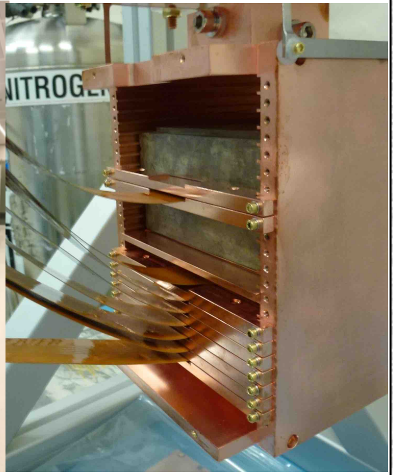
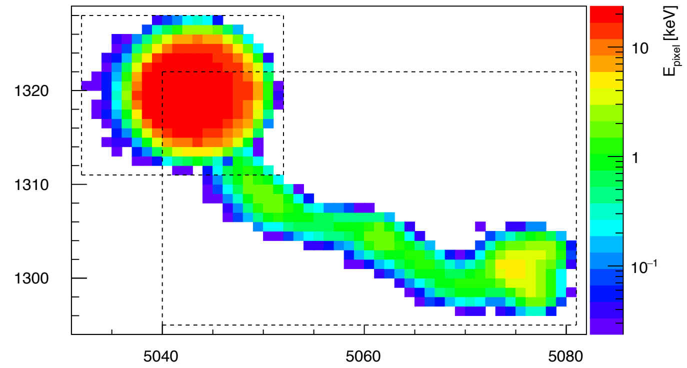
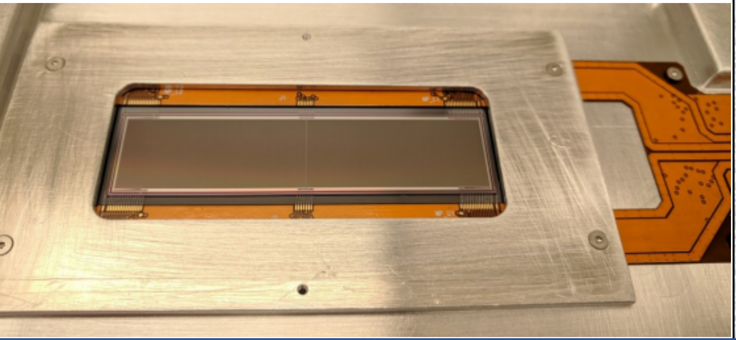




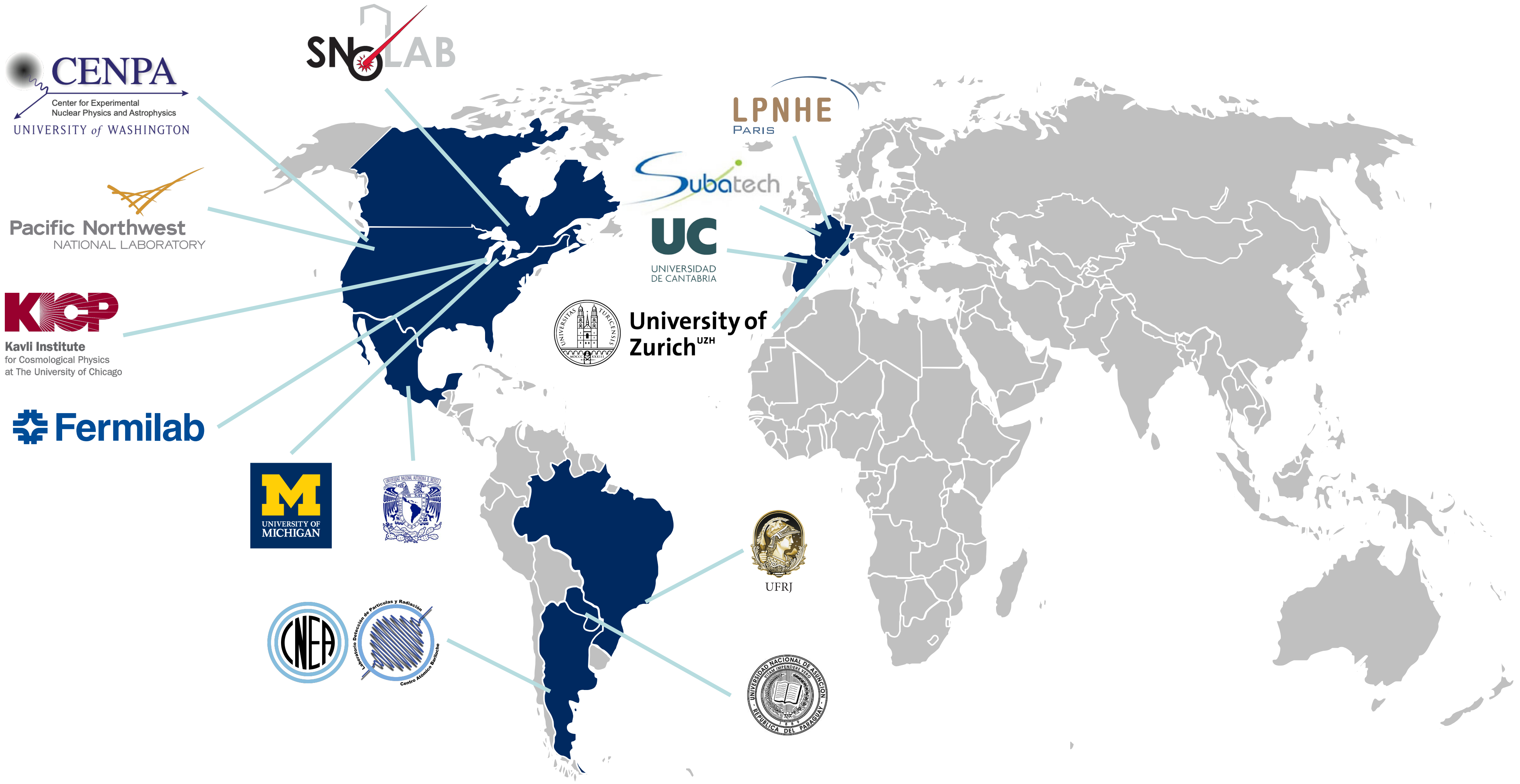


The Search for Light Dark Matter with DAMIC

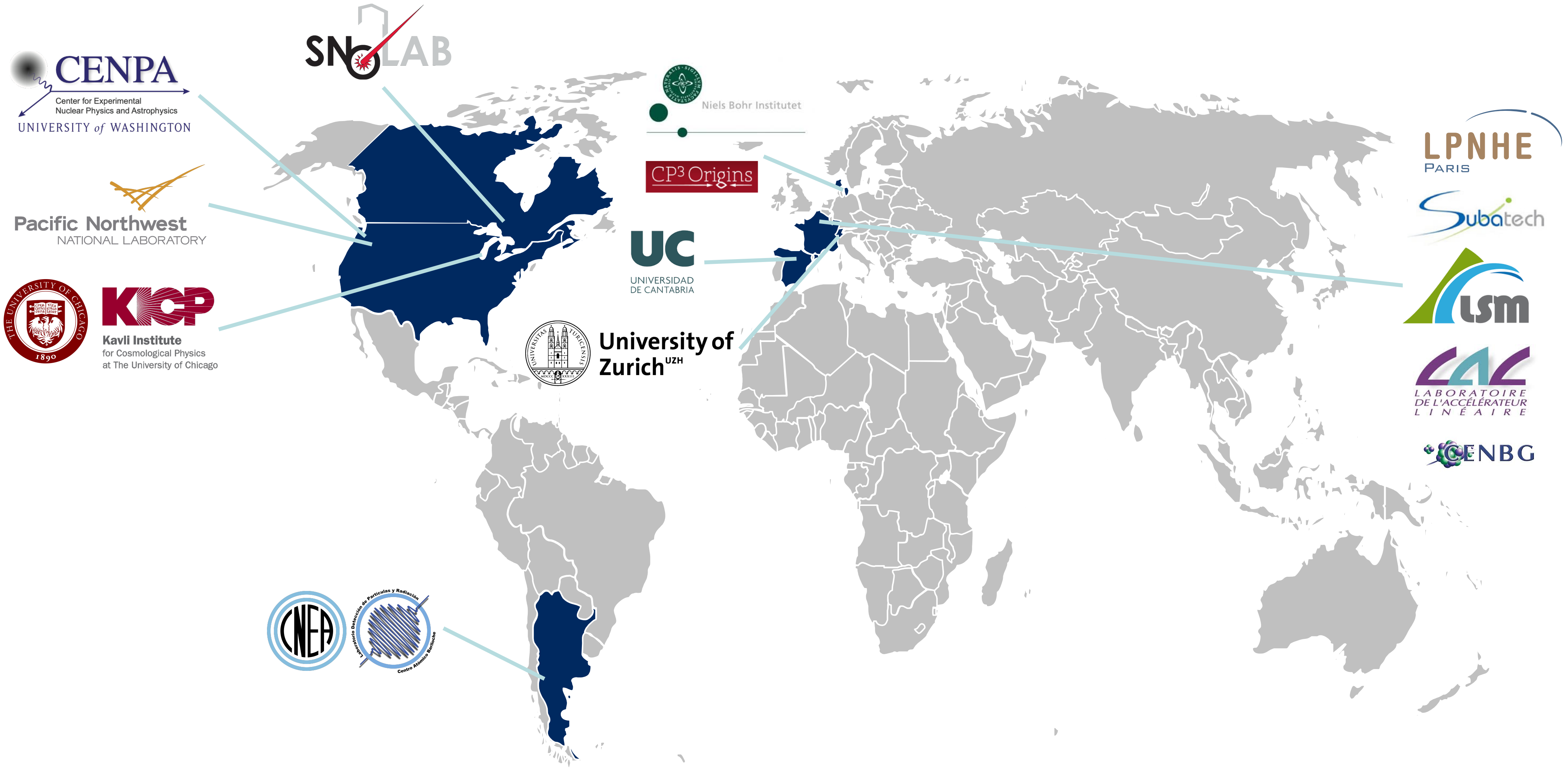
Detector Development and Analysis Efforts for Next-Generation Dark Matter Programs

Ariel Matalon
amatalon@lpnhe.in2p3.fr
KICP, University of Chicago | LPNHE, Sorbonne Université
Advisors: Paolo Privitera, Antoine Letessier Selvon

DAMIC Collaboration



DAMIC-M Collaboration



“Kouign-amann: the fattiest pastry in all of Europe” - NYT

“DAMIC-M: the best DM program in all of Europe” - NYT

"If you want to keep people's attention you can present anything… you can discuss football" – Romain Gaior

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The true nature of Dark Matter is yet to be determined: Weakly-Interacting Massive Particles are well-motivated candidates

Astrophysical & cosmological evidence:

- Missing matter inferred from galaxy clusters
- Galactic rotation curve discrepancies
- CMB power spectrum peaks

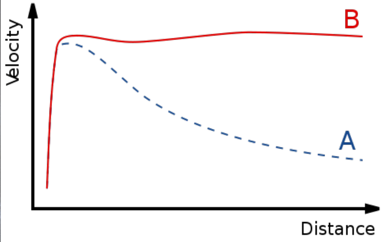
An attractive paradigm for BSM physics:

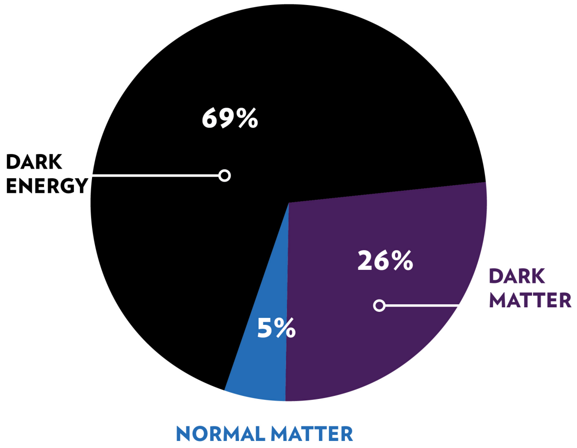
- WIMPs created in the early universe (until T < m_χ)
- Expansion limited self-annihilation → "freeze-out"
- Predicted mass O(100 GeV), above accelerators!

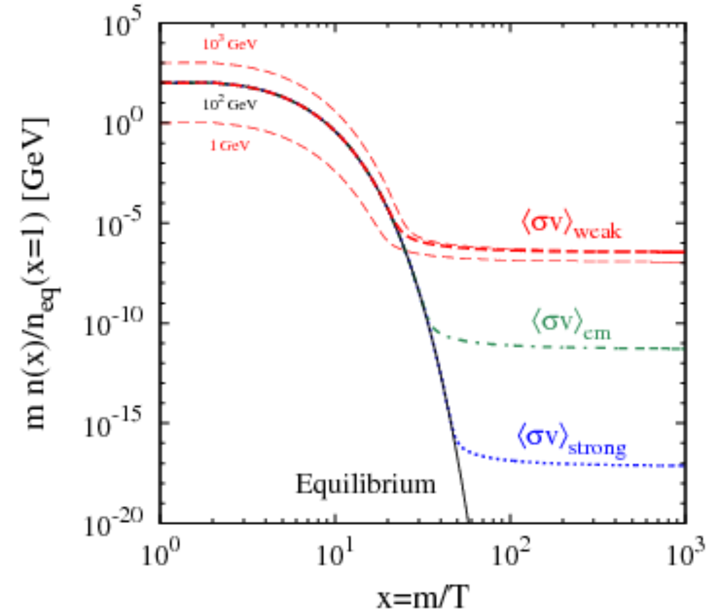
$$K + U = E$$

$$K + U = \frac{1}{2}U$$

$$2K + U = 0$$



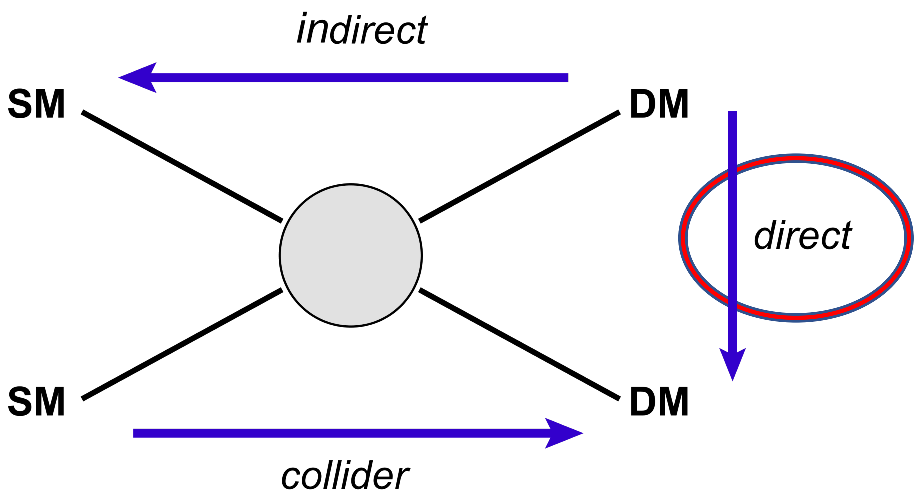




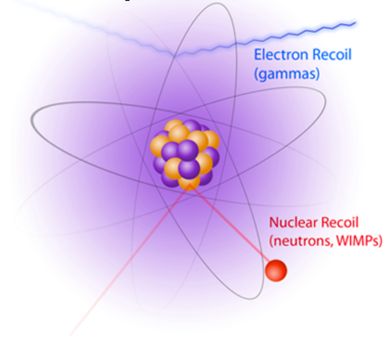
Dark Matter → Cosmic Structure

WIMP Abundance

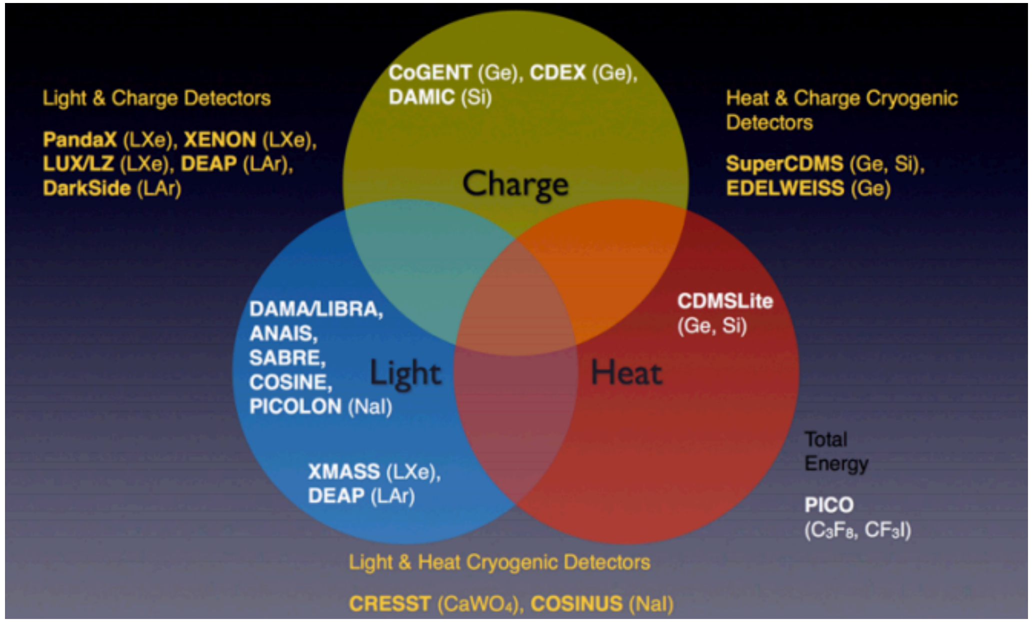
Experiments pursue direct detection, indirect detection, and production at colliders; null-results have led to broader searches



Principle of Detection



Recoils at keV-scale, need sub-keV thresholds!



