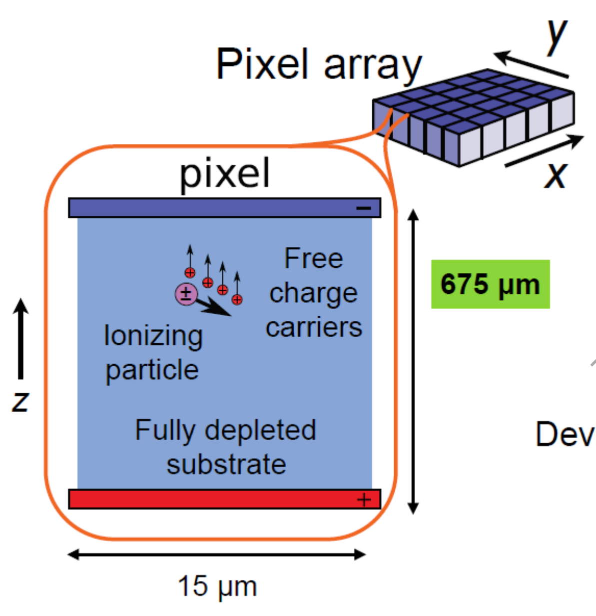
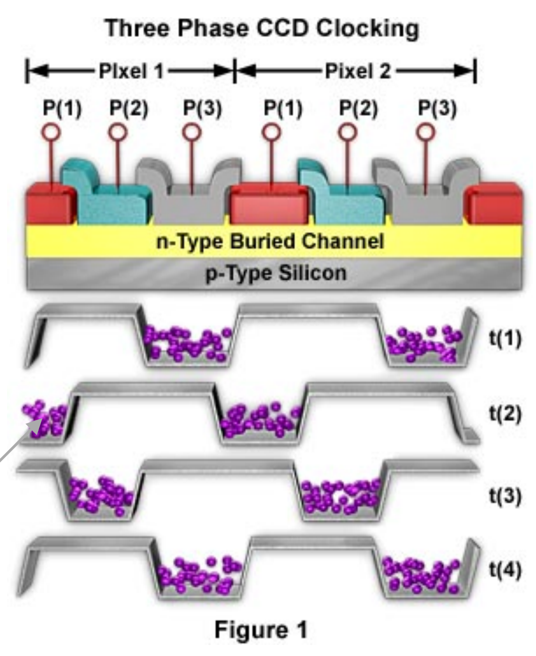
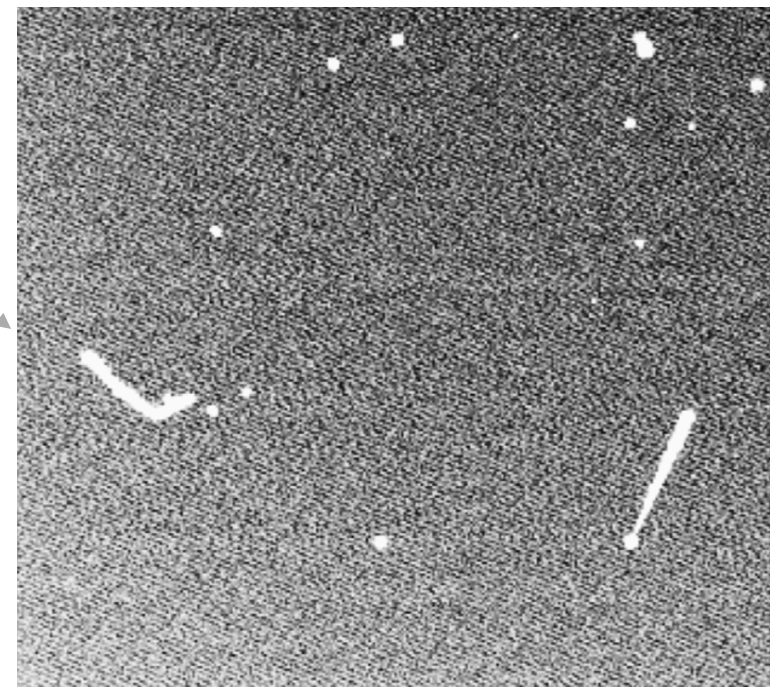
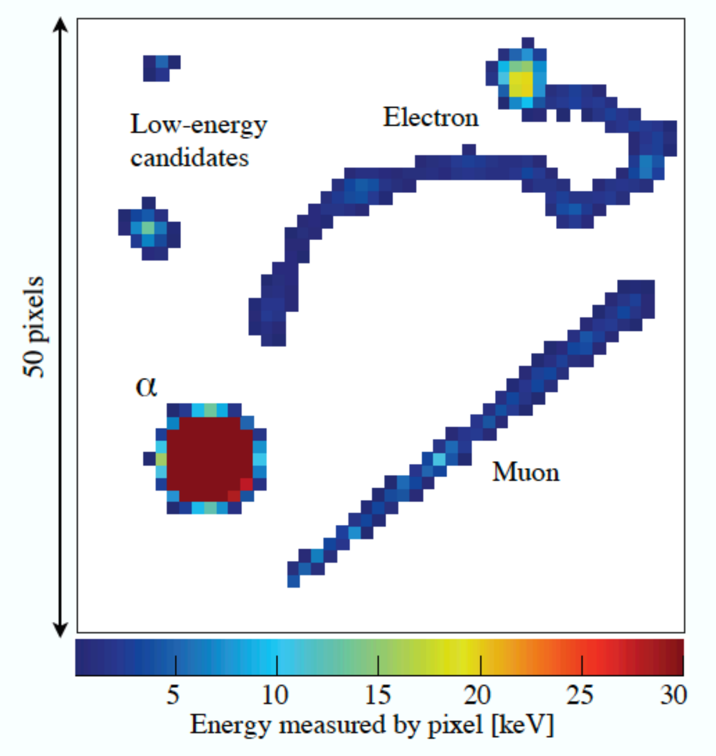


Devi



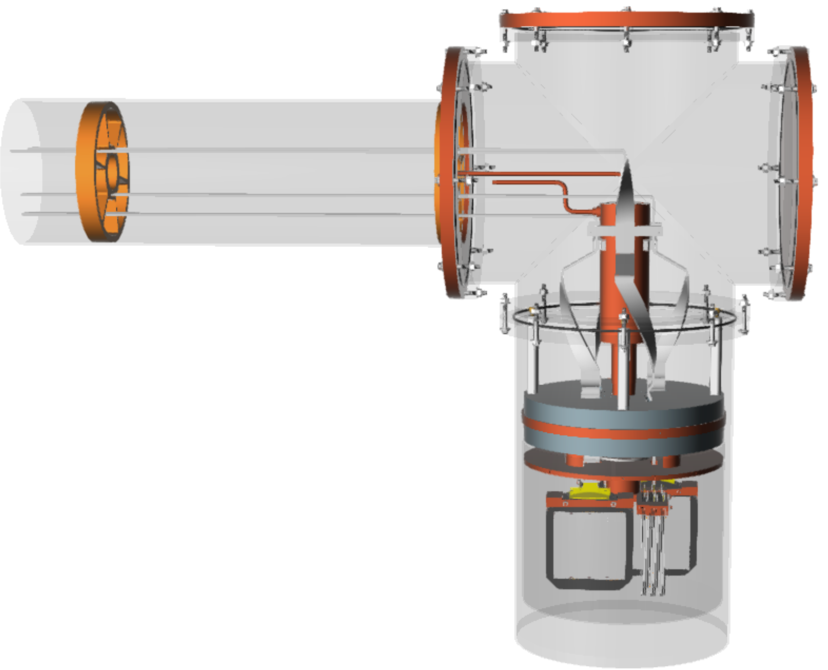


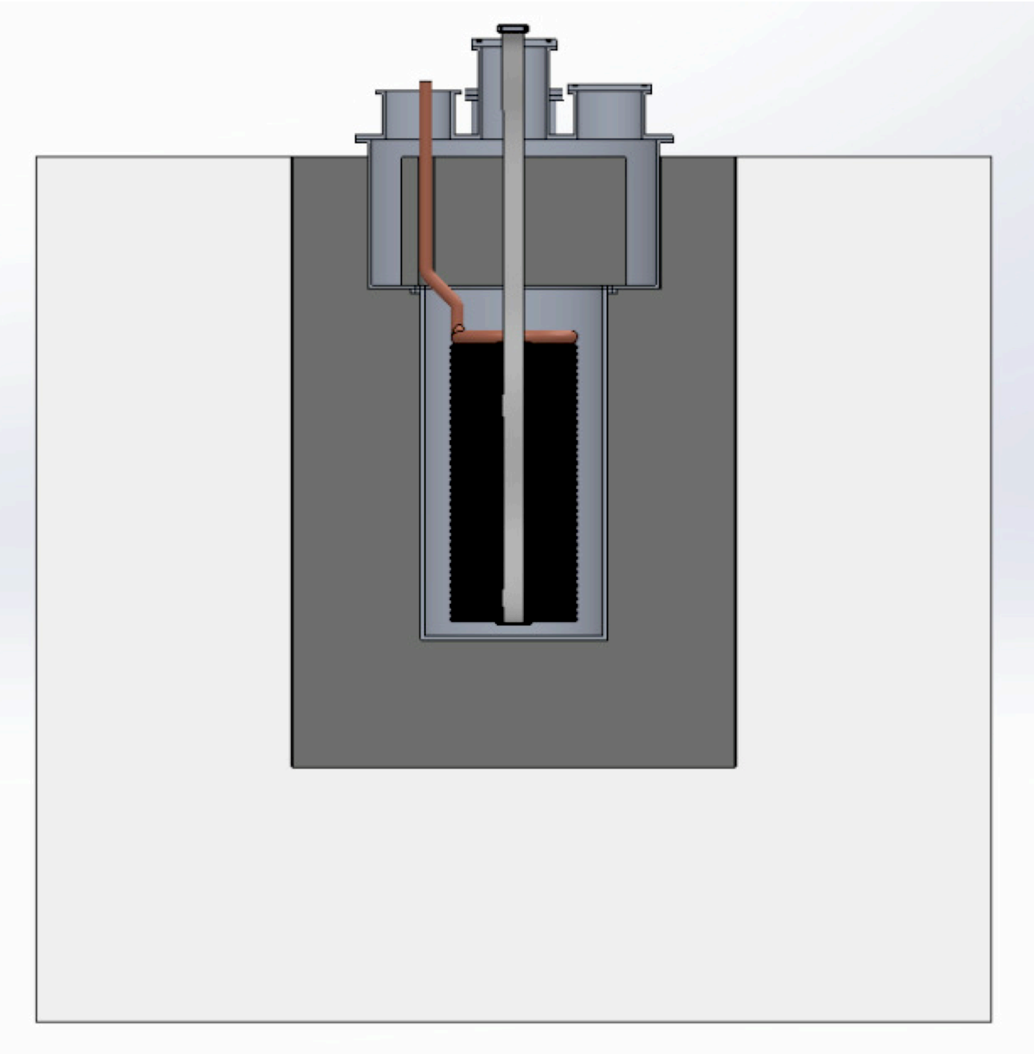


Status of the Dark Matter Search with CCDs

R. Vilar Cortabitarte

Special thanks to prepare the slides to Danielle Norcini, Michelangelo Traina, Claudia de Dominicis, Alex Pier, Dan Baxter, Pitam Mitra ,Nuria Castello and others



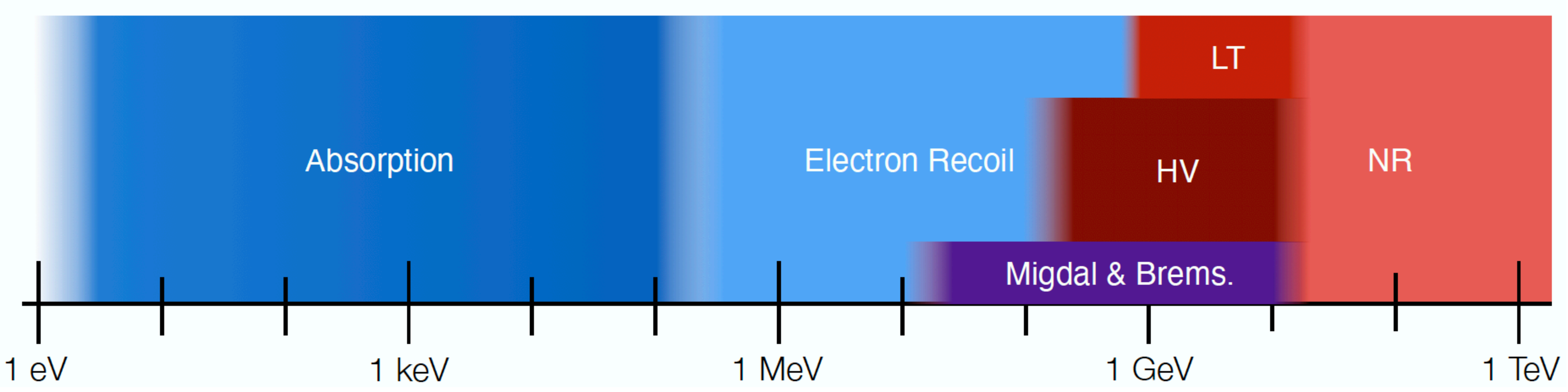


Outline

- Introduction
  - CCDs
- DAMIC at SNOLAB results
- Skippers CCDs
  - DAMIC@SNOLAB Upgrade
  - Status of DAMIC-M
  - LBC
- Conclusions

Introduction

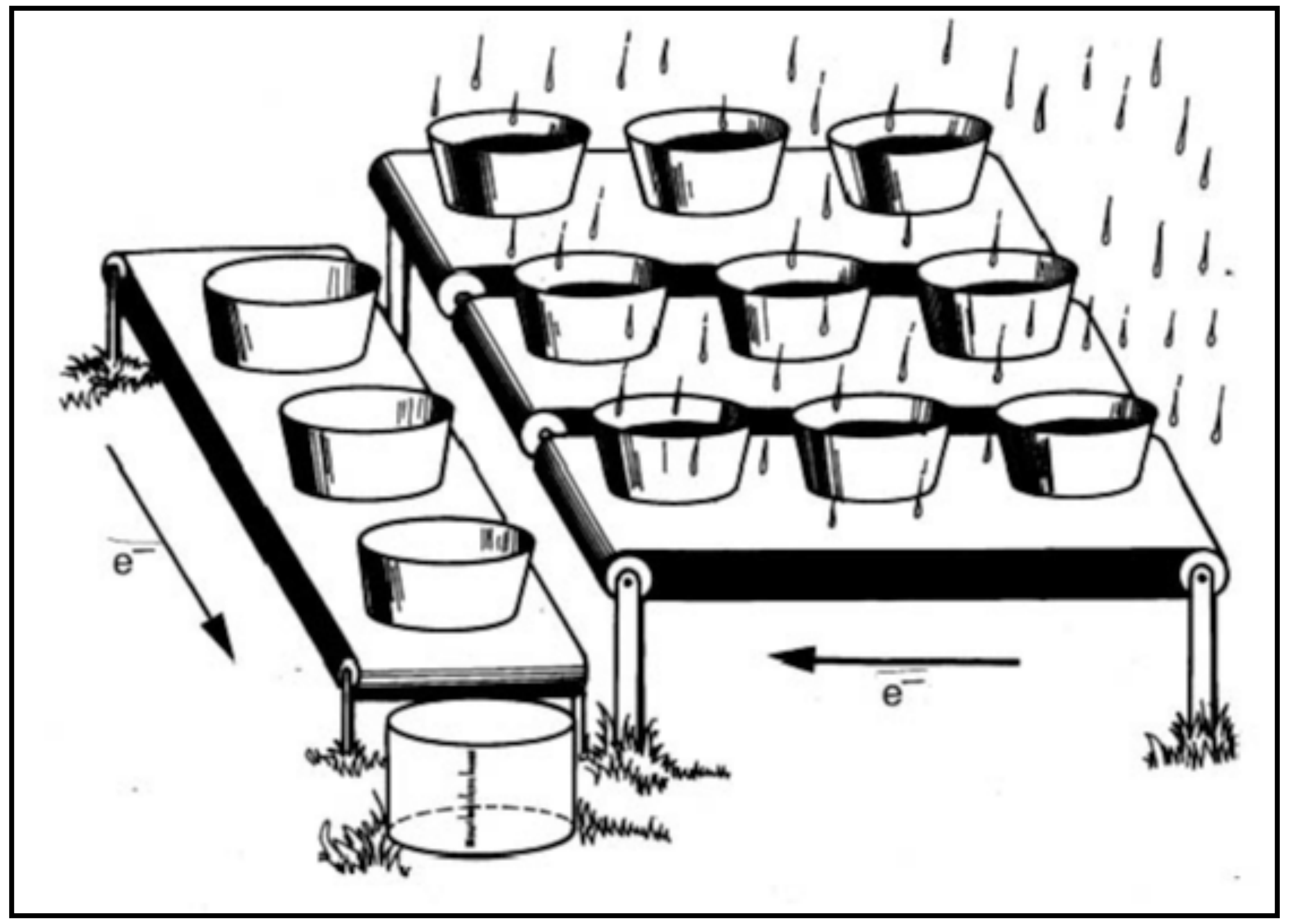
- Theoretical motivation combined with technological opportunities makes the moment right for the search below 1 GeV.
- Small experiments (that are growing) can have a huge impact in meaningful dark matter models.
- What we need for low masses:
  - Low threshold to access smaller WIMP masses.
  - Scalable technologies to increase the number of interactions in the target.
  - Low and controlled backgrounds to identify the rarest signals and probe the smallest cross sections.
- Aim to measure interactions with matter:
  - Elastic scattering off nuclei (standard WIMP scenario) ->. m_χ = 1-1000 GeV c^{-2}
  - Inelastic scattering off electrons (dark sector coupling) -> m_χ = 1-1000 MeV c^{-2}
  - DM absorption by bound electron (dark sector and ALP). -> m_χ = 1-1000 eV c^{-2}

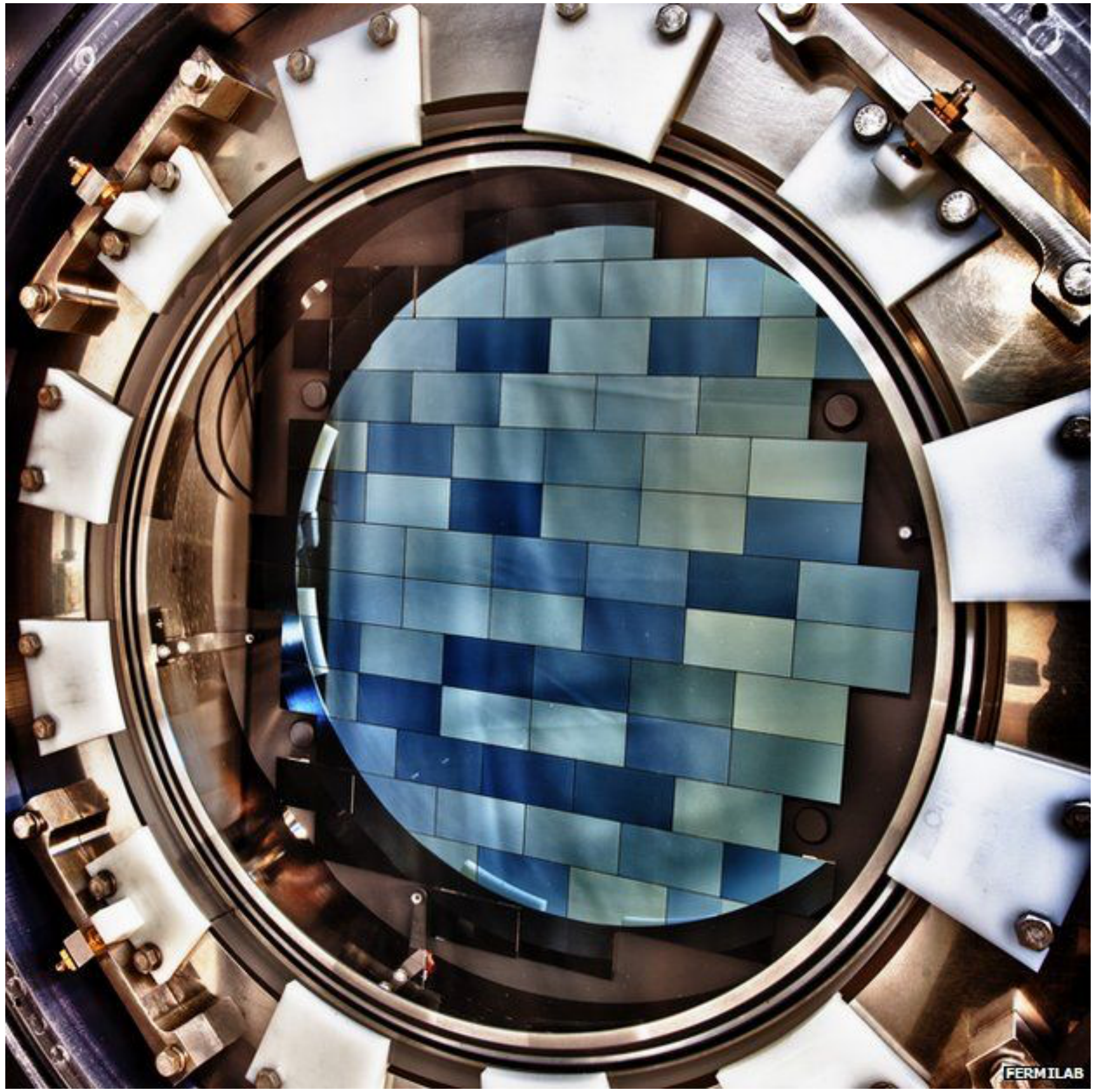


Use of CCDs for the search of Dark Matter

Photon detector:

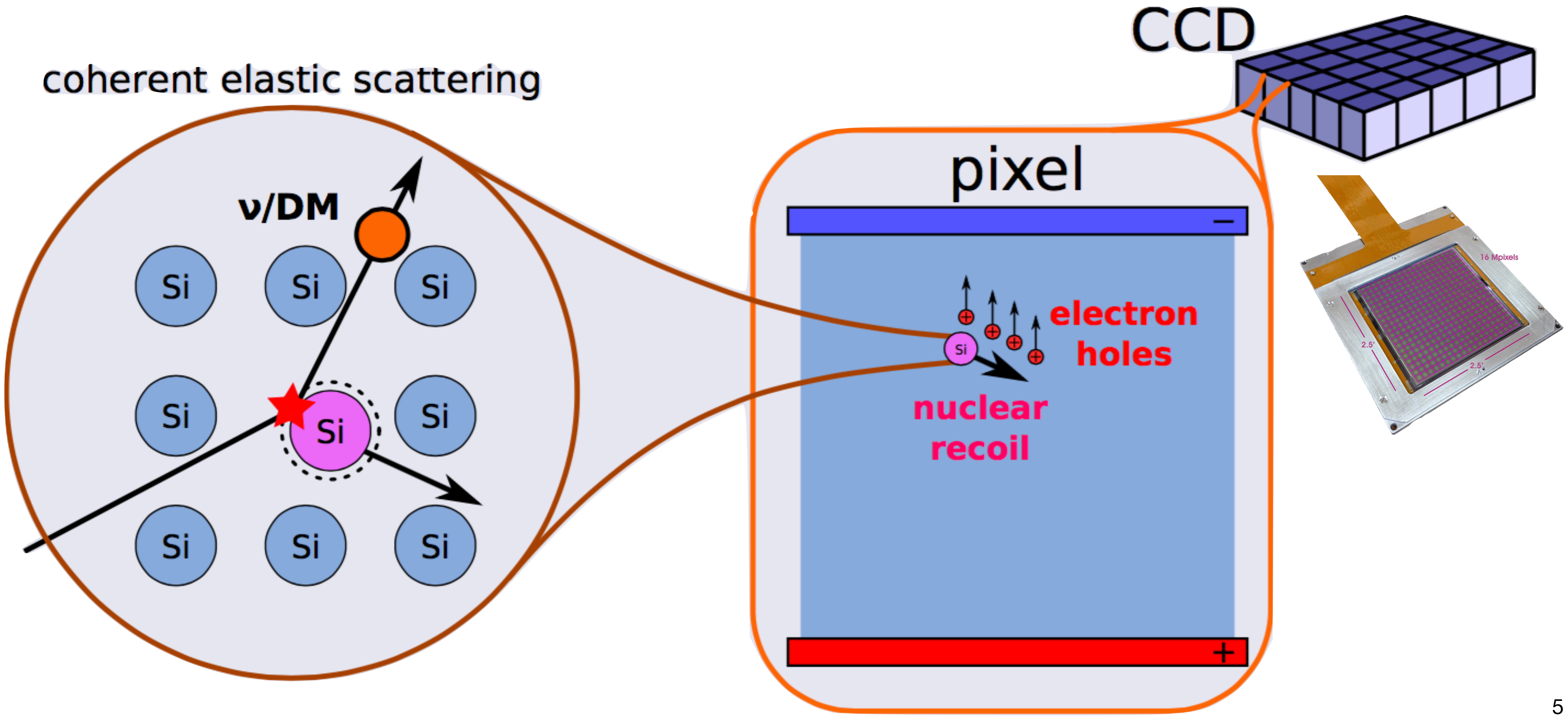
Charge coupling makes the detectors ideal for low noise measurements, typical noise for scientific CCDs is 2e- RMS (7.2eV). Very recent work pushing this to "0" noise.





Why CCDs

- Goal: Lower the energy threshold in Si detectors to detect coherent DM-nucleus/e$^-$ interactions, by measuring the ionisation produced by the recoils
  - Slow + non-destructive, very low noise sub-e-
- Idea: Use the CCDs as target and record the ionization produced. Detection of point-like energy deposits from recoils induced by DM interactions
- Sensitive to DM masses:
  - < 10 GeV (nuclear recoil)
  - ~MeV-eV (electron recoil)



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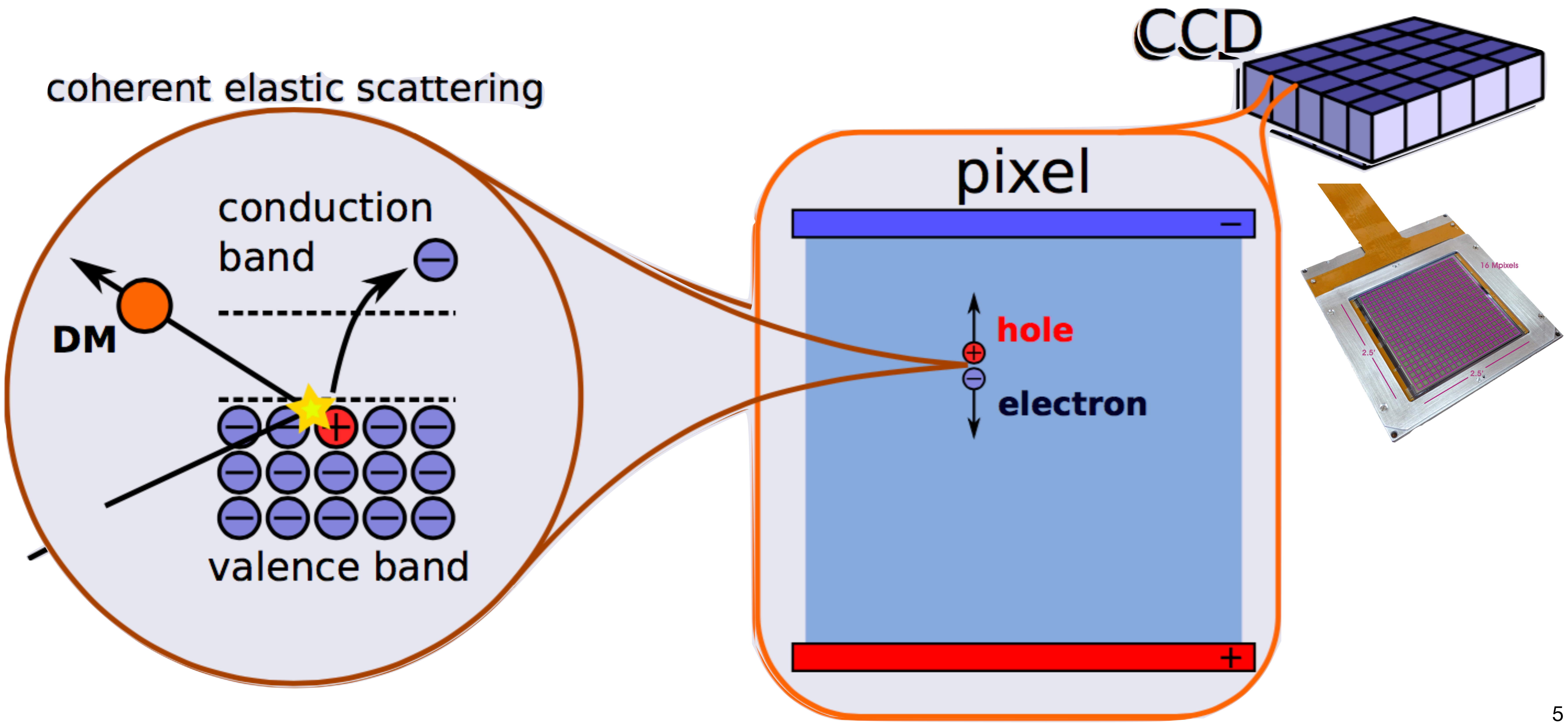
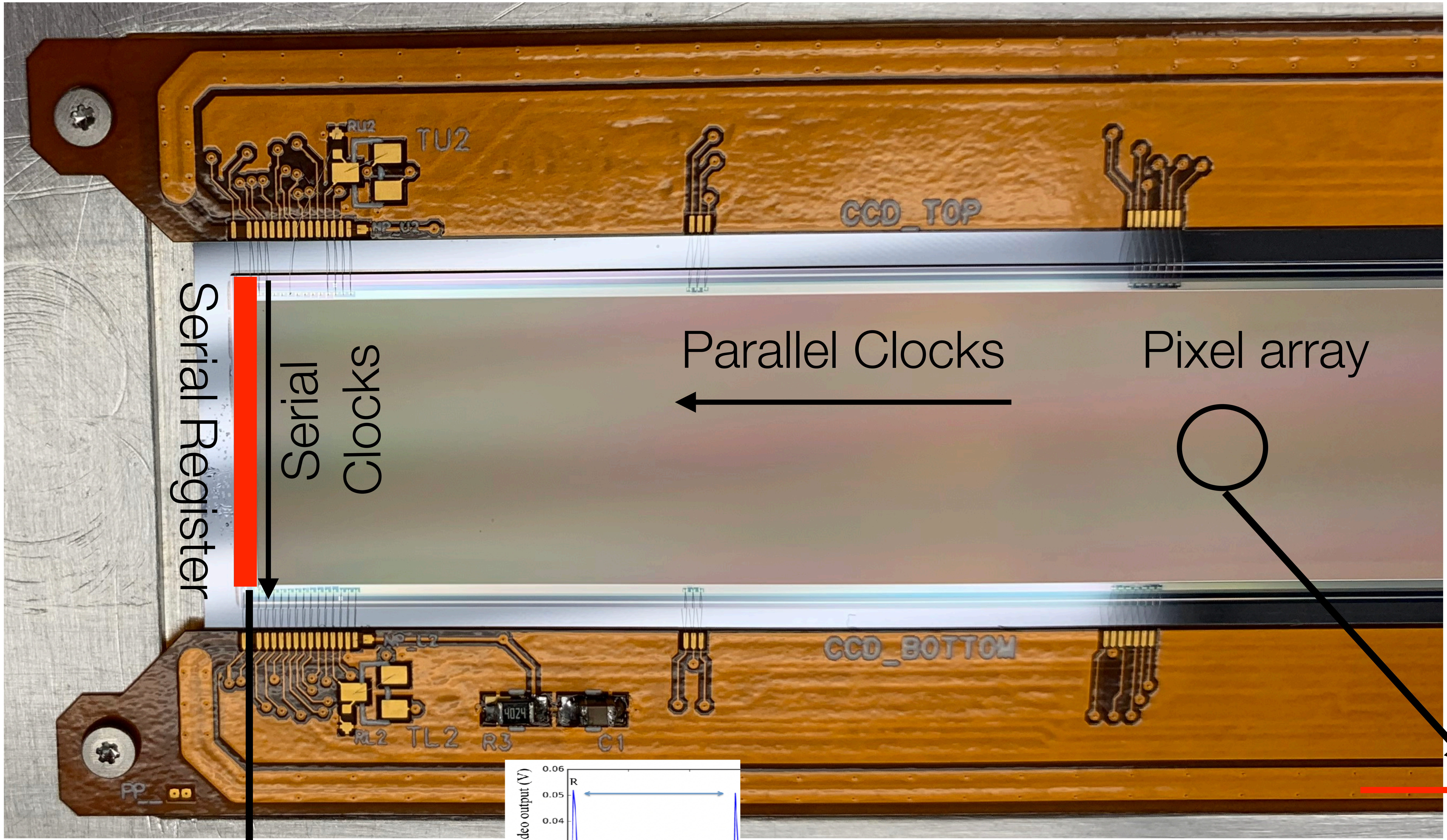
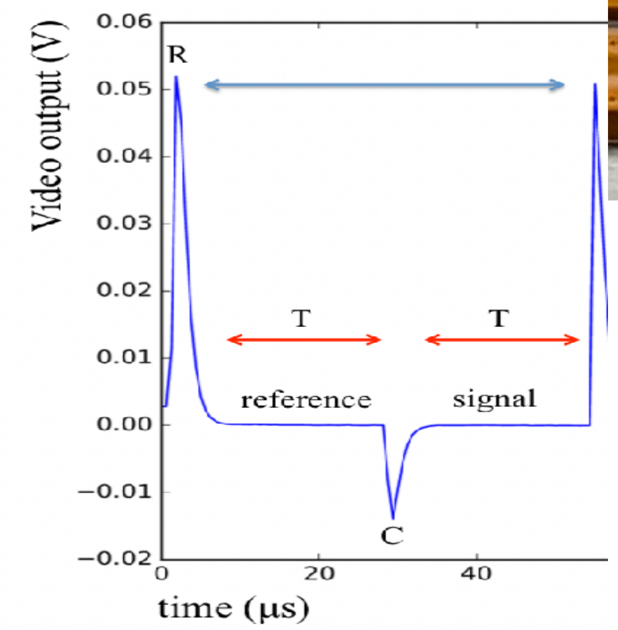


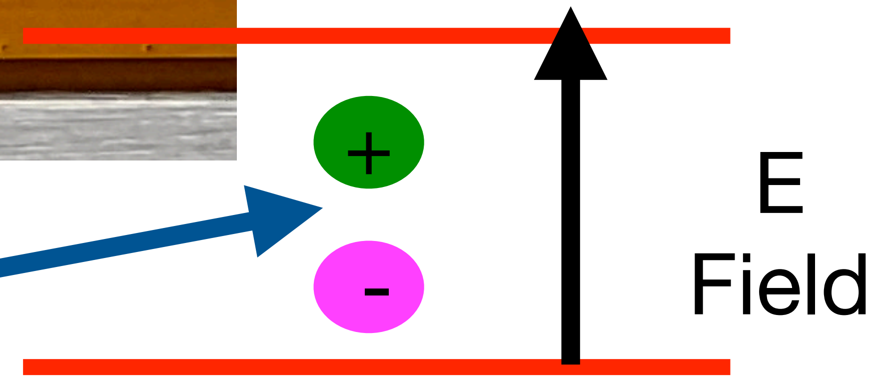
CCD: Moving Charges





Correlated double sampling

$\int Signal - \int Reference$



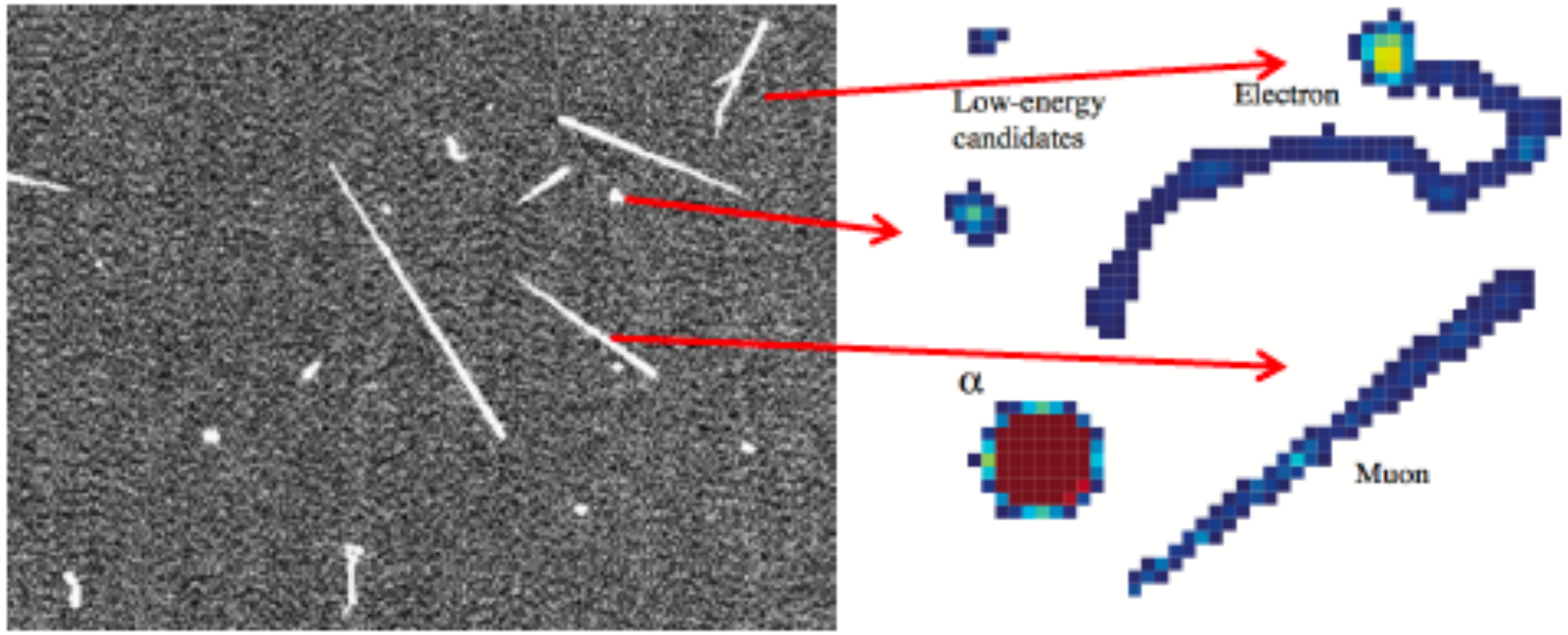
DAMIC

- Very low noise and dark current, DAMIC reached the lowest DC ever measured in Silicon detectors
  - 2×10^{-22} A/cm2, <0.001 e/pixel/day (at 140K)
- CCD spatial resolution provides a unique handle to the understanding of the background, and reject it

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

1. Tight deposition:
   - nuclear recoil
   - low-E electron recoil

   Signal
2. Elongated track:
   - high-E electron recoil
   - muon
3. Large blob:
   - alpha decay



Coincidence Analysis

Main Surface Contaminants

Decay Sequence	$t_{1/2}$	Q-value
$^{210}\mathrm{Pb} \longrightarrow {}^{210}\mathrm{Bi} + \beta^- + \mathrm{IC}/\gamma$	22.3 y	63.5 keV
$^{210}\mathrm{Bi} \longrightarrow {}^{210}\mathrm{Po} + \beta^-$	5.01 d	1.16 MeV
$^{210}\mathrm{Po} \longrightarrow {}^{206}\mathrm{Po}\,(\mathrm{stable}) + \alpha$	138 d	5.41 MeV

Deposition

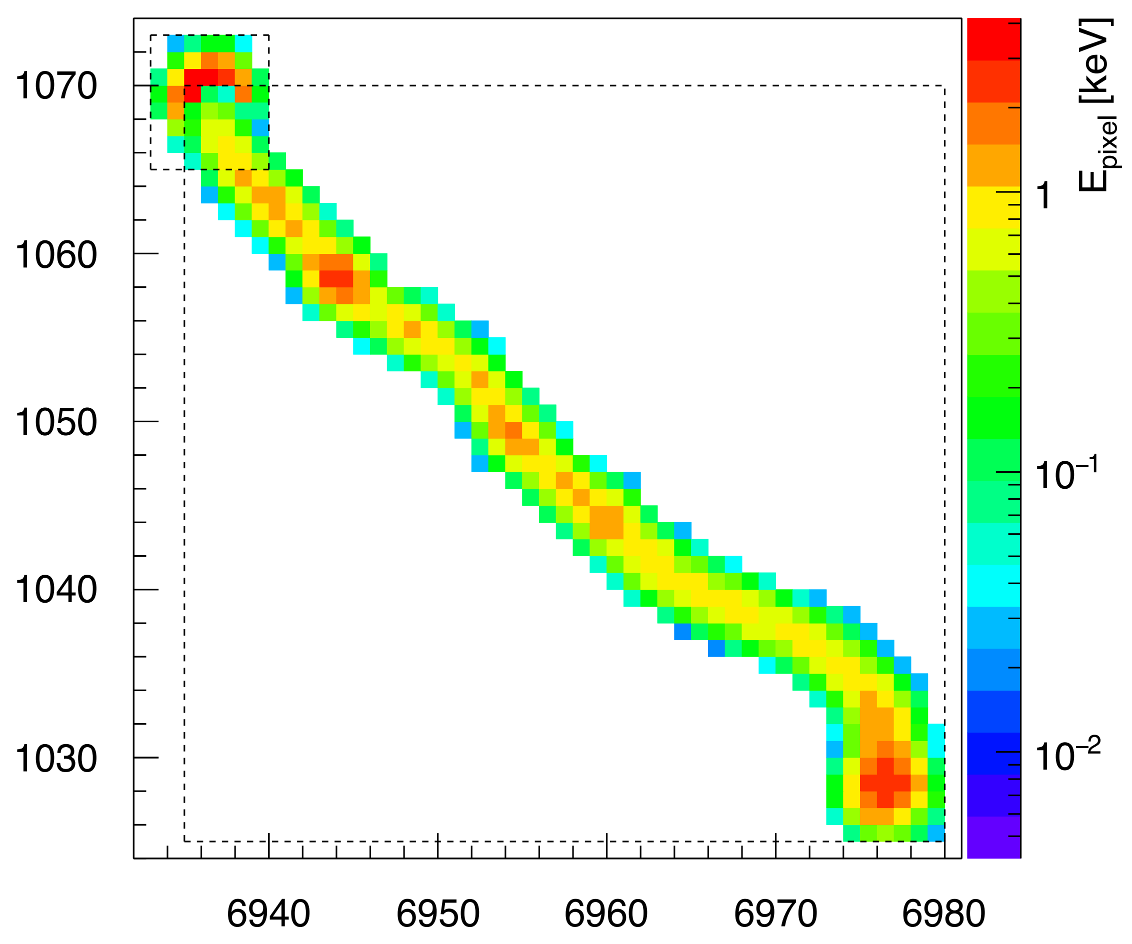
Main Bulk Contaminants

Decay Sequence	$t_{1/2}$	Q-value
$^{32}\mathrm{Si} \longrightarrow {}^{32}\mathrm{P} + \beta^-$	150 y	225 keV
$^{32}\mathrm{P} \longrightarrow {}^{32}\mathrm{S}\,(\mathrm{stable}) + \beta^-$	14.3 d	1.71 MeV

Decay	$t_{1/2}$	Q-value
$^{3}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \beta^-$	12.3 y	18.6 keV

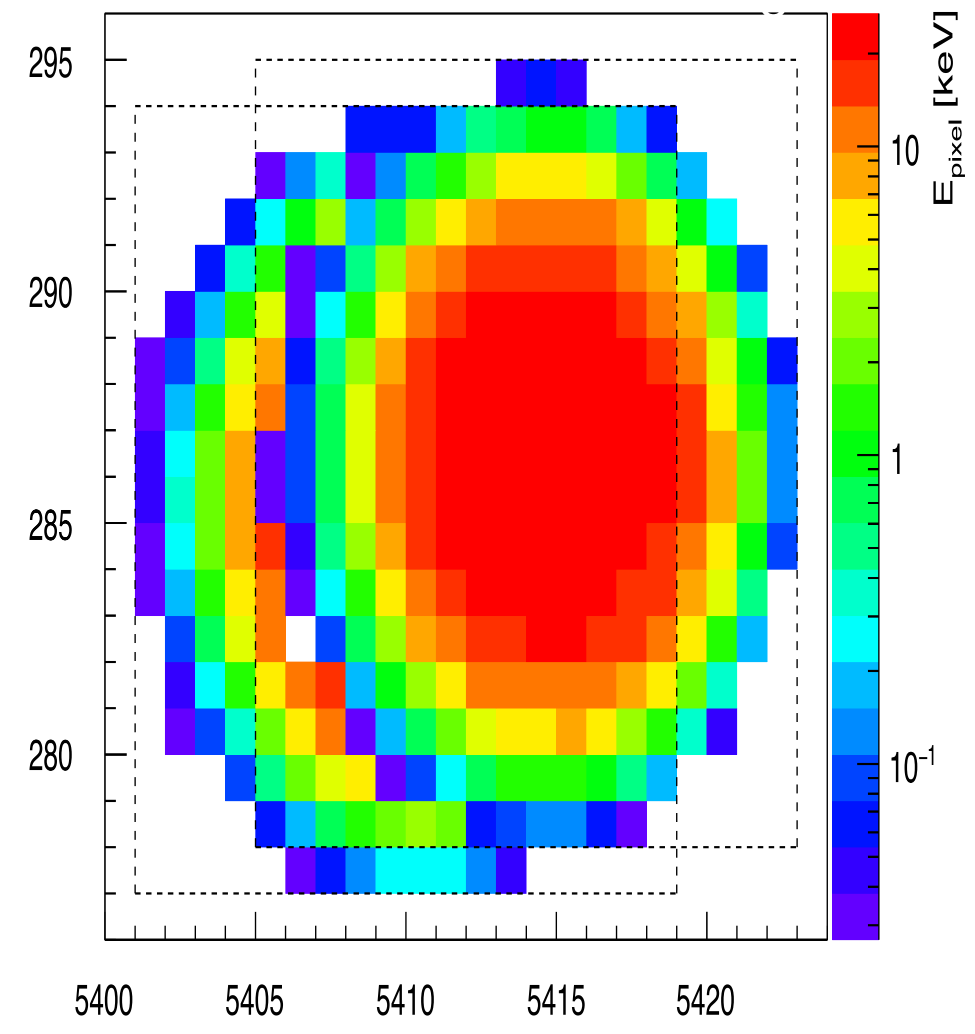
Activation in CCD

^{32}Si β_1-β_2



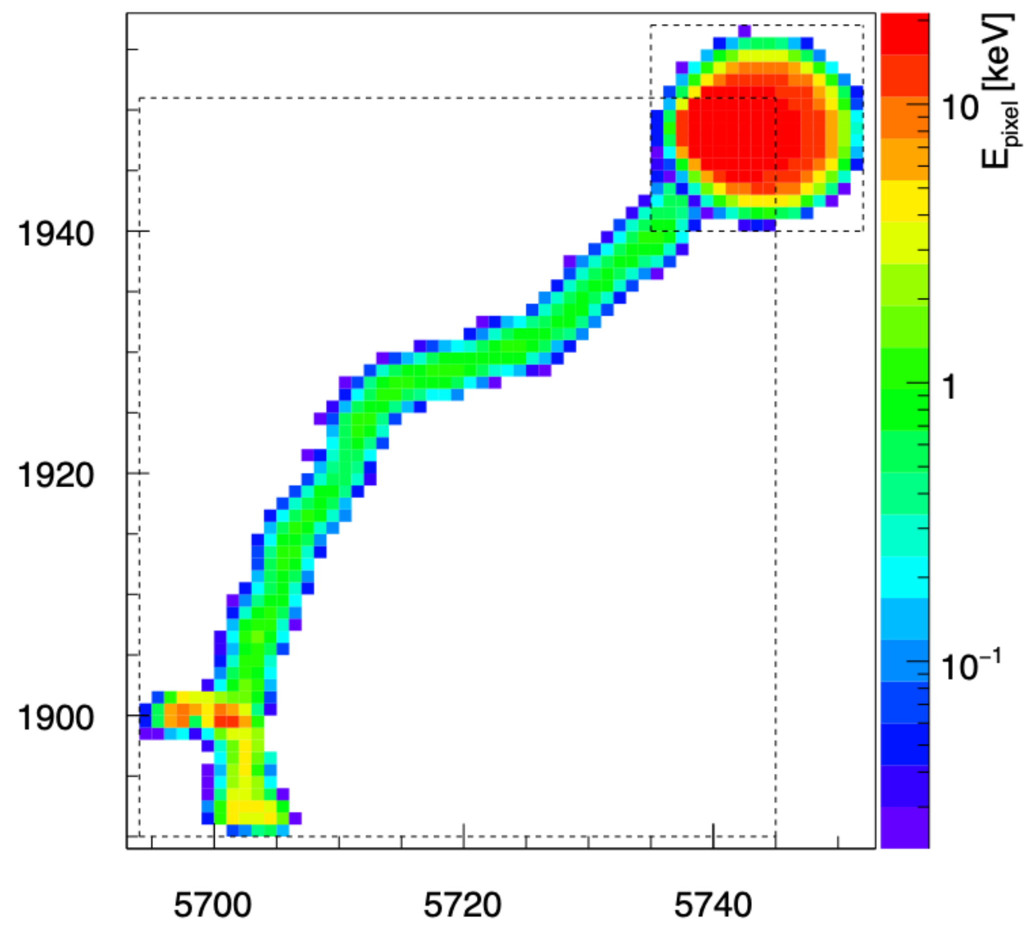
$E_{\beta 1}$ = 110 keV
$E_{\beta 2}$ = 361 keV
Δt = 11.7 d

^{238}U or ^{232}Th α-α



$E_{\alpha 1}$ = 4.3 MeV
$E_{\alpha 2}$ = 3.8 MeV
Δt = 5.2 d

^{210}Pb β_1-α



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

- Limits on radioactive contaminants:
  - ^{210}Pb: < 160 µBq/kg
  - ^{32}Si: 140±30 µBq/kg
  - ^{238}U: < 11 µBq/kg
  - ^{232}Th: < 7.3 µBq/kg

Spatially-correlated sequences are identified over long periods

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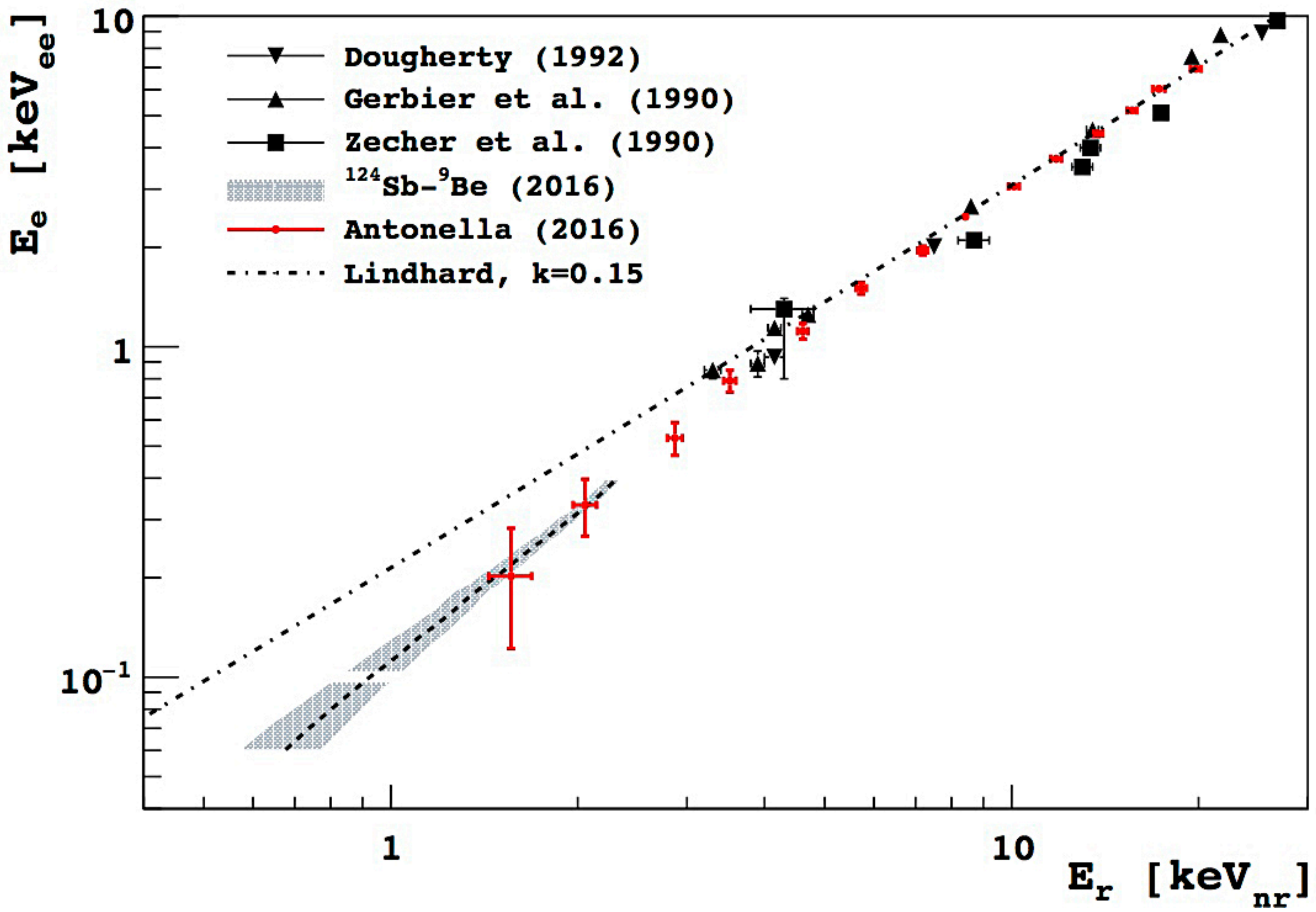
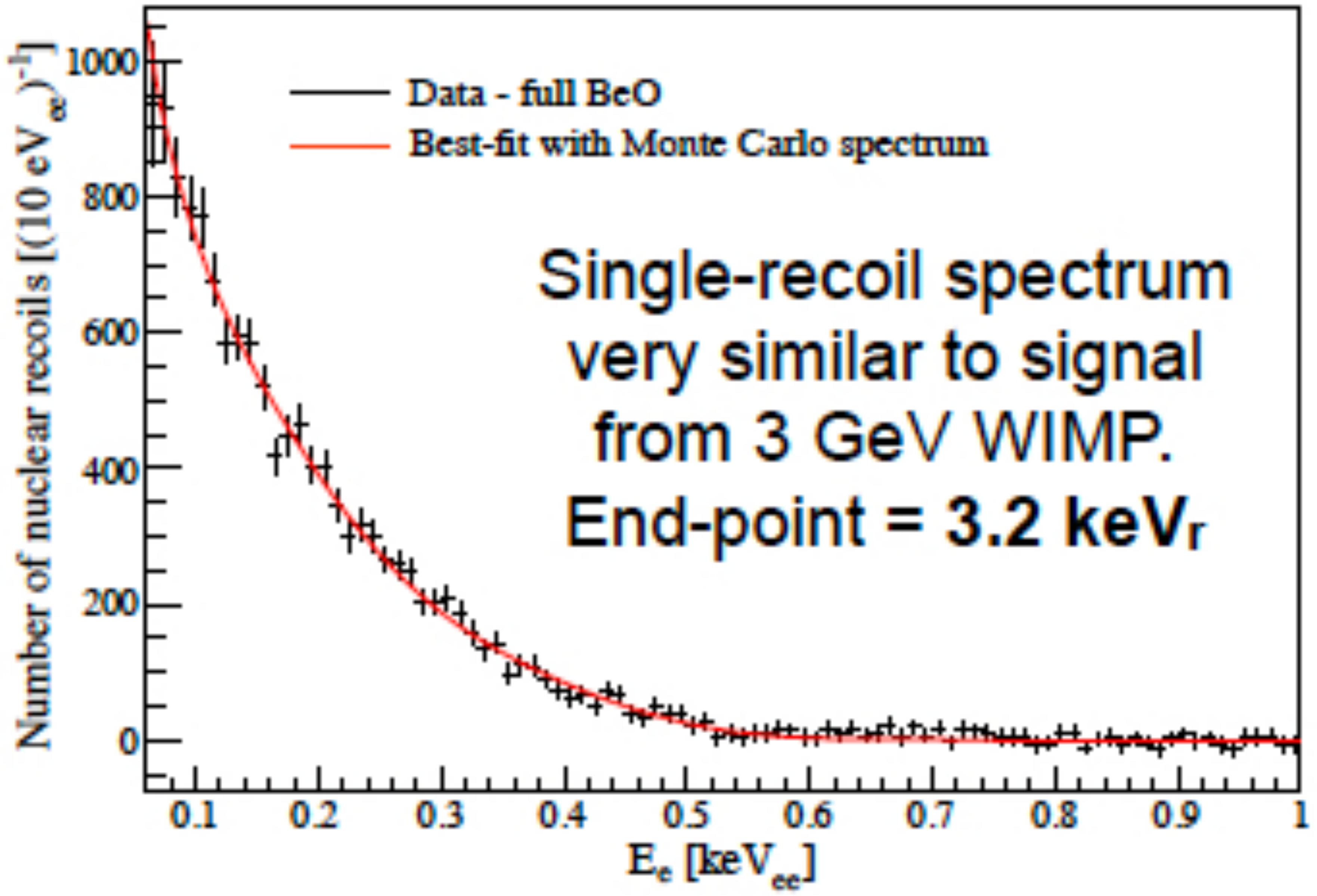
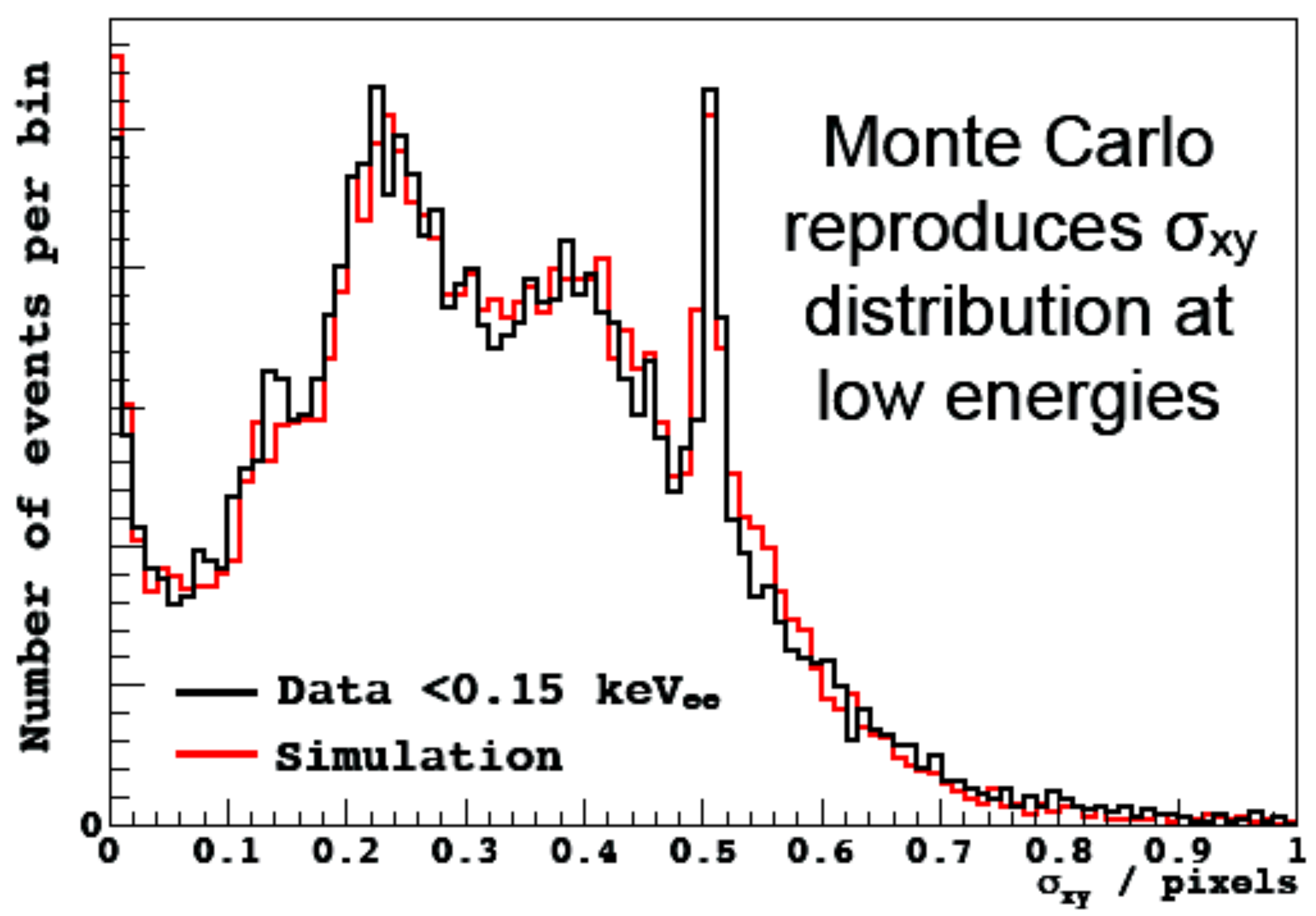
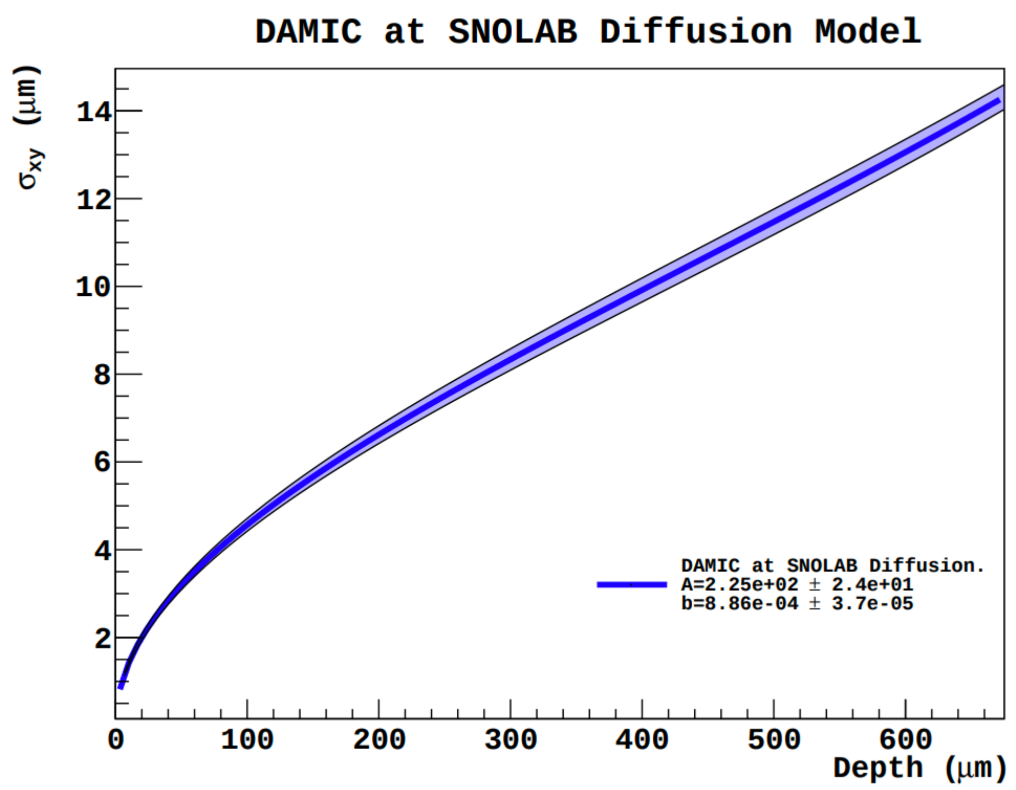
DAMIC Characterisation

- Detector response calibrated with 24 keV neutrons from $^{9}Be(\gamma,n)$ reaction and check with a neutron beam .
- By comparing data and Monte Carlo spectra, ionization efficiency was measured to be lower than predicted by Lindhard model.
- Also validates diffusion model at low energies
  - Calibrated with muons and X-rays
- very nice linearity response of the CCDs down to 40eV using optical photons









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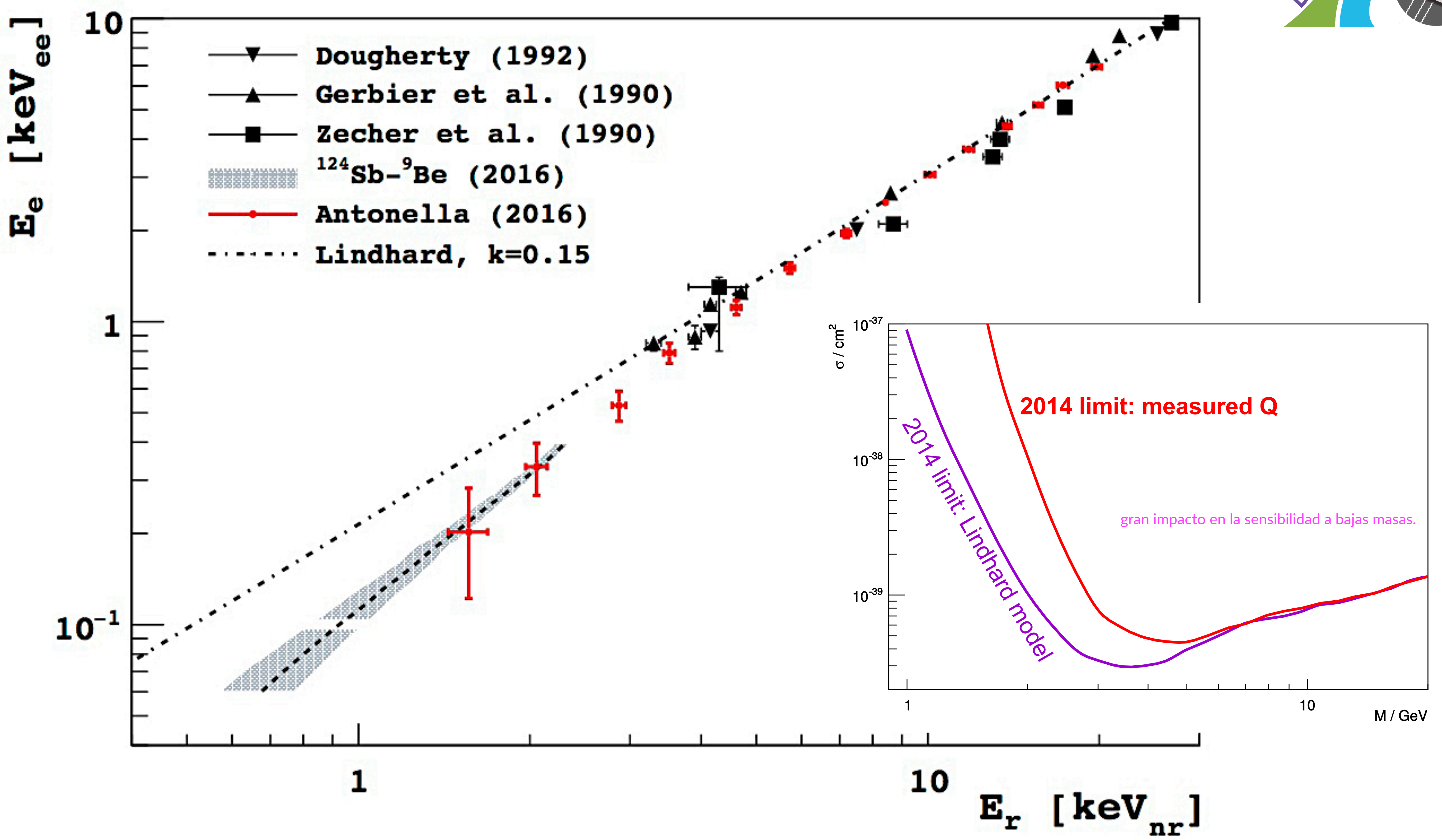
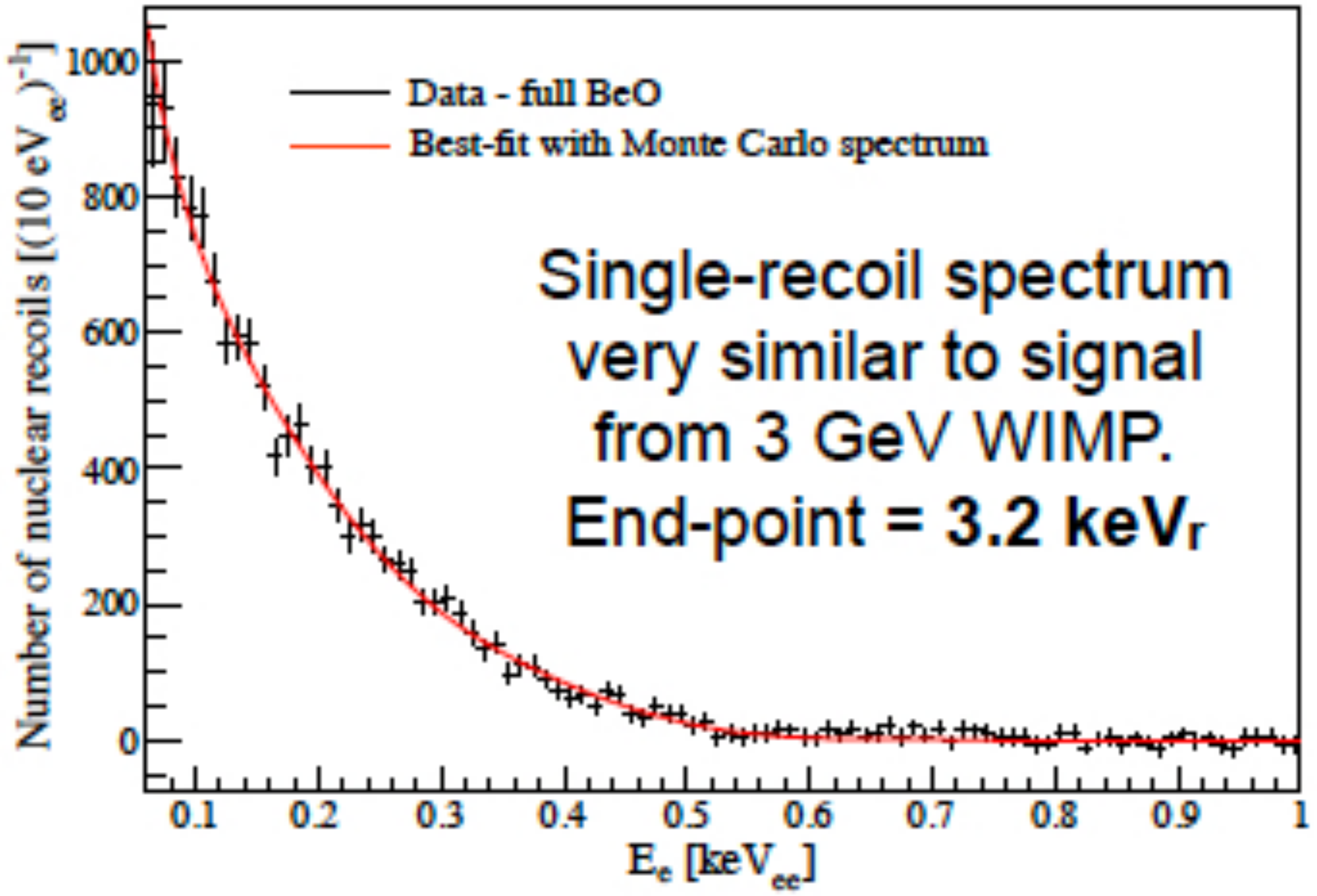
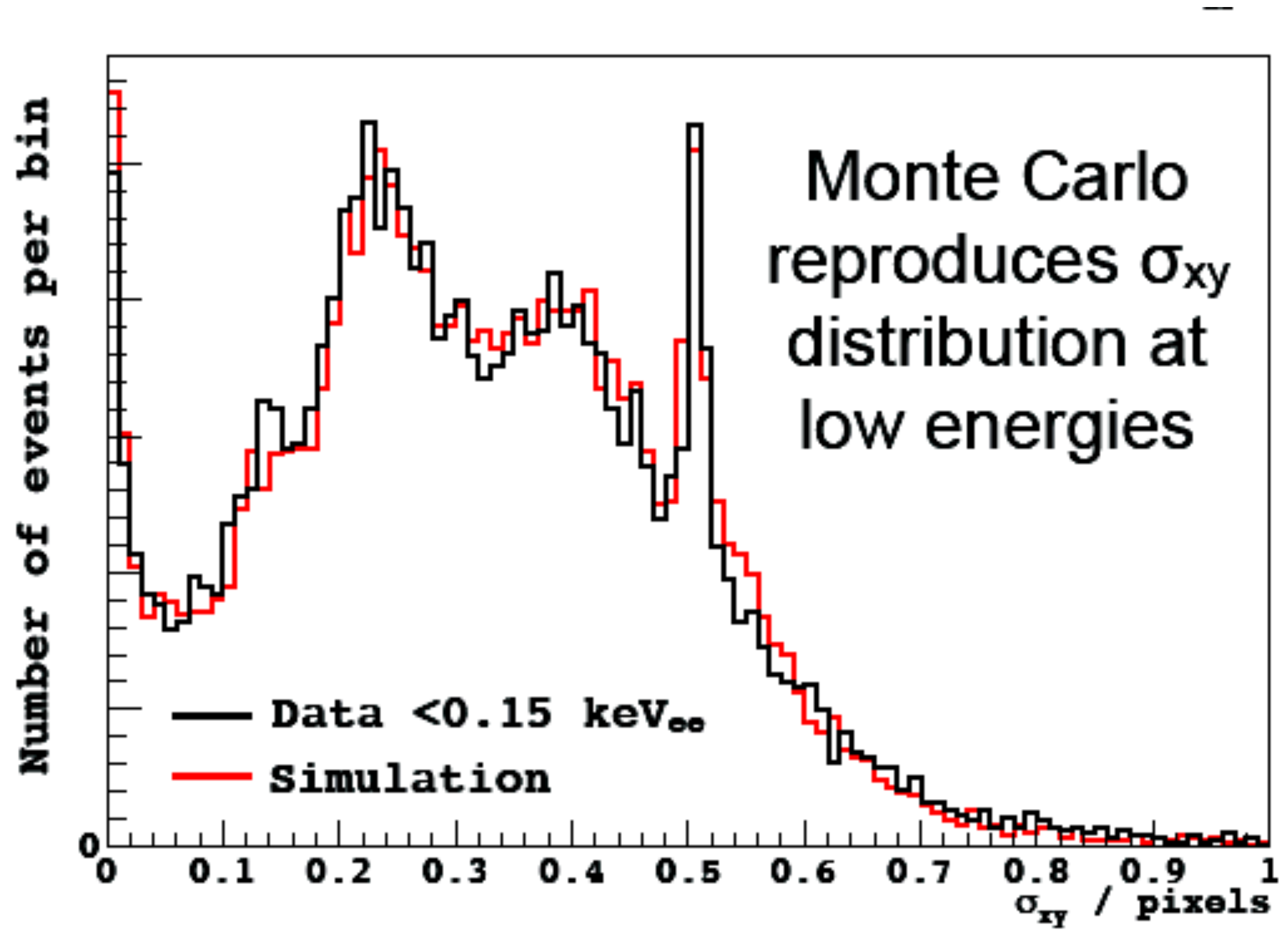
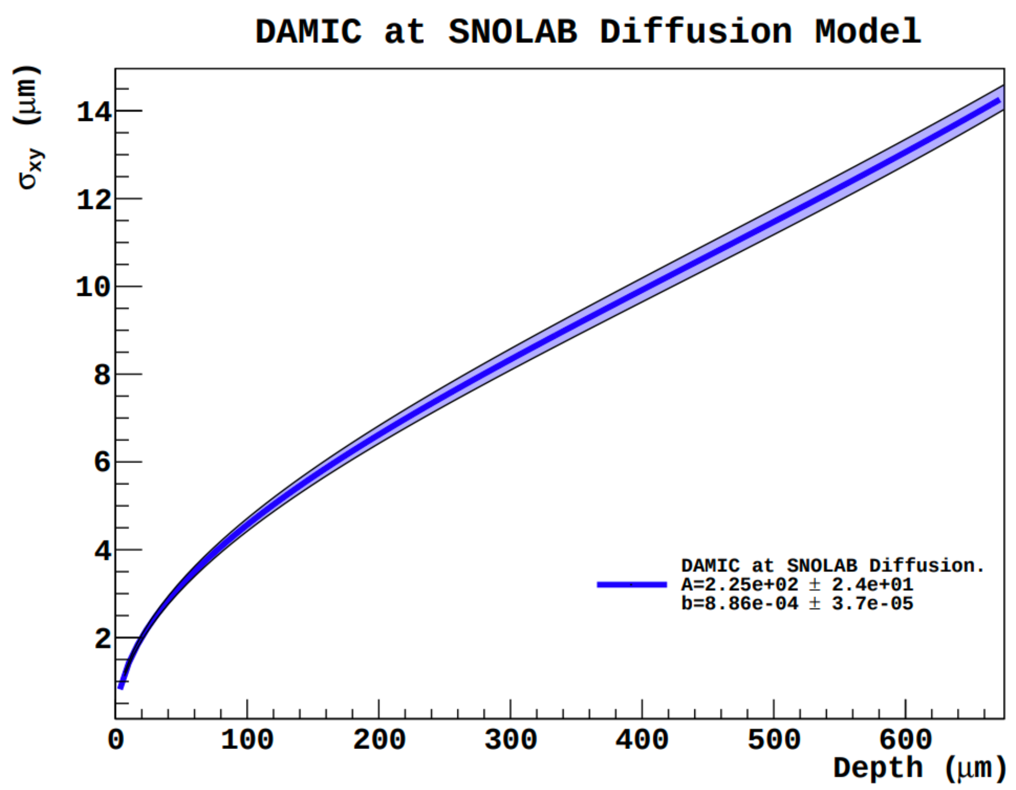


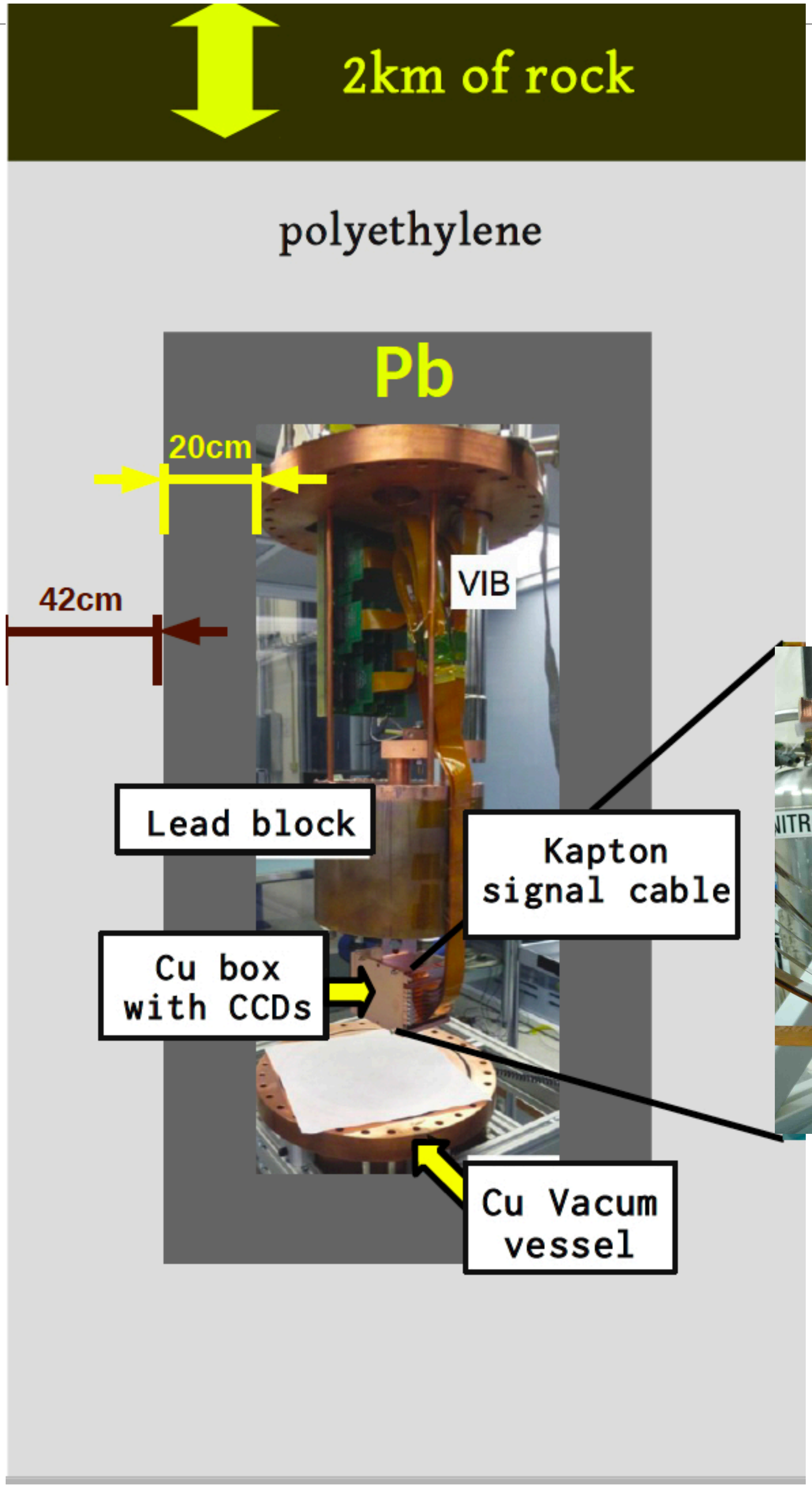




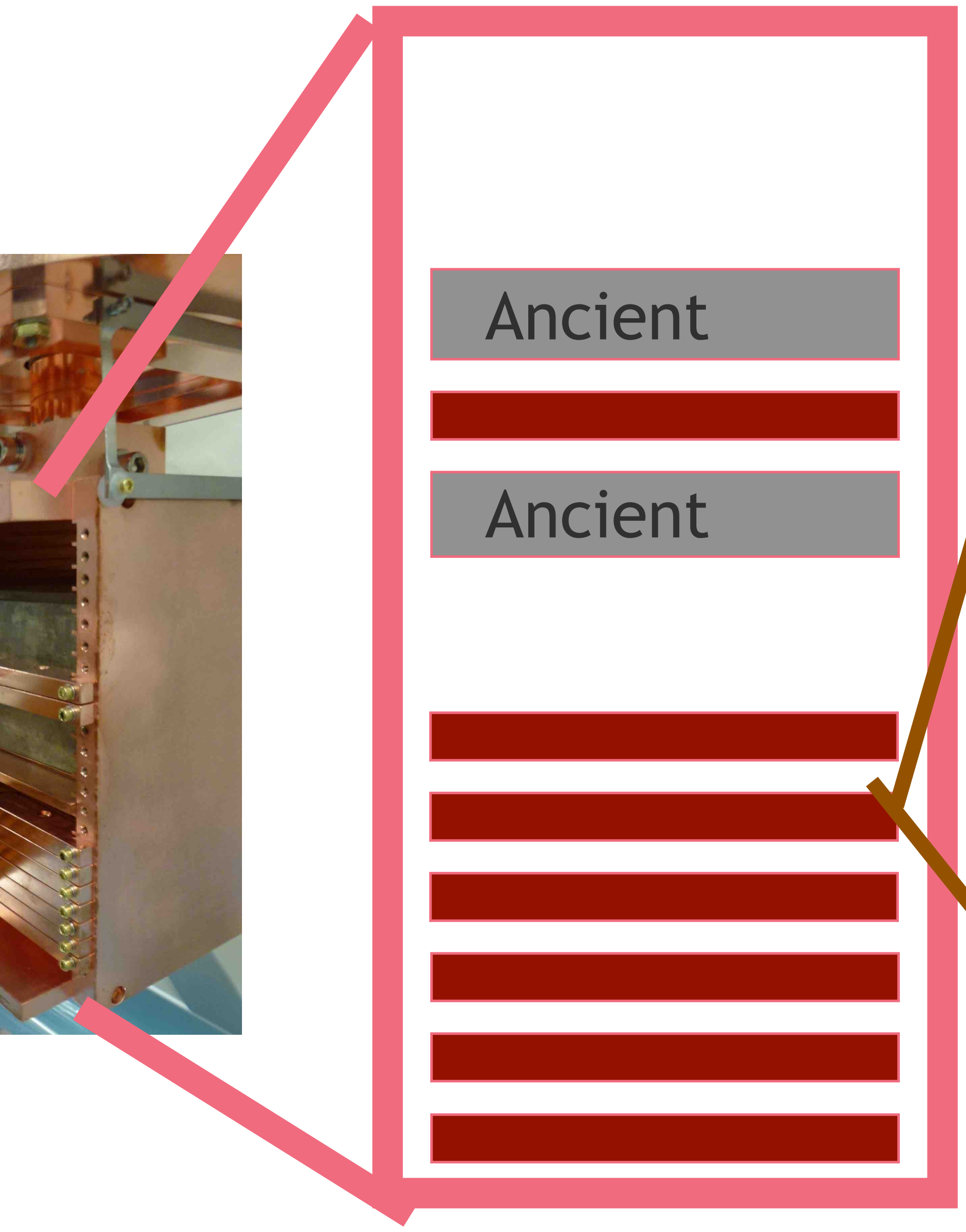


DAMIC@SNOLAB

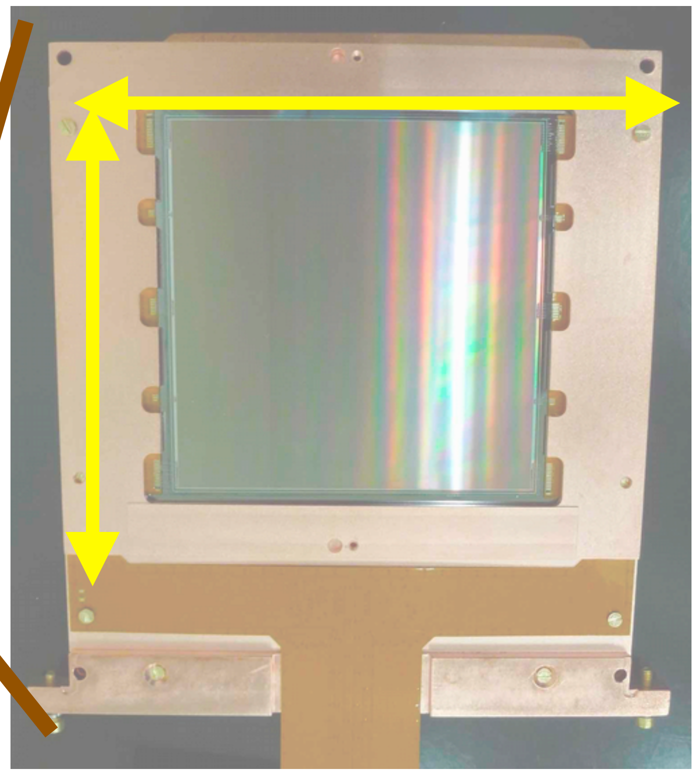
- 7 CCDs in stable data taken since 2017 at 140-135K,
- 40g detector with one layer sandwiched in ancient lead
- Data set (7.6 Kg/day) collected with:
  - full spatial resolution (1x1 binning) optimise for background characterisation (^{32}Si and ^{210}Pb) and measurement
  - A second data set collected (4.5kg/day) with best energy resolution (1x100 binning) for science data
- We currently have background reading around ~11,8 dru (events/keV/kg/day). Less tan 5 dru when removing surface contaminants.



Extremely pure silicon ~10^{11} donors/cm^{-3}, which leads to fully depleted operation at reasonably low values of the applied bias voltage, ~70V

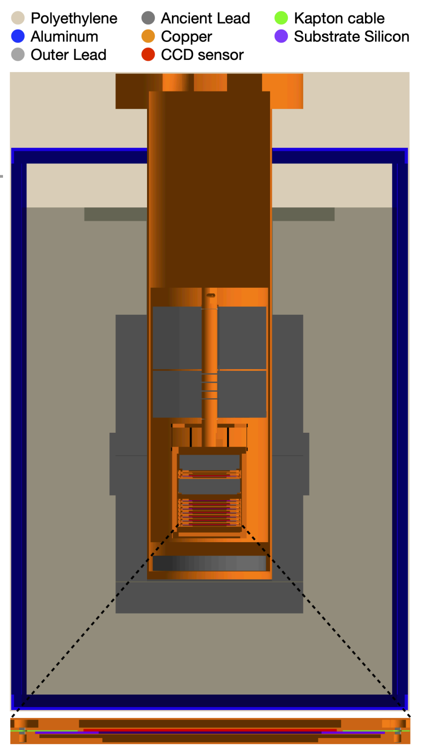


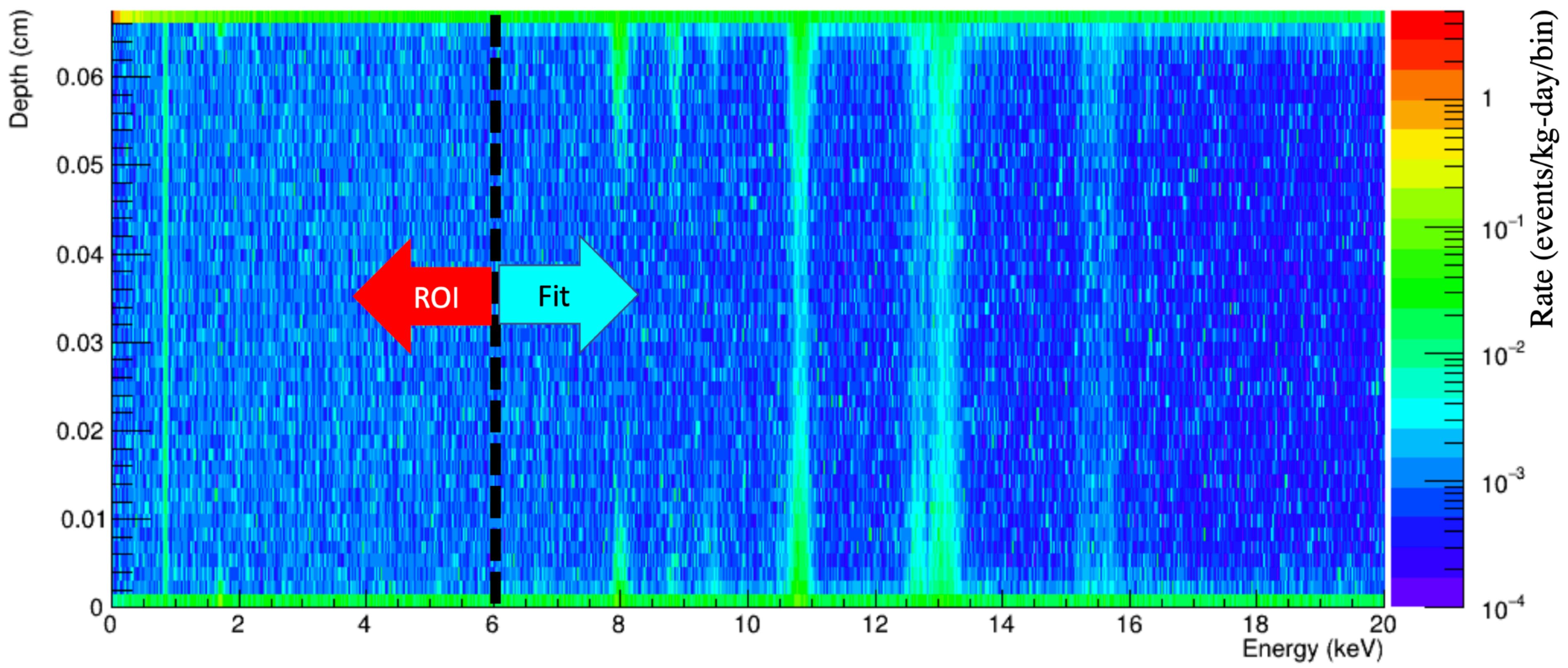
6 cm x 6 cm
4k X 4K pix
15 x 15 microns

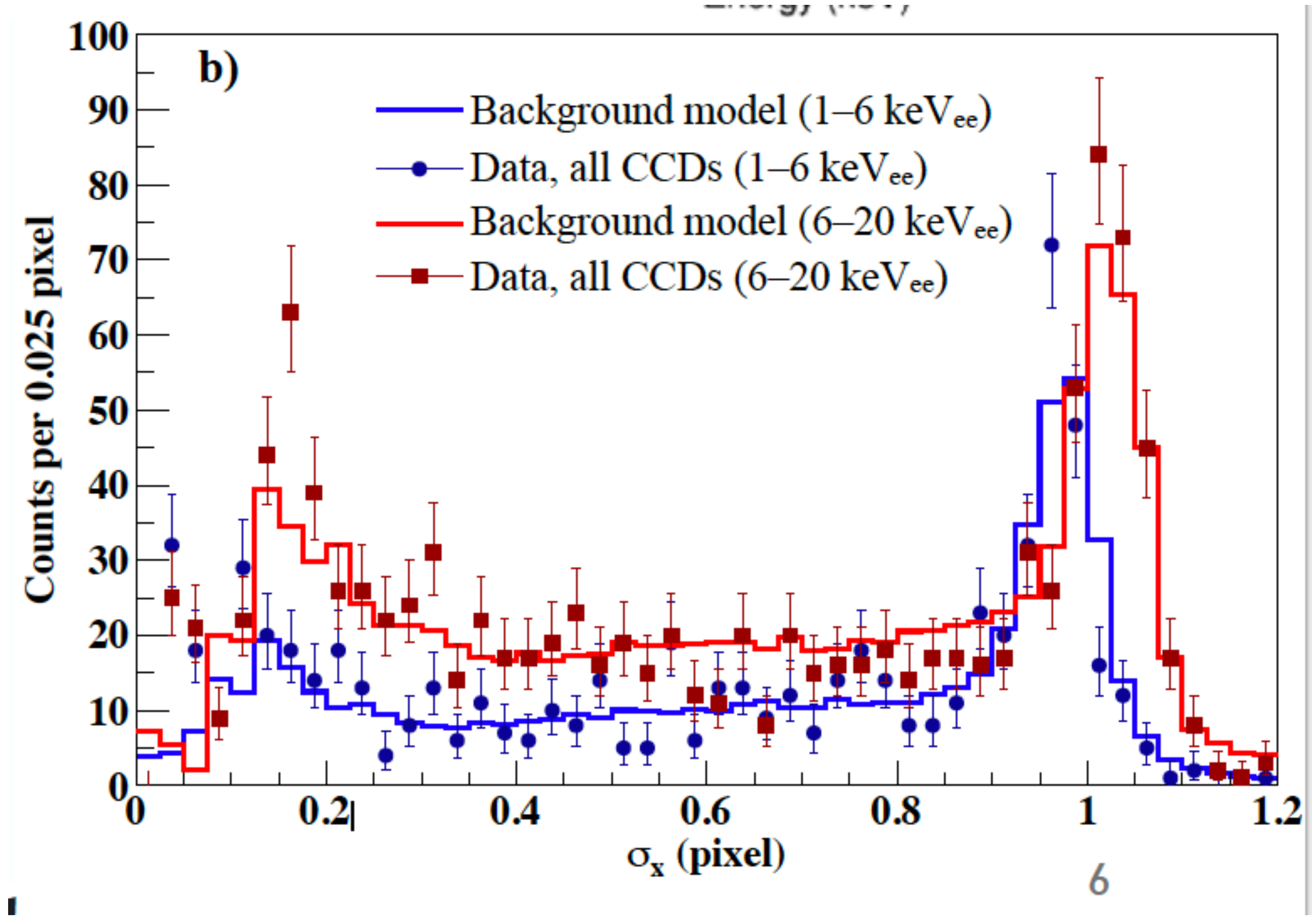


Background model construction in CCDs

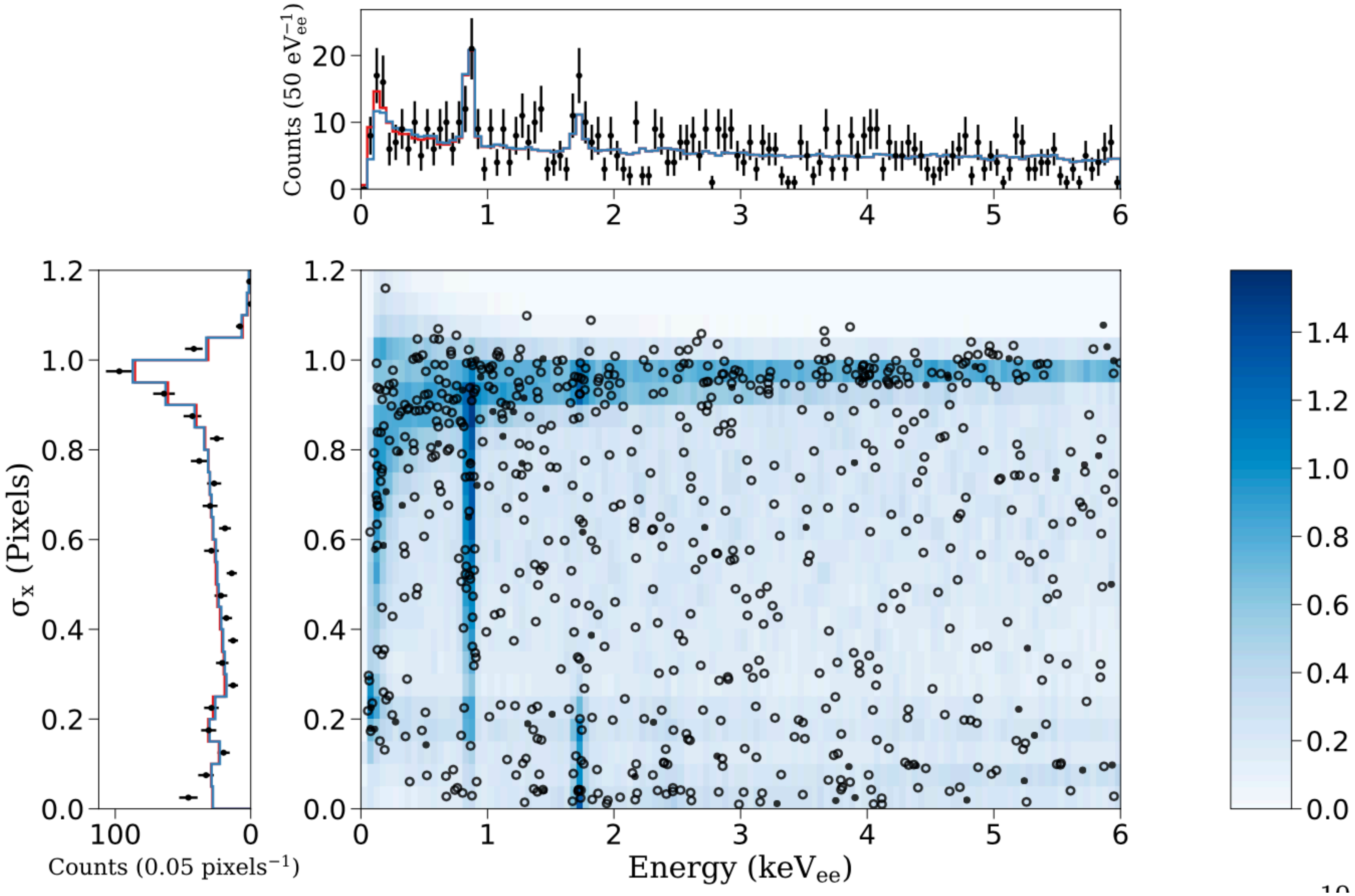
- Simulate full detector geometry and radioactive contaminants in Geant4
  - Detail down to CCD structure. Bulk and surface simulation
  - Isotopes simulated in the volumes
    - 15 common to all volumes: U/Th chains.
    - 7 cosmogenics in the copper, produced by spallation from cosmic rays.
    - only in the CCD ^{32}Si, ^{32}P, ^{3}H, ^{22}Na.
  - isotopes simulated on the surface:
    - ^{210}Pb, ^{210}Bi:
- Model construction steps:
  - Decay+tracking across detector geometry with Geant4
  - CCDs response simulation: charge generation and (partial) collection/transport, pixelation, binning and readout noise
  - Clustering E,σx distribution
  - Binned likelihood fit in WIMP-safe region (6-20 keV) → extrapolate in ROI (0-6 keV)
    - Constraint to assays and coincidence analysis

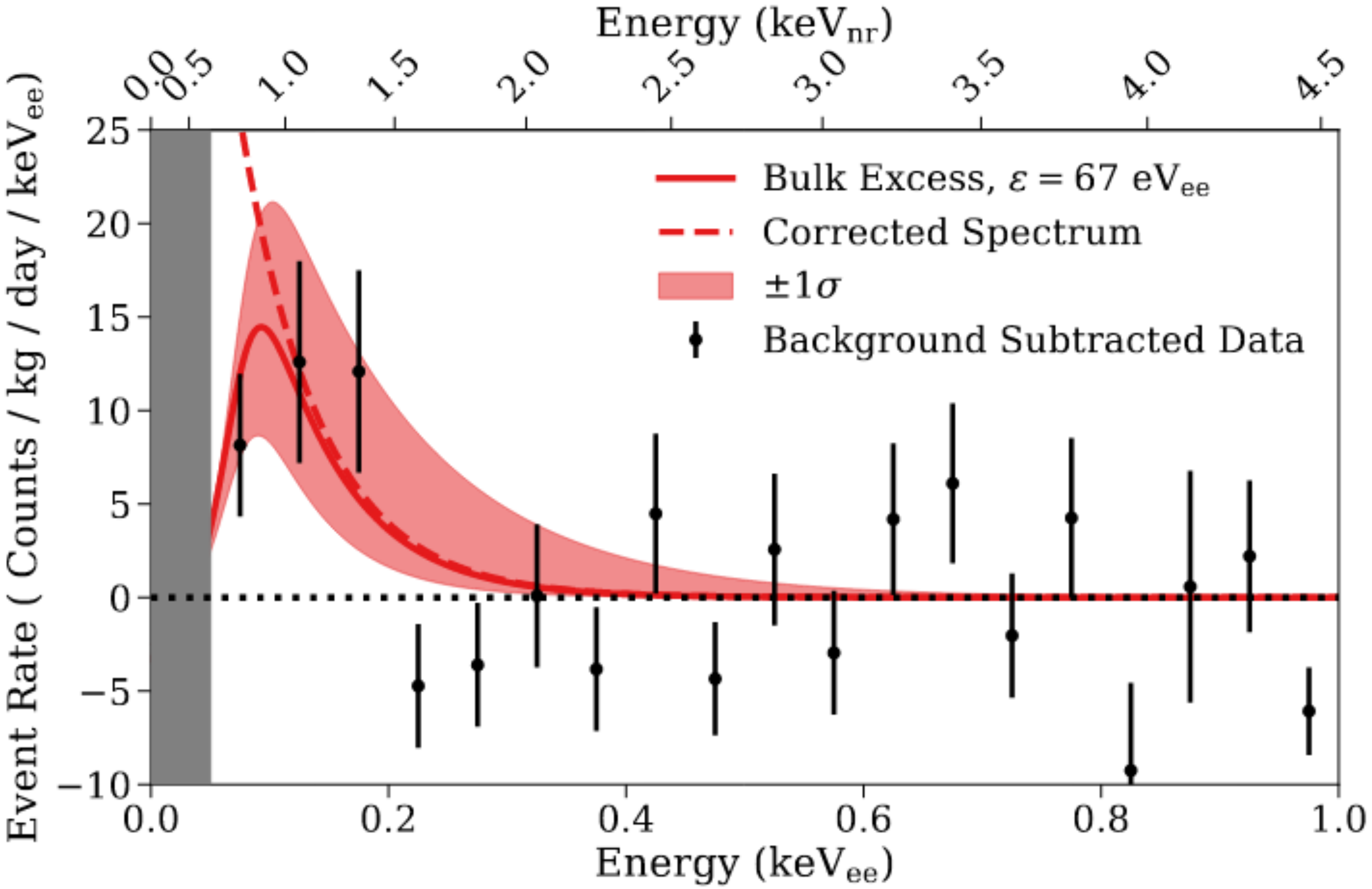






DAMIC Results





- Excess of 17.1 ± 7.6 events.
- Exponential decay spectrum with ε = 67 ± 37 eVee .
- Fit prefers signal + background over background-only with p-value 2.2 x 10 $^{-4}$

Possible Interpretations of the Excess

- Missing front component in bkg model
- Unaccounted detector front-side effect
- Unknown physics in Silicon
- New physics (e.g., dark matter?)

