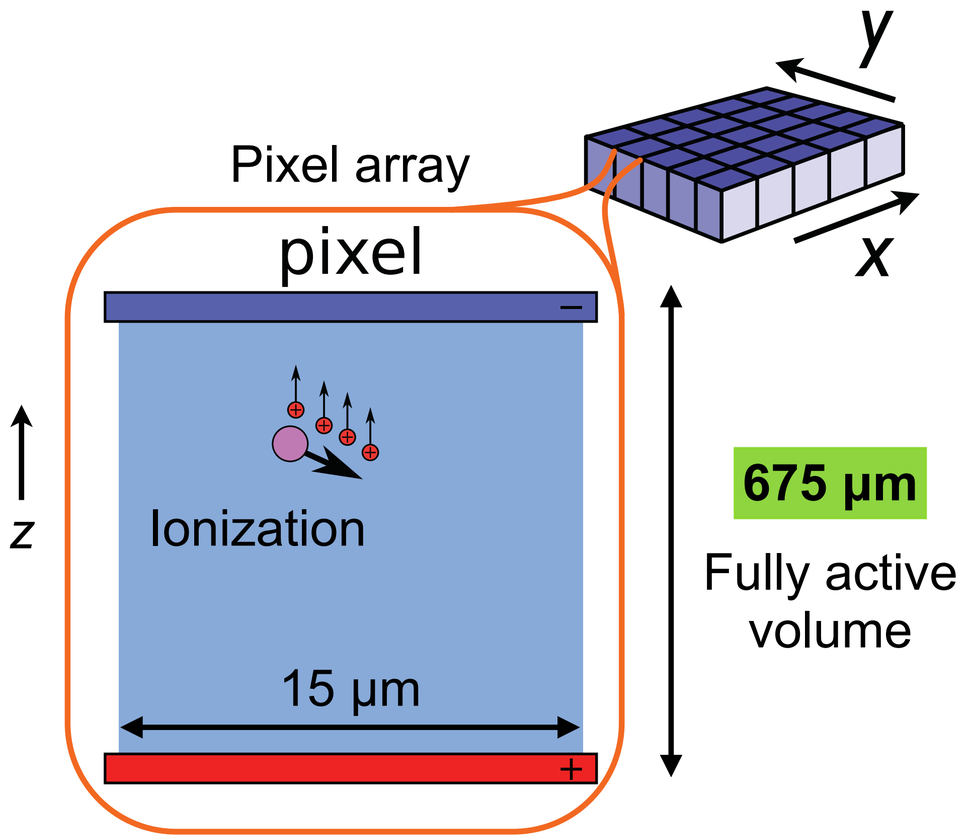
CCDs for DM and ν Physics

Alvaro E. Chavarria
University of Washington

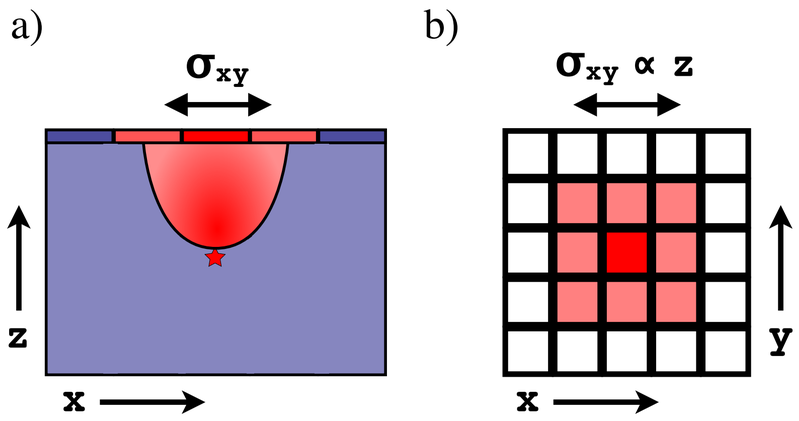
Outline

- Charge-coupled devices (CCDs).
- Search for light DM with DM-e^- scattering.
- DAMIC and other CCD dark matter experiments.
- CONNIE: search for CEνNS with CCDs.
- Low-energy spectroscopy with CCDs.
- Radioactive backgrounds in CCDs.
- Spin-off: The Selena Neutrino Experiment.

