DAMIC-M: Background and Dark Current Studies with Low Background Chamber

Radomir Smida
for DAMIC-M Collaboration

- Low Background Chamber (LBC)
- Skipper CCD
- Background
- Dark current

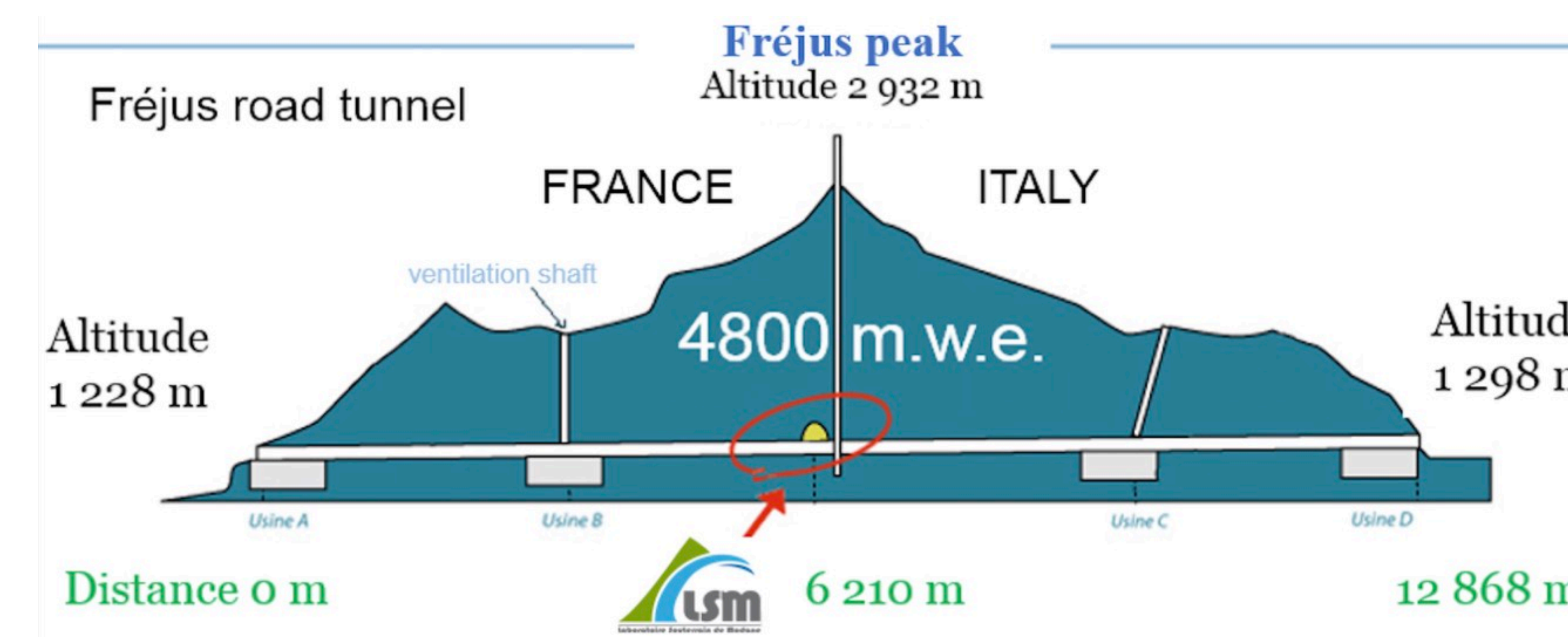
Low Background Chamber (LBC) at LSM

LBC is DAMIC-M prototype/test detector

1. Low background studies (materials, cleaning procedures, surface vs bulk, etc.),
2. Characterization of CCDs in low background environment (with a special attention to dark current and noise),
3. Cooperation with the Laboratory and other experiments,
4. Science results
   - *First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons*, PRL 130 (2023) 171003.
   - *Search for Daily Modulation of MeV Dark Matter Signals with DAMIC-M*, arXiv:2307.07251.
   - Other papers are in preparation.

TAUP talk by P. Privitera on Aug 31

Modane Underground Laboratory (LSM)

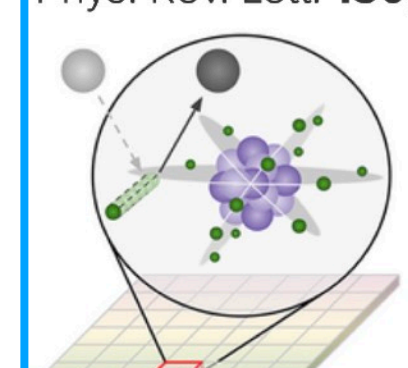


Editors' Suggestion

First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons

I. Arnquist *et al.* (DAMIC-M Collaboration)

Phys. Rev. Lett. **130**, 171003 (2023) – Published 28 April 2023

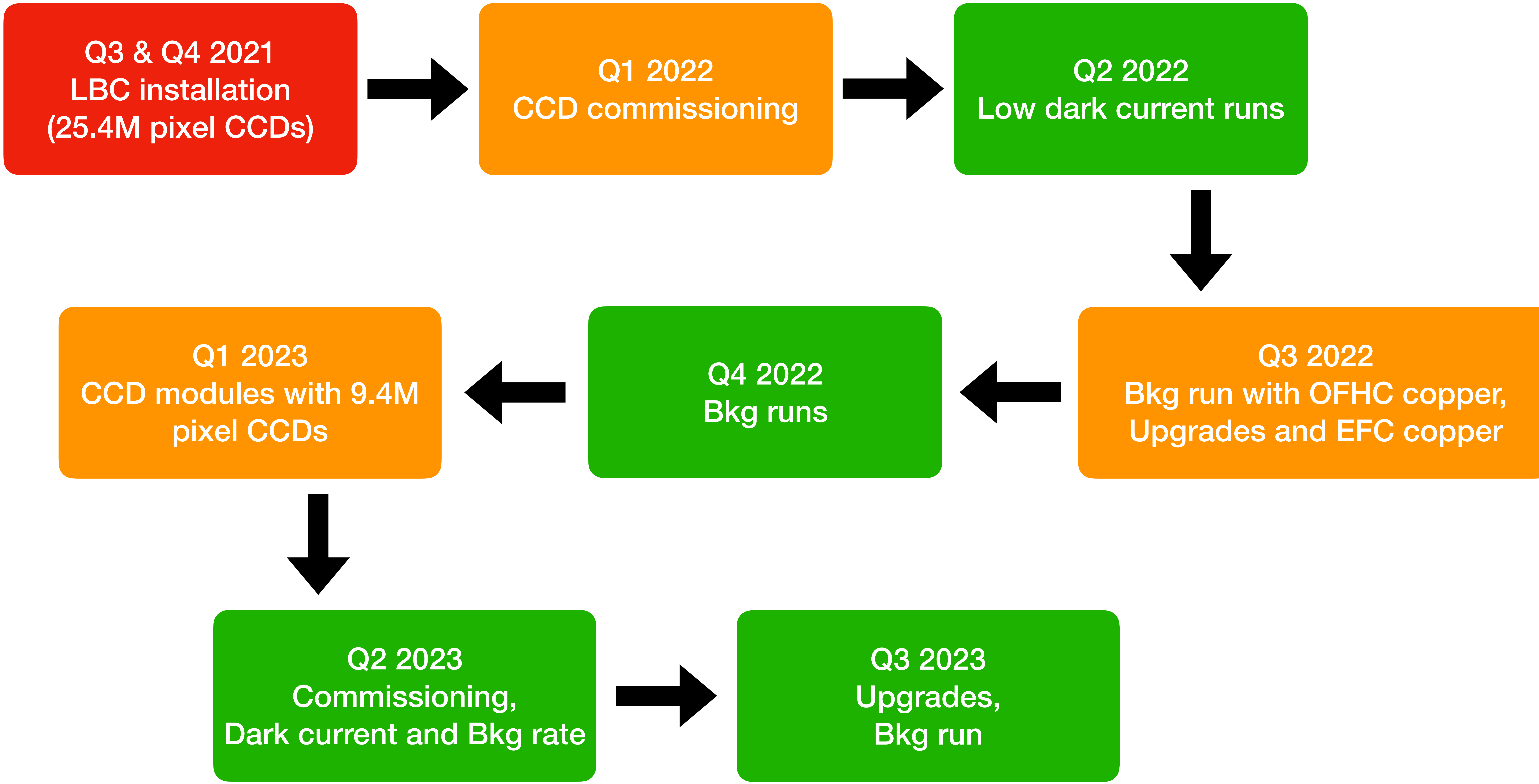


World-leading constraints are placed on electron interactions with dark matter in the MeV to GeV range by the first underground operation of a new CCD detector.

