Development of innovative methods for fission trigger construction

Brigitte PERTILLE RITTER
3rd year PhD thesis

CONTENTS:

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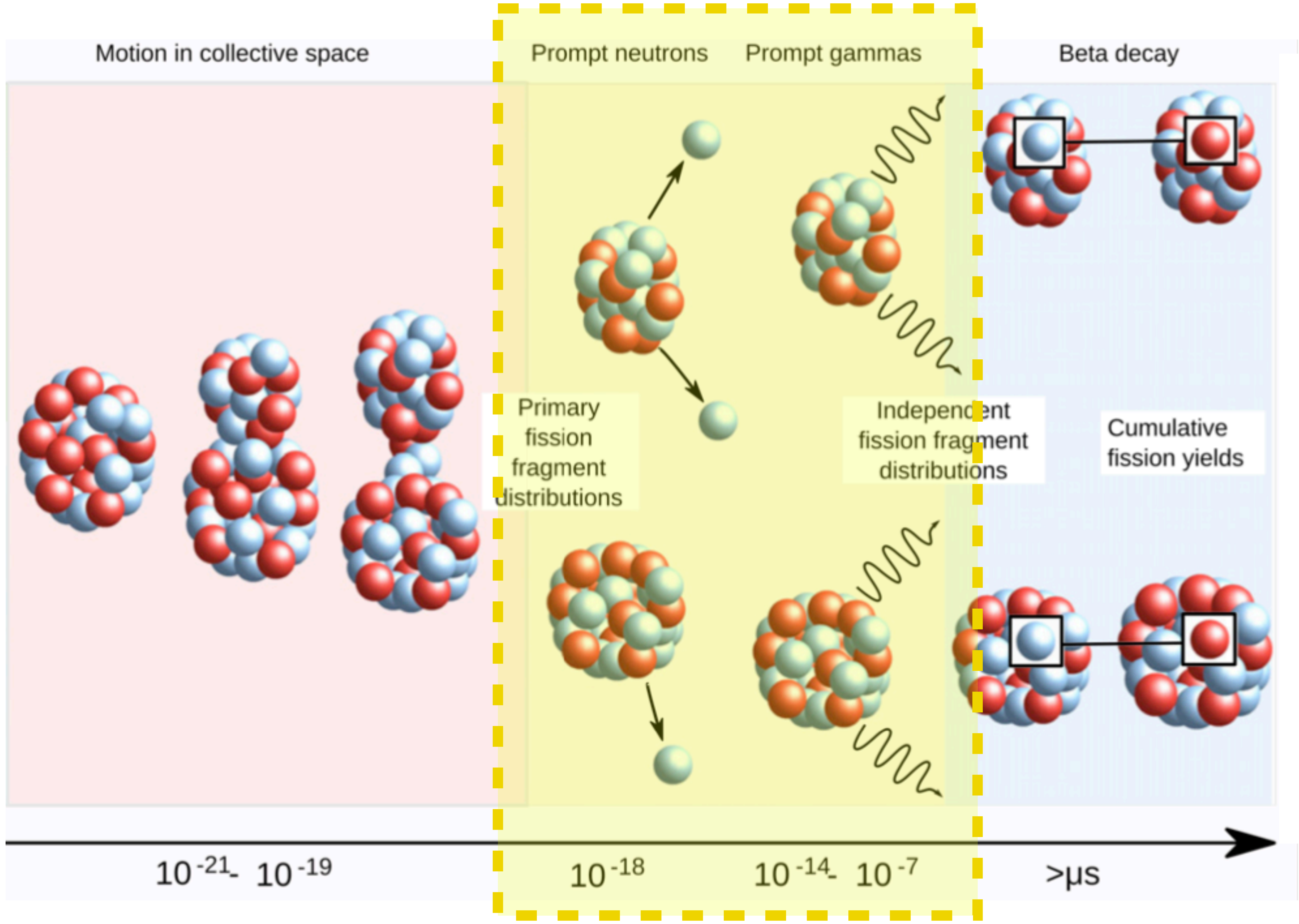
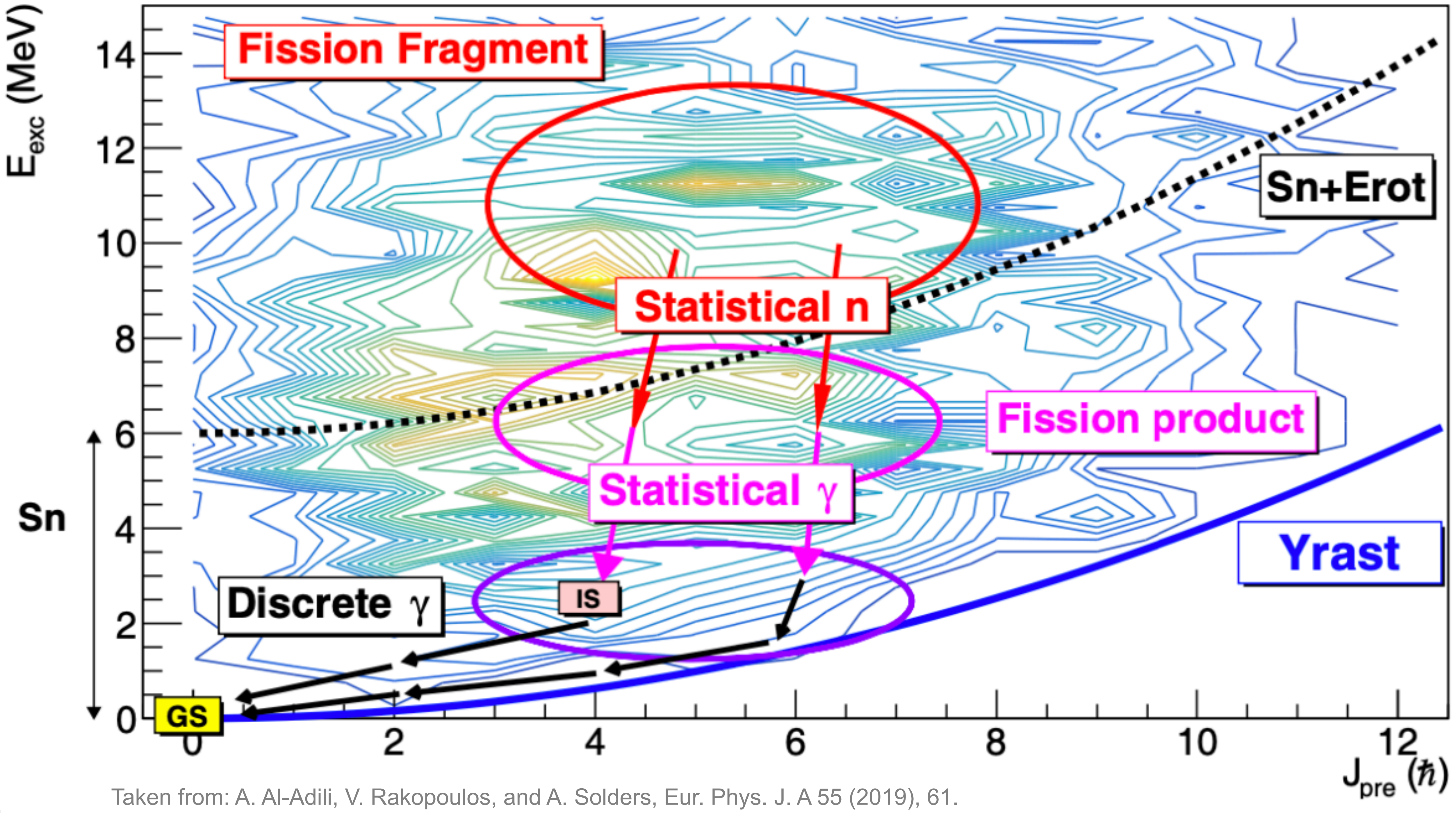
Nuclear fission

FROZEN

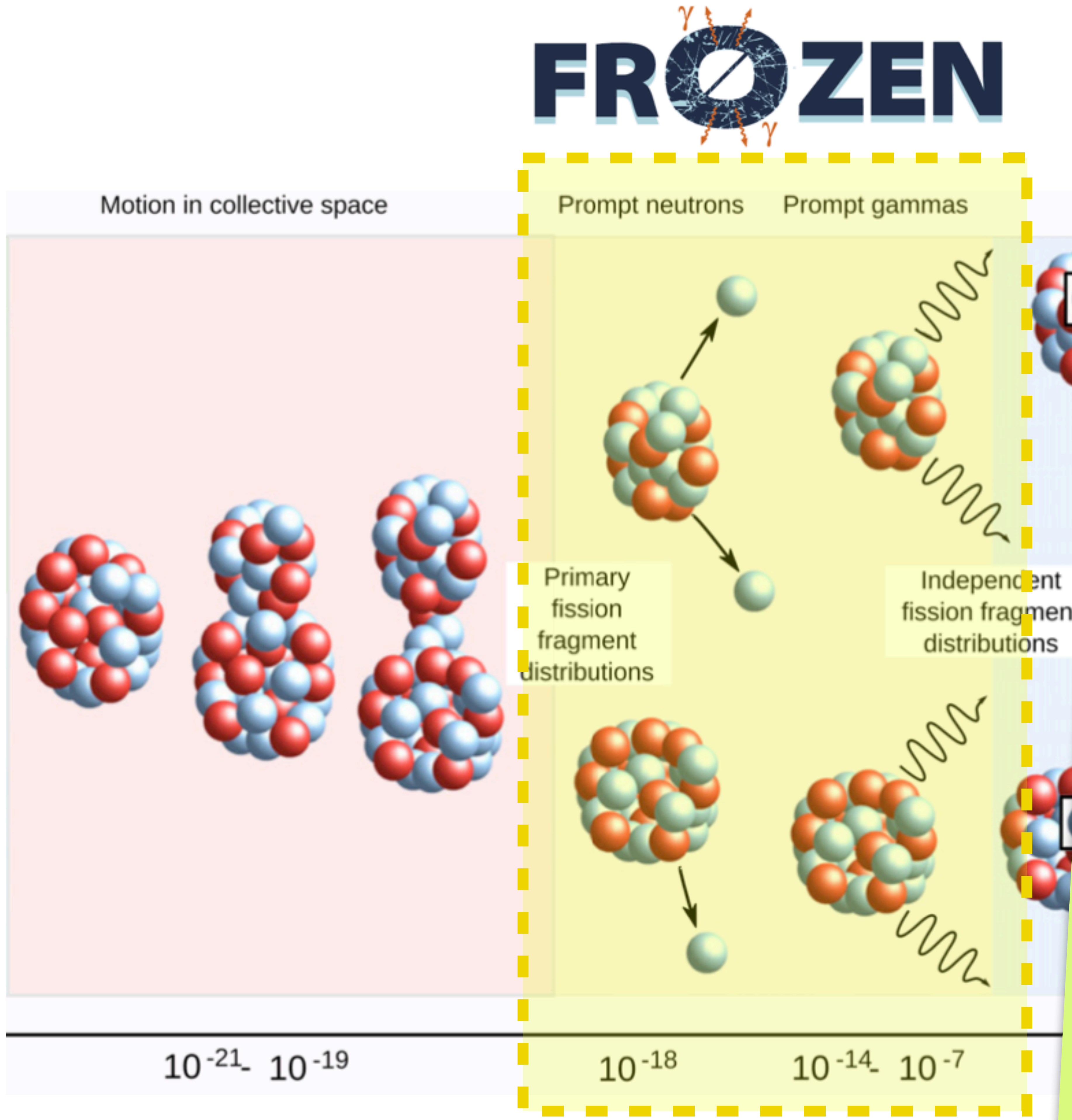


Adapted from: M. Bender, *et al*. Future of nuclear fission theory. Journal of Physics G: Nuclear and Particle Physics, 47(11):113002, oct 2020.



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

Nuclear fission



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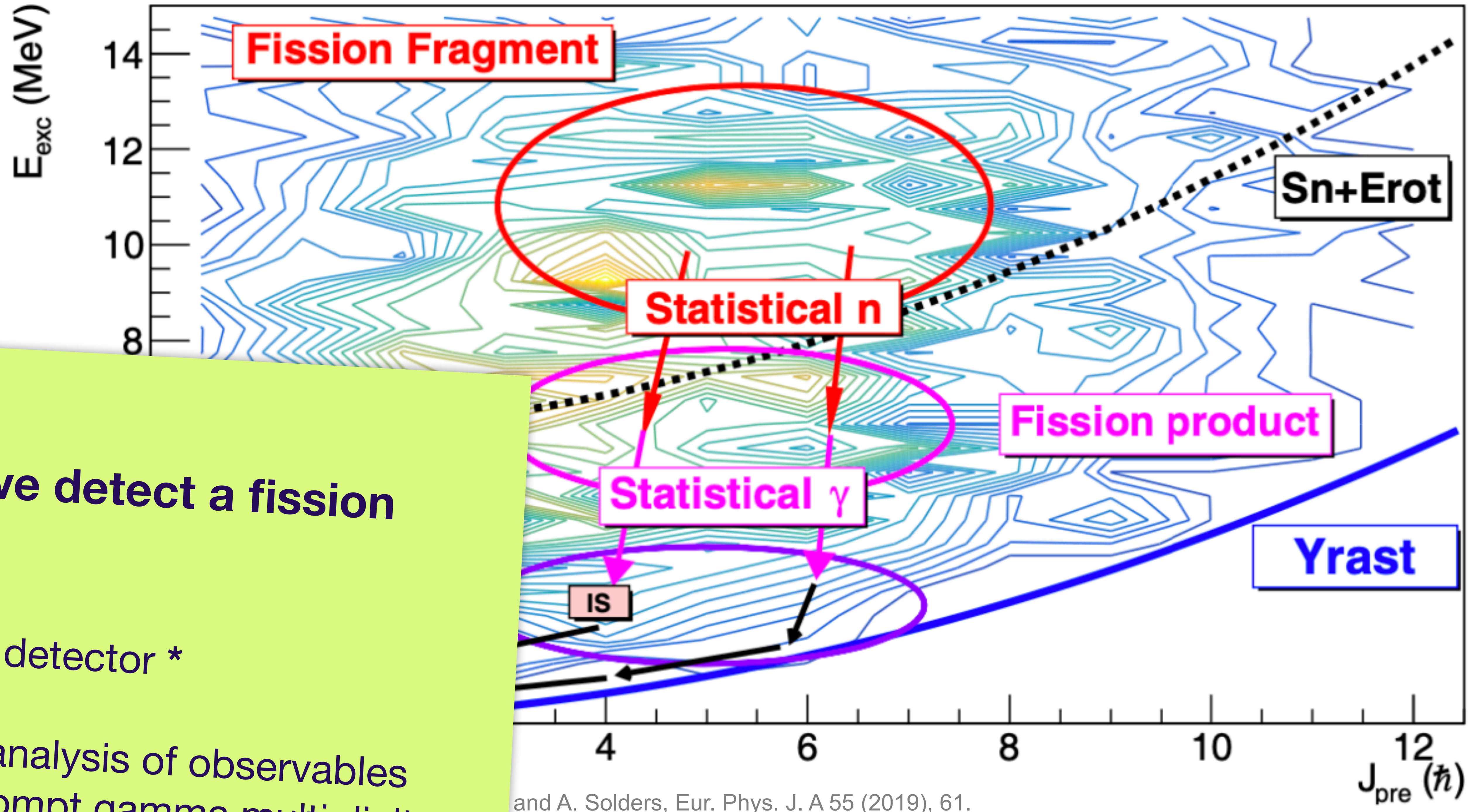


and A. Solders, Eur. Phys. J. A 55 (2019), 61.

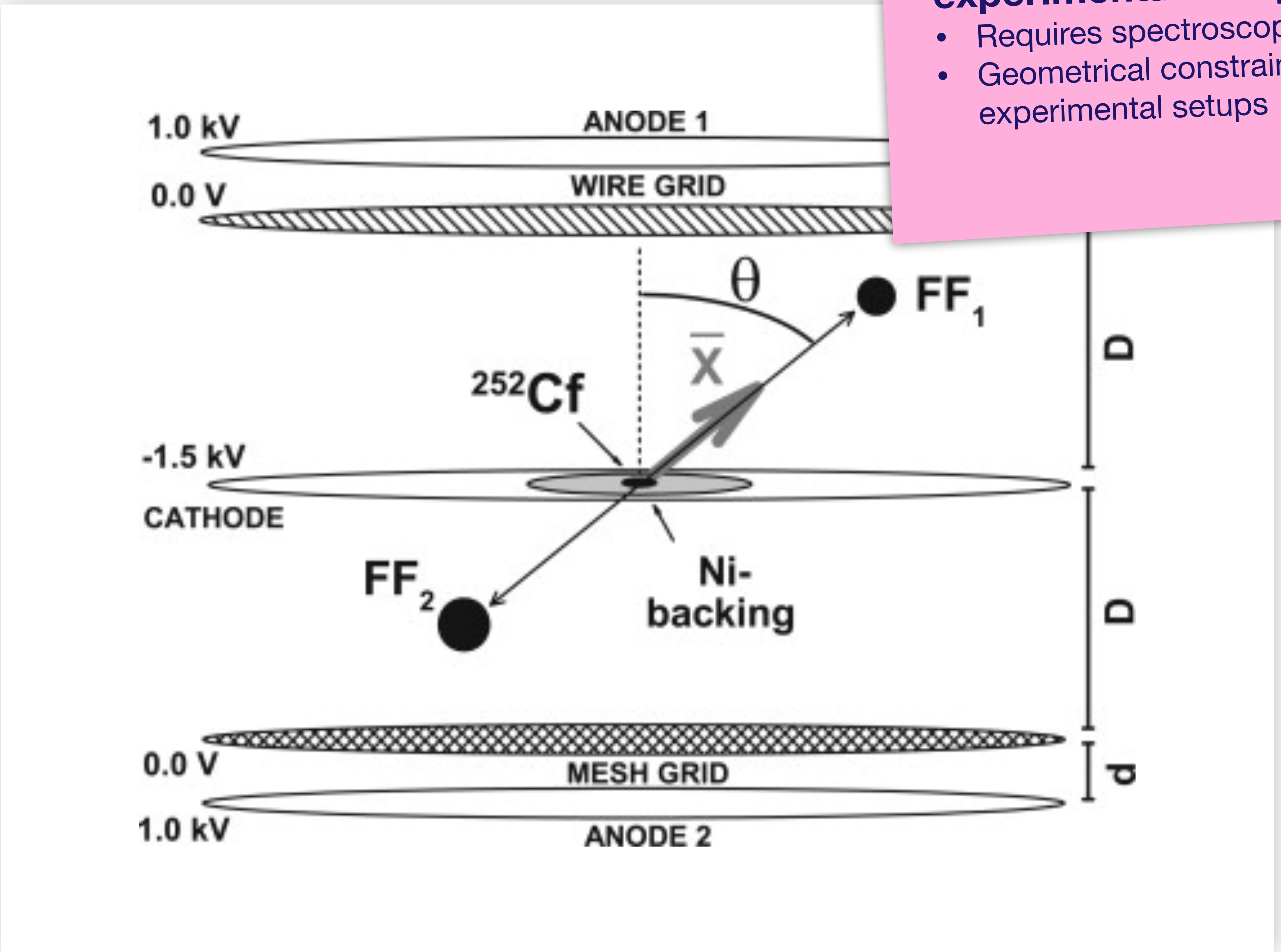
How can we detect a fission occurred?

