Background rejection in highly pixelated solid-state detectors

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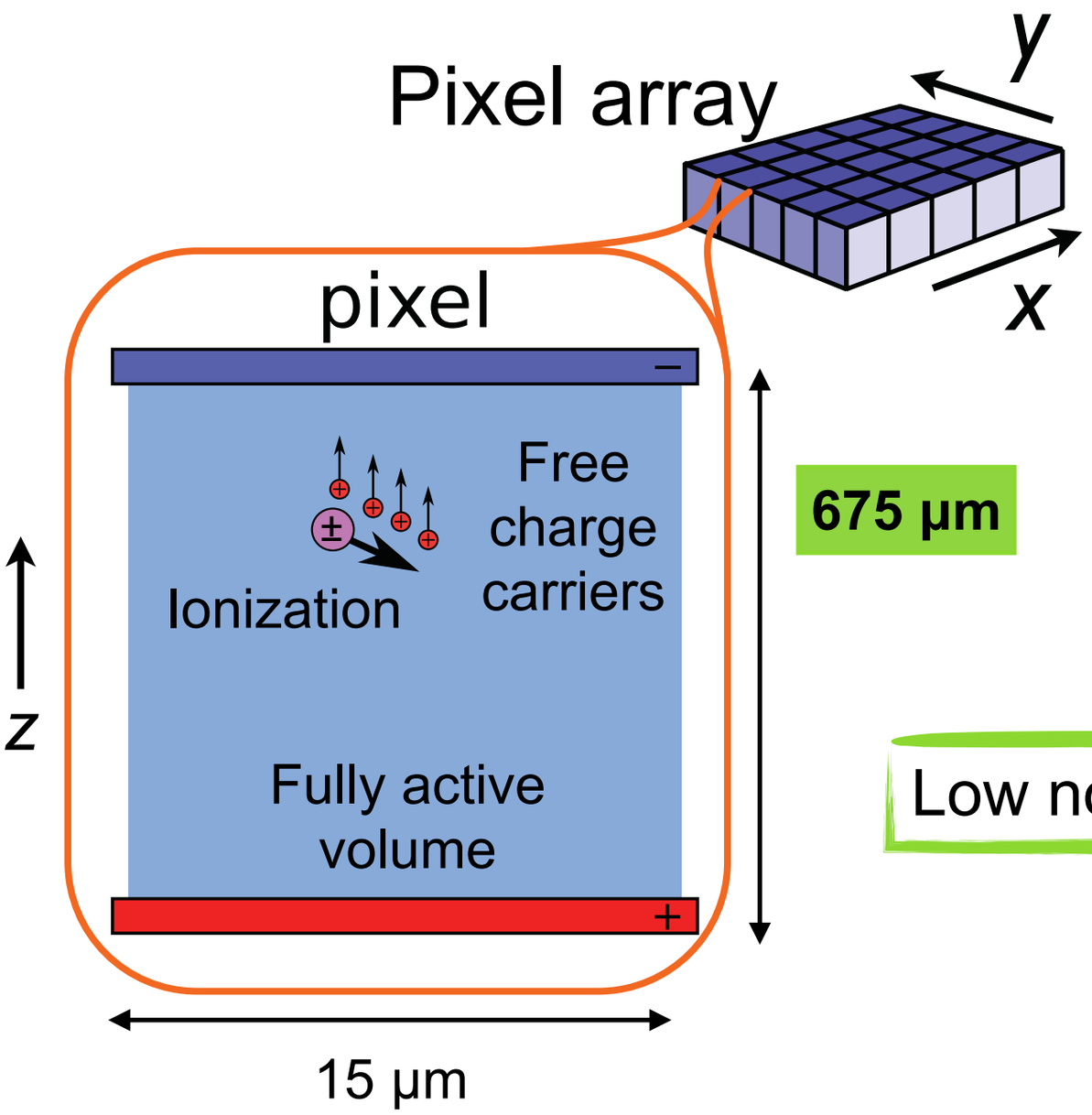
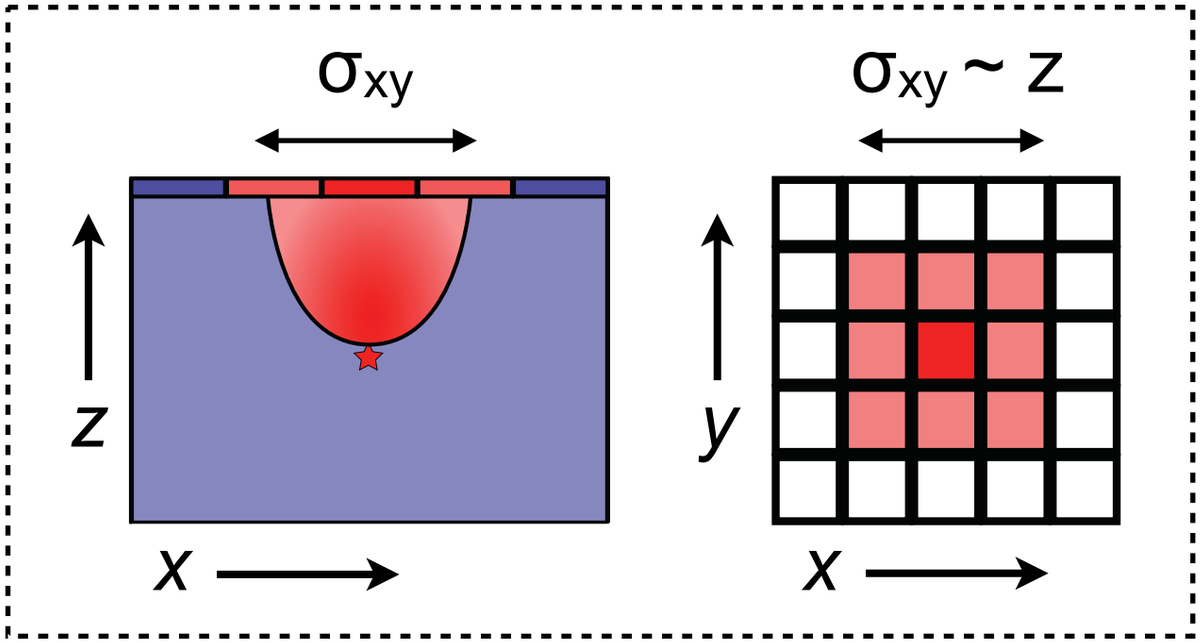
Outline

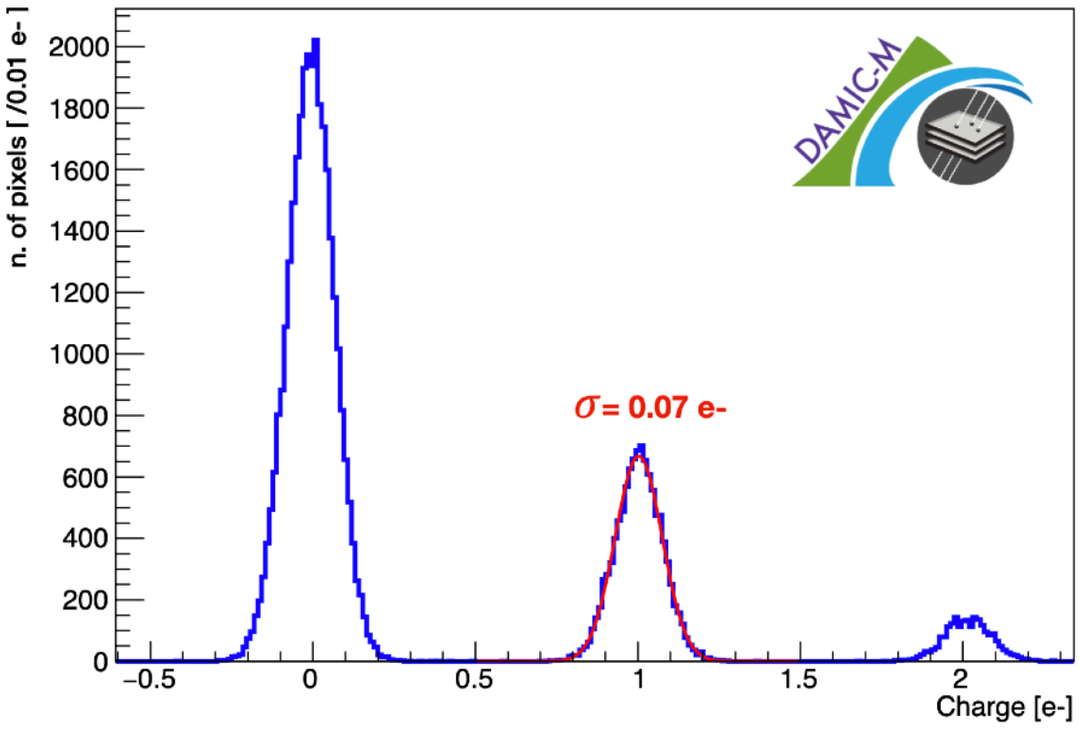
- Highly pixelated solid-state detectors.
- DAMIC and Selena technologies.
- Background identification in DAMIC.
- Signals and backgrounds in Selena.
- Conclusion.

