Searching for Light Dark Matter with DAMIC & DAMIC-M

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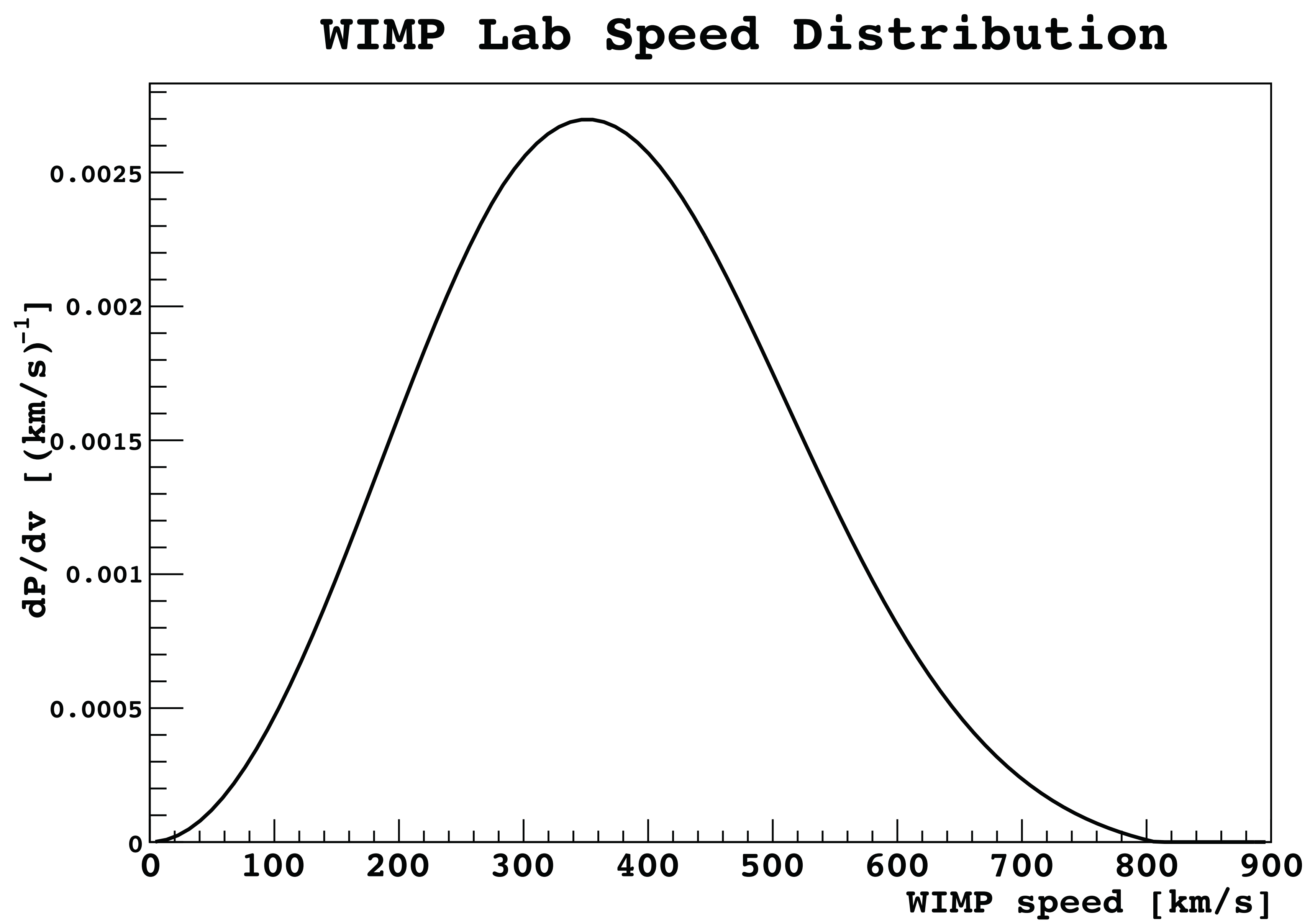
Outline

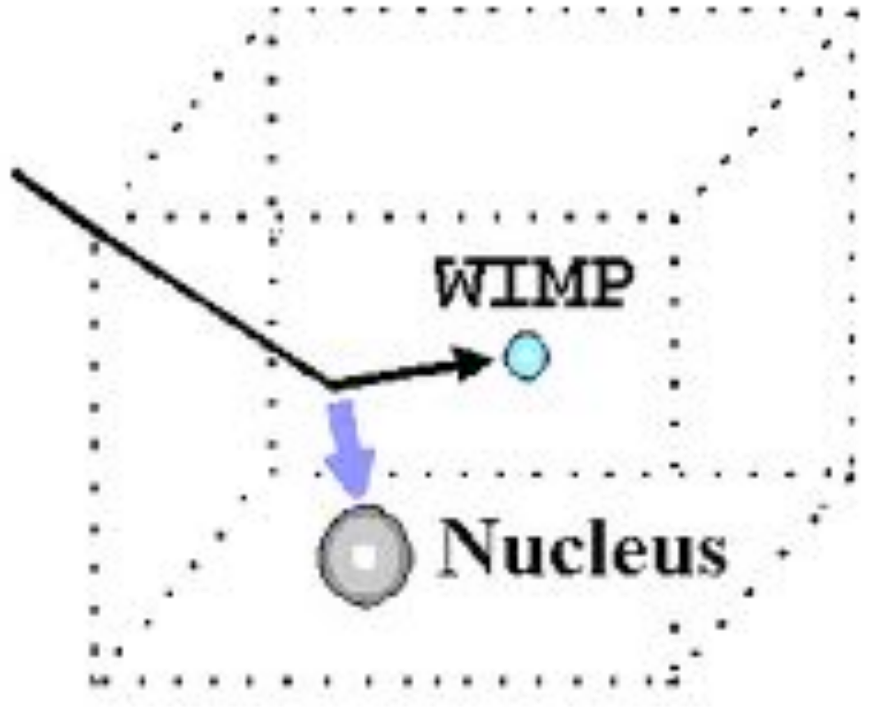
- Dark matter (DM) direct-detection signal.
- Electronic recoils to search for light DM.
- Charge-coupled devices (CCDs) fundamentals and performance.
- DAMIC at SNOLAB and the DAMIC excess.
- DAMIC-M and the Low Background Chamber (LBC).
- Outlook.

Dark matter signal

- Local density is ~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:



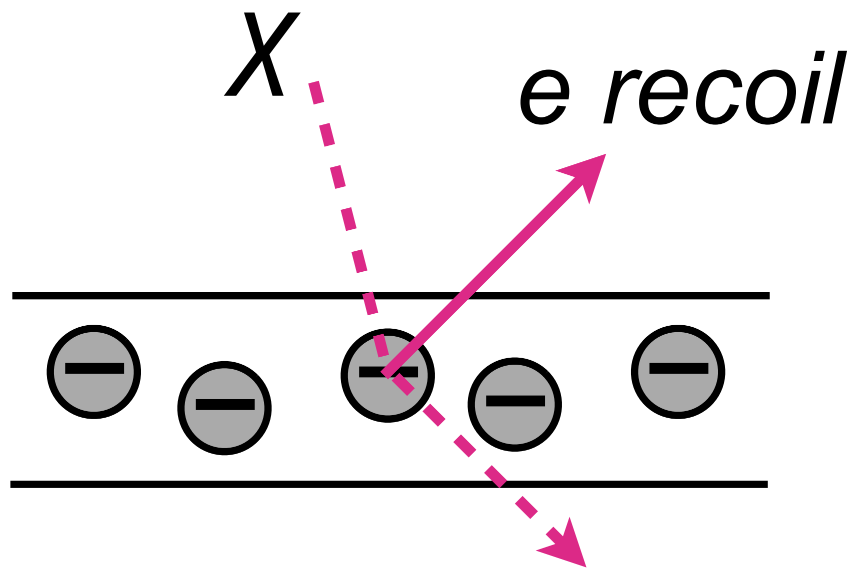
Coherent enhancement: $\sigma_N \propto A^2$

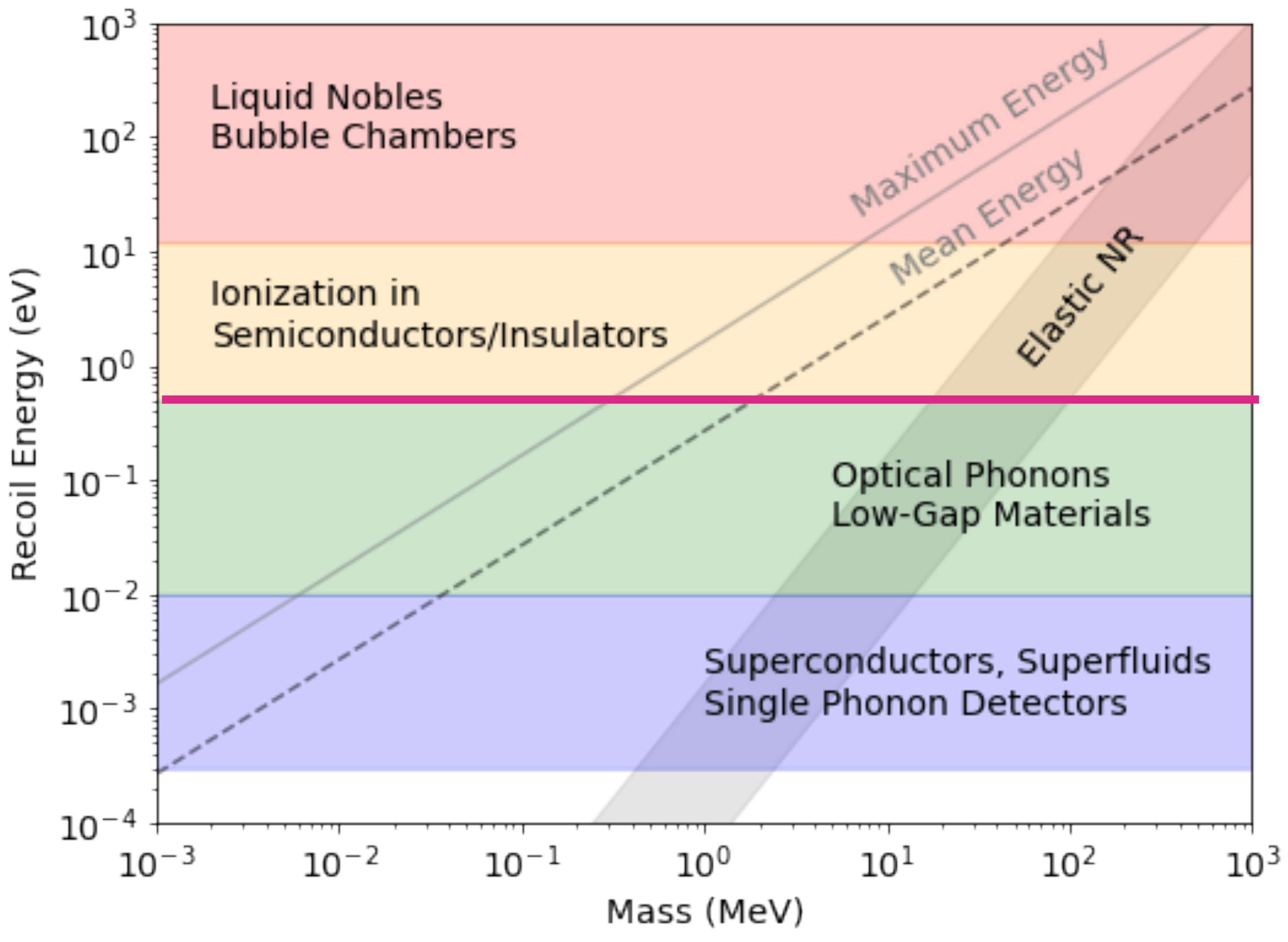
For low-mass WIMP: $M_T \gg M_\chi$

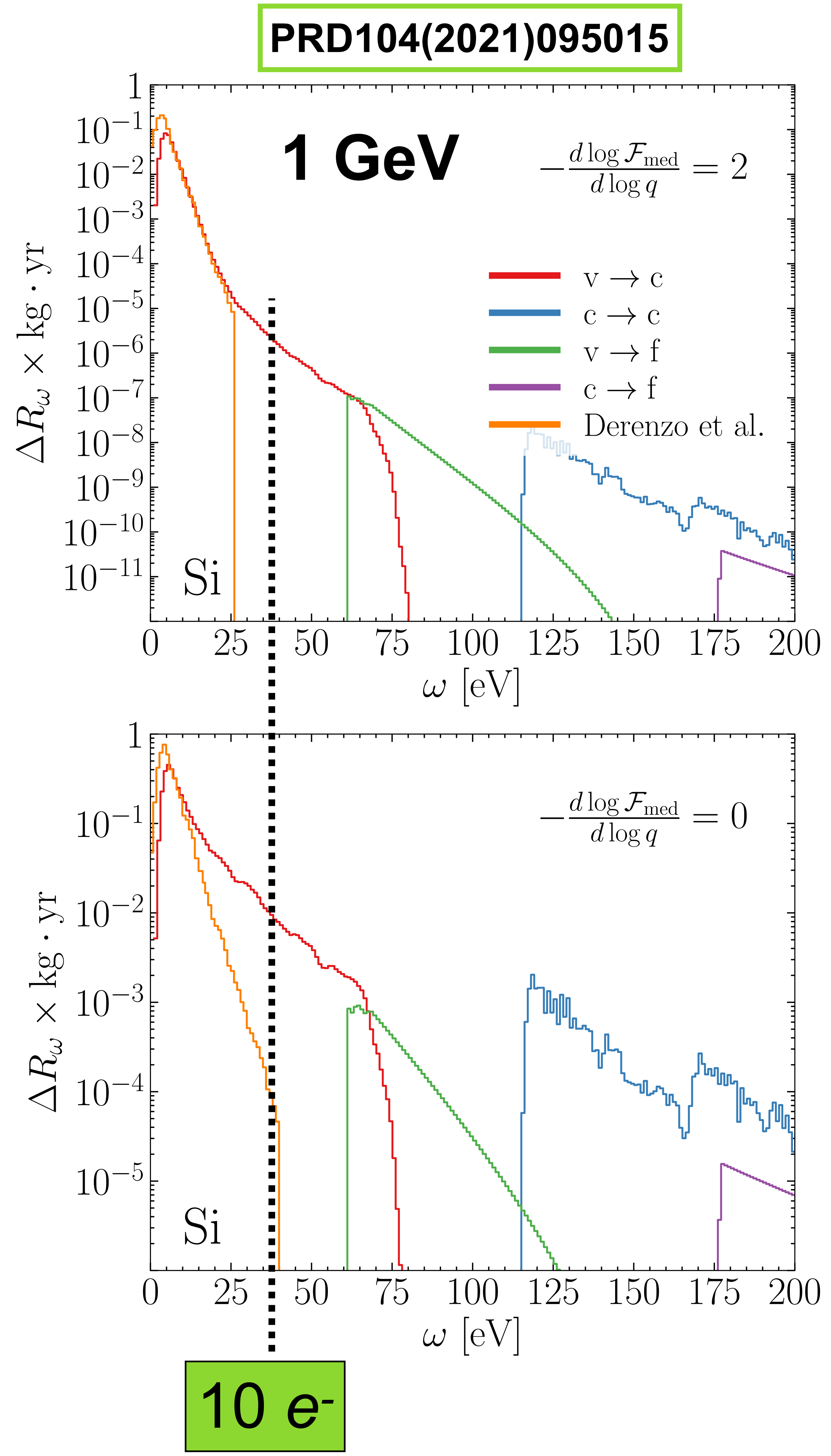
$$E_T < 4\frac{M_\chi}{M_T}E_\chi$$

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.



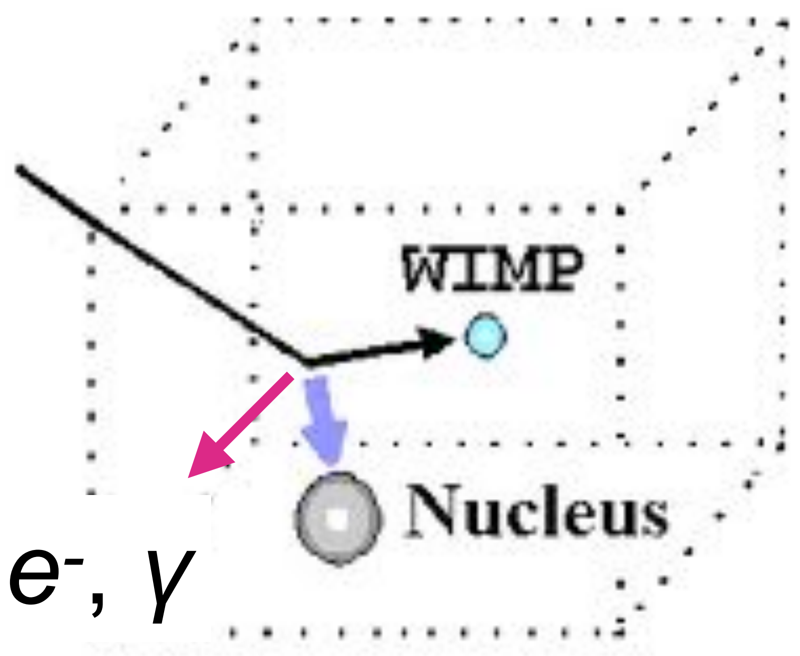




- Momentum distributions in some targets better “kinematically matched” to the DM than others.
- Phase-space ‘penalty,’ no coherent enhancement and probing DM-e interaction cross-section.

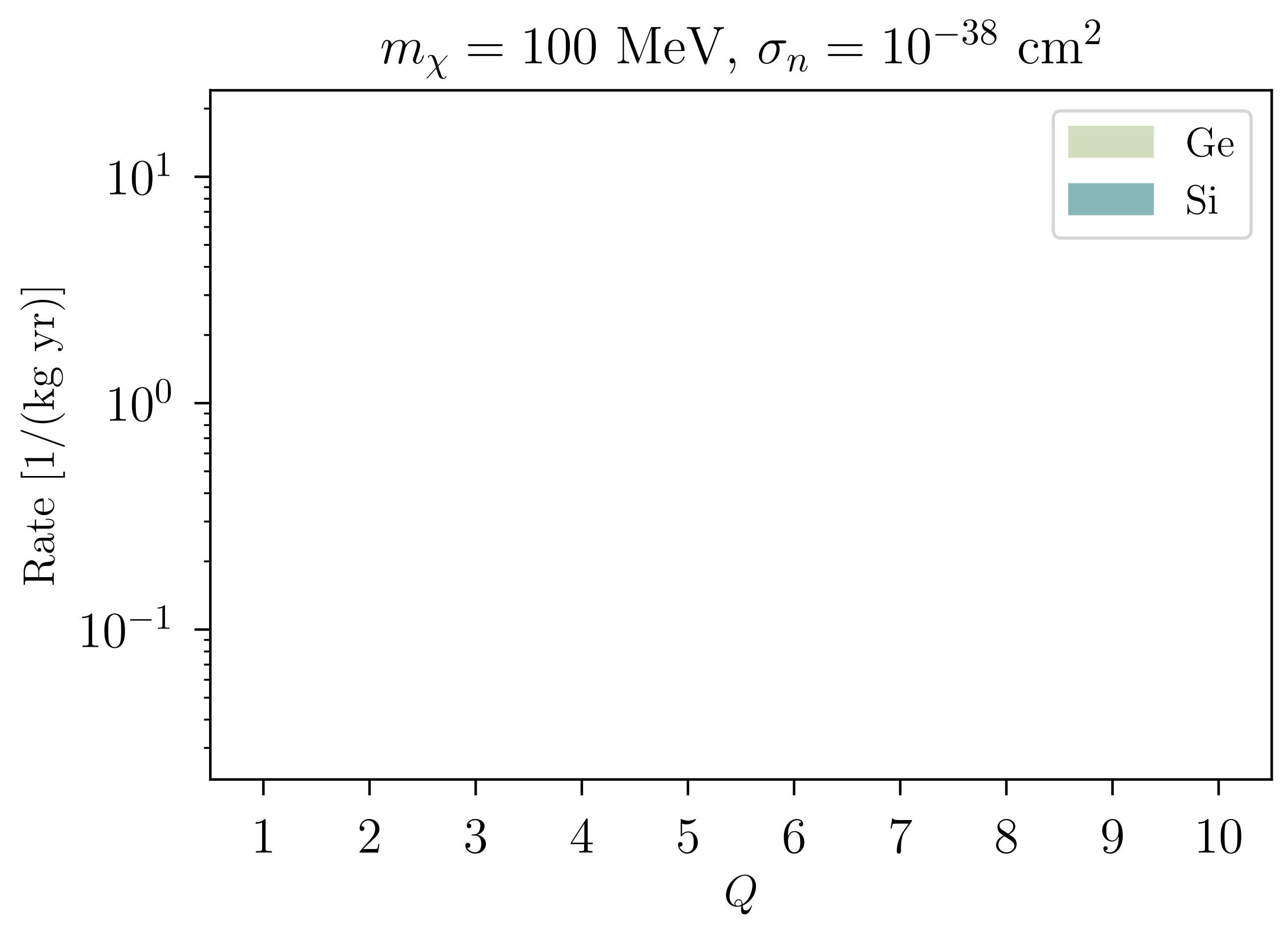
Other e-recoils

Three-body final state:



- An additional e^- or γ in the final state.
- Migdal effect (atomic e^-) or Bremsstrahlung (γ).
- *E* and *p* can be conserved even when e^- or γ take most of the WIMP kinetic energy.
- Probability of e^- or γ emission $<10^{-6}$. Rare.
- Never observed for recoils with keV energies. Uncalibrated.

