SINAPSE: Deep neural networks in FASTER v3 for online data analysis

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Experimental setup

VENDETA: VErsatile Neutron DETector Array

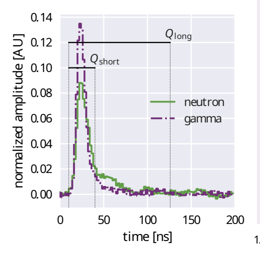
Authors: *O. Syrett , C. Lenain, B. Mauss, J. Taieb, P. Morfouace, A. Chatillon, D. Etasse*

- Fission chamber surrounded by VENDETA array (72 detectors).
- Neutron kinetic energy derived from double time-of-flight (ToF) measurement: T_0: incident neutron ToF; T_1: emitted neutron ToF.

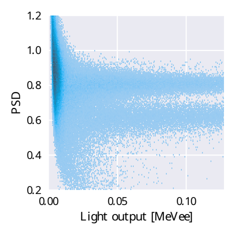
Figure: Picture of the VENDETA array surrounding the fission chamber. Adapted from [Syr+25].

Neutron-γ discrimination

- Fission fragments emit both neutrons and γ rays.



$$\mathrm{PSD} = \frac{Q_{\text{short}}}{Q_{\text{long}}}$$



Context

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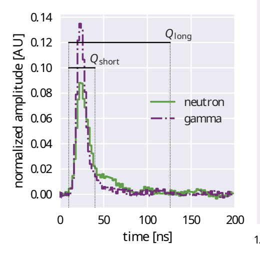

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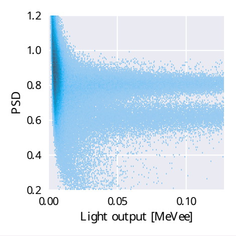
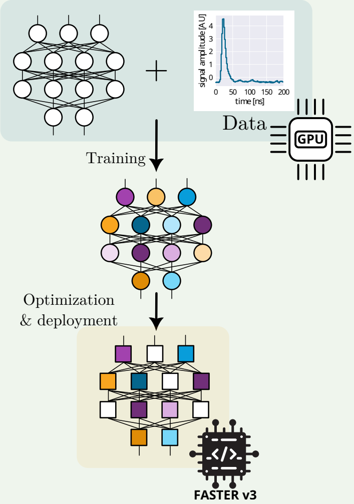


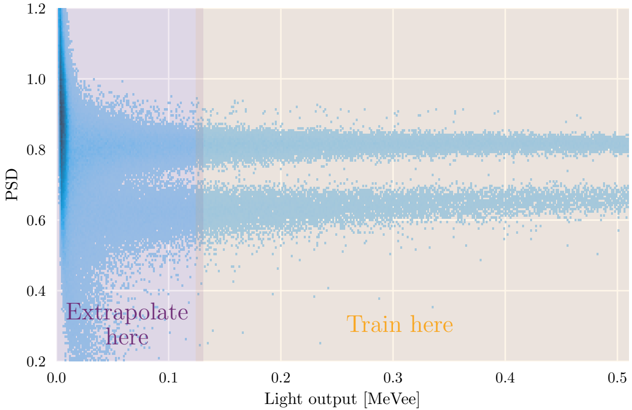
Neural networks in FASTER



Training data

PSD labels

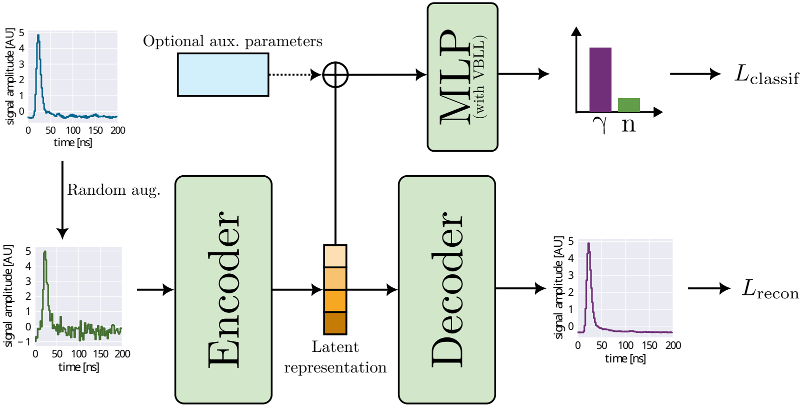
- Complete separation (FoM ≥ 3) above ~ 100 keVee with PSD method.
- Low SNR $\longrightarrow$ unreliable PSD labels.