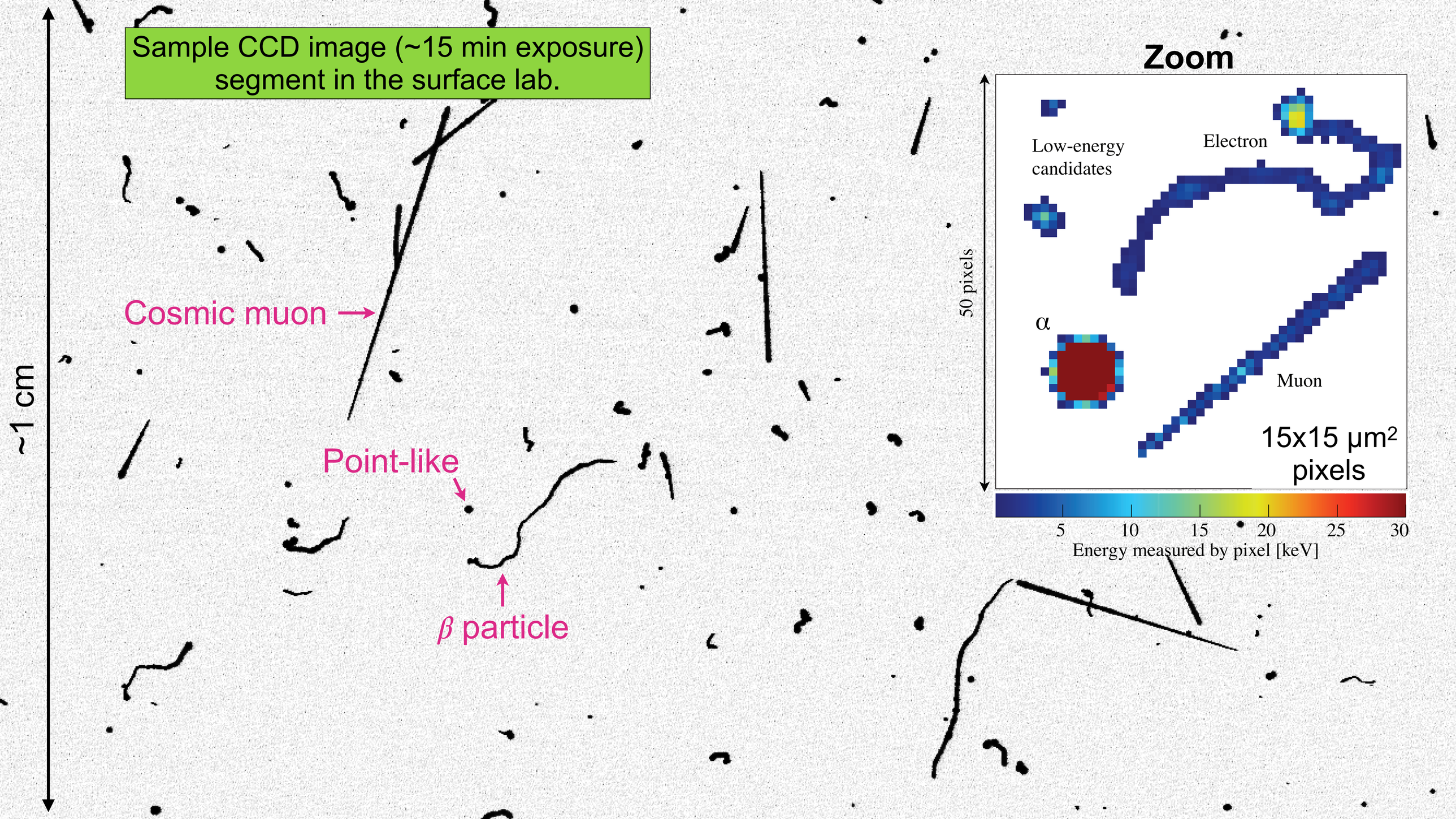
Charge-coupled devices



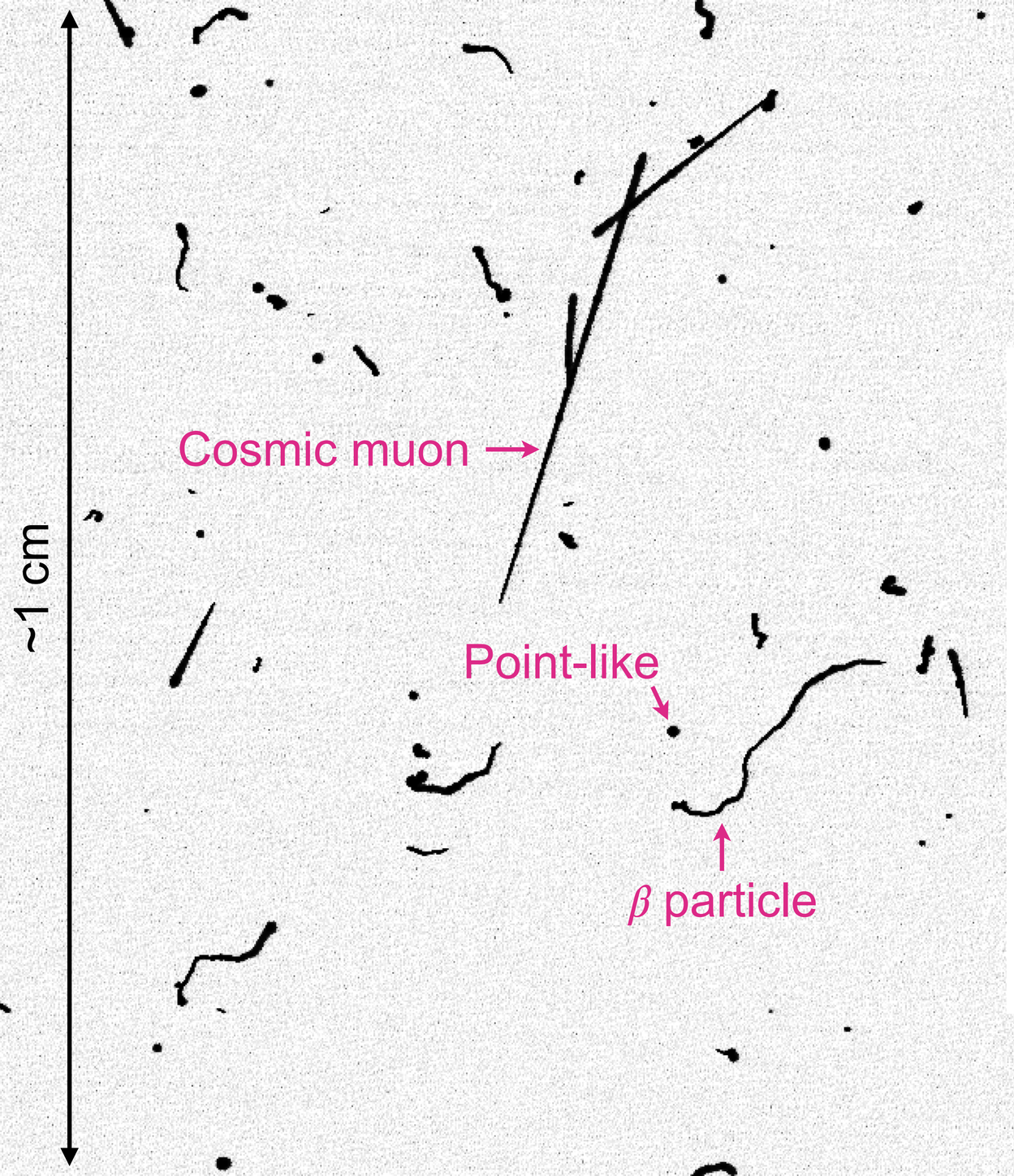
Silicon band-gap: 1.2 eV.
Mean energy for 1 e-h pair: 3.8 eV.

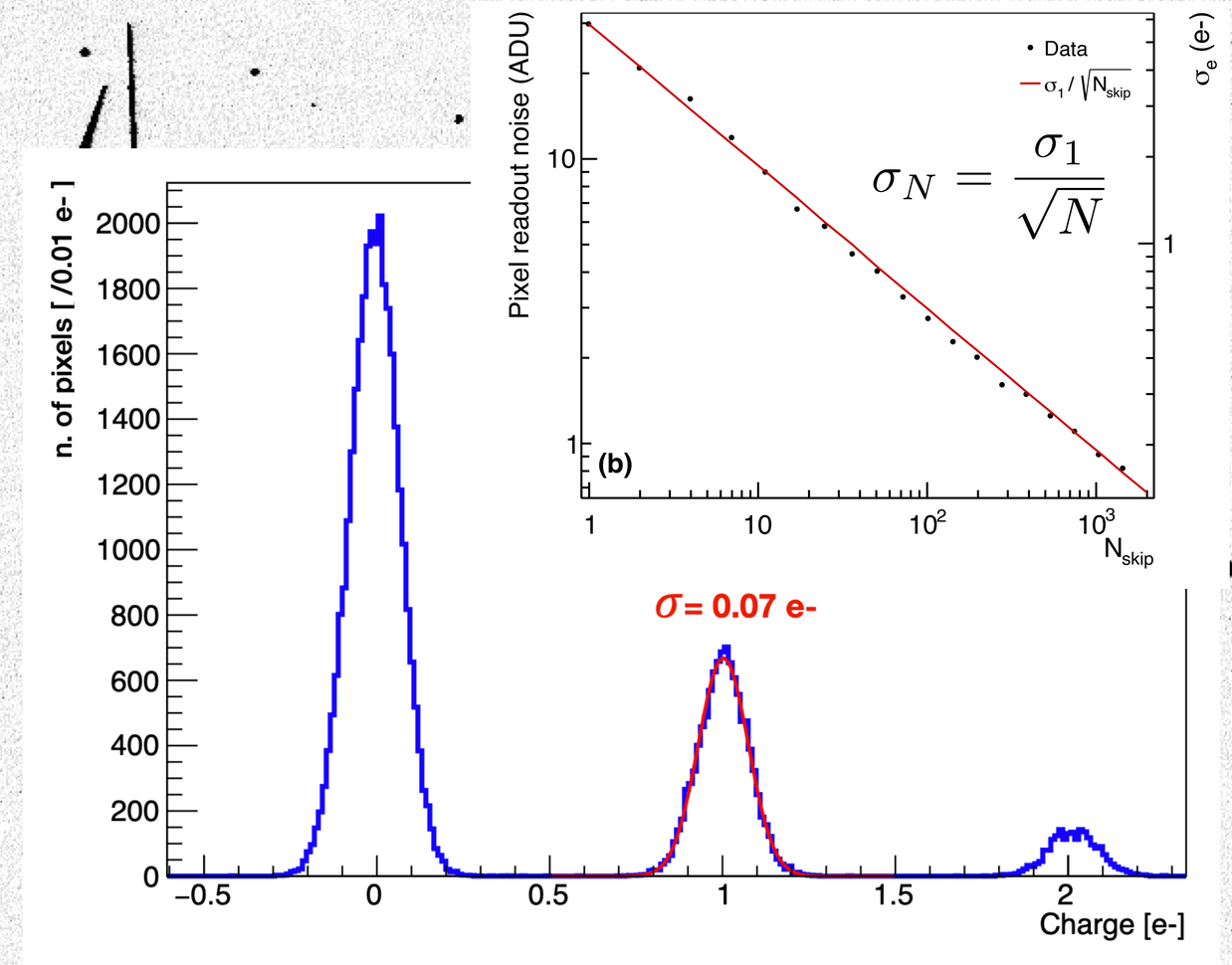


- Depth (z) reconstructed from distribution of charge on pixel array.
- Device is “exposed,” collecting charge until user commands readout.
- Readout can be slow : **low noise (few e-).**
- Standard fabrication in semiconductor industry and easy cryogenics (~100 K).