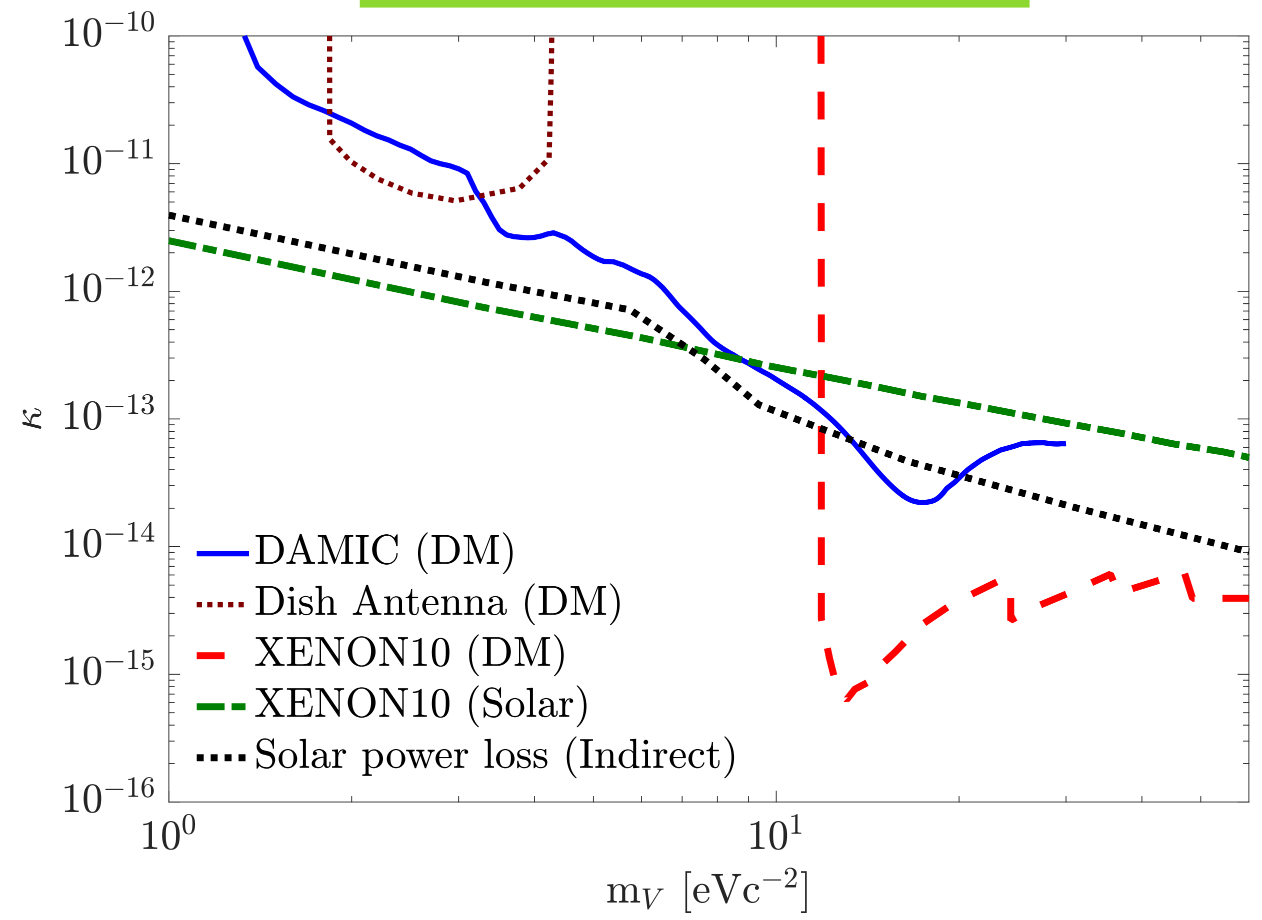
PRL127(2021)081805



Bosonic DM absorption:

- DM particle is a boson that couples to the electron, e.g., a “dark” or “hidden” photon.
- DM is absorbed by the target electron and its rest energy released as electronic recoil K.E.

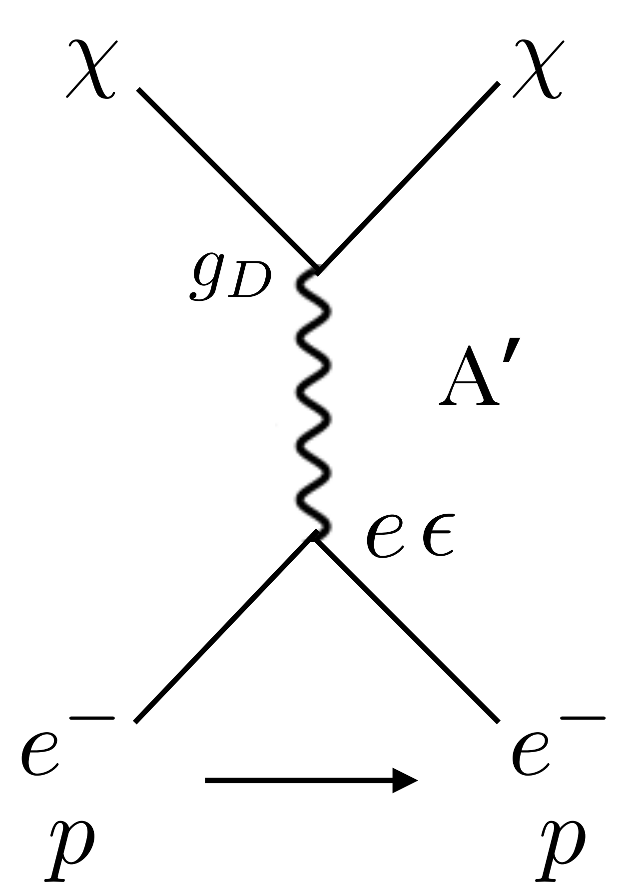
PRL118(2017)141803

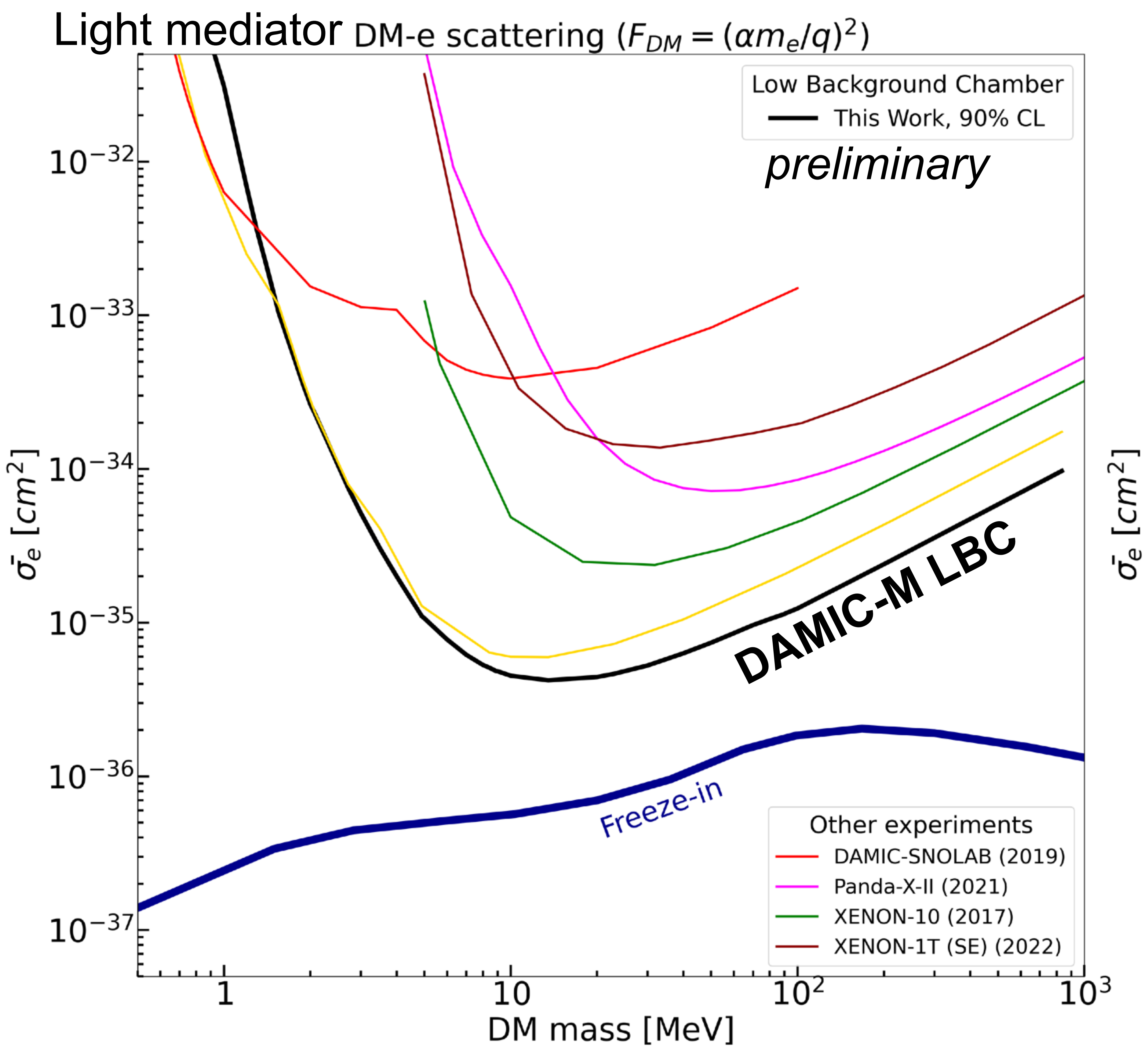


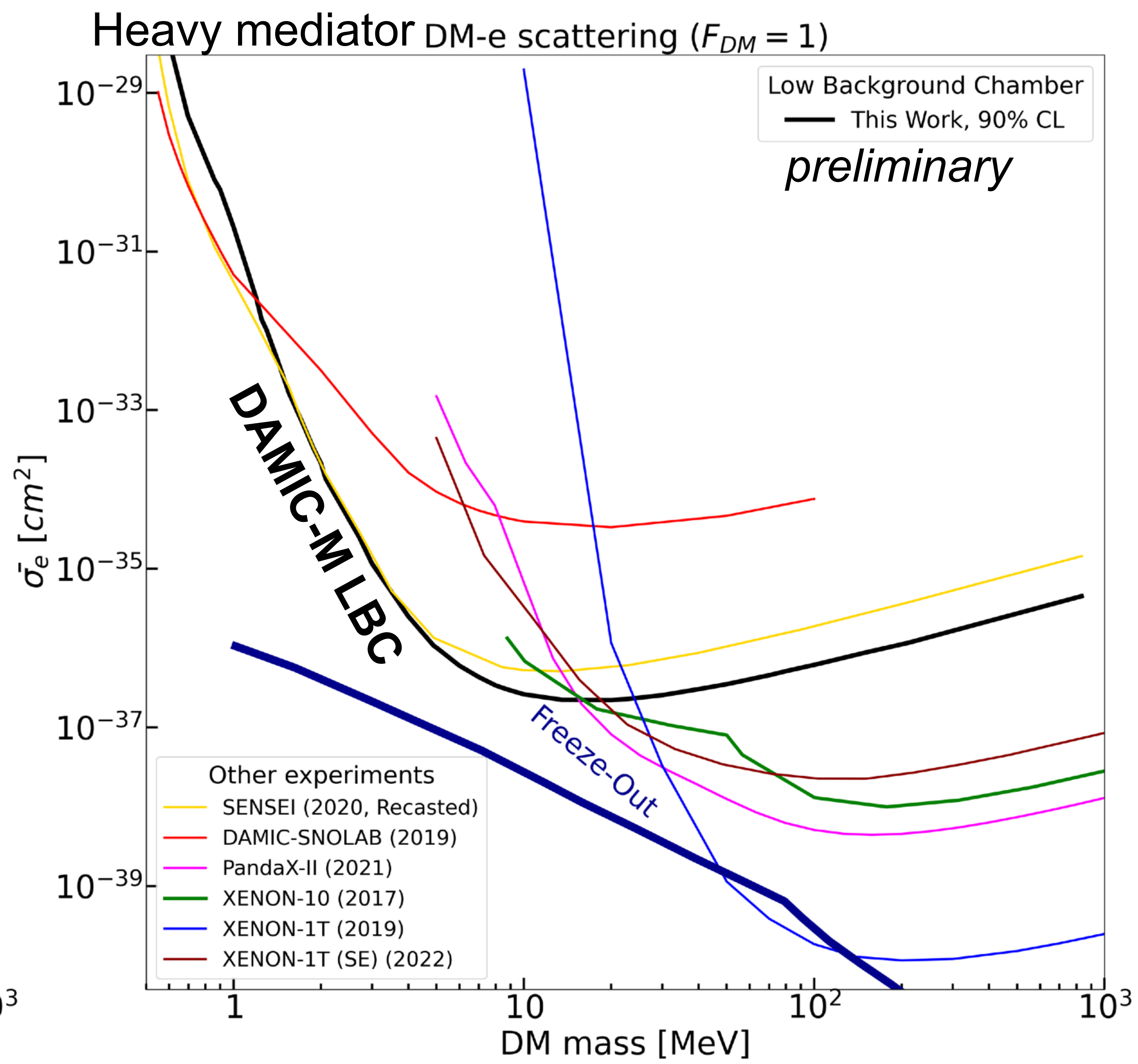
Electronic recoil result could also be interpreted as limit on DM-N scattering (Migdal) or DM absorption

I will use DM-e scattering parameter space as benchmark

DM-e exclusion limits



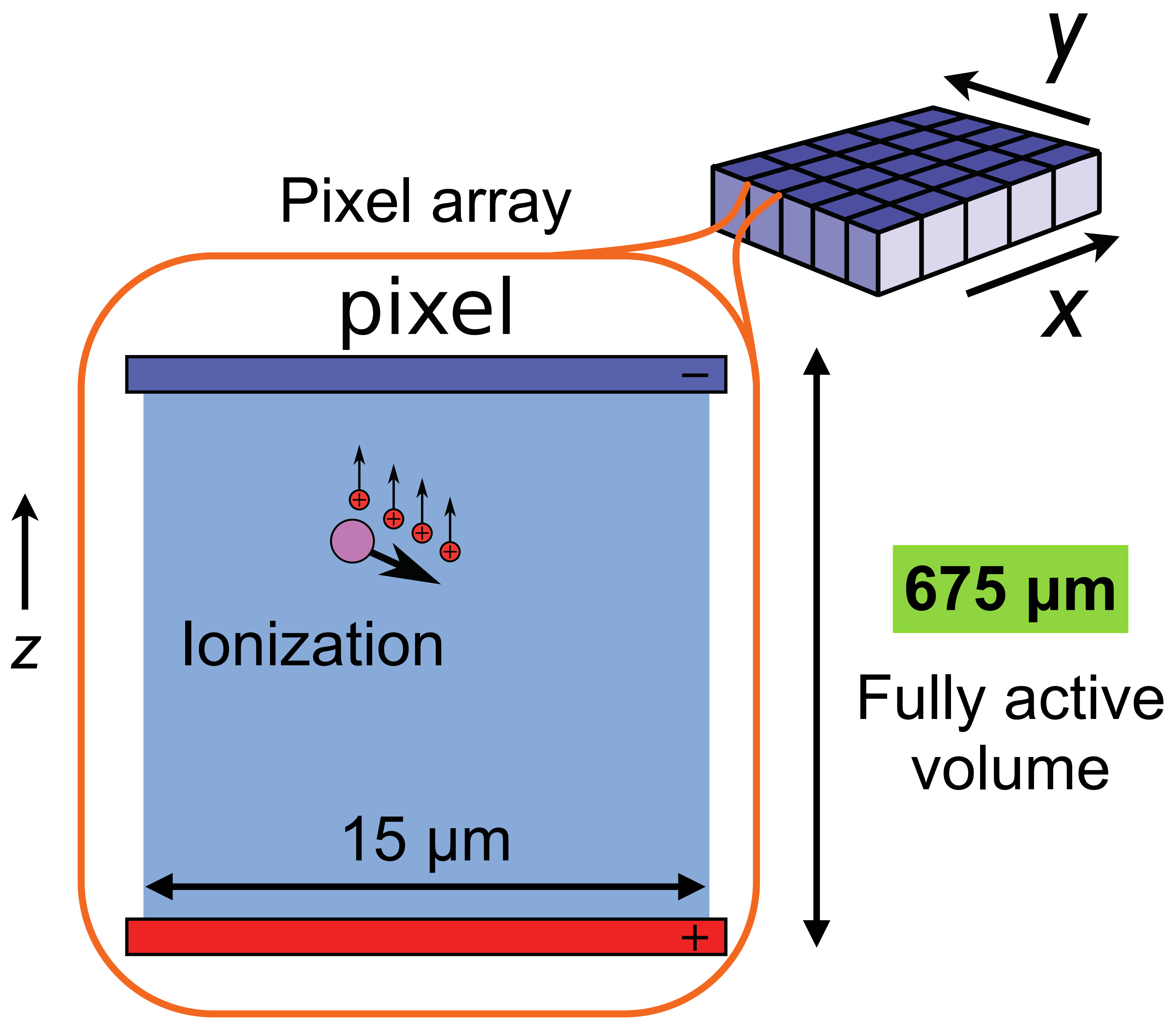




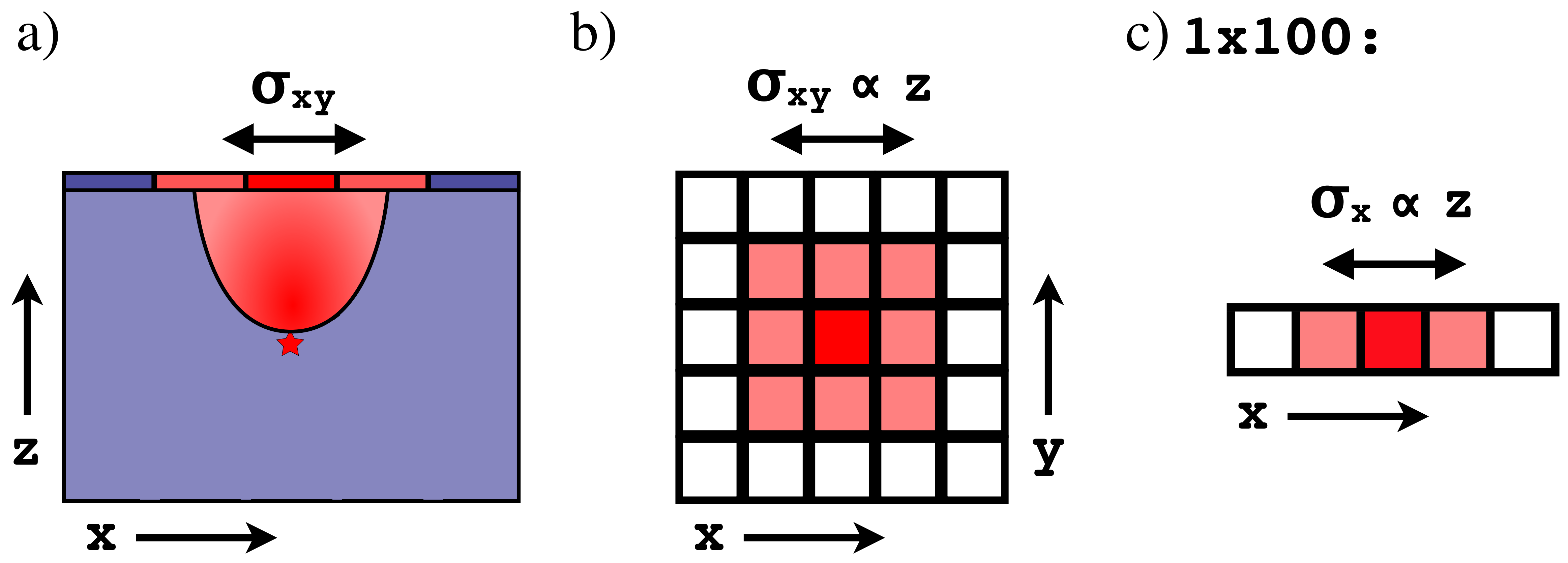
- ER searches allow us to probe DM masses as small as ~**MeV**!

- Skipper-CCD detectors have the best limits.
- **DAMIC-M LBC result released at IDM2022.**

Charge-coupled devices



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

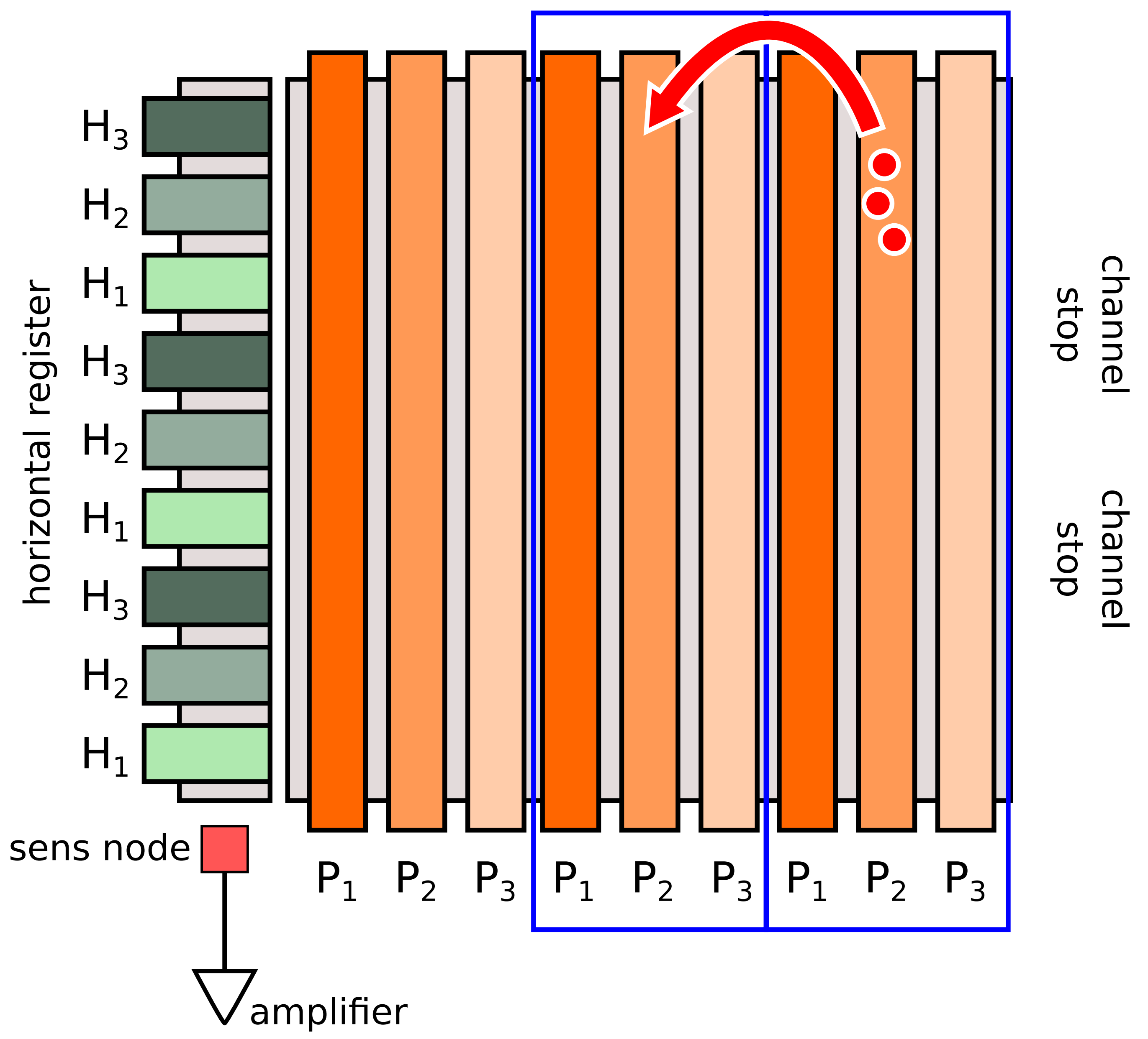


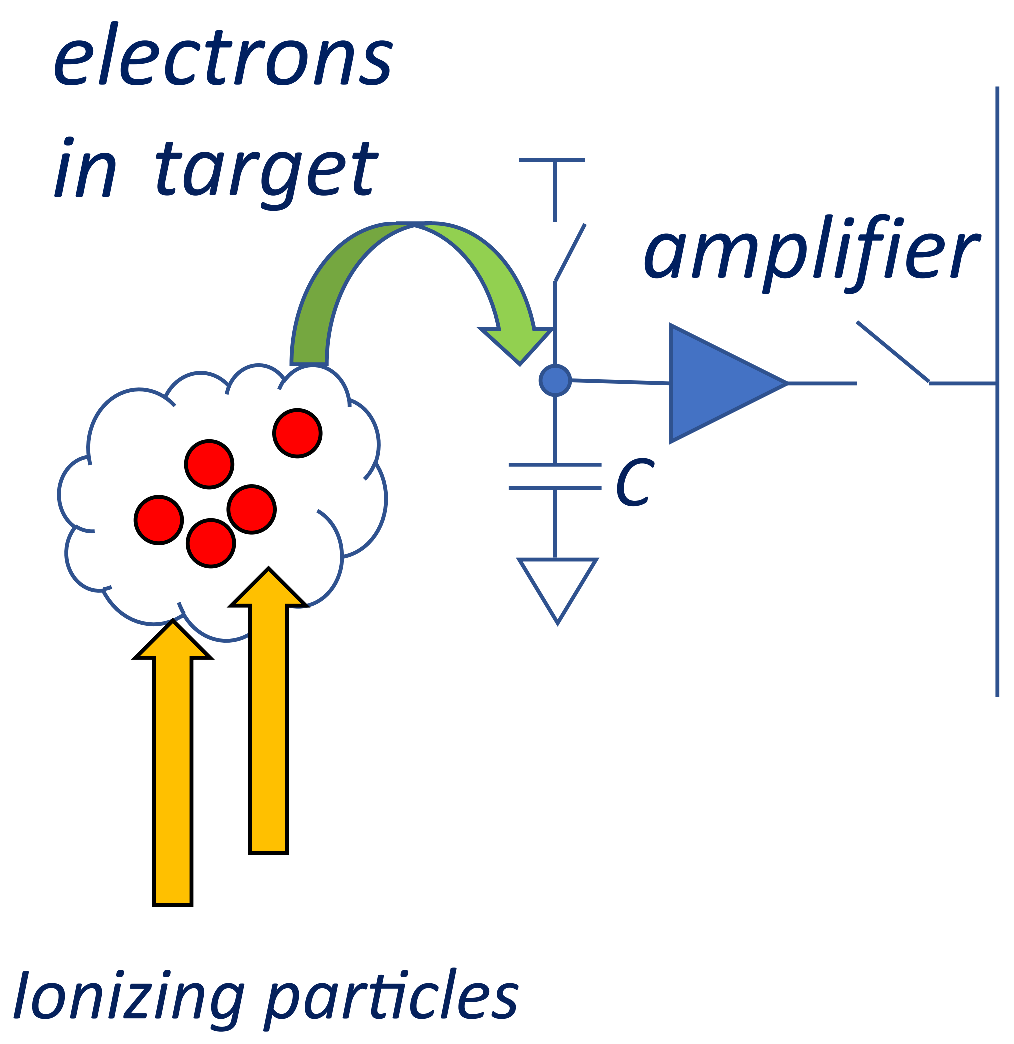
- Depth (z) reconstructed from distribution of charge on pixel array.
- Device is "exposed," collecting charge until user commands readout.
- Readout can be slow: **low noise.**
- Standard fabrication in semiconductor industry and easy cryogenics (~100 K).

