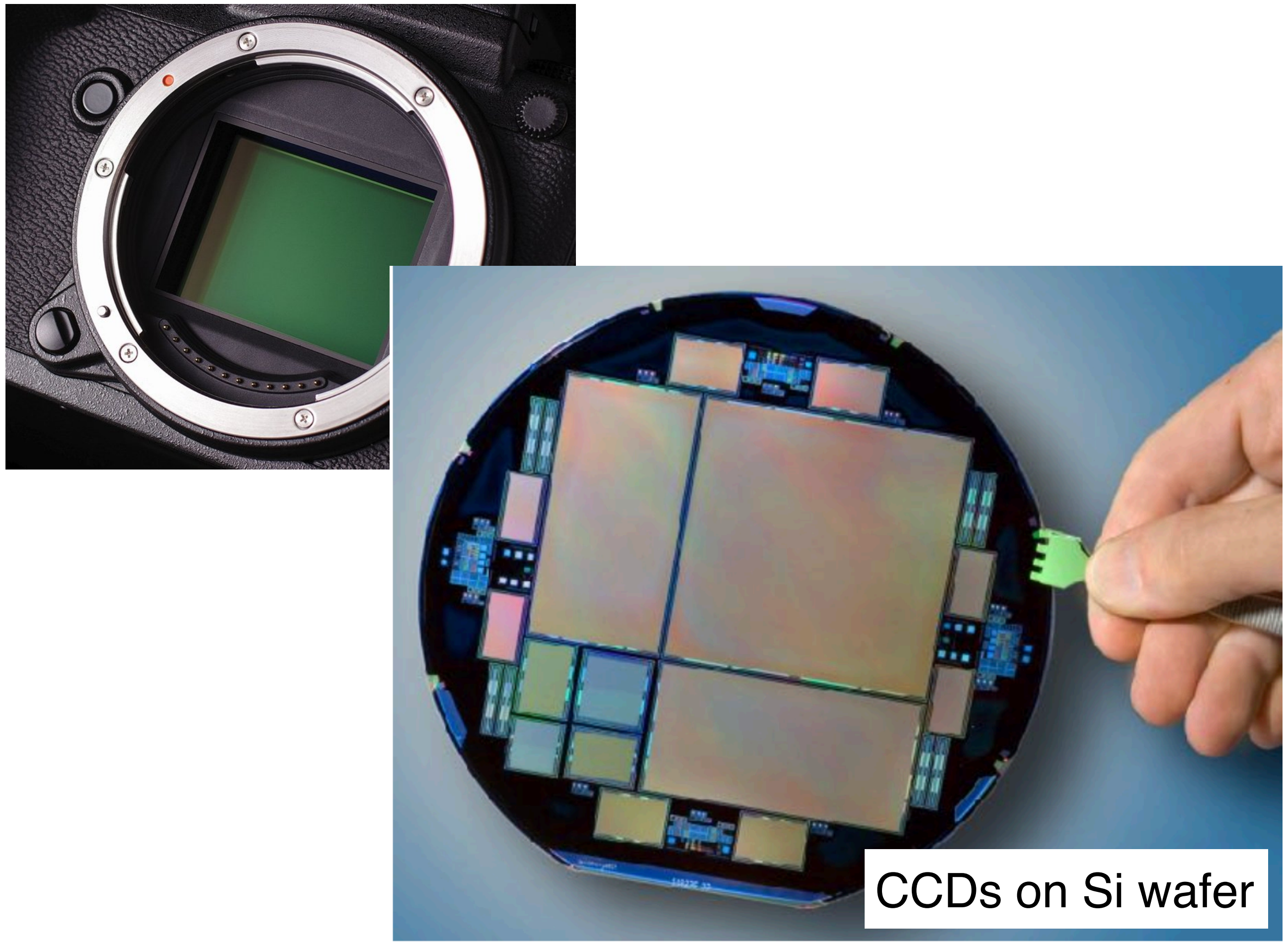
The search for light dark matter with DAMIC-M

Danielle Norcini
Johns Hopkins University

CCDs as dark matter detectors

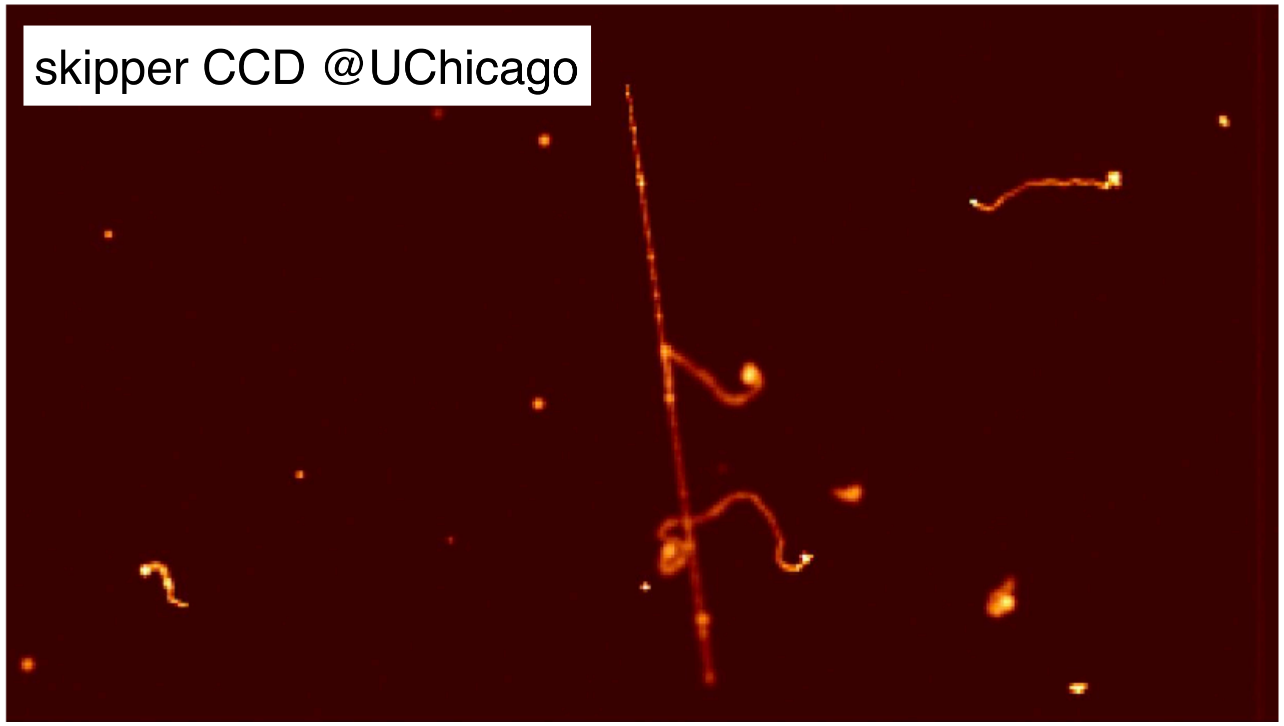
Charge-coupled devices have been used for a long time as telescope cameras.


DES camera


CCDs on Si wafer

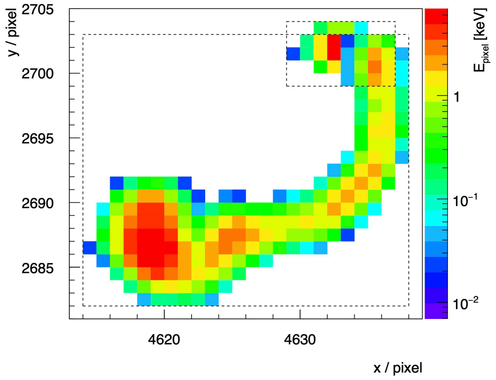
Devices were adapted and reimagined for underground dark matter detection:

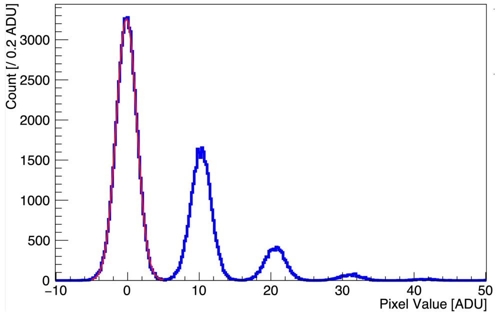
- demonstrated by DAMIC at SNOLAB
- on-going experiments DAMIC-M and SENSEI
- R&D work on OSCURA


skipper CCD @UChicago

Why Silicon CCDs?

To explore sub-GeV range, detectors with **extremely low thresholds** (~few eV) and **extremely low backgrounds** (~sub dru) are required to detect both nuclear/electronic recoils from DM-interactions. Silicon CCDs have many advantages:





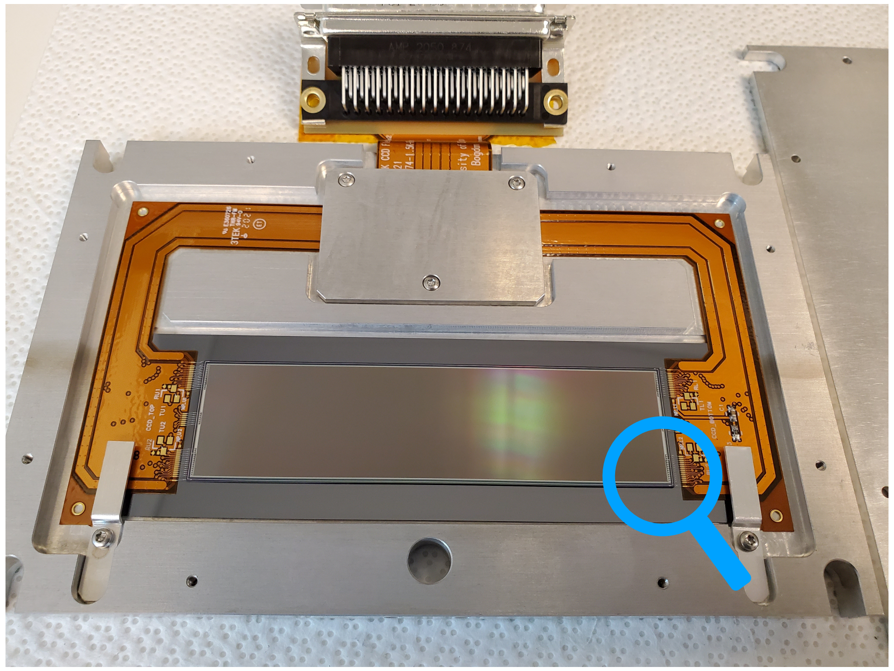
- light nucleus (A=28)
- average electron-hole ionization of 3.78eV
- mono-crystalline material is clean, uniform, and can make thick
- industry has invested $$$ in ultra-clean fabrication facilities
- pixelization allows for very good spatial resolution
- achieved very low dark current rates (2x10^{-4} e-/pixel/day, PRL 123, 181802 (2019))
- technological advances have turned CCDs into **single-electron detectors**

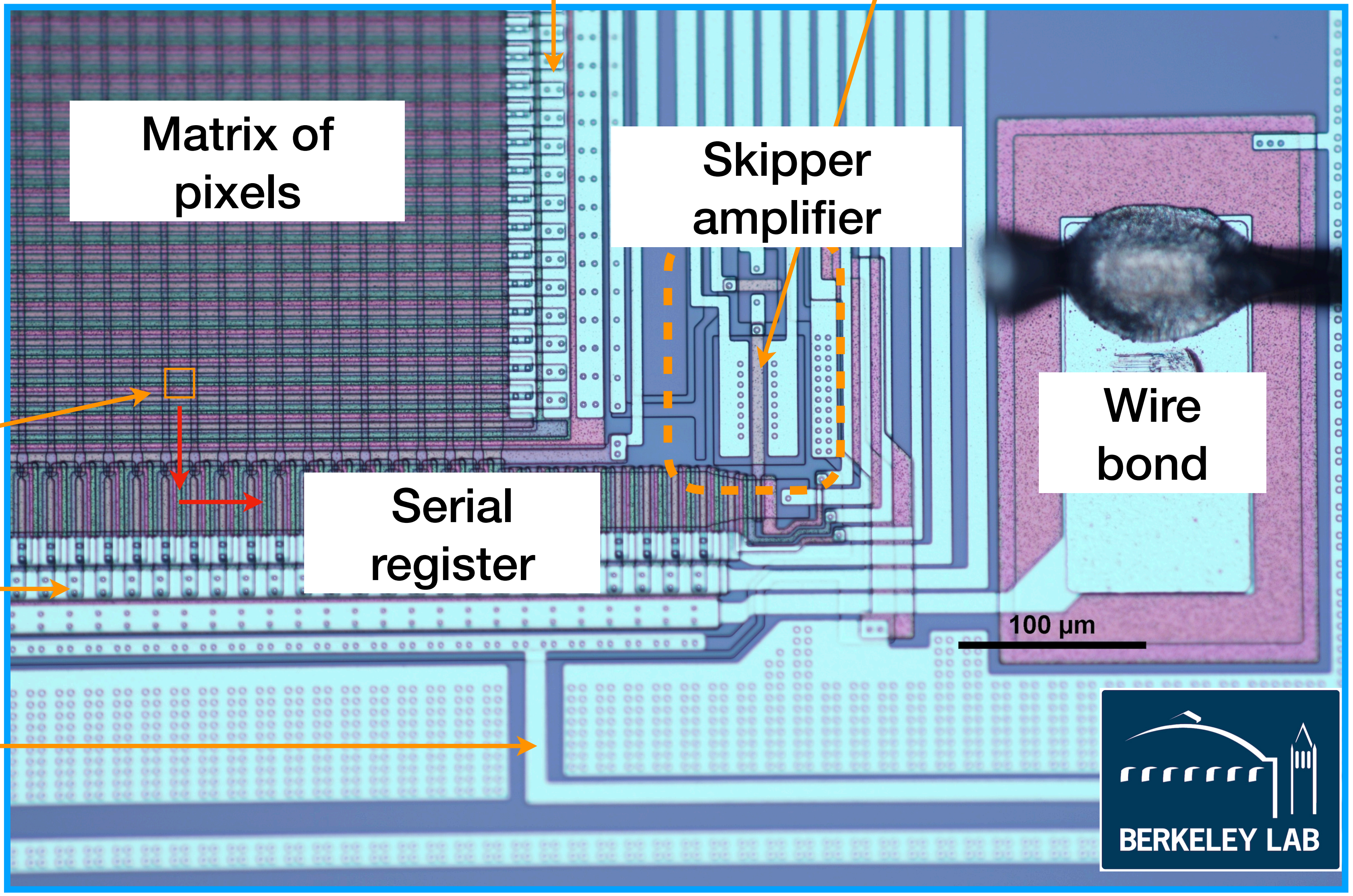
A CCD up-close

Mono-crystal silicon, n-type and high resistivity (>10000 Ωcm)

Slice large crystals into 150mm diameter wafers to produce device in nanofab facility

Masks deposited on the front side of wafers, 3-phase polysilicon gate structure to hold and transfer the charge serially





Vertical clock line (3×)

Sense node

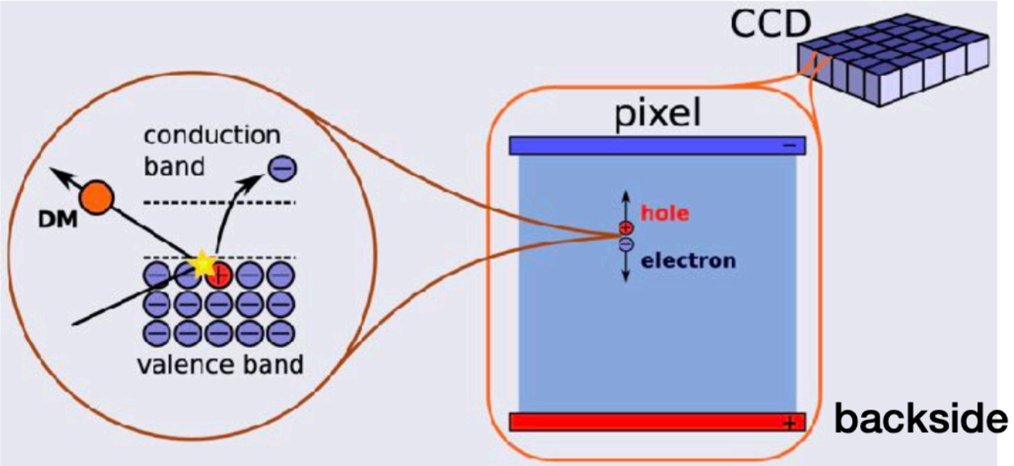
Pixel (15 µm × 15 µm)

Horizontal clock line (3×)

N+ grounding trace

20× zoom

CCD charge transfer steps



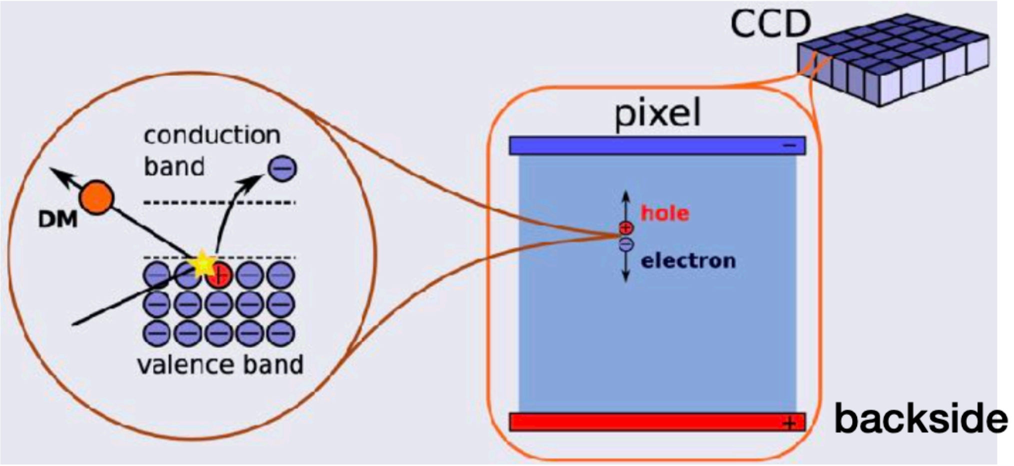
1. Incident particle ionizes electron-hole pairs in fully-depleted Si bulk.

