Capturing dark matter with underground cameras

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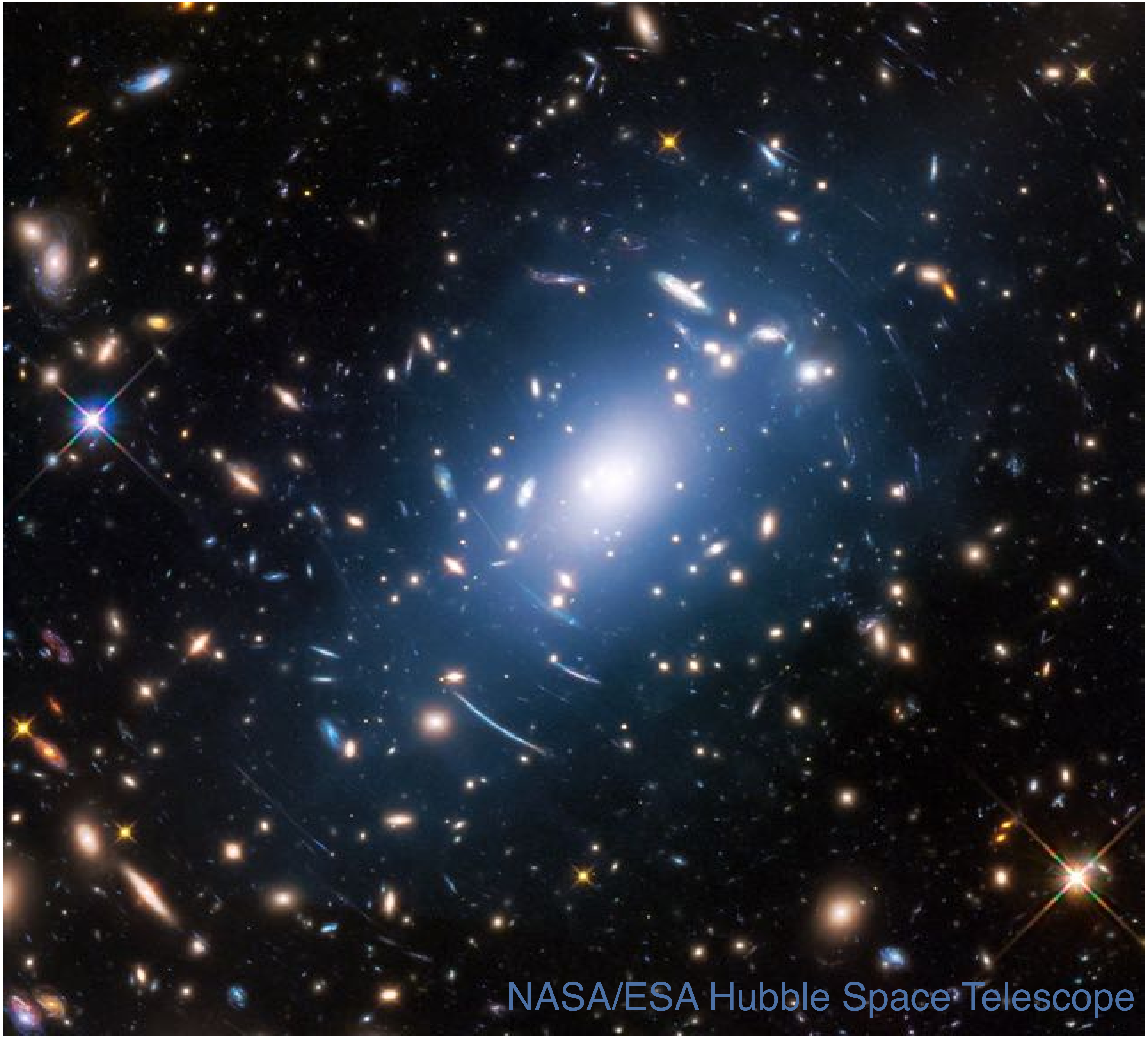
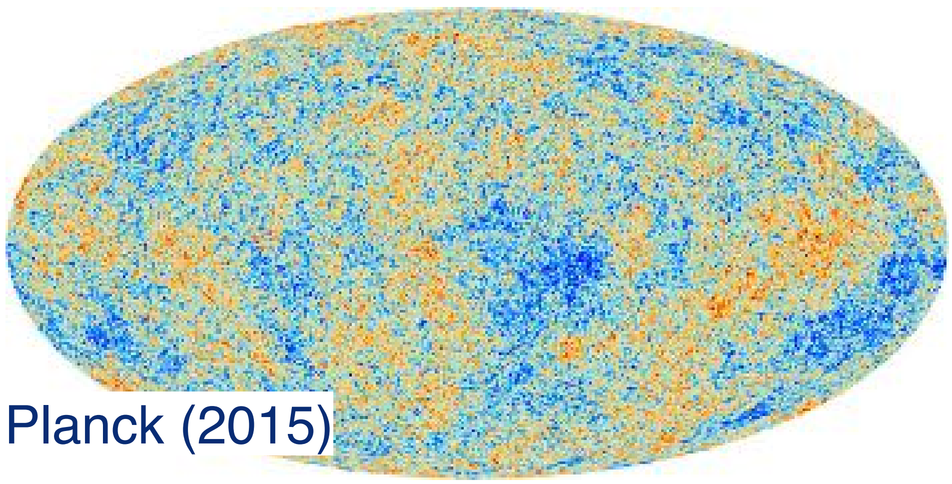
Abell S1063 galaxy cluster



What do we know about dark matter?

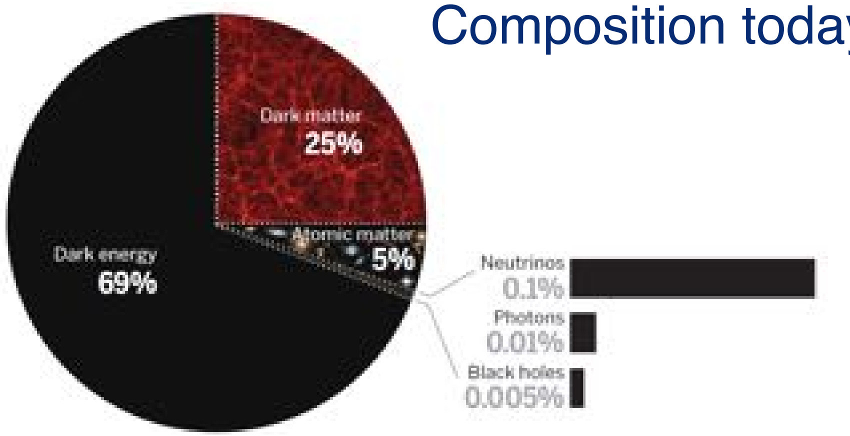
Does not scatter, emit, or absorb light (no EM) but has mass (gravity)

Accounts for ~84% of matter in the universe (non-baryonic)

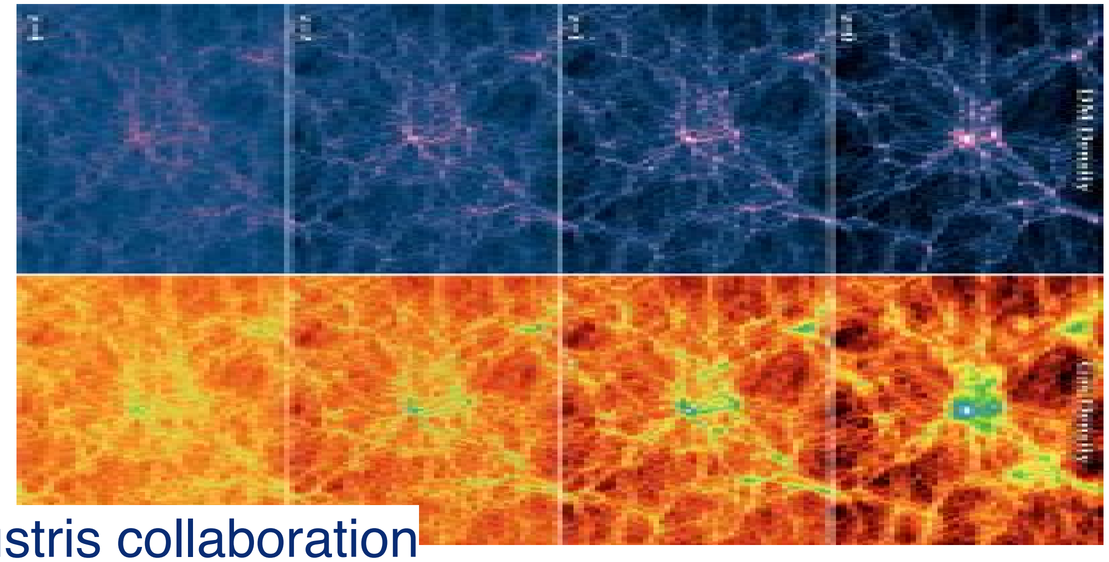


CMB, Planck (2015)

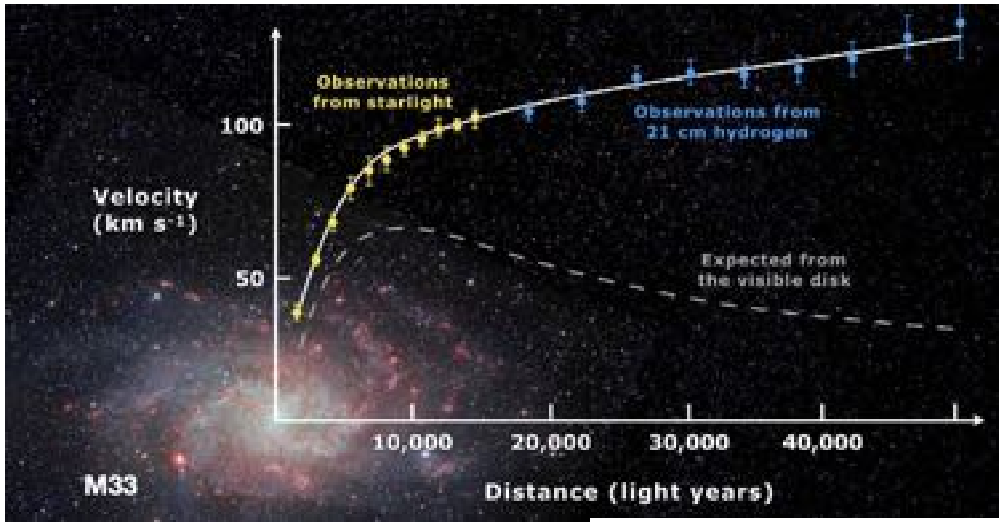
Composition today



Forms cosmic "scaffolding" for galaxies (cold, ~stable) and halos



Illustris collaboration



arXiv:astro-ph/9909252

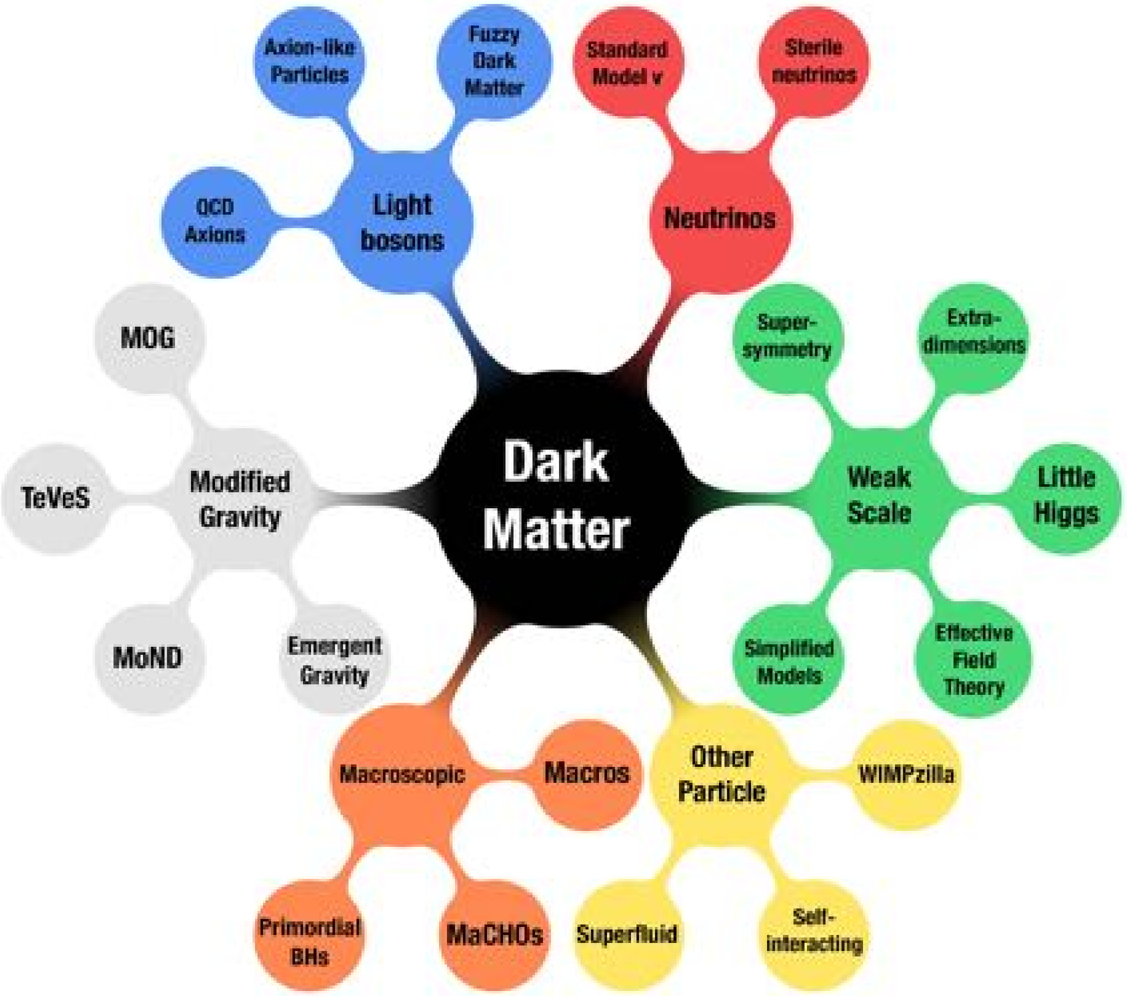
Interactions with Standard Model particles are tiny, possibly through "dark" physics

What don't we know about dark matter?

The physics laws that govern it!! **Cannot be explained by physics we currently know.**

Why do we see the abundance that we see today?

What is it made out of?

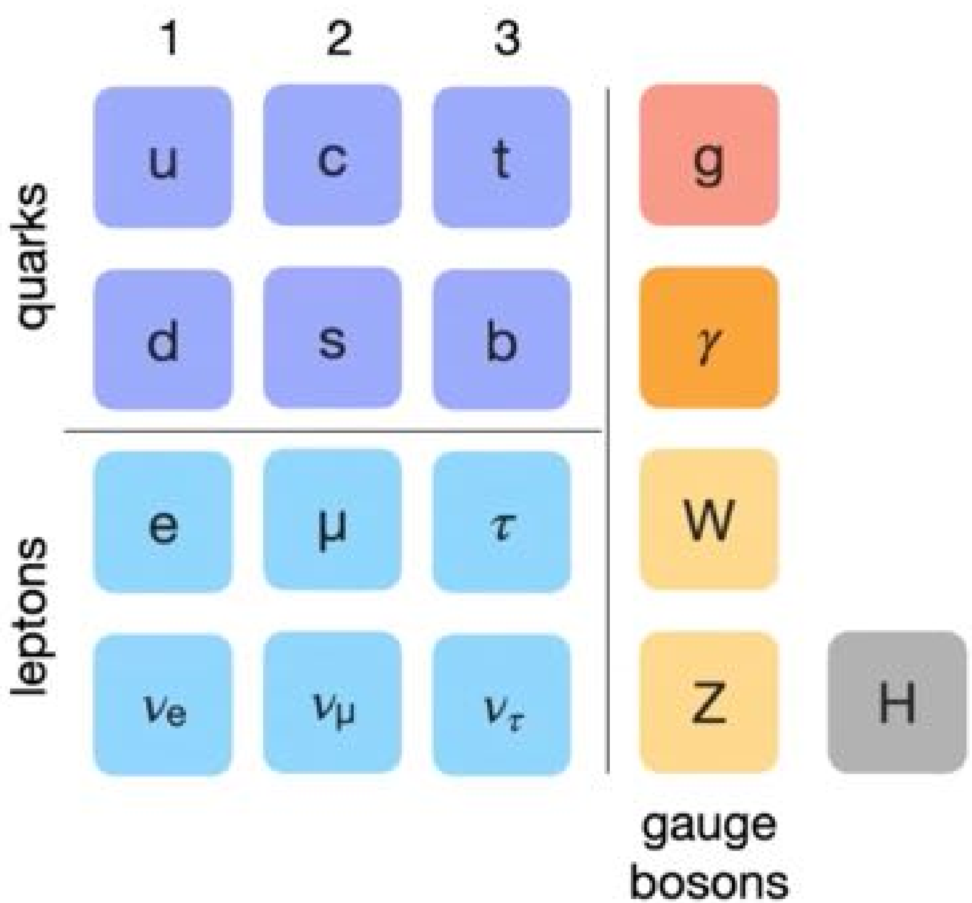


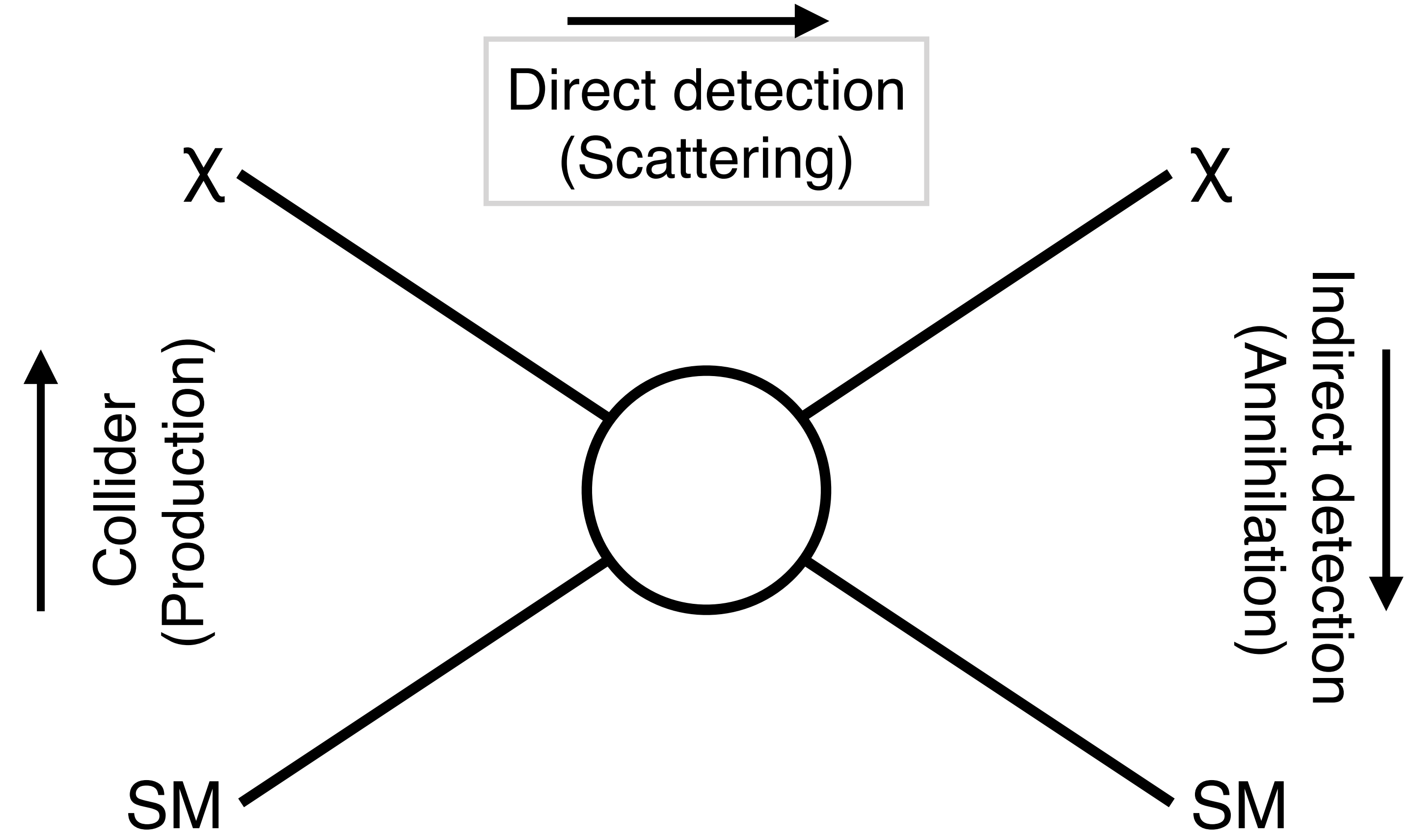
Is it a new particle (ΛCDM suggests)? Is it many new particles, a whole dark sector?

Properties: What is its mass? How would it interact with other particles?

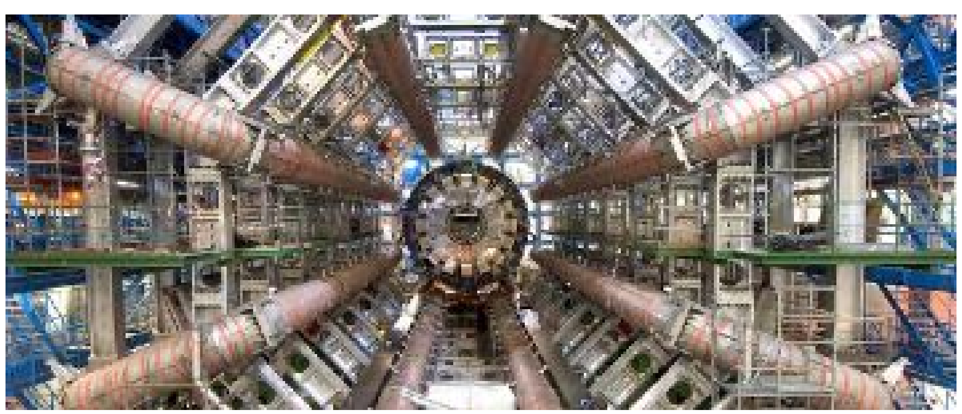
How can we look for it?

Standard Model of particle physics





ATLAS @ LHC



Fermi-LAT telescope

LZ detector

The direct detection strategy

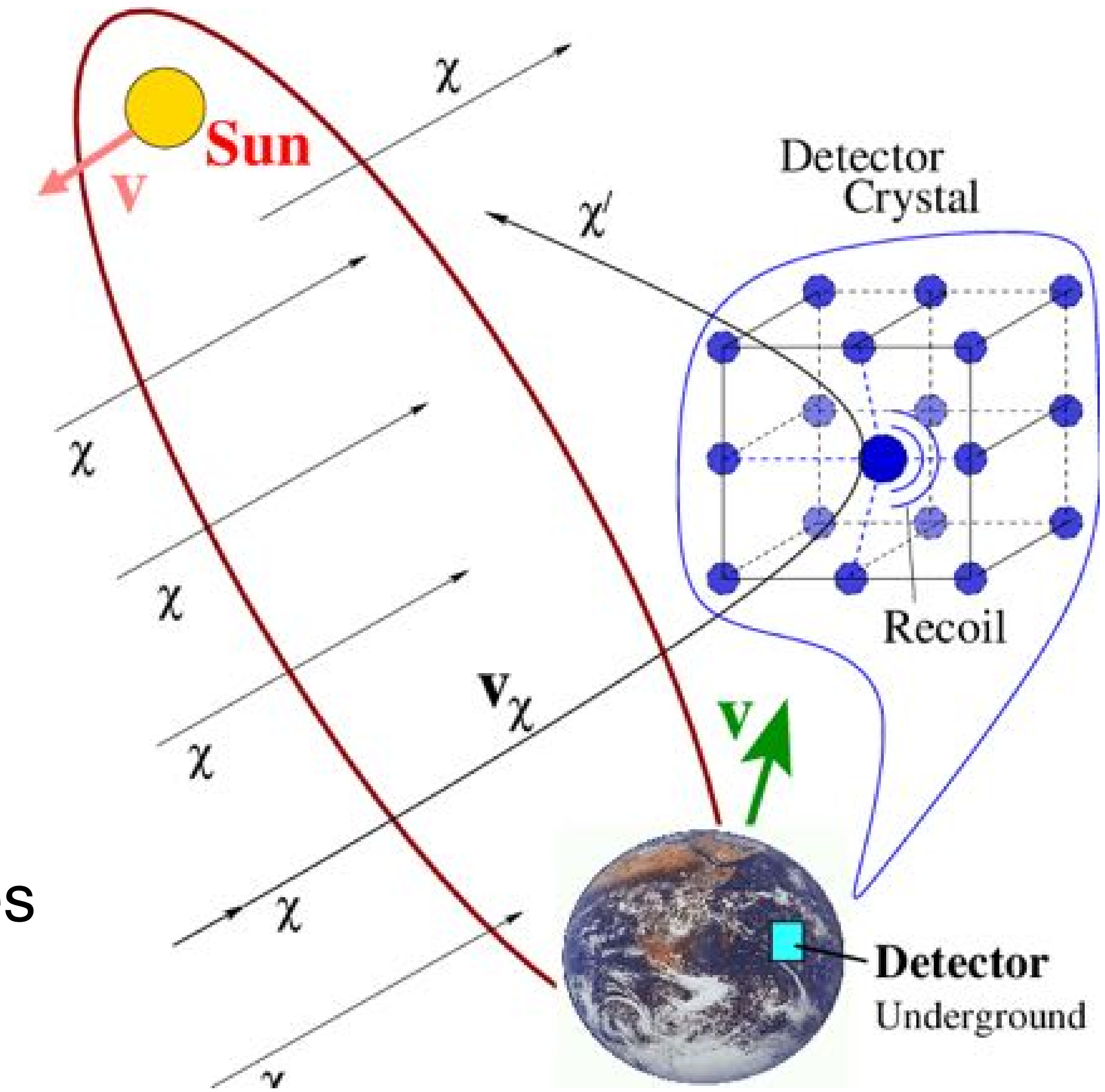
It's all scattering physics!

