Development of innovative methods for fission trigger construction

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[b] - European Commission, Belgium
[c] - Atomic Energy Commission (CEA), France

CONTENTS:

- The FRØZEN project in a nutshell & the N-SI-125 experiment setup
  - … motivation for innovative fission trigger
- Fission annotations through dFGIC analysis
- Challenges of trace analysis
- Innovative methods based in AI
  - … for trace analysis
  - … for fission trigger construction

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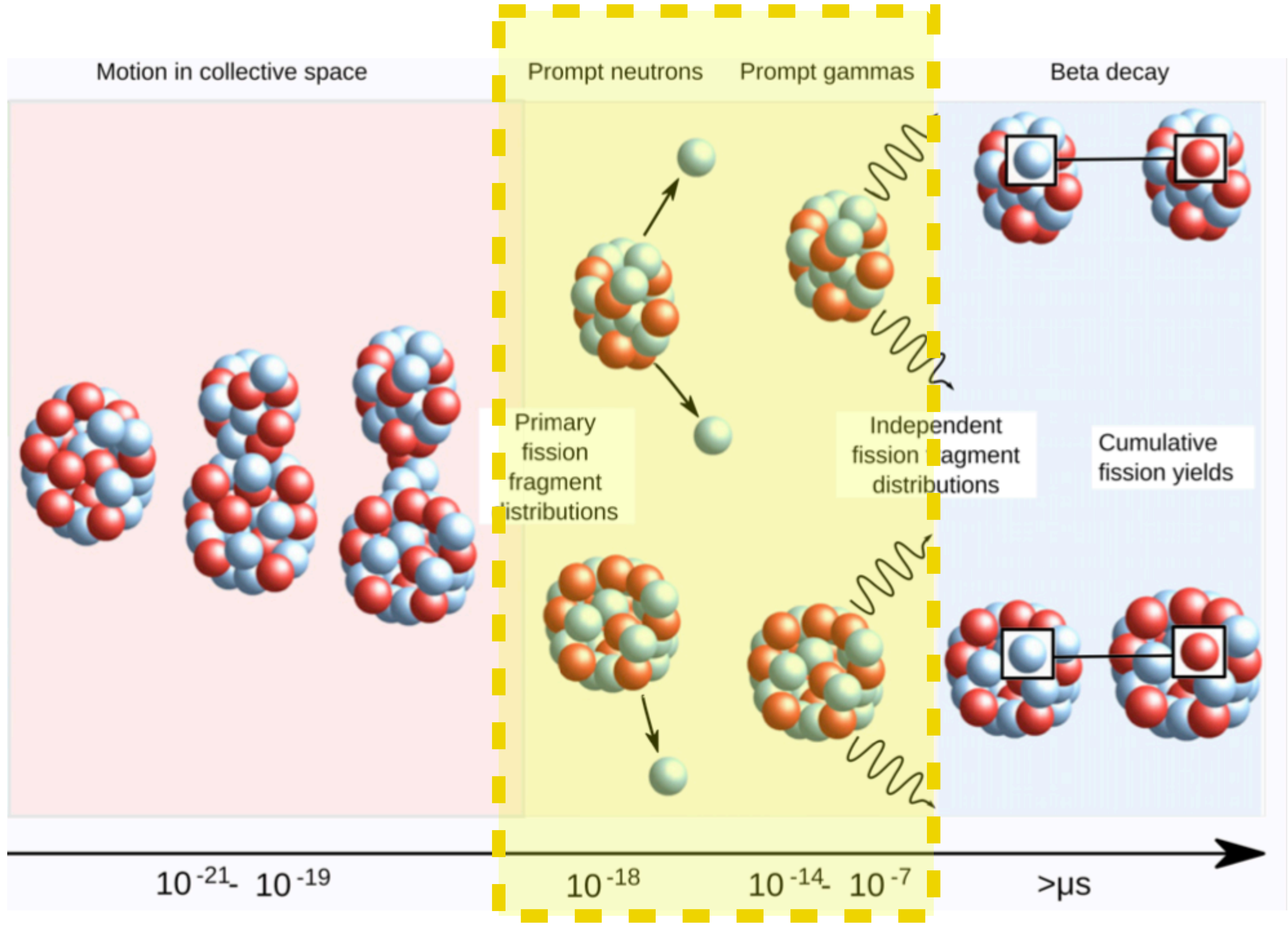


Adapted from: M. Bender, *et al*. Future of nuclear fission theory. Journal of Physics G: Nuclear and Particle Physics, 47(11):113002, oct 2020.

Gamma detection energy and multiplicity

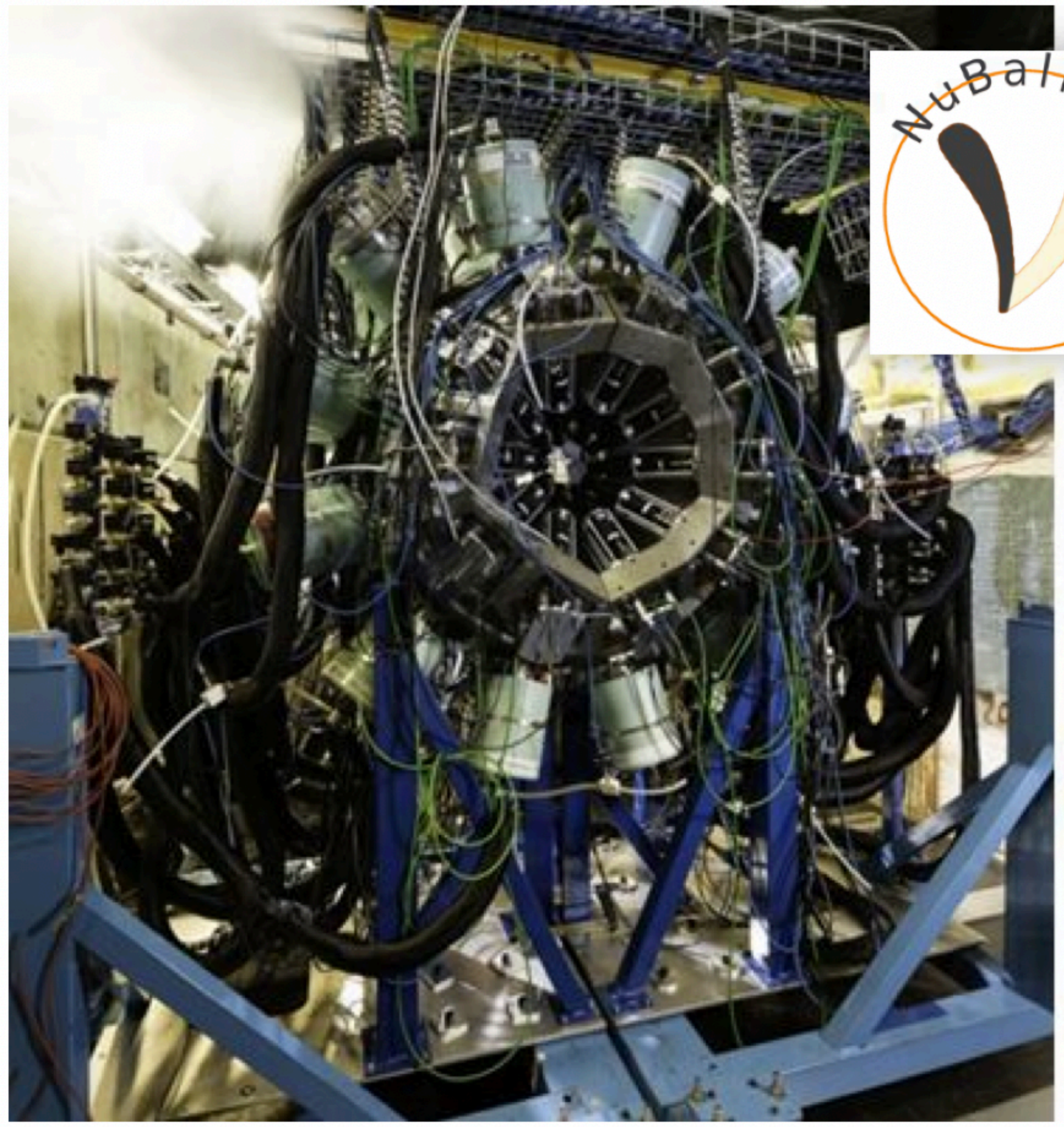
- 24 High-Purity Germanium clovers (HPGe)
- PARIS array 72 phoswhiches La(Ce)Br_3:NaI
- Thalia LaBr3

Neutron detection energy and multiplicity

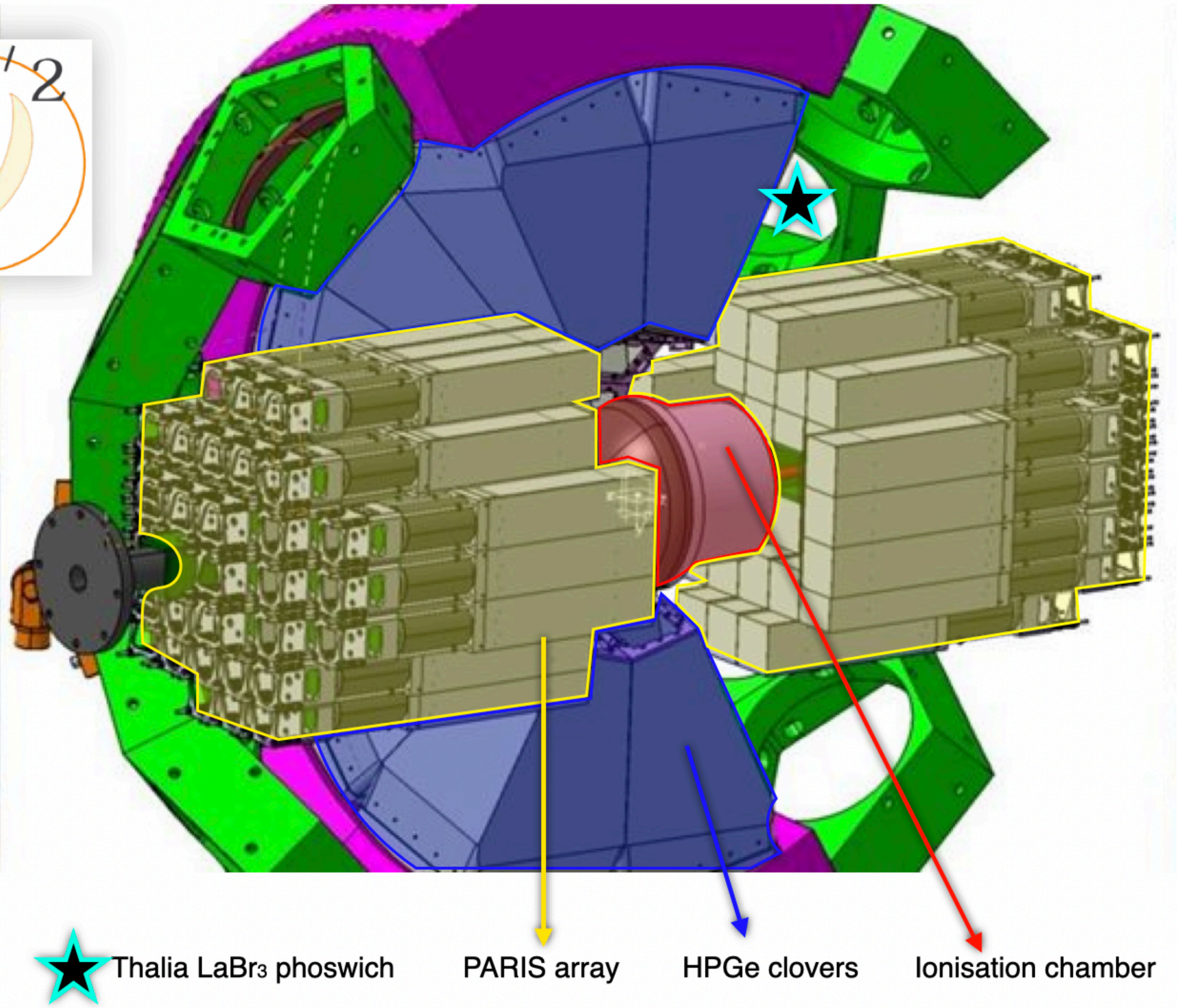
- PARIS array
- Thalia LaBr3

Fission fragments detection

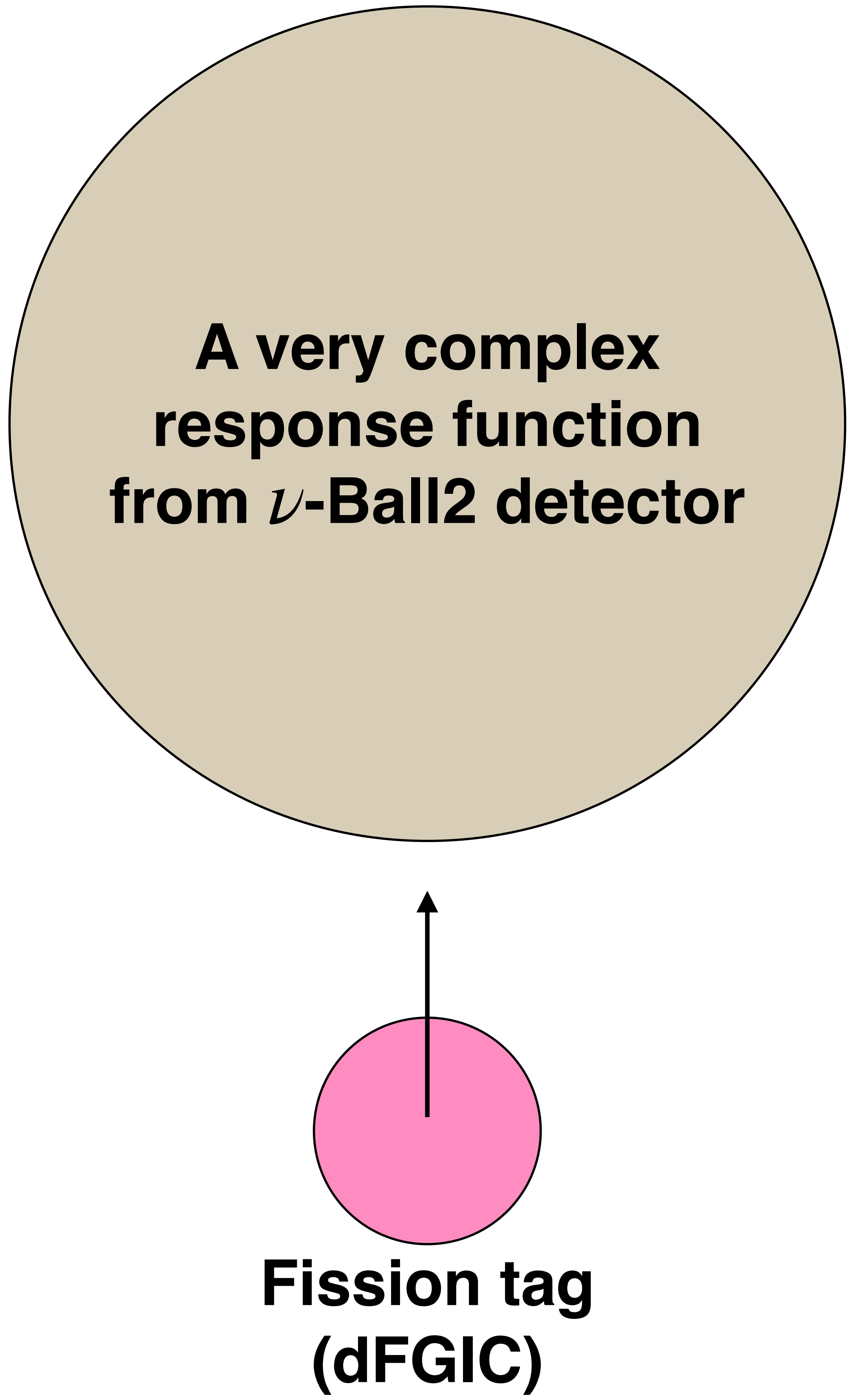
- **Ionisation chamber**



Taken from: https://alto.ijclab.in2p3.fr/en/nu-ball2-online-scientific-workshop-2/



The N-SI-125 experiment setup



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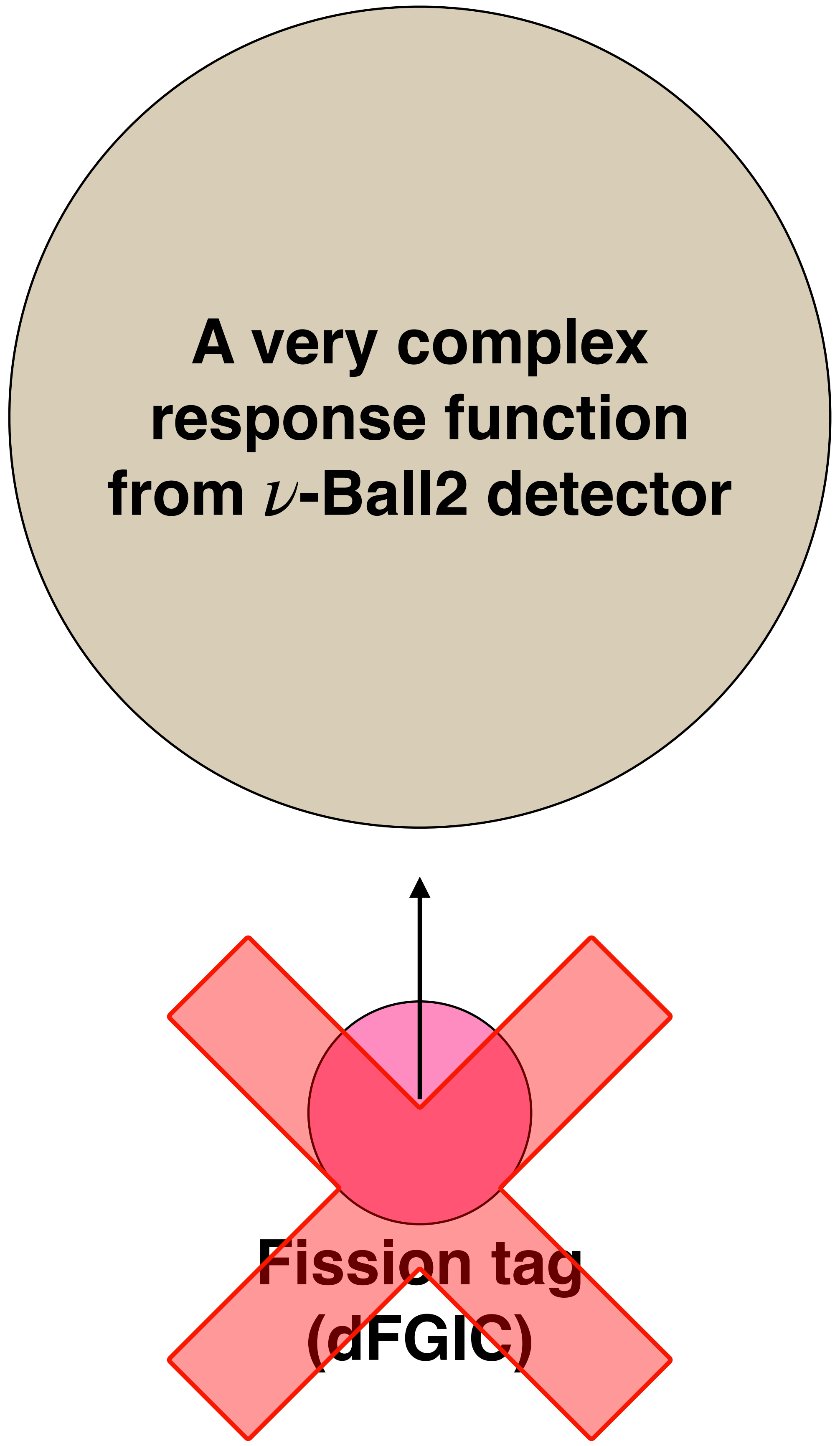


Create a model capable of recognizing fission solely based on detector response function

The N-SI-125 experiment setup

A very complex response function from ν-Ball2 detector

Fission tag (dFGIC)

Classification labels

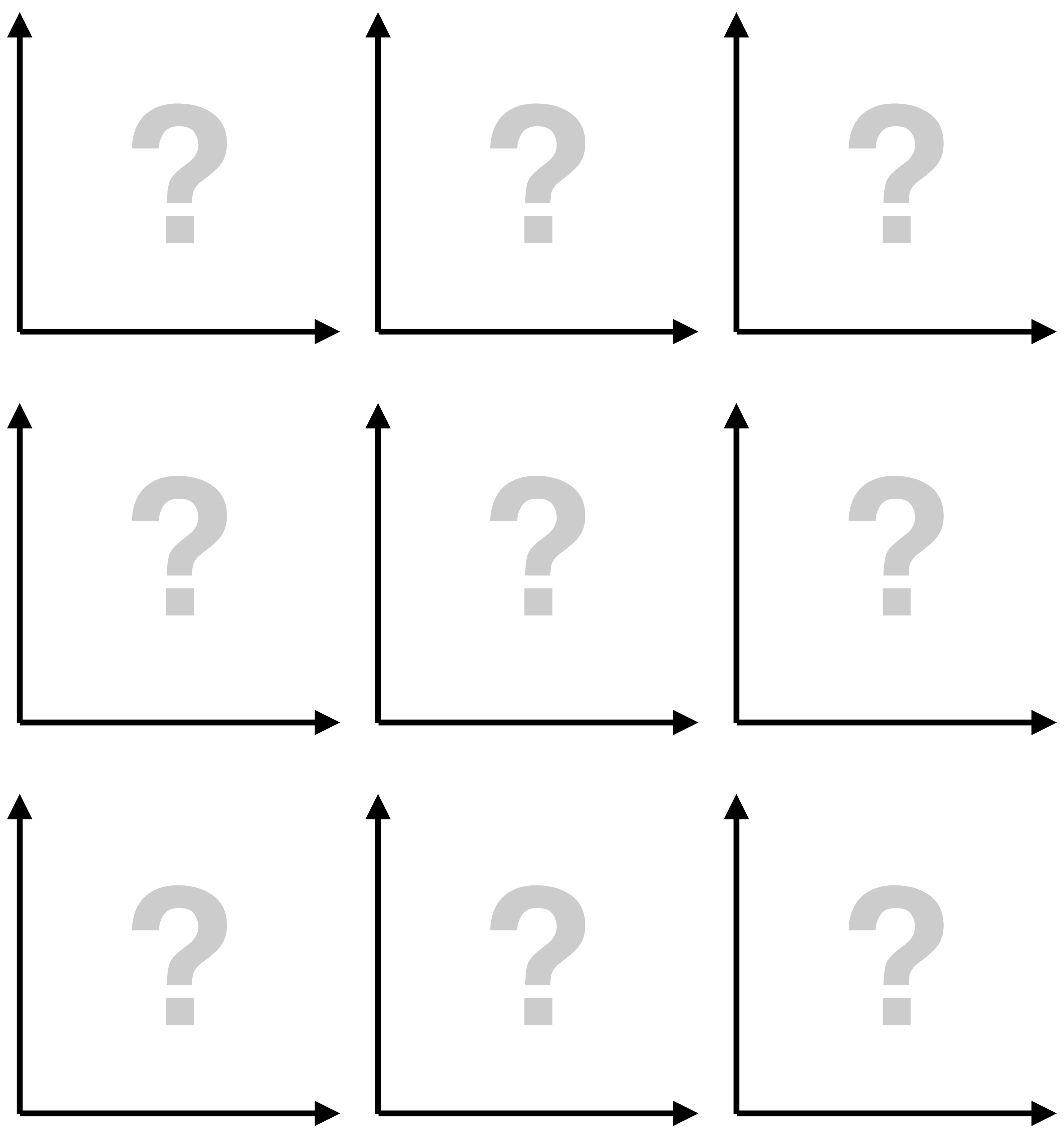
Create a model capable of recognizing fission solely based on detector response function

O_a

2D plots to evaluate which fission observables are more or less relevant for fission recognition.

