The search for dark matter with DAMIC and DAMIC-M

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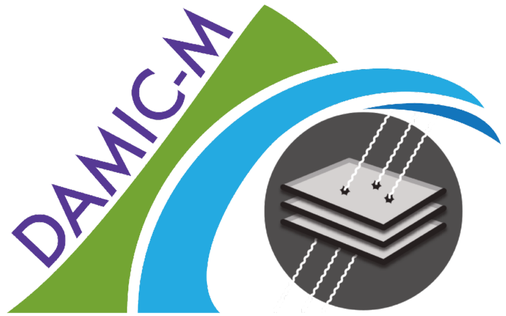
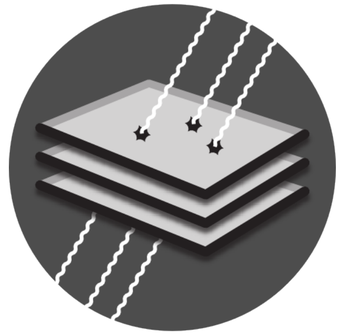


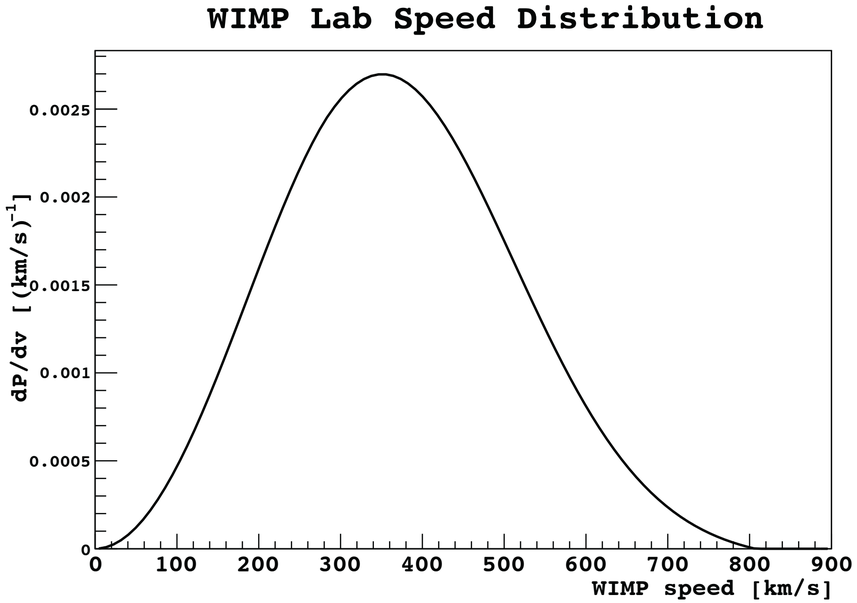


Outline

- Dark matter (DM) direct-detection signal.
- Electronic recoils to search for sub-GeV DM.
- Charge-coupled devices (CCDs) fundamentals and performance.
- DAMIC at SNOLAB and previous results.
- DAMIC-M and its prototype detectors.
- World-leading results in the search for sub-GeV DM!
- Outlook.

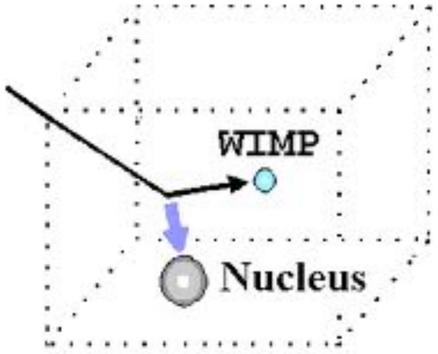
Dark matter signal

- Local density in ~0.3 GeV c^{-2} cm^{-3}.
- Interaction cross-section is small.
- Dark matter is cold, kinetic energy is ~10^{-6} Mc^2.
- Need detector with low energy threshold, largest possible exposure and correspondingly low backgrounds.



Traditional mechanism for WIMP searches:

Coherent enhancement: $\sigma_N \propto A^2$

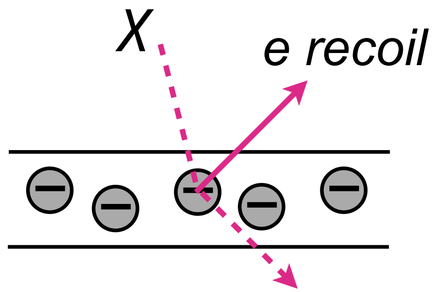


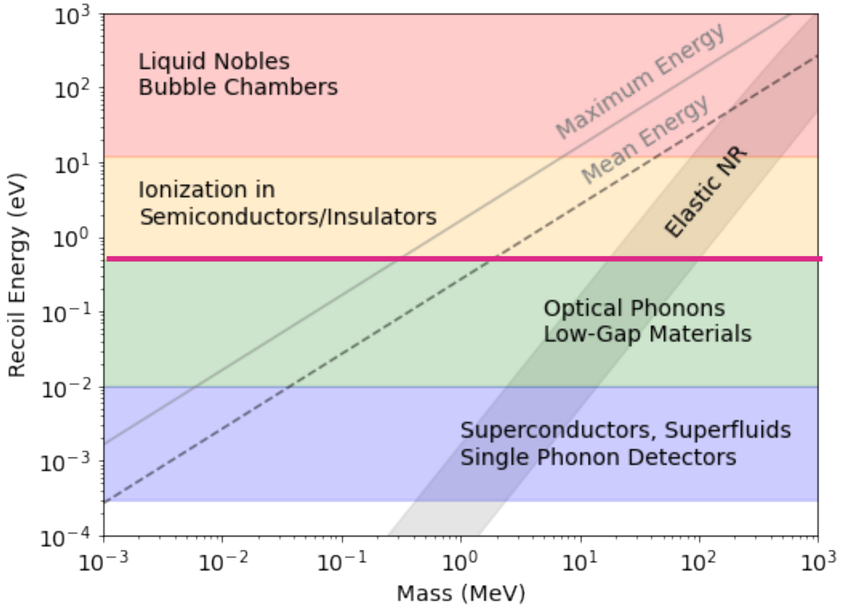
For low-mass WIMP: $M_T \gg M_\chi$

$$E_T < 4\frac{M_\chi}{M_T}E_\chi$$

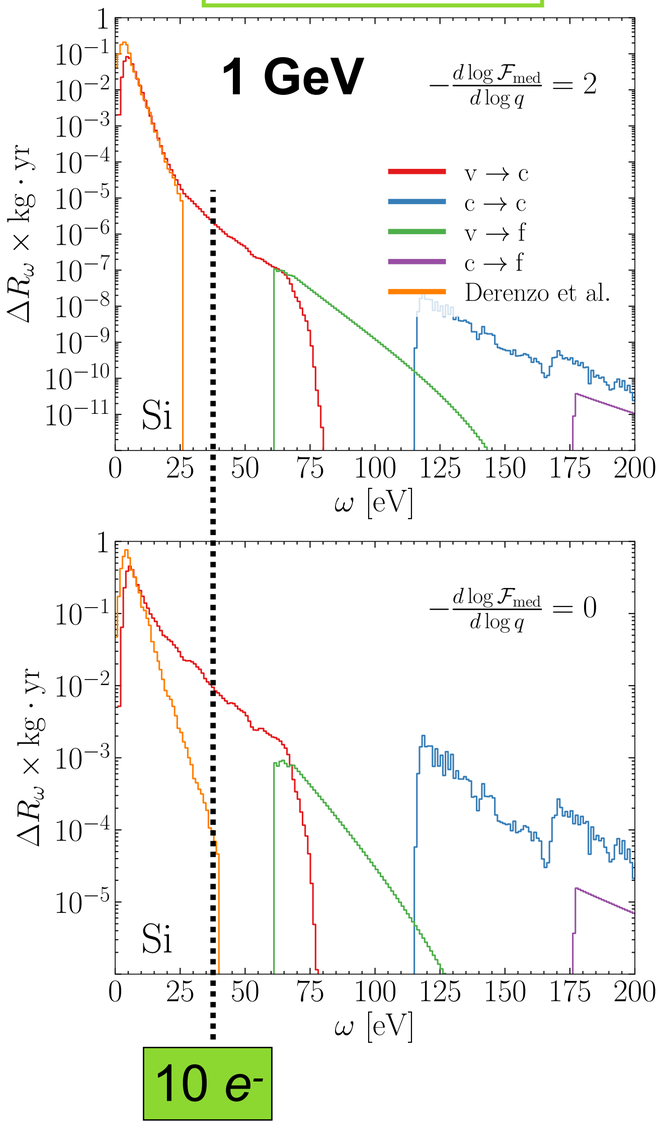
DM-e scattering

- Electrons are a lighter target and *ER visible as ionization*.
- Electrons bound with some momentum; there is a region of phase-space where the electron carries most of the WIMP kinetic energy.