Pixelated solid-state devices





Low noise:



Standard fabrication in semiconductor industry

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

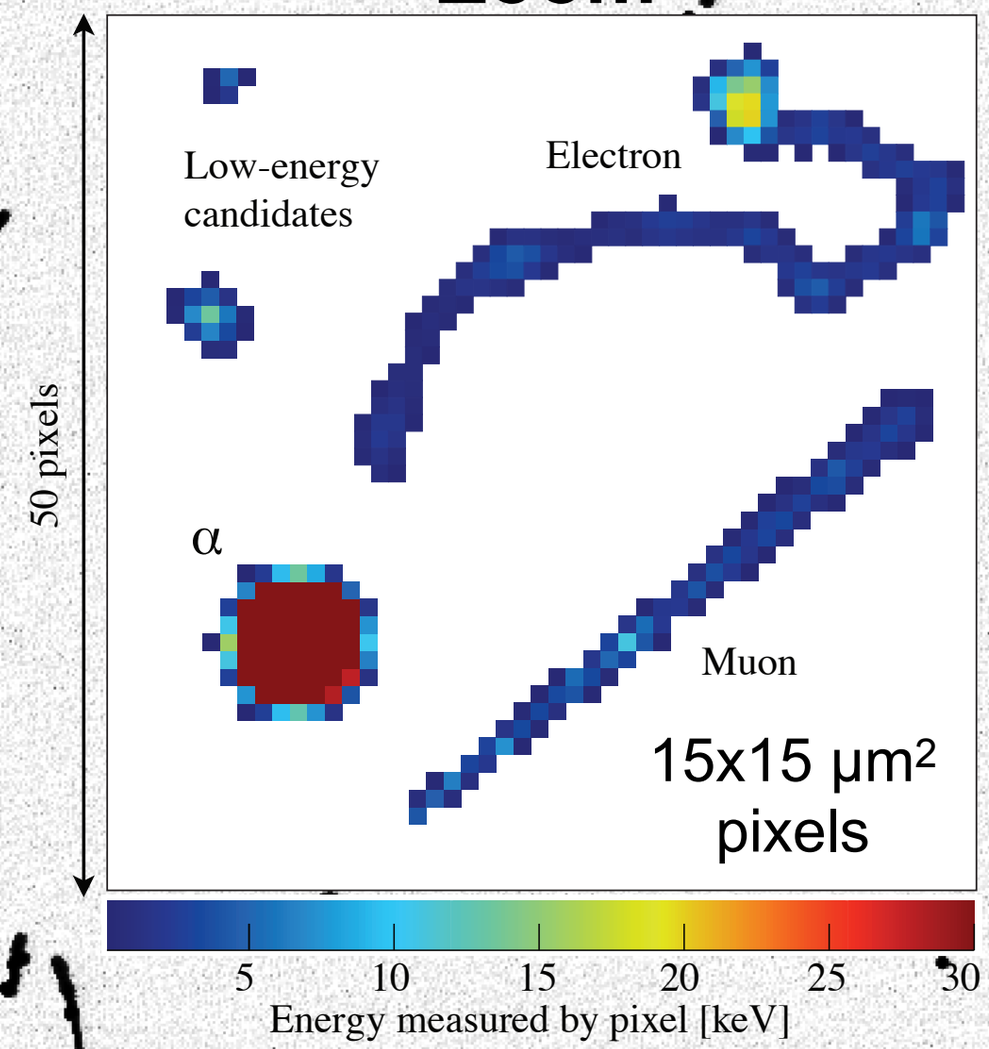
~1 cm

Cosmic muon

Point-like

β particle

Zoom

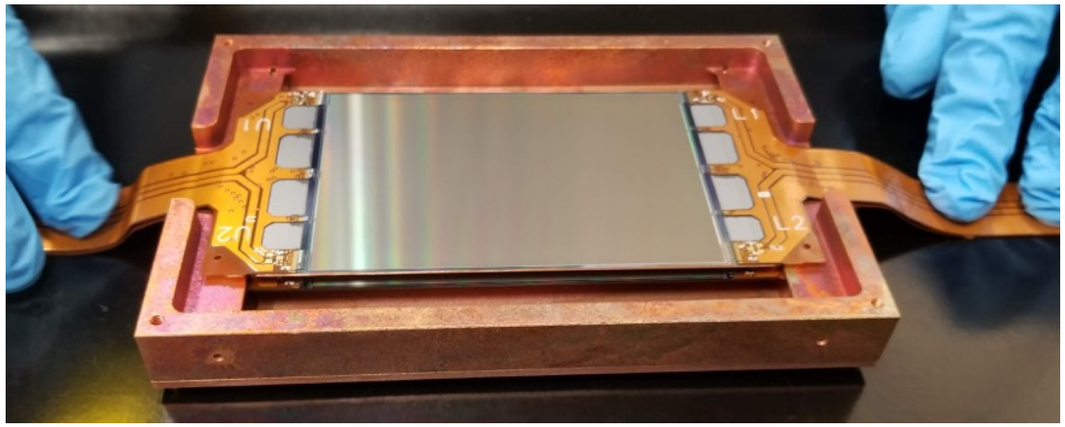


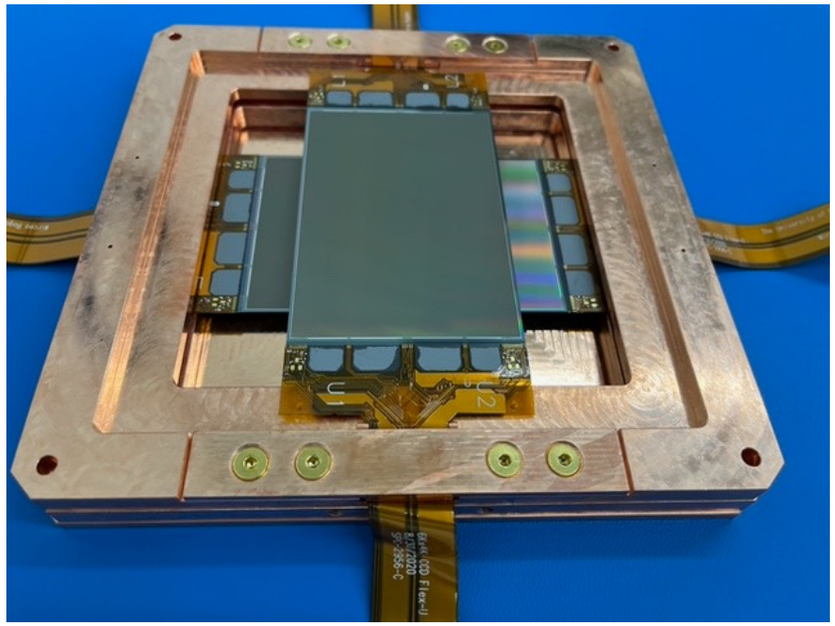
DAMIC

- CCDs for direct dark matter search.
- Multi-CCD array operating at SNOLAB since 2012.
- 50x more sensitive DAMIC-M will start operations at LSM in 2024.

