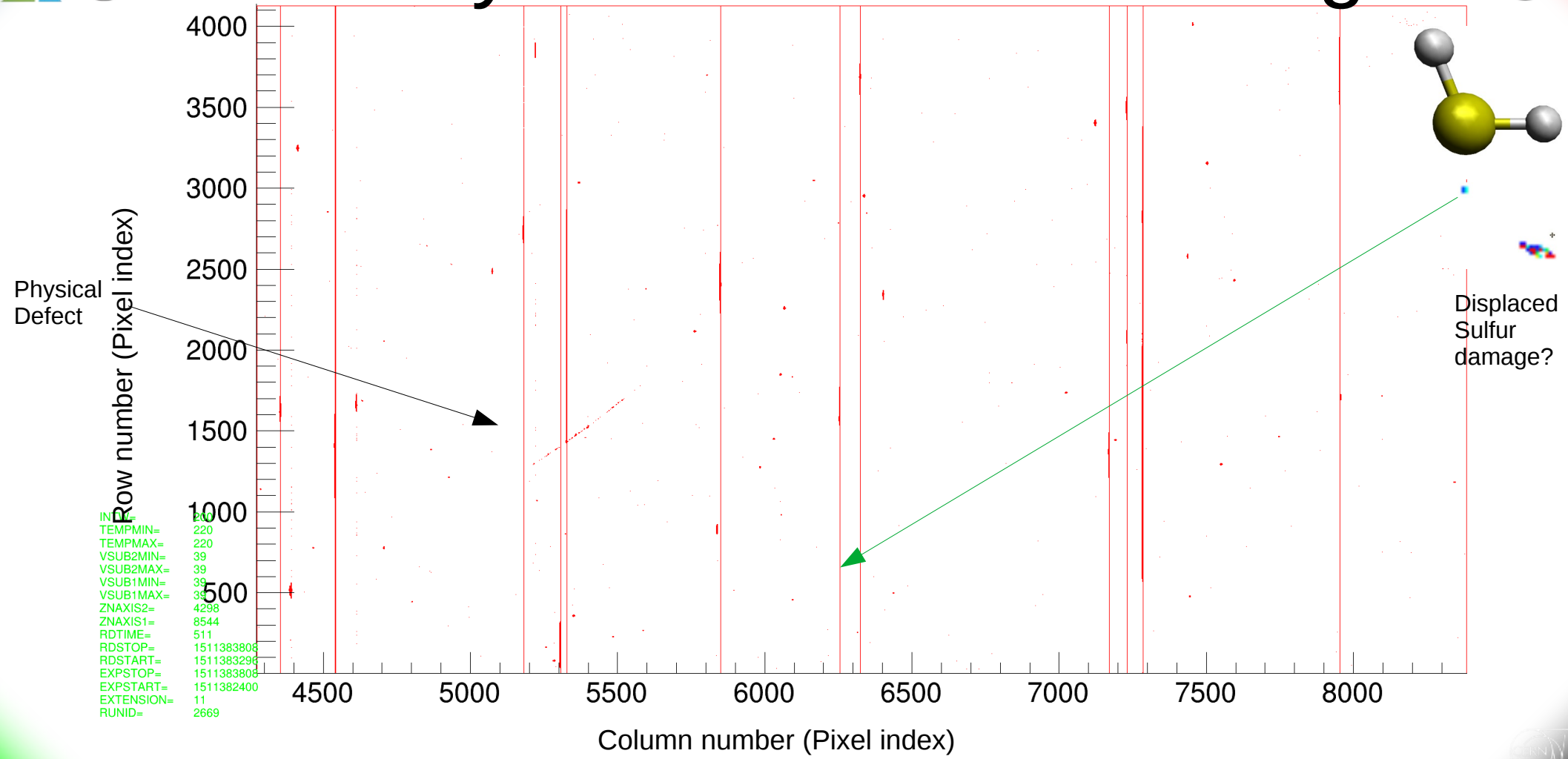
Thermally stimulated VS damage



Radioactive lattice atoms

As P-32 loses an electron at 695keV (more than 25 eV required to displace a silicon atom), the Sulfur can be displaced as the loss of electron will recoil the nucleon.

Even if no displacement damage occurs, as Si-32 is replaced by S-32, the resulting effect is identical to VS (similar to VO). Properties of VS will be characterized.