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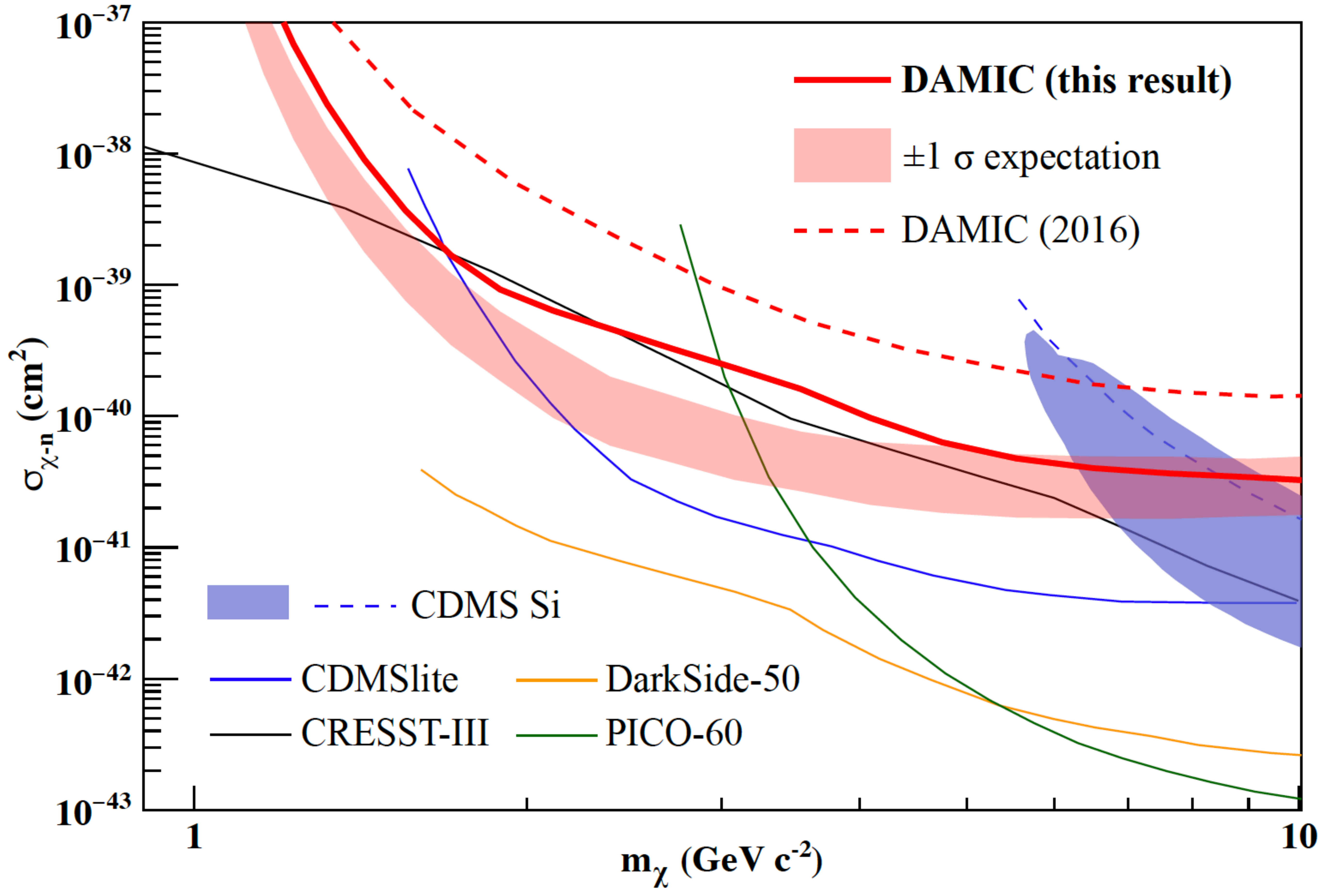
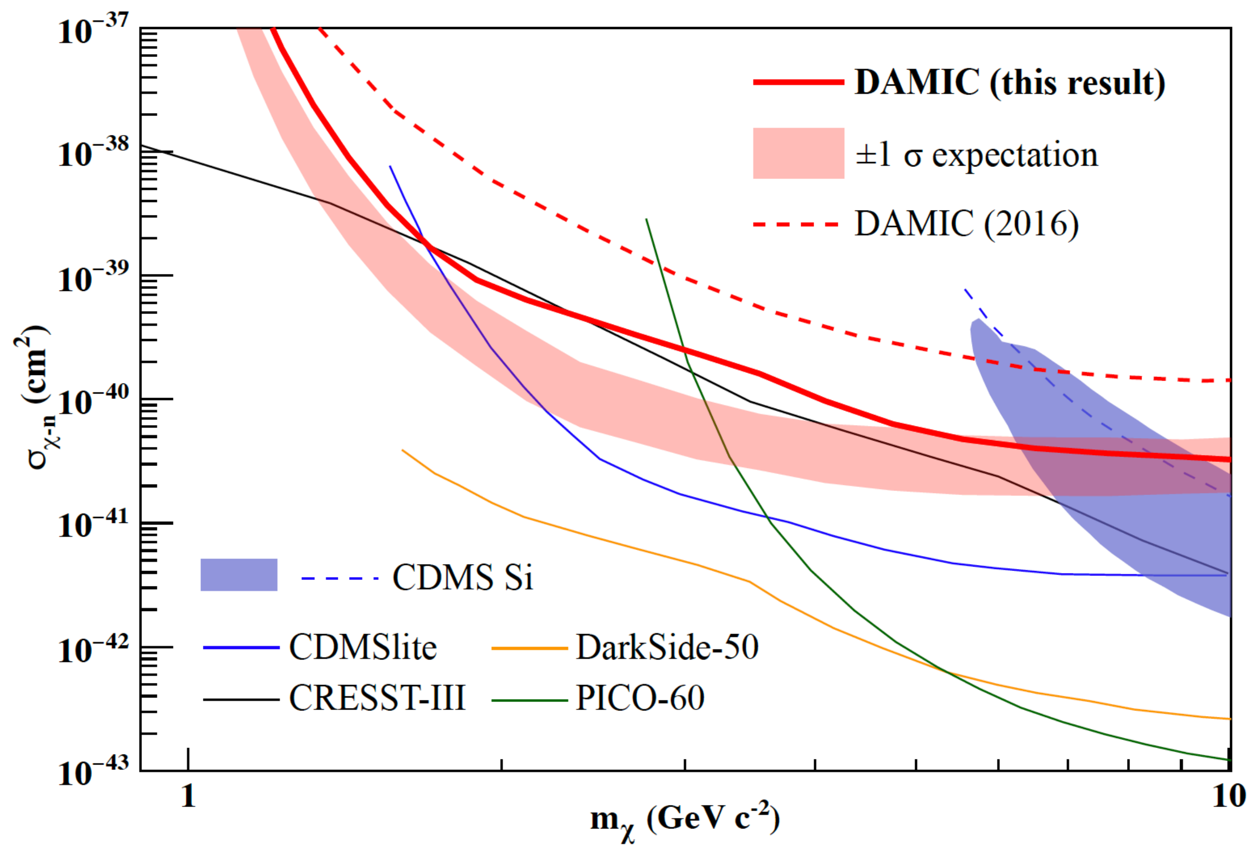
DAMIC Results



- Even in the presence of the excess, we can place exclusion limits on WIMP-nucleus coherent elastic scattering.
- Nuclear recoil response fully calibrated.
- Excludes the lower mass region of the CDMSII-Si excess (2013)

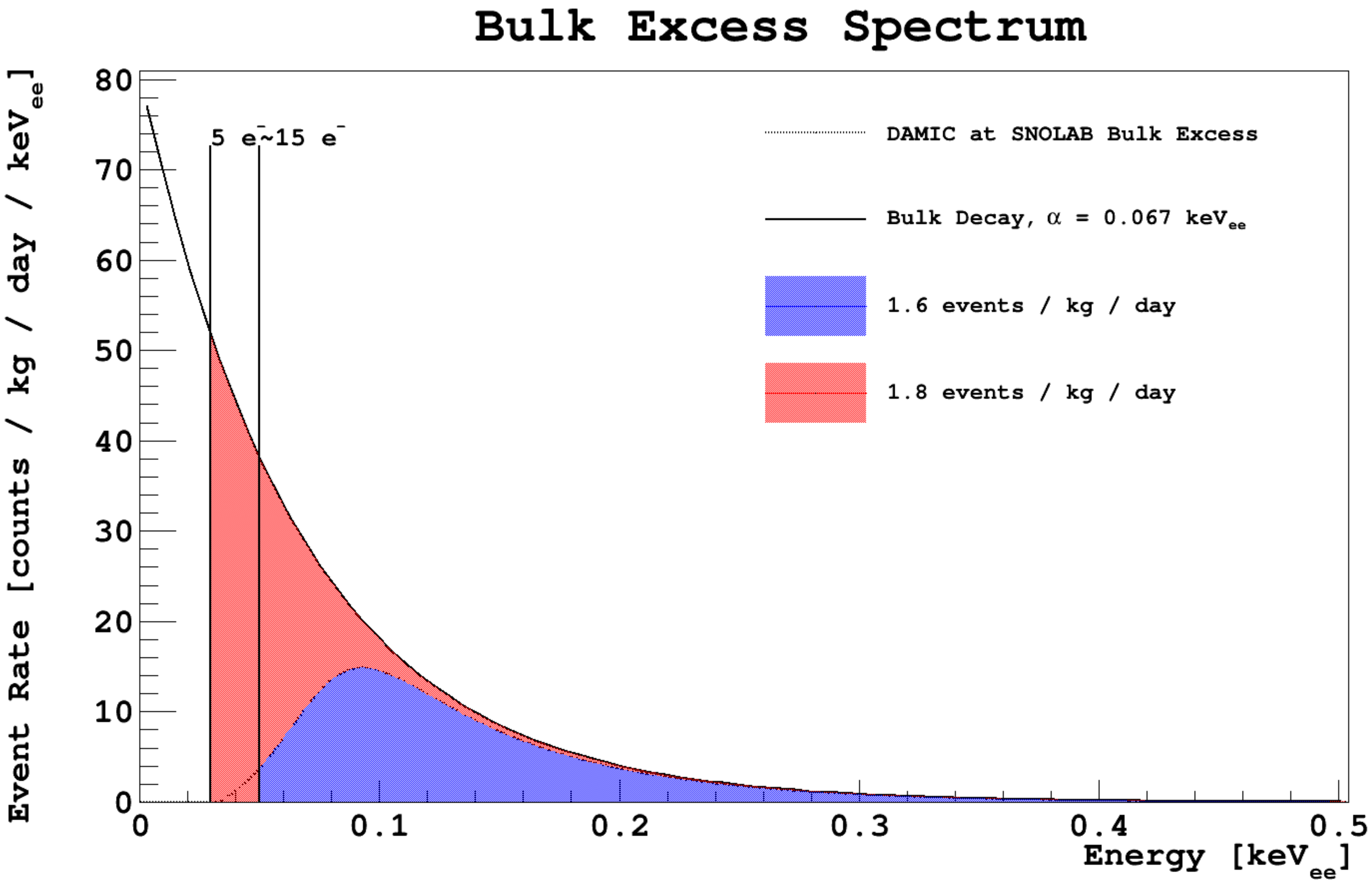
—> improving the resolution to < 1 e- would change the game

DAMIC Results



We report a limit on WIMP - nucleon SI interaction

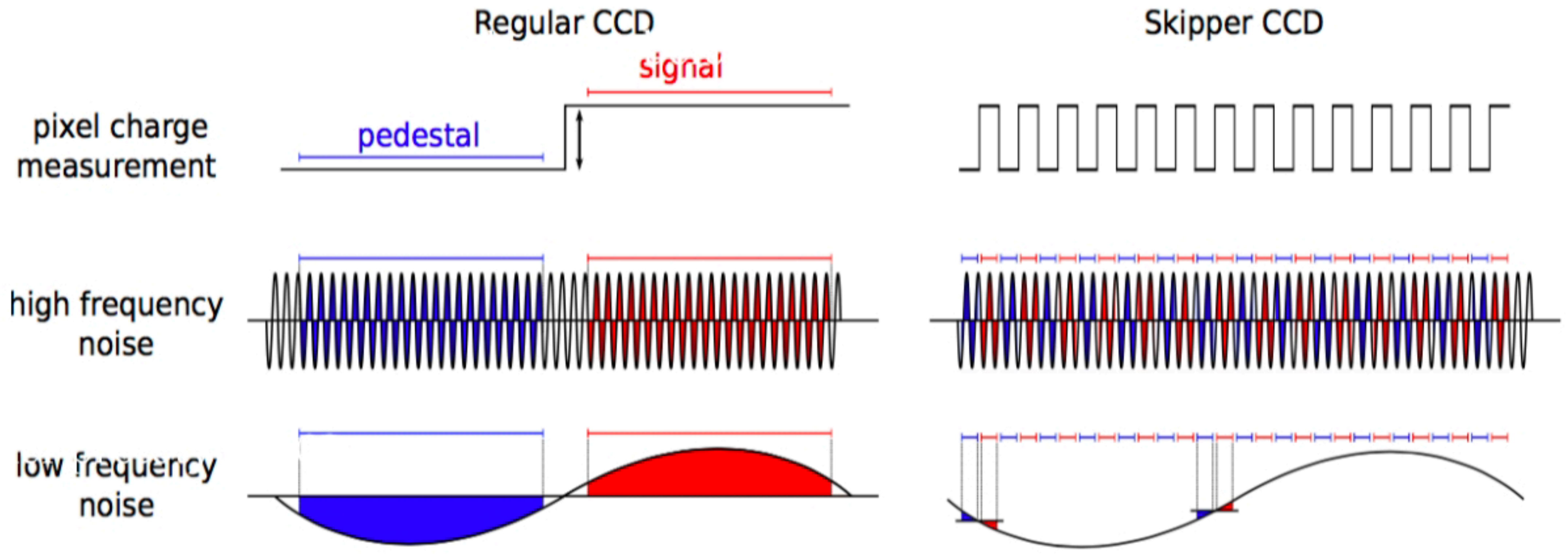
- Significant fraction of the CDMS Si excluded

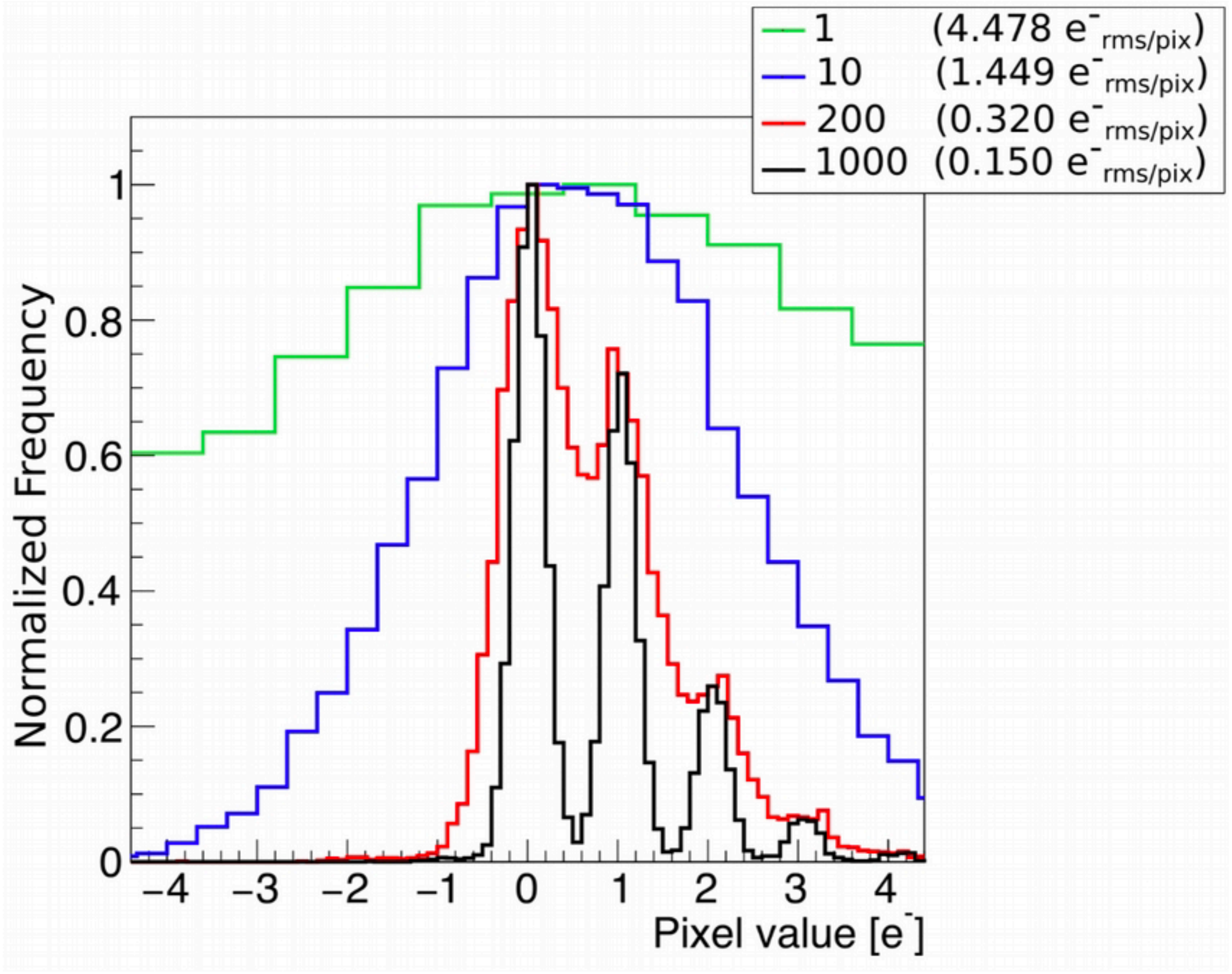


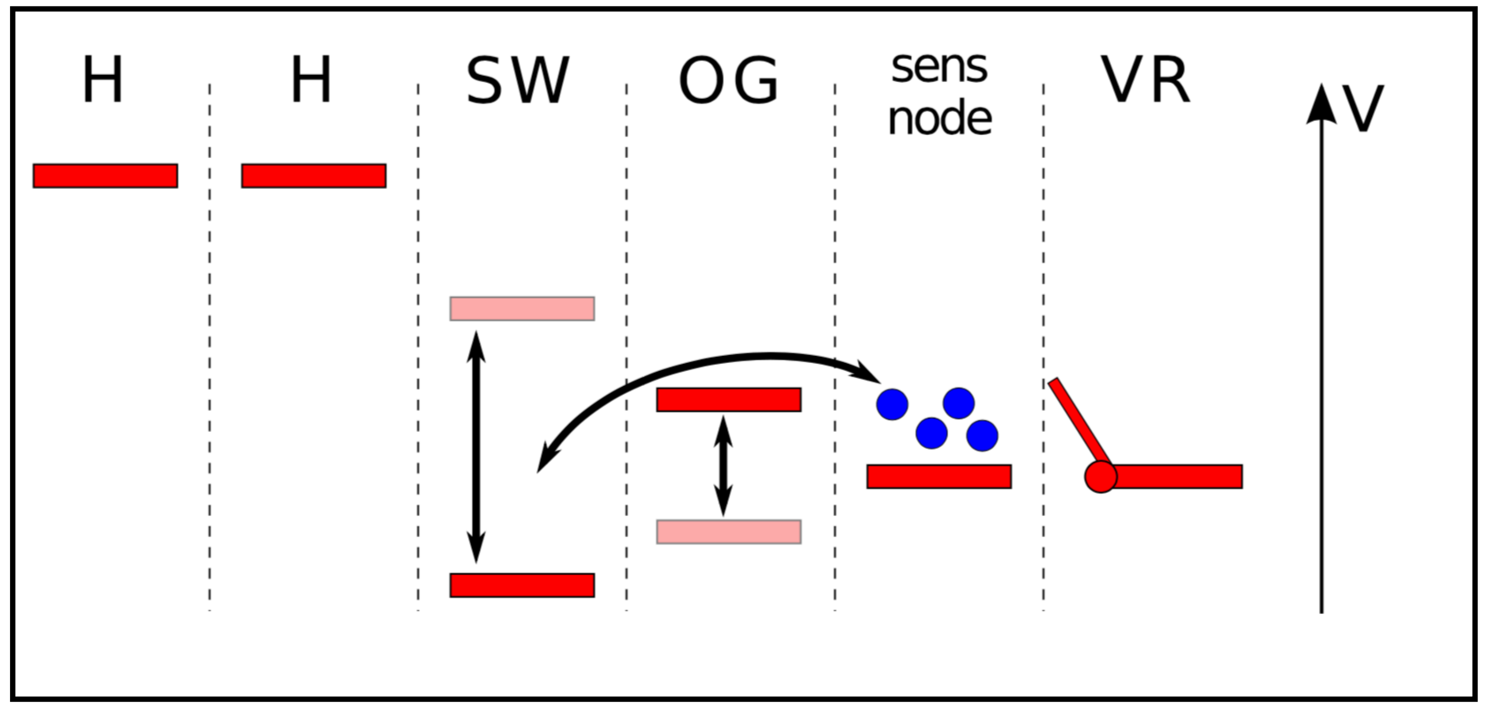
—> improving the resolution to < 1 e- would change the game

Single Electron Resolution: skipper amplifiers

- Conventional CCD 1/f low frequency noise of amplifier dominates readout noise level (integration time ~40-50 μs)
- Skipper amplifier (floating gate) allows charge to move back-and-forth across measurement node before destruction
- Measure charge fast (kill 1/f, single skip integration time ~O(1 μs), N times, readout noise follows ~1/sqrt(N)
- Can see single electron ionization signals!



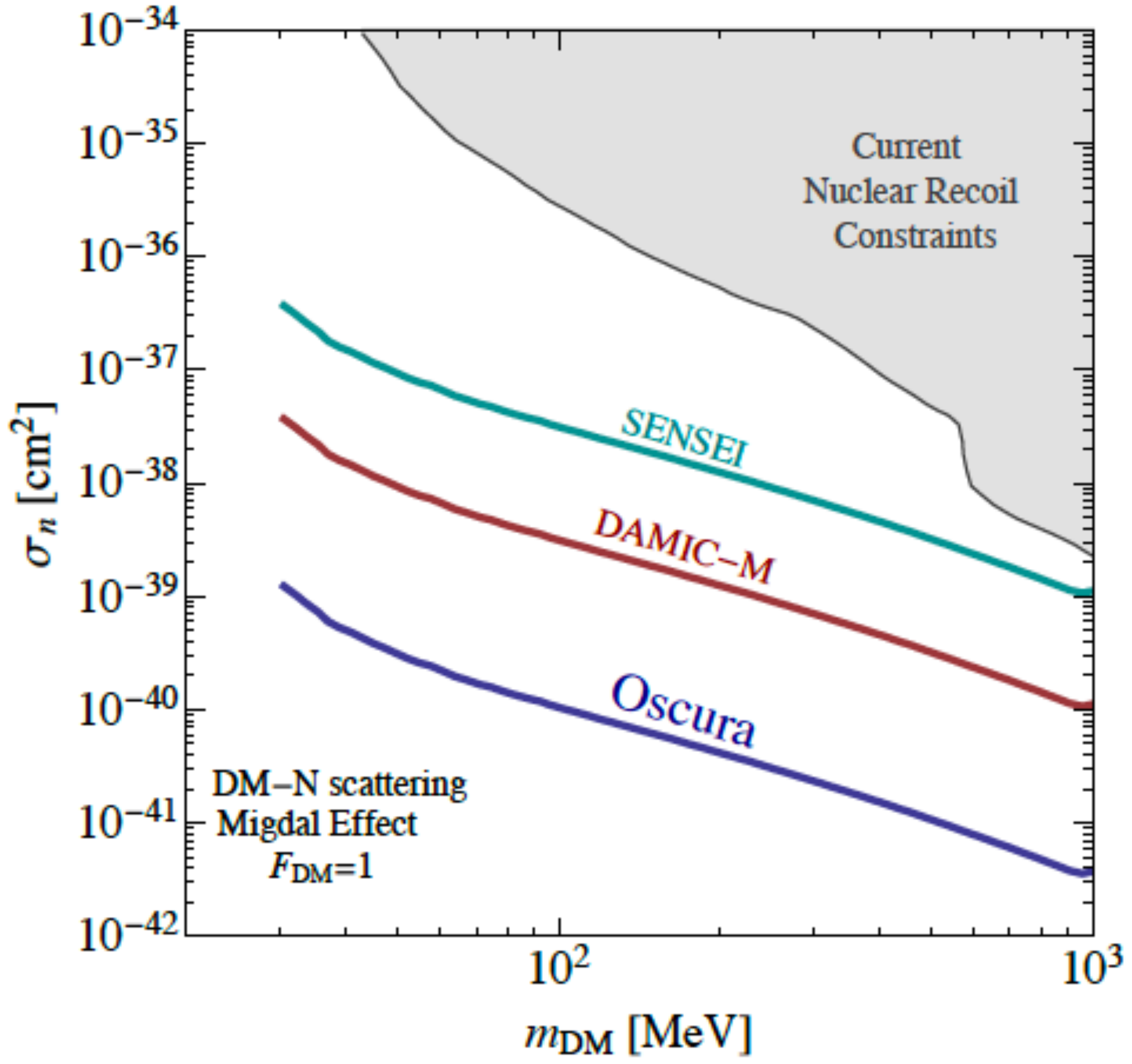


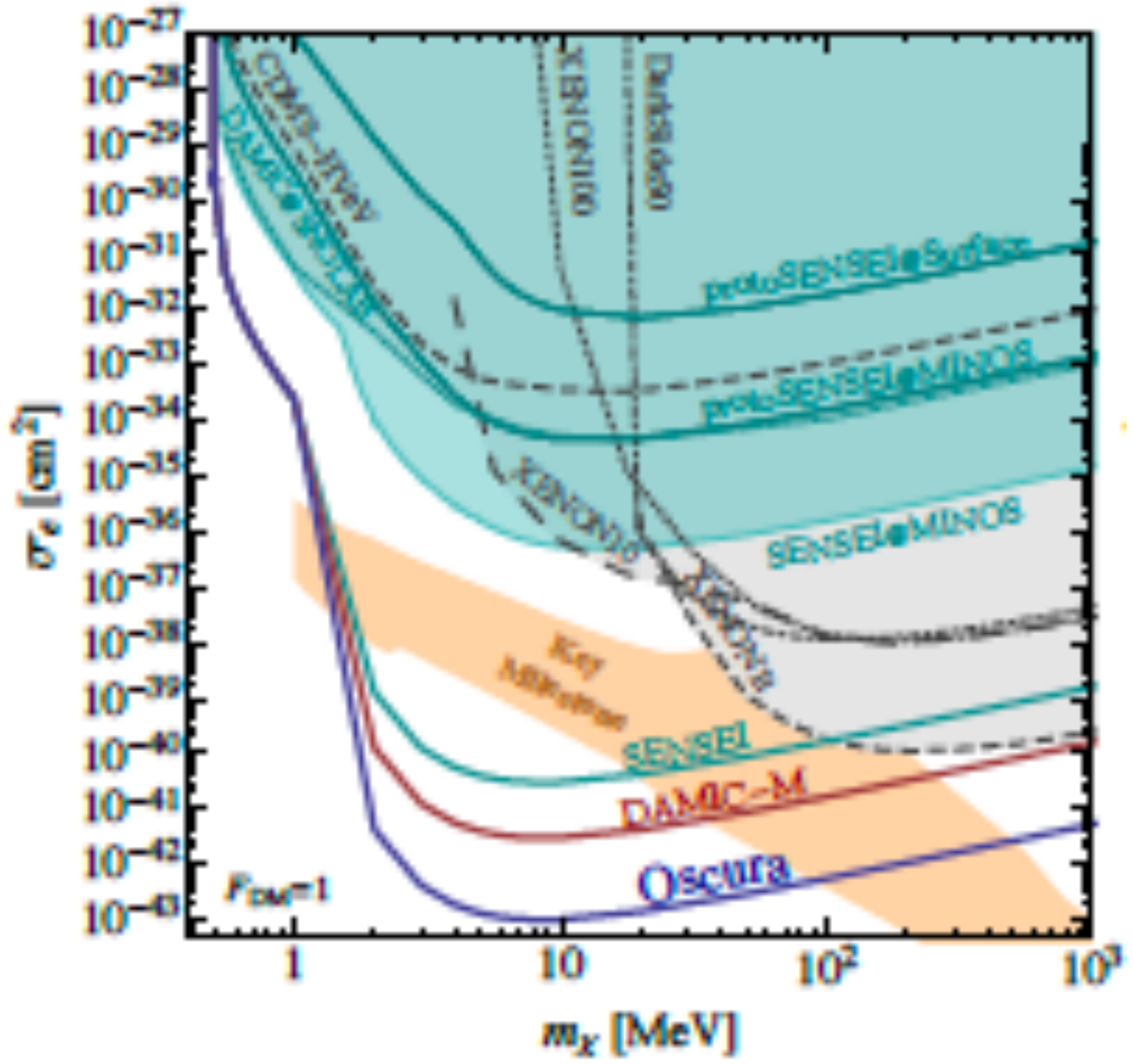


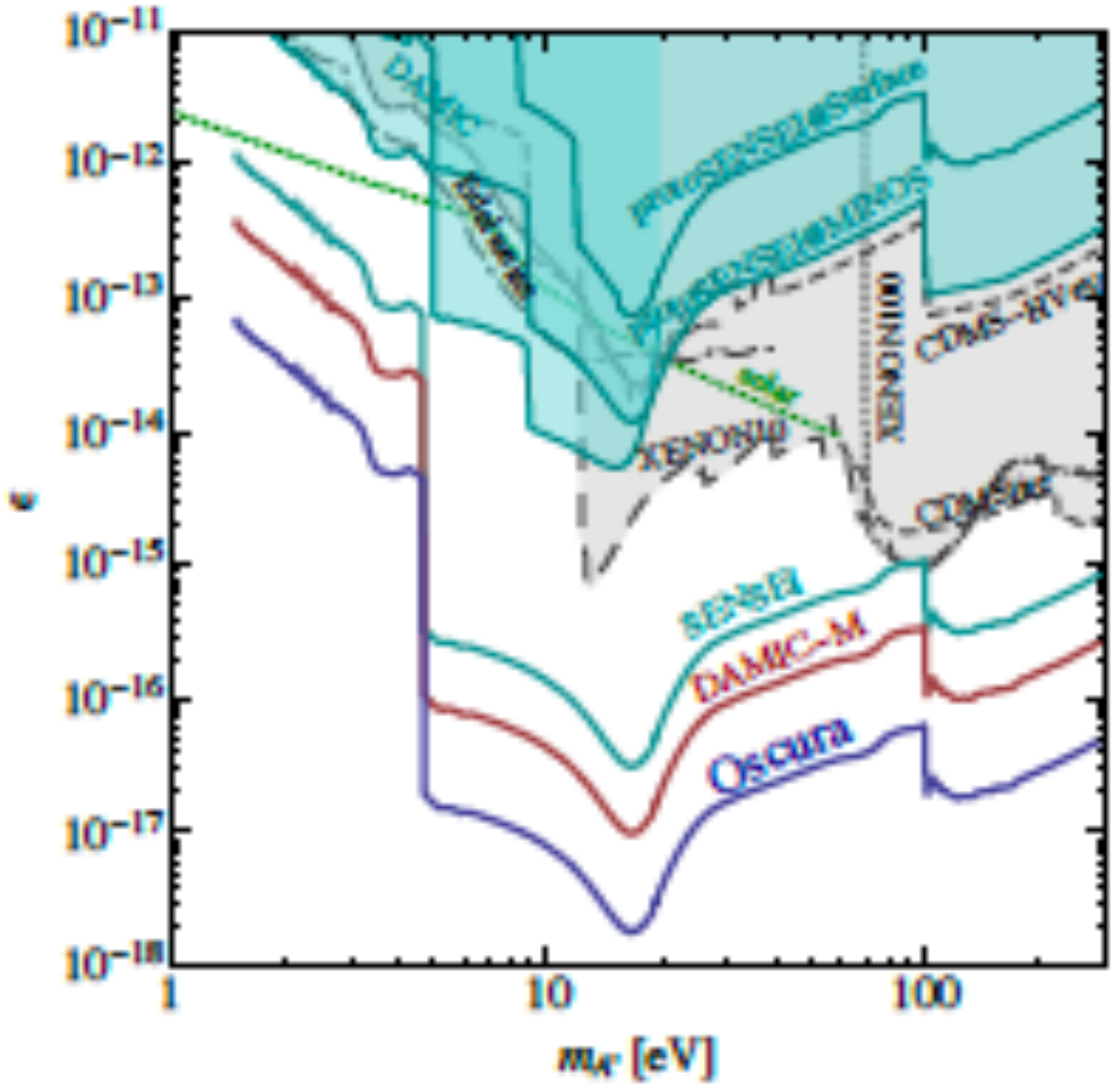
Skipper CCDs future

Several active and planned experiments.

- DAMIC at SNOLAB Upgrade. ~ 18 g (taking data)
- SENSEI (O(100) g started in 2021): first DM experiment using skipper-CCDs
  - Physics results from prototypes and test runs; full scale experiment being commissioned at SNOLAB. Active mass and radiopurity similar to DAMIC
- DMSquared (surface run since late 2020)->Daily modulation
- DAMIC-M (O(1) kg starting 2024): next-generation Skipper experiment
  - Scaling up in mass, very low backgrounds (O(0.1dru))
  - DAMIC-M Low Background Chamber (LBC). ~ 18 g (taking data)
- Oscura (O(10) kg, in development): next-generation Skipper experiment
  - Major R&D for readout, cooling, integration

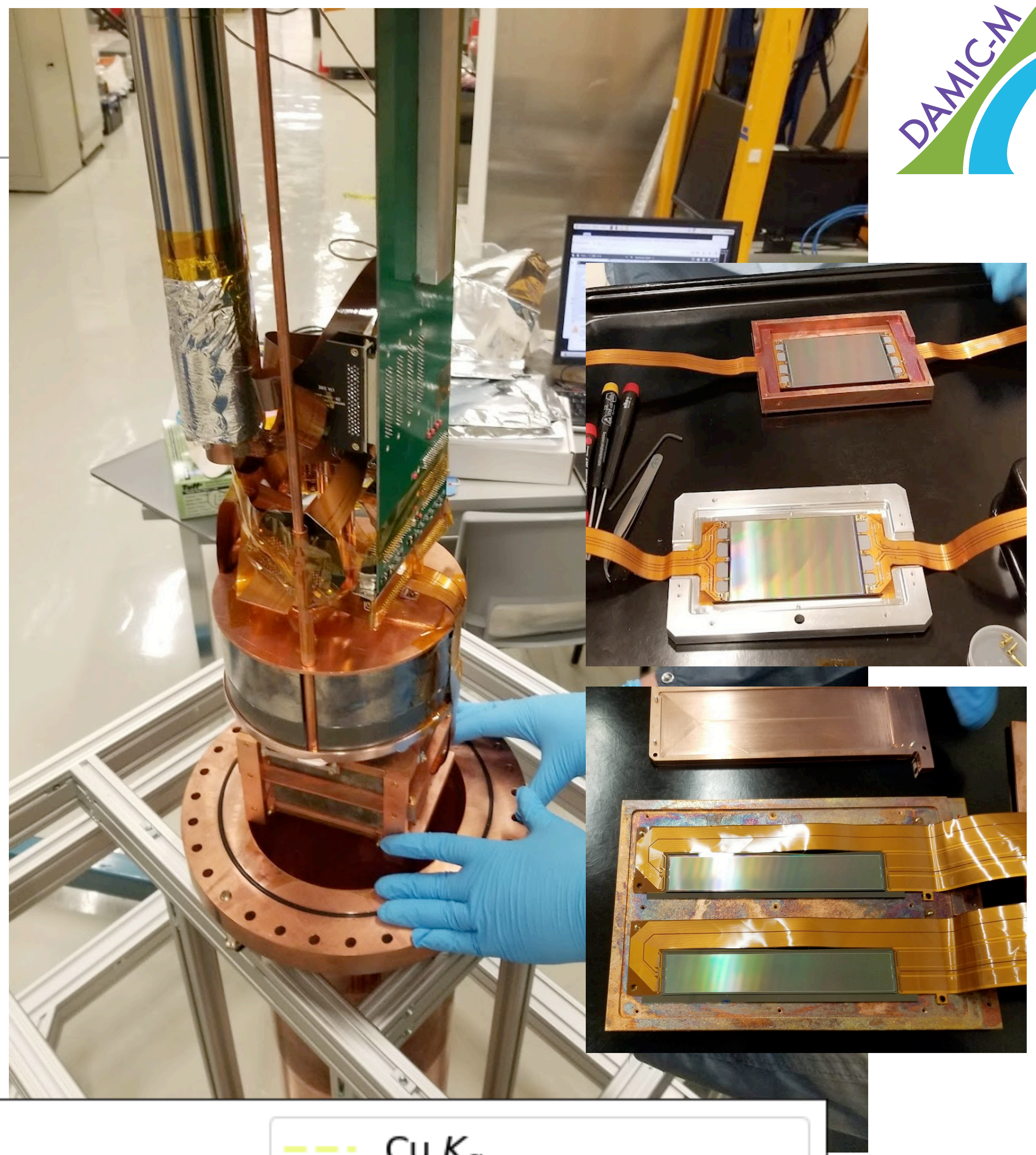


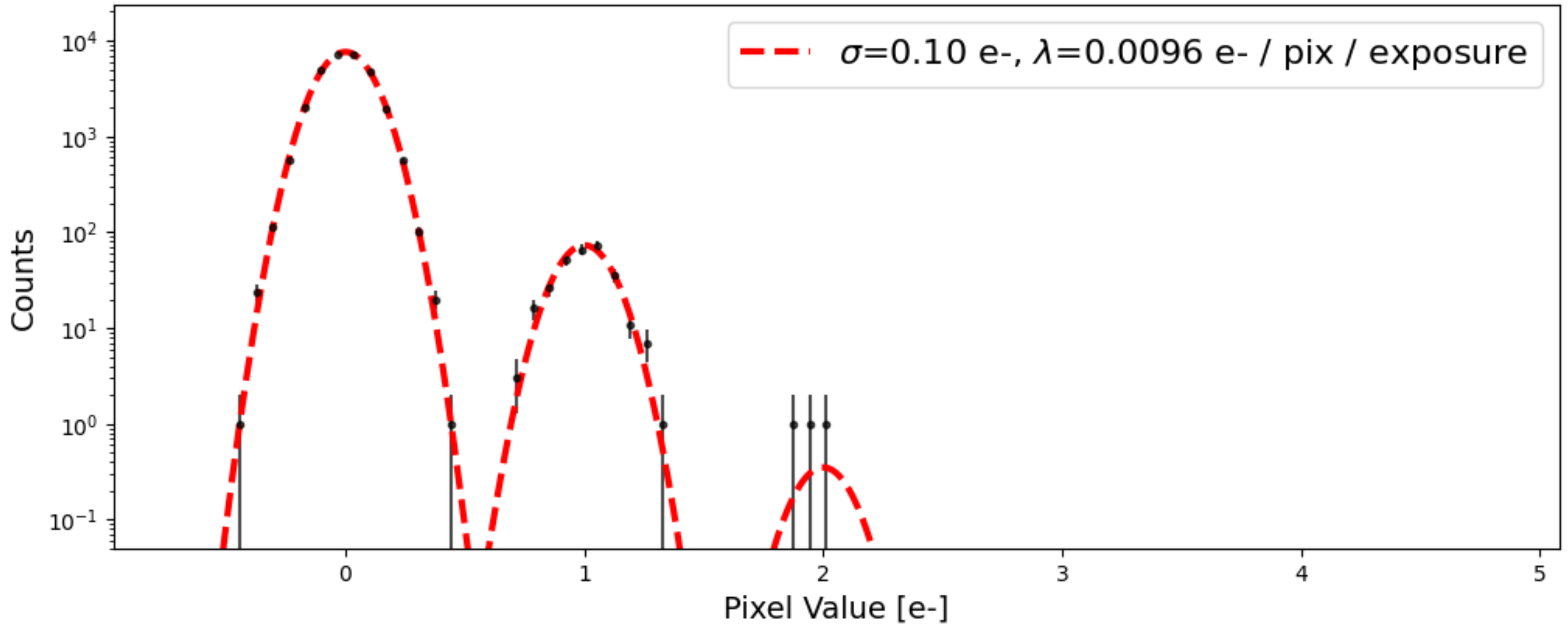


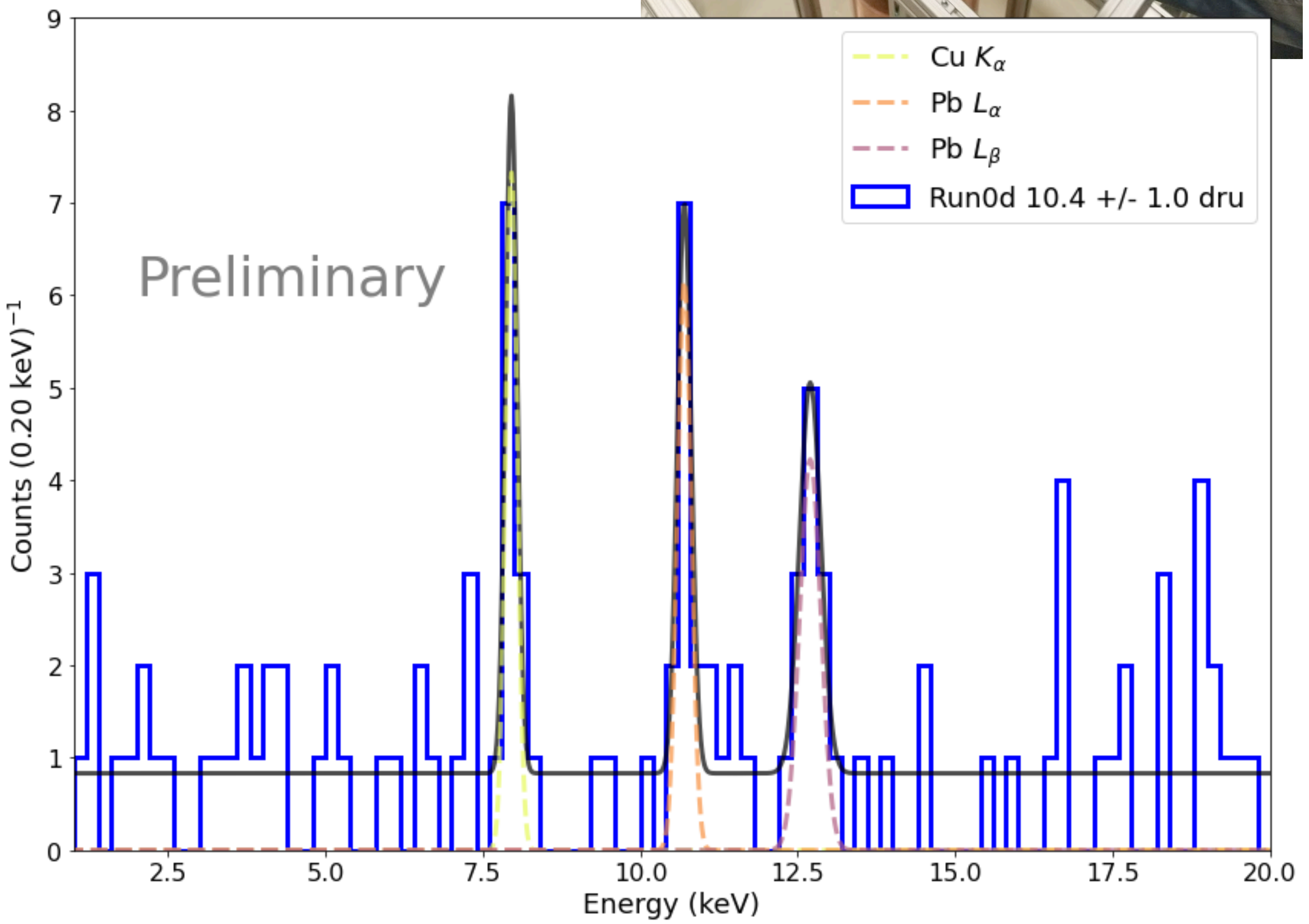


DAMIC@SNOLAB upgrade

- Understand event excess found in DAMIC
- Two 6k X 4k DAMIC-M and two 6k X 1.5K Sensei skipper CCDs installed end 2021.
- Detector commissioning completed in early 2022.
- Demonstrated single-electron resolution and adequate leakage current levels.
- Expect new spectrum measurement with much lower noise by end of 2022!







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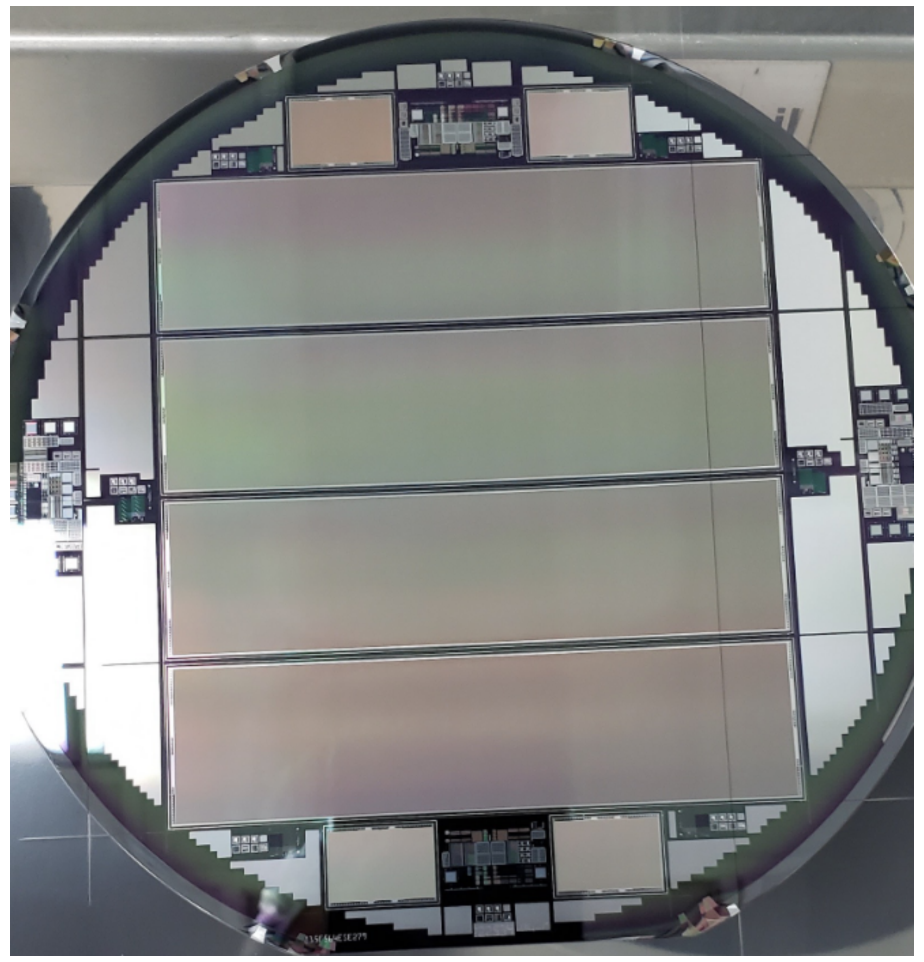
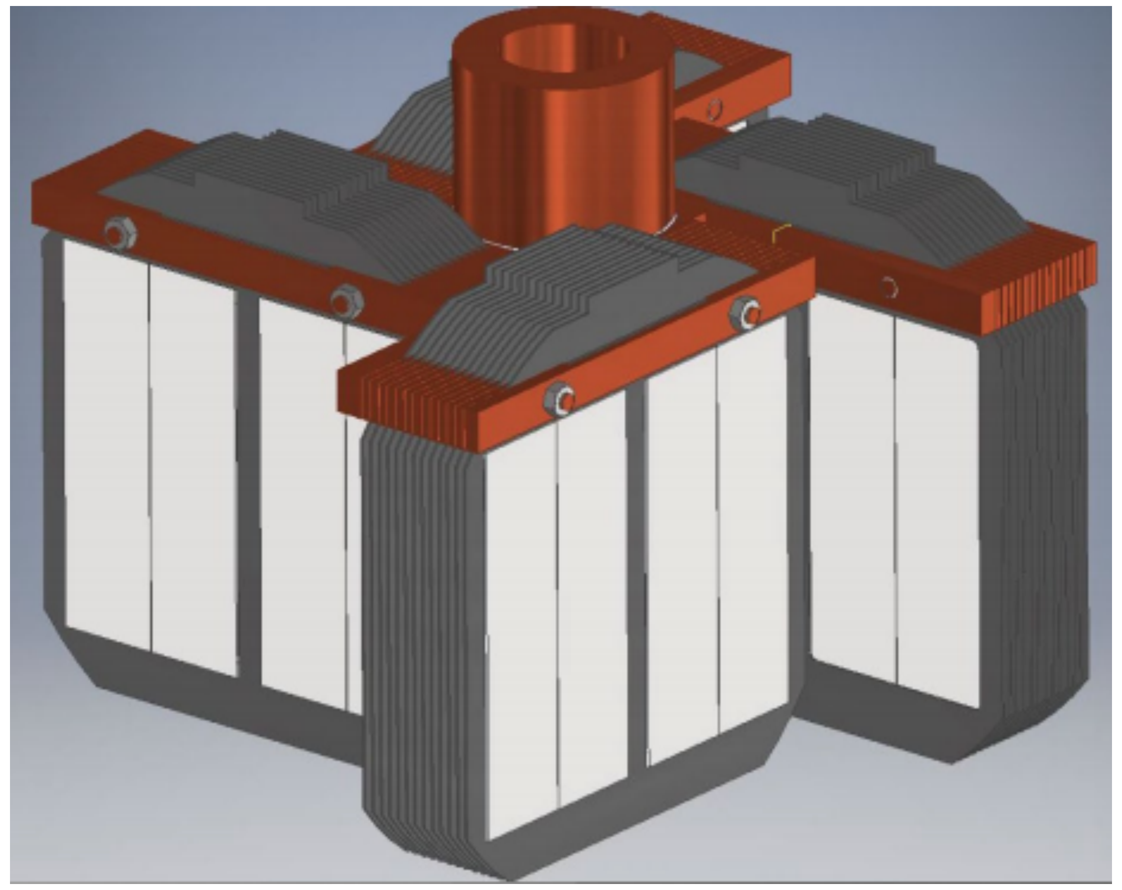
DAMIC-M detector

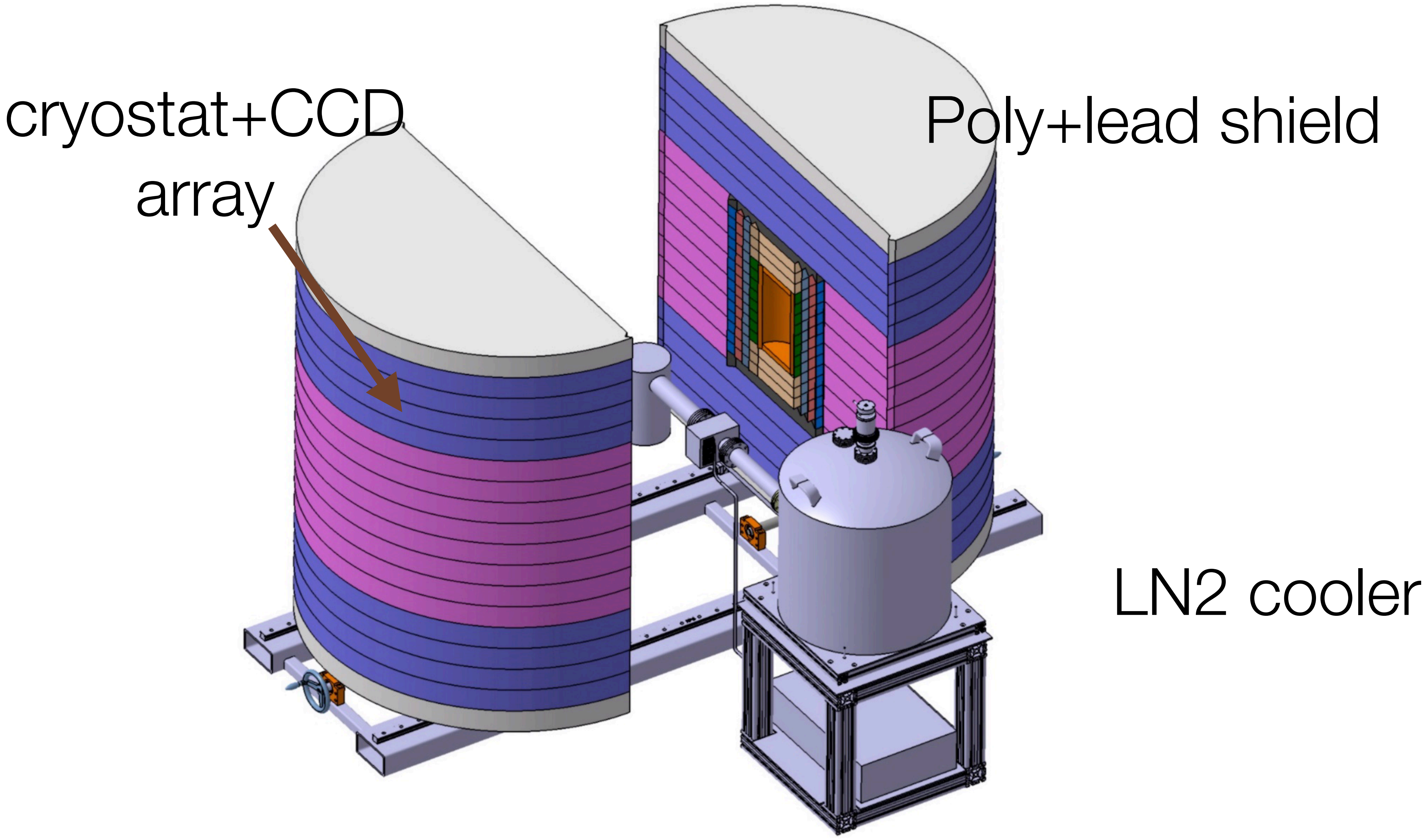
- CCDs:
  - High resistivity, n-type, high purity silicon; 6k x 1.5k pixels (15 x 15 x 675 μm3)
  - Fully depleted (no charge loss when drifting)
  - 47/6 μm^2 skipper amplifiers
  - Low background flex cable
- Detector:
  - kg-scale, 4 CCDs per wafer in array
  - Electro-formed copper cryostat, IR shield (at PNNL)
  - Operate at 110K and $1e^{-7}$ mbar
  - Layered poly + lead shielding, innermost layer of ancient lead
  - Custom electronics for fast readout and low noise
- Background controls:
  - Cosmic activation and radon → limited the time above ground/in air (fabrication, transportation, etc). Test and packaging done underground.
  - Careful selection of the materials
  - CCD treatment to properly clean the surfaces.
  - Spatially correlated sequences identification as radioactive decay chains.



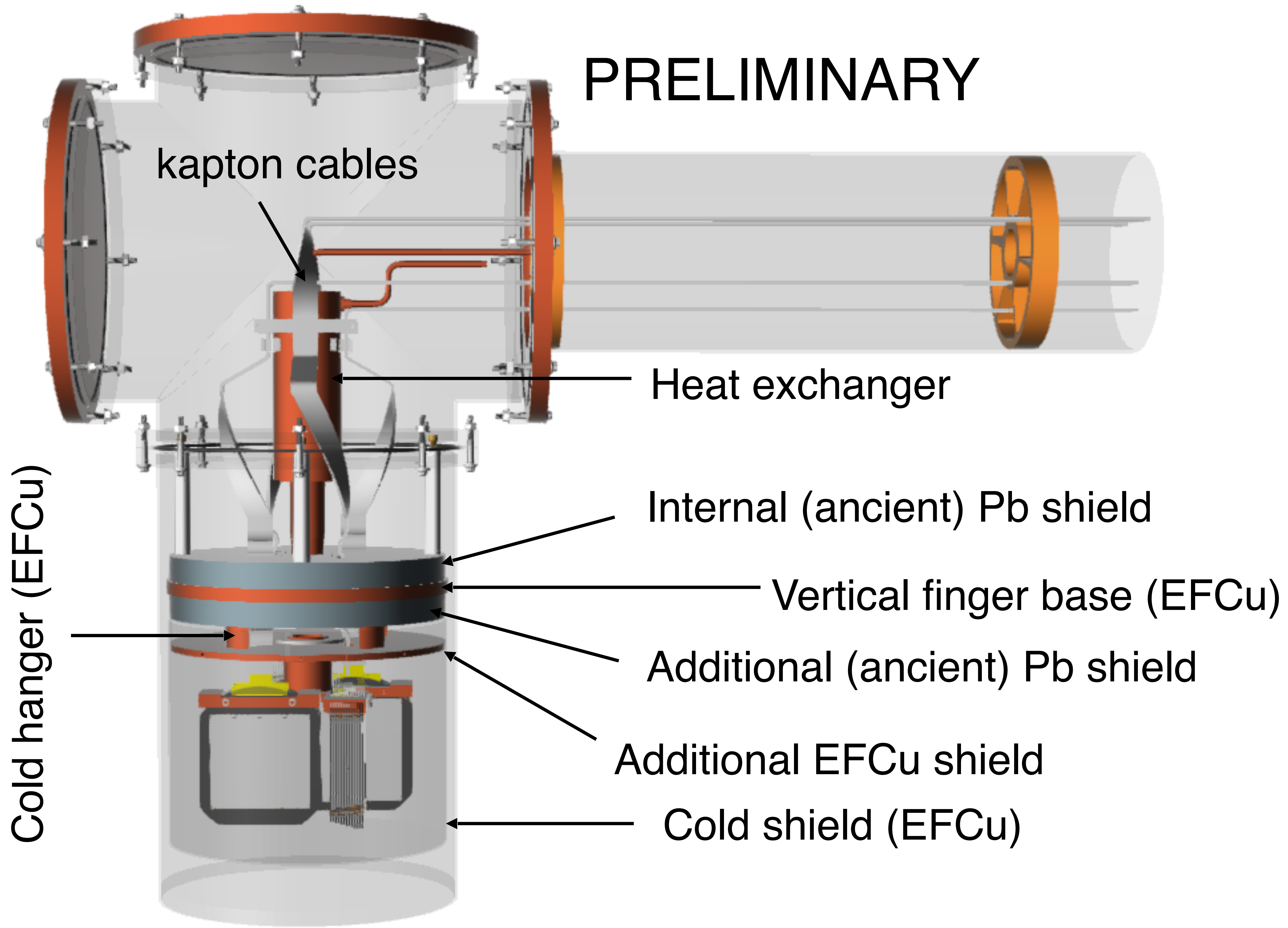
CCD pre-production

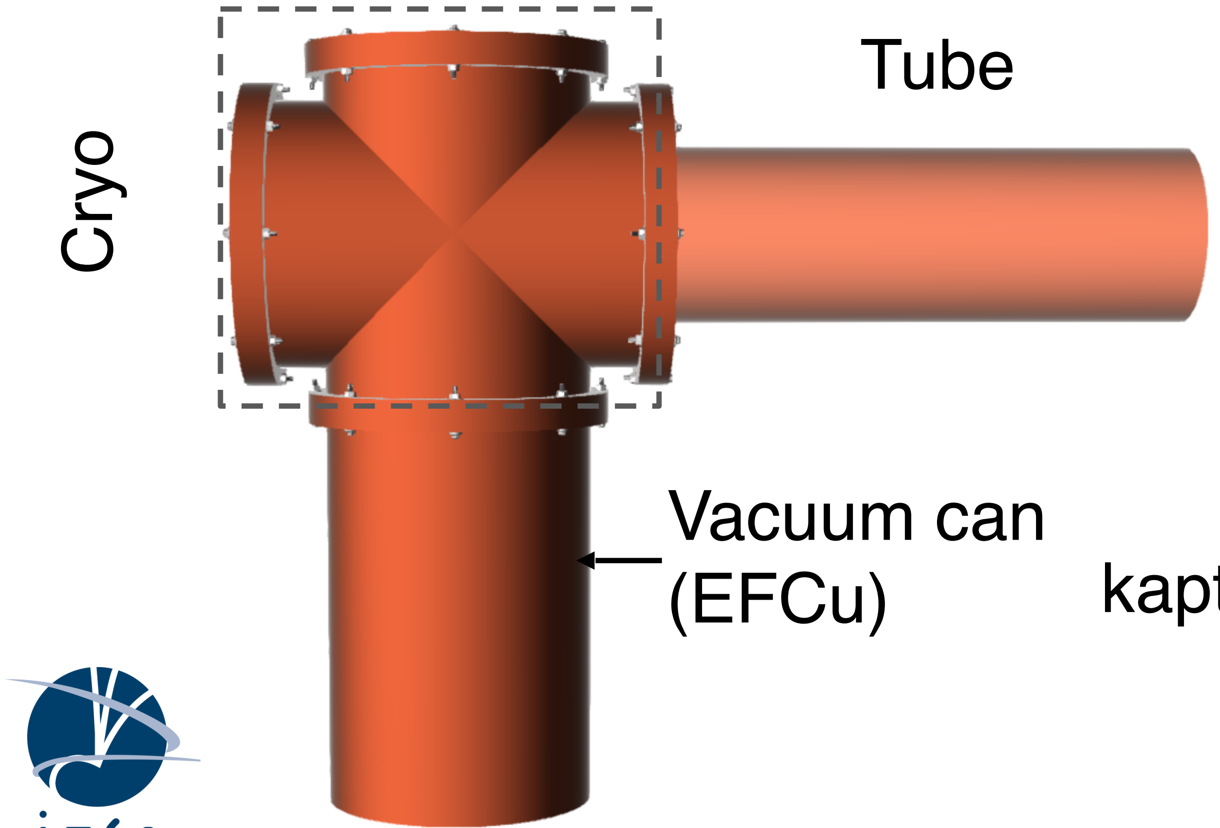
CCD array

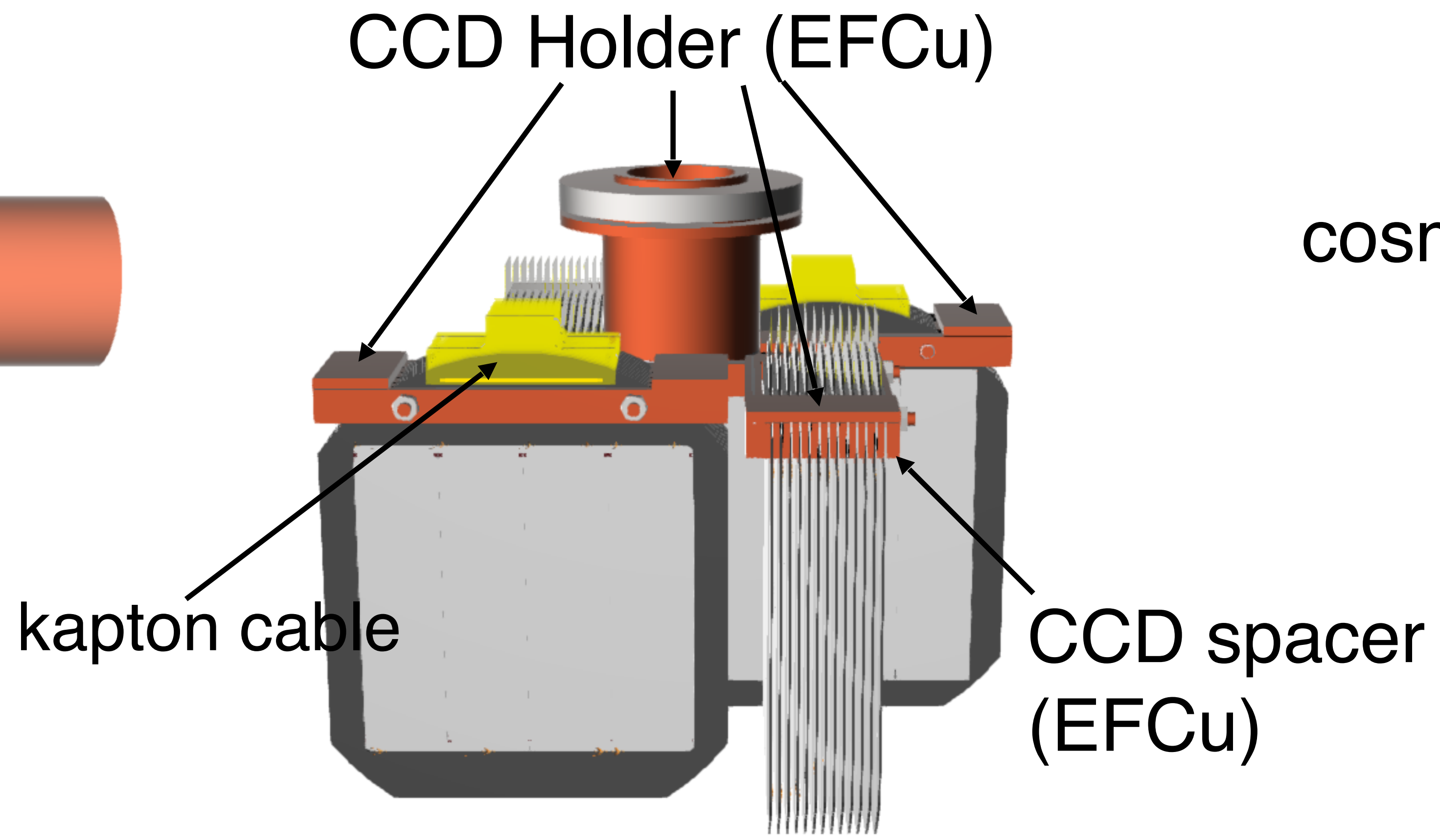




DAMIC- M background estimate and design optimization

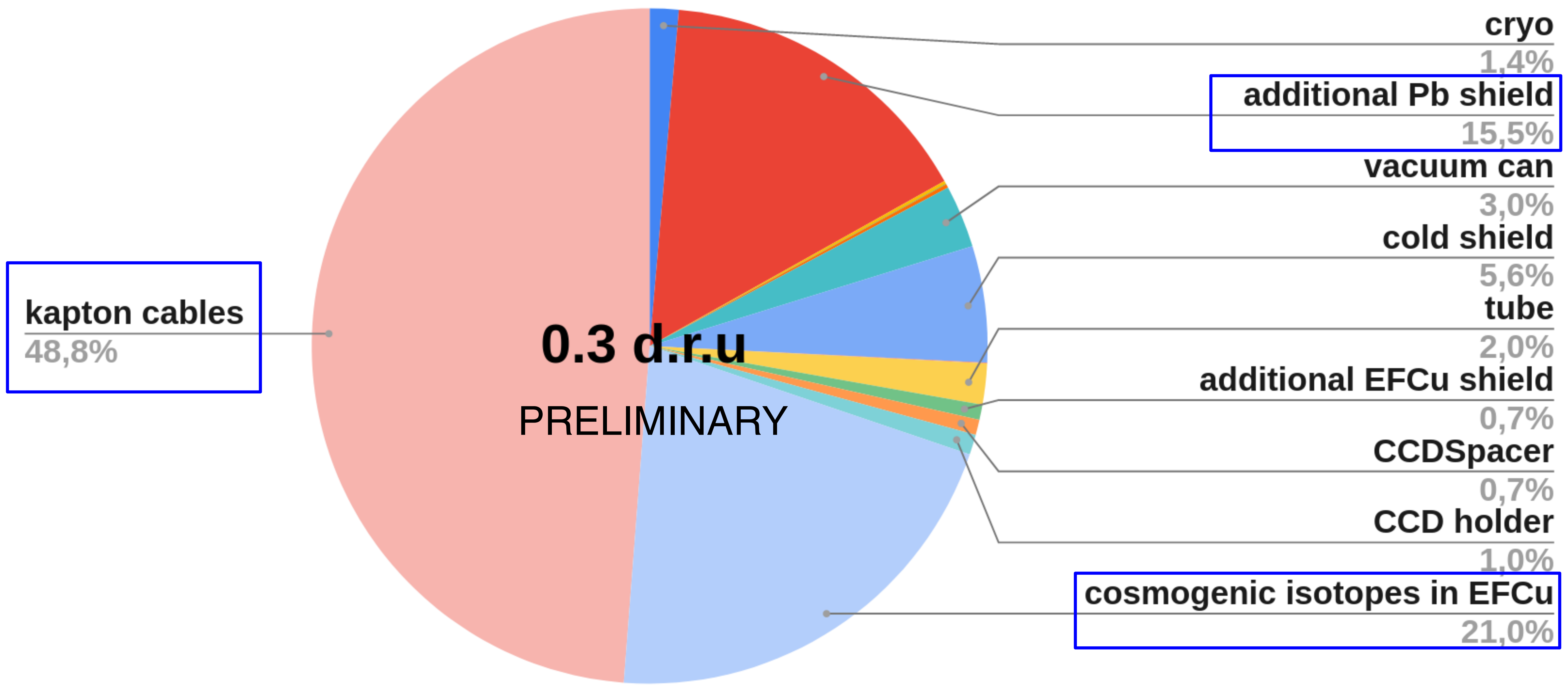






Simulations to estimate design background level:

Geant4 + custom detector response simulation

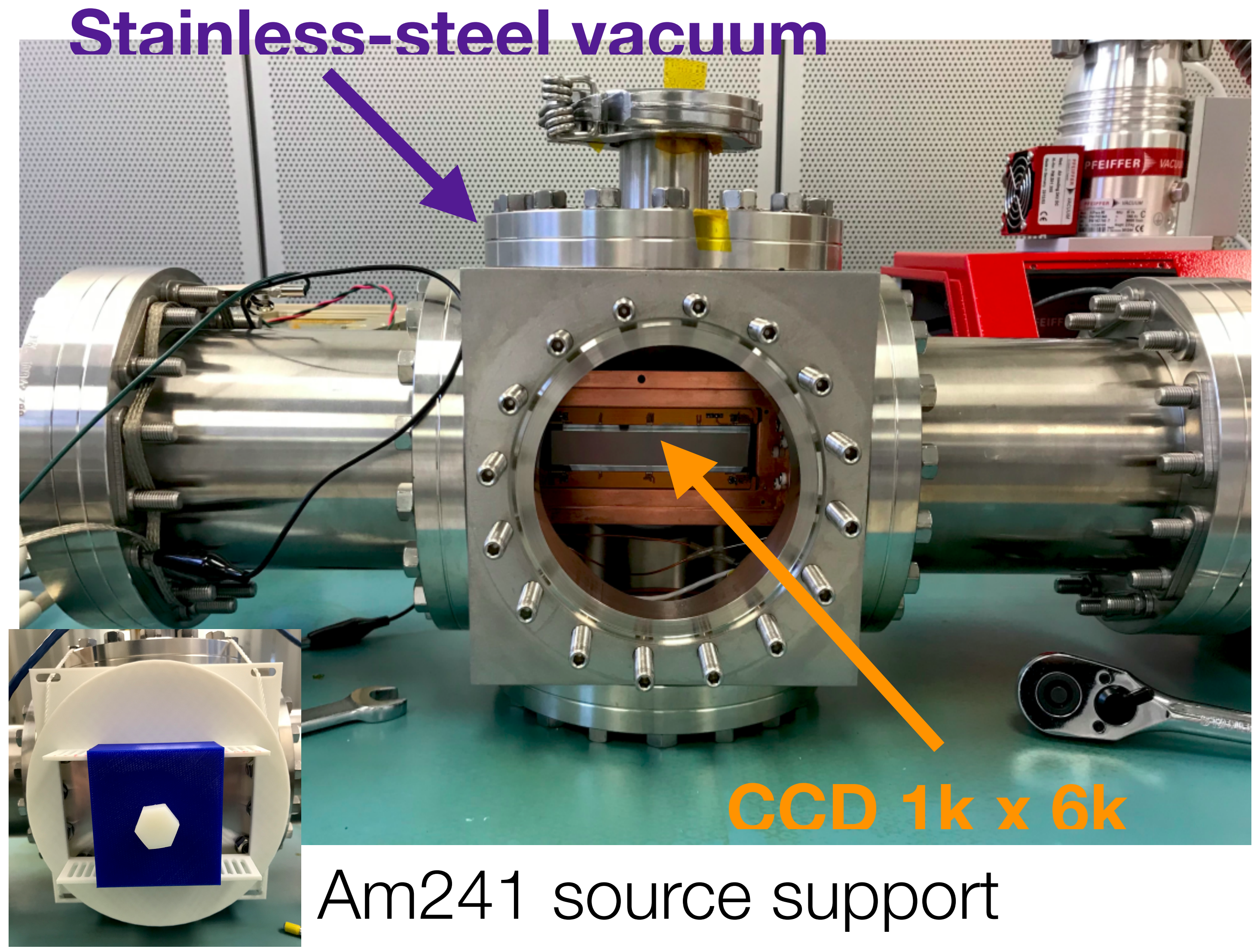


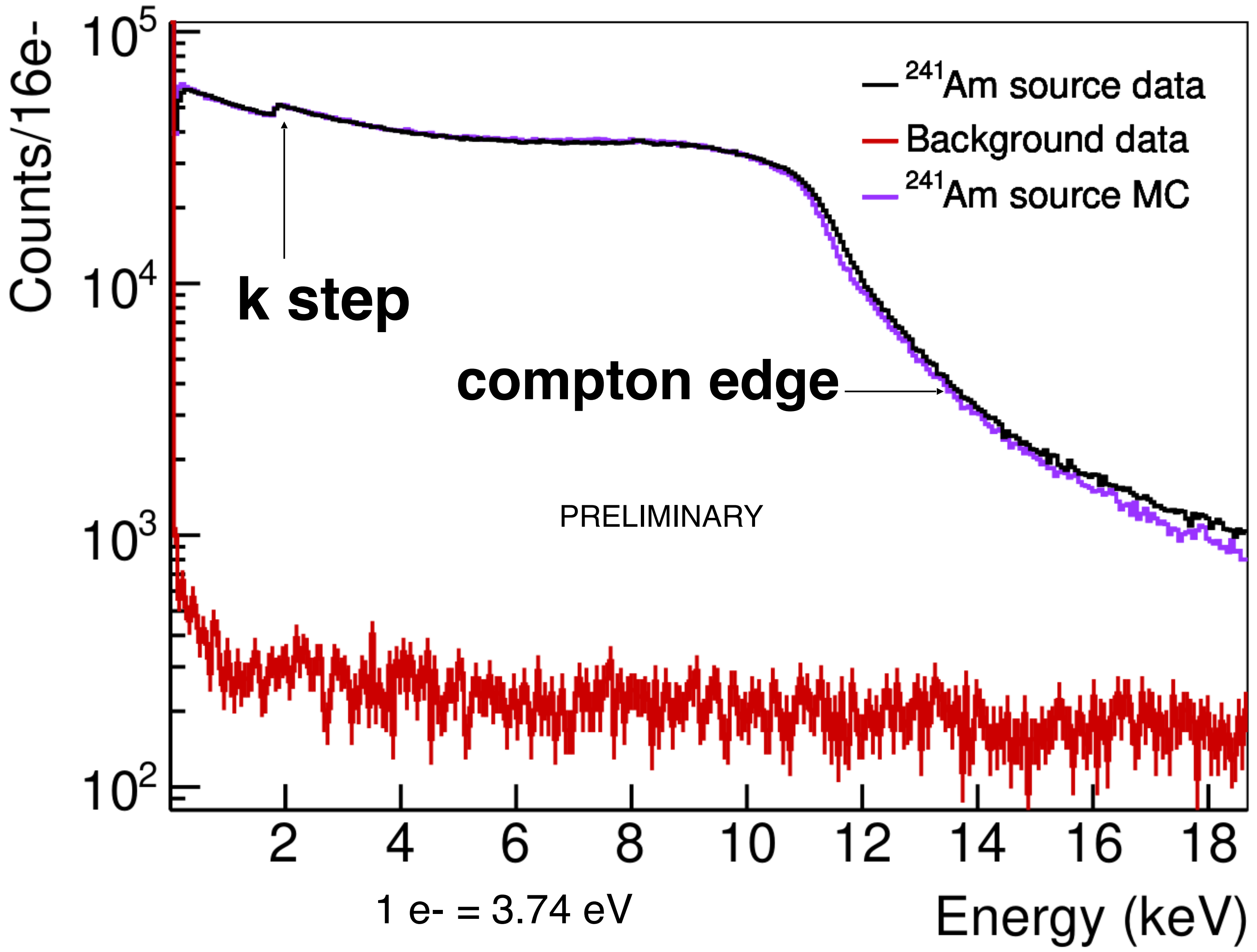
cosmogenic isotopes in Electro-Formed Cu assuming: exposure time= 10 , cooling time underground = 180 d, experiment running time = 1 yr

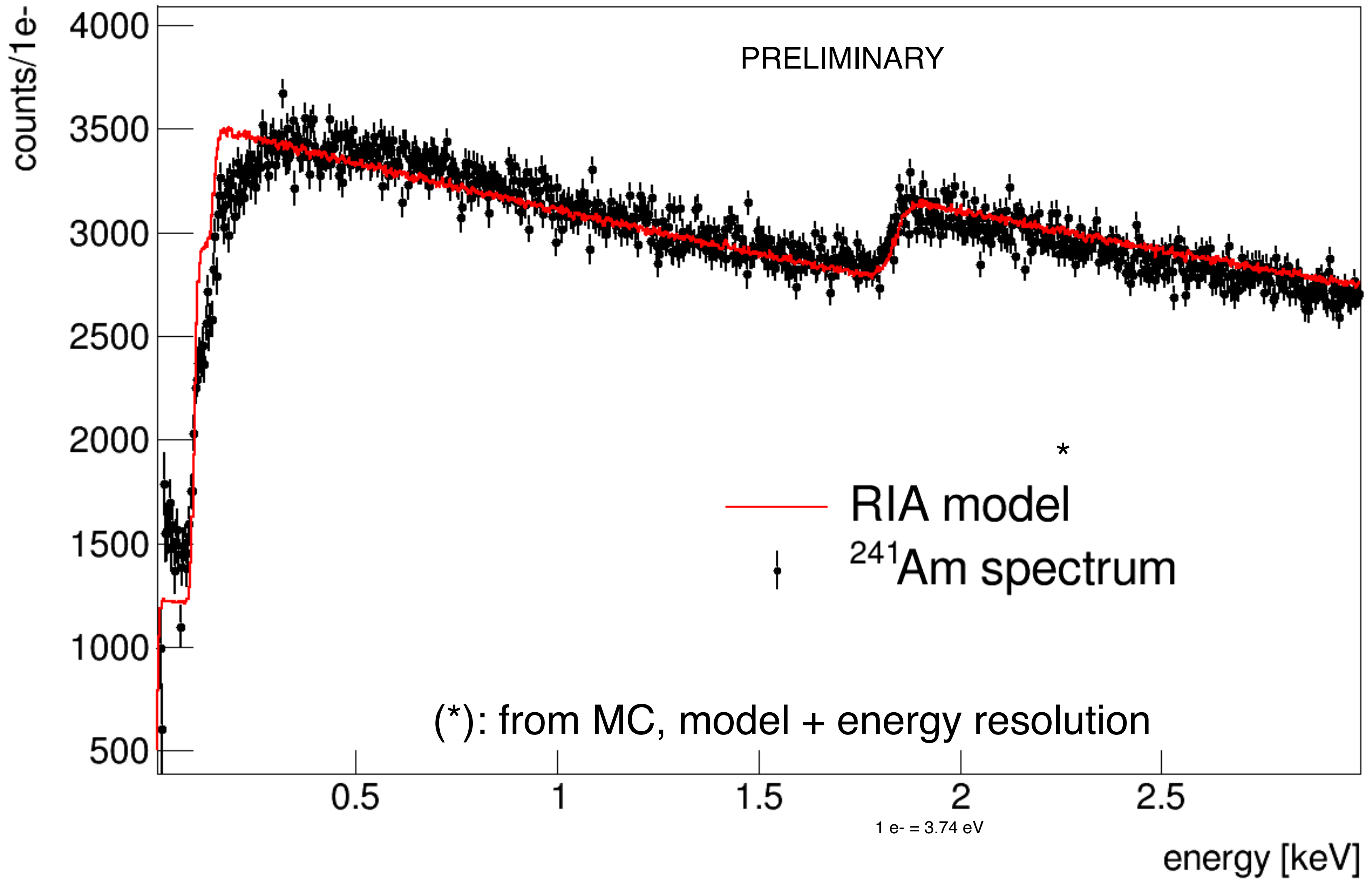
Background level goal within reach

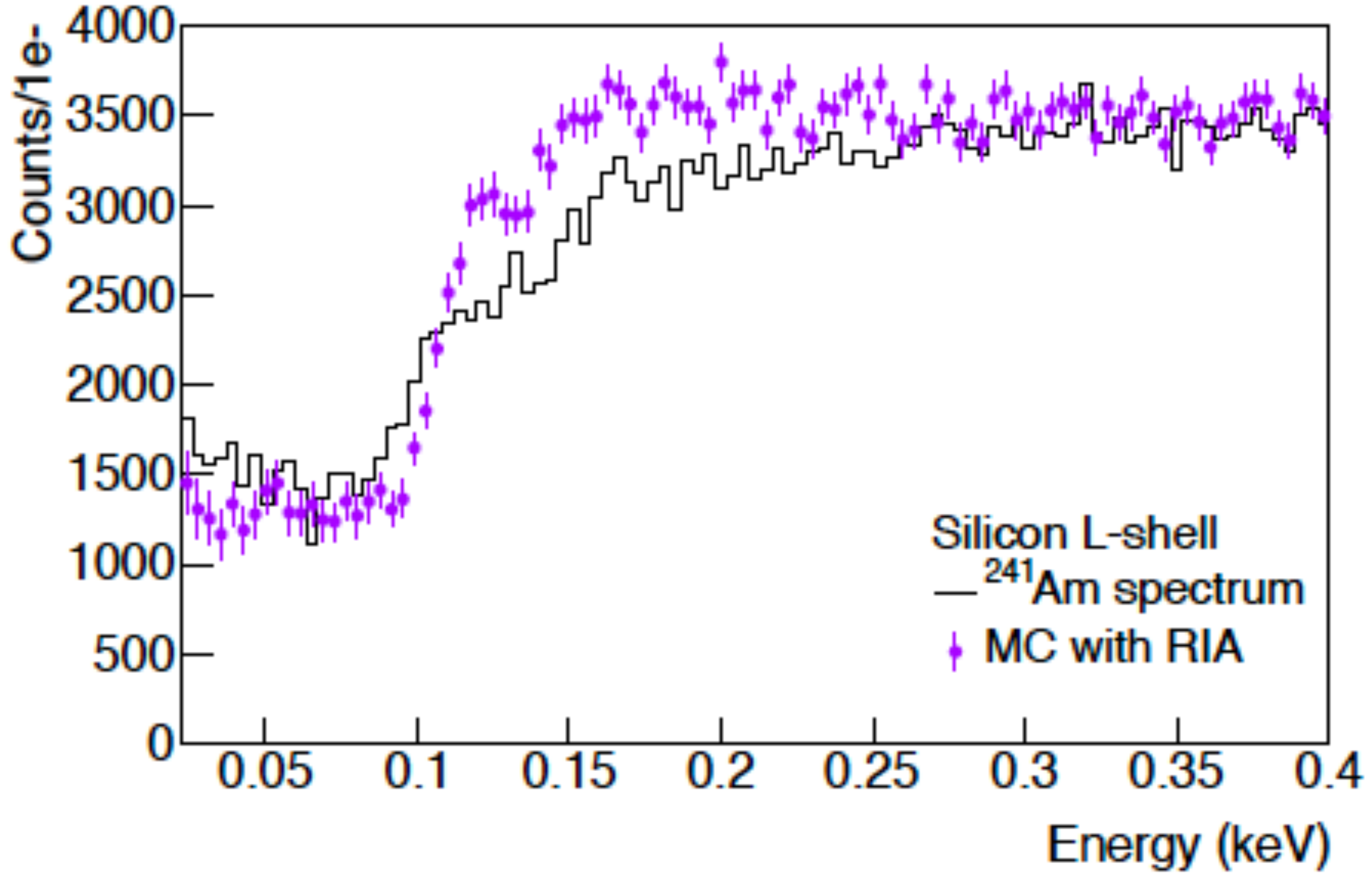
Compton scattering Measurement

- Calibrate low-energy spectra from Compton scattering on atomic shell electrons in the silicon of skipper CCDs
- Characterise spectrum shape near threshold for more constrained background model
- Improved resolution by 3x (to ~0.6e-) threshold by 2x (to ~30eV) compared to previous measurement
- Building a model to determine validity of predictions
  - Data vs Relativistic Impulse Approximation model:
  - agreement in the K-shell region
  - softening of the spectrum below 250 eV is observed



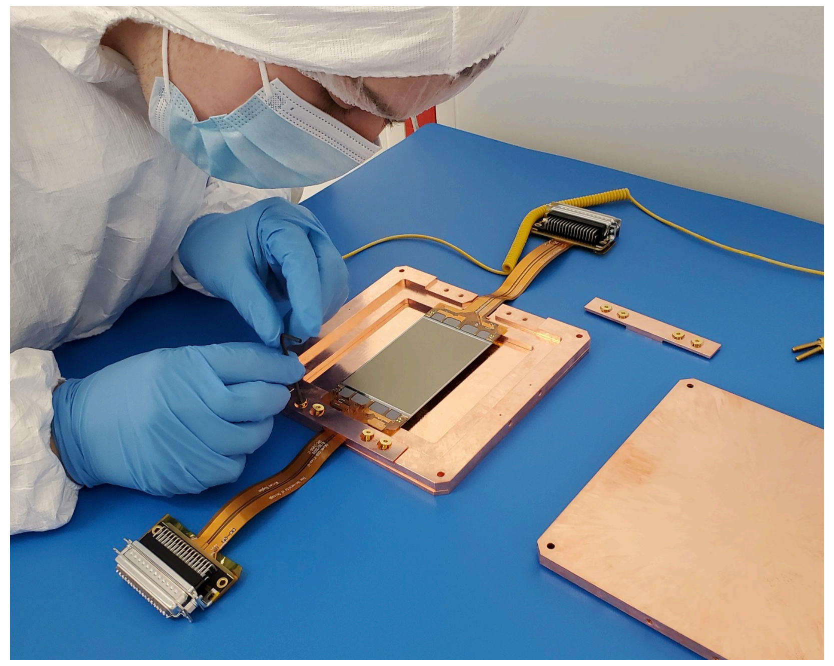


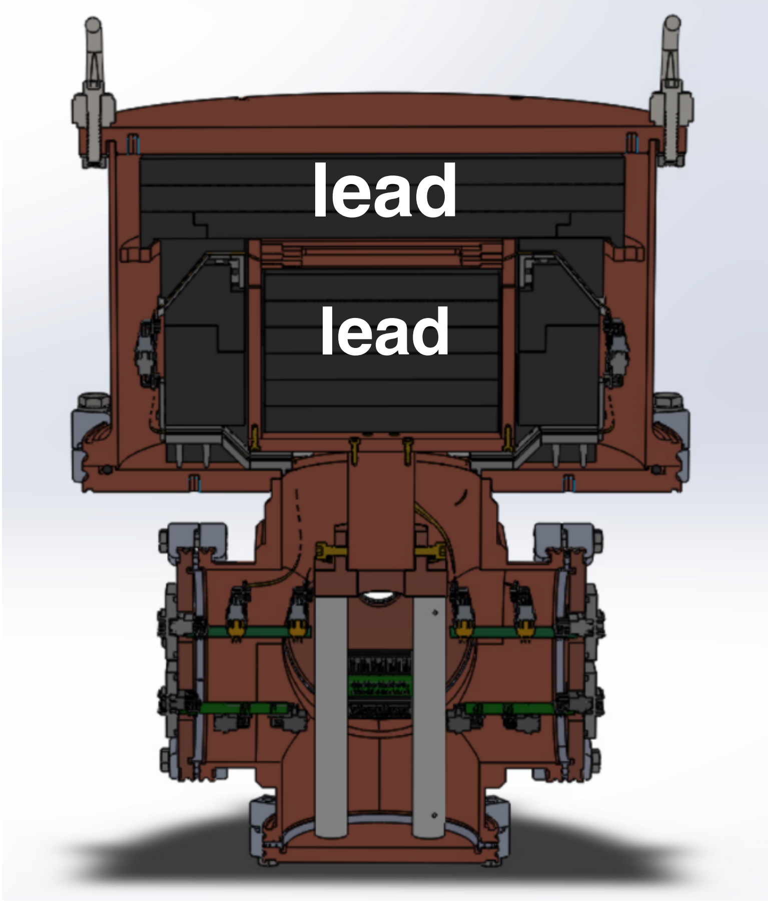


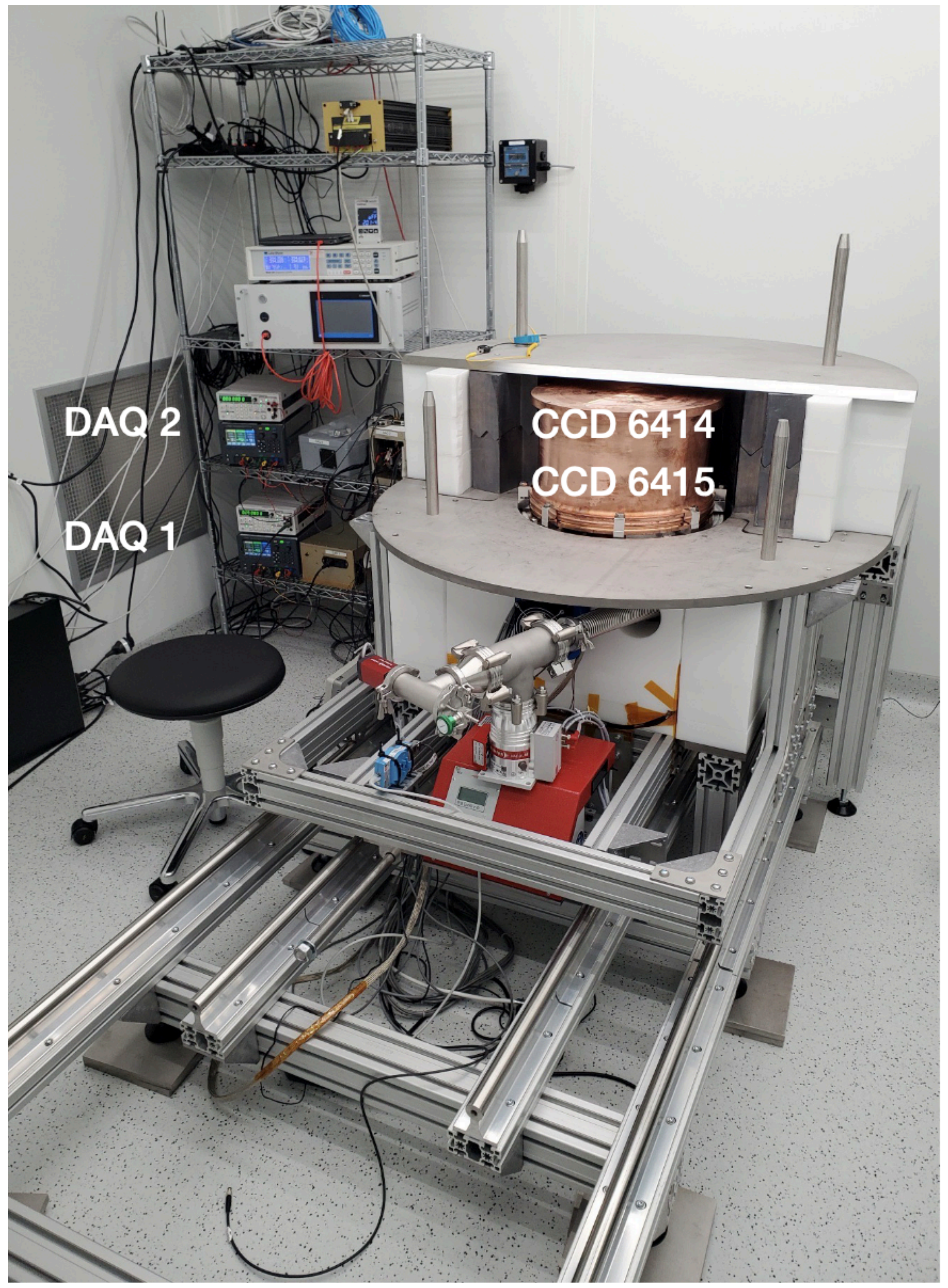


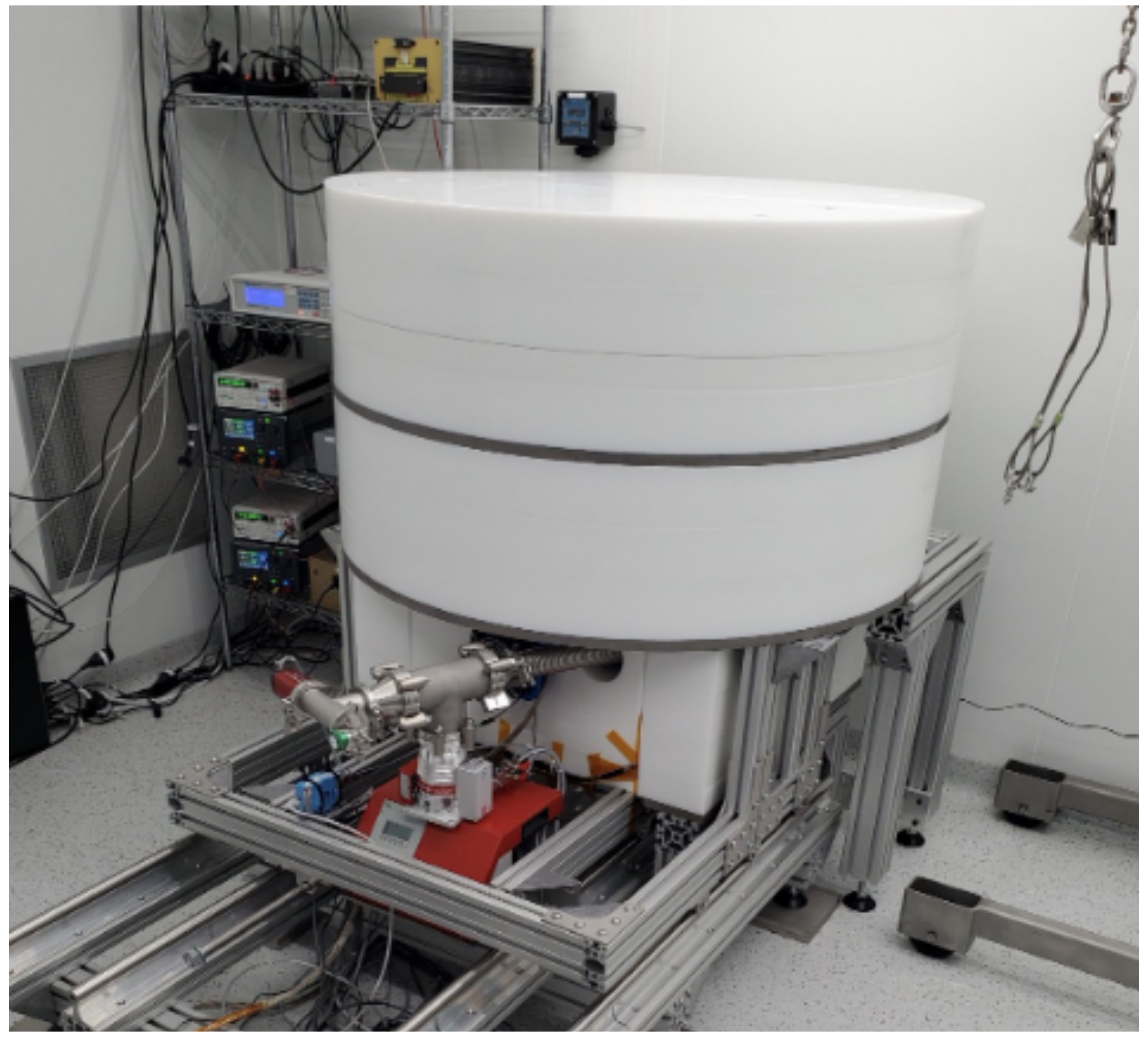
Low Background Chamber at LSM (LBC)