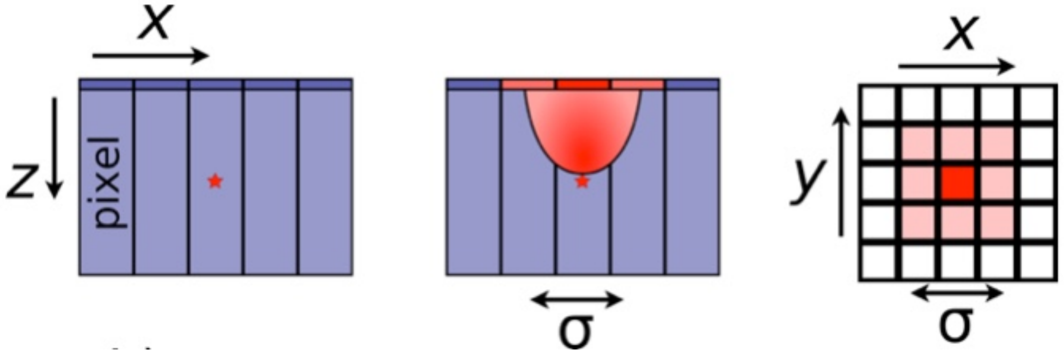
2. Holes are drifted up to the buried channel by applied field across bulk. Diffusion will spread charge to neighboring pixels, profile gives depth information.

3. Vertical and horizontal “clocks”, i.e. timed voltage gates, move charge across the active region and out to the amplifier. Transfer efficiency is >99.9999%.

4. Amplifier converts charge to voltage, which is proportional to the energy deposition of the incident particle.
   $\Delta V = \Delta Q/C$
   $C = 37$ fF
   $\Delta V = 4\ \mu V/e^-$
   Small!! Amplified further in front end chain.

CCD charge transfer steps





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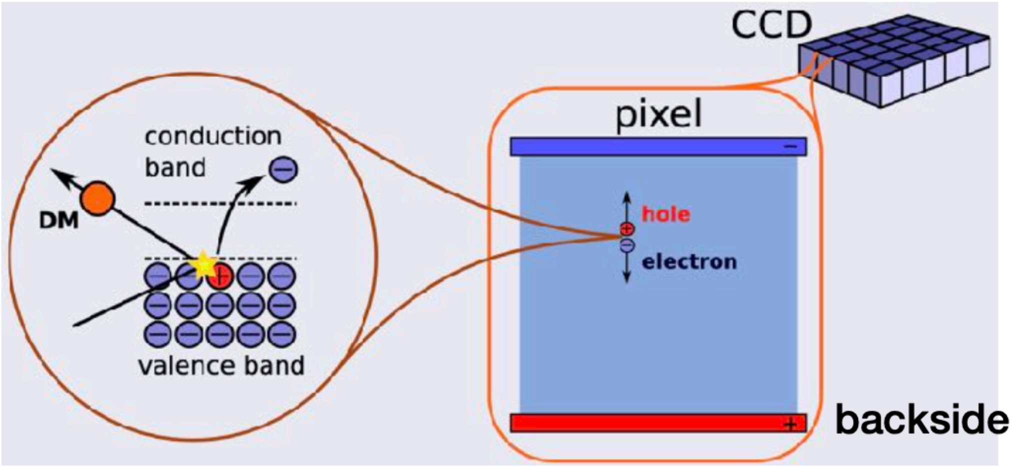
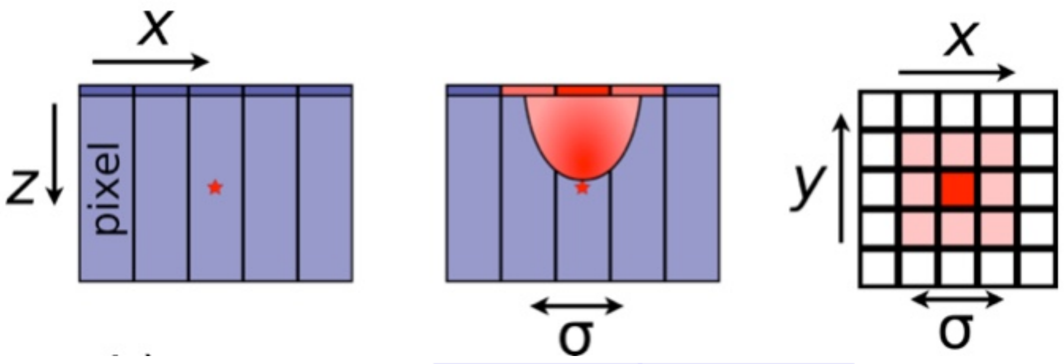
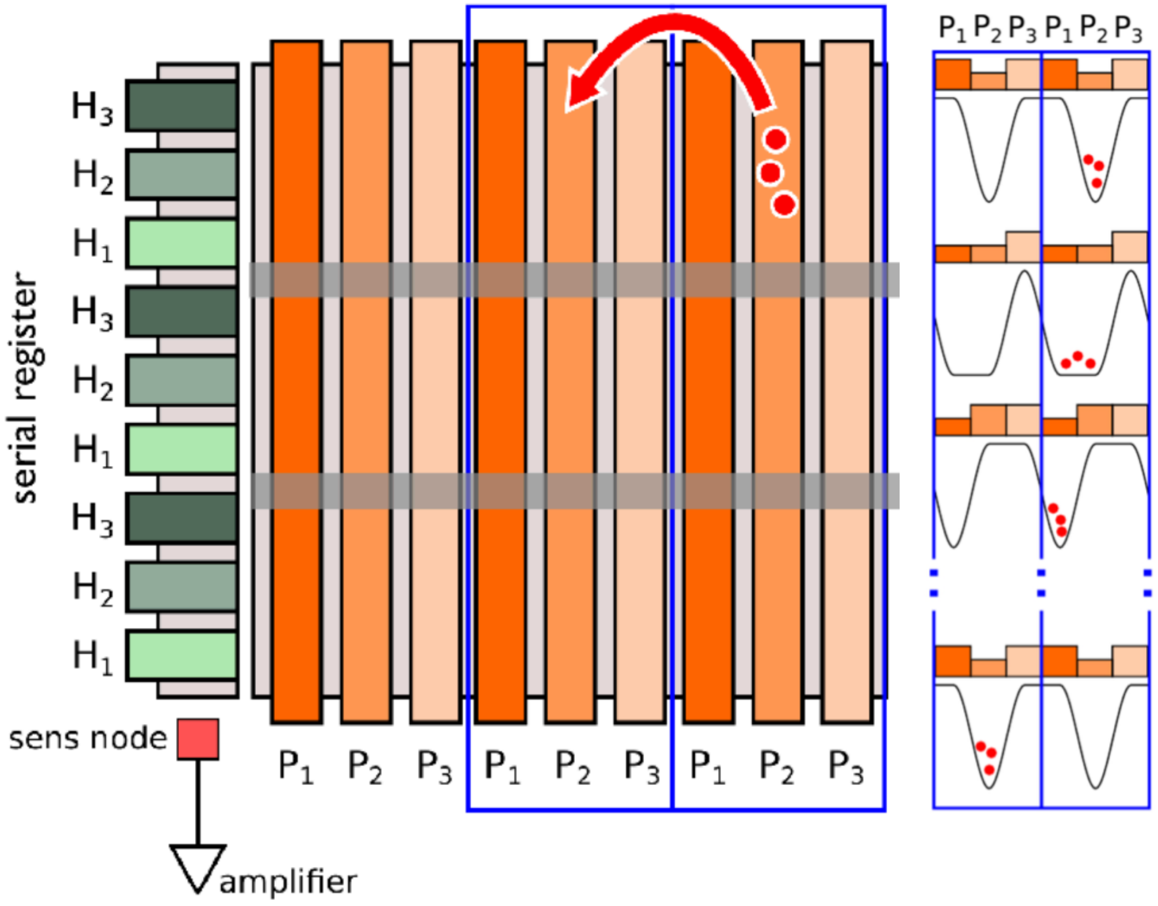




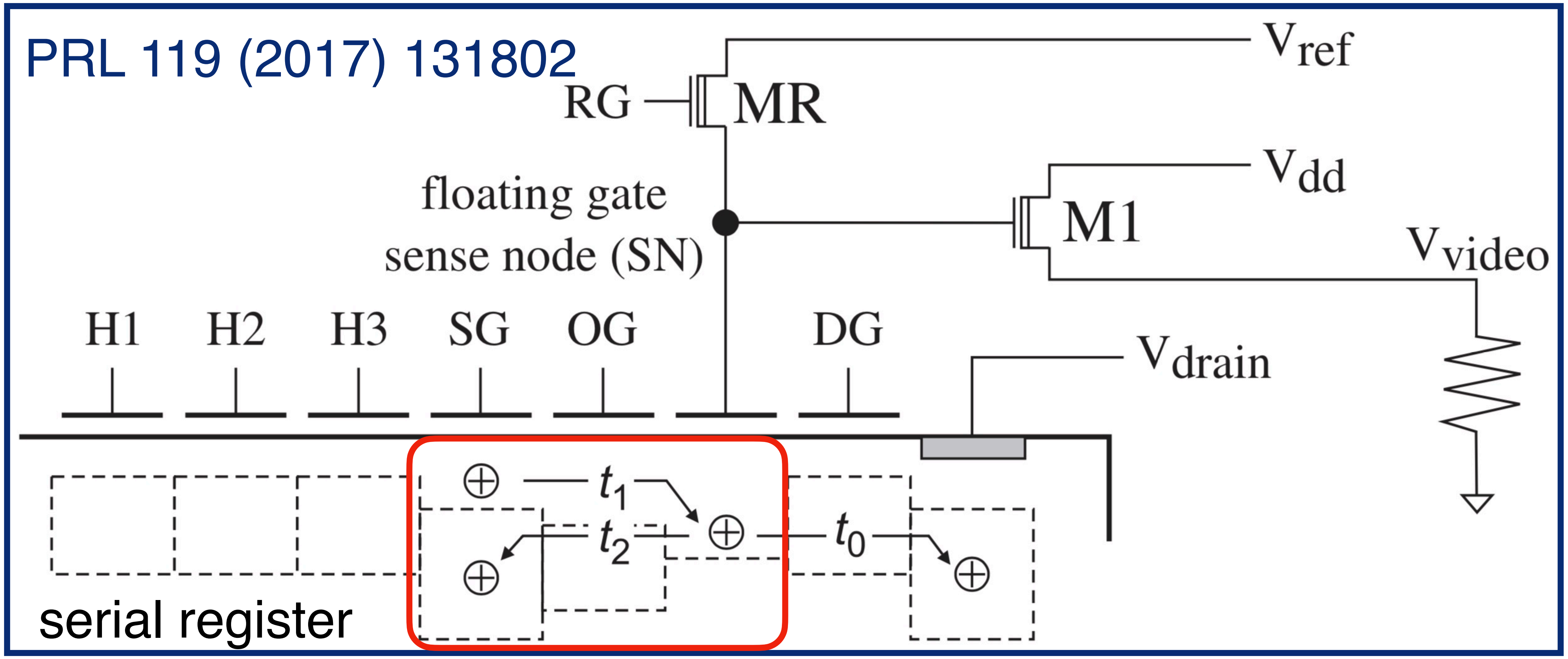


Skipper CCDs: single electron detectors

Conventional CCDs read out each pixel once, best achieved RMS noise of ~2e- (~10eV). We want single-electron resolutions at eV-scale thresholds!

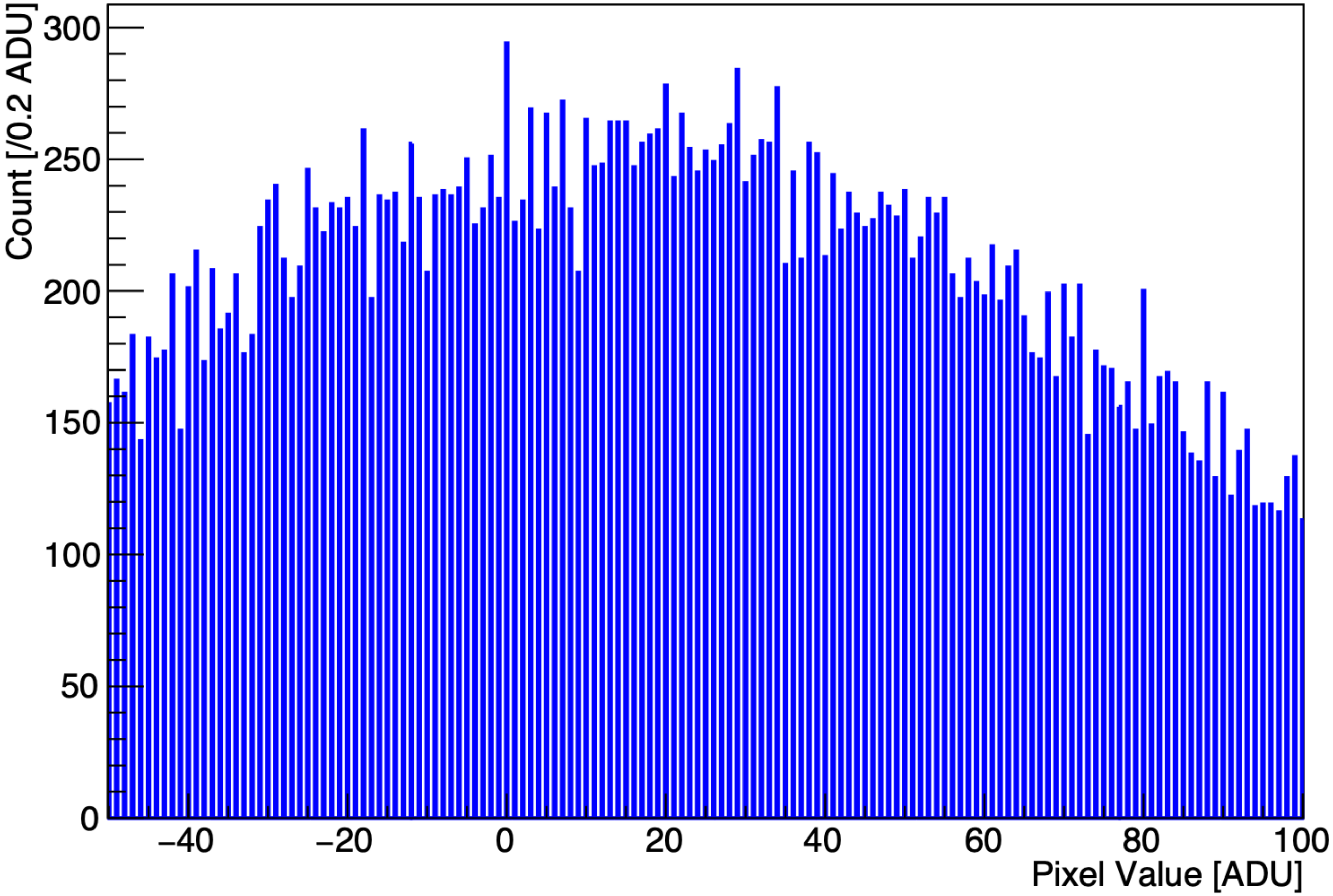
CCDs with “skipper” amplifiers from Janesick et al in 1990. Move charge on and off sense node to make multiple, non-destructive charge measurements. Later demonstrated the **ability to detect single electrons** (PRL 119, 131802 (2017)).

Reduces readout noise by 1/sqrt(N_{skips}).