We hope to study the non ionizing energy loss of the electrons and the parent/daughter nucleons by thermally stimulating the sensor.

Si-32 to S-32 decay chain is one of the many radioactive contaminants observed with DAMIC-SNOLAB. Other events are also being studied.

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

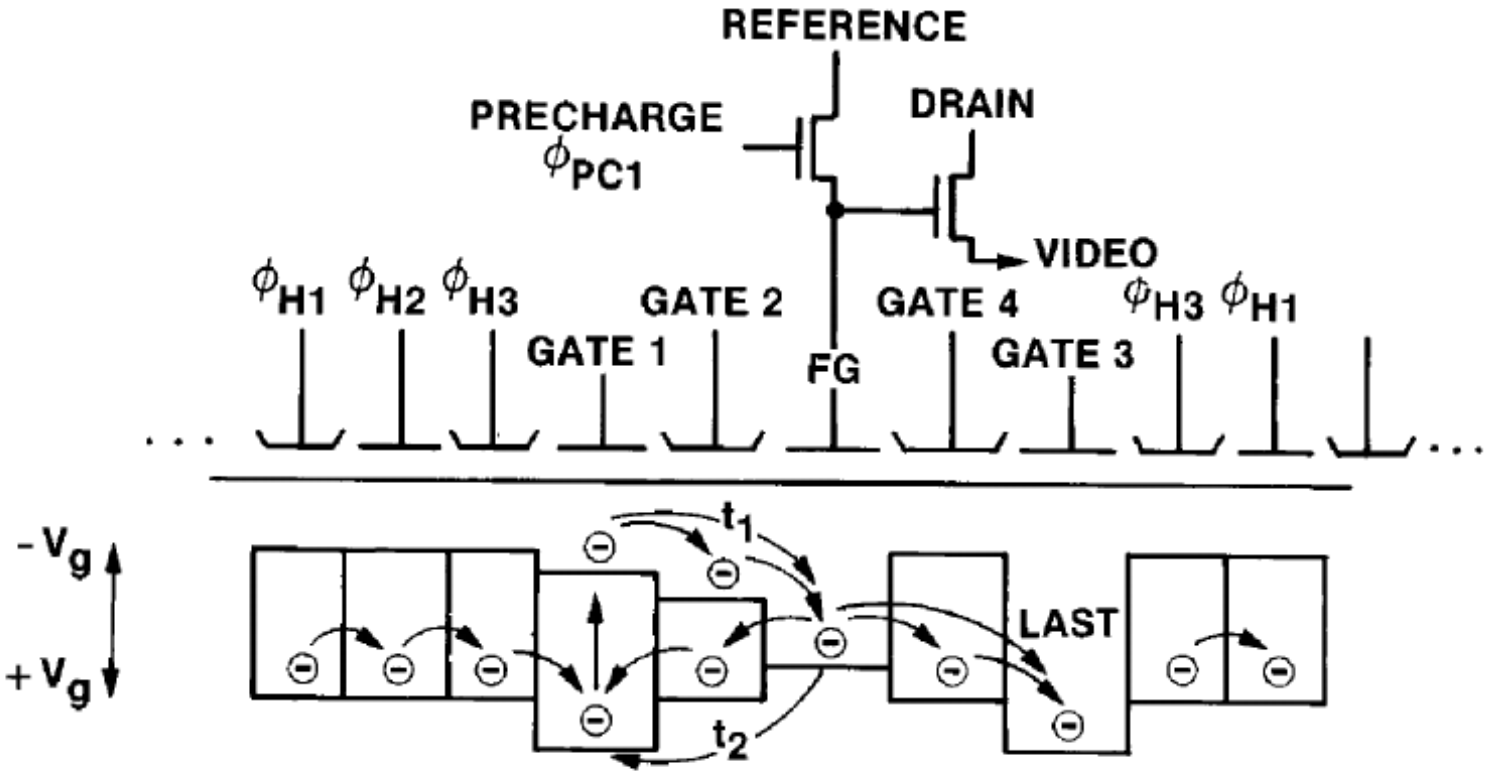


Figure from e)