- Prototype goals:
  - Ability to control backgrounds for DAMIC-M, O(1 dru)
  - Validate detector components and subsystems
  - Data to model backgrounds near 2e- threshold at Modane
  - Start probing open light mass dark matter parameter space
- Detector:
  - 2 CCDs, 6k x 4k, ~17g target mass
  - Copper cryostat, IR shield
  - Layered poly+lead shielding, innermost layer of ancient lead
  - Air-driven cryocooler and vacuum pump
  - Integrate the new electronics and test the overall acquisition system.
- TimeLine
  - Installed at LSM at the end of 2021
  - 1st run collected (with open shielding and 1 CCD)
  - 2nd run ongoing! (with closed shielding & 2 CCDs)
  - next runs: swap the OFHC packaging with an EFCu one







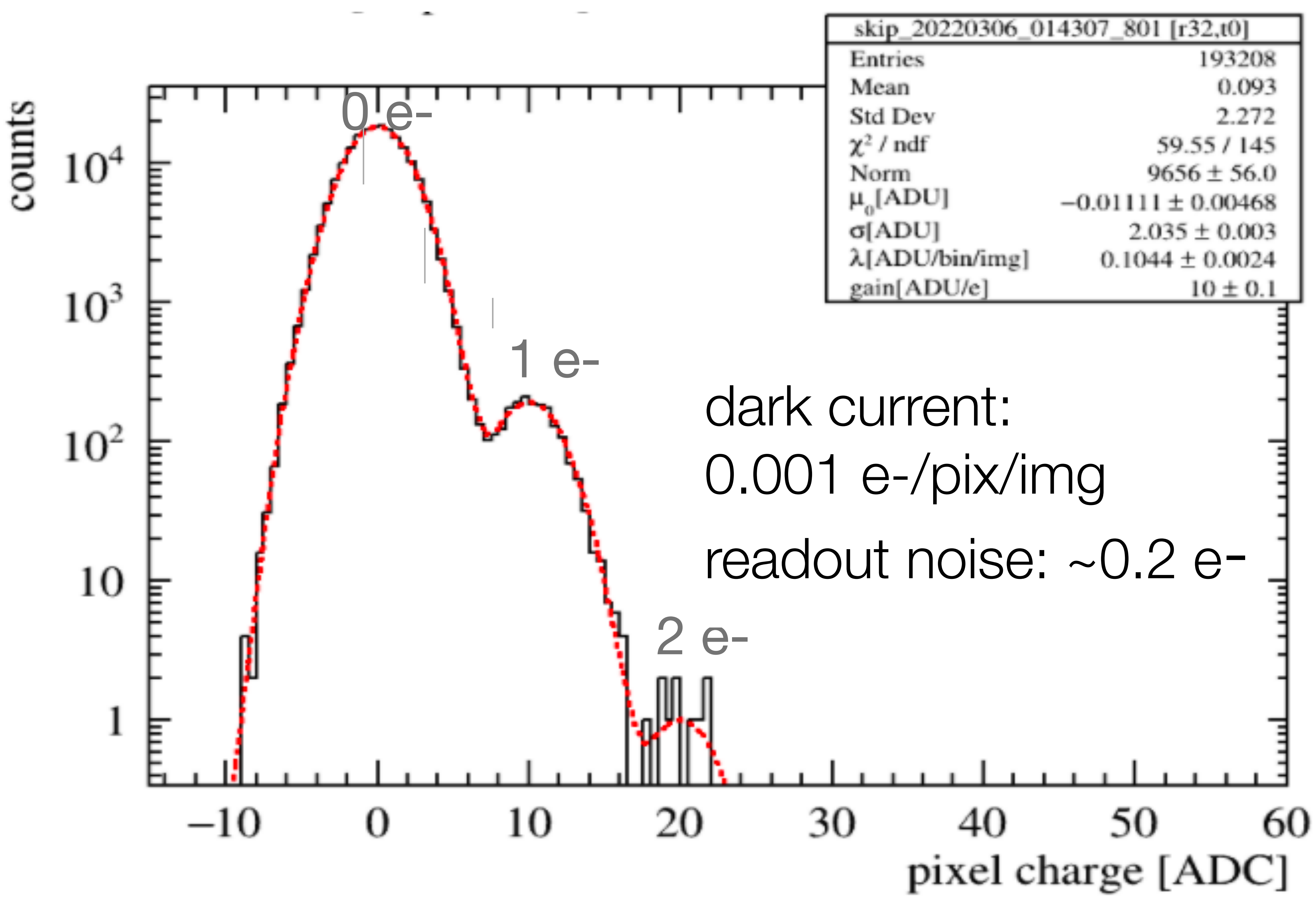


Low Background Chamber data

Data taking: 12/02 -7/03 2022, 10/05 2022- now

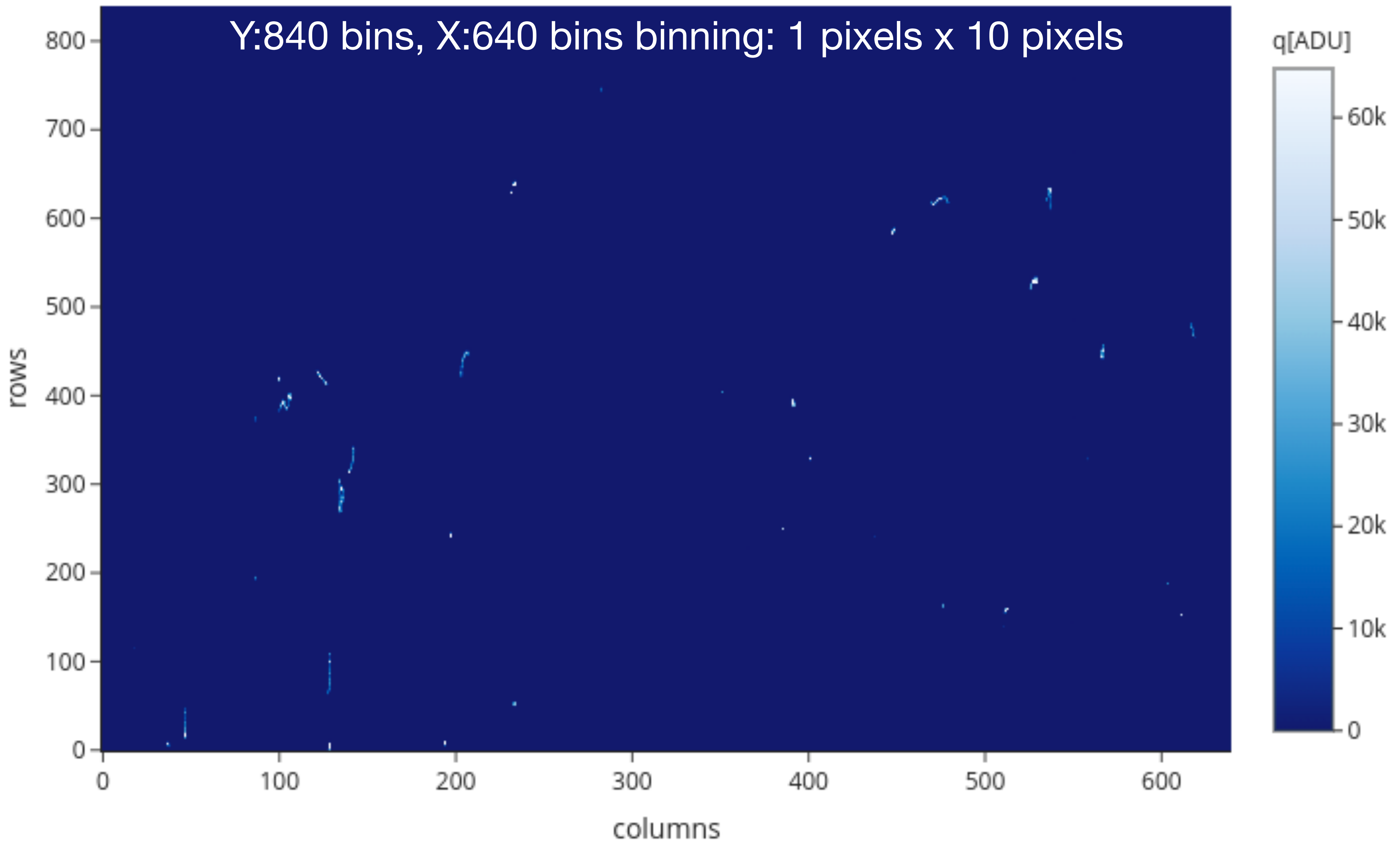
Temperature: ~110 K

650 skips



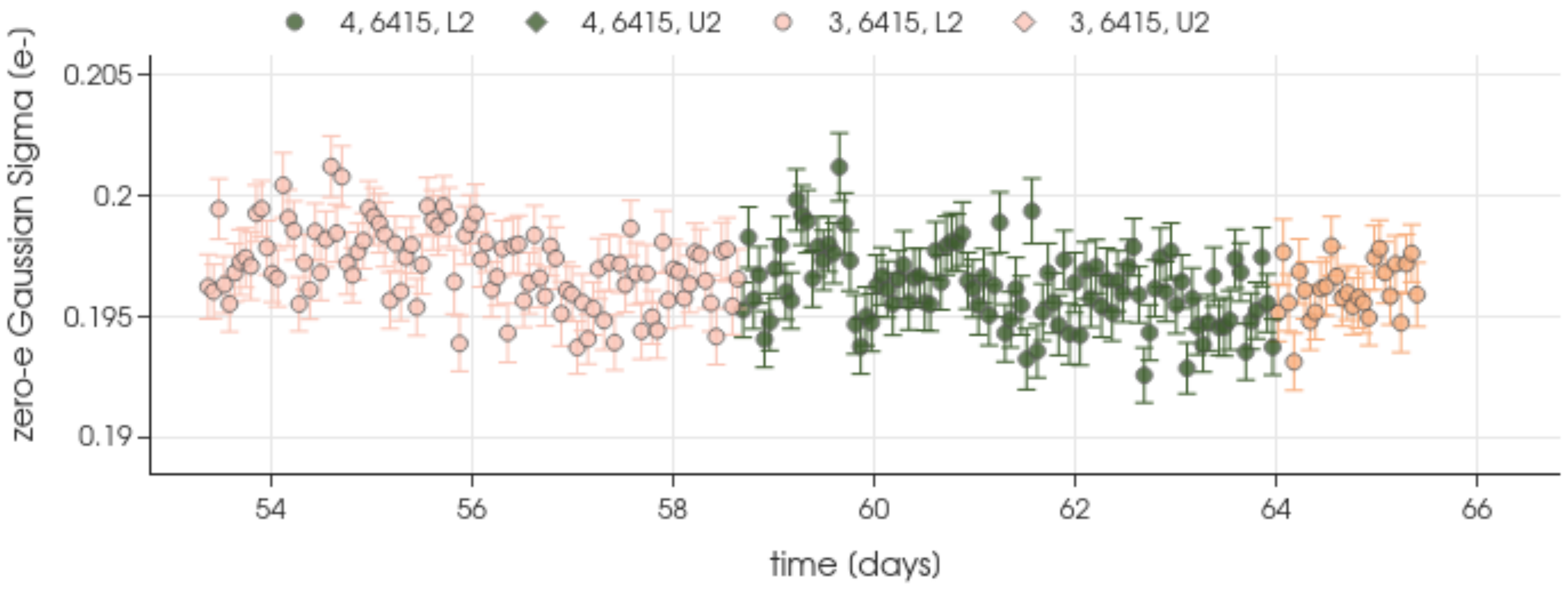
dark current:
0.001 e-/pix/img

readout noise: ~0.2 e-



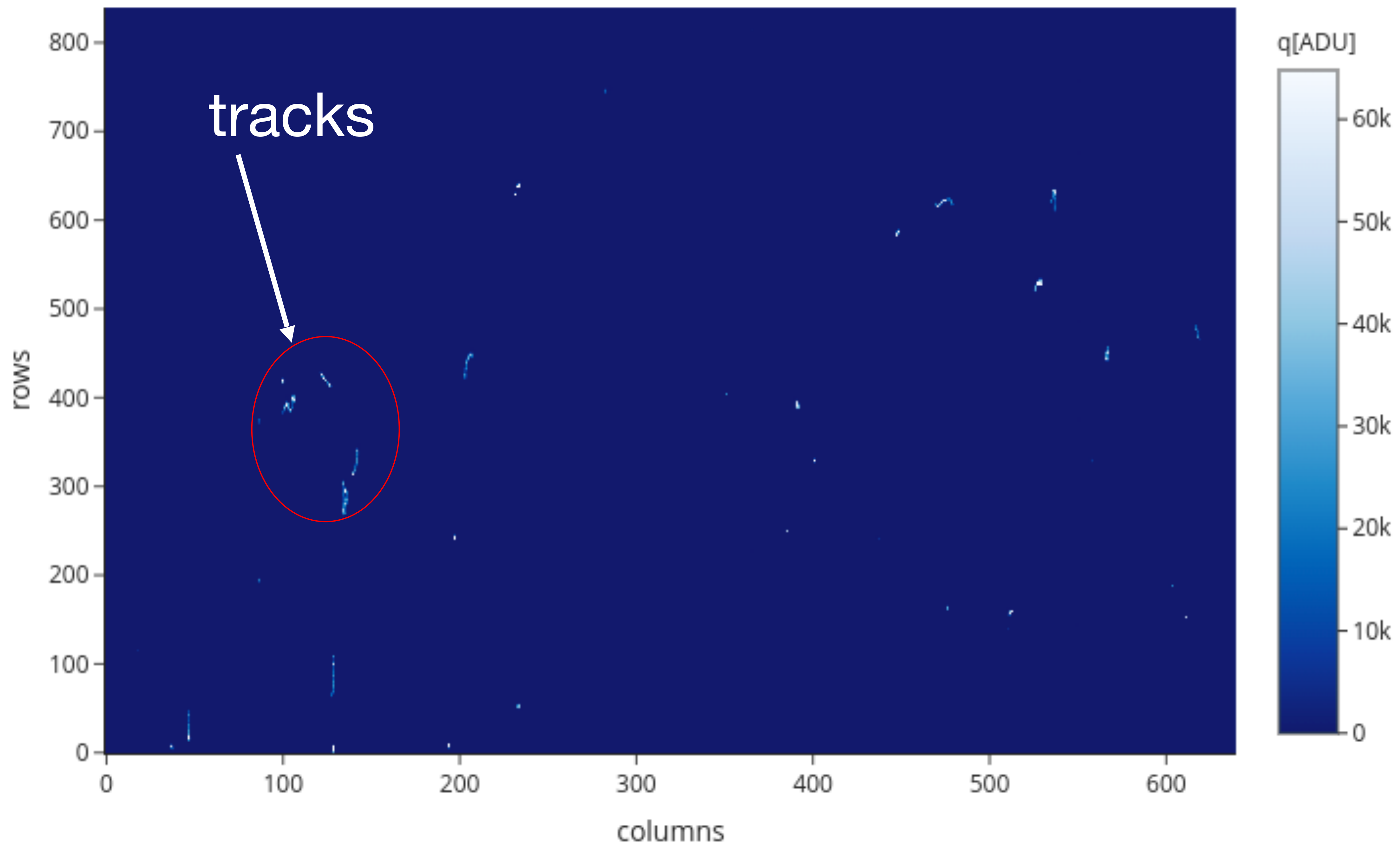
RESOLUTION

run ID: 3, 4, 5



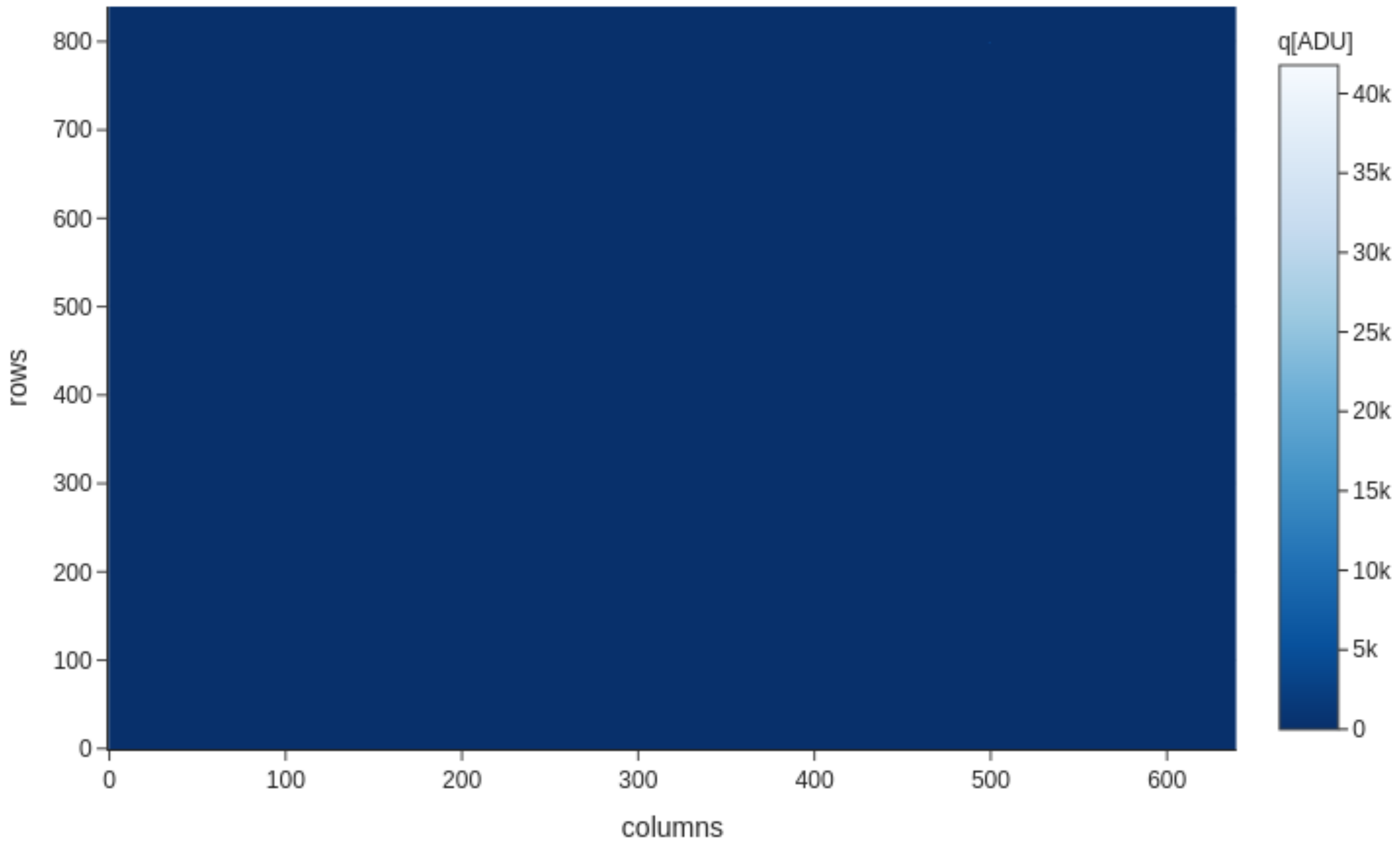
Low Background Chamber data

Open shielding



~300 dru

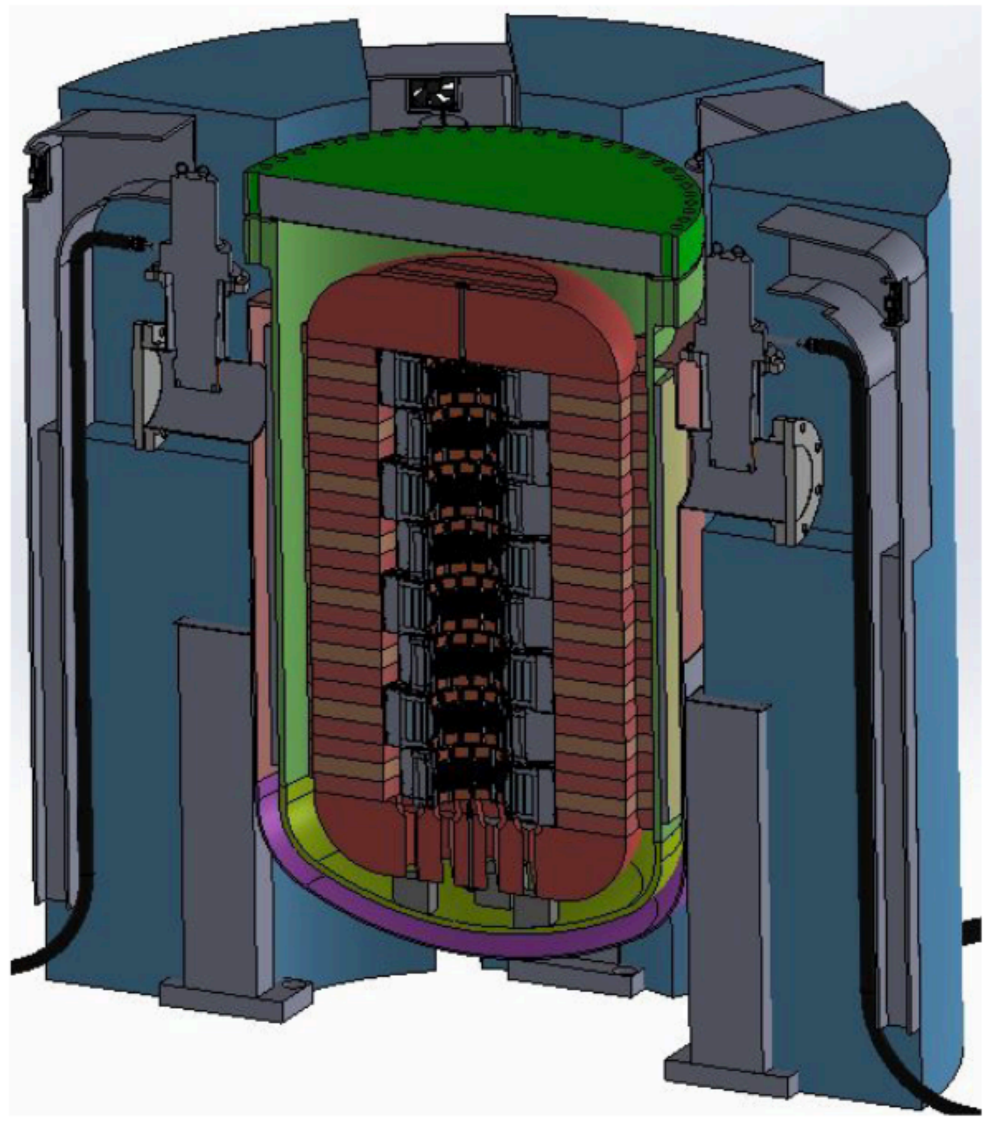
Closed shielding



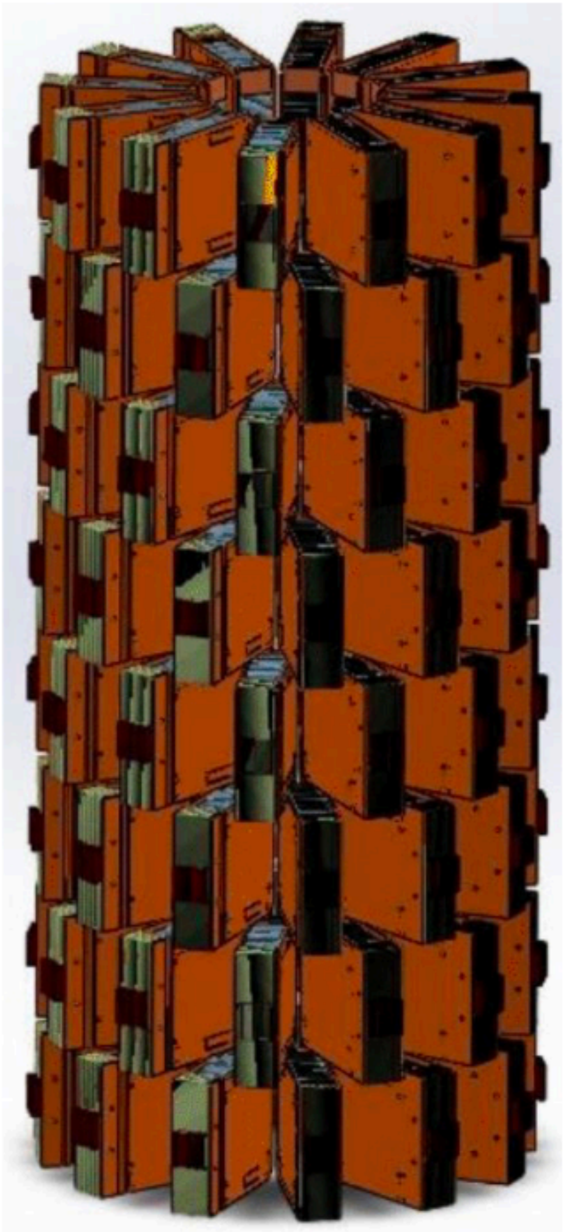
10 dru ~rate same level damic@SNOLAB, to be reduced by changing OFHC CCD box with an EFCU one

OSCURA

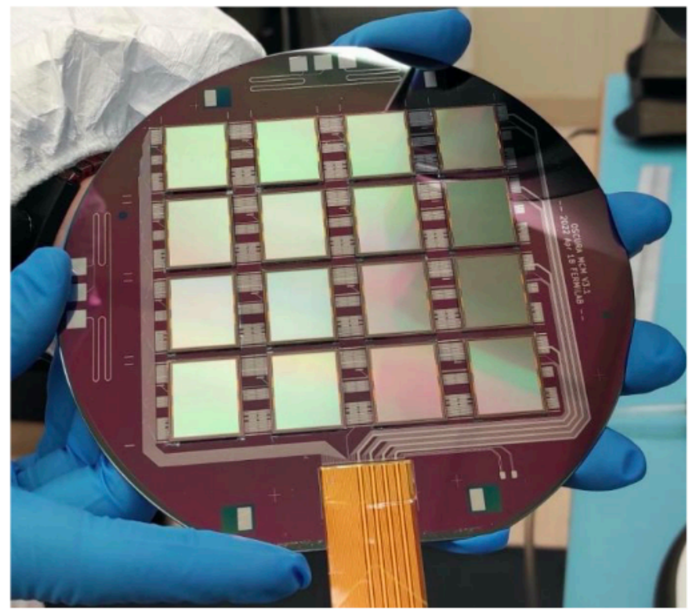
- Science goal: electron recoil low-mass direct DM search (1 MeV-1 GeV)
- Technology: skipper-CCD array at underground lab (planning for SNOLAB)
- R&D: scale the existing technology towards a 10 kg experiment to be deployed at 2028
  - 28 gigapixels (16 CCD on silicon wafer, 16 MCM housed in EFC, 100 SMs)
  - Oscura will require ~24,000 readout channels and a readout time of ~2 hours for the full instrument
  - Achieve a radiation background rate of 0.01 counts/kg/keV/day
  - Cool skipper CCDs to operational temperatures in pressurized LN2 bath



10 kg vessel

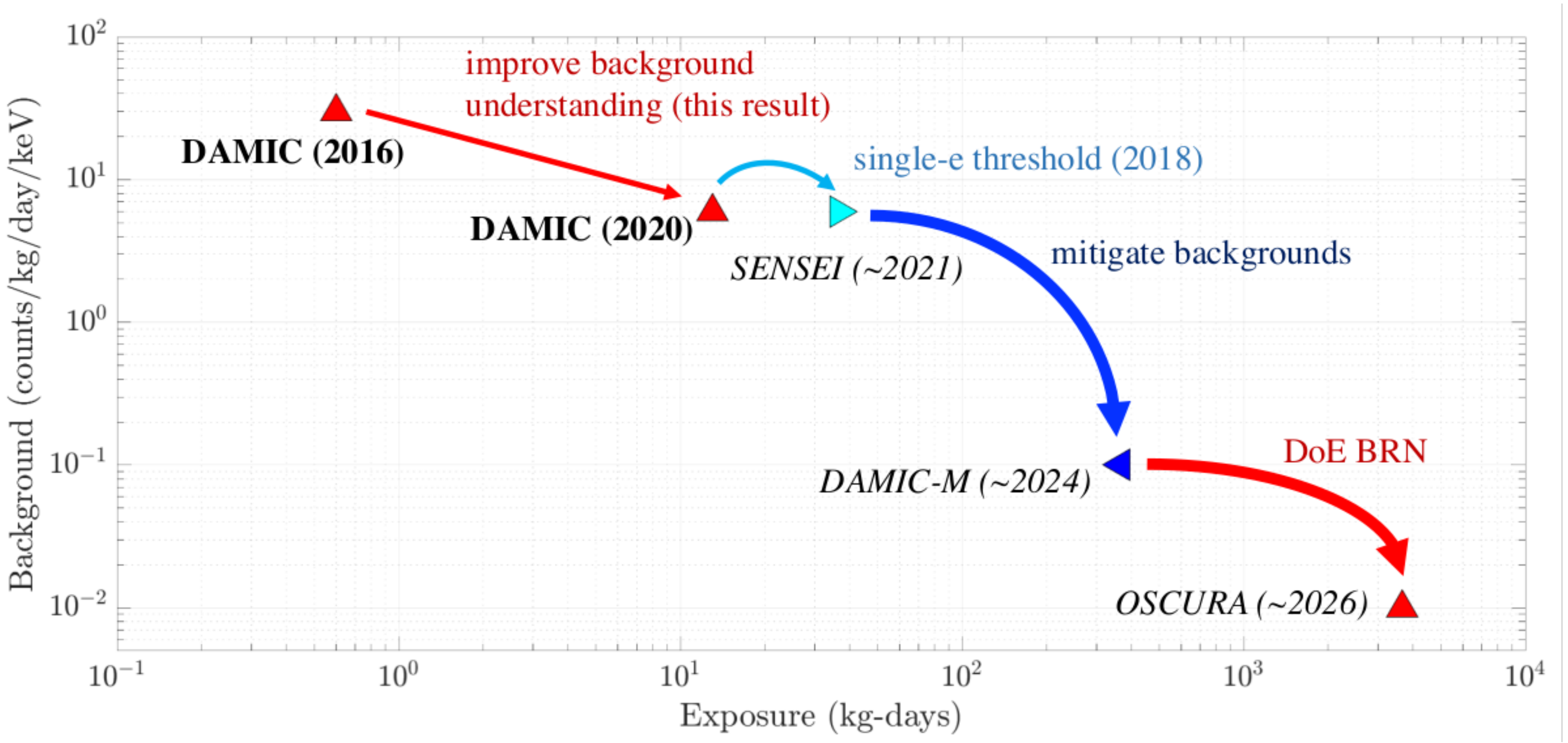


detector payload



Conclusions

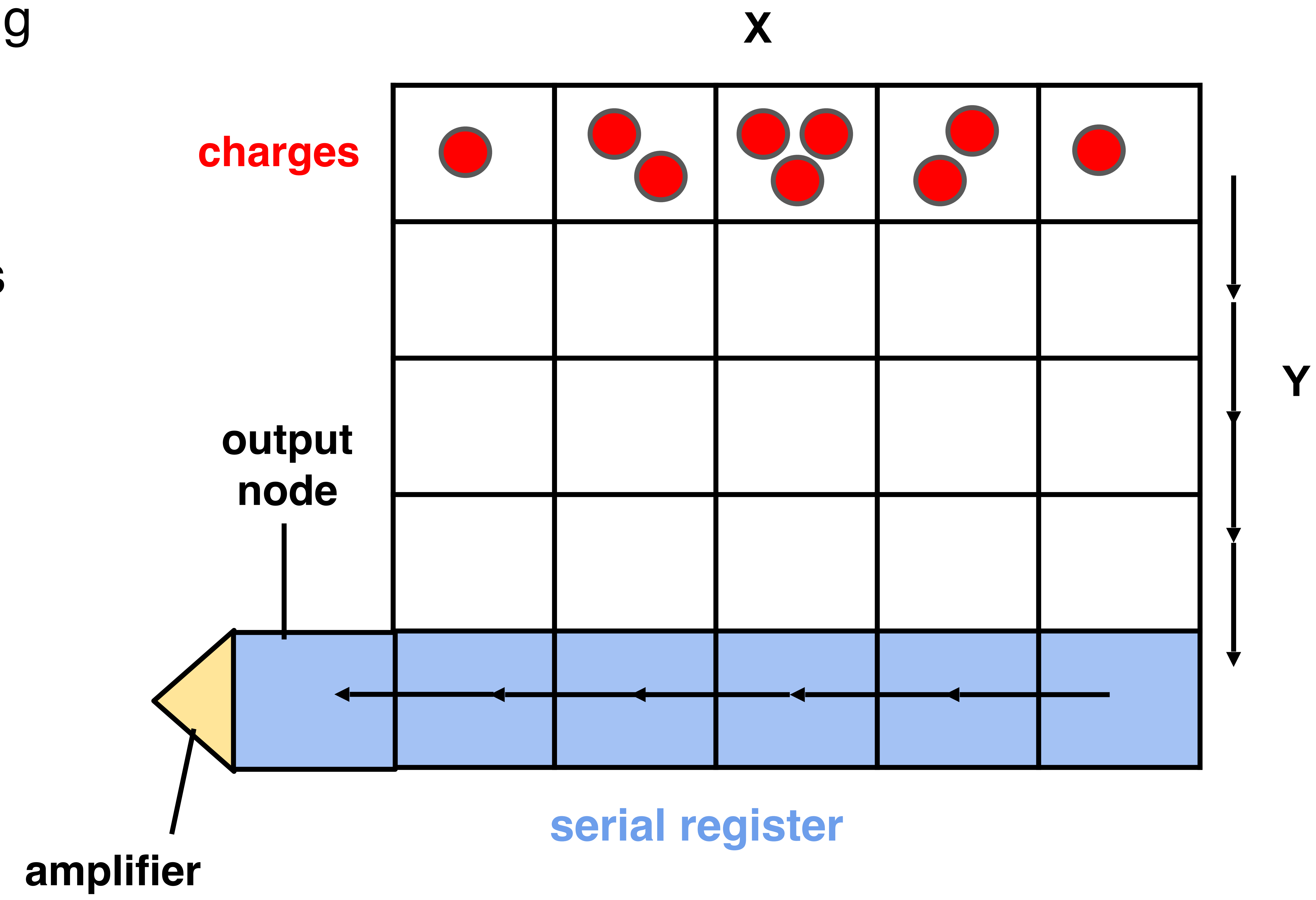
- Very interesting moment of scientific opportunities in low mass dark matter searches that can be addressed with new low threshold technology
- CCDs is a good technology for this purpose
  - A “Zero-ish” detector
- DAMIC@Snolab presented the results showing an inconclusive excess
- DAMIC program is well established: DAMIC@SNOLAB upgrade, LBC and DAMIC-M.
- DAMIC-M will bring CCD DM search experiments to the forefront in sensitivity.
- OSCURA will be the next detector



Backup

CCD readout

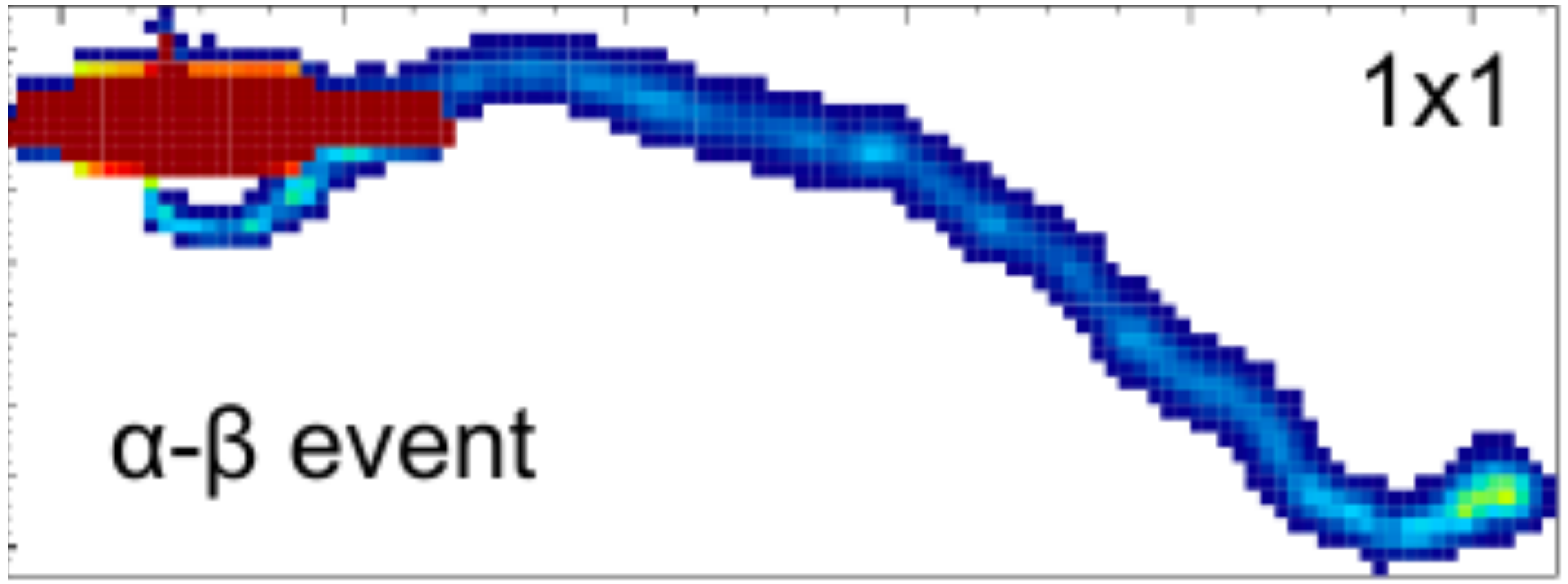
- charges in a row moved in the following row
- charges in serial register moved pixels by pixels in X direction
- charges in output node read by amplifier
- In DAMIC-M: Skipper Amplifier



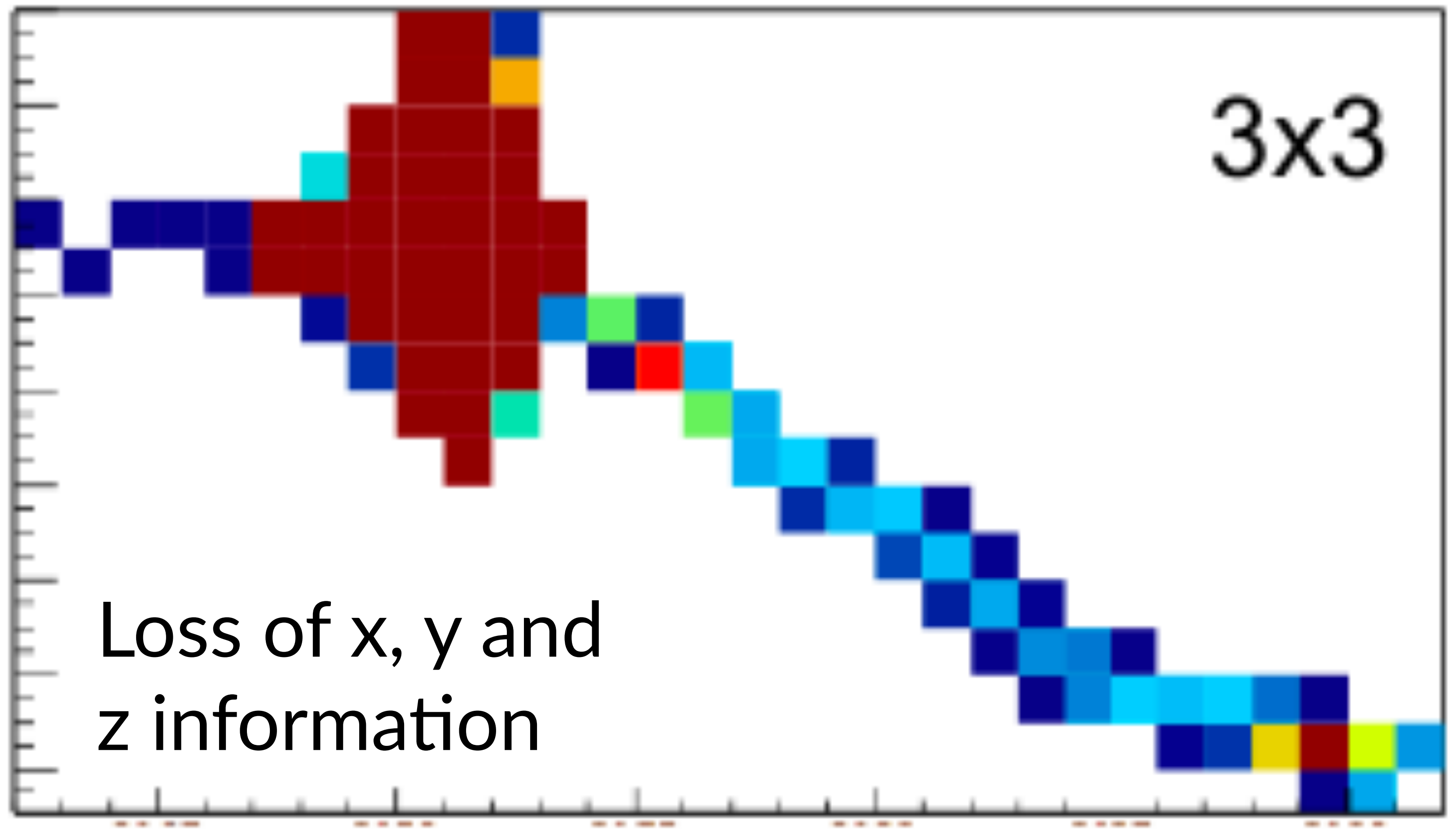
Readout Flexibility

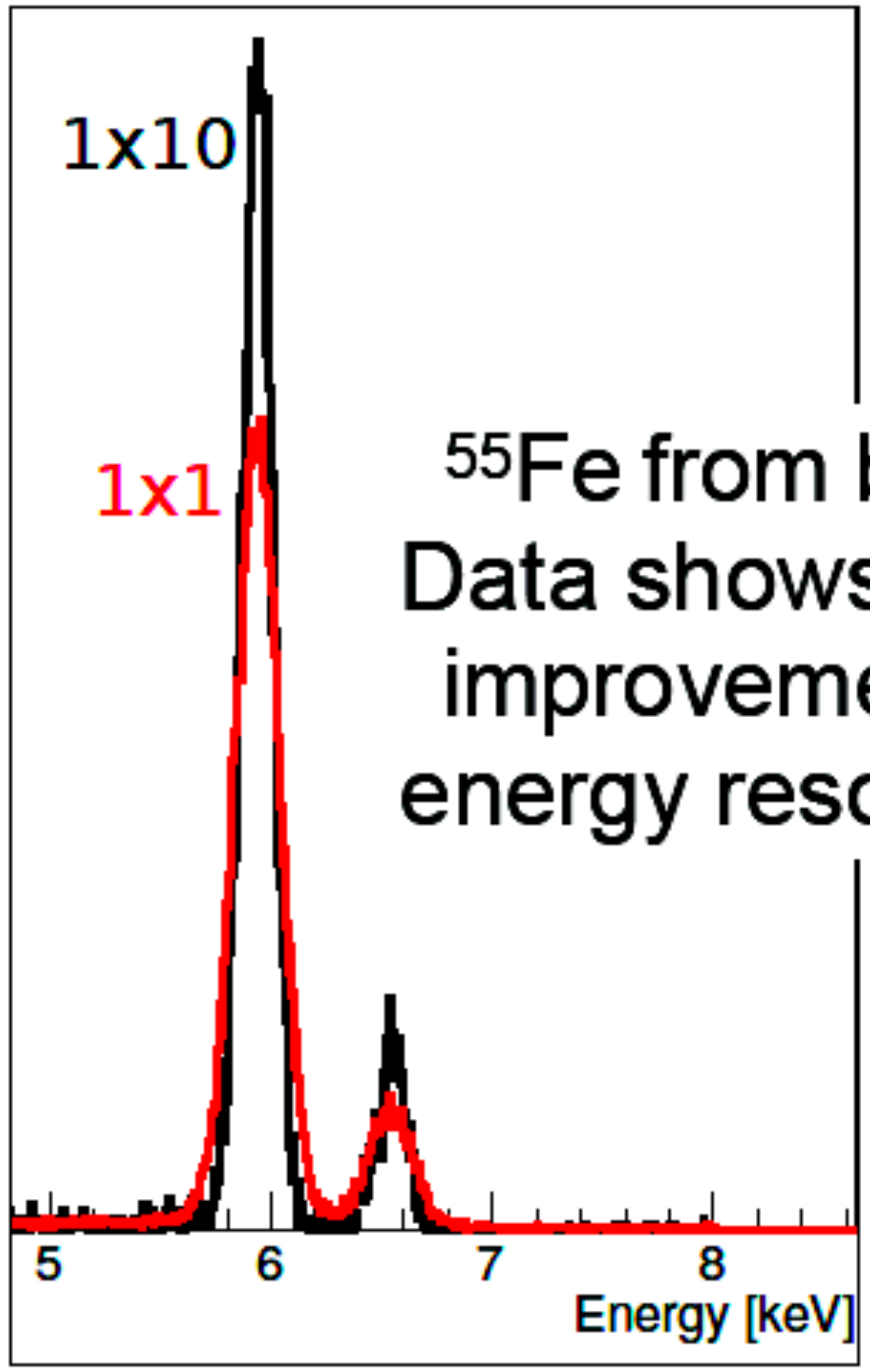
Binning: Several pixels are added together before data taken at hardware level

Less pixels but same noise per pixel!



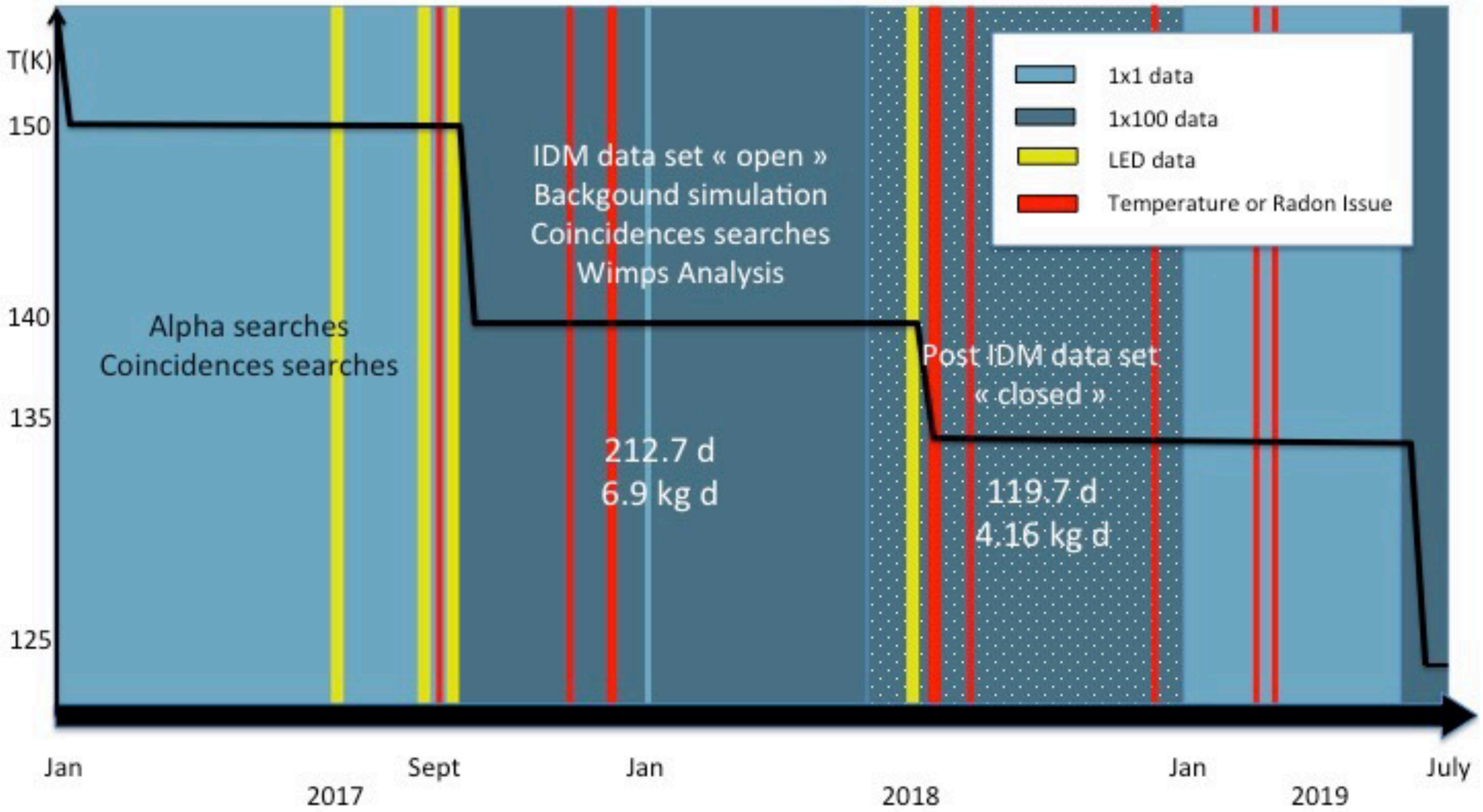
Some loss of spatial resolution, losing resolution in the y-coordinate (x, z remains the same), but improve S/N and energy resolution





^{55}Fe from back: Data shows clear improvement in energy resolution

DAMIC DATA TAKEN

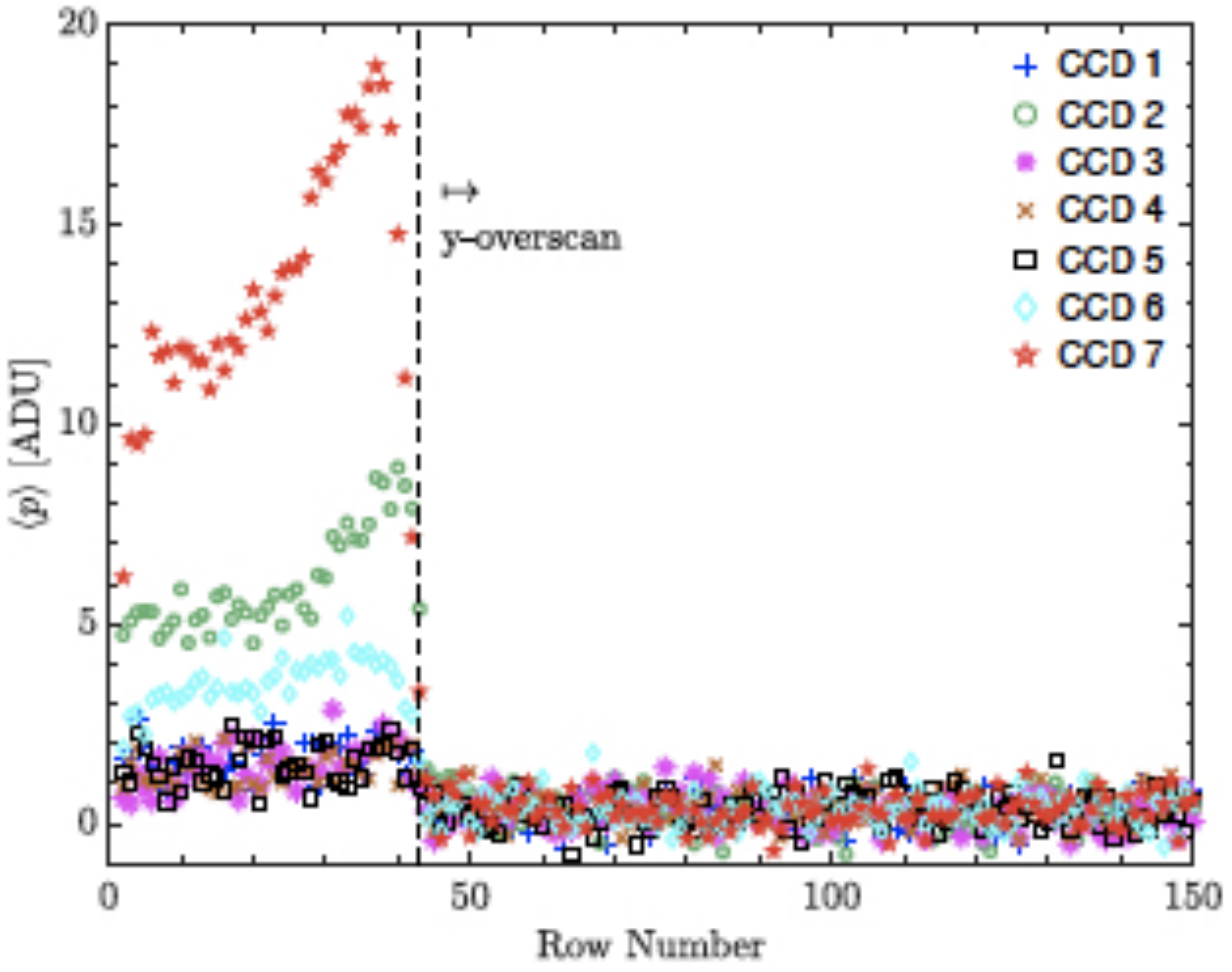


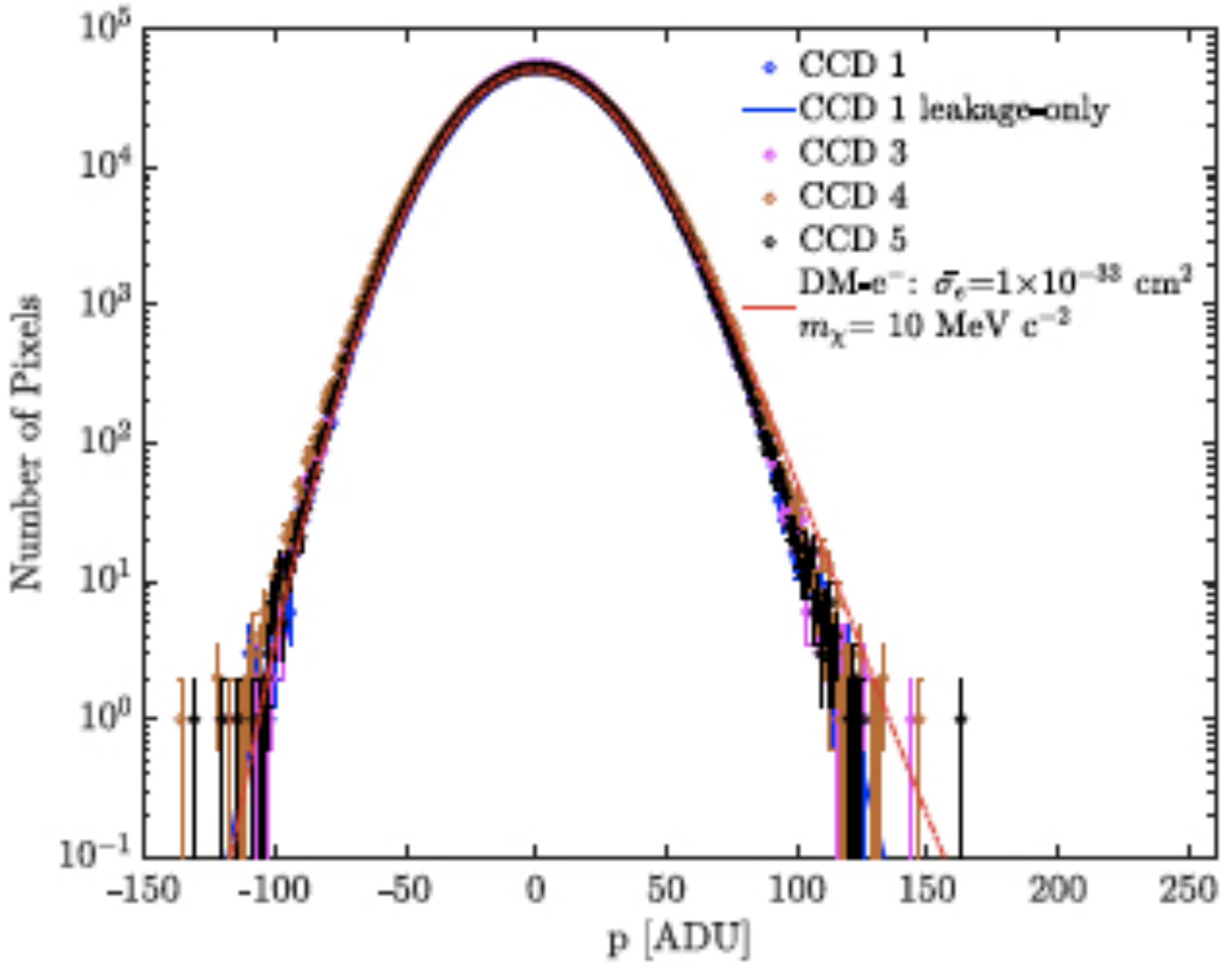
Results: Leakage Current analysis, DM-e

- Select CCDs with constant leakage current from 200 g-d of data in 100 ks exposures
- Model pixel charge distribution to .(p) with and without the hypothesis of DM-e signal (S)

$$\Pi(p) = N \sum_{n_c=0}^{\infty} \sum_{n_l=0}^{\infty} \left(\left[\sum_{j=0}^{n_c} \overbrace{S(j \mid \bar{\sigma}_e, m_\chi)}^{\text{DM-e signal}} \overbrace{\mathrm{Pois}(n_c - j \mid \lambda)}^{\text{Leakage current}} \right] \overbrace{\mathrm{Pois}(n_l \mid \lambda_d) \mathrm{Gaus}(p \mid \Omega \left[(n_c + n_l) + \mu_0 \right], \Omega \sigma_{\mathrm{pix}})}^{\text{pixel readout noise (blank+overscan)}} \right)$$

e bound && crystalline band structure
→ QEDark





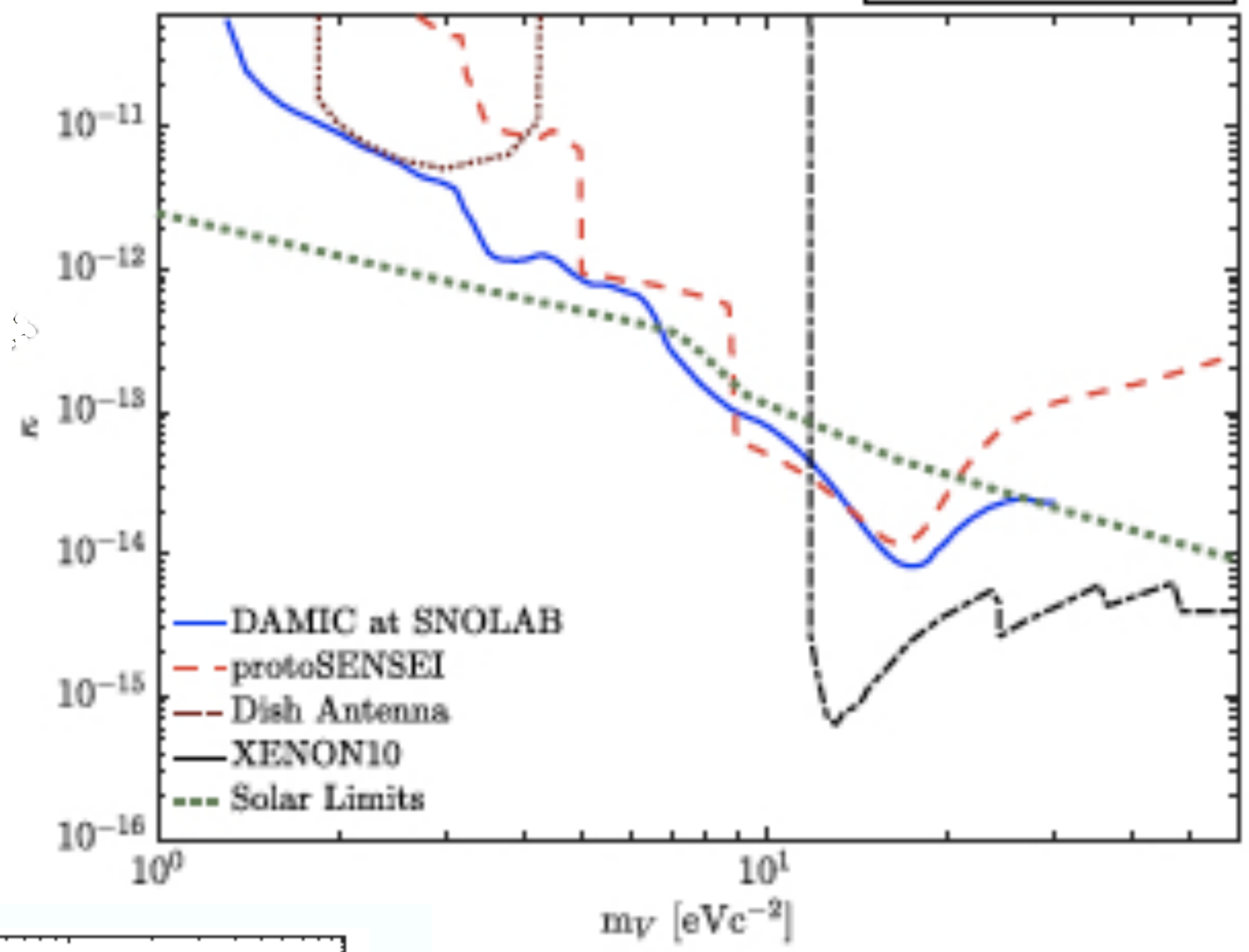
N total number of pixels;
n_c charges from DM;
n_l charges from readout shot nois
Ω e- to ADCu
$\mu_o, \lambda_d, \sigma_{pix}$ noise parameters

CCD n.	$\lambda = \lambda_{tot} - \lambda_d$ $[\mathrm{e}^- \mathrm{mm}^{-2} \mathrm{d}^{-1}]$
1	2.8(2)
3	1.7(2)
4	1.0(2)
5	2.0(2)

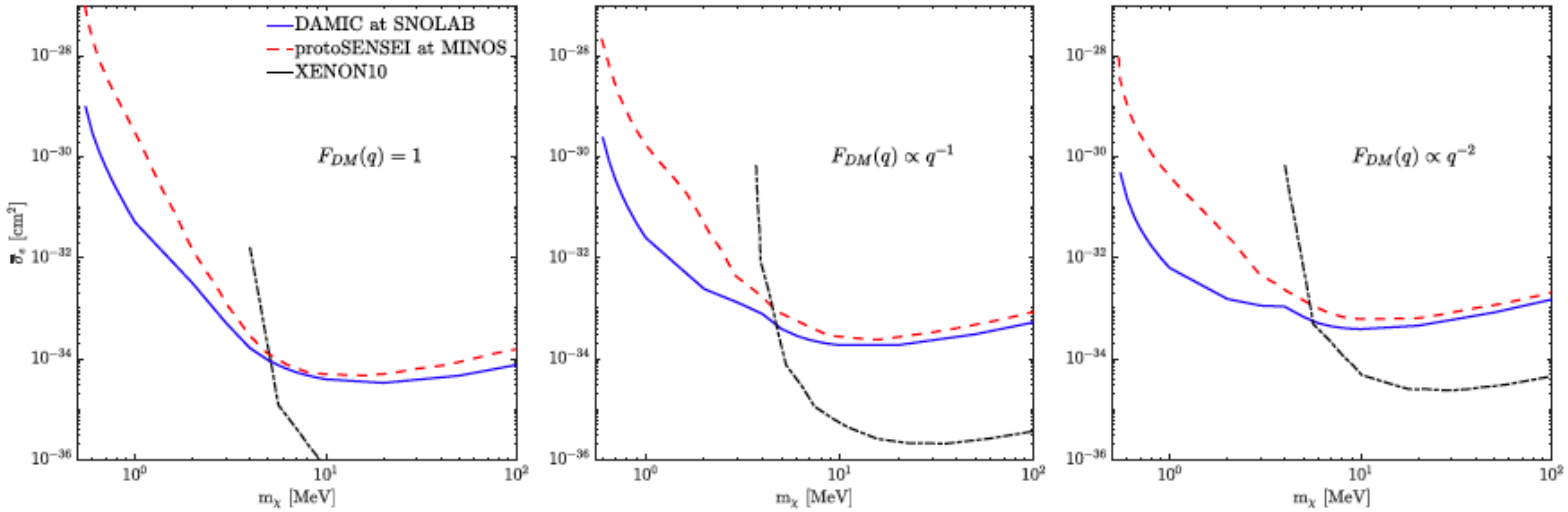
Results: Leakage Current analysis, DM-e

arXiv:1907.12628

Best exclusion limit for the absorption of hidden photons with masses 1-10 eV/c²



Best exclusion limits for the scattering of dark matter particles with masses <5 MeV/c2

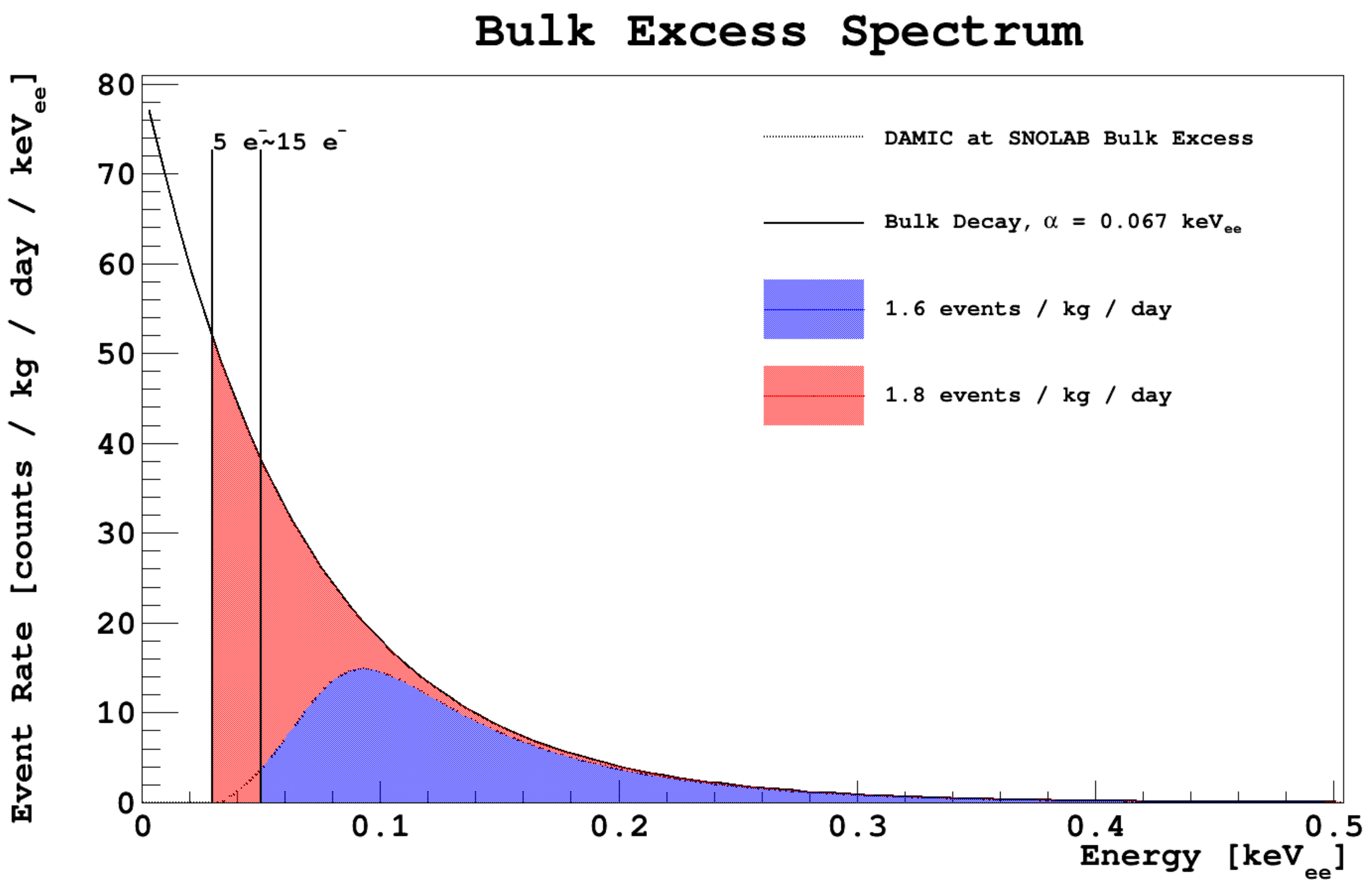


DAMIC at SNOLAB (using standard CCDs, but demonstrating lower dark current and larger mass)

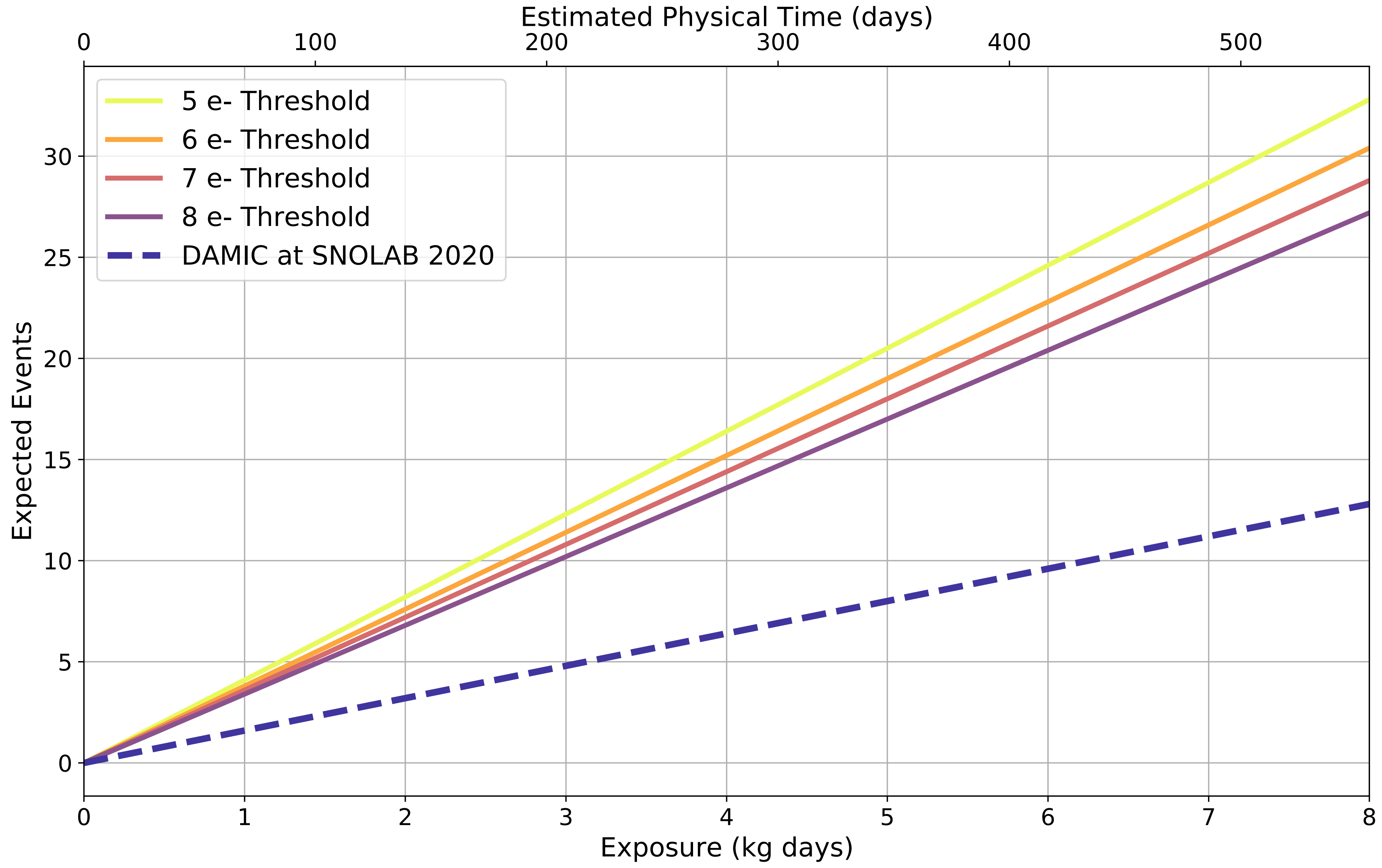
get the world record.

Upgrade Forecast

With the a lower threshold due to the skipper mechanism we can probe this unexpected bulk spectrum with better signal-to-noise ratio and better depth reconstruction.



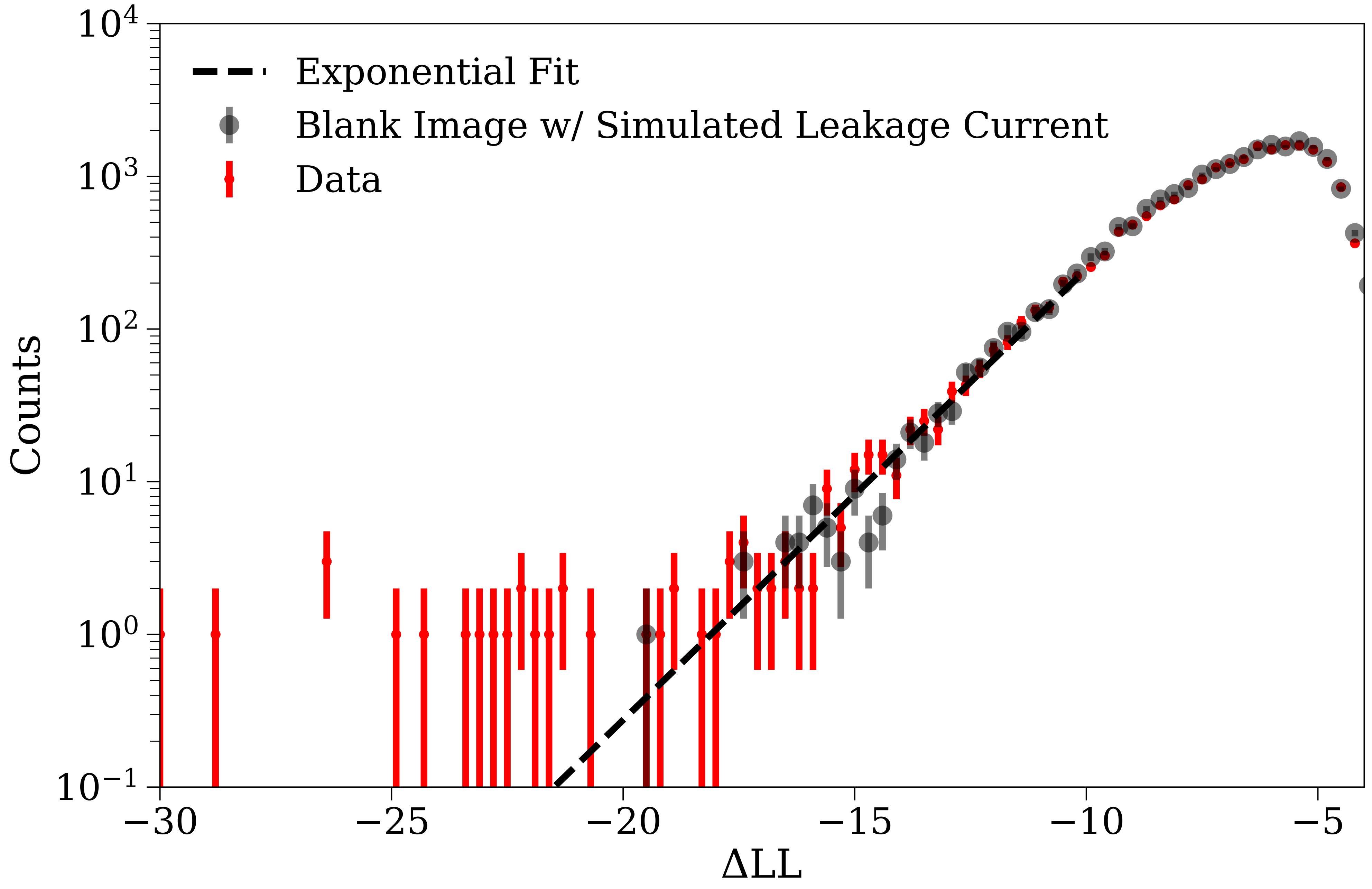
Bulk spectrum measured (blue) and projected with upgrade (red)



Expected number of “excess” events vs. exposure for different analysis thresholds

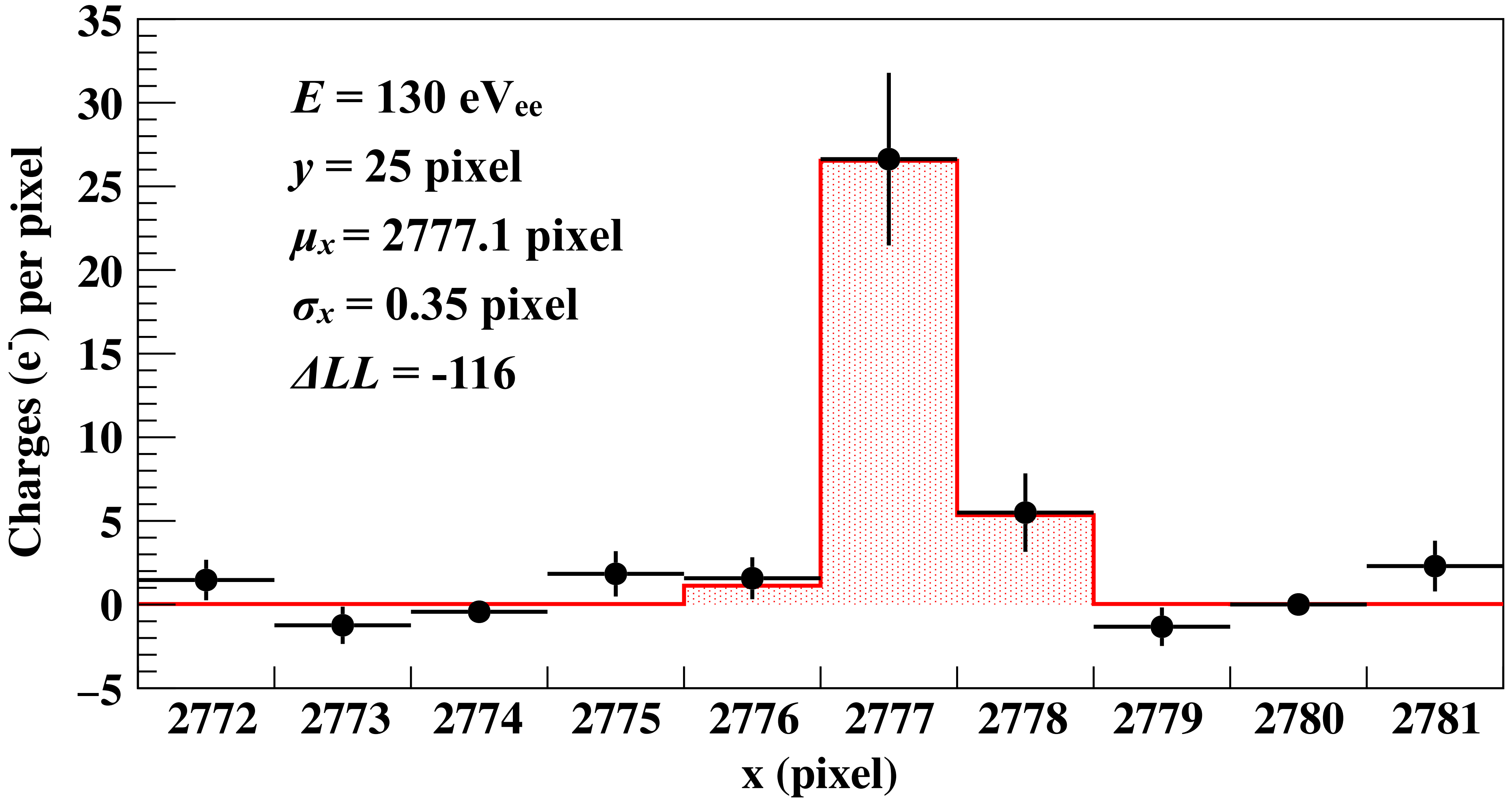
Event Reconstruction

Compare likelihood of clustered pixels to originate from Gaussian (real ionization events) vs. noise. WIMP search cut of $\Delta LL < -22$ gives 0.1 expected noise event.

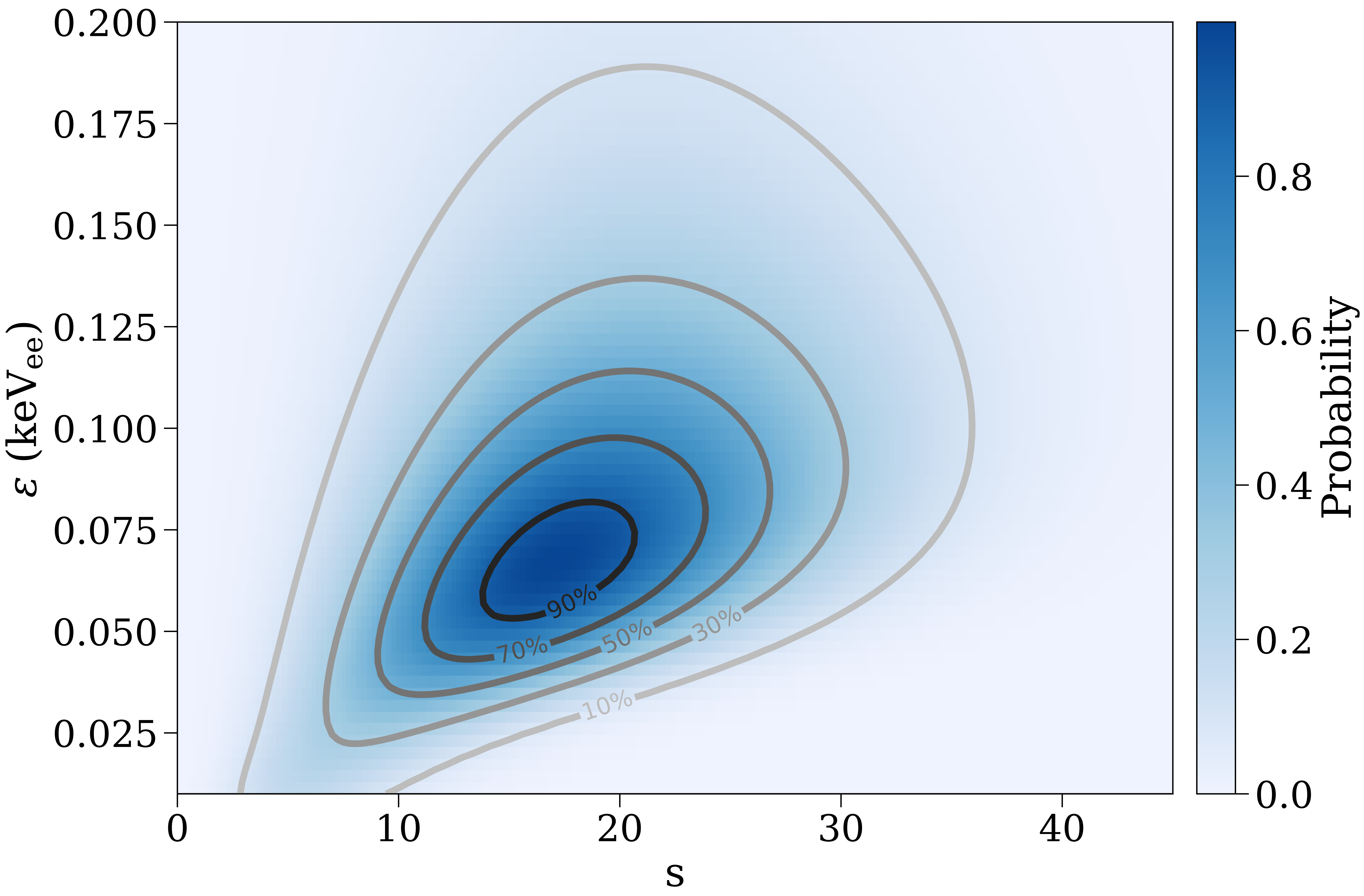


Sample Low Energy Event

One low energy event that contributes to the excess is shown below. Very inconsistent with detector noise!

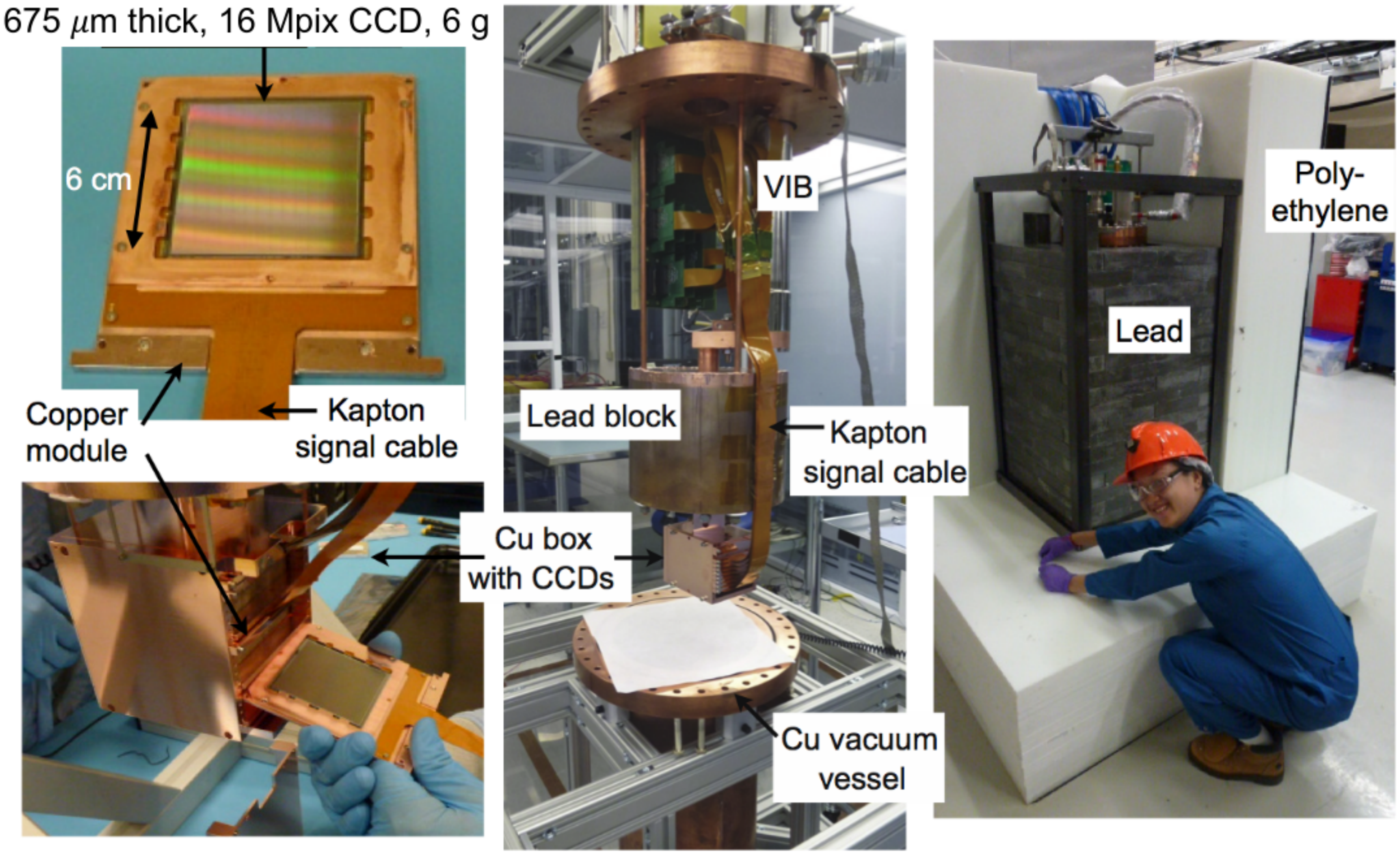


Excess Parameter Contour



Fit uncertainty on excess parameters (s and ϵ)

DAMIC at SNOLAB



Detector: 7 CCDs, 4kx4k pixels, 0.675 mm thick, 6g/CCD

Temperature: ~140 K

Location: SNOLAB (Canada)

Resolution: 1.6 e-

Dark current:
< 0.001 e–/pix/day

Operation: 2017-2019, upgrade in 2021, data taking ongoing

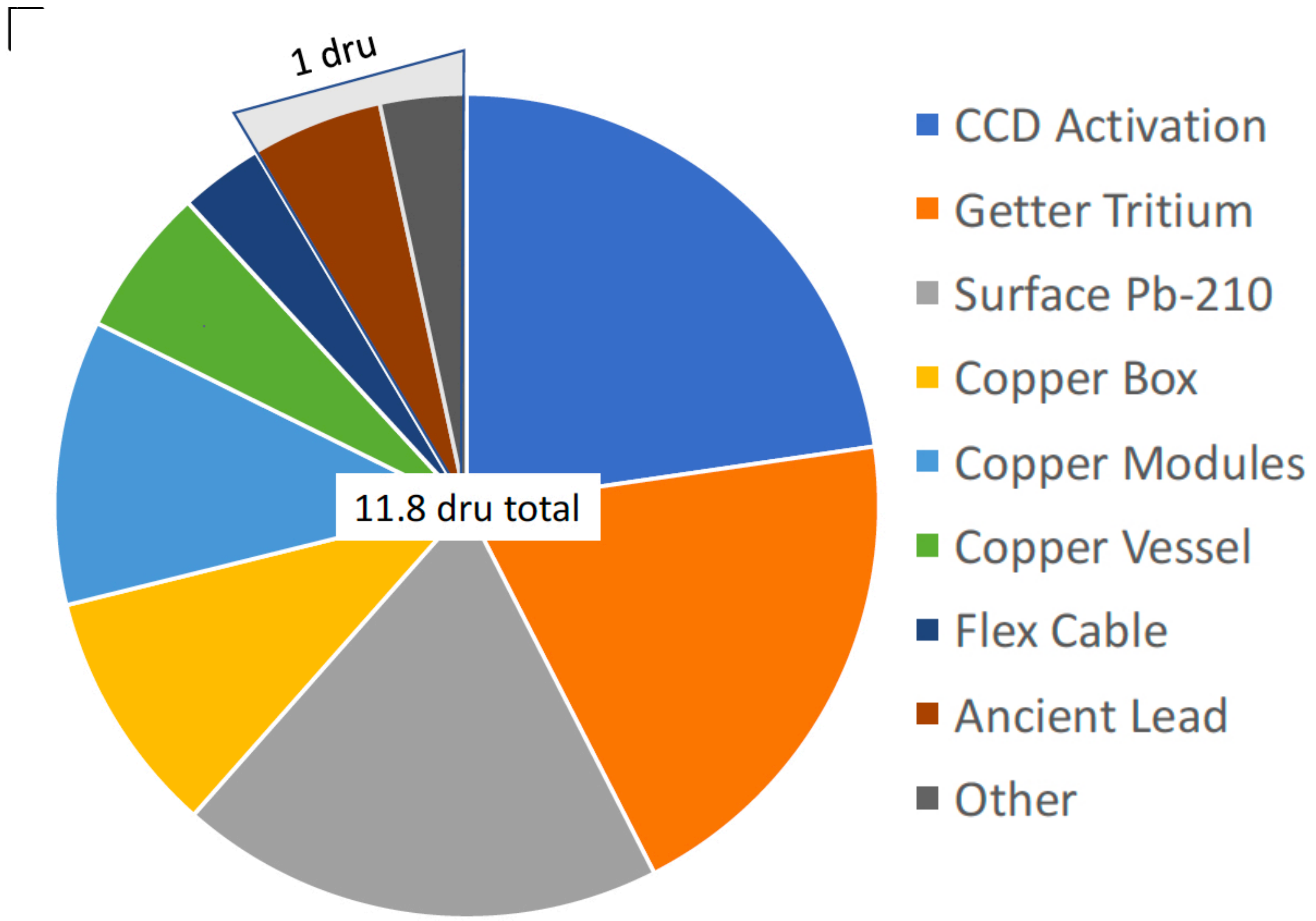
Background: ~12 d.r.u*

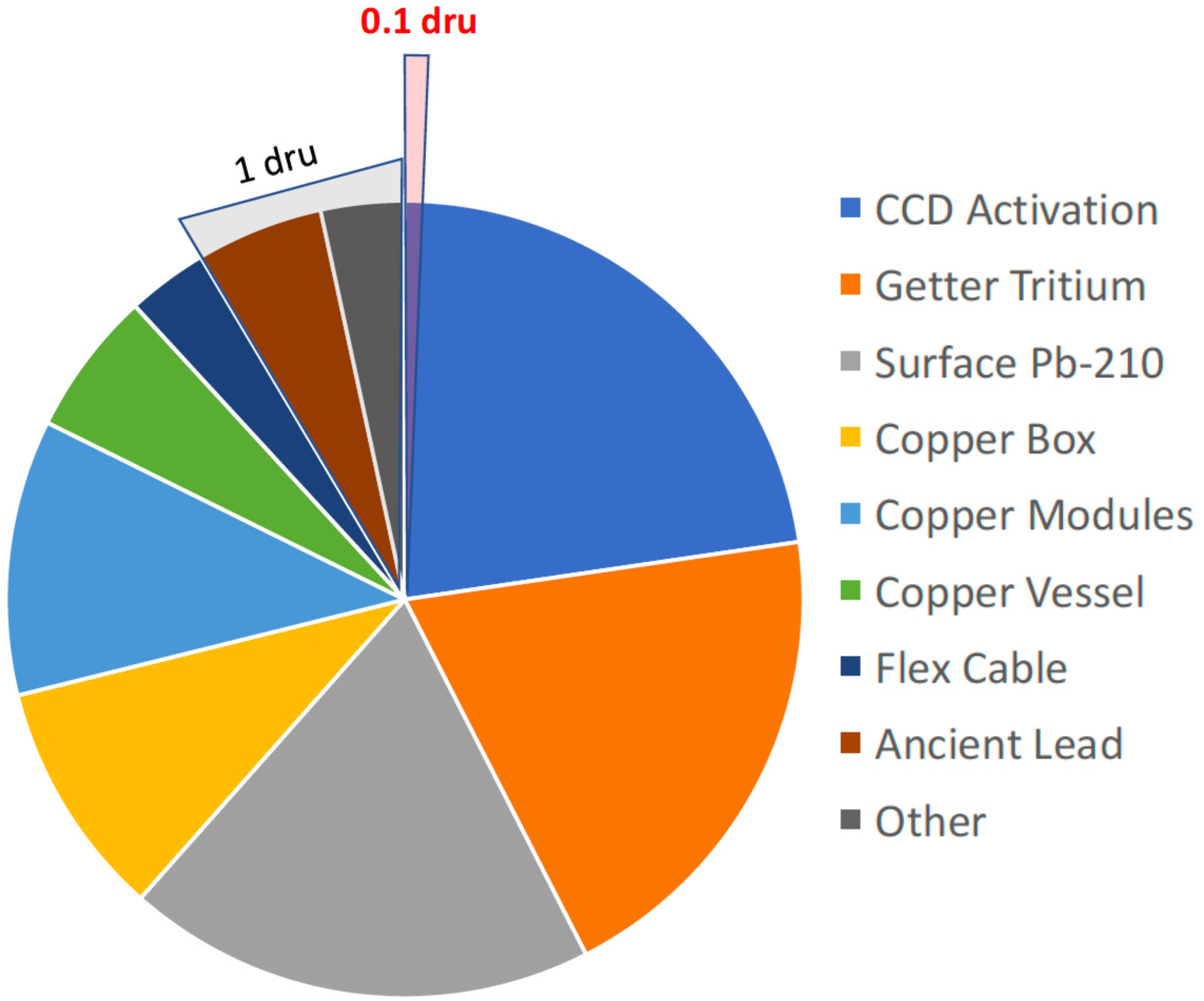
(*) 1 d.r.u = 1 decay/kg/day/keV

Background Composition: From DAMIC to DAMIC-M

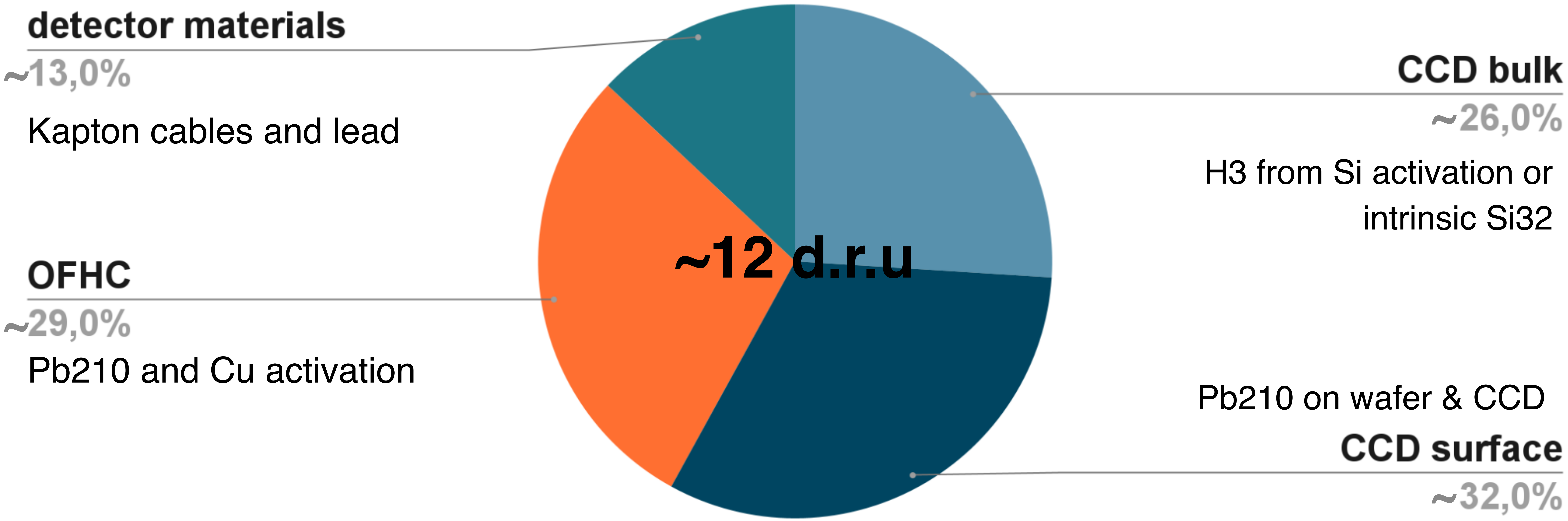
- 20% of background from ^{3}H production from silicon activation
- 20% of background from tritium in the getter
- 20% of background from ^{210}Pb
- 20% of background from OFC copper
- ...remaining 20% from a mixed bag of detector materials (mostly kapton cabling)

- 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)**





DAMIC at SNOLAB - Background



Phys. Rev. D 105, 062003 (2022)

for DAMIC-M better material selection and handling:

- Limit exposure time to cosmic rays (mostly Cu and Si)
- Limit the detector surfaces' exposure to radon (also of Si wafers prior CCD fabrication)
- Remove Si wafer surface (to reduce surface Pb210 and Partial Charge Collection region in backside)
- New materials: Electro-Formed copper, low-background cables