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]

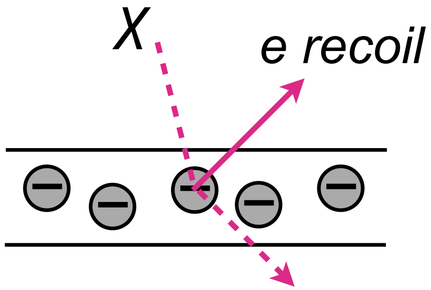
“Skipper” readout: Perform *N* uncorrelated measurements of the same pixel.

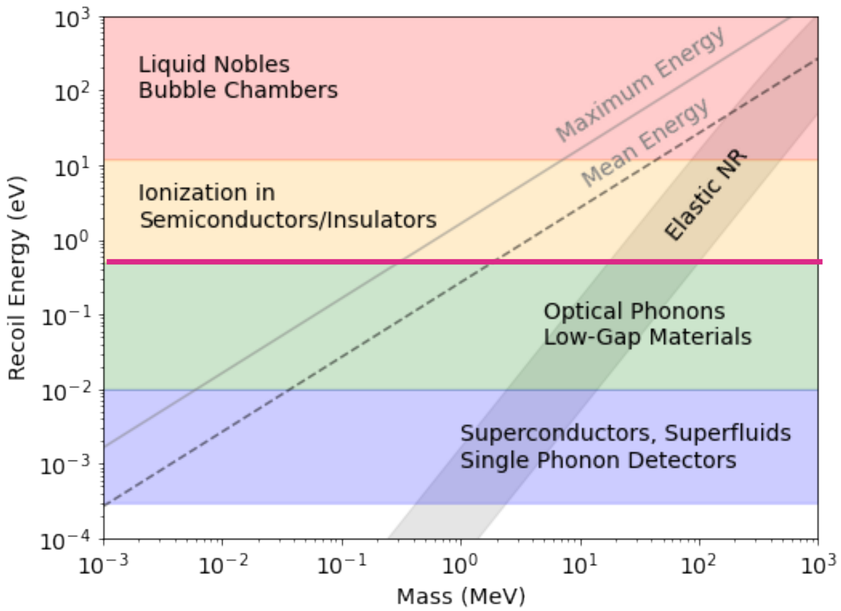




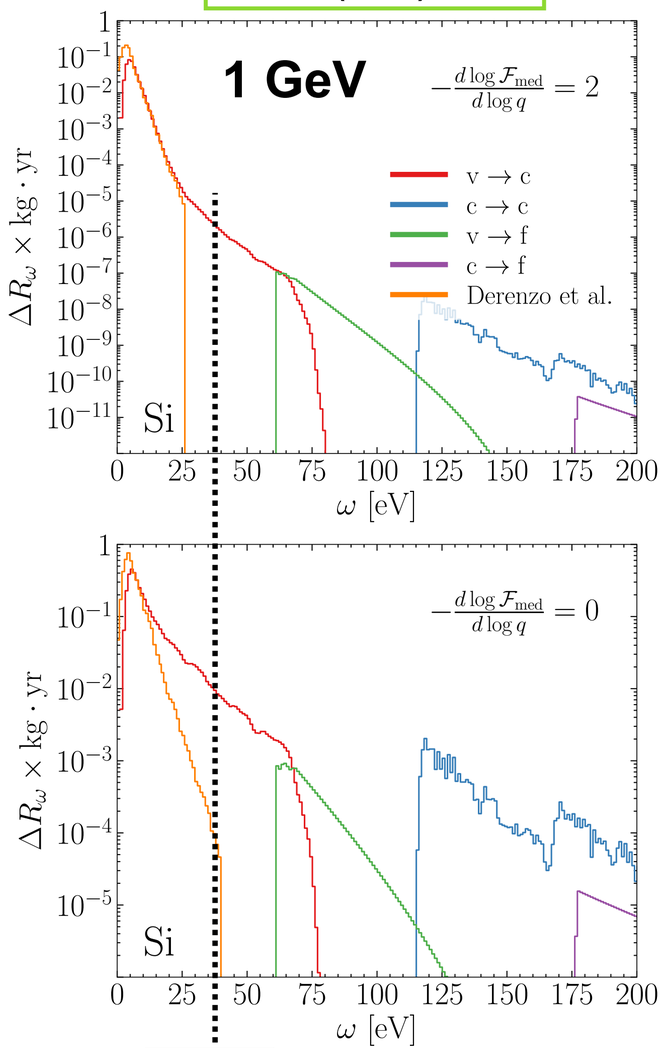
DM-e scattering

- Electrons are a lighter target than nuclei 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.

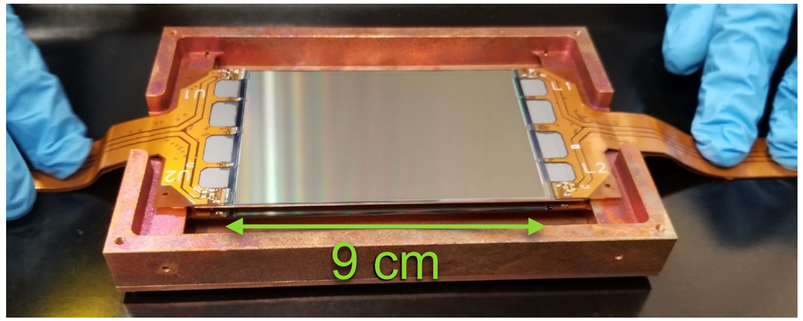
DAMIC at SNOLAB

- CCDs for direct dark matter search.
- Multi-CCD array operating at SNOLAB since 2012.
- First DM search results from ~eV ionization signals: PRL118(2017)141803

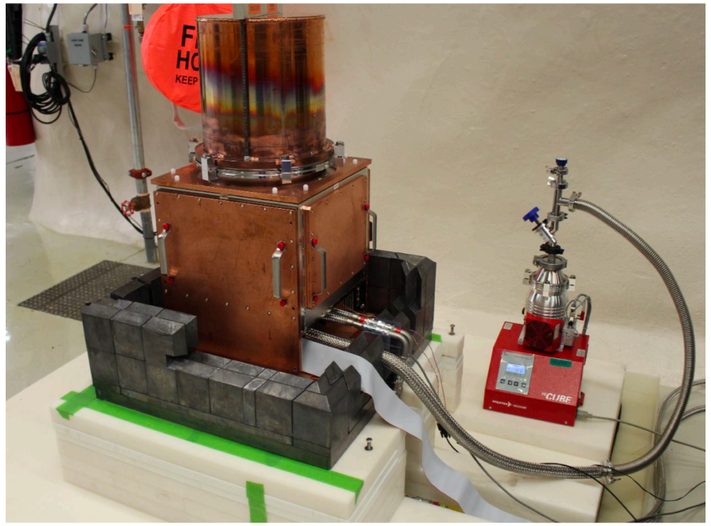
- **WIMP search:** PRL125(2020)241803
  - 11 kg-day of data from seven-CCD array.
  - First full background model in CCDs.
  - Recently upgraded with skipper CCDs.

