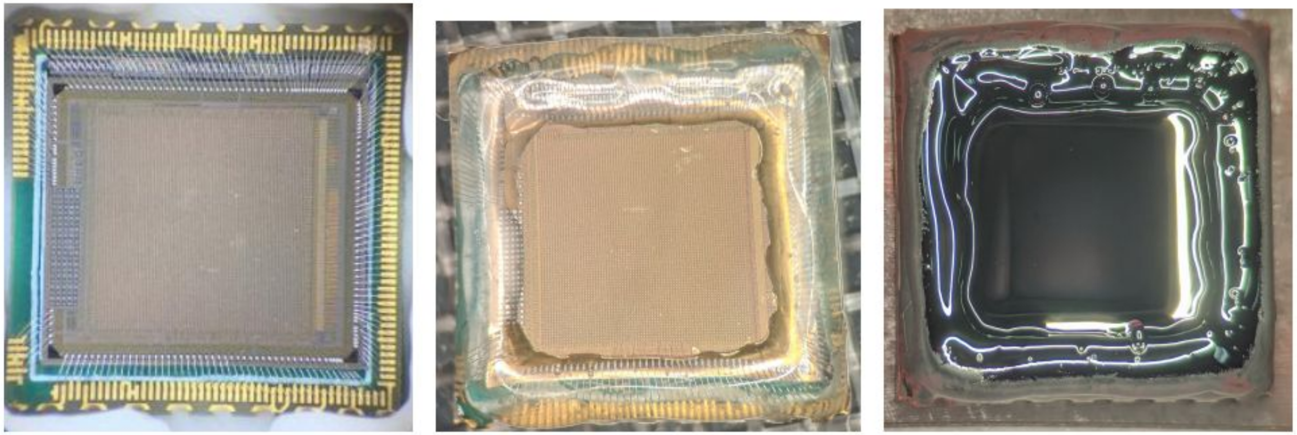
Selena, a high-resolution selenium imaging detector for neutrinoless ββ decay and solar neutrinos

Xinran Li
Department of Physics, Lawrence Berkeley National Laboratory

Outline

- Introduction to neutrinoless double beta decay and amorphous selenium
- Conceptual design of the imaging detector
- Solar neutrino
- Physics behind the charge signal in a-Se
- Machine learning tasks and brain-storm



Topmetal-II^{-} - aSe prototype detector

Neutrinoless Double β Decay ($0\nu\beta\beta$)

$2\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

$0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

- ➢ Neutrinos are Majorana particles
- ➢ Explicit violation of lepton number
- ➢ Indication of neutrino mass

Half-life of $0\nu\beta\beta$ $$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}|\mathcal{M}|^2|m_{\beta\beta}|^2$$

Phase space factor

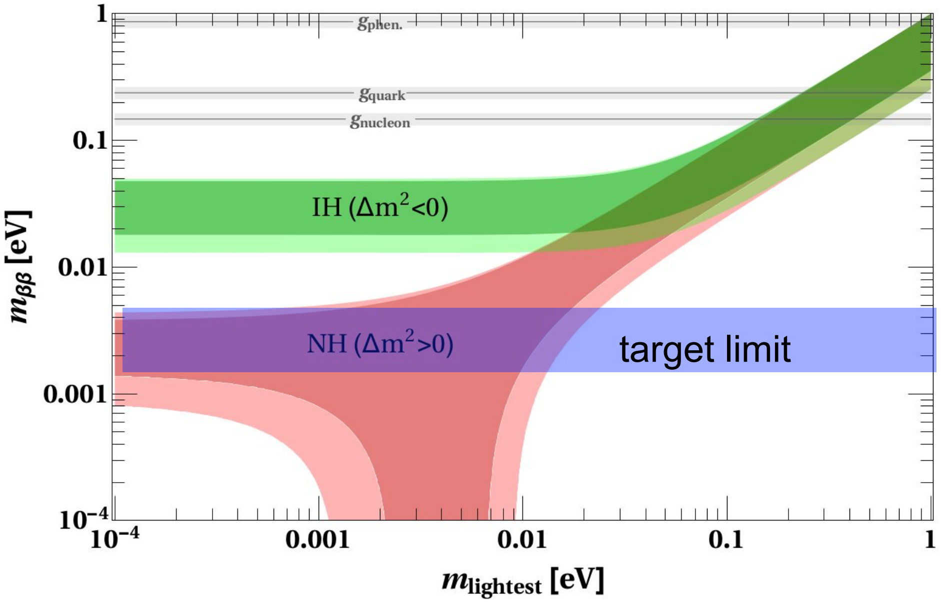
Nuclear matrix element
$\mathcal{M} \propto g_A^2$

Effective Majorana mass

$$g_A = \begin{cases} g_{\text{nucleon}} & = 1.269 \\ g_{\text{quark}} & = 1 \\ g_{\text{phen.}} & = g_{\text{nucleon}} \cdot A^{-0.18} \end{cases}$$

⬆ Possible values of axial coupling constant

Predictions on $m_{\beta\beta}$ from oscillations as a function of the lightest neutrino mass and combined experimental limit from ^{136}Xe ➡
arXiv:1601.07512



Selenium

^{82}Se is a good candidate for the search of $0\nu\beta\beta$

- High $Q_{\beta\beta}$. Large phase space and low background
- Long $2\nu\beta\beta$ life time

$$T^{2\nu}_{1/2} = 1 \times 10^{20}\mathrm{y}$$

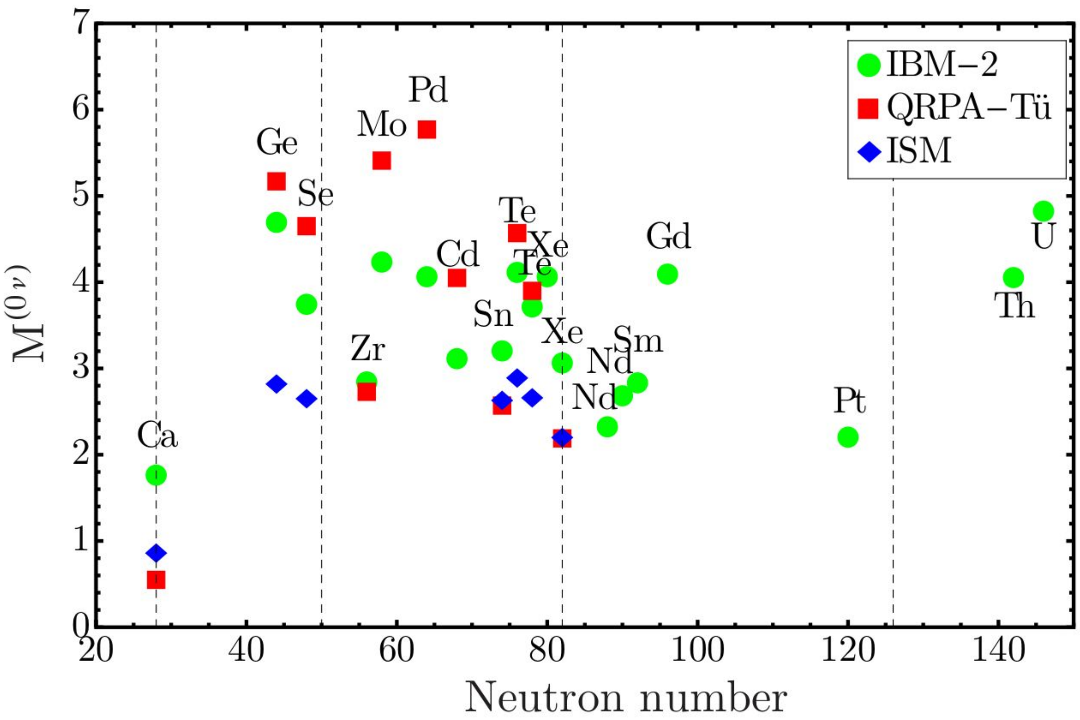
- Relatively high abundance

LUCIFER: ZnSe

Advances in High Energy Physics 2013 (2013).

