In View of Large Detector Arrays: Automated Analysis Modules for Direct Dark Matter Search

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IMPRS recruiting workshop
Garching, 25.11.2024

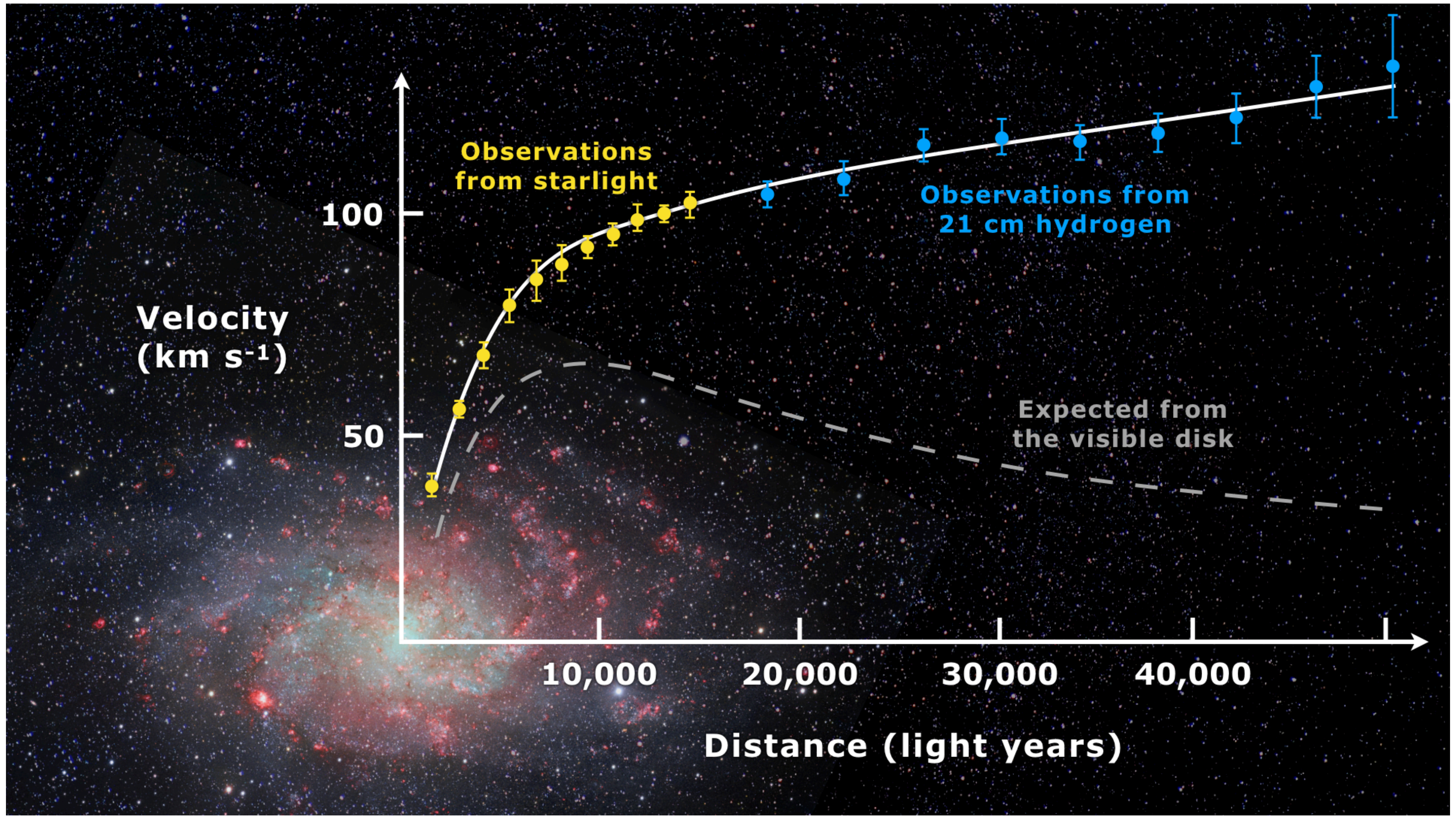
MAX-PLANCK-INSTITUT FÜR PHYSIK

COSINUS

Dark Matter

- 84% of the matter in our universe is made of dark matter
- Evidence on all length scales
- Nature after ~100 years of research still unknown

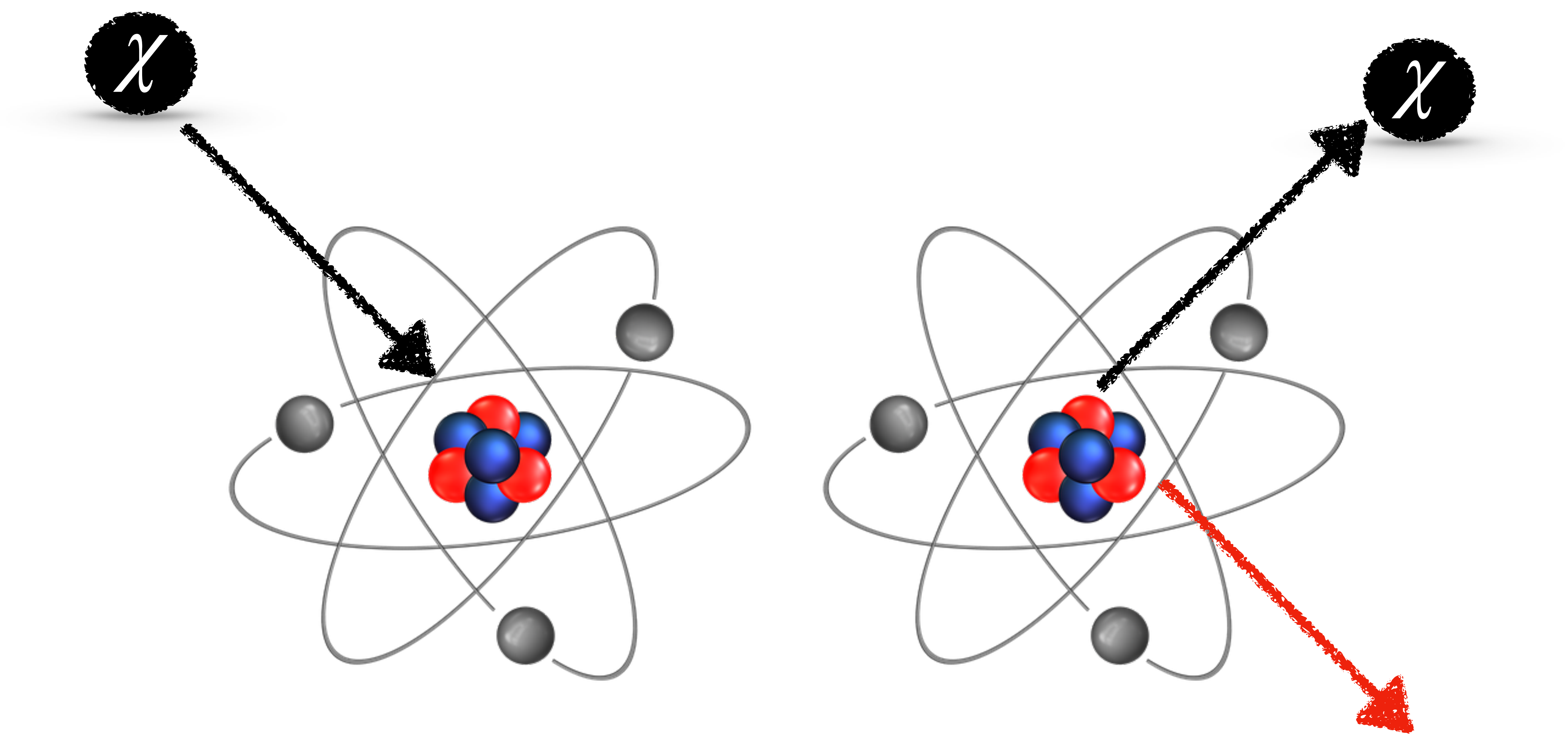
➡ One way to search for dark matter: Direct detection



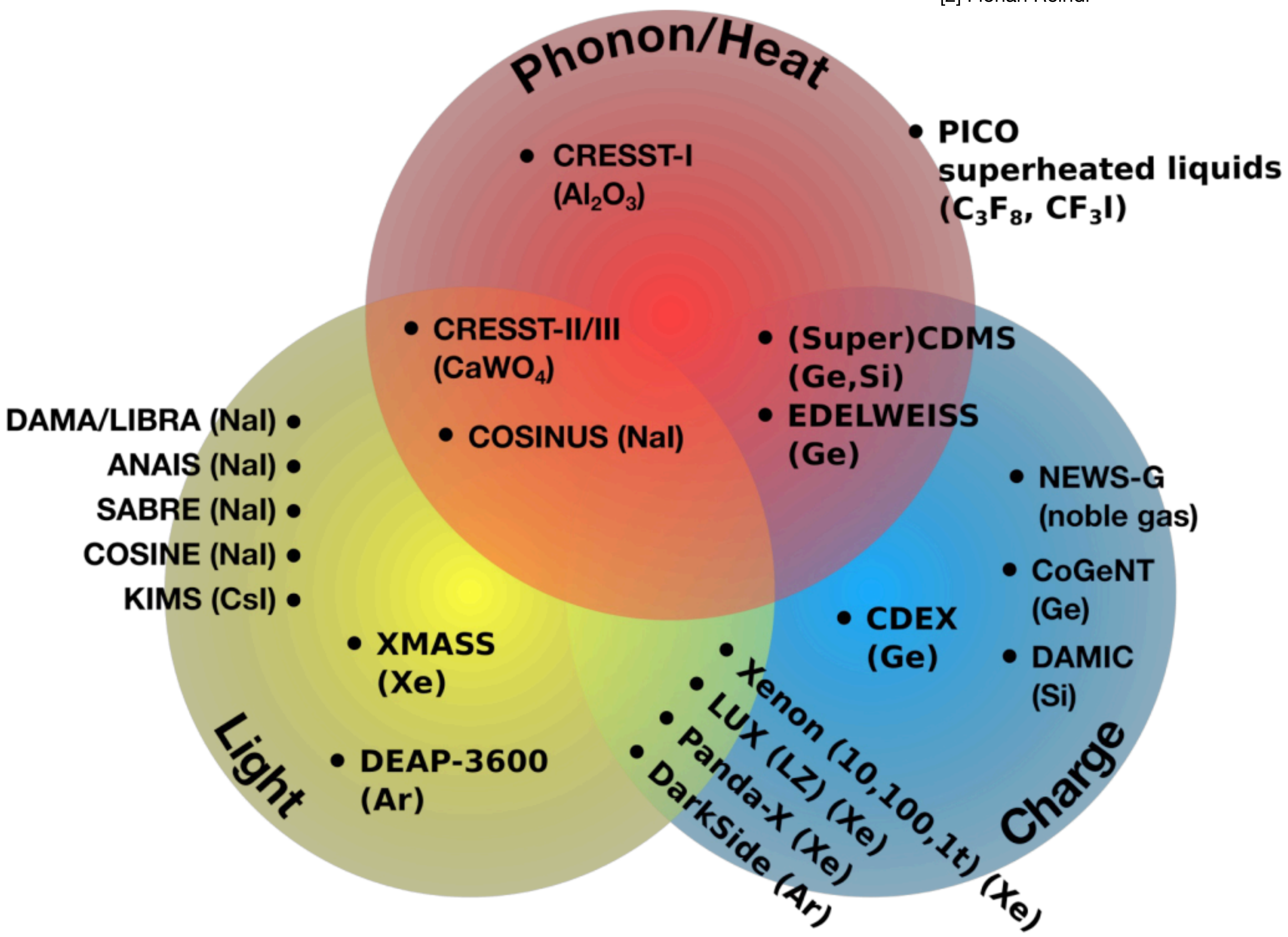
[1] Saeqa Dil Vrtilek 2022

Dark Matter Direct Detection

- Scattering of DM off Standard Model particle
- Most common scenario: Detection of nuclear recoil



[2] Florian Reindl



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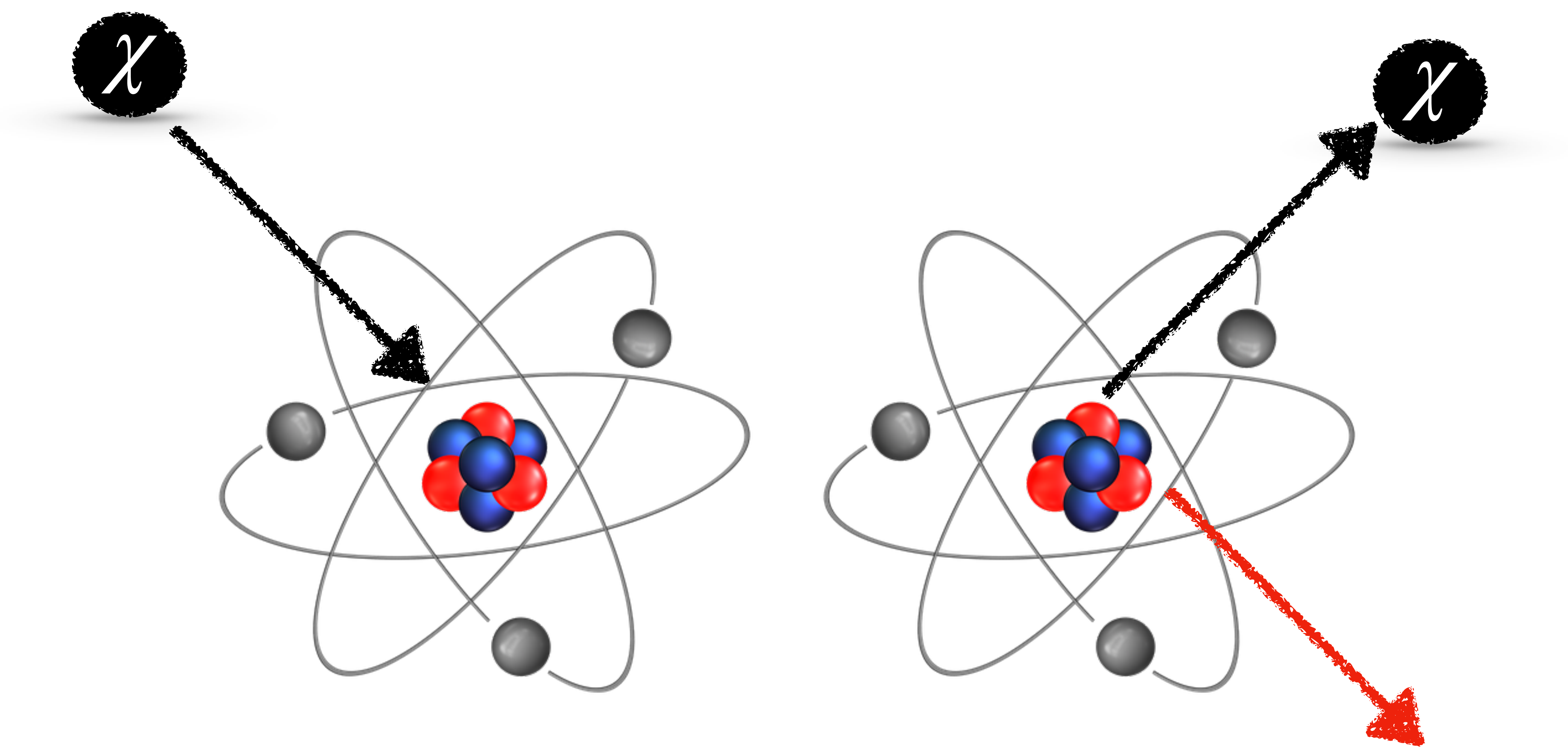

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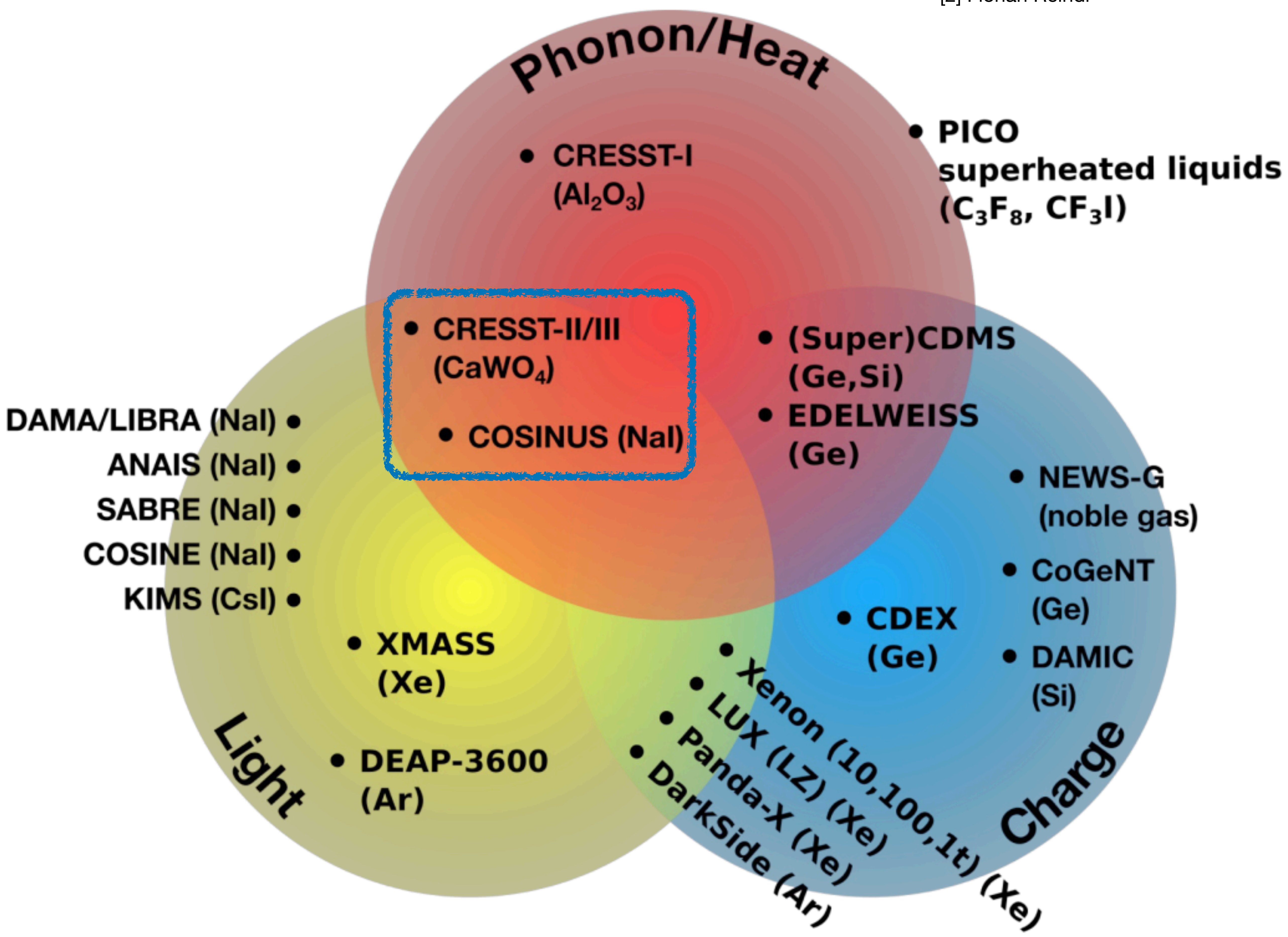
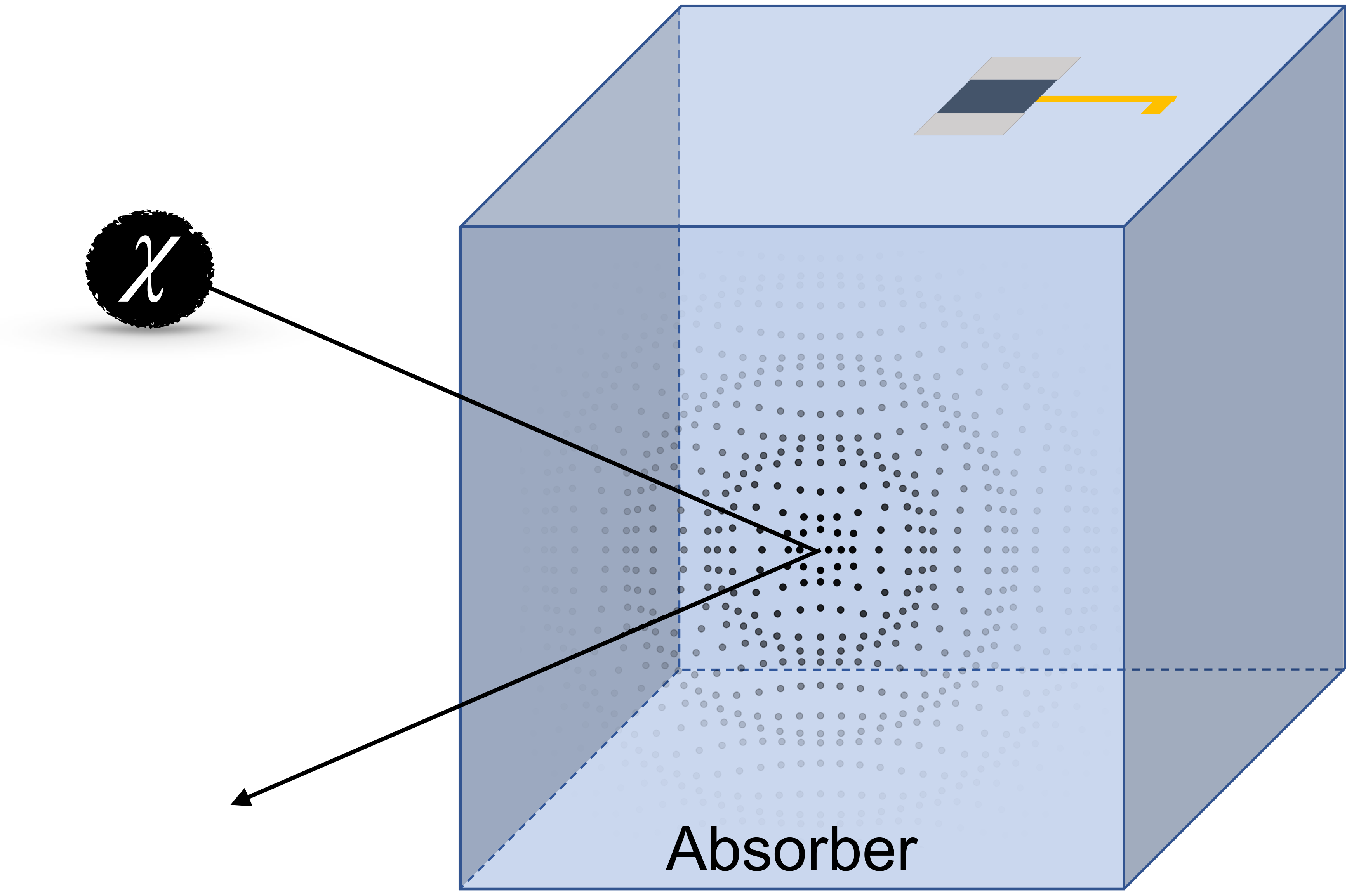
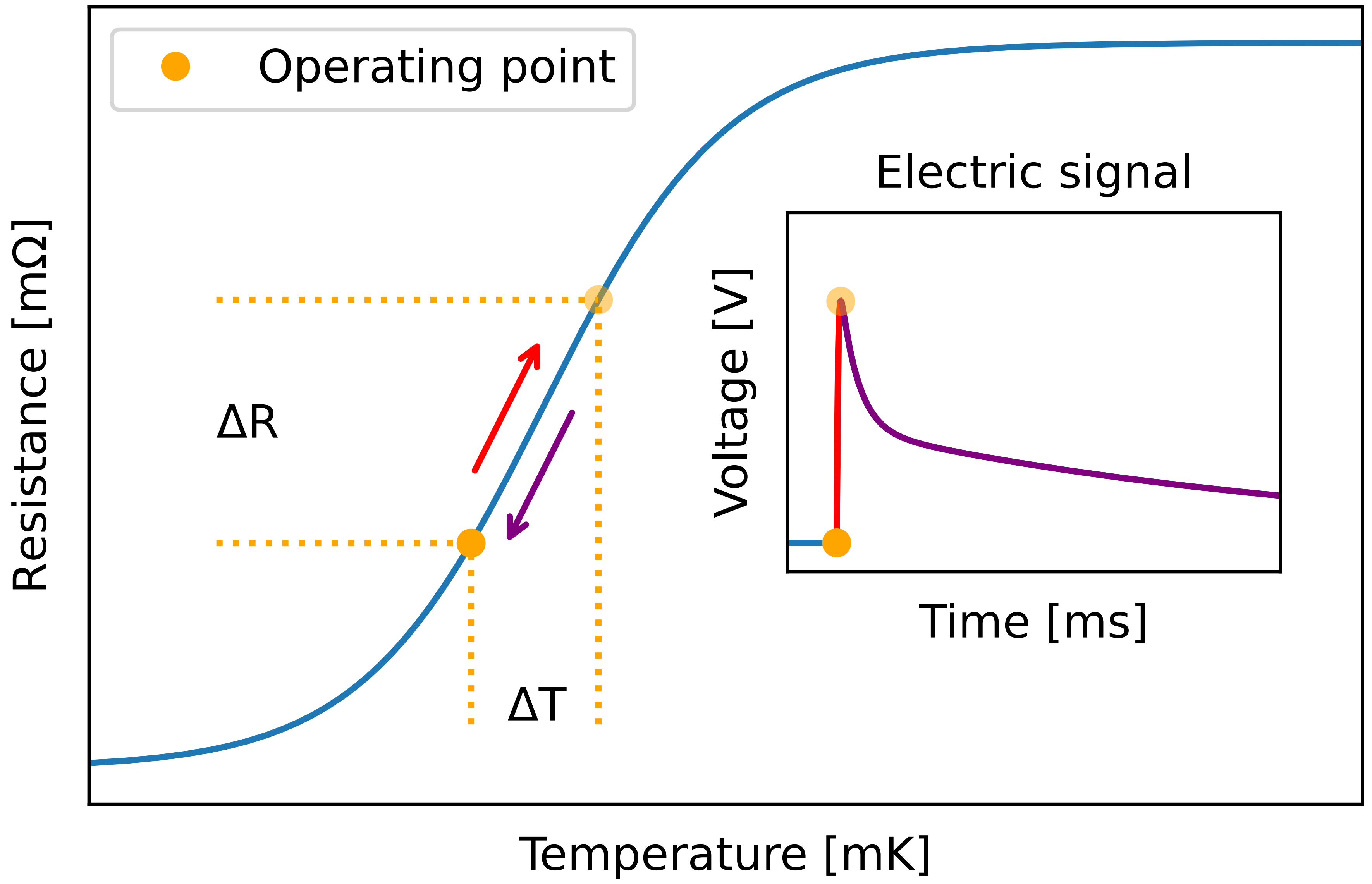
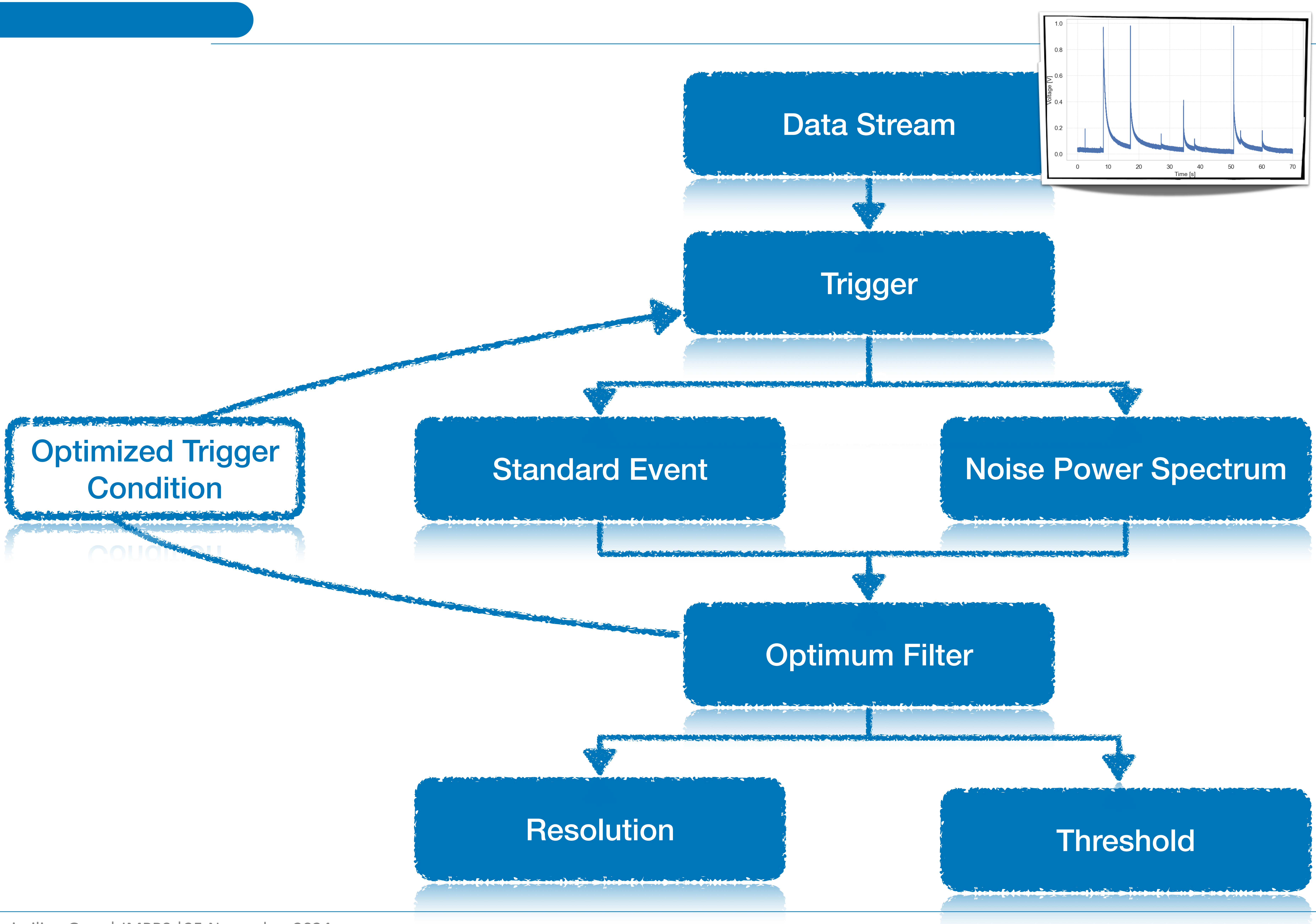