- **DM-e^- interactions:**
  - First DM search results from ~eV ionization signals: **PRL 118 (2017) 141803**
  - Latest DM-e^- scattering results: **PRL 123 181802 (2019)**

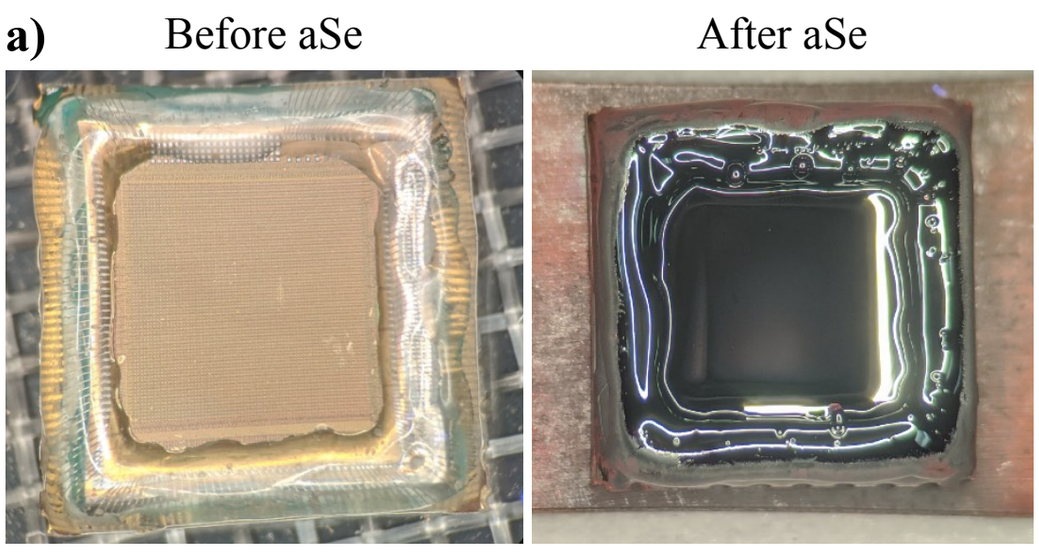
- **WIMP search:** **PRL 125 (2020) 241803** **Full details:** **PRD 105 (2022) 062003**
  - 11 kg-day of data from seven-CCD array.
  - First full background model in CCDs.

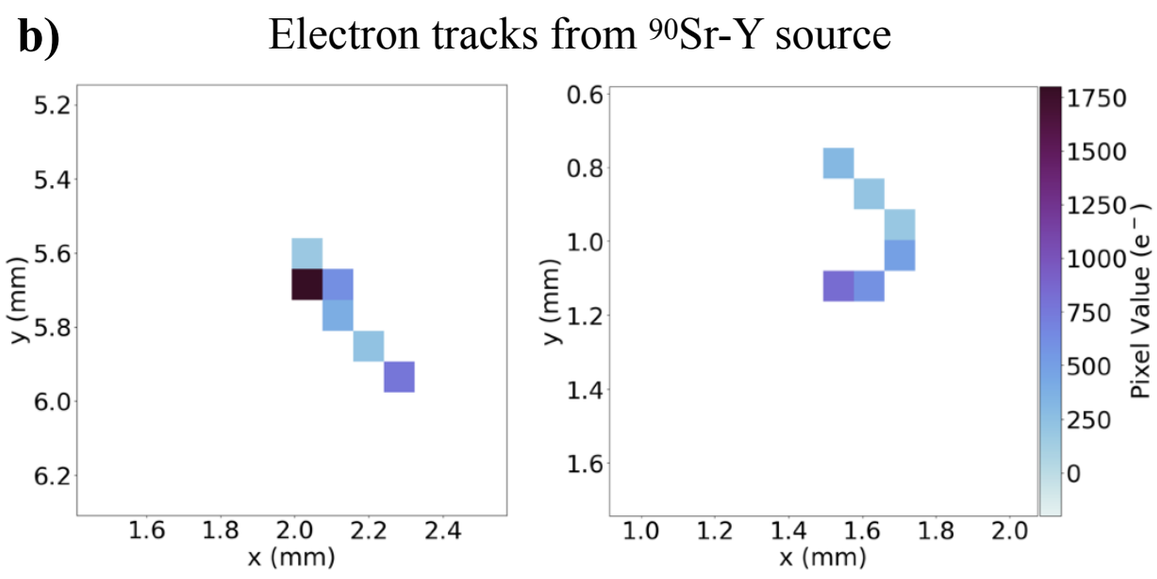




Selena

- 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 (2022)**
- First demonstration of imaging electron tracks in a hybrid CMOS/ aSe device:

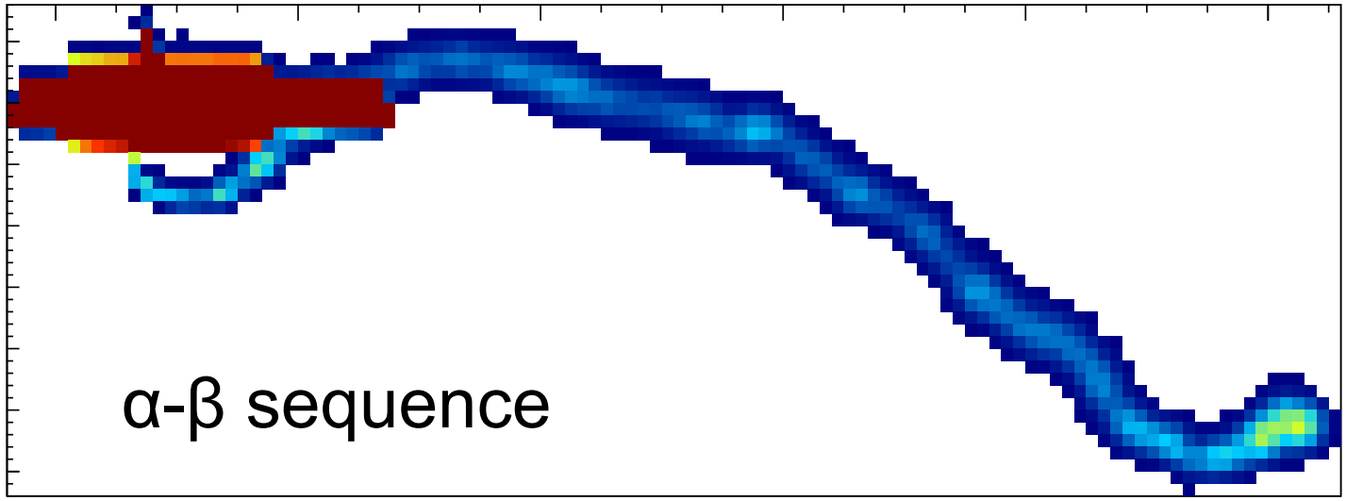




Background suppression

High resolution imaging in a solid-state target provides unique opportunities for signal/background discrimination!

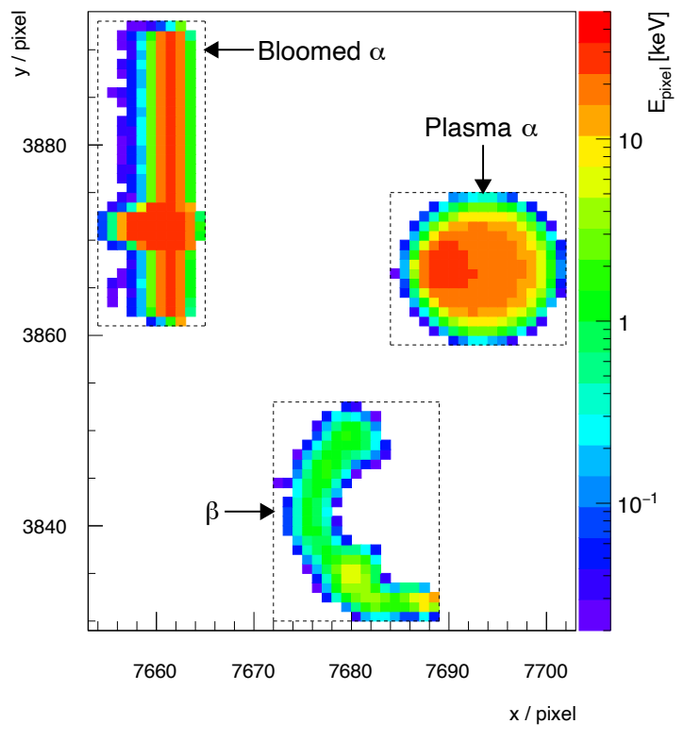
- Determine the number and types of particles (β, α, etc.).
- Determine the end-point of β tracks by identifying the Bragg peak.
- Since atoms remain immobile in the solid target, we can identify radioactive decay sequences with time separations of up to weeks!