CCD operation

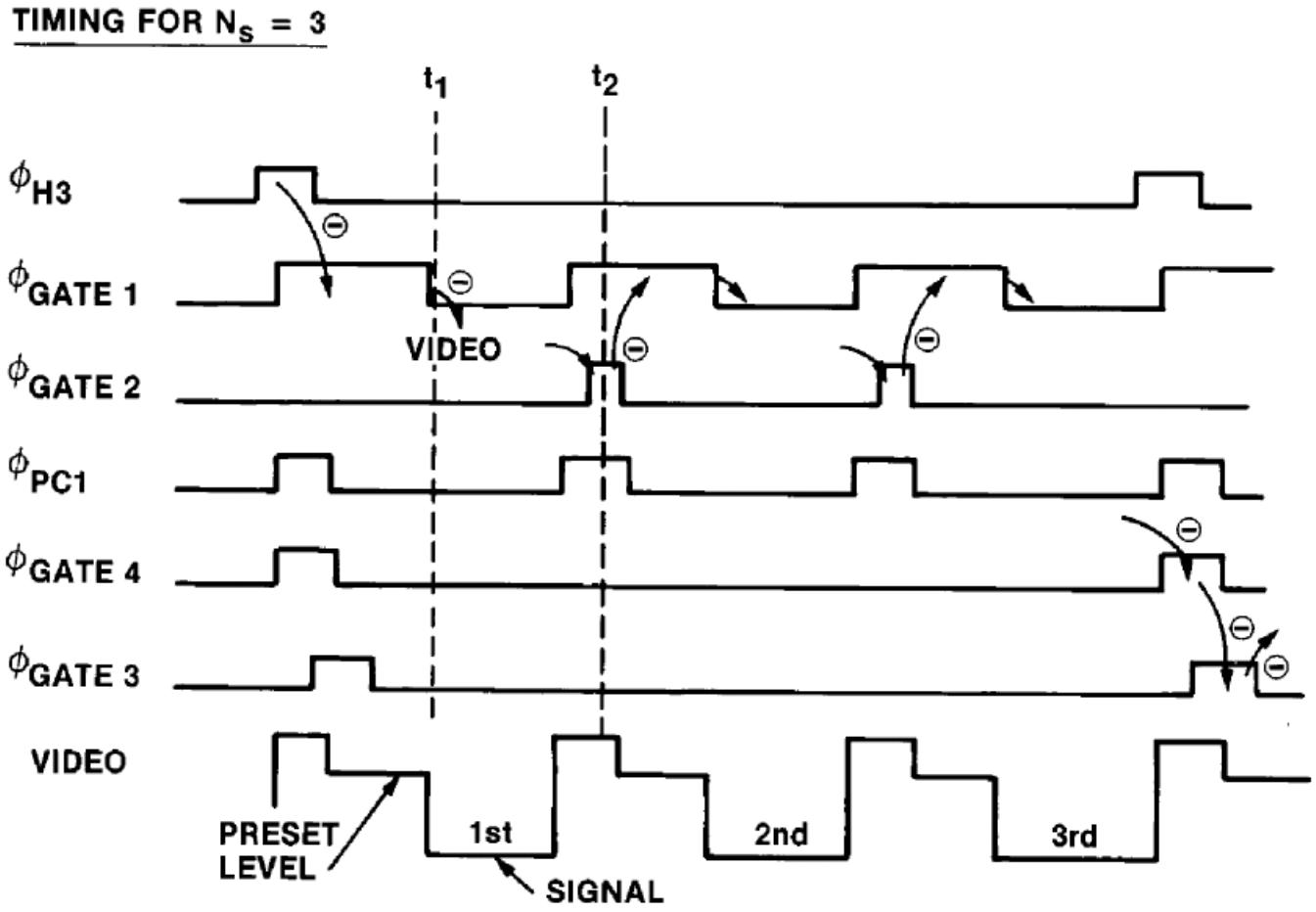
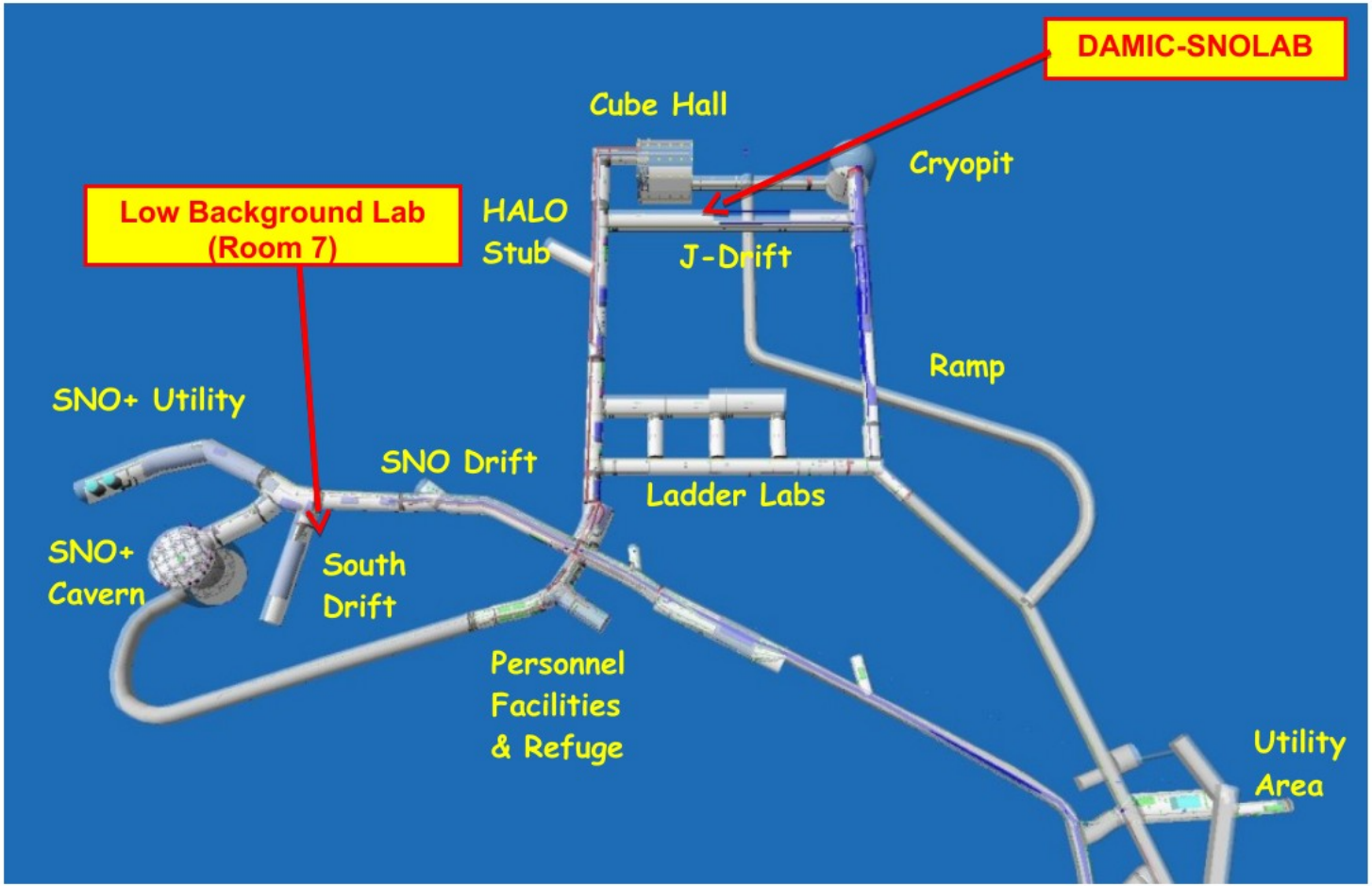