Exploring the low-mass dark matter regime

- Sensitive limits already placed on WIMPs O(100 Gev)
- No supersymmetry observed at the LHC
- Motivation to probe low-mass, and dark sector candidates

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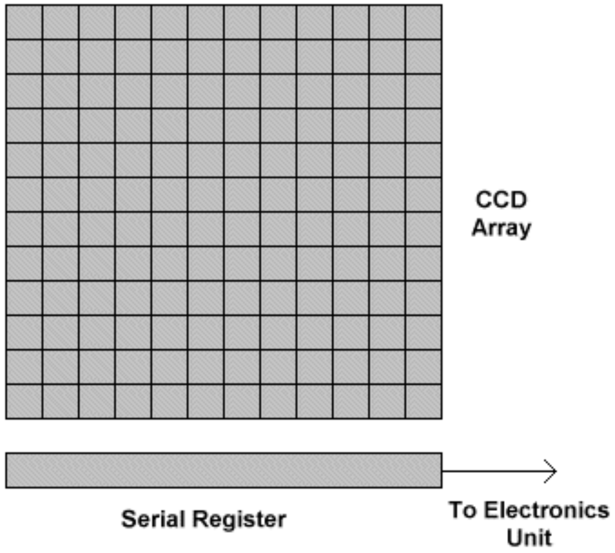
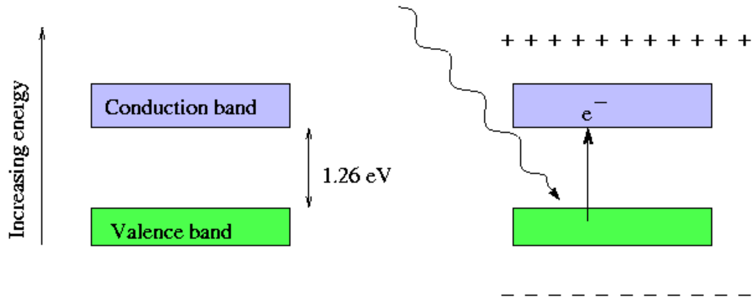
The unique characteristics and principle of operation of modern charge-coupled devices (CCDs) enable particle detection

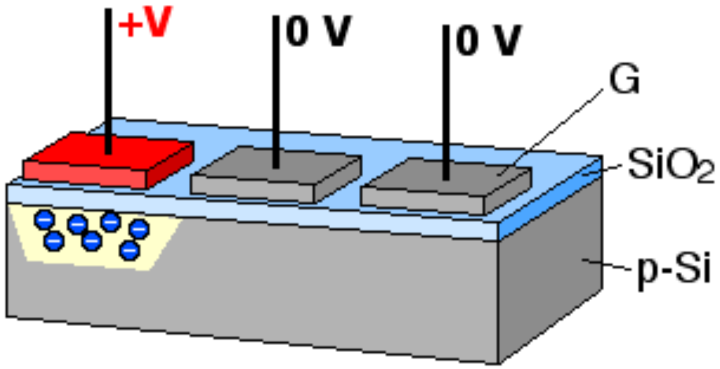
CCD Operation

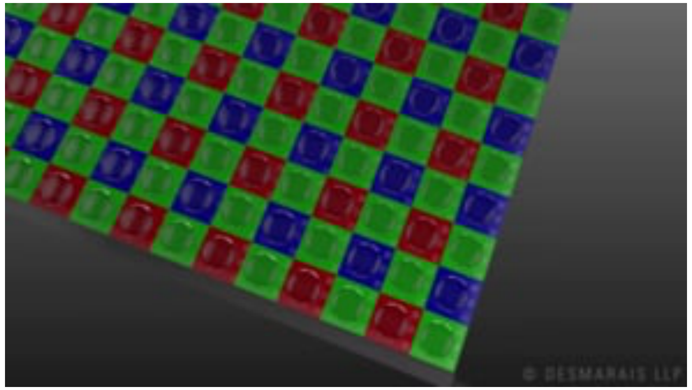




CCD Clocking

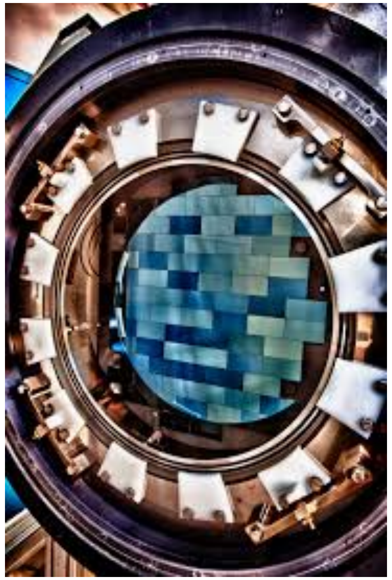
➢ Modulation of gate electrodes in order to transfer charge





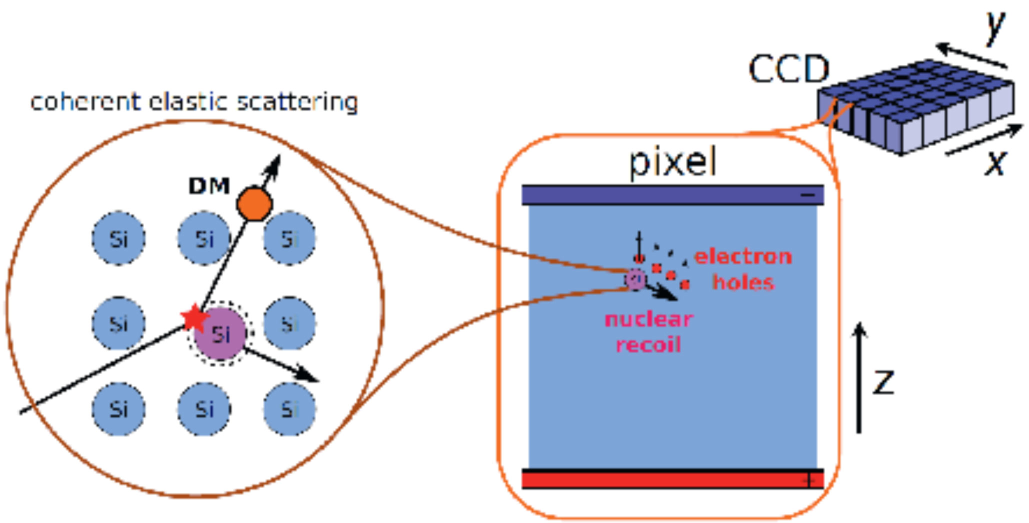
CCD Technology

➢ Correlated double sampling to improve readout process
➢ Developments in CCD design for IR cameras have enabled massive detectors

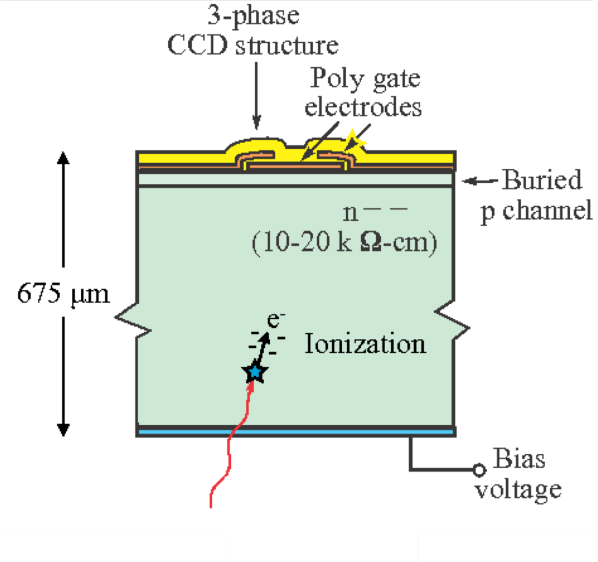


DAMIC at SNOLAB employs the bulk-silicon of scientific-grade CCDs to detect DM-nucleus/electron coherent elastic scattering

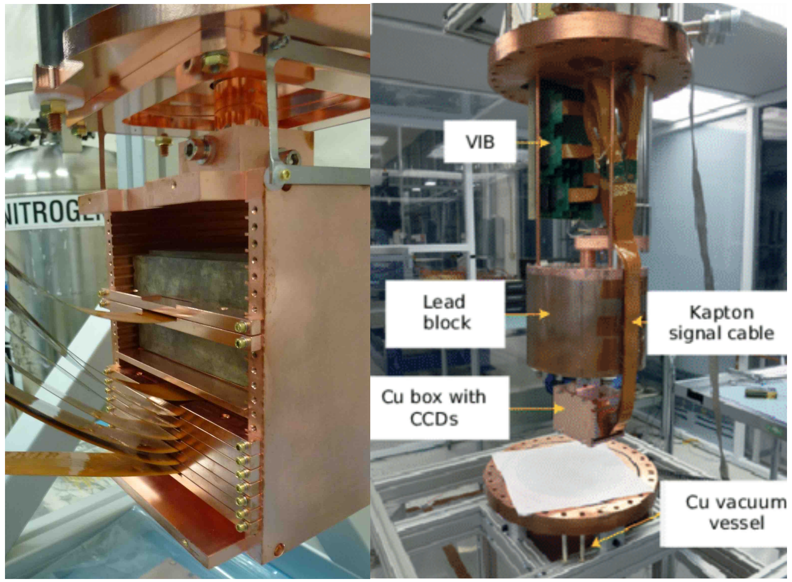
WIMP Detection Principle in a CCD



CCD Pixel



Setup at SNOLAB



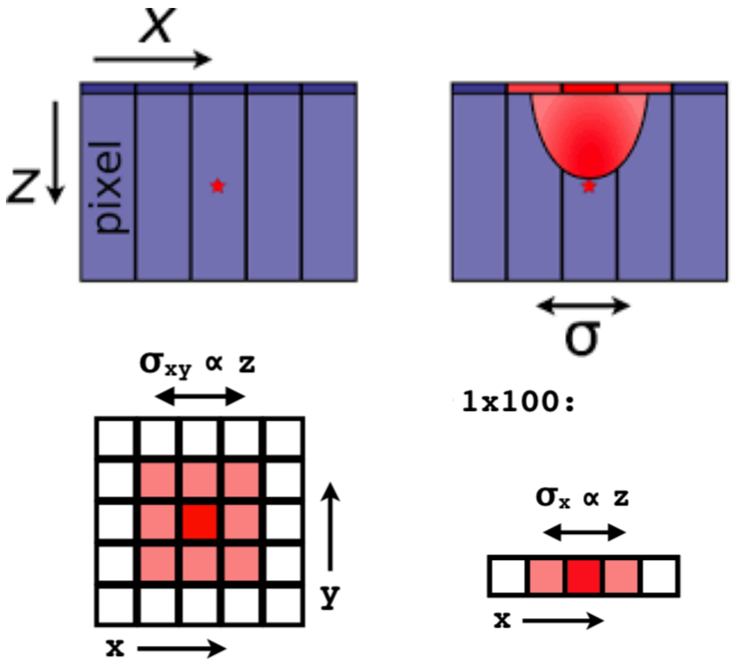
- e^--h pairs produced by WIMP NR
- Charge drifted to CCD pixel gate

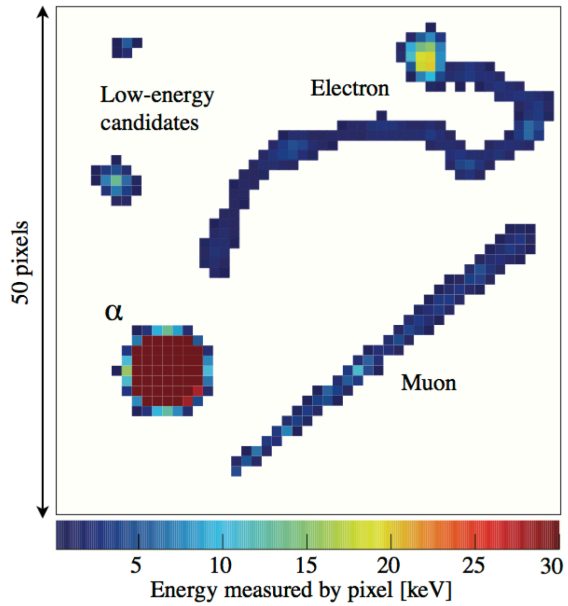
- High-resistivity, pure n-type Si
- 675-µm thick, 3-phase gate

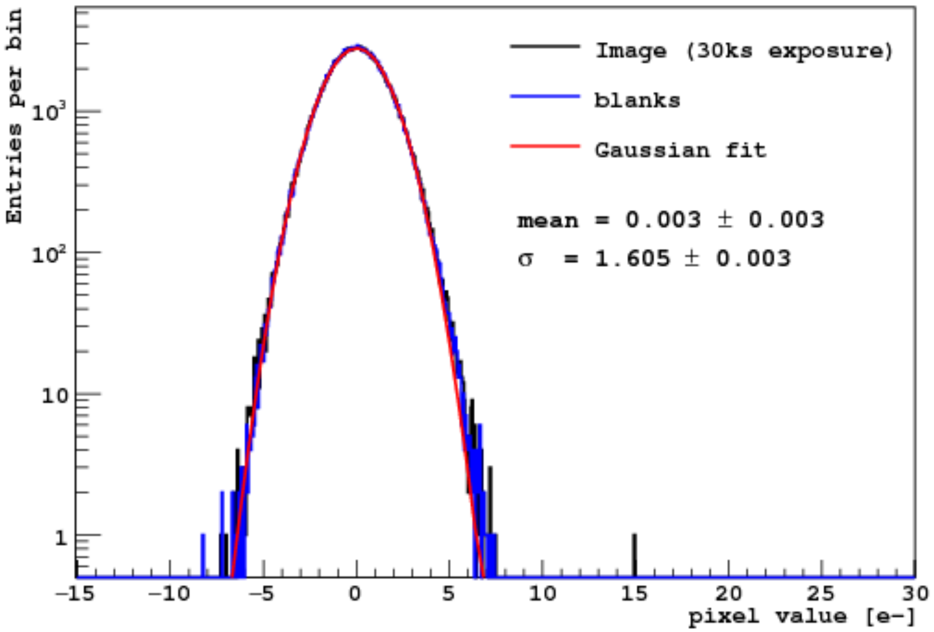
- 2 km rock; Pb & polyethelene shields
- OHFC Cu modules (1 electroformed)

➡ Seven DAMIC-100 4k x 4k CCDs ("extensions") have been acquiring data since commissioning in 2017

DAMIC CCDs exhibit properties that enable unique particle ID, excellent charge resolution, and 3D event reconstruction







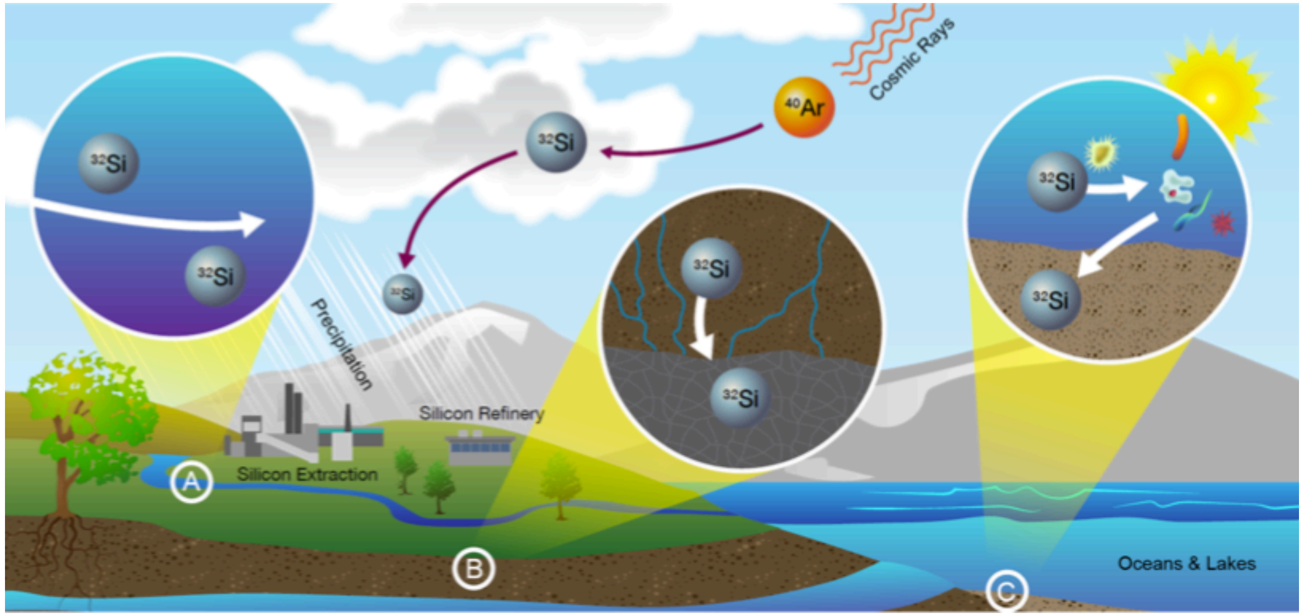
- 1x1 readout for spatial
- 1x100 readout for noise
- Depth from diffusion

- Electrons: worms
- Muons: straight tracks
- Alphas: MeV-level-charge

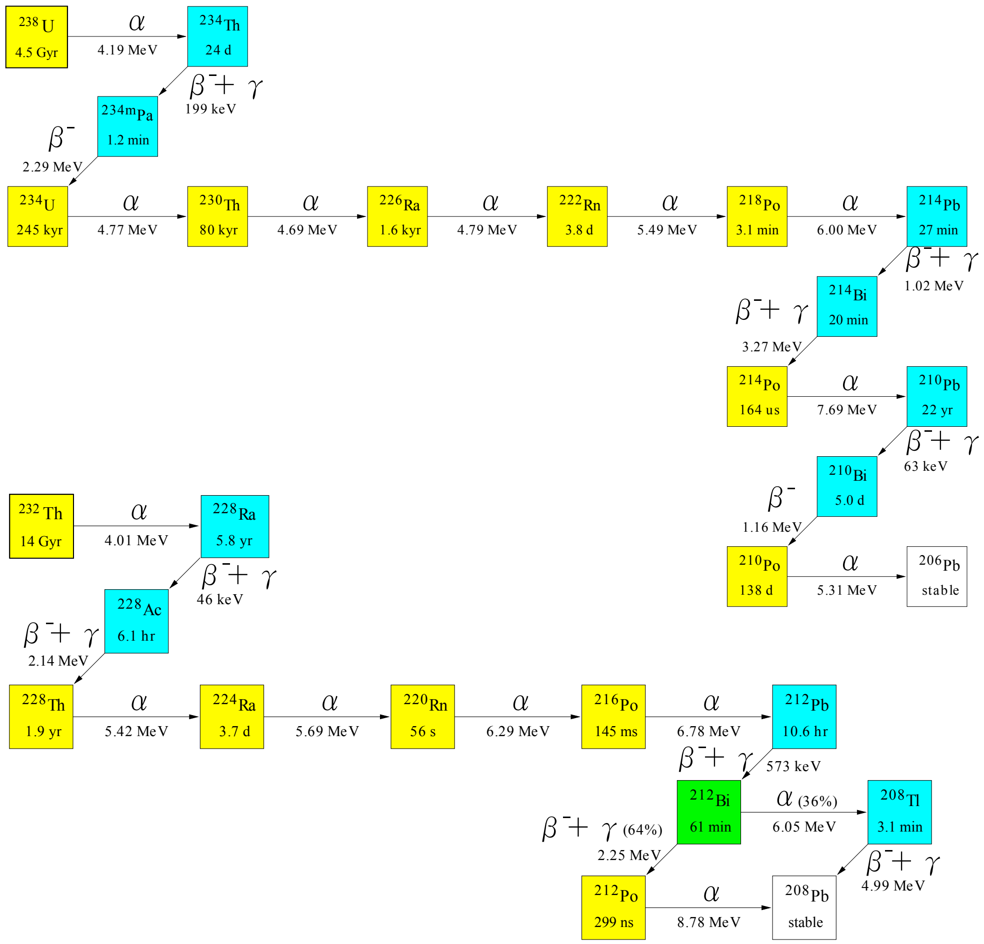
- Pixel charge r.m.s. < 2e$^-$!
- Incredibly low energy threshold
- 3.77 eV average for e$^-$-h pair

The sensitivity of direct-detection experiments is determined by the ability to identify & mitigate radioactive backgrounds

Cosmogenic isotopes



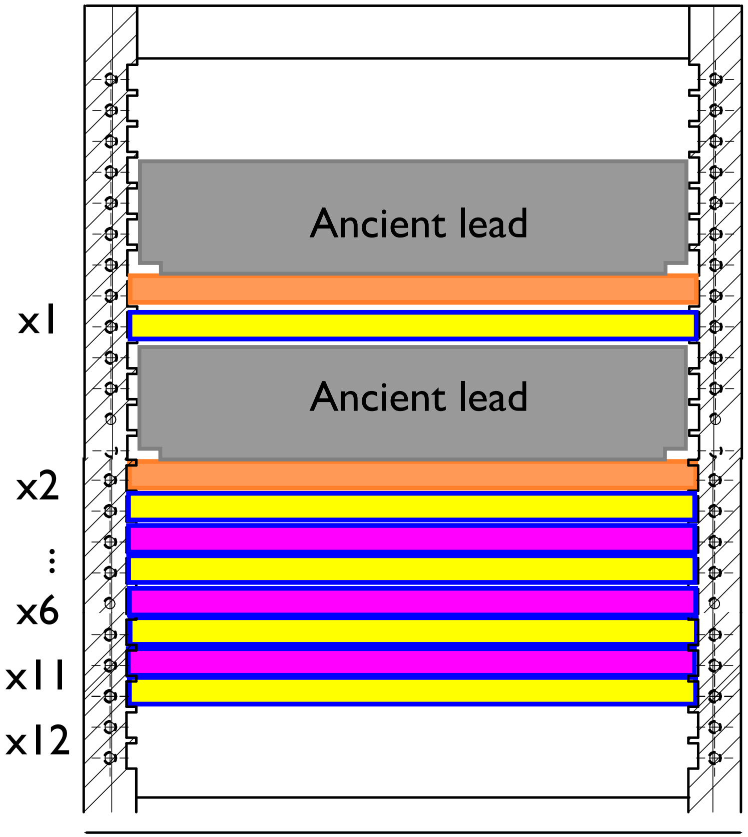
Natural Radioactivity

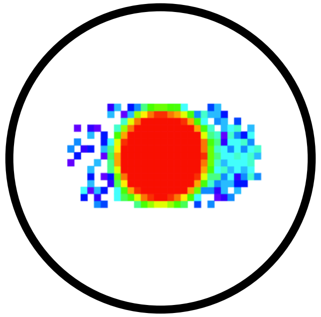


Of particular concern…

- ^{32}**Si**, produced by cosmic ray spallation → **bulk contamination**
- ^{210}**Pb**, a daughter of radon decay → **surface contamination**

DAMIC at SNOLAB acquired background-focused data in order to measure radioactive contamination in CCDs