NEMO-3: Film source with tracker and calorimeter.

arXiv:1806.05553 (2018)



Isotope	isotopic abundance (%)	$Q_{\beta\beta}$ [MeV]
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	9.2	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.6	3.035
^{116}Cd	7.6	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

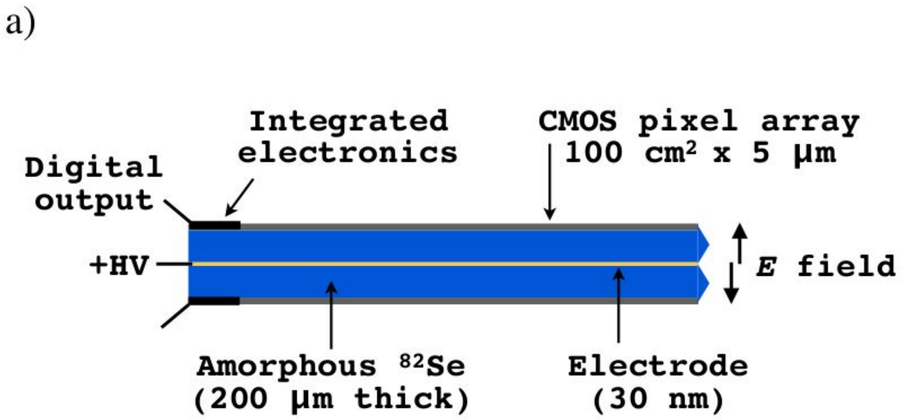
arXiv:1601.07512

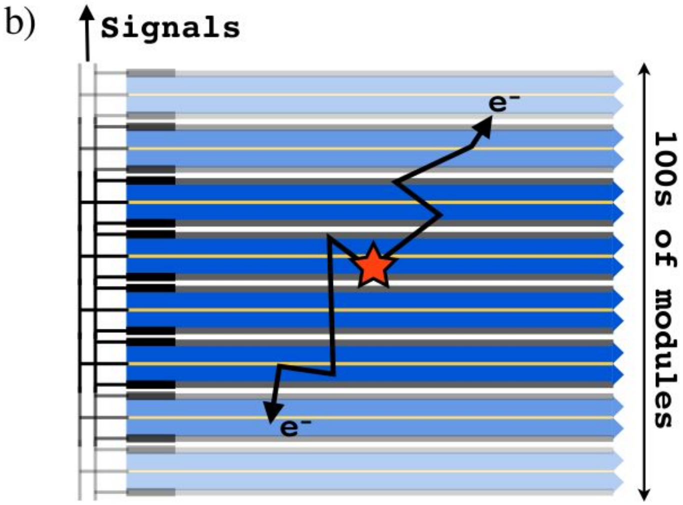
Conceptual Design of The Imaging Detector

Amorphous ^{82}Se deposits on CMOS or CCD arrays. Operates at room temperature in underground lab.
Long exposure O(10s) for charge readout.

“Background free” : $M \cdot T \cdot B \cdot \Delta \leq 1$

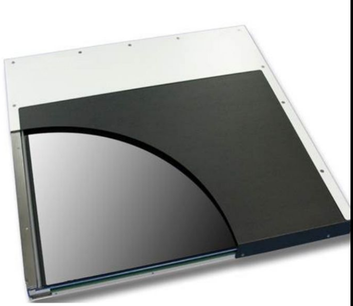
- M : Compact and modular design, easy to scale up
- Δ : Fine energy resolution
- B : Low internal background + track geometry discrimination





Chavarria, A. E., C. Galbiati, X. Li, and J. A. Rowlands.
Journal of Instrumentation 12, no. 03 (2017): P03022.

Selenium X-ray plate detector

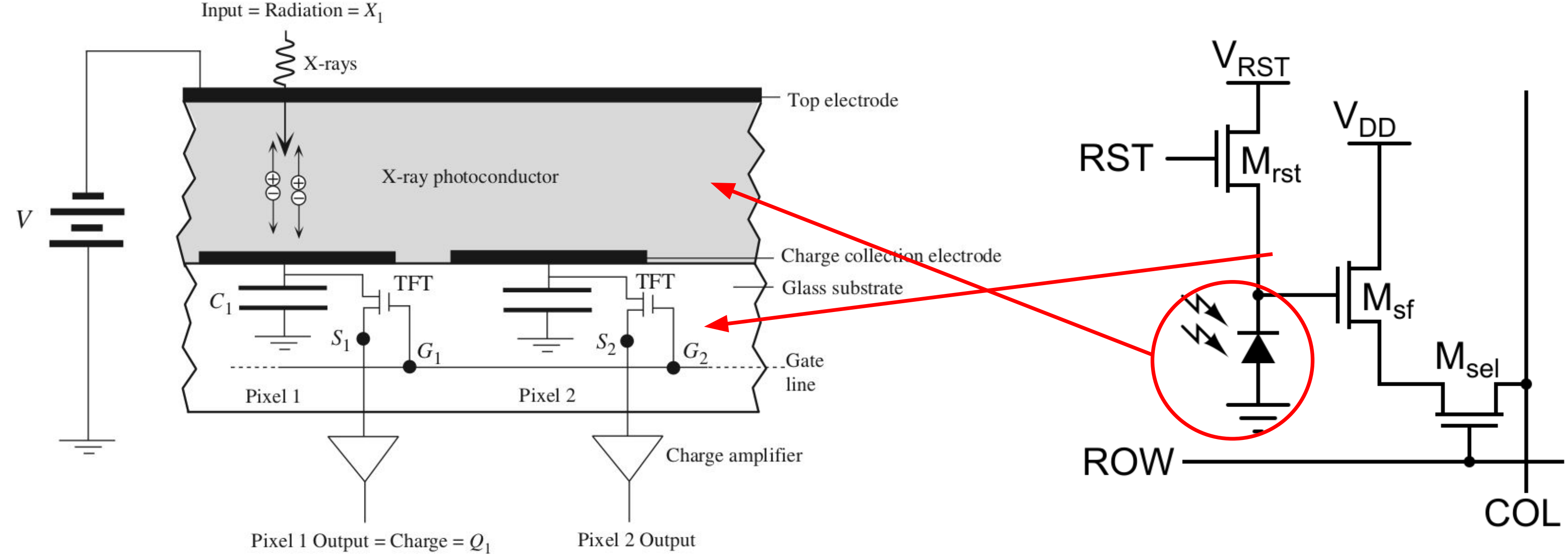


Amorphous Se X-ray detectors are used in medical imaging.
(Commercial device: 720 cm^2, 1 mm thick, 85 um pixel size.)

Large band gap, negligible dark current at room temperature. Bias voltage ~20V/um.

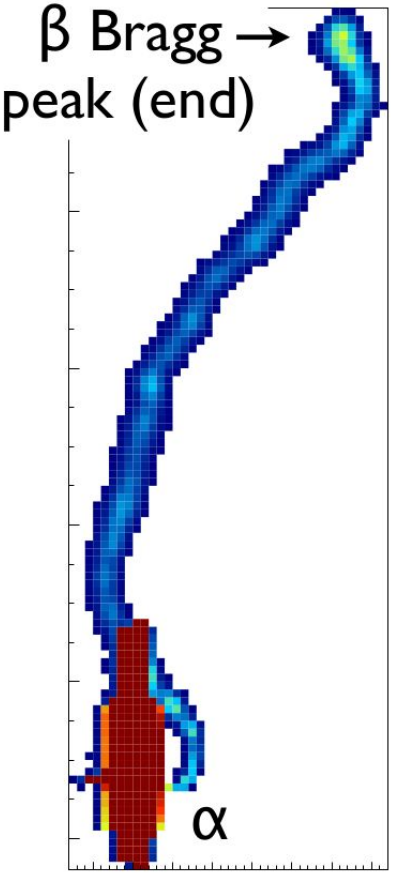
Replace current TFT pixel array to CMOS or CCD pixel array to achieve
< 100 e-h/pixel noise

CMOS active pixel array



Current Applied Physics 6.3 (2006): 288-292

Particle track imaging



α and β (right: an example from silicon CCD)

β stopping power << α stopping power

DAMIC Aguilar-Arevalo, A., et al. *Journal of Instrumentation* 10.08 (2015): P08014.