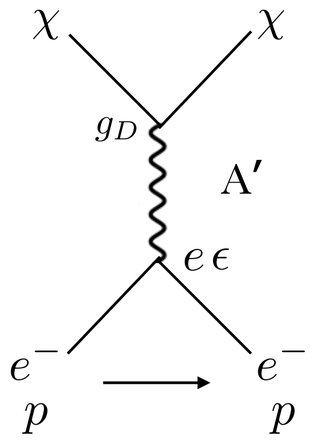
PRD104(2021)095015



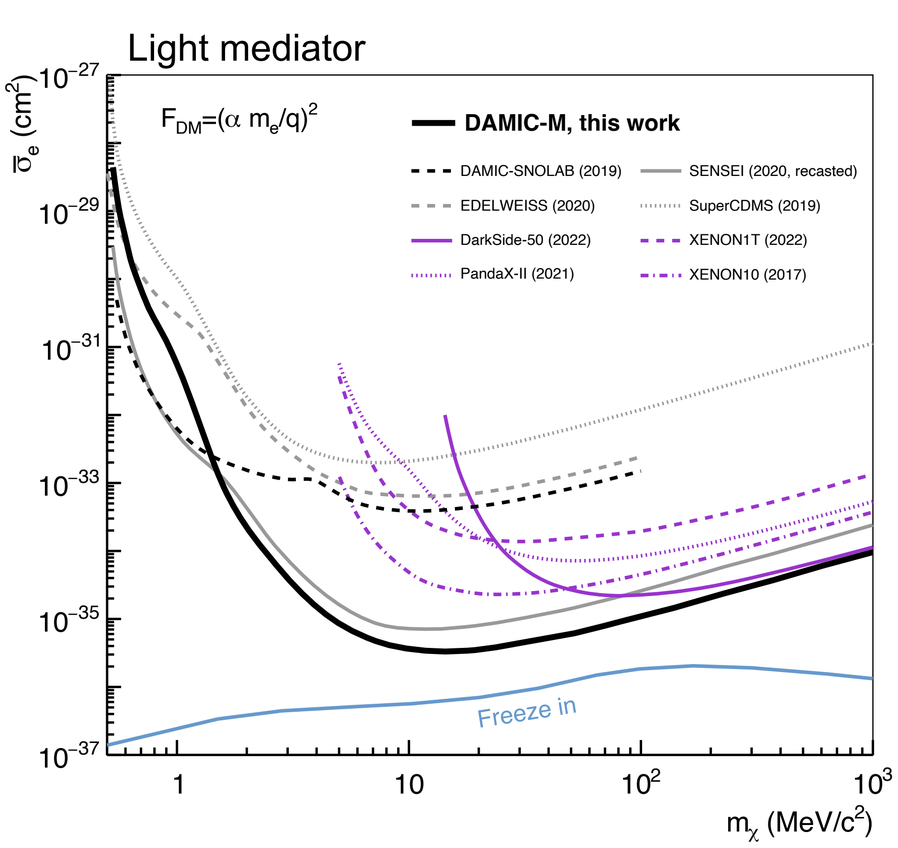
10 e^-

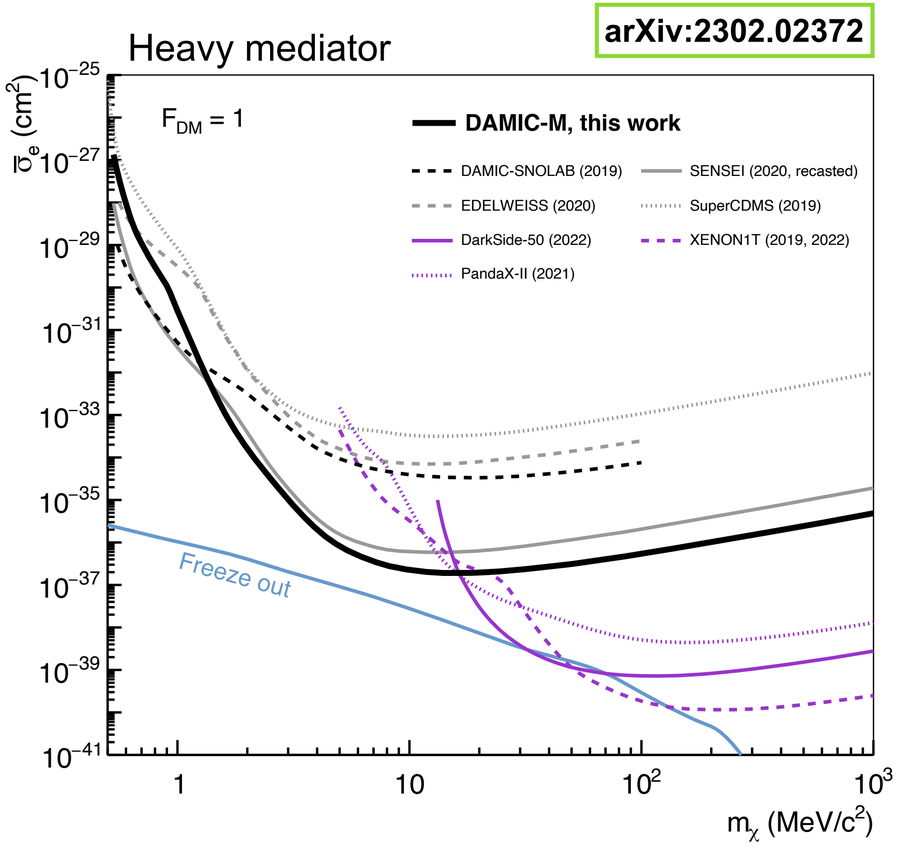
- Momentum distributions in some targets better “kinematically matched” to the DM than others.
- Phase-space ‘penalty,’ no coherent enhancement and probing DM-e interaction cross-section.

DM-e exclusion limits



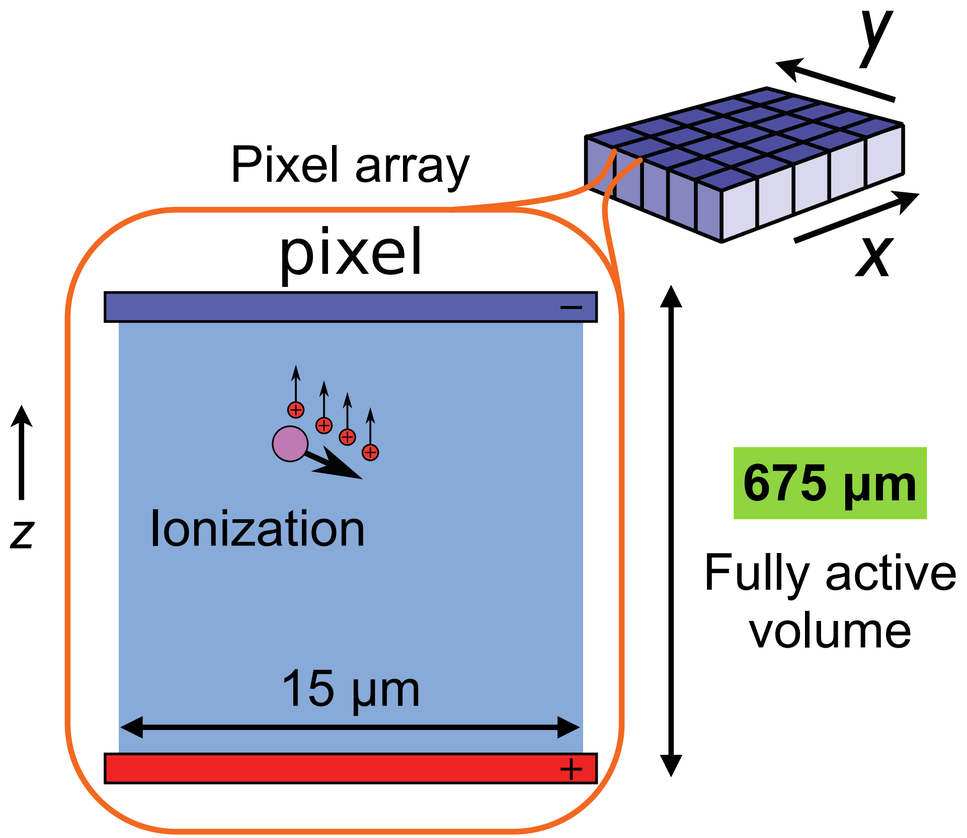
- ER searches allow us to probe DM masses as small as ~**MeV**!



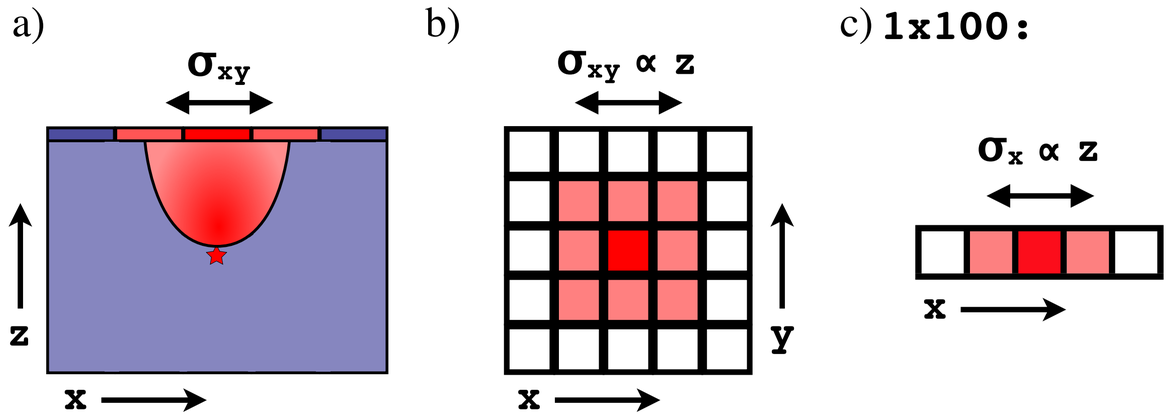


- **DAMIC-M has world-leading exclusion limits for sub-GeV hidden-sector DM!**

Charge-coupled devices



Silicon band-gap: 1.2 eV.
Mean energy for 1 e-h pair: 3.8 eV.



- Depth (z) reconstructed from distribution of charge on pixel array.
- Device is “exposed,” collecting charge until user commands readout.
- Readout can be slow: **very low noise.**
- Standard fabrication in semiconductor industry and easy cryogenics (~100 K).

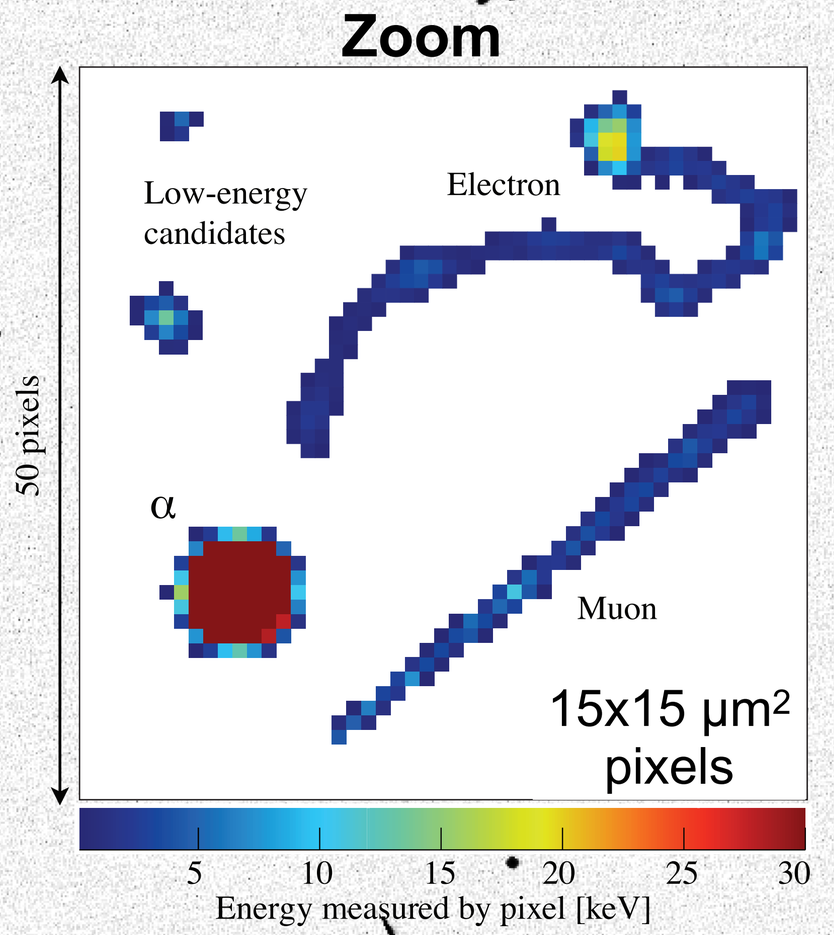
Sample CCD image (~15 min exposure) segment in the surface lab.