Show Abstract +

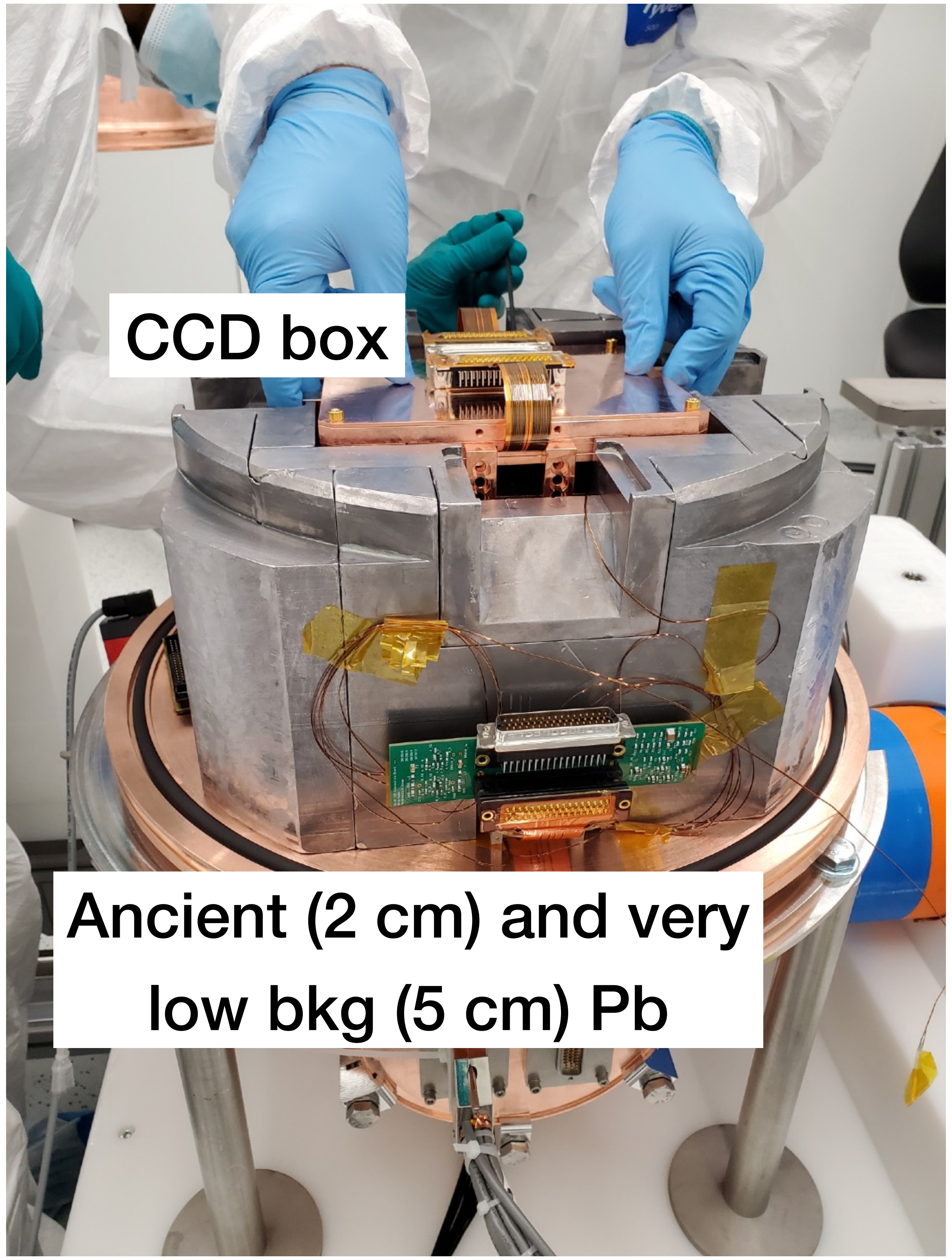
LBC timeline

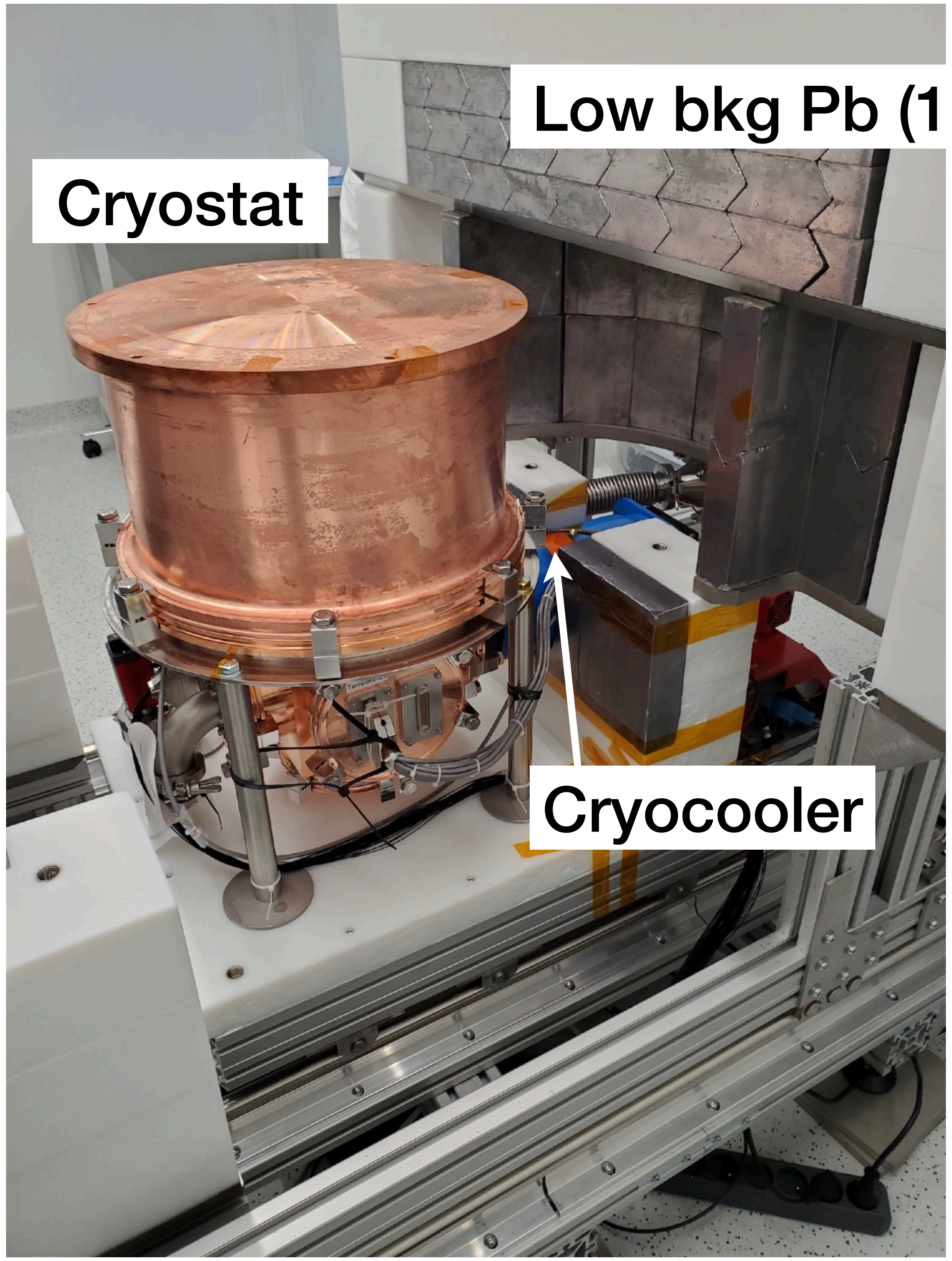
Complex schedule due to numerous and various goals.

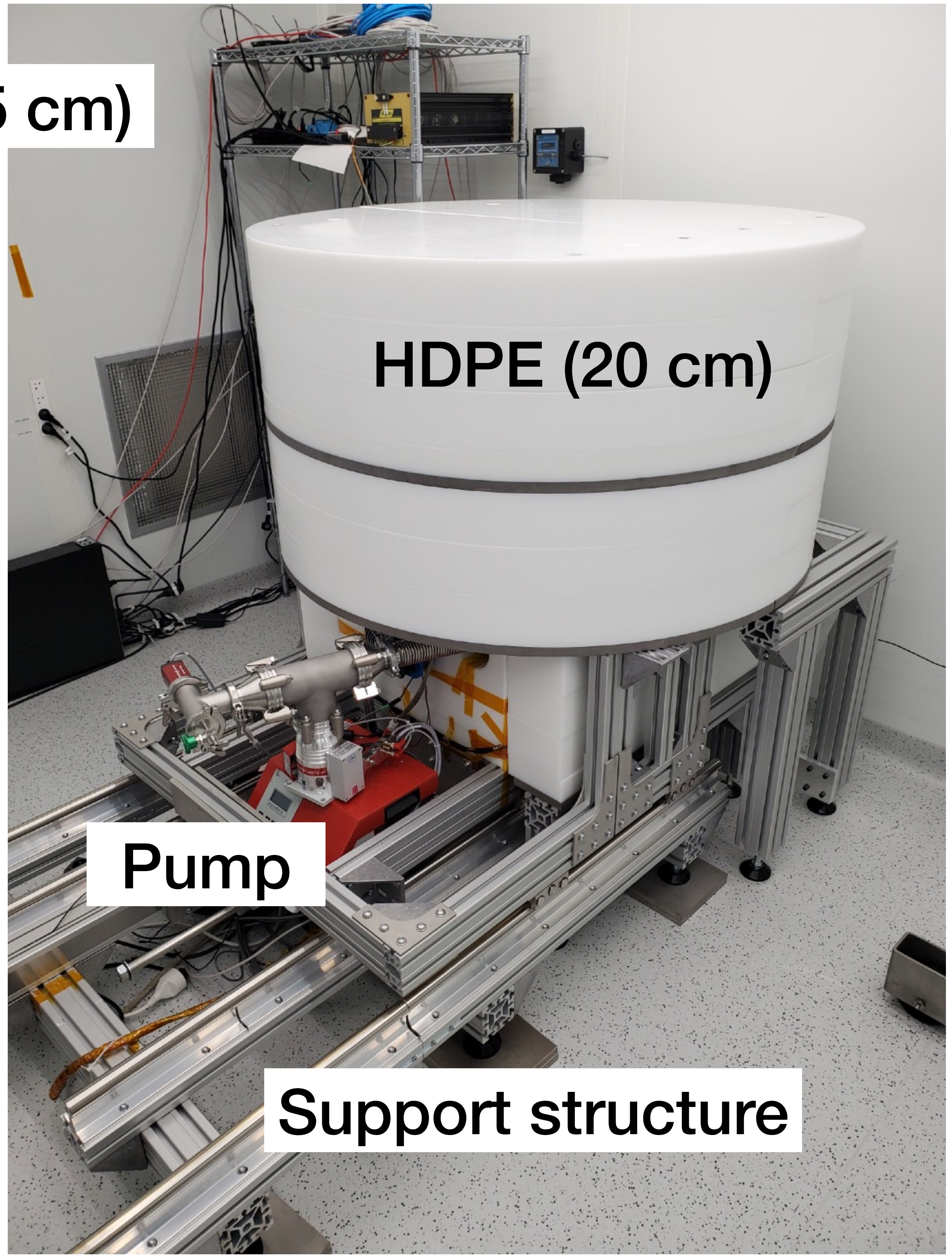


LBC detector

LBC went through several upgrades.







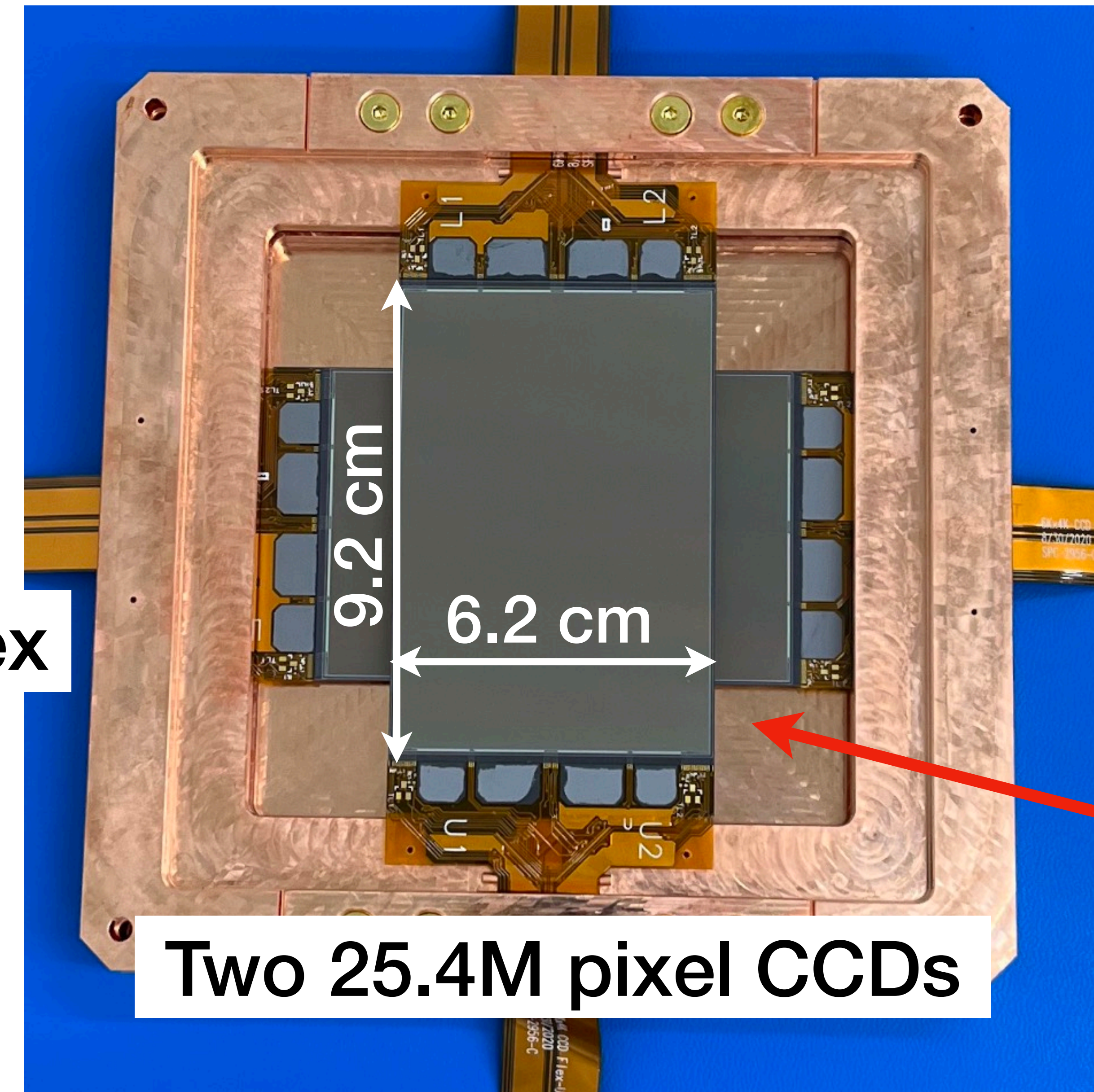
- CCDs in copper box are shielded from radioactive and IR background.

- Cleanest materials are closest to CCD devices.
- Temperature of cold copper is typically 120 K.

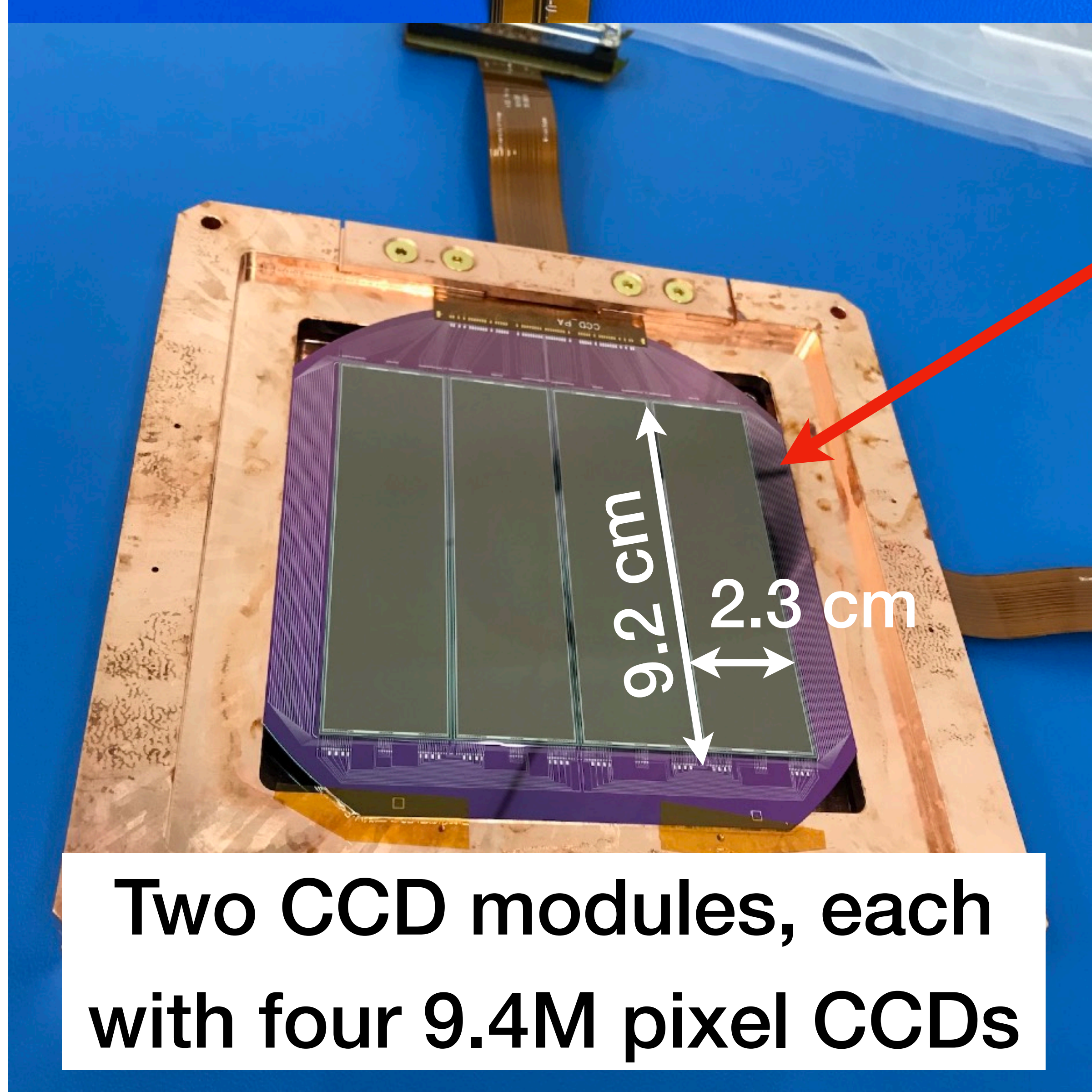
- Structure can be opened.
- Electronics and slow control system (cooling and vacuum).