DAMIC at SNOLAB - BACKGROUND

~30% of background comes from the CCD bulk

^{3}H production from silicon activation or intrinsic ^{32}Si

~15% of background comes from wafer surface ^{210}Pb

~10% of background comes from CCD surface ^{210}Pb

~30% of background comes from OFHC copper

..remaining ~15% comes from a mixed bag of detector materials

o Kapton cables and lead

The DAMIC-M Collaboration

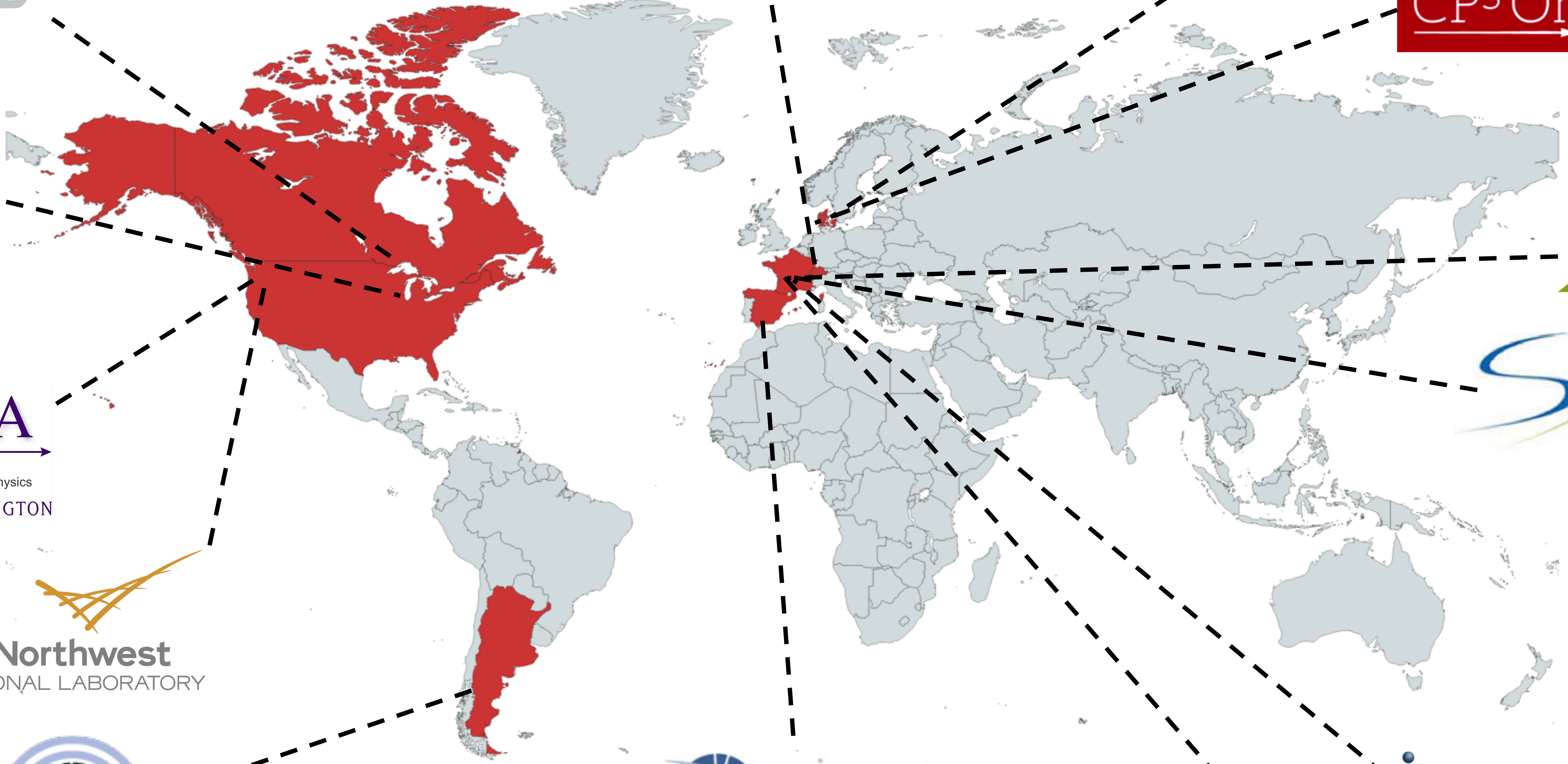
SNOLAB

THE UNIVERSITY OF CHICAGO 1890

CENPA
Center for Experimental Nuclear Physics and Astrophysics
UNIVERSITY of WASHINGTON

Pacific Northwest
NATIONAL LABORATORY

CNEA



University of Zurich[UZH]

Niels Bohr Institutet

CP3 Origins

LSM

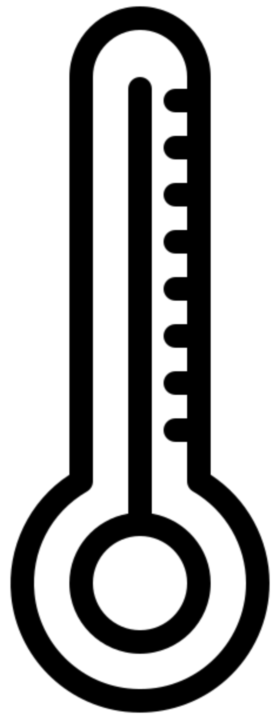
Subatech

IFCA
Instituto de Física de Cantabria

LPNHE
PARIS

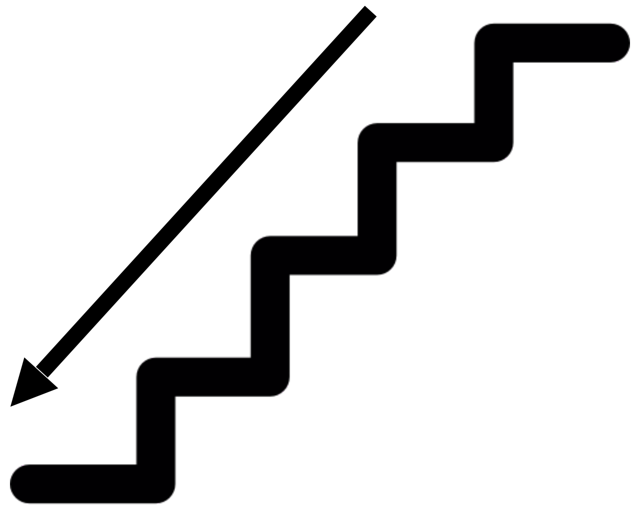
IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

DAMIC-M detector features



~100 K

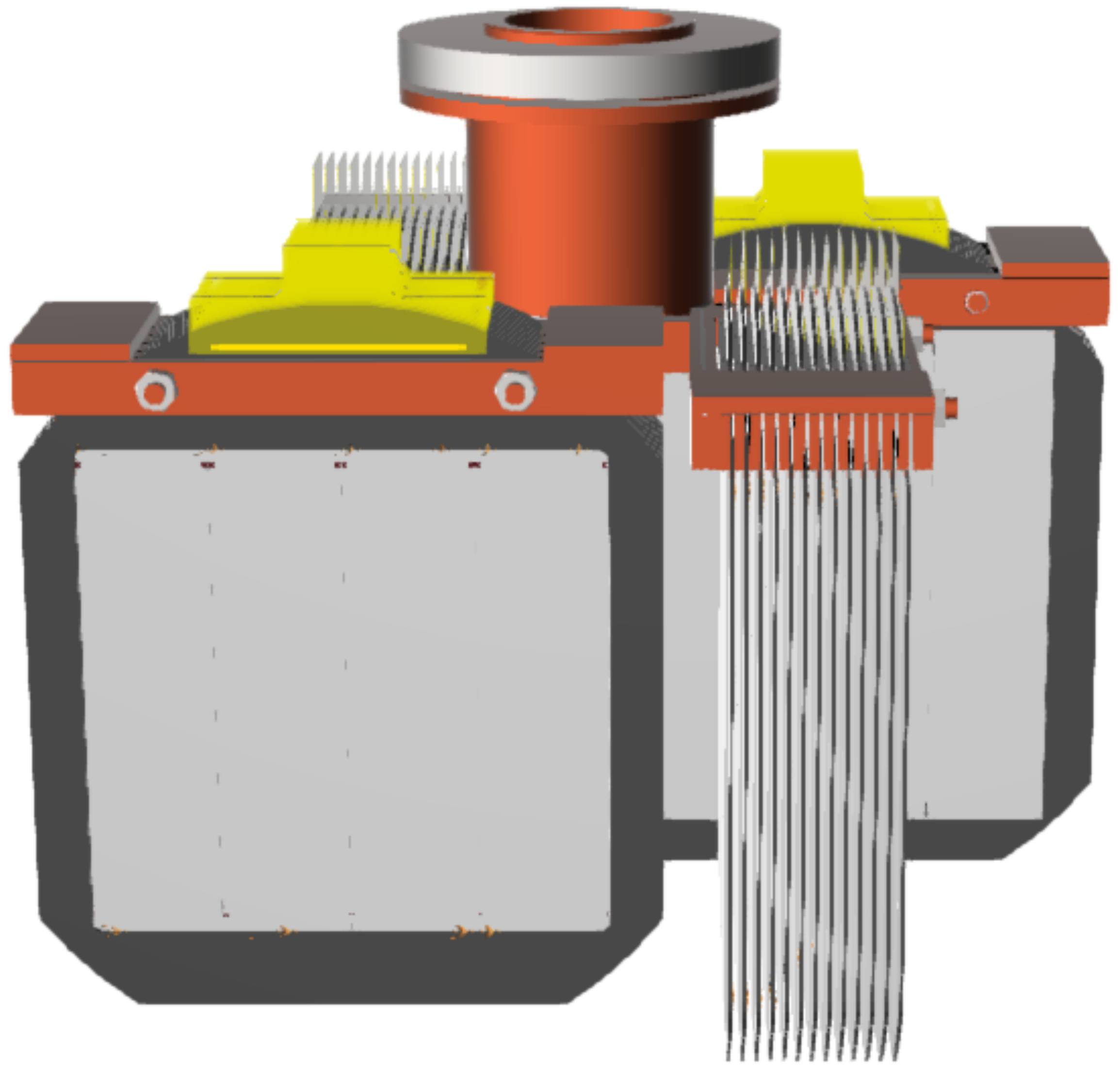
Temperature



1 d.r.u*

Background Level
O(0.1) d.ru

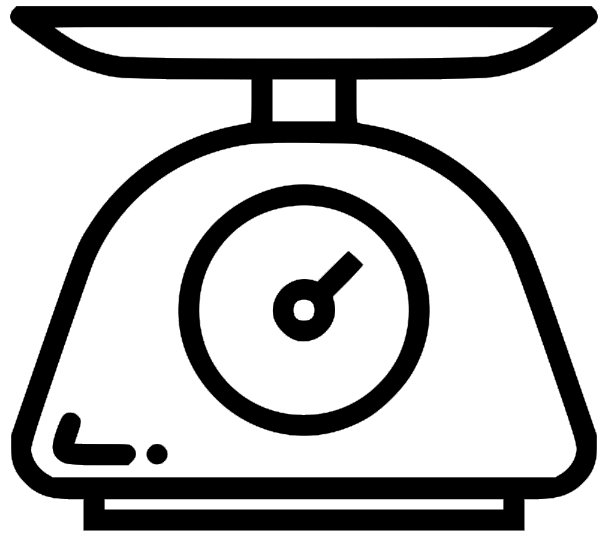
DAMIC-M CCD stack



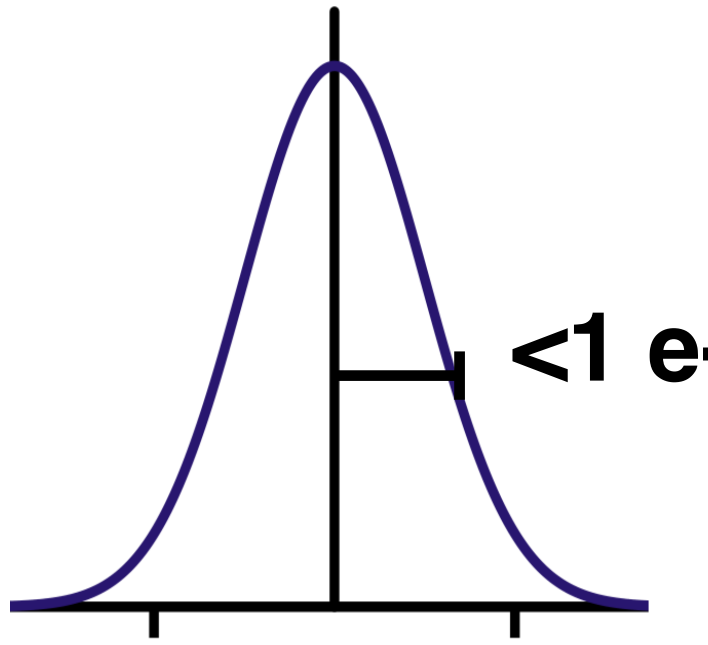
~200 SKIPPER CCDs

6000 pix x 1500 pix

~1 kg



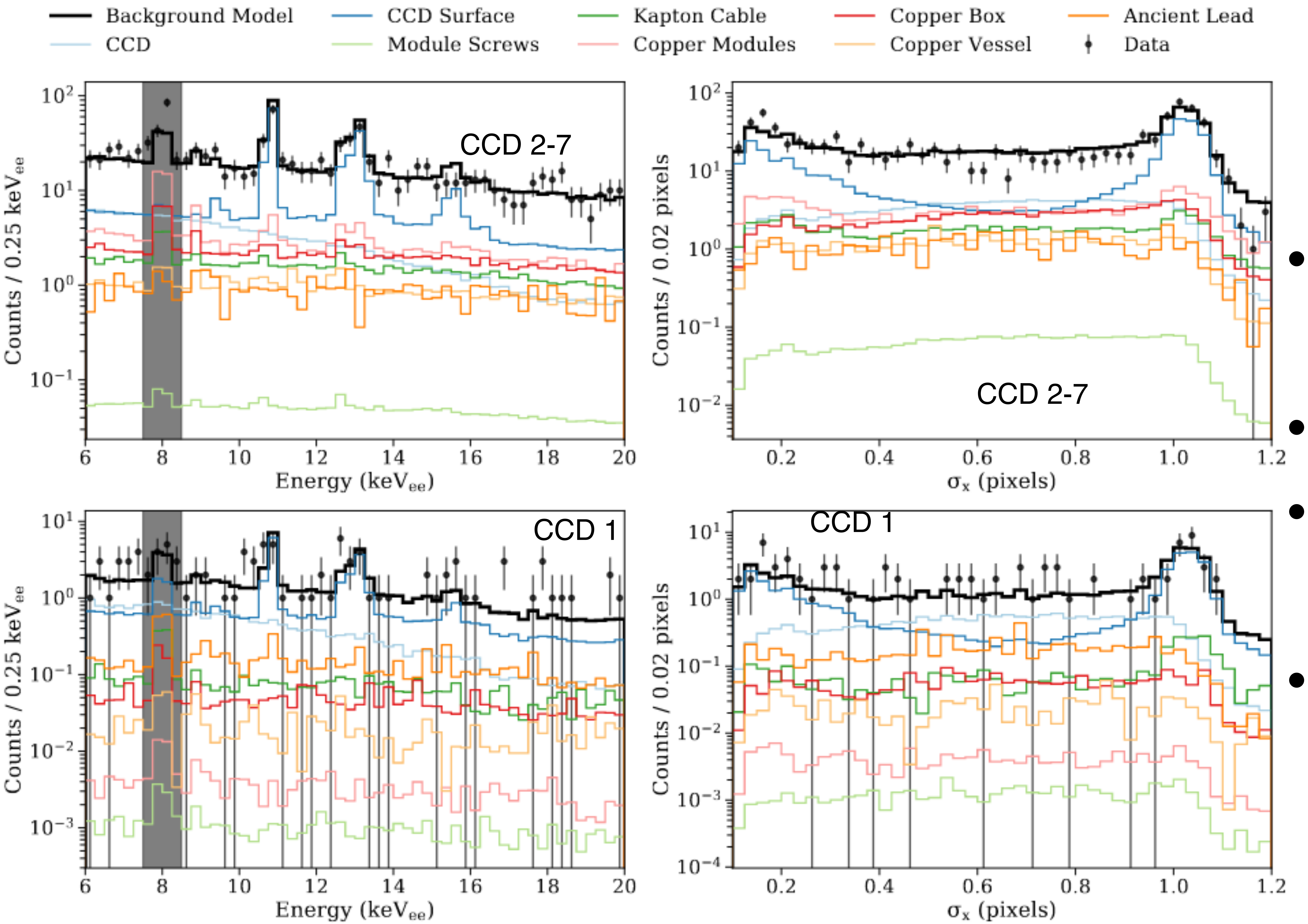
Sensitive Mass



Resolution (readout noise)
~0.1 eV

(*) 1 d.r.u = 1 decay/kg/day/keV

DAMIC at SNOLAB - BACKGROUND

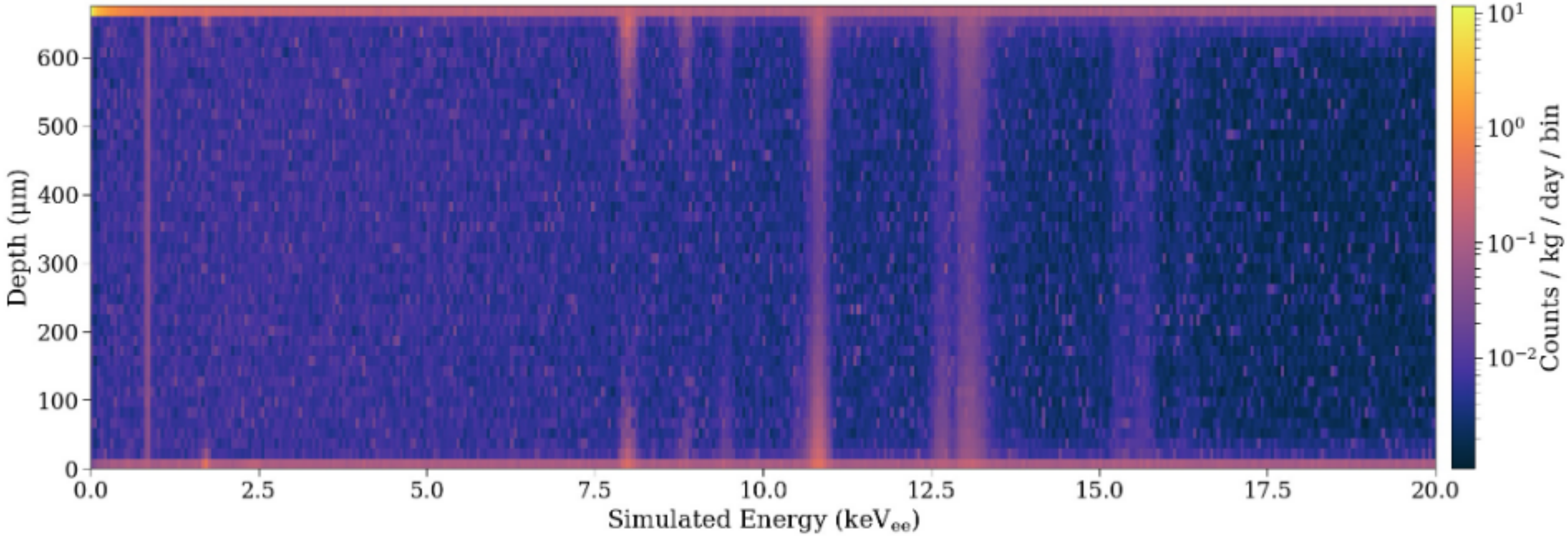


Output of the template background fit between energies of 6–20 keV$_{ee}$

- background model from fit to data (CCDs 2–7) above 6 keV$_{ee}$ with templates from GEANT4 simulation.
- Validation fit result with CCD 1 above 6 keV$_{ee}$
- consistency with independent estimates of ^{210}Pb surface activity from individual event identification.
- background model is extrapolated below 6 keV$_{ee}$ for WIMP search.

doi:10.1103/PhysRevD.105.062003

DAMIC at SNOLAB - BACKGROUND



The background model template (for CCDs 2–7) in raw simulated energy E_{sim} and depth (z = 0 corresponds to the front of the CCD)

doi:10.1103/PhysRevD.105.062003

DAMIC-M Timeline

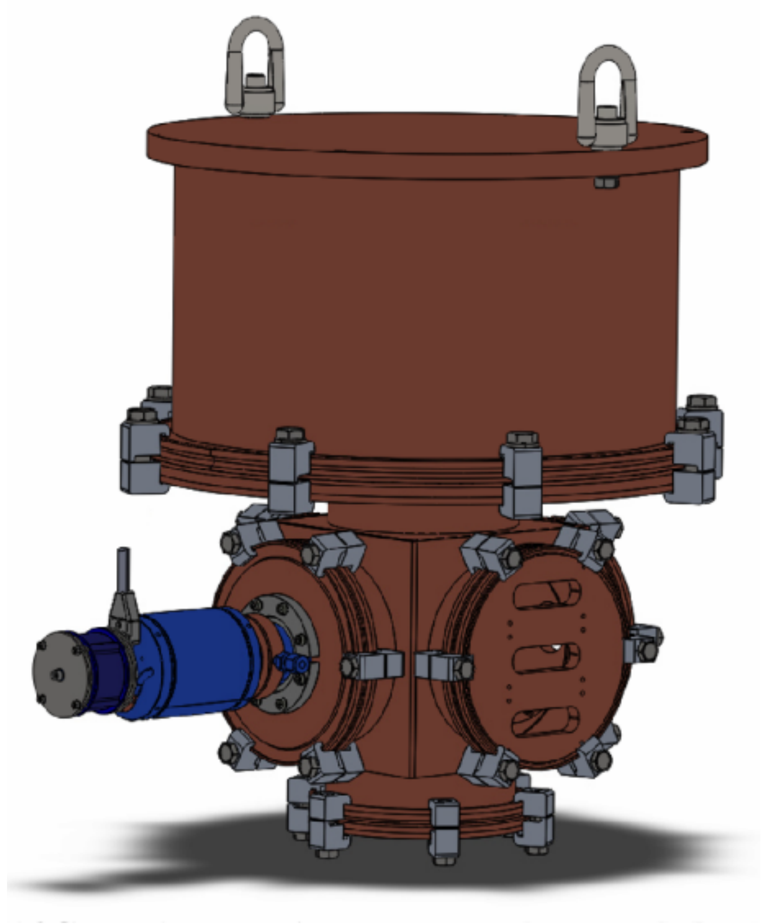
2021 | 2022 | 2023

Finalization DAMIC-M design

CCD production and testing

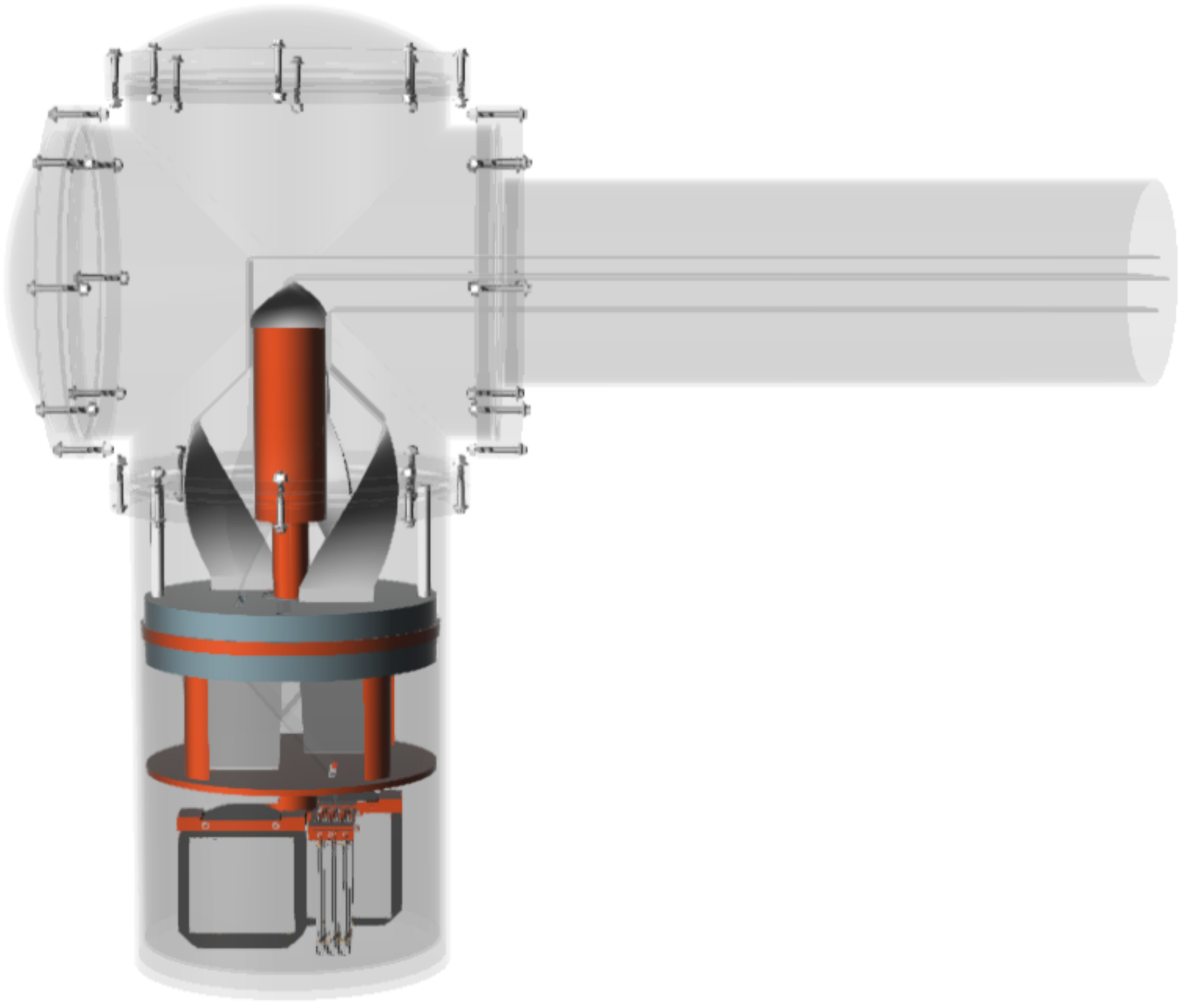
LBC (Low Background Chamber):

- being installed now, data by the end of 2021



DAMIC-M

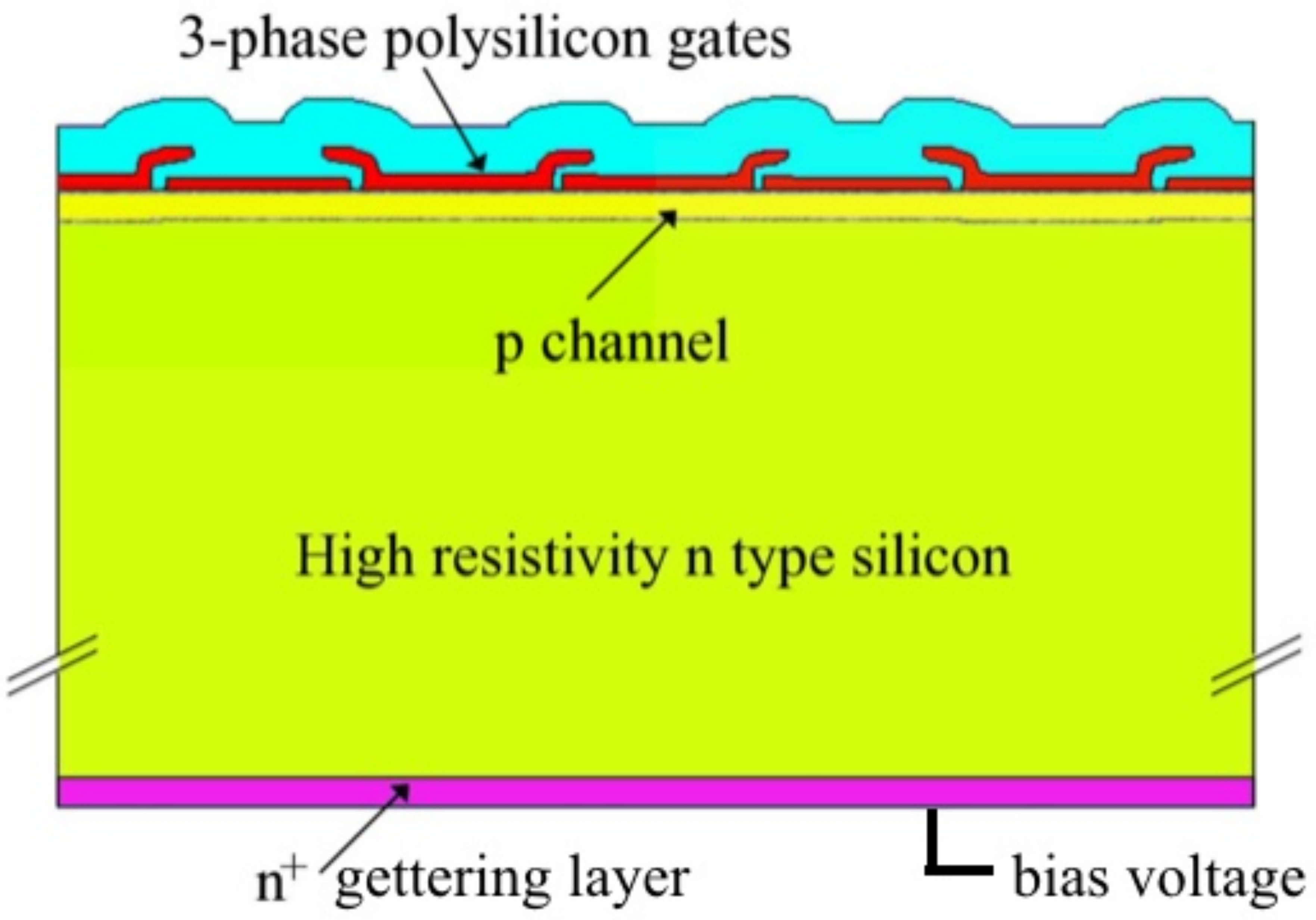
- Installation & data

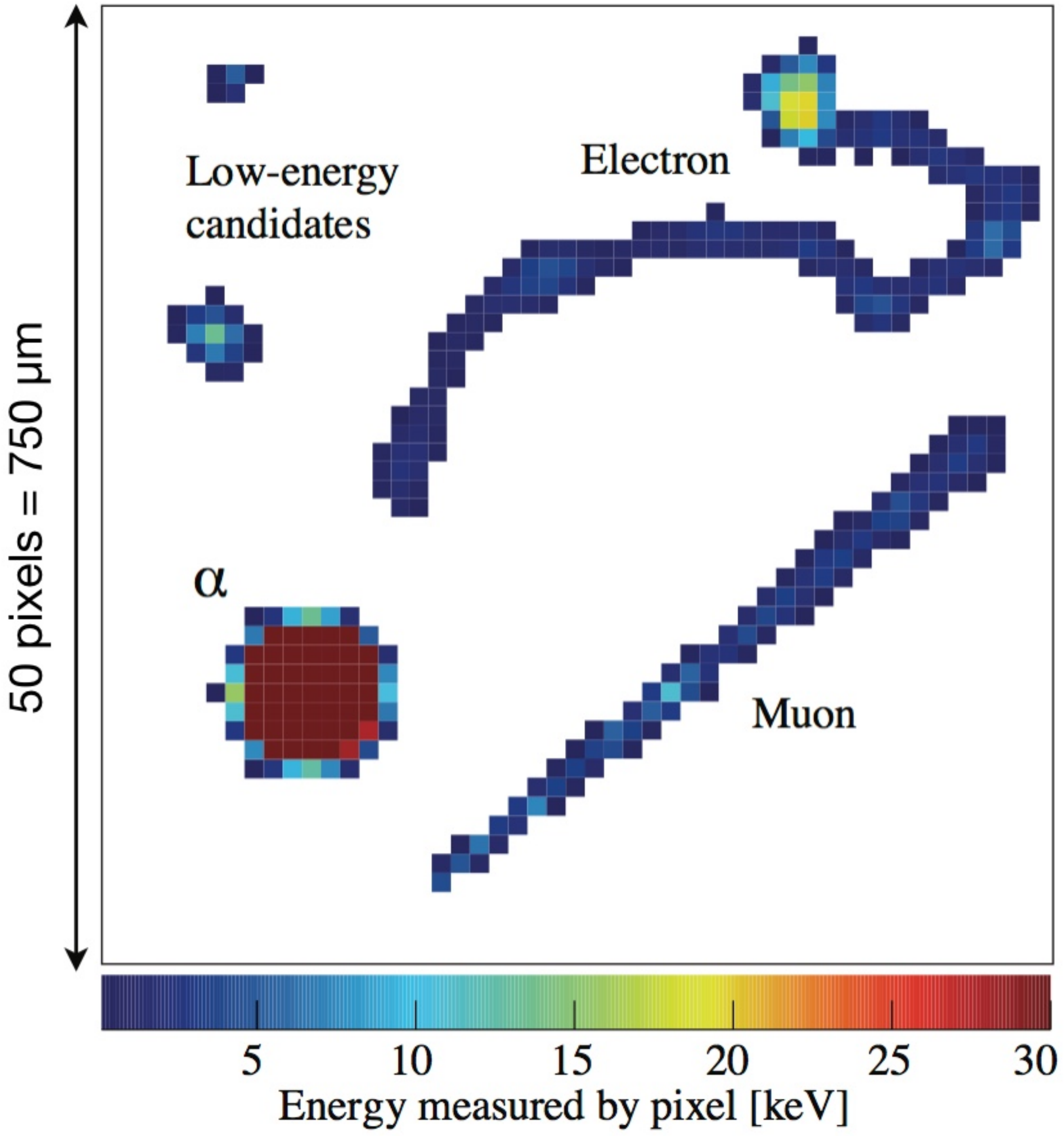


CCD properties

tracks in the CCD

pixel structure





Diffusion and z reconstruction

$$\sigma_{xy}^2 = -A \ln|1 - bz|.$$

$$A = \frac{\epsilon}{\rho_n}\frac{2k_B T}{e},$$

$$b = \left(\frac{\epsilon}{\rho_n}\frac{V_b}{z_D} + \frac{z_D}{2}\right)^{-1}$$

ϵ permittivity of silicon,

ρ_n : donor charge density in the substrate

k_B: Boltzmann's constant

T: operating temperature (120 K in DAMIC)

e: electron's charge

V_b: bias applied across the substrate (40V in DAMIC)

z_D: thickness of the device

IN DAMIC: σ_{max}=(21±1)μm≈1.4 pix.

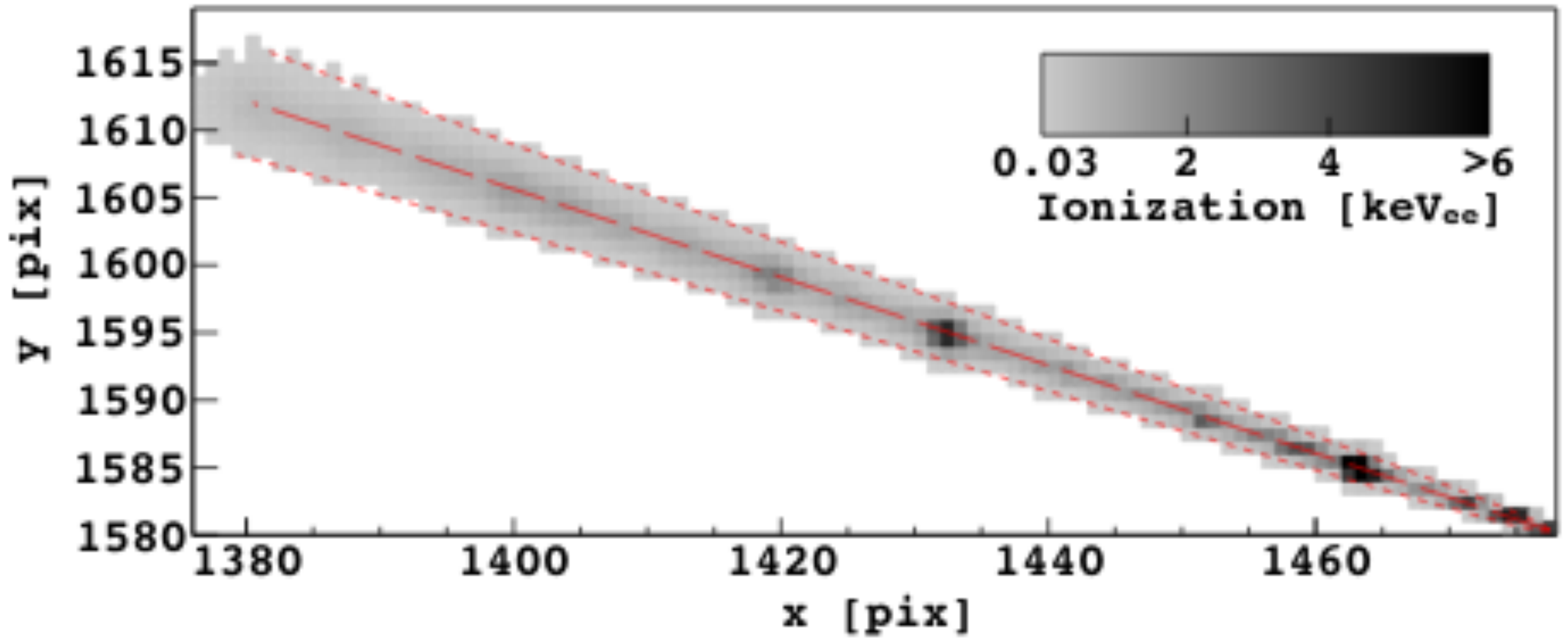


FIG. 4. A MIP observed in cosmic ray background data acquired on the surface. Only pixels whose values are above the noise in the image are colored. The large area of diffusion on the top left corner of the image is where the MIP crosses the back of the CCD. Conversely, the narrow end on the bottom right corner is where the MIP crosses the front of the device. The reconstructed track is shown by the long-dashed line. The short-dashed lines show the 3 σ band of the charge distribution according to the best-fit diffusion model.

Search for low-mass WIMPs in a 0.6 kg day exposure of the DAMIC experiment at SNOLAB; *Phys. Rev. D 94, 082006 (2016)*
DAMIC Collaboration (A. Aguilar-Arevalo et al.)

Background isotopes

Parent Chain	Isotope	Q value
^{238}U	^{234}Th	274 keV
	^{234m}Pa	2.27 MeV
^{226}Ra	^{214}Pb	1.02 MeV
	^{214}Bi	3.27 MeV
^{210}Pb	^{210}Pb	63.5 keV
	^{210}Bi	1.16 MeV
^{232}Th	^{228}Ra	45.5 keV
	^{228}Ac	2.12 MeV
	^{212}Pb	569 keV
	^{212}Bi	2.25 MeV
	^{208}Tl	5.00 MeV
^{40}K	^{40}K	1.31 MeV
Copper Activation	^{60}Co	2.82 MeV
	^{59}Fe	1.56 MeV
	^{58}Co	2.31 MeV
	^{57}Co	836 keV
	^{56}Co	4.57 MeV
	^{54}Mn	1.38 MeV
	^{46}Sc	2.37 MeV
^{32}Si	^{32}Si	227 keV
	^{32}P	1.71 MeV
Silicon Activation	^{22}Na	2.84 MeV
	^{3}H	18.6 keV

TABLE II. Isotopes considered for the background model grouped by parent decay chain classification. Q values are provided for convenience from Ref. [54, 55].

Characterization of the background spectrum in DAMIC at SNOLAB:

https://arxiv.org/abs/2110.13133

Isotope	Half-life [yrs]	Decay mode	Q-value [keV]
^{3}H	12.32 ± 0.02	β-	18.591 ± 0.003
^{7}Be	0.1457 ± 0.0020	EC	861.82 ± 0.02
^{10}Be	$(1.51 \pm 0.06) \times 10^6$	β-	556.0 ± 0.6
^{14}C	5700 ± 30	β-	156.475 ± 0.004
^{22}Na	2.6018 ± 0.0022	β+	2842.2 ± 0.2
^{26}Al	$(7.17 \pm 0.24) \times 10^5$	EC	4004.14 ± 6.00

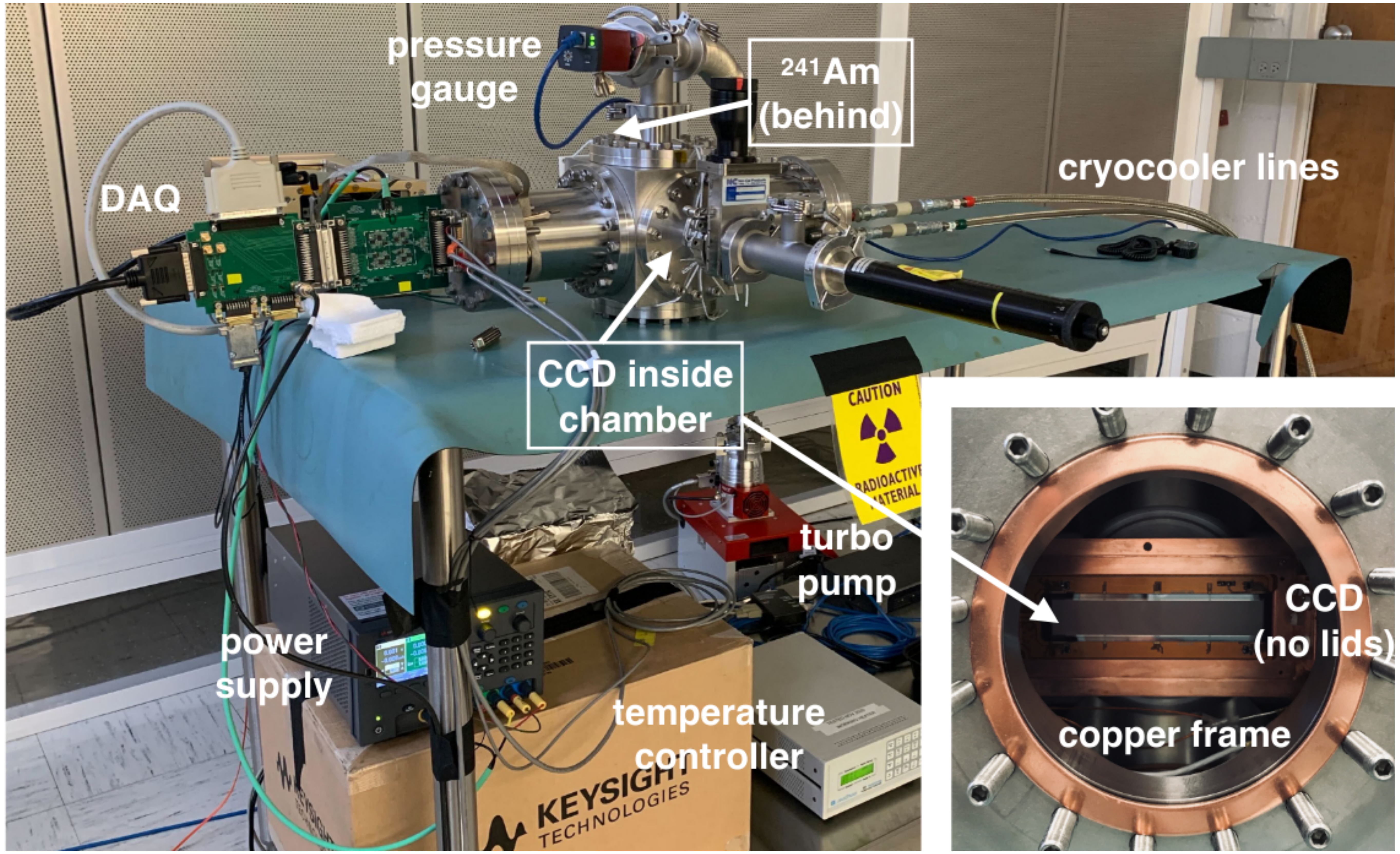
TABLE I. List of all radioisotopes with half-lives >30 days that can be produced by cosmogenic interactions with natural silicon. All data is taken from NNDC databases [14]. [a]

[a] Unless stated otherwise, all uncertainties quoted in this paper are at 1σ (68.3%) confidence.

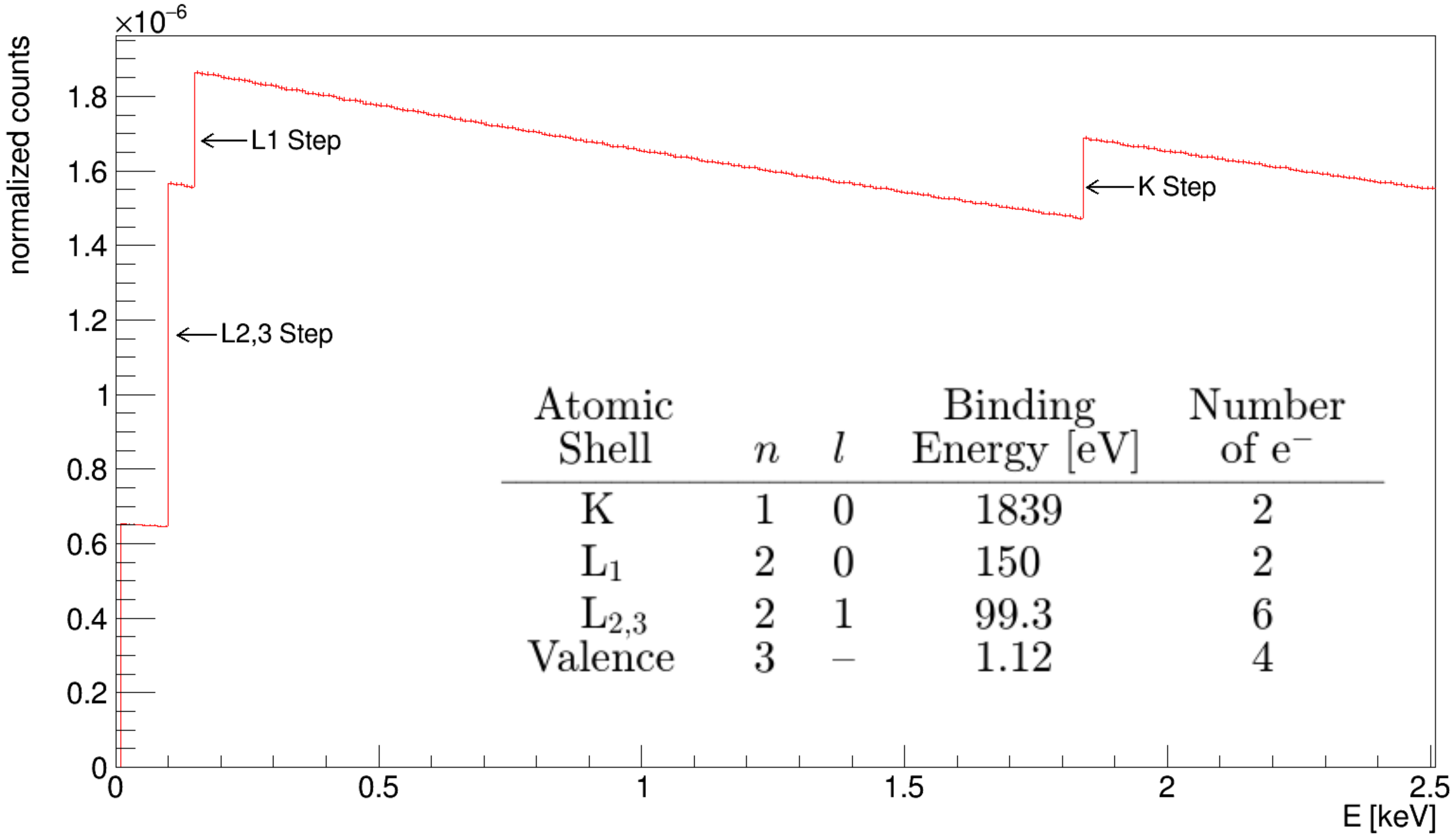
Cosmogenic activation of silicon

https://arxiv.org/abs/2007.10584

Compton measurement

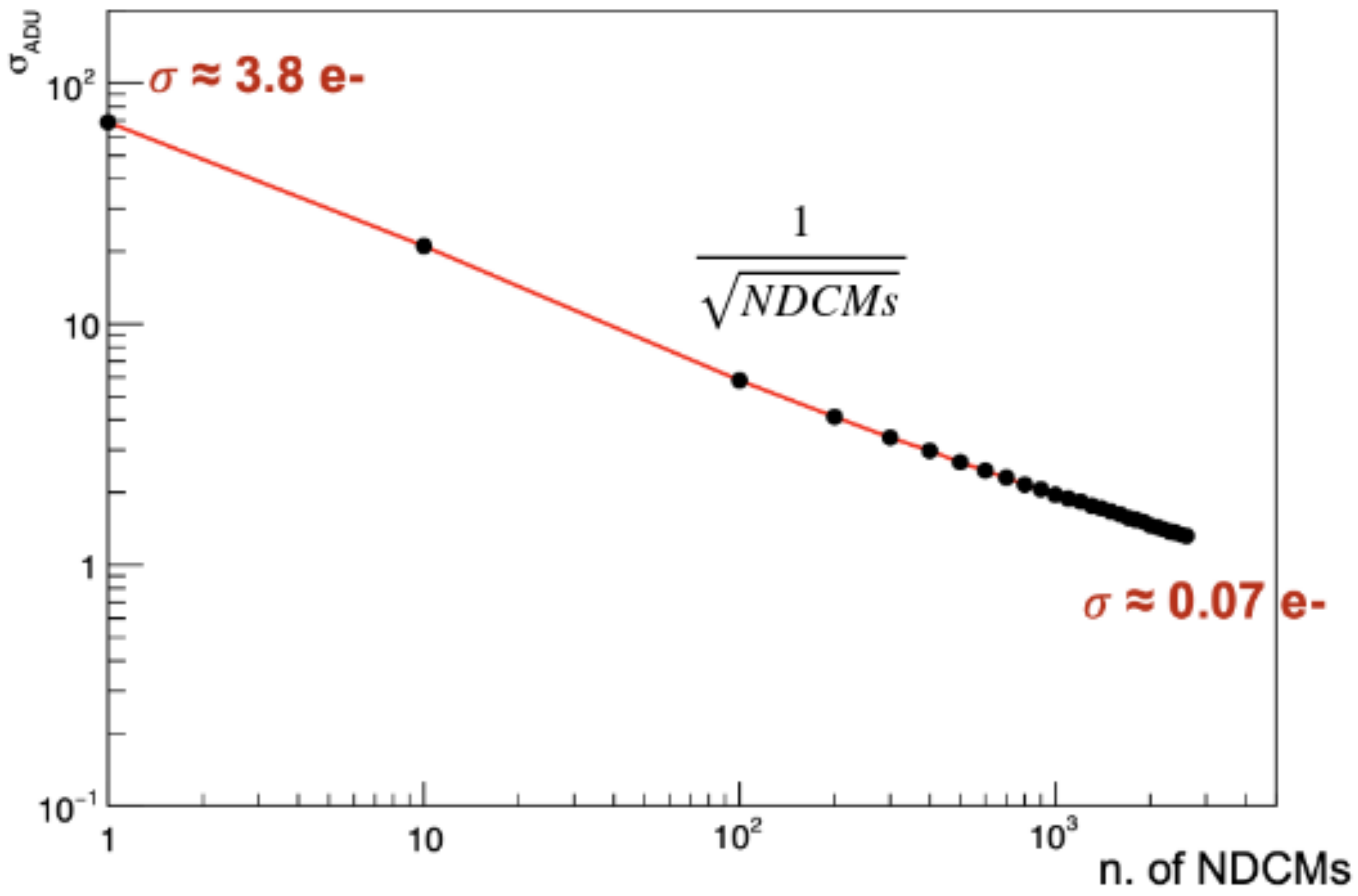


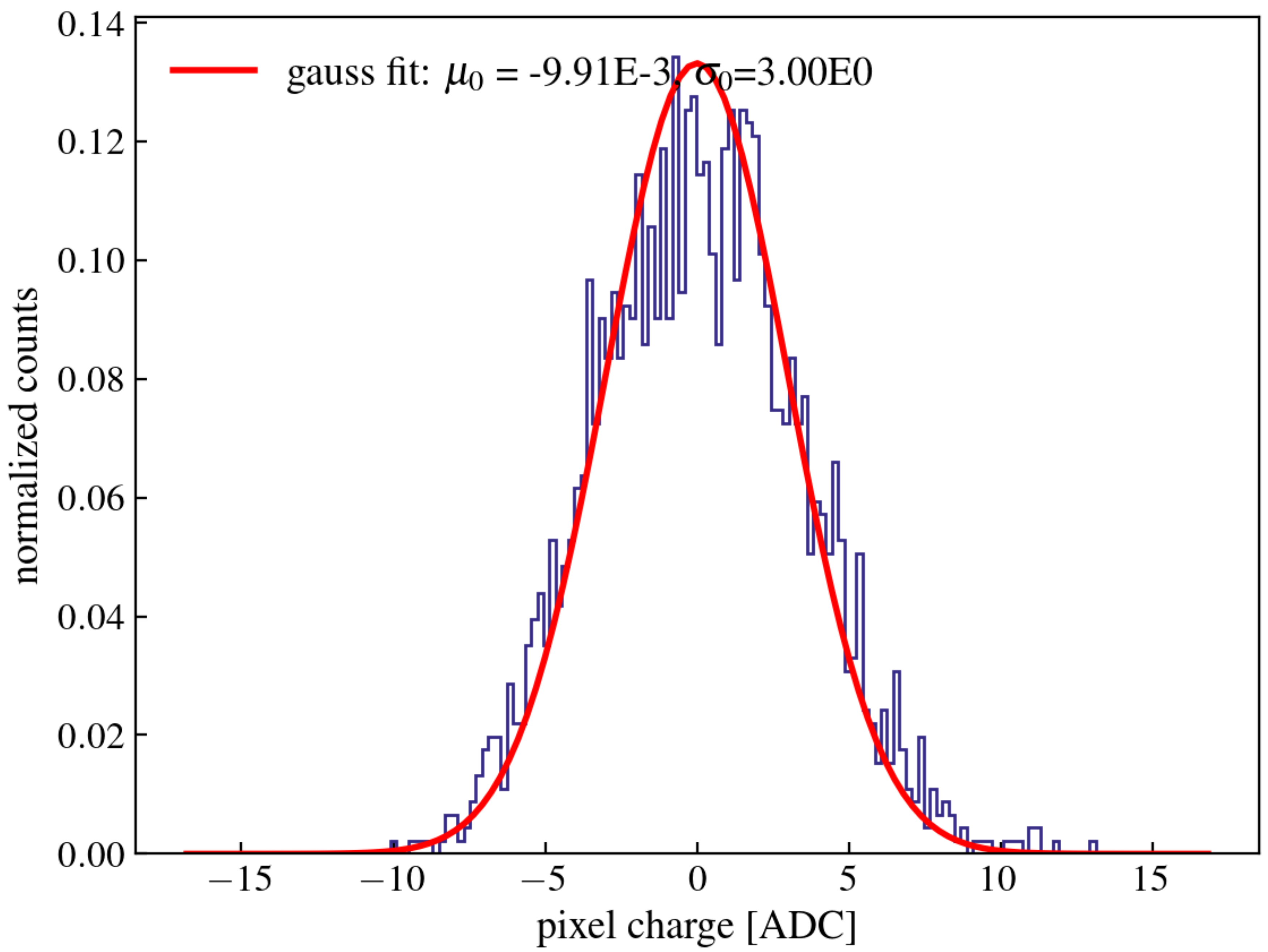
Expected normalized low-energy spectrum from Compton scattering of 59.5 keV γ rays in silicon (RIA model)



Source	γ Energy
Am241	26.3 keV **59.5 keV**

Compton Analysis chain





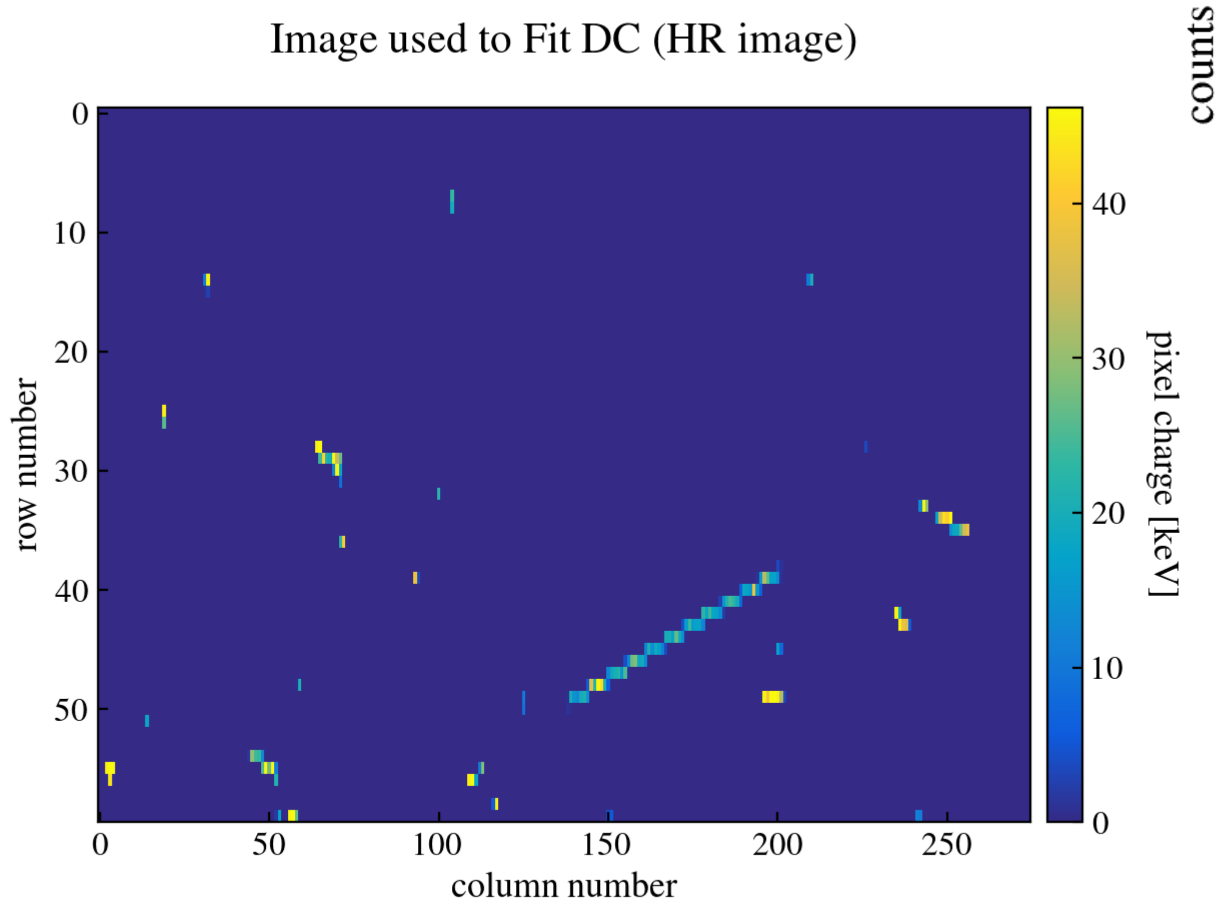
1 Image = mean all skipper images

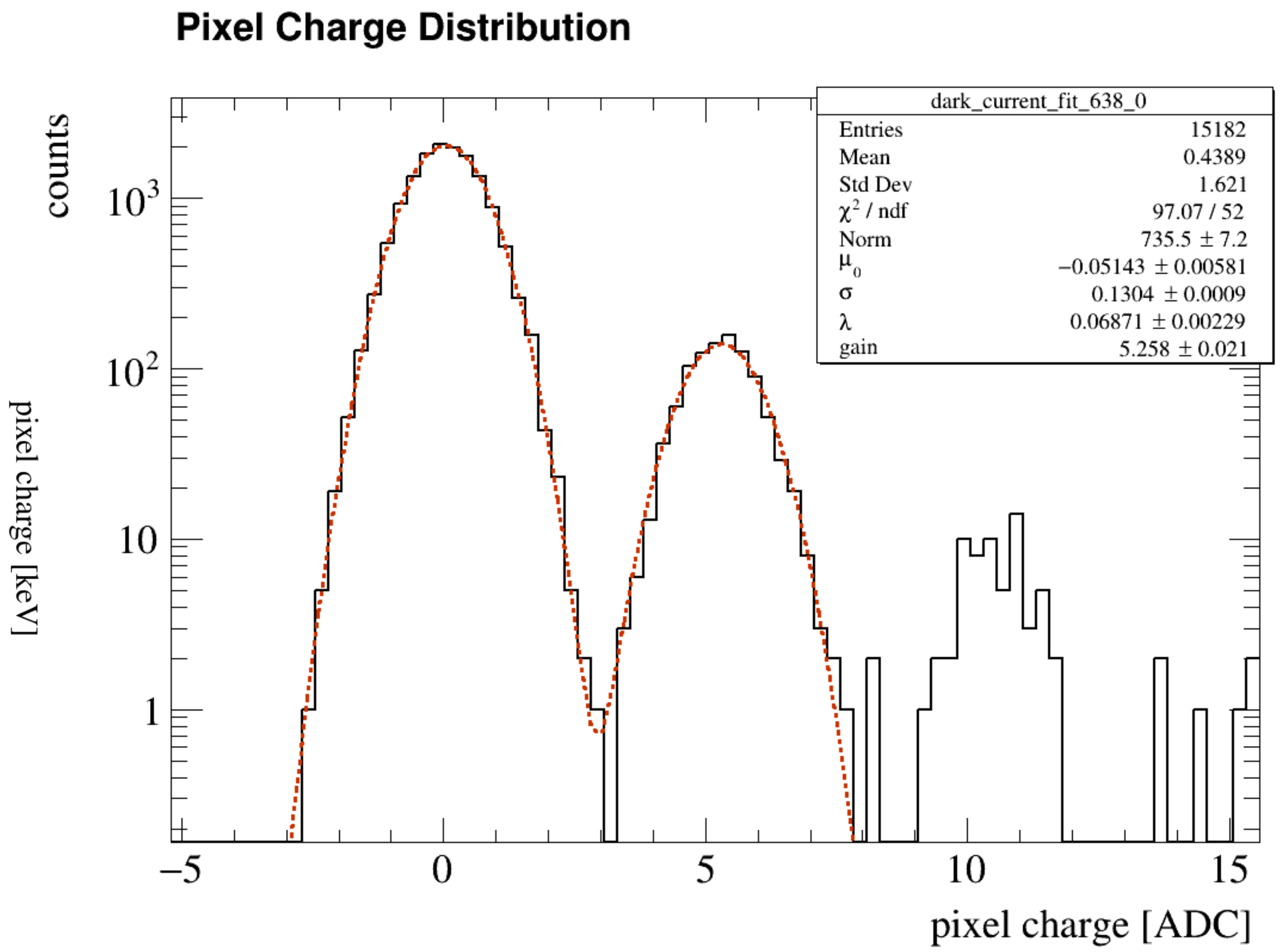
skips = Non-Destructive Charge Measurements

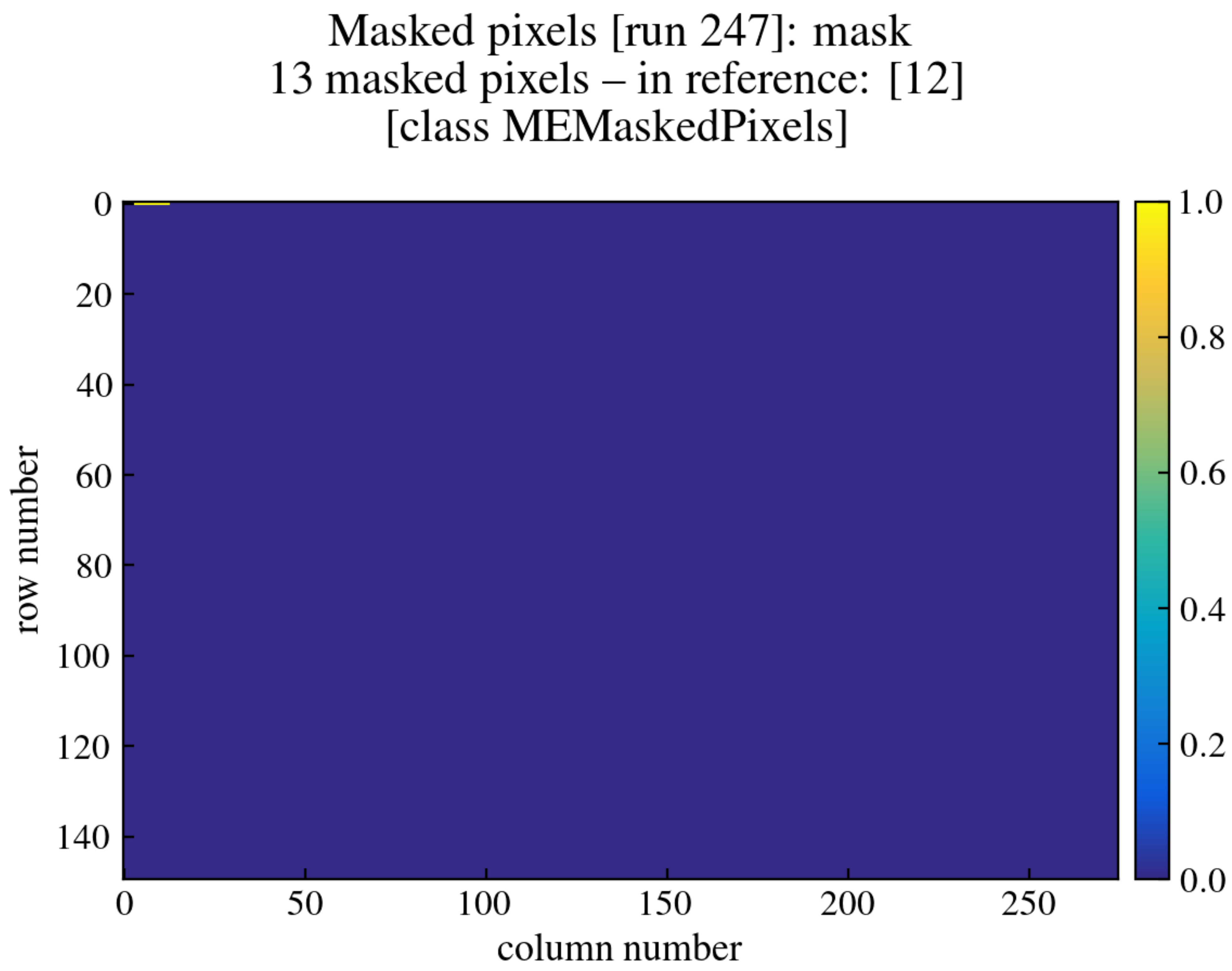
2 Pedestal subtraction:

- gaussian fit row by row overscan: μ_{row} σ_{row}
- subtraction μ_{row} in active area
- readout noise σ = median[σ_{row}]

Compton Analysis chain







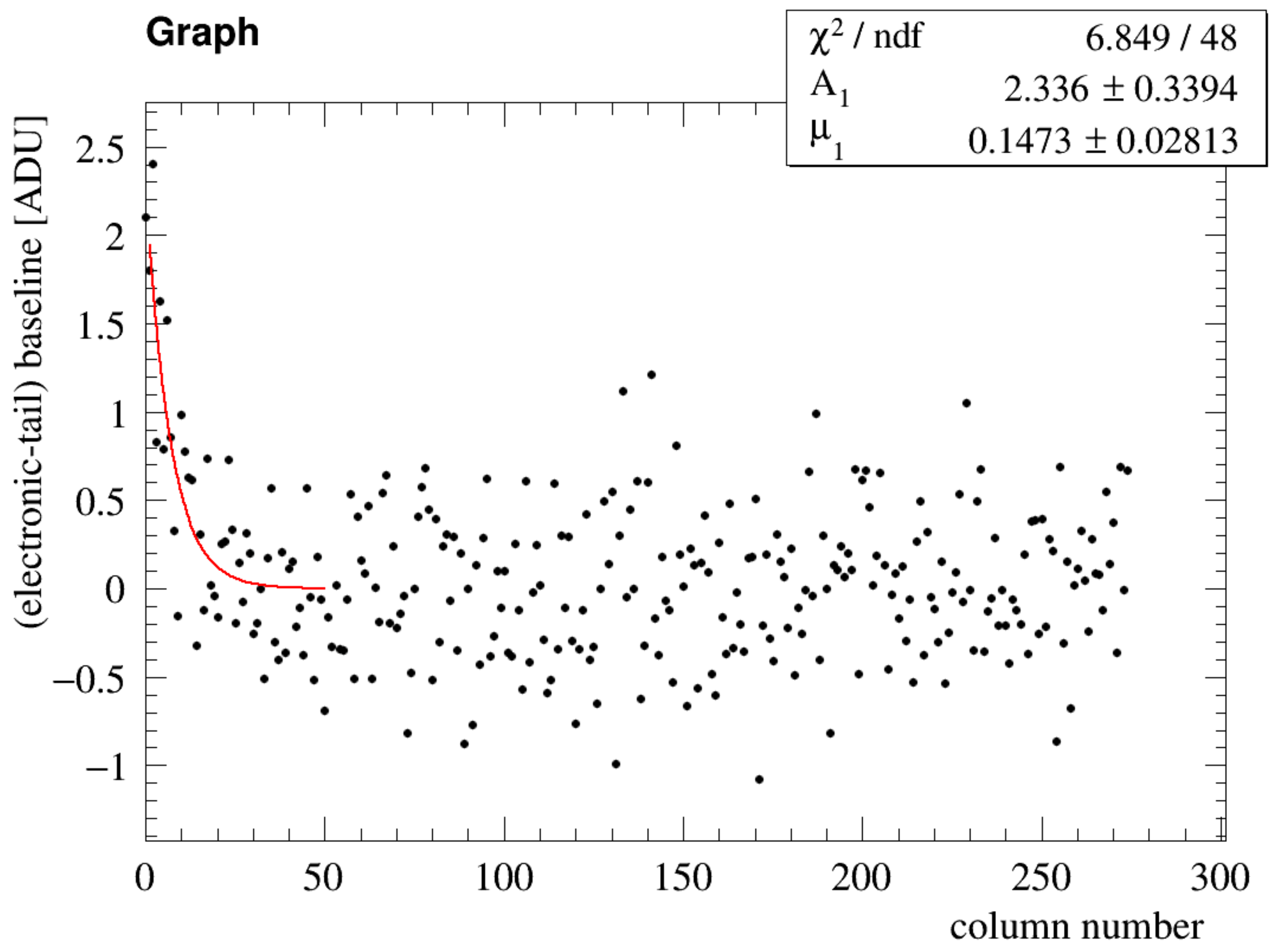
3 Fit Dark Current + Calibration (using image with 2000 skips):

- Fit active area convolution Poisson(λ [e-/pix]) and Gaussian(μ [ADU], σ [e-])
- gain [ADC/e-]= conversion ADC in e-

4 Mask hot pixels and columns/rows:

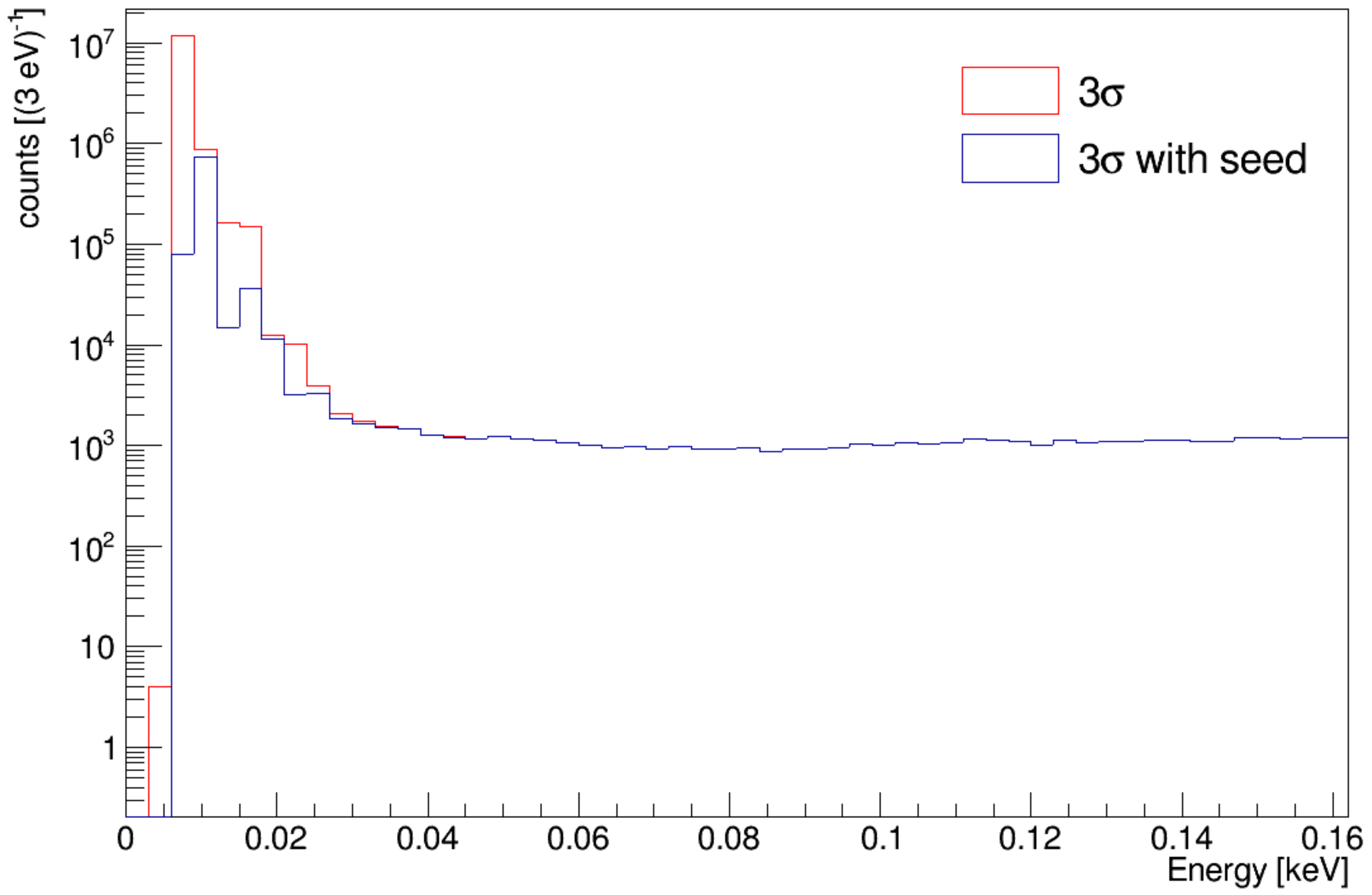
- hot pixels: if in 50% images of a run the pixel charge > median(μrows) + 3MAD
- hot column/row: 30% of pixels are hot

Compton Analysis chain



5 Correction Column transient effect:

- calculate median of charge in a given column: median[col]
- calculate median MED of median[col] from col50 to col260
- subtract MED to median[col1] to median[col49]: median[col1] - MED, …., med[col49]-MED
- fit with an exponential y(col) = [0]*exp(- [1]* col)
- subtract fit result y to col 1 to col 49

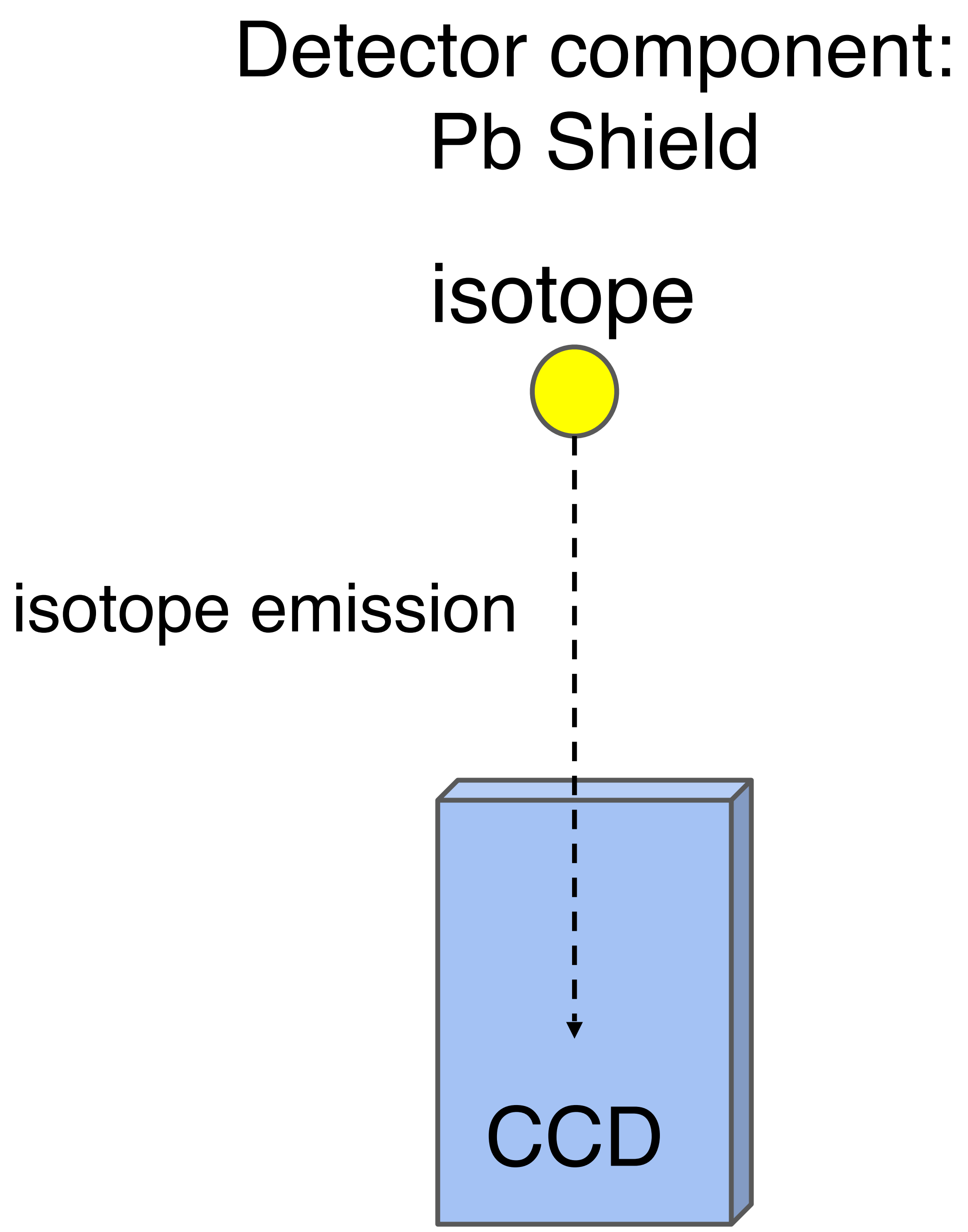


6 Clusters = all contiguous pixels with:

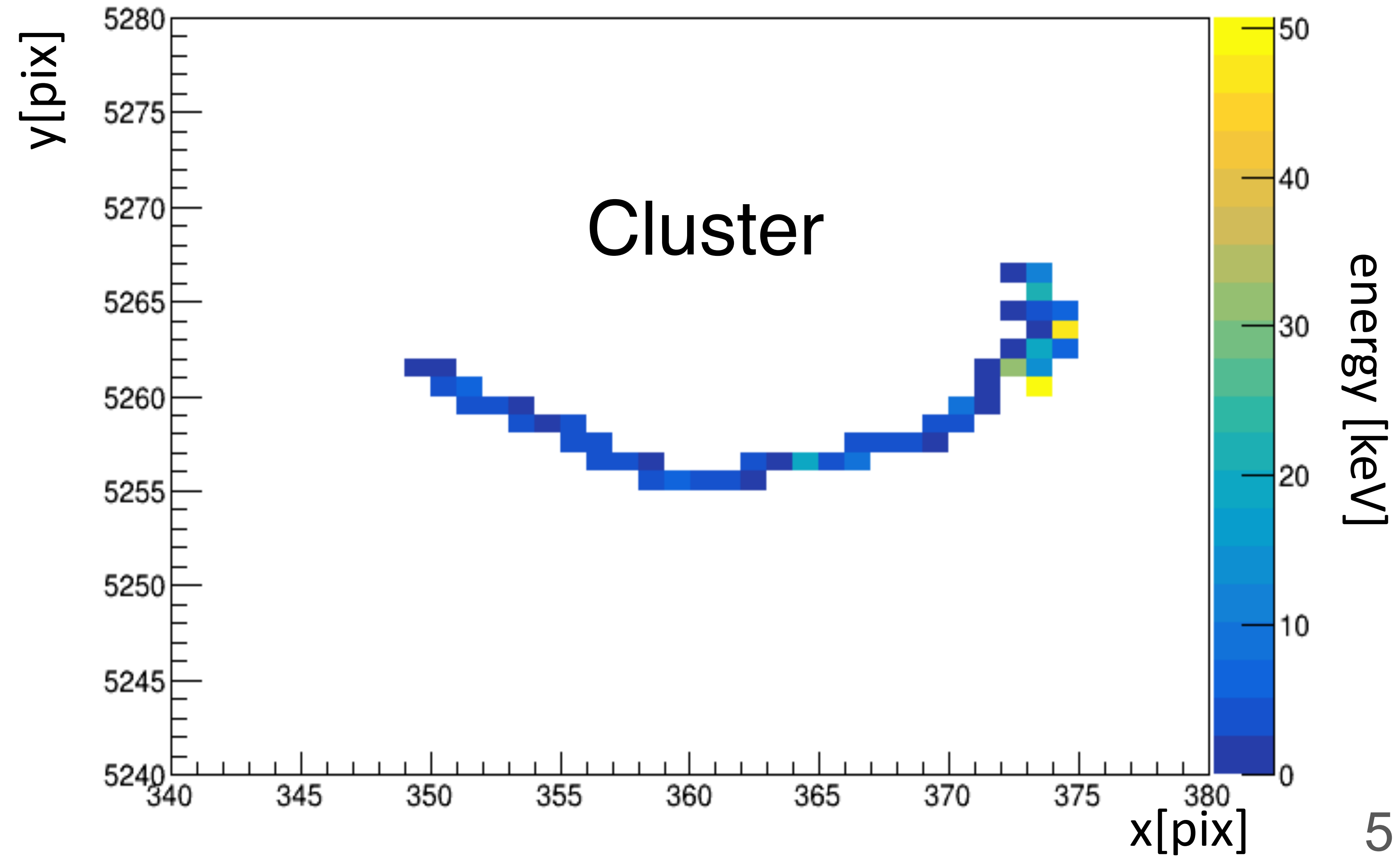
- all pixels with charge above 3σ (readout noise from pedestal subtraction)
- at least 1 pixel above 4σ (SEED)

Simulation chain

1. Geant4:
   - simulate passage of particles through matter
   - geometry implementation
   - simulation isotopes in detector components
   - energy deposits of isotopes emission in CCD



1. Python code:
   - reproduce CCD response
   - cluster information: a cluster is a set of contiguous pixels with charges



Simulation chain

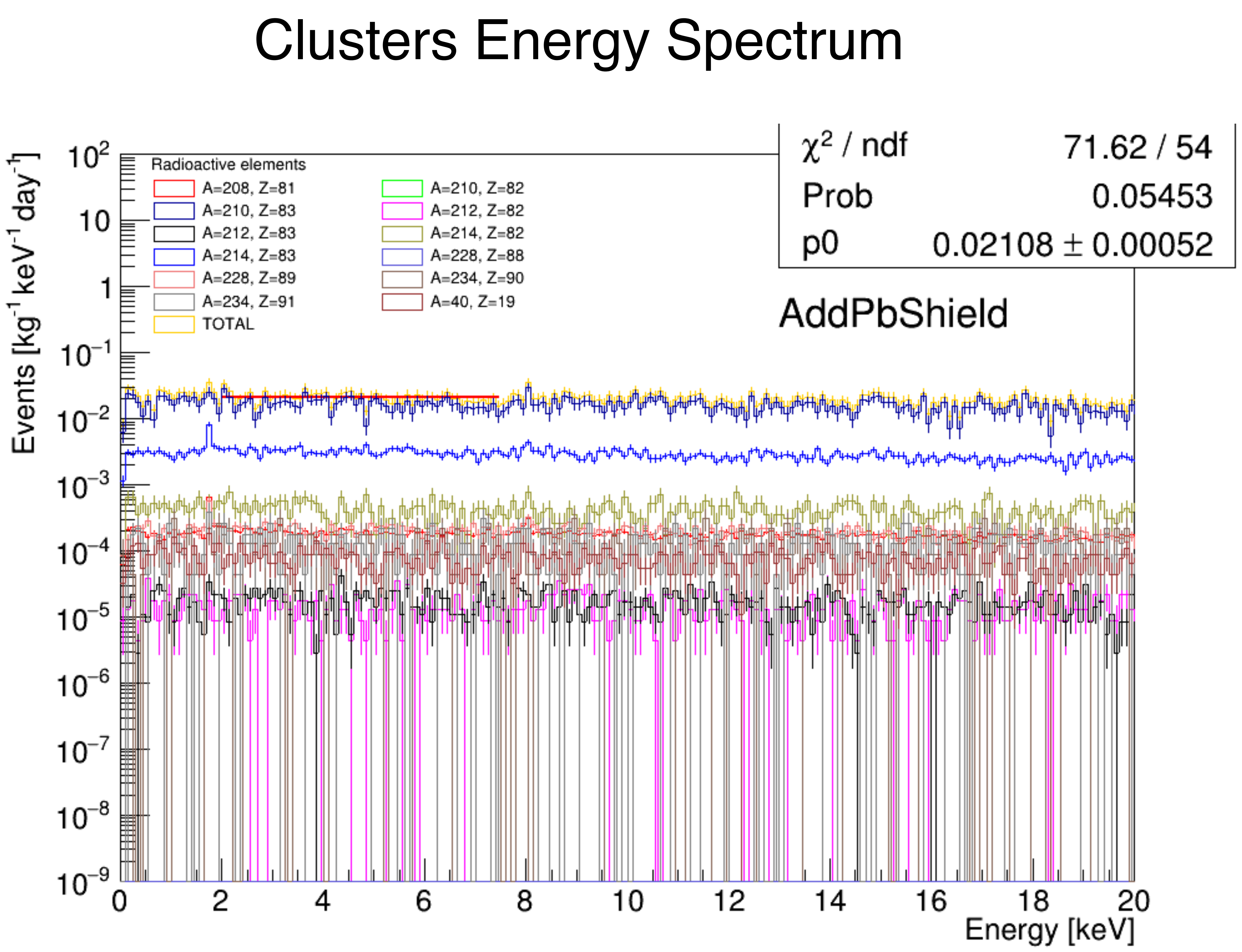
3. Personal script:

- each isotope cluster energy spectrum scaled by:

Activity x component mass /
(detector mass x number simulated evts)

- sum all isotopes contributions

background rate =
linear fit between 2 and 7.5 keV



Simulation details

- Livermore physics list + neutron processes and radioactive decays.

  The Livermore low-energy electromagnetic models are used to describe the interactions with matter of electrons and photons between 20 eV and 100 GeV.

- The DAMIC-M detector design and the relative materials are implemented through a GDML
- Production cuts for $e^{\pm}$, γ and protons
  - 0.0001 mm nearest component to the CCD Stack
  - 0.001 mm farther components

Simulated Isotopes and activities

from DAMIC

material suppliers

assumption: measured/ 10

calculated:
Texp = 3m, Tcool=6m, Trun= 1y

U238 & Th232

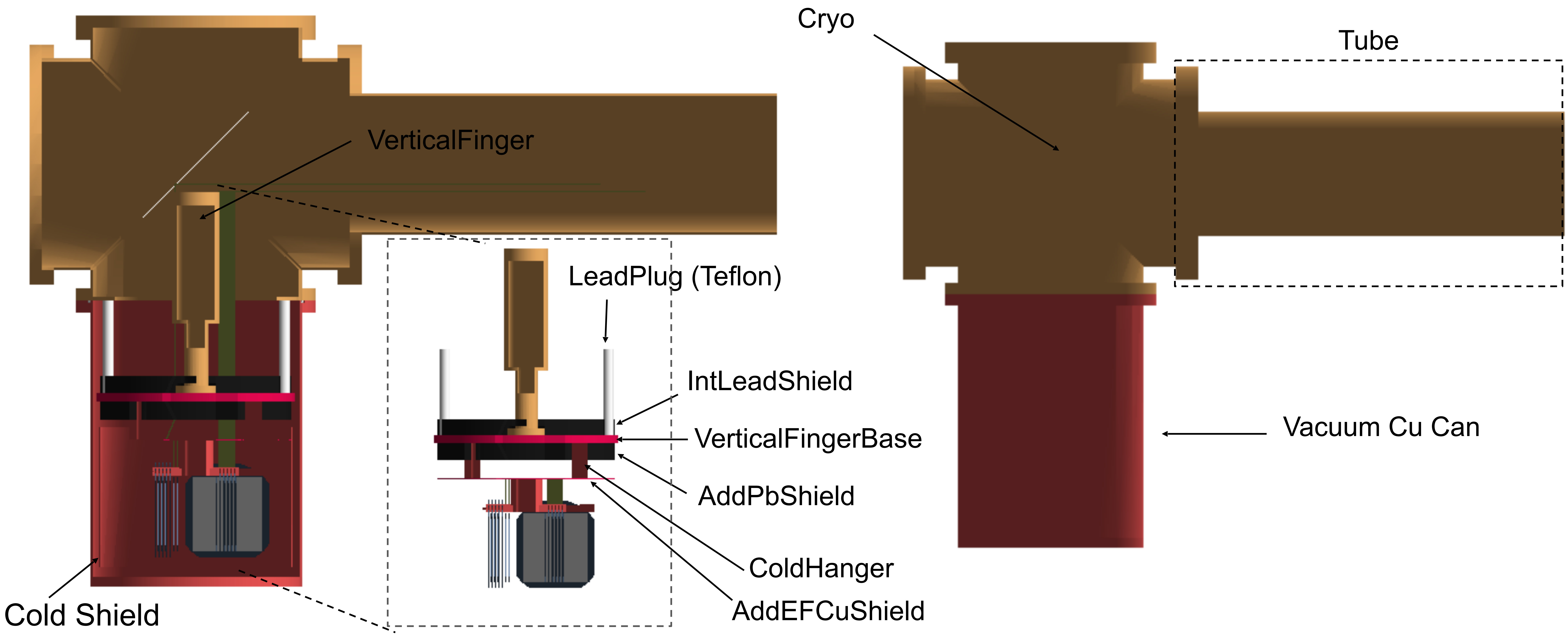
cosmogenic isotopes

in Epoxy & Cu

		Activities [decays/kg/day]				
A	Z	Copper	EF Copper	Ancient Lead	Dirty Lead	Kapton 2 layers
208	81	<1.26	<0.000792	0.072	<0.144	15.3
210	82	2350	<45.8	2850	1560000	1182
210	83	2350	<45.8	2850	1560000	1182
212	82	<3.5	<0.0022	0.2	<0.4	42.5
212	83	<2.24	<0.0014	0.128	<0.256	27.2
214	82	<11.2	<0.018	<2.0	<17.6	1182
214	83	<11.2	<0.018	<2.0	<17.6	1182
228	88	<3.5	<0.0022	0.2	<0.4	42.5
228	89	<3.5	<0.0022	0.2	<0.4	42.5
234	90	<10.7	<0.018	<2	<1.1	1182
234	91	<10.7	<0.018	<2	<1.1	1182
40	19	<2.7	<2.7	<0.5	<19	2480
87	37	7.4	7.4			7.4
54	25	1.55	**NB cosmo iso in EFCu always treated <u>separately,</u> not in bkg rate of the individual components!**			
56	27	0.64				
57	27	13.12				
58	27	3.9				
59	26	0.31				
60	27	5.08				
46	21	0.17				

Current detector Design

OFC
EFCu
Pb



Dark matter mass scale

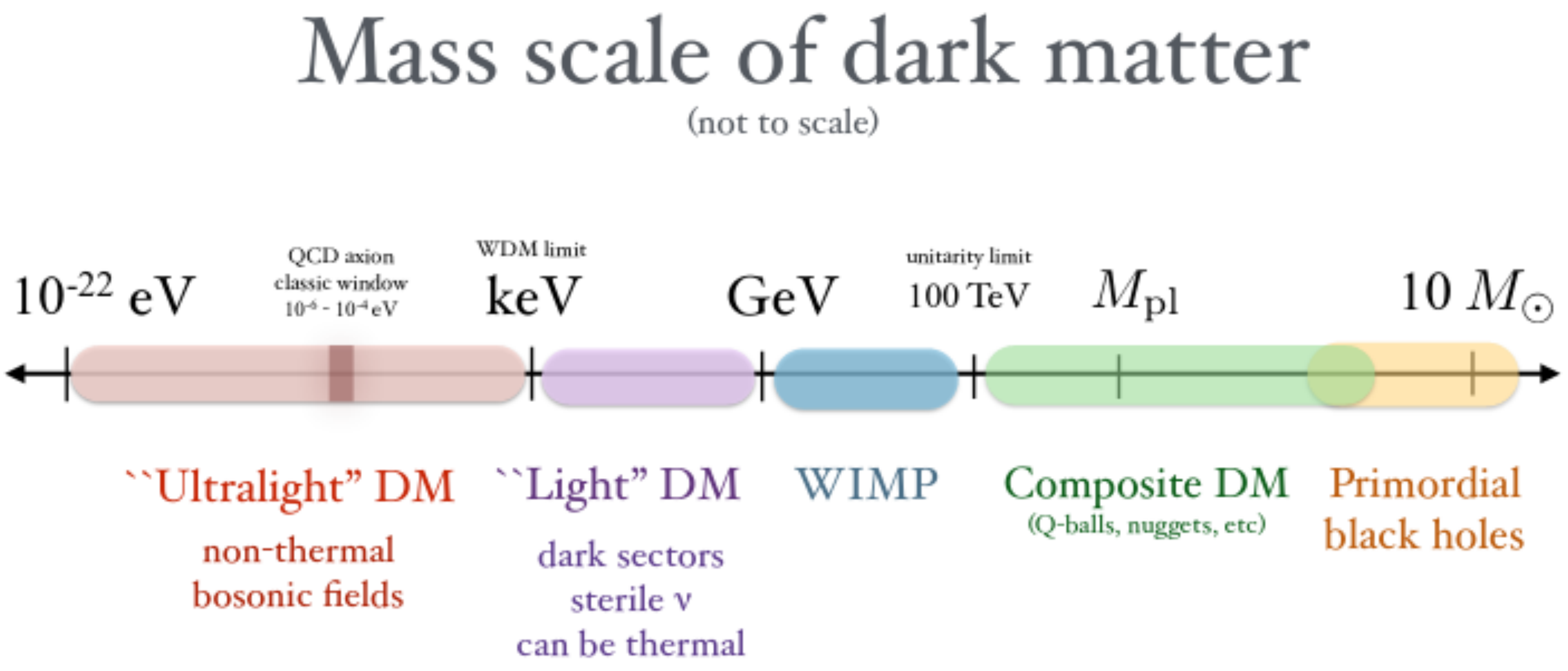


FIG. 3. The mass range of allowed DM candidates, comprising both particle candidates and primordial black holes. Mass ranges are only approximate (in order of magnitude), and meant to indicate general considerations.