~1 cm

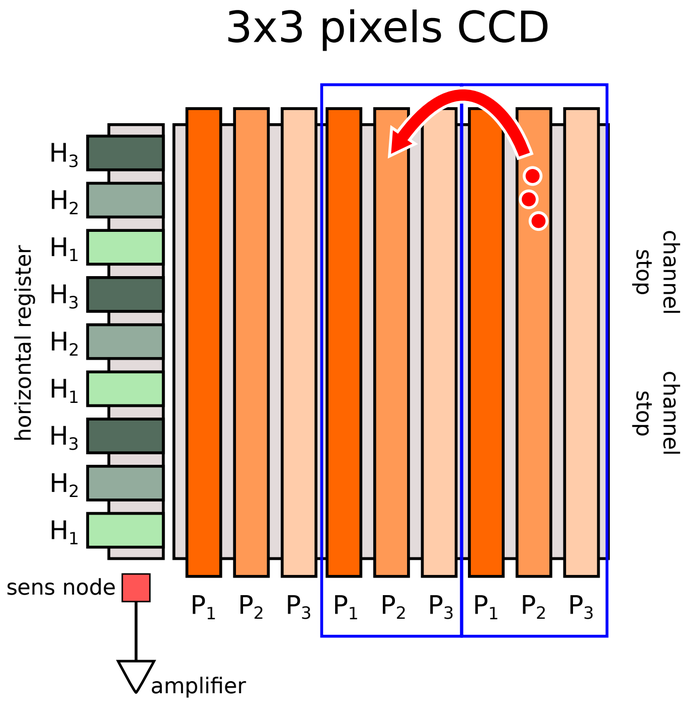
Cosmic muon

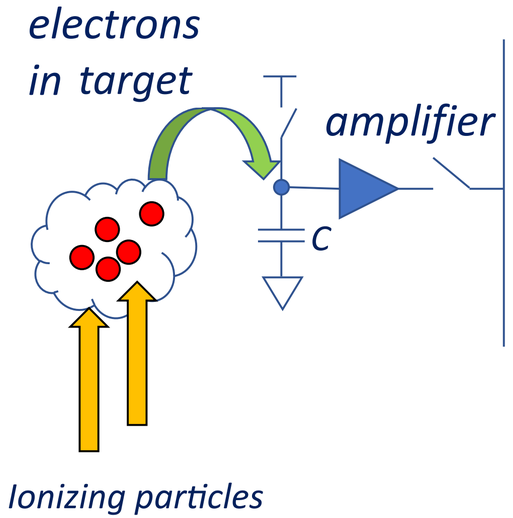
Point-like

β particle



Readout





$$\Delta V = \Delta Q / C$$

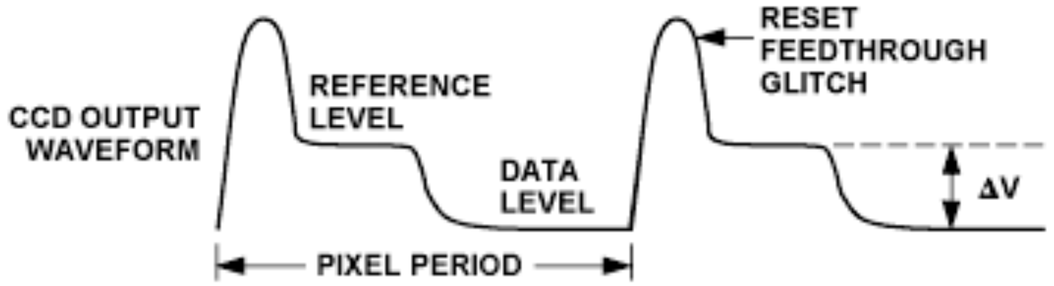
For ***C*** **~ 10 fF**: **ΔV/ΔQ ~ 16 μV/e⁻**

Signal that you can measure

Small capacitance with ***physically*** **small** components, e.g., $C \propto A/d$ ~ *linear scaling* for a parallel plate capacitor.

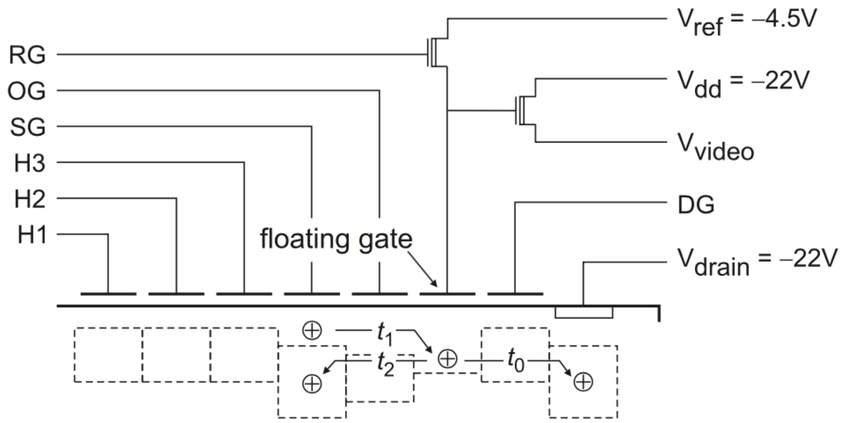
Correlated double sampling (CDS):

Readout strategy to efficiently filter "reset" and high frequency noise



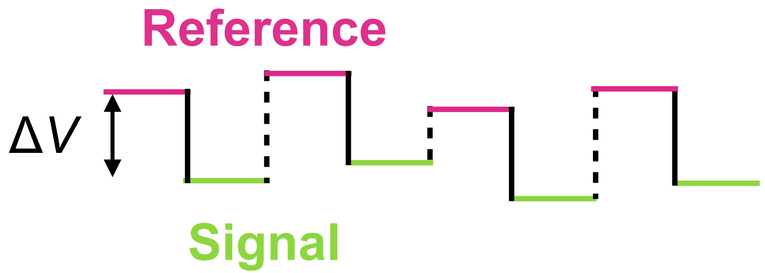
Skipper CCD

“Skipper” readout: Perform *N* uncorrelated measurements of the same pixel.

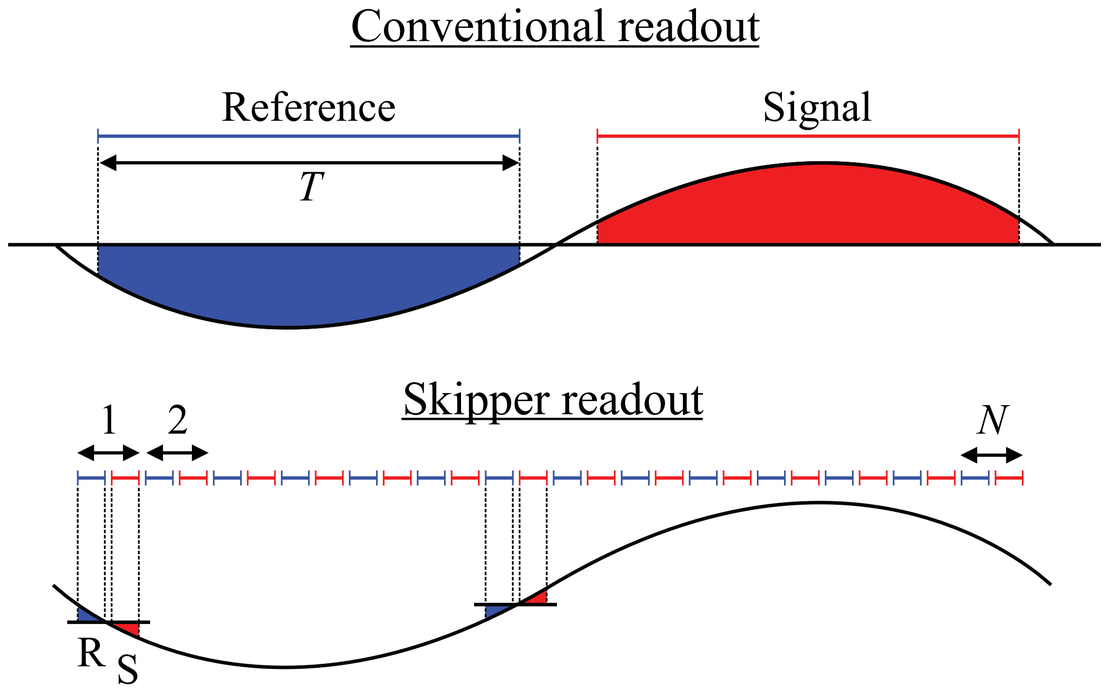


move charge back and forth

Measure Δ*V* *N* times:



Effect on low frequency noise:



Design by S. Holland at Berkeley Lab

Skipper CCD

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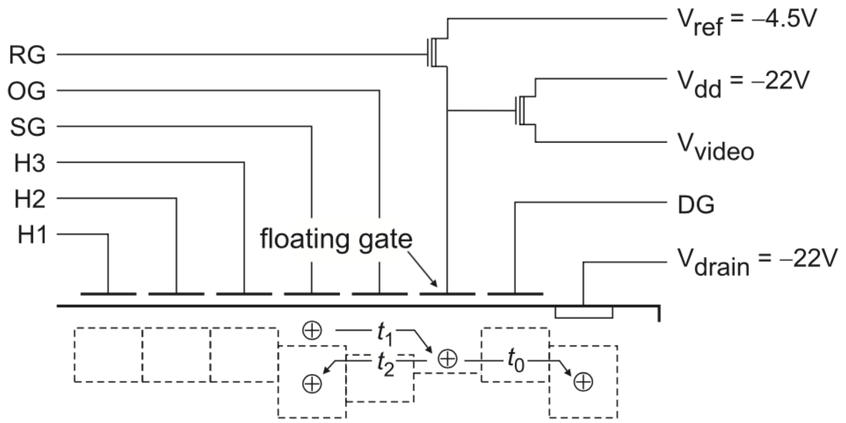
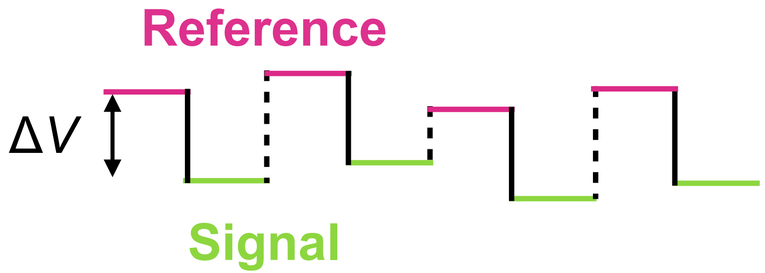
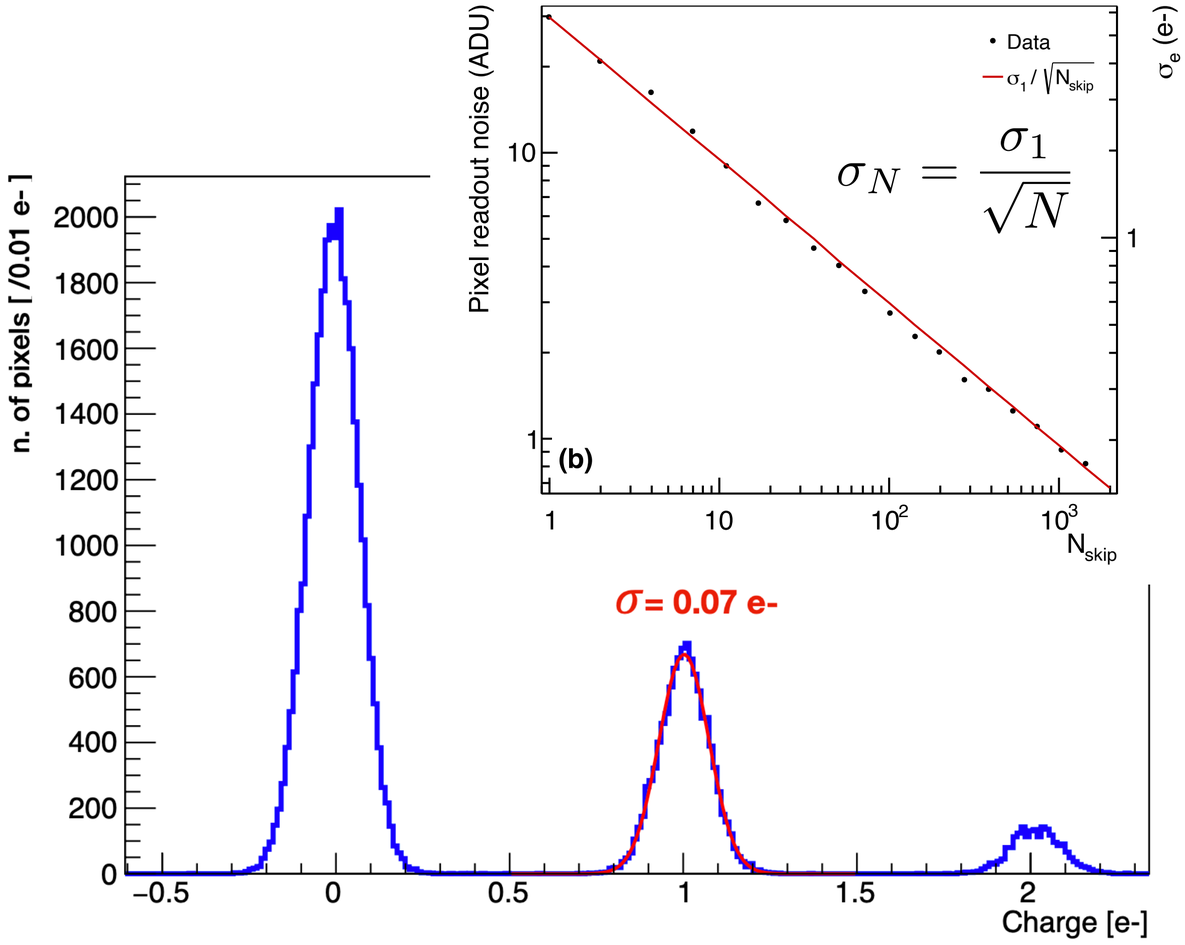


⟷ move charge back and forth

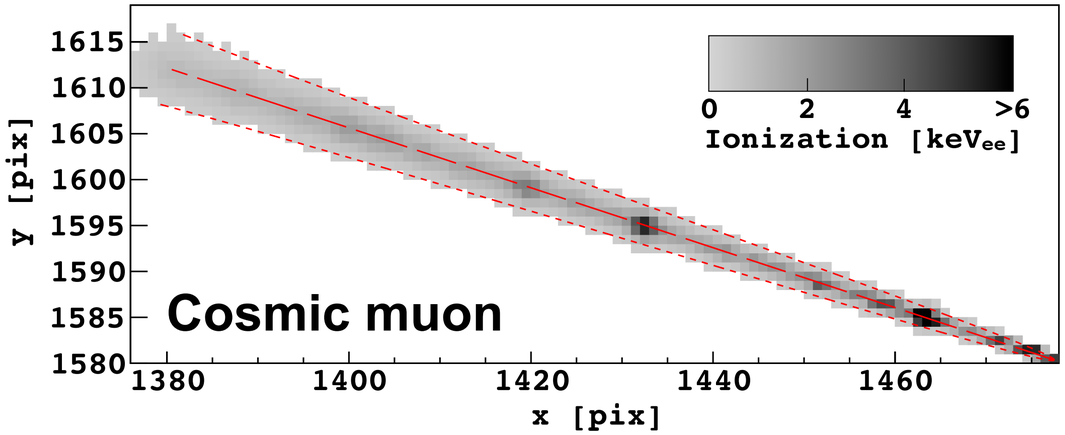
Measure Δ*V* *N* times:

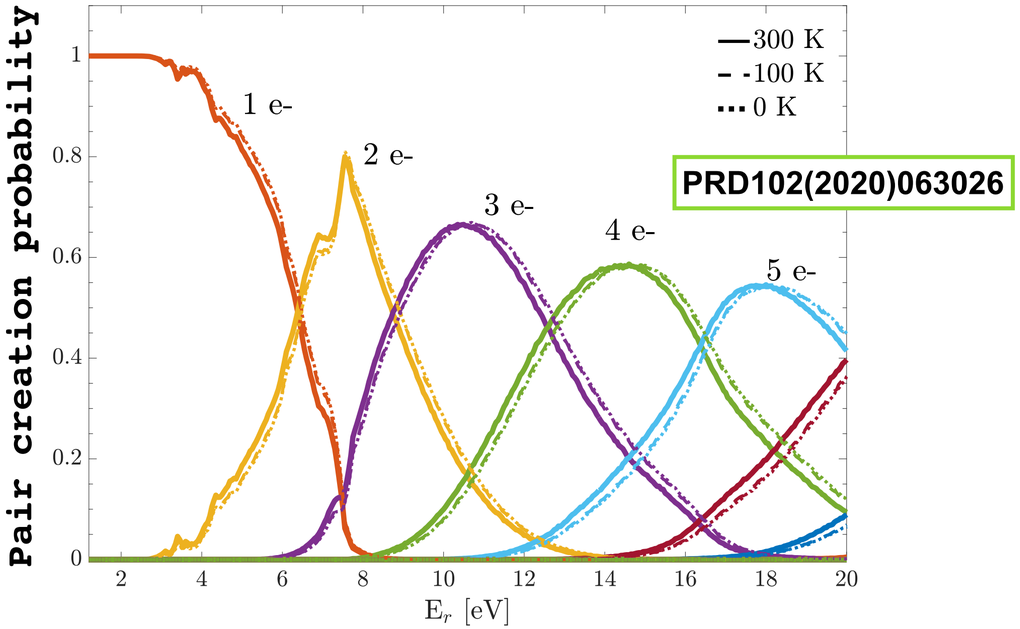


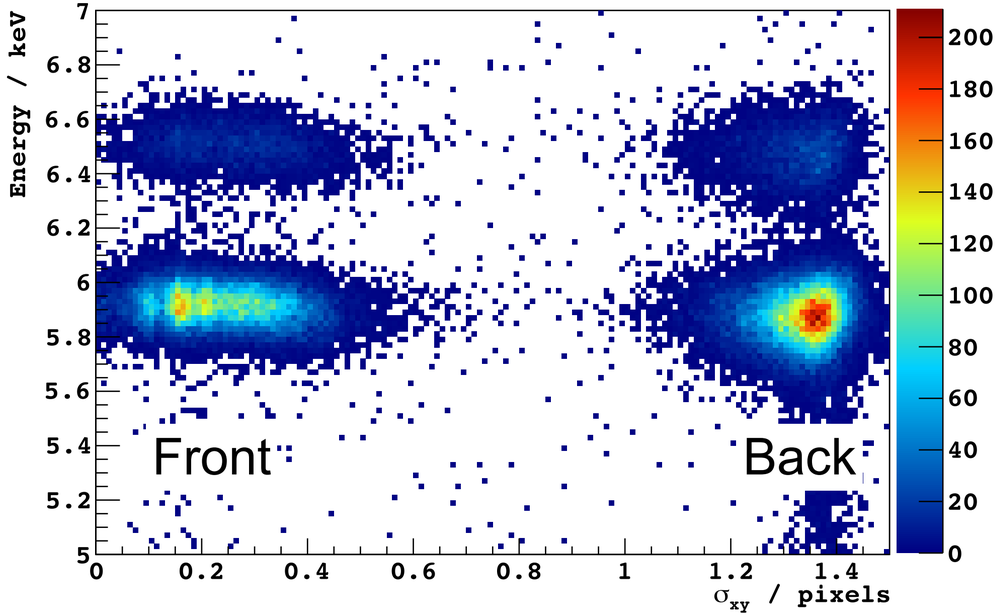


Characterization

- Extensive research program to characterize the response of CCDs: energy / *z* recon.
- Sources: optical photons, X rays, γ rays, neutron sources, etc.
- Detailed models, e.g., charge generation, diffusion and collection.