Fission observables:
- γ multiplicity / energy
- Neutron multiplicity / energy
- Calorimetry
- …

O_b



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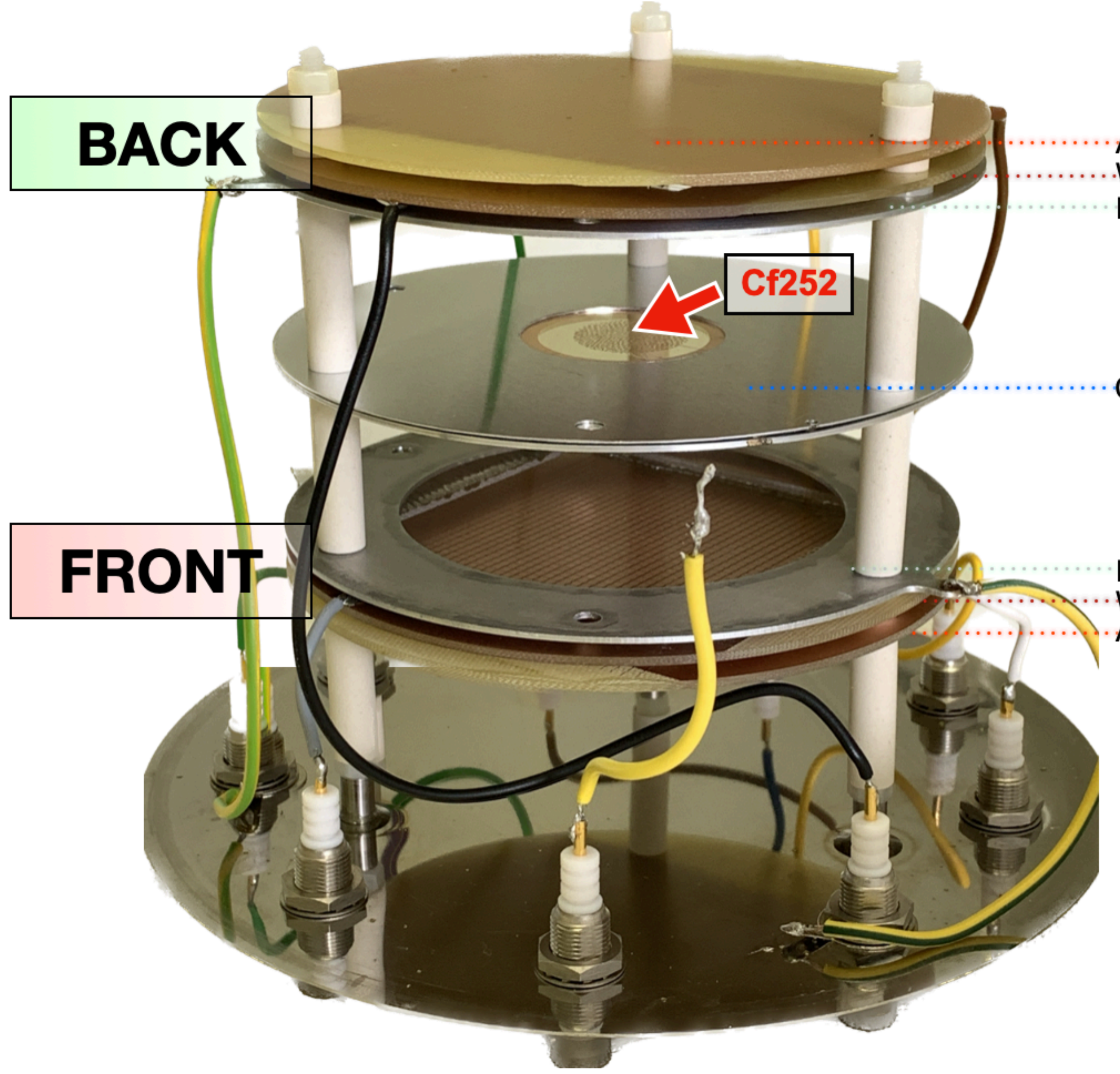
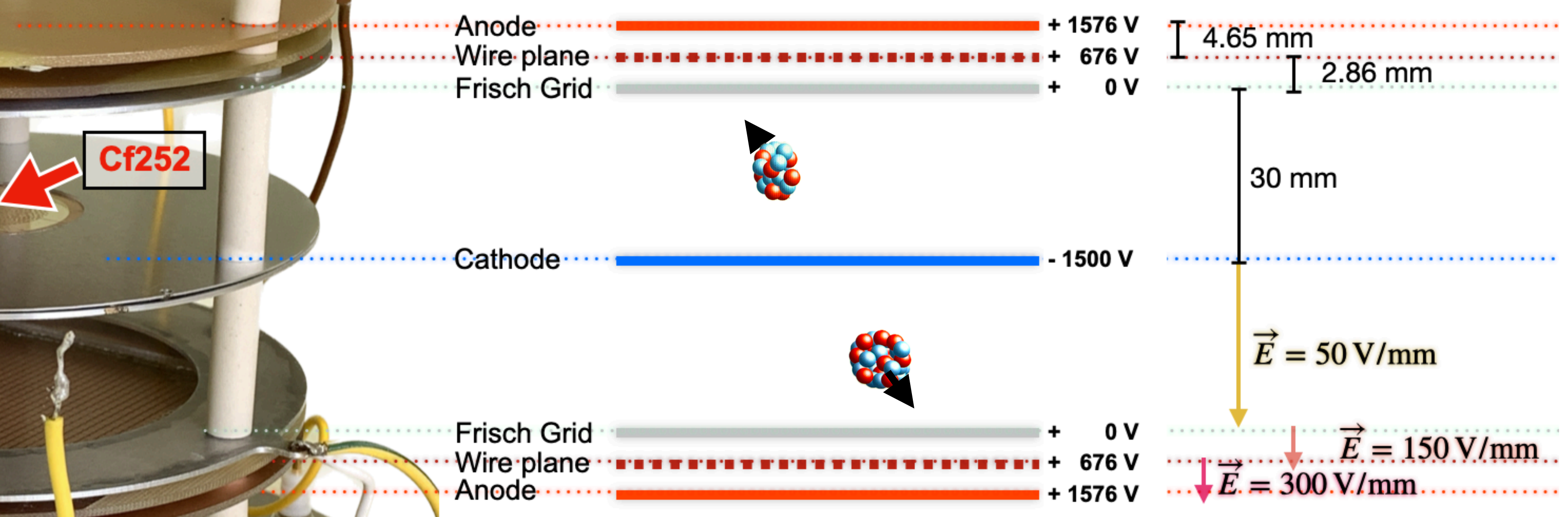
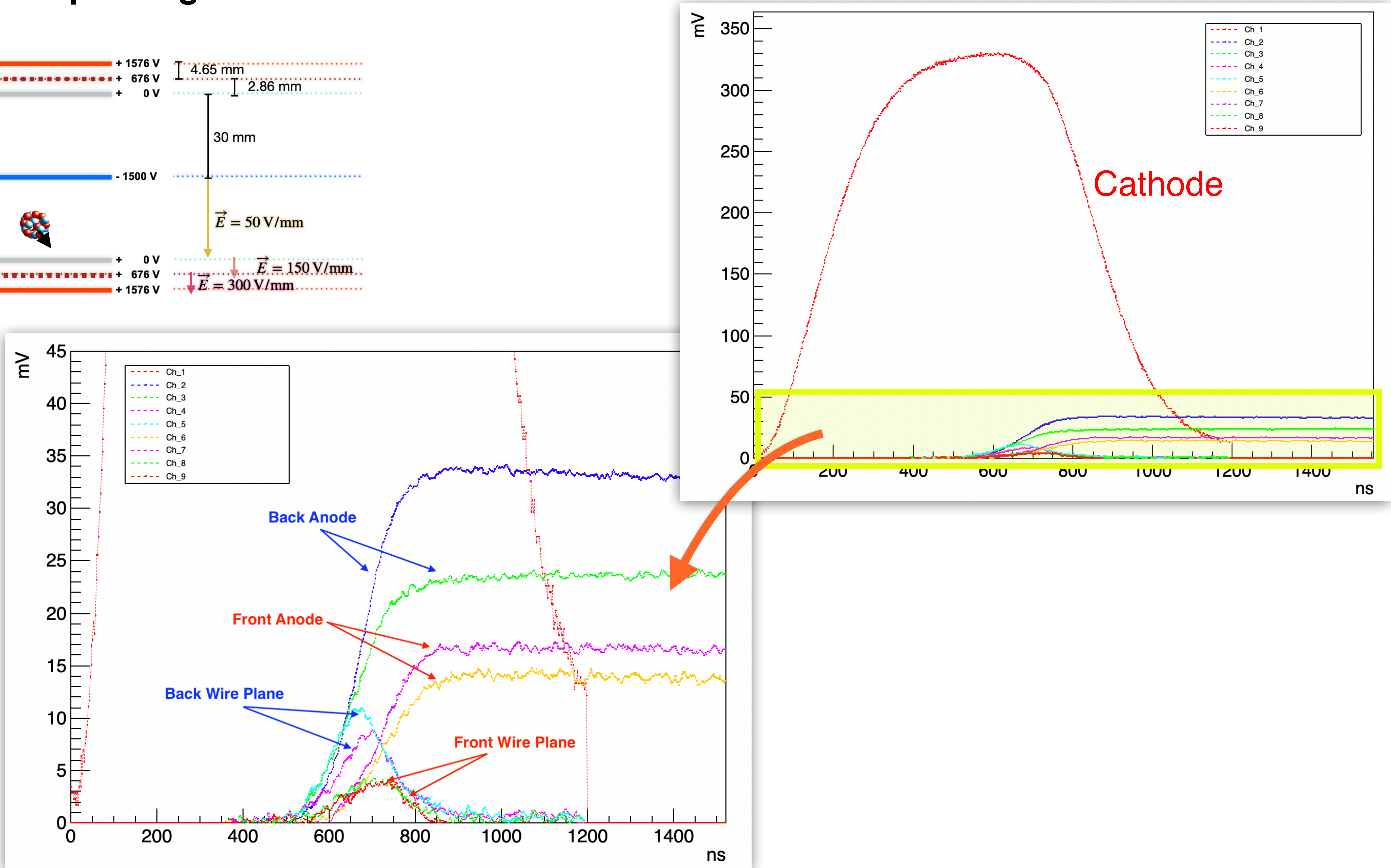
Double Frisch-Grid Ionisation Chamber (dFGIC)

Ionisation chamber signals sampled every 2ns

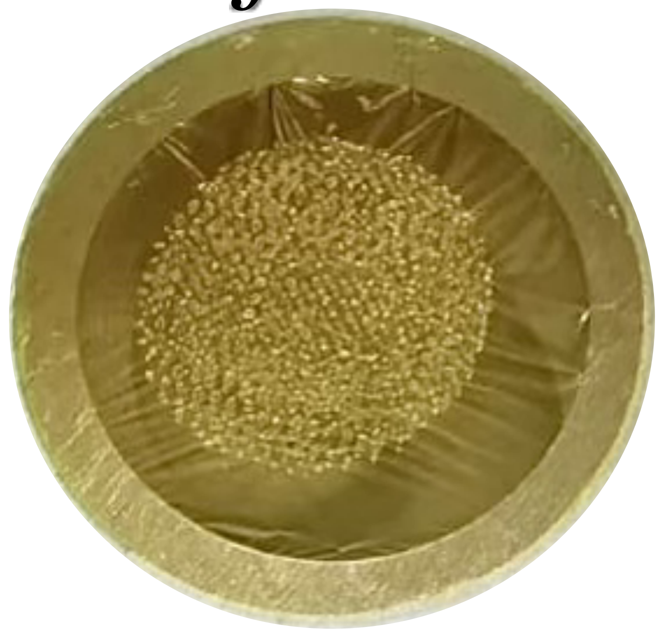
A sampled signal is here referred as « trace »







^{252}Cf source



$96.9\ \%\ \alpha$ decay

$3.1\ \%$ fission

~330 fissions $\cdot\ s^{-1}$

CONTENTS:

Trace analysis

Trace analysis through most frequently used methods

- Moving average algorithm;
- RC filter;
- Signal baseline correction;

→ **BOTH TIME AND ENERGY MEASUREMENTS**

- CR-RC and CR-RC4 shaping filters;
- Trapezoidal shaping filter;
- Signal integration (deposited charge)

→ **« ENERGY » MEASUREMENTS**

- Constant Fraction Discrimination (CFD) **TIME MEASUREMENTS**

Trace analysis

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- Constant Fraction Discrimination (CFD)

TIME CONSUMING

Trace analysis takes **~2s per 1k fission events**

3 weeks of data acquisition -> 600M events

300 h or 13 days to process the traces

=> yes, we are working with an optimized multi-threading algorithm

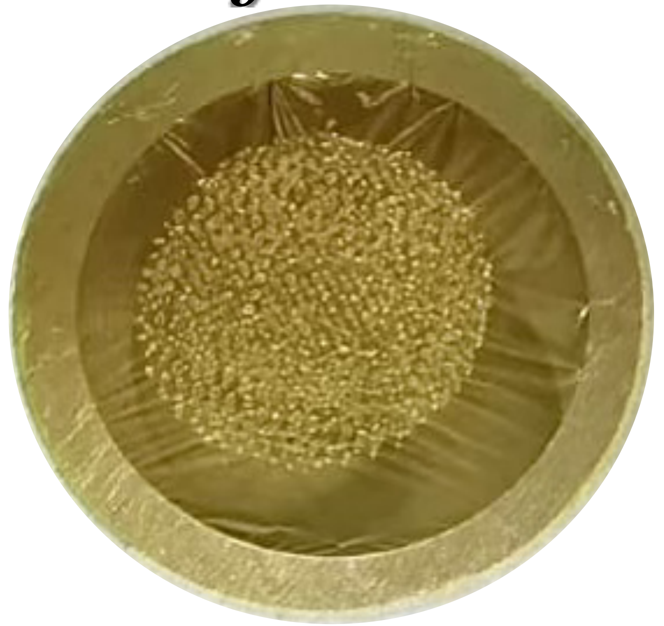
Cathode time resolution: $R(t)$ = ~5 ns

Innovative methods to explore if…

… we can reduce the computational cost

… we can improve the cathode time resolution

^{252}Cf **source**



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Neural Networks

Supervised vs. unsupervised learning

Regression vs. classification model

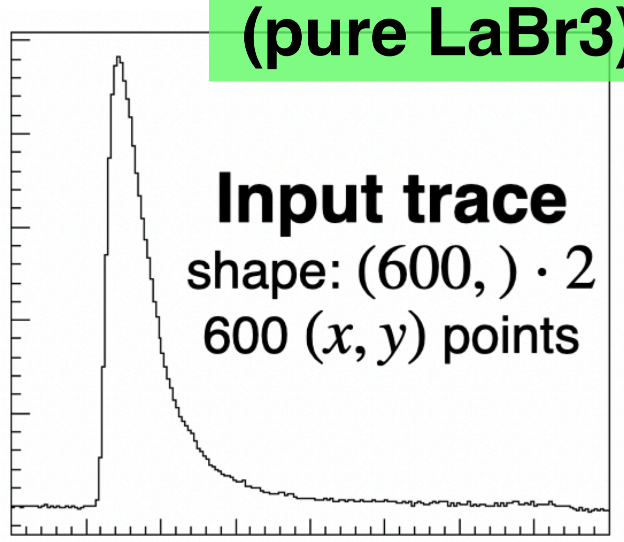
Hyperparameters

- Activation function
- Batch size
- Epochs
- Learning rate
- Loss function
- Number of hidden layers
- Number of neurons per layer

Parameters

- Weights and biases

Validate NN for THALIA (pure LaBr3) signal trigger



Input trace
shape: $(600,) \cdot 2$
600 (x, y) points

FCNN →

Hidden layer 1
shape: $(600,)$
$actv.f$: ReLu or sigmoid

FCNN →

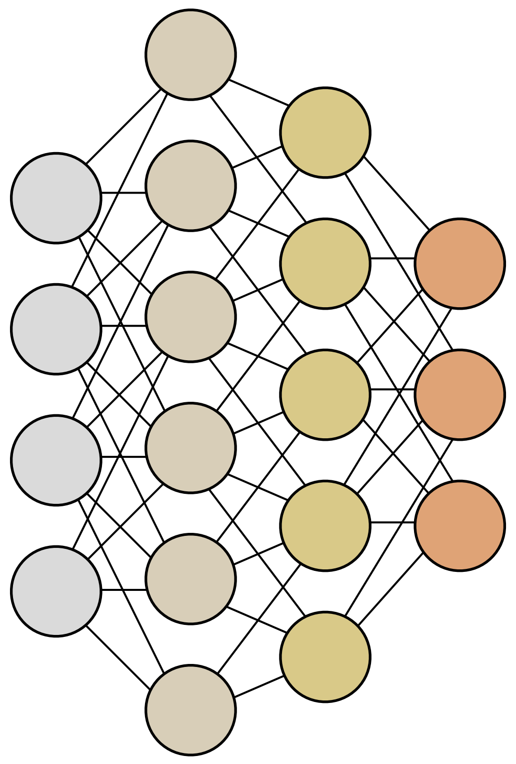
Hidden layer 2
shape: $(600,)$
$actv.f$: ReLu or sigmoid

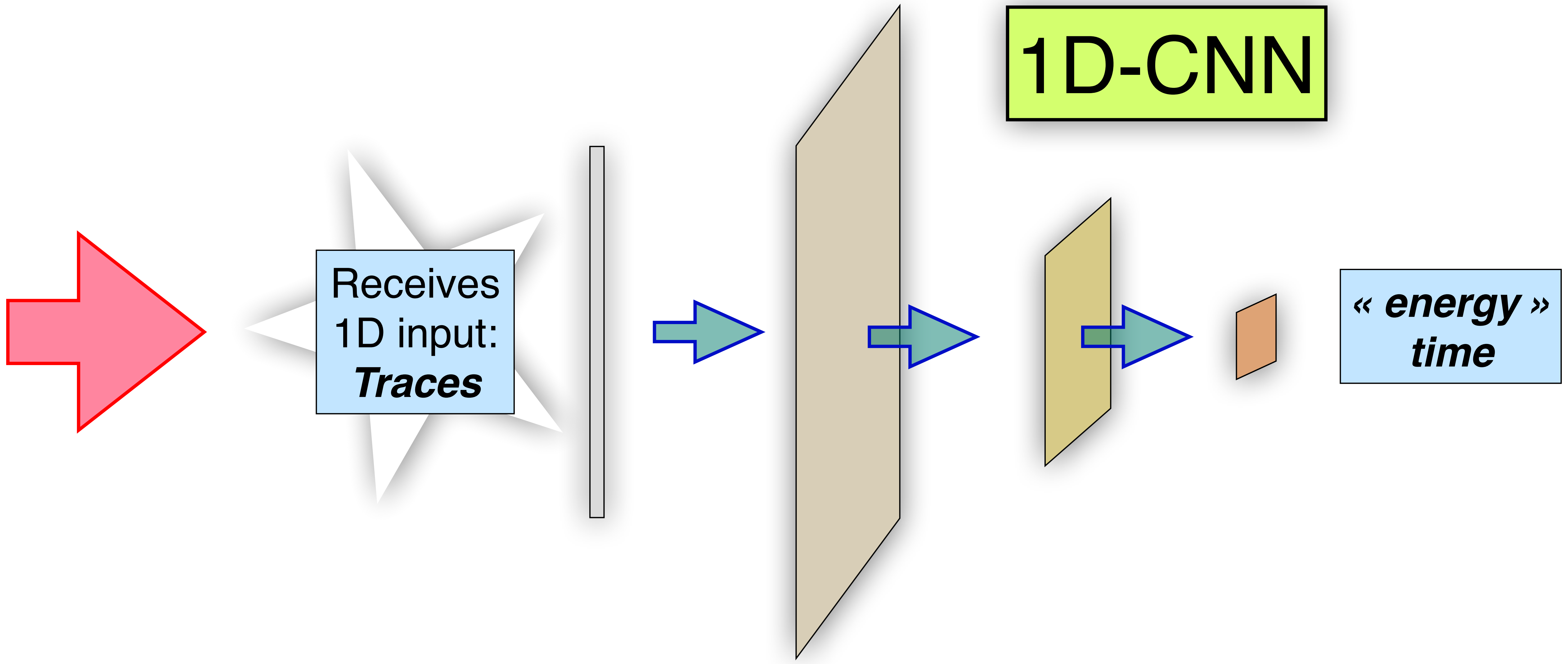
FCNN →

Outputs:
shape: $(2,)$
(« energy », « time »)