SINAPSE framework

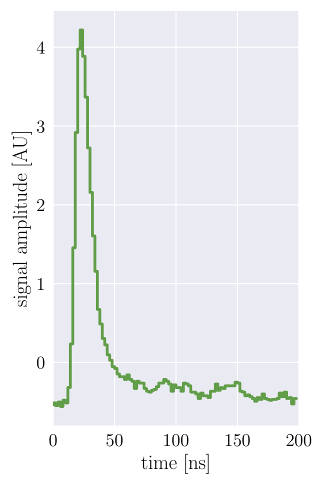
Semi-supervised learning

Semi-supervised learning consists in training machine learning models using both labeled and unlabeled data.



Data augmentation

Raw signal



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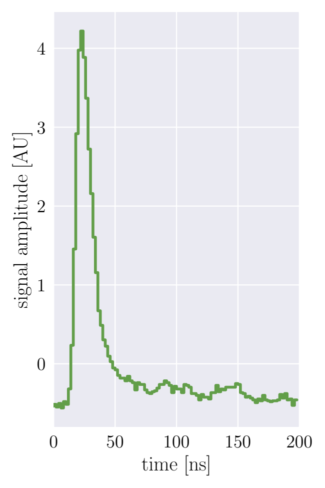
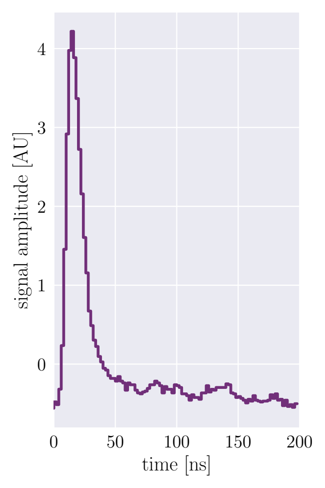


Time shift



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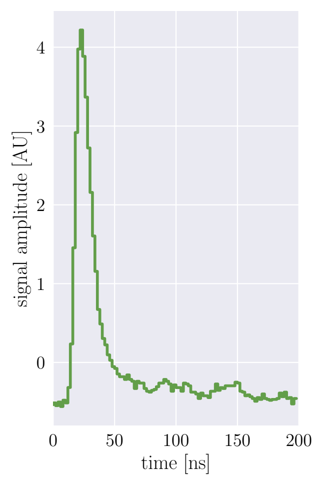