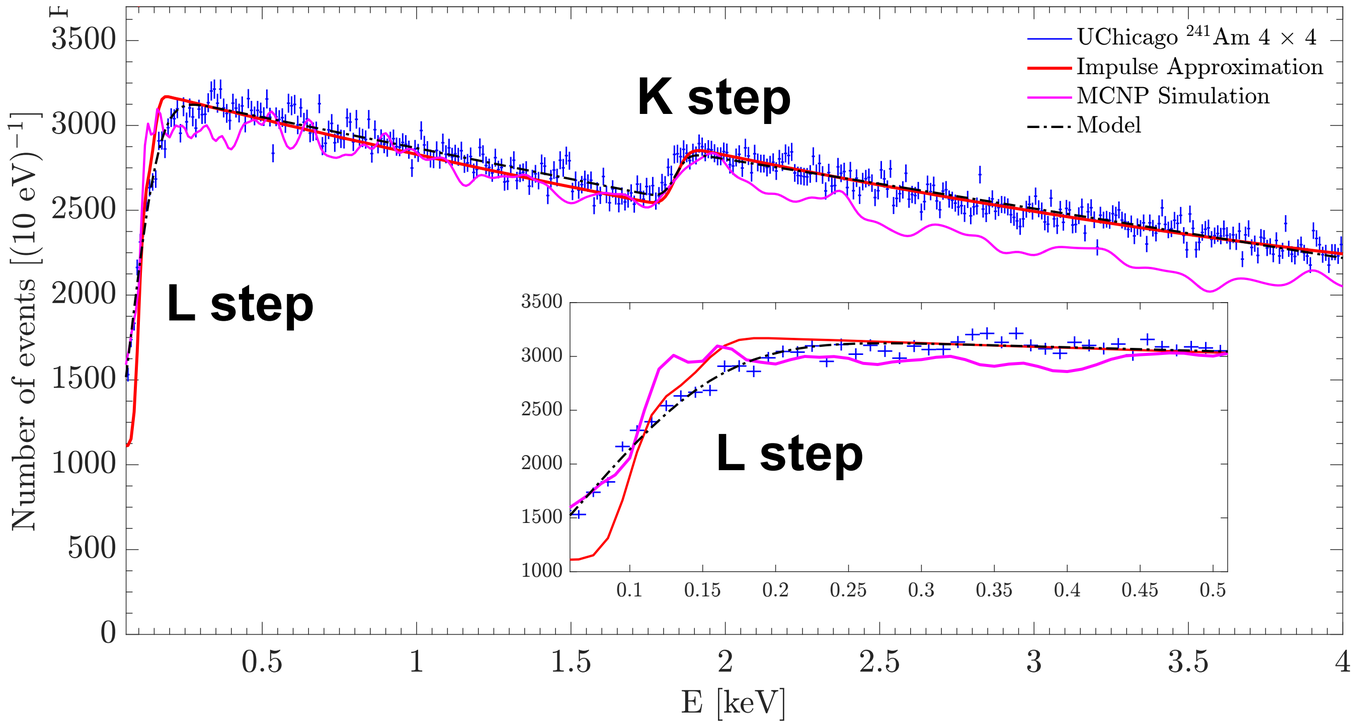






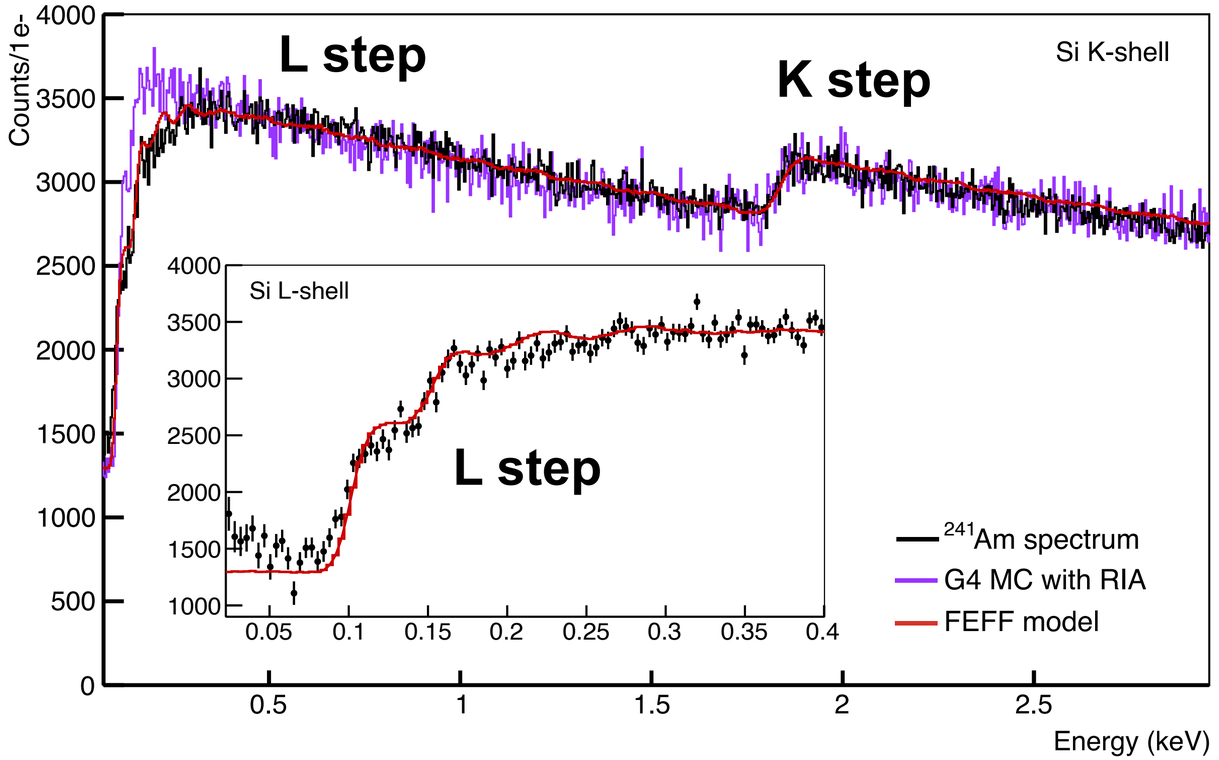
Example

- First measurement of the electronic-recoil spectrum from Compton scattering at low energies: PRD96(2017)042002
- Used original DAMIC CCDs with conventional readout. Threshold: 60 eV_{ee}.
- Observed steps at the binding energies of the atomic shells in silicon.
- Apparent softening of the L step at 100-150 eV.
- Incorrect detector response model or physics?



Example

- Precision measurement with a skipper CCD improved energy resolution and decreasing threshold to 23 eV_{ee}: **PRD106(2022)092001**
- Confirmed softening of the L step, observed structure in the L step.
- Detector response model is good!
- Softening reproduced with *FEFF* code, which performs full atomic physics treatment.
- Atomic effects must be considered to correctly describe electronic recoil spectra.

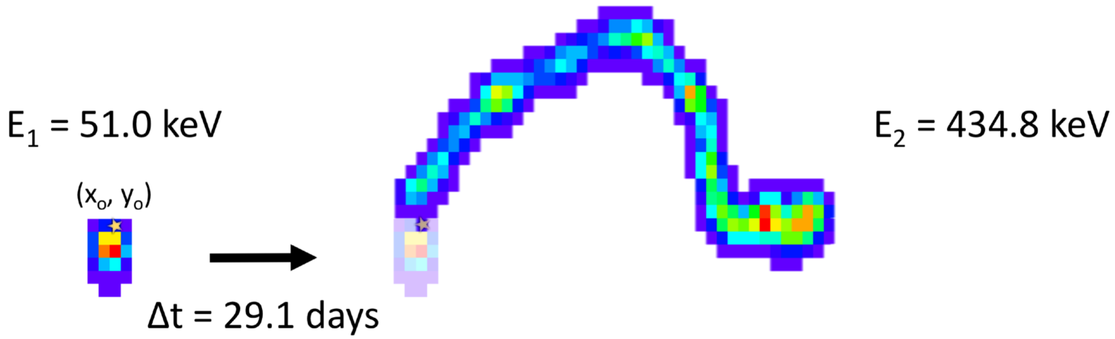


Radioactive backgrounds

- Particle classification (α, β, NR) by track topology (at high E>100 keV_{ee}).
- Spatial coincidence searches to identify decay sequences: JINST16(2021)P06019
  - **Cosmogenic ^{32}Si:** ^{32}Si ($T_{1/2}$= 150 y, β) ➔ ^{32}P ($T_{1/2}$= 14 days, β)

    140 ± 30 μBq / kg

  - Also upper limits on every β emitter in the U/Th chain.



- Measurement of the cosmogenic activation of ^{3}H in silicon by exposing a CCD to a neutron beam: PRD102(2020)102006

  112 ± 24 atoms / kg /day

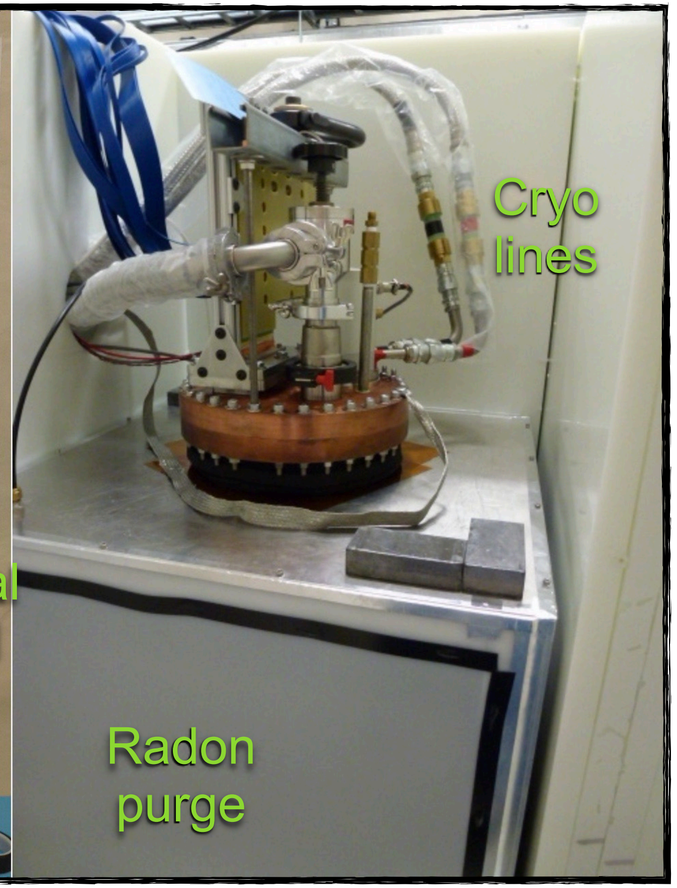
- Exhaustive radio-assay program: PRD105(2022)062003

