Time-sensitive pulse extraction using ML with NuDot

Masooma Sarfraz, Spencer Axani, Miles Garcia, on behalf of NuDot collaboration

UNIVERSITY OF DELAWARE
BARTOL RESEARCH INSTITUTE

Machine learning workshop
January 30, 2025

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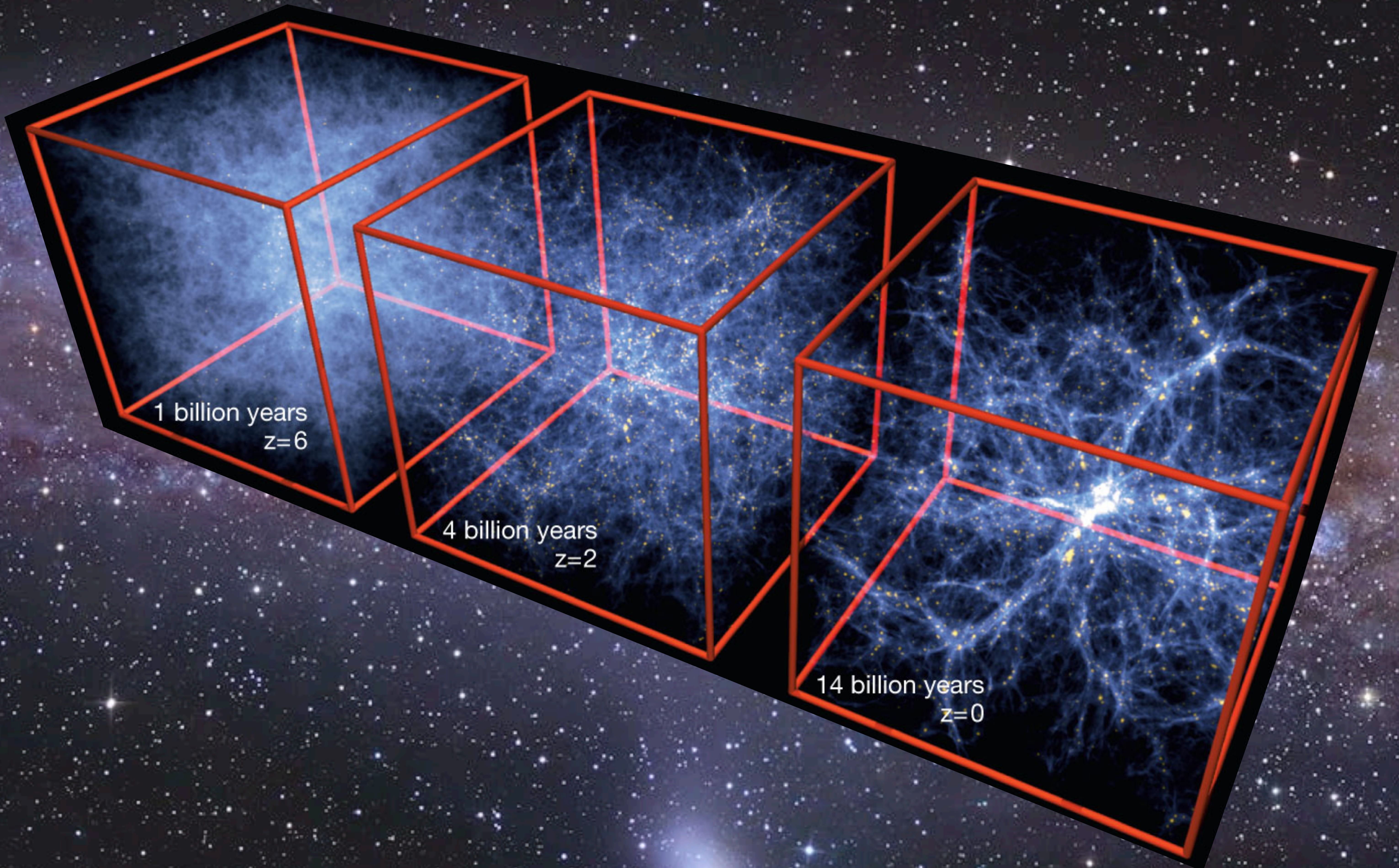
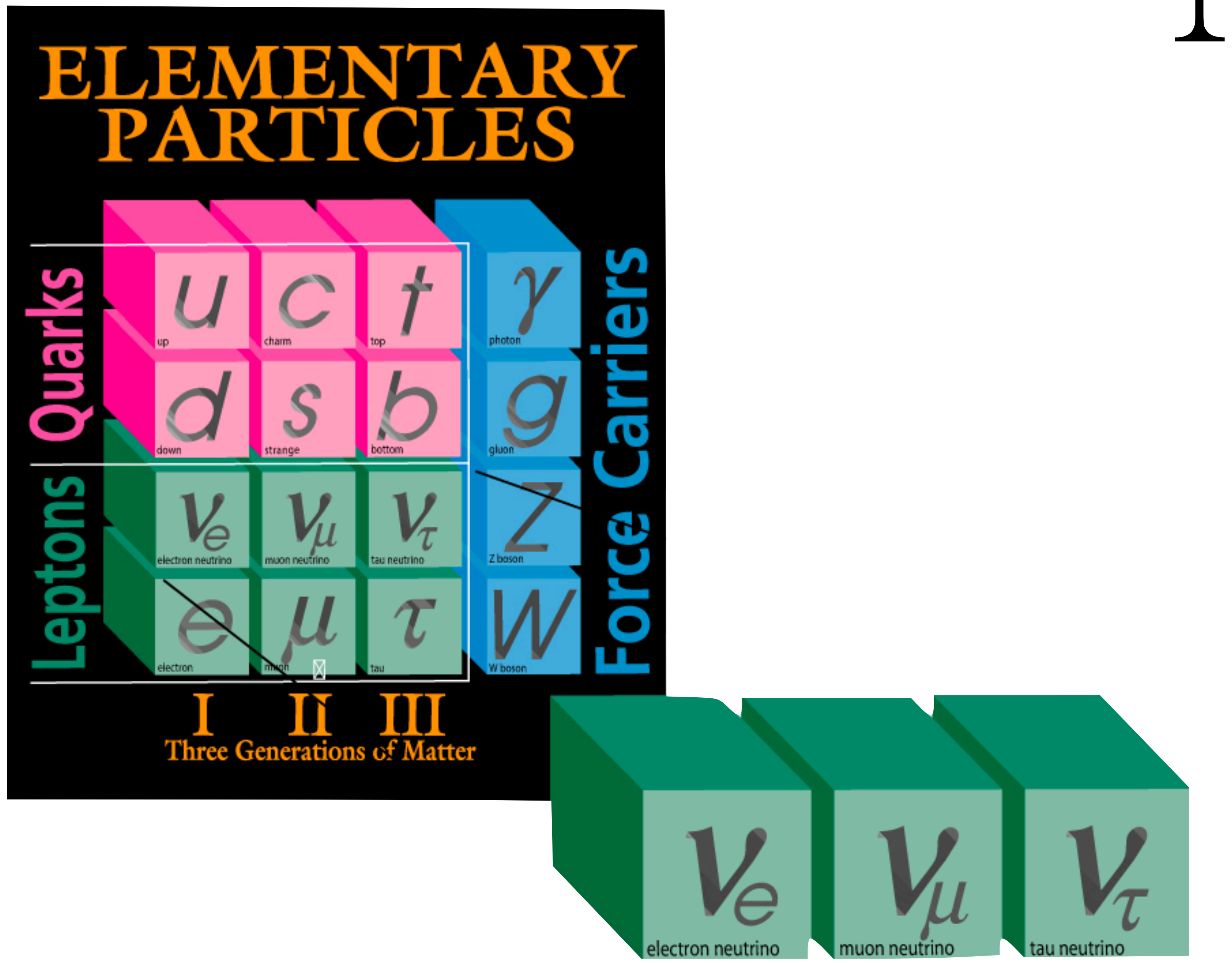
Outline:

- Motivation
- NuDot
- Active efforts in Machine learning
- Summary

Matter Anti-matter asymmetry

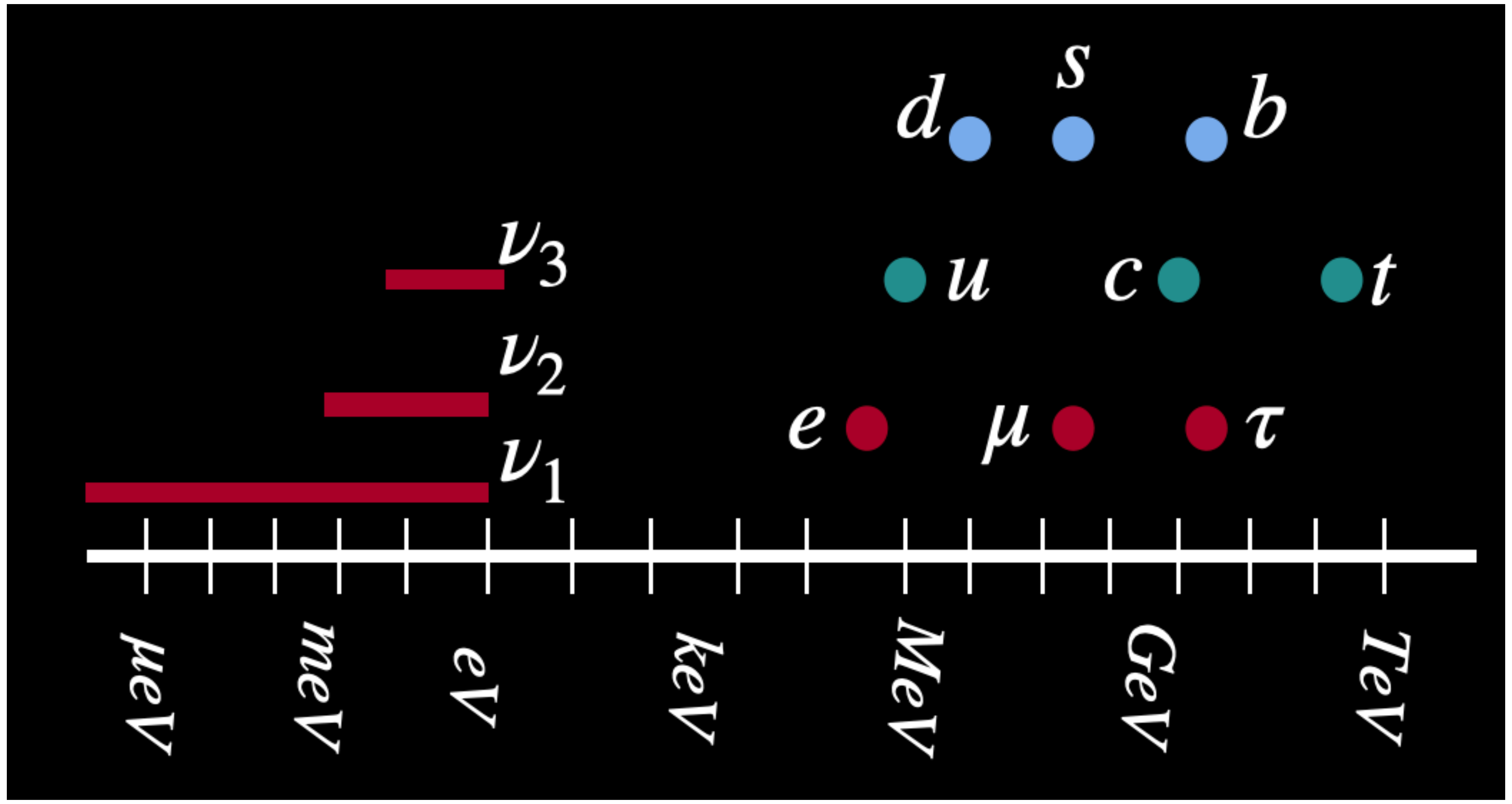


Motivation:



Dirac particles?

Majorana particles?



Neutrino mass hierarchy

Absolute mass

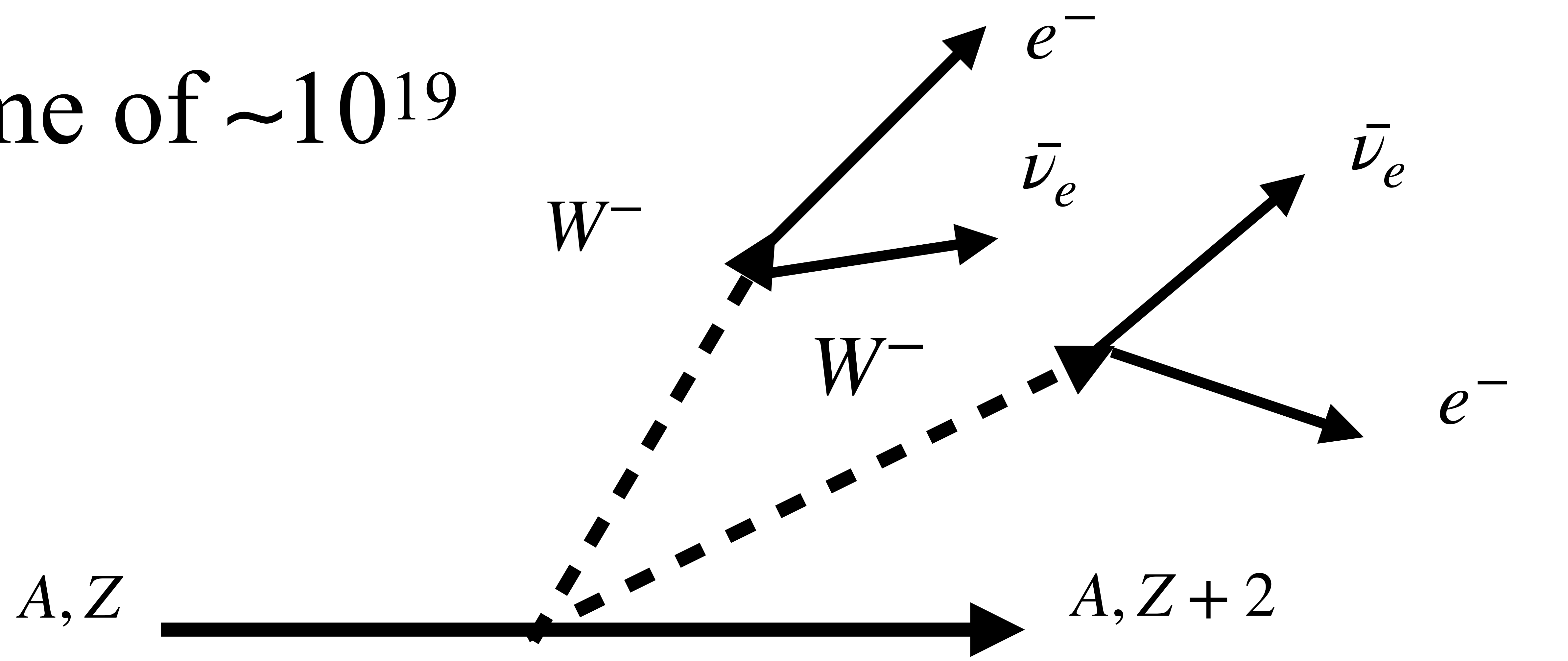
Mechanism of neutrino's mass

Why double beta decay?

2νββ : Observed rare decay with a lifetime of ~10^{19} years

$2n \rightarrow 2p^{+} + 2e^{-} + 2\bar{\nu}_e$

Standard model process



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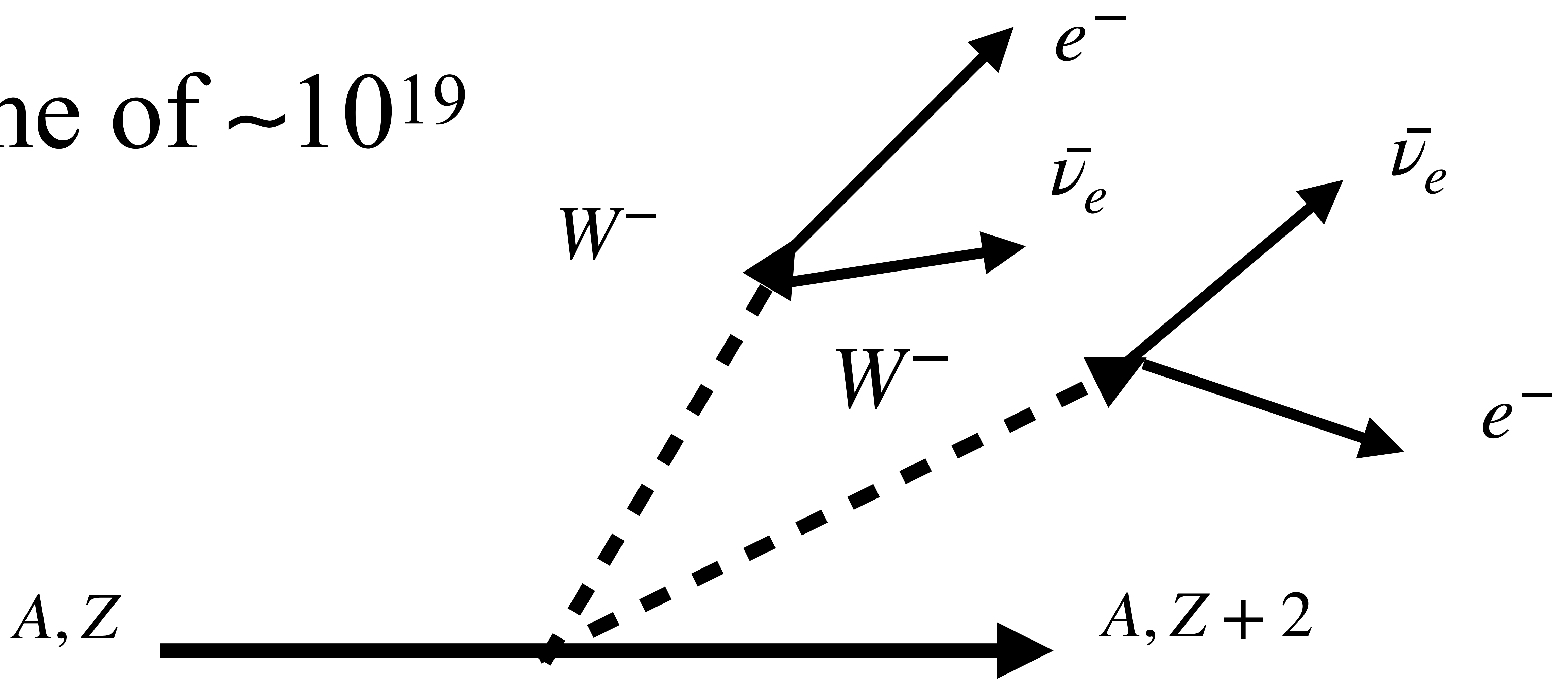
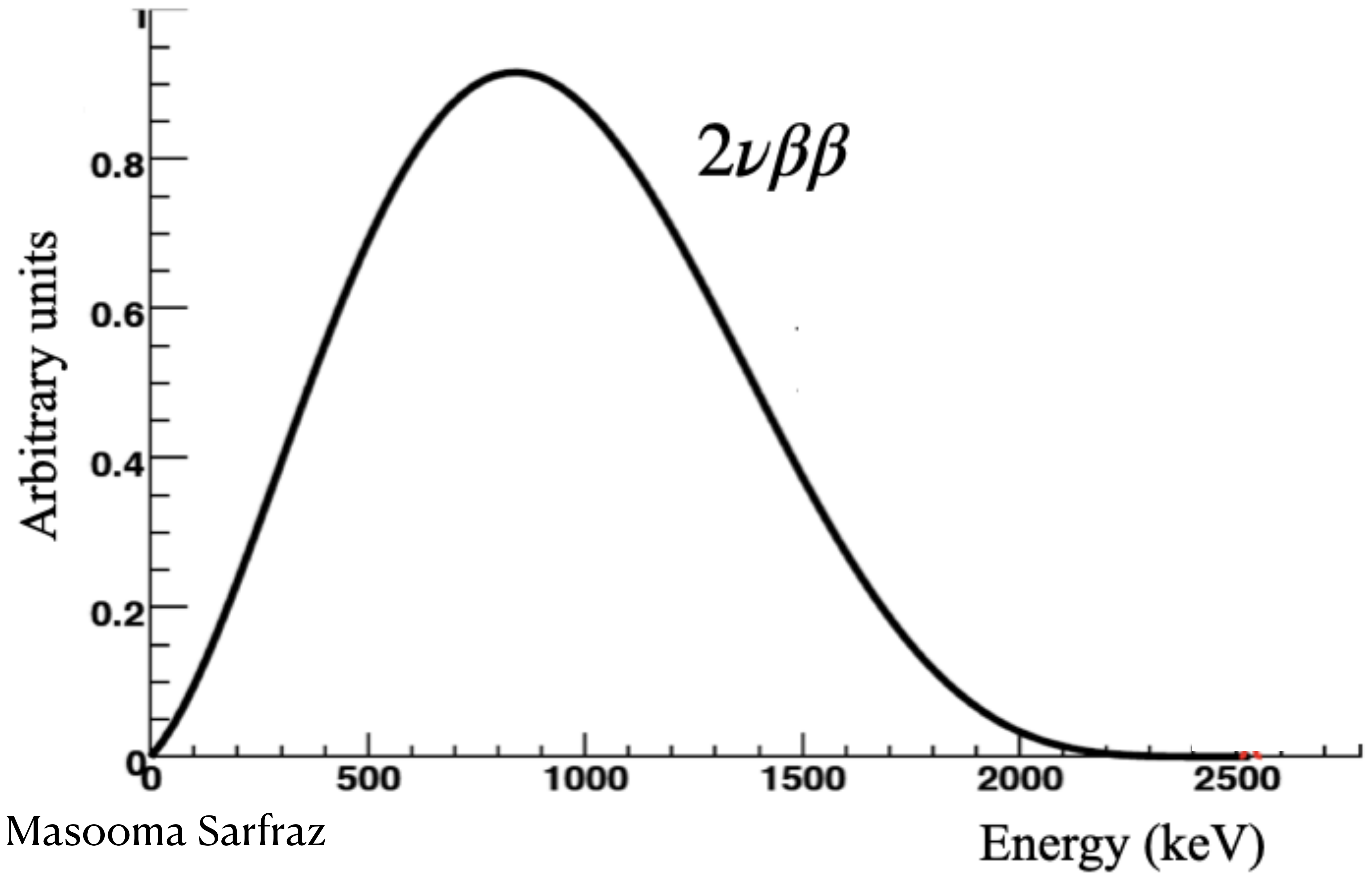
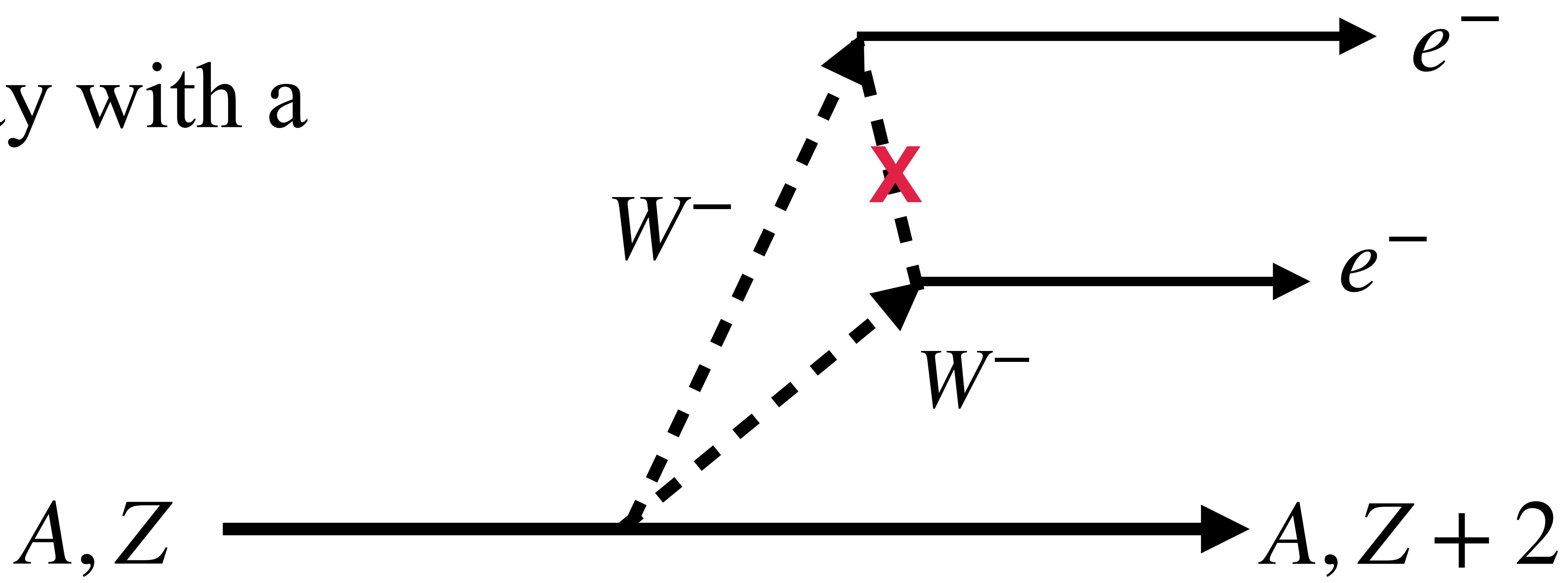




Why double beta decay?

0νββ : Ultra-rare hypothesized decay with a lifetime of >10^{26} yrs

$2n \rightarrow 2p^{+} + 2e^{-}$



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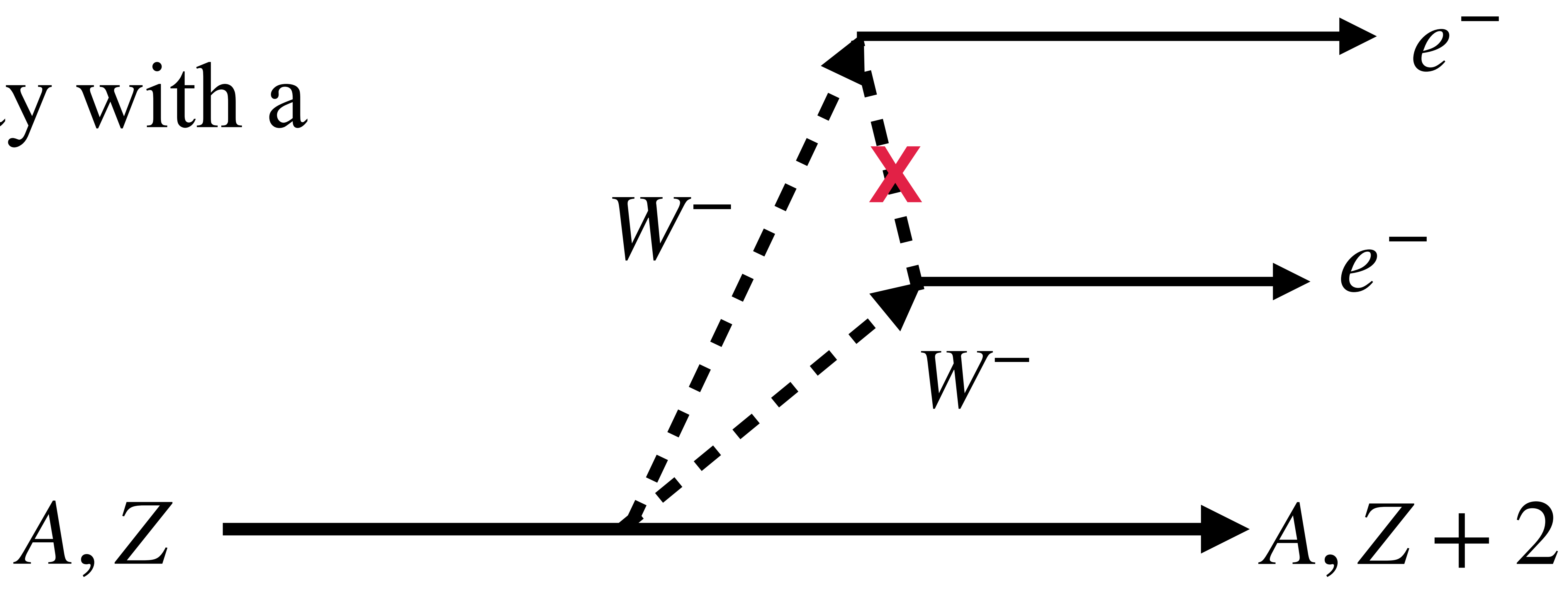
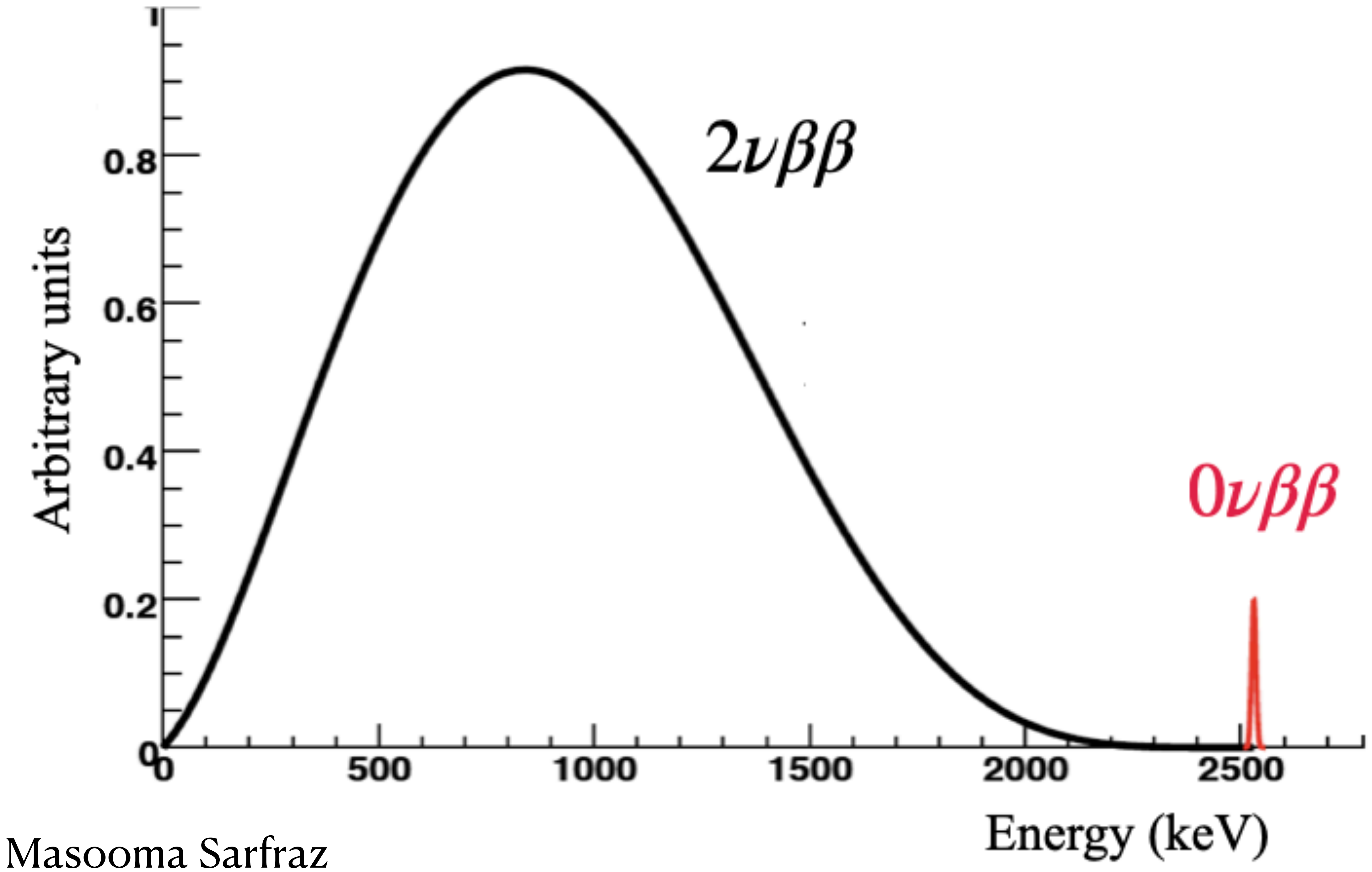
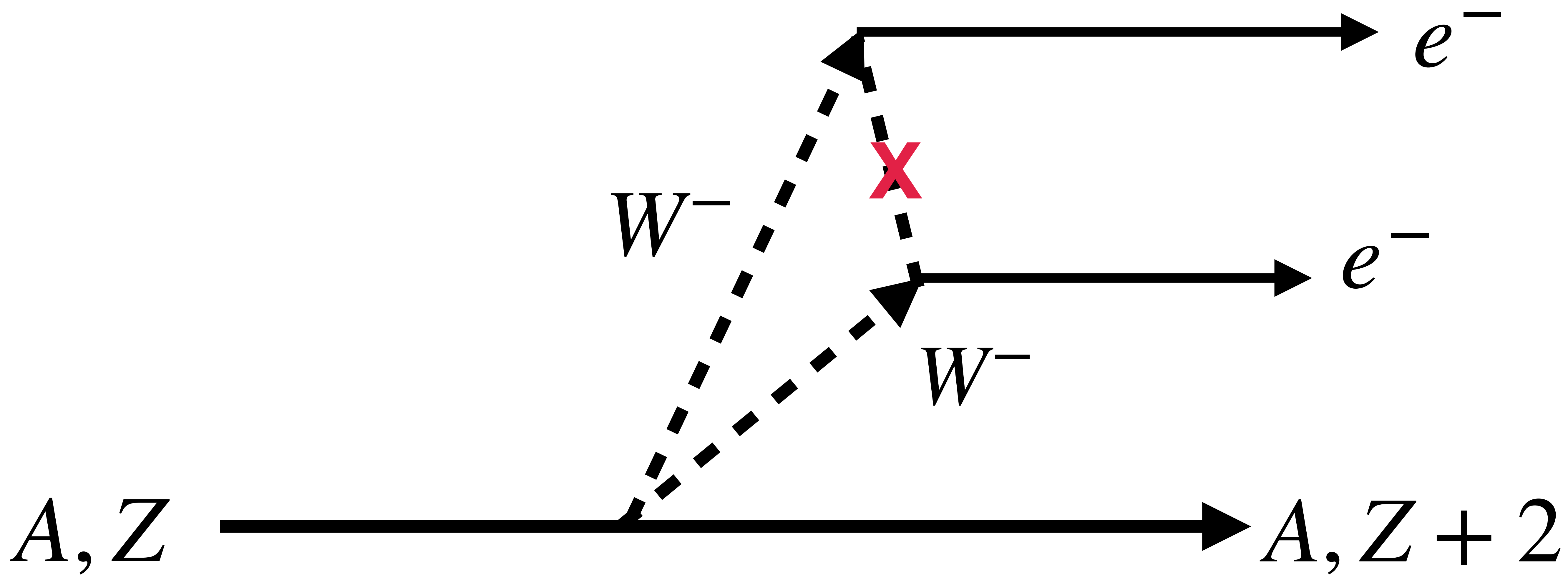
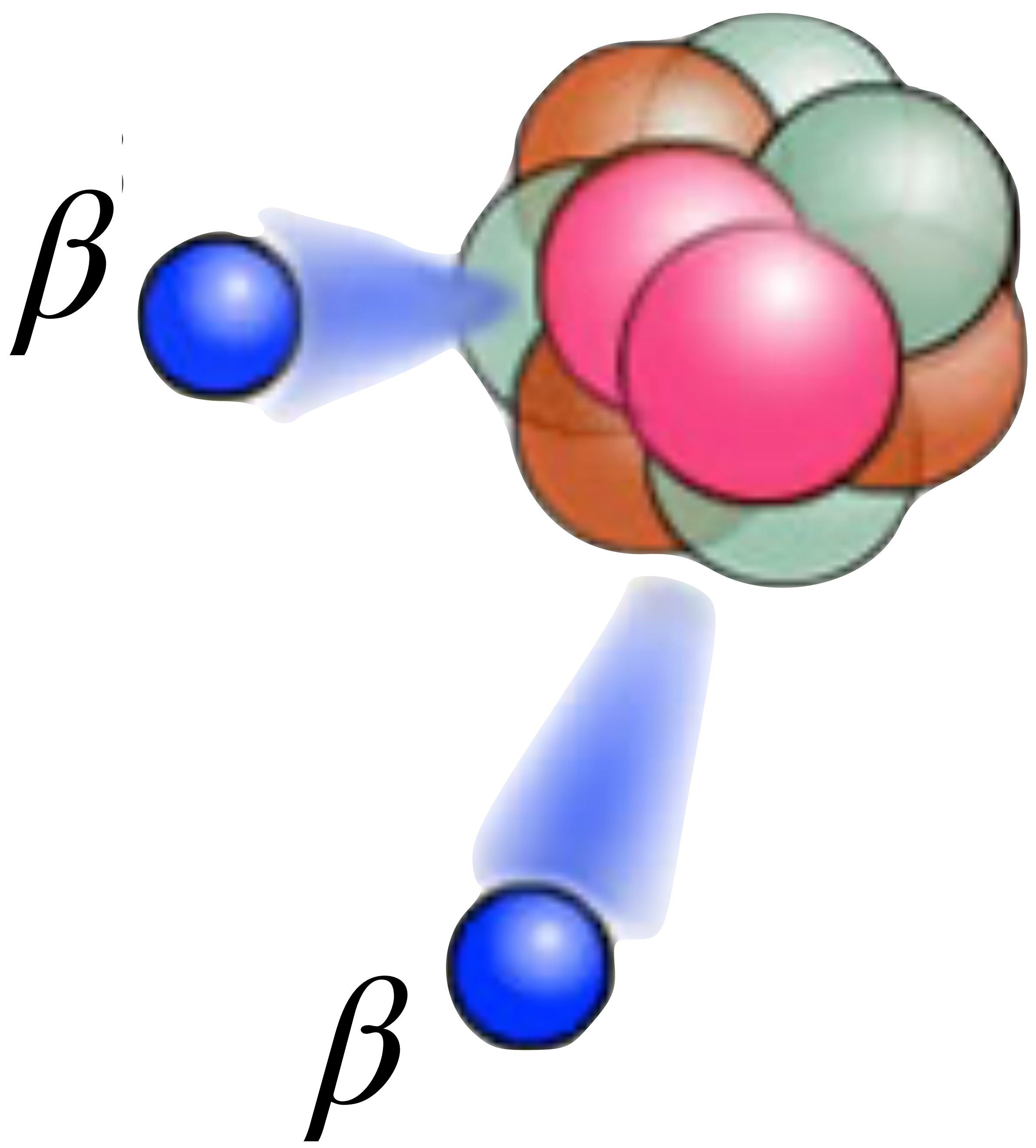




Observation of neutrinoless double-beta decay (0νββ) would be a groundbreaking discovery, providing direct evidence of Majorana nature of neutrinos.