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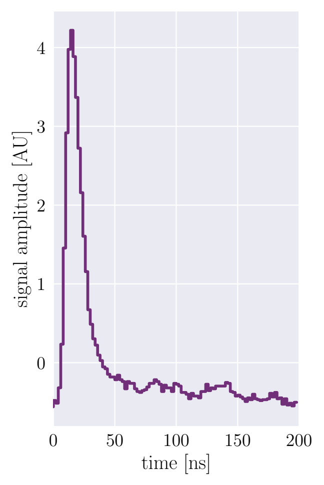
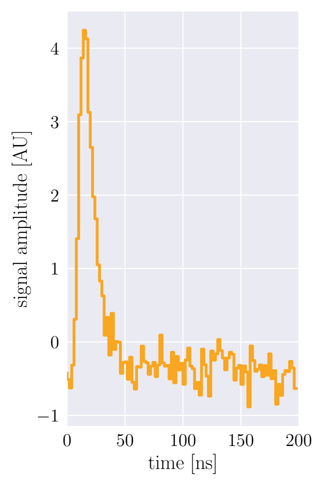
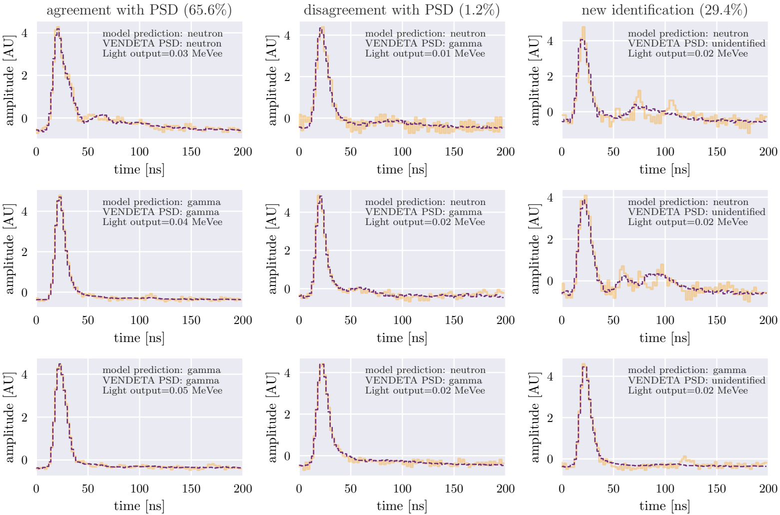


TS+Gaussian noise



Signal denoising



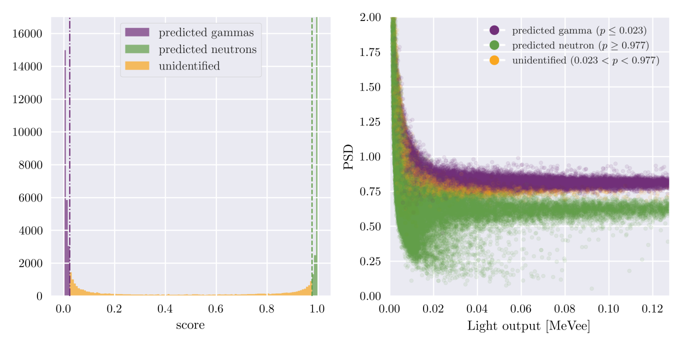
$\longrightarrow$ Compression ratio = 25

Classification

Conformal prediction

Ensures predictions are correct with 95% probablity on calibration set.
$\longrightarrow$ Translates into **13% low-confidence predictions on test set** (unidentified).

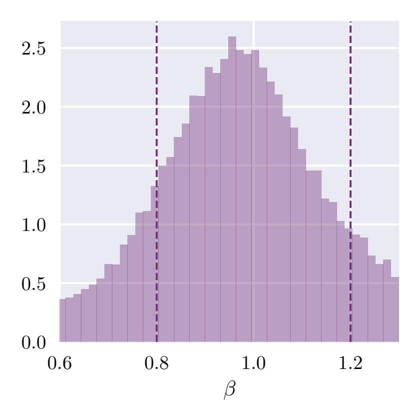
Results for ^{240}Pu (test set)



Validating the results

Prompt γ selection

$$\beta = \frac{1}{c}\frac{d_{\mathrm{det}}}{\mathrm{ToF}} \tag{1}$$



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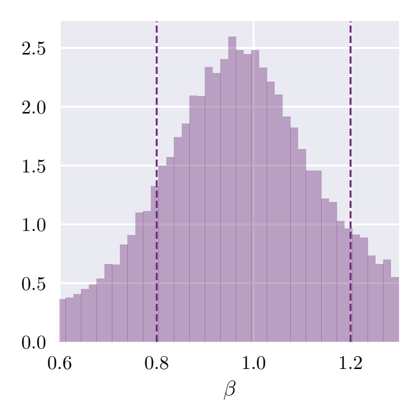
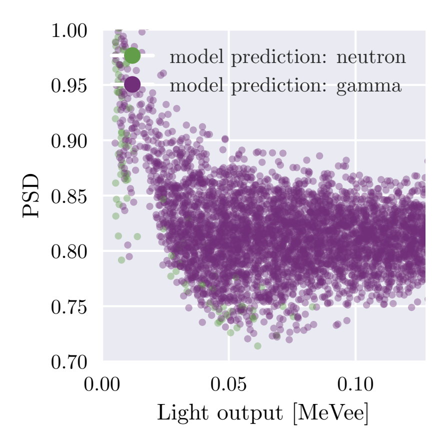