Cryogenic Detectors

- Target material cooled to <10 mK
- Particle deposits energy in the form of phonons/heat
- Temperature change ~μK measured with Transition Edge Sensor (TES)






Data Stream
Voltage [V]
Time [s]
Trigger
Optimized Trigger Condition
Standard Event
Noise Power Spectrum
Optimum Filter
Resolution
Threshold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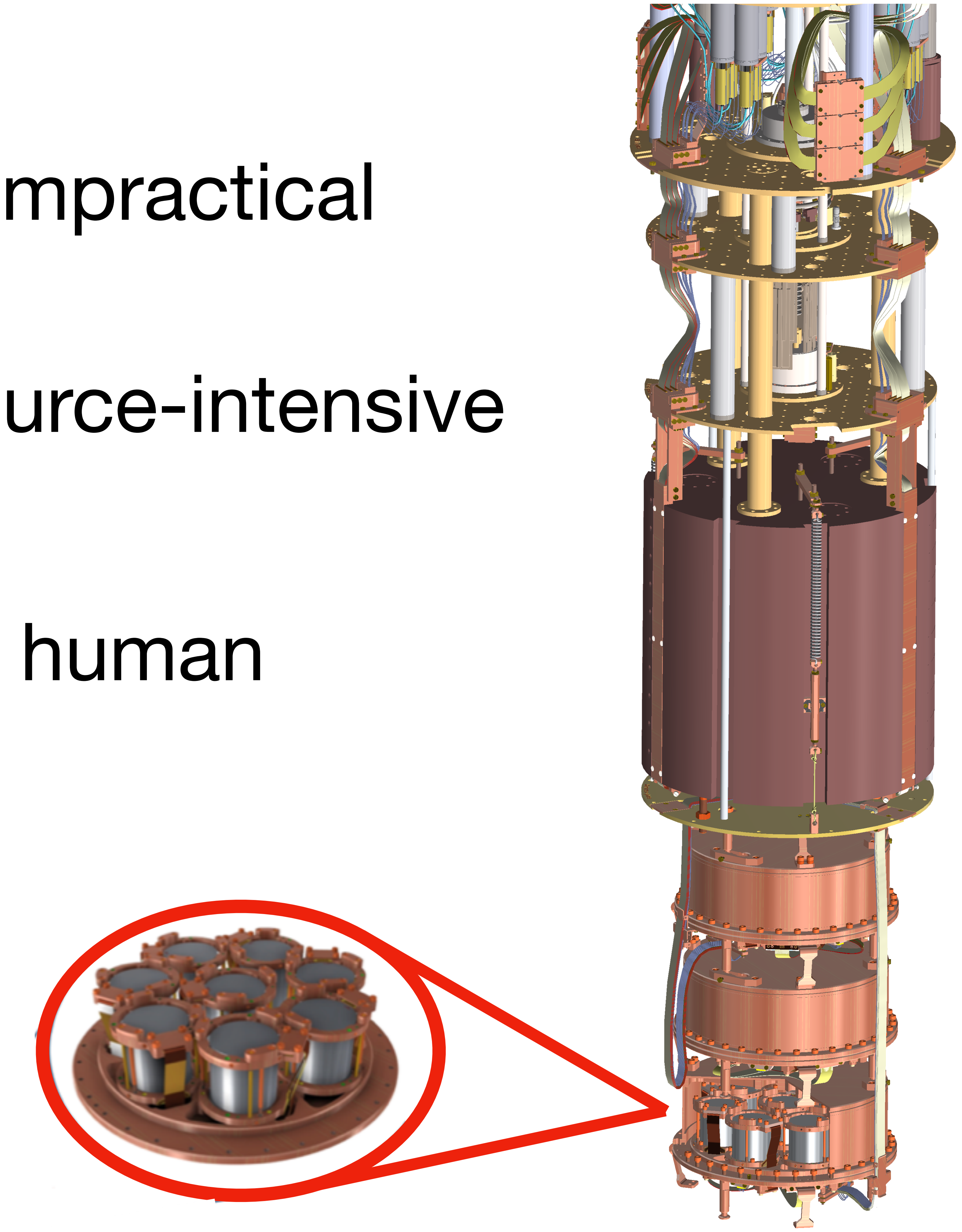
Why Automation?

- **Scaling:** Analysing larger detector arrays is currently impractical
  Planned: COSINUS (48 channels) and CRESST upgrade (288 channels)

- **Time Constraints:** Manual data analysis is slow, resource-intensive and requires experience

- **Bias:** Automated tools provide an unbiased check for human analyses, boosting confidence



Objectives

- **Automate where Possible:** Streamline the analysis process, reducing manual effort and saving time
- **Minimize Human Input:** Limit reliance on assumptions, ensuring unbiased and reproducible results
- **Be Adaptable:** Design to accommodate diverse detector modules with varying characteristics

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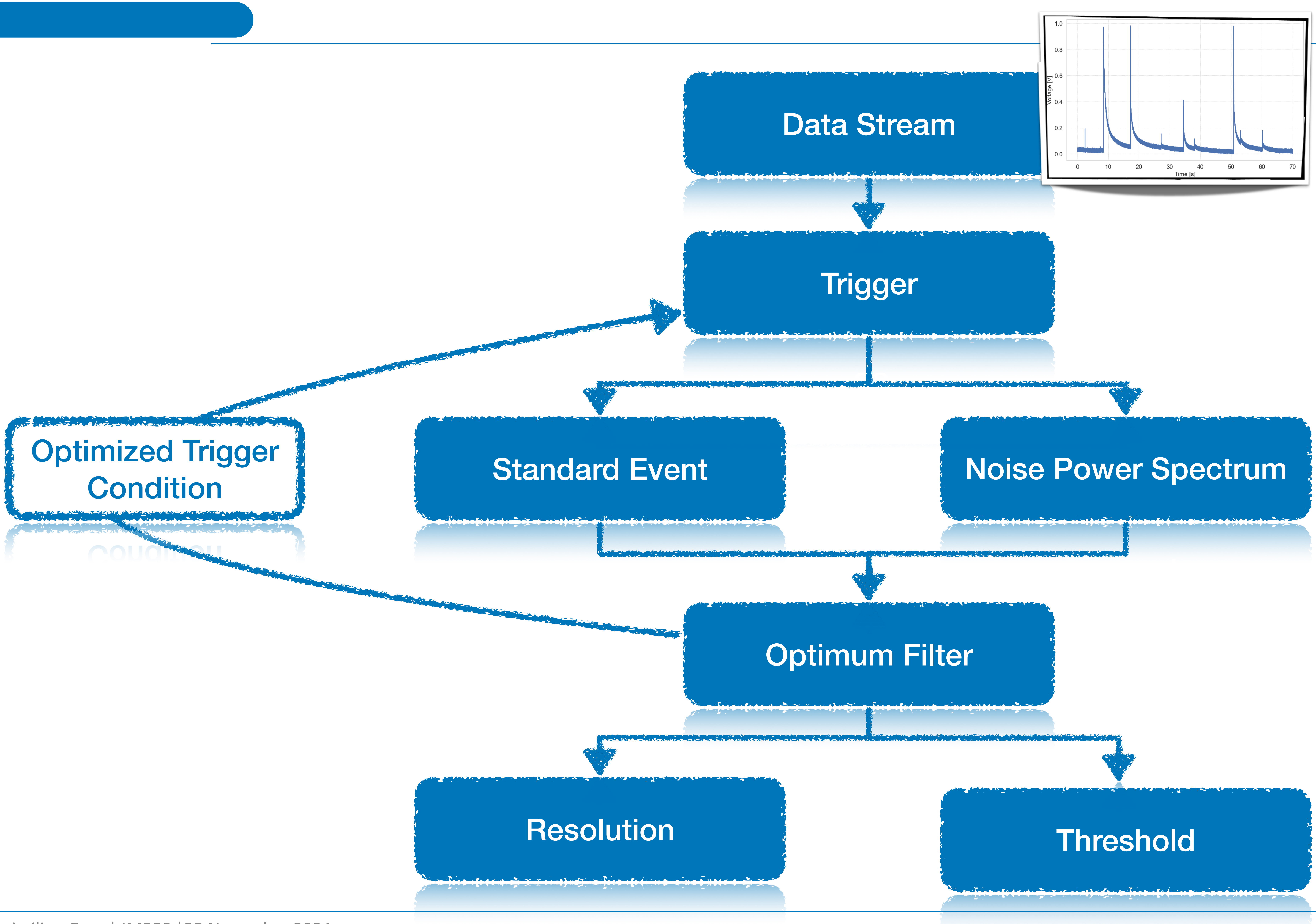
Focus of my Thesis:
Development and verification of an automated analysis workflow designed to efficiently characterize COSINUS prototype detectors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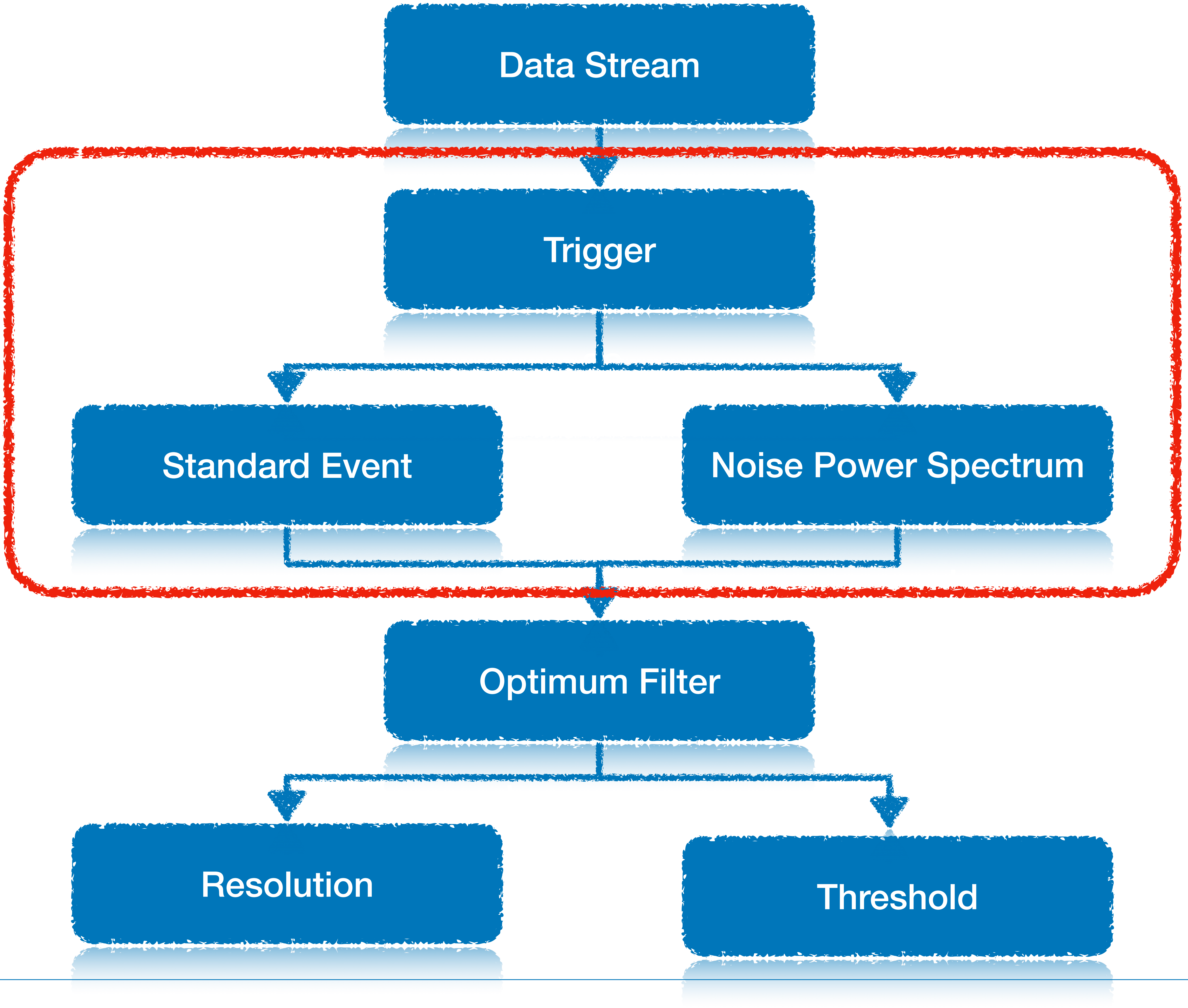
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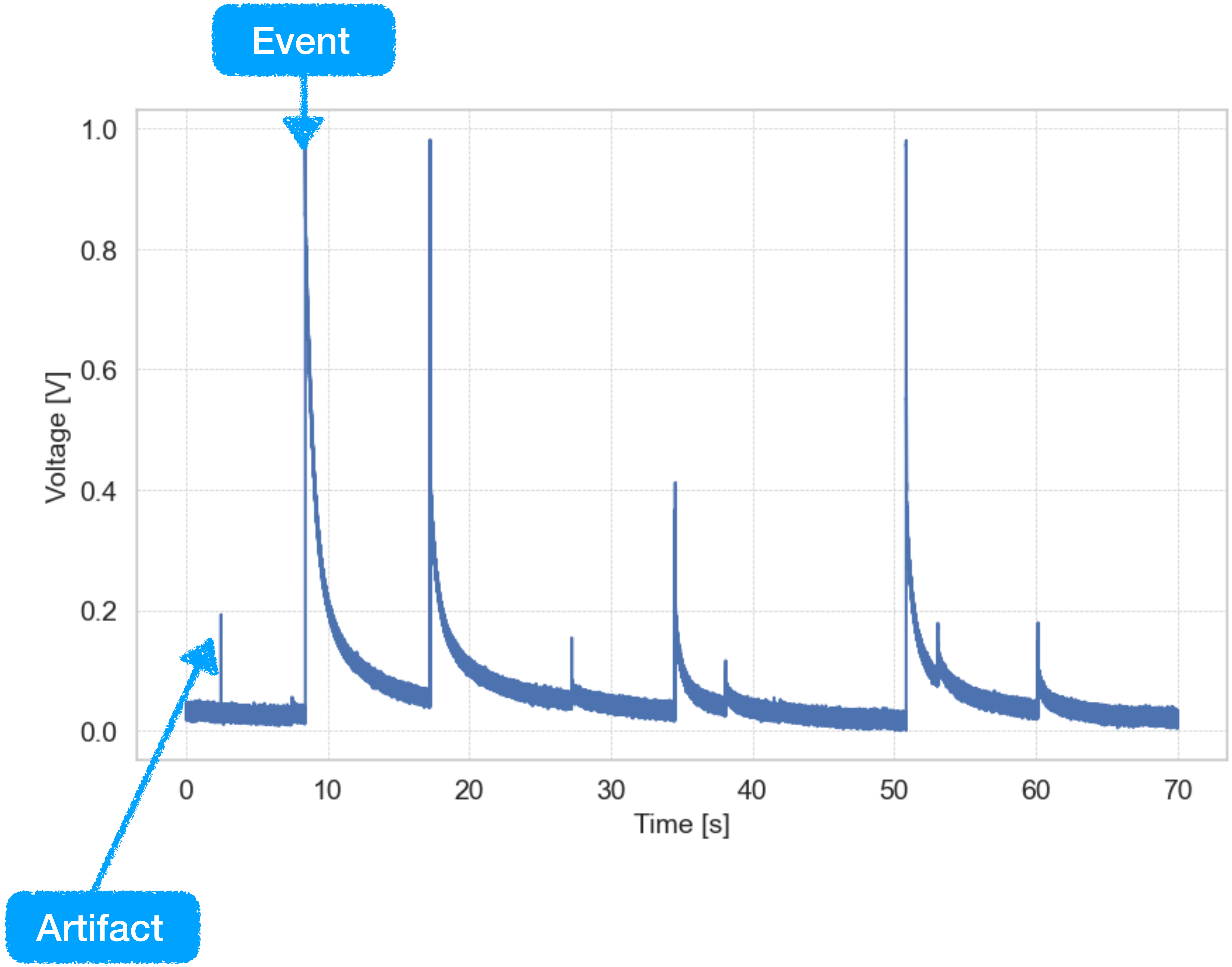
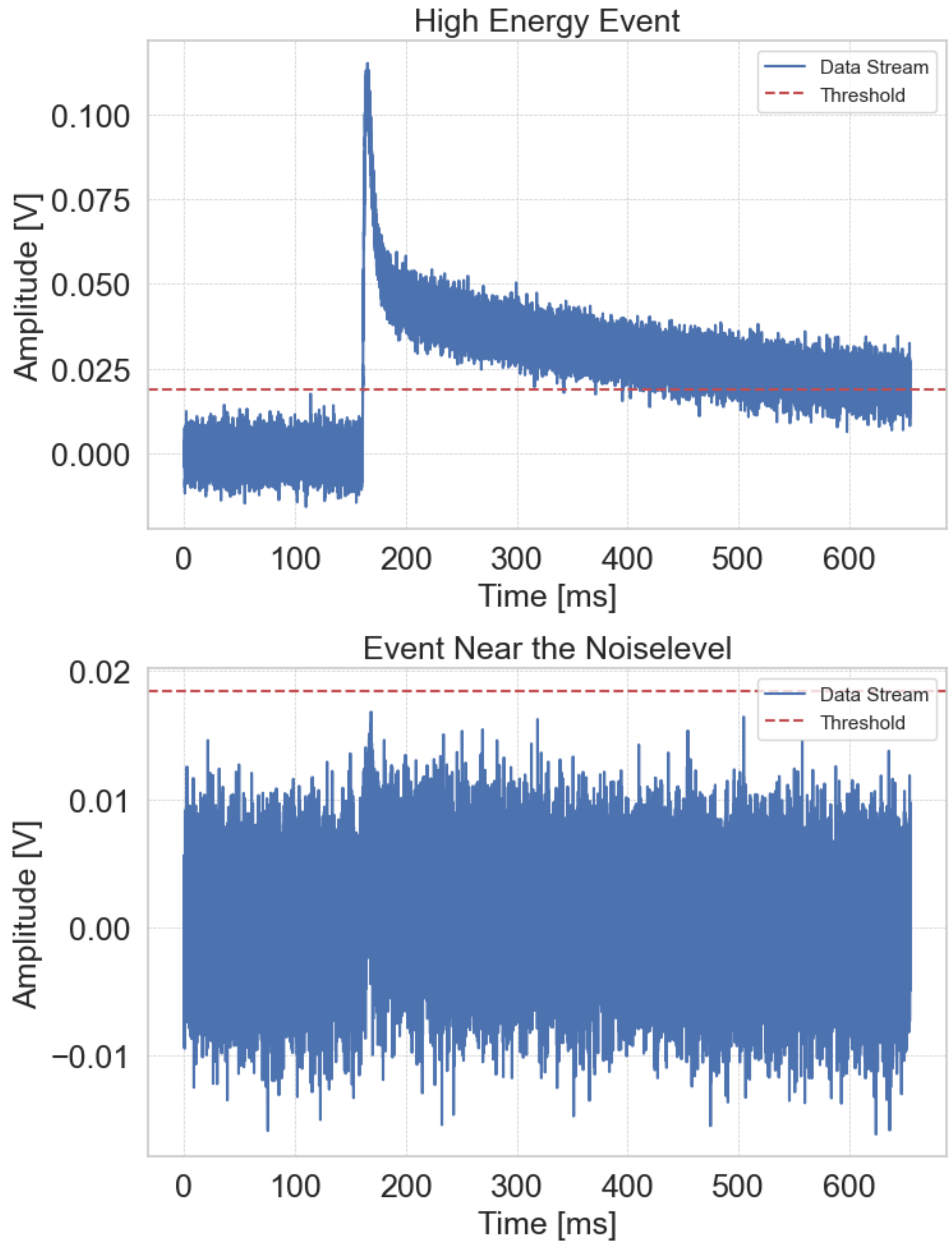
Trigger

- Raw data: voltage stream
- Apply a trigger with as few assumptions as possible
- Minimize deadtime



Mean-Trigger

- Typical trigger algorithm
- Moving average trigger
- No assumption on pulse-shape

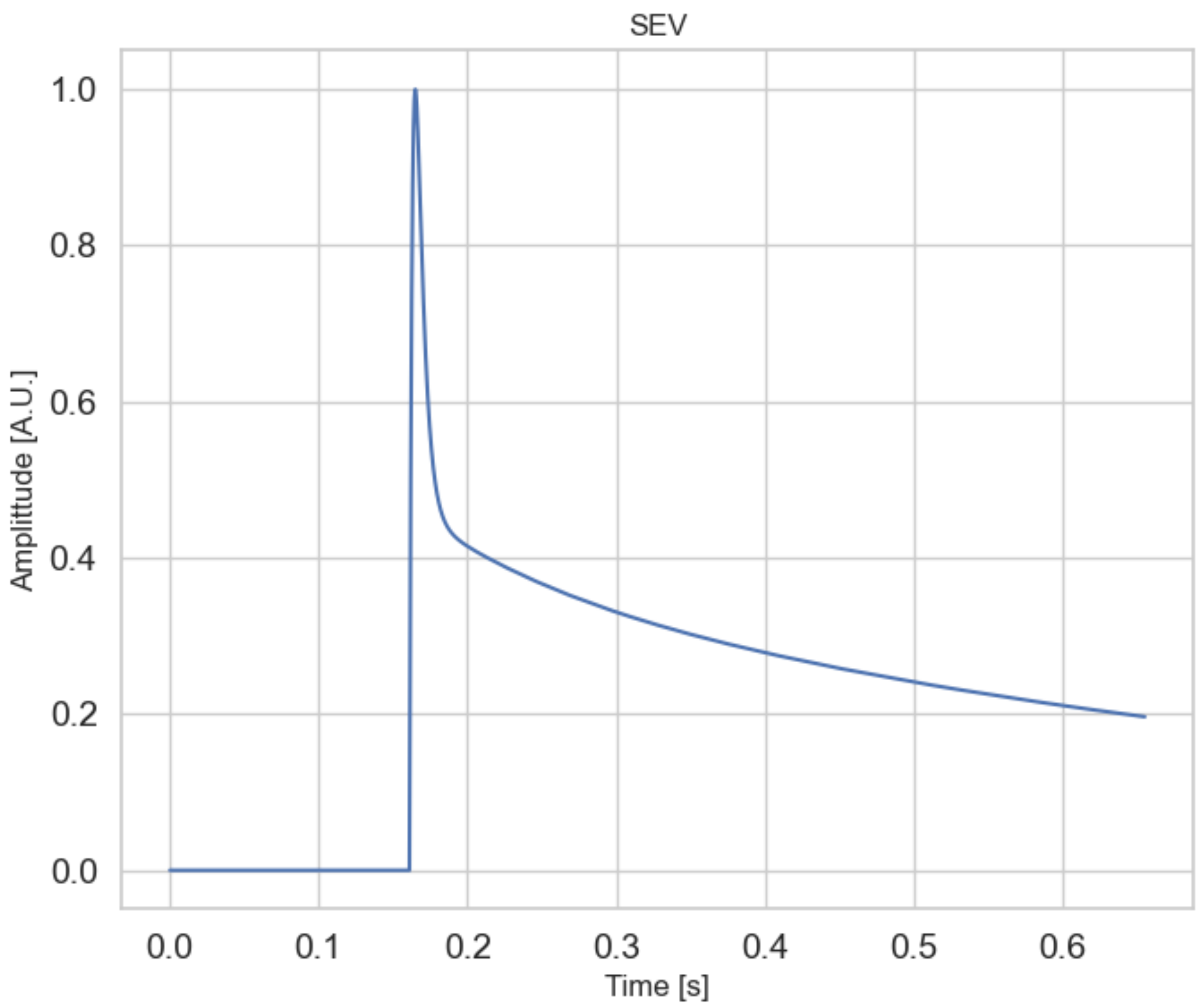


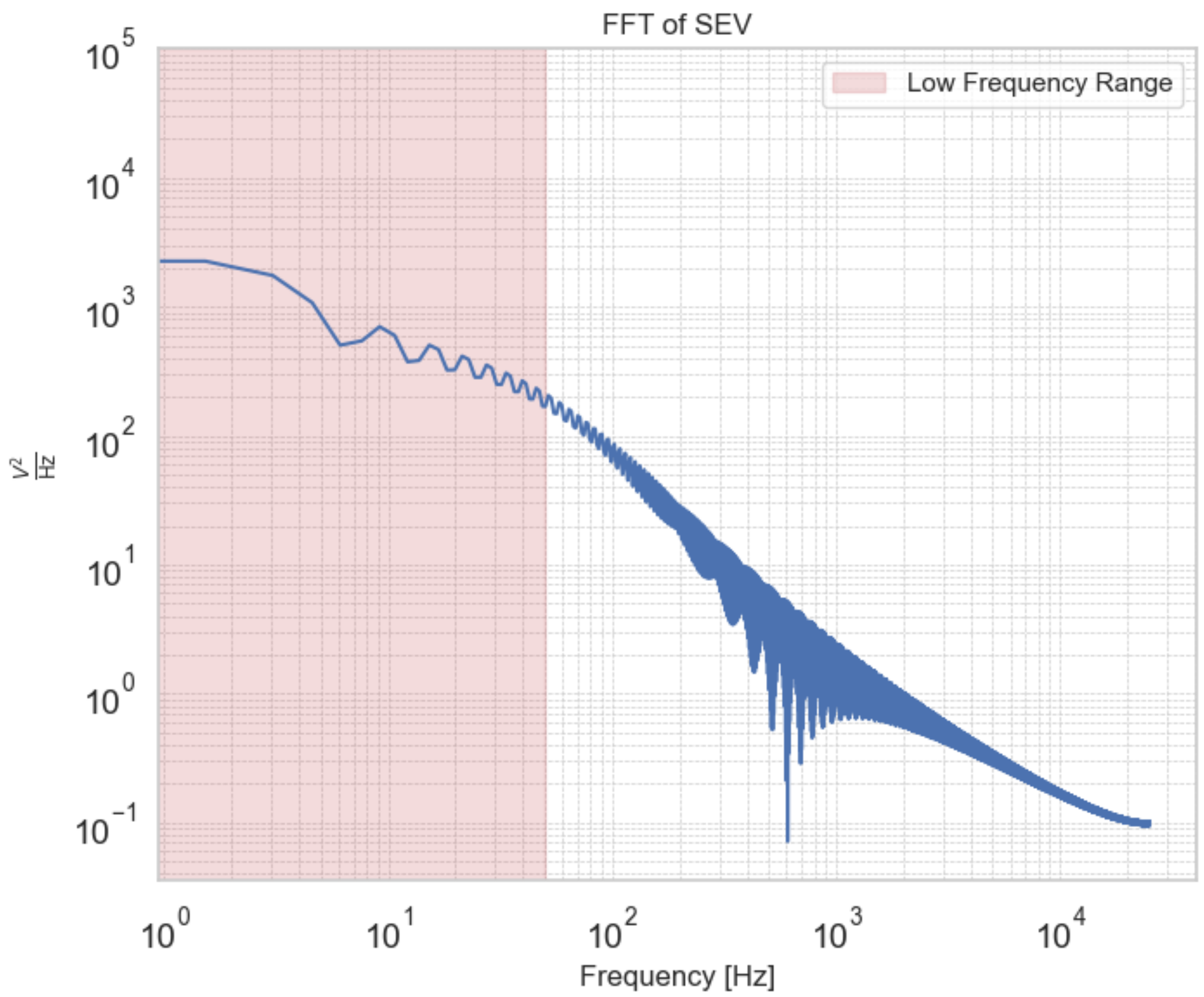
Frequency-Trigger

- **Assumption:**
  Frequency content of a pulse consists mainly of low frequencies

- Trigger on change of integrated low-frequency content

- Assumption: Cutoff frequency (50 Hz)





More Details: E. Agletdinov, “A New Method of Low Amplitude Signal Detection and Its Application in Acoustic Emission”