- ☑ Neutrino is a Majorana particle
- ☑ New mechanism for neutrino's mass
- ☑ Lepton number violation





Liquid scintillator detectors

Pros:

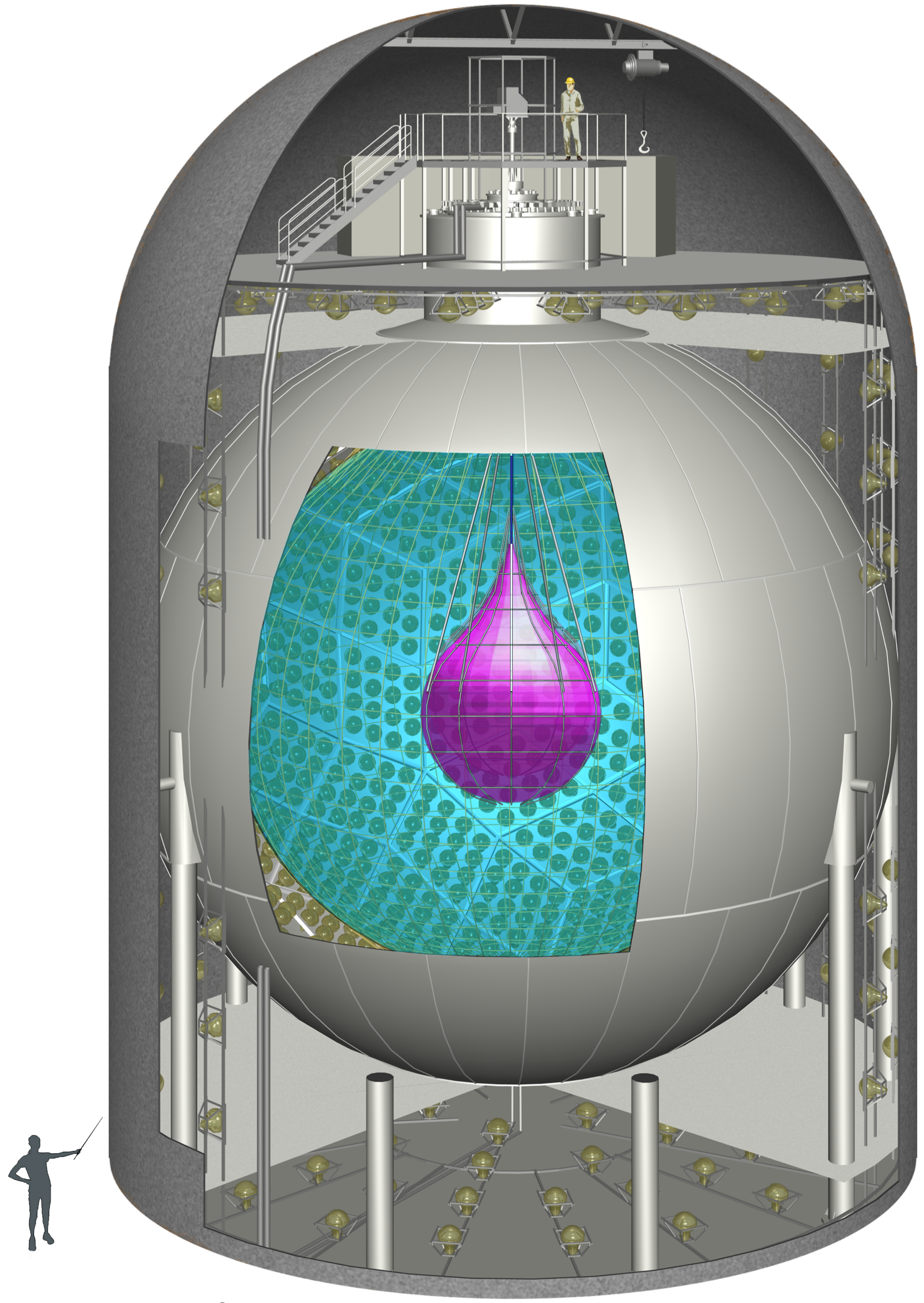
- Self-shielding
- Multi-purpose neutrinos measurement
- Scaling

Cons:

- Low energy resolution
- Some irreducible backgrounds

Liquid scintillator detectors

KamLAND-Zen800



World's leading limits on effective Majorana mass.
$\mathbf{T_{1/2} > 4.3 \times 10^{26}}$ **years** for ^{136}Xe at 90% C.L.

PRL pre-print: arXiv:2406.11438

KamLAND (the Kamioka Liquid Scintillator Antineutrino Detector)

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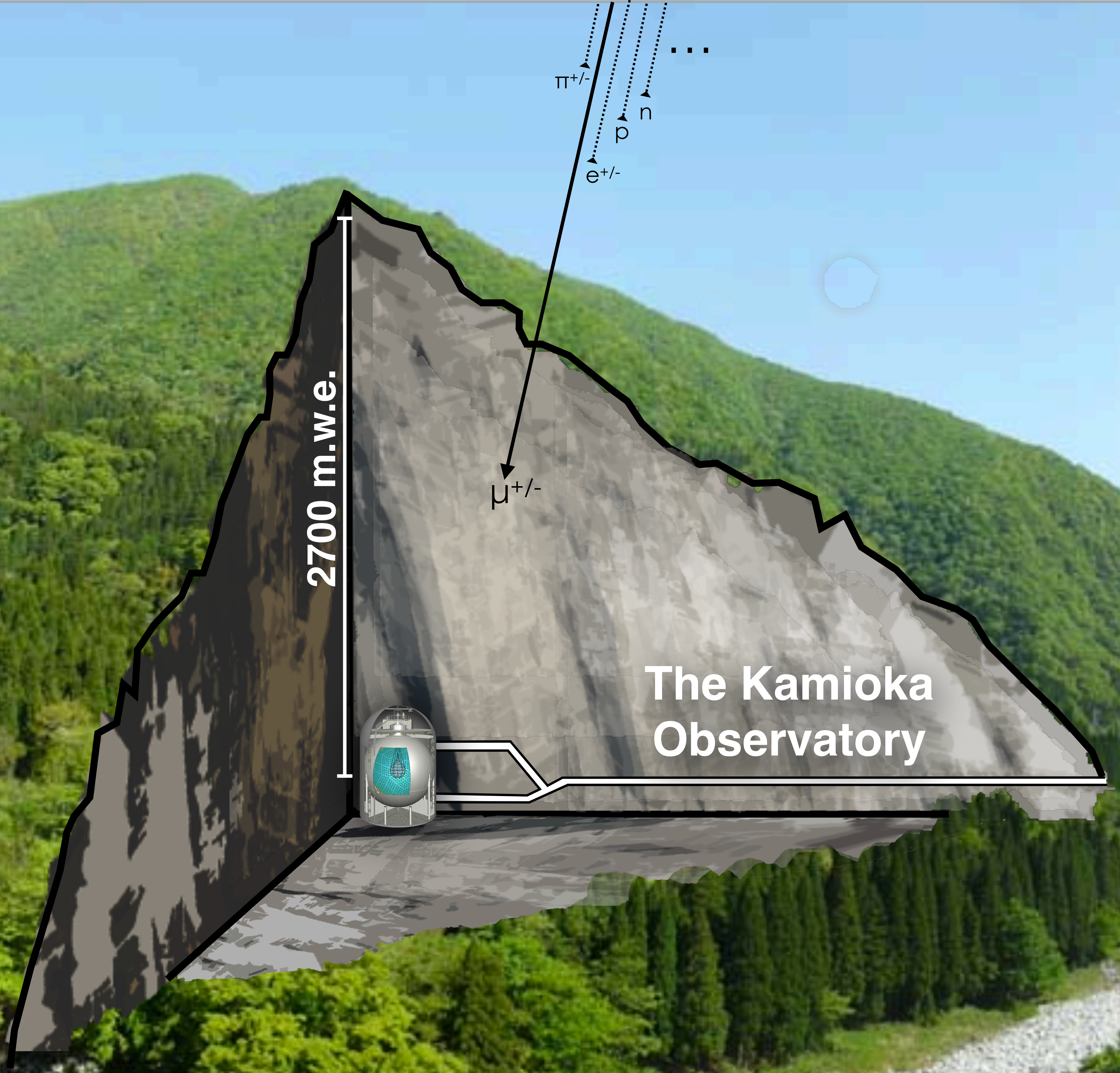

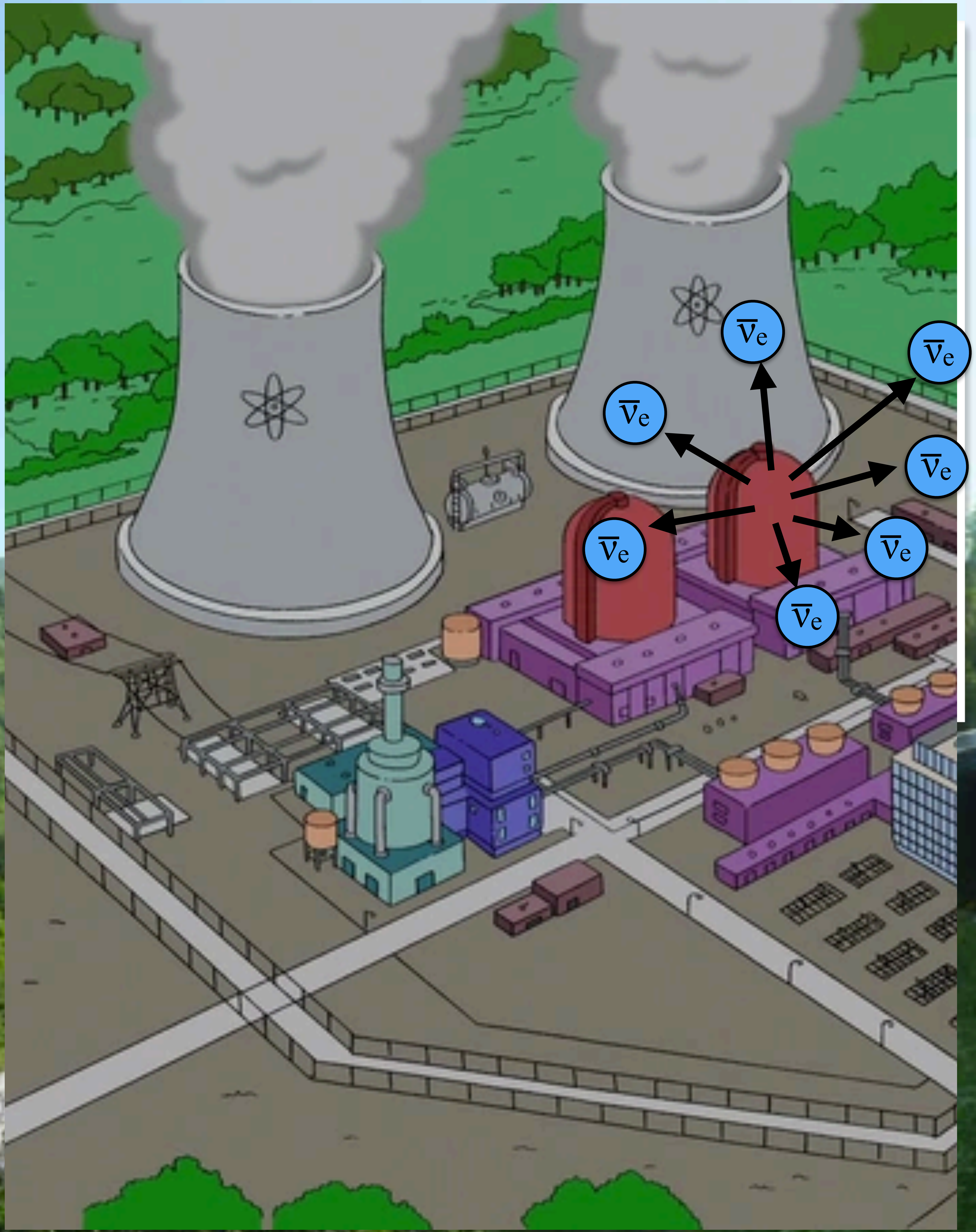

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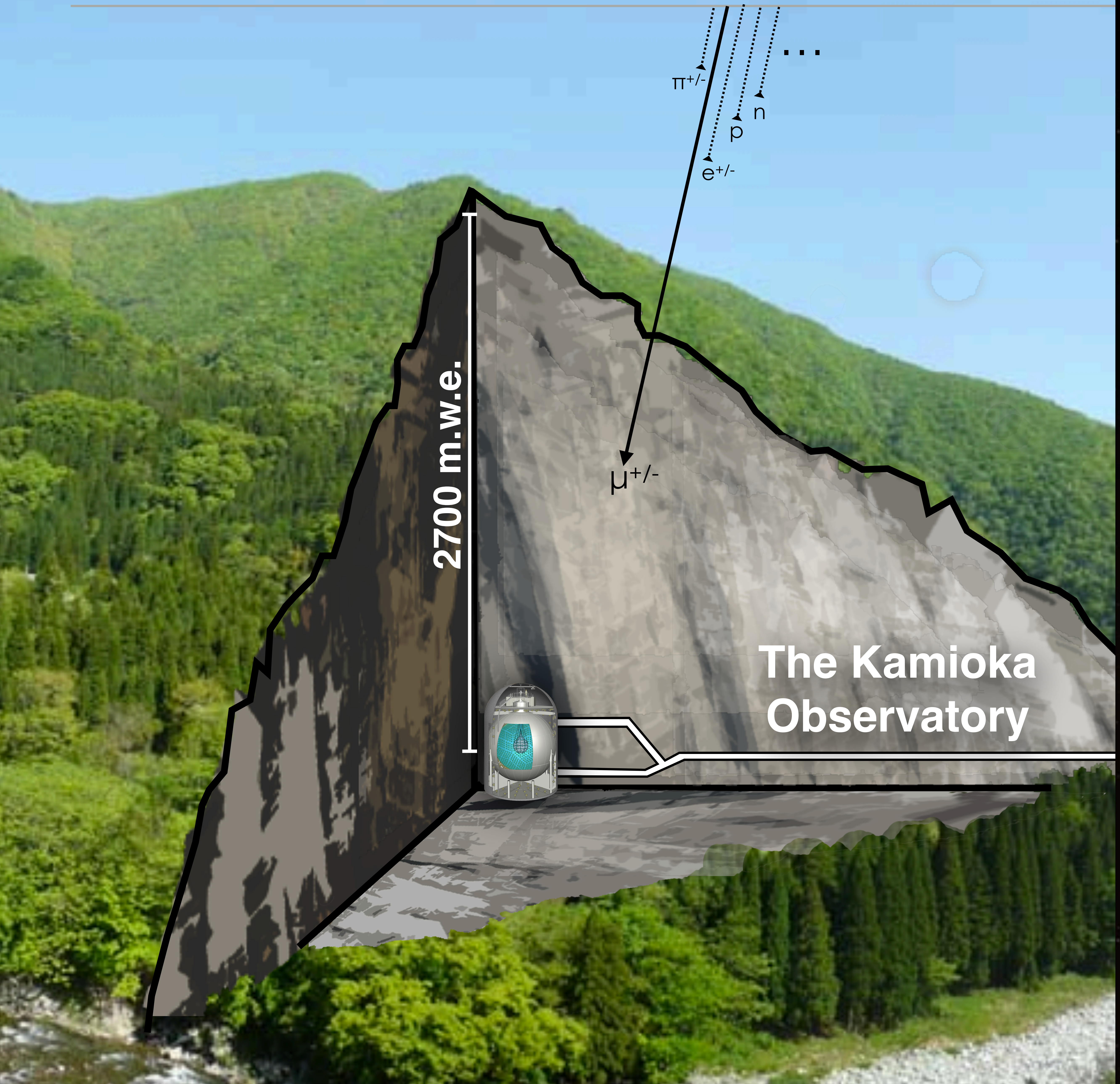
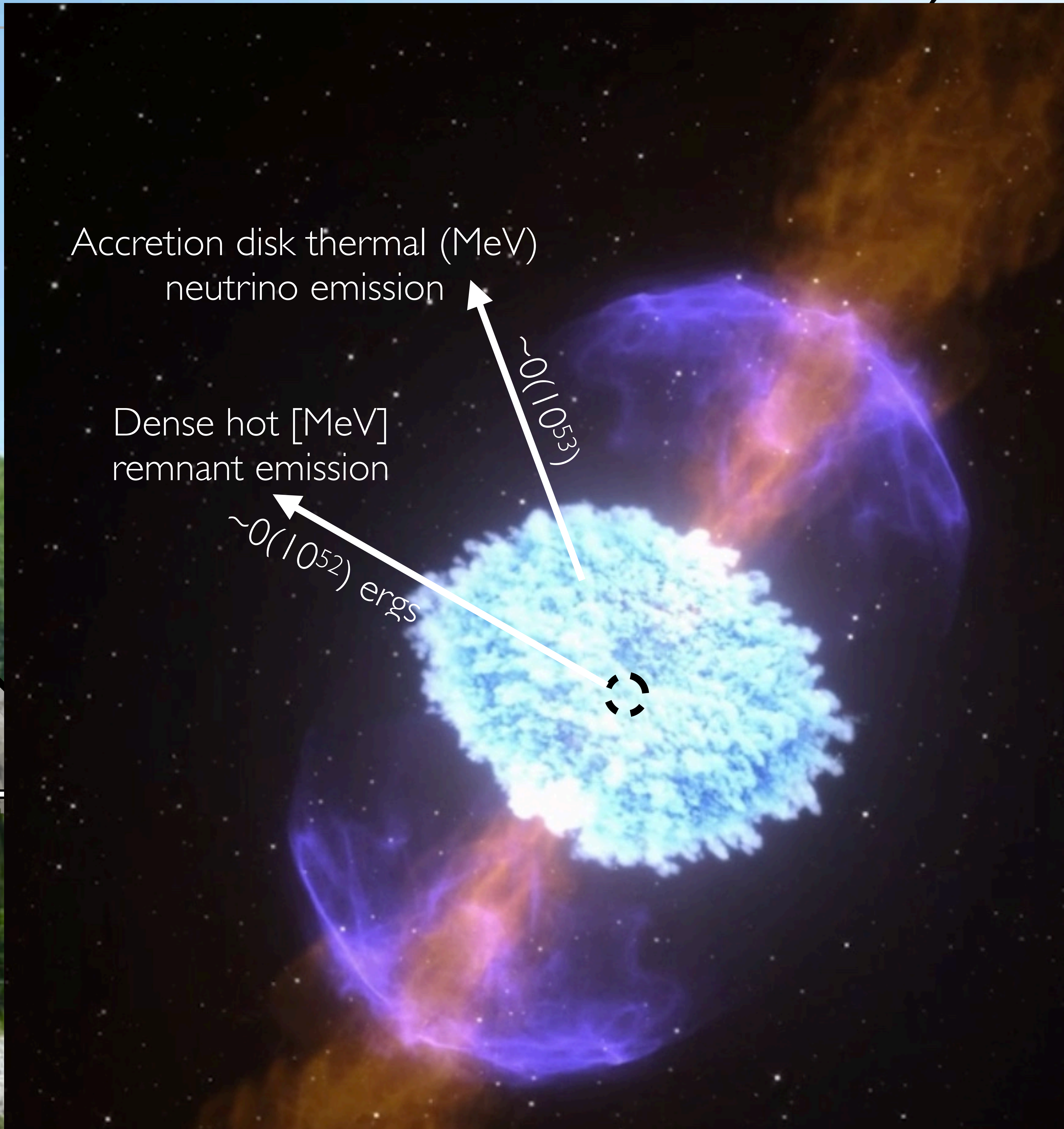
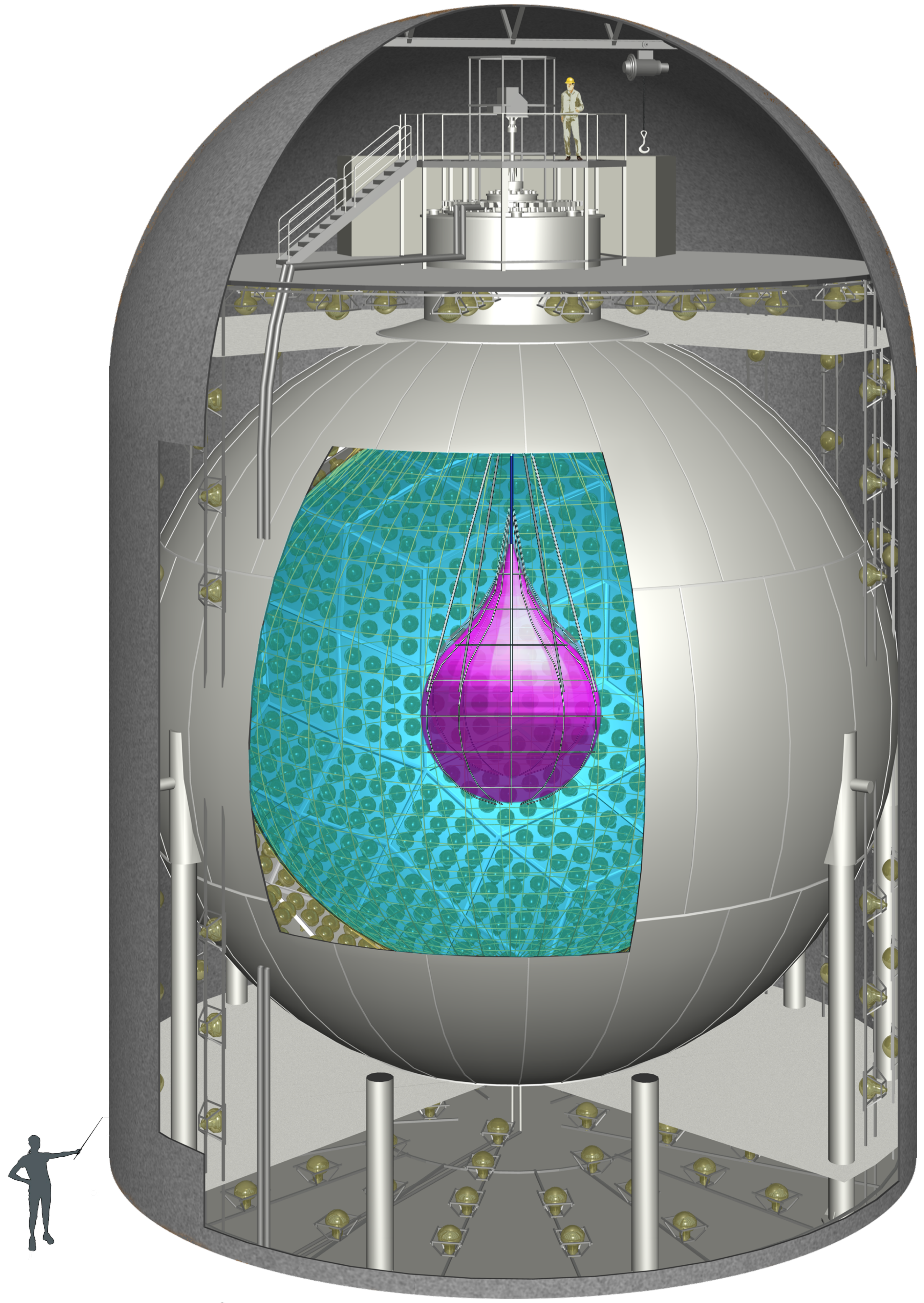


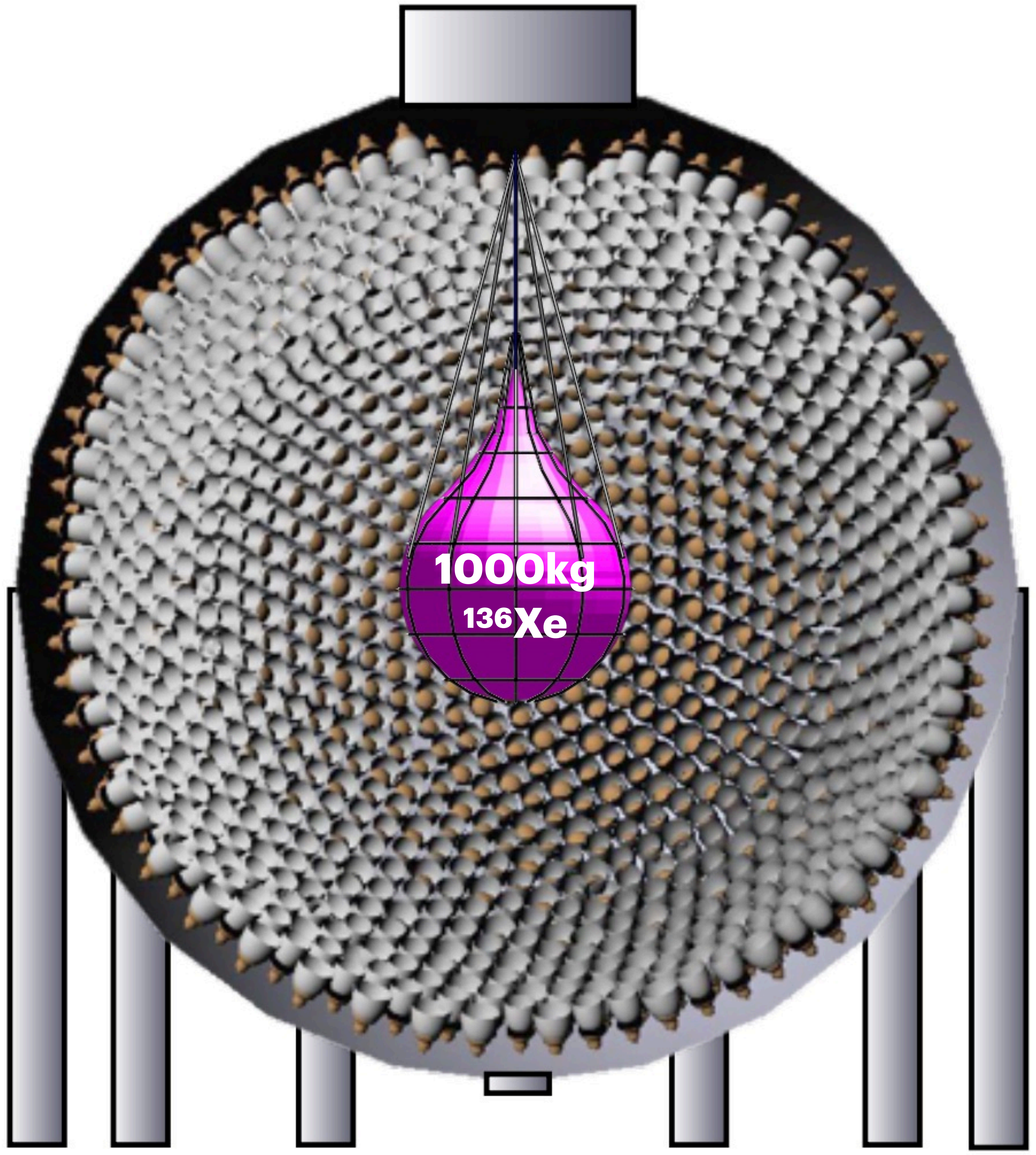


Liquid scintillator detectors

KamLAND-Zen800



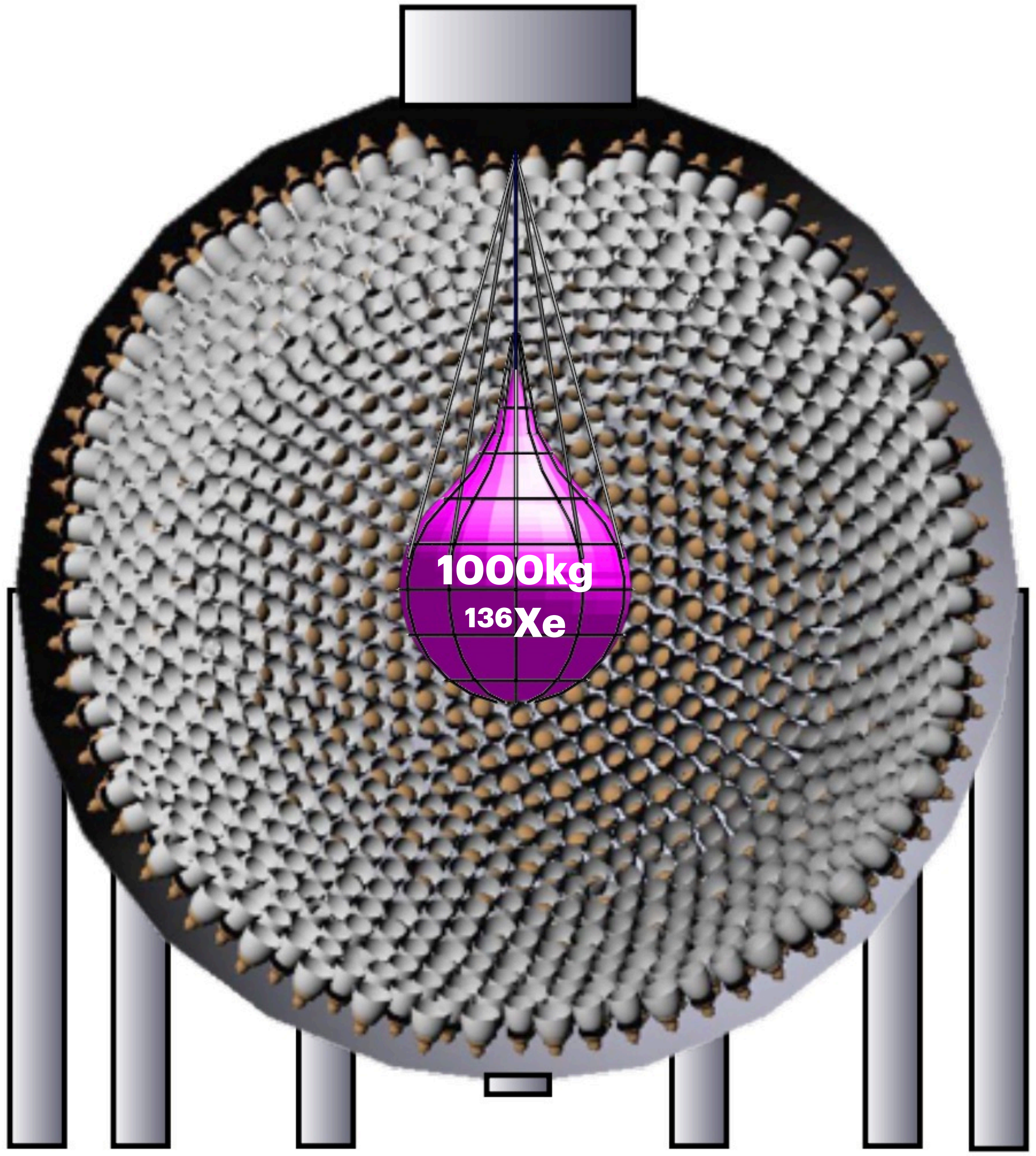
Future: KamLAND2-Zen

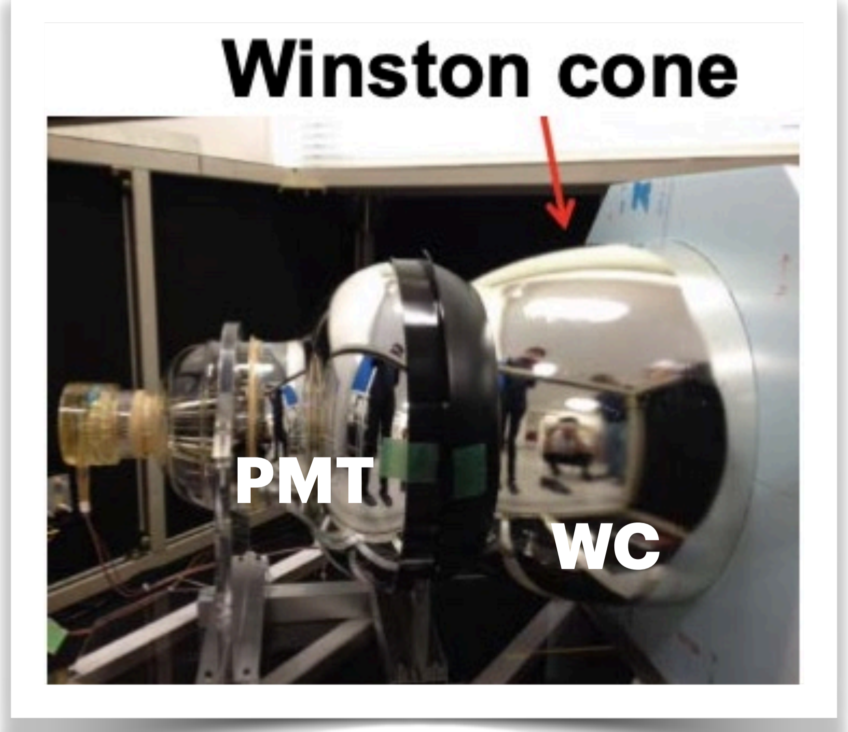


KamLAND2-Zen is funded and will bootup in **2028**.

KamLAND2-Zen

KamLAND2-Zen aims to cover the Inverted Ordering region.