Identification of β track end:

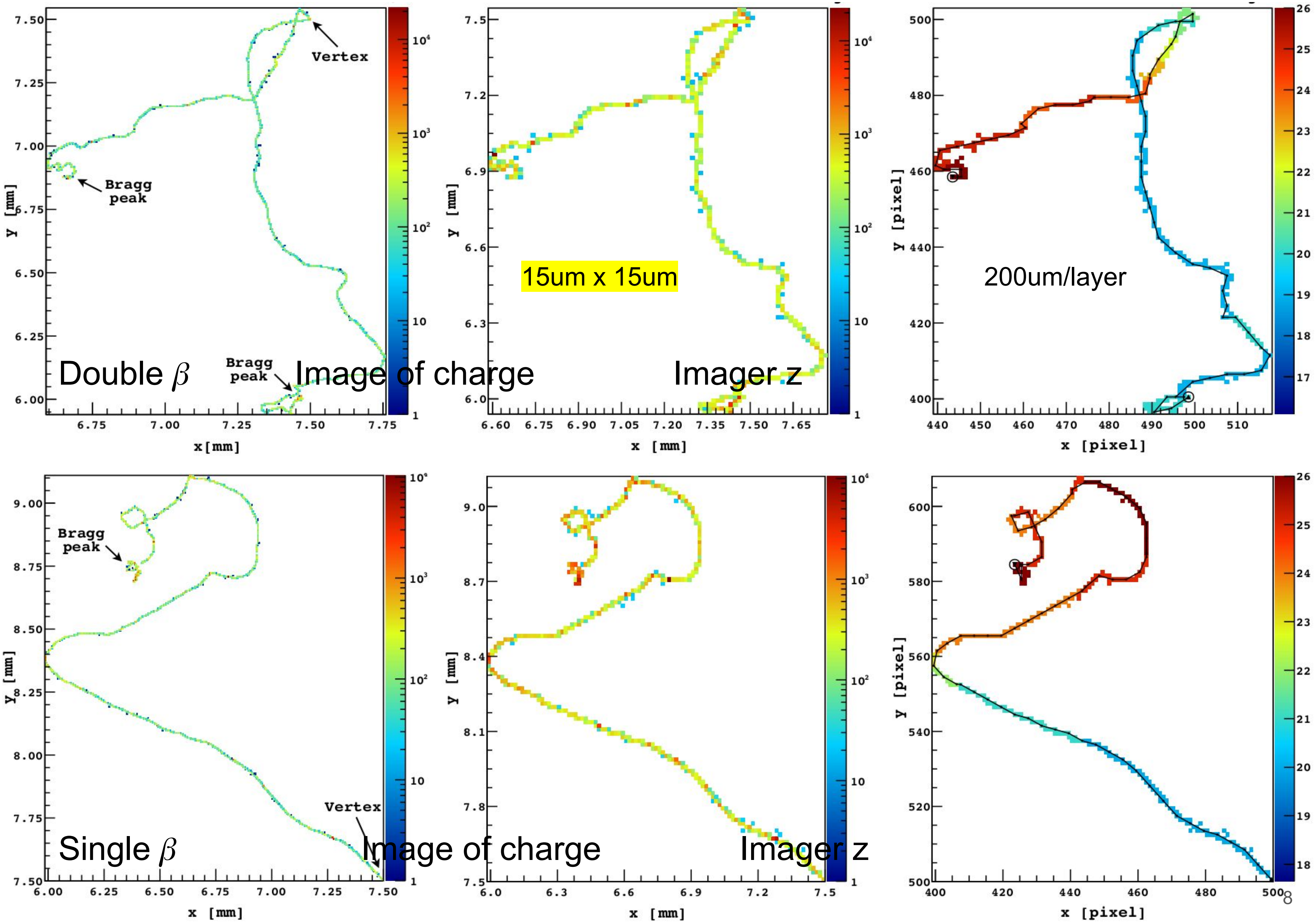
Time information is lost. Look for Bragg peak.

10^{-3} rejection of single β decay achieved with 50% double β acceptance. Limited by delta ray emission near primary vertex.

Limitations:

Pixel size, due to constraints from design, fabrication, power, and readout speed.

Deadlayer (Si readout structure) between aSe layers.



Double β

Image of charge

Imager z

15um x 15um

200um/layer

Single β

Image of charge

Imager z

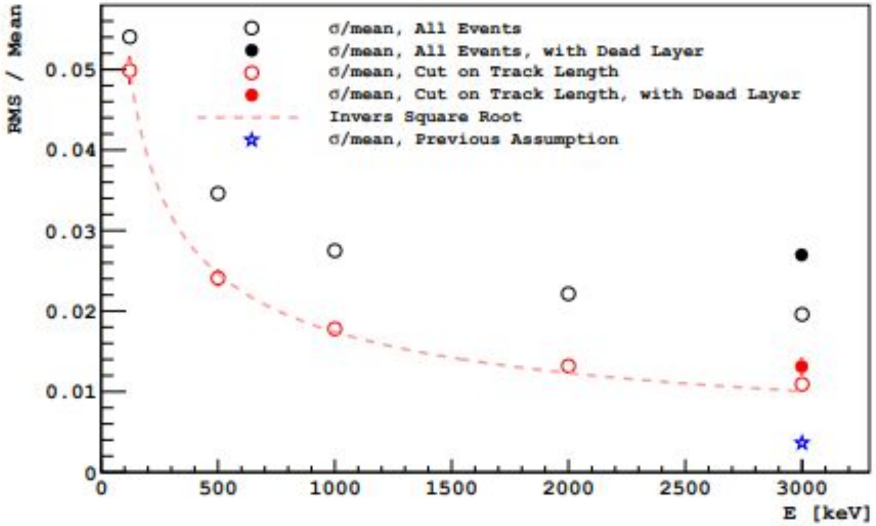
Simulated double beta decay spectrum.

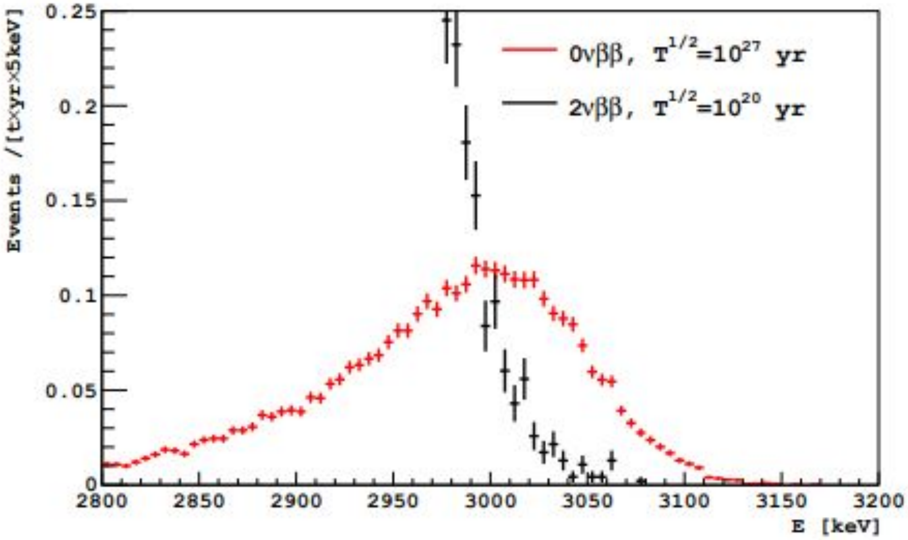
Charge yield and energy resolution of aSe was measured in this work JINST16(2021)P06018

The intrinsic aSe energy resolution dominates the detector resolution.

Charge yield has strong correlation with electron track length!