DAMIC at SNOLAB

CCD Box

Cryostat insert

In shield

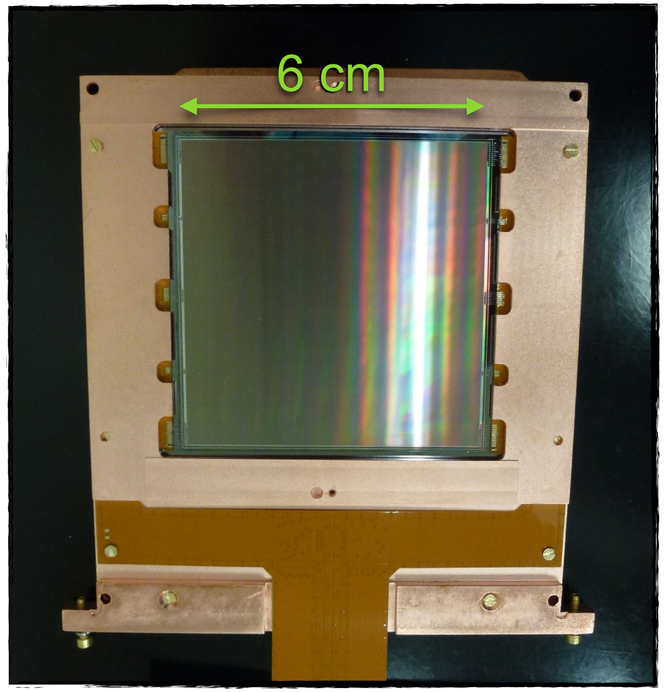


External shield

DAMIC at SNOLAB

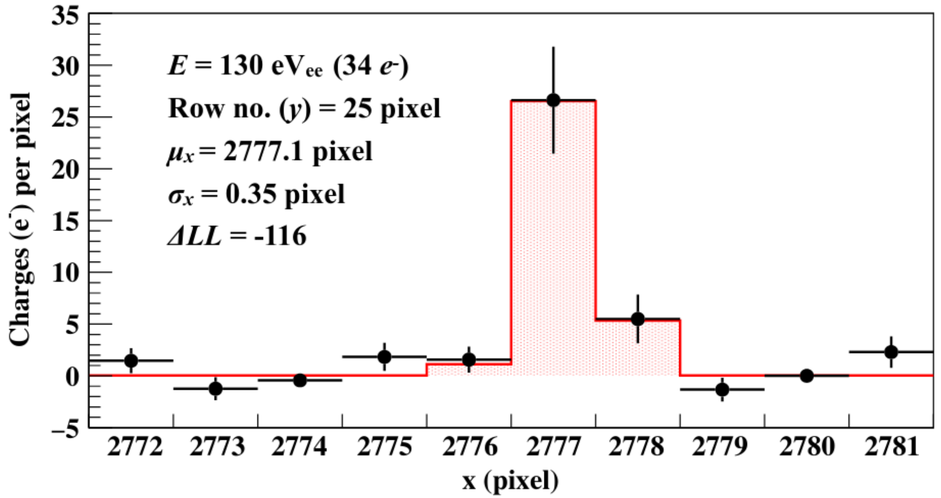
- First array of CCDs operated underground for a DM search. Several iterations from 2012 to 2019.
- 7 CCDs (6.0 g, 16 Mpix) cooled to 140 K.
- Total (bulk) background rate: ~10 (5) d.r.u.
- Low pixel noise 1.6 e^- with conventional readout.
- Extremely low leakage current: 2 x 10^{-22} A cm^{-2}.
- DM-e^- scattering results: PRL123(2019)181802
- "WIMP search" with 11 kg-y exposure:

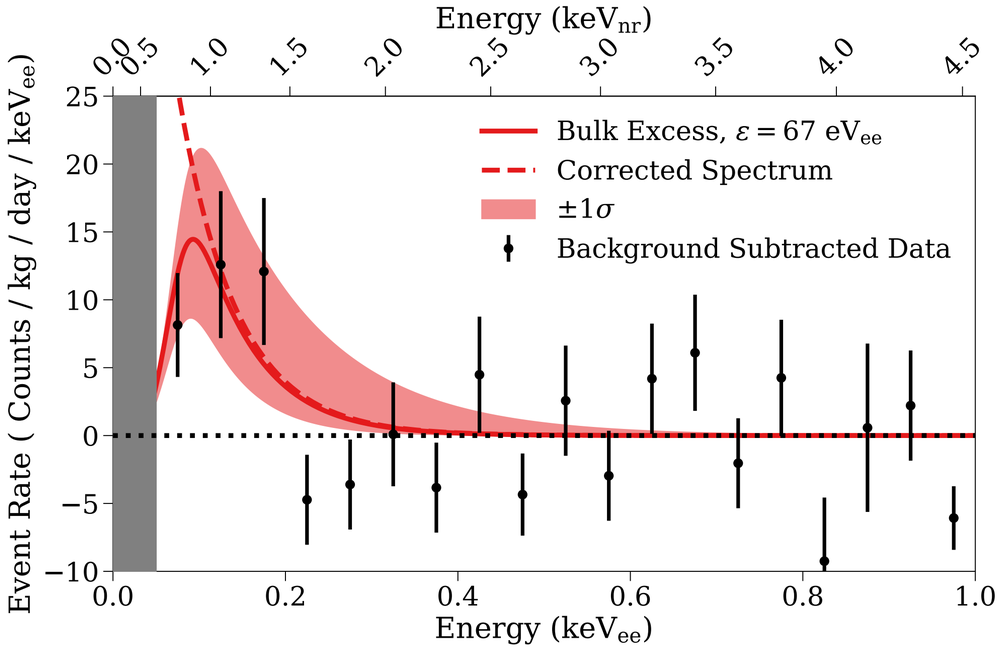
  Exclusion limit: PRL125(2020)241803 **Full details:** PRD105(2022)062003



DAMIC Excess

- Constructed full background based on extensive knowledge about radioactive background sources and detector response.
- Performed a fit to the data ionization events with the background model in (E, σ_x) parameter space.
- Excess of 17.1 ± 7.6 events with 50-200 eV_{ee}, 3.7 σ significance.
- If not addressed, limiting background for next generation experiments.

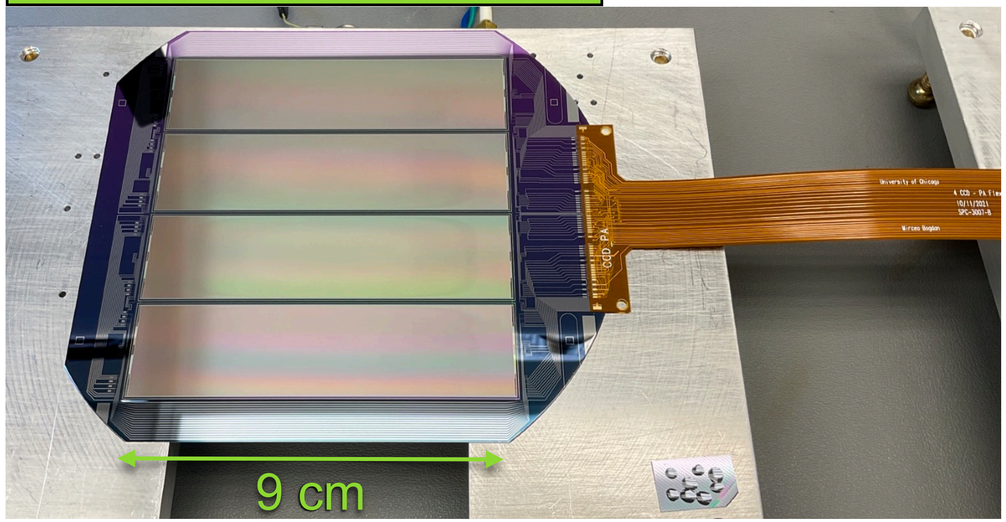


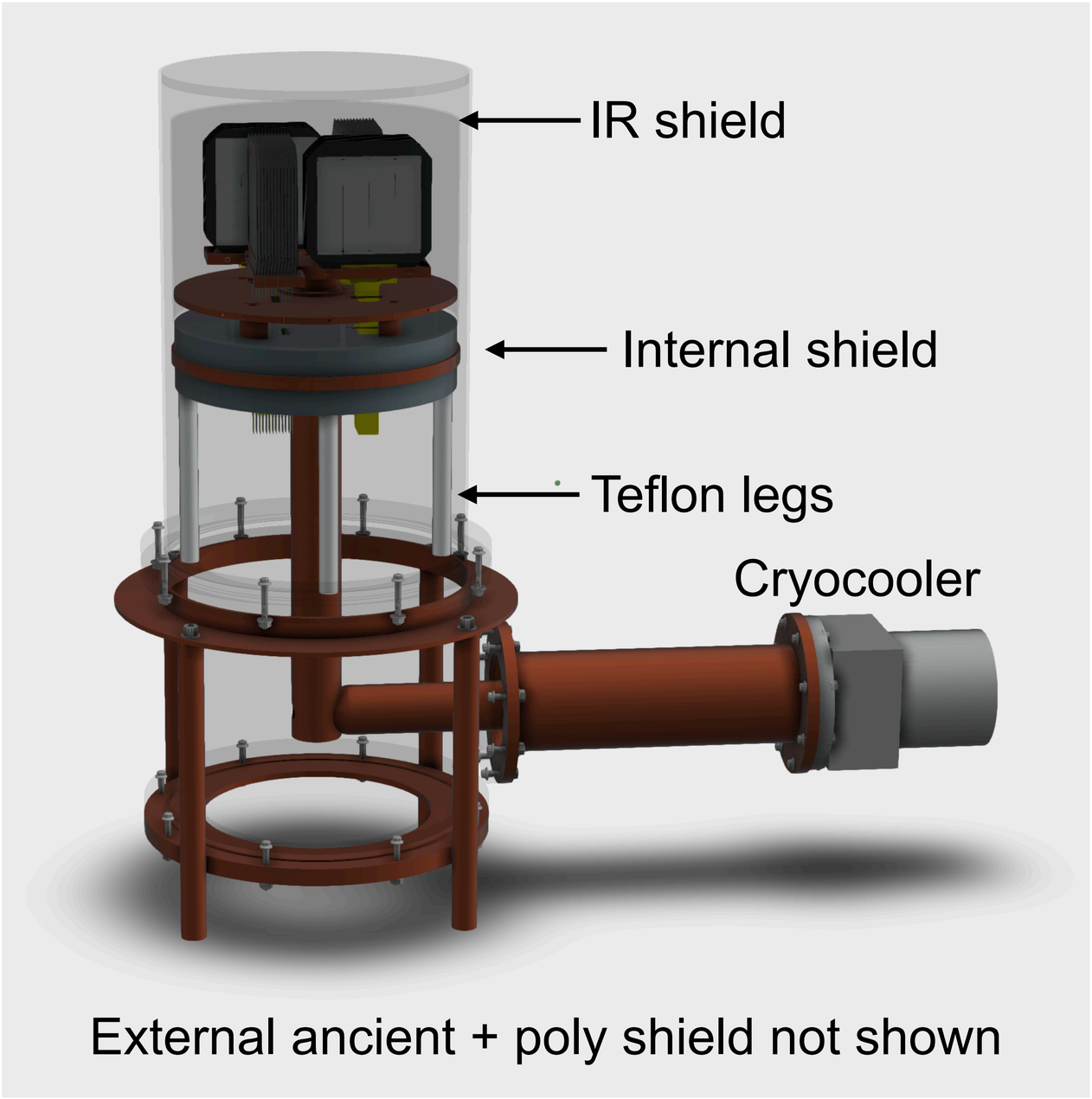


DAMIC-M

- 52 CCD modules in LSM (France) for kg-year target exposures.
- Skipper readout for 2 or 3 e- threshold.
- Background reduction to a fraction of d.r.u. (events per kg-day).
- Under construction. Commissioned by end of 2024. Science run to start in 2025!