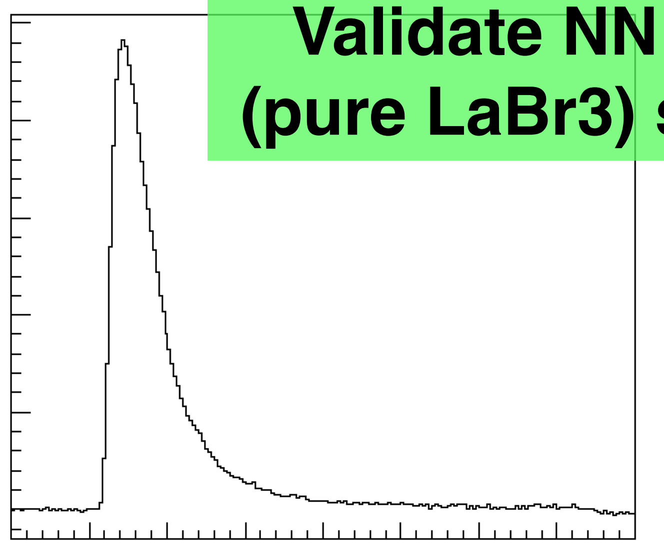
FCNN

Energy resolution: **ok**
Time resolution: **unsatisfactory**





CNN 1D models for trace analysis



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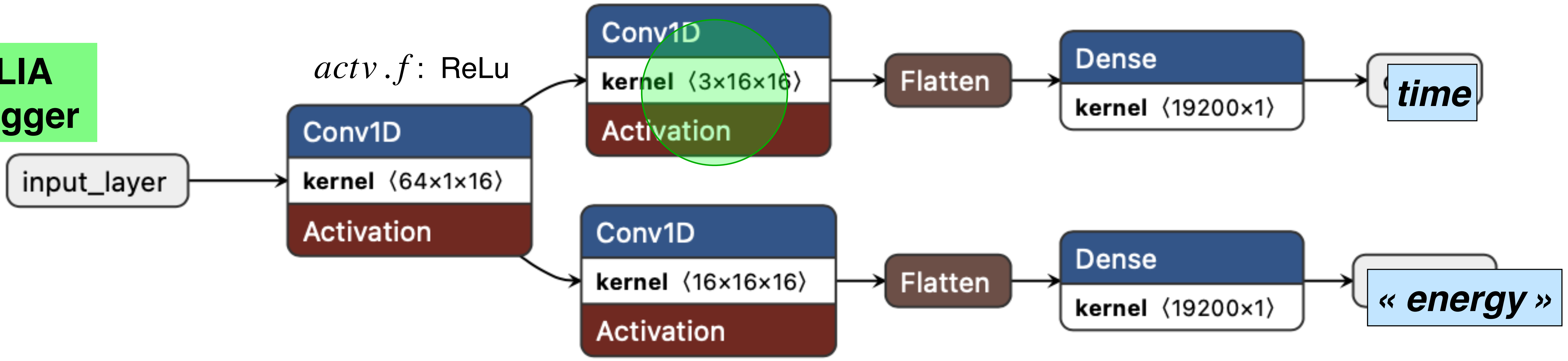
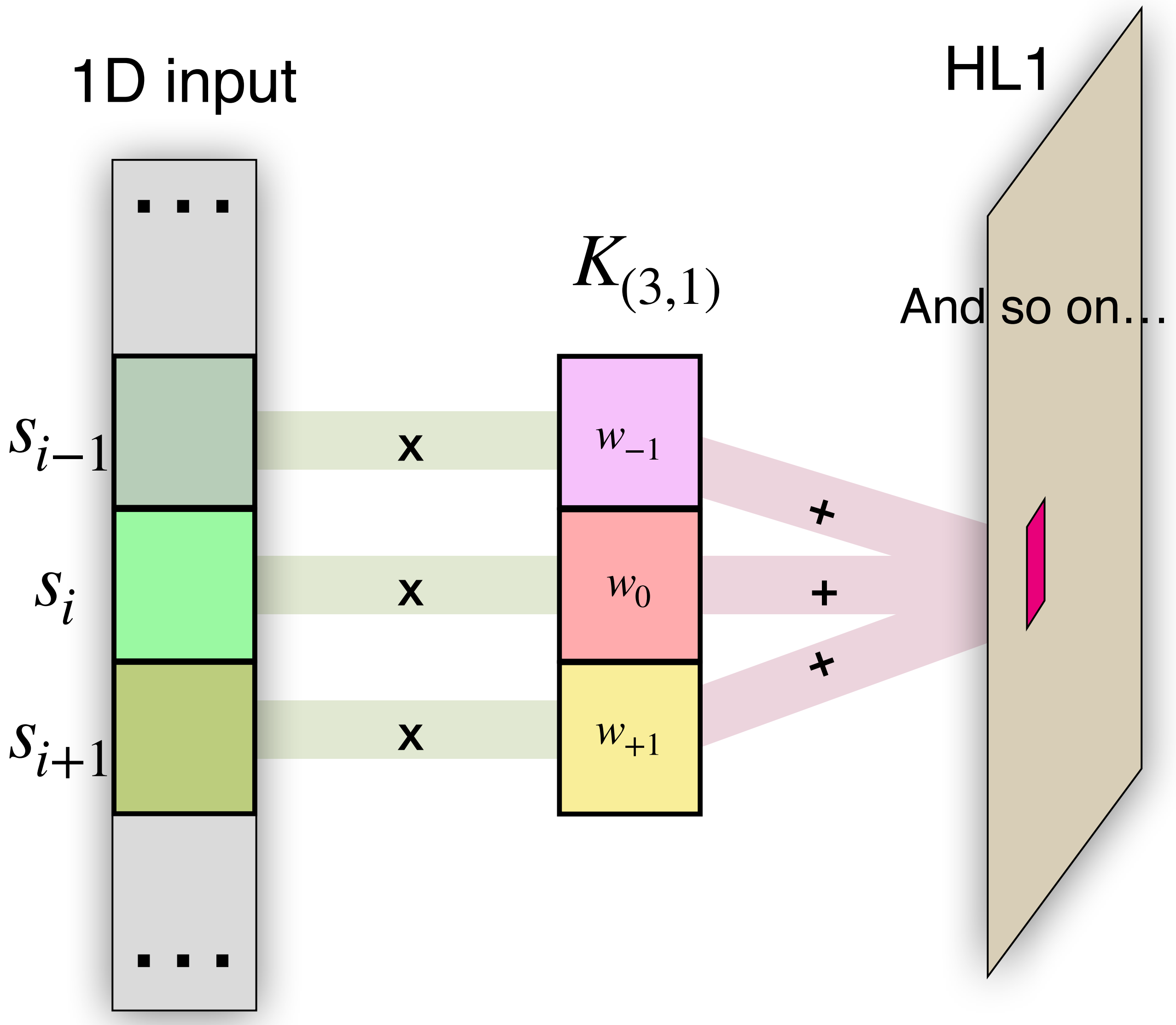
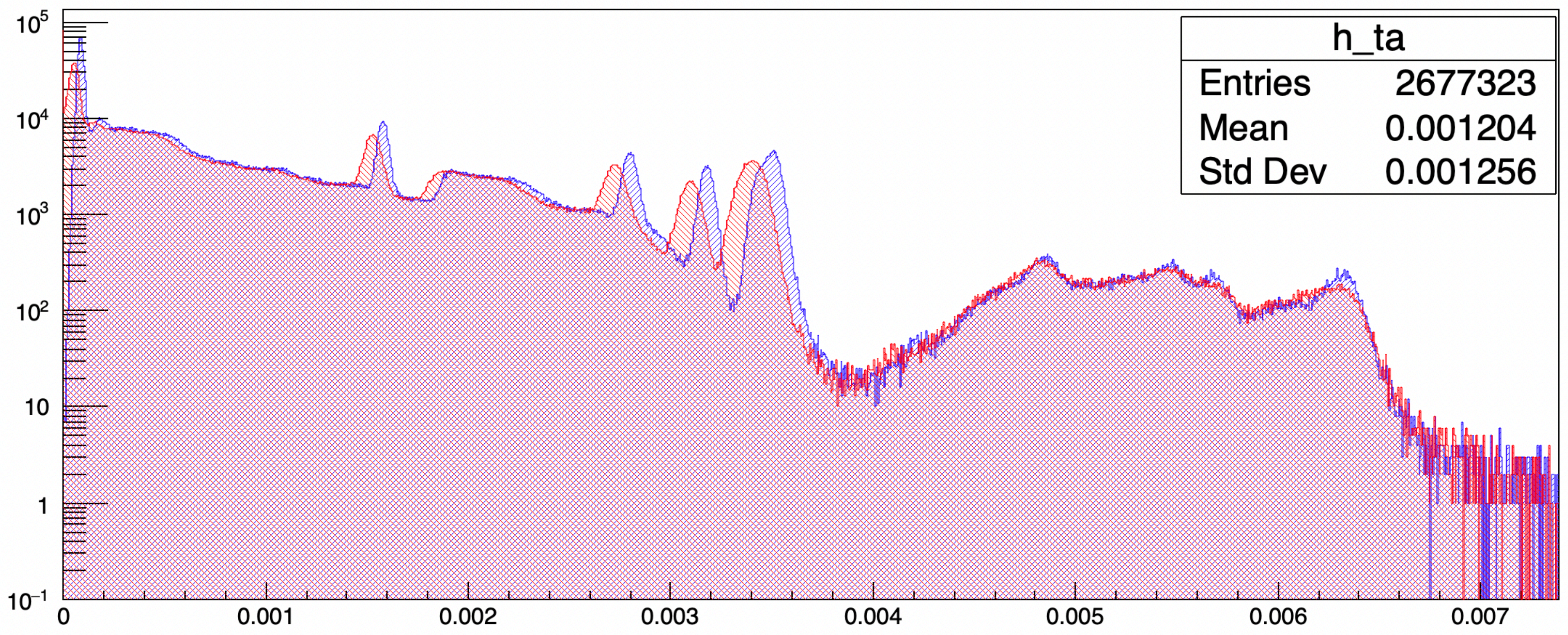


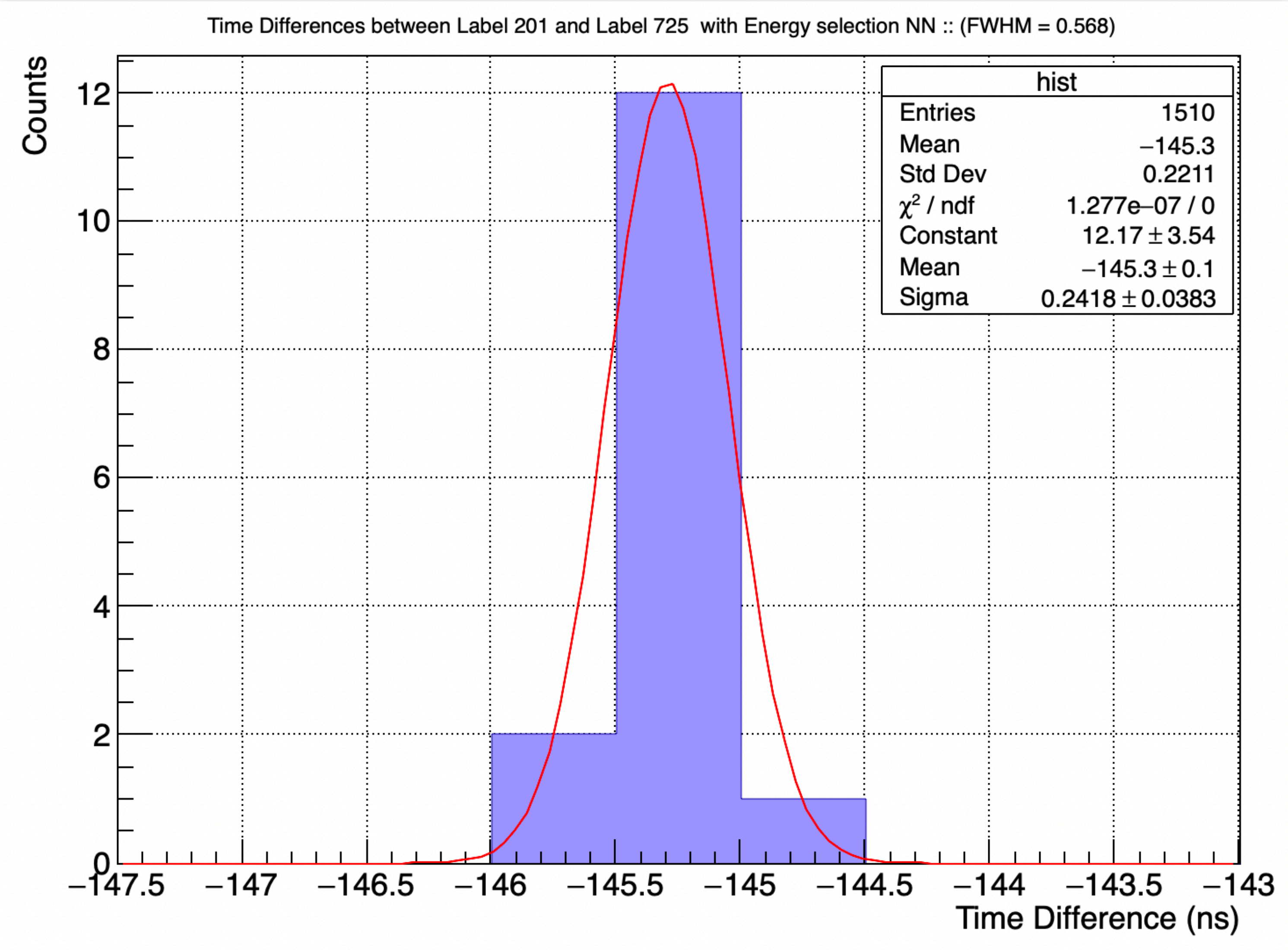
*** Loss: MSE**

31.7 keV @ 1170 keV
$R(t)$ = 569 ps

With NN:
46.4 keV @ 1170 keV
$R(t)$ = 568 ps







CNN 1D models for trace analysis

- *Very* degraded cathode time resolution
- Target values might not be optimal

Loss: MSE

- Automatized search for model / model tuner
- Custom loss function: **time resolution**

CNN 1D models for trace analysis

- Very degraded cathode time resolution
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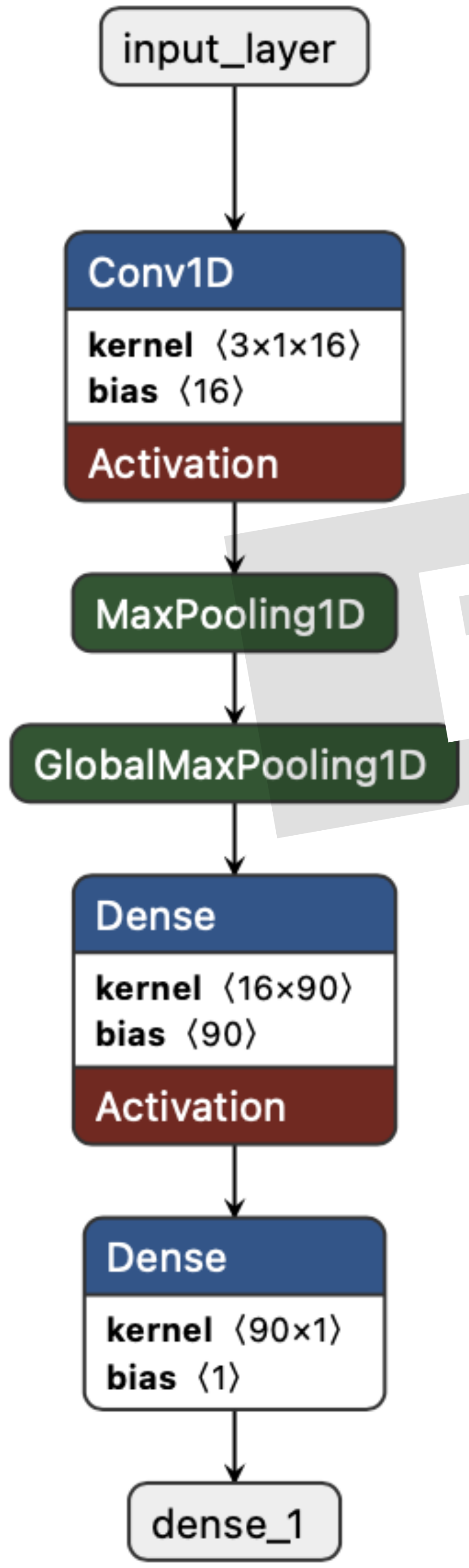
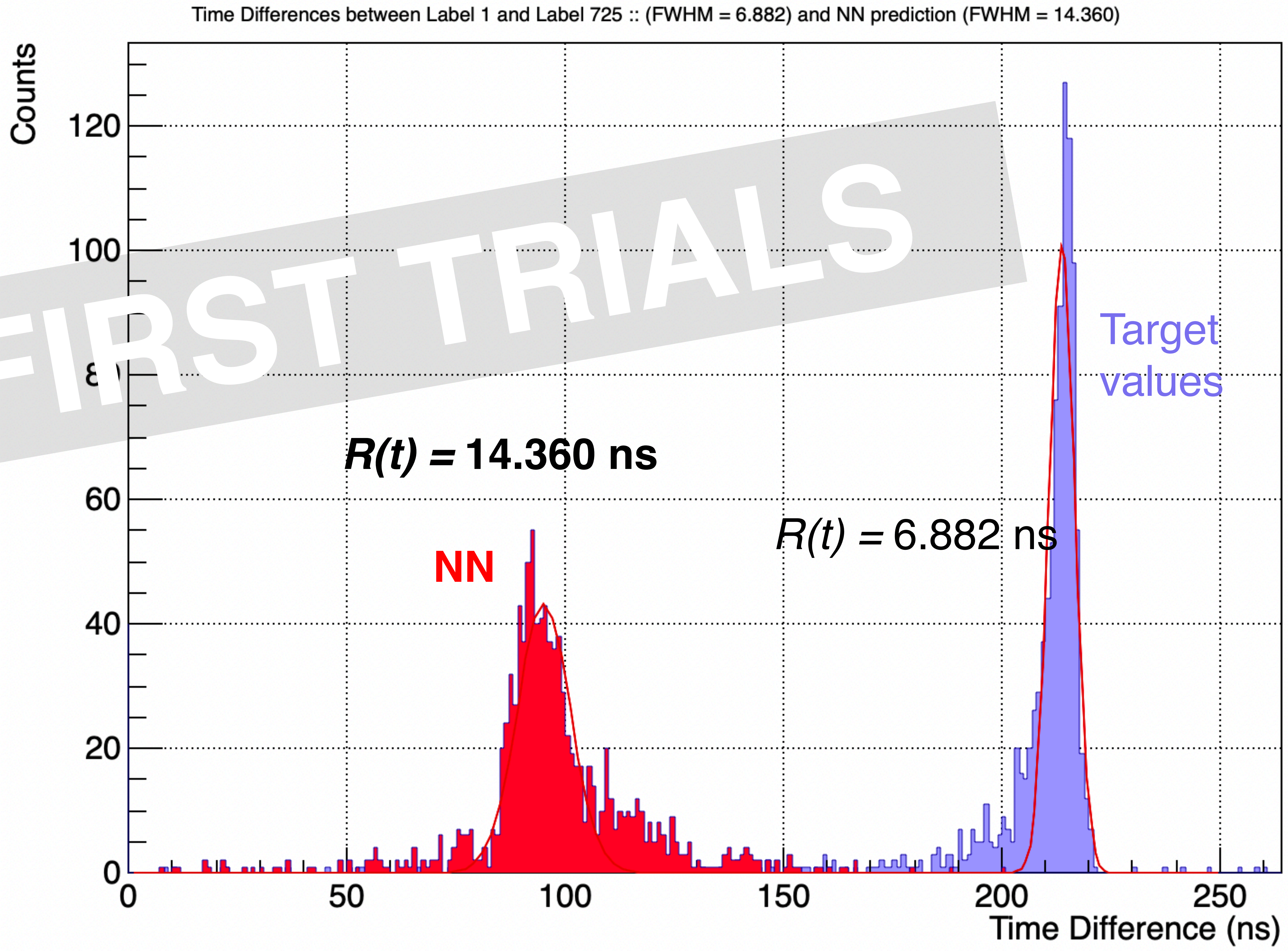
Problems:

- Keras/Tensorflow environment constraints
- Not enough statistics to follow this approach

Next steps:

- Build model « by hand »
- Perform new acquisition to validate models *(experiment with dFGIC ongoing)*
- Build robust CFD NN -> *also requires more data to validate with time resolution*





Perspectives

Short term

- Converge to a more robust NN model for trace analysis
- Implement a complete model for dFGIC adapting hyperparameters
- **Detailed evaluation of computational costs**
  - Prediction time
  - Number and complexity of operations …

Long term

- Develop new AI algorithms for fission trigger based on ν-Ball2 response function
- Evaluate the correlation between fission observables such as energy and multiplicity of neutrons and gammas for fission recognition

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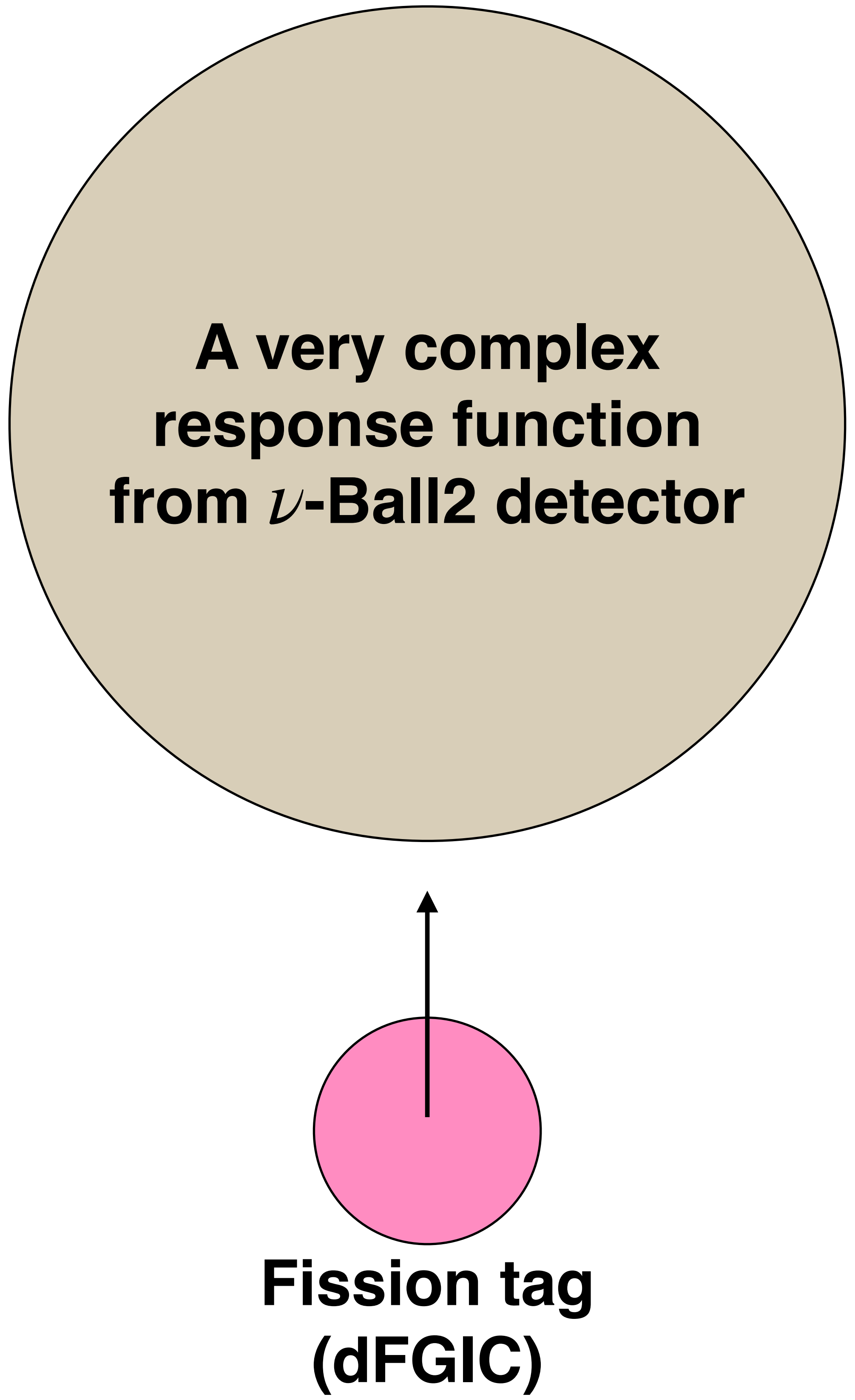
The N-SI-125 experiment setup



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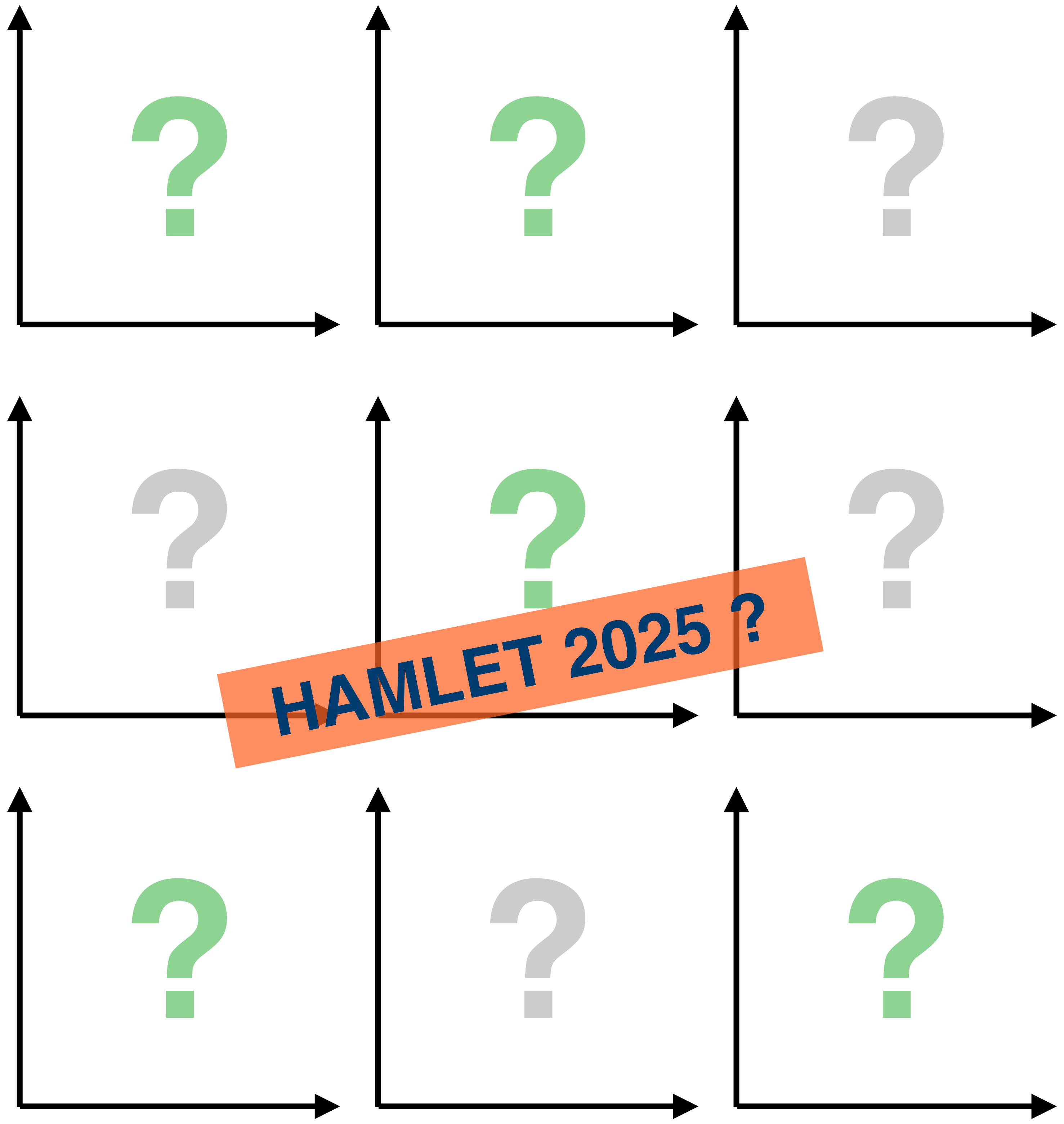