CCD box

Flex



Two 25.4M pixel CCDs



Two CCD modules, each with four 9.4M pixel CCDs

The copper box includes frames, t-bars and lids.

No material between CCDs.

Box can accommodate CCDs of different formats:

1. Published papers use data measured by these two big CCDs (25.4M pixels, 4128 rows × 6144 columns, 8.9 g).

2. CCD module with four DAMIC-M pre-production devices. Each CCD has 9.4M pixels, 1536 rows × 6144 columns and 3.3 g.

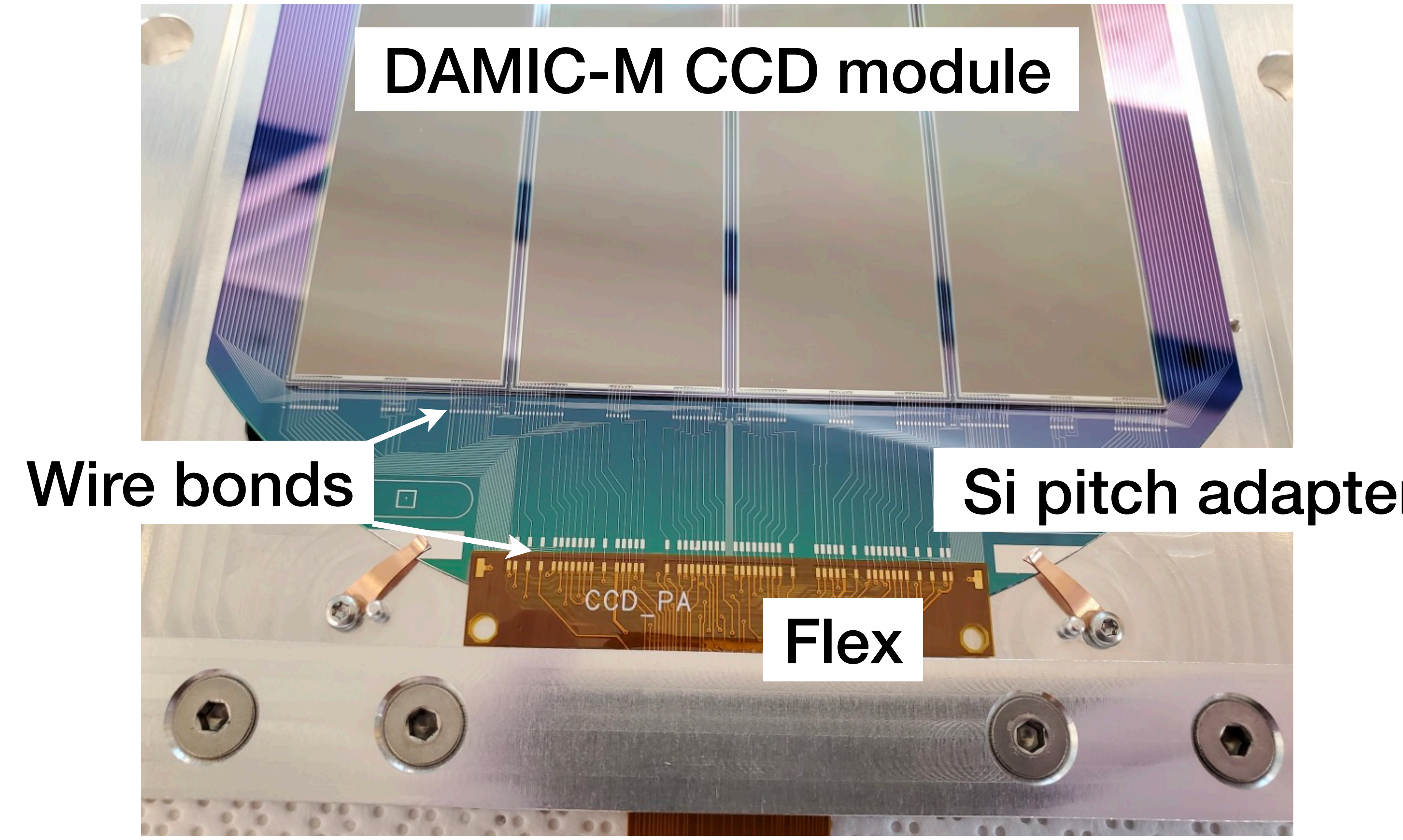
Silicon pitch adapter has traces delivering voltage clocks and biases from wire bonded CCD flex.

CCD devices

CCDs were designed by LBNL and fabricated at Teledyne DALSA.

CCD packaging at the Univ. of Washington

Pixel’s size 15 µm × 15 µm and 669 µm thick



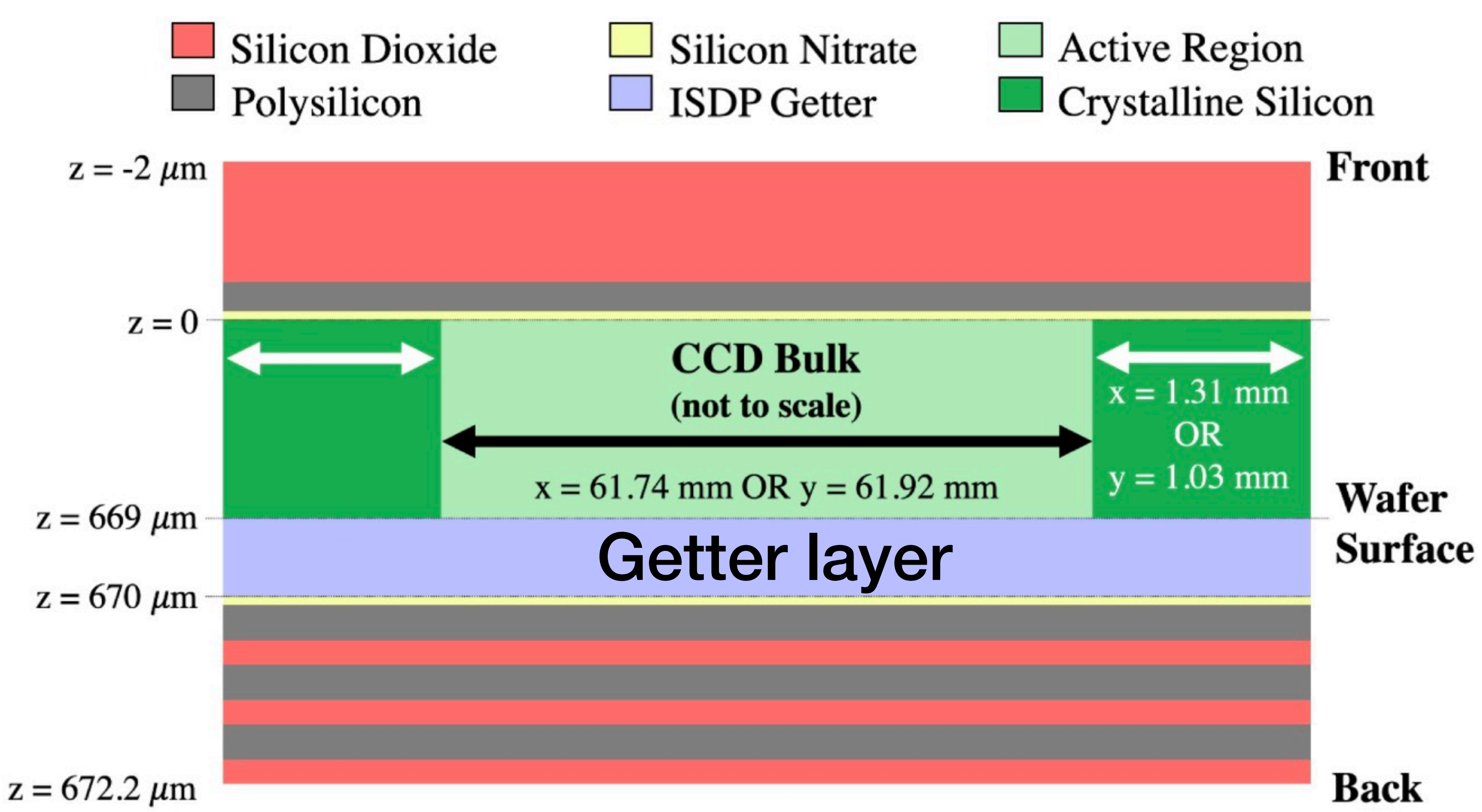


FIG. 6. Cross-section of the GEANT4 geometry of the DAMIC at SNOLAB CCD sensor, with each sub-layer colored according to the top legend. Key dimensions are indicated, with further detail in the text. PRD 105 (2022) 062003

Cross section of a CCD used in DAMIC at SNOLAB

The CCD bulk is fully depleted by applying the substrate voltage (V_{sub} = 45 V).

Free charge carriers collect in a p-type buried channel on the frontside.

Skipper CCD

Image shows a CCD corner with a skipper amplifier.

Free charge carriers produced in the bulk accumulate in the buried channel below pixels during the exposure.