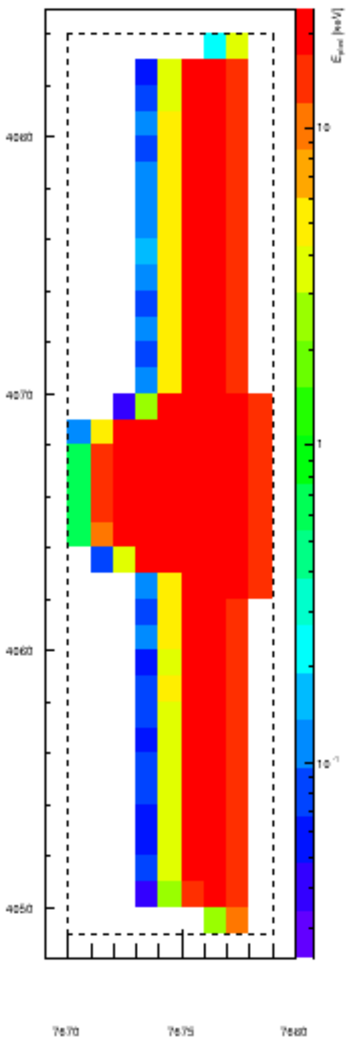




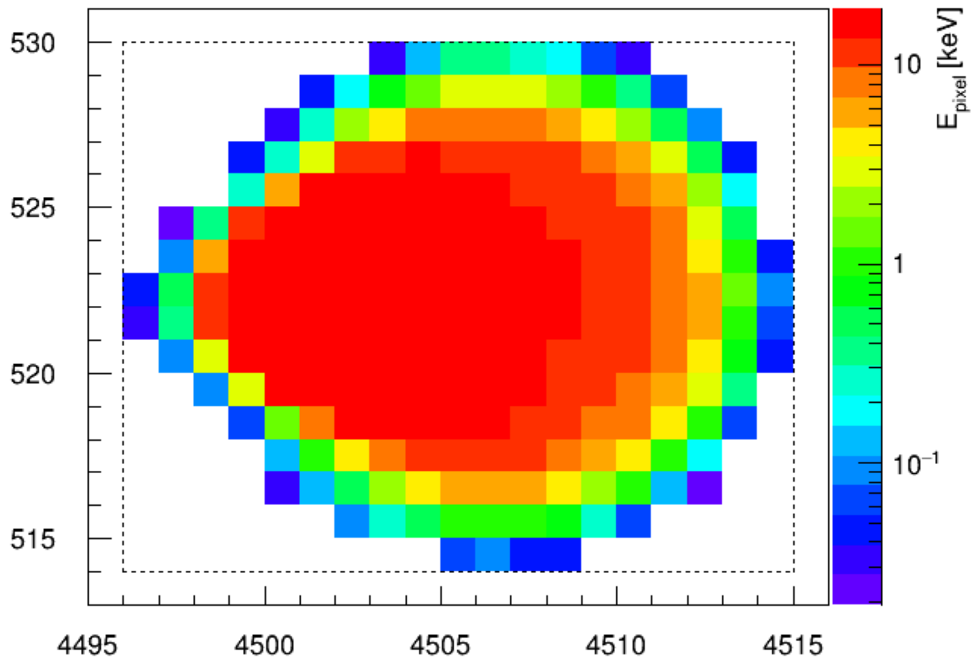
- 200.4 days from 6 active CCDs (35.4 g)
- Images taken in 1x1 readout mode
- LED energy calibration performed at SNOLAB

Cluster properties match characteristics of α and β particles

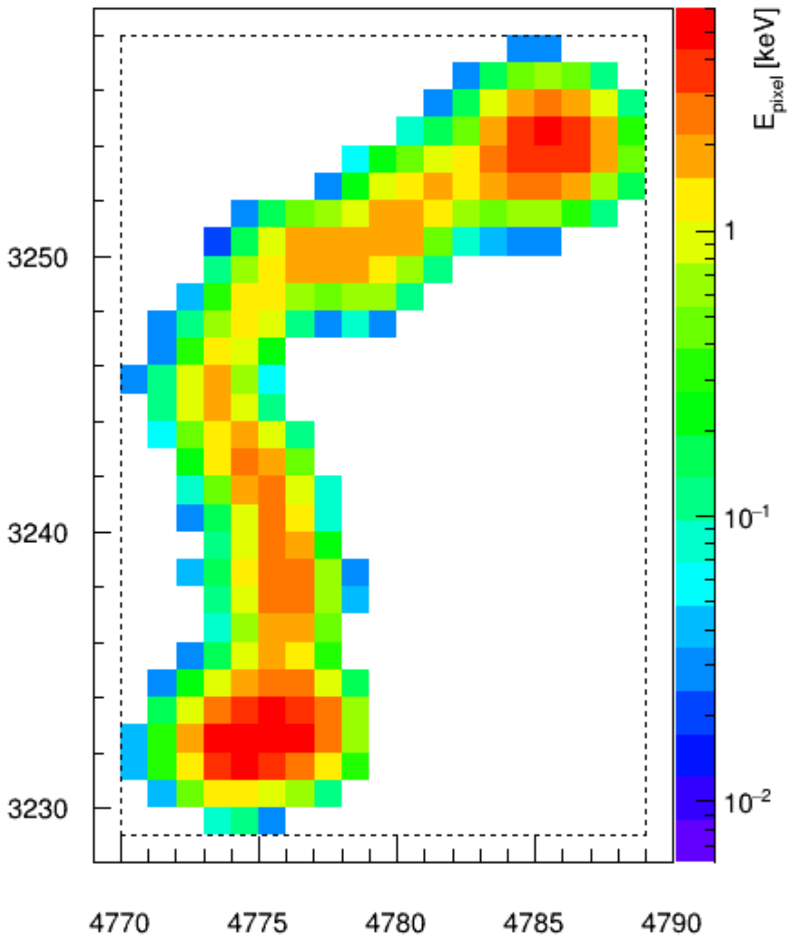
Bloomed α



Plasma α

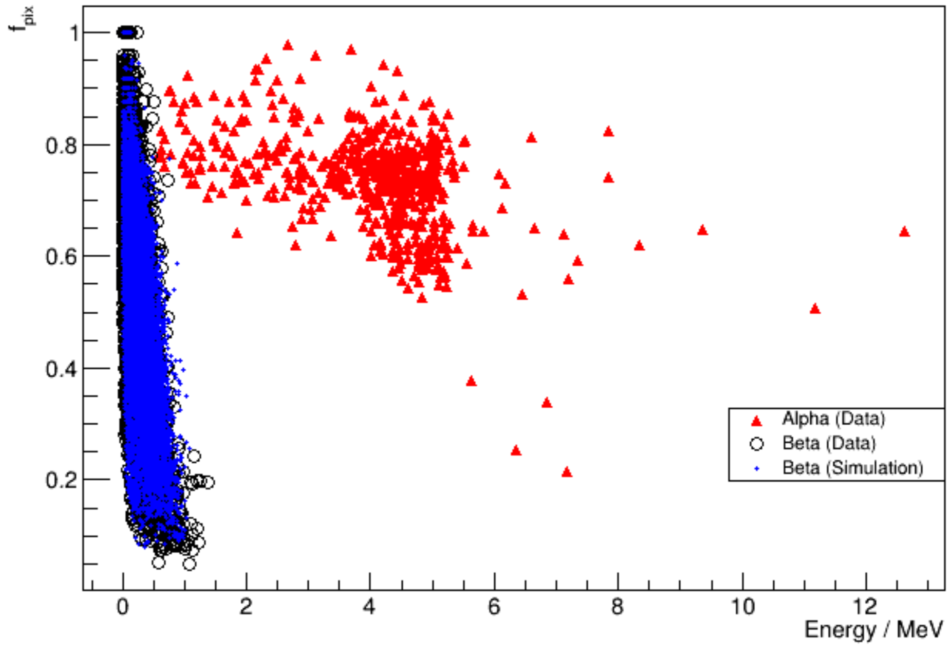


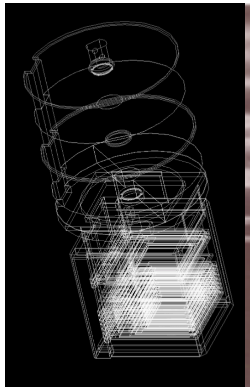
β

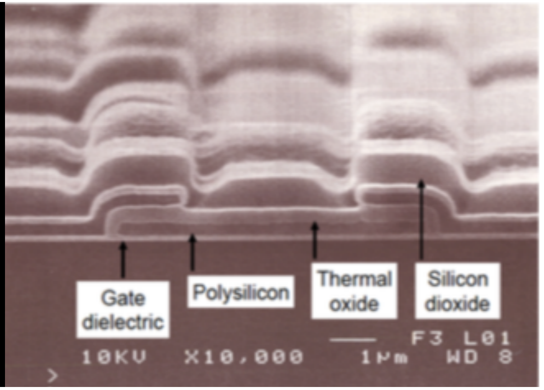


- Circular α's: bulk or back of CCD, "**plasma**" effect
- Vertical α's: front of CCD, charge spilling over potential barriers between vertical pixels, i.e. "**blooming**"
- β's: lower energy and longer tracks

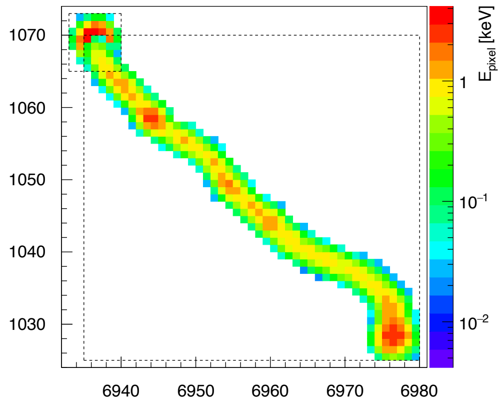
Radioactive contamination of ^{210}Pb and ^{32}Si measured in CCDs; limits placed on ^{238}U and ^{232}Th contamination



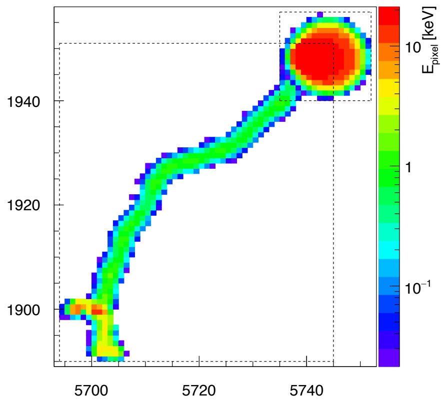




^{32}Si β_1-β_2 (Δt = 11.7 d)



^{210}Pb β_1-α (Δt = 32.3 d)



^{32}Si
- 133.3 ± 27.8 μBq/kg

^{210}Pb
- 83.1 ± 11.8 nBq/cm^2

^{238}U
- No α-β sequences
- Upper limit:

0.53/kg/day or 1.5 ppt [95%]

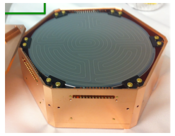
^{232}Th
- No α's with E = 18.7 MeV
- Upper limit:

0.35/kg/day or 1 ppt [95%]

This analysis has major implications for next-generation silicon-based dark matter experiments

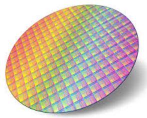
External

DARK MATTER COMMUNITY



- Other leading silicon-based experiments rely on DAMIC's measurement of contamination

STUDIES ON SILICON & ISOTOPES



- First comparison to ^{32}Si level in detector-grade silicon
- Confirmation that ^{32}Si levels vary locally

Internal

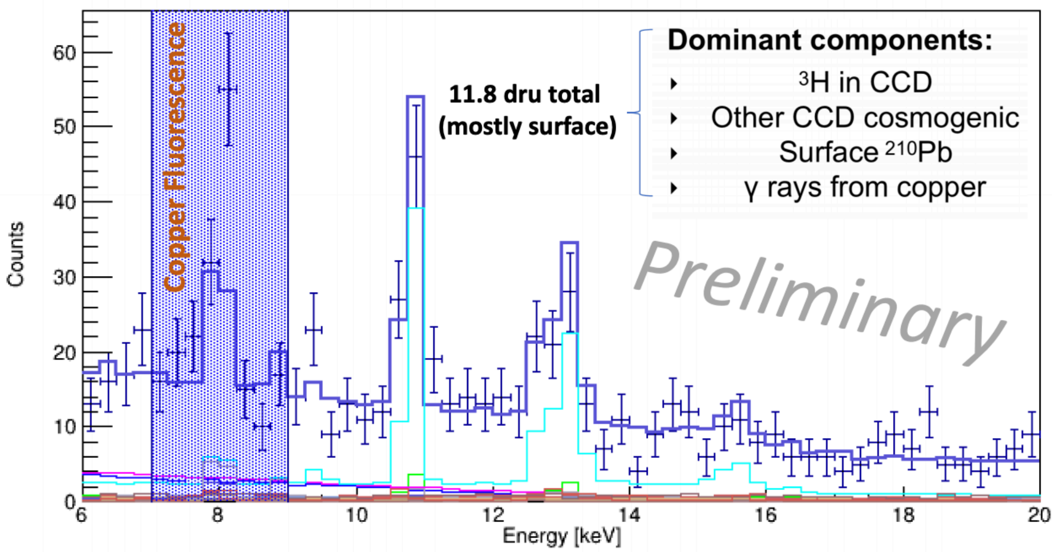
FUTURE IMPROVEMENTS

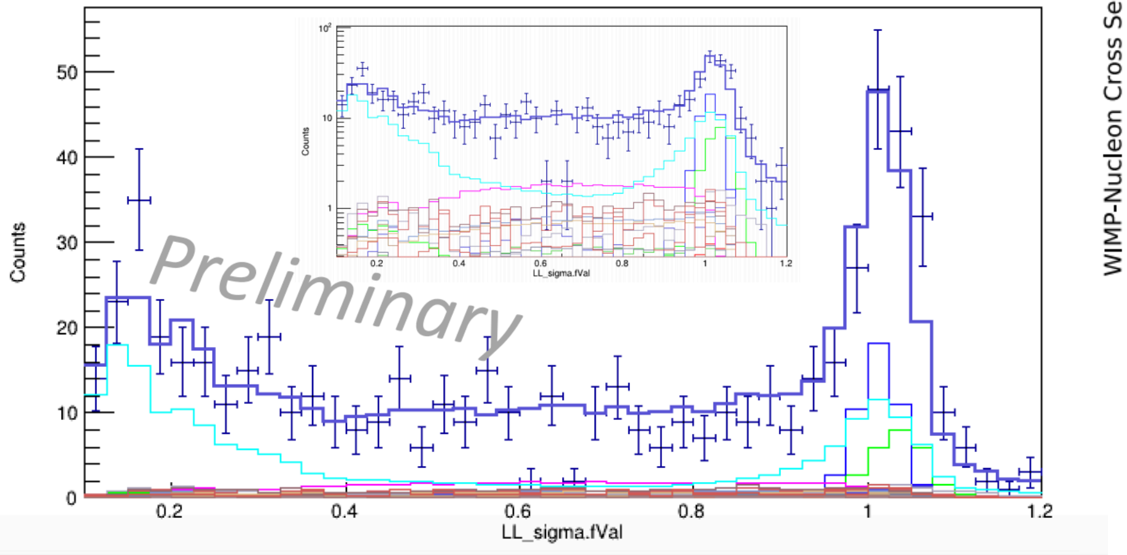
- Potential to optimize silicon ingot selection
- Need to lower Rn exposure in packaging

BACKGROUND MODEL

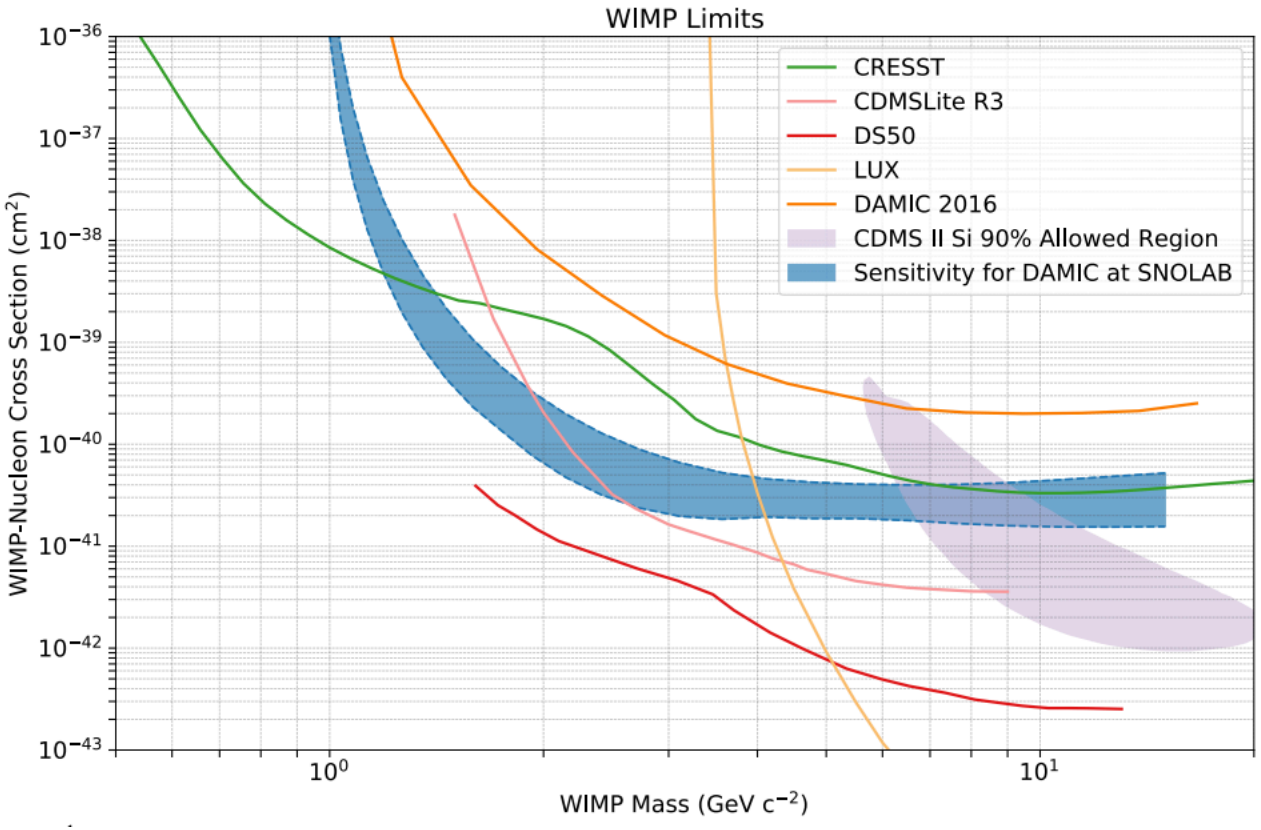
- Constrain parameters for background model used in WIMP search

The are several upcoming results from DAMIC at SNOLAB!





- Perform likelihood fit in energy-sigma space
- Achieve 11.8 dru (^{3}H, ^{210}Pb, OFC Cu, detector materials, etc.)