T. Lin, TASI lectures on DM models and direct detection, arXiv:1904.07915

Physics reach direct DM experiment

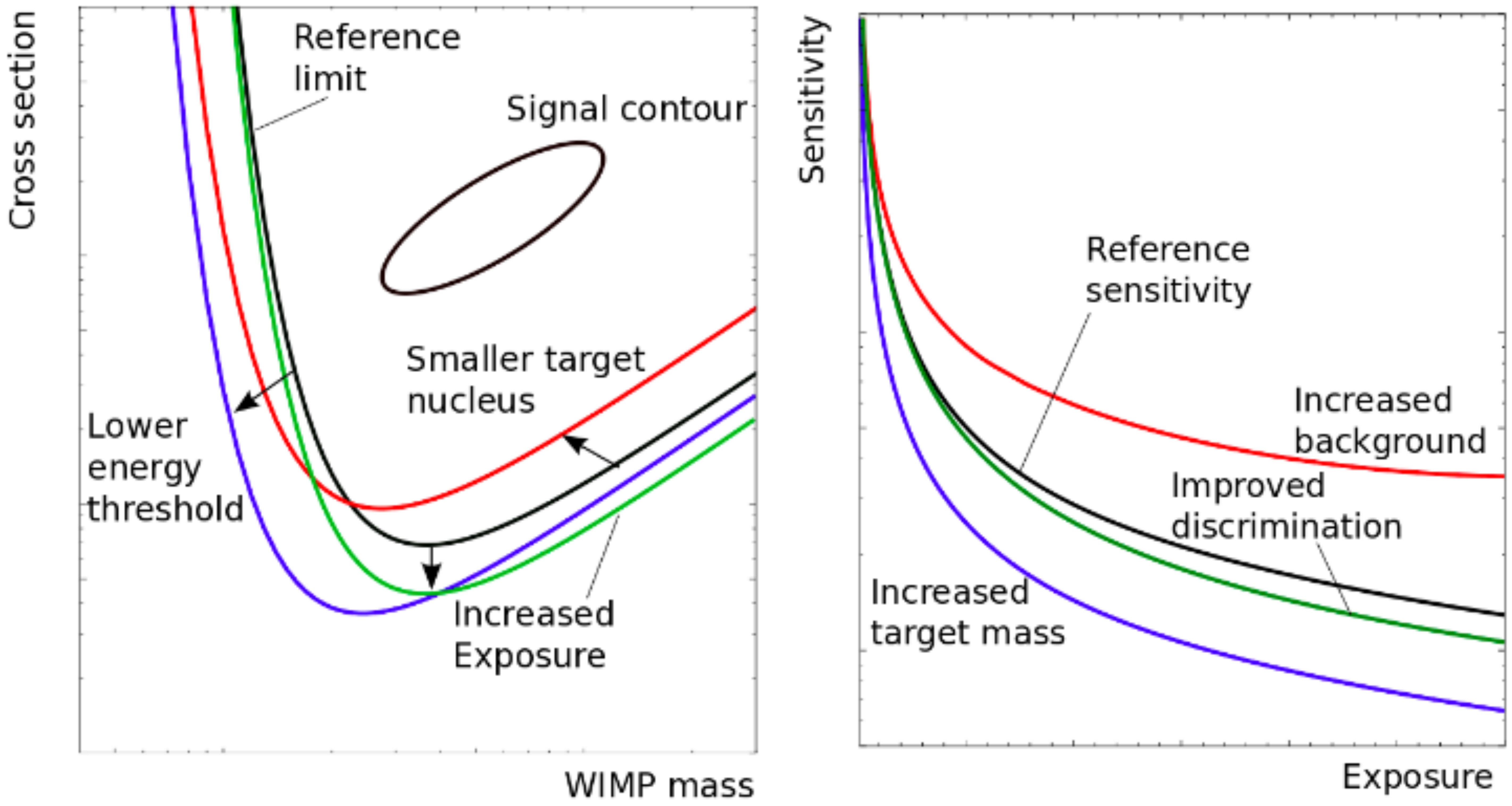


Figure 6. Left: Illustration of a result from a direct dark-matter detector derived as a cross-section with matter as function of the WIMP mass. The black line shows a limit and signal for reference, while the coloured limits illustrate the variation of an upper limit due to changes in the detector design or properties. Right: Evolution of the sensitivity versus the exposure. For more information see text.

differential recoil spectrum DM-nuclei interaction:

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{2\mu_A^2 \cdot m_\chi} \cdot \sigma_0 \cdot A^2 \cdot F^2 \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v},t)}{v} \, \mathrm{d}^3 v,$$

$$v_{min} = \sqrt{\frac{m_A \cdot E_{thr}}{2\mu_A^2}}.$$

T. M. Undagoitia, L. Rauch,
Dark matter direct-detection experiments,
arXiv:1509.08767

Differential rate

Integral over momentum transfer

Dependence on DM velocity

electronic recoil

$$\frac{dR^{ER}}{dE_e} = \boxed{\overline{\sigma}_e}\boxed{\frac{\rho_\chi}{M_\chi}\frac{1}{8\mu_{e\chi}^2}}\int \boxed{q dq}\boxed{|F_{DM}(q)|^2}\boxed{|f_{n,l}^{ion}(q, E_e)|^2}\boxed{\eta(v_{min})}$$

$$|f_{n,l}^{ion}(q, E_e)|^2 = \frac{k'^3}{4\pi^3}\sum_{n,l}|\langle\psi_{E_e}|e^{-i\sum_\alpha \mathbf{q}\cdot\mathbf{x}^\alpha}|\psi_{n,l}\rangle|^2$$

ionization form factor

Properties of the DM

Rate scales linearly with DM-electron cross section

DM Form Factor

- Choice of DM interaction mediator

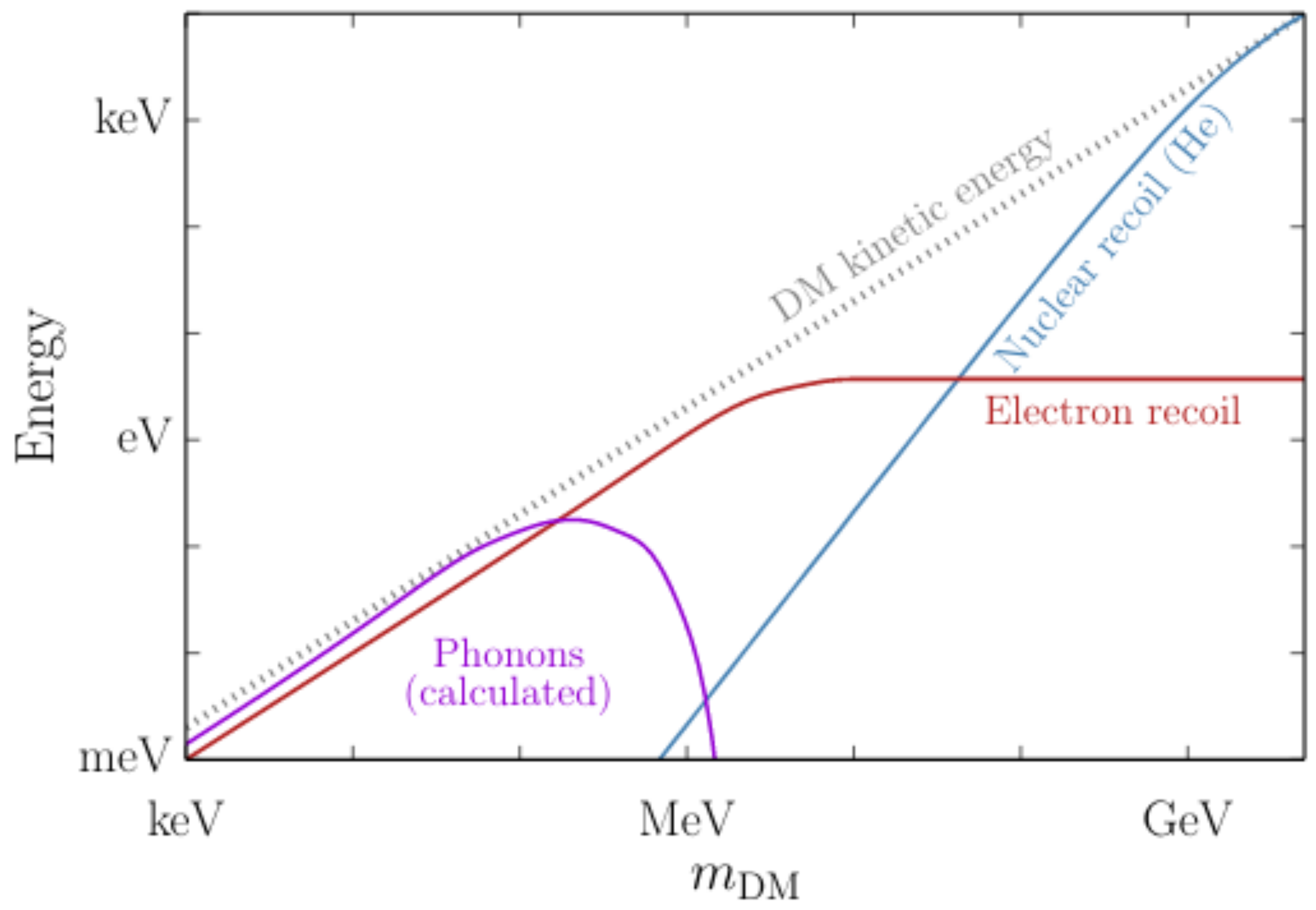
nuclear recoil

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{2\mu_A^2 \cdot m_\chi} \cdot \sigma_0 \cdot A^2 \cdot F^2 \int_{v_{min}}^{v_{esc}} \frac{f(\mathbf{v},t)}{v}\, \mathrm{d}^3 v,$$

$$v_{min} = \sqrt{\frac{m_A \cdot E_{thr}}{2\mu_A^2}}.$$

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3 v$$

Deposited energy as a function of DM mass

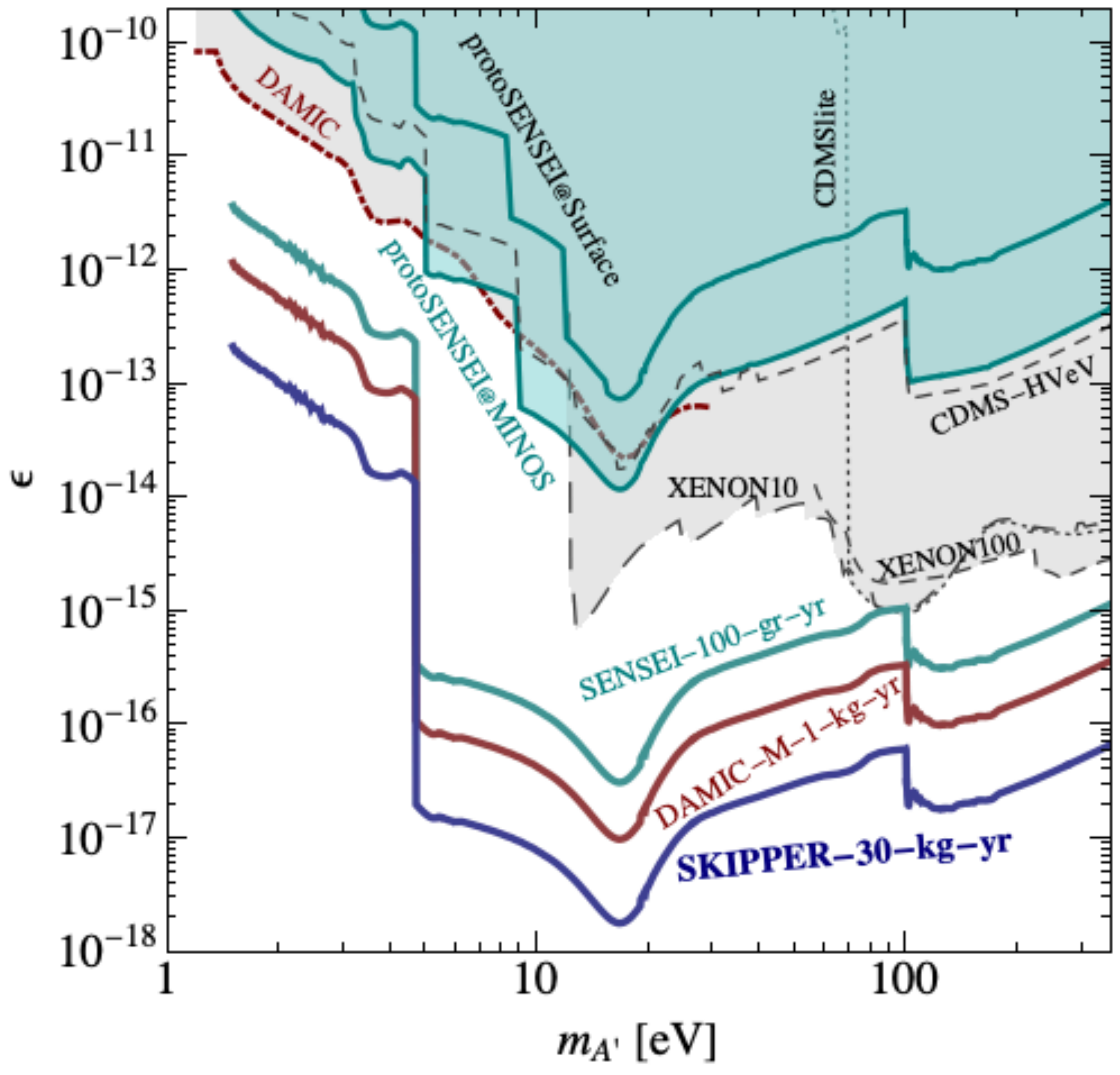


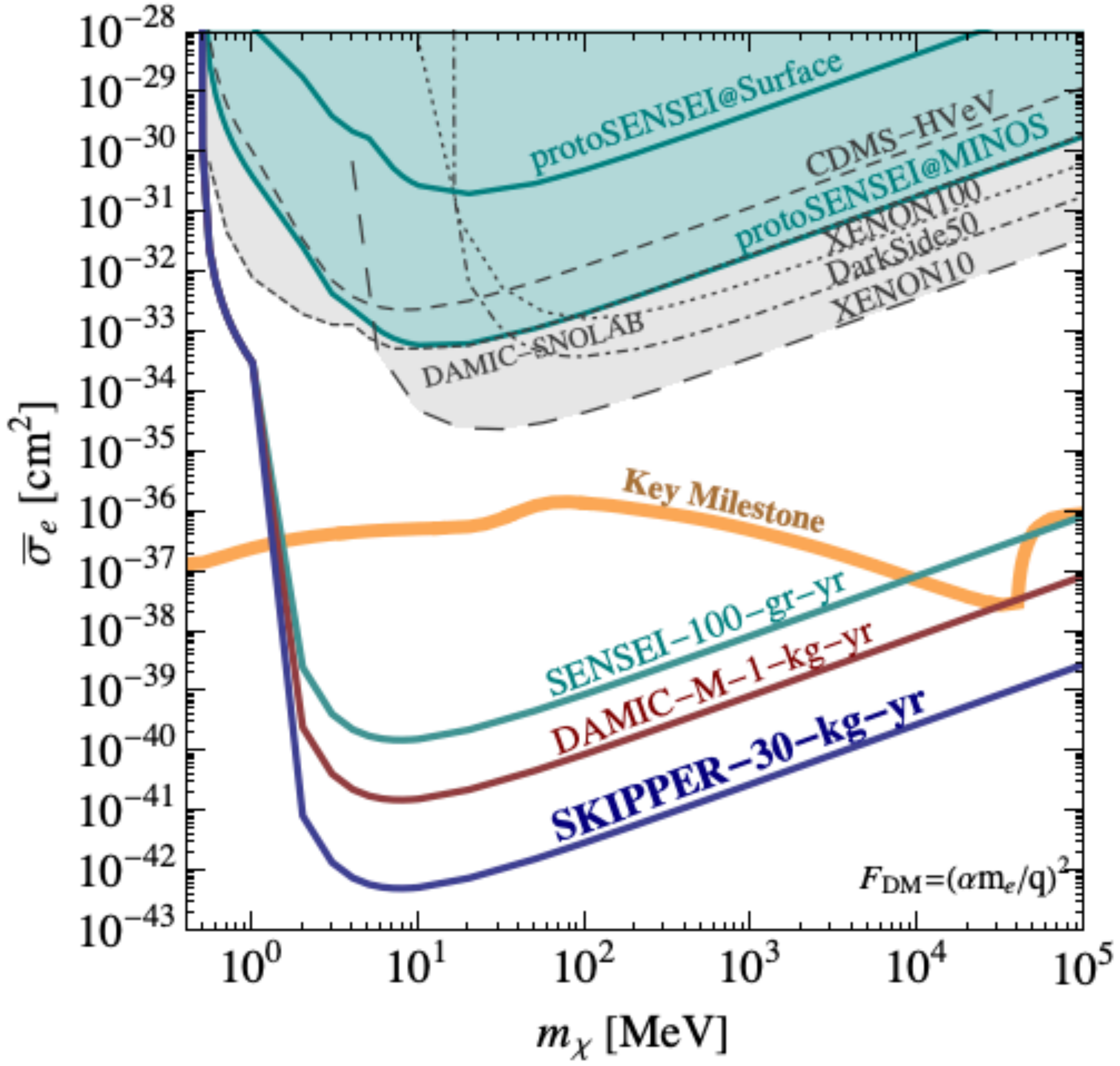
T. Lin, TASI lectures on DM models and direct detection, arXiv:1904.07915

FIG. 19. A schematic comparison of the total DM kinetic energy (dotted, gray) with the energy deposited in a regular nuclear recoil (blue, taking a helium target), the typical energy deposited in an electron recoil (red), and the typical energy in phonon excitations (purple). Note that the phonon excitation case cuts off above DM masses above an MeV only because the current theoretical calculations focus on sub-MeV DM; see Section V B for more details.

FUTURE

- For low mass Dark Matter we are planning experiments that will take this technology to its full potential 100g (SENSEI), 1kg (DAMIC-M) and 10kg CCDs (R&D recently funded by DoE),). Awesome program!
- the future is all skipper…
-

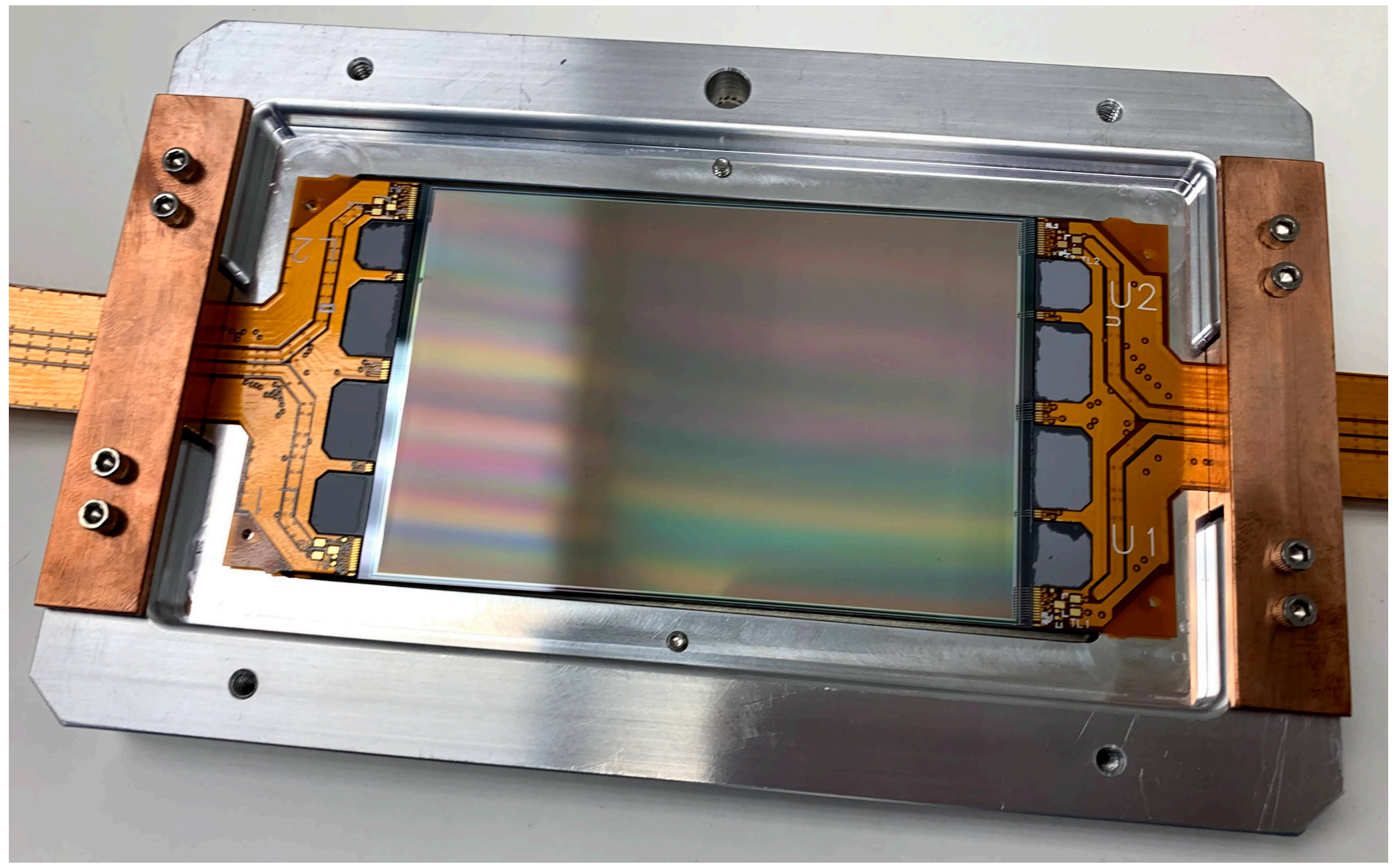




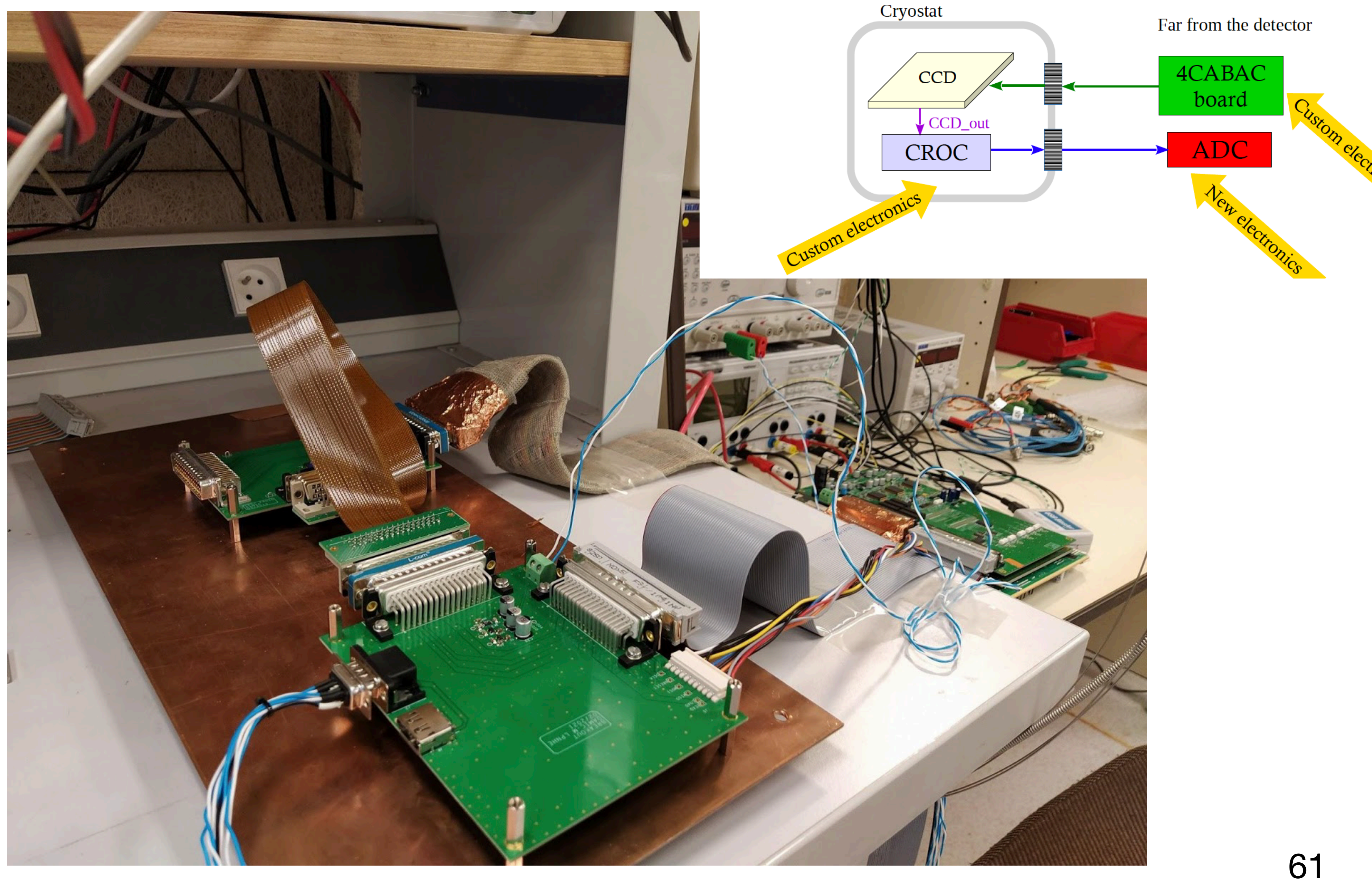
Status of the experiment

- Accomplishments:
  - Silicon ingot production with low cosmogenic exposure
  - Demonstrated single electron resolution with large format, thick skipper CCDs
  - Tested multiple format CCDs to understand performance and inform detector design
  - Developed low background CCD packaging procedures
- In progress:
  - Building analysis/simulation frameworks (IFCA responsible)
  - Development of low-background infrastructure + models
  - Testing new CCD controller electronics
  - Packaging newly produced DAMIC-M CCDs
  - Evaluating performance of DAMIC-M CCDs
  - Performing low-energy calibration measurements
  - Installation of Low Background Chamber prototype

packaging @ UW

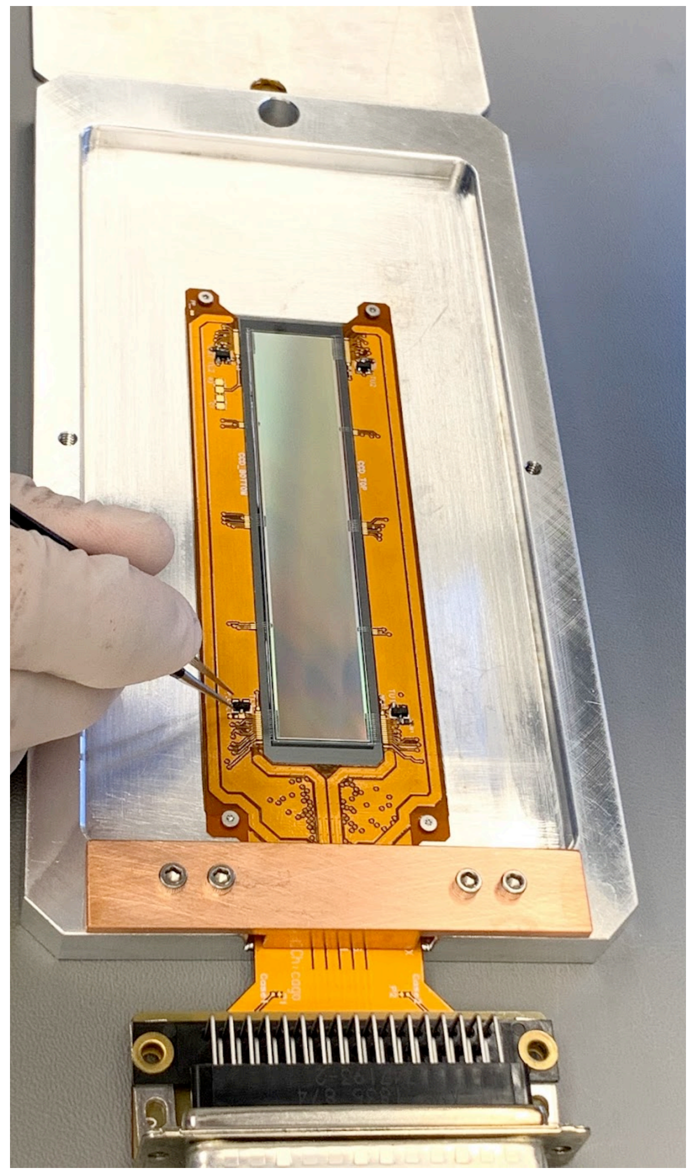


Electronics @ LPNHE

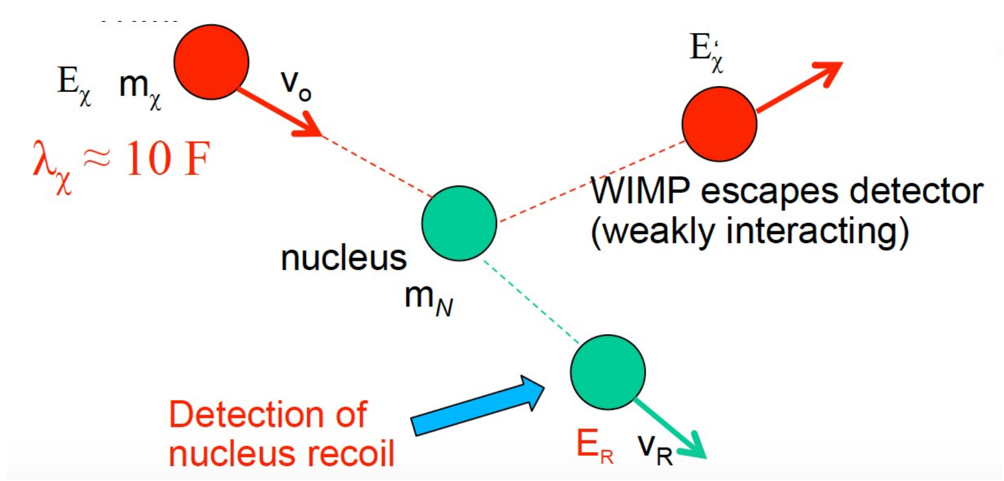


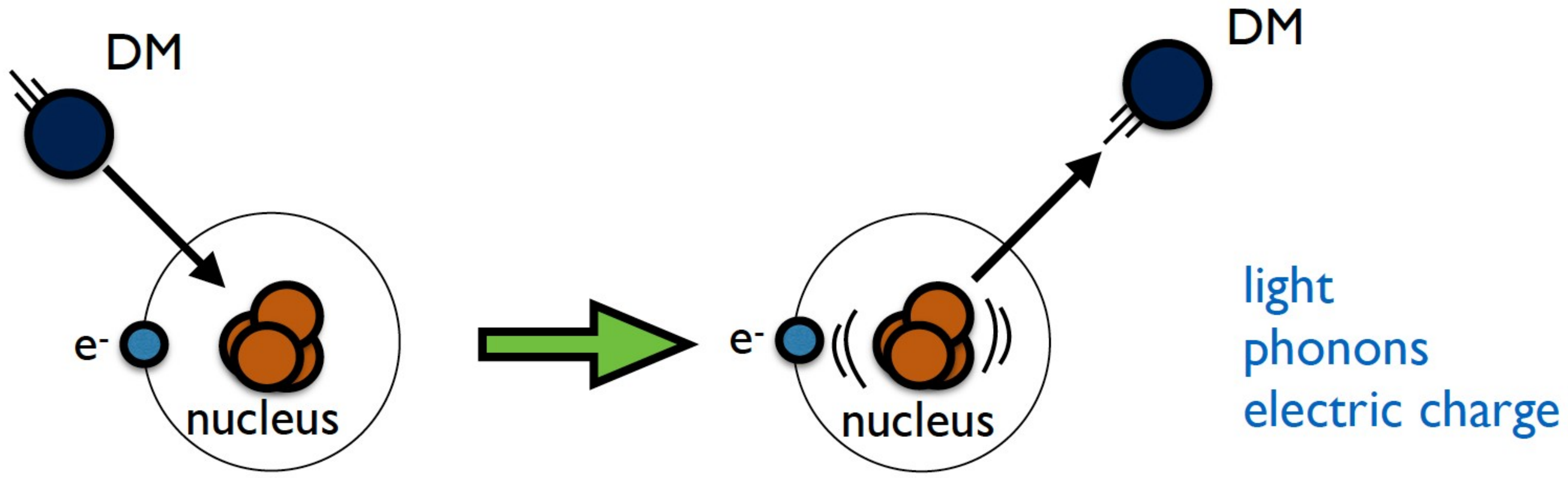
Performance testing of skipper CCDs

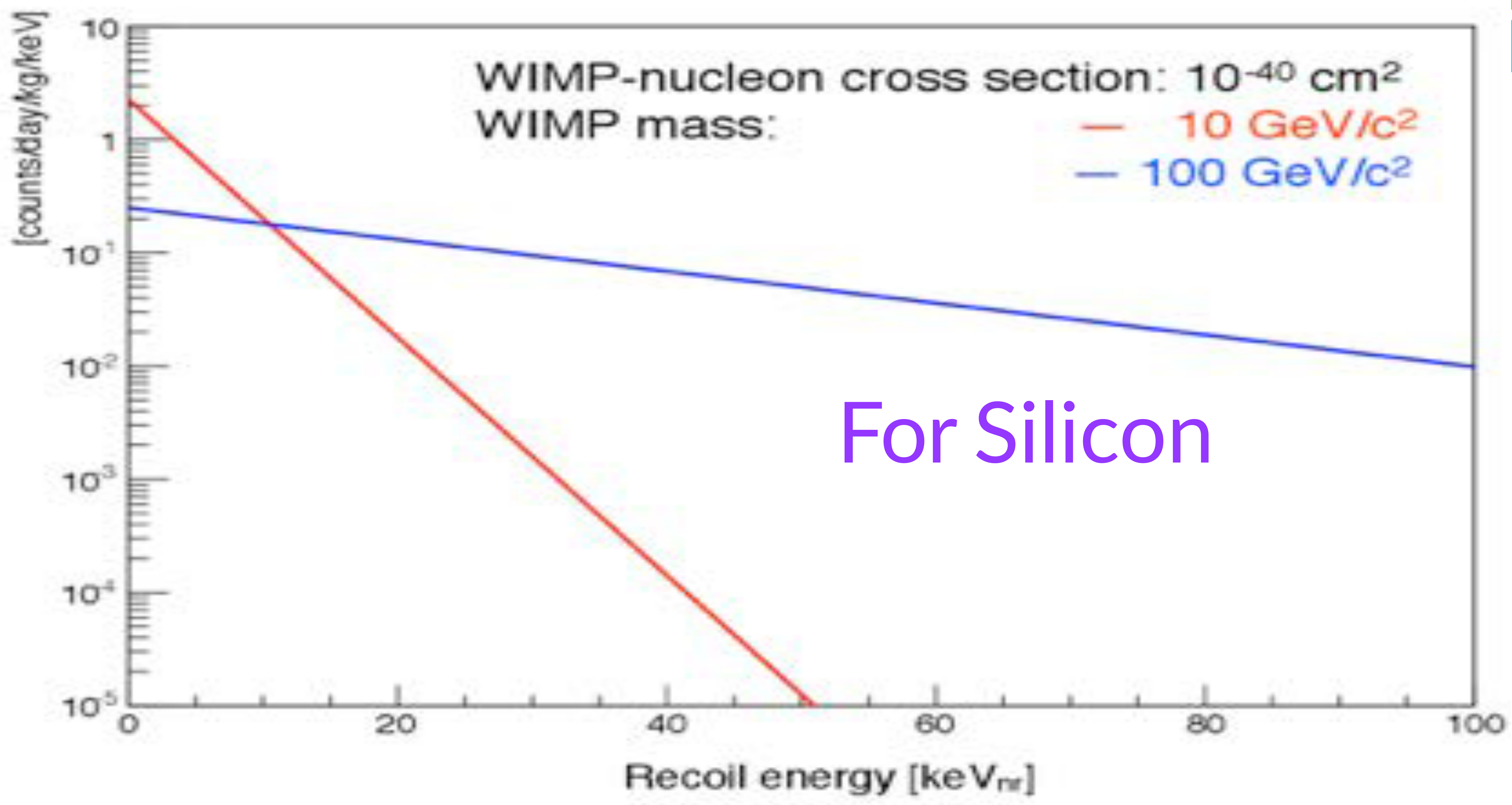
- Goals:
  - Develop flexible hardware, formal procedures, and robust software for evaluating CCDs of different formats
  - Determine variability in CCD parameters required to operate “science-grade” detectors (single e- resolution)
  - Test “pre-production” 6k x 1.5k CCDs to inform production of DAMIC-M CCDs
- Achievements:
  - Demonstrated operation of skipper CCDs with similar bias/clock parameters with reproducible performance
  - Observe single electron resolution (<0.07 e-, sub-eV) in all science-grade CCDs
  - Reproduce expected amplifier noise of 1/sqrt(N)
  - Measure low leakage current of ~0.03e-/pix/day



How to detect WIMPs



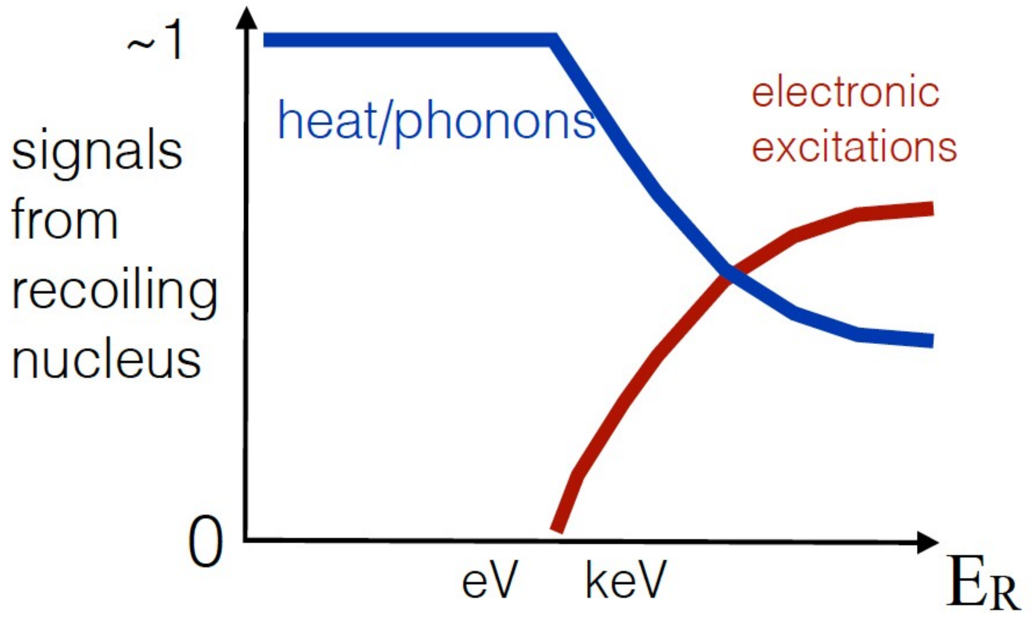


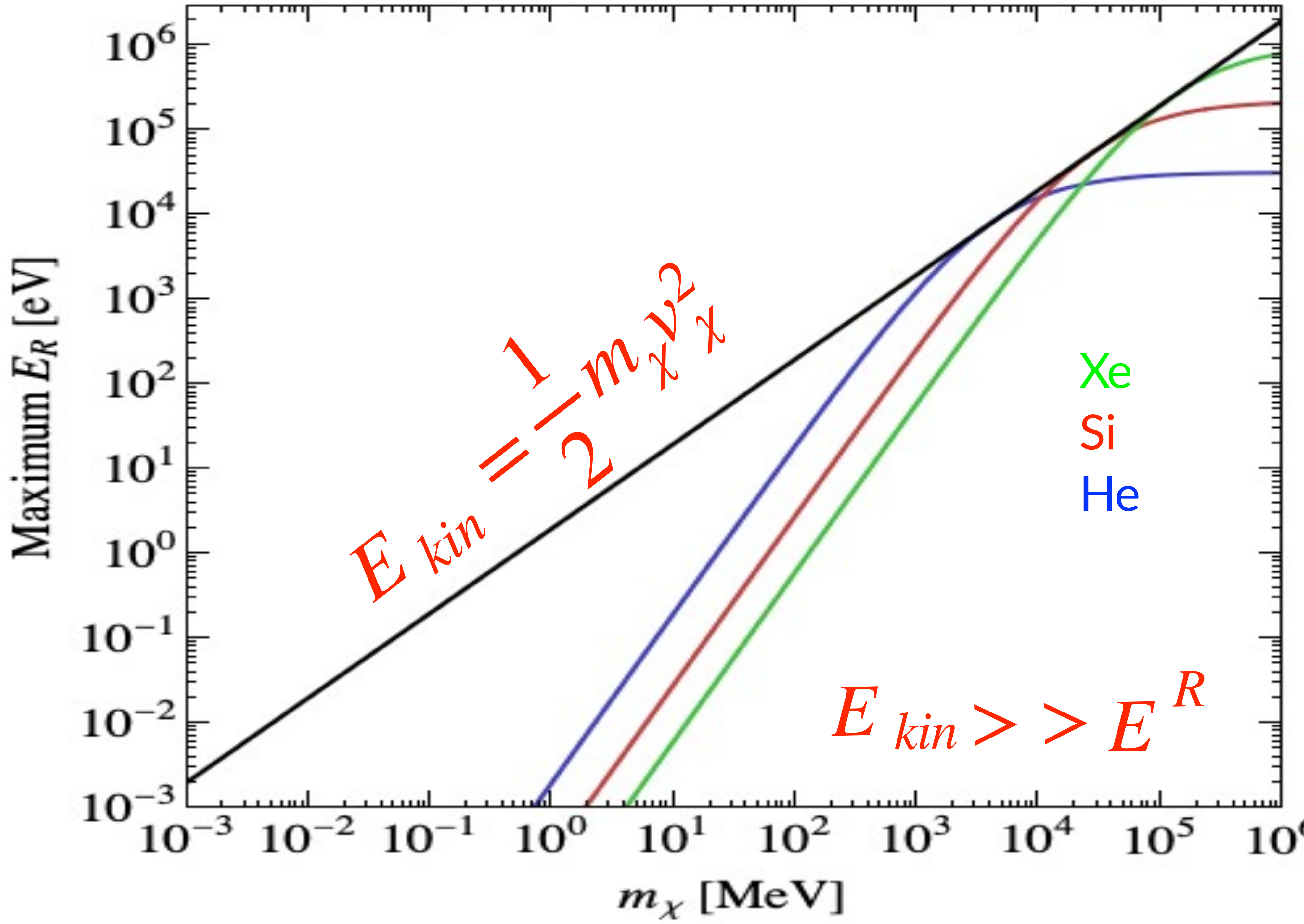


$$E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \approx \frac{2m_\chi^2 v_\chi^2}{m_N}$$

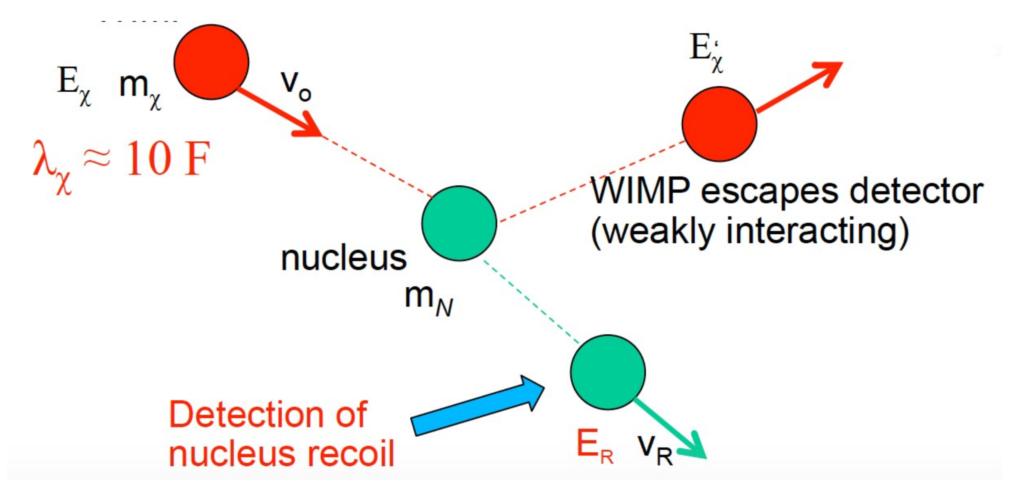
$$E^R_{det} < E^e_{det}$$

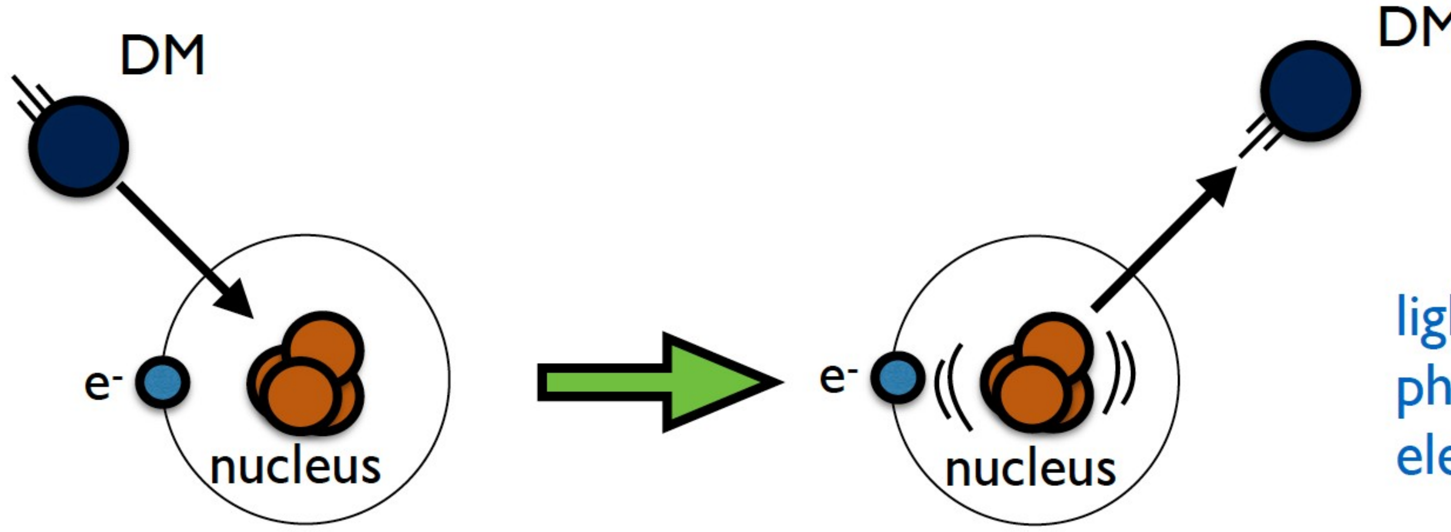
the nucleus dissipates its energy through mechanism other than ionisation -> Lindhard Theory



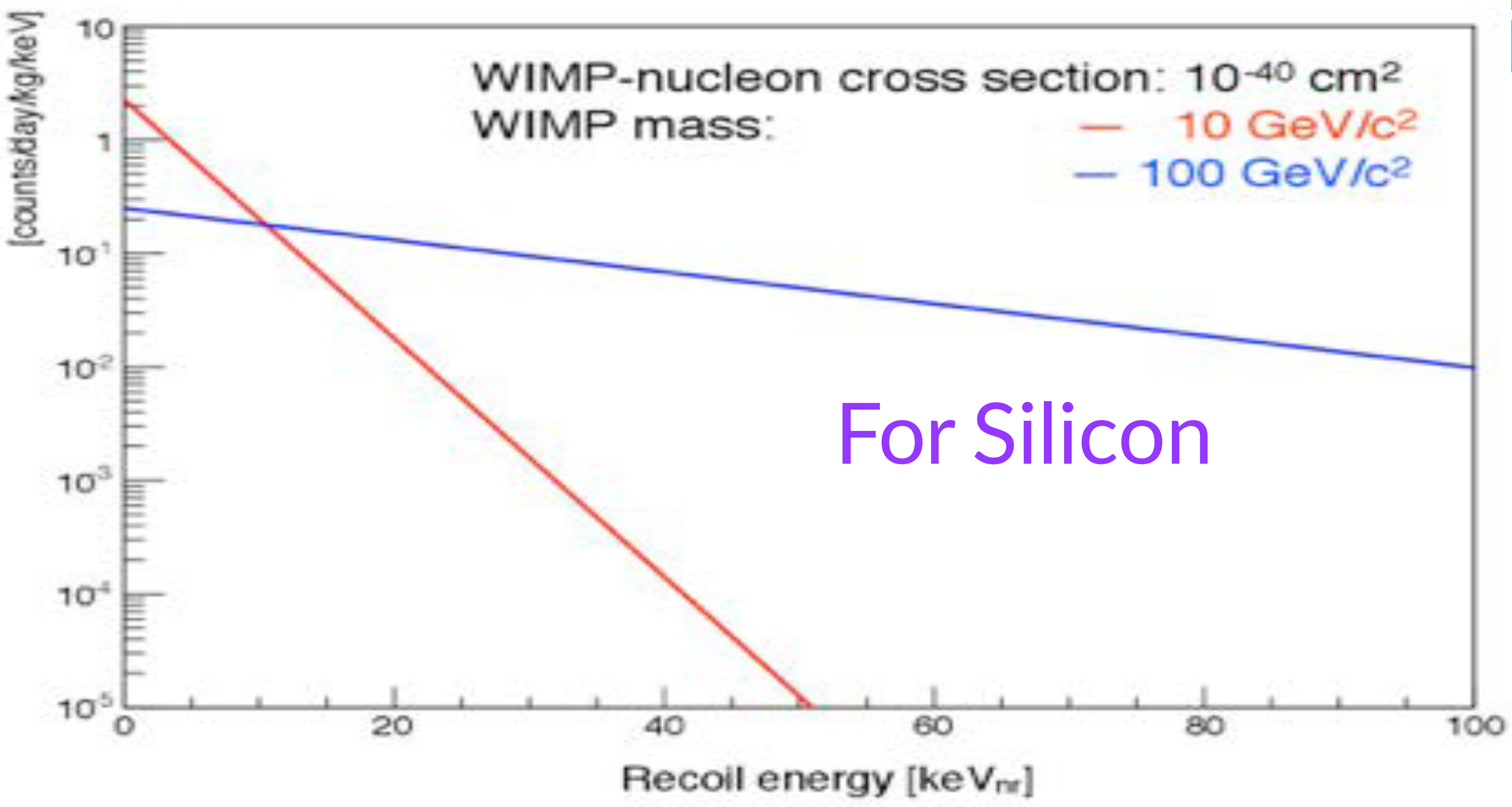


How to detect WIMPs





light
phonons
electric charge



$$E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \approx \frac{2m_\chi^2 v_\chi^2}{m_N}$$

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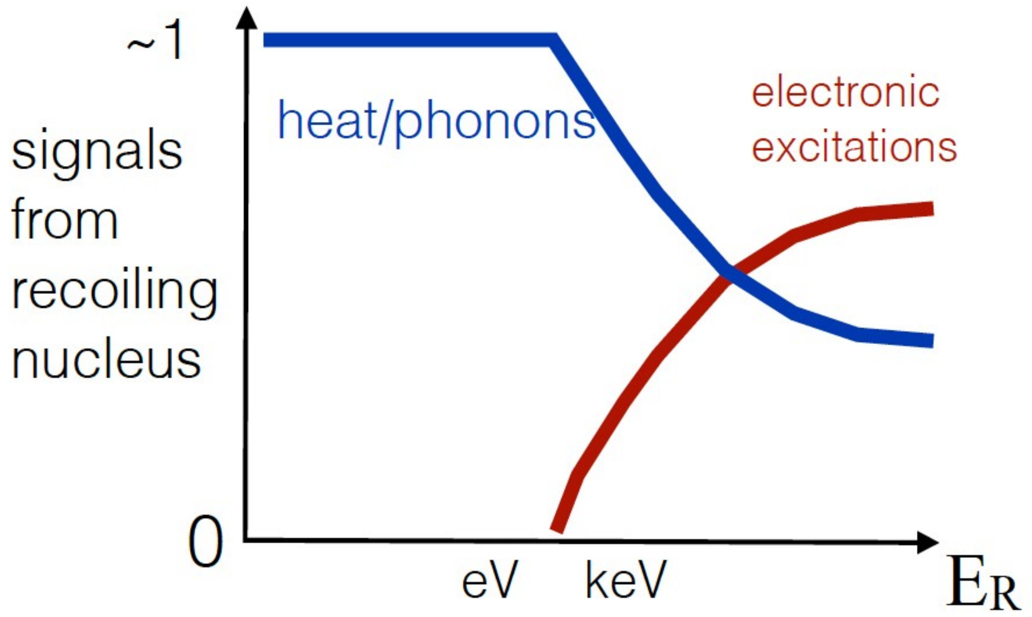
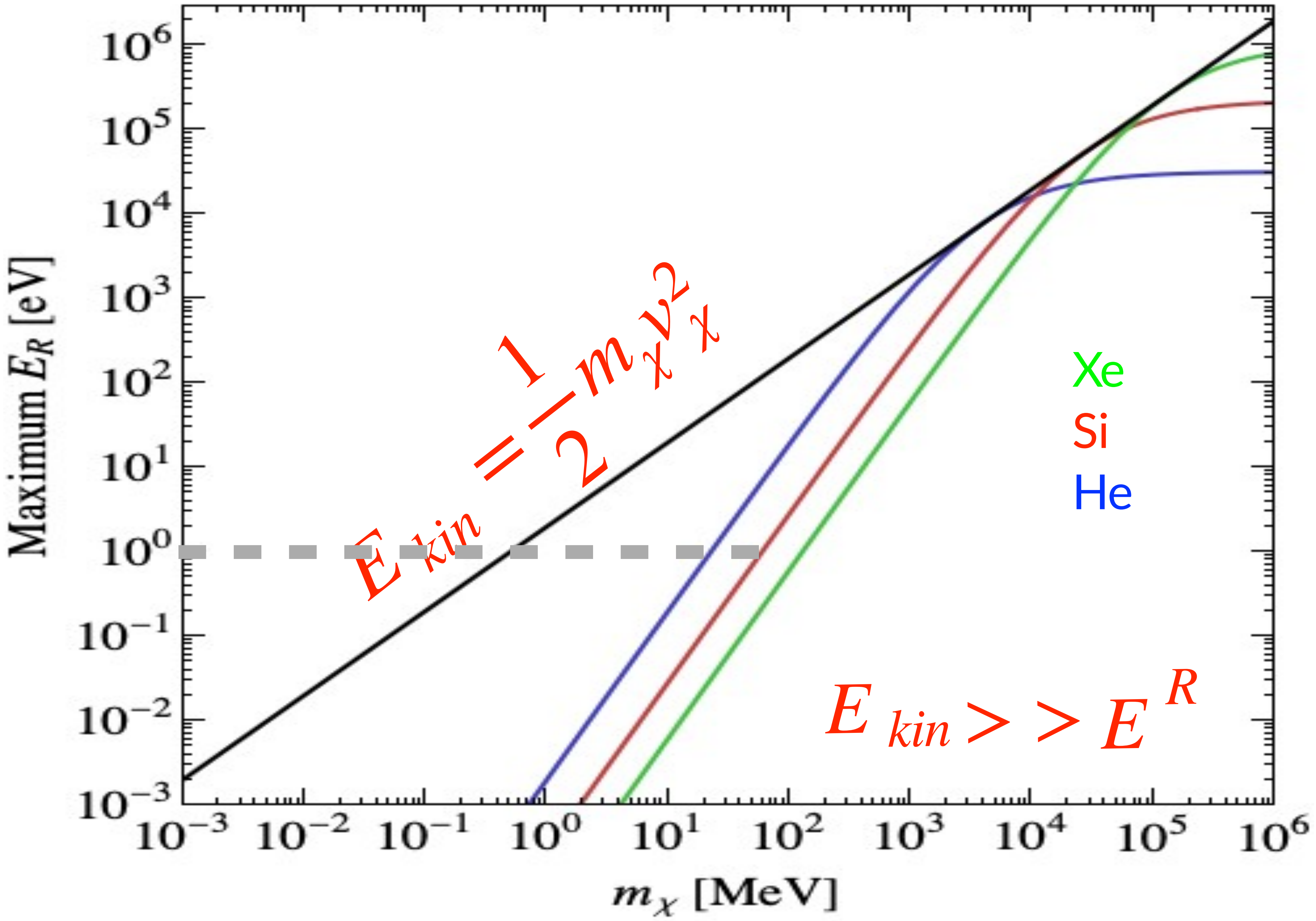
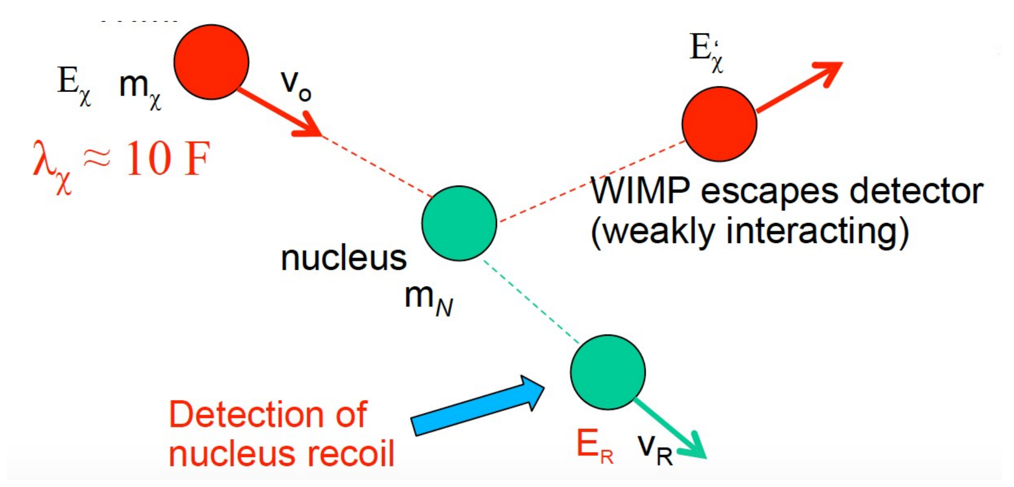
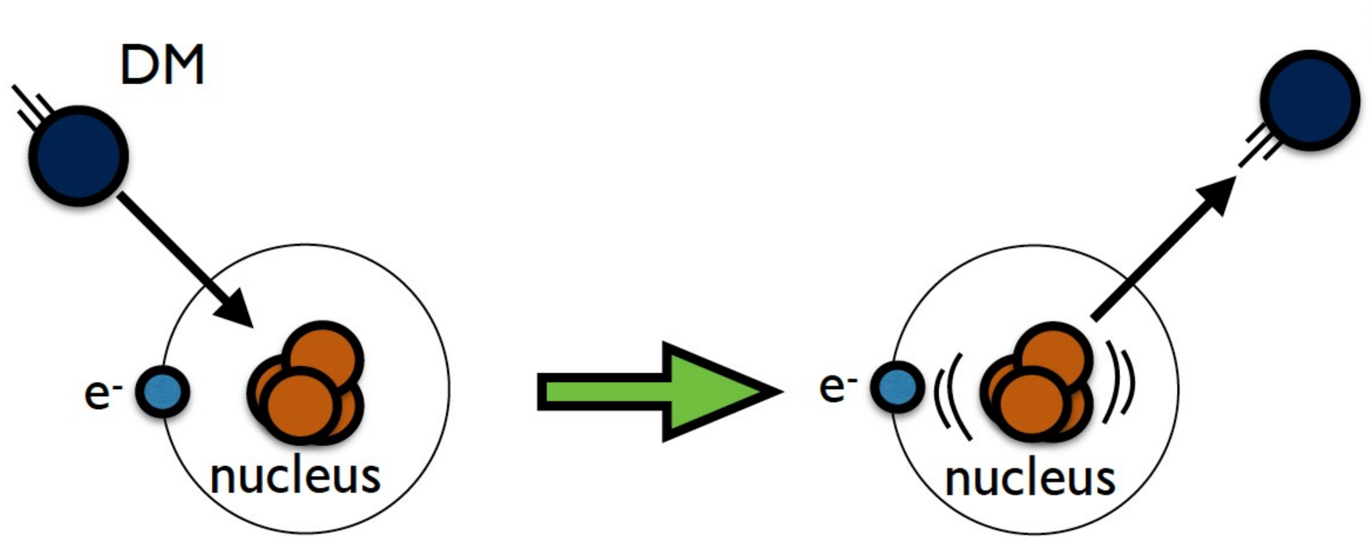




How to detect WIMPs





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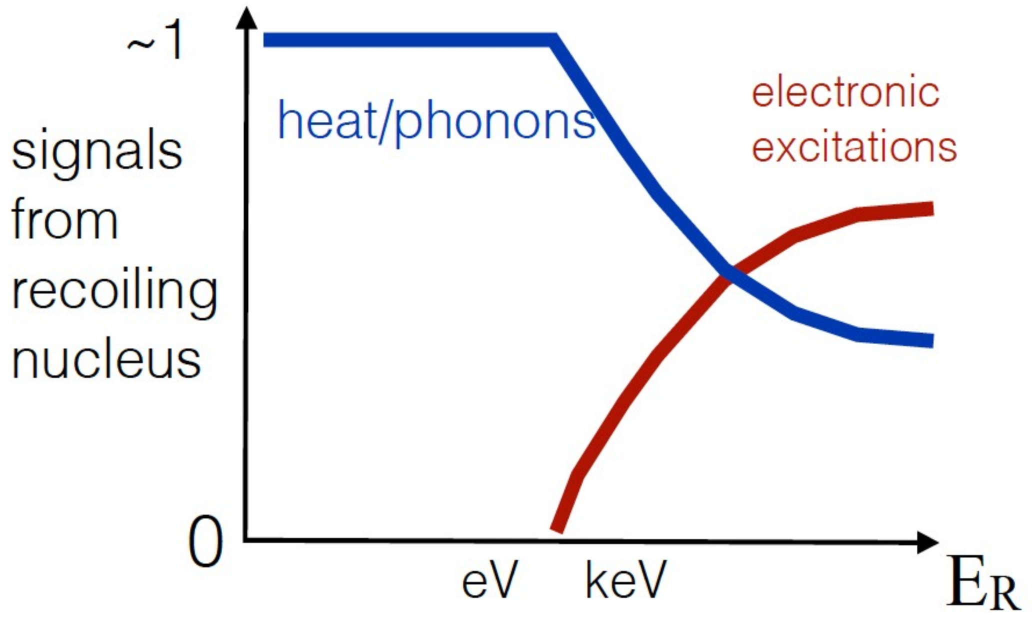
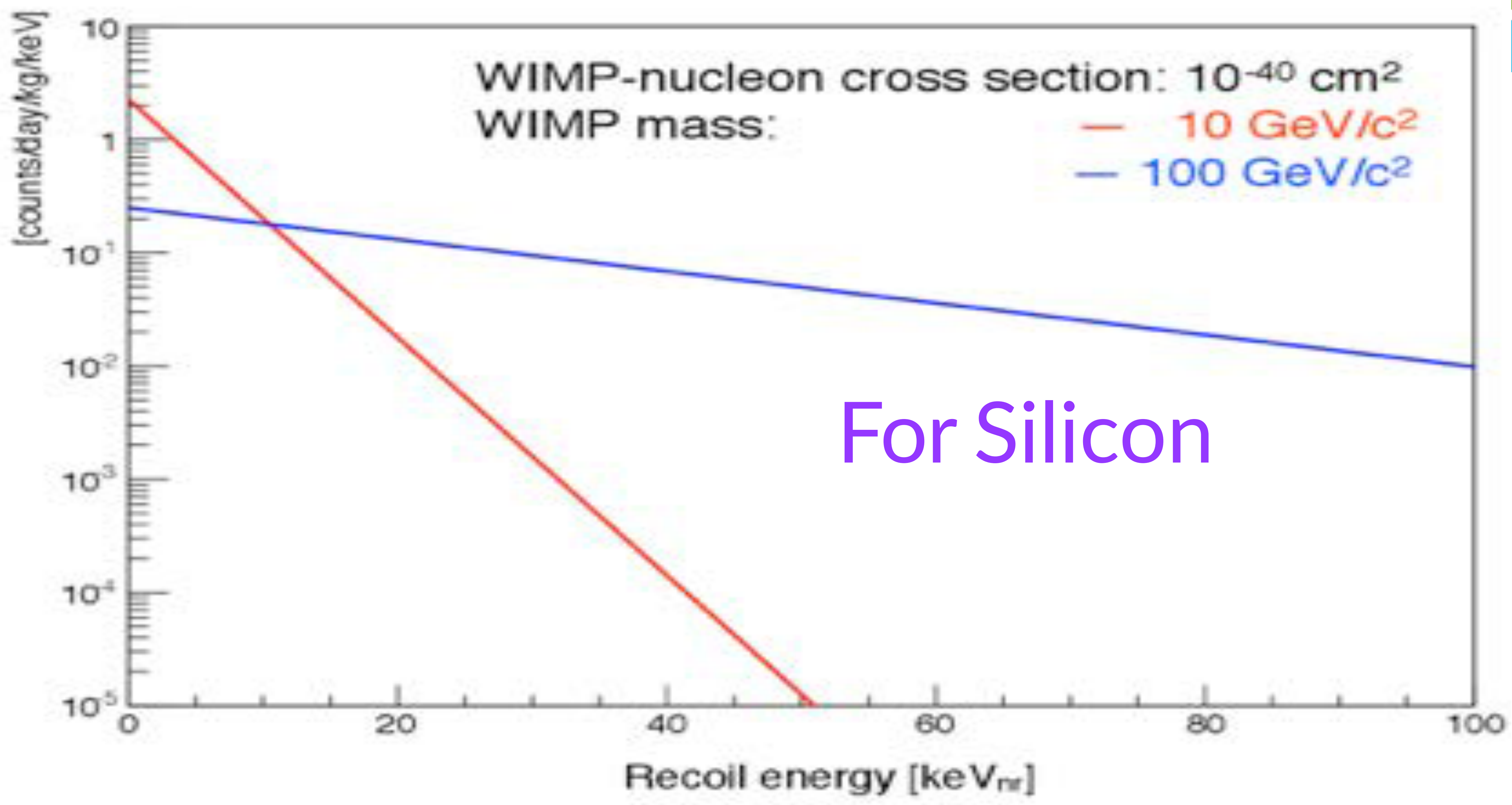
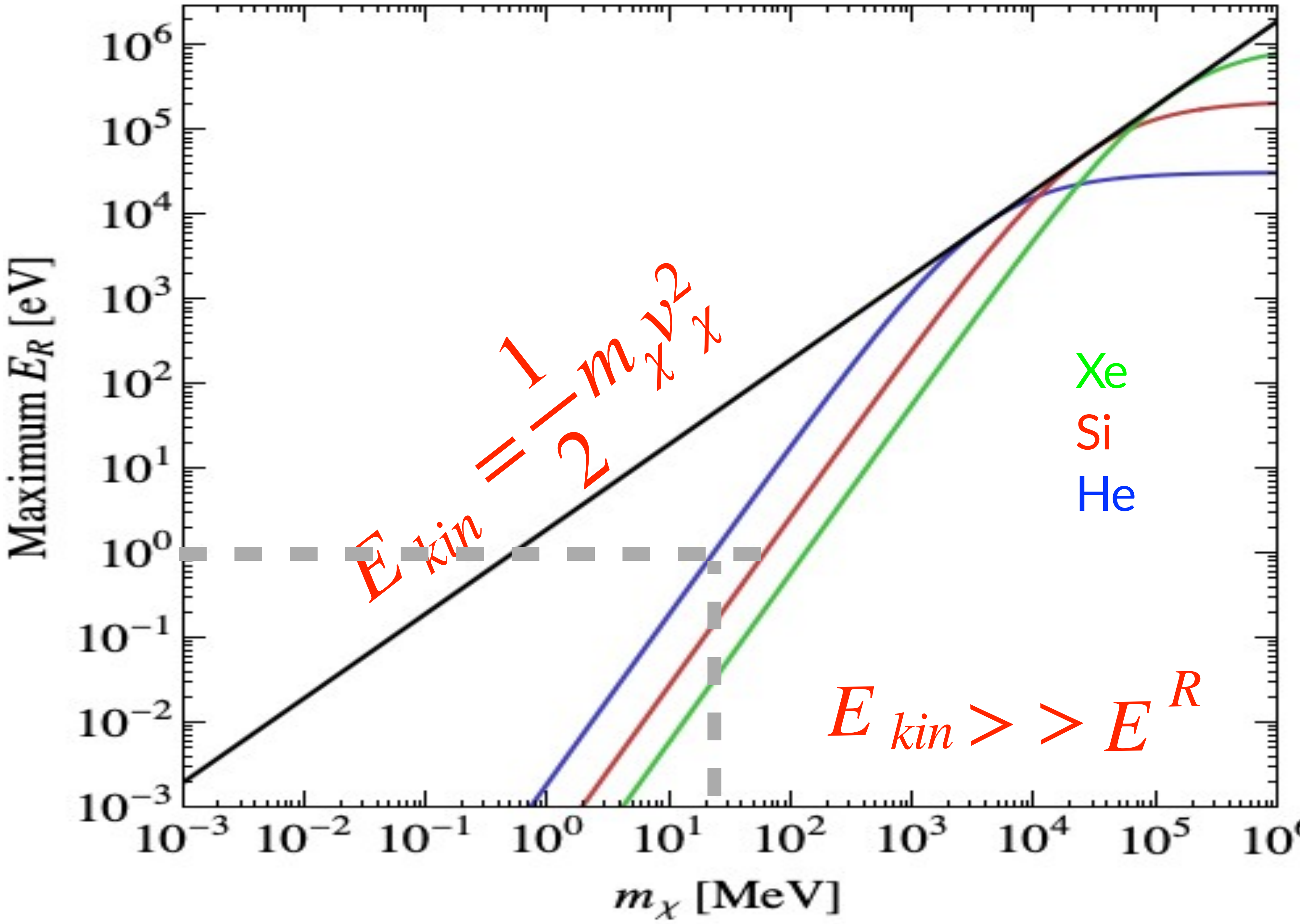
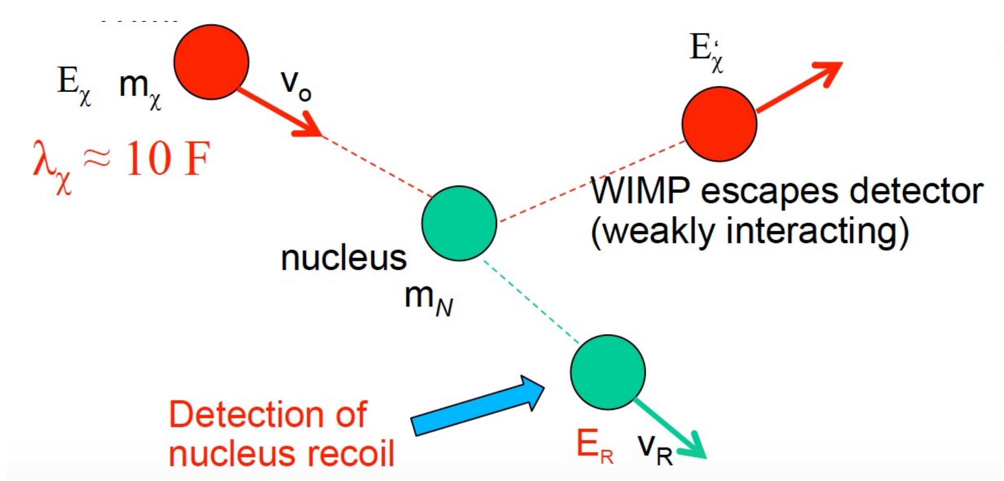
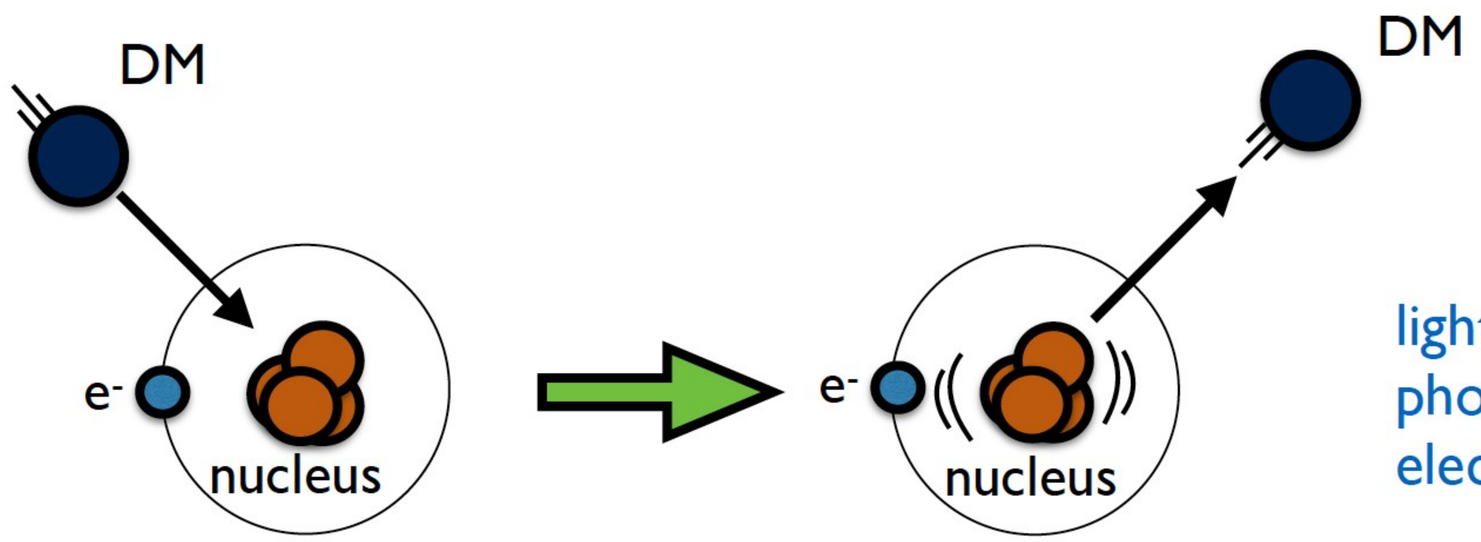






How to detect WIMPs





light
phonons
electric charge

$$E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \approx \frac{2m_\chi^2 v_\chi^2}{m_N}$$

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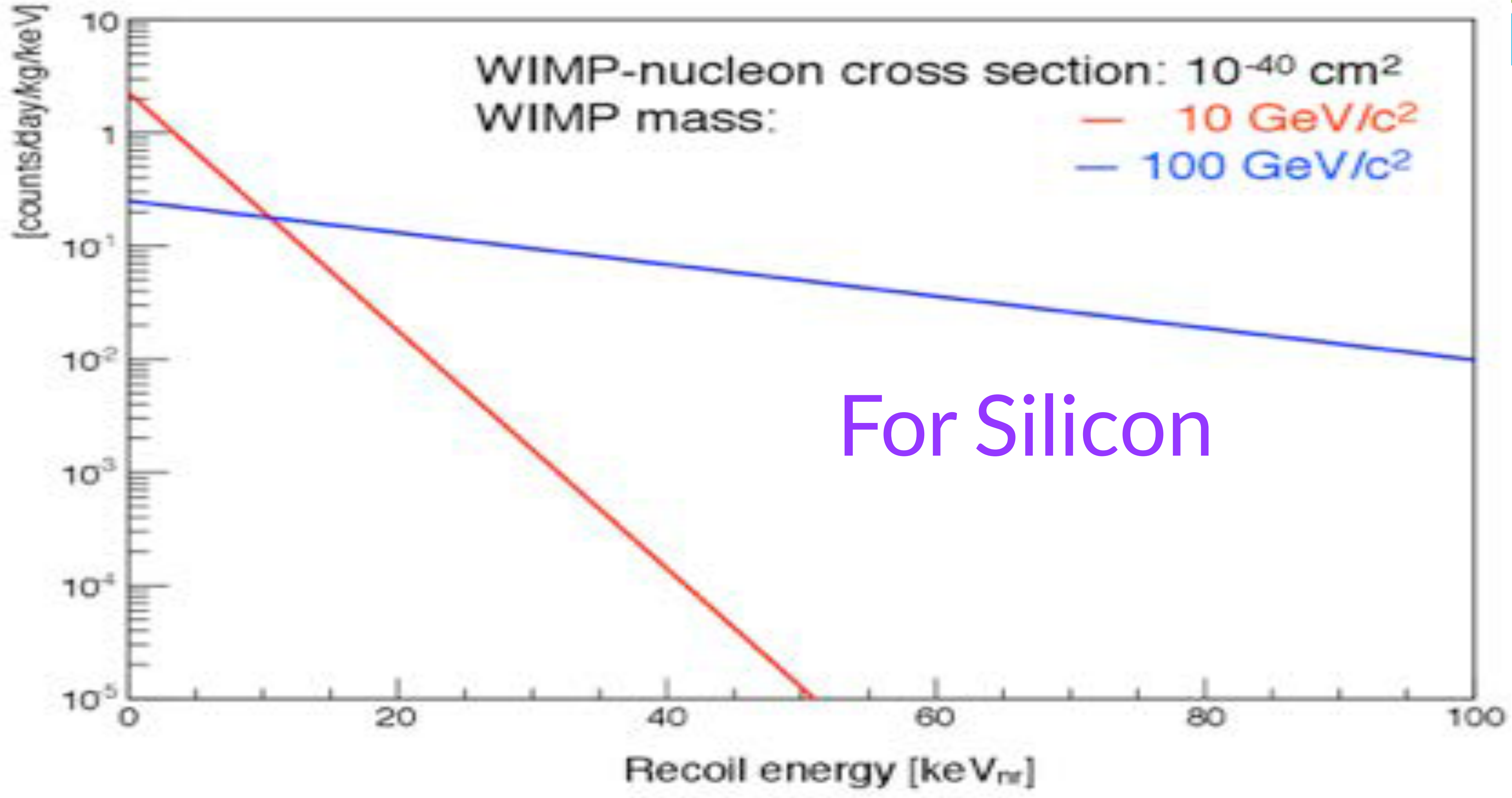
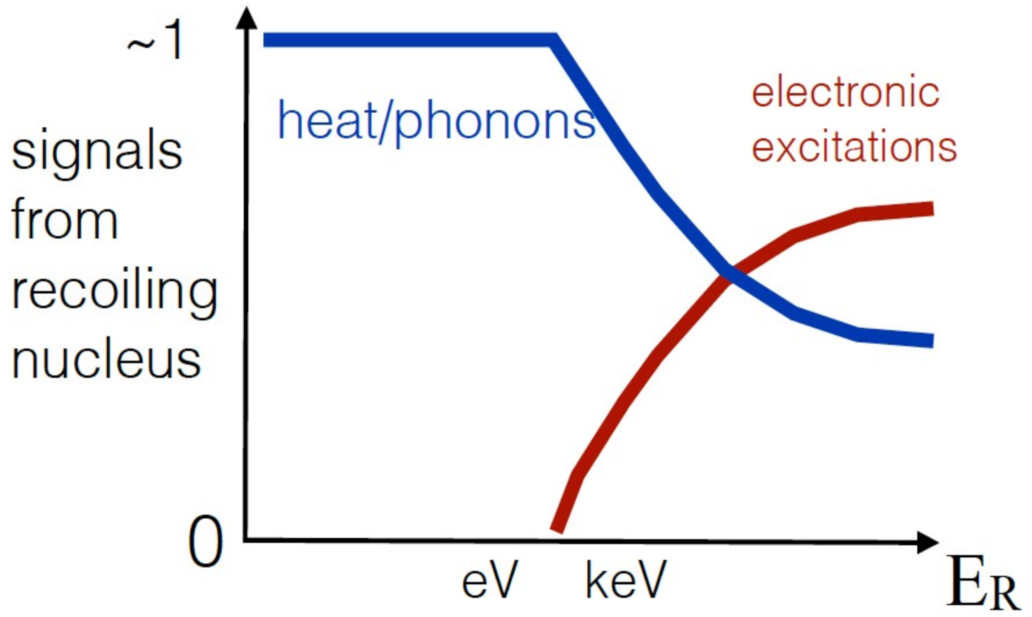
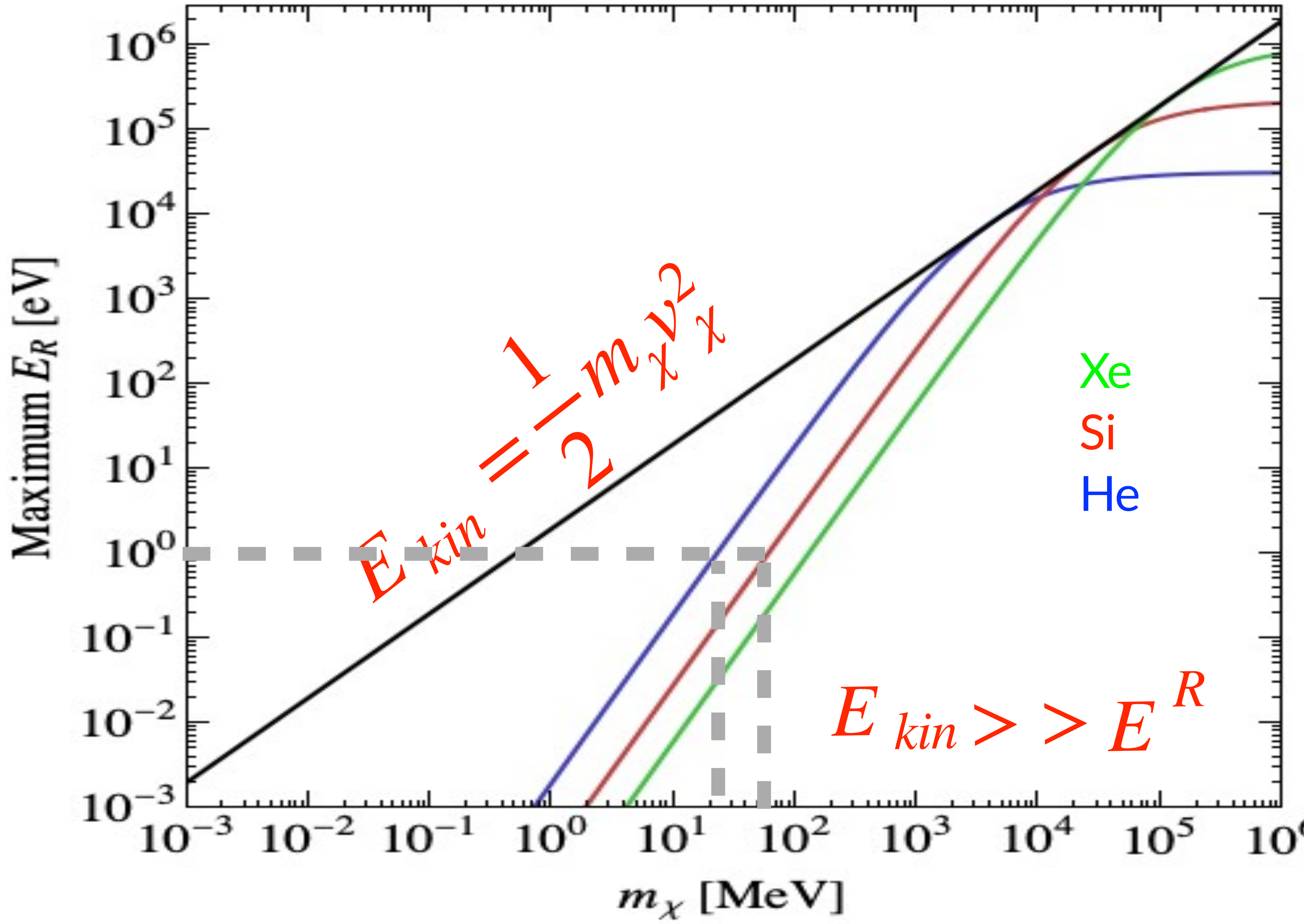
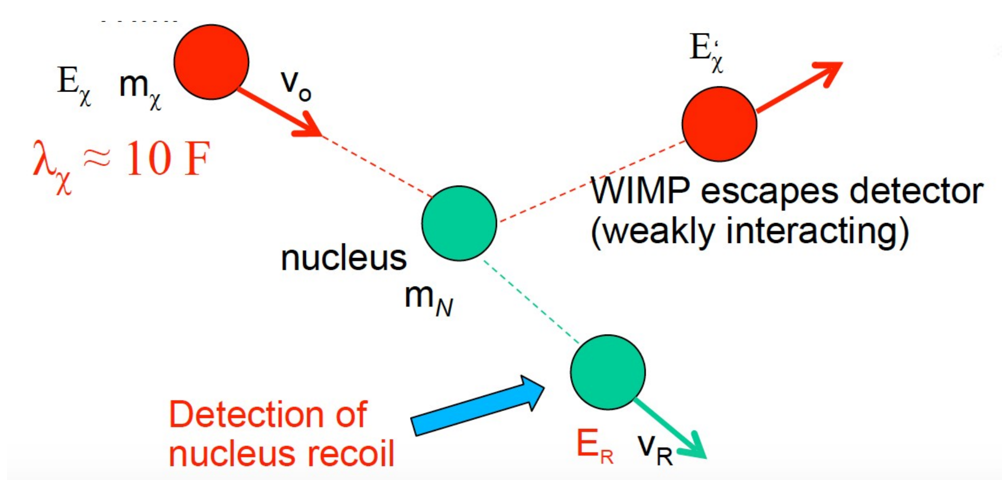
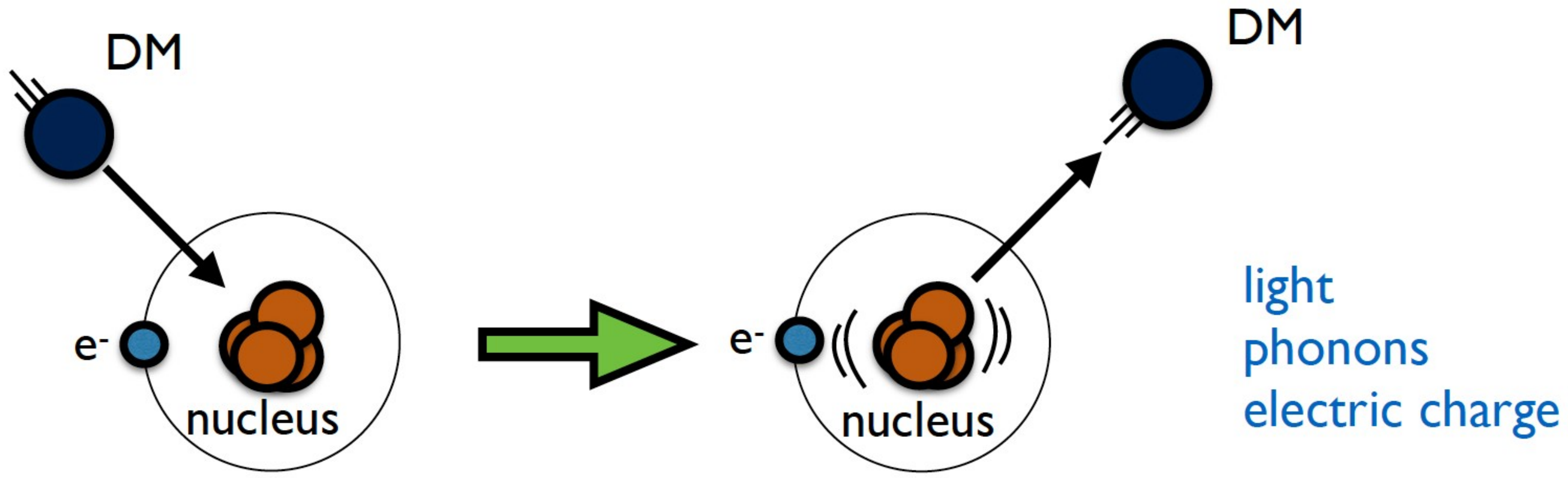


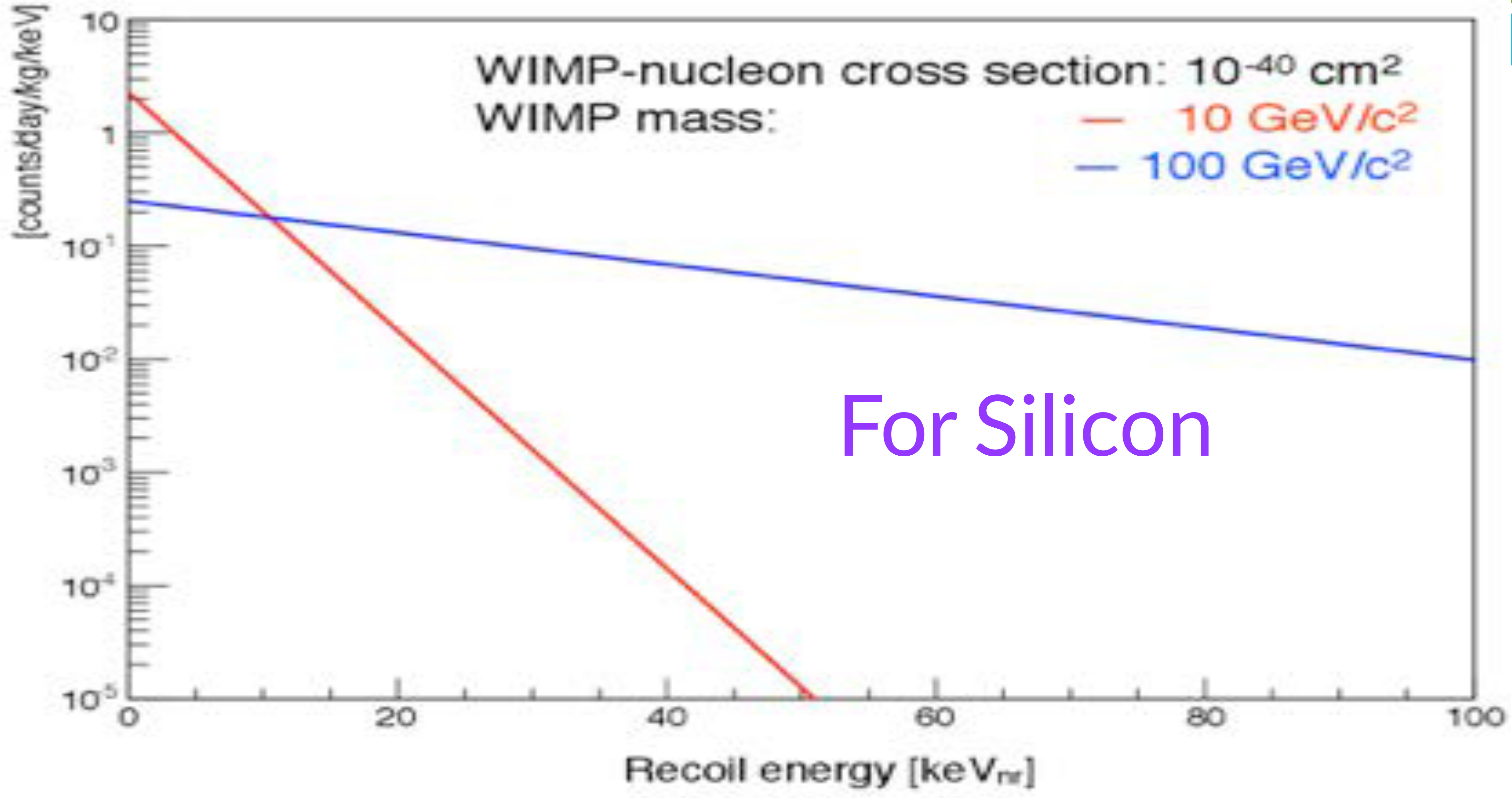




How to detect WIMPs



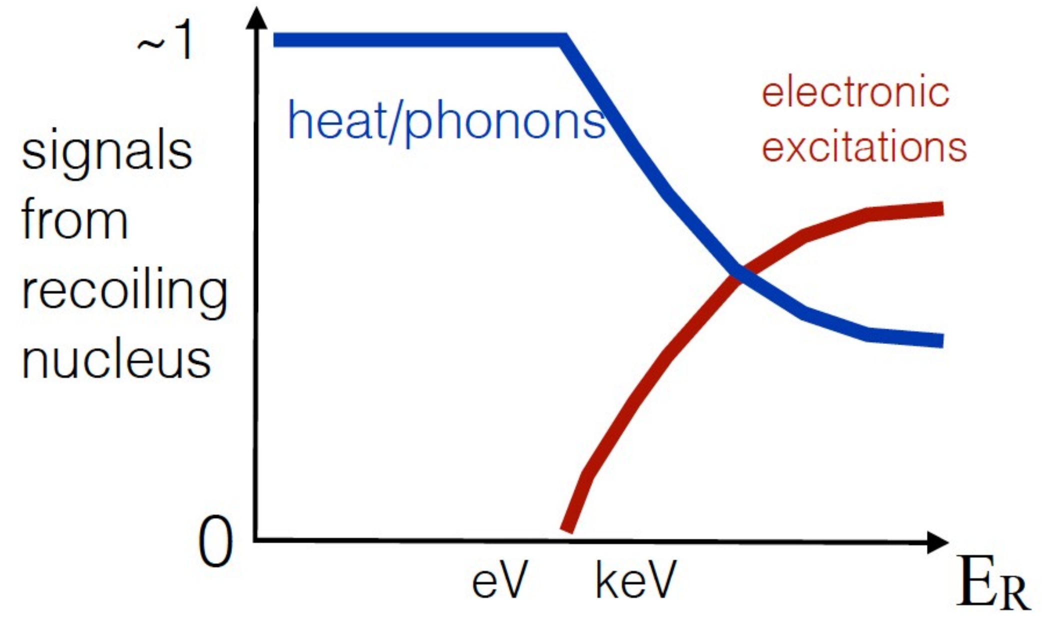


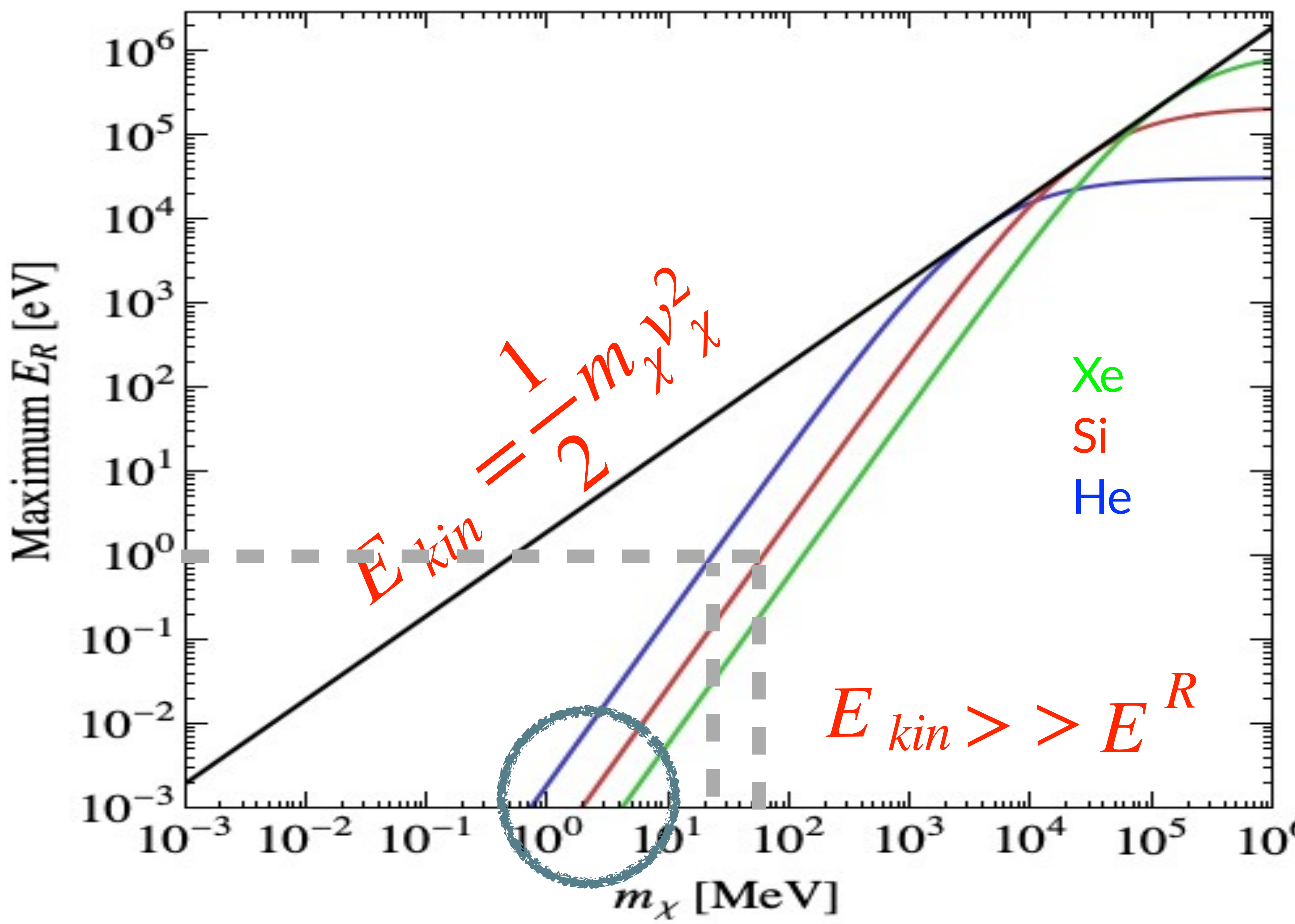


$$E_{NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \approx \frac{2m_\chi^2 v_\chi^2}{m_N}$$

$$E_{det}^R < E_{det}^e$$

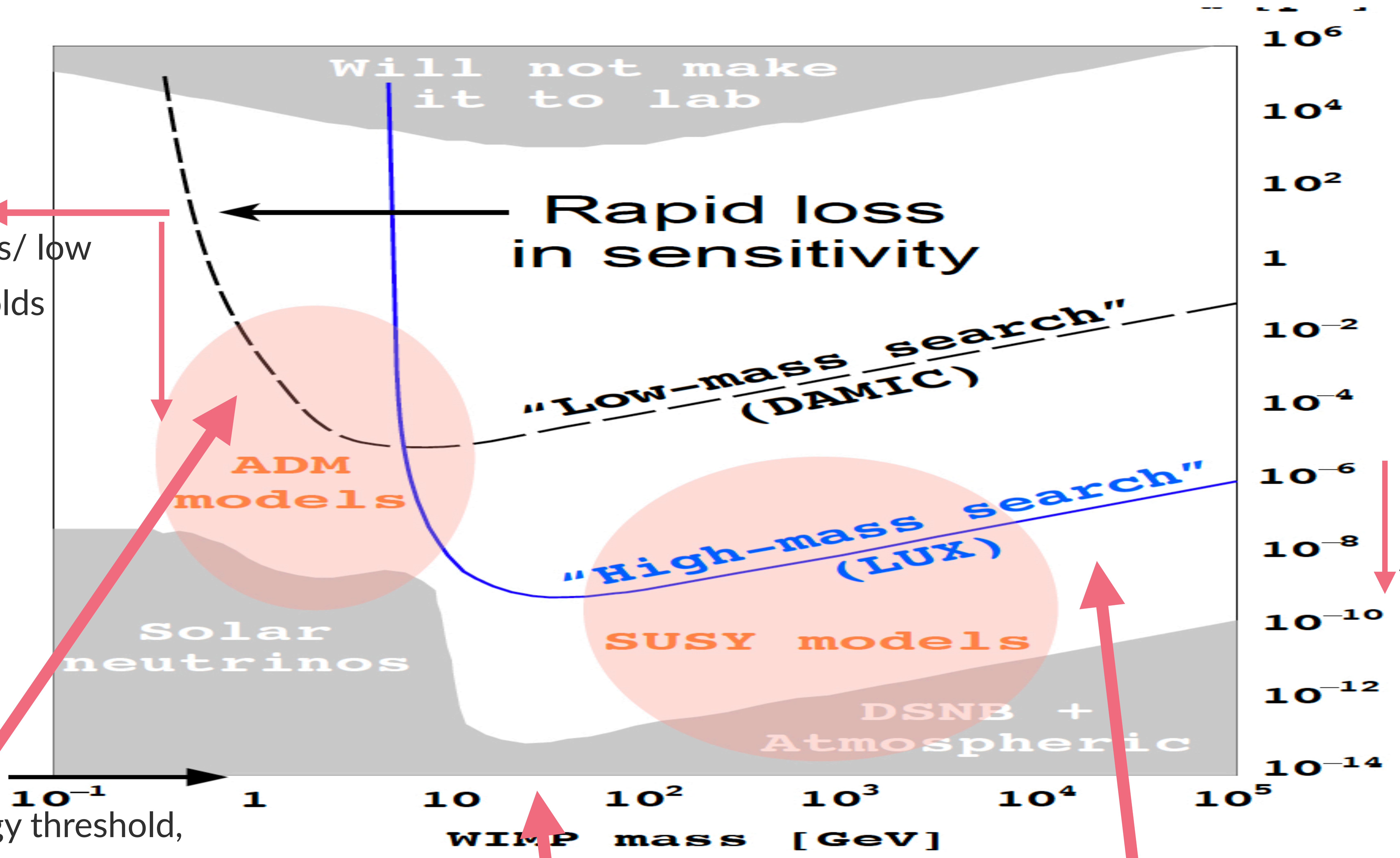
the nucleus dissipates its energy through mechanism other than ionisation -> Lindhard Theory





WIMPs Limits

WIMPs Limits



Kg mass/ low thresholds

>Tons mass/ Xenon Argon

- Detector energy threshold,
- Resolution
- quenching factor

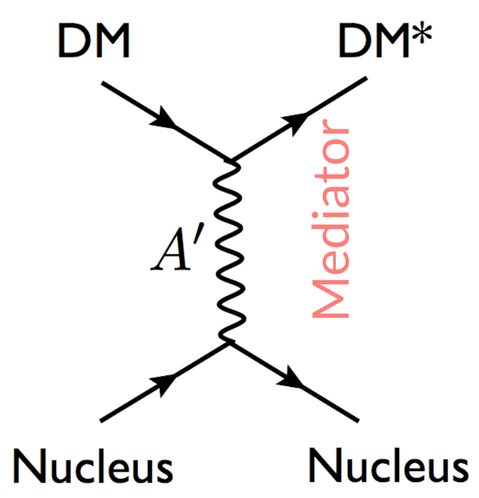
- $m_\chi = m_N$

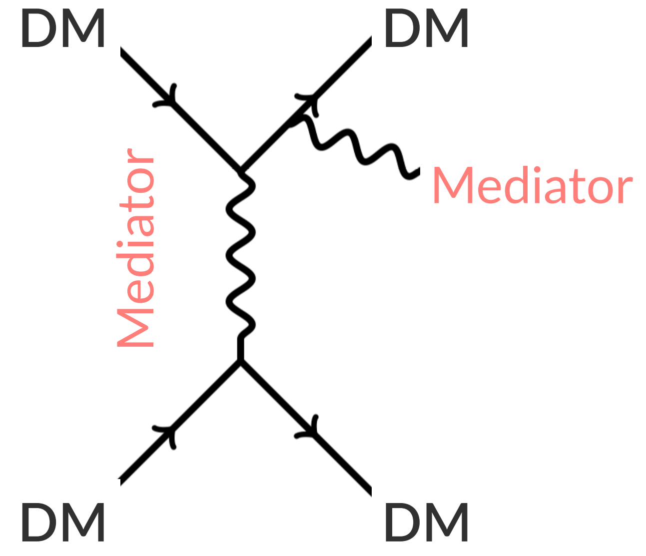
- $n \approx \rho / m_\chi \qquad E_R \approx 0.5 m_N v^2$

Beyond WIMPs

Well-motivated models & DM production scenarios make sharp, testable predictions for astrophysical & terrestrial observables → new ideas and experiments now allow us to explore much of it in coming decade