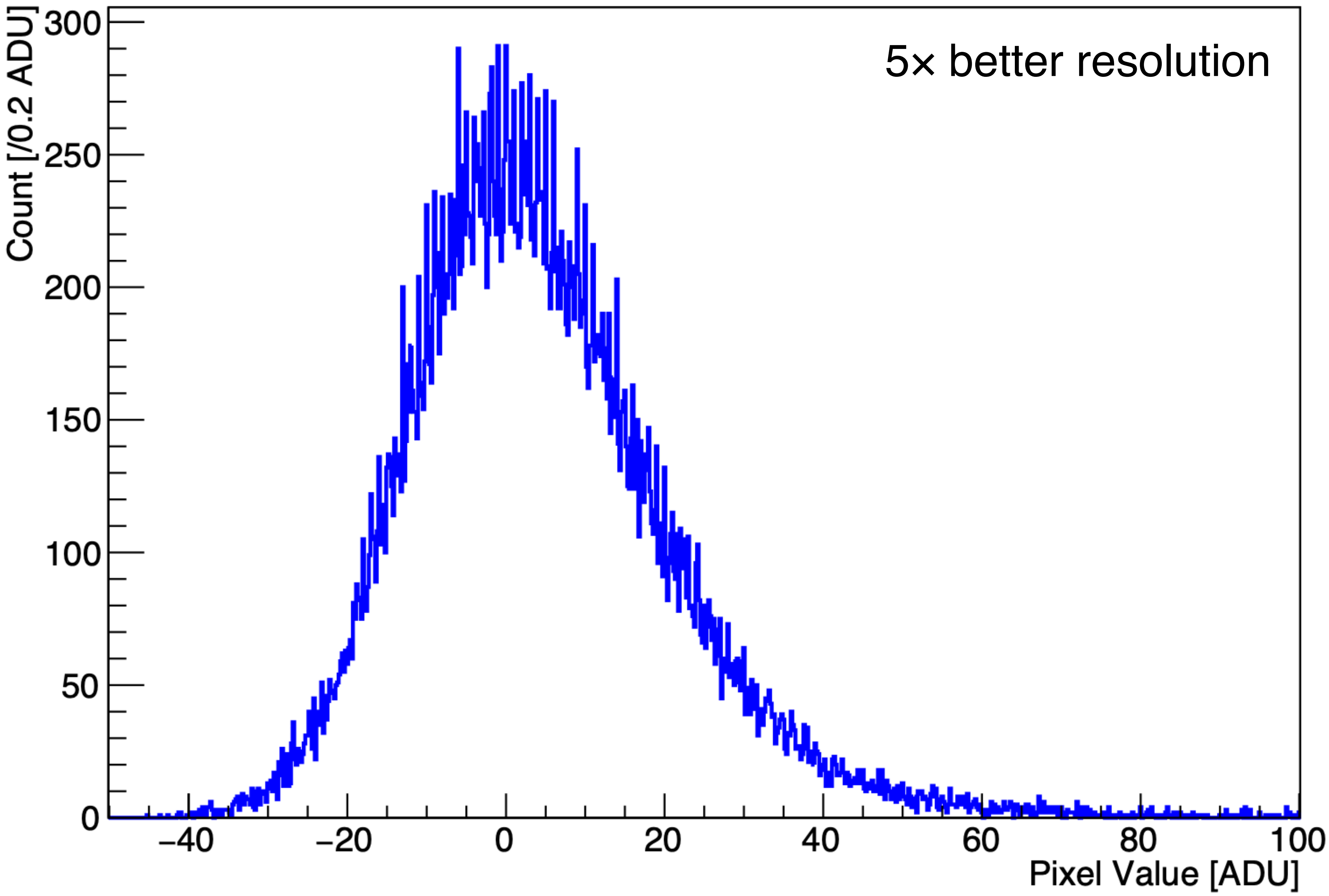


PRL 119 (2017) 131802

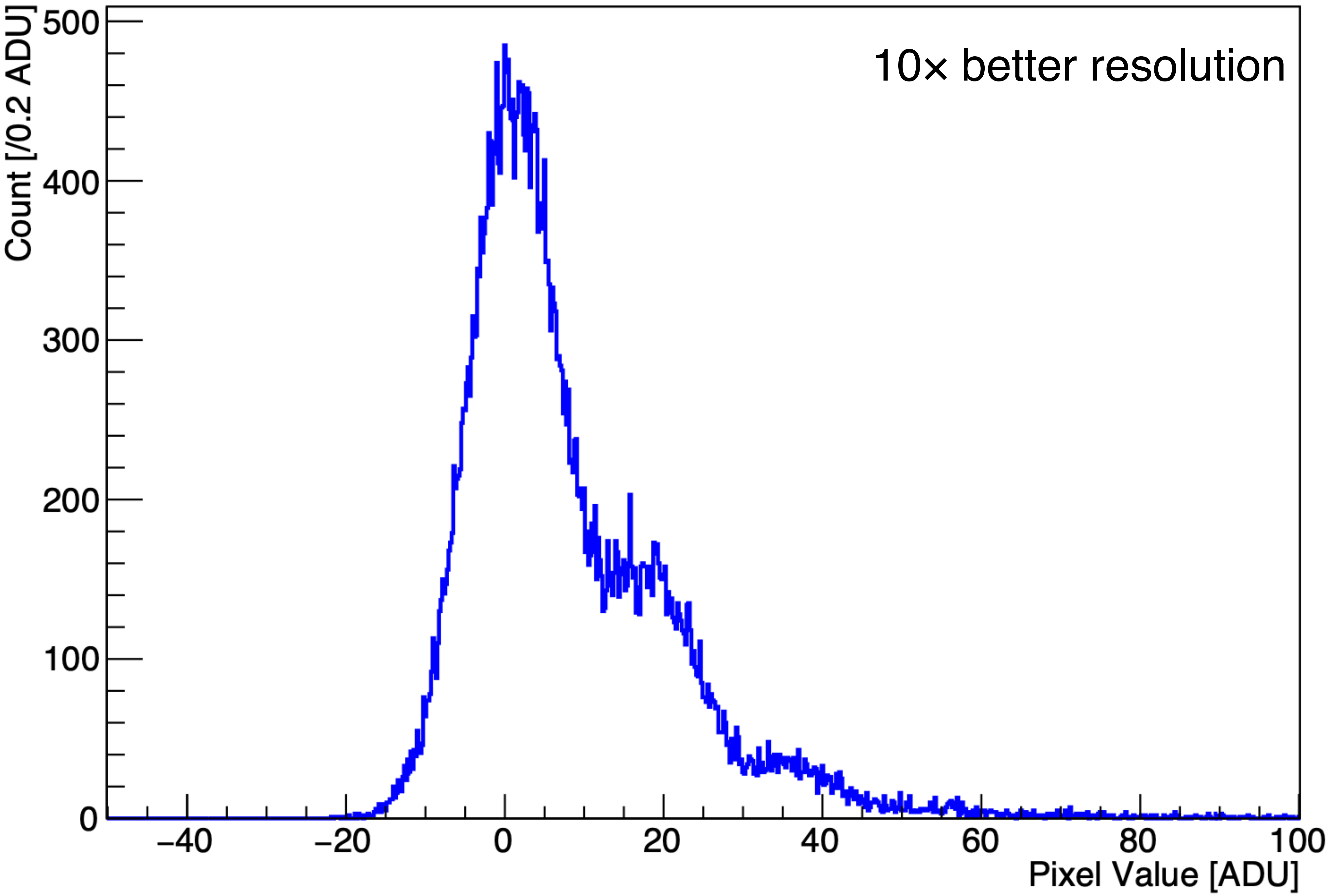
Charge resolution: Nskip = 1 (conventional CCD)



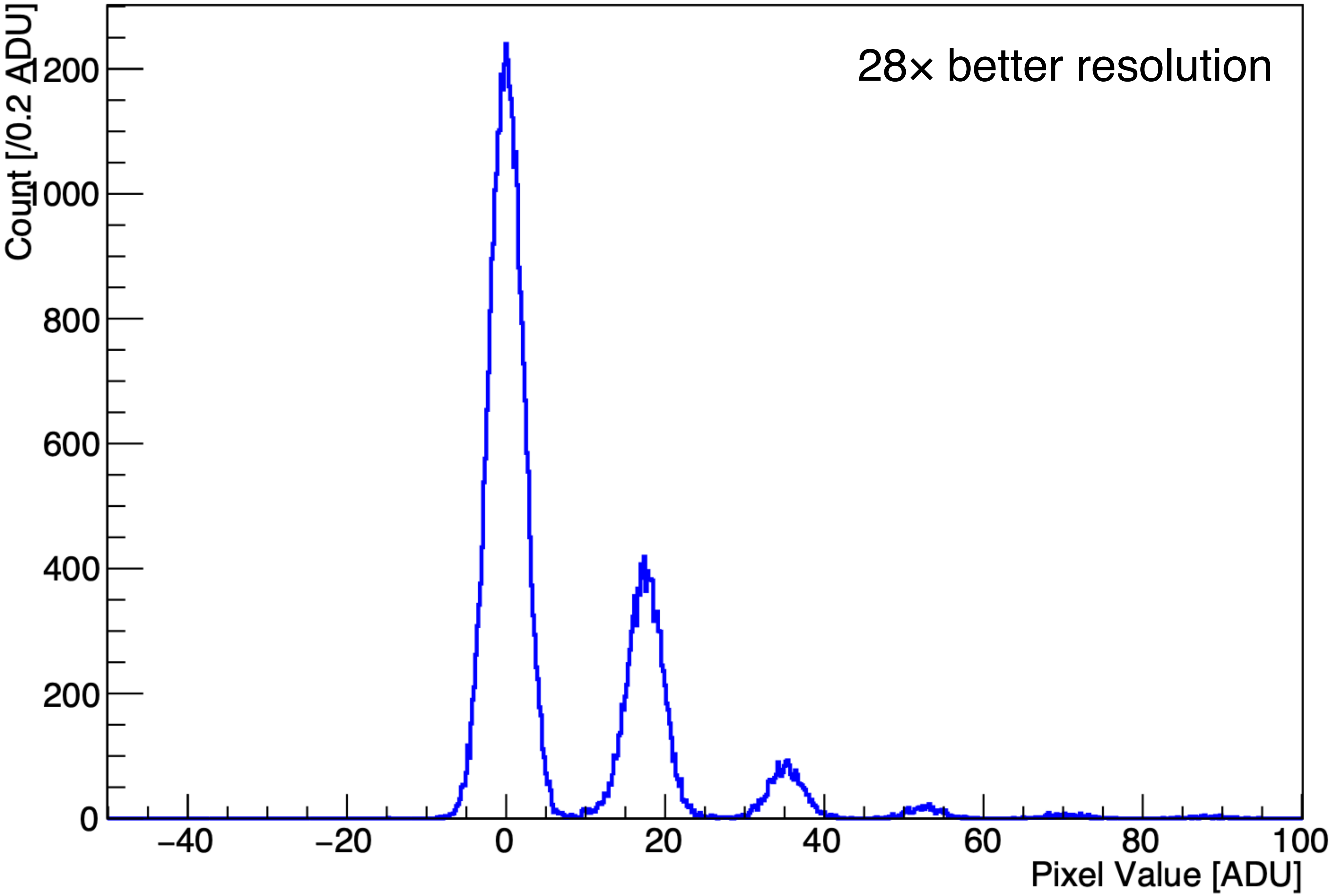
Charge resolution: Nskip = 25



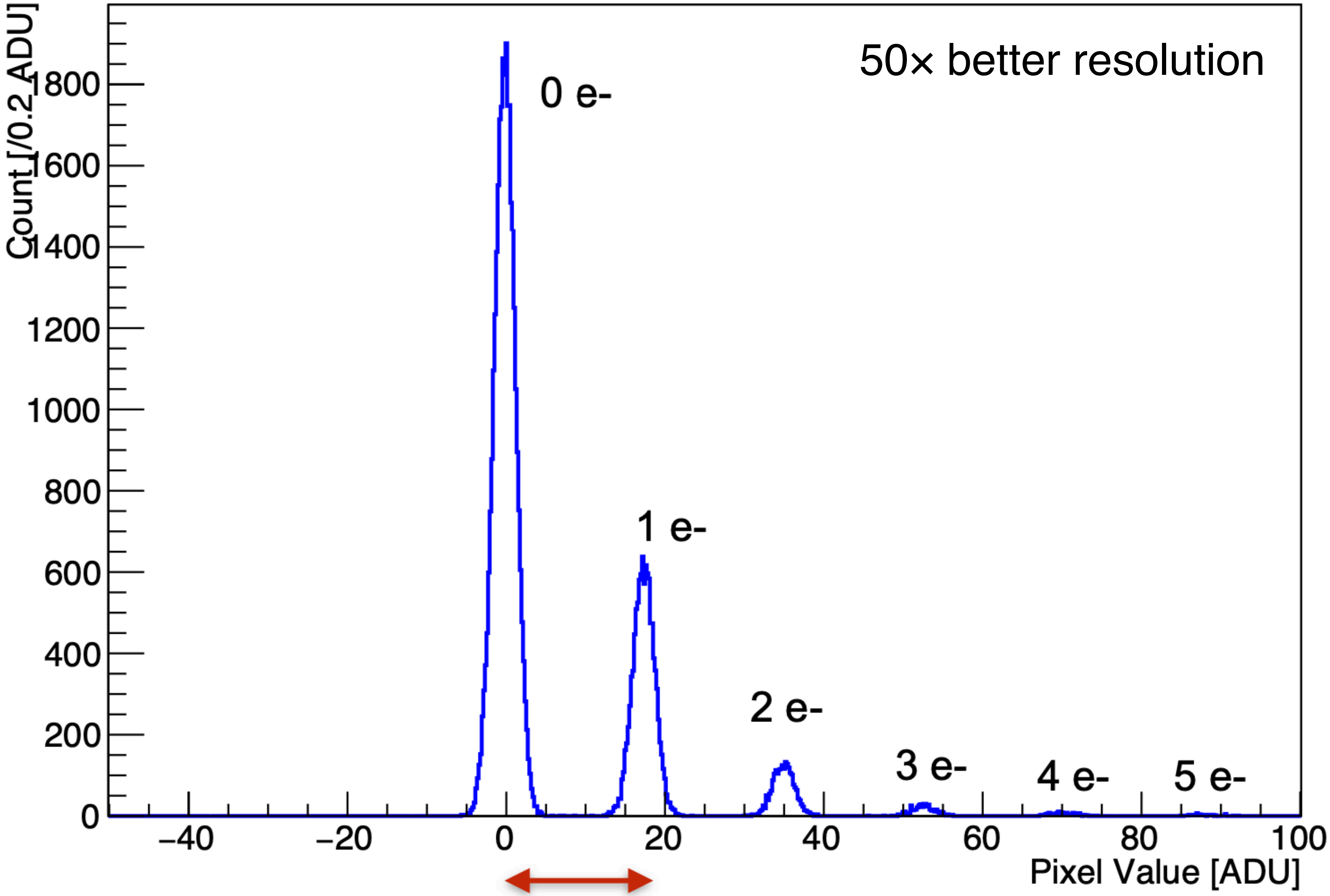
Charge resolution: Nskip = 100



Charge resolution: Nskip = 800



Charge resolution: Nskip = 2500



1 e- = 17.3 ADU

self-calibrating device!!