Sample CCD image (~15 min exposure) segment in the surface lab.
~1 cm
Cosmic muon
Point-like
β particle
Zoom
Low-energy candidates
Electron
α
Muon
50 pixels
15x15 μm² pixels
5 10 15 20 25 30
Energy measured by pixel [keV]

Readout

3x3 pixels CCD





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

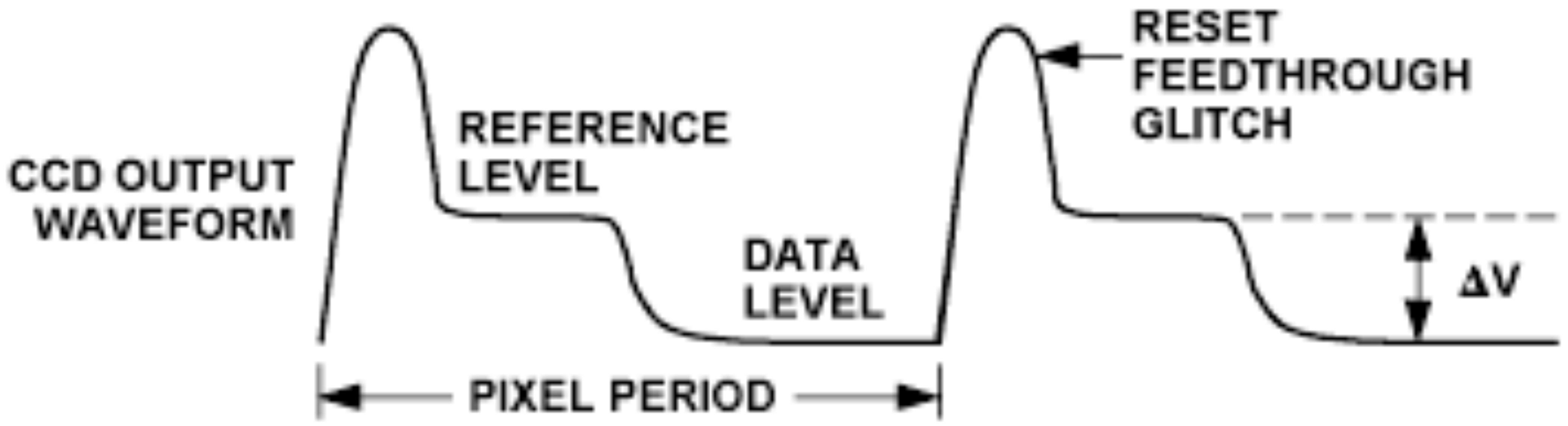
For ***C*** **~ 10 fF**: **ΔV/ΔQ ~ 16 μV/e⁻**

Signal that you can measure

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

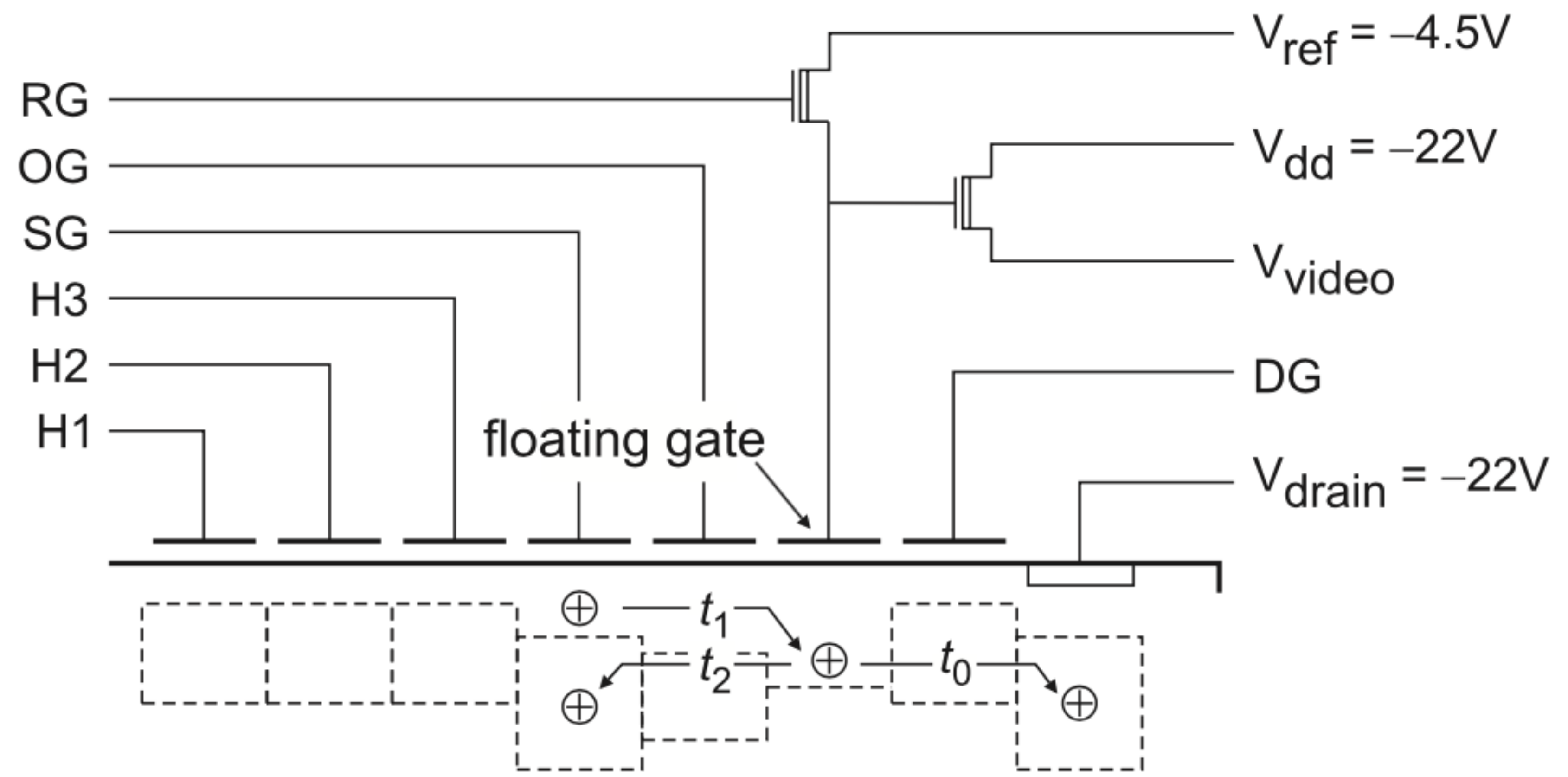
Correlated double sampling (**CDS**):

Readout strategy to efficiently filter “reset” and high frequency noise



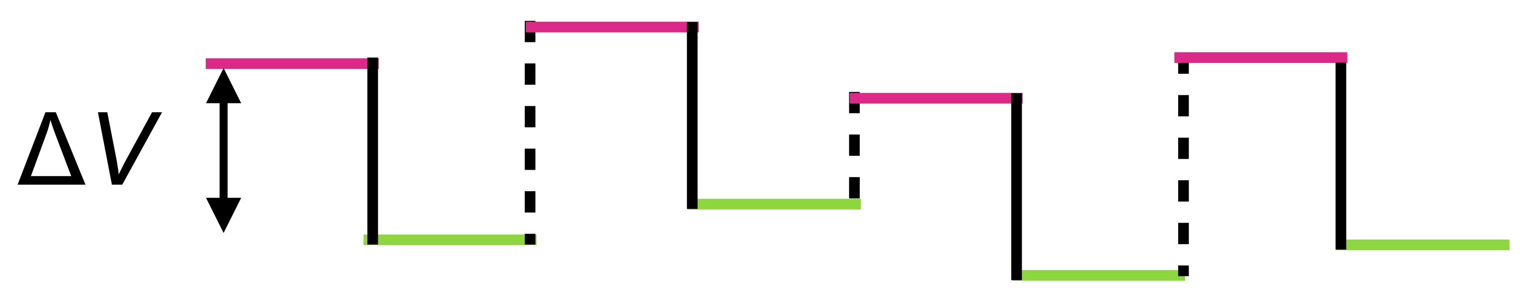
Skipper CCD

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

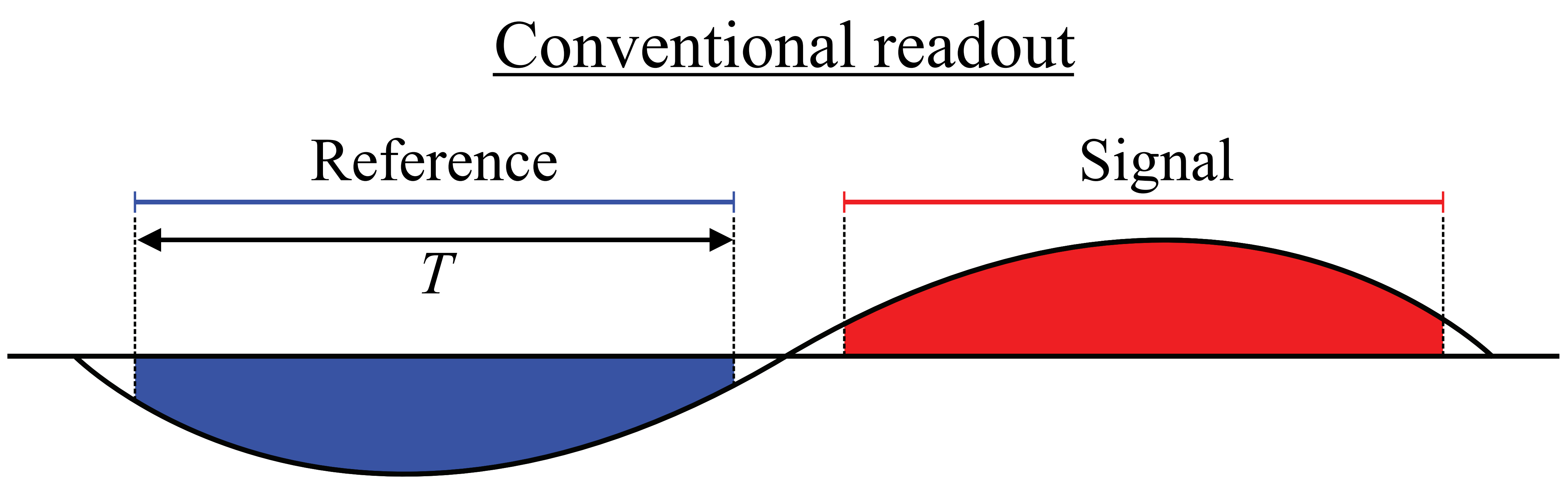


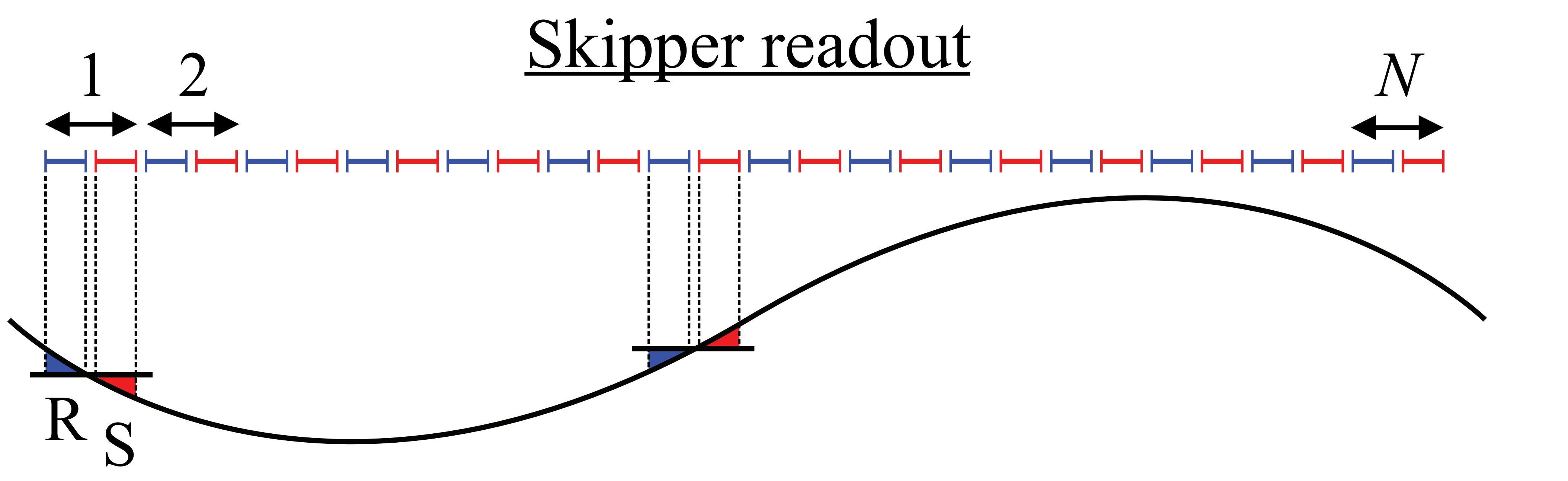
⟷ move charge back and forth

Measure ΔV N times:



Effect on low frequency noise:

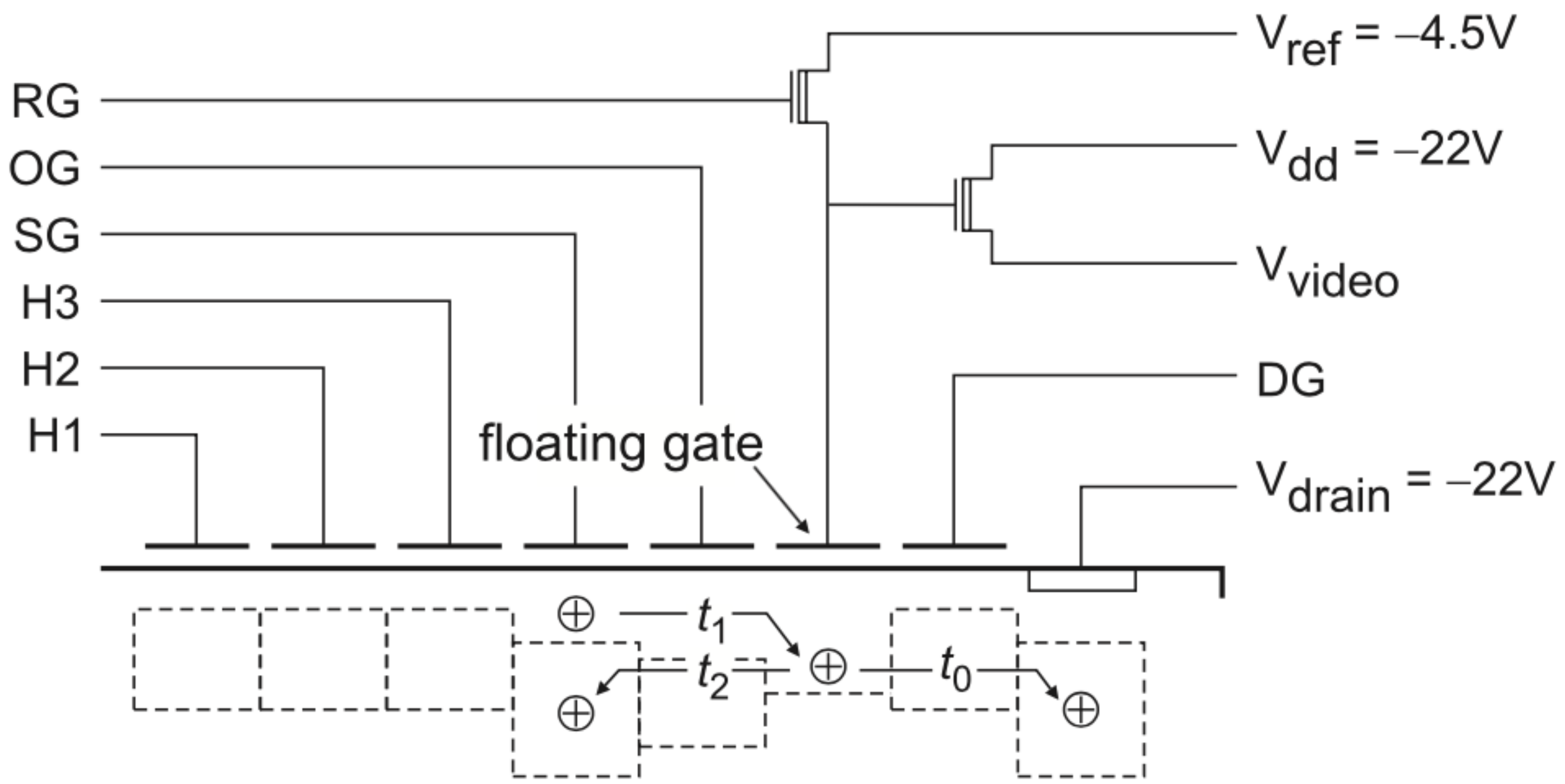




Design by S. Holland at Berkeley Lab

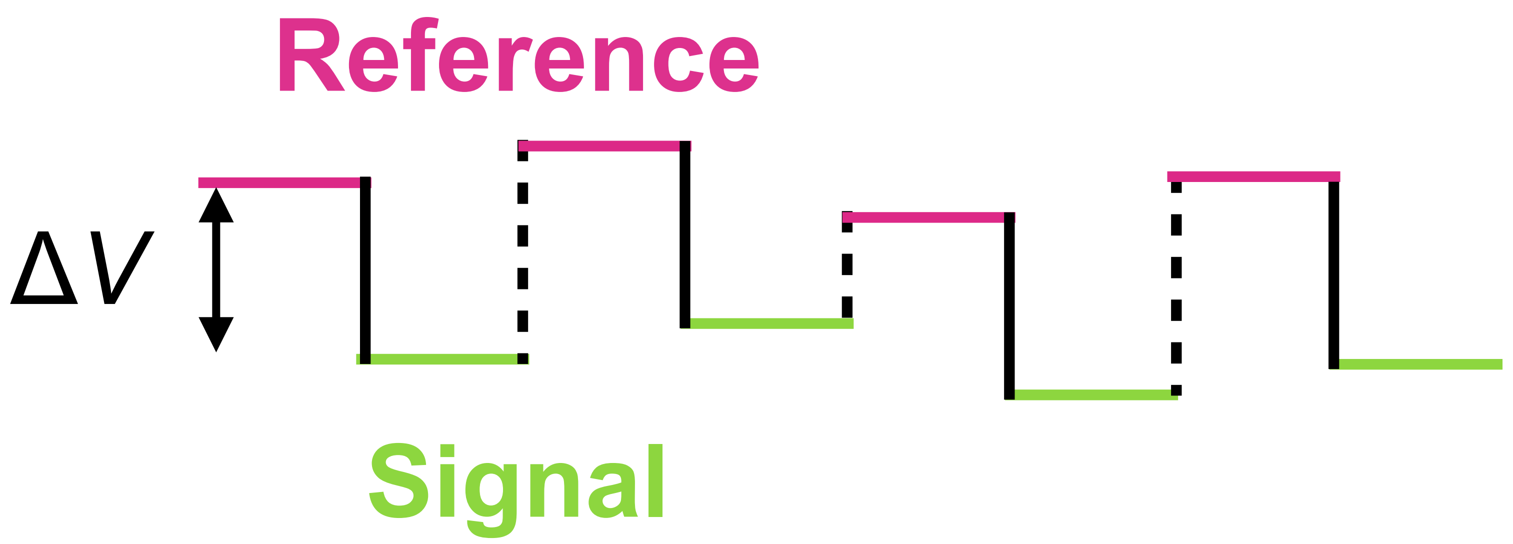
Skipper CCD

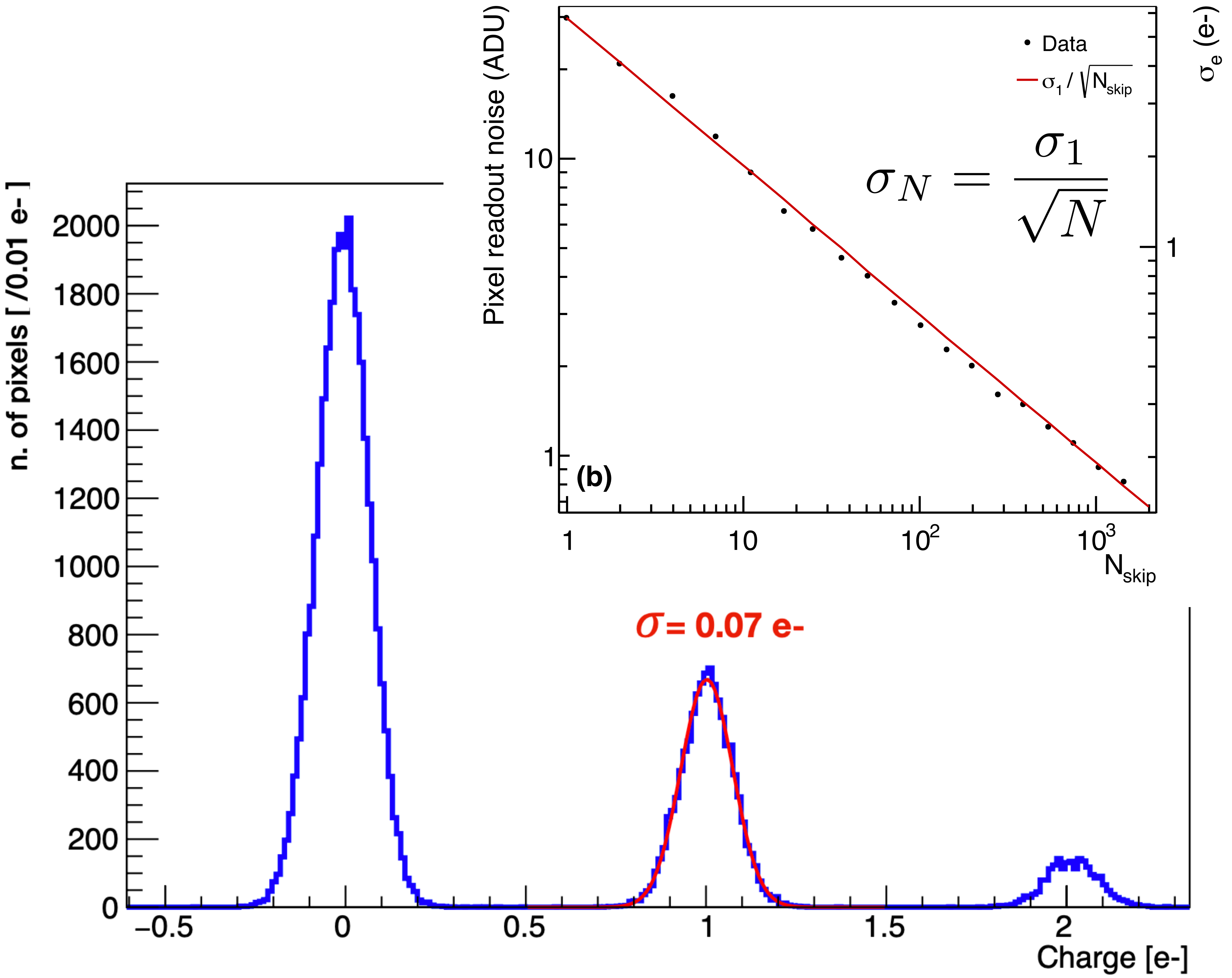
"Skipper" readout: Perform *N* uncorrelated measurements of the same pixel.