Readout of charge in pixels

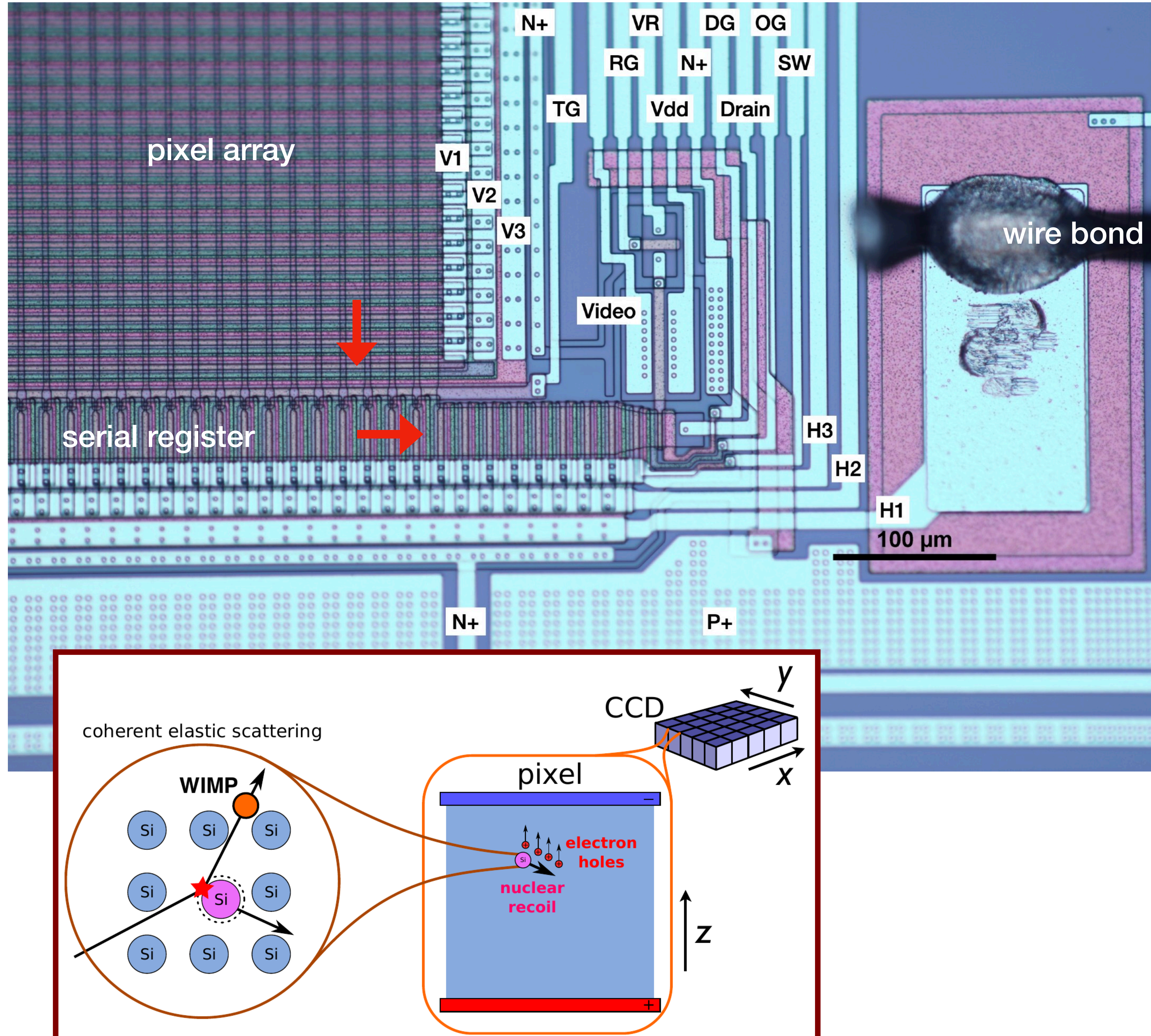
Pixel array

↓

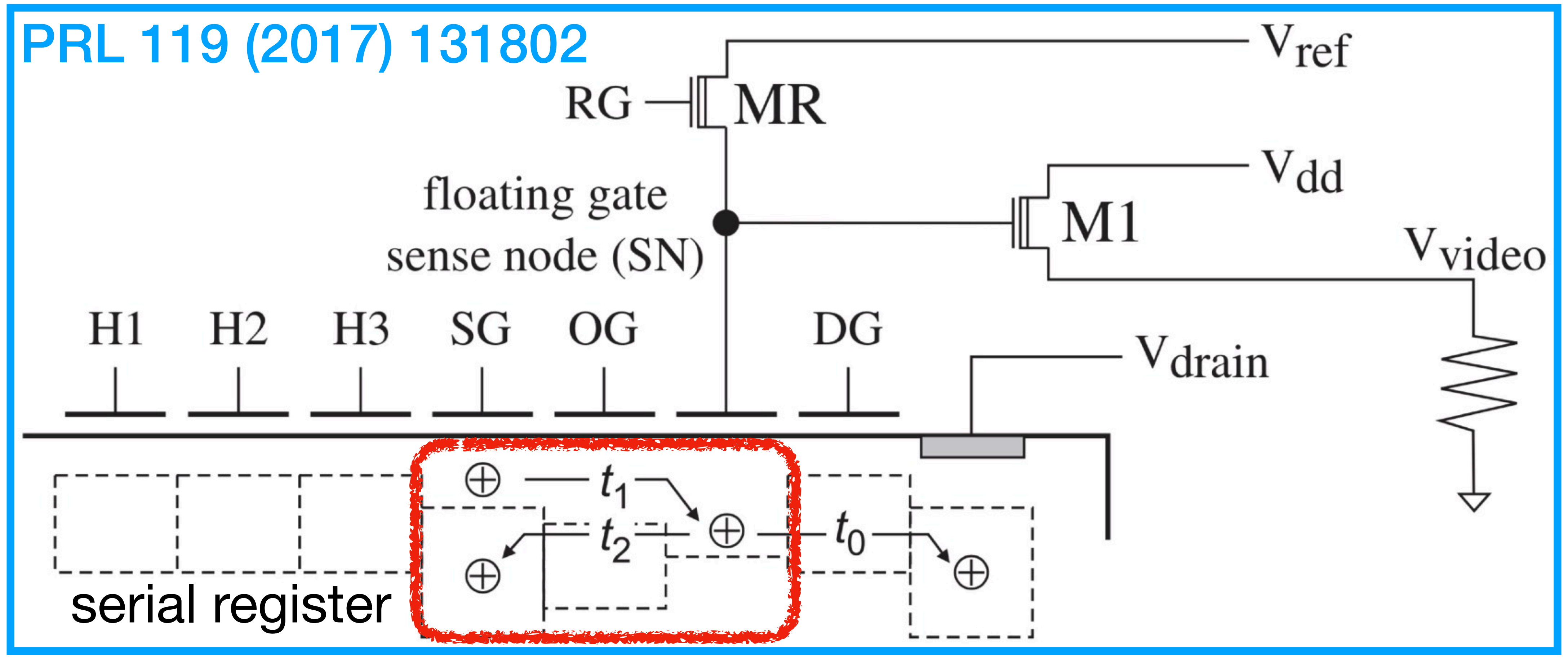
The charge is moved by clocking 3-phase V and H voltages.

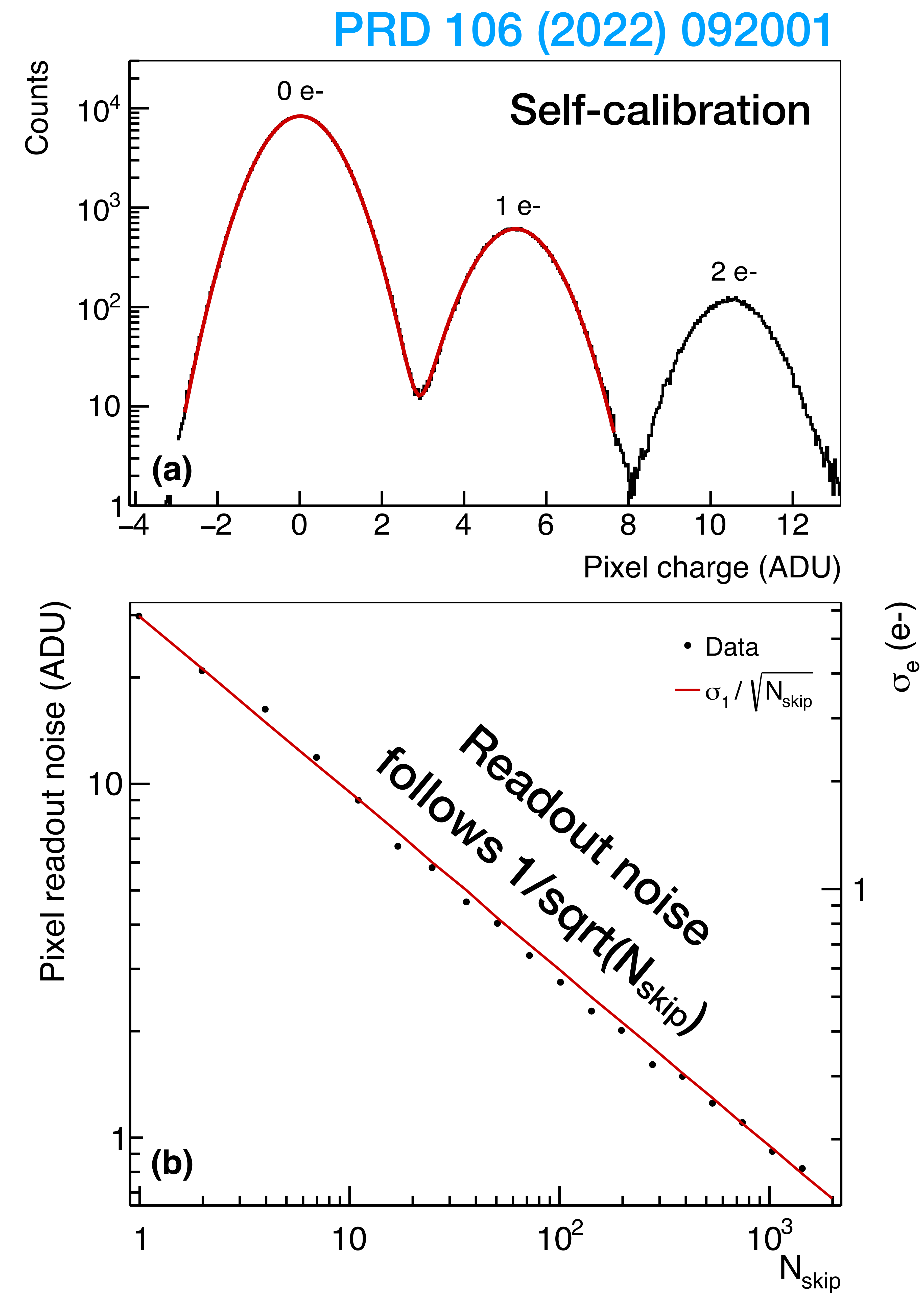
↓

Skipper amplifier



Skipper readout





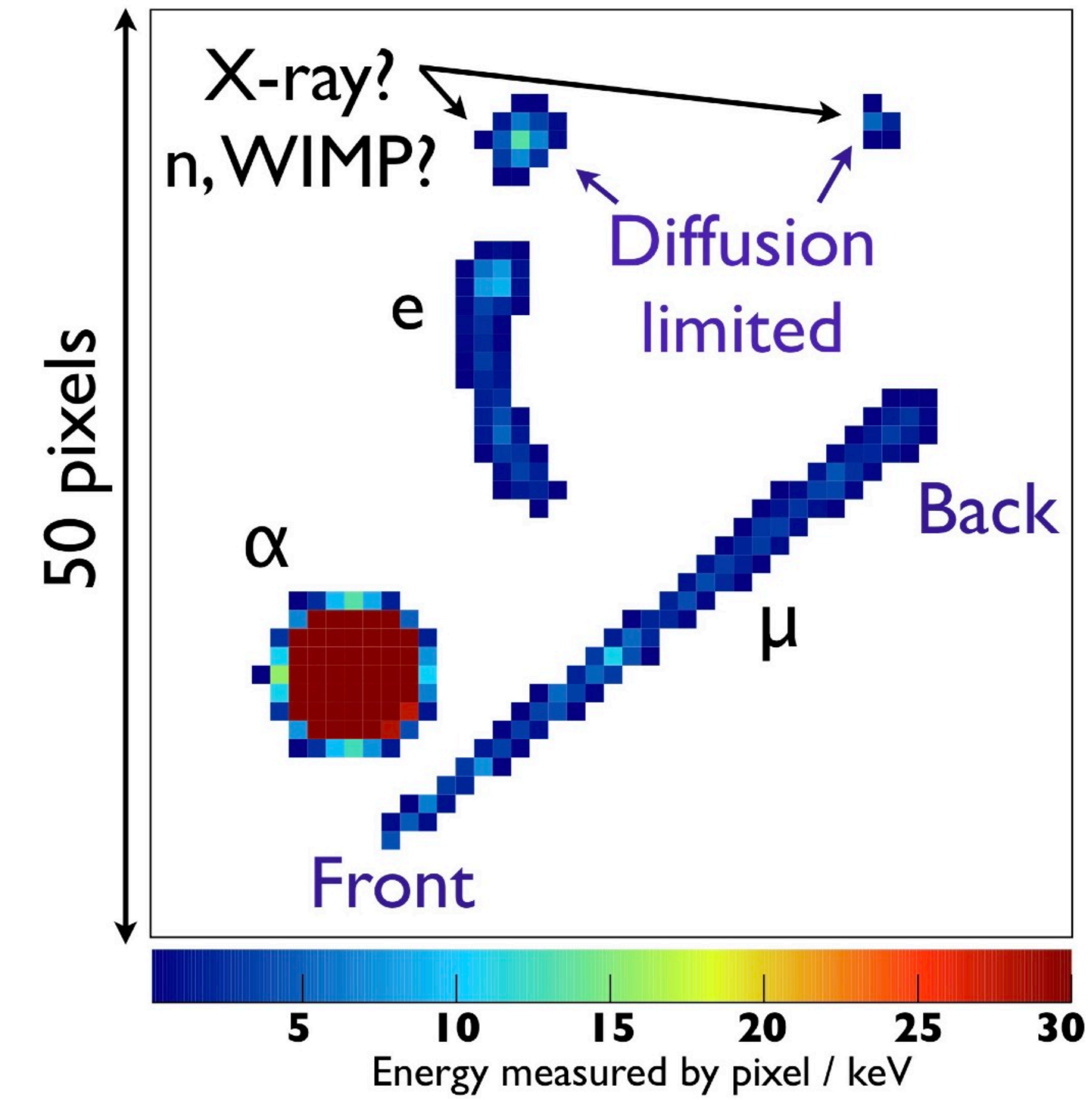
Multiple non-destructive charge measurements (skips) reduce the readout noise as ~1/sqrt(N_{skip}).

But readout time is much longer than in a standard CCD (~N_{skip}). Summing charge from more pixels (or binning) speeds up the readout.

Optimization of voltages and timings reduces noise, eliminates charge transfer inefficiency (CTI) and amp glow.

Background (Bkg)

- CCDs provides exquisite spatial resolution (15×15 μm² pixels) and charge diffusion allows 3-D reconstruction => particle identification.

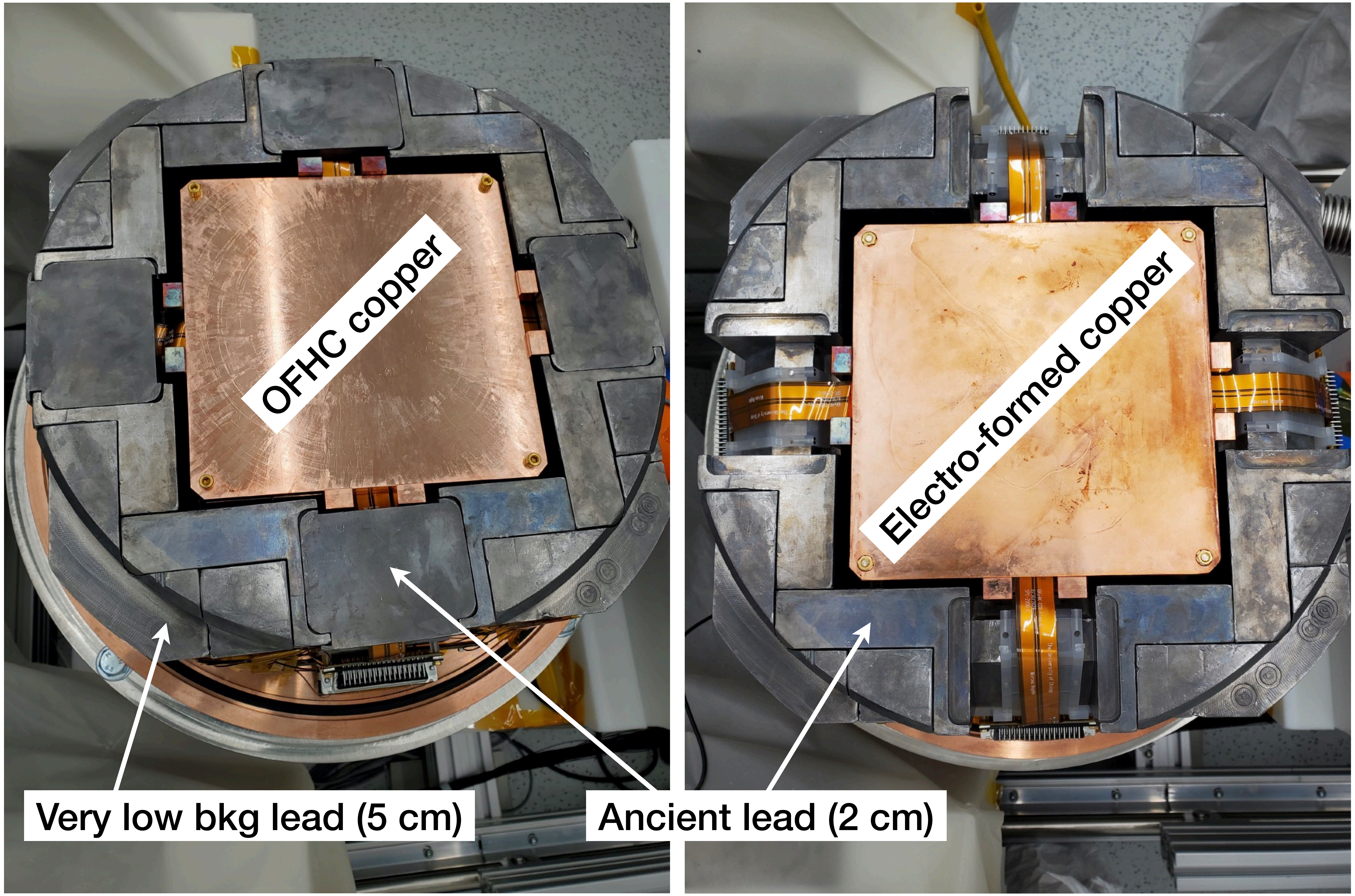


- Low background studies for full-scale DAMIC-M detector are among LBC goals.