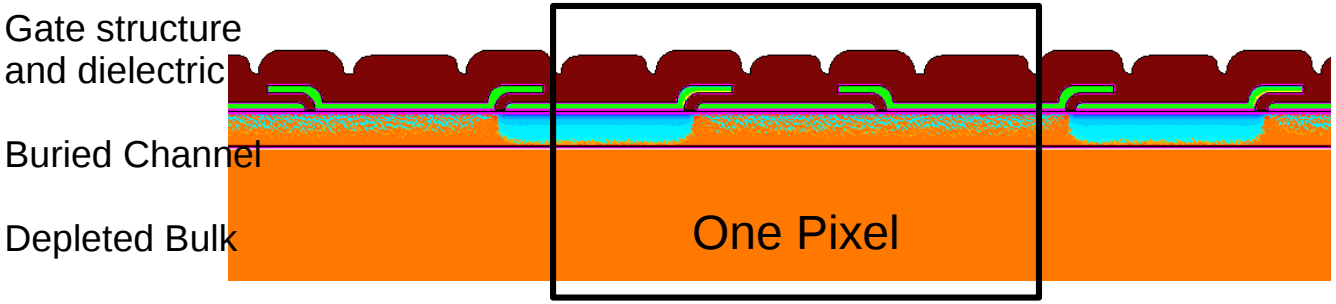
Figure from e)