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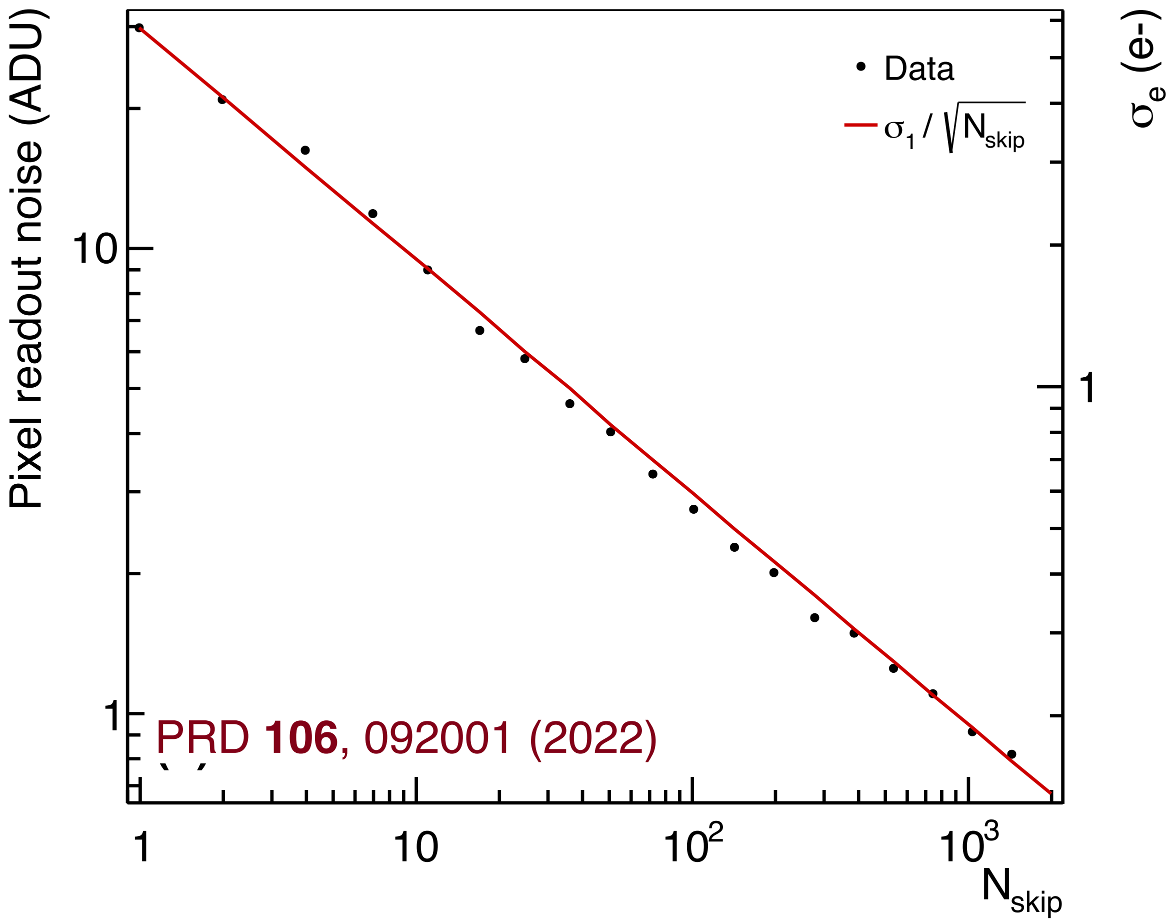
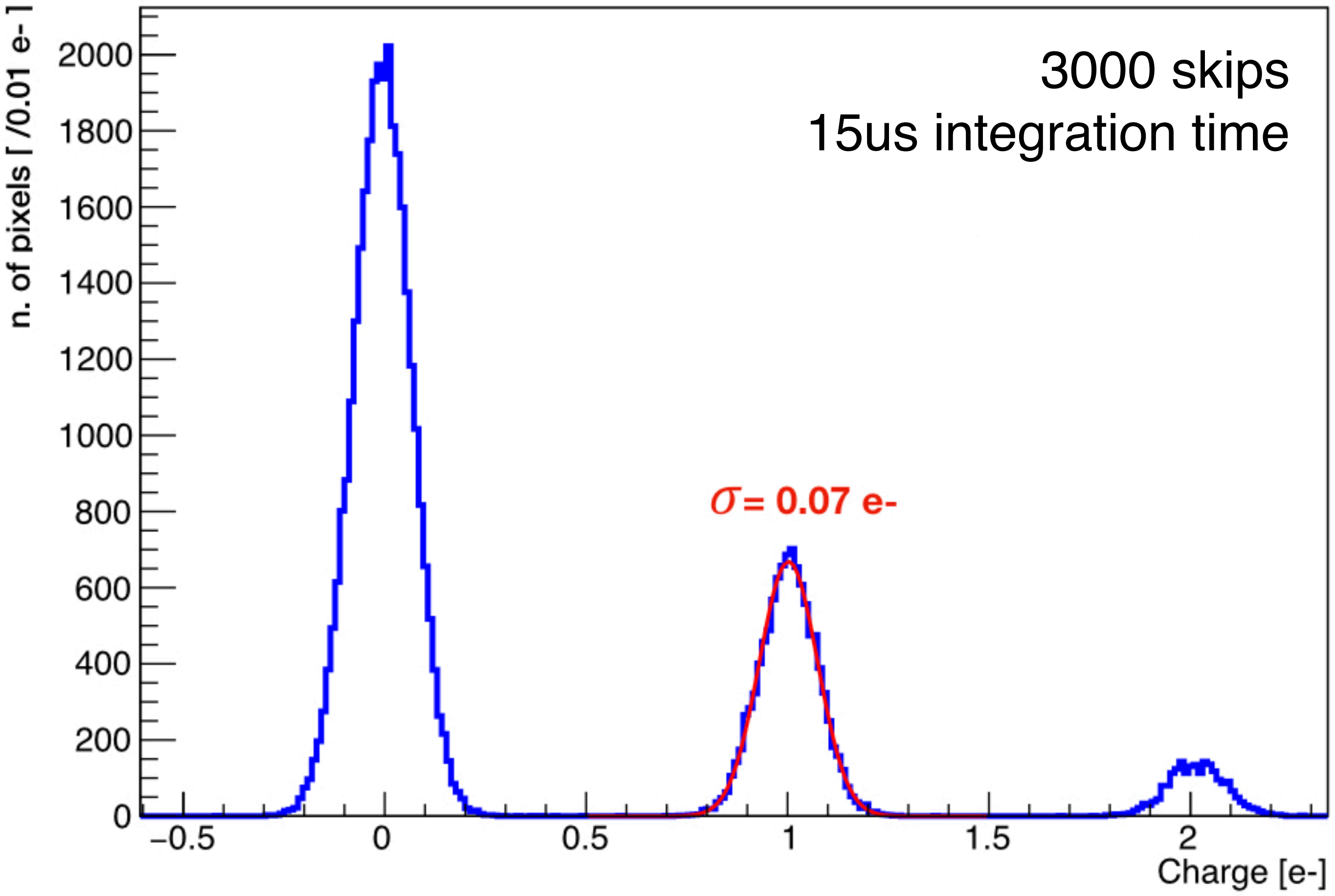
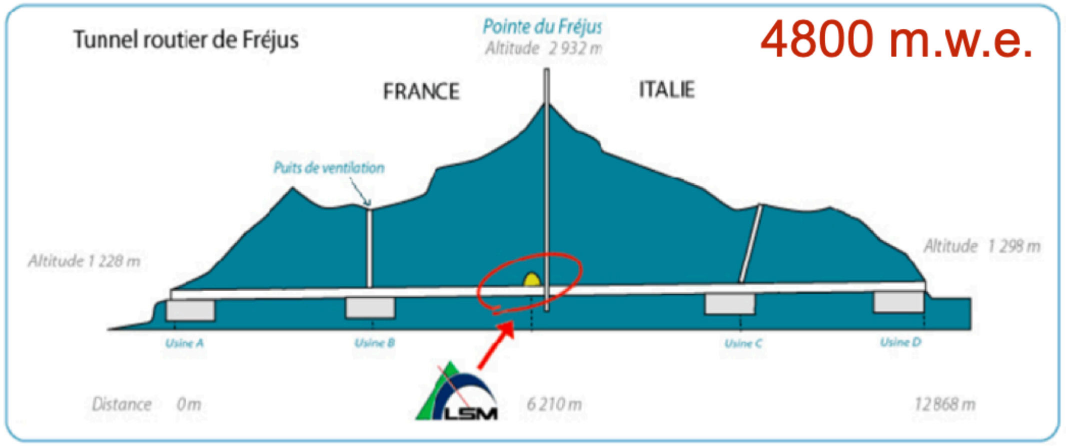




DArk Matter In CCDs at Modane

Laboratoire Souterrain de Modane (LSM)

4800 mwe overburden from Fréjus Peak
(meter water equivalent to 1700m of rock)

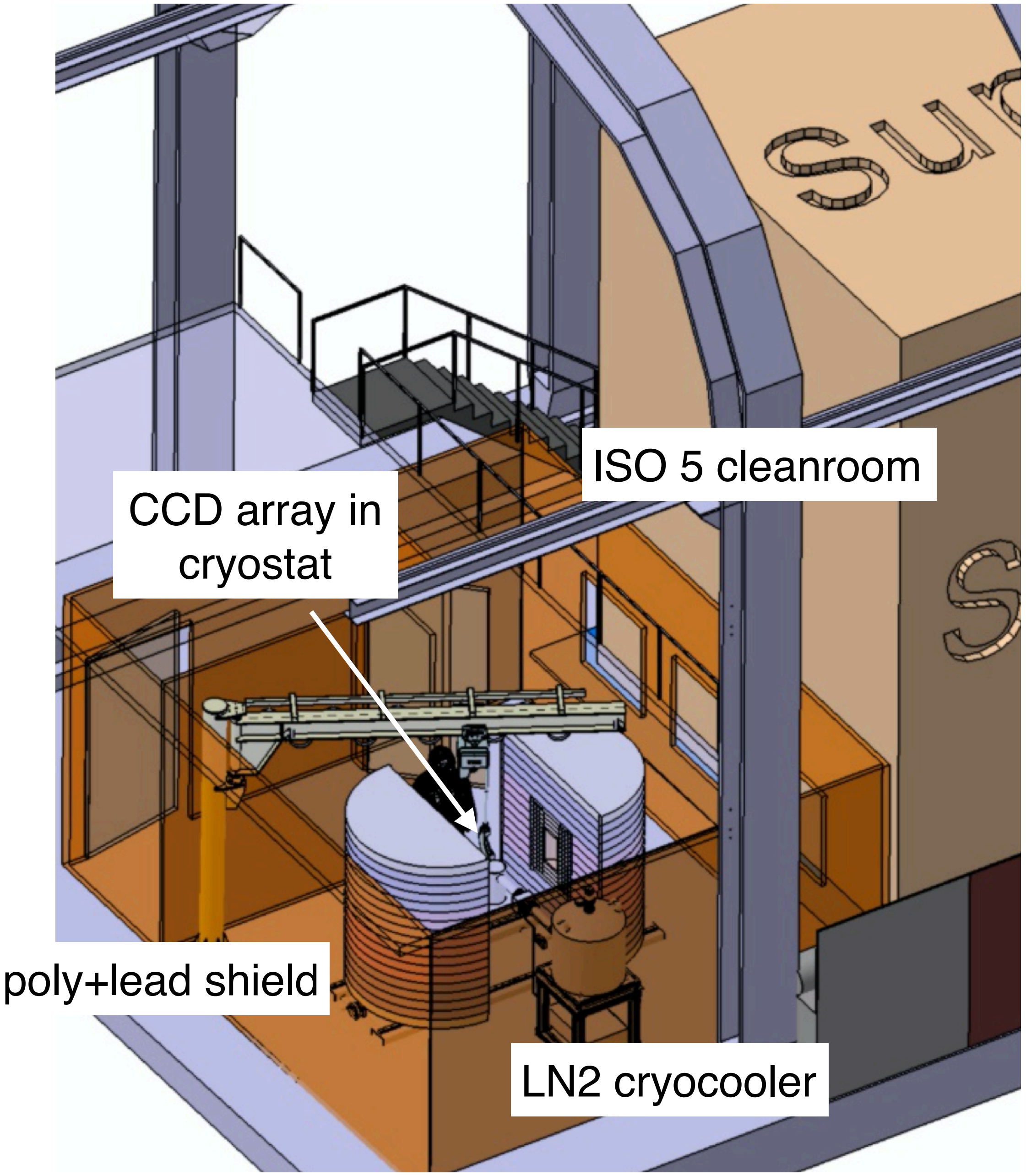


Physics goals

- detect nuclear and electron recoils to search for light dark matter candidates (eV to GeV)
- achieve ~0.1 dru background rate
  (1 differential rate unit = 1 event/keV/kg/day)
- operate ionization detector with 2-3 electron threshold (~eV)

Detector specs

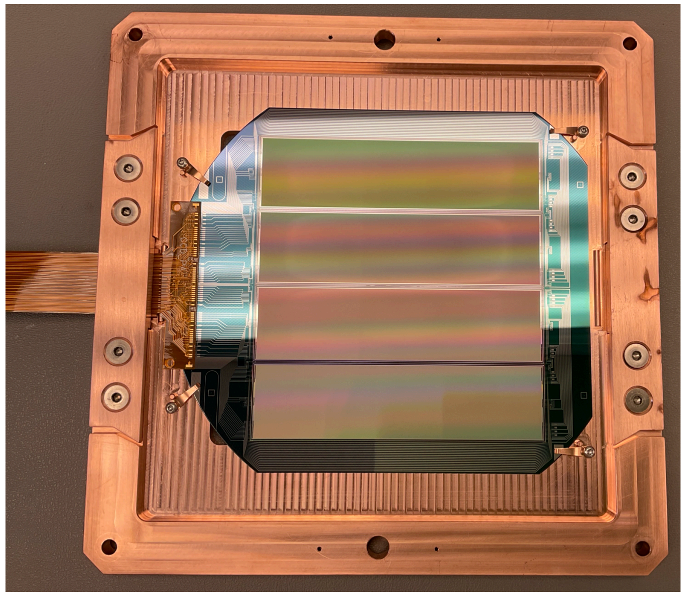
- thick (675um), massive (~3.5g), 9Mpixel CCDs
- array of 208 CCDs for kg-scale mass
- “skipper” amplifier readout for single electron energy resolution (sub-eV) and self-calibration
- pixelization for background rejection
- 1kg-year exposure to make significant impact!



DAMIC-M detector design

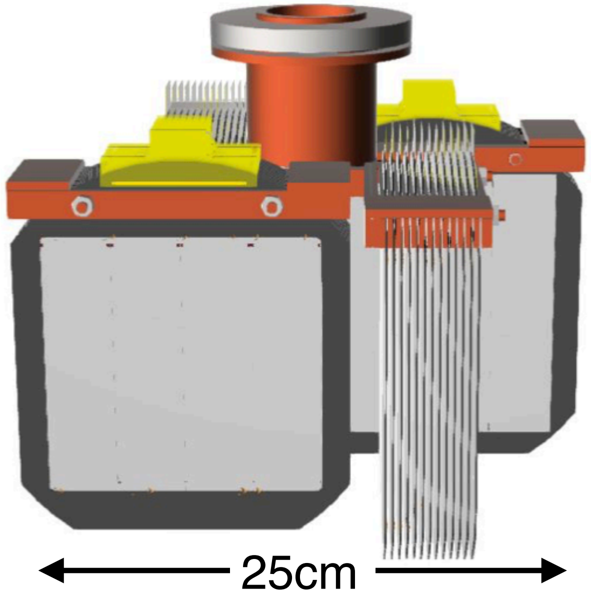
208 skipper CCDs

- high resistivity (>10kΩcm) n-type, high purity silicon
- 6k x 1.5k pixels (15 x 15 x 675 um^3)
- fully depleted (no charge loss when drifting)
- 47/6um^2 skipper amplifiers
- low background flex cable



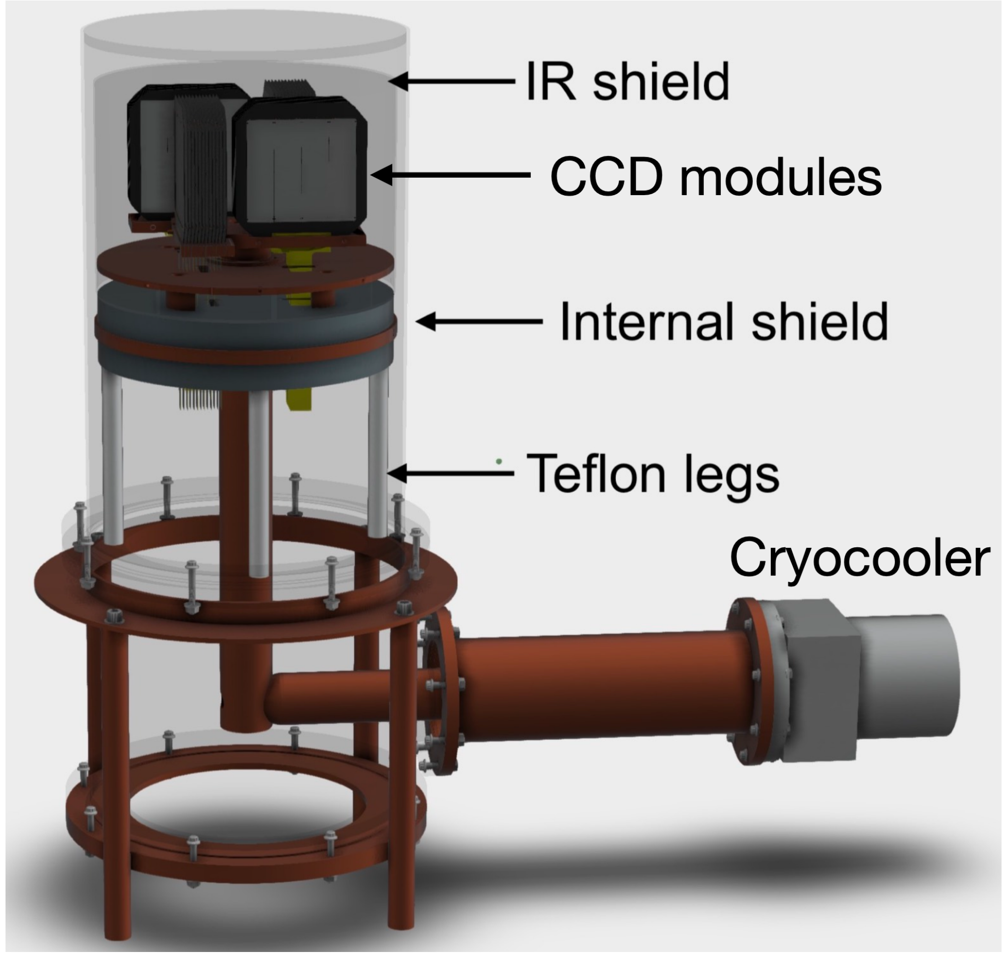
CCD module

CCD module array



Detector

- kg-scale, 4 CCDs per module
- electro-formed copper cryostat, IR shield
- operate at ~120K and 1e-7 mbar
- layered polyethylene + lead shielding, innermost layer of ancient lead
- custom electronics for fast readout and low noise



Background controls

- cosmic activation and radon limited by time above ground/in air (fabrication, transportation, etc)

Background mitigation efforts

CCD activation (expedite production, storage underground, transport in a container with 16-ton iron shielding)
PRD 102, 102006 (2020)

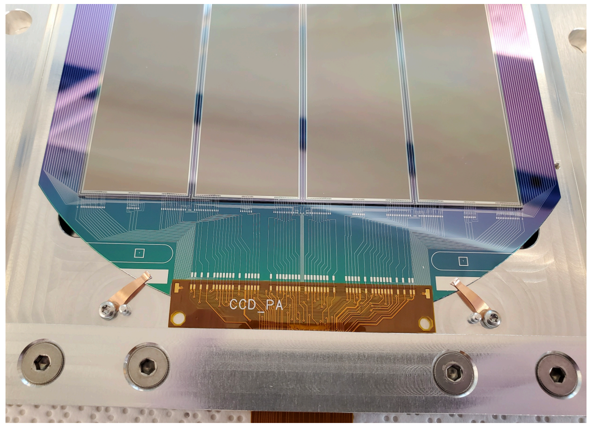
Strict control of exposure to Radon and dust

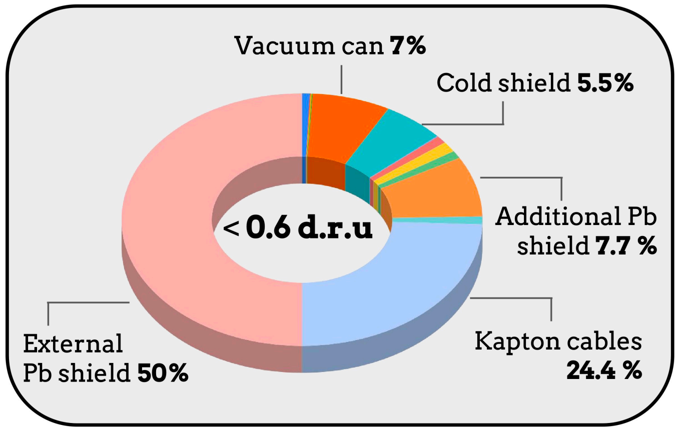
Ultra-clean CCD flex cables, further away from CCDs
EPJ Tech. Inst. 10, 17 (2023)

Copper electro-formed and machined underground
NIM A 828, 22 (2016)
AIP Conf. Proc. 1921, 020001 (2018)
*working to have some of this done at SURF!