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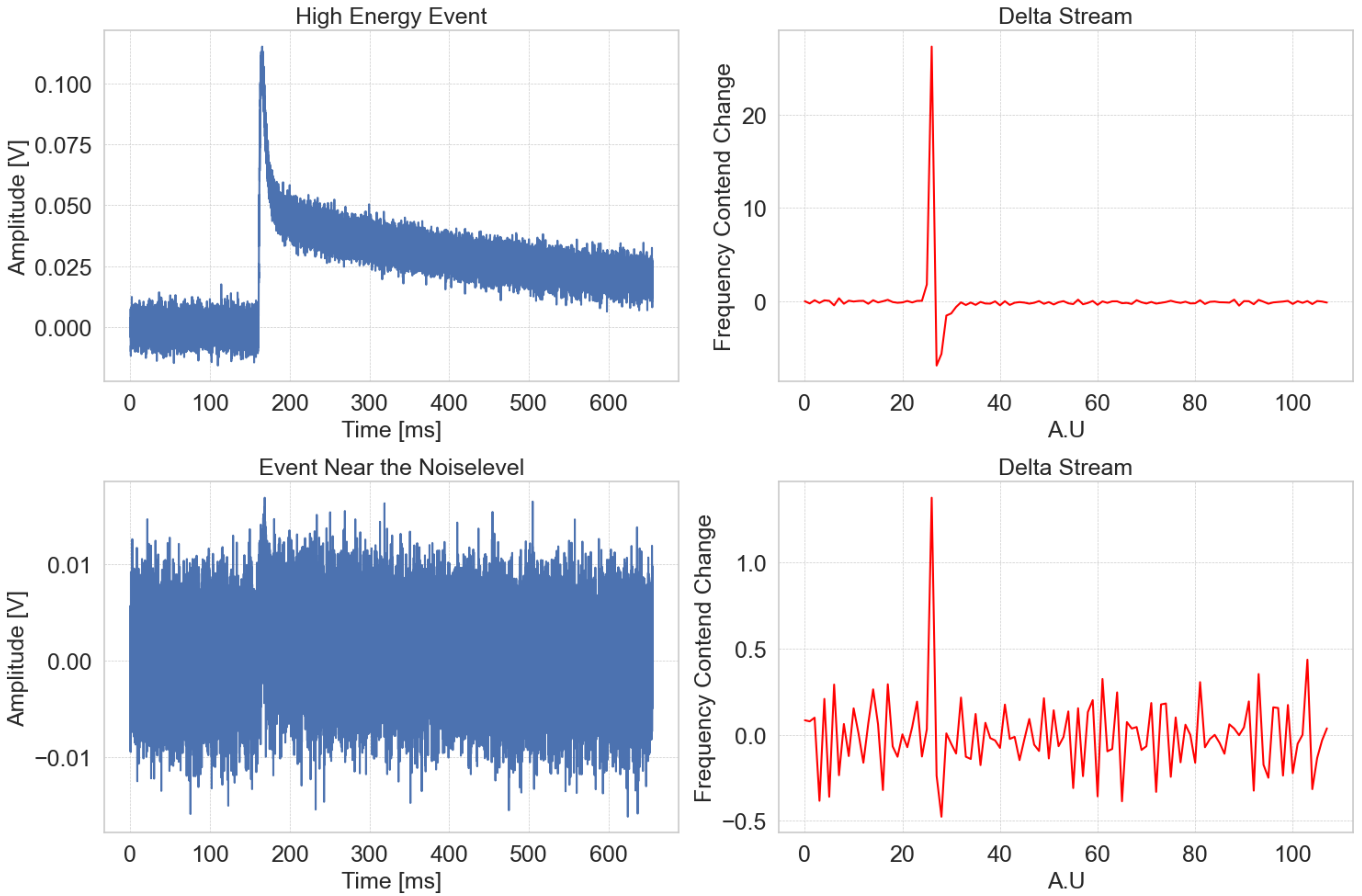

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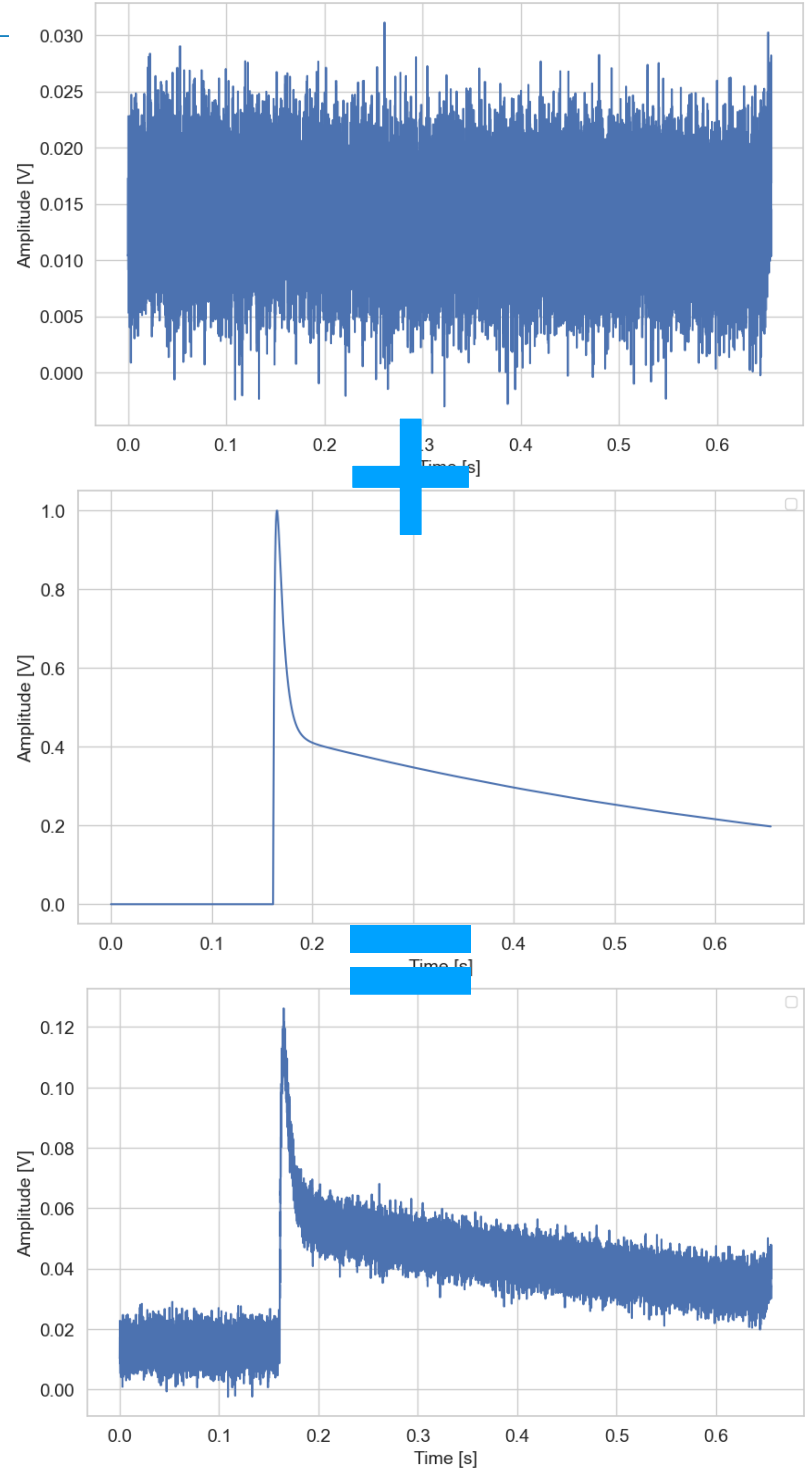
Performance Comparison

- Superimpose random drawn windows with event of different amplitudes

- If trigger and simulation point coincide, consider as valid

- Frequency trigger best candidate for first trigger



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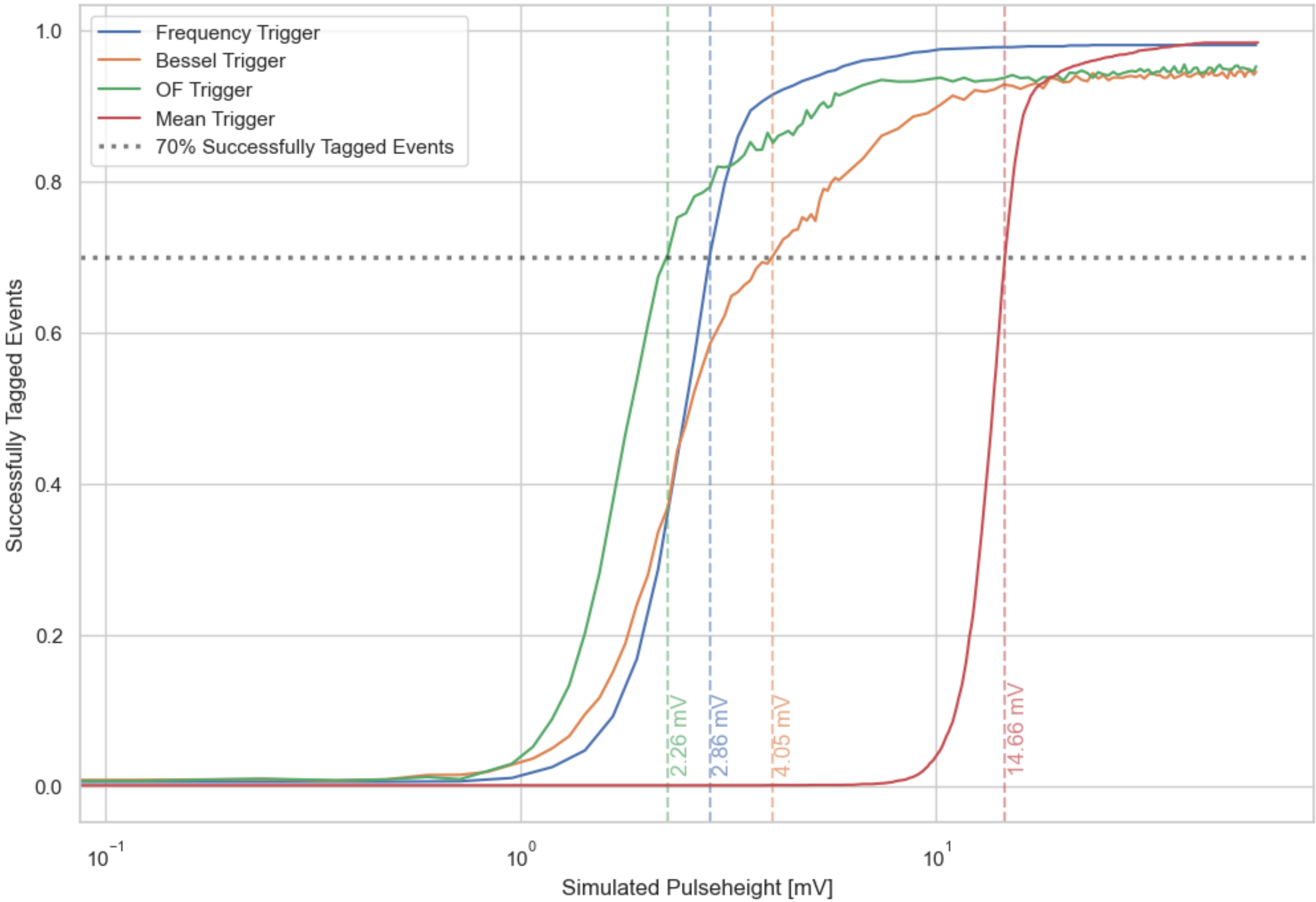

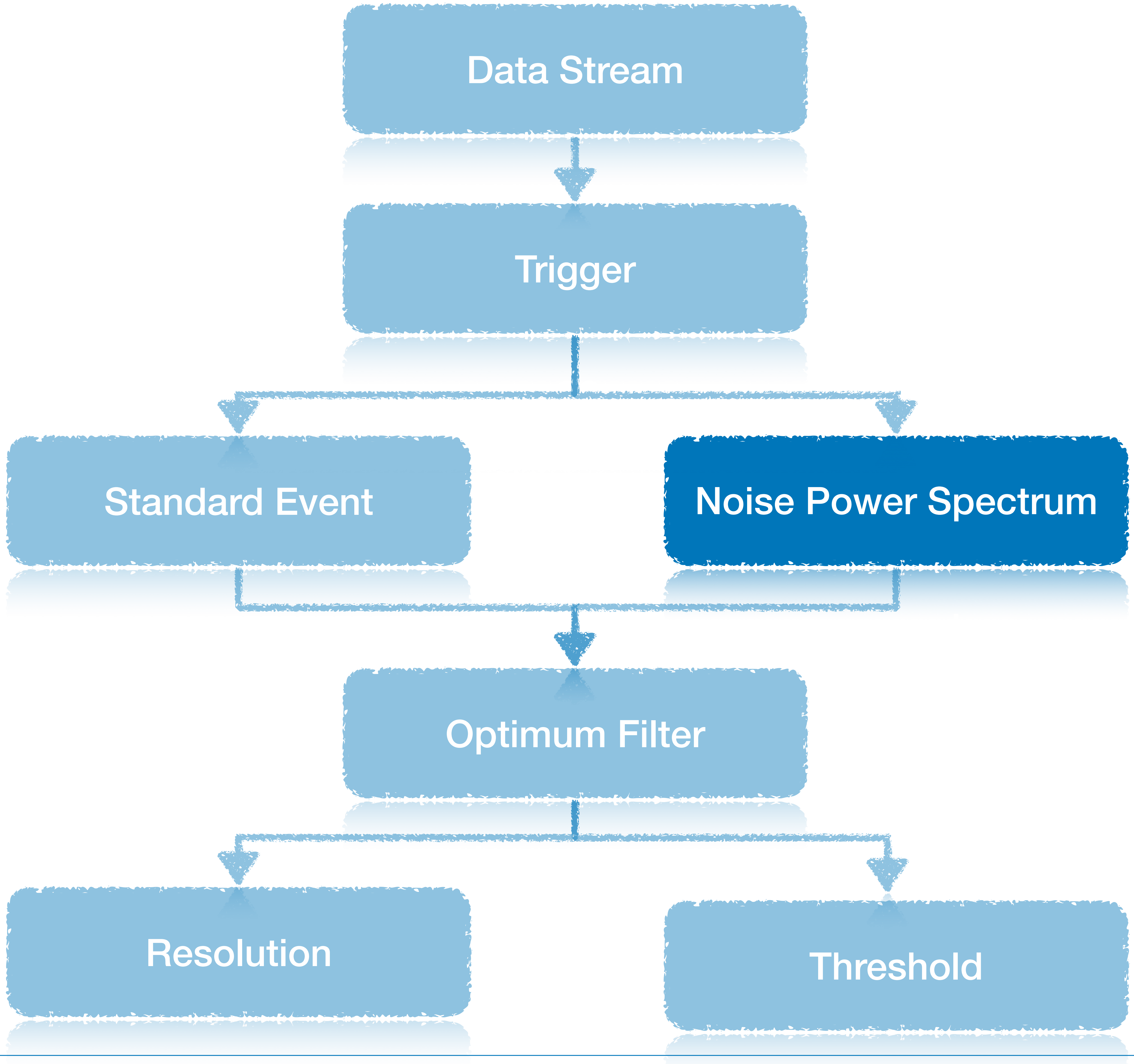
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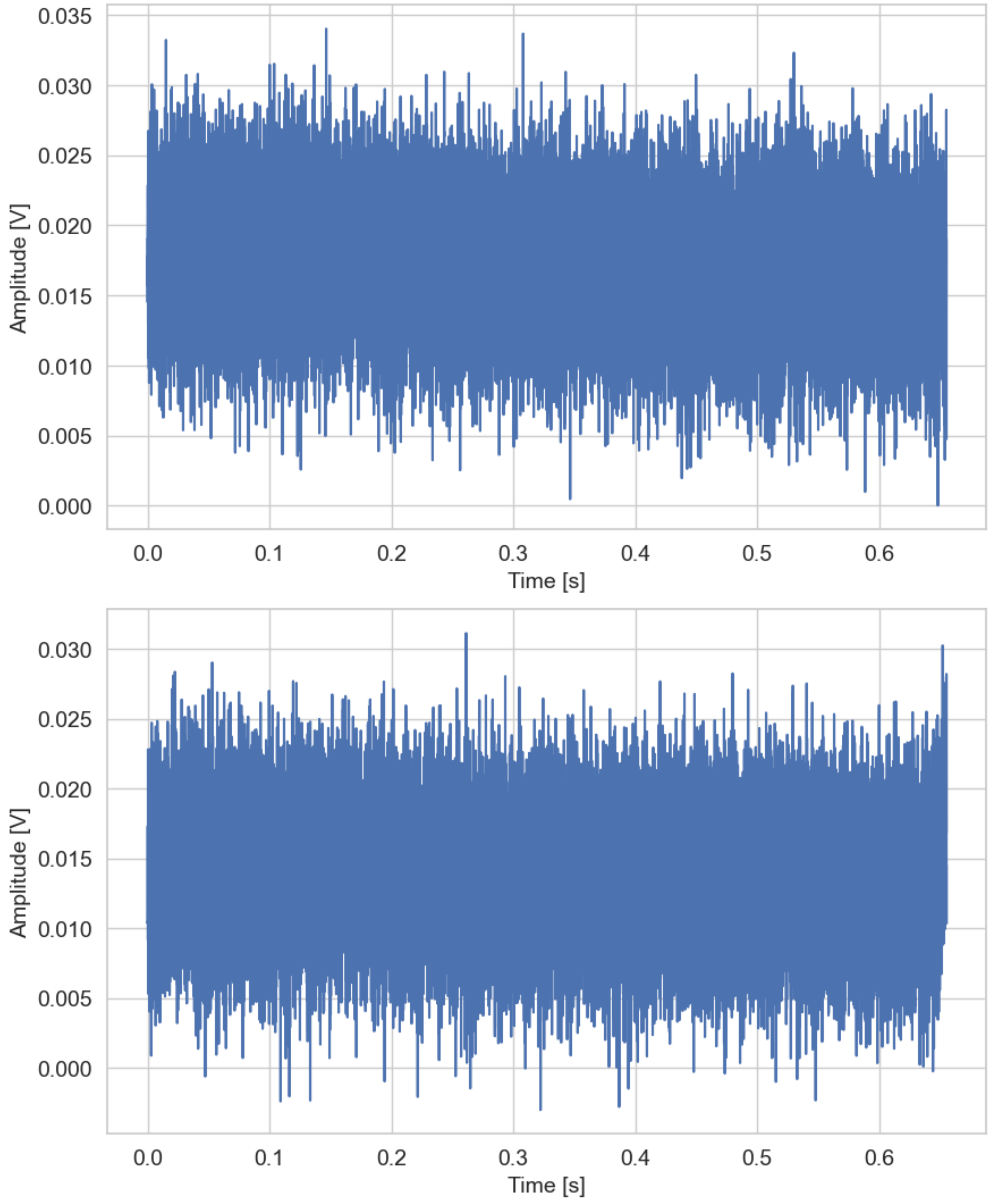
Characterize the Noise

- Draw and clean empty traces
- Create a Noise Power Spectrum (NPS)
- Characterizes the average noise conditions



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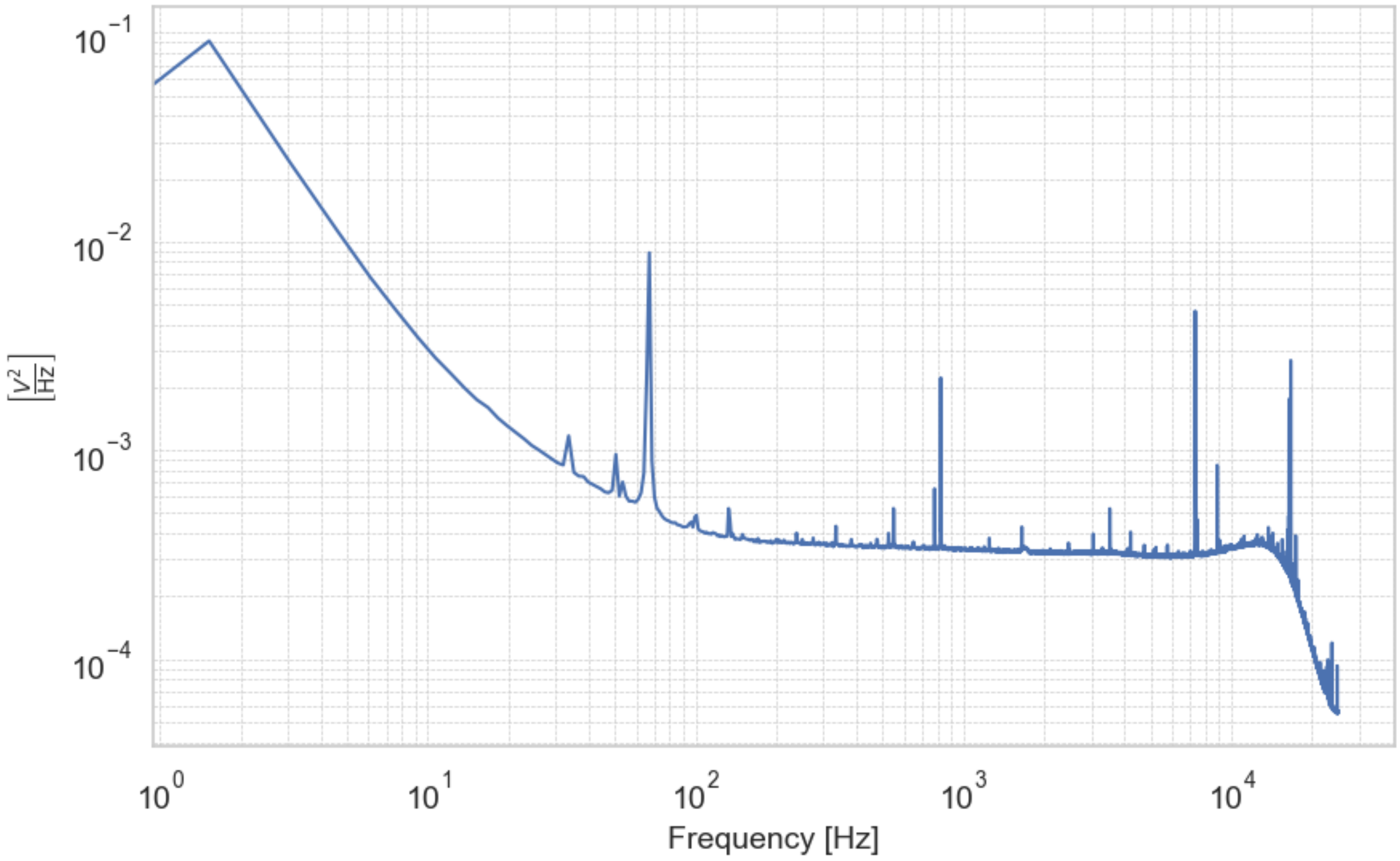
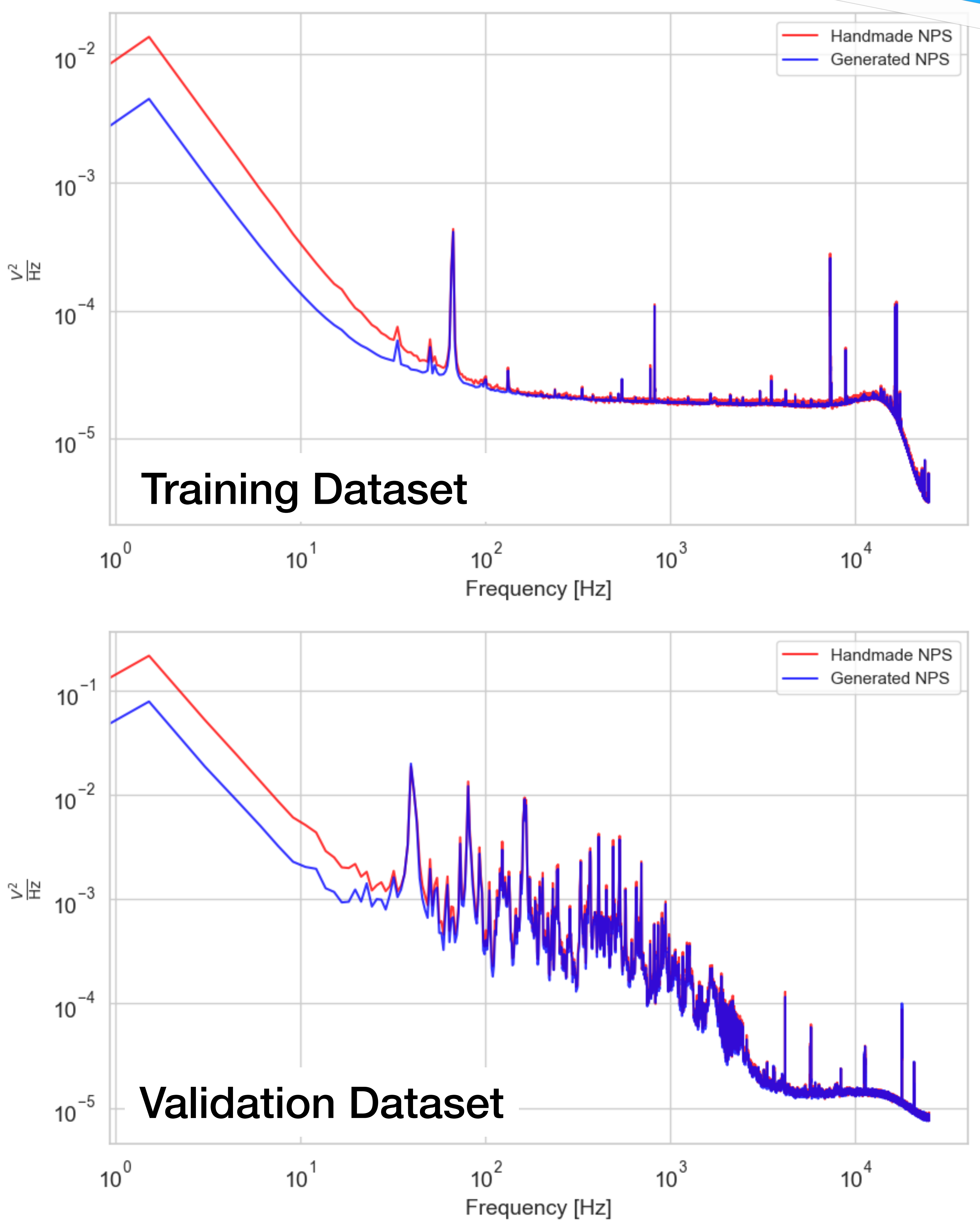
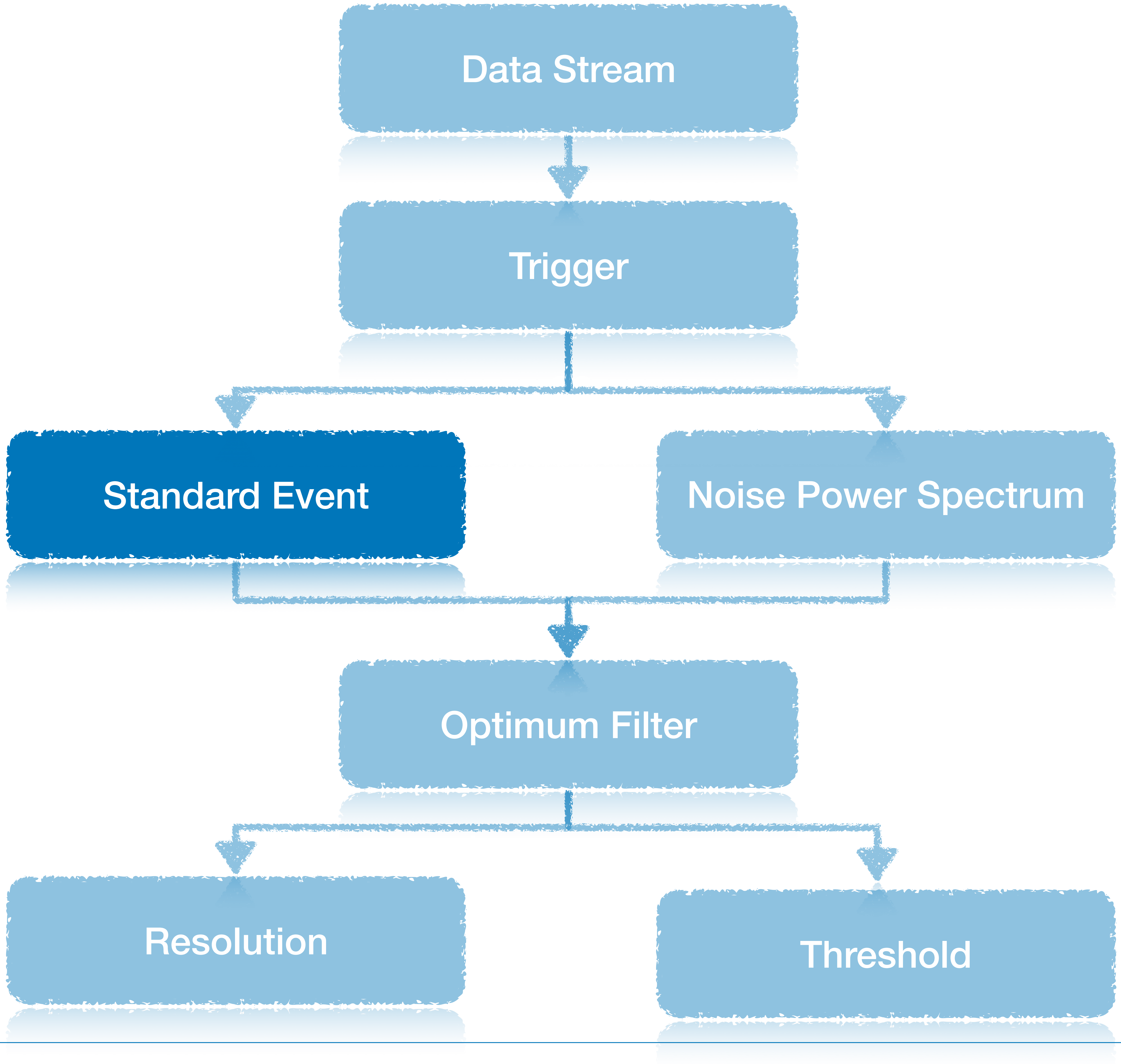


