Improving the abilities of HPGe detectors with machine learning and applications to positron-based spectroscopy

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Work performed mostly at

The University of Texas at Arlington

Outline

Motivation
(A quick review)

I. Positron annihilation-induced Auger electron spectroscopy (PAES) and Doppler-broadening spectroscopy (DBS)

II. The recently developed positron beam and electron time-of-flight & gamma spectrometers

Direct applications

III. Conventional and machine learning-based methods for extracting *timing* information from HPGe detectors

IV. Conventional and machine learning-based methods for extracting *energy* information from HPGe detectors

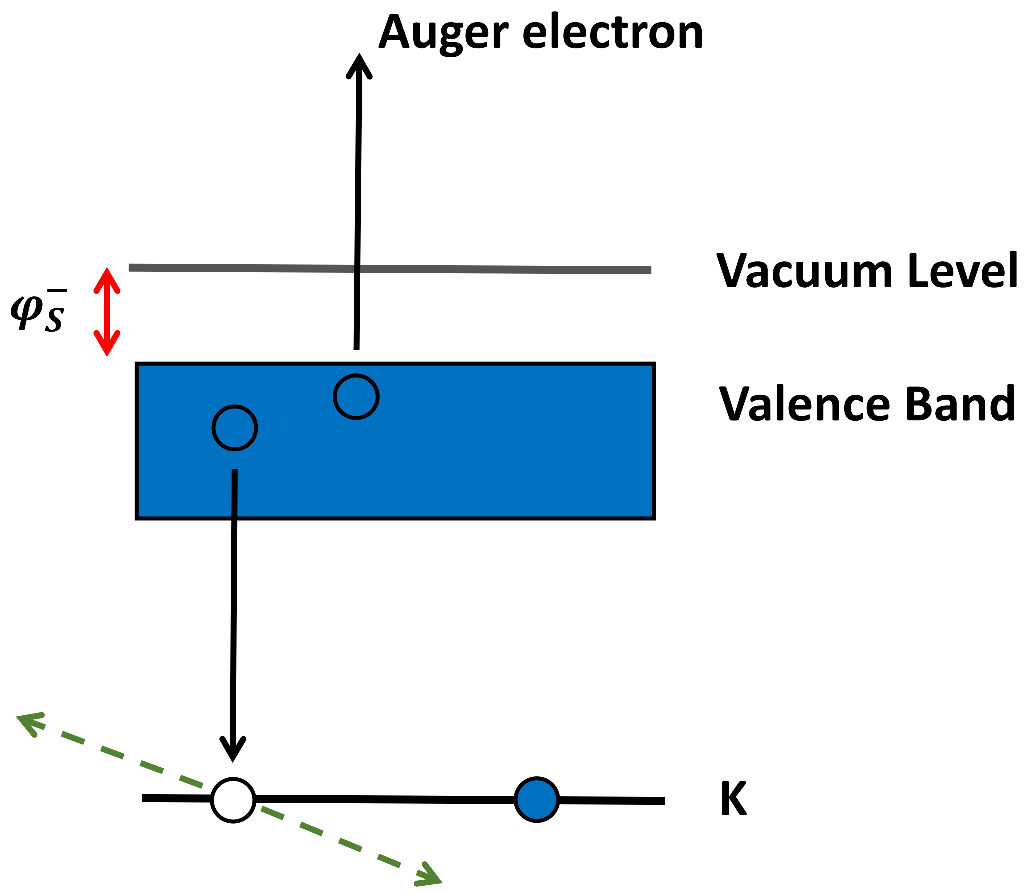
And beyond

V. Introducing the ability to estimate source direction with HPGe detectors using machine learning

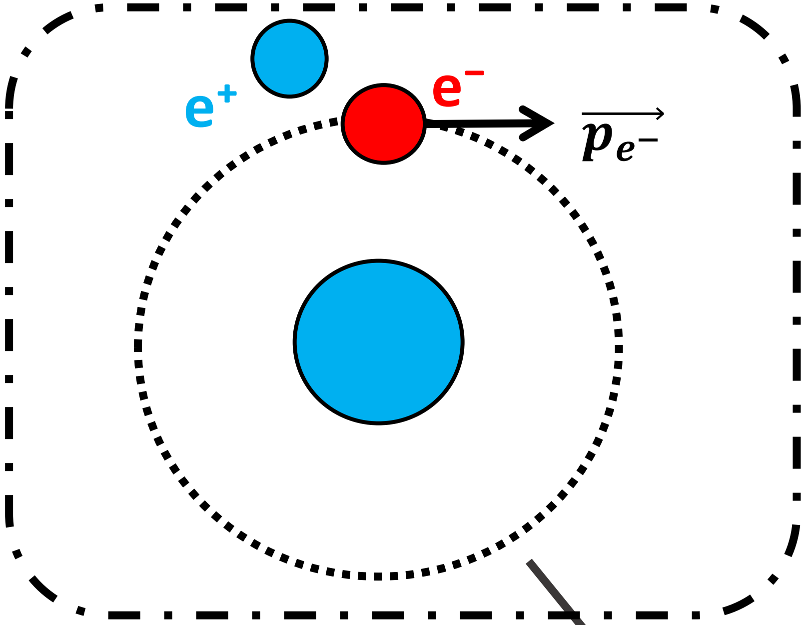
Positron Annihilation-Induced Auger Process

$$E_{auger} = E_{core} - E_{val1} - E_{val2} - \varphi_a$$

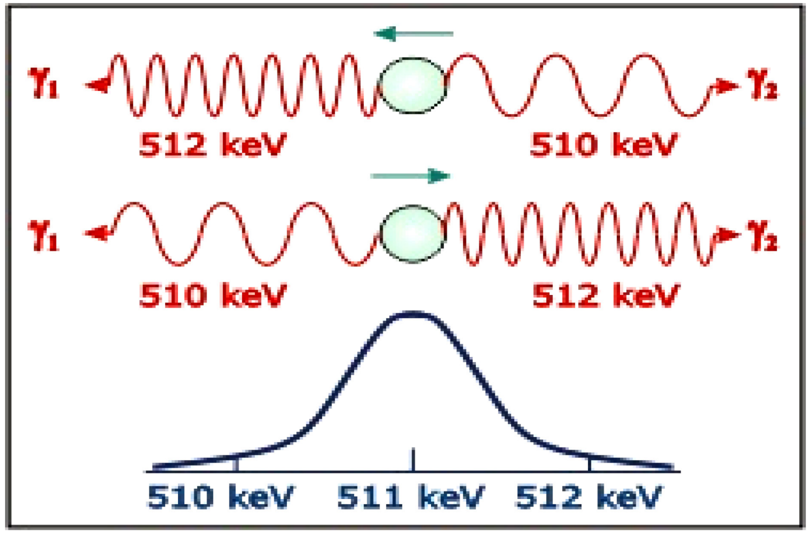
If the positron energy remains below the work function of the material, impact-induced secondary electron contributions will be suppressed

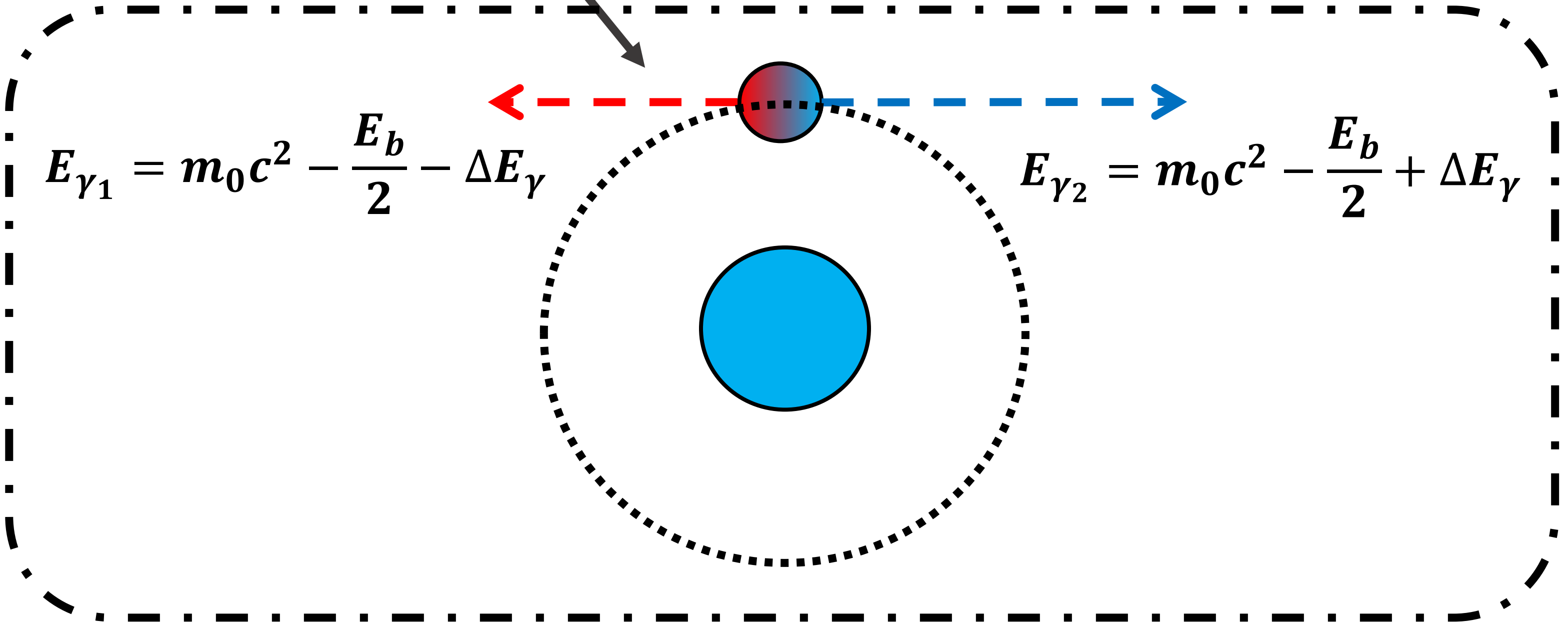


Annihilation Gamma Doppler Shift



$\overrightarrow{p_{e^-}}$





$$E_{\gamma_1} = m_0c^2 - \frac{E_b}{2} - \Delta E_\gamma$$

$$E_{\gamma_2} = m_0c^2 - \frac{E_b}{2} + \Delta E_\gamma$$

Conservation of momentum and energy:

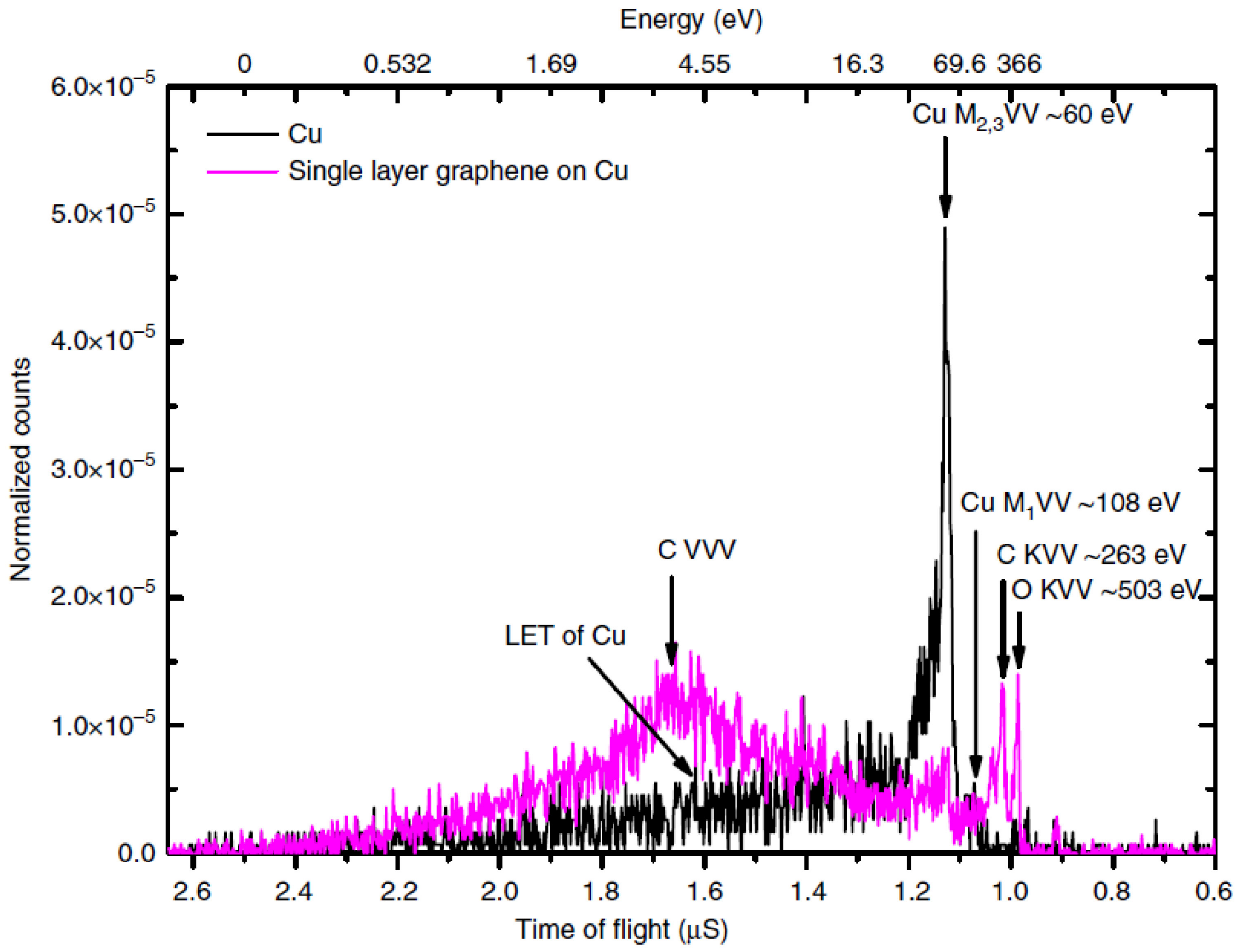
$$\frac{E_{\gamma_2}}{c} - \frac{E_{\gamma_1}}{c} = p_{||e^-}$$

$$E_{\gamma_2} + E_{\gamma_1} = 2m_0c^2 - E_b$$

$$m_0c^2 = 511\ keV$$

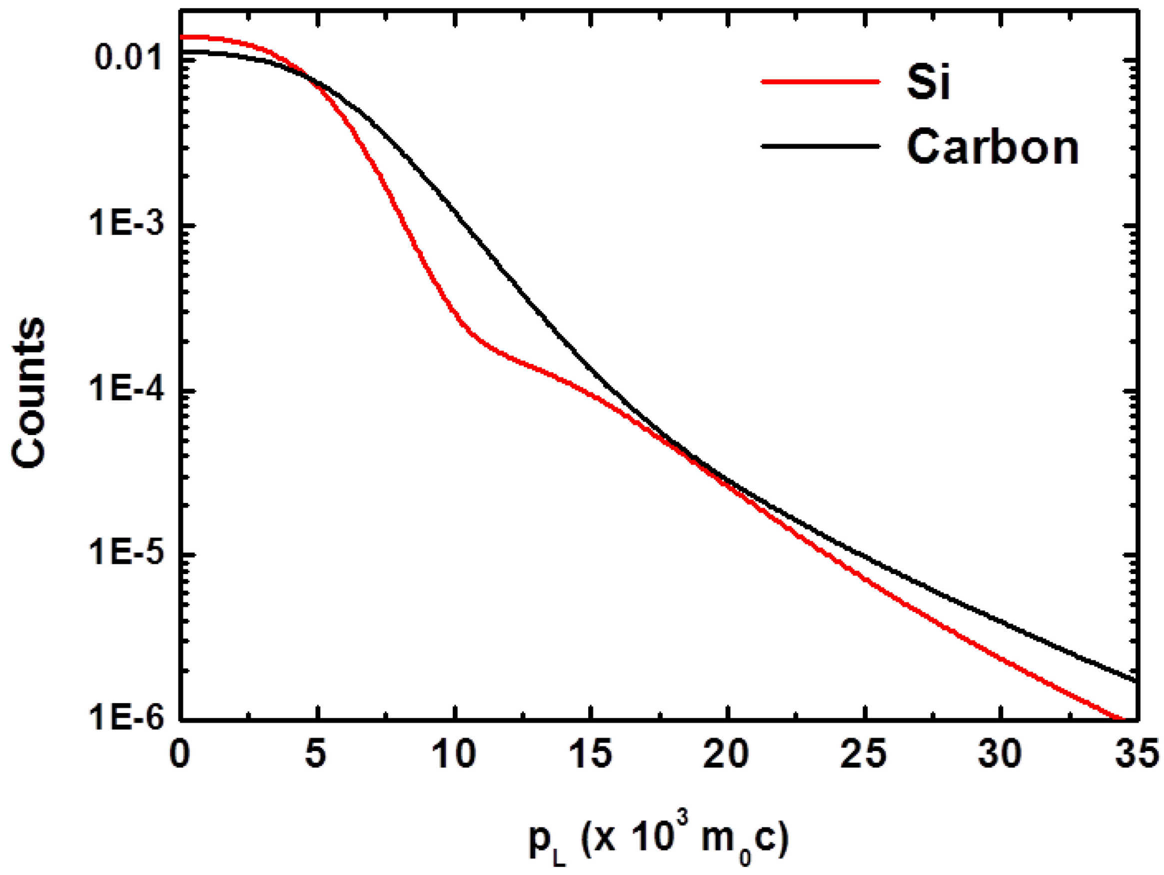
D. G. Green, *Phys. Rev. Lett.* **119**, 203403 (2017)
P. Hautojärvi. *Positrons in Solids* (1979)

