Status of DAMIC

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DAMIC-M

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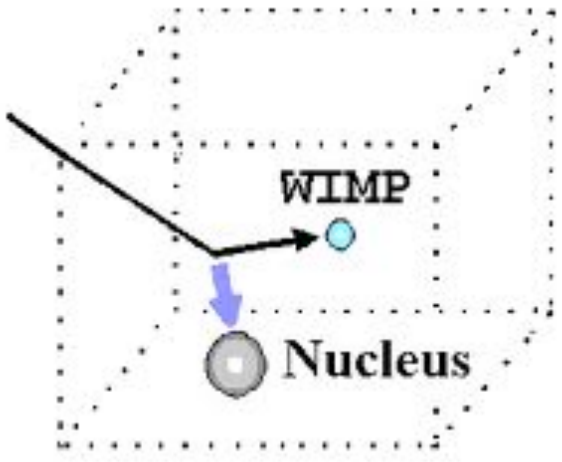
Outline

- Direct detection of (light) dark matter.
- Charge-coupled devices.
- DAMIC at SNOLAB.
- DM-e scattering search (**preliminary** results).
- CCD backgrounds (**preliminary** results).
- WIMP search (status).
- DAMIC-M at LSM: low background 1-kg silicon detector with single-electron response.

DM-nucleus ES

Traditional mechanism for WIMP searches:

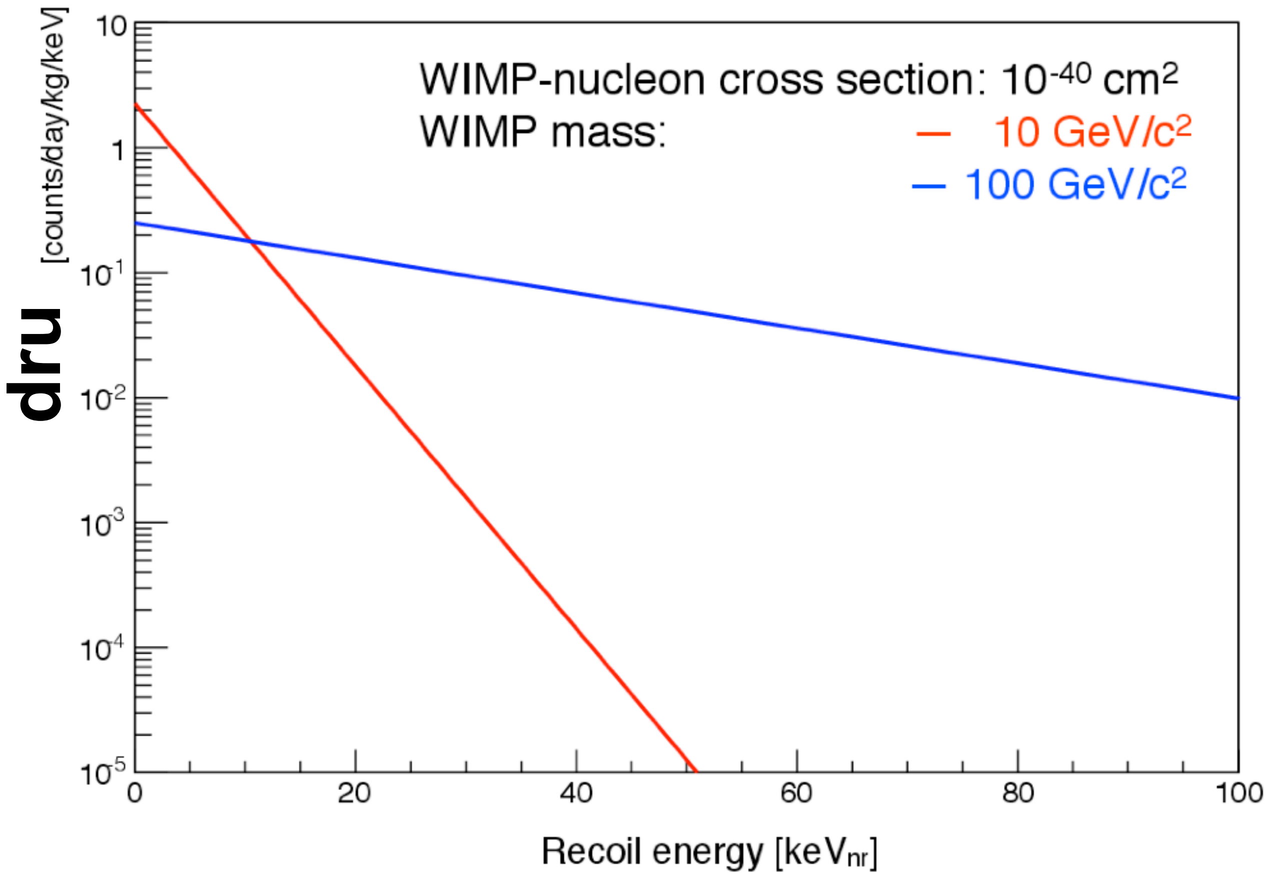


Maximum energy transfer when *M* ~ *A*

For low-mass WIMP:

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

Recoil spectrum in Si target



Lower recoil energies for smaller WIMP masses

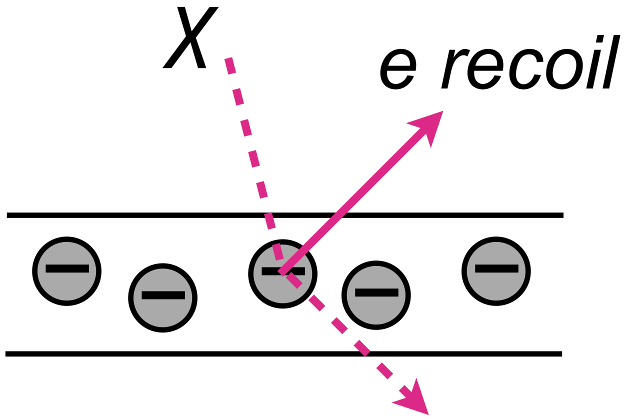
Coherent enhancement:

$$\sigma_N \propto A^2$$

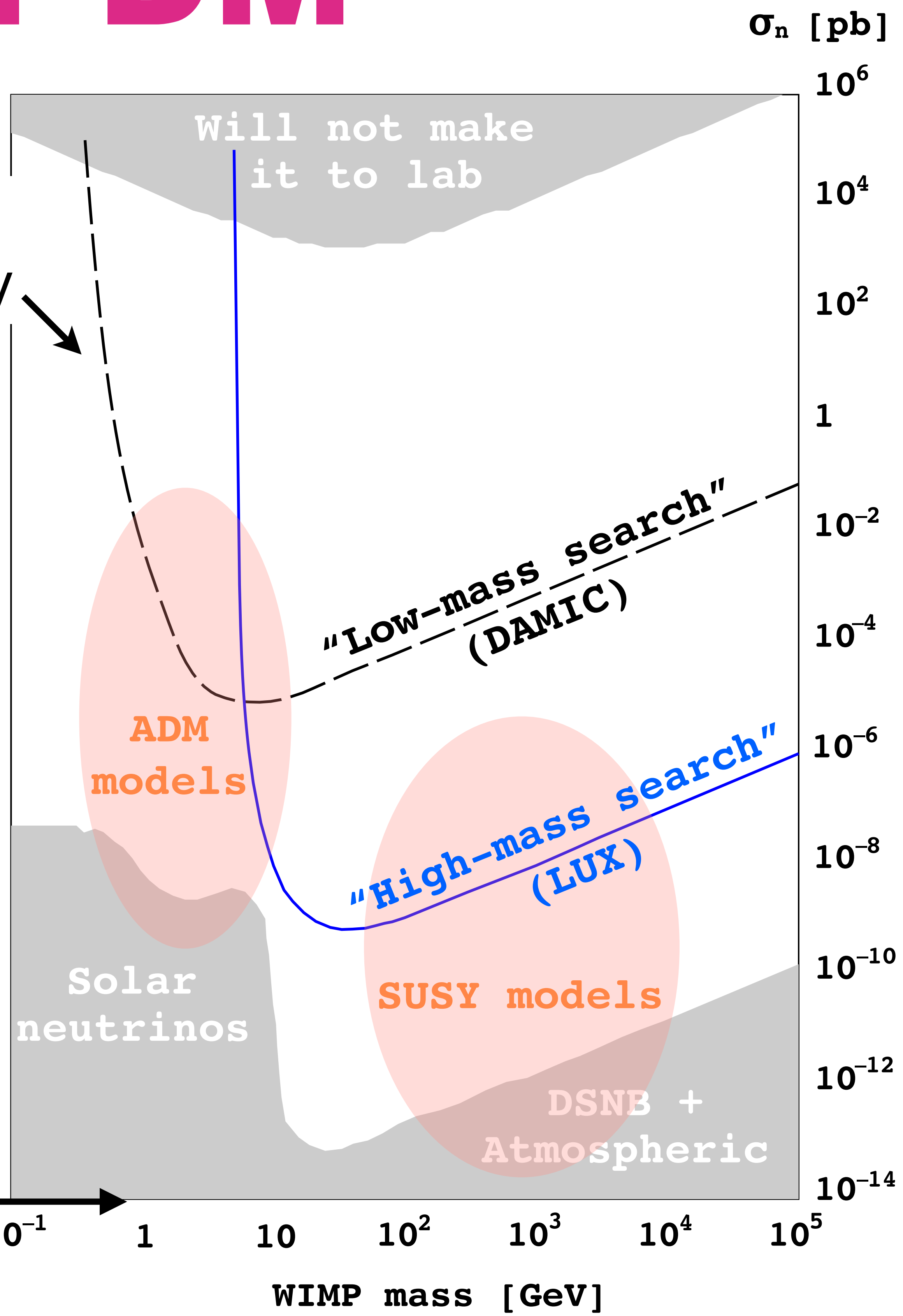
Lighter DM

Lighter target: lighter nucleus or *electron*

Electrons bound with some momentum, inelastic process.



Rapid loss in sensitivity

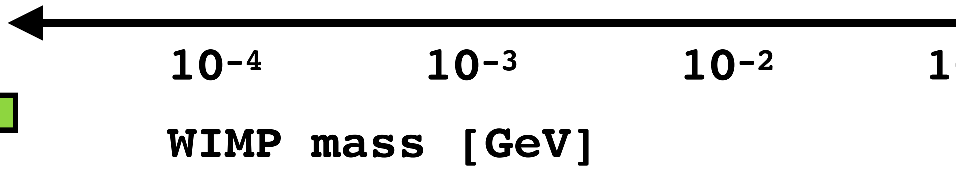


Lower threshold, smaller band gap

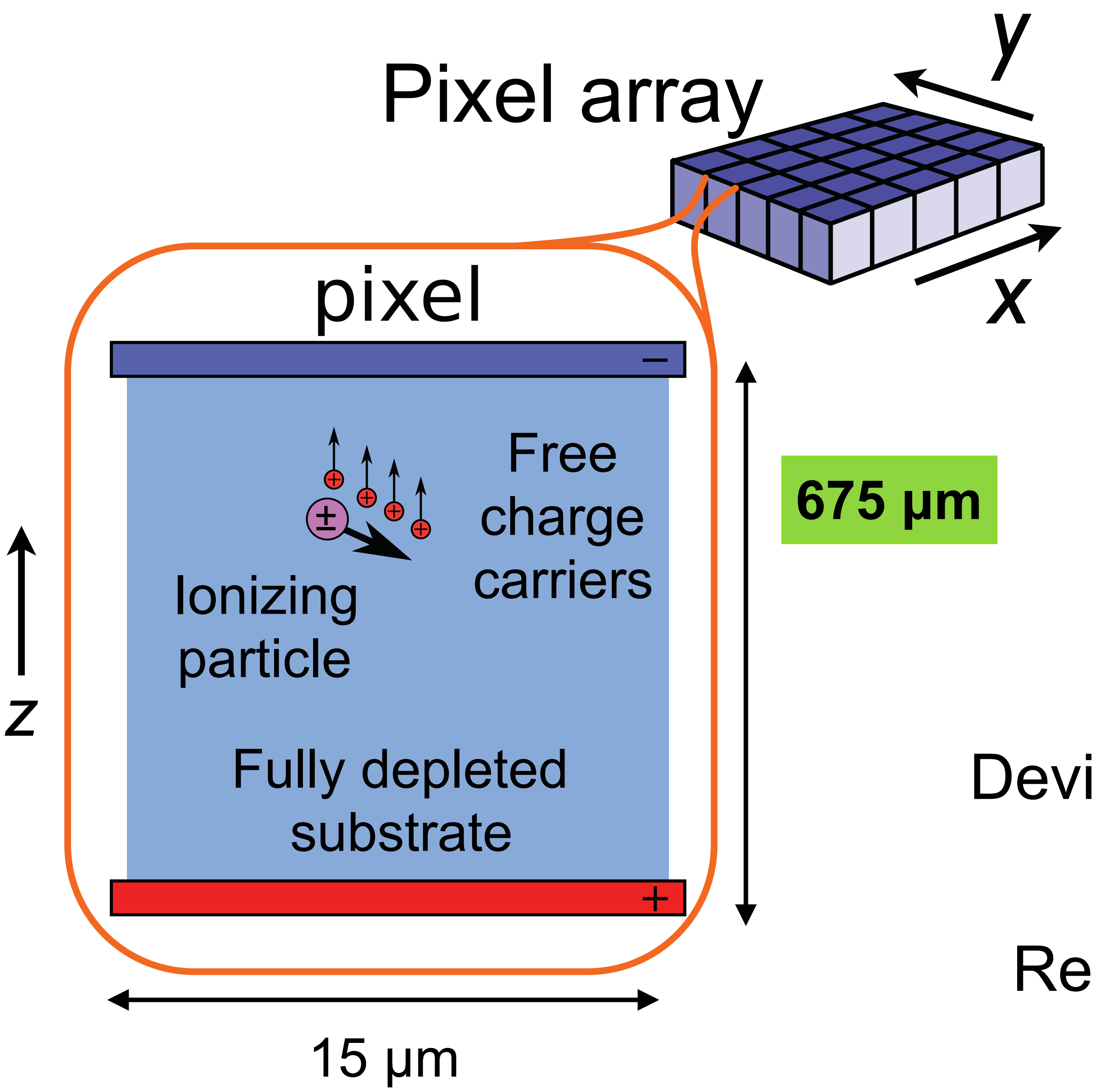
Ionization energy of noble liquids ~ 10 eV

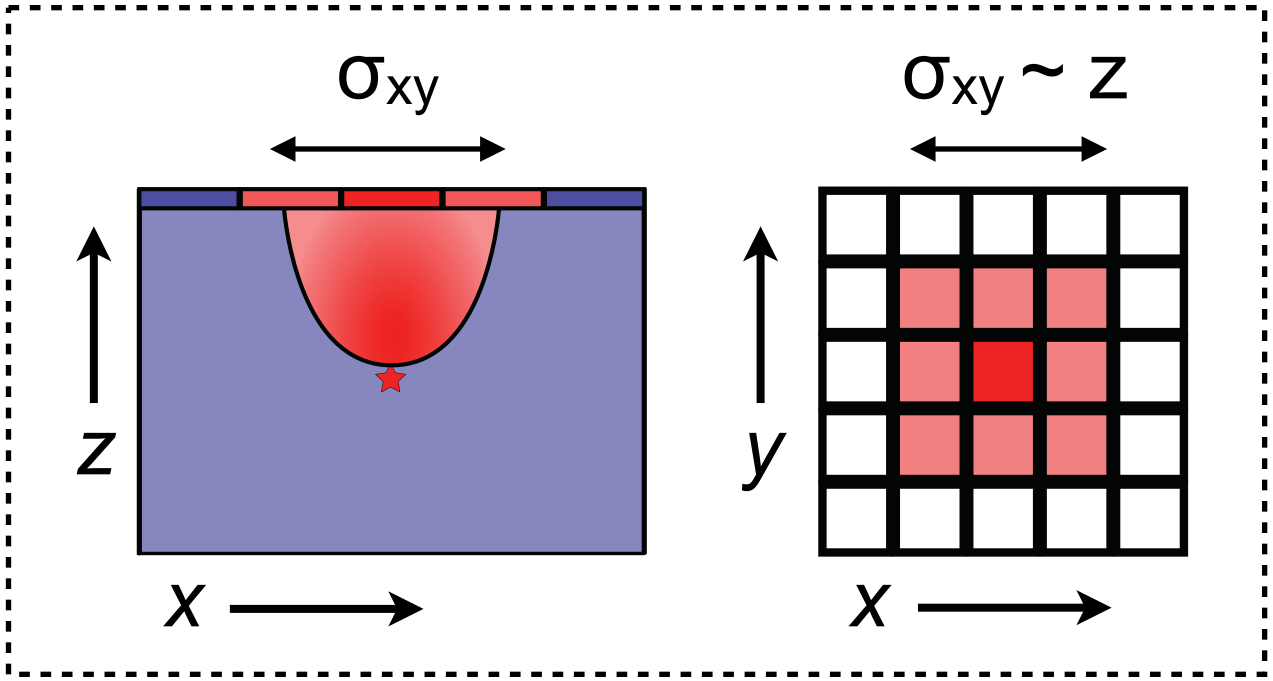
Semiconductor band gap ~ 1 eV!

Warm DM



Charge coupled device





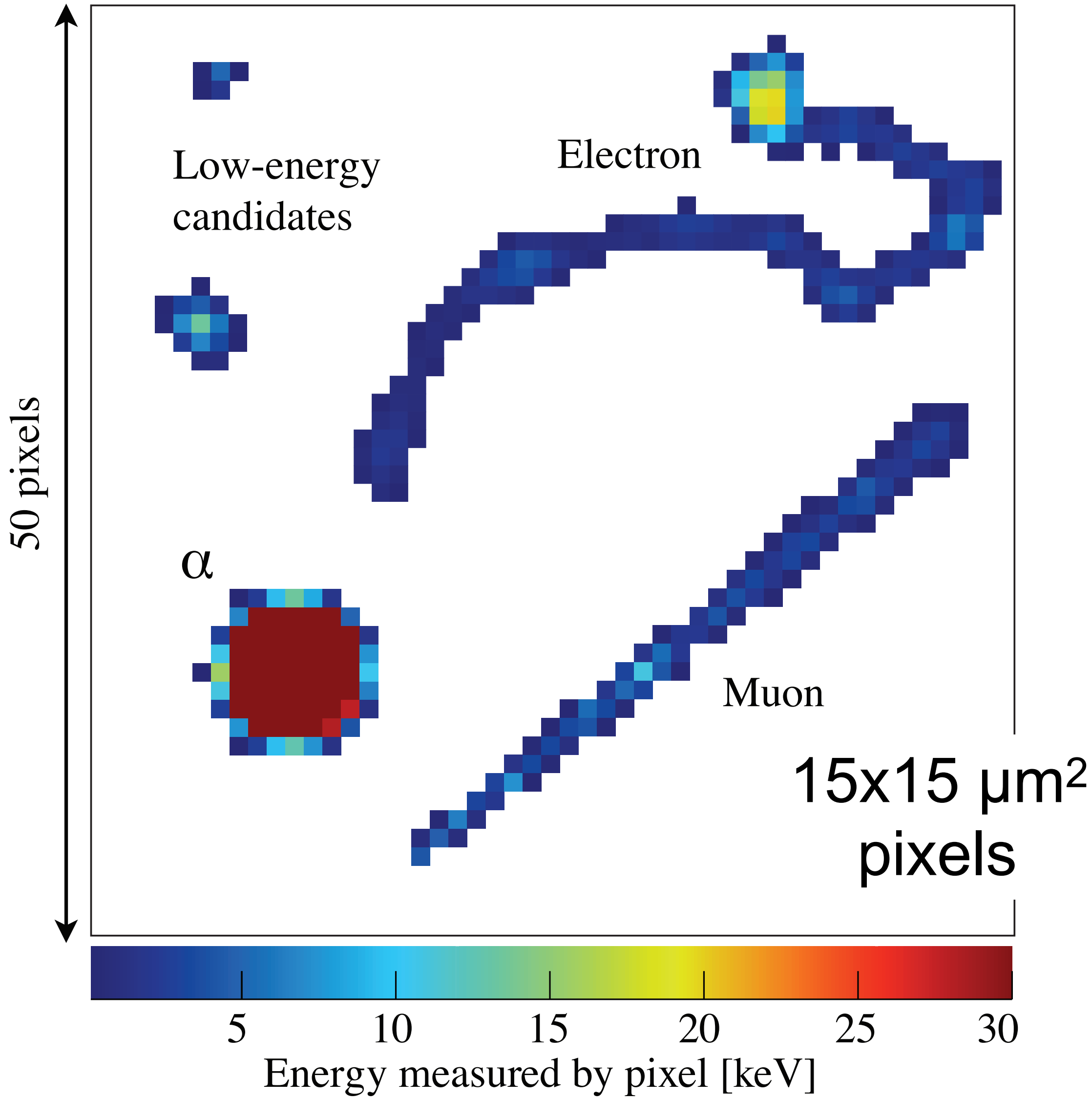
Standard fabrication in semiconductor industry and easy cryogenics (~100 K).