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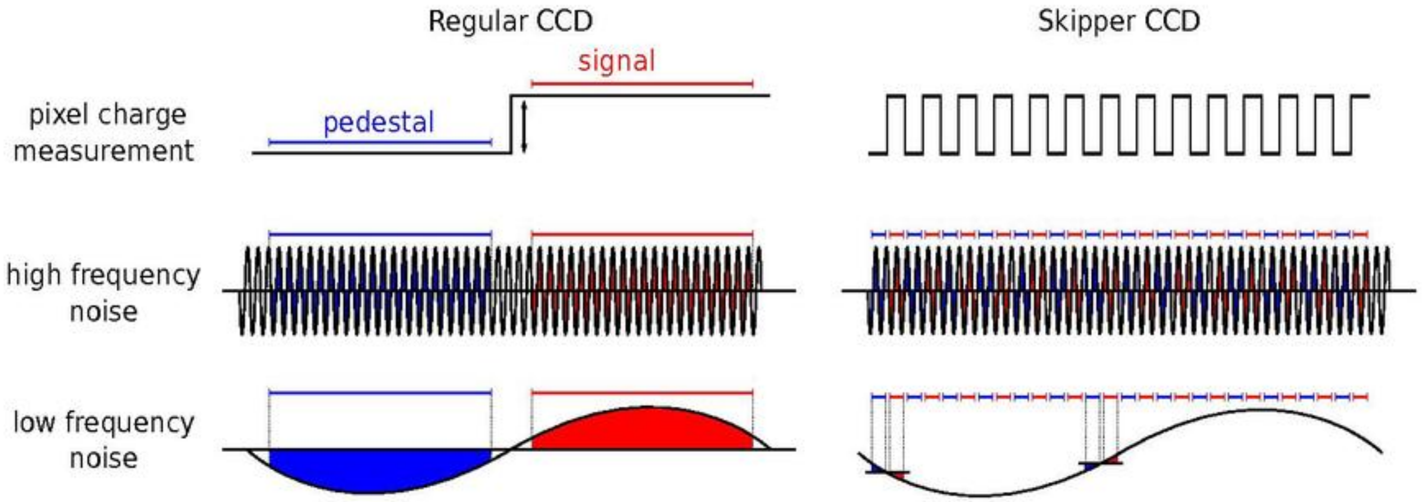
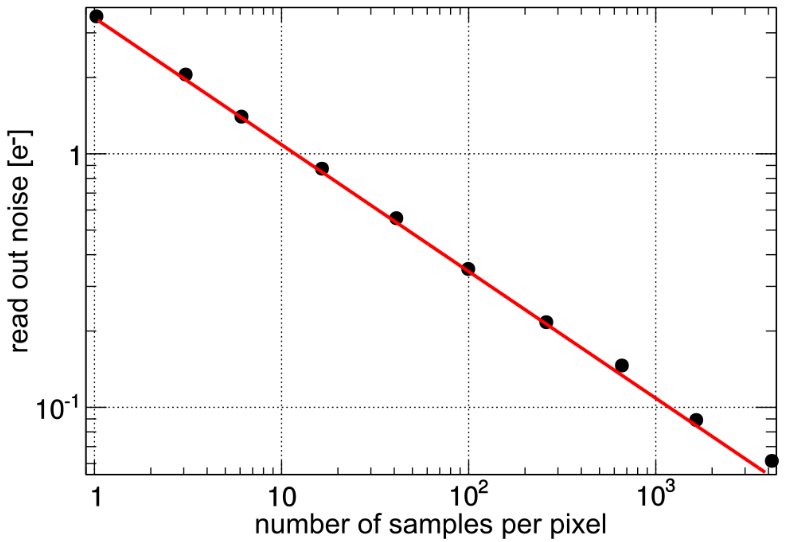
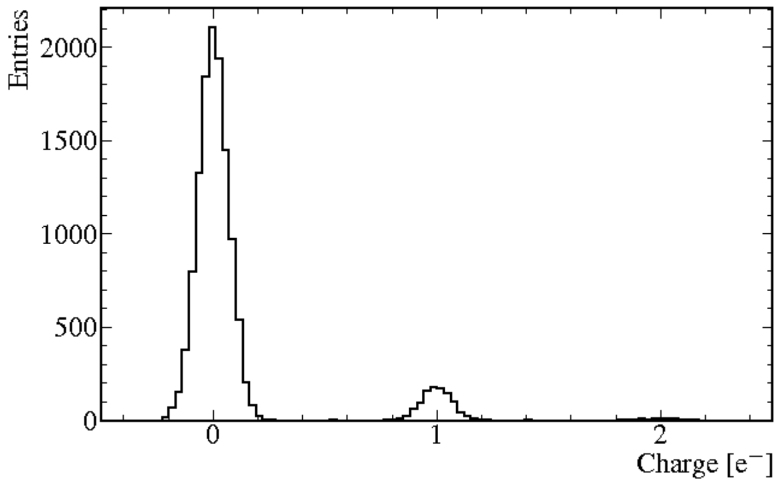
Recent developments in novel "Skipper" readout techniques will enable CCDs to achieve sub-electron resolution





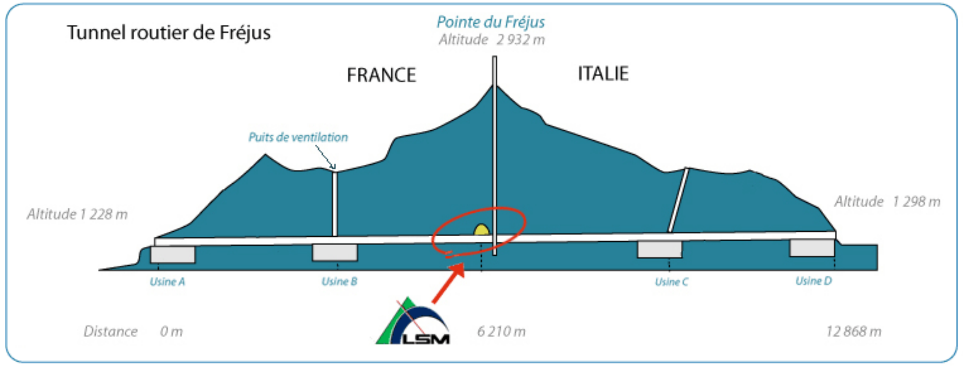
- Utilize a **non-destructive, multiple measurement** of pixel charge in order to get single-electron sensitivity
- Readout noise decreases by $1/\sqrt{N}$ for N charge measurements; decrease integration time for each measurement to reduce 1/f noise
- DAMIC-M goal: 0.1 e^- charge resolution for 1 ms pixel readout time



PRL 119.13 (2017): 131802

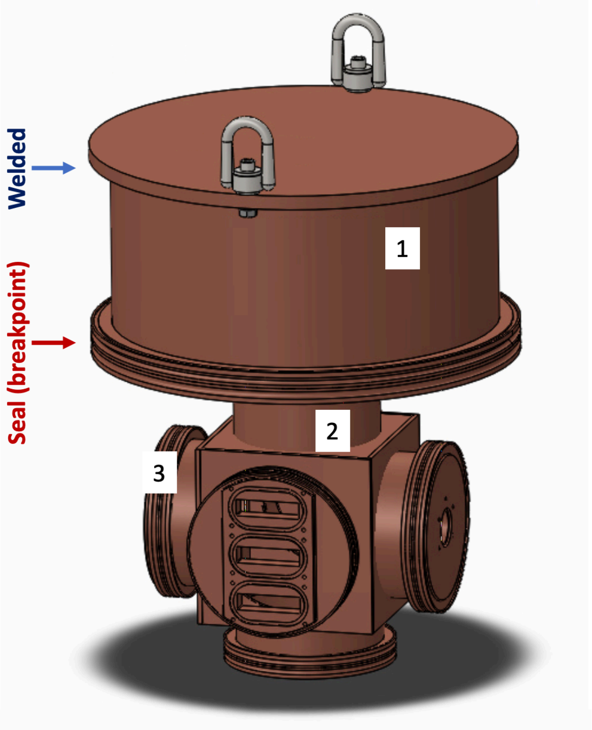
DAMIC-M (Dark Matter in CCDs at Modane), a kg-scale detector with record-mass CCDs and novel readout, is being developed

Modane Lab



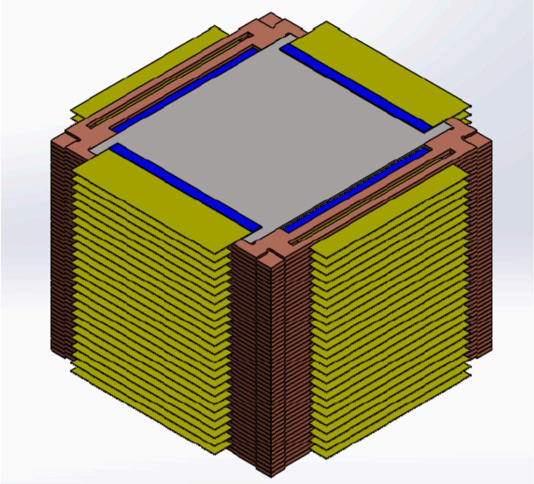
- Shield cosmic rays; easy access
- 125 m^3/h source of Rn-free air for underground packaging and testing

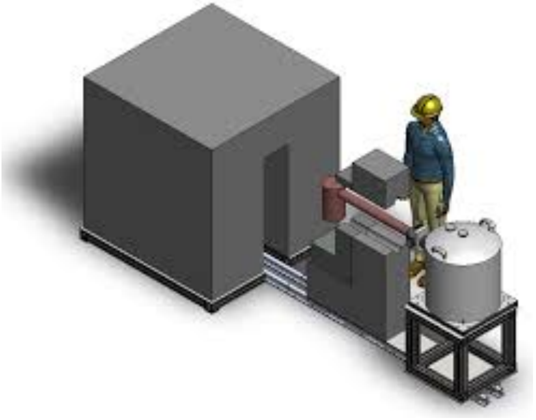
Prototype Detector



- Measure leakage current and background; verify packaging
- Produce new science results!

Final Tower of 50 CCDs





- Expected deployment 2022

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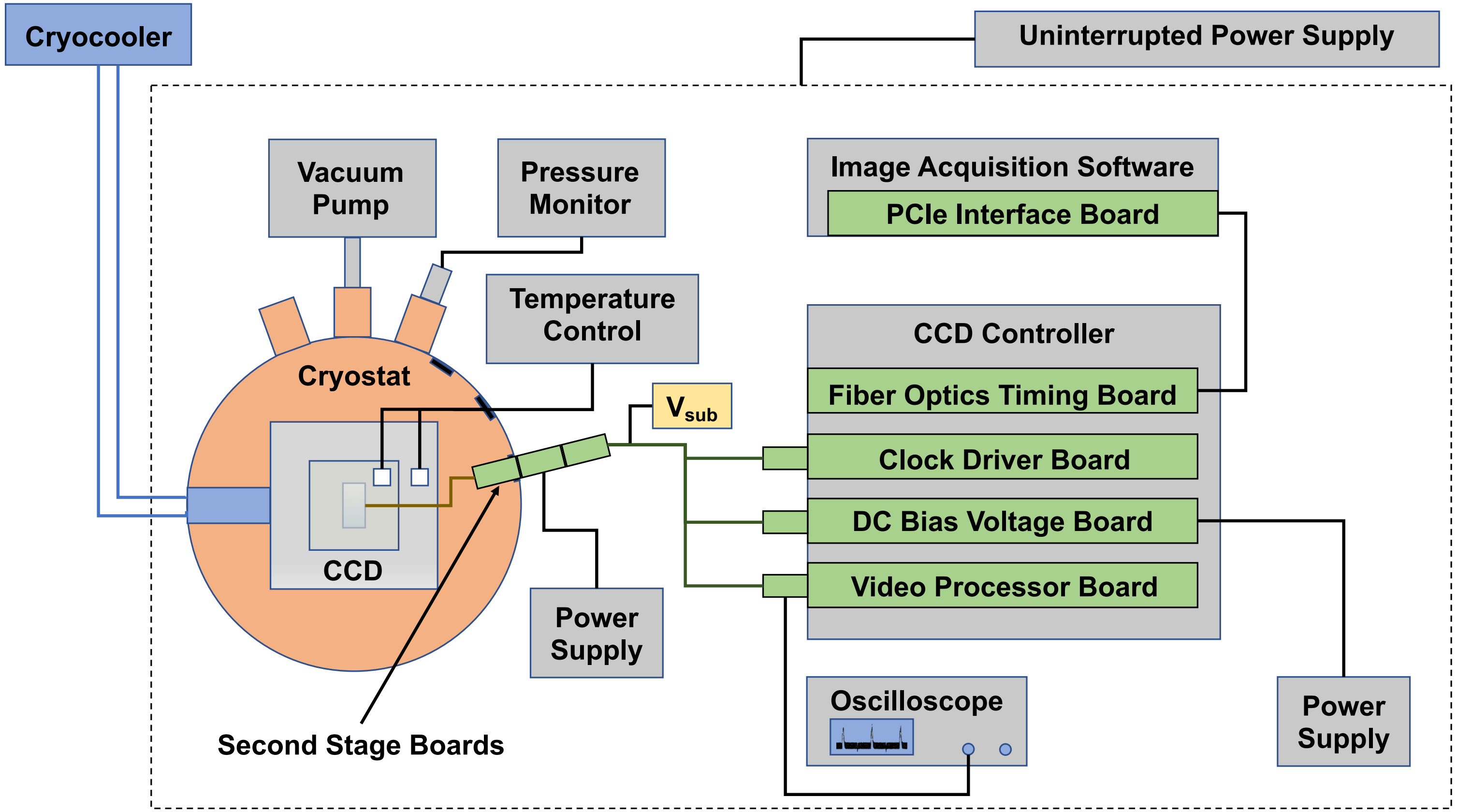
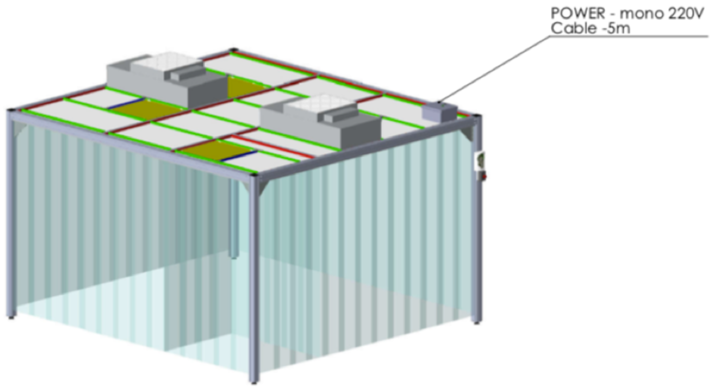
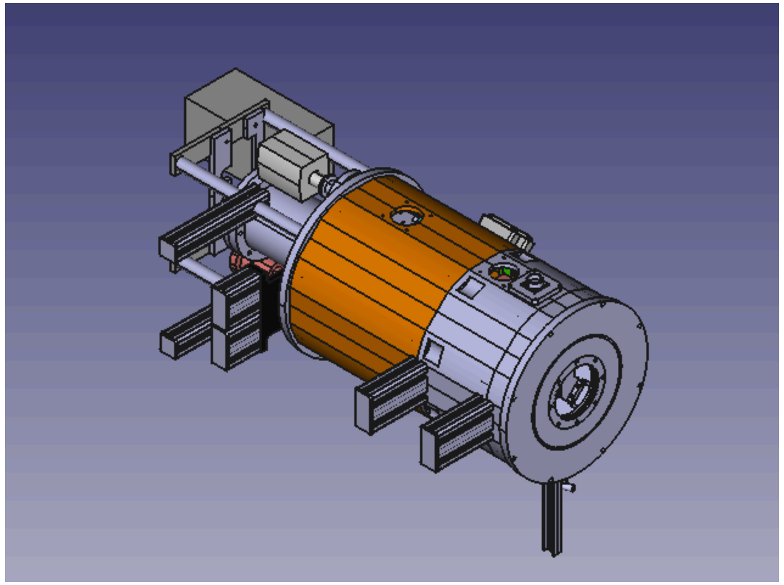
DAMIC-M pre-production studies are critical for its success; a CCD system for electronics and calibration tests has been developed





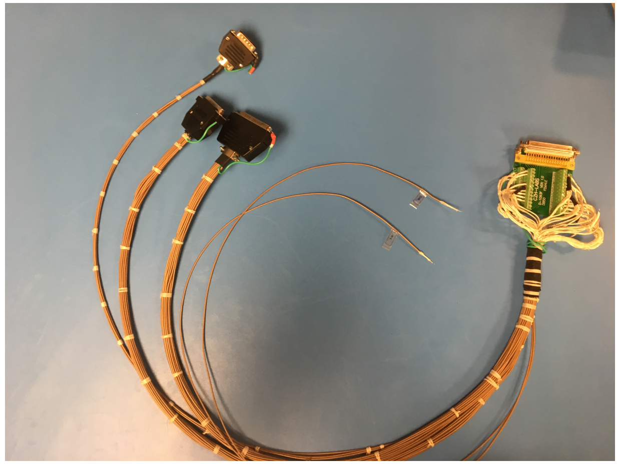


- System dedicated to tests of novel readout and CCD characterization
- Operated in ISO Class 7 cleanroom under cryogenic conditions
- Used to guide design features of prototype and final detector at LSM

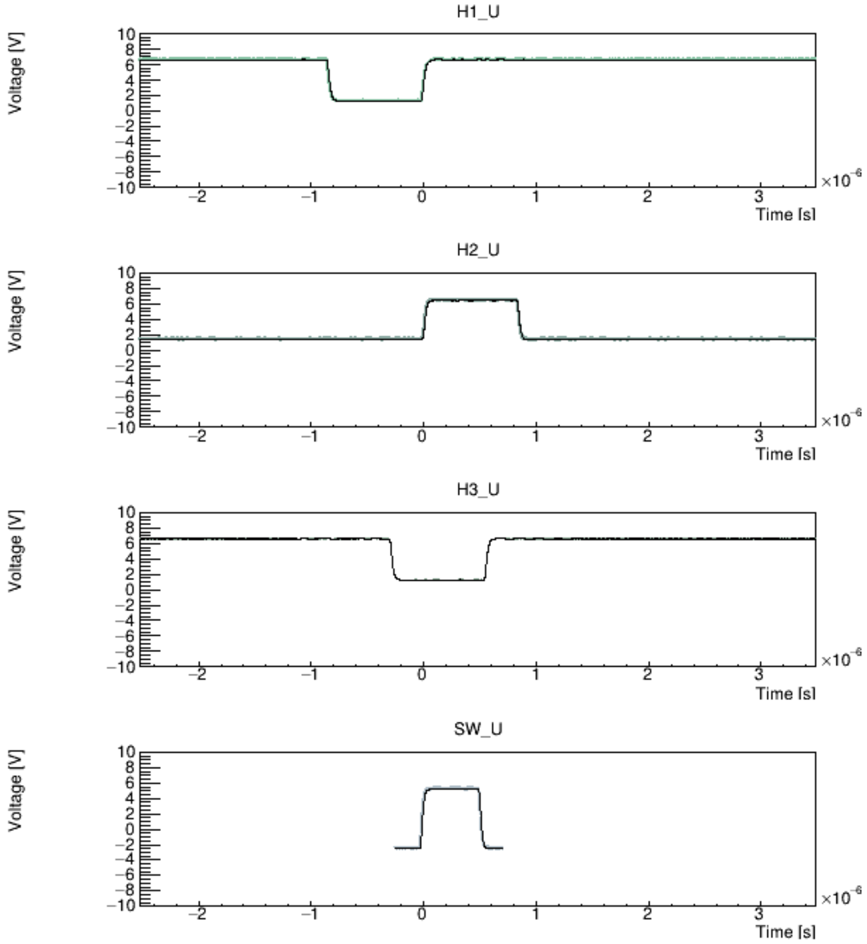
The CCD is operated with a specialized controller unit; all clock and bias voltages are monitored before deployment

"Leach" Controller

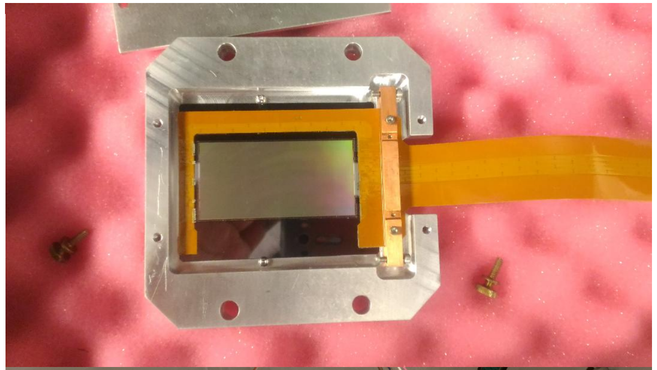
Leach Controller Components
ARC-22 Fiber Optic Timing Board
ARC-32 CCD Clock Driver Board
ARC-33 DC Bias Board
ARC-45 Two-Channel Video Board
ARC-66 PCI Interface Board

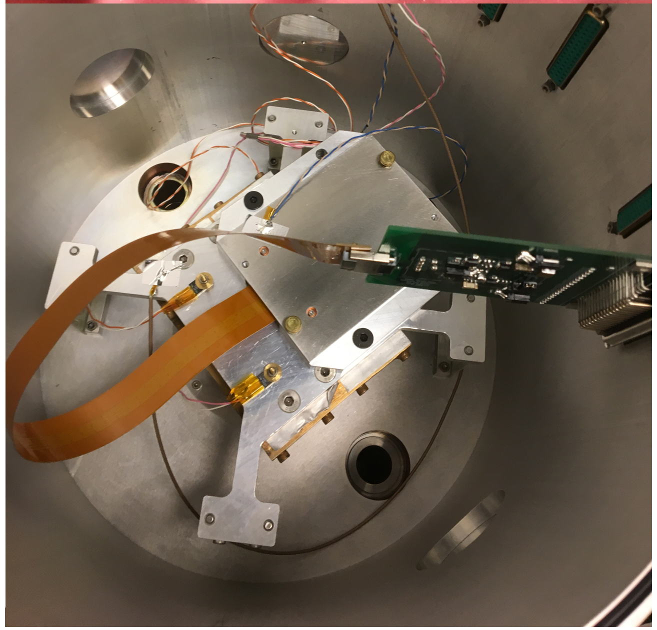


Clock Voltage Checks

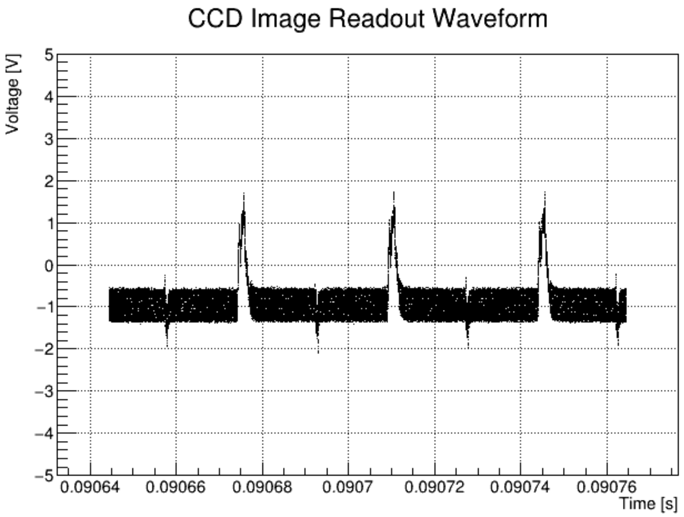


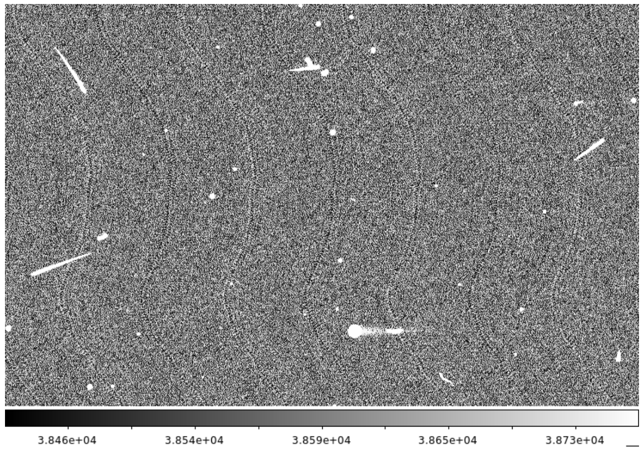
CCD D3500 (4k x 2k)