↔ move charge back and forth

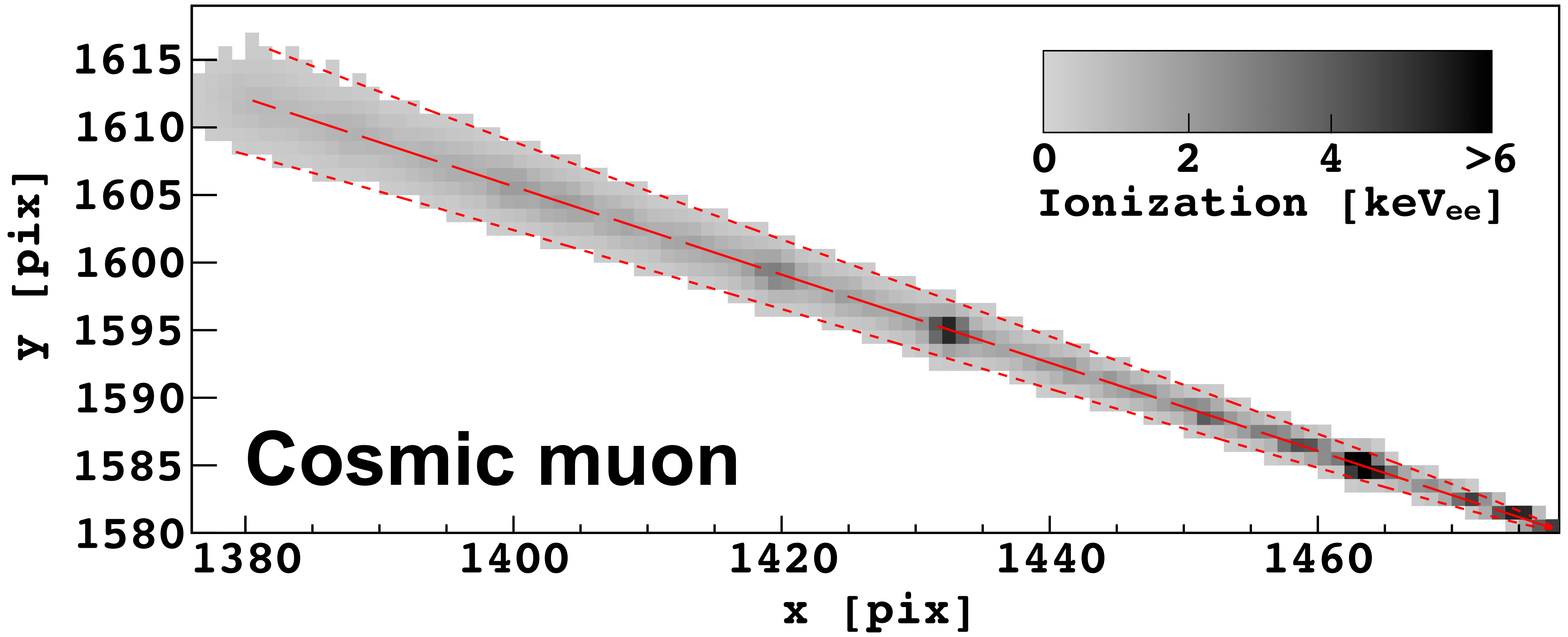
Measure ΔV *N* times:

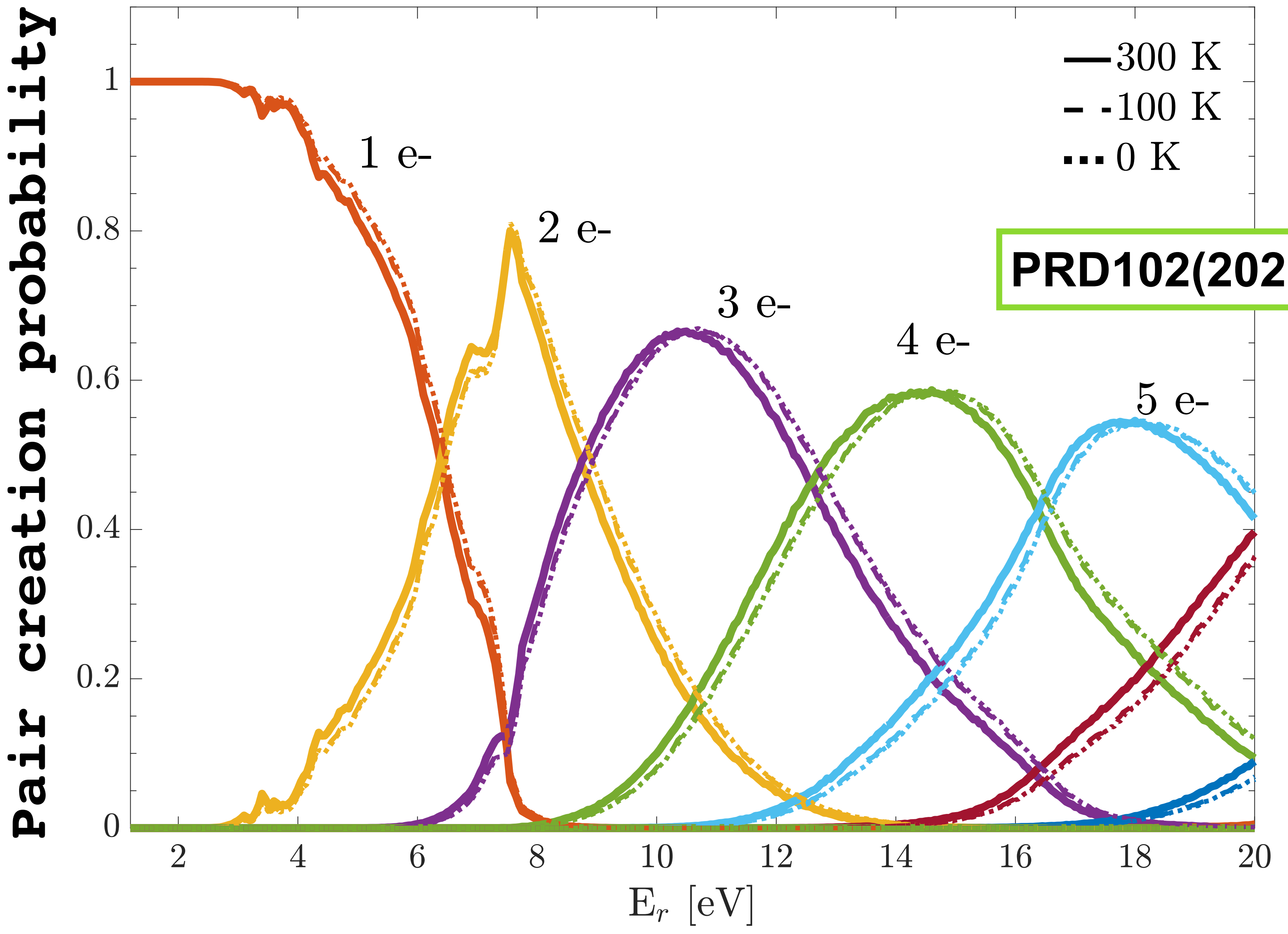




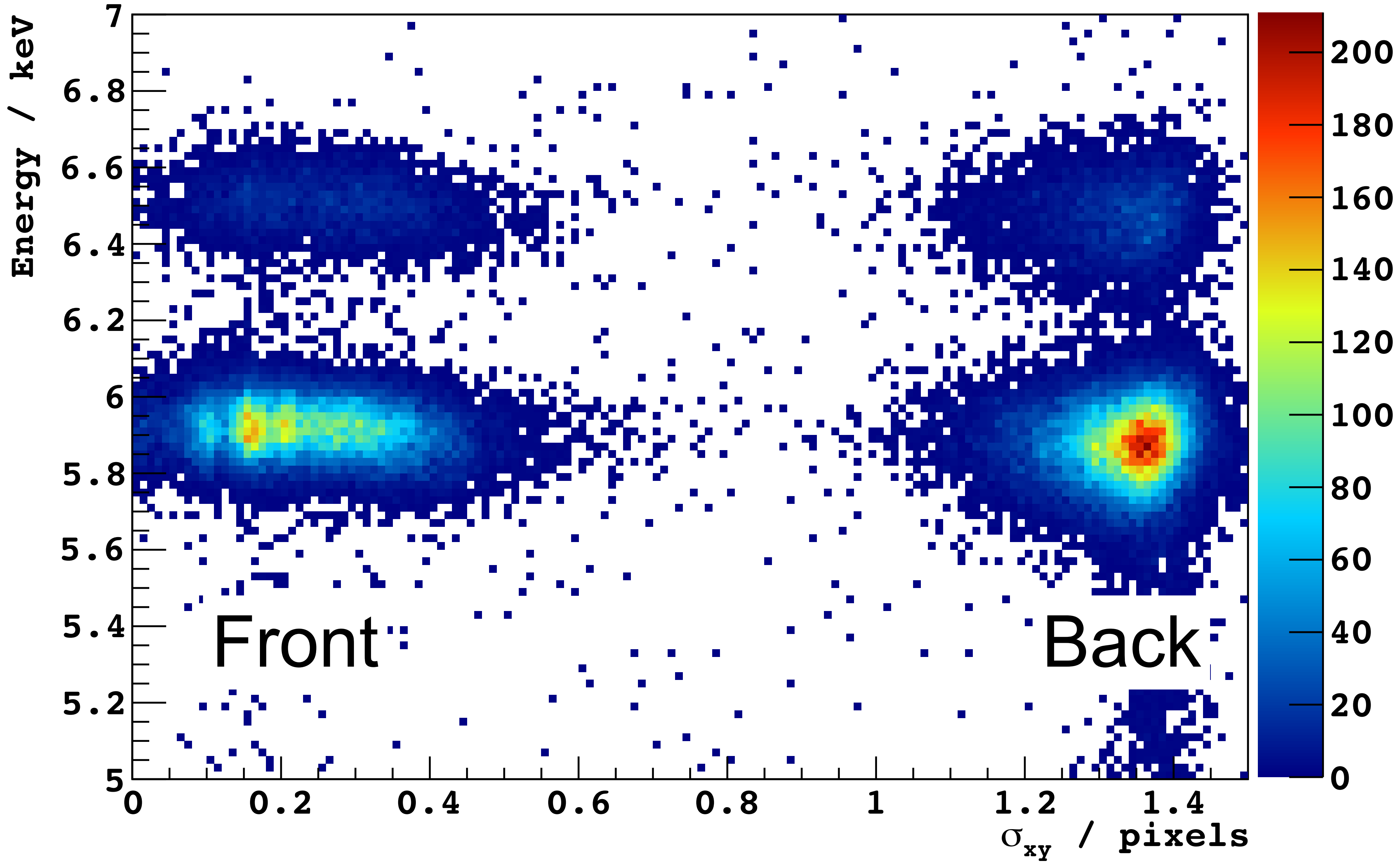
Characterization

- 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.



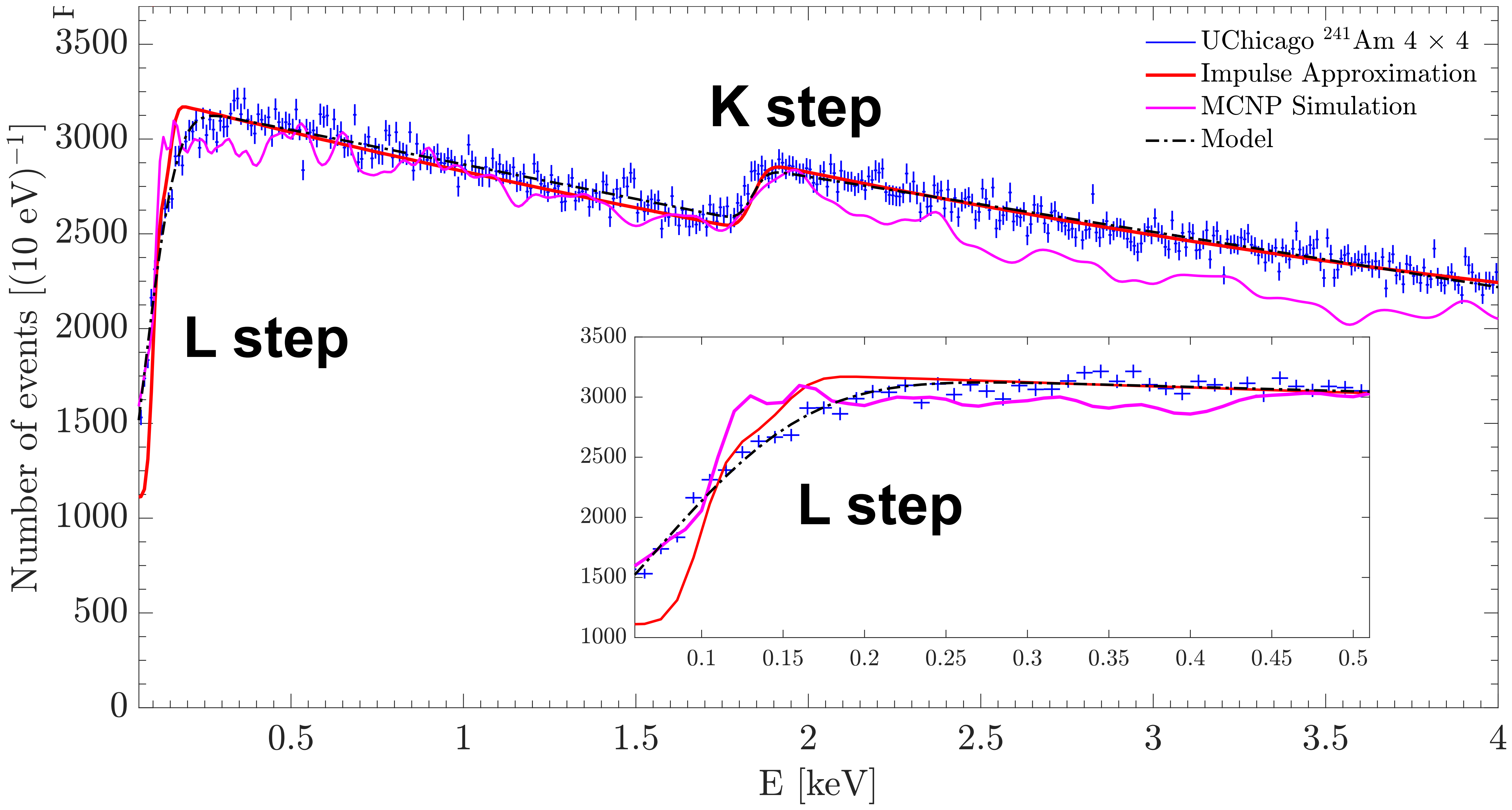


PRD102(2020)063026



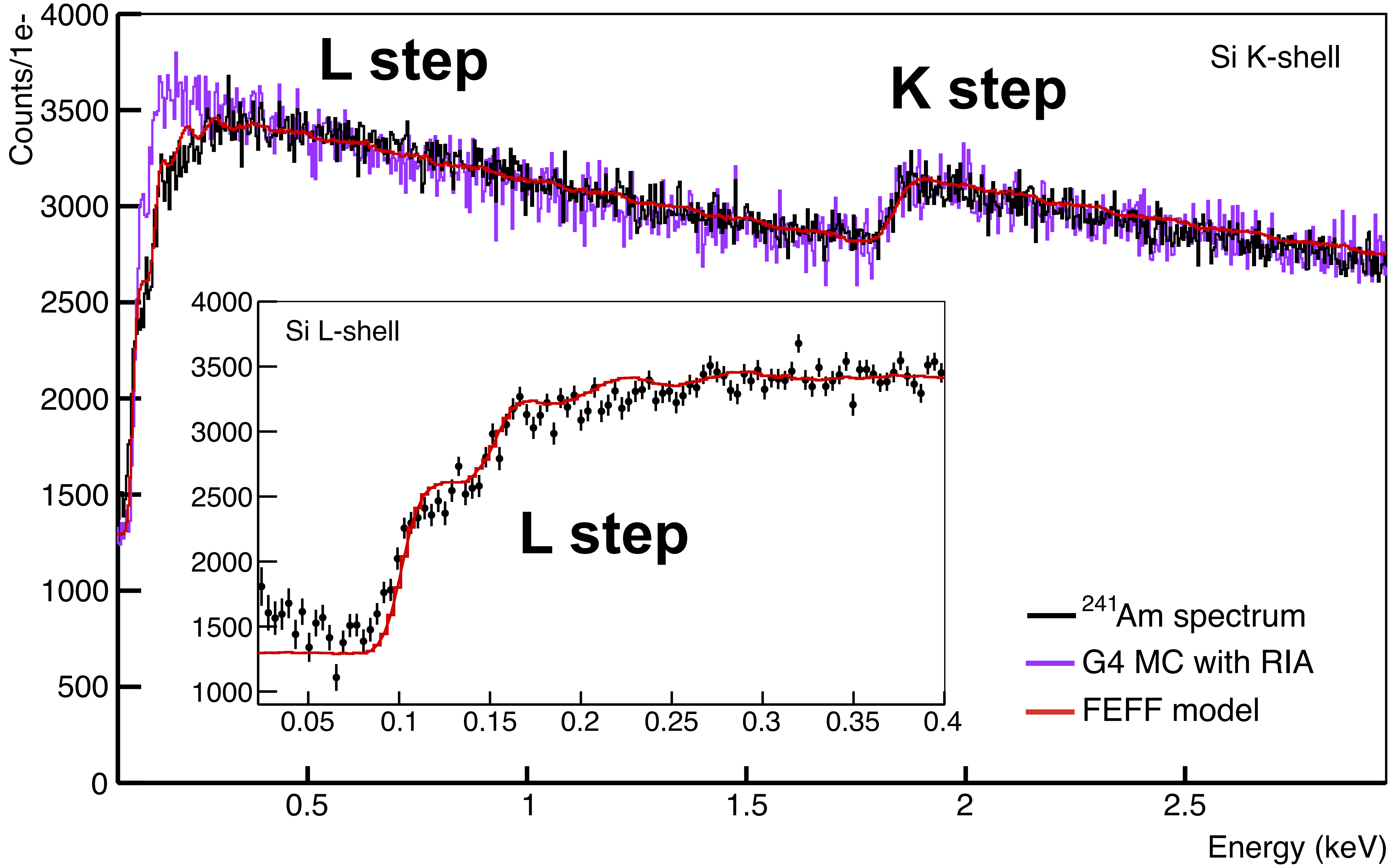
Example

- 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}: arXiv:2207.00809(2022)
- 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 QM treatment.
- Full QM calculations may be needed to correctly describe electronic-recoil spectra.