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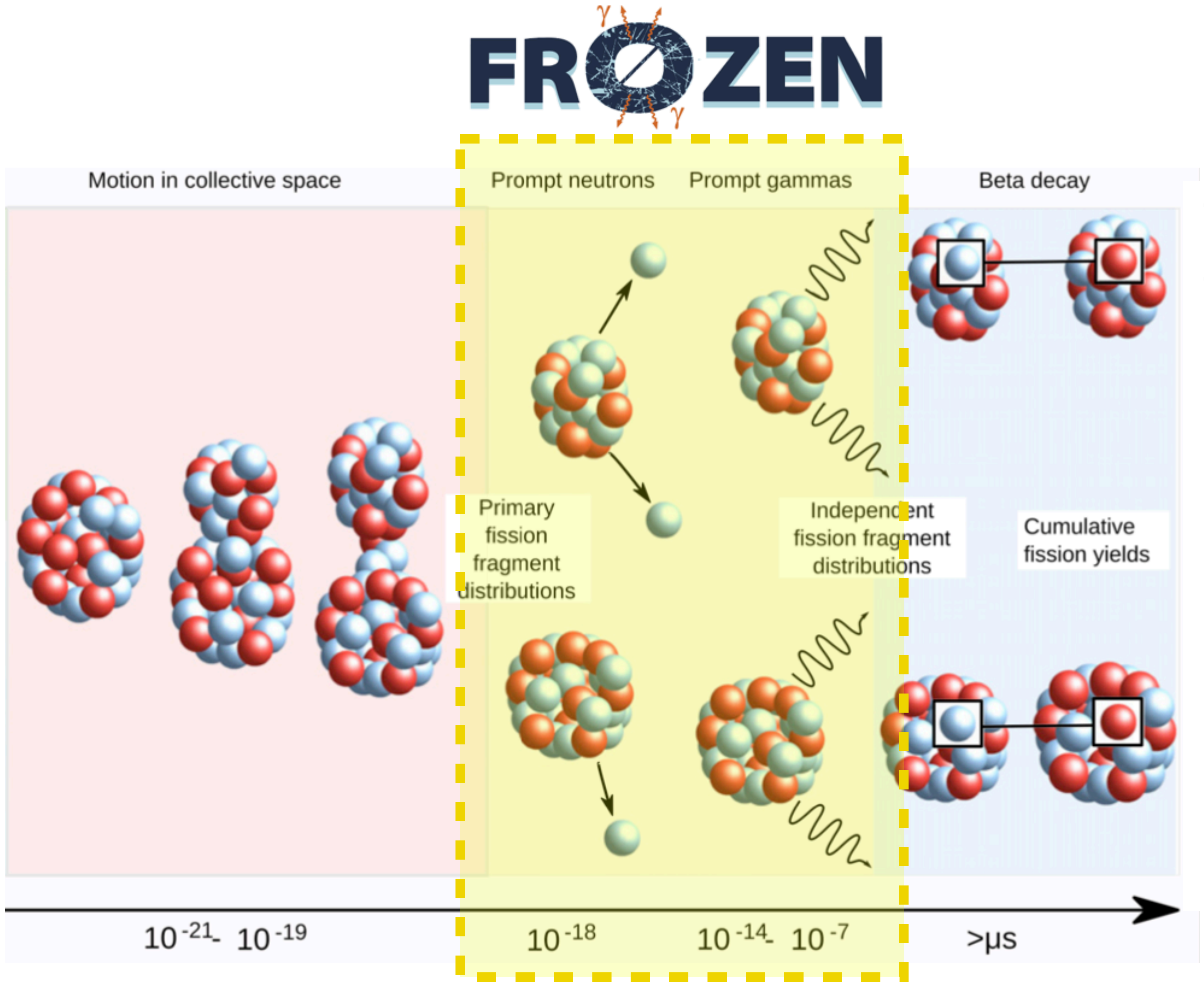
- BACKUP SLIDES

Physics motivation for the FRØZEN project



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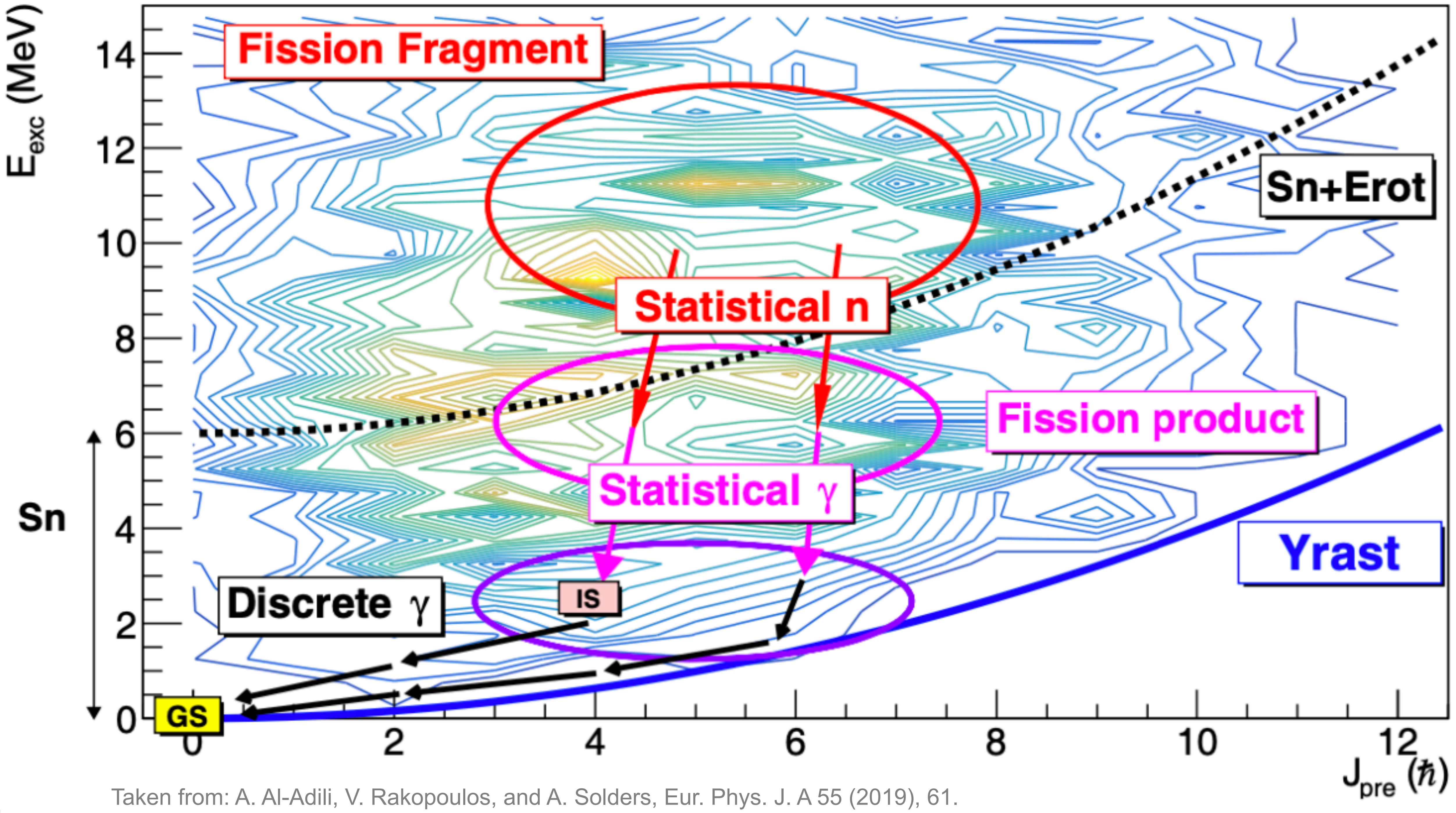

Taken from: A. Al-Adili, V. Rakopoulos, and A. Solders, Eur. Phys. J. A 55 (2019), 61.

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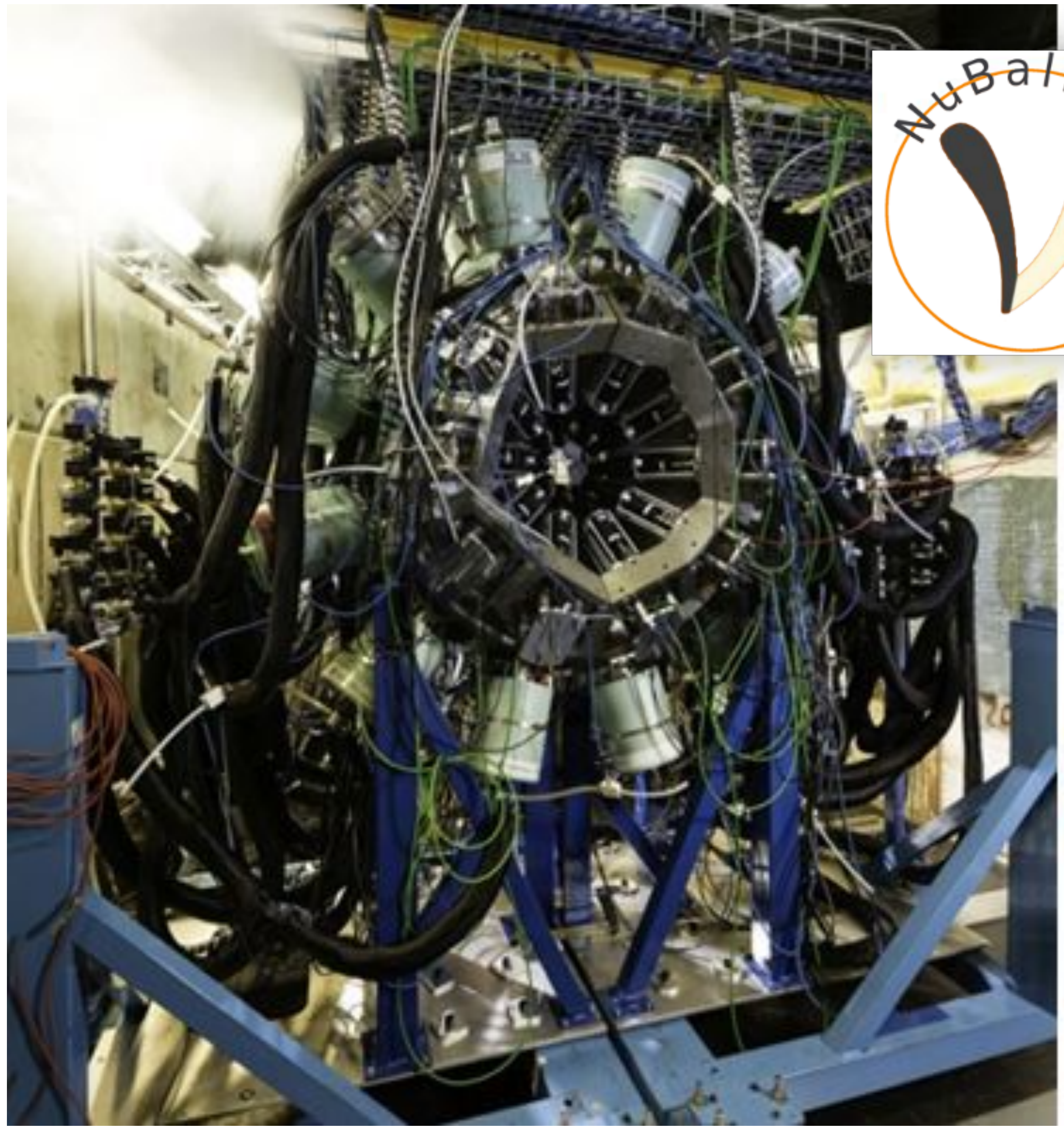

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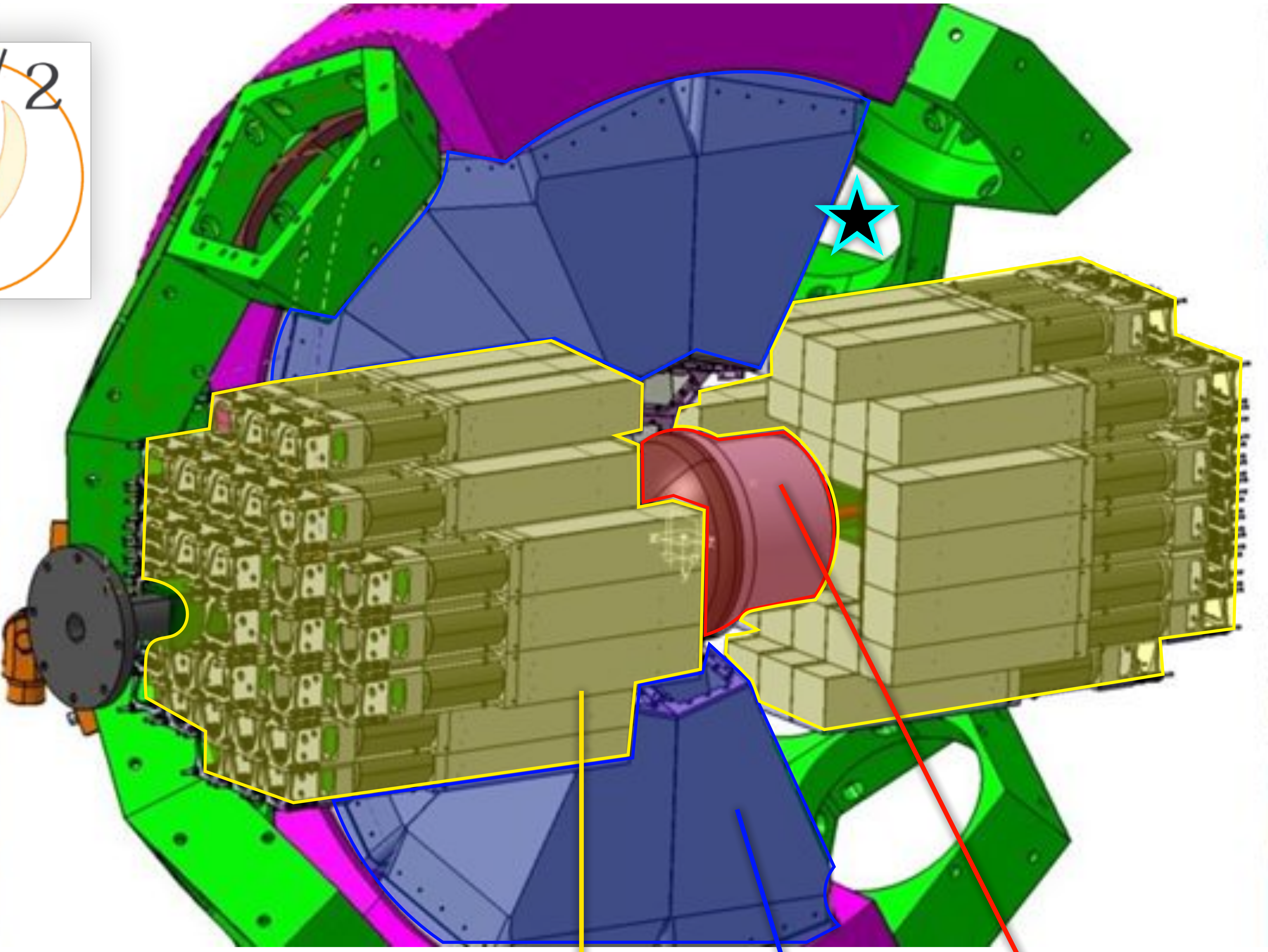


ALTO
Accélérateur Linéaire auprès du Tandem d'Orsay

Gamma detection
energy and multiplicity

24 High-Purity Germanium clovers (HPGe)

PARIS array
72 phoswhiches La(Ce)Br_3:NaI

Thalia LaBr3

Neutron detection
energy and multiplicity

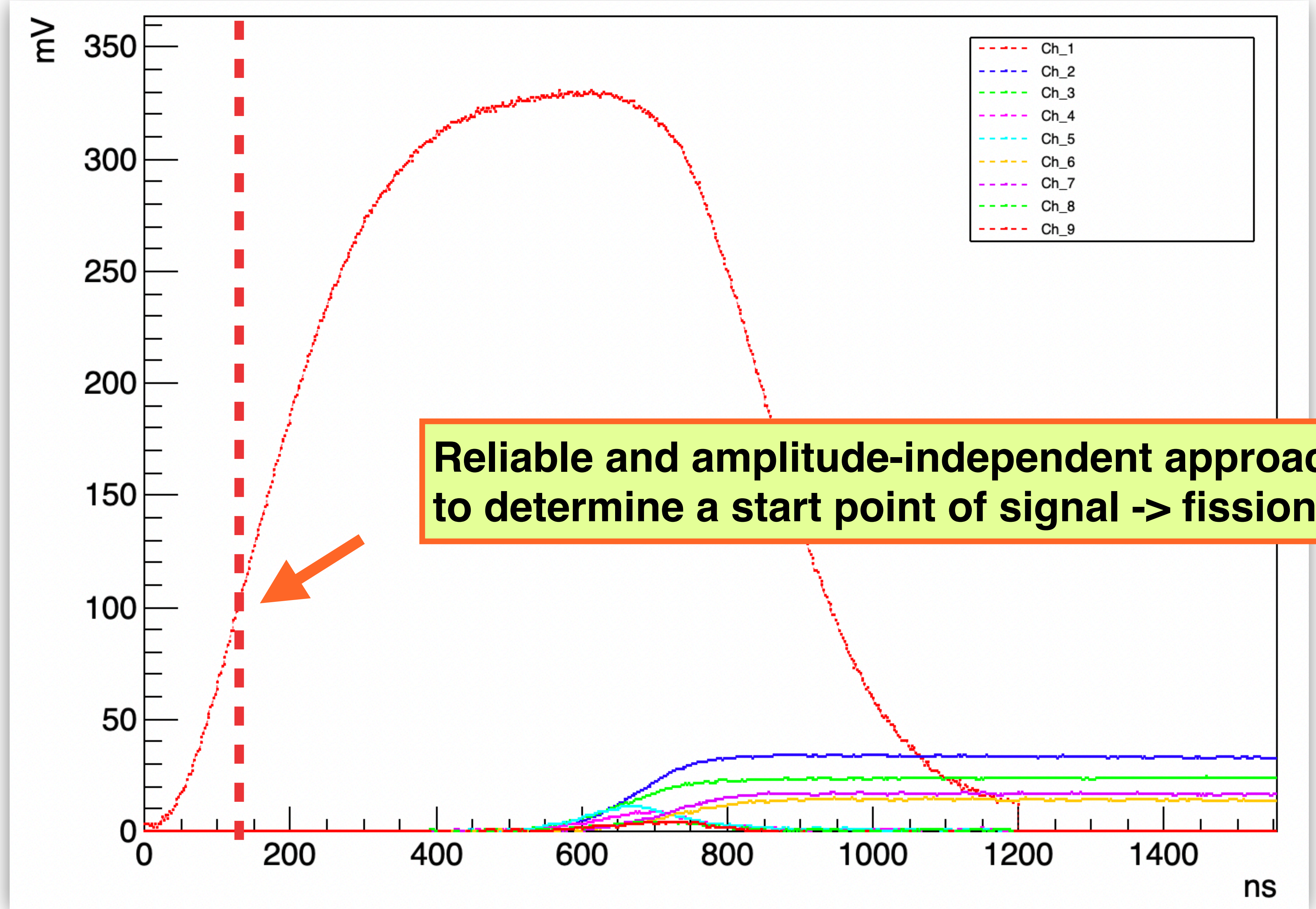
PARIS array

Thalia LaBr3

Fission fragments detection

Ionisation chamber

Constant Fraction Discrimination (CFD)

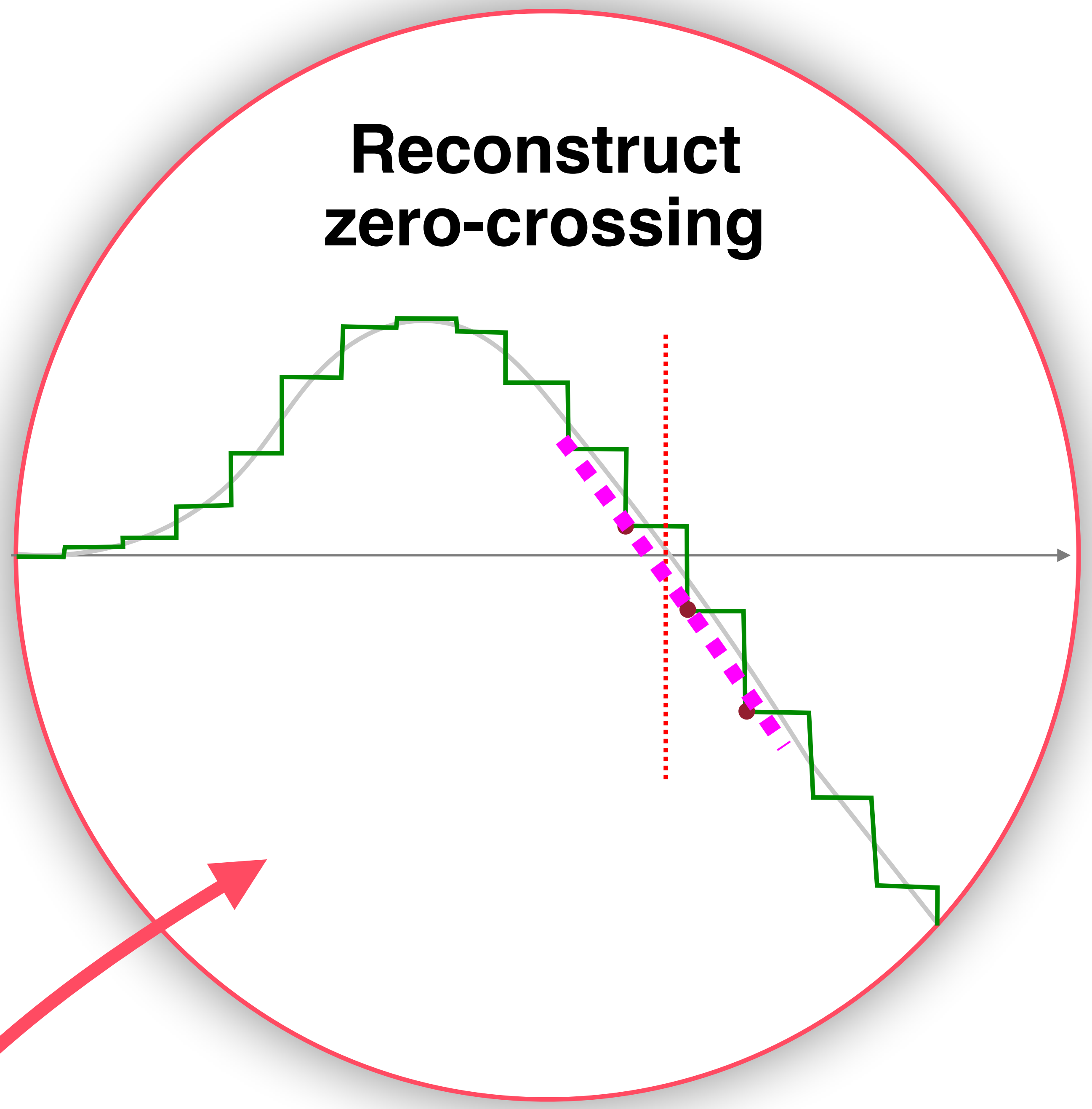


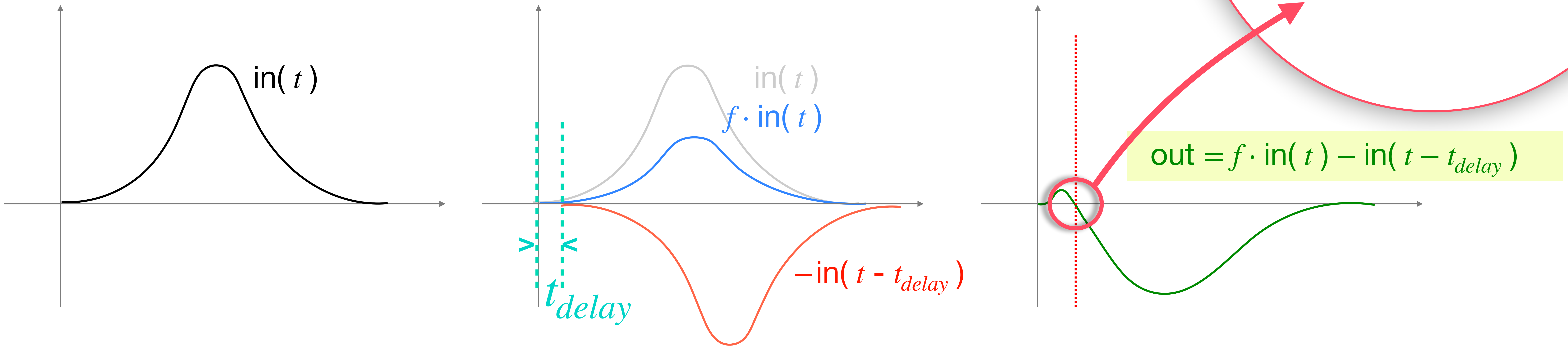
Reliable and amplitude-independent approach to determine a start point of signal -> fission event