Background rate < 6 x 10^{-5} /keV/ton/year
$T^{1/2} > 10^{28}$ years limit on ^{82}Se $0\nu\beta\beta$





Solar neutrino spectroscopy with 0 background

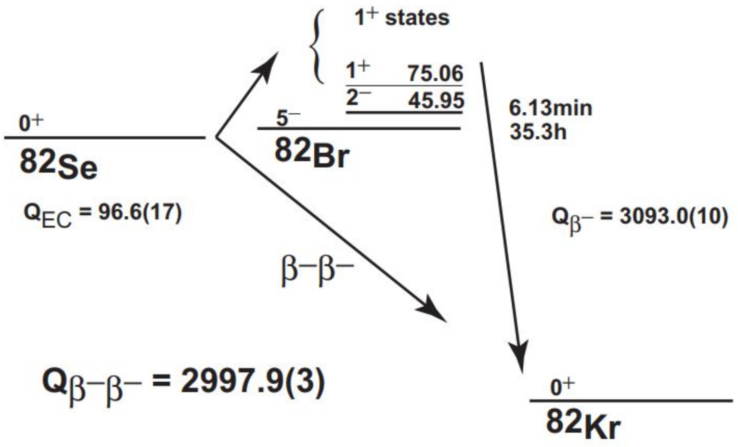
The Selena Neutrino Experiment | Alvaro E. Chavarria | TAUP2021 - YouTube

Triple sequence:

$\nu_e + {}^{82}\mathrm{Se} \longrightarrow {}^{82}\mathrm{Br}^* + \overset{E_\nu - 172\ \mathrm{keV}}{\overset{\downarrow}{e^-}} + \mathrm{C.E.}\ (29\ \mathrm{keV})$ "prompt"

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

${}^{82}\mathrm{Br} \longrightarrow {}^{82}\mathrm{Kr} + \gamma + \underset{\text{445 keV end-point}}{\underset{\uparrow}{\beta^-}}$ $\tau_{1/2} = 35$ hours



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

A-Se Energy Resolution Measurement

Experimentally demonstrate the intrinsic energy resolution of amorphous selenium, and measure the charge yield.

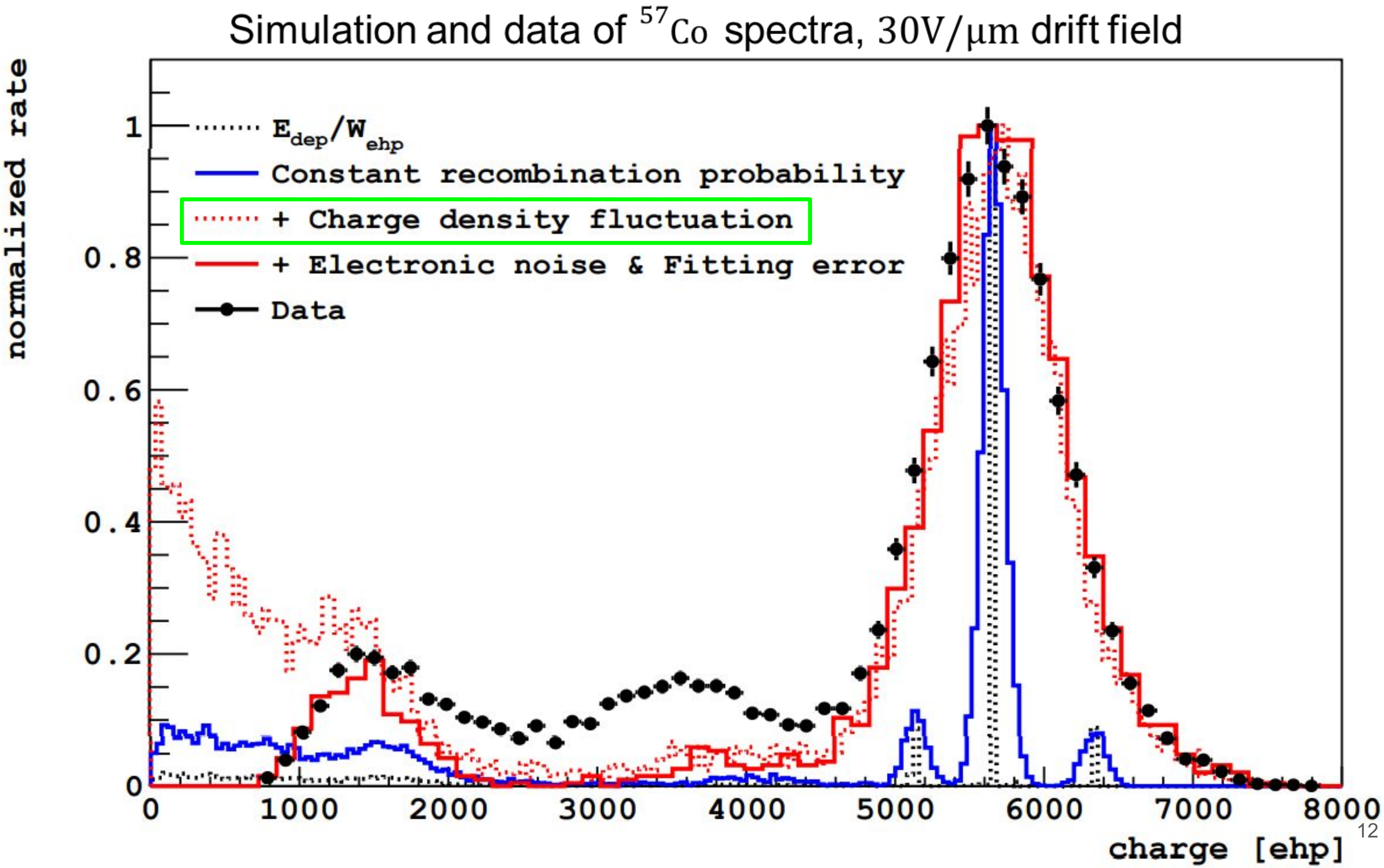
A-Se is known to have low carrier mobility:

Material	E_g[eV]	W_0[eV]	mu_e [cm^2 V^{-1} s^{-1}]	mu_h[cm^2 V^{-1} s^{-1}]
Ge	0.67	2.96	3900	1900
Si	1.12	3.6	1350	450
a-Si	1.9	6	1-4	0.05
a-Se	2.3	4-7	0.0036	0.13

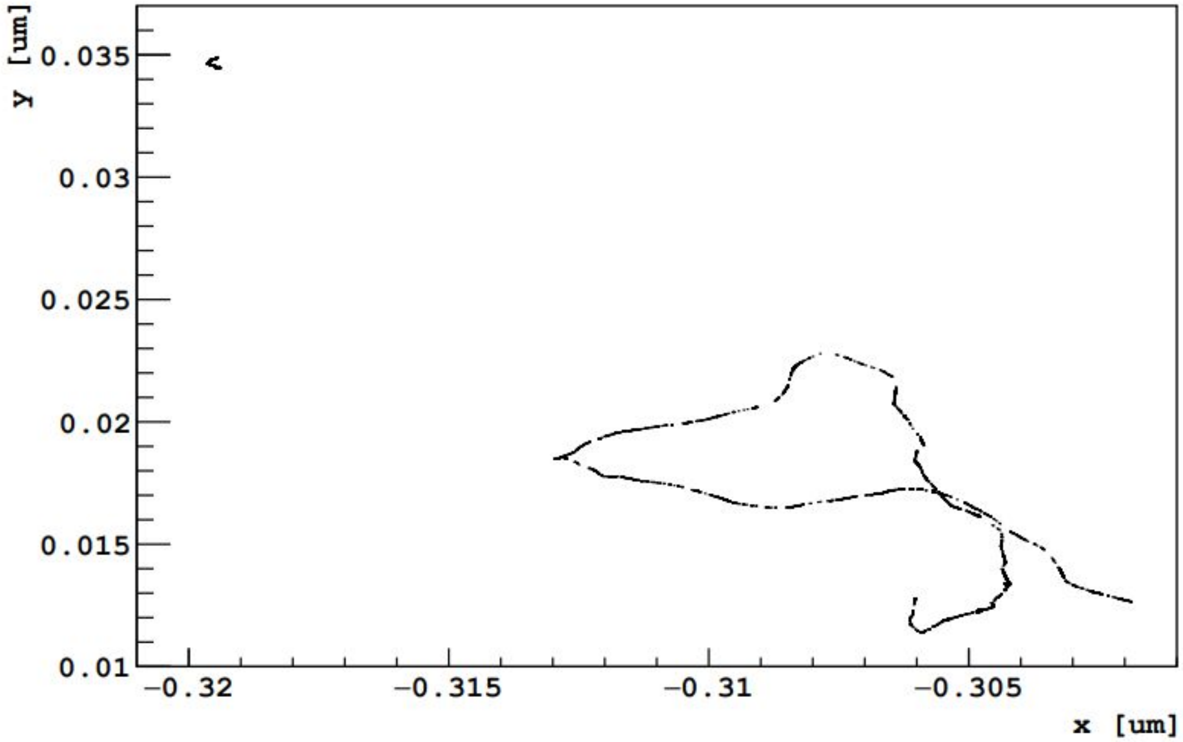
Pulse shape measurement of $^{57}\mathrm{Co}\ 122\mathrm{keV}\ \gamma$ in single pixel a-Se detector.