Full details: PRD105(2022)062003

24 Mpix skipper CCD @ SNOLAB



SENSEI @ SNOLAB



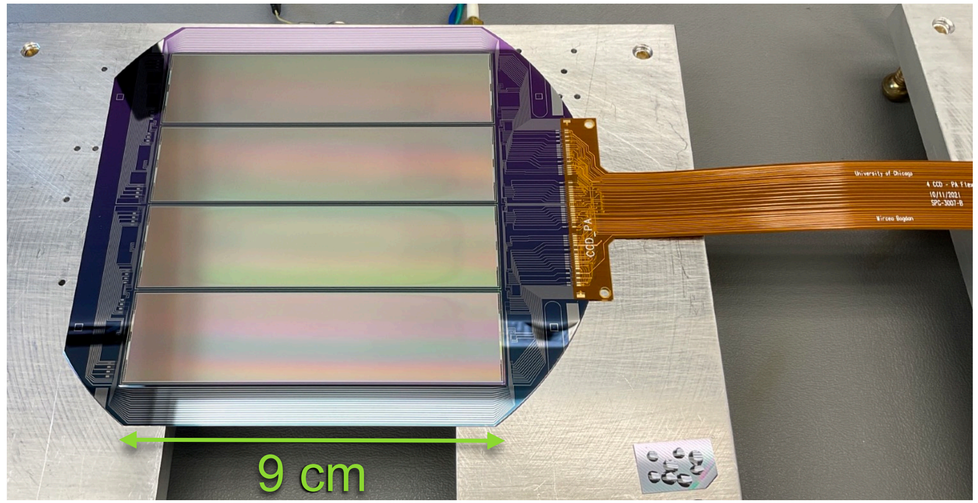
SENSEI

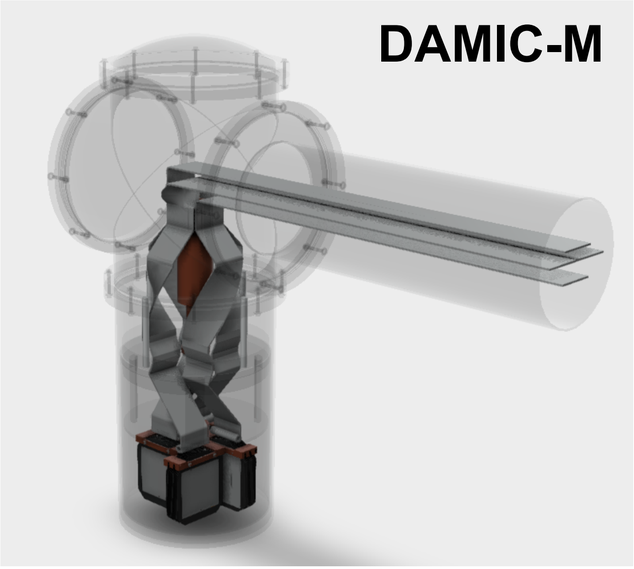
- First DM-search with skipper CCDs at Fermilab. PRL125(2020)171802
- Experimental / simulations studies on single e^- backgrounds:
- 10 skipper CCDs (~25g) deployed at SNOLAB. PRX12(2022)011009
- Science goal: DM-e^- search with 100 g-year. PRAppl17(2022) 014022

DAMIC-M

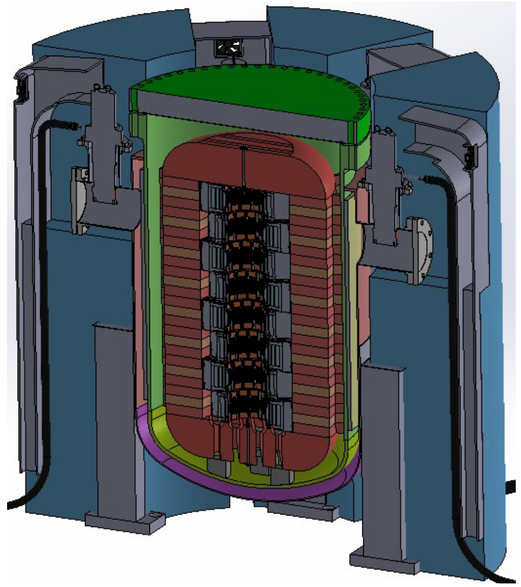
- 52 skipper-CCD modules in LSM (France) for kg-year target exposures.
- 50x background reduction from DAMIC at SNOLAB.
- Besides ER searches, NR result may have comparable sensitivity to HV detectors of SuperCDMS SNOLAB.
- Commissioning in early 2024.
- **LBC**: small prototype detector at LSM just released best exclusion limits of DM-e^- scattering.

DAMIC-M 4-CCD Module @ UW





Oscura



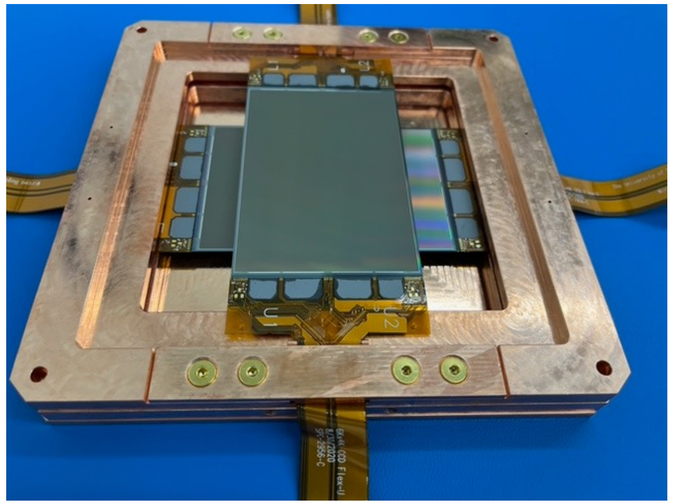
Oscura

- **R&D**: scale the existing technology towards a 10 kg experiment.
- **Goal**: DM-e^- scattering search with 30 kg-yr exposure.

IDM2022 Parallel Session 1A

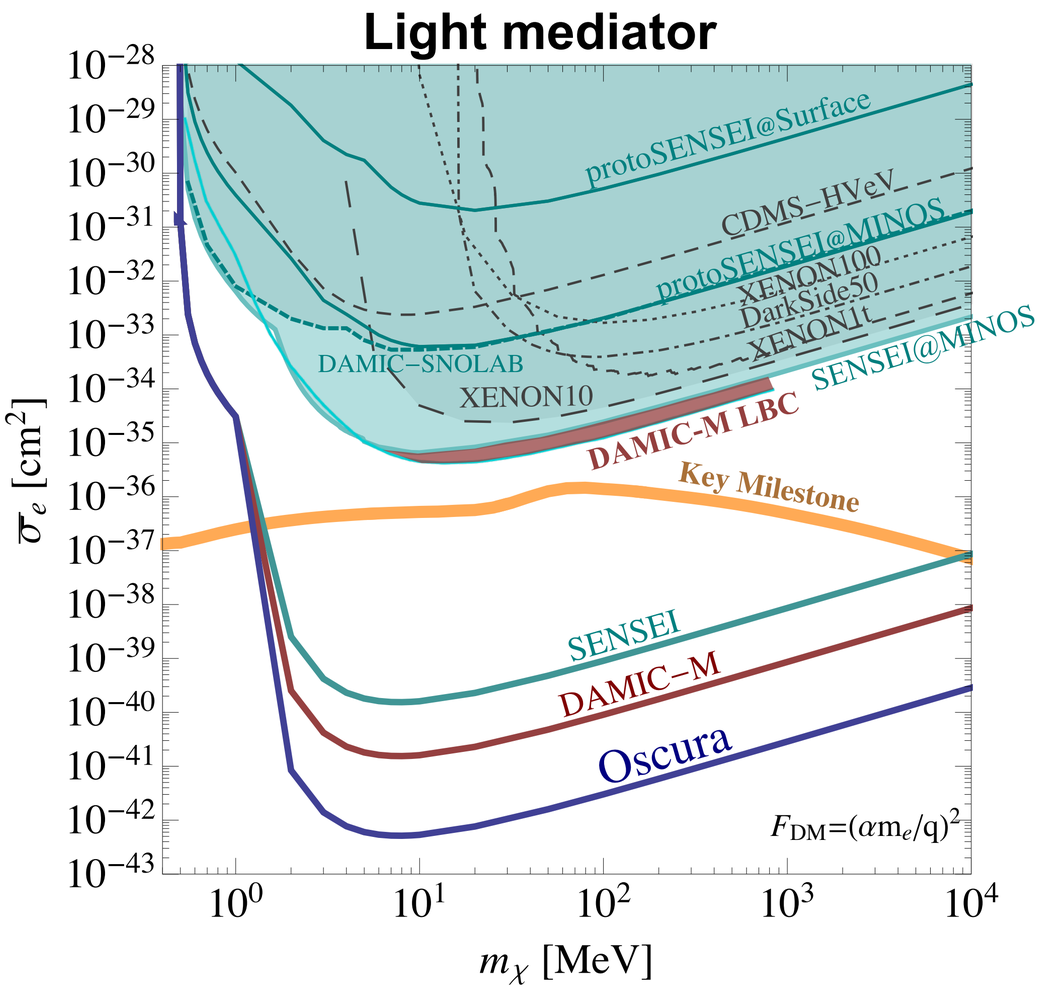
14:00	The DAMIC-M Experiment: Status and First Results	*Danielle Norcini*	
	EI7	14:00 - 14:20	
	The low-energy spectrum in DAMIC at SNOLAB	*Alvaro Chavarria*	
	EI7	14:20 - 14:40	
	SENSEI: Sub-GeV Dark Matter Search with Skipper CCDs	*Mariano Cababie*	
	EI7	14:40 - 15:00	
15:00	The Oscura experiment – searching for low-mass dark matter with a very-large array of skipper-CCDs	*Nathan Saffold*	
	EI7	15:00 - 15:20	
	First 100 eV nuclear recoil ionization yield measurement in silicon	*Dr Valentina Novati*	
	EI7	15:20 - 15:40	
	Measurement of low-energy Compton and neutron scattering in Si CCDs for dark matter searches	*R Smida*	
	EI7	15:40 - 16:00	
16:00			