- Bkg mitigation efforts were less strict than are planned for the full-scale DAMIC-M detector (e.g. cosmogenic activation of CCDs and copper).

- Bkg studies are ongoing work. Not enough statistics due to other priorities and modifications of the detector.

CCD box lids



CCDs face directly the lids.

EFC was grown and machined by LSC.

All parts were chemically cleaned.

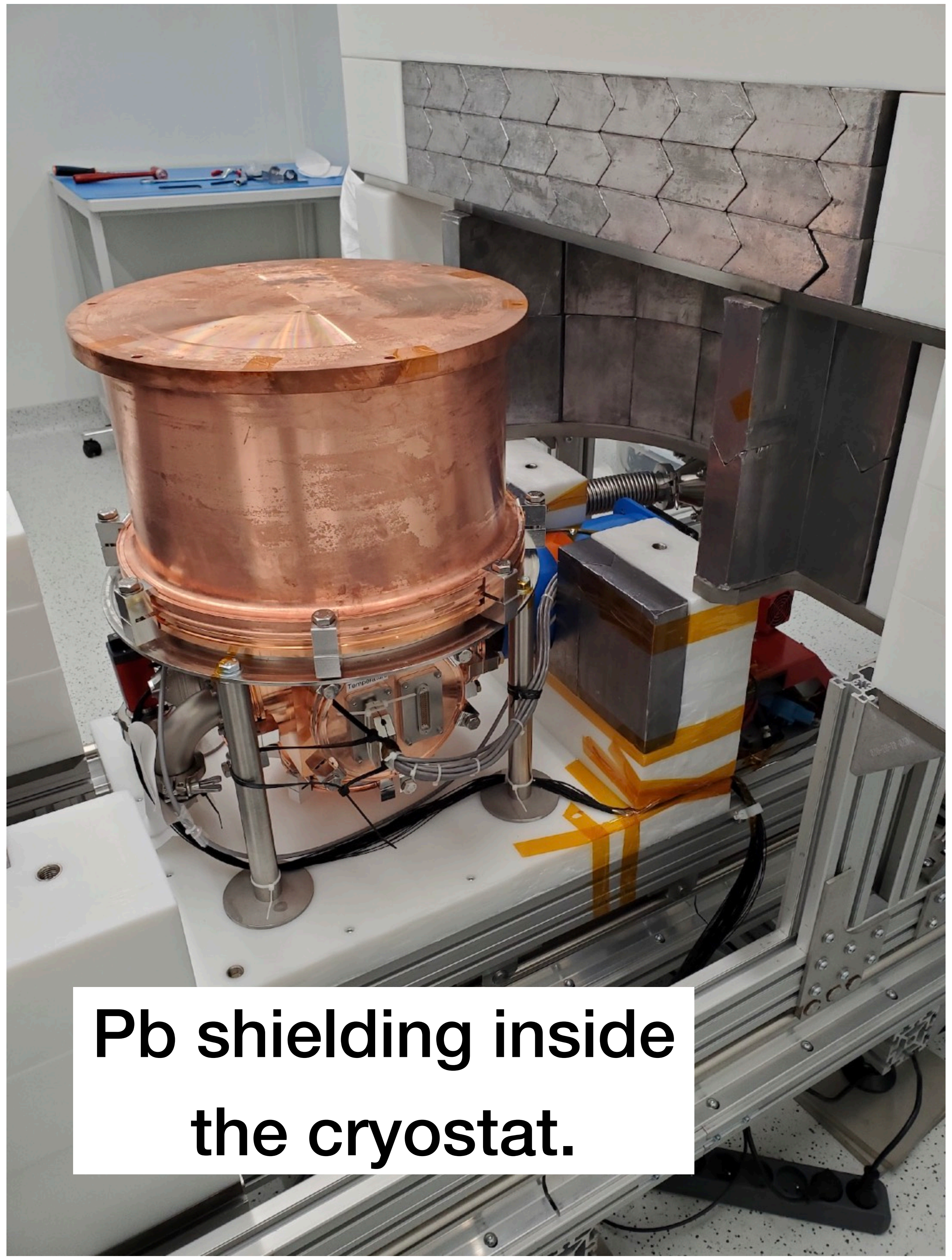
Assay measurements with HPGe, ICP-MS and XIA.

Light tightness has been improved with Cu foil, which was stored at LSM for 5+ years.

PRELIMINARY results with OFHC copper lids: ~9.5 dru (1-20 keV), ~1 clusters/g/d (E>1 keV), alpha rate ~4e-3/cm2/d per CCD side.

External neutrons and gammas

Measurements with open and closed external shielding



Gammas are major background in the open configuration.
Data are compared with our GEANT4 simulations.

Outlook

Background rates for EFC copper lids and CCD modules.

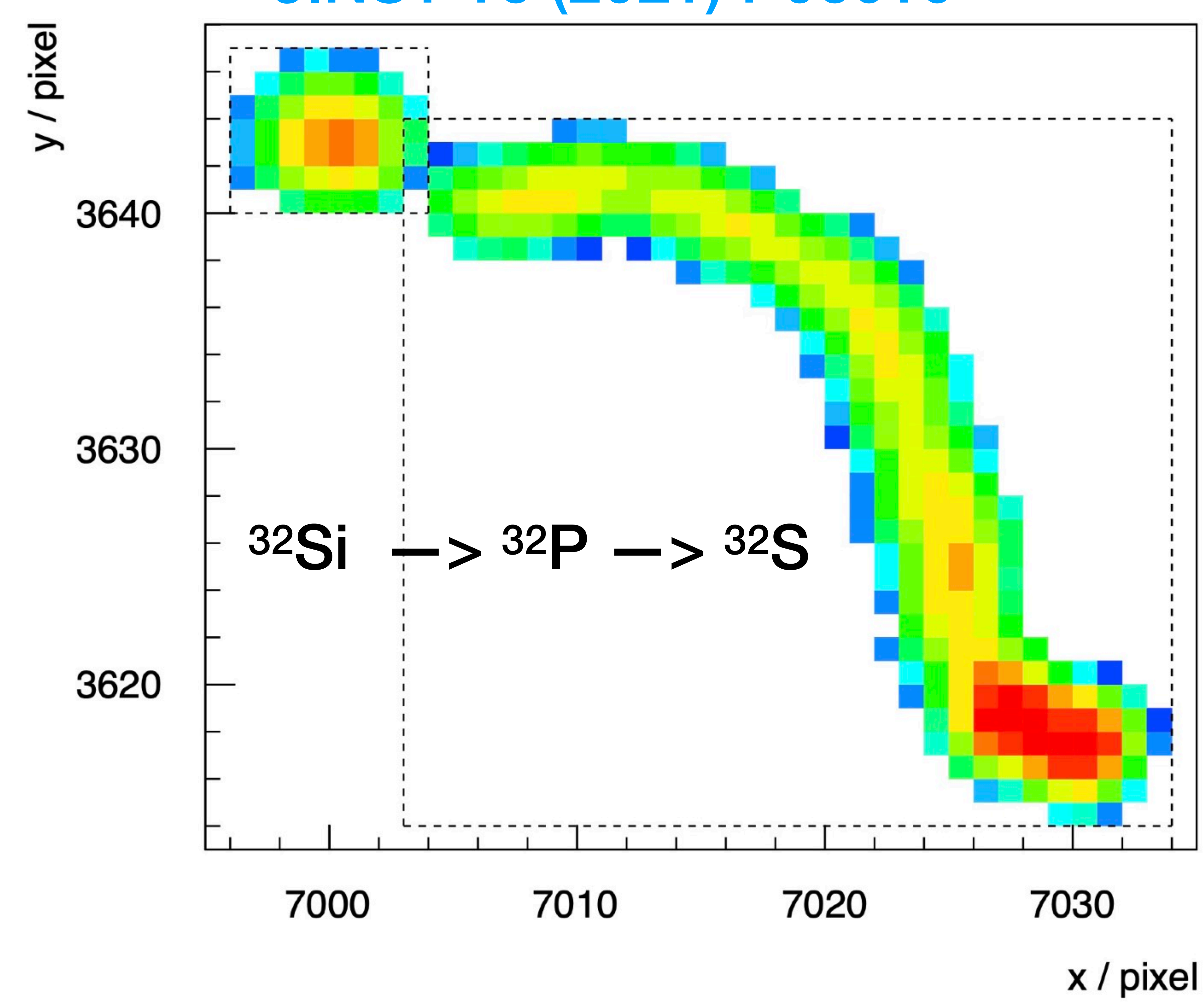
Alpha rates in the both CCDs.

Studies requiring continuous months-long data taking and developing a background model:

- Spatial and time coincidences (decay chains, e.g. 32Si and 210Pb)
- Low-energy excess measured by DAMIC at SNOLAB (PRD 105 (2022) 062003 and arxiv:2306.01717).

EXCESS talk by M. Traina today,
TAUP talk by A. Chavarria on Aug 31

JINST 16 (2021) P06019



Dark current (DC)

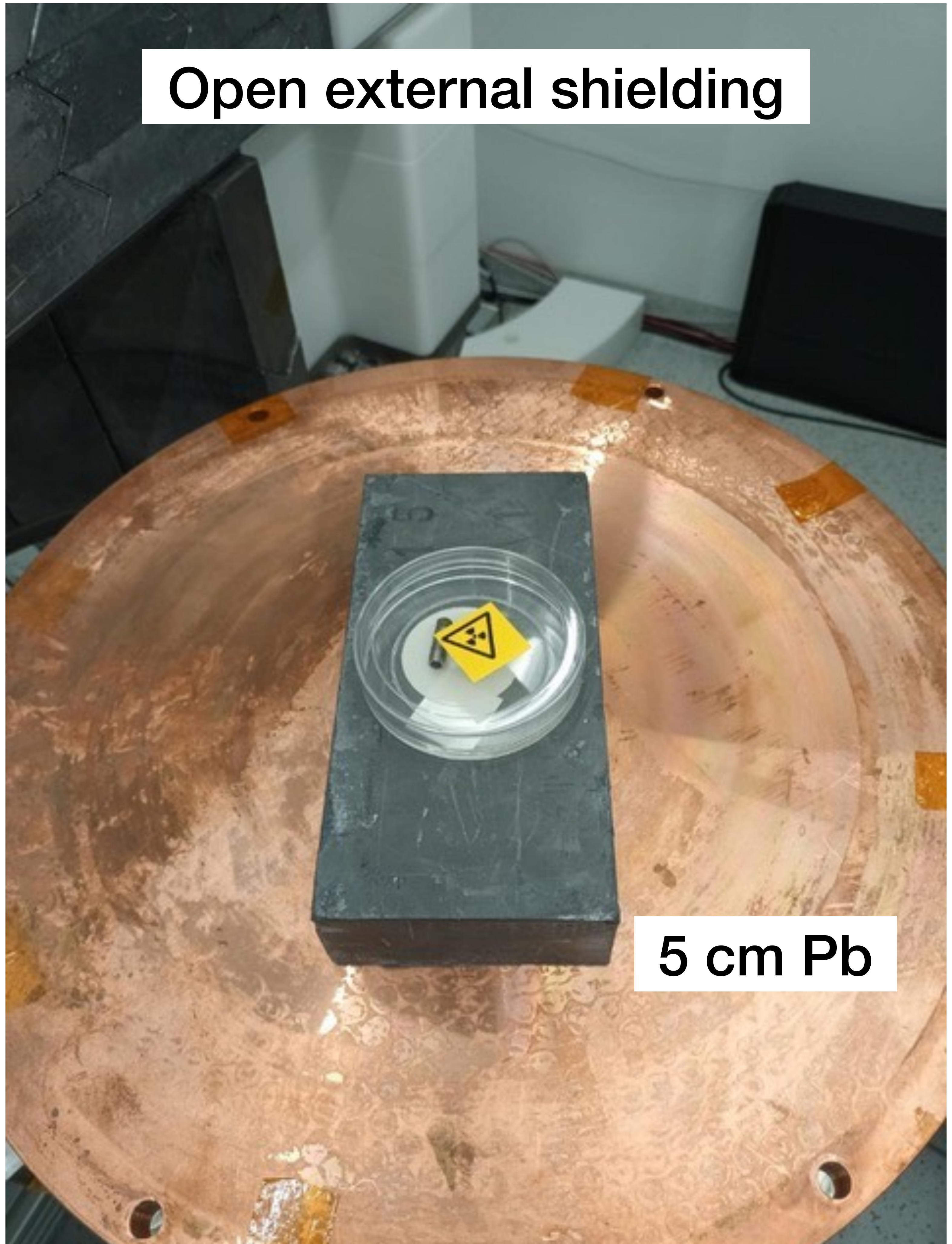
Goal: DC below 1e-4 e^-/pix/d.