CFD CONSTRAINT:

$$t_{delay} > t_r \cdot (1 - f)\,,$$

where t_r is the signal rise time

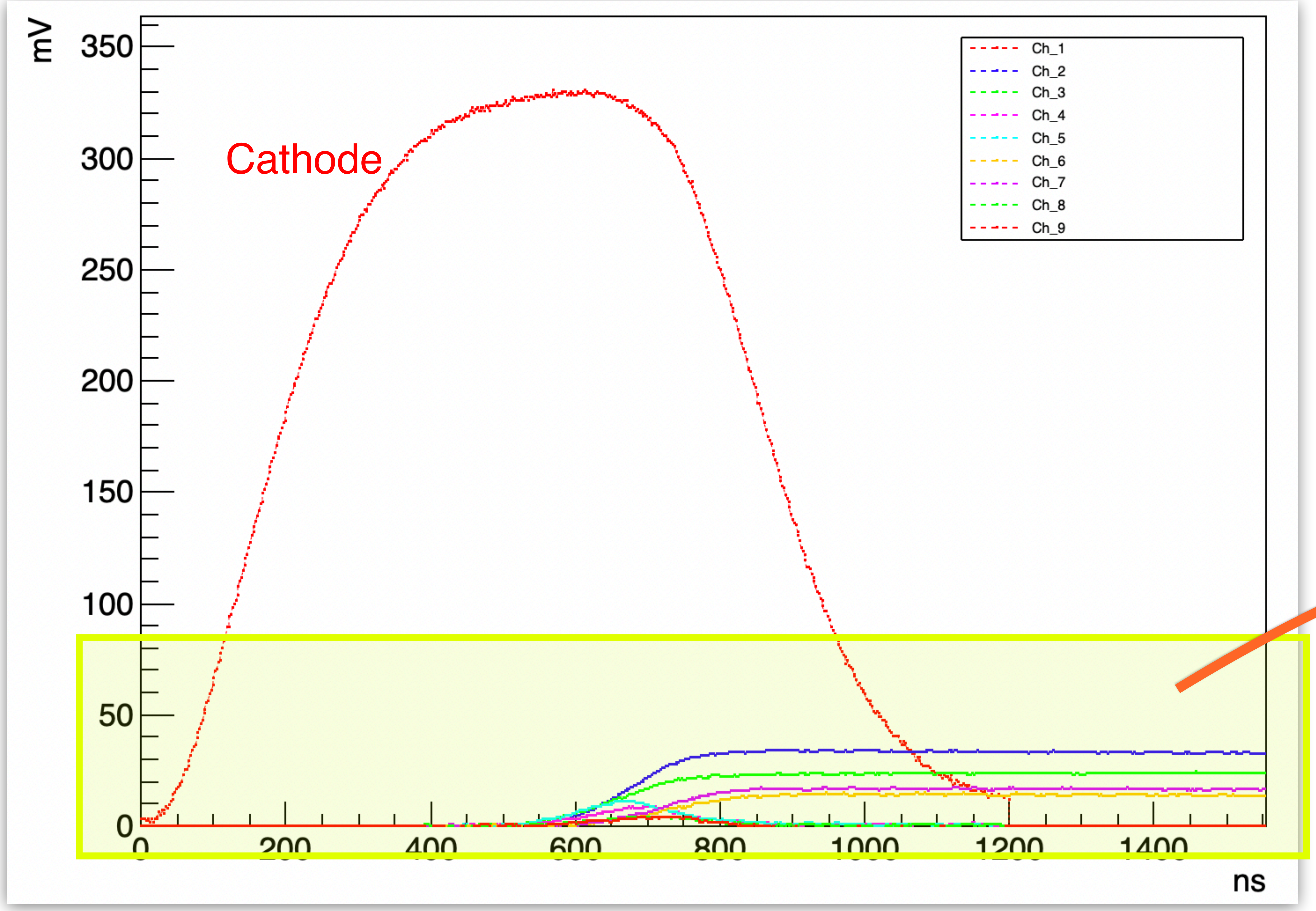


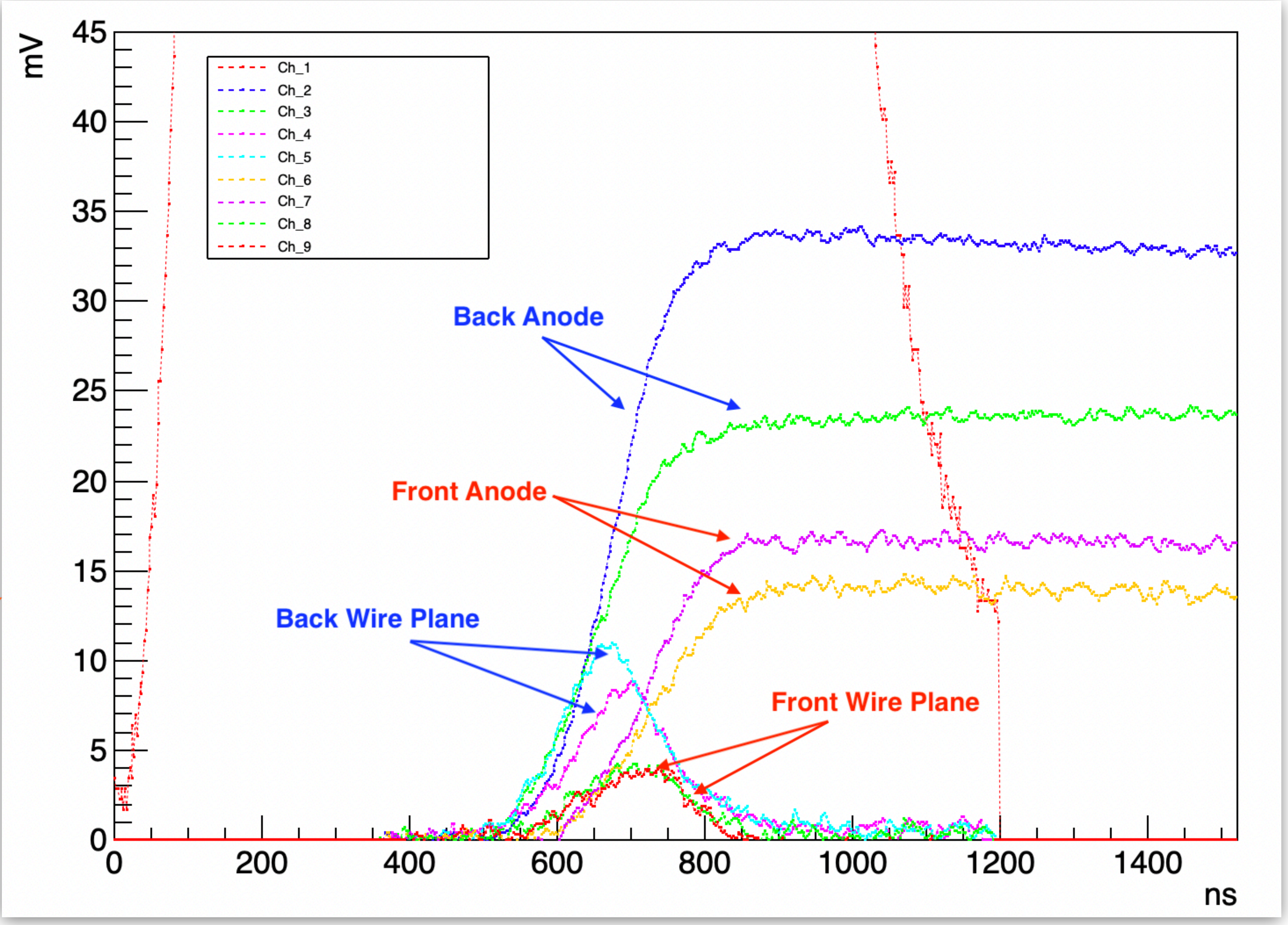


Double Frisch-Grid Ionisation Chamber (dFGIC)

Ionisation chamber signals sampled every 2ns

A sampled signal is here referred as « trace »





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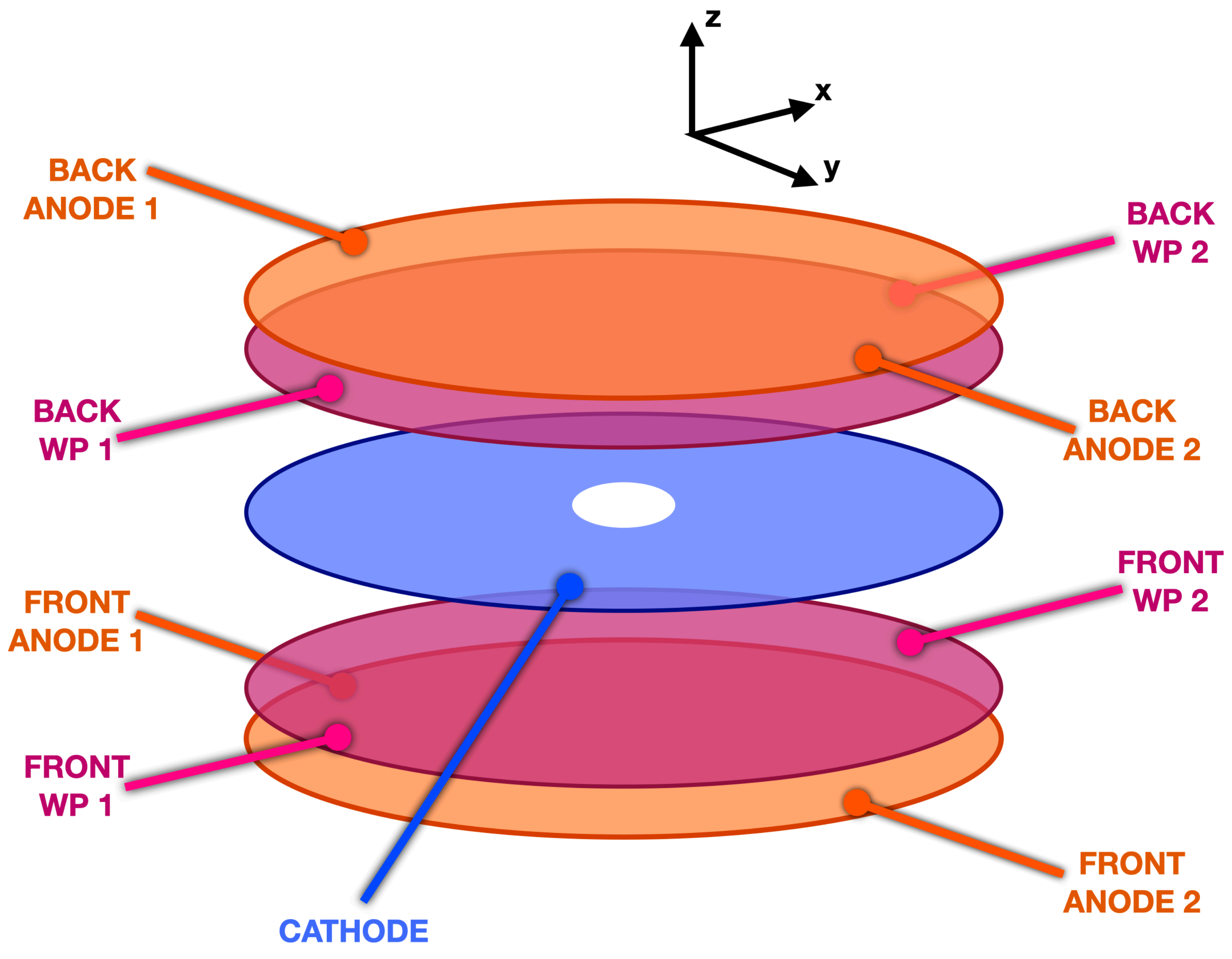
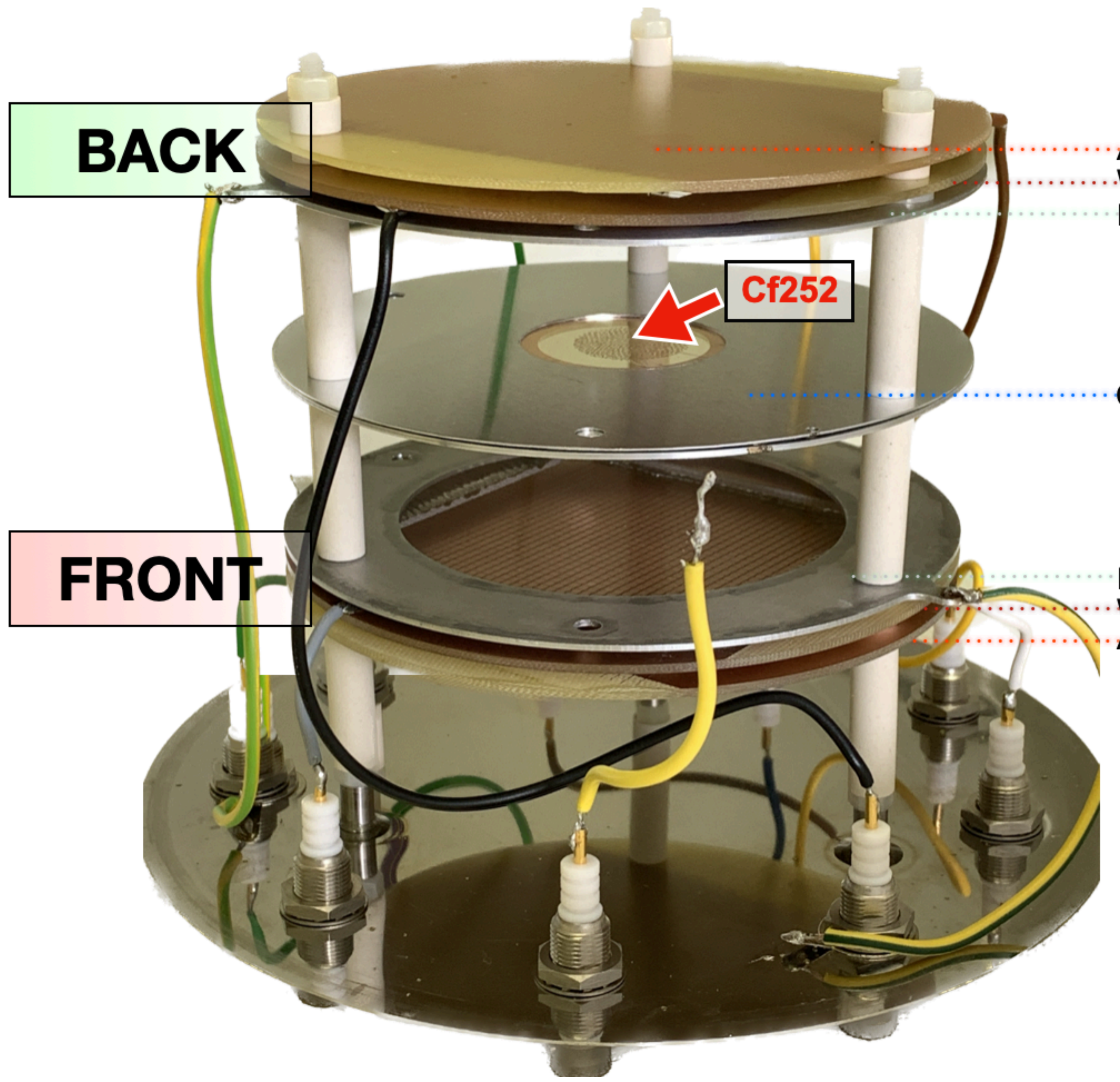
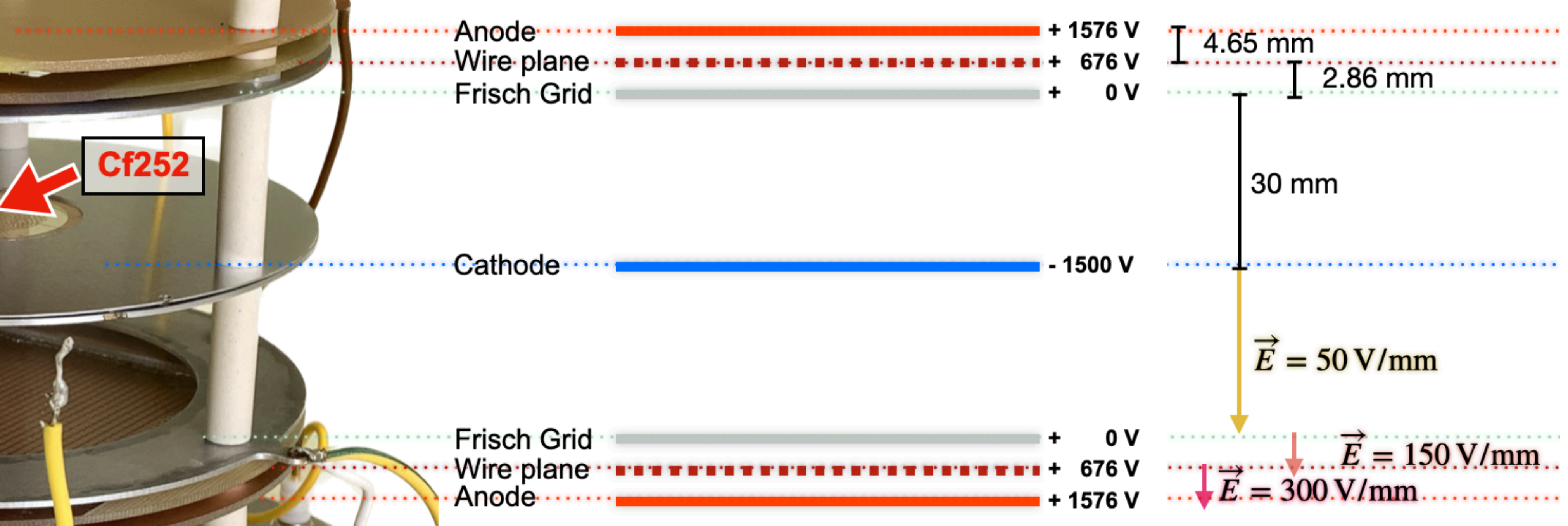






CFD for a reliable cathode signal trigger: start of our fission event

CFD* CONSTRAINT:

$$t_{delay} > t_r \cdot (1 - f),$$

where t_r is the signal rise time

$$\bar{x} = k_x \frac{P_1 - P_2}{P_1 + P_2}, \quad \bar{y} = k_y \frac{A_1 - A_2}{A_1 + A_2}$$

calibration constants

$$\bar{z} = v_d \cdot (\bar{t}_{(0^\circ,0^\circ)} - \bar{t}_{(\theta_x^\circ,\theta_y^\circ)})$$

average electron drift time

electron drift velocity

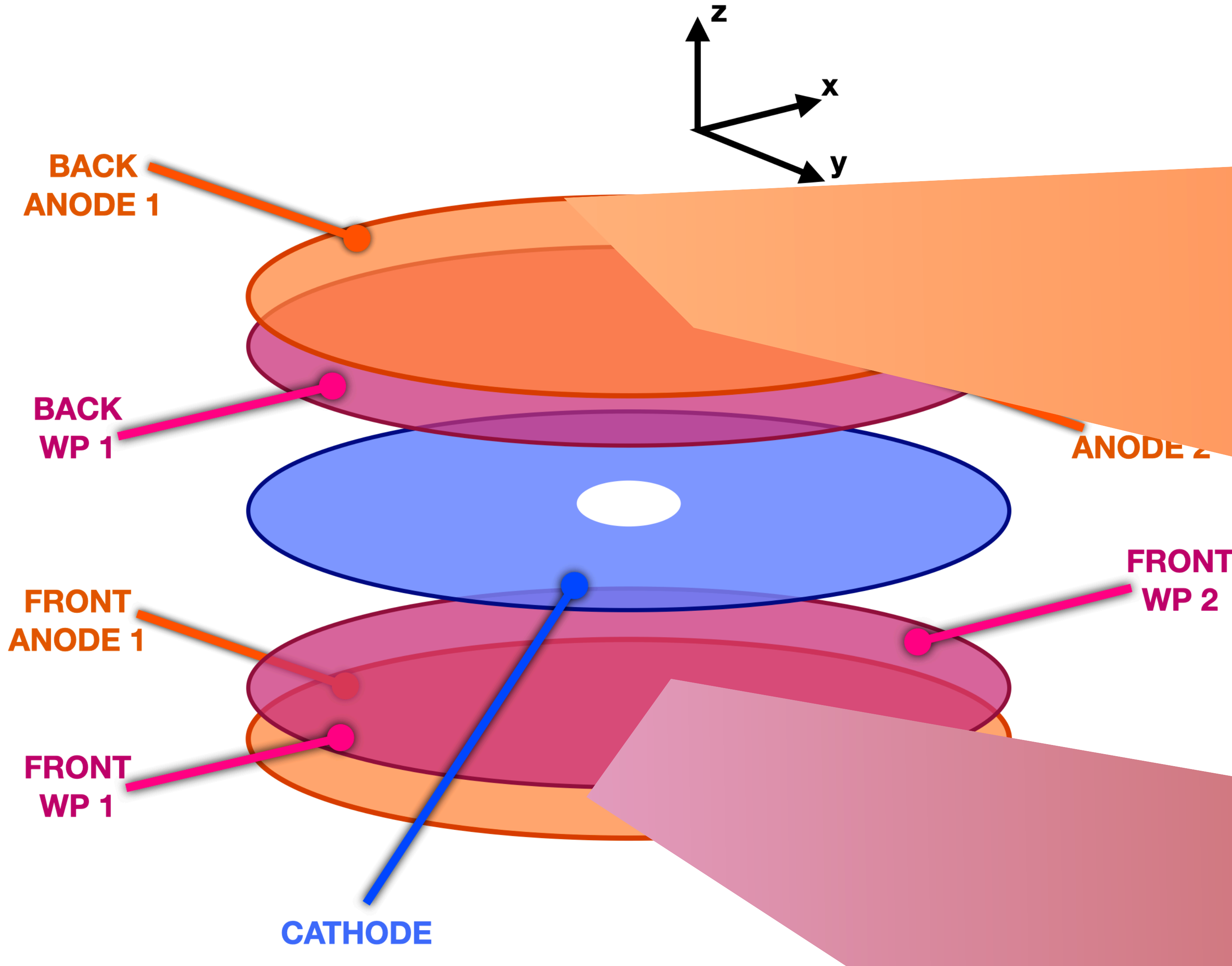
The average electron drift time is the maxima of the resulting wave form of the anode sum signal shaped using the following equation:

$$t_n = \frac{1}{Q_{max}} \cdot \sum_{k=k_0}^{k_0+n} (q_{k+1} - q_k)(k - k_0) \cdot \frac{1}{f_s}$$