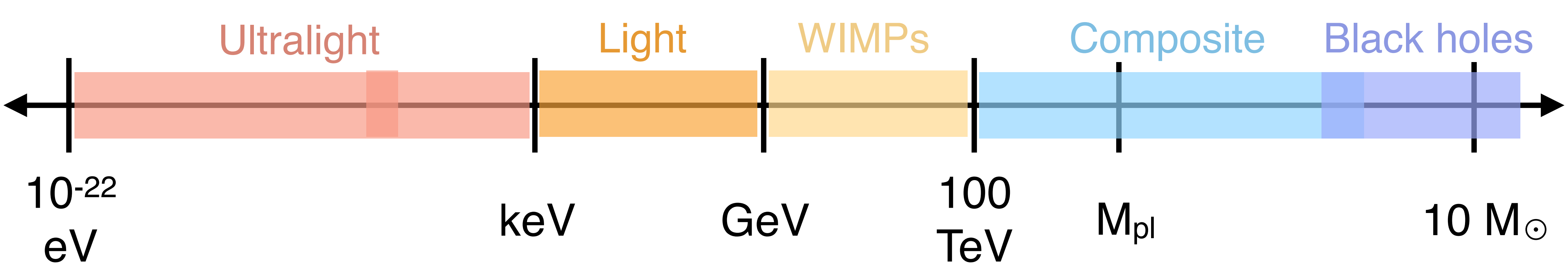
1. Detectors optimized for kinematics, e.g. dark matter mass, cross section
→ energy thresholds, target mass

For example:
$m_\chi = 100\text{GeV}/c^2$, $v_\chi = 10^{-3}c$, $E_{n,recoil} \sim 10\text{keV}$

2. Detectors also have to be radio-pure and operated underground to shield from particles that have stronger interactions.

BUT, theory doesn't tell us where to look…





The WIMP

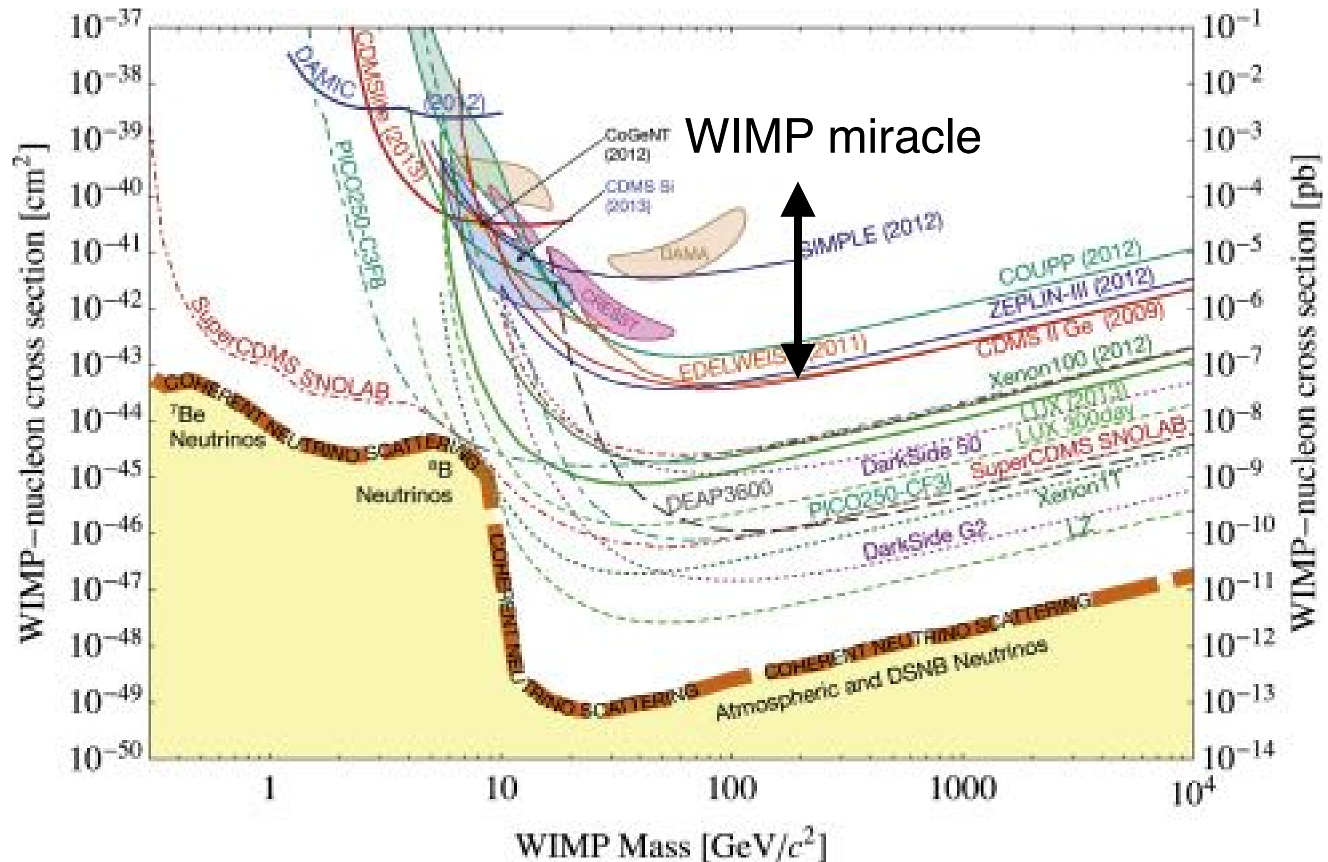
The field has been dominated by searches for the Weakly Interacting Massive Particle (WIMP). Historically, there is good or “natural” reasons for that.

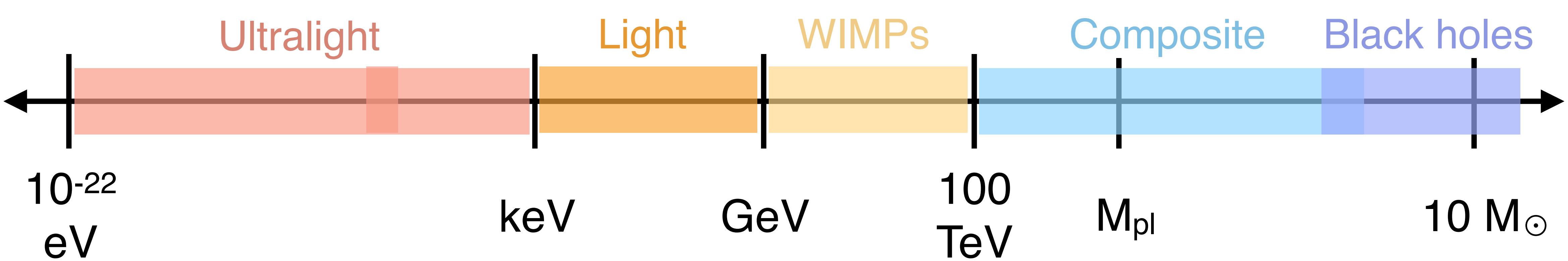
“WIMP miracle” (abundance, SUSY): annihilation cross section (σv)~10^{-26} cm^3/s, i.e. weak-scale physics.

GeV-scale (~proton mass), use heavy nuclei as targets

Has been pursued by many experiments, now multi-ton, including at SURF!

Limits shown are old (Phys. Rev. D, 89 (2014)), but show the complex landscape!



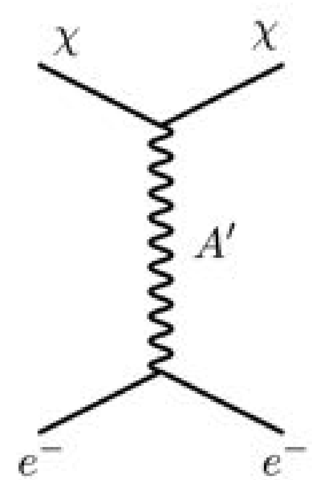


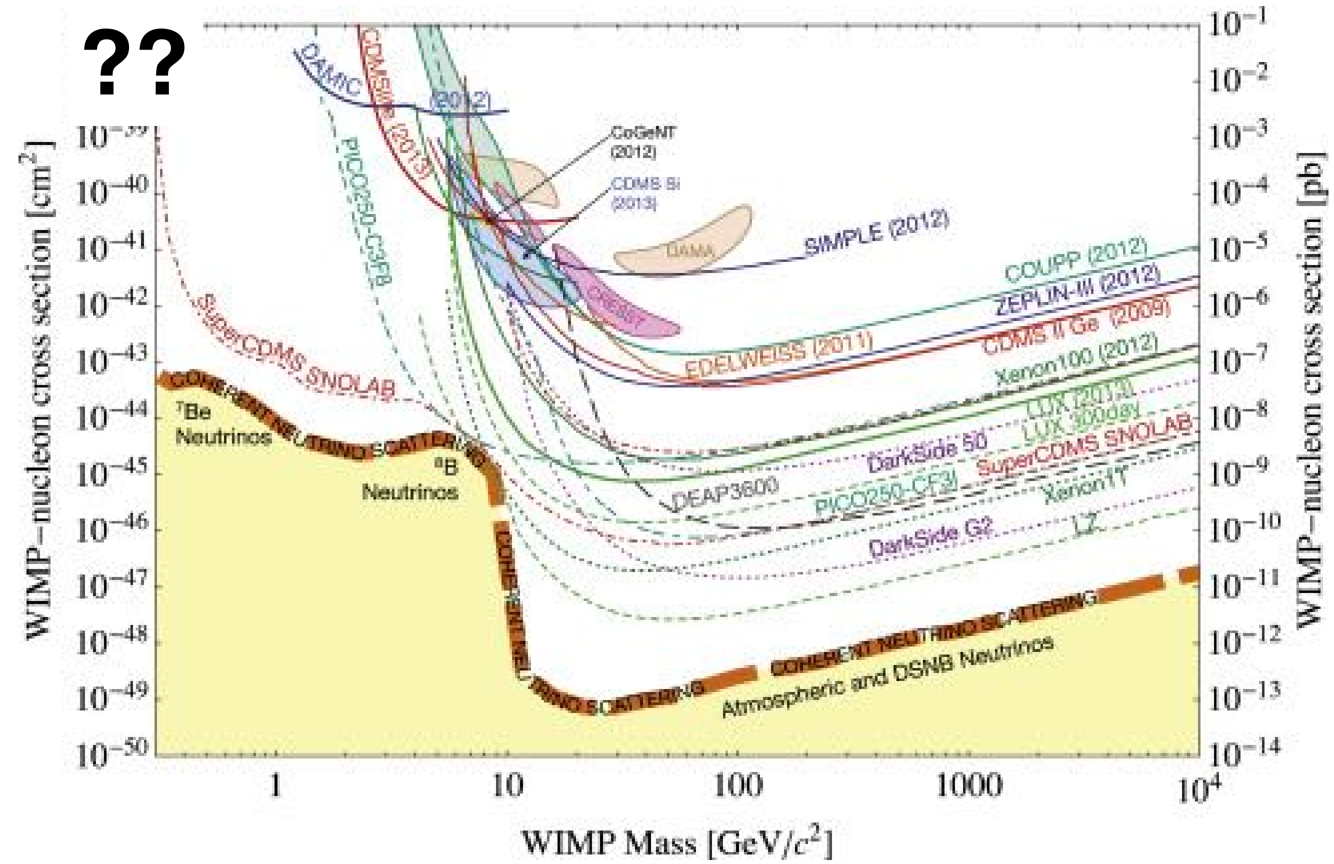
Wimpier than the WIMP

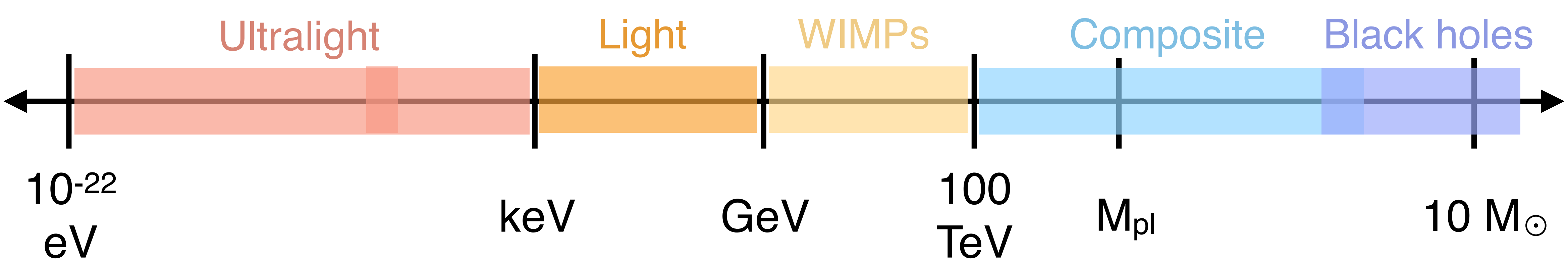
However, the WIMP has yet to appear: strong upper limits but no new particle. Beyond "naturalness", theory becomes much richer, constraints more open.

For **sub-GeV candidates**, new forces, mediators below weak-scale are required.

This **"hidden" or "dark" sector** is linked to the Standard Model through kinematic mixing. The most minimal scenario (need benchmarks!) is "dark" photon mediator:

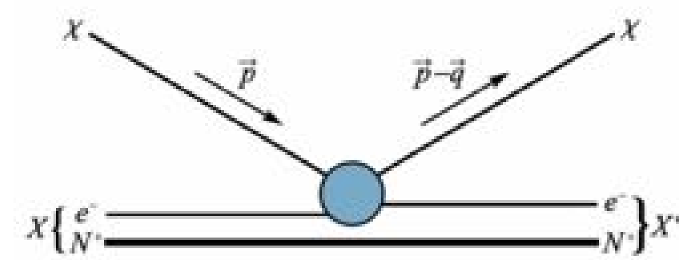






Light, low mass, sub-GeV, … dark matter

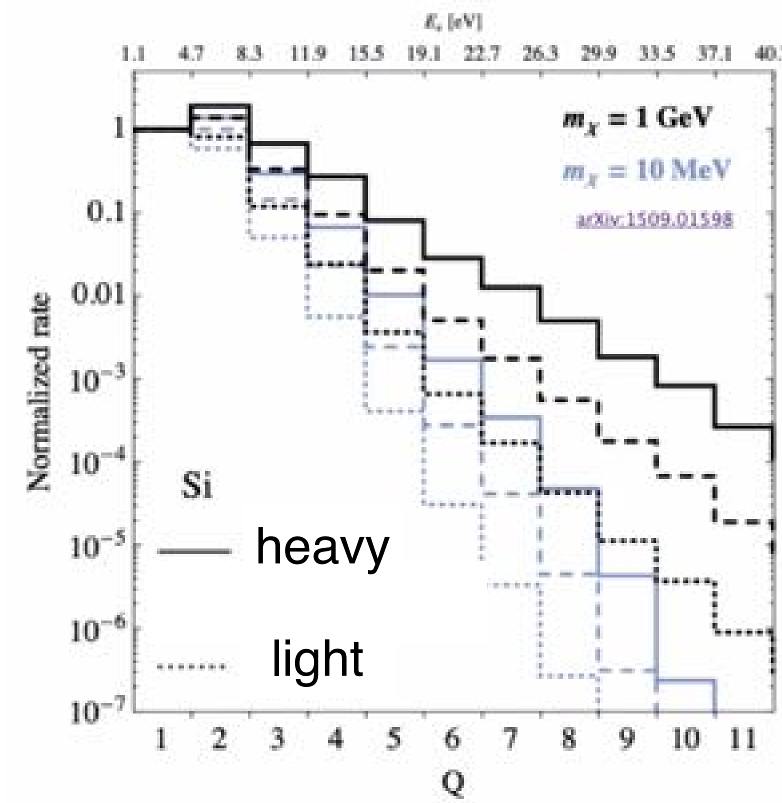
Back to scattering kinematics…
Parameter space is open, targets from freeze-out/in.
Less than proton mass, **use bound electrons as targets!**

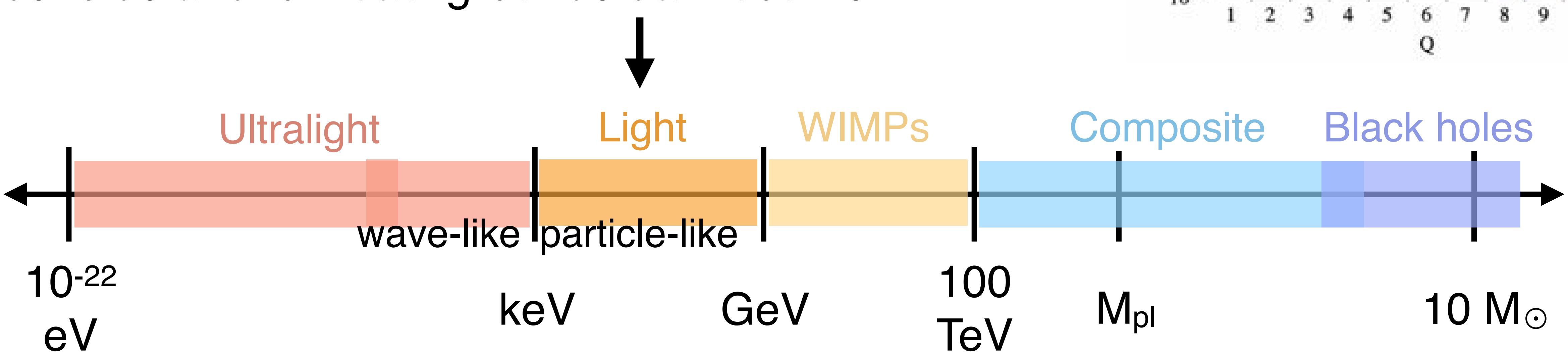


This is difficult:
1. DM-electron scattering is SMALL! but no quenching..
$m_\chi = 10 \mathrm{MeV/c^2}$, $v_\chi = 10^{-3}c$, $\mathbf{E_{e,recoil}} \sim \mathbf{eV}$

2. More complicated to predict rate, as small momentum transfers can't neglect inter-atom interactions.

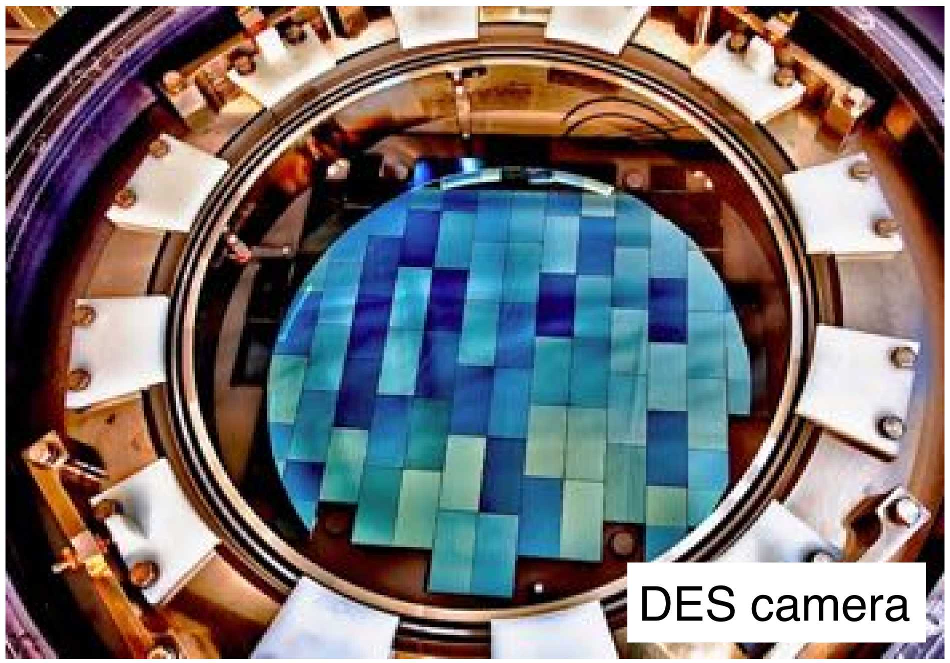
Previously did not have the technology or calculations to do this. Semiconductor detectors optimized for low thresholds and low backgrounds/dark counts.

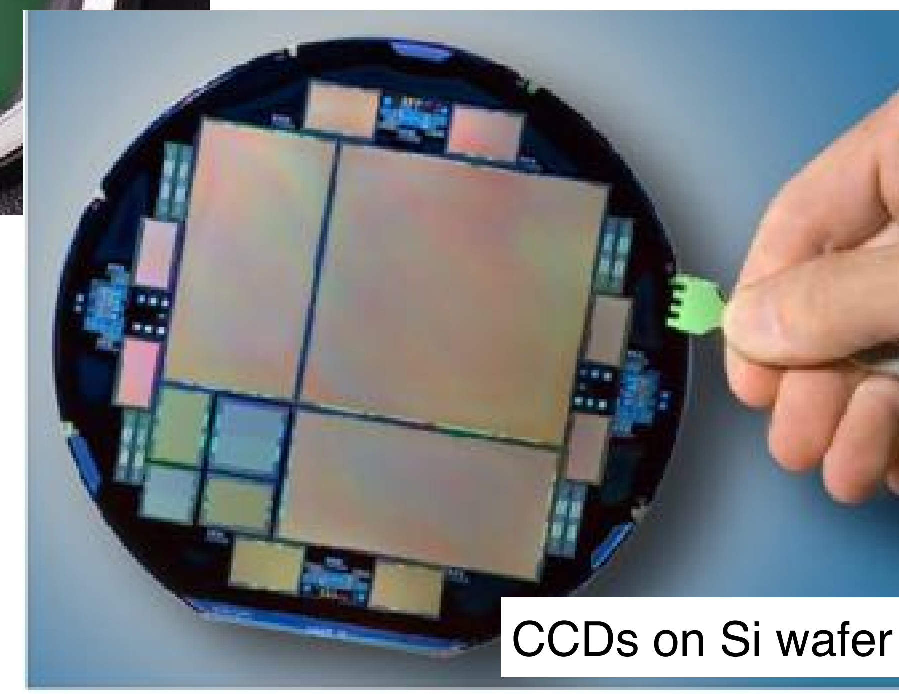




CCDs as dark matter detectors

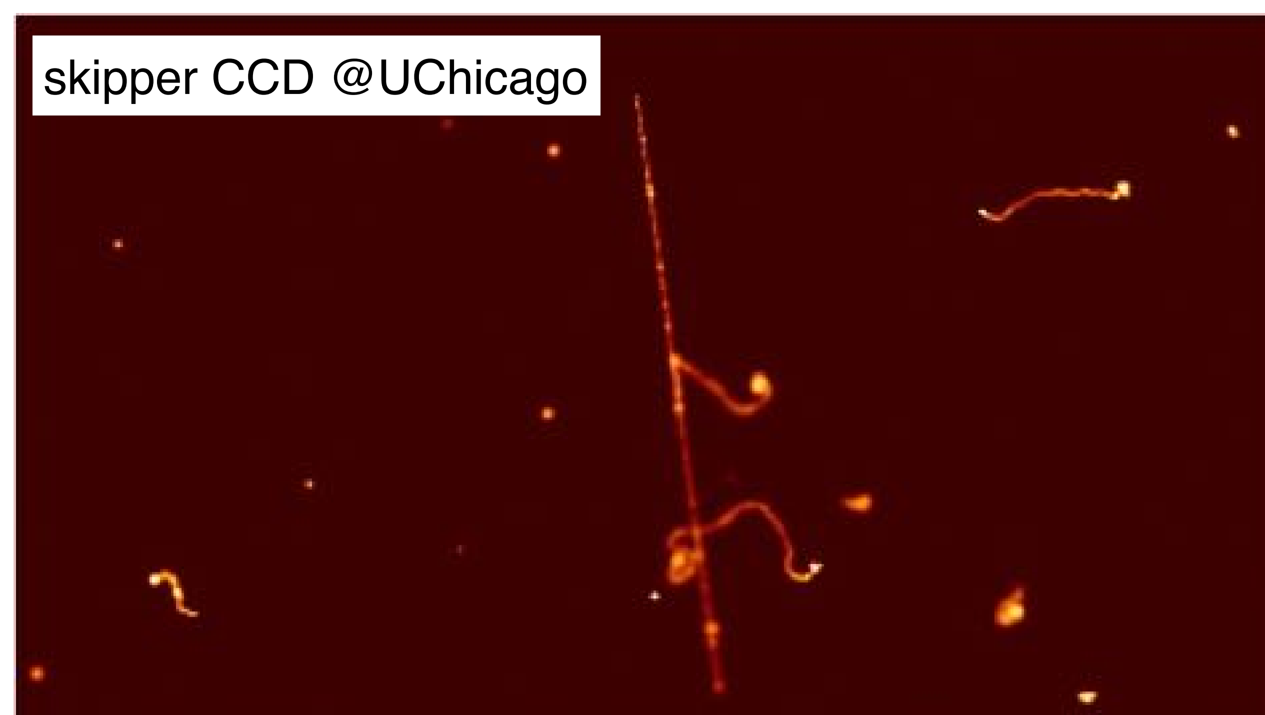
Charge-coupled devices have been used for a long time as telescope cameras.