- High bias field.
- Low electronic noise.
- Carrier discrimination from pulse shape.

Decomposition of The Resolution



Why?



Escaped charge:

$$\frac{Q}{Q_0} = \frac{\mathcal{E}}{\xi} \ln\left(1 + \frac{\xi}{\mathcal{E}}\right)$$

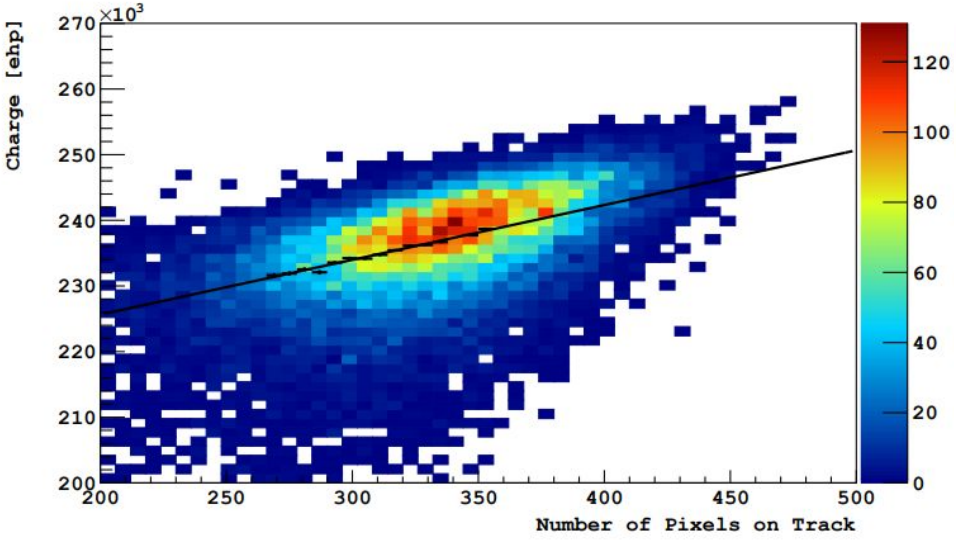
$$\xi = \alpha Q_0 / 4a^2(\mu_- + \mu_+)$$

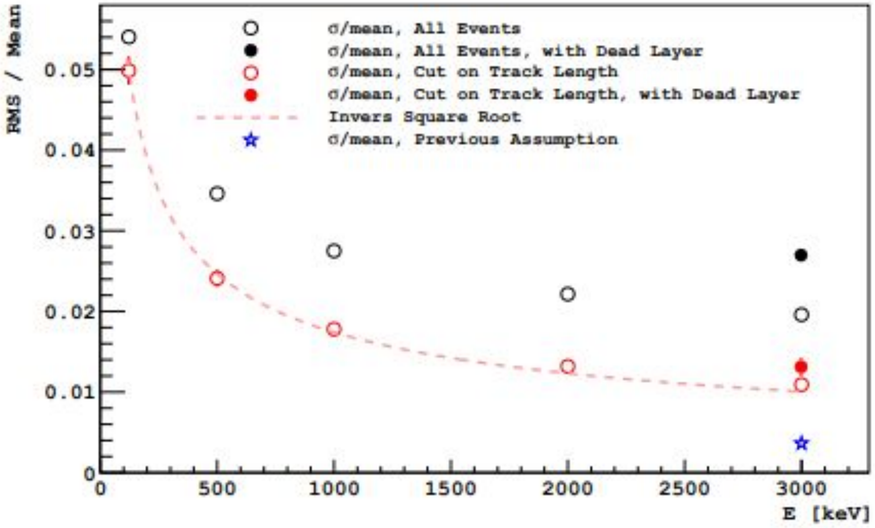
Higher charge density → Higher recombination.
dE/dx **Landau distribution**! → Large fluctuation in charge density! Delta rays!

Not a problem in traditional detectors, where the recombination probability is low.

a-Se low charge mobility → Low initial thermalization diffusion → Less smearing and larger fluctuation.

First order correction





2998 keV single β events
Correct with track length (number of pixels on track)

For mono energy peak, the correction is equivalent to a selection on track length.
Energy resolution scales as 1/Sqrt(E) again!

Second order correction?

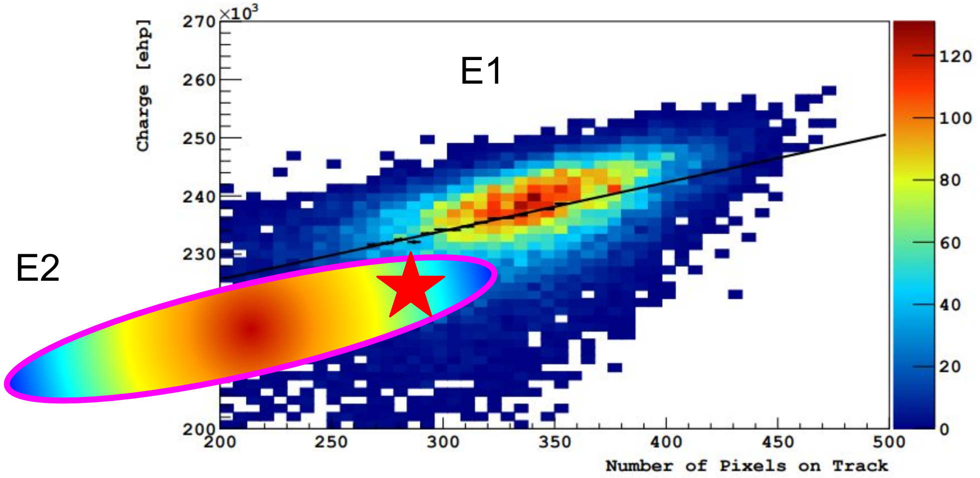
Given a 3D matrix of the pixelated charge of an electron track, what is the electron energy?

Not deterministic.
A distribution

Deterministic?

True energy ⟹ Track ⟹ Energy

Is this a well-defined question?



If a certain track image do not uniquely related to one energy, what can we do?
What is the distribution of the energy related to the track?

What about a pixelated track image?

Machine learning attempts

We use the 122keV gamma data to tune a customized recombination model implemented in Geant4. Then generate simulations as training data set.

Feed DNN / CNN the whole 3D matrix → Even worse than using charge as energy variable

Train on small 16*16*3 matrices of track segments → No significant improvement

Use a tracing algorithm to serialize the track to 1D, convert the 3D matrix to 1D data of (charge density, trace curvature) pairs. → Slightly better than the track-length corrected energy resolution.

And other random attempts… No guidance and systematic study, didn’t see significant improvements.

Tasks

Order by importance:

1) Energy reconstruction.
2) Tracing.
   Complexity from dead layers, large delta-rays and the bad resolution in Z direction.
3) Background rejection. (Classification)
   Base on the performance of the tracing algorithm.
   Find the start of a single electron track, which is not a Bragg peak.
   Identify the track as single electron background.

Questions

What type of algorithm better matches the problem?

How large should the training data set be? What computation power do we need?

How to implement the physics into the algorithm?

- Use the symmetries in the system:
  - Translation symmetry.
  - Rotation symmetry (partially broken by the pixelization).
  - Rotation symmetry of the trace along each local forward direction.
  - High energy tracks contains tracks of lower energies!
- Define features as multi-variable input instead of using the image?
  - Track length, total charge +
  - Number of Bragg peaks? Number of bifurcations?
  - Moments?
  - Curvature or straightness?

Ideas

Hadron calorimeter: shower, clustering, energy regression.

Use two variable regression works.

Intermediate steps, introduce more features step by step.

Improve dE/dX fitting by segment the tract to start/middle/end…
Build a rule-based model first.

Build a toy data, with the simplest feature and train the model first.