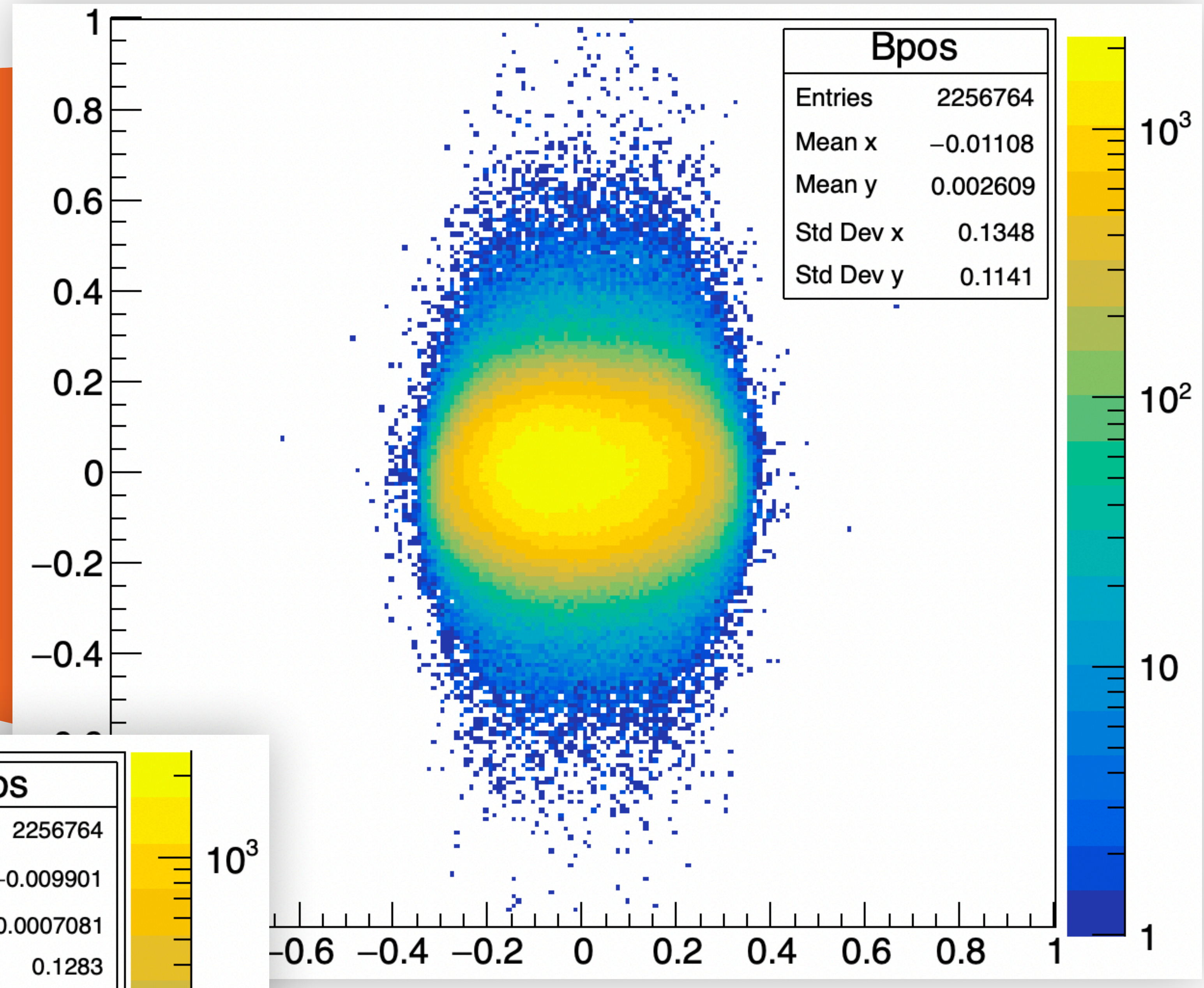
Adapted from: A. Göök, *et al.* A position-sensitive twin ionization chamber for fission fragment and prompt neutron correlation experiments. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 830:366–374, 2016.

* CFD: Constant Fraction Discrimination

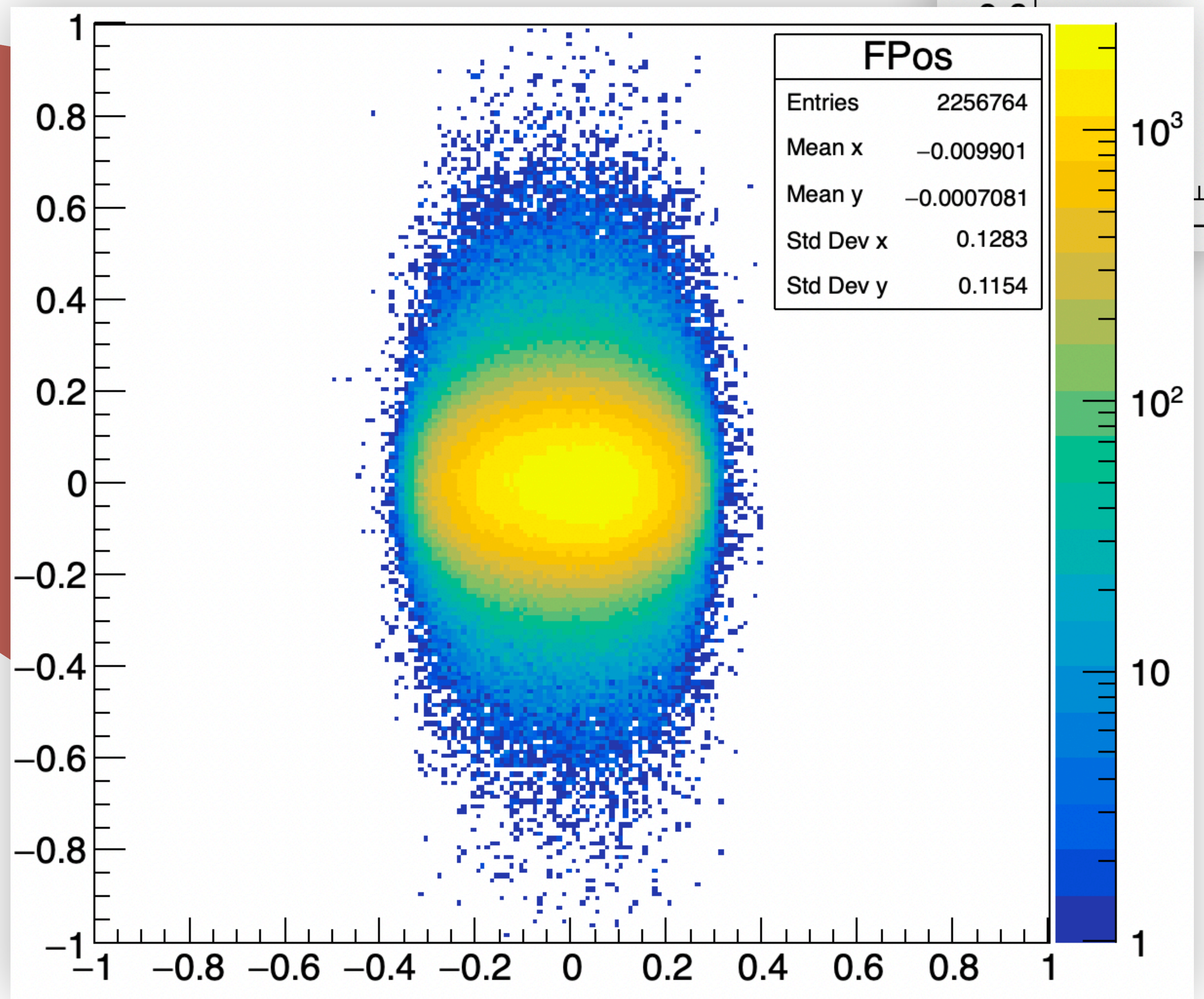
Double Frisch-Grid Ionisation Chamber (dFGIC)



Back Anode



Front Anode



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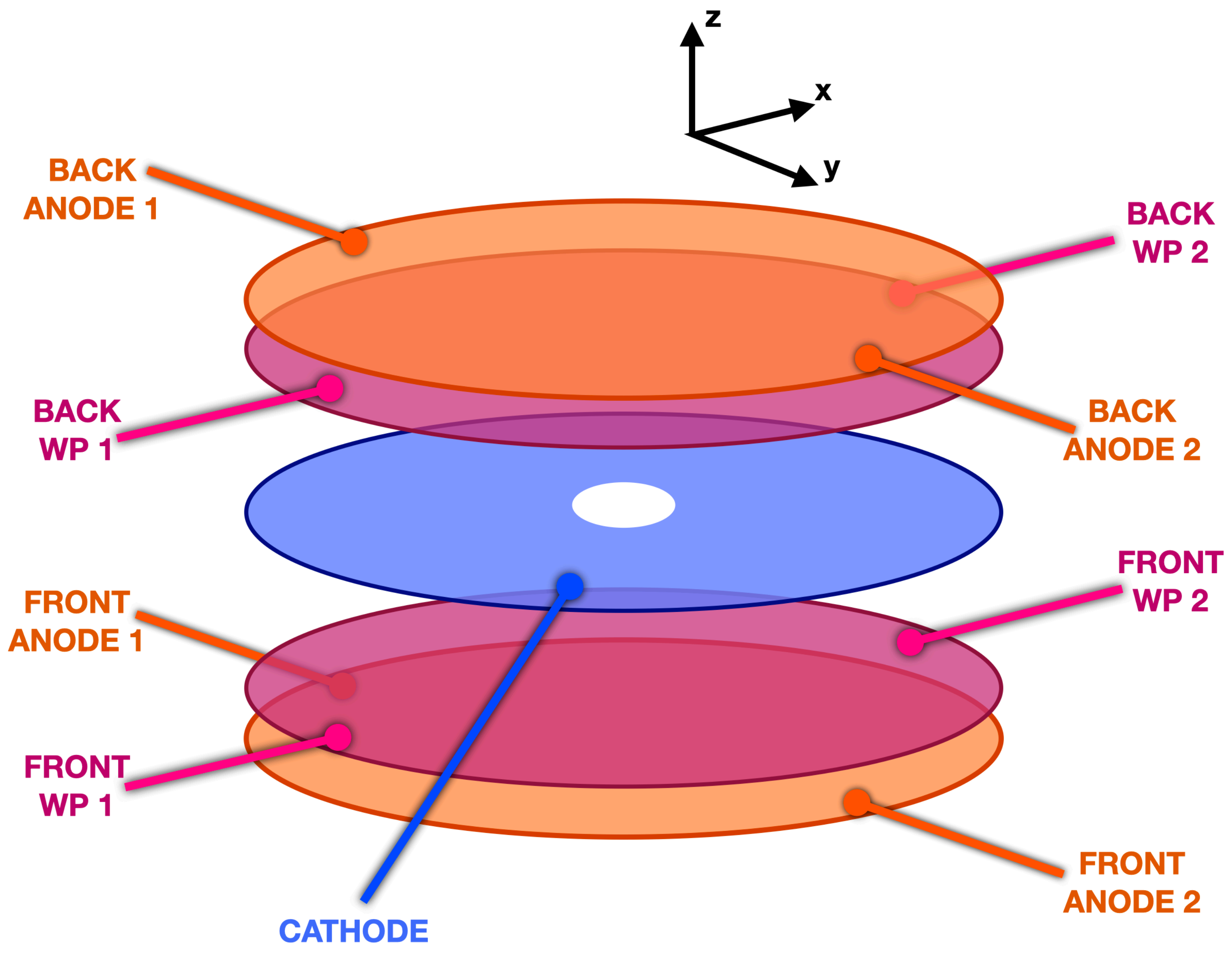

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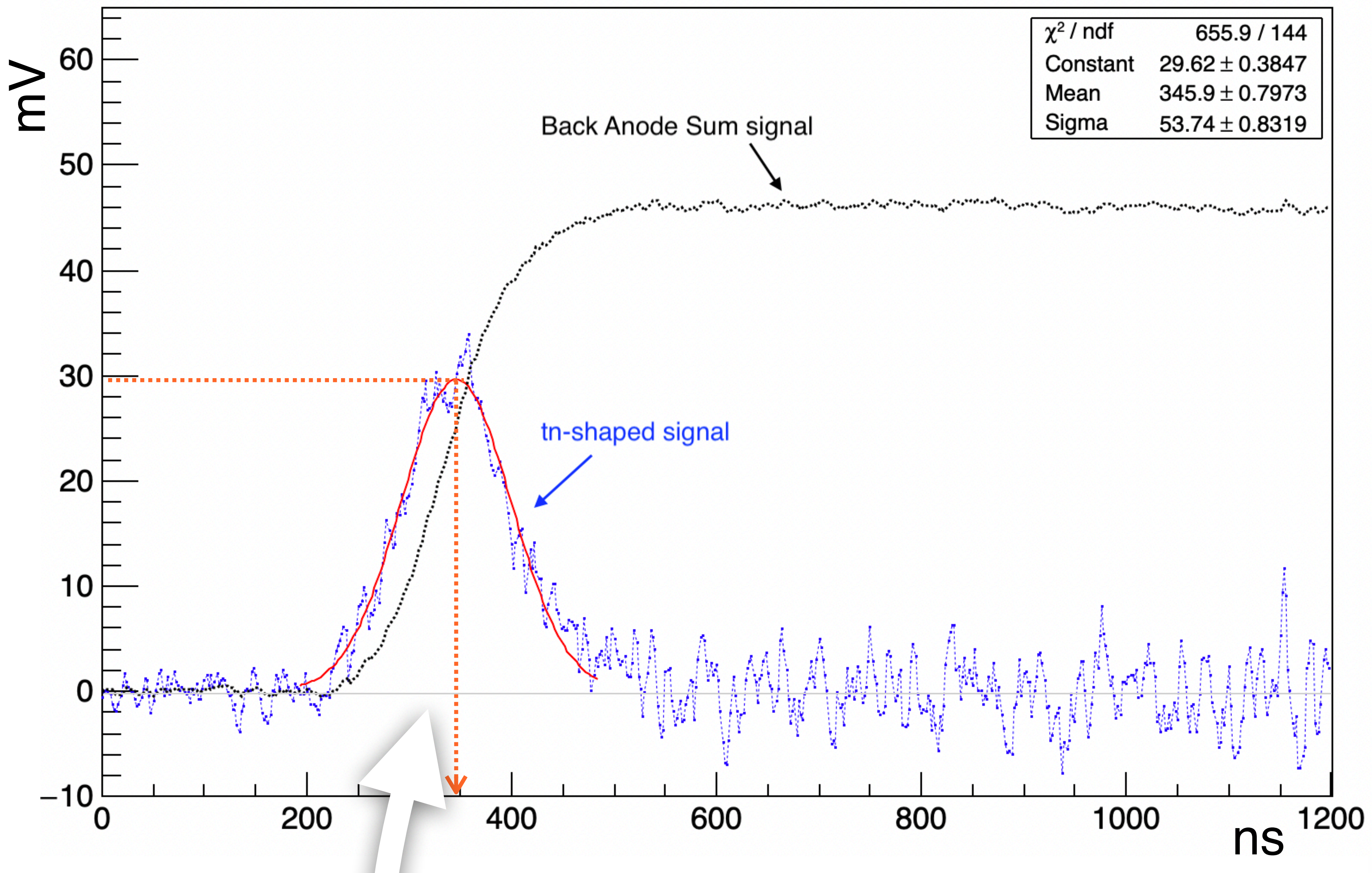

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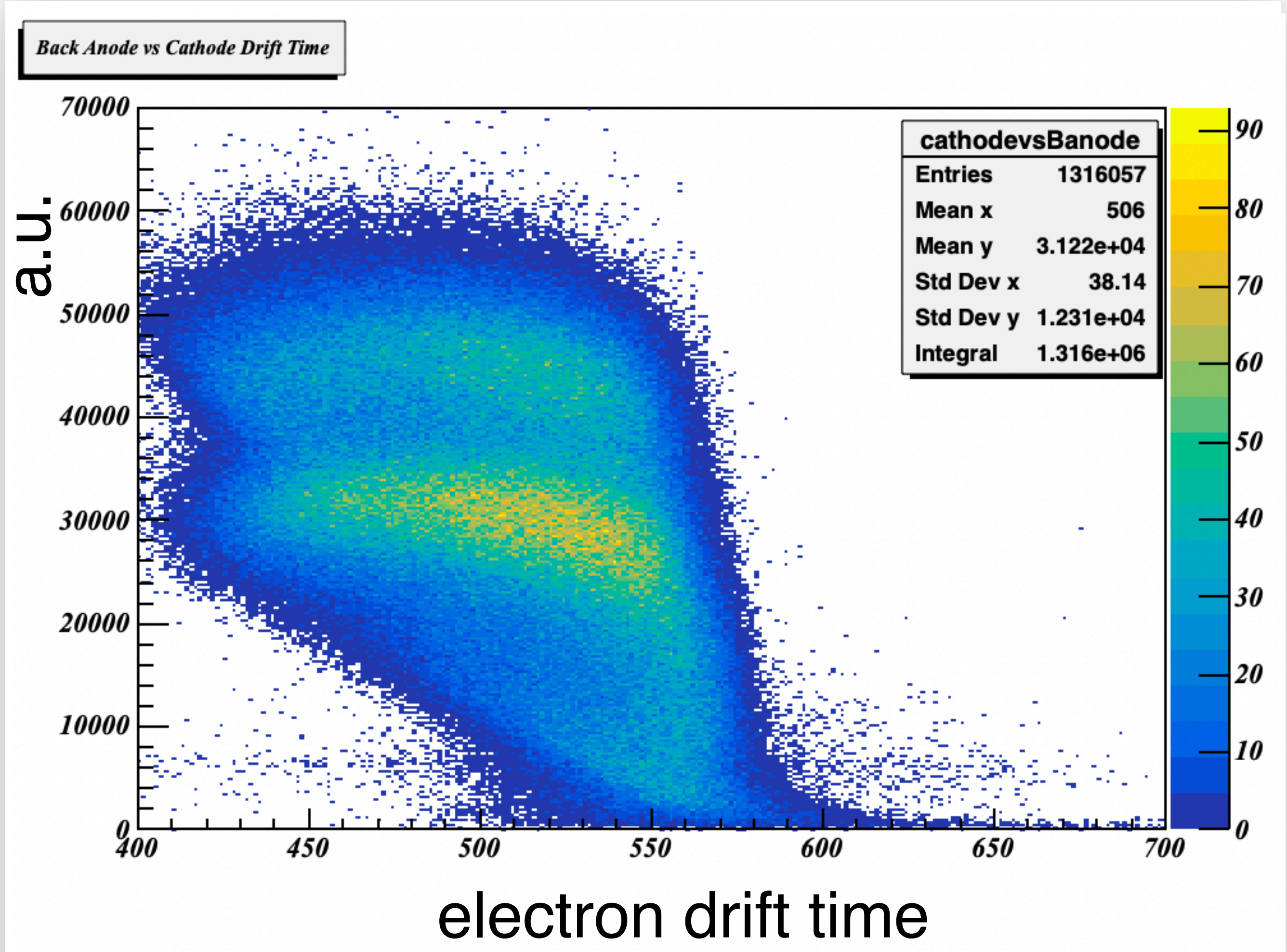
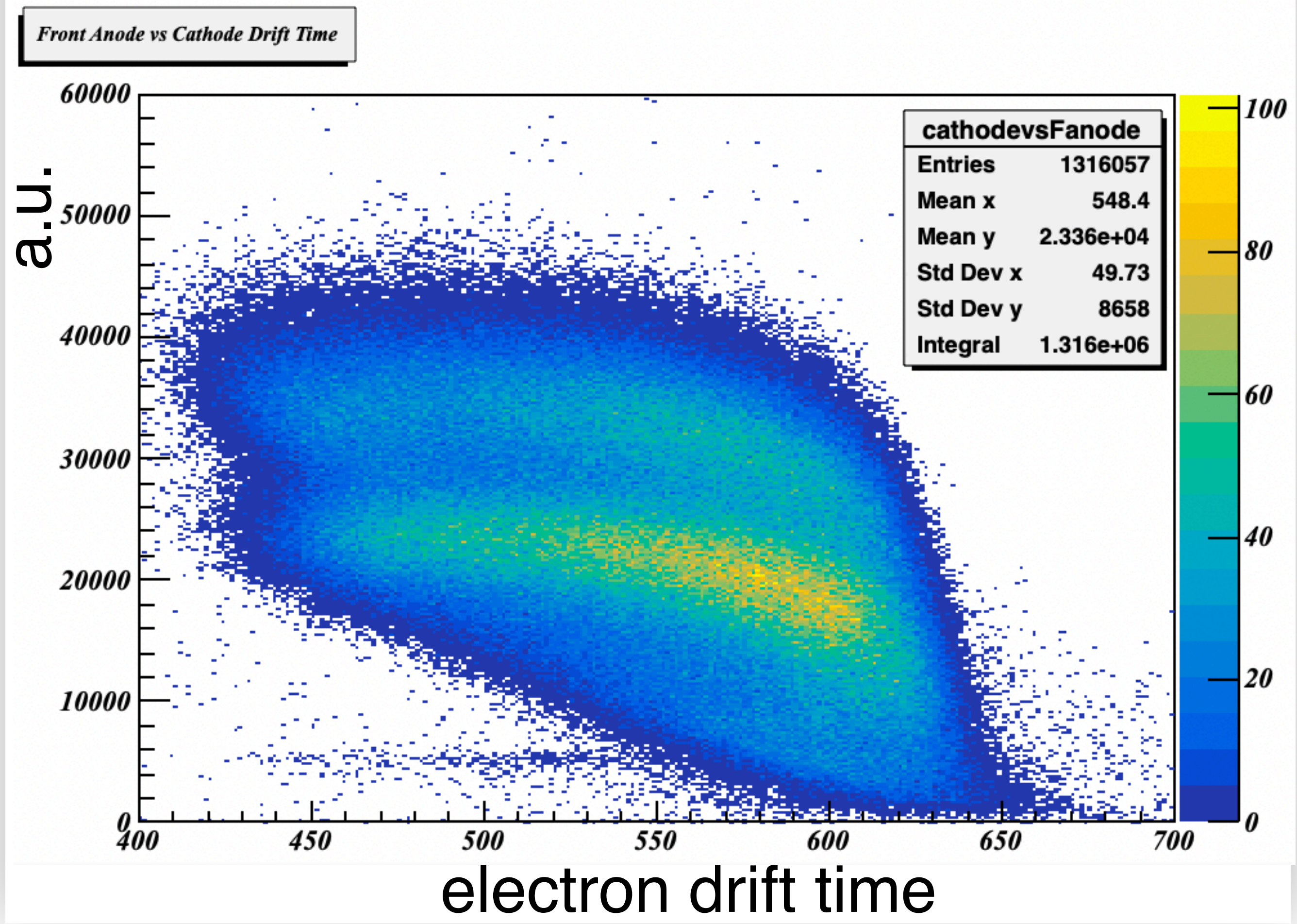
average electron drift time

Electron drift velocity

$$t_n = \frac{1}{Q_{max}} \cdot \sum_{k=k_0}^{k_0+n} (q_{k+1} - q_k)(k - k_0) \cdot \frac{1}{f_s}$$

Energy vs. Electron drift time





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→ « ENERGY » MEASUREMENTS

- Constant Fraction Discrimination (CFD) TIME MEASUREMENTS

How do we know if the method works?

