"particle"

Light DM: Experiment

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DAMIC-M

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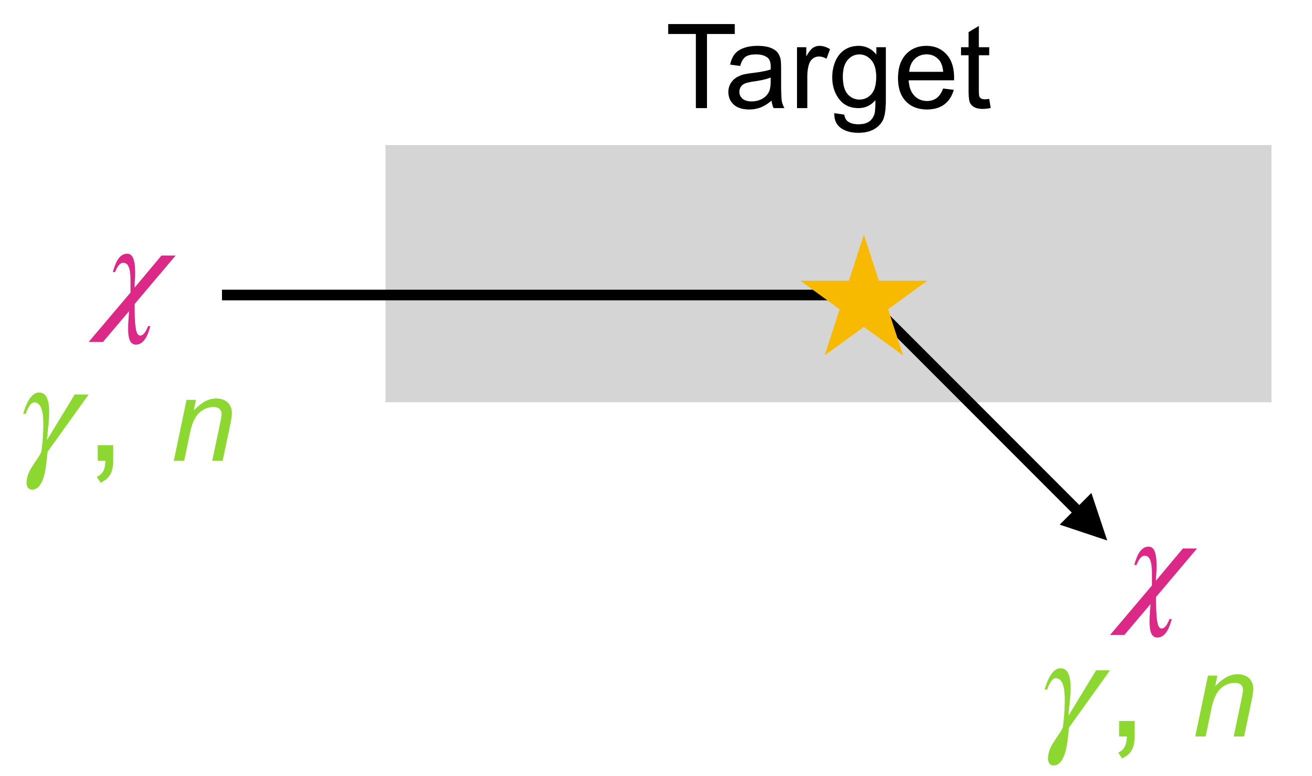
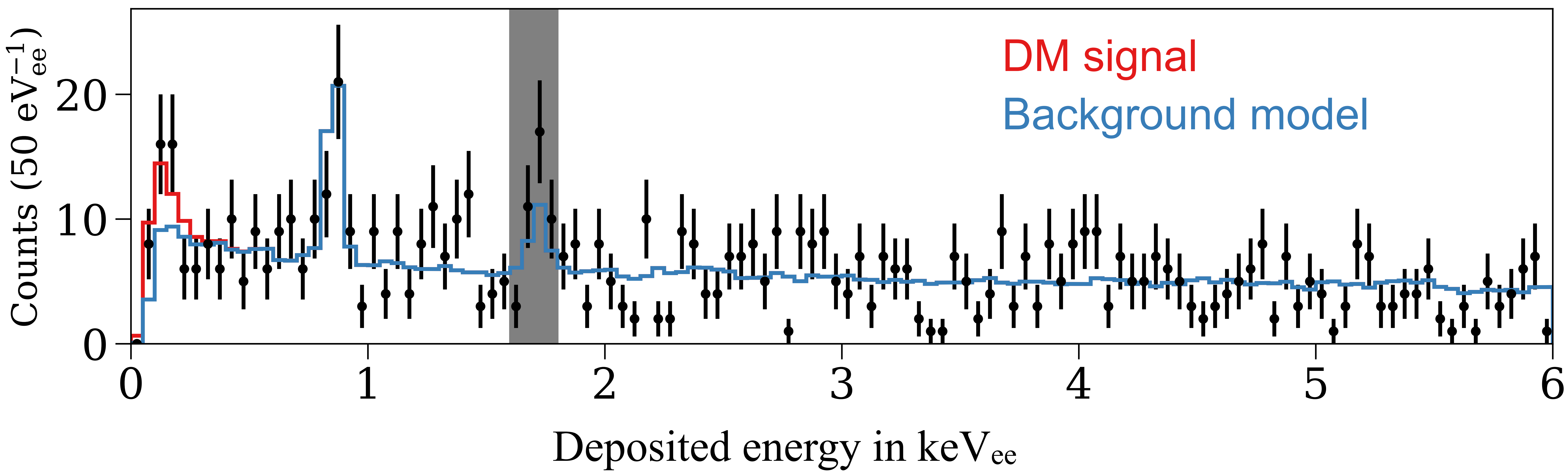
Outline

- Low-energy spectroscopy for dark matter (DM) direct detection (DD).
- 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 other skipper CCD experiments.
- SuperCDMS and EDELWEISS HV detectors.
- Outlook.

Spectroscopy for DM DD



- DM particle χ from the Galactic Halo deposits energy in target.
- Environmental backgrounds γ, n also deposit energy in target.
- Signal amplitude positively correlated to energy deposited.
- Compare measured spectrum in target with predicted signal + background spectrum.



Signal spectrum

- Many ingredients go into the construction of the spectrum.

DM Flux + Interaction cross section = Deposited energy spectrum

Exciting astrophysics   Exciting particle theory

Deposited energy spectrum + Target response + Instrumental response = Measured signal spectrum

Boring solid-state physics   Instrumentation

"**Boring**": No "new" physics. Theorists tend not to work on it.

Background Spectrum

- Many ingredients go into the construction of the spectrum.

Environmental background flux + Interaction cross section = Deposited energy spectrum

Boring survey — Boring particle/nuclear theory

Deposited energy spectrum + Target response + Instrumental response = Measured background spectrum

Boring solid-state physics — Instrumentation

“**Boring**”: No “new” physics. Theorists tend not to work on it.

Calibration Spectrum

- Signal and background spectra must be validated!

Calibration source flux + Interaction cross section = Deposited energy spectrum

Boring particle/nuclear theory

Deposited energy spectrum + Target response + Instrumental response = Measured calibration spectrum

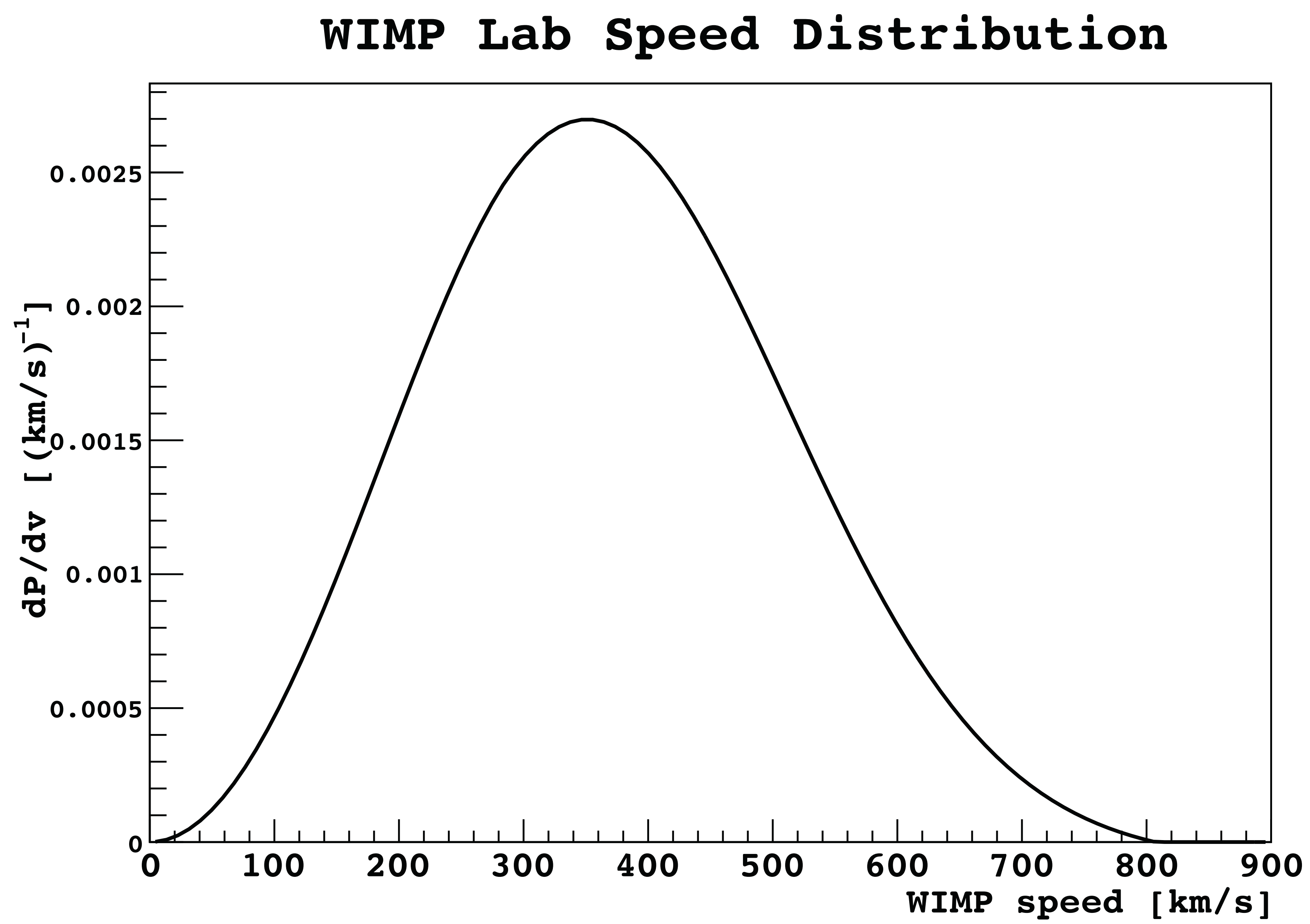
Boring solid-state physics

Instrumentation

“**Boring**”: No “new” physics. Theorists tend not to work on it.

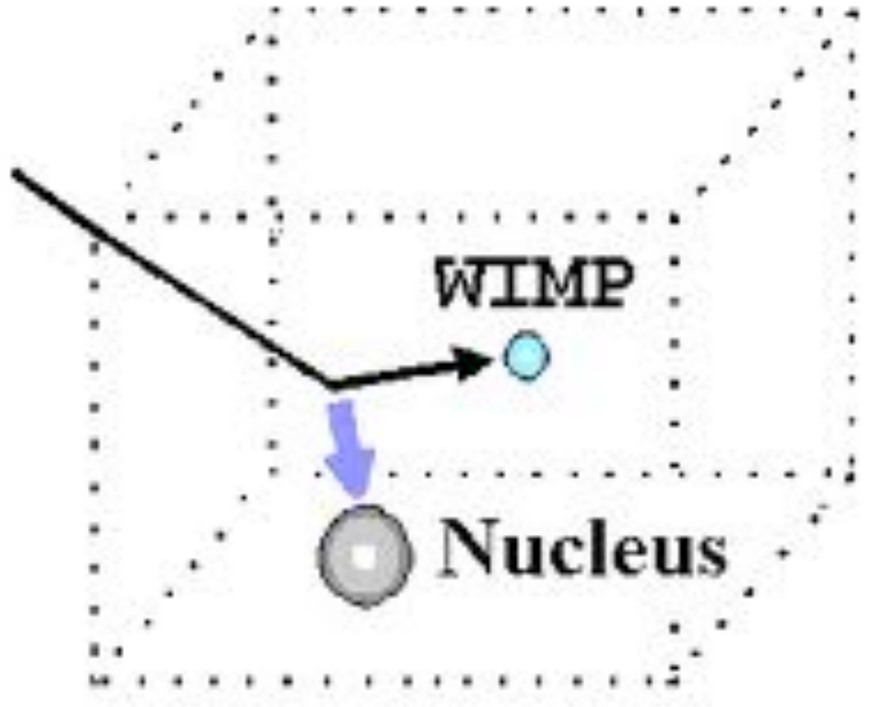
Dark matter signal

- 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: $\sigma_N \propto A^2$

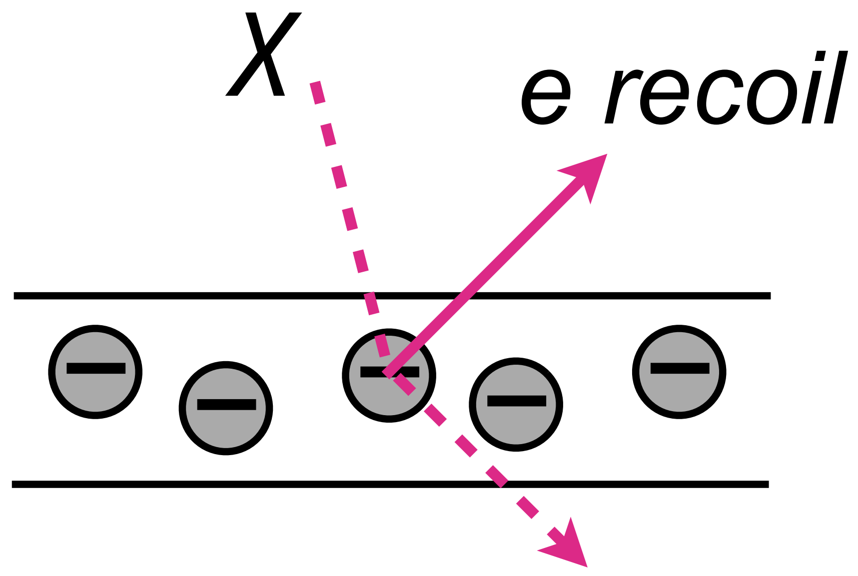


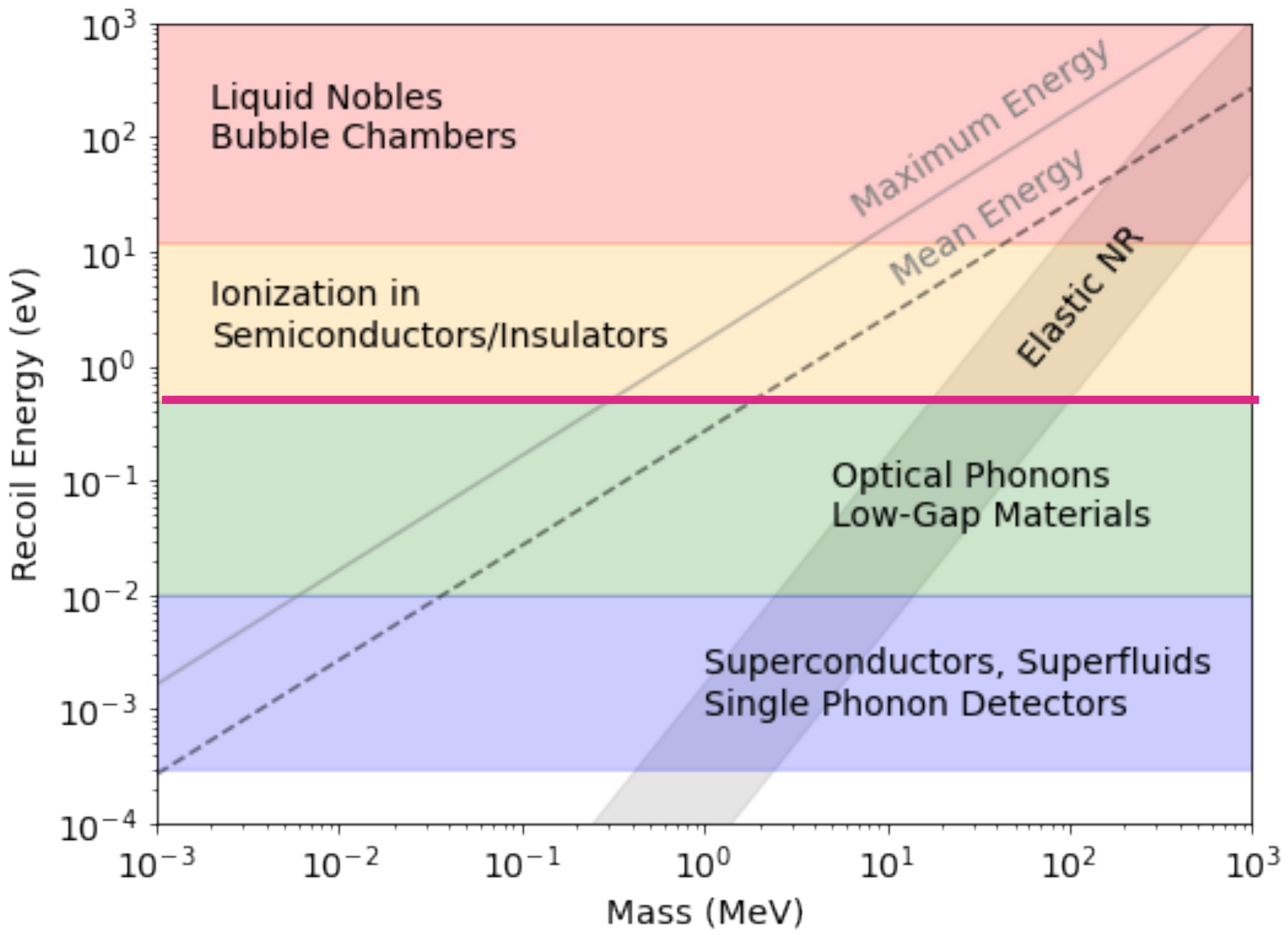
For low-mass WIMP: $M_T \gg M_\chi$

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

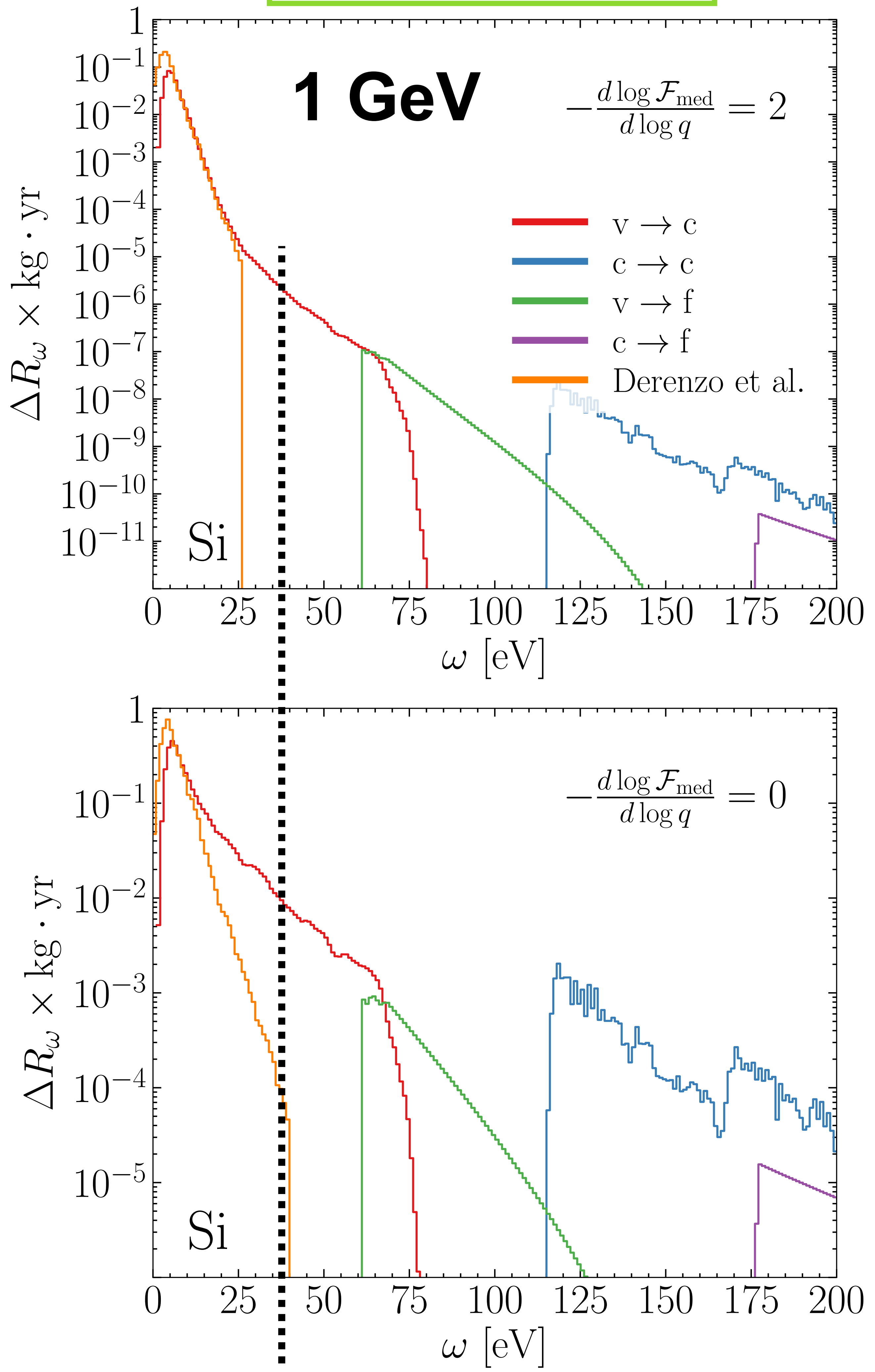
DM-e scattering

- 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

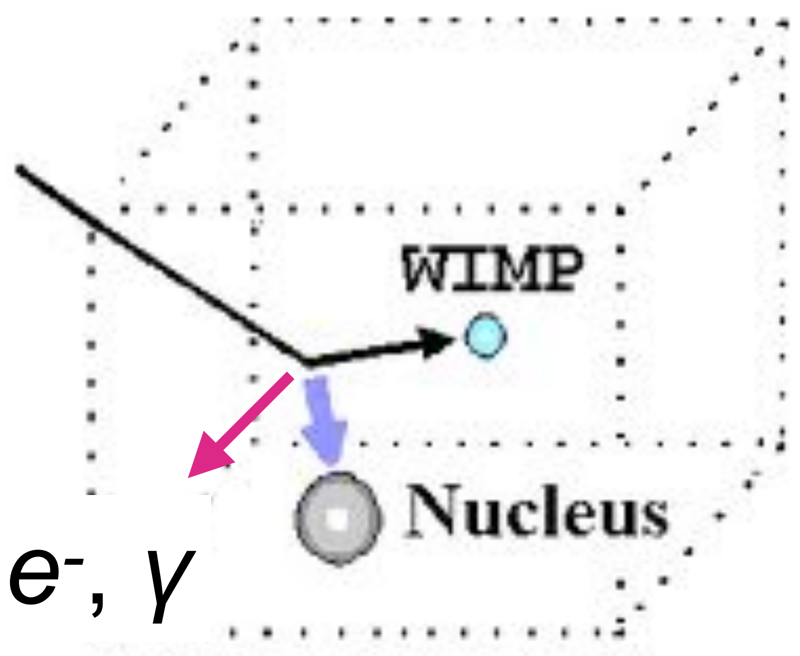


10 e^-

- 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.

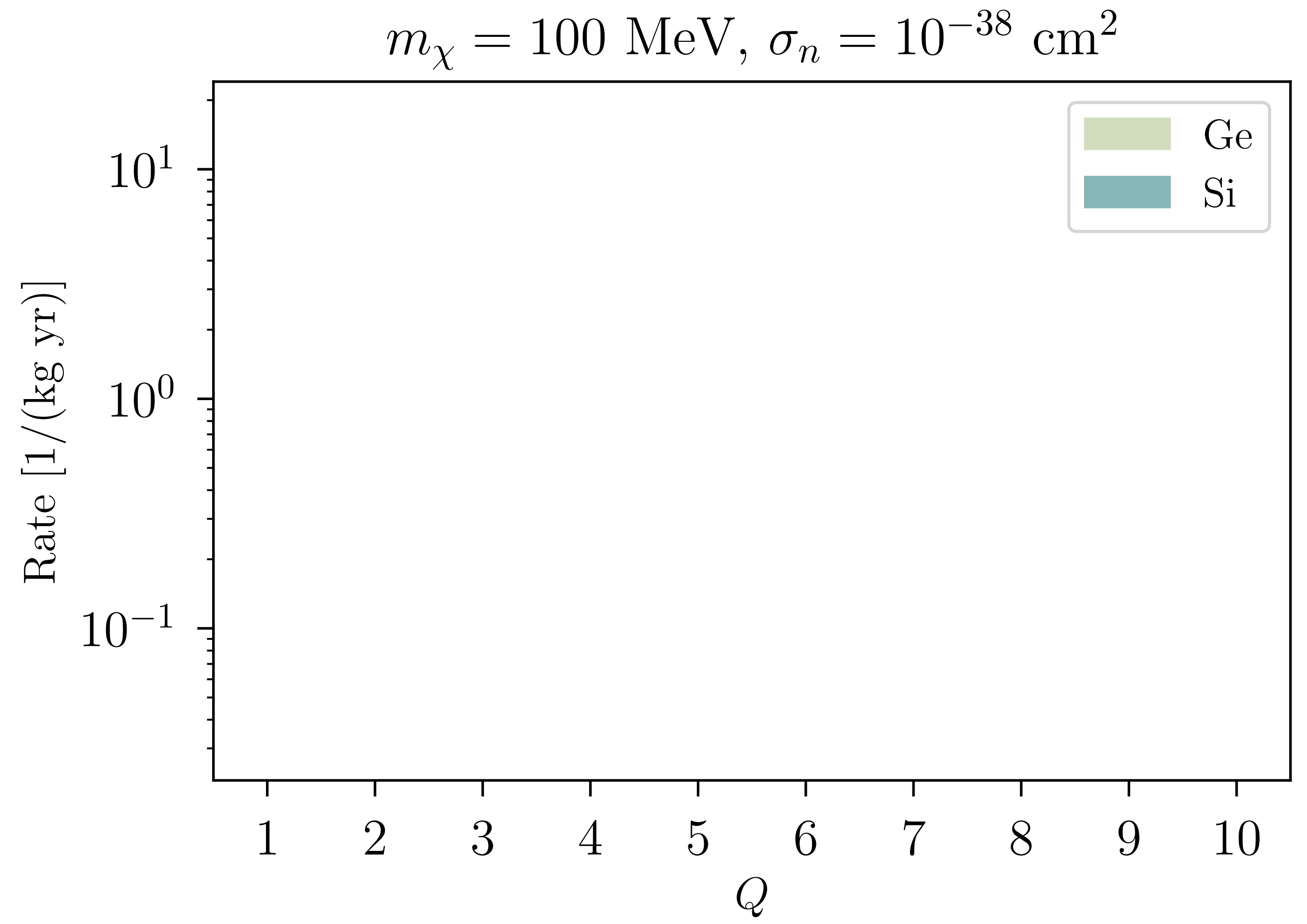
Other e-recoils

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.