Reminder: 2 Prototypes

NPS-Generator

- Sequence of different trigger/cleaning modules
- Cleans data stream from events and artifacts
- **Advantages**
    - ➡ NPS creation without human input
    - ➡ Fast and reliable results

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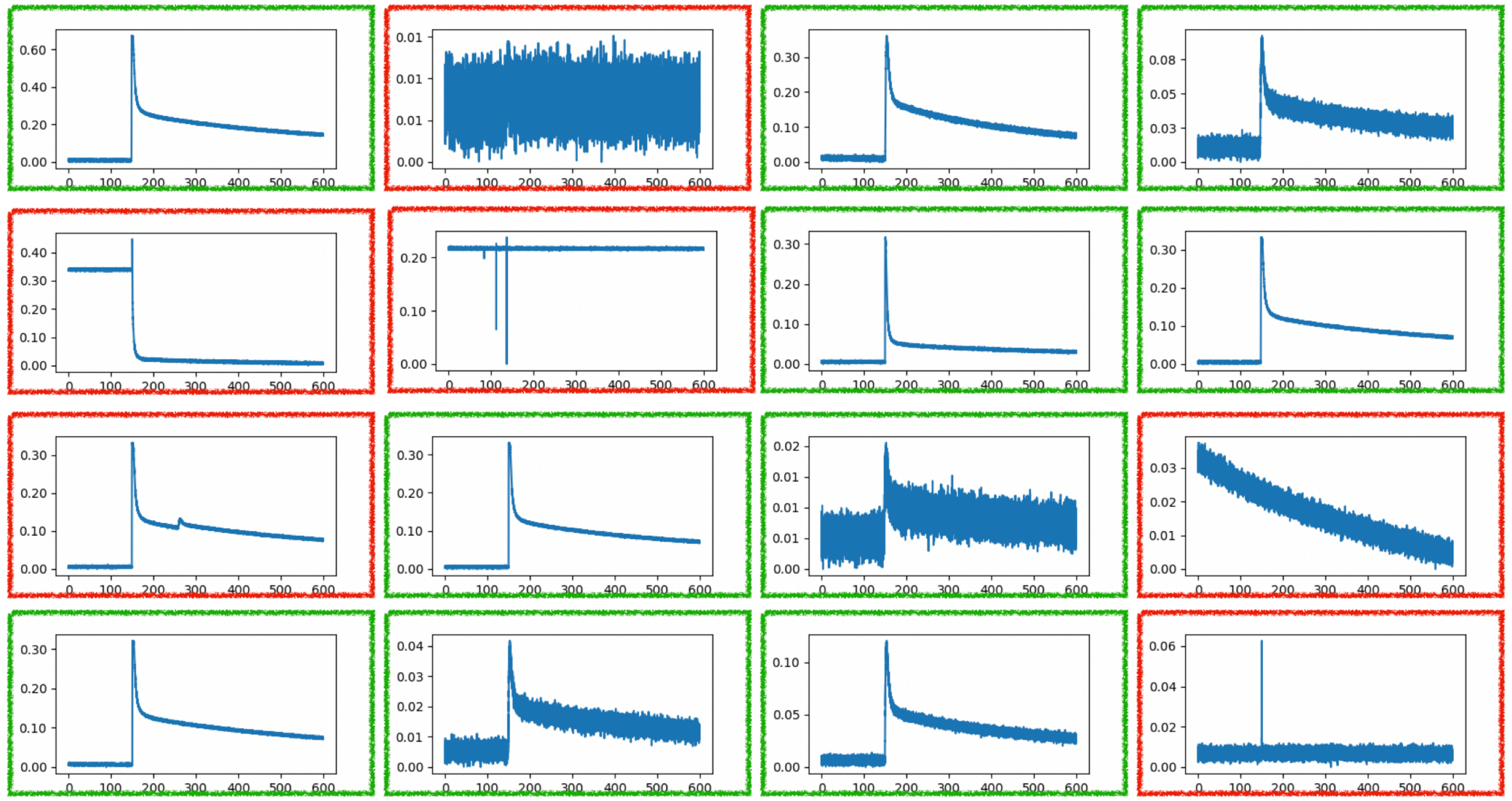
Validate Events

- Distinguish valid events from artifacts
- **Neural Network Approach**:

  ➡ Train Neural Network with real events and artifacts

  ➡ Network learns to identify patterns in the pulse shapes

  ➡ Existing Neural Network from CRESST (trained with one million real events)



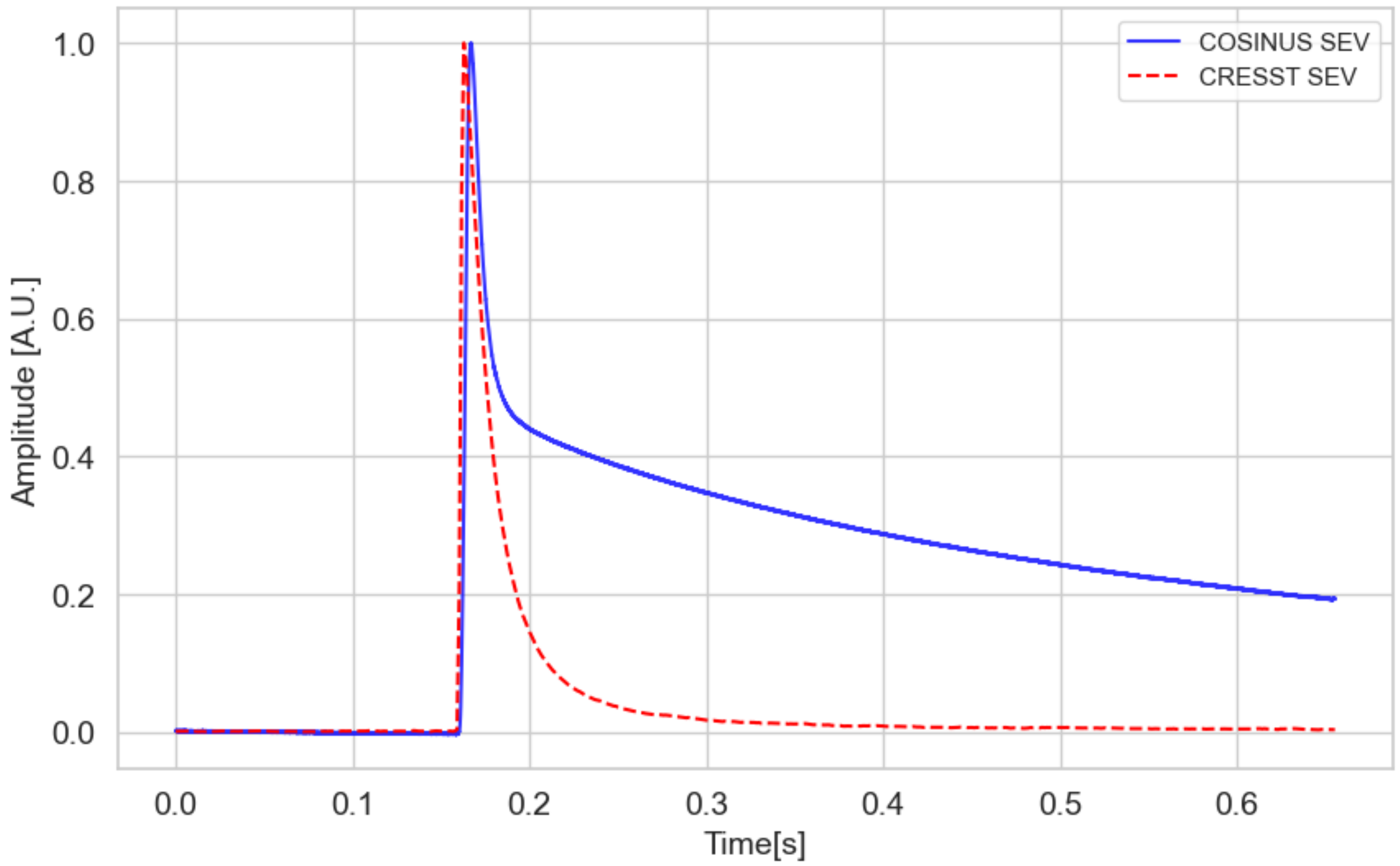
CRESST
Cryogenic **Rare Event Search** with Superconducting Thermometers

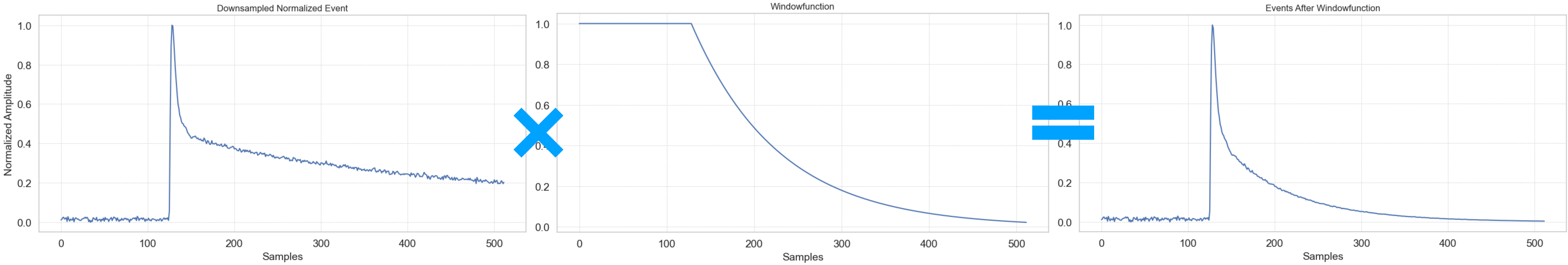
More Details: F. Wagner, “Towards next-generation cryogenic dark matter searches with superconducting thermometers.”

Adaptation of the Neural Network

- COSINUS-pulses are slower than CRESST-pulses

- **Solution:**
  Introduce window function



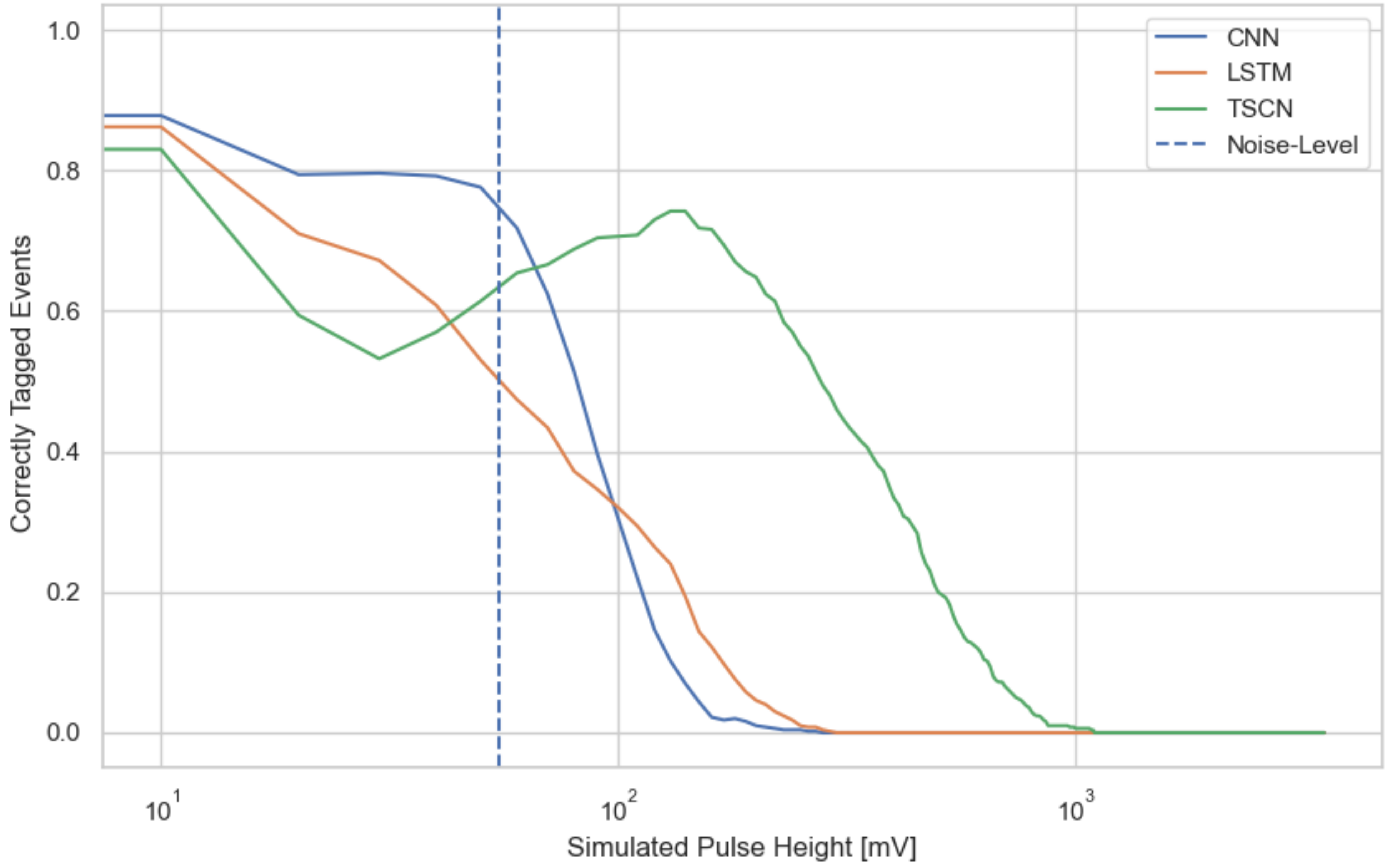


Adaptation of the Neural Network

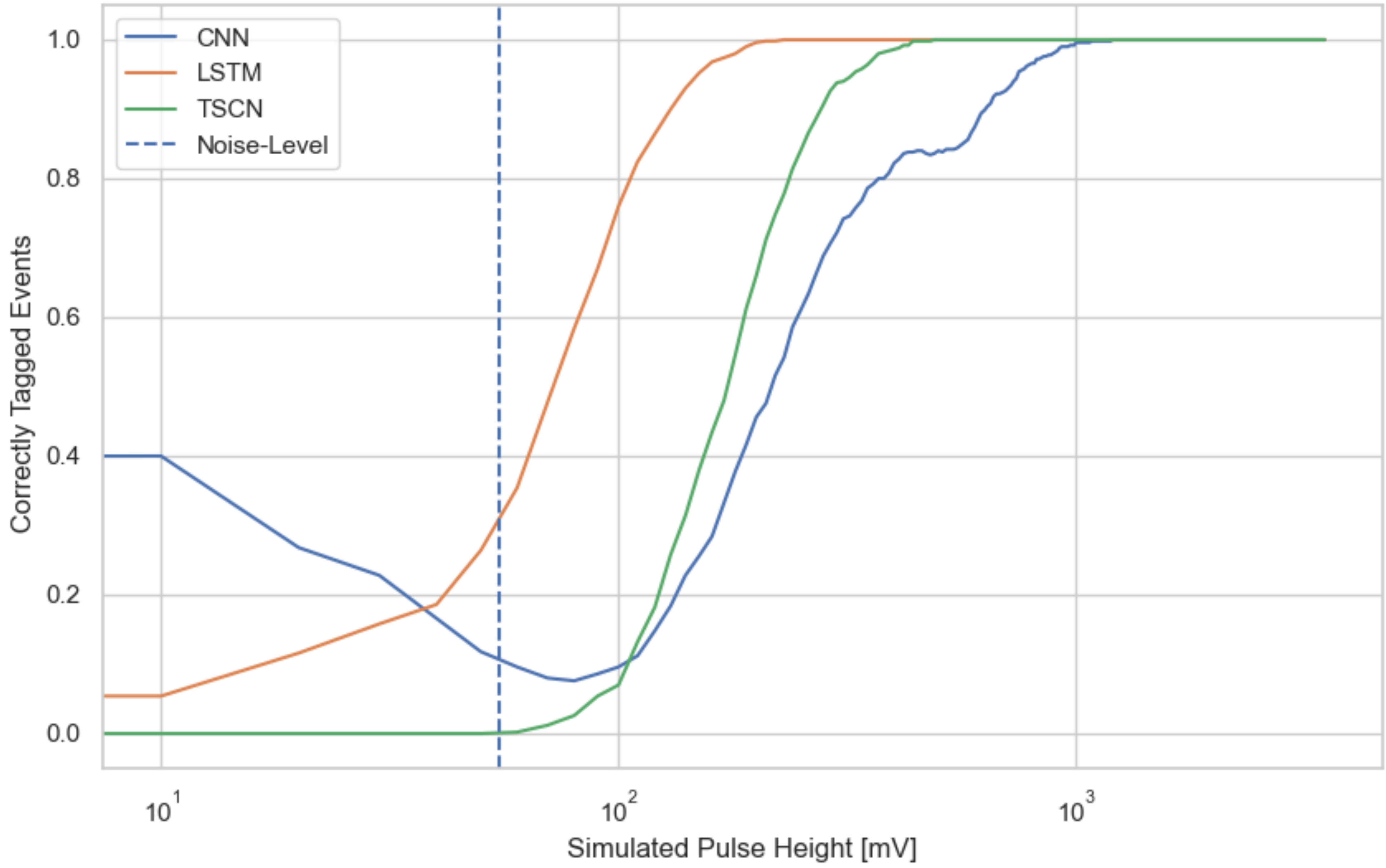
- Poor performance on simulated COSINUS events

- Good performance for events above noise level

- Some artifacts mislabeled as valid events



Window function



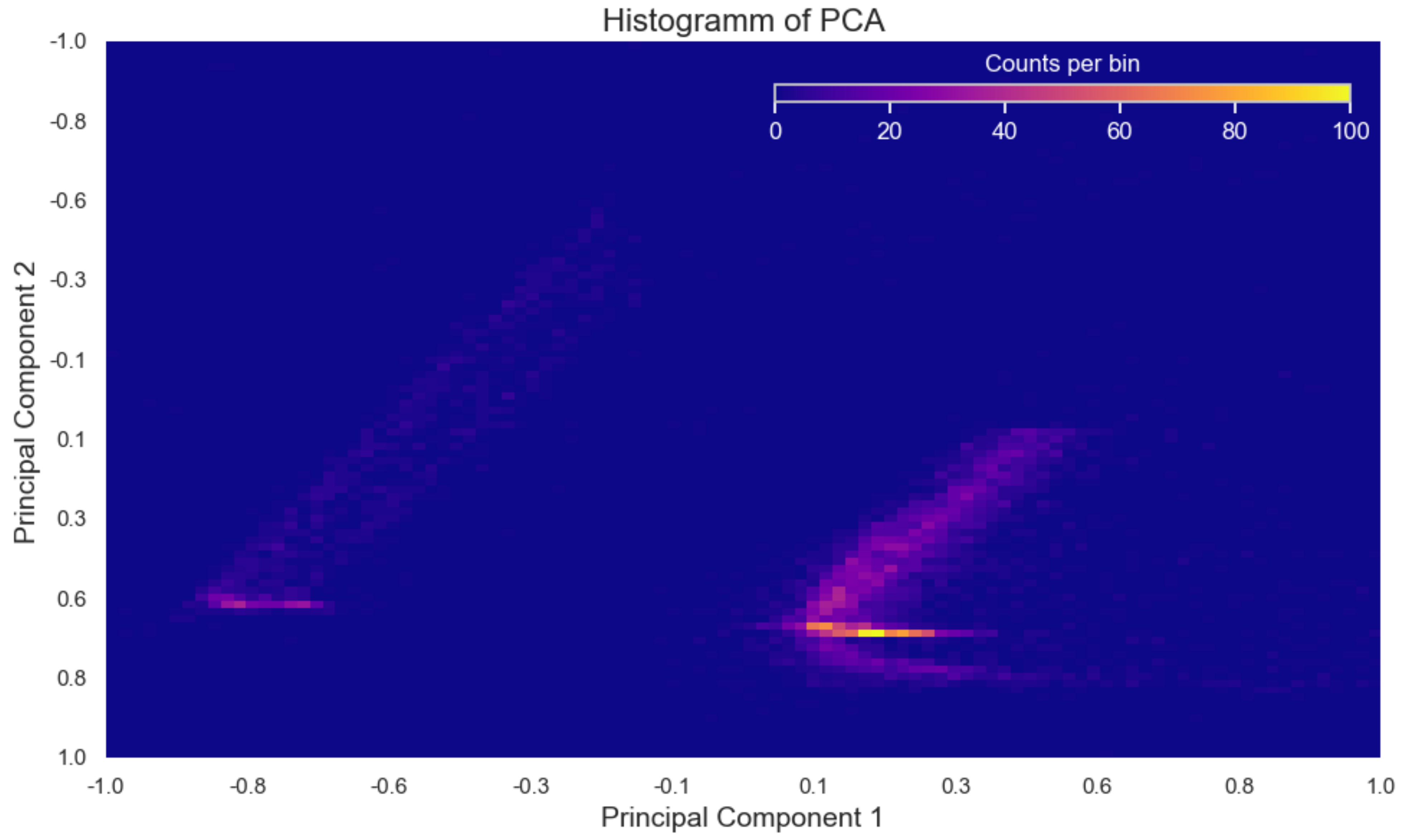
Classify Event types

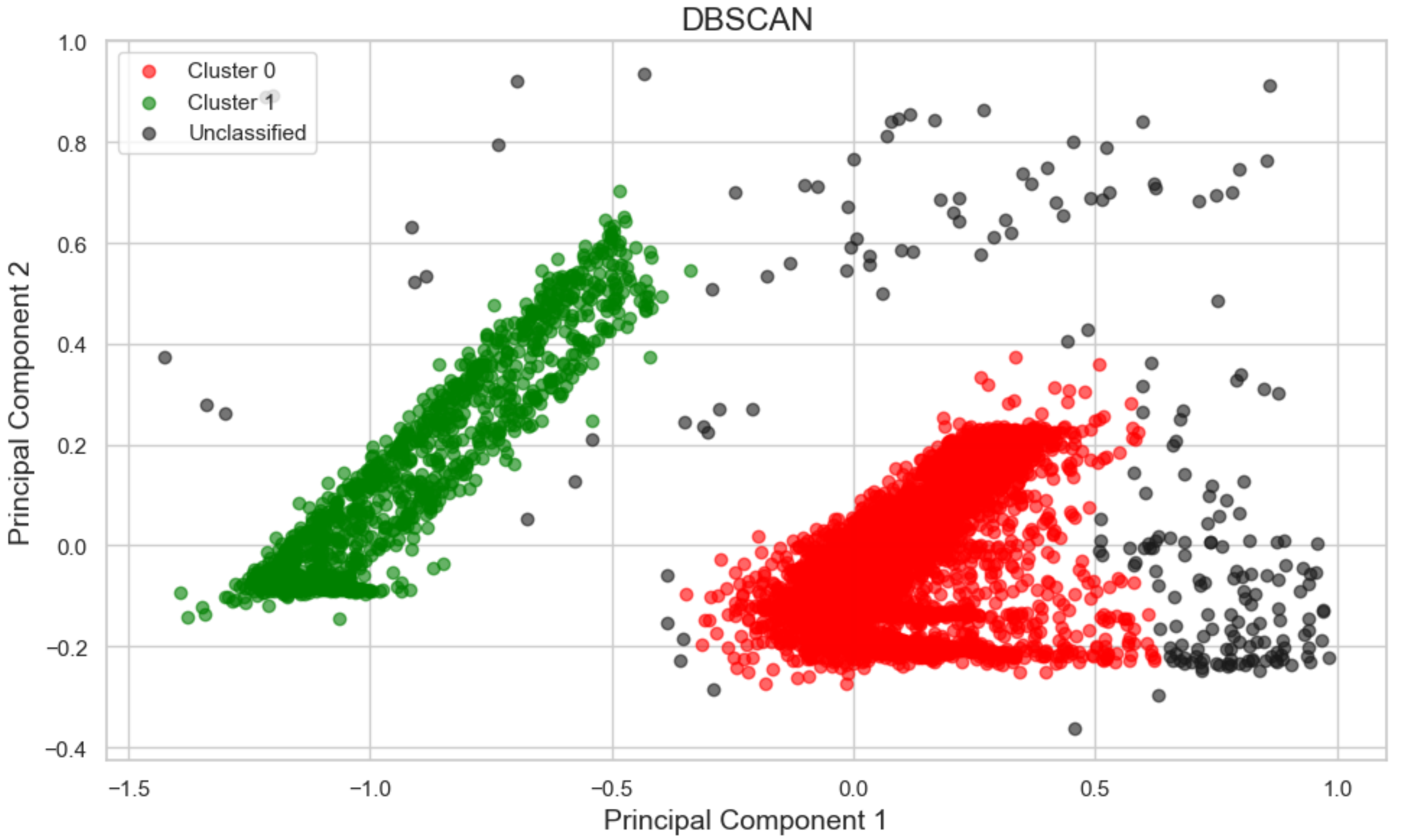
- **Possible approach**

➡ Apply principal component analysis

➡ Cluster with DBSCAN
(Density-Based Spatial Clustering of Applications with Noise)