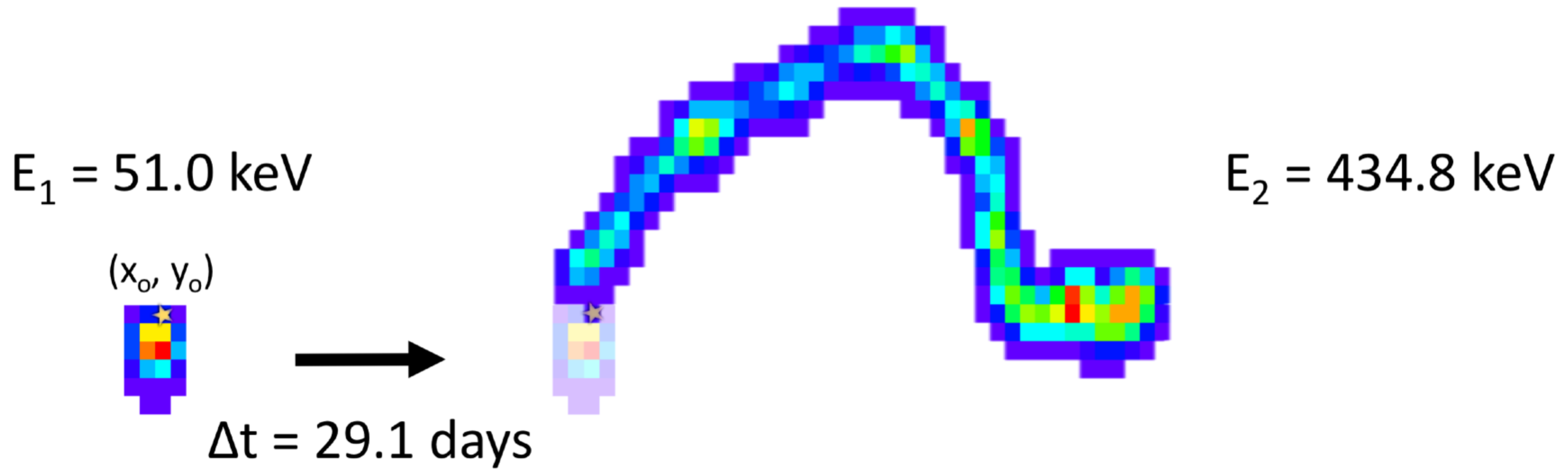


Radioactive backgrounds

- 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

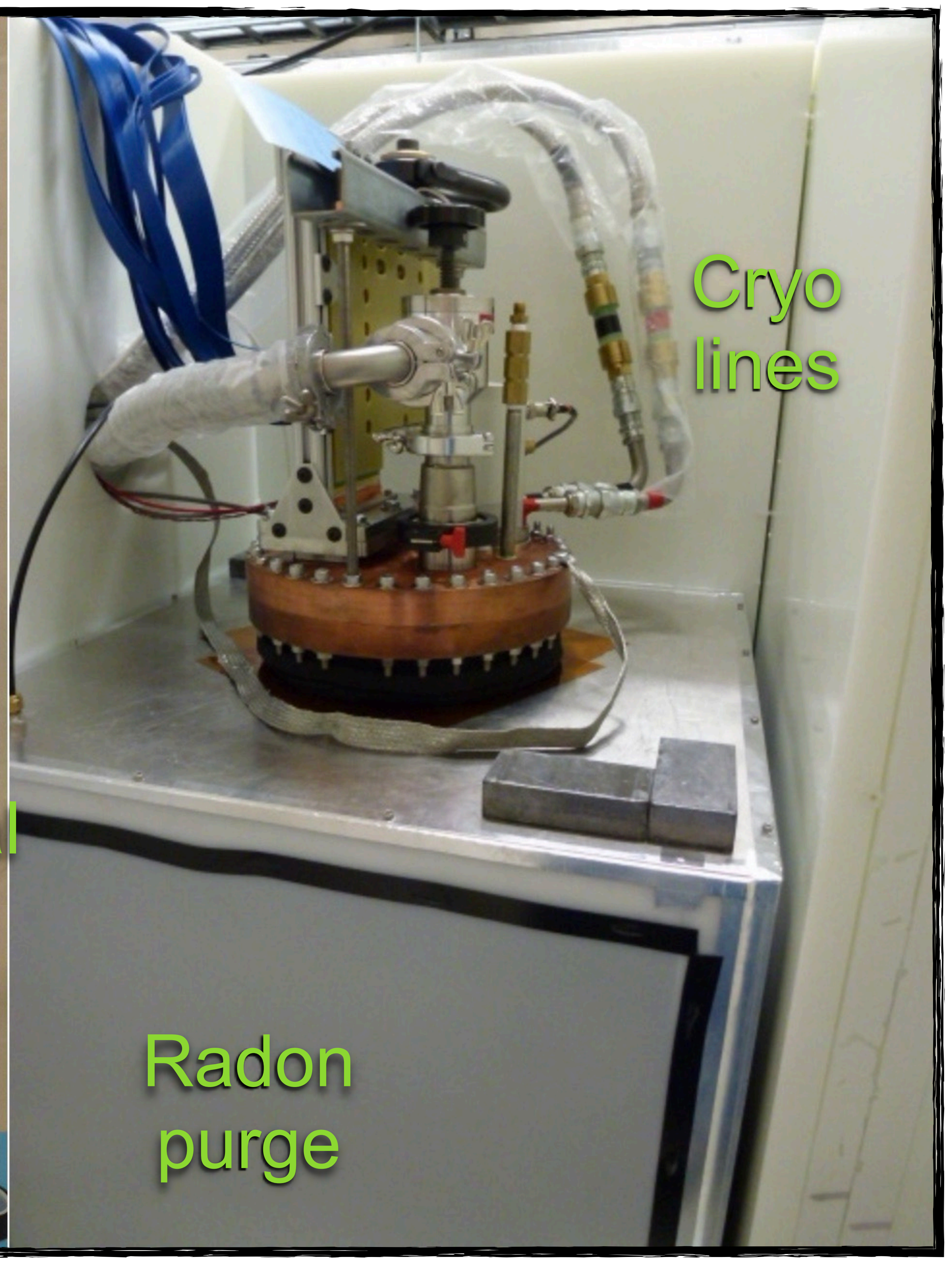
- Exhaustive radio-assay program: PRD105(2022)062003

DAMIC at SNOLAB

CCD Box

Cryostat insert

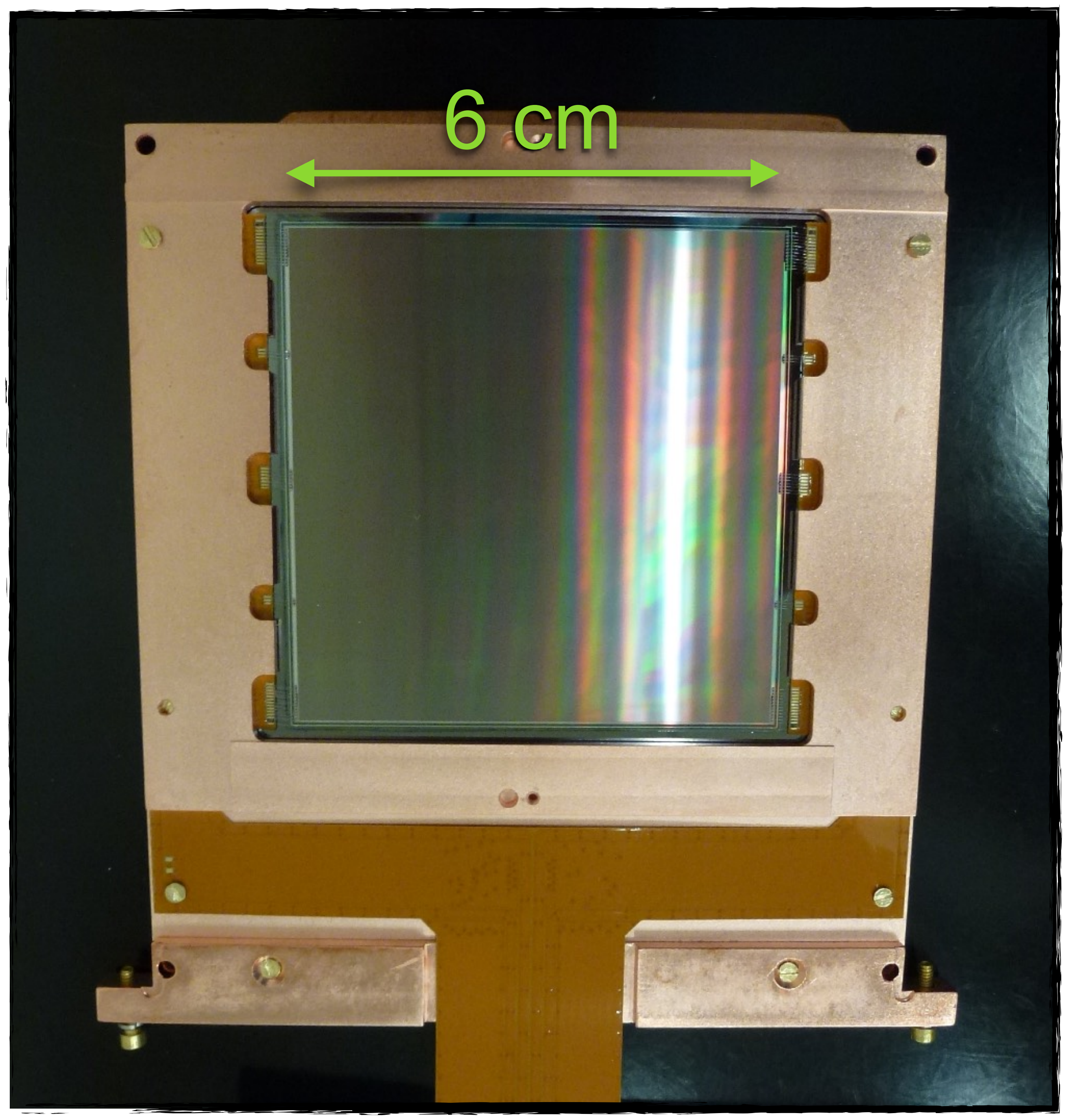
In shield



External shield

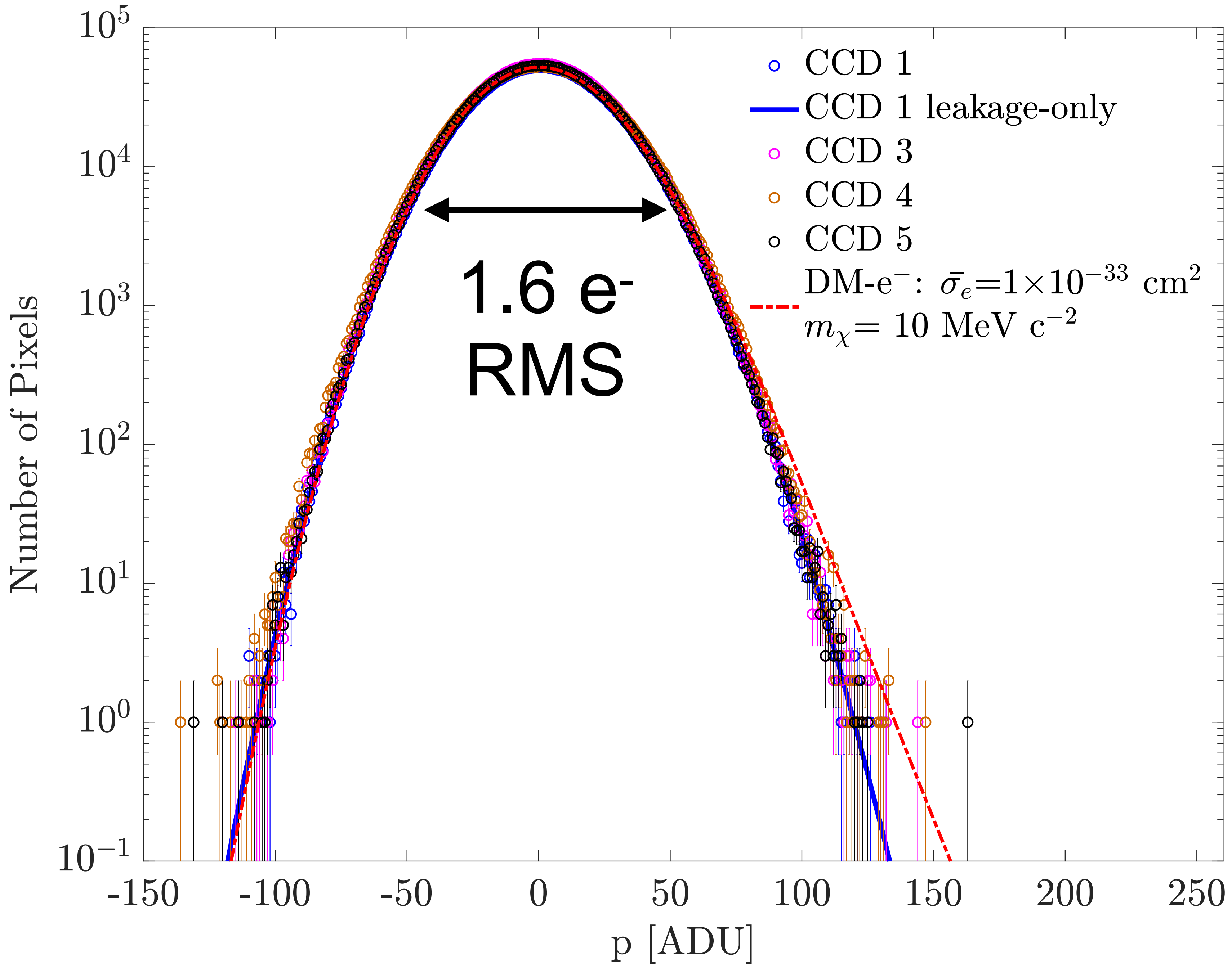
DAMIC at SNOLAB

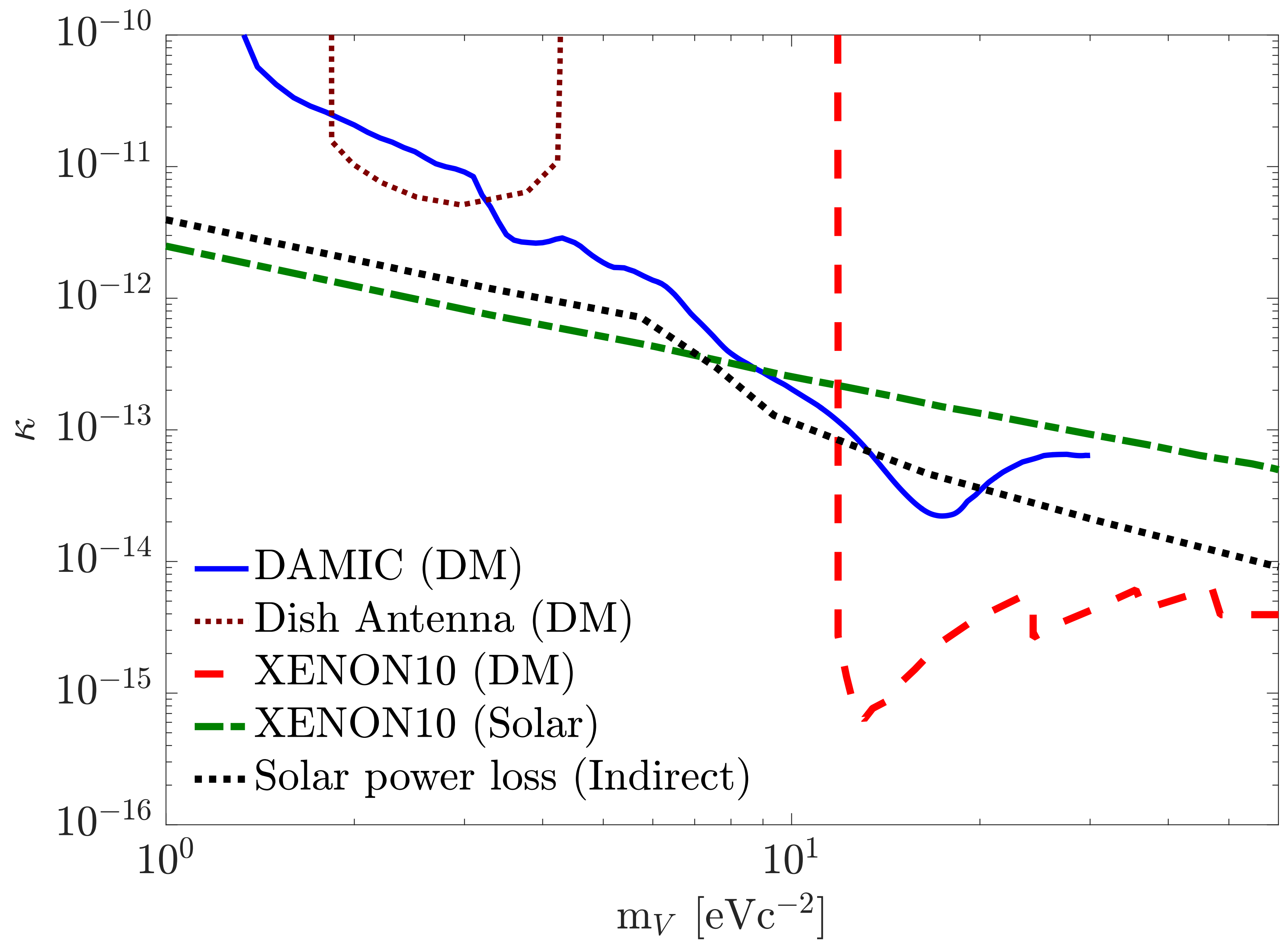
- First array of CCDs operated underground for a DM search. Since 2012.
- 7 CCDs (6.0 g, 16 Mpix) cooled to 140 K.
- Total (bulk) background rate: ~10 (5) d.r.u.
- Low pixel noise 1.6 e^- with conventional readout.
- Extremely low leakage current: 2 x 10^{-22} A cm^{-2}.



Results summary

- **DM-e⁻ interactions:** PRL118(2017)141803
  - First DM search results from ~eV ionization signals.
  - Latest DM-e- scattering results. PRL123(2019)181802

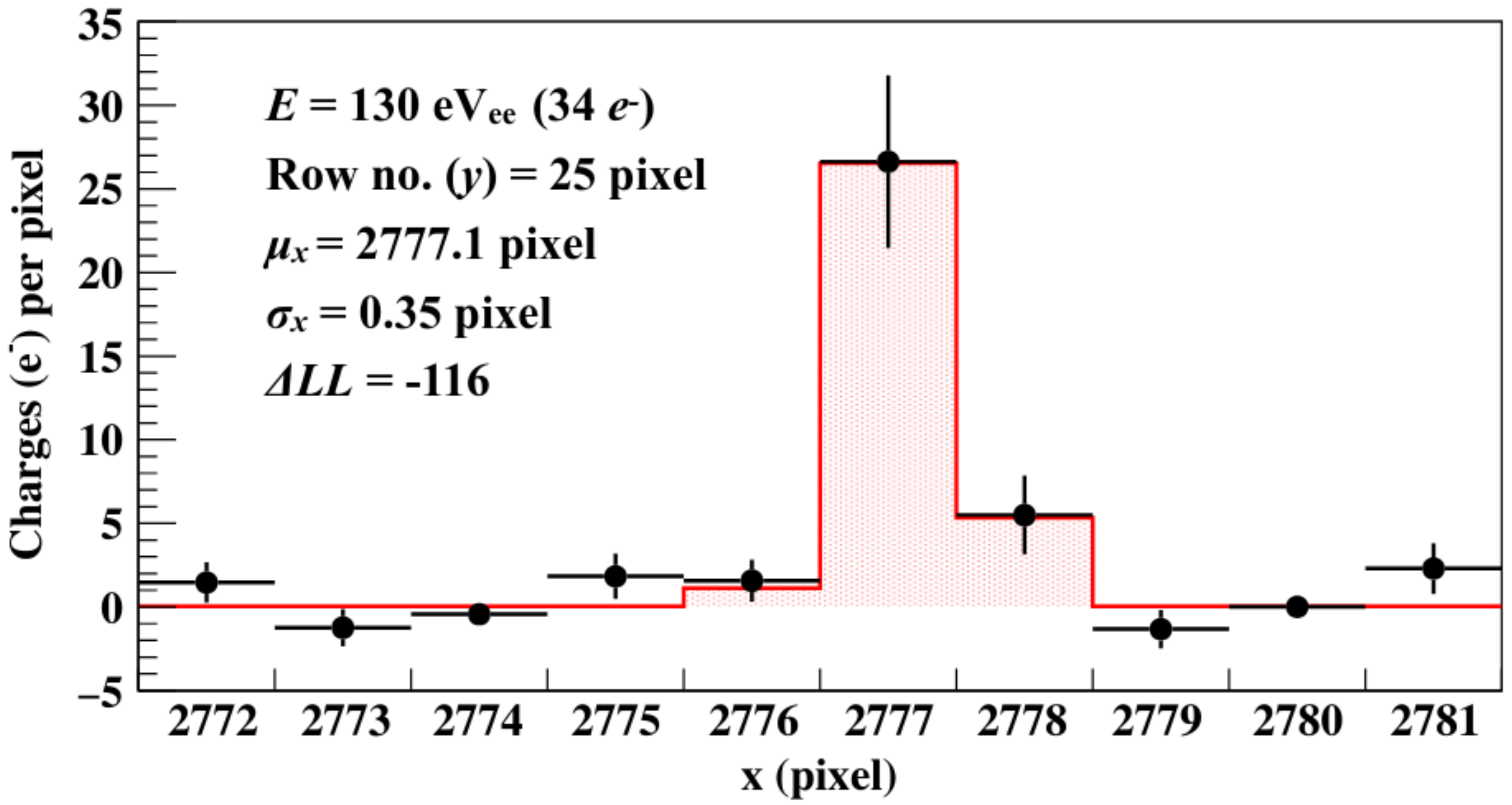


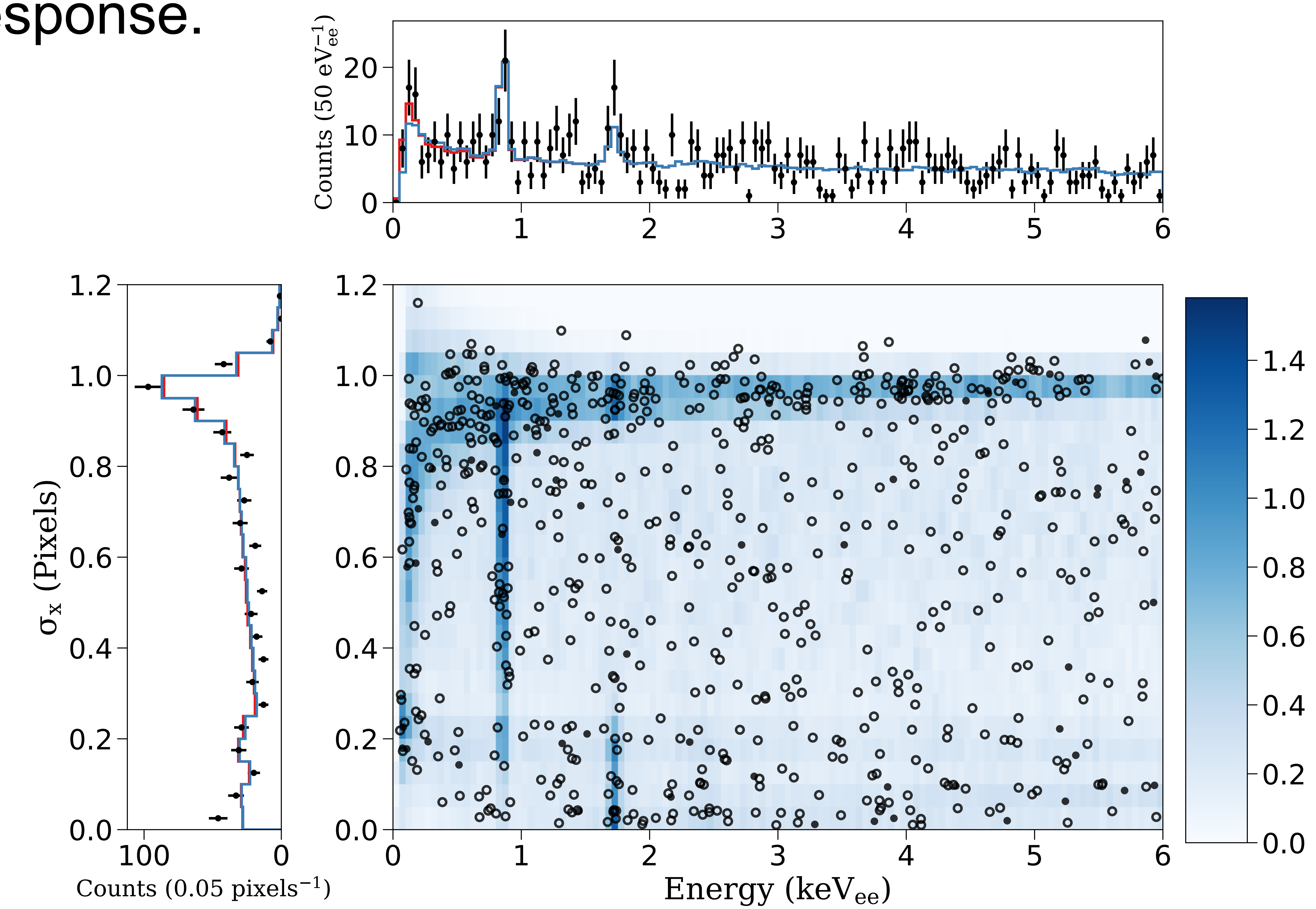


- **WIMP search:** PRL125(2020)241803 PRD105(2022)062003
  - 11 kg-day of data from seven-CCD array.
  - 50 eV_{ee} analysis threshold.
  - First full background model in CCDs.