- Dedicated detector *
- Based on analysis of observables such as prompt gamma multiplicity and total energy

Fission Tagging

Dedicated detector:

…such as an ionisation chamber

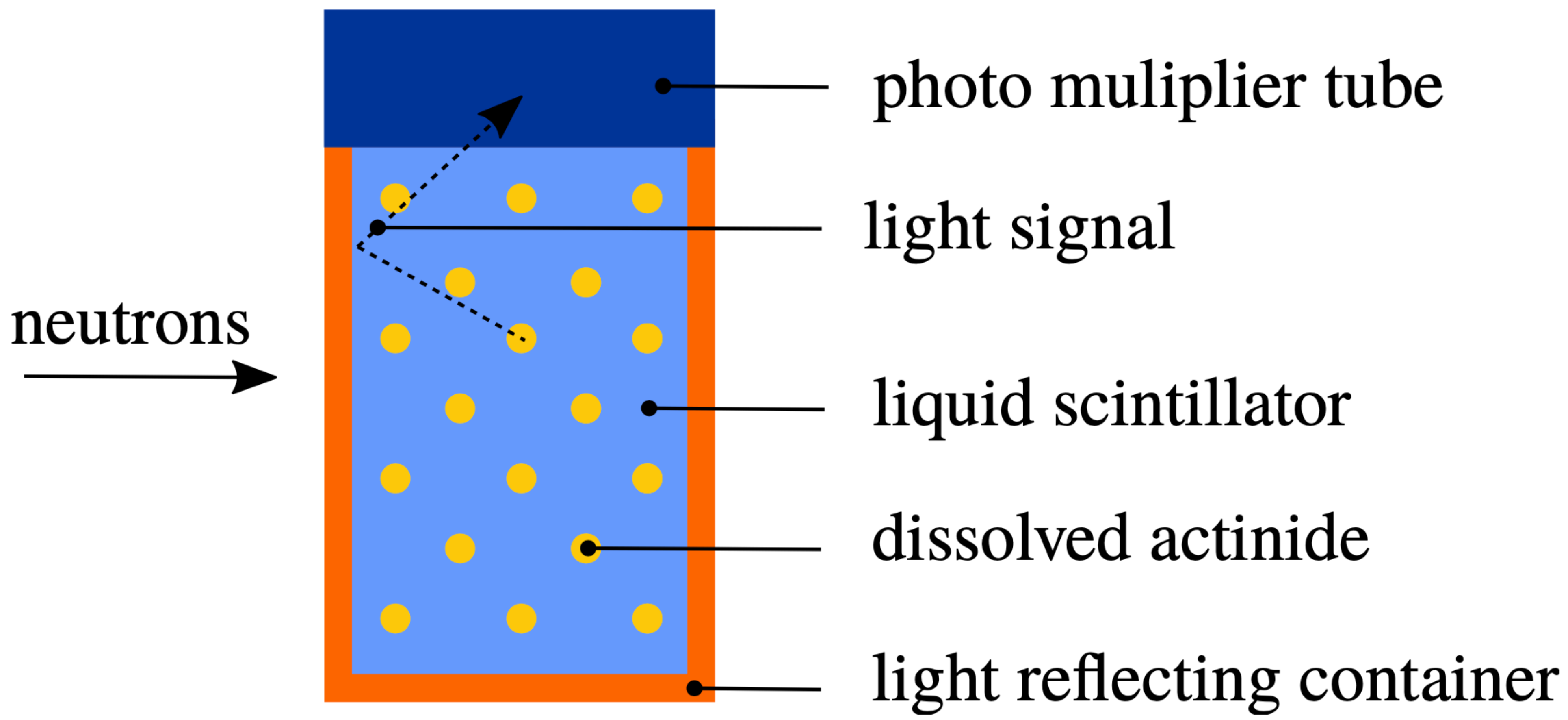


Taken from: L. Bardelli et al., Nucl. Instrum. Methods Phys. Res. A, vol. 654, pp. 272-278, 2011.

It is NOT suitable for all experimental setups:

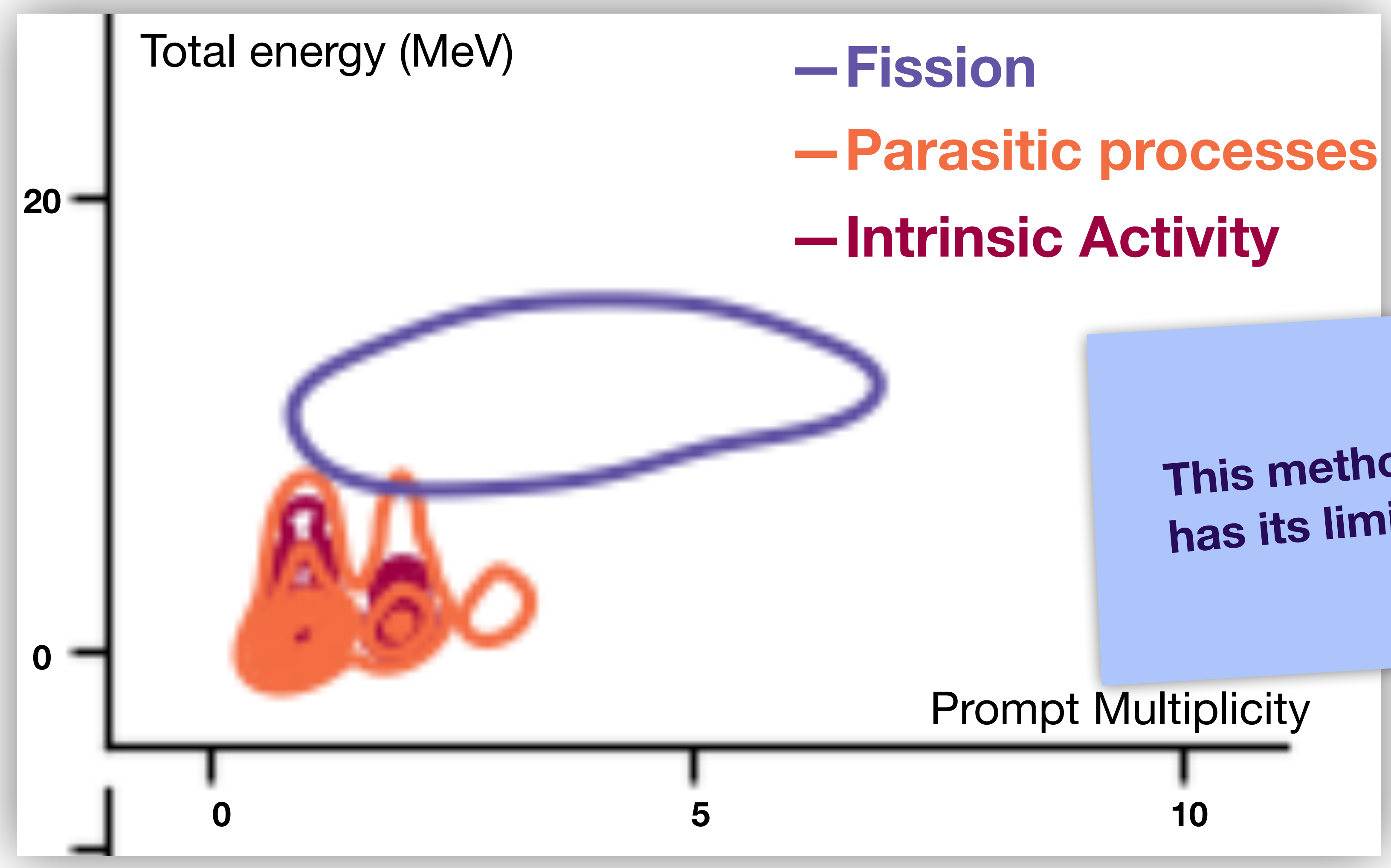
- Requires spectroscopic target
- Geometrical constraints experimental setups

…such as an active target



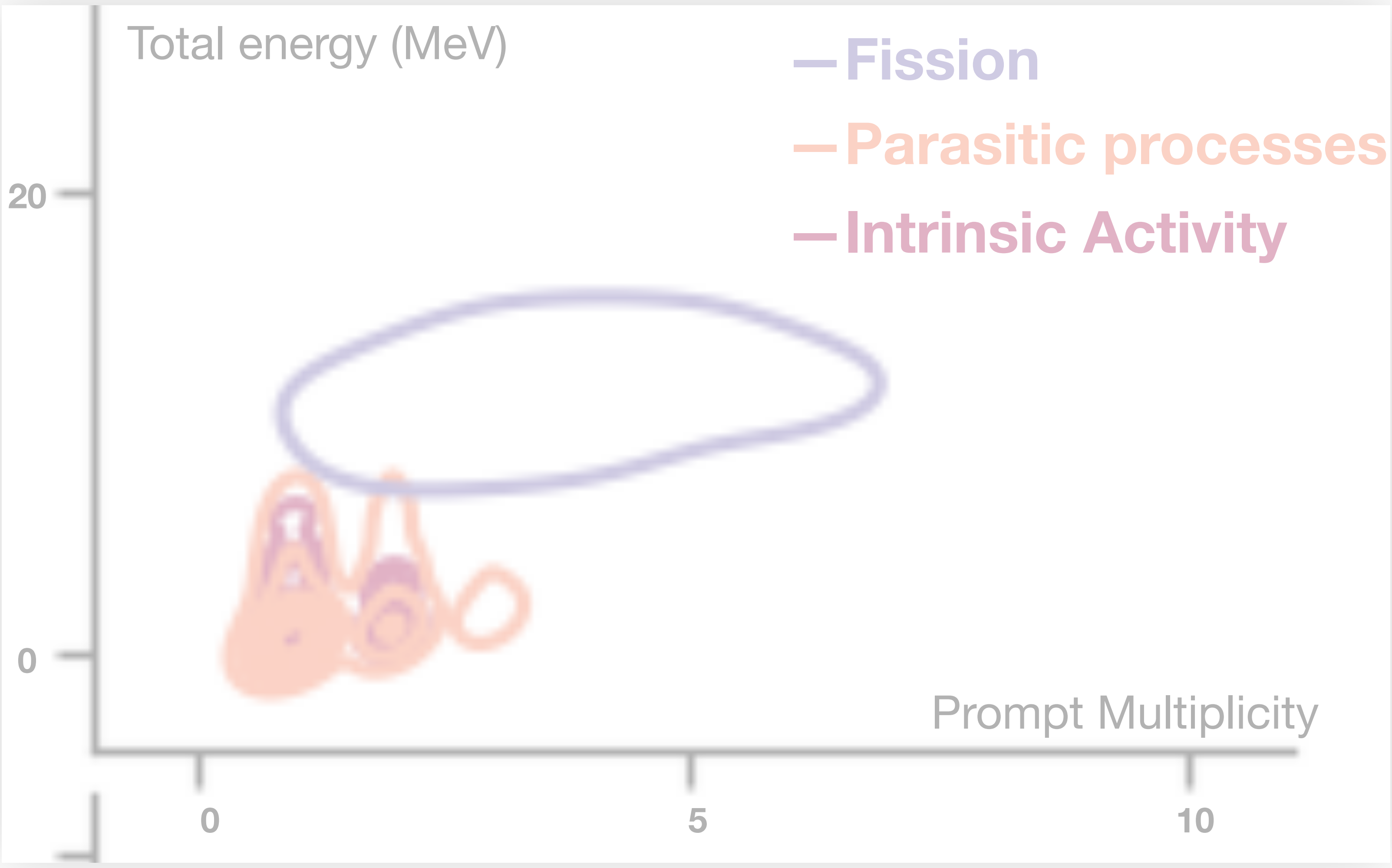
PhD thesis: Dennis Wilmsen. Nuclear structure studies with neutron-induced reactions : fission fragments in the N=50-60 region, a fission tagger for FIPPS, and production of the isomer Pt-195m. Physics [physics]. Normandie Université, 2017. English. <NNT : 2017NORMC269>. <tel-01768580>

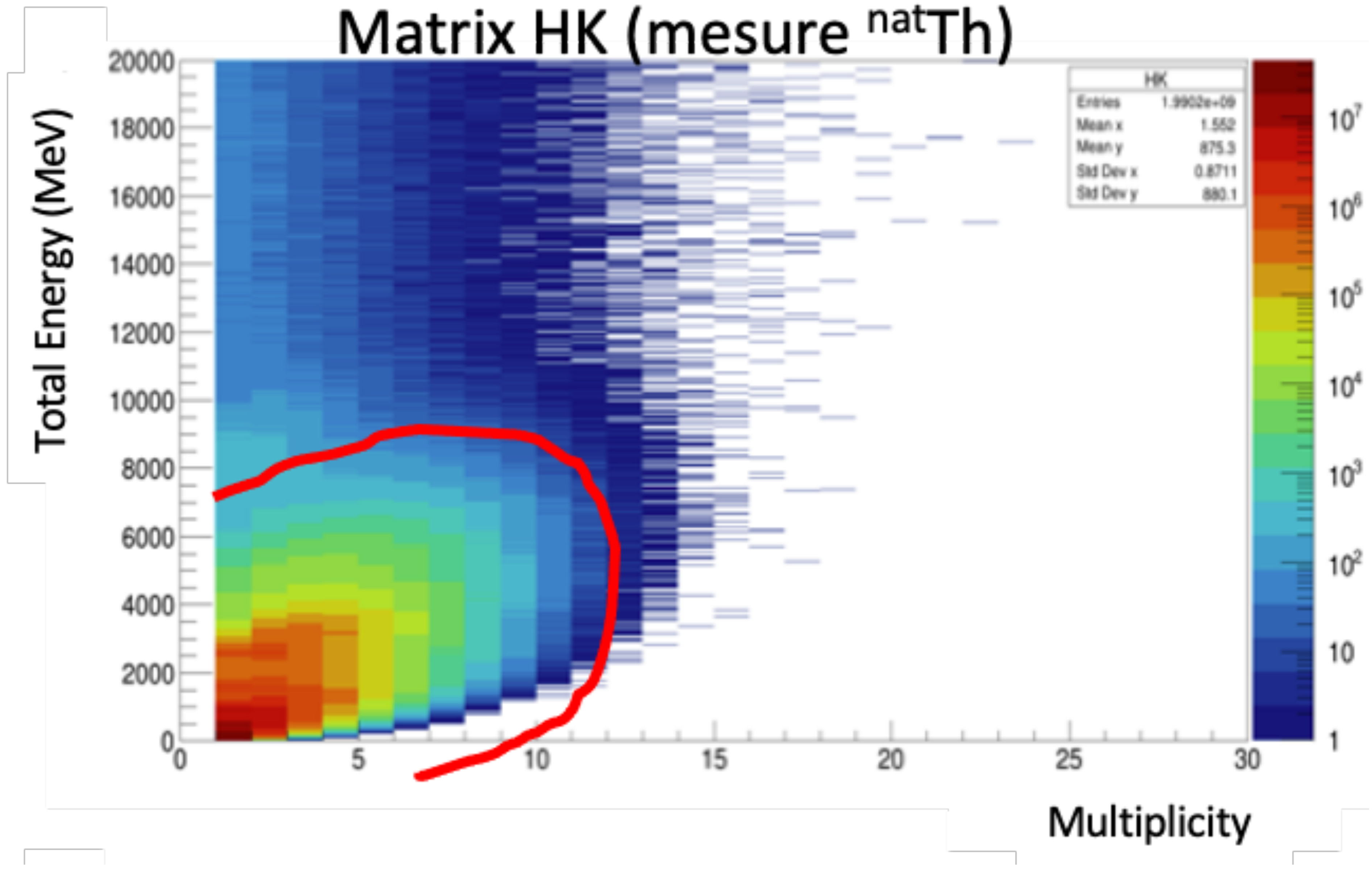
Calorimetry for fission event recognition



This method also has its limitations…

Calorimetry for fission event recognition





D. Thisse, Paris-Saclay, PhD thesis (2021)

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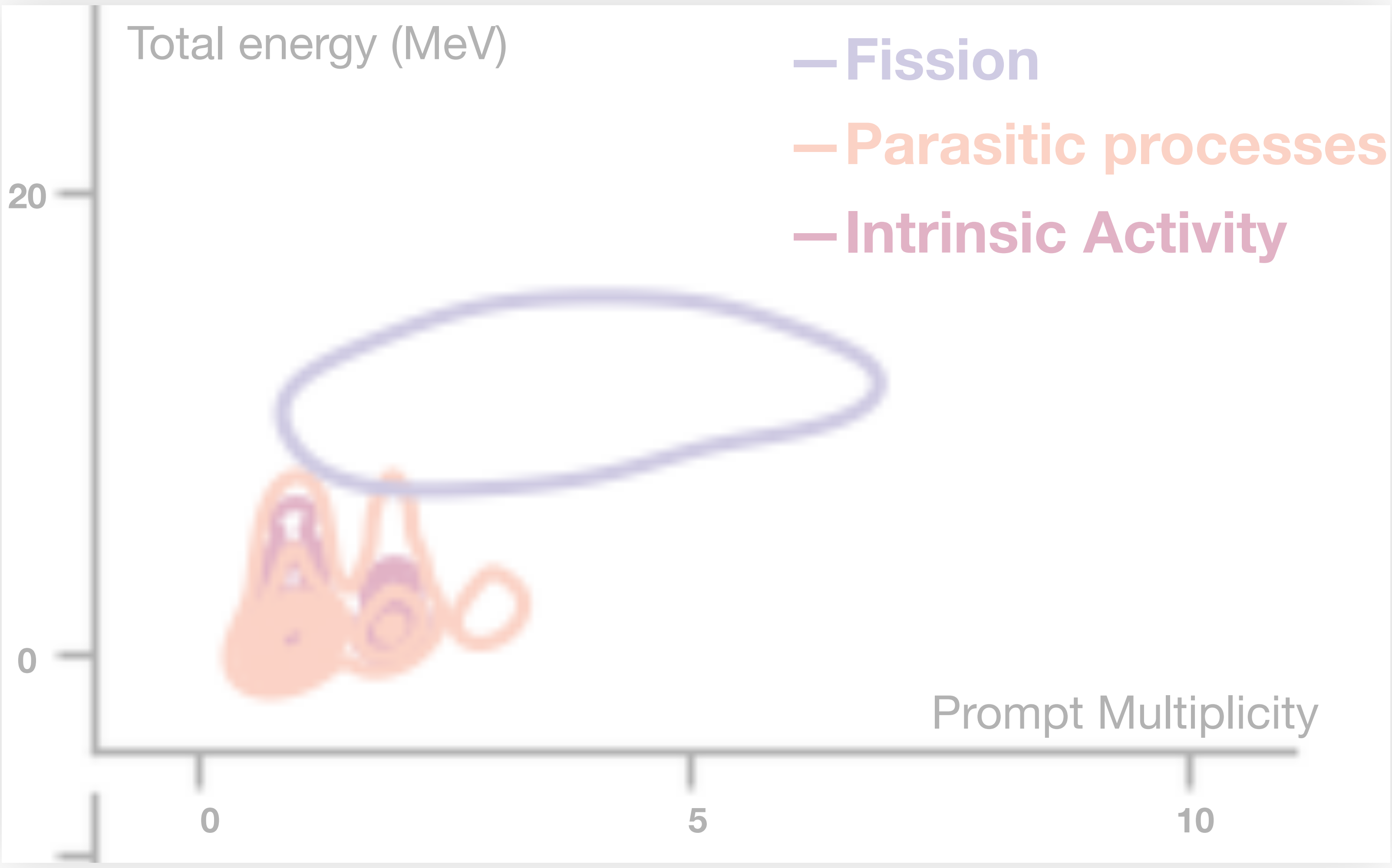