Beyond WIMPs

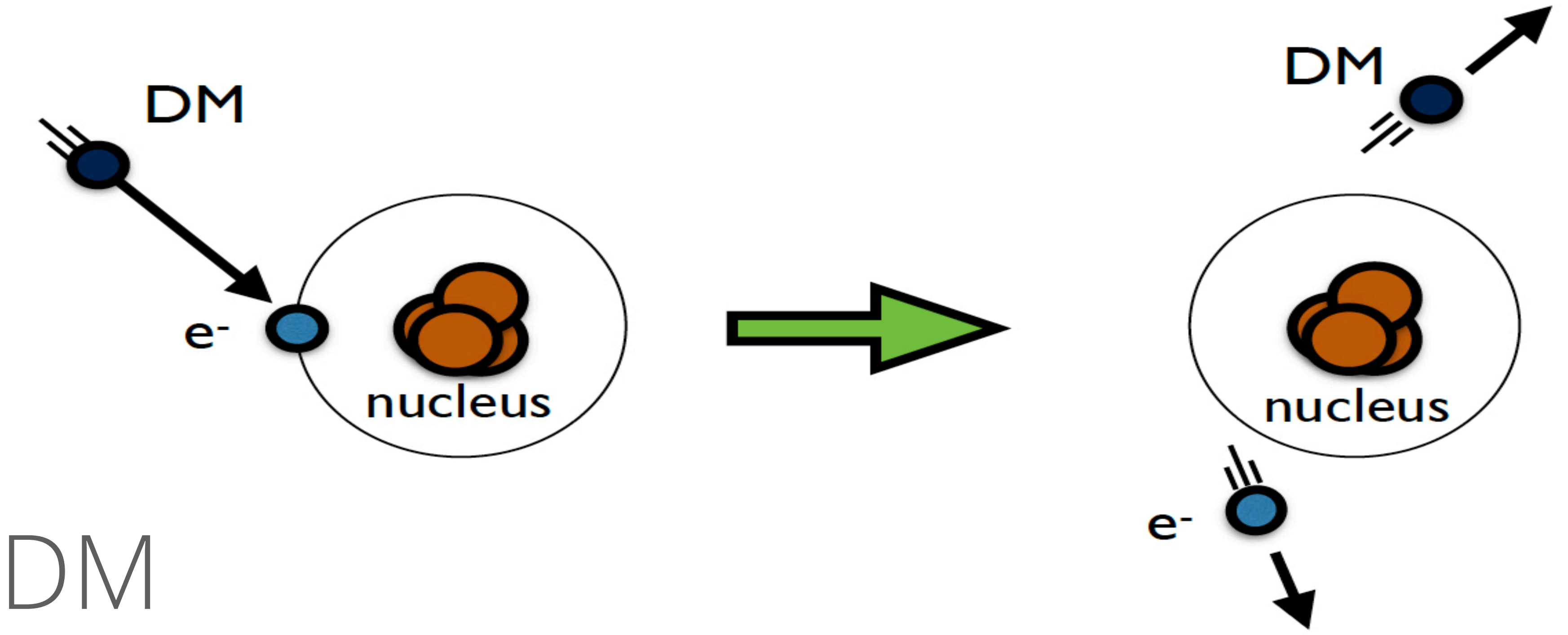


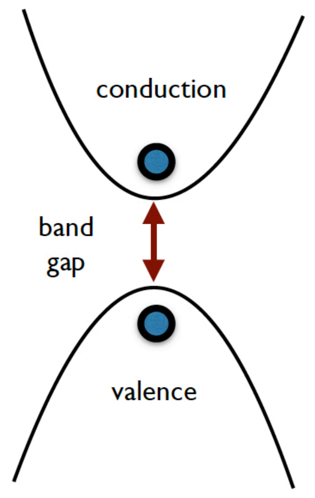


Well-motivated models & DM production scenarios make sharp, testable predictions for astrophysical & terrestrial observables → new ideas and experiments now allow us to explore much of it in coming decade

Inelastic scattering: electron scattering or absorption

- Typically signals of few electrons
- Allows transfer of O(1) amount DM kinetic energy
- The momentum transfers is set by the e- not DM





$$E_{DM} \sim \frac{1}{2} m_\chi v_\chi^2 > \Delta E$$

- if, $v_\chi \lesssim 800 km/s \rightarrow m_\chi \gtrsim 300 keV(\frac{\Delta E}{1eV})$

Typical momentum transfer

$$q_{typ} \simeq \mu_{\chi e} v_{rel} \approx m_e v_e \simeq Z_{eff} \alpha m_e \simeq Z_{eff} \times 4keV$$

For outer shell electron

transfer energy : $\Delta E \sim \vec{q}\,\vec{v}_{DM} \rightarrow \Delta E \sim 4ev$

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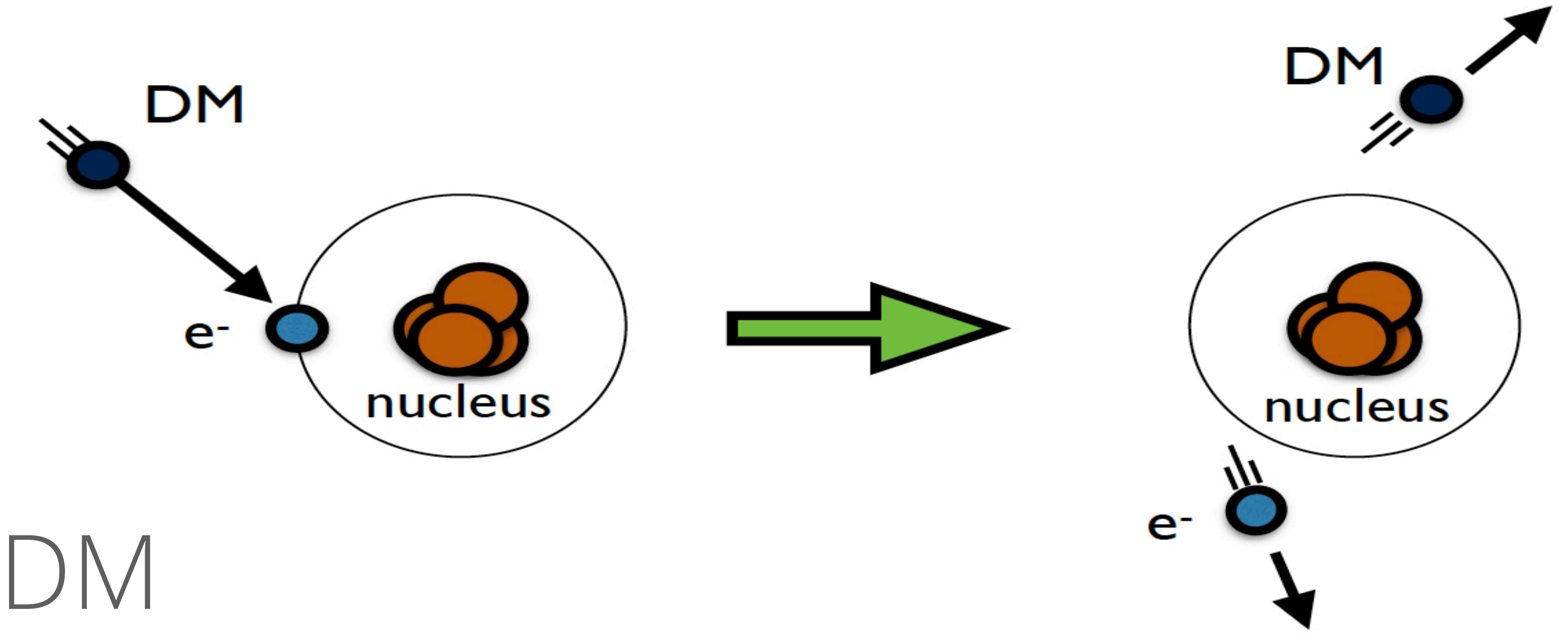

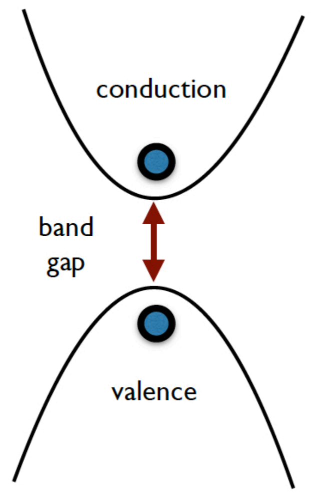

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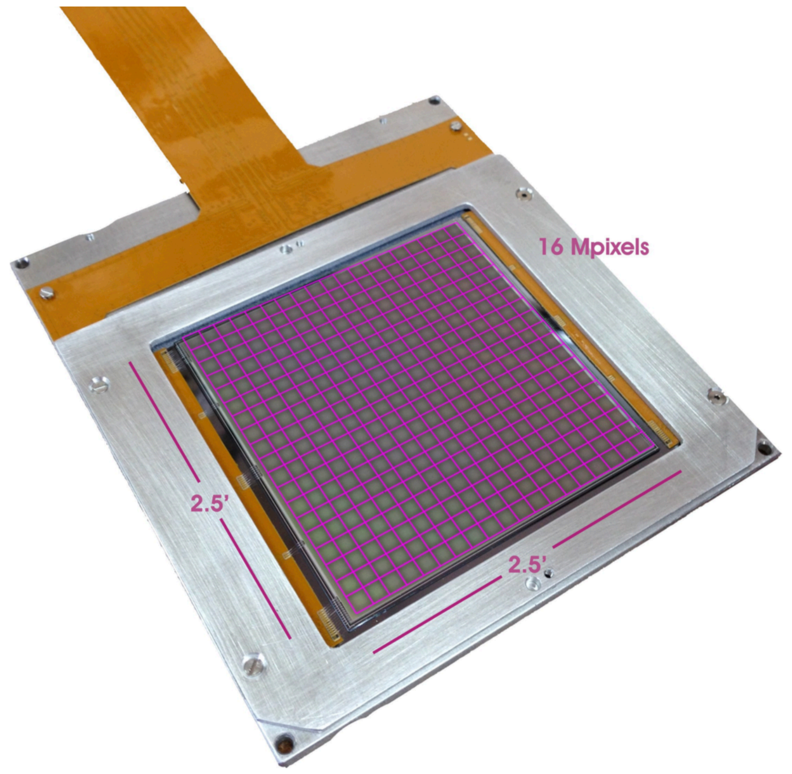
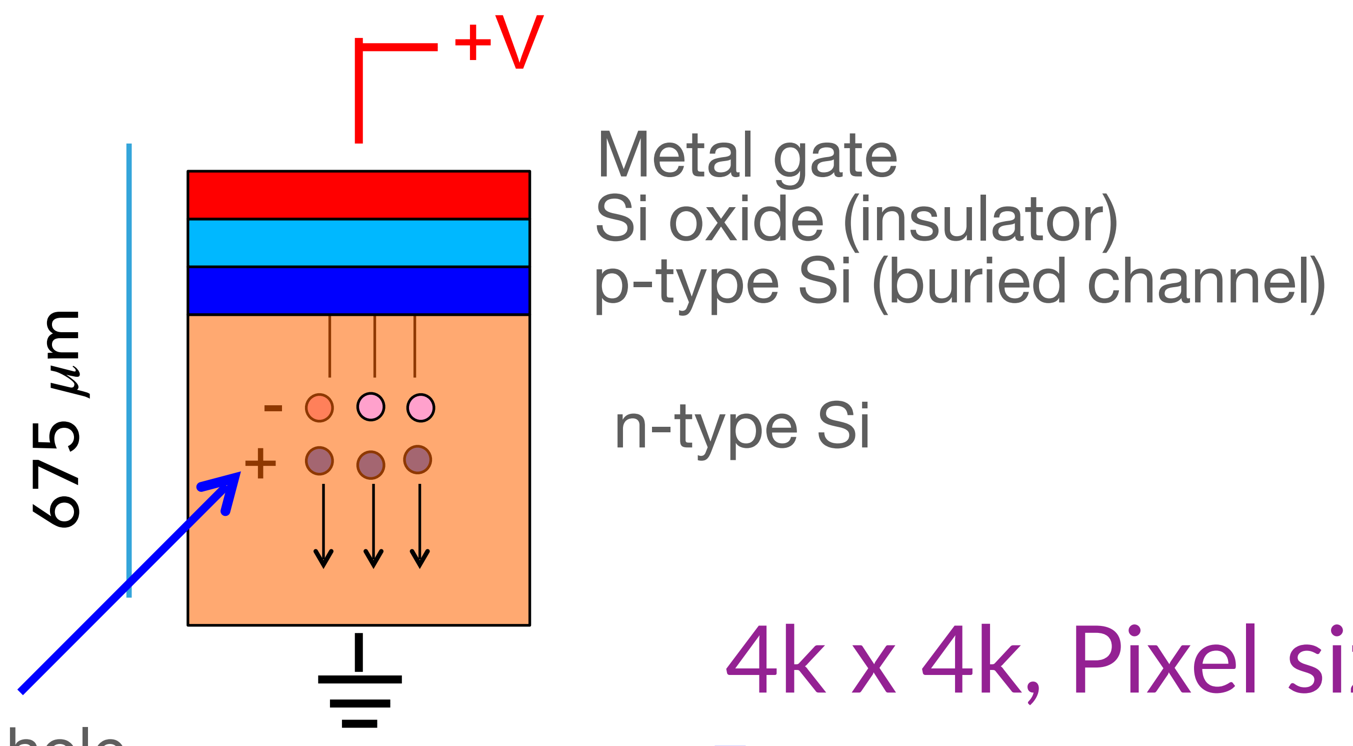
Type	examples	Mass threshold	ΔE	Status
Noble liquid	Xenon Argon Helium	~5 MeV	~10 eV (Atom)	Done w/Xenon 10/100 & DarkSide50; New Proposal LBECA
Semiconductor	silicon	~200-500 keV	~1 eV (Bandgap)	First succes by SENSEI& SuperCMDS; funded experiments SENSEI (100gr),DAMIC-M (1KG) and OSCURA (10Kg)
Scintillator	gallium Arsenai NaI	~500 keV	~1 eV (bandgap)	R&D ongoing on GaAs and photodetectors
Many Other Ideas	Graphene, superconductors, Dirac materiasl, polar crystal.....	Various (> keV)	Various (> meV)	R&D ongoing/ requiered

CCDs principle



Metal-Oxide-Semiconductor capacitor

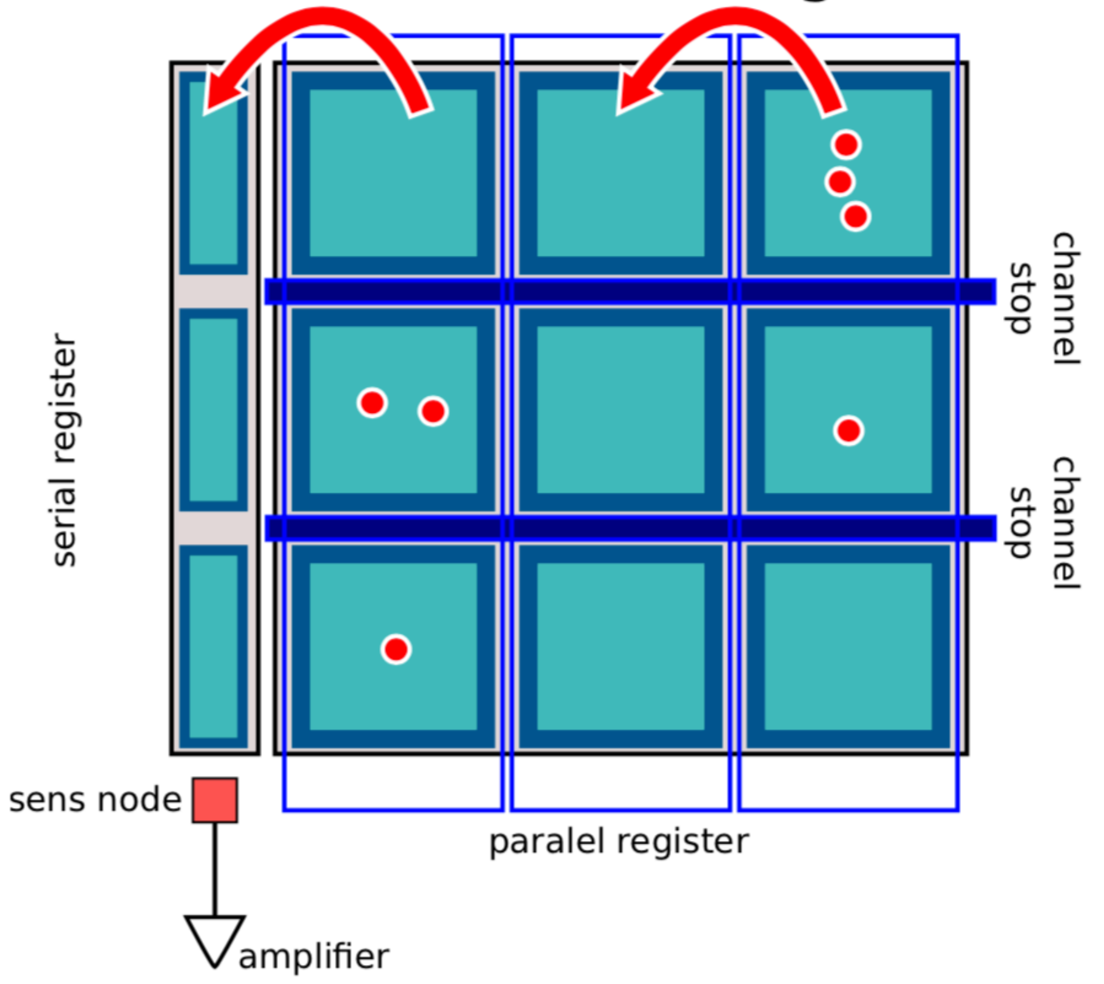


electron-hole pairs generated by a photon or ionizing particle

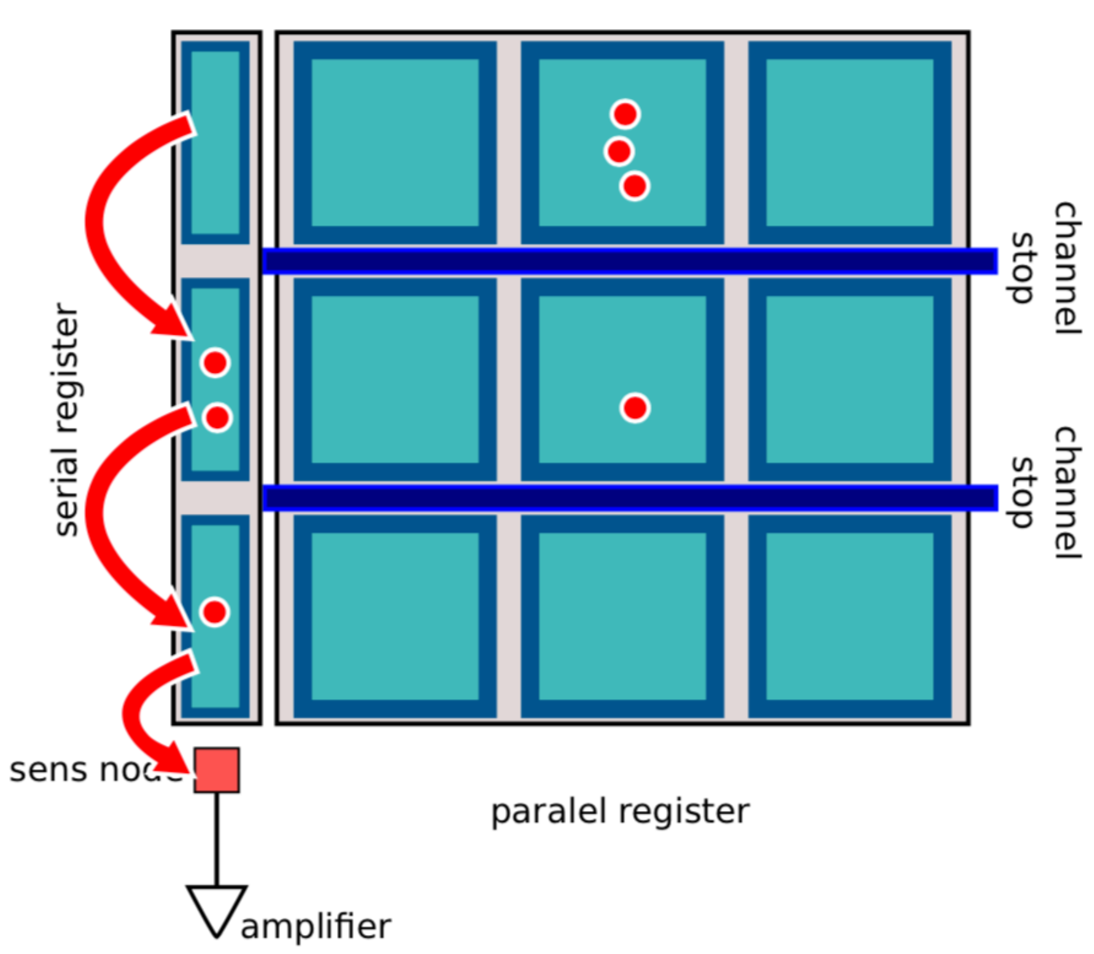
4k x 4k, Pixel size 15 μm x15 μm

5.9 gr per CCD

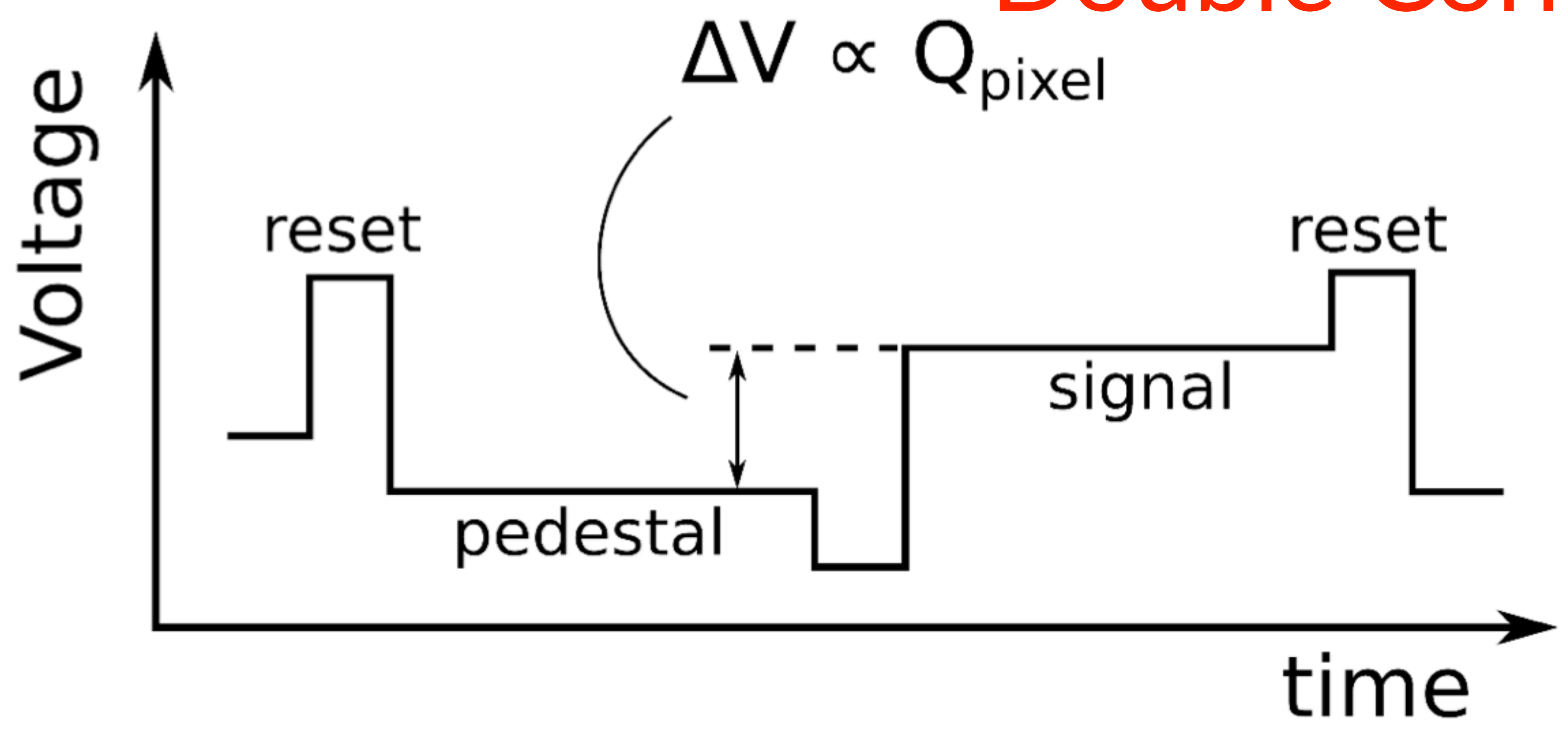
Shift charge one column to tha right



Shift charge in serial register one pixel down (3 times)

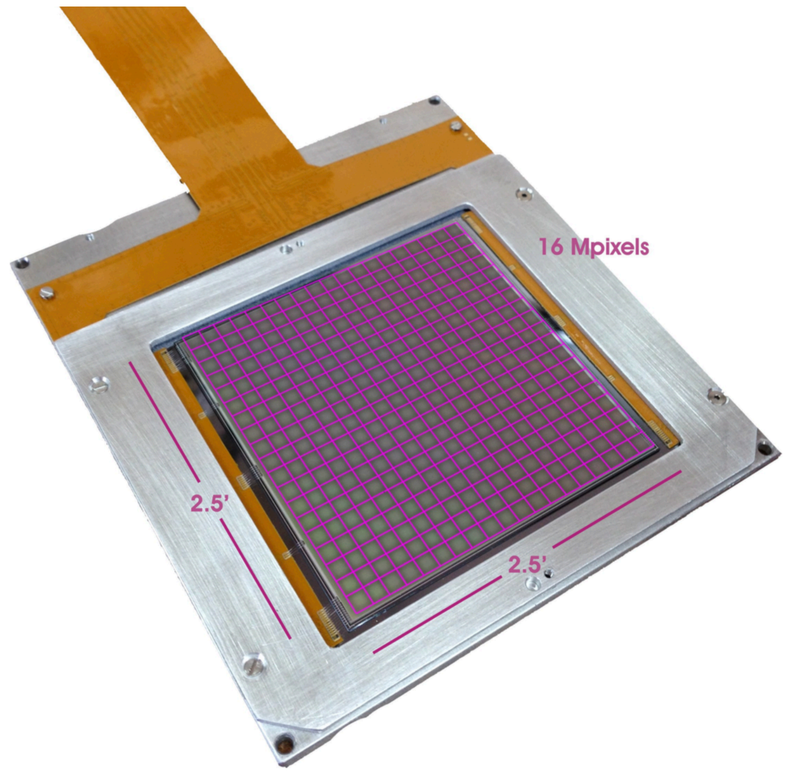


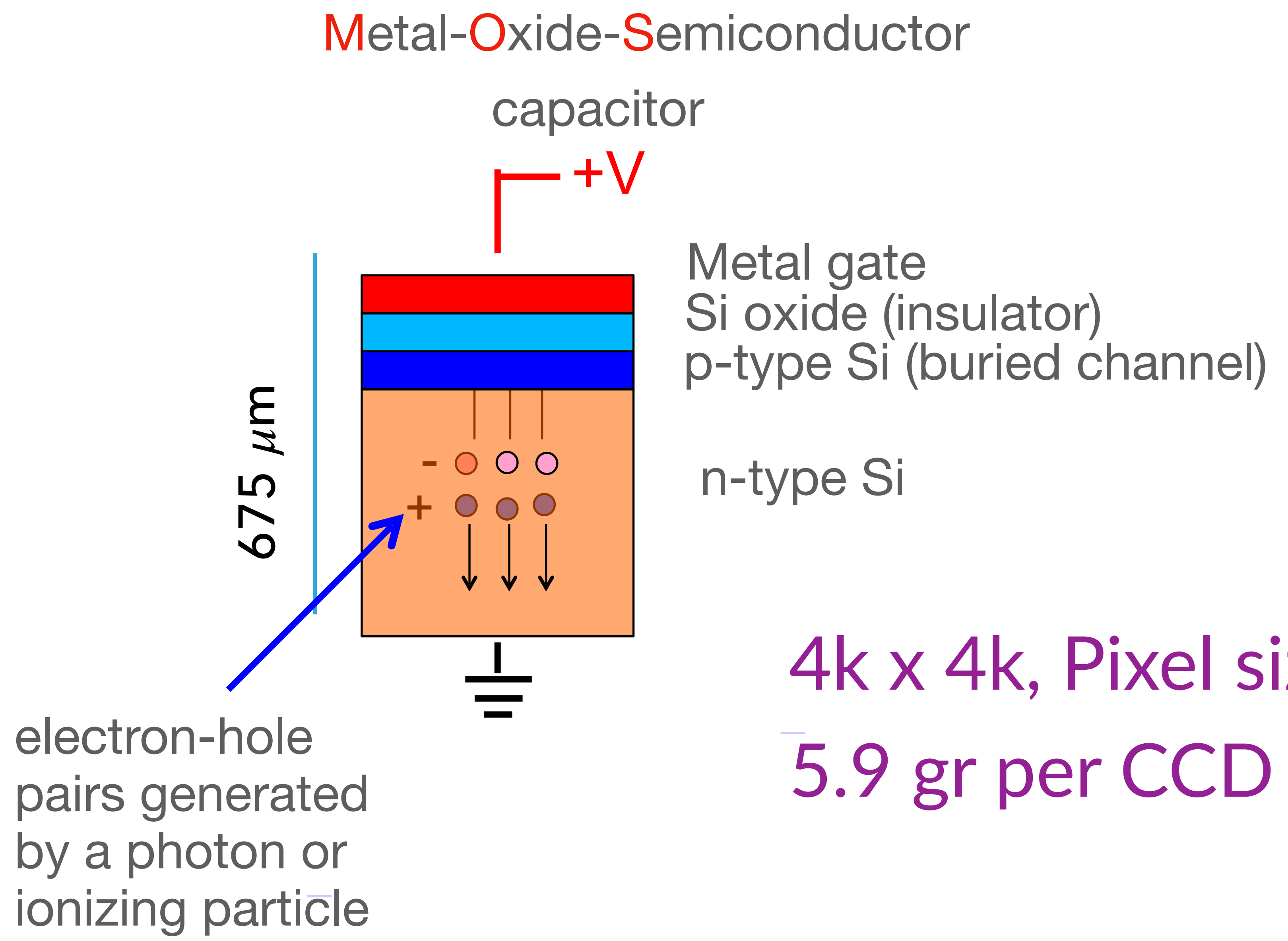
Double Correlated Sample



$$V_{out} \sim 3\ \frac{\mu V}{e^-}$$

CCDs principle





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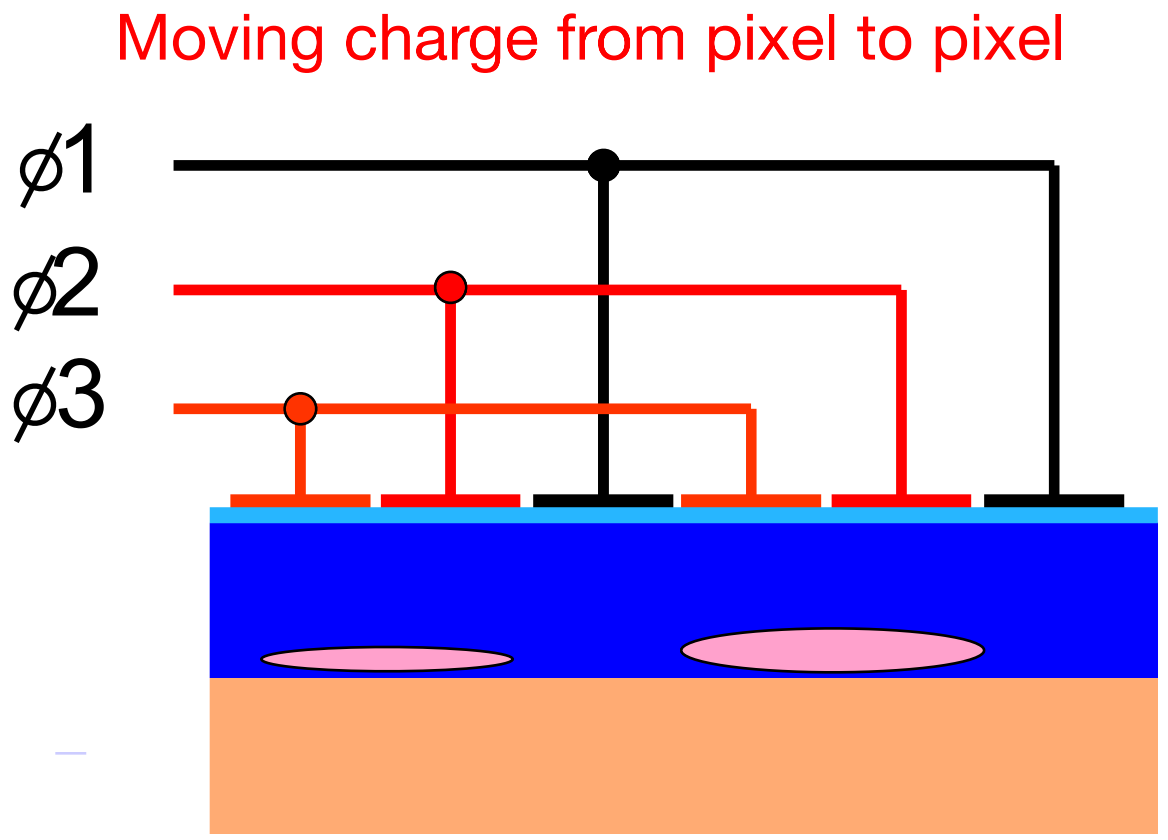

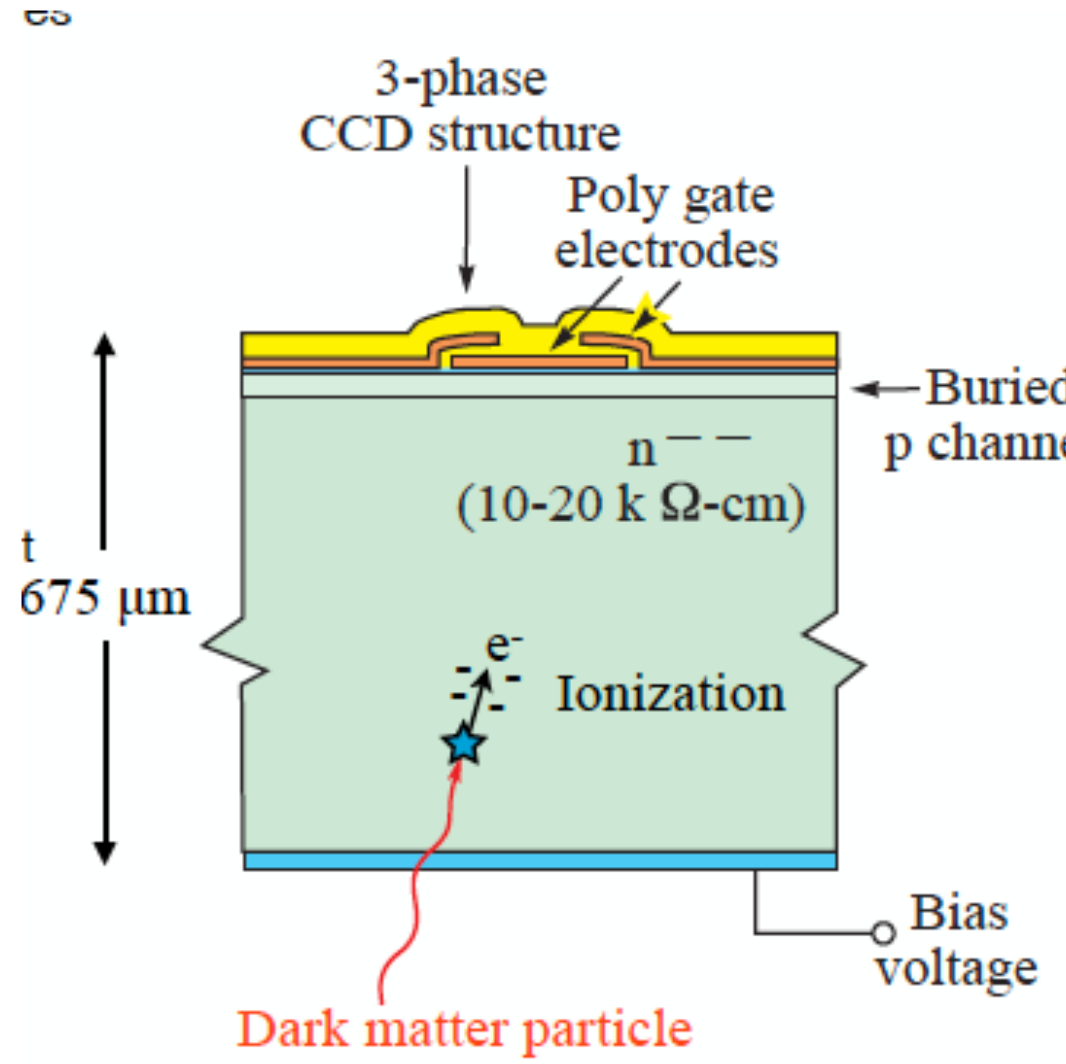

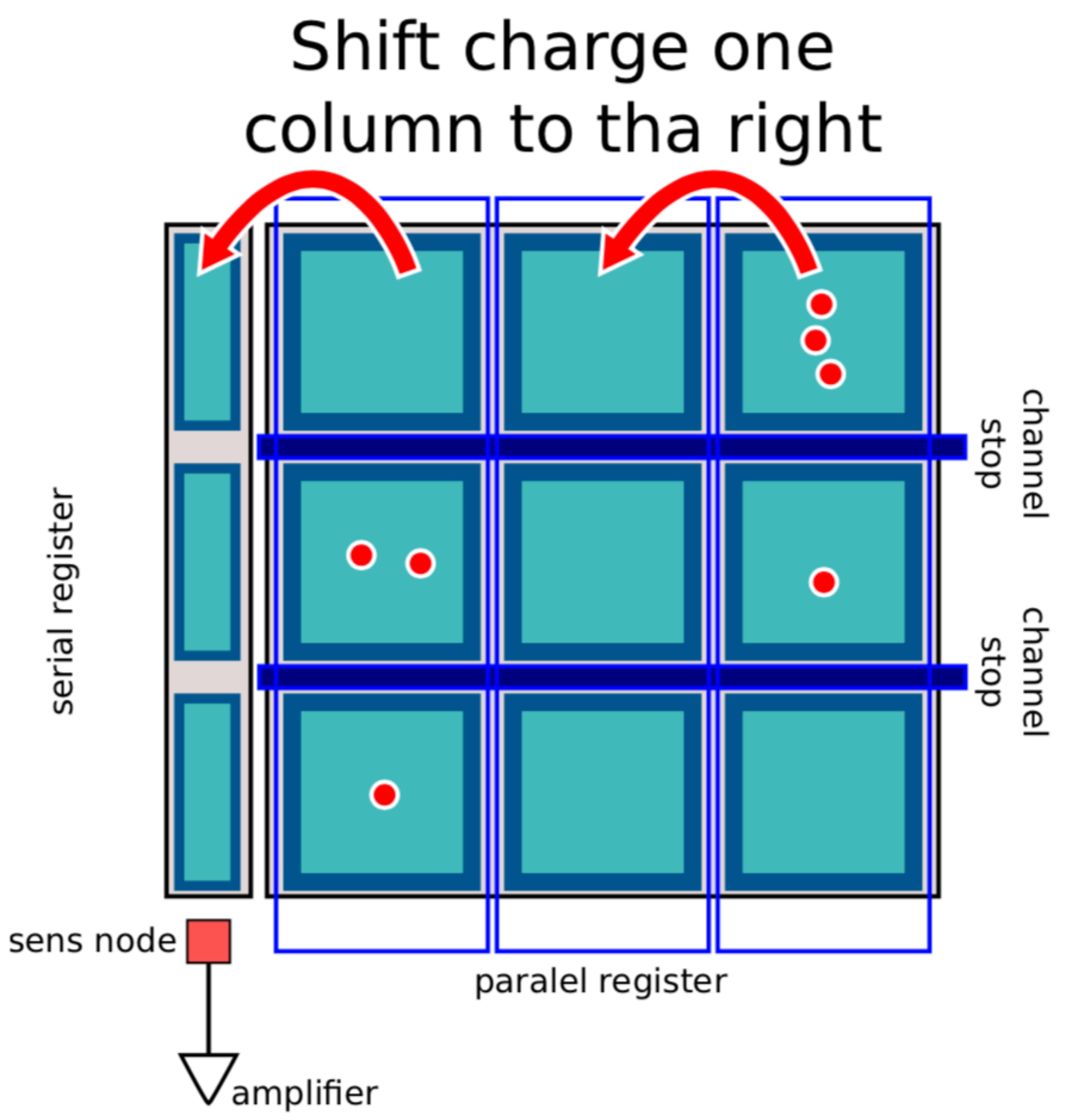

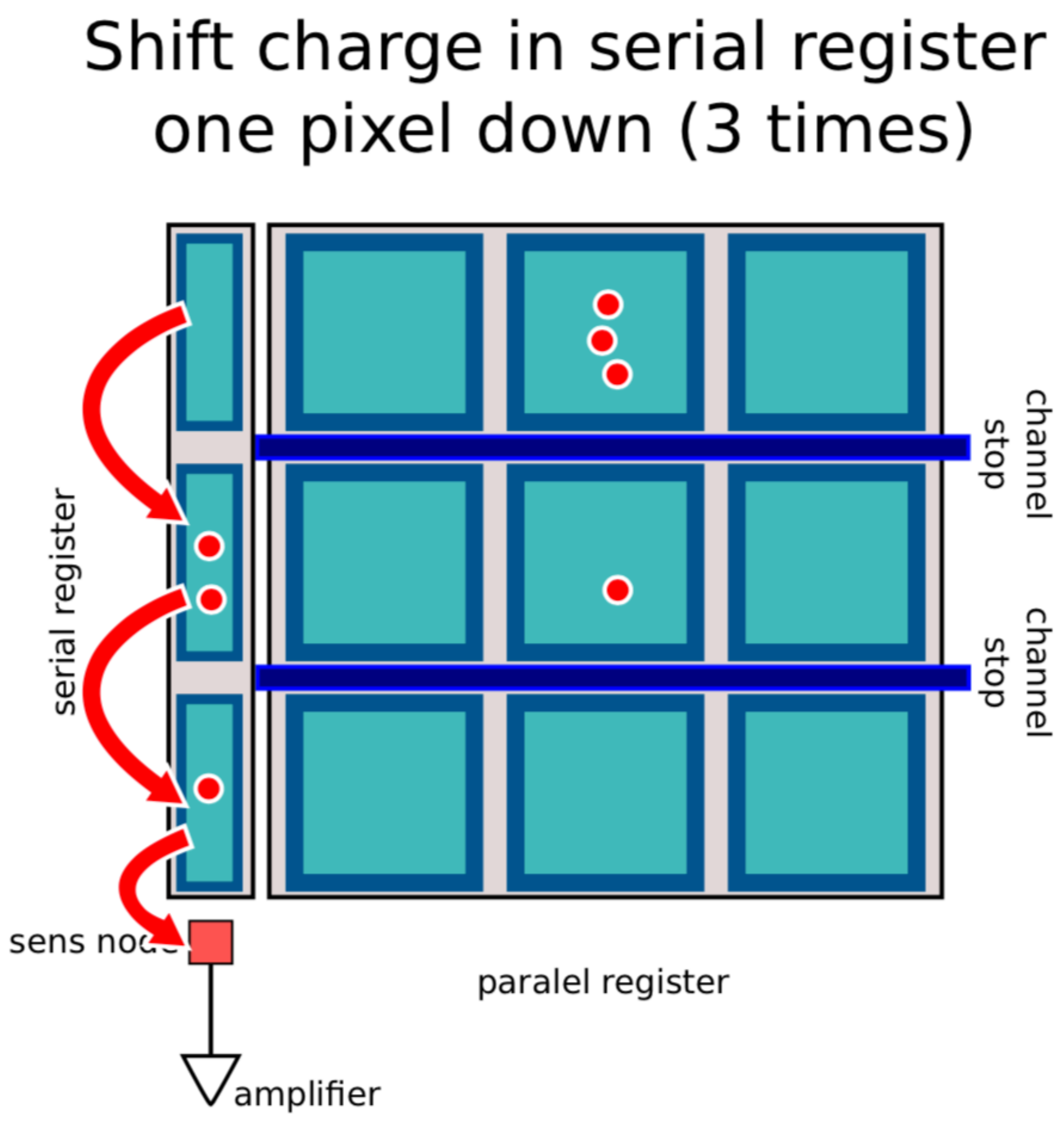

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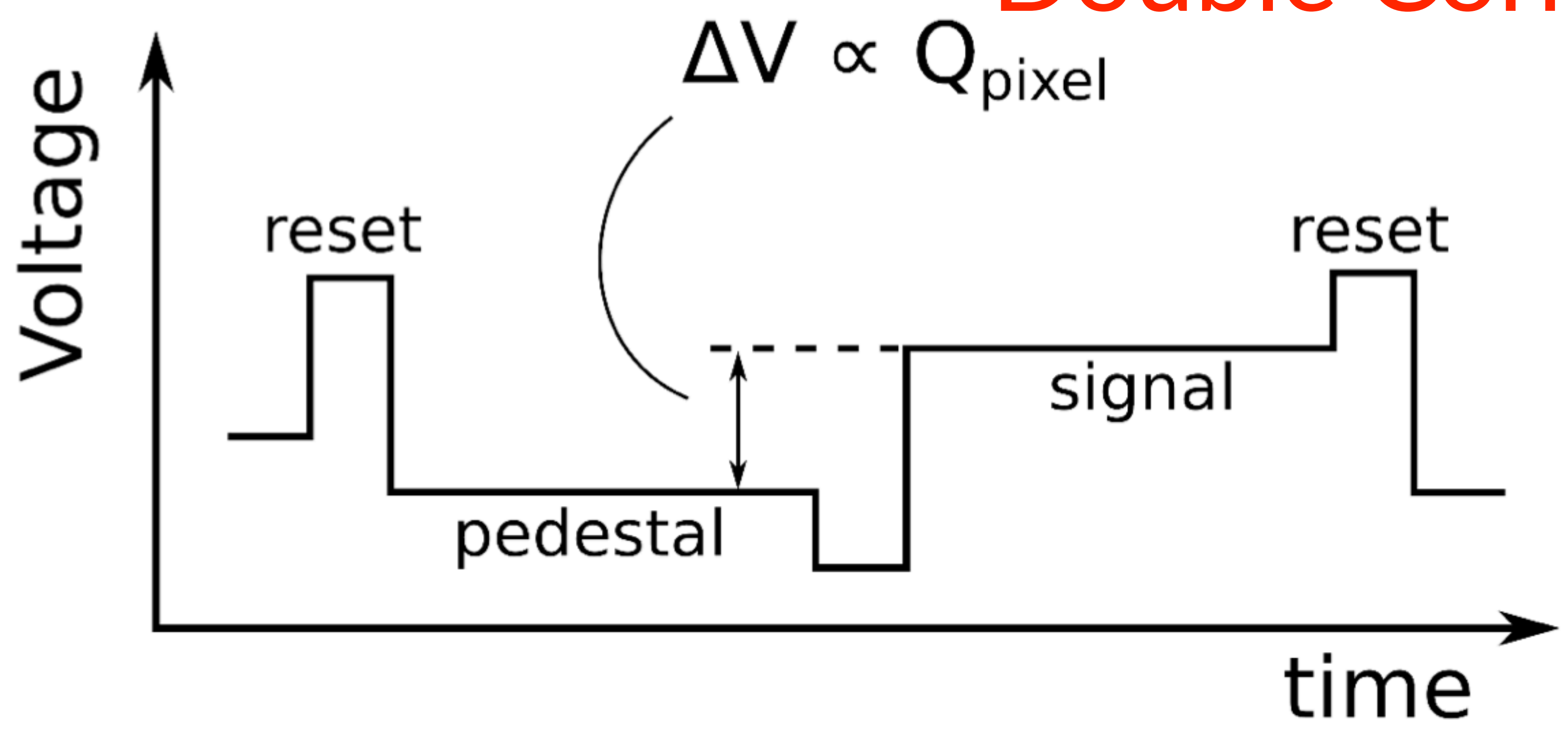

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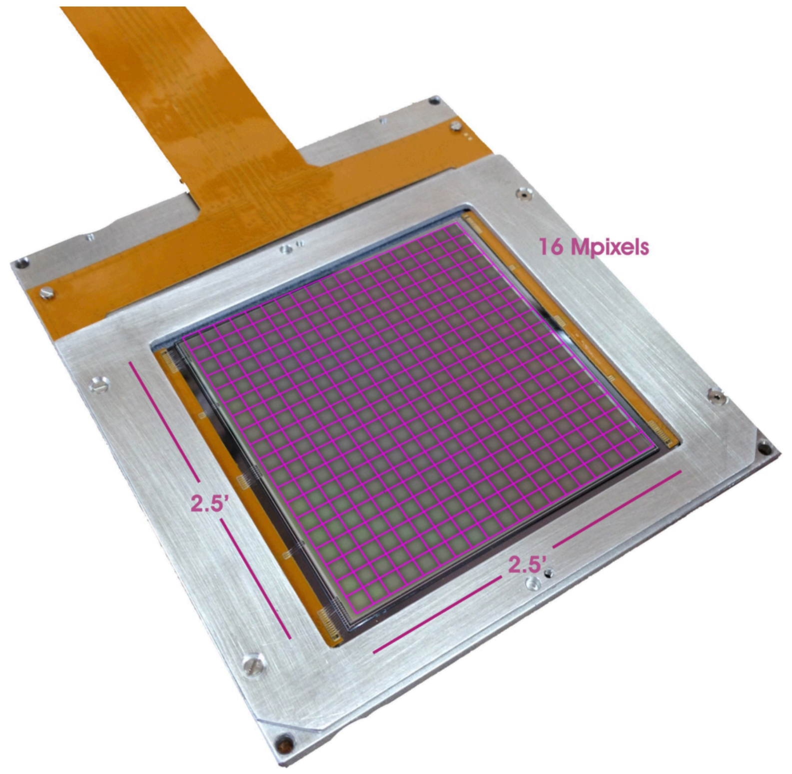
CCDs principle



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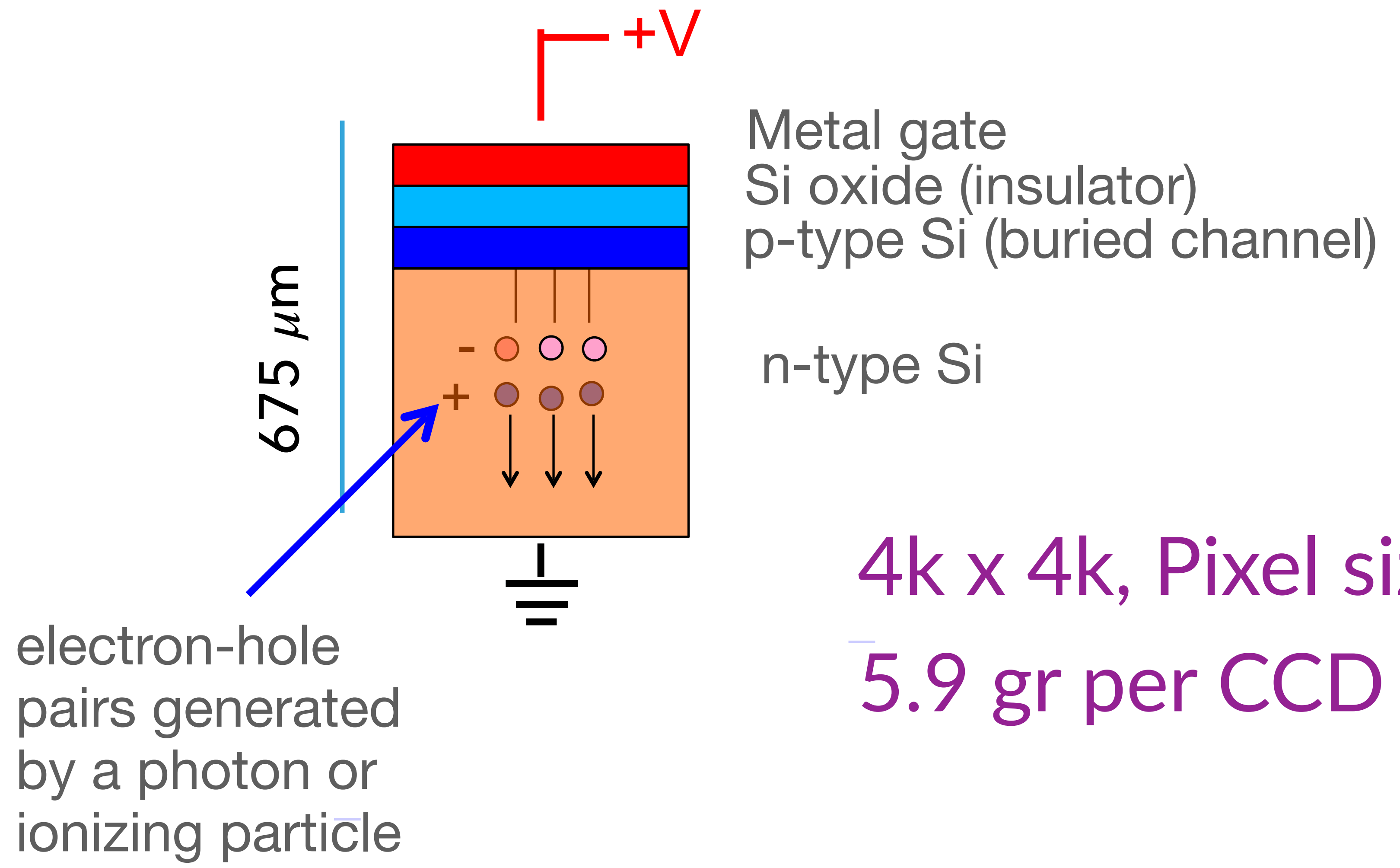
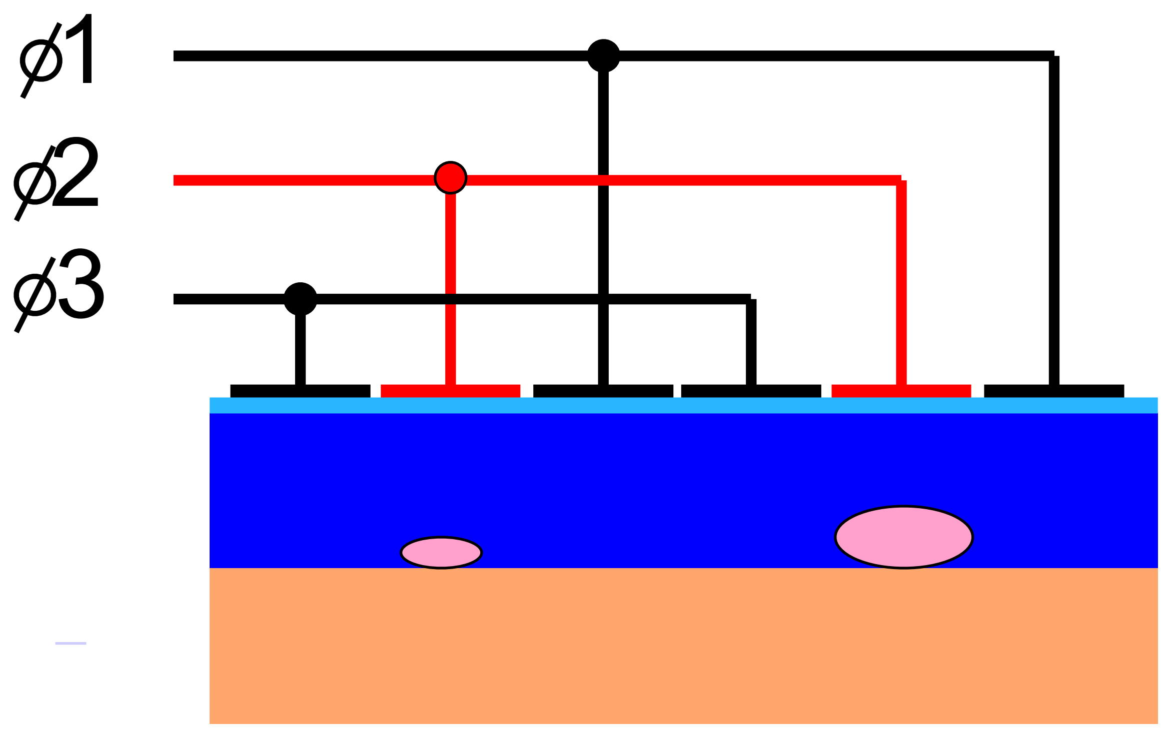
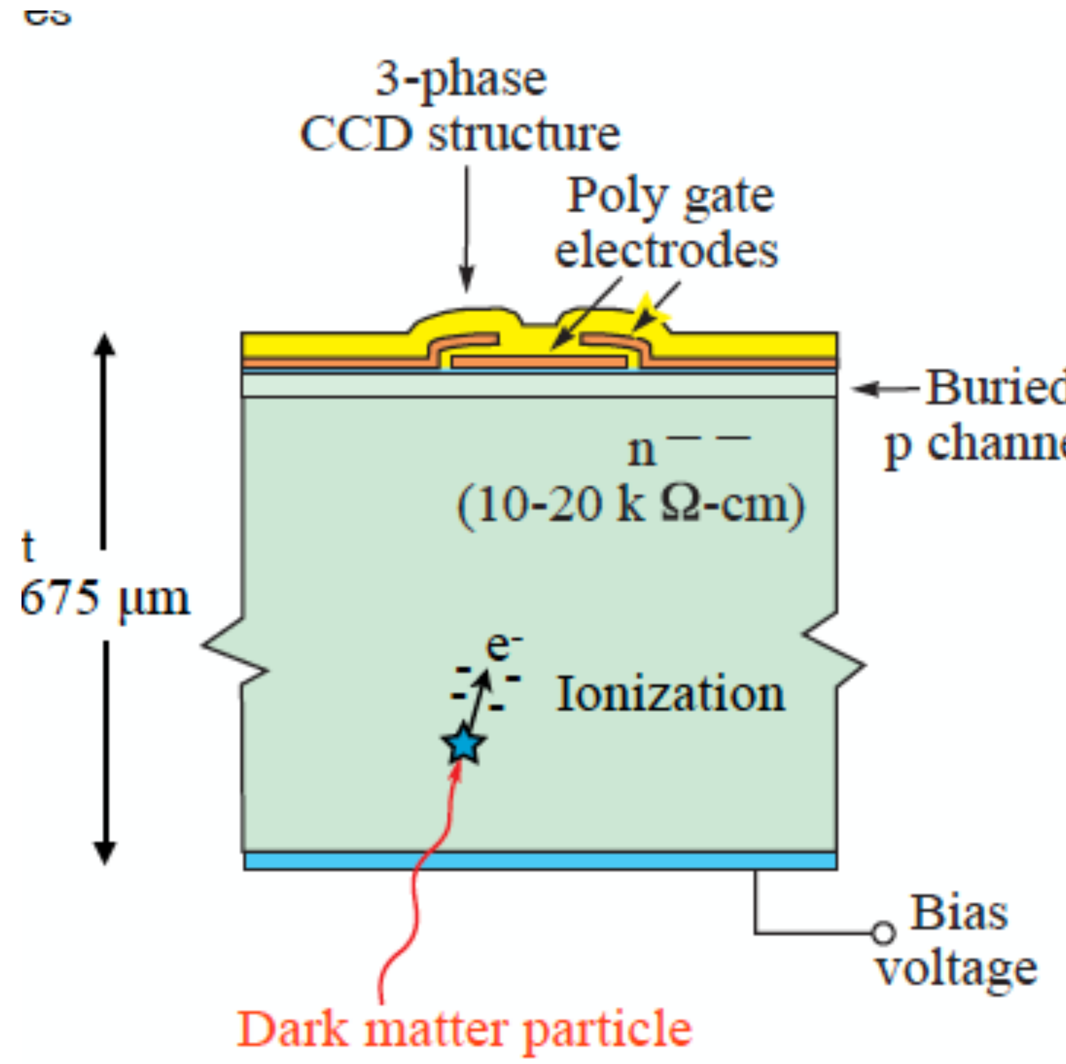


4k x 4k, Pixel size 15 μm x15 μm

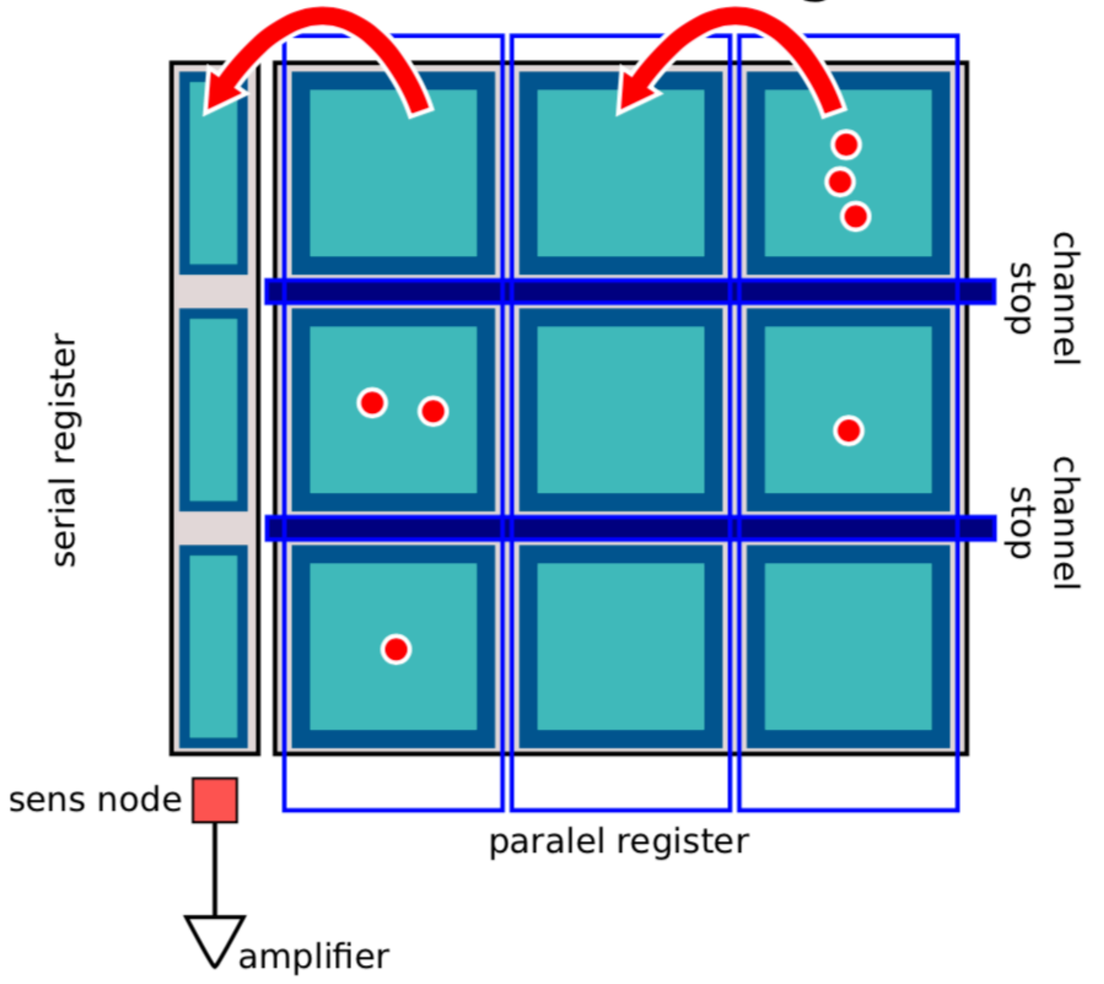
5.9 gr per CCD

Moving charge from pixel to pixel





Shift charge one column to tha right



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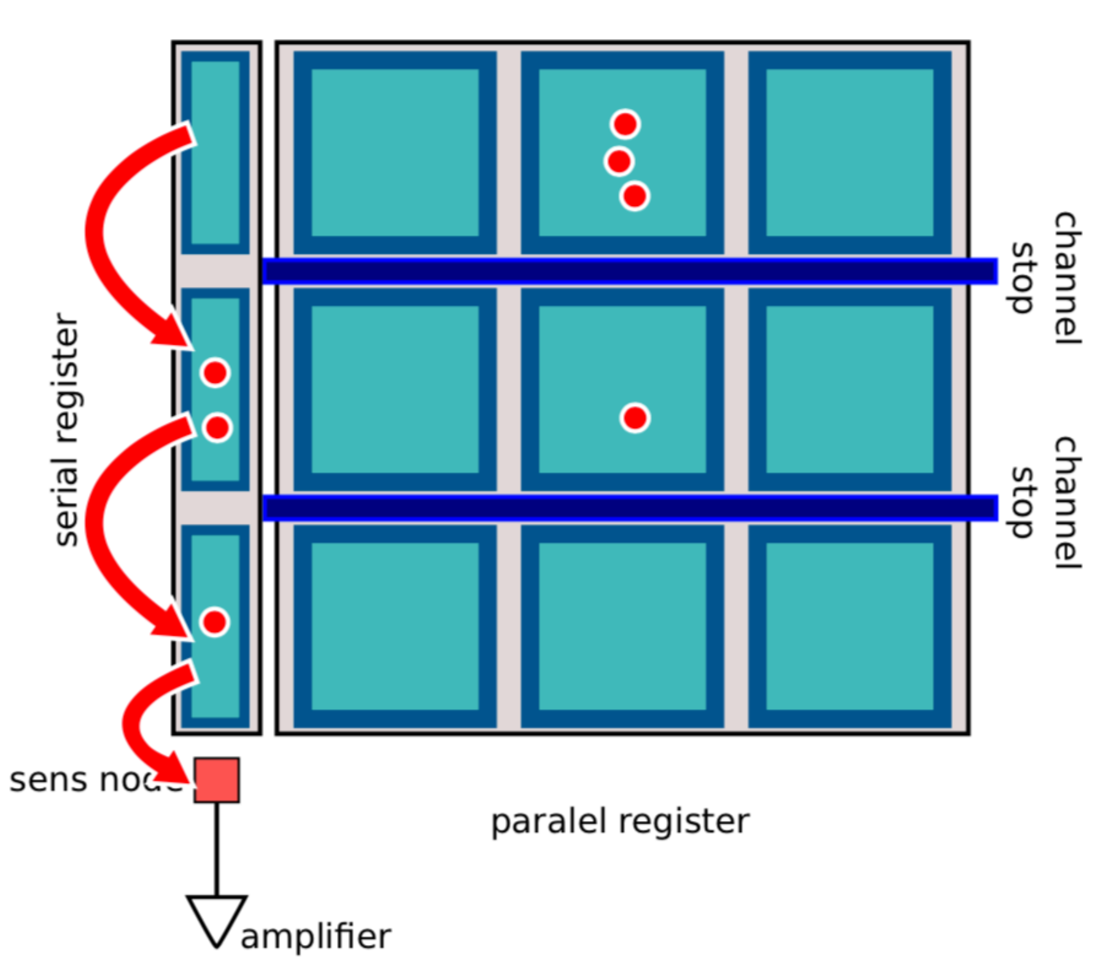

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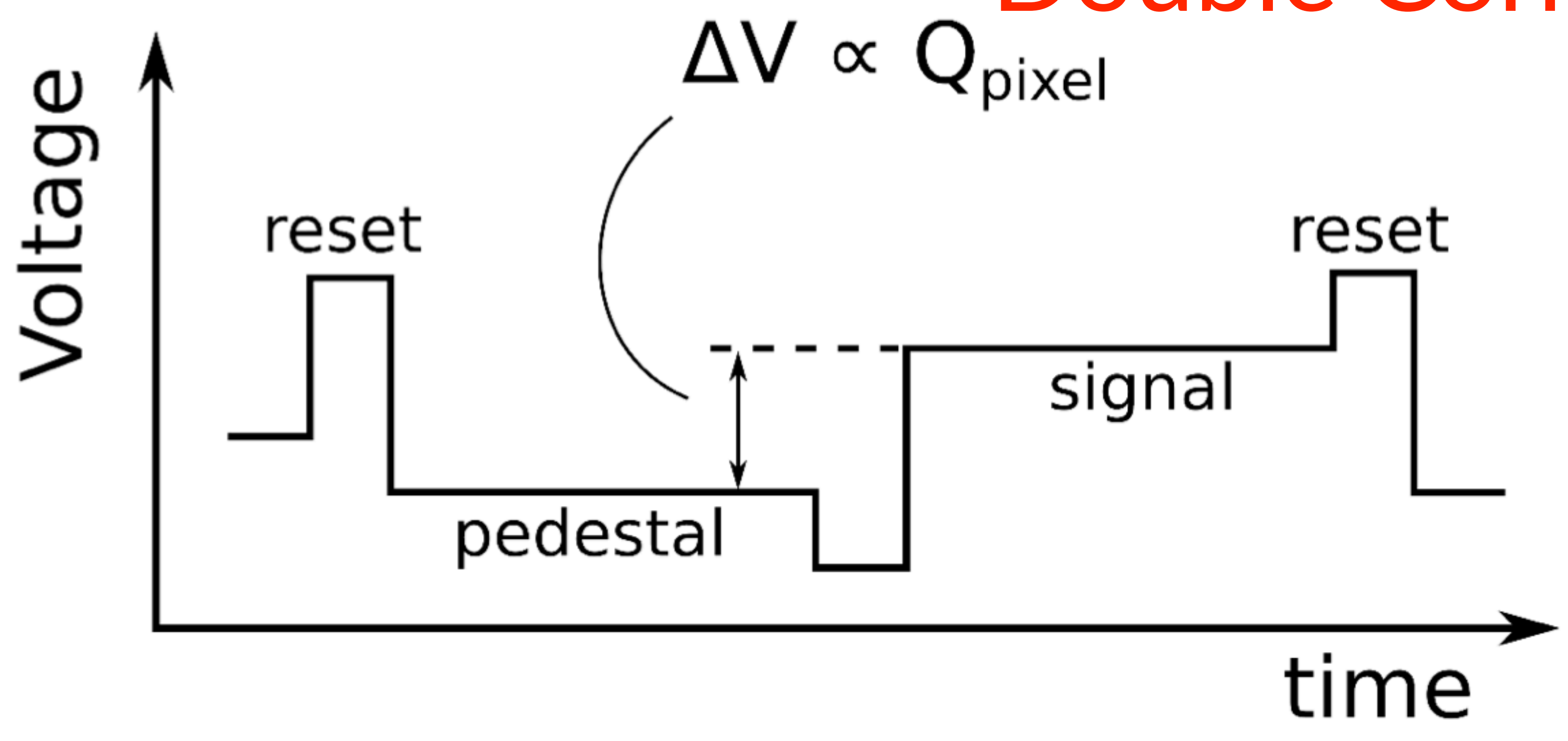

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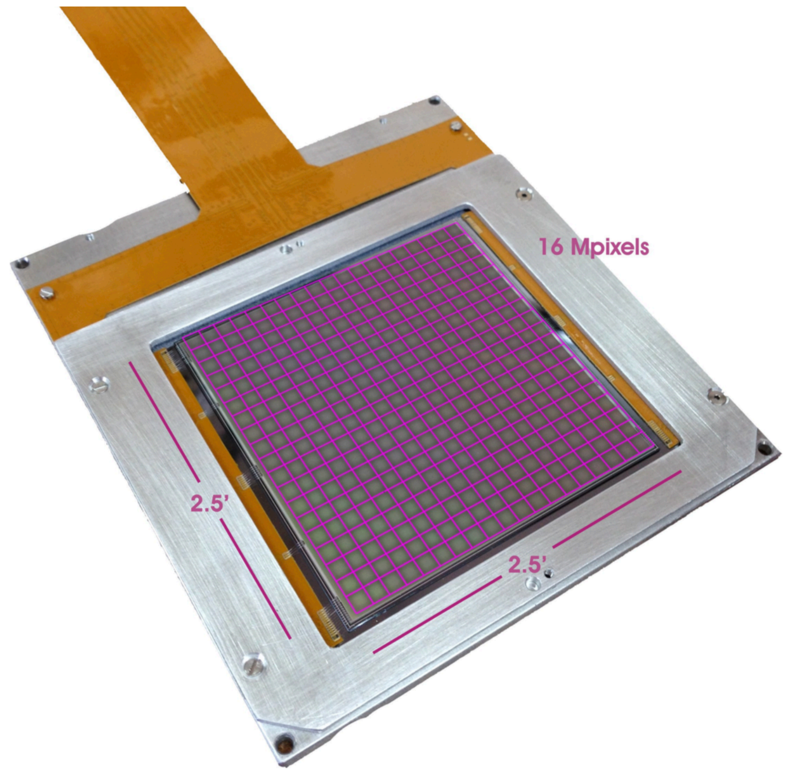

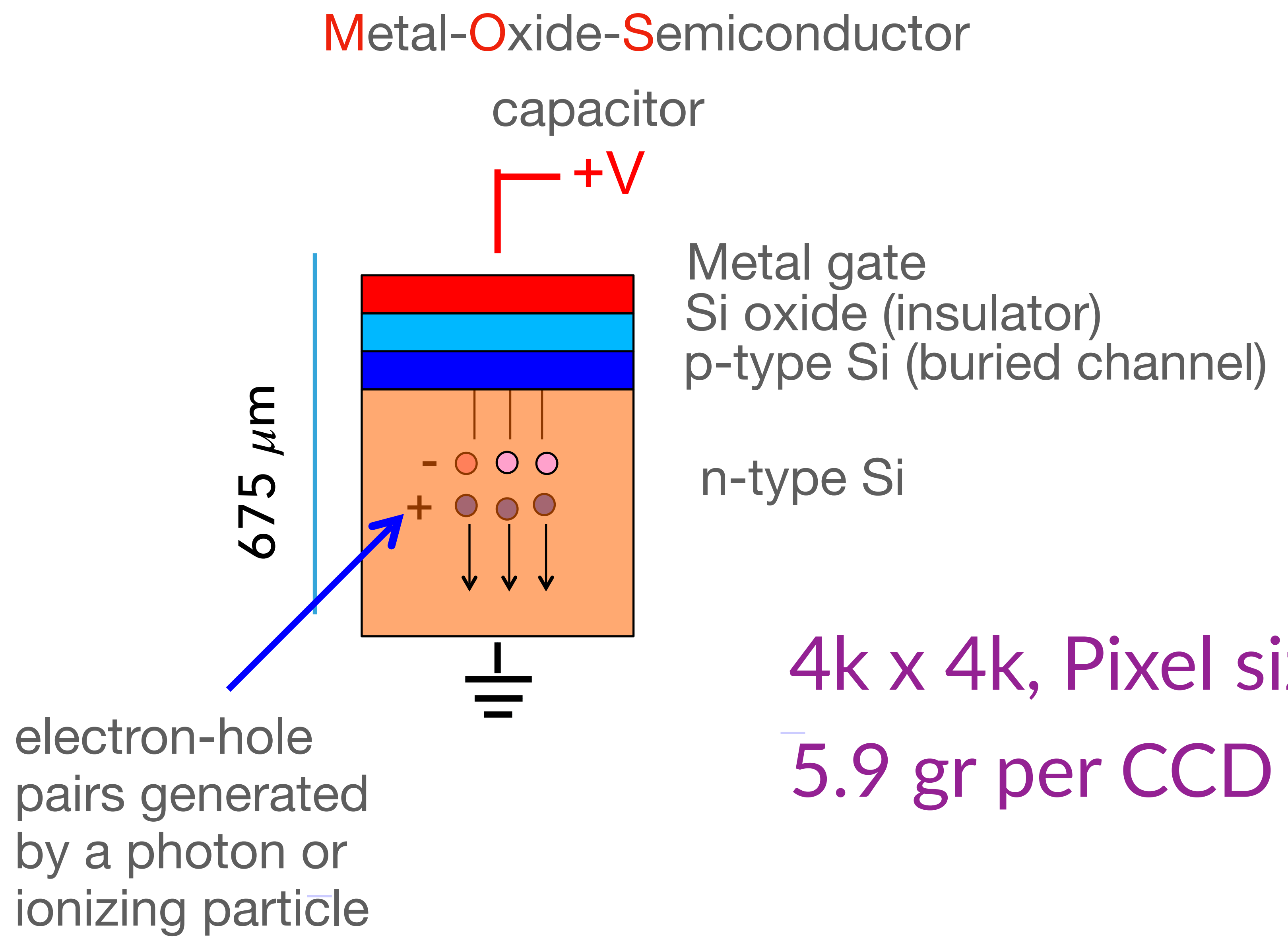

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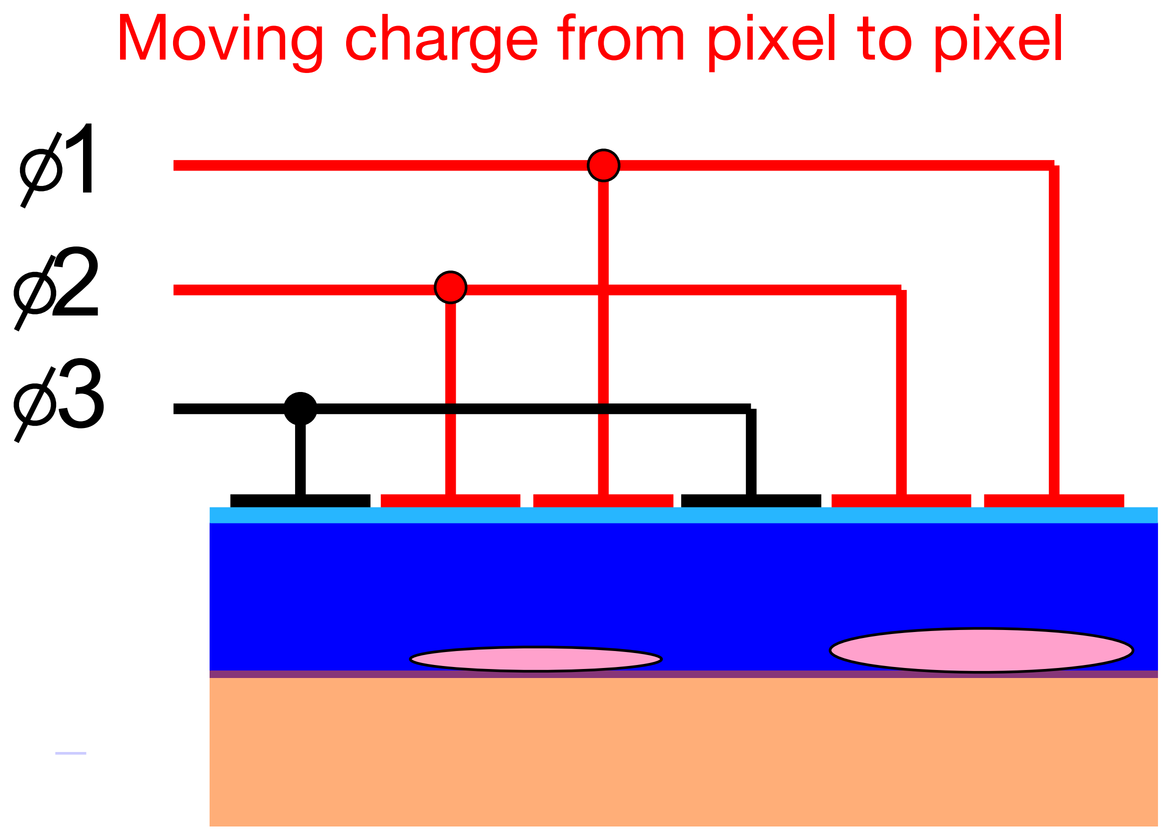

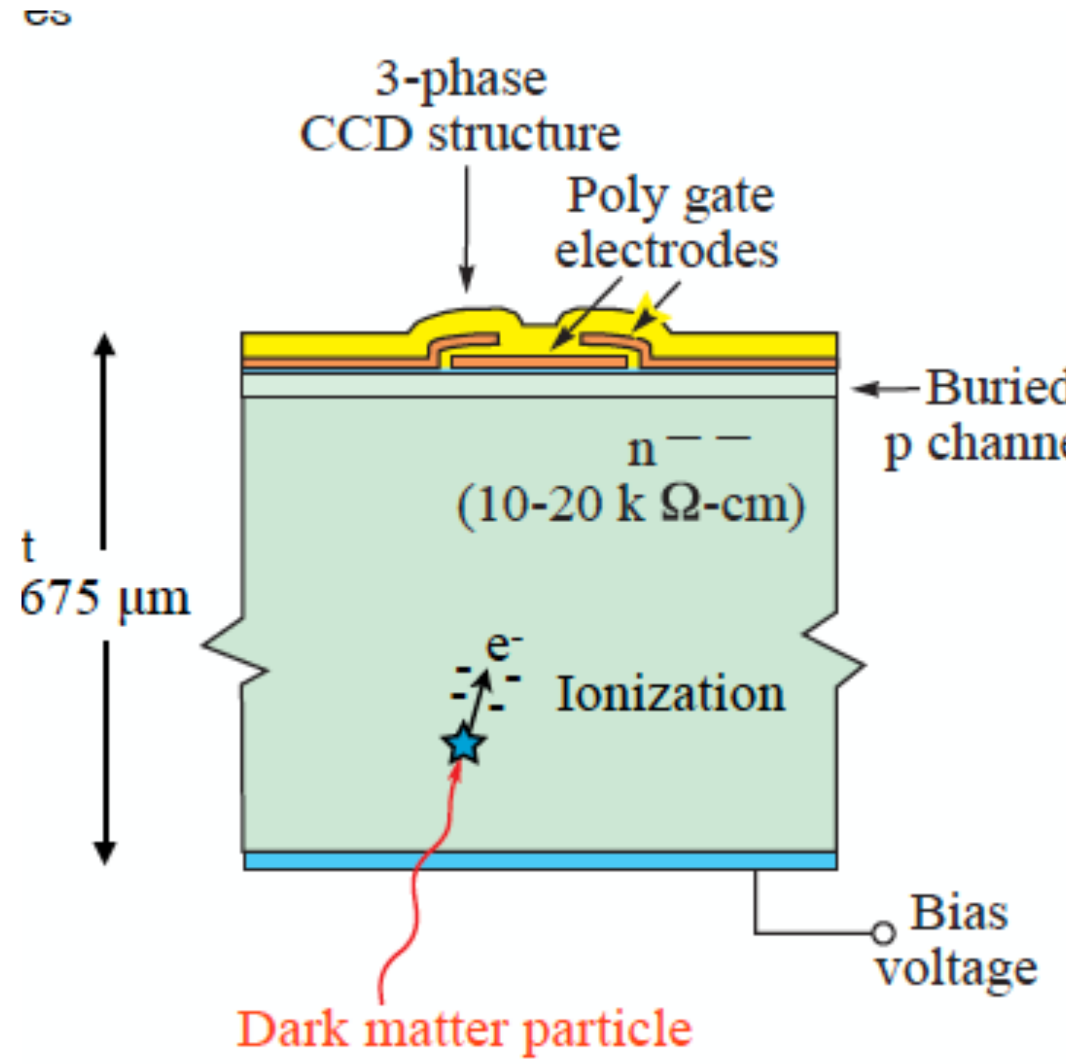

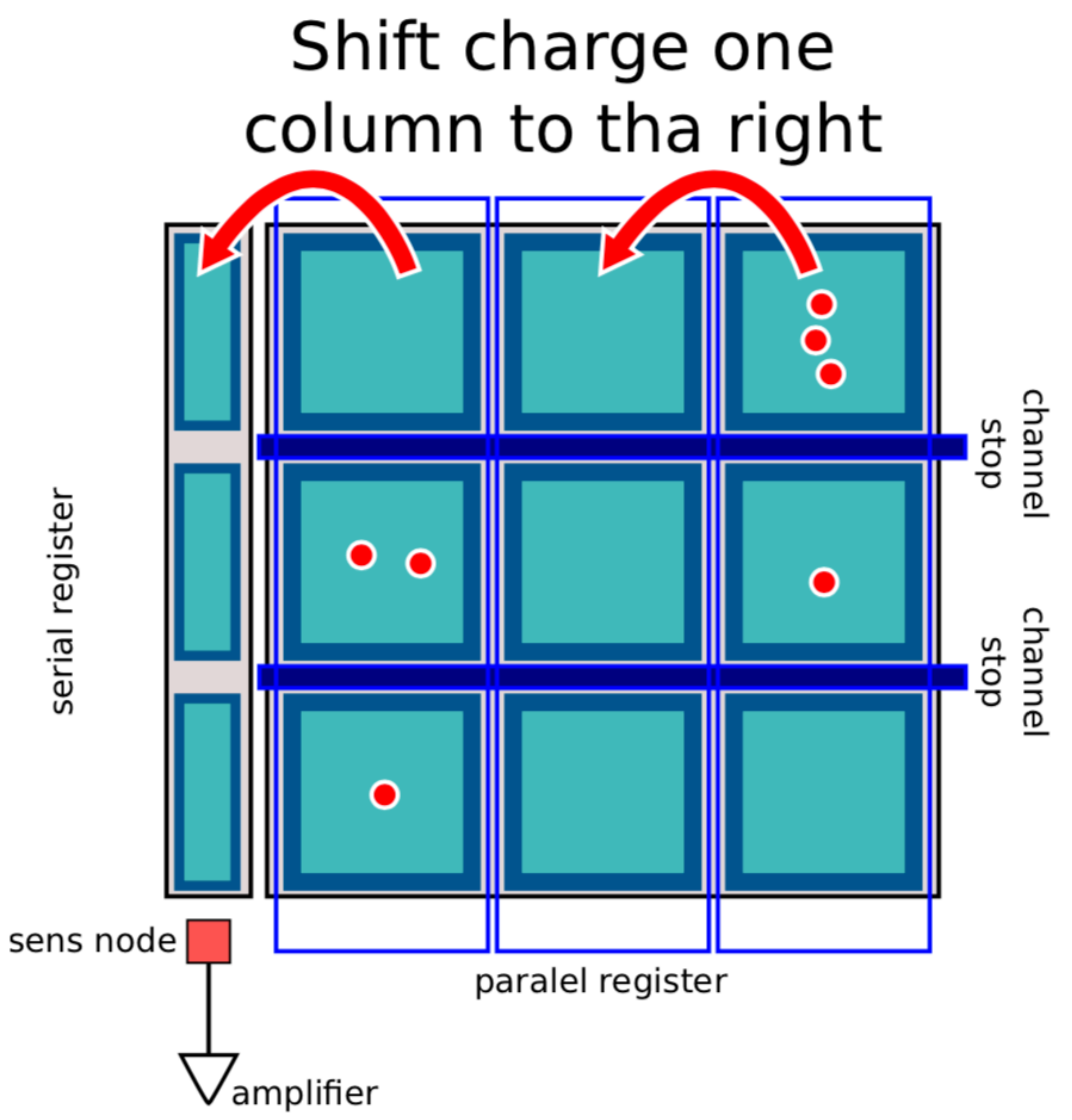

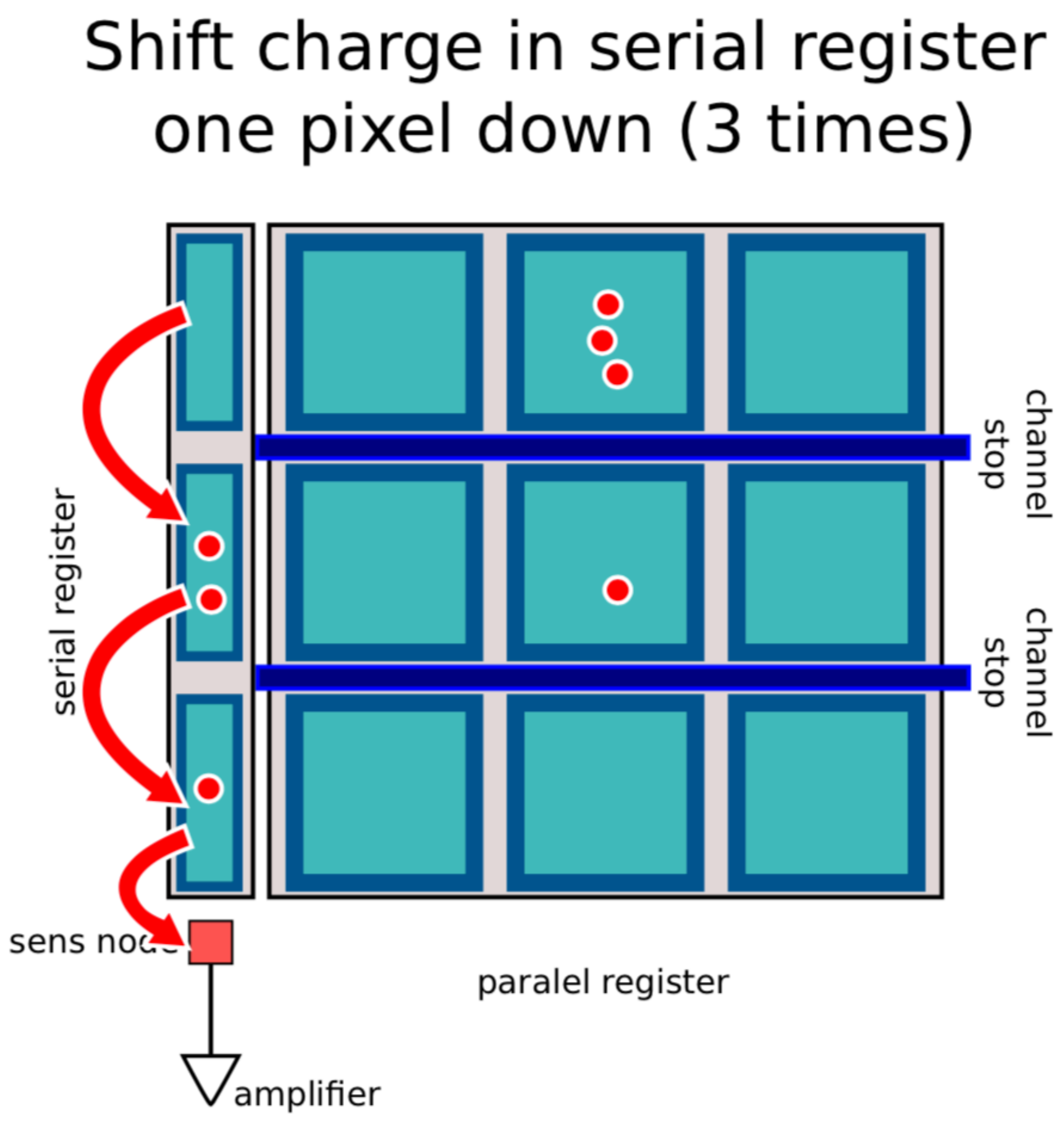

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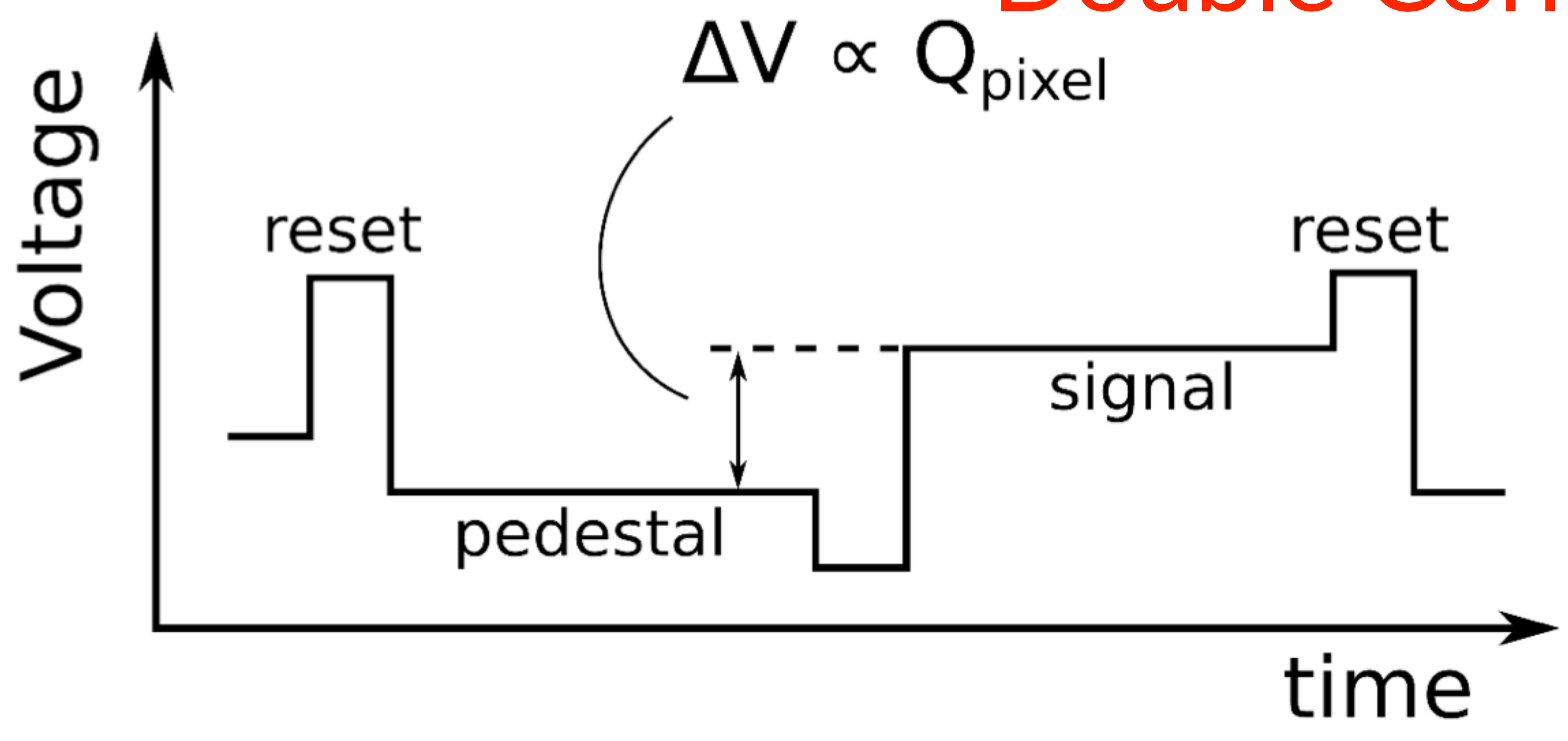

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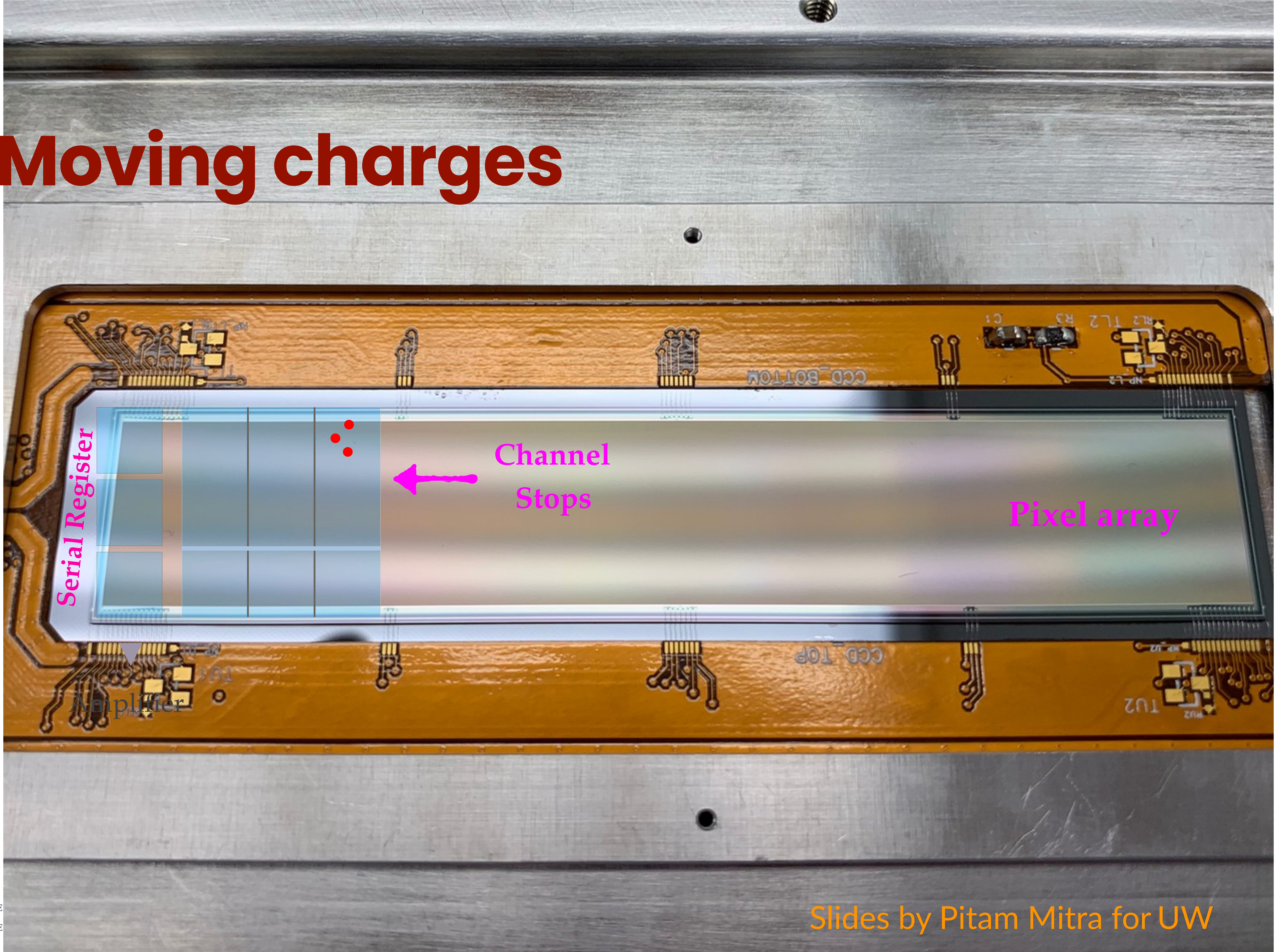
CCD: Moving charges



