Pb-210 measurements in DAMIC

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Kick off meetging: Assay Pb-210 in Water
23 October 2018, UNAM

Measure ^{32}Si and ^{210}Pb in DAMIC

^{32}Si and ^{210}Pb are expected to be present at some level in the DAMIC CCDs. They could limit the experiment's sensitivity to Dark Matter.

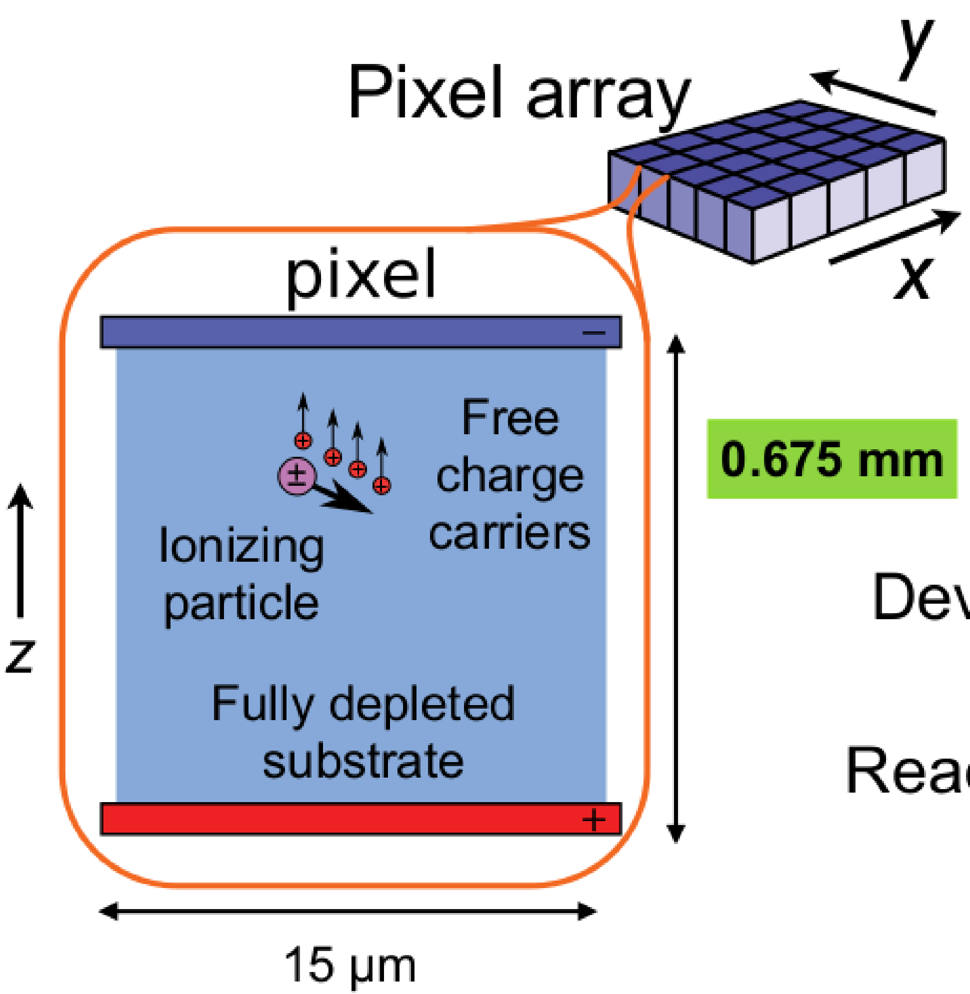
Due to their long half-lives and small concentrations they are hard to be screened by other techniques.

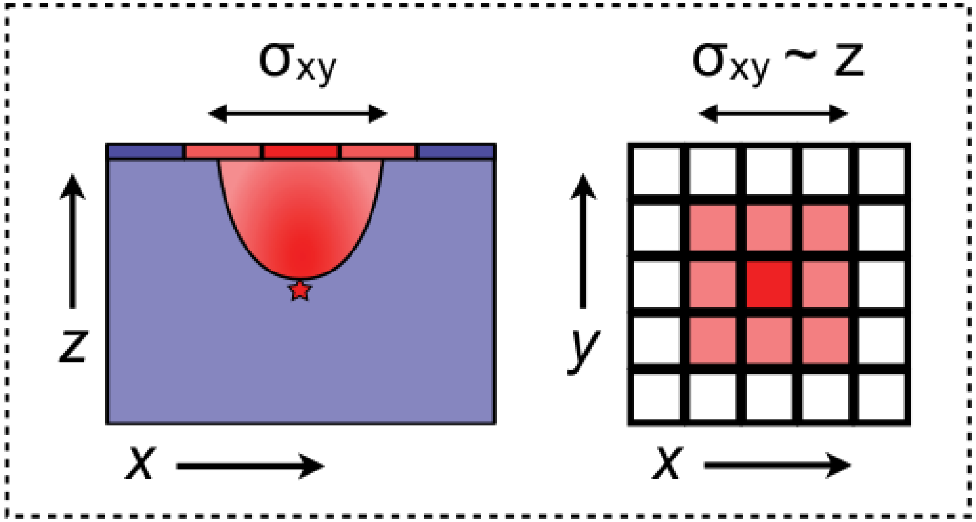
DAMIC setup makes it possible to study the ^{32}Si and ^{210}Pb decay decays with spatial coincidences.

Alpha spectroscopy also allows to have a handle on the concentration of ^{210}Pb.

JINST, 10, P08015 (2015)

Charge Coupled Device



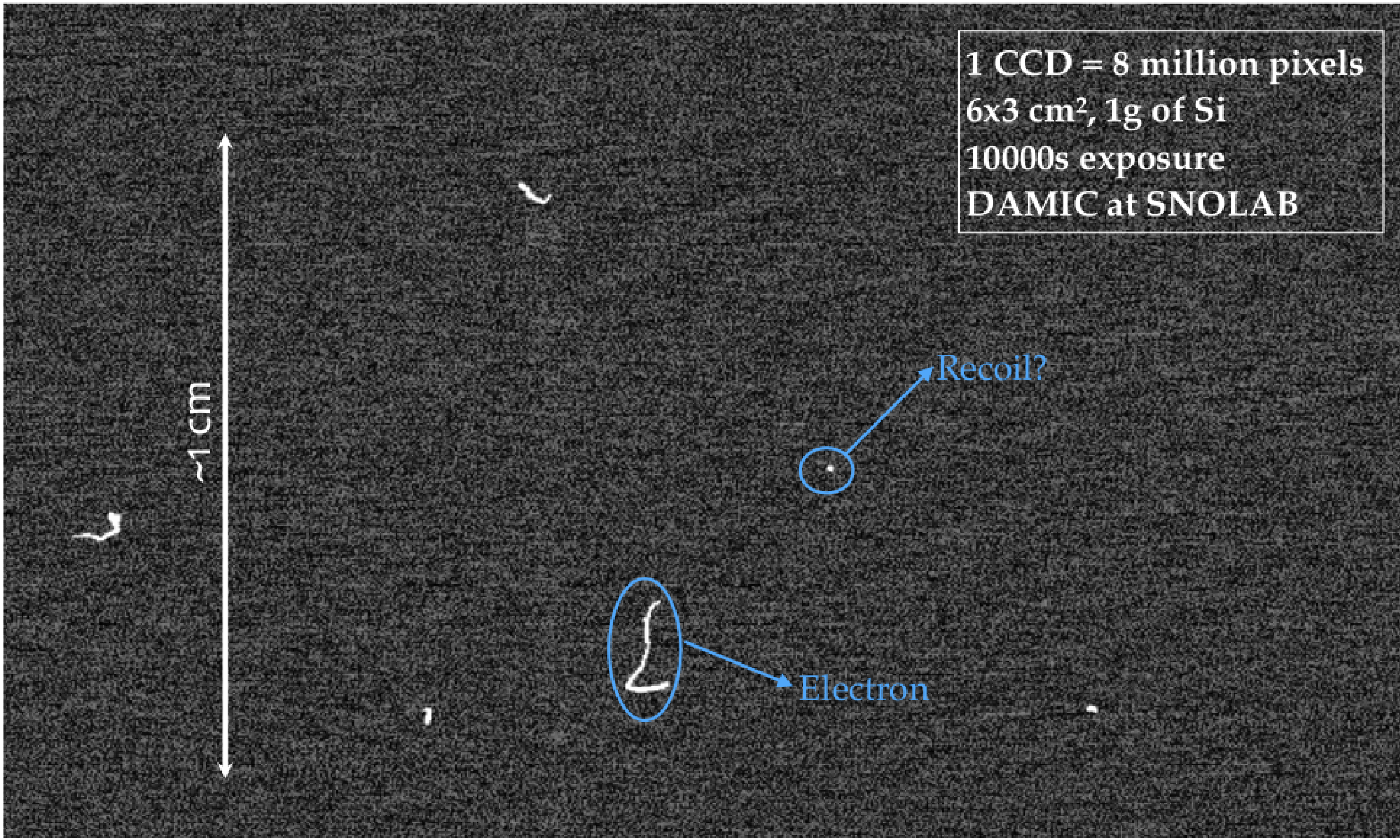


Device is “exposed,” collecting charge until user commands readout.

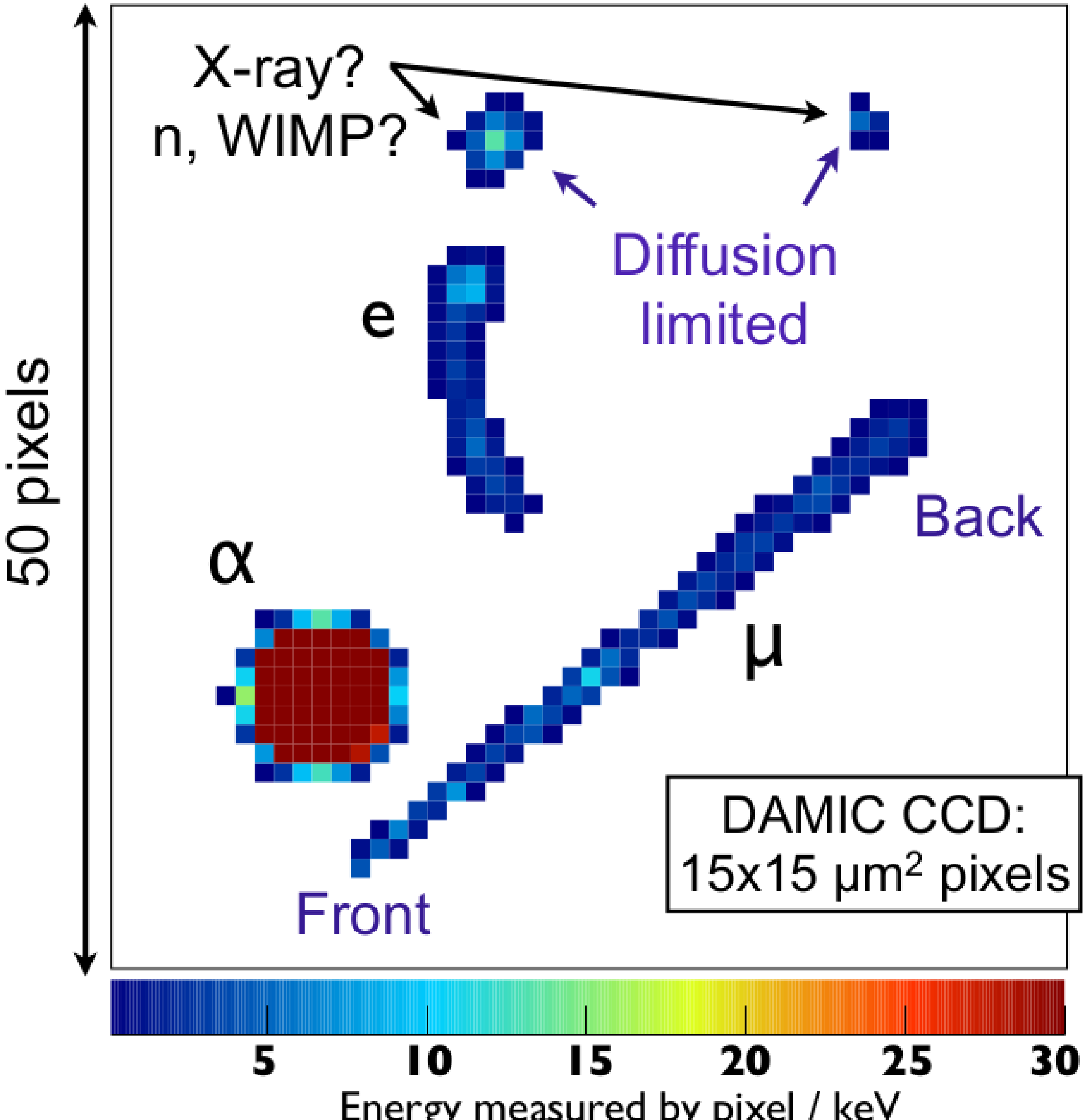
Readout can be slow / non-destructive : **very low noise (few e-).**