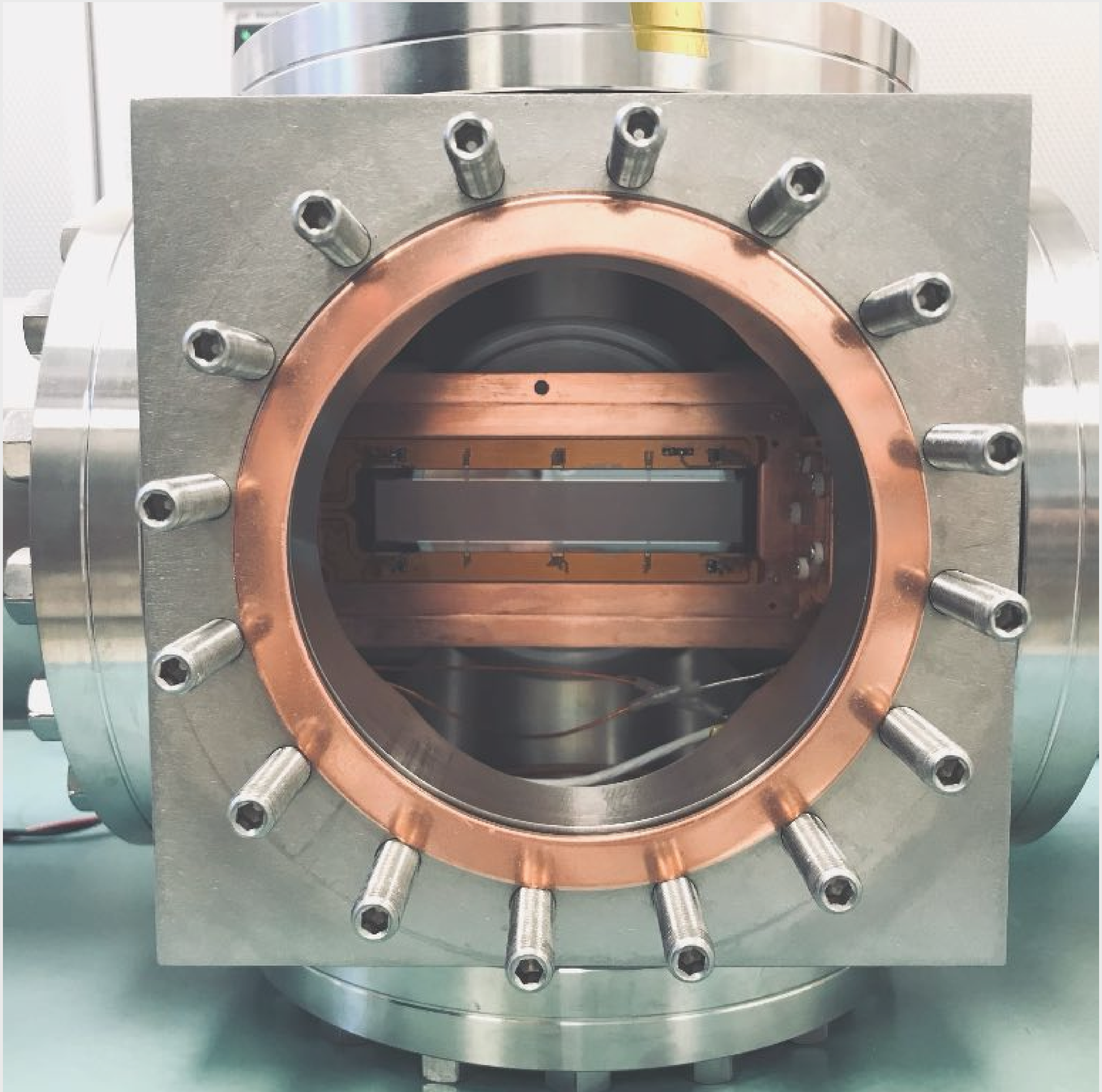

DES camera

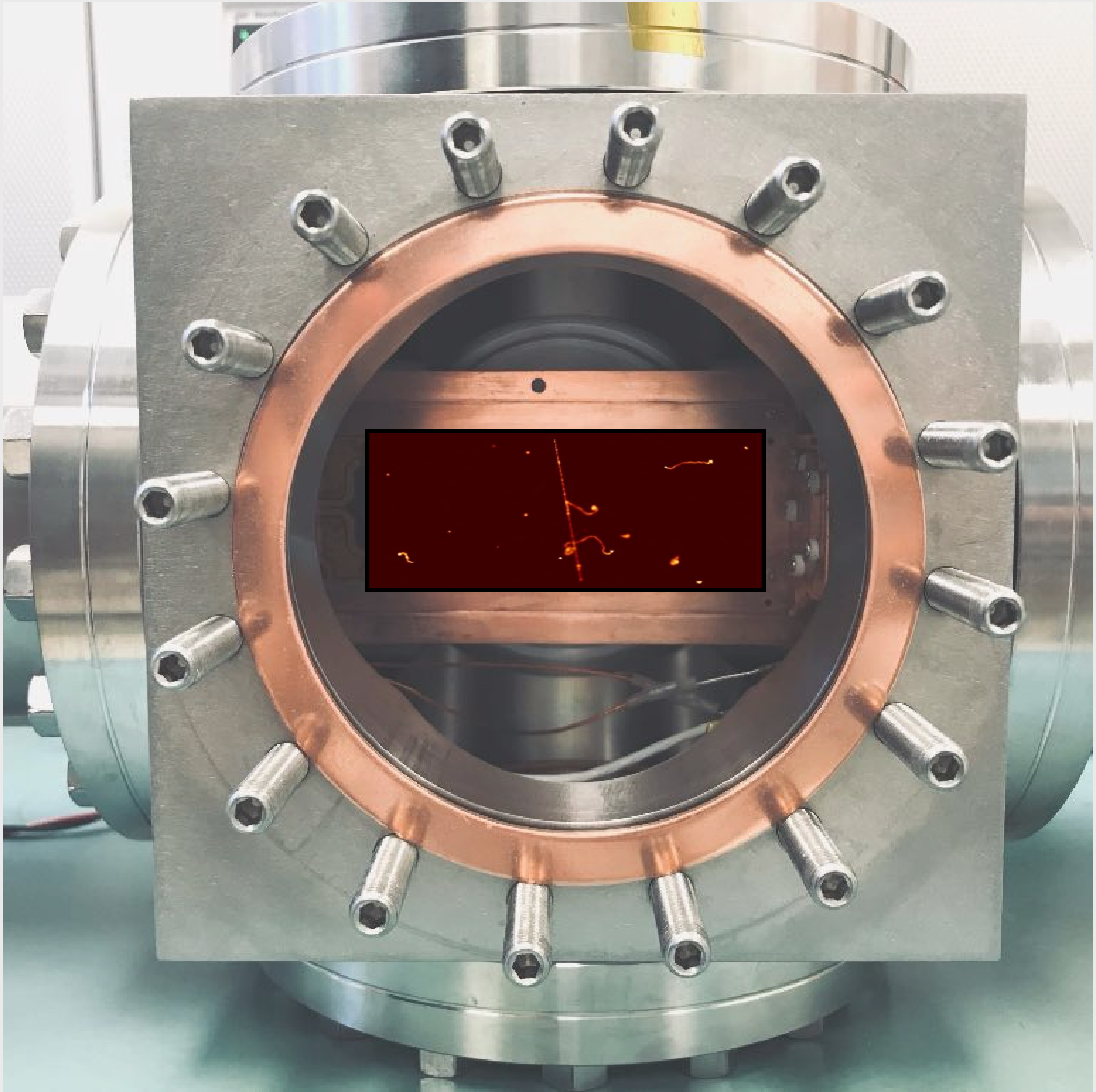

CCDs on Si wafer

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



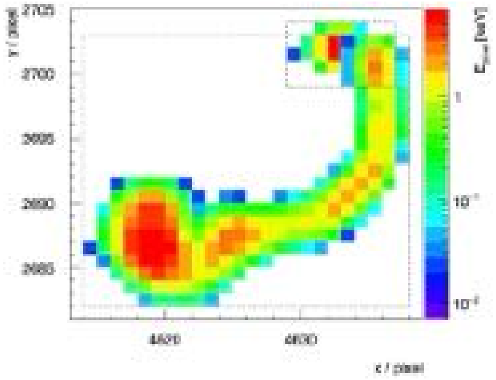


Why silicon CCDs?

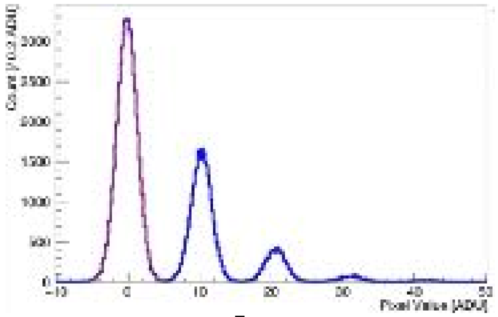
To explore sub-GeV range, detectors with **extremely low thresholds** (~few eV) and **extremely low backgrounds** (~sub dru) are required to detect both nuclear/electronic recoils from DM-interactions. Silicon CCDs have many advantages:

- 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



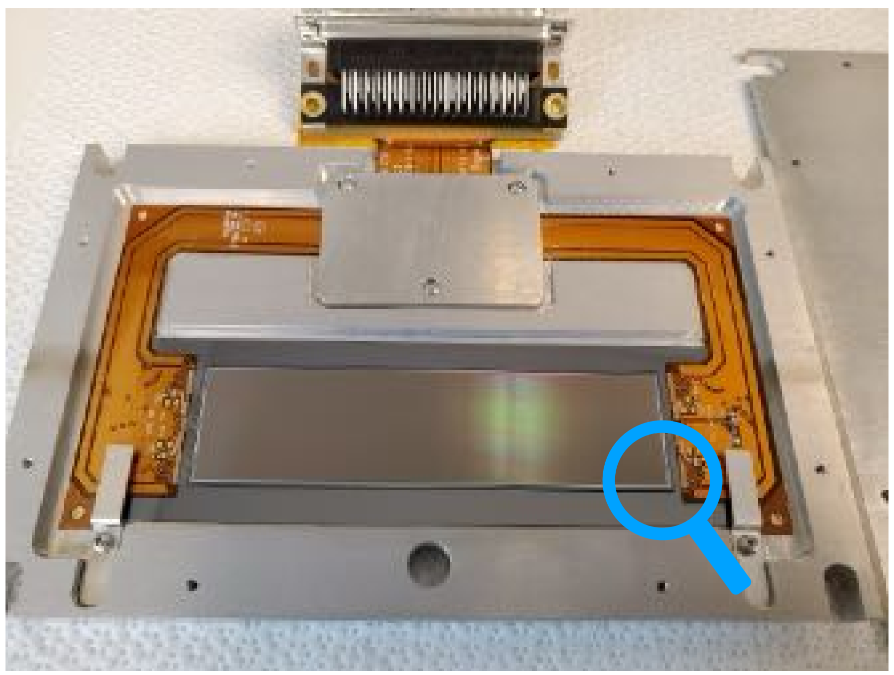
- achieved very low dark current rates (2×10^{-4} e-/pixel/day, PRL 123, 181802 (2019))
- technological advances have turned CCDs into **single-electron detectors**

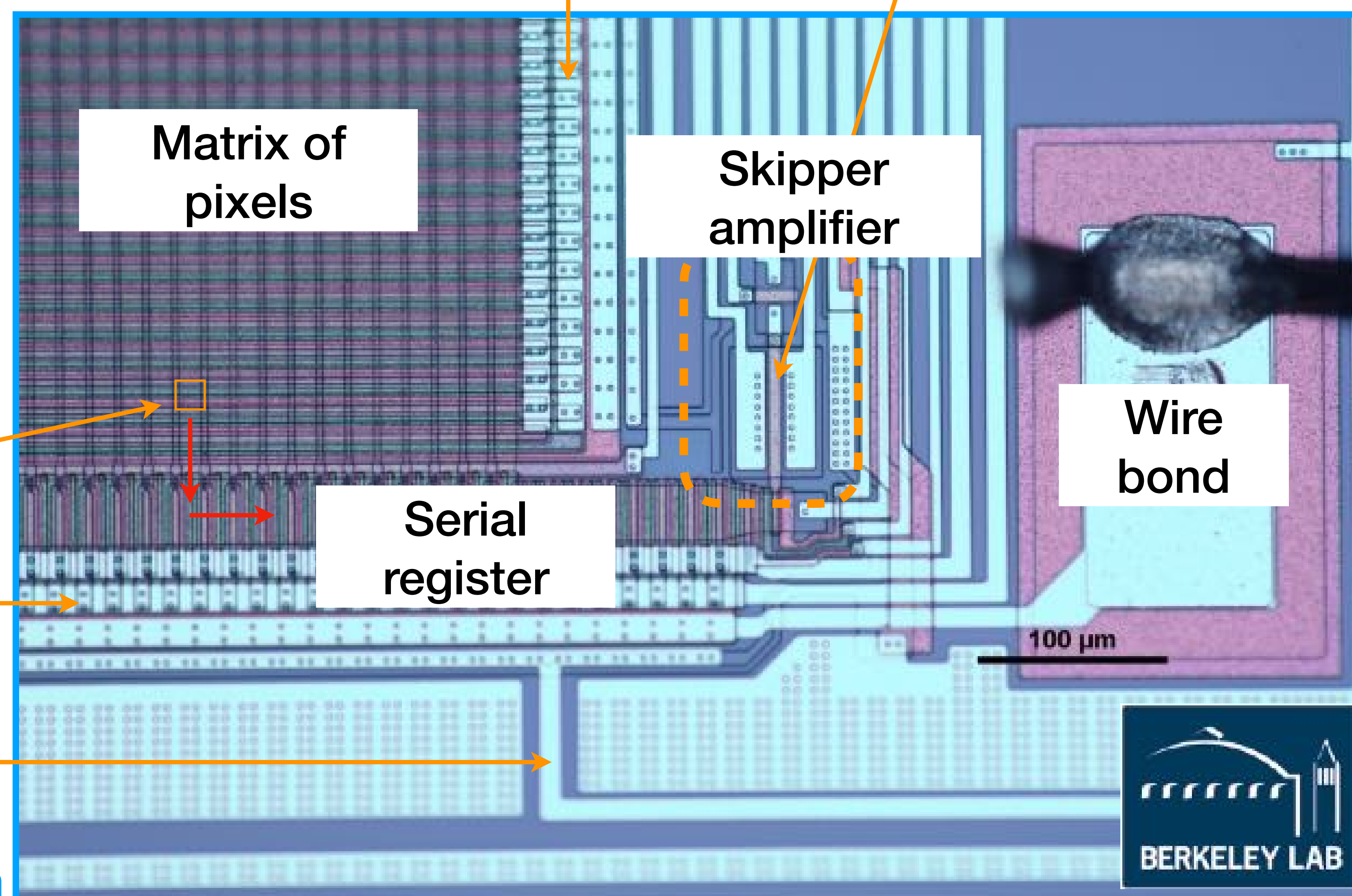
A CCD up-close

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

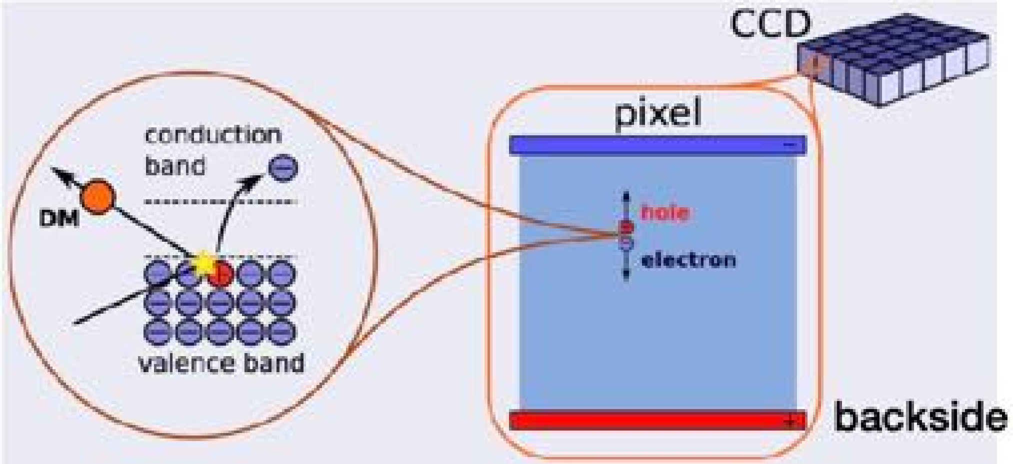
Slice large crystals into 150mm diameter wafers to produce device in nanofab facility

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





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.

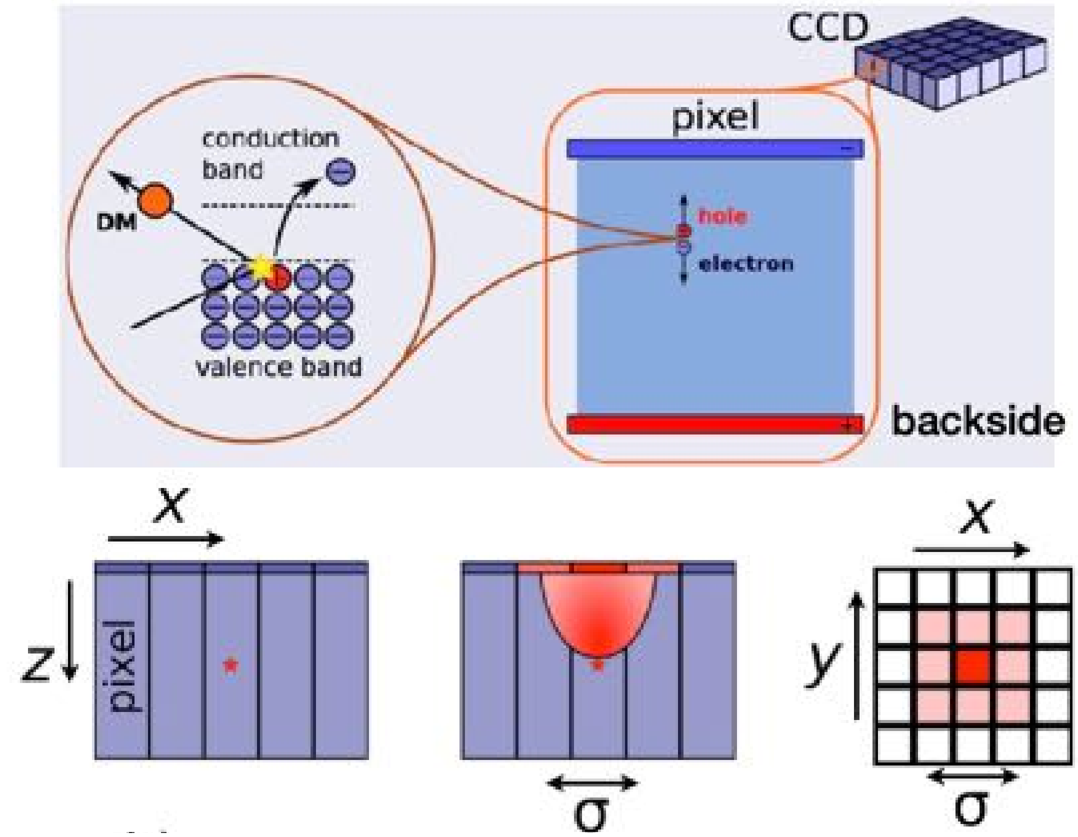
   $\Delta V = \Delta Q/C$

   $C = 37$ fF

   $\Delta V = 4\ \mu V/e^-$

   Small!! Amplified further in front end chain.

CCD charge transfer steps



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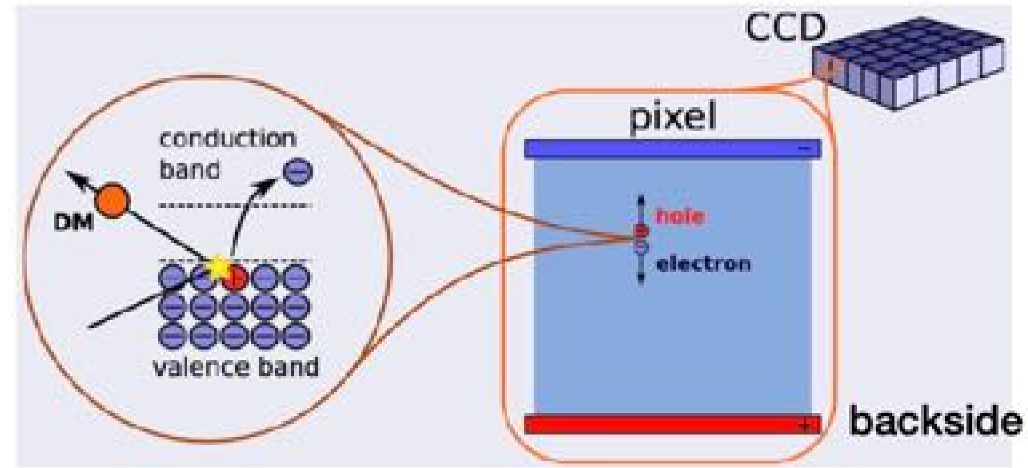
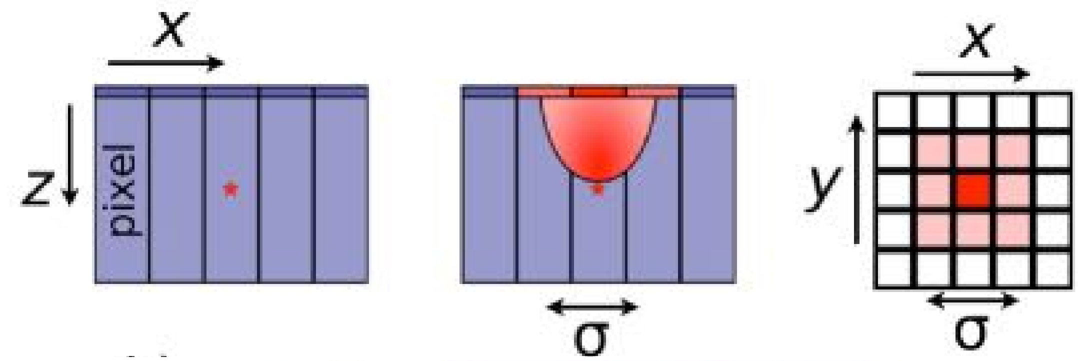
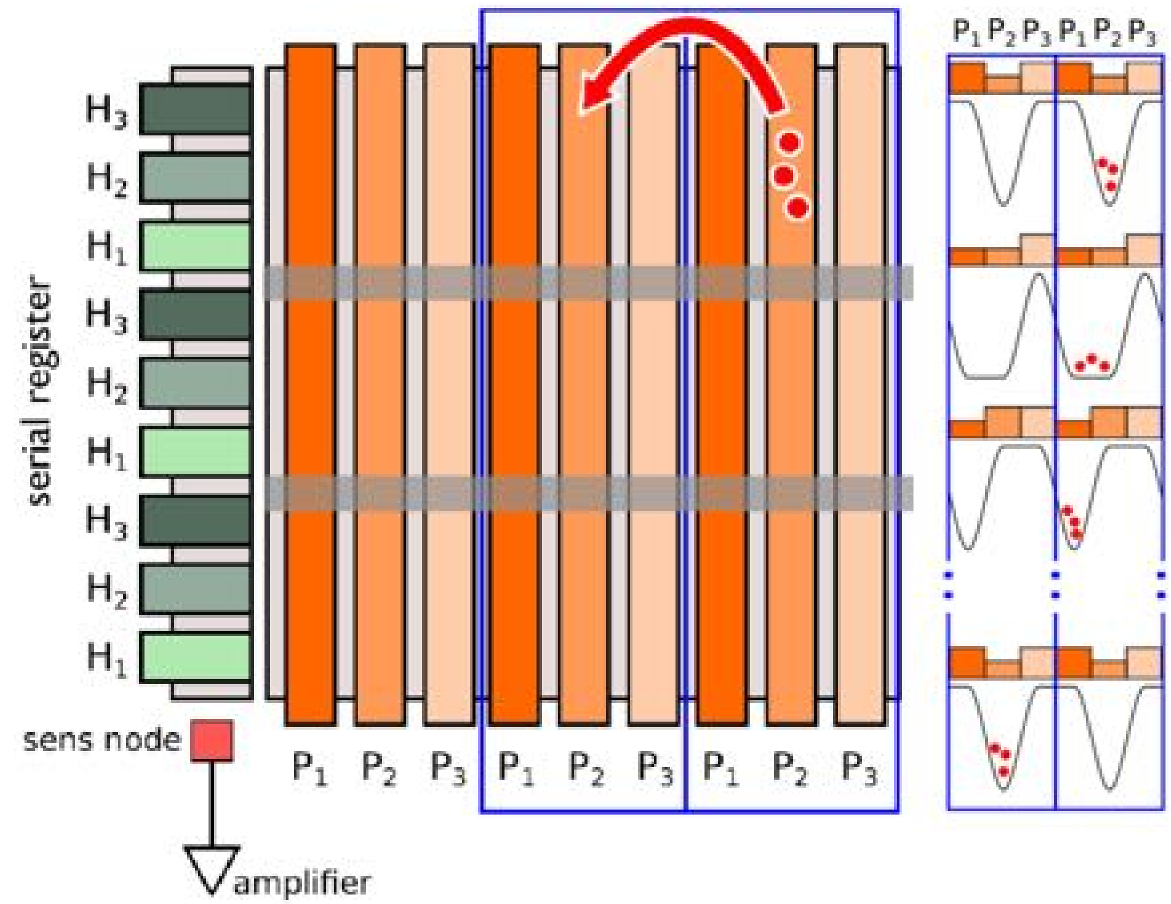