Improved energy resolution

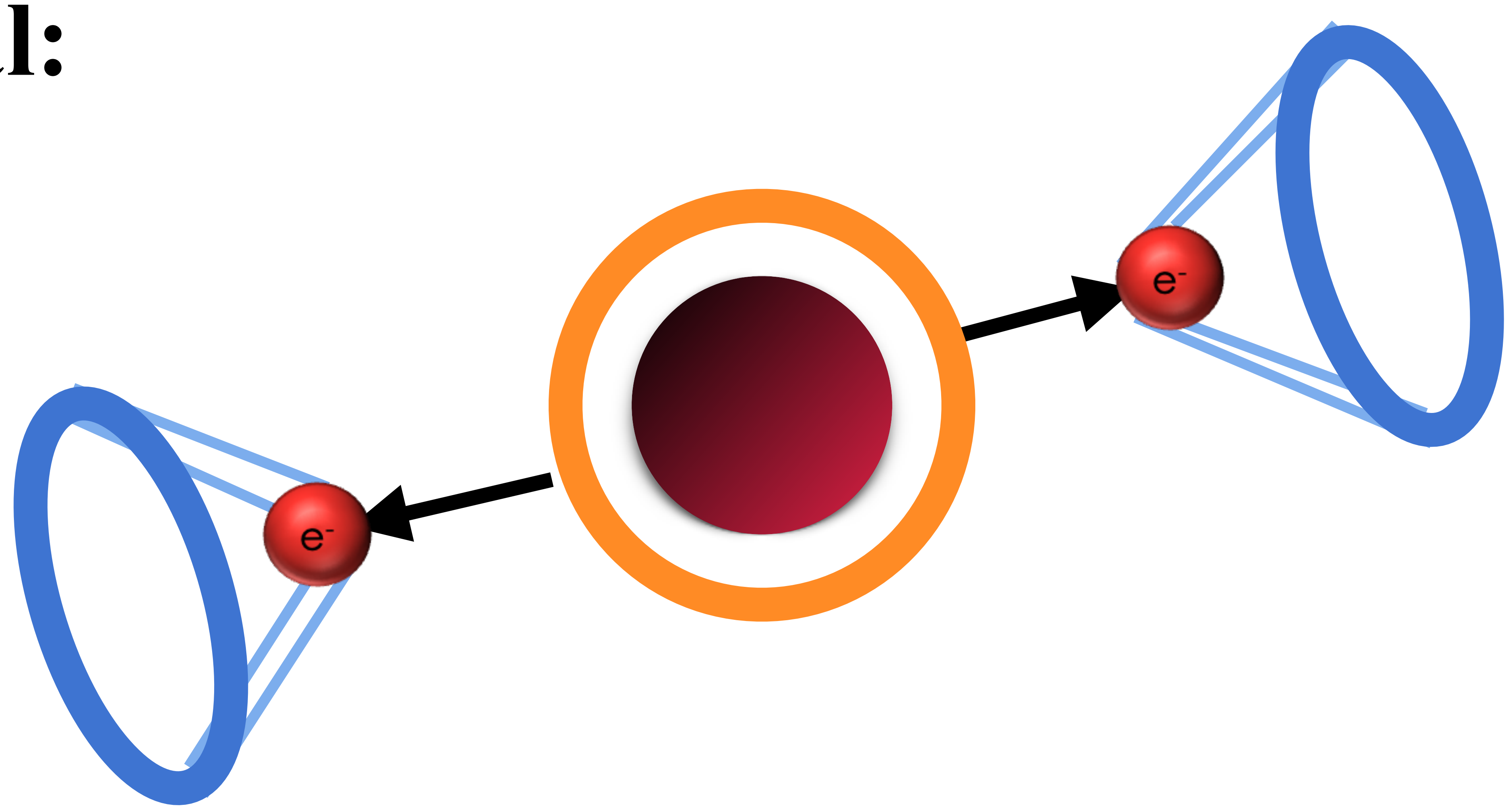
Purpose: further separate **2νββ** from the **0νββ**.

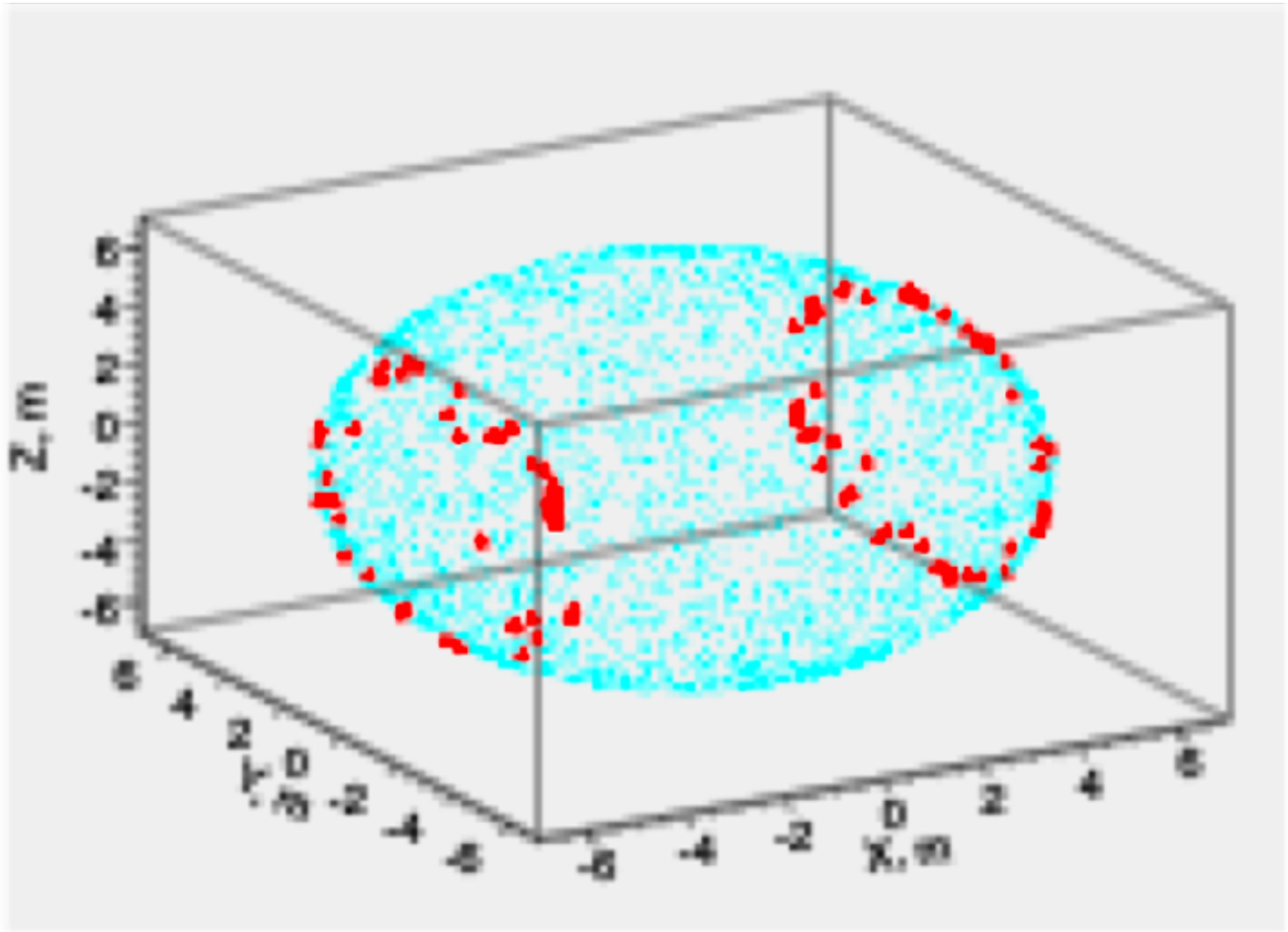
State-of-the-art electronics

Purpose: Improve background suppression.

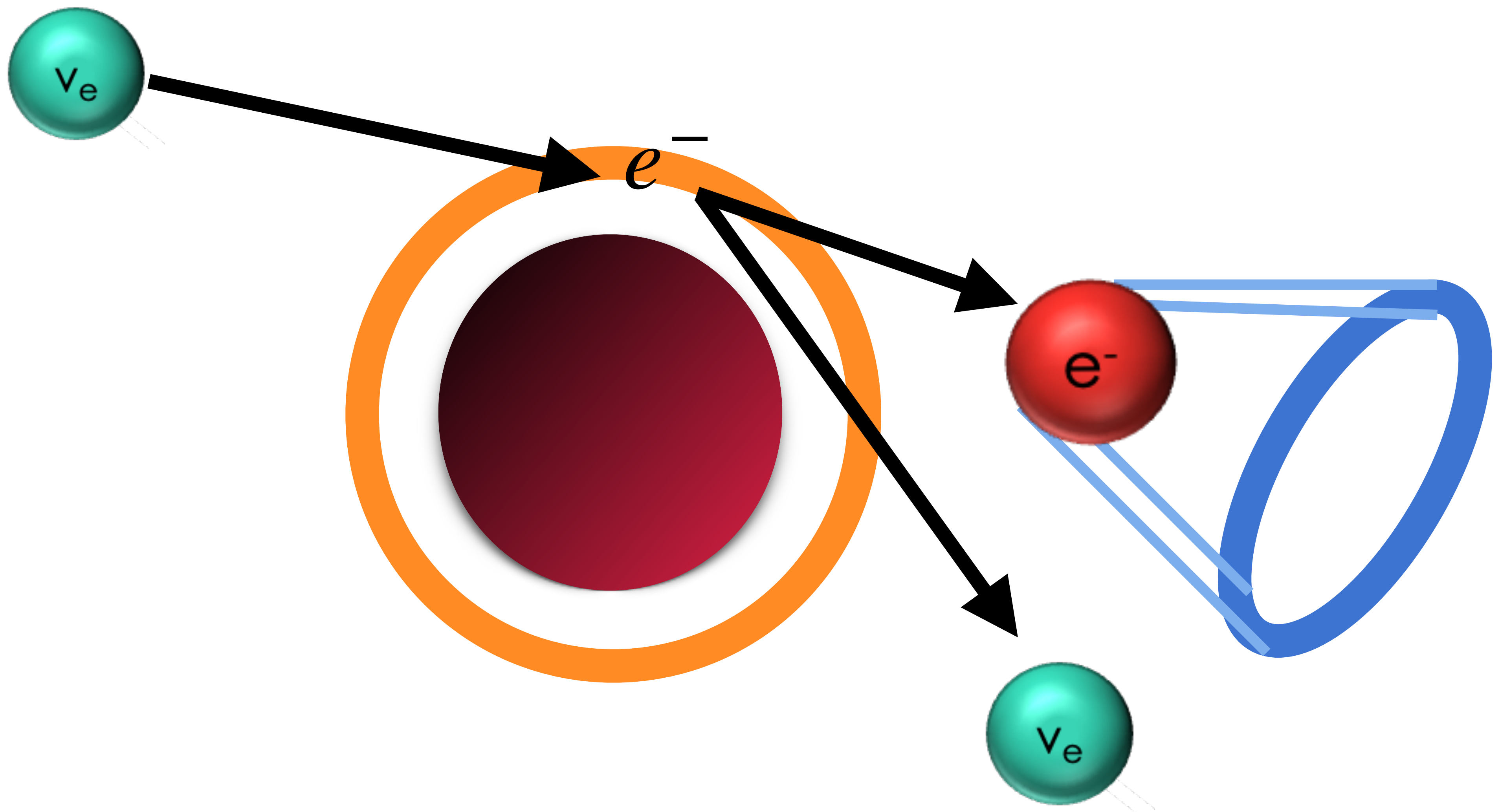
Separating solar neutrino backgrounds from 0νββ signal

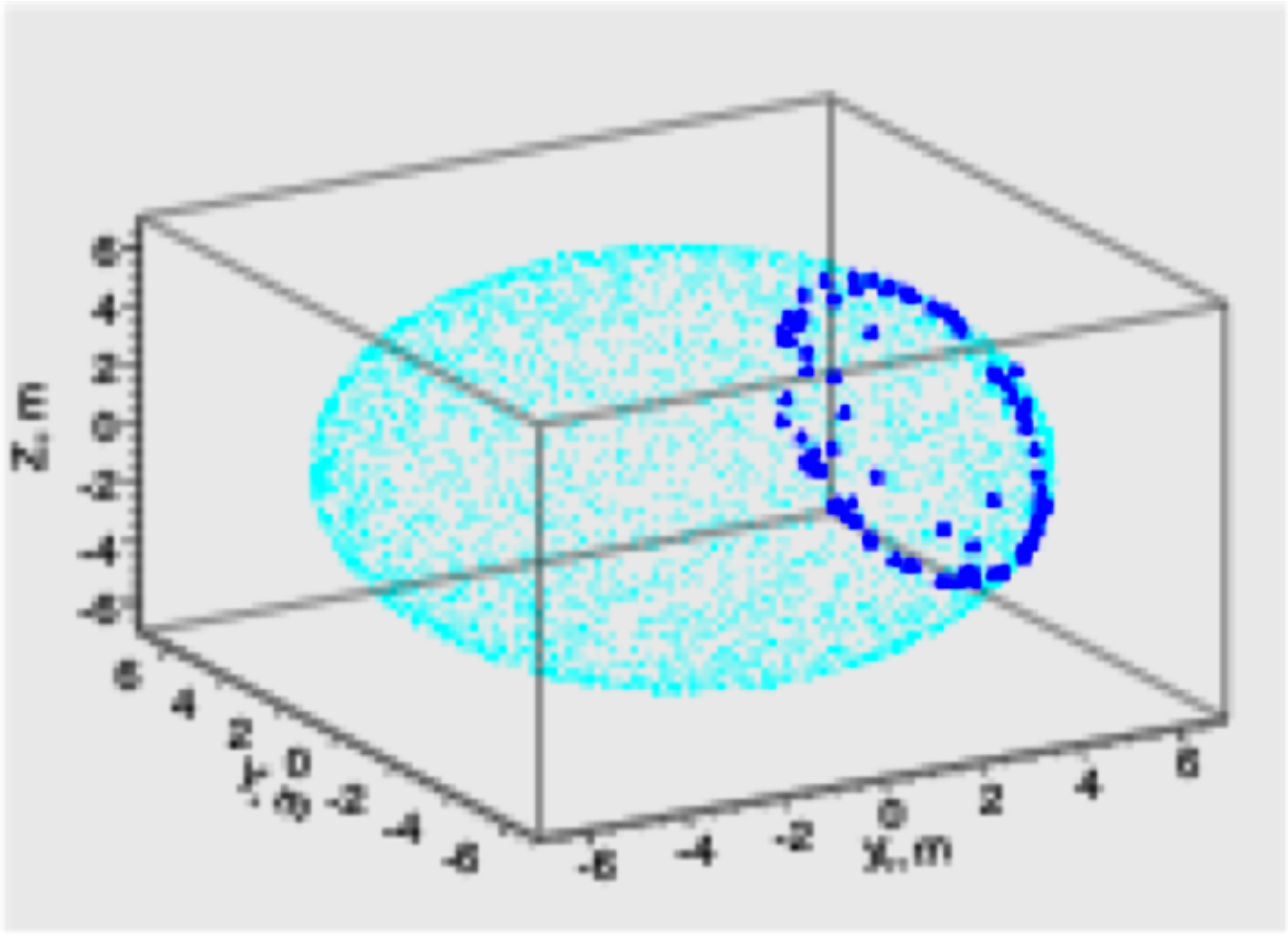
Signal:





Background:

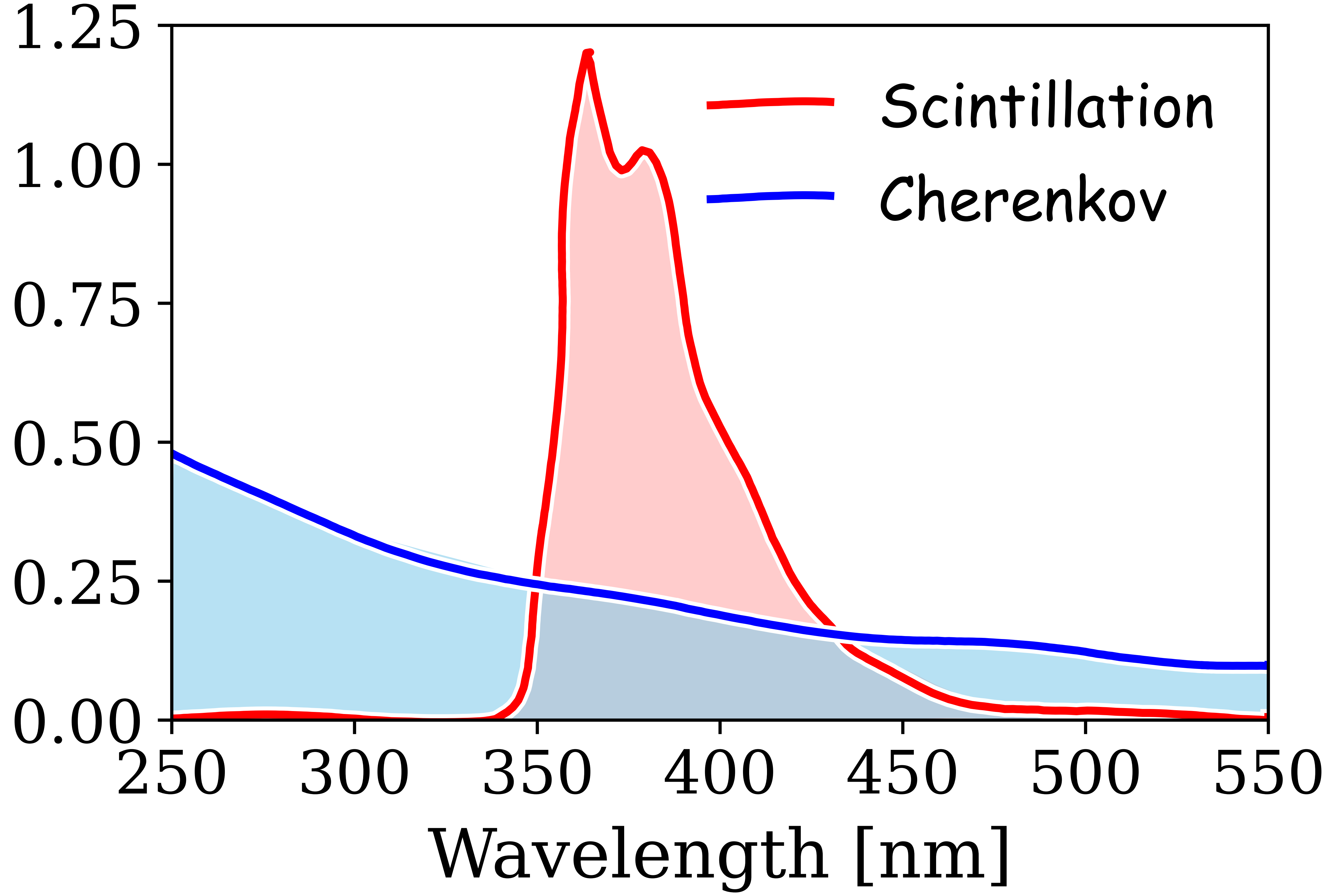




Figs. courtesy of A. Elagin

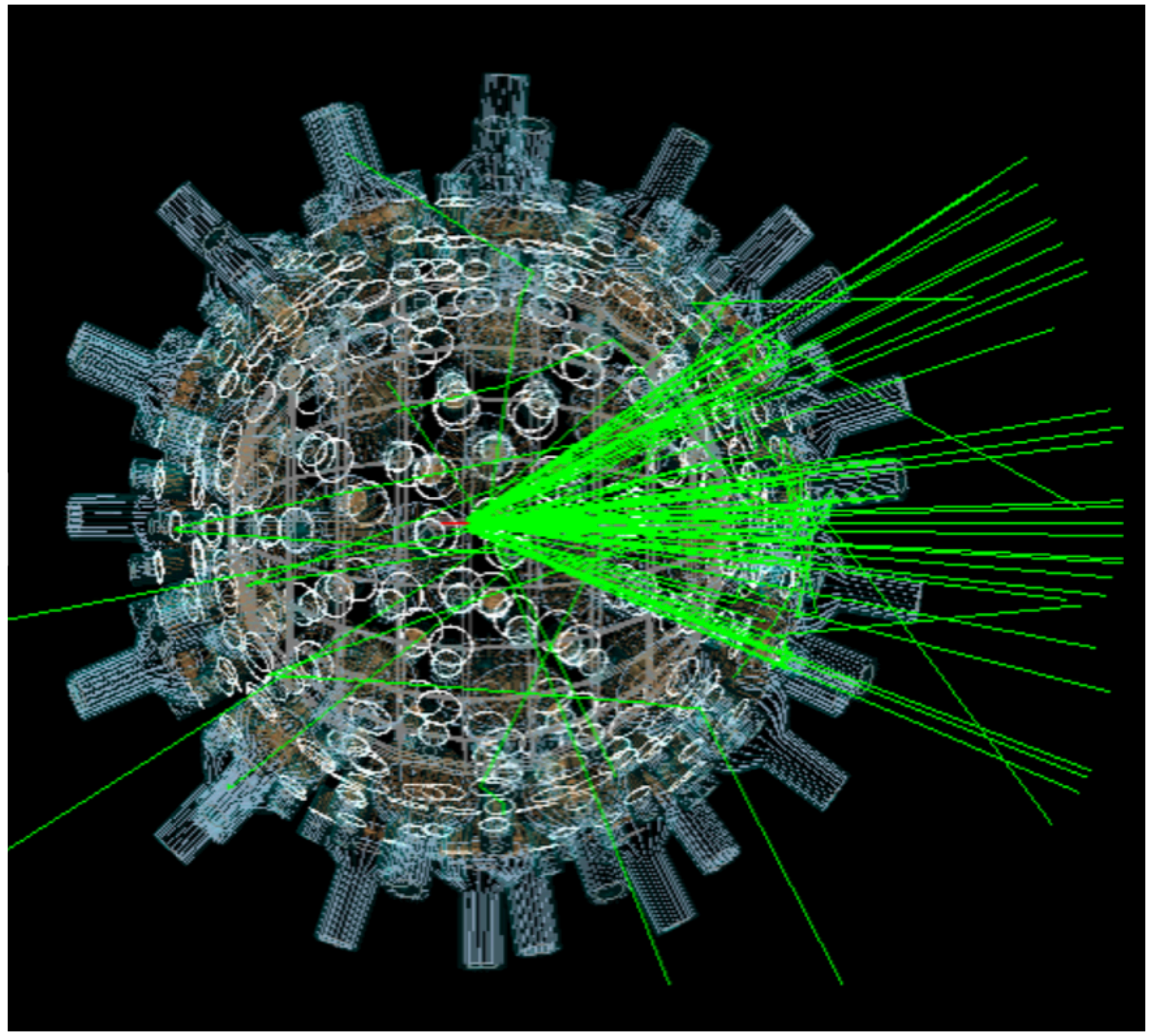
Ways to reduce background

1. Using wavelength-shifting materials

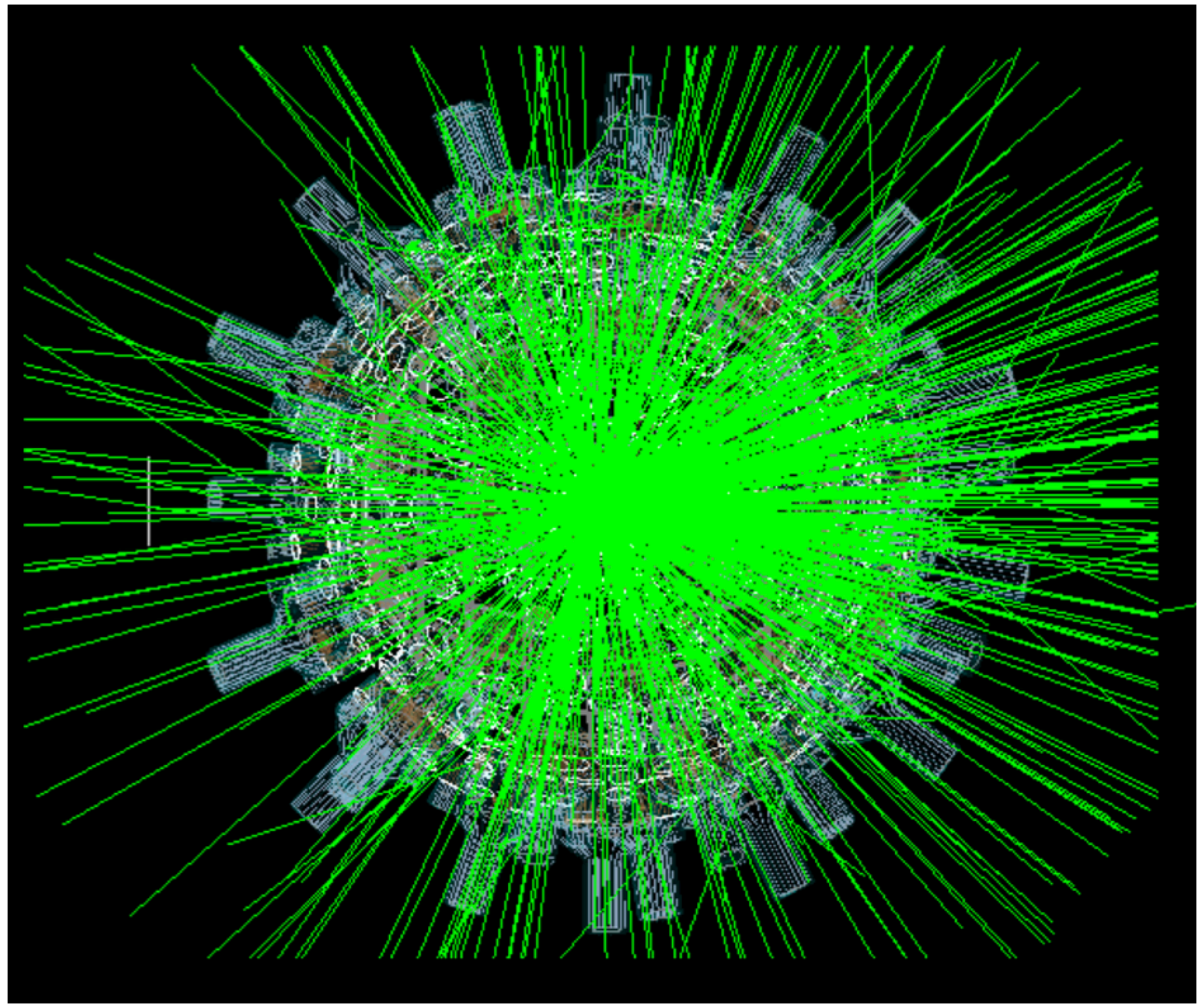


Ways to reduce background

1. Using wavelength-shifting materials
2. Using directional reconstruction



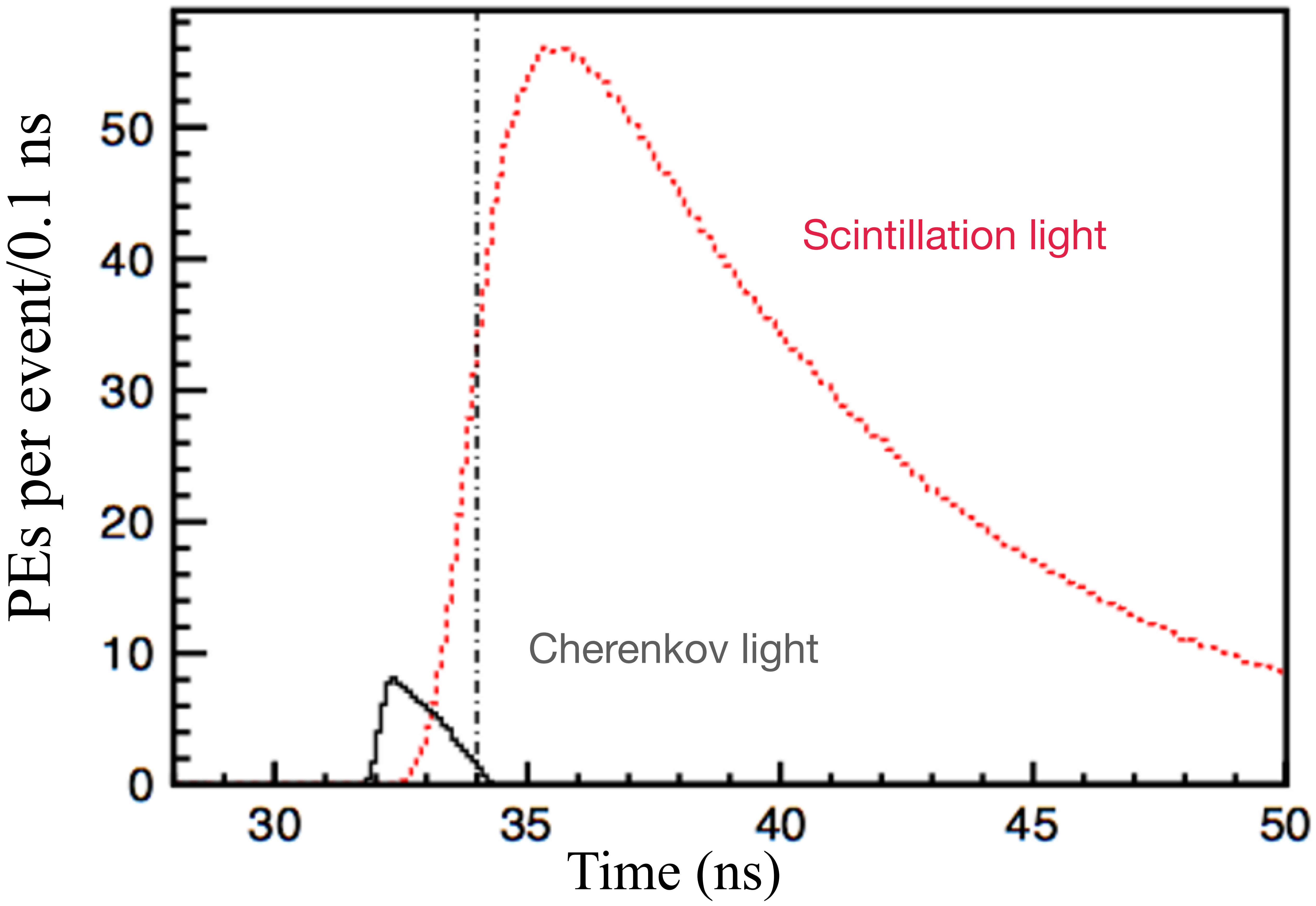
Cherenkov light



Scintillation light

Ways to reduce background

1. Using wavelength-shifting materials
2. Using directional reconstruction
3. Using precise timing resolution



Simulation of KamLAND-Zen type detector for separating Cherenkov from prompt scintillation emission.

NuDot detector @UD

NuDot detector is a 1m diameter acrylic vessel that is surrounded by 4π array of high precision photomultiplier tubes (PMT) and large light collection PMTs.

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x151 Hamamatsu R13089

- 2” PMTs
- Low time-transit spread (σ = 200ps)

NuDot detector @UD

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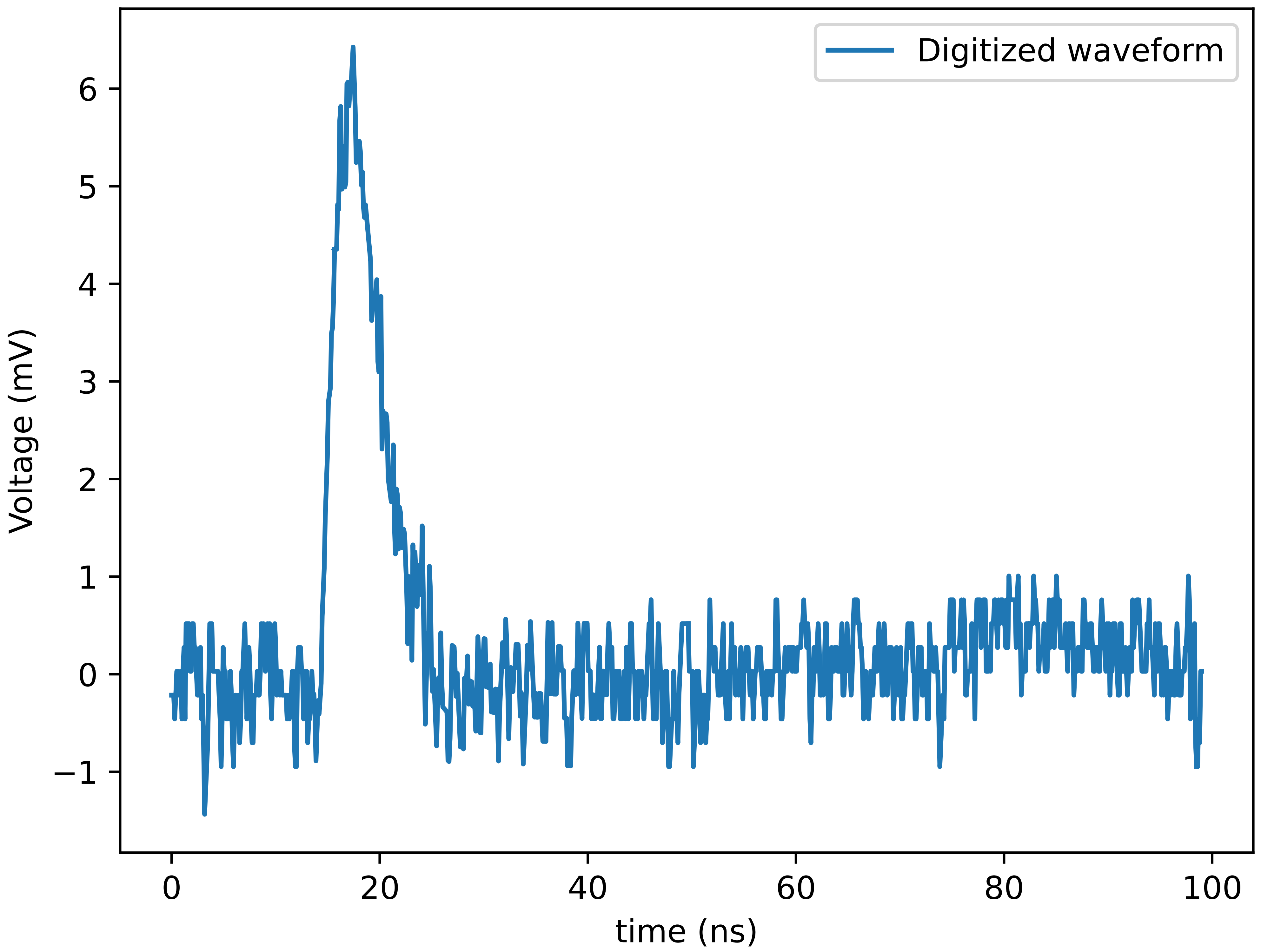
x151 Hamamatsu R13089
- 2” PMTs
- Low time-transit spread (σ = 200ps)

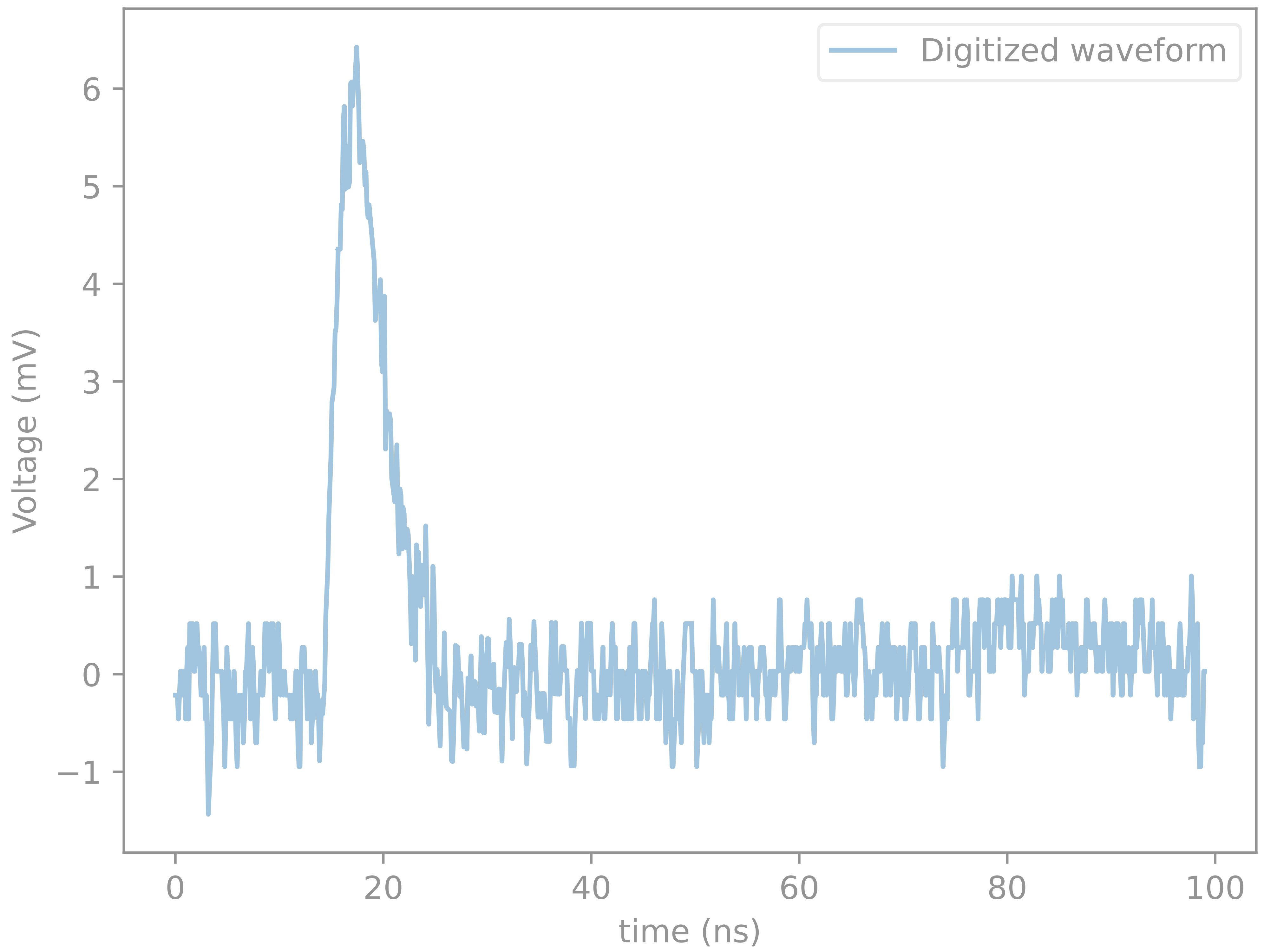
x59 Hamamatsu
- 8” PMTs
- Large light collection area and high quantum efficiency

The acrylic vessel contains liquid scintillator, surrounded by PMTs, submerged in mineral oil buffer to provide structural support, passive shielding and optical coupling.