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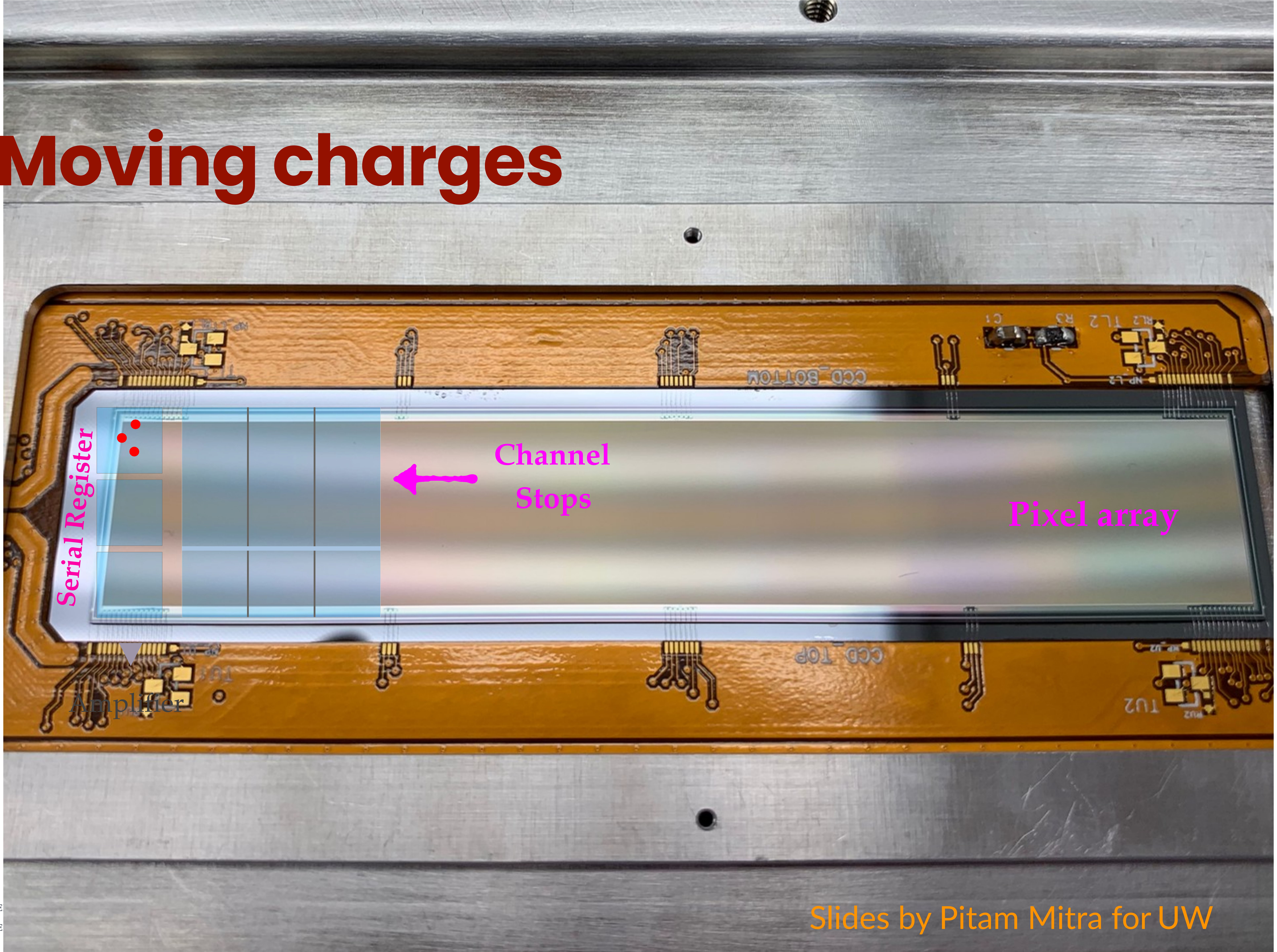
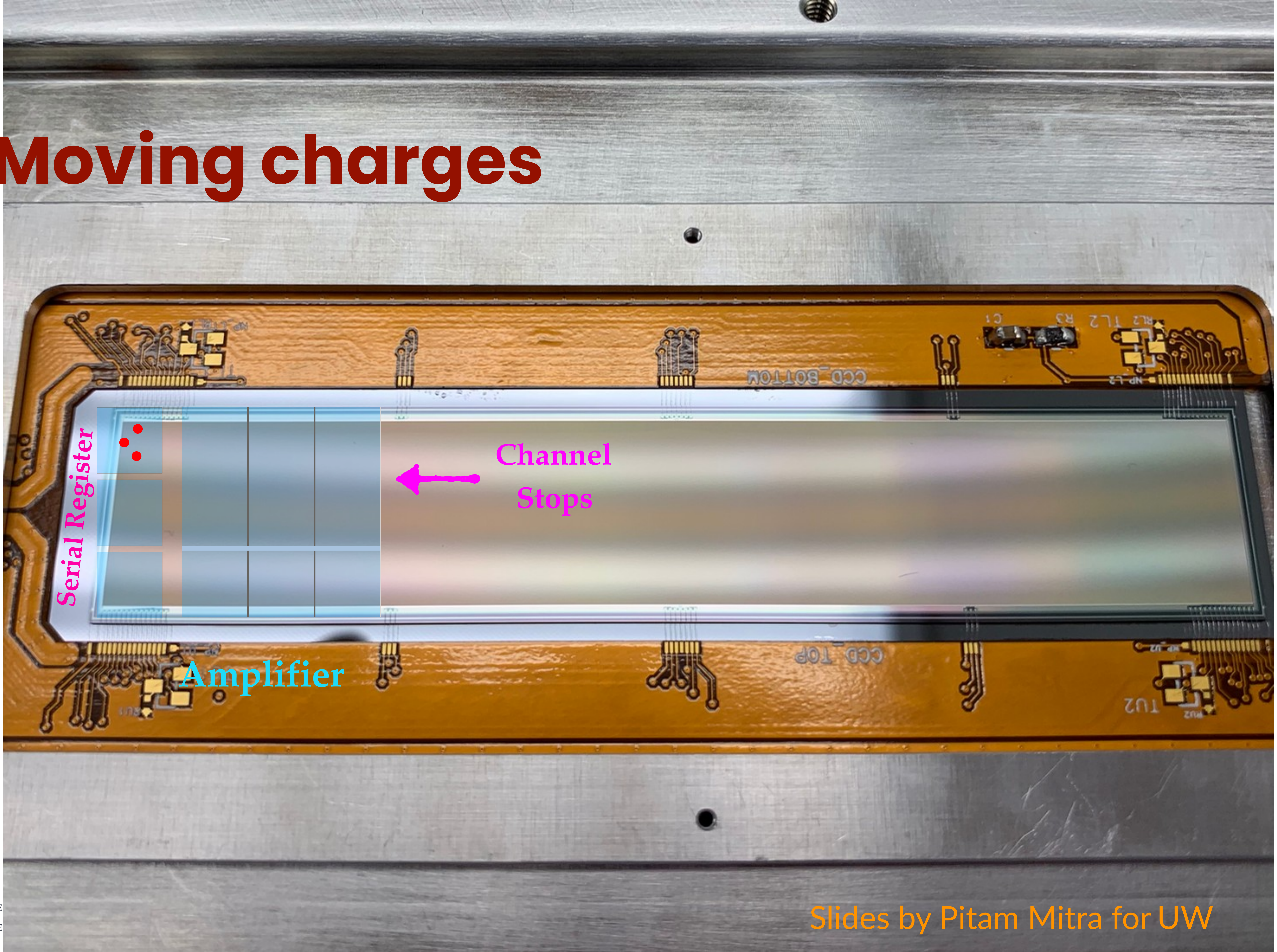


Slides by Pitam Mitra for UW

CCD: Moving charges



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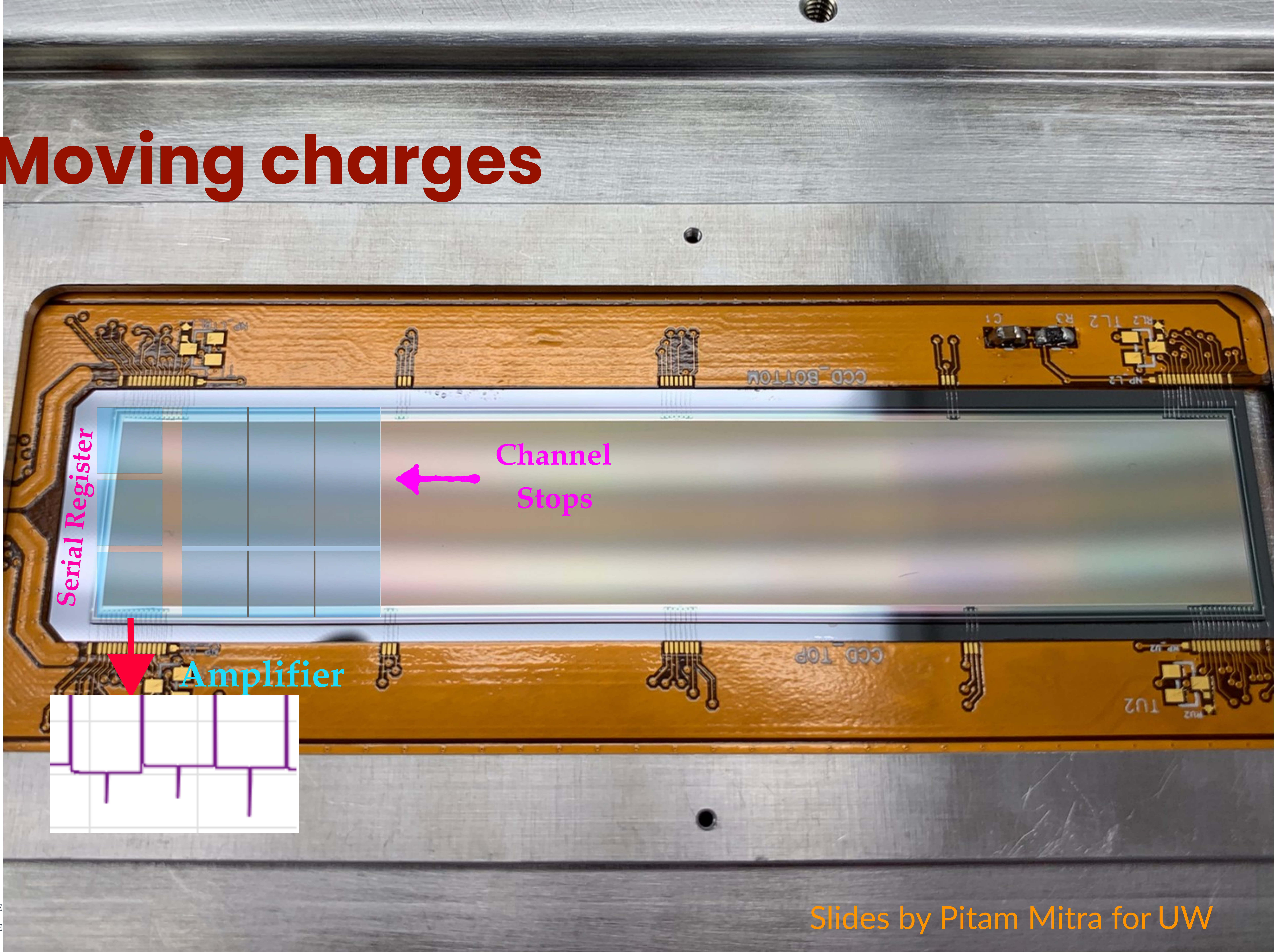

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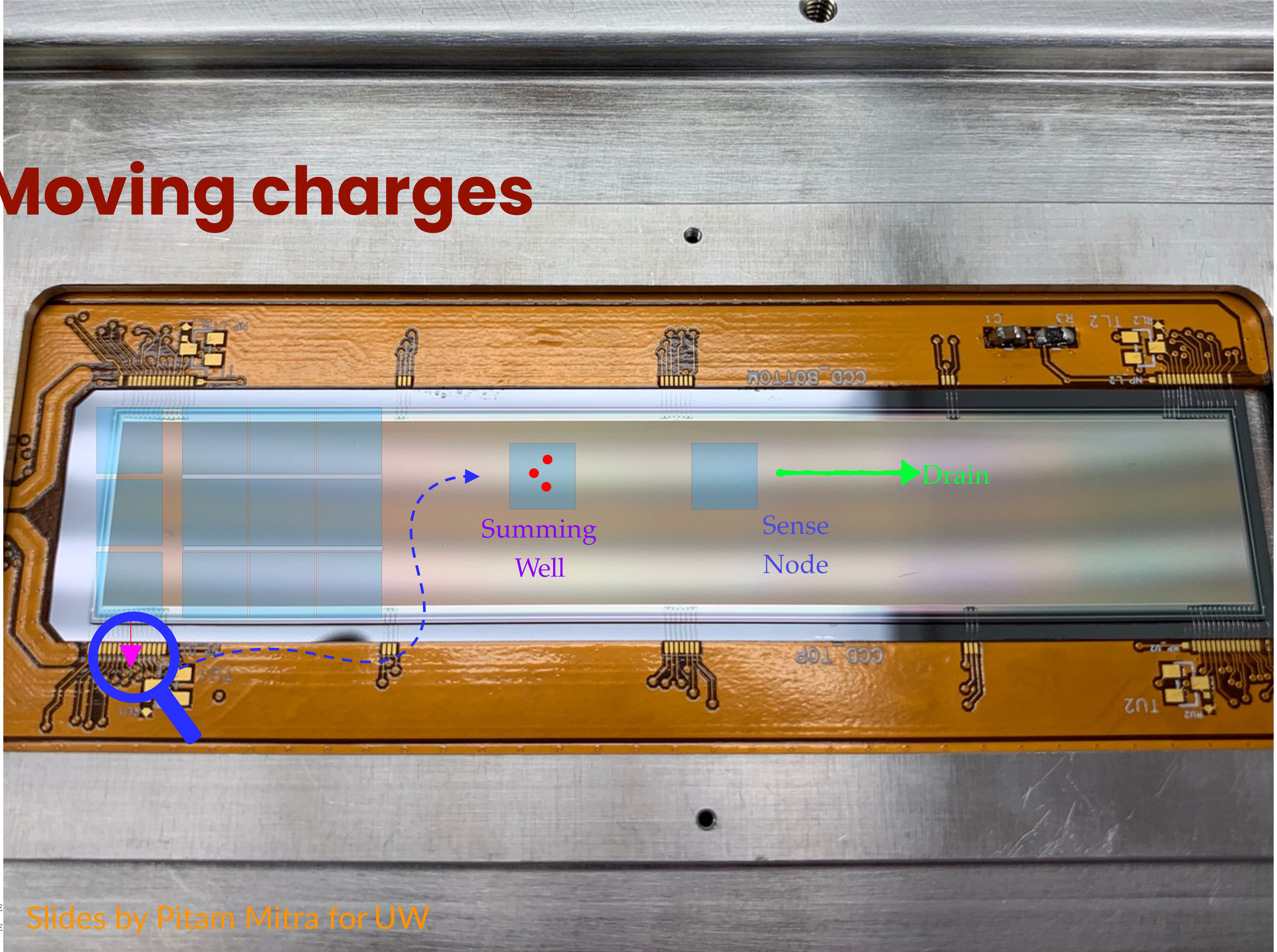

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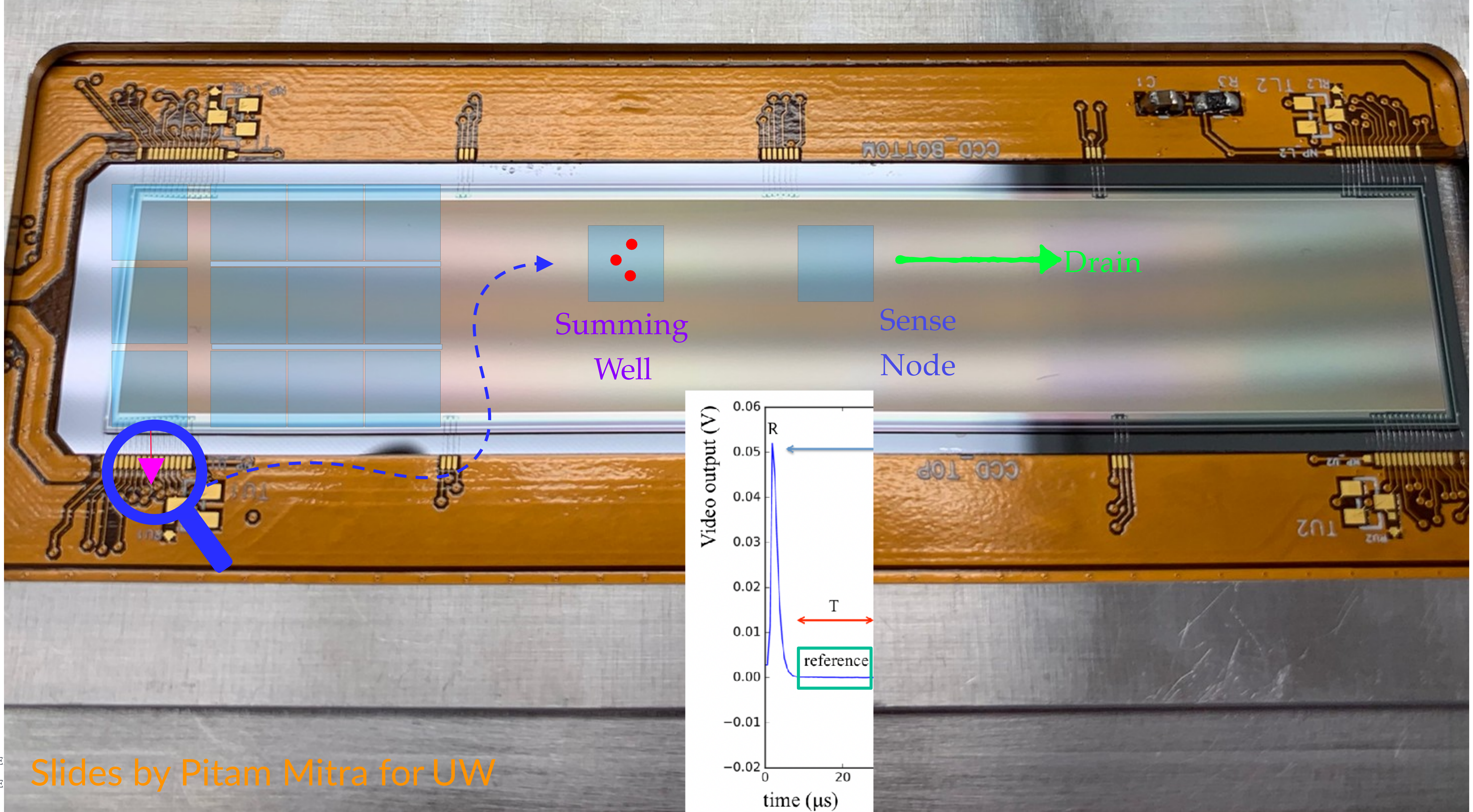

CCD: Moving charges

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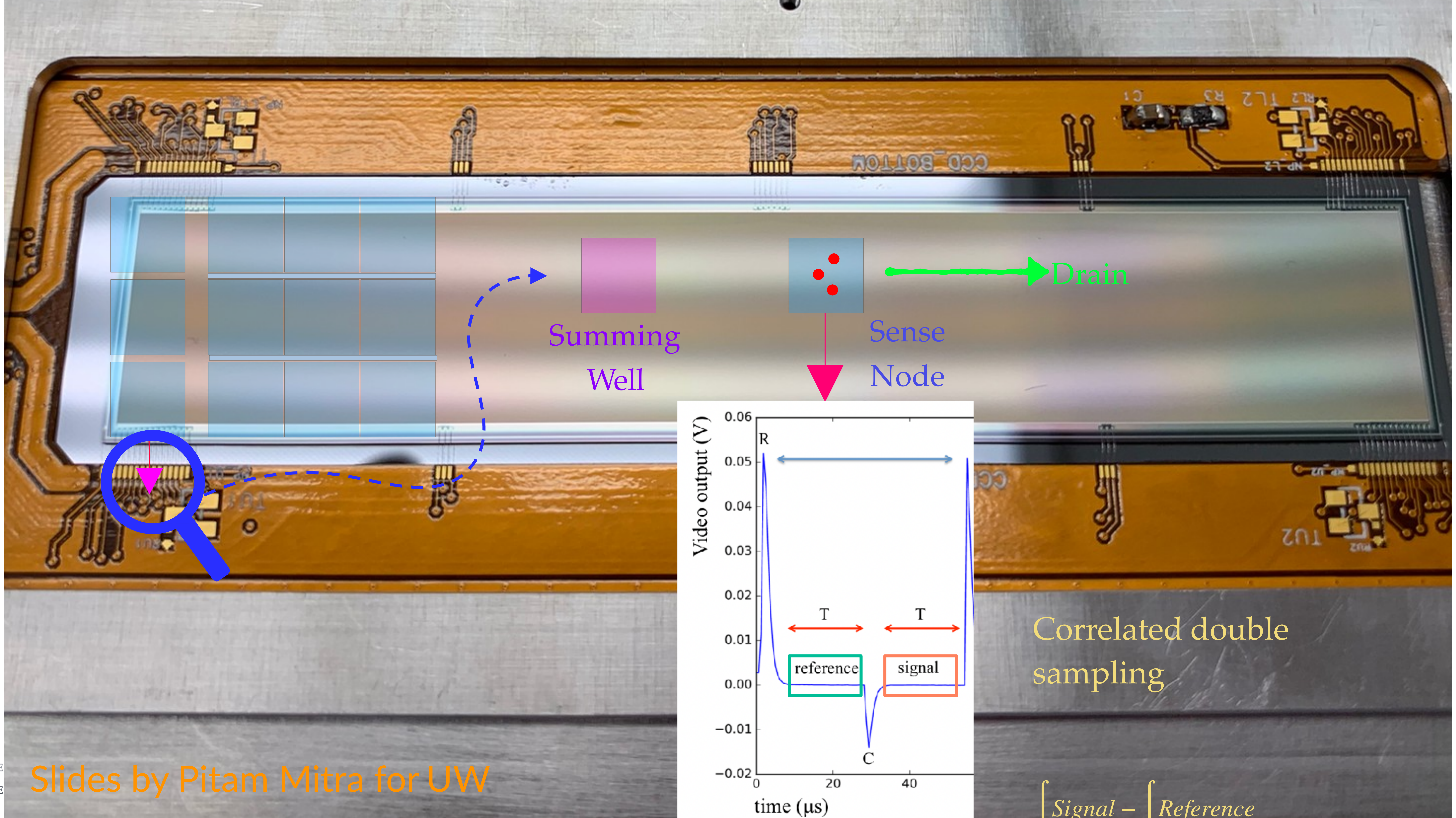

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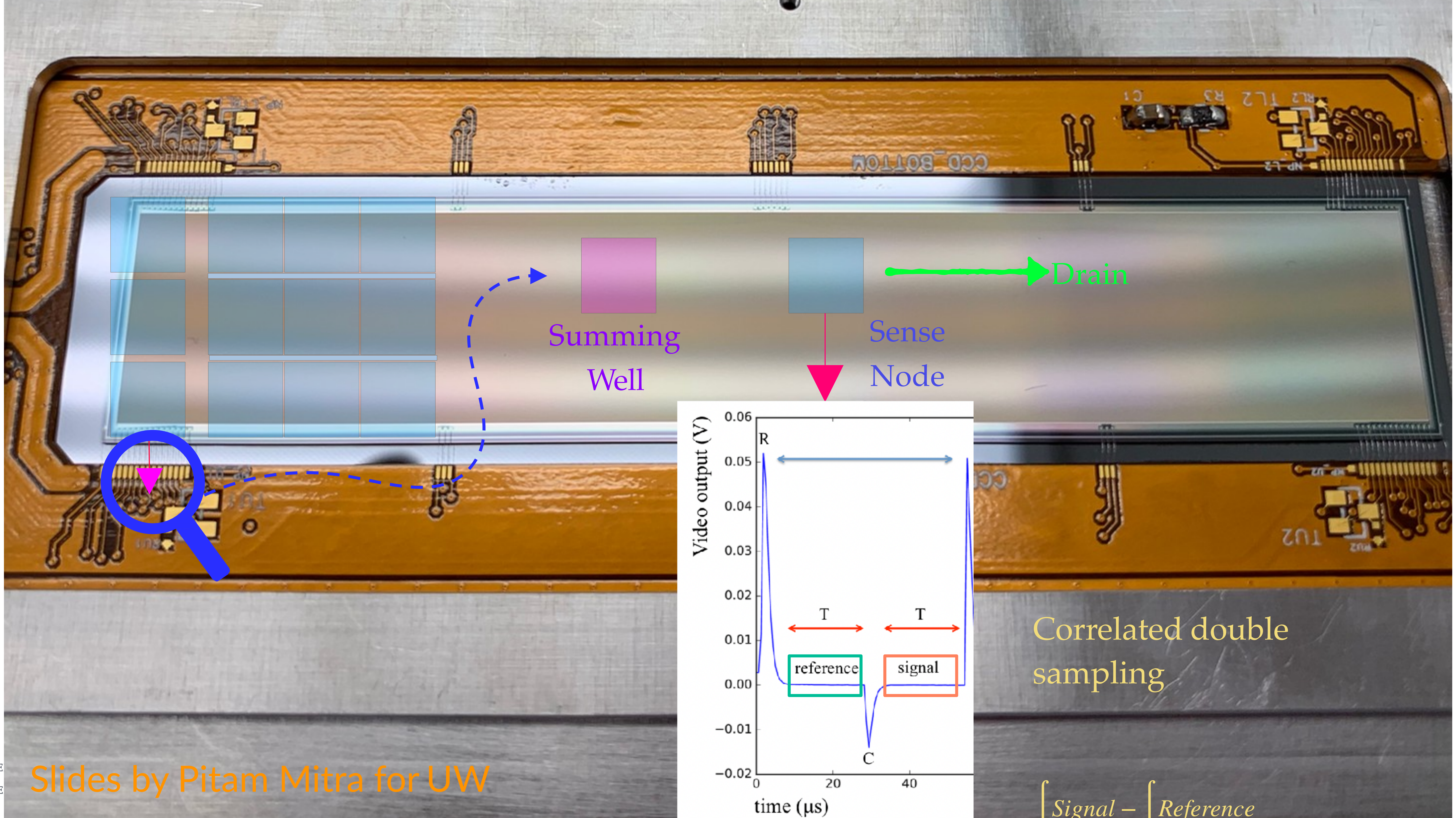

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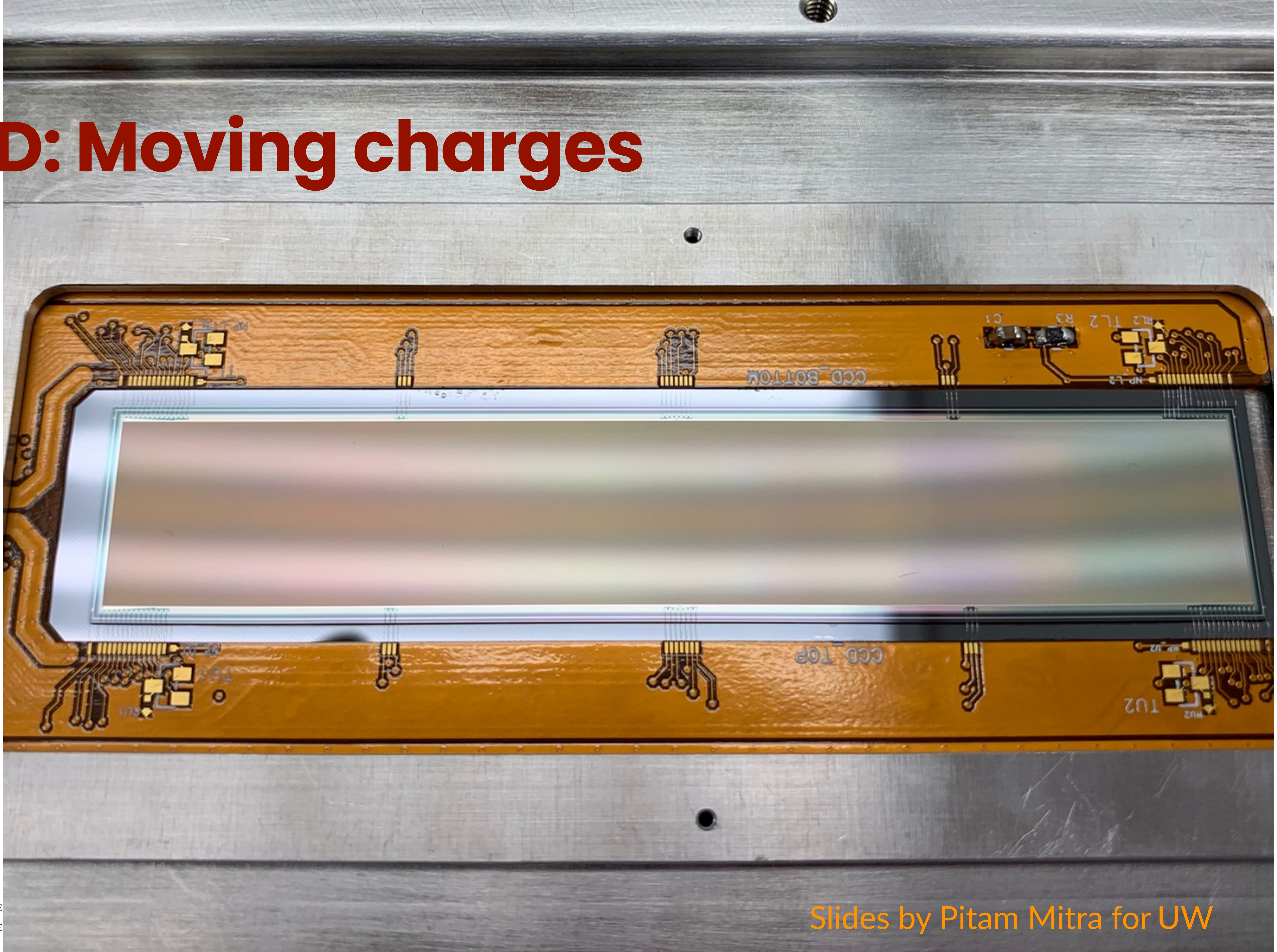
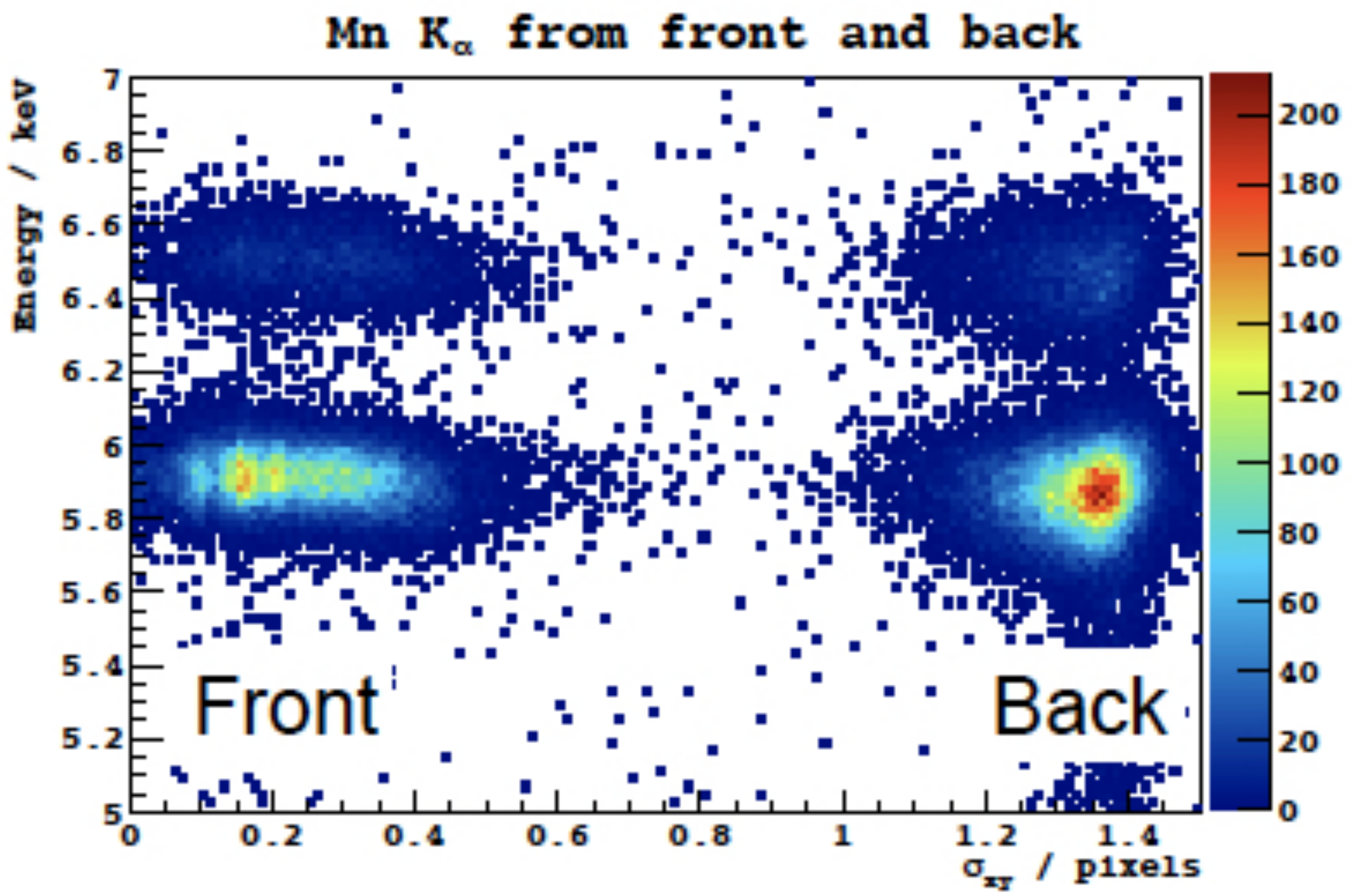
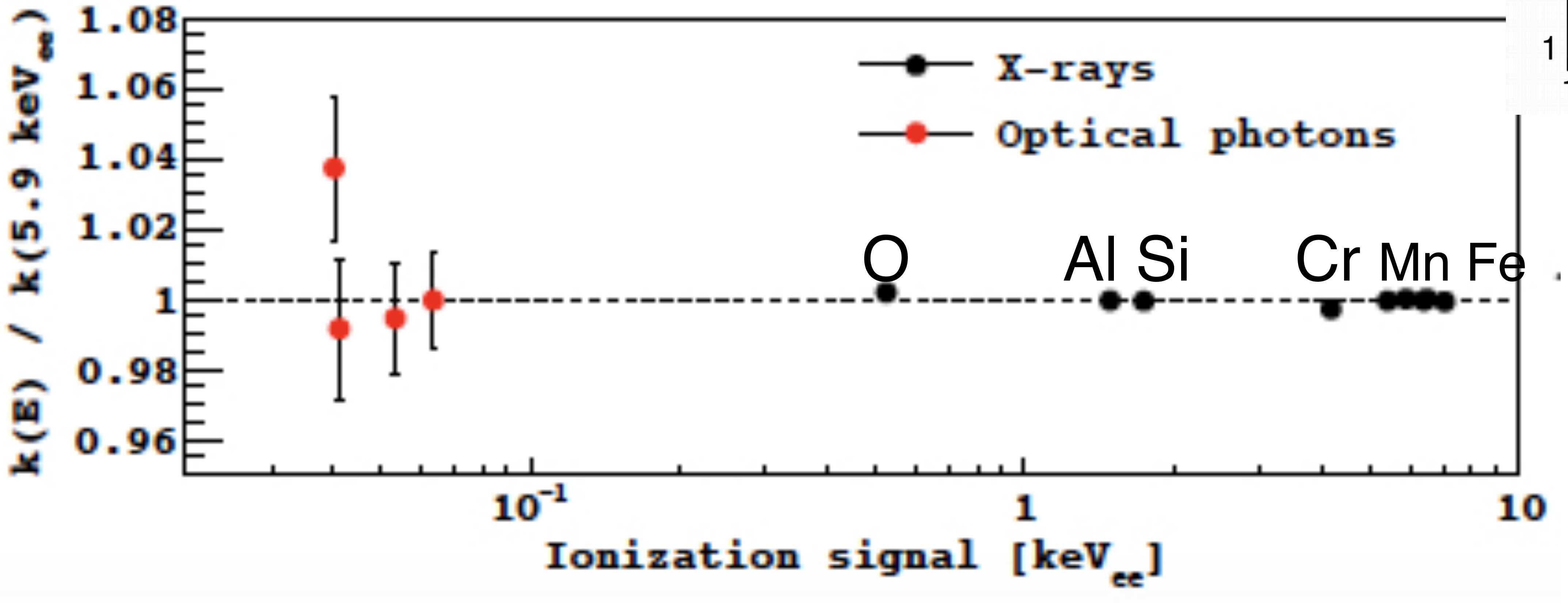
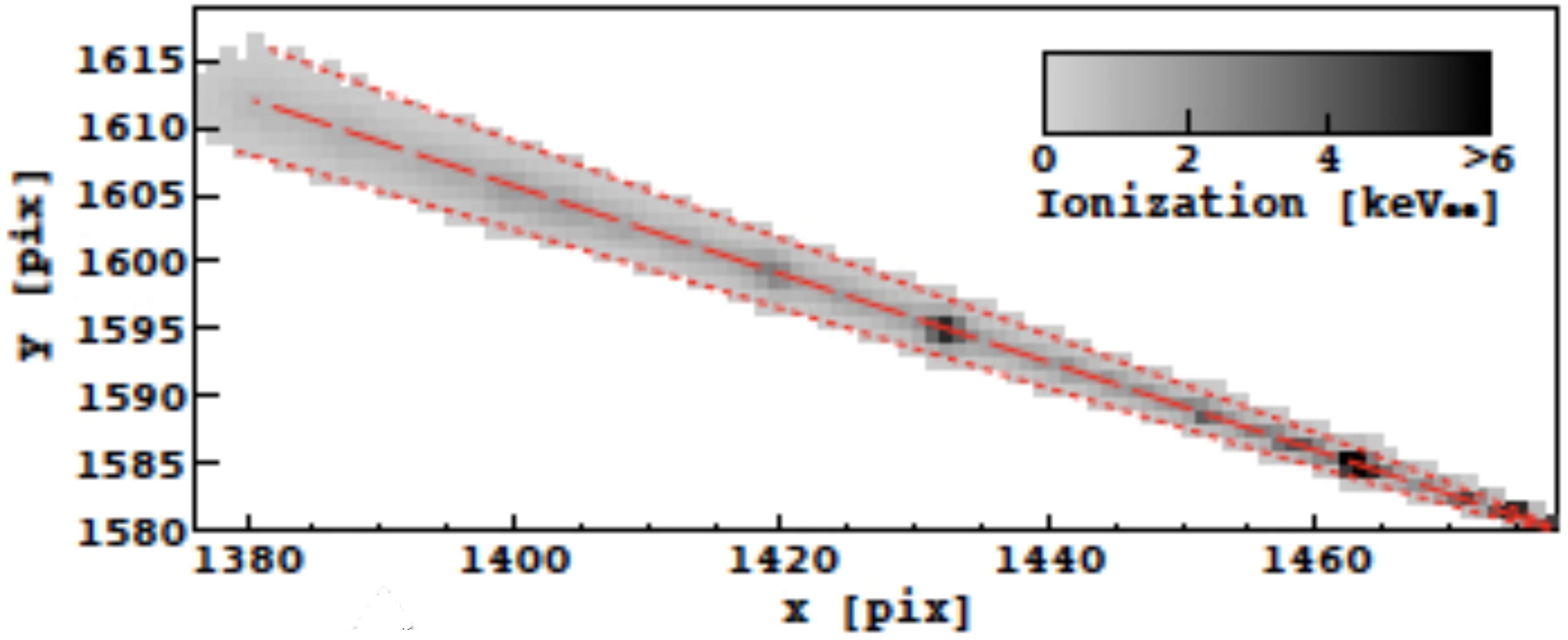


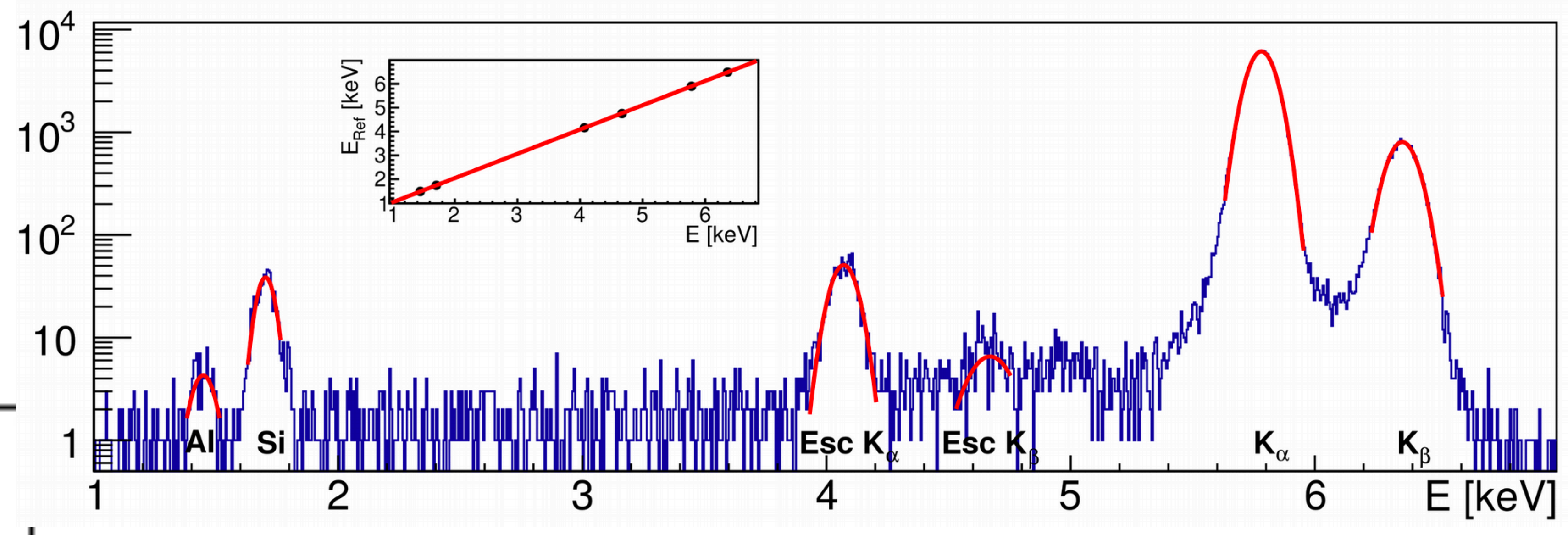
Detector Response

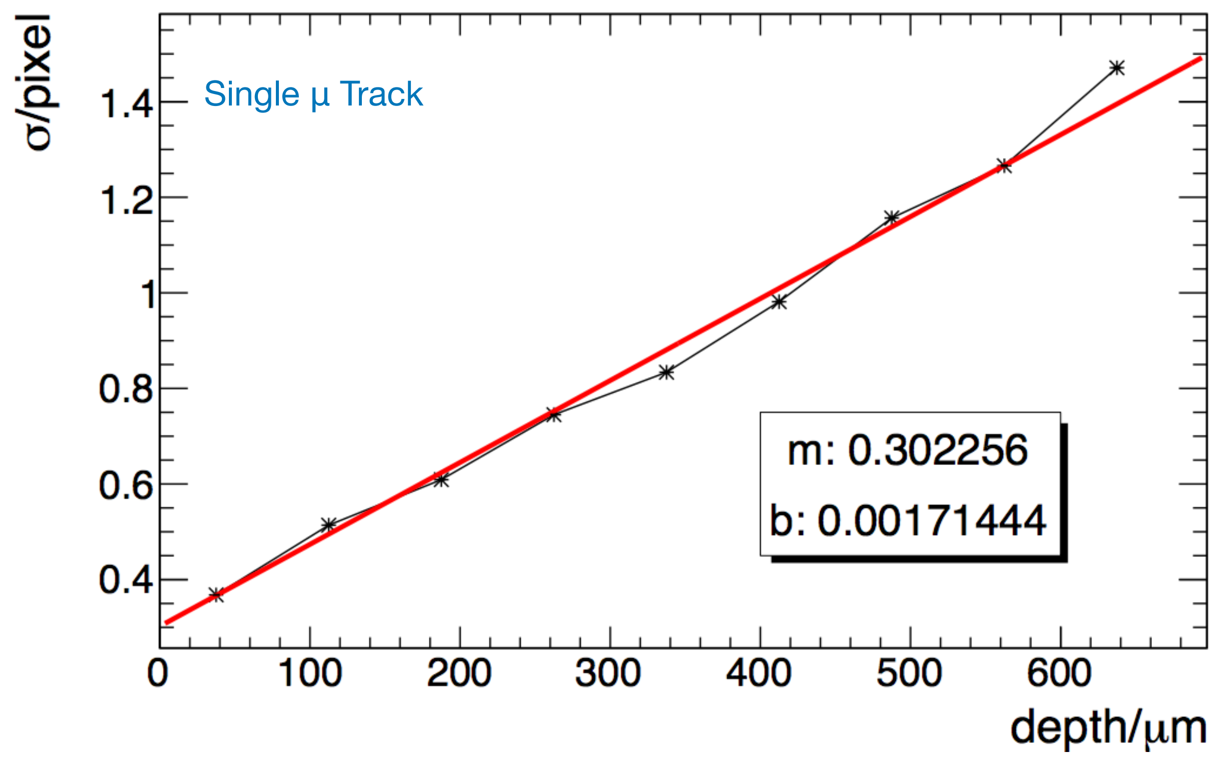


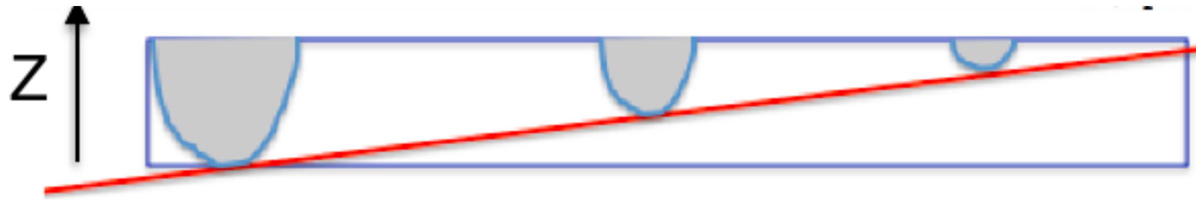




z reconstruction with X rays and cosmic rays



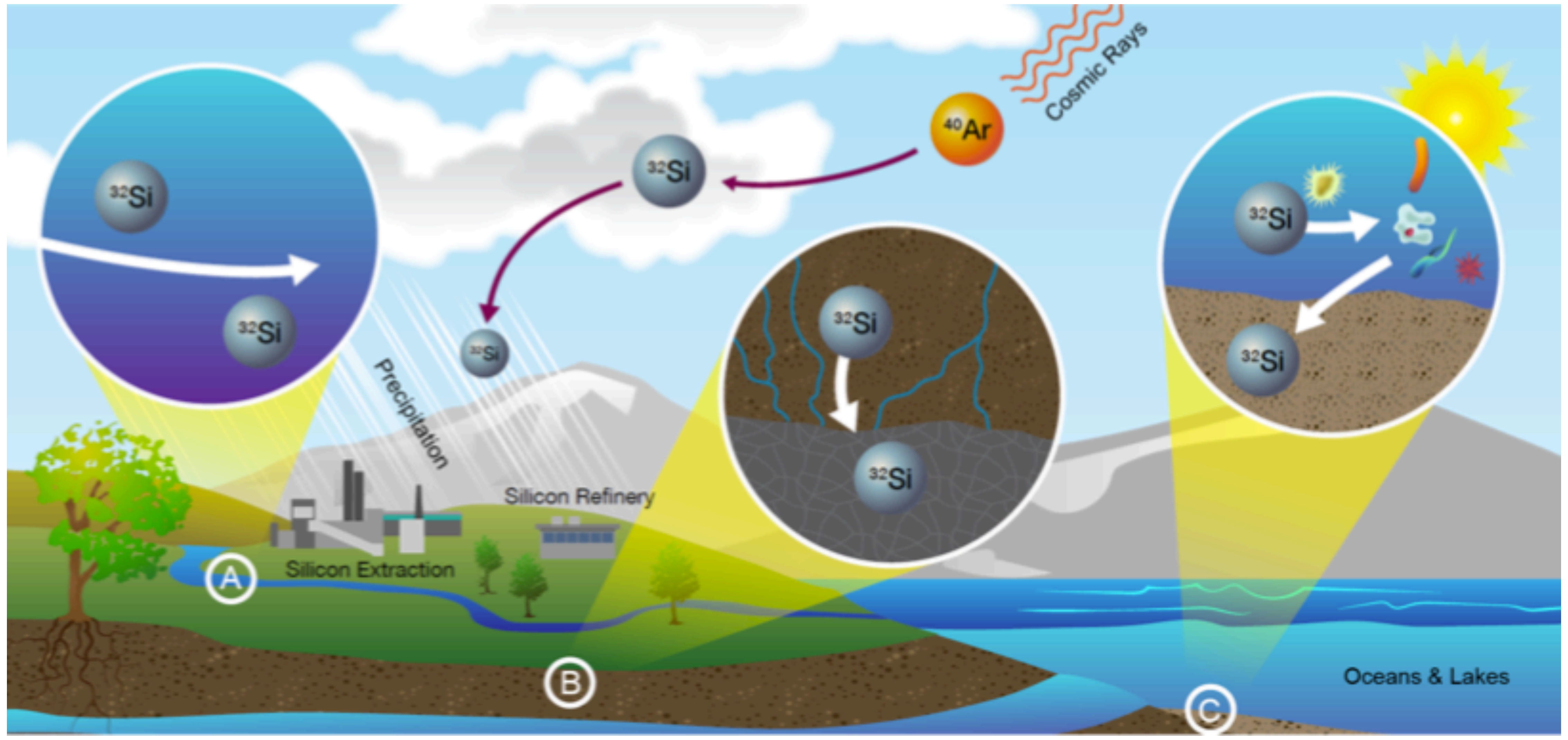




very nice linearity response of the CCDs down to 40eV using optical photons

Backgrounds

Cosmogenic isotopes

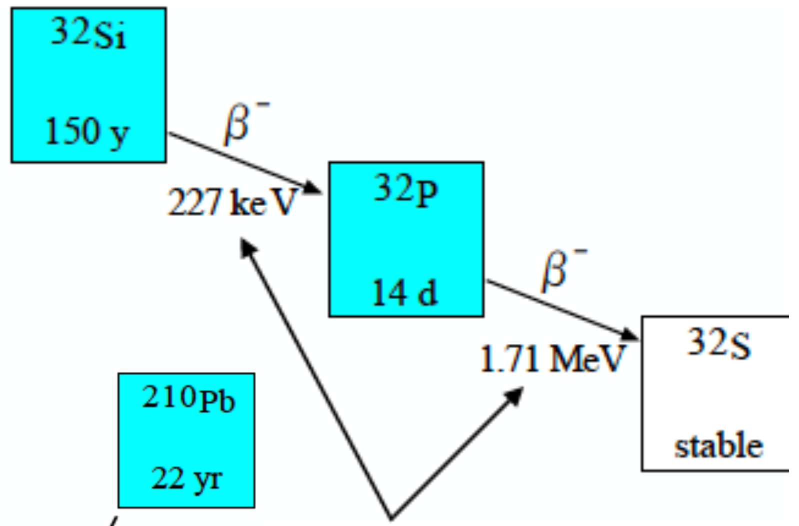


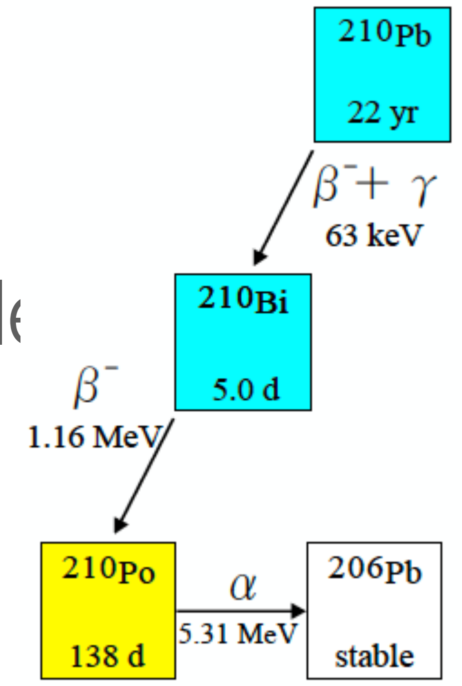
arXiv:1708.00110

^{32}Si, produced by cosmic ray spallation → bulk contamination

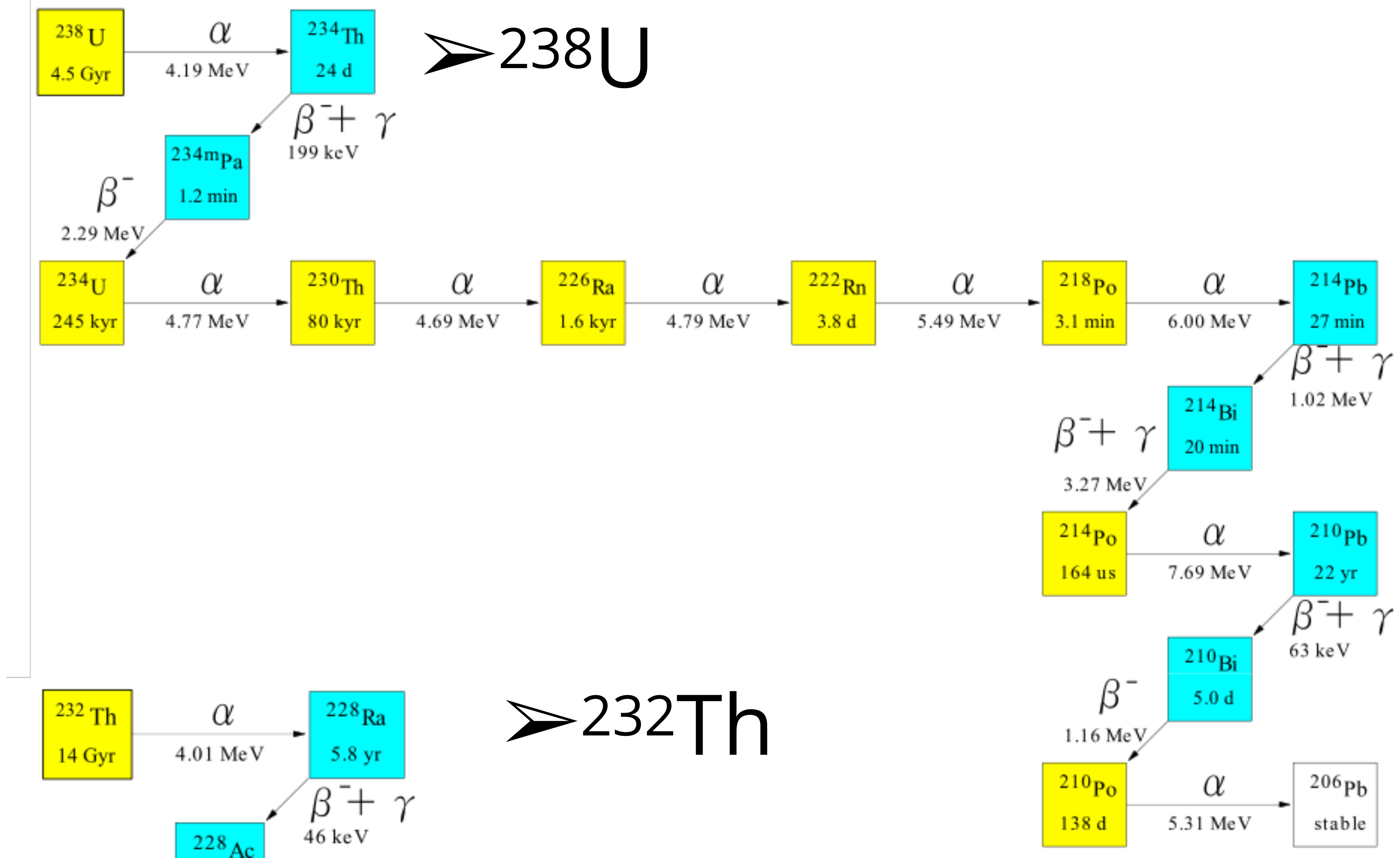
^{210}Pb, a daughter of radon decay → surface contamination

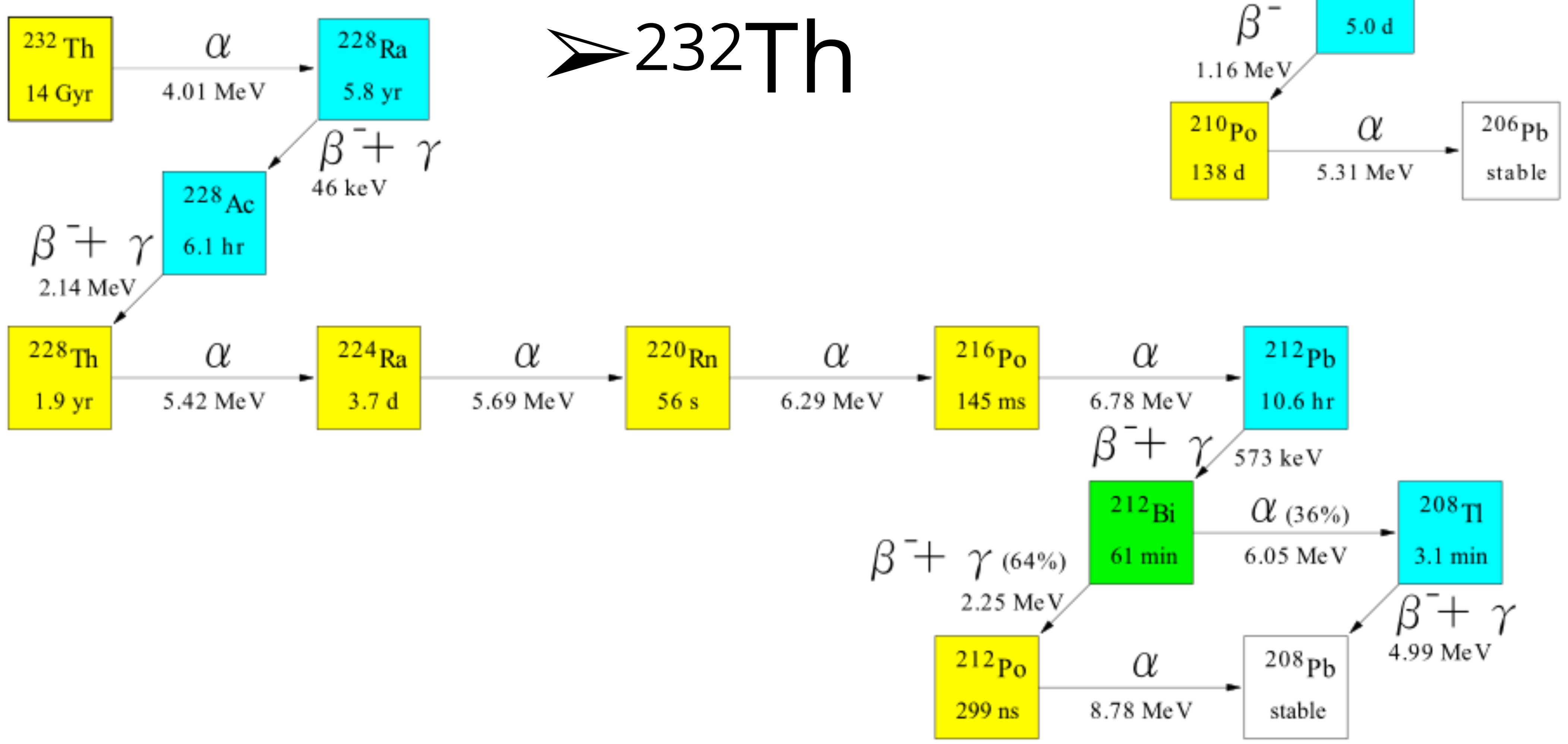
^{3}H produce by cosmogenic activation of Si while being on surface → surface and bulk contamination





Natural Radioactivity

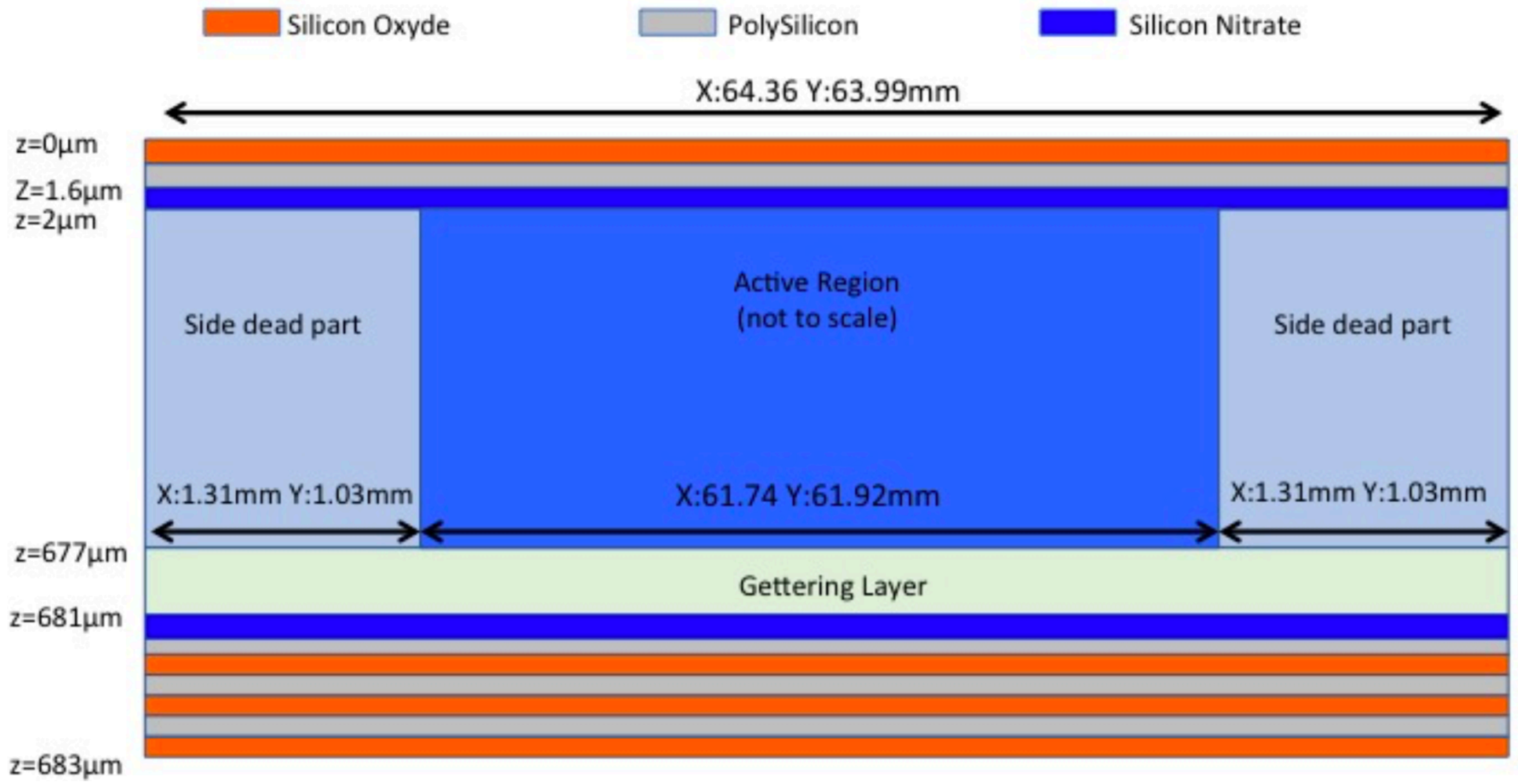




see A. Matalon presentation at LRT 2019 or A. Aguilar-Arevalo et al, Journal of Instrumentation, Volume 16, June 2021 for details

DAMIC SPATIAL COINCIDENCE ANALYSIS

Journal of Instrumentation, Volume 16, June 2021



Main Surface Contaminants

Deposition

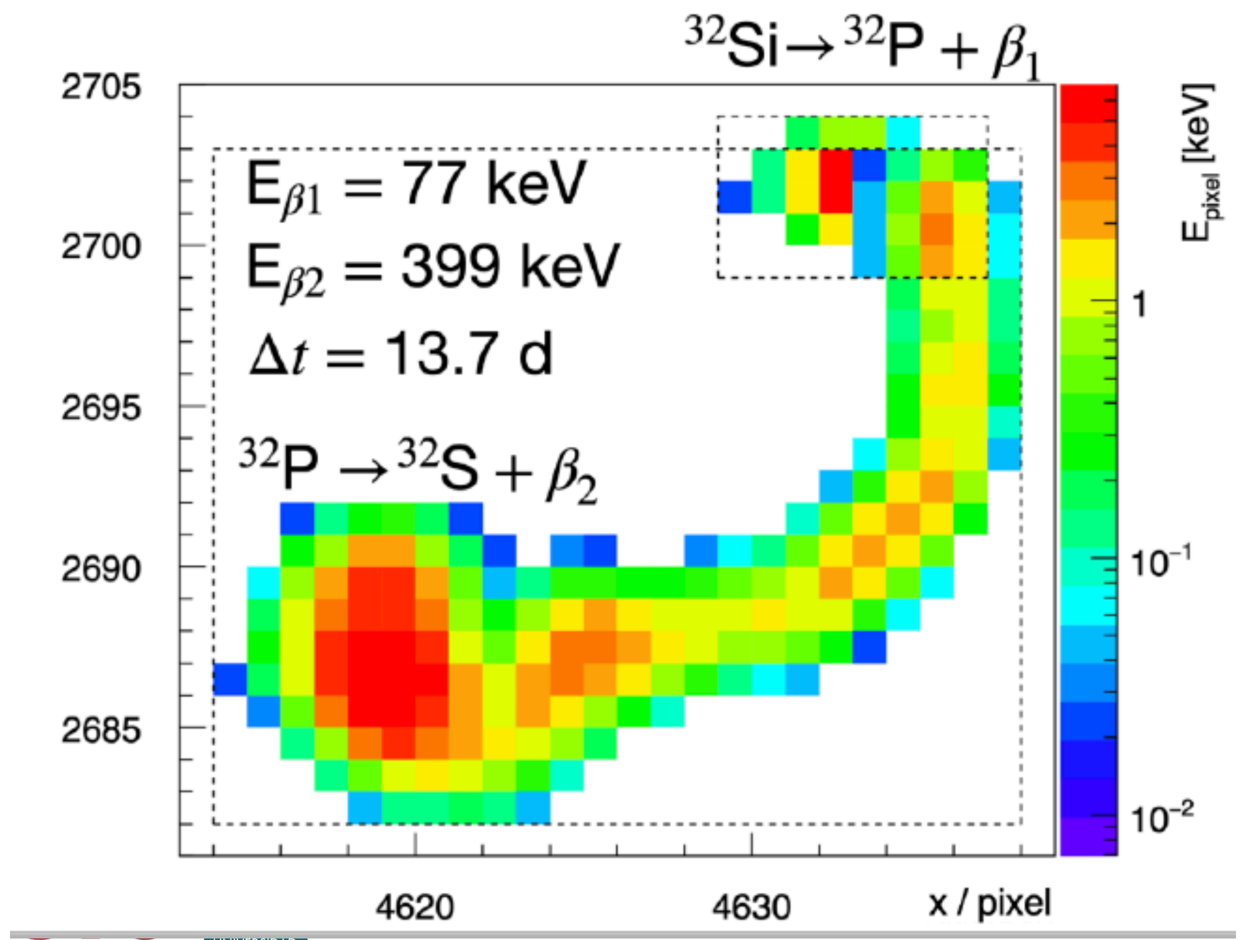
Decay Sequence	$t_{1/2}$	Q-value
$^{210}\mathrm{Pb} \longrightarrow {}^{210}\mathrm{Bi} + \beta^- + \mathrm{IC}/\gamma$	22.3 y	63.5 keV
$^{210}\mathrm{Bi} \longrightarrow {}^{210}\mathrm{Po} + \beta^-$	5.01 d	1.16 MeV
$^{210}\mathrm{Po} \longrightarrow {}^{206}\mathrm{Po}\,(\mathrm{stable}) + \alpha$	138 d	5.41 MeV

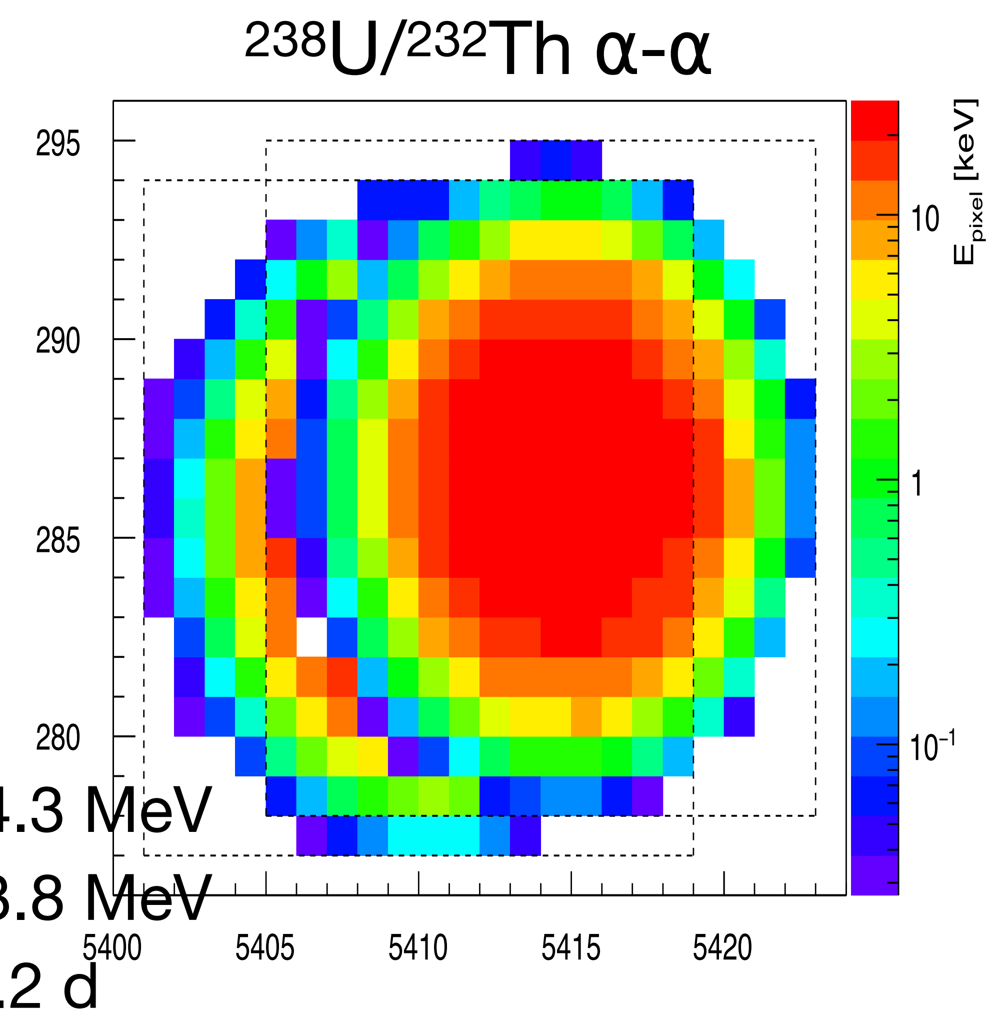
Main Bulk Contaminants

Activation in CCD

Decay Sequence	$t_{1/2}$	Q-value
$^{32}\mathrm{Si} \longrightarrow {}^{32}\mathrm{P} + \beta^-$	150 y	225 keV
$^{32}\mathrm{P} \longrightarrow {}^{32}\mathrm{S}\,(\mathrm{stable}) + \beta^-$	14.3 d	1.71 MeV

Decay	$t_{1/2}$	Q-value
$^{3}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + \beta^-$	12.3 y	18.6 keV





- Limits on radioactive contaminants:
  - ^{210}Pb: < 160 µBq/kg
  - ^{32}Si: 140±30 µBq/kg
  - ^{238}U: < 11 µBq/kg
  - ^{232}Th: < 7.3 µBq/kg

EXCELENCIA MARÍA DE MAEZTU

Calibration: Compton measurements

Aim:

- Parametrize Compton spectrum at low energy (main source of background for DM search)
- Provide detector calibration

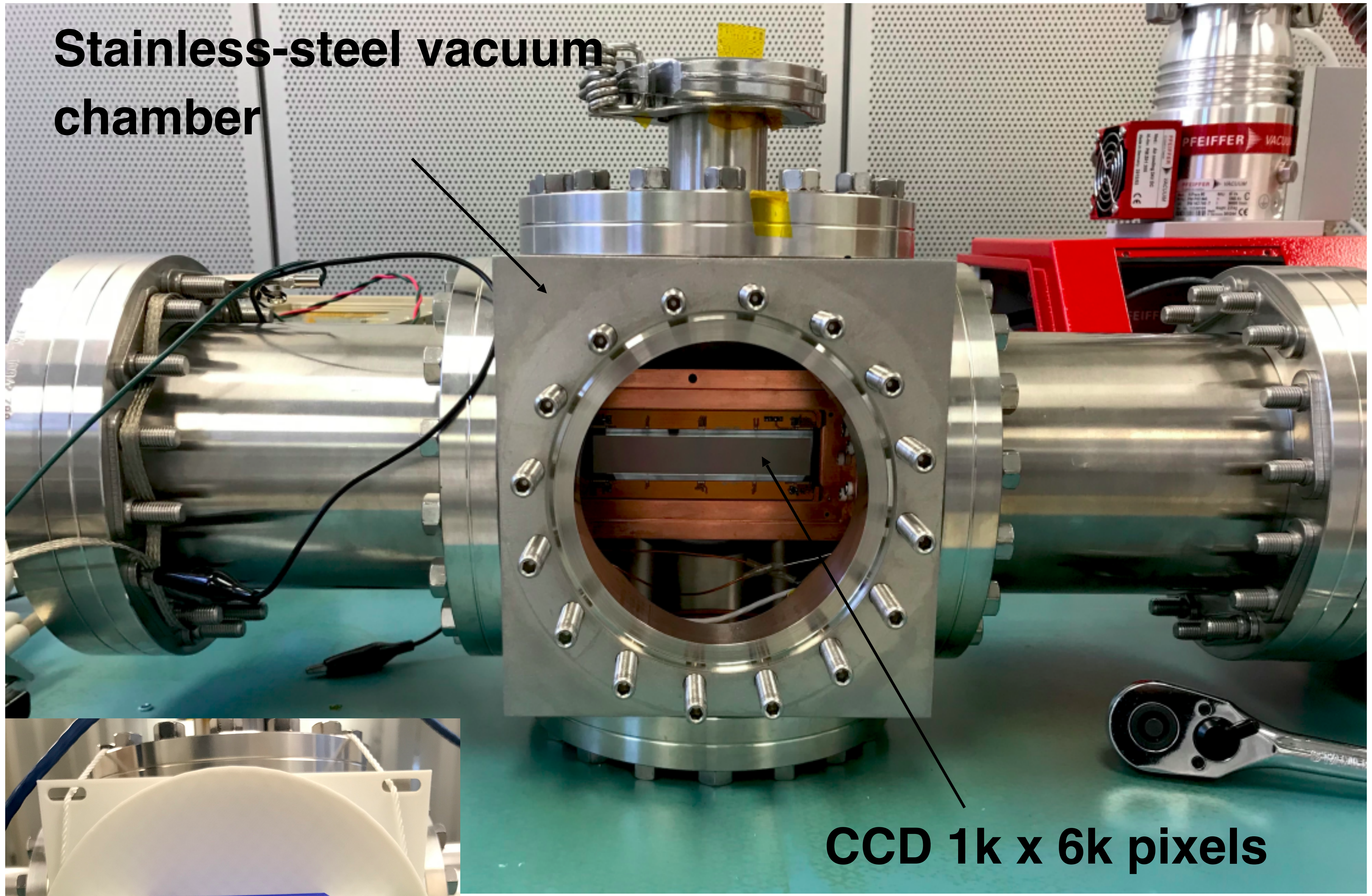
Setup:

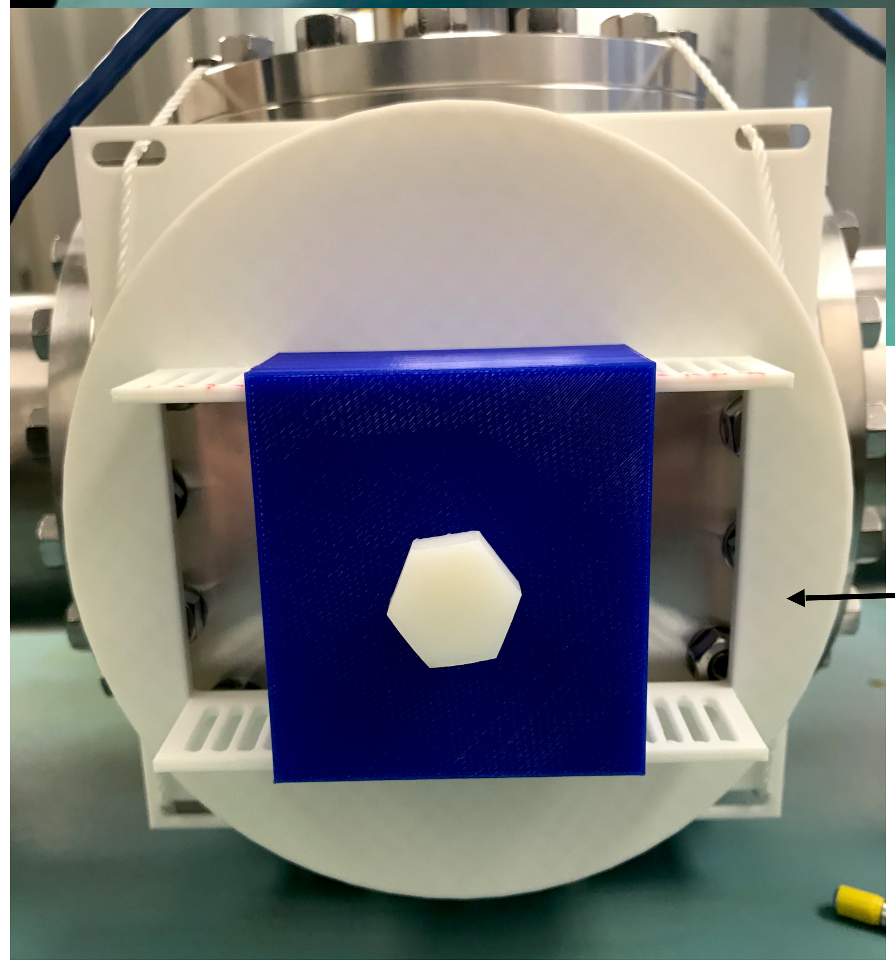
- Temperature: 126 K
- γ source: Am241 (γ Energy: 26.3 keV & **59.5 keV)**
- 1 skipper CCD (1k x 6k pixels)

Readout:

- 64 skips
- 0.7 e- readout noise (~2.6 eV)
- binning: 4 pixels x 4 pixels

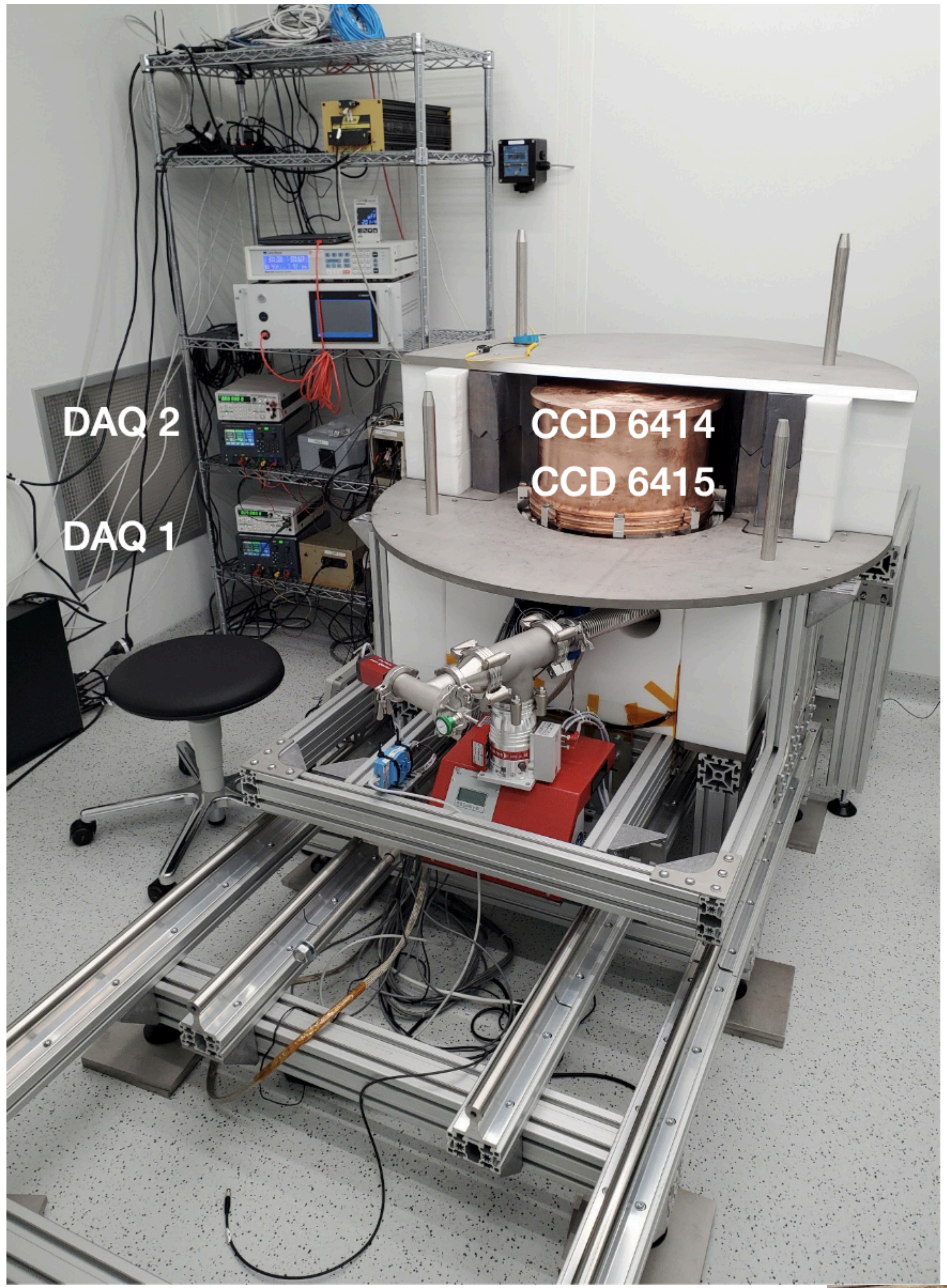
We are starting neutron source measurement

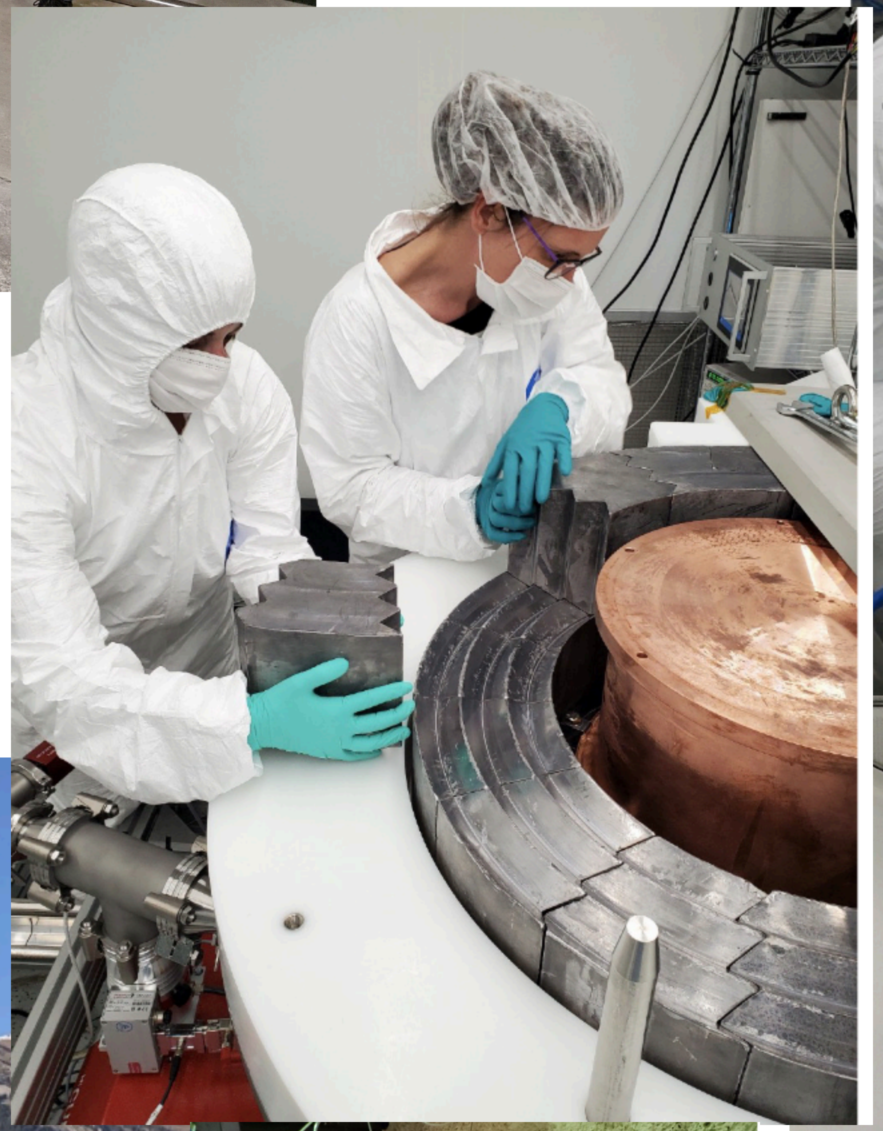


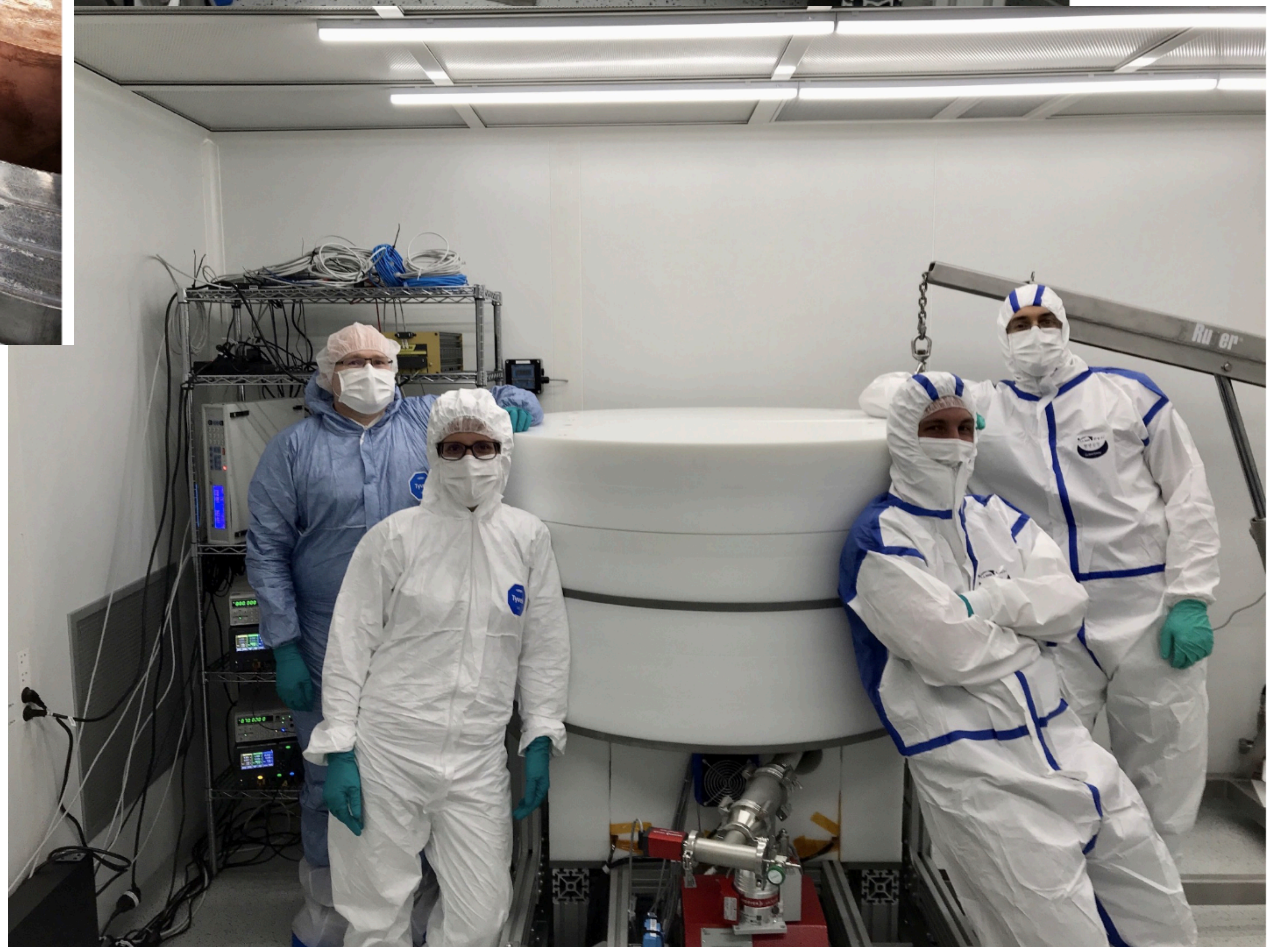


Am241 source support

Low Background Chamber

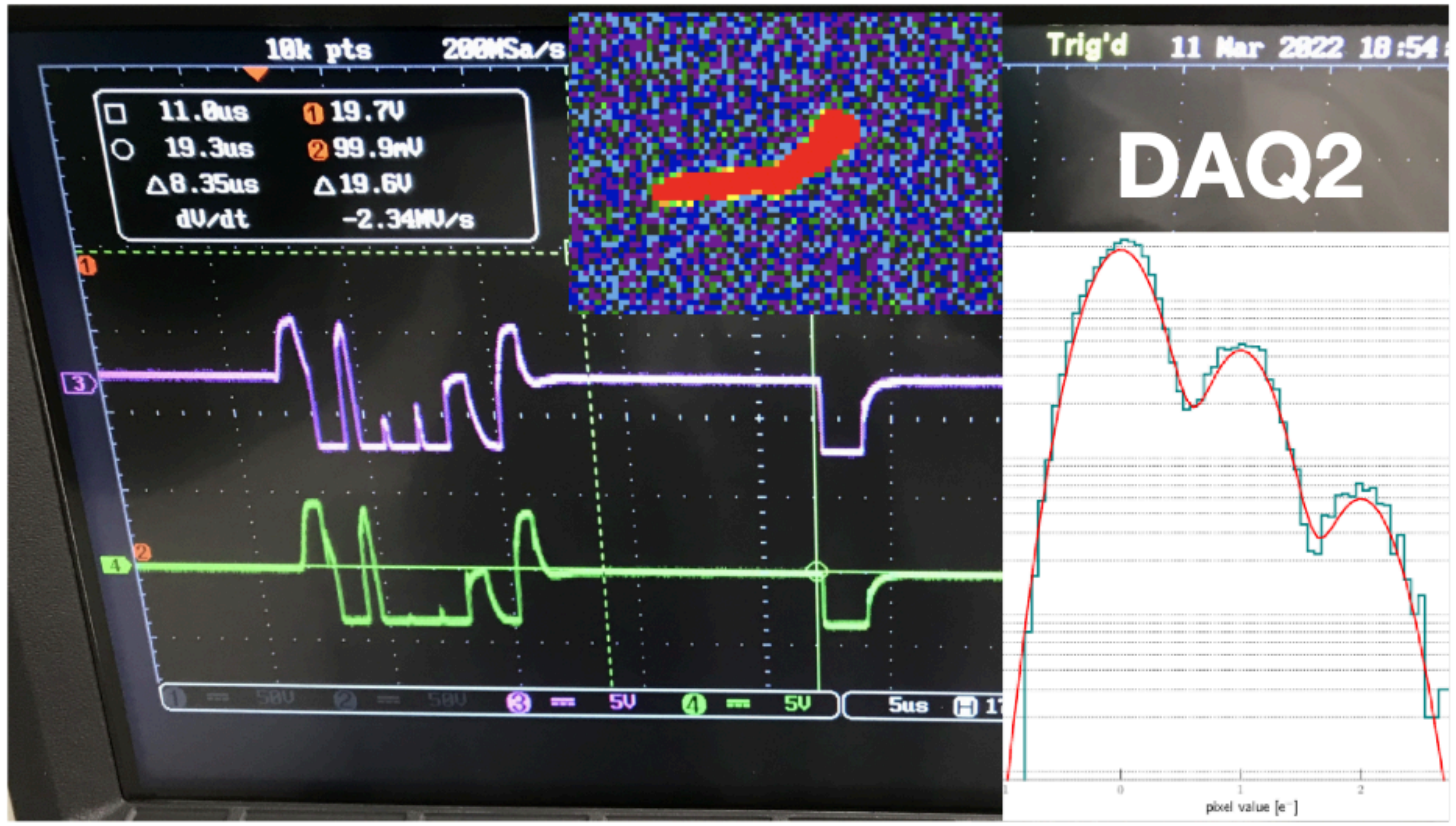


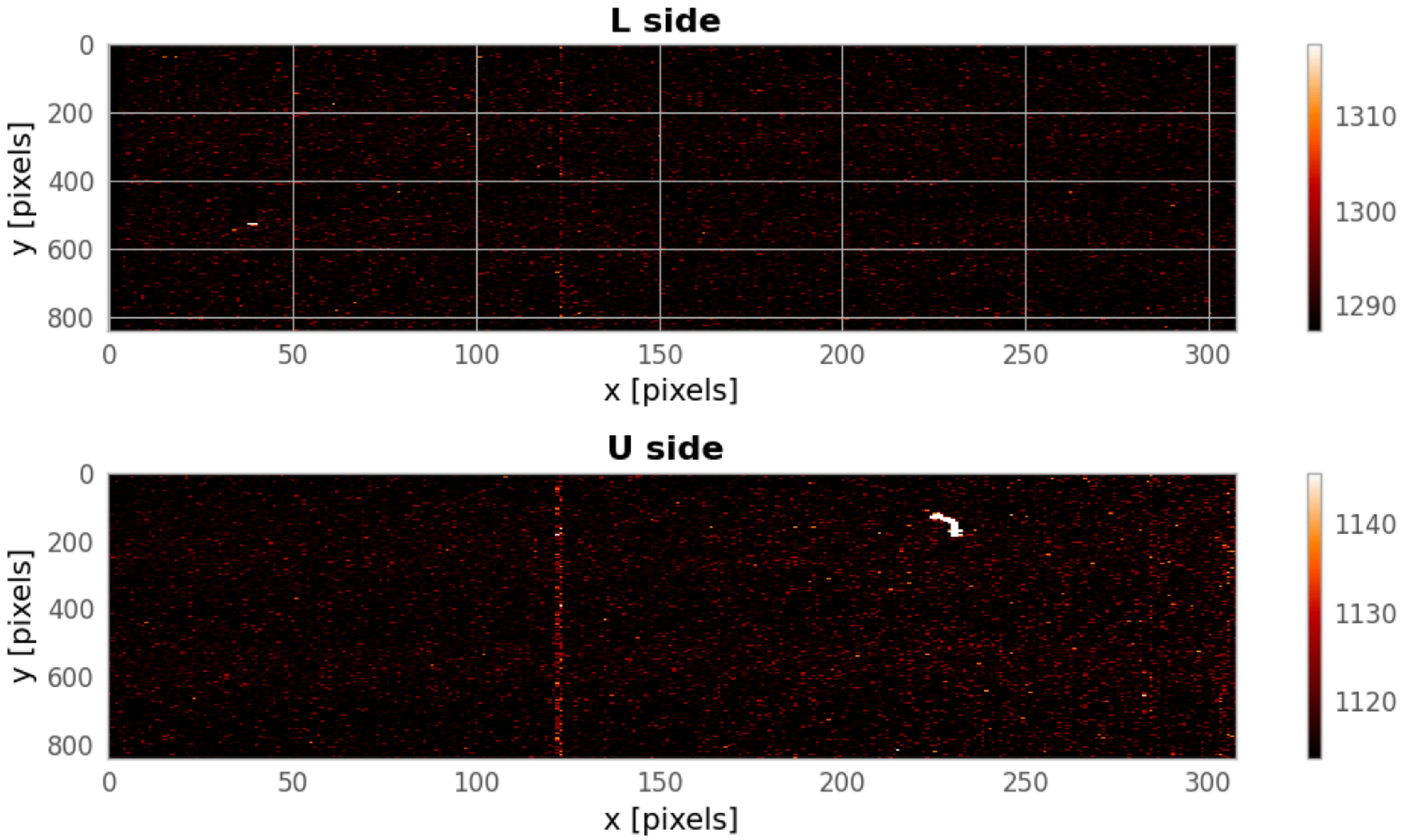


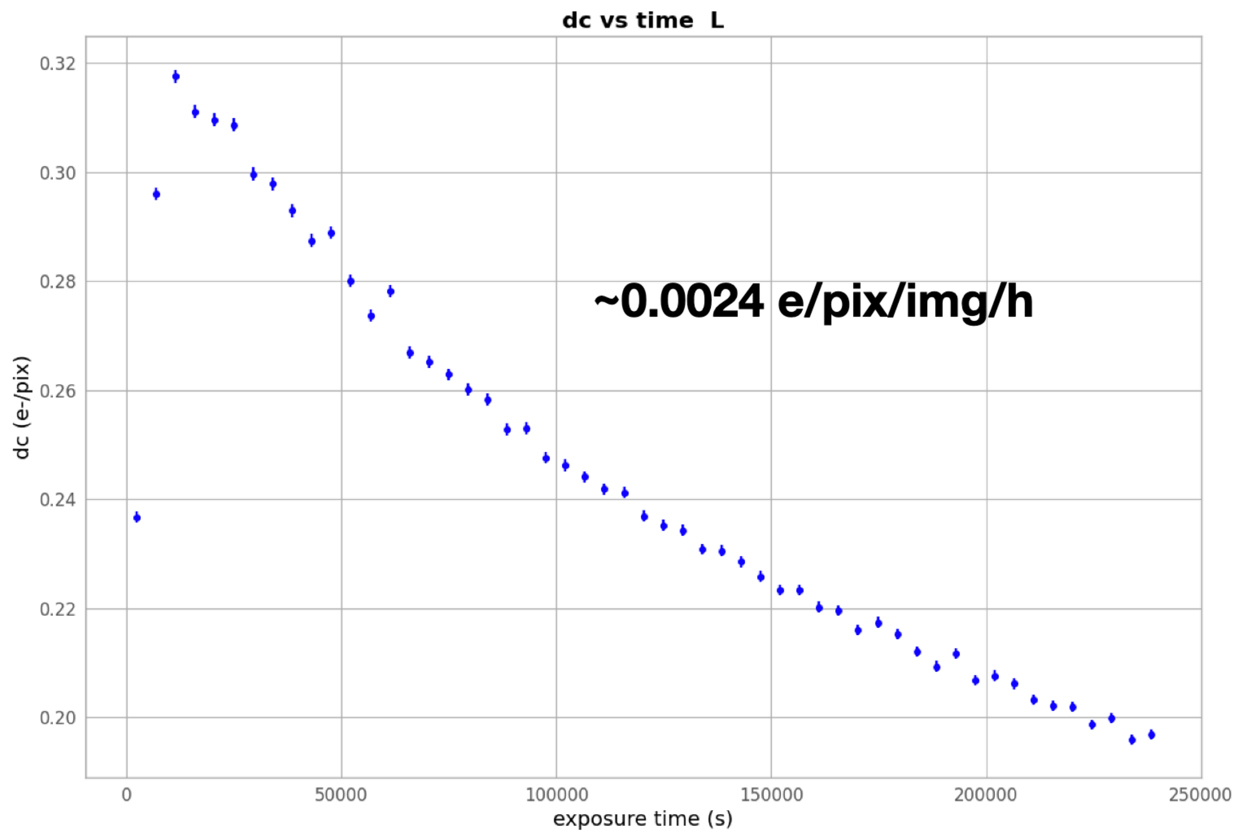


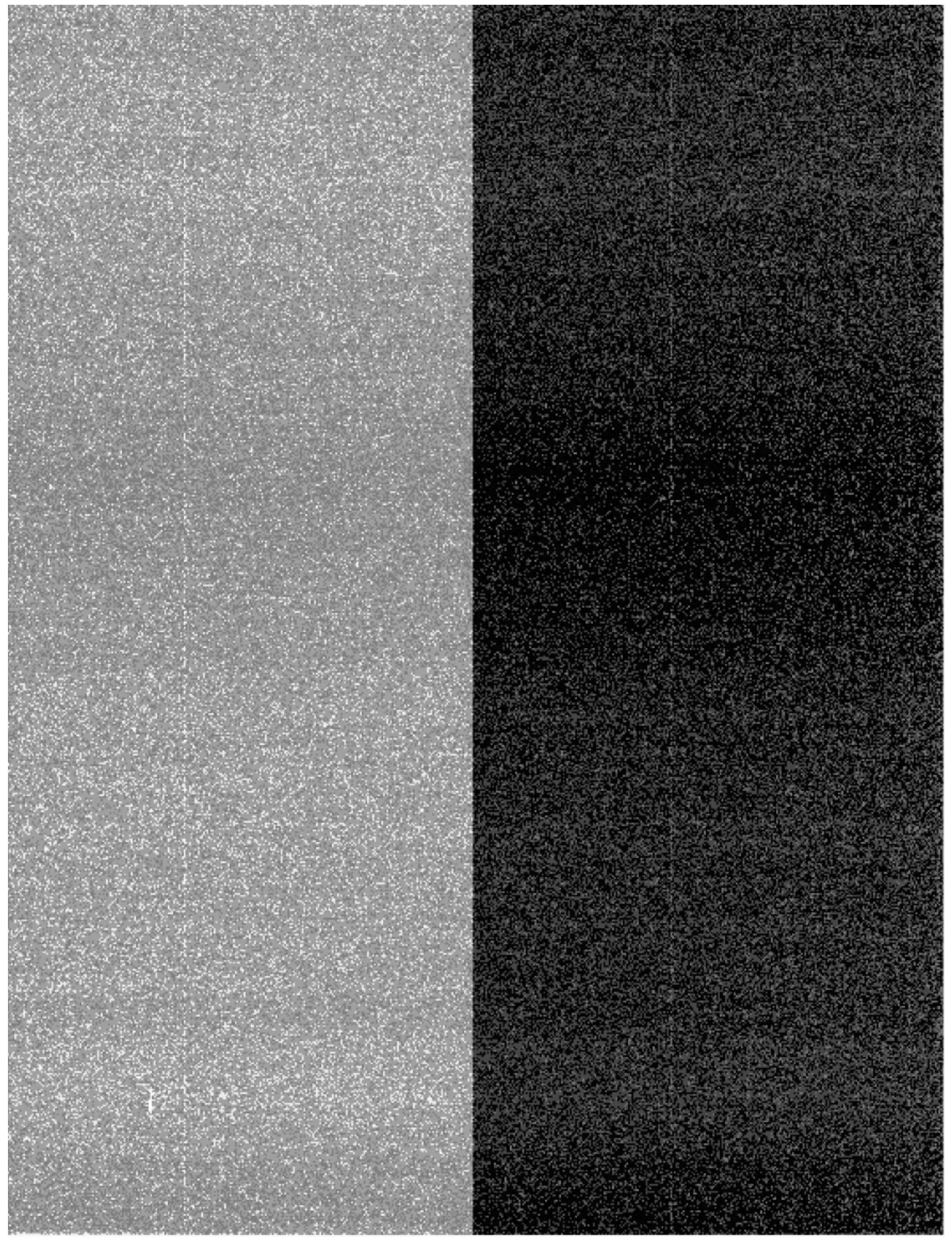
LBC


DAQ1
10k pts
200MSa/s
Trig'd
-150ns
300ns
△450ns
dV/dt
281V
1.88V
△280V
-444MV/s
pixel value [e⁻]