Device is “exposed,” collecting charge until user commands readout

Readout can be slow / non-destructive :
very low noise (few e^-)

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

Perfomance

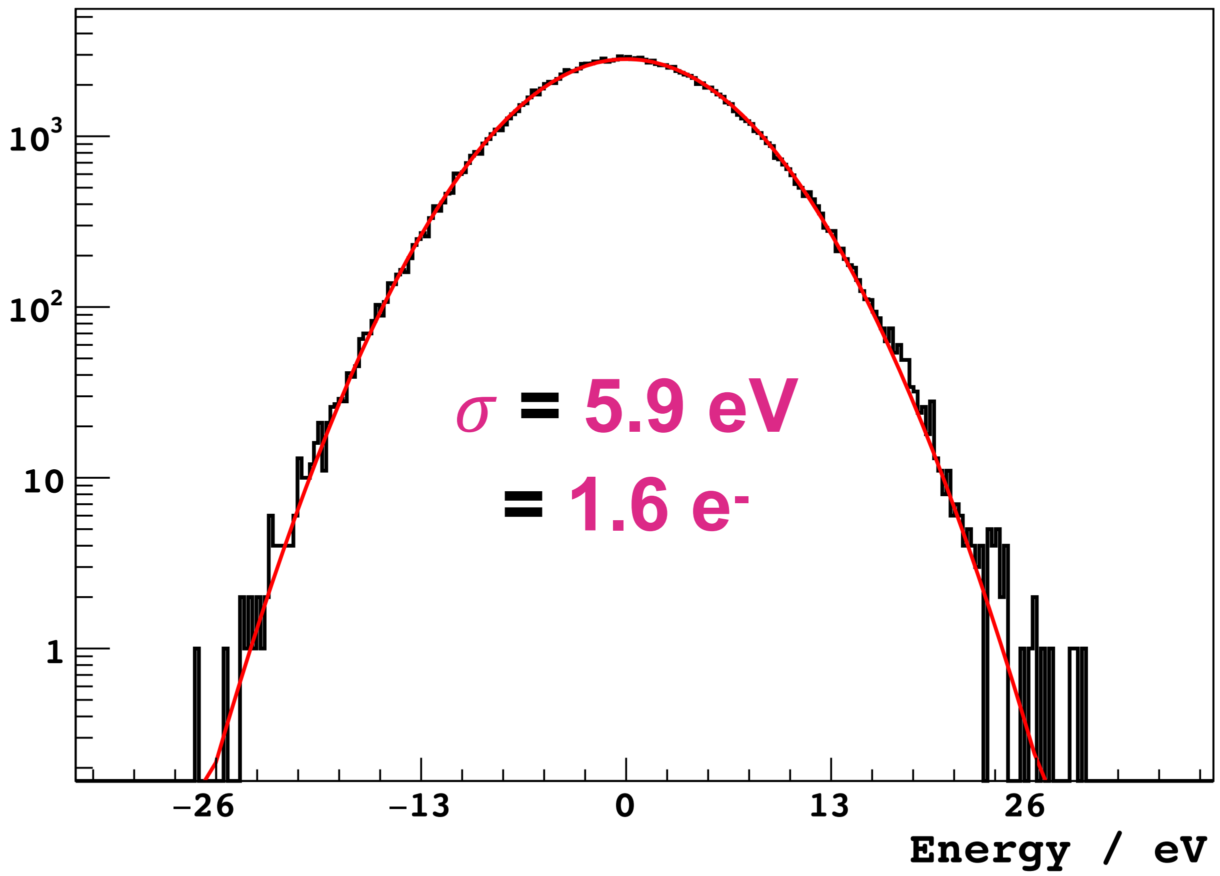


15x15 µm² pixels

particle identification and background characterization

$\sigma_{xy} \approx z$: fiducial volume definition

Pixel charge distribution



σ = 5.9 eV

= 1.6 e-

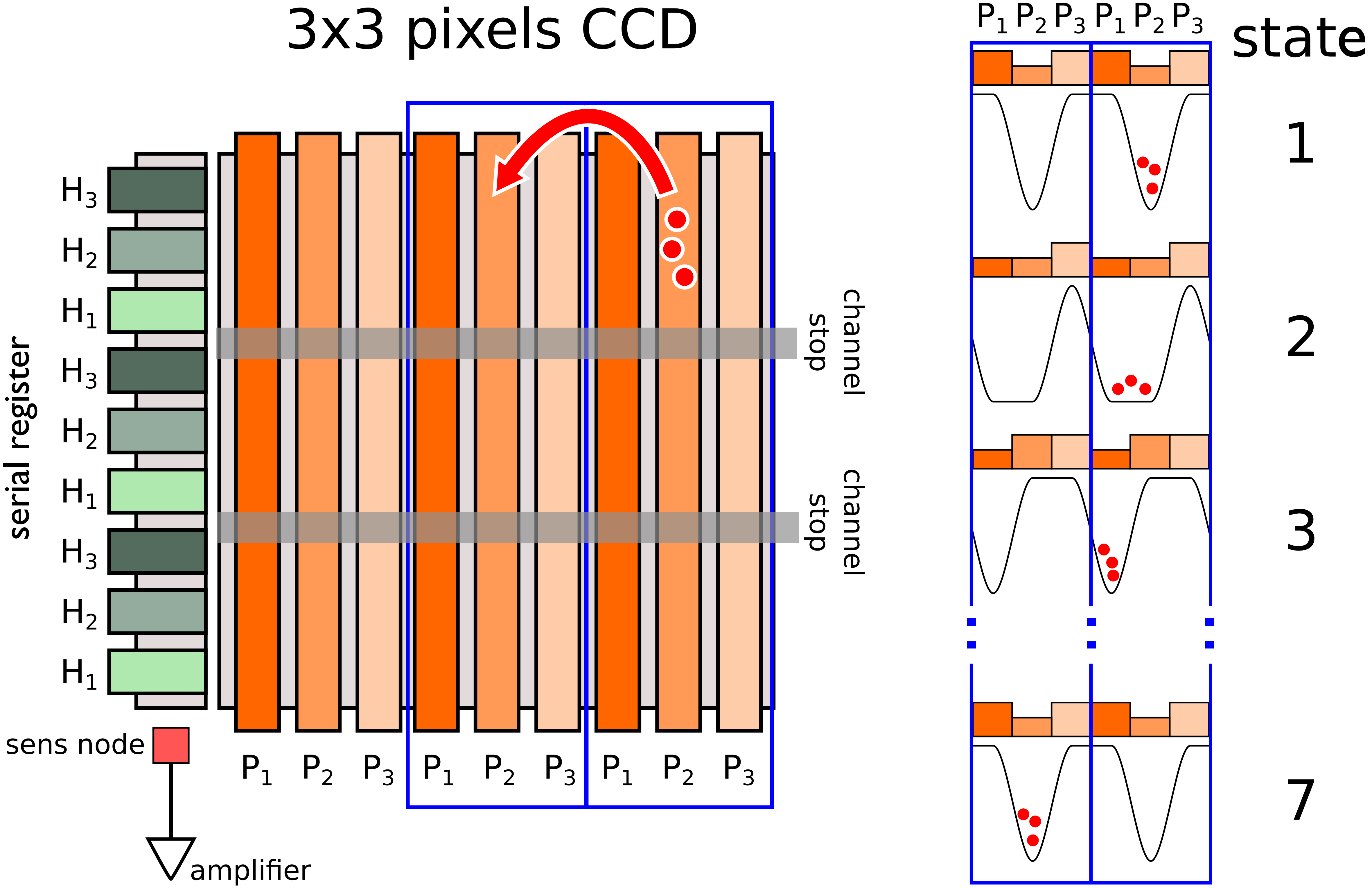
Very low noise and dark current

lowest dark current ever measured in a silicon detector:

5×10^{-22} A/cm² (at 140 K)

CCD readout

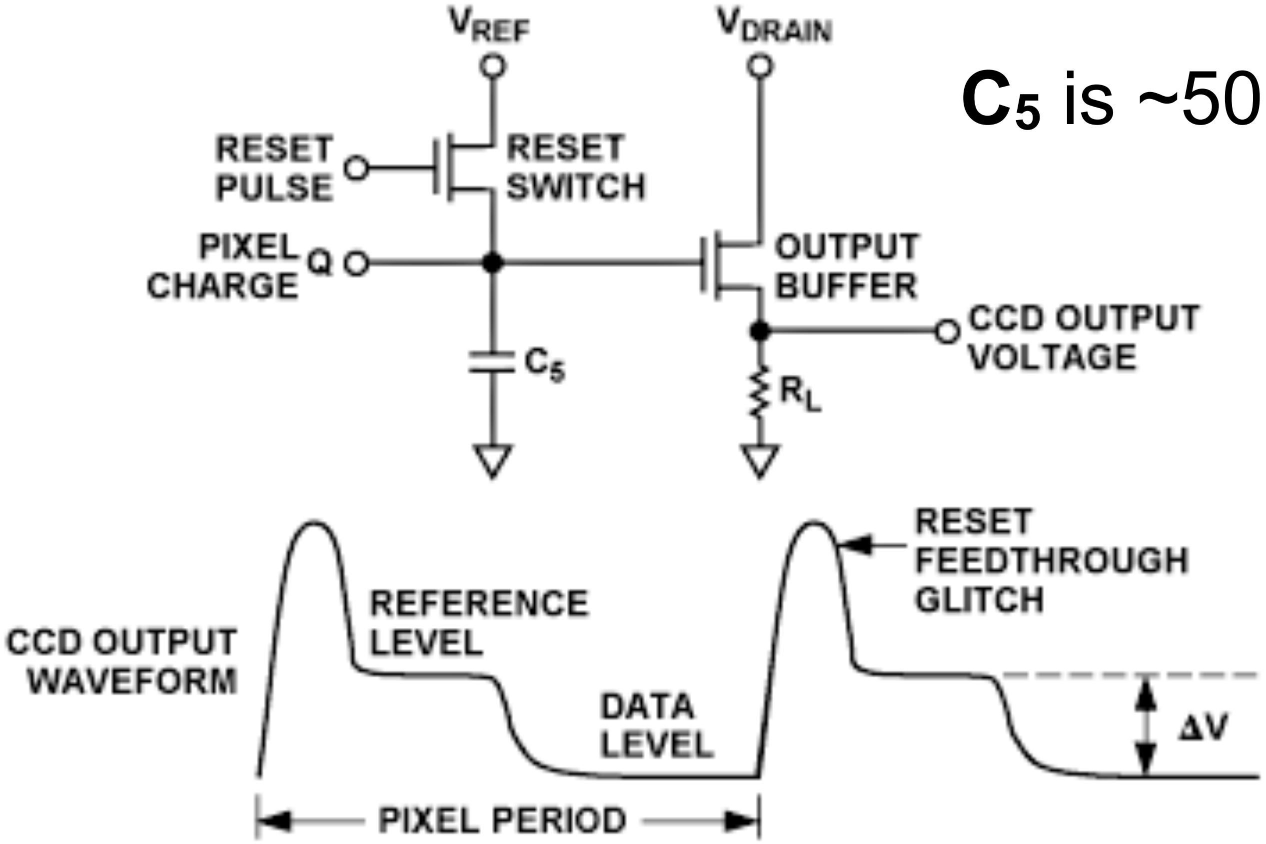
3x3 pixels CCD



CDS readout

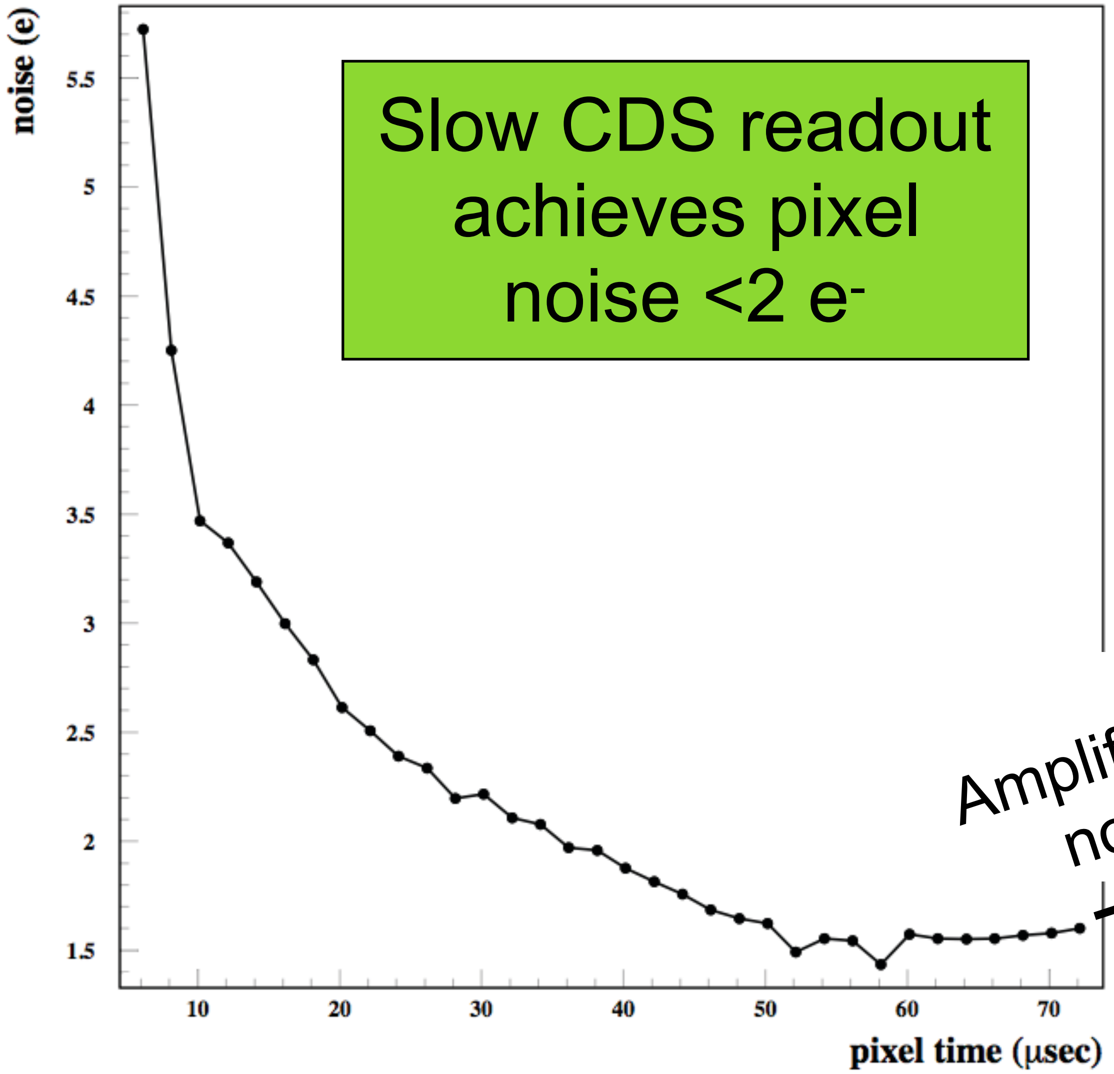
C_5 is ~50 fF

CDS: “Correlated double sampling”



ΔV is ~3 µV per e^-

“Skipper” readout can improve noise further



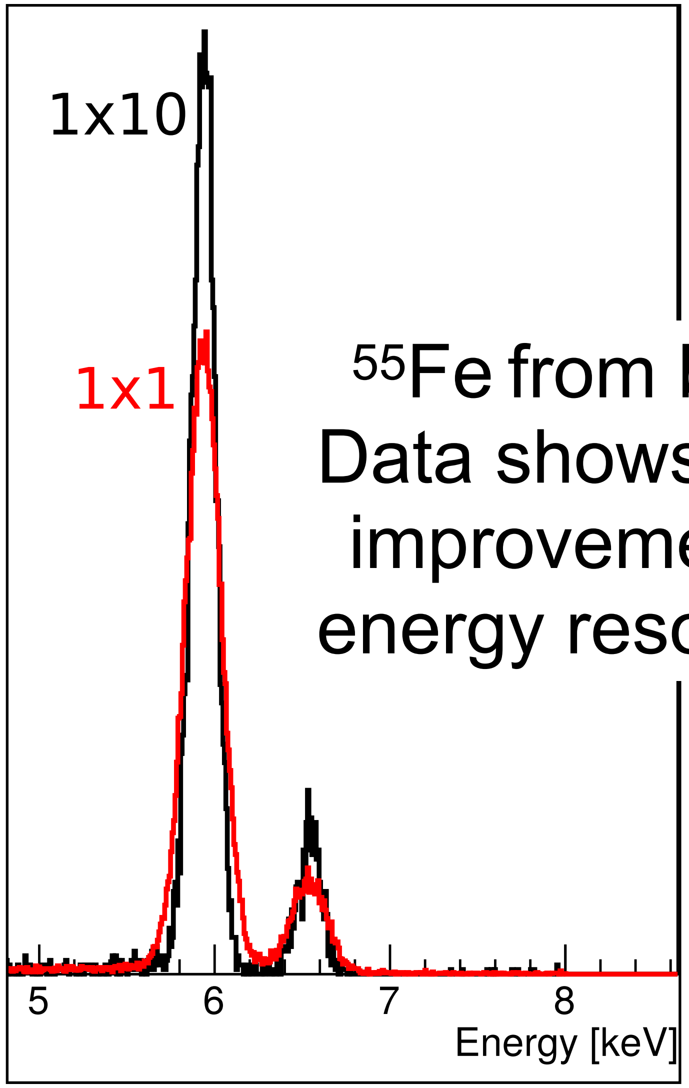
Slow CDS readout achieves pixel noise <2 e^-

Amplifier 1/f noise

Flexibility in readout

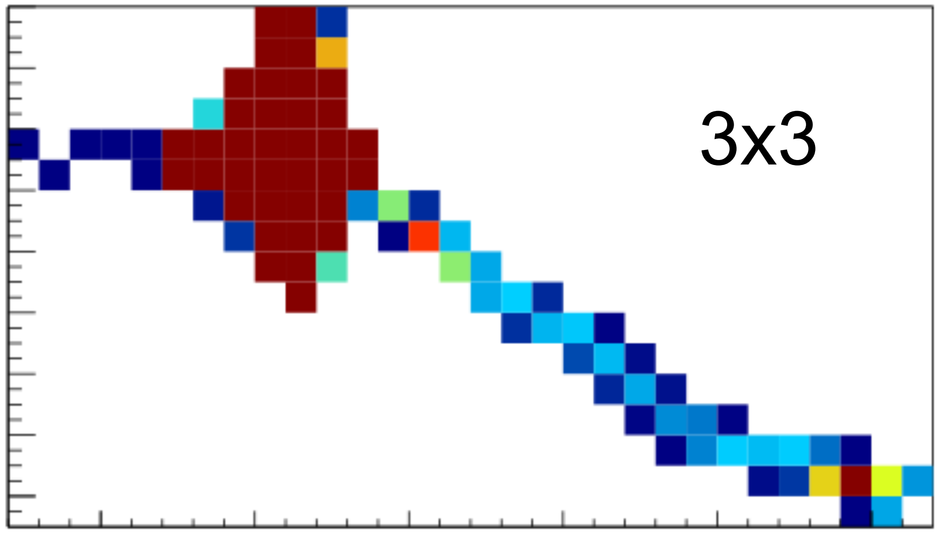
Pixels can be readout in “groups” and the total charge estimated in a single measurement.

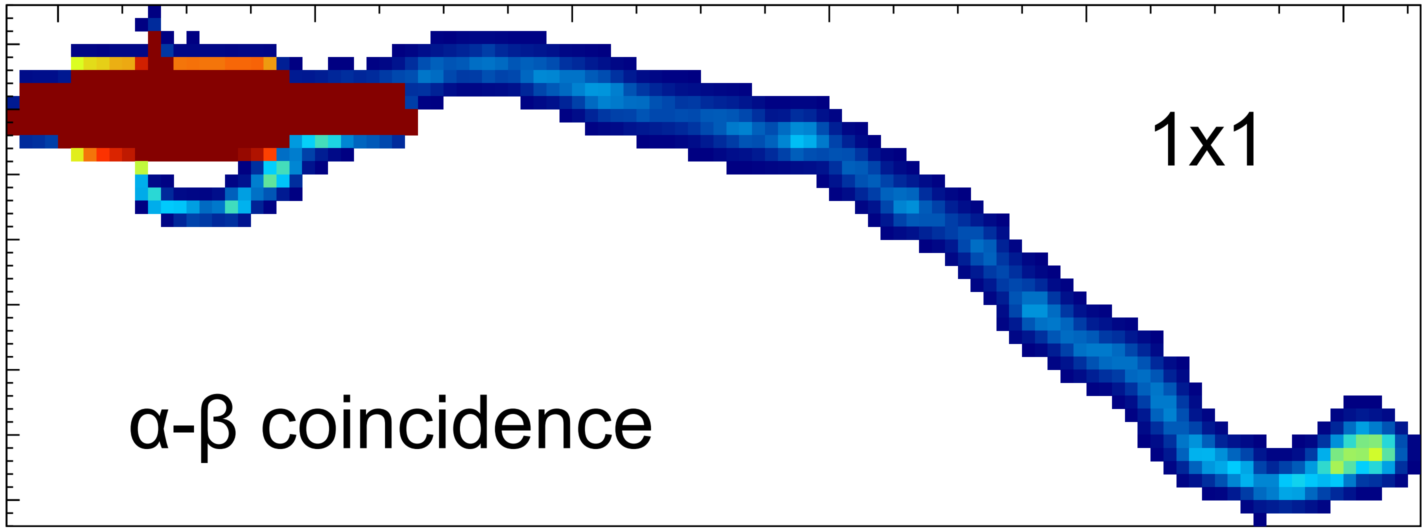
Less pixels but same noise *per* pixel!