➡ Create average pulse of clusters and select pulse shape of absorber events





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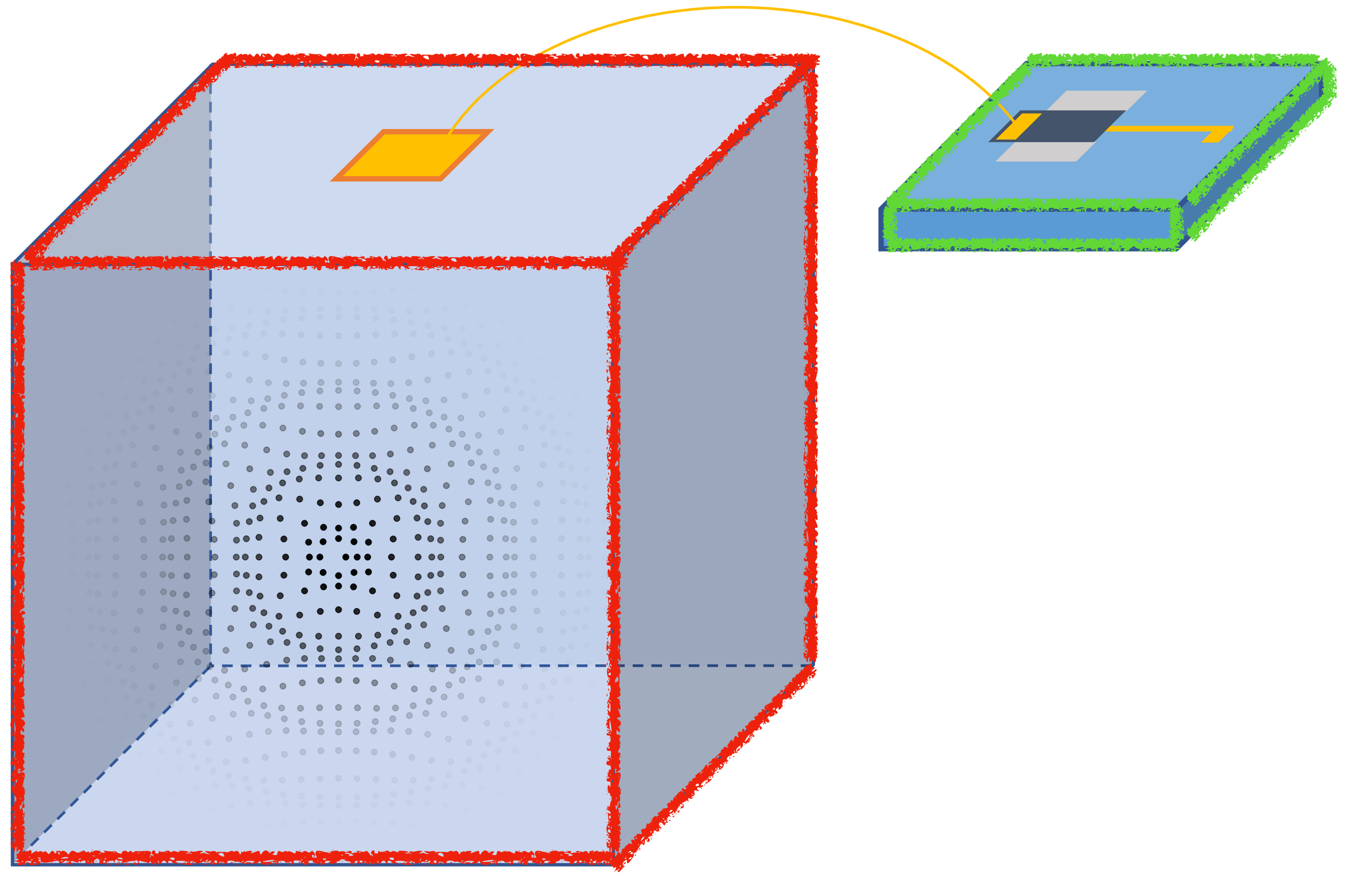
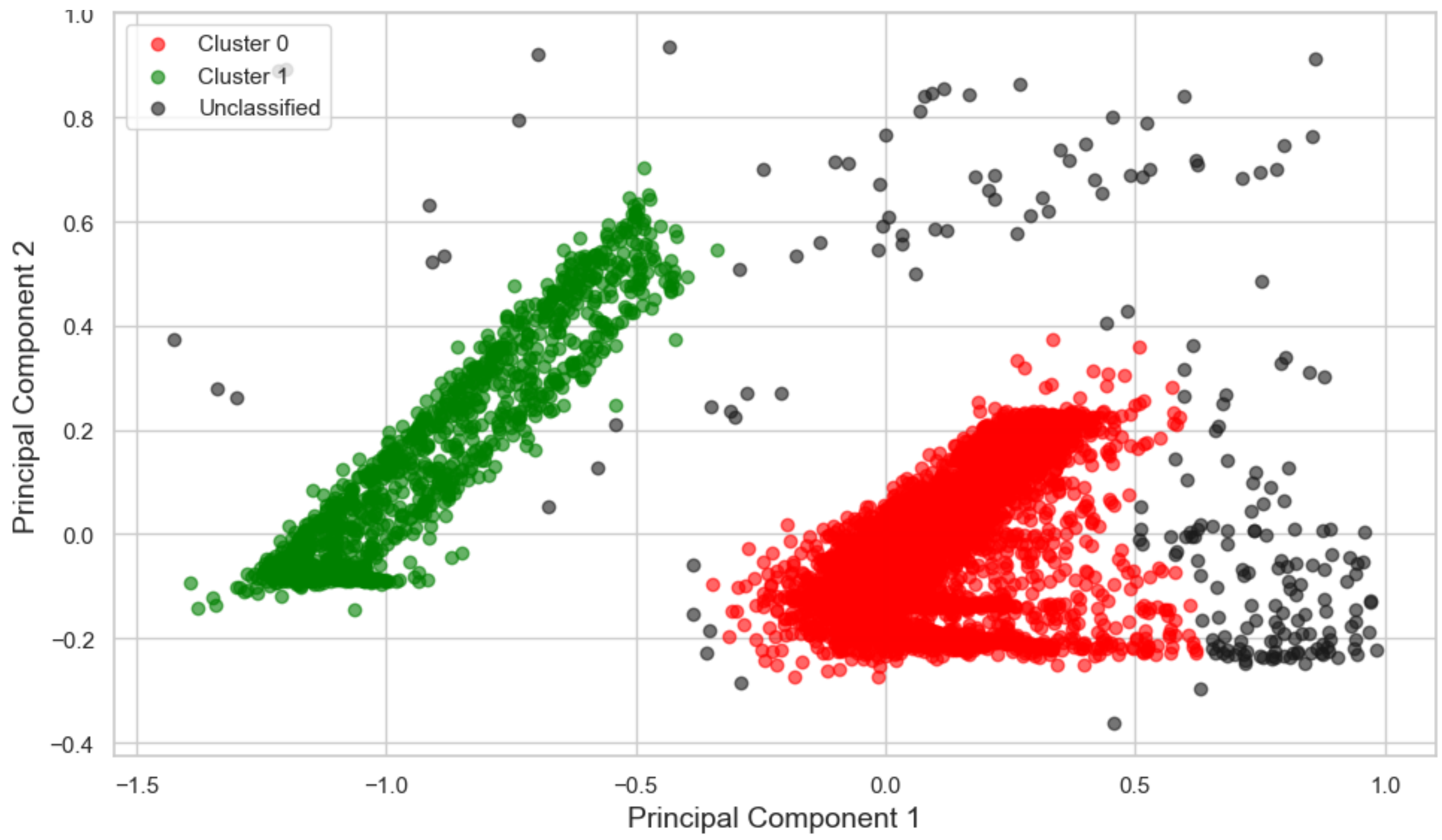
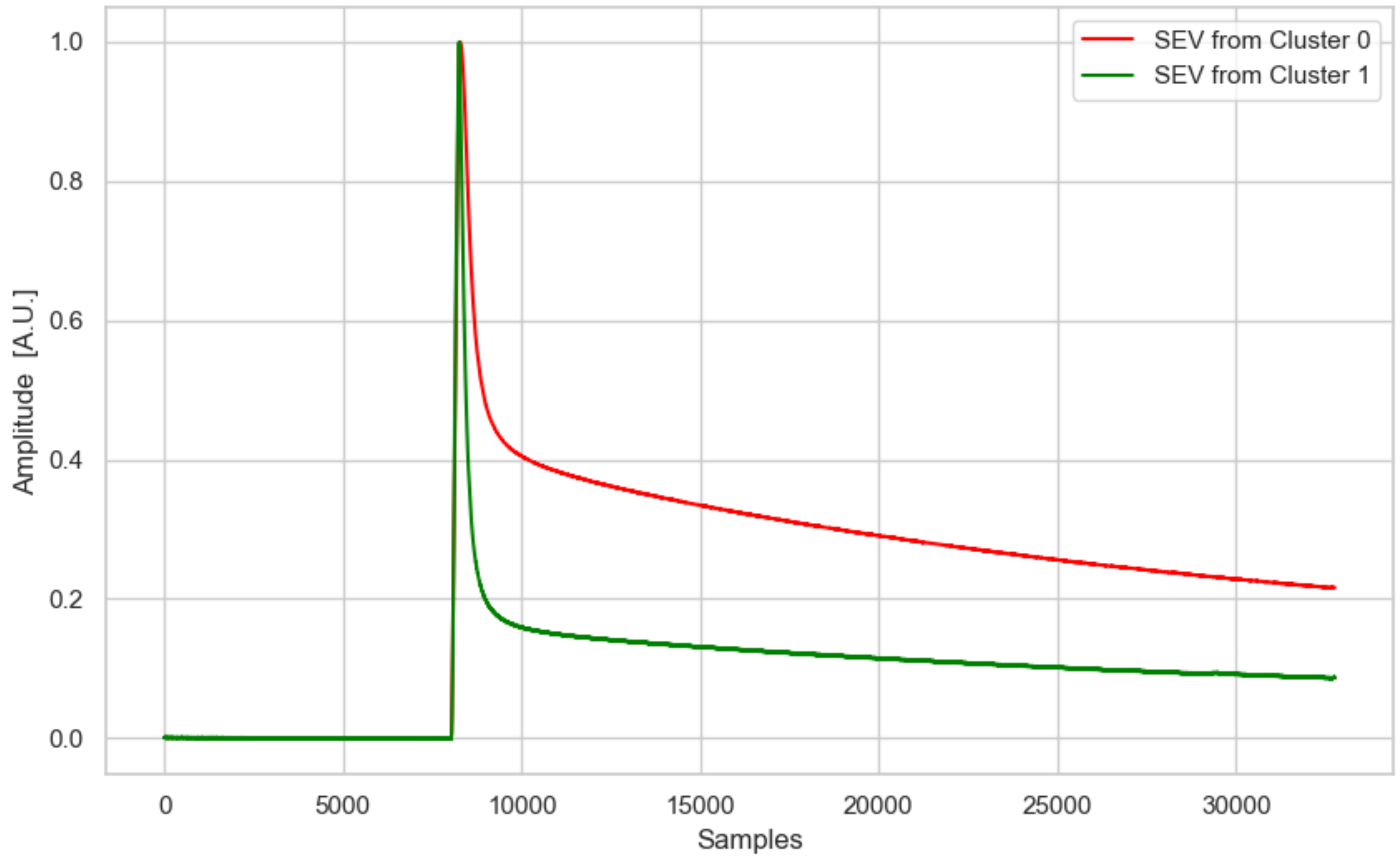
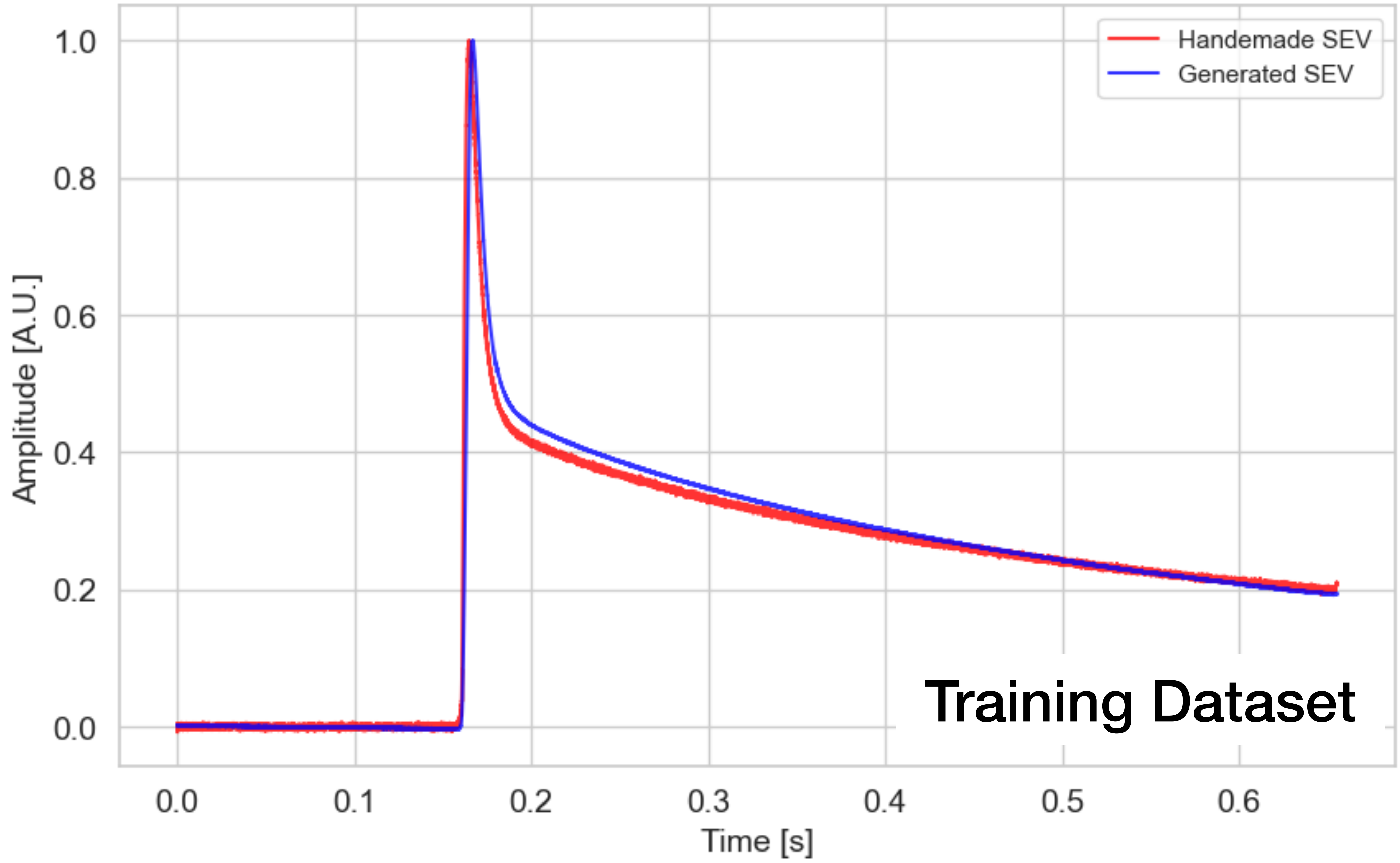
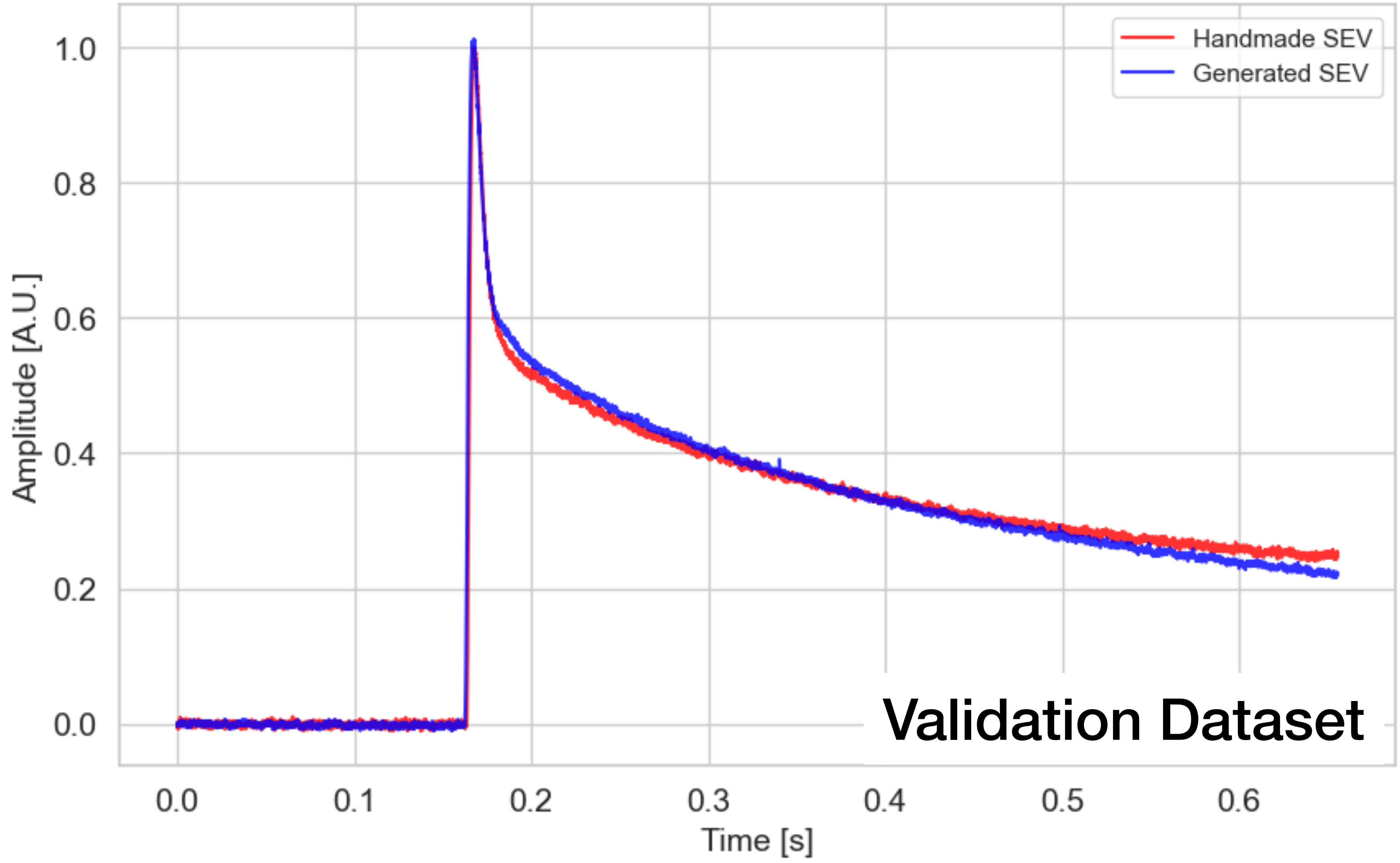







Handmade SEV
Generated SEV
Training Dataset
Amplitude [A.U.]
Time [s]
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6


Handmade SEV
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0.8
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0.2
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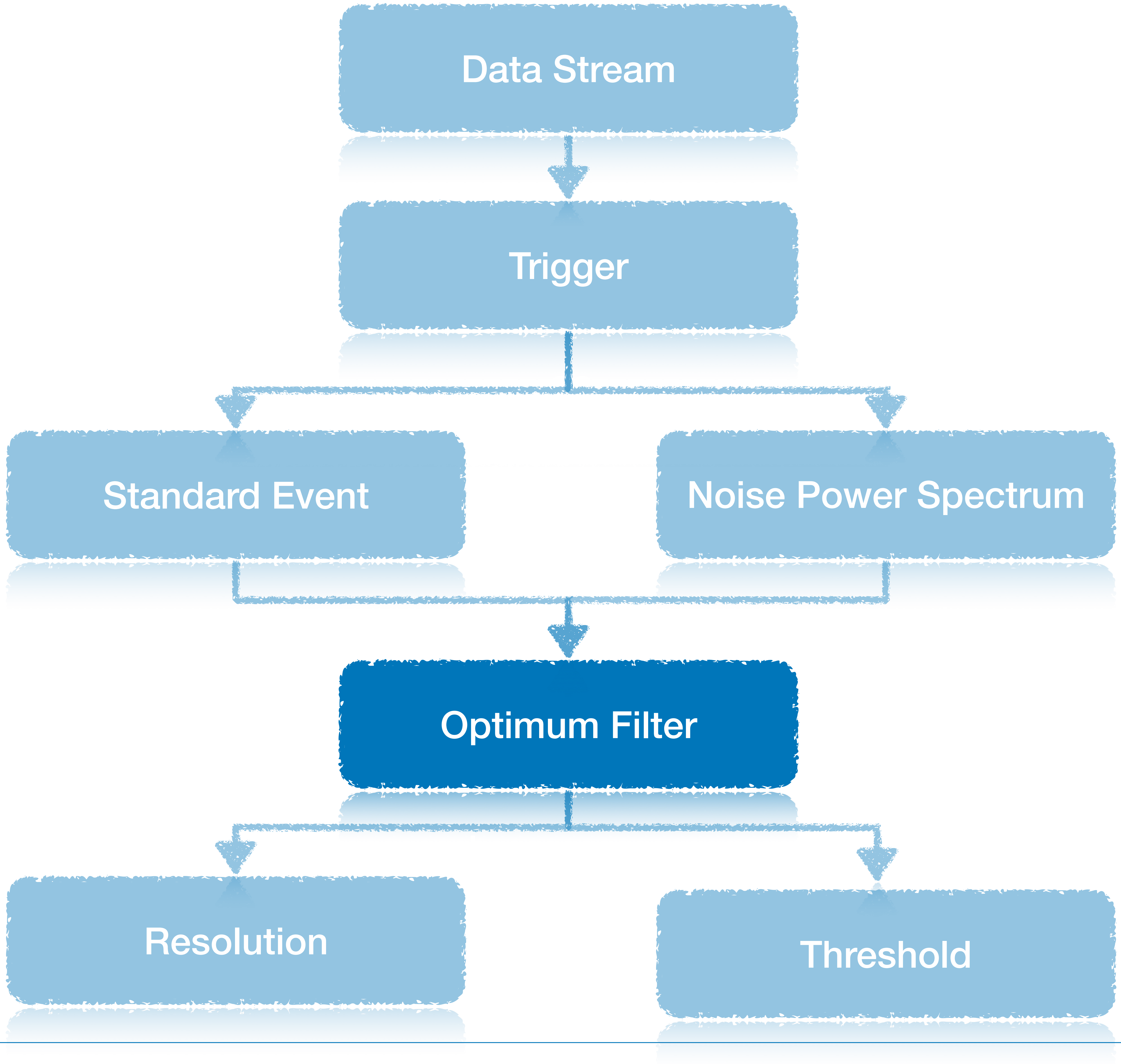
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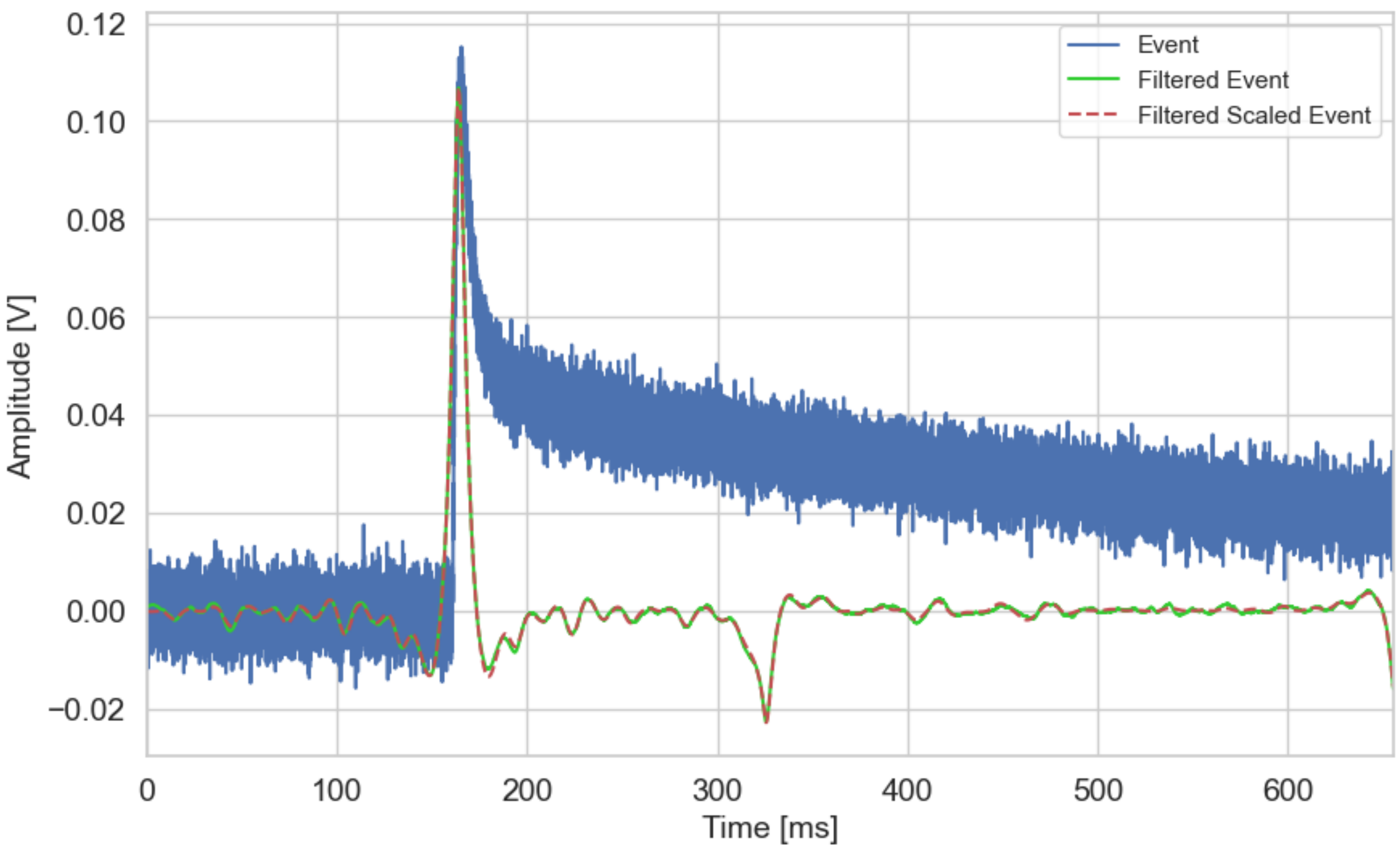
Create the Optimum Filter

- Create optimum filter from SEV and NPS

$$H(\omega) = h\frac{SEV^*(\omega)}{NPS(\omega)}e^{-2\pi i\omega\tau}$$

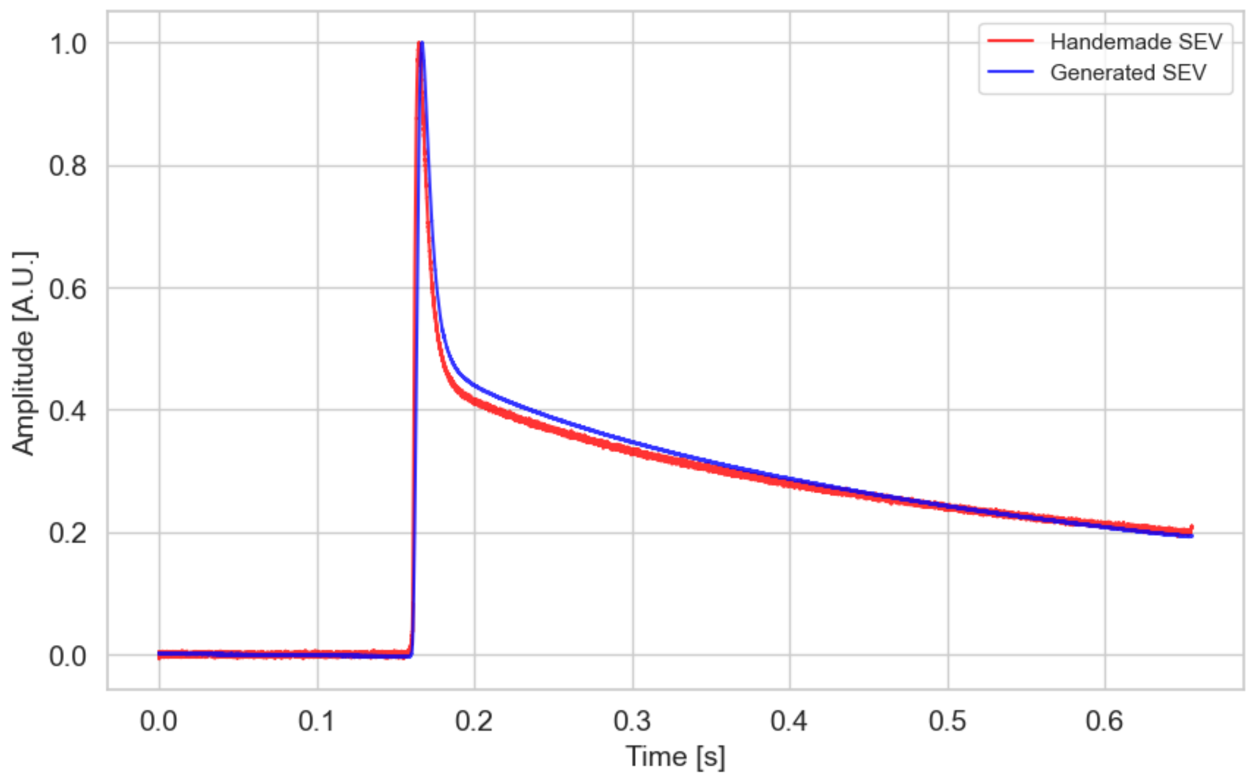
- Well established pulse height reconstruction method

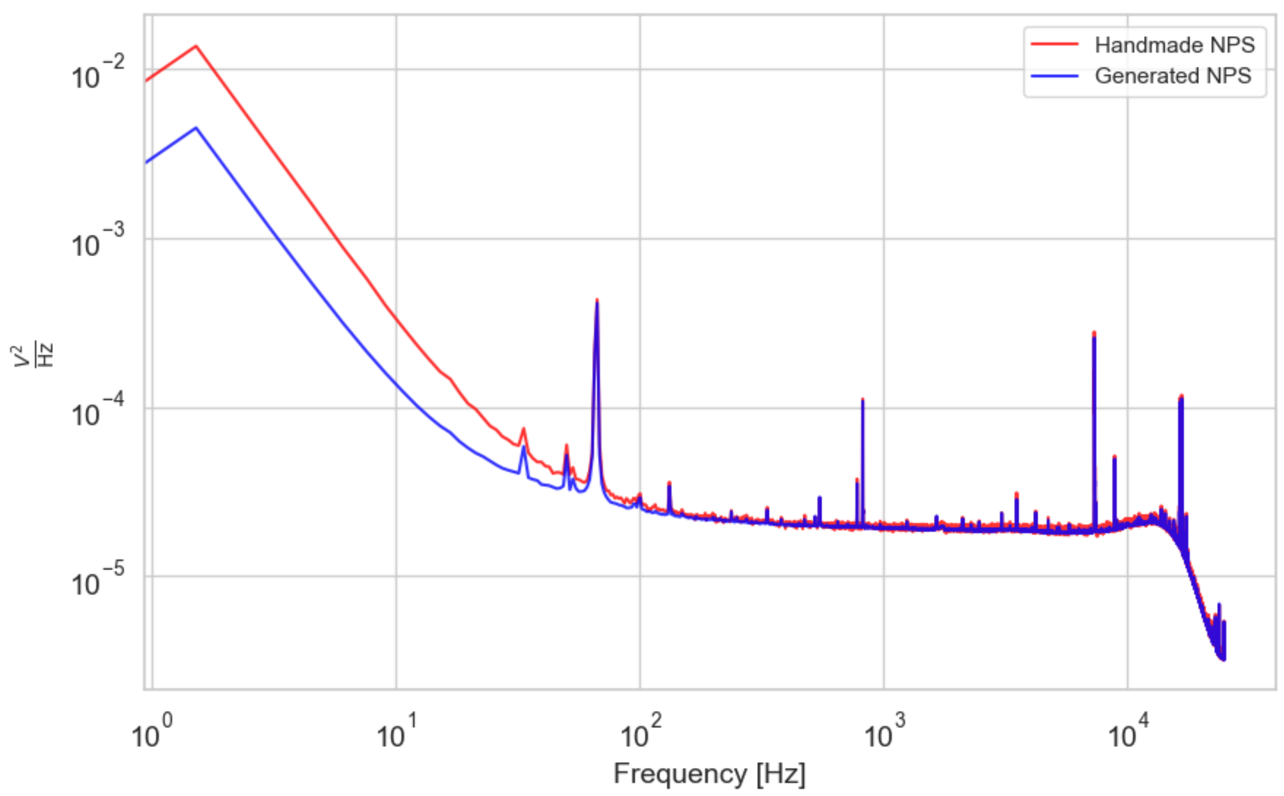
- Best signal/noise ratio for the given signal shape and assuming constant noise conditions (NPS)