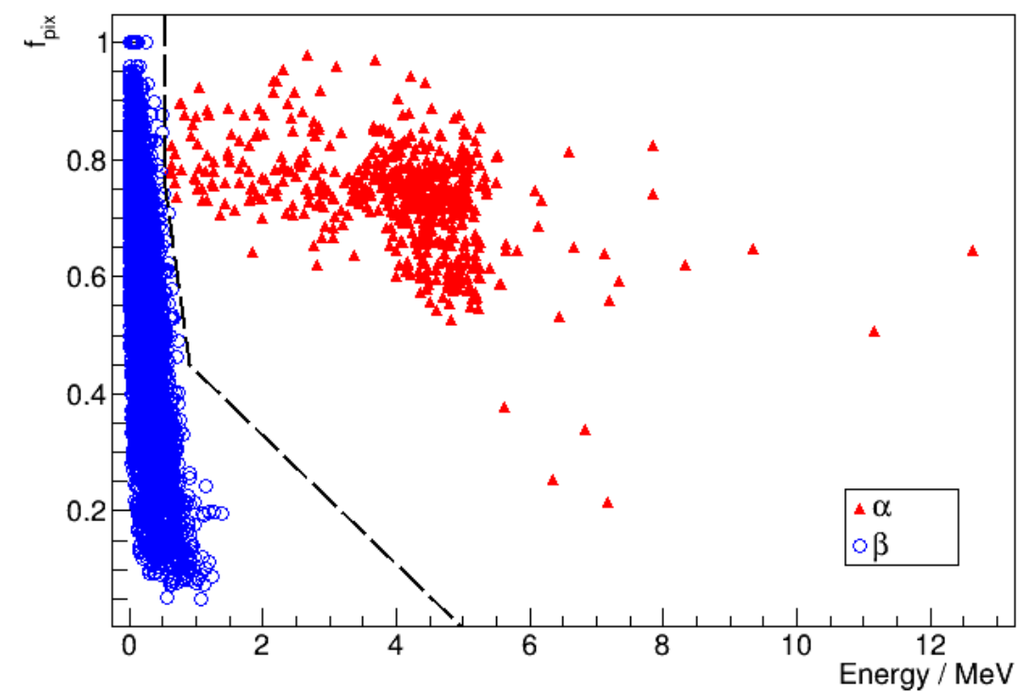


Particle ID in CCDs

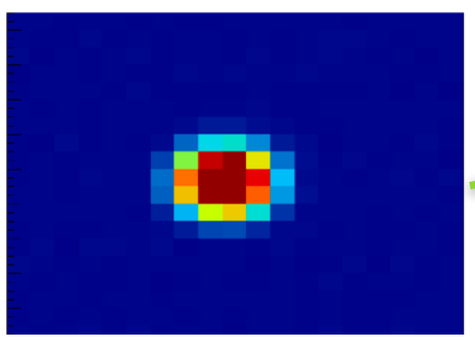
- Based on cluster topology.

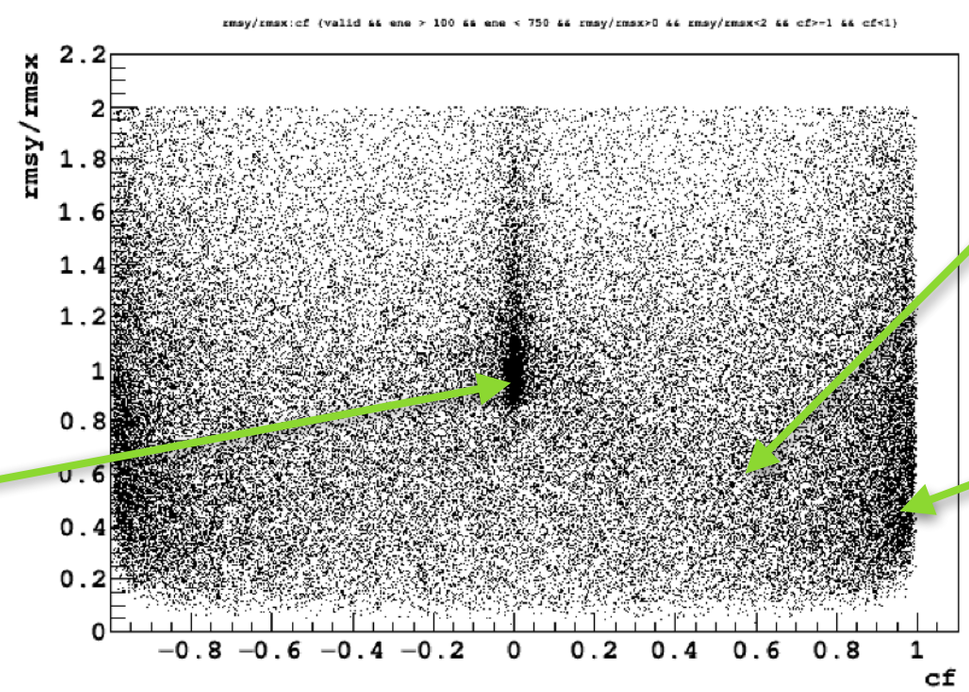
- **α particles:**
- Very high efficiency in selecting αs with E>100 keV$_{ee}$.

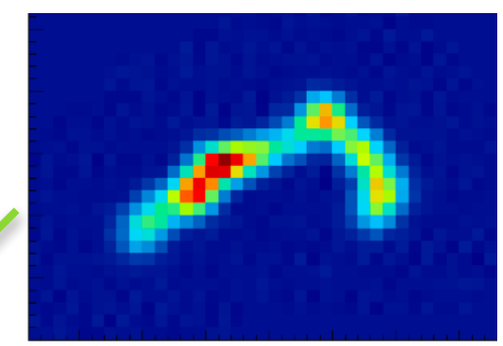


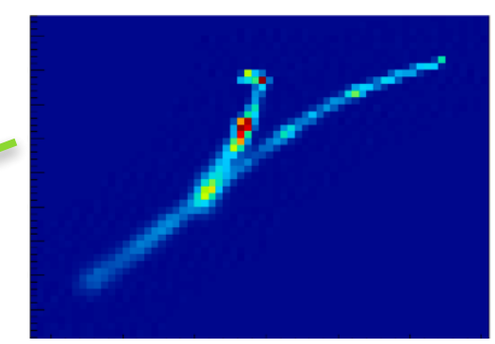


- **Nuclear recoils:**
- Select 95% NR and <1% ER with E>100 keV$_{ee}$.