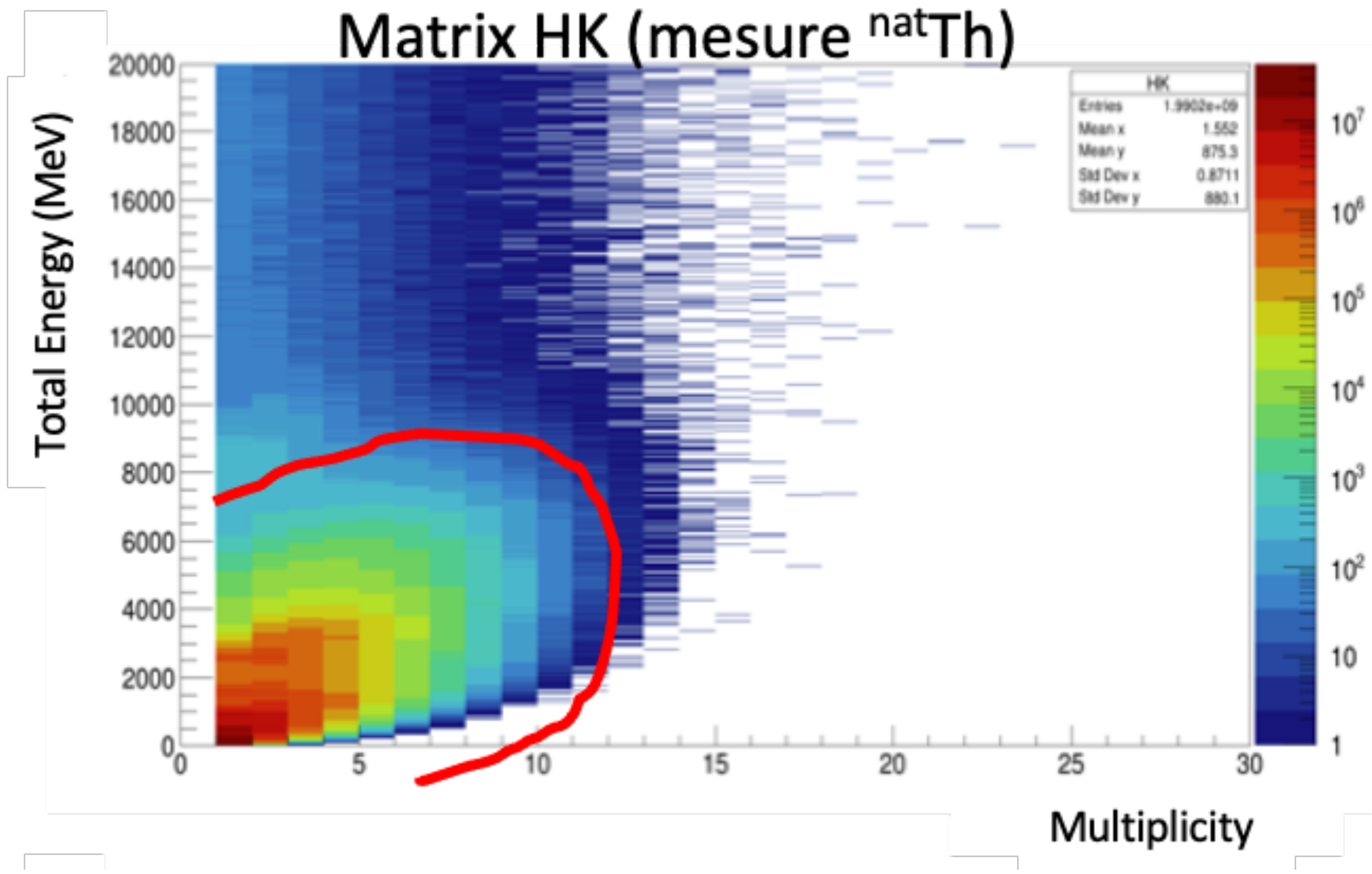

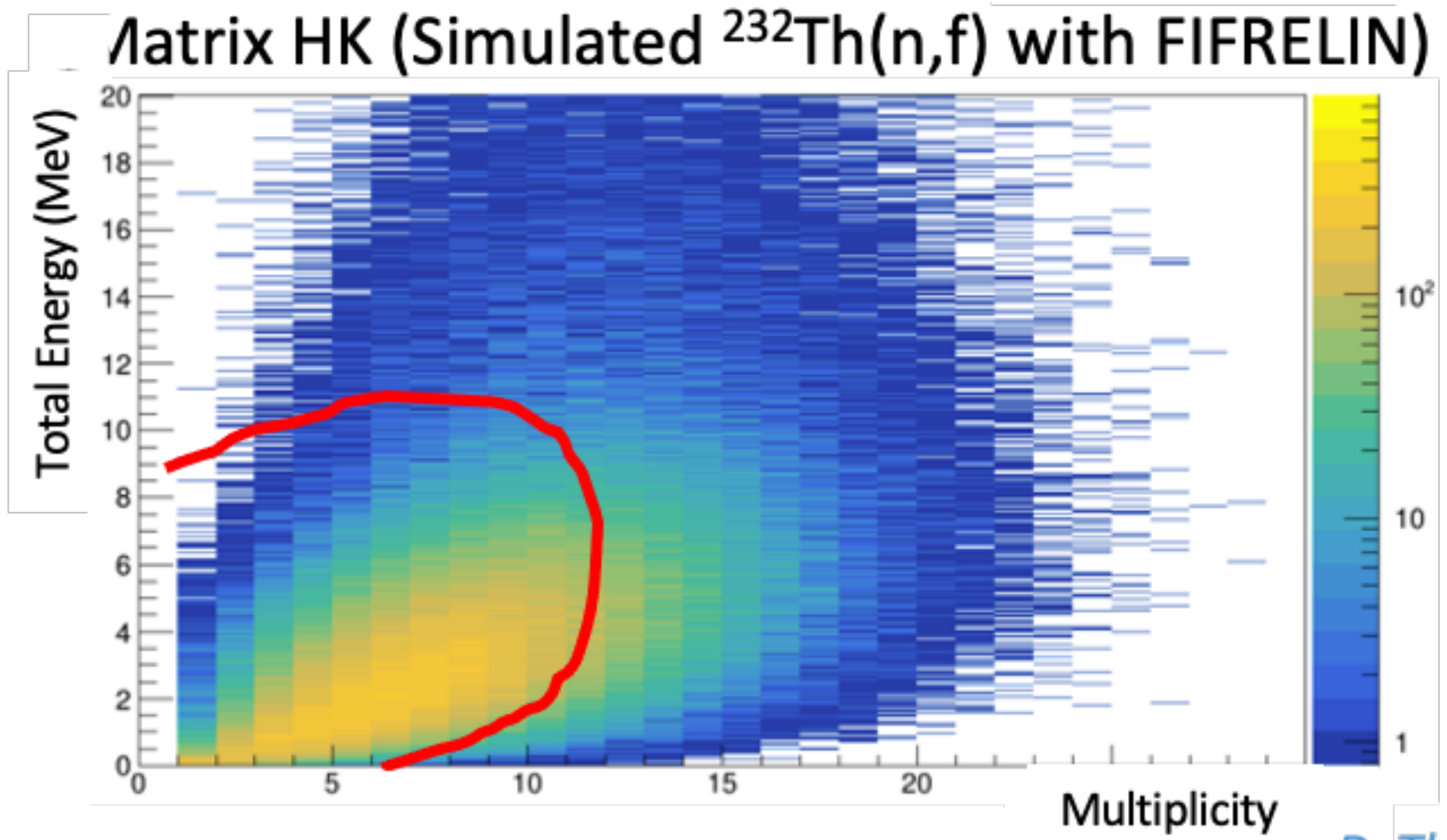

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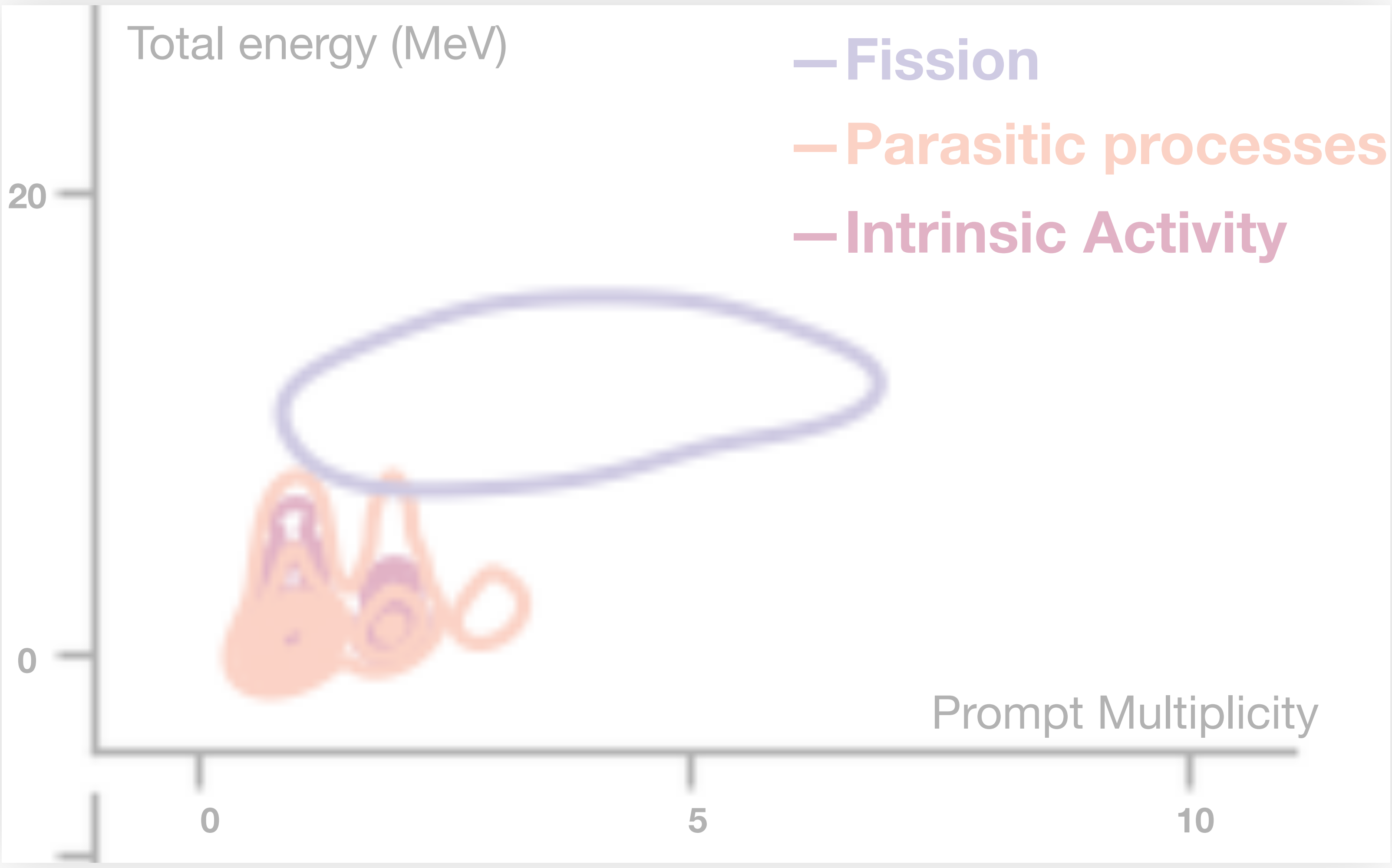
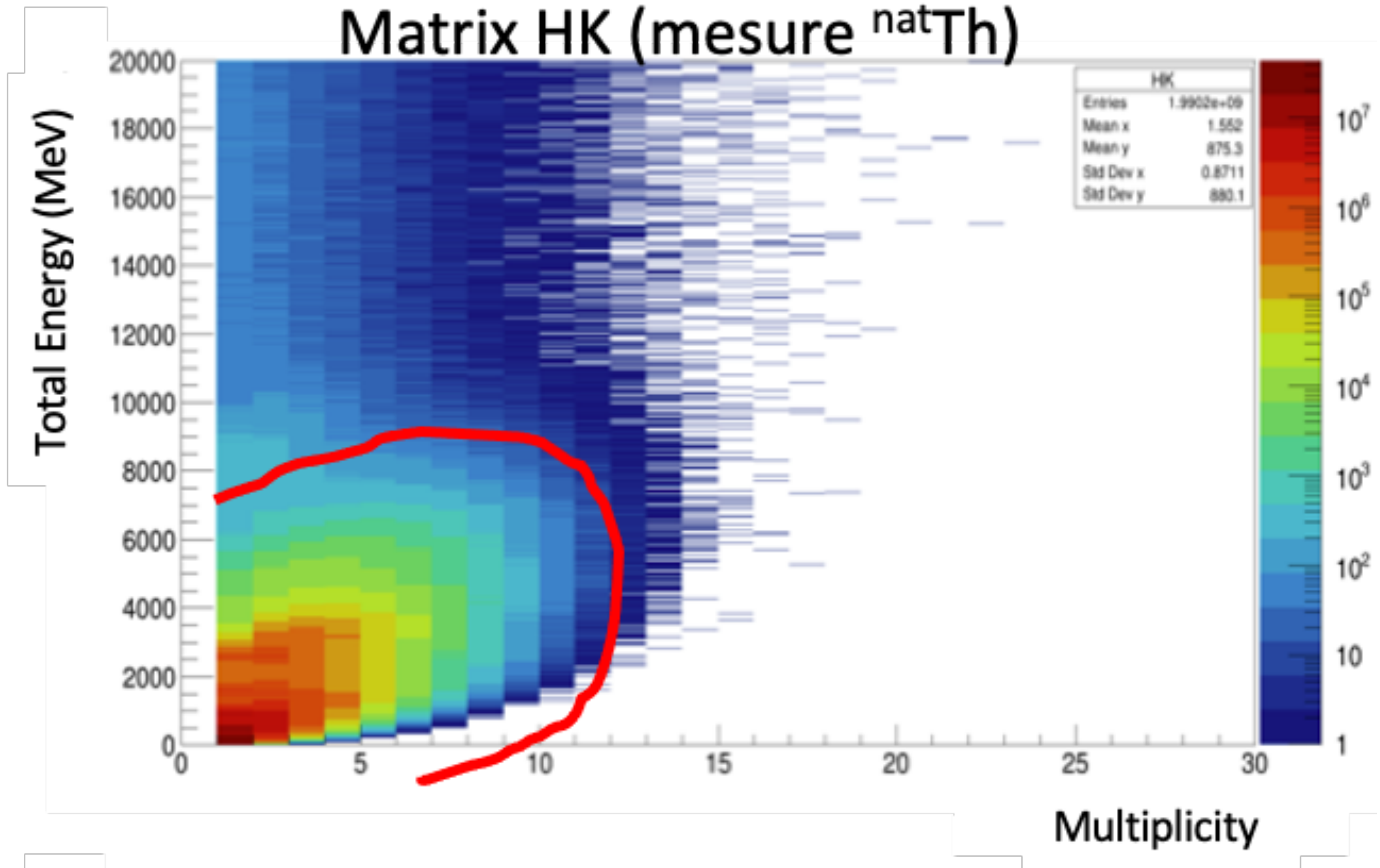
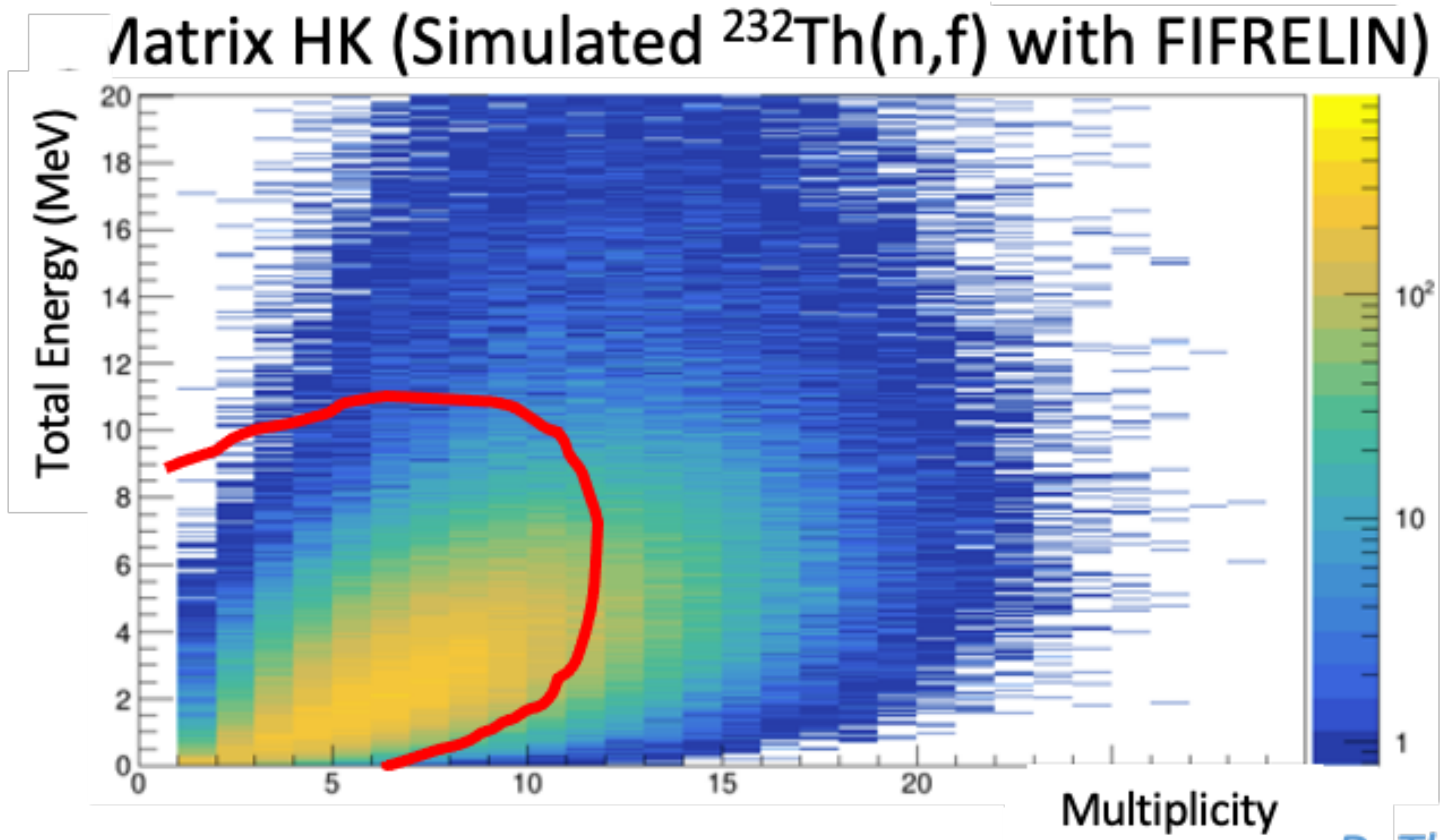
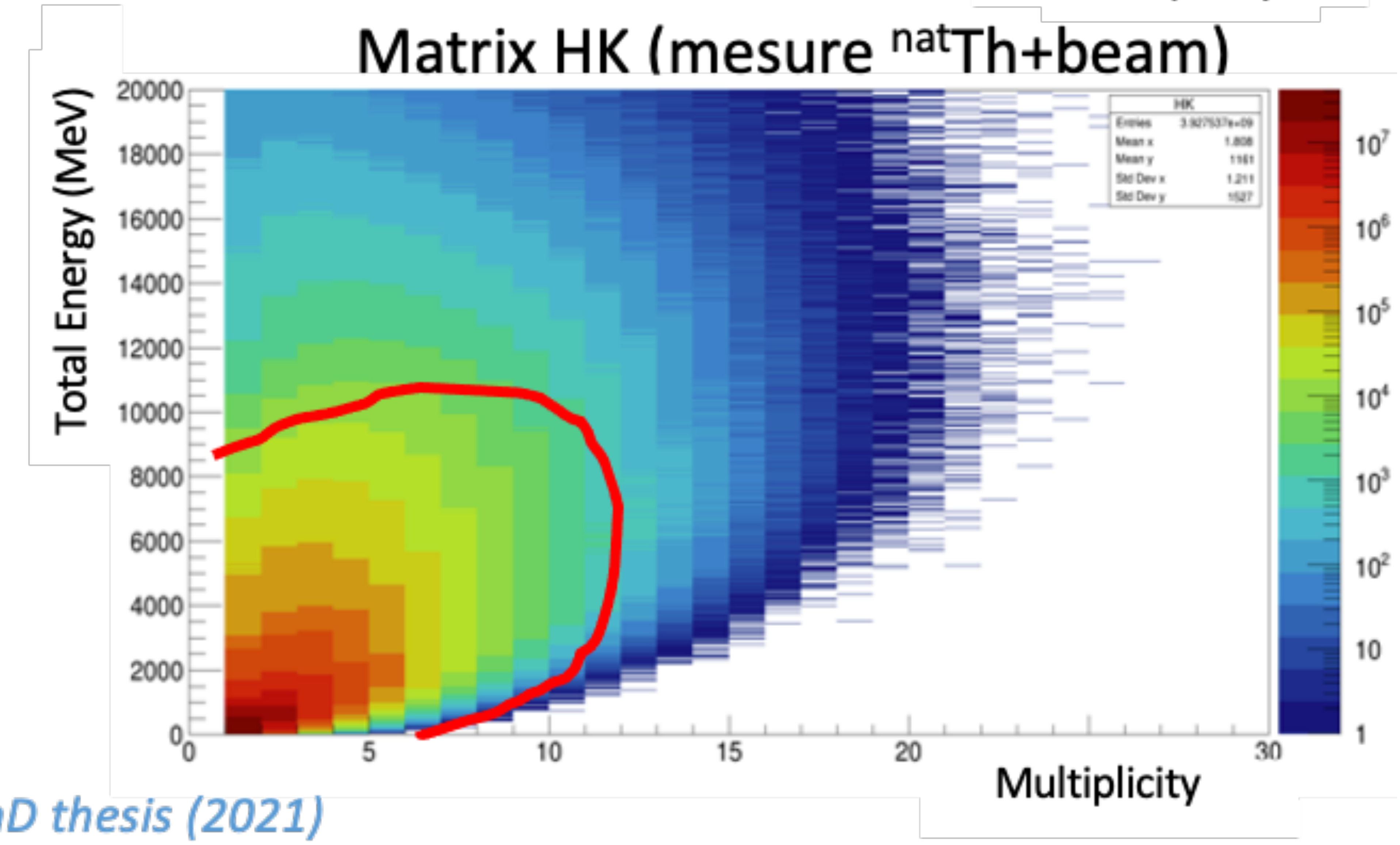