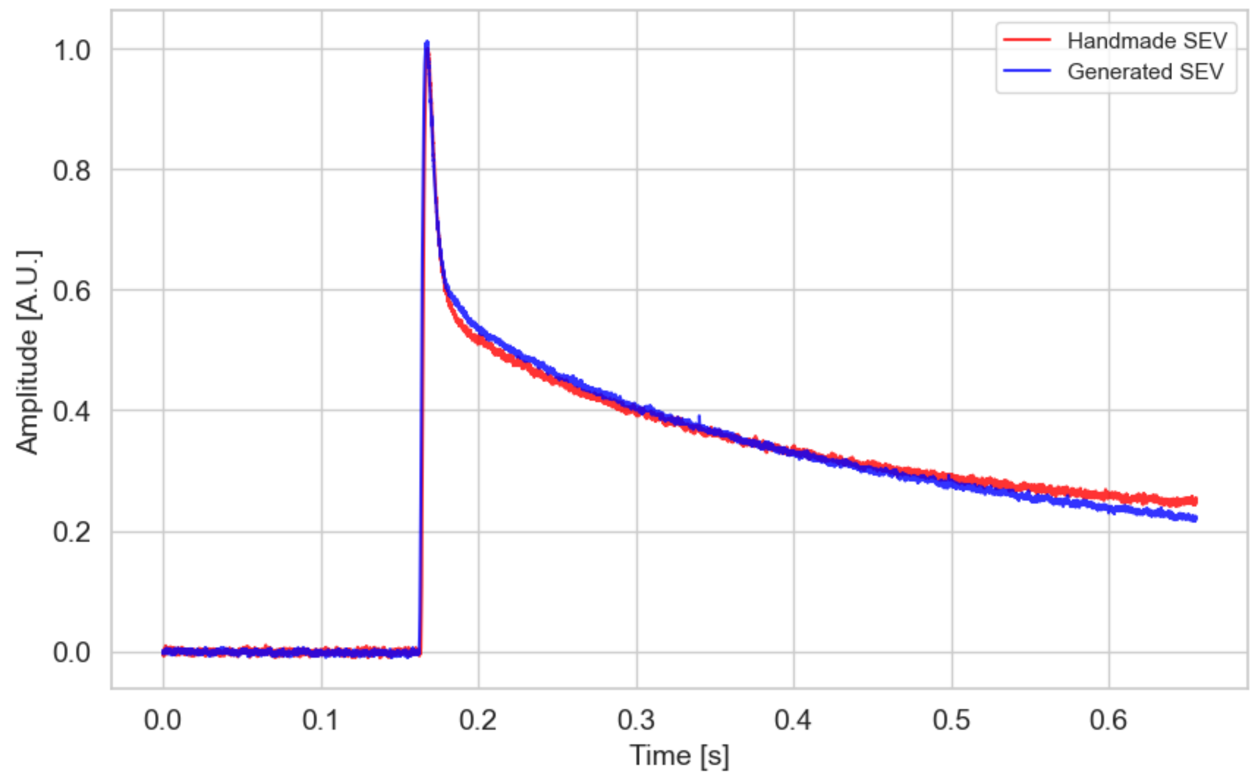


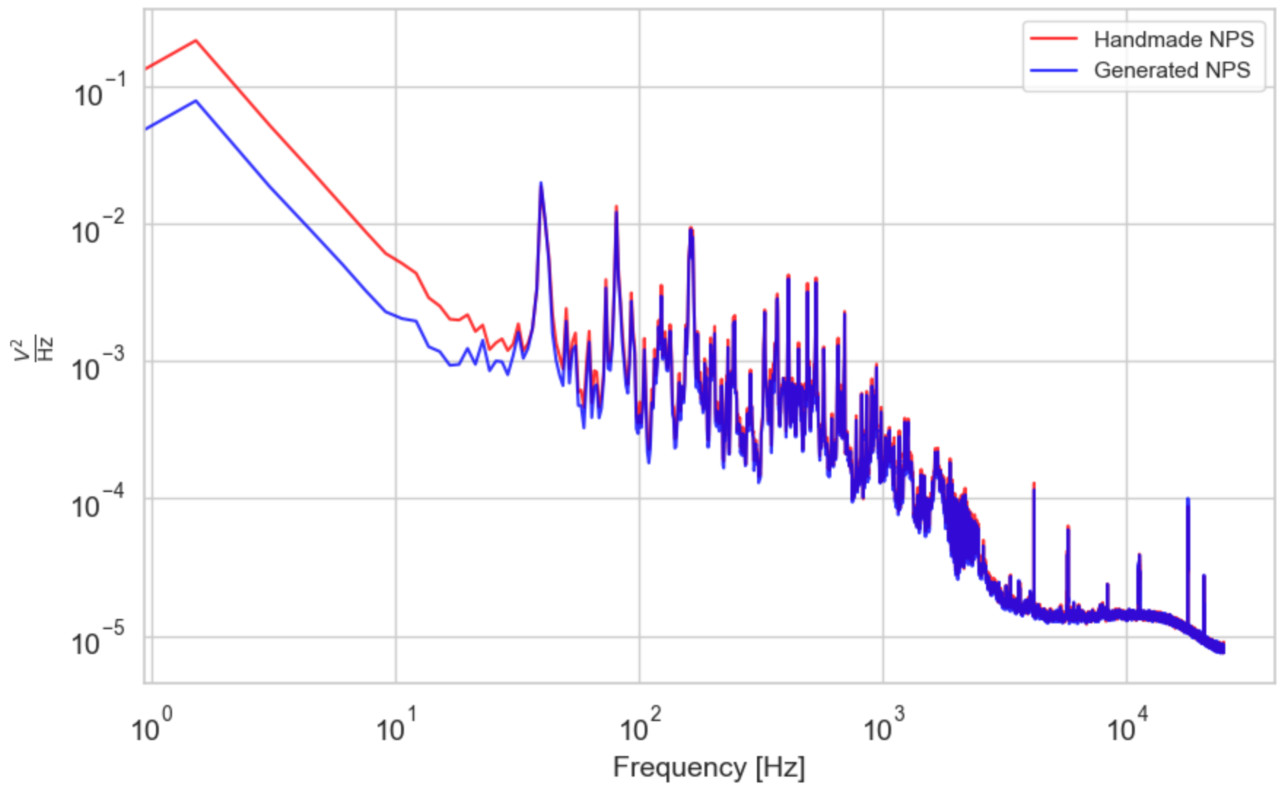
Results

	What analyse type	Resolution [mV]
Training Dataset	Handmade [Me]	0.420±0.002
	Handmade [Published]	0.379±0.009*
	Automation	0.377±0.002
Validation Dataset	Handmade [Me]	2.90±0.03
	Handmade [Published]	1.86±0.04**
	Automation	2.35±0.02









* In Energy: 0.441±0.011keV

** In Energy: 2.07±0.02keV

G. Angloher *et al.*, Deep underground dark matter search with a COSINUS detector prototype, Phys. Rev. D 110, 043010
G. Angloher *et al.*, Particle discrimination in a NaI crystal using the COSINUS remote TES design, Phys. Rev. D 109, 082003

What’s next?

- Implementation of control levels to avoid using modules as a black box
- Training of a neural network on COSINUS pulses
- Modules soon available in analysis packages Cait and CAT

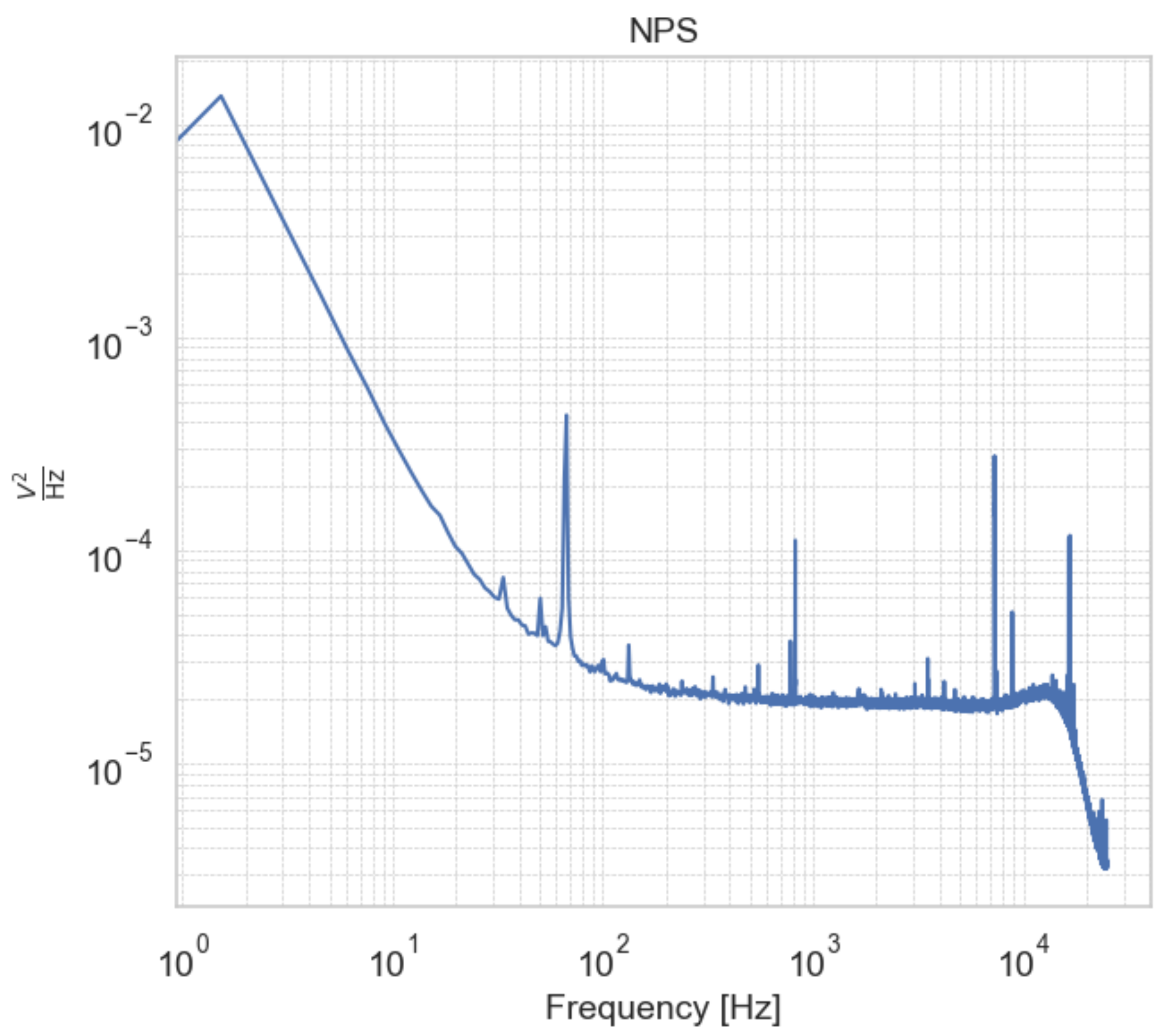
cait

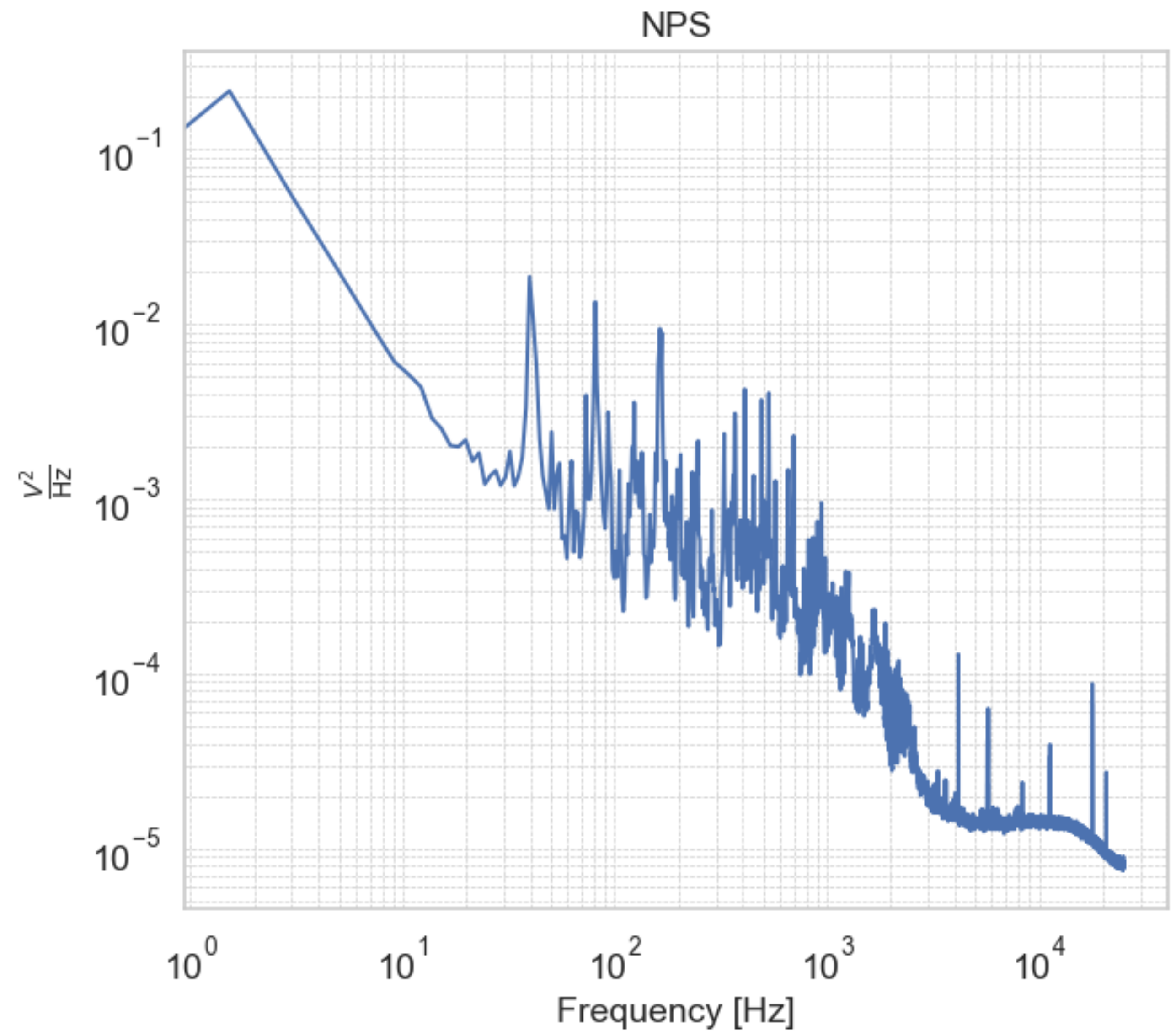
CAT

Backup

„Summer Run“

- Underground measurement carried out in a cryostat from CRESST at Laboratori Nazionali del Gran Sasso
- Low noise level
- All modules developed and optimized on this dataset
- Best module performance expected
- For more details, see https://arxiv.org/pdf/2307.11139



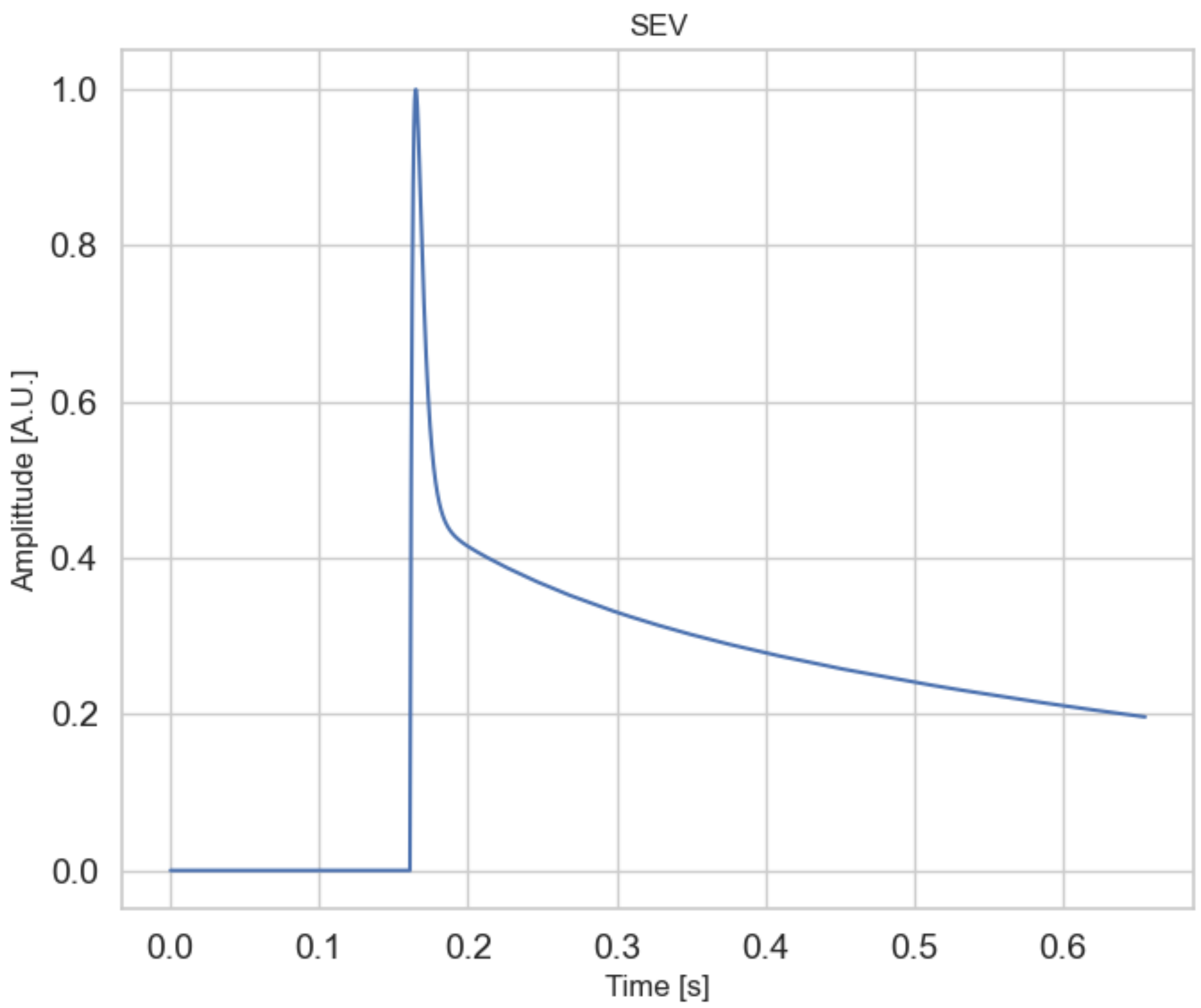


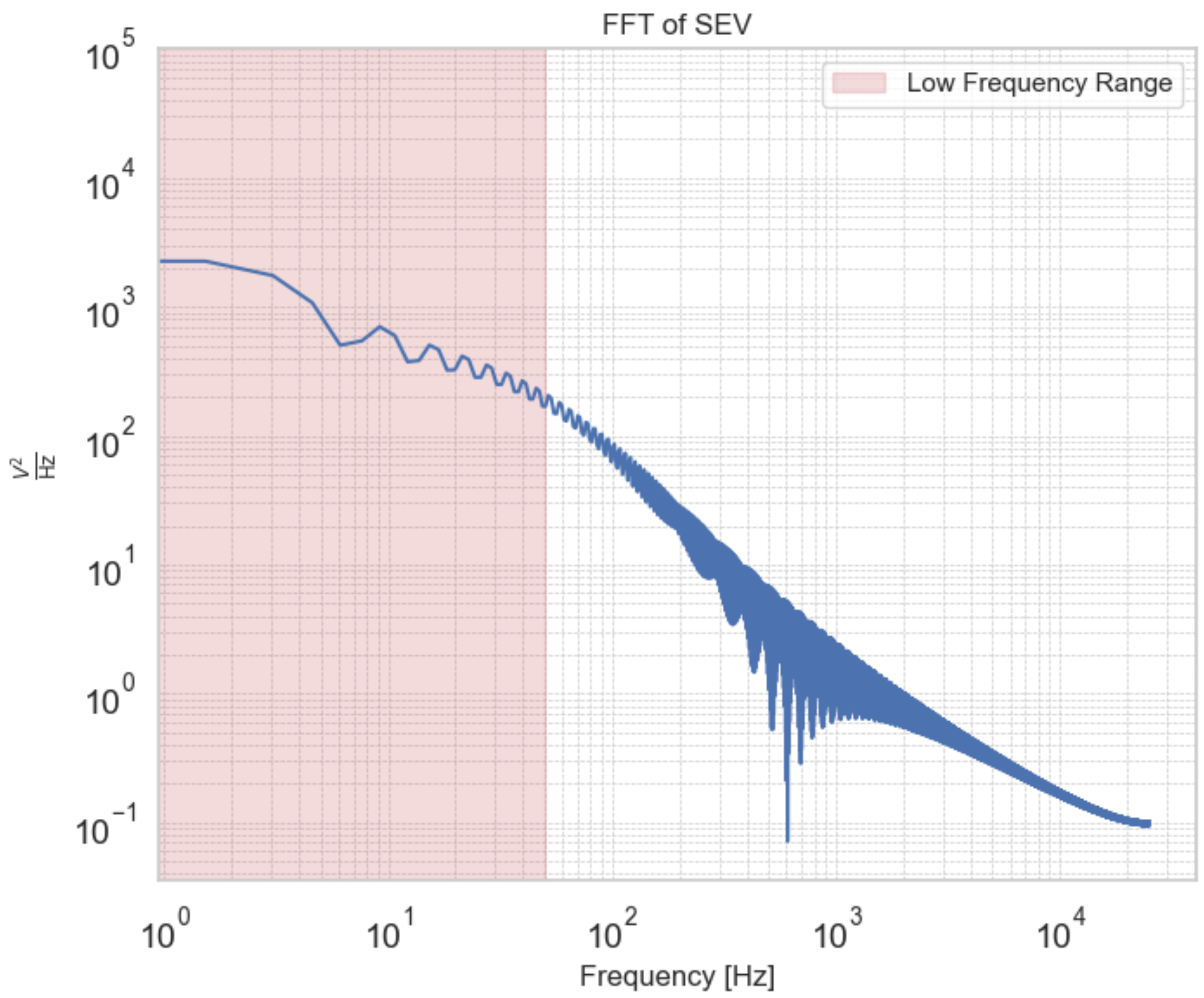
„Christmas Run“

- Above-Ground-Data carried out in a cryostat from CRESST in Munich
- Higher noise level and data rate
- „Stress test“ for the modules
- For more details, see https://arxiv.org/pdf/2307.11066

Frequency-Trigger

- **Assumption:**
  Pulse-shape is defined mainly by low-frequency content
- Calculate Forurietranform for a moving window
- Integrate up to cutoff frequency (50 Hz)
- Build difference between two consecutive windows





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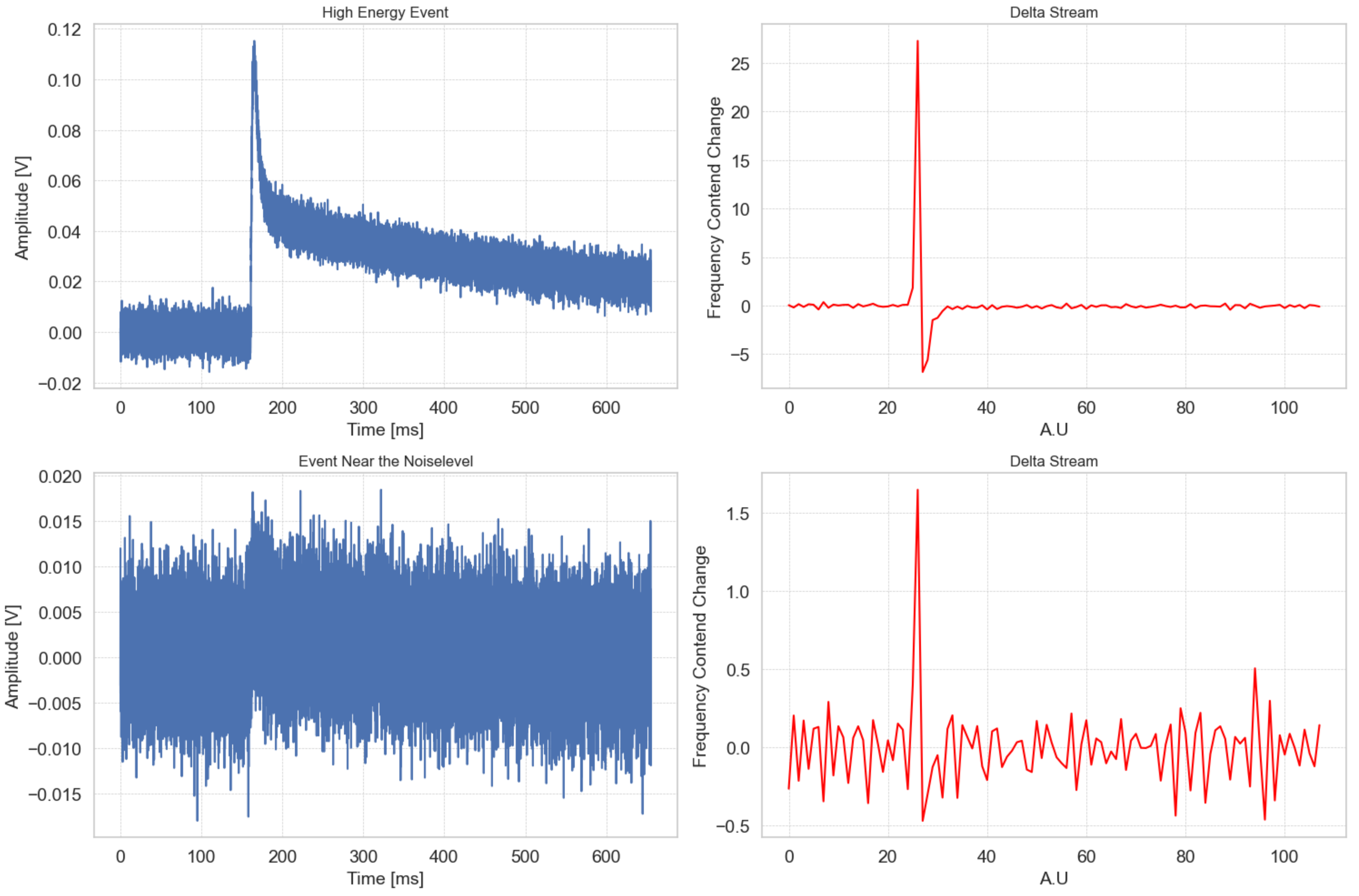
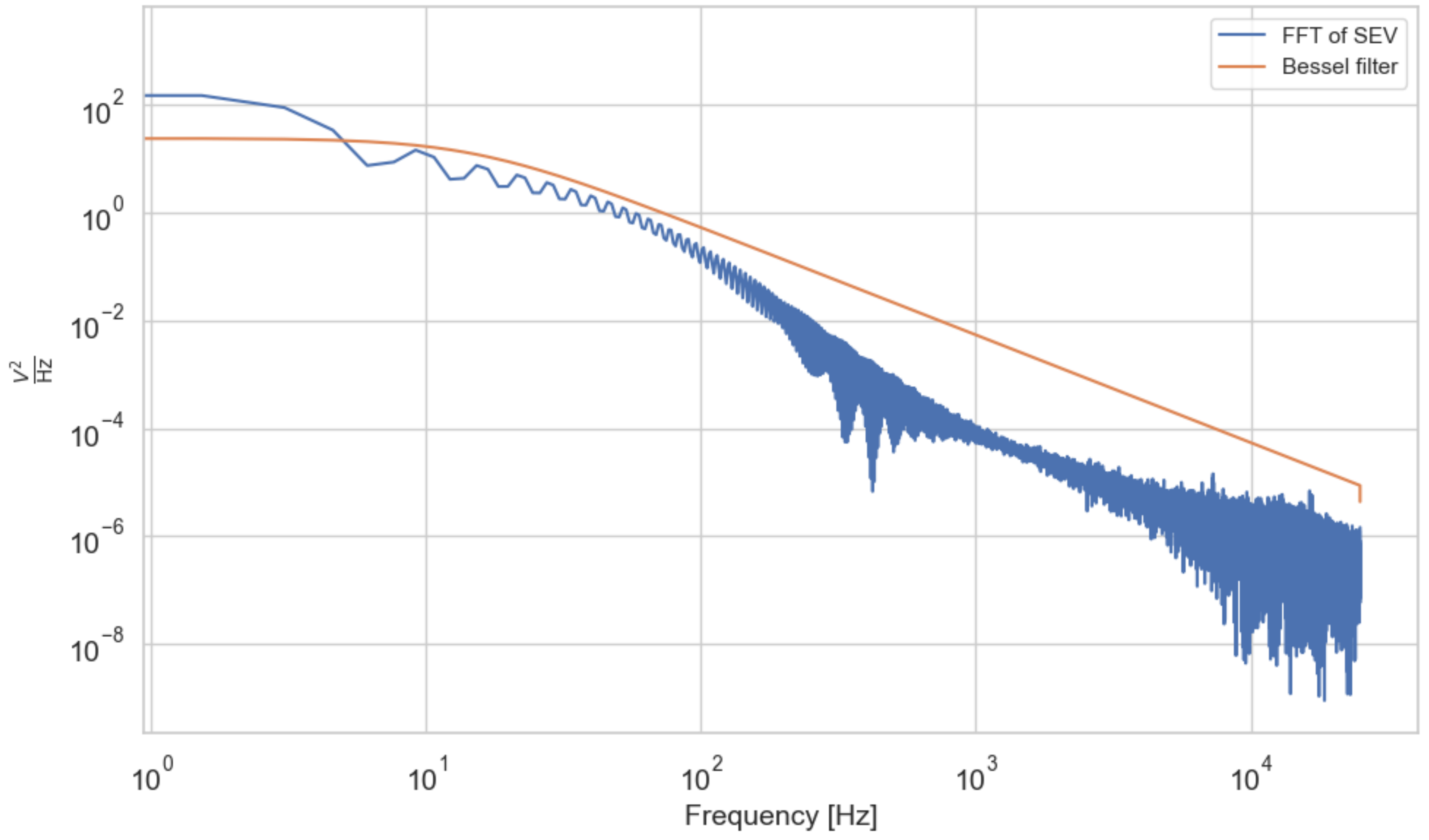
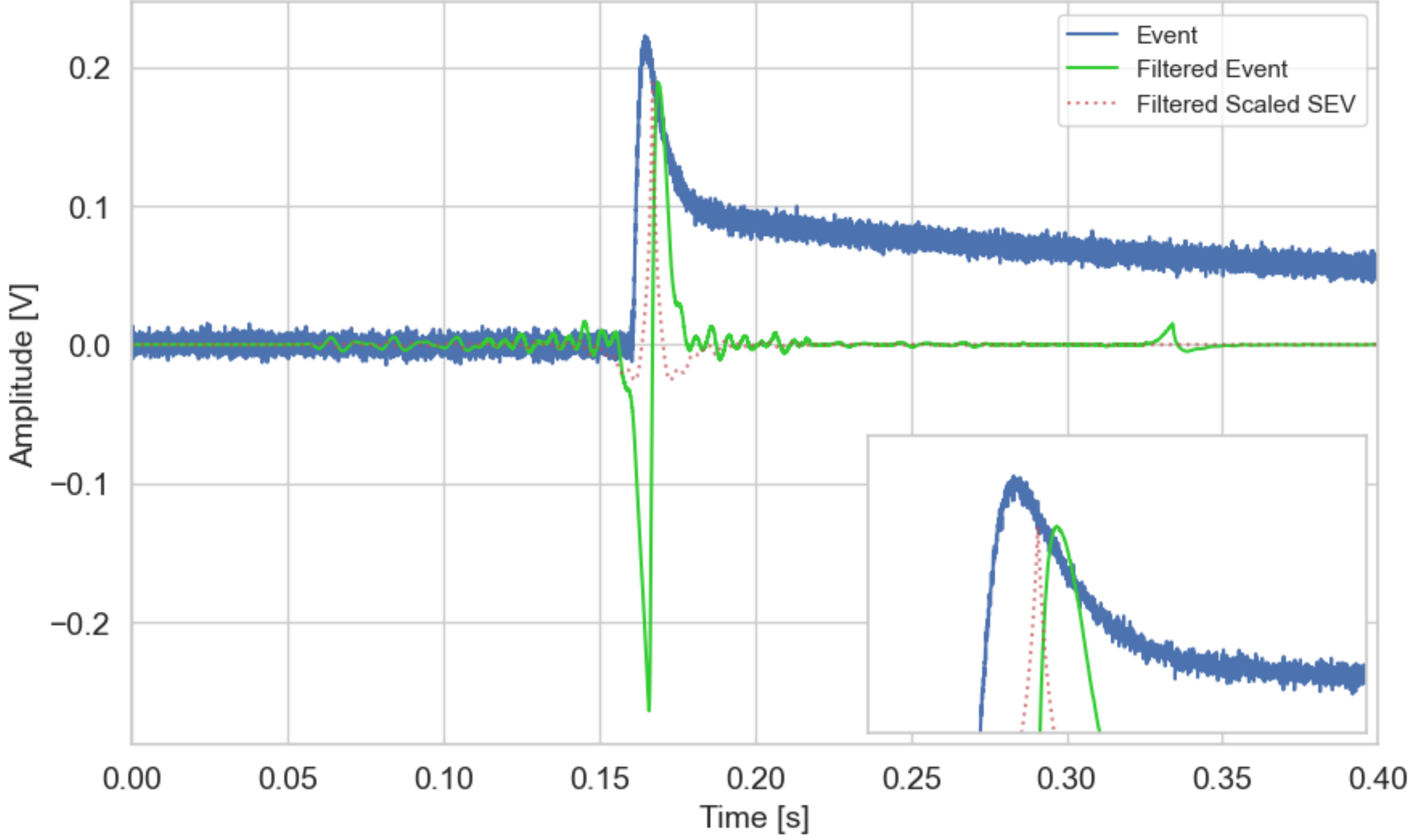