DAMIC-M module at UW:



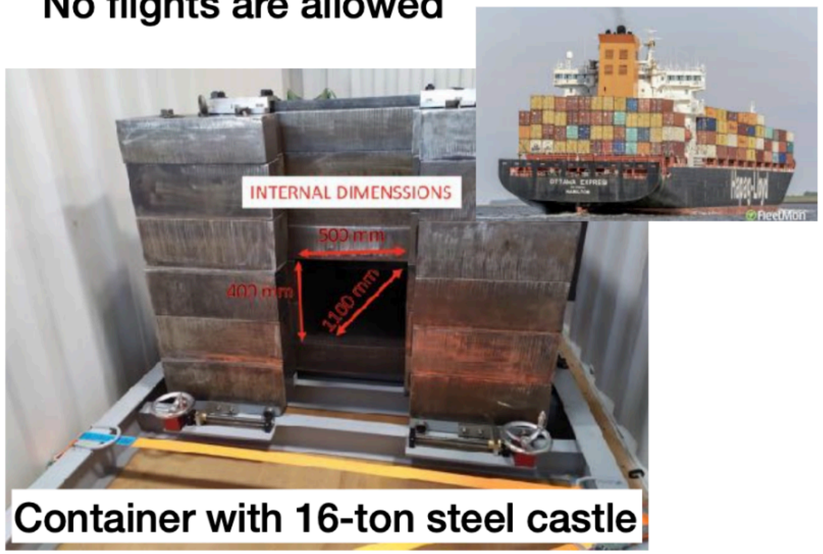


Background mitigation

CCD fab protocols:

Transport in a custom-made shielding container (activation reduced to ~5%)

No flights are allowed



Container with 16-ton steel castle

Storage at SNOLAB

Storage at Boulby

Shielding box for the CCD production

Expedite processing
Radon limited environments

Other activities:

- Low-radioactivity flex cables with PNNL and QFlex.

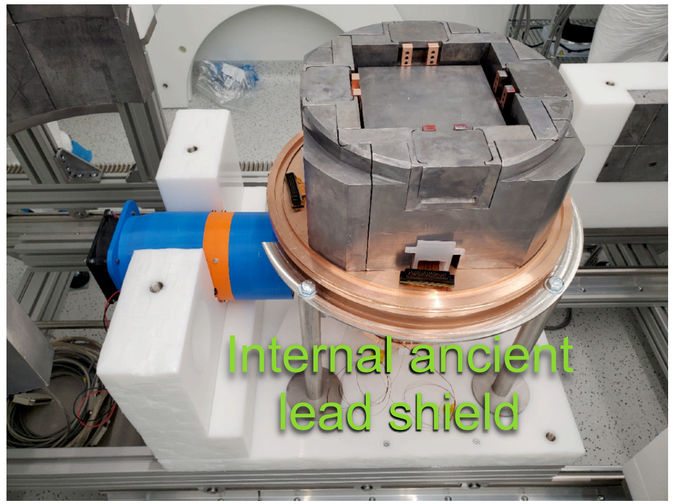
NIMA959(2020)163573

- Electroforming copper underground at LS Canfranc.
- Full Geant4 simulation.

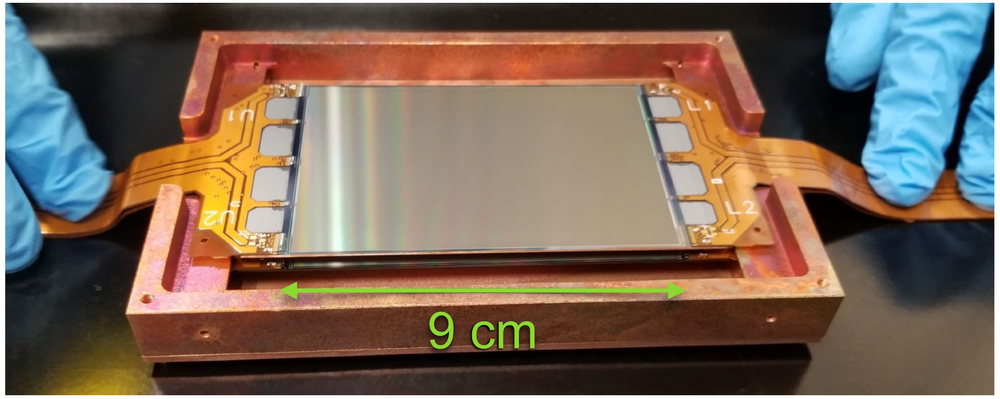
Current is exposure count is 14 days, versus the typical 1.5 years at this stage.

Prototype detectors

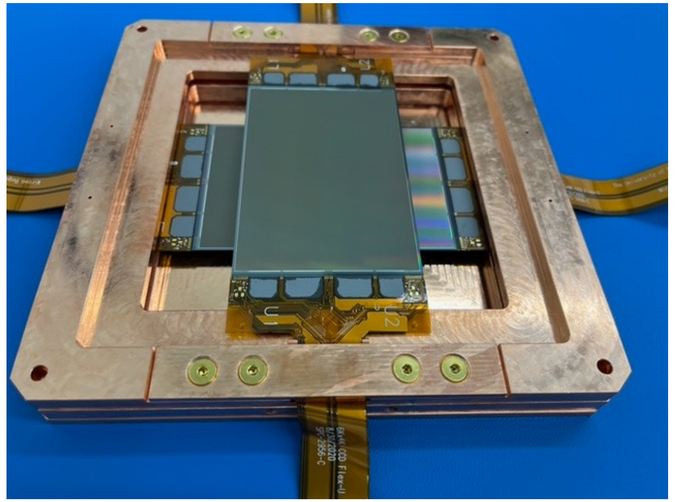
- Four 24 Mpixel DAMIC-M prototype skipper CCDs.
- Two deployed in DAMIC at SNOLAB, two in the LBC.
- Low Background Chamber (LBC) test setup for DAMIC-M at LSM for performance and background studies.
- Single-e^- resolution, 2 x 10^{-3} e^-/pix/day, 10 d.r.u., 18 g.
- Understand DAMIC excess, **DM search results**.



SNOLAB:

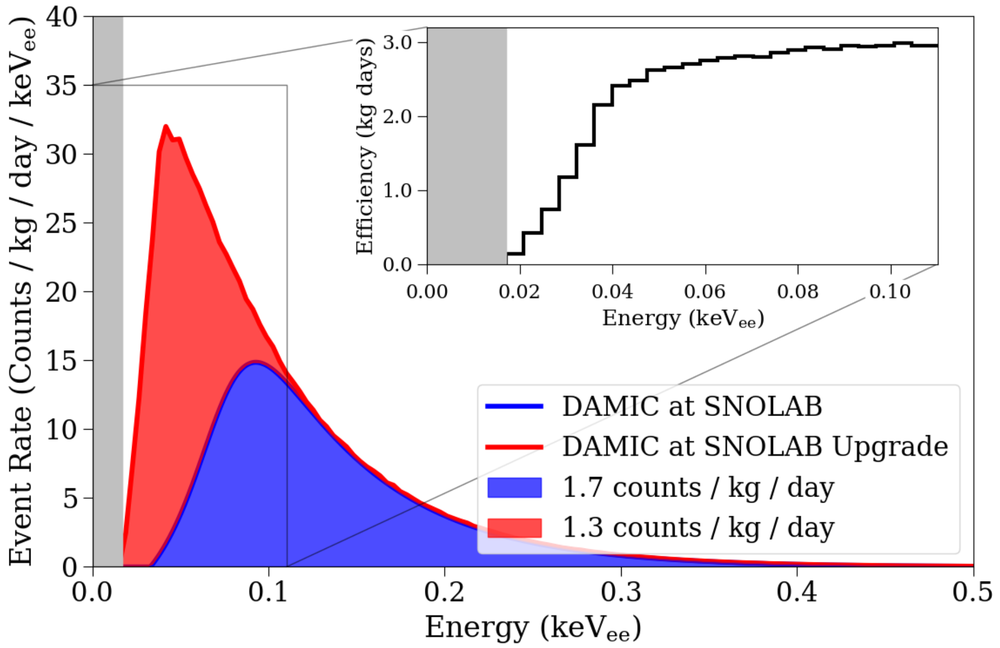


LBC:



Skippers at SNOLAB

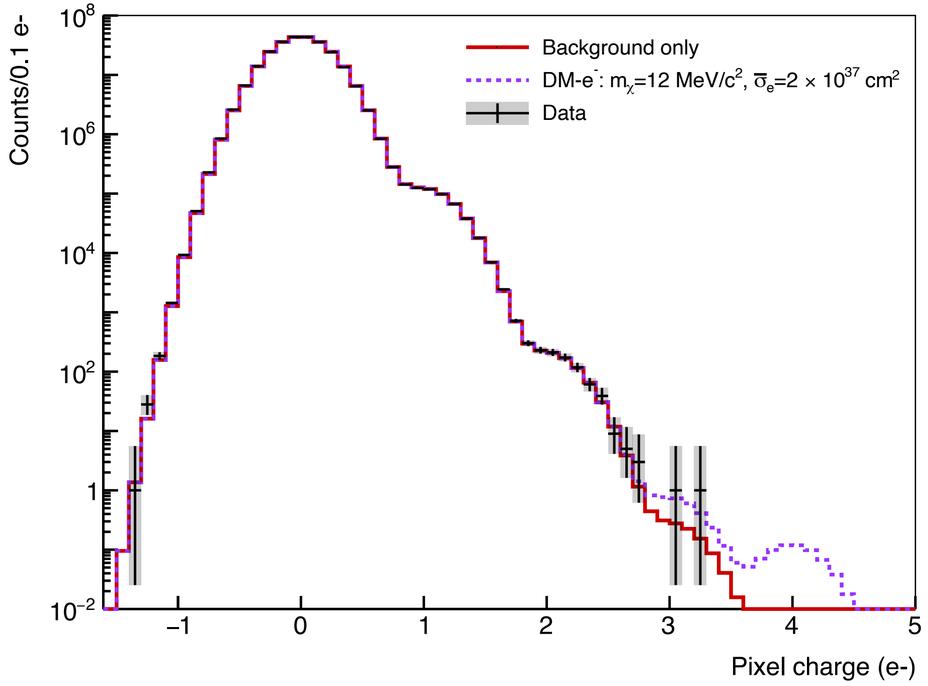
- Science run started in **March 2022**.
- Already analyzed 4.8 kg-day exposure.
- Same background rate as before:
  11.2 ± 0.8 d.r.u. total and 5.2 ± 0.6 d.r.u. bulk, **10x** lower noise.
- Blind energy region below 0.4 keV_{ee}.
- We expect ~10 excess events (over ~few background) with better energy + depth reconstruction.