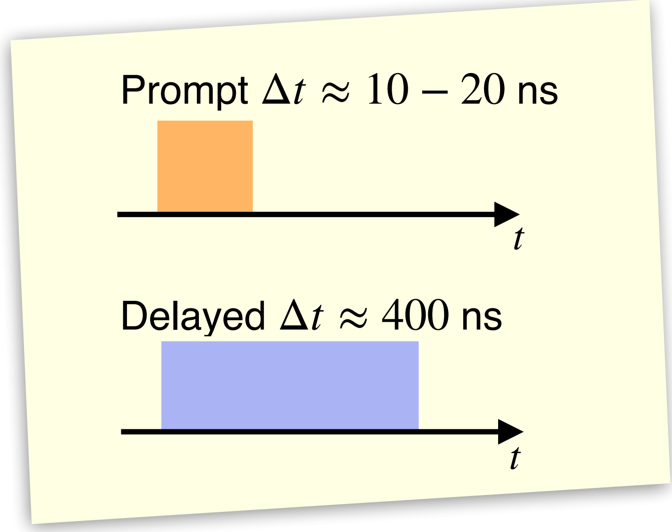


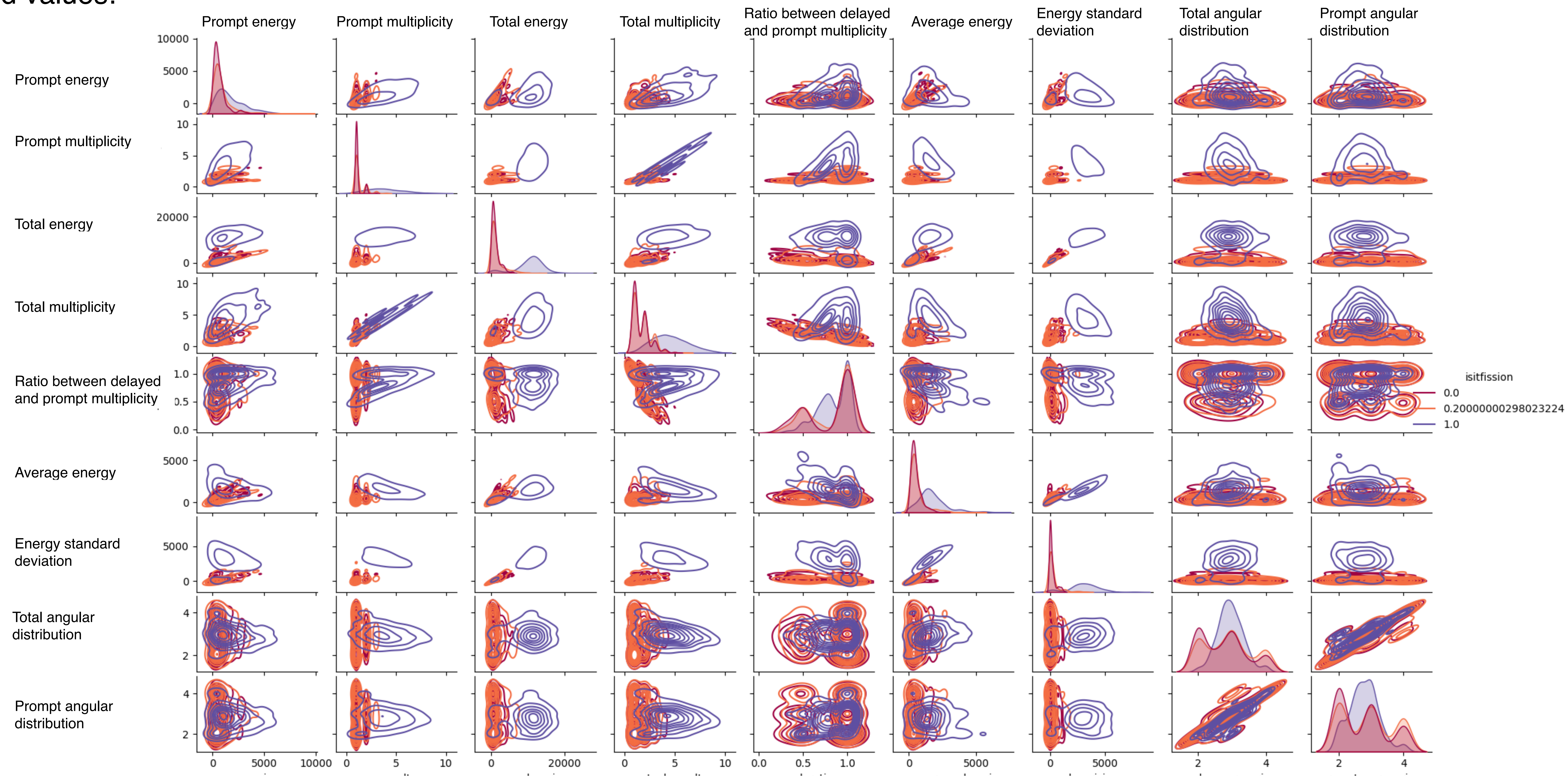


D. Thisse, Paris-Saclay, PhD thesis (2021)

Fission event recognition

Measured values:





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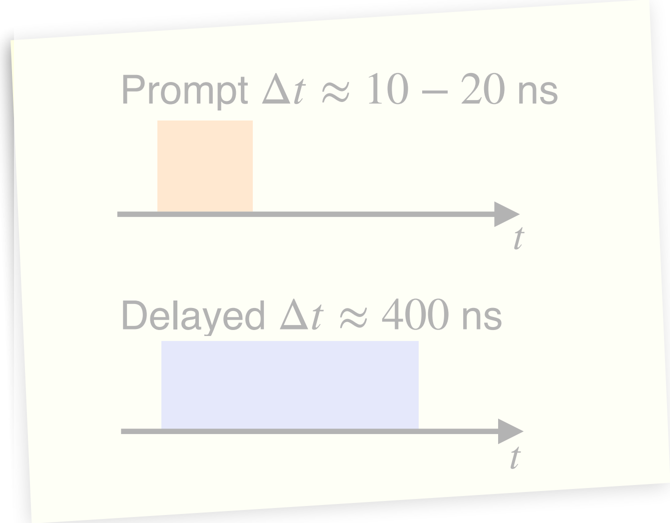

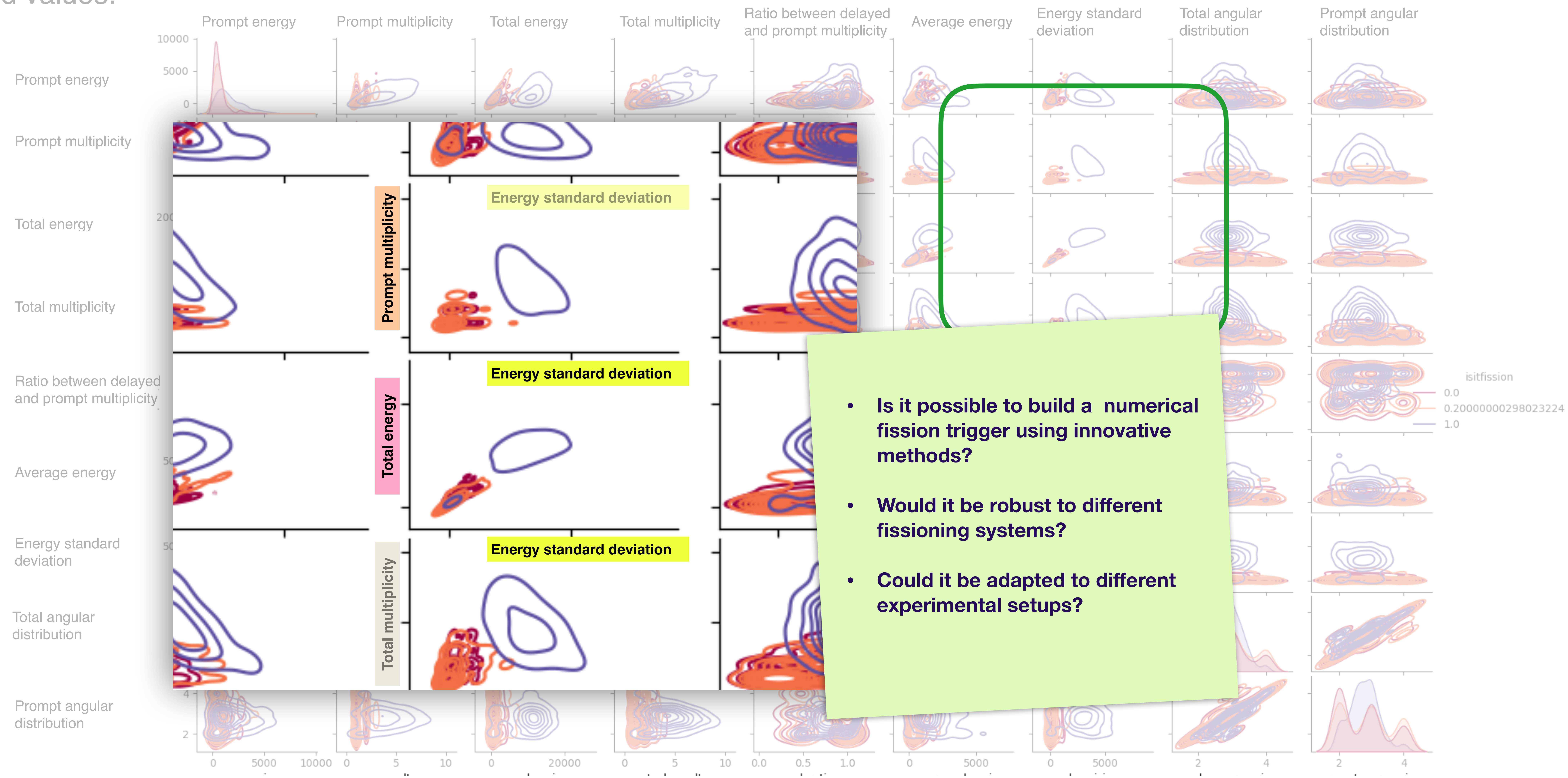

- **Is it possible to build a numerical fission trigger using innovative methods?**
- **Would it be robust to different fissioning systems?**
- **Could it be adapted to different experimental setups?**

Fission event recognition

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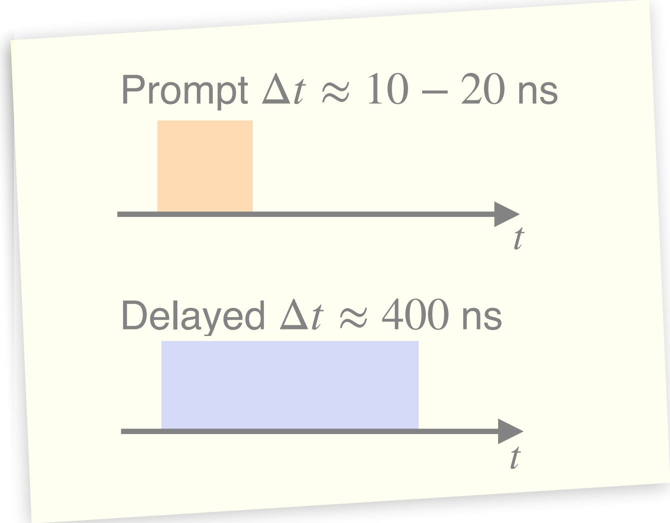

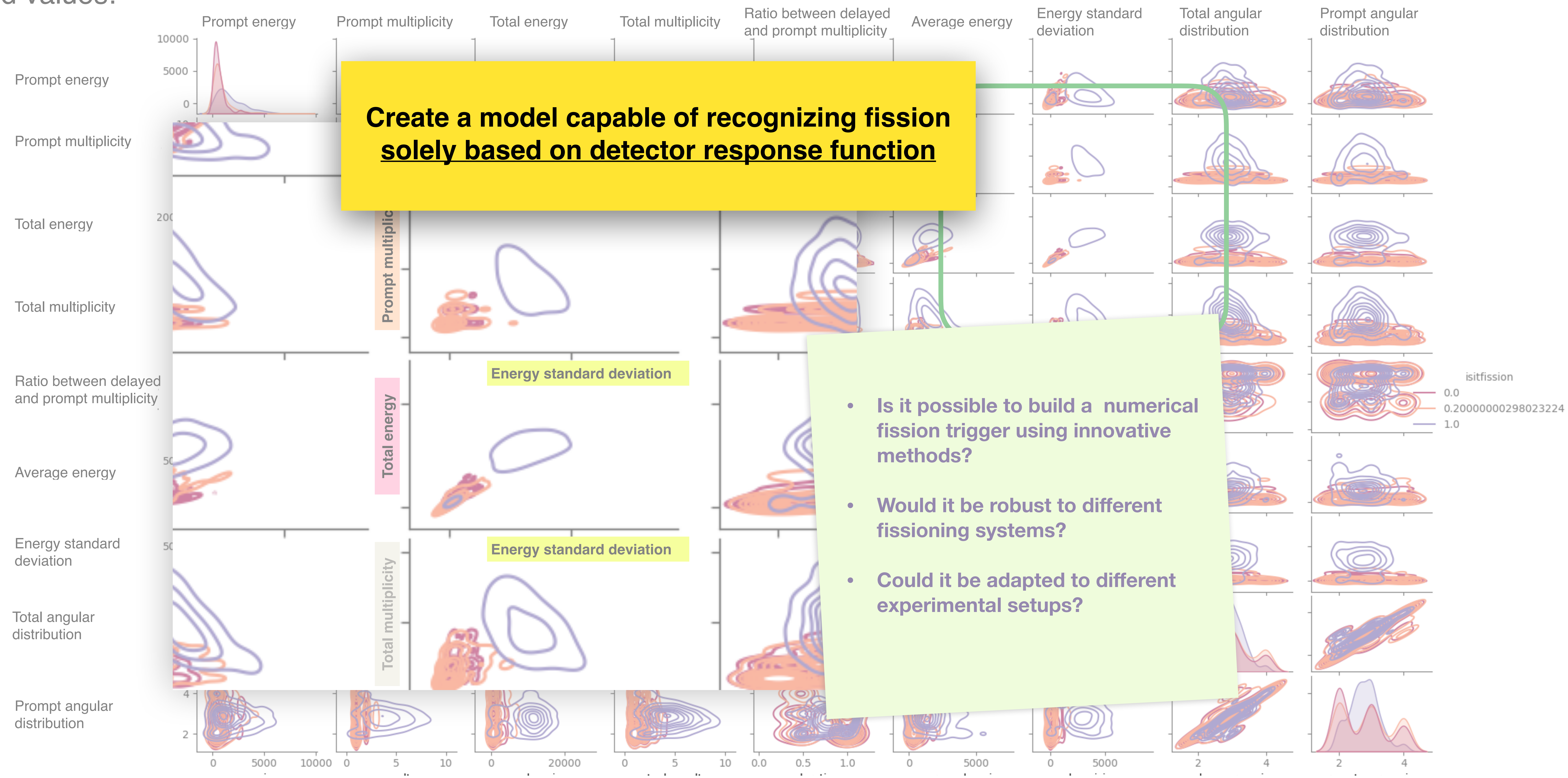

Create a model capable of recognizing fission <u>solely based on detector response function</u>