DAQ2
10k pts
200MSa/s
Trig'd
11 Mar 2022 18:54
11.0us
19.3us
△8.35us
dV/dt
19.7V
99.9mV
△19.6V
-2.34MV/s
pixel value [e⁻]

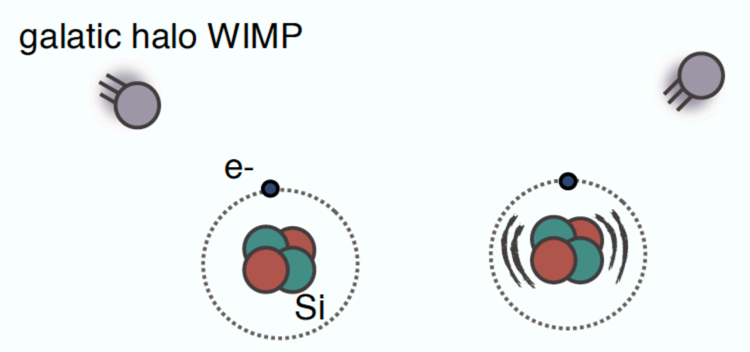

L side
U side
y [pixels]
x [pixels]
0
200
400
600
800
50
100
150
200
250
300
1310
1300
1290
1140
1130
1120


dc vs time L
~0.0024 e/pix/img/h
dc (e-/pix)
exposure time (s)
0
50000
100000
150000
200000
250000
0.20
0.22
0.24
0.26
0.28
0.30
0.32



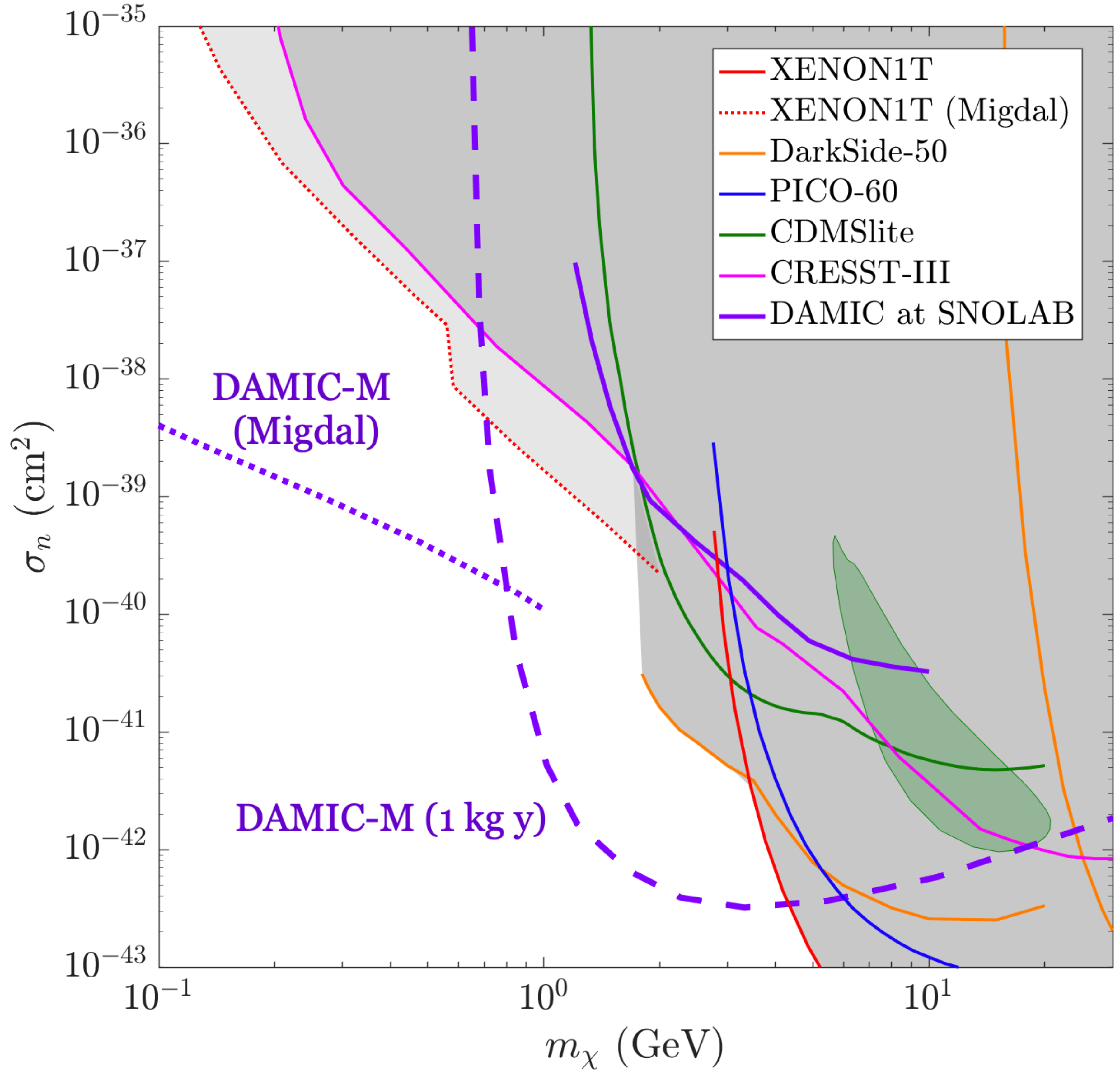
DAMIC-M Sensitivity

Light WIMPs

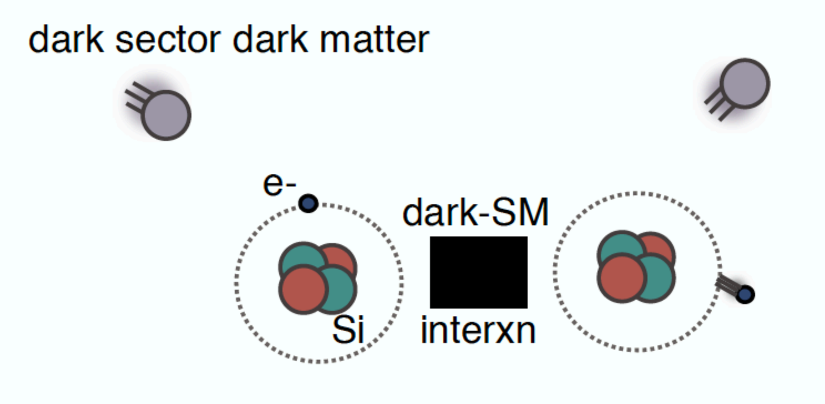


WIMP-nucleus elastic scattering:

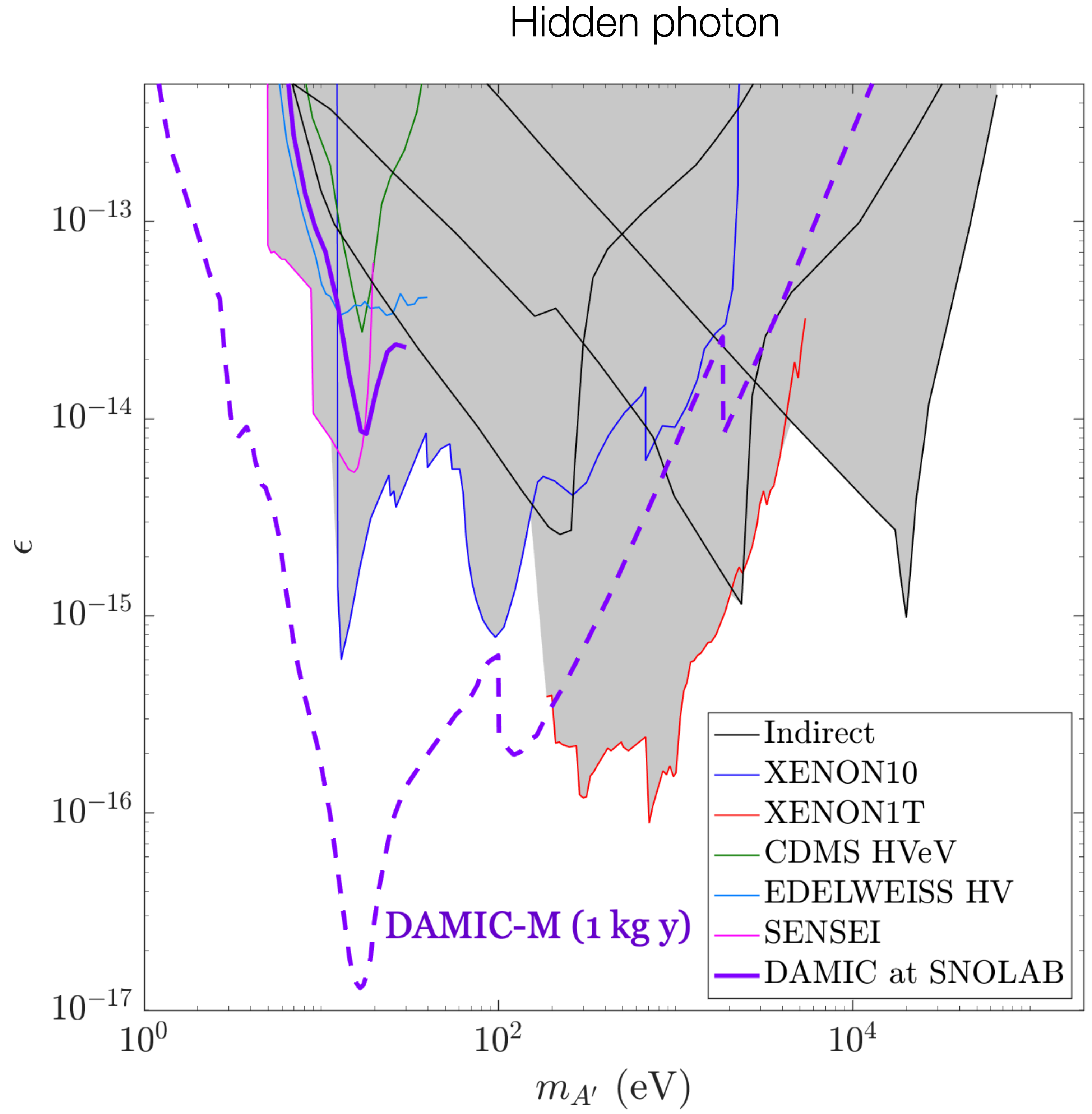
*can also detect secondary electron recoils from inelastic Migdal effect

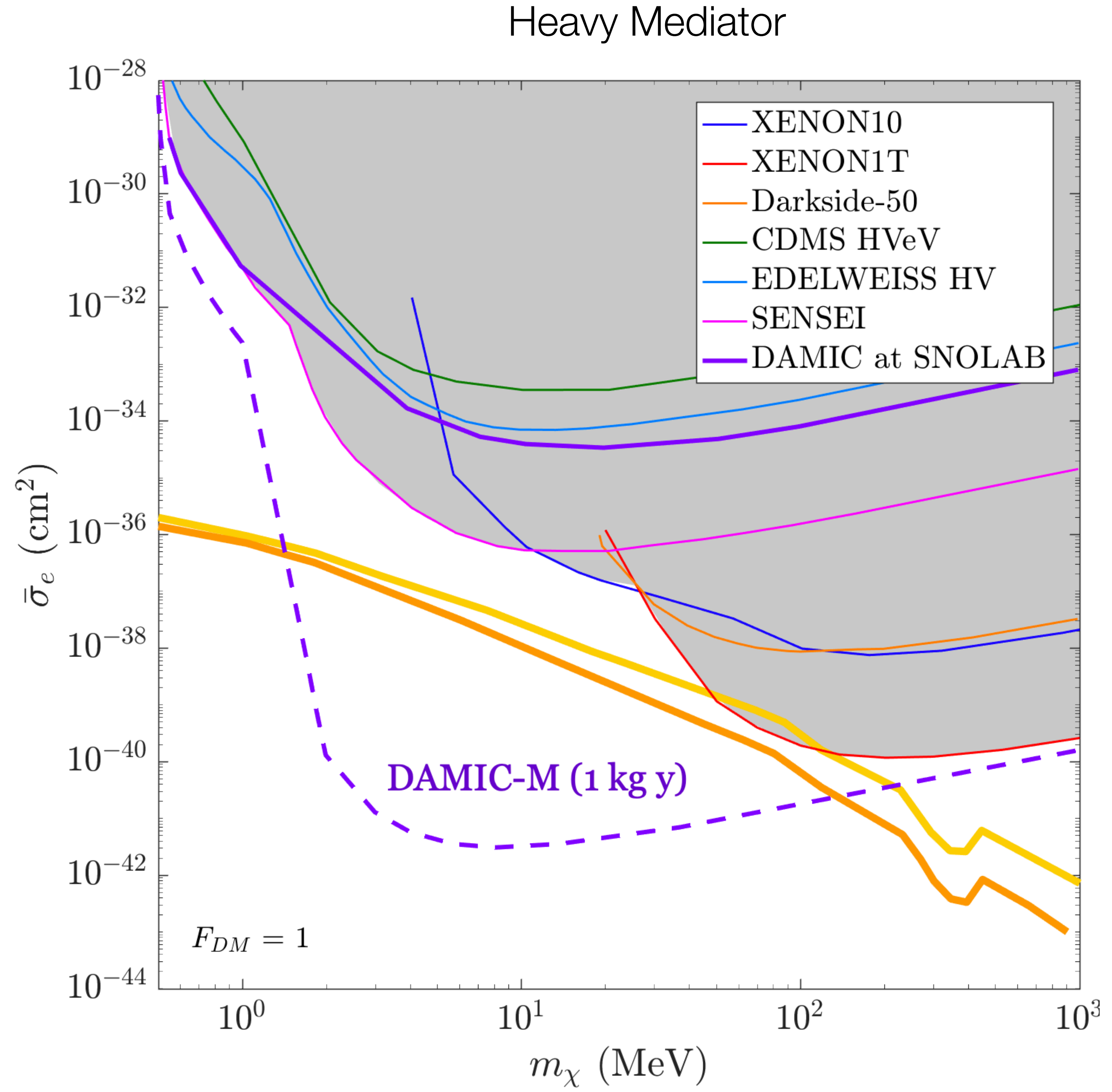


Dark Sectors



Dark sector-electron elastic scattering:

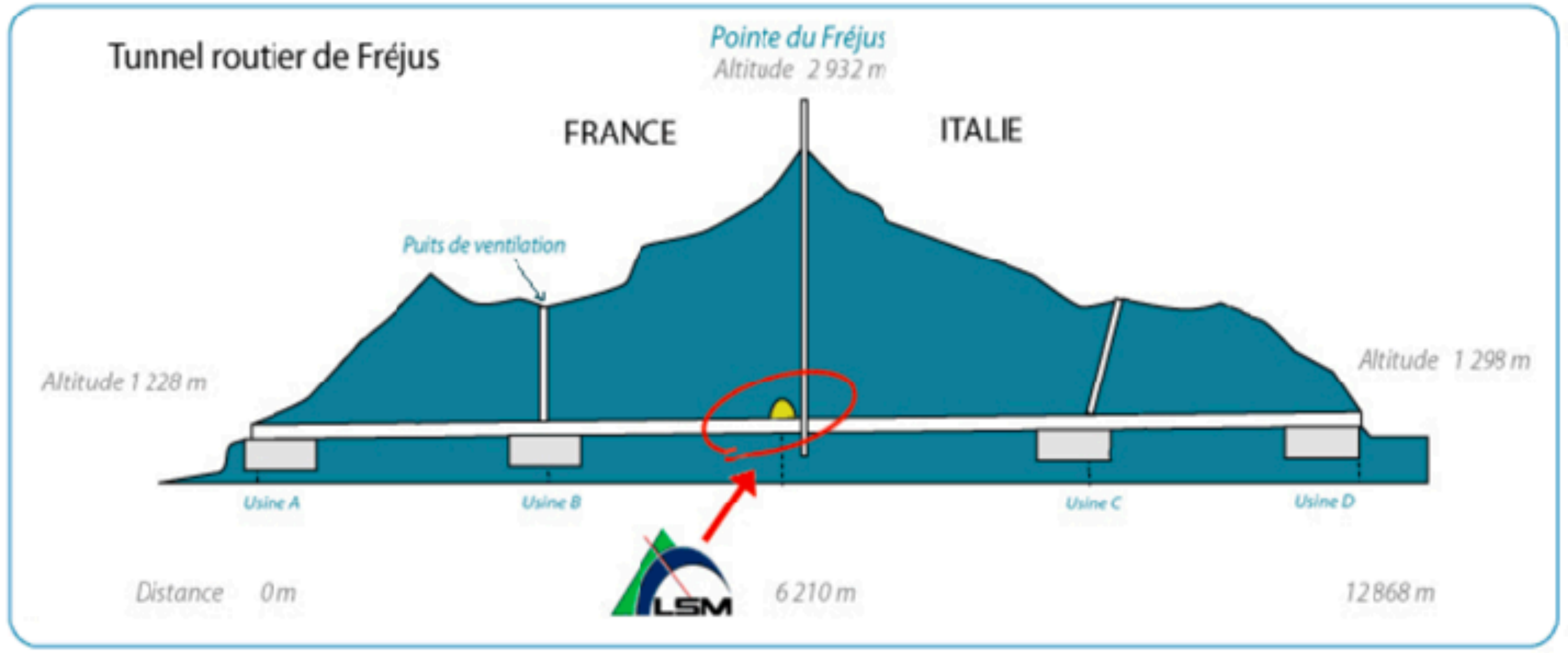


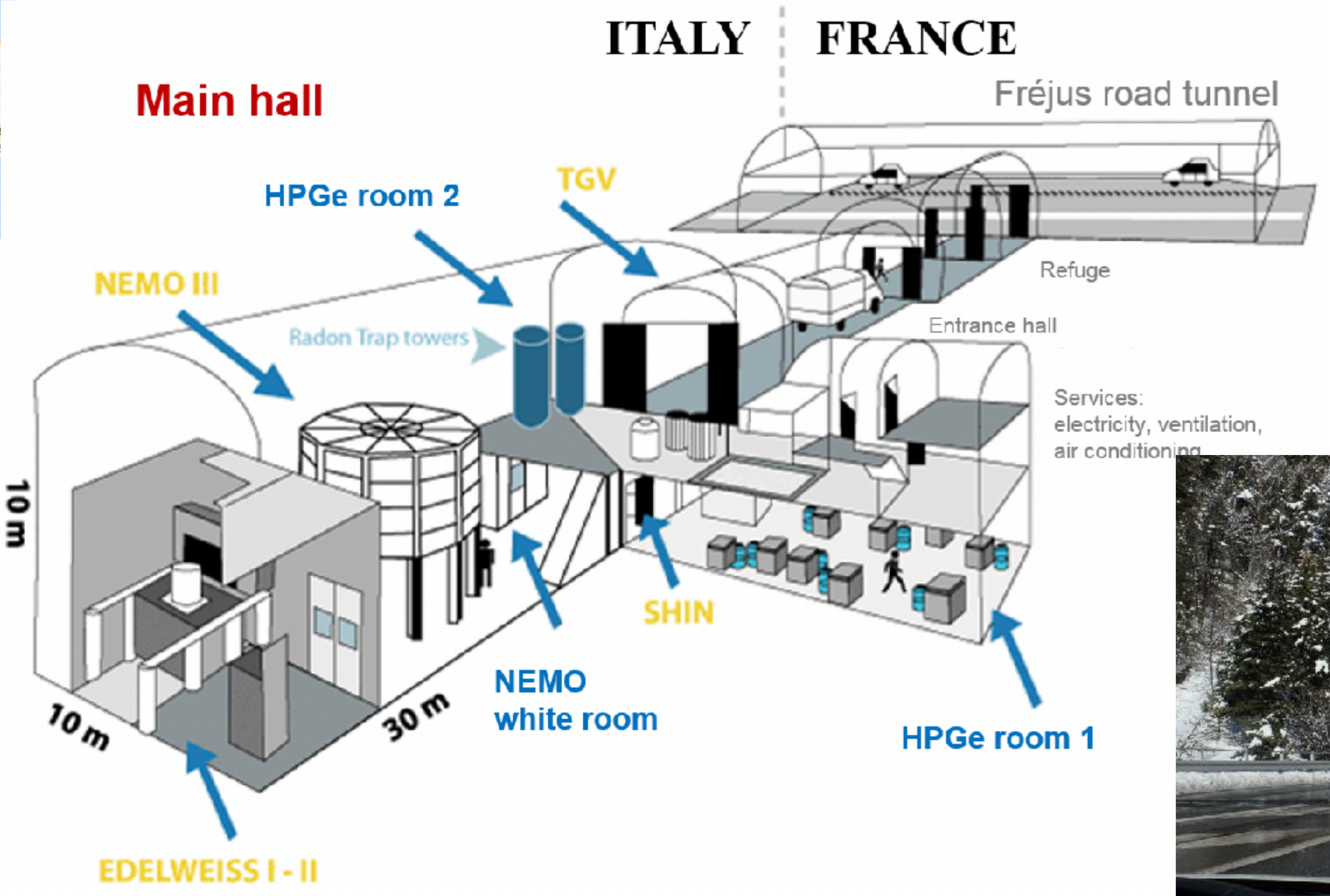


EXCELENCIA MARÍA DE MAEZTU

DAMIC-M @ LSM

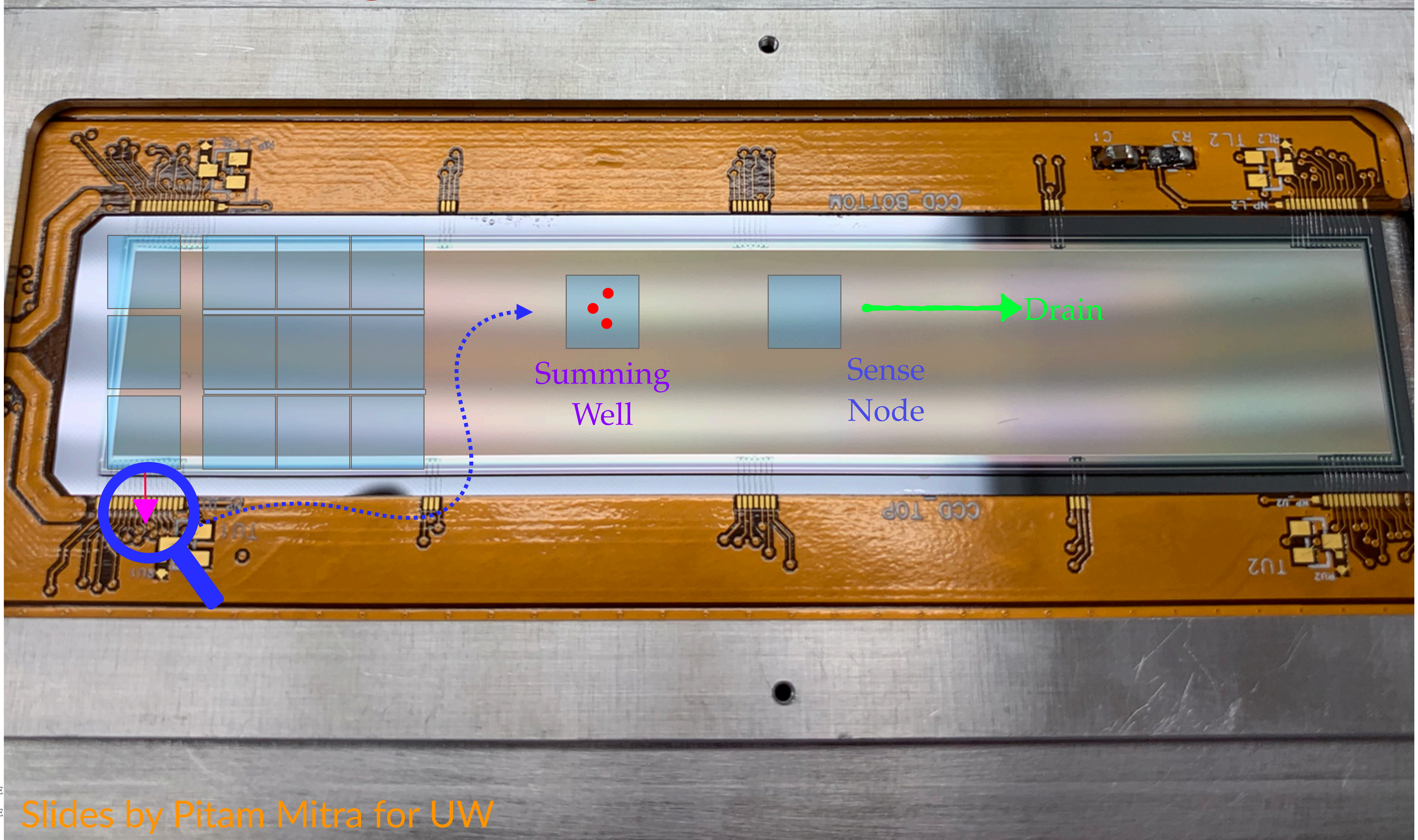

France
Switzerland
Austria
Italy
Croatia
Slovenia
Liechtenstein
Andorra
Monaco
San Marino
Paris
Nantes
Rennes
Tours
La Rochelle
Limoges
Clermont-Ferrand
Lyon
Geneva
Grenoble
Turin
Milan
Como
Verona
Venice
Padua
Trieste
Genoa
Bologna
Rimini
Pisa
Florence
Rome
Naples
Bordeaux
Toulouse
Montpellier
Marseille
Cannes
Corse
Sardegna
Donostia-San Sebastian
Zaragoza
Barcelona
Girona
Tarragona
Strasbourg
Augsburg
Munich
Salzburg
Zürich
Graz
Tyrrhenian Sea


Tunnel routier de Fréjus
Pointe du Fréjus
Altitude 2 932 m
FRANCE
ITALIE
Puits de ventilation
Altitude 1 228 m
Altitude 1 298 m
Usine A
Usine B
Usine C
Usine D
Distance 0 m
LSM
6 210 m
12 868 m

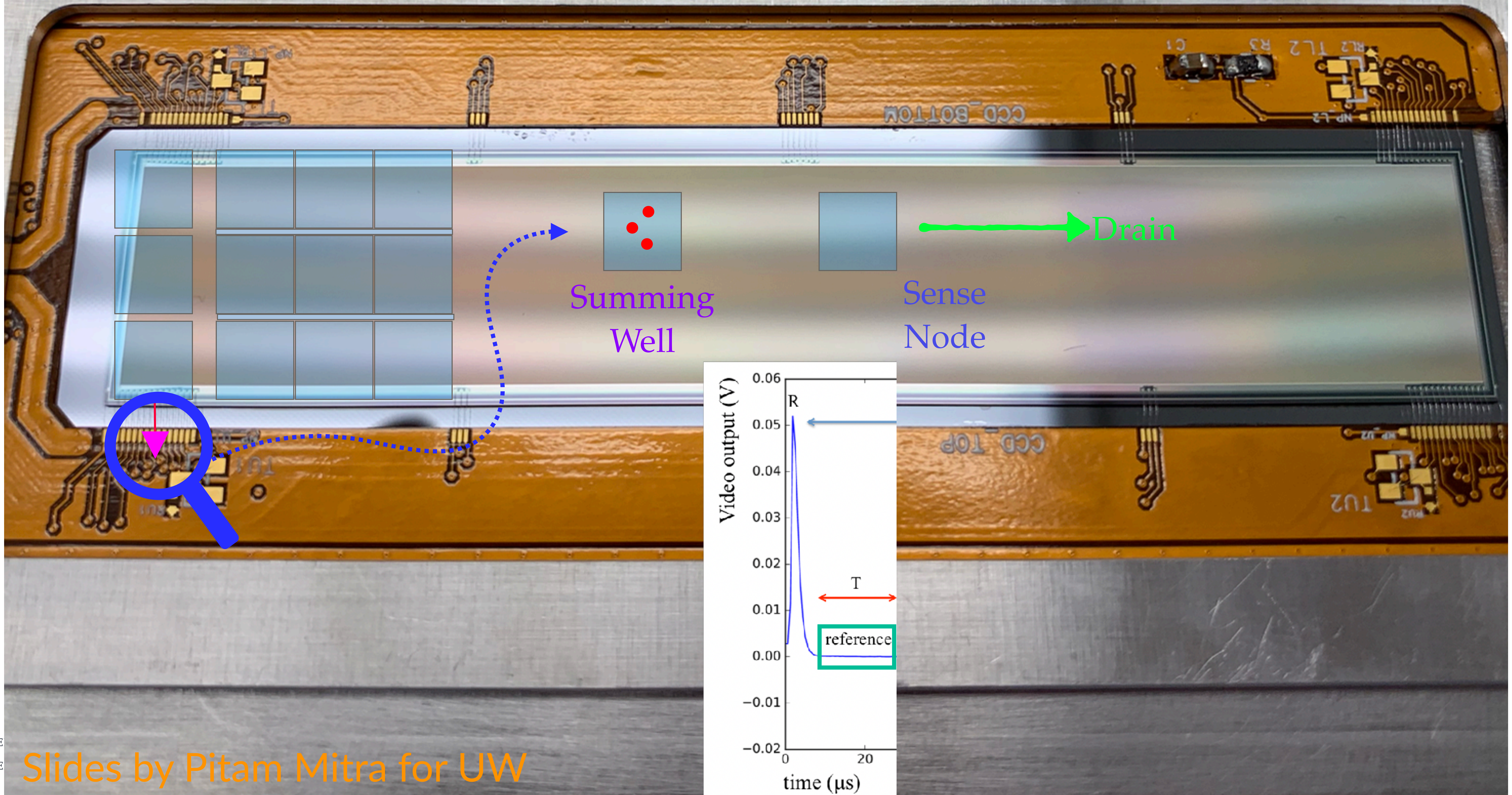

ITALY
FRANCE
Main hall
Fréjus road tunnel
HPGe room 2
TGV
NEMO III
Radon Trap towers
Refuge
Entrance hall
Services:
electricity, ventilation,
air conditioning
10 m
10 m
30 m
SHIN
NEMO
white room
HPGe room 1
EDELWEISS I - II


© PHOTOTHEQUE IN2P3 / CNRS

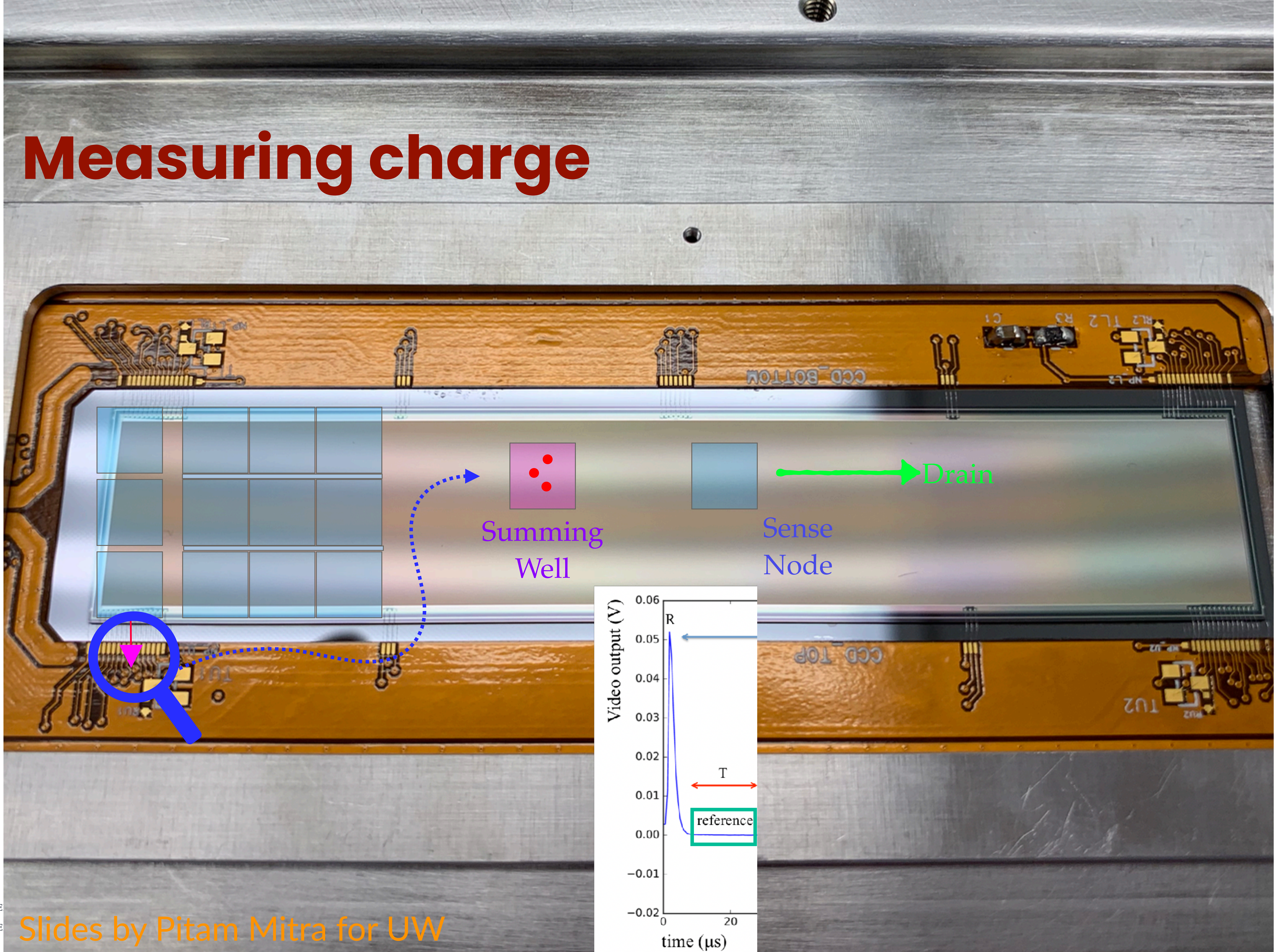
Measuring charge



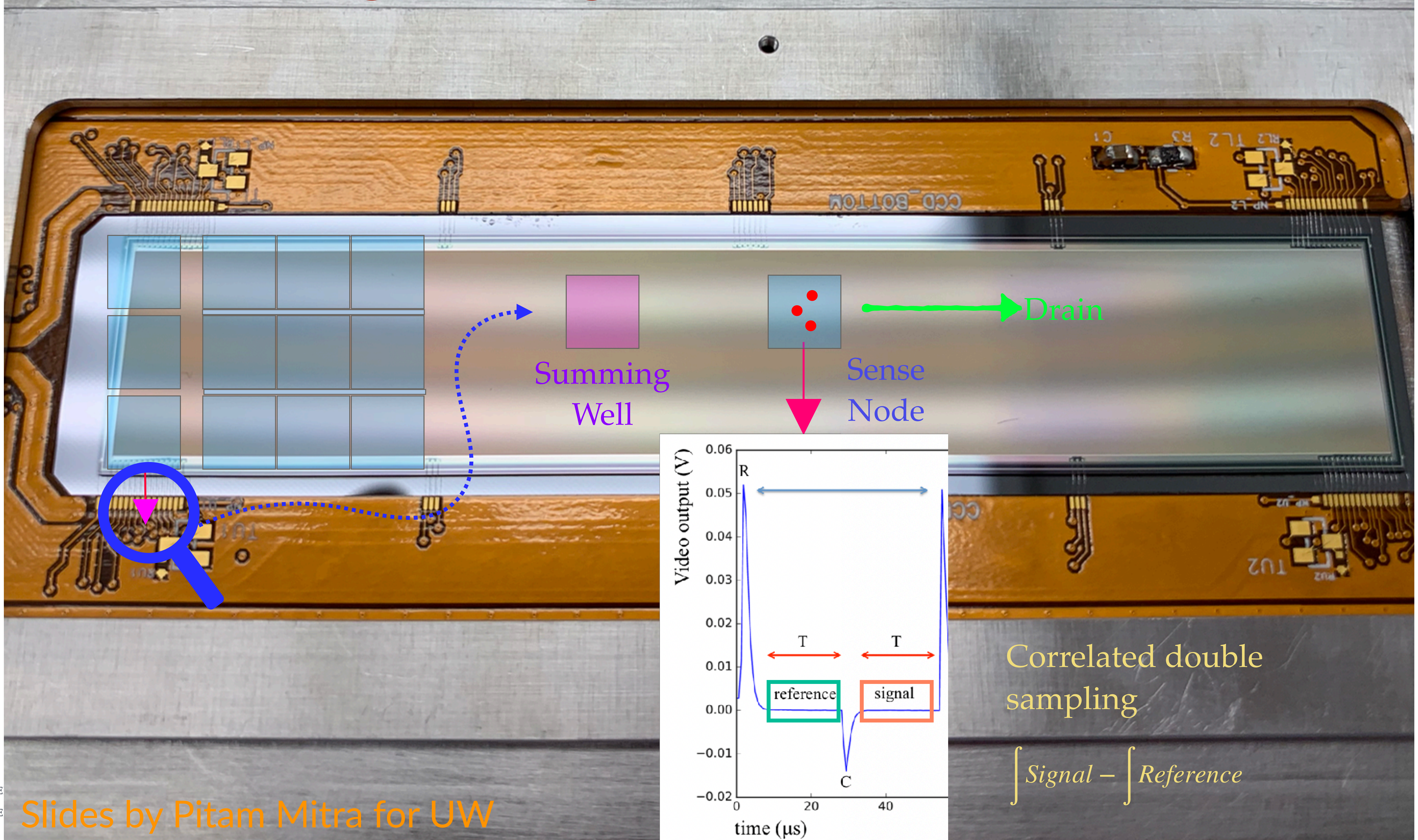
Measuring charge



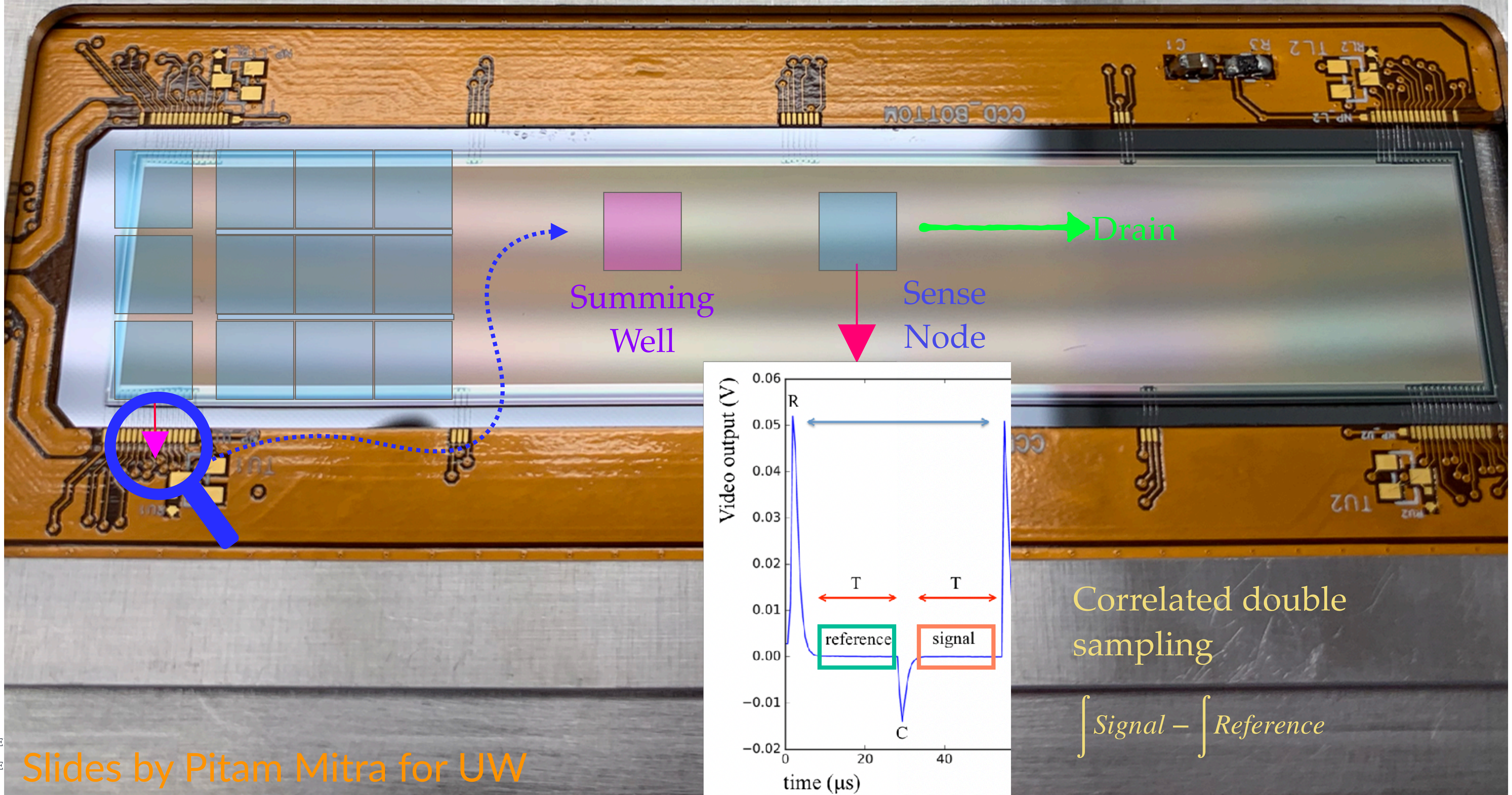
Measuring charge



Measuring charge



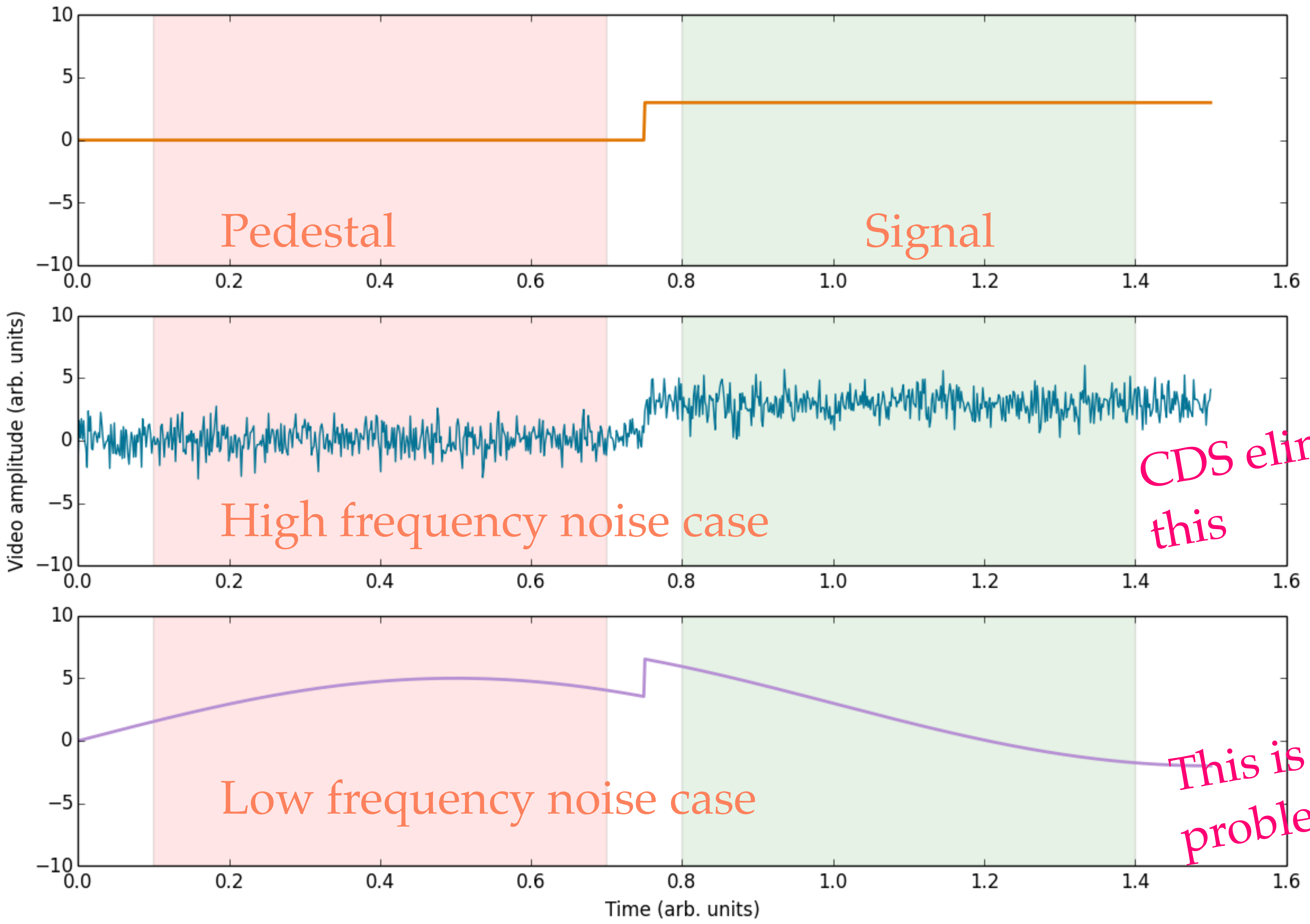
Measuring charge



Correlated double sampling

$$\int Signal - \int Reference$$

CCD: Moving charges

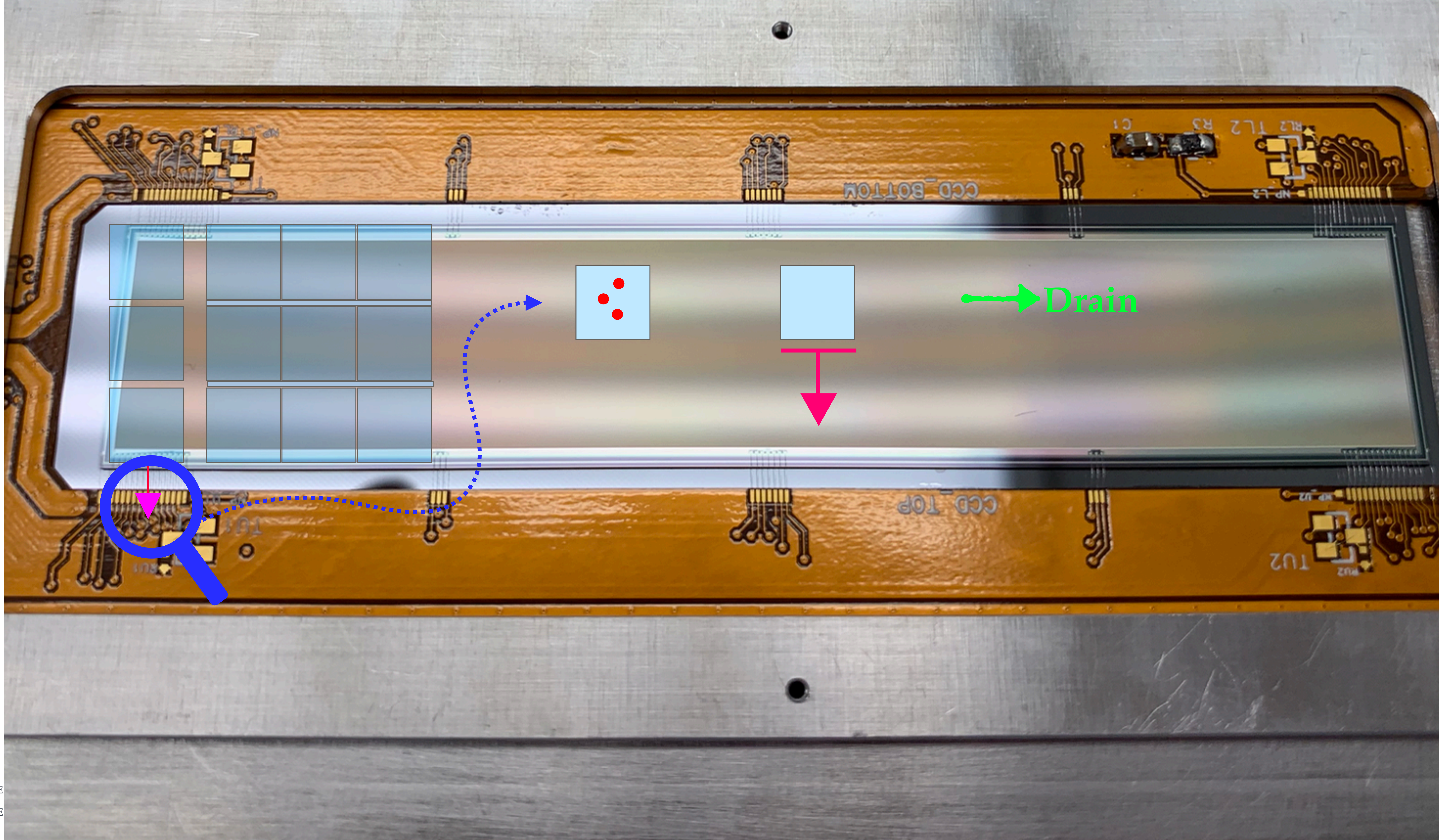


CDS eliminates this

This is still a problem

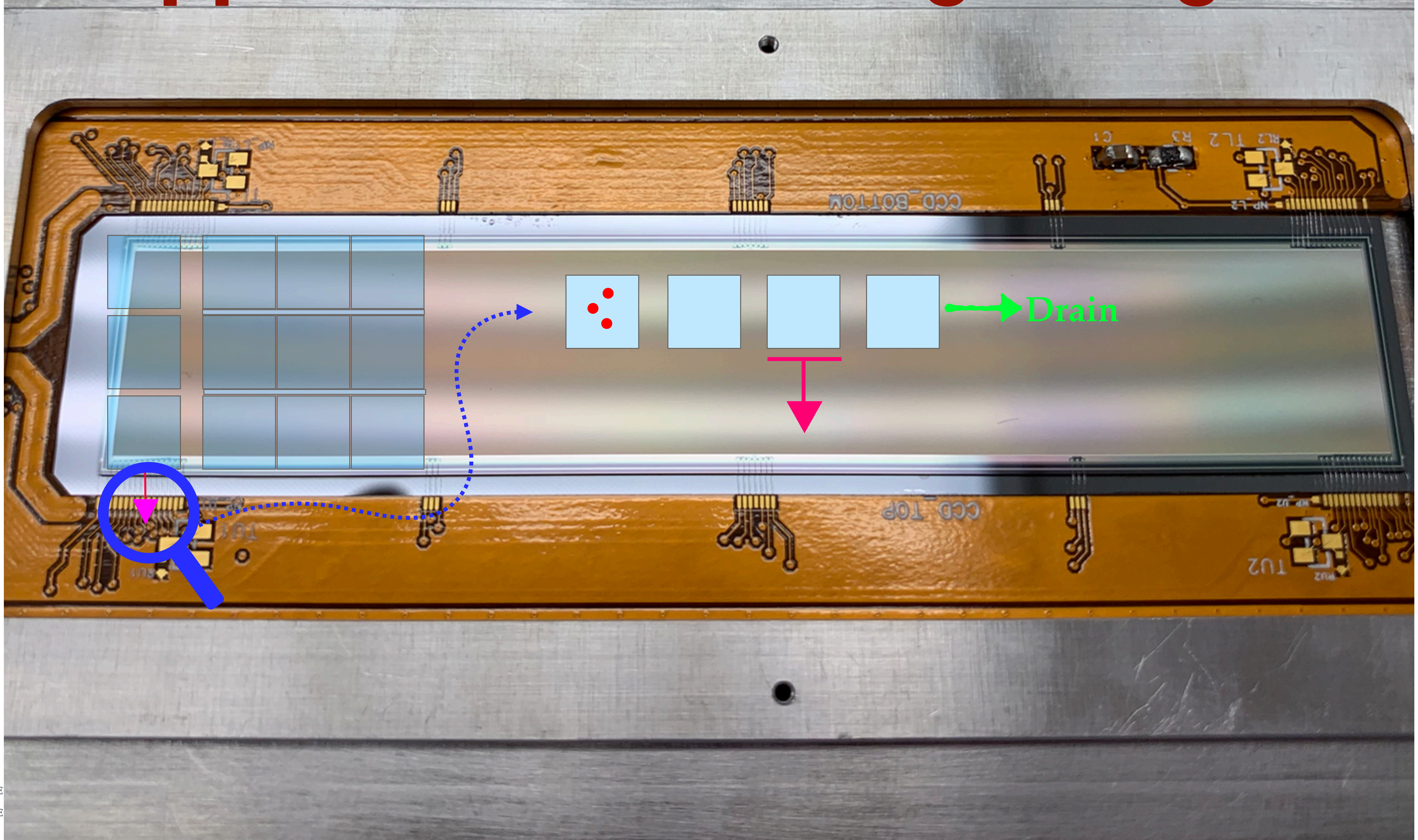
IFCA EXCELE MARÍA DE MAE

Skipper CCD:Measuring charges

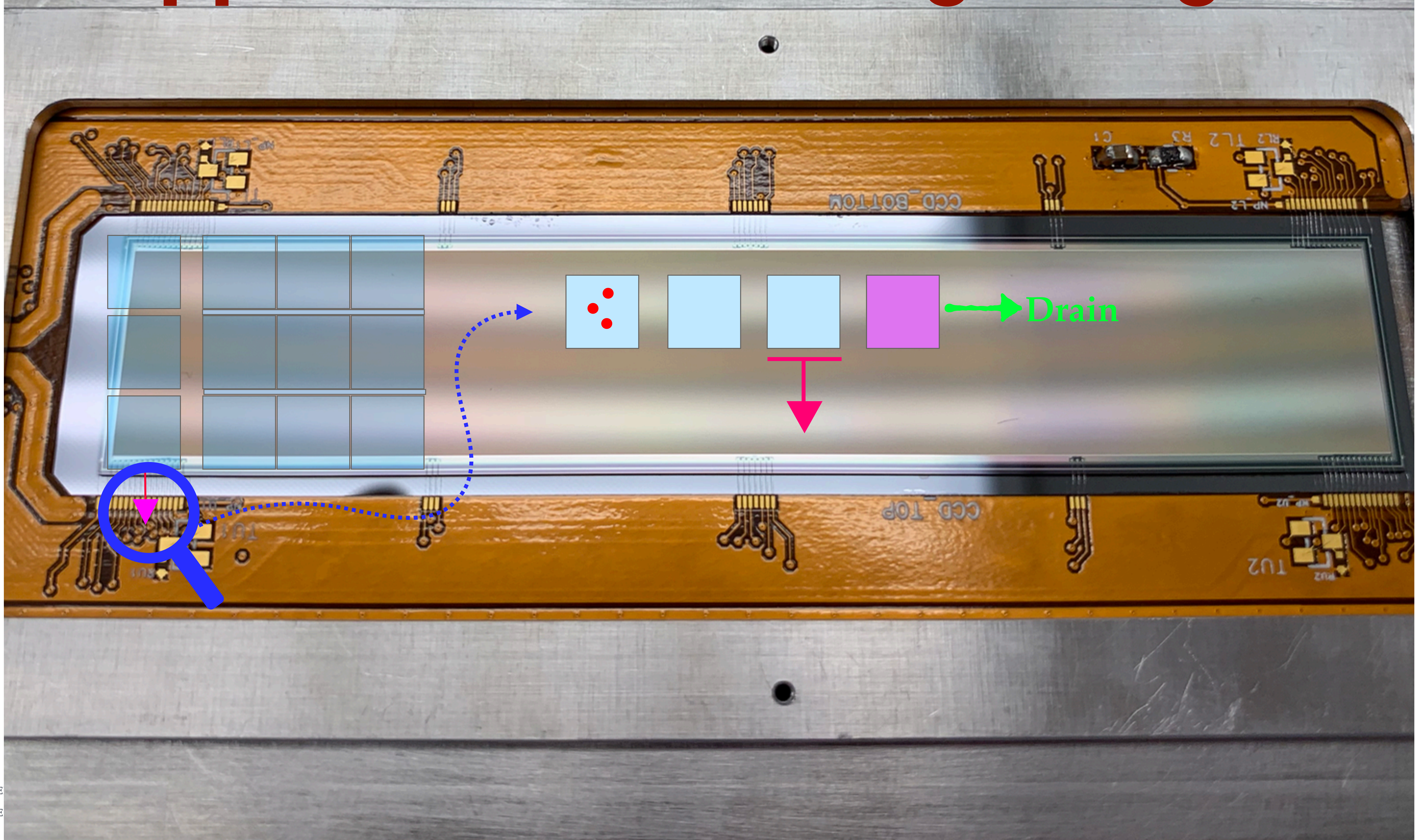


EXCELE
MARÍA
DE MAE

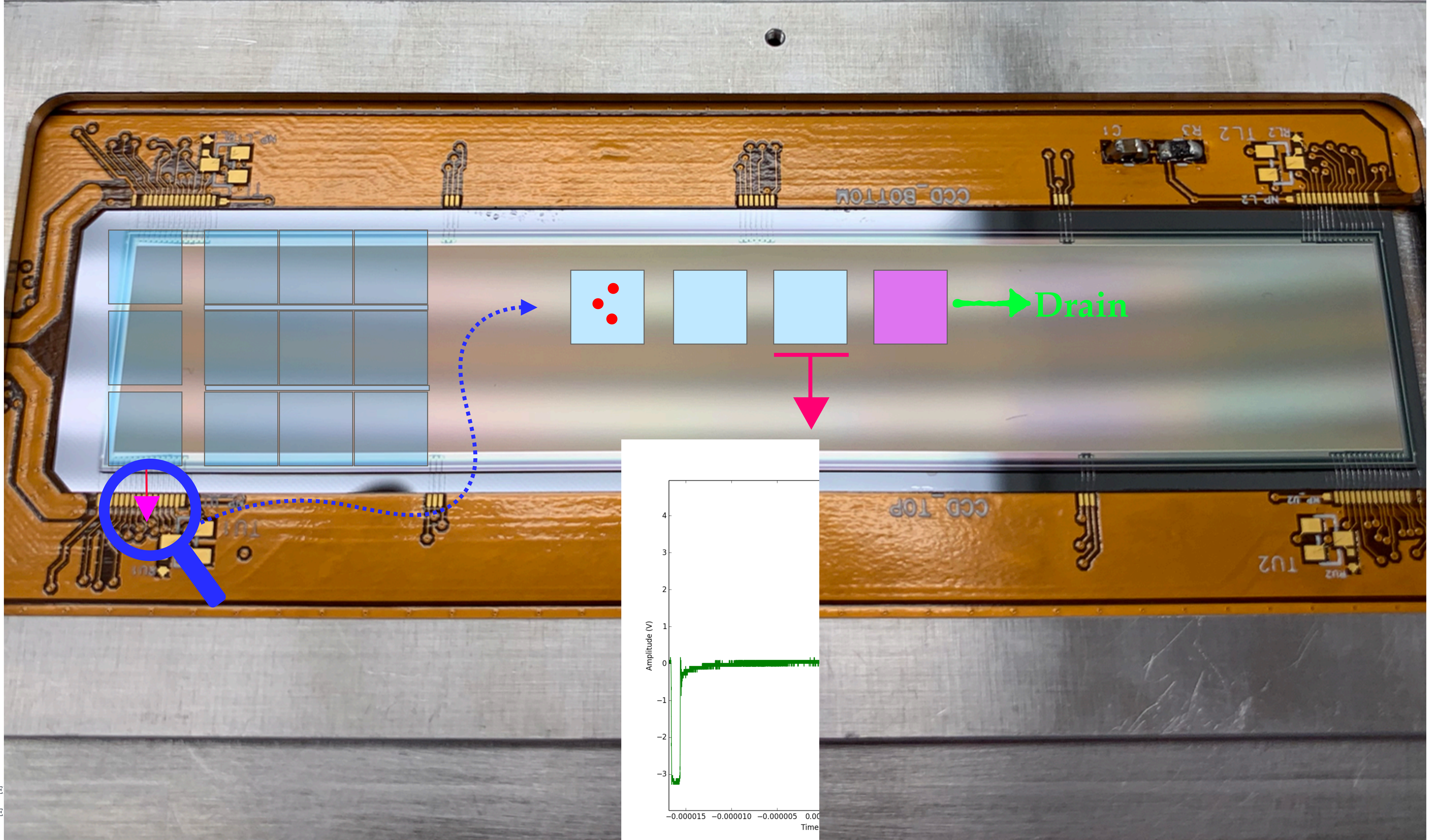
Skipper CCD:Measuring charges



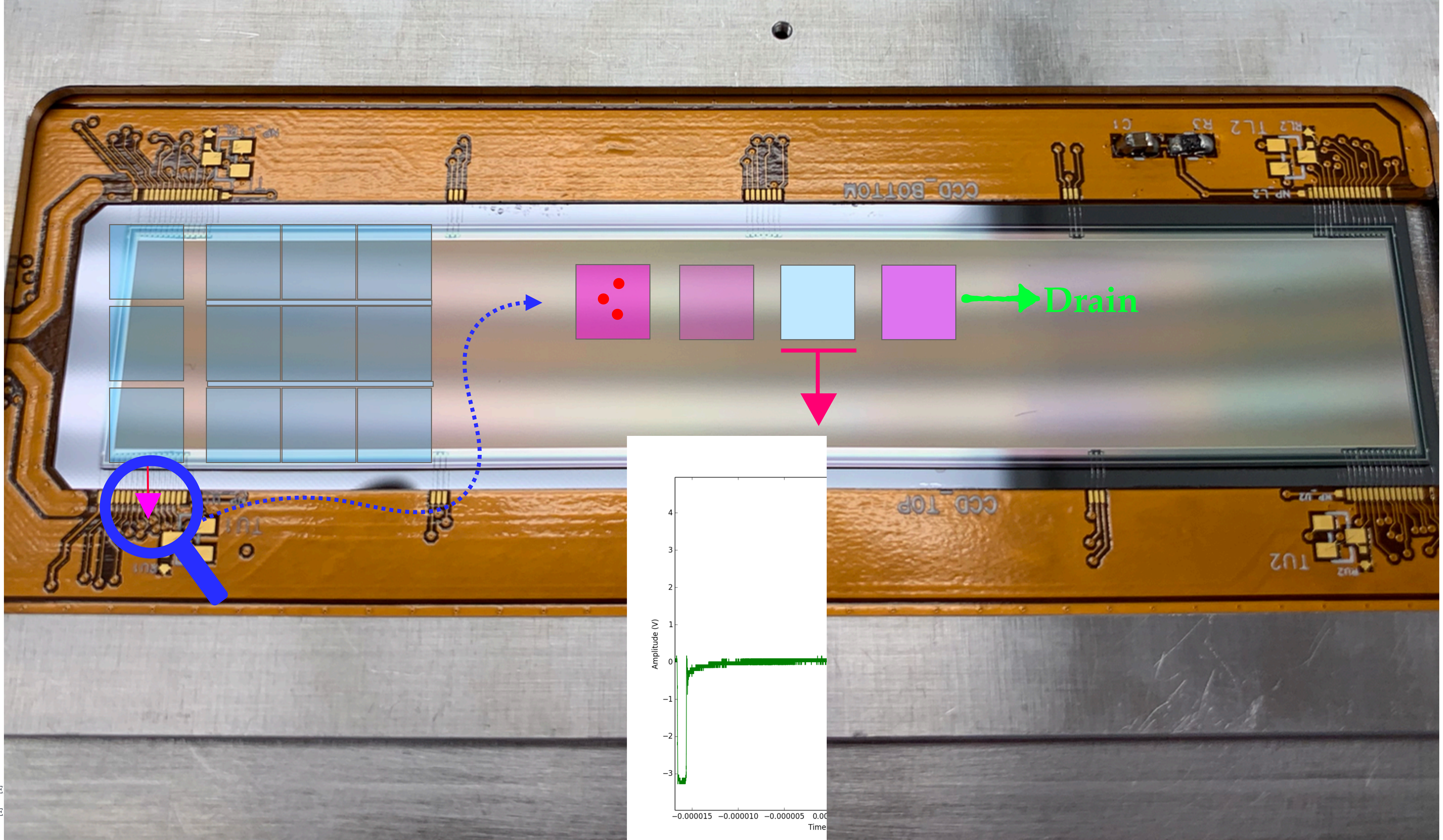
Skipper CCD:Measuring charges



Skipper CCD:Measuring charges



Skipper CCD:Measuring charges



EXCELE
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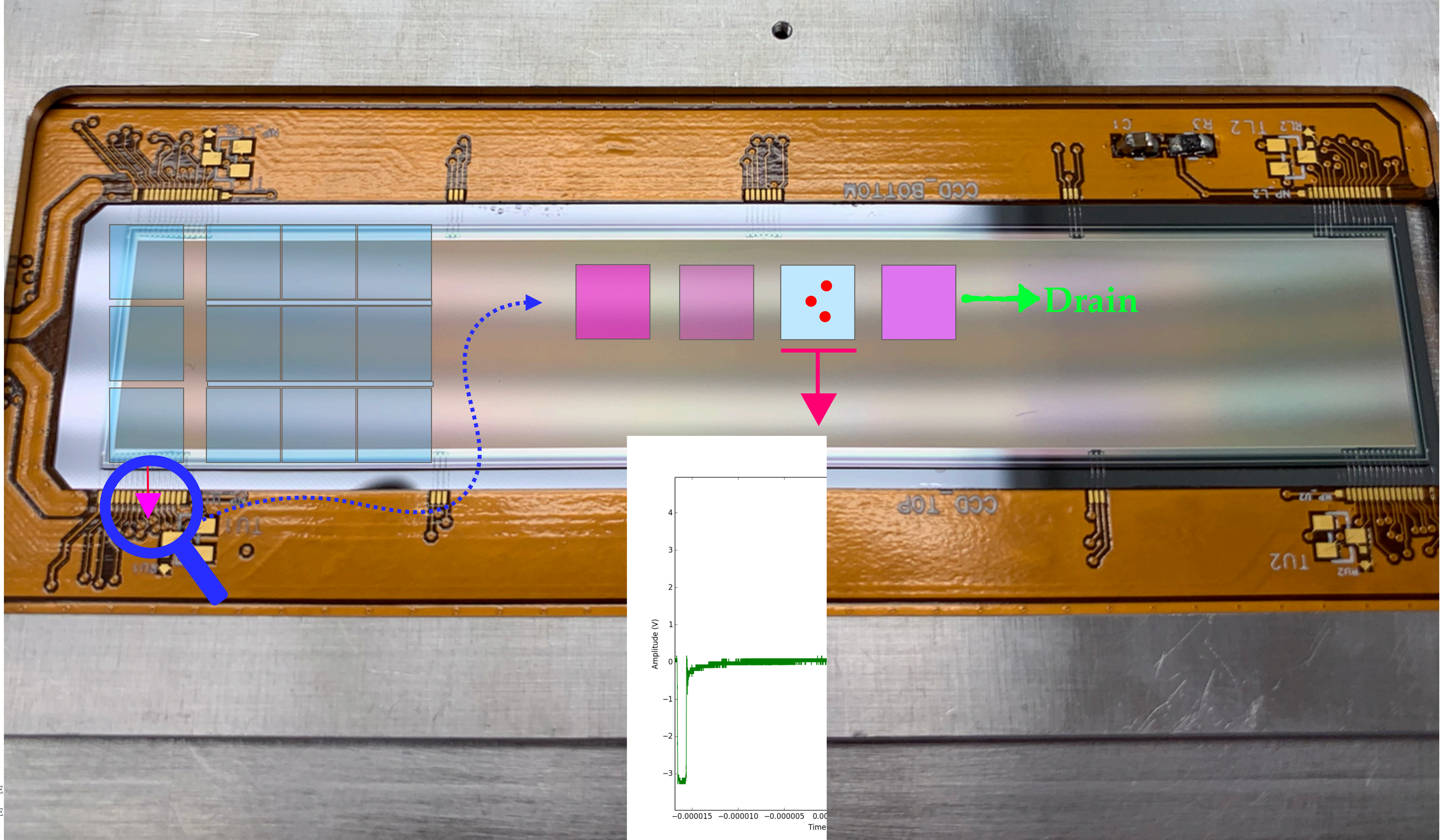
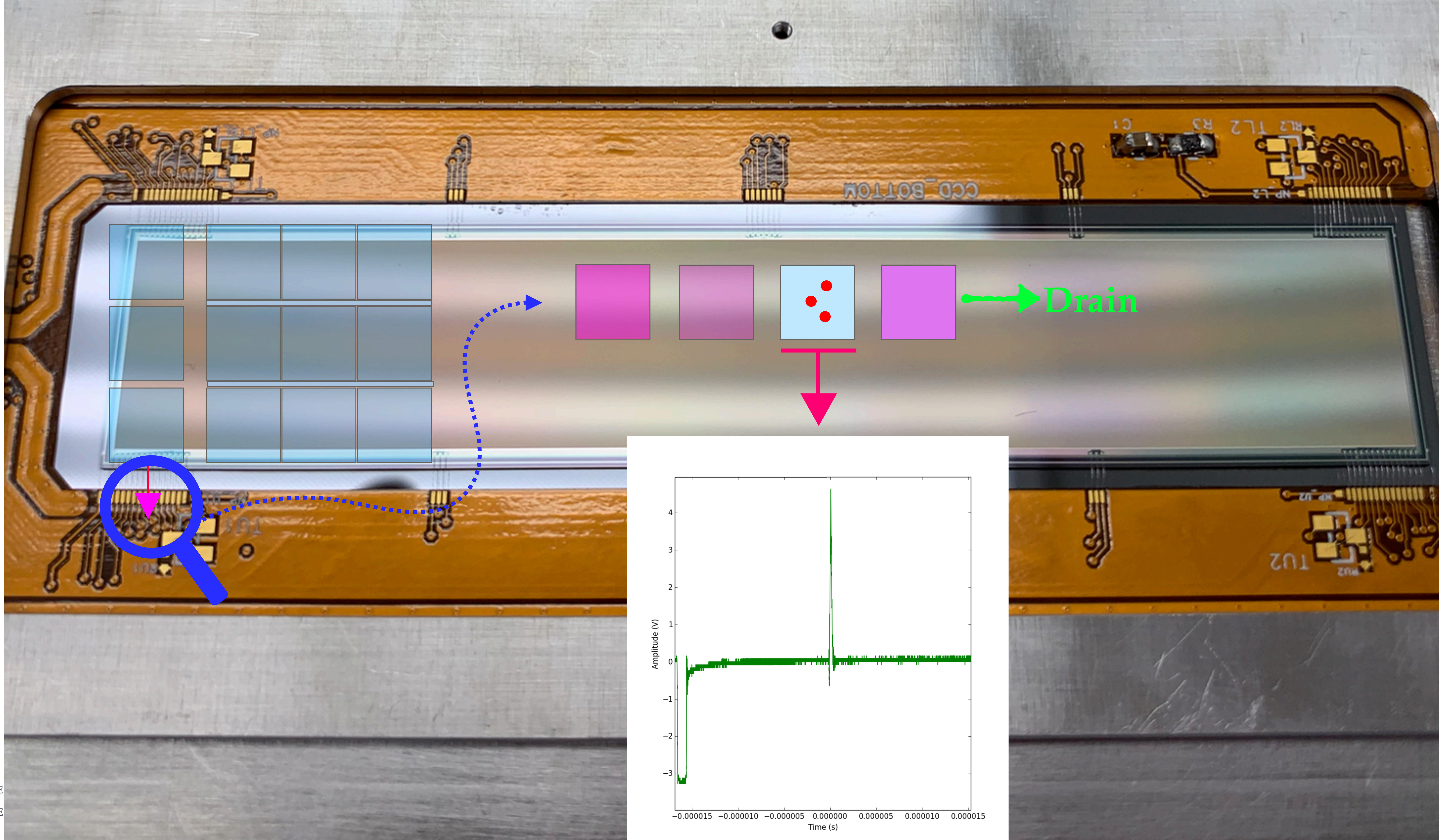
DE MAE

Skipper CCD:Measuring charges

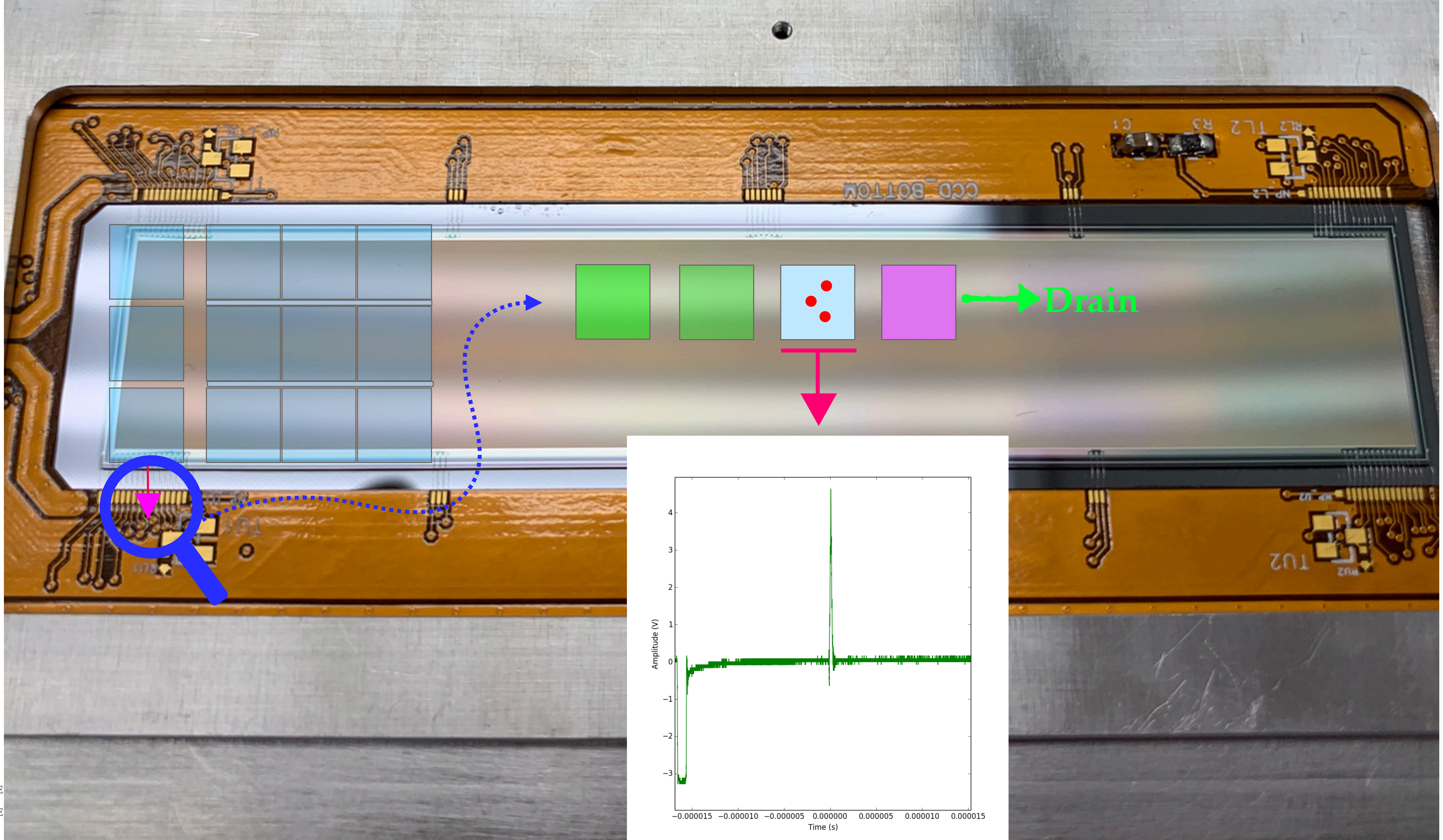


Skipper CCD:Measuring charges

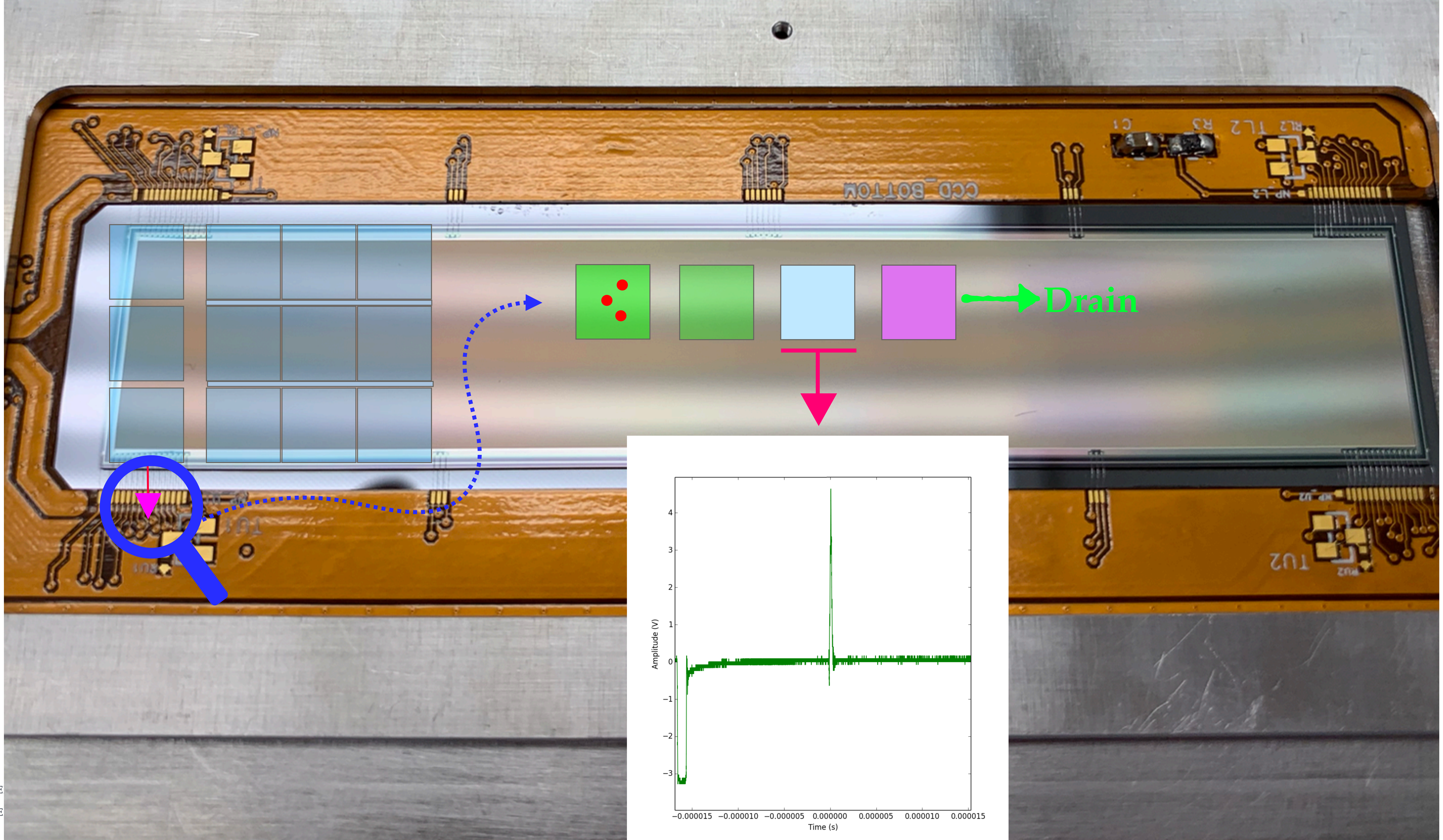


IFCA EXCELE MARÍA DE MAE

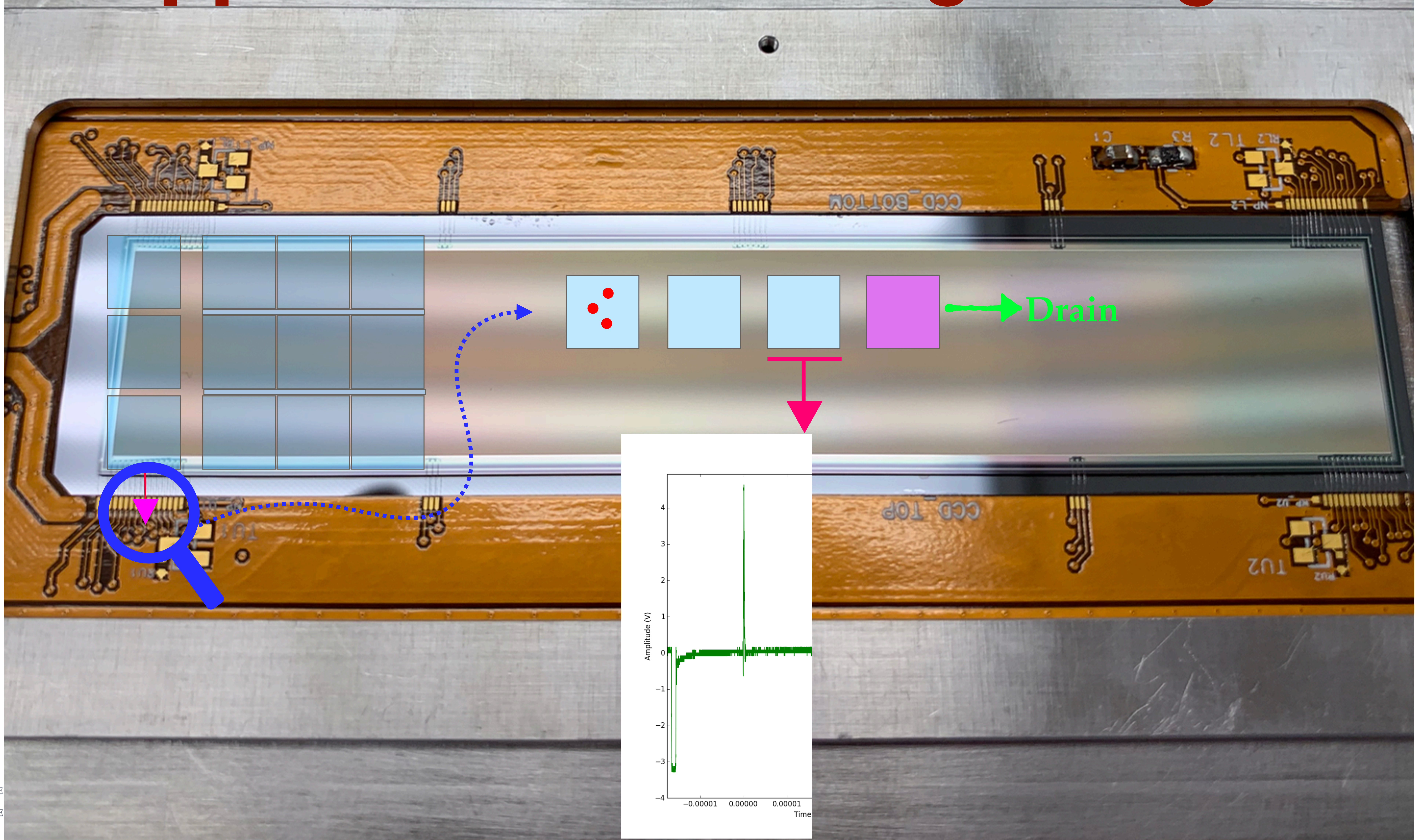
Skipper CCD:Measuring charges



Skipper CCD:Measuring charges

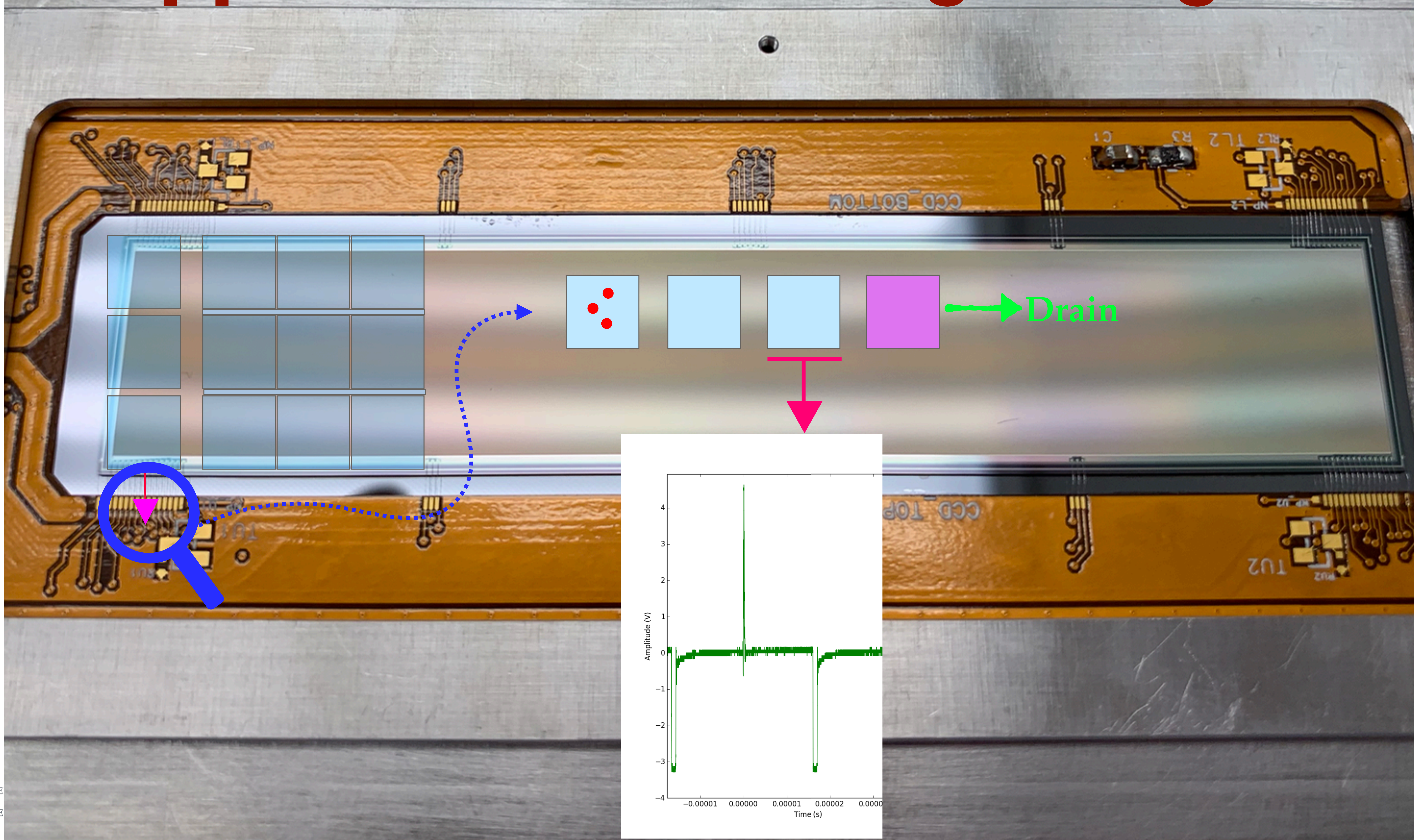


Skipper CCD:Measuring charges

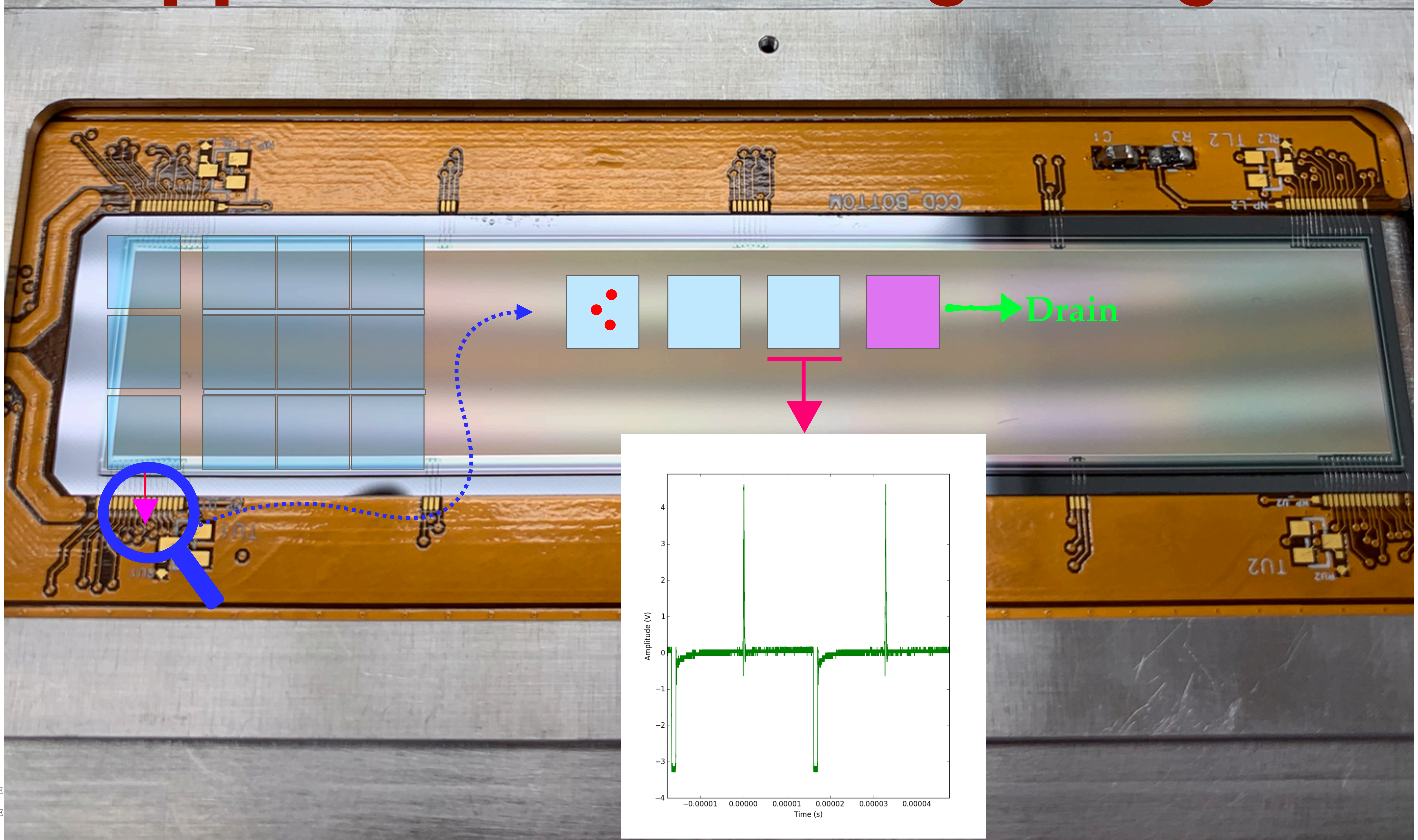


EXCELE
MARÍA
DE MAE

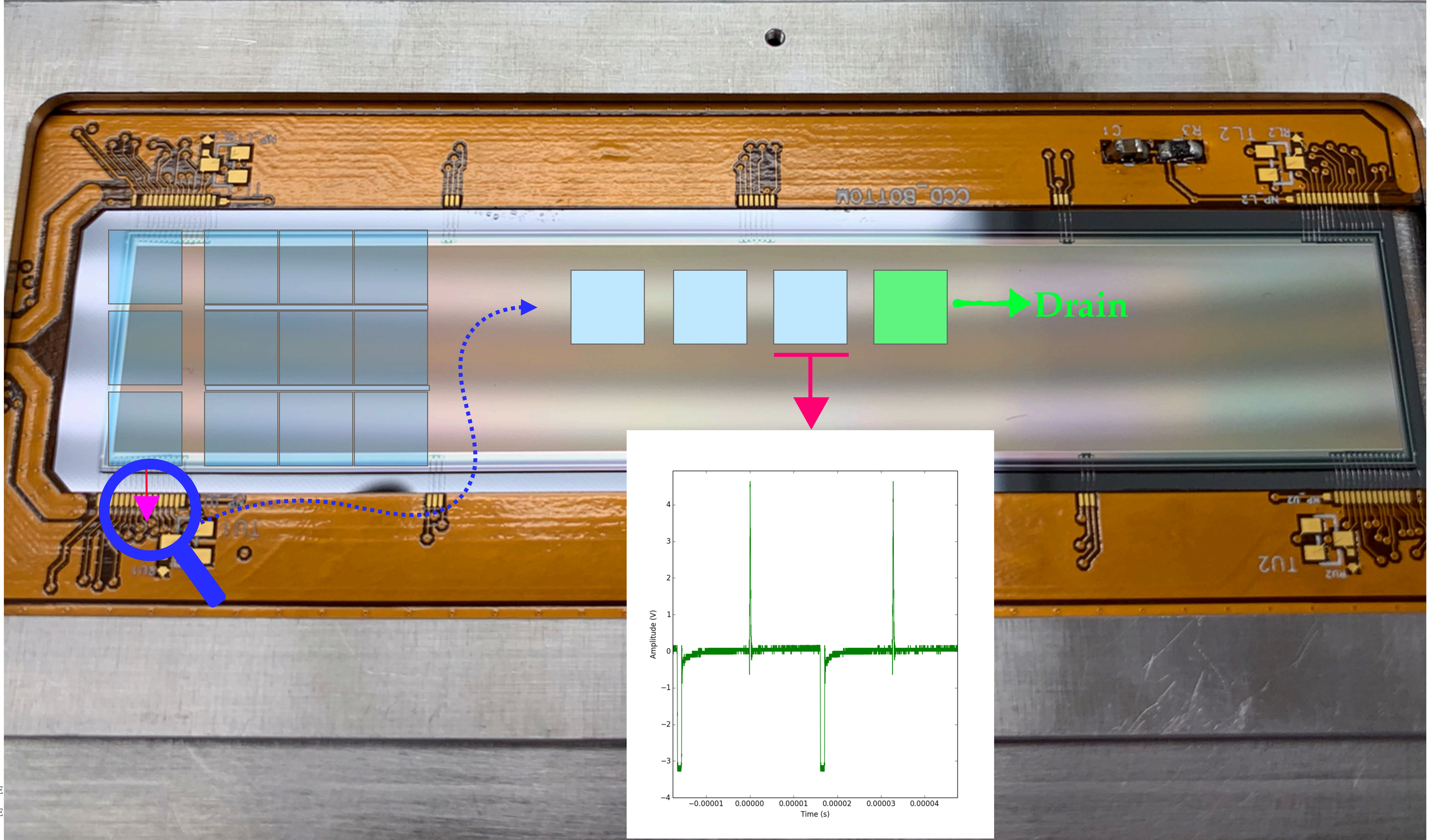
Skipper CCD:Measuring charges



Skipper CCD:Measuring charges

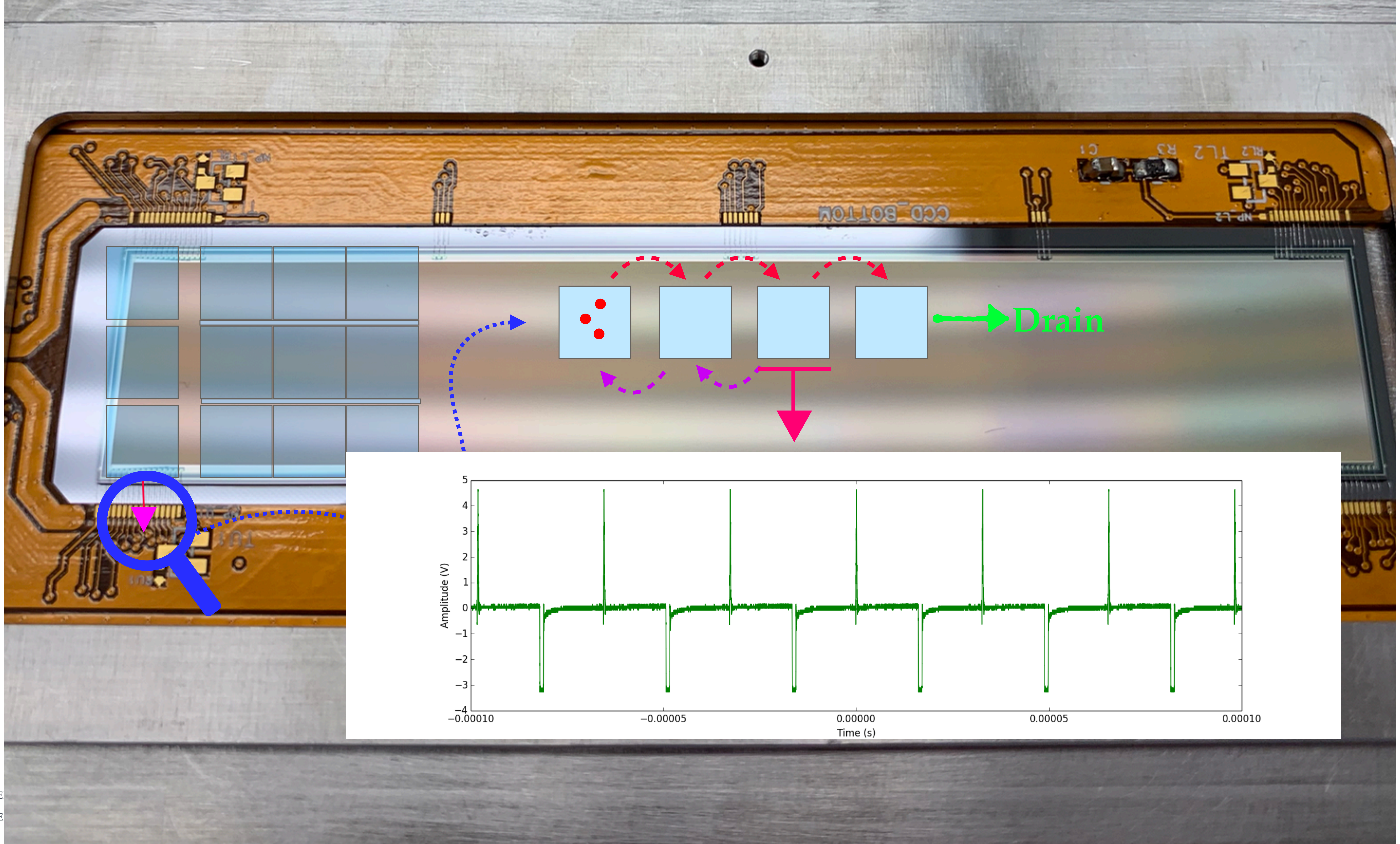


Skipper CCD:Measuring charges



EXCELE
MARÍA
DE MAE

Skipper CCD: Measuring charges



Skipper CCD: Measuring charges