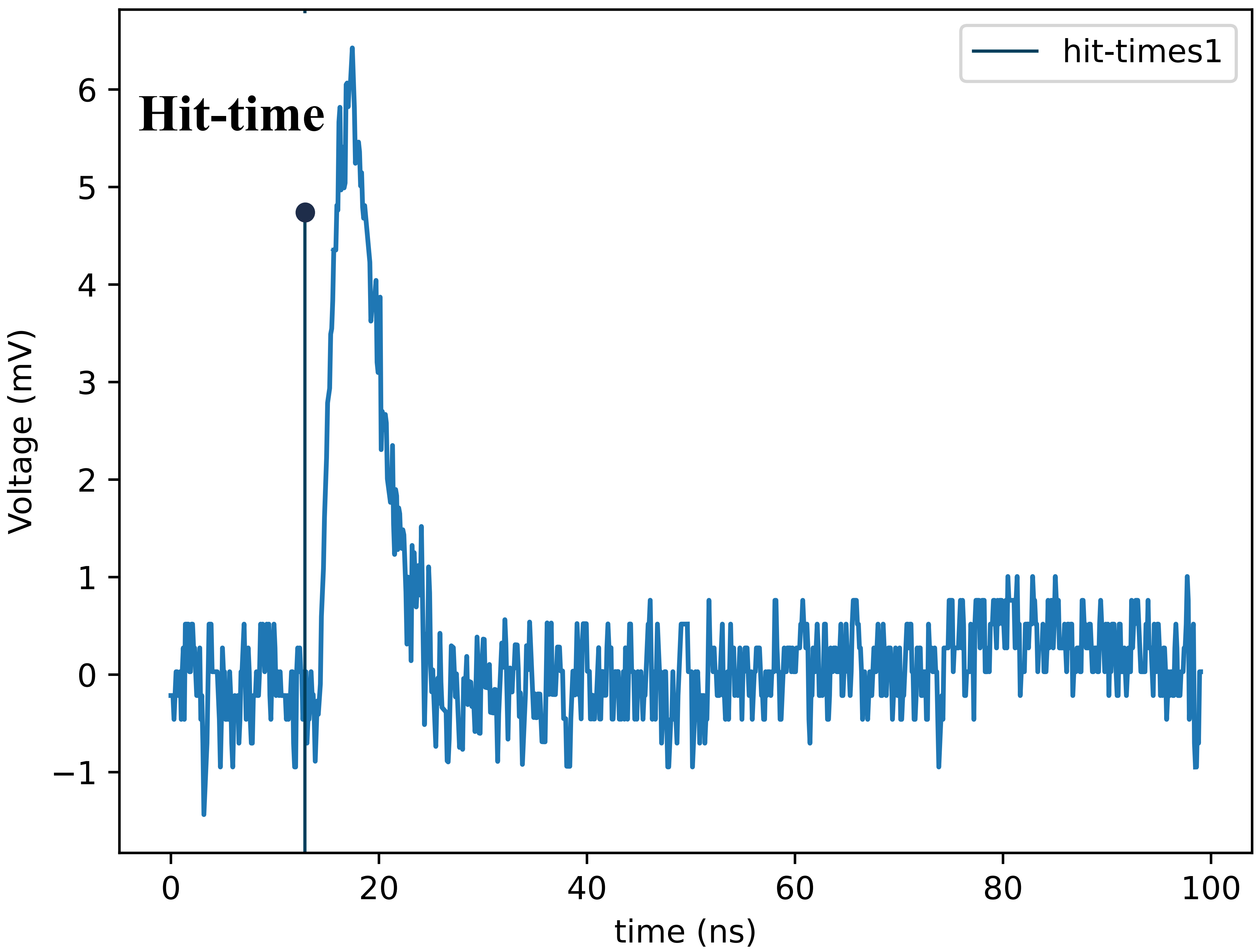
Goals with ML



Goals with ML



Find the rising time of the pulse in digitized waveform.



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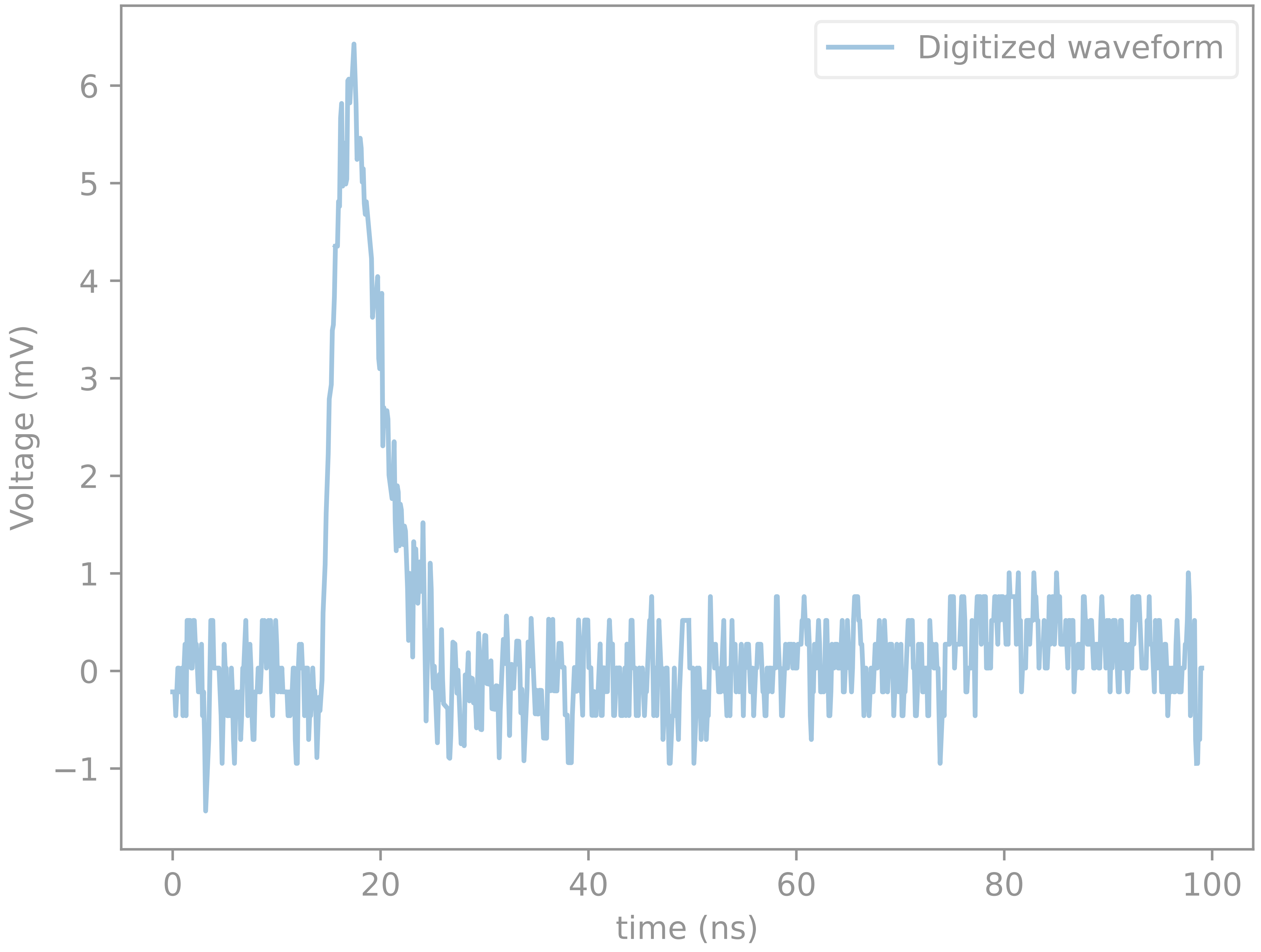

[0,0,0,0,0........1,1,1,1..........0,0,0,0,0]

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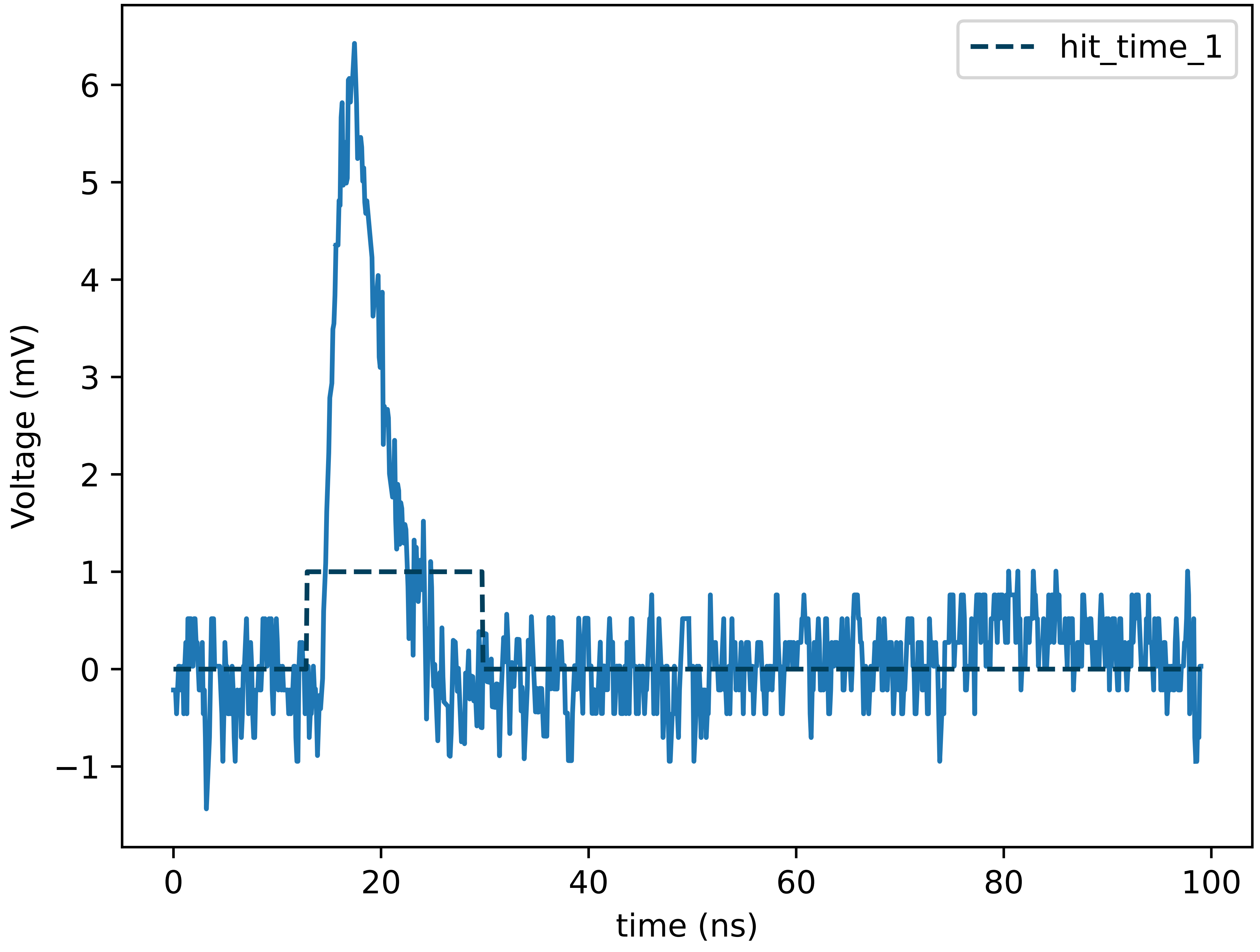

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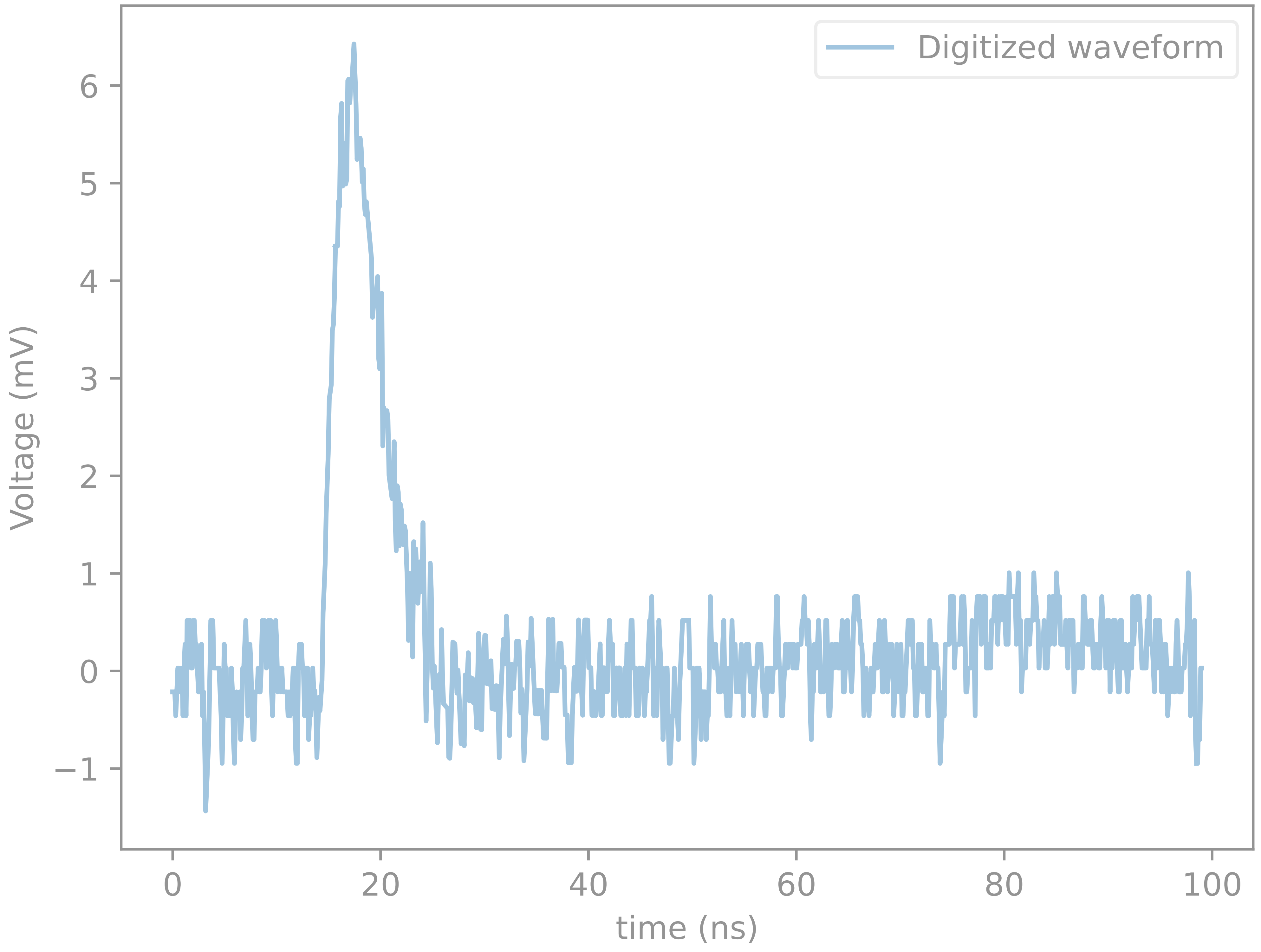
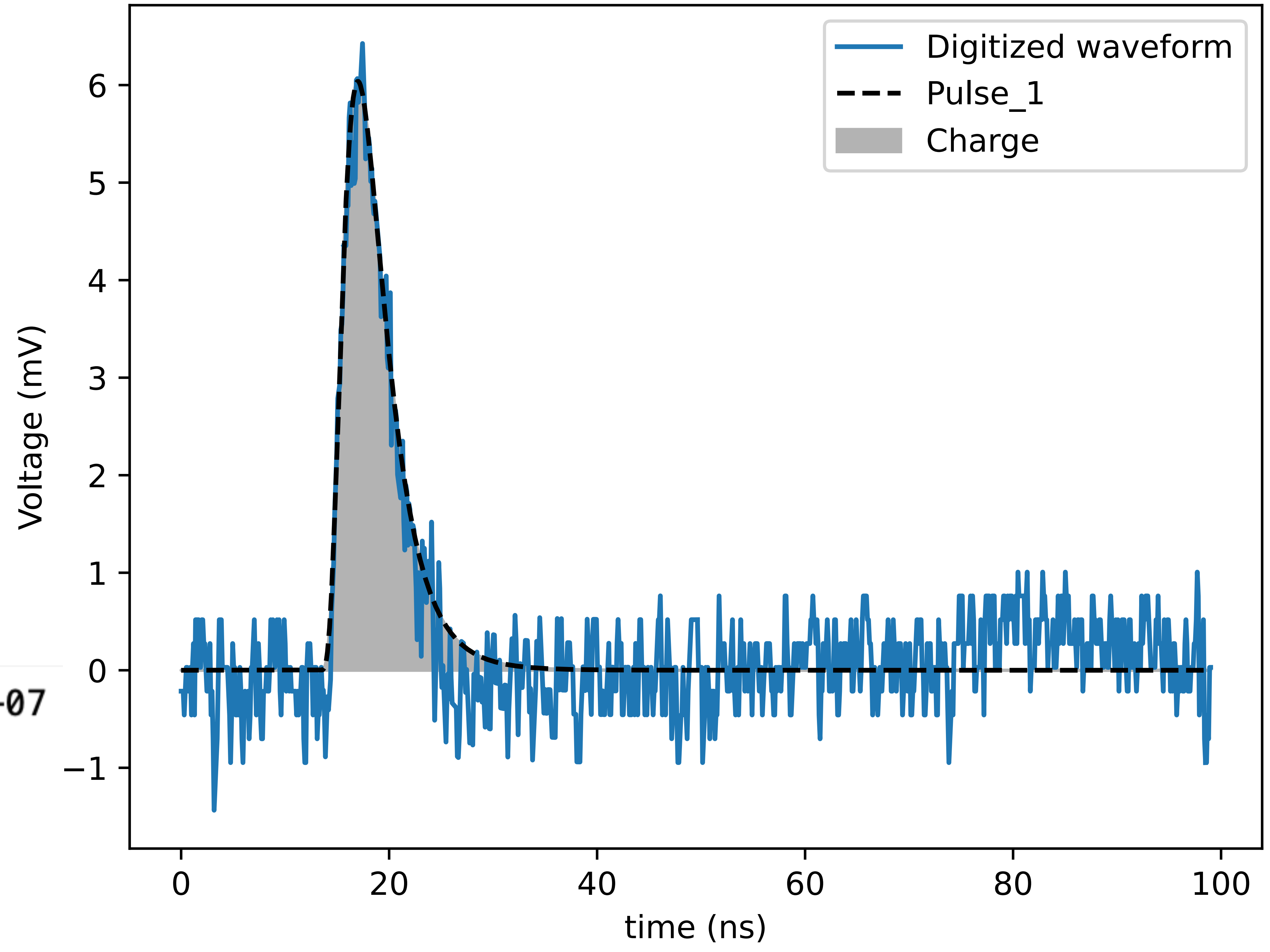
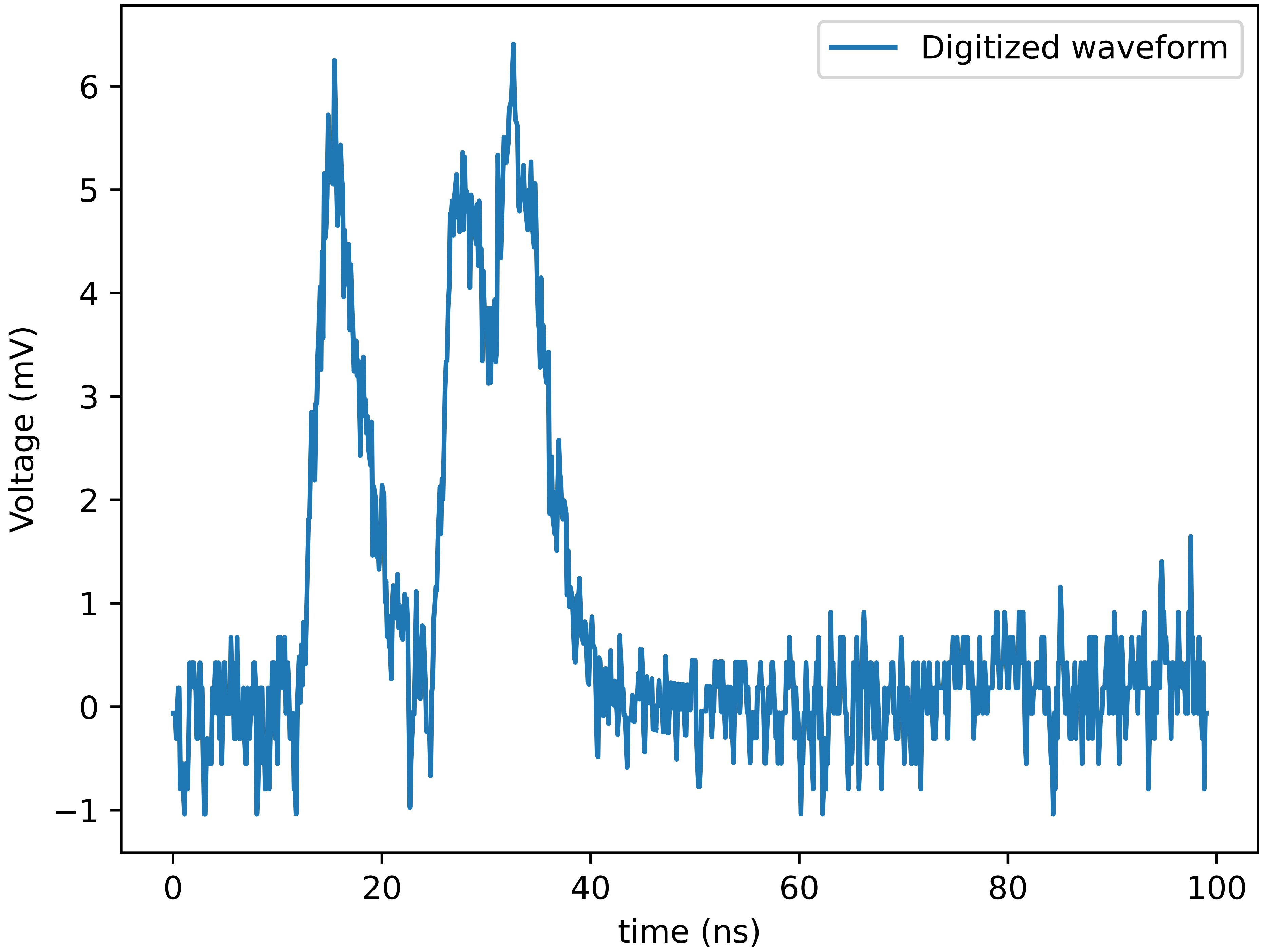



```
[[0.00000000e+00 0.00000000e+00 0.00000000e+00 ... 1.40309027e-07
  1.38124454e-07 1.35975779e-07]]
```

Find the charge of the pulse in the digitized waveform.

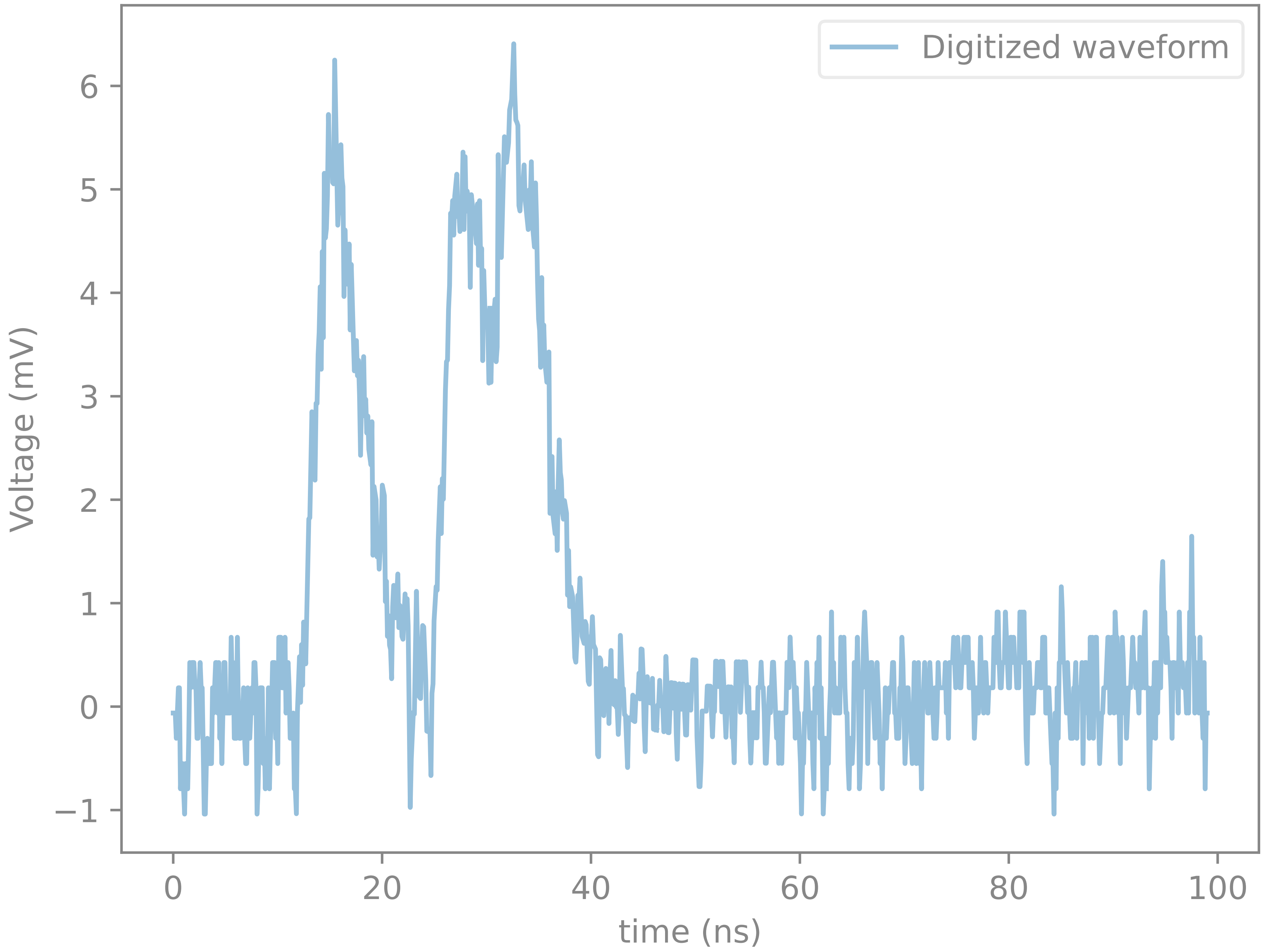


Goals with ML



Can the model do the same for more than a pulse?

Goals with ML



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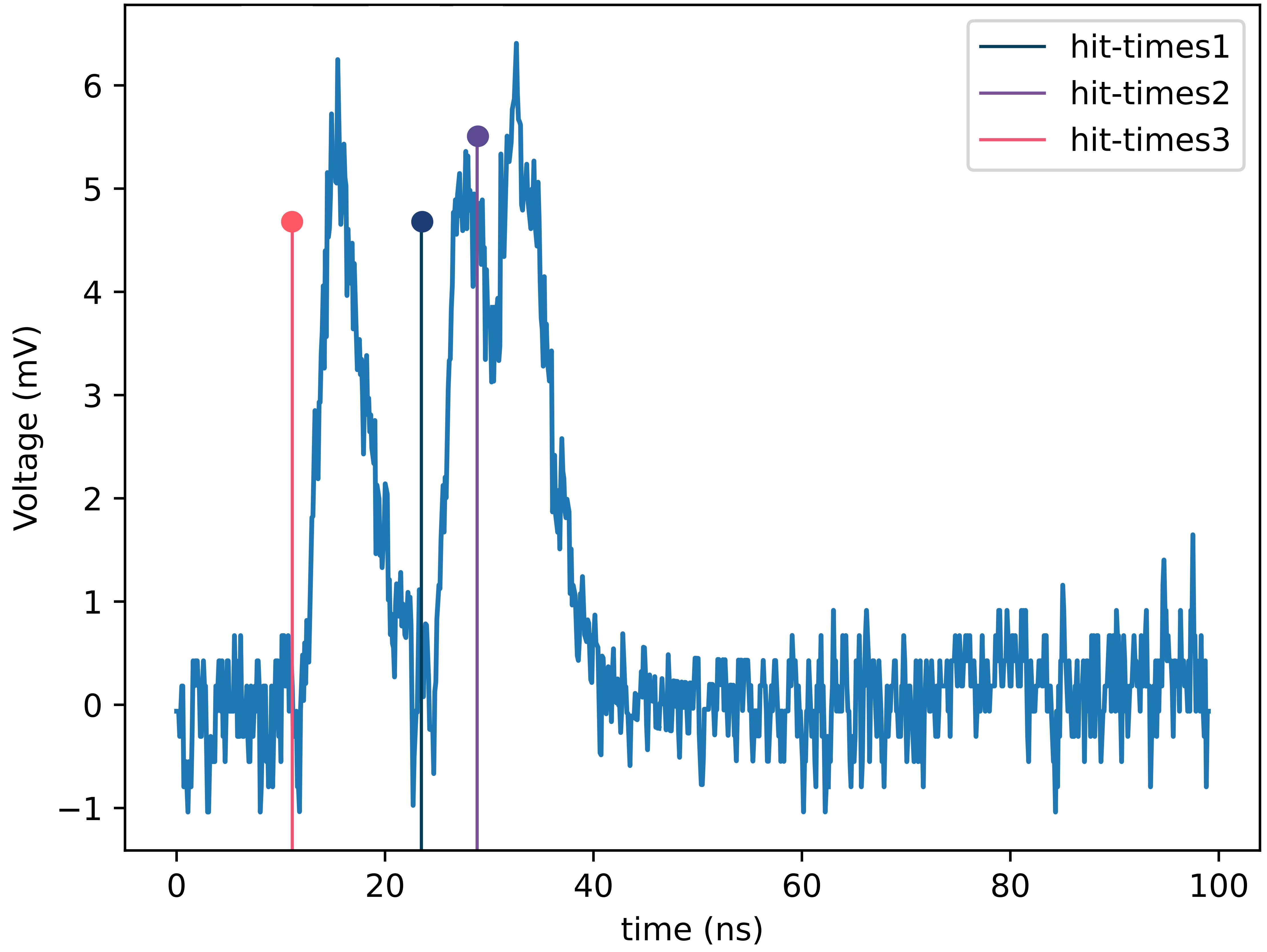
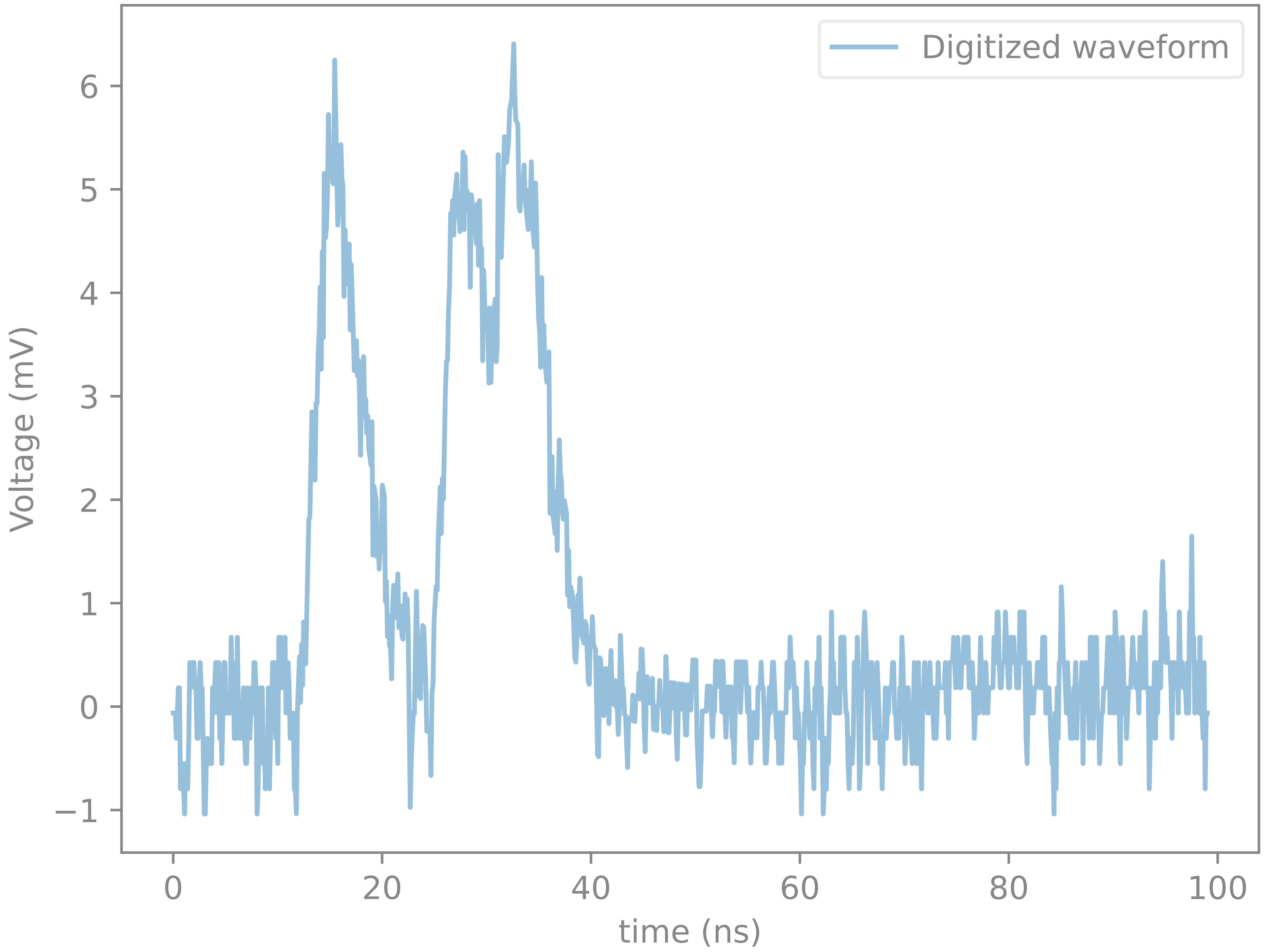


Find the hit times of all the pulses in a waveform.