^{55}Fe from back: Data shows clear improvement in energy resolution

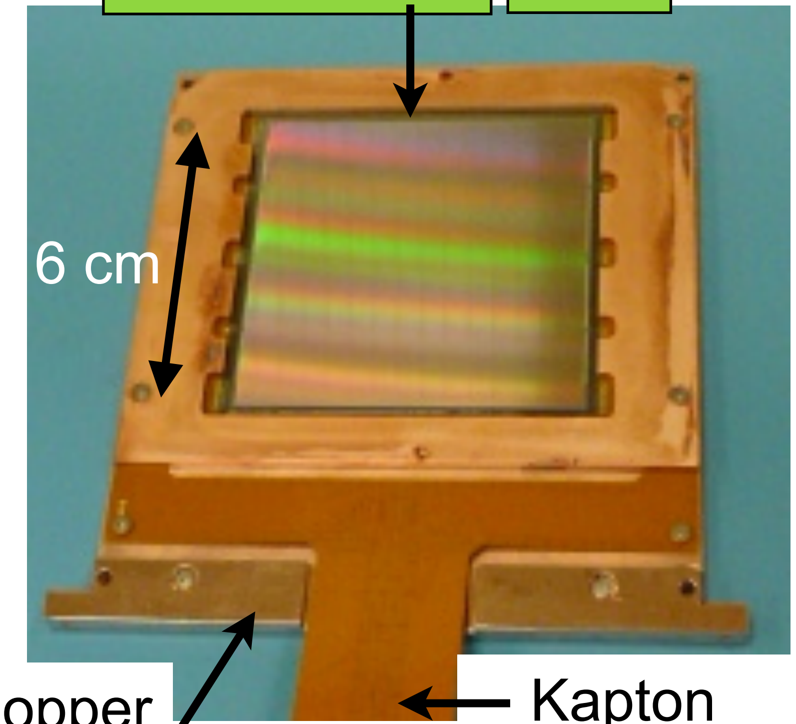
Loss of x, y and z information

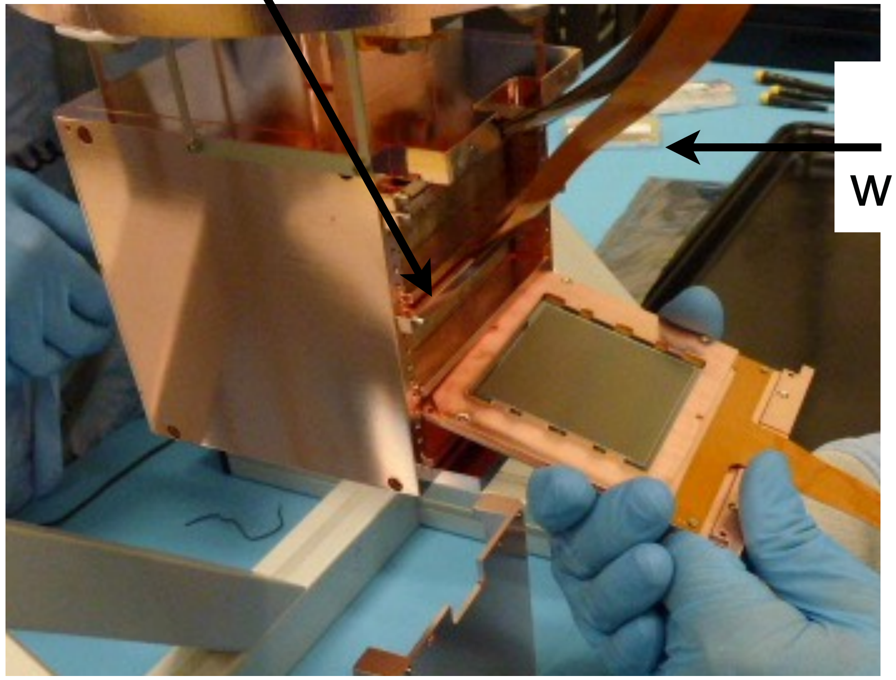


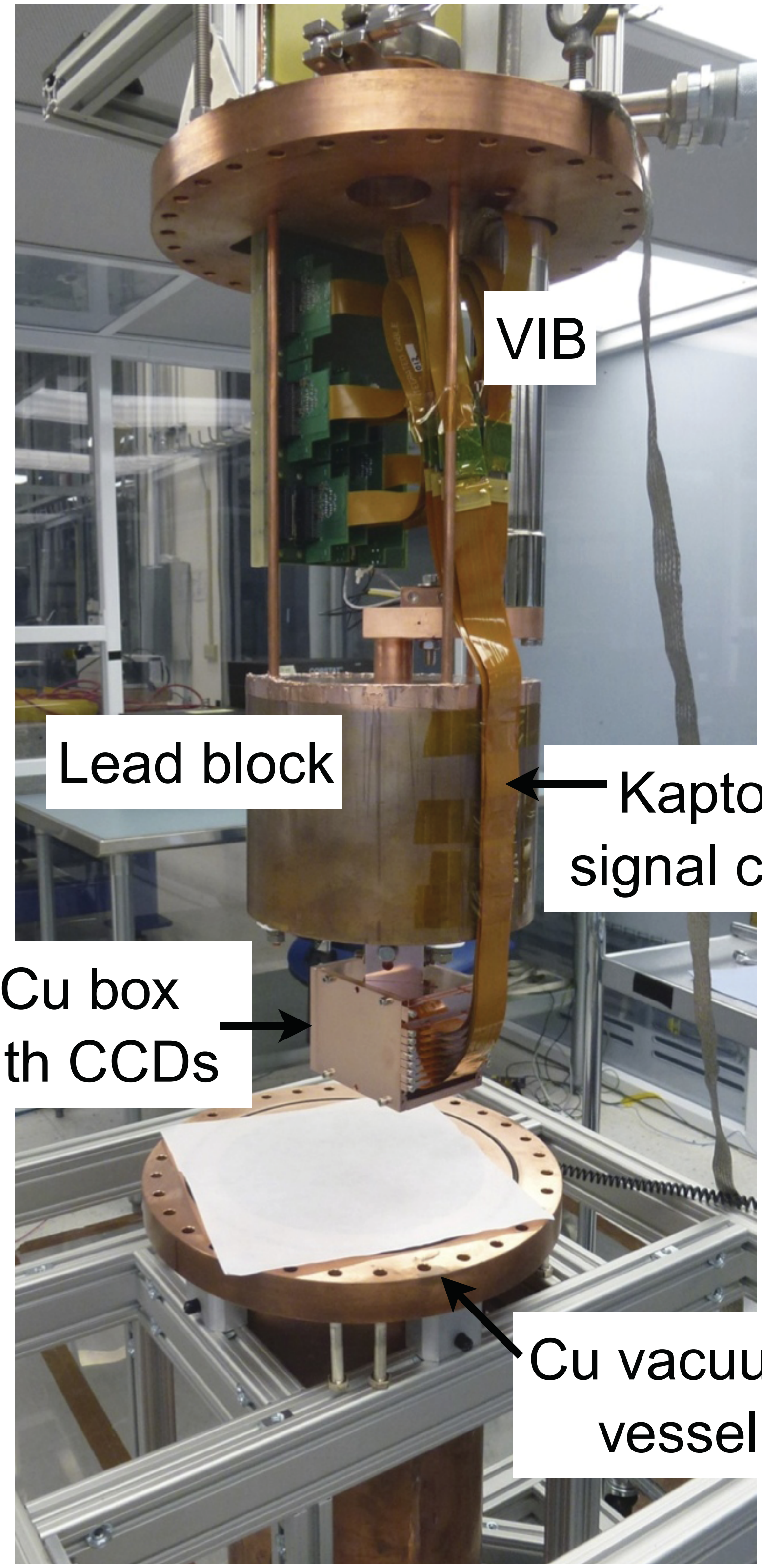


α-β coincidence

SNOLAB Installation

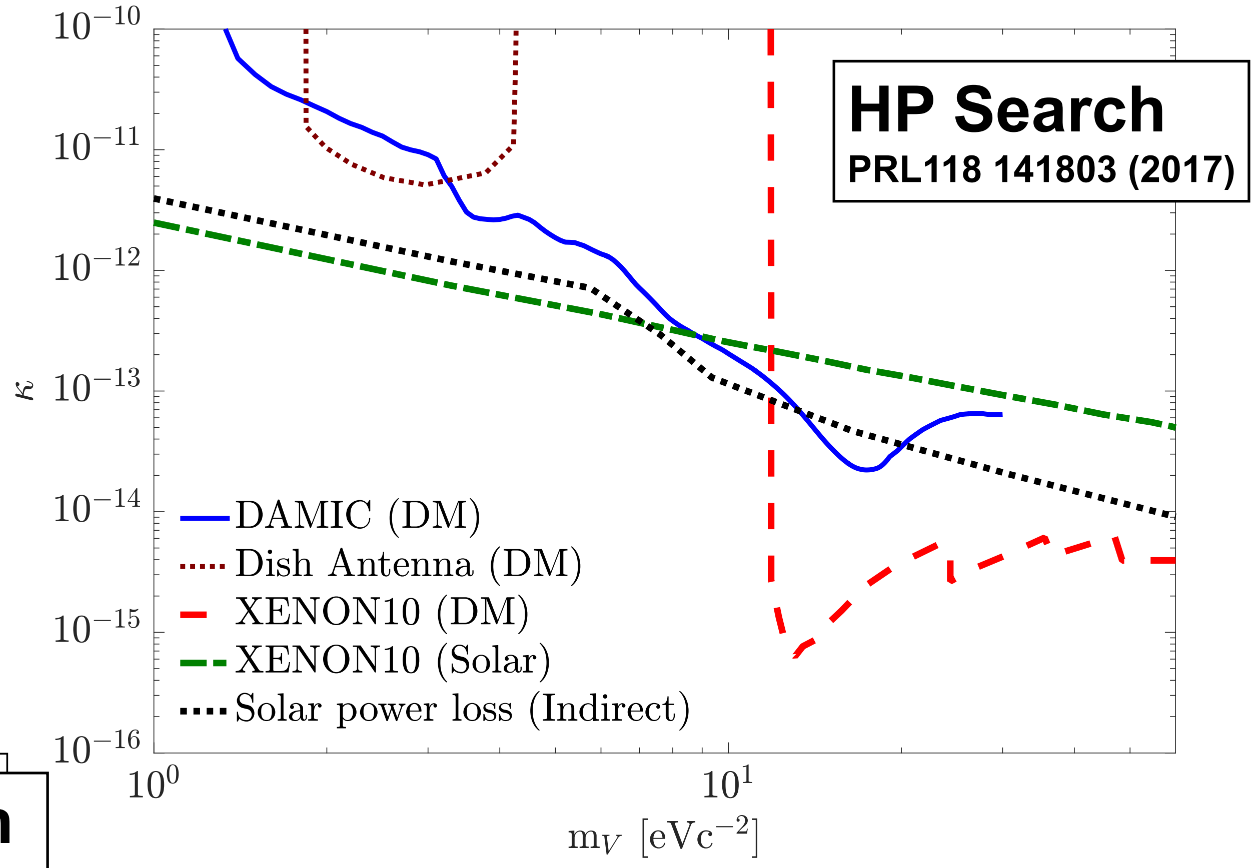






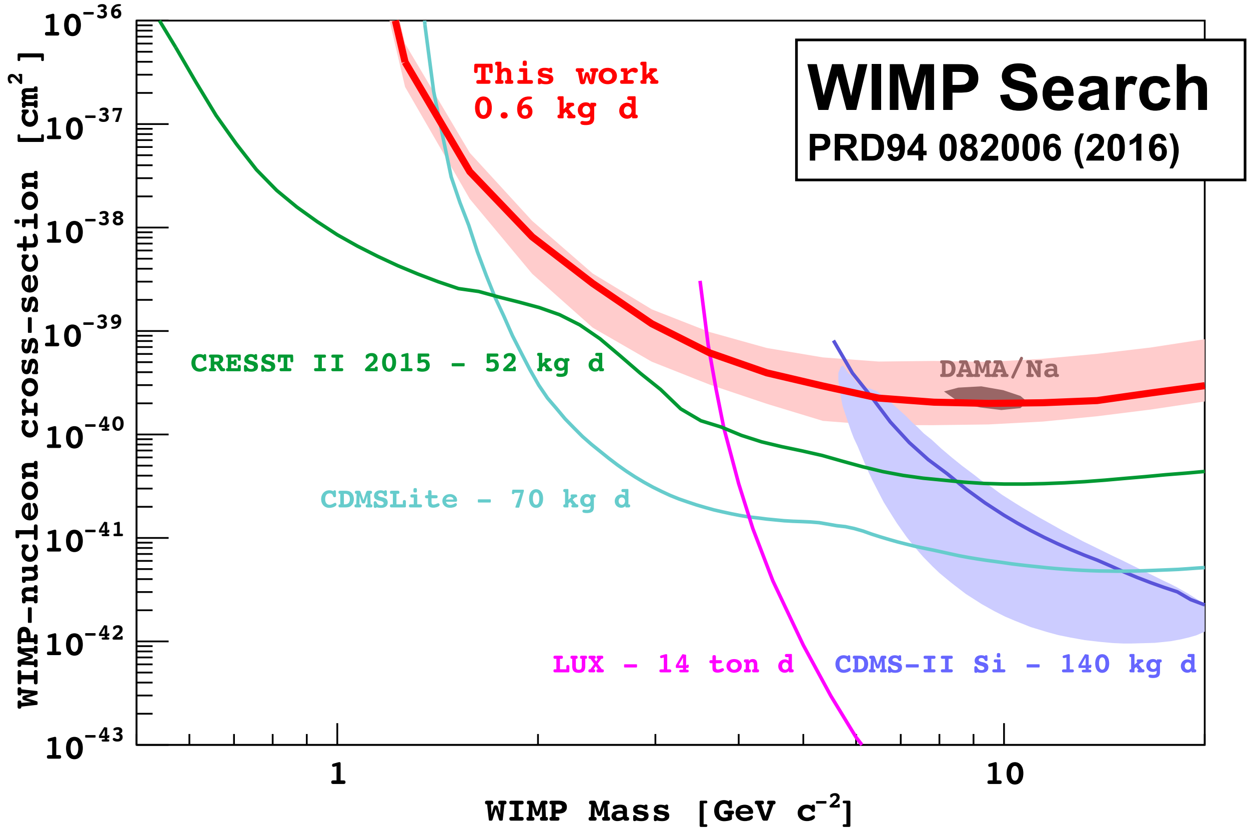
Timeline

- First CCDs installed at SNOLAB in December 2012.
- Three years 2013-2015 to achieve low radioactive background.
- WIMP and HP results with R&D data.



HP Search

PRL118 141803 (2017)



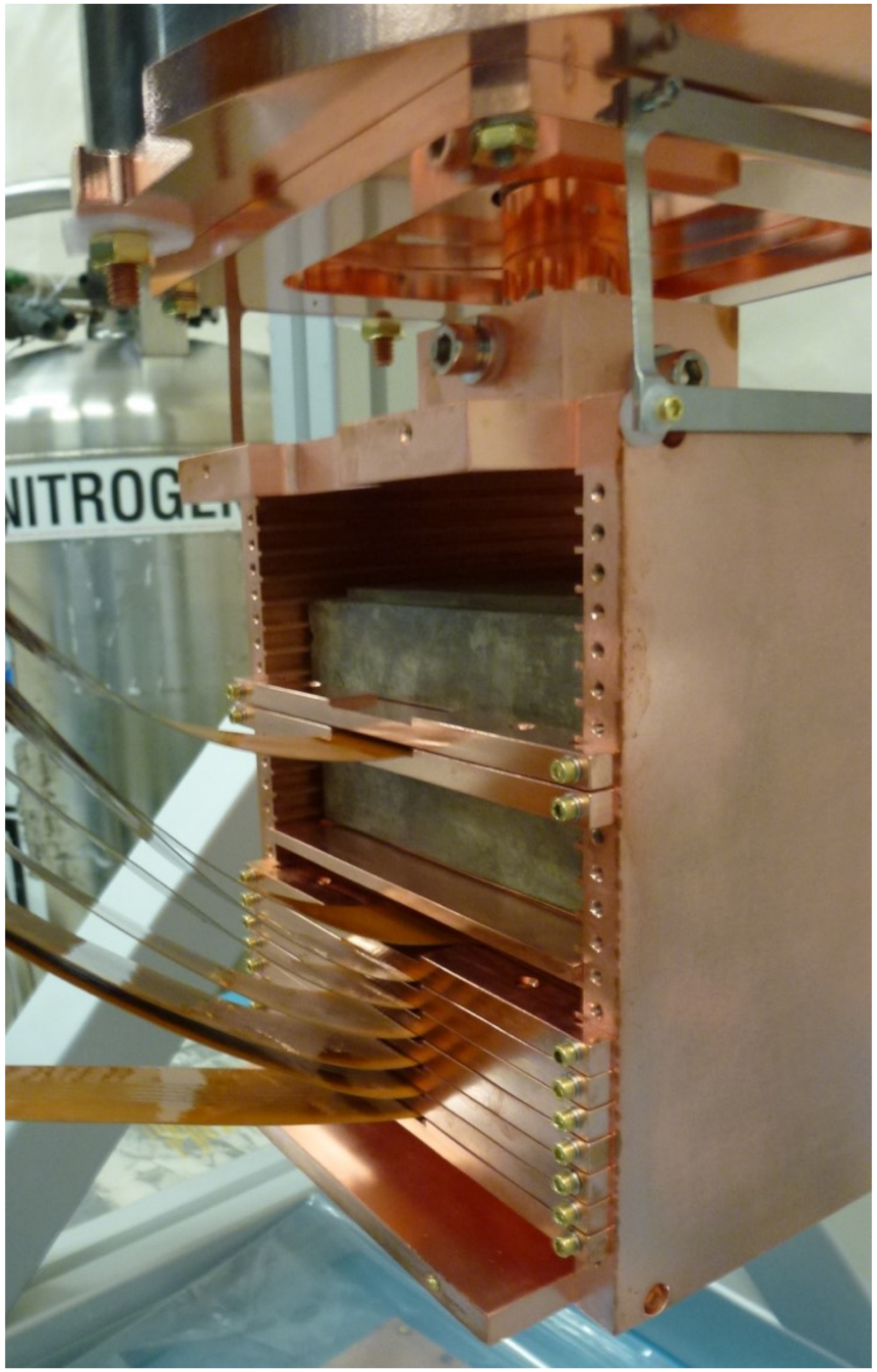
WIMP Search

PRD94 082006 (2016)

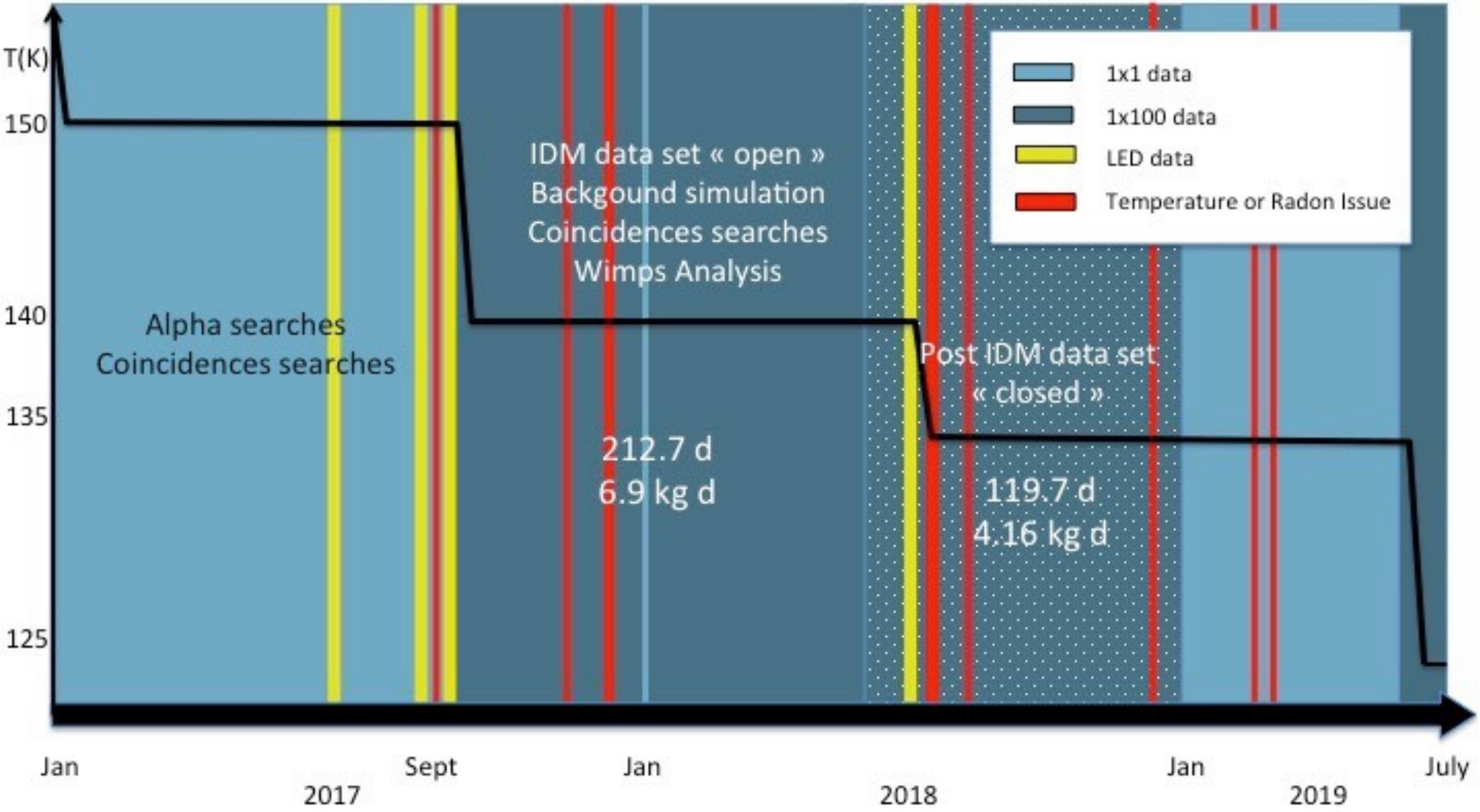
- First deployment early 2016: problems with mechanics of CCD package.
- Second deployment early 2017.
- Taking data since.

