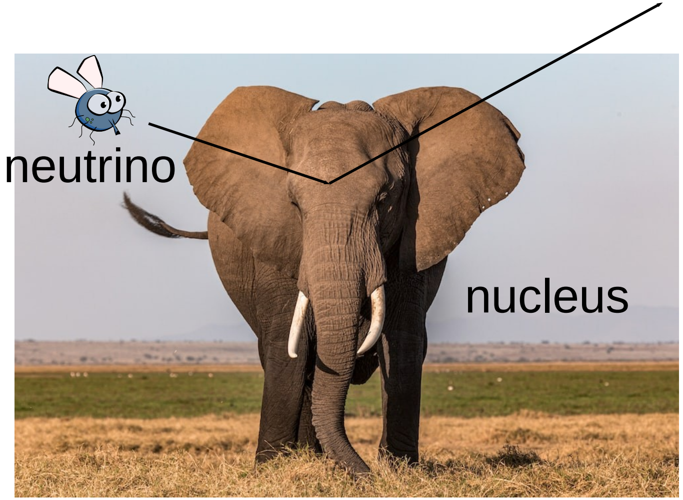
Towards a machine learning trigger for high-purity germanium spectrometers

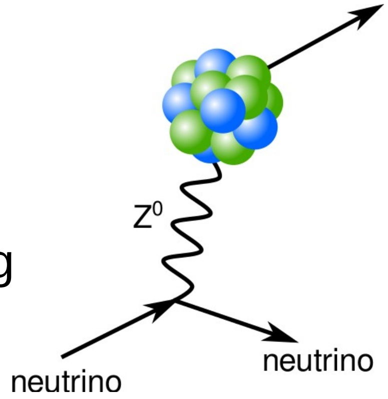
Janina Hakenmüller for the COHERENT collaboration

FastML 2024, Purdue University, 10/17/2024

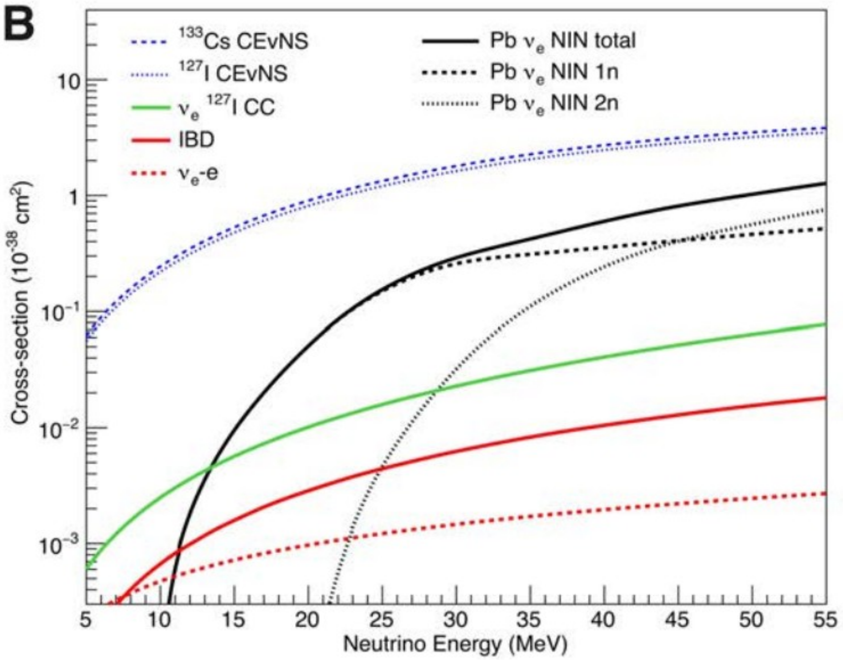
What is CEvNS?



coherent
elastic
neutrino
nucleus
scattering



D. Akimov et al., Science 10.1126/science.aao0990, 2017



- standard model interaction
- coherence → large cross section
  → upper limit on neutrino energy

https://ih1.redbubble.net/image.551360631.9903/raf,750x1000,075,t,FFFFFF:97ab1c12de.u1.jpg
https://images.unsplash.com/photo-1631646109235-0d6b33cb3034?ixlib=rb1.2.1&ixid=MnwxMjA3fDB8MHxzZWFyY2h8MXx8ZWxlZmFudHxlbnwwfHwwfHw%3D&w=1000&q=80

Neutrino sources and motivation

Neutrino sources for CEvNS:

pion-decay at rest <53 MeV

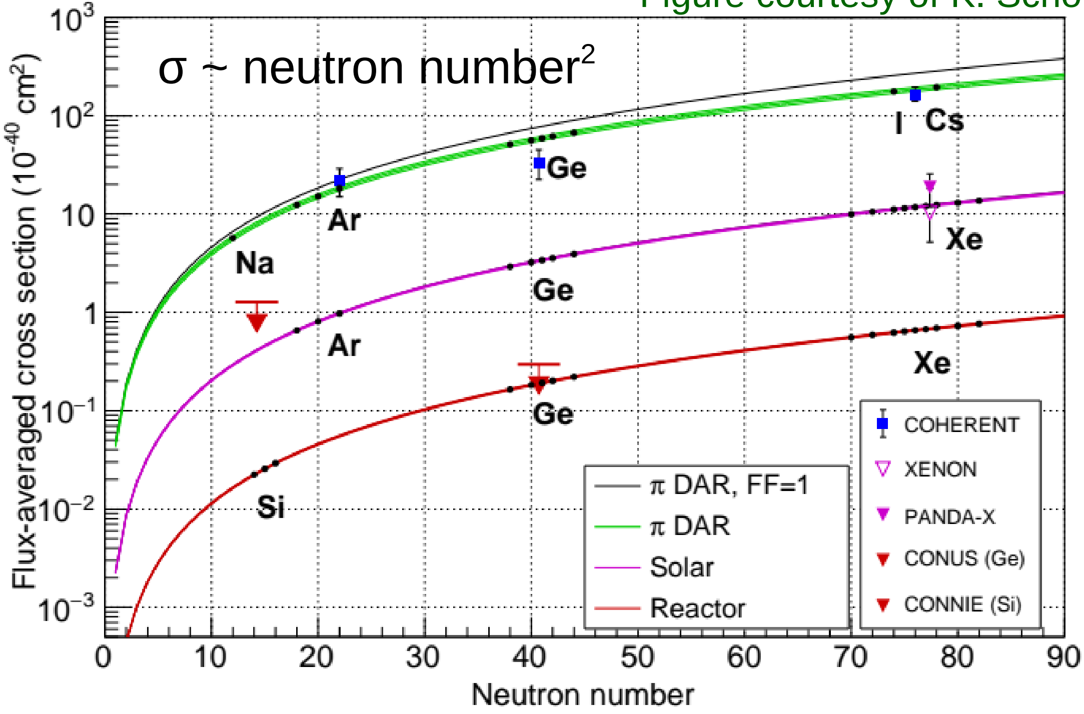
super nova neutrino

nuclear reactor <12 MeV

solar neutrinos

radioactive decays O(1) MeV

Figure courtesy of K. Scholberg



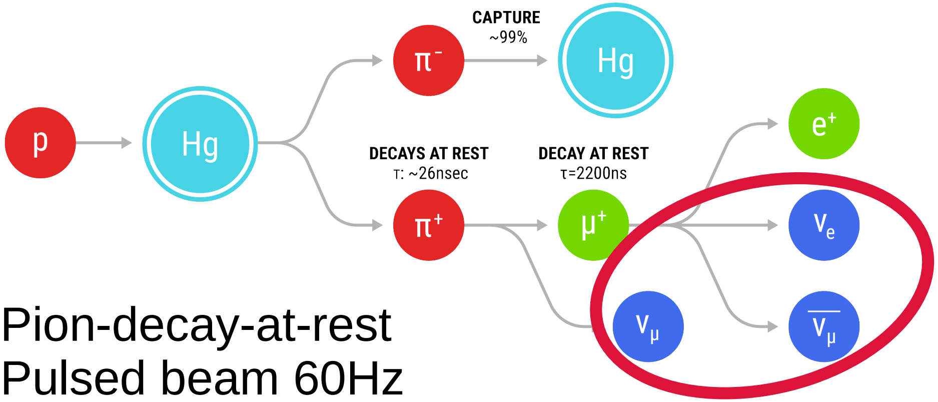
→ **precision test of the standard model of particle physics**

→ rich physics program: neutrino floor/fog, supernova neutrinos, NSI, light mediators, neutrino magnetic moment, Weinberg angle at low energies, nuclear form factor,...

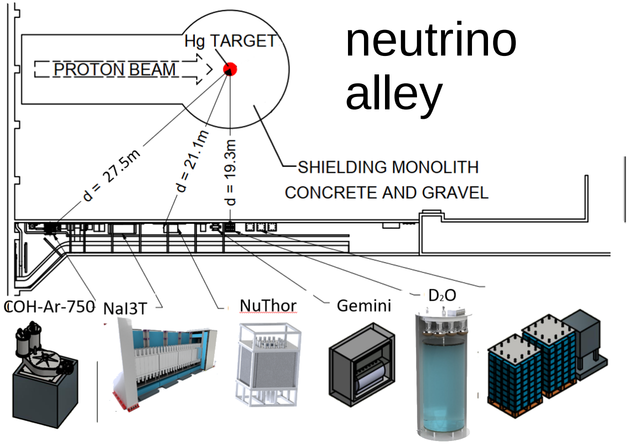
Detecting CEvNS

COHERENT experiment at SNS
(spallation neutron source, Oak Ridge, Tennesse):

- First detection in 2017: D. Akimov et al., Science 10.1126/science.aao0990, 2017
  - with CsI scintillating crystals
  - full data set 11.6 sigma D. Akimov et al. Phys. Rev. Lett. 129, 081801,2022
- LAr: 3.5 sigma 2021 D. Akimov et al. Phys. Rev. Lett. 126, 012002, 2021
- HPGe: 3.9 sigma 2023 Adamski, S., et al., arXiv:2406.13806 (2024).



Pion-decay-at-rest
Pulsed beam 60Hz
~10^{20} protons on target/d (POT)