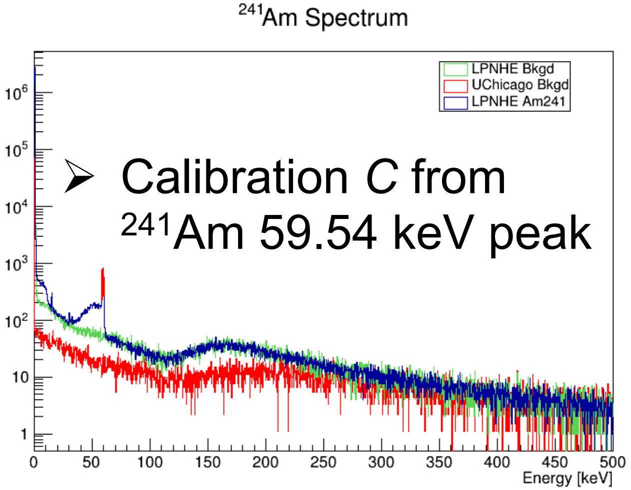




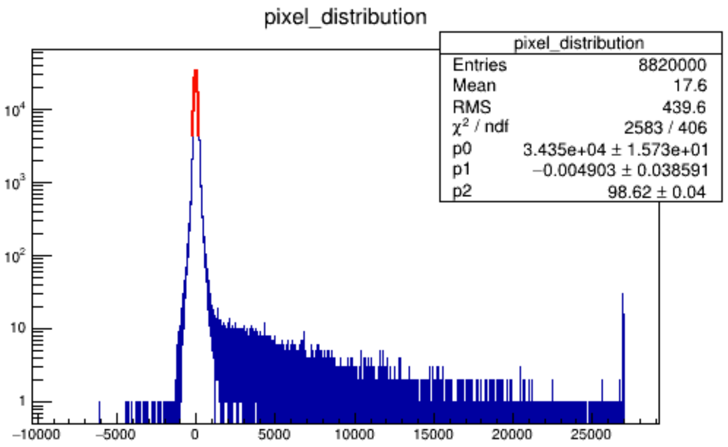
Successful image acquisition and calibration was completed in order to cross-check system performance with collaborators

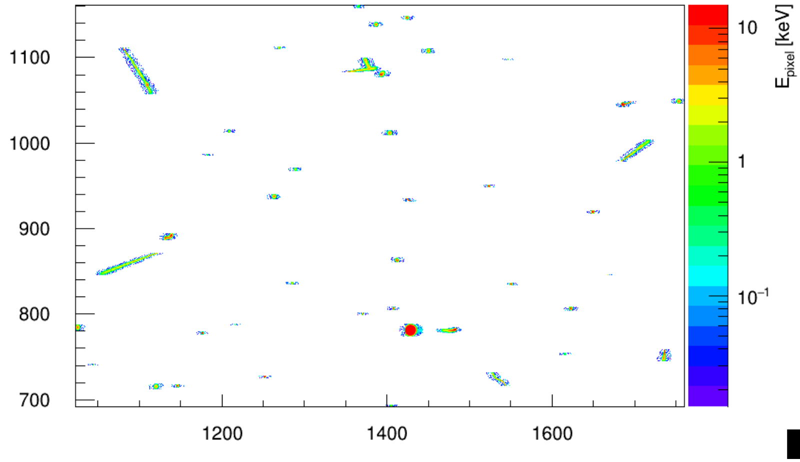


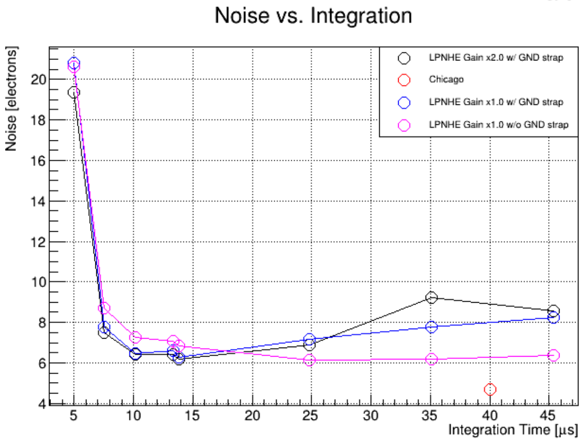




- Calibration *C* from ^{241}Am 59.54 keV peak

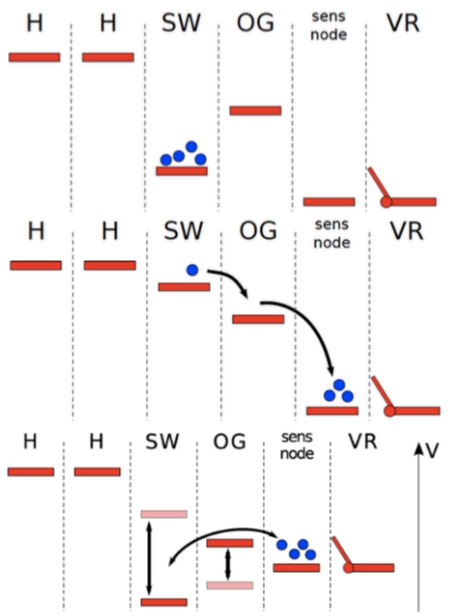


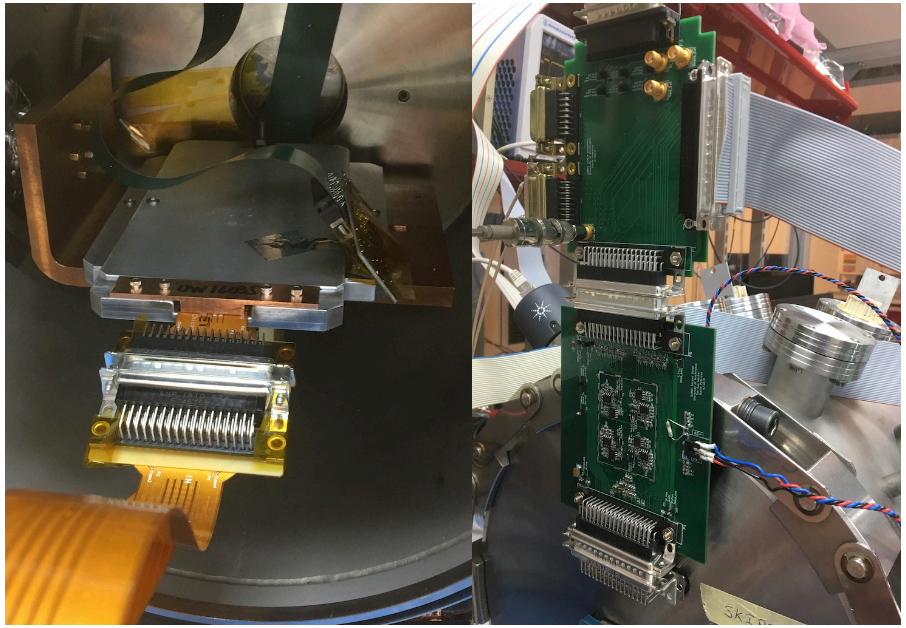




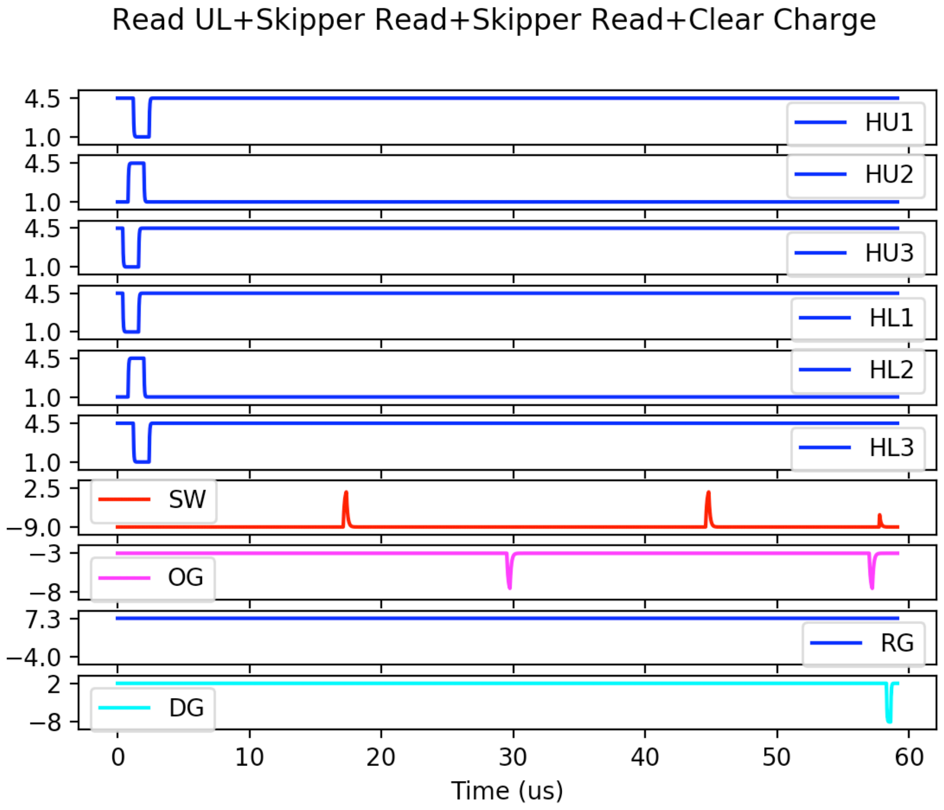
Chicago: 5 e^-
LPNHE: 14 e^- (February '19)
LPNHE: 6 e^- (April '19)

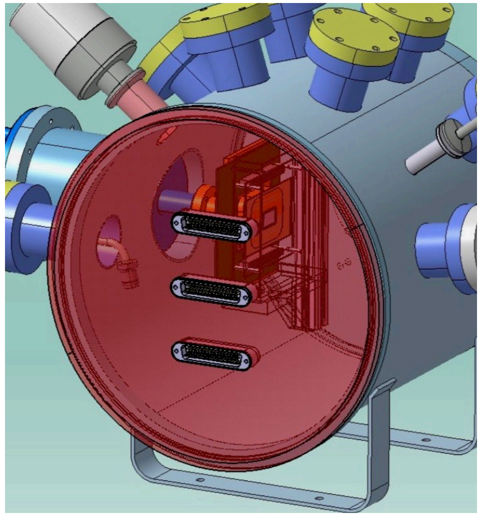
A test chamber is currently operating with a 1k x 6k Skipper CCD





CCD UW1403S

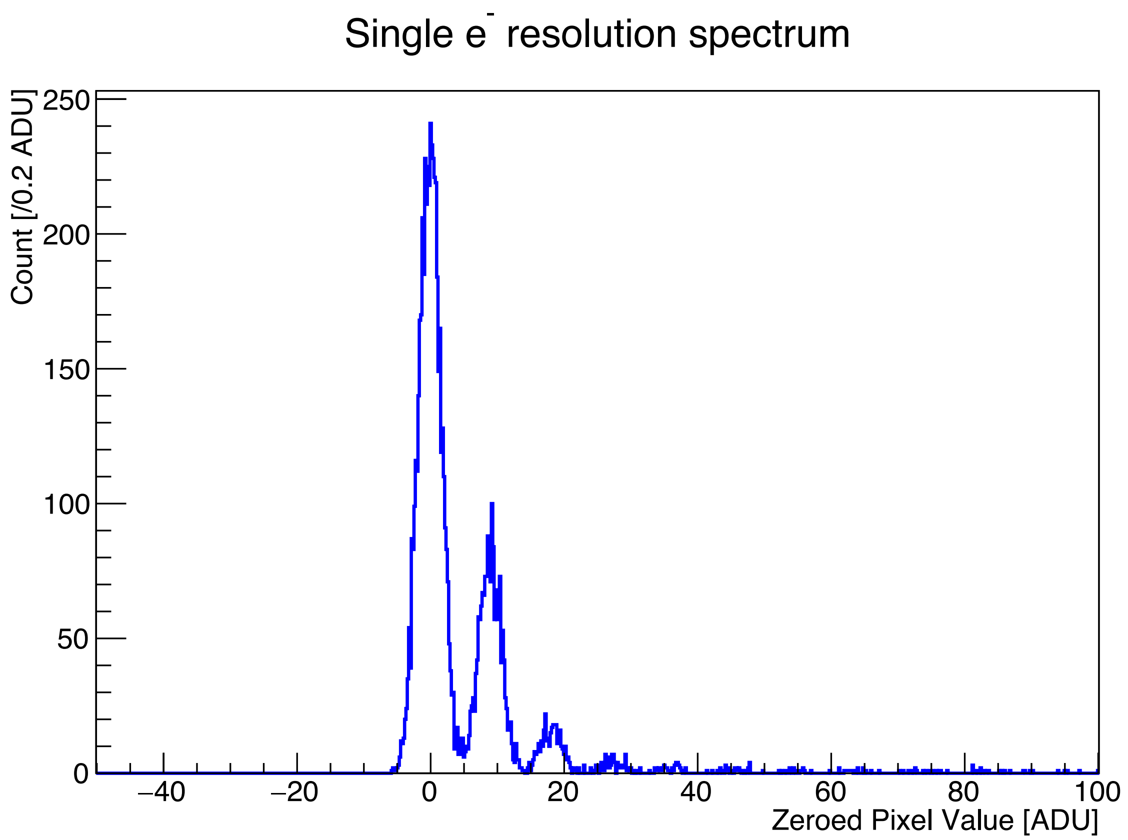


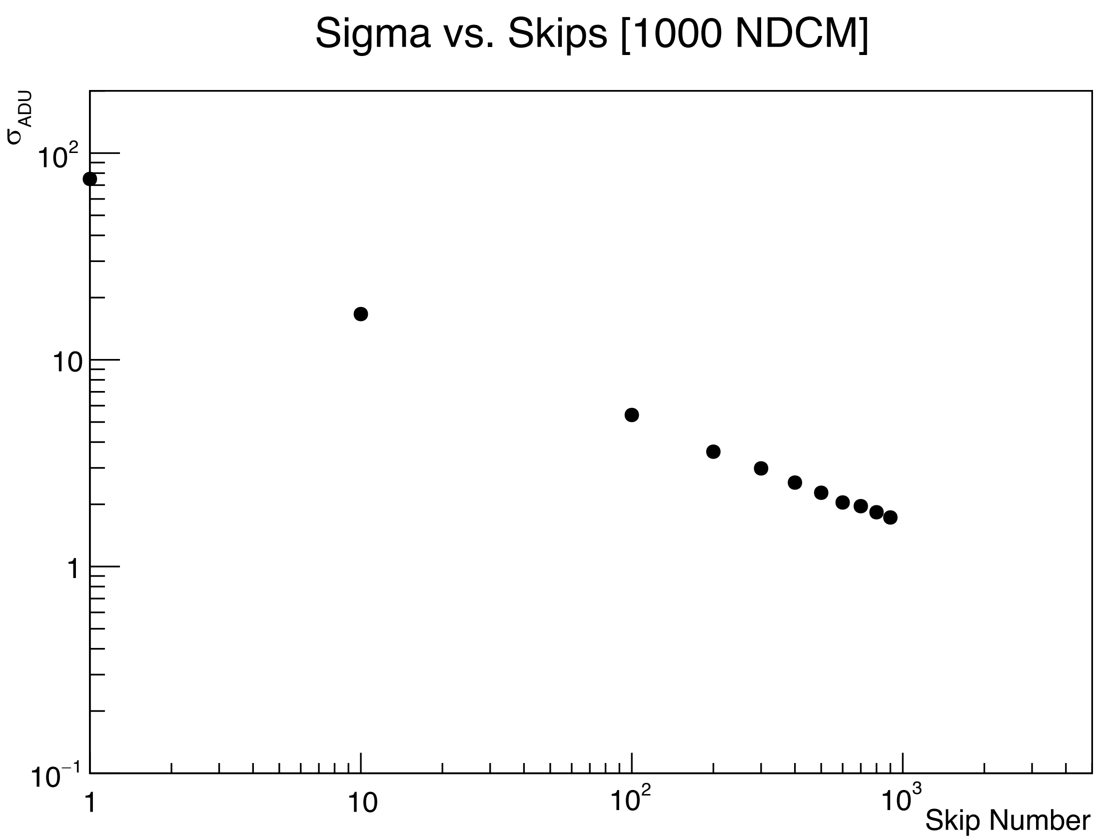


Implemented several improvements:

- ➢ Breakout board replaces medusa; second stage exterior to cryostat
- ➢ Packaging with reduced curing time, optimized thermal contact
- ➢ Image acquisition with customized control software

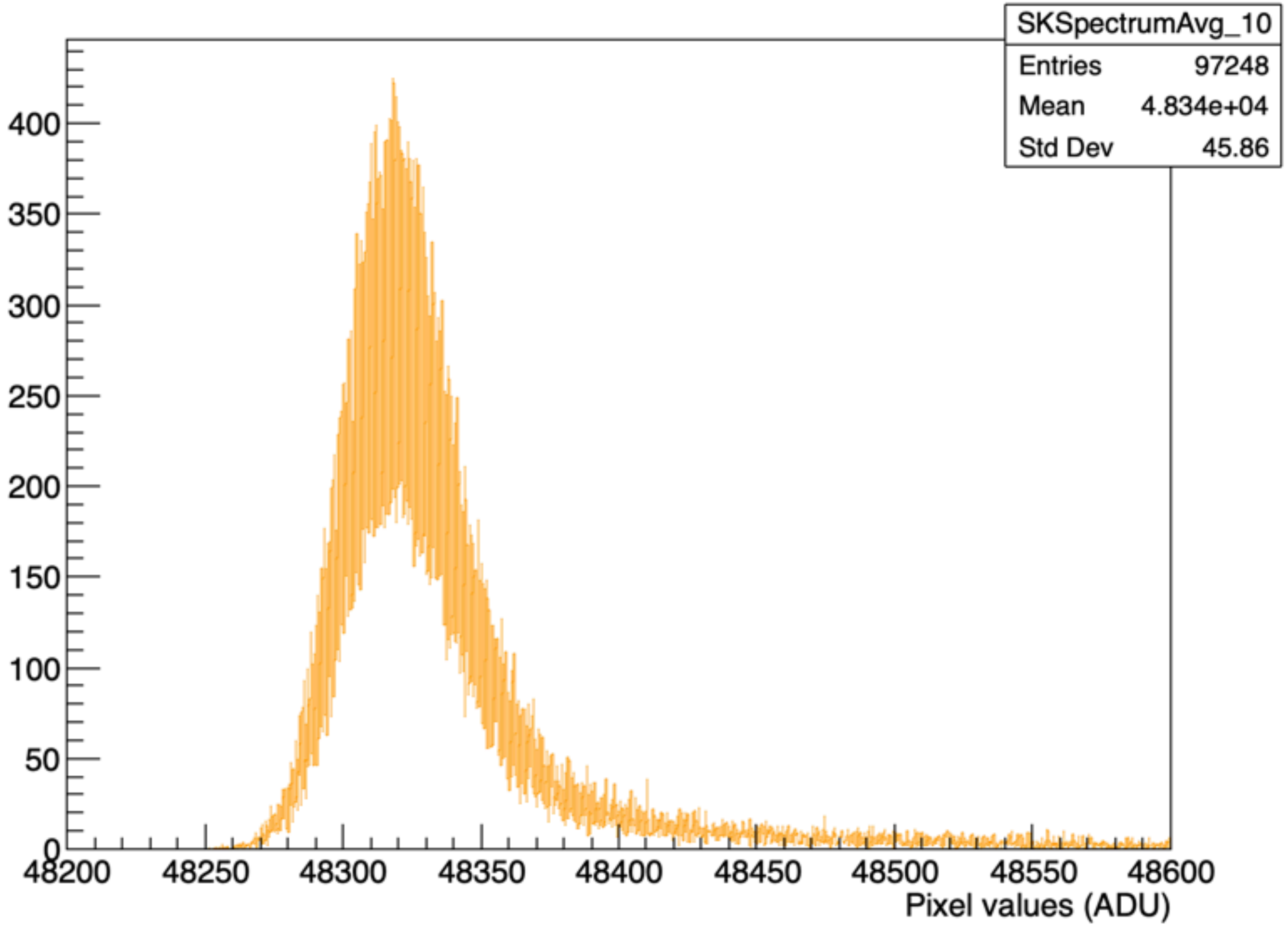
Single-electron resolution achieved at LPNHE! Extensive tests were run to optimize parameters and mitigate charge loss