[0,0..1,1...1,1..1,1.....0,0.......................0,0,0]

Goals with ML



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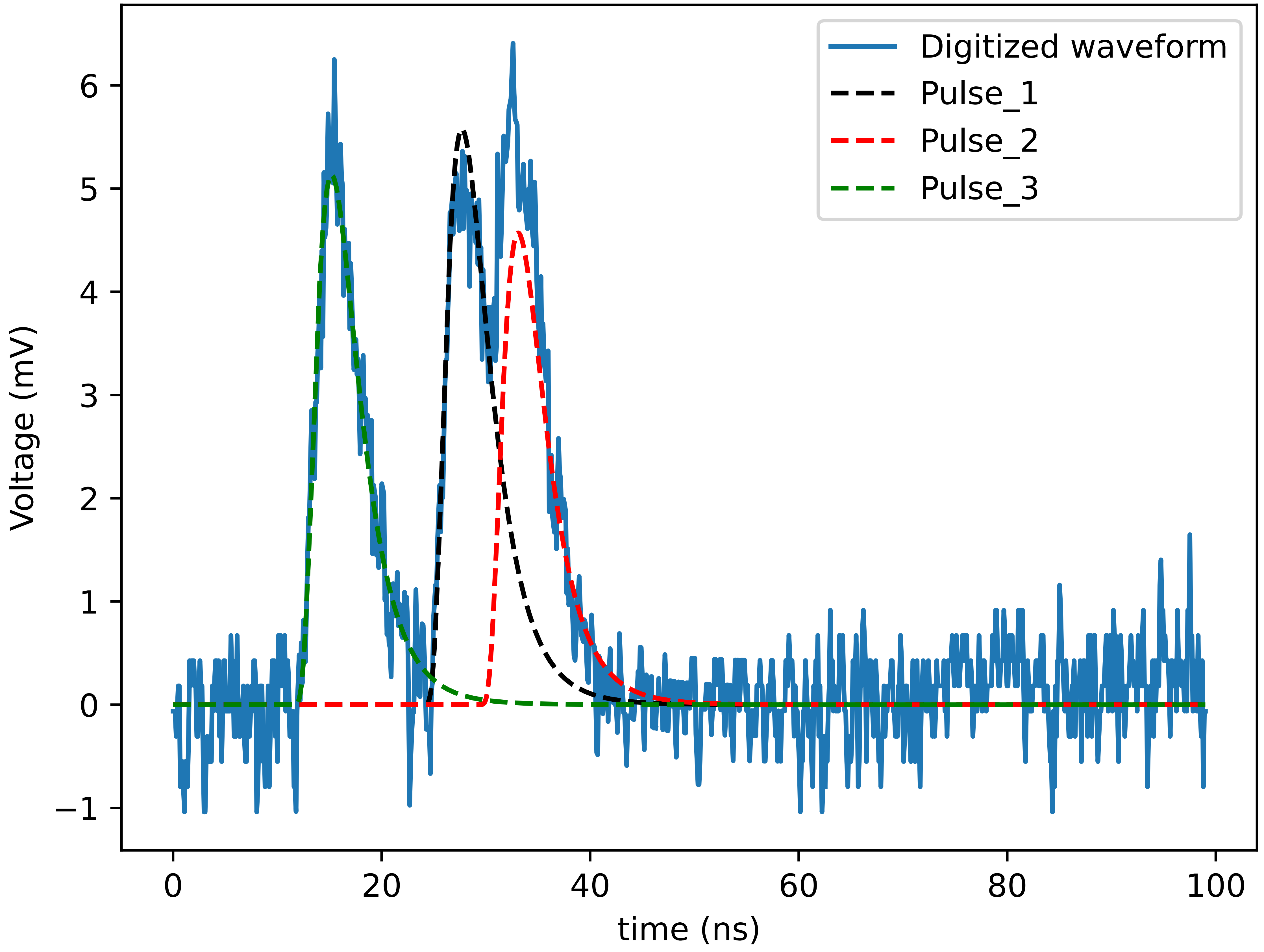


Find the charge of all the pulses in a waveform.

Machine Learning

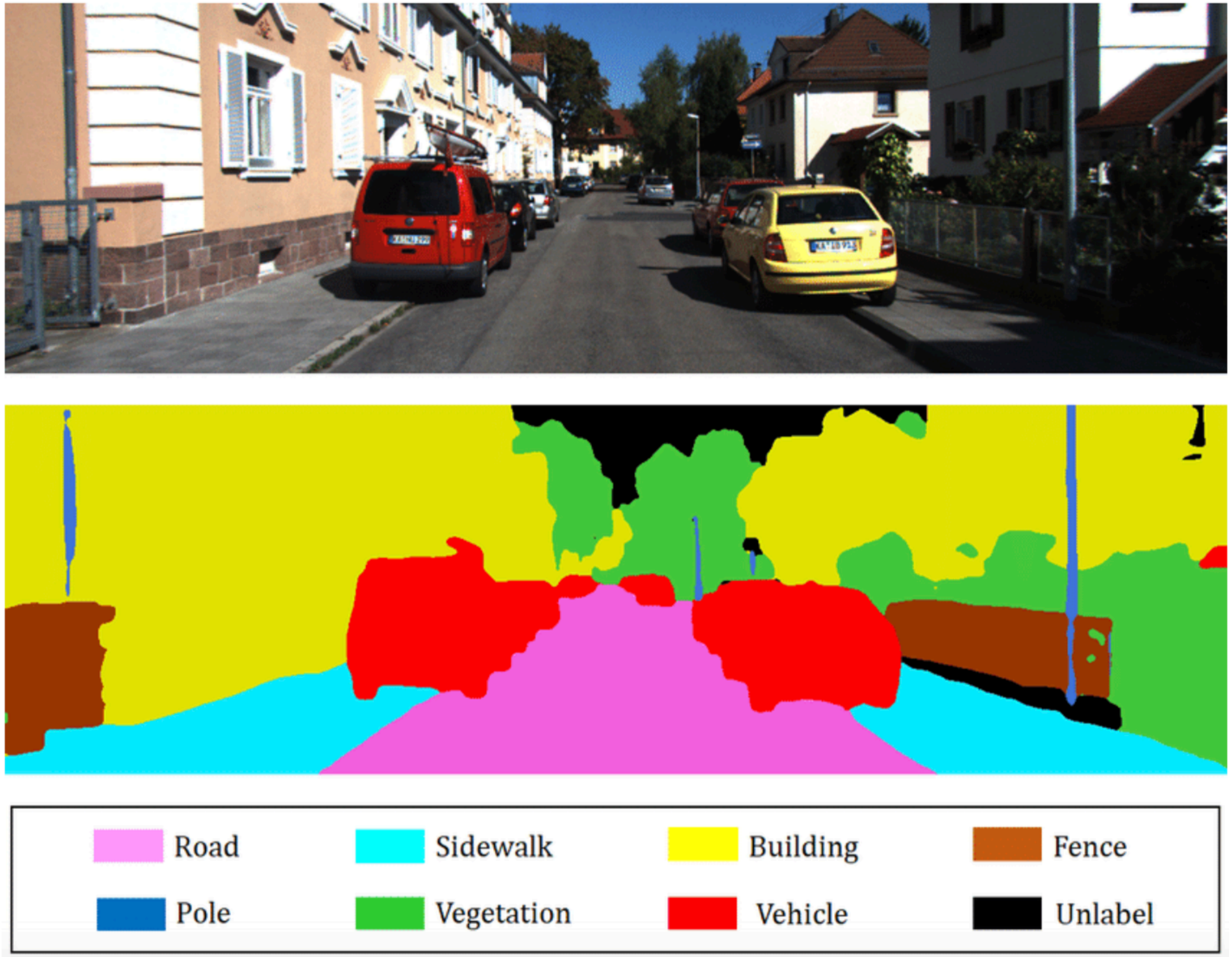
UNet architecture

- U-Net is a deep learning model designed for **semantic segmentation.**
- It is commonly used in **medical imaging** (e.g., tumor detection) and **satellite image analysis**.

UNet architecture

Semantic Segmentation

- **Semantic segmentation** involves pixel by pixel categorization in a meaningful way.

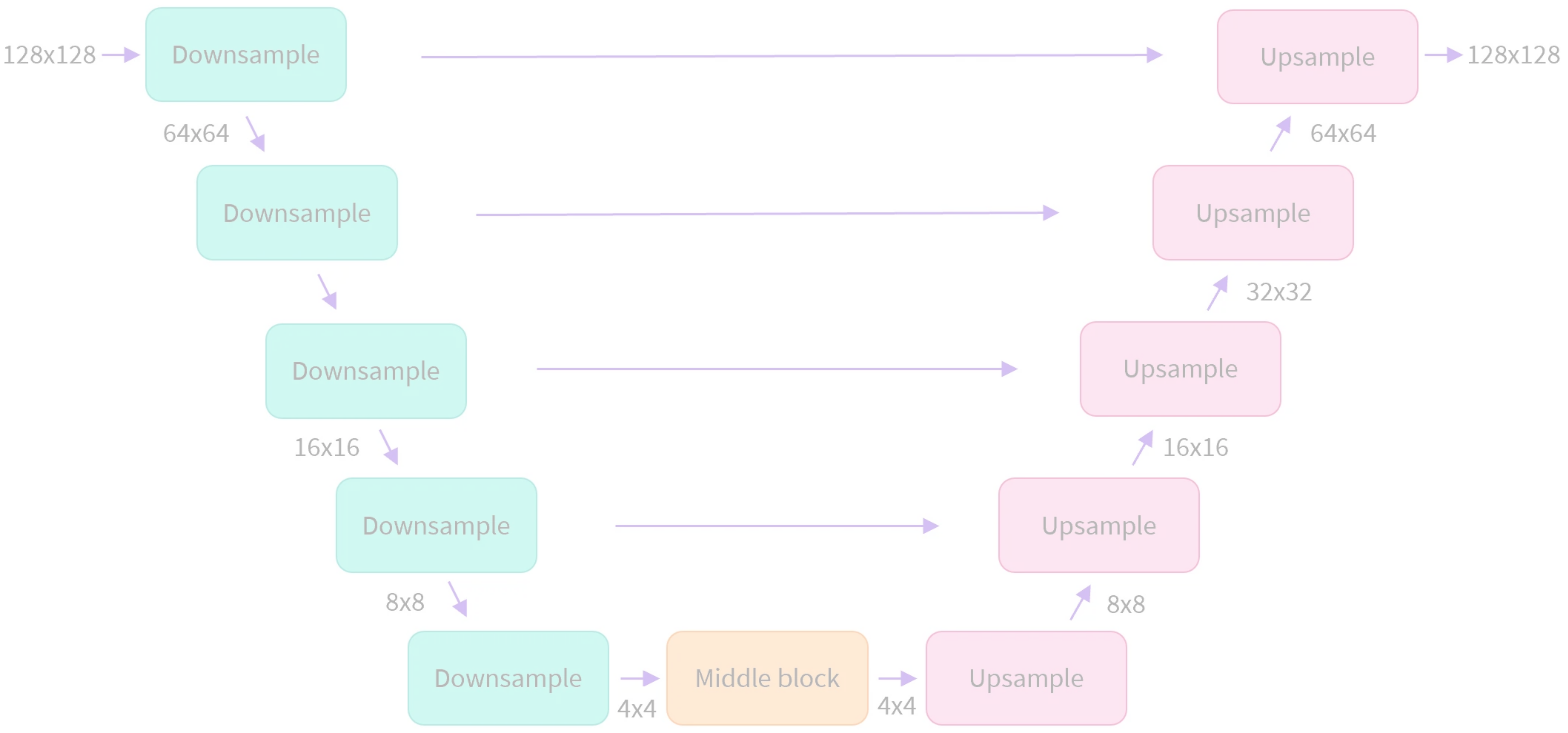


Machine Learning

U-Shape Design:

The architecture has two parts: an **encoder** (left side) and a **decoder** (right side).

UNet architecture



Machine Learning

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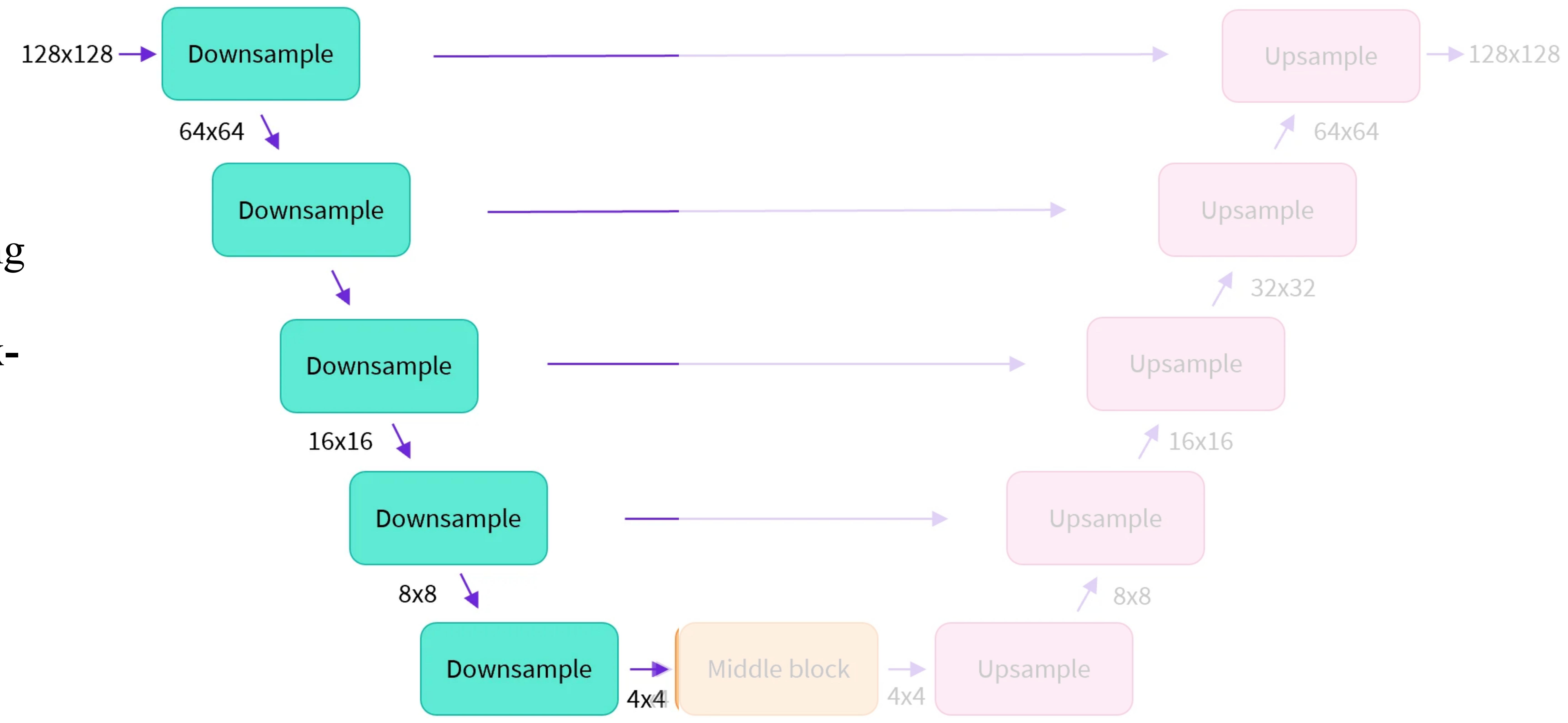
The architecture has two parts: an **encoder** (left side) and a **decoder** (right side).

Encoder (Downsampling):

Extracts important features by reducing the image size step by step.
Uses layers like **convolution** and **max-pooling** to focus on the "what" of the image.

UNet architecture



Machine Learning

U-Shape Design:

The architecture has two parts: an **encoder** (left side) and a **decoder** (right side).

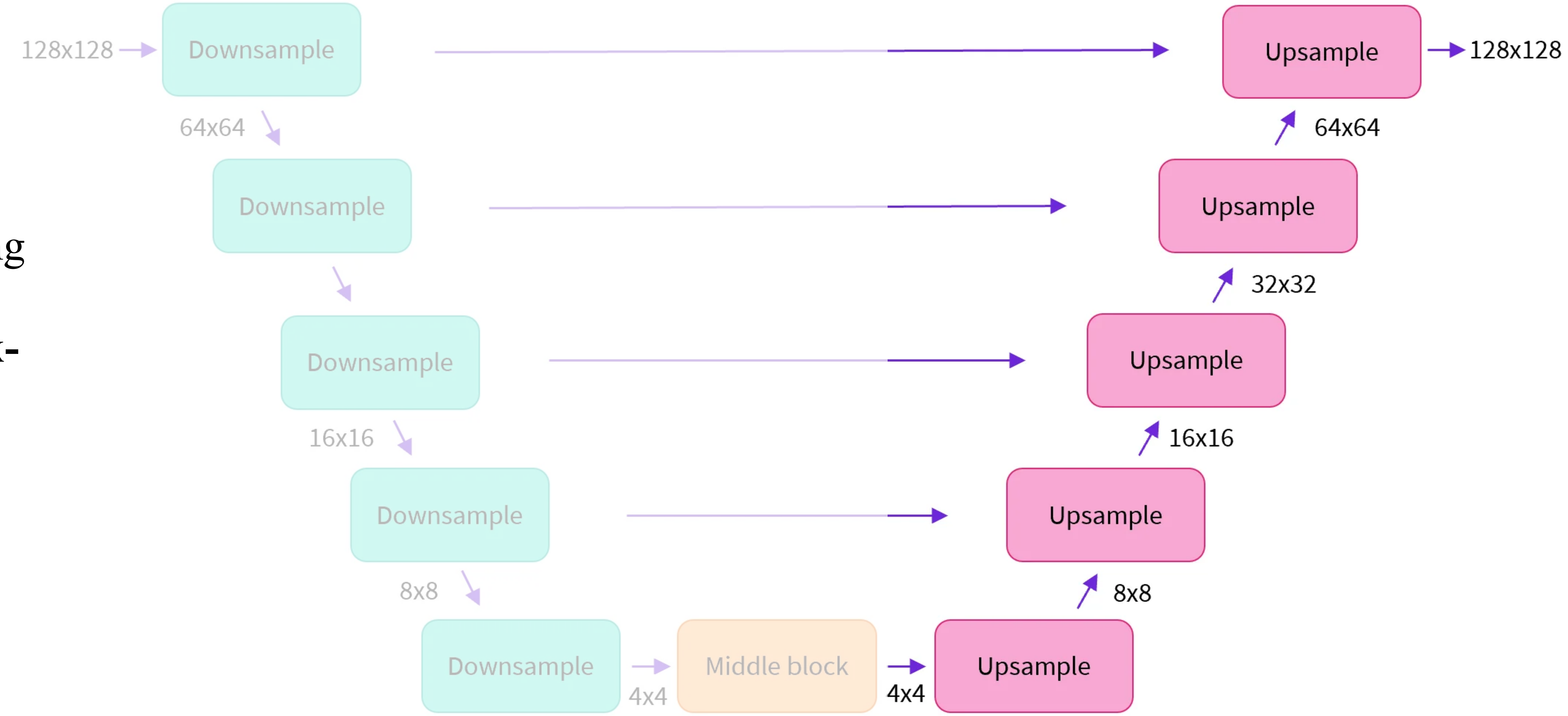
Encoder (Downsampling):

Extracts important features by reducing the image size step by step.
Uses layers like **convolution** and **max-pooling** to focus on the "what" of the image.

Decoder (Upsampling):

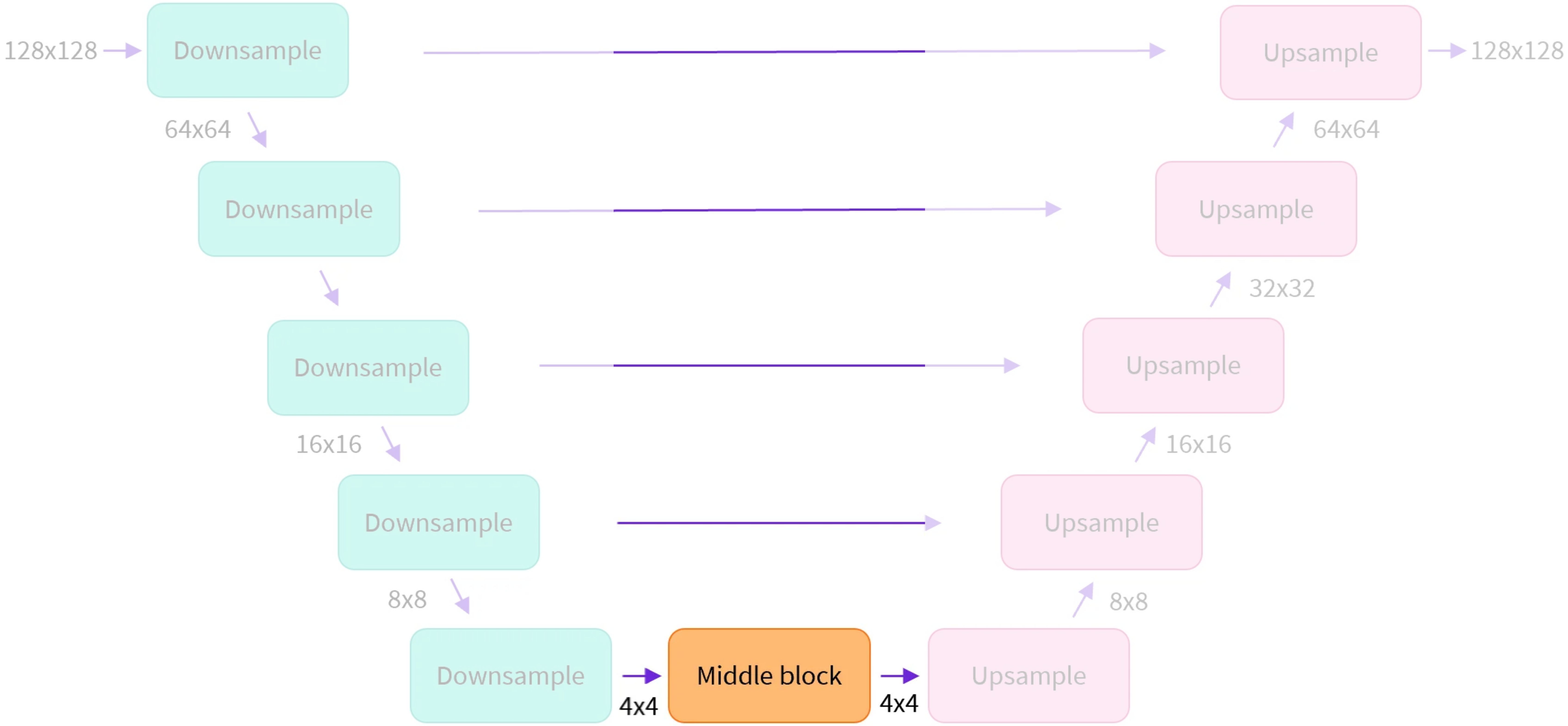
Reconstructs the image size while assigning each pixel a category.
Combines **features from the encoder** with upsampled data to retain details.

UNet architecture



Machine Learning

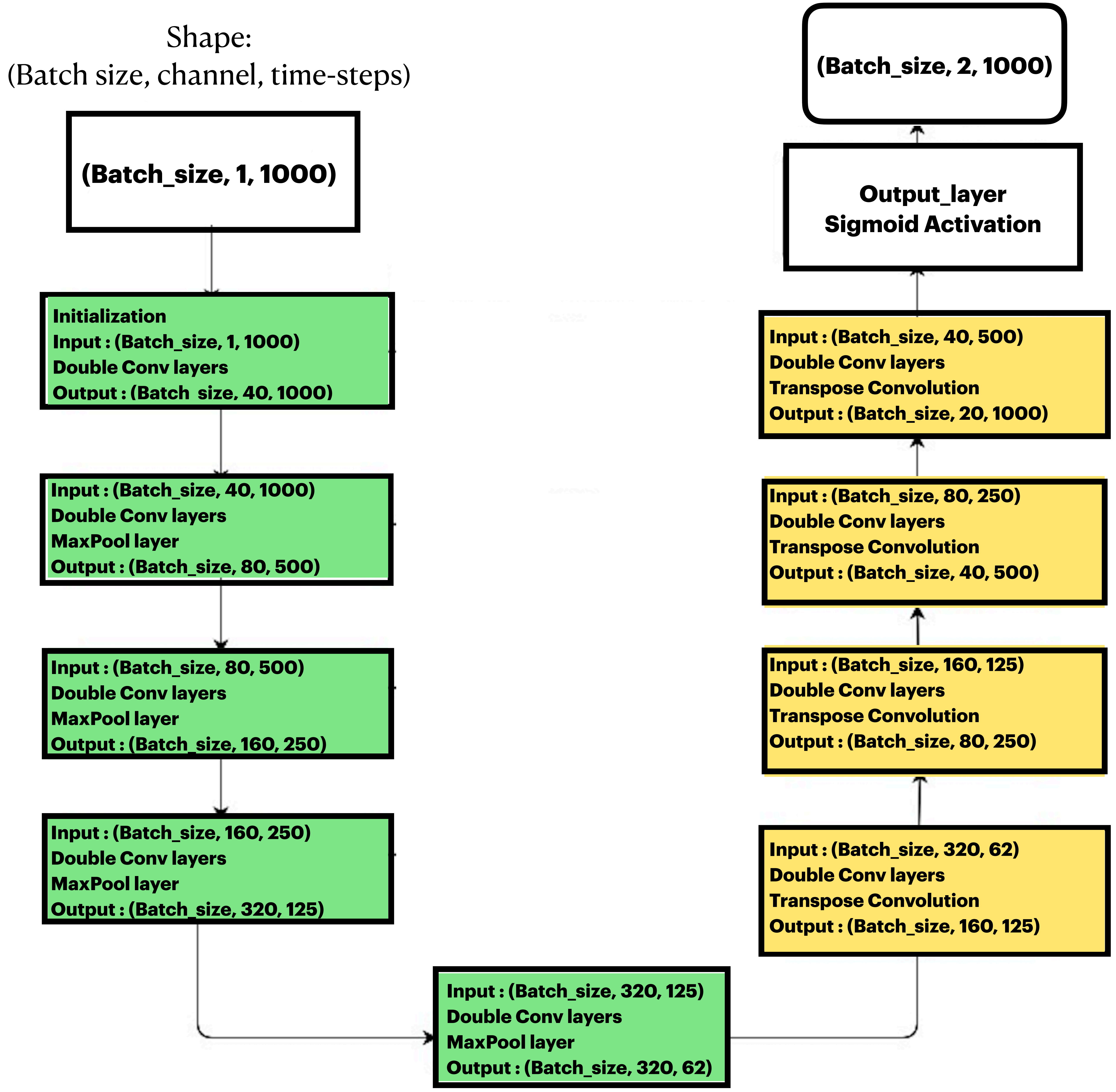
UNet architecture



Skip Connections:

Links encoder and decoder layers to preserve fine details during reconstruction.

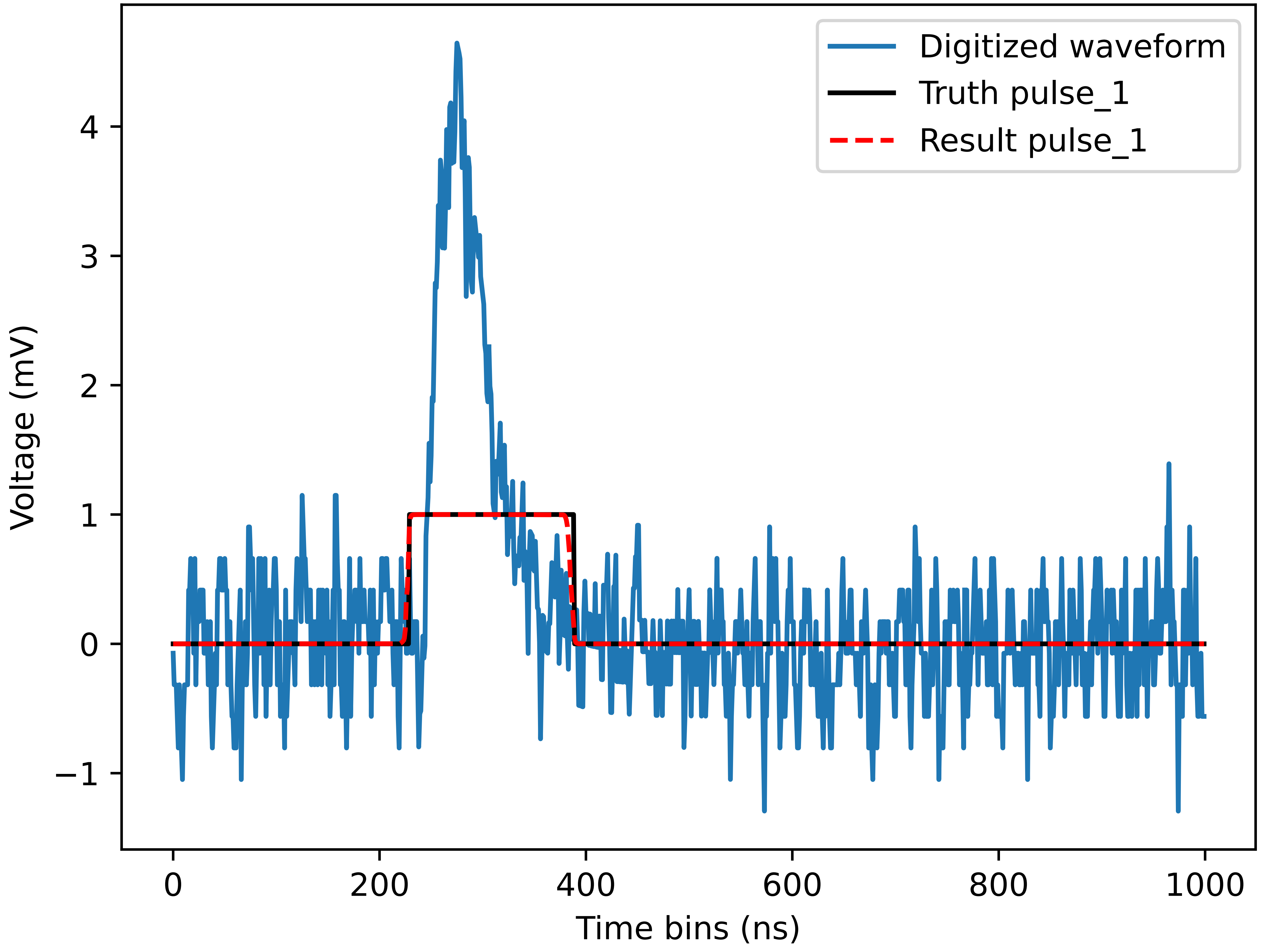
Classification UNet architecture



Pulse analysis using machine learning

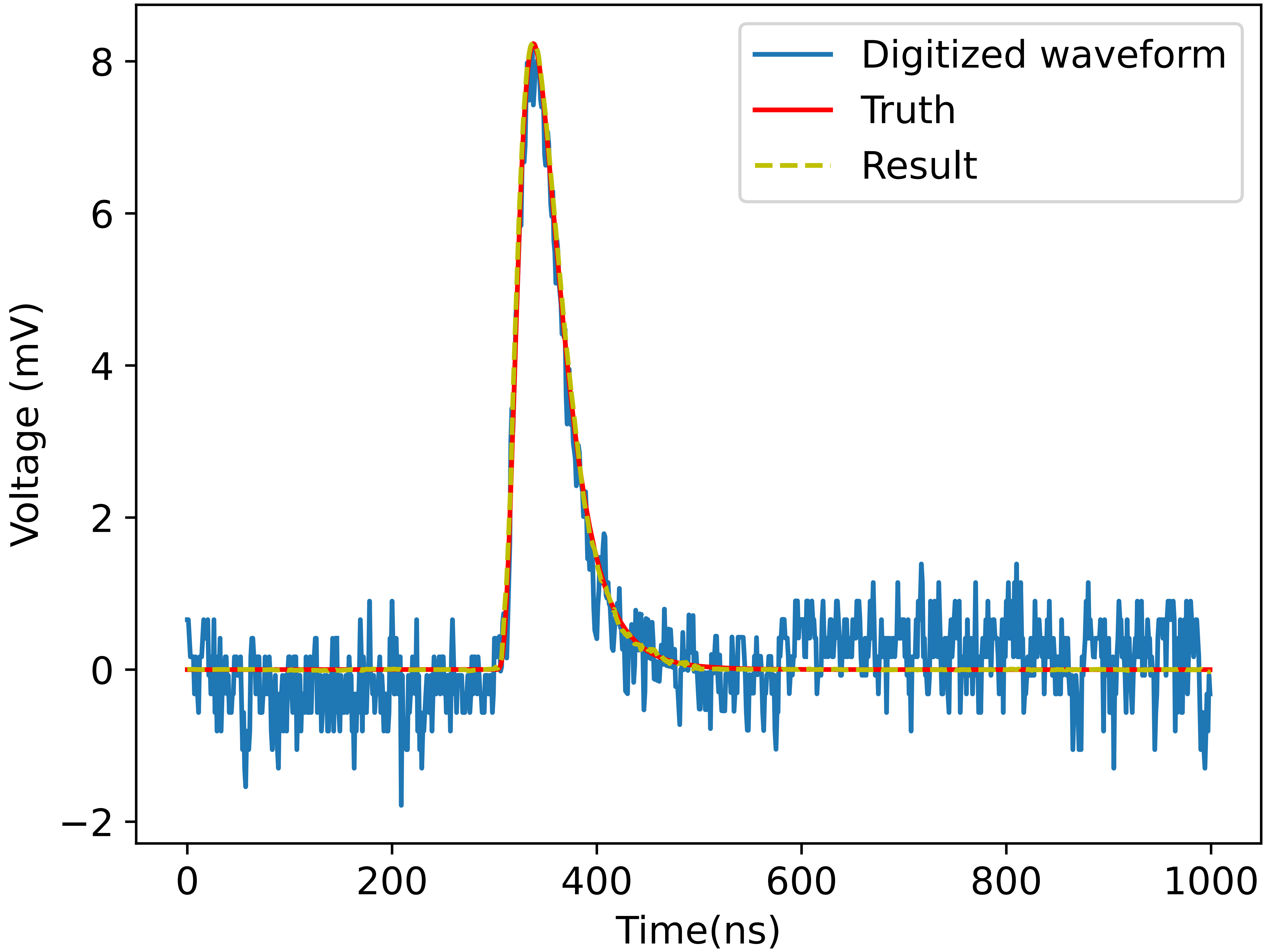
Classification:

Hit time:



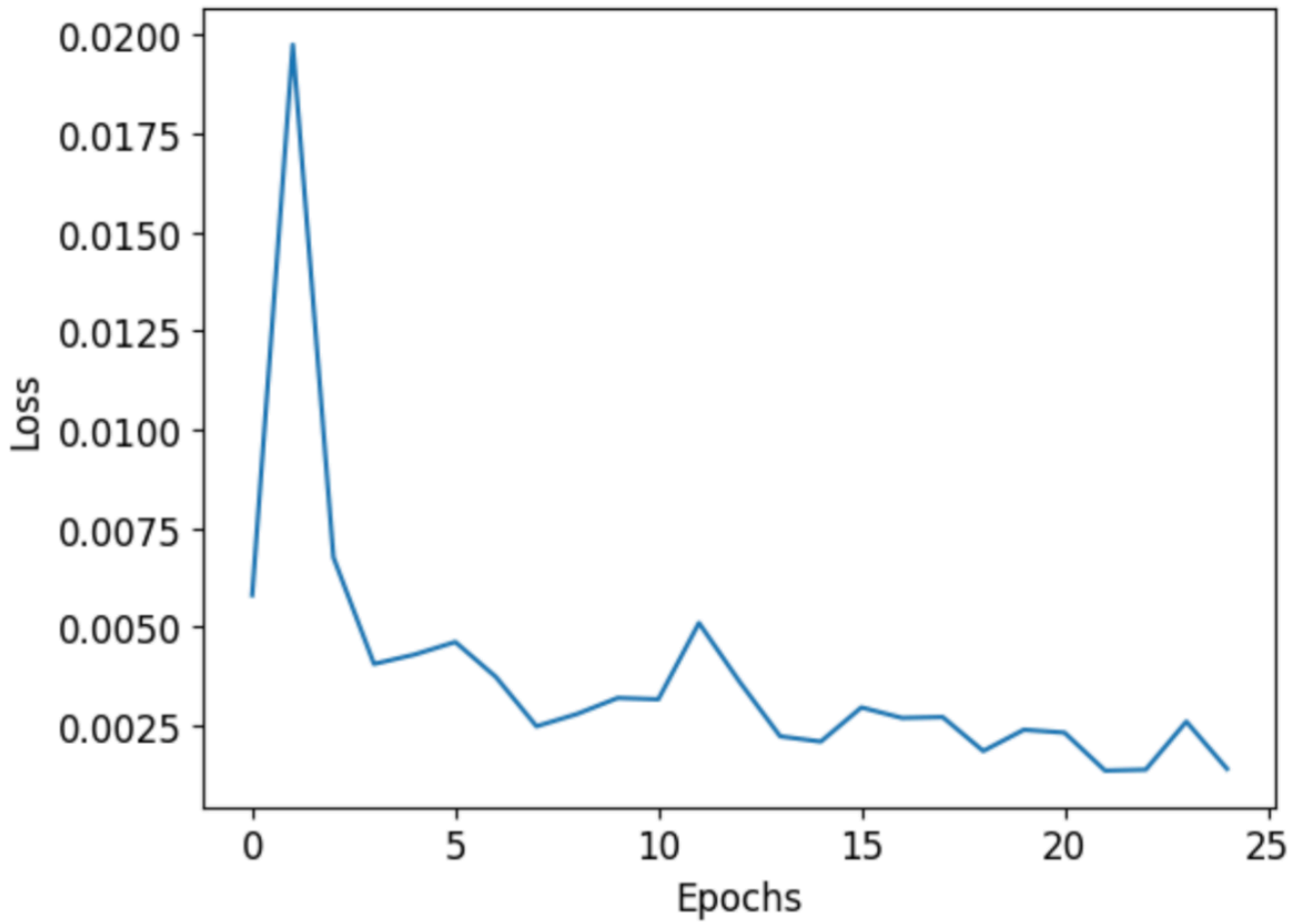
Regression:

Charge:

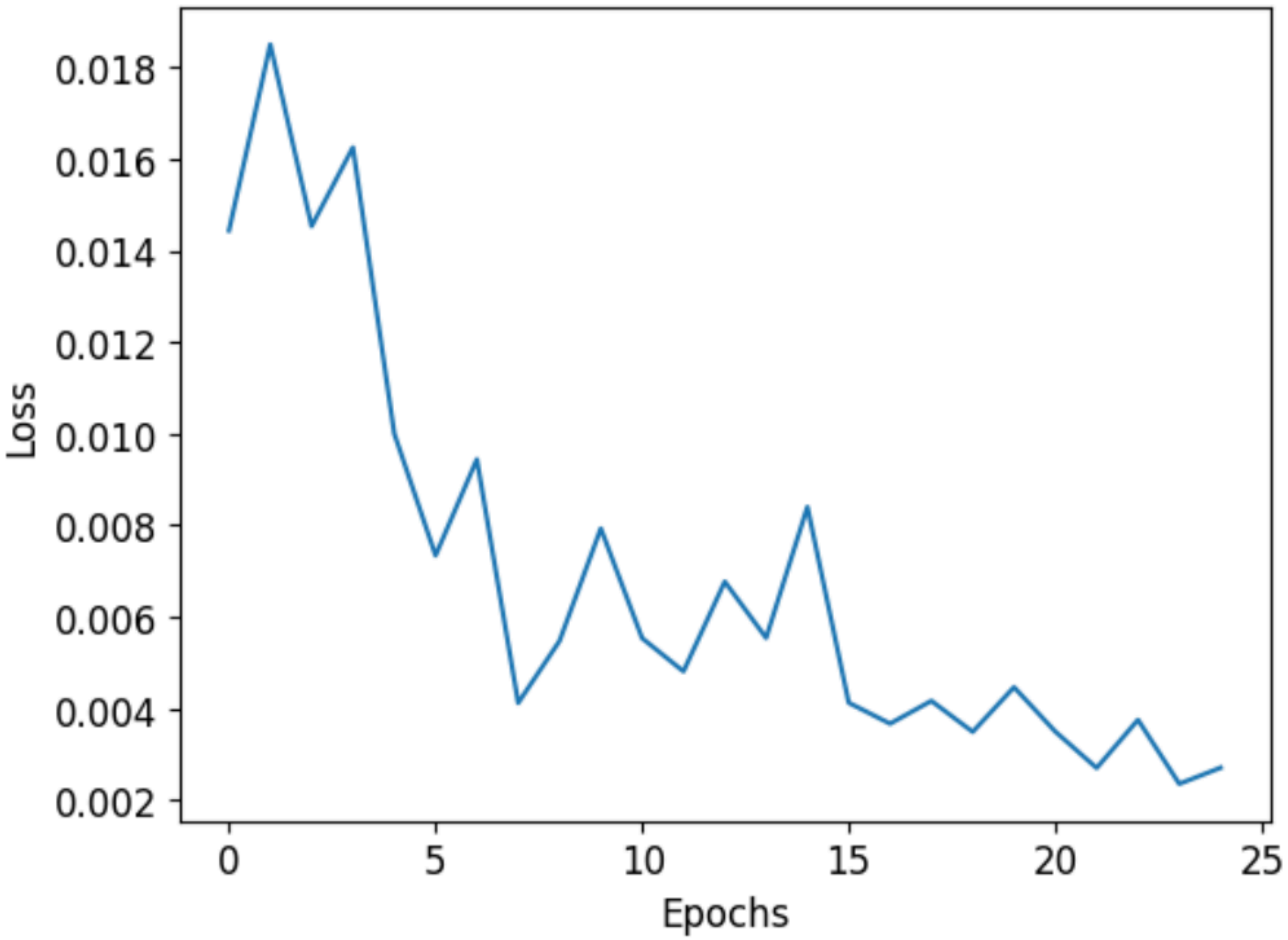


Loss curves

Regression

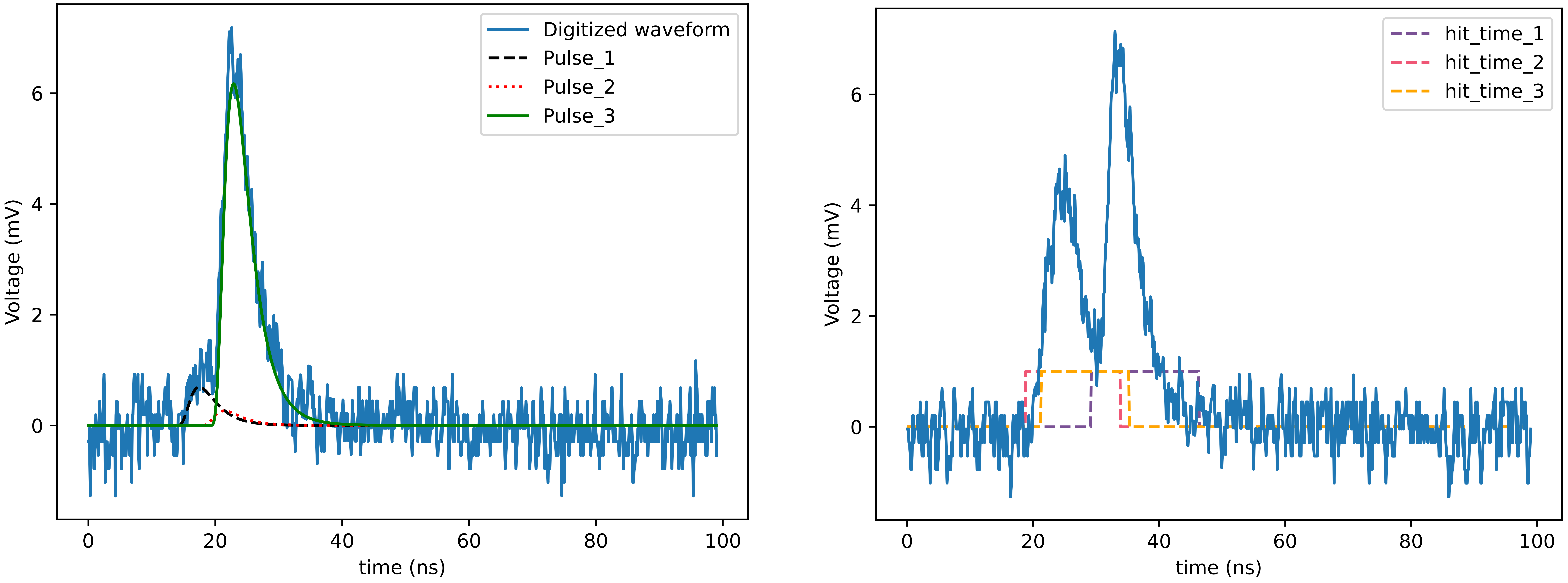


Classification



Future work

✴Working on multi-pulse analysis



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Future work

- Developing new DAQ state-of-the-art hardware -> RFSoC technology
  - Generic technology for pulse extraction

Summary

- We are trying to explain matter anti-matter asymmetry using liquid scintillator technology by looking for rare $0\nu\beta\beta$ events.
- Building up NuDot as a R&D testbed for reducing backgrounds in these detectors.
- The particular solar neutrino background requires precise timing resolution, so the ML algorithm aims to extract the time.
- We can extract a single photoelectron's time and charge. However, there is still room for improvement.

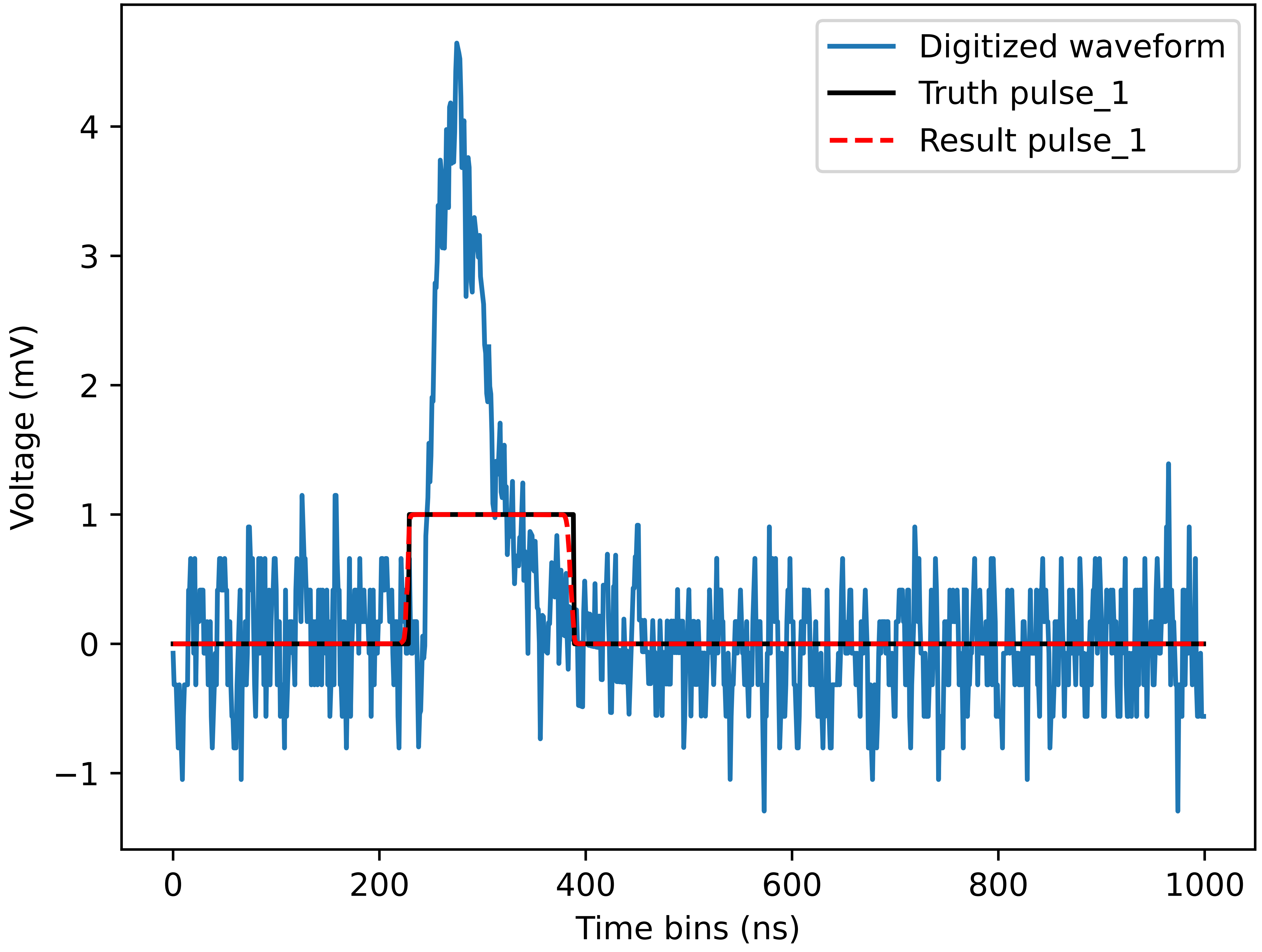
Input from the ML experts, ideas on scaling, multi-pulses, and architecture.

Suggestions for ML on chip.

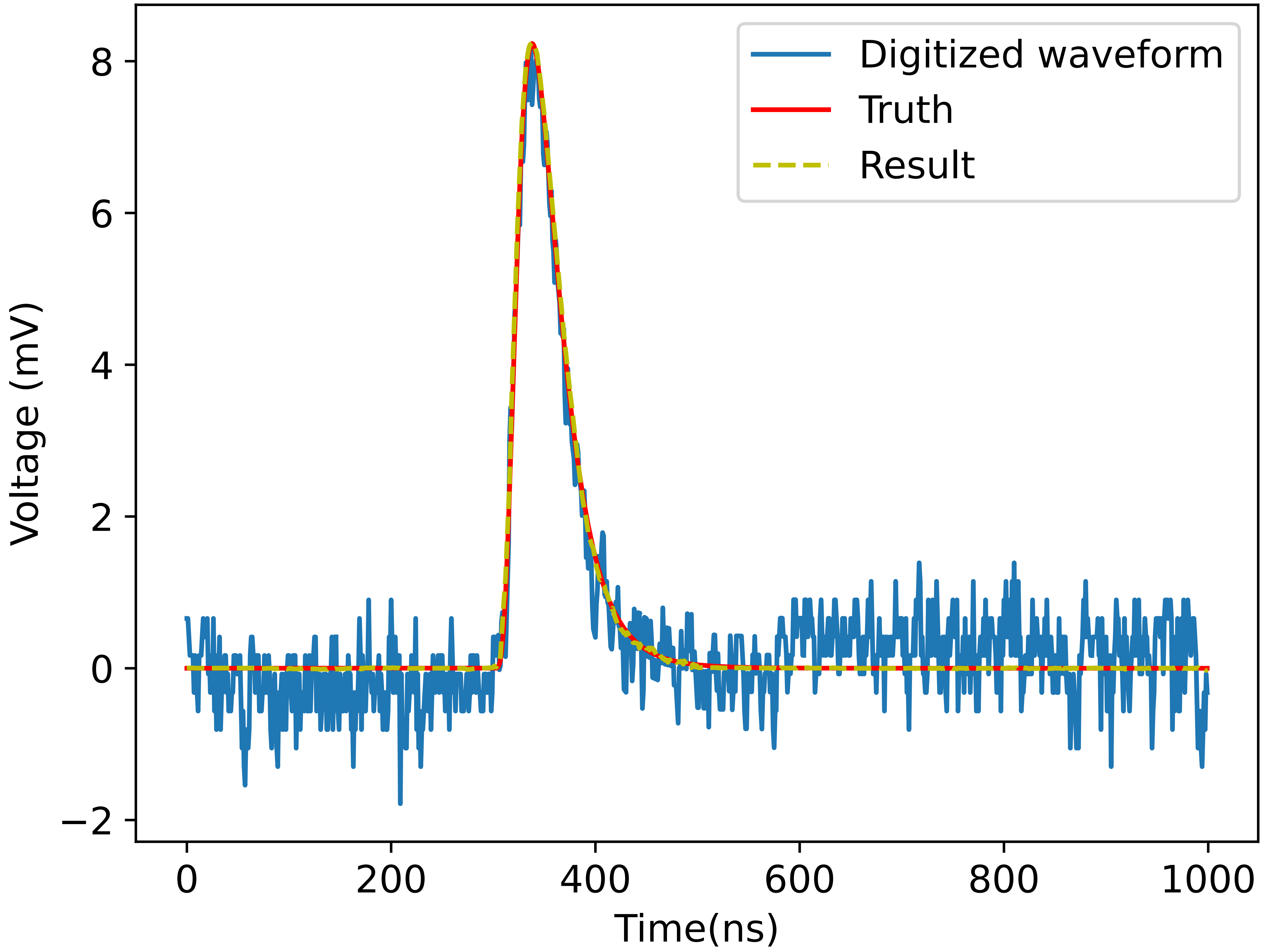
Backup slides

Pulse analysis using machine learning

Loss function : BCELoss
Activation function: LeakyReLU
Optimizer: Adam
Output layer activation : Sigmoid

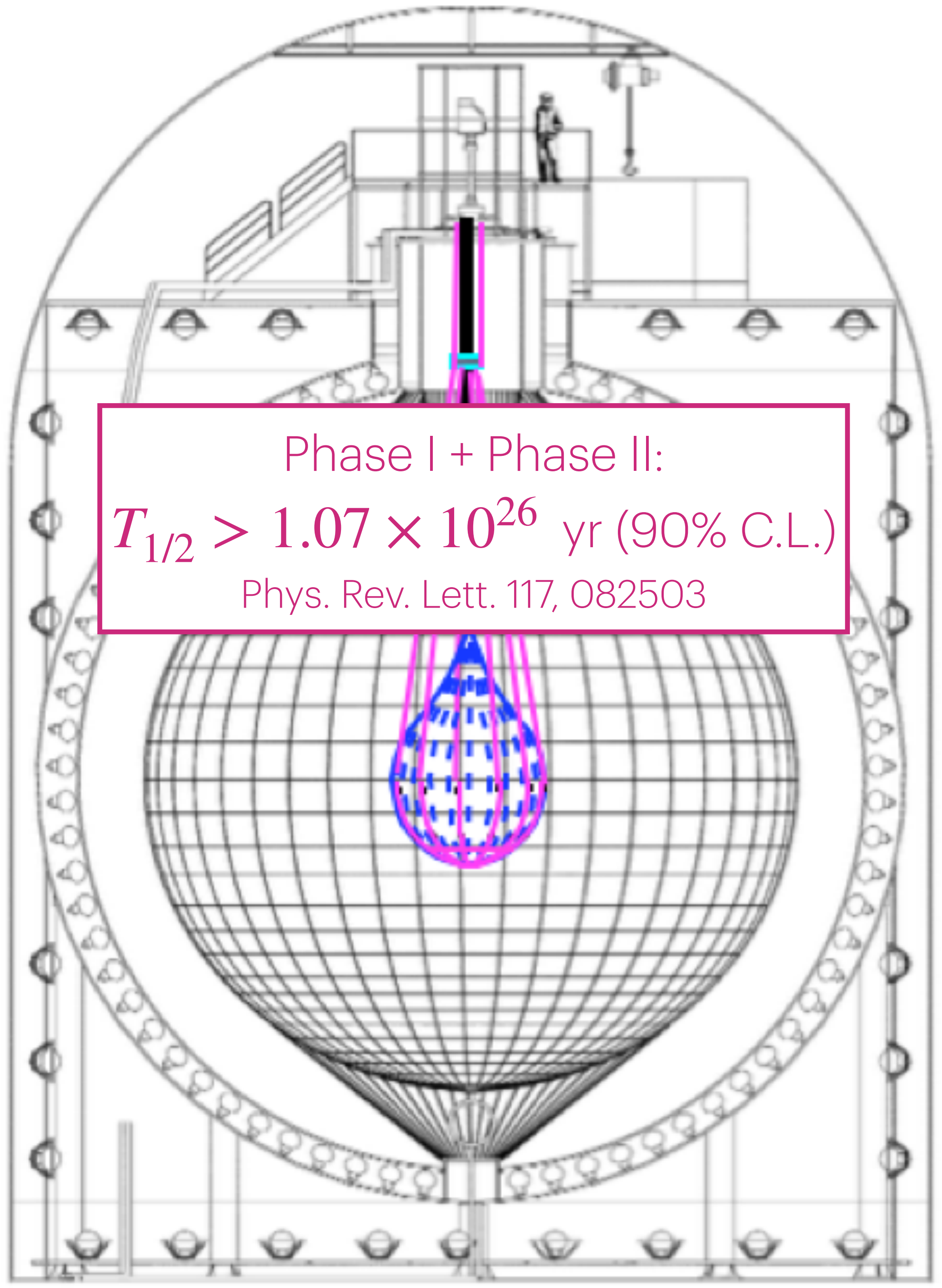


Loss function : MSELoss
Activation function: LeakyReLU
Optimizer: SGD



The evolution of KamLAND-Zen

Past

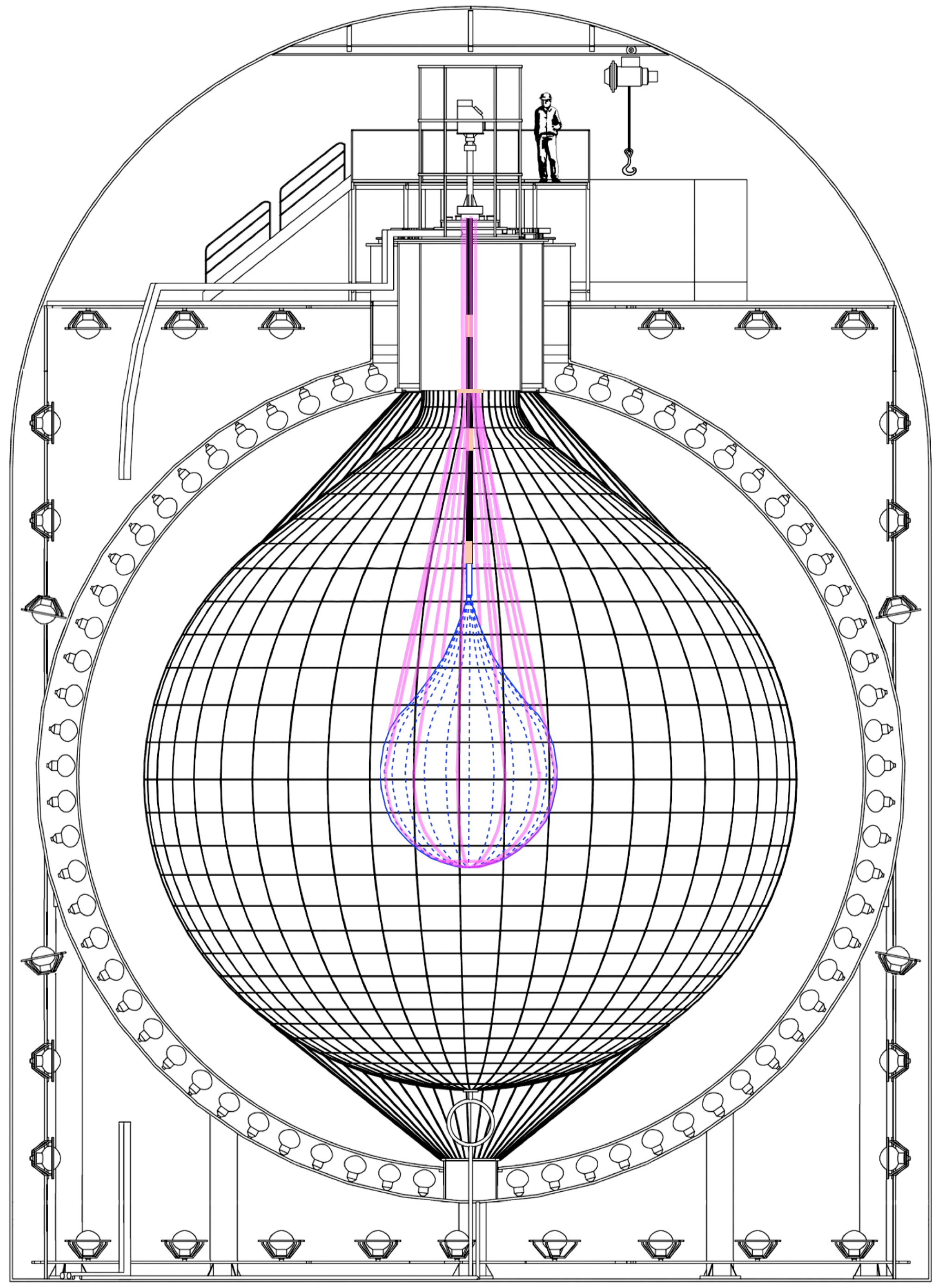


KamLAND-Zen 400:

- Inner-balloon Radius = 1.54 m
- Xenon mass = 320 ~ 381 kg
- Duration: 2011 ~ 2015

Excited states: Nuclear Physics A 946 (2016): 171-181.

Present

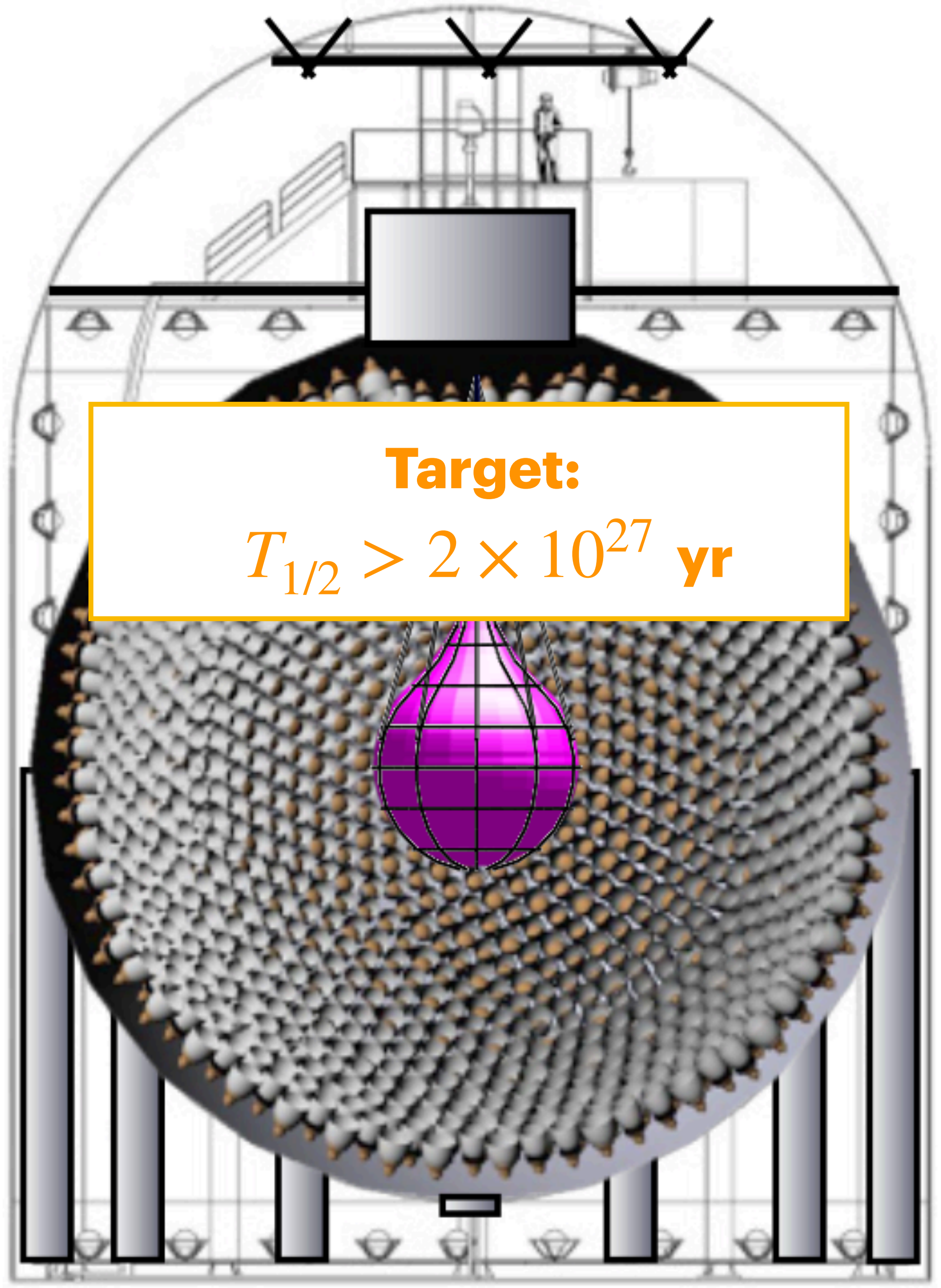


KamLAND-Zen 800:

- Inner-balloon Radius = 1.90 m
- Xenon mass = 745±3 kg
- Data taking starts Jan. 2019

Physical Review Letters 130.5 (2023): 051801.
PRL preprint: arXiv:2406.11438 (2024).

Future

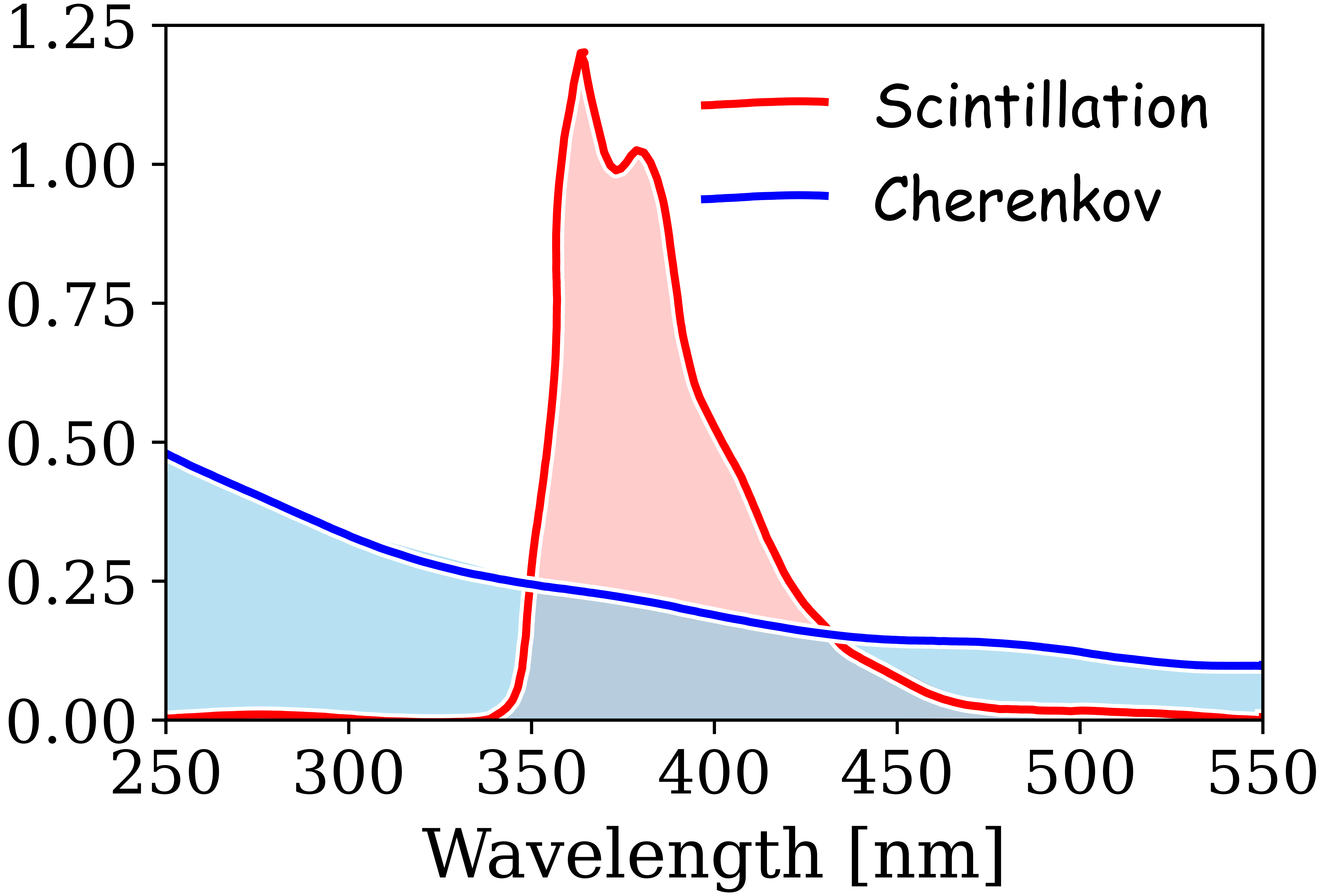


KamLAND2-Zen:

- Xenon mass ~ 1ton
- Aiming at 100% Photocoverage
- PEN scintillation balloon film
- Updated readout electronics