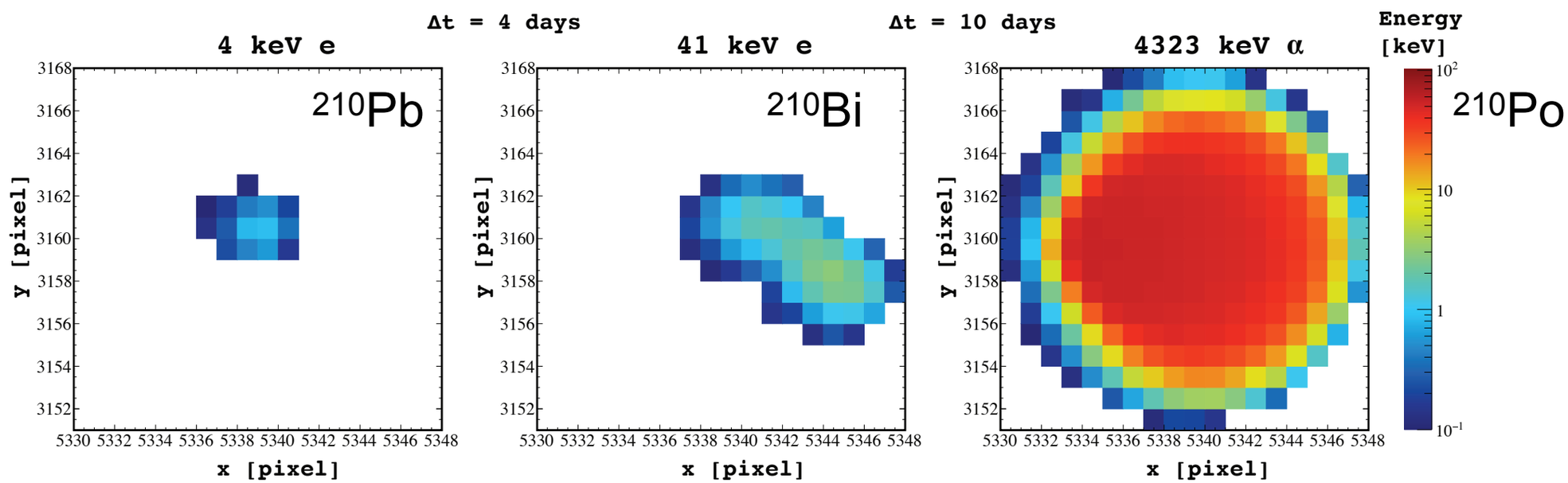






Spatial correlations in DAMIC

- **^{210}Pb surface background:**



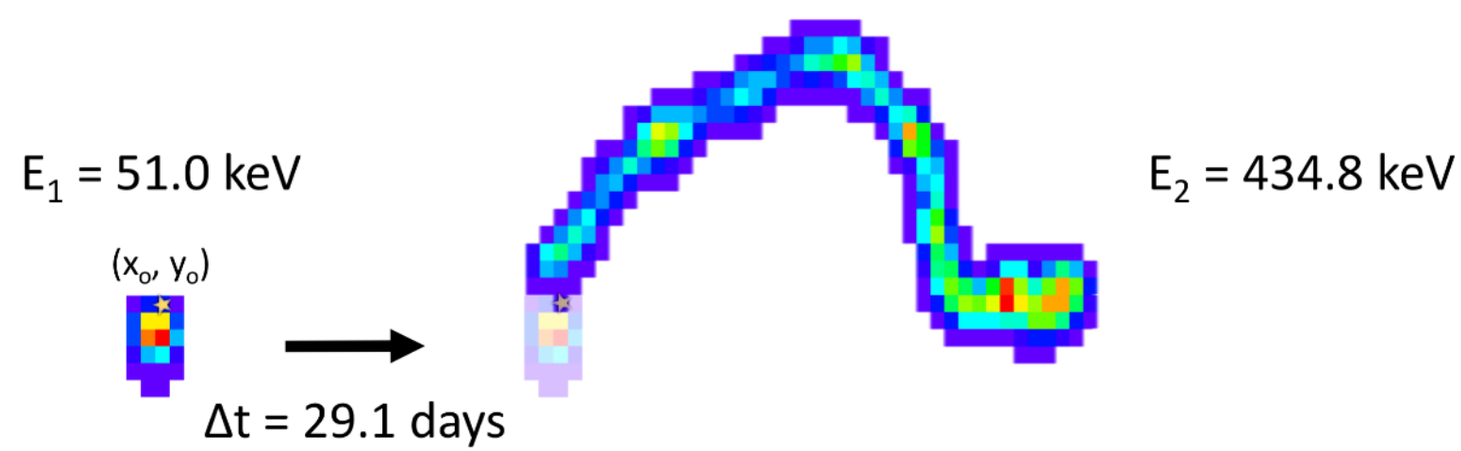
- **Cosmogenic ^{32}Si:**

  Search for spatially correlated β decays.

  Sensitivity with current data is a fraction of Bq/kg.

  JINST16 (2021) P06019

^{32}Si ($T_{1/2}$= 150 y, β) ➔ ^{32}P ($T_{1/2}$= 14 days, β)



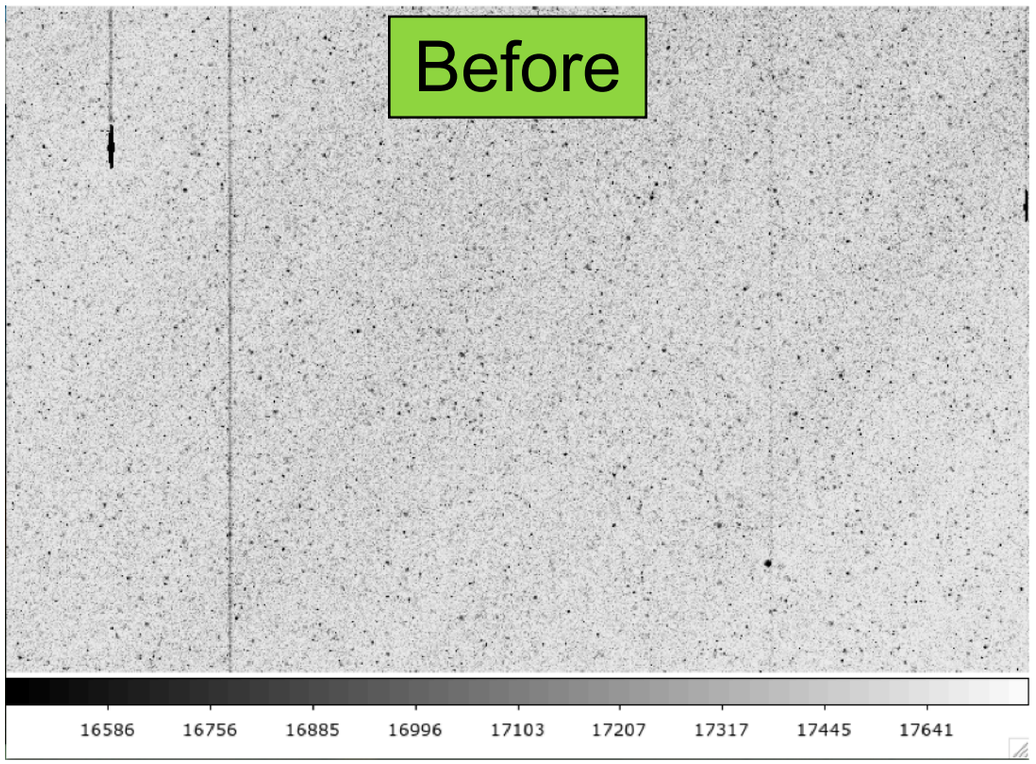
Limits from DAMIC on the U and Th chains from coincidence analysis:

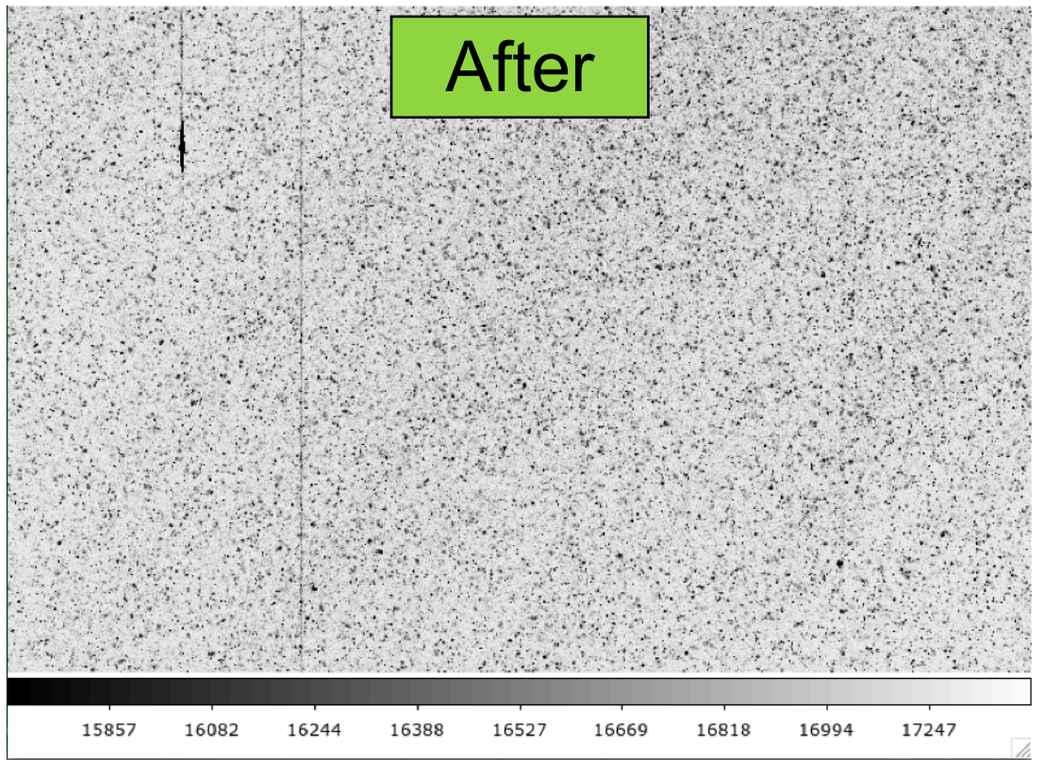
	Decay	$t_{1/2}$	Q value	Search	Energy cut [keV]	Time cut [d]	ϵ	n_{ev}	A [μBq/kg]
^{32}Si Chain									
^{32}Si	β	153 yr	227 keV	$\beta \rightarrow \beta$ (1a)	$70 < E_{\beta 1} < 230$	$\Delta t < 70$	0.279	19.5	140 ± 30
^{32}P	β	14.3 d	1.71 MeV	$\beta \rightarrow \beta$ (1b)	$0.5 < E_{\beta 1} < 70$	$25 < \Delta t < 70$	0.088	12.7	
^{238}U Chain									
^{238}U	α	4.47 Gyr	4.27 MeV	$\alpha \rightarrow \beta$	$3800 < E_{\alpha 1} < 4600$, $E_{\beta 2} > 0.5$	$\Delta t < 120$	0.650	-0.2	< 11
^{234}Th	β	24.1 d	274 keV						
^{234m}Pa	β	1.16 min	2.27 MeV						
^{234}U	α	246 kyr	4.86 MeV	^{238}U (s.e.)					
^{230}Th	α	75.4 kyr	4.77 MeV						no limit
^{226}Ra	α	1.60 kyr	4.87 MeV						< 5.3
^{222}Rn	α	3.82 d	5.59 MeV	$(\alpha + \alpha + \alpha)$ OR $(\alpha + \alpha) \rightarrow \beta/\alpha$	$E_{\alpha} > 15000$, $E_{\alpha 1} > 10000$	$\Delta t = 0$, $\Delta t = t_{exp}$	~ 1	0	
^{218}Po	α	3.10 min	6.11 MeV						
^{214}Pb	β	27.1 min	1.02 MeV						
^{214}Bi	β	19.9 min	3.27 MeV						
^{214}Po	α	164 μs	7.83 MeV						
^{210}Pb	β	22.2 yr	63.5 keV	$\beta \rightarrow \beta$ (2)	$0.5 < E_{\beta 1} < 70$	$\Delta t < 25$	0.734	47.1	< 160
^{210}Bi	β	5.01 d	1.16 MeV						
^{210}Po	α	138 d	5.41 MeV						
^{232}Th Chain									
^{232}Th	α	14.0 Gyr	4.08 MeV	^{228}Th (s.e.)					< 7.3
^{228}Ra	β	5.75 yr	45.5 keV	$\beta \rightarrow \beta$ (3)	$0.5 < E_{\beta 1} < 55$	$\Delta t < 1.3$	0.440	2.6	< 40
^{228}Ac	β	6.15 hr	2.12 MeV						
^{228}Th	α	1.91 yr	5.52 MeV	$\alpha \rightarrow (\alpha + \alpha)$	$E_{\alpha 2} > 10000$	$\Delta t = t_{exp}$	0.727	0	< 7.3
^{224}Ra	α	3.63 d	5.79 MeV						
^{220}Rn	α	55.6 s	6.40 MeV						
^{216}Po	α	145 ms	6.91 MeV						
^{212}Pb	β	10.6 hr	569 keV						
...									

JINST16 (2021) P06019

NR ID by spatial correlations

- Record ionization events at nominal operating T ~ 120 K.
- Warm up CCD.
- Identify defects (“hot spots” from leakage current) during warmup.
- Correlate them!
- *Preliminary*: >80% of of NR with E>100 keV_{ee} produce a measurable defect (generates >10 e^- per min).
- Investigating how much it improves NR/ER discrimination.

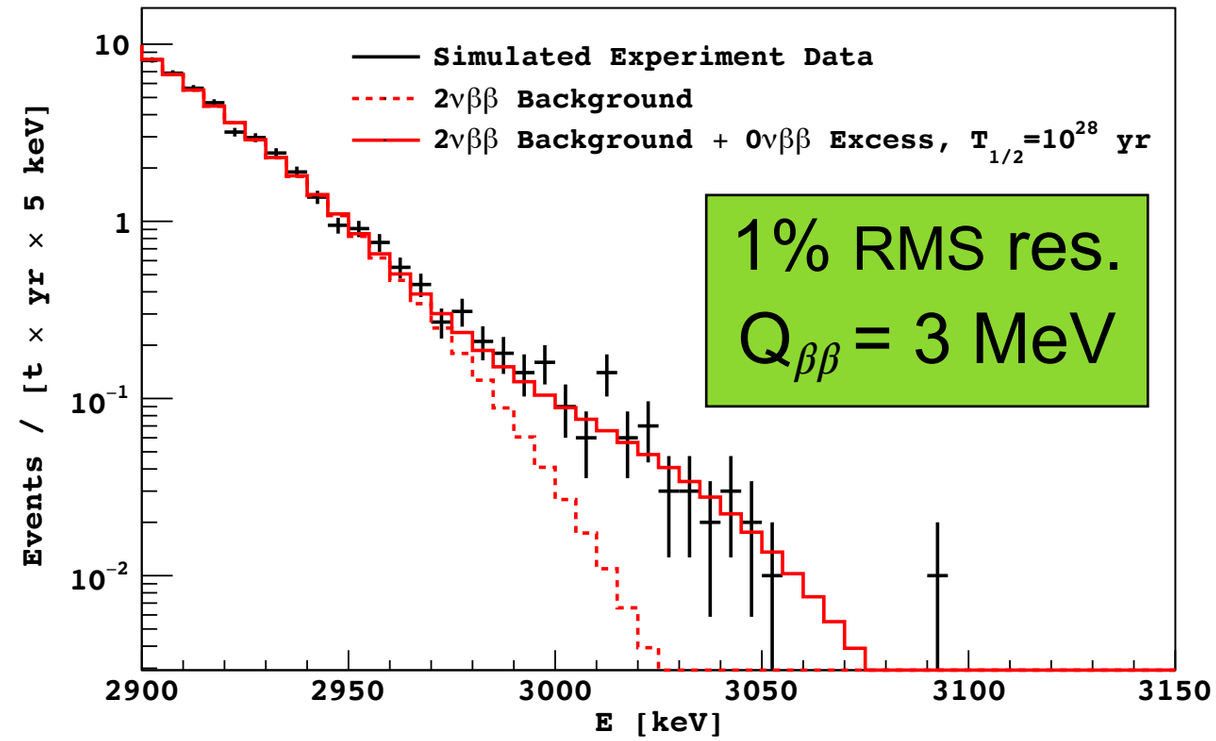




Selena $\beta\beta$

JINST16 (2021) P06018

- By identification of Bragg peak we can achieve 10^{-3} suppression of single electron background, with 50% signal acceptance.
- Bulk backgrounds suppressed by α/β particle ID, spatial correlations.