Current status

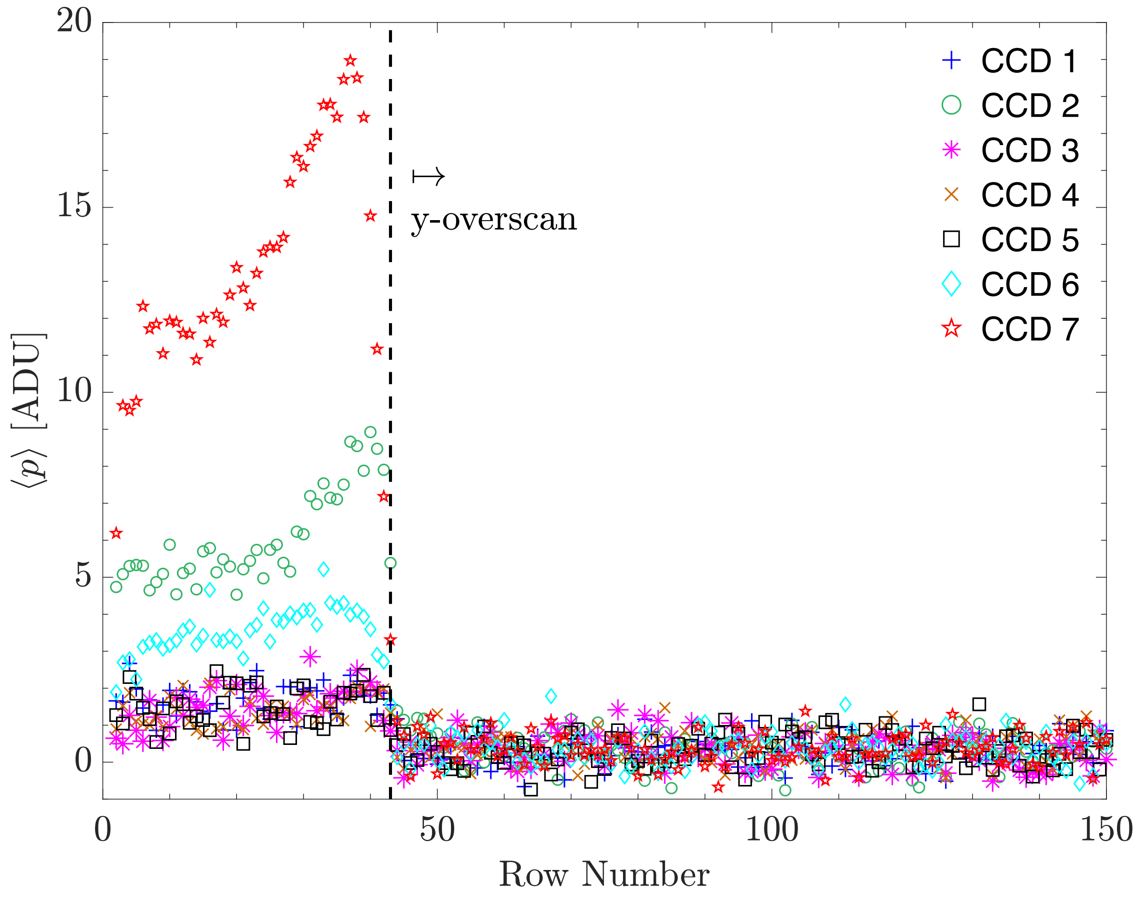
- **7 CCDs** in stable data taking since 2017 (1 CCD sandwiched in ancient lead).
- **40 g** target mass.
- Operating temperature of **~140K.**
- **Exposure for image: 8h and 24h** (each image acquisition is followed by a “blank” exposure).
- **7.6 kg-day** of data for **background** characterization in 1x1 format.
- **13 kg-day** of data collected for **DM search** in **1x100** format.
- Since Jan 2019, resumed background run and detector studies (e.g., **125 K** operation for lower leakage current).
- Some detector maintenance required.

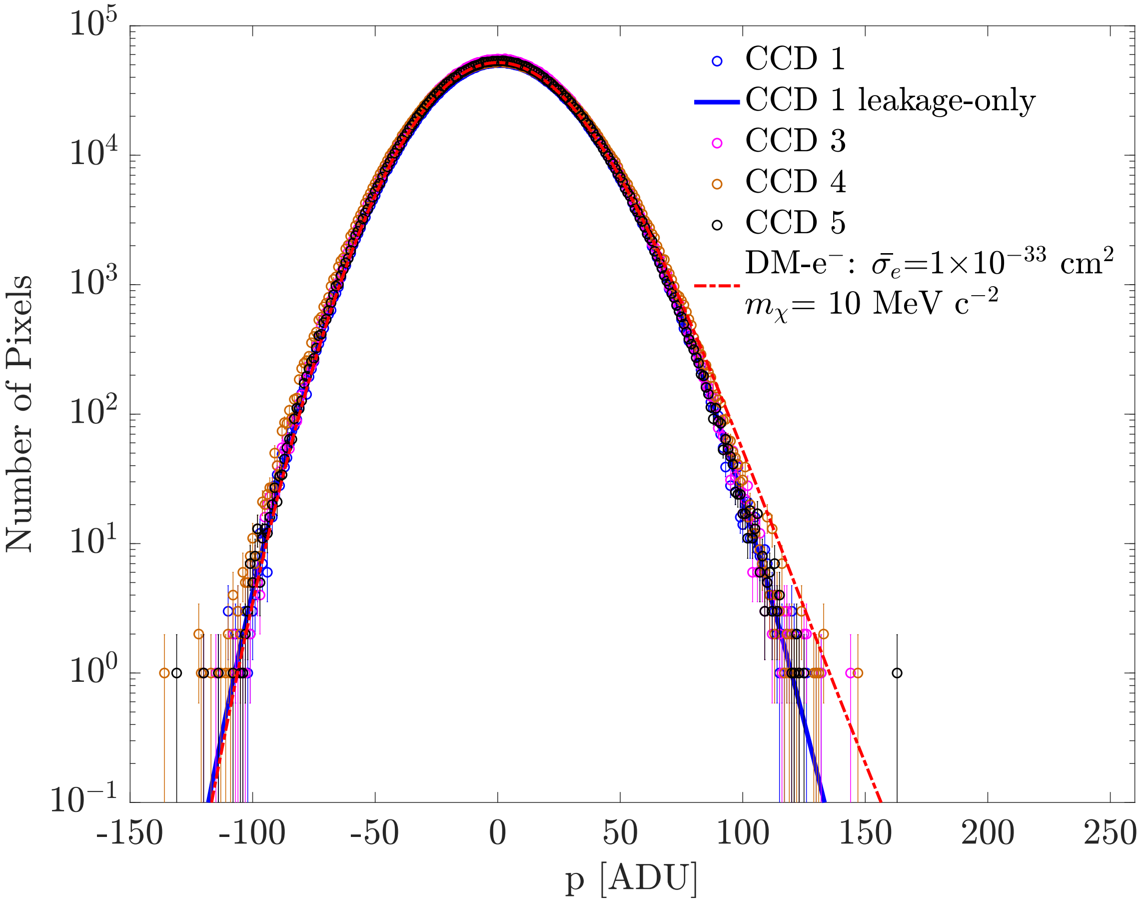


Detector history



Leakage current analysis





- Select CCDs with constant leakage current.
- Compare pixel distribution to leakage-only hypothesis + signal from DM-e scatters.

Pixel distribution of **200 g-d** of data in 100 ks exposures

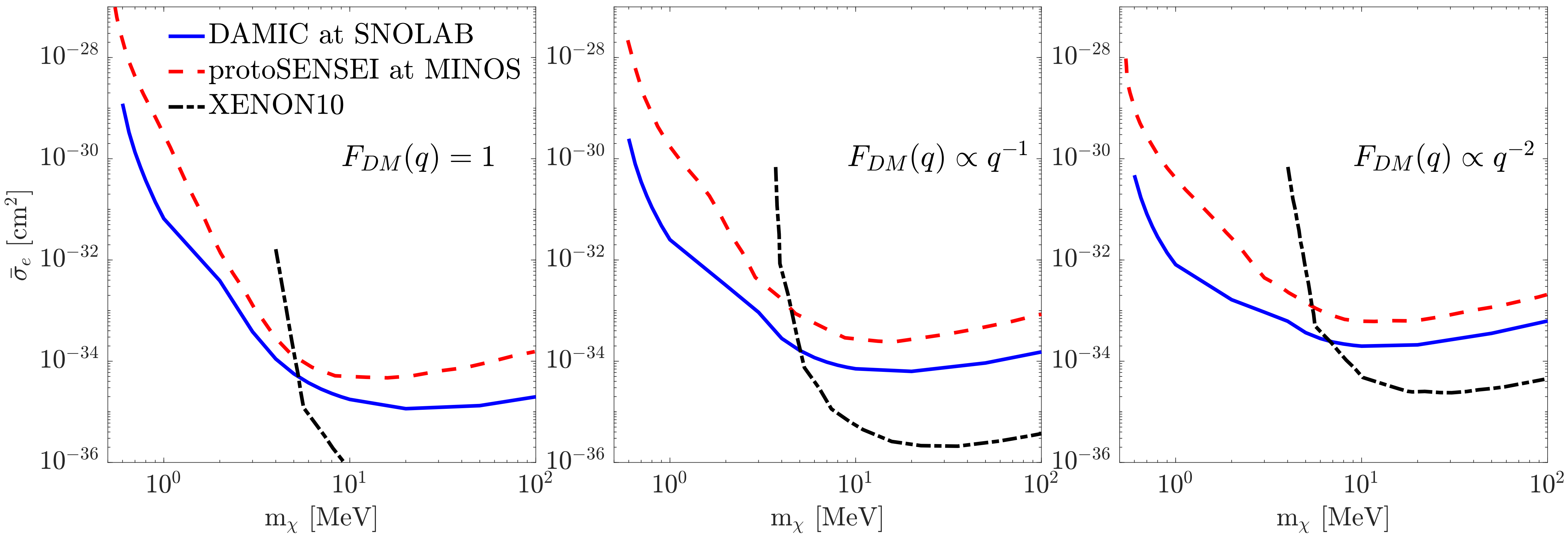
Bulk leakage current at the level of **2 e$^-$ mm^{-2} d^{-1}** at **~140 K**

(Before **4 e$^-$ mm^{-2} d^{-1}** at 105 K)

Interpretation as limit

Preliminary results!

Going over final cross-checks on the DM-e scattering spectrum…



Spatial coincidence search

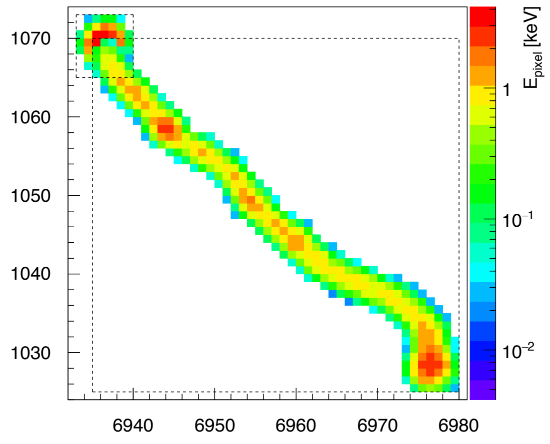
Bulk Contamination

$^{32}Si \rightarrow {}^{32}P$	Q = 224.5 keV	$t_{1/2}$ = 150 y
$^{32}P \rightarrow {}^{32}S$	Q = 1710 keV	$t_{1/2}$ = 14.3 d

Surface Contamination

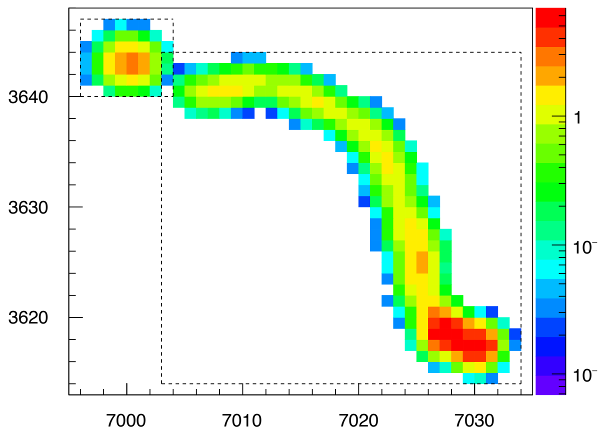
$^{210}Pb \rightarrow {}^{210}Bi$	Q = 63.5 keV	$t_{1/2}$ = 22.3 y
$^{210}Bi \rightarrow {}^{210}Po$	Q = 1161 keV	$t_{1/2}$ = 5.01 d
$^{210}Po \rightarrow {}^{206}Po$	Q = 5407 keV	$t_{1/2}$ = 138 d

^{32}Si β_1-β_2



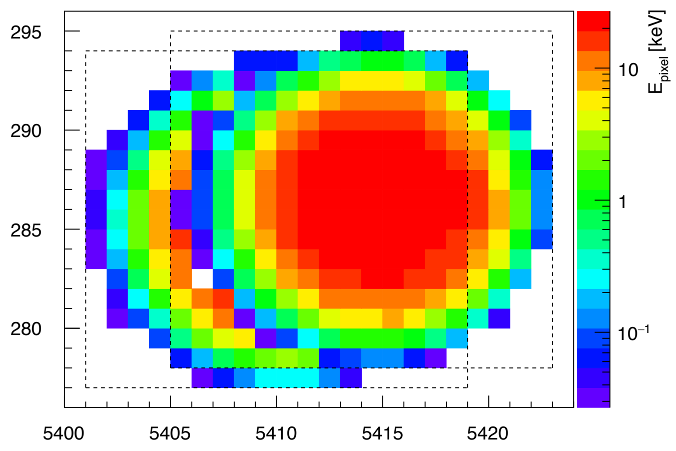
- $E_{\beta1}$ = 110 keV
- $E_{\beta2}$ = 361 keV
- Δt = 11.7 d

^{210}Pb β_1-β_2



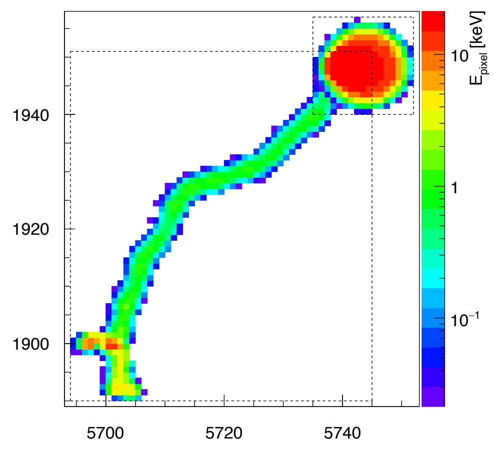
- $E_{\beta1}$ = 57 keV
- $E_{\beta2}$ = 376 keV
- Δt = 1.4 d

α-α



- $E_{\alpha1}$ = 4.3 MeV
- $E_{\alpha2}$ = 3.8 MeV
- Δt = 5.2 d

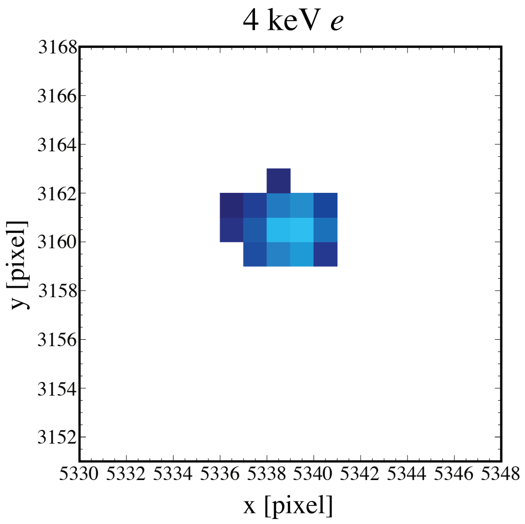
^{210}Pb β_1-α

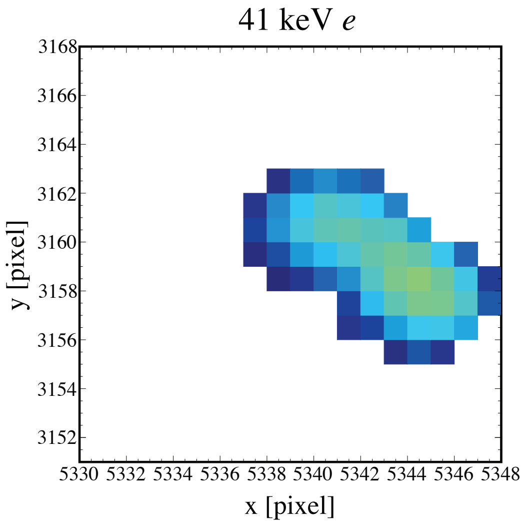


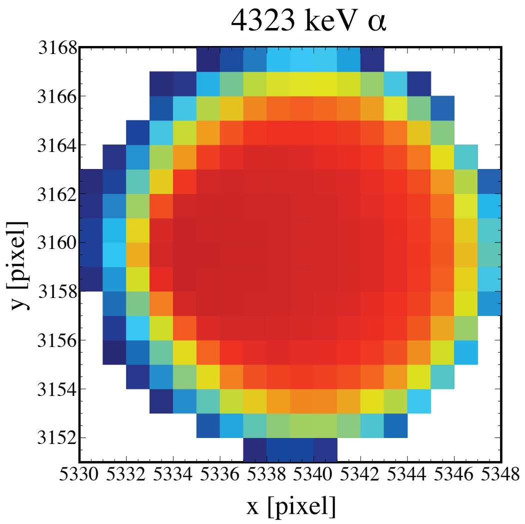
- $E_{\beta1}$ = 717 keV
- E_{α} = 3.62 MeV
- Δt = 32.3 d

See A. Matalon presentation at LRT 2019 for details!

Search results







We even see
^{210}Pb-^{210}Bi-^{210}Po
β-β-α
sequences!