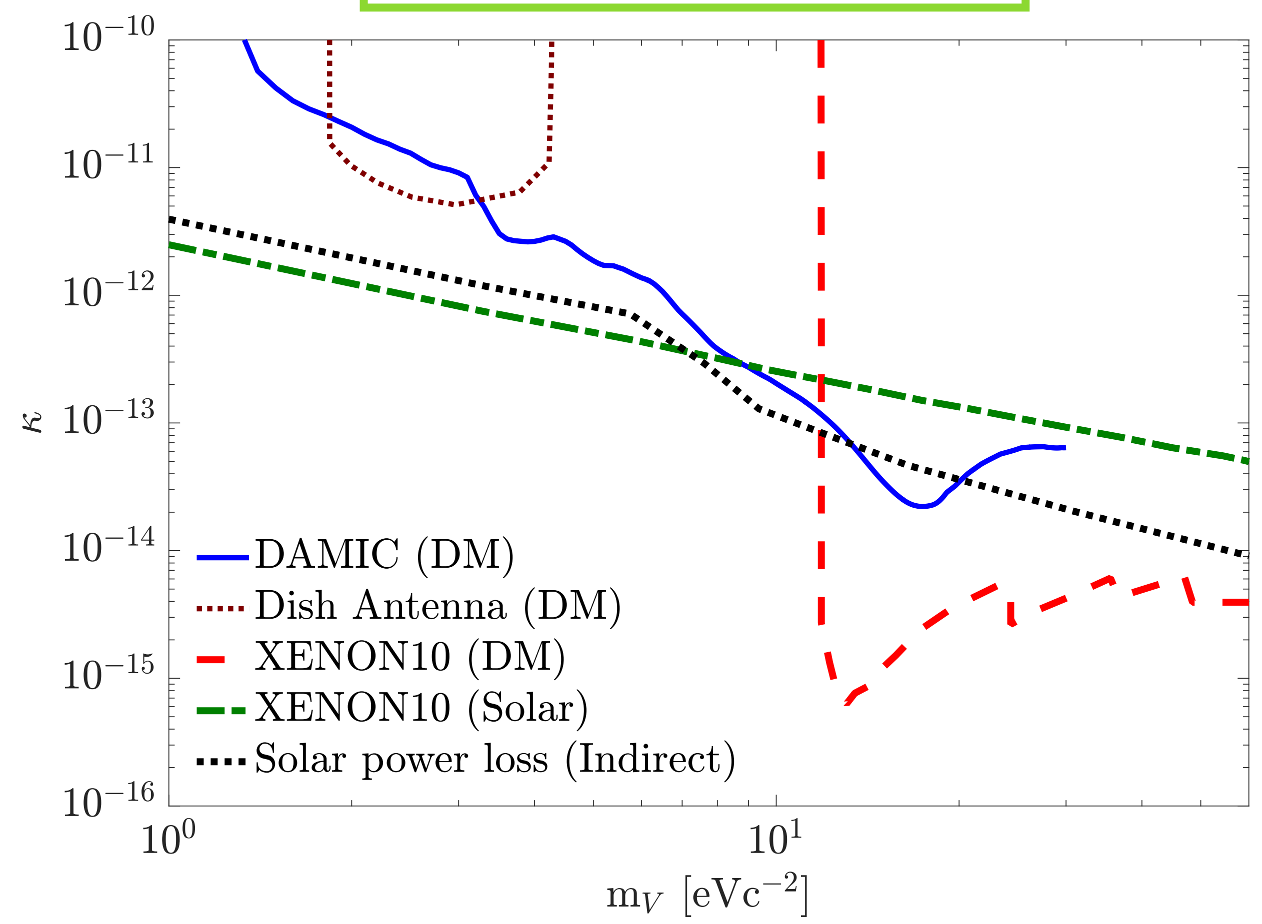
PRL127(2021)081805



Bosonic DM absorption:

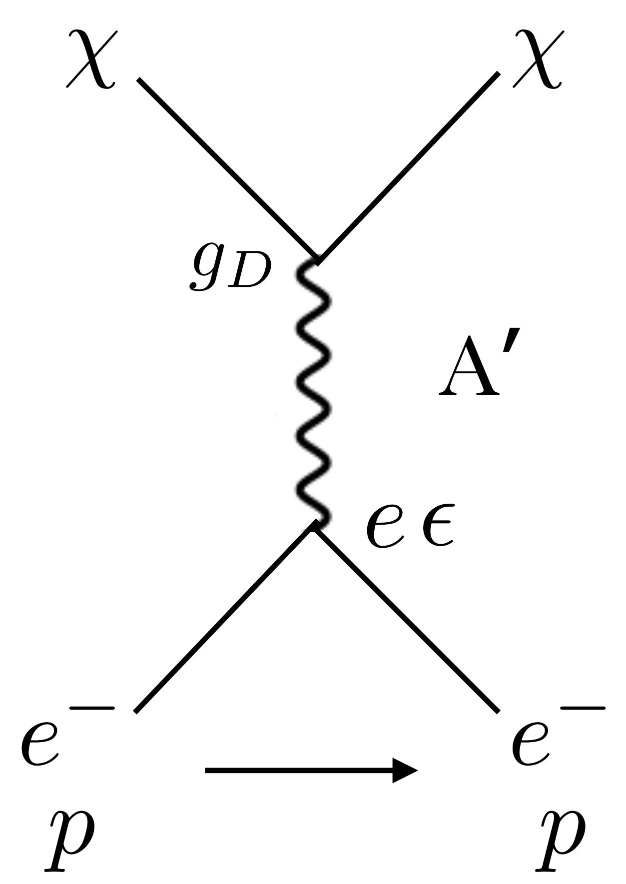
- DM particle is a boson that couples to the electron, e.g., a “dark” or “hidden” photon.
- DM is absorbed by the target electron and its rest energy released as electronic recoil K.E.

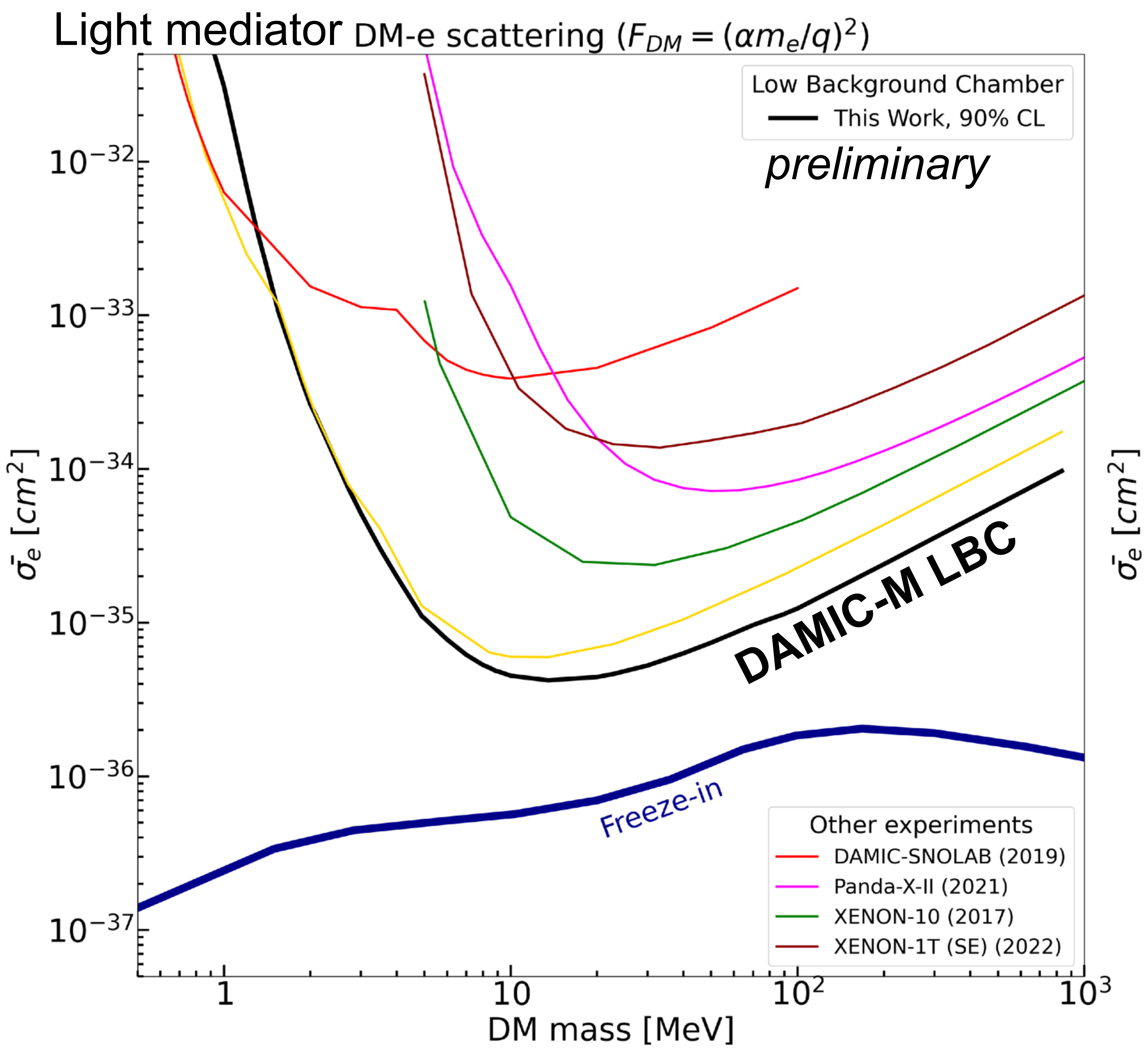
PRL118(2017)141803

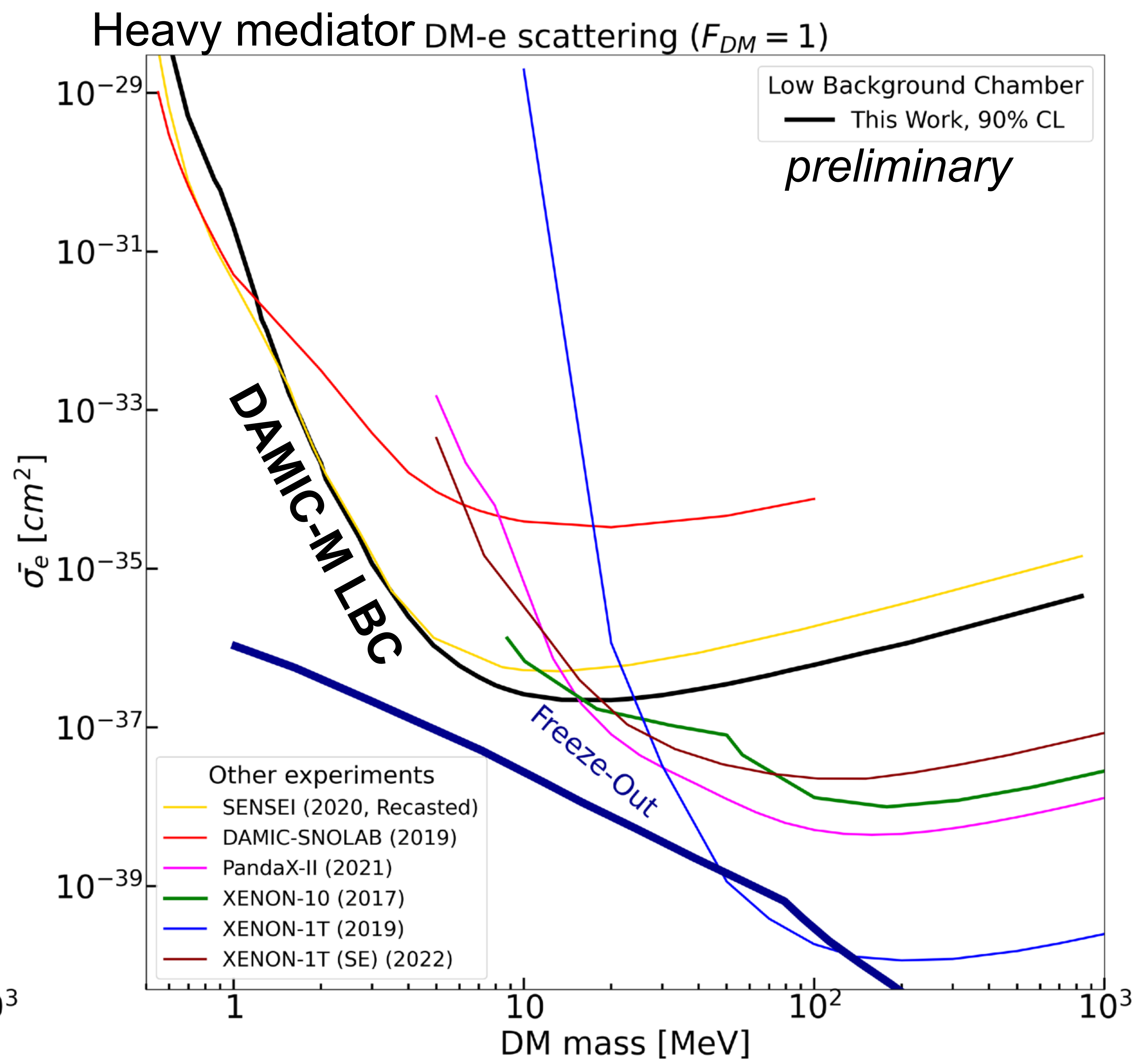


Electronic recoil result could also be interpreted as limit on DM-N scattering (Migdal) or DM absorption
I will use DM-e scattering parameter space as benchmark

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.**

Note!

- DM exclusion limits depend on the code used to generate the DM signal.
- Multiple codes available in the literature: QEDark, DarkELF, EXCEED-DM.

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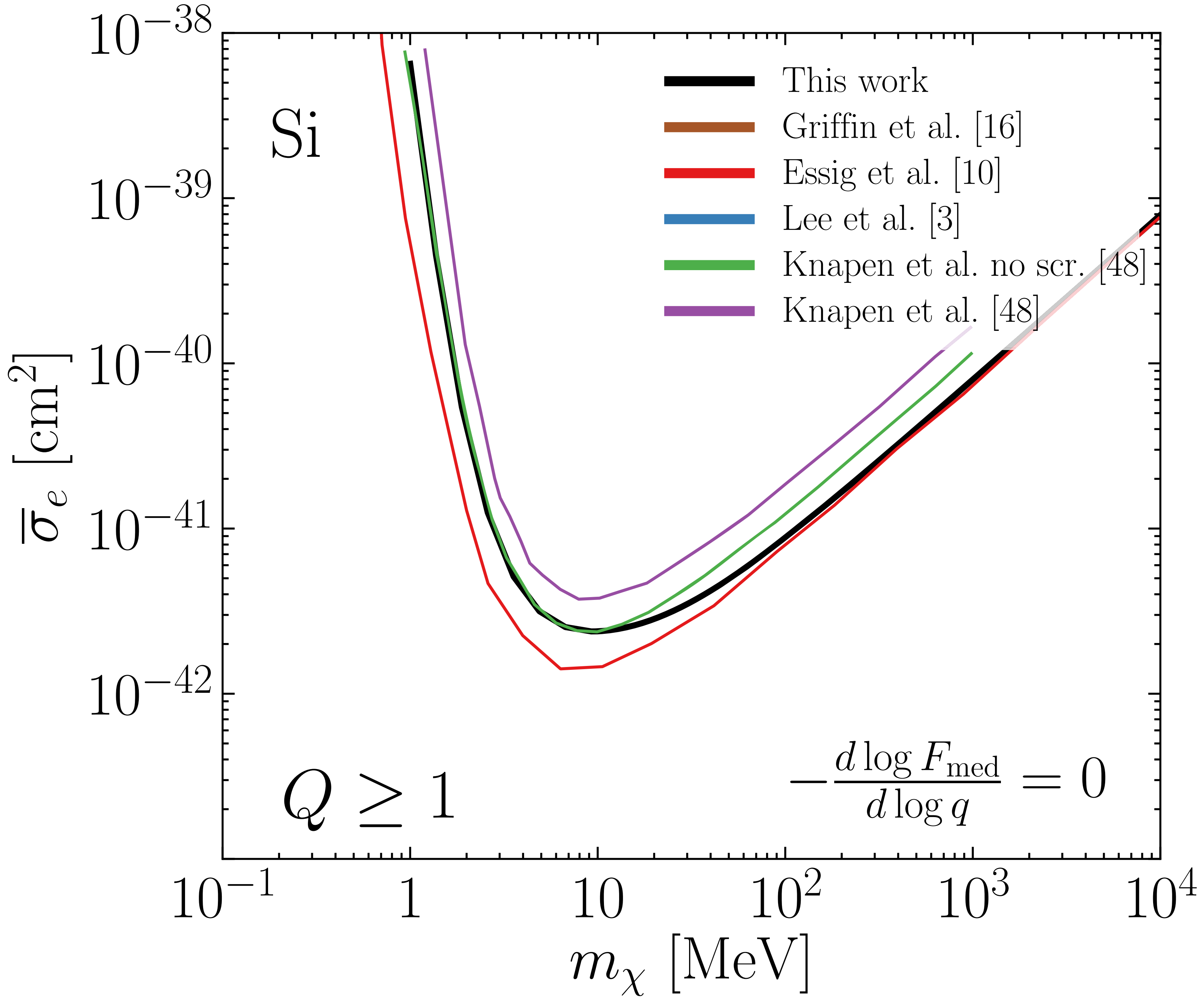
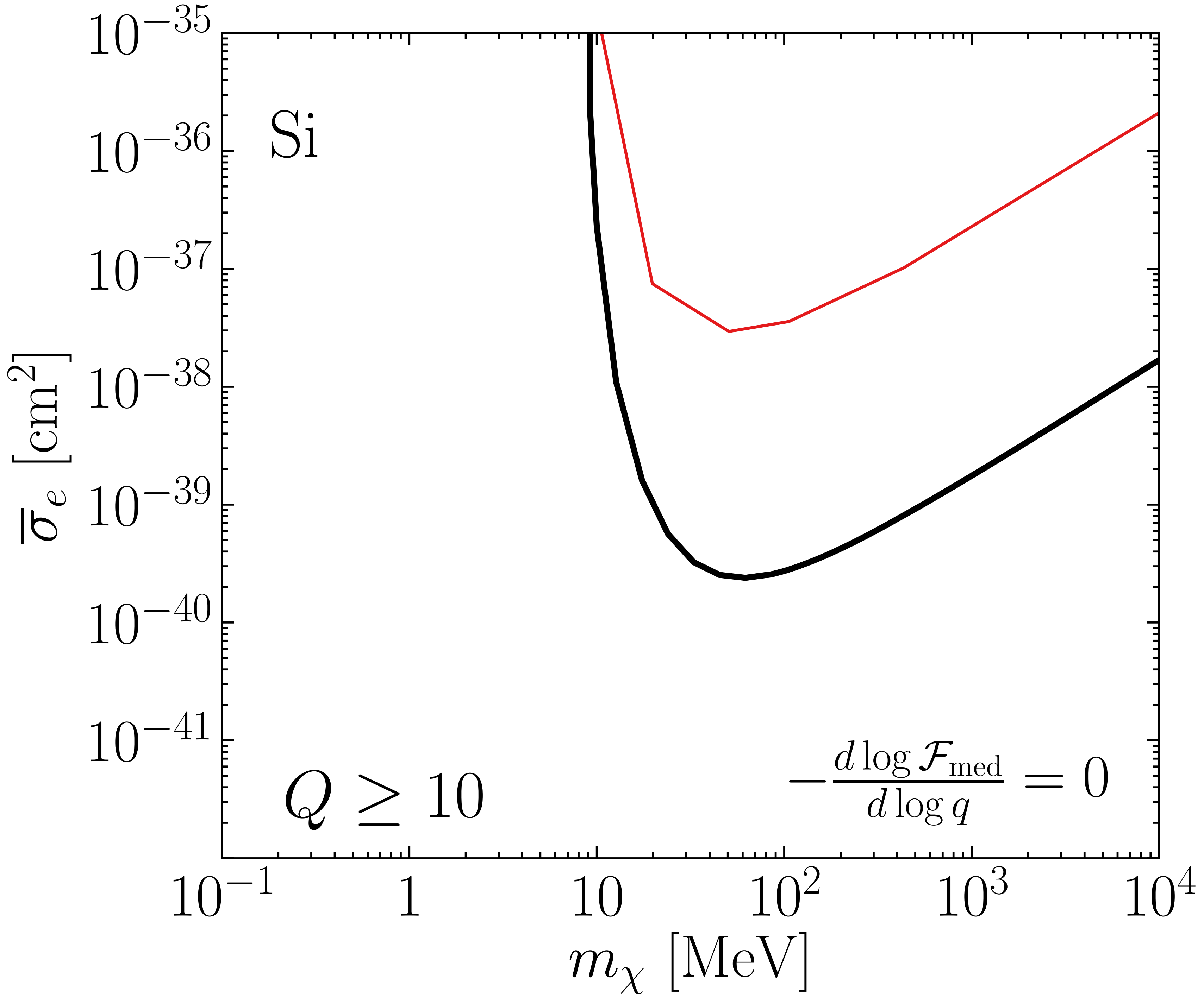
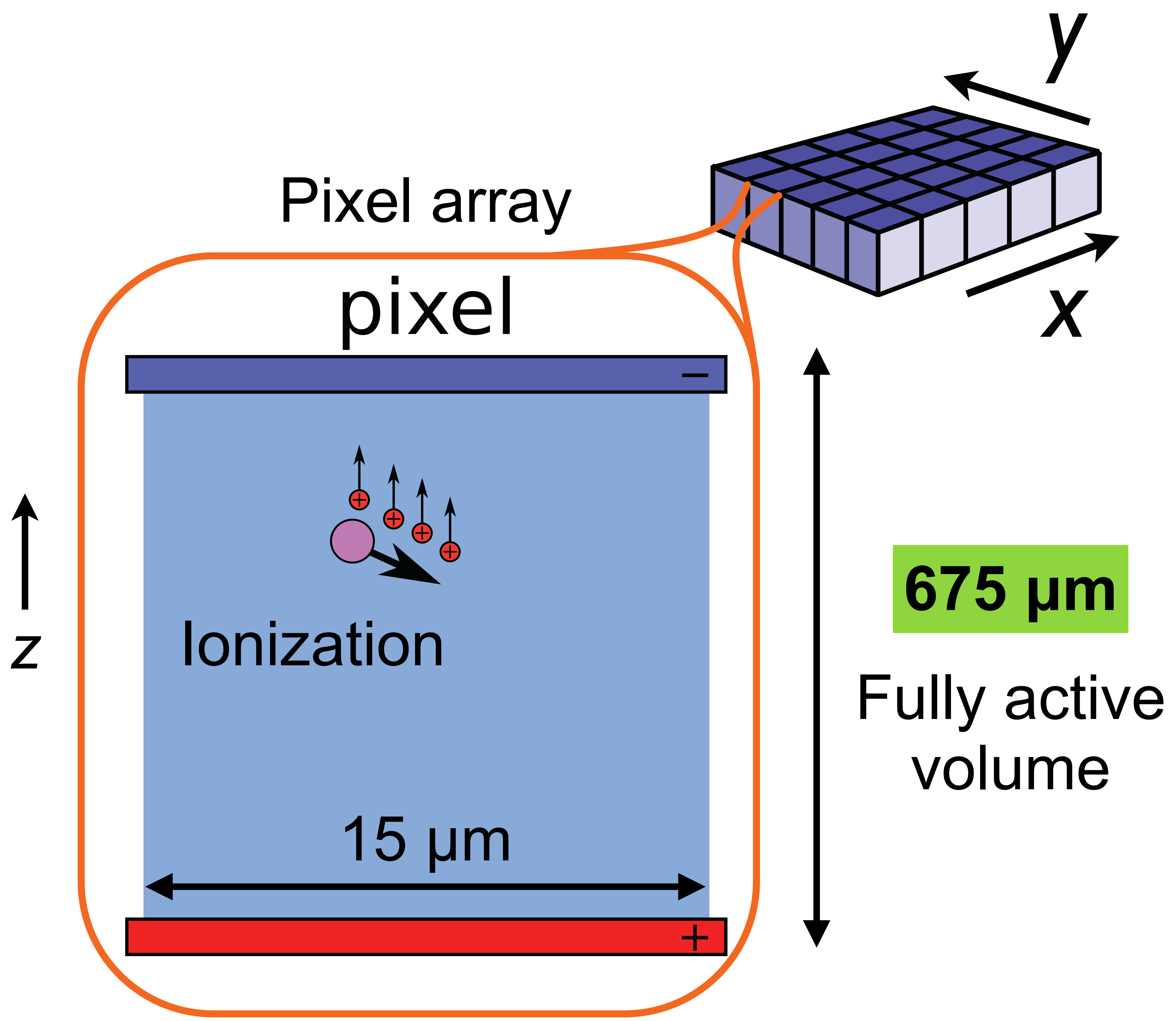
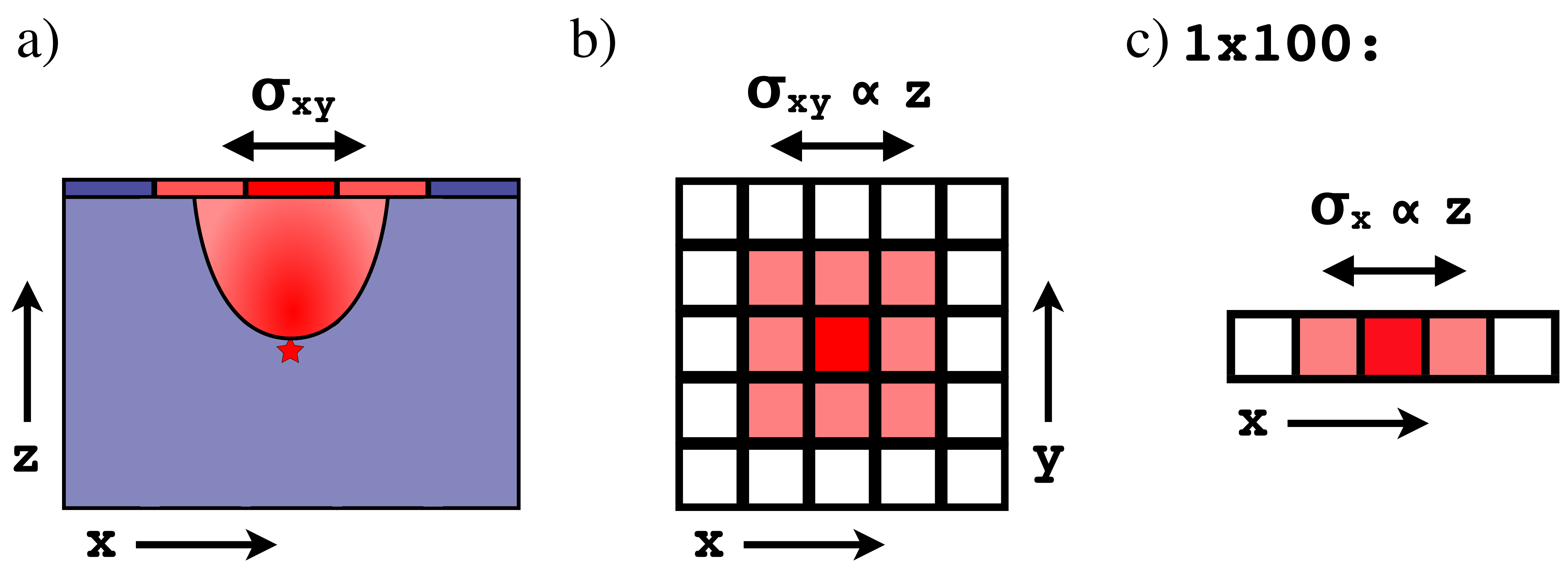