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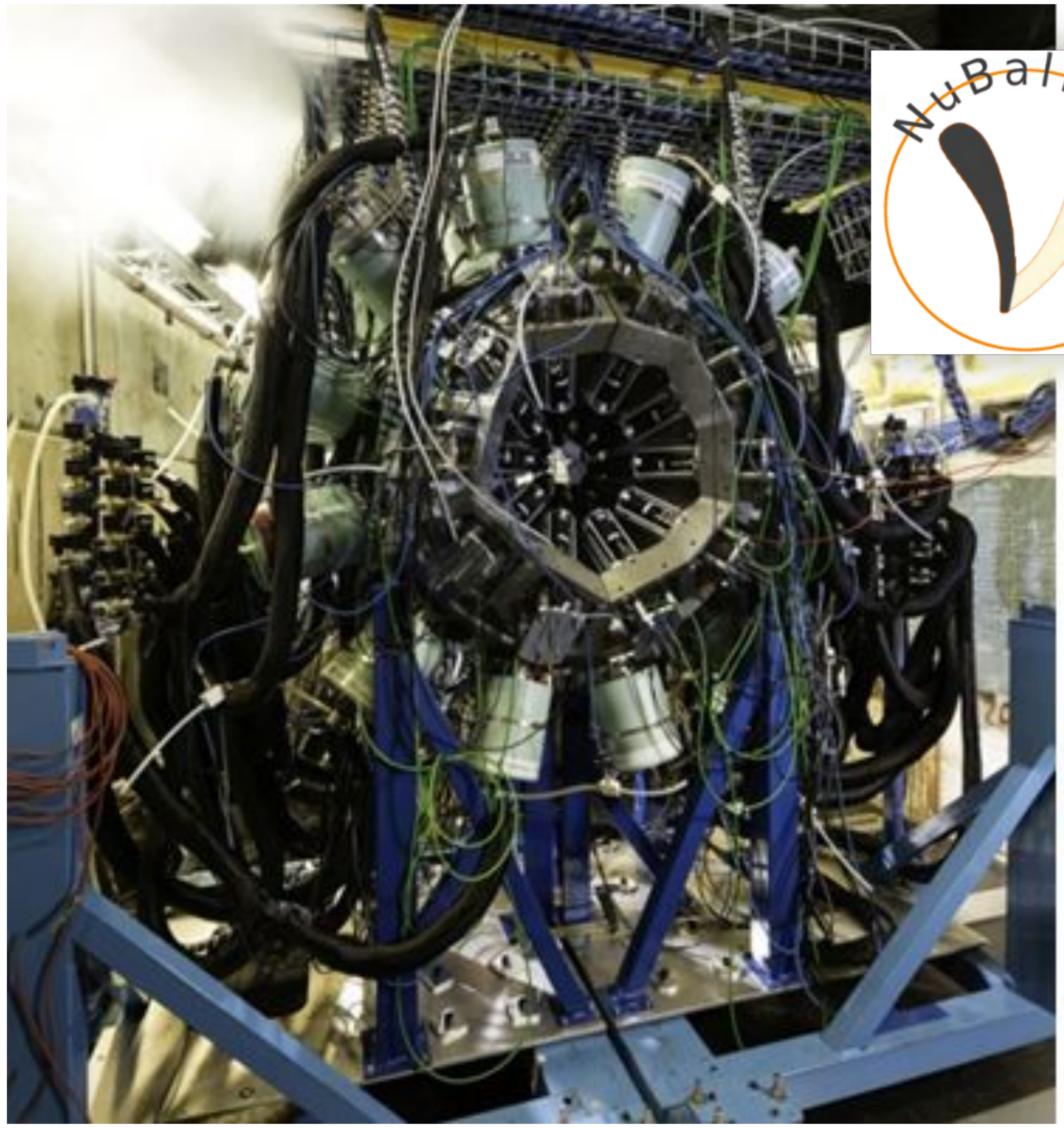
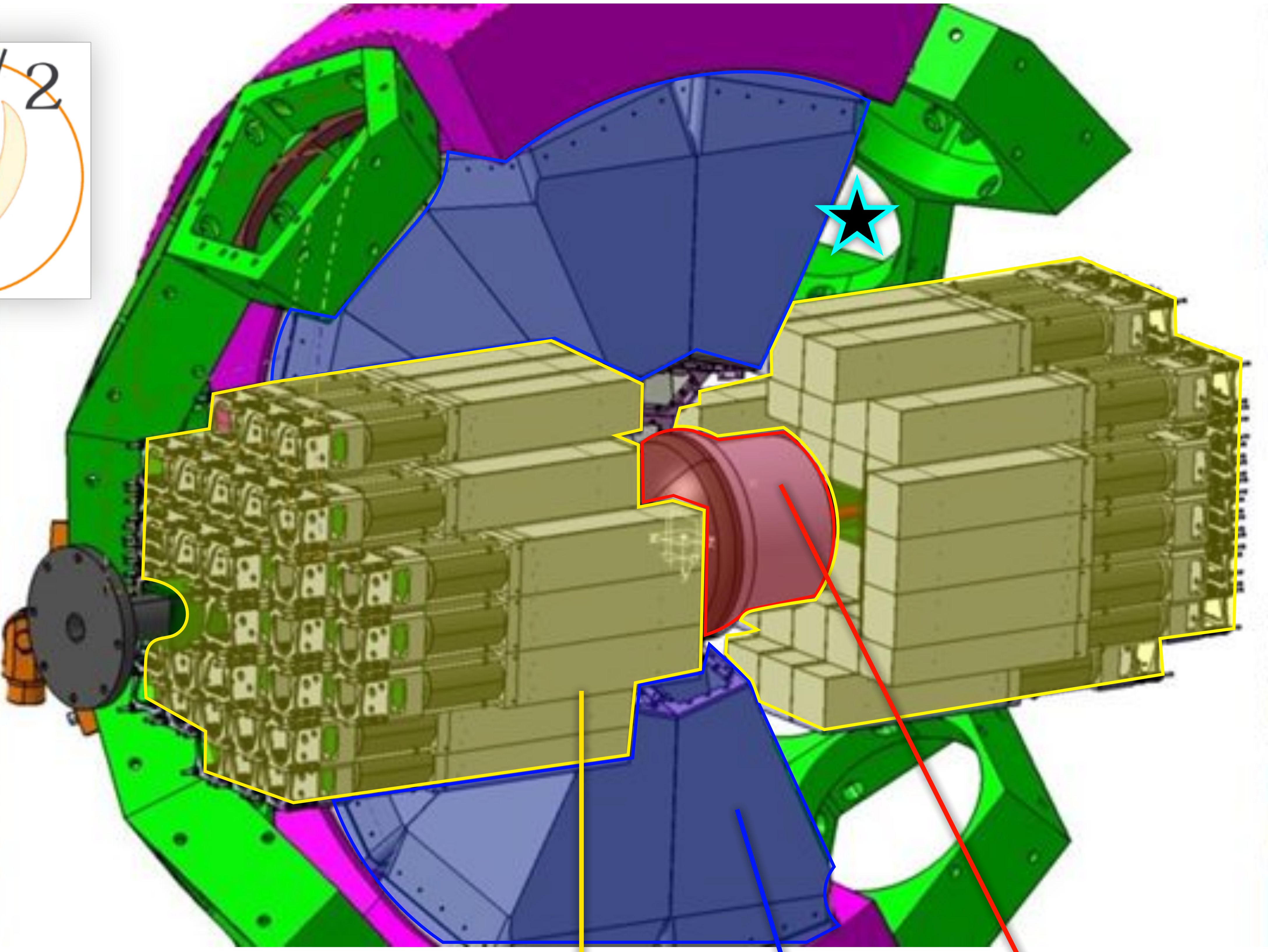
The N-SI-125 experiment setup



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



★ Thalia $LaBr_3$ phoswich | PARIS array | HPGe clovers | Ionisation chamber

Gamma detection
energy and multiplicity

- 24 High-Purity Germanium clovers (HPGe)
- PARIS array
  72 phoswhiches $La(Ce)Br_3$:NaI
- Thalia $LaBr_3$

Neutron detection
energy and multiplicity

- PARIS array
- Thalia $LaBr_3$

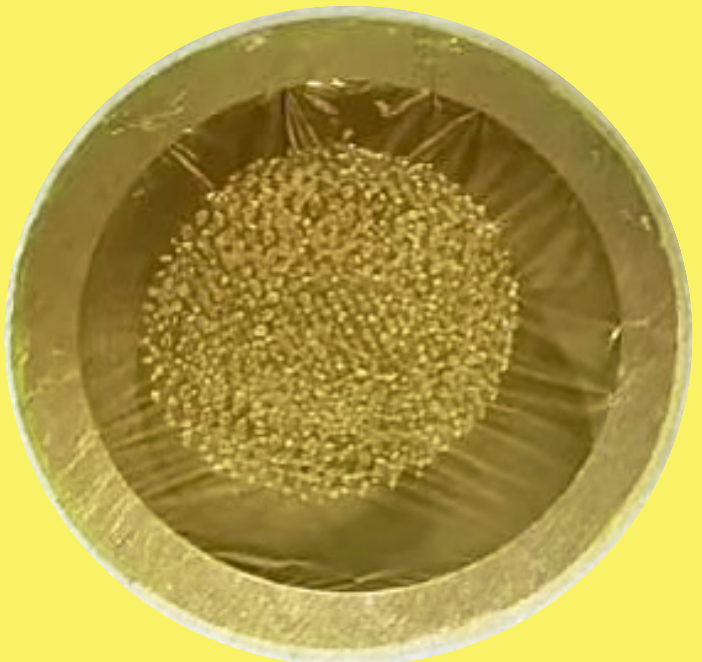
Exploratory

Fission fragments detection

- Ionisation chamber

The N-SI-125 experiment setup

Taken from: https://alt

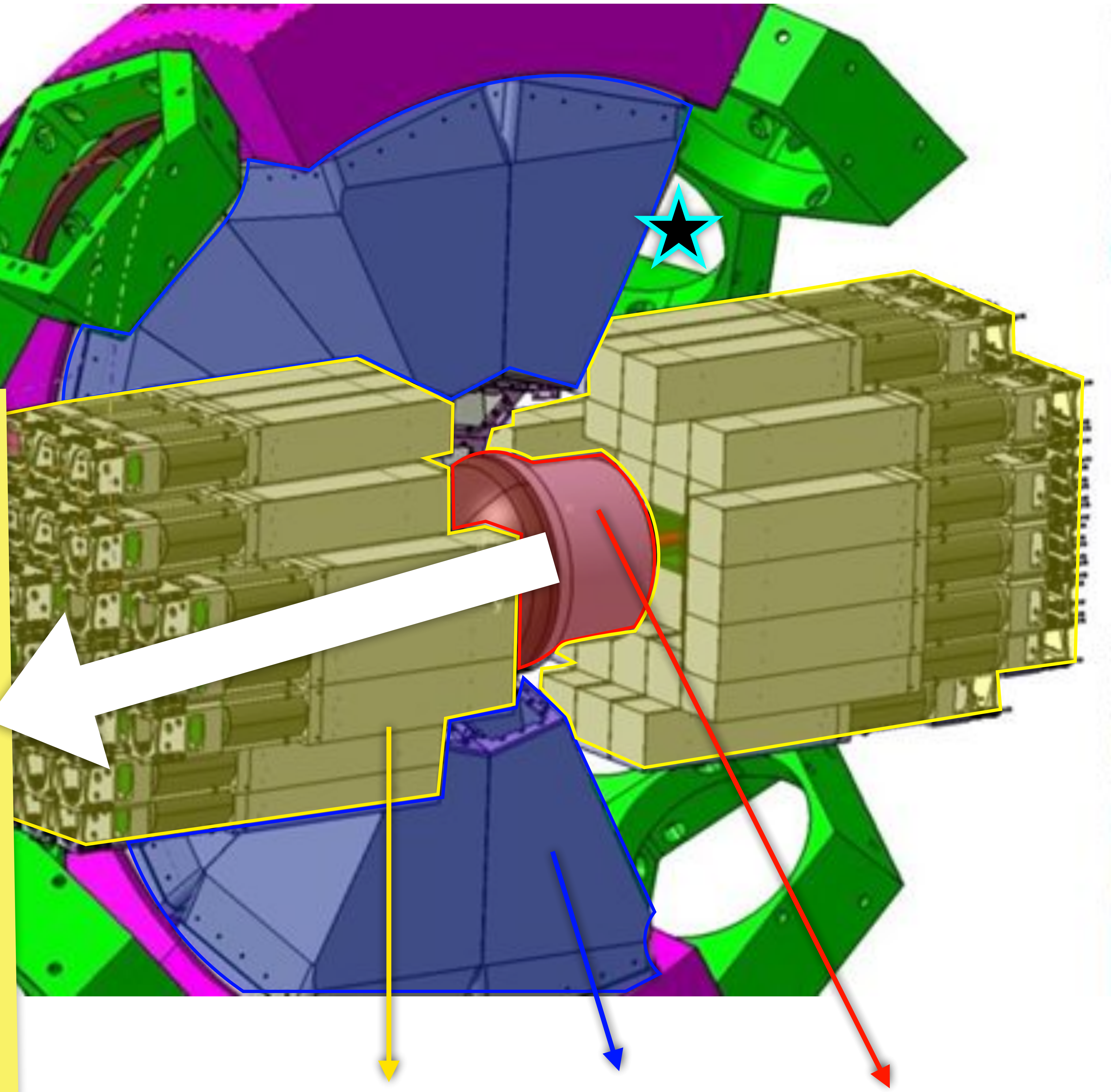


^{252}Cf source

$96.9\,\%$ α decay
$3.1\,\%$ fission

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

- Al ring $\varnothing_{out} = 40$ mm , $\varnothing_{in} = 30$ mm
- PI foil $36\,\mu g/cm^2$ + Au $52\,\mu g/cm^2$



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Thalia LaBr3
Exploratory

Fission fragments detection

Ionisation chamber

ALTO
Accélérateur Linéaire auprès du Tandem d'Orsay

The N-SI-125 experiment setup

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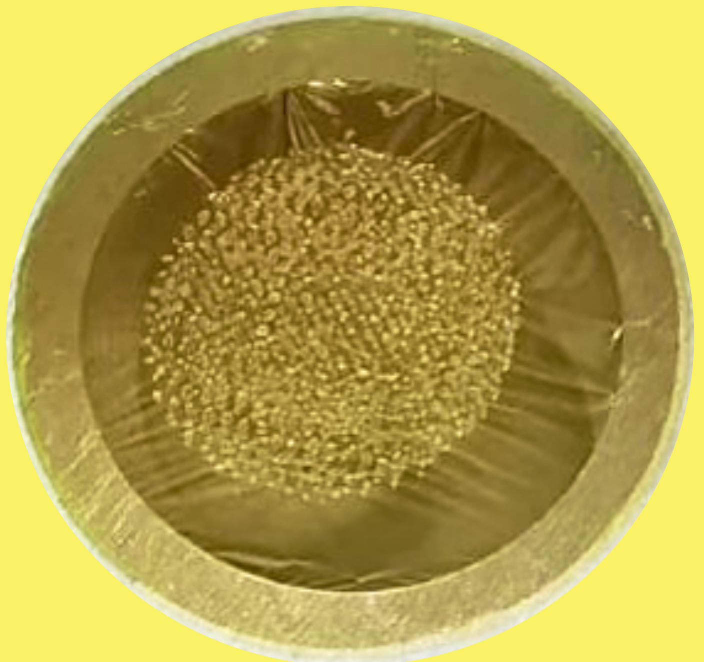

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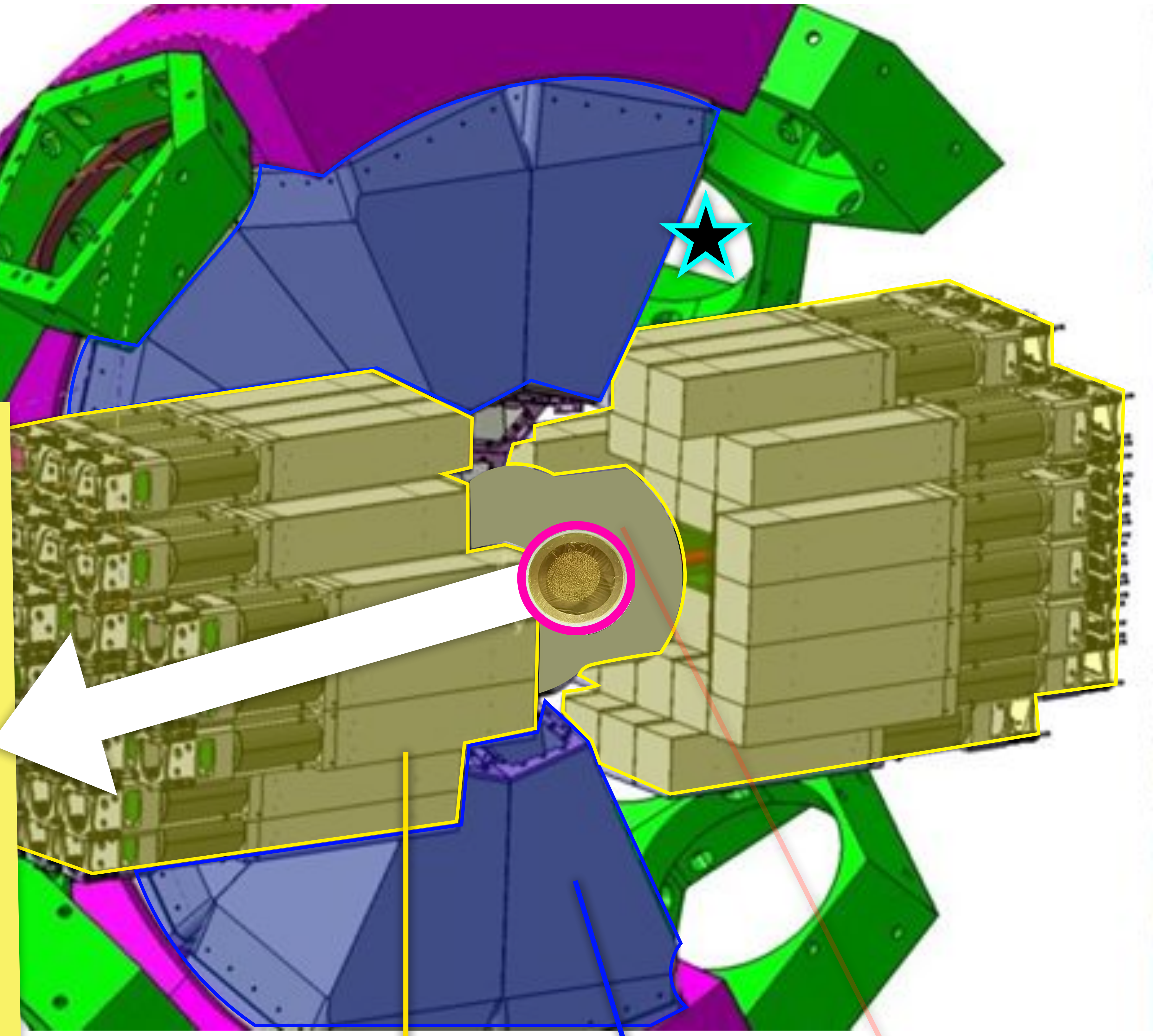