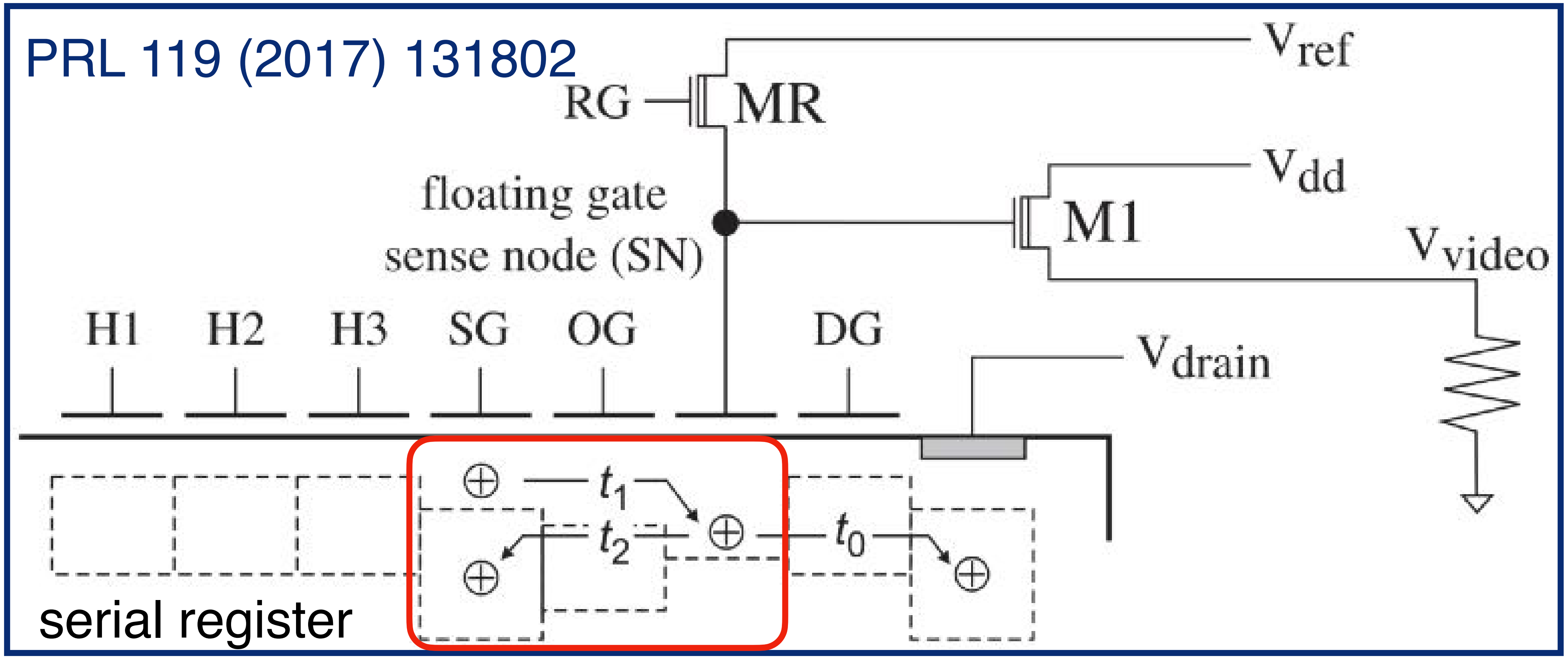


Skipper CCDs: single electron detectors

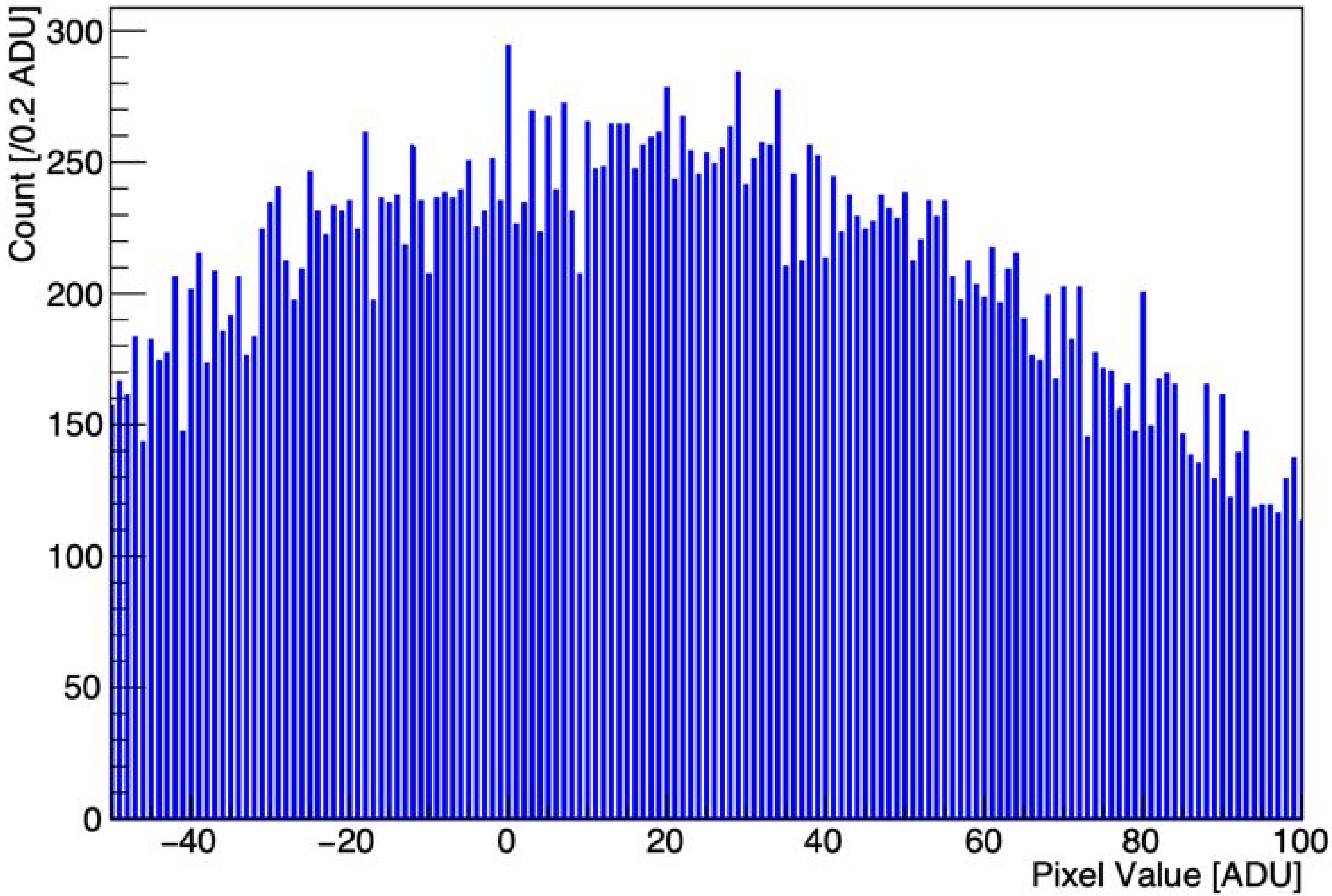
Conventional CCDs read out each pixel once, best achieved RMS noise of ~2e- (~10eV). We want single-electron resolutions at eV-scale thresholds!

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)).

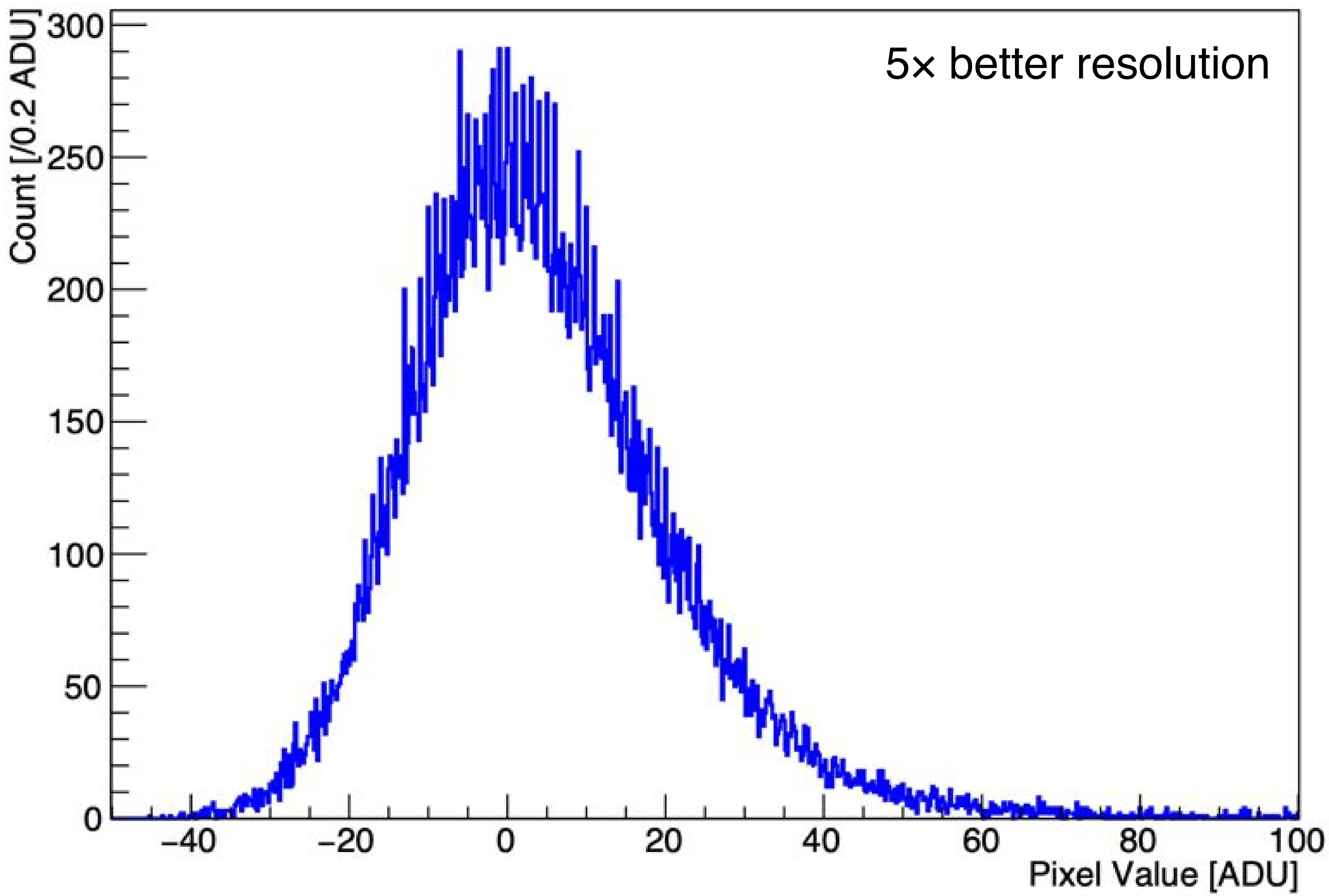
Reduces readout noise by 1/sqrt(N_{skips}).



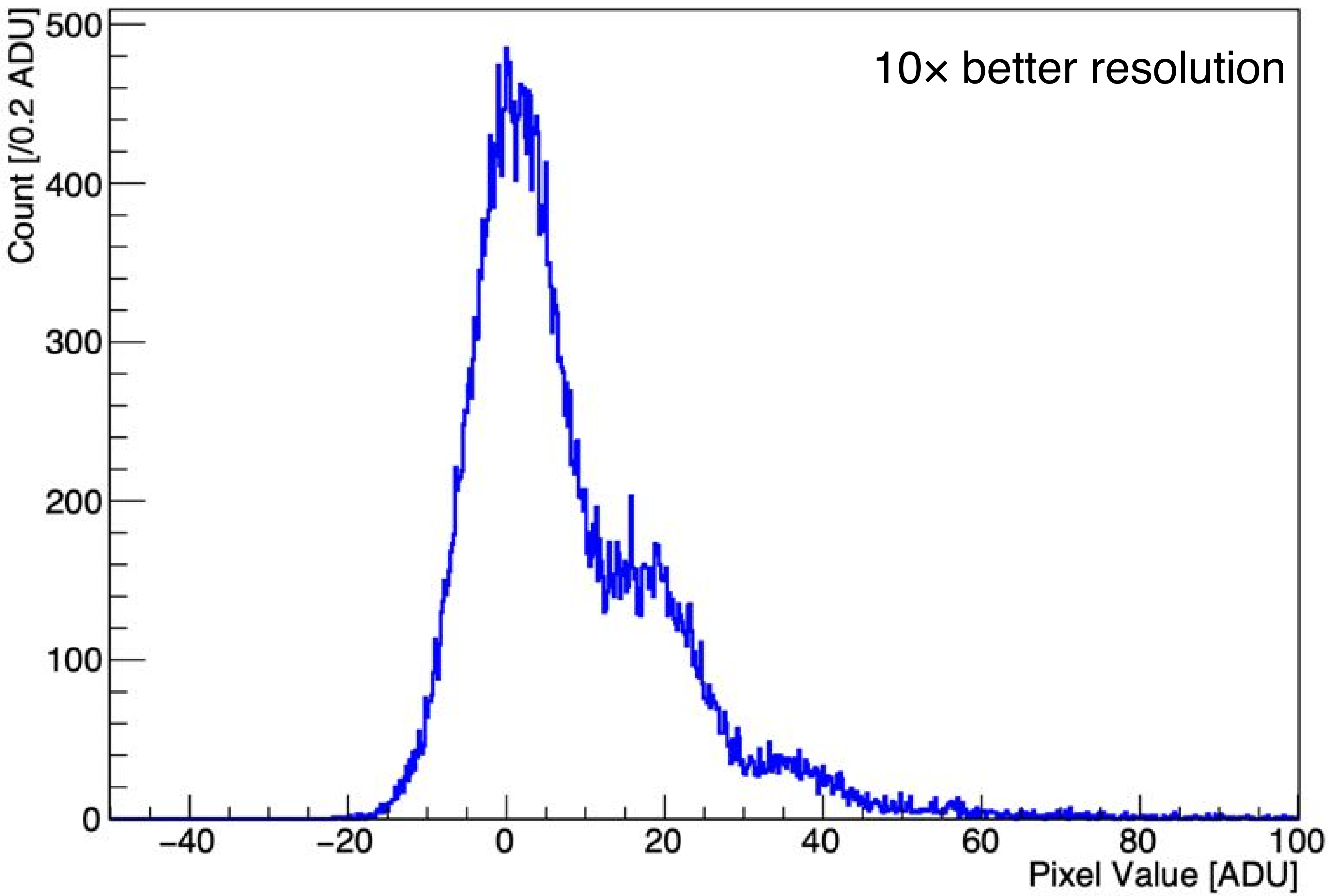
Charge resolution: Nskip = 1 (conventional CCD)



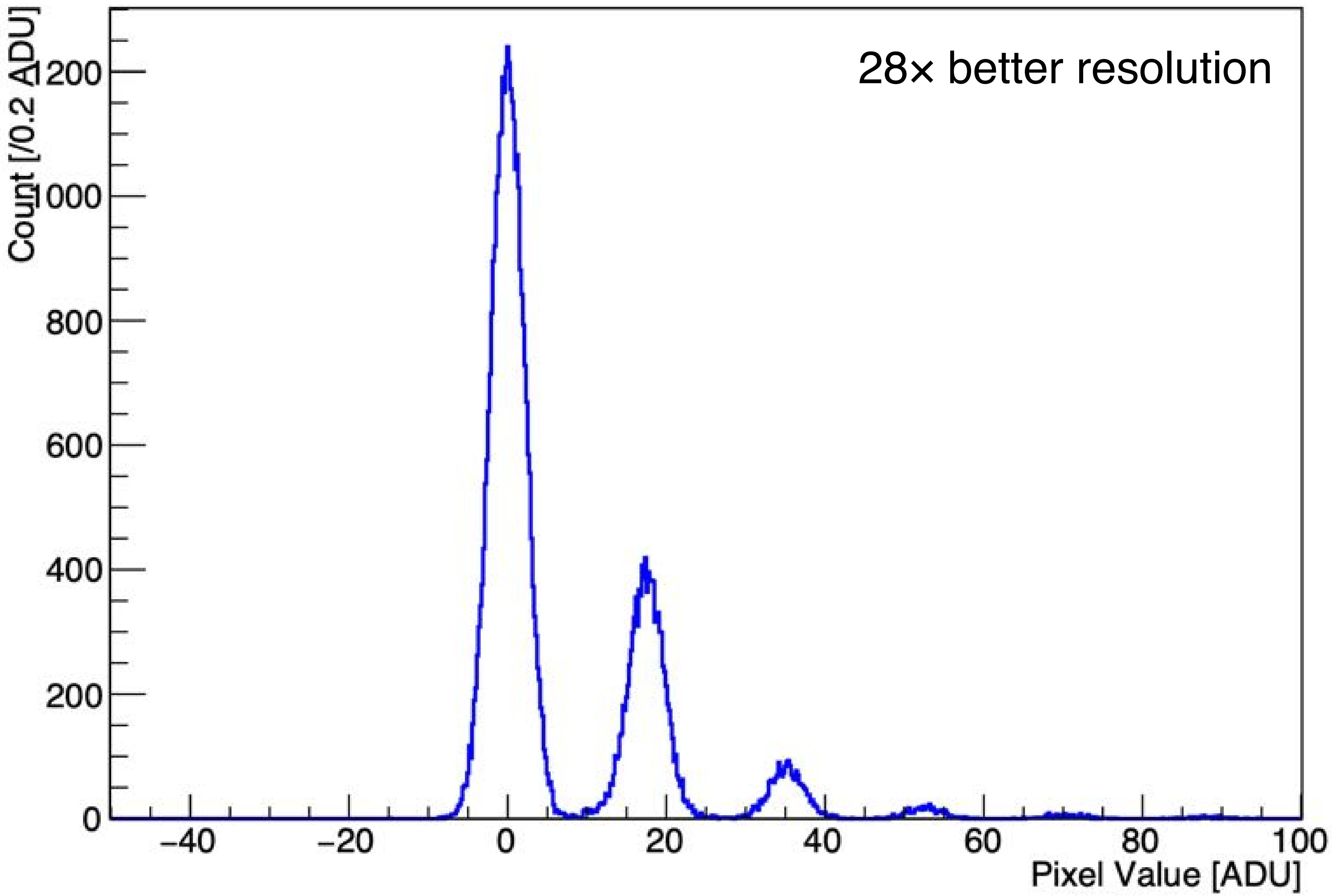
Charge resolution: Nskip = 25



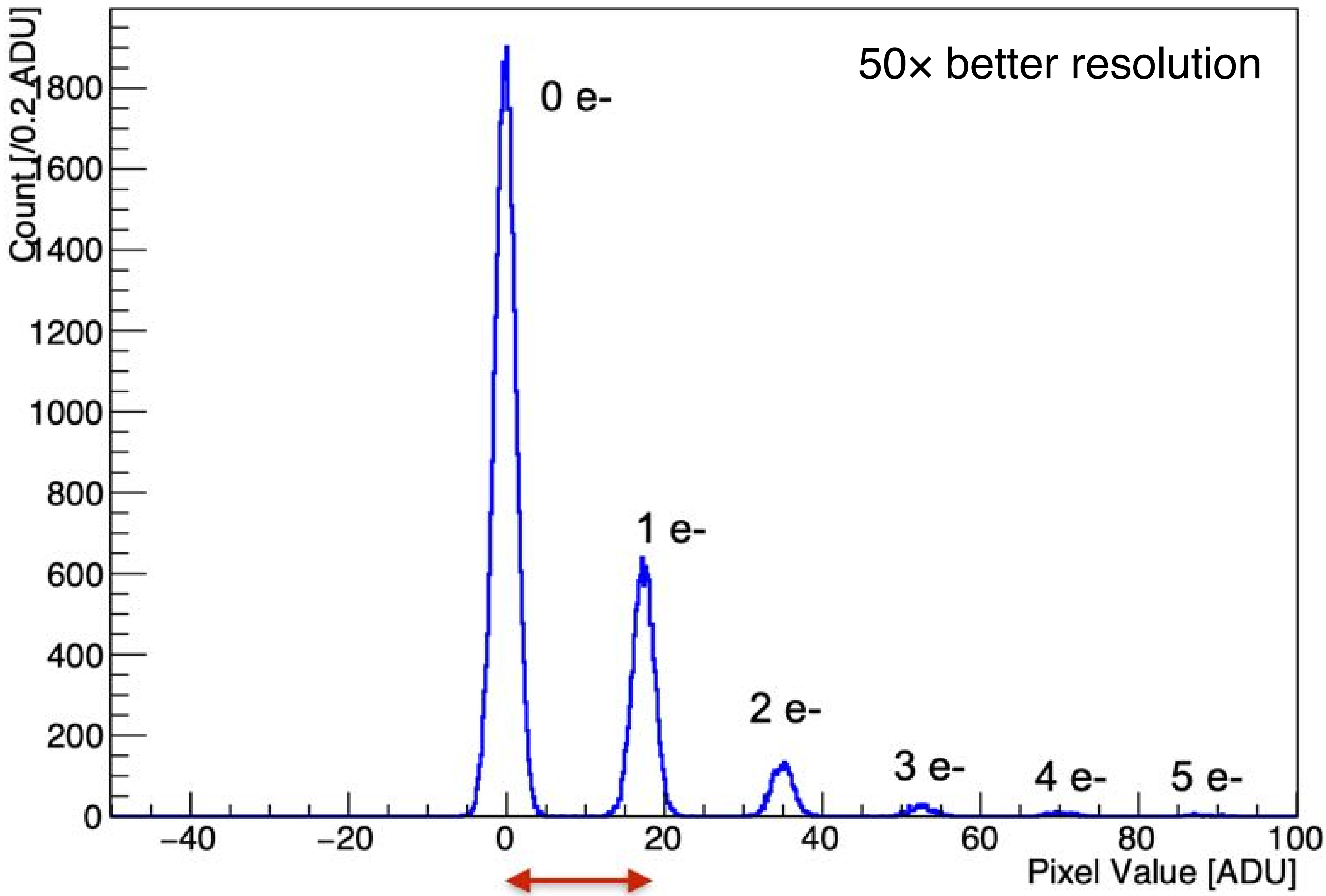
Charge resolution: Nskip = 100



Charge resolution: Nskip = 800



Charge resolution: Nskip = 2500



1 e- = 17.3 ADU

self-calibrating device!!

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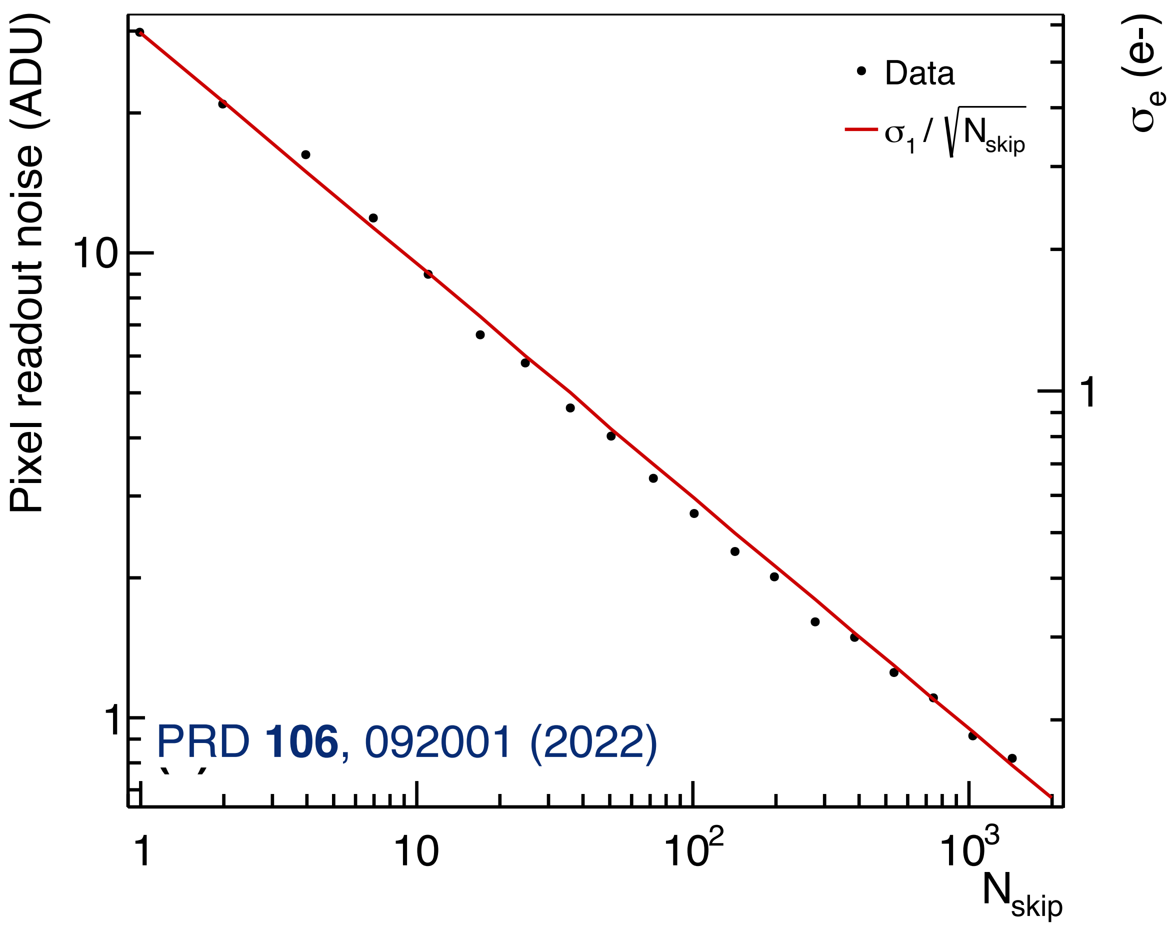
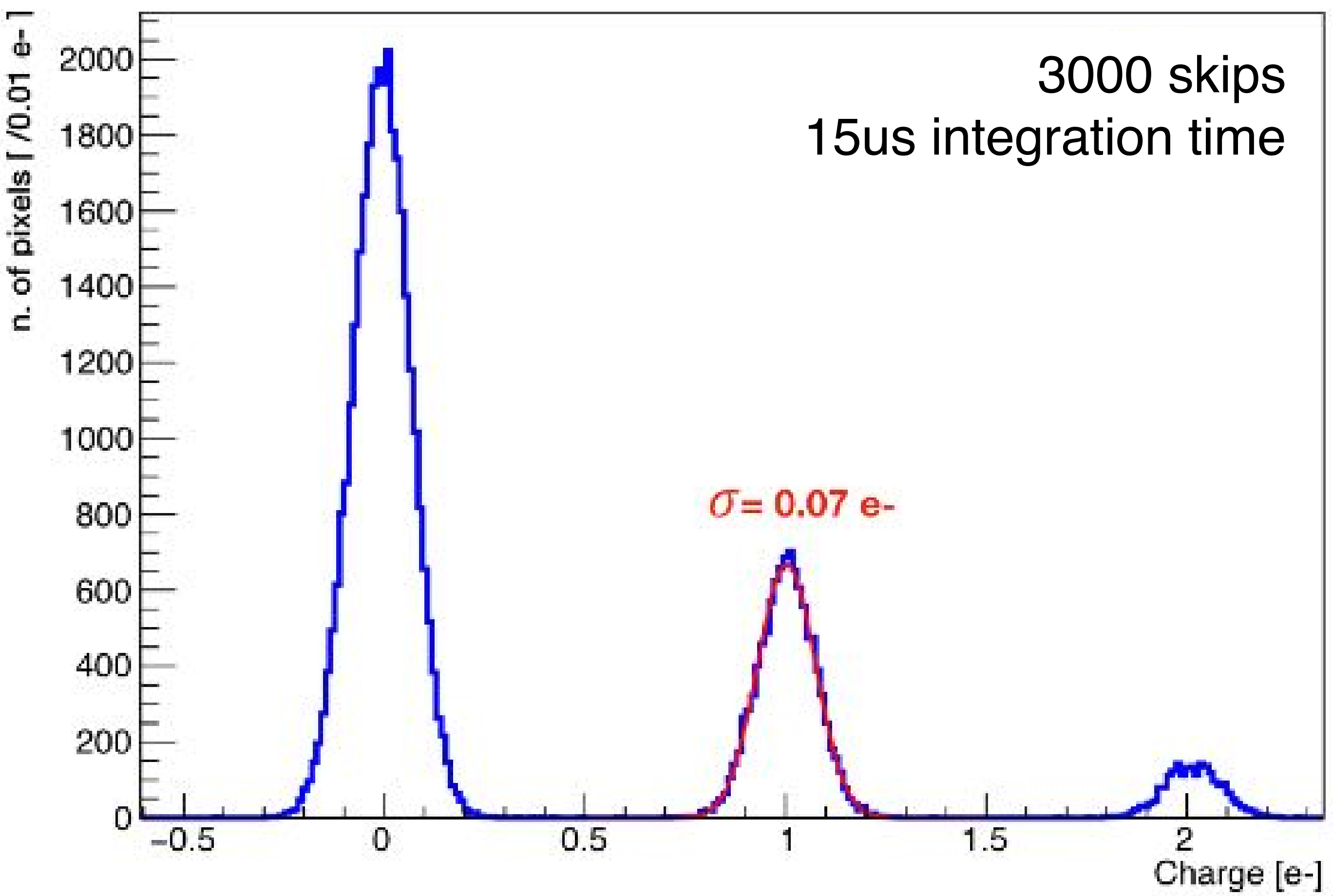