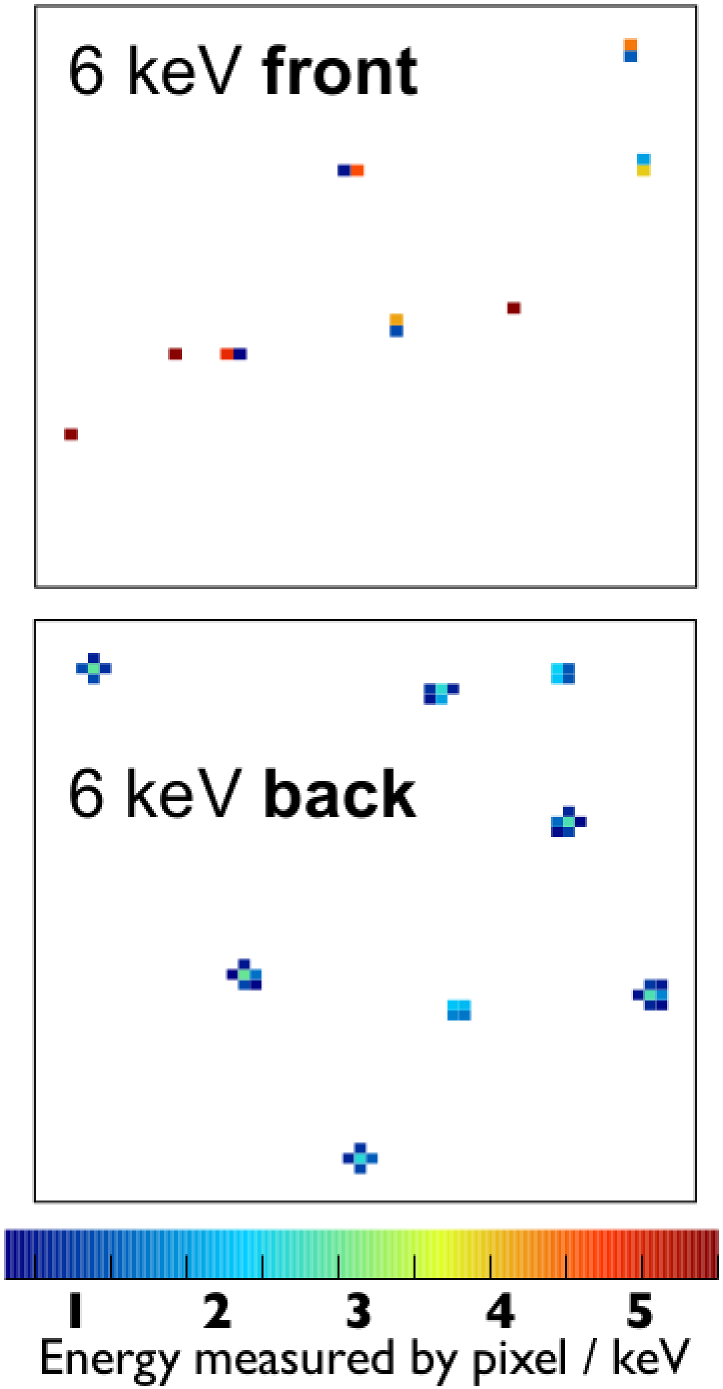
Silicon band-gap: 1.2 eV.
Mean energy for 1 e-h pair: 3.8 eV.