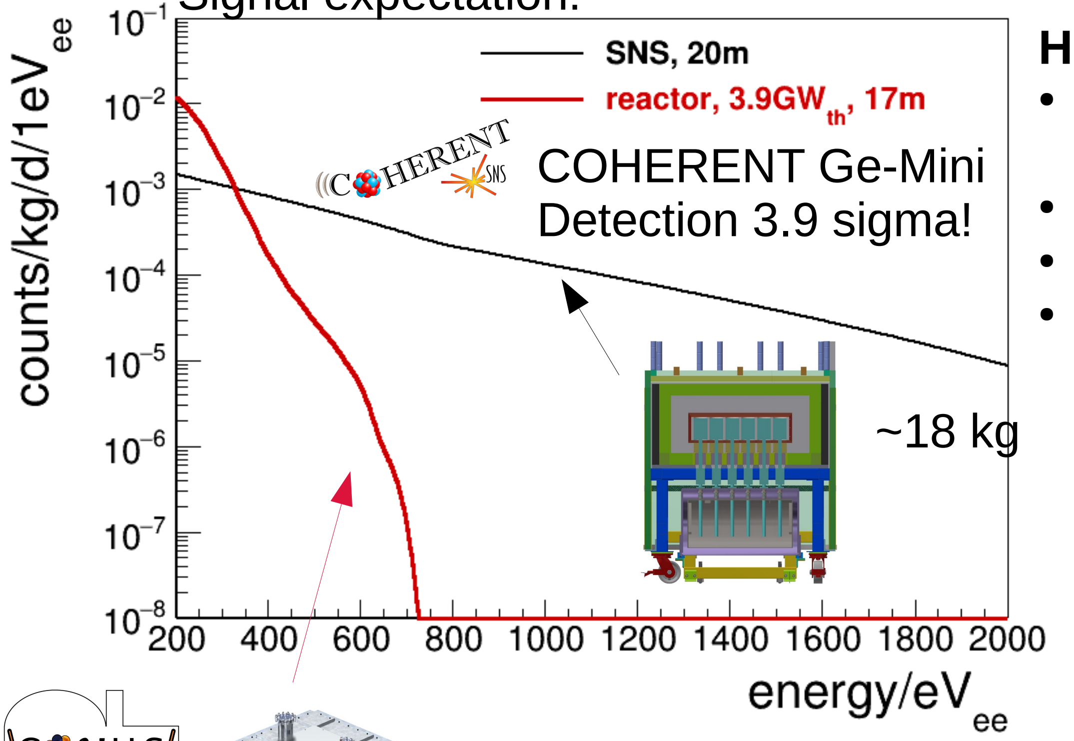


neutrino alley

large cross section
→ small experiments!

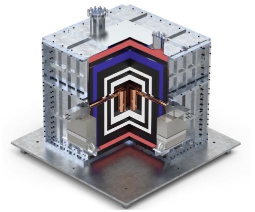
Detecting CEvNS

Signal expectation:



COHERENT Ge-Mini
Detection 3.9 sigma!

~18 kg



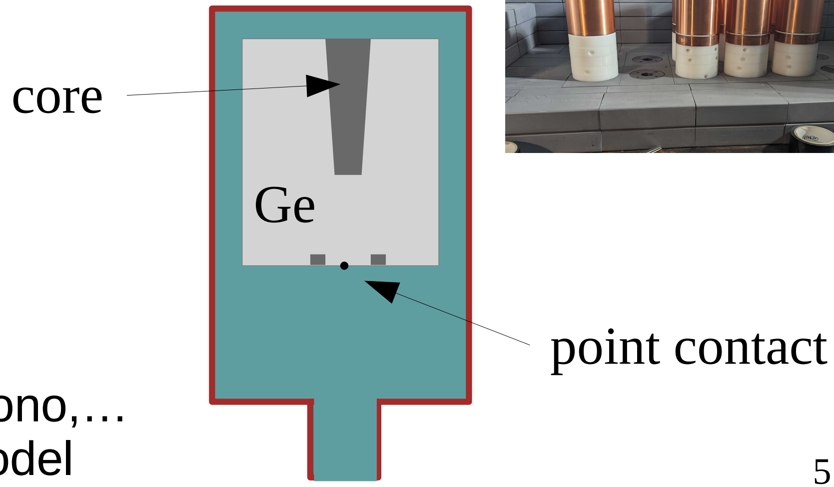
~4 kg

CONUS, CONUS+, NuGen, Texono,…
Best limit: factor 2 > standard model

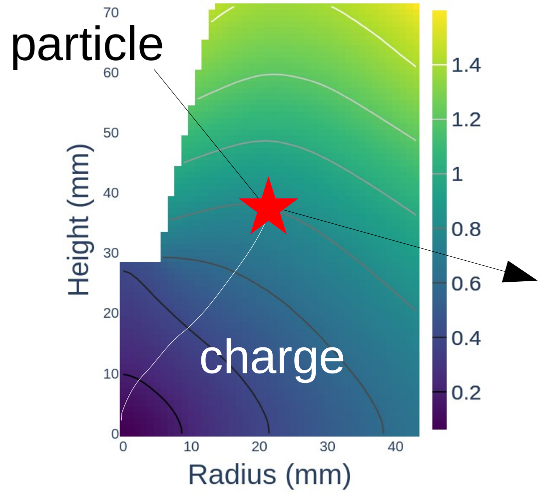
arXiv:2308.12105

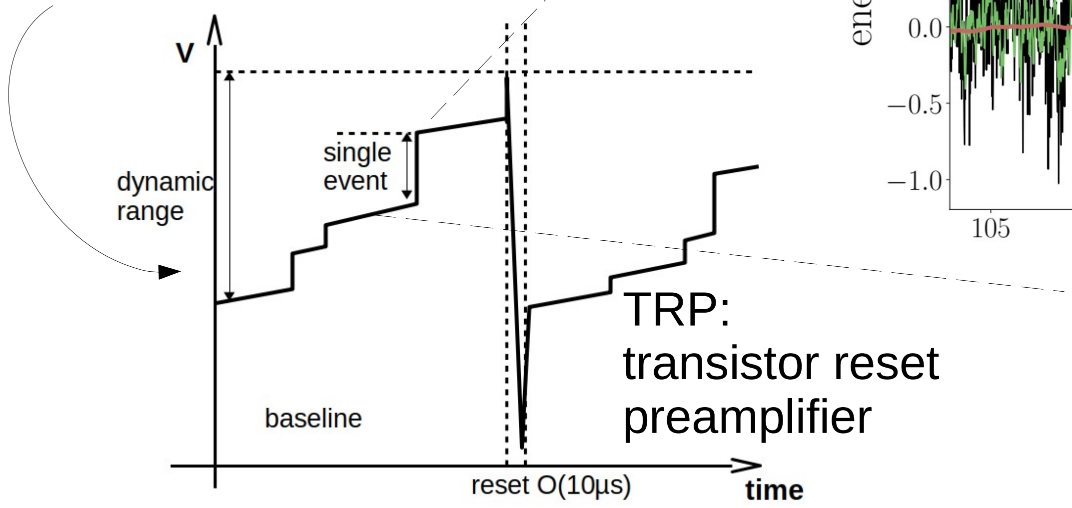
High-purity germanium spectrometer (HPGe):