Example Spectra



Time-of Flight Positron Annihilation-induced Auger Electron Spectroscopy

Doppler Broadening Spectroscopy Theoretical Spectra

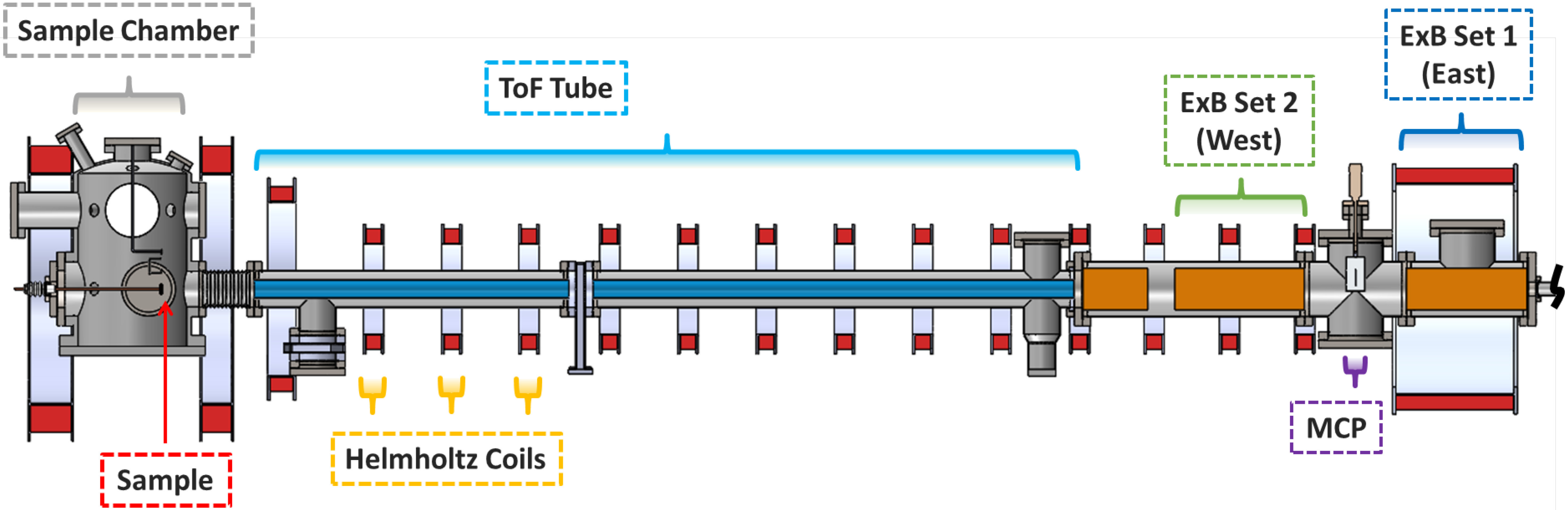


V. A. Chirayath, et al., Nat. Comm. **8** (2017) 16116

P. A. Sterne

Apparatus

Scale Schematic of the positron beam and time-of-flight spectrometer



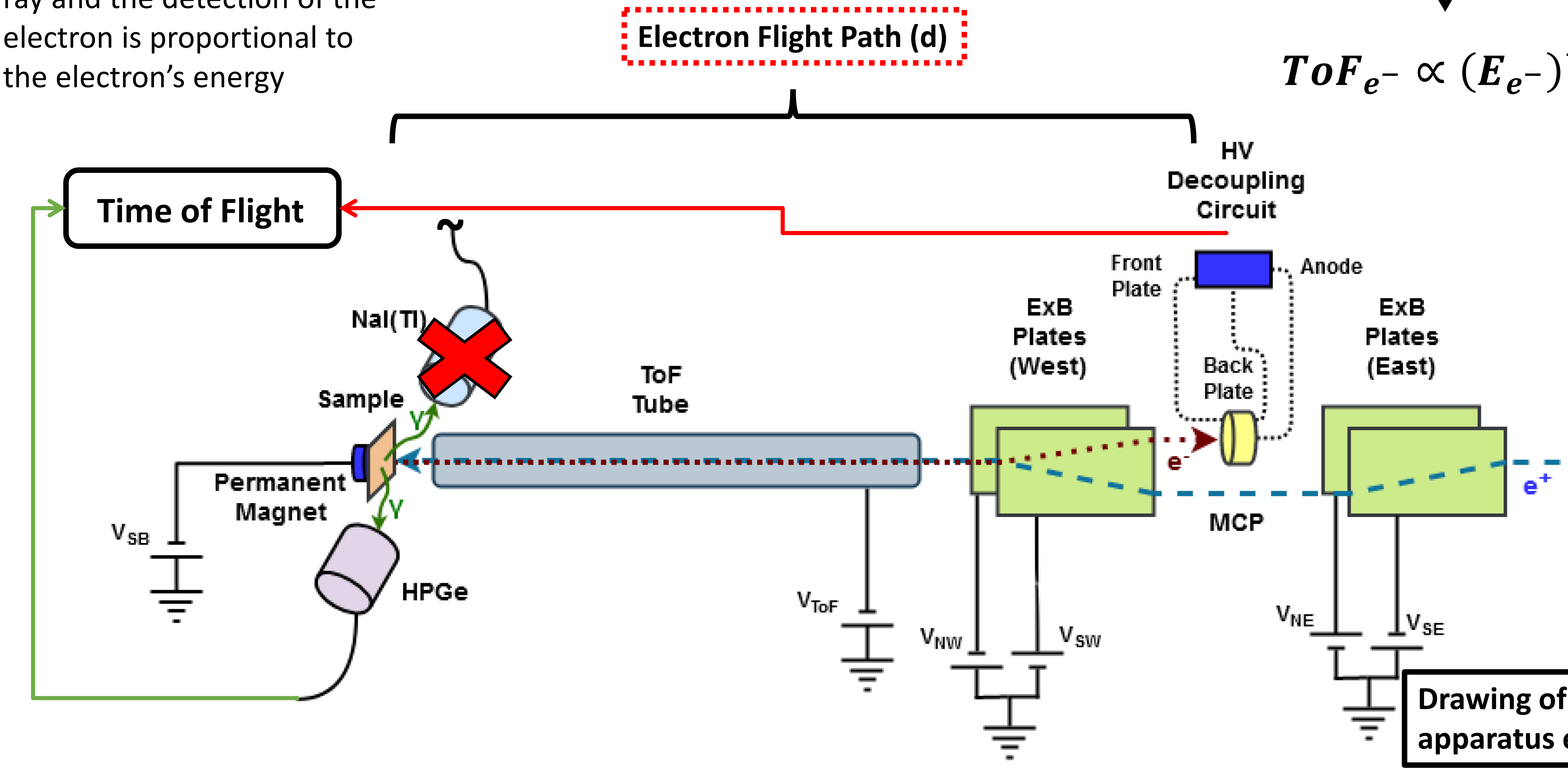
Apparatus | Electronics

The time difference between the detection of the gamma ray and the detection of the electron is proportional to the electron's energy

$$E_{e^-} = \frac{1}{2} m_{e^-} \left(\frac{d_{FlightPath}}{ToF_{e^-}} \right)^2$$

$$\downarrow$$

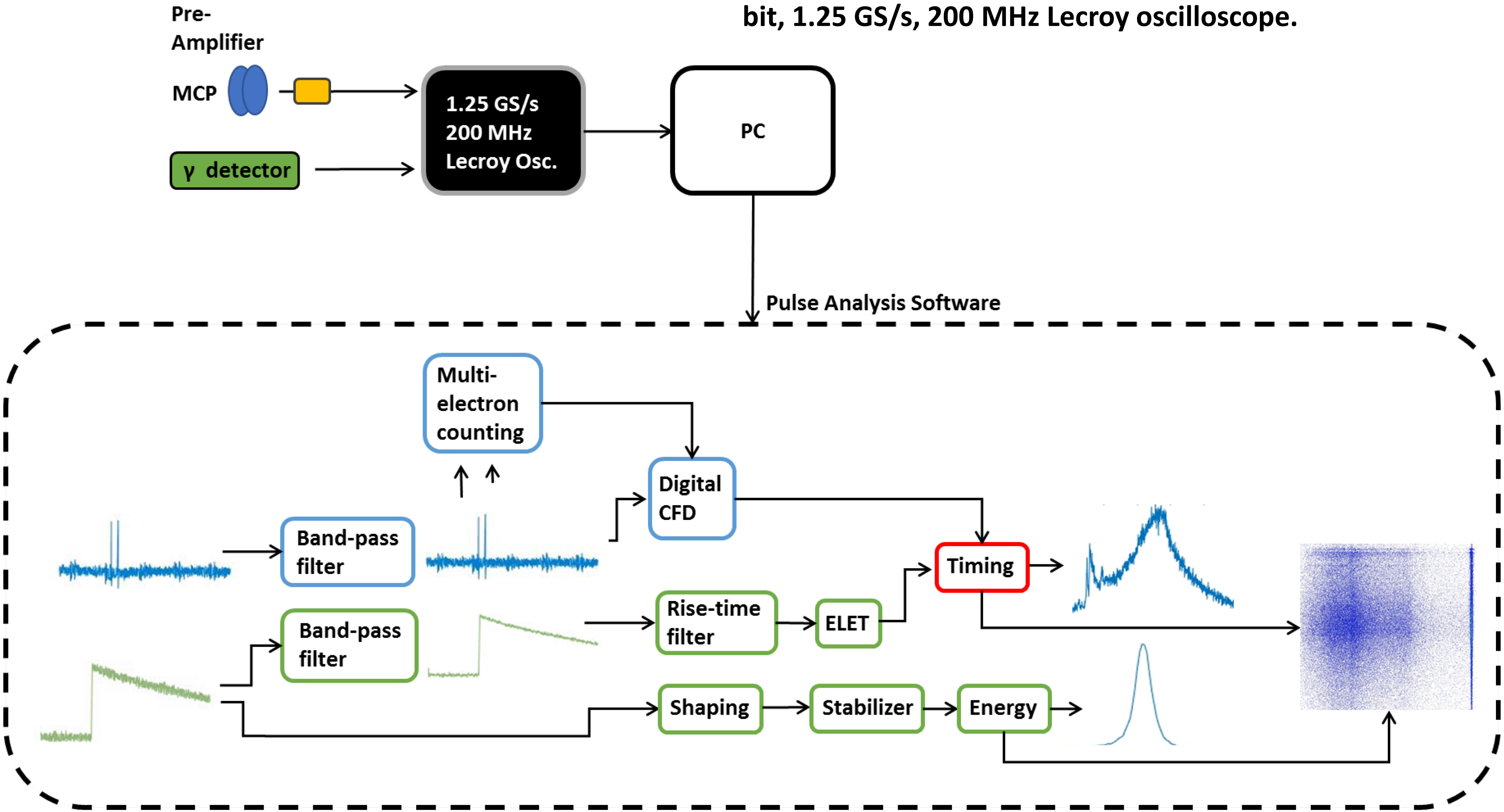
$$ToF_{e^-} \propto (E_{e^-})^{-\frac{1}{2}}$$