Ancient lead shielding
Astropart. Phys. 47, 1 (2013)

Chemical cleaning
NIM A 579, 486 (2007)



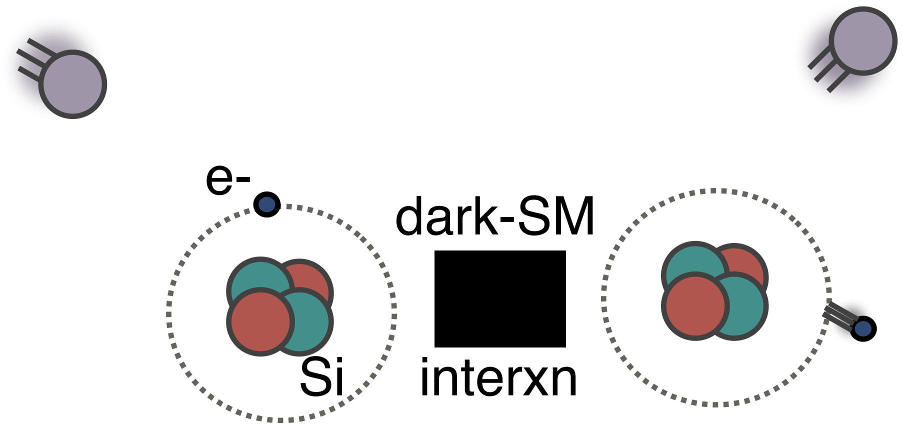


CCD are not included

and design improvements suggested by Geant4 simulations.

Electron recoils: sensitivity to dark sector

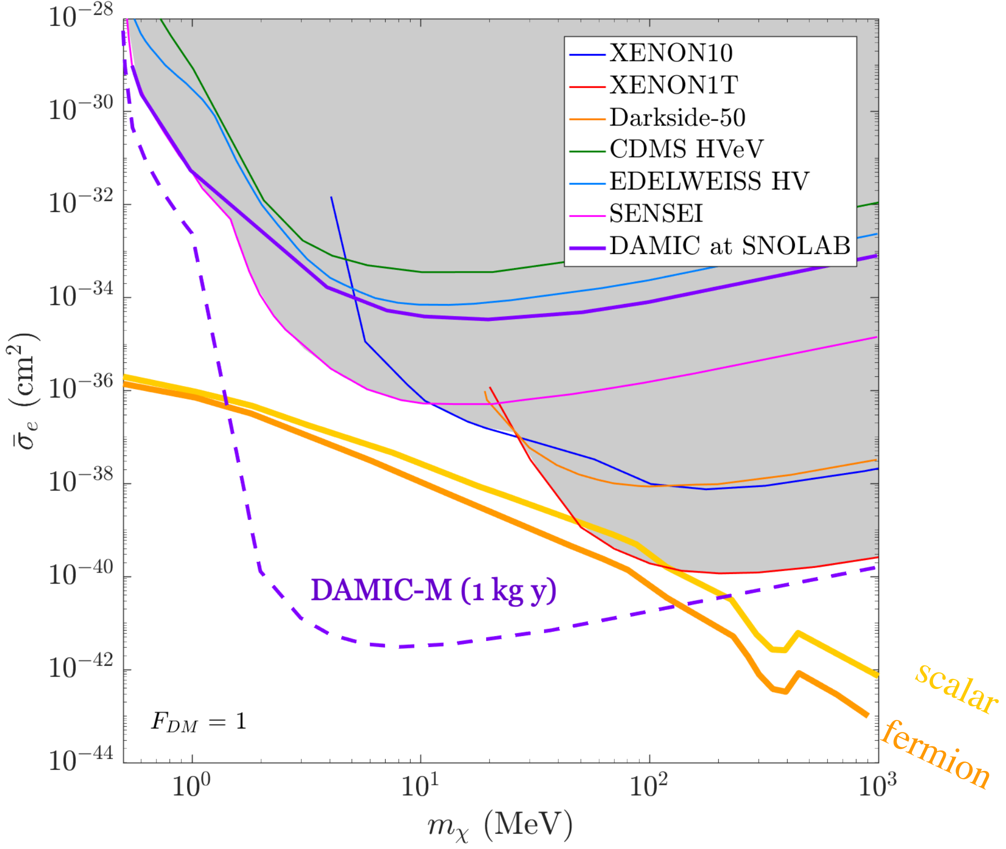
dark sector dark matter



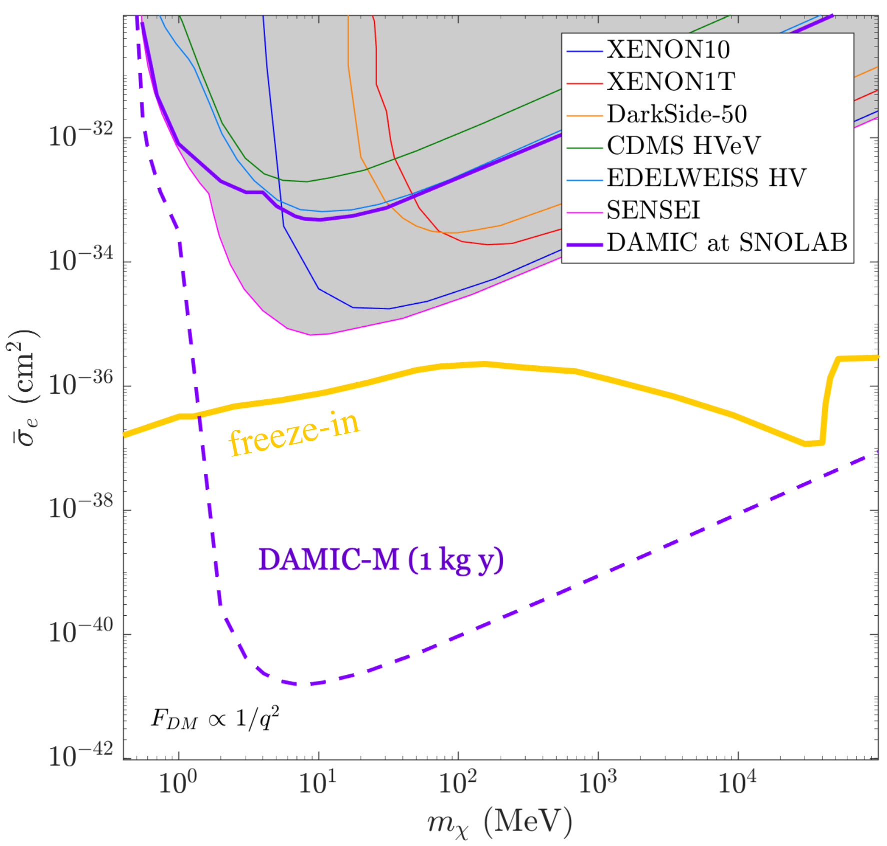
dark sector-electron scattering:

- dark sector DM interacts with target silicon bound electron through dark-SM interxn
- electron absorbs some energy and recoils
- creates electron-hole pairs
- CCD drifts charges and reads out

heavy mediator



ultra-light mediator



single electron sensitivity to probe predictions in sub-GeV regime

DAMIC-M about to start construction

Accomplishments

- produced, stored wafers for CCDs with low cosmogenic exposure
- demonstrated single electron resolution with large format, thick skipper CCDs
- developed low background packaging procedures
- first tracks on DAMIC-M prototype module
- analysis/simulation frameworks ready and continuous efforts for improvements
- developed new CCD controller electronics
- precision measurement of Compton scattering in silicon down to 23eV
- evaluated performance of DAMIC-M prototype CCDs for production
- installed Low Background Chamber (LBC), first dark matter-electron results and modulation analysis
- DAMIC-M skipper CCDs at SNOLAB, low energy excess update
- production of final DAMIC-M CCDs

In progress

- performing nuclear ionization efficiency measurements
- fabrication, assays of low-background parts
- preparations for on-site work, including CCD packaging, testing, assembly

DAMIC-M on-line by 2025!

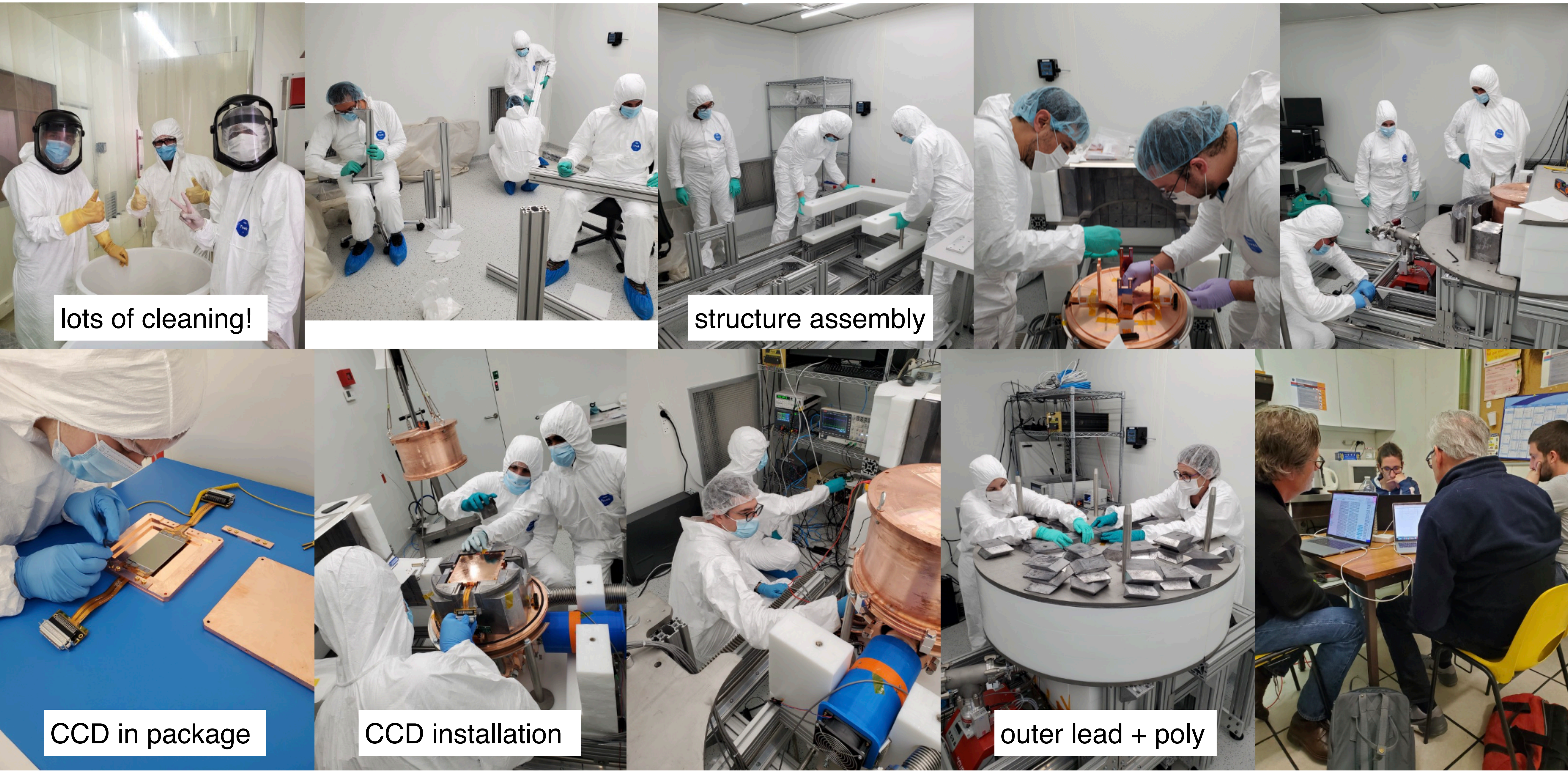
Low Background Chamber (LBC)

DAMIC-M prototype at LSM
operating since February 2022

Objectives:

1. Gain working experience at LSM
2. Characterize DAMIC-M components in a low background environment (~dru)
3. Test of other subsystems (CCD controller and electronics, slow control, DAQ software, data transfer and data quality monitoring)
4. **First science results with small detector**
   - DM-electron scattering search
   - daily modulation search