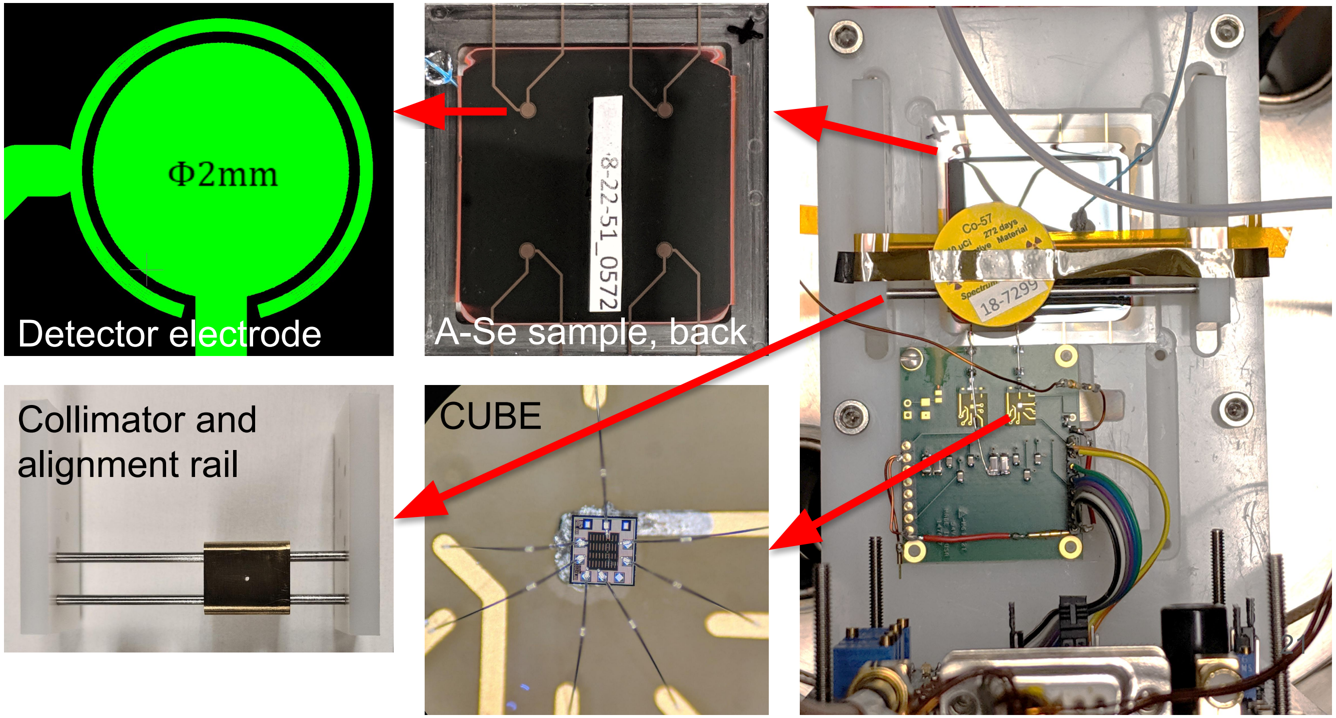
Emulsion detector.

Back up

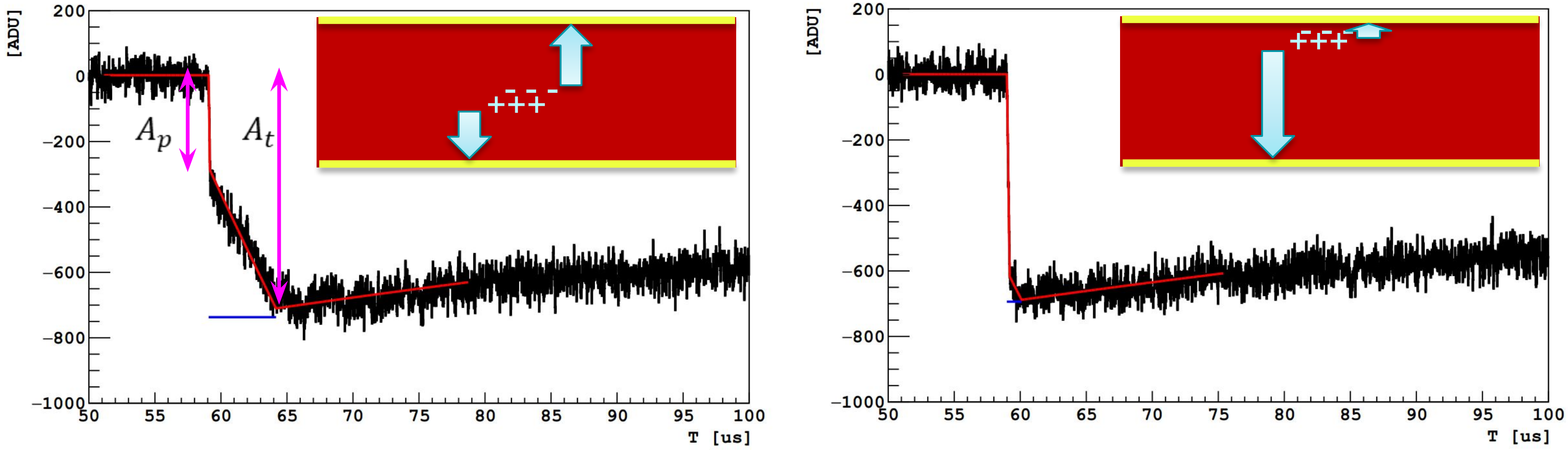
System Setup

- 200µm thick a-Se sample from Hologic.
- 2mm diameter single pixel detector with guarding ring.
- CUBE charge sensitive amplifier from XGLab.
- Brass collimator.
- ^{57}Co source, 122keV and 136keV γ.
- Vacuum chamber to hold voltage up to 10kV.

Thanks Hanguo for the support on the equipment



Signal Formation in a-Se



Two example of waveforms under $30\mathrm{V}/\mu\mathrm{m}$

Left: event happening in the middle of the layer. Right: near anode (top).

Black: Raw waveform

Red: Fit to model

Blue dash: corrected pulse height.

Interaction depth λ: $1 - A_p/A_t$

Estimation of the uncertainty from electronics noise and the fit:

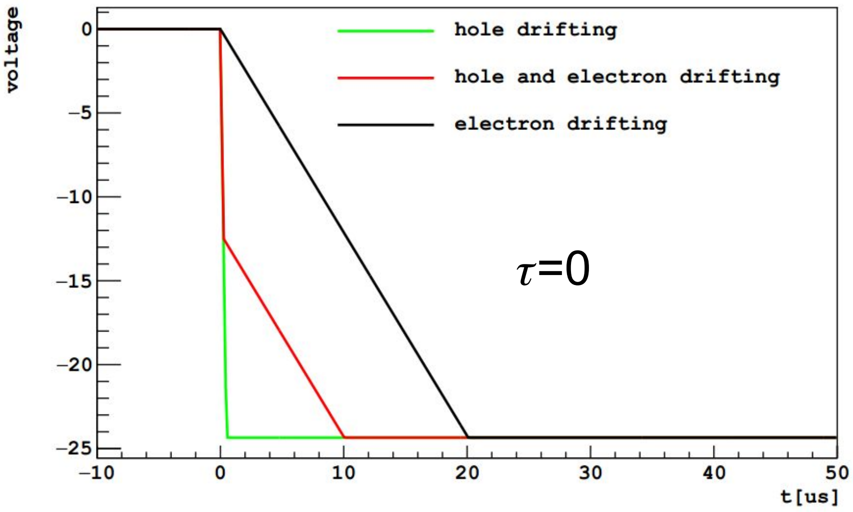
Geant4 simulation + charge propagation + electronics response simulation