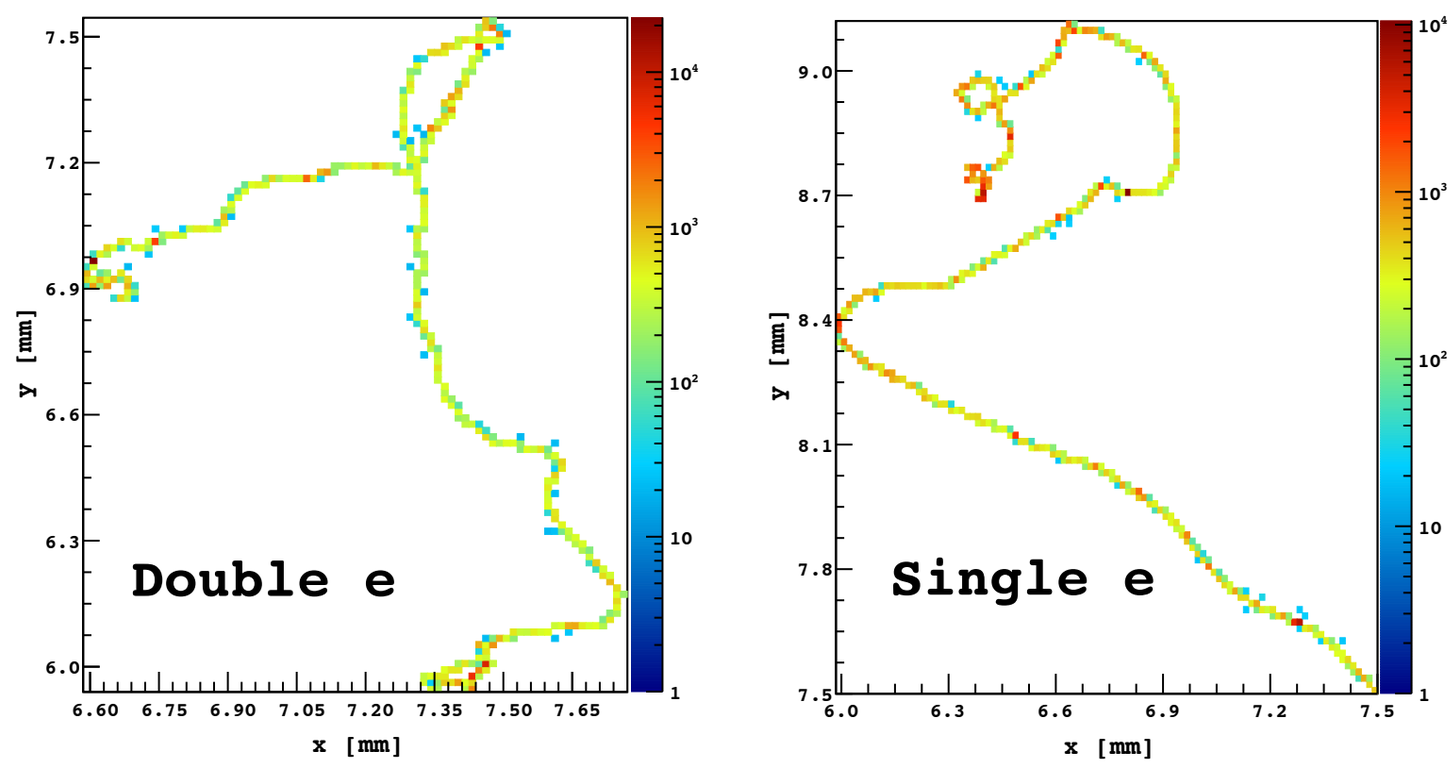
Background rate <6 x 10^{-5} /keV/ton/year!

JINST12 (2017) P03022

$T_{1/2}$ > **10^{28} years** limit on ^{82}Se $0\nu\beta\beta$

- Pixel size 15 μm^2 and few mm thick aSe.

Simulation:



$\beta\beta$ backgrounds

Background source	Raw rate / (keV ton y)$^{-1}$	After disc.
β-decay (bulk)	5.8	6.4×10^{-8}
β-decay (surface)	7.1	2.1×10^{-7}
β-decay (cosmogenic)	1.7×10^{-3}	2.6×10^{-6}
γ-ray (photoelectric)	1.3×10^{-2}	1.3×10^{-5}
γ-ray (Compton)	2.8×10^{-2}	7.1×10^{-6}
γ-ray (pair production)	3.3×10^{-5}	3.3×10^{-6}

JINST12 (2017) P03022

Background challenges very different from other experiments

- **Example U+Th γ:**

^{214}Bi

3000.0 *2*	0.0086 % *9*
3053.9 *2*	0.0209 % *23*
3081.79 *25*	0.0059 % *18*
3094.0 *4*	5.9E-4 % *18*
3142.6 *4*	0.00123 % *14*
3149.0 *5*	8.6E-5 % *9*
3160.7 *6*	5.5E-4 % *14*
3183.6 *4*	0.00136 % *23*

← Photoelectric absorption

^{208}Tl

3475.1	0.0015 % *15*
3708.4	0.0020 % *20*
3960.9	0.0015 % *15*

← Compton scattering

U+Th γ rays contribute <1 background in ROI every 10^9 decays (<1 in 100 ton year at 10 ppt)

ν_e detection

Triple sequence:

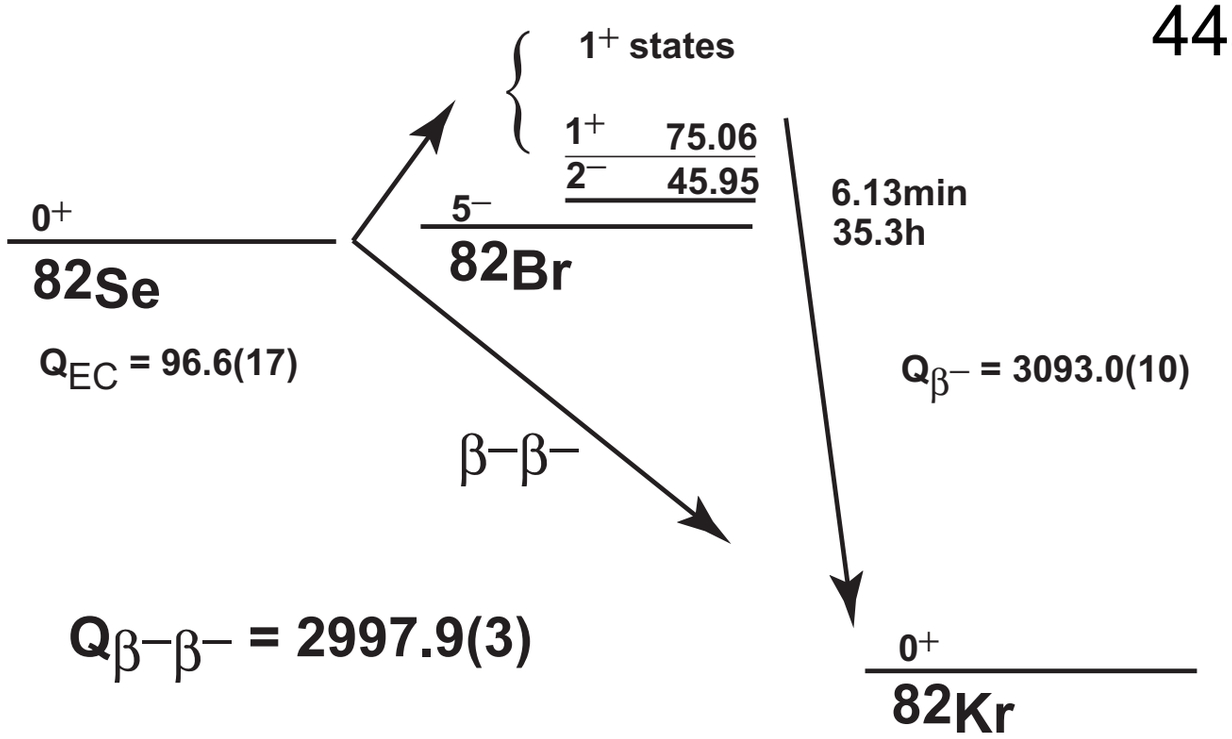
E_ν – 172 keV

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

${}^{82}Br^* \longrightarrow {}^{82}Br + C.E.\ (46\ keV)$ $\tau_{1/2}$ = 6.1 min

${}^{82}Br \longrightarrow {}^{82}Kr + \gamma + \beta^-$ $\tau_{1/2}$ = 35 hours

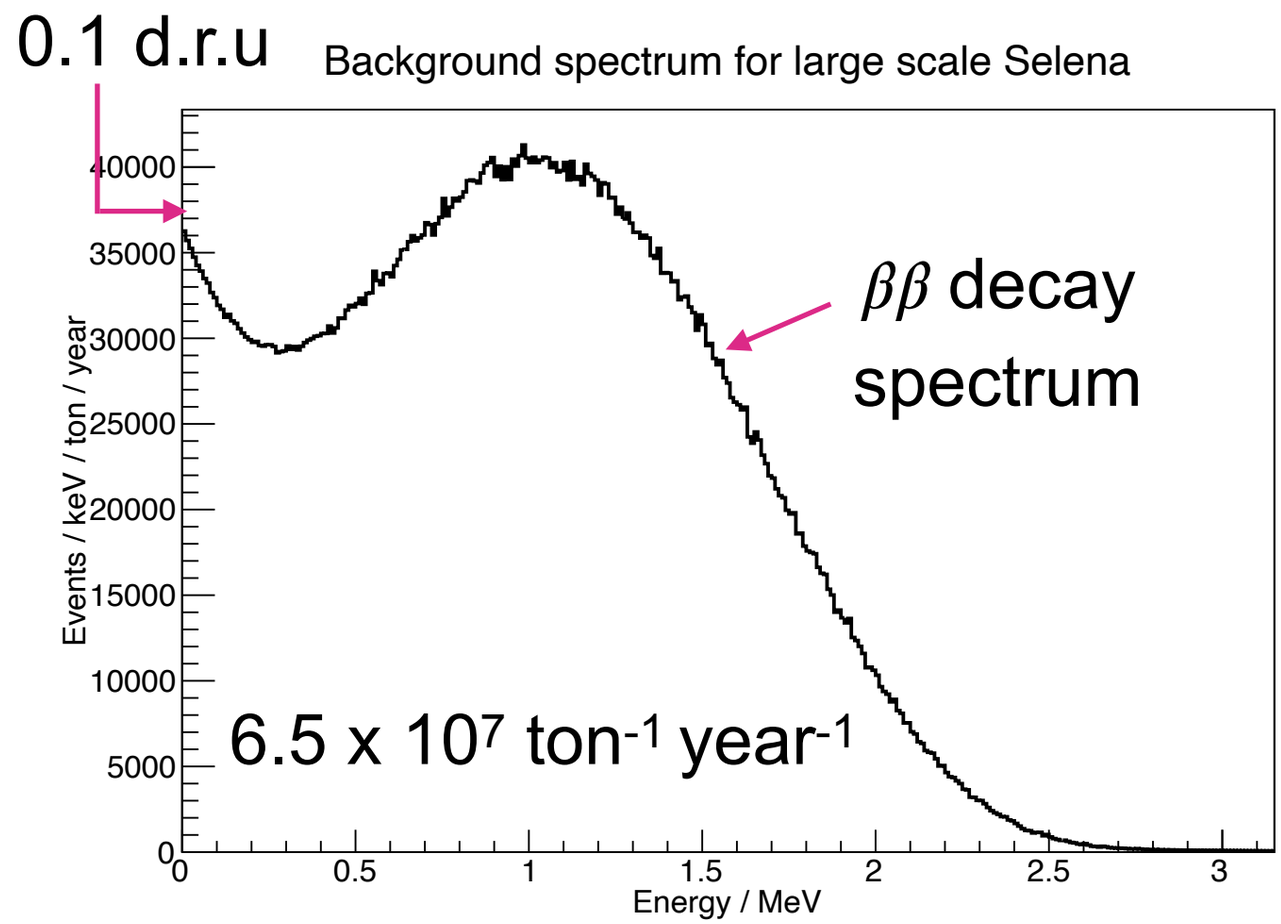
445 keV end-point



We can use the prompt events to perform solar ν spectroscopy!

ν_e backgrounds

- Expected number of three accidental events in 100 μm^2 (22 µg) is **<10^{-4} in 100 ton year**.
- Other α, *p*, or *n* reactions that make ^{82}Br* have a different prompt event topology.
- No cosmogenic isotope starts a decay chain that mimics the triple sequence.



- Some neutron captures on Se isotopes can give triple sequences but their event topologies are also very different.

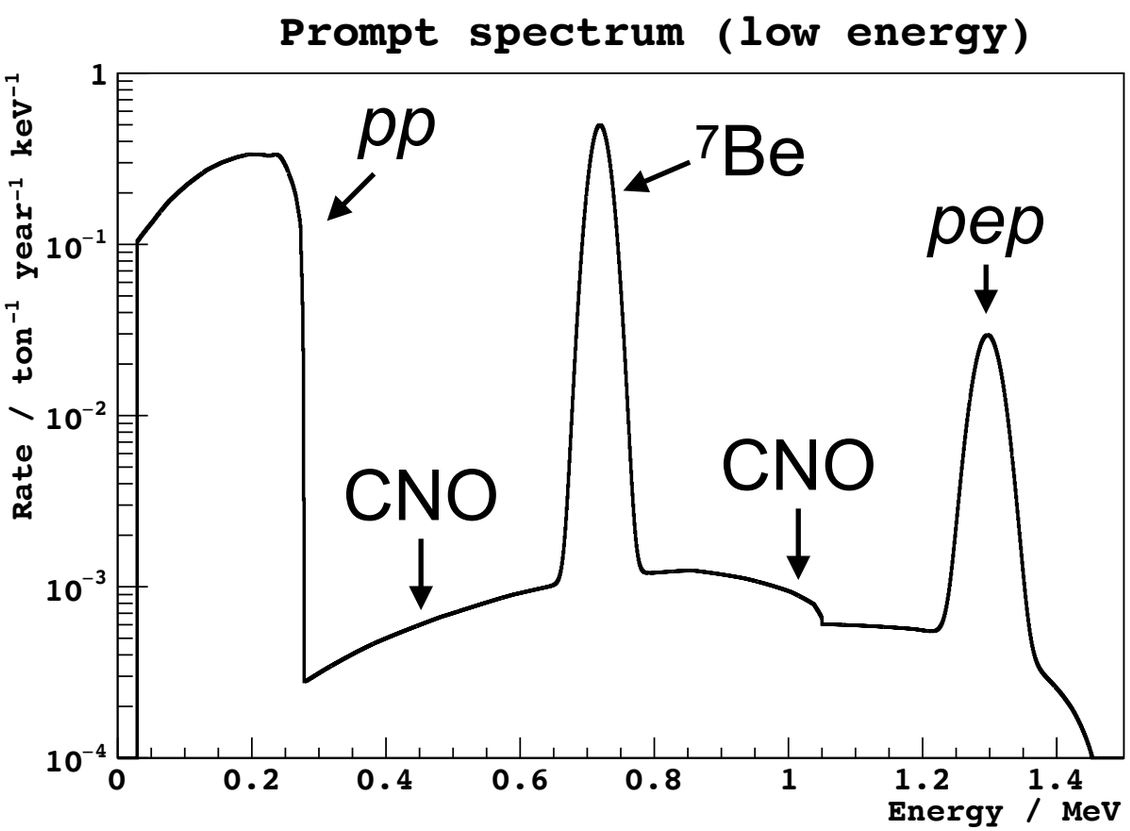
No identified background to mimic the triple sequence.
Possibility of zero background υ spectroscopy!

Solar ν spectrum

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

$\uparrow$

$E_\nu - 172$ keV



Constraints on solar luminosity, solar metallicity, solar core temperature, onset of matter effects in ν oscillations, etc.

100 ton-year

Species	E range (keV)	N	$1/\sqrt{N}$
pp	29 - 278	6170	**1.3%**
^{7}Be	665 - 775	1850	**2.3%**
pep	1230 - 1360	151	**8.1%**
CNO	278 - 655 785 - 1220	63	**12.6%**
^{8}B	(1.5 - 15) x 10^3	209	**6.9%**

Conclusions

- High spatial resolution of DAMIC CCDs provide unique capabilities in particle ID.
- Cluster topology to identify αs, βs and NR with high efficiency.
- Constraints on the activities of the ^{32}Si, ^{238}U and ^{232}Th decay chains by coincidence analysis.
- Possible significant improvement in NR by spatial coincidence analysis with lattice defects.
- Particle ID capabilities can be extended to hybrid aSe/CMOS devices proposed for the Selena experiment.
- Selena may be able to perform background-free $\beta\beta$ decay and solar ν spectroscopy in 100 ton-year exposure.