Typical CCD image

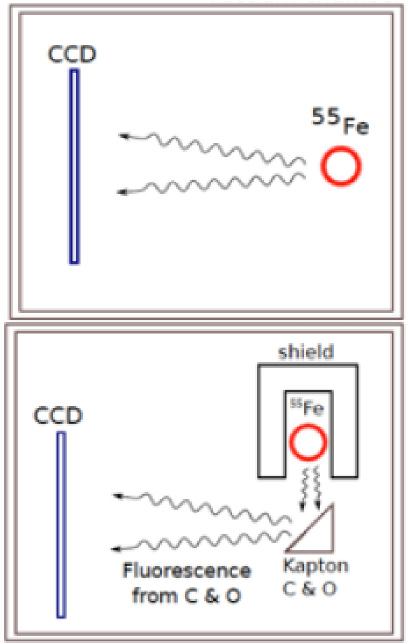


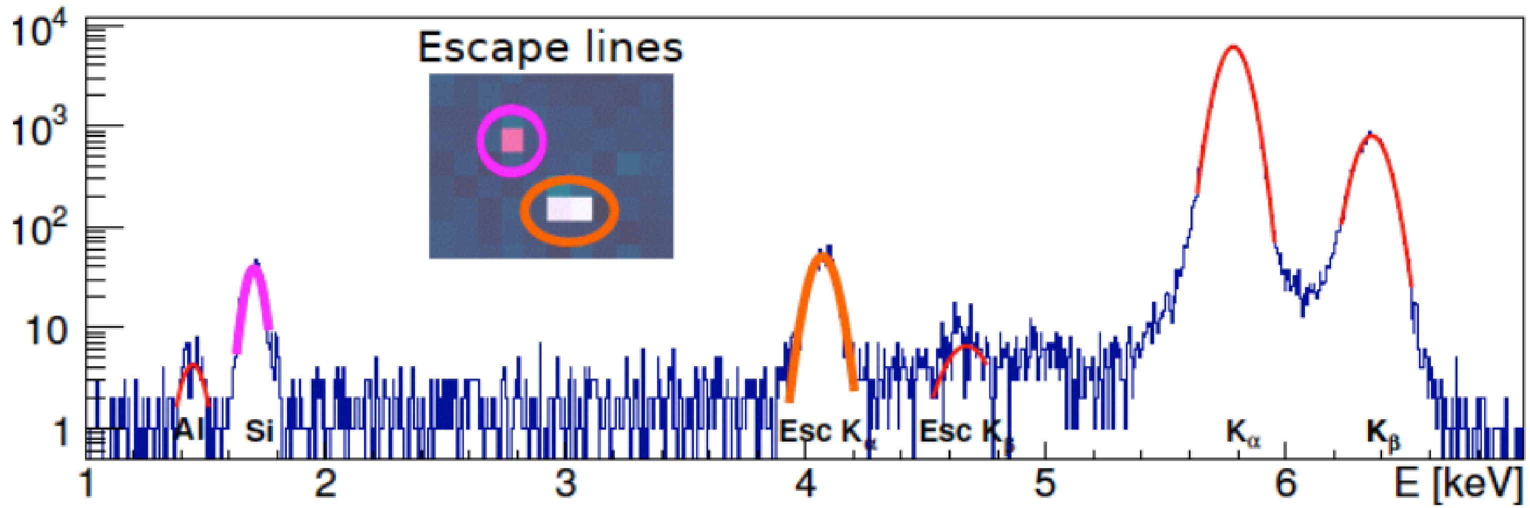
Particle Tracks



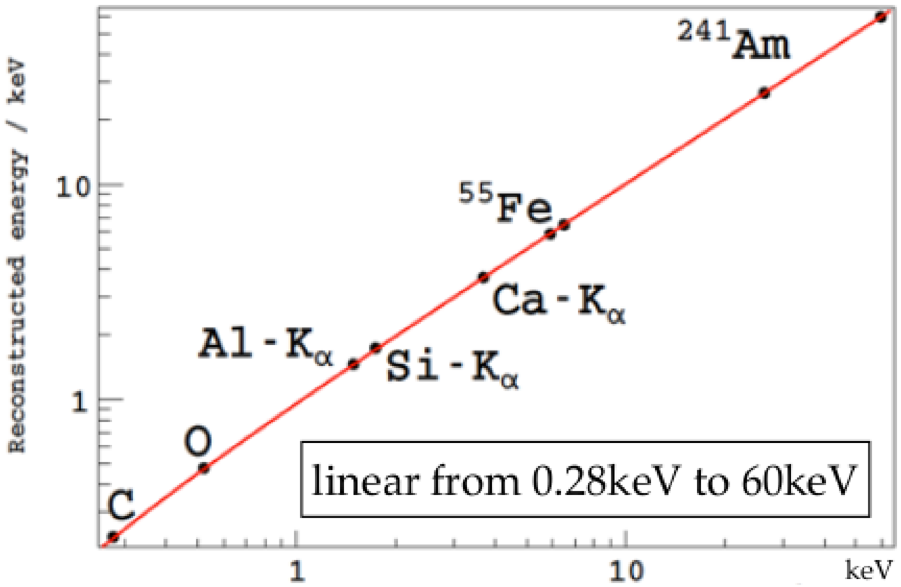


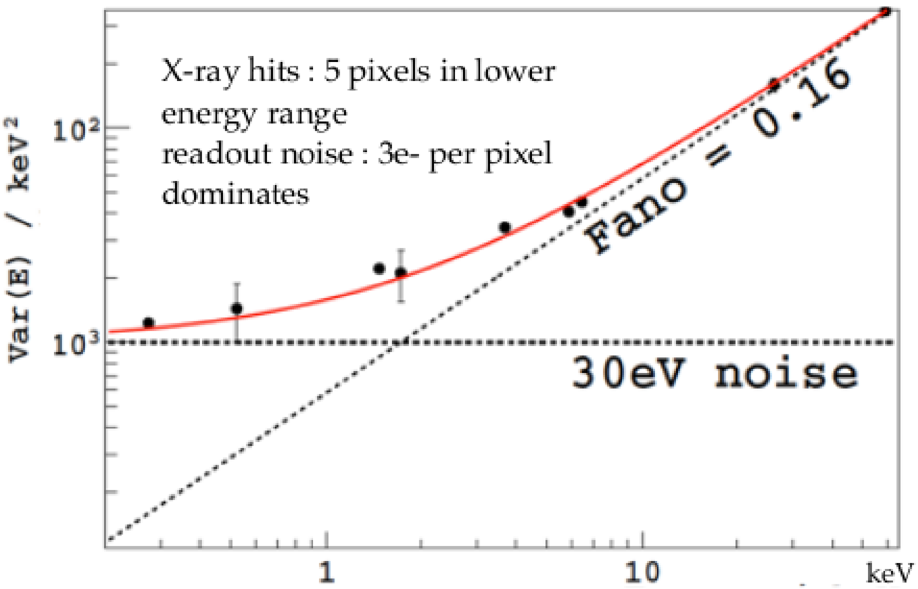
Calibration





X-rays can be used to calibrate the CCDs

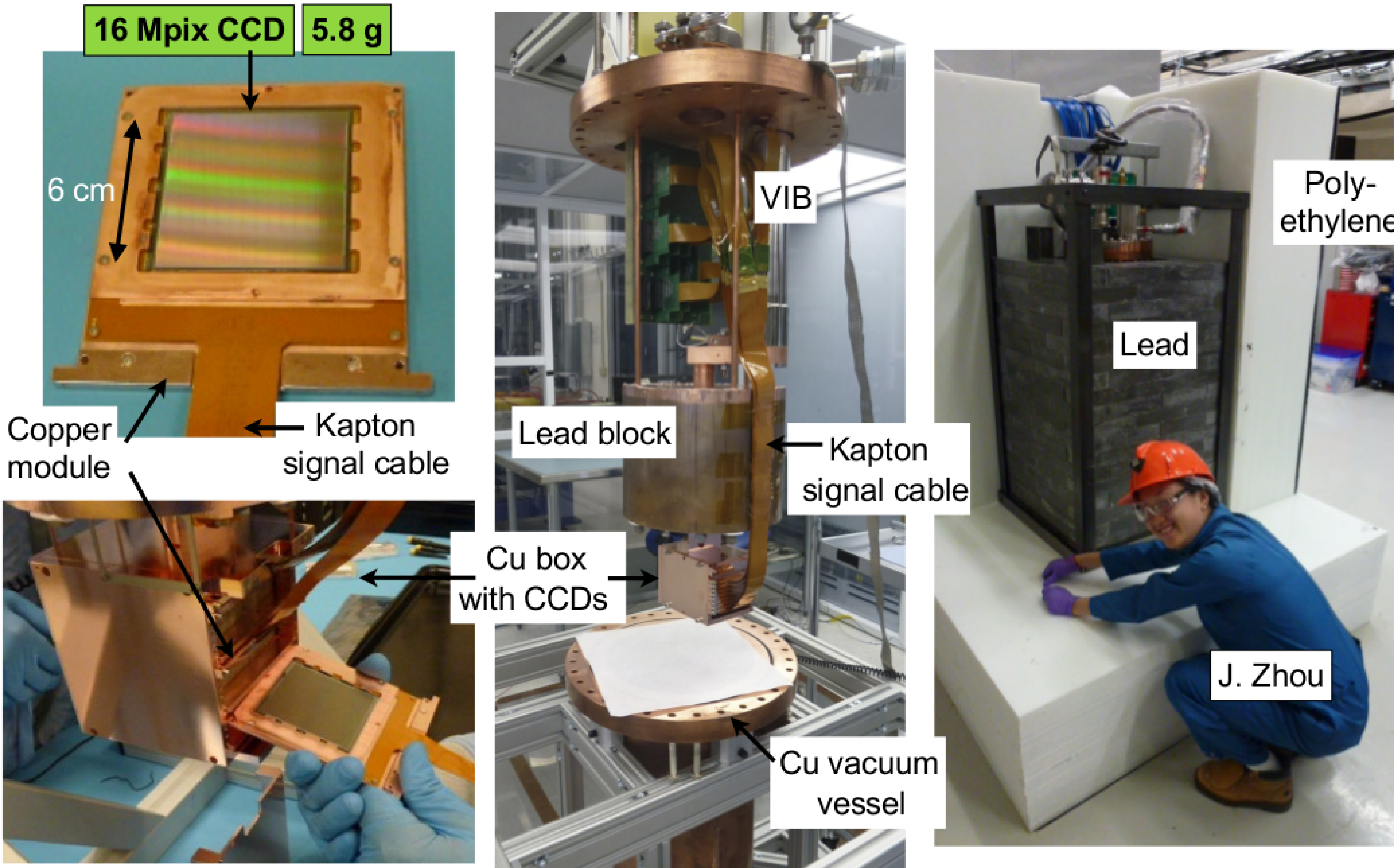




2 km underground

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

SNOLAB Installation

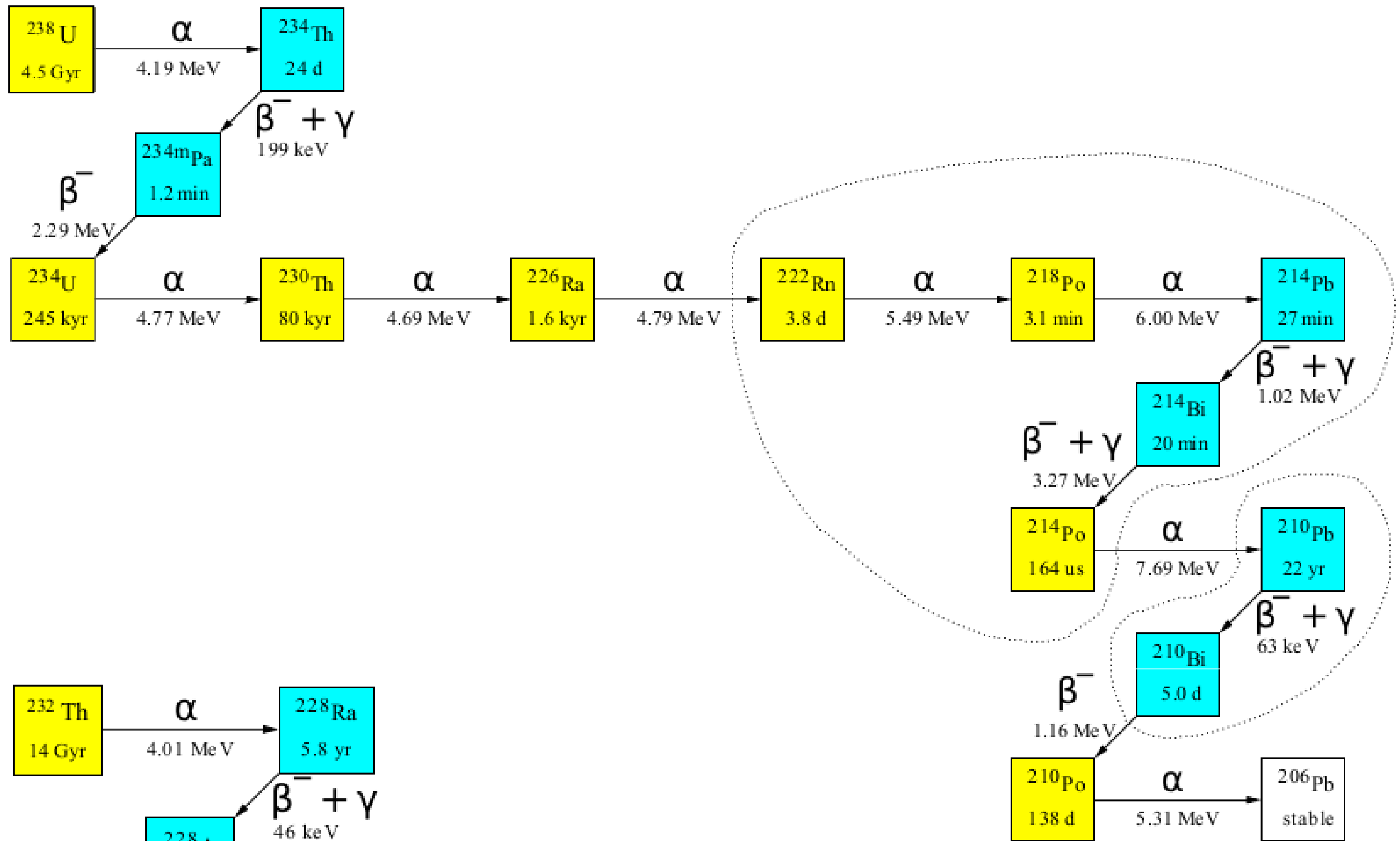


^{32}Si and ^{210}Pb

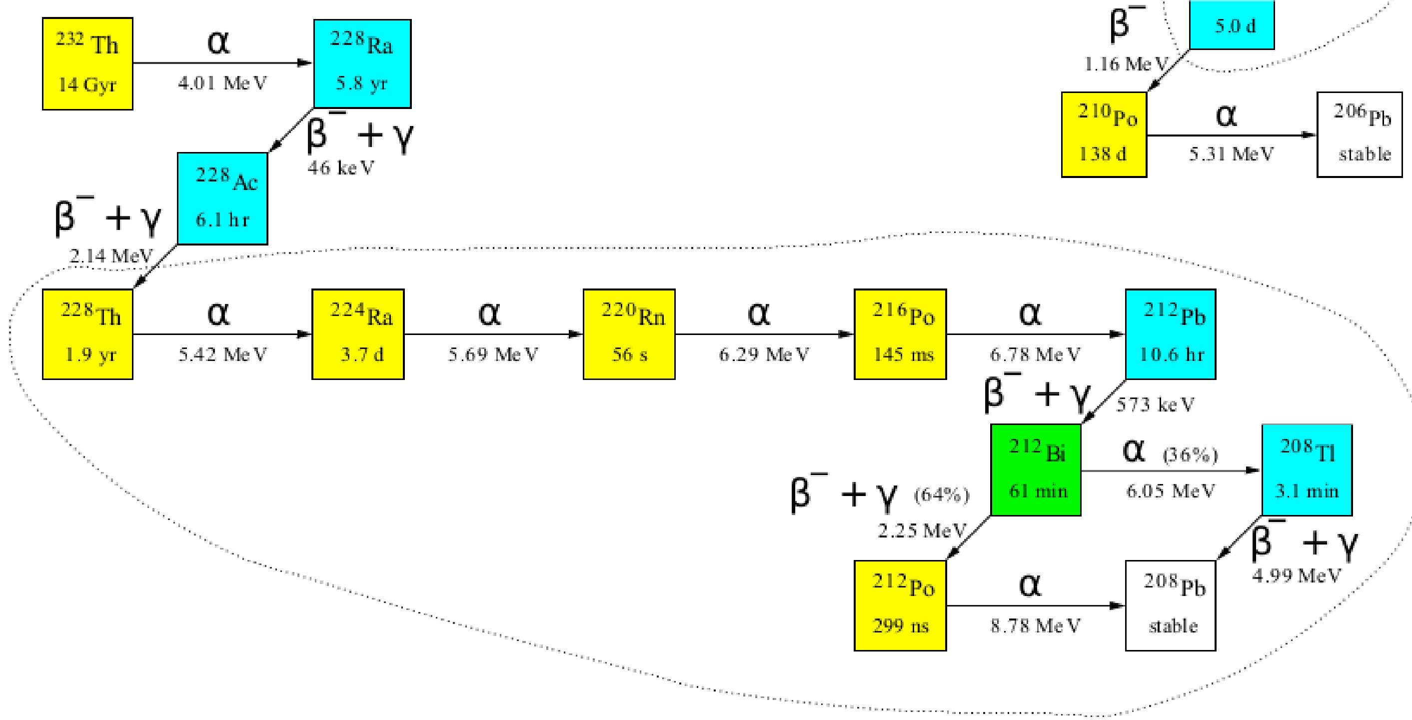
^{32}Si is produced by cosmic ray spallation of argon in the atmosphere, and then transported to the Earth's surface, mainly by rain and snow. Si content of a silicon detector should be close to its natural abundance in the raw silica.

^{210}Pb is a member of the ^{238}U decay chain. It is often found out of secular equilibrium, as chemical processes in the manufacture of materials separate it from other ^{238}U daughters. It may also remain as a long-term surface contaminant following exposure to environmental ^{222}Rn.