Trace analysis through most frequently used methods

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- RC filter;
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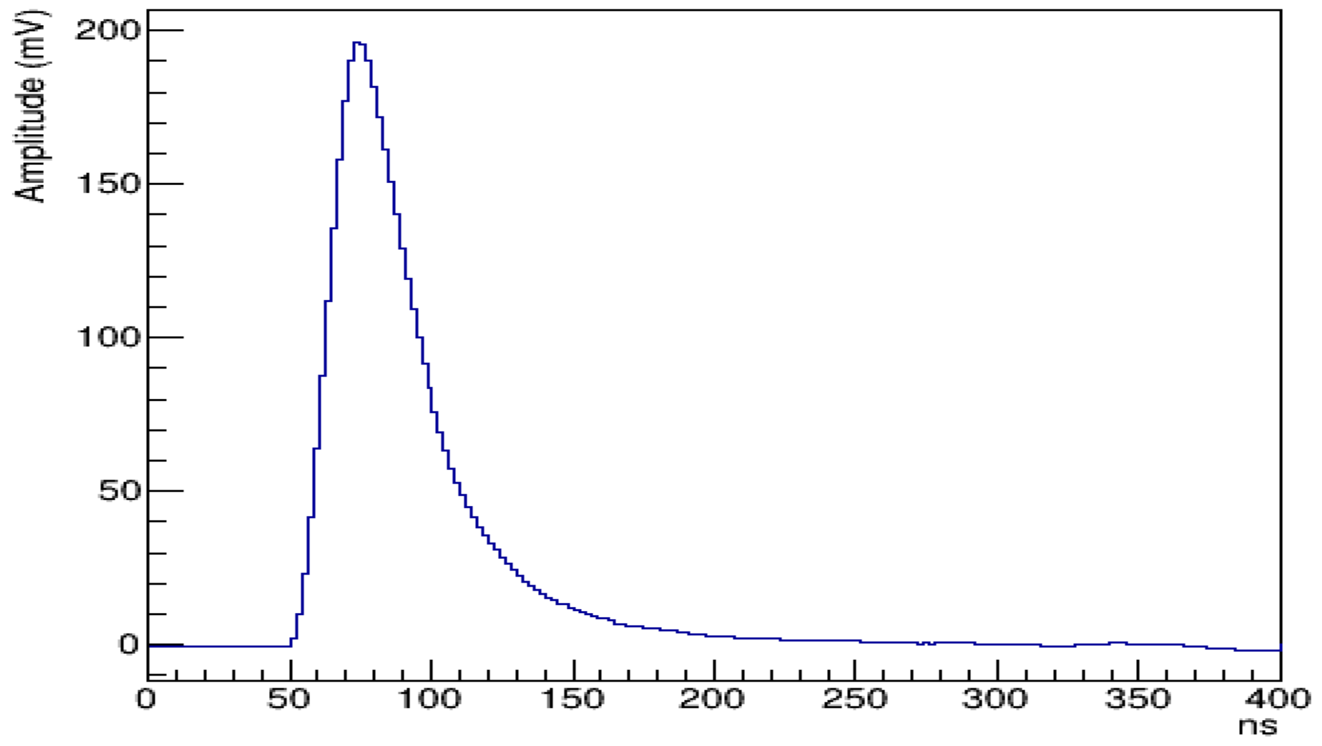
- Constant Fraction Discrimination (CFD) **TIME MEASUREMENTS**

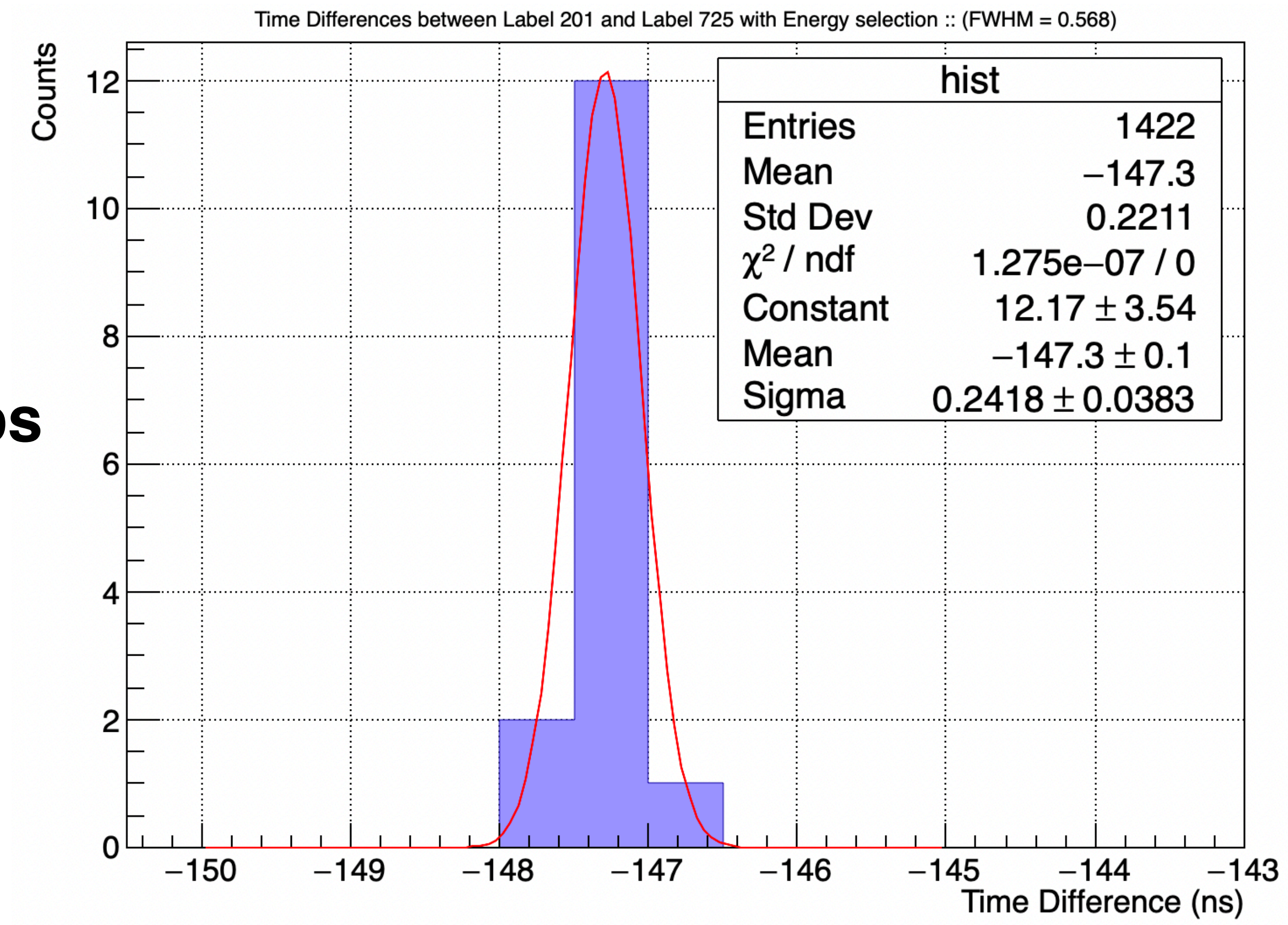
THALIA $LaBr_3$ data stored as a trace:



~31.7 keV @ 1170 keV

Time resolution of ~570 ps

* with gamma energy selection: 1170 & 1330 peaks on ^{60}Co calibration run



How do we know if the method works?

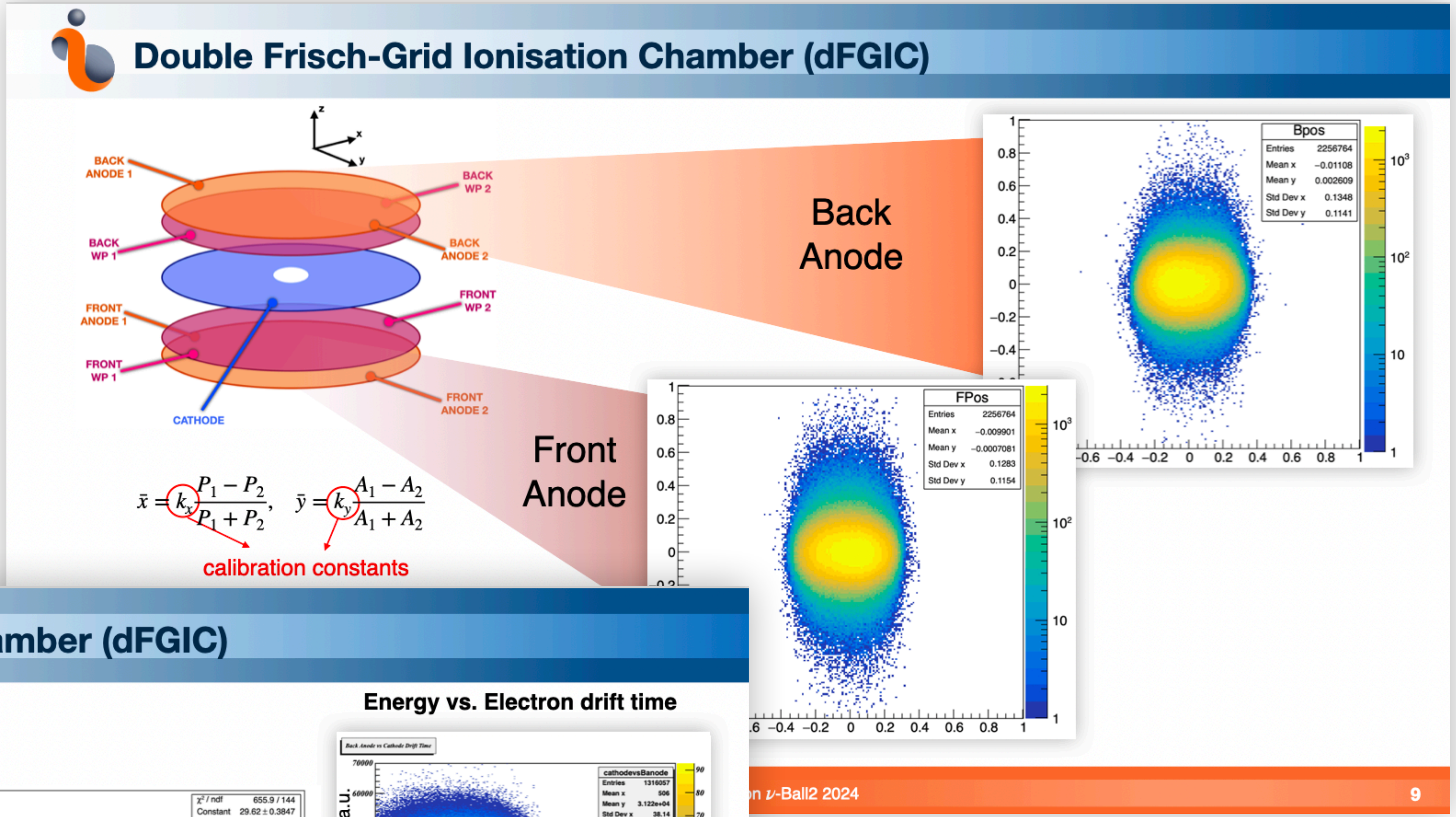
By evaluating the results obtained from a well-known detector => $LaBr_3$

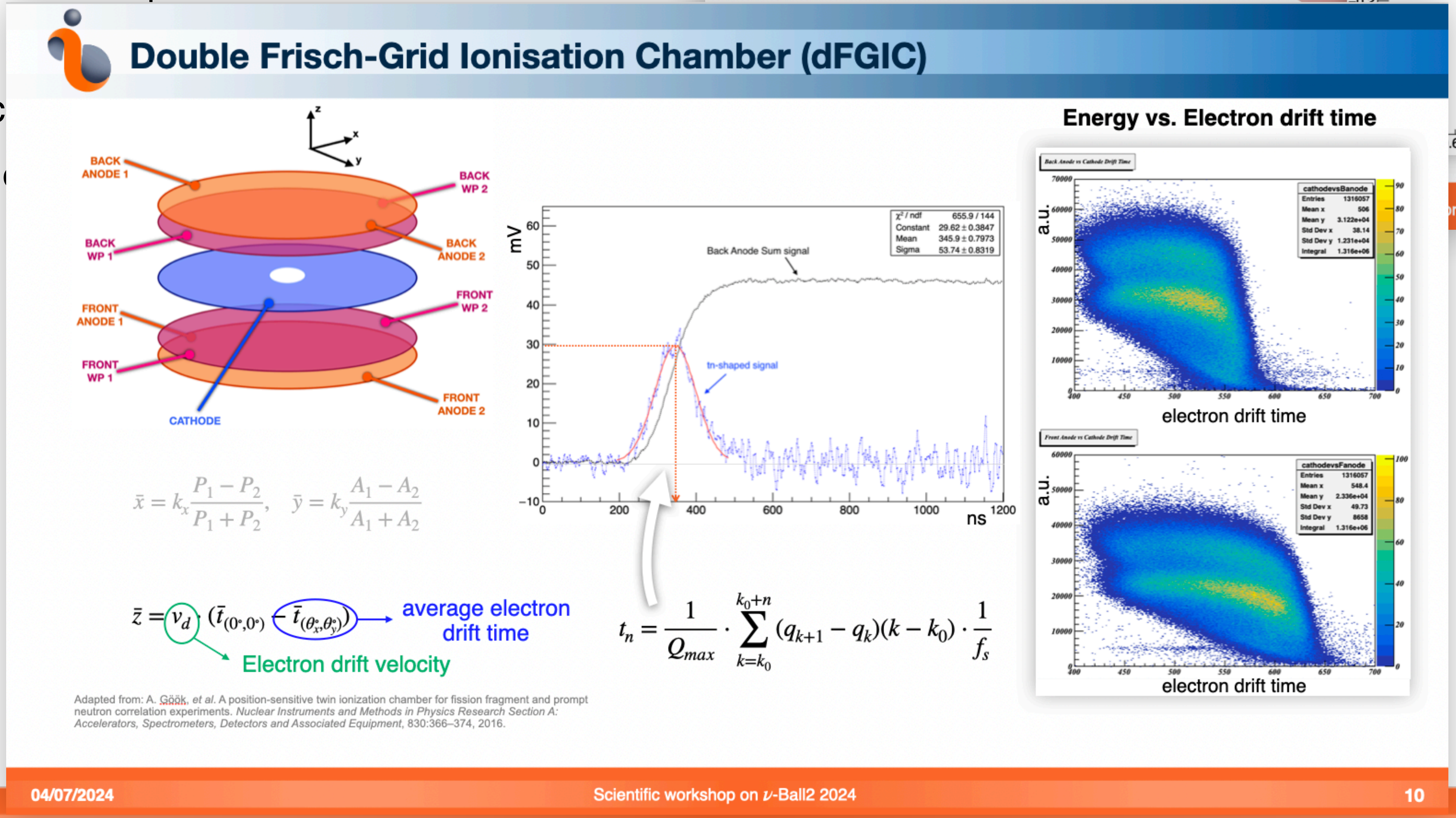
Trace analysis

Trace analysis through most frequently used methods

- Moving average algorithm;
- RC filter;
- Signal baseline correction;
- CR-RC and CR-RC4 shaping filters;
- Trapezoidal shaping filter;
- Signal integration (deposited c
- Constant Fraction Discriminati

BOTH TIME AND ENERGY MEASUREMENTS





Cathode time resolution:

R(t) = ~5 ns

Trace analysis

Trace analysis through most frequently used methods

- Moving average algorithm;
- RC filter;
- Signal baseline correction;
- CR-RC and CR-RC4 shaping filters;
- Trapezoidal shaping filter;
- Signal integration (deposited charge)
- Constant Fraction Discrimination (CFD)

TIME CONSUMING

Trace analysis takes **~2s per 1k fission events**

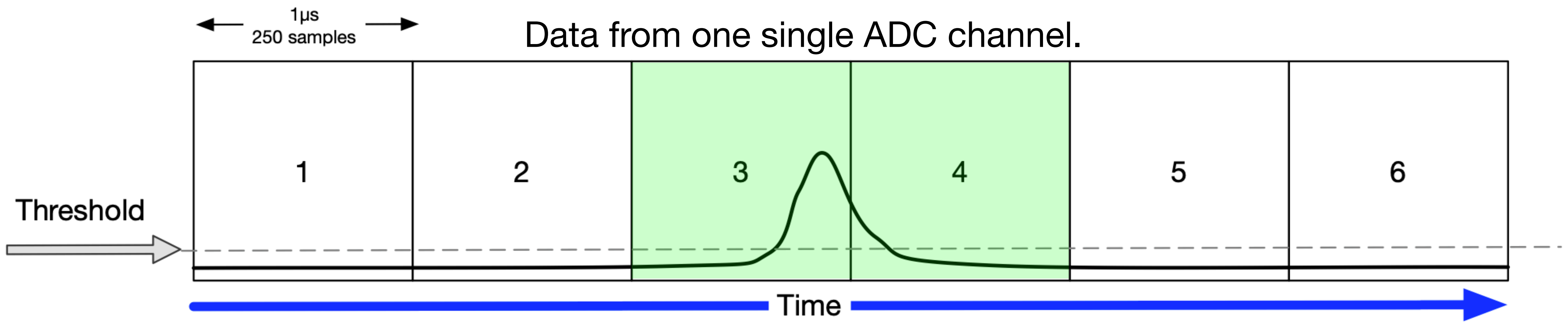
3 weeks of data acquisition -> 600M events

300 h or 13 days to process the traces

=> yes, we are working with an optimized multi-threading algorithm

Streaming readout data acquisition

Taken from: A. Boehnlein et al. Rev. Mod. Phys. 94, 031003 (2022)



Adapted from: Streaming mode Data Acquitiion at Jefferson Lab

A virtual trigger based on an unsupervised hierarchical cluster algorithm selects the relevant data to reconstruct the physics event

Neural Networks

Supervised vs. unsupervised learning

Regression vs. classification model

Hyperparameters

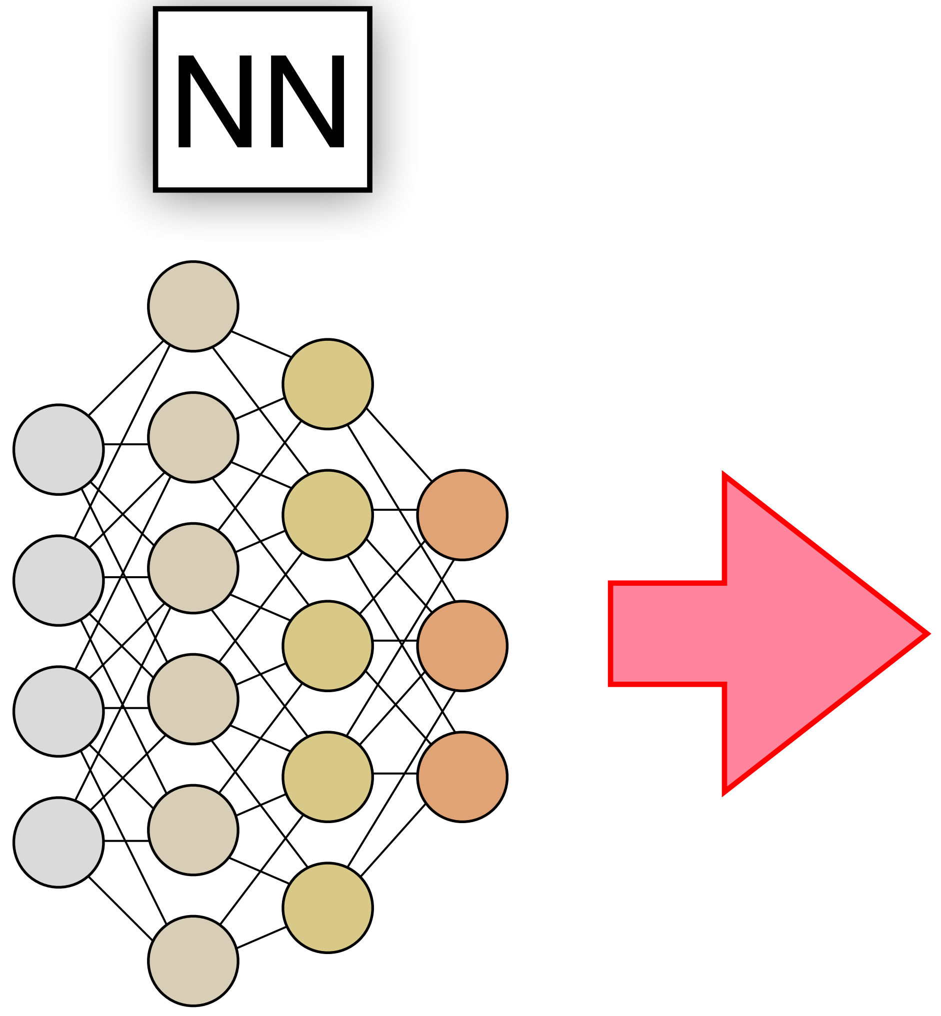
- Activation function
- Batch size
- Epochs
- Learning rate
- Loss function
- Number of hidd...
- Number of neur...