The DAMIC-M Collaboration

erc
European Research Council
Established by the European Commission

NSF

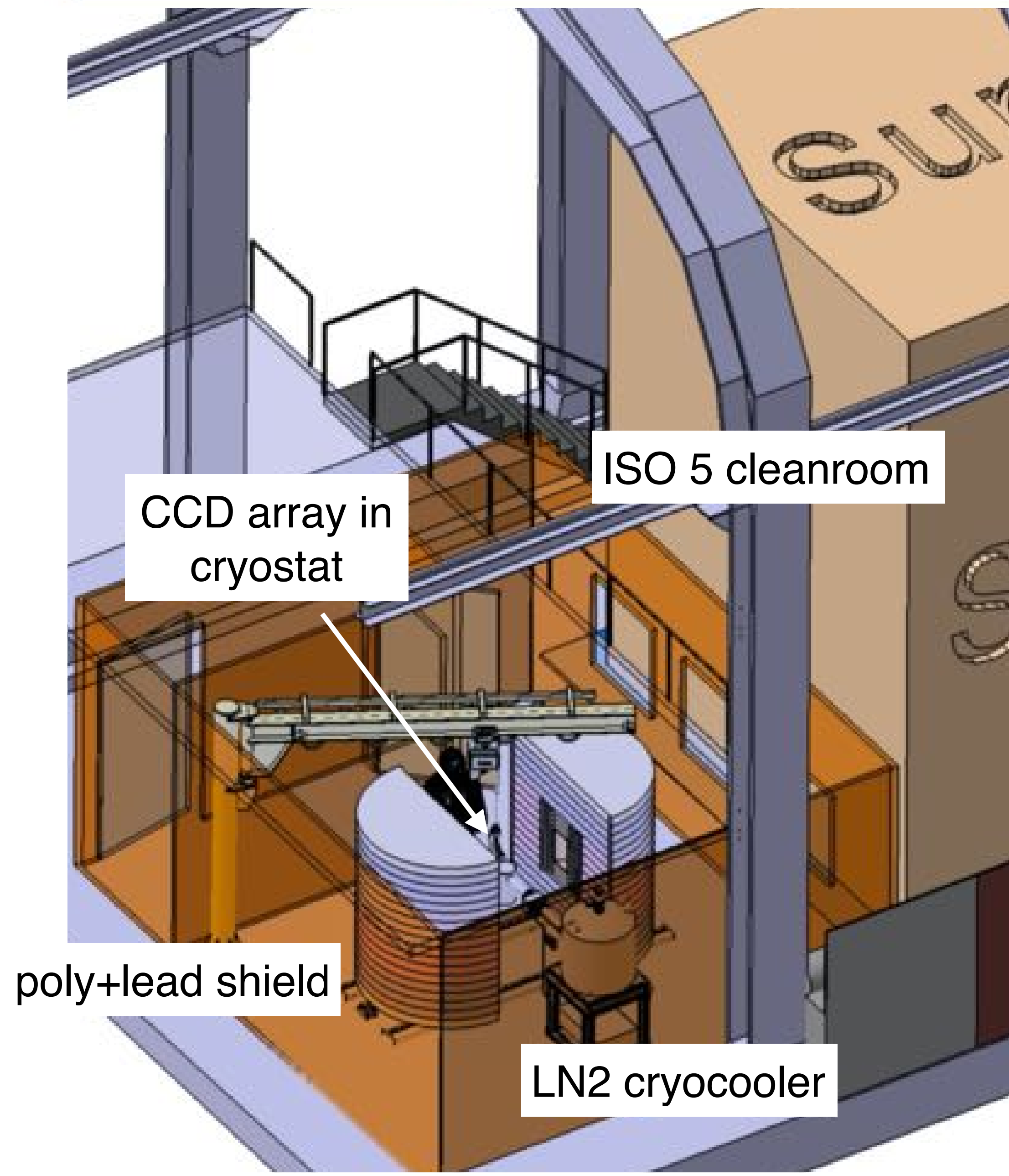
DAMIC-M

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

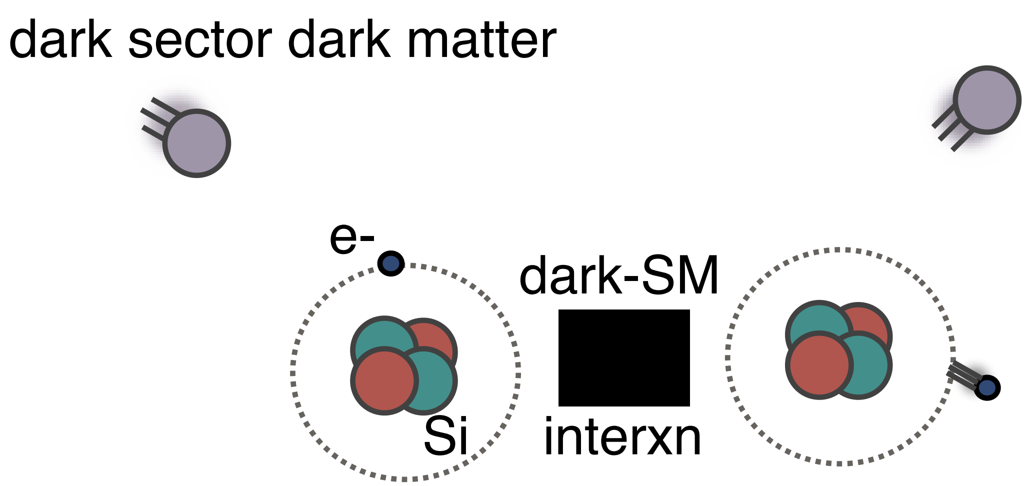
- detect nuclear and electron recoils to search for light dark matter candidates (eV to GeV)
- achieve ~0.1 dru background rate (1 differential rate unit = 1 event/keV/kg/day)
- operate ionization detector with 2-3 electron threshold (~eV)



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!

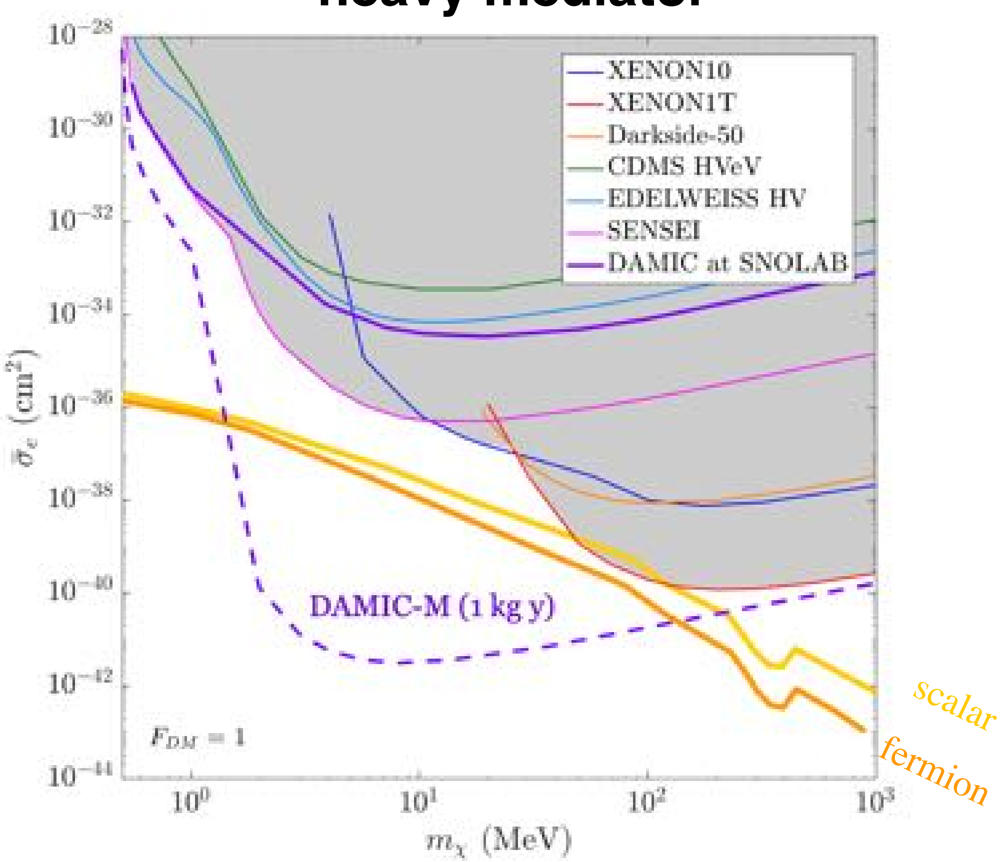
Electron recoils: sensitivity to dark sector



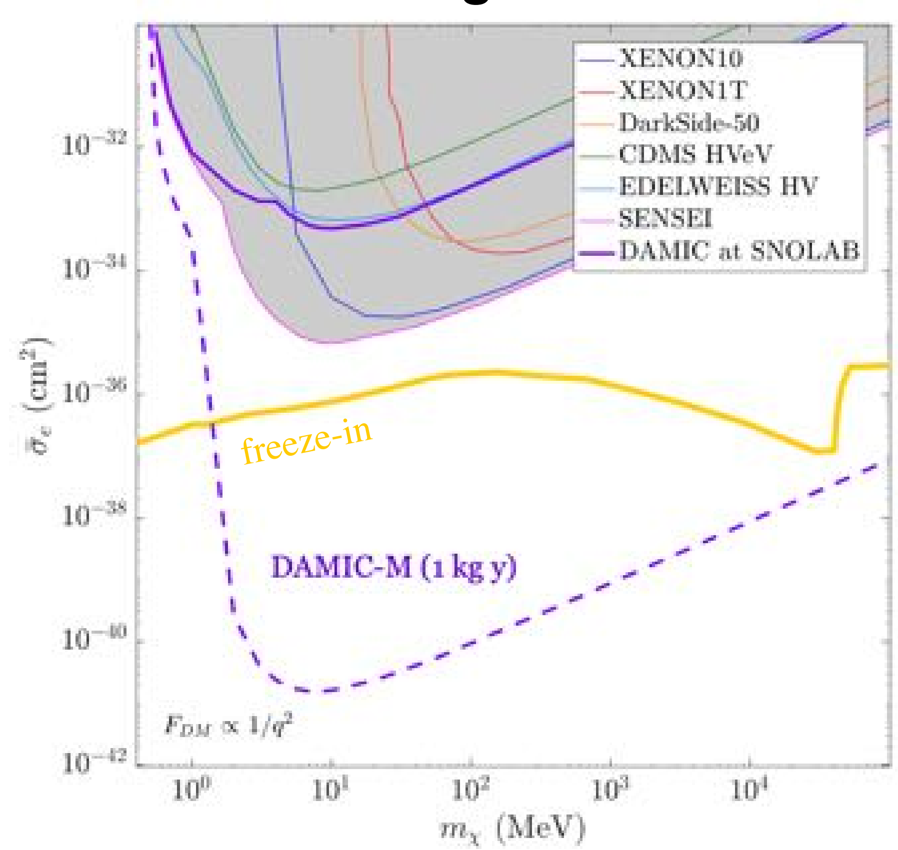
dark sector-electron scattering:

- 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

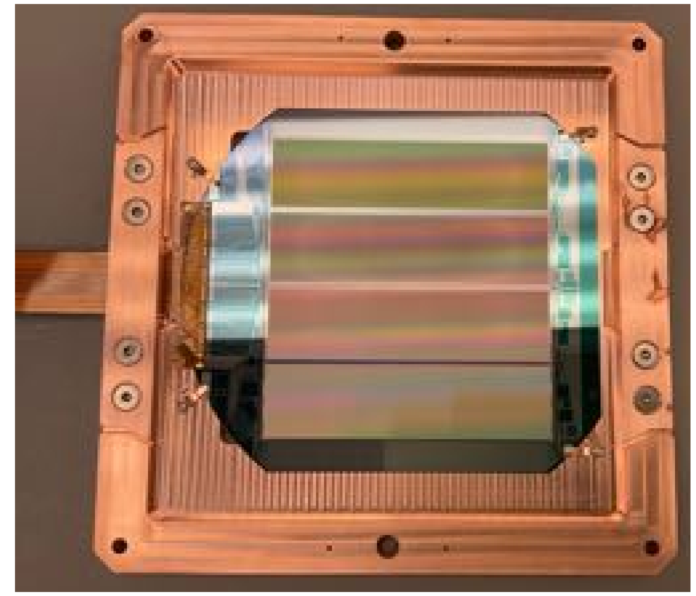


single electron sensitivity to probe predictions in sub-GeV regime

DAMIC-M detector design

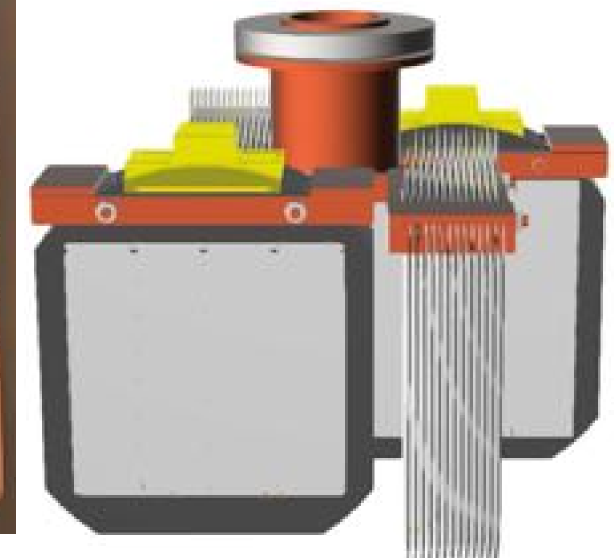
208 skipper CCDs

- 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

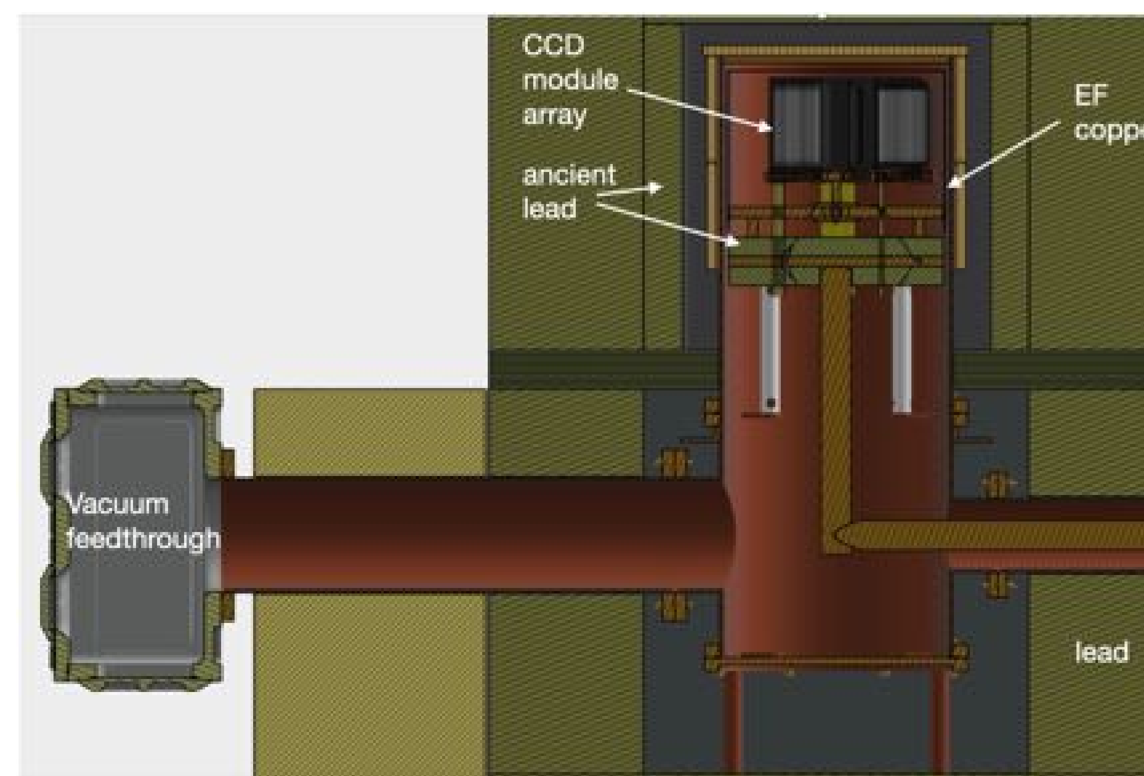
CCD module array



25cm

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



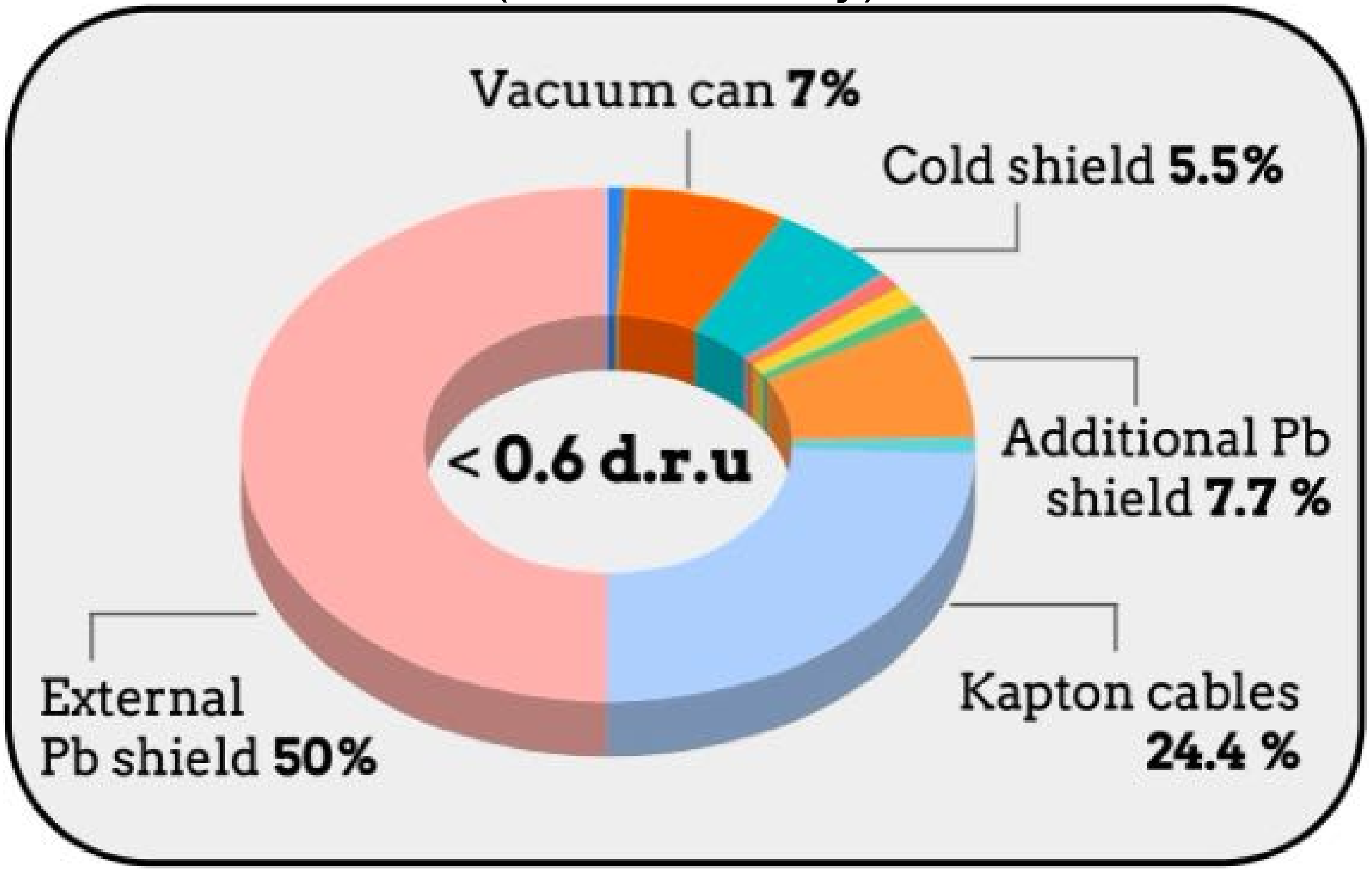
Background controls

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

DAMIC-M background progress

for reference

approaching 0.1dru goal
(materials only)



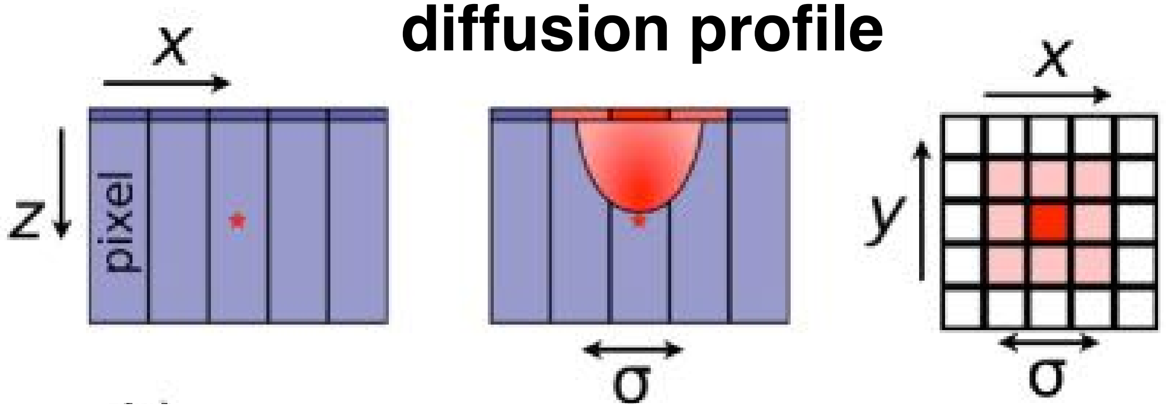
Si bulk not included (~0.4dru), spatial coincidence to reject some

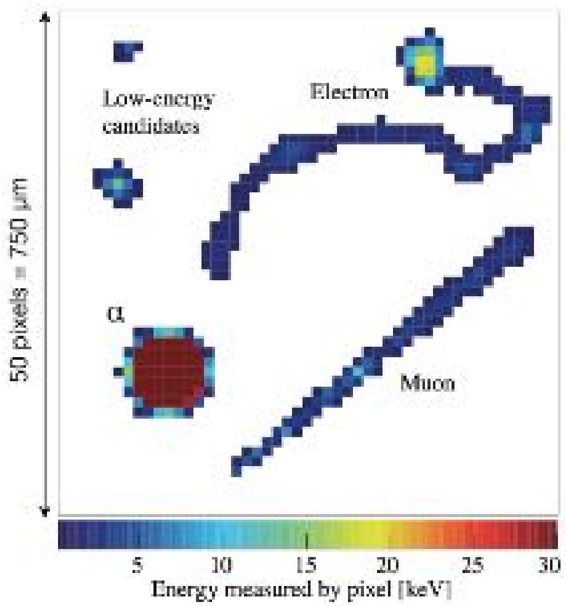
Geant4 + detector response simulation to inform detector design. Lessons from SNOLAB.

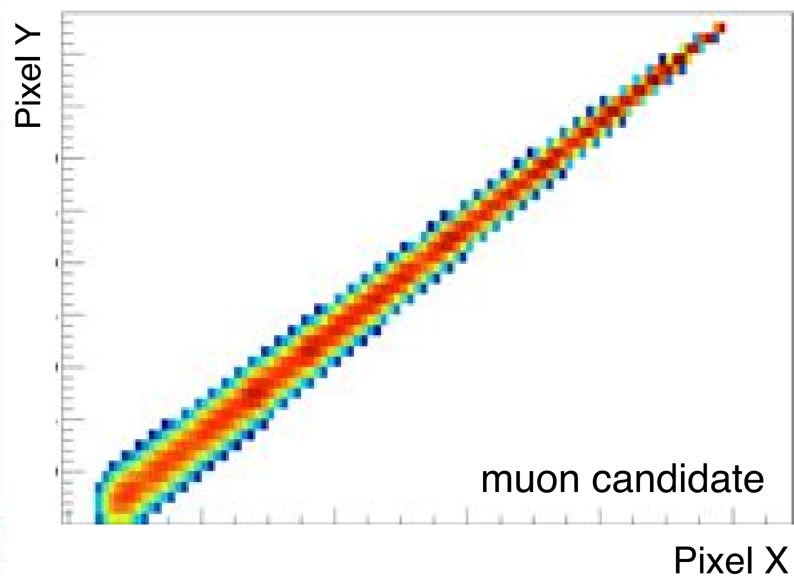
Material assays on-going, developing cleaning procedures, utilizing storage in radon-free environments underground, working on electro-formed copper production Canfranc (LRT2022), R&D on low background flex cables (PNNL, LRT2022), optimizing design and analysis techniques **all to achieve fraction of dru**!