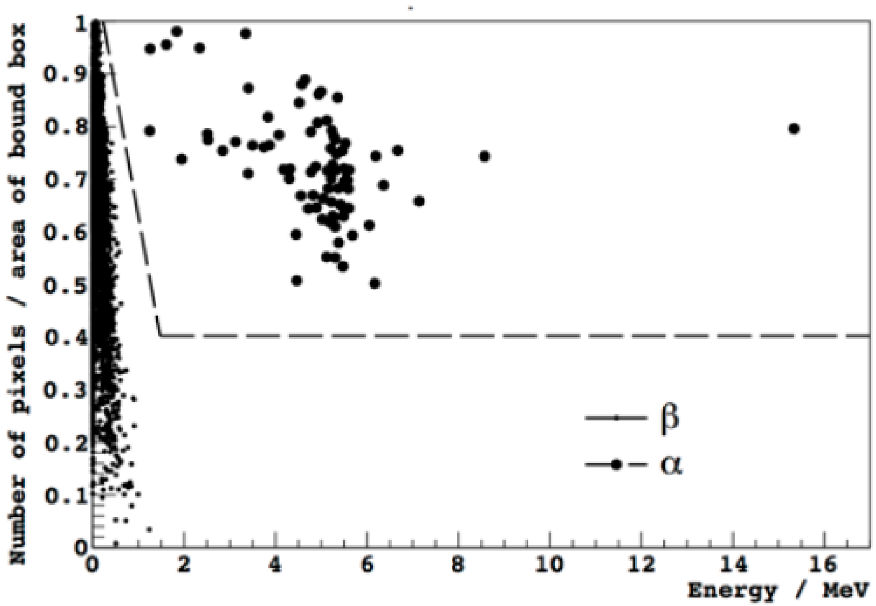
^{238}U

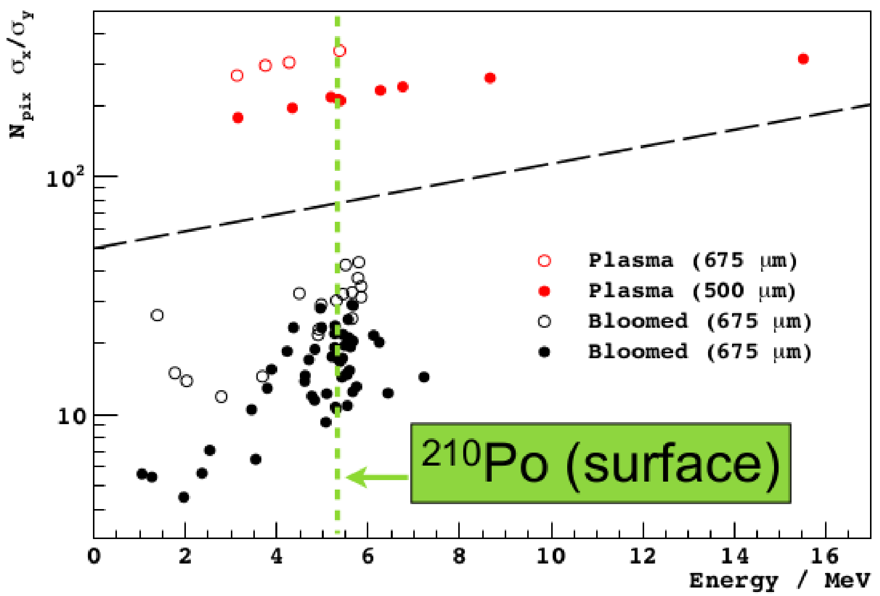

238U 4.5 Gyr
α 4.19 MeV
234Th 24 d
β⁻ + γ 199 keV
234mPa 1.2 min
β⁻ 2.29 MeV
234U 245 kyr
α 4.77 MeV
230Th 80 kyr
α 4.69 MeV
226Ra 1.6 kyr
α 4.79 MeV
222Rn 3.8 d
α 5.49 MeV
218Po 3.1 min
α 6.00 MeV
214Pb 27 min
β⁻ + γ 1.02 MeV
214Bi 20 min
β⁻ + γ 3.27 MeV
214Po 164 us
α 7.69 MeV
210Pb 22 yr
β⁻ + γ 63 keV
210Bi 5.0 d
β⁻ 1.16 MeV
210Po 138 d
α 5.31 MeV
206Pb stable

^{232}Th


232 Th 14 Gyr
α 4.01 MeV
228Ra 5.8 yr
β⁻ + γ 46 keV
228Ac 6.1 hr
β⁻ + γ 2.14 MeV
228Th 1.9 yr
α 5.42 MeV
224Ra 3.7 d
α 5.69 MeV
220Rn 56 s
α 6.29 MeV
216Po 145 ms
α 6.78 MeV
212Pb 10.6 hr
β⁻ + γ 573 keV
212 Bi 61 min
α (36%) 6.05 MeV
208 Tl 3.1 min
β⁻ + γ (64%) 2.25 MeV
212Po 299 ns
α 8.78 MeV
208Pb stable
β⁻ + γ 4.99 MeV

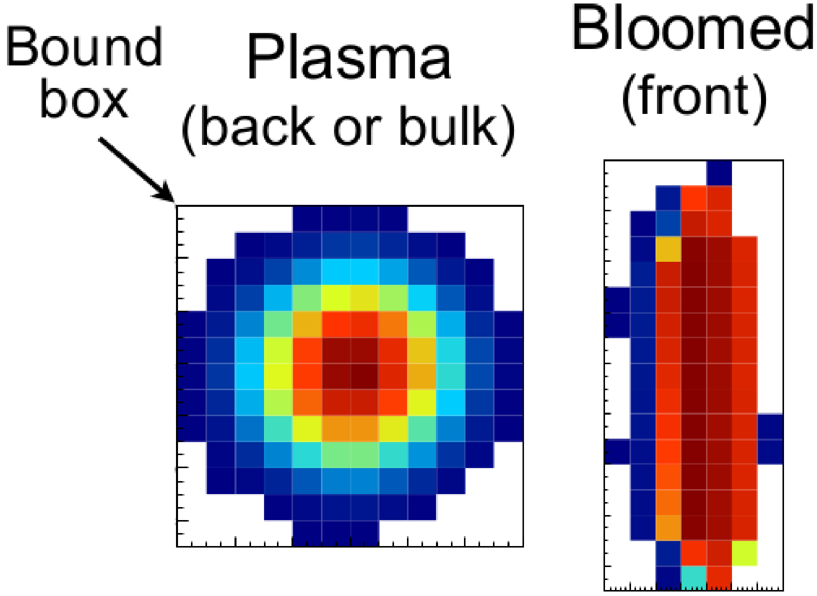
α particles





α-β discrimination based on shape of track.

α spectroscopy to measure U/Th contamination in CCDs: **JINST 10 P08014**



α particles

Table 2. CCD physical properties and rate of observed αs for the three CCDs installed at SNOLAB.

CCD	Mass / g	Area / cm^2	Bloomed rate / d^{-1}	Plasma rate / d^{-1}
500 μm top	2.2	19	0.87±0.17	0.21±0.09
500 μm bottom	2.2	19	0.87±0.17	0.14±0.07
675 μm	2.9	19	0.63±0.15	0.14±0.07
Average	2.4	19	0.79±0.10	0.16± 0.04

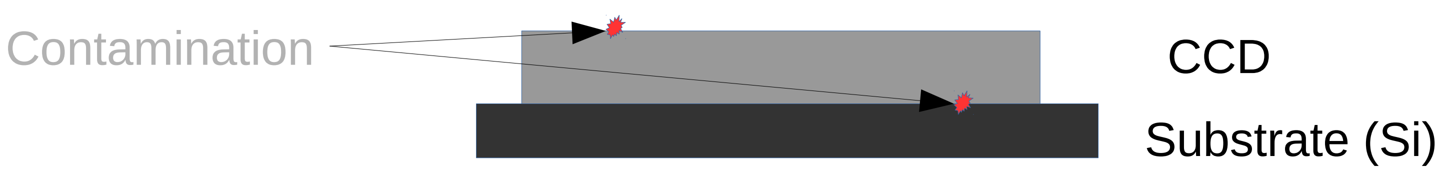
[JINST 10 P08014]

Bloomed α's: Occur at the front (top) surface

Plasma α's: Occur at the back (bot) surface
or in the bulk

Limits from α spectroscopy

Counting of α's can be used to place a limit on the amount of ^{210}Pb contamination.



$A = 19\ cm^2$

$T = 28.7\ d$

If all bloomed α's (E<6 MeV) come from ^{210}Po decays from ^{210}Pb contamination in the **top surface**:

$$Act = (0.078 \pm 0.010)\ cm^{-2} d^{-1}$$

If all plasma α's (E<6 MeV) come from ^{210}Po decays from ^{210}Pb contamination in the **bottom surface**:

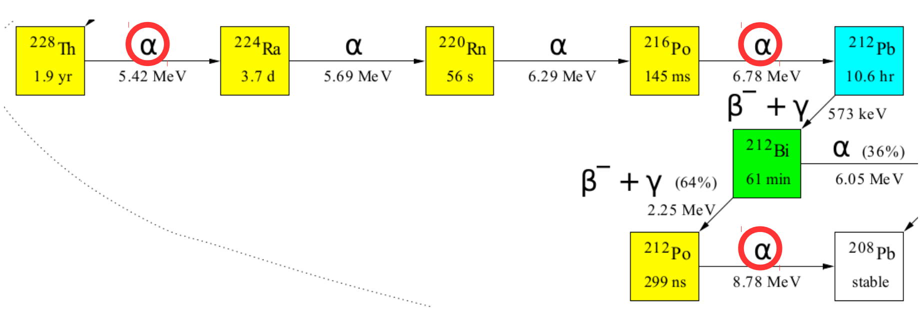
$$Act = (0.012 \pm 0.004)\ cm^{-2} d^{-1}$$

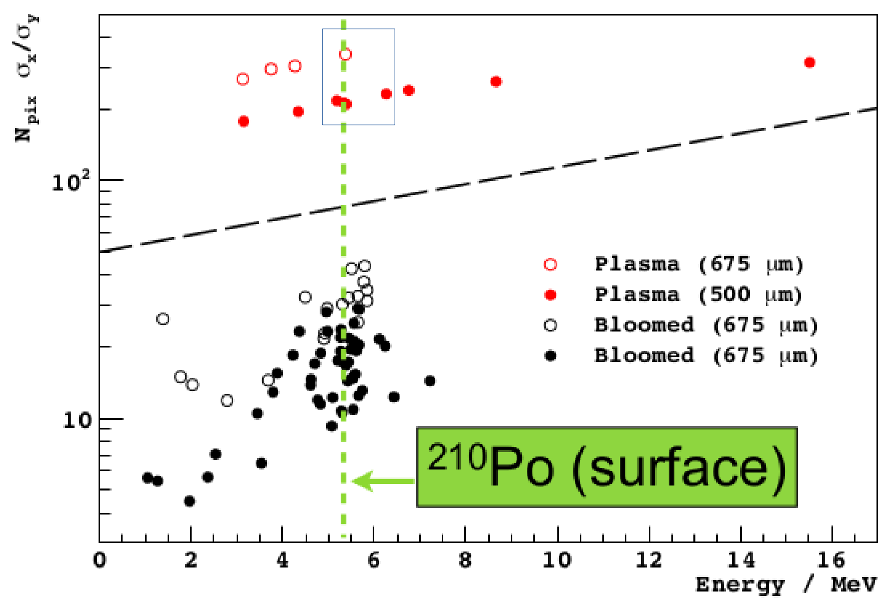
Limits from α spectroscopy

There are 4 plasma α's with E~5.3 MeV (^{210}Po). One can be discarded* → 3. Assuming these are all from bulk contamination of ^{210}Po (from ^{210}Pb):

Upper limit: ^{210}**Pb** < 37 kg^{-1}d^{-1} (95% C.L.)	**bulk**

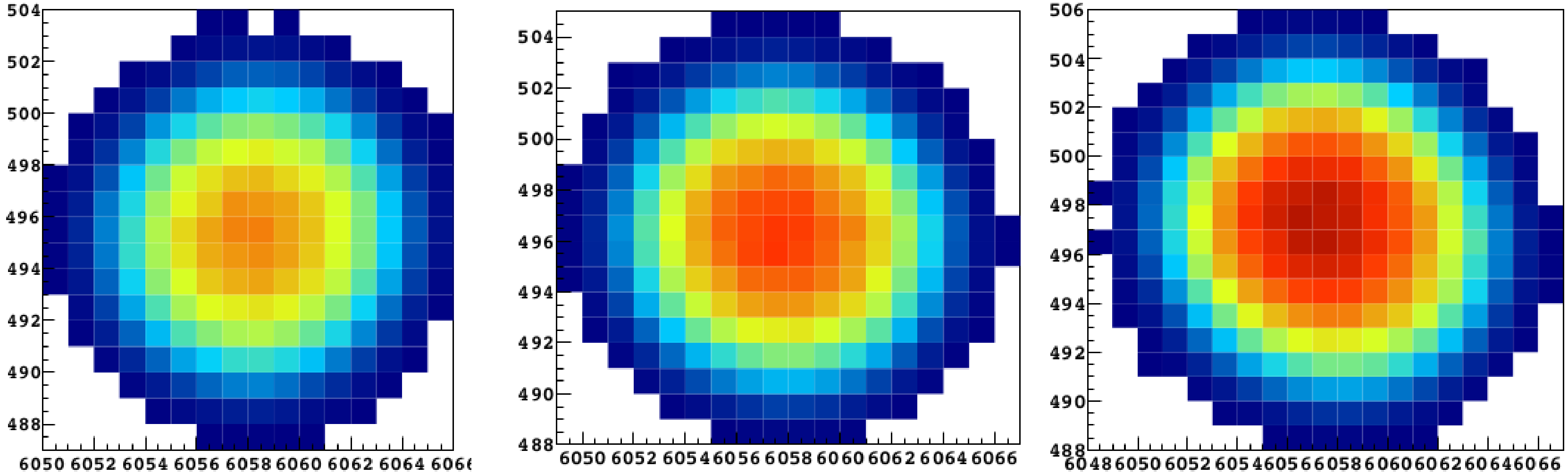
* The discarded α coincides spatially with 2 higher energy α's in different images. These are candidates for a triple α sequence from the ^{232}Th decay chain.