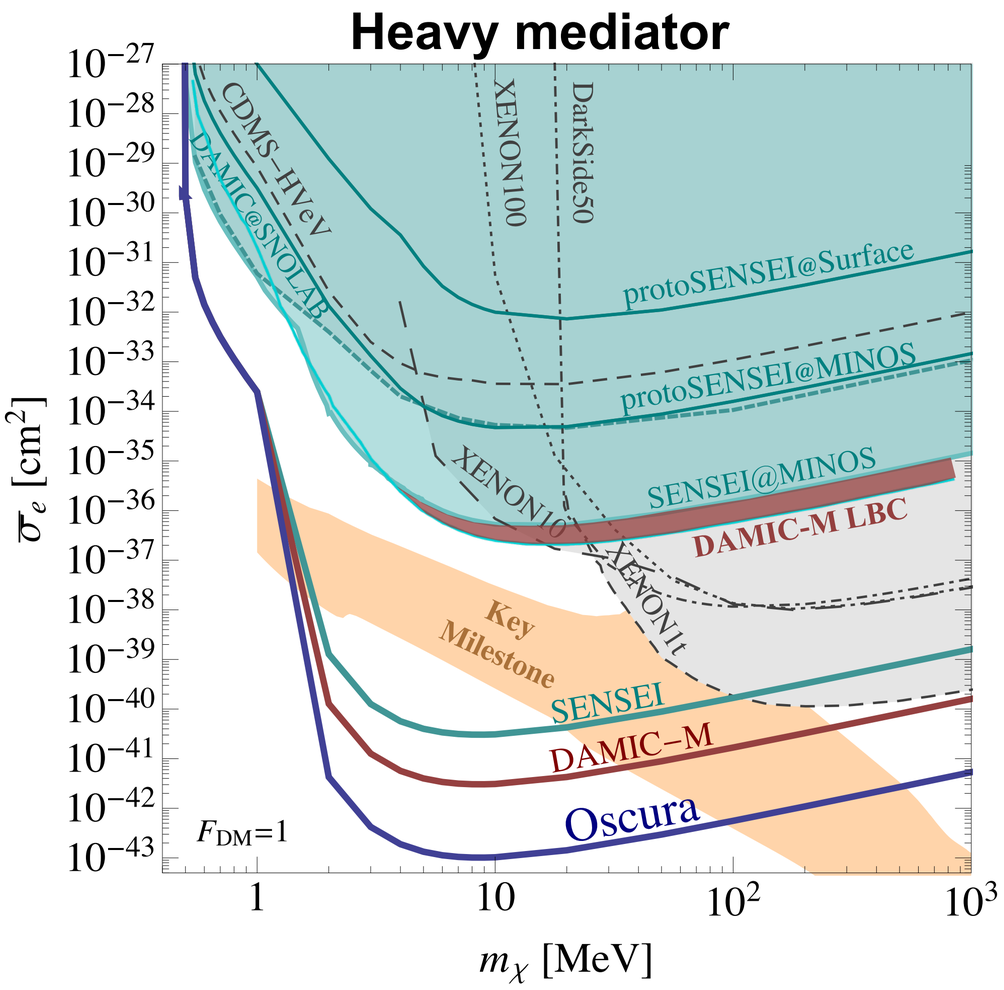
New results!
DAMIC-M LBC



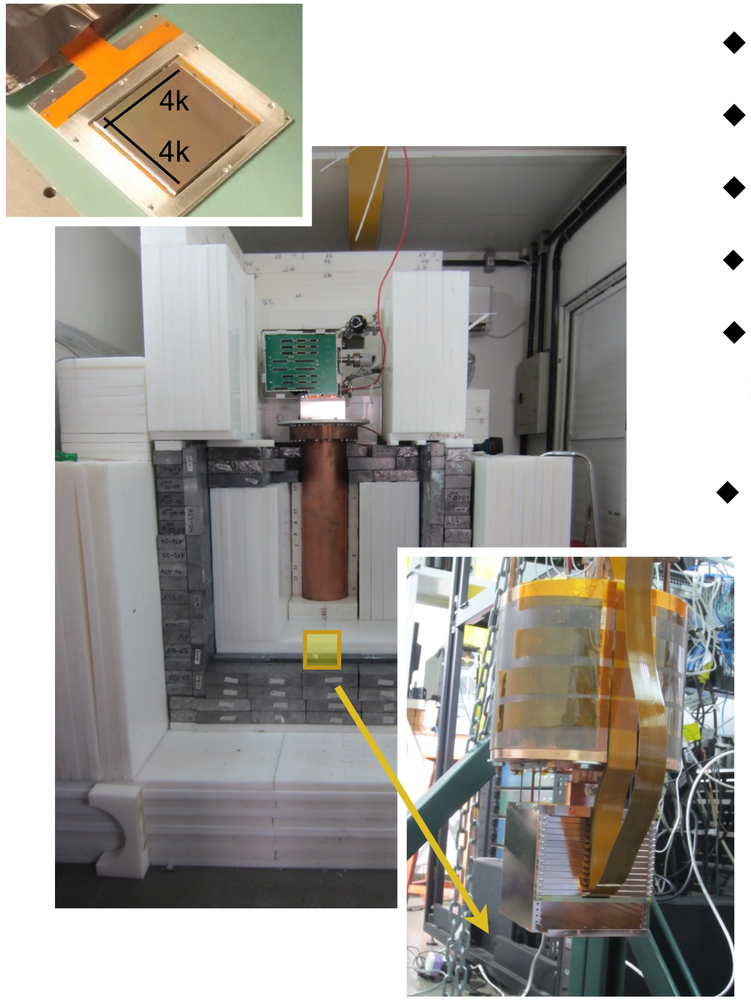
- One parallel session at latest IDM Conference dedicated to CCDs!

Outlook


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

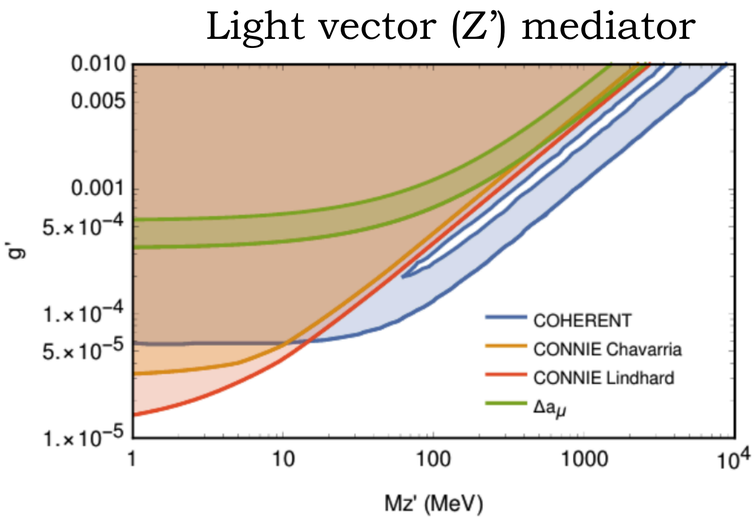

Heavy mediator
CDMS−HVeV
XENON100
DarkSide50
DAMIC@SNOLAB
protoSENSEI@Surface
protoSENSEI@MINOS
SENSEI@MINOS
XENON10
DAMIC-M LBC
XENON1t
Key Milestone
SENSEI
DAMIC−M
Oscura
$F_{DM}=1$
σ_e [cm^2]
m_χ [MeV]