Bessel-Trigger

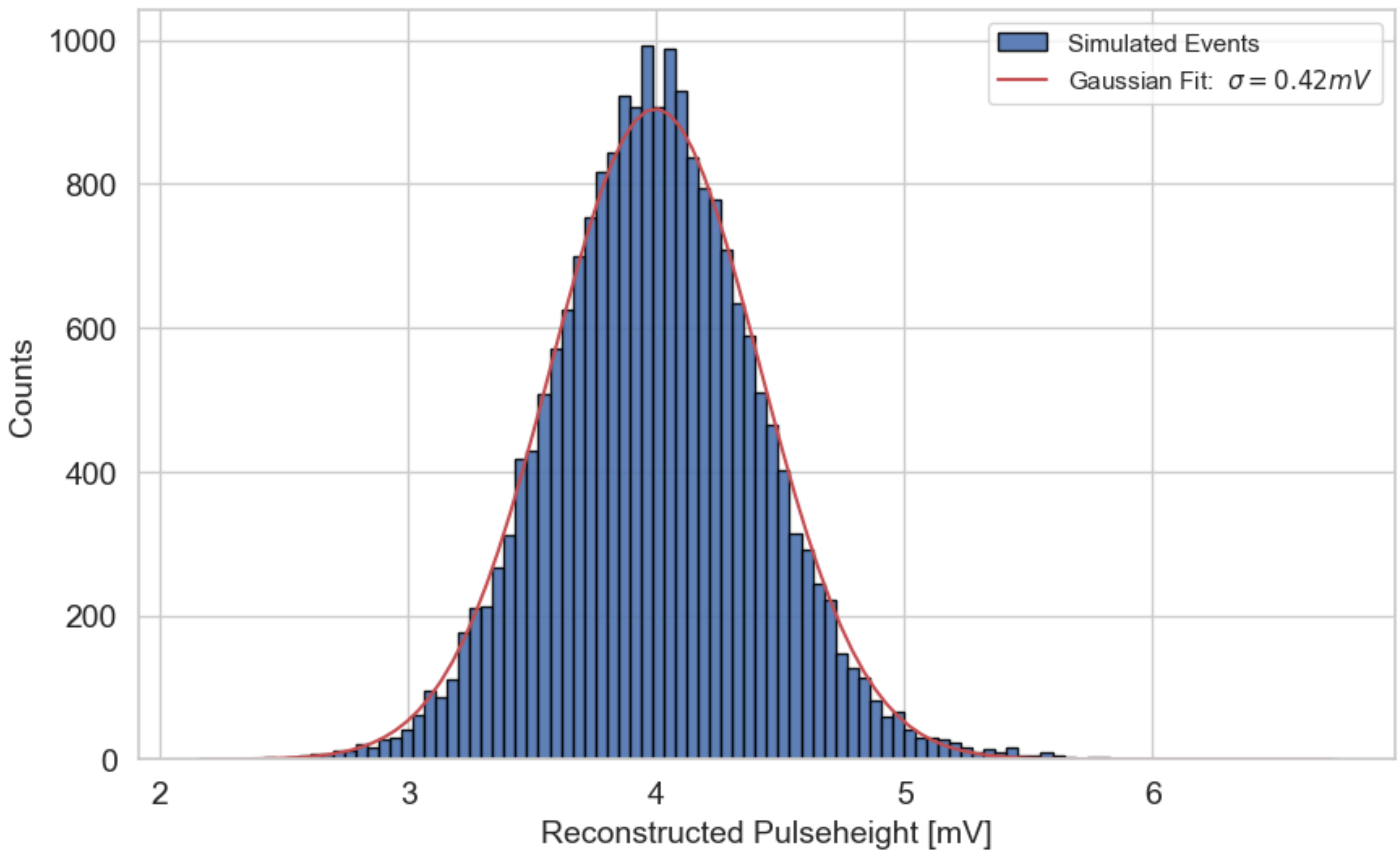
- Create a matched filter using Noise Power Spectrum and Bessel filter as an approximation of pulse shape
- Assumption on pulse shape: cutoff frequency
- Noise Power Spectrum needed





Baseline Resolution Determination

- Define set of clean empty baselines
- Superimpose with scaled SEV
- Reconstruct pulse height with OF
- Determine the standard deviation

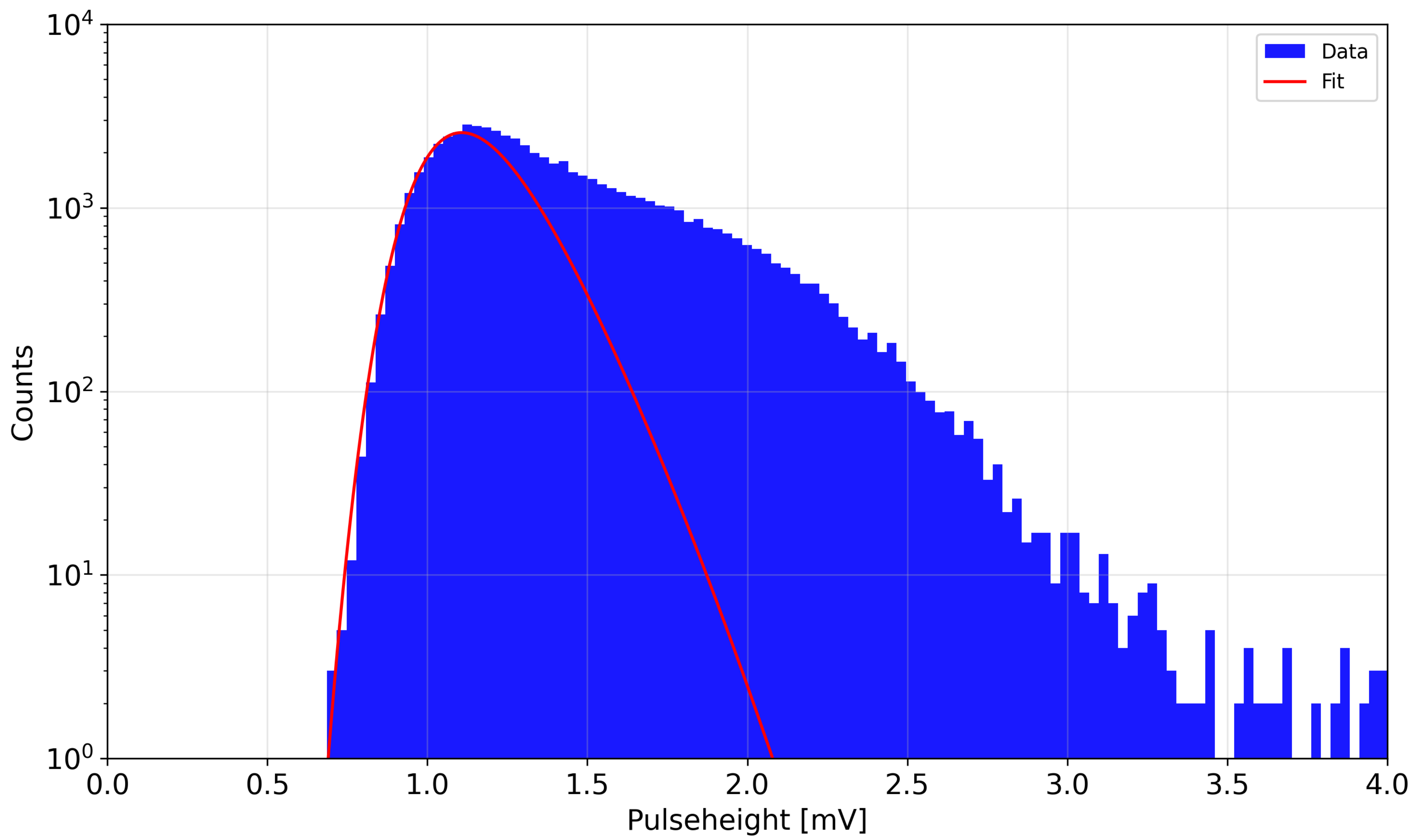


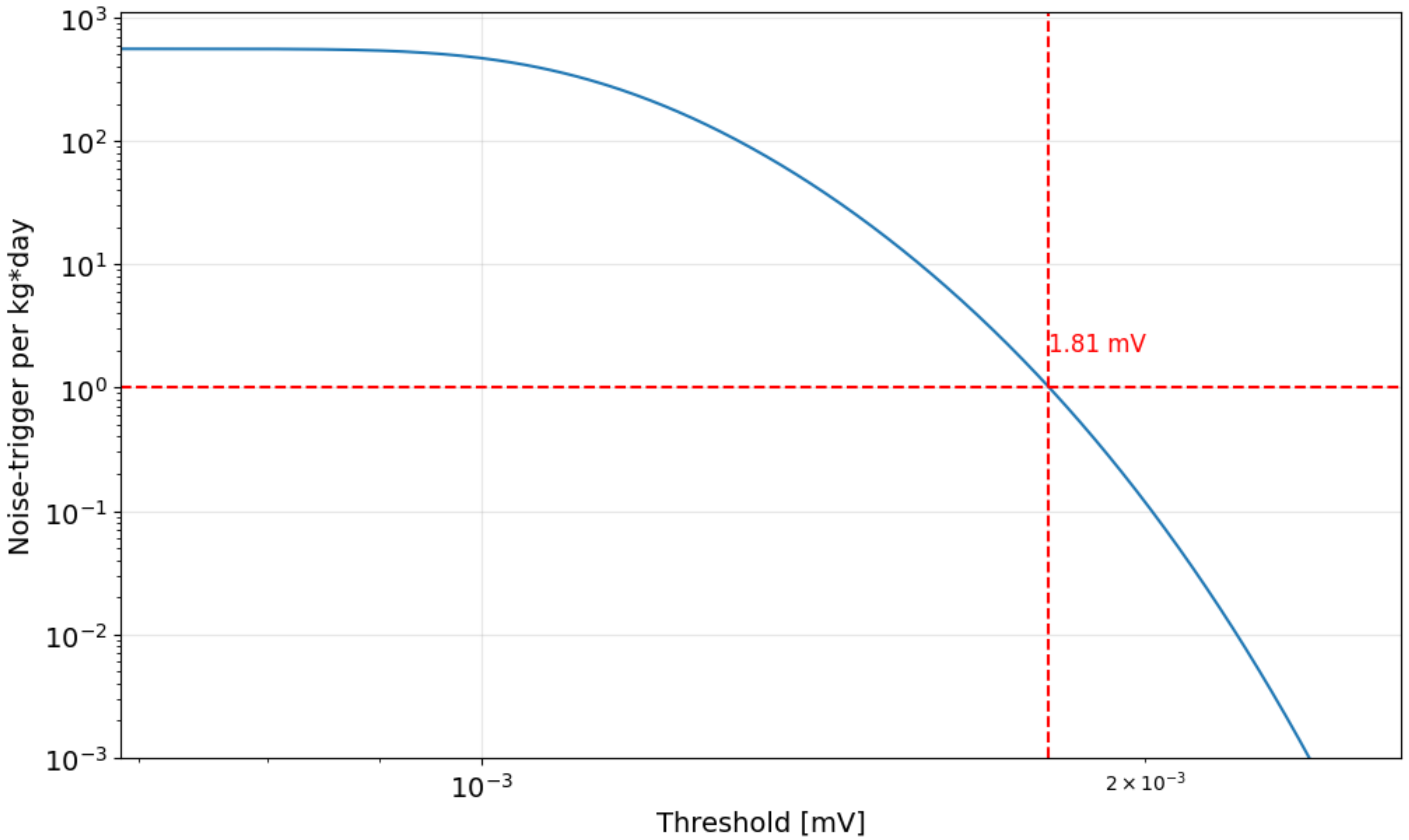
Threshold

- Apply OF on cleaned baselines
- Fit probability function to the histogram of pulse heights

$$P_d(x) = \frac{d}{\sqrt{2\pi}\sigma}\left(e^{-(\frac{x}{\sqrt{2}\sigma})^2}\right)\left(0.5 + \frac{erf(x/(\sqrt{2}\sigma))}{2}\right)^{d-1}$$

$$NTR(x_{th}) = \frac{1}{t \cdot m}\int_{x_{th}}^{\infty} P_d(x)dx$$





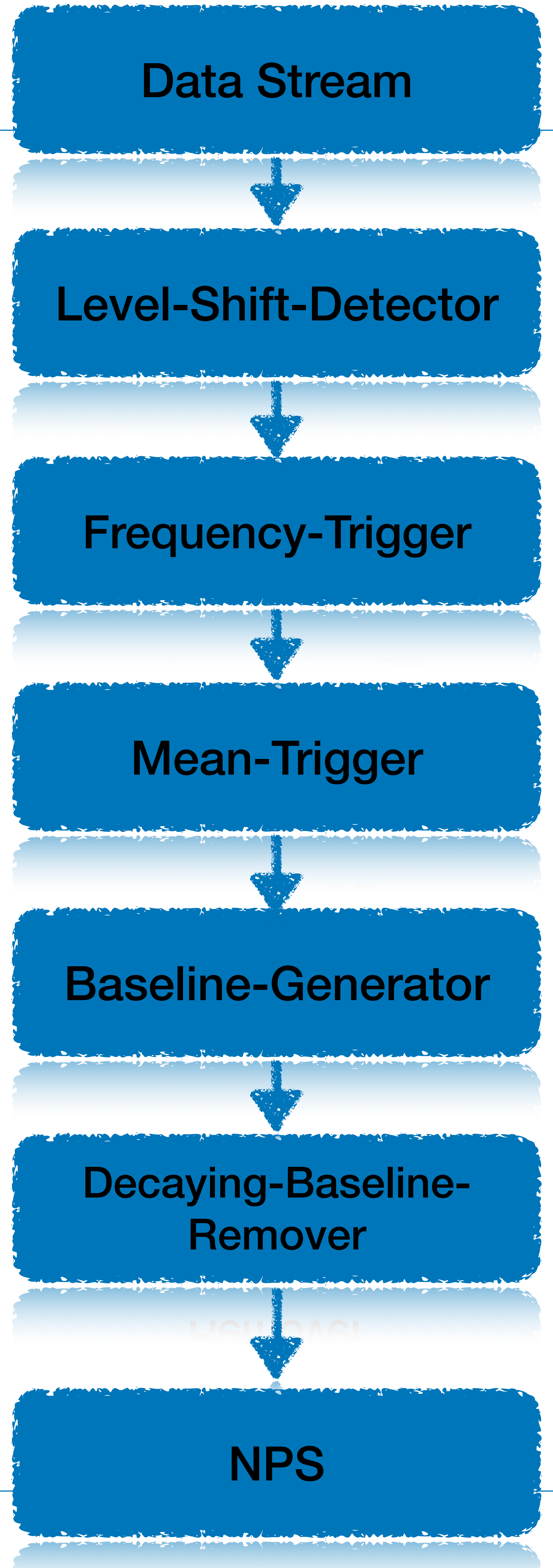
More Details: M. Mancuso, A. Bento, N. F. Iachellini, D. Hauff, F. Petricca, F. Pro¨bst, J. Rothe, and R. Strauss, “A method to define the energy threshold depending on noise level for rare event searches,” 2019.

NPS-Generator

- Sequence of different trigger/cleaning modules
- Cleans data stream from events and artifacts
- **Advantages**

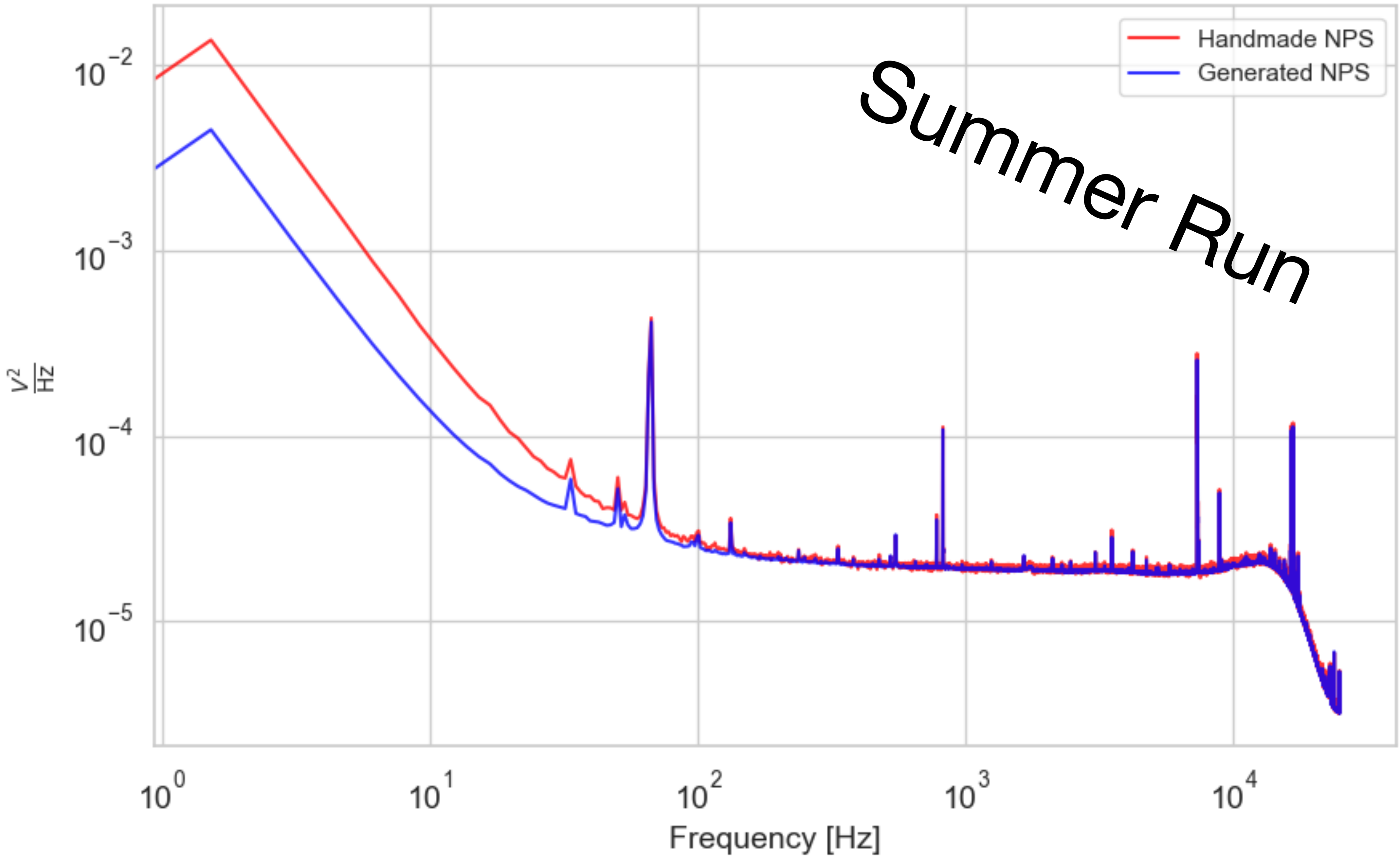
  ➡ NPS creation without human input

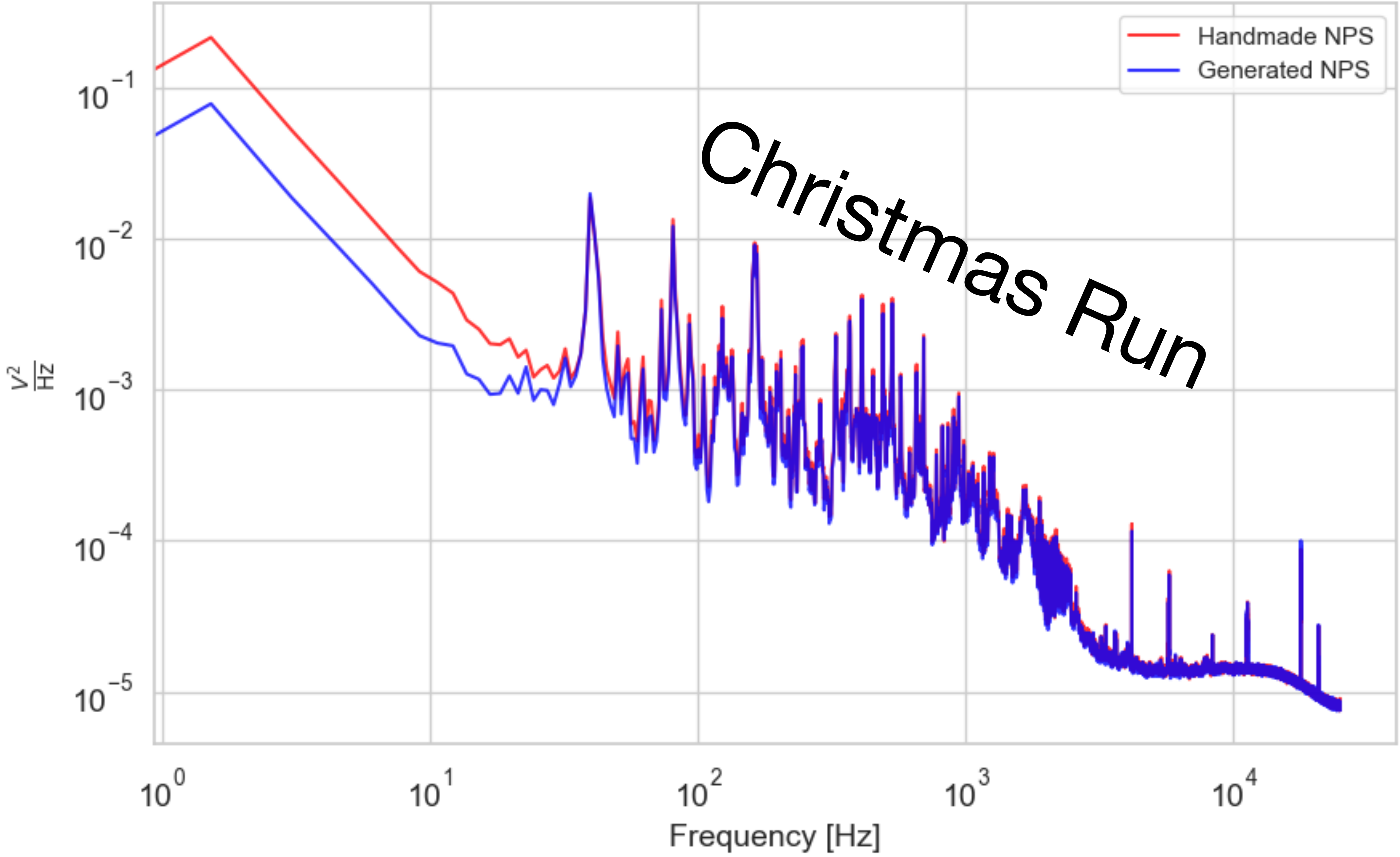
  ➡ Fast and reliable results



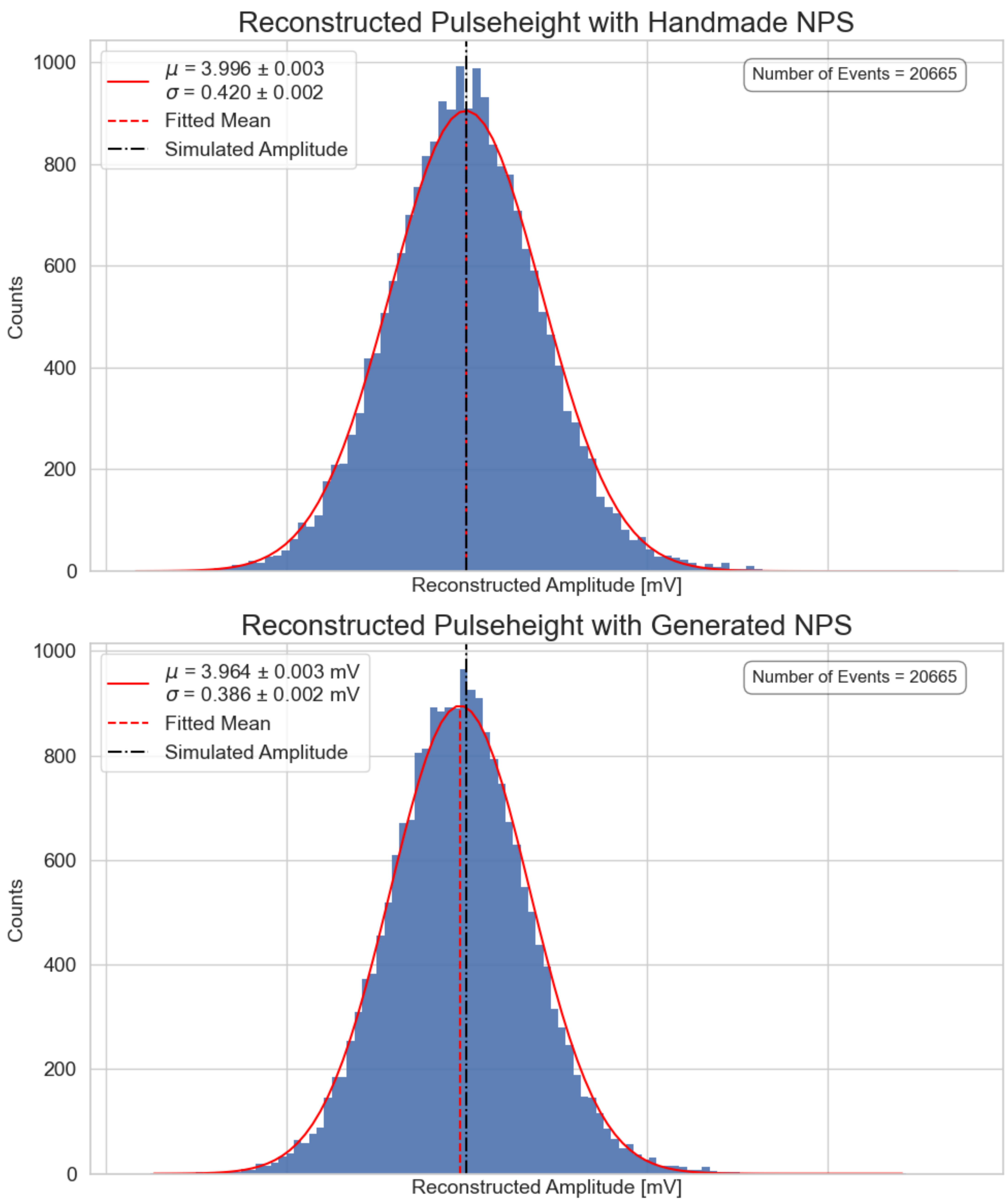
Performance Test

- Handmade and generated NPS very similar
- Create OF with handmade and generated NPS