This Analysis (*preliminary*)

^{32}Si
- 133.3 ± 27.8 μBq/kg

^{210}Pb
- 83.1 ± 11.8 nBq/cm^2

^{238}U
- No α-β sequences
- Upper limit:
0.53/kg/day or 1.5 ppt [95%]

^{232}Th
- No α's with E = 18.7 MeV
- Upper limit:
0.35/kg/day or 1 ppt [95%]

DAMIC 2015 R&D result

^{32}Si
- 925.9 ± 1273 / 752 μBq/kg

^{210}Pb
- 902.8 ± 115.8 nBq/cm^2

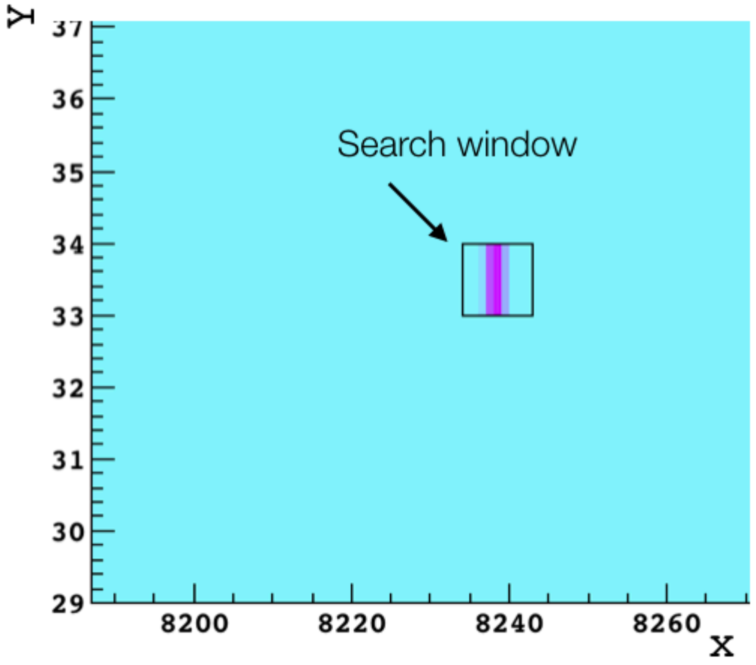
^{238}U
- Upper limit: 5/kg/day [95%]

^{232}Th
- Upper limit: 15/kg/day [95%]

See A. Matalon presentation at LRT 2019 for details!

WIMP Search

- Pedestal and correlated noise subtraction.
- Masking of defects.
- Image selection.
- LL fit of the signal in a moving window across the image.



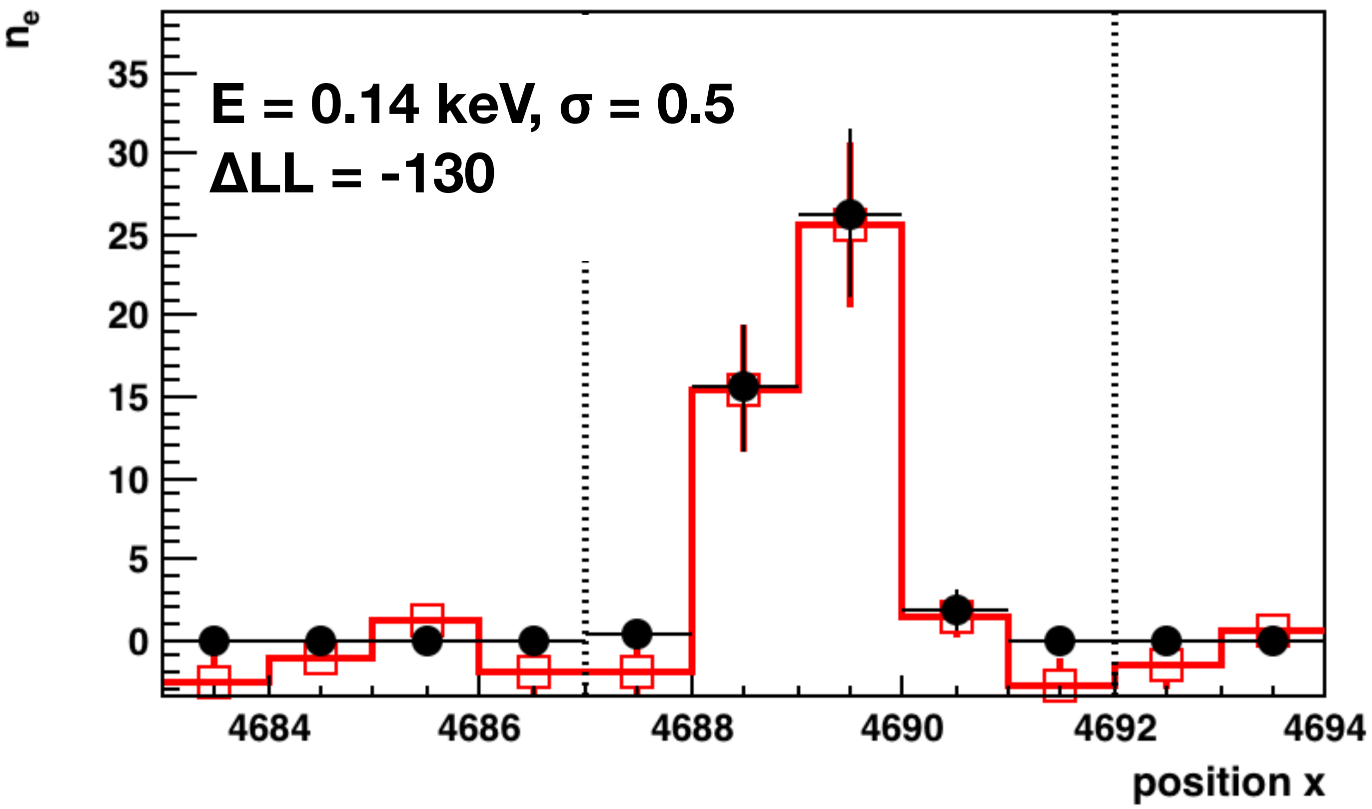
$$\Delta LL = \mathscr{L}_n - \mathscr{L}_s$$

flat noise

Gauss signal + flat noise

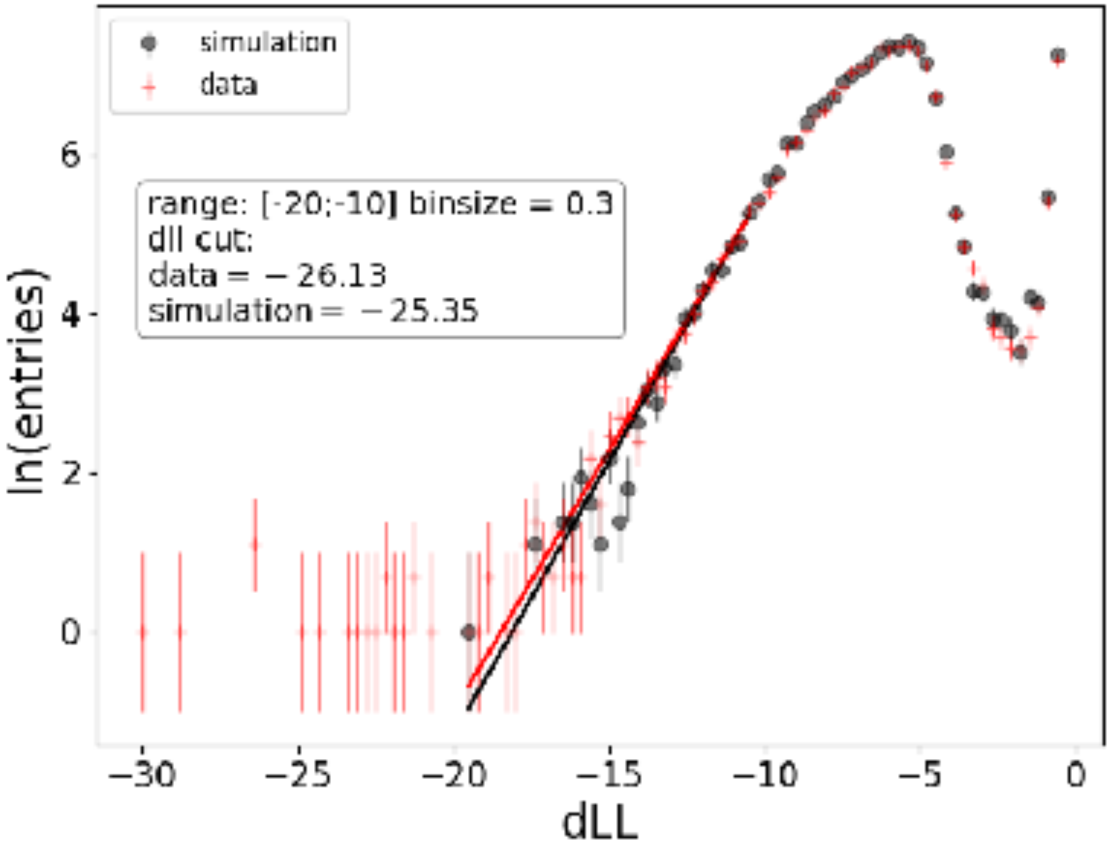
For every event we have its statistical significance *ΔLL* above noise, its amplitude (*E*, energy) and its spread (σ_x proportional to *z*)

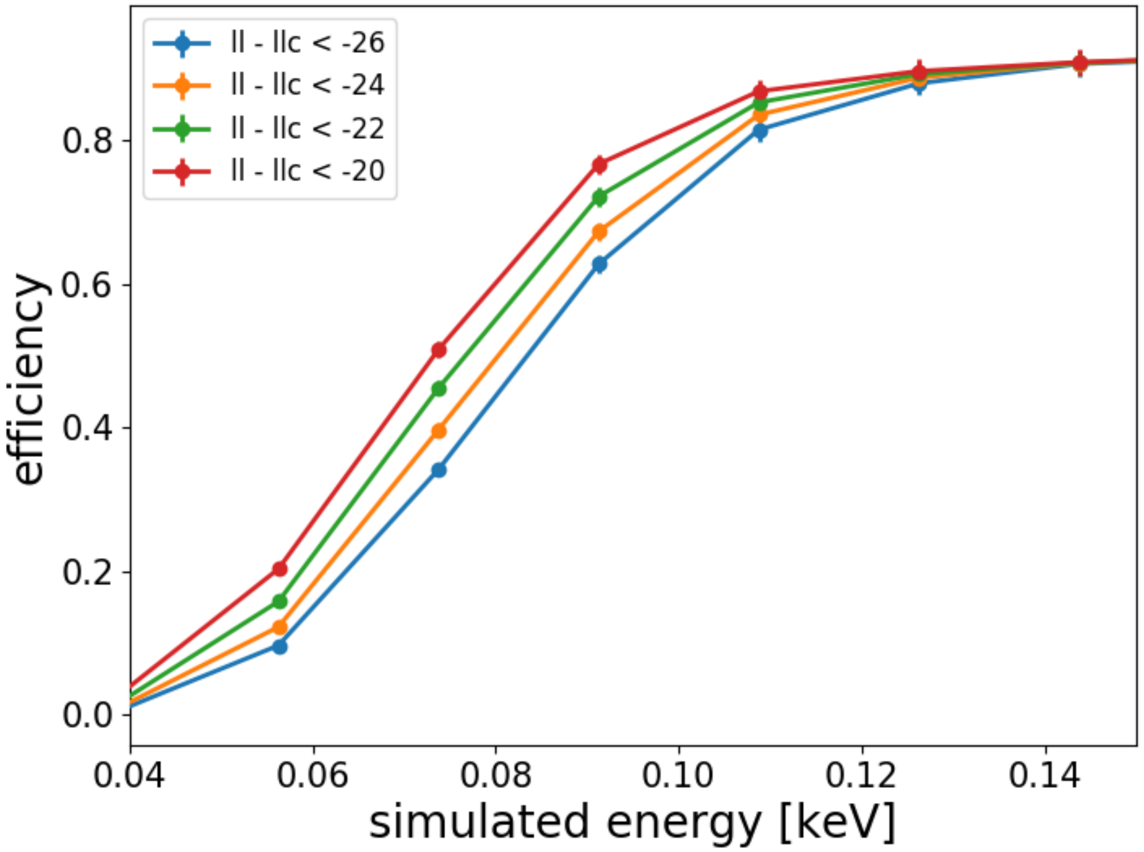
Example of one event



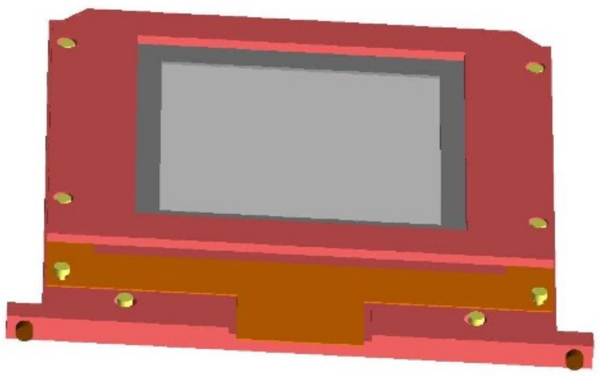
Noise rejection

- We construct a model by including leakage current on the blank (zero-exposure) images.
- We run the full cluster extraction to obtain the *ΔLL* profile for “noise” clusters.
- Select a *ΔLL* value that removes all noise and calculate the event selection efficiency.



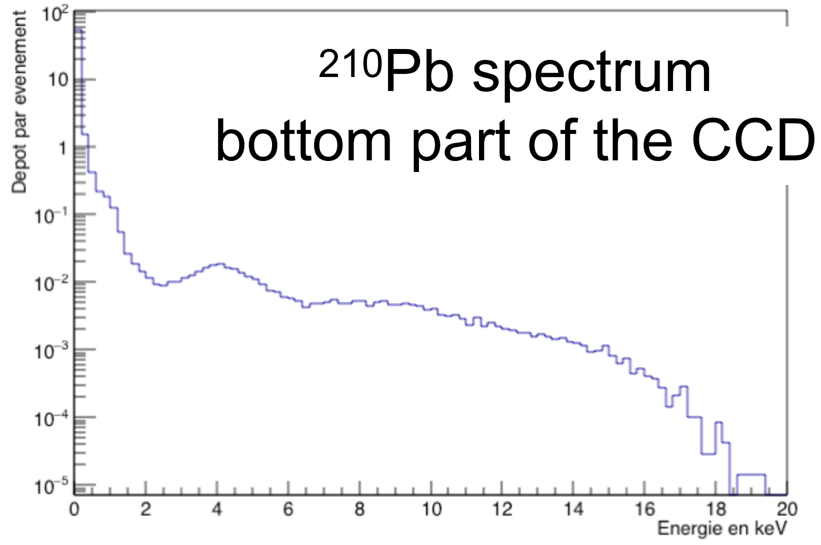


Background simulation



- Geant4 Simulation of the detector
- Energy deposition on the sensitive part of the CCD.
- Diffusion, binning and saturation are handled after the Geant4 simulations
- Using Livermore Physics List.

Geant4 Output



^{210}Pb spectrum
bottom part of the CCD

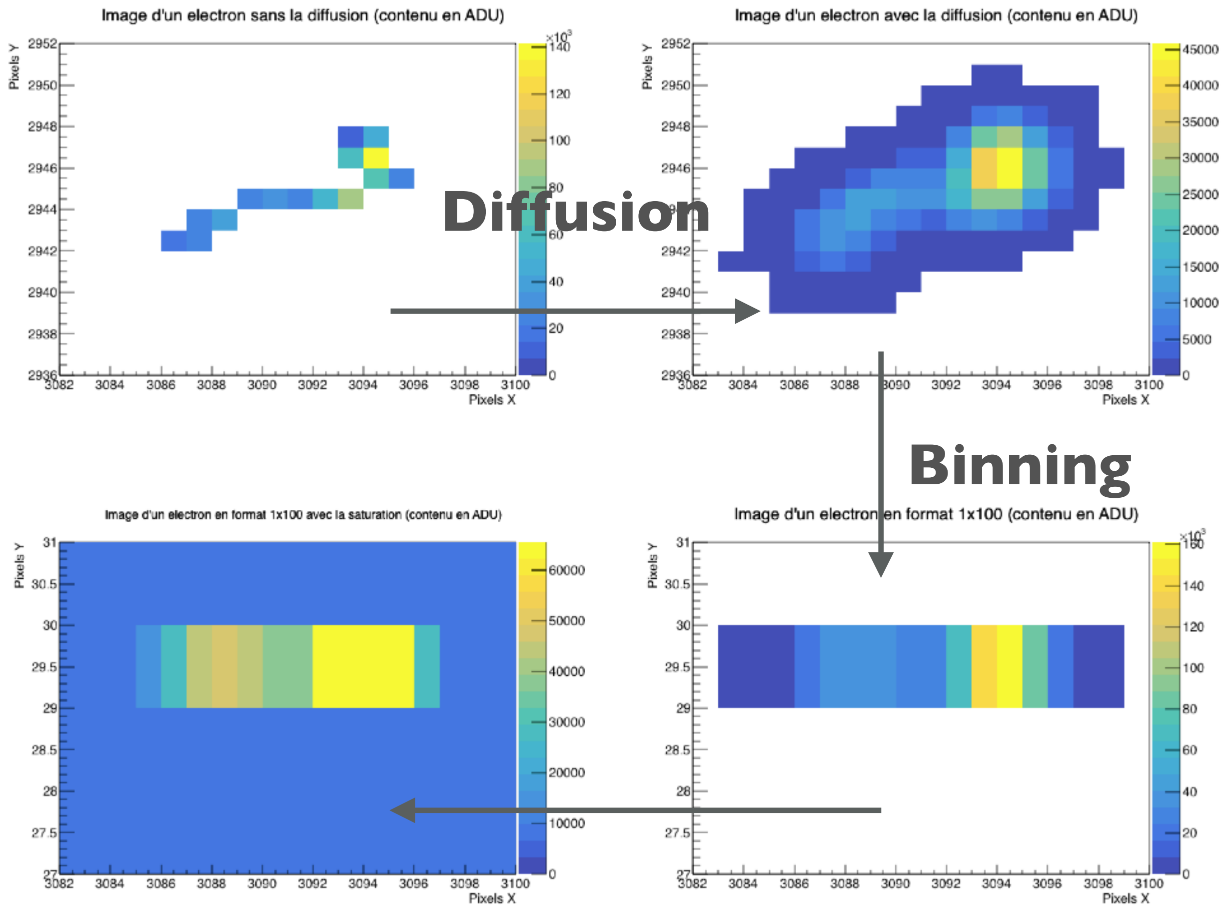


Image d'un electron sans la diffusion (contenu en ADU)

Image d'un electron avec la diffusion (contenu en ADU)

Image d'un electron en format 1x100 avec la saturation (contenu en ADU)

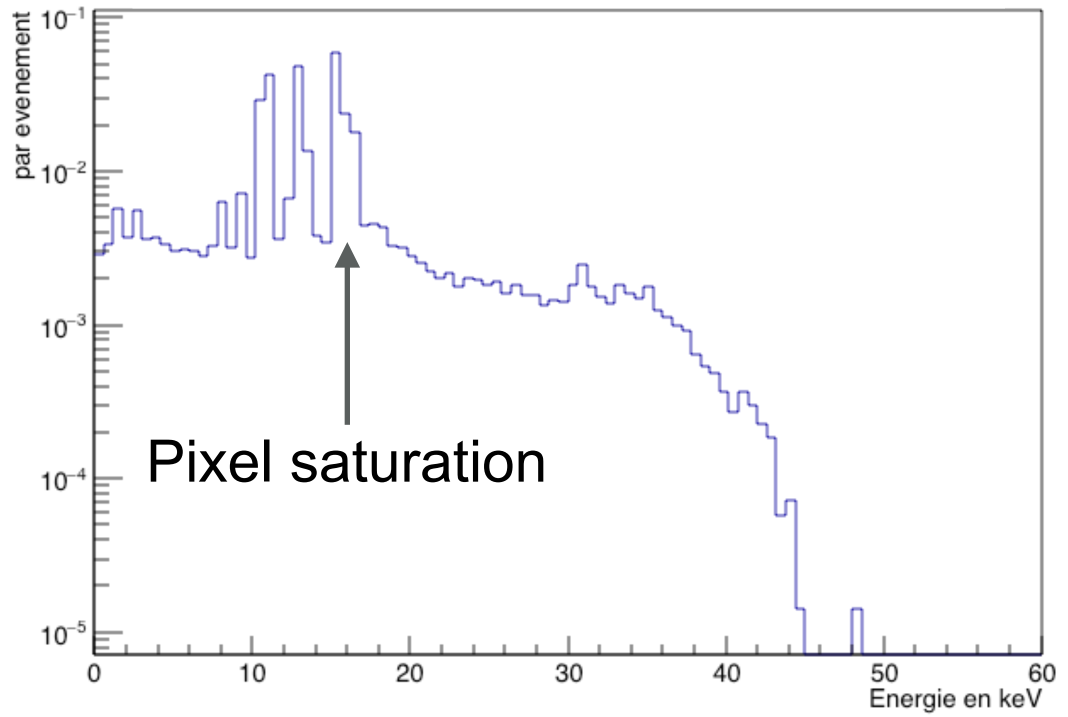
Image d'un electron en format 1x100 (contenu en ADU)