Unblinded on February 2nd! We will release results soon…

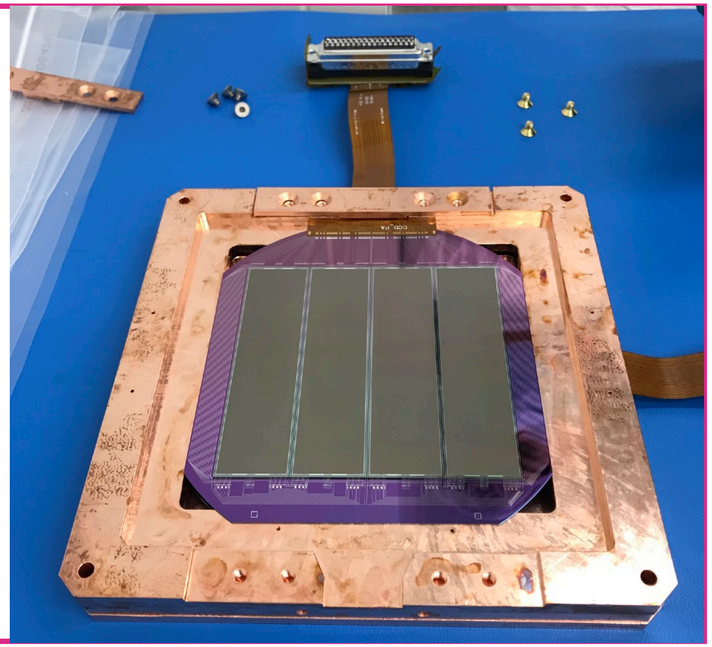
LBC at LSM

- Extensive studies of the CCD performance to select clean CCD region.
- Fit to the distribution of pixels with 0 to 7 e^- in 85 g-day of data with a Poisson background model + signal (including detector response).
- Pixel distribution consistent with background-only hypothesis.

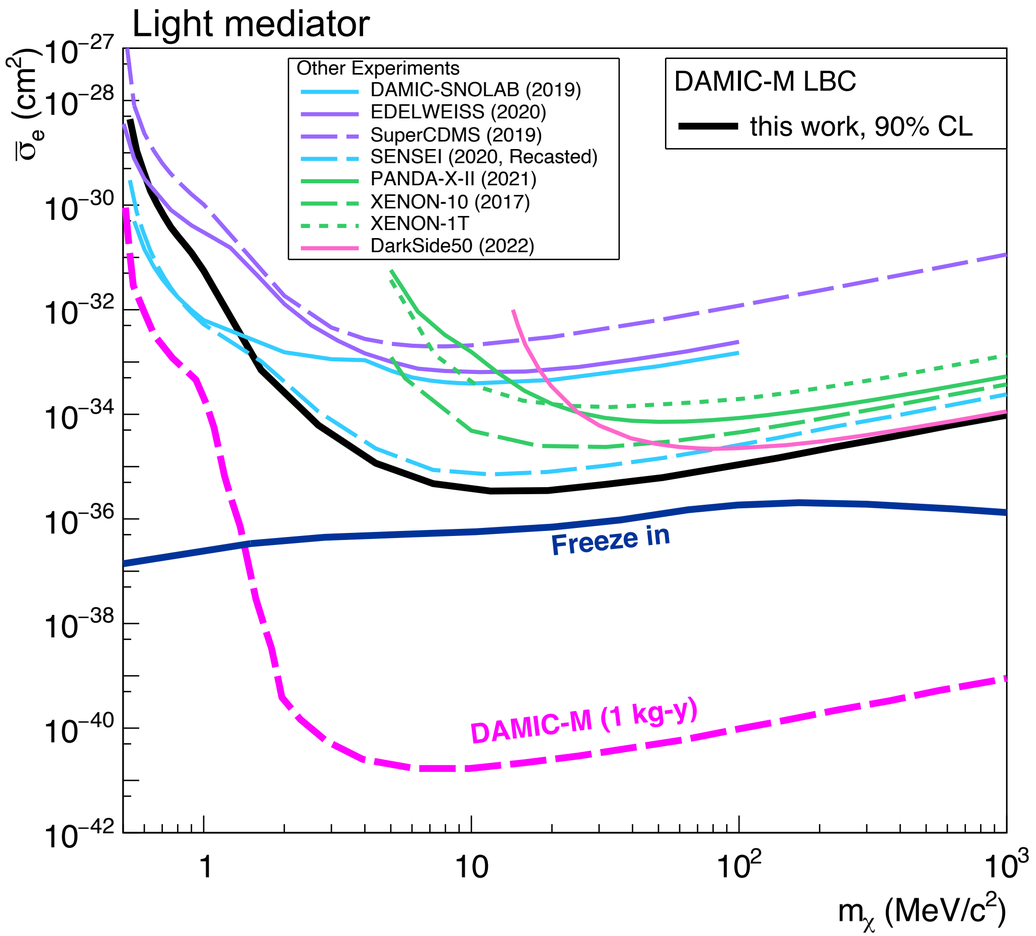


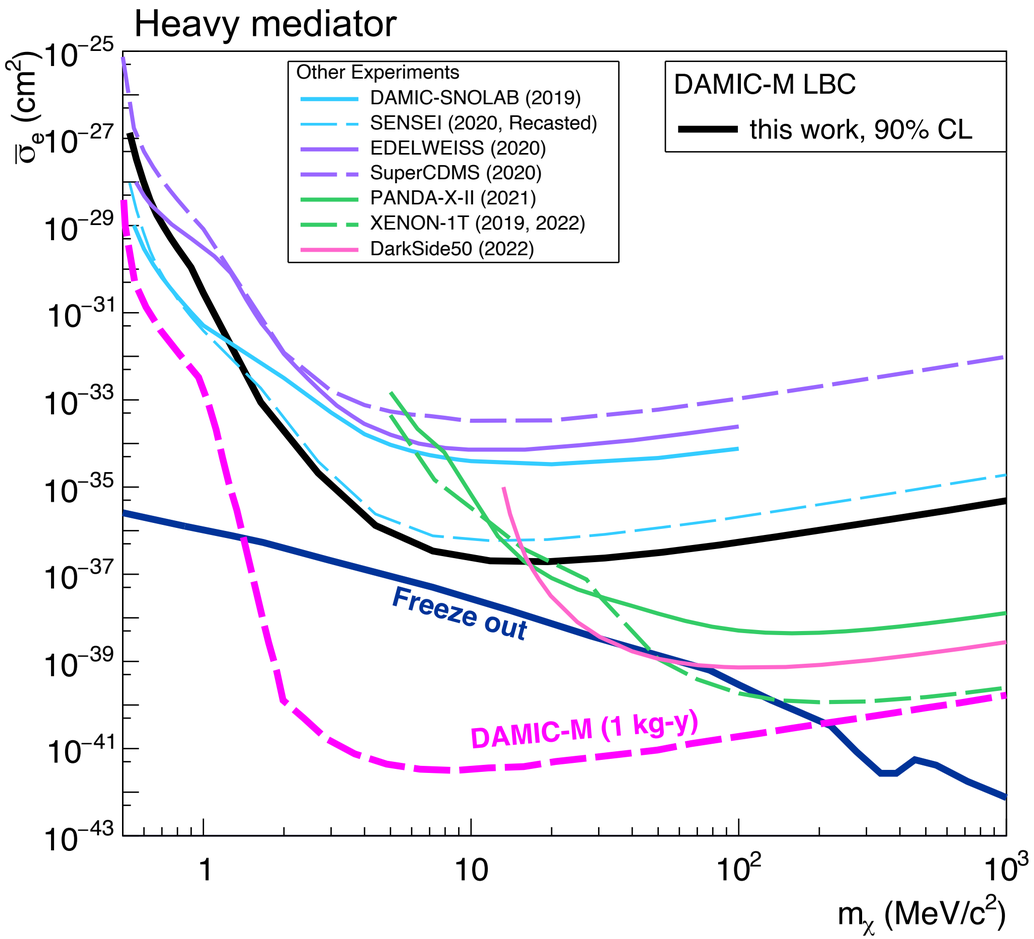
Activities continue!

DAMIC-M prototype modules installed in LBC in Feb 2023



Outlook





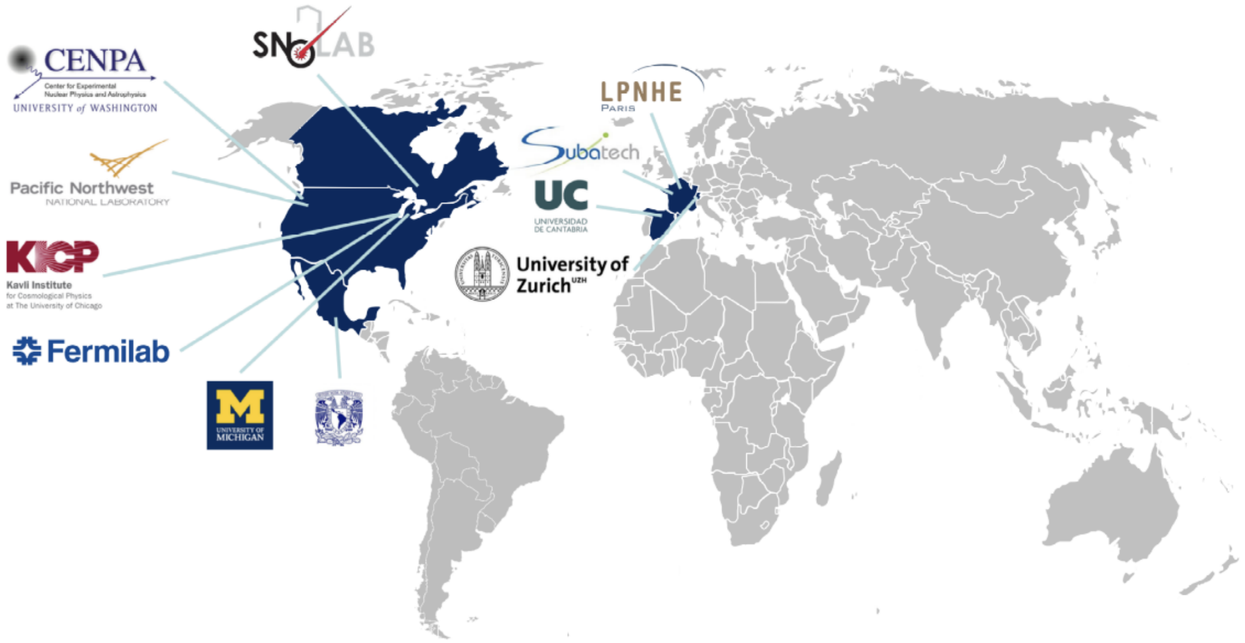
Note: NR result may have comparable sensitivity to Si HV detectors of SuperCDMS SNOLAB

Conclusions

- Electronic recoil searches allow us to search for sub-GeV DM.
- Require sensitivity to only a few charges ionized in the target.
- DAMIC demonstrated CCD arrays can be operated as DM detectors deep underground.
- DAMIC-M skipper CCDs demonstrated few-electron (eV-scale) energy thresholds.
- DAMIC-M's LBC placed world-leading exclusion limits on sub-GeV DM!
- DAMIC-M will improve sensitivity by orders of magnitude in the coming years.

Thank you!

DAMIC Collaboration



The DAMIC-M Collaboration