3D reconstruction and spatial correlation

diffusion profile

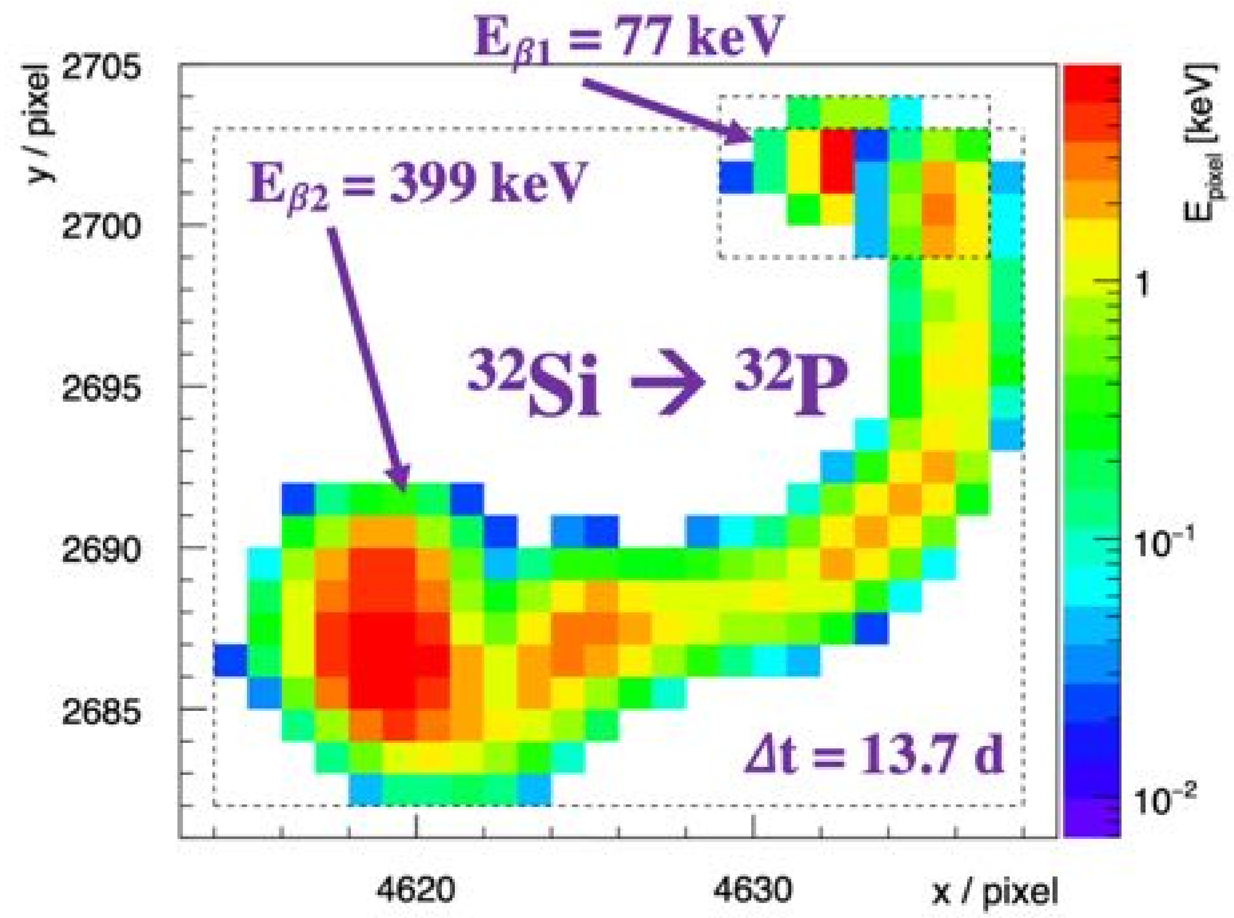






intrinsic decay

^{32}Si → ^{32}P + β^- → ^{32}S + β^-



JINST **10** P08014 (2015)

- use pixel structure + charge diffusion (depth) to reconstruct tracks in 3D
- energy deposit profile depends on particle type, efficiently identify from cluster shape
- unique ability to reject backgrounds with spatially-correlated decay products over time
- greatest challenge for DM searches are radiogenic and cosmogenic backgrounds, these topological tools can help reduce with particle and decay ID

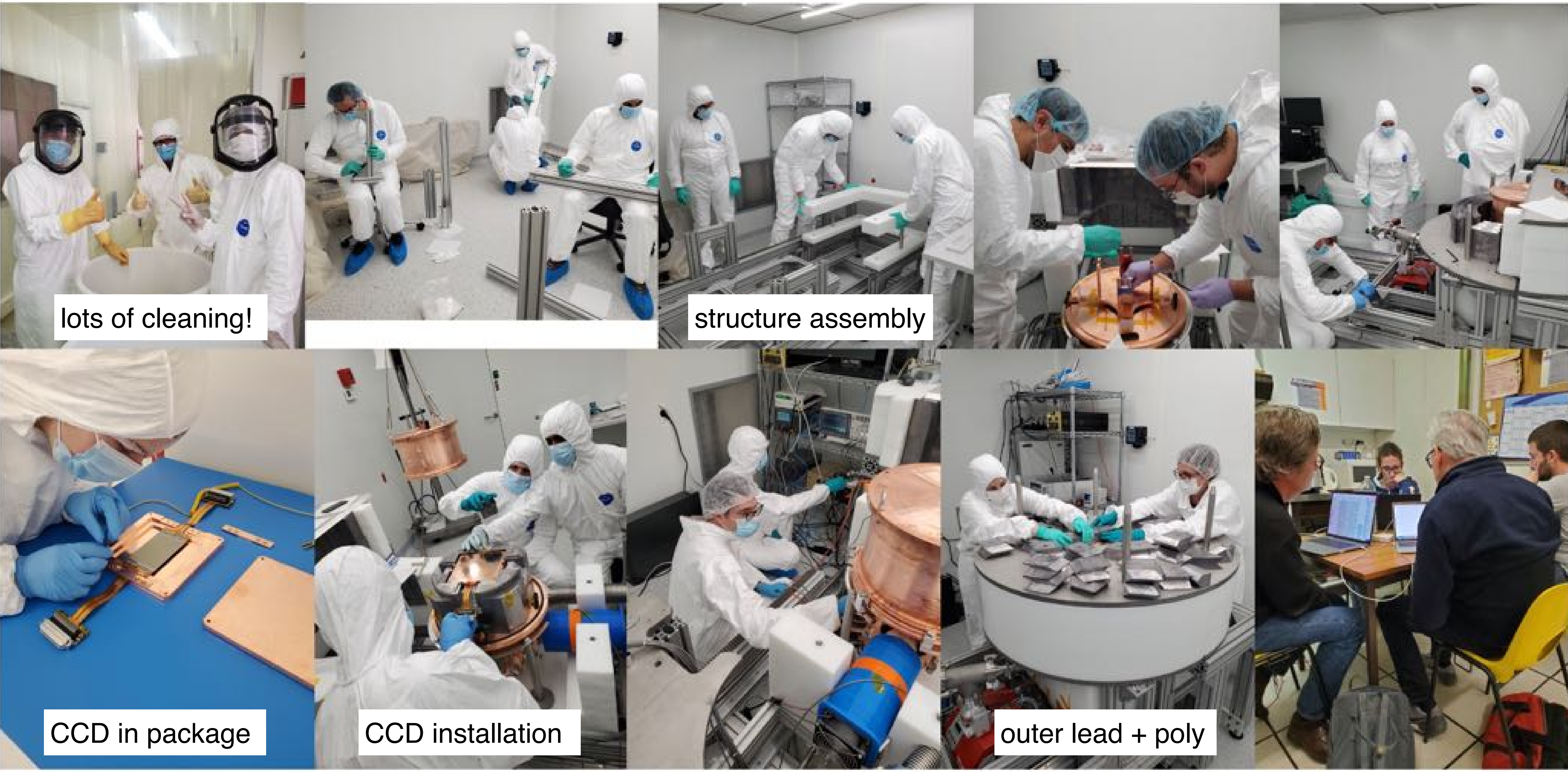
Low Background Chamber (LBC)

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

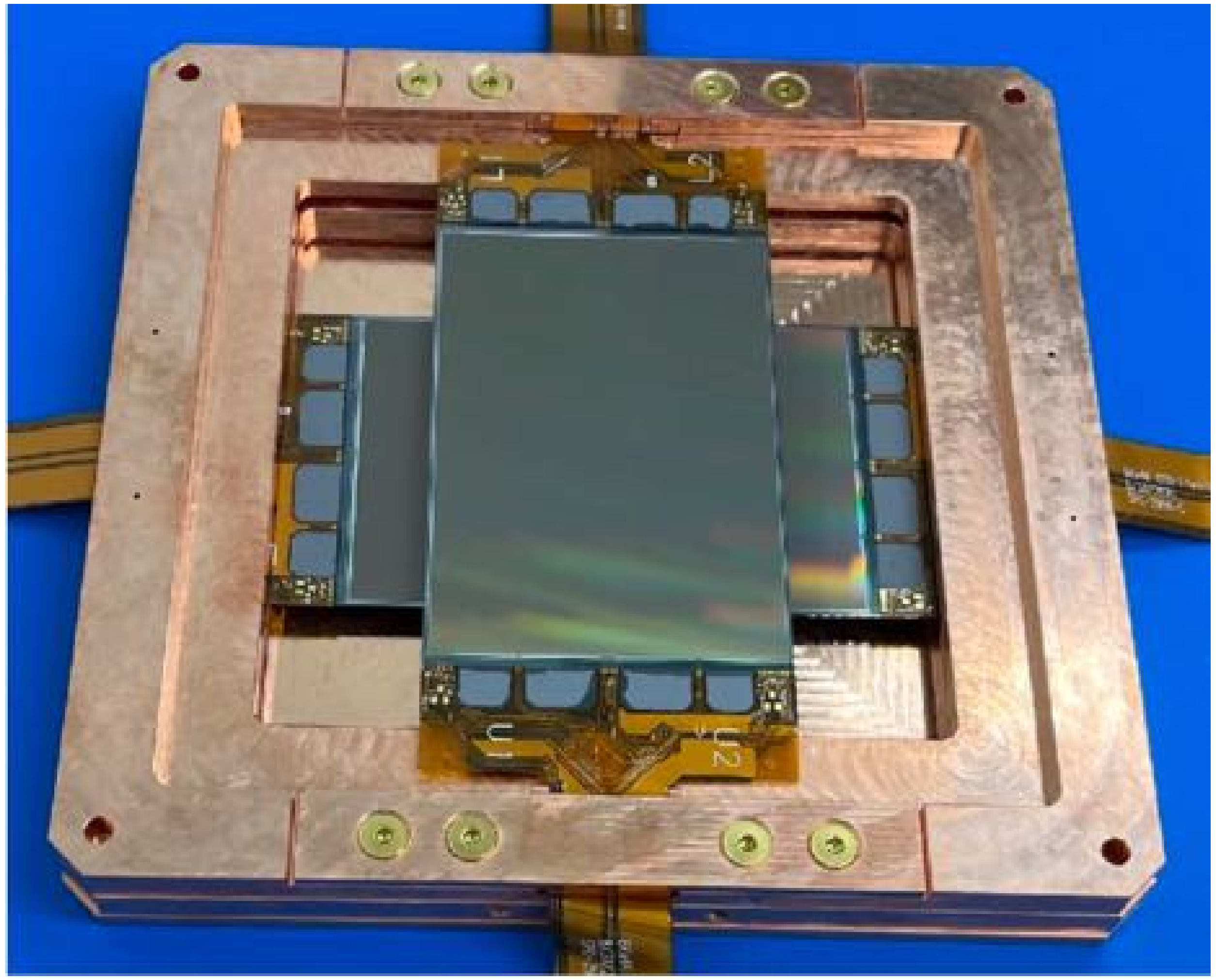
Construction of the LBC

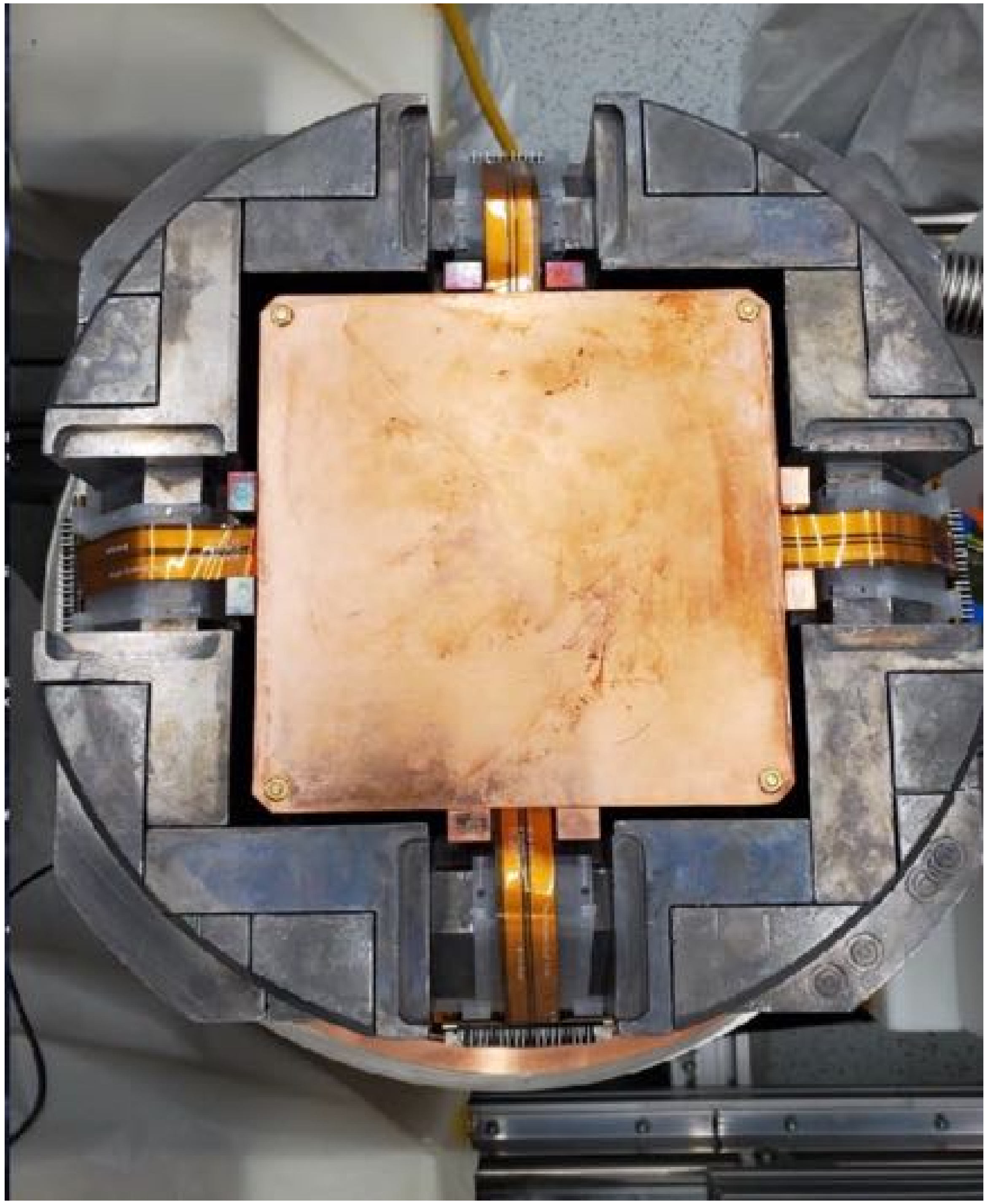


cleaning, clean room preparation, support structure, cryostat, CCDs, external shielding, electronics, slow control, grounding, troubleshooting, ...

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

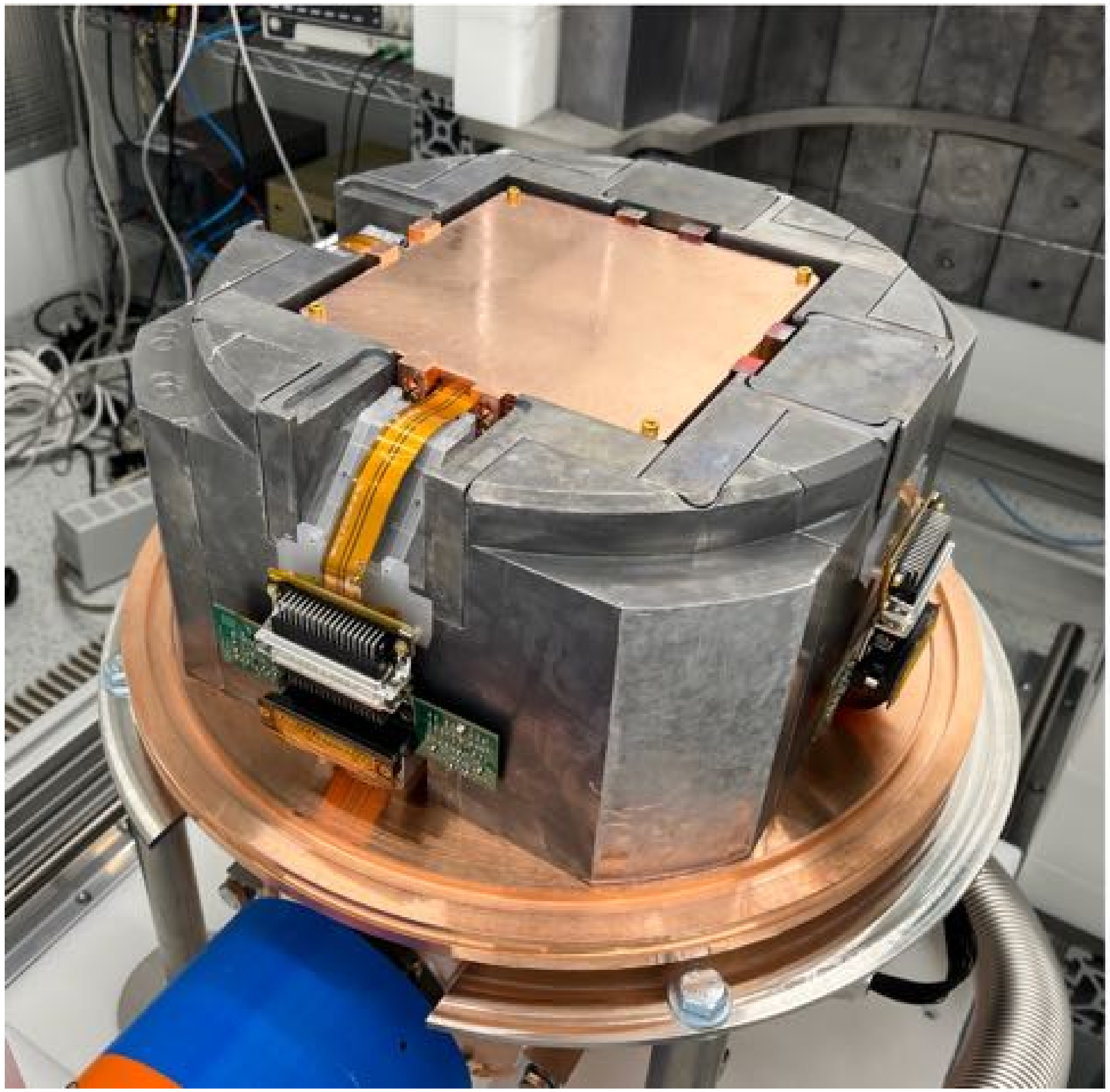




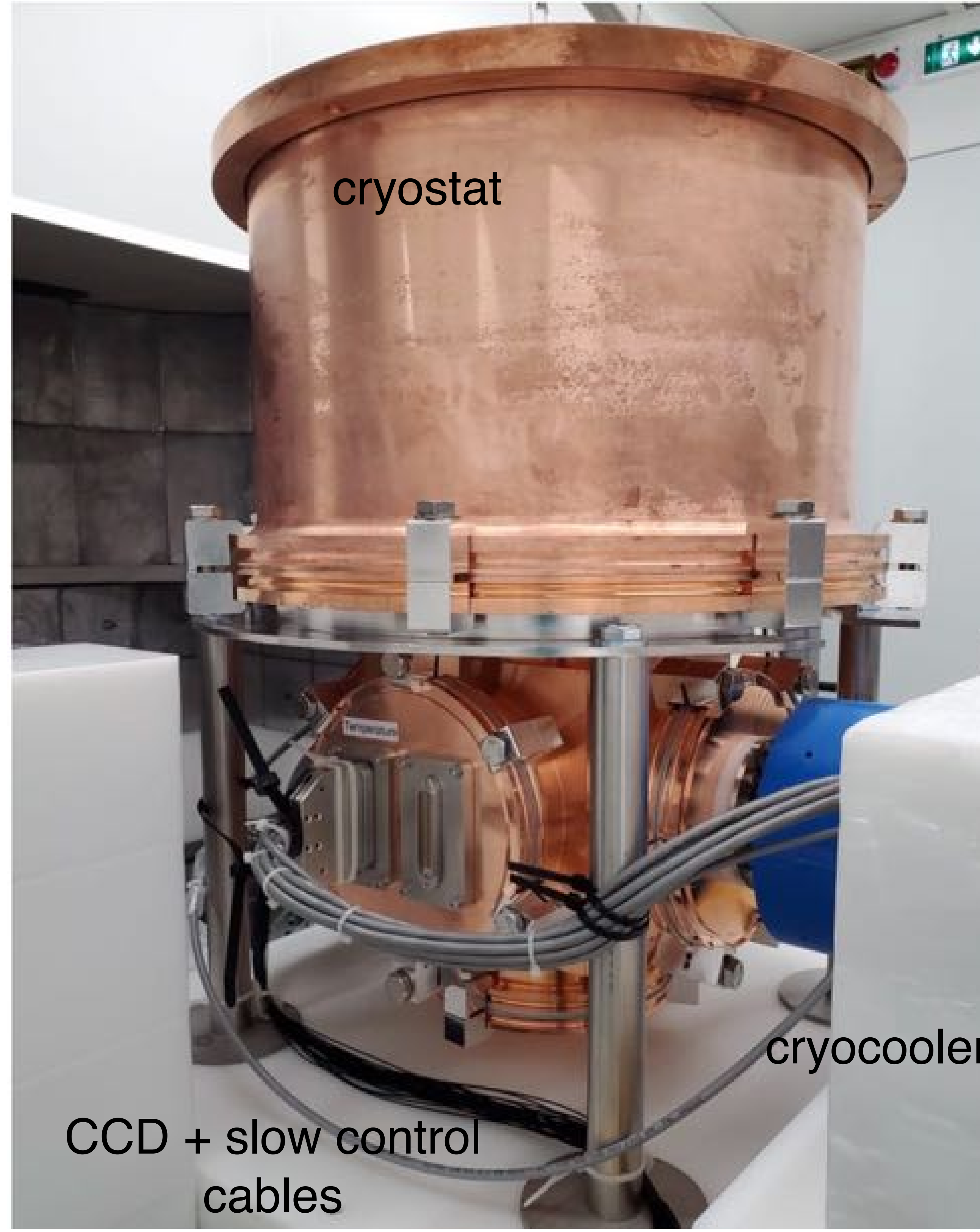
*later upgraded to DAMIC-M modules, electrofromed copper, low bkgd flex, custom electronics

LBC detector - electronics and slow control

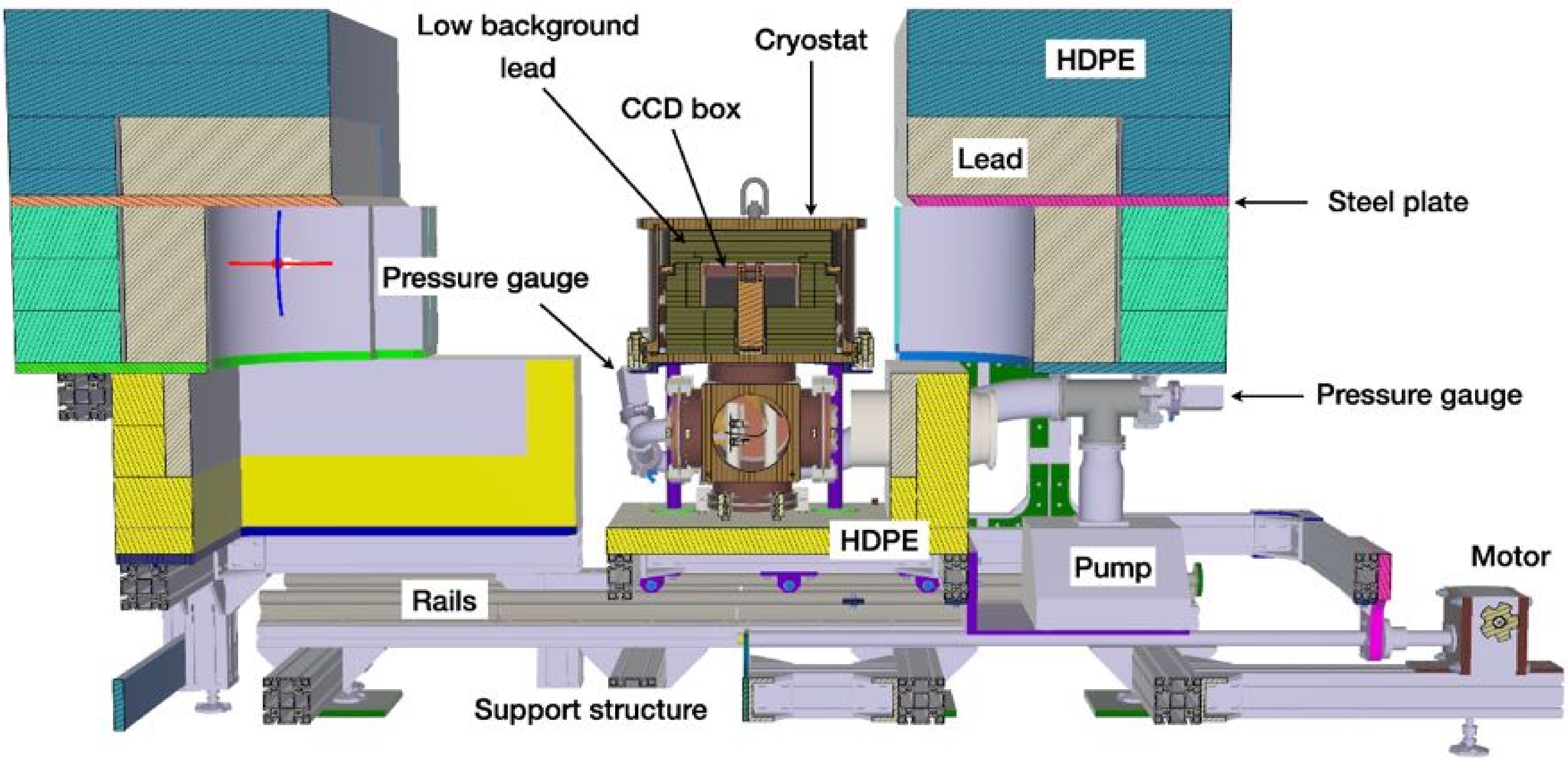
front-end electronics for amplifiers and clock shaping
Leach as controller and data acquisition