Drawing of the apparatus electronics

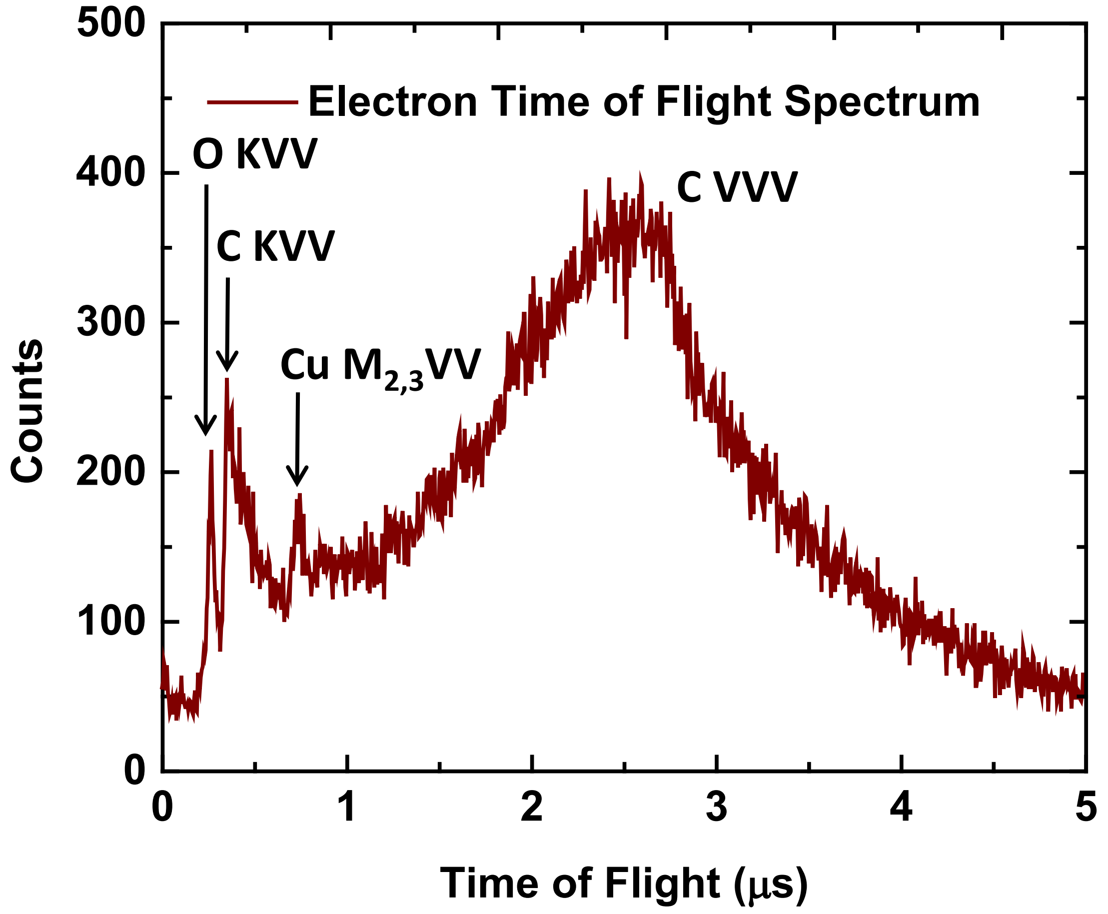
Digital Pulse Analysis

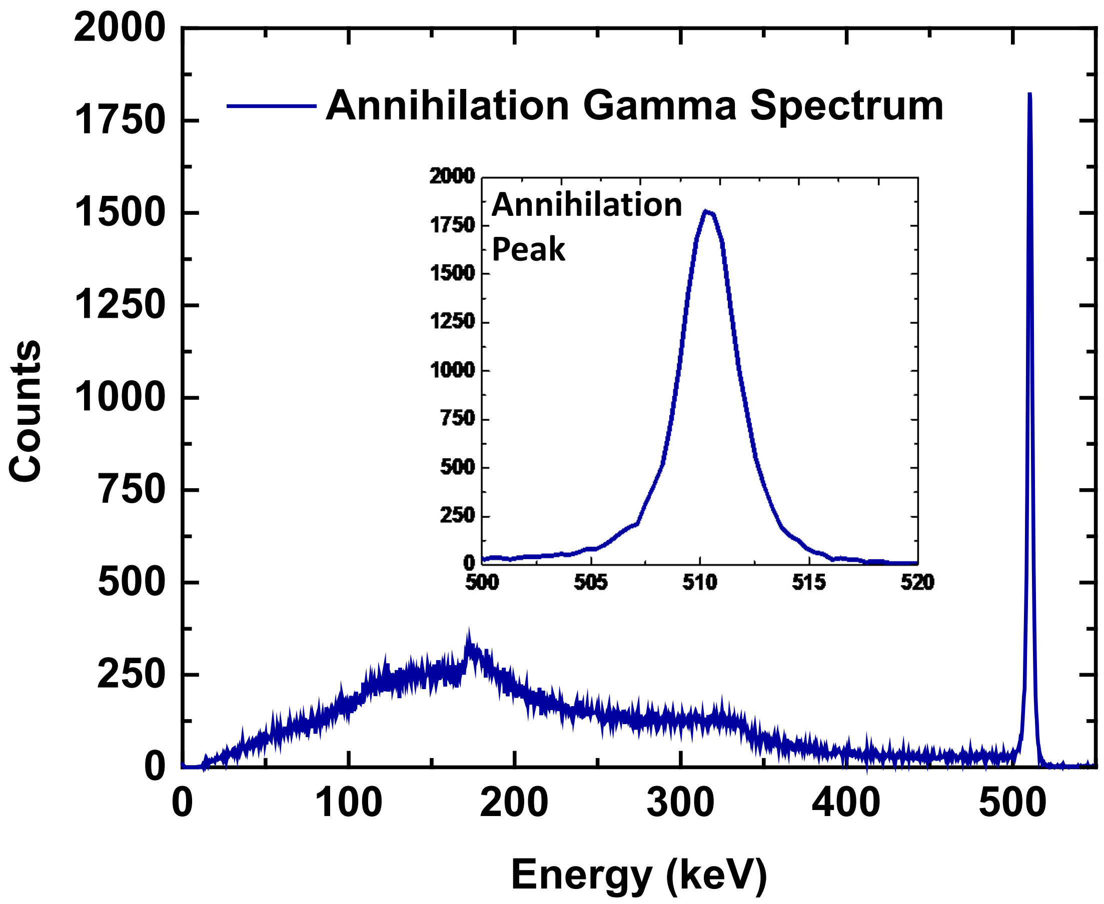
A diagram of the software developed to perform Gamma-electron coincidence. The digital pulses are acquired by a 12-bit, 1.25 GS/s, 200 MHz Lecroy oscilloscope.



Gamma–Auger Coincidence

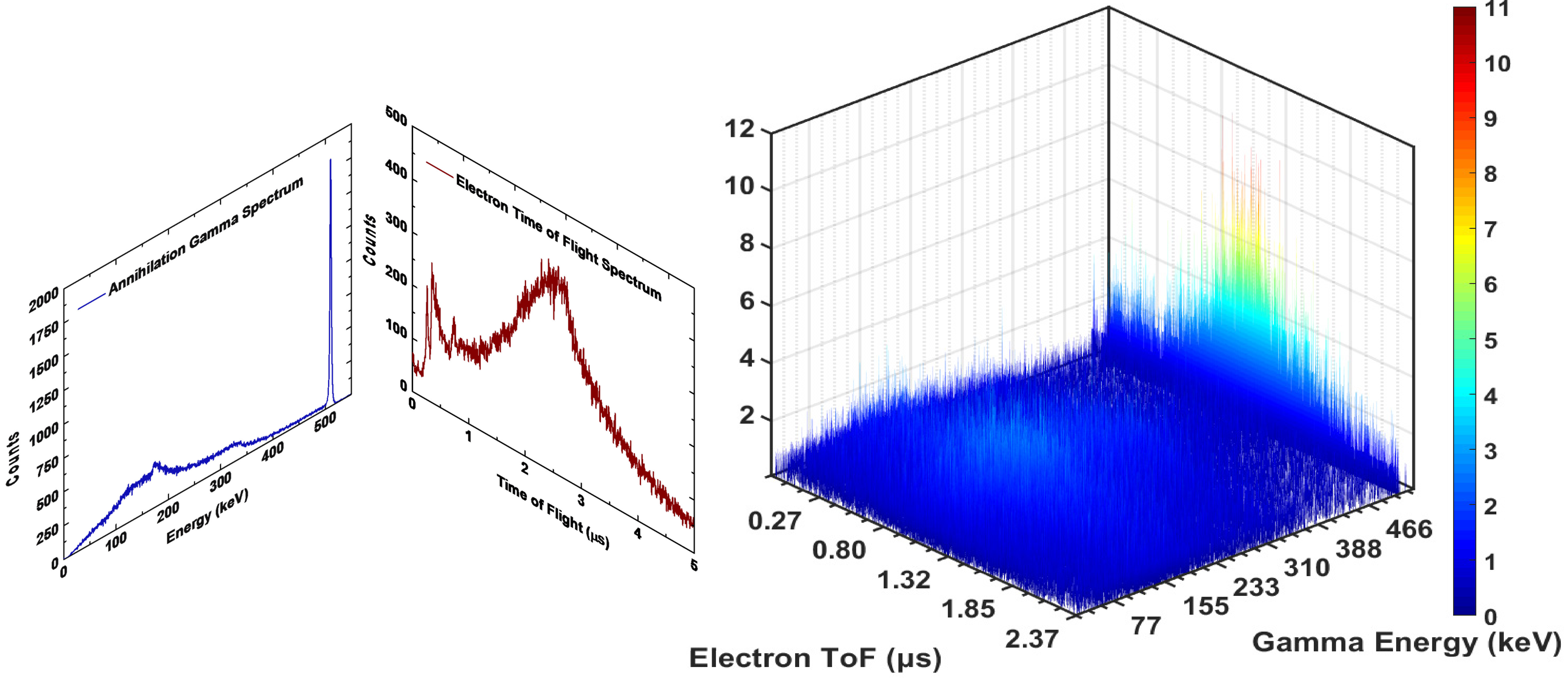
The original goal of the experiments





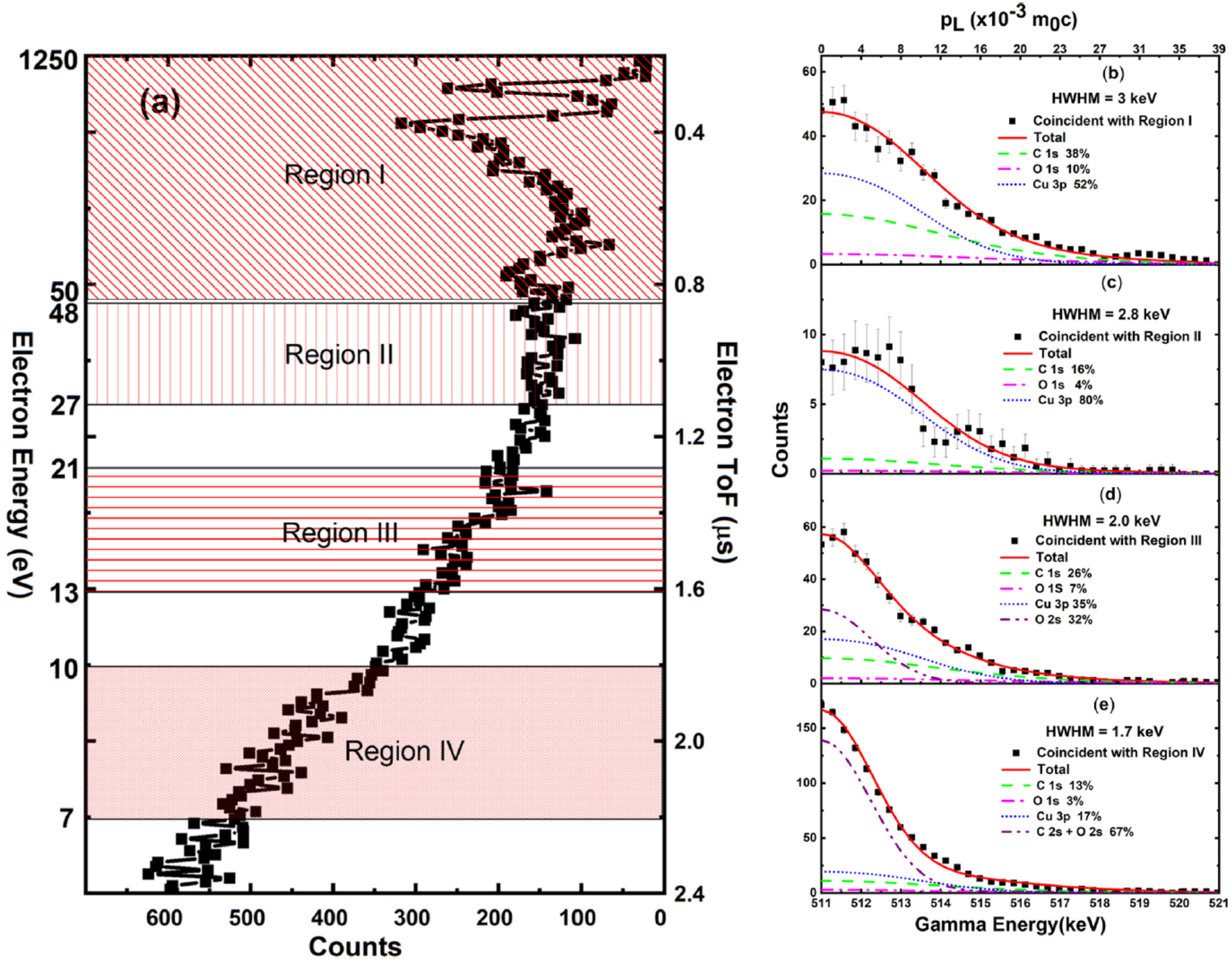
Gamma–Auger Coincidence

The spectrum



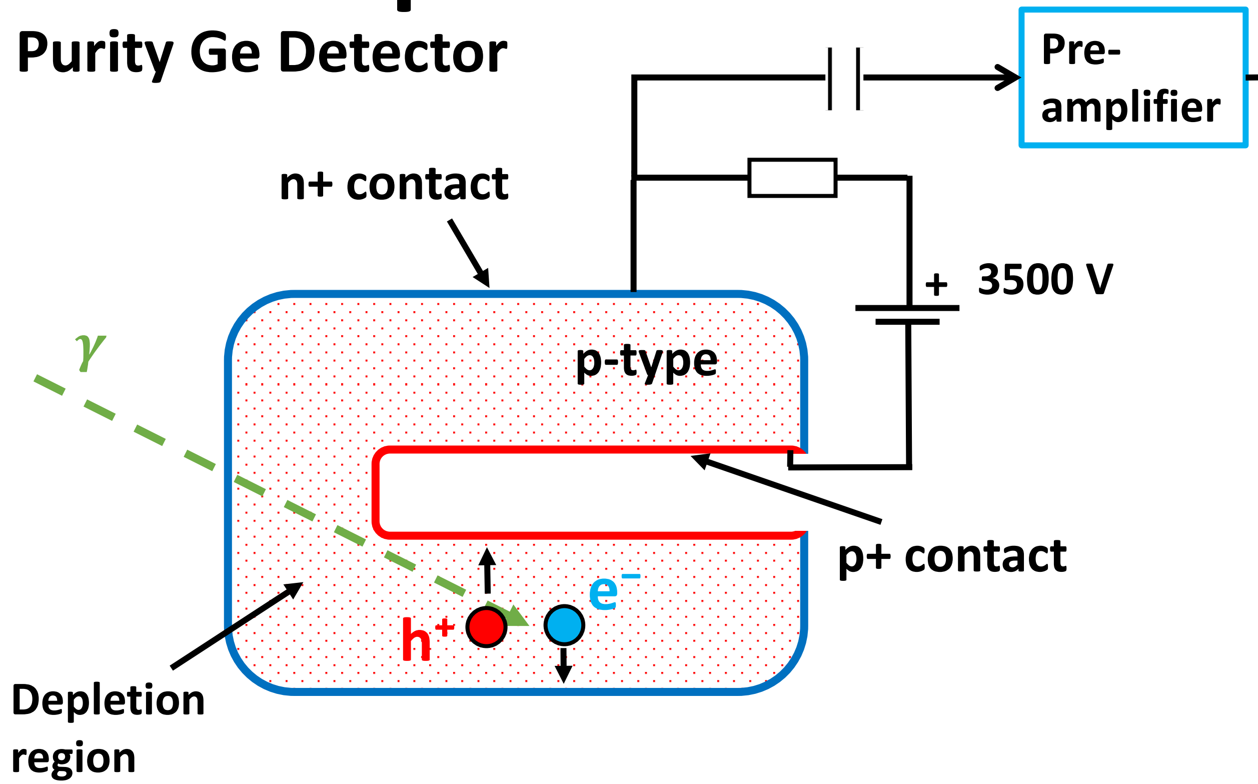
Gamma–Auger Coincidence

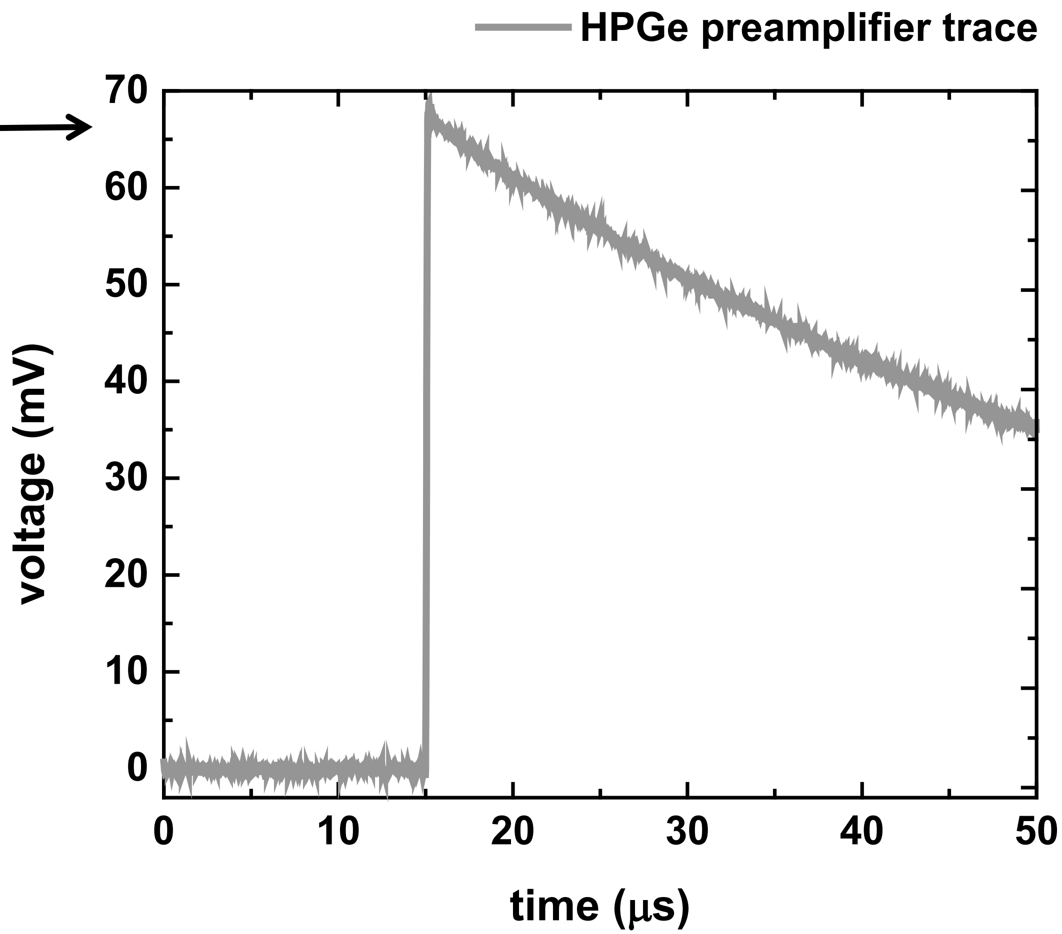
The analysis/results



Detectors | HPGe

High Purity Ge Detector





Ideal resolution at 511 keV:

$$\Delta E = 1.27\sqrt{E} = 908\ eV$$

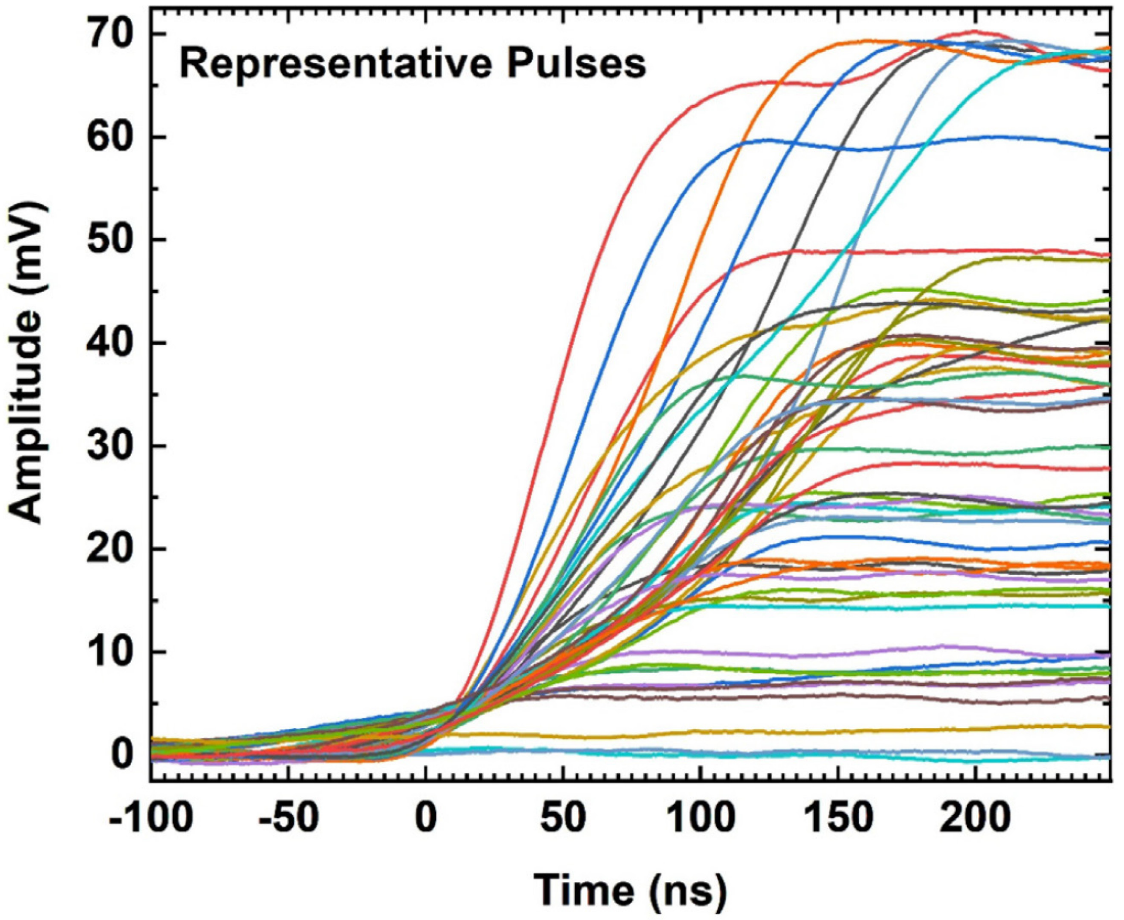
$$\Delta E_S = \sqrt{(\Delta E)^2 + (\Delta N)^2} + \Delta E_\gamma$$

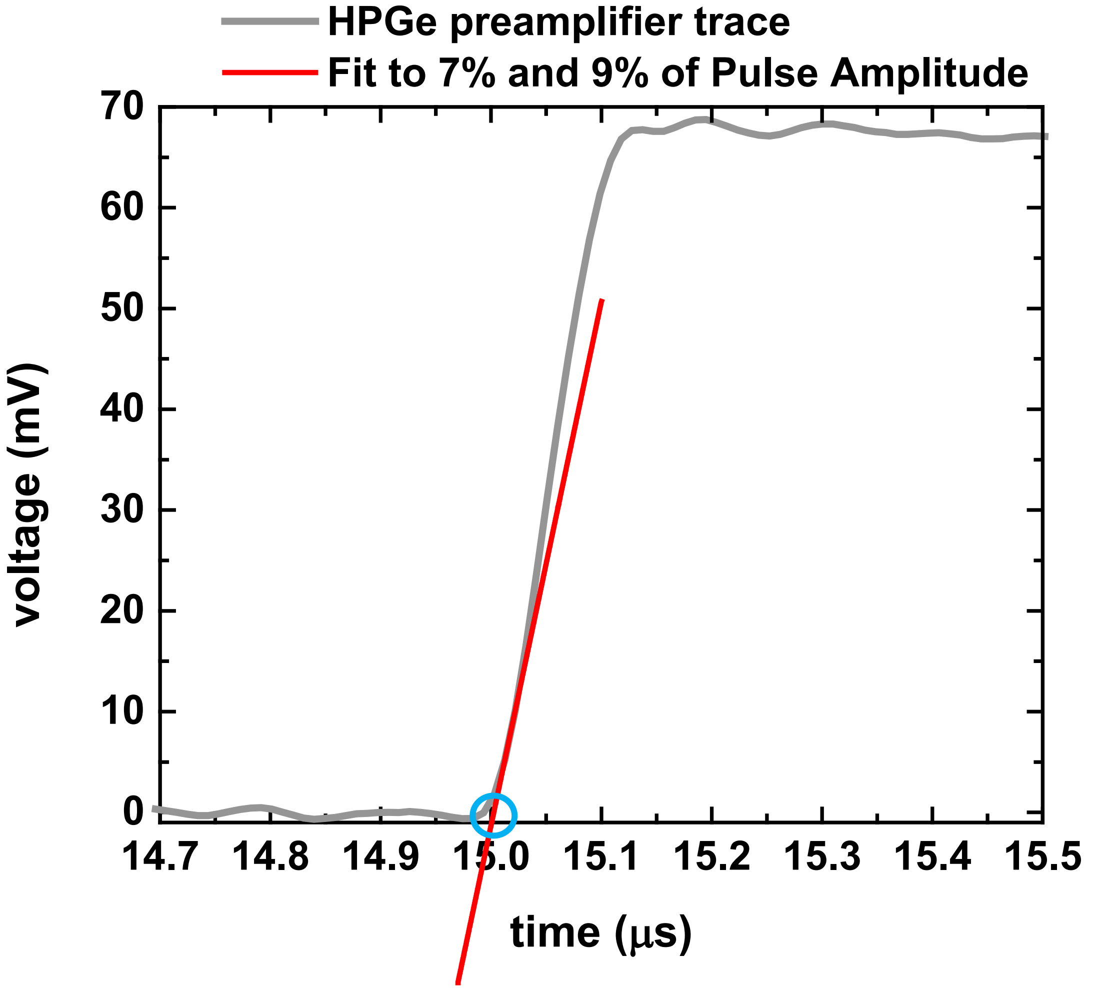
$\Delta E_\gamma = Doppler\ shift$ $\Delta N = Noise$

Glenn F. Knoll. *Radiation Detection and Measurement (4th)*

Extraction of Gamma Timing

Extrapolated Leading Edge Timing (ELET)