- excellent intrinsic energy resolution due to small bandgap
- point contact design → low noise
- kilogramm-sized detectors
- (electrical cryocooler)

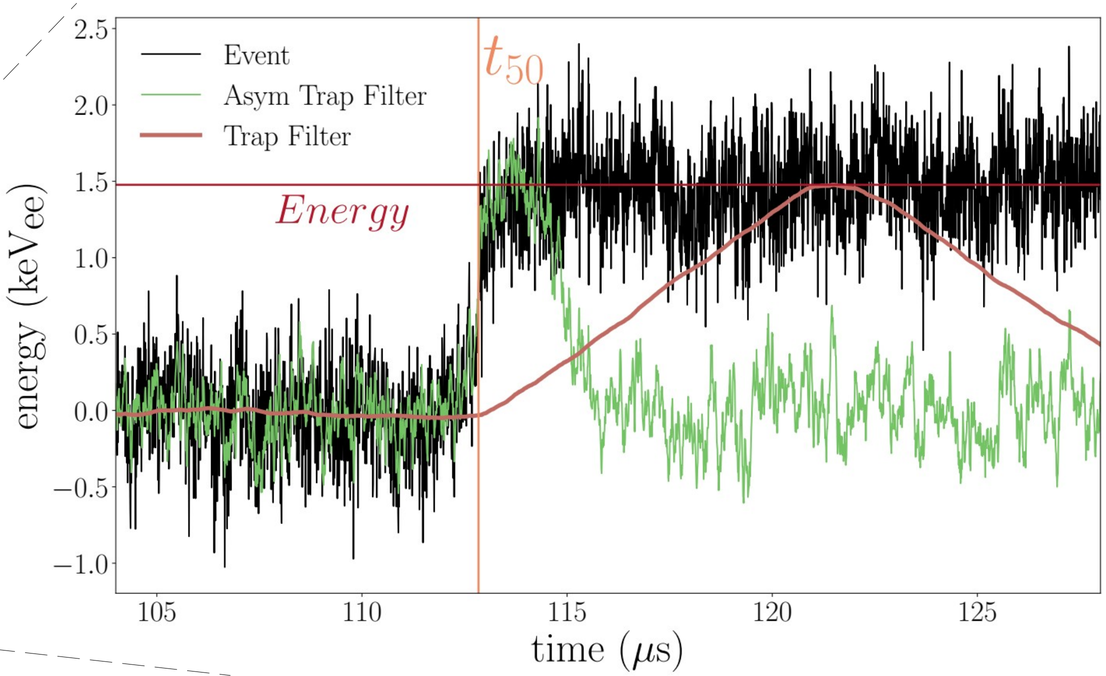


HPGe detectors





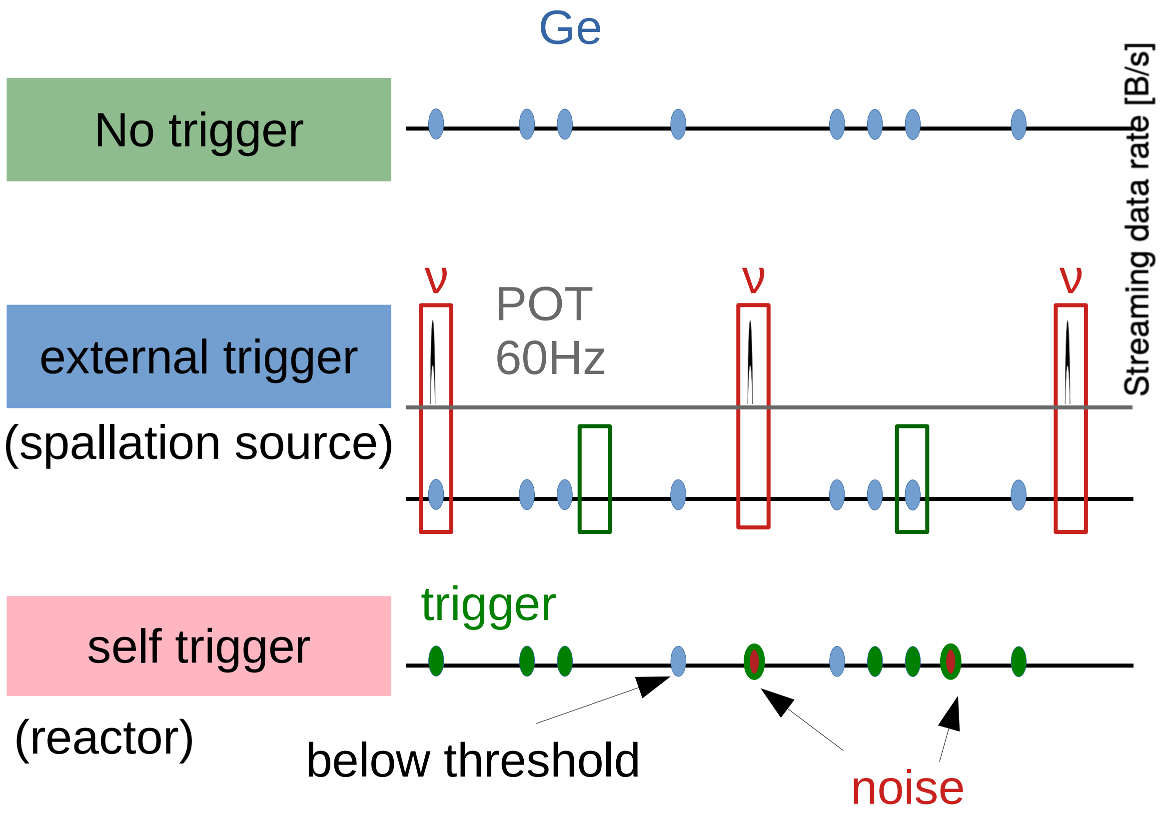
TRP:
transistor reset preamplifier