WIMP search fit result

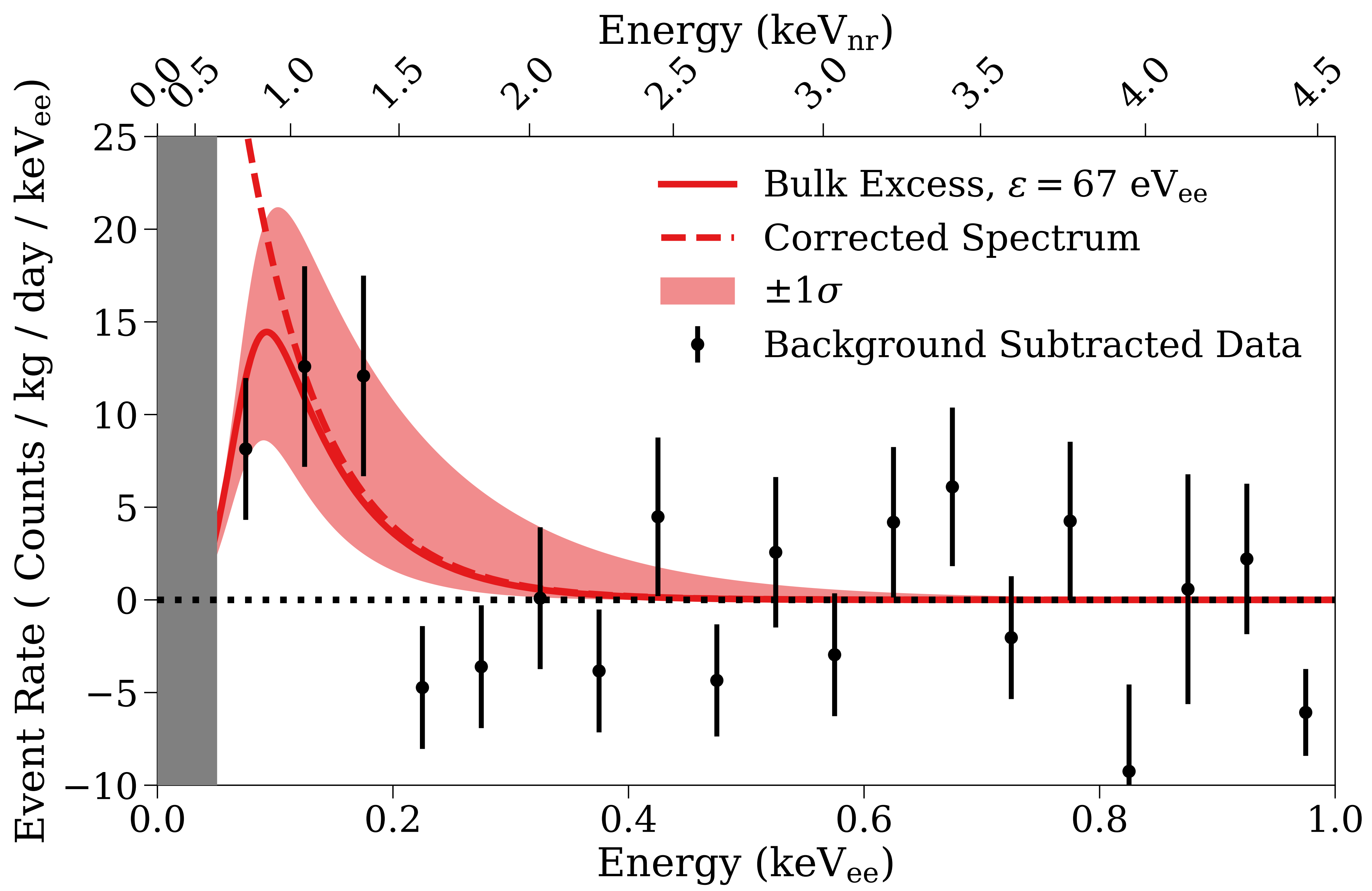
- Constructed full background based on extensive knowledge about radioactive background sources and detector response.
- Performed a fit to the data ionization events with the background model in (E, σ_x) parameter space.

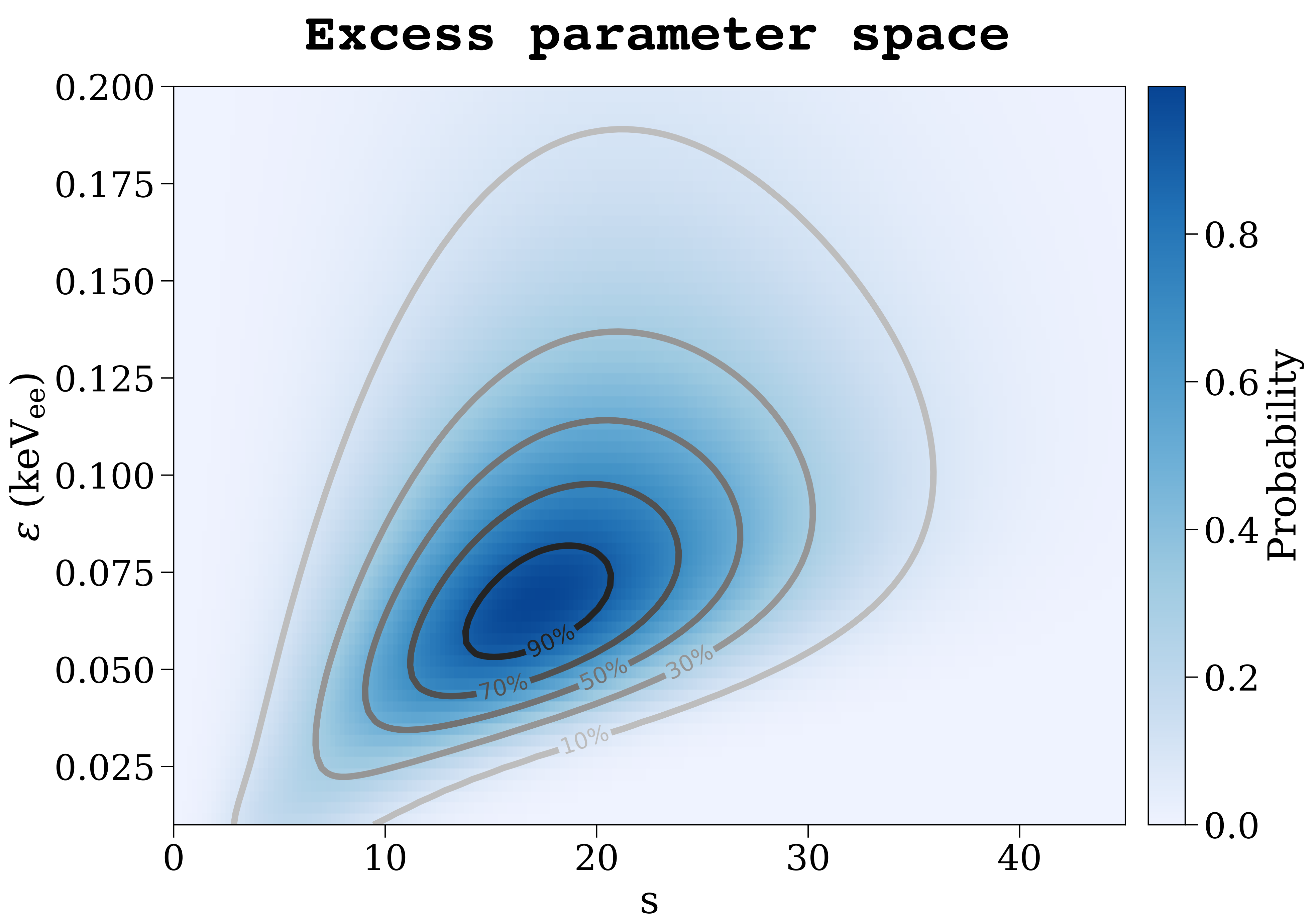




DAMIC Excess

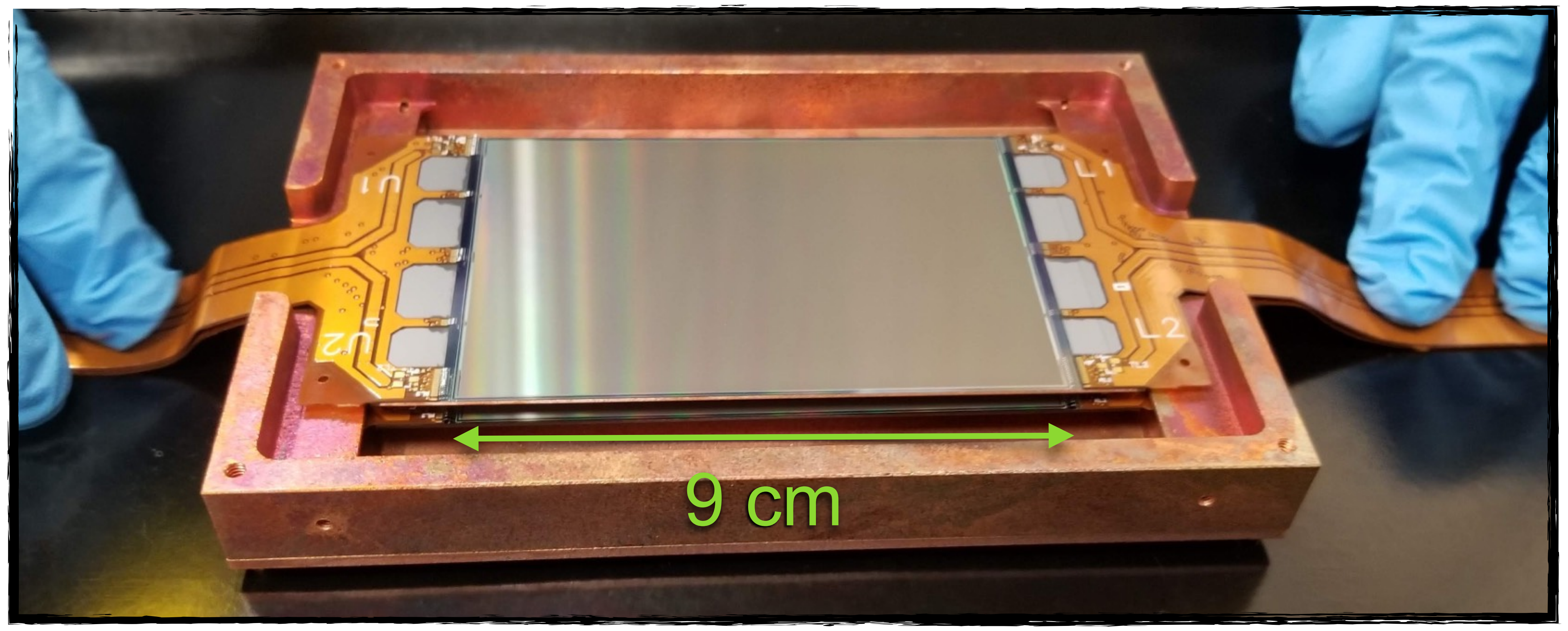
- Excess of 17.1 ± 7.6 events with 50-200 eV_{ee}, 3.7 σ significance.
- If not addressed, limiting background for next generation experiments.

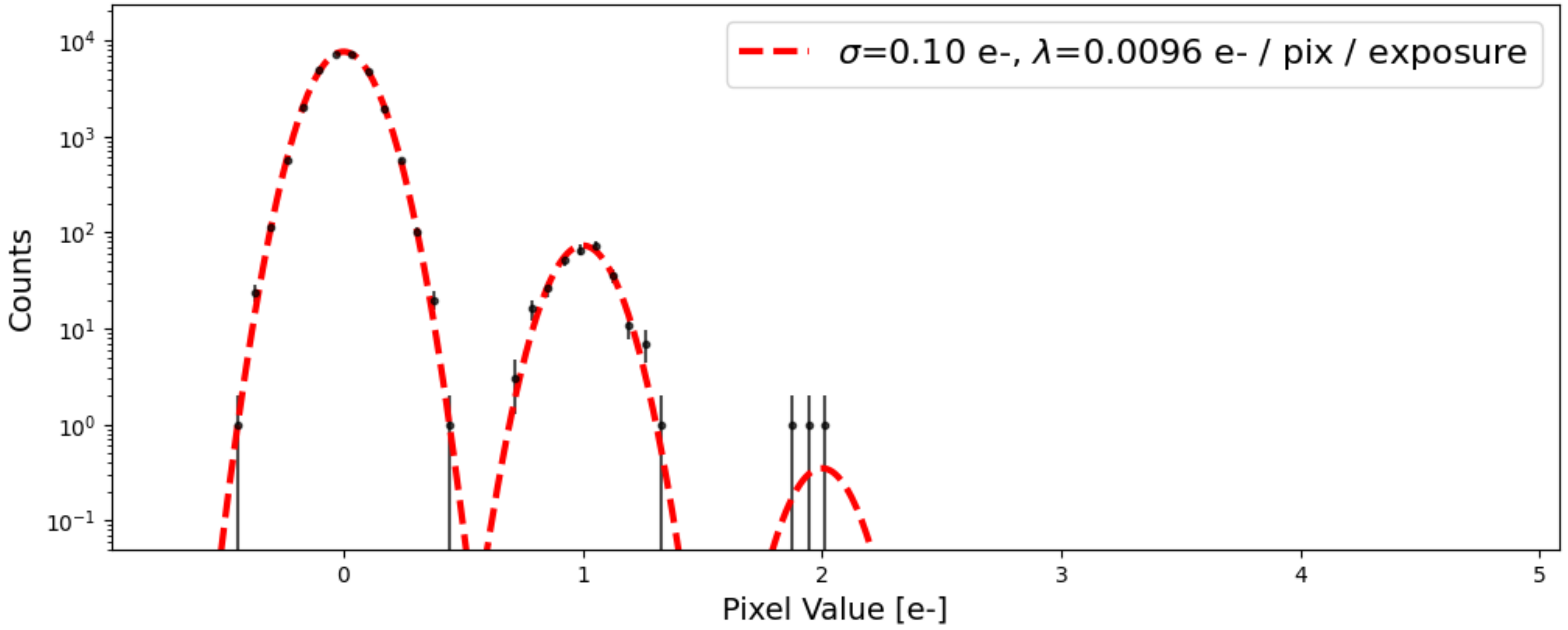




SNOLAB Upgrade

- Two 24 Mpix DAMIC-M skipper CCDs (18 g Si target) packaged and tested at UW. Installed in Oct-Nov 2021.
- New science run started in early March 2022.
- Single-charge resolution (σ_{pix} = 0.16 e^-) and low leakage current (2.4 x 10^{-3} e^-/pix/day).





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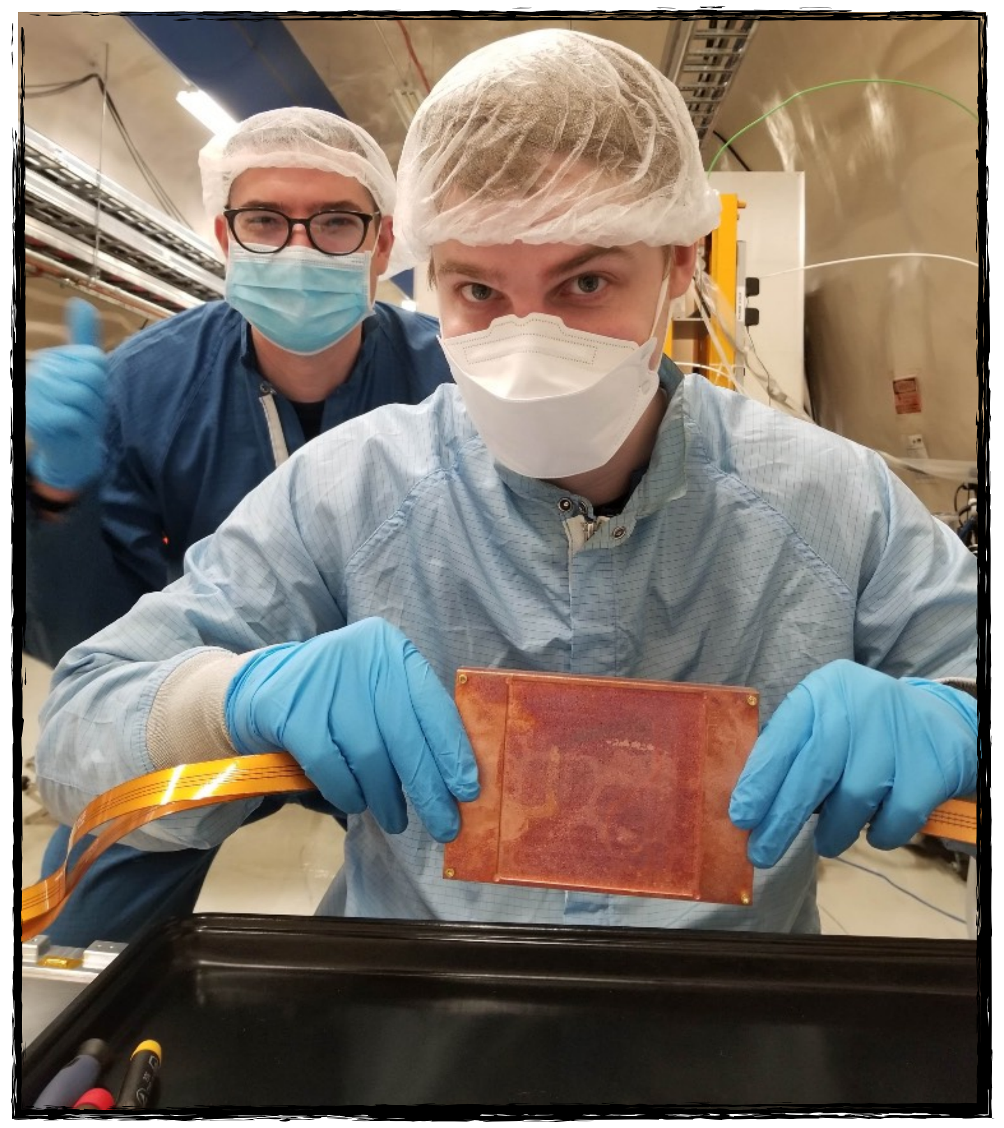
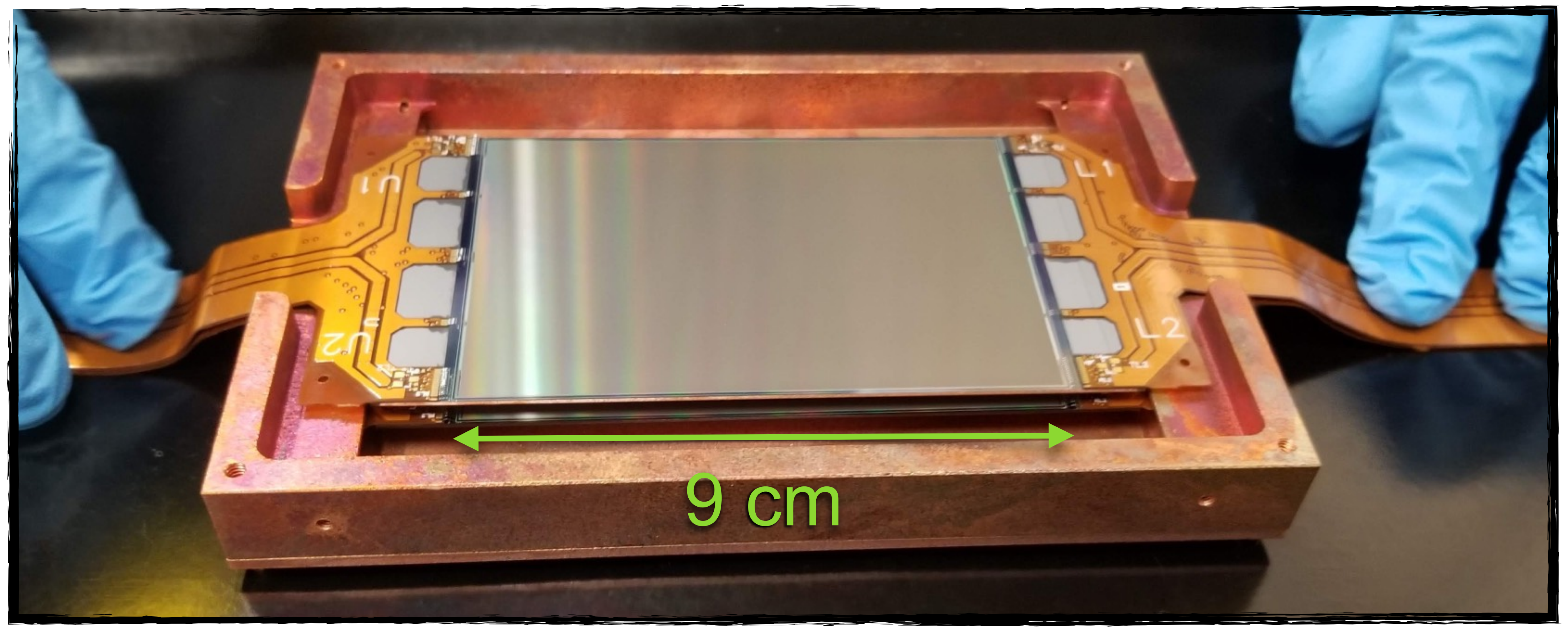
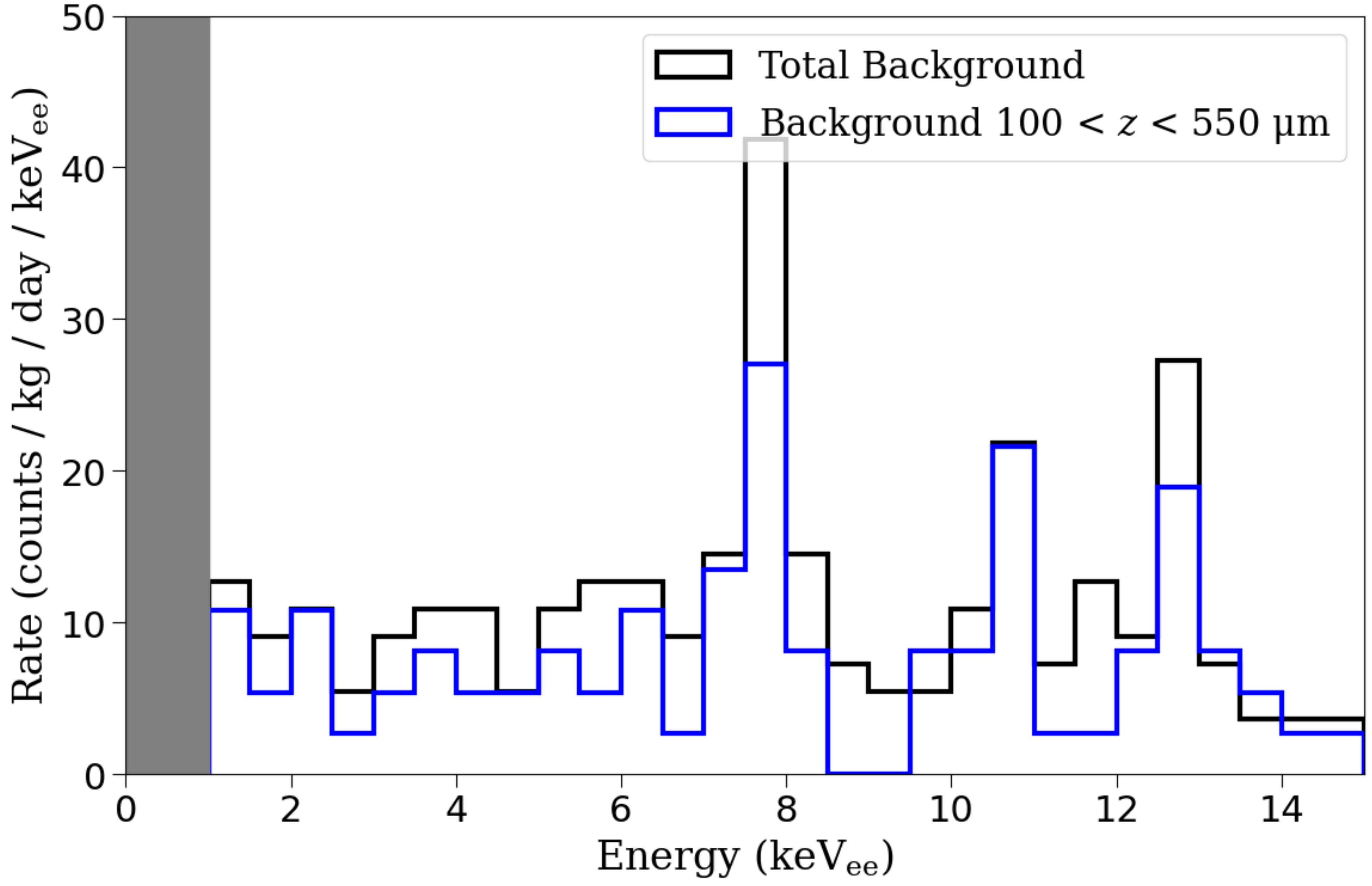