Diffusion

Binning

Saturation + noise

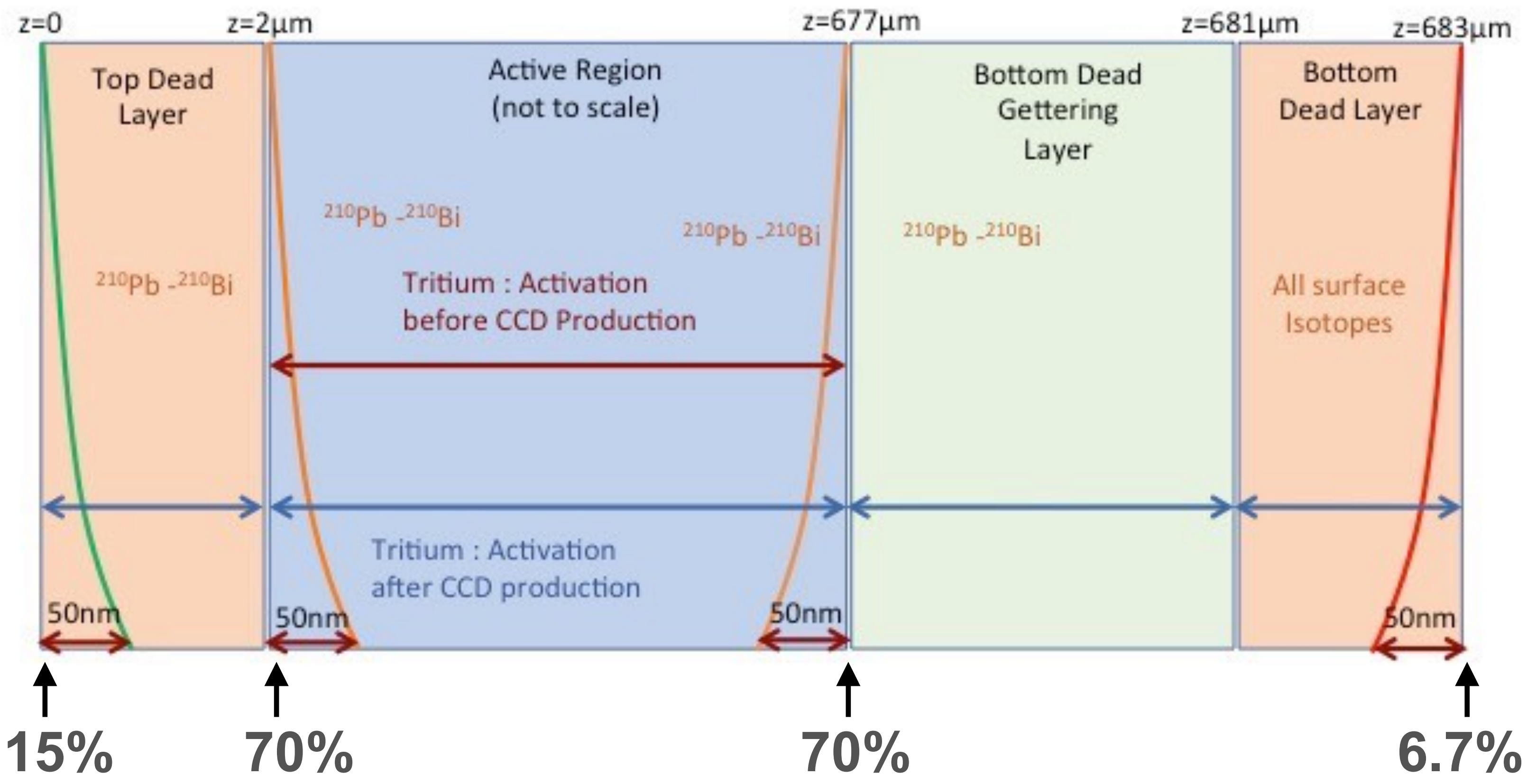
After processing



Pixel saturation

Radio contaminants

- 28 isotopes simulated in the volumes
  - 15 common to all volumes: U/Th chains.
  - 7 cosmogenics in the copper, produced by spallation from cosmic rays.
  - 4 only in the CCD ^{32}Si, ^{32}P, ^{3}H, ^{22}Na.
- 2 isotopes simulated on the surface:
  - ^{210}Pb, ^{210}Bi:

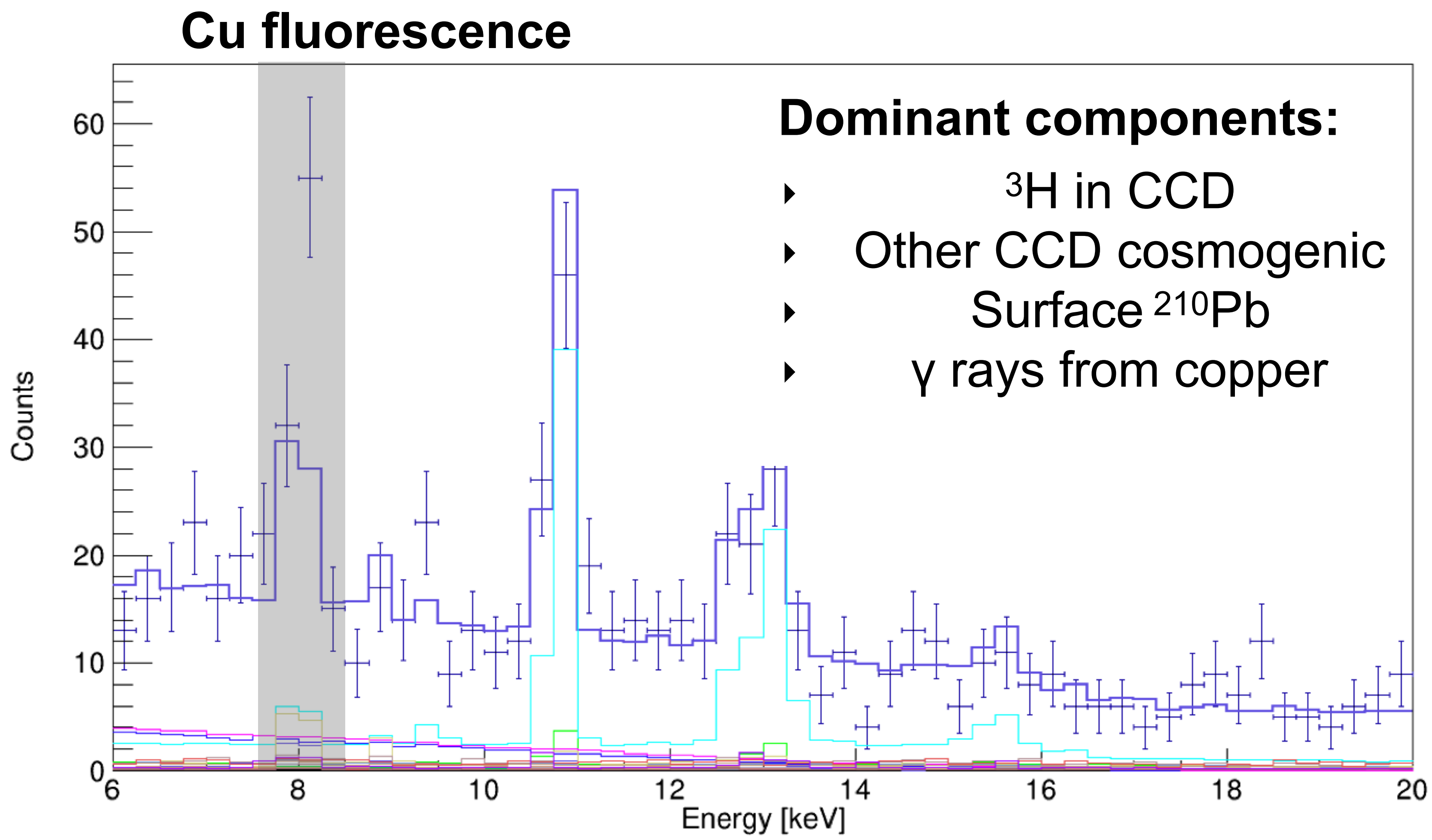


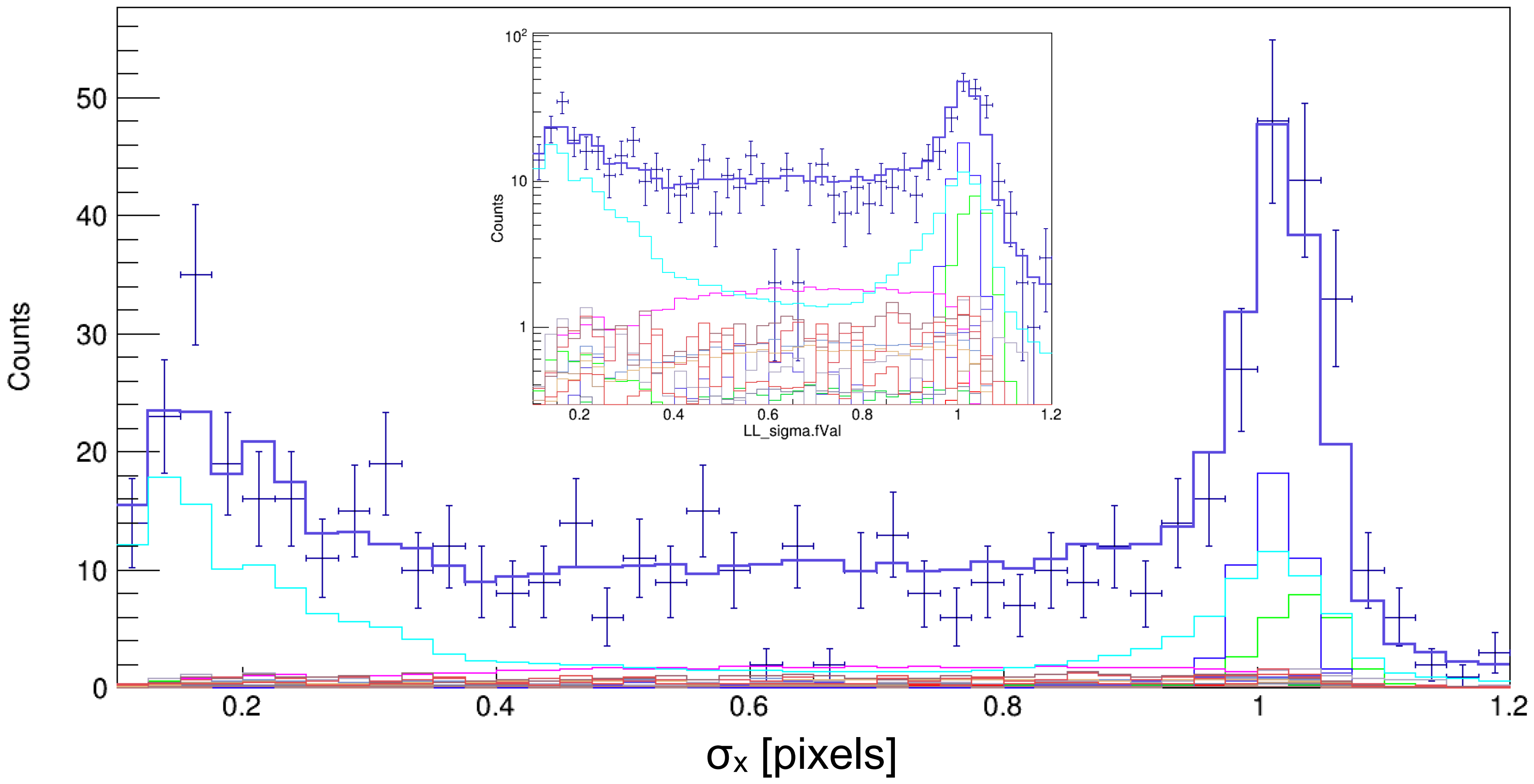
^{210}Pb efficiency to detect a coincidence

- ^{210}Pb on multiple possible locations based on the history of CCD fabrication and handling.
- Combining spectral information (total event rate) and observed number of ^{210}Pb-Bi spatial coincidences, we have some discrimination between them.

Results

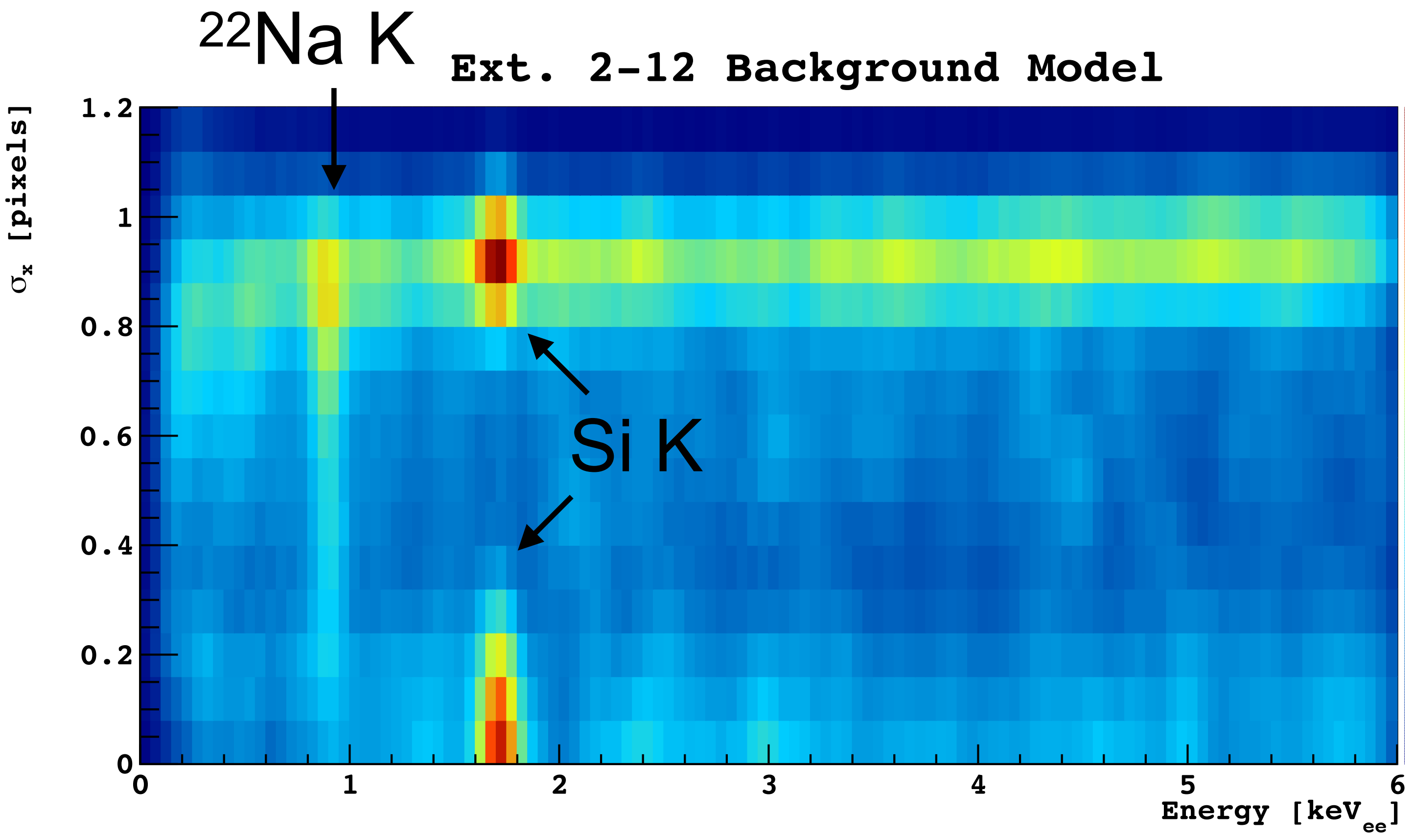
- Background model from 2D fit to ***E***, σ_x parameter space above 6 keV (no dark matter signal).
- Exclude CCD #1 (in between ancient lead) from background model.
- Cu K fluorescence masked because haven't validated Geant4 to atomic processes.
- 1D projections of the best fit shown on the right.
- Overall good match to the data.

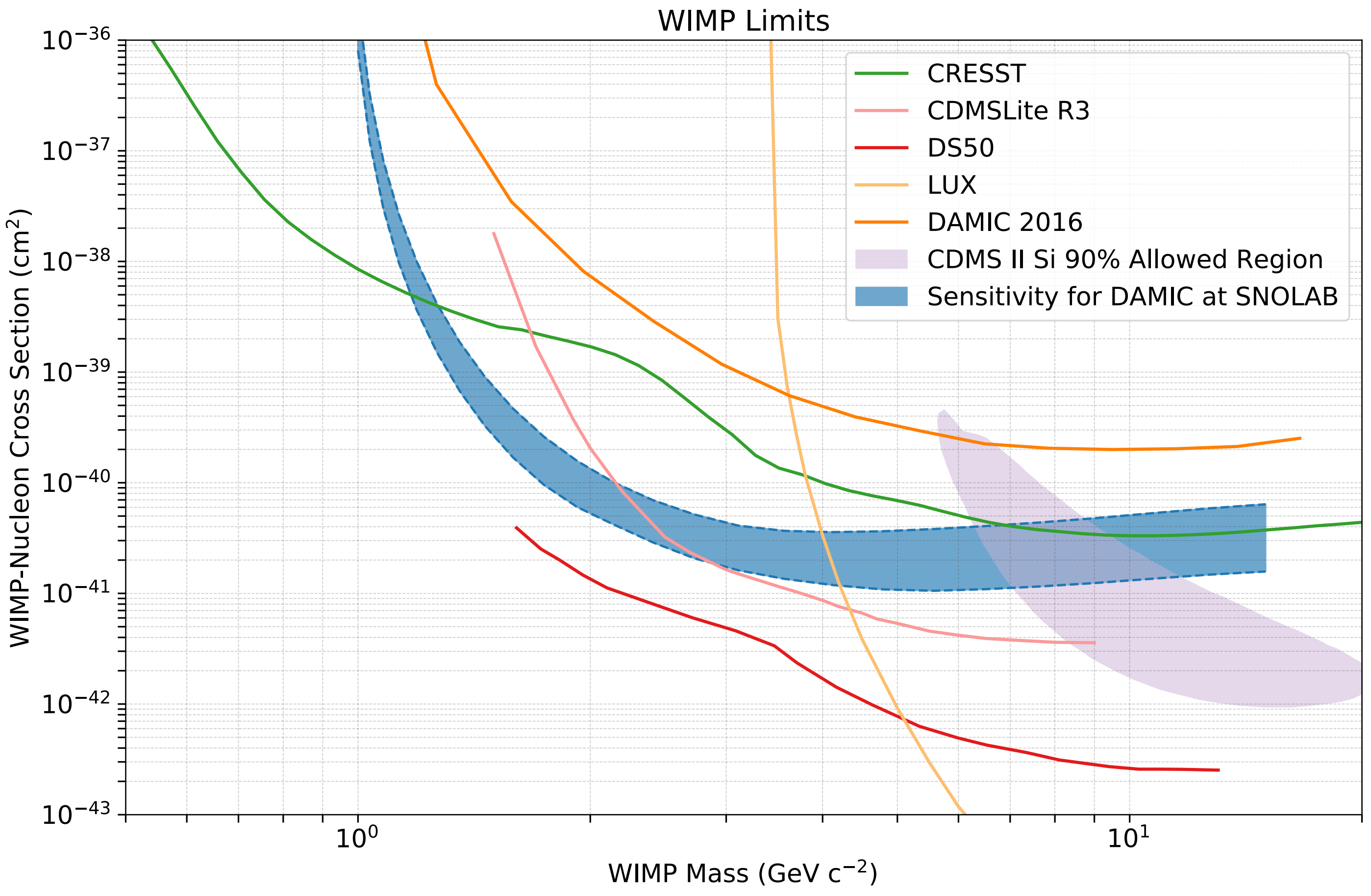




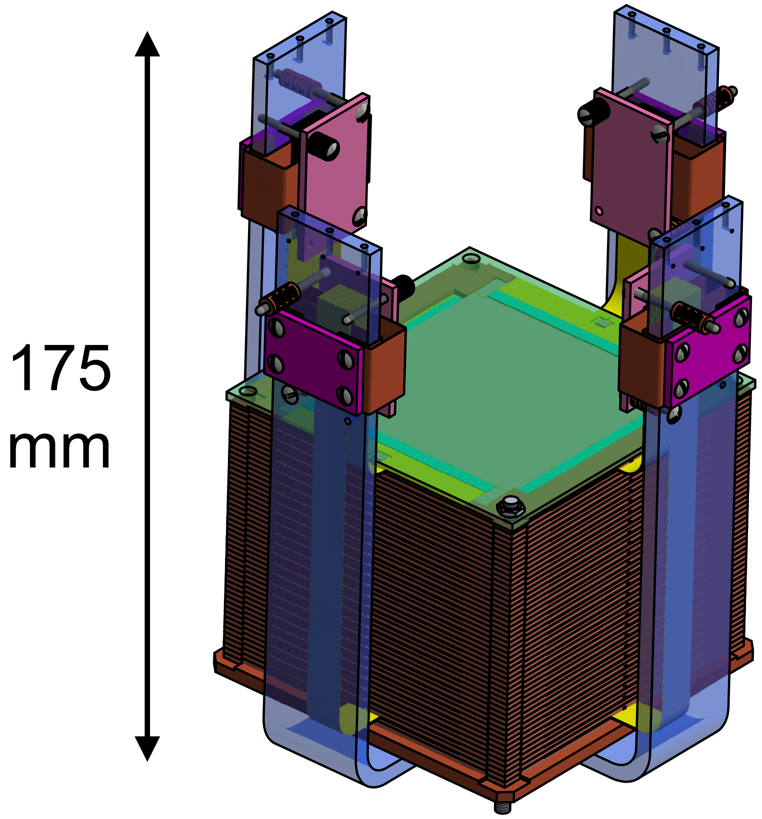
Expected sensitivity

- Analysis in its final stages. Results soon!
- We use best-fit of latest background model to generate expected sensitivity.
- Includes CCD #1 with the same background model except for γ ray background from copper OFF.
- Will be competitive with CRESST and CDMS-Lite, and exclude a large fraction of CDMS II-Si (our original goal).