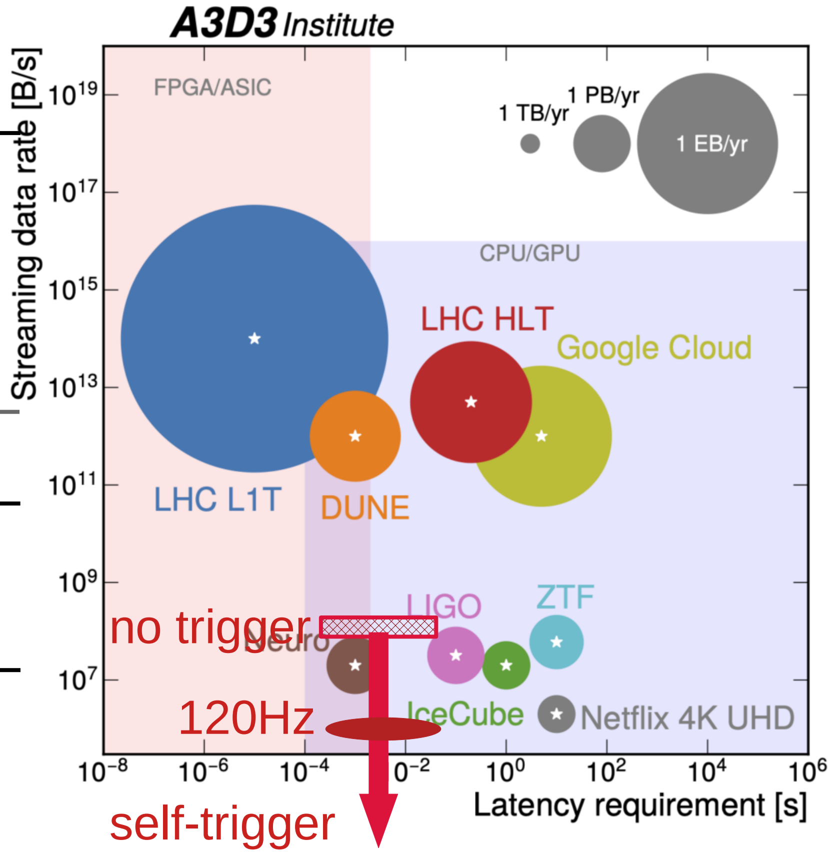


height of step ~ energy of particle
→ need baseline before step

125 MHz sampling

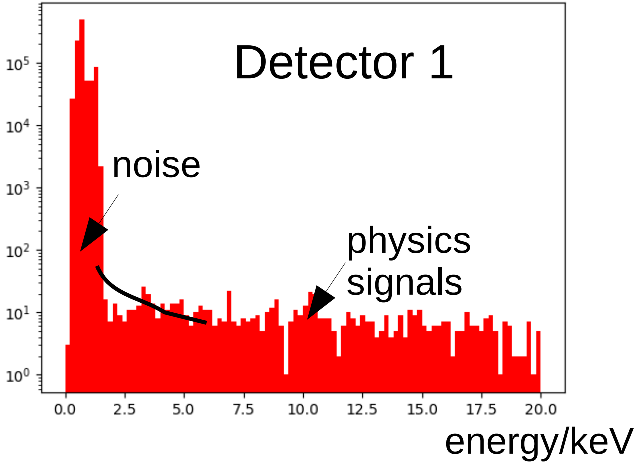
HPGe triggering



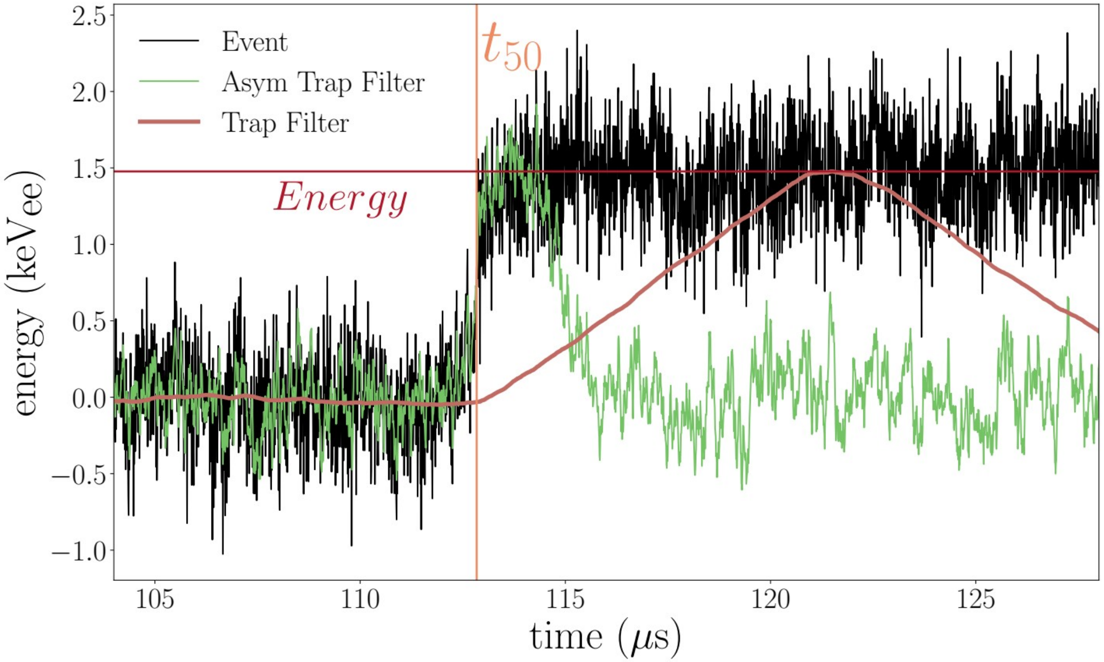


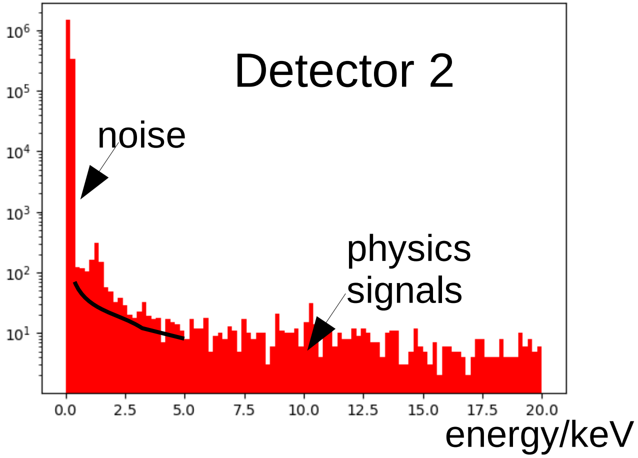
https://a3d3.ai/about/

HPGe triggering