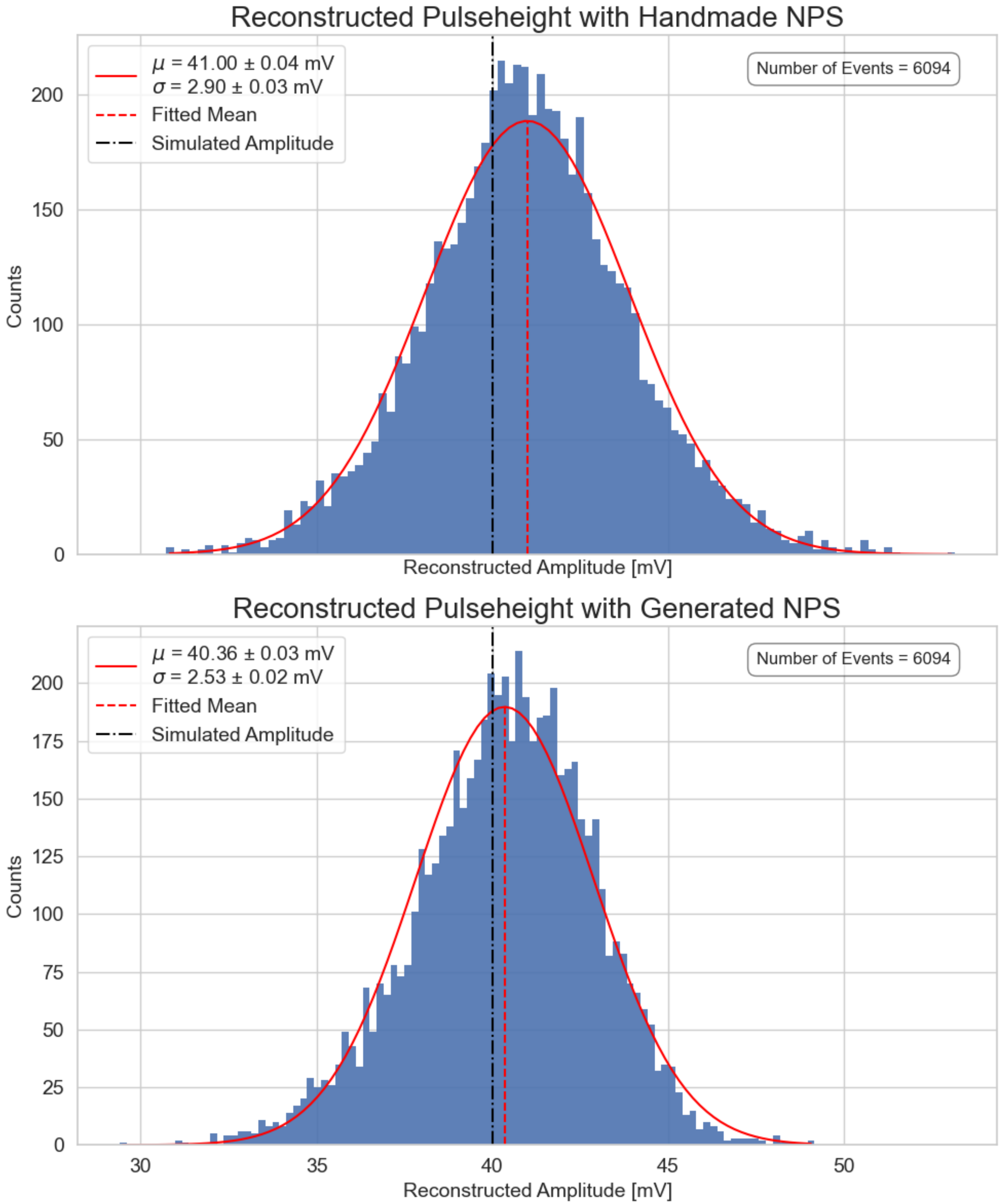


Summer Run



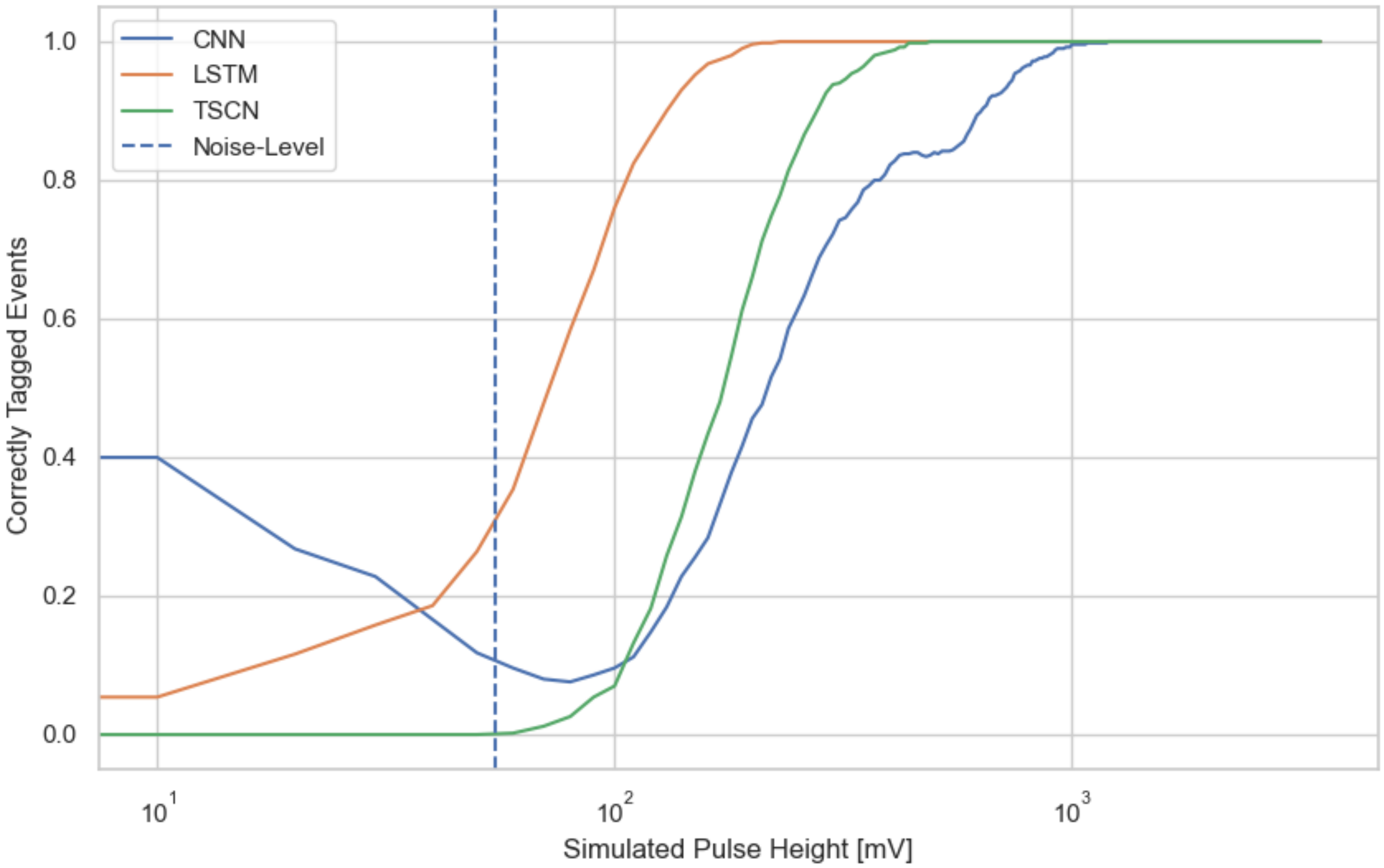
Reconstructed Pulseheight with Handmade NPS
μ = 3.996 ± 0.003
σ = 0.420 ± 0.002
Fitted Mean
Simulated Amplitude
Number of Events = 20665
Counts
Reconstructed Amplitude [mV]
Reconstructed Pulseheight with Generated NPS
μ = 3.964 ± 0.003 mV
σ = 0.386 ± 0.002 mV
Fitted Mean
Simulated Amplitude
Number of Events = 20665
Counts
Reconstructed Amplitude [mV]

Christmas Run



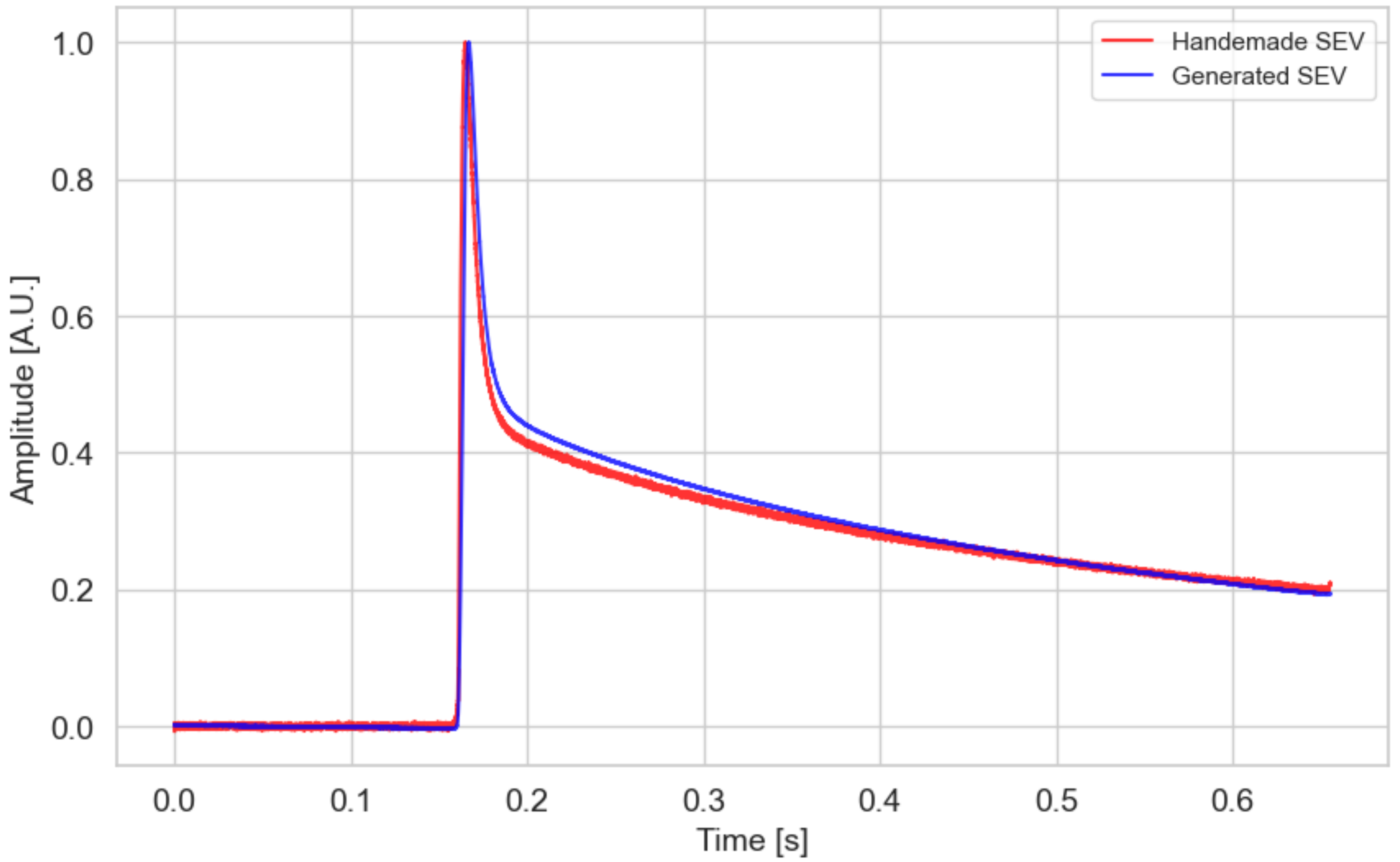
Adaptation of the Neural Network

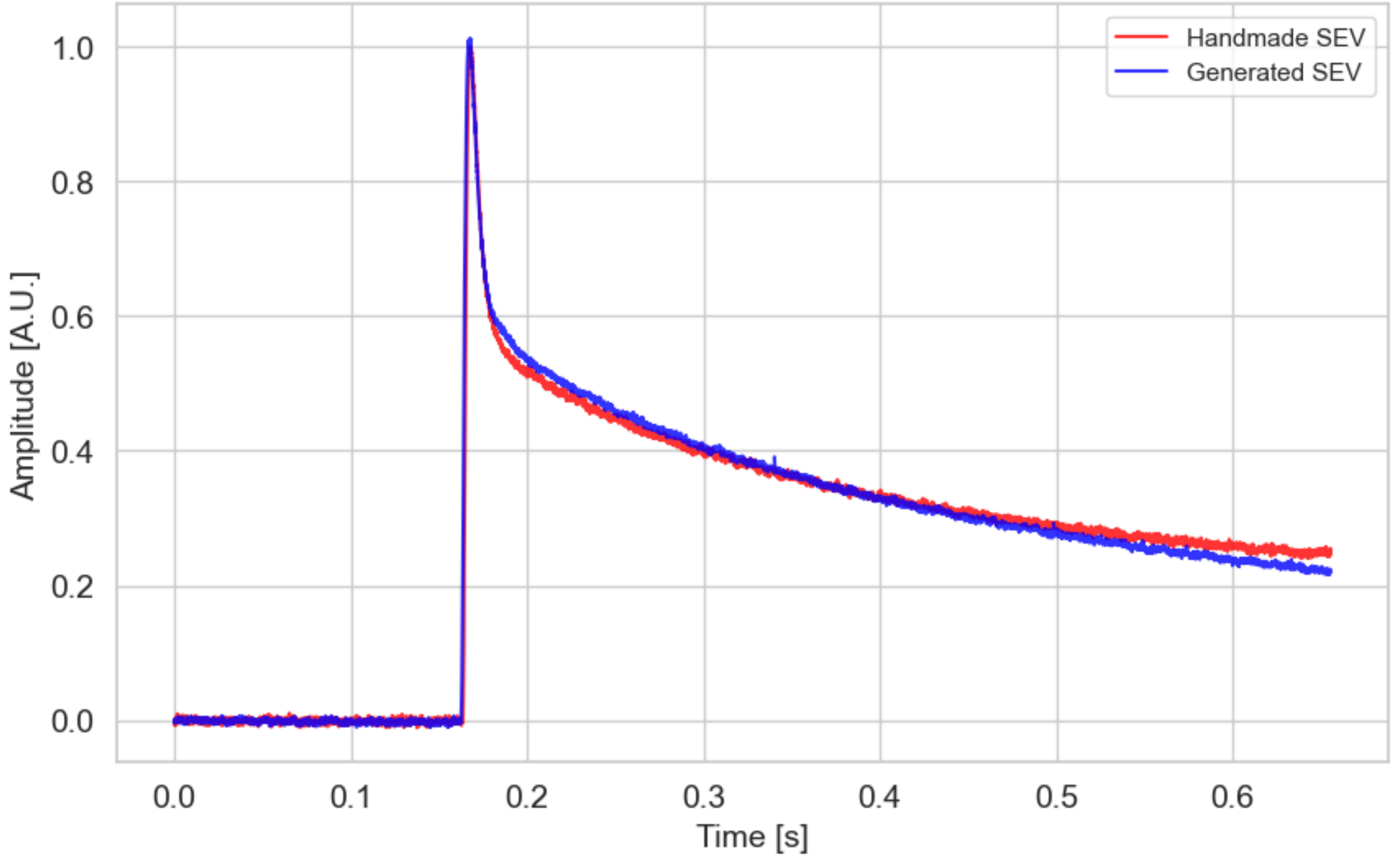
- Good performance for events above noise level
- Some artifacts mislabeled as valid events



Performance Test

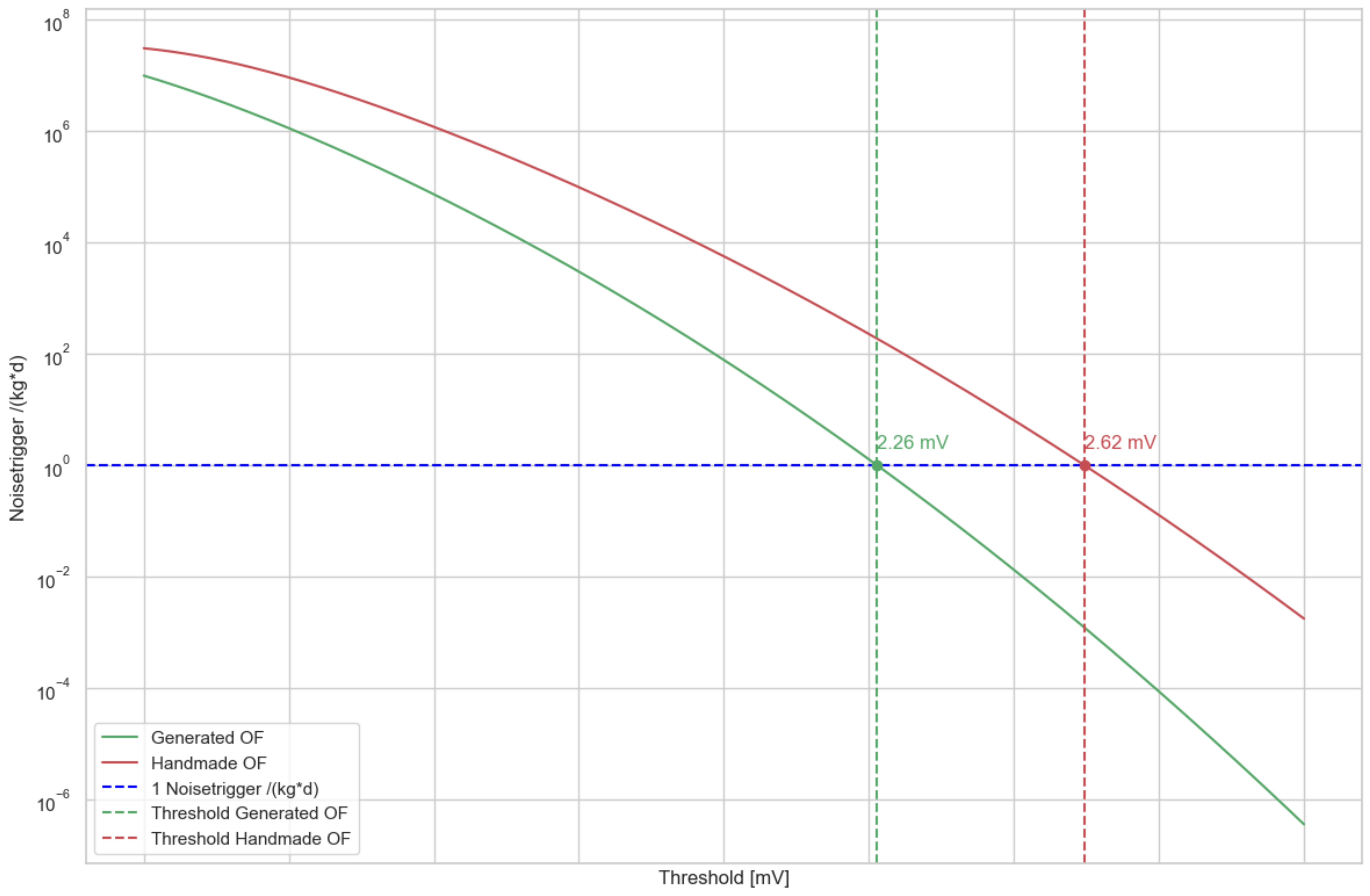
- Generated SEV similar to handmade SEV
- Compare the performance of fully generated OF vs. handmade OF

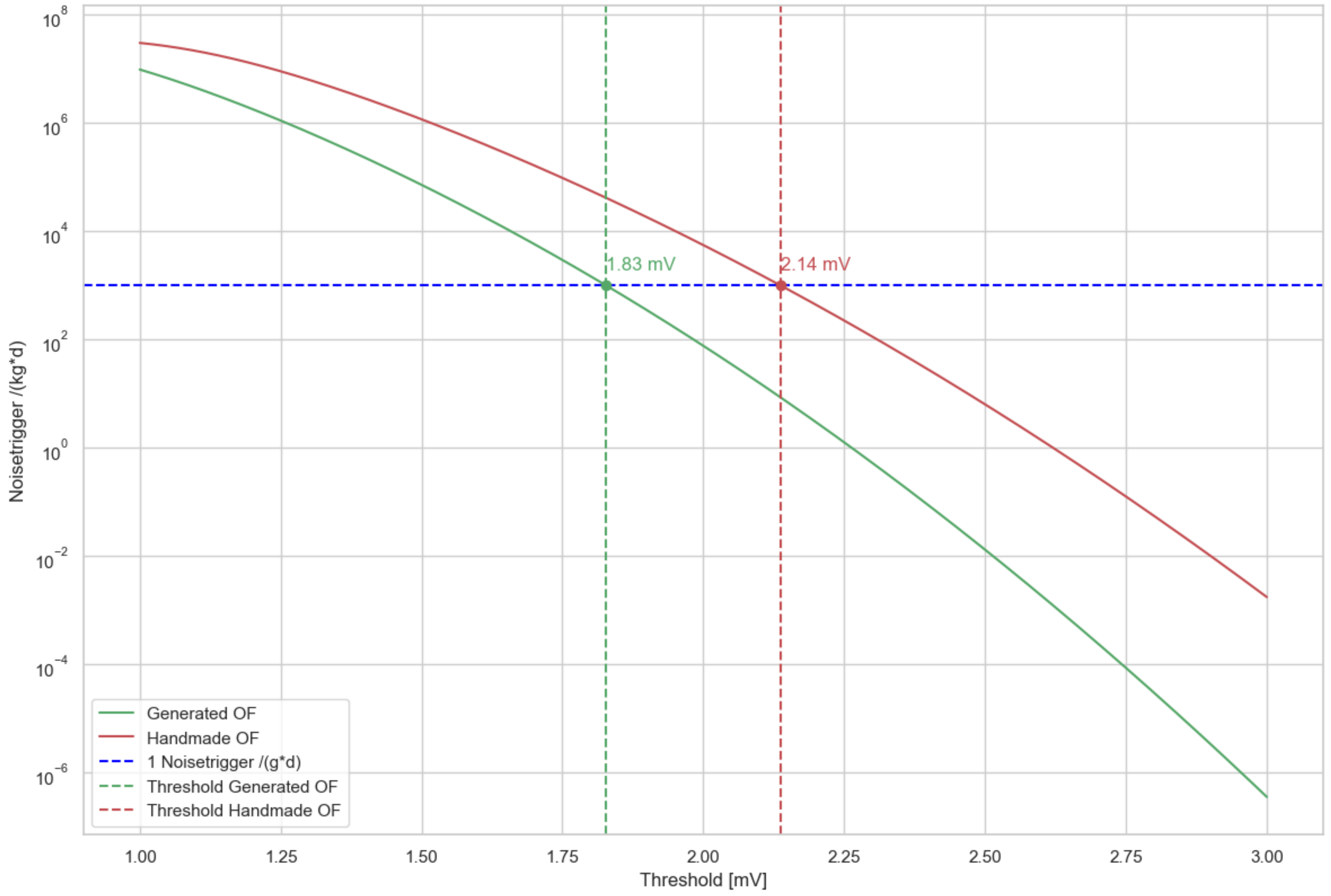




Summer Run

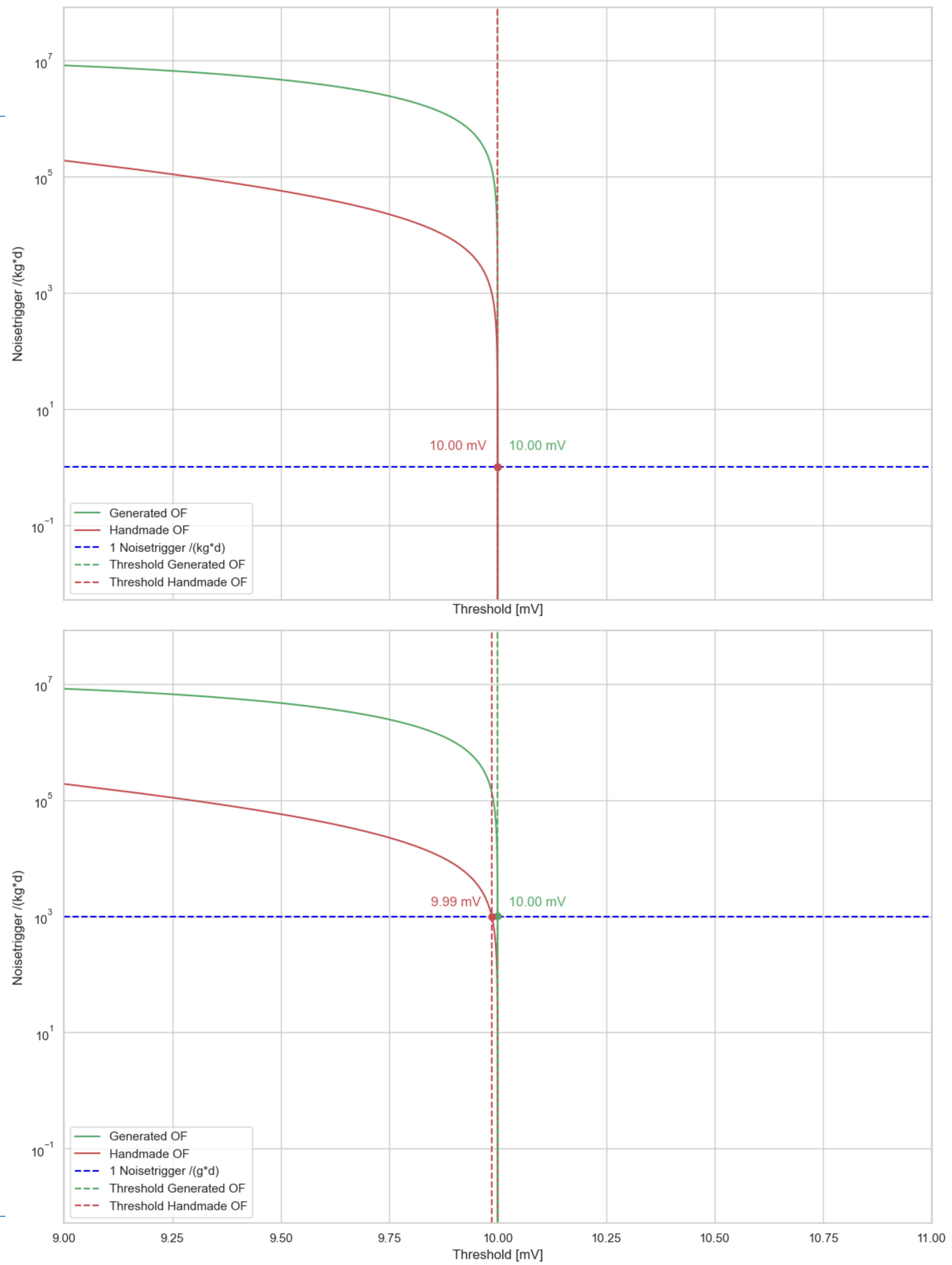
- Generated OF has a superior threshold compared to the handmade OF





Christmas Run

- Same threshold for both OF
- Relative high noise level forces threshold to be set to high values



Images

- [1] https://iopscience.iop.org/book/mono/978-0-7503-3731-1/chapter/bk978-0-7503-3731-1ch6
- [2] Florian Reindl