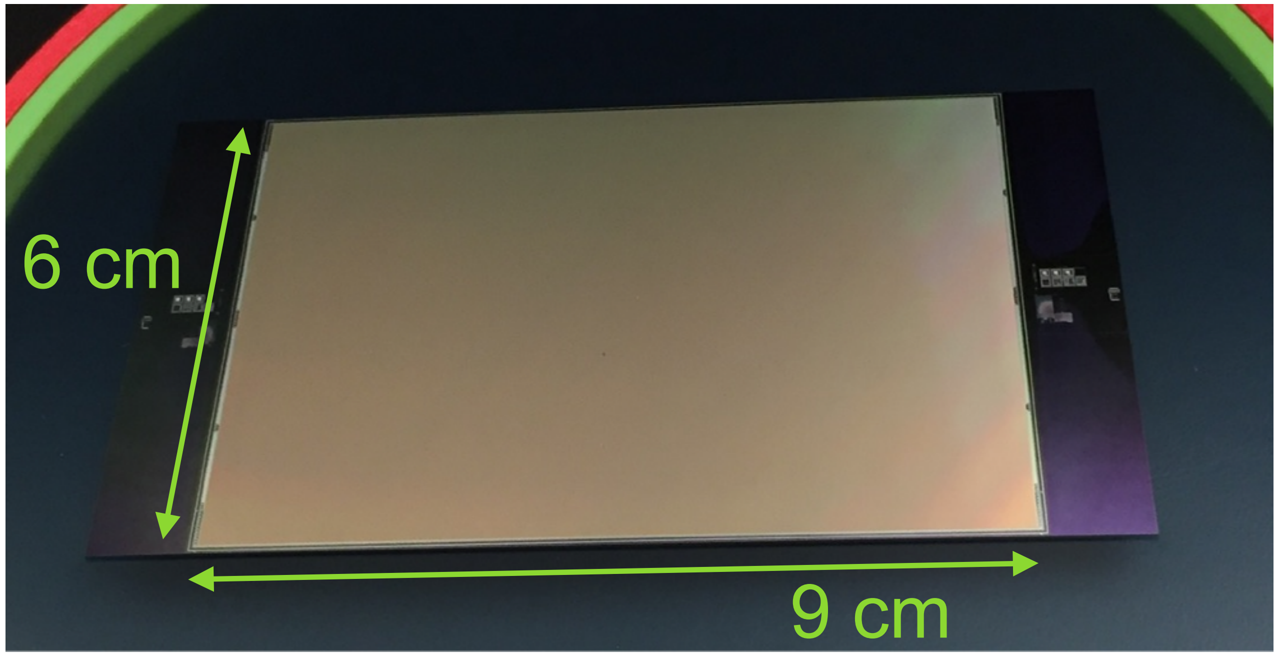


DAMIC-M



- **50 CCDs** (0.7 kg target mass) at LSM (France).
- Most massive CCDs ever built (**6k x 6k x 0.675 mm, mass 14 g**).
- Skipper readout for **sub-eV noise.**
- **Background reduction to a fraction of dru** (improved design, materials, procedures).

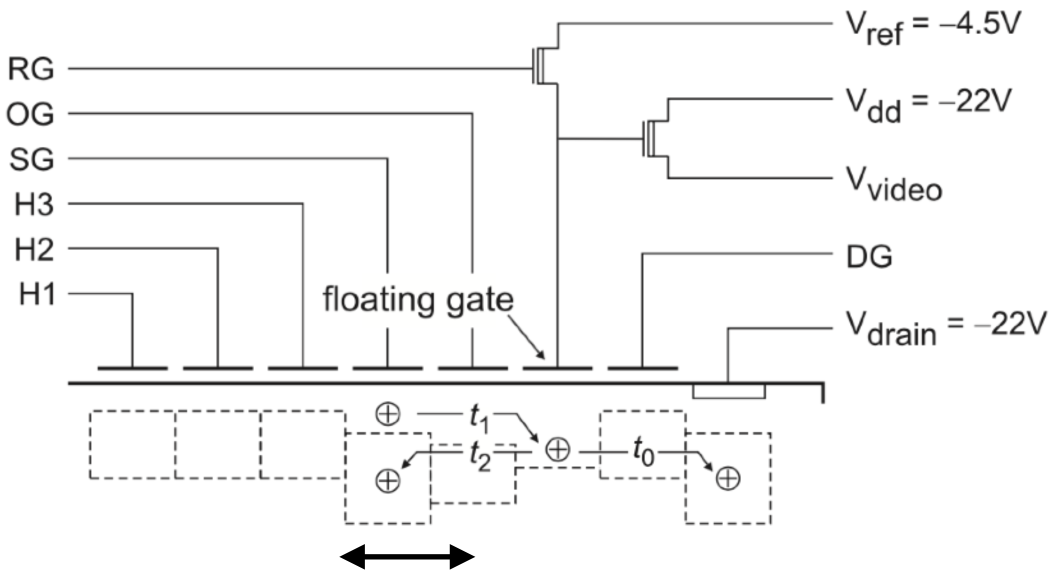
24 Mpix CCD at UW: 10 g!



Institutions:

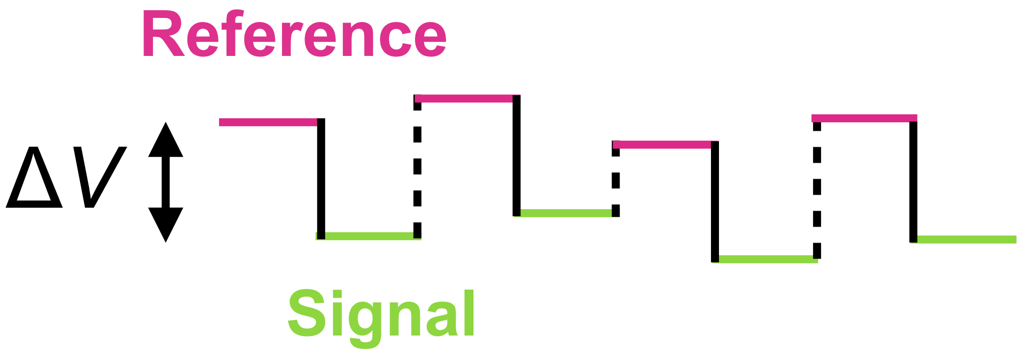
The University of **Chicago**, University of **Washington**, Pacific Northwest National Laboratory (**PNNL**), **SNOLAB**, Laboratoire de Physique Nucléaire et de Hautes Energies (**LPNHE**), Laboratoire de l'Accélérateur Linéaire (**LAL**), the Laboratoire Souterrain de Modane/Grenoble (**LSM**), University of **Zurich**, **Niels Bohr Institute**, University of **Southern Denmark**, University of **Santander**, Centro Atómico **Bariloche**

Skipper CCD



move charge back and forth

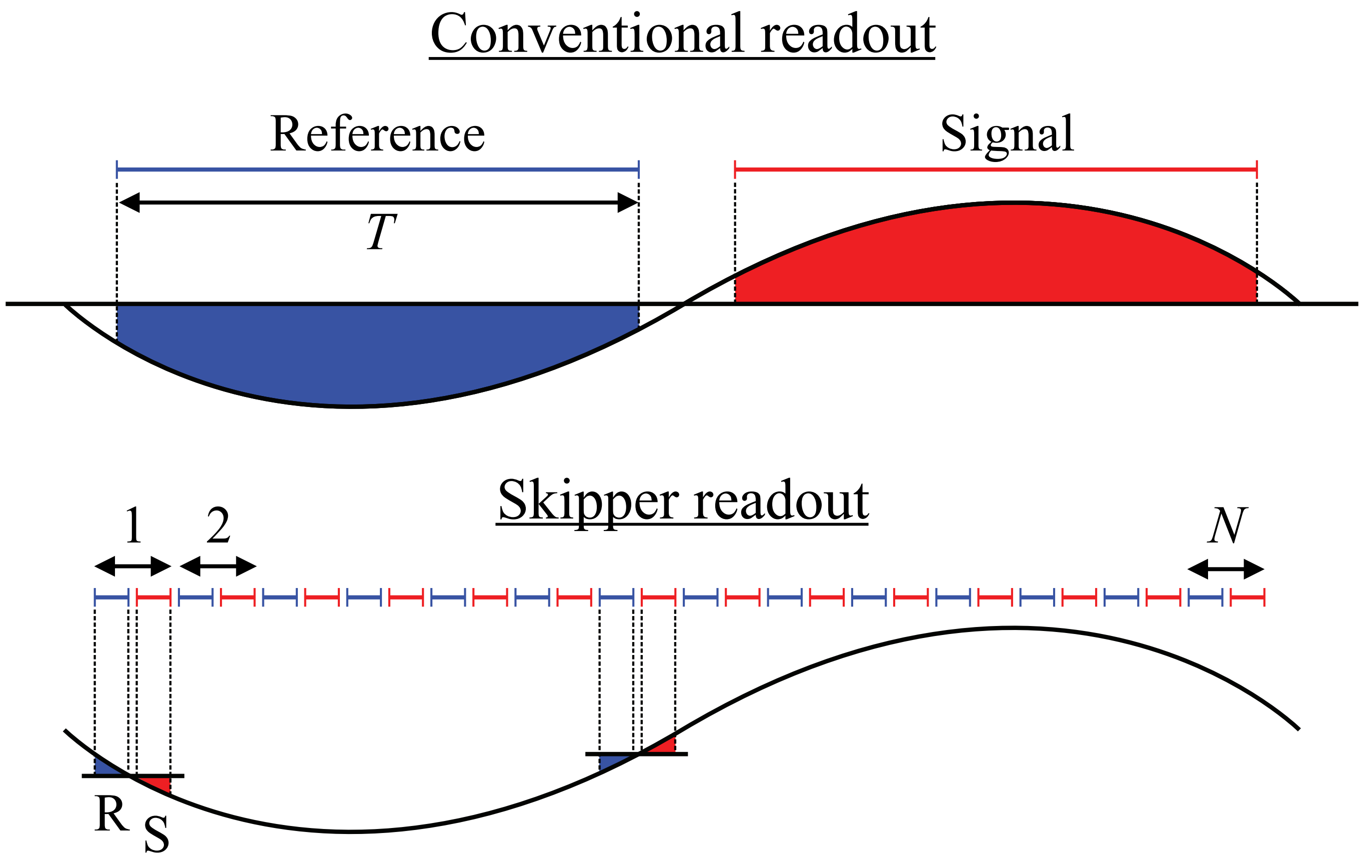
Measure Δ*V* *N* times



Technology proposed in the 1990s

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

Effect on low frequency noise

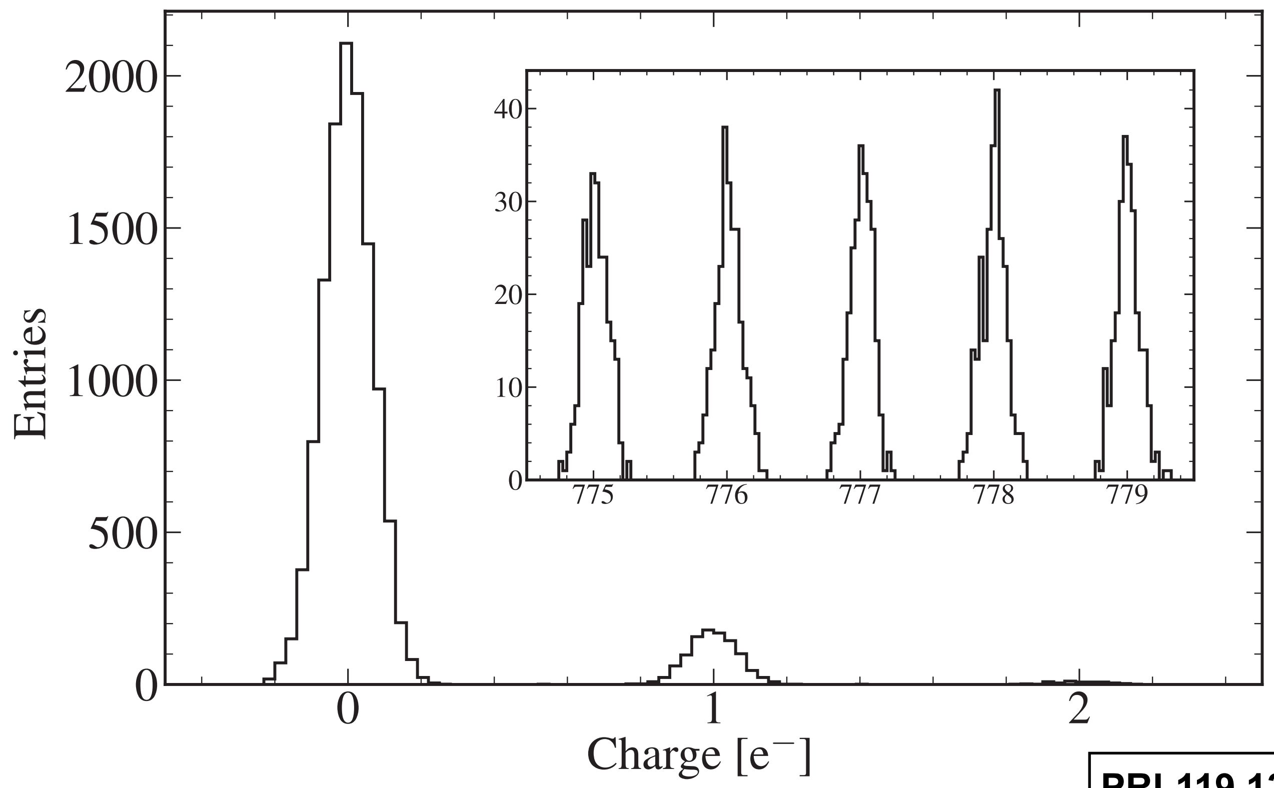


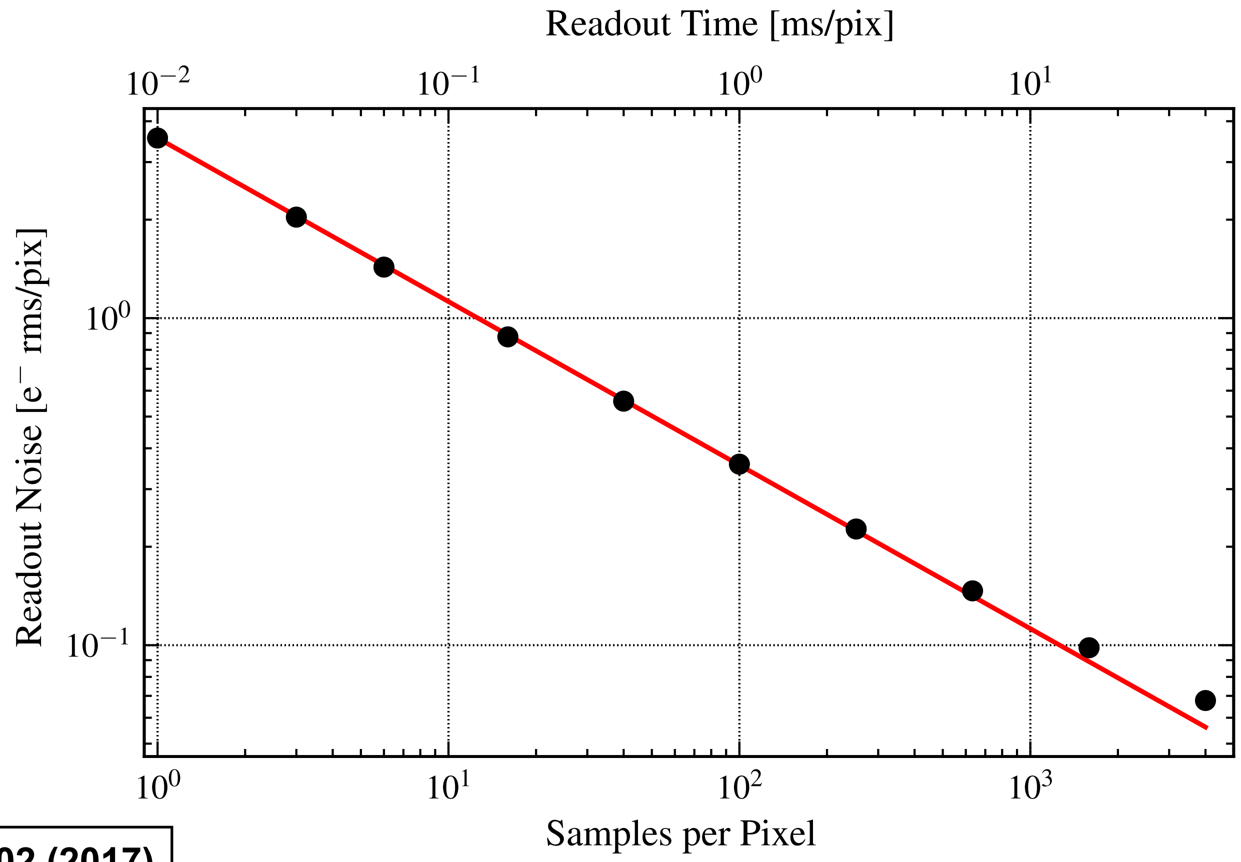
SENSEI

LDRD at Fermilab: Skipper CCDs (**LBNL design**) successfully tested with sub e$^-$ noise. X-ray spectroscopy demonstrated.

Technology will allow 2 e$^-$ (few eV) threshold.