DAMIC in SNOLAB

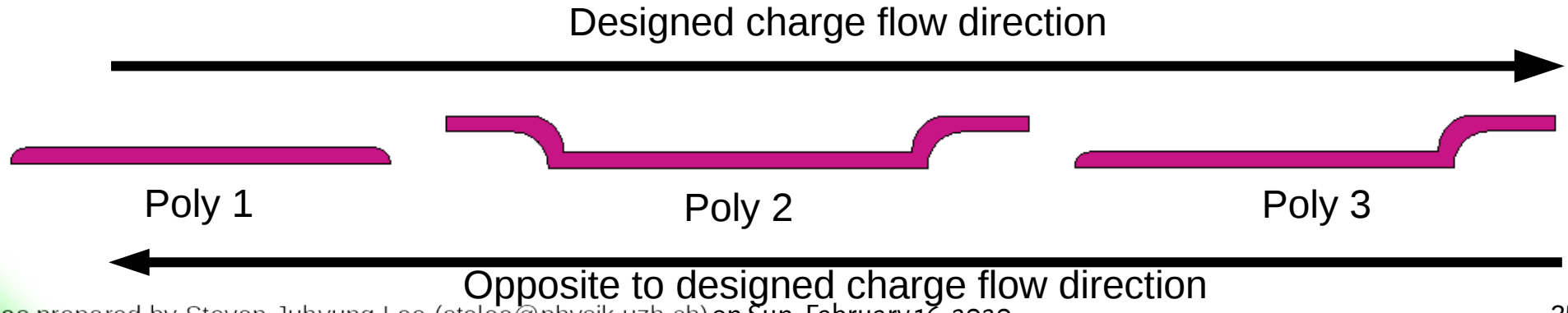


CCD Gate structures.

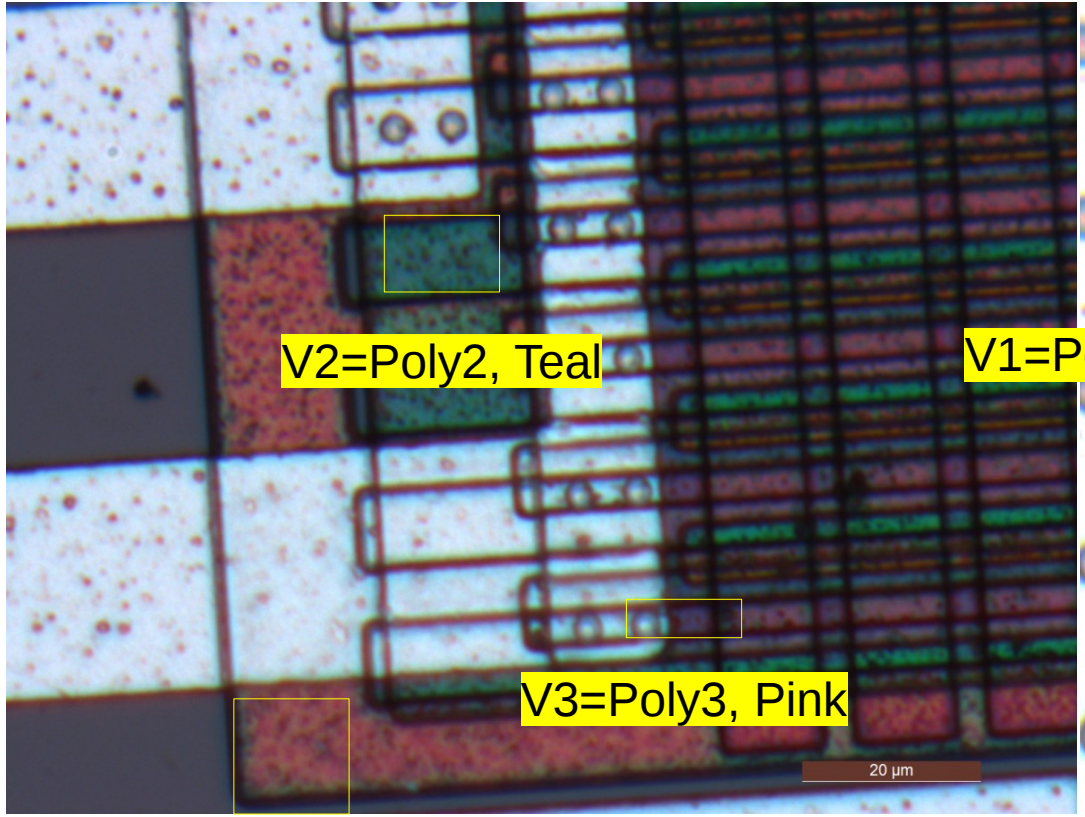
A typical presentation of LBNL CCD shows only the top symmetrical surface structure.