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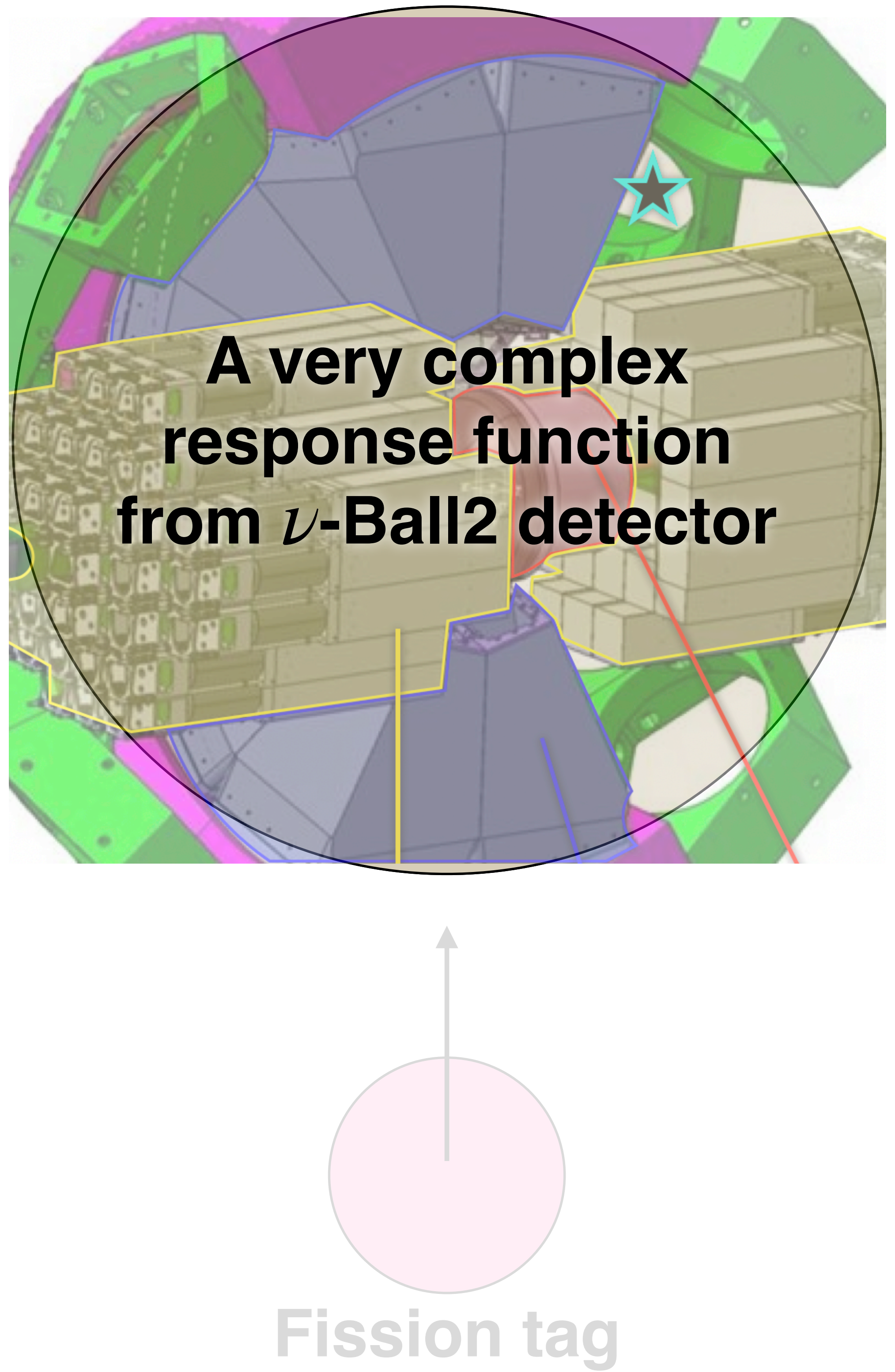
Fission trigger based on ν-Ball2 response function



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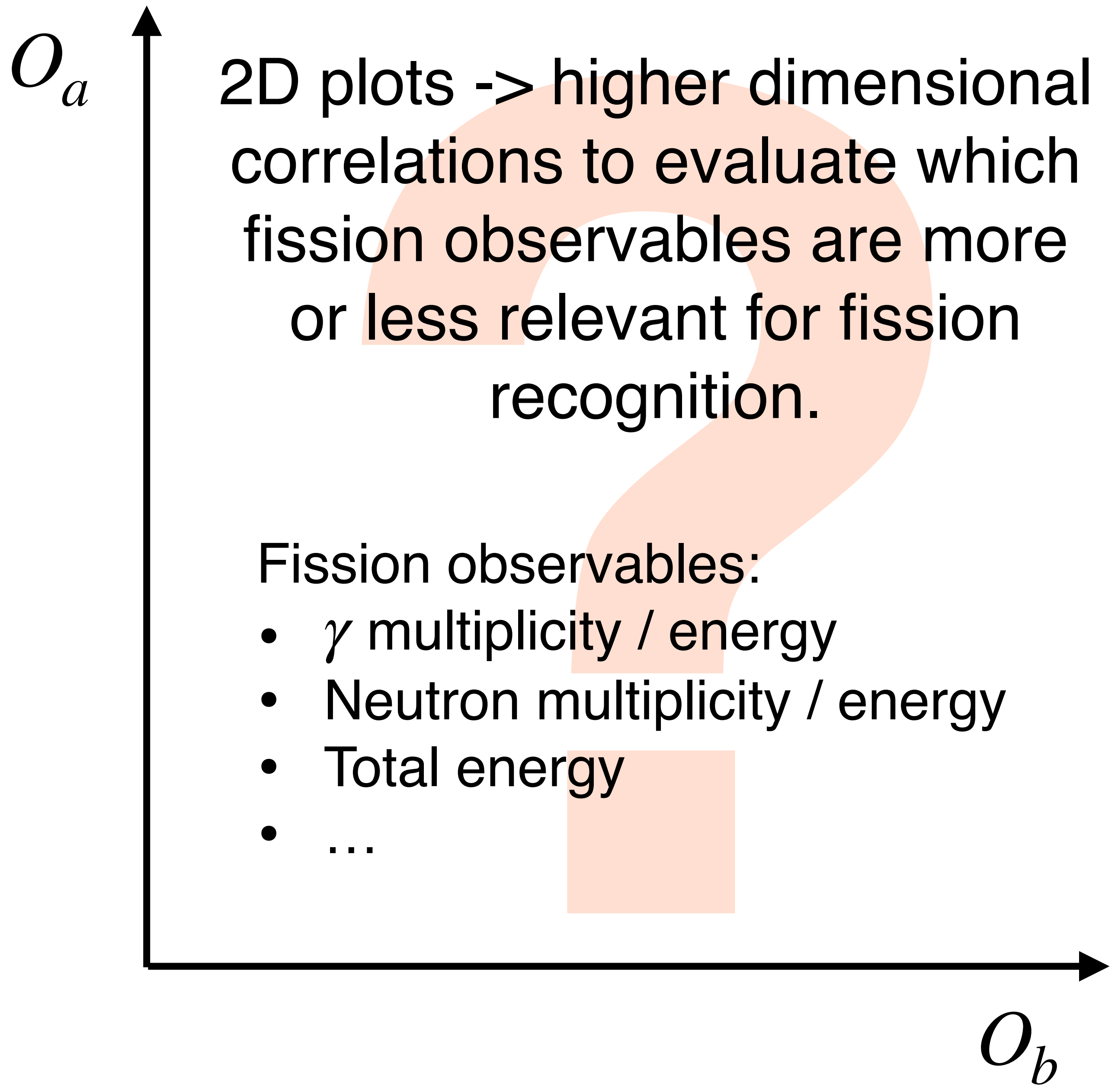
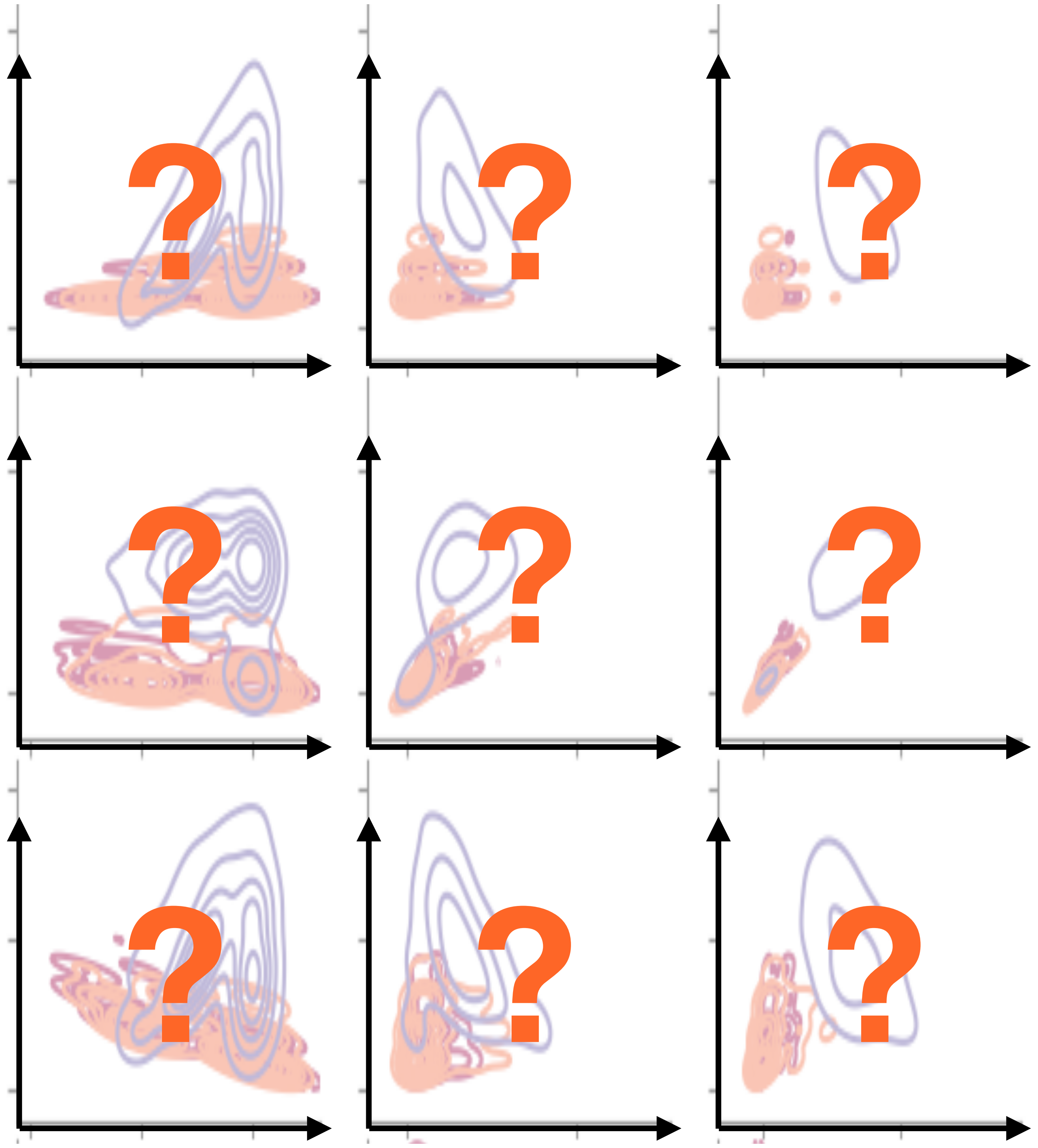


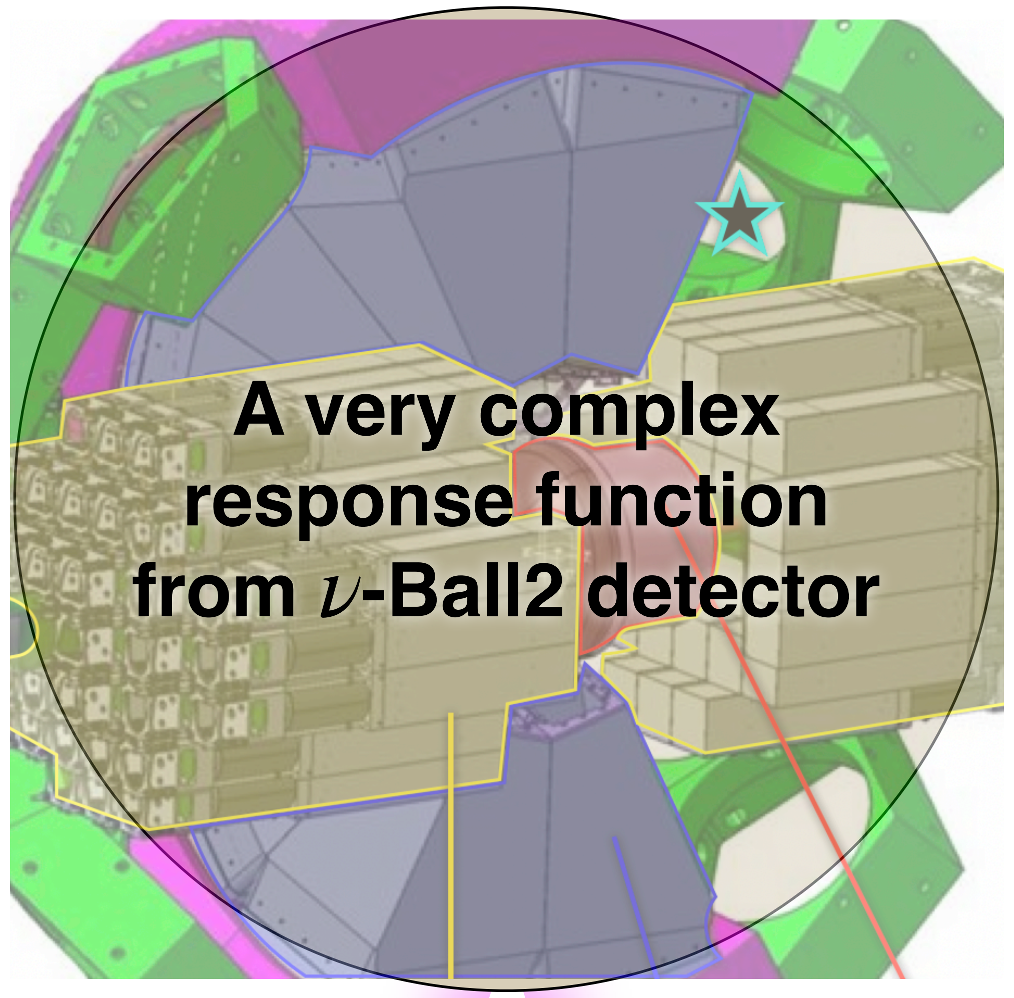
2D plots -> higher dimensional correlations to evaluate which fission observables are more or less relevant for fission recognition.

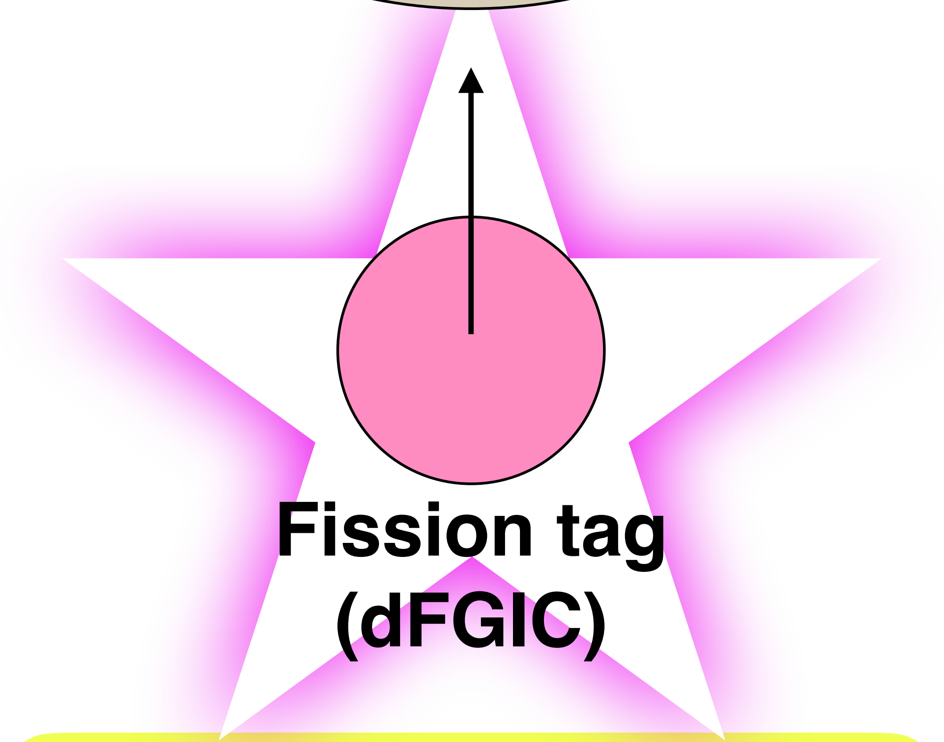
Fission observables:

- γ multiplicity / energy
- Neutron multiplicity / energy
- Total energy
- …



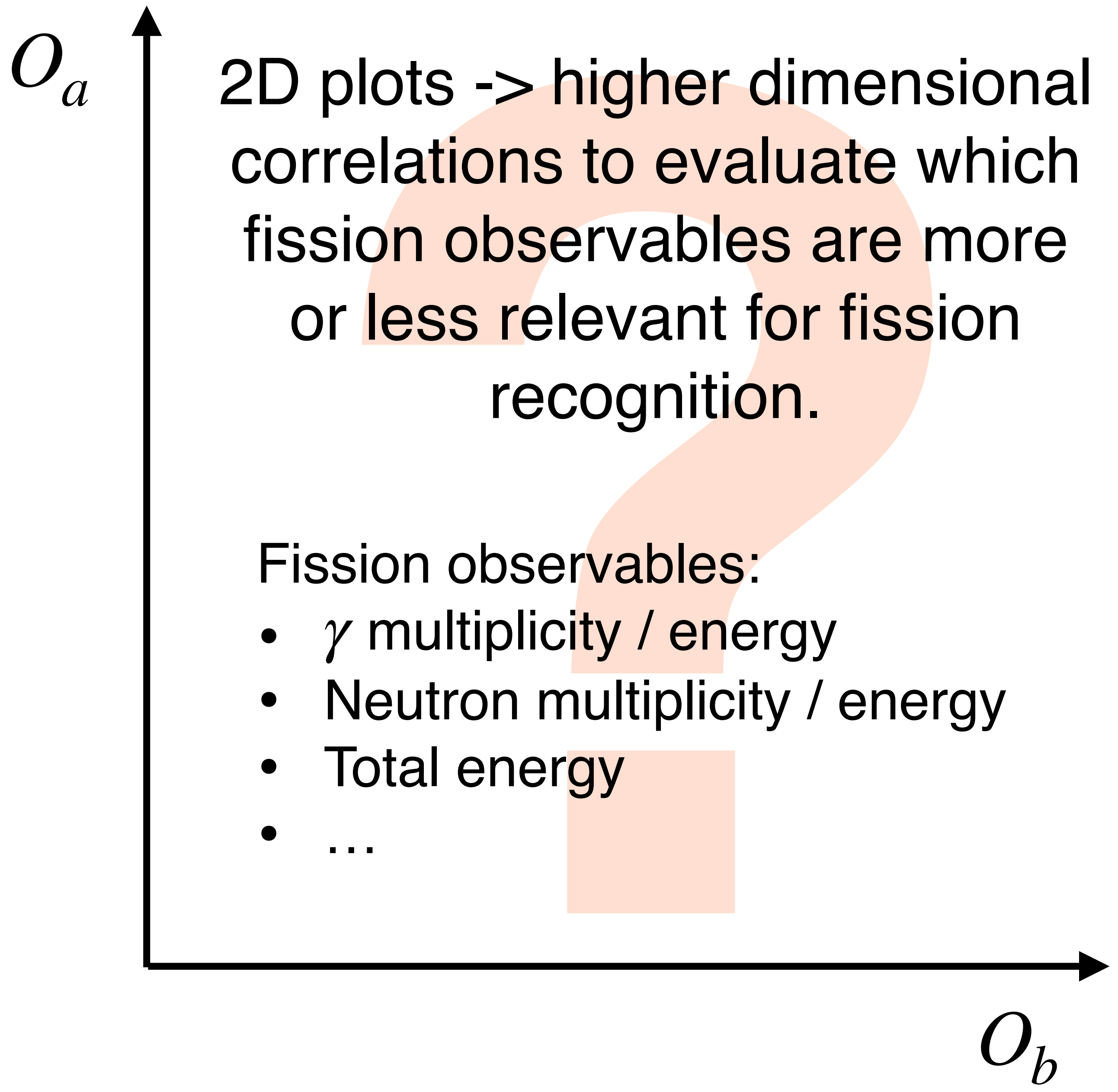
Fission trigger based on ν-Ball2 response function