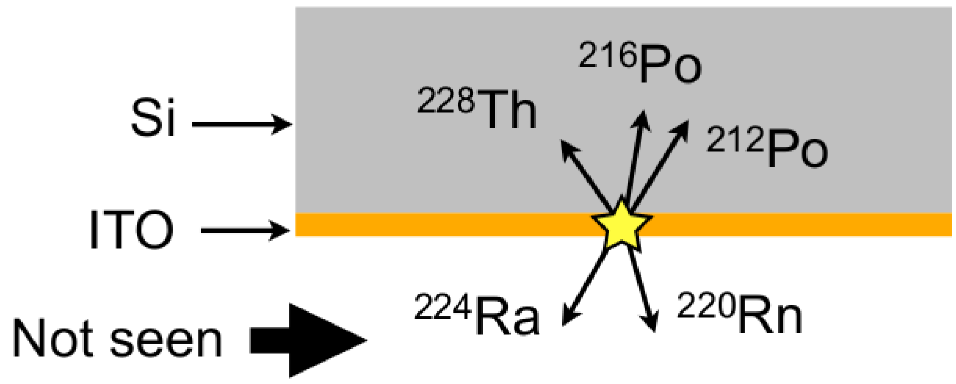
Triple alpha sequence

E = 5.39 MeV E = 6.75 MeV E = 8.66 MeV



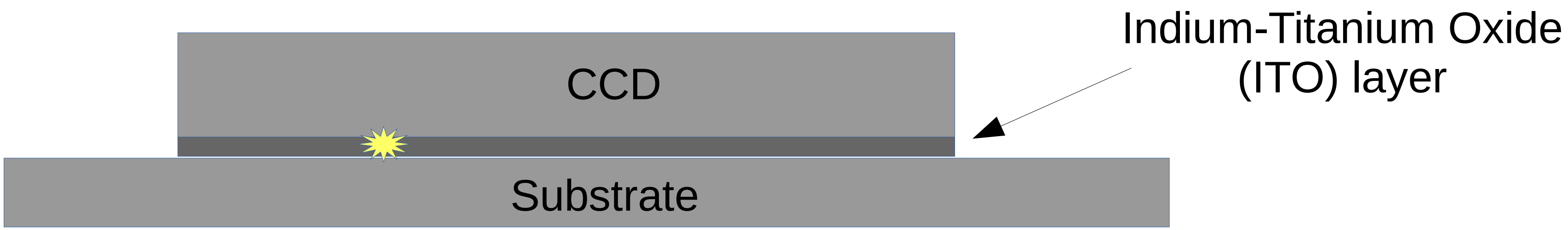
^{228}Th Δt = 17.8 d ^{216}Po Δt < 5.5 h ^{212}Po

Identification of ^{228}Th decay sequence below device.



Triple-α sequence

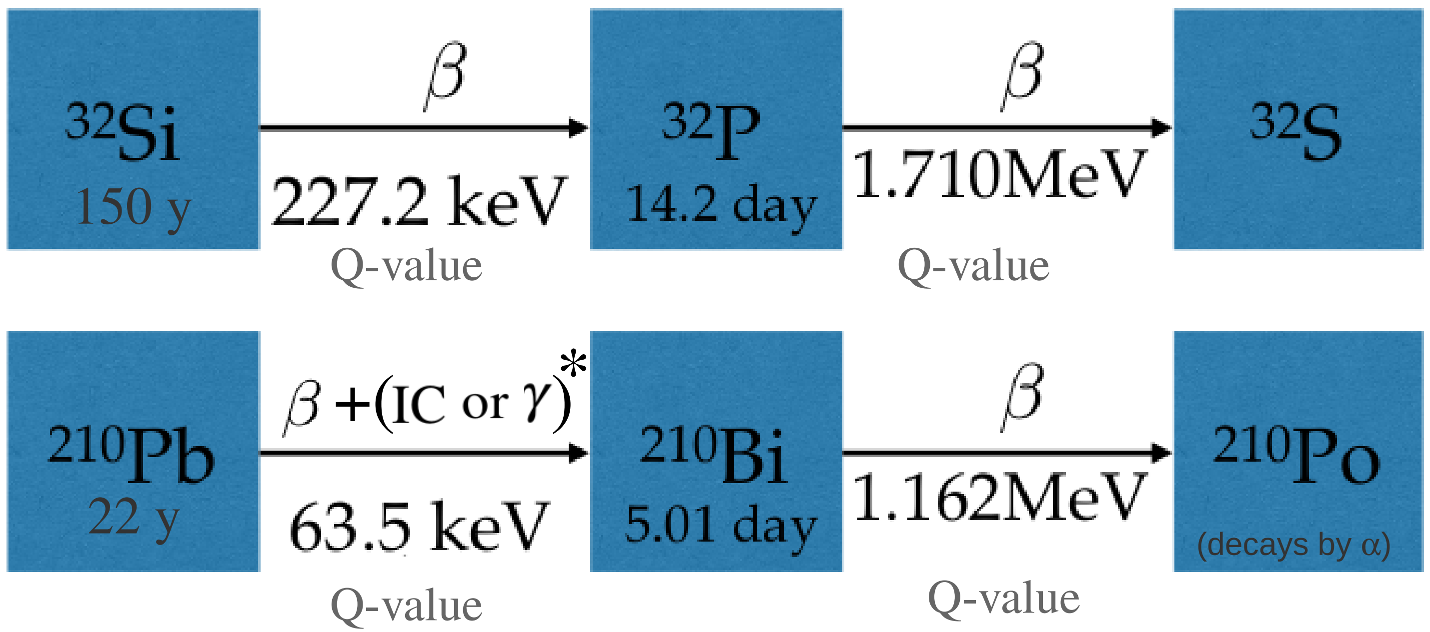
See four plasma α's with E>5.5 MeV. Cannot be ^{210}Po decay.



This CCD has an ITO layer on the back surface. Cancidate. Possible origin of the ^{232}Th.

This single decay sequence is compatible with ∼100 ppb of ^{232}Th contamination in the ITO layer.

Decay chains of ^{32}Si and ^{210}Pb



* Prompt 46.5 keV from excited ^{210}Bi:
IC (80%) / γ (4%)

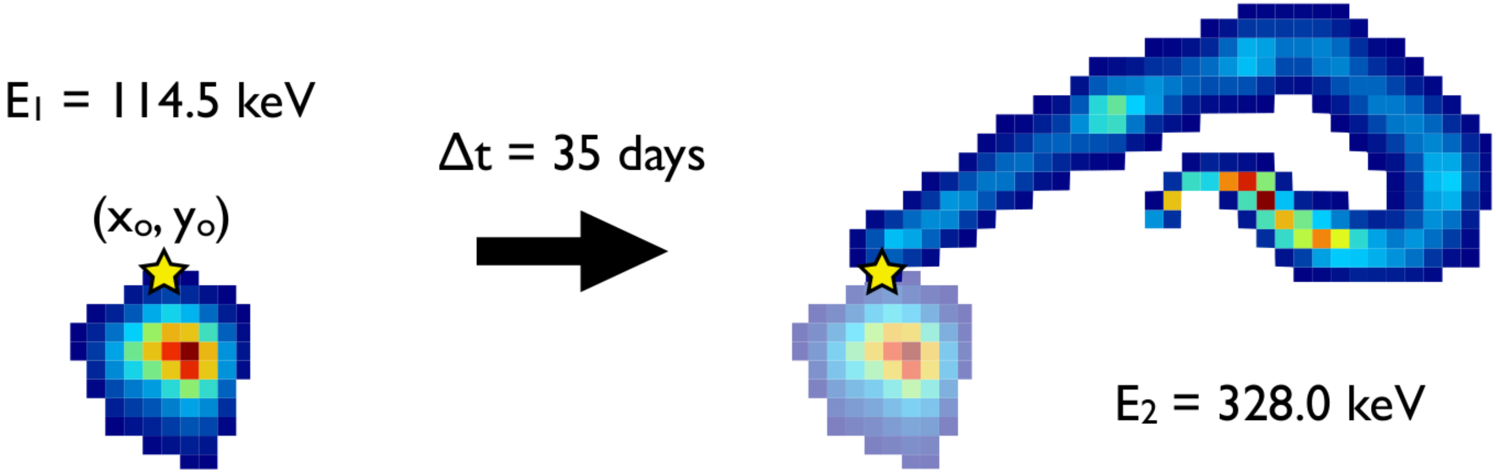
The β s produced by each decay pair should originate from the same pixel.

Spatial coincidence example

The precise reconstruction in the CCD allows us to study spatial coincidences and measure ^{32}Si and ^{210}Pb in the CCD by identifying decay sequences.

1) $^{32}\mathrm{Si} \longrightarrow {}^{32}\mathrm{P} + \beta^{-}$ with $\tau_{1/2} = 150\,\mathrm{y}$, $\mathrm{Q-value} = 227\,\mathrm{keV}$

2) $^{32}\mathrm{P} \longrightarrow {}^{32}\mathrm{S} + \beta^{-}$ with $\tau_{1/2} = 14\,\mathrm{d}$, $\mathrm{Q-value} = 1.71\,\mathrm{MeV}$



Same idea for ^{210}Pb.

Selecting spatial ββ coincidences

1. Find end-points of all β tracks (clusters)

2. Calculate the distance to β cluster in later images

$$d_c = \min\{\text{4 end-point combinations of cluster pair}\}$$

3. Apply the selection cuts:

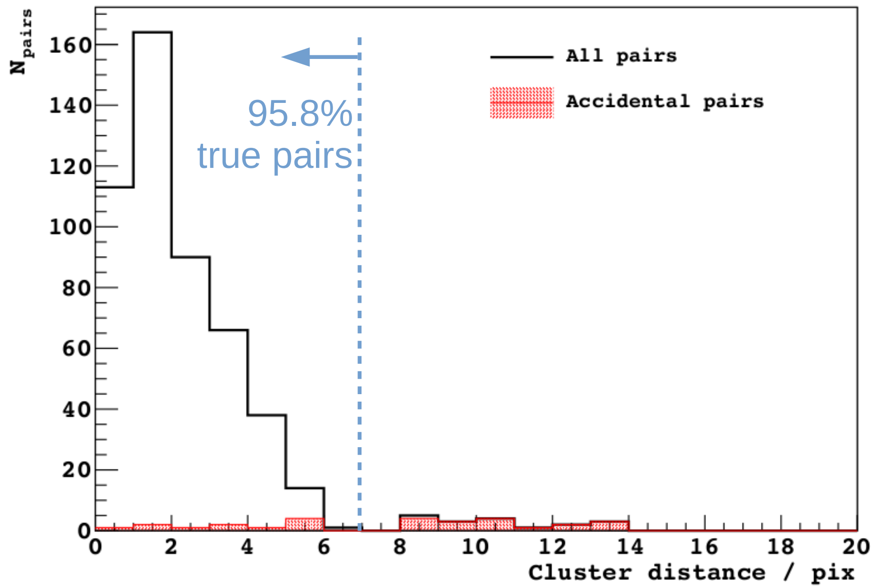
cut 1: $d_c < 7$ pix & share 1 or more pixels.

cut 2: $E_1 < 230$ keV, $E_2 < 1.8$ MeV } ^{32}**Si** ; E_1 in [30-65] keV, $E_2 < 1.2$ MeV } ^{210}**Pb**

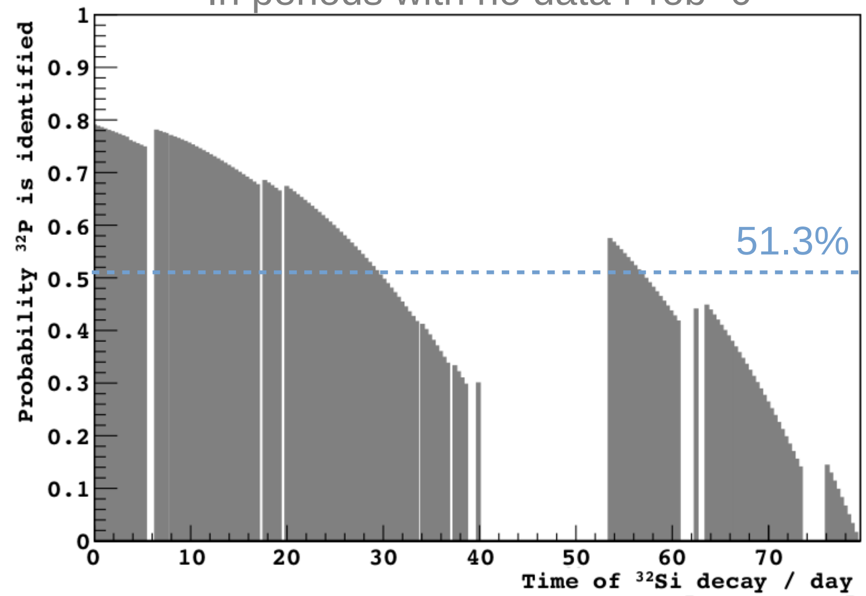
cut 3: $\Delta t_{\text{pair}} < 5 \times t_{1/2}$ (70 day, ^{32}**Si**) (25 day, ^{210}**Pb**)

ββ pair selection efficiency

From MCNPX5 simulation



(a) Simulated sample search.