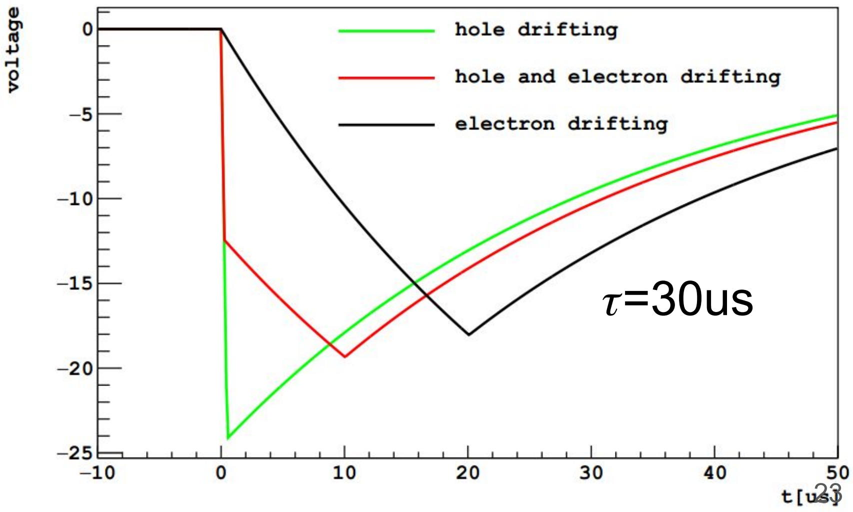
Fluctuation on the pulse amplitude $\sim 100e^-$

Fitting function:

$$A(t) = A\frac{V}{d^2}\sum_{i=\mathrm{e,h}}\begin{cases}0 & t<0\\ \mu_i\tau_i\left(1-e^{-\frac{t}{\tau_i}}\right) & 0<t<t_i\\ \mu_i\tau_i\left(1-e^{-\frac{t_i}{\tau_i}}\right)e^{-\frac{t-t_i}{\tau}} & t>t_i\end{cases}$$

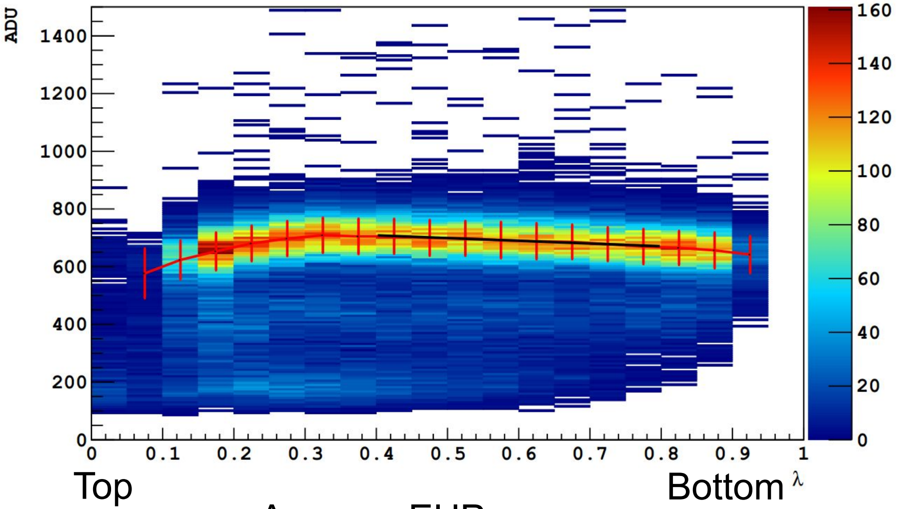
	pulse starts at t=0,	V	biasing voltage,
d	sample thickness,	A	Amplitude,
μ	carrier mobility (Fixed)		
τ	time constant of output high pass filter (Fixed)		
$\tau_{e,h}$	carrier trapping time constant. (Not the trapped electron release time, Fixed)		
$t_{e,h}$	carrier majority collection time		



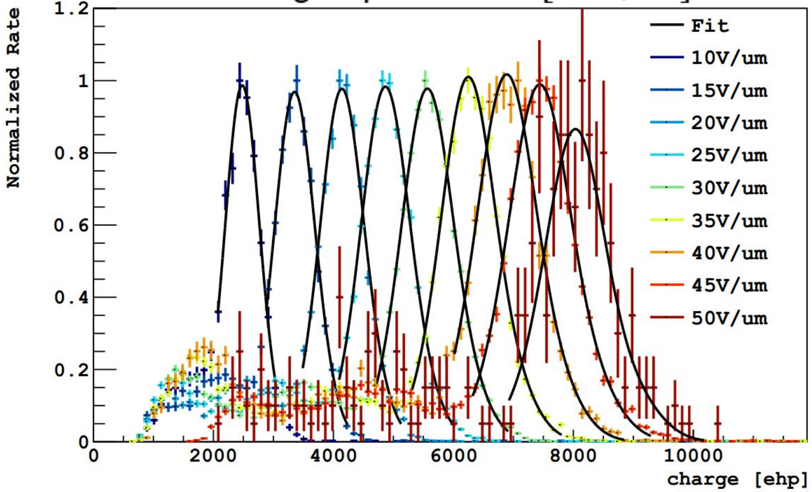


Results – Spectra, Gain, Energy Resolution

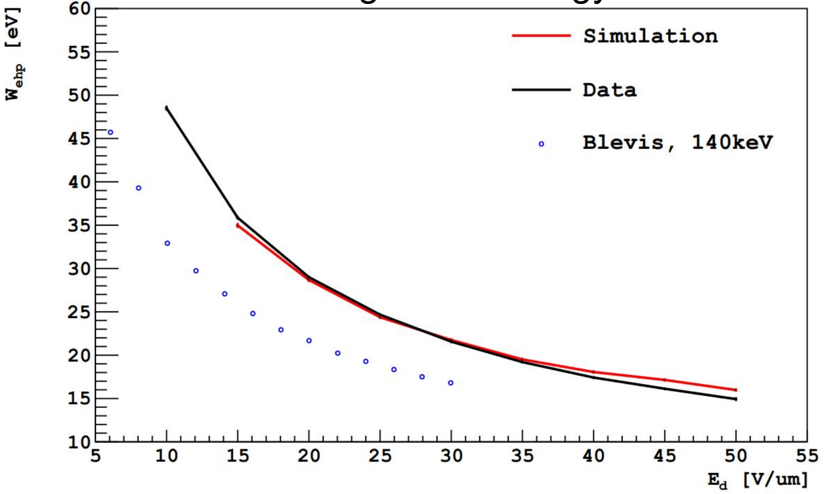
Amplitude vs interaction depth, 30V/um



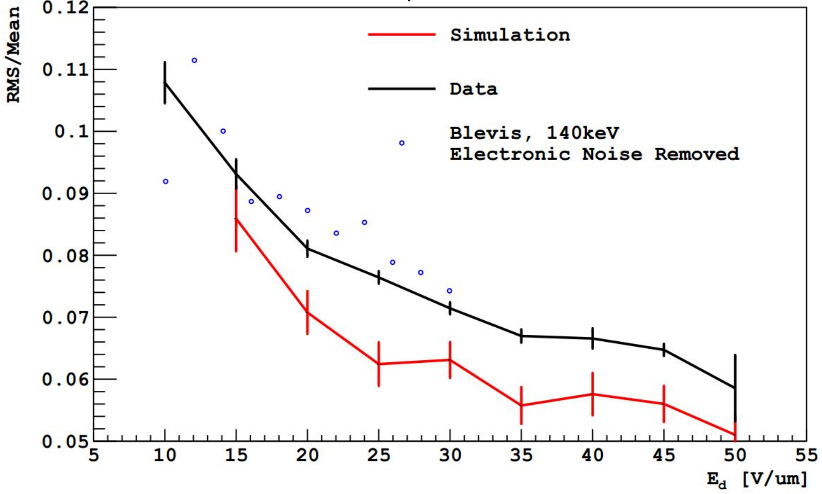
Charge spectra $\lambda \in [0.25,0.5]$



Average EHP energy



Resolution, RMS/mean



Background estimation

Only β tracks which total energy falls in ROI are regard as background.

β from decay chain ^{238}U, ^{232}Th:

- Se: $< 110\mu$Bq/kg

LUCIFER, Eur. Phys. J. C 75 (Dec.,2015) 591–597.

- CMOS array: $< 0.01\mu$Bq/cm^2
- Surface ^{210}Po: $< 0.1\mu$Bq/cm^2

DAMIC, JINST 10 (Aug., 2015) P08014.