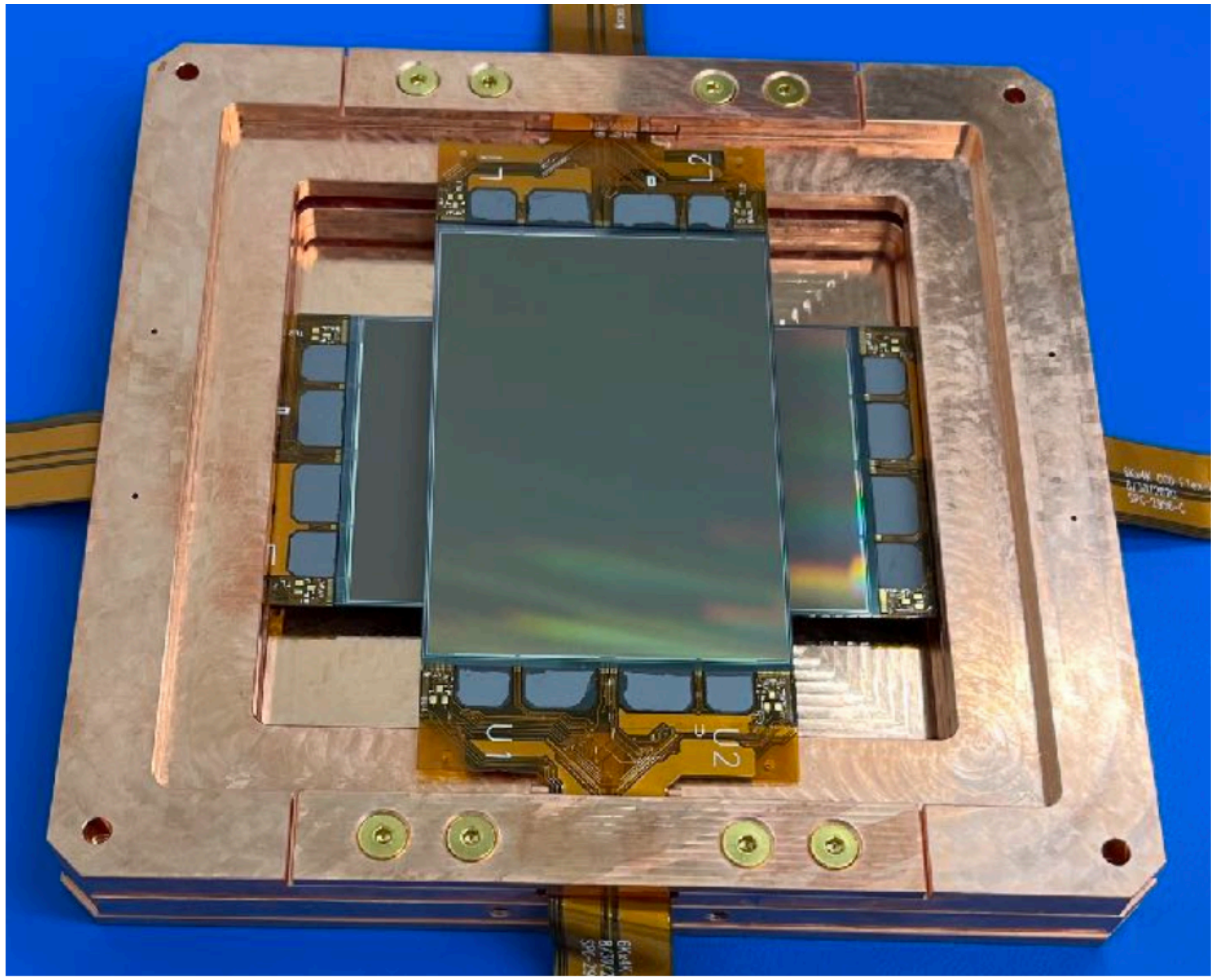
Construction of the LBC

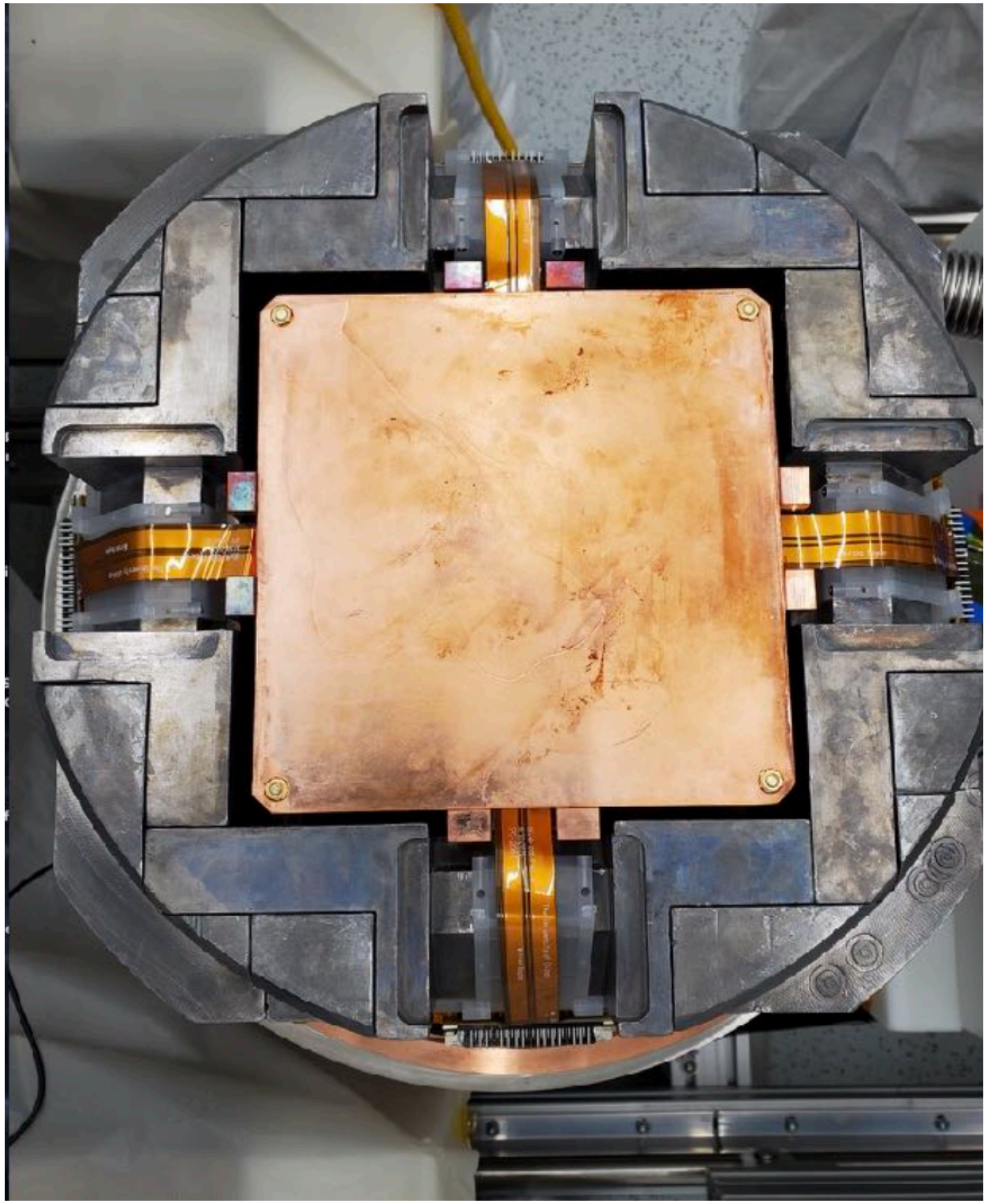


cleaning, clean room preparation, support structure, cryostat, CCDs, external shielding, electronics, slow control, grounding, troubleshooting, ...

LBC detector - CCDs

2 skipper CCDs
6k x 4k format (24M pixels)
~17g target mass
no material between CCDs
new 2-layer flex cable
copper box as infrared shield
ancient lead innermost castle layer

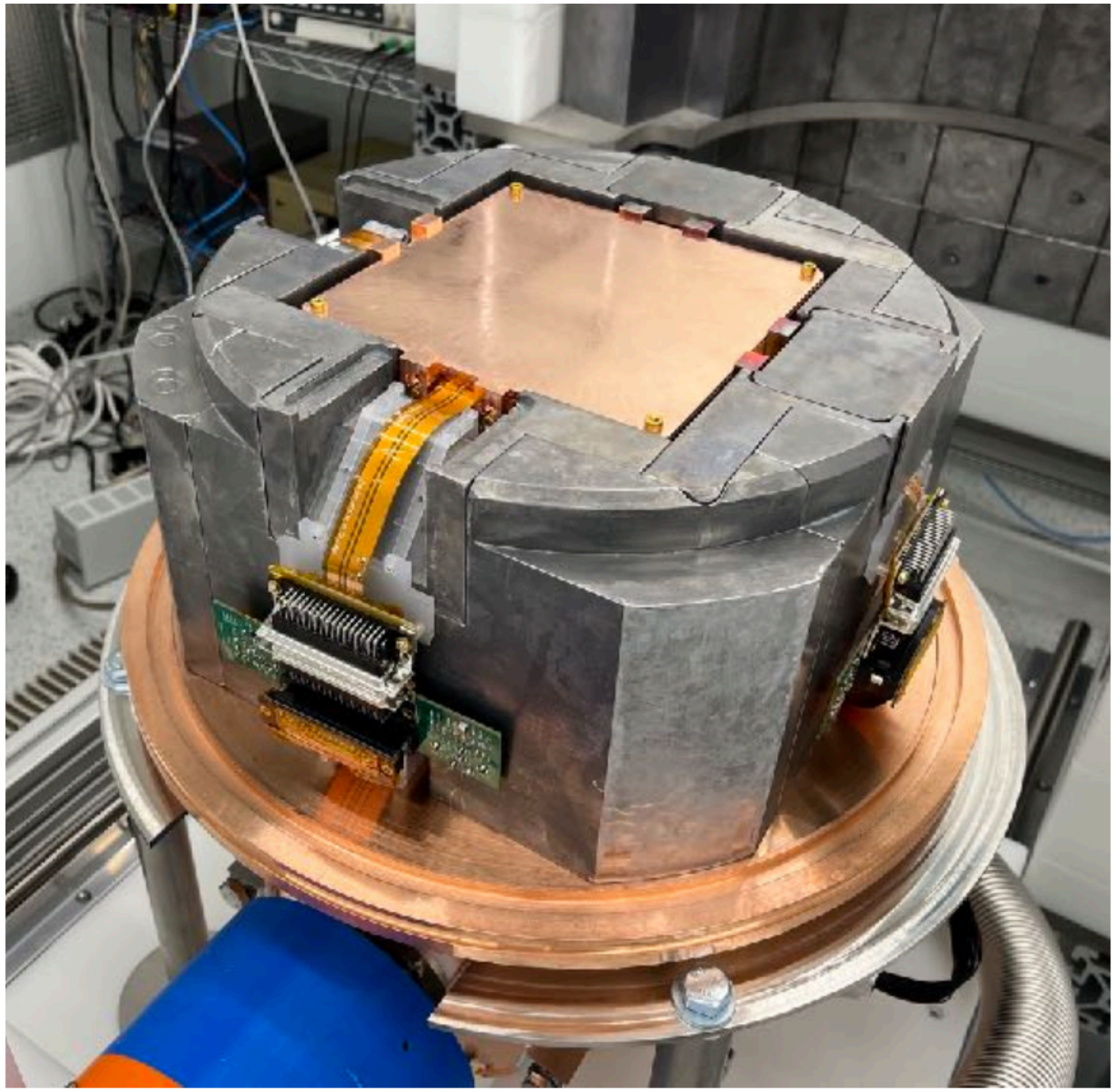




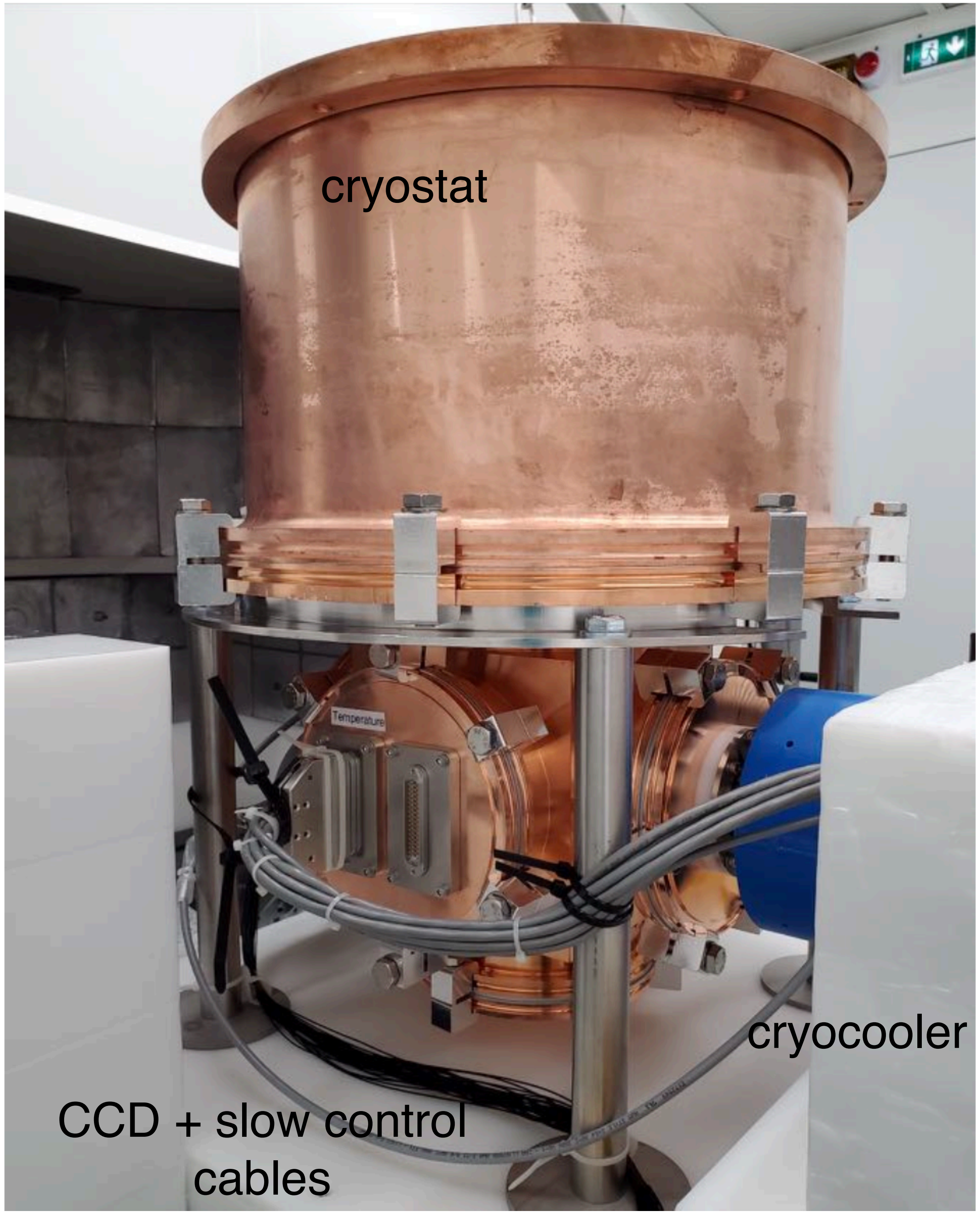
recently installed DAMIC-M modules

LBC detector - electronics and slow control

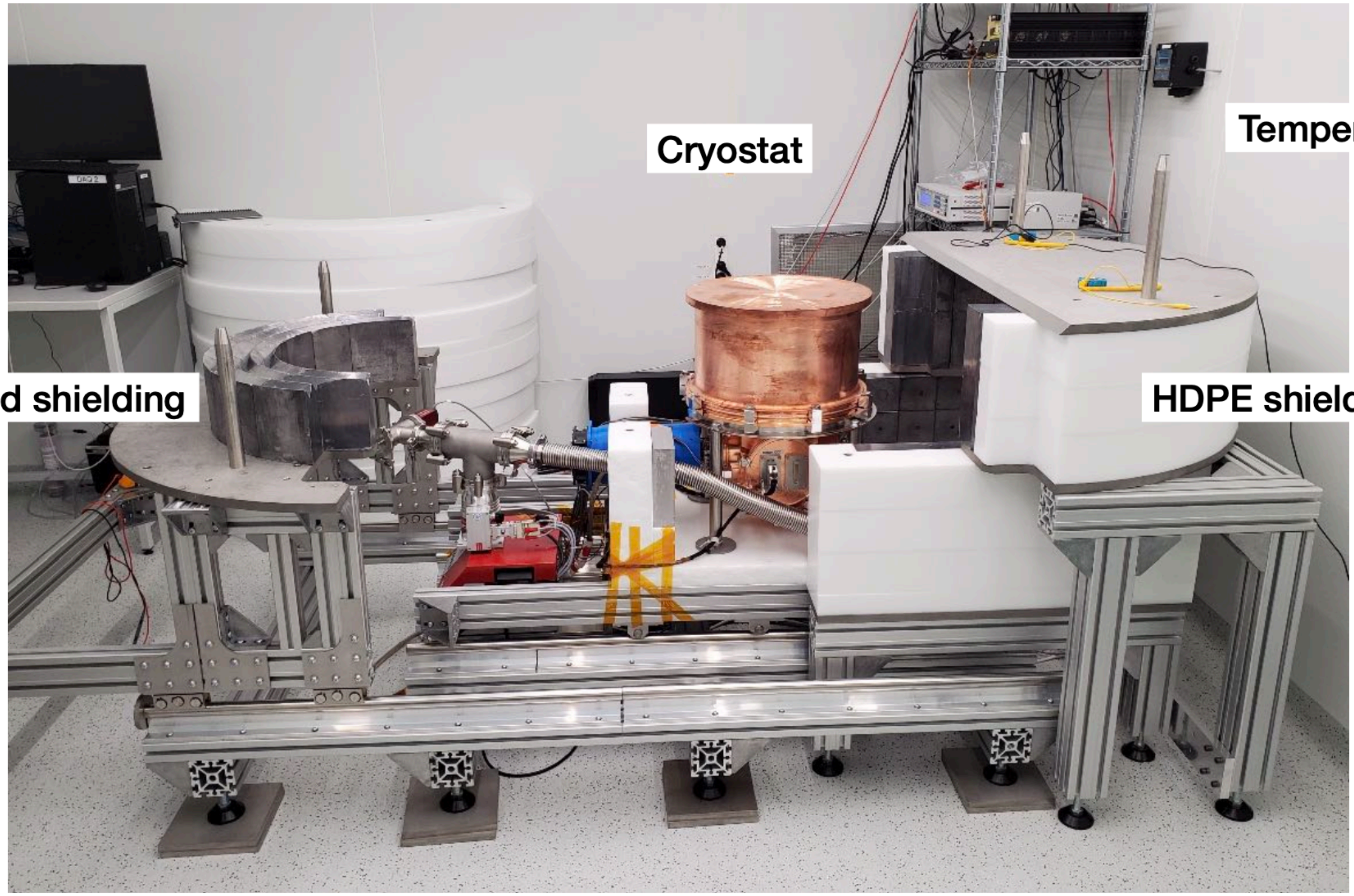
front-end electronics for amplifiers and clock shaping
Leach as controller and data acquisition