Charge-coupled devices



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

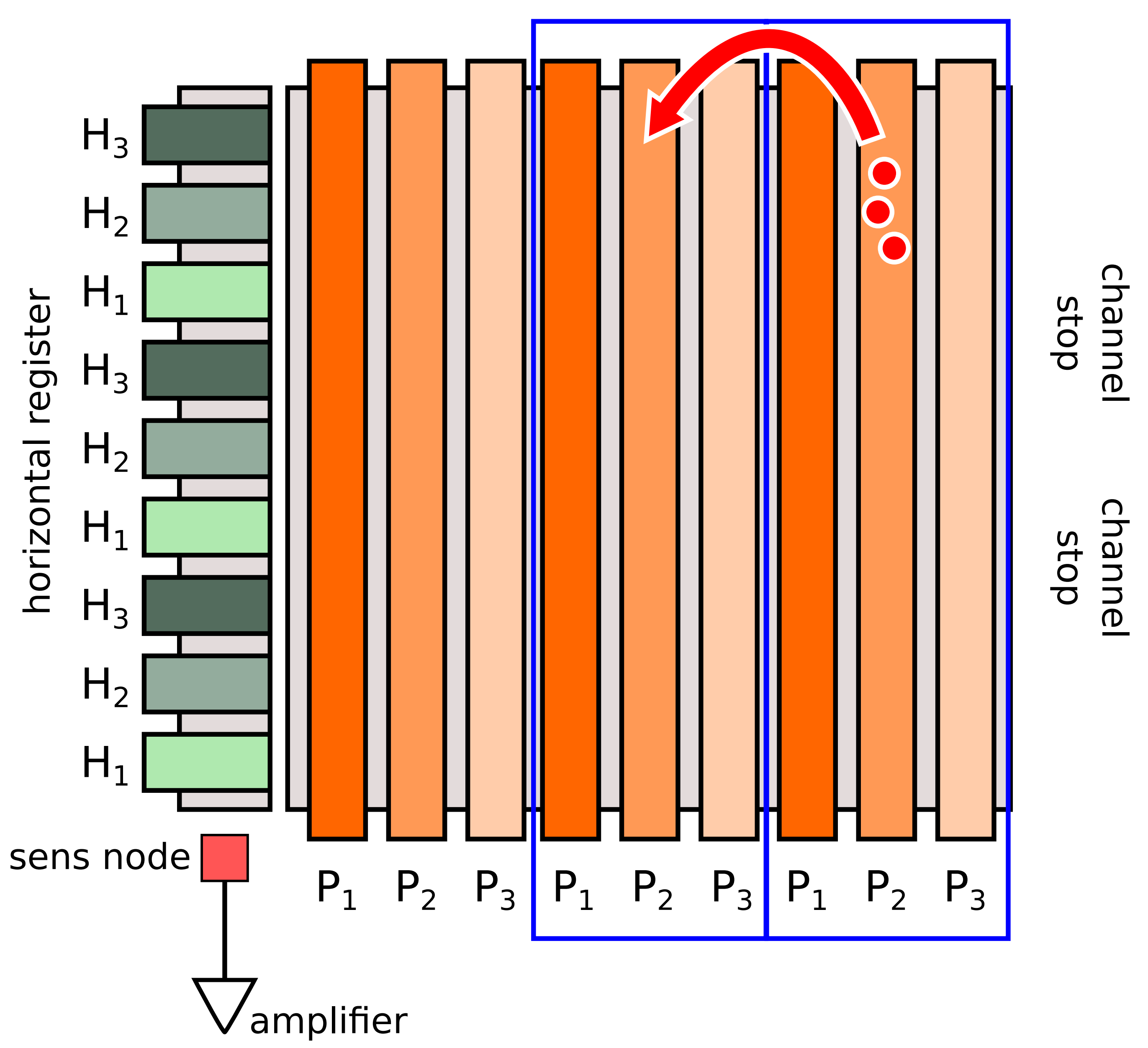


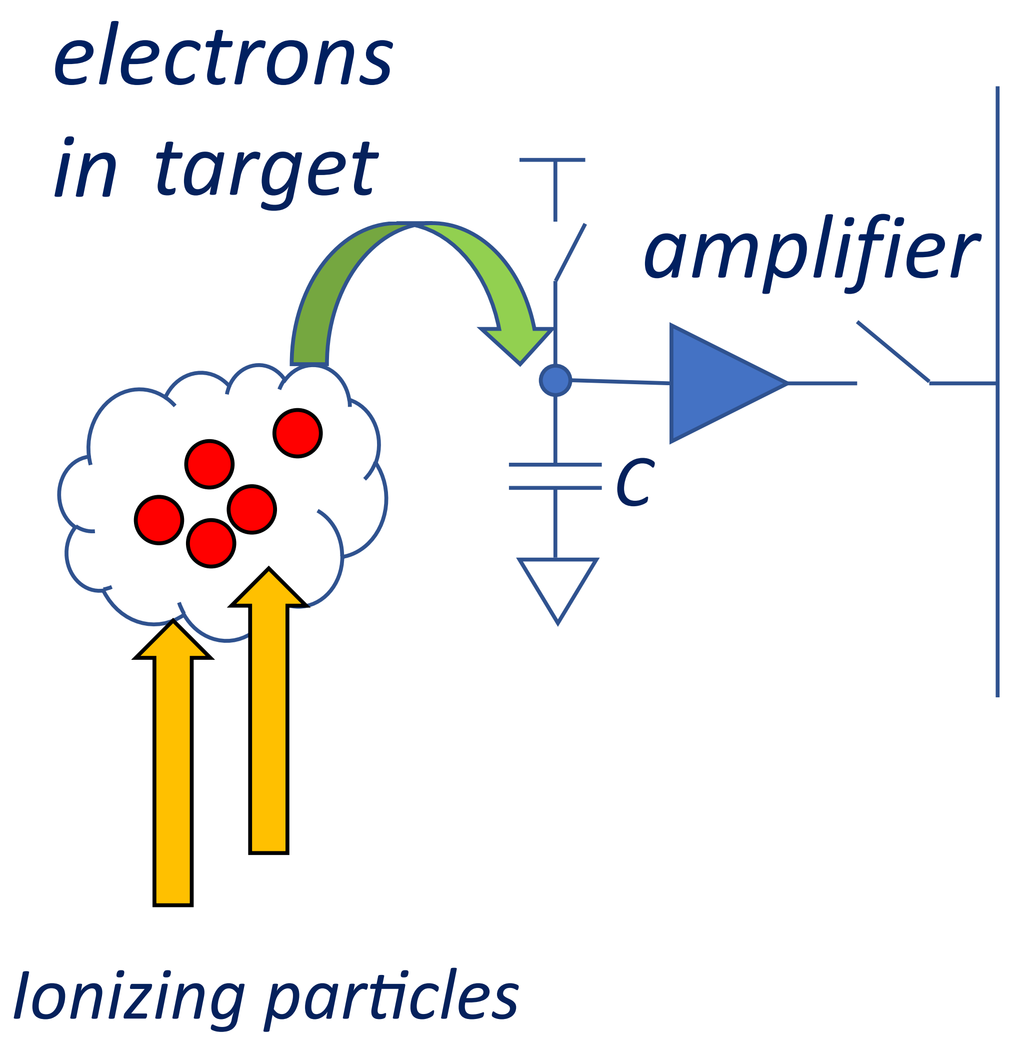
- Depth (z) reconstructed from distribution of charge on pixel array.
- Device is "exposed," collecting charge until user commands readout.
- Readout can be slow: **low noise (few e-).**
- Standard fabrication in semiconductor industry and easy cryogenics (~100 K).


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





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

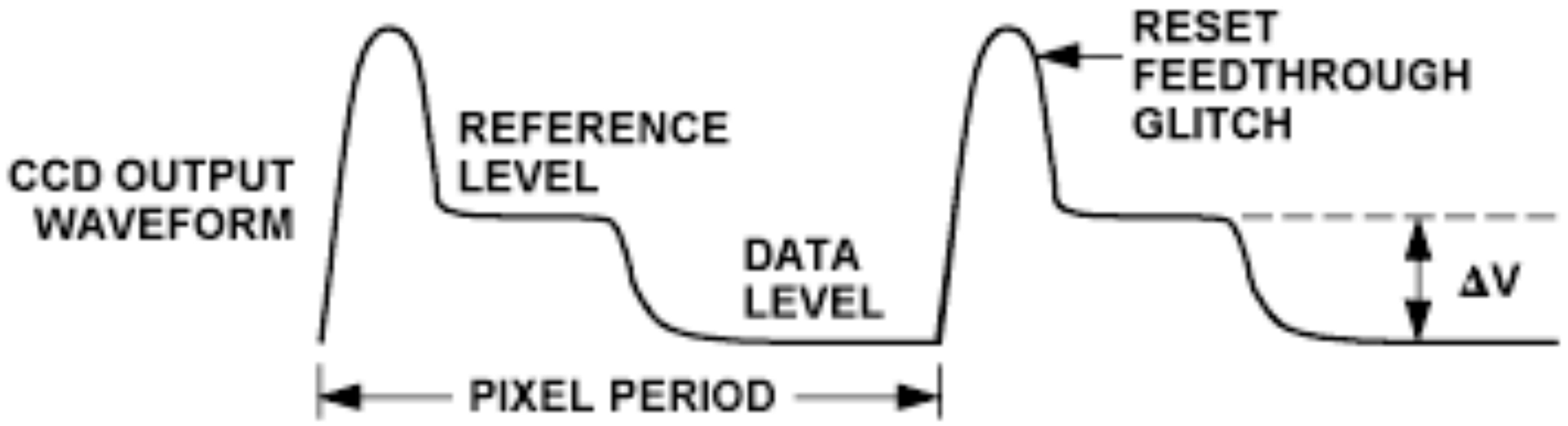
For ***C*** **~ 10 fF**: **ΔV/ΔQ ~ 16 μV/e$^-$**

Signal that you can measure

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

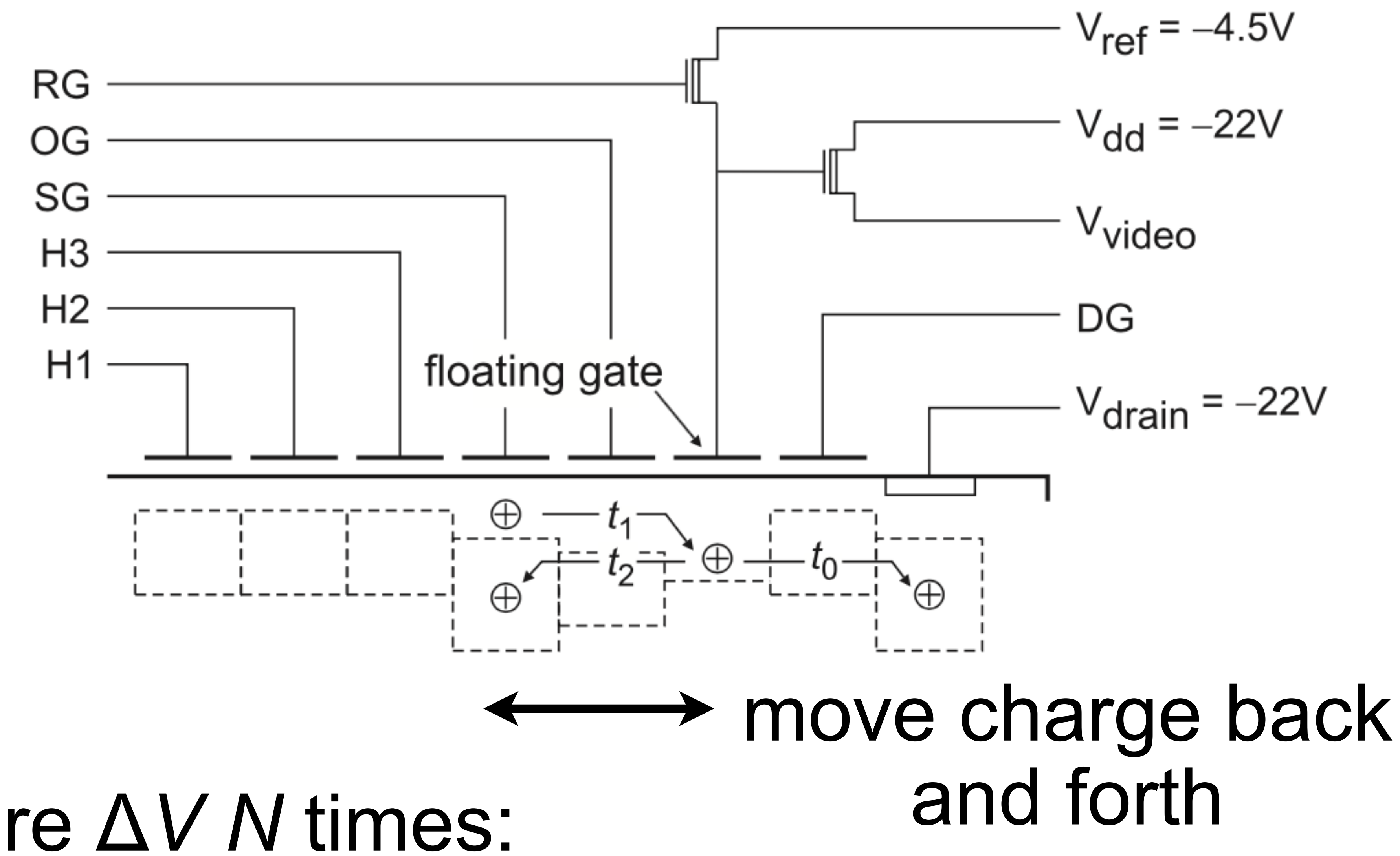
Correlated double sampling (**CDS**):

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

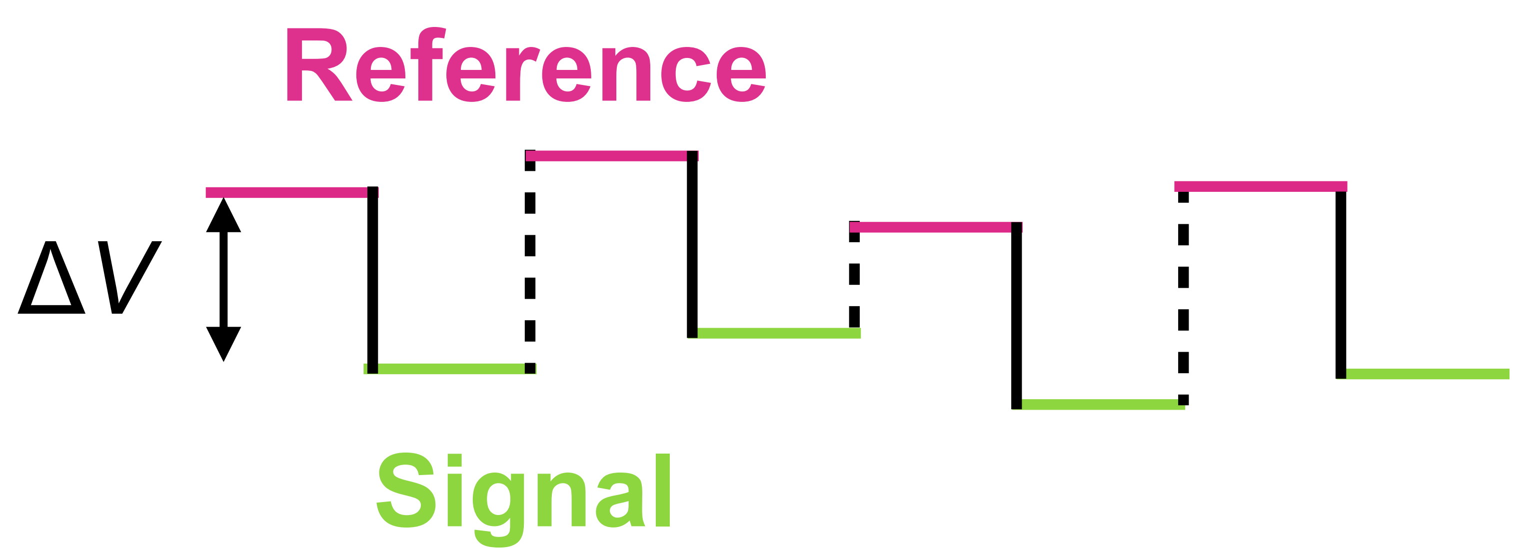


Skipper CCD

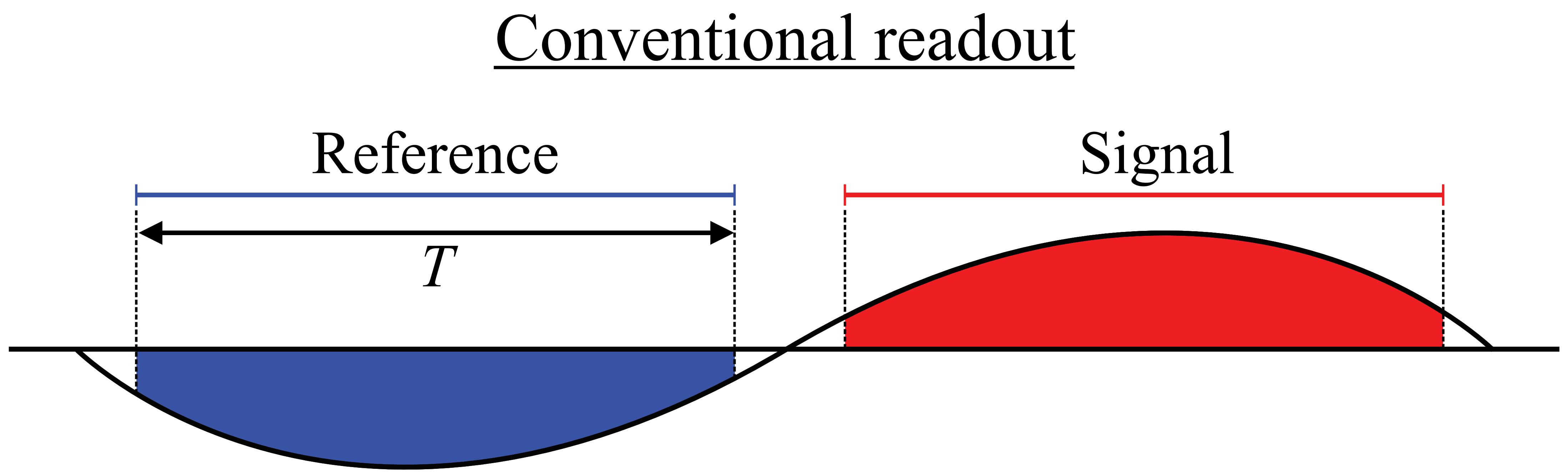
“Skipper” readout: Perform *N* uncorrelated measurements of the same pixel.

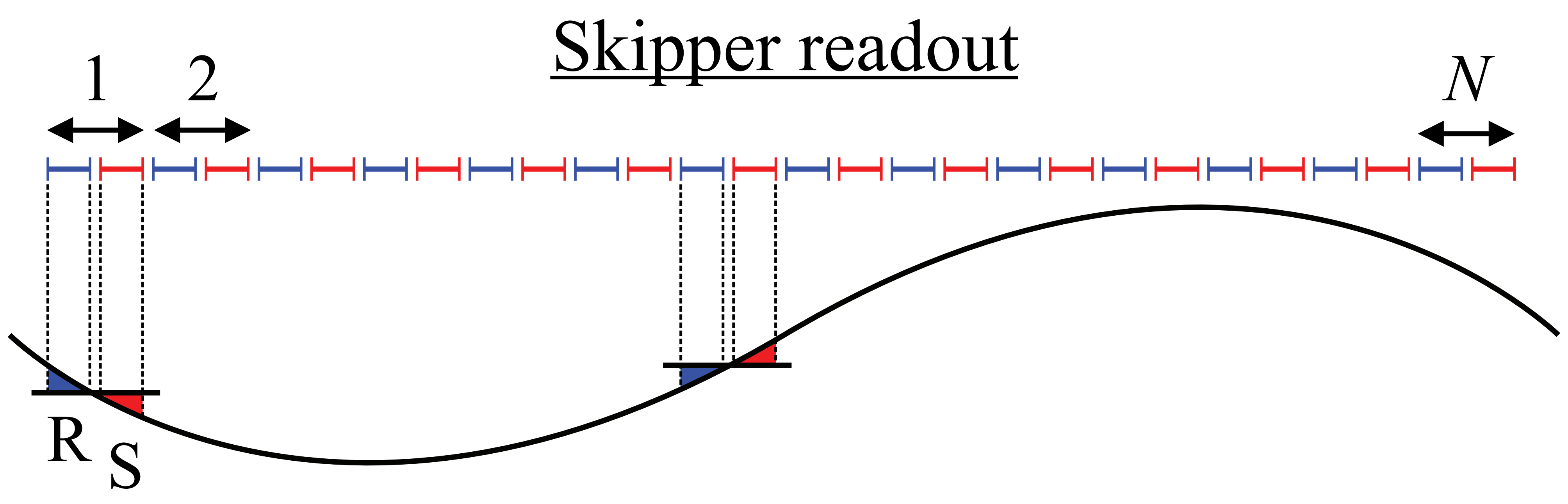


Measure ΔV *N* times:



Effect on low frequency noise:

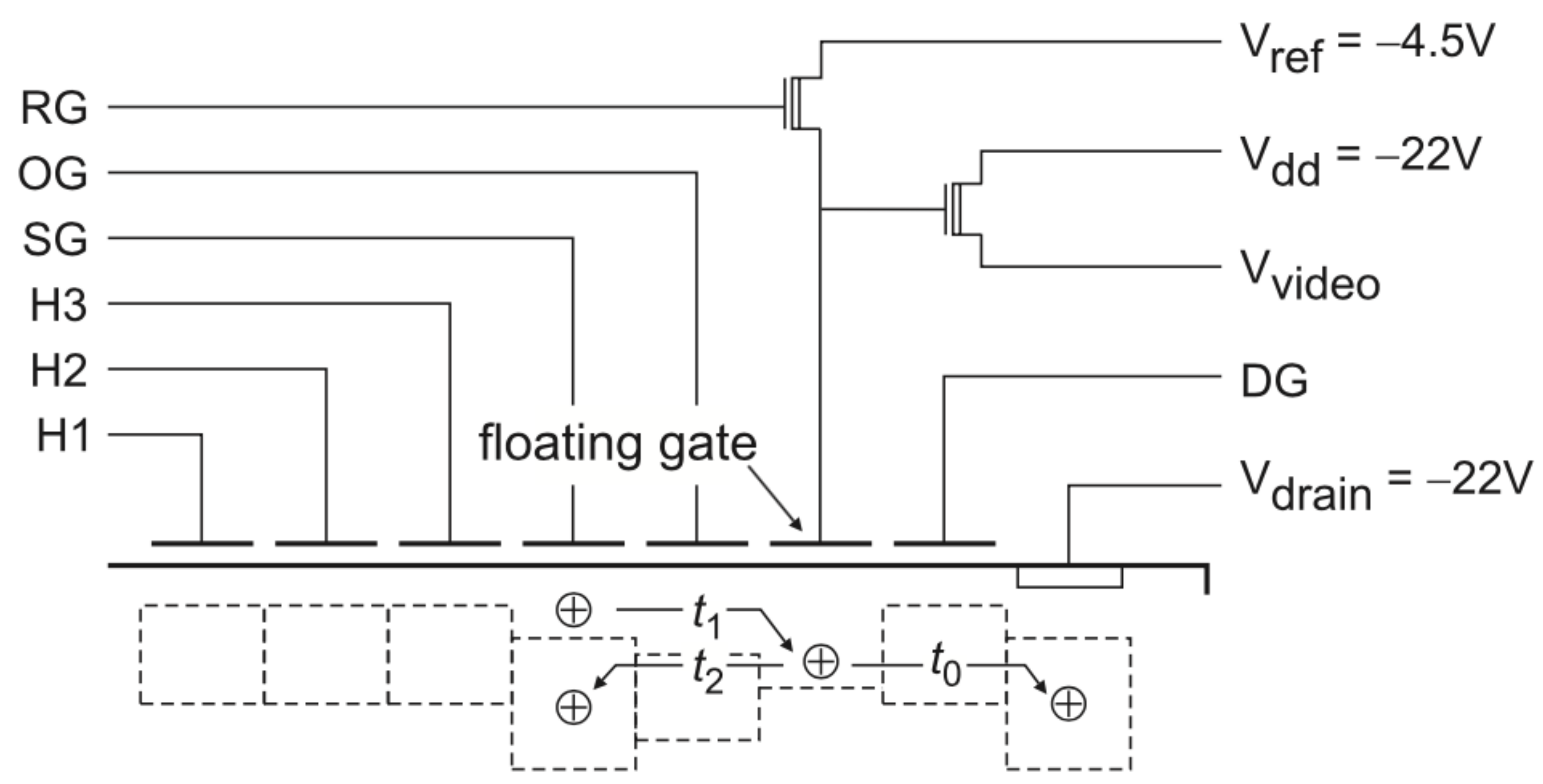




Design by S. Holland at Berkeley Lab

Skipper CCD

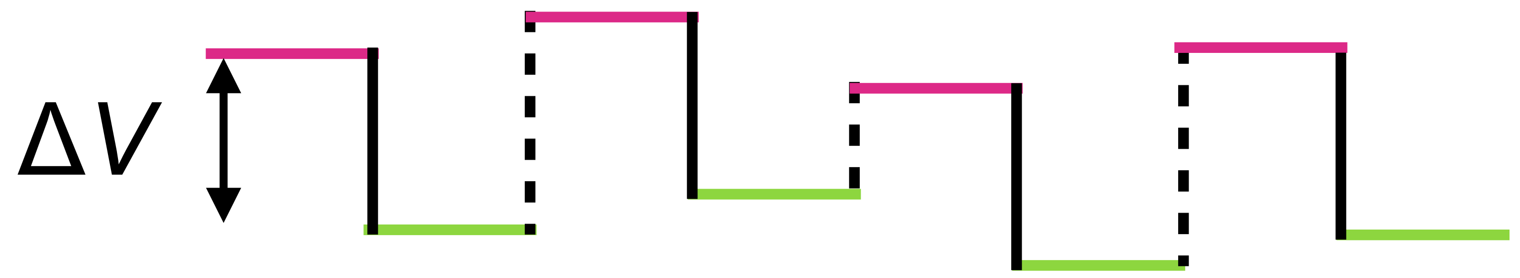
“Skipper” readout: Perform N uncorrelated measurements of the same pixel.