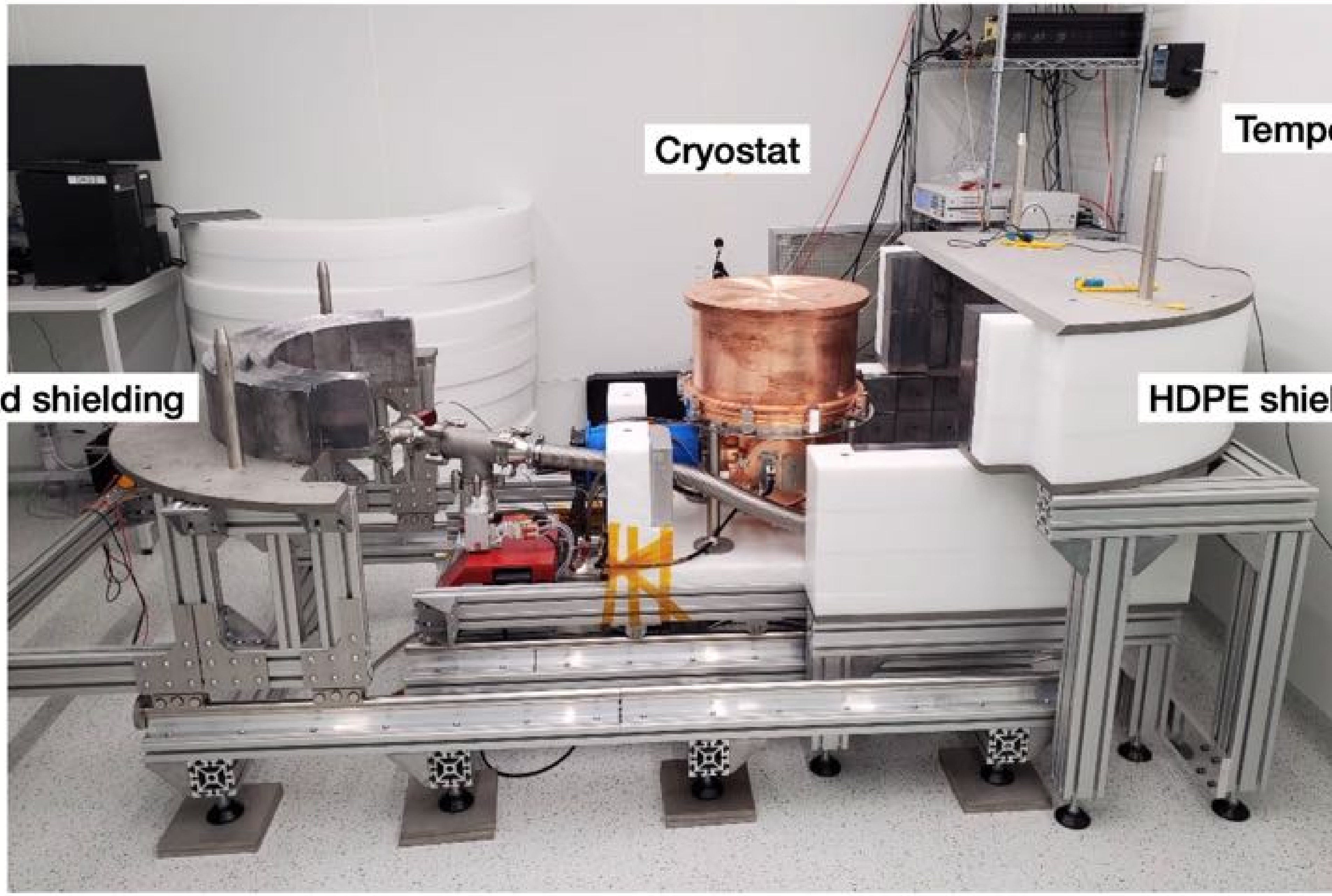
using slow control system from UChicago



LBC detector - layout (design)

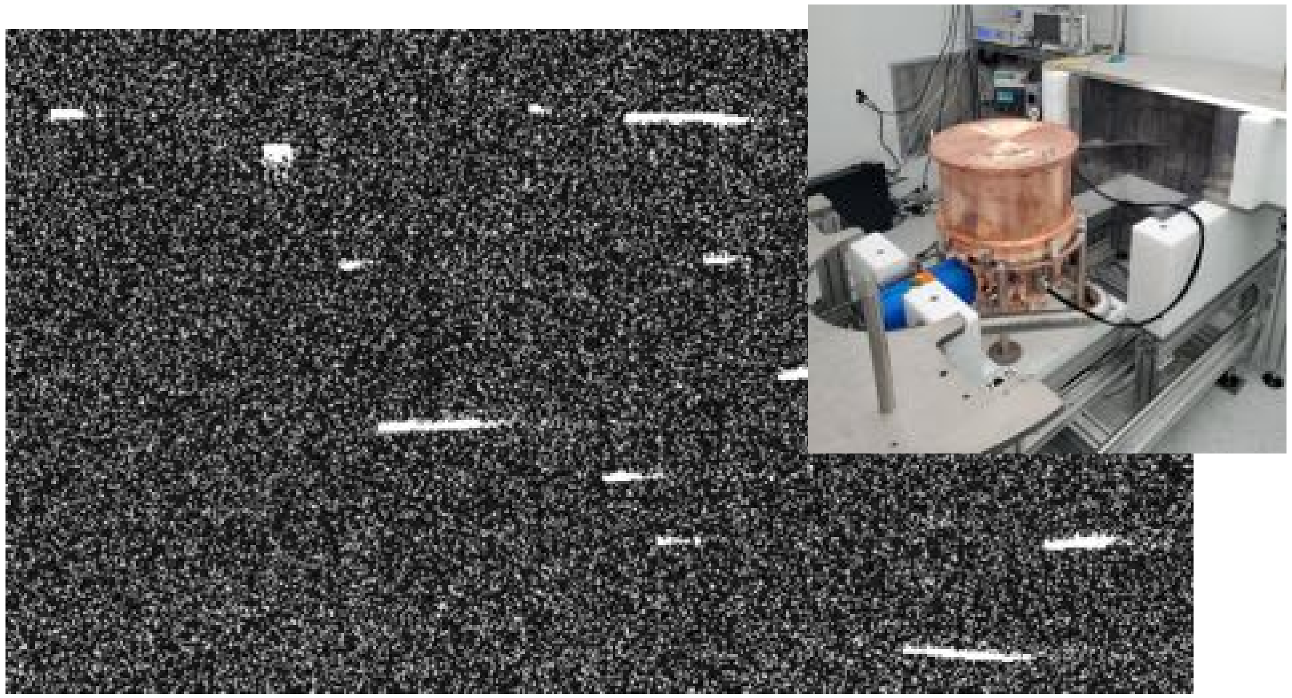


LBC detector - layout (reality)

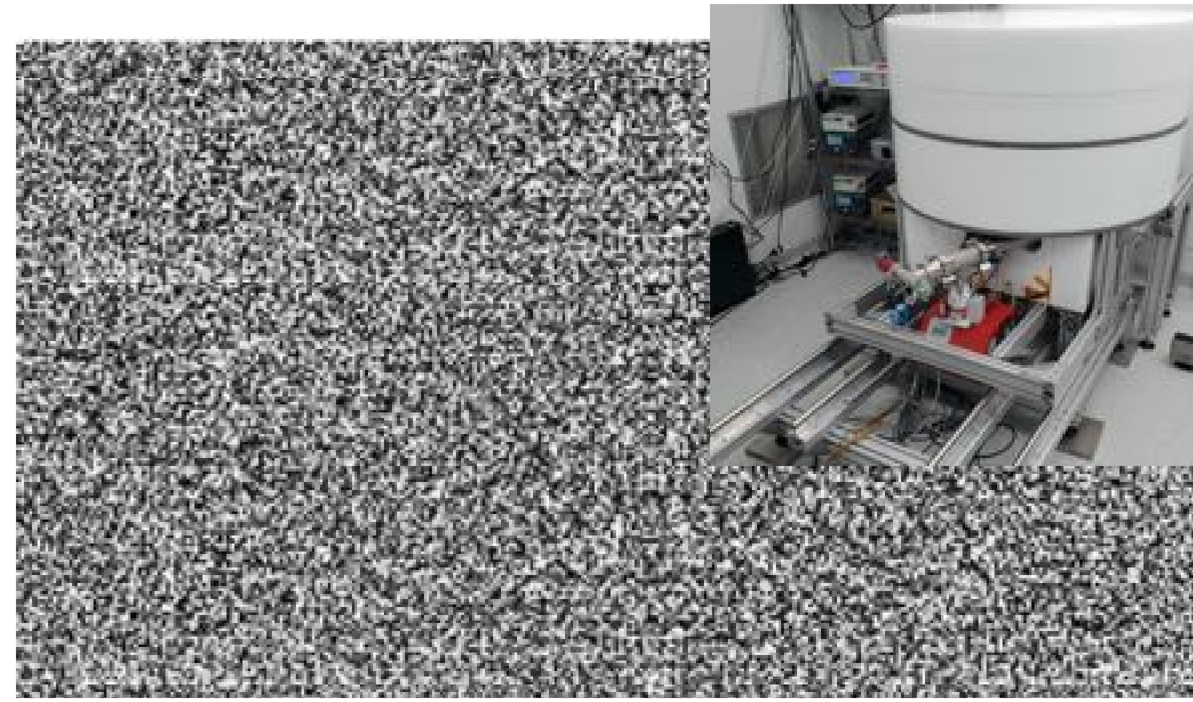


Published LBC data sets

Internal shield



Internal + external shield



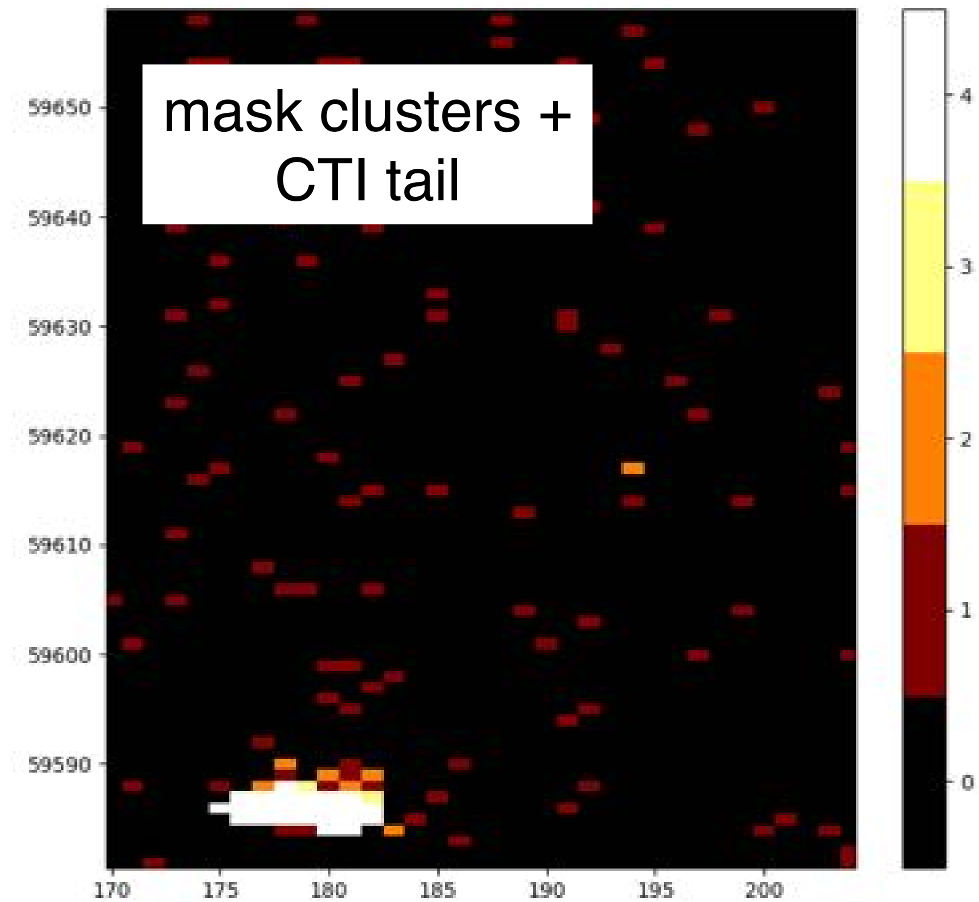
Commissioning runs (Feb - May)
- verify performance of detector
- optimize CCD parameters (e.g. CTI)
- confirm calibration and develop analysis
- internal shield (300dru)
- dark current reduction with thermal tests (slower cool-down/warm-up (0.1 K/min))

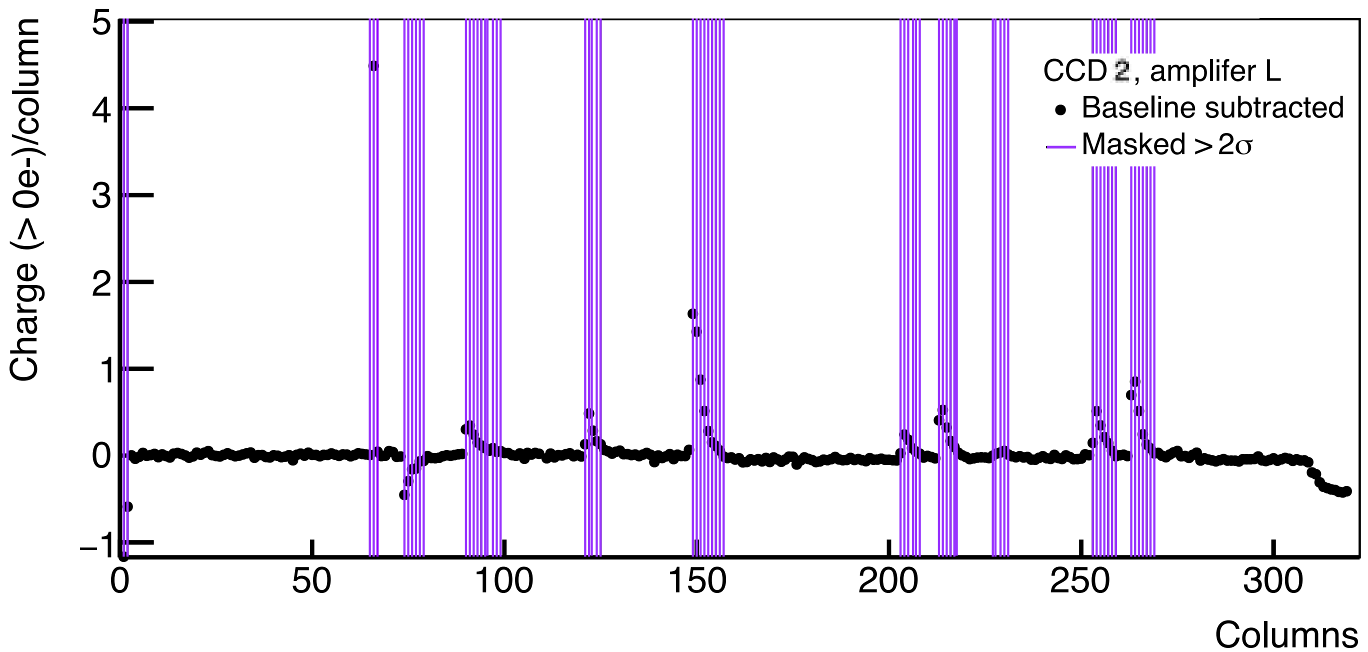
Science runs (May - November)
- internal+external shield (~10 dru*)
- 0.2 e- energy resolution (650skips)
- dark current 3.0e-3 e-/pixel/day, under investigation
- DM-electron analysis with 85.23 g-days
- daily mod search with 39.97 g-days

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

Image cleaning and event selection

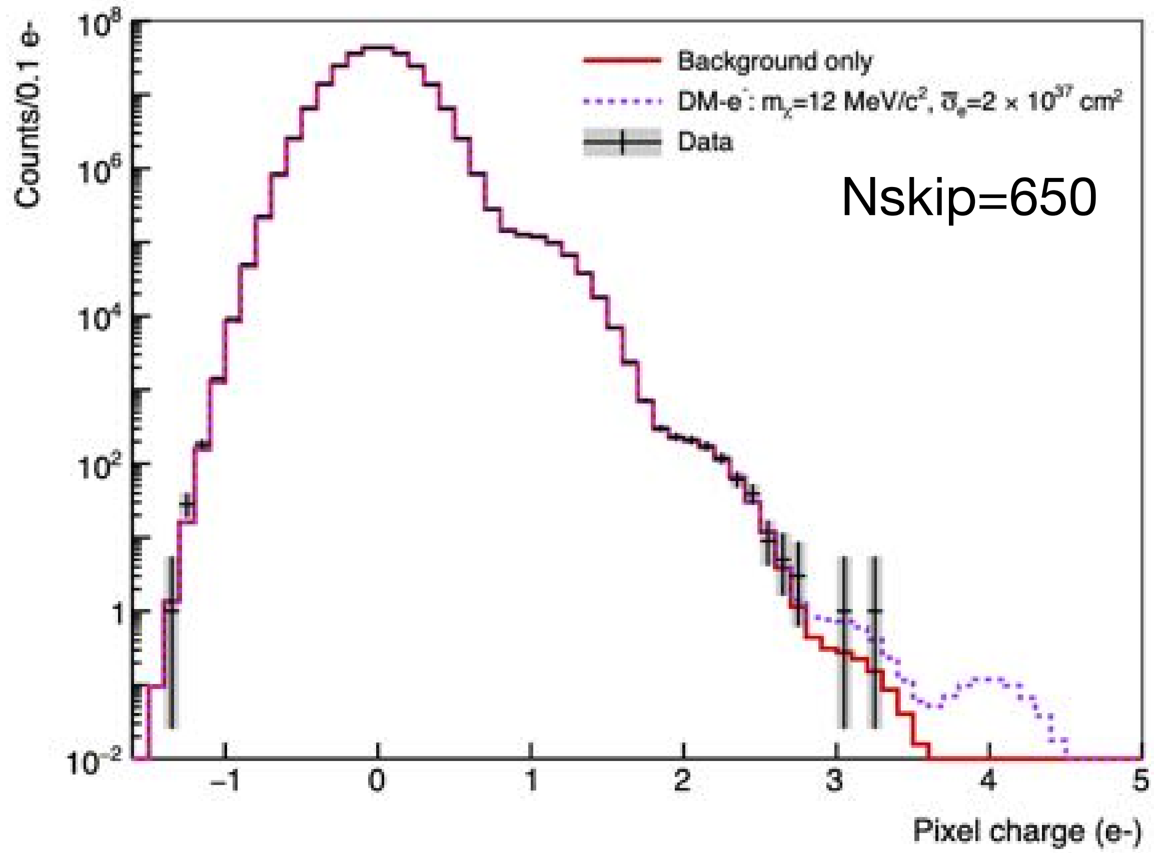
1. **Image selection**
   exclude images with outlier dark current
2. **Cluster reconstruction**
   use seed threshold to group pixel hits adjacent $>3\sigma_{elec}$ with one pixel >2e-
   remove single pixel with >7e-
3. **Masking**
   remove clusters, 10 trailing pixels in horz, vert direction from 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



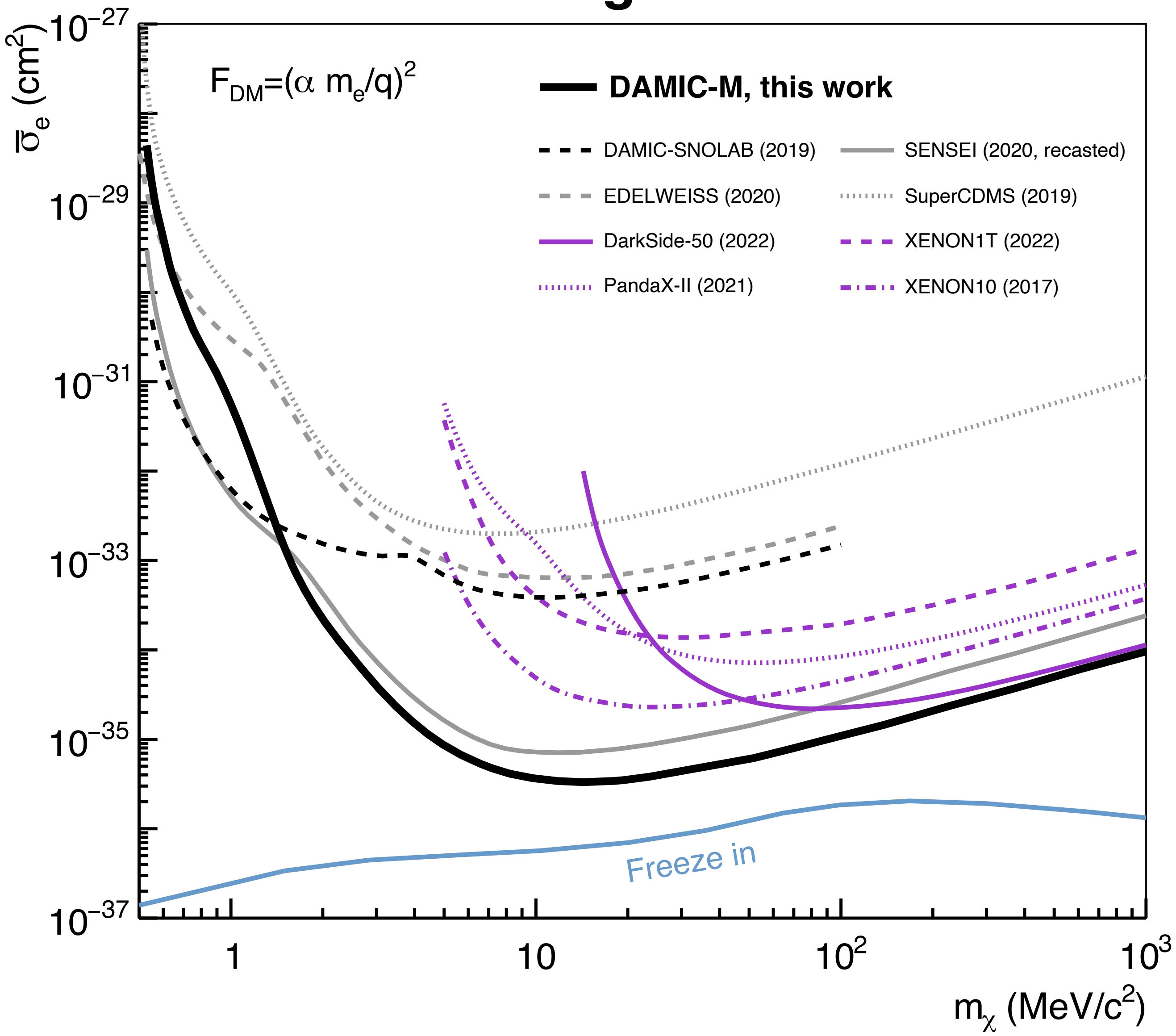
PRL 130, 171003 (2023)

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

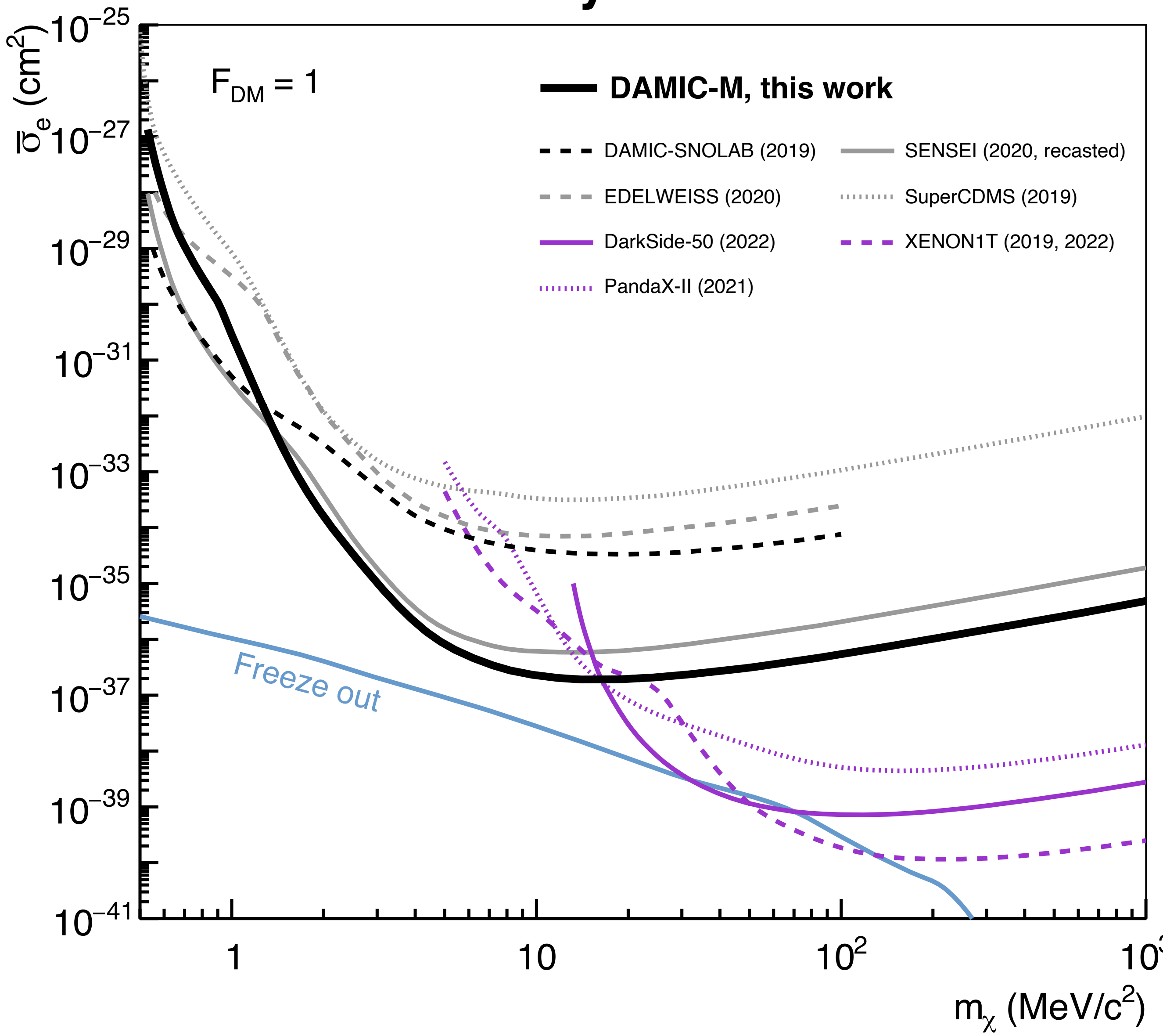
First results: dark matter-electron scattering