(b) ϵ_{time} for ^{32}Si–^{32}P.

^{32}Si

$$\left.\begin{array}{l}\epsilon_{pair} = 95.8\% \\ \epsilon_{time} = 51.3\%\end{array}\right\} \epsilon_{Si} = 49.2\%$$

$$\epsilon_X = \epsilon_{pair}\epsilon_{time}$$

^{210}Pb

$$\left.\begin{array}{l}\epsilon_{pair} = 71.0\% \\ \epsilon_{time} = 65.1\%\end{array}\right\} \epsilon_{Pb} = 46.2\%$$

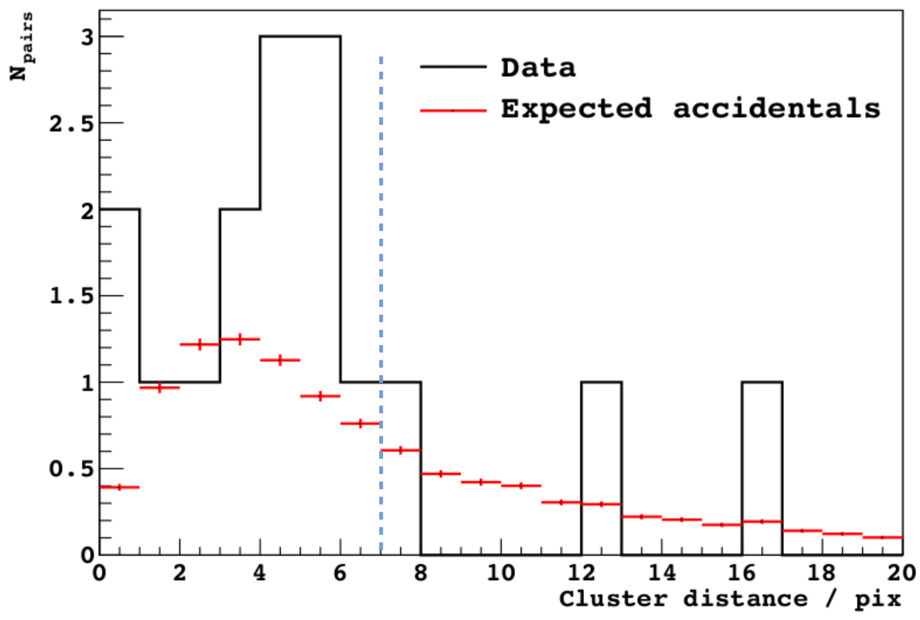
Search results, ^{32}Si and ^{210}Pb

57 days of data with 1 CCD (2.9 g) **[JINST 10 P08014]**

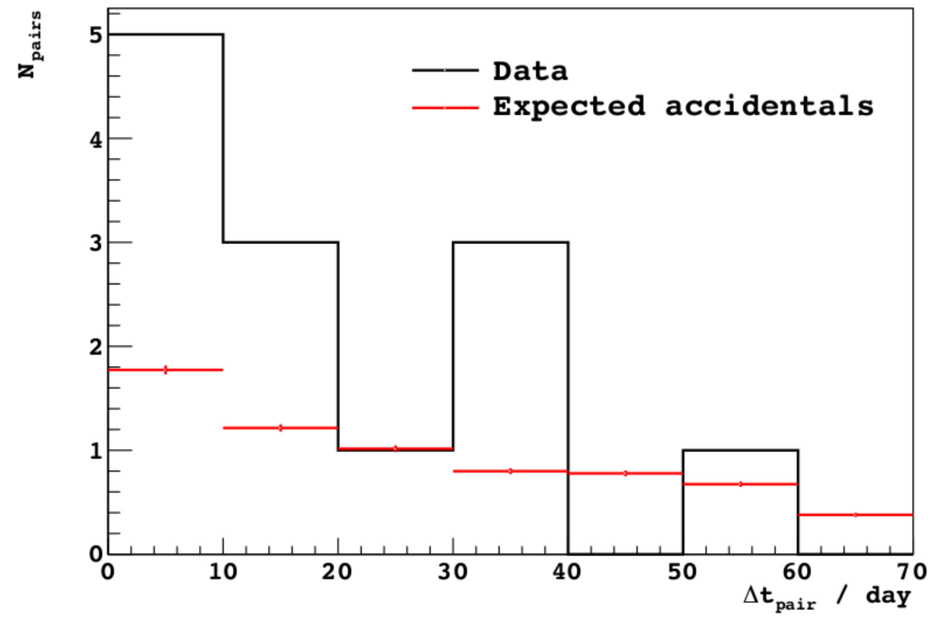
Applying the search procedure to the data yielded:

- No candidates for $^{210}Pb \rightarrow {}^{210}Bi$
- 13 candidates for $^{32}Si \rightarrow {}^{32}P$

Accidentals:
Data clusters with randomized (x1000) positions passed through search criteria.



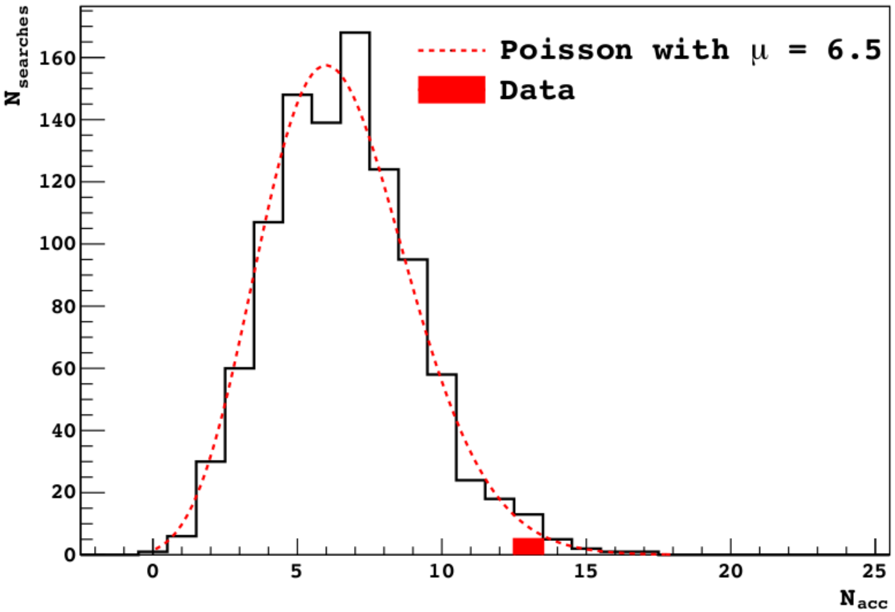
(a) ^{32}Si–^{32}P.



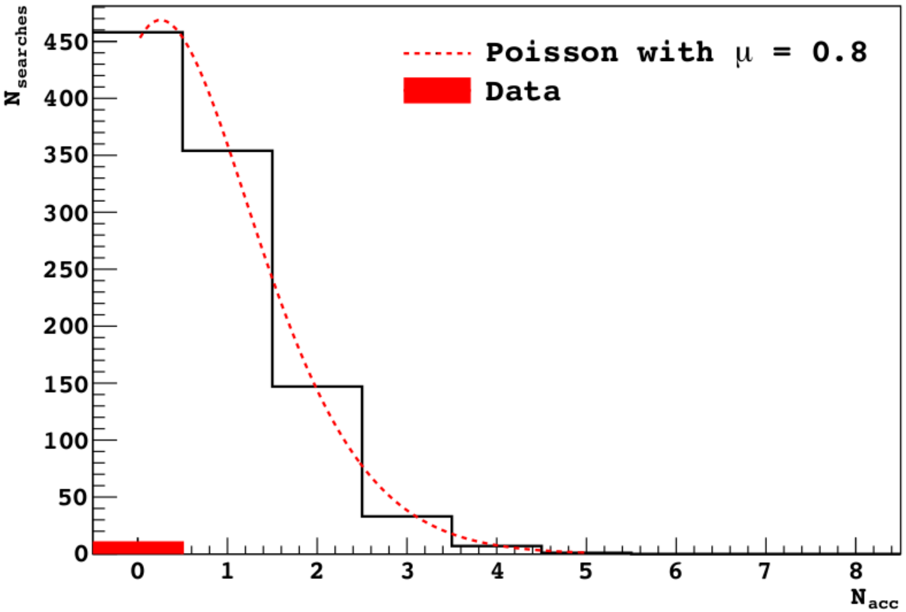
(b) ^{32}Si–^{32}P.

Accidentals ^{32}Si, ^{210}Pb

Data clusters with randomized (x1000) positions passed through search criteria (d_c < 7 pix).



(a) ^{32}Si – ^{32}P.



(b) ^{210}Pb – ^{210}Bi.

Confidence intervals: Poisson process with unknown signal mean and known background mean

$$P(n|\mu)=(\mu+b)^n \exp[-(\mu+b)]/n!$$

Limits on ^{32}Si, ^{210}Pb in the bulk

57 days of data with 1 CCD (2.9 g)

JINST 10 P08014

- 13 observed events with $\langle N_{acc} \rangle = 6.5$

$$1.2 < N_{Si} < 15.3 \text{ (95\% CI)}$$

^{32}Si

- NO observed events with $\langle N_{acc} \rangle = 0.8$

$$N_{Pb} < 2.5 \text{ (95\% CL)}$$

^{210}Pb

These values correspond to rates [$kg^{-1}d^{-1}$]:

$$R = \frac{N_X}{\epsilon_X \times m \times t}$$

m = 2.9 g

t = 56.8 d

Limits on ^{32}Si, ^{210}Pb in the bulk

<u>57 days of data with 1 CCD (2.9 g)</u>

^{210}**Pb** < 33 $kg^{-1}d^{-1}$ (95% C.L.)

^{32}**Si** = 80^{+110}_{-65} $kg^{-1}d^{-1}$ (95% C.L.)

exposure: 0.165 kg·d

JINST 10 P08014

The ^{210}Pb limit is consistent with the one derived from the α counting method.

Ongoing analysis

200 days of data with 6 CCD (35 g)

β–β spatial coincidence analysis:

^{210}**Pb** = (0.00944 ± 0.00212) $cm^{-2}d^{-1}$

^{32}**Si** = ~10-20 $kg^{-1}d^{-1}$

exposure: ~7 kg·d

ongoing analysis

Differences with previous measurements expected from silicon originating from different batches in each case.

α spectroscopy:

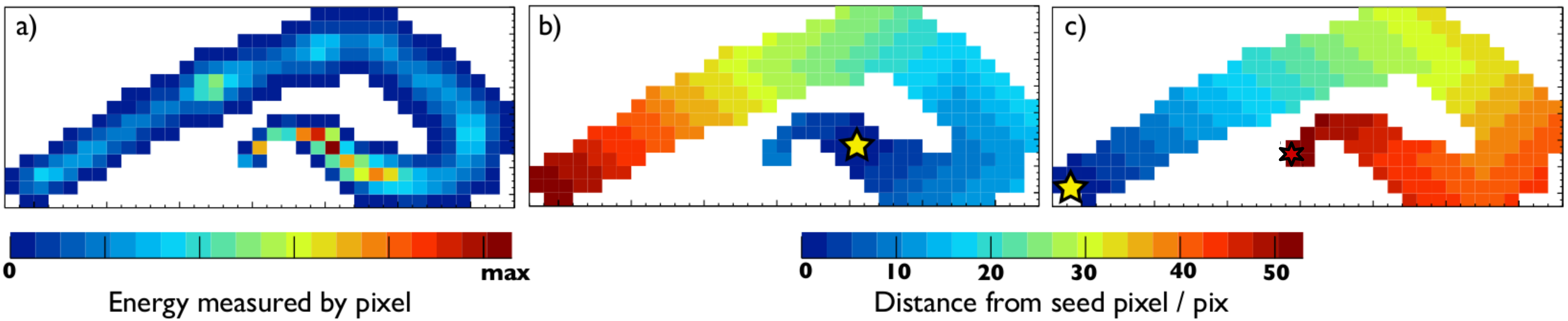
All alphas observed are consistent with 210 Pb

Summary

- DAMIC uses **α** spectroscopy and identification of β–β decay sequences to measure levels of ^{210}Pb and ^{32}Si contamination in the silicon of its CCDs.
- Early results measured the rate of ^{32}Si decays, and a limit on the ^{210}Pb rate [**JINST 10 P08014**].
- Ongoing analysis with the 4k $\times$ 4k CCDs of DAMIC100 yields measurements for both decay rates.
- Differences expected from silicon originating from different batches in each case.
- Updated results to be published soon.