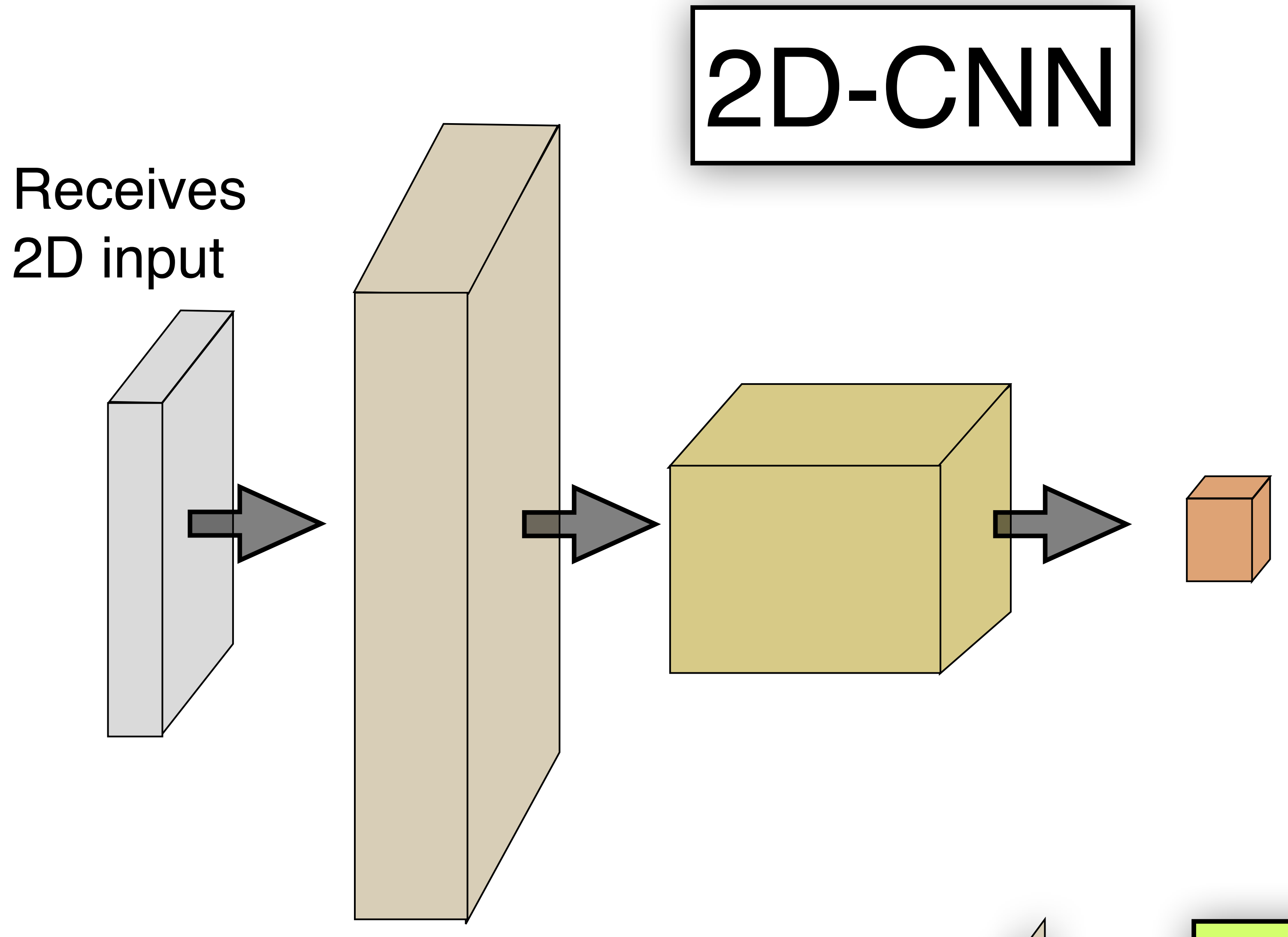
$$Y_{i,j,k} = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \sum_{c=0}^{C-1} (X_{i+m,j+n,c} \cdot W_{m,n,c,k}) + bias_k$$

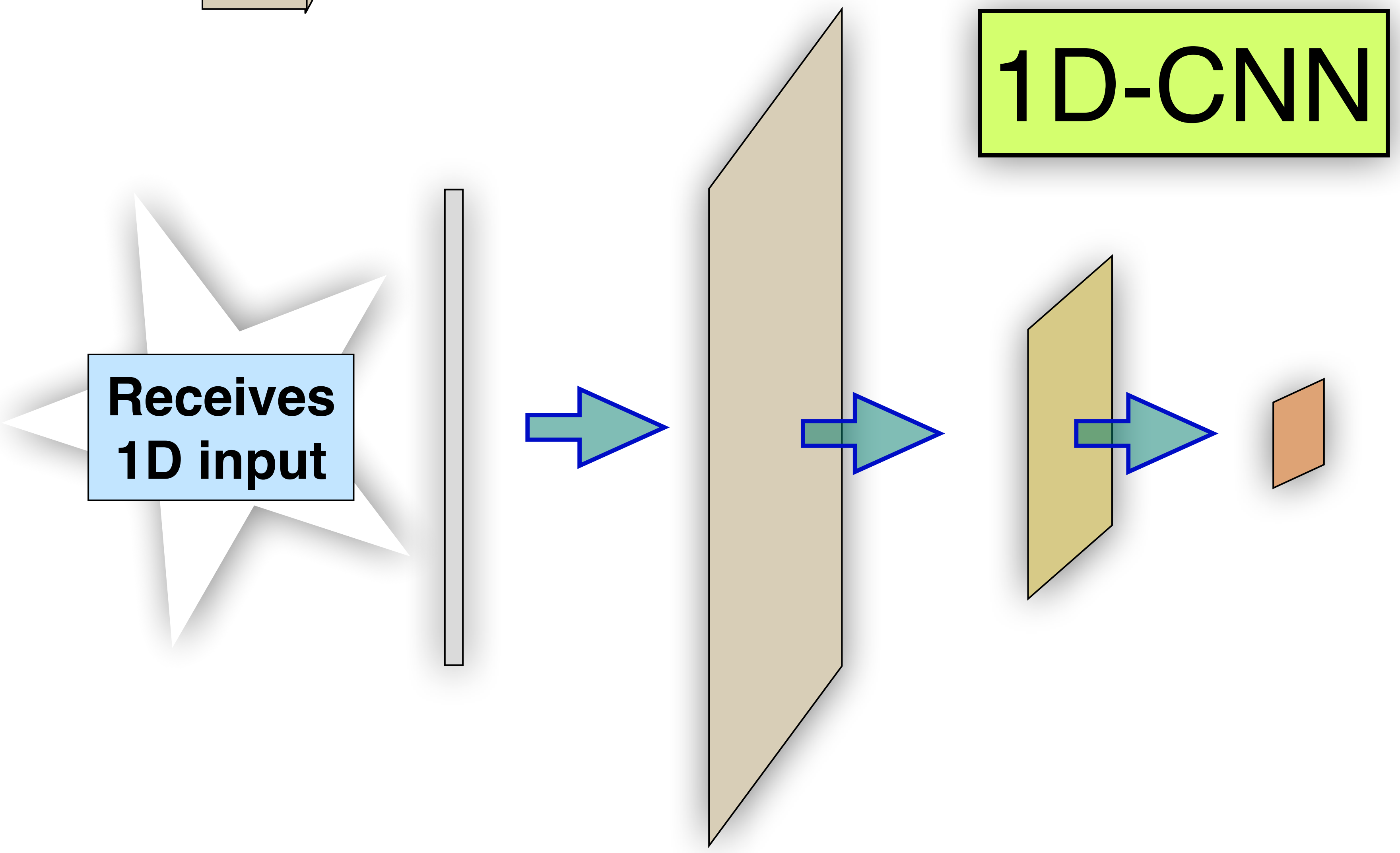
Parameters

- Weights and biases

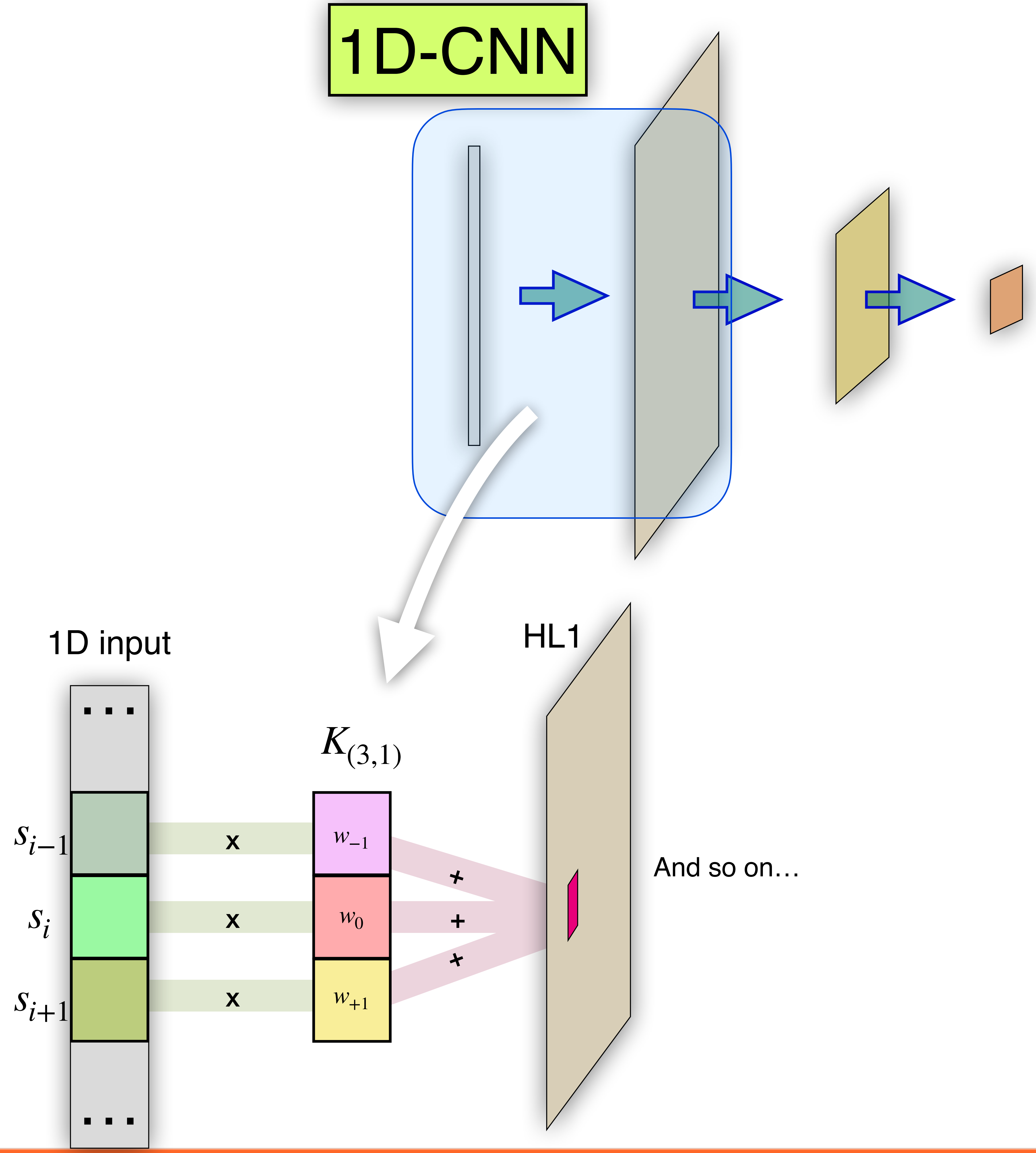
$$Y = \sum_i (weight_i \cdot input_i) + bias$$







Neural Networks



Neural Networks

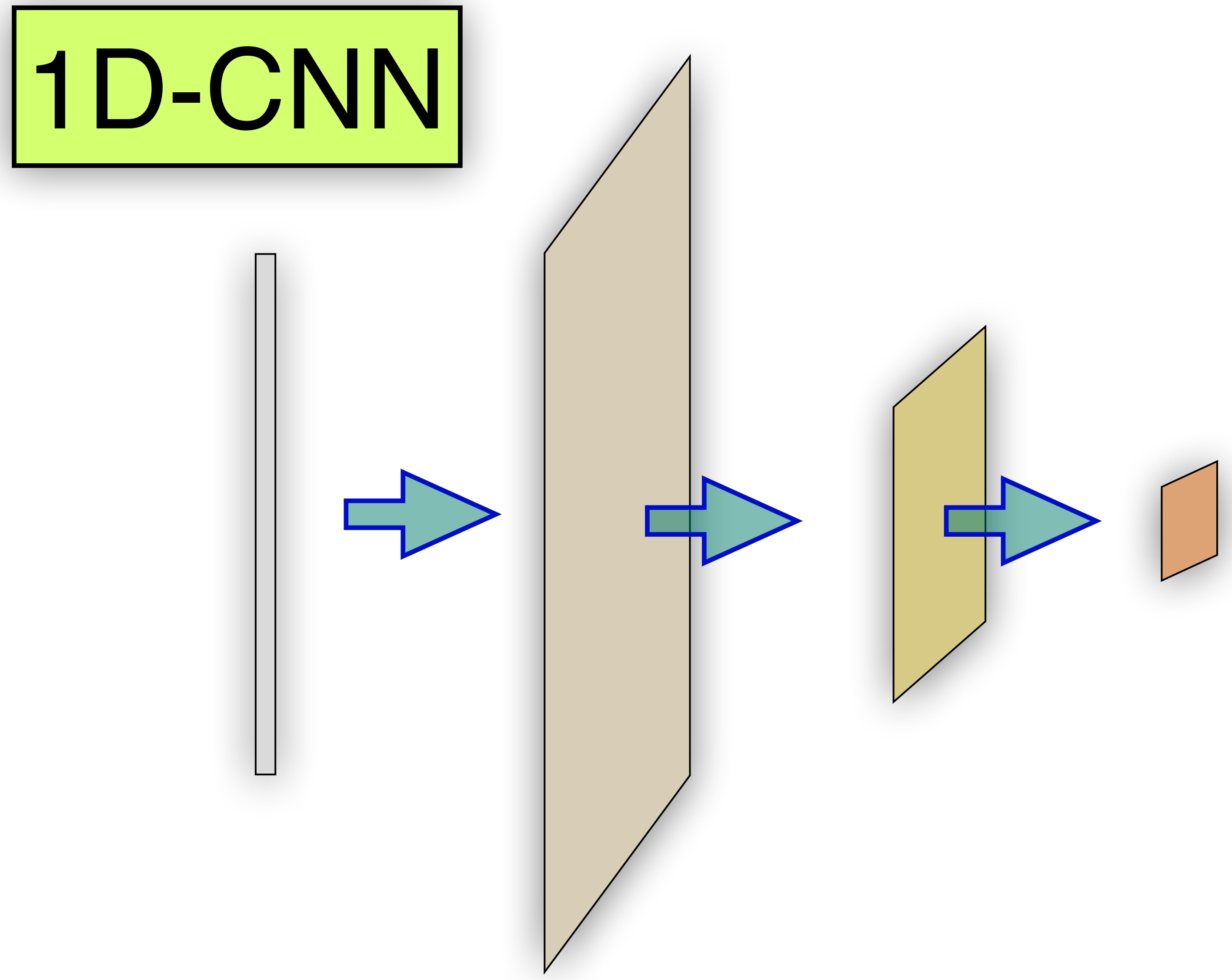
Parameters

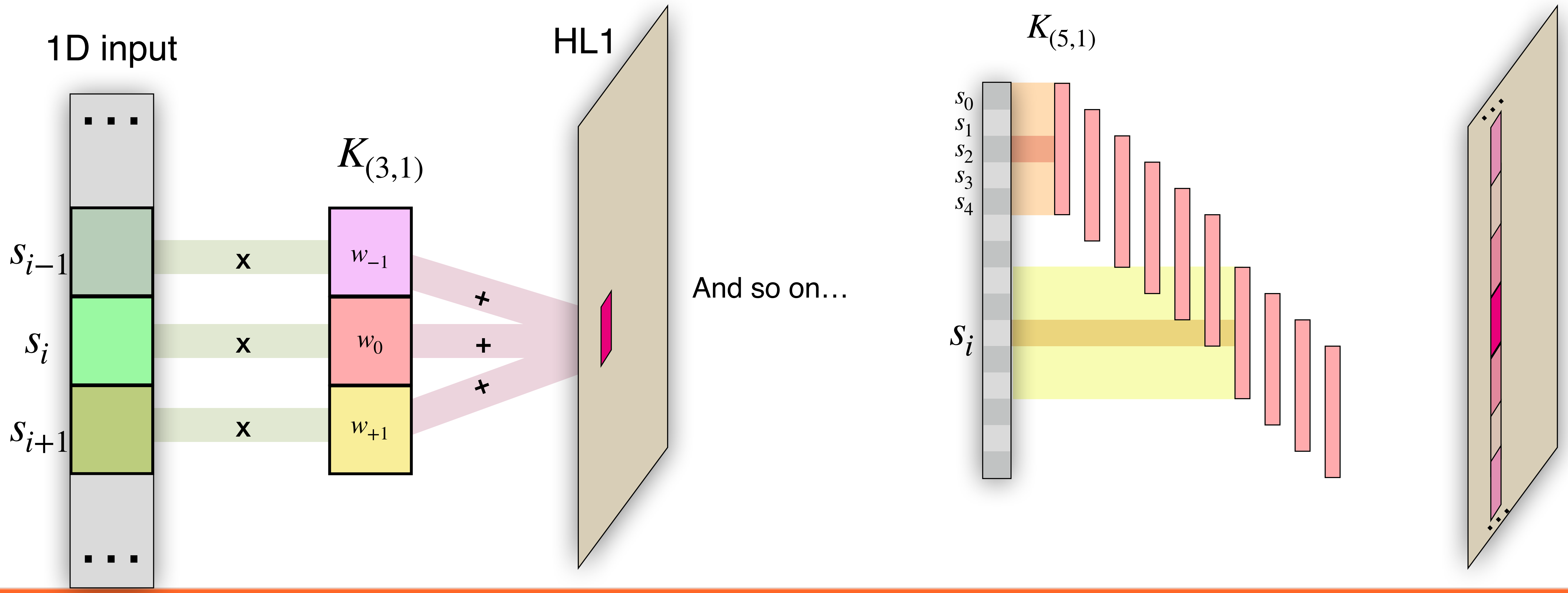
Weights and biases

$$Y_{i,j,k} = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \sum_{c=0}^{C-1} (X_{i+m,j+n,c} \cdot W_{m,n,c,k}) + bias_k$$

Kernel size vs. filters

- Kernel size $K_{(n,m)}$
- Number of filters





Parameters

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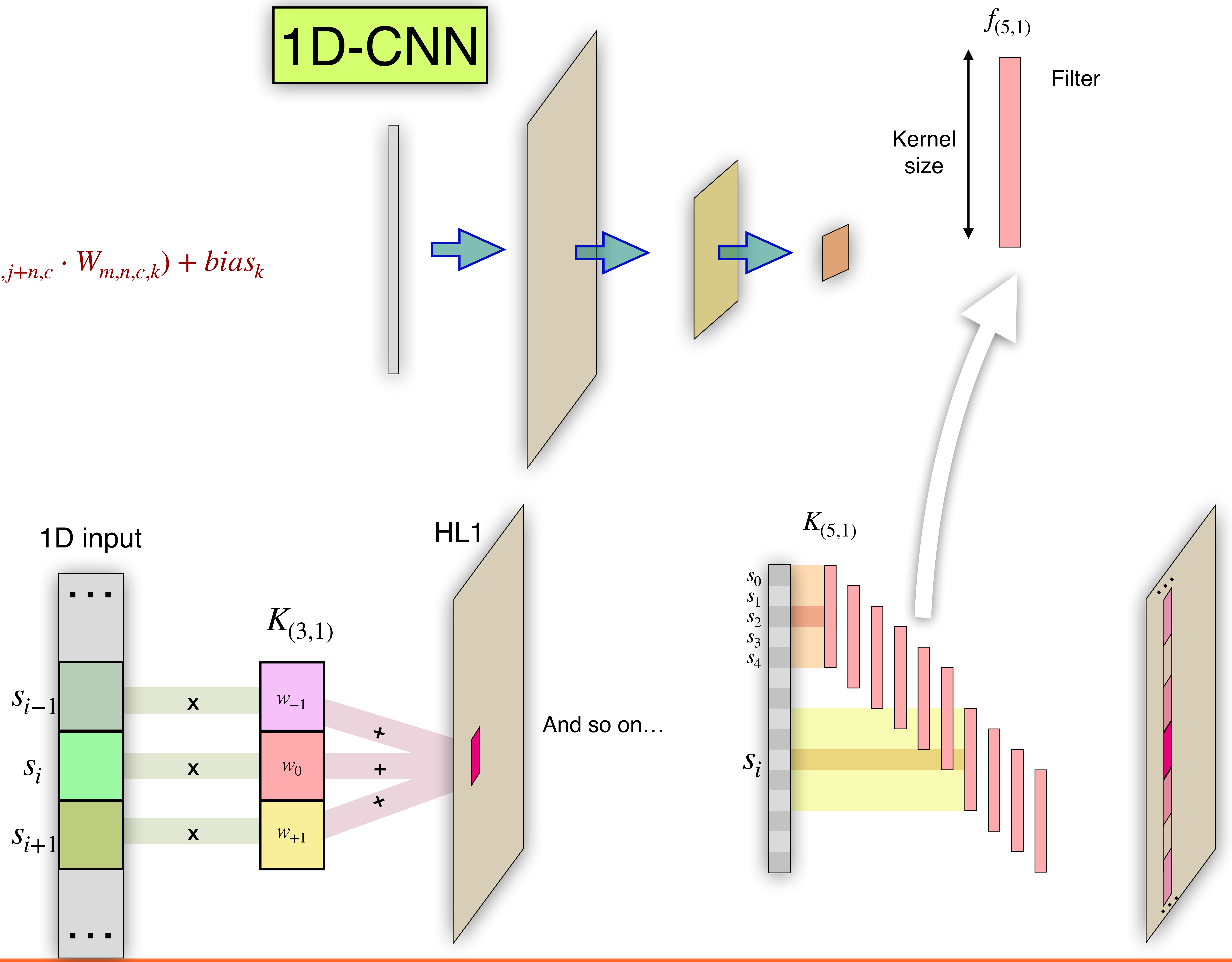
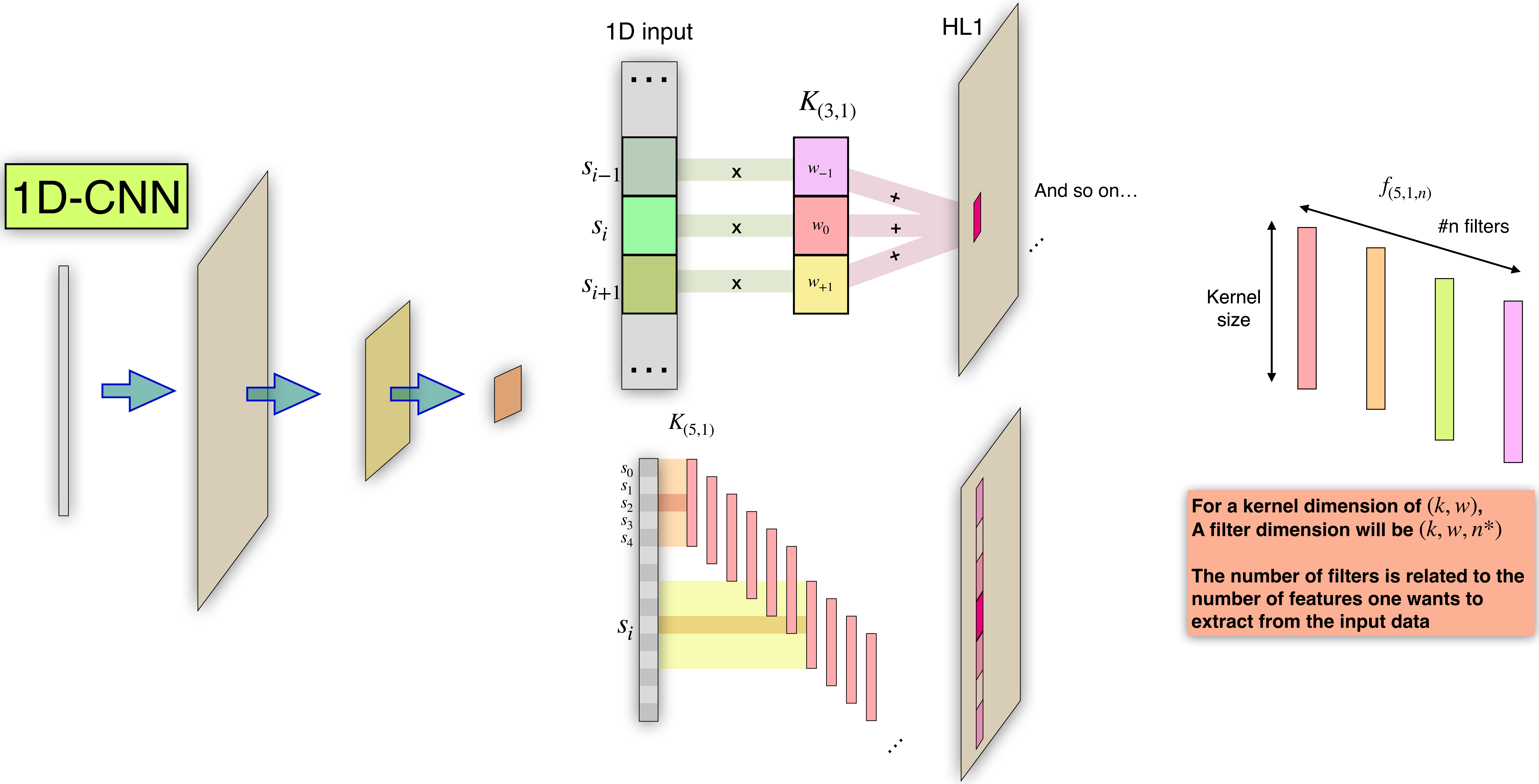


Neural Networks



For a kernel dimension of (k, w),
A filter dimension will be (k, w, n^*)

The number of filters is related to the number of features one wants to extract from the input data