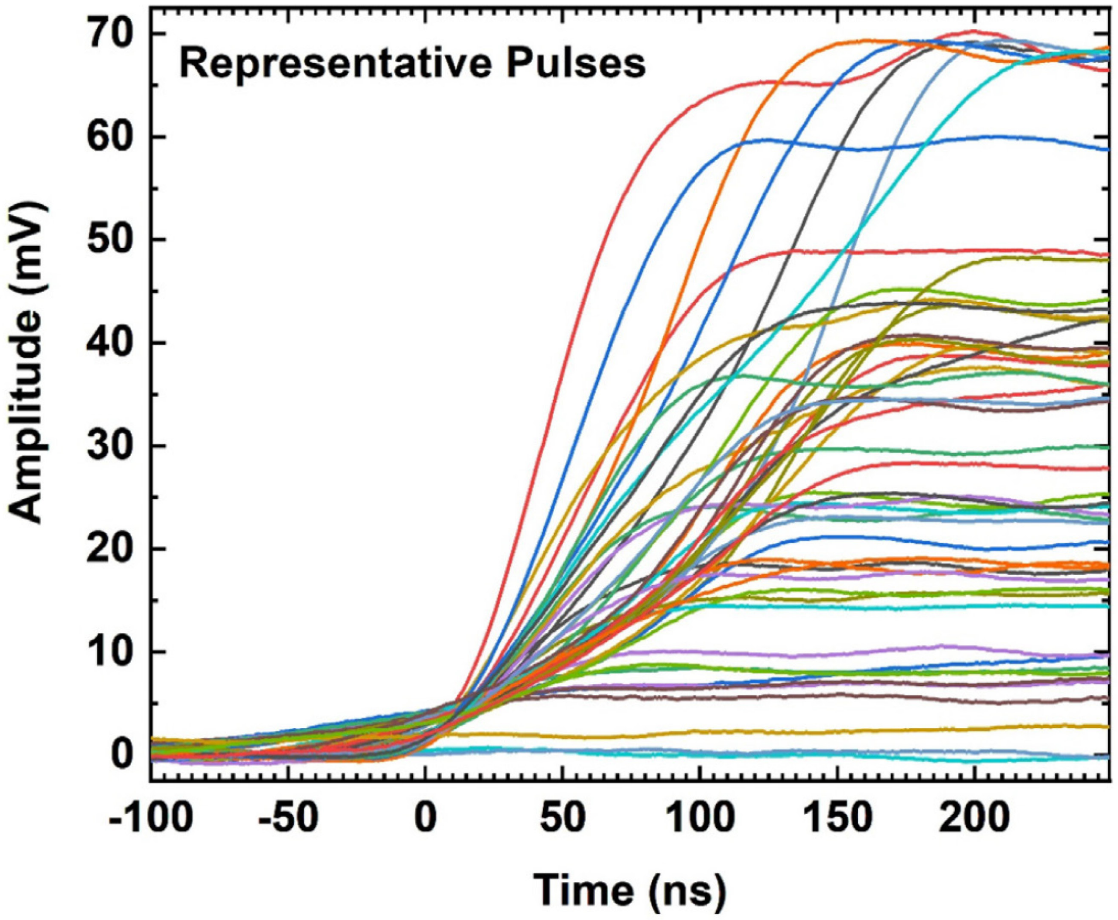


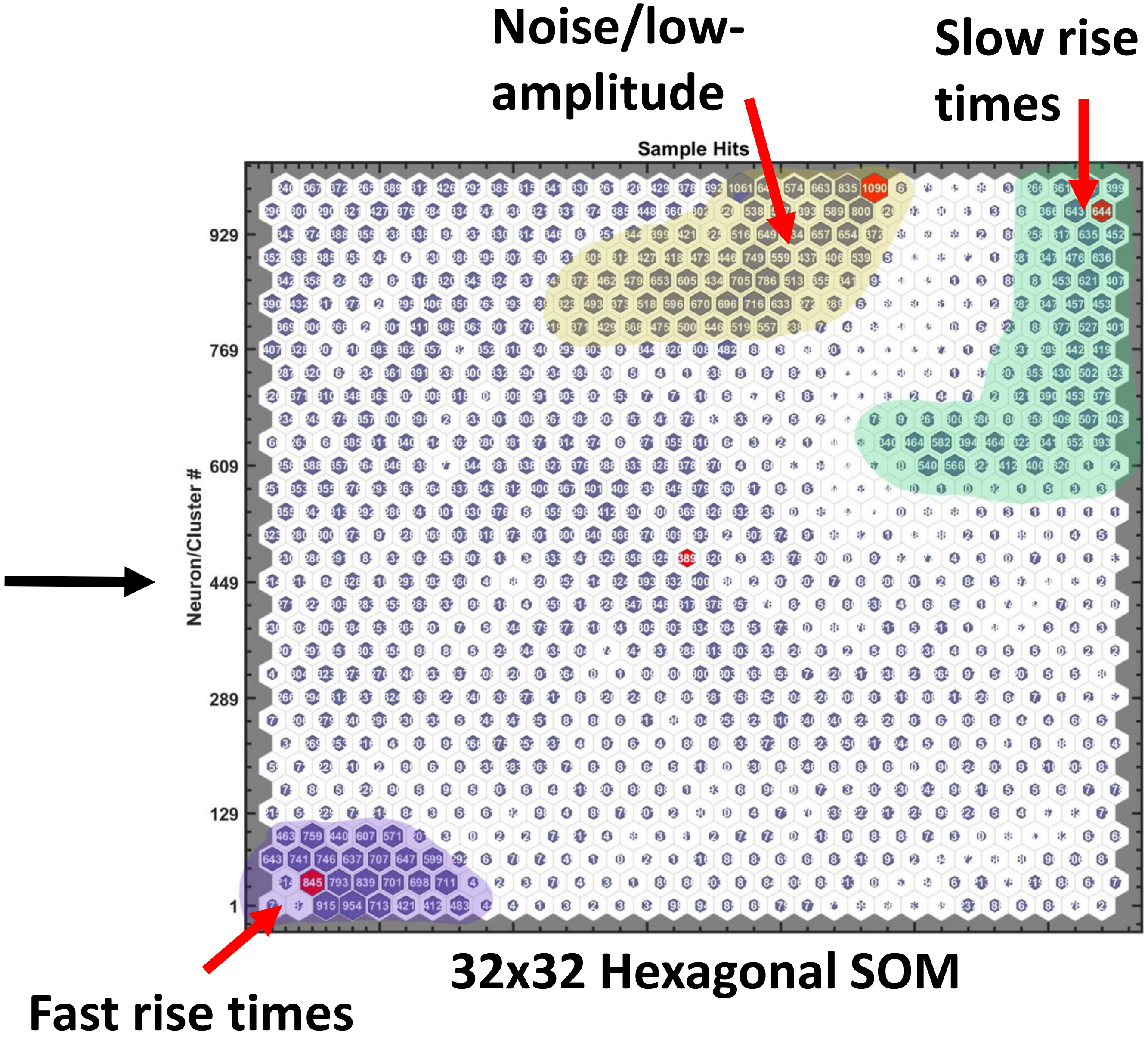


Glenn F. Knoll. *Radiation Detection and Measurement (4th)*

Extraction of Timing Information | SOM

Self-Organizing Map

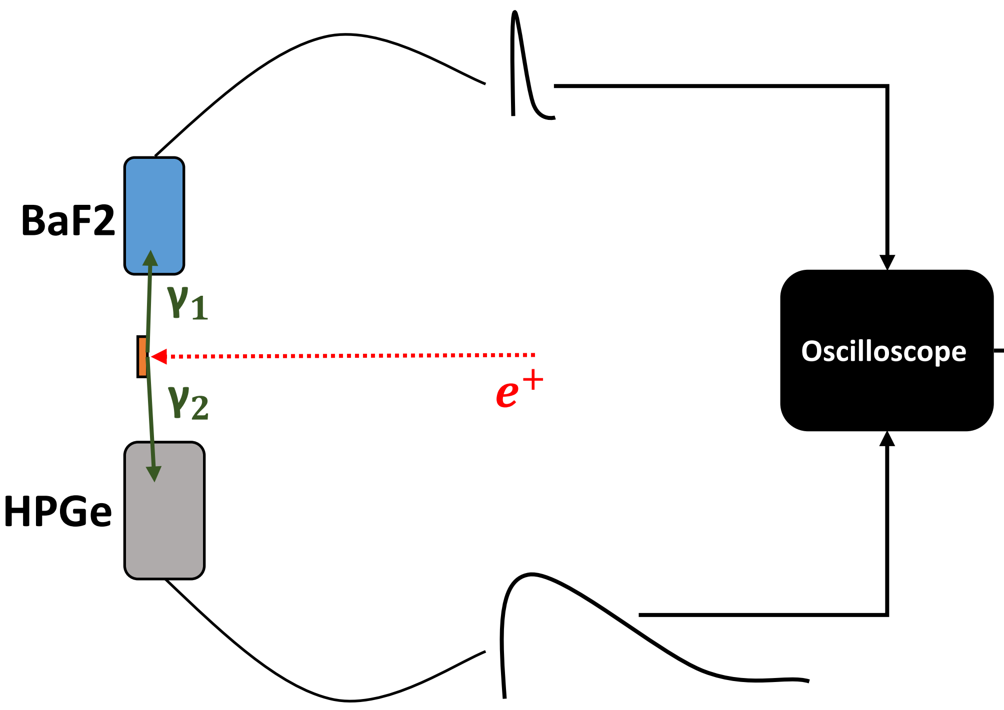


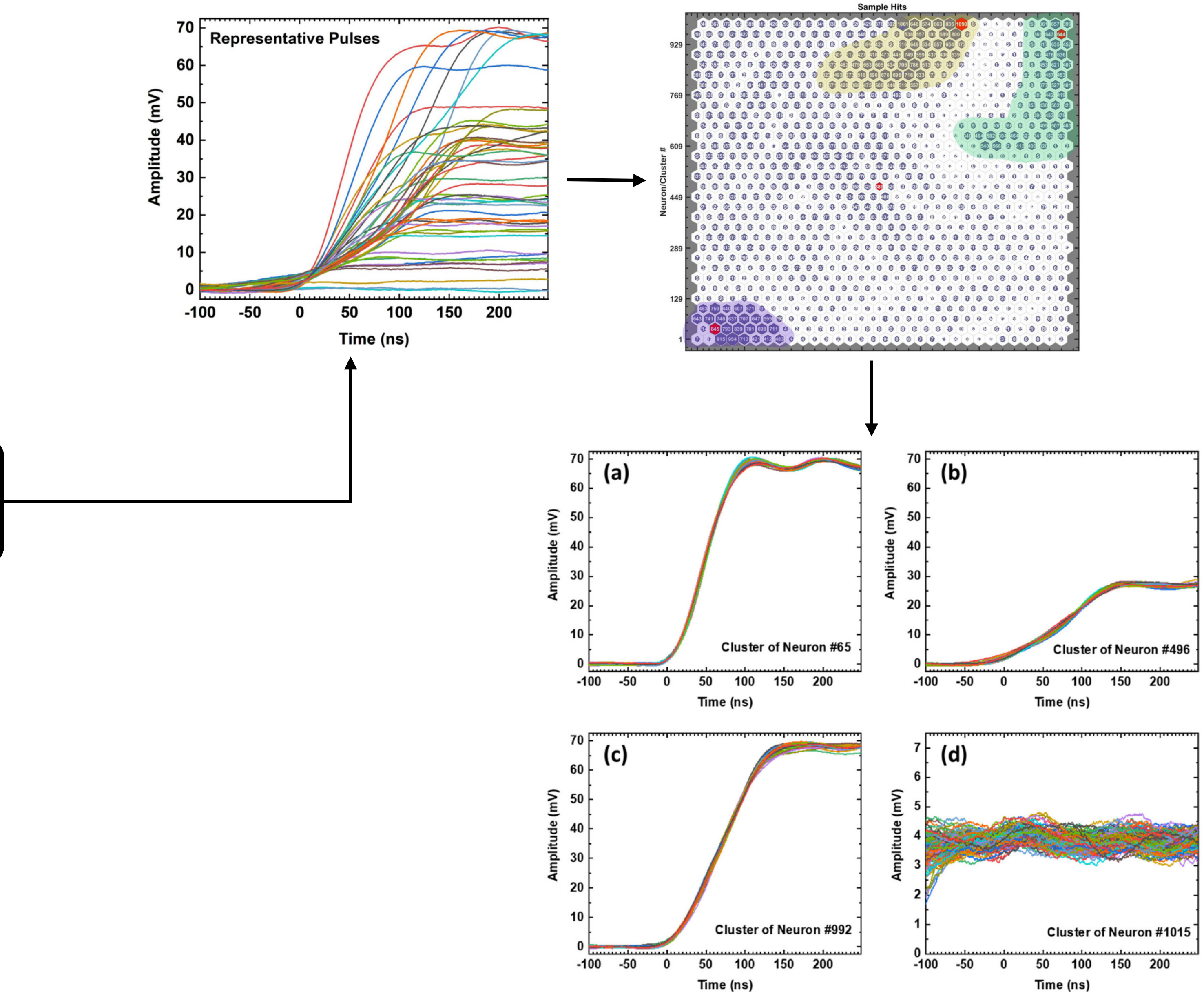


32x32 Hexagonal SOM

Extraction of Gamma Timing | SOM

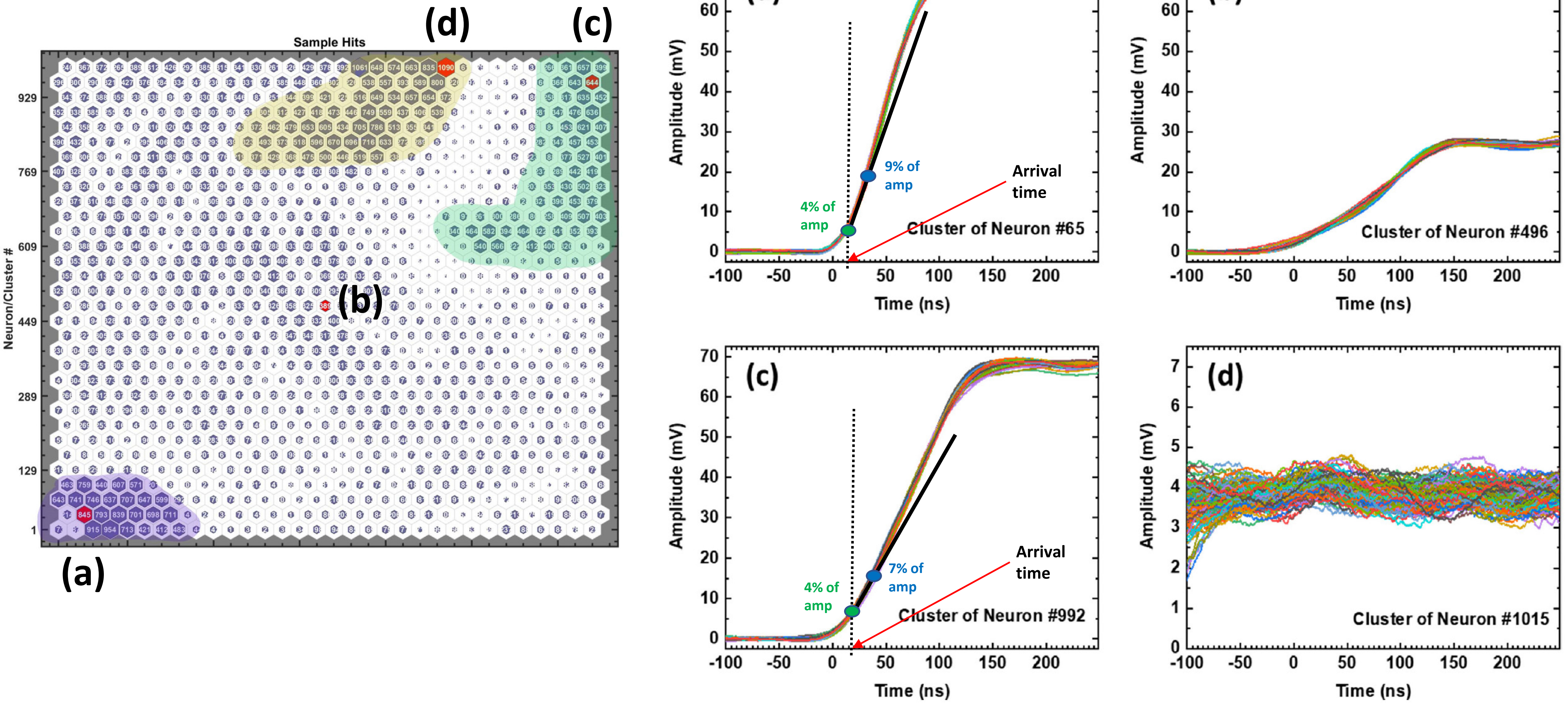
Experimental Setup





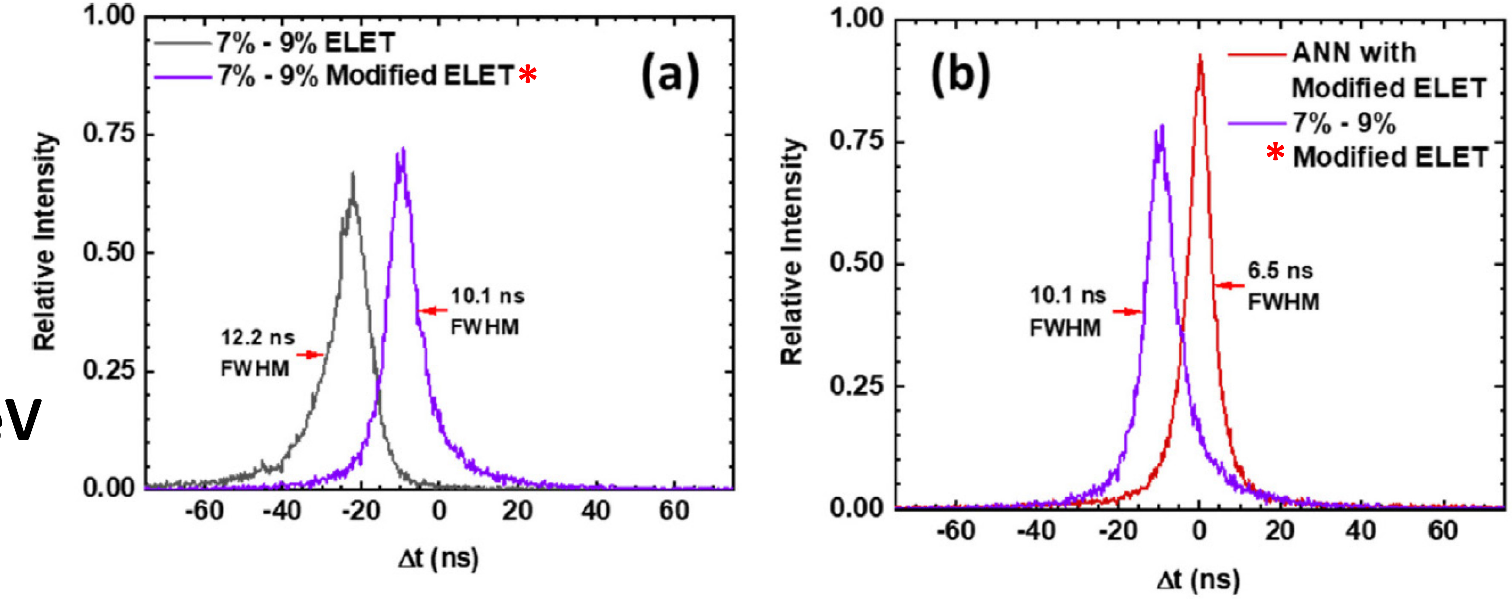
Extraction of Timing Information | SOM

Self-Organizing Map



Extraction of Timi

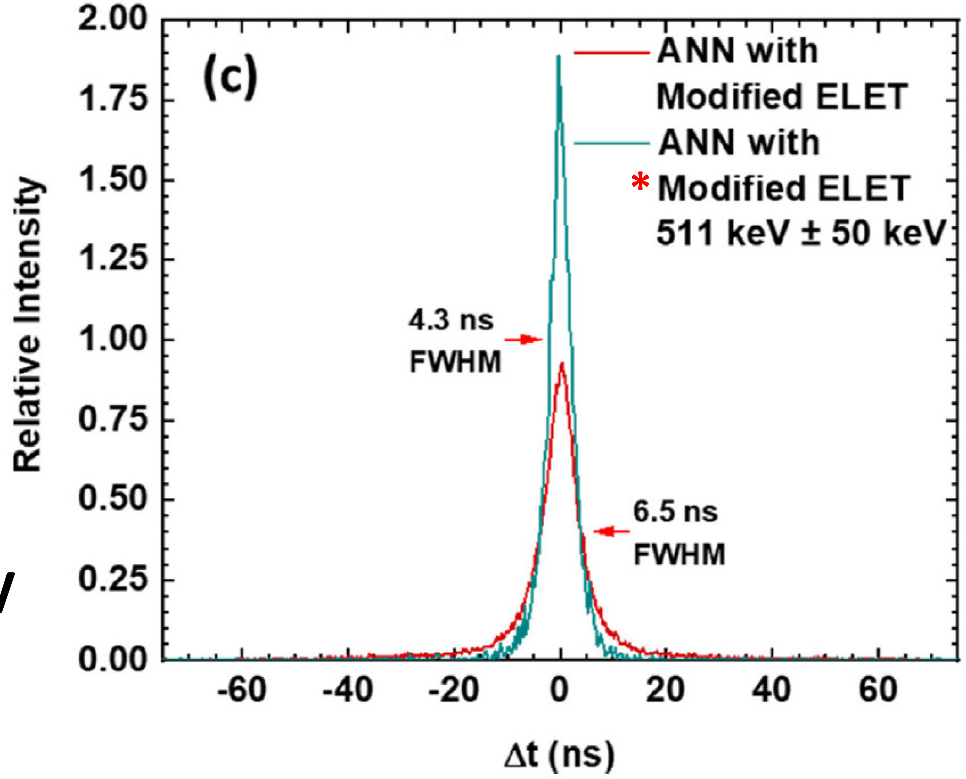
HPGe-BaF2 coincidence peaks



40 keV to 561 keV

*"Modified ELET":
A modification to conventional ELET in which the "lower" point of the fit is taken as the arrival time, rather than extrapolating the fit to cross the x-axis

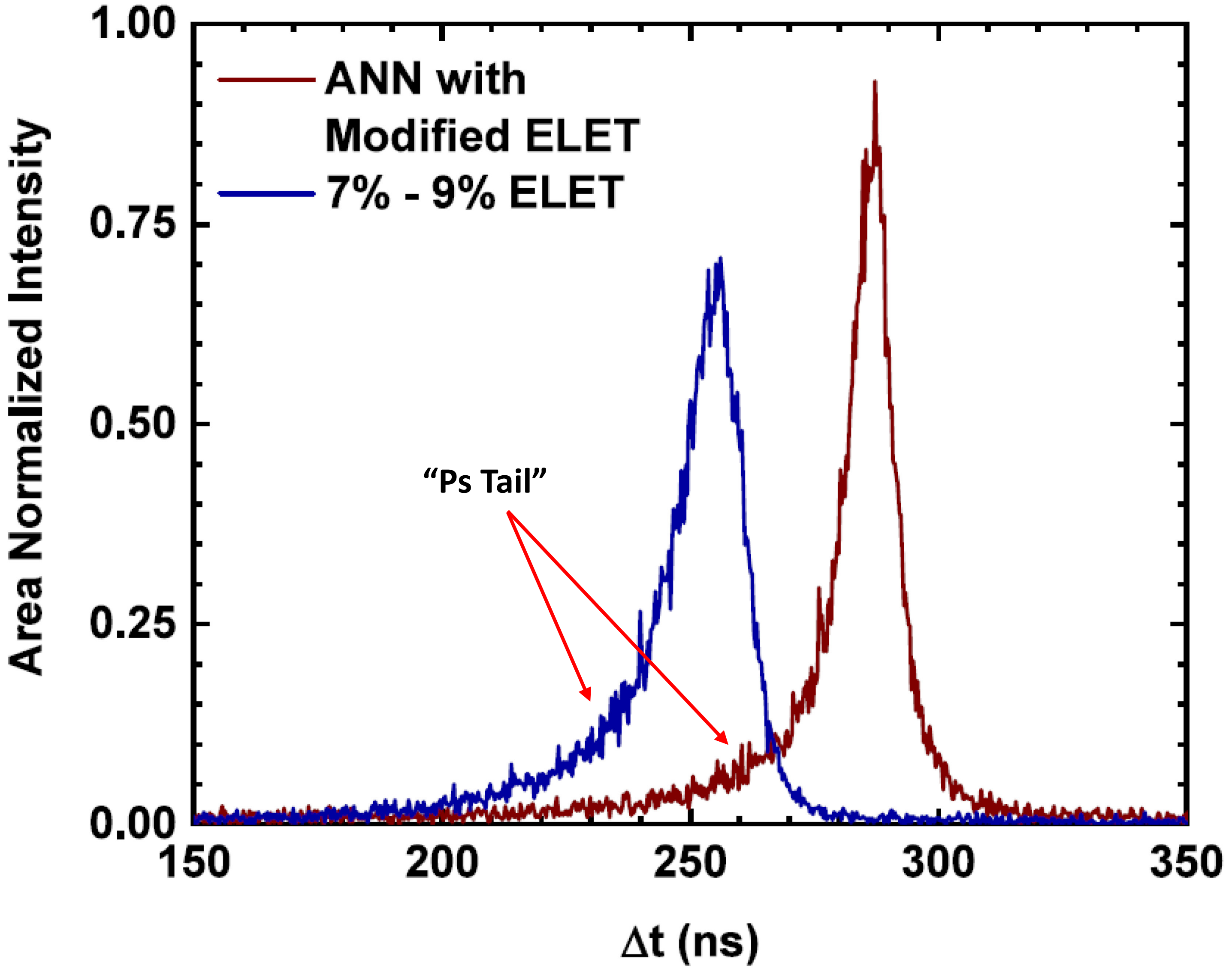
511 keV ± 50 keV



Extraction of Timing Information | SOM

Positron-induced secondary electron peaks

Both peaks are comprised of the same data (raw pulses from the HPGe and MCP detectors) in a real experiment (i.e., not in a setup specific to this technique), but with different analysis procedures.