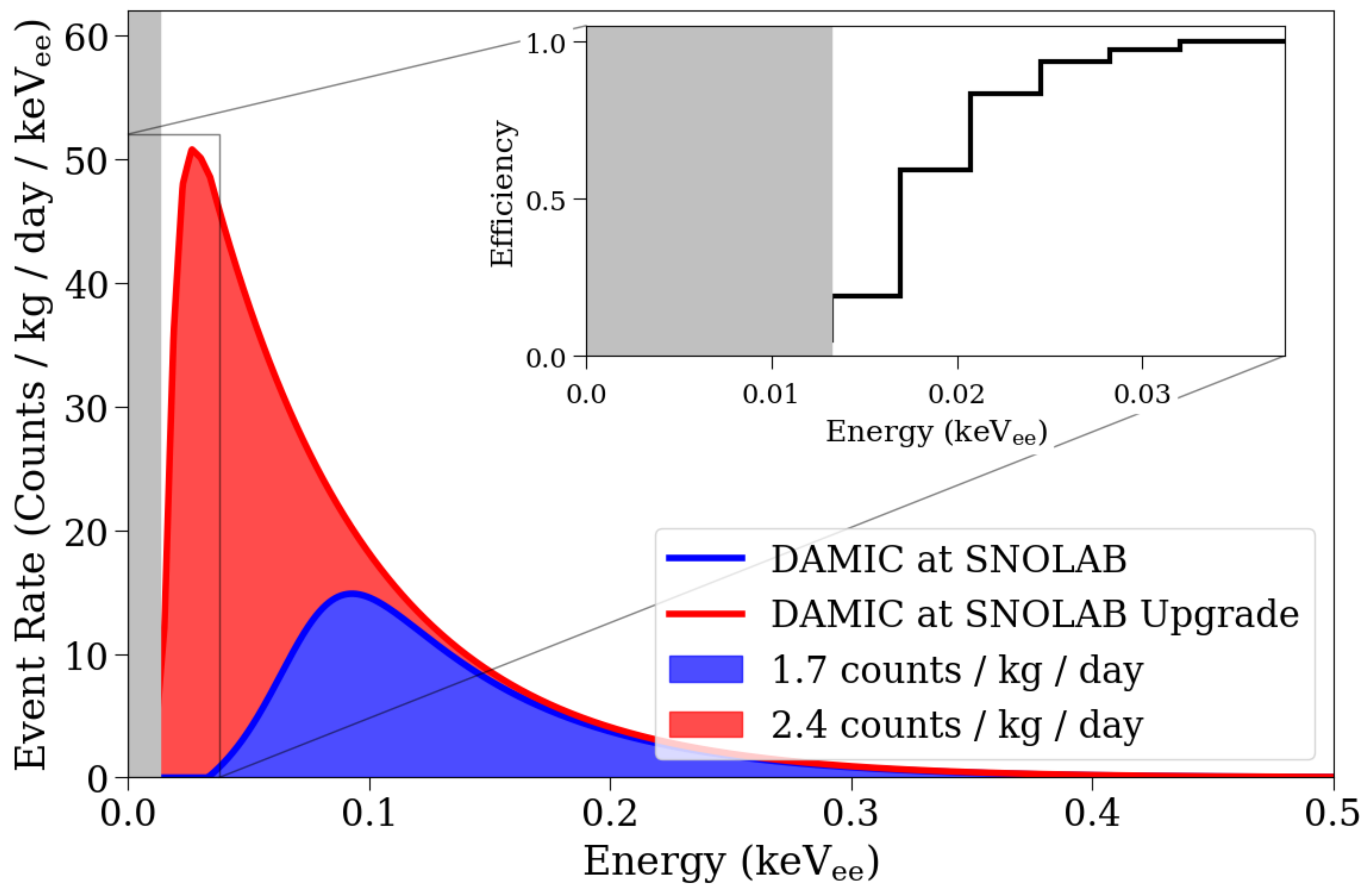
- Two 24 Mpix DAMIC-M skipper CCDs (18 g Si target) packaged and tested at UW. Installed in Oct-Nov 2021.
- New science run started in early March 2022.
- Reproduce background rate from before: 9 ± 1 d.r.u. total and 6 ± 2 d.r.u. bulk.

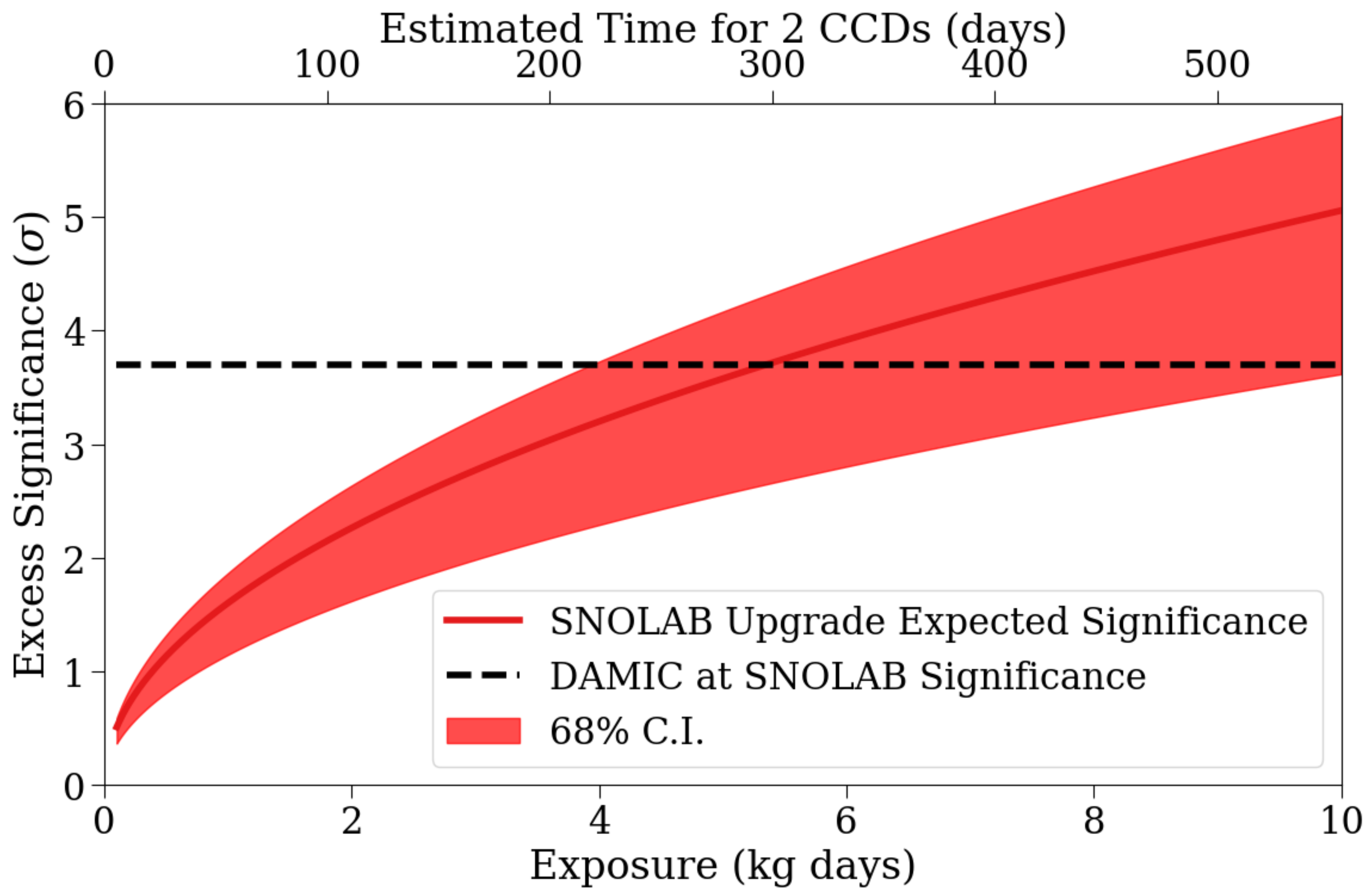




Upgrade sensitivity

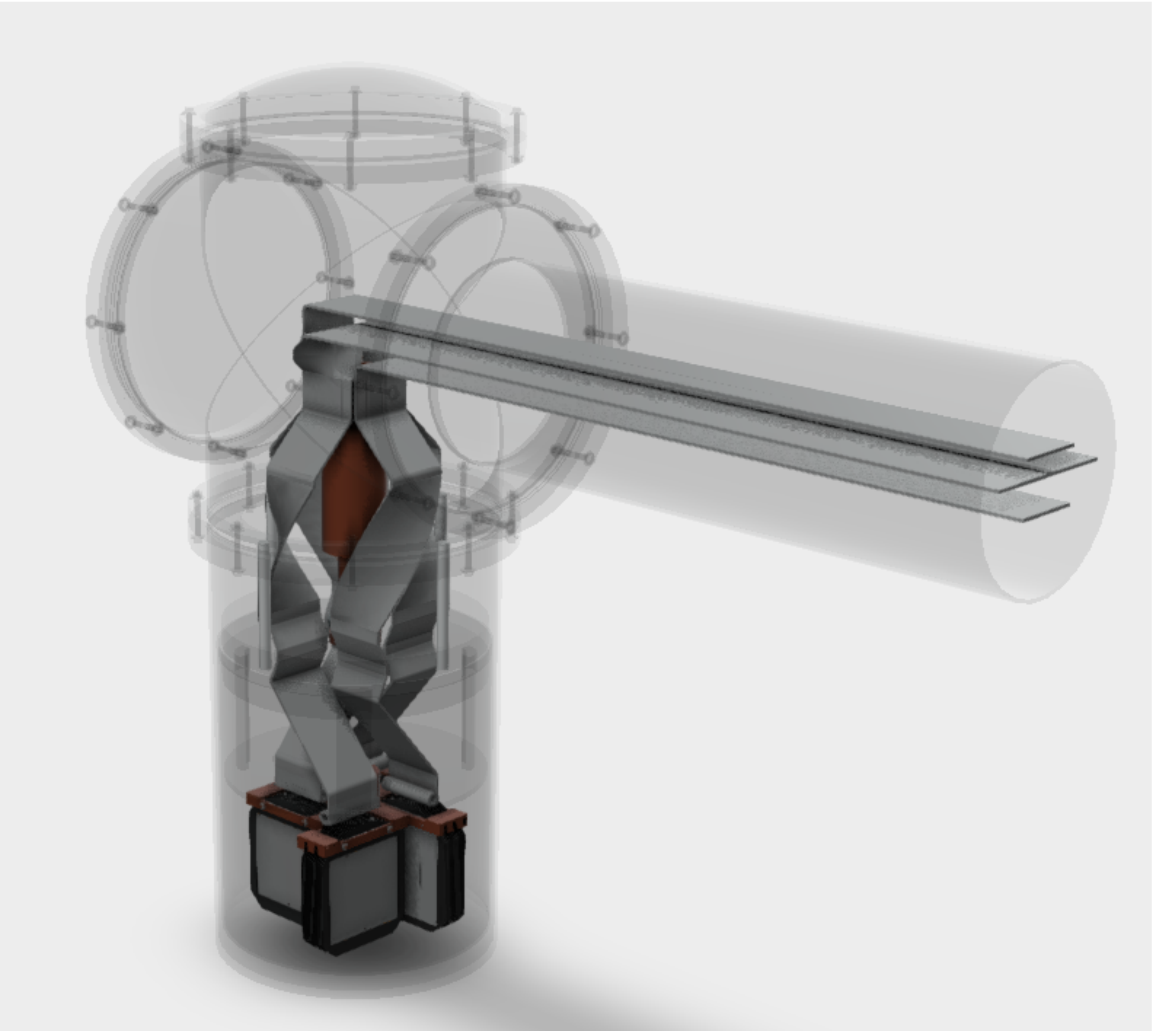
- Simulated data set with measured detector performance.
- Performed event clustering, reconstruction and selection with methodology from previous analysis.
- Threshold decreased from 50 eV_{ee} to 15 eV_{ee} (4 e-).
- If exponential excess present, should observe with high significance in <1 year.





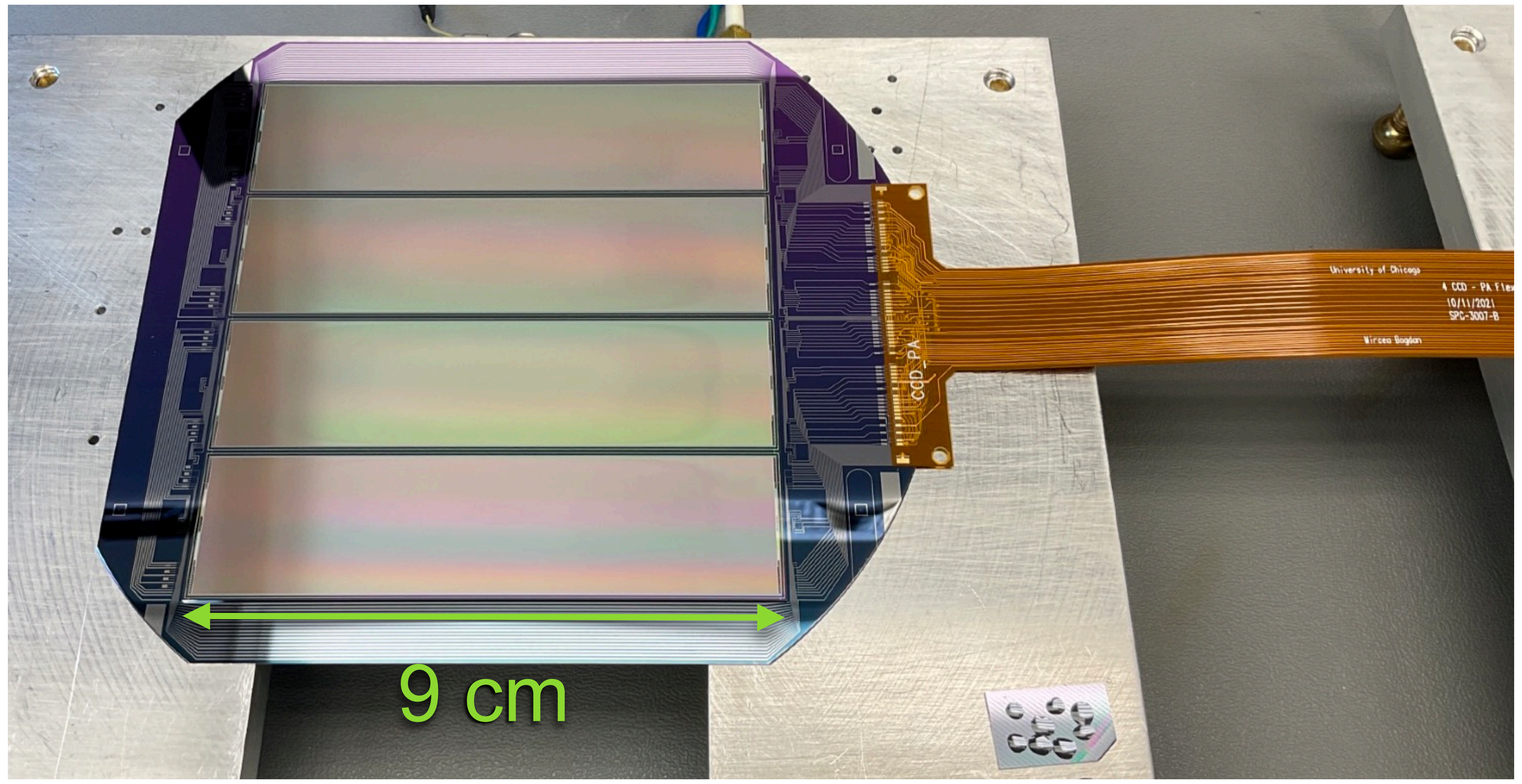
DAMIC-M

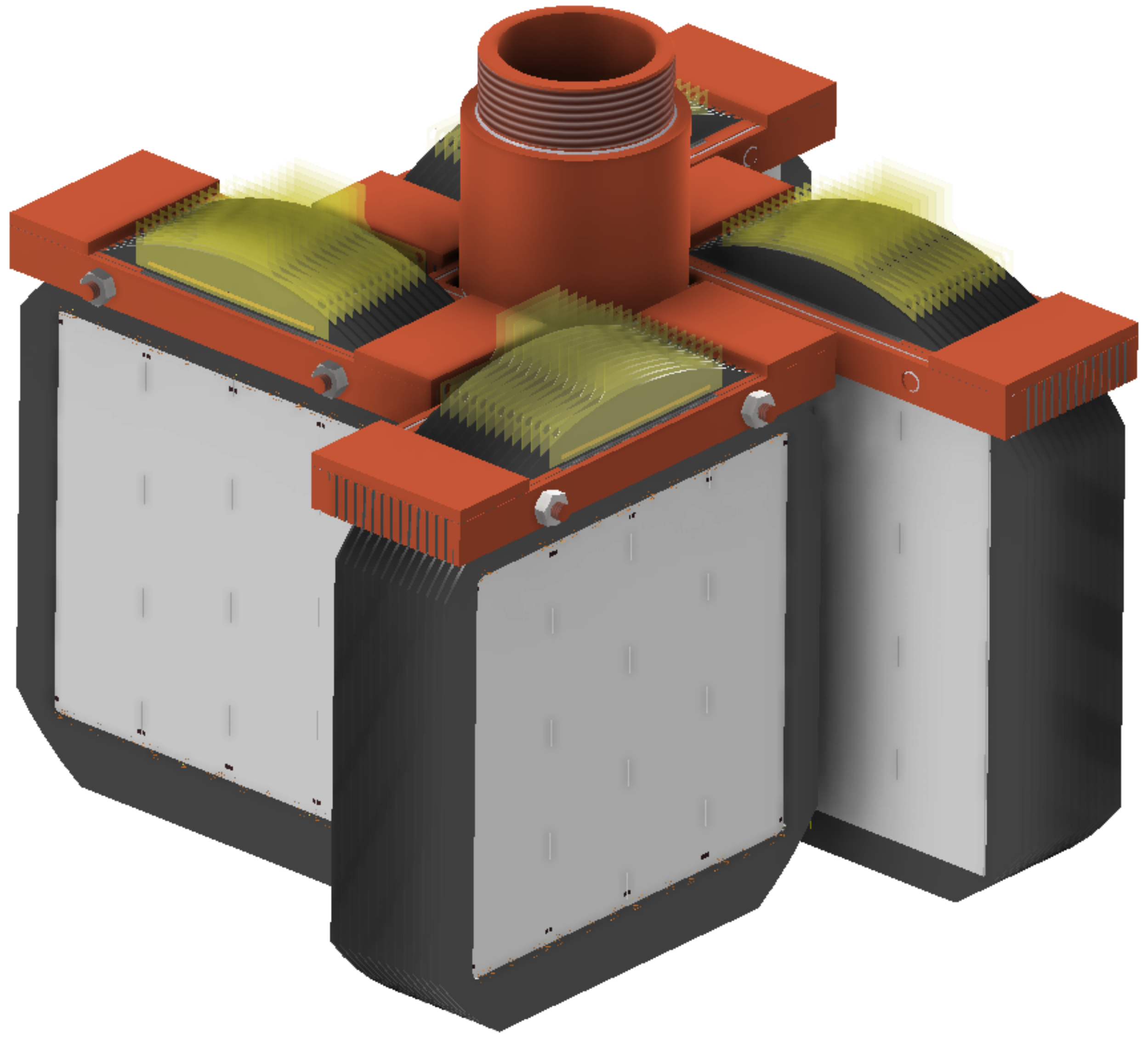
- 52 CCD modules in LSM (France) for kg-year target exposures.
- Skipper readout for 2 or 3 e^- threshold.
- Background reduction to a fraction of d.r.u. (improved design, materials, procedures).
- Main challenges: cosmogenic activation, surface contamination, backside CCD response.
- Besides DM-e searches, DM-N result may have comparable sensitivity to HV detectors of SuperCDMS SNOLAB.