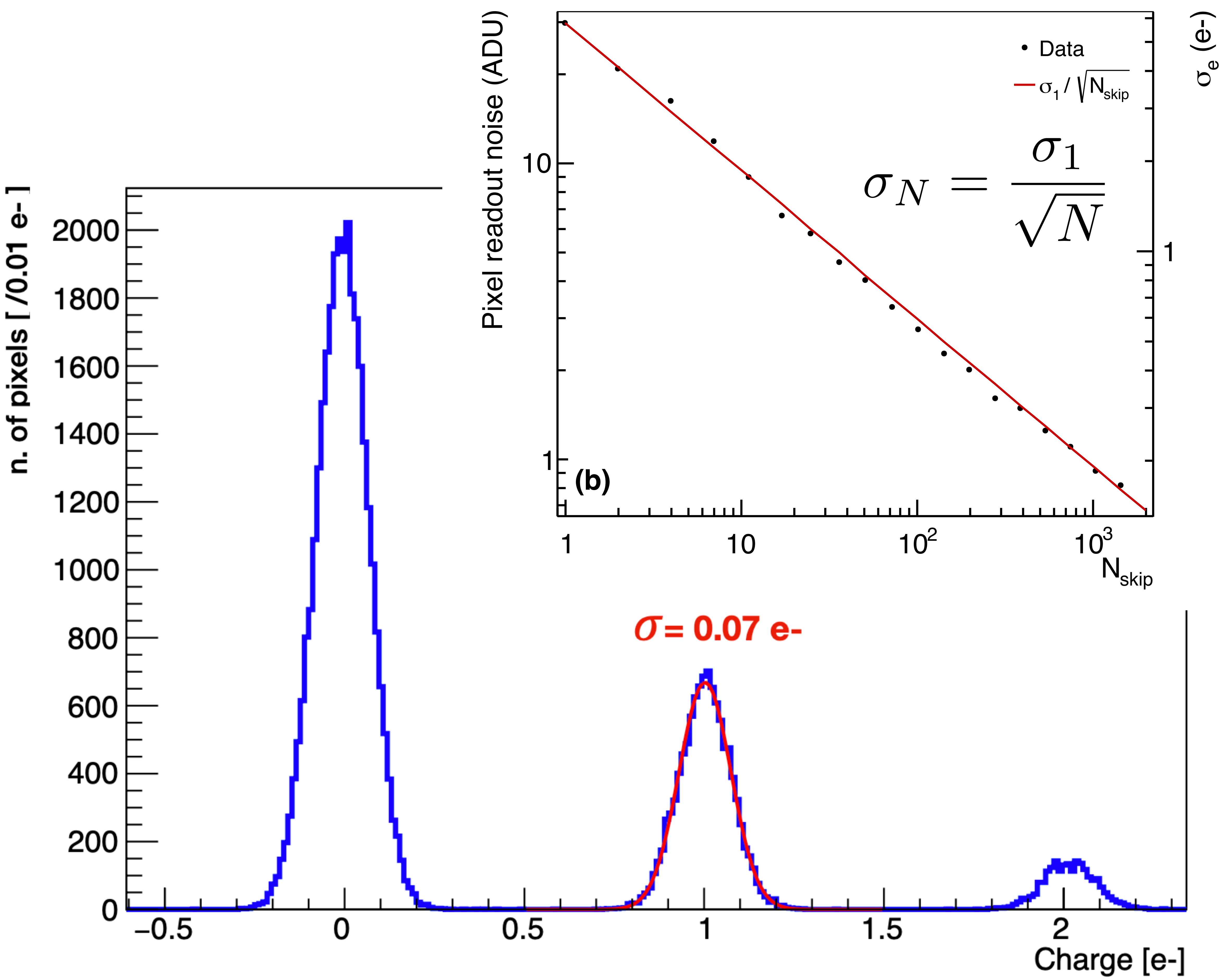
⟷ move charge back and forth

Measure ΔV N times:

Reference

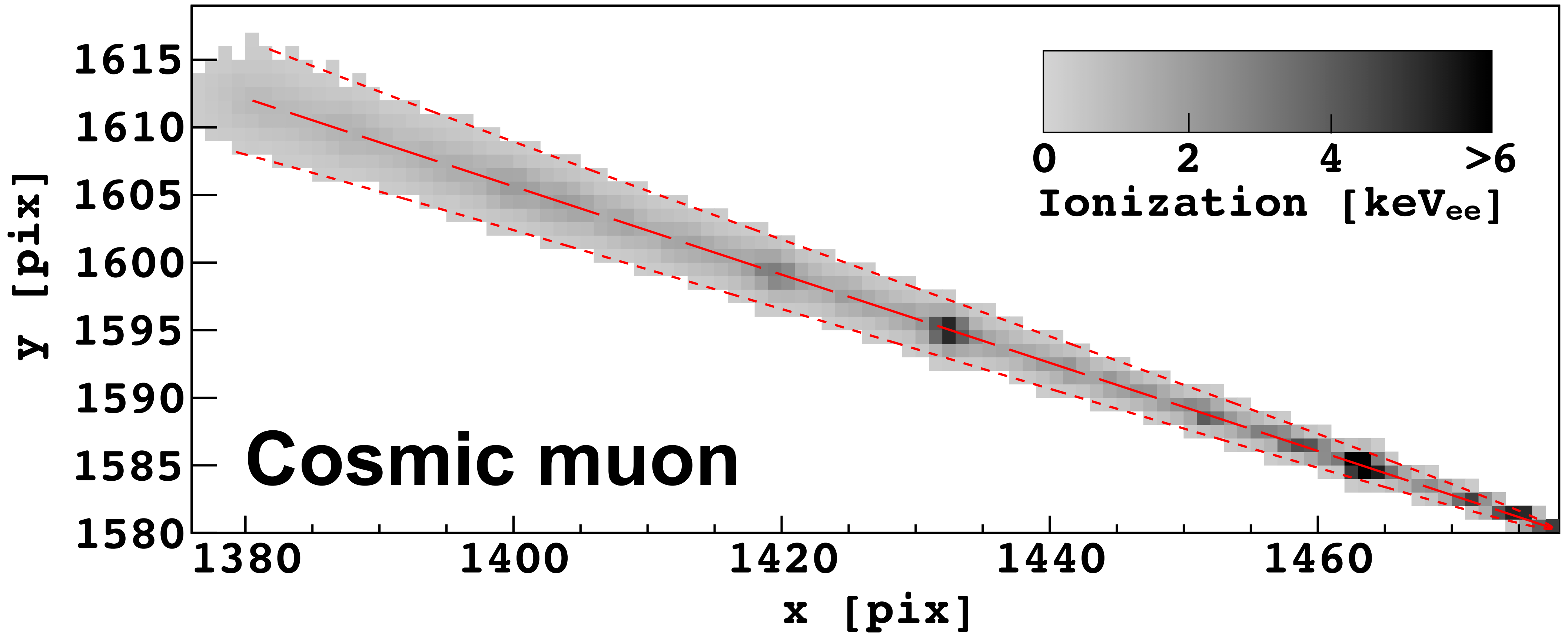


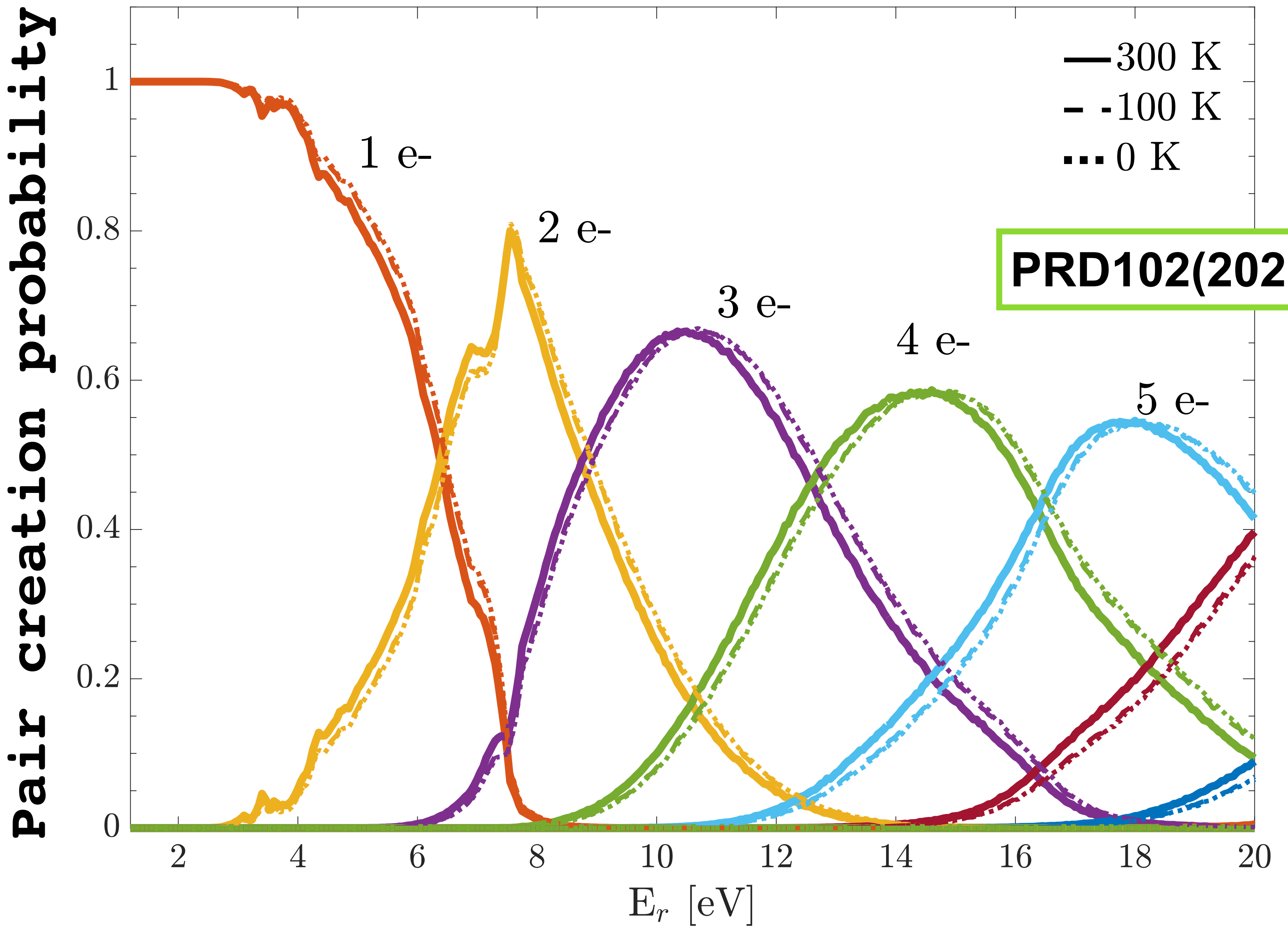
Signal



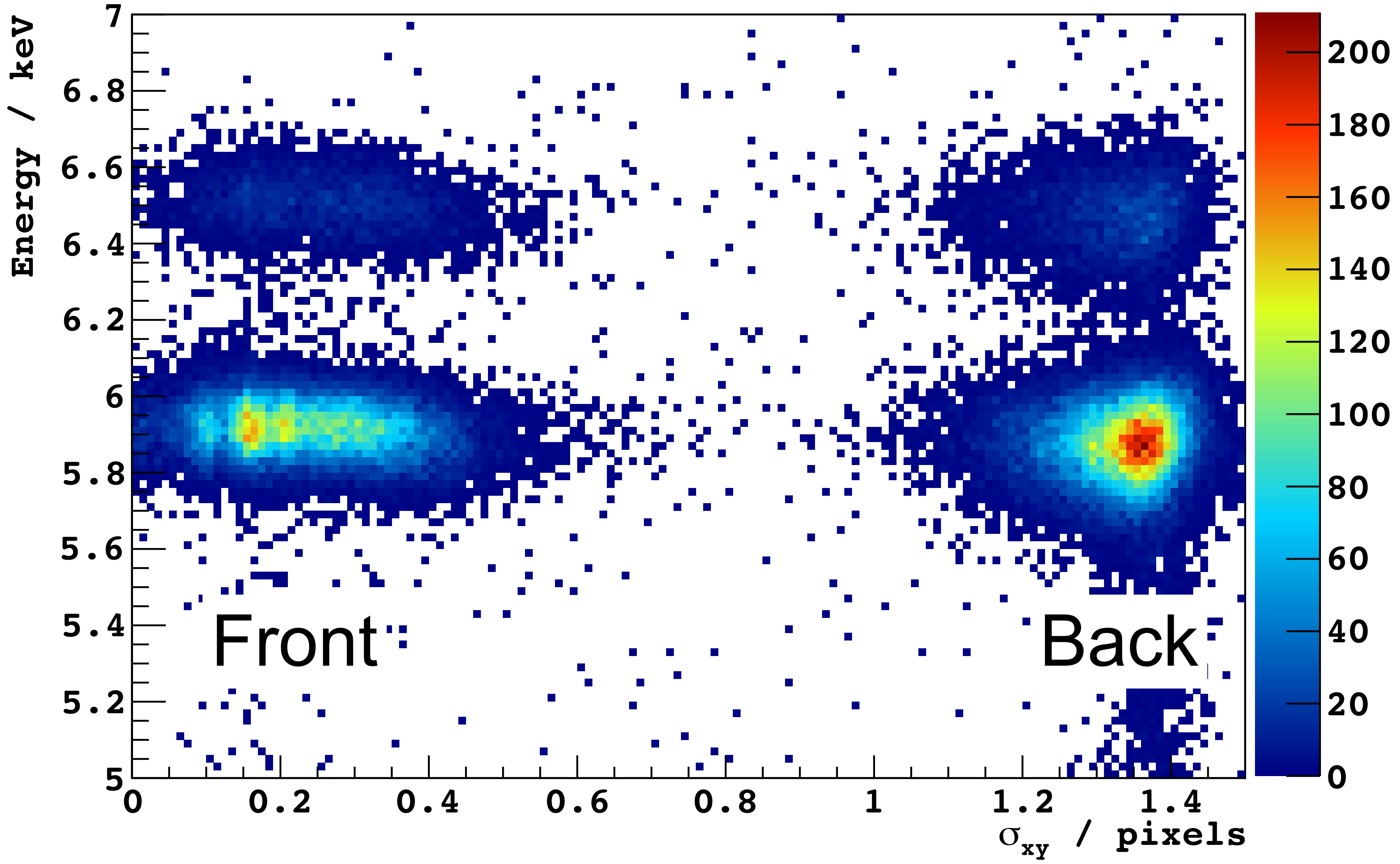
Characterization

- 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.



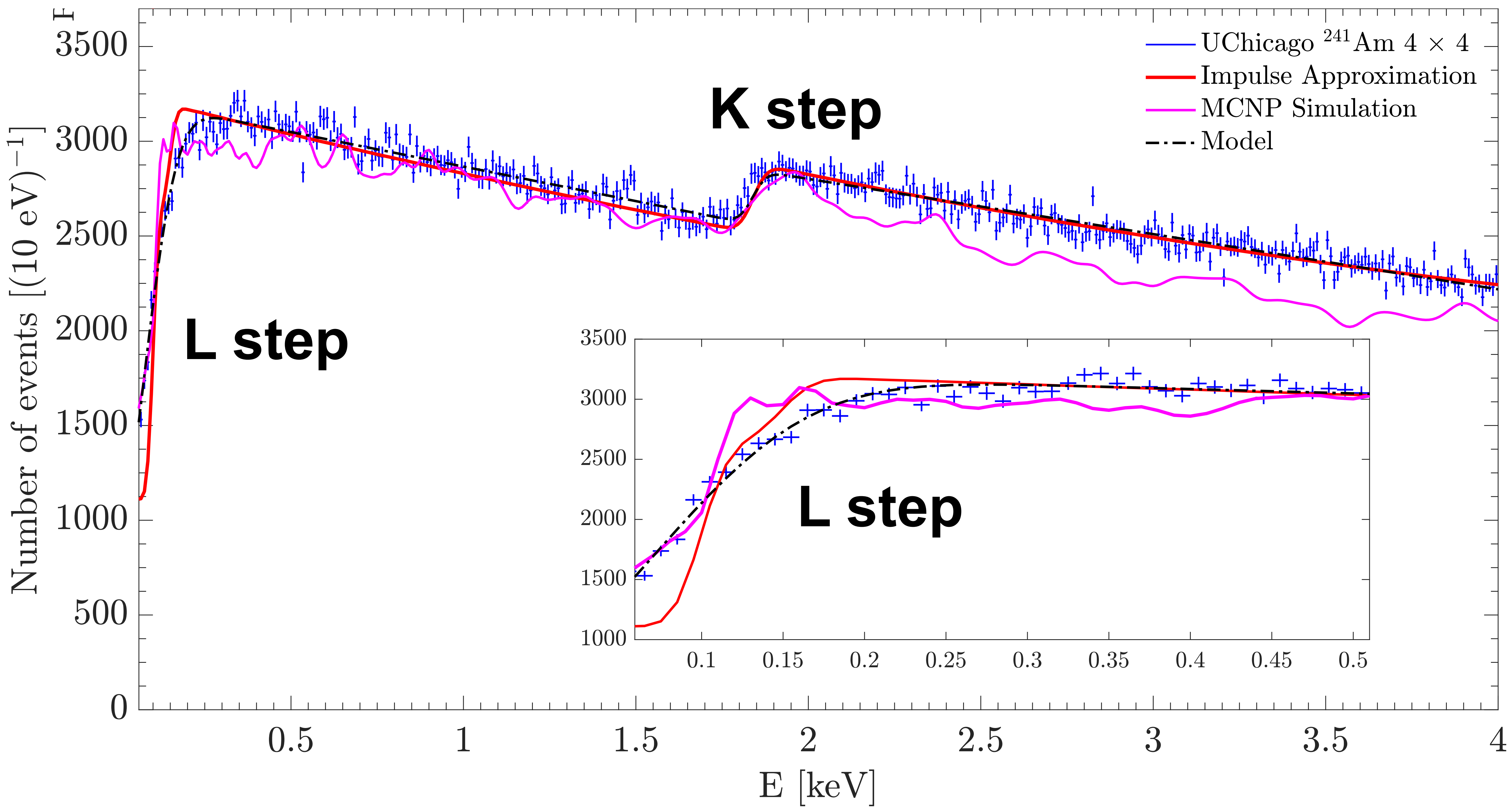


PRD102(2020)063026



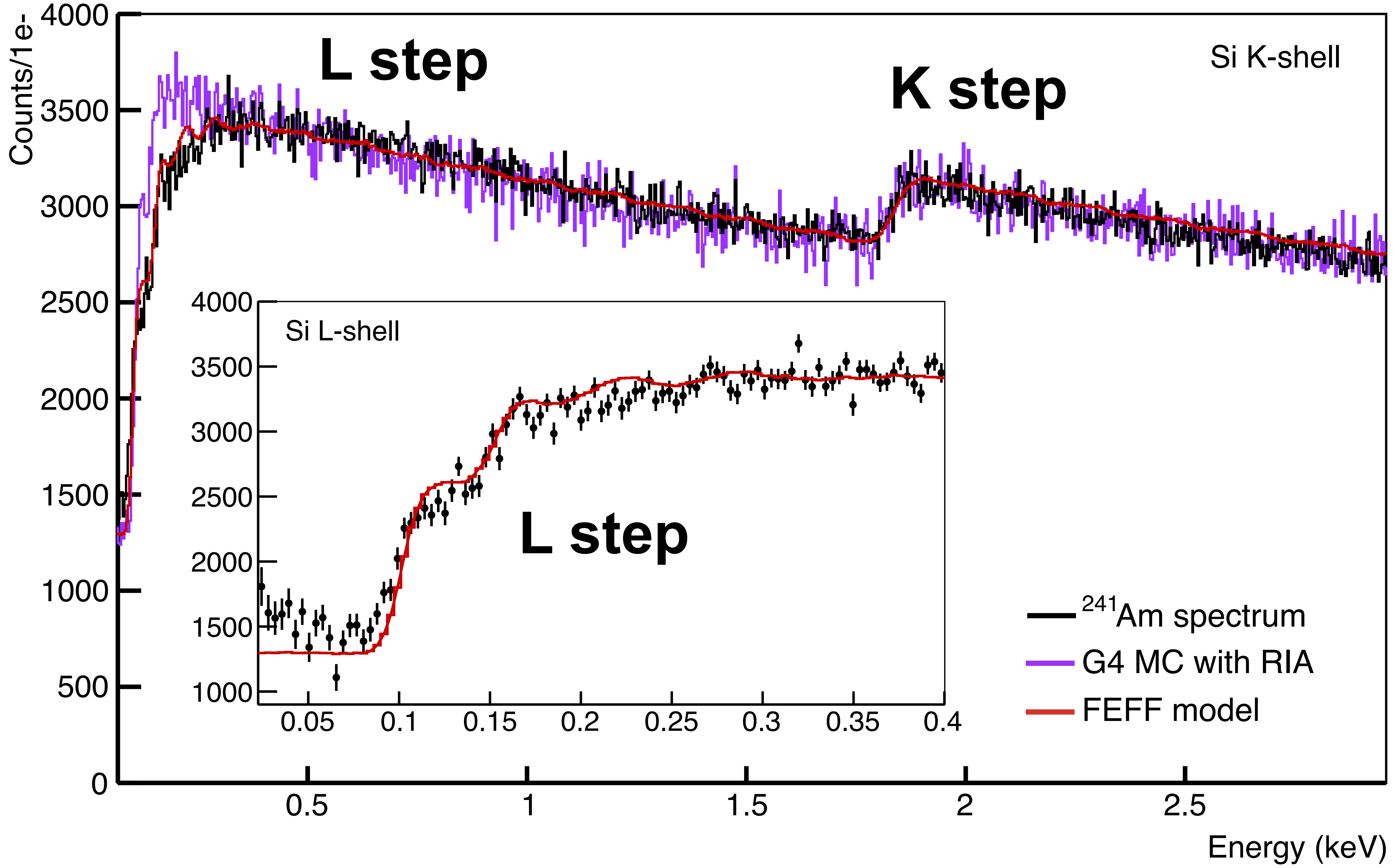
Example

- 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?



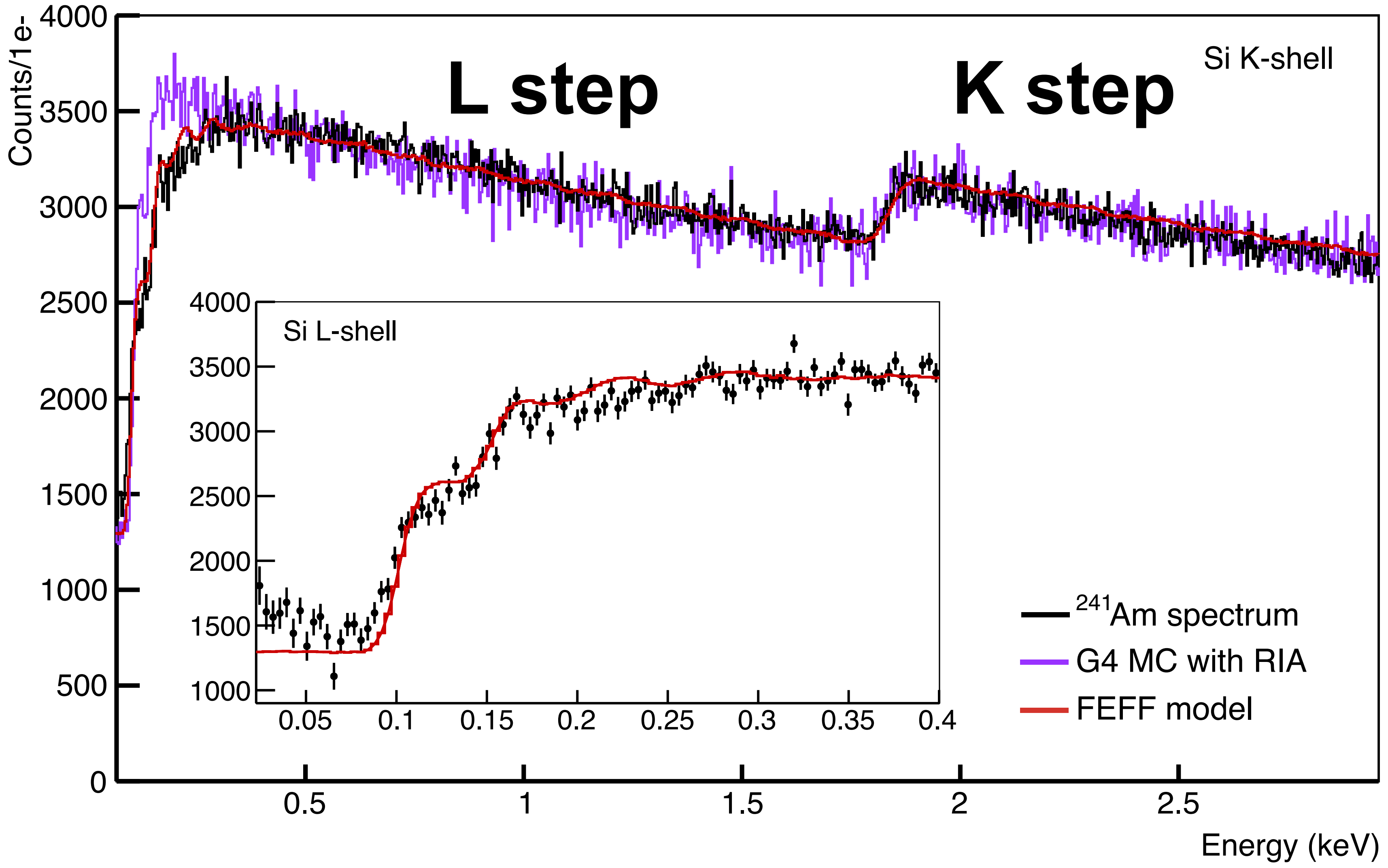
Example

- 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.

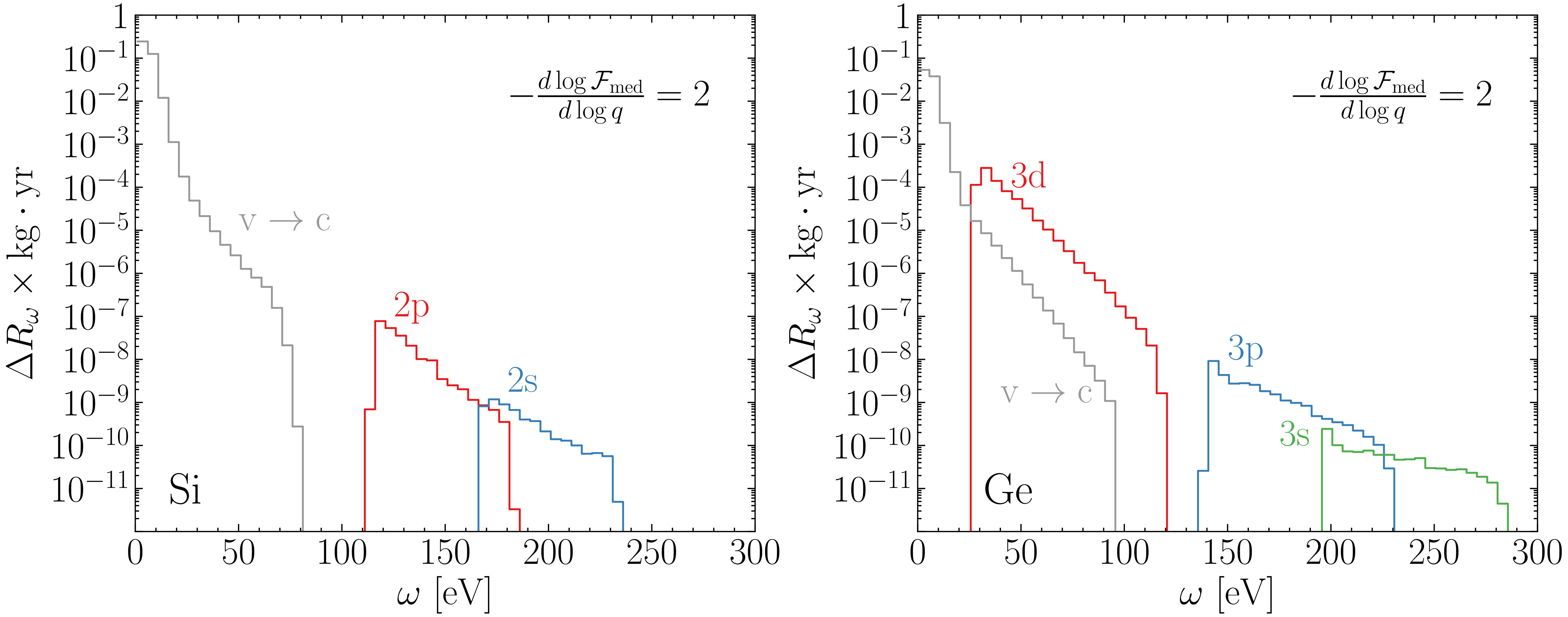


Related?

arXiv:2207.00809(2022)



PRD104(2021)095015



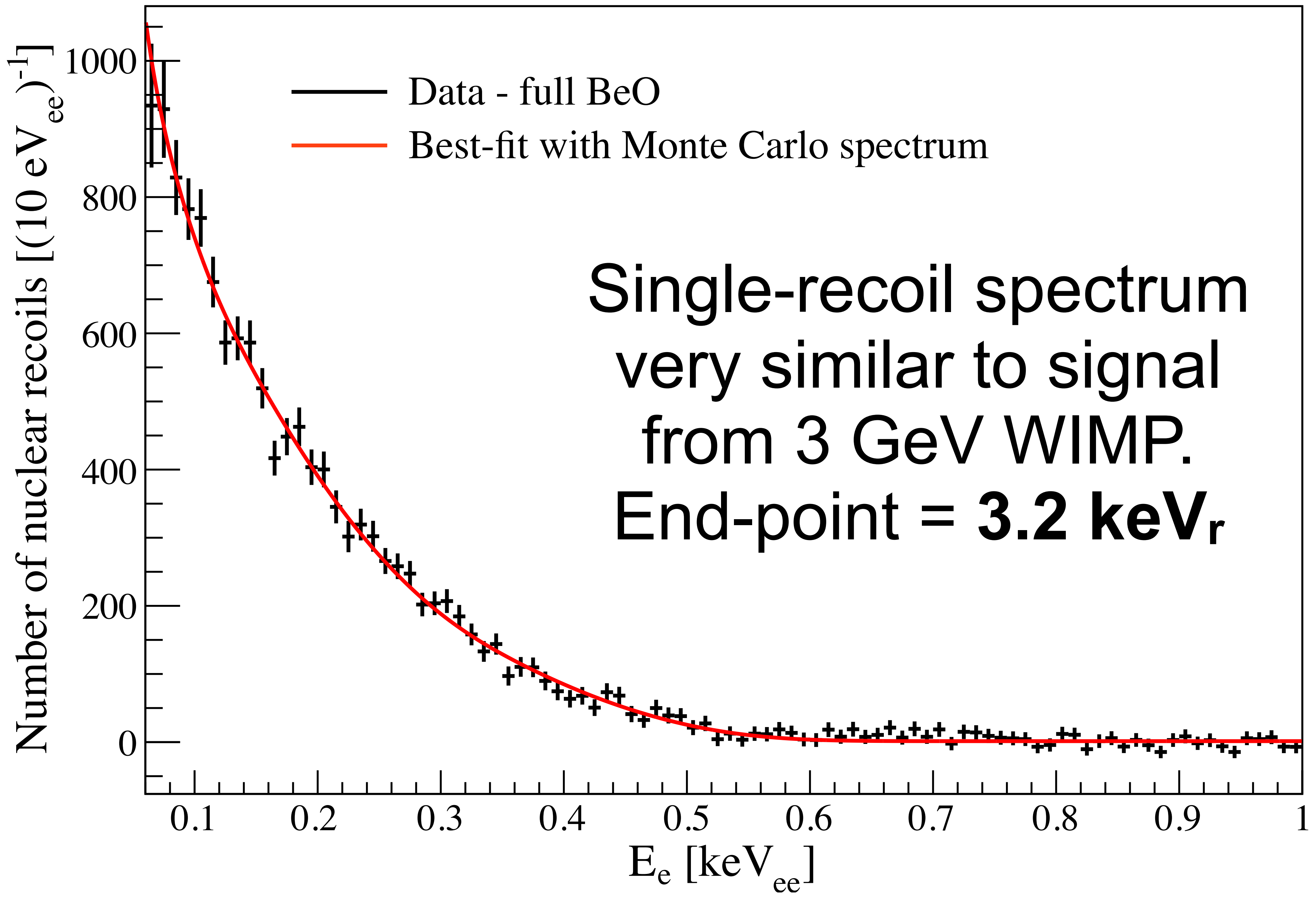
- γ scattering from core electrons in Si.
- Boring background.