Observed ~1/√*N*

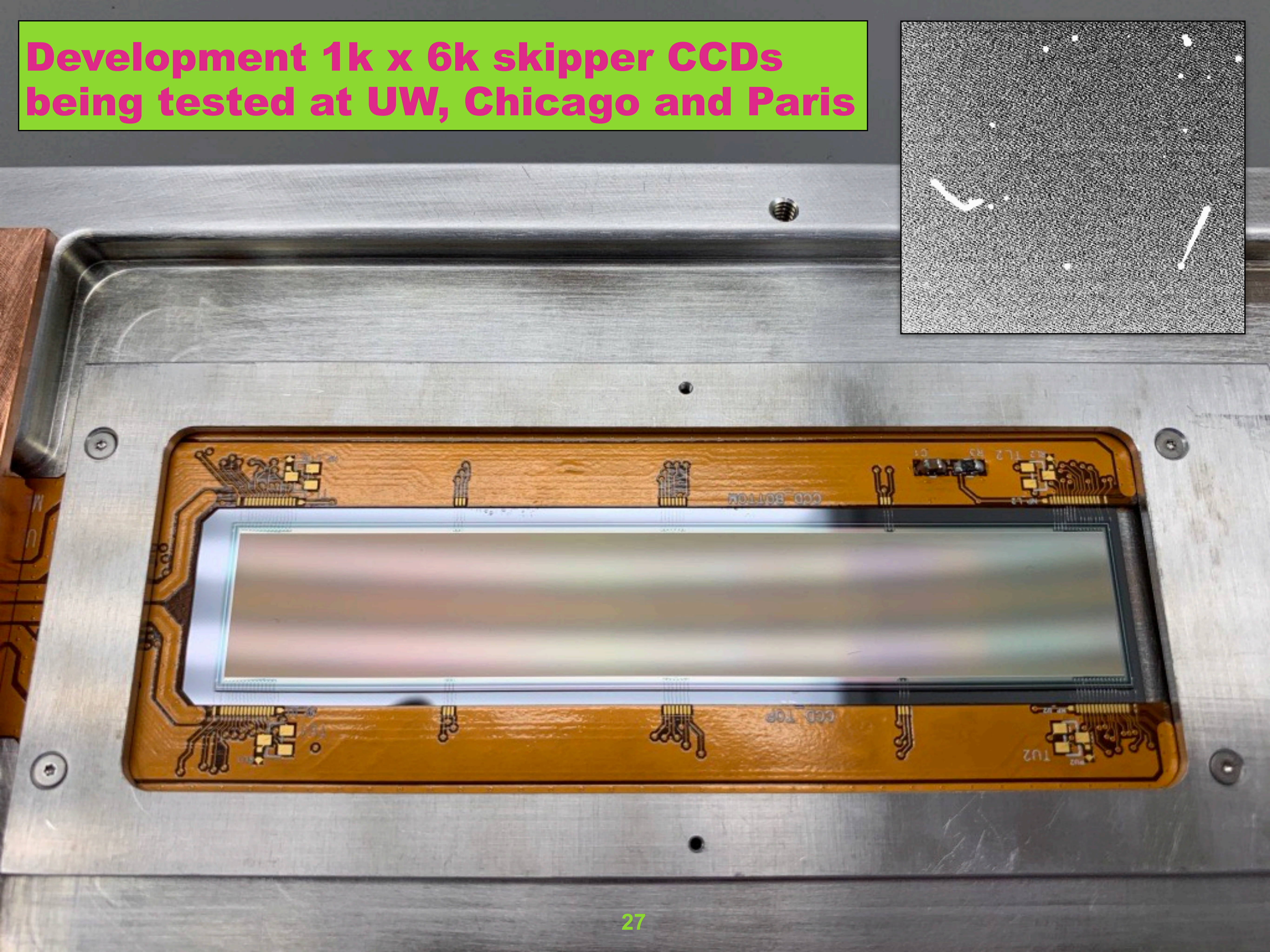




PRL119 131802 (2017)

DAMIC-M will adopt LBNL skipper design tested by SENSEI

Development 1k x 6k skipper CCDs being tested at UW, Chicago and Paris

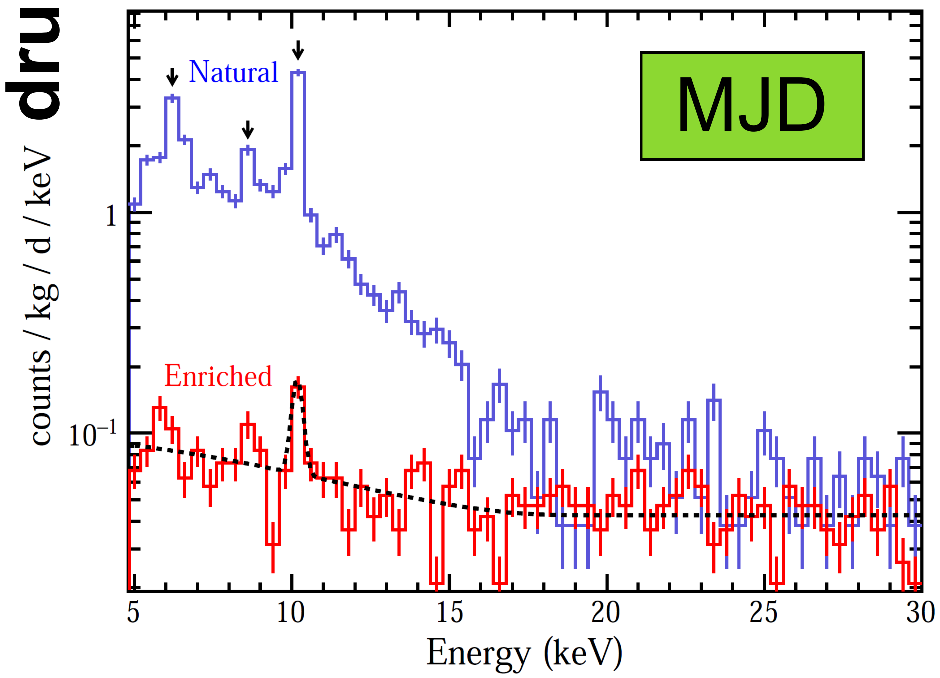


Improvements

CCDs: DAMIC-M CCDs will combine **low dark current** demonstrated by DAMIC at SNOLAB with **skipper readout** tested by SENSEI for devices with few e^- threshold for kg-year exposures underground.

Low radioactive background:

- Goal for DAMIC-M **0.1 dru** (already achieved by MJD and C4, dominated by cosmogenic ^{3}H).
- Cryostat by support with PNNL **electroformed copper**.
- Improved design / operation for background mitigation / tagging.
- CCD packaging and detector assembly in **radon-free** cleanroom at LSM.
- Measuring cosmogenic ^{3}H activation in Si at **LANSCE** this summer.
- Store silicon underground + shielded shipping container.

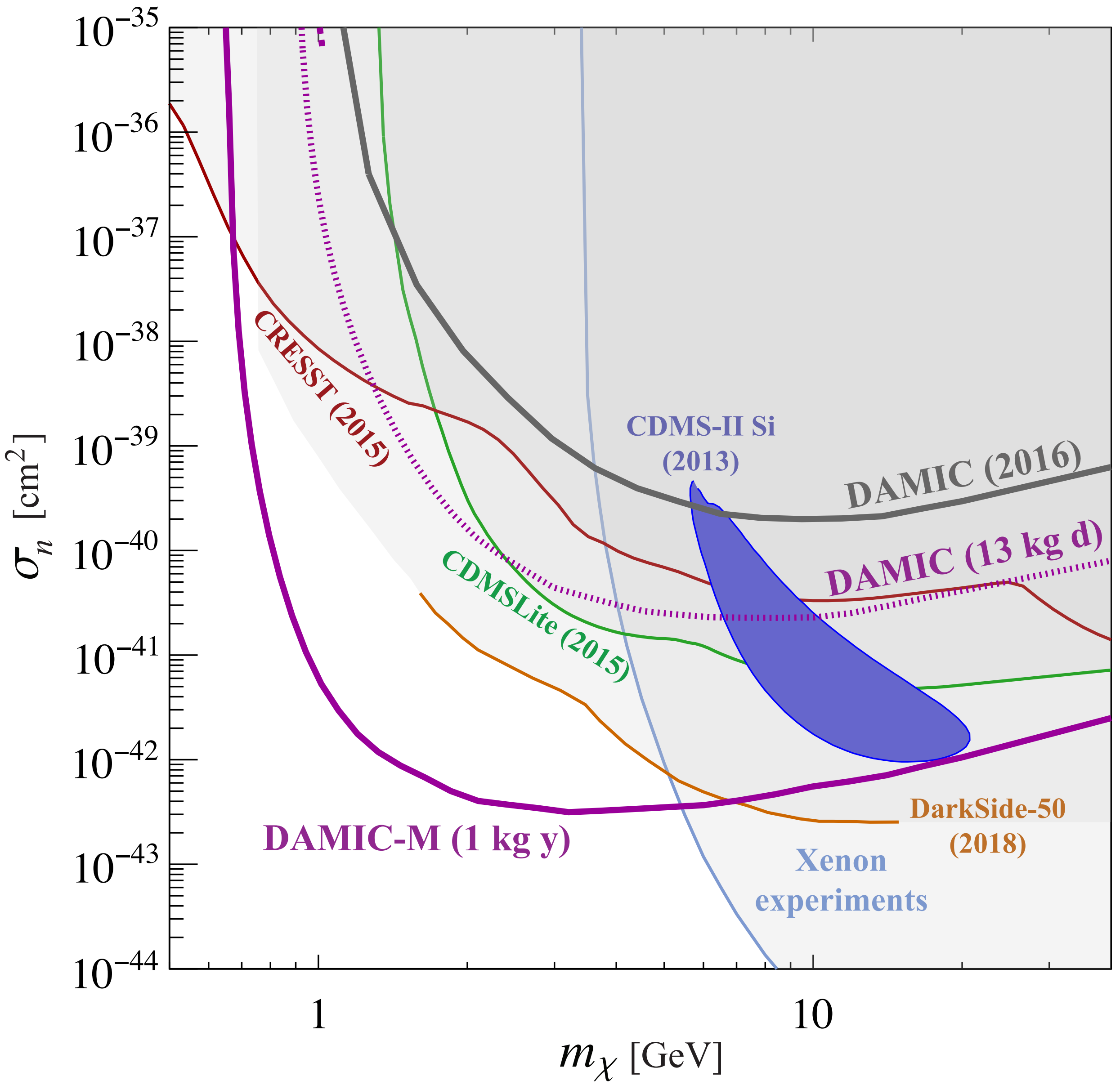


Facility at SNOLAB

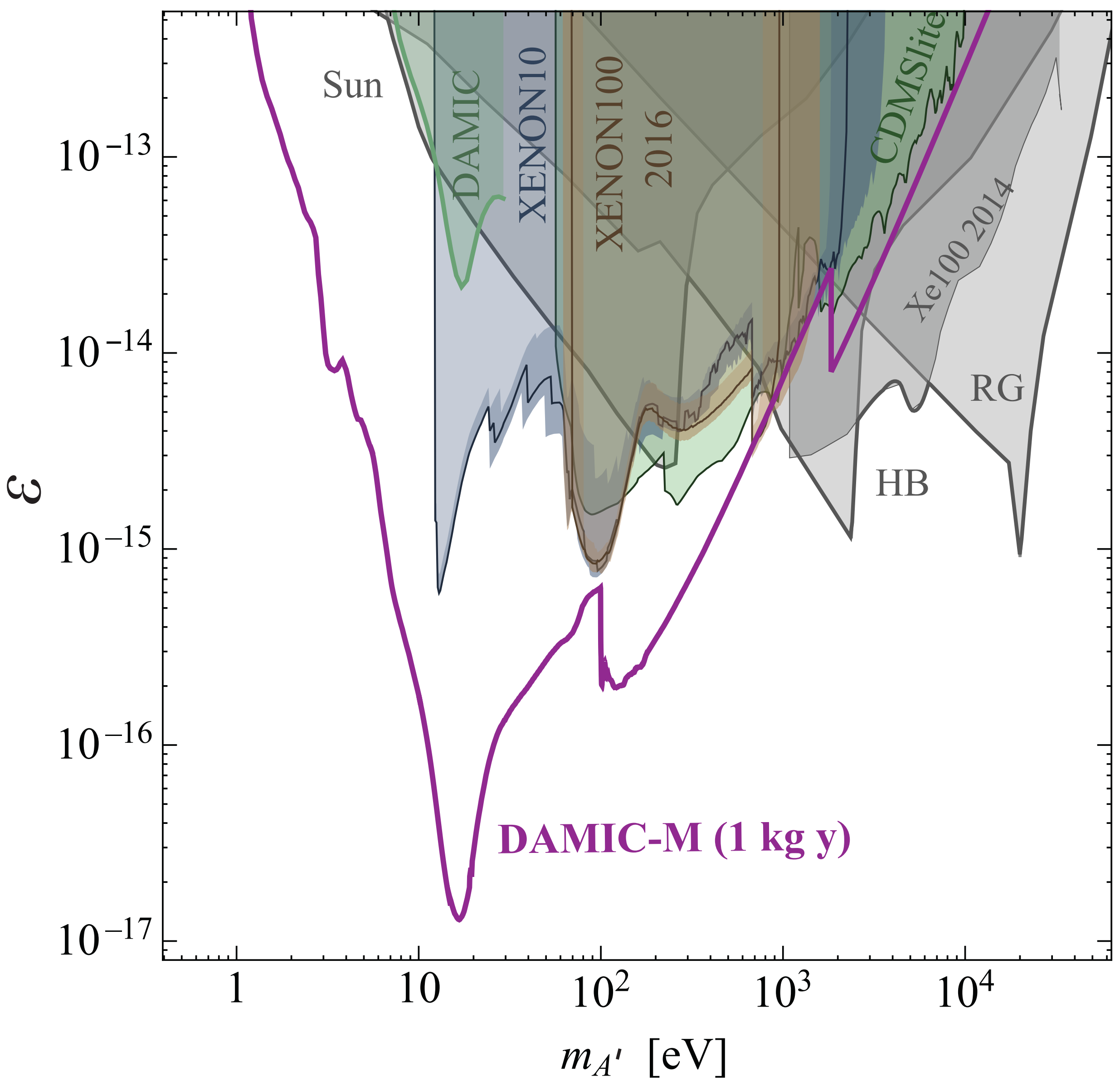
- We plan to continue DAMIC at SNOLAB for at least two years. (We have a deadline to return ancient lead to Modane in 2021.)
- Maintenance required: unstable cryocooler operation and one bad “video” board (currently reading out 5 CCDs).
- Doing tests to decrease leakage current: ***crucial*** for DAMIC-M science goals.
- DALSA foundry (for DAMIC-M CCDs) in Quebec. We request a Rn-free storage box (LN flush) underground to store CCDs temporarily.
- Possibility to for tests with new CCDs based on the R&D needs of the skipper CCD community.

Forecast I

WIMP nuclear recoil search



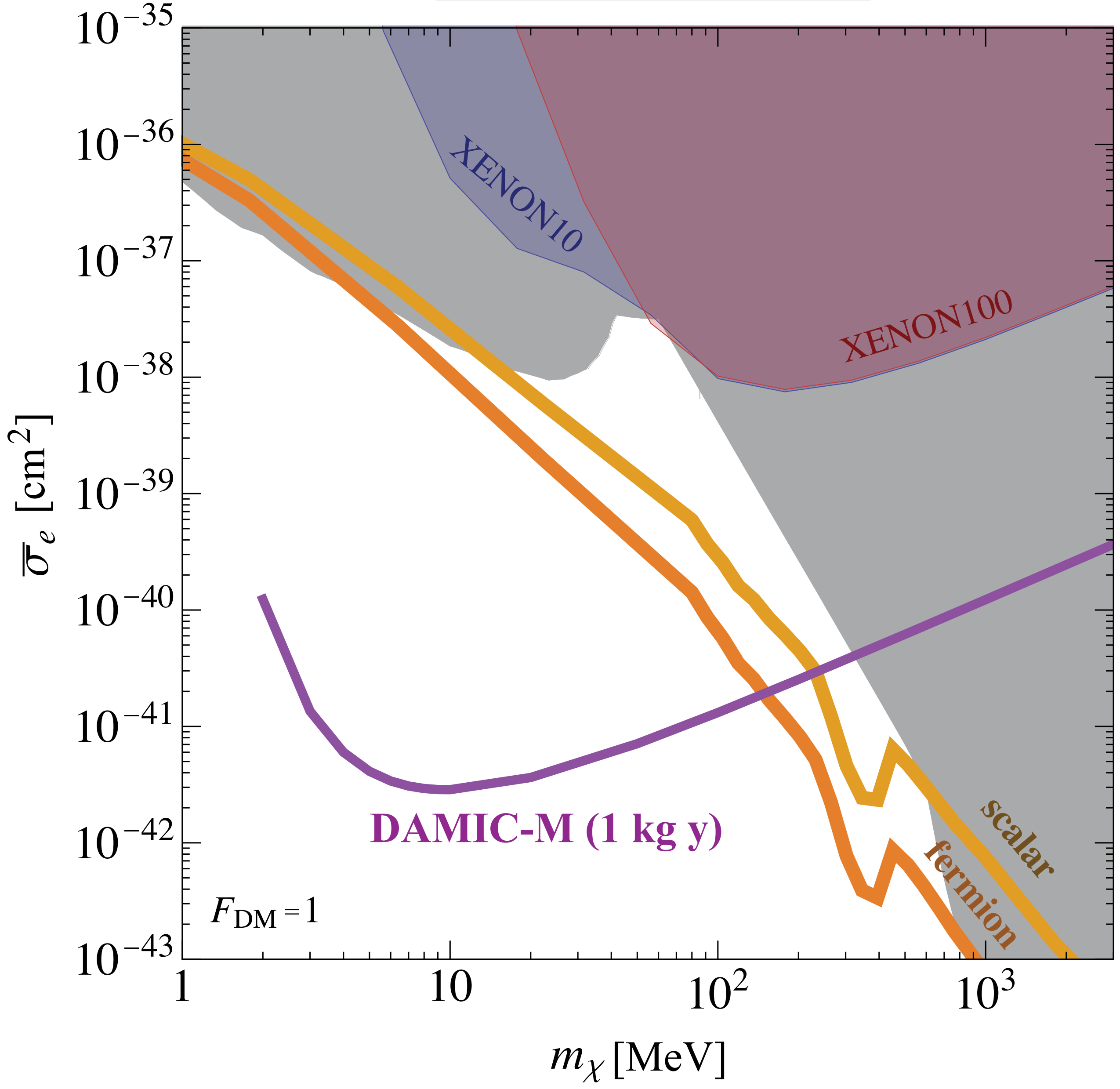
Hidden photon search



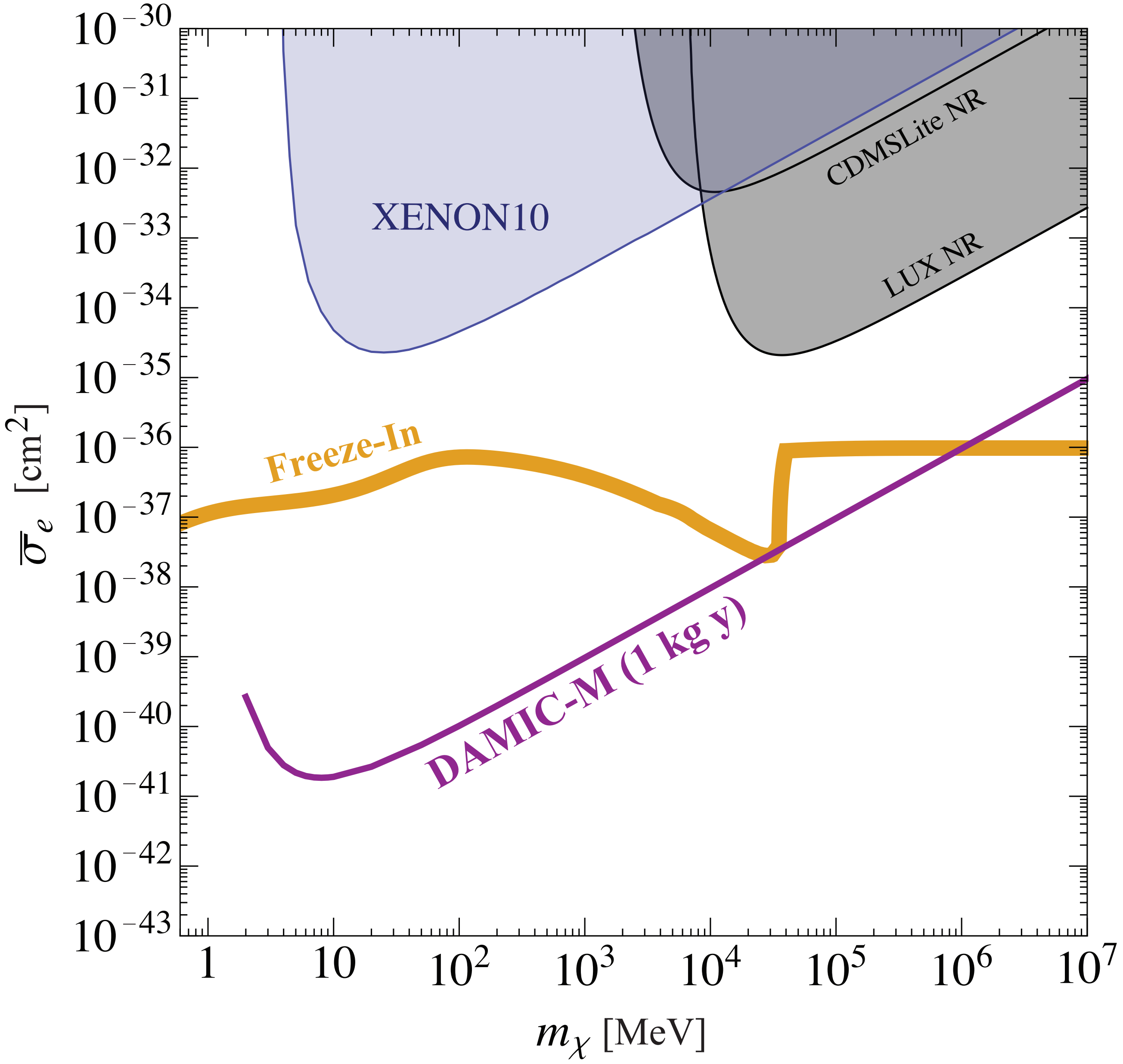
Forecast II

Light dark matter - electron scattering

Heavy mediator



Light mediator



Conclusions

- After almost 7 years in SNOLAB, DAMIC has demonstrated CCDs as an excellent technology for dark matter detection.
- About to meet our original goal for a leading low-mass WIMP search (stay tuned!).
- Expanded our science to interactions of dark matter with electrons. First hidden photons and now the best limits on DM-e scattering.
- Extensive understanding of CCD response and backgrounds from radioactivity for an experiment with potential for discovery.
- Lessons learned at SNOLAB gives us confidence that we can achieve the background goals fro a kg-year exposure with DAMIC-M.
- DAMIC will run at SNOLAB in the near future with an R&D program to support upcoming skipper CCD dark matter experiments.