Classical approach: triangular discriminator





→ ML triggering by noise identification

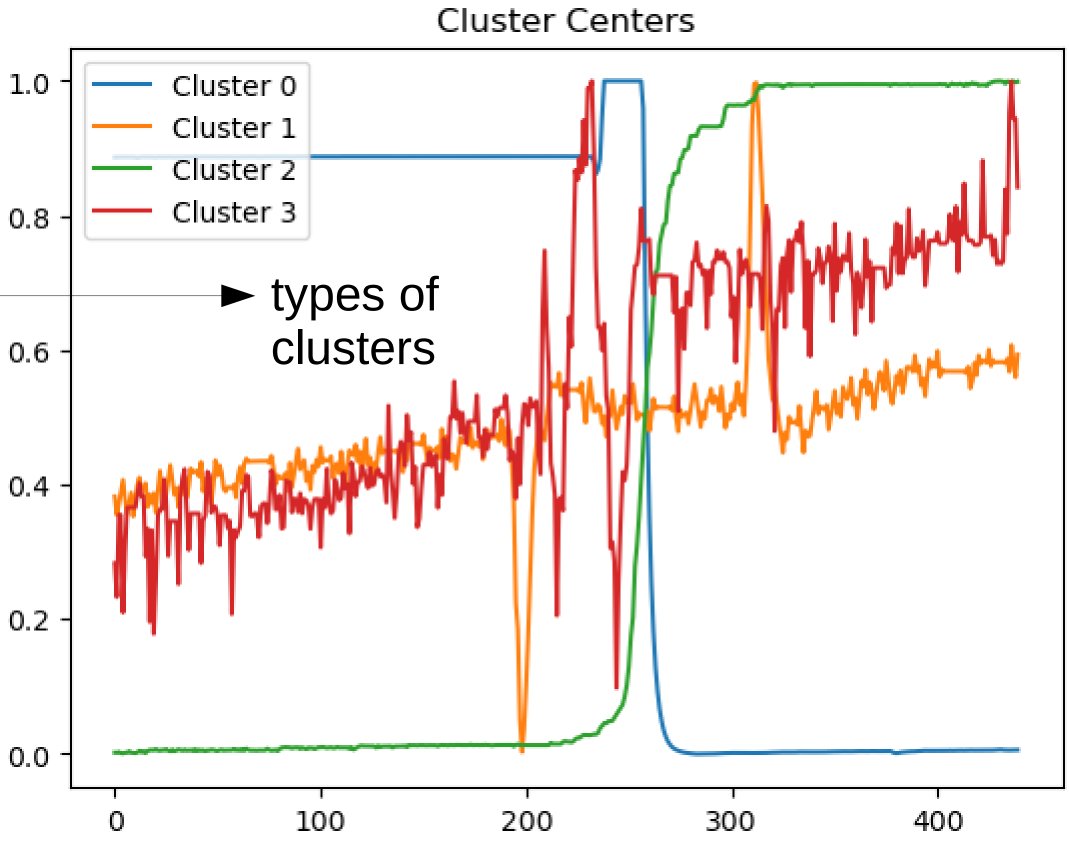
Waveform classification

TSLearn python algorithm:
https://tslearn.readthedocs.io/en/stable/

- DTW Dynamic time warping
- down sampling
- normalization
- training on 1000 pulses ► types of clusters