- χ scattering from core electrons in Si and Ge.
- Exciting opportunity to search for DM!

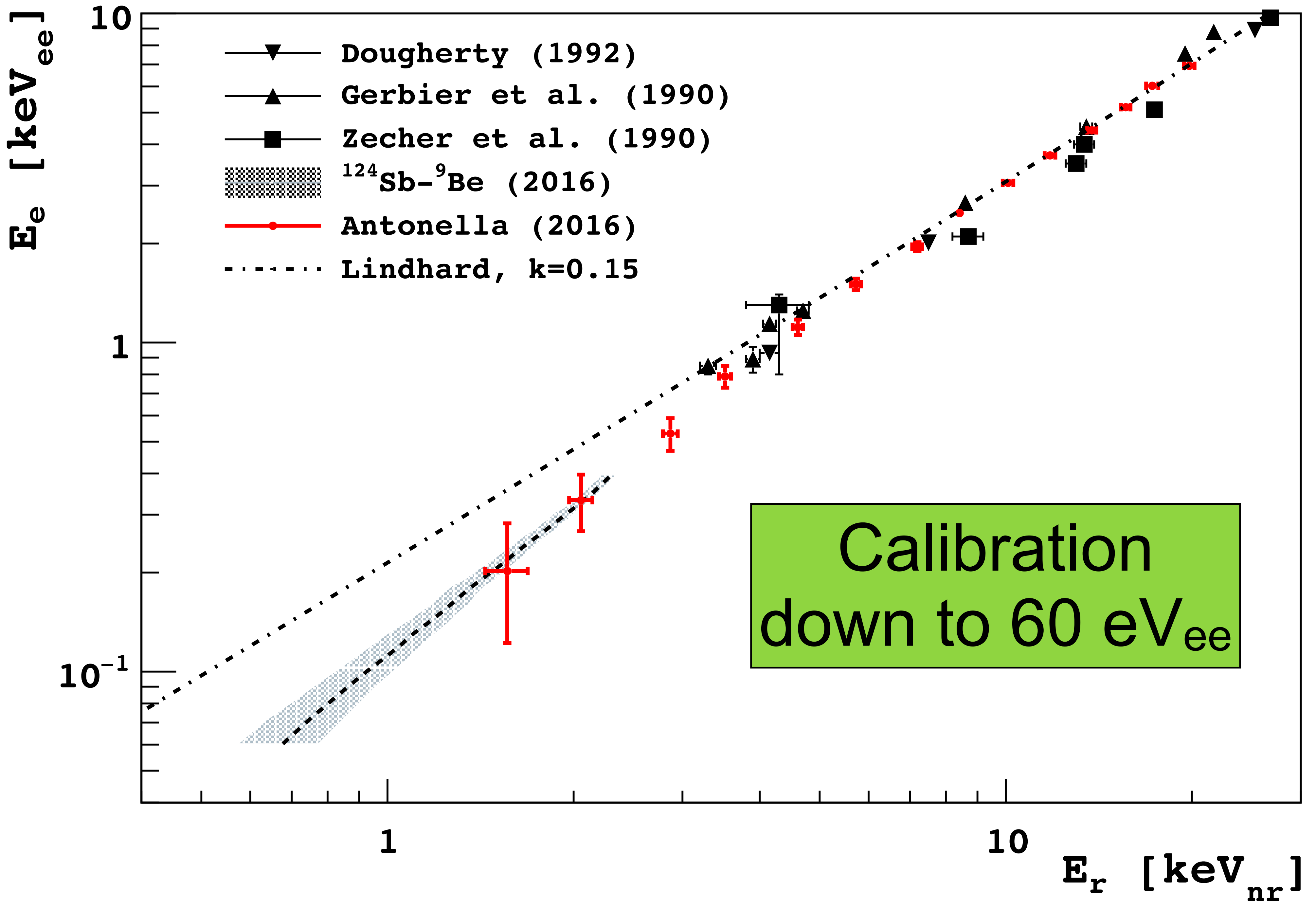
Can the γ calibration data or ***FEFF*** be used to test the validity of the EXCEED-DM code?

Nuclear recoil response

- Detector response calibrated with 24 keV neutrons from ^{9}Be(γ,n) reaction.
- By comparing data and Monte Carlo spectra, ionization signal was measured to be lower than predicted by Lindhard model.
- Still no data or model to describe N_e probability distributions at low energies.
- No observed Migdal effect at low energies.

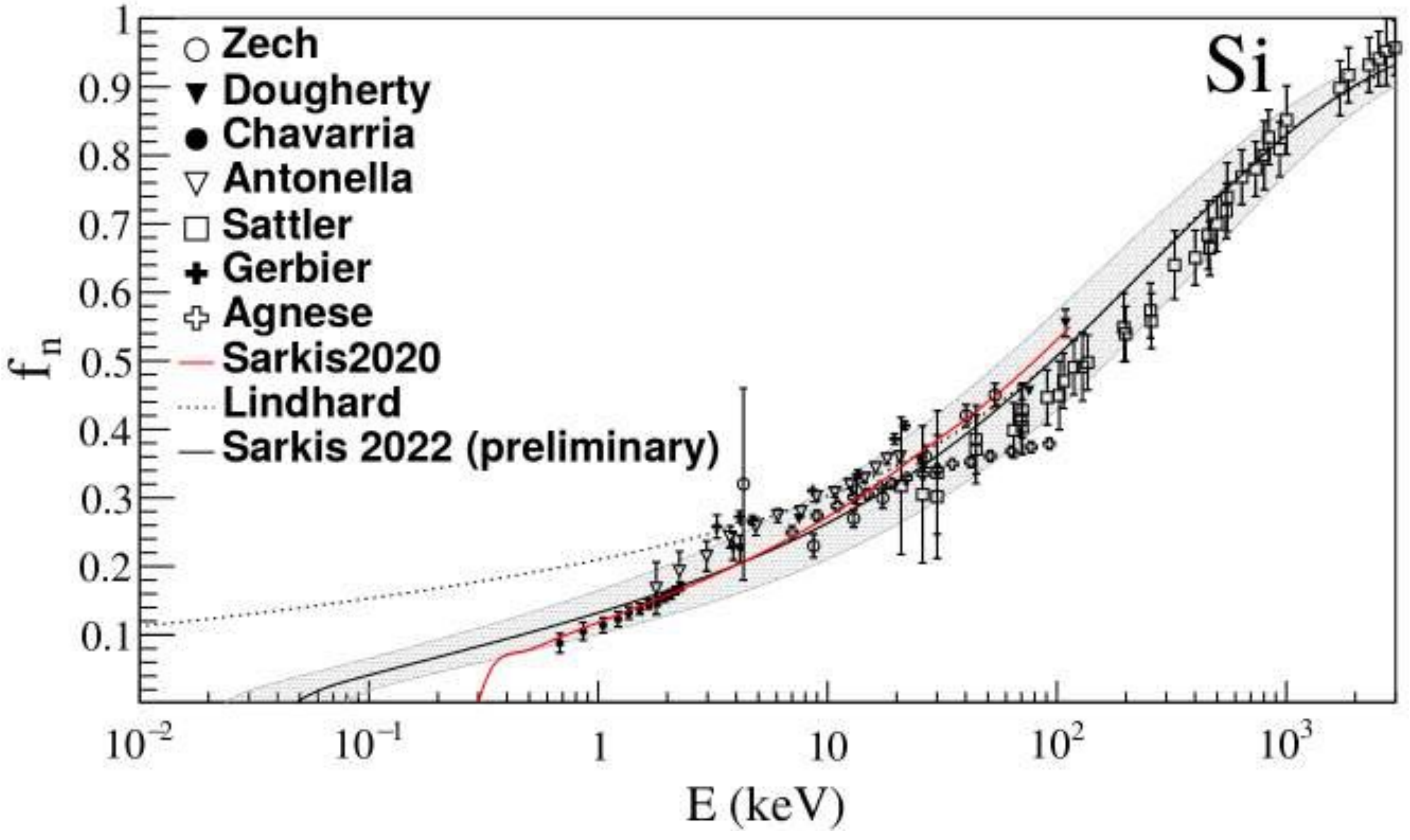


PRD94(2016)082007



Lindhard model

- The amplitude of the signal is crucial to estimate the sensitivity of an experiment to DM-N elastic scattering, *i.e.*, to make meaningful comparisons between experiments.
- Lindhard model predicts the number of ionized electrons (ionization signal) from a recoiling nucleus of a given energy.
- Lindhard model's approximations are not adequate at low energies (*e.g.*, it neglects the binding energy of the target atom).
- Not much theoretical progress since the 1960s because it's "boring."
- Recent work by Y. Sarkis (UNAM) relaxing Lindhard's assumptions shows promise: PRD101(2020)102001

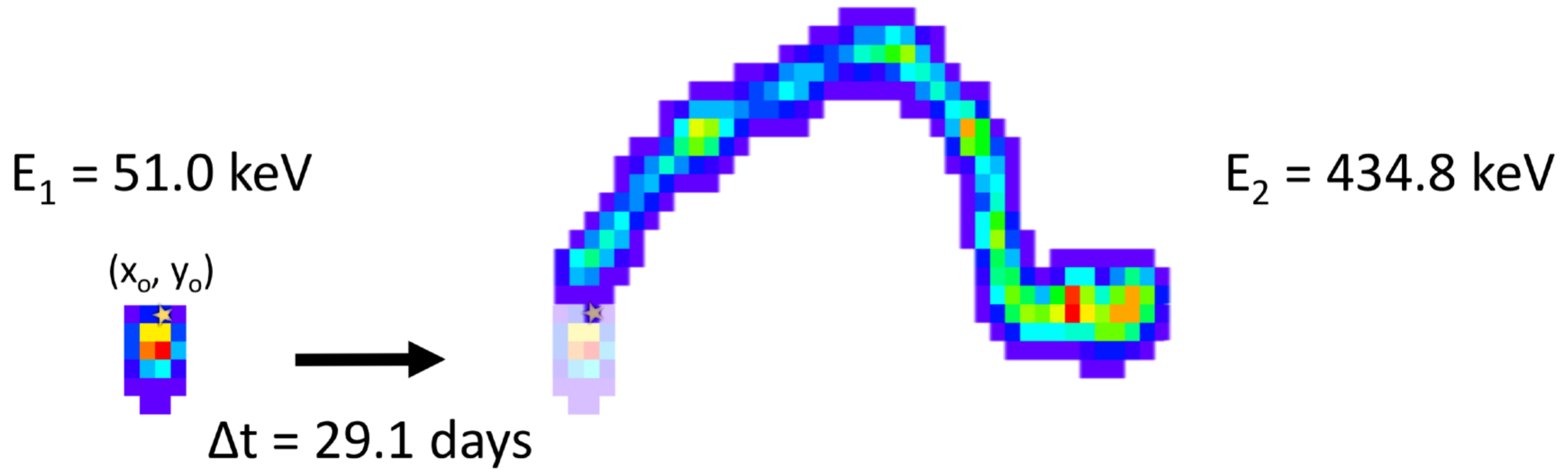


Radioactive backgrounds

- 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

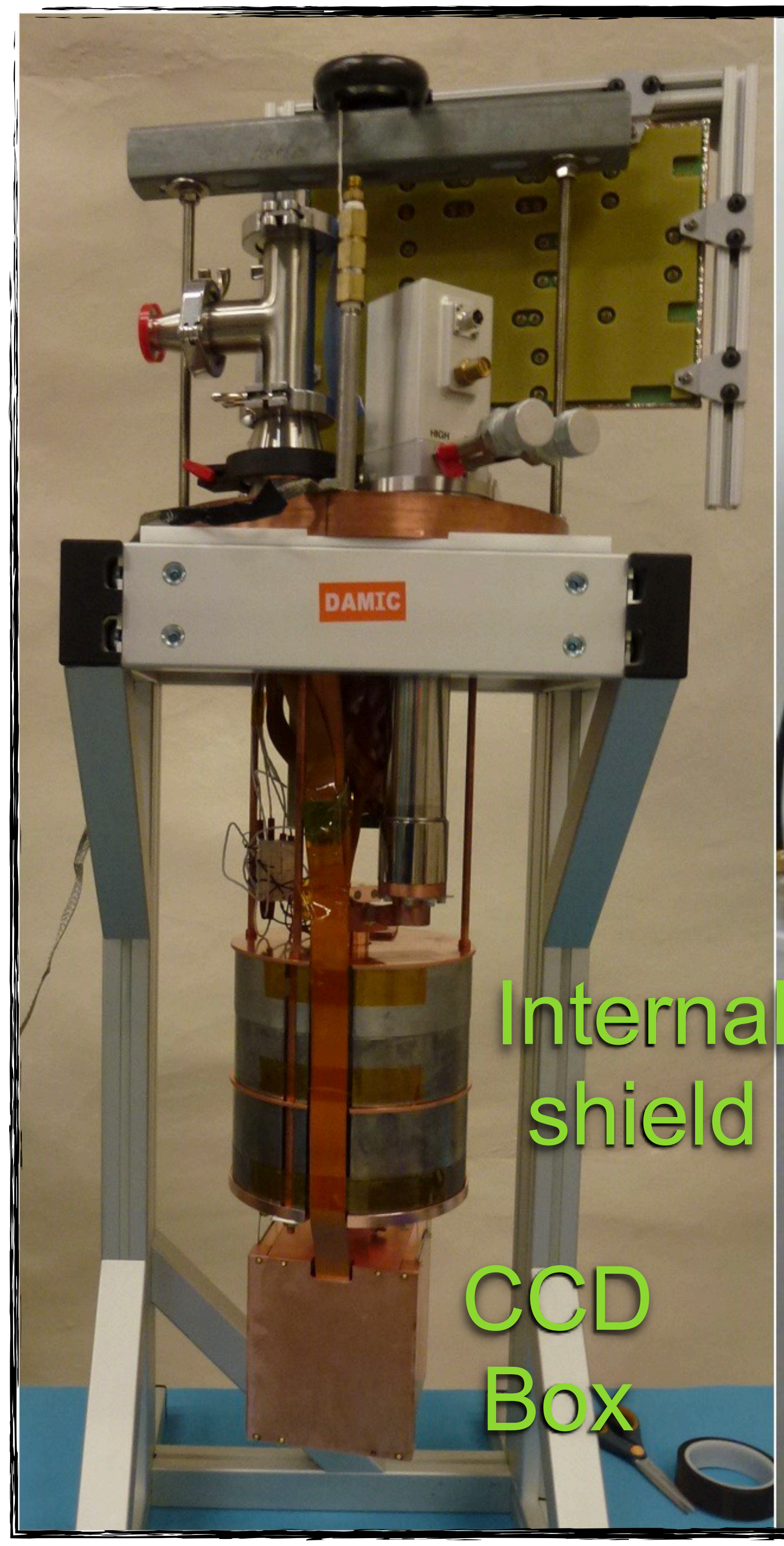
112 ± 24 atoms / kg /day

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

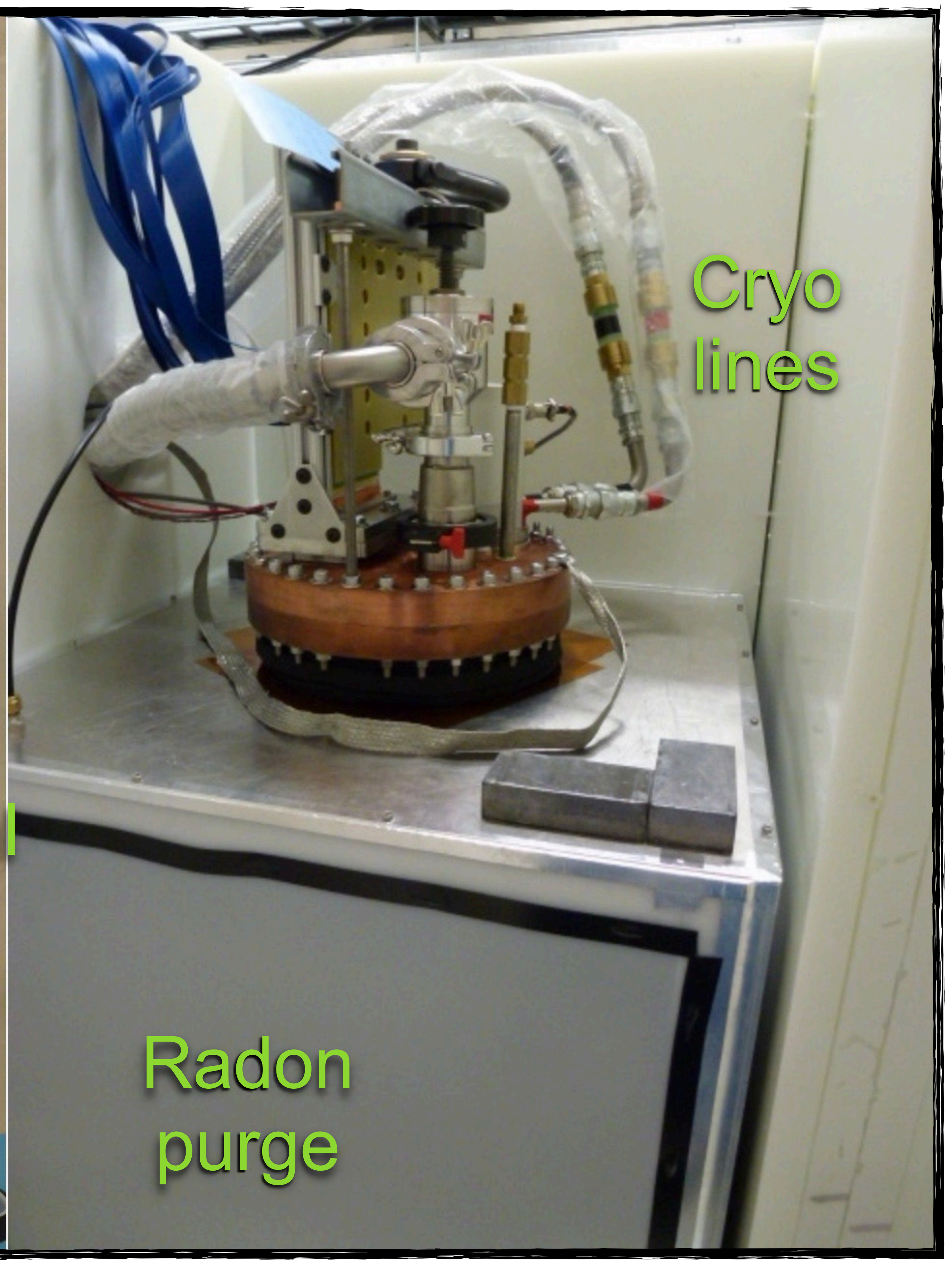
DAMIC at SNOLAB

CCD Box

Cryostat insert



In shield

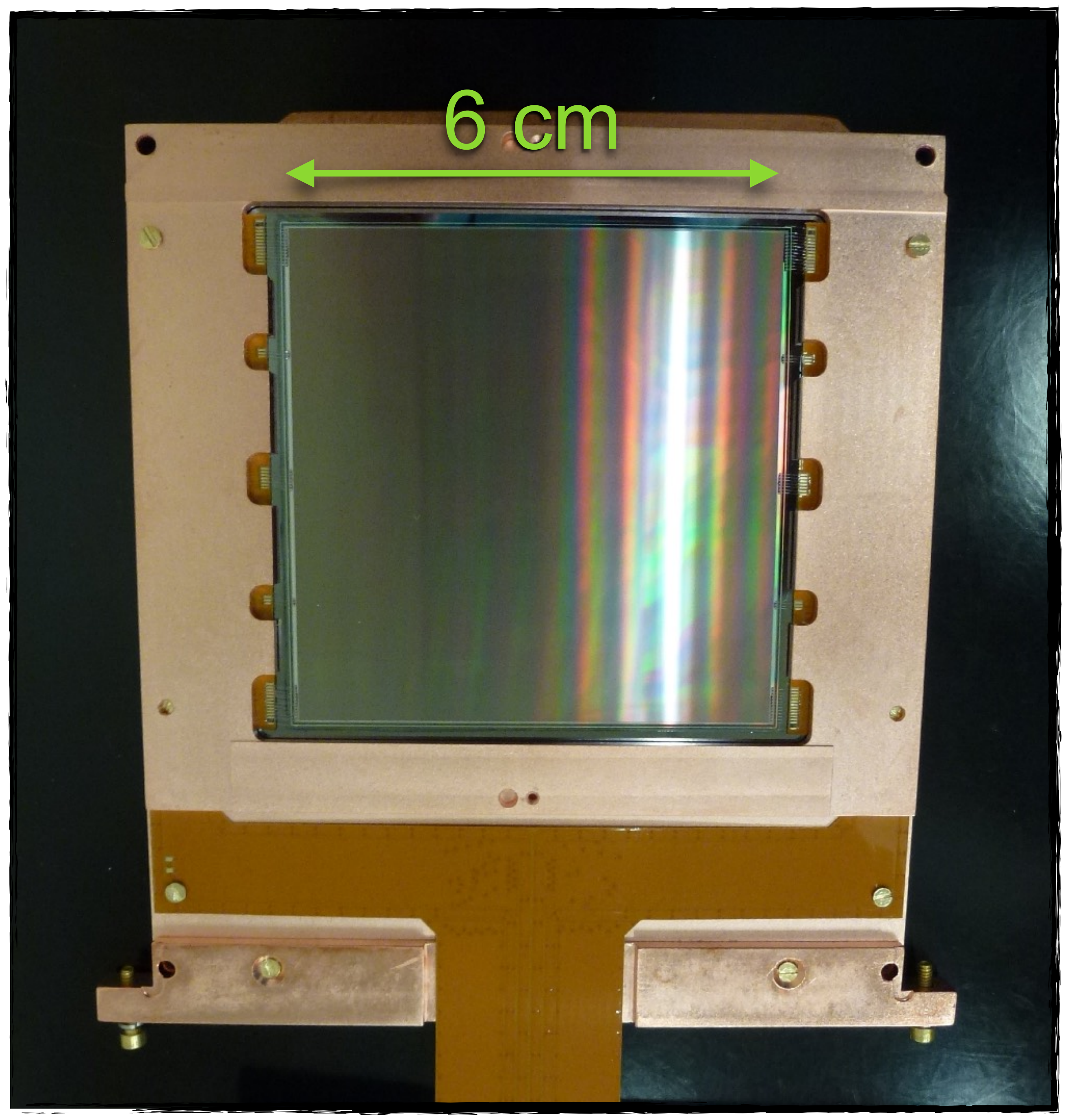


External shield

DAMIC at SNOLAB

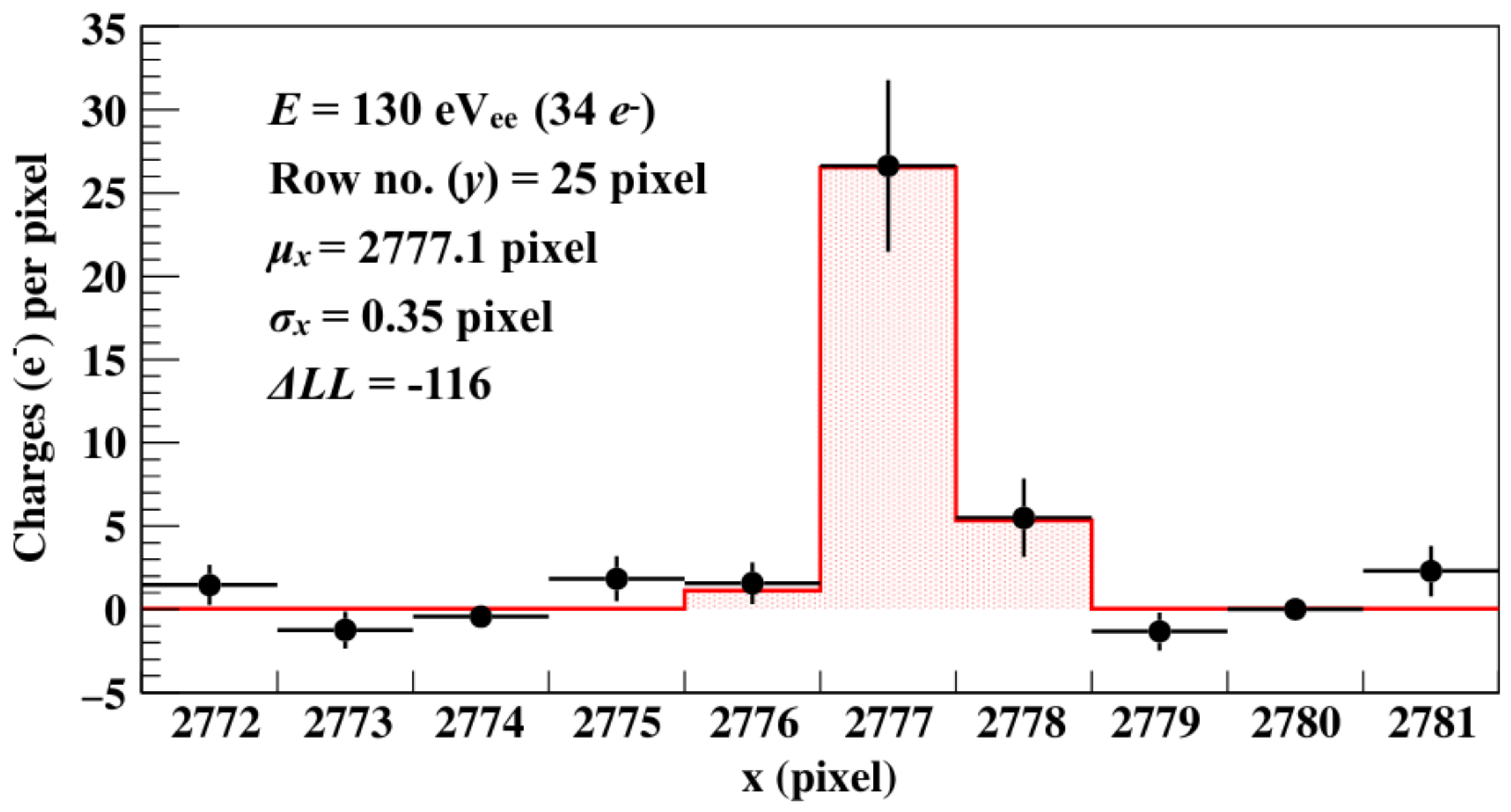
- First array of CCDs operated underground for a DM search. Since 2012.
- 7 CCDs (6.0 g, 16 Mpix) cooled to 140 K.
- Total (bulk) background rate: ~10 (5) d.r.u.
- Low pixel noise 1.6 e^- with conventional readout.
- Extremely low leakage current: 2×10^{-22} A cm^{-2}.
- DM-e^- scattering results: PRL123(2019)181802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