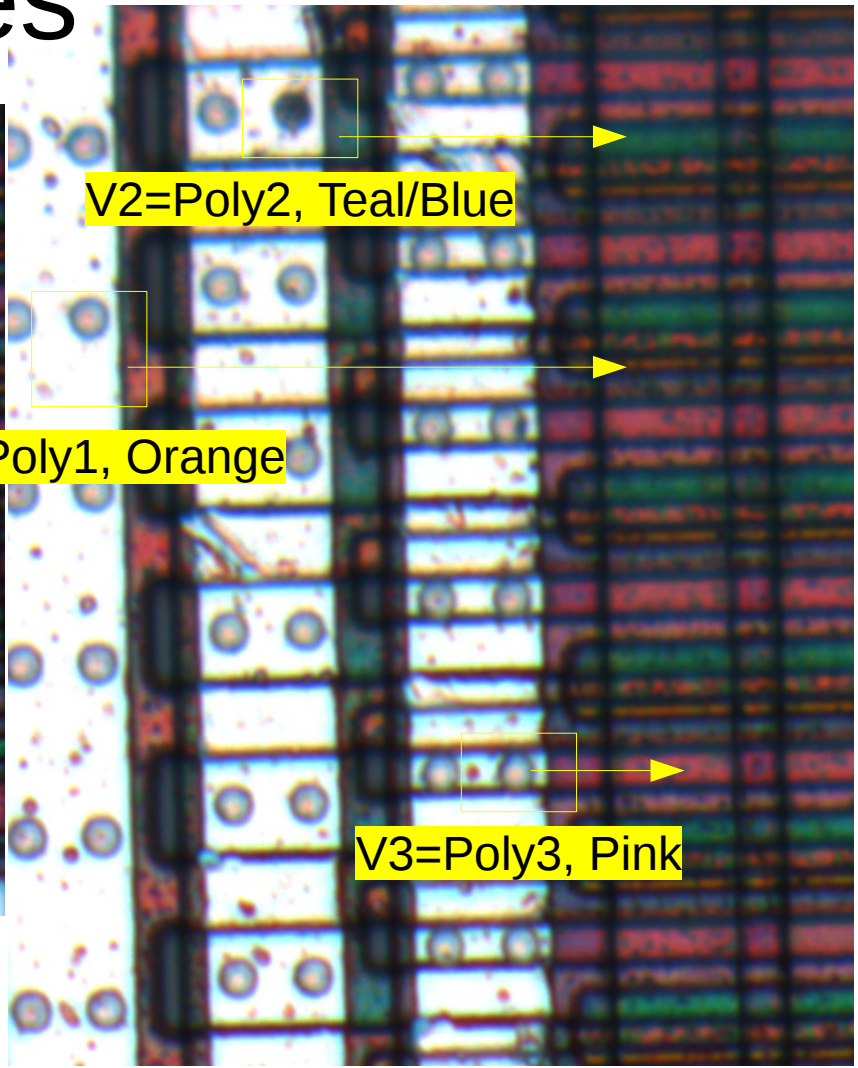
However we have to keep in mind that there are 3 gate structures which do not form a symmetric structure.



Vertical clock gates



V1=Poly1, Orange



Horizontal clock gates