Prototype CCD module:

Can read four 6k x 1.5k CCDs with a single electronics controller



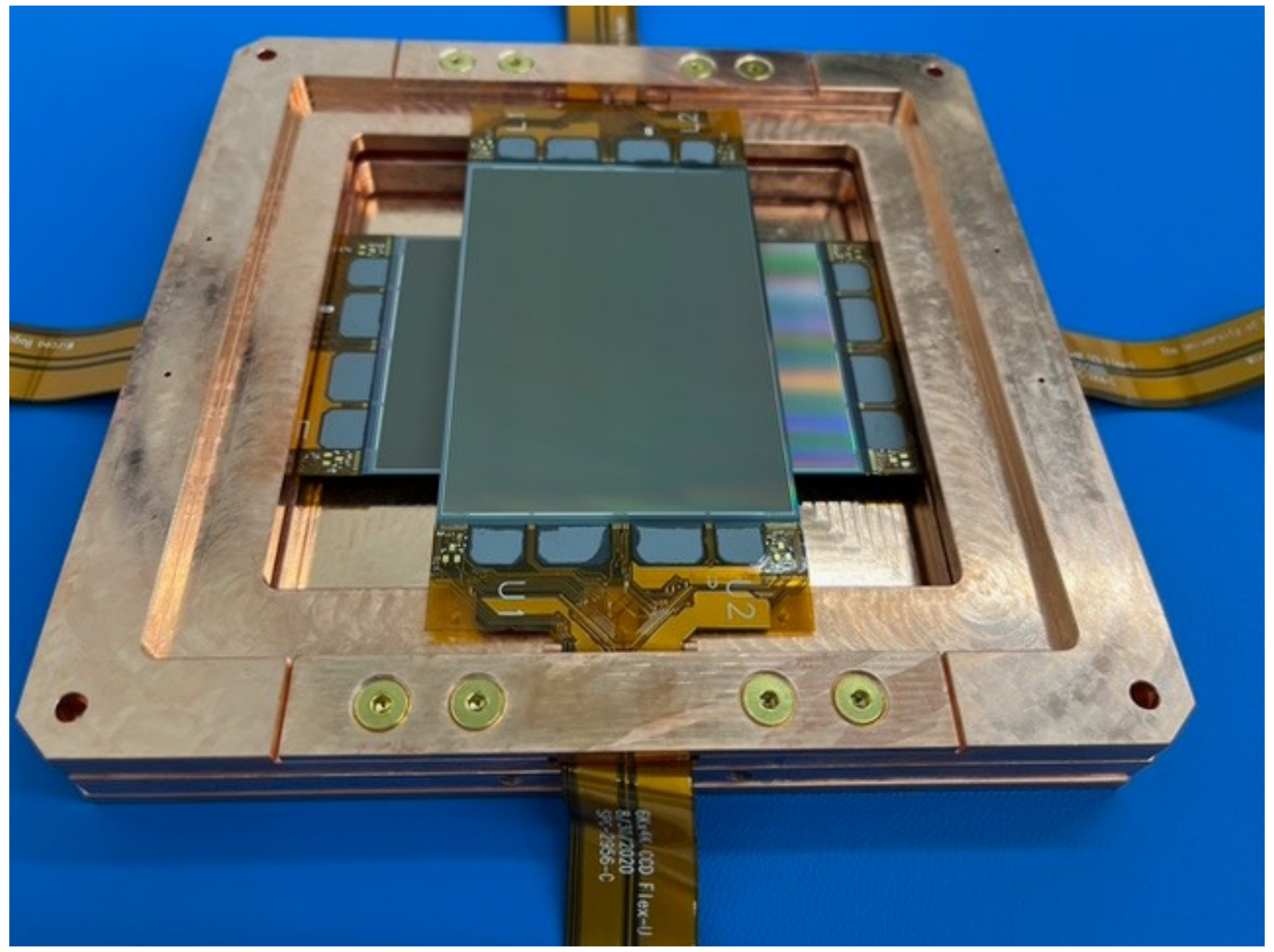


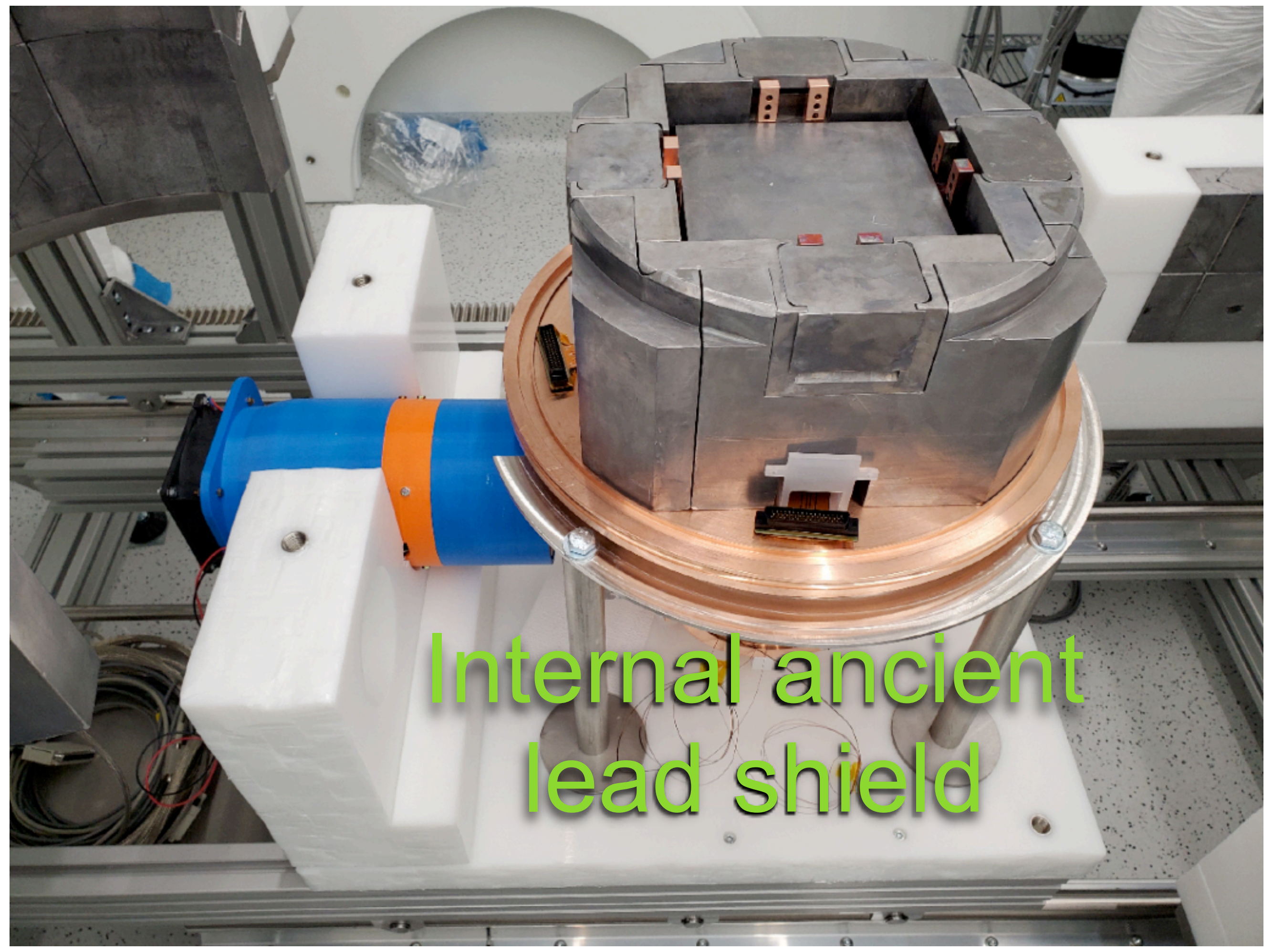
DAMIC-M Progress

- DAMIC-M clean room at LSM since 2021.
- Currently hosts the Low Background Chamber (LBC).
  Ultimate goal: demonstrate background rates ~1 d.r.u. and a path to 0.1 d.r.u.
- Second batch of 100 “pre-production” CCDs arrived at UW at the end of August.
  Devices currently being tested.
  Final CCD production to start before end of 2022. Wafers stored at SNOLAB.
- CCD electronics controller + IC front end being finalized.
- Low-background CCD array design being finalized.
  PNNL identified a provider for highly radiopure flexes (R. Saldanha LRT 2022).
- First cryostat design complete (including full background simulations).
  May need to be modified depending on final detector location in LSM.
- Growth of electroformed copper to start at LSCanfranc before end 2022.
- **Detector construction in 2023. Commissioning in 2024.**

DAMIC-M LBC

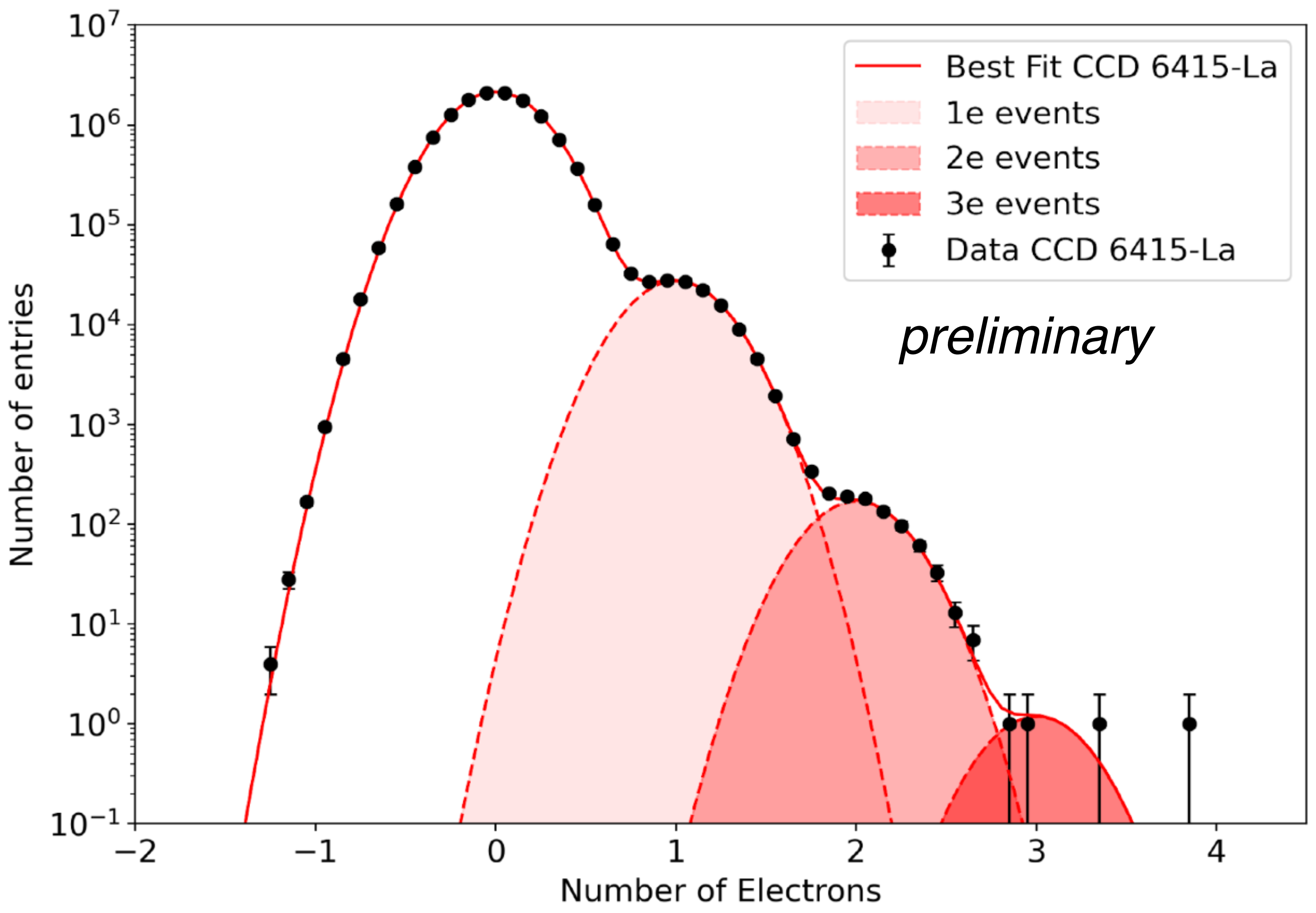
- Two 24 Mpixel DAMIC-M prototype skipper CCDs installed in Oct 2021.
- Low Background Chamber (LBC) test setup for DAMIC-M at LSM for performance and background studies.
- Single-e^- resolution, 2 x 10^{-3} e^-/pix/day, 10 d.r.u., 18 g.

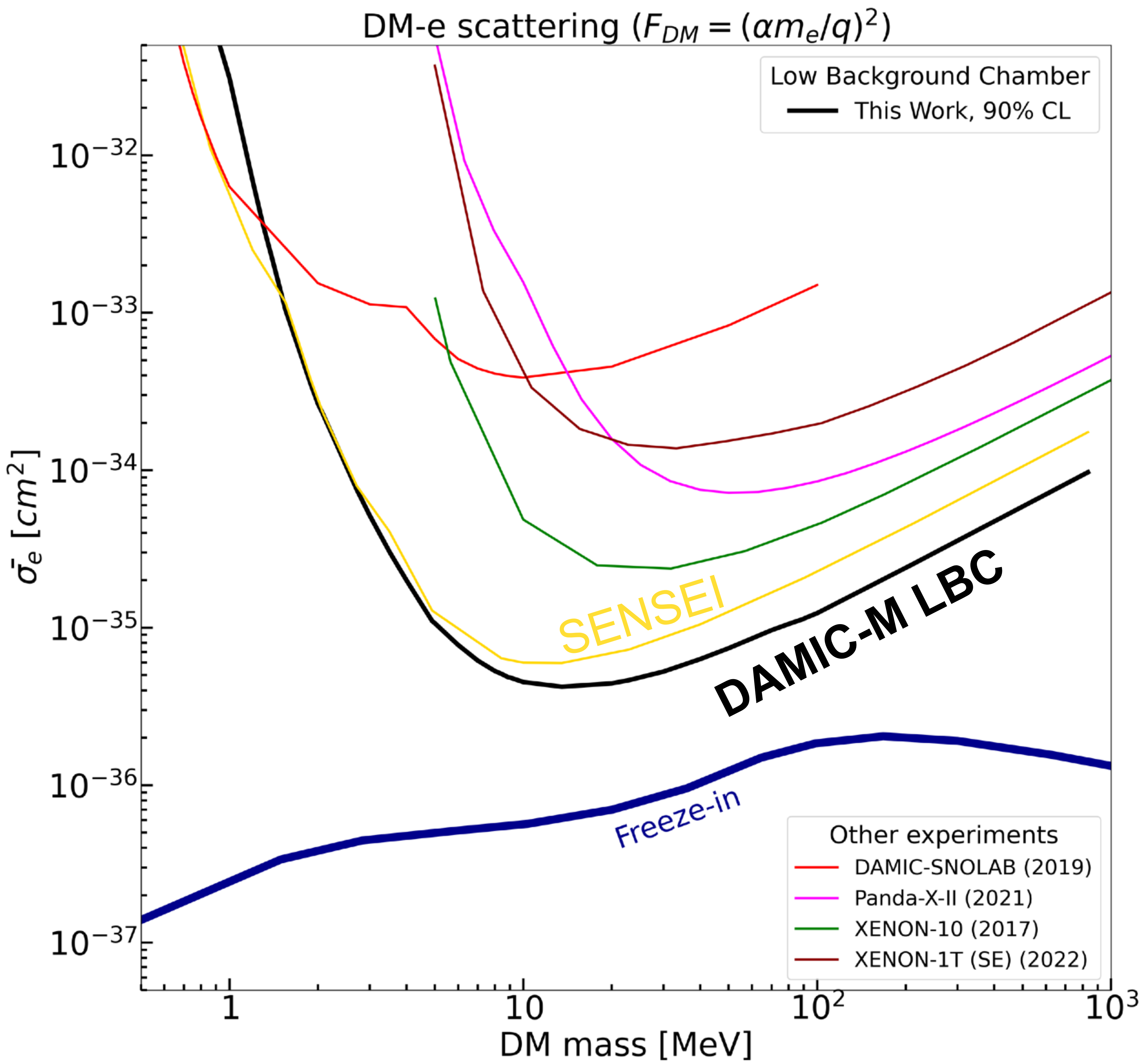




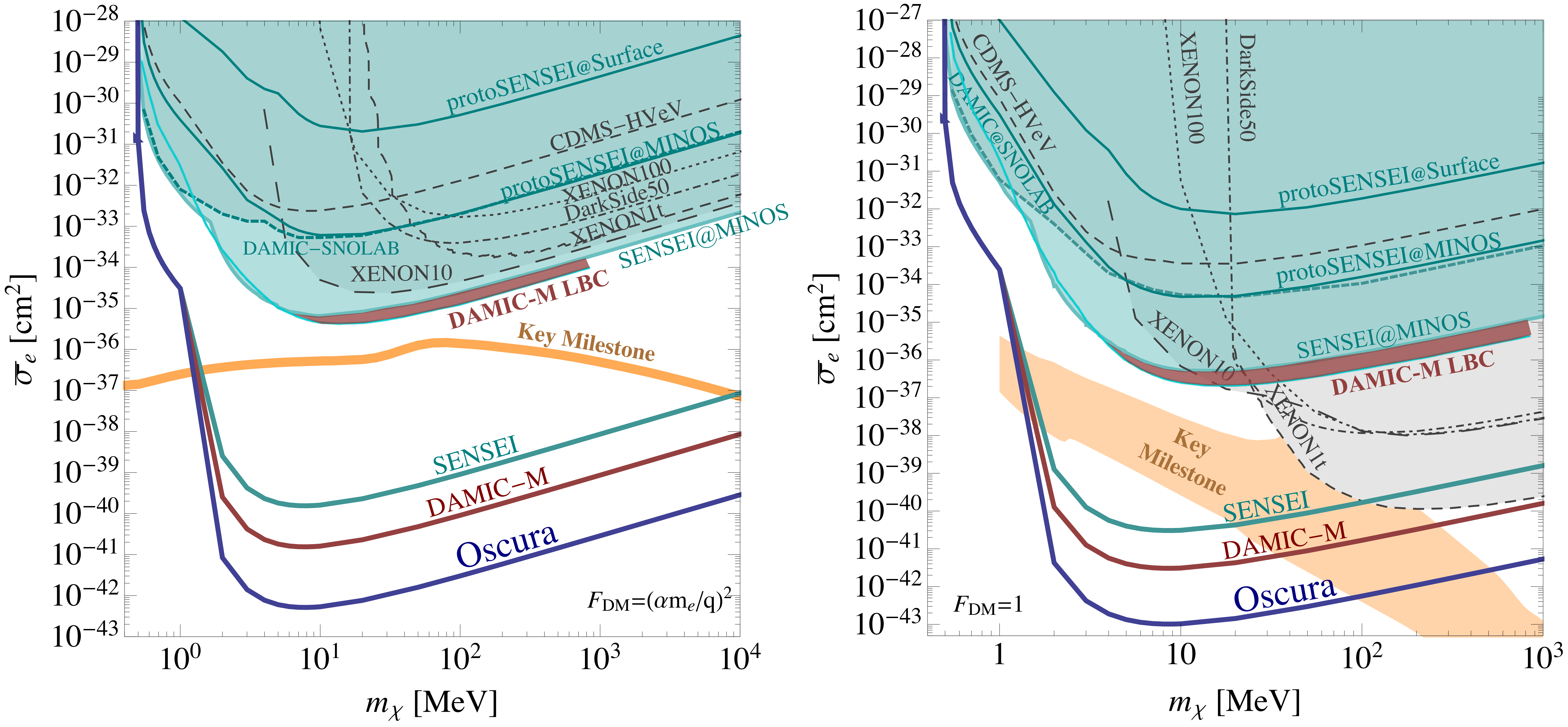
DAMIC-M LBC result

- Pixel distribution from 115 g-d of data.
- Image selection; mask high E ionization events, regions of elevated leakage current (defects) ~10% of the CCDs.
- Background model: leakage current in the CCDs (ionization events are negligible).
- Signal model: QEDark to generate differential rate of DM signal, ionization model from PRD **102** (2020) 063026, diffusion model from our surface calibrations.
- Fit distribution to set 90% C.L. upper limits in cross section-DM mass parameter space.
- Observe one 4e- event with probability of 15%.





Outlook



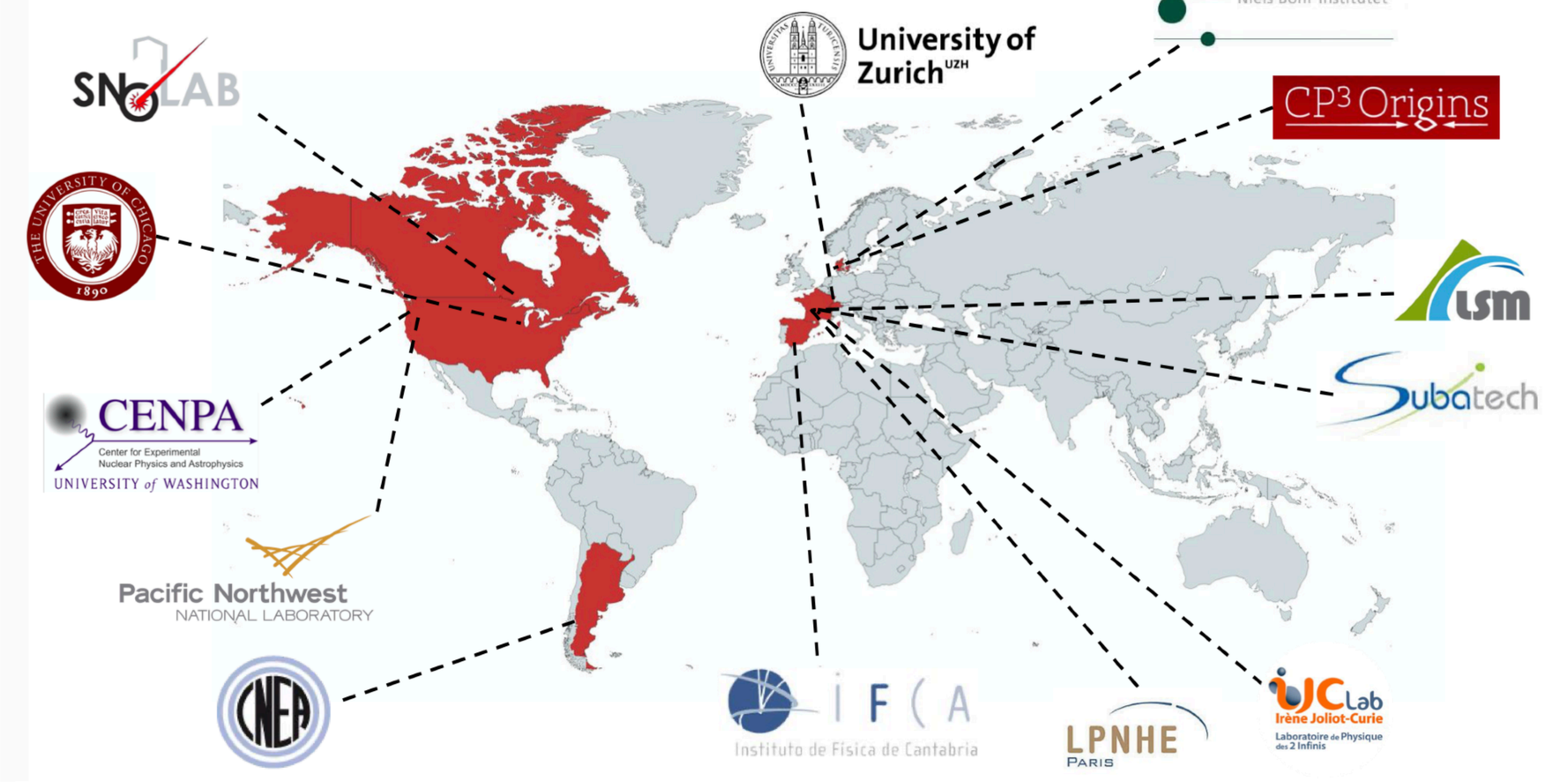
protoSENSEI@Surface
CDMS-HVeV
protoSENSEI@MINOS
XENON100
DarkSide50
XENON1t
SENSEI@MINOS
DAMIC-SNOLAB
XENON10
DAMIC-M LBC
Key Milestone
SENSEI
DAMIC-M
Oscura
$F_{DM}=(\alpha m_e/q)^2$
$\bar{\sigma}_e$ [cm^2]
m_χ [MeV]
DAMIC@SNOLAB
$F_{DM}=1$

Conclusions

- Electronic recoil searches allow us to search for light DM.
- For DM-e scattering, ~MeV masses. Also Migdal, DM absorption.
- Require sensitivity to only a few charges ionized in the target.
- DAMIC pioneered the search for DM with CCDs.
- DAMIC-M will scale to kg-year exposures with single-charge resolution and correspondingly low backgrounds.
- Active experimental program with orders-of-magnitude improvement in sensitivity to light DM in the coming years.

Thank you!

The DAMIC-M Collaboration



DAMIC Collaboration