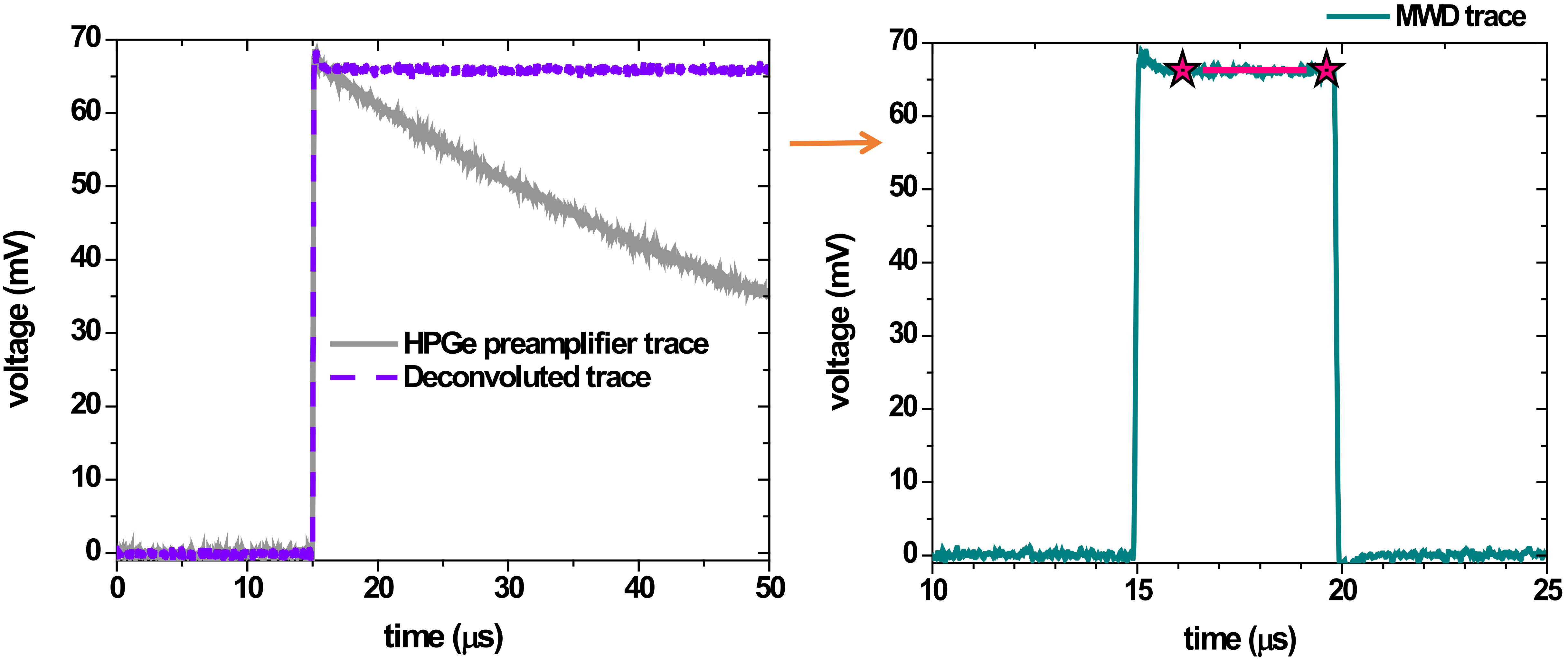


Extraction of Gamma Energy | Conventional

Moving Window Deconvolution

1.39 keV FWHM at 356 keV

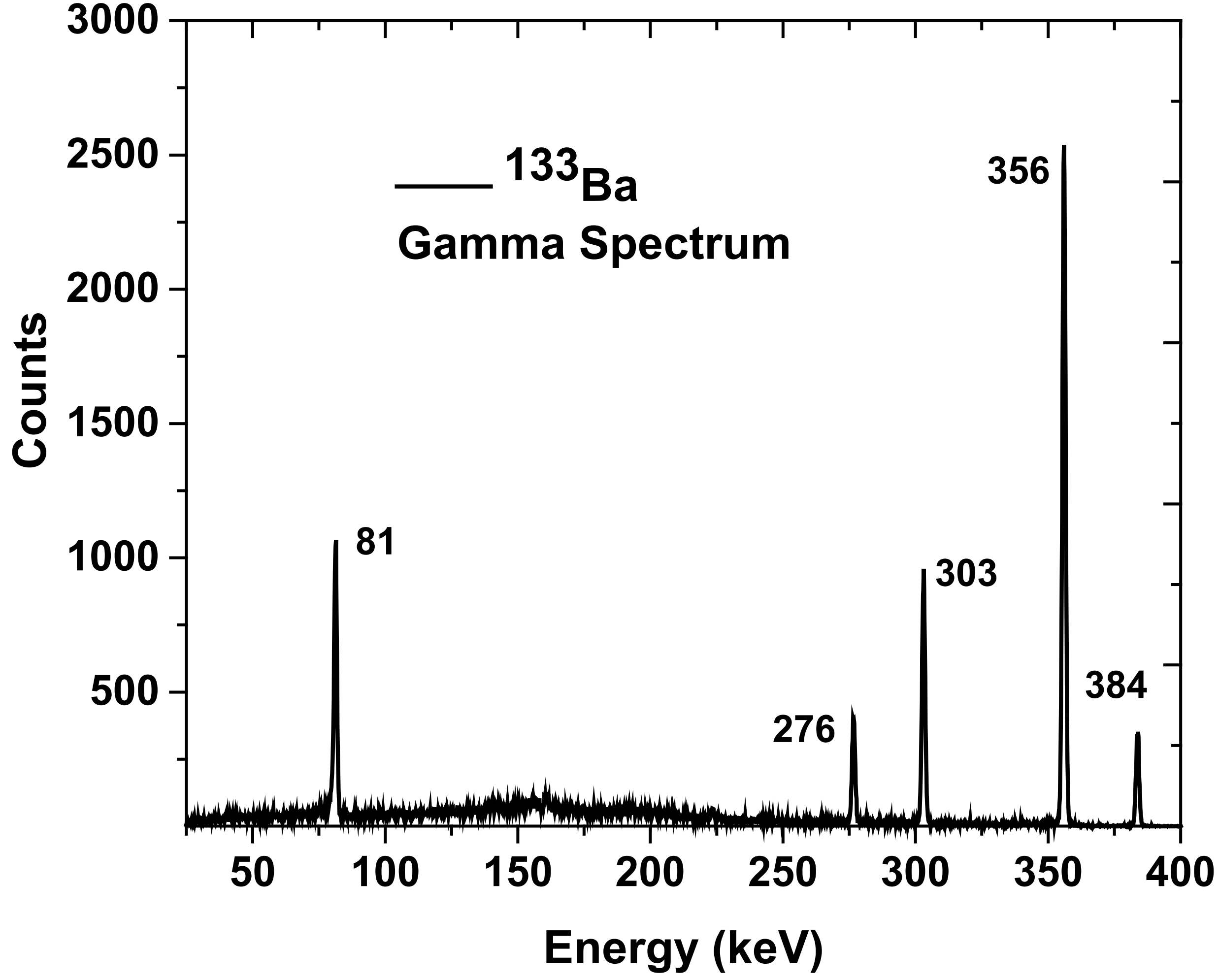
$$[n] = D[n-1] + P[n] - P[n-1] + \frac{P[n-1]}{\tau}$$