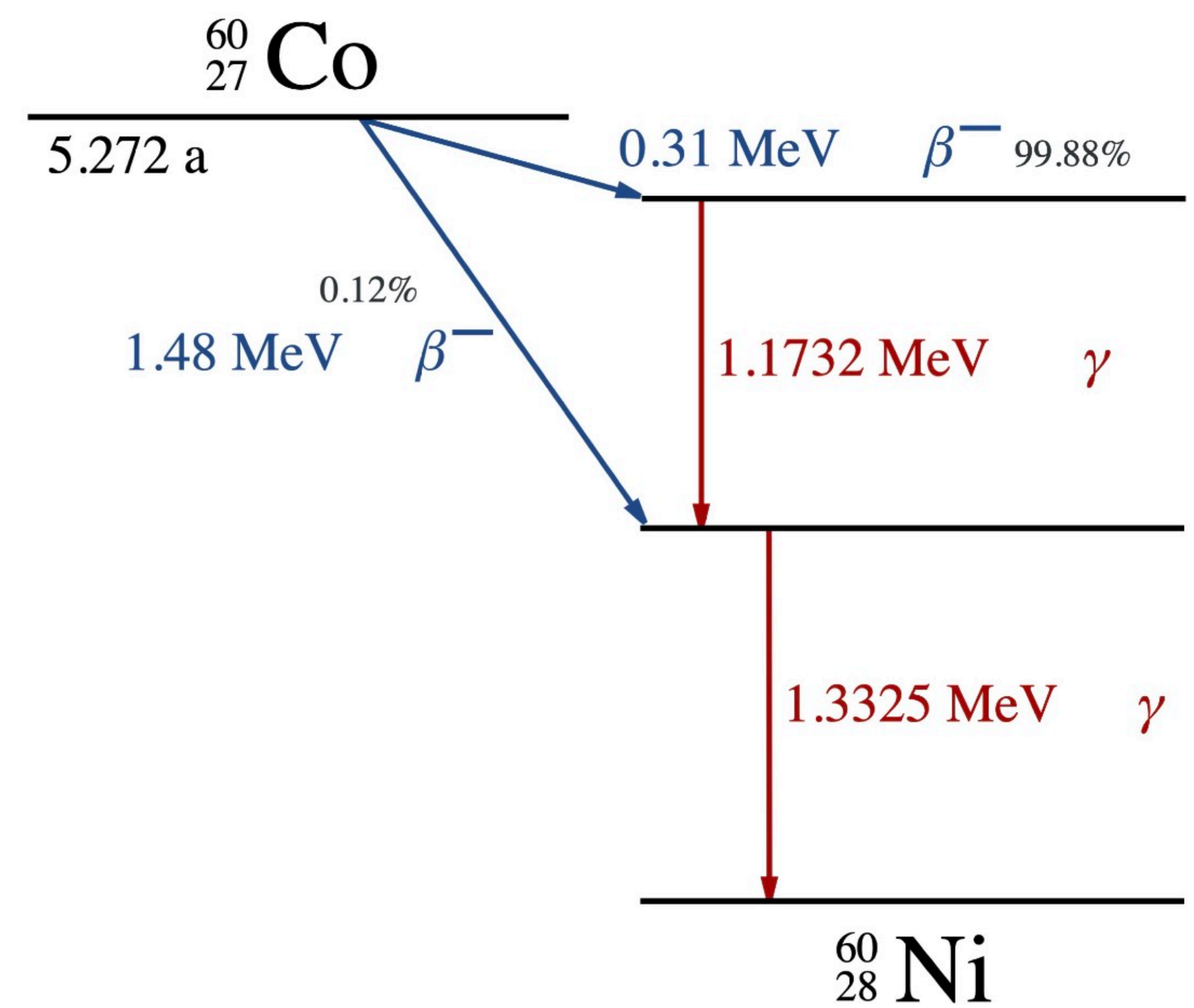
Extensive study of thermal cycles, startup and erase procedures, clock-induced charge, charge transfer inefficiency, amplifier glowing, flushing serial register, etc.

Presentation about nuclear recoil induced defects at TAUP (R. Smida on Aug 28)

Two measurements of DC increase during/after irradiation

Measurement with ^{60}Co



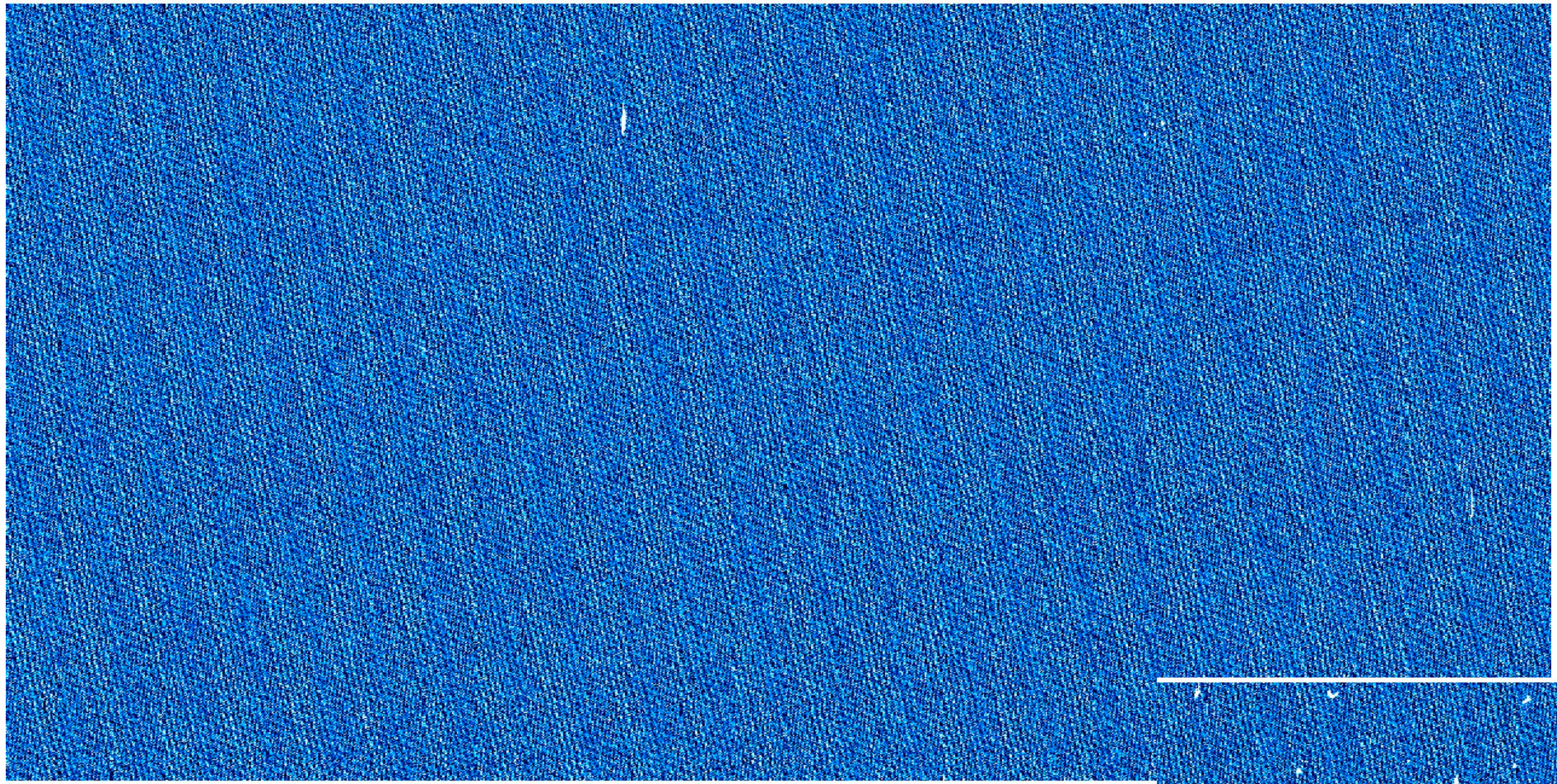


^{60}Co emits two gammas: 1.17 and 1.33 MeV

Attenuation by Pb inside the cryostat and Pb added below the source.

Seven source configurations between May 31 and Jun 25. Some of them were repeated.

Background images



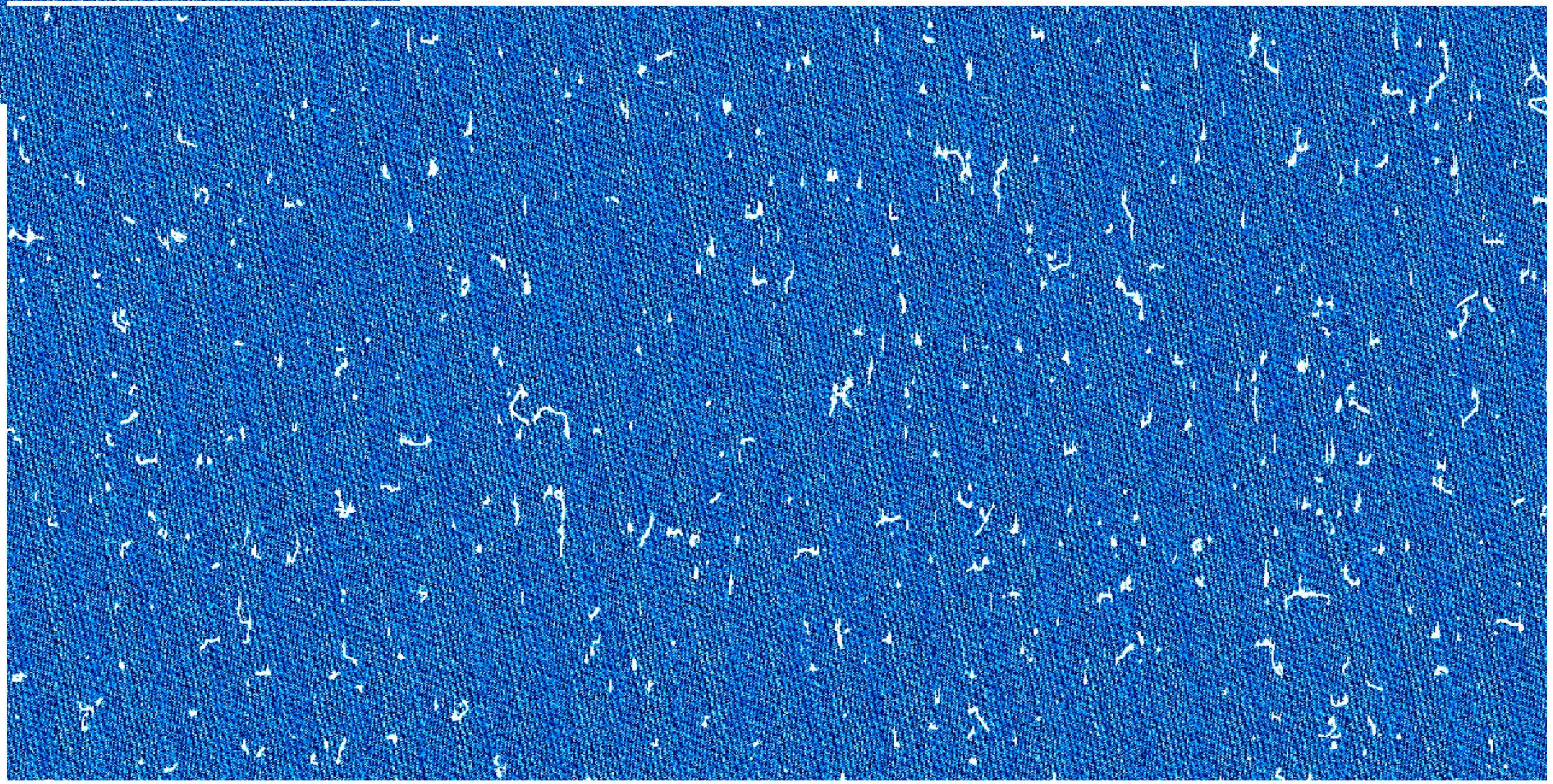
Images: Full CCD, long exposure (reduced for high particle fluxes), no binning and fast readout.

Bkg rate in ev./g/day (E>1 keV) or dru for 1<E<20 keV.

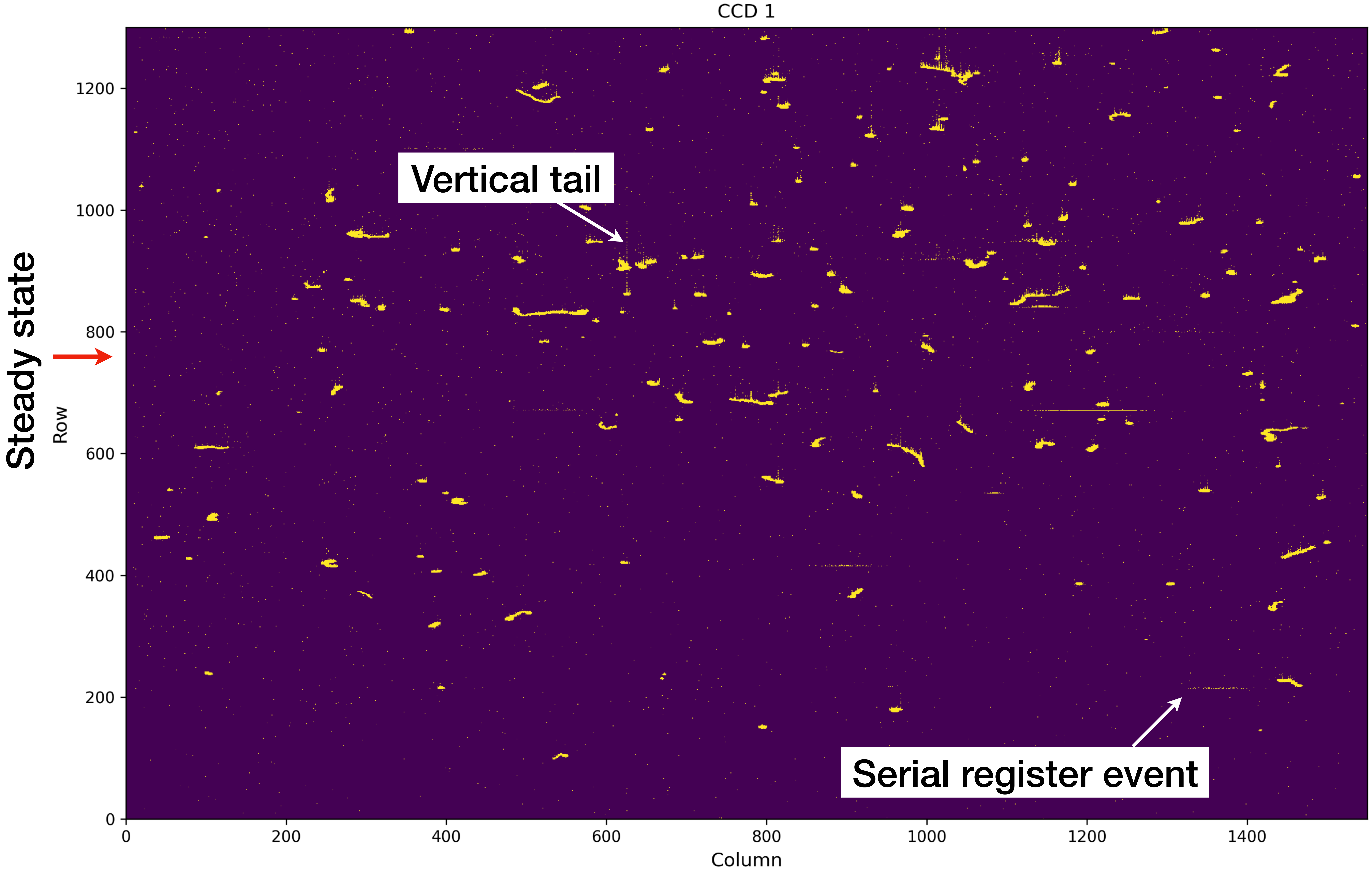
No ^{60}Co source
Rate (E > 1 keV) ~10 ev./CCD/h

^{60}Co without added Pb below it
Rate (E > 1 keV) ~950 ev./CCD/h

Opened external shielding!