using slow control system from UChicago

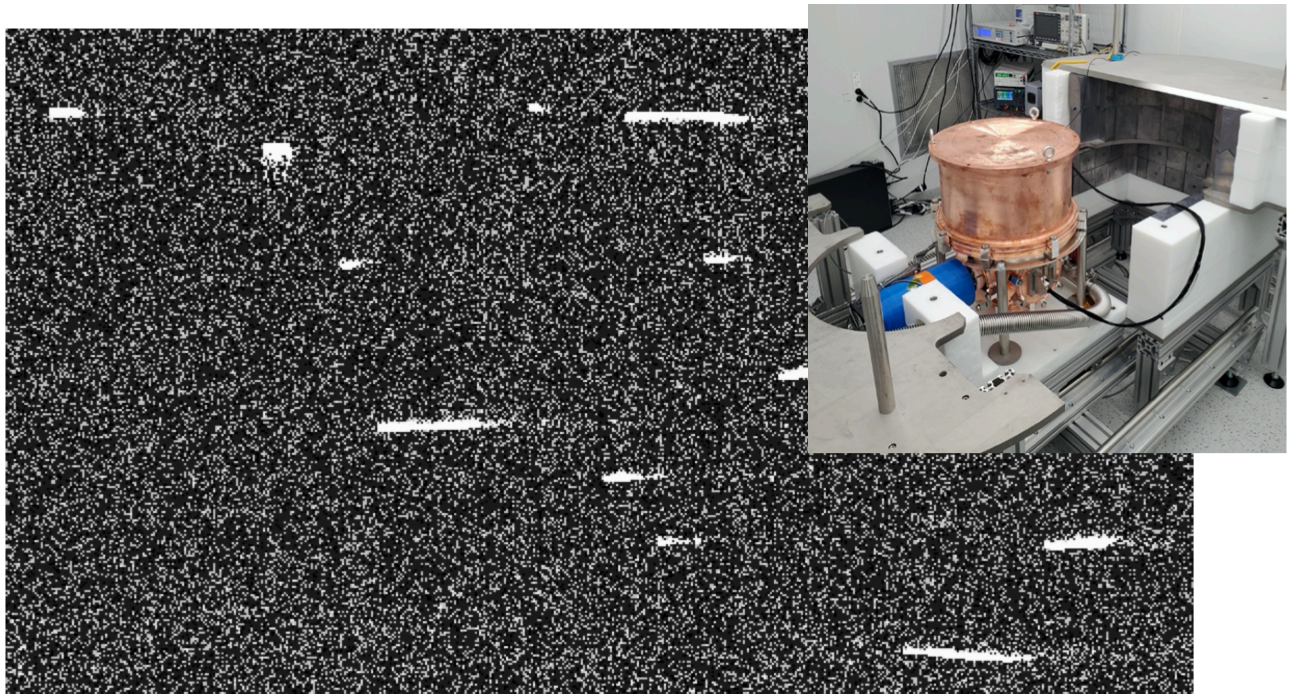


LBC detector - layout

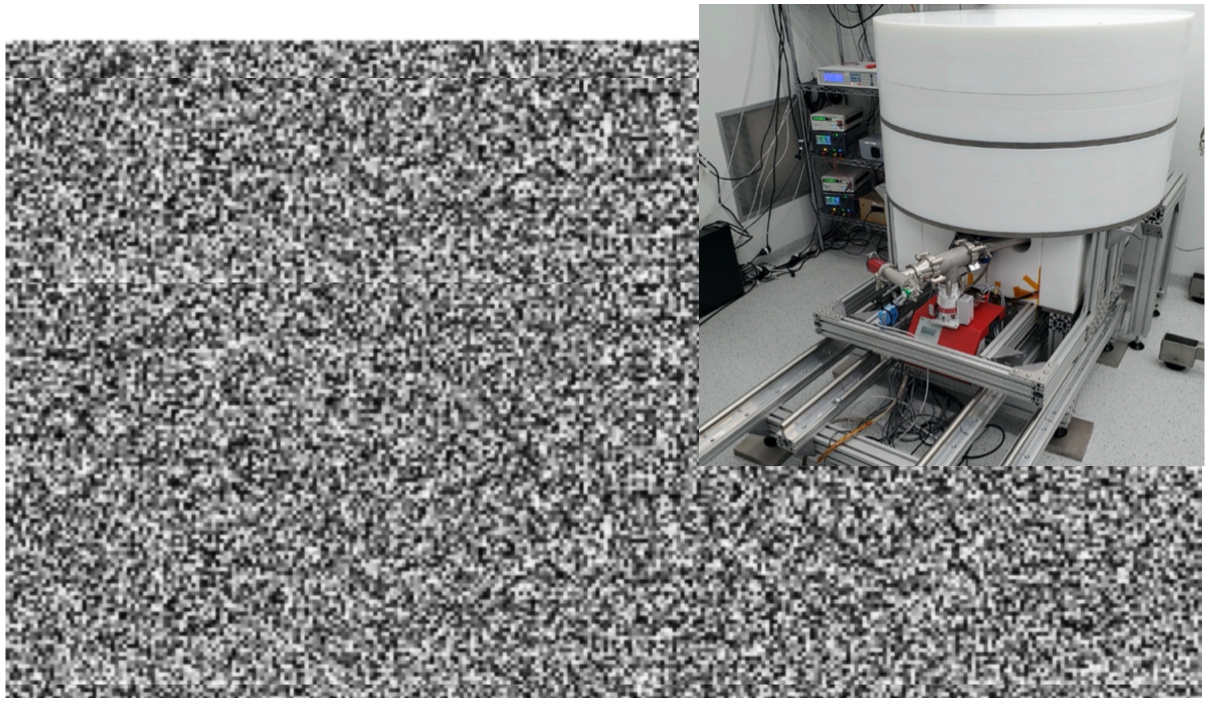


LBC data sets

Internal shield



Internal + external shield



Commissioning runs (Feb - May)

- verify performance of detector
- optimize CCD parameters (e.g. CTI)
- confirm calibration and develop analysis
- internal shield (300dru)
- dark current reduction with thermal tests (slower cool-down/warm-up (0.1 K/min))

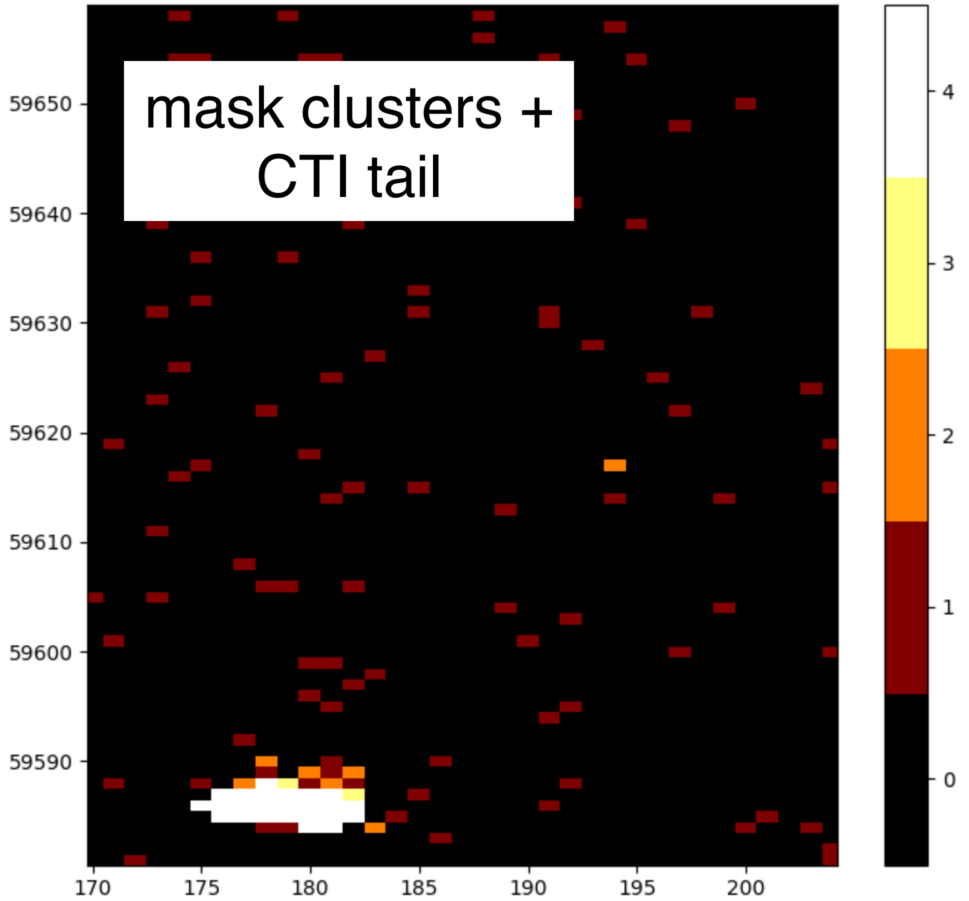
Science runs (May - November)

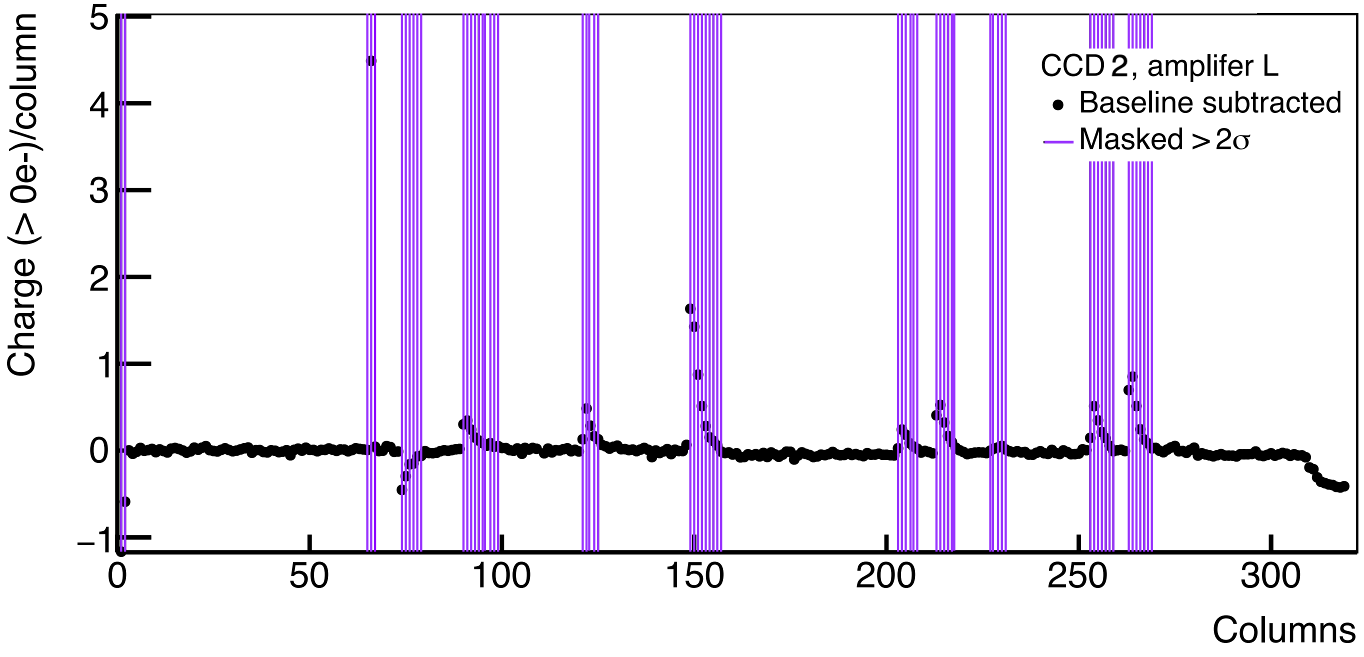
- internal+external shield (~10 dru*)
- 0.2 e- energy resolution (650skips)
- dark current 3.0e-3 e-/pixel/day, under investigation
- DM-electron analysis with 85.23 g-days
- daily mod search with 39.97 g-days

*backgrounds reduced to ~1 dru with electroformed copper and new flex cables

Image cleaning and event selection

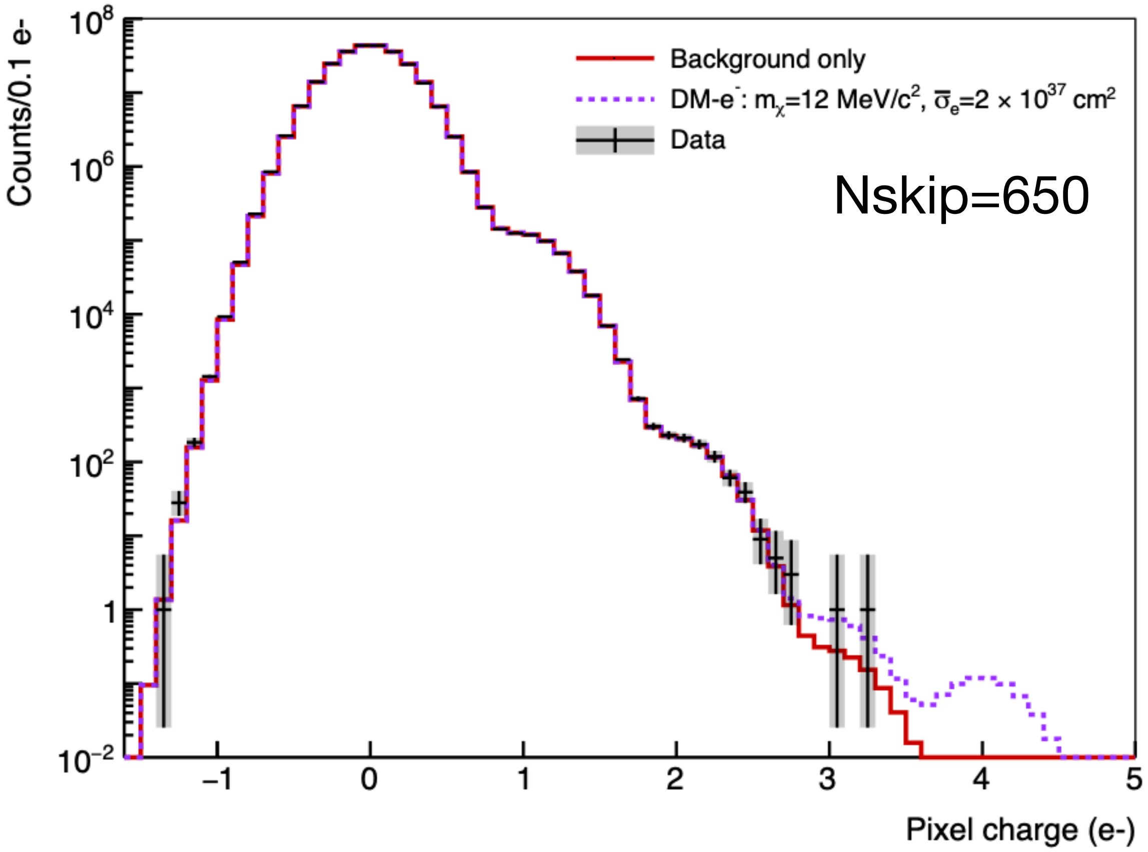
1. **Image selection**
   exclude images with outlier dark current
2. **Cluster reconstruction**
   use seed threshold to group pixel hits
   adjacent $>3\sigma_{elec}$ with one pixel >2e-
   remove single pixel with >7e-
3. **Masking**
   remove clusters, 10 trailing pixels in
   horz, vert direction from CTI
   ~1% of area masked in science runs
4. **Amplifier cross-talk evaluation**
   remove pixels if high charge signal is
   observed in both amplifiers
5. **Search for defects**
   remove “hot” columns with high charge,
   $>2\sigma_{DC}$ of DC distribution





Dark matter-electron limit setting

1. **Use QEdark to generate differential rate of DM signal (interactions with bound e-)**
   - halo parameters from PhystatDM (arXiv: 2105.00599)
2. **Apply detector response to obtain PDF of signal, including:**
   - eV to ionized e- conversion with low energy ionization yield (PRD 102, 063026 (2020))
   - diffusion model using parameters measured with LBC CCDs
3. **Measure single pixel charge distribution (PCD) in each amplifier of each CCD,** assumes Poisson background model with a Gaussian noise resolution