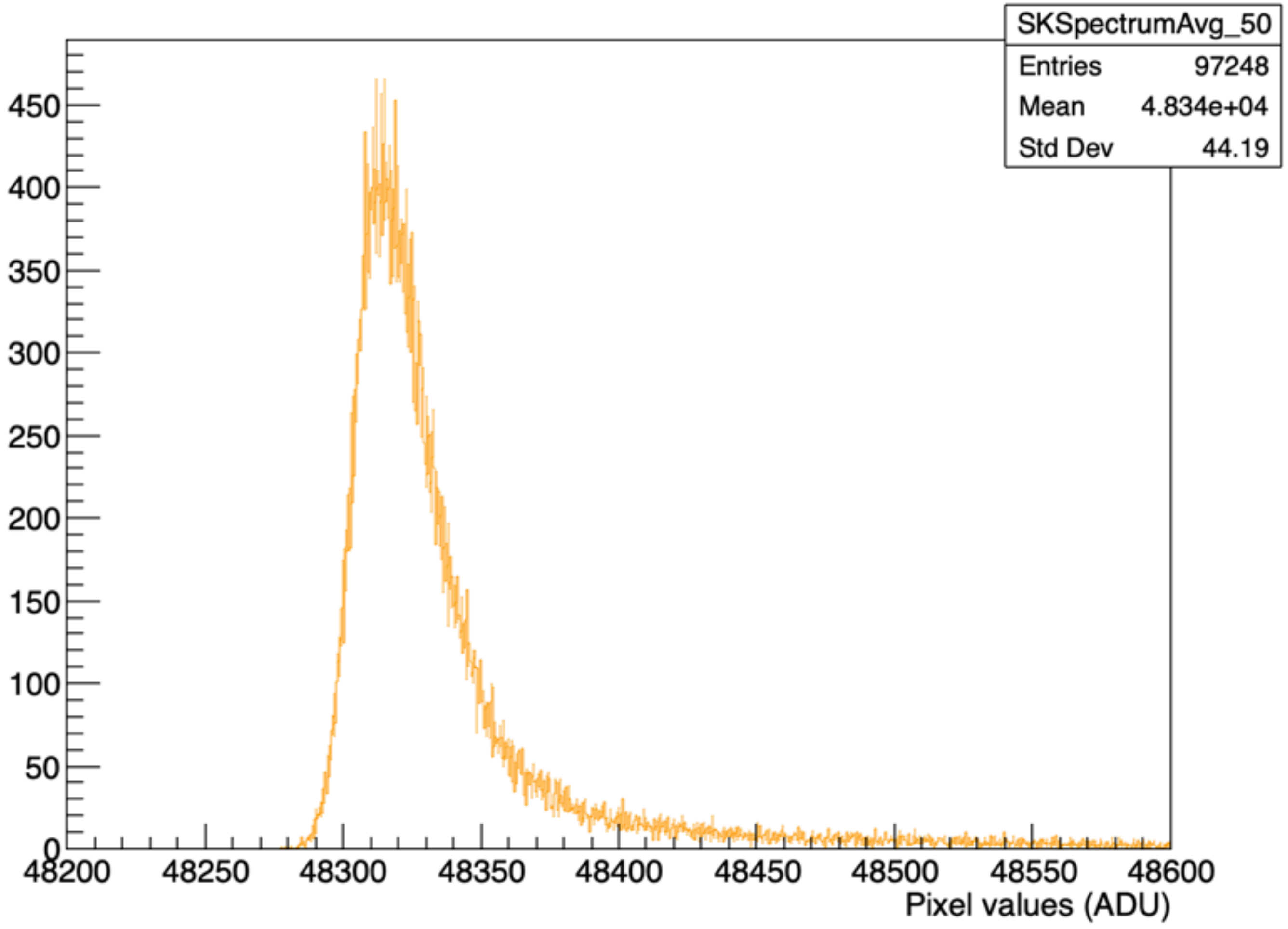
- ➢ Calibration directly from 1-electron peak (~10 ADU/e$^-$)
- ➢ Single-electron resolution achieved for several $T_{integration}$
- ➢ NDCM = Non-destructive charge measurements
- ➢ See 1/√N noise reduction to 0.18 e- after 1000 NDCM

10 NDCM



SKSpectrumAvg_10
Entries 97248
Mean 4.834e+04
Std Dev 45.86
400
350
300
250
200
150
100
50
0
48200
48250
48300
48350
48400
48450
48500
48550
48600
Pixel values (ADU)

50 NDCM


SKSpectrumAvg_50
Entries 97248
Mean 4.834e+04
Std Dev 44.19
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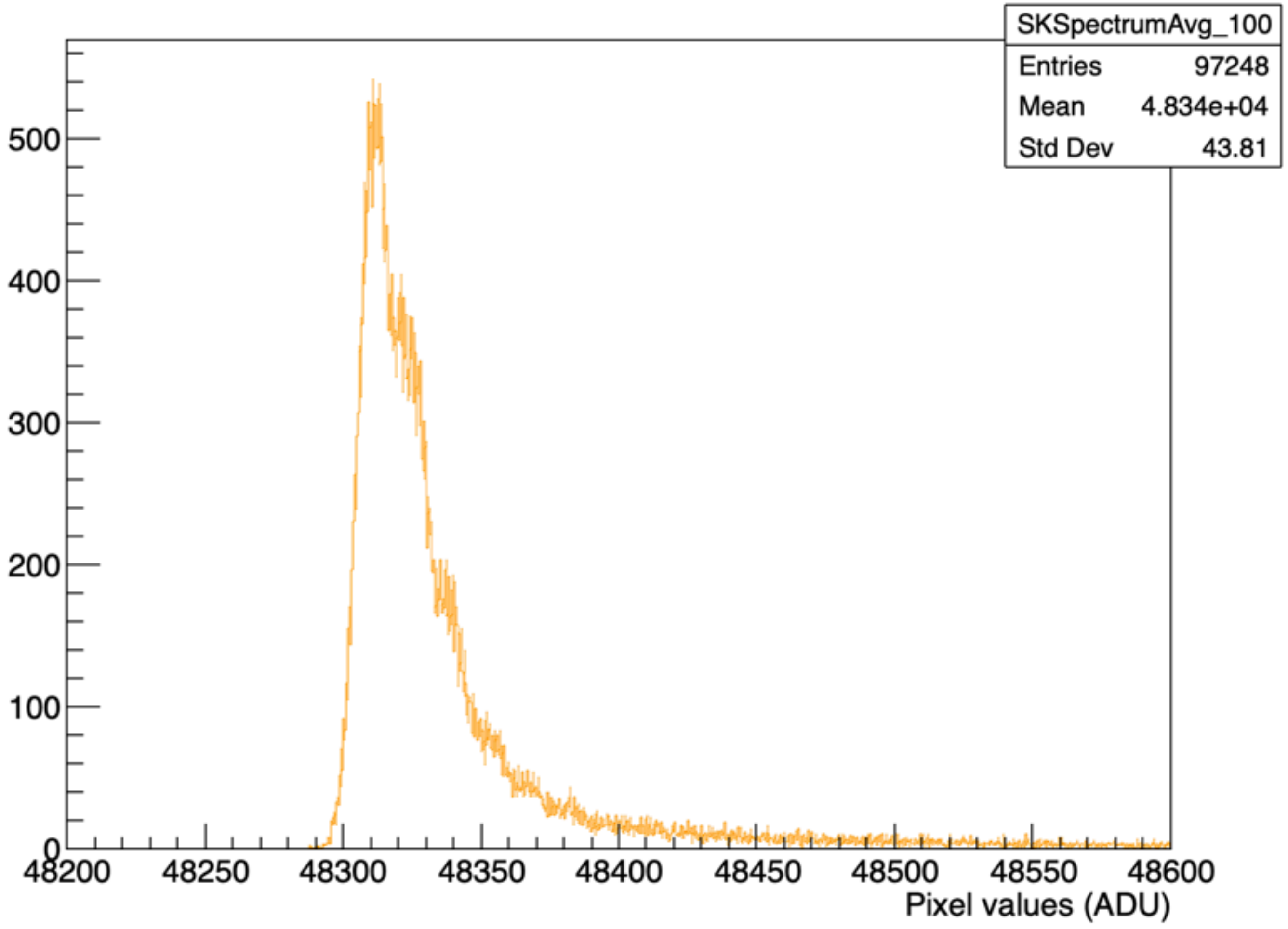
50
100
150
200
250
300
350
400
450
48200
48250
48300
48350
48400
48450
48500
48550
48600
Pixel values (ADU)

100 NDCM



SKSpectrumAvg_100
Entries 97248
Mean 4.834e+04
Std Dev 43.81
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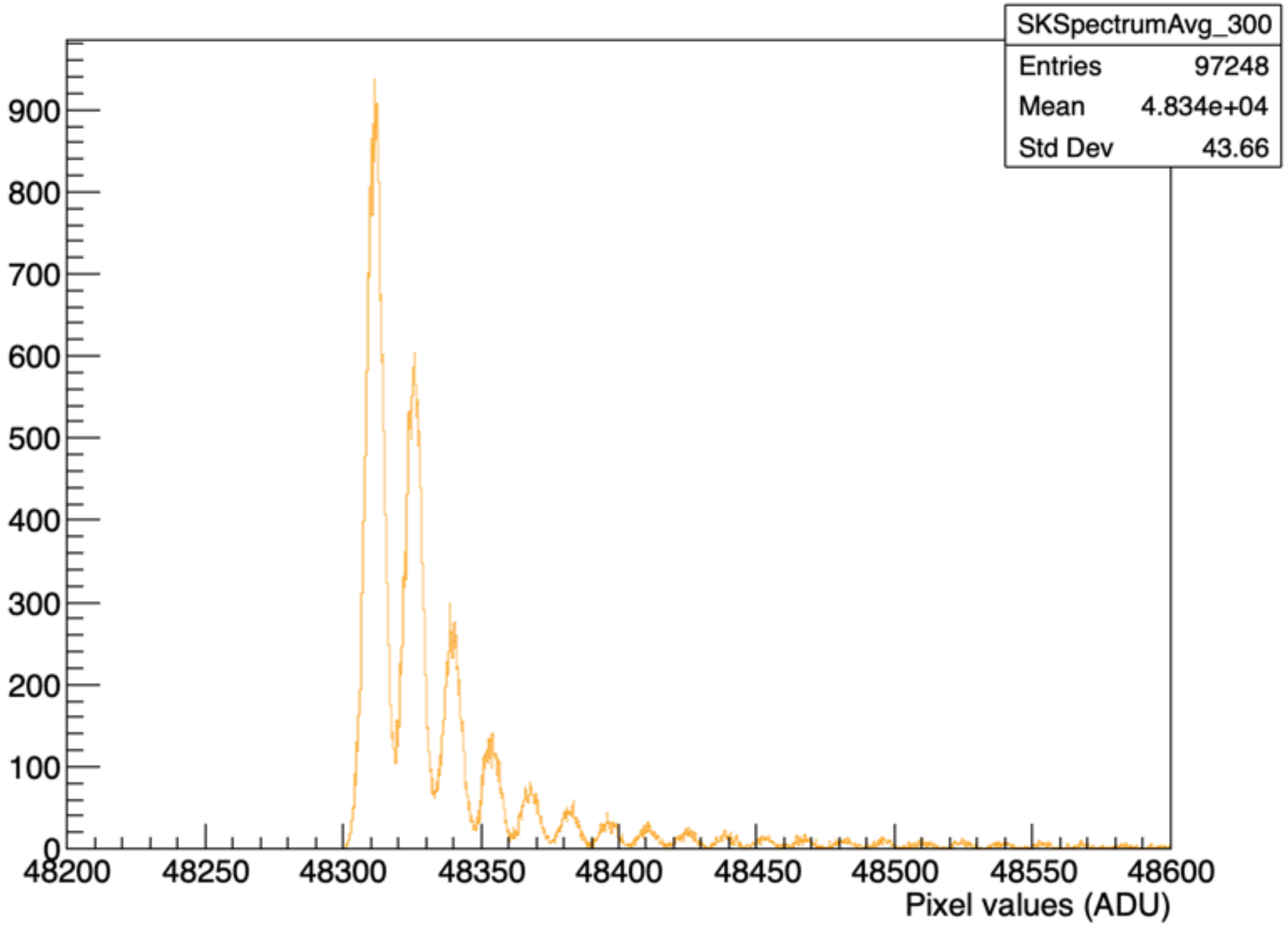
100
200
300
400
500
48200
48250
48300
48350
48400
48450
48500
48550
48600
Pixel values (ADU)

300 NDCM


SKSpectrumAvg_300
Entries 97248
Mean 4.834e+04
Std Dev 43.66
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800
700
600
500
400
300
200
100
0
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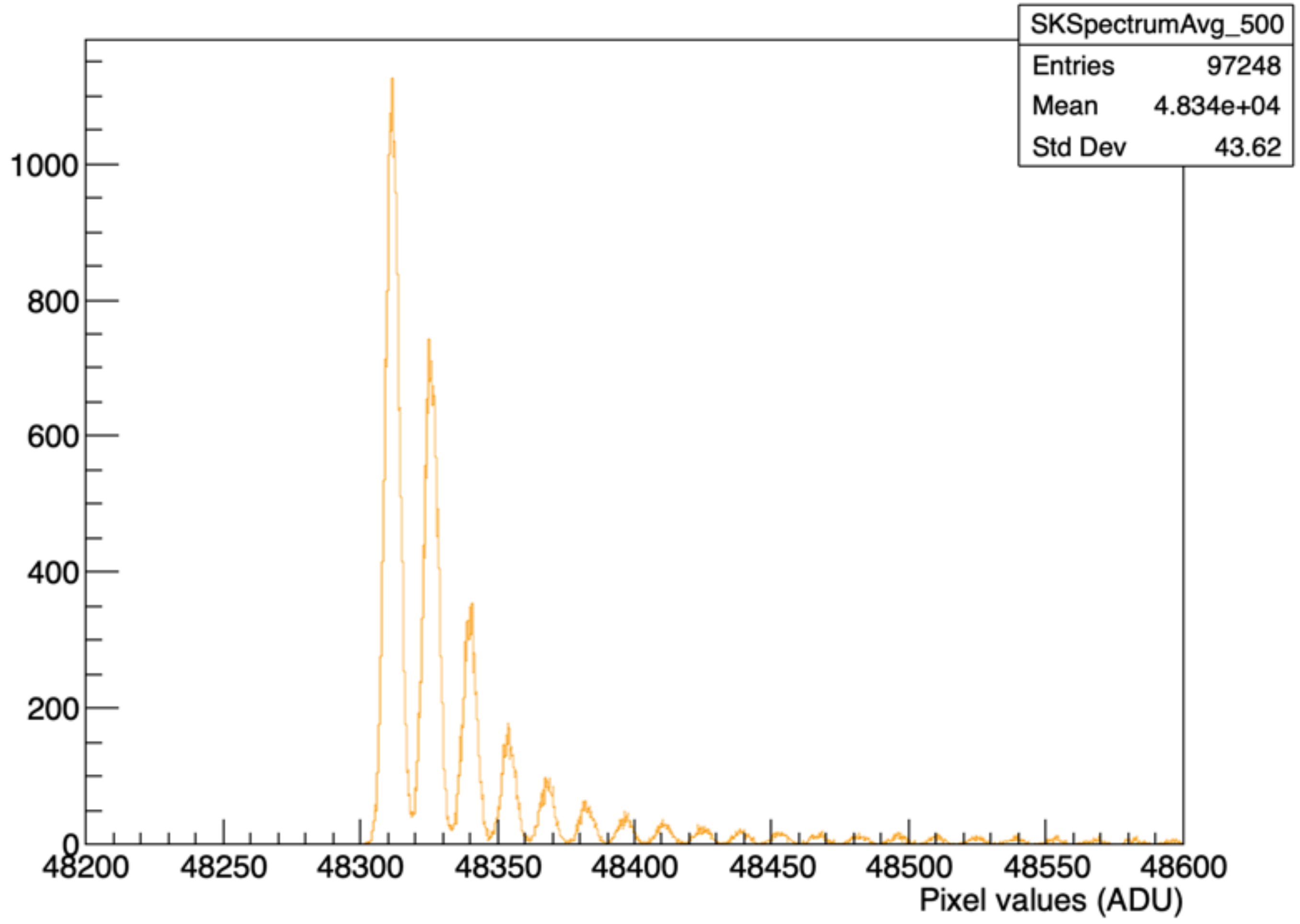
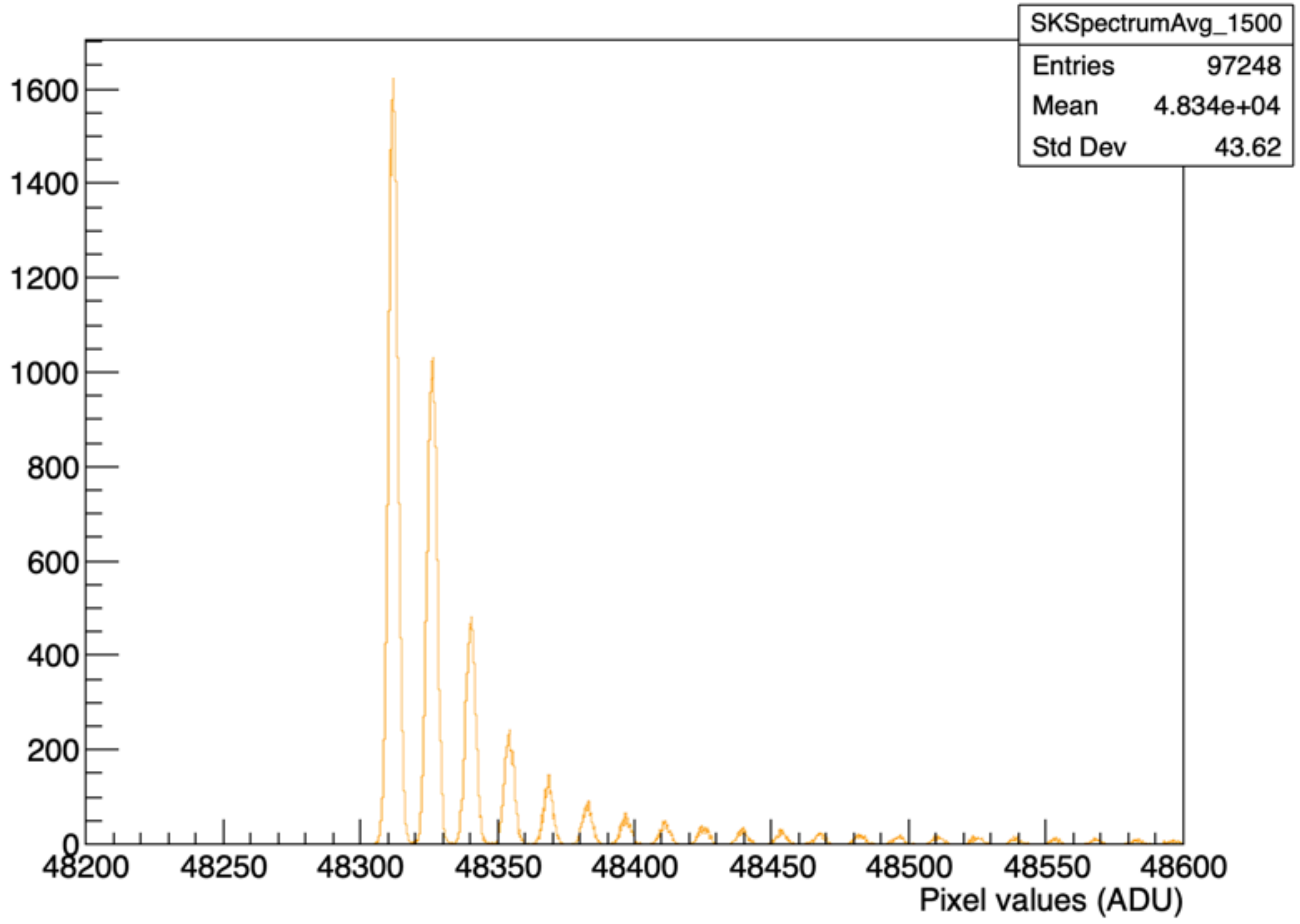
48250
48300
48350
48400
48450
48500
48550
48600
Pixel values (ADU)