Continuous readout



^{60}Co with 2.8 cm Pb

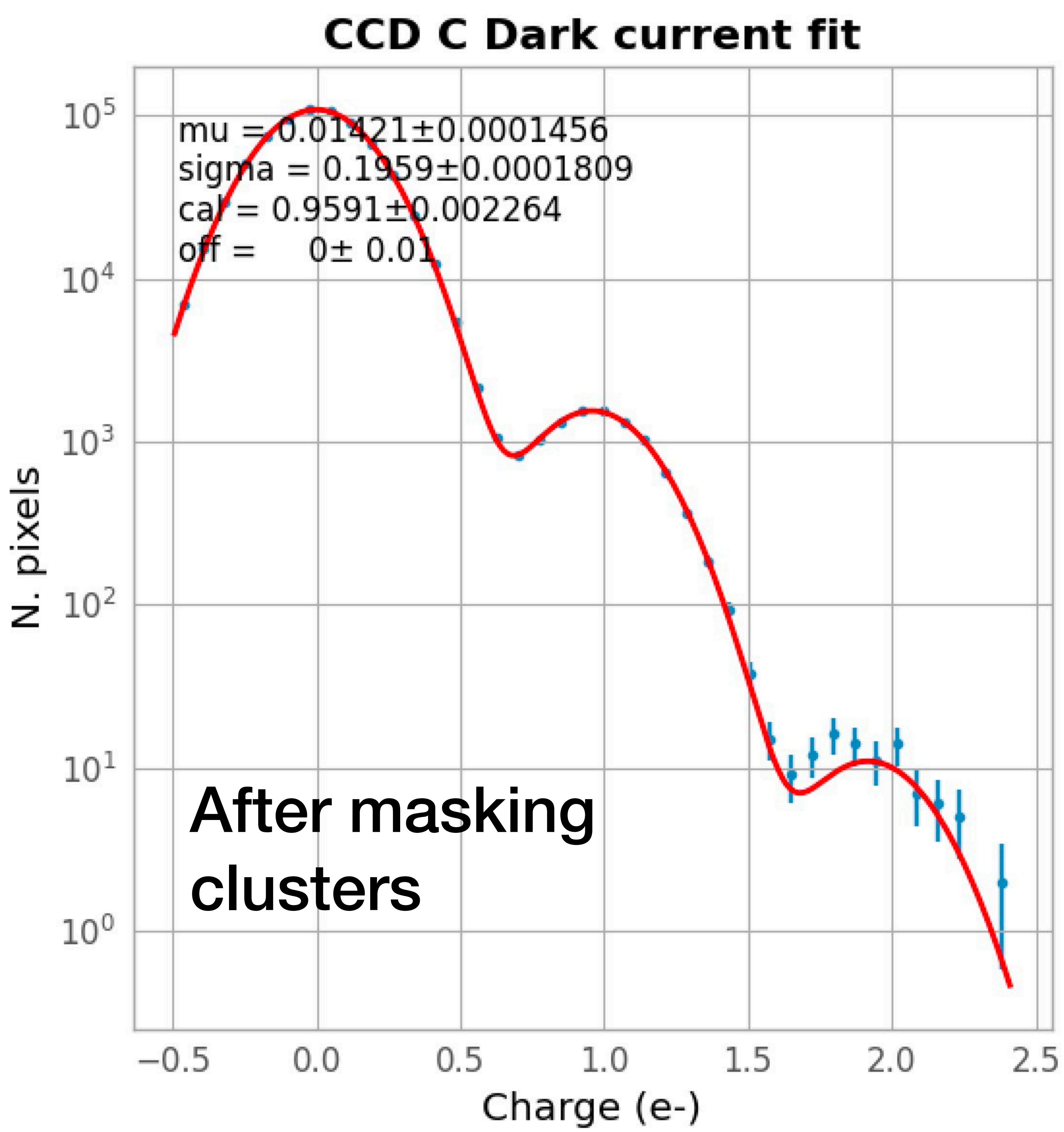
Pixels with non-zero charge are yellow

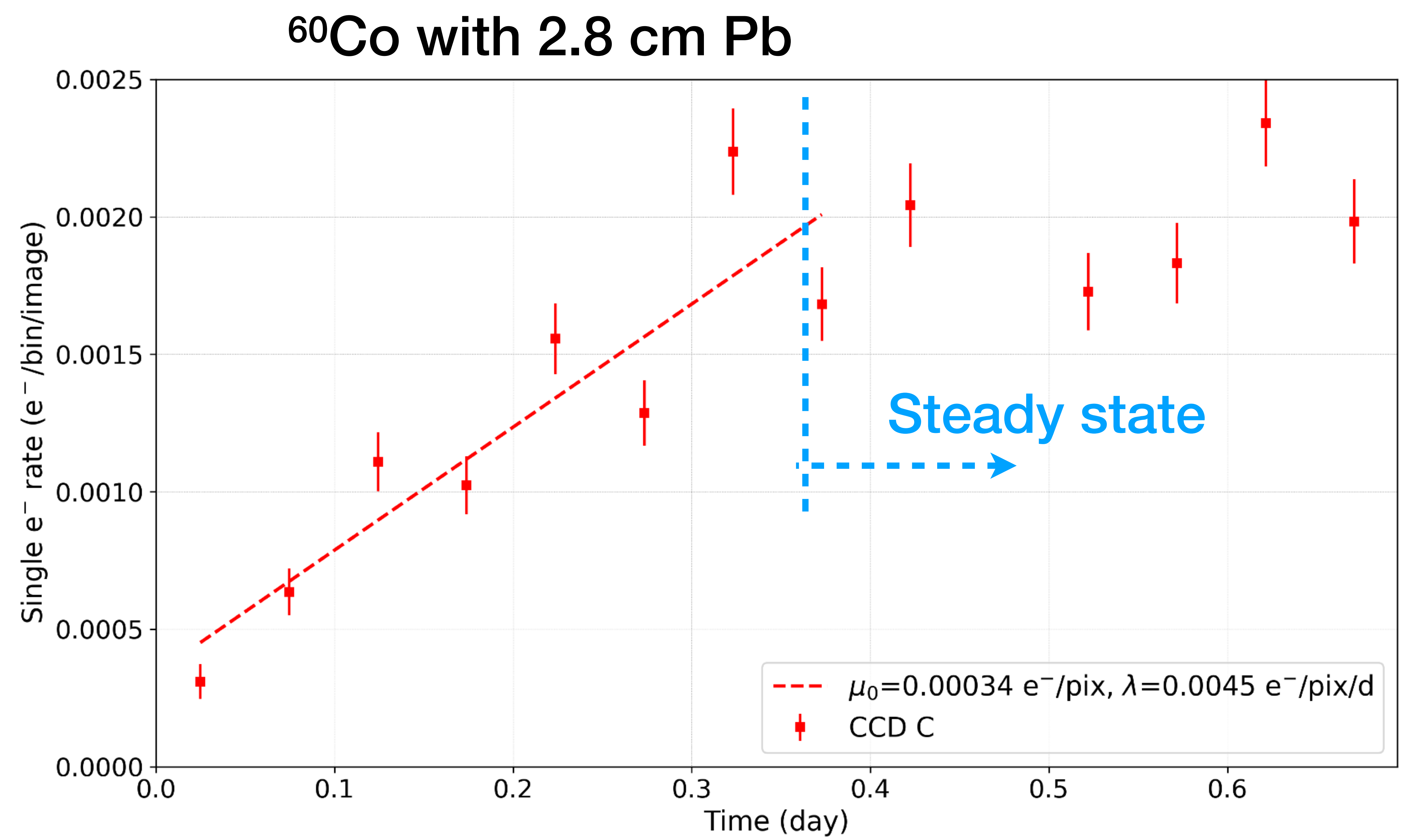
Parallel binning 2x

Vertical tails are caused by charge traps slowly releasing accumulated charge.

Dark current images

Continuous readout, reading 1/4 of columns, 100 rows per image with parallel binning 2x, and 1000 skips (resolution 0.2 e-)

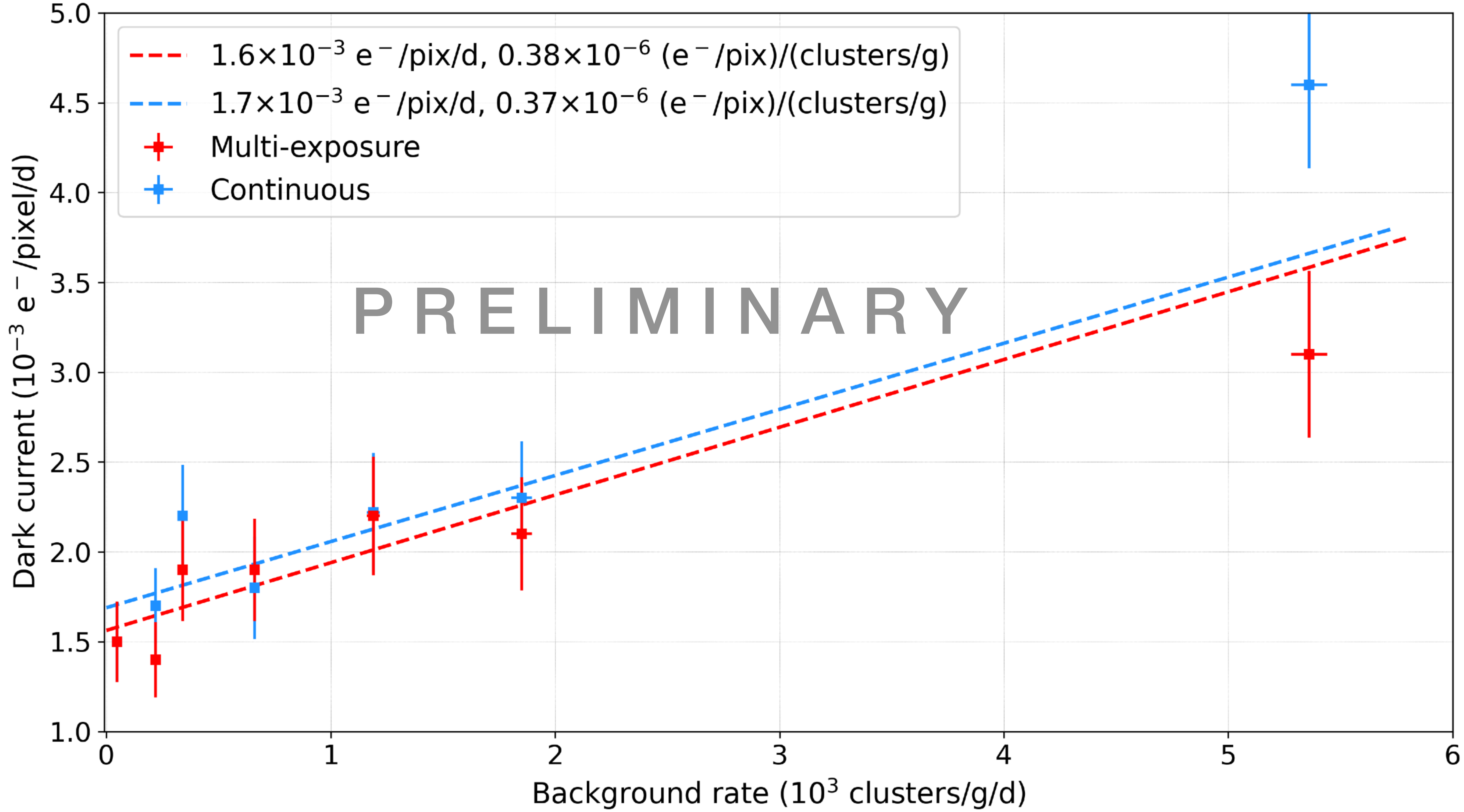




Spurious charge = (1.7±1.0)e-4 e-/pix
DC = (2.2±0.5)e-3 e-/pix/d (slope)

DC = 2.3e-3 e-/pix/d (steady state)

DC vs Bkg rate



Linear increase of DC with higher background rate

Ongoing investigation on the origin (e.g. Cherenkov photons, recombination in P-doped layer, charge traps)

Other studies:
PRX 12 (2022) 011009,
PRL 122 (2019) 161801,
Phys. Rev. Appl. 17 (2022) 014022.