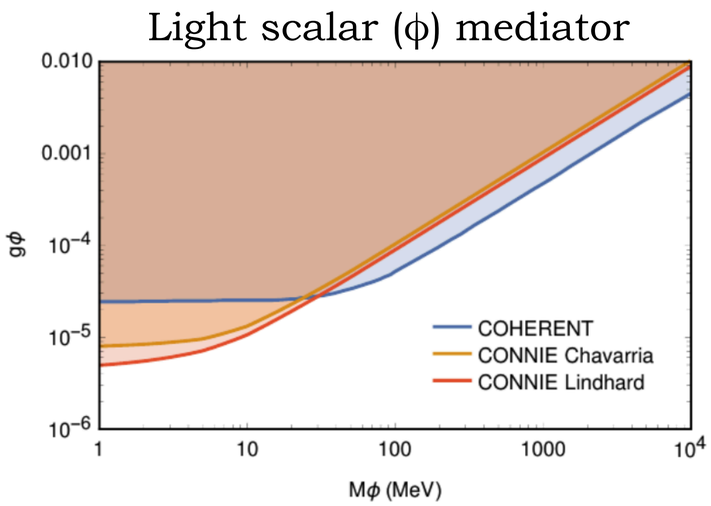
CONNIE: COherent Neutrino-Nucleus Interaction Experiment



- Experiment @ 30 m from the 3.9 GW reactor core
- Flux: $\sim 10^{12}\ \bar{\nu}_e\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- **2016-2018**: CCD array with 47.6 g active mass.
- Energy threshold ~50-70 eV_{ee}
- Reactor ON (2.1 kg-day) vs. OFF (1.6 kg-day) spectral comparison leads to

- First competitive BSM constraints from CEvNS at reactors:





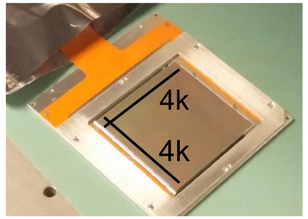
Slides from C. Bonifazi

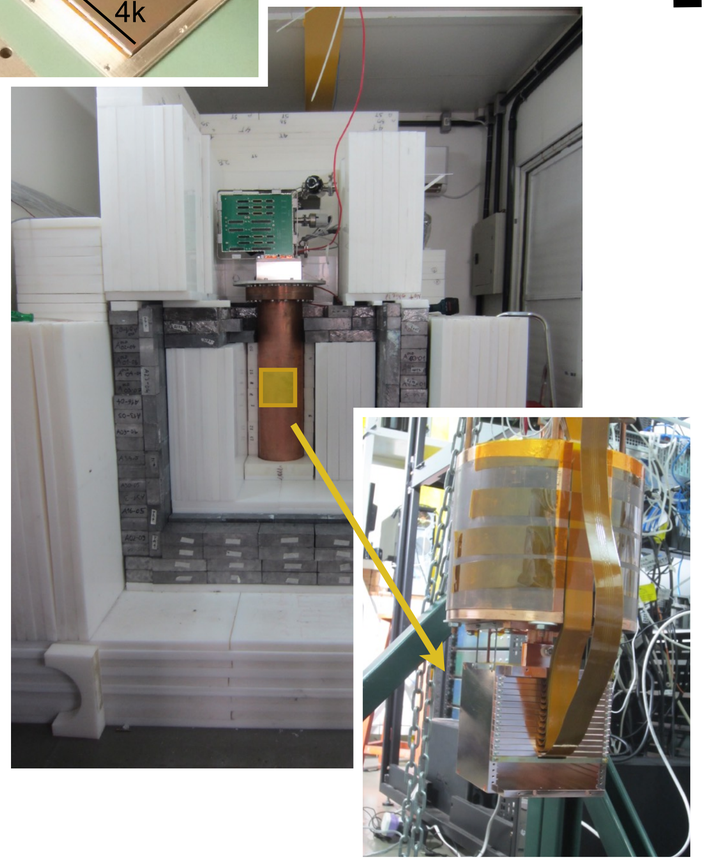
CONNIE, JHEP 04, 054 (2020); arXiv:1910.04951

CONNIE 2019

- Higher efficiency, lower background, improved analysis.
- Results compatible with previous analysis
- Expected limit in in the lowest-energy bin ~35 times the SM prediction (c.f. ~ 65 times from before).

CONNIE, JHEP 05, 17 (2022); arXiv:2110.13033

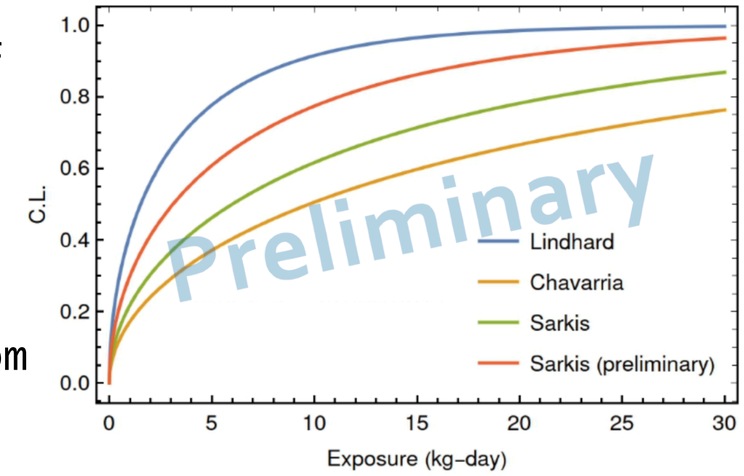




CONNIE Skipper-CCDs

- Skipper-CCDs @ CONNIE since July 2021
  - 2 skipper-CCDs (1022 x 682 pixel)
  - Data taking in ongoing
    - Readout noise: ~0.15e- RMS
    - Single electron rate: ~ 0.05 e-/pix/day
  - Energy threshold 15 eV_{ee}: x2.2 CEvNS rate

- Considering 4 kdru of background (measured) and a future detector of 1 kg at the CONNIE site, 9 days (Lindhard) or 2 months (Chavarria) to observe CEvNS at 90% C.L.