PRL 130, 171003 (2023)

ultra-light mediator



heavy mediator

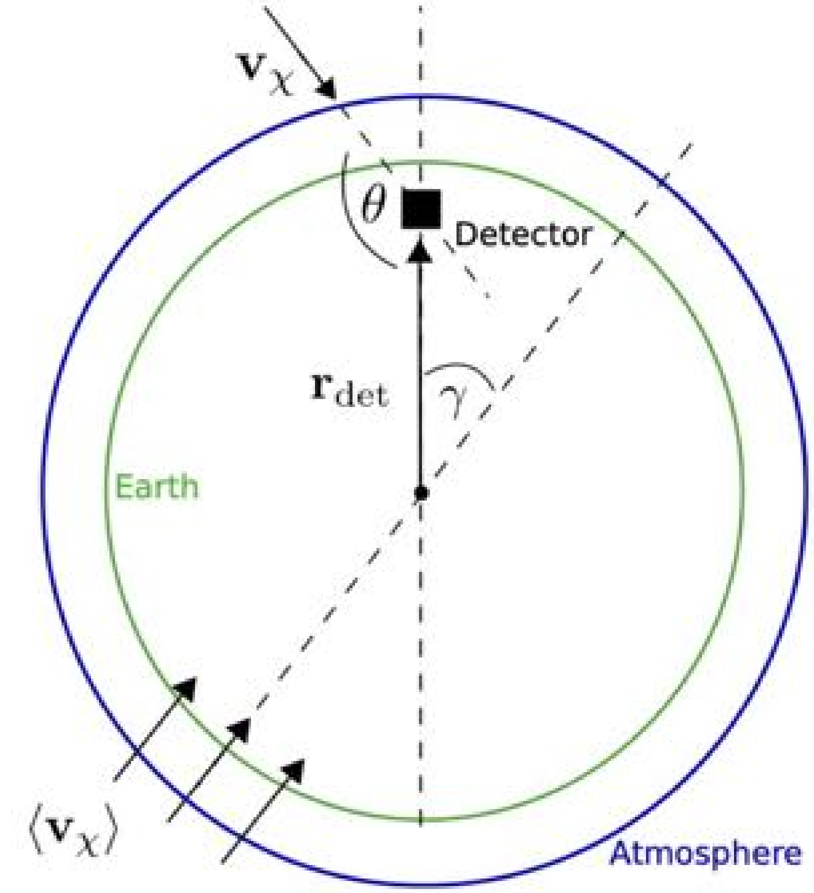


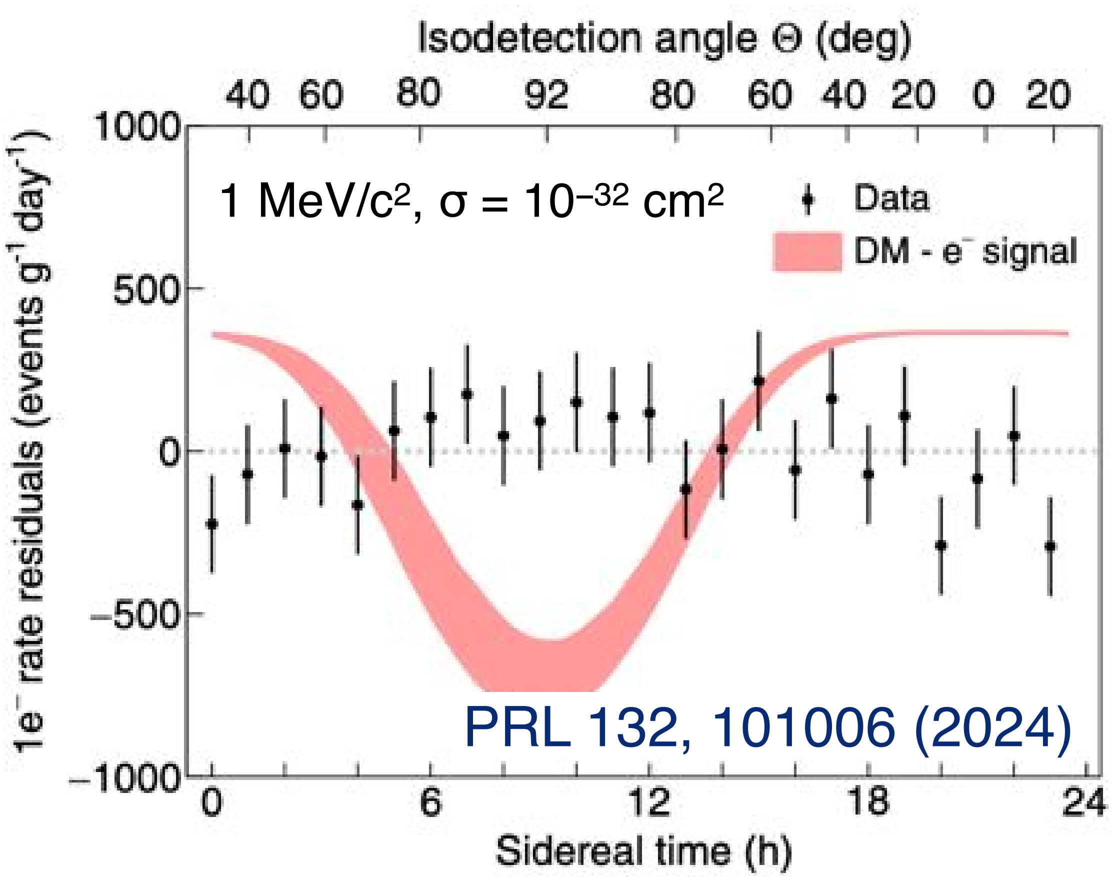
world-leading results with just 2 CCDs in a few months!

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



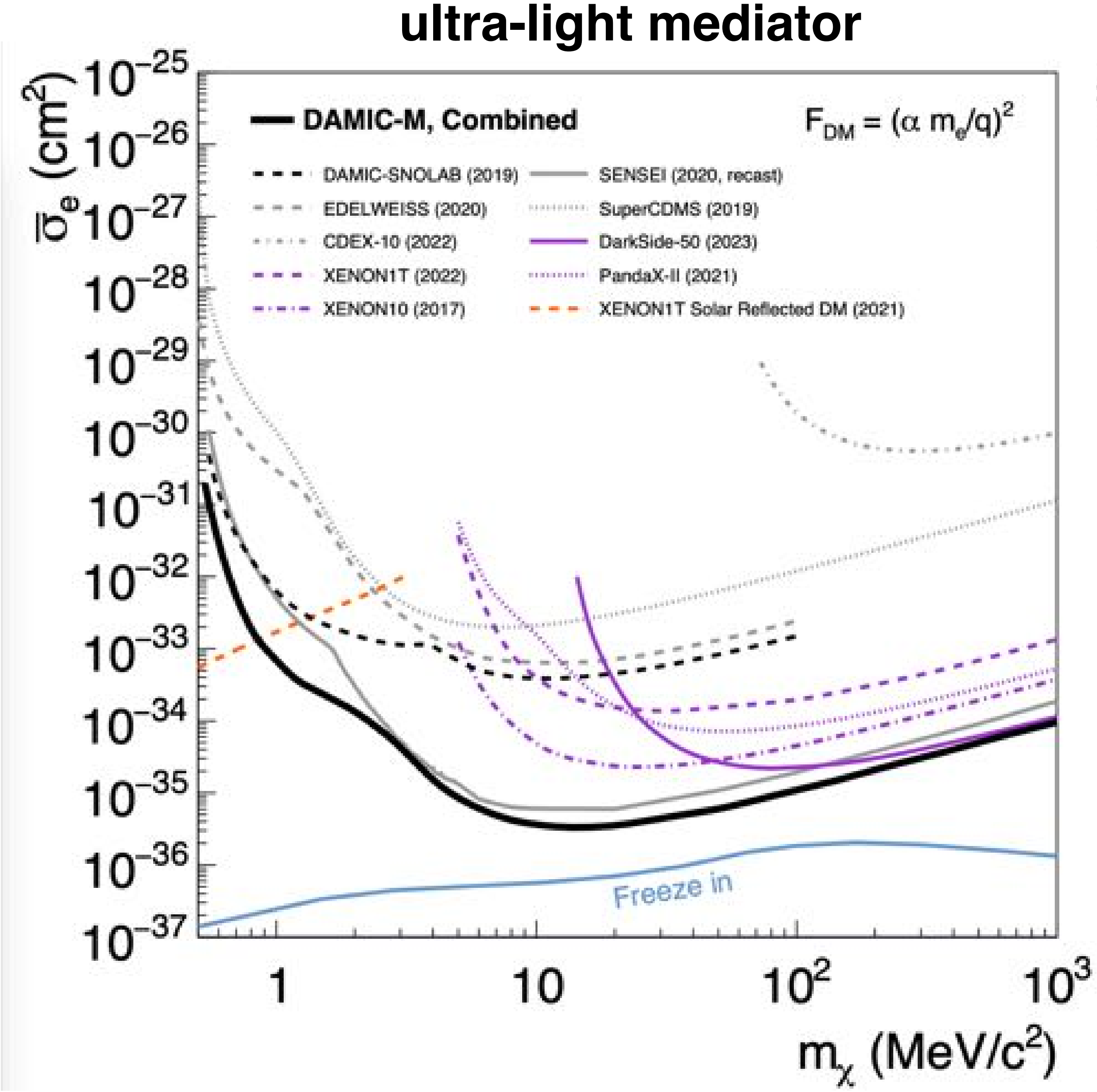


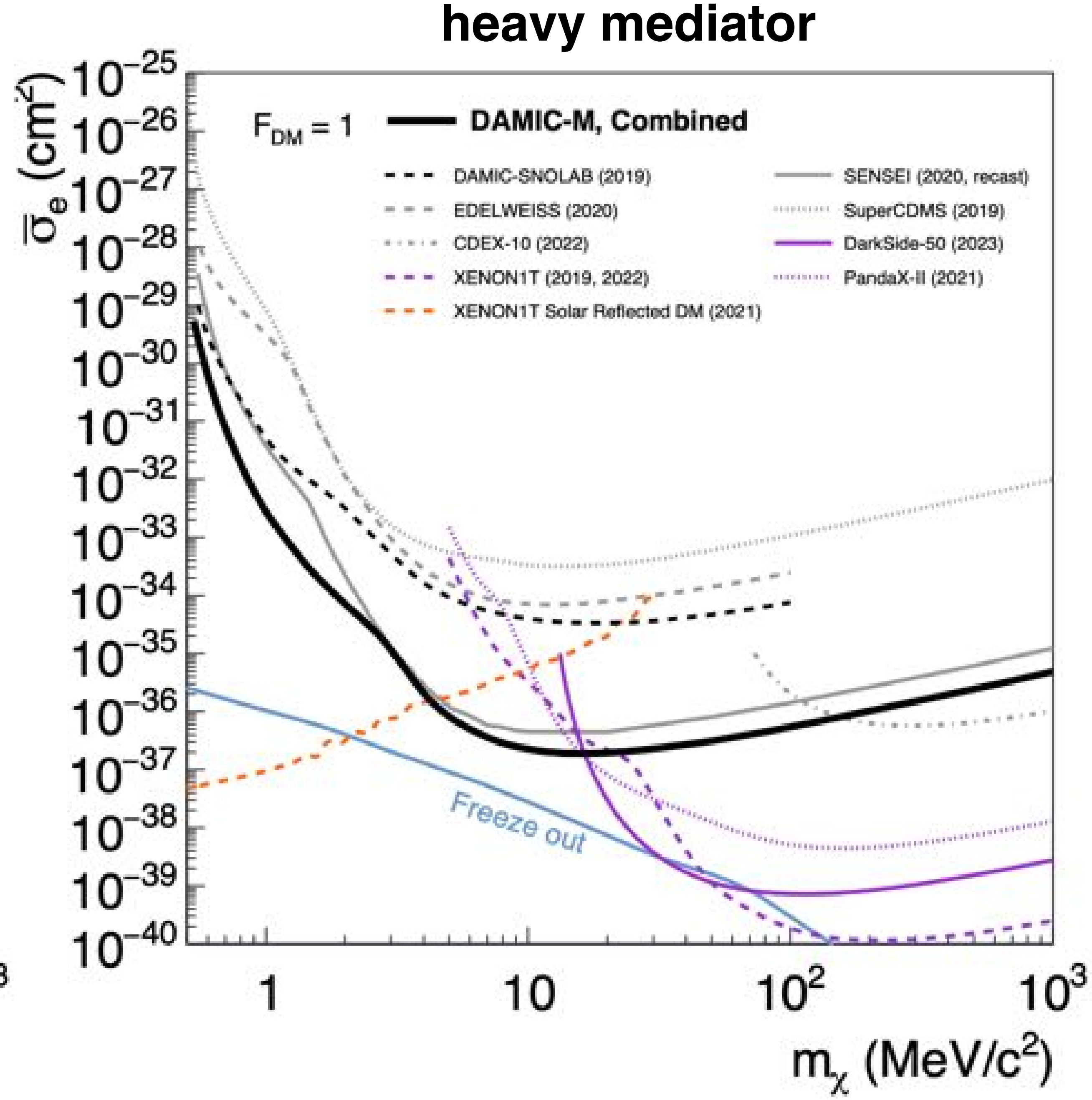
LBC result:

- 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

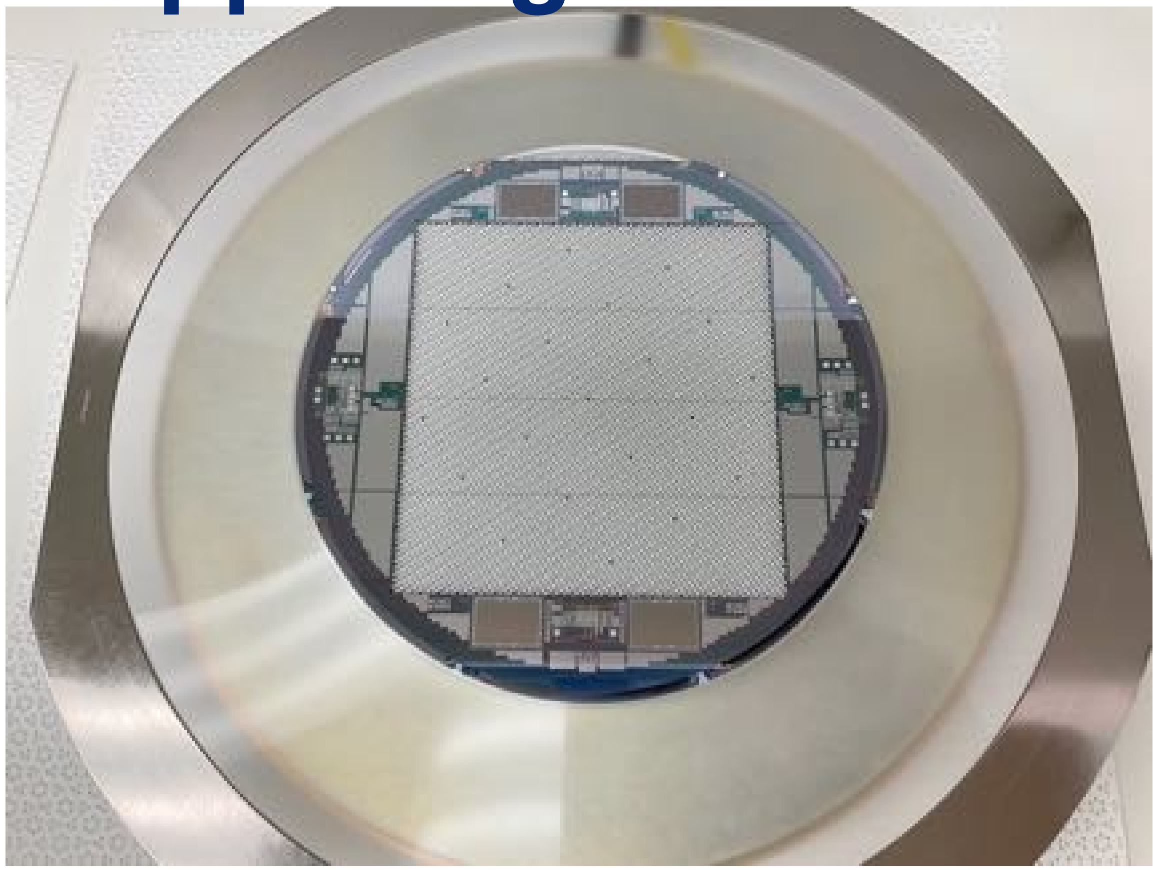
PRL 132, 101006 (2024)

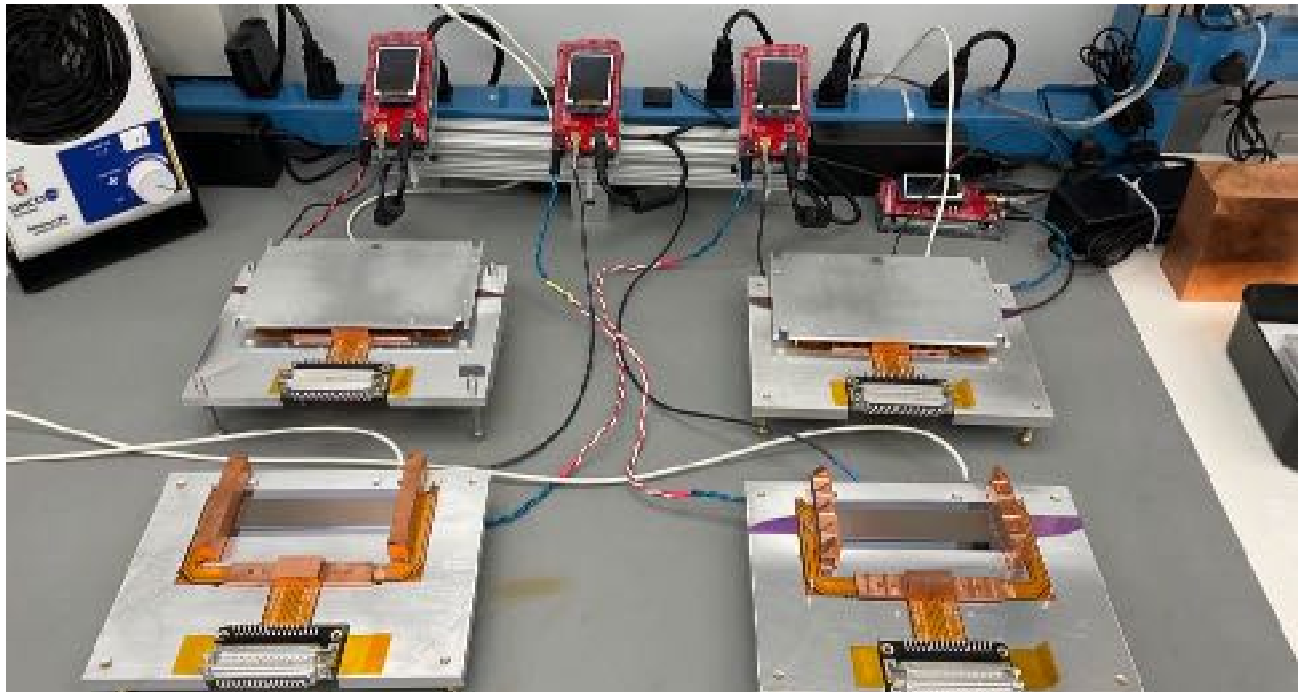


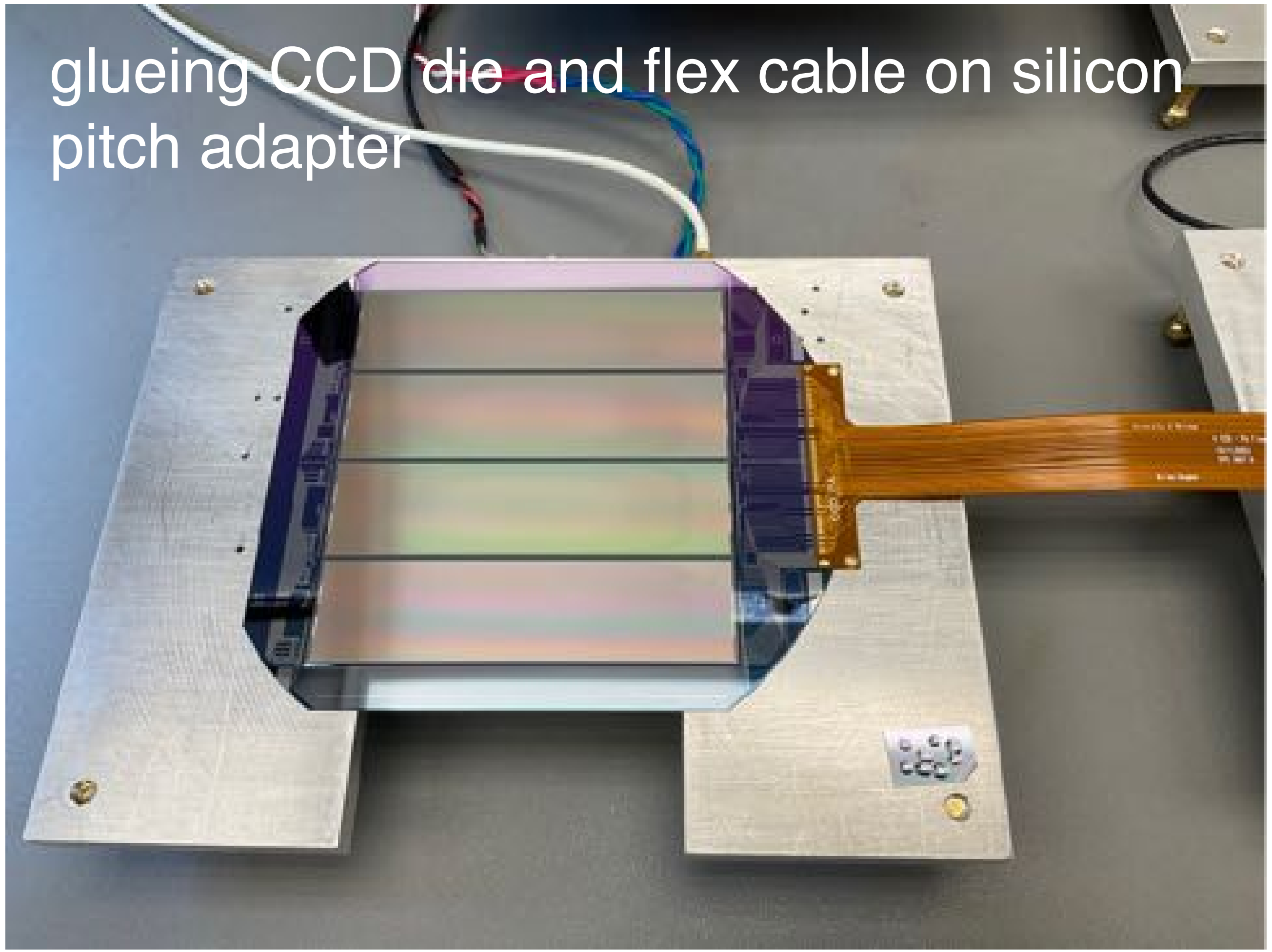


deep improvements in 1e- sensitivity, world leading results!

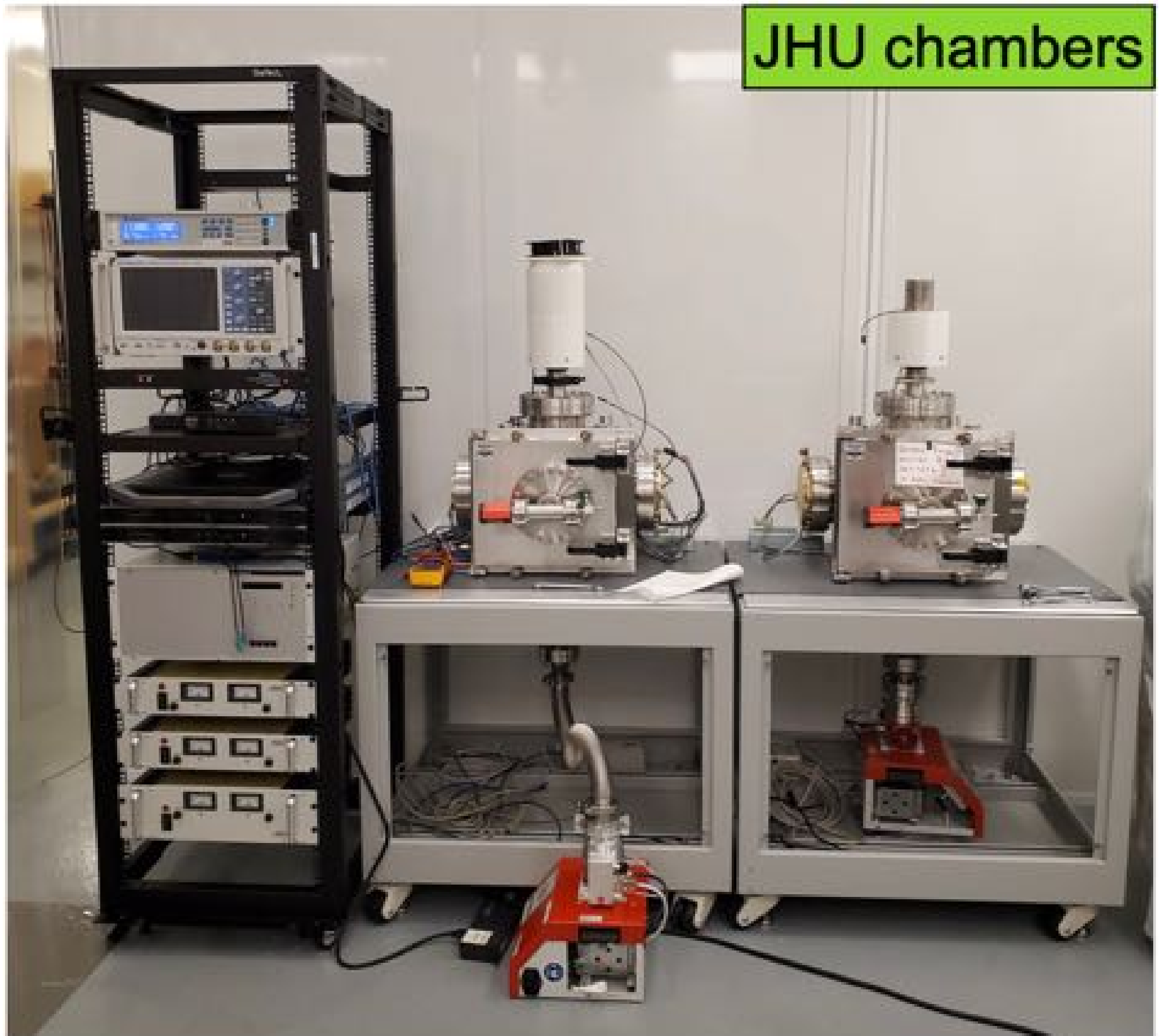
Happening now!







glueing CCD die and flex cable on silicon pitch adapter



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