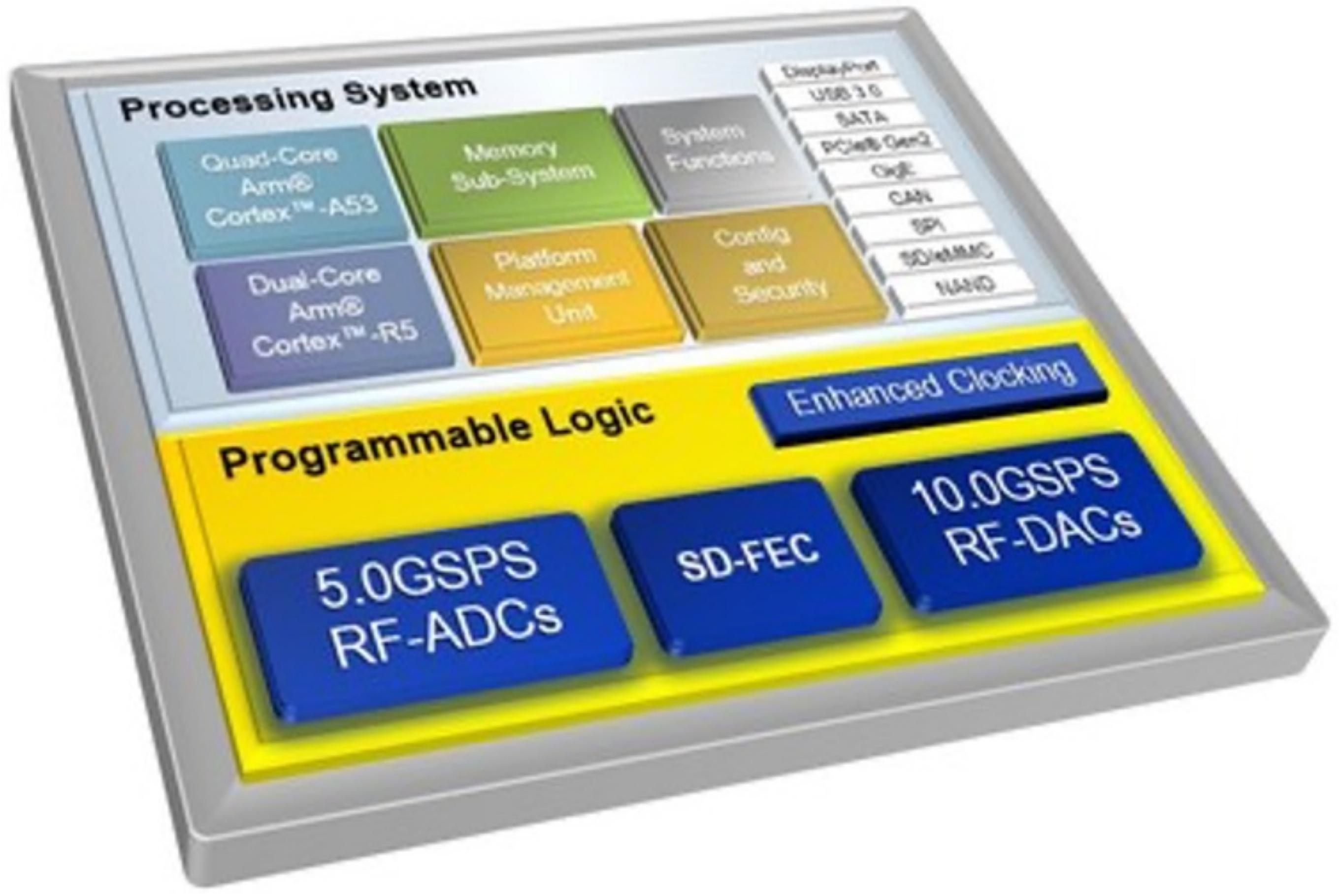
Ways to reduce background

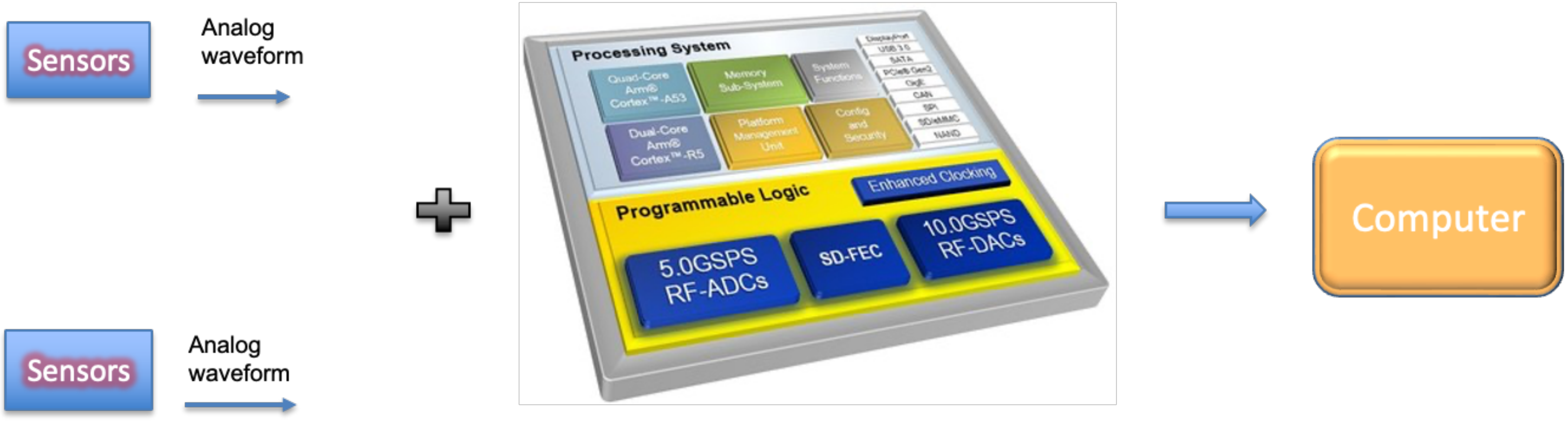
1. Using wavelength-shifting materials



Radio-Frequency System on a Chip

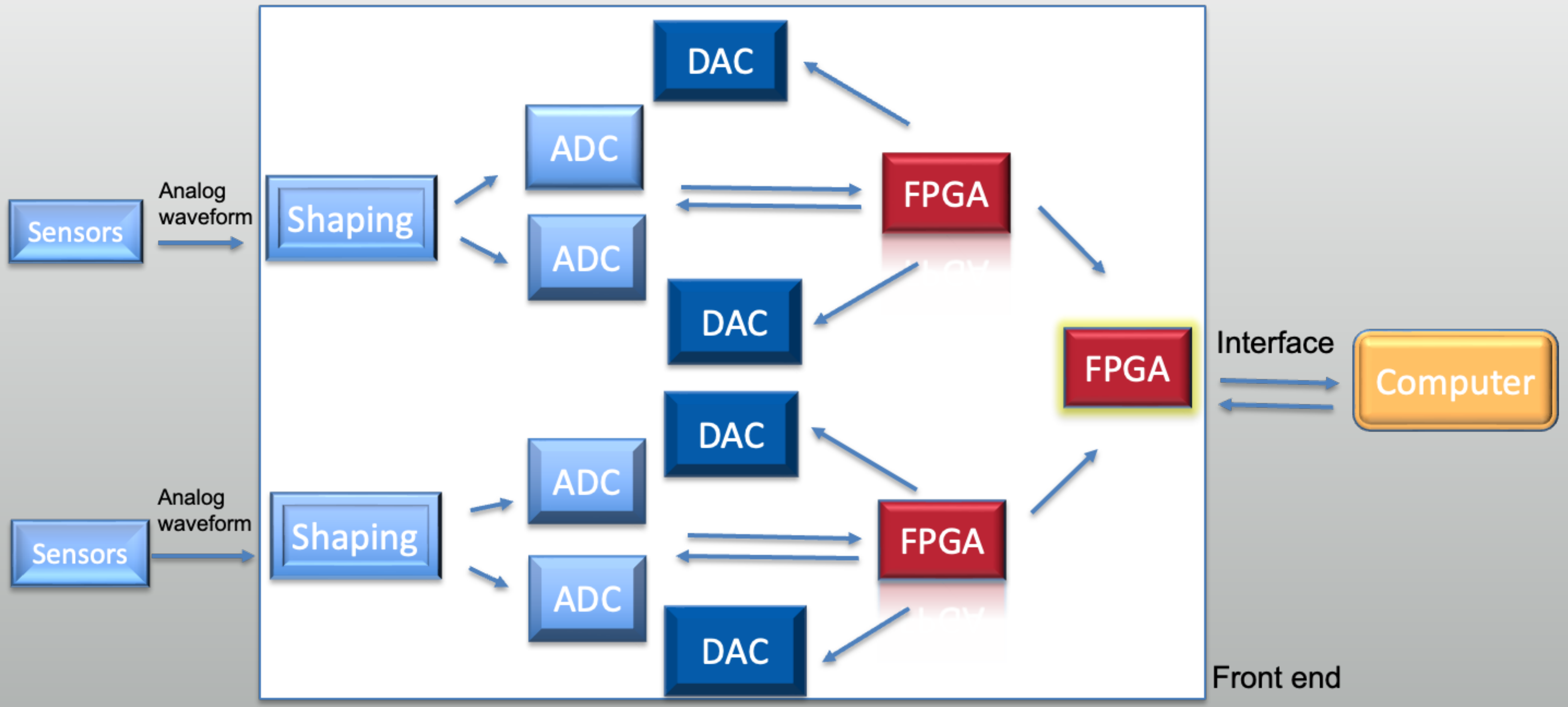
What is RFSoC?
A single chip that contain nearly all the component which are required for high performance data aquisition system front end





RFSoC

A Conventional System

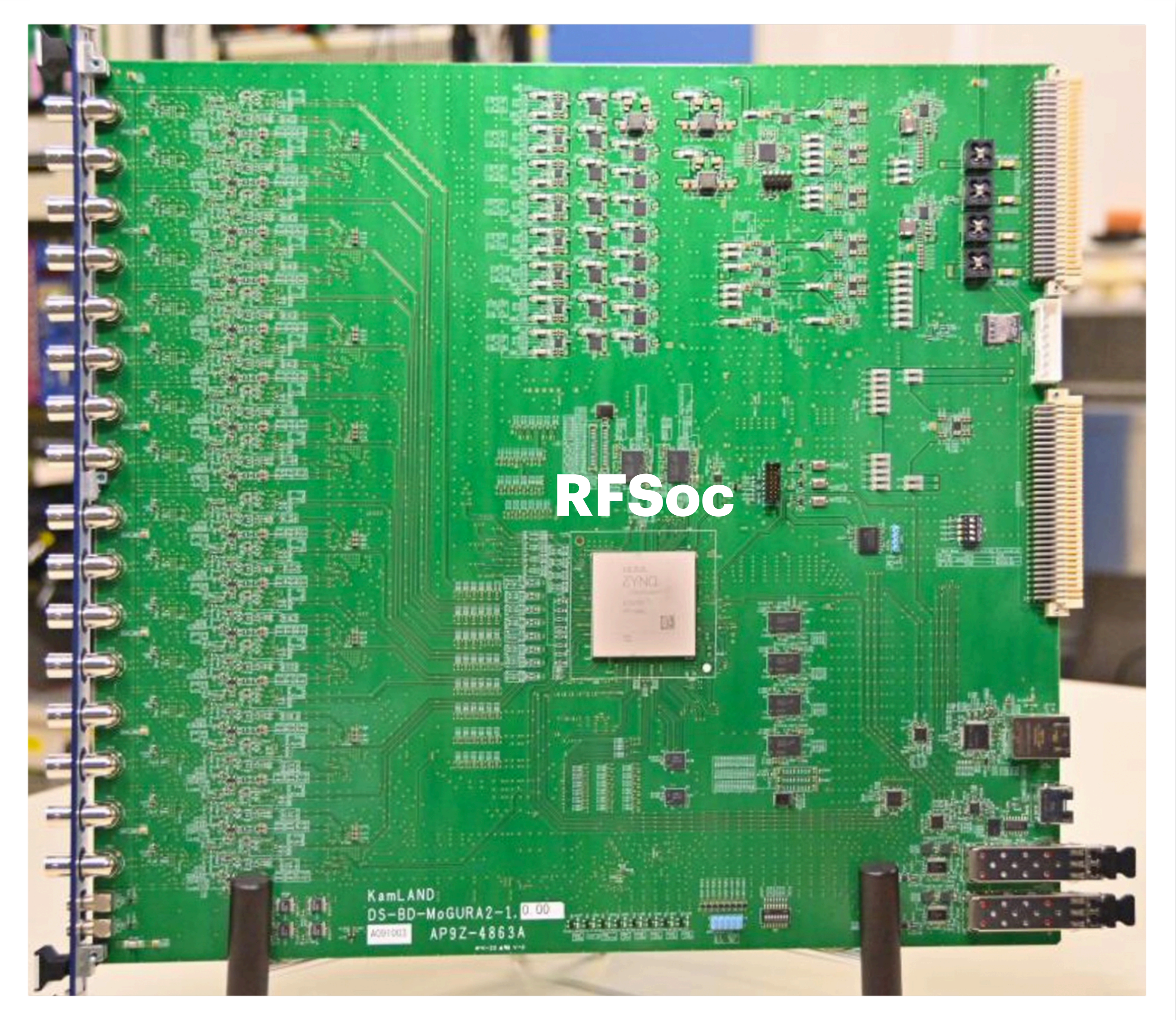


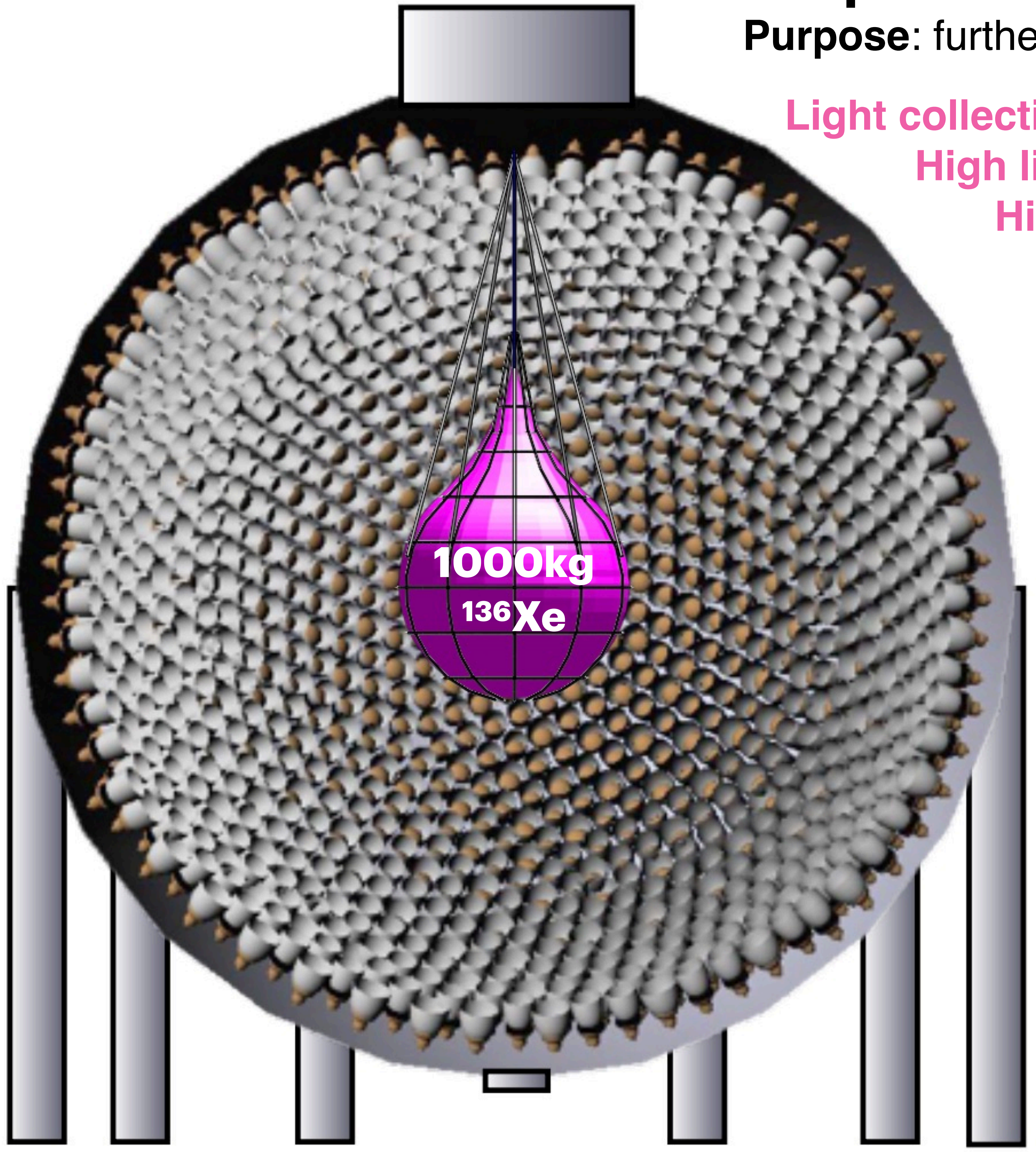
Introducing KamLAND2-Zen

KamLAND2-Zen aims to cover the Inverted Ordering region.
5yr sensitivity: 2×10^{27}yr

State-of-the-art electronics

Purpose: Improve background suppression. Tagging long lived isotope from cosmic ray spallation.

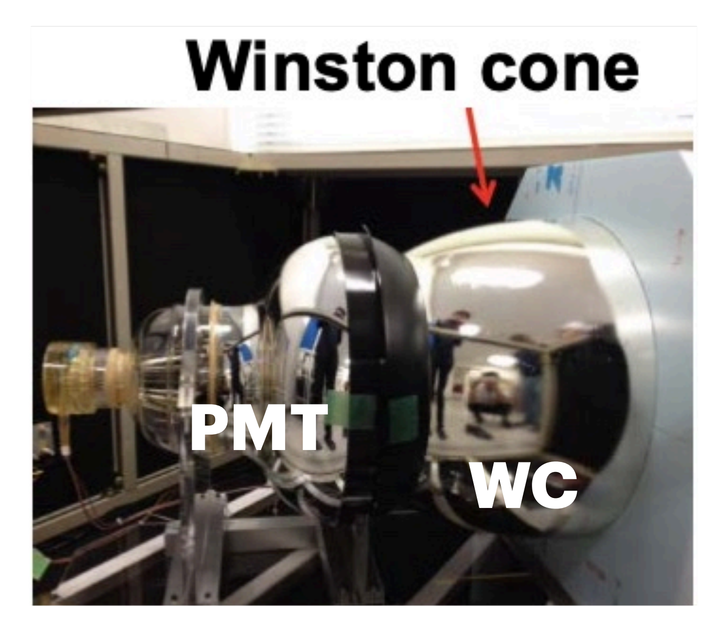




Improved energy resolution

Purpose: further separate **2νββ** from the **0νββ**.

Light collection with Winston Cones (x1.8)
High light yield scintillator (x1.4)
High QE 20" PMTs (x1.9)

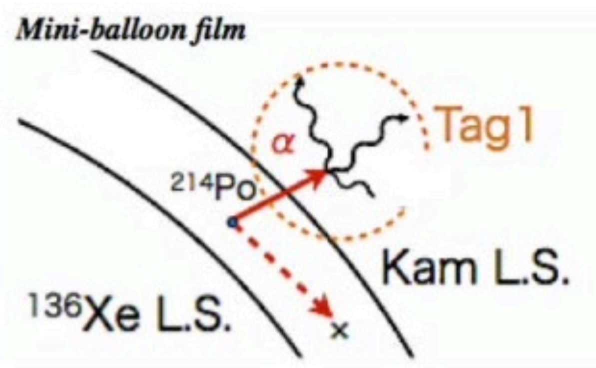


4% → 2% energy resolution

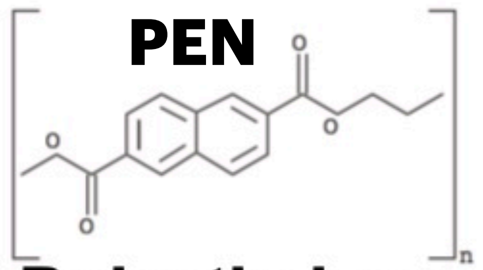
x100 reduction in 2νββ background rate.

Improved inner balloon

Purpose: reduce backgrounds originating from balloon.



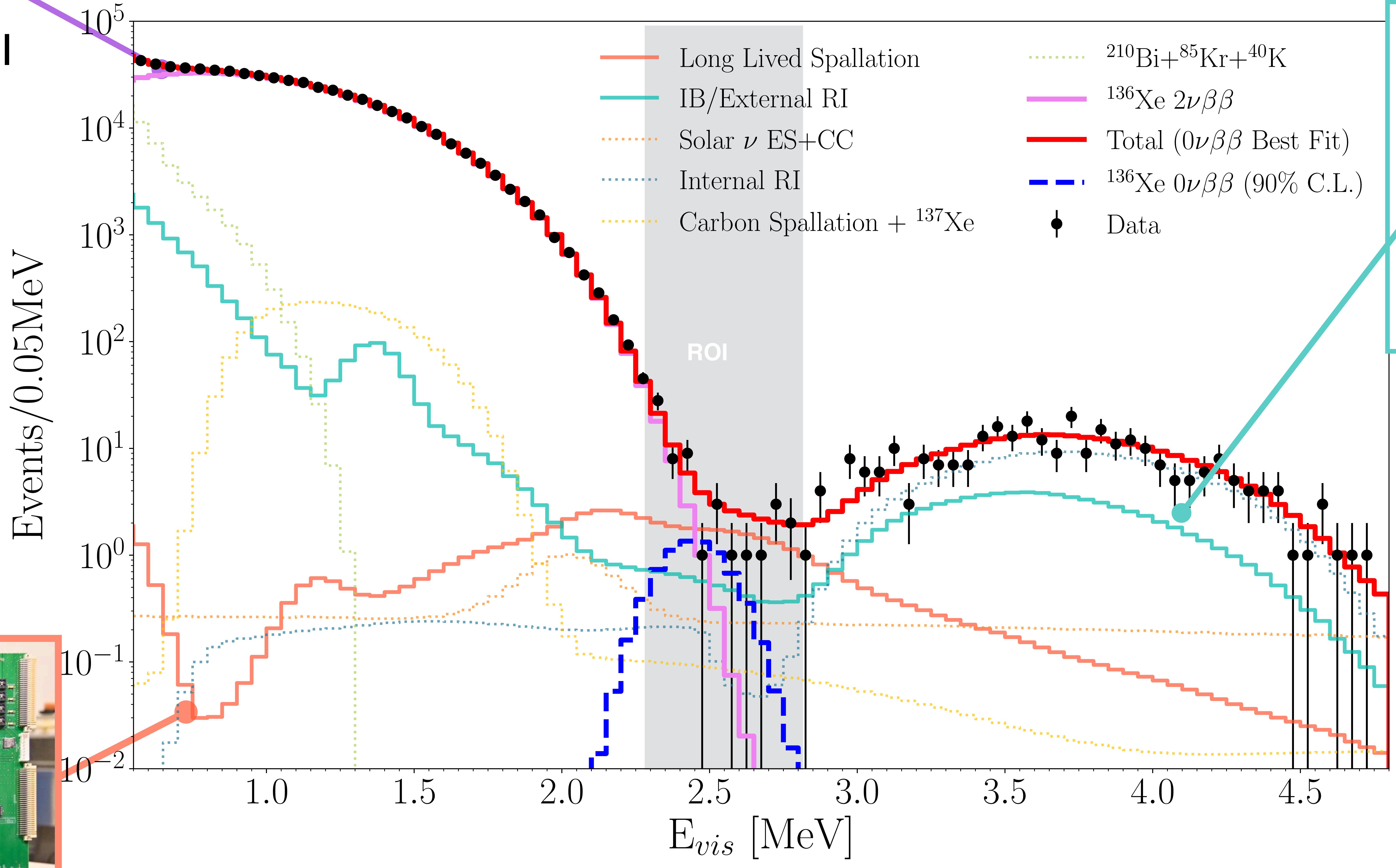
Tag ^{214}Bi decays.

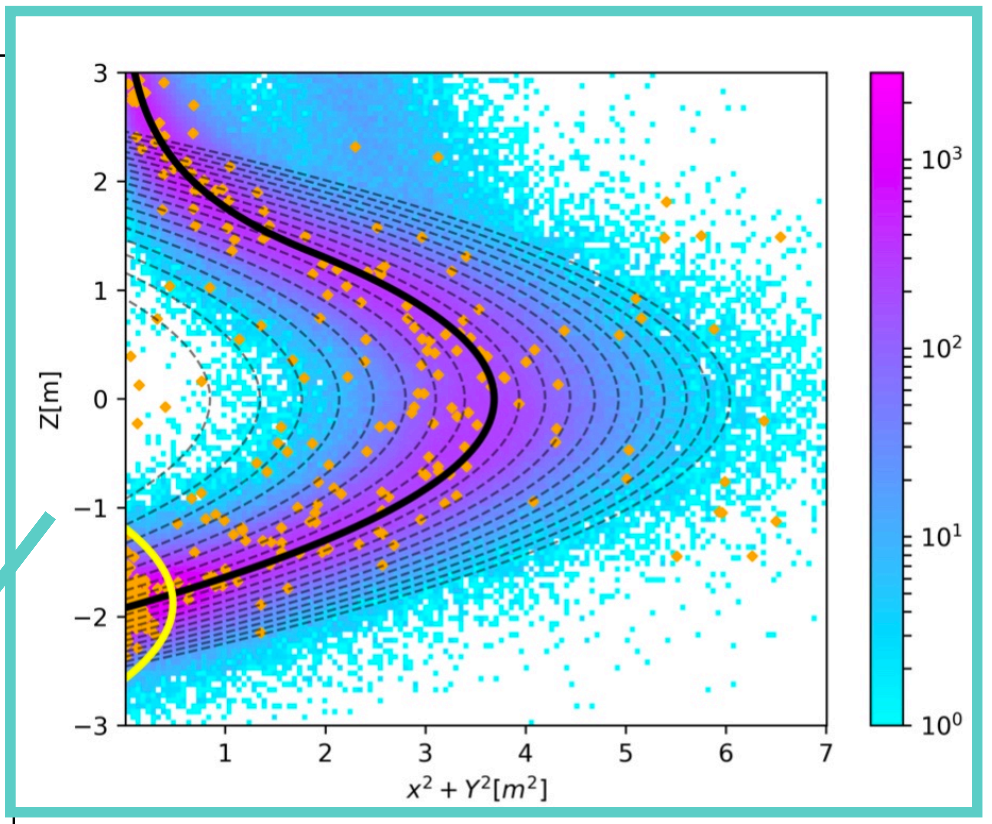


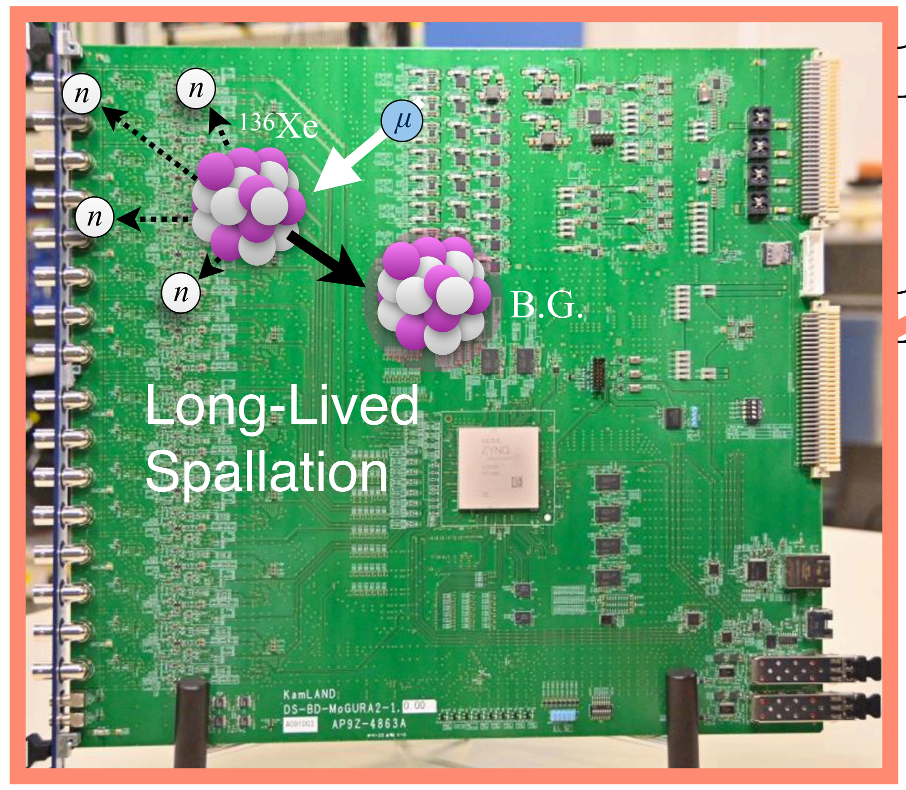
Polyethylene naphthalate

KamLAND-Zen800 energy spectrum

2νββ energy tail
Most dominant &
inevitable bkg.
~ 12 events/ROI



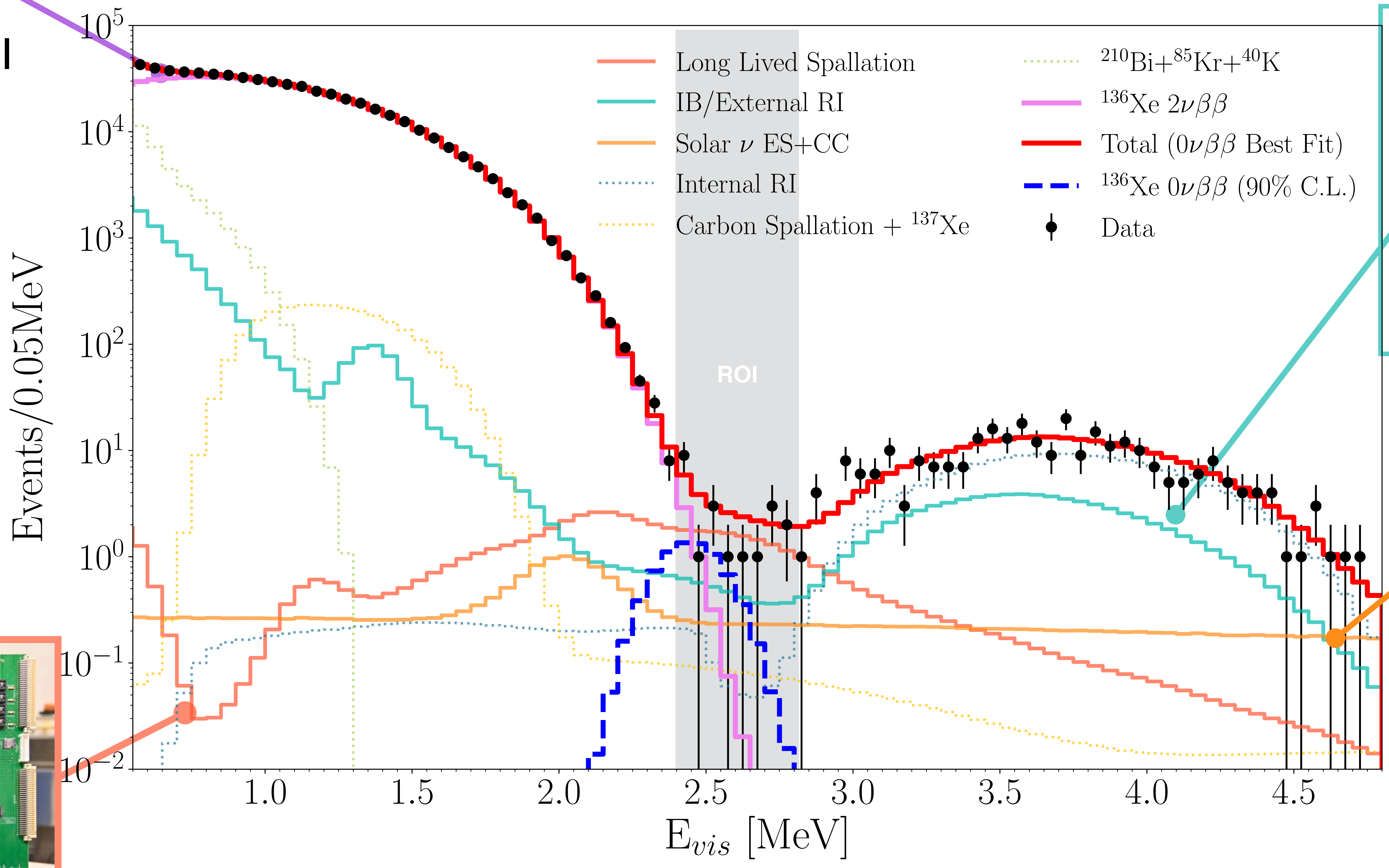


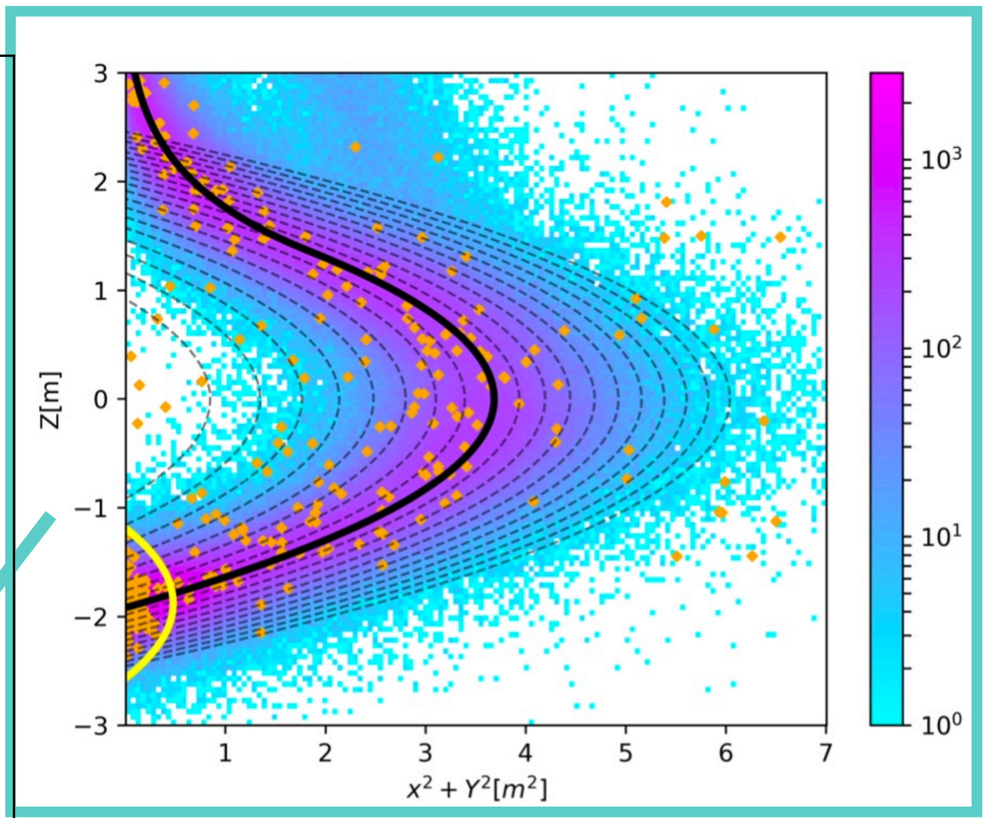


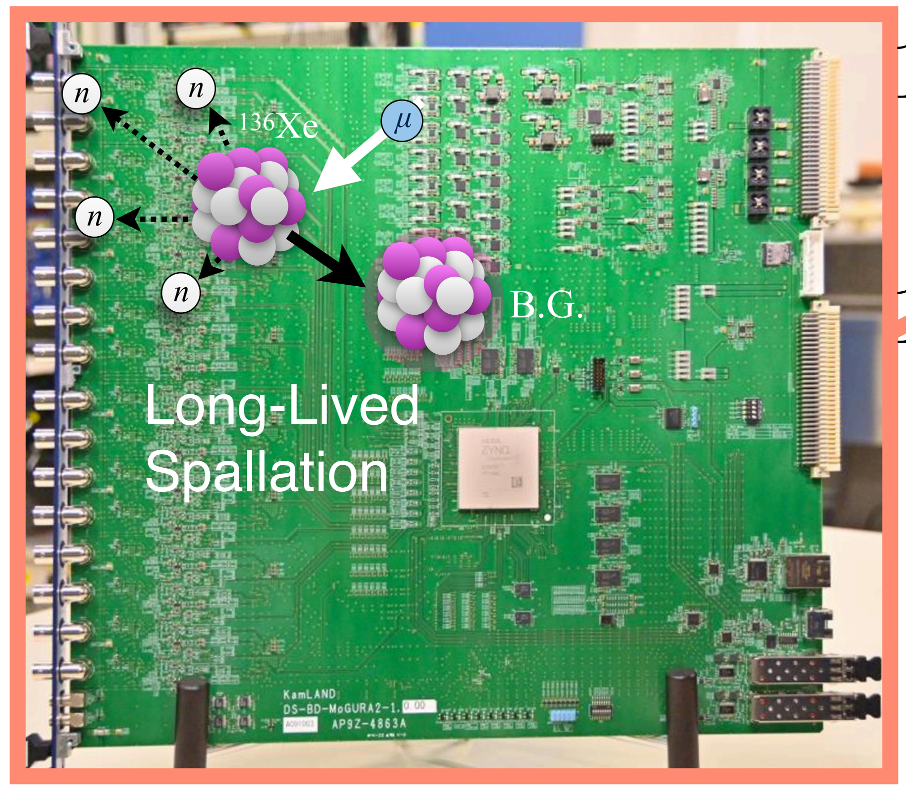
$$T_{1/2} > 4.3 \times 10^{26}\text{years}$$