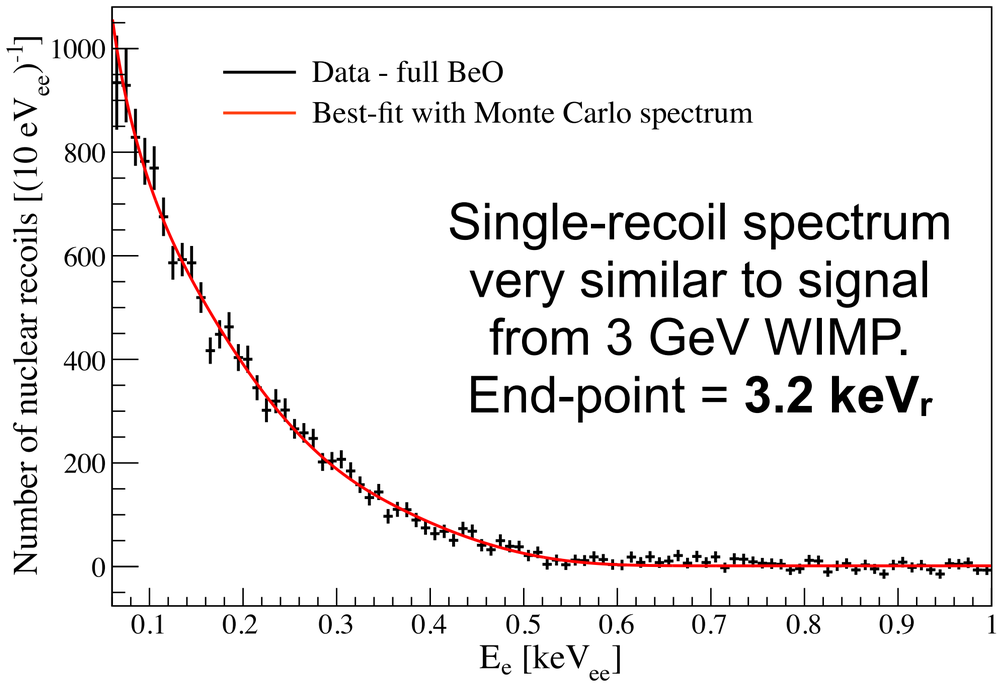


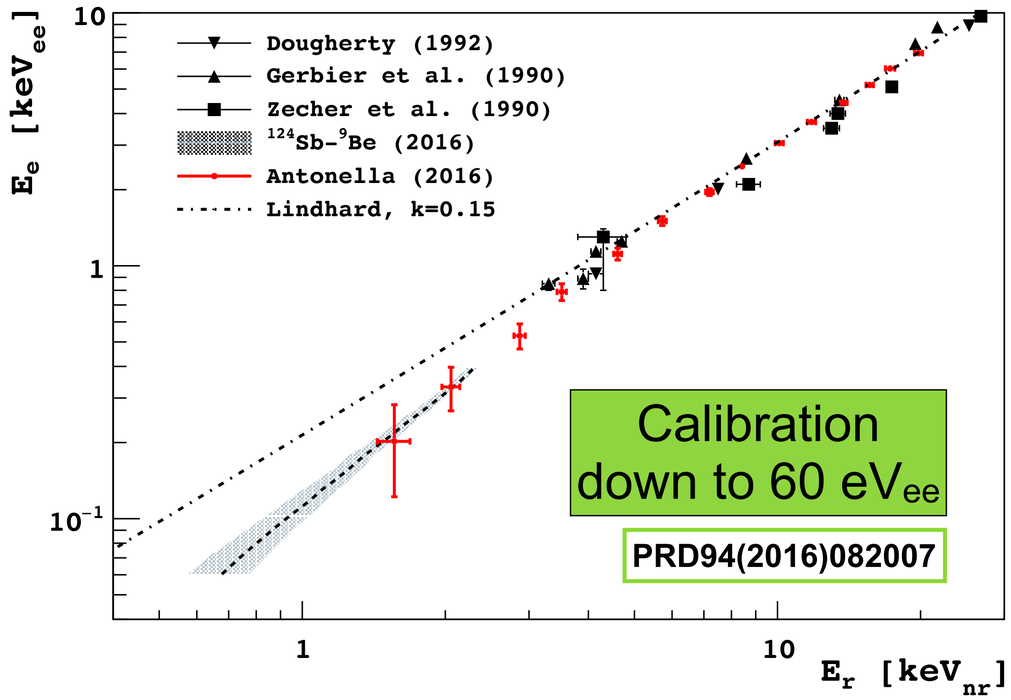
- Skipper CCD installed 12 meters from Atucha-2 2 GW reactor in Argentina.
- Inside reactor dome.

Slides from C. Bonifazi

Nuclear recoil response

- Detector response calibrated with 24 keV neutrons from $^{9}Be(\gamma,n)$ reaction.
- By comparing data and Monte Carlo spectra, ionization efficiency was measured to be lower than predicted by Lindhard model.
- Ionization efficiency for NR measured down to 60 eV_{ee}. On going efforts with skipper CCDs!

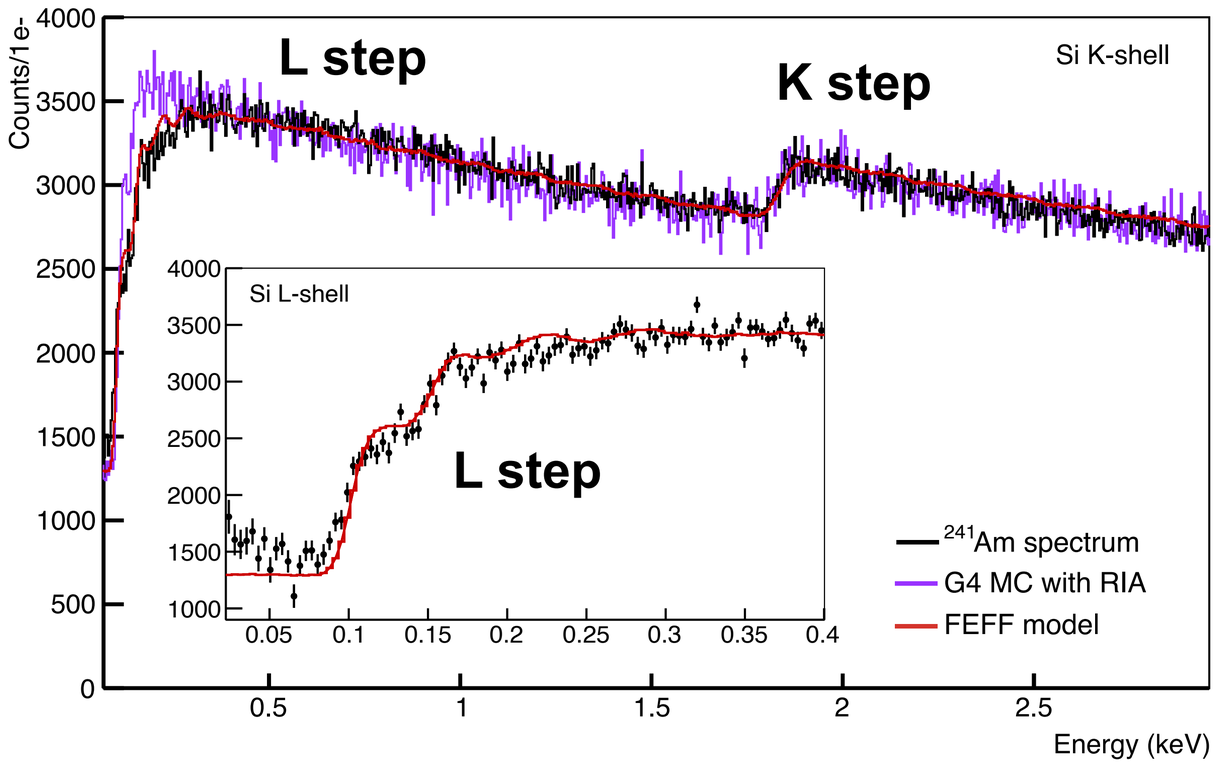




Spectroscopy with CCDs

- Precision measurement with a skipper CCD improved energy resolution and decreasing threshold to 23 eV_{ee}: arXiv:2207.00809
- Confirmed softening of the L step, observed structure in the L step.
- Softening reproduced with *FEFF* code, which performs full QM treatment.
- Detector response model is good!

CCDs can resolve spectral features in the *ionization* spectrum near threshold!

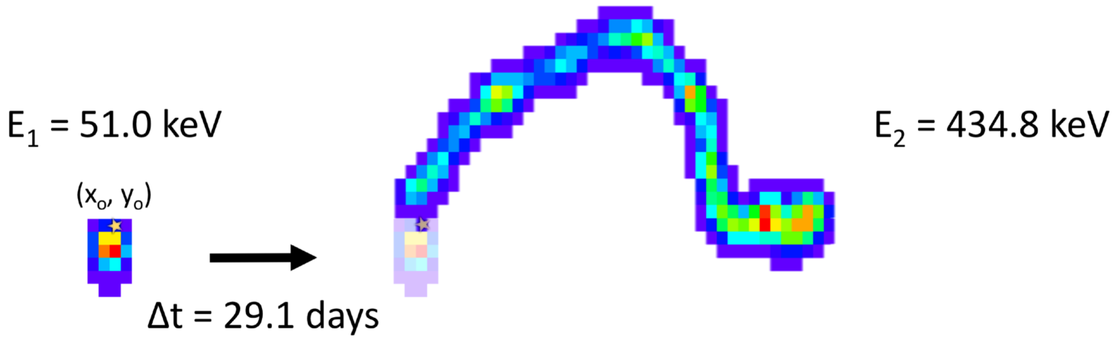


Radioactive backgrounds

- 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.