Extras

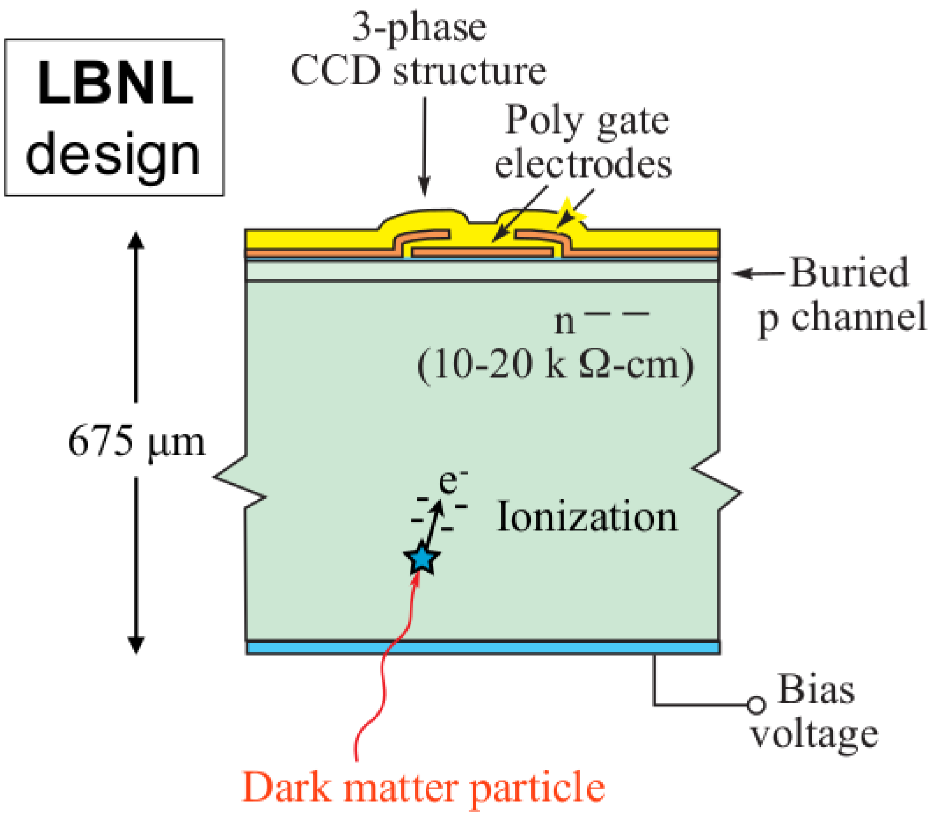
Cluster end-points

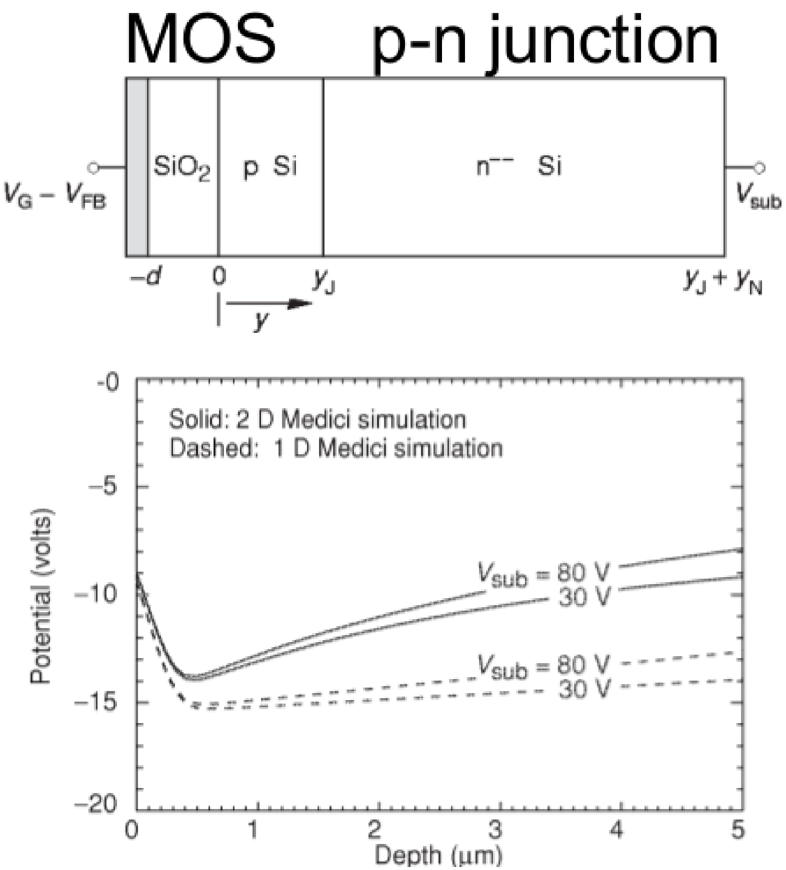


a) The pixel with maximum signal is chosen as seed point.
b) The distance of each pixel in the cluster to the seed point (star) is computed.
c) The pixel with the largest distance is chosen as the first end-point (☆). Distances to the first end-point are calculated, and the pixel with the largest distance is taken as the second end-point (✶).

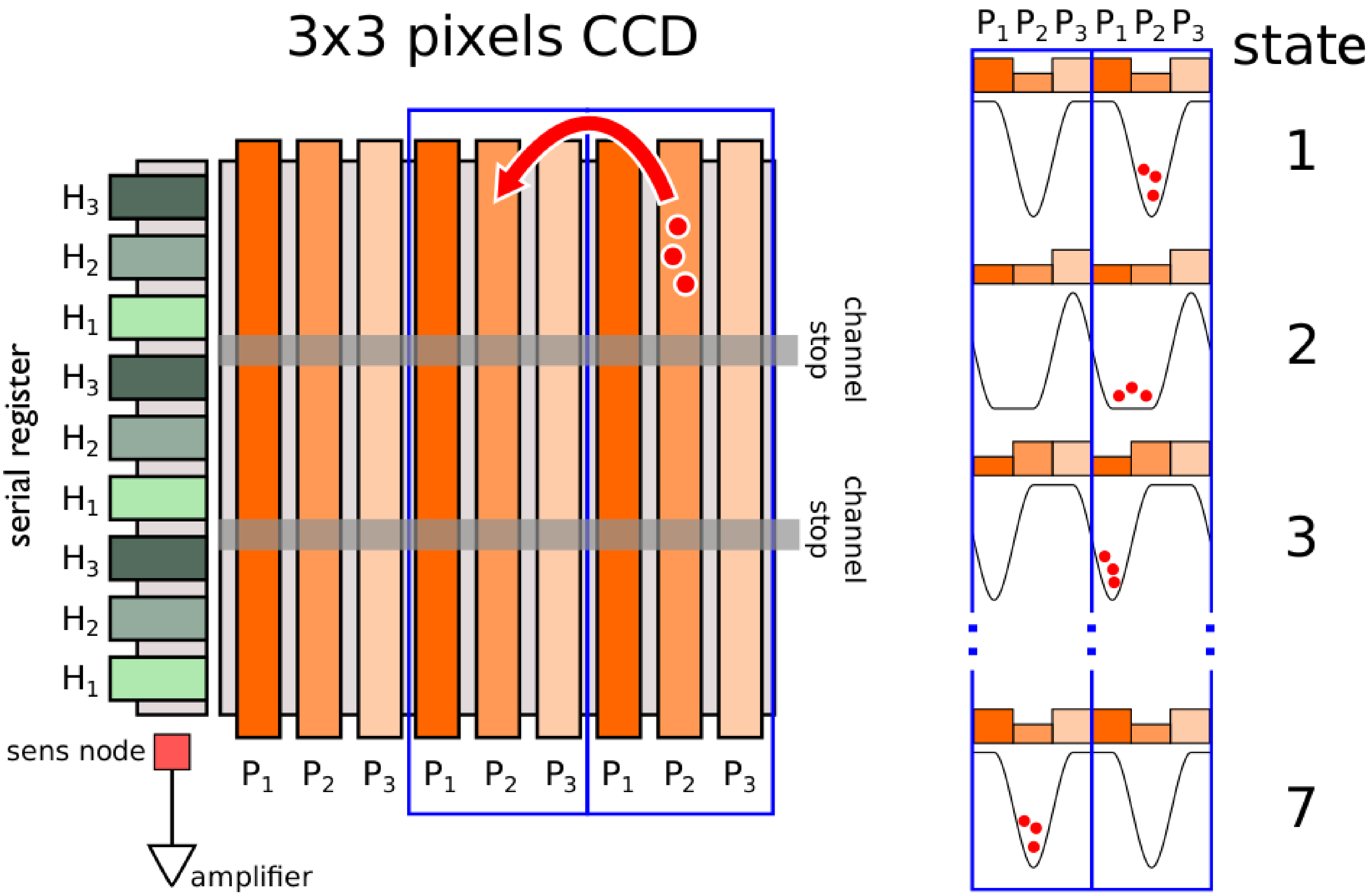
DAMIC

Fully depleted substrate of charge-coupled devices (CCDs) as target for interactions of dark matter particles in the Galactic Halo.



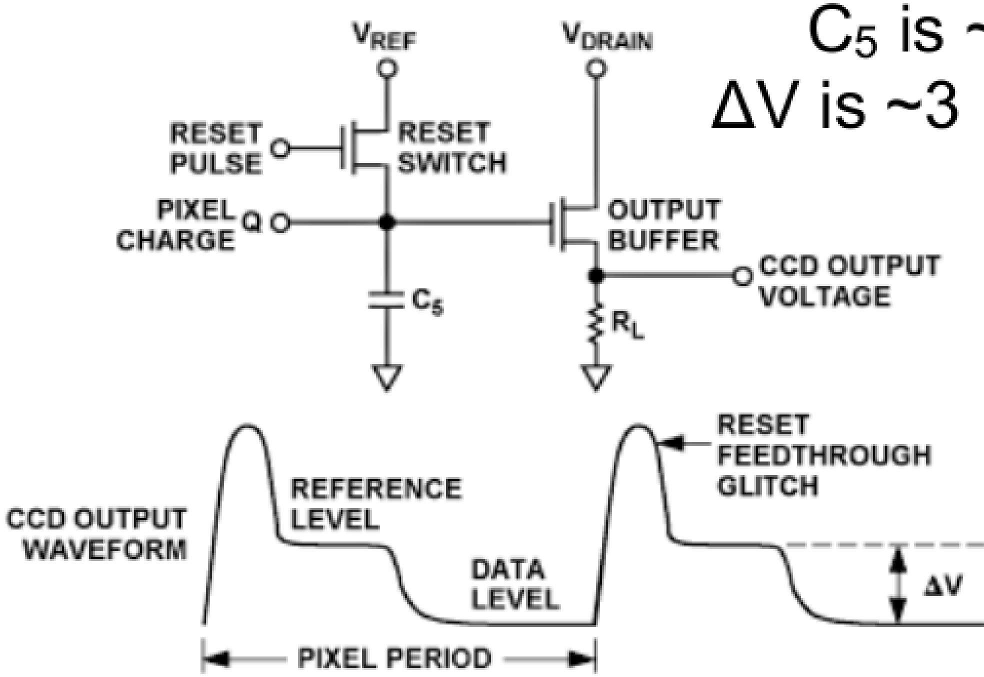


CCD readout



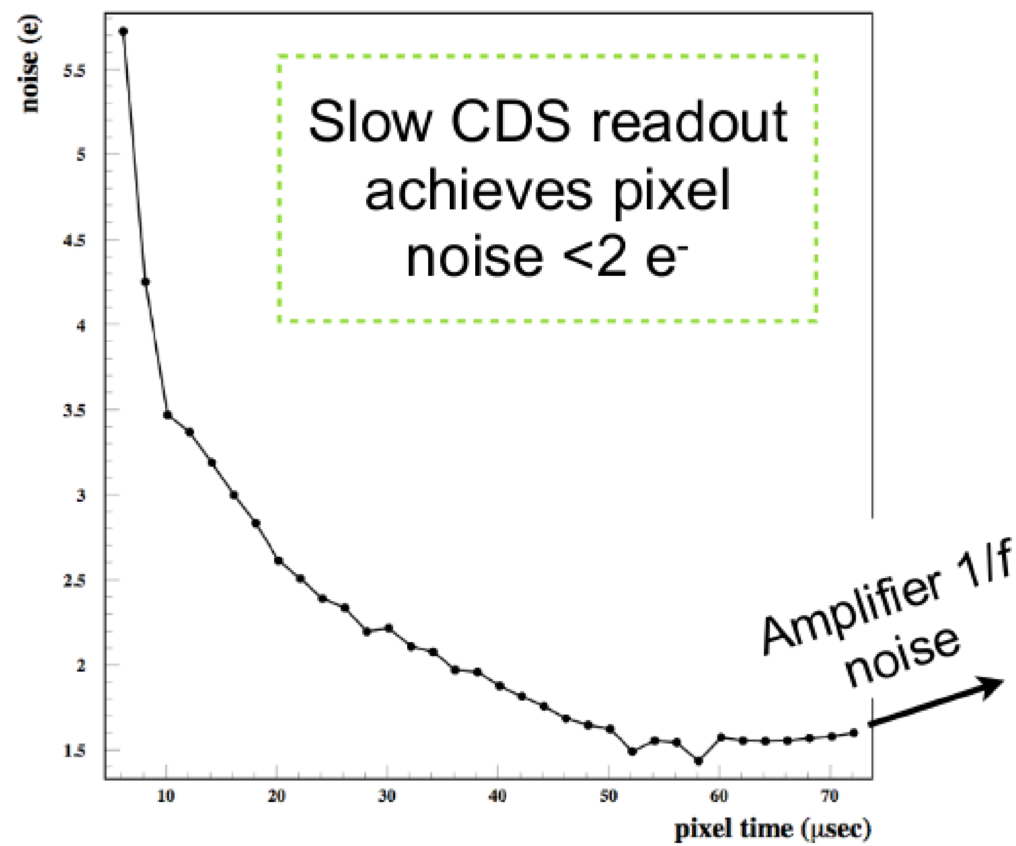
3x3 pixels CCD
serial register
H3
H2
H1
H3
H2
H1
H3
H2
H1
channel stop
channel stop
sens node
amplifier
P1 P2 P3 P1 P2 P3 P1 P2 P3
P1 P2 P3 P1 P2 P3
state
1
2
3
7

CCD readout



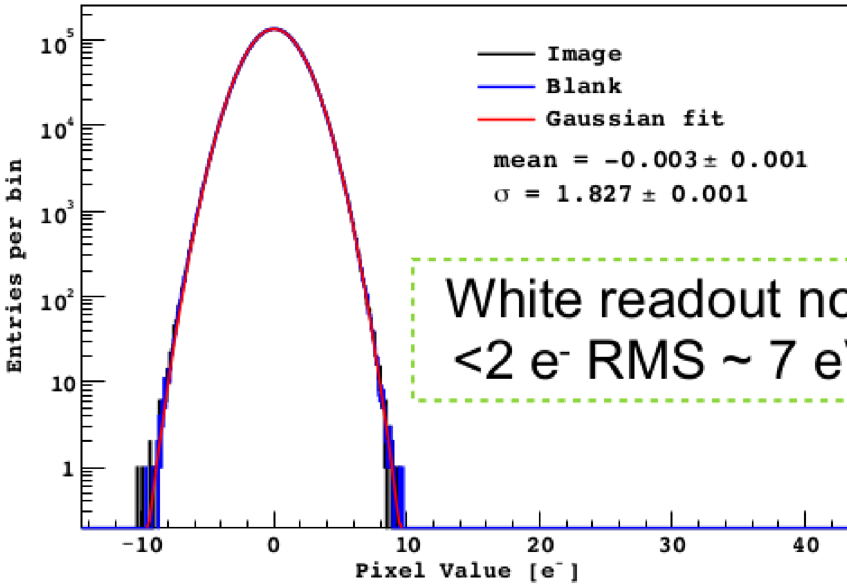
C_5 is ~50 fF
ΔV is ~3 μV per e^-

CDS: "Correlated double sampling"



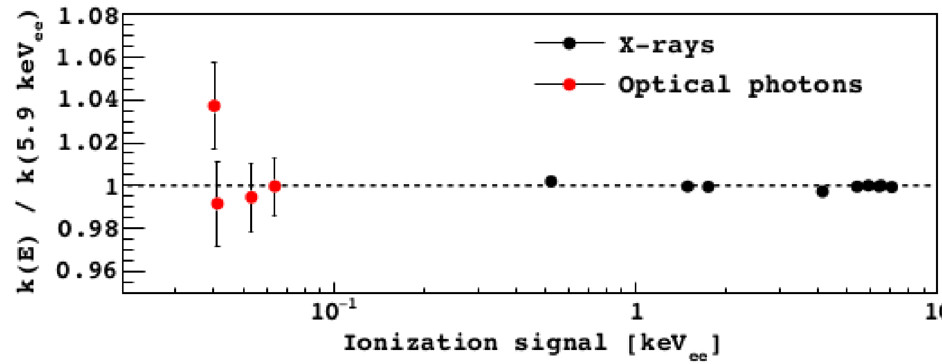
Non-destructive readout e.g. CCD "skipper" readout can improve noise further.

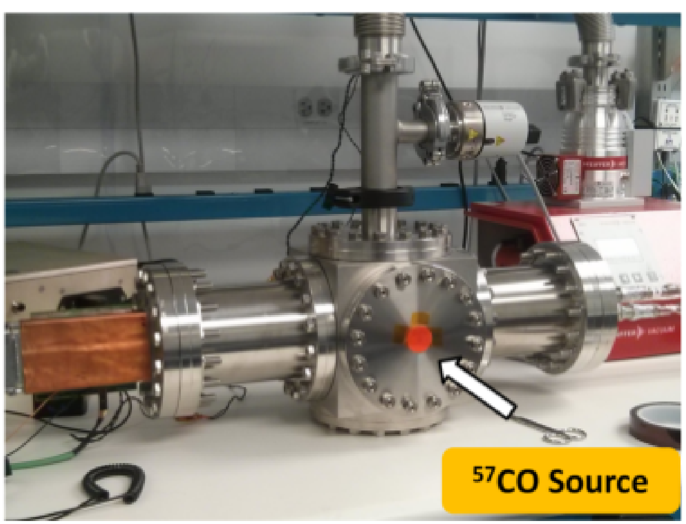
Device performance



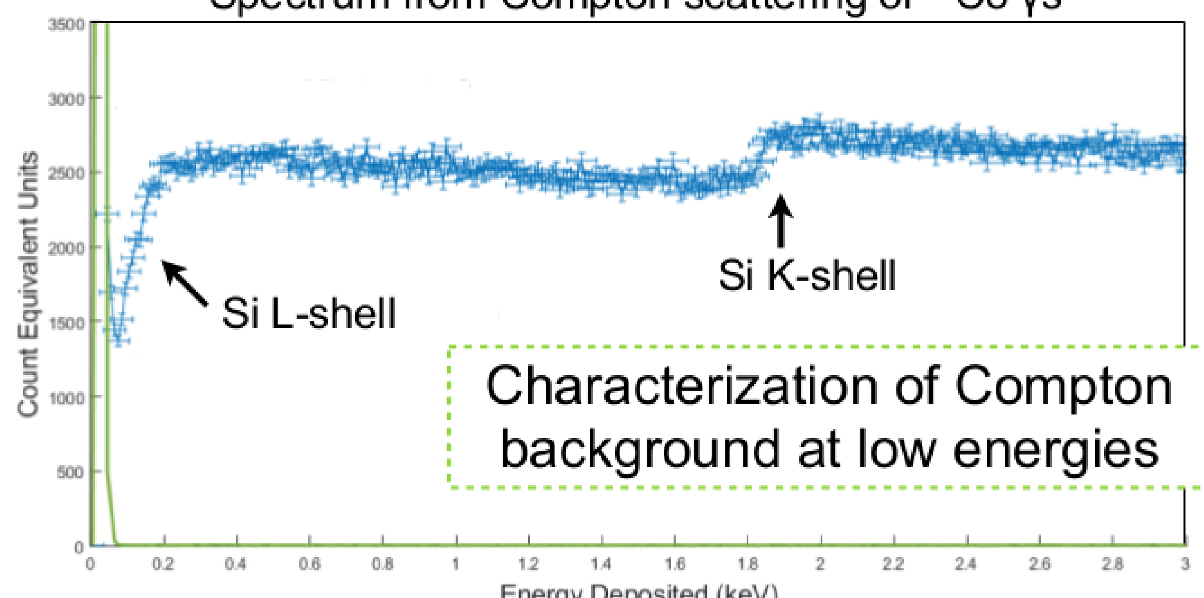
White readout noise
<2 e⁻ RMS ~ 7 eV_{ee}

Linearity demonstrated for
signals <10 e⁻.



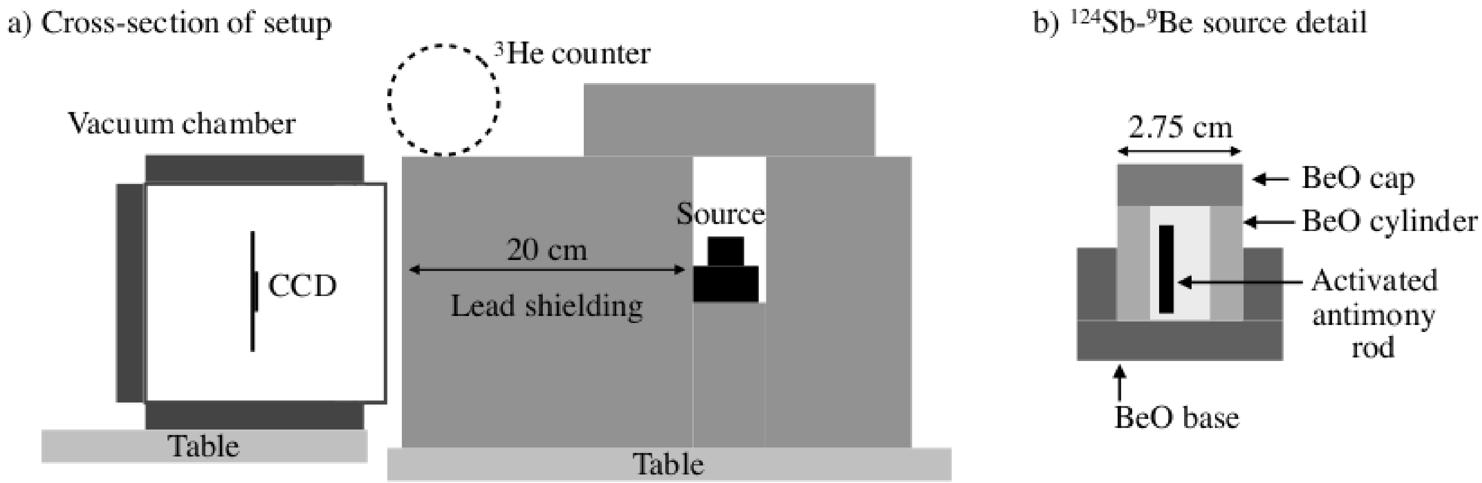


Spectrum from Compton scattering of ^{57}Co γs



Characterization of Compton
background at low energies

Nuclear recoil response



24 keV neutrons from ^{9}Be(γ,n) reaction