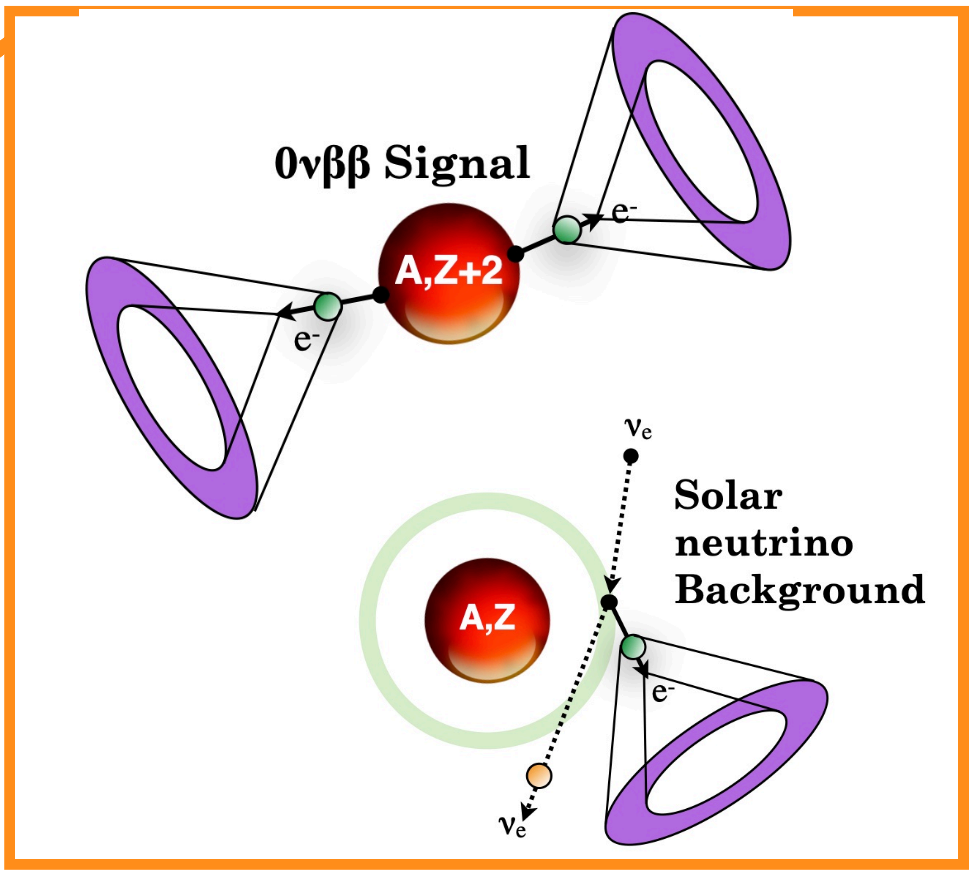
KamLAND-Zen800 energy spectrum

2νββ energy tail
Most dominant &
inevitable bkg.
~ 12 events/ROI



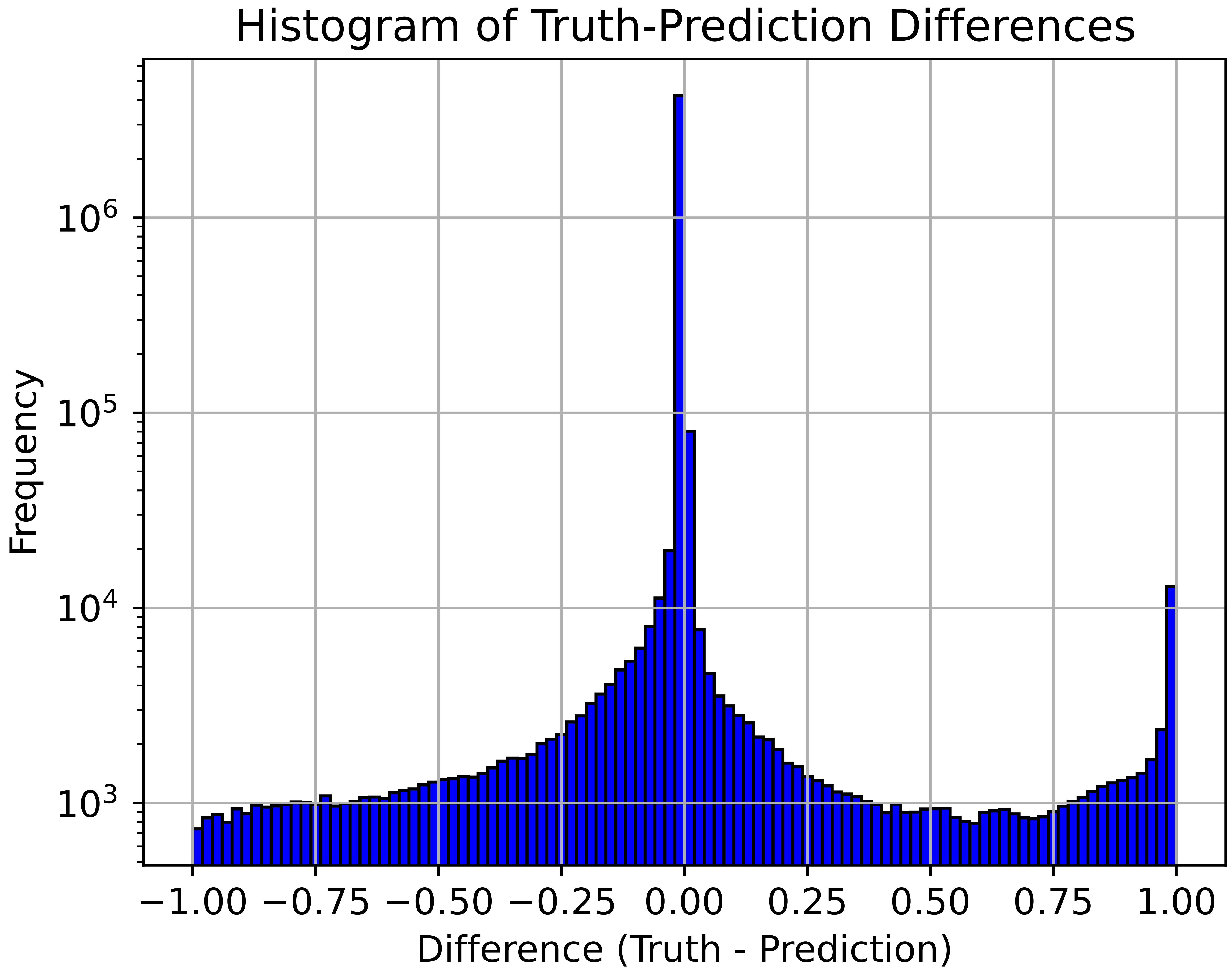


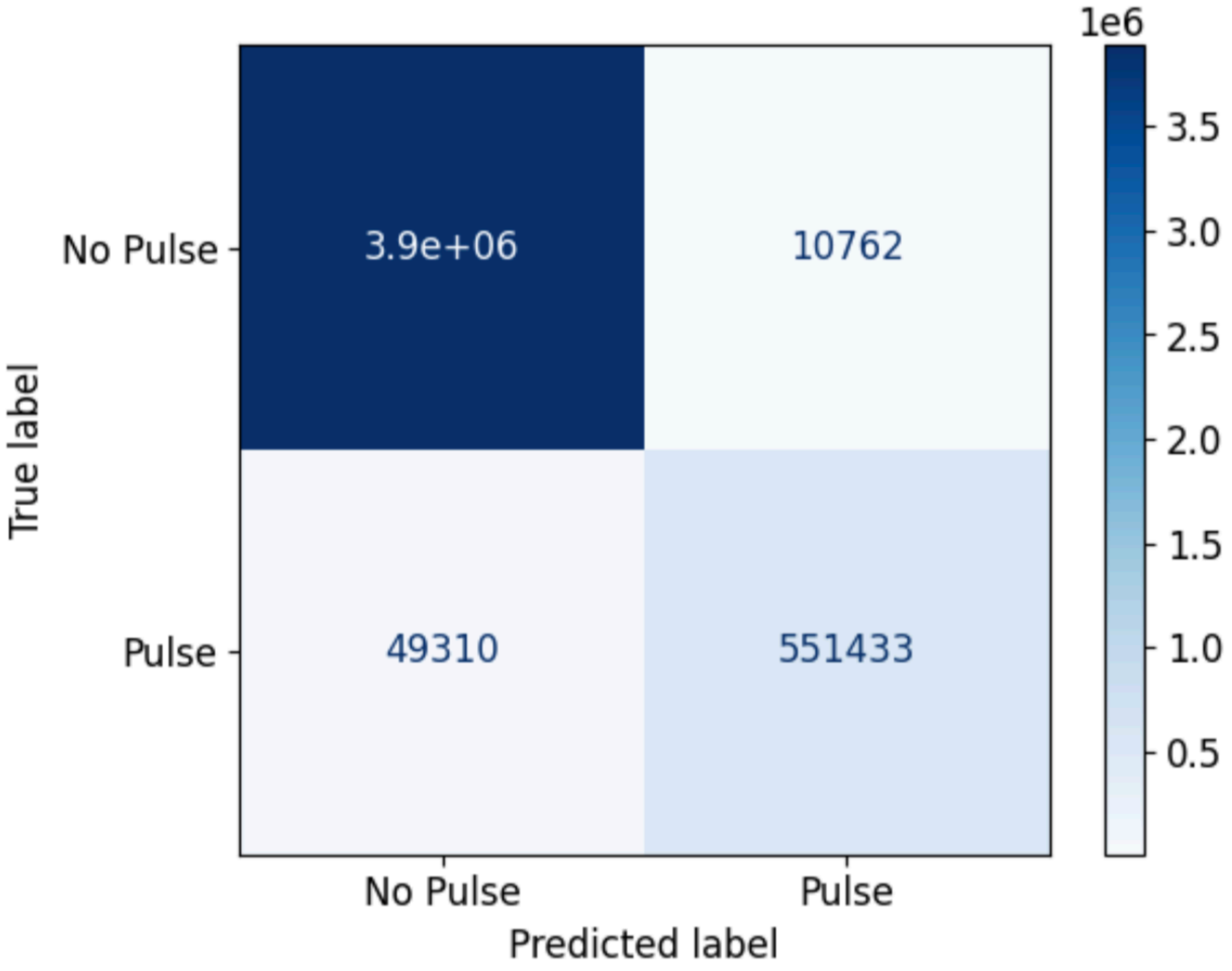




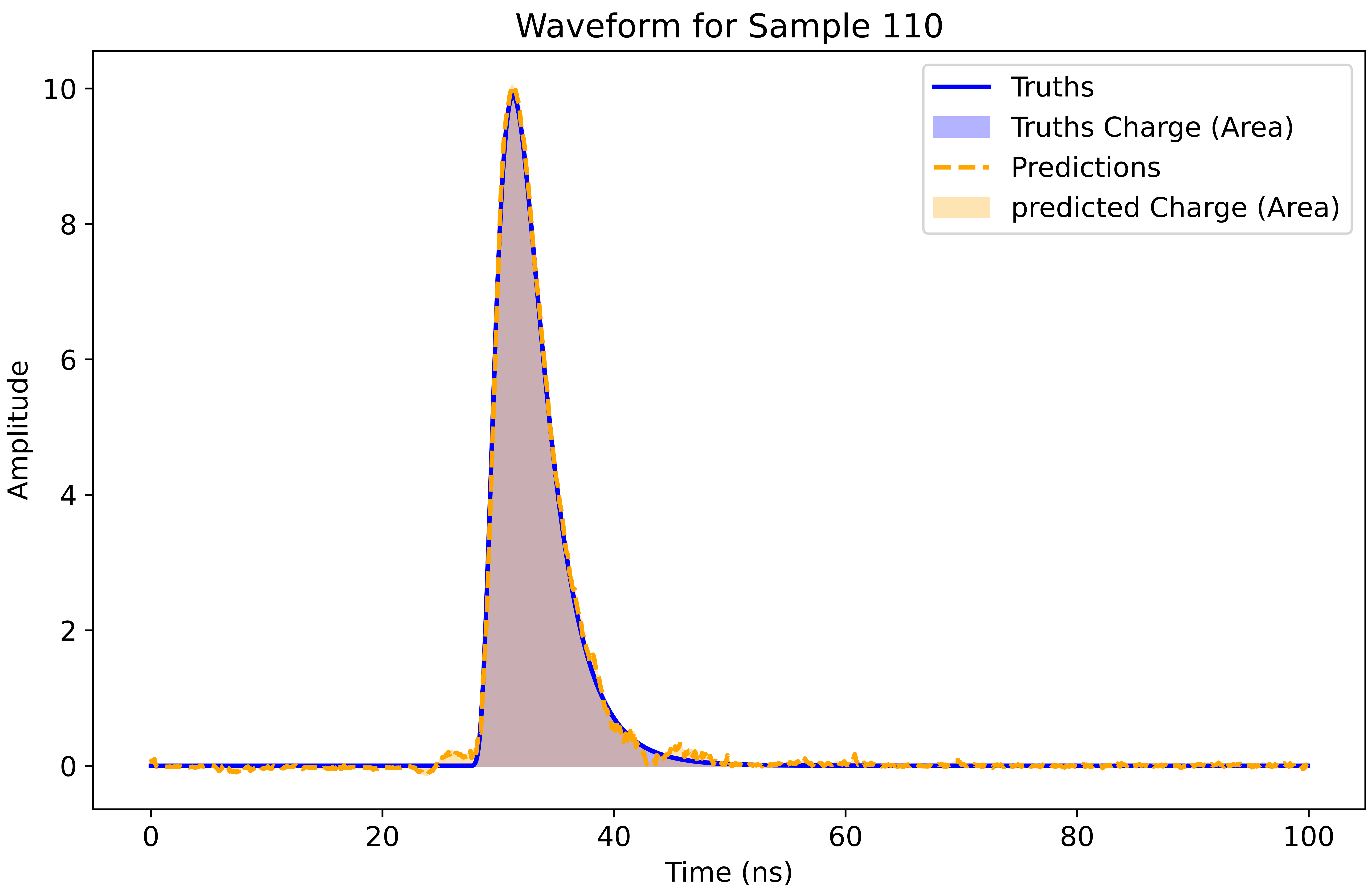
$$T_{1/2} > 4.3 \times 10^{26} \text{years}$$

Classification



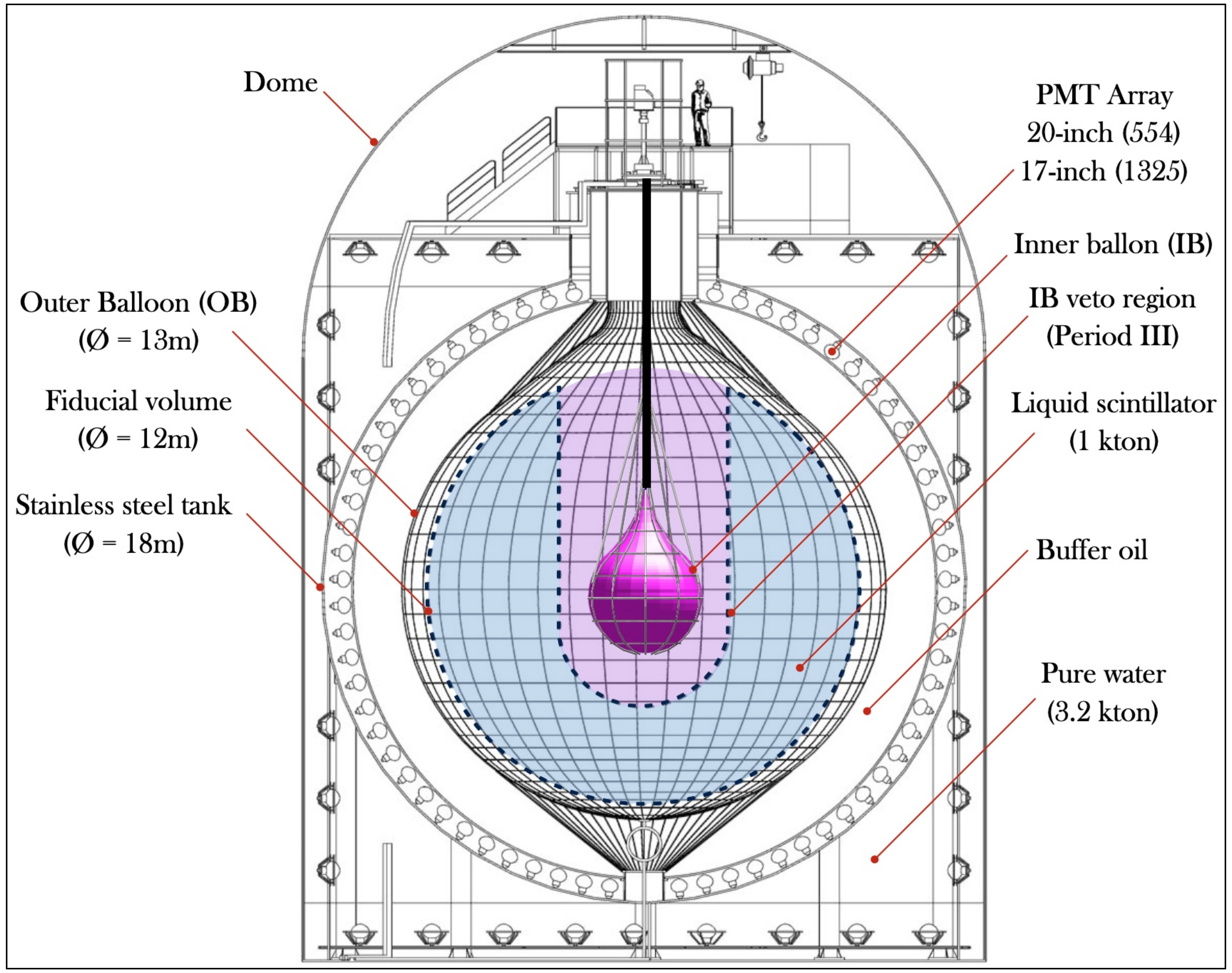


Regression


Waveform for Sample 110
Truths
Truths Charge (Area)
Predictions
predicted Charge (Area)
Amplitude
Time (ns)
0
2
4
6
8
10
0
20
40
60
80
100

Liquid scintillator detectors

KamLAND-Zen800



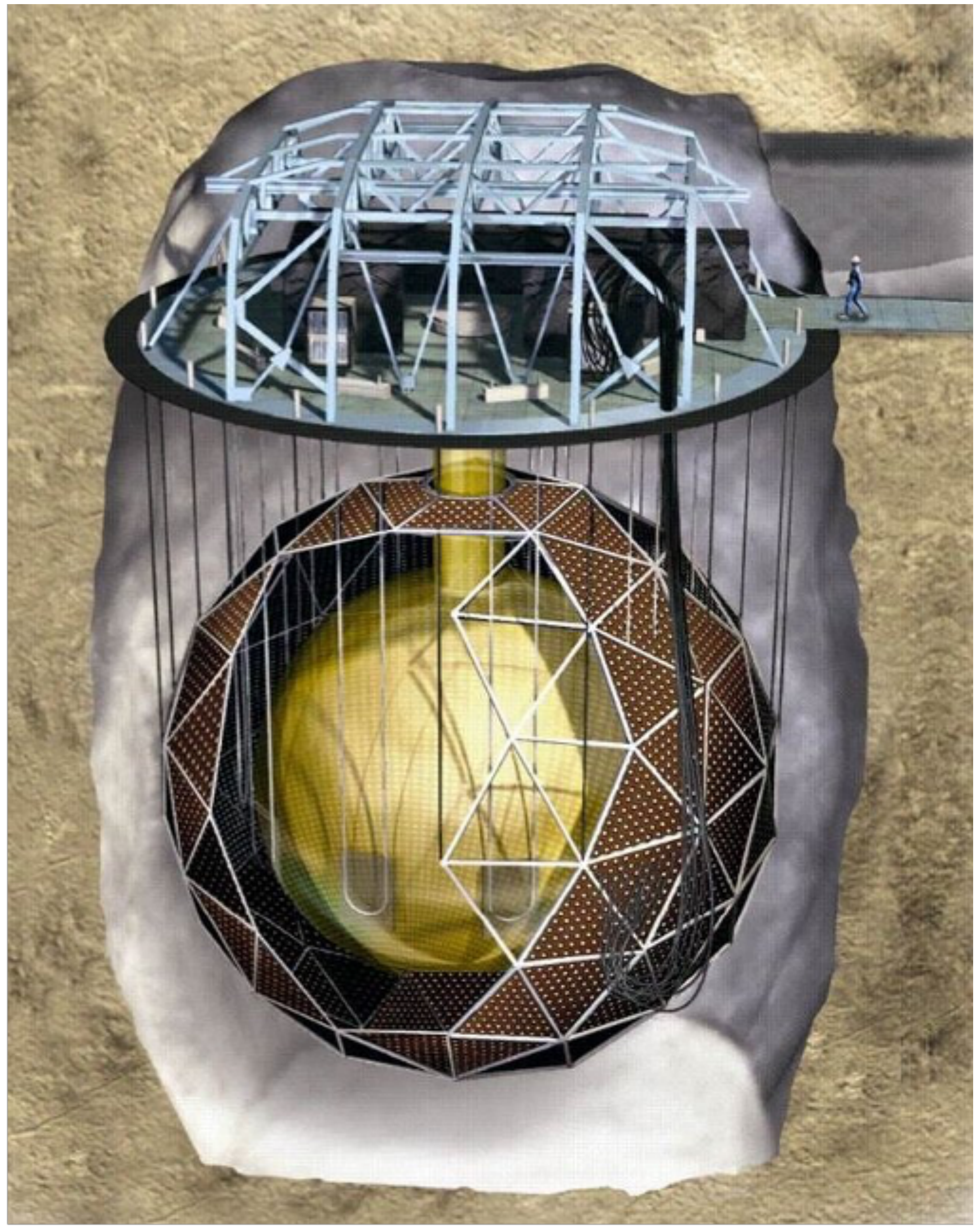
Pros:

- Self-shielding
- Multi-purpose neutrinos measurement
- Scaling

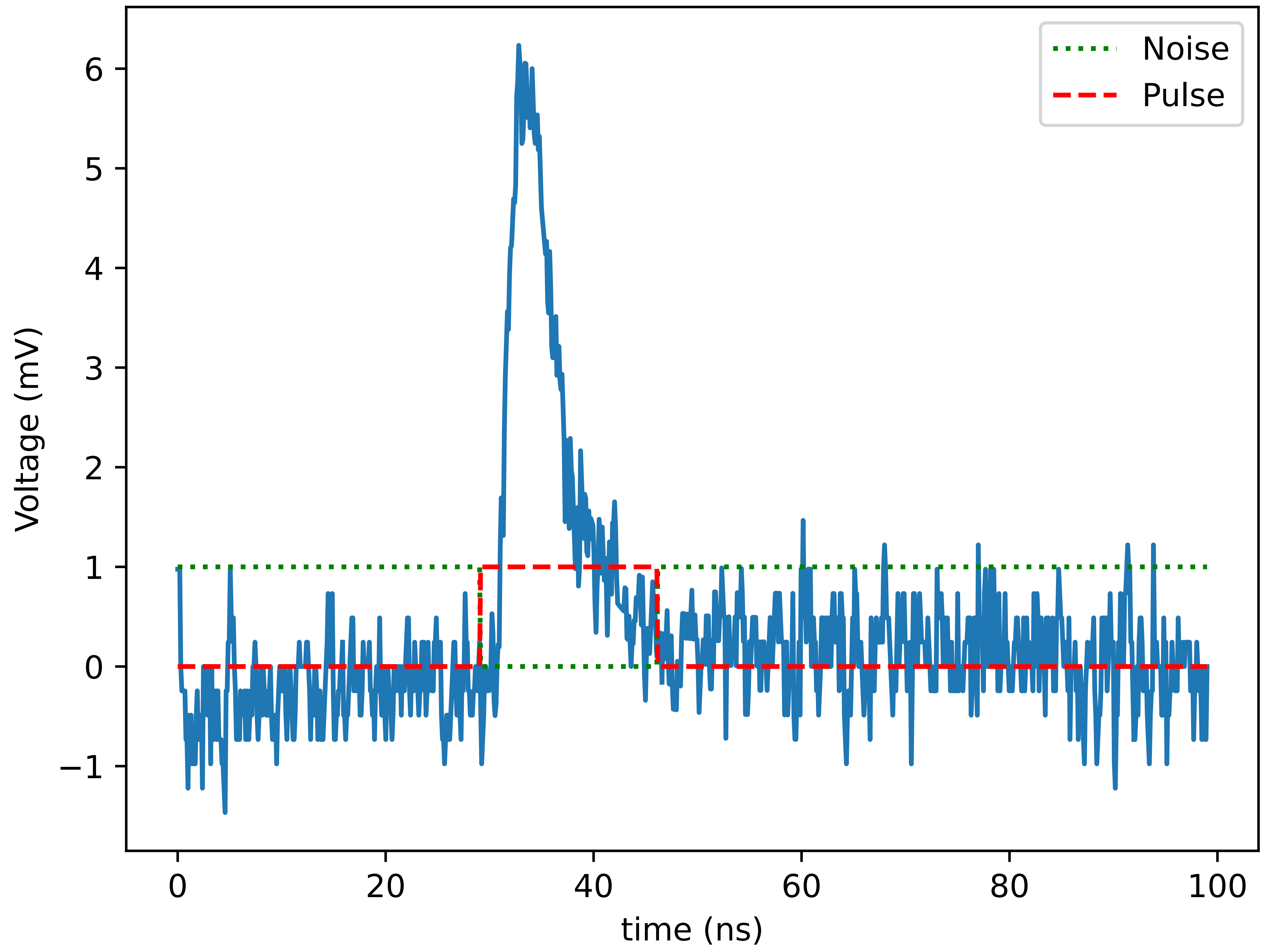
Cons:

- Low energy resolution
- Some irreducible backgrounds

Future: KamLAND2-Zen



Goals with ML

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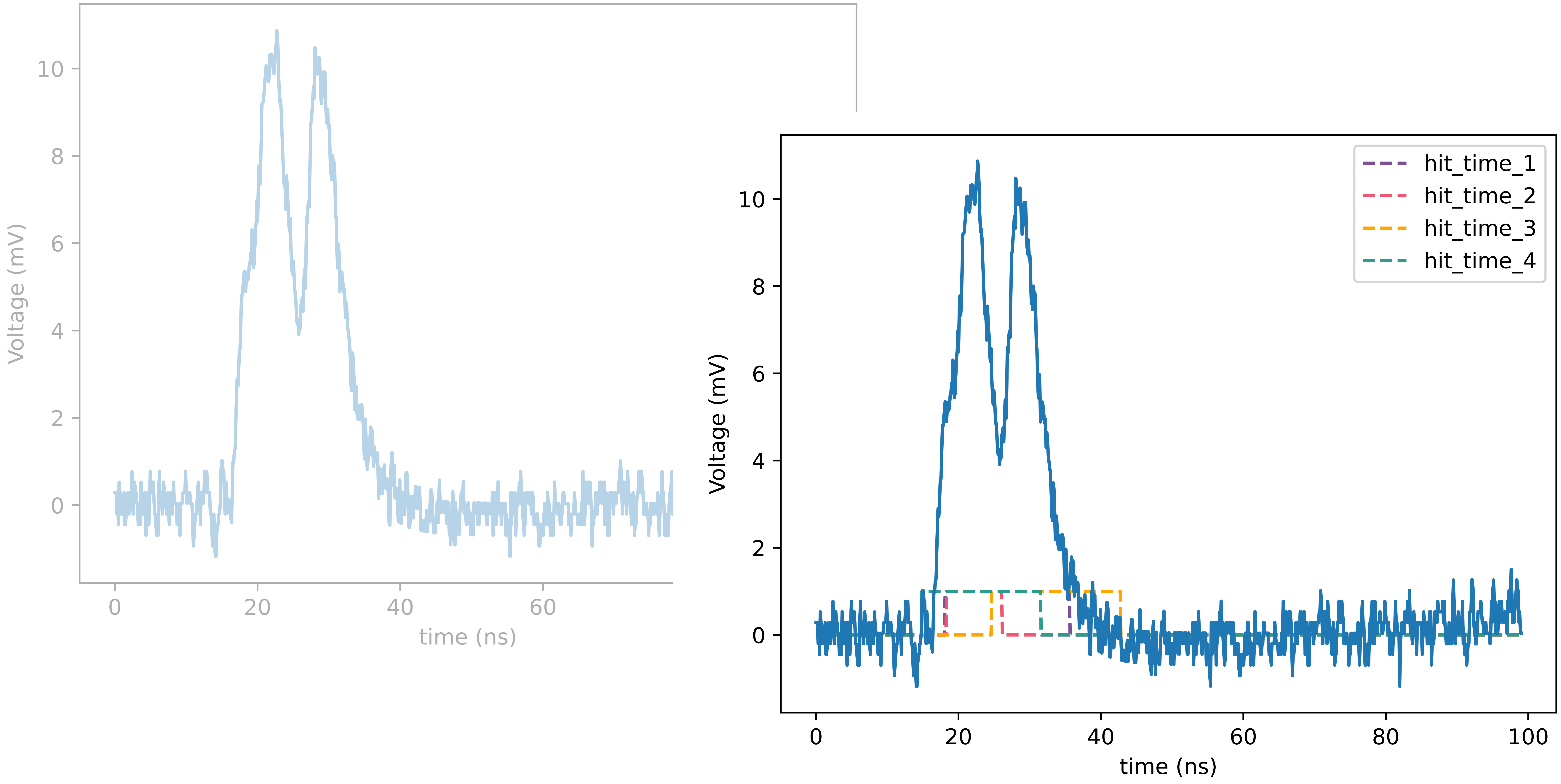
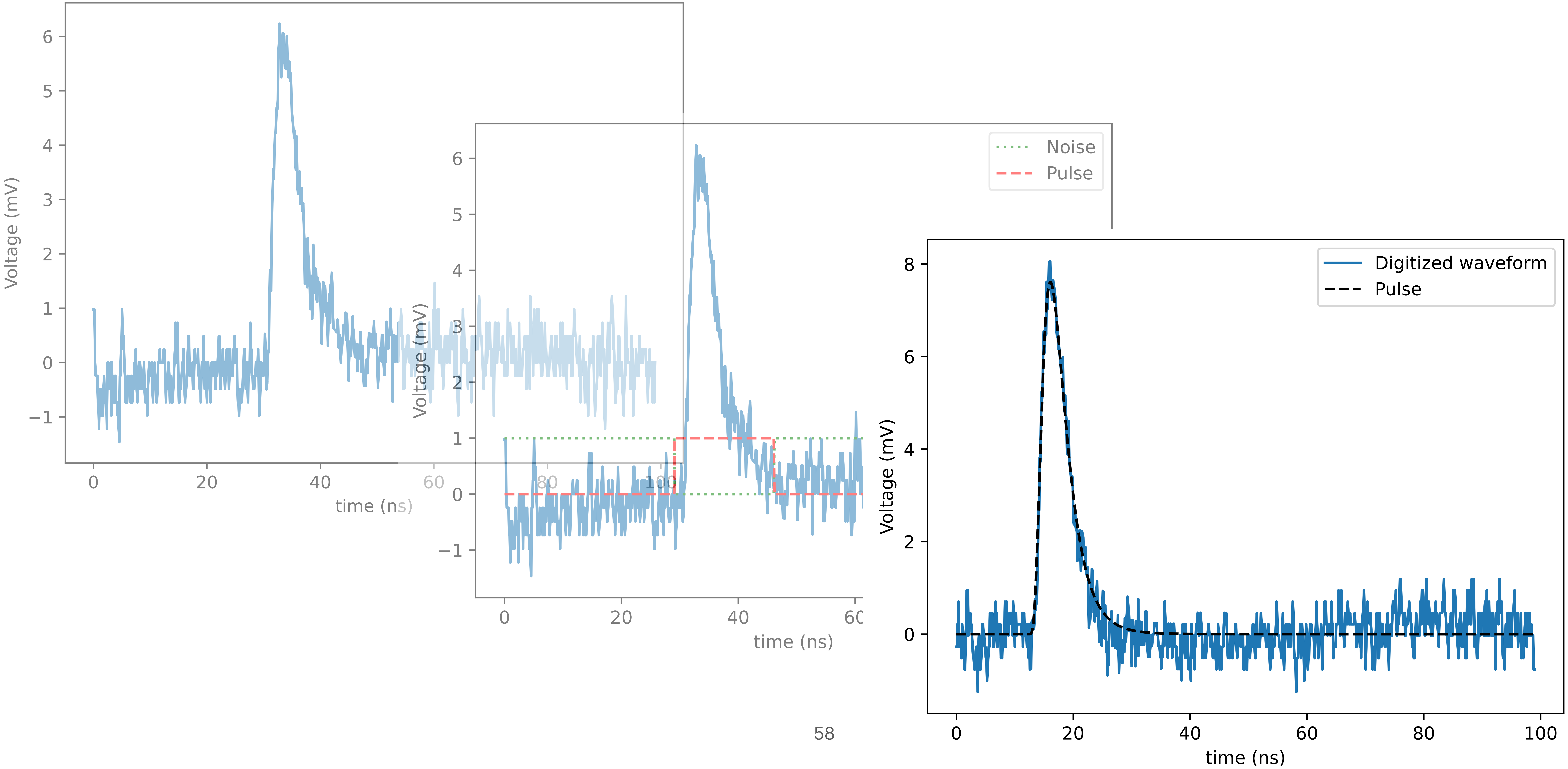
[[1, 1, 1, ..., 1, 1, 1],
 [0, 0, 0, ..., 0, 0, 0]]
```

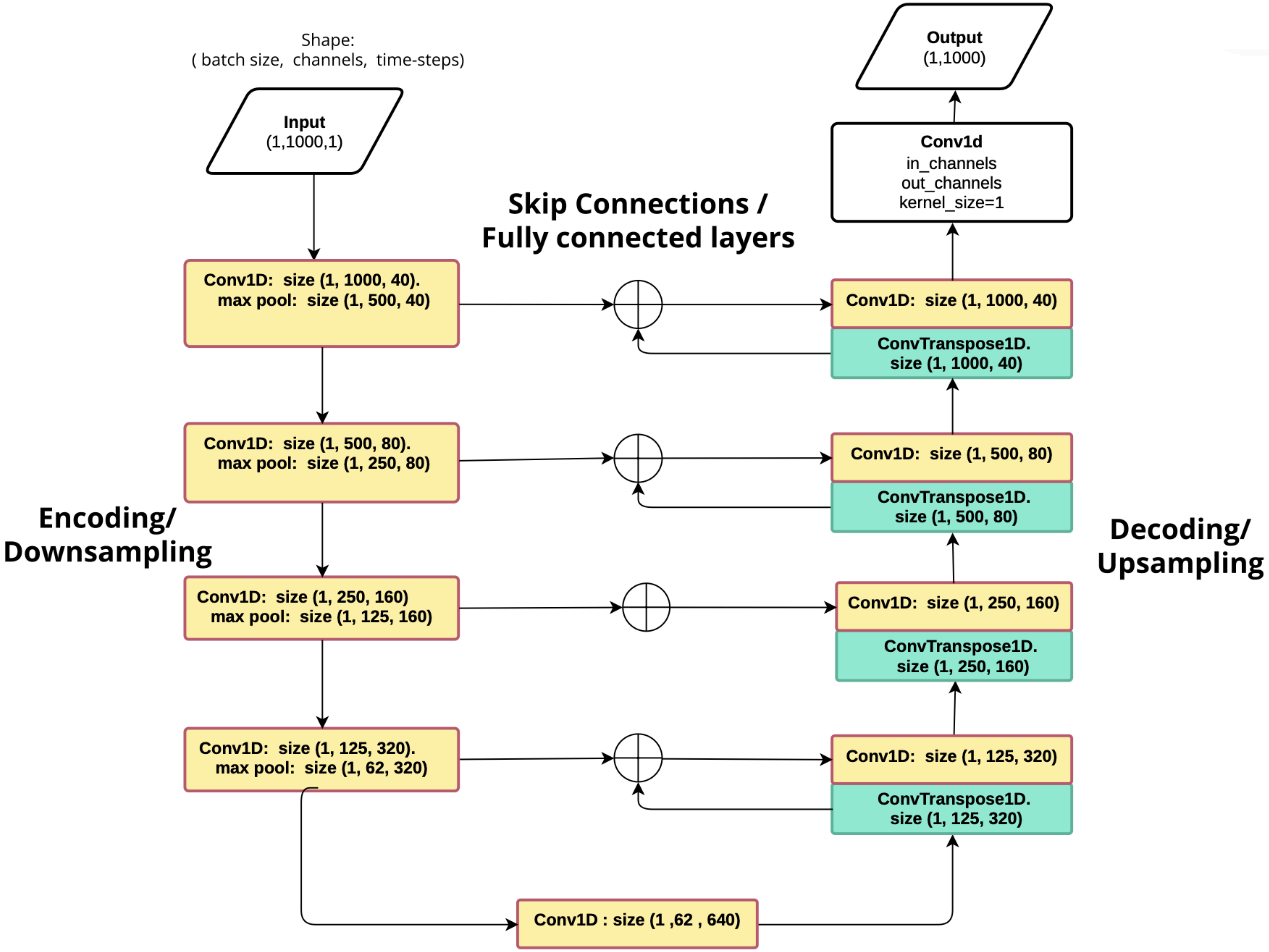
Goals with ML



Digitized waveforms



UNet for pulse extraction



Goals with ML