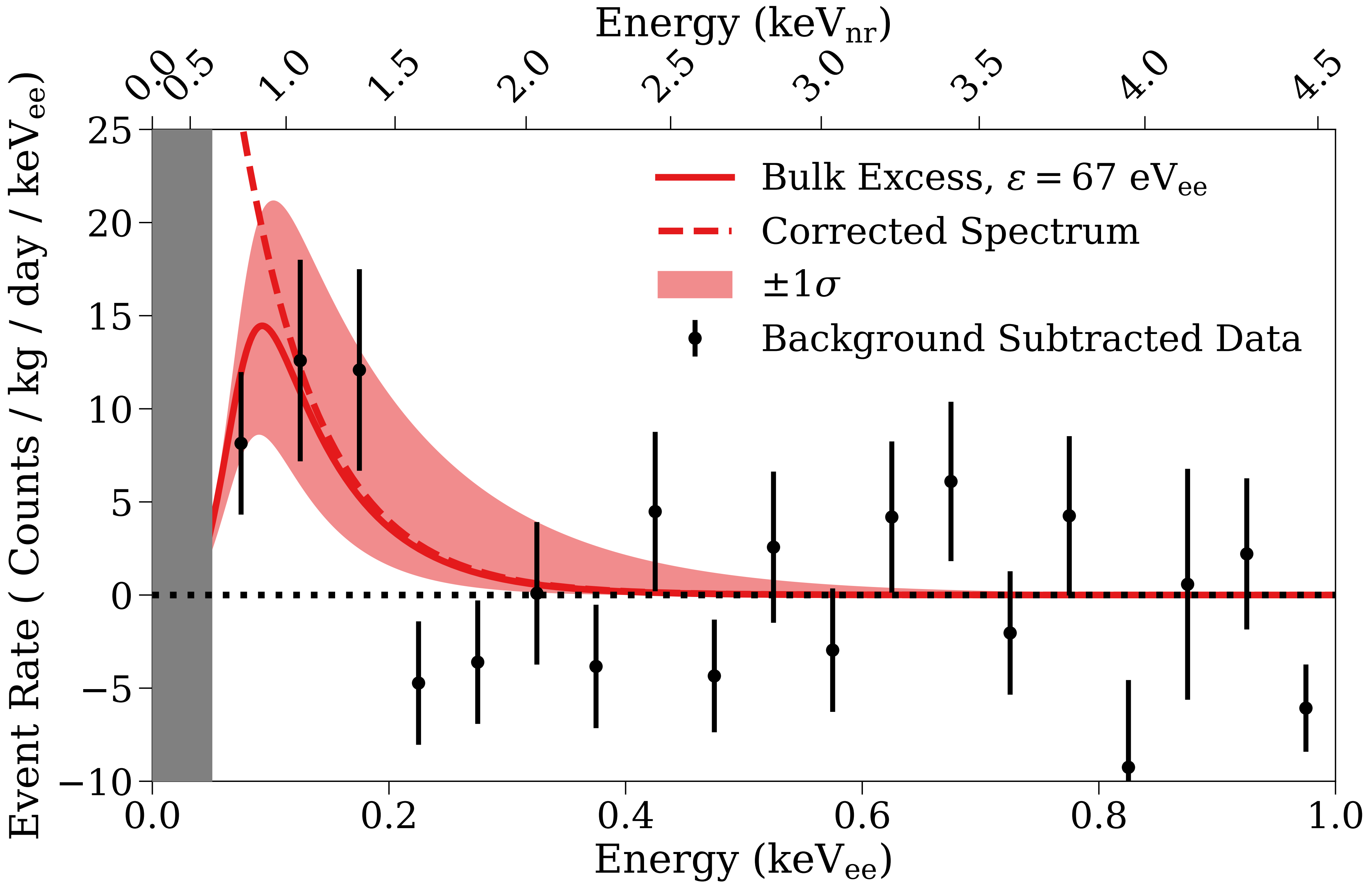
Exclusion limit: PRL125(2020)241803 **Full details:** PRD105(2022)062003



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.





SENSEI

- **Research highlights:**

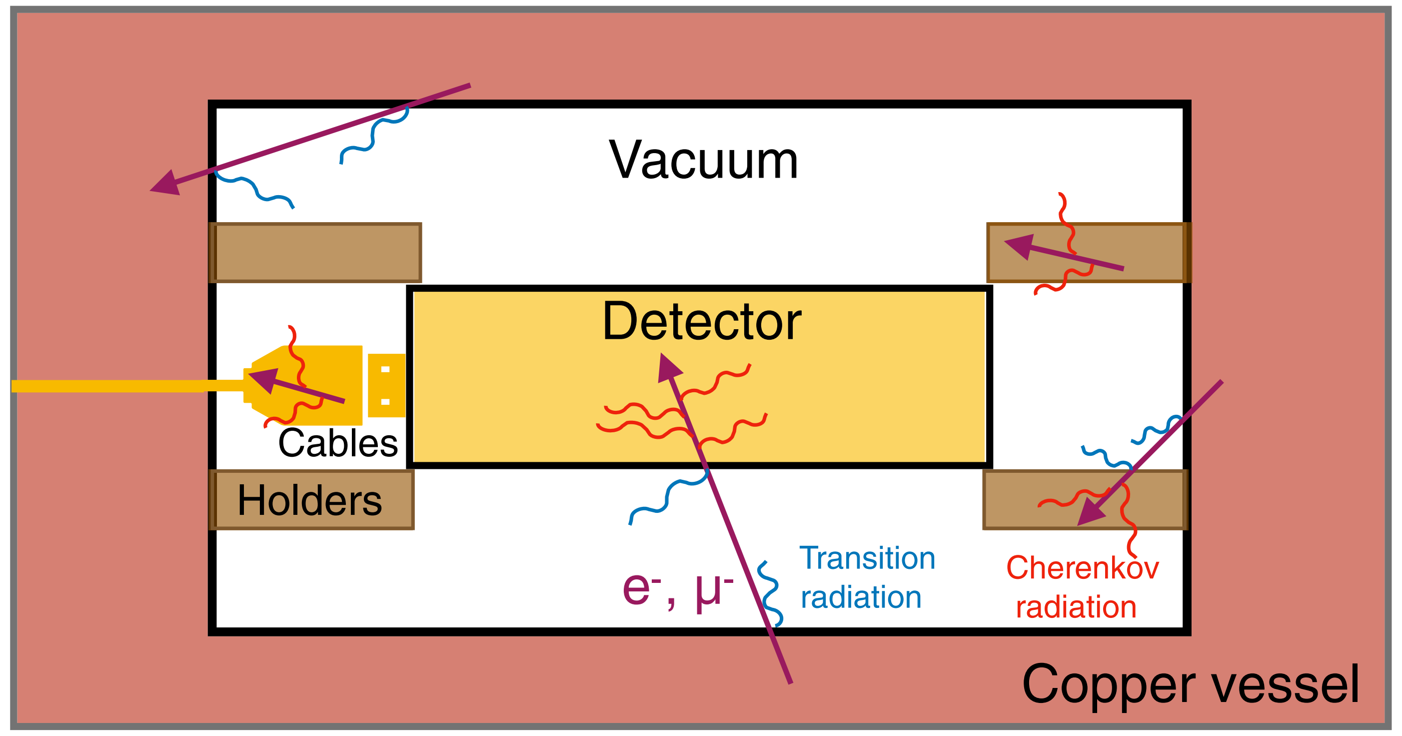
PRL125(2020)171802

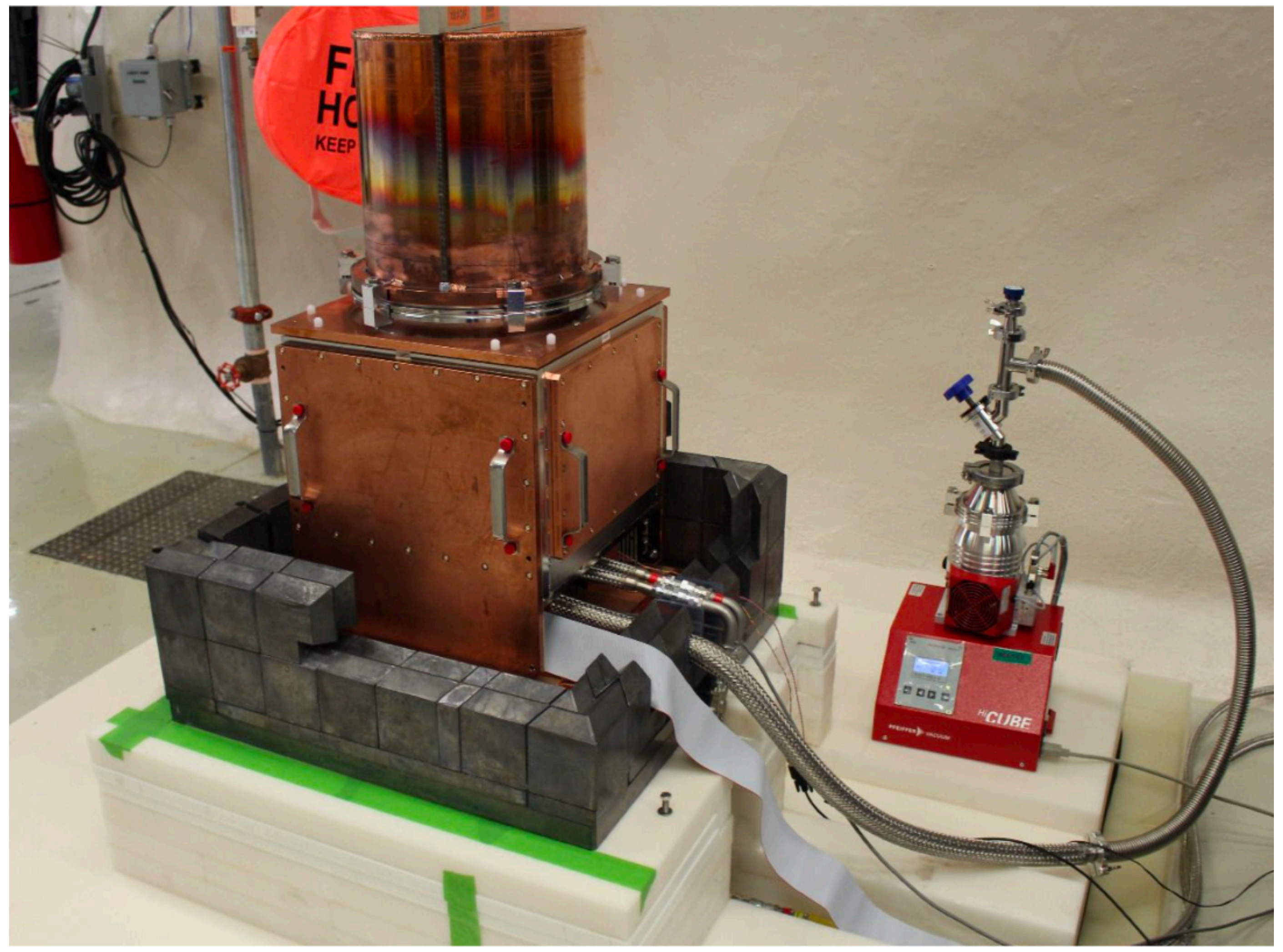
  - First DM-search with skipper CCDs at Fermilab.
  - Simulation studies on physical origins of single-electron / photon backgrounds. PRX12(2022)011009
  - Experimental studies on instrumental effects to understand origin of single-e^- backgrounds.

PRAppl17(2022) 014022

- **SENSEI at SNOLAB:**
  - 10 skipper CCDs (~25g) deployed already.
  - Performance test runs before science run!
  - Packaged and tested at Fermilab.
  - **Final goal:** 100 g traget with 5 d.r.u. background.

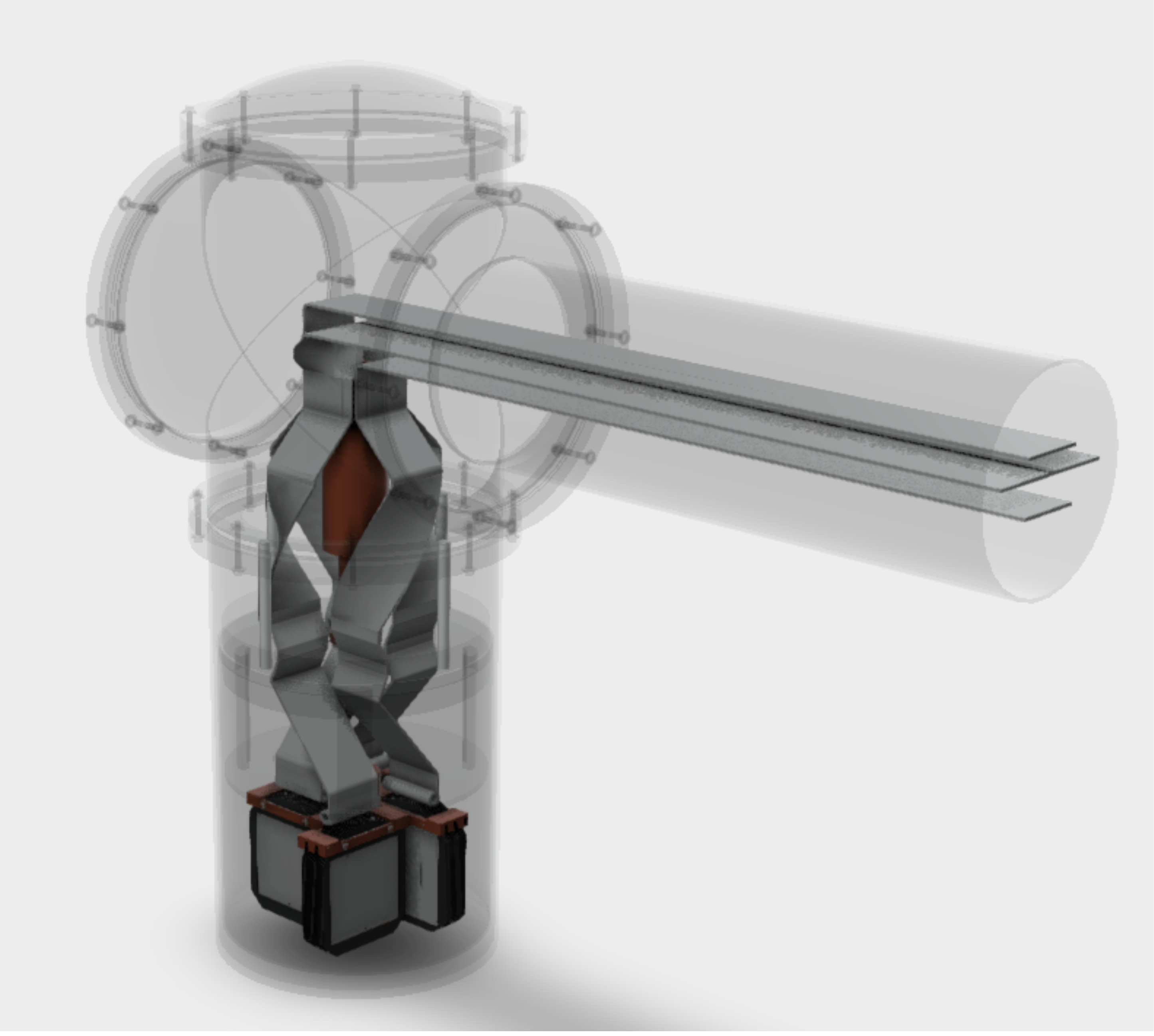
Single photon backgrounds in CCD detector:



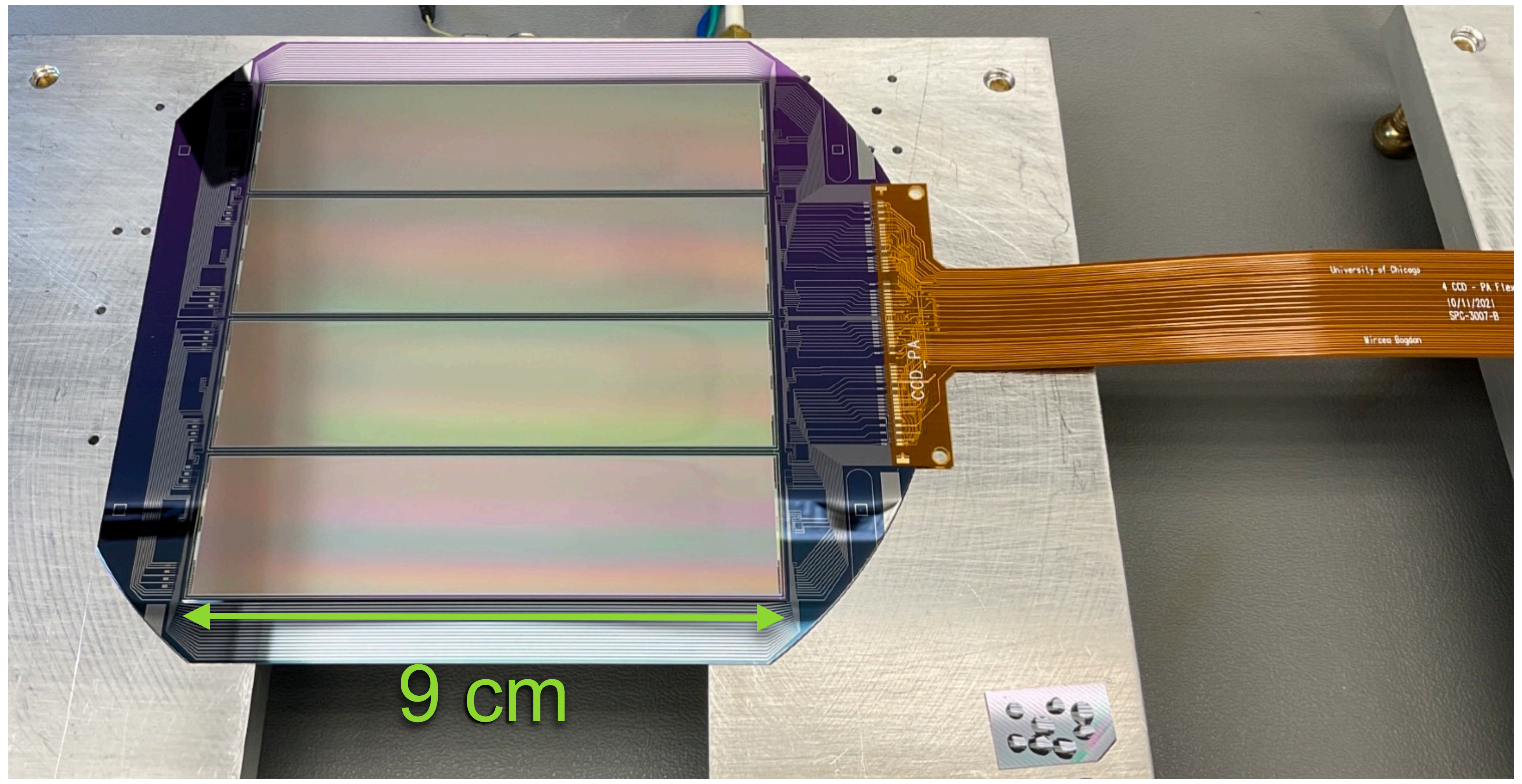


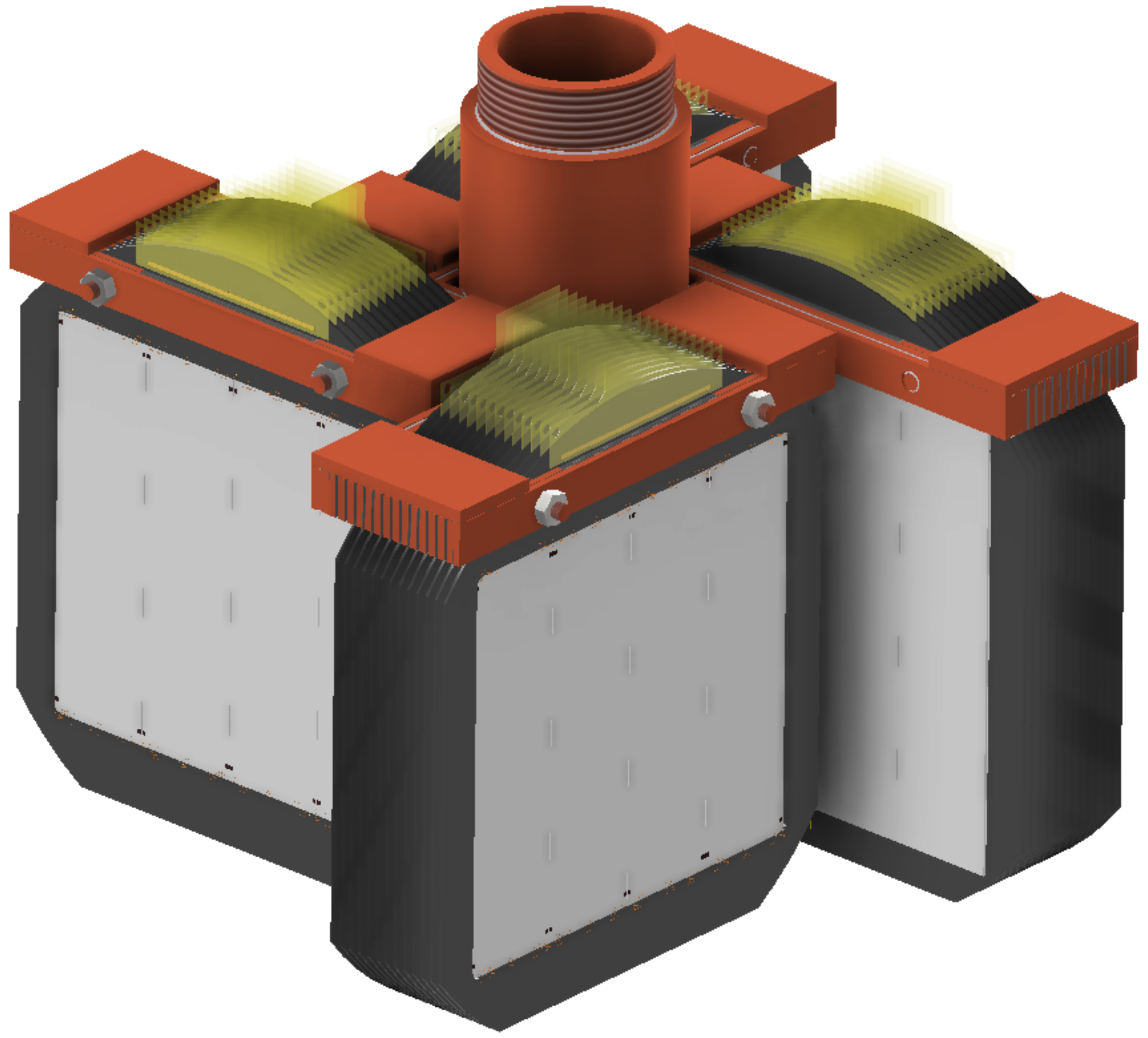
DAMIC-M

- 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.



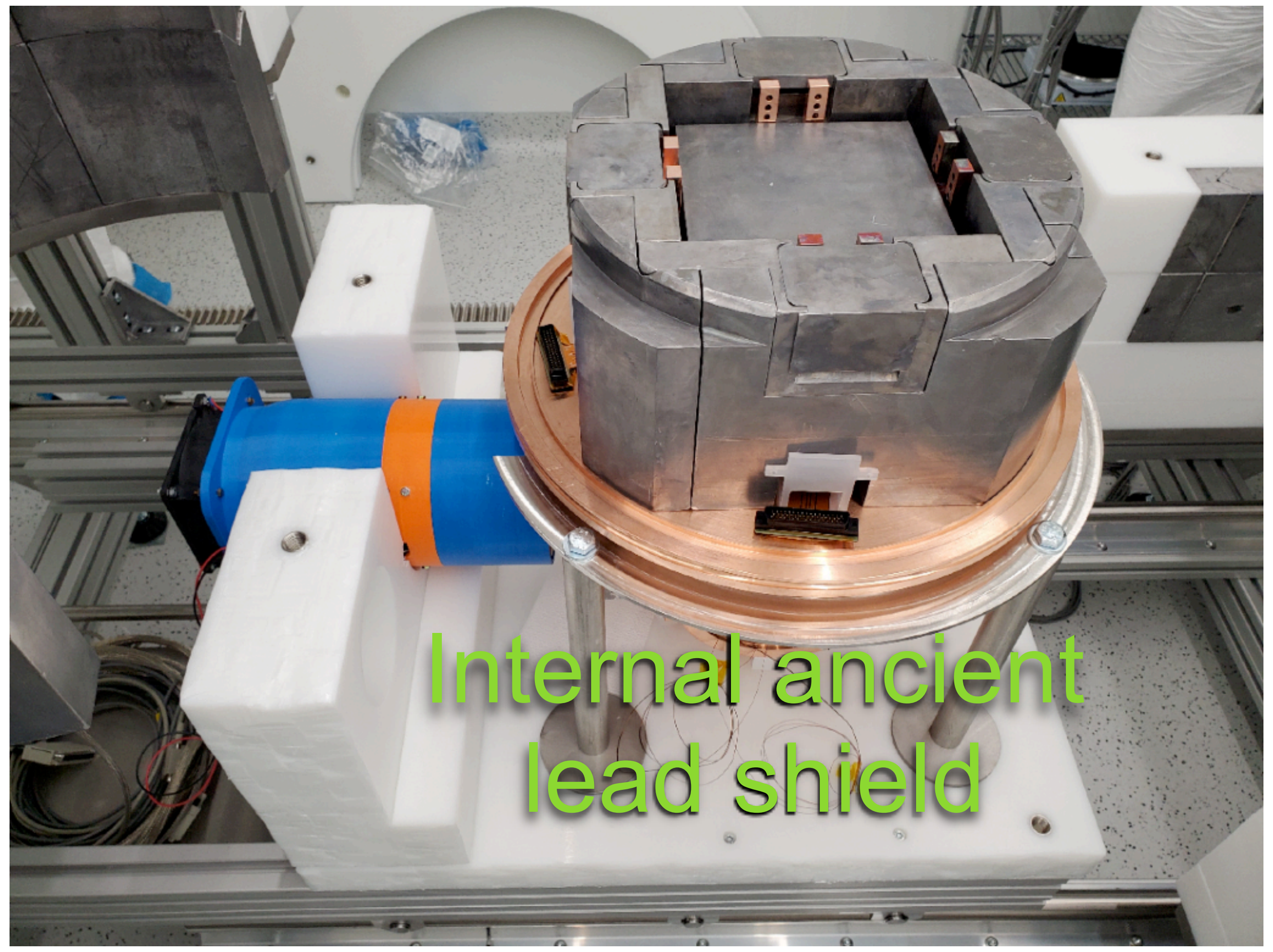
Commissioning in early 2024!