Performance on low-energy γ

- Accuracy = 98.6% → very few FN



Model interpretability

Saliency maps

Gradient of the score with respect to the input samples:

$$S(\mathbf{x}_0) = \left.\frac{\delta y}{\delta \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}_0} \tag{2}$$

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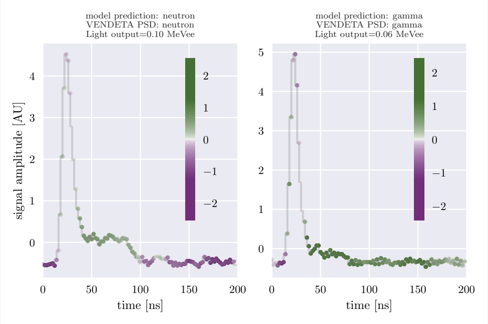
Results

- Elevated baseline shifts the saliency score toward the γ class.
- Large time window is crucial for accurate neutron identification.
- Increasing the tail amplitude shifts the score toward the neutron class.



Improving calibration with a variational Bayesian last layer

Traditional fully-connected layers versus VBLL

	Last FC Layer	**VBLL**
Weight representation	Learns fixed weights	Learns a pdf over classifier weights
Calibration	Easily overconfident	Better-calibrated probabilities
Uncertainty quantification	Does not model uncertainty	Uncertainty via weight distributions

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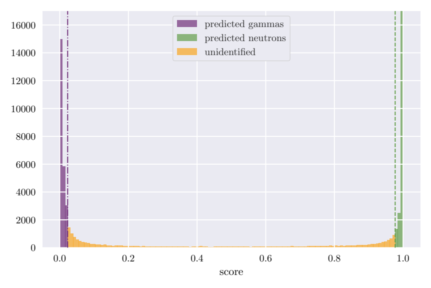
FC layer scores



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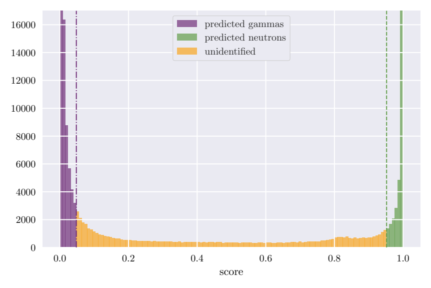

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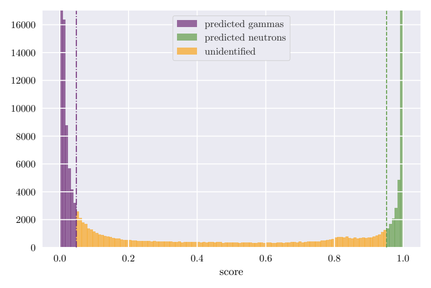
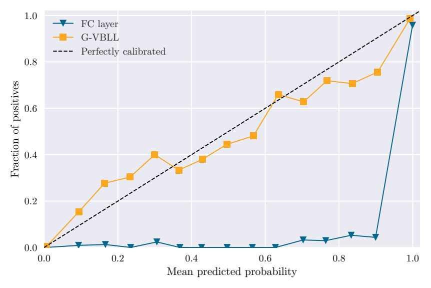


Calibration curve



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- Using random augmentations allows for reliable extrapolation at low-energy and robust signal denoising.
- Model interpretability is permitted by saliency methods.
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Next steps

- Enrich training data:
  - Low-energy non-annotated samples (semi-supervised learning)
  - Low-energy γ signals (^{137}Cs)
- Continue exploring uncertainty estimation methods (Bayesian NN).
- Optimize model inference for deployment on FASTER v3 (TensorRT, model quantization).
- PSA based particle discrimination with GRIT.

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