Classification labels

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



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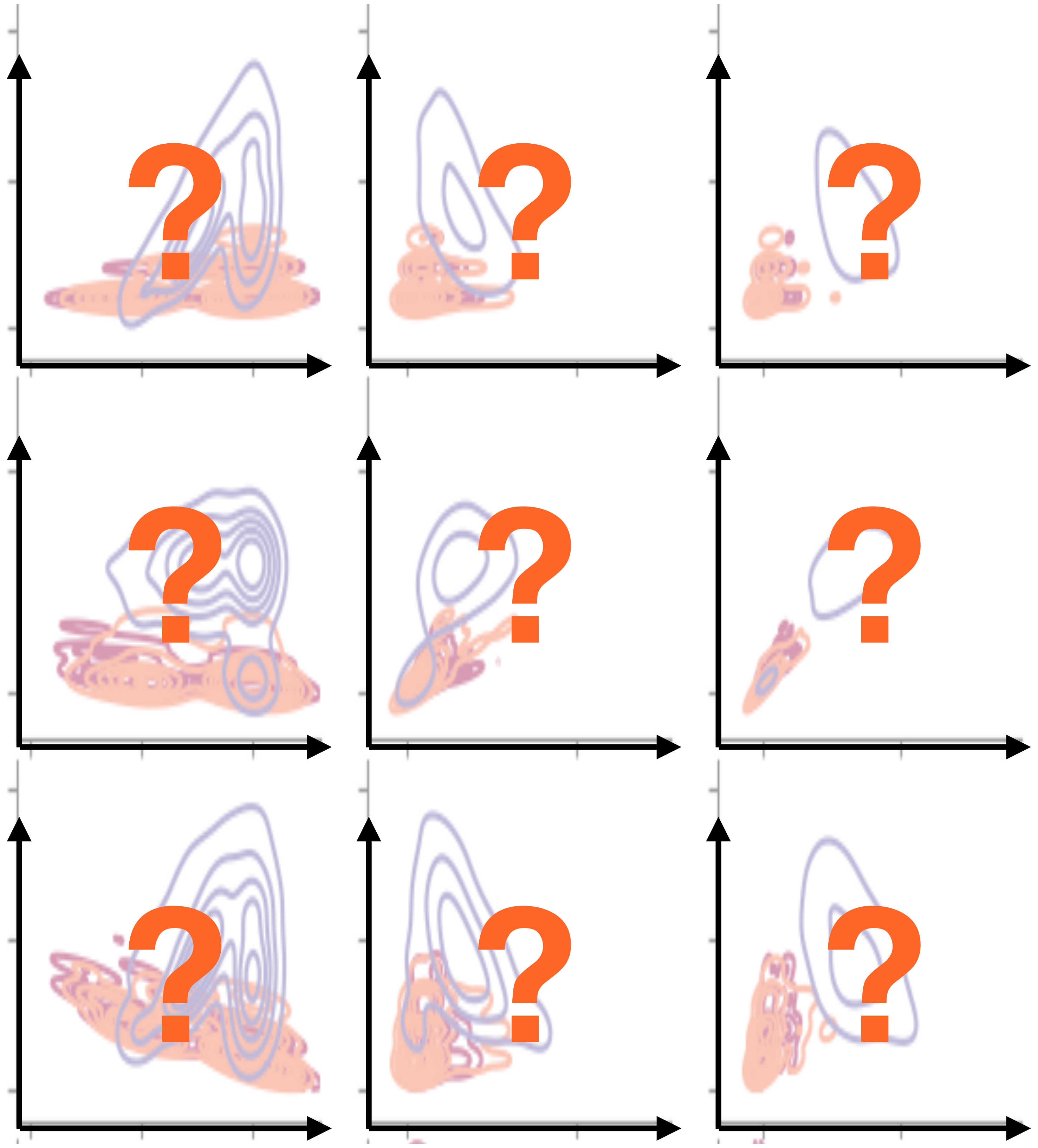
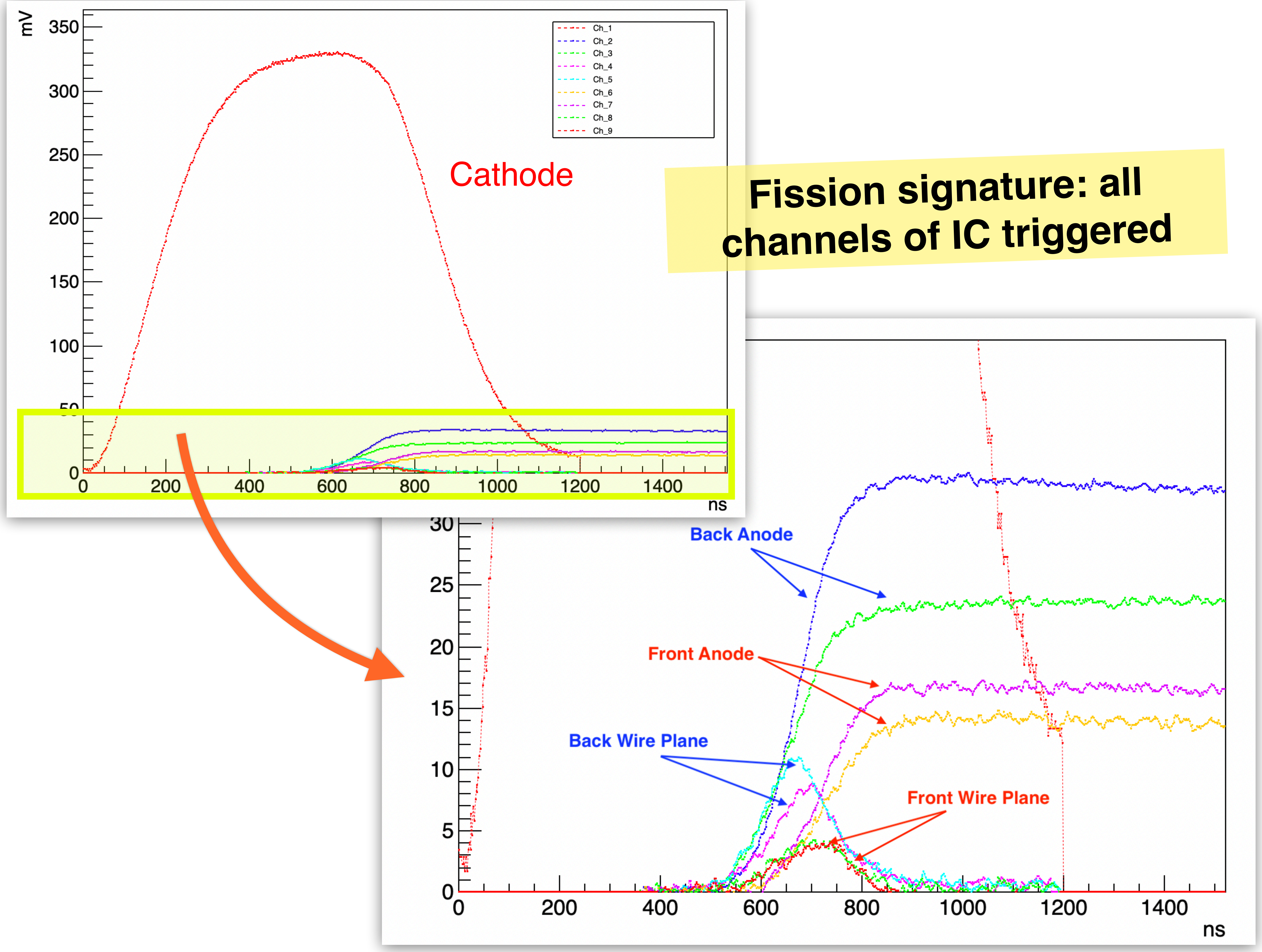
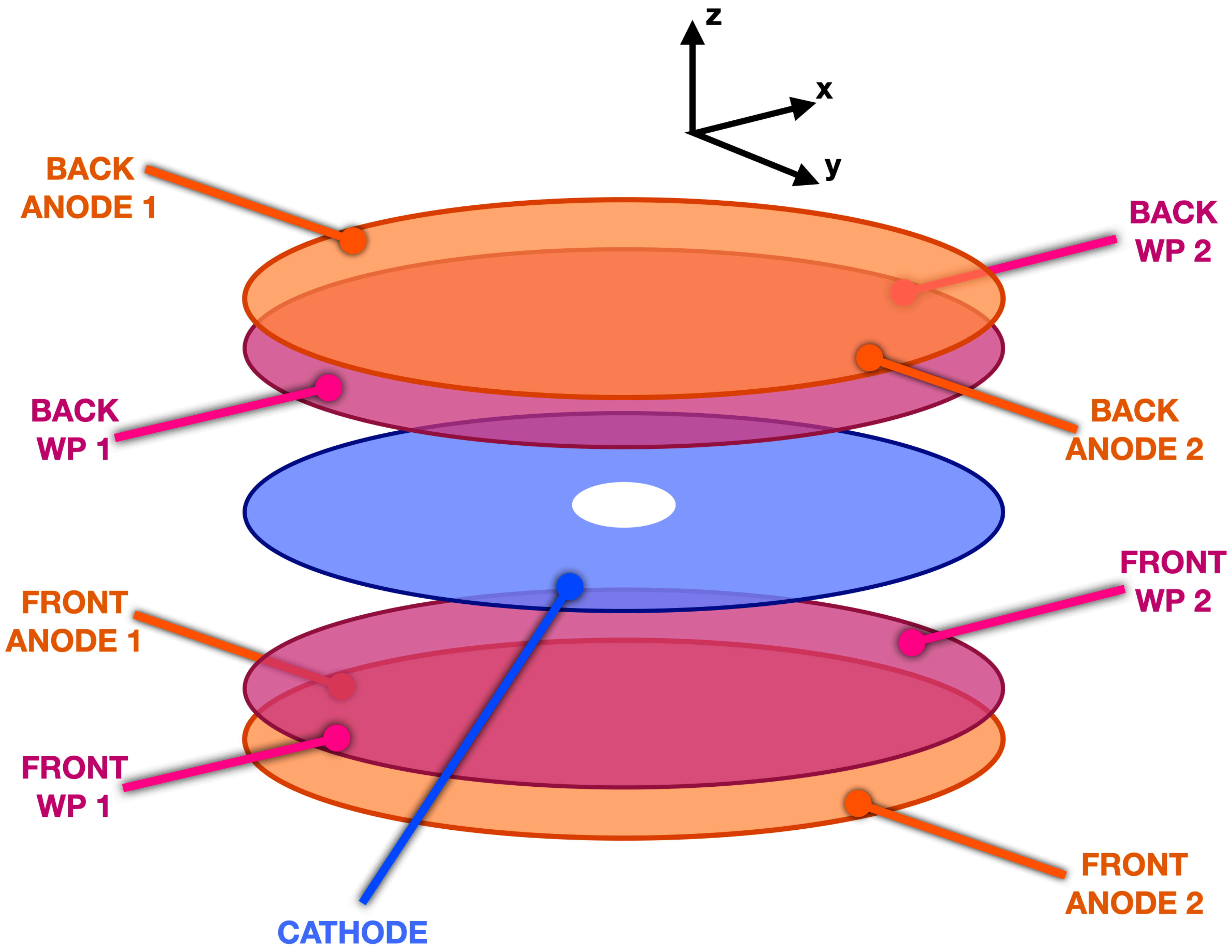


CONTENTS:

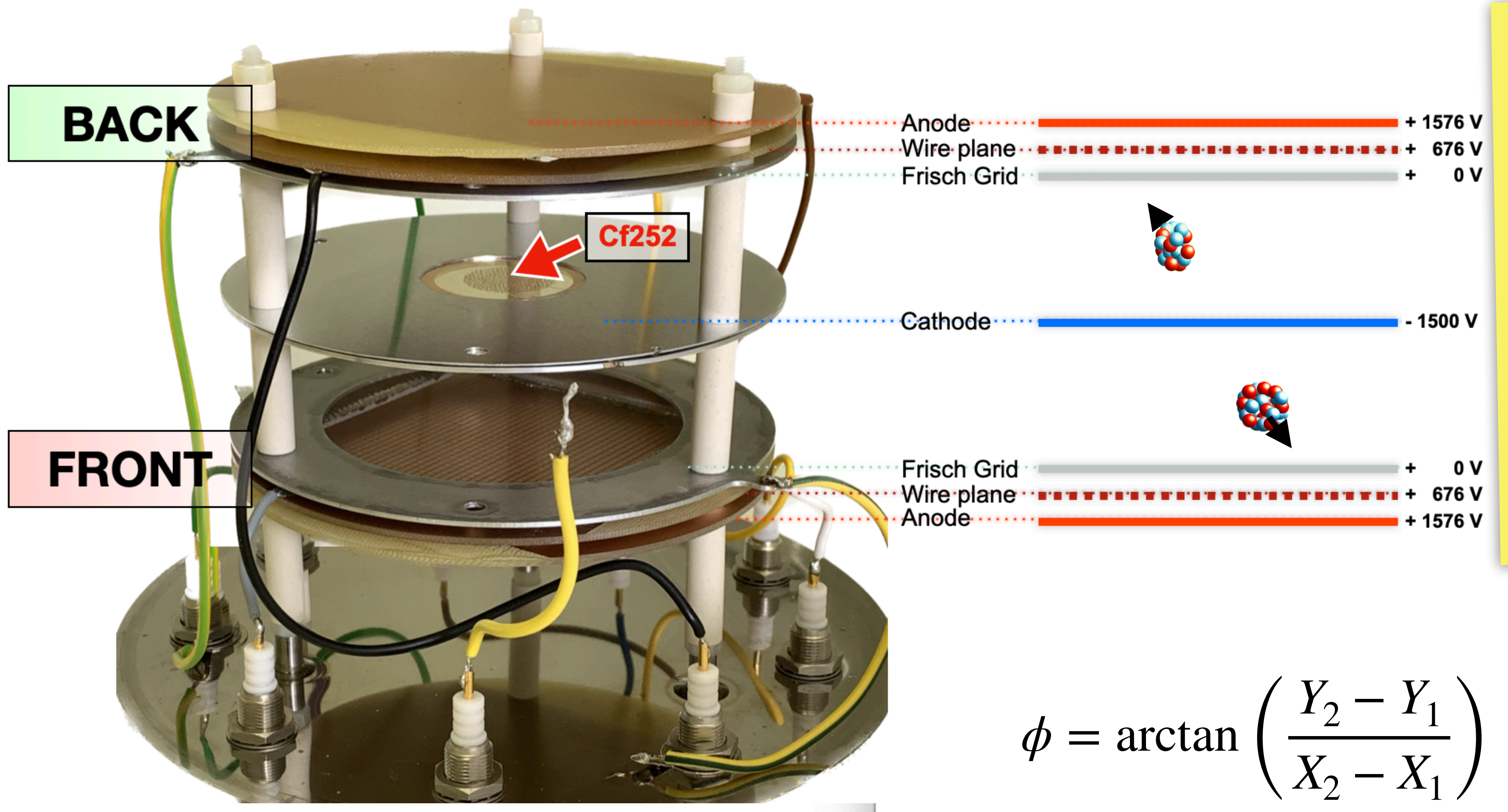
Ionisation chamber signals sampled every 2ns



Fission signature: all channels of IC triggered



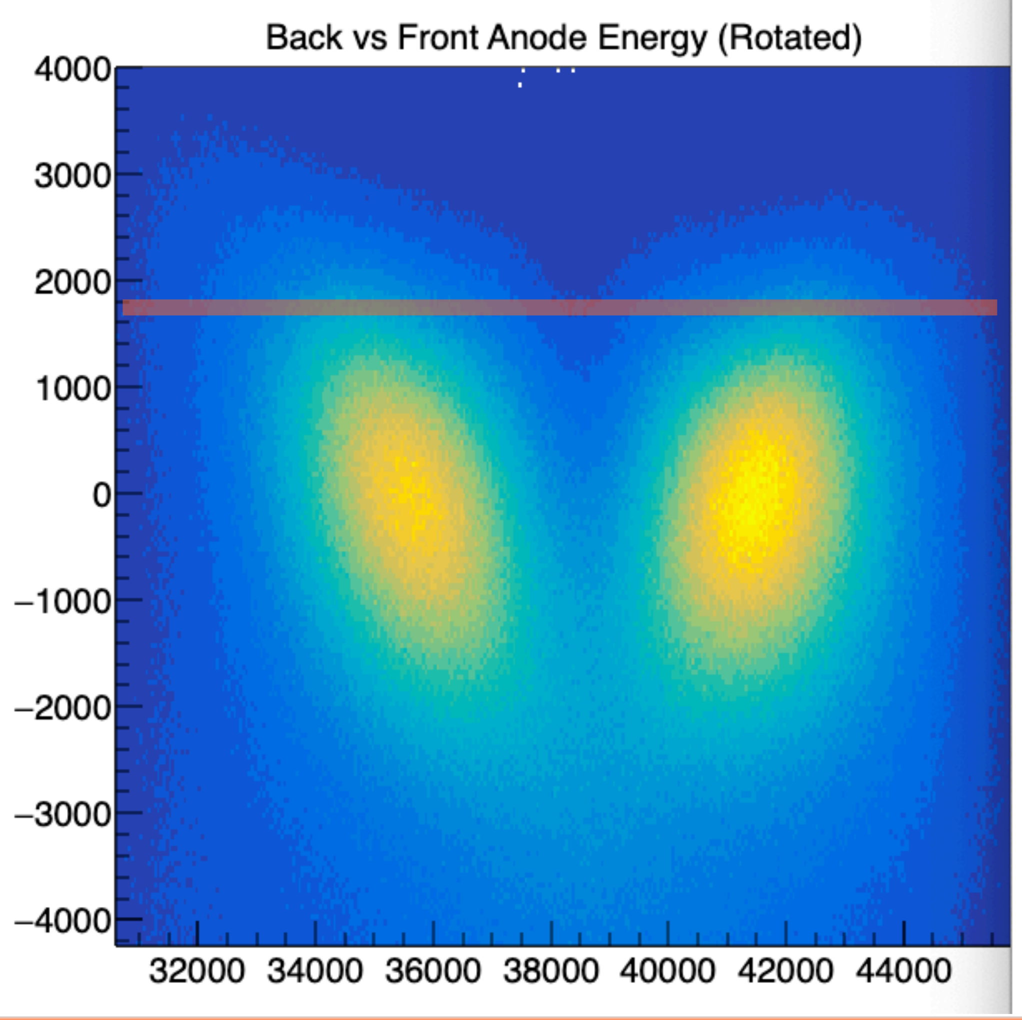
Event reconstruction (dFGIC)