Extraction of Gamma Energy |ANN

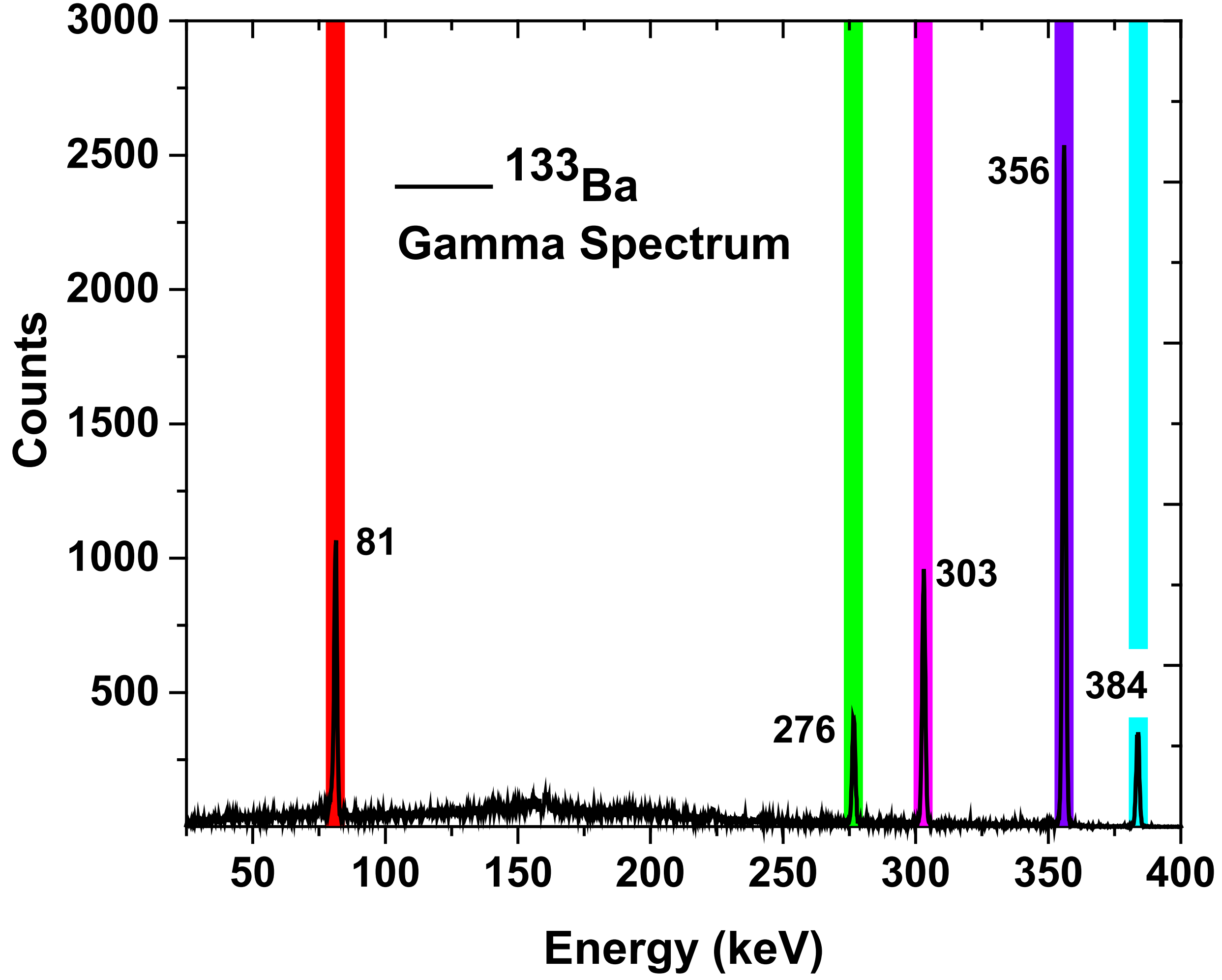
First Attempts

1.44 keV FWHM at 356 keV



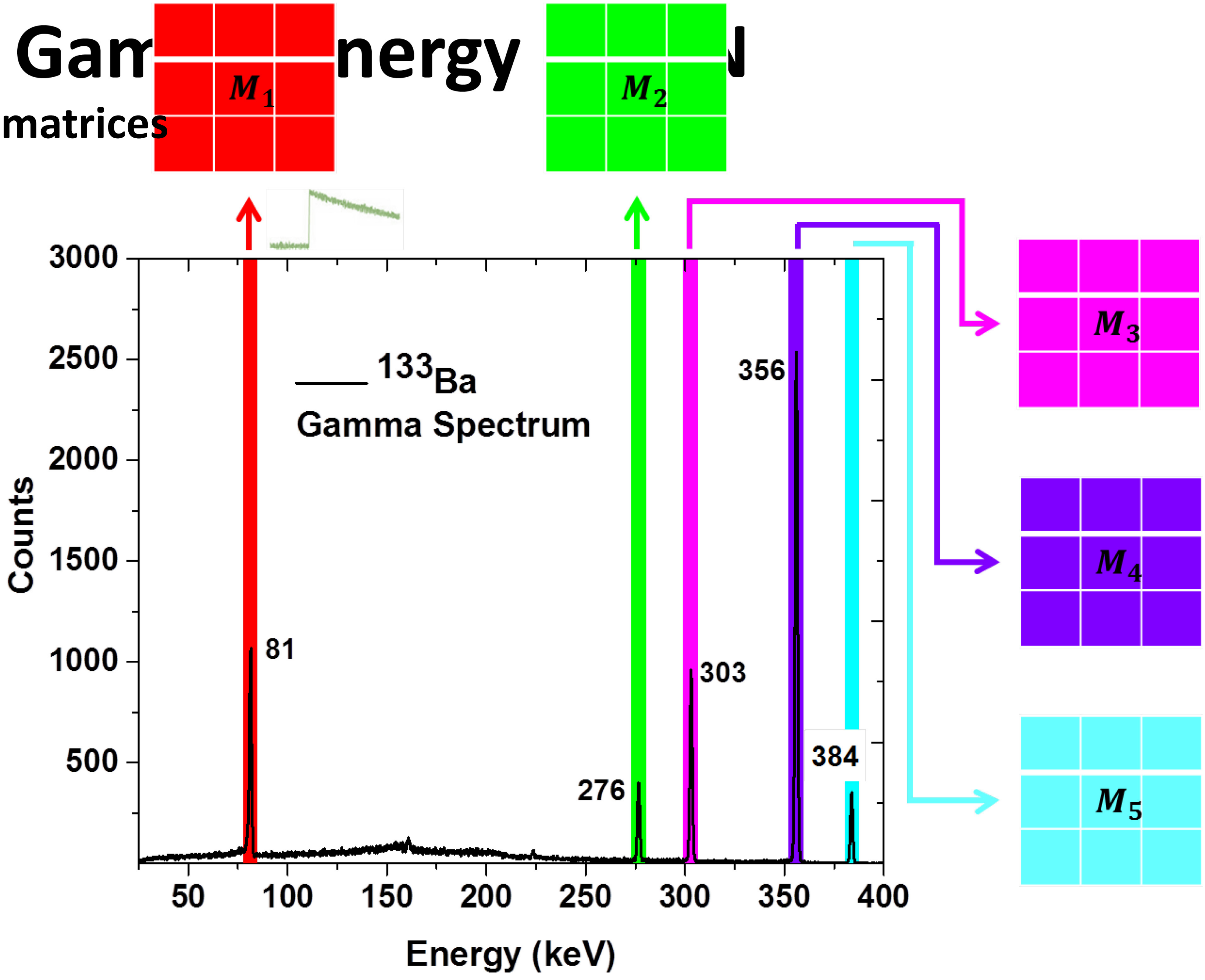
Extraction of Gamma Energy | ANN

Locating and labeling peaks



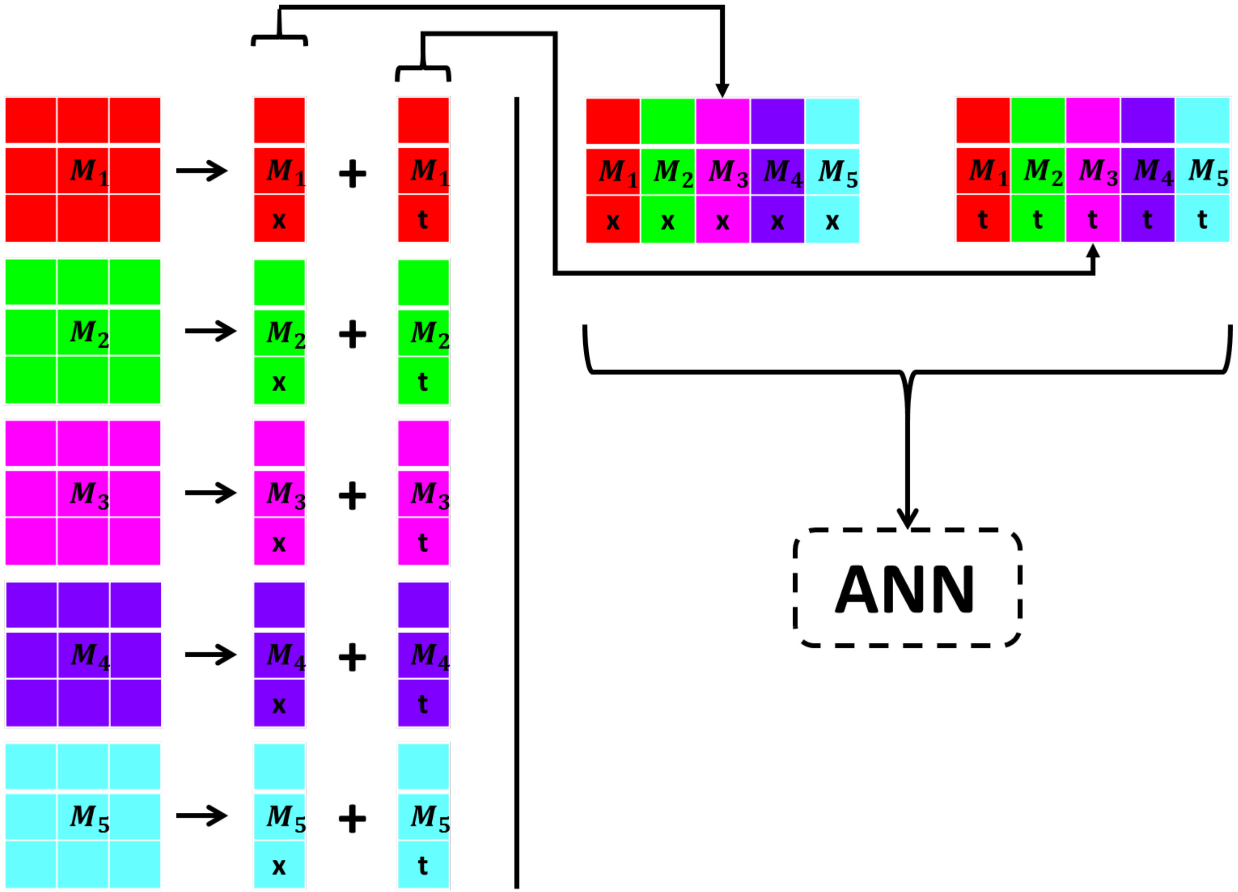
Extraction of Gam nergy N

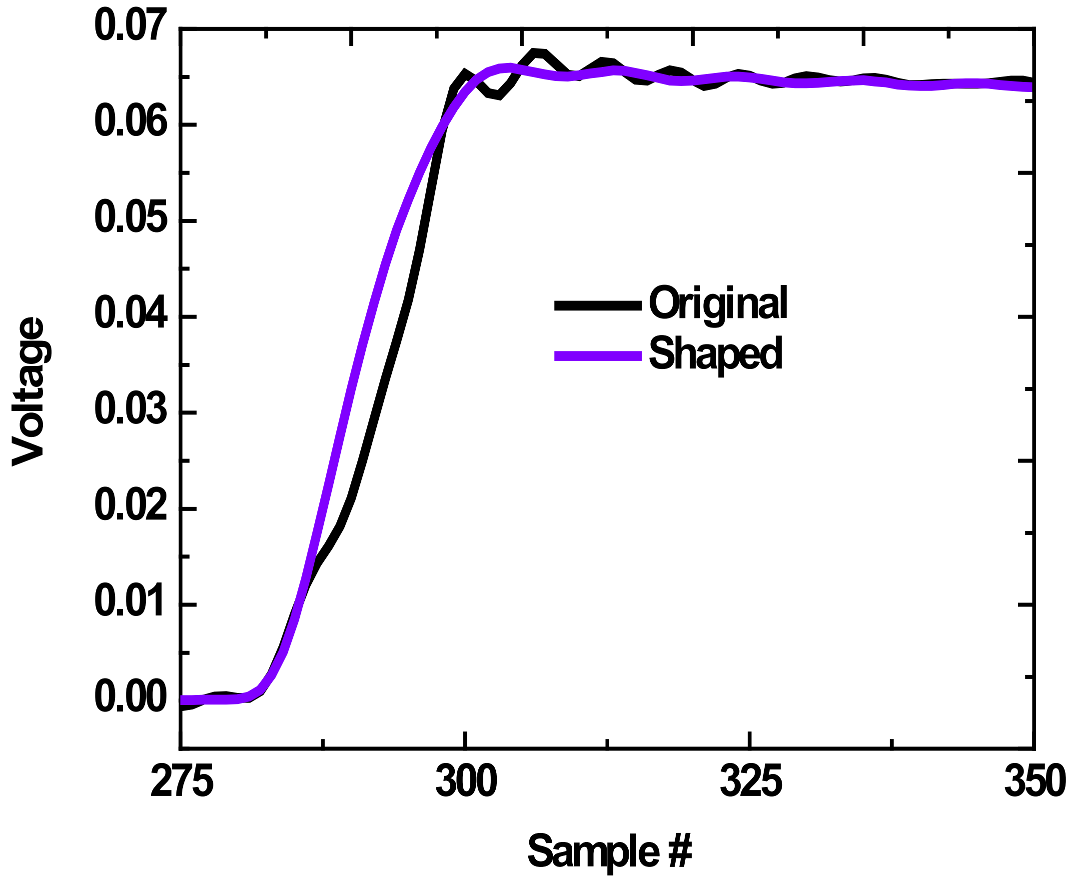
Organizing peaks into matrices



Extraction of Gamma Energy | ANN

Training ANN with only noisy peaks

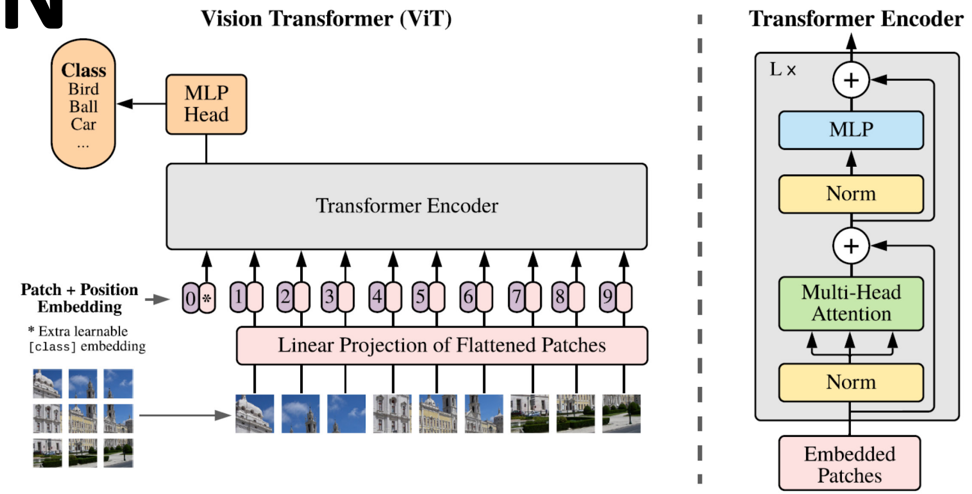




Extraction of Gamma Energy | ANN

Future Work?

arXiv:2010.11929



<u>Architecture:</u>
First attempts were done with CNN, but convolutional networks are phasing out in favor of transformers (not entirely phased out yet, of course).

Transformers? Vision Transformers?

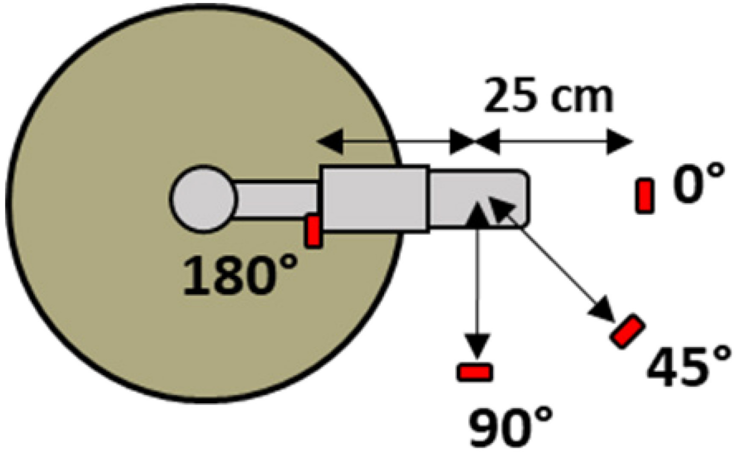
<u>Input:</u>
Raw pulses?
Spectrograms?

Inspired by “Noise2Noise” (2018)
Similar techniques have been experimented with in several different fields

arXiv:1803.04189

Estimating Gamma-Ray Direction

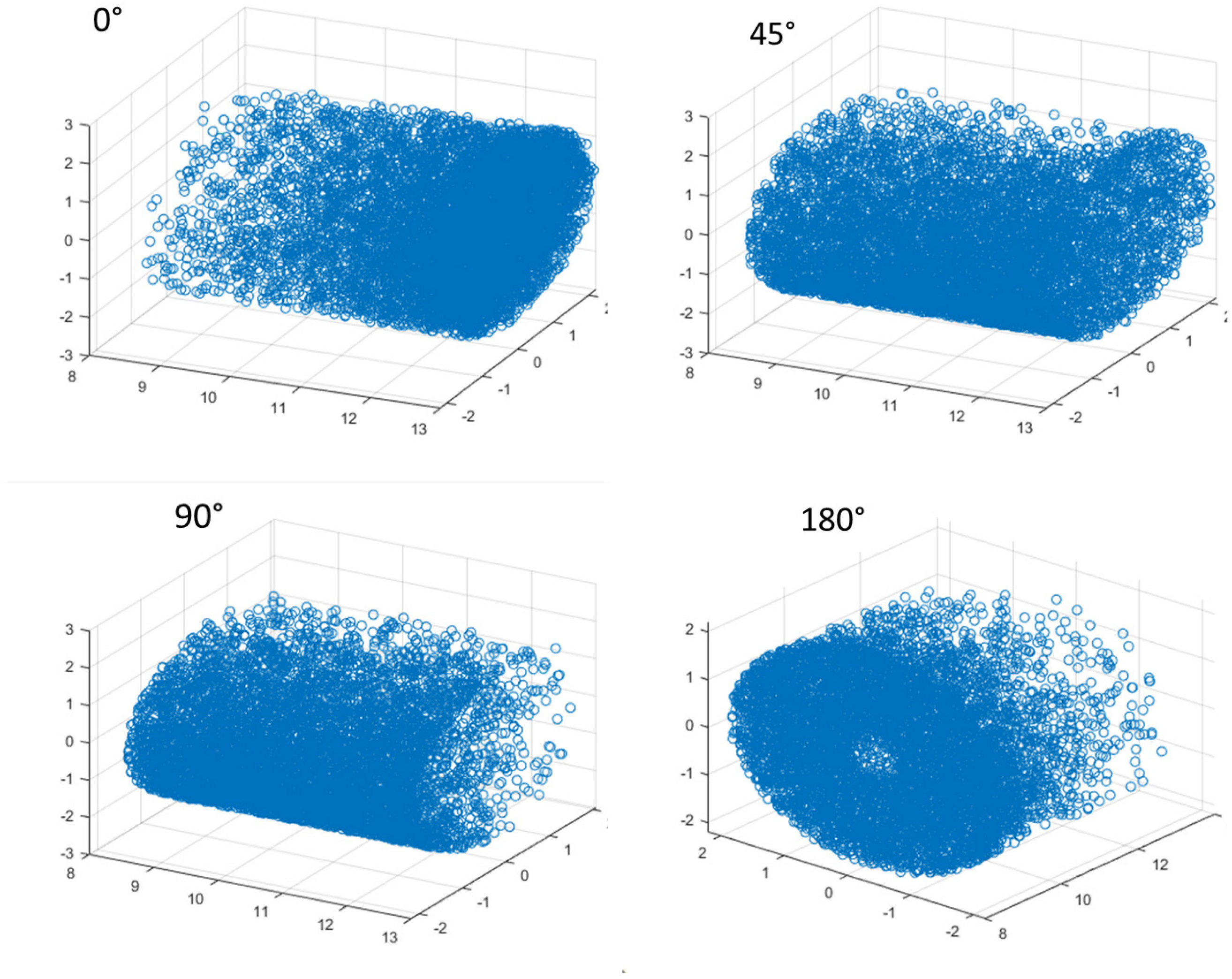
With Coaxial HPGe Detectors



Experimental Setup

Overhead view of a coaxial HPGe detector (grey) in an LN2 dewar (beige)