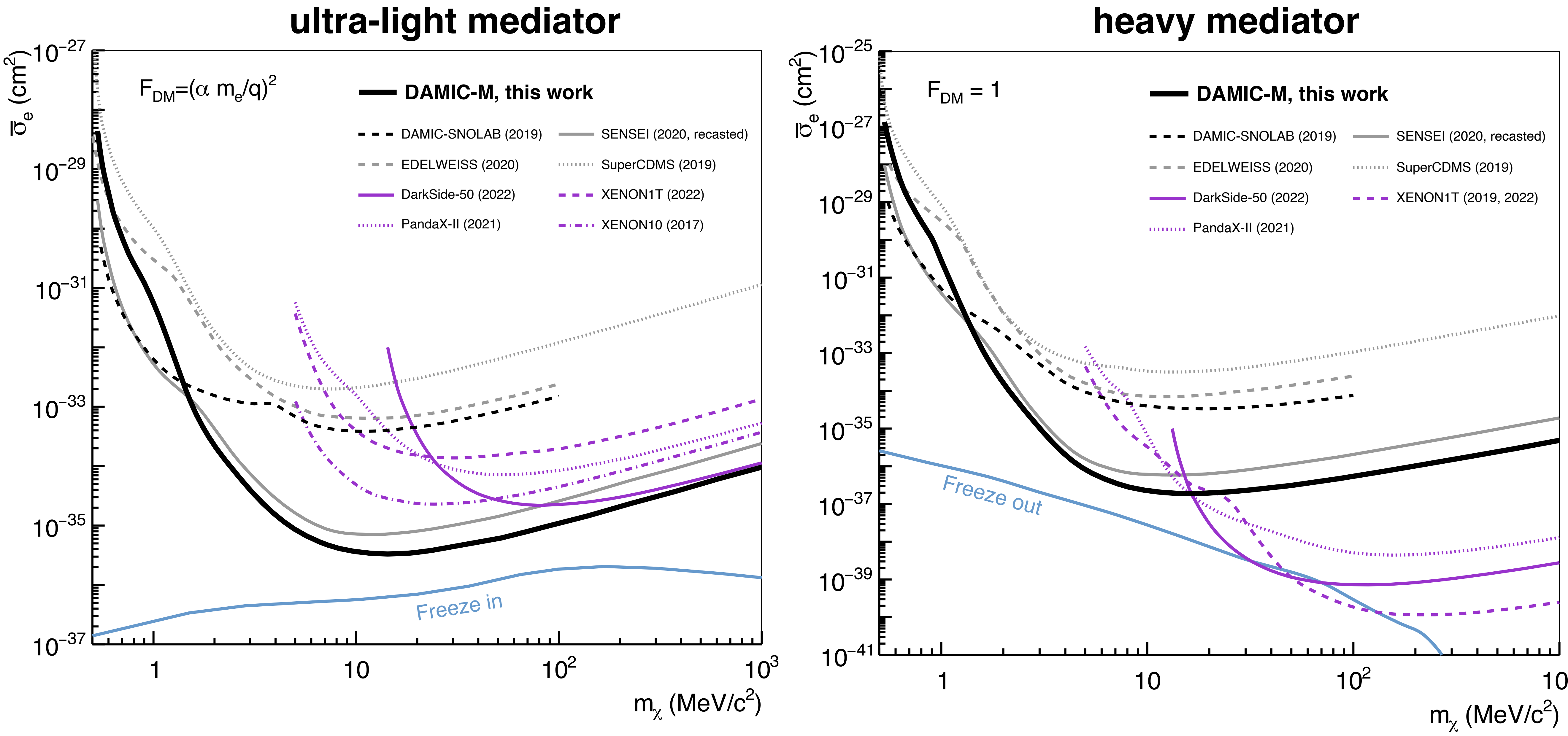


PRL 130, 171003 (2023)

4. **Fit whole PCD and perform binned joint likelihood fit** to set 90% C.L. upper limits in cross section-DM mass parameter space

First results: dark matter-electron scattering

PRL 130, 171003 (2023)

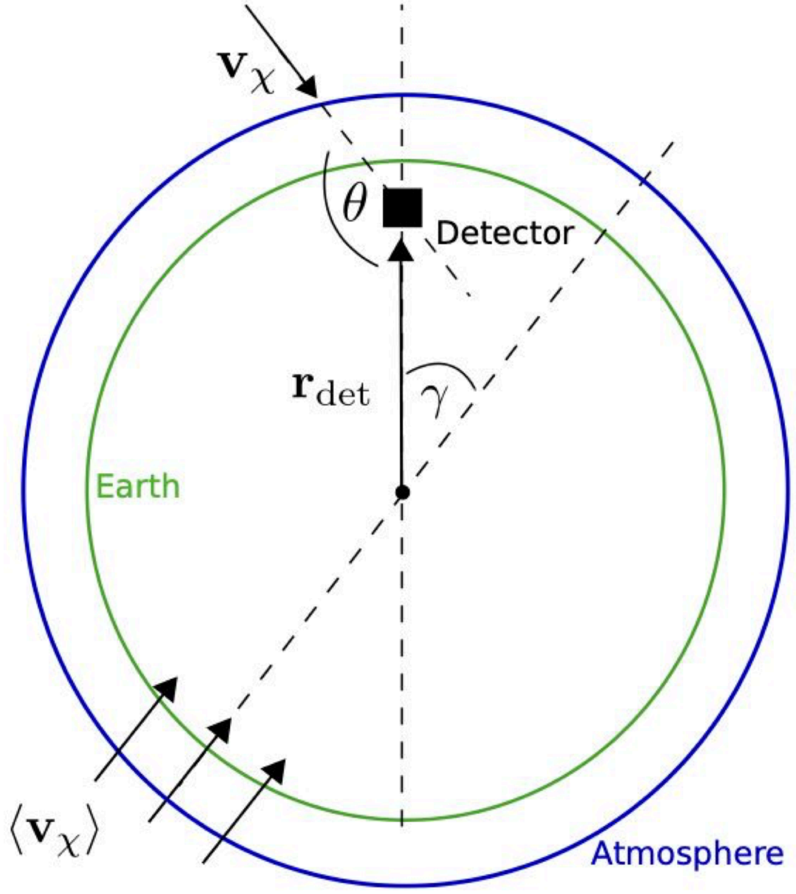


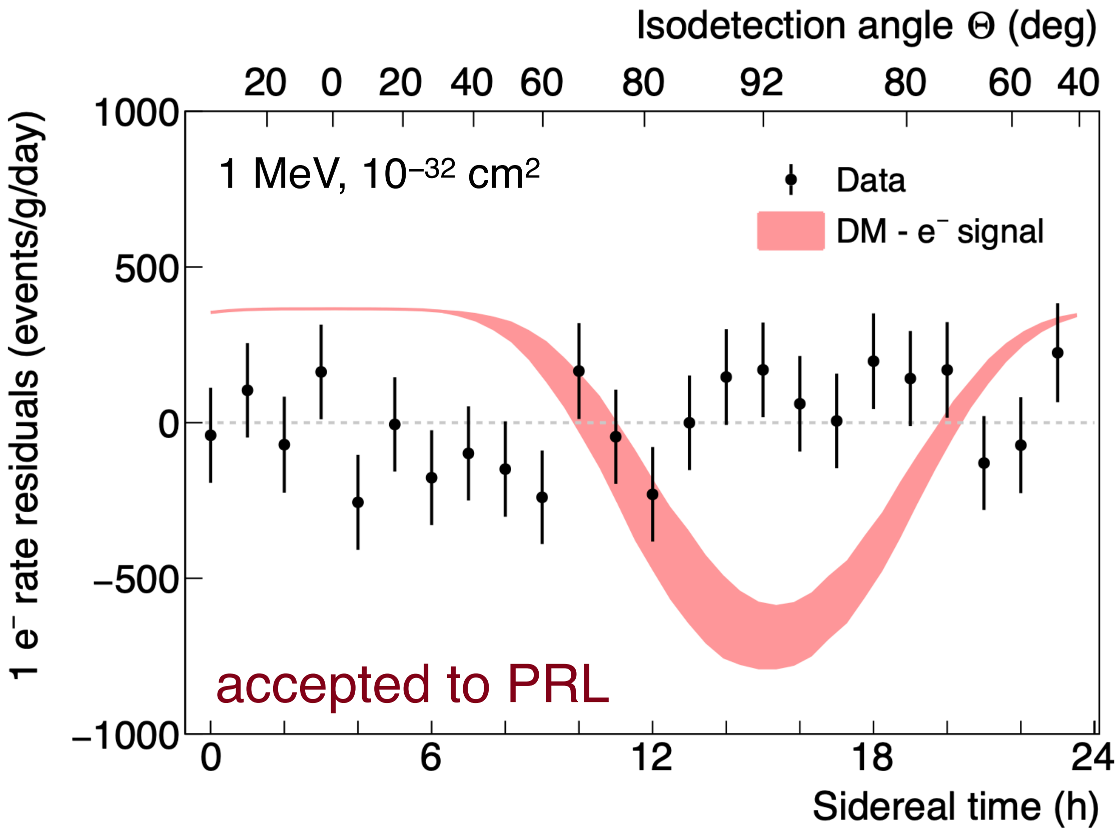
world-leading results with just 2 CCDs in a few months!

Daily modulation search

Motivation:

- MeV-scale DM candidates with large cross sections have not been ruled out
- scattering in Earth's bulk becomes relevant for flux/velocity distribution, DM signal can modulate over day
- in LBC, time-dependent signal vs. independent background strong discriminating power
- new approach for constraining DM-e scattering





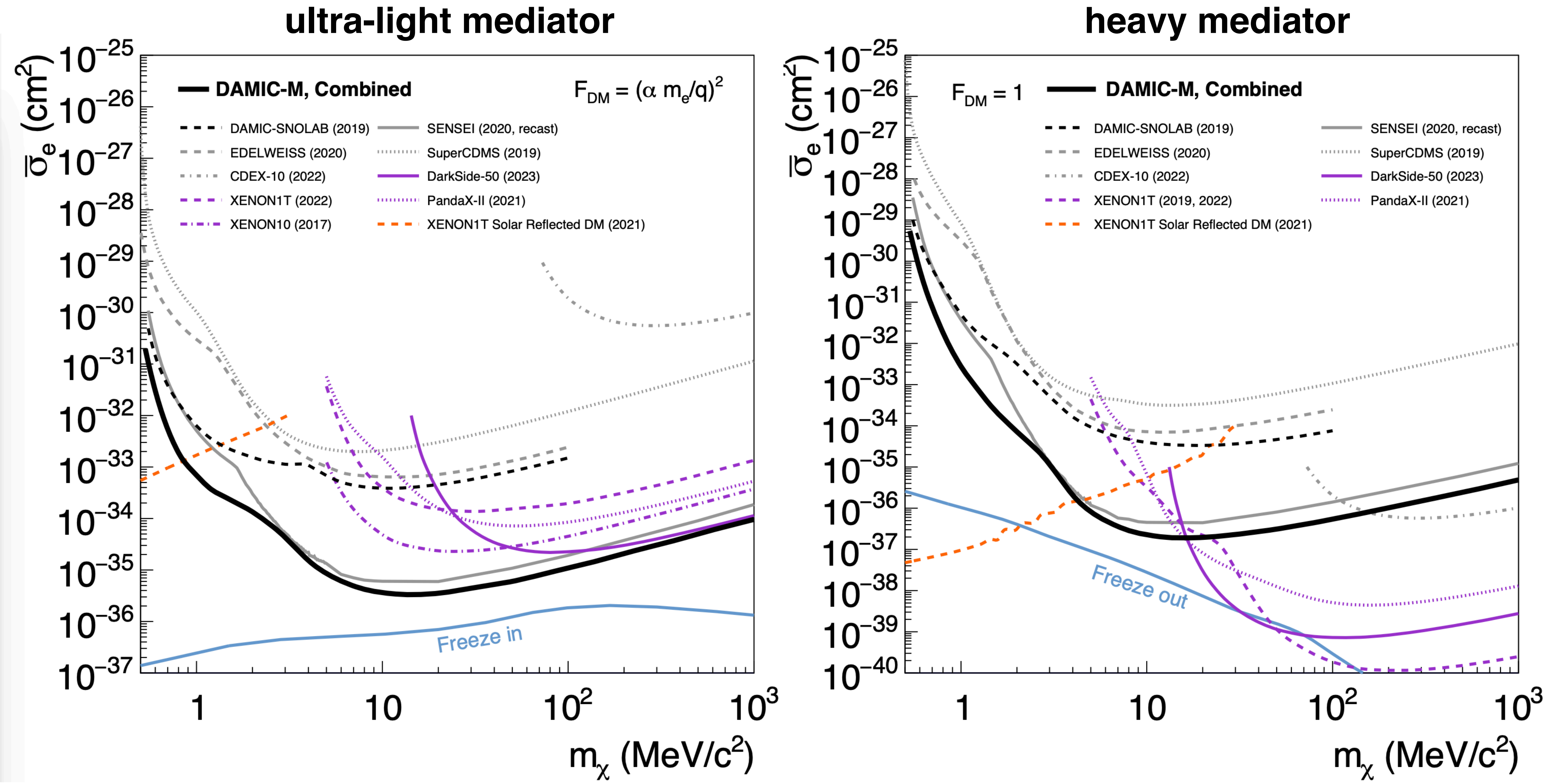
accepted to PRL

LBC result:

- search in 1e- bin, as >1e- already constrained
- same data set as DM-e scattering, except using images taken consecutively every 10min
- no modulation signal found for periods of 1-48 hr
- improves first LBC DM-e by 2 orders of magnitude

Combined DM-electron scattering results

PRL 132, 101006 (2024)



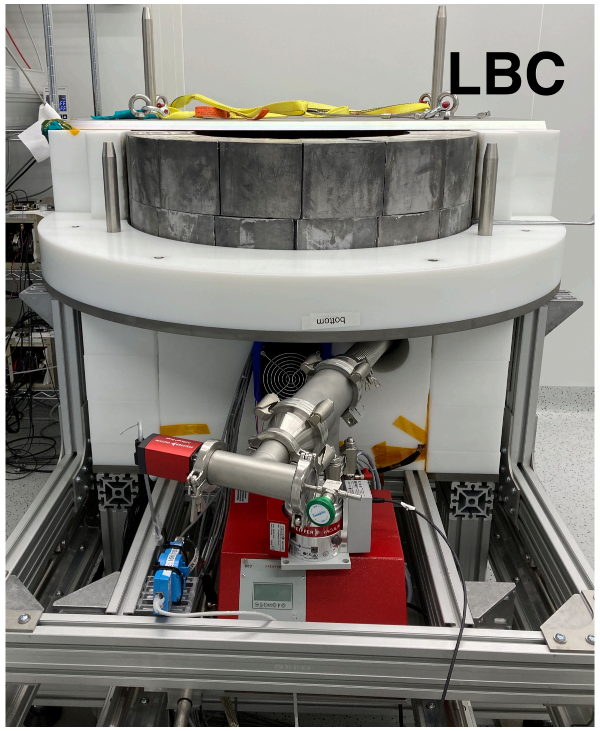
world-leading for all masses results with new modulation analysis!

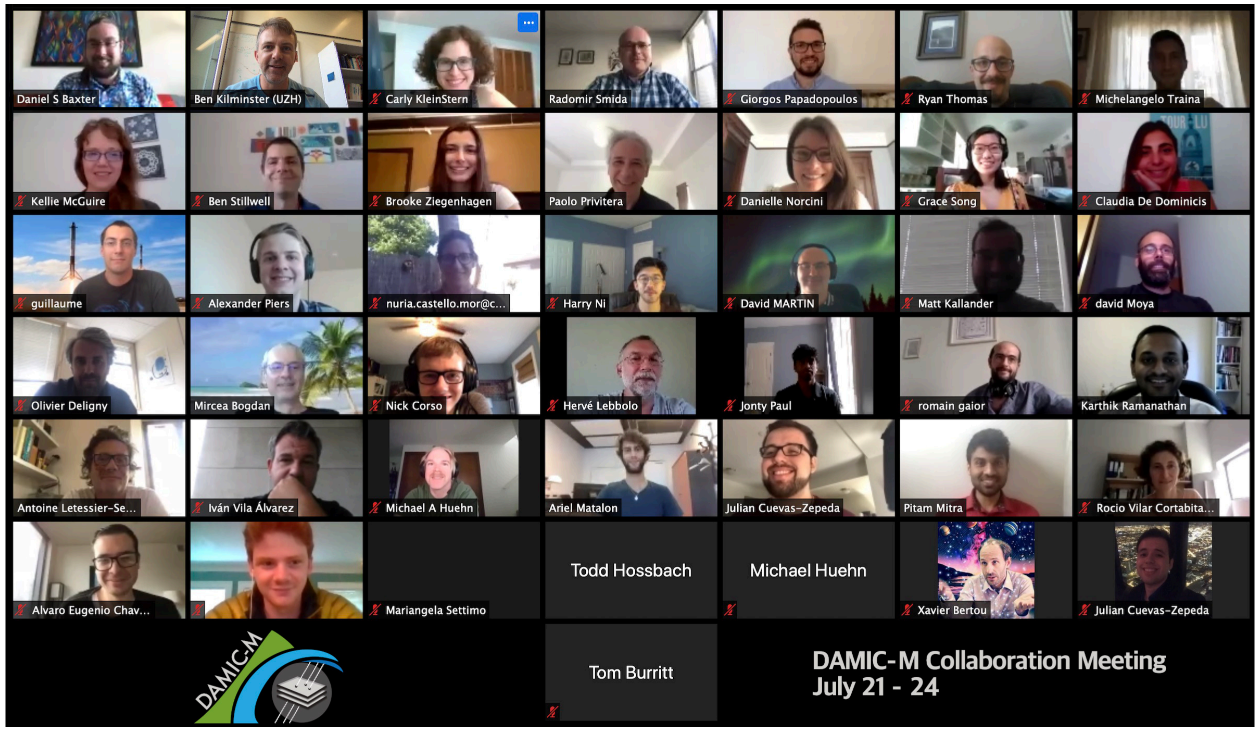
Outlook

DAMIC-M is using novel skipper CCDs to push energy threshold limits
The experiment is in the pre-construction phase towards building a kg-scale CCD array housed within an extremely low background environment at LSM. Prototypes have proven the technology works for science.

We are pushing the search for dark matter into new, unexplored regions
Vast range of theoretically motivated light dark matter candidates that were previously non-accessible due to detector limitations. Skipper CCDs have the potential for new discovery.

Coming soon!
We will start test CCDs soon and finish construction in the Fall.. **detector online in 2025!**





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