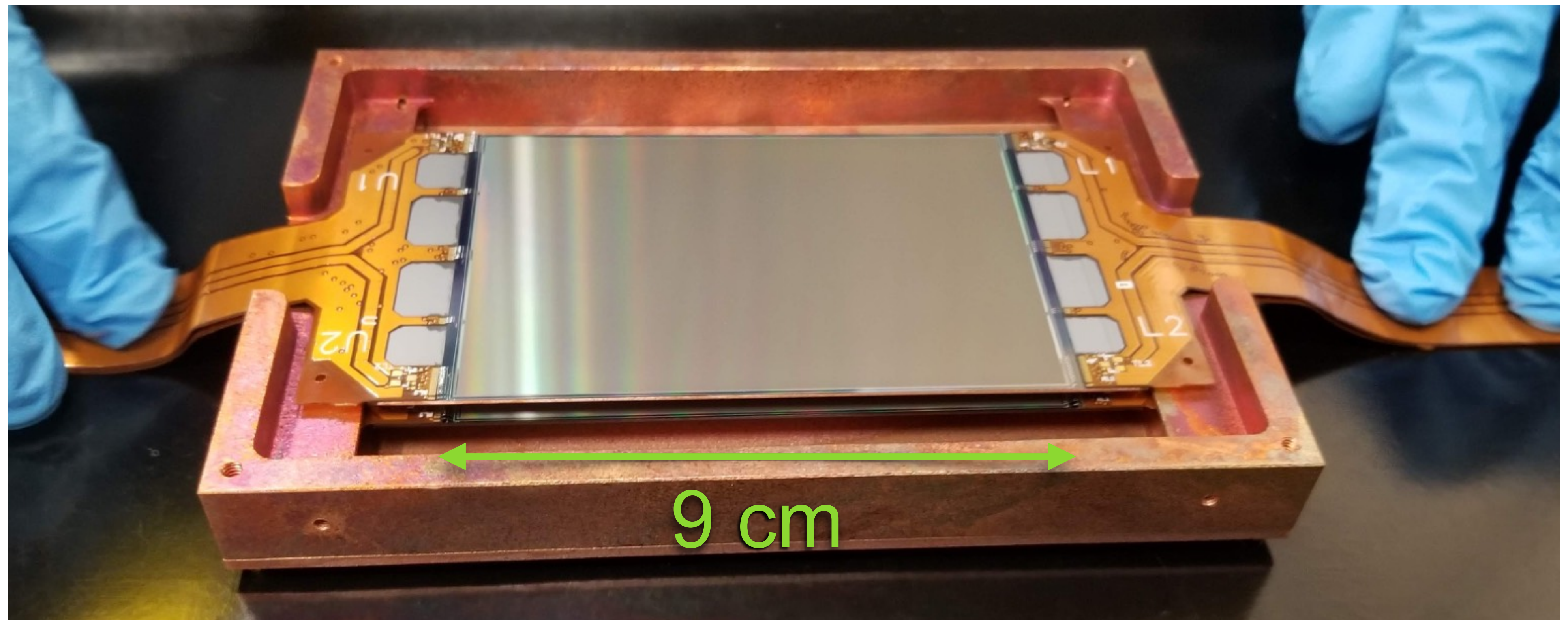


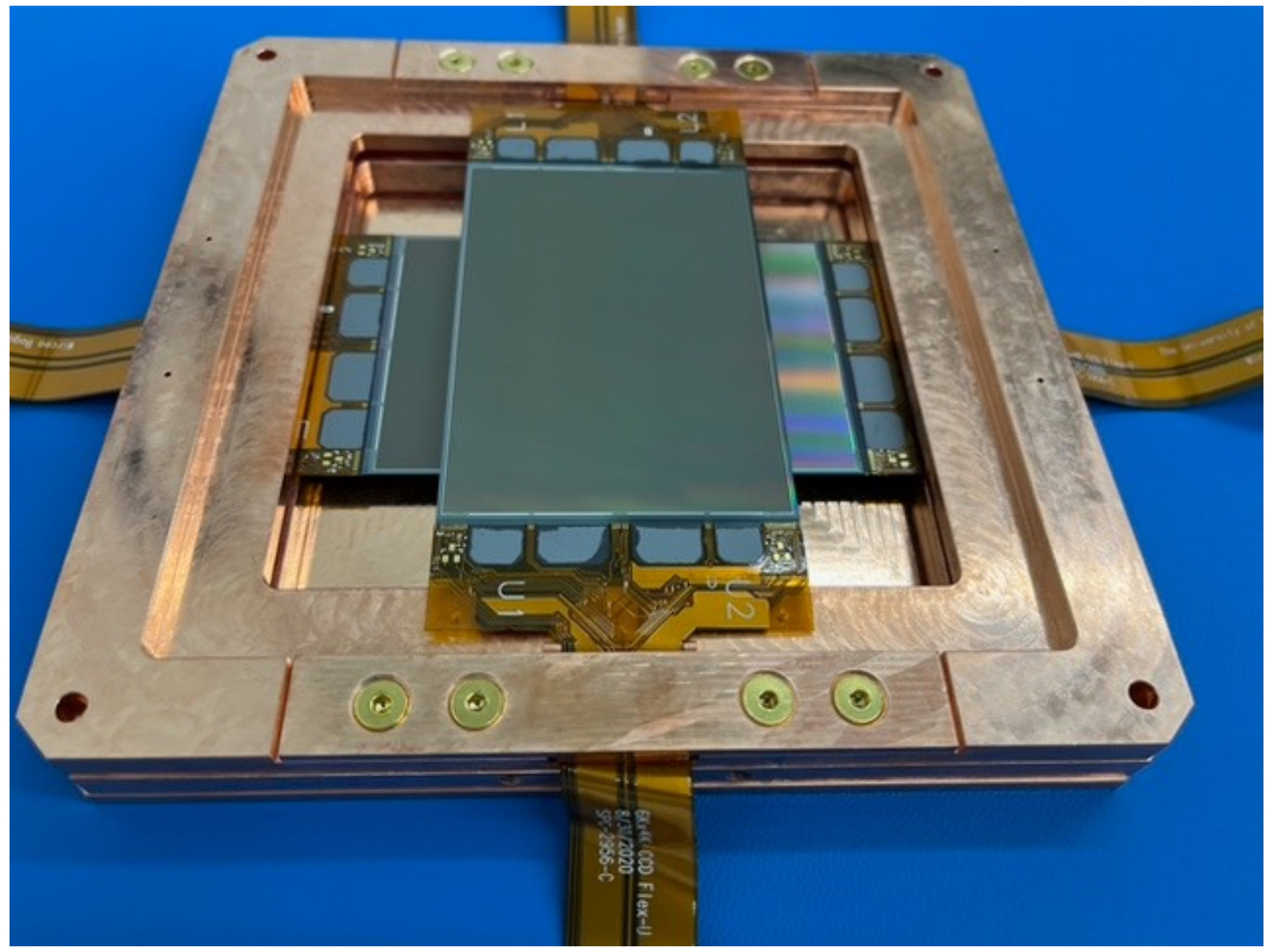


Prototype detectors

- 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, 2×10^{-3} e^-/pix/day, 10 d.r.u., 18 g.
- Understand DAMIC excess, **DM search results**.

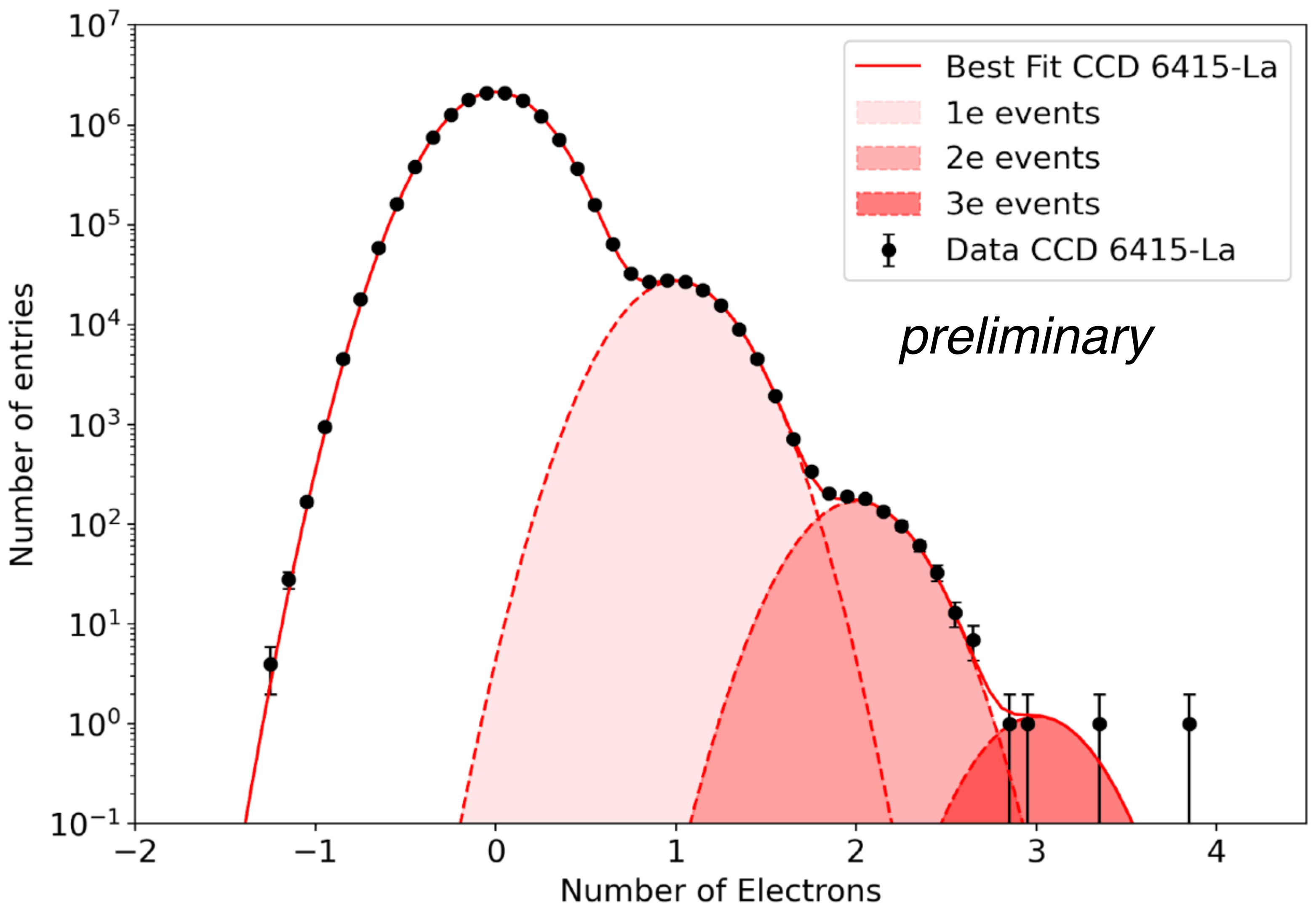


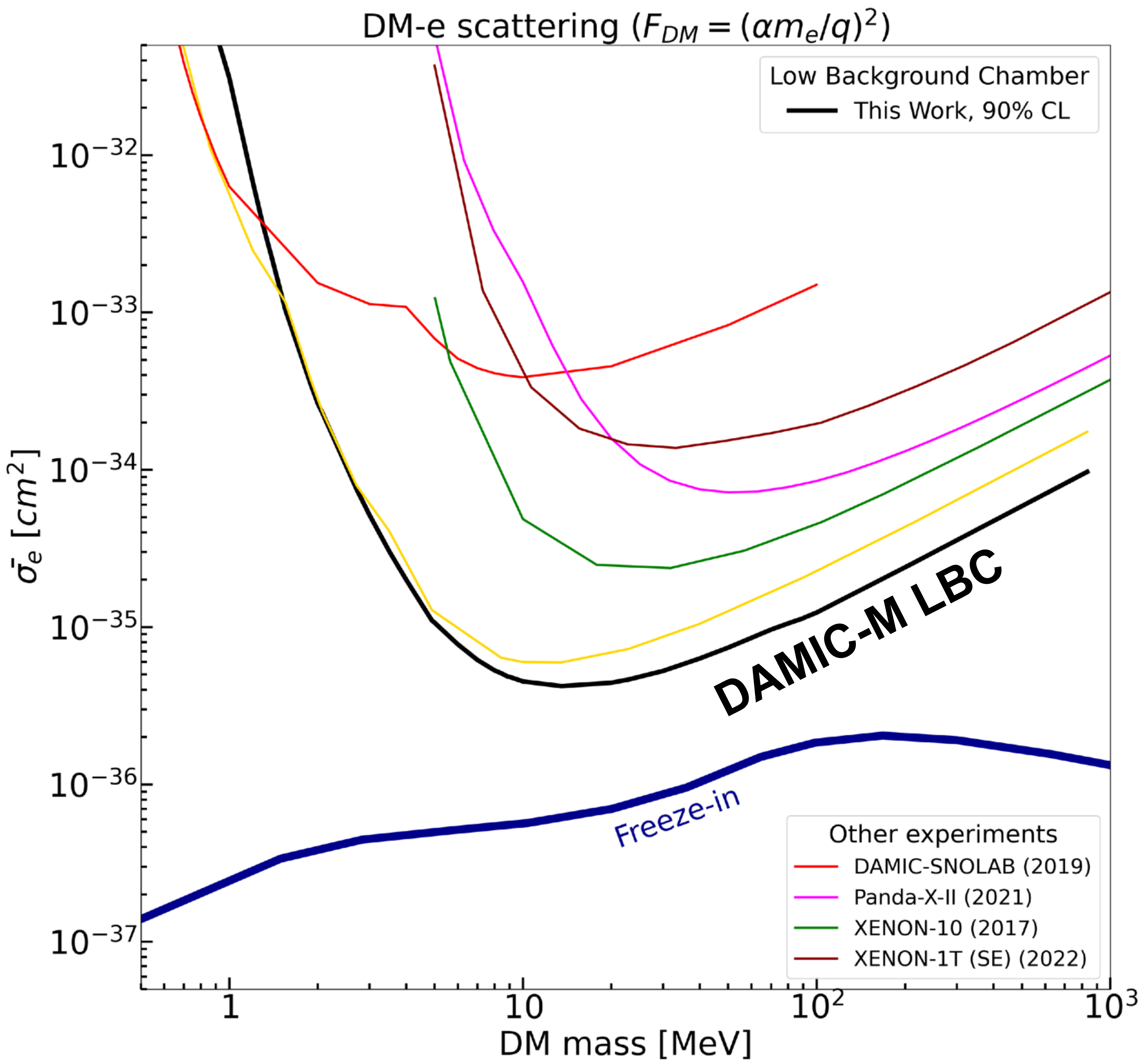




DAMIC-M LBC result

- 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%.

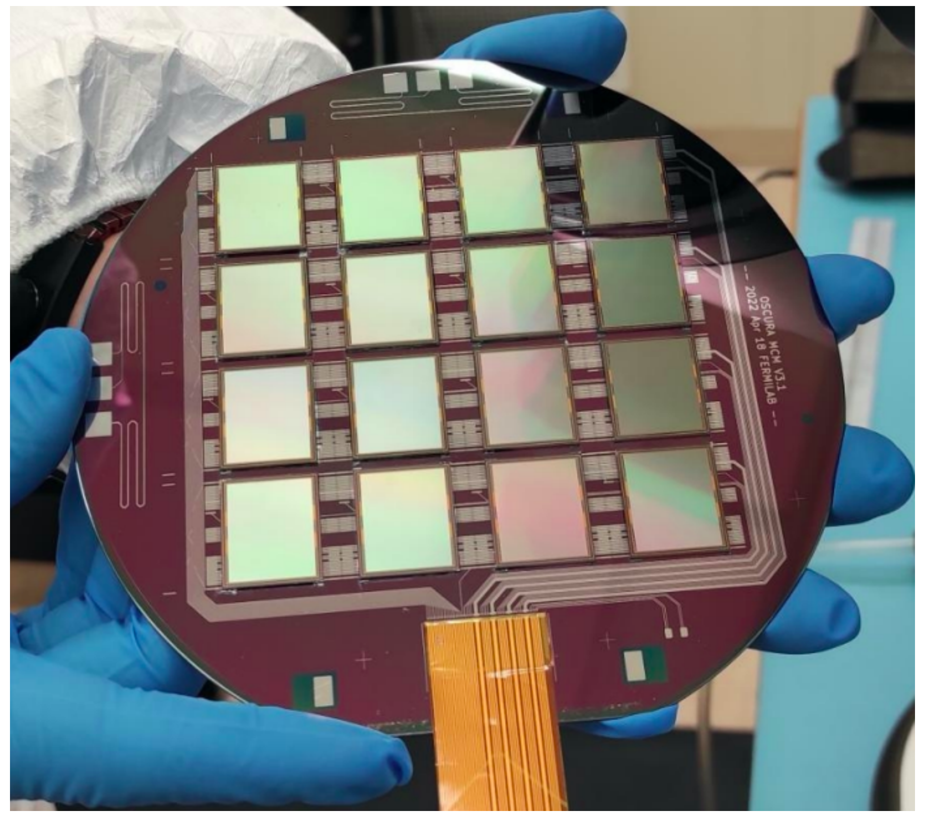




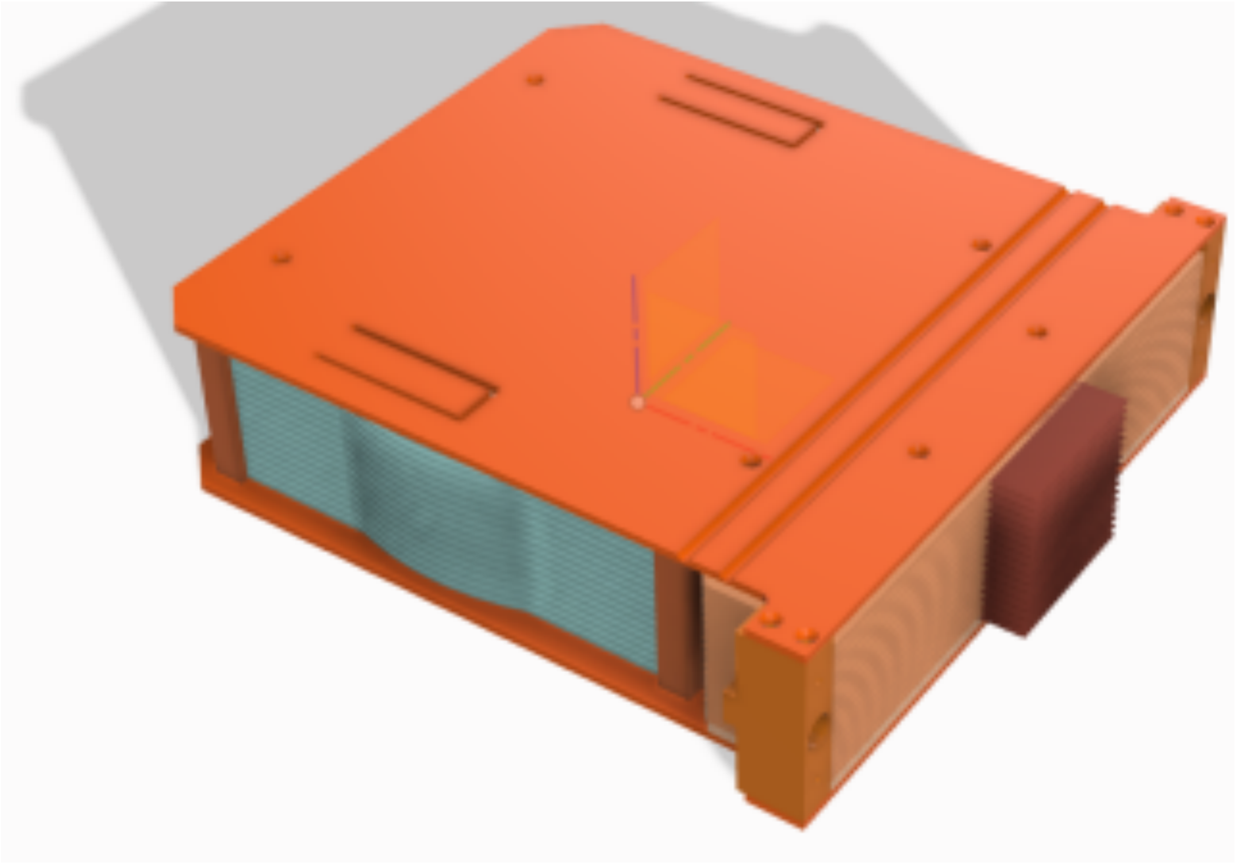
Oscura

arXiv:2202.10518(2022)

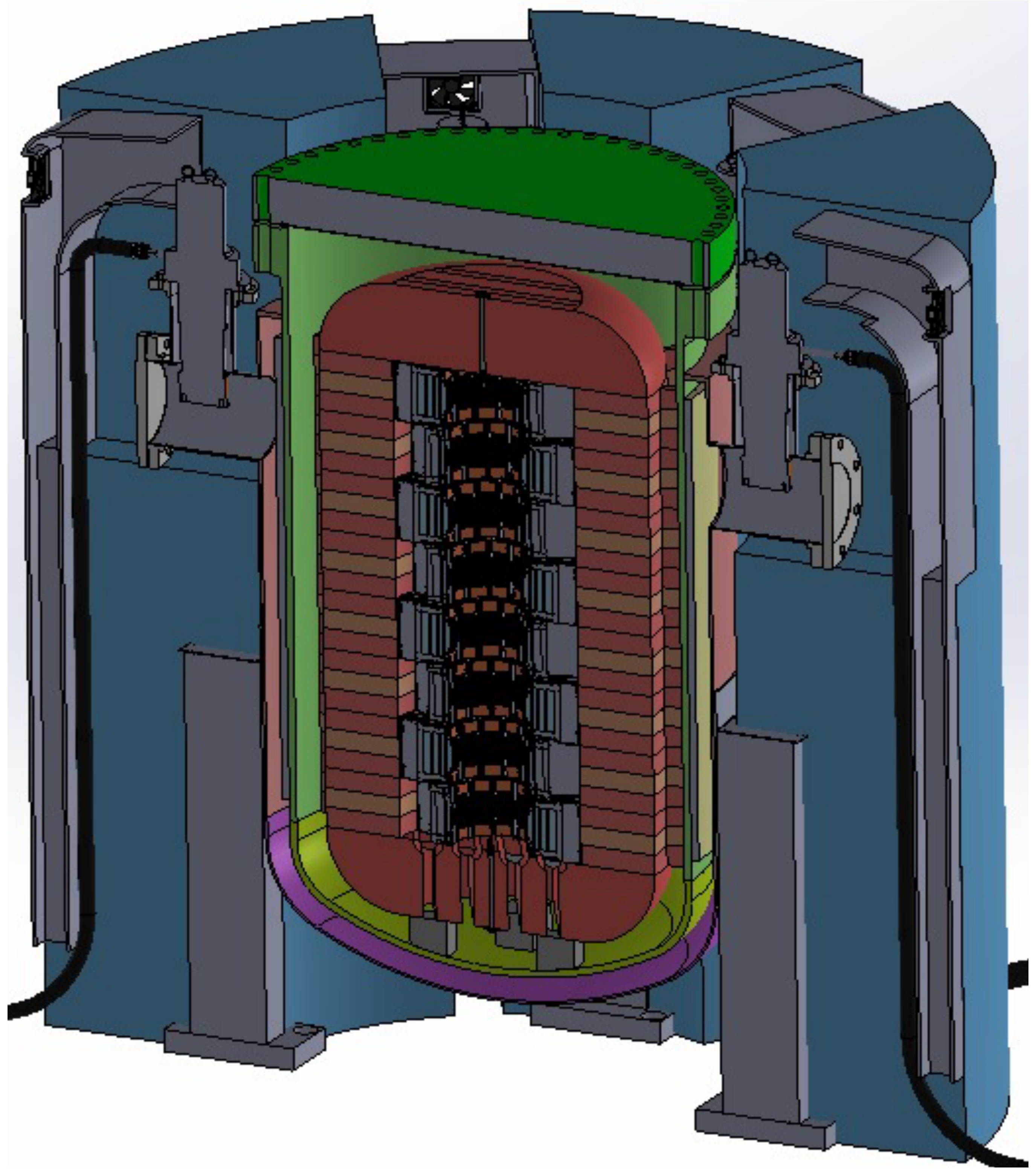
- **R&D**: scale the existing technology towards a 10 kg experiment.
- **Goal**: 30 kg-yr exposure with background level of 0.01 d.r.u.
- 28 Gpix in full Oscura instrument! c.f. LSST camera's 3.2 Gpix.
- Cold front-end electronics required for multiplexing and signal processing from ~24,000 channels.



16-CCD Multi Chip Module (MCM)



Super Module (SM): 16 MCMs in EFCu



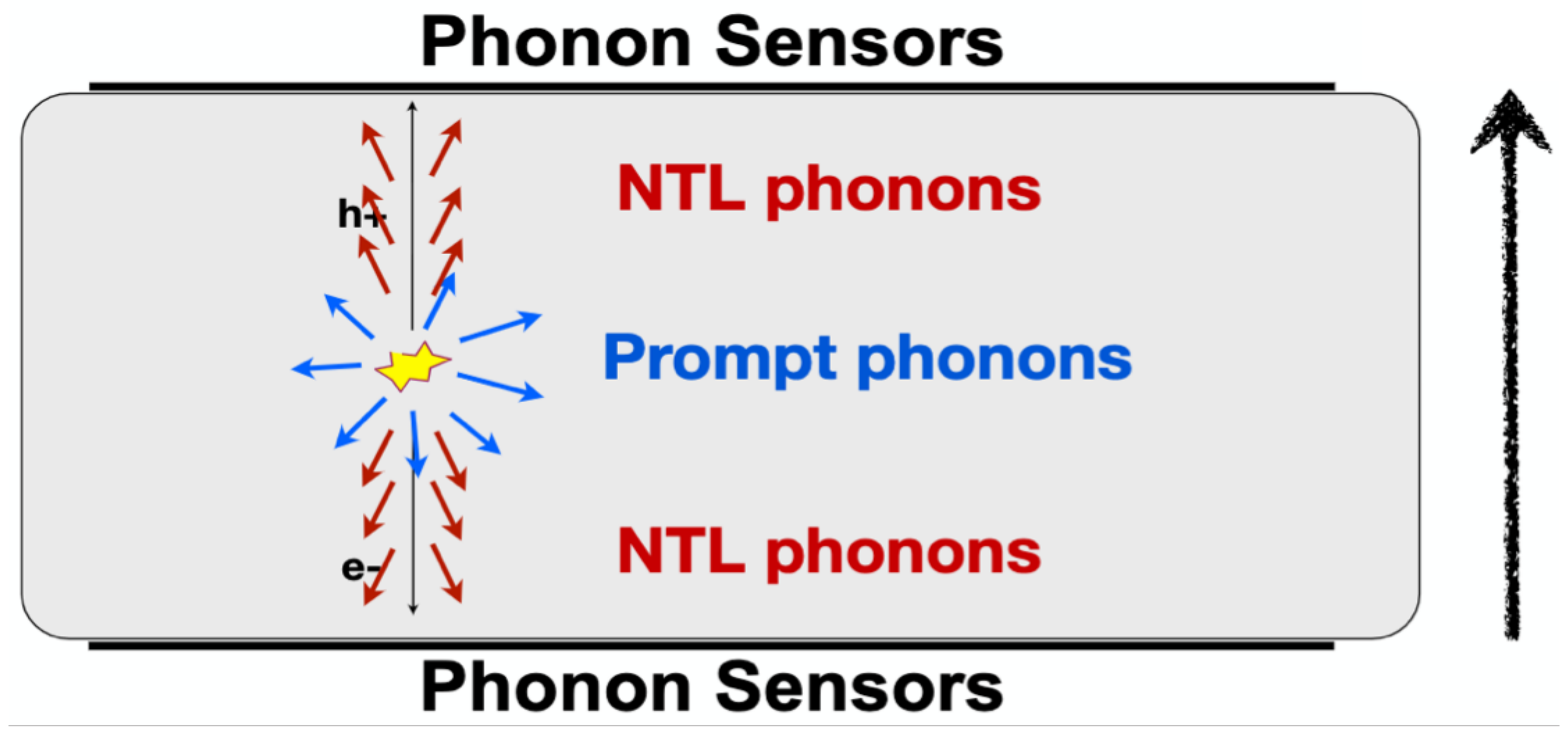
Full payload 100 SMs: 10 kg!