500 NDCM



SKSpectrumAvg_500
Entries 97248
Mean 4.834e+04
Std Dev 43.62
1000
800
600
400
200
0
48200
48250
48300
48350
48400
48450
48500
48550
48600
Pixel values (ADU)

1500 NDCM


SKSpectrumAvg_1500
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Mean 4.834e+04
Std Dev 43.62
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800
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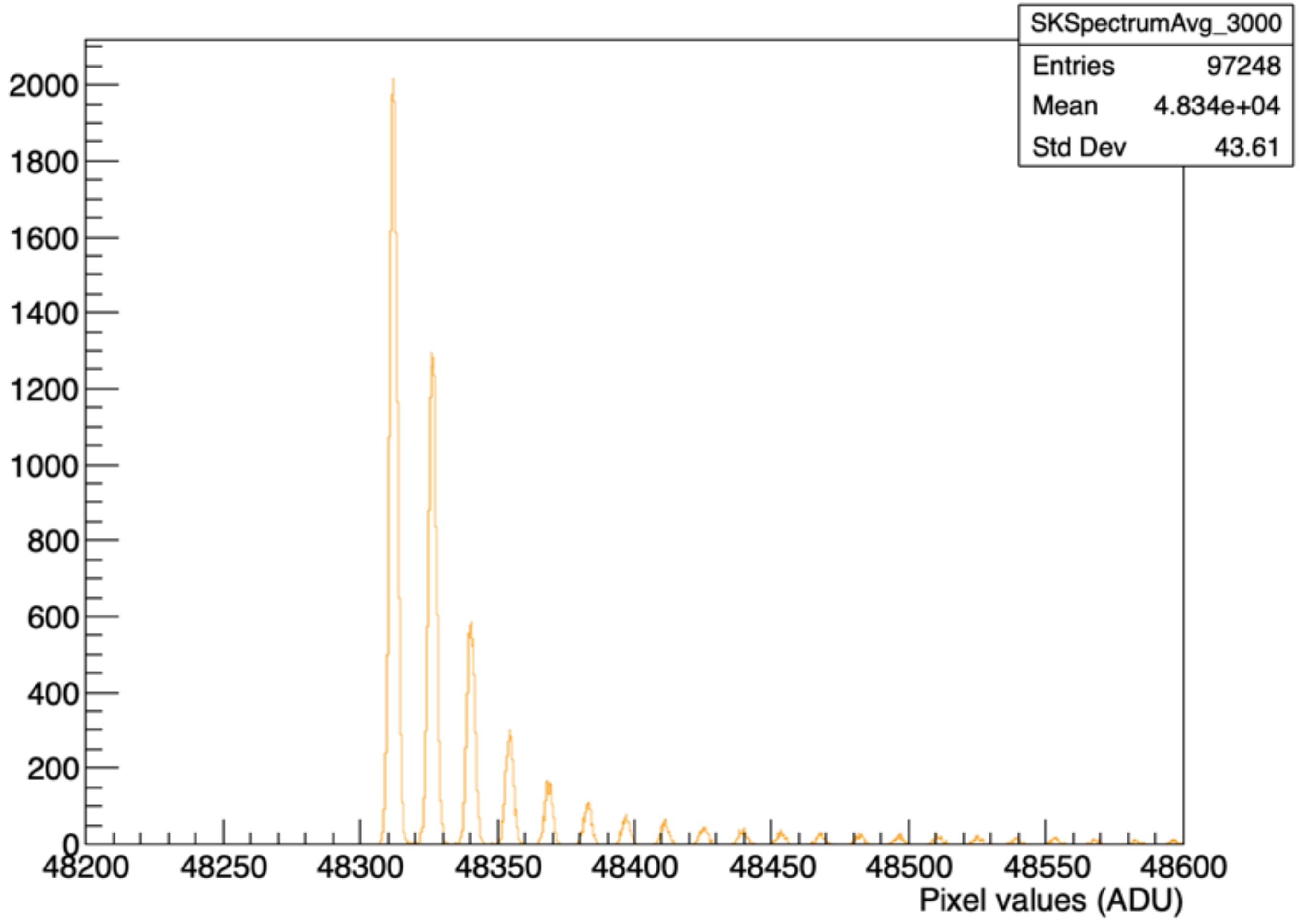
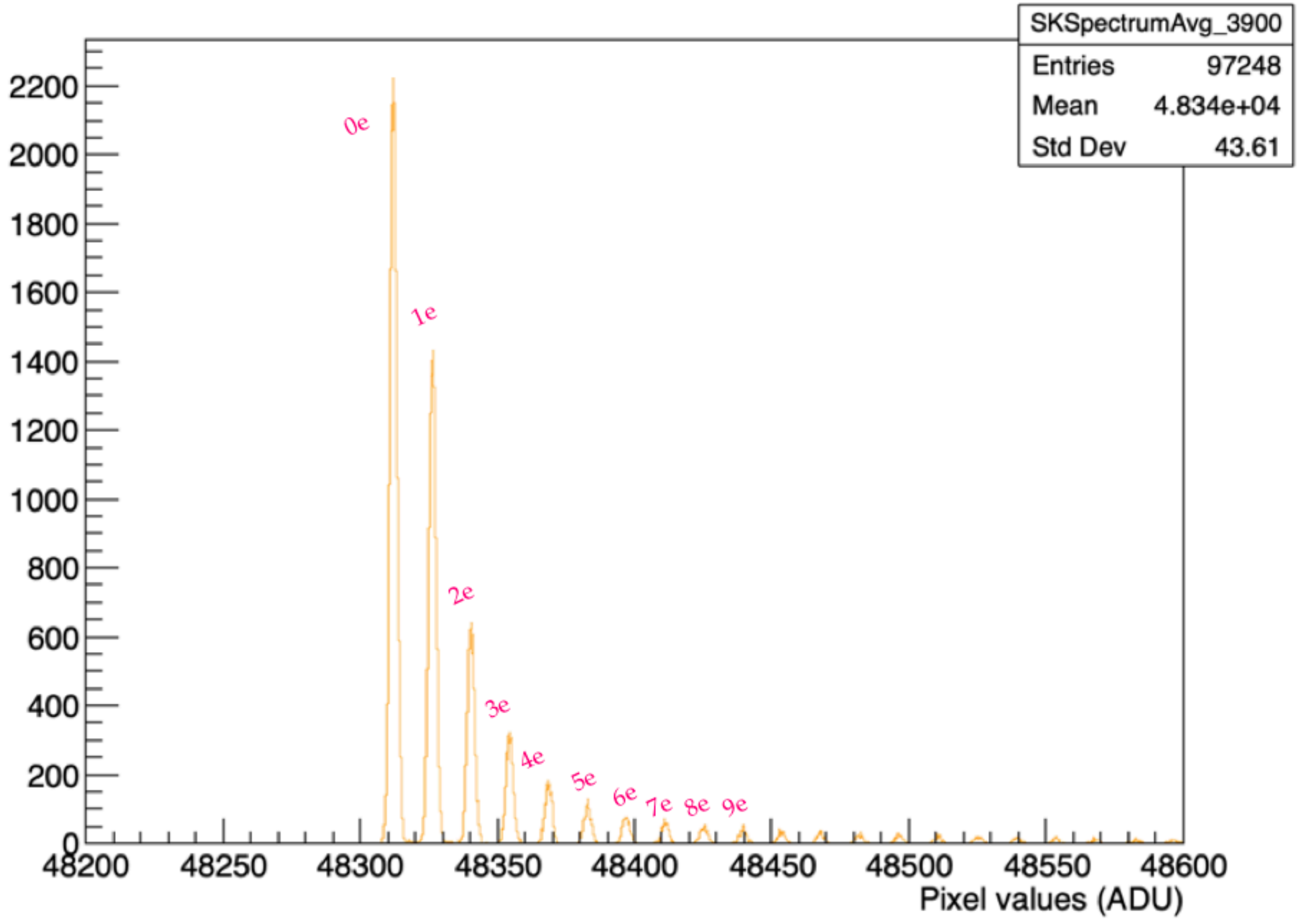
48450
48500
48550
48600
Pixel values (ADU)

3000 NDCM



SKSpectrumAvg_3000
Entries 97248
Mean 4.834e+04
Std Dev 43.61
2000
1800
1600
1400
1200
1000
800
600
400
200
0
48200 48250 48300 48350 48400 48450 48500 48550 48600
Pixel values (ADU)

3900 NDCM



SKSpectrumAvg_3900
Entries 97248
Mean 4.834e+04
Std Dev 43.61
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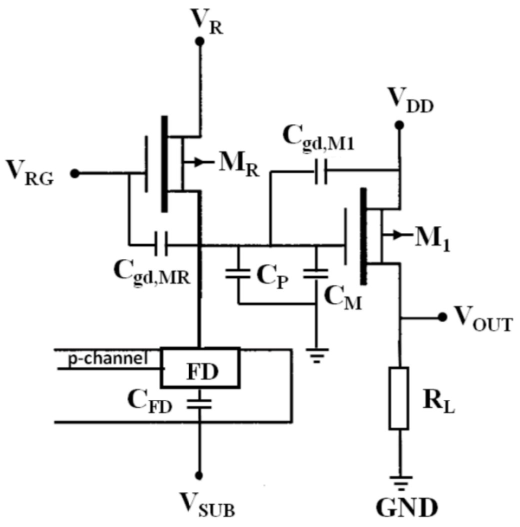
1e
2e
3e
4e
5e
6e
7e
8e
9e
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
48200
48250
48300
48350
48400
48450
48500
48550
48600
Pixel values (ADU)

There is a multi-institutional effort to study performance of Skipper CCDs and to evaluate amplifier options for the final mask design

- Current 1k x 6k Skipper CCDs feature two single-stage, source-follow amplifiers: investigating buried-contact technology, different geometry, and varied biases

- First 6k x 4k Skipper CCDs packaged! To be tested at LPNHE, deployed at SNOLAB
- Prototype at LSM will feature 6k x 6k CCDs



doi: 10.1117/12.905460

Table of Contents

Summary

- DAMIC at SNOLAB shows CCDs as excellent detectors to search for DM; results for background model and 13 kg-d exposure in WIMP search coming!
- The development of DAMIC-M is rapidly progressing; major advancements have been made towards reaching the program's aggressive scientific goals
- LPNHE is at the heart of the collaboration, with activities in detector characterization, electronics development, background studies, and analysis. We are operating several test systems to guide the experiment forward

Acknowledgements

Big thanks to all the members of the DAMIC and DAMIC-M collaborations, especially the UChicago & LPNHE teams. A very sincere thank you to my advisors, Paolo Privitera and Antoine Letessier Selvon. I am happy to be conducting my dissertation work under their supervision.

Special thanks as well to the JRJC organizers!

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RÉPUBLIQUE FRANÇAISE
AMBASSADE DE FRANCE

Cheers!

Chouchen
14% ABV

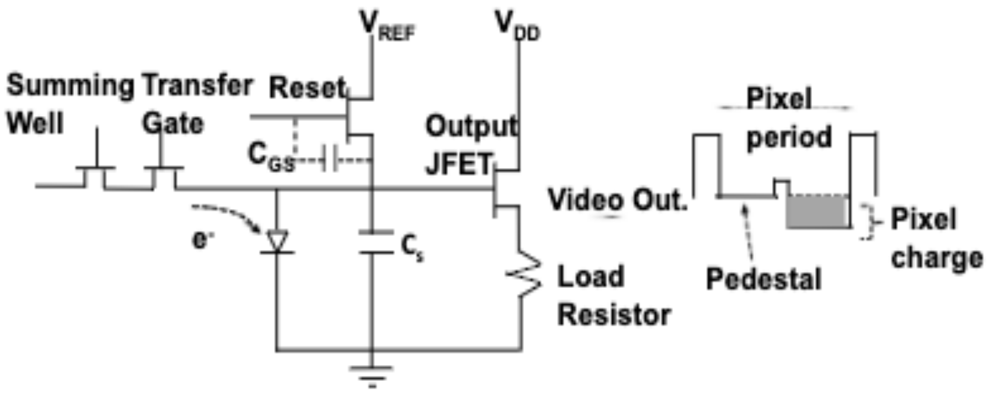
Thank you!

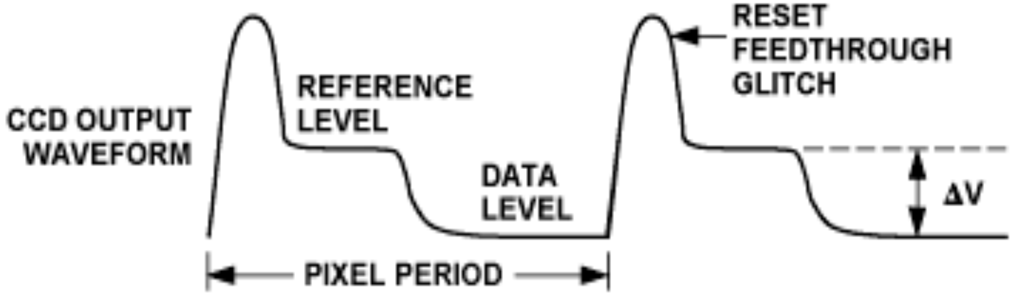
Backup

CCD Operation

Correlated double sampling applied analogically can improve the CCD pixel charge readout process

- Subtracting pedestal from signal cancels reset noise and filters frequencies above 1/T
- 1/f noise of amplifier dominates

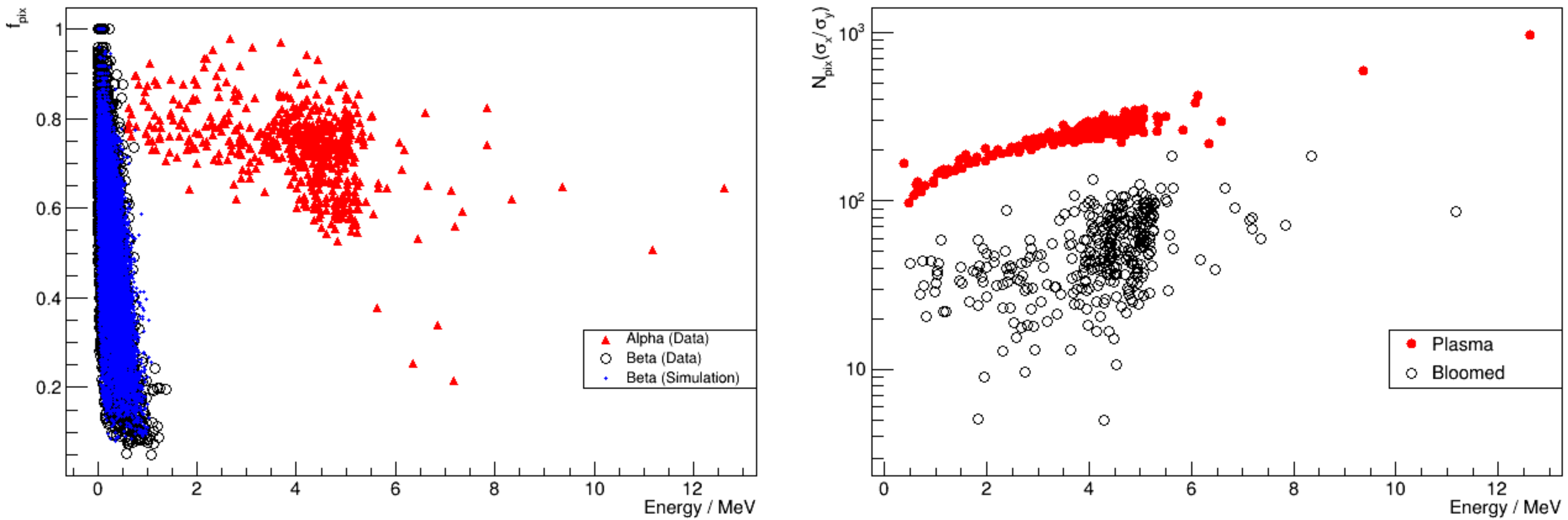




Signal	Description
V_1, V_2, V_3	Clock (parallel): charge transfer to CCD output
H	Clock (serial): charge transfer to empty row
TG	Clock (parallel): transfer gate
SW	Clock (serial): summing well
RG	Clock (serial): reset gate
V_{og}	Bias: summing well
V_r	Bias: reset reference
V_{dd}	Bias: drain
V_{out}	Bias: output
V_{sub}	Bias: substrate depletion

Measurement of Radioactive Contamination in DAMIC CCDs

Cluster characteristics subsequently enable successful discrimination between α and β particles



- ➢ α-β discrimination from energy and f_{pix}, ratio of number of pixels (N_{pix}) to smallest box around cluster
- ➢ Plasma-bloomed discrimination from N_{pix} and ratio of x:y spatial r.m.s.

Characteristics of radioactive isotope decays guide searches

Bulk Contamination

$^{32}Si \rightarrow {}^{32}P$	Q = 224.5 keV	$t_{1/2}$ = 150 y
$^{32}P \rightarrow {}^{32}S$	Q = 1710 keV	$t_{1/2}$ = 14.3 d

Surface Contamination

$^{210}Pb \rightarrow {}^{210}Bi$	Q = 63.5 keV	$t_{1/2}$ = 22.3 y
$^{210}Bi \rightarrow {}^{210}Po$	Q = 1161 keV	$t_{1/2}$ = 5.01 d
$^{210}Po \rightarrow {}^{206}Po$	Q = 5407 keV	$t_{1/2}$ = 138 d

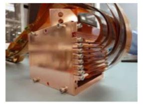
Searches

Search ID	**Relevant Isotope**	**Decay Sequence**	**Cluster 1 Energy Cut**	**Cluster 2 Energy Cut**	**Cluster Separation Time**
1	^{32}Si	β_1-β_2	$E_{\beta1}$ > 70 keV	$E_{\beta2}$ < 230 keV	Δt < 70 d
2***	^{32}Si	β_1-β_2	$E_{\beta1}$ > 0.5 keV	$E_{\beta2}$ < 70 keV	25 d < Δt < 70 d
3	^{210}Pb	β_1-β_2	$E_{\beta1}$ > 0.5 keV	$E_{\beta2}$ < 70 keV	Δt < 25 d
4a	^{210}Pb	β_1-α	$E_{\beta1}$ < 70 keV	E_{α} < 5.4 MeV	Δt < 715 d
4b	^{210}Pb	β_2-α	$E_{\beta2}$ < 1.2 MeV	E_{α} < 5.4 MeV	Δt < 690 d
5	^{238}U, ^{232}Th	α-α	-	-	-

- *** Lower bound set on separation time criteria to remove ^{210}Pb events within search

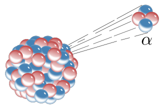
Further constraints are placed for final search criteria

1



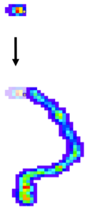
Events in same CCD; daughters in later images