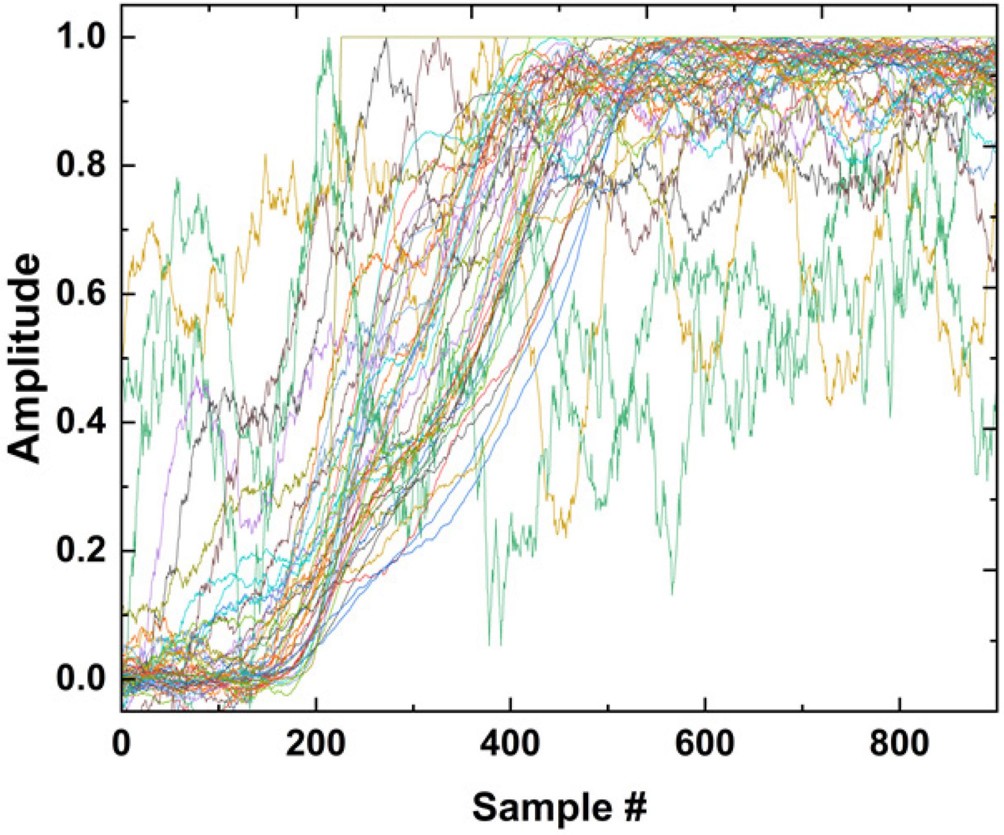
The red box is a Ba-133 source



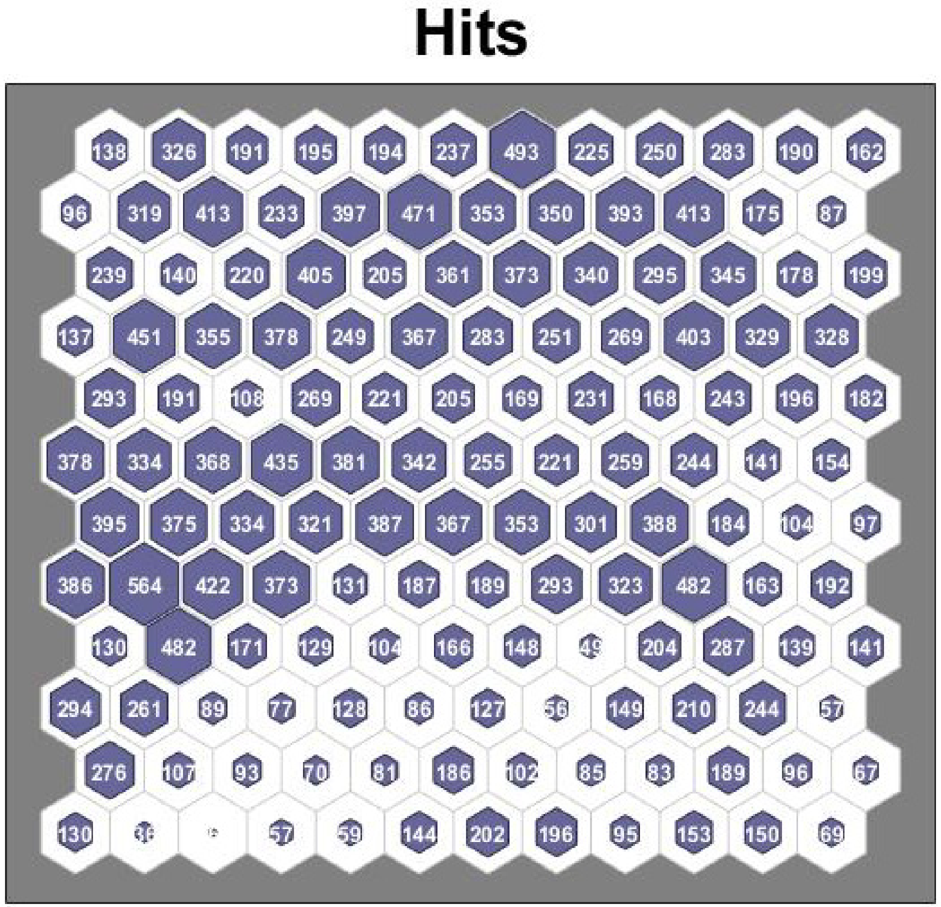
MCNP Simulation Results

Estimating Gamma-Ray Direction

Another application of SOM



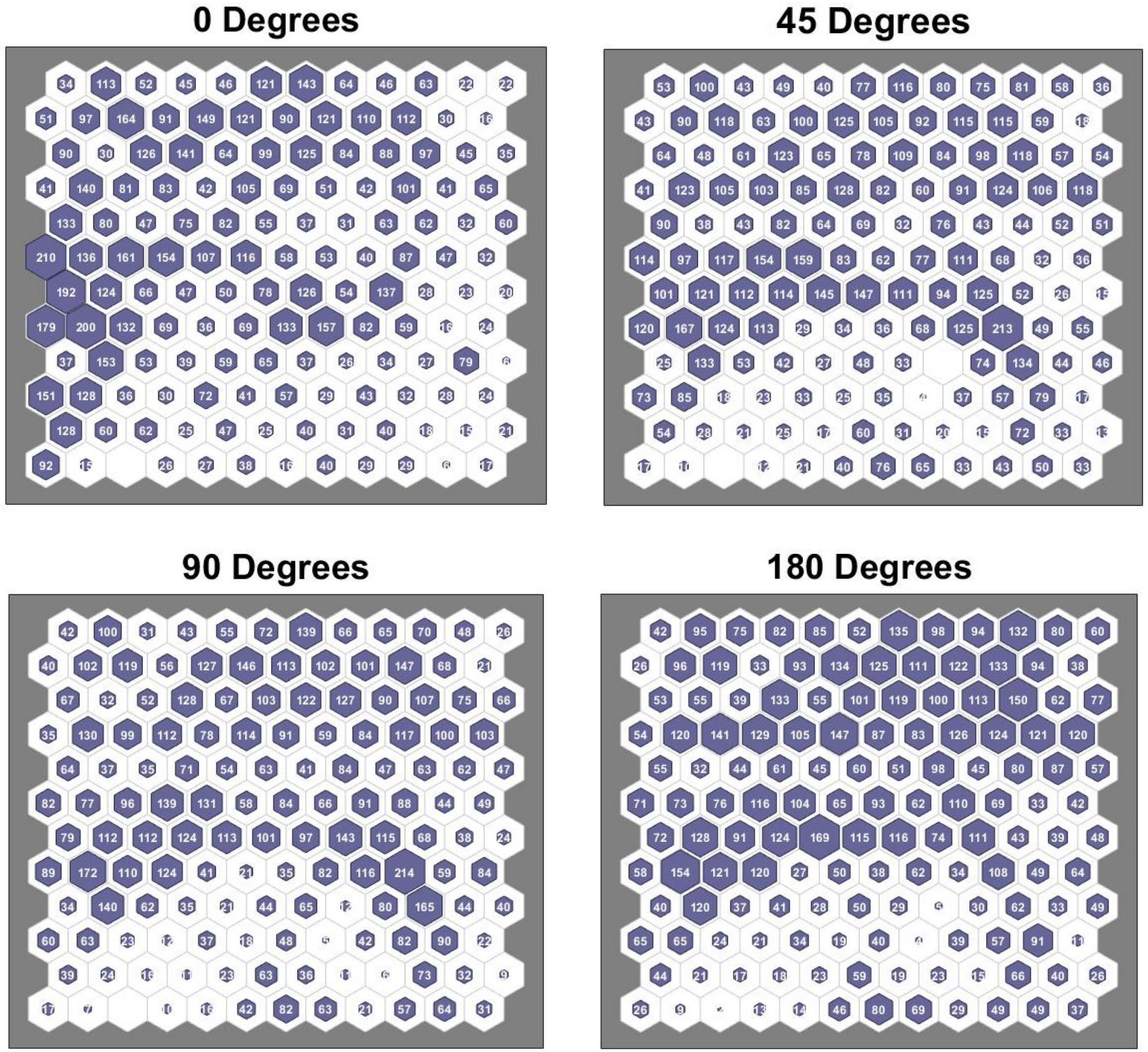
Training Pulses



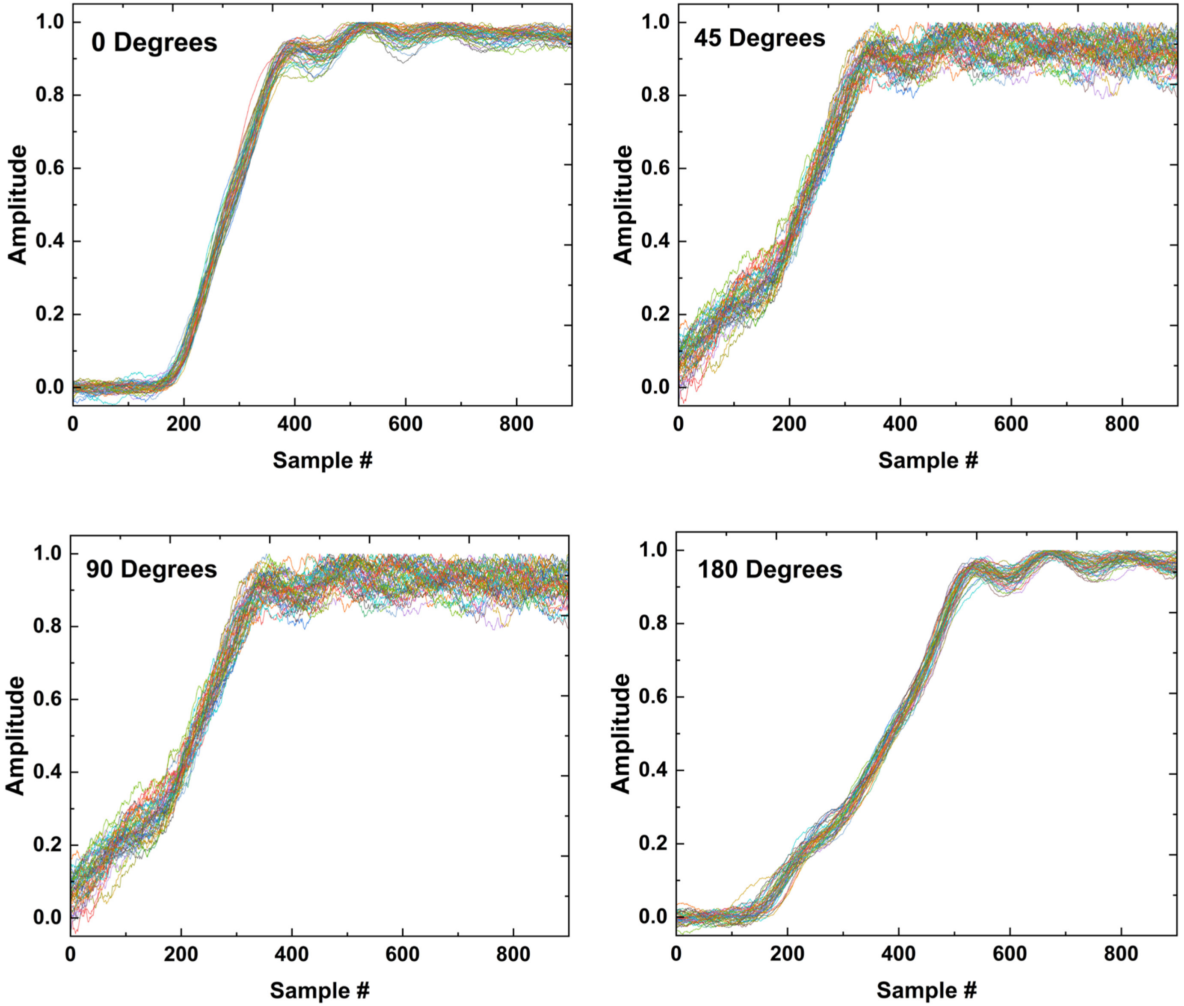
12x12 SOM Sample Hits

Estimating Gamma-Ray Direction

Clustering pulses based on shape



SOM Maps (1000 pulses)



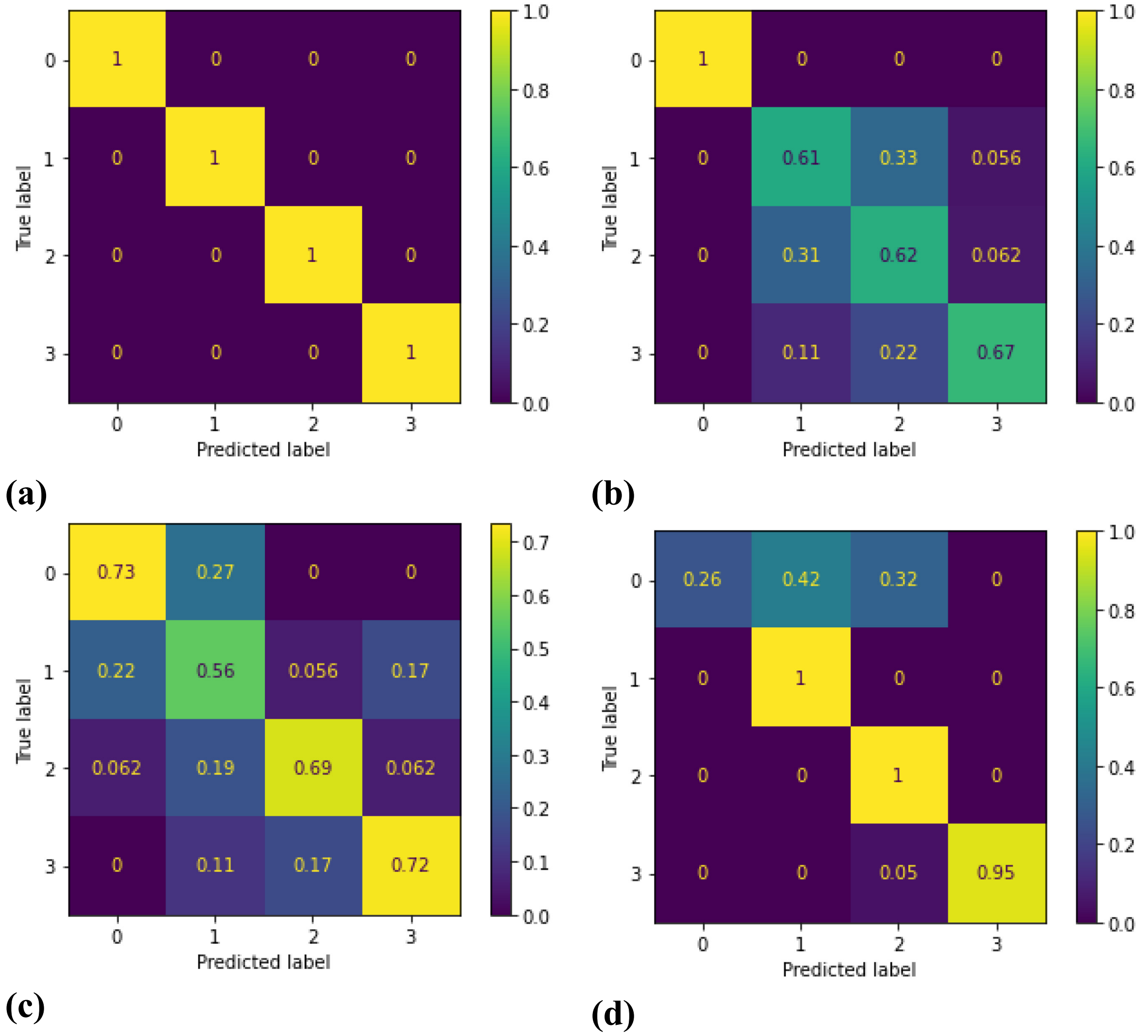
Clustered Pulses (most active neuron)

Estimating Gamma-Ray Direction

Estimating position based on SOM patterns

1000 Train
1000 Test

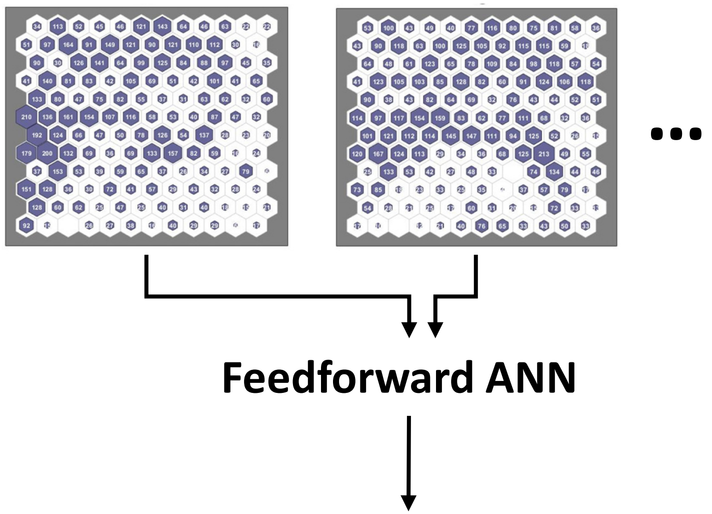
1000 Train
100 Test



100 Train
100 Test

100 Train
1000 Test

Each map can represent either 100 or 1000 pulses



Feedforward ANN

Target (0 Degrees; 45 Degrees, etc.)