SuperCDMS / EDELWEISS HV

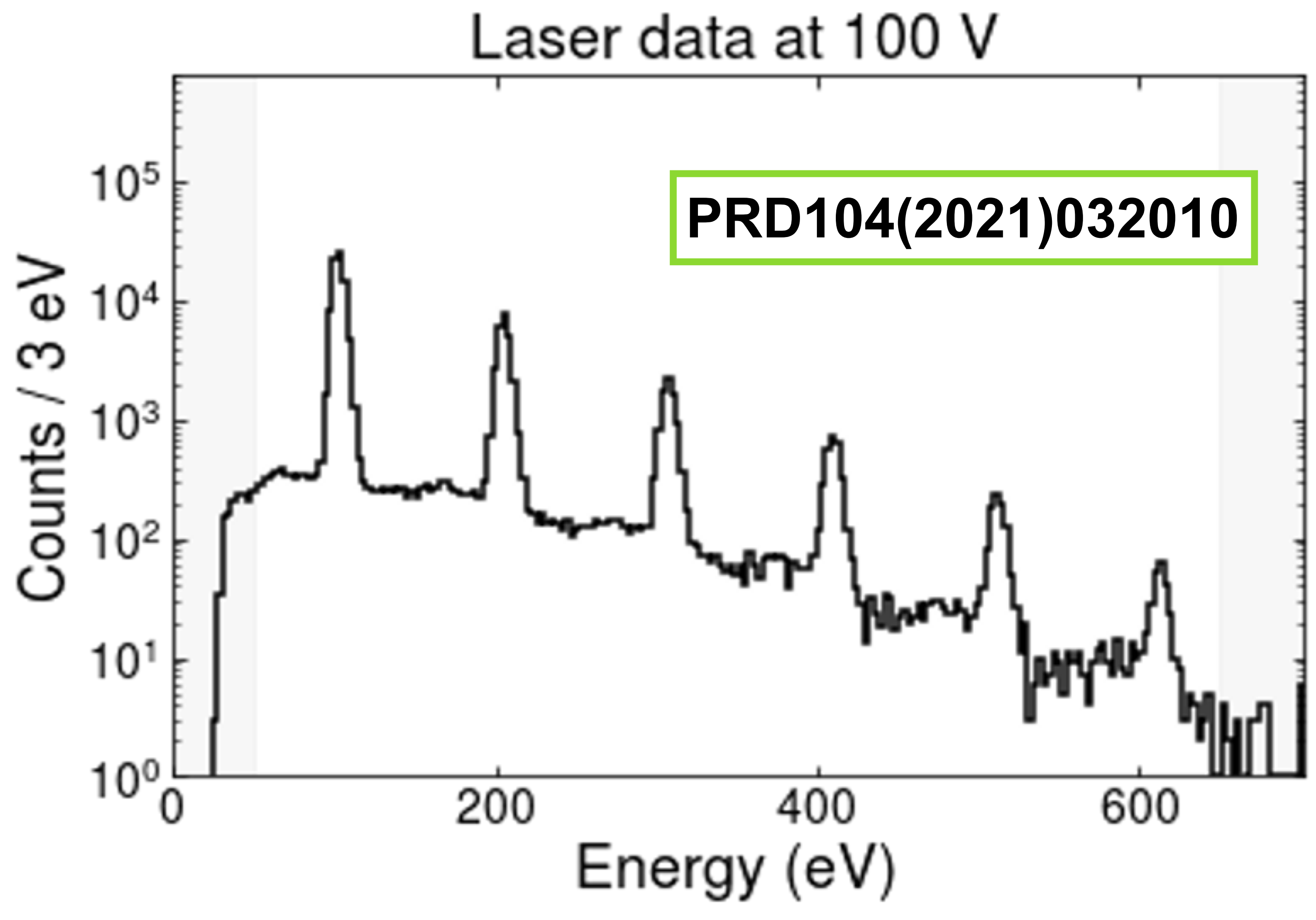
- Cryogenic calorimeters.
- Amplification of heat signal from charges drifting in electric field:

$$E_{heat} = E_{recoil} + E_{Luke} = E_{recoil} + N_p \, \Delta V$$

$$E_{heat} = E_{recoil}\left(1 + \frac{\Delta V}{\epsilon}\right) \quad \textit{particle-ID dependent}$$



- Amplification proportional to ionization signal and to applied bias
- No ER/NR discrimination as heat is dominated by ionization signal.
- Heat-only events are a source of backgrounds.
- Strategies to reject surface events: multiple electrodes, timing.

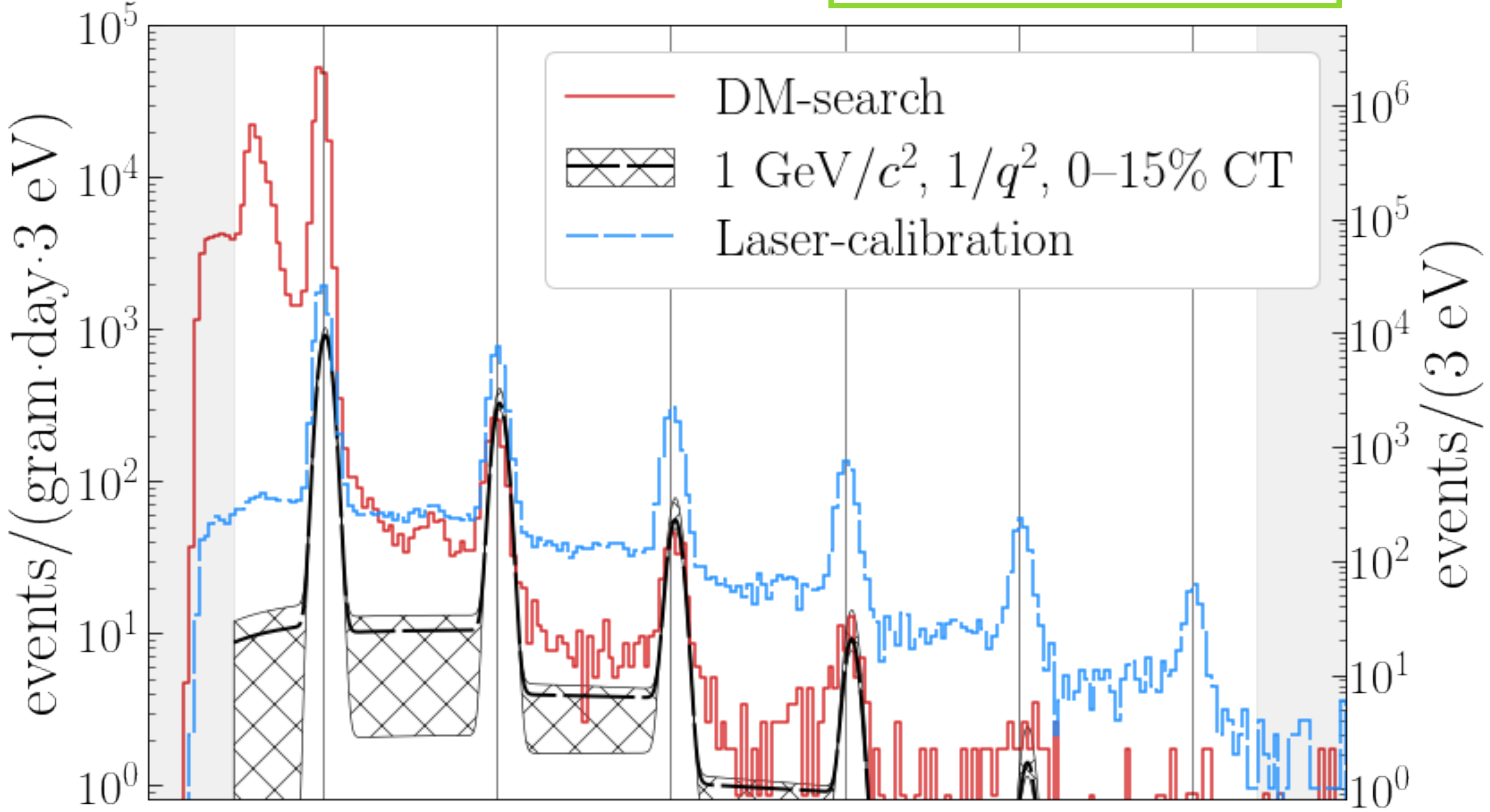


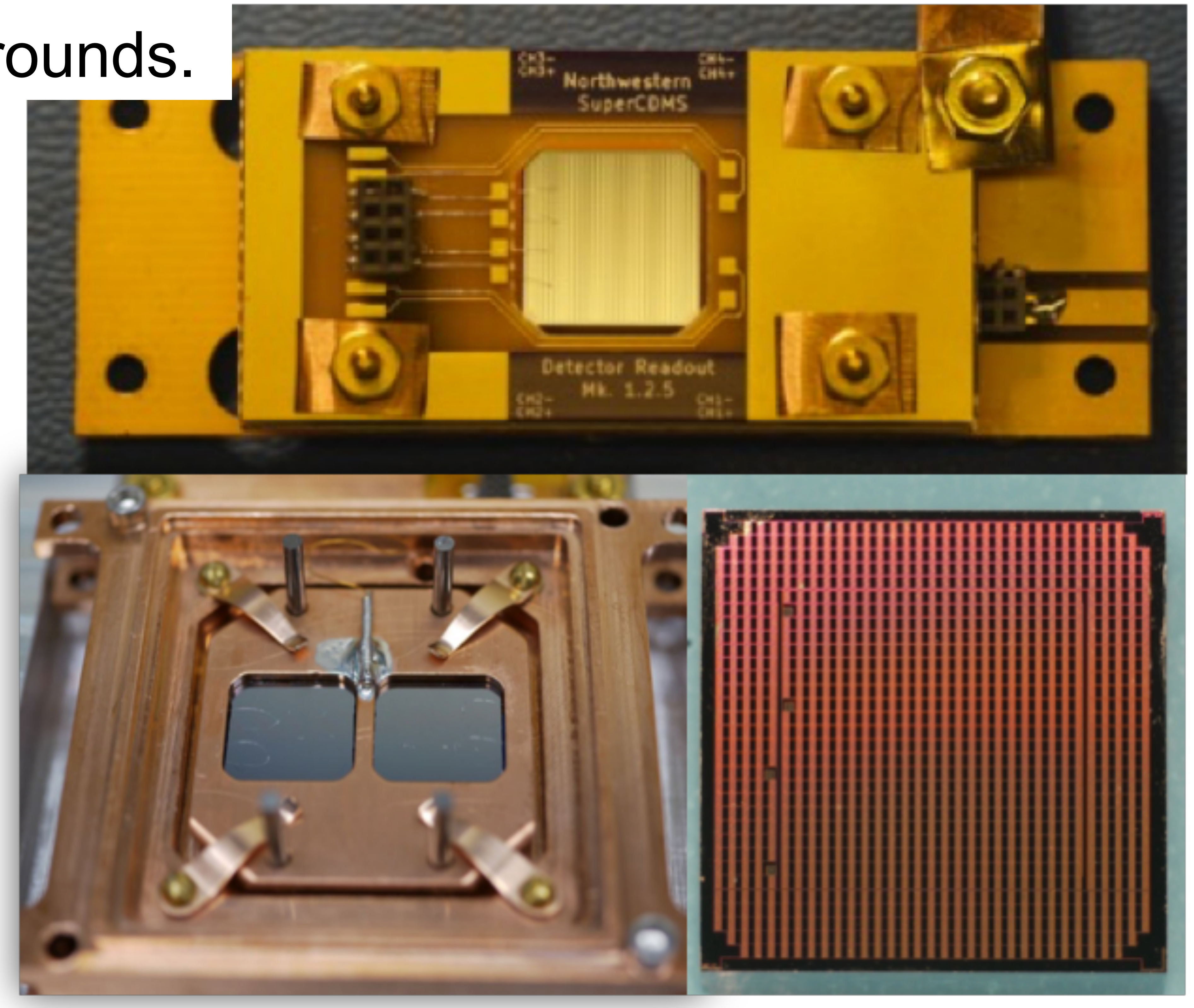
(= Recoil energy + Neganov Luke effect gain)

SuperCDMS HVeV

- HVeV detectors "best in class:" 2.7 eV baseline resolution, 9.2 eV threshold, large dynamic range, 1-g target.
- Running underground in NEXUS at Fermilab (300 m.w.e.)
- Four science runs with progressively lower backgrounds.

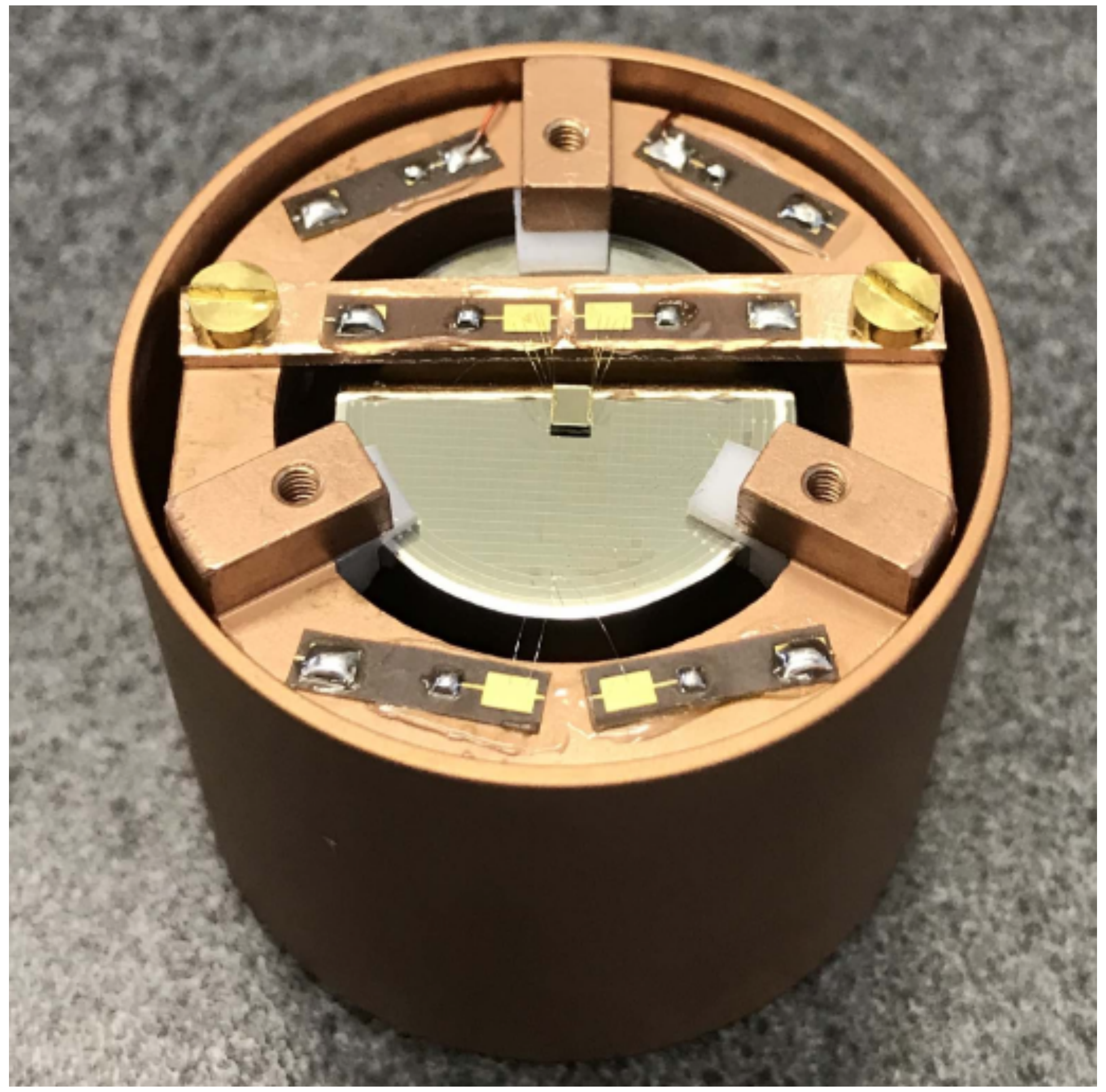
PRD102(2020)091101(R)

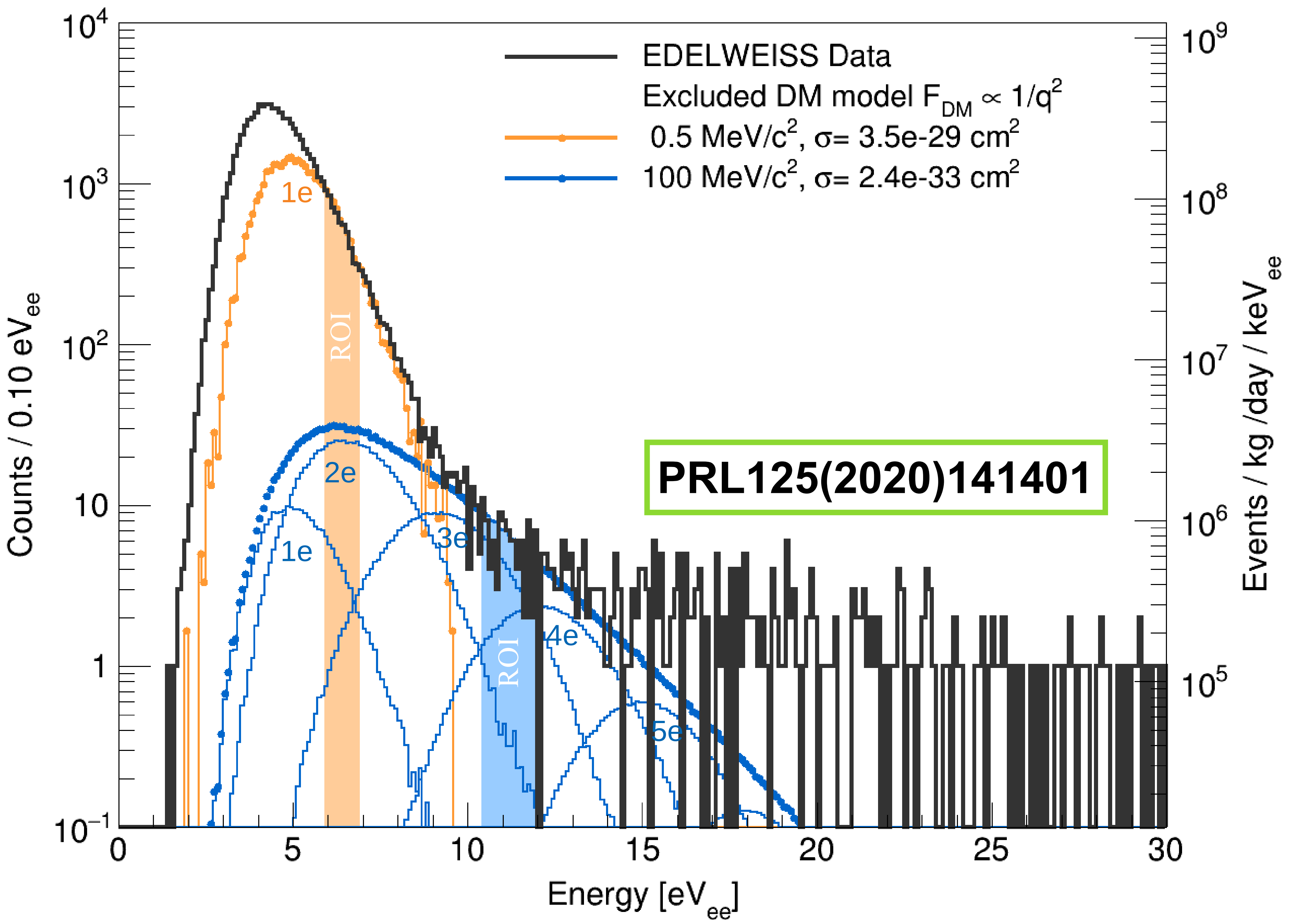




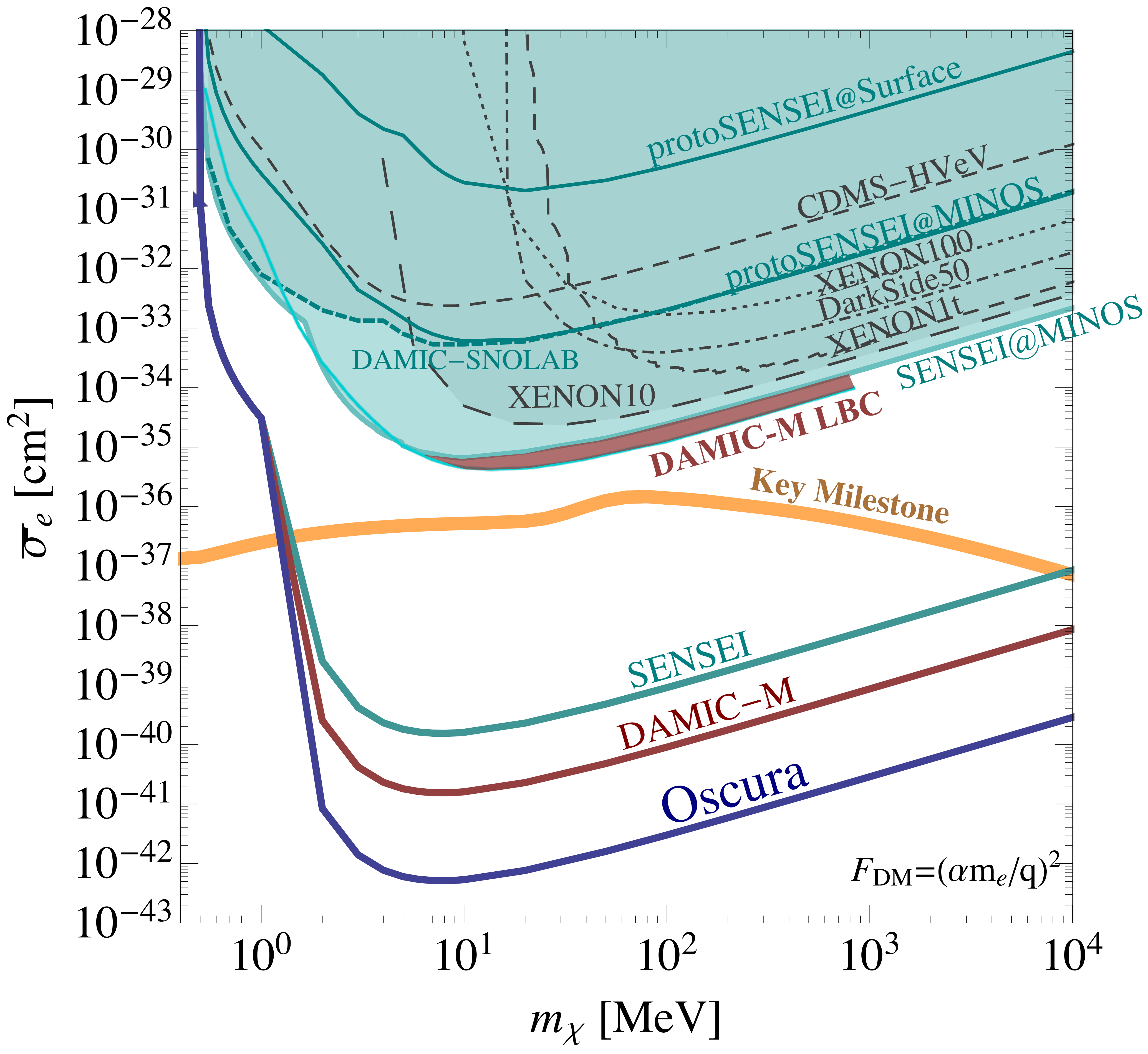
EDELWEISS

- RED30: 42 eV baseline resolution, 0.53 e-. Operated underground at LSM.
- Better exclusion limit than SuperCDMS HVeV because of larger exposure, lower surface-to-volume and lower background environment (despite x10 noisier).
- Plans for CRYOSEL: 30g Ge detector, σ_{phonon} = 20 eV, sustaining 200 V bias.

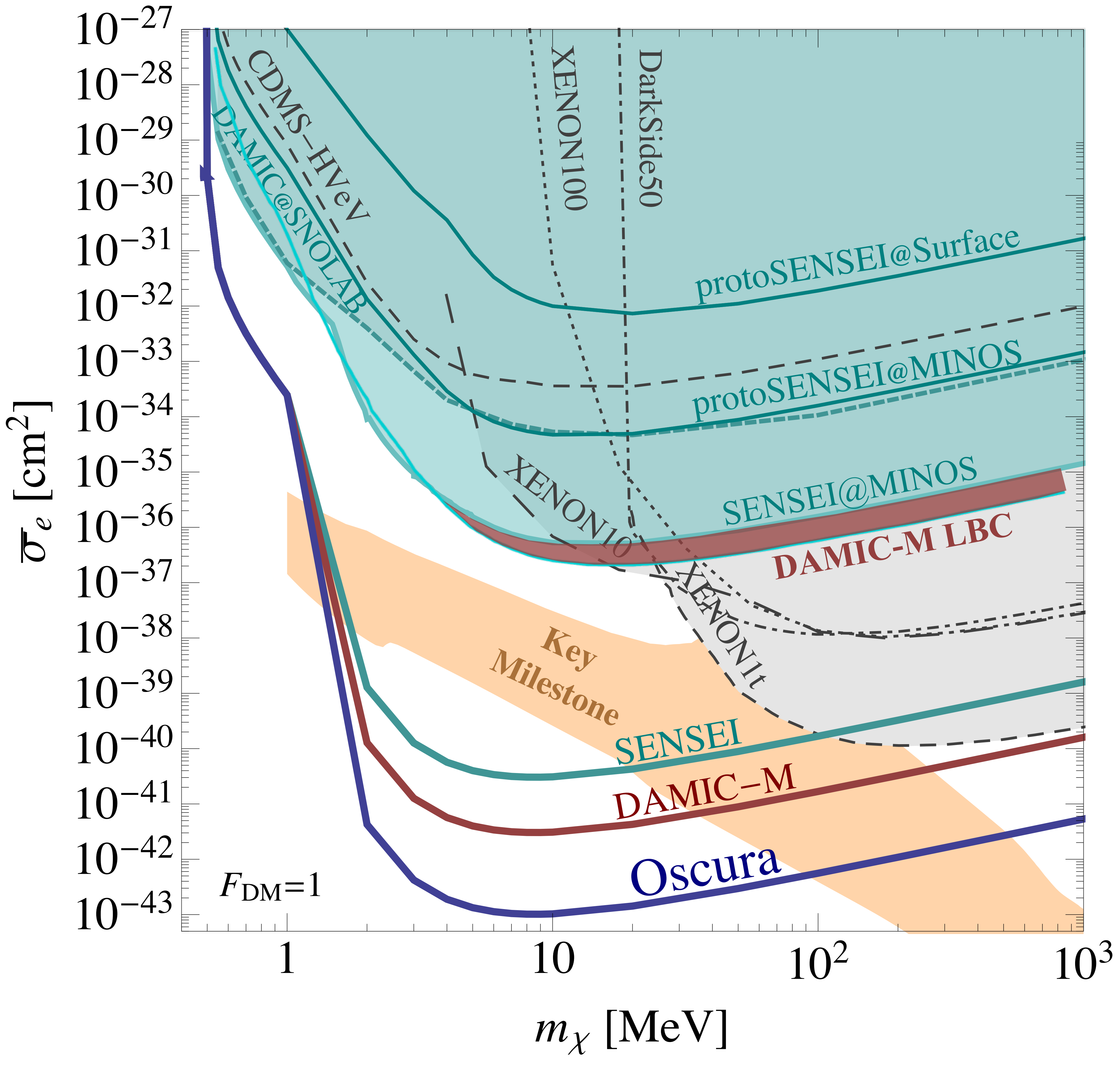




Outlook



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



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

Conclusions

- Electronic recoil searches allow us to search for even lighter DM.
- For DM-e scattering, ~MeV masses. Also Migdal, DM absorption.
- Require sensitivity to only a few charges ionized in the target.
- CCD detectors are scaling to kg-scale targets with single-charge resolution and correspondingly low backgrounds.
- Broad research program to understand the response of CCD detectors to the DM signal and backgrounds.
- Significant progress in single-charge resolution in cryogenic calorimeters.
- Active experimental program with orders-of-magnitude improvement in sensitivity in the coming years.

Thank you!