2



Correct α and β classification for decay sequence

3

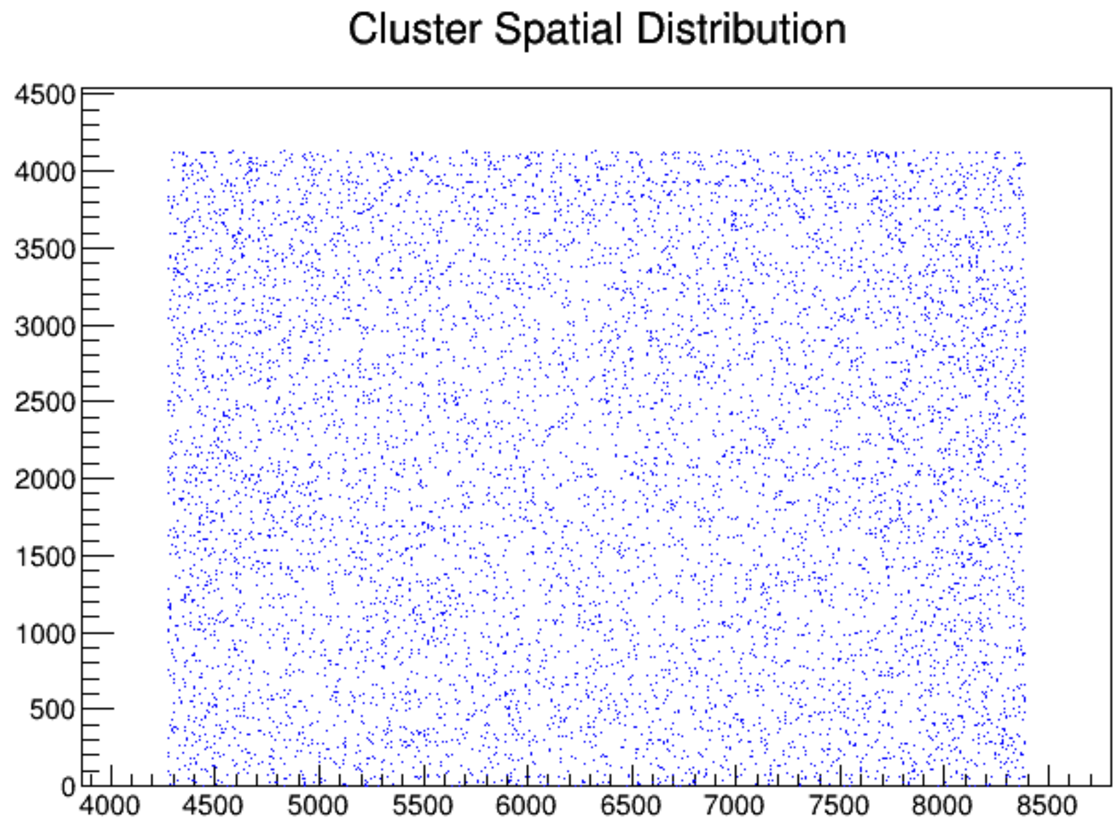


Clusters spatially coinciding, not in masked regions

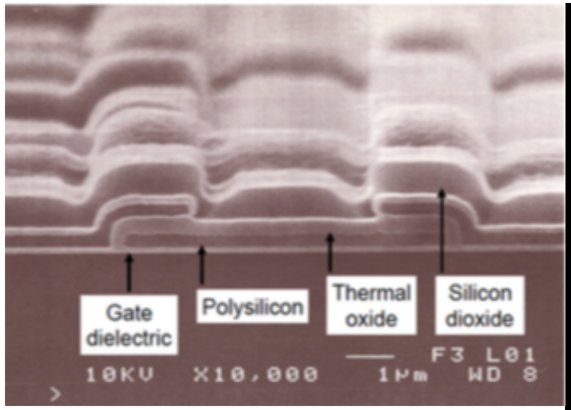
4

Sequences fit energy and time cuts from decays

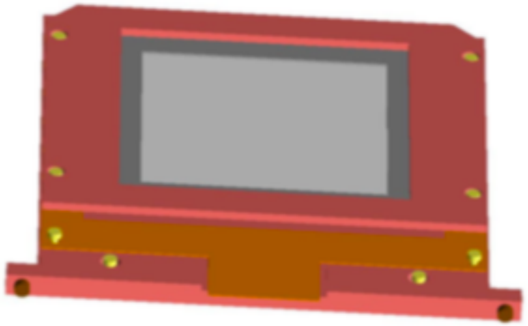
The number of sequences is adjusted for accidentals; Geant4 simulations and probability of seeing decays give search efficiency



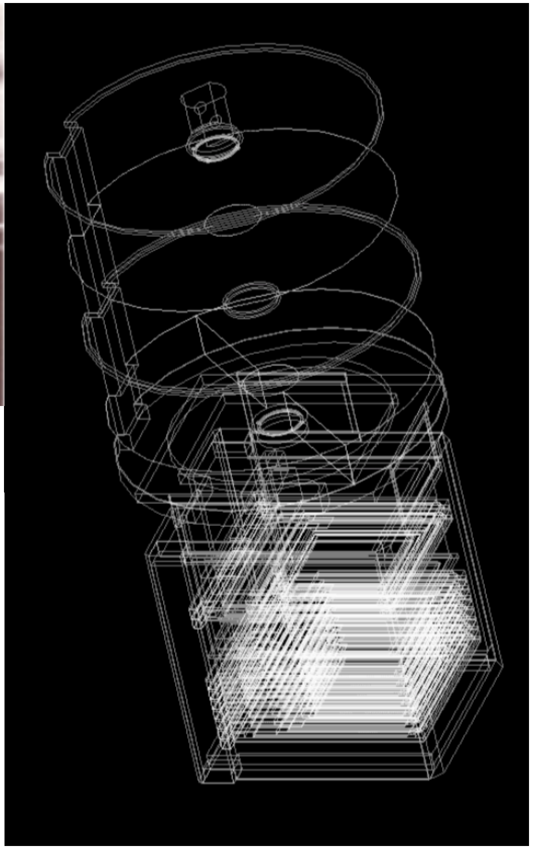
CCD top layer



CCD module



Geant4 geometry



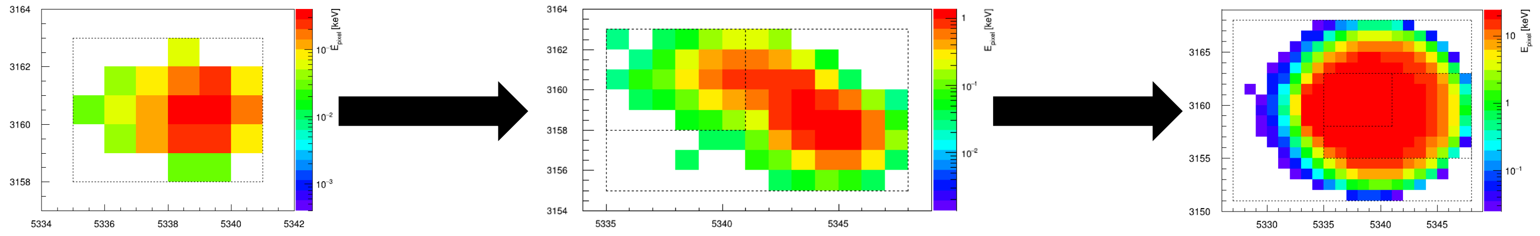
- Apply search criteria to many iterations of spatially-randomized data in order to estimate accidental events

The α's measured are consistent with the ^{210}Pb contamination rate, and ^{210}Pb β-β-α sequences are observed

- Expected α (central CCD stack): 276.3 ± 39.2 decays
- Observed α (central CCD stack): 279 decays

CCD Extension	Plasma α	Bloomed α	Total α
3	25	42	67
4	34	35	69
6	24	41	65
11	34	44	78

- Expected β-β-α: 1.9 ± 0.3 decay sequences
- Observed β-β-α : 4 decay sequences



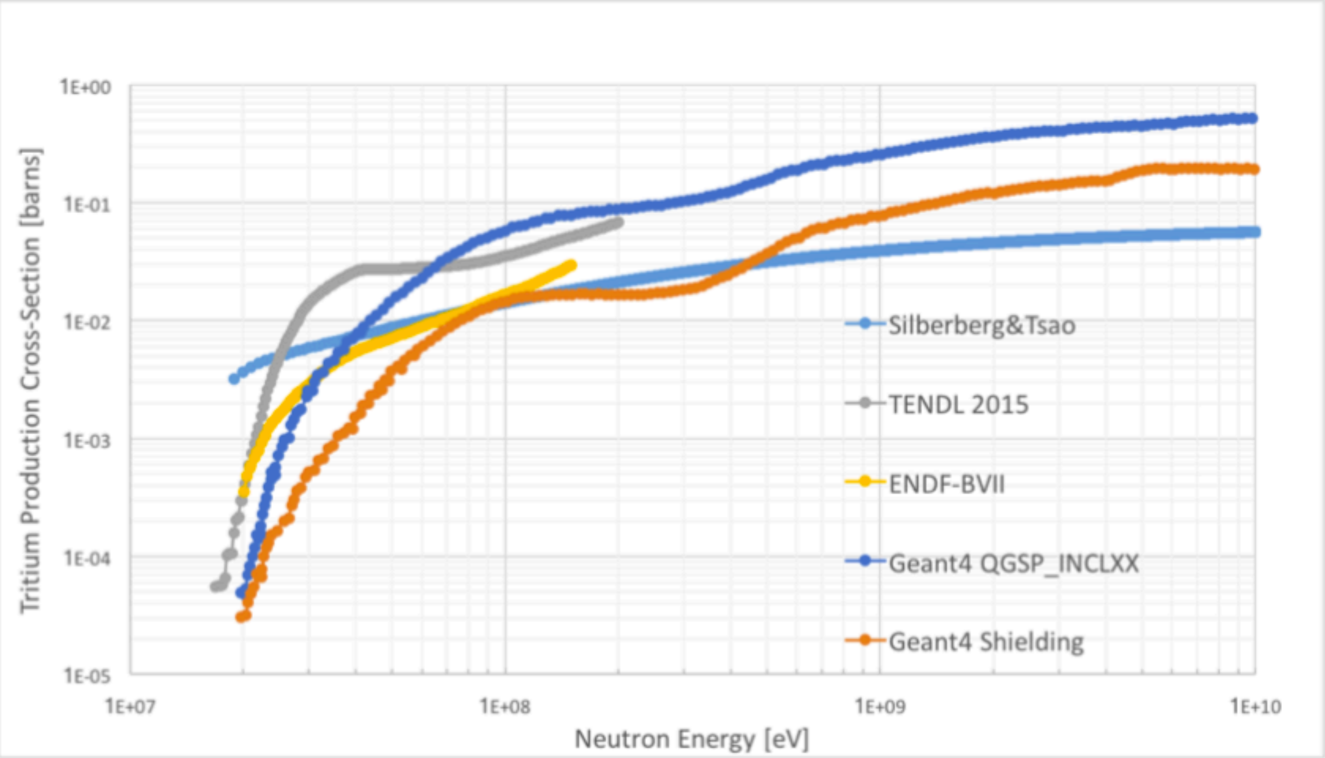
- $E_{\beta 1}$ = 4.4 keV
- $E_{\beta 2}$ = 41.4 keV
- Δt = 3.9 d

- $E_{\beta 2}$ = 41.4 keV
- E_{α} = 4.3 MeV
- Δt = 9.6 d

N_{CCD} = 6 (4 in central stack)
M = 5.9 g / CCD
t = 200.4 d
A_{CCD} = 36 cm^2

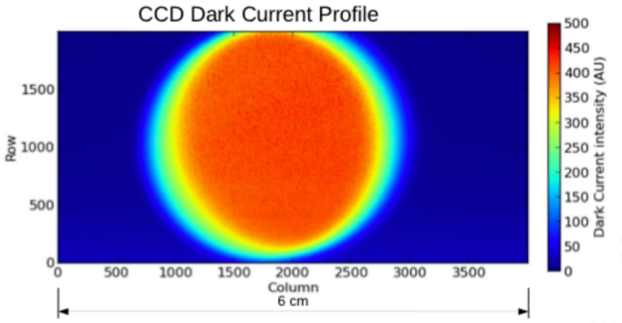
Estimating Cosmogenic Tritium Production in Silicon: Irradiating CCDs

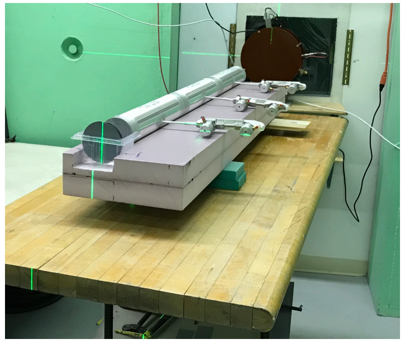
Tritium is an expected dominant background for future programs; we aim for the first direct measure of its production cross section



CCD	Beam Exposure (neutrons)
UW4204	6.16E12
UW4203	1.34E12
UW4202	3.68E12

Irradiation in September 2018



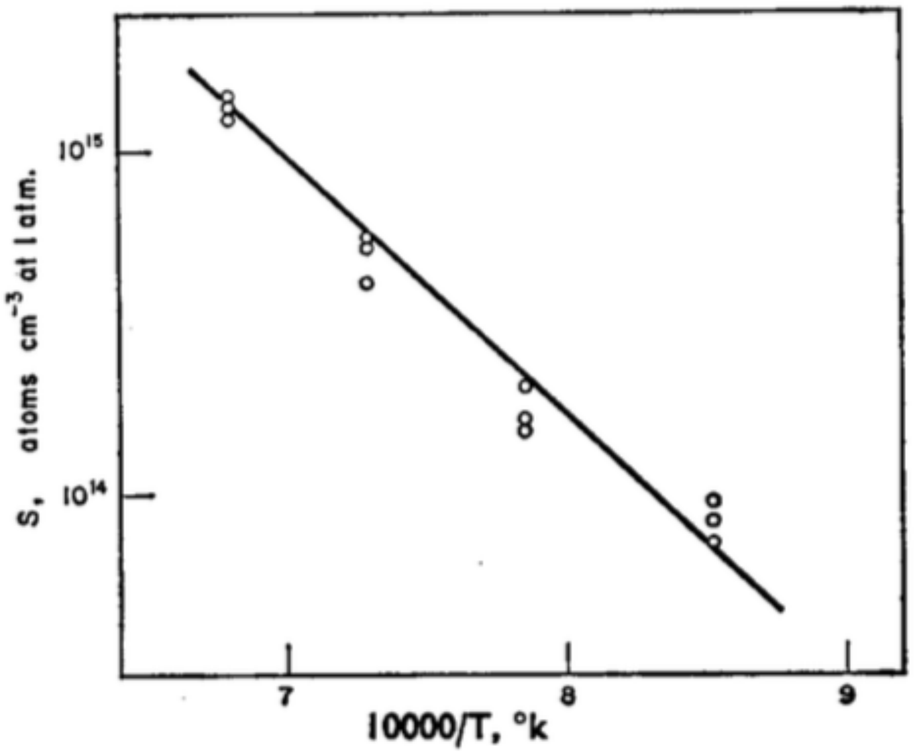


LANSCE 4FP30R beam setup

- No experimental measurements of ^{3}H production – estimates vary
- Direct measurement to improve sensitivity of dark matter experiments
- Irradiation of silicon wafers and CCDs at Los Alamos National Lab

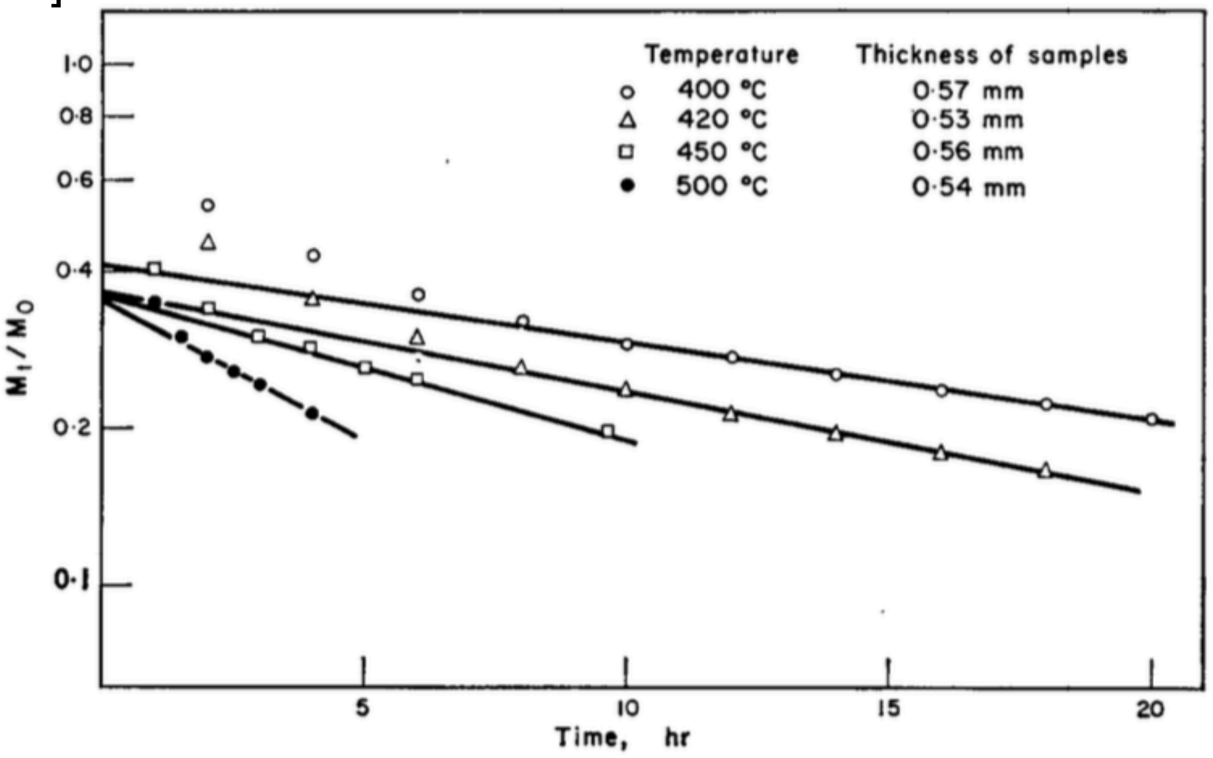
Past studies on the solubility and diffusion of tritium in silicon could open the door for further background reduction in DAMIC-M

Solubility of ^3H



Ref. [15]

Relative quantity of ^3H after baking

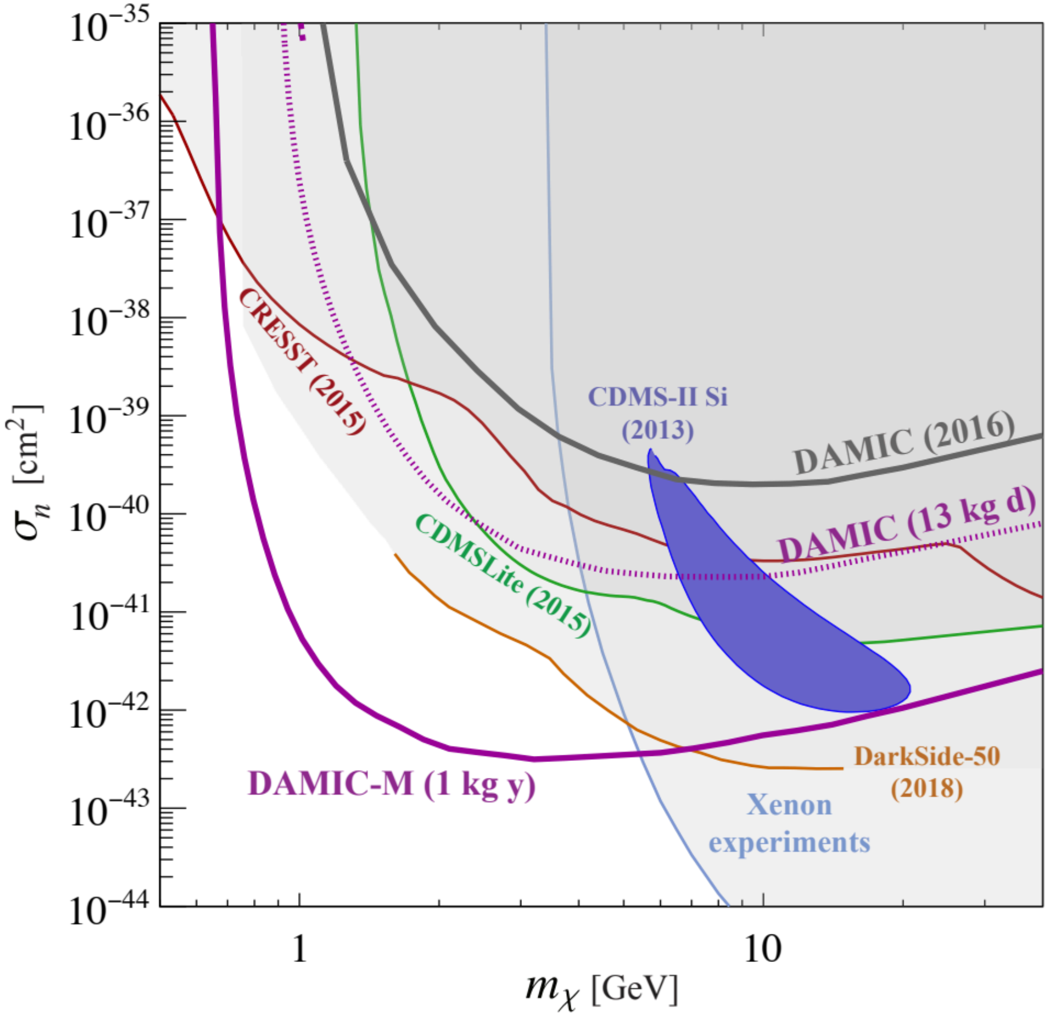


- ➢ Several steps in CCD fabrication process reach sufficiently high temperatures at which ^3H could diffuse out
- ➢ OKTEMIC wafer production opportunity: >1000 C wafer anneal after neutron transmutation doping
- ➢ Will complete analysis after baking tritiated wafers at Pacific Northwest National Laboratory

DAMIC-M

DAMIC-M projected sensitivity

WIMP-nucleus cross section



Dark photon sensitivity