Measurement with ^{14}C

A complementary measurement with beta source ^{14}C (mean energy 49 keV)

Surface events in a 25.4M-pixel CCD

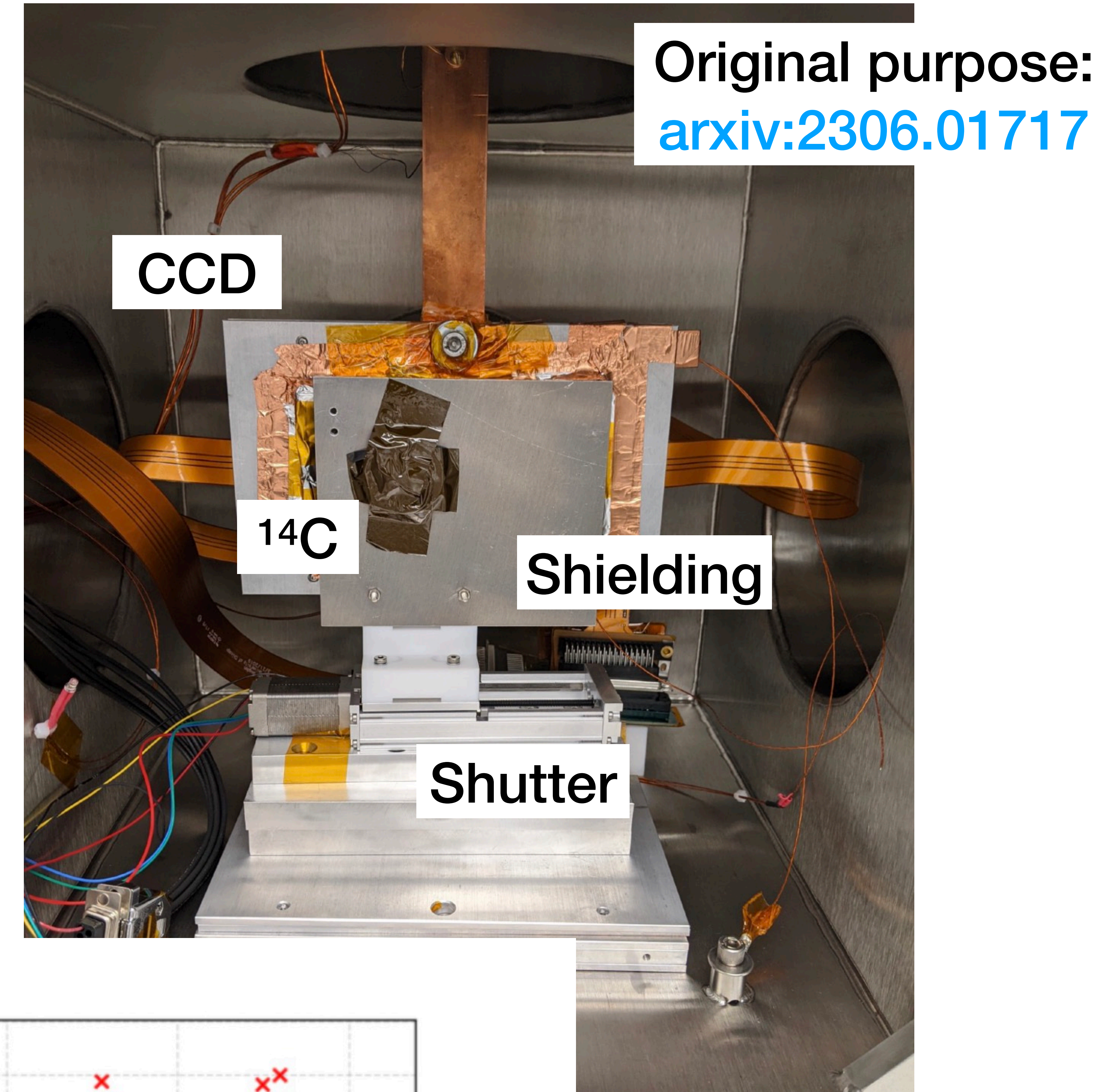
Source-on and -off measurements

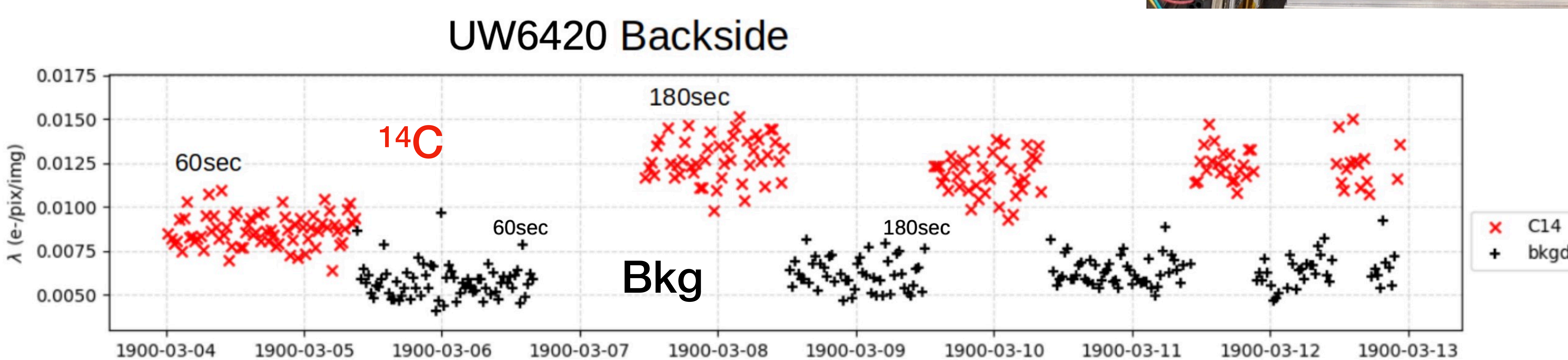
0.14 cm^2 window in a shielding plate

Source on the front- and back-side

Number of clusters and change in dark current

In a surface laboratory at UWashington





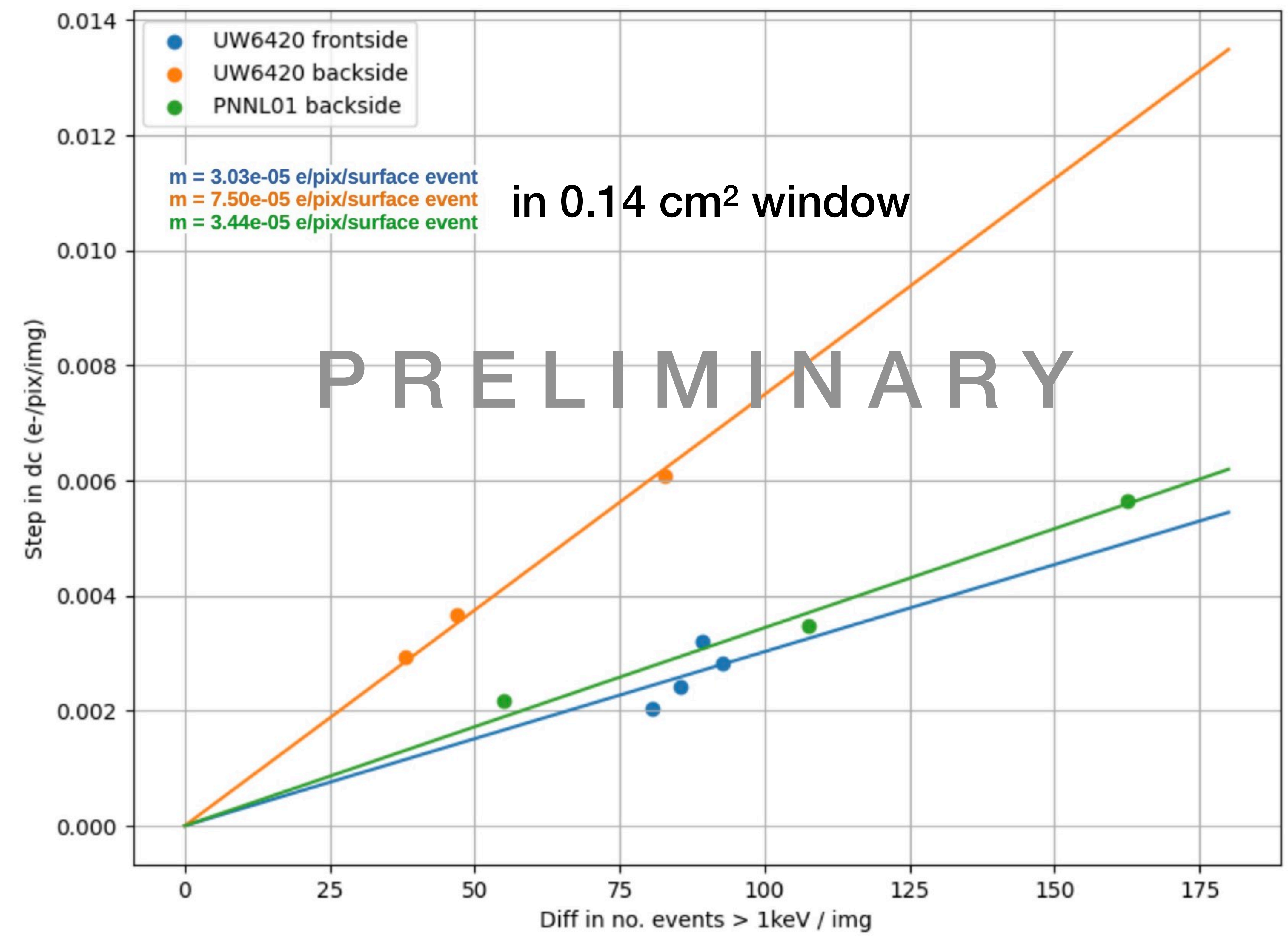
Betas rate and DC

Measured DC increase for ^{14}C is about
3.6e-4 e^{-}/pix per surface event/cm^2.

DC returns to its baseline value after closing the shutter => DC increase comes from photo-electrons produced by the ionizing radiation.

DAMIC at SNOLAB with 11 kg-day exposure had surface ^{210}Pb contamination 60 nBq/cm^2, see PRD 105 (2022) 062003.

By combining both numbers, DC increase = 1.8e-6 e^{-}/pix/day.



If the C-14 source is representative of the surface events that we have underground, we should expect surface backgrounds to be a negligible contribution to the DC that we have observed so far in our CCDs.

The DAMIC-M Collaboration

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European Research Council
Established by the European Commission

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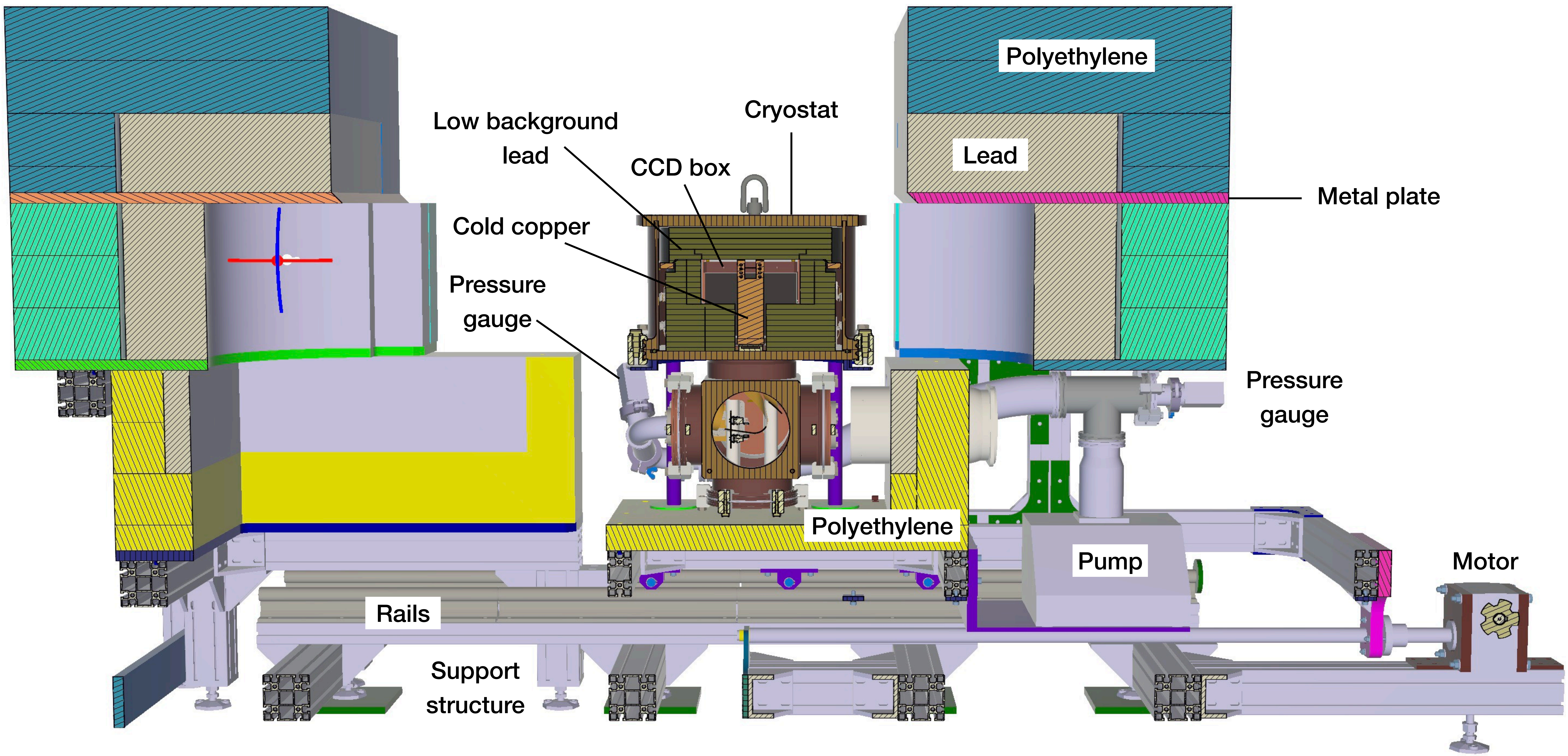
DAMIC-M

https://damic.uchicago.edu/



Polyethylene
Lead
Metal plate
Cryostat
Low background lead
CCD box
Cold copper
Pressure gauge
Pressure gauge
Polyethylene
Pump
Motor
Rails
Support structure