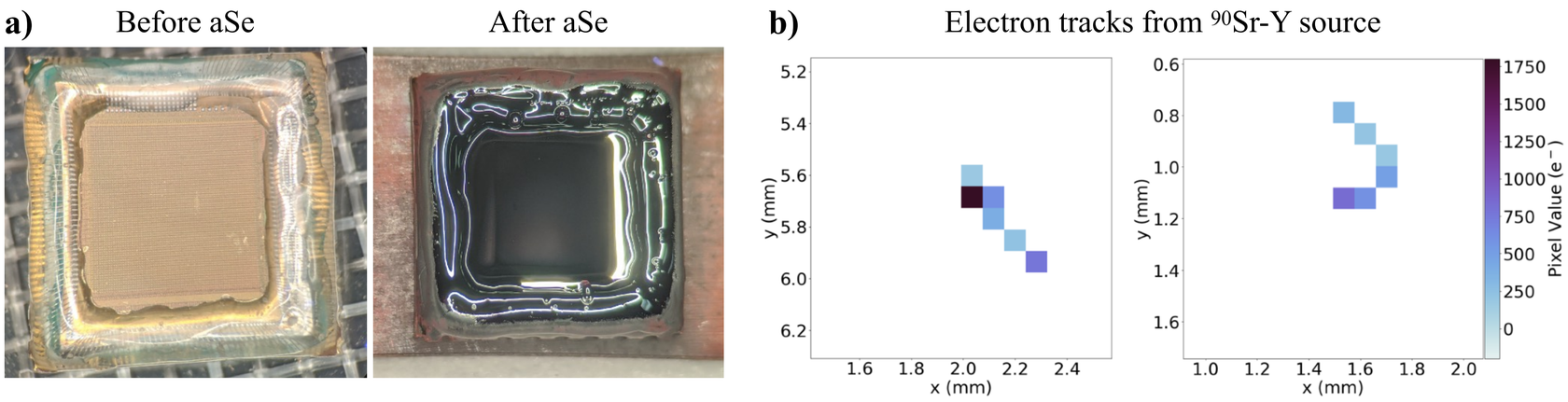
- Measurement of the cosmogenic activation of ^{3}H in silicon by exposing a CCD to a neutron beam: PRD102(2020)102006

  112 ± 24 atoms / kg /day

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

Selena Neutrino Experiment

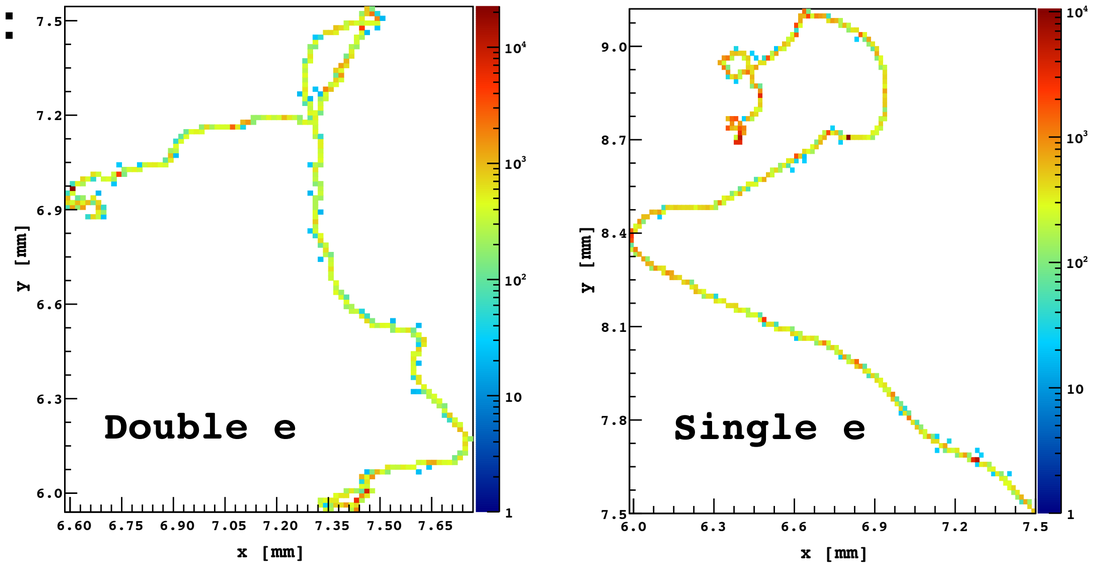
- Next generation neutrino experiment to perform zero-background spectroscopy of $\beta\beta$ decay and electron neutrinos in ^{82}Se.
- Low-noise CMOS charge readout sensor coupled to few mm-thick amorphous selenium (aSe) target layers.
- Concept paper with background estimates: JINST12(2017)P03022
- Measurement of charge response: JINST16(2021)P06018
- Snowmass 2021 white paper: arXiv:2203.08779
- First demonstration of imaging electron tracks in a hybrid CMOS/aSe device:



Selena Goals

- 100 ton-year exposure of ^{82}Se.
- Single vs. double β discrimination.
- Bulk backgrounds suppressed by α/β particle ID, spatial correlations.
- Background rate <6 x 10^{-5} /keV/ton/year!
- **$T_{1/2}$ = 5 x 10^{28} y: limit on ^{82}Se 0$\nu\beta\beta$.**

Simulation:

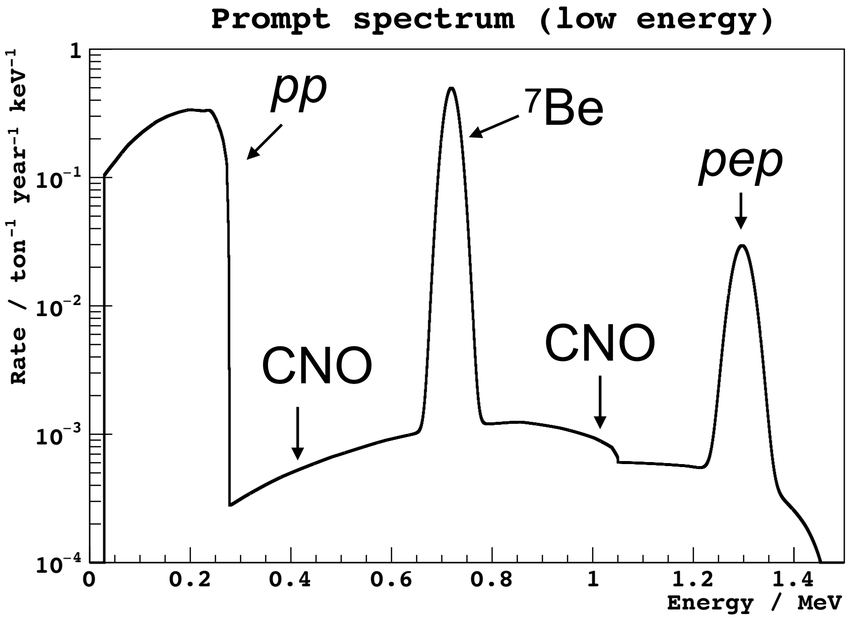


- **Solar ν spectroscopy from reaction:**

E_ν – 172 keV

$$\nu_e + {}^{82}\text{Se} \longrightarrow {}^{82}\text{Br}^* + \text{C.E. (29 keV)} + e^-$$

- Captures individually tagged from the spatial correlation with ^{82}Br* decay sequence. *Zero-background.*
- Constraints on solar luminosity, solar metallicity, solar core temperature, onset of matter effects in ν oscillations, etc.



Conclusions

- CCD particle detectors have demonstrated unique capabilities for low-energy particle physics.
- Decade-long program in detector characterization / background studies.
- Low-energy threshold to probe light DM from DM-e^- interactions.
- Skipper CCD kg-scale detectors (**DAMIC-M**) already under way.
- CONNIE plans a similar detector to measure CEνNS from a reactor.
- Selena to leverage on the low-background capabilities developed for CCD detectors to do neutrino physics with a ^{82}Se target.

Thank you!