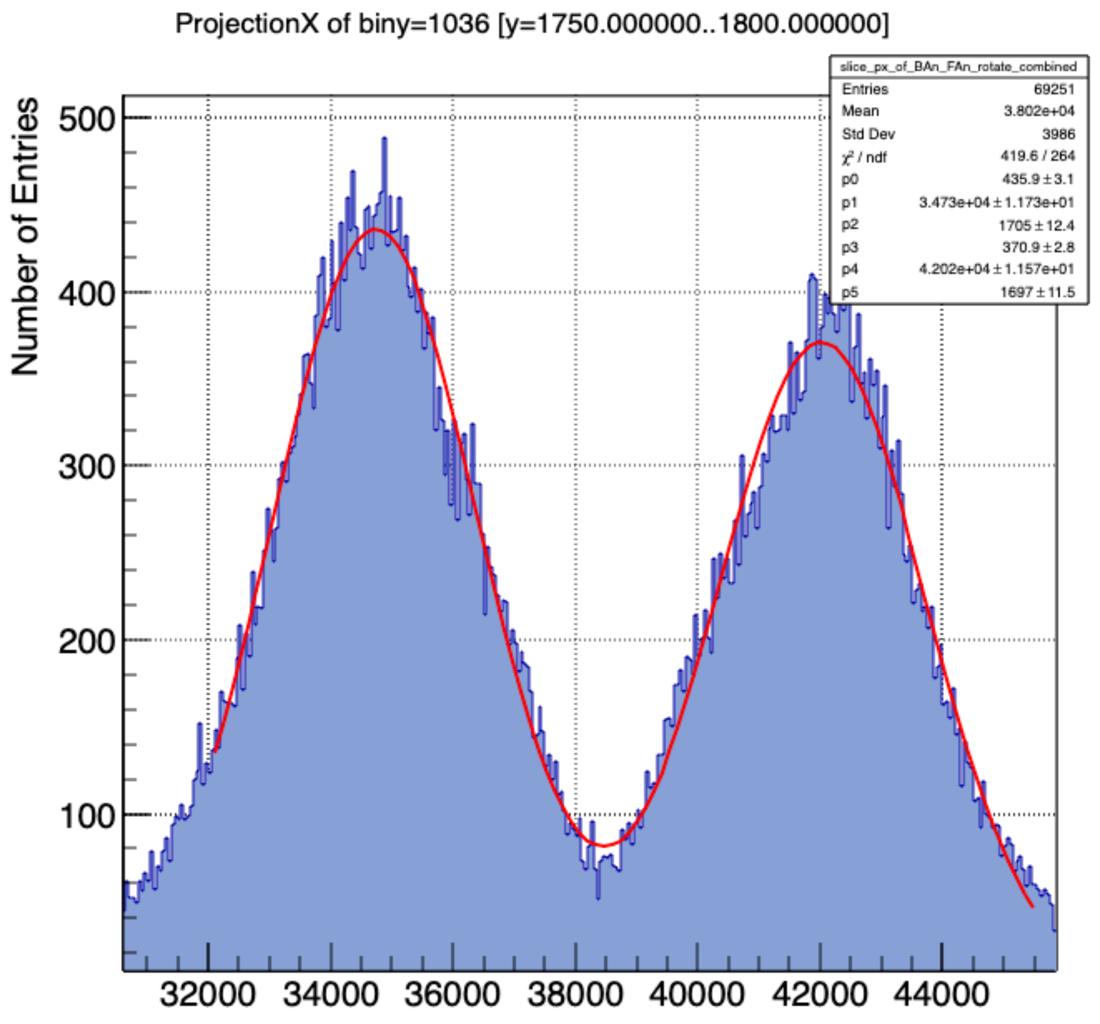


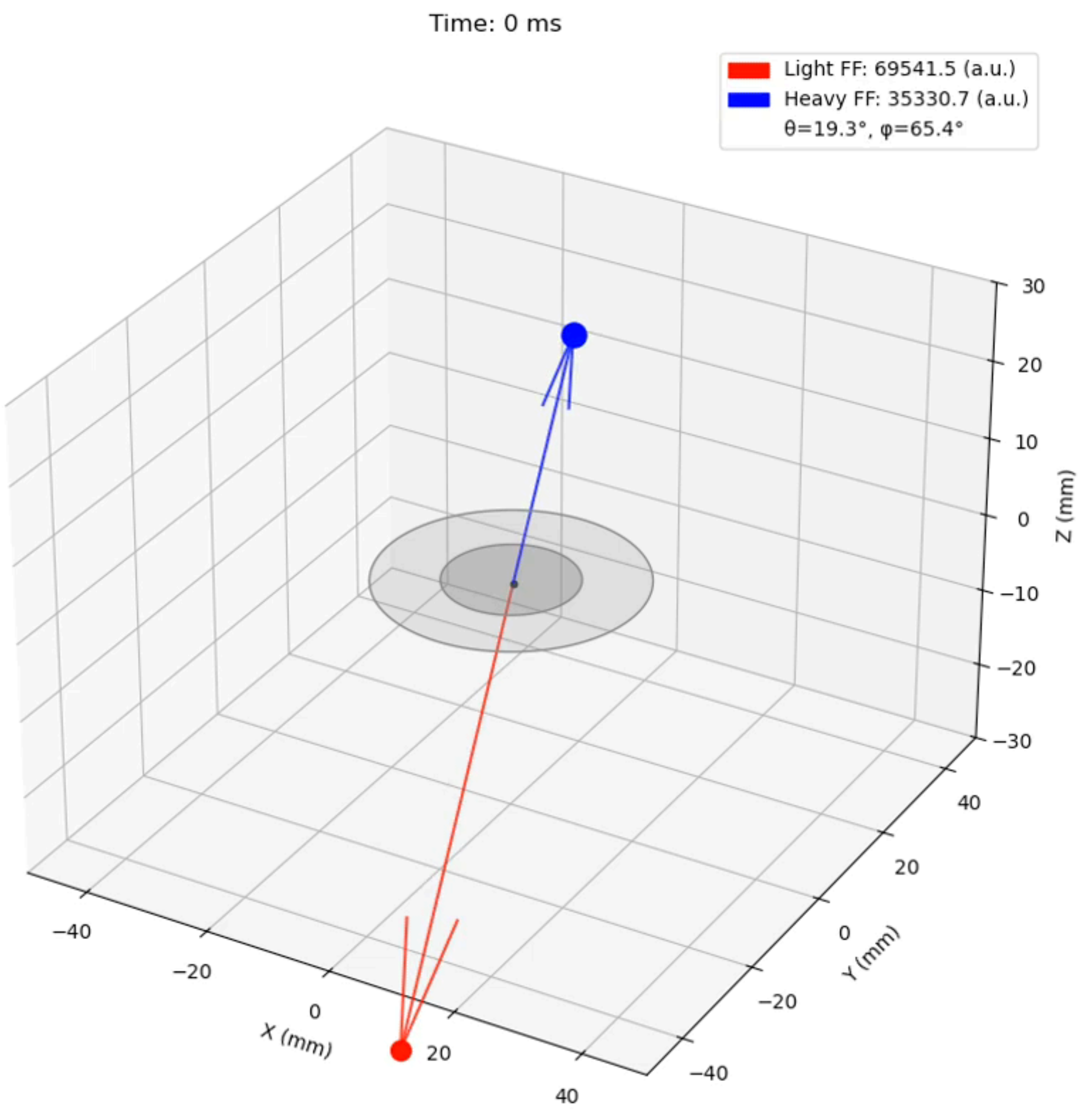
Fission event reconstruction:

Event *i* : { *timestamp*; θ_1, ϕ_1, PAn_1; θ_2, ϕ_2, PAn_2 }

$$\phi = \arctan\left(\frac{Y_2 - Y_1}{X_2 - X_1}\right) \qquad \cos\theta_{1,2} = \frac{\bar{z}_{1,2}}{\bar{r}_{1,2}} = \frac{\nu\left(\bar{t}_{\theta_{max}} - \bar{t}_{1,2}\right)}{\bar{r}_{1,2}}$$







Waveform analysis

Waveform 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**

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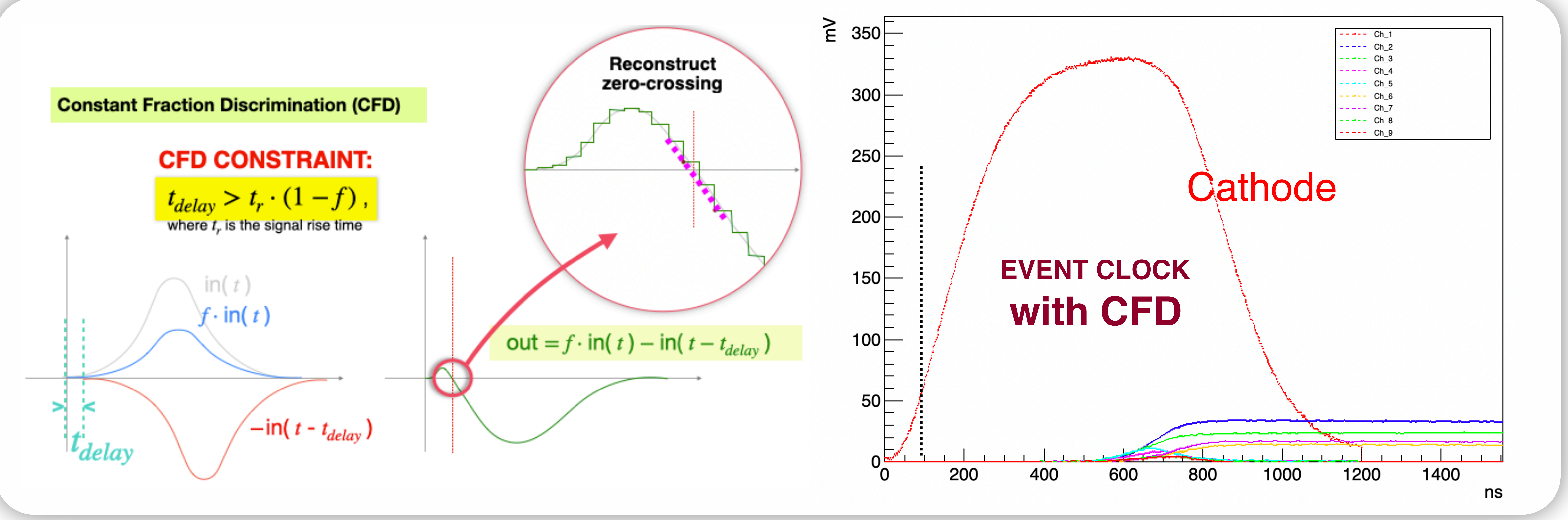
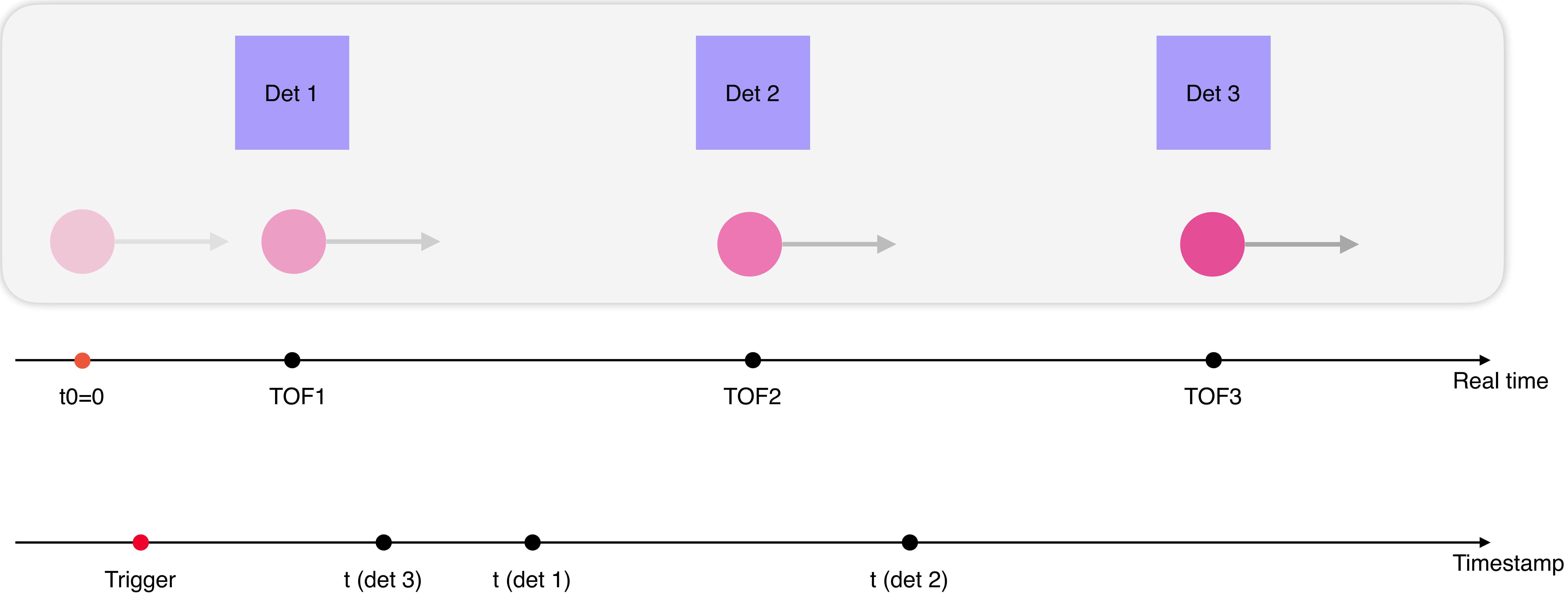


Event time reconstruction



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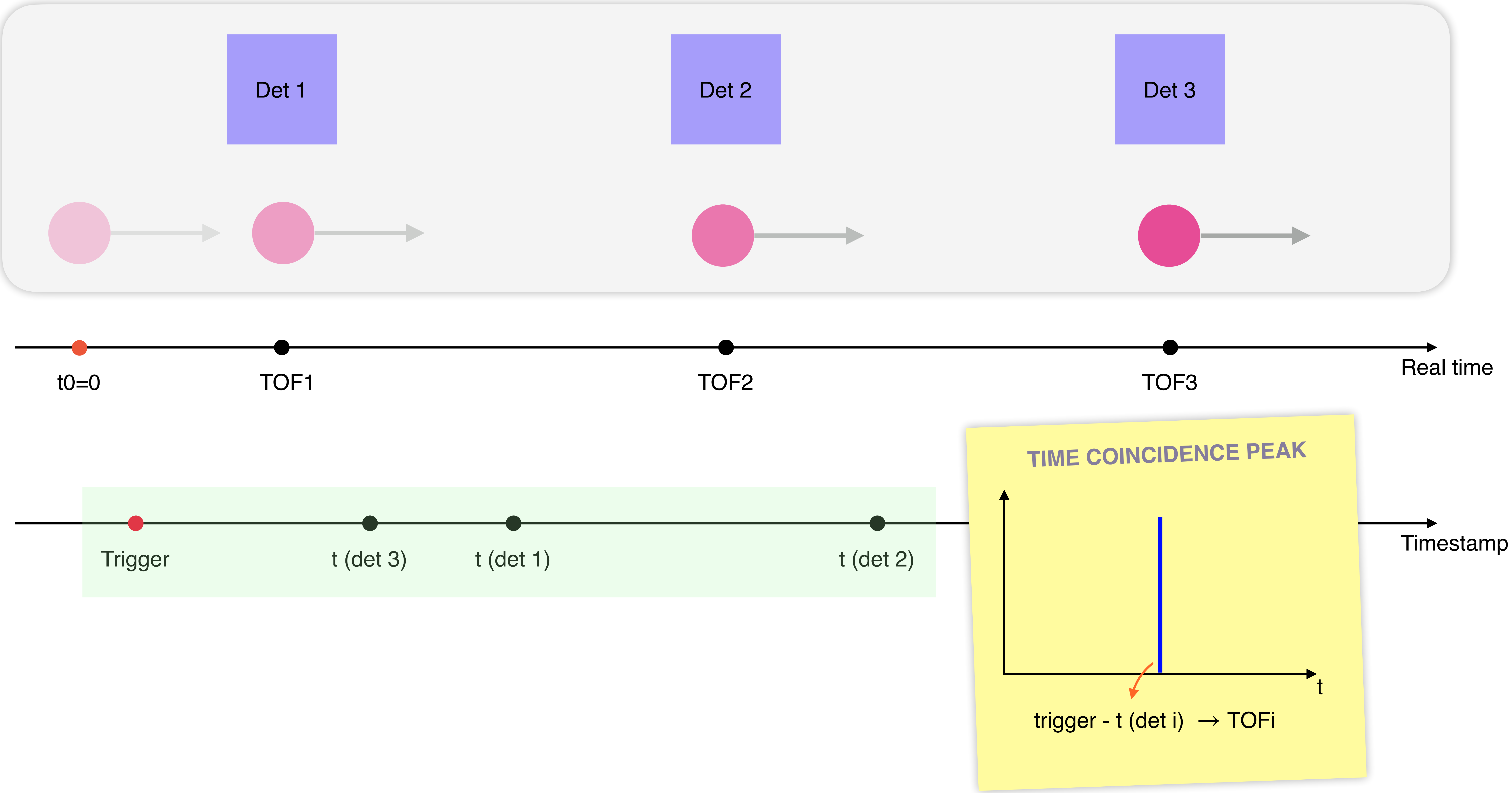

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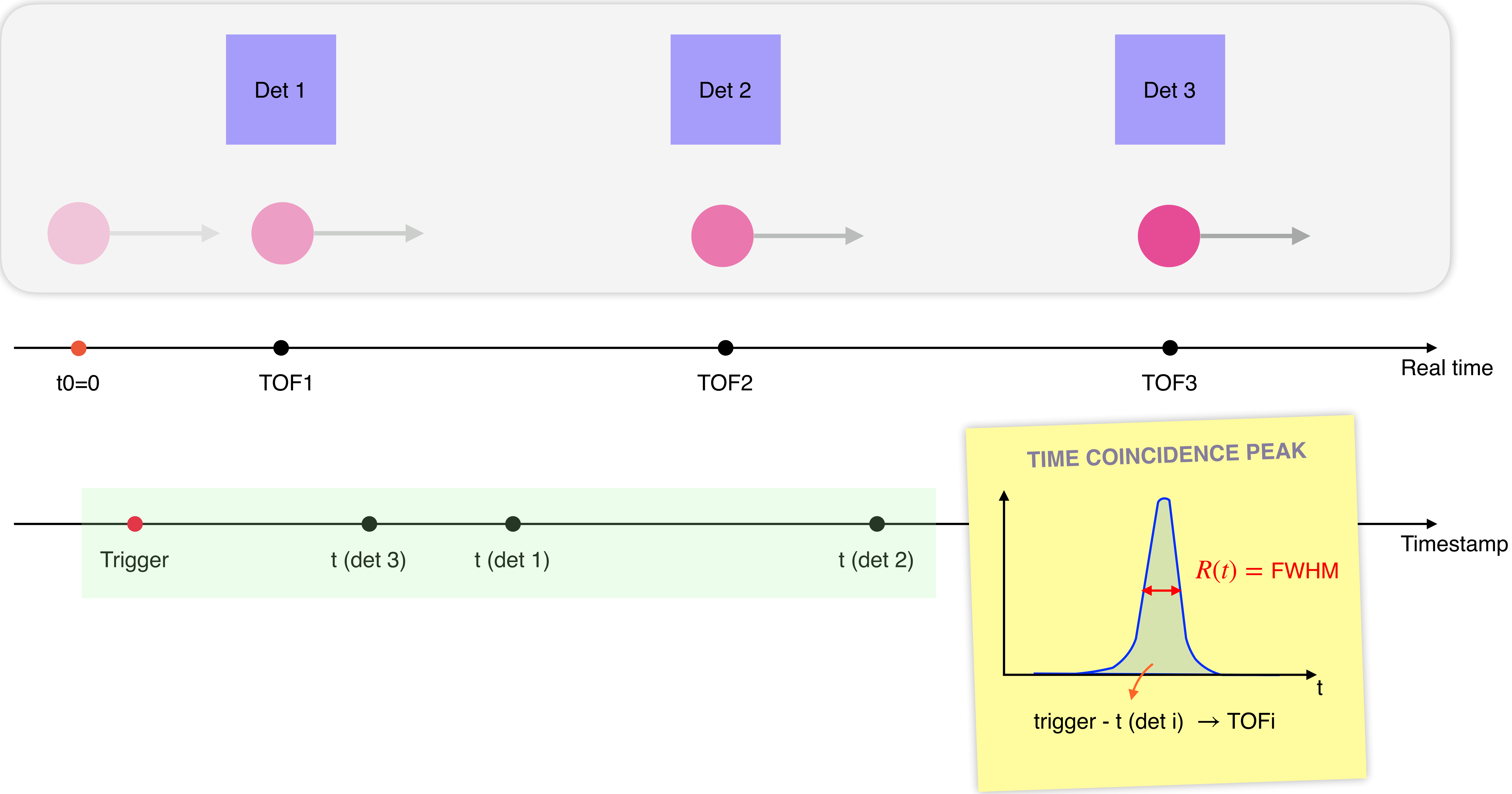

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