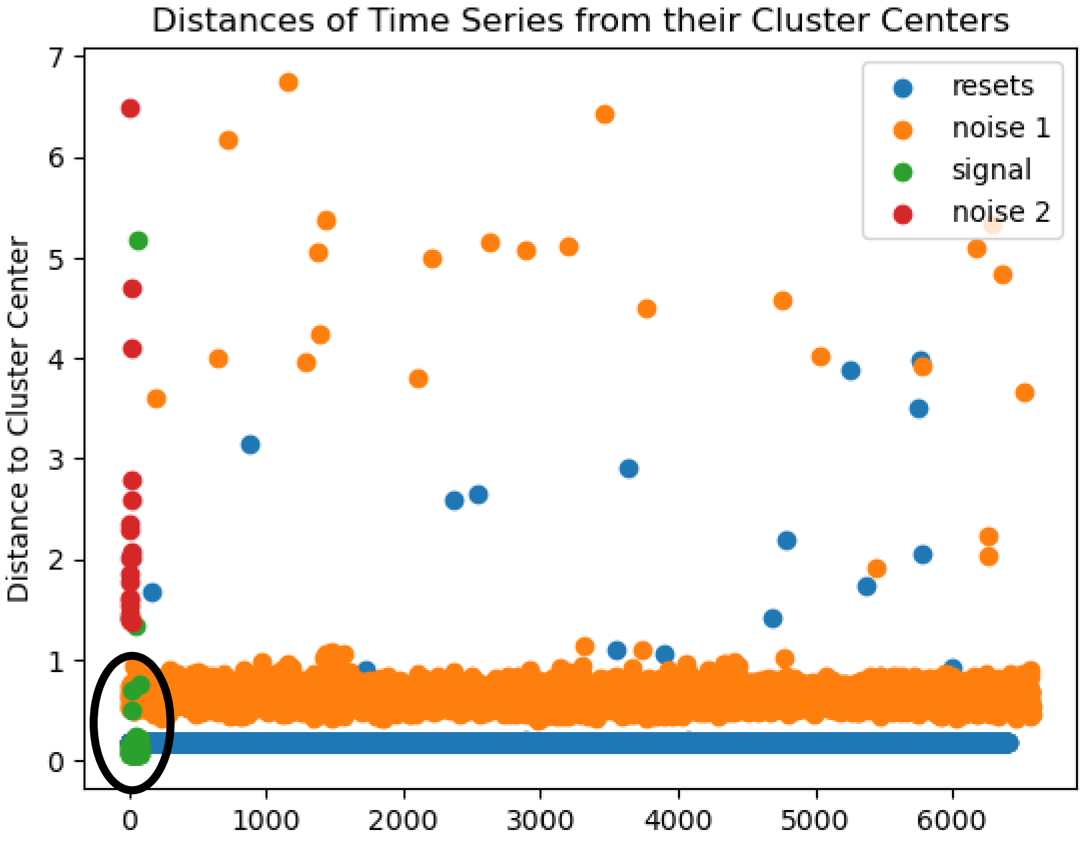
→ several types of clusters:
physics events (Cluster 2)
resets (Cluster 0)
noise (Cluster 1, Cluster 3)
→ classify pulses into clusters