- Cosmogenic ^{83}Se: $< 0.02\ \mu$Bq/kg

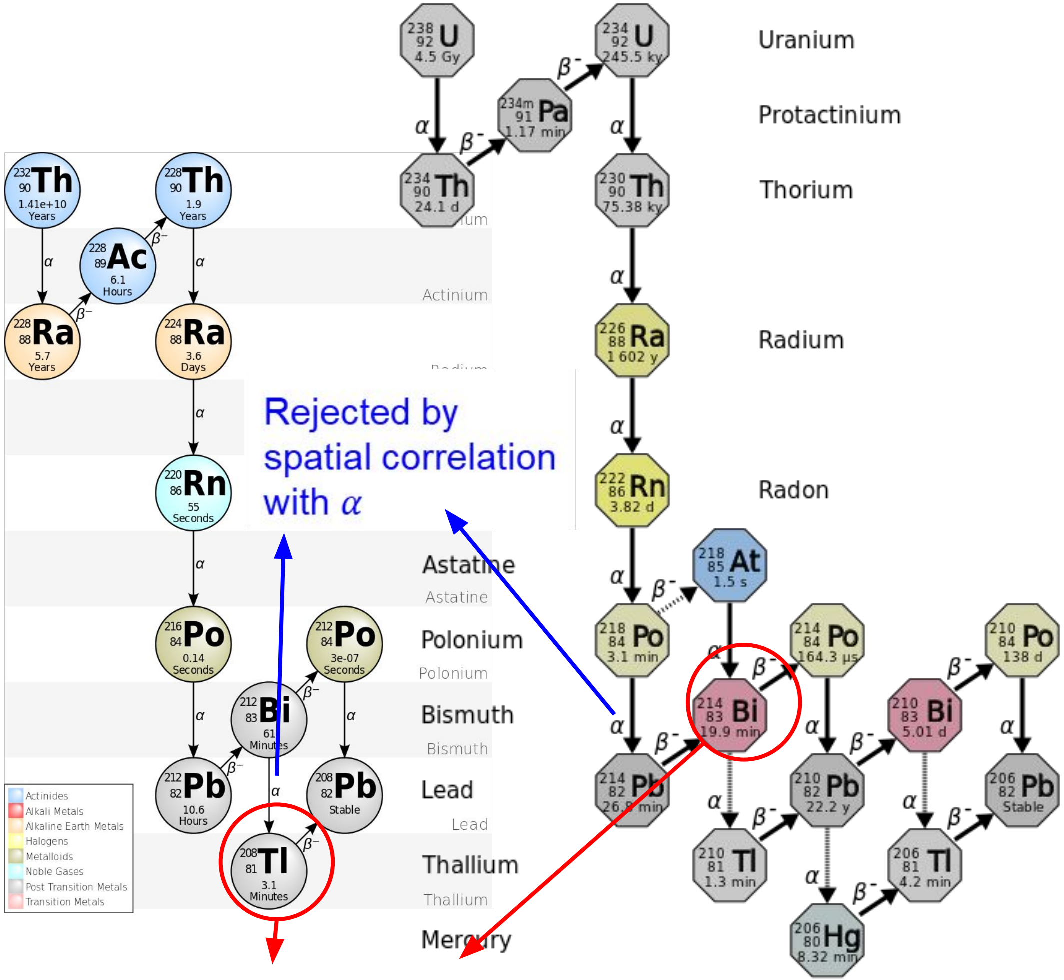
^{78,80,81,82}As: < 0.3 nBq/kg

EXO, JCAP 1308 (Aug.,2013) 049.
EXO, JCAP 2016 (Apr., 2016) 029.

γ with energy > ROI:

- (α,n) reaction
- Cosmogenic ^{56}Co: $< 0.02\ \mu$Bq/kg

LUCIFER, Eur. Phys. J. C 76 (July, 2016) 364.

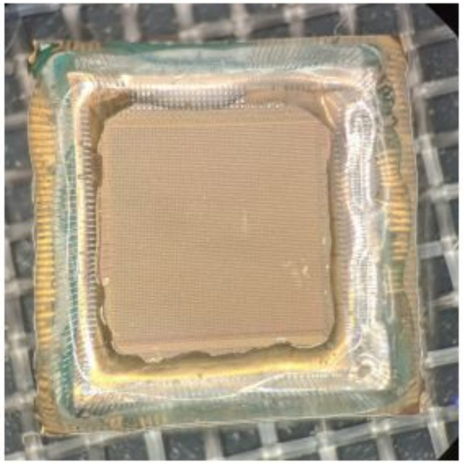


Rejected by spatial correlation with α

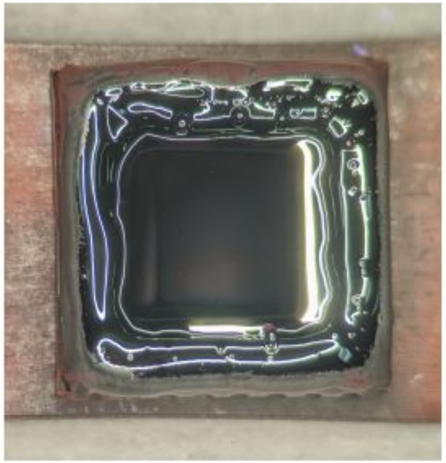
Only β decay in ROI

R&D: Topmetal-II$^-$

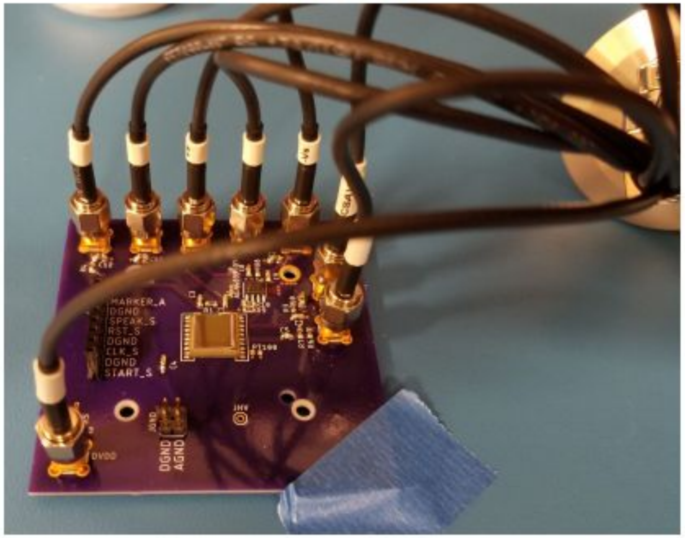
Before aSe



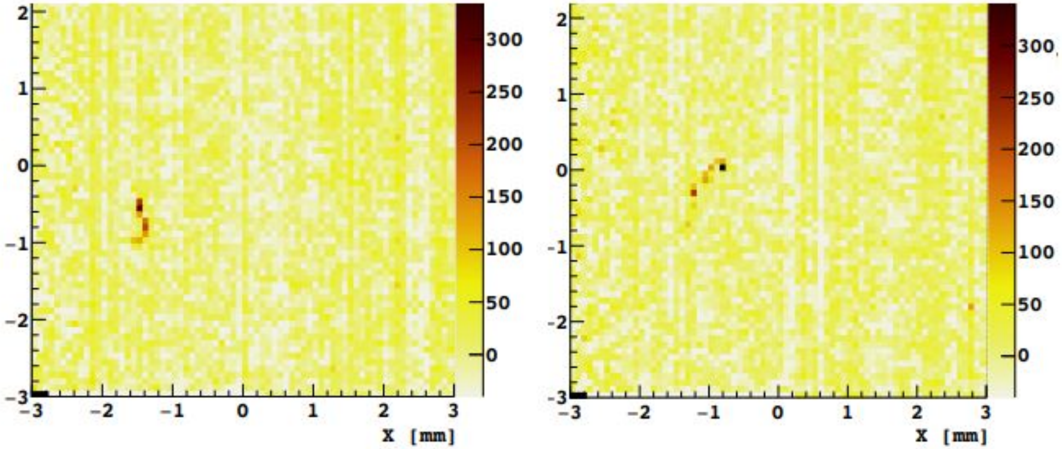
After aSe



Test board



Electron tracks from ^{90}Sr-Y!



- From Y. Mei at LBNL.

NIMA810(2016)144

- CMOS pixel array with exposed metal electrodes.
- (83 μm)^2 pixels
- 15 e^- pixel noise.