detector-dependence

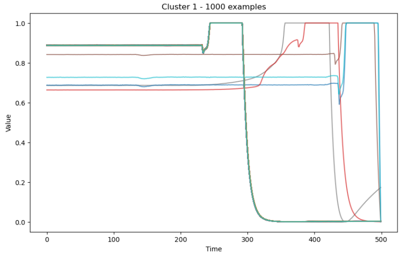


time series index

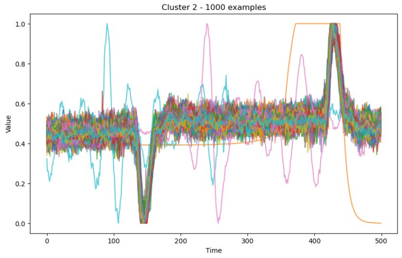
Time series clustering



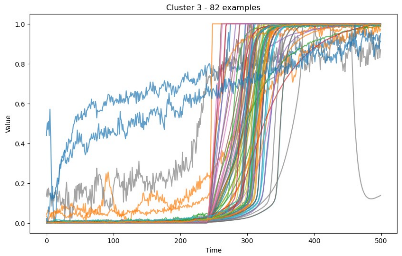
index of waveform in cluster



resets

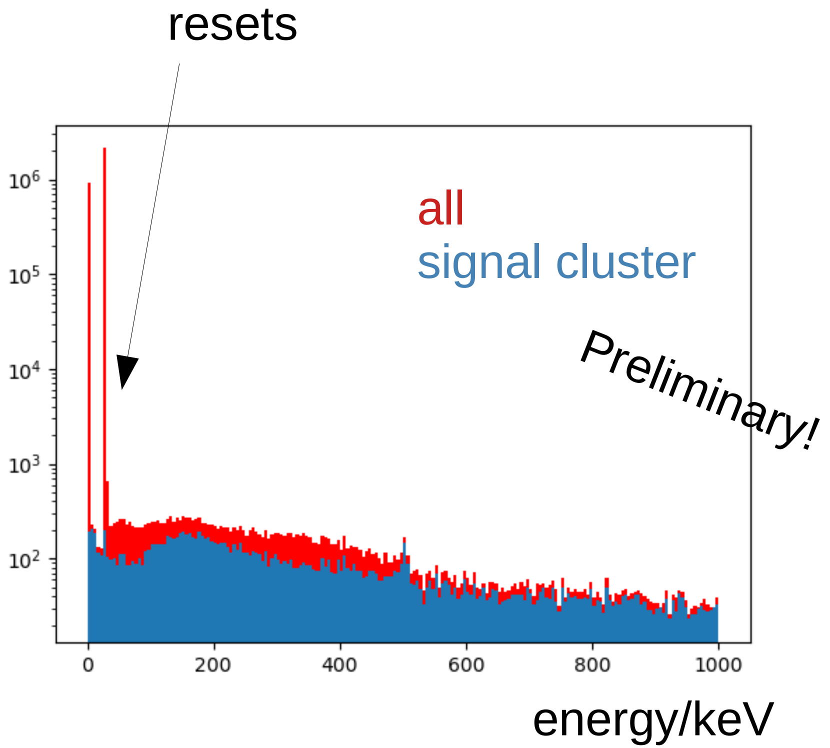


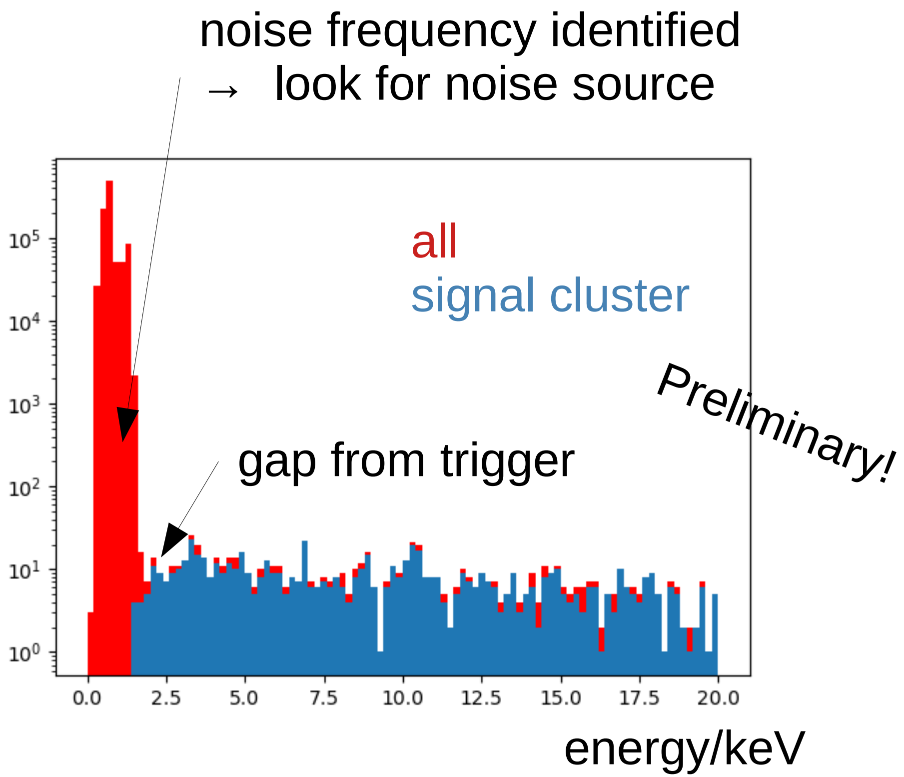
noise 1



signals

First evaluation of performance

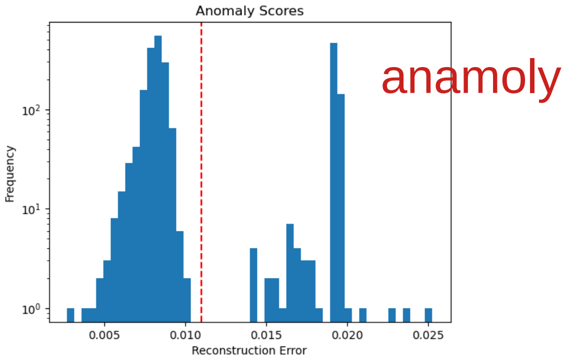


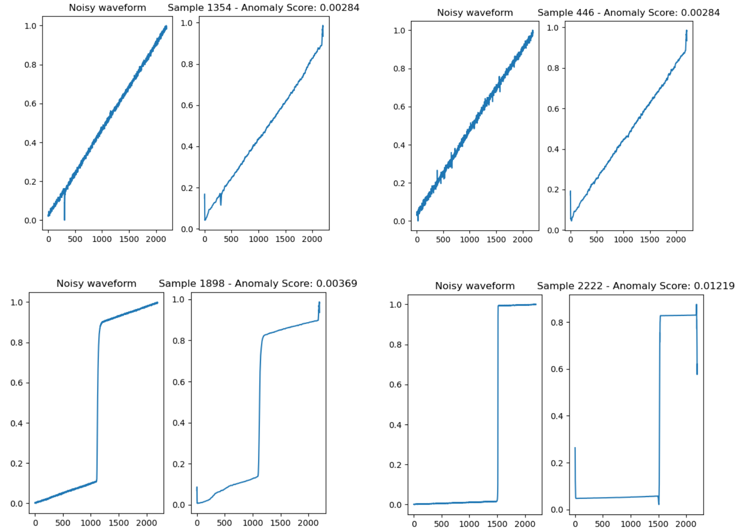


Summary

- **CEvNS:** neutrino interacts with the nucleus as a whole
  → precision test of the standard model
  → detected for recoil energies above 6.7keV, below still pending

- **Trigger HPGe:** overwhelmed by noise at low energies → Machine Learning
  → time series clustering: performing well in sorting between signals and noise
  → anomaly detection with variational denoising autoencoder:
  noise: normal
  signal: anomaly (sort by time clustering)





noise

events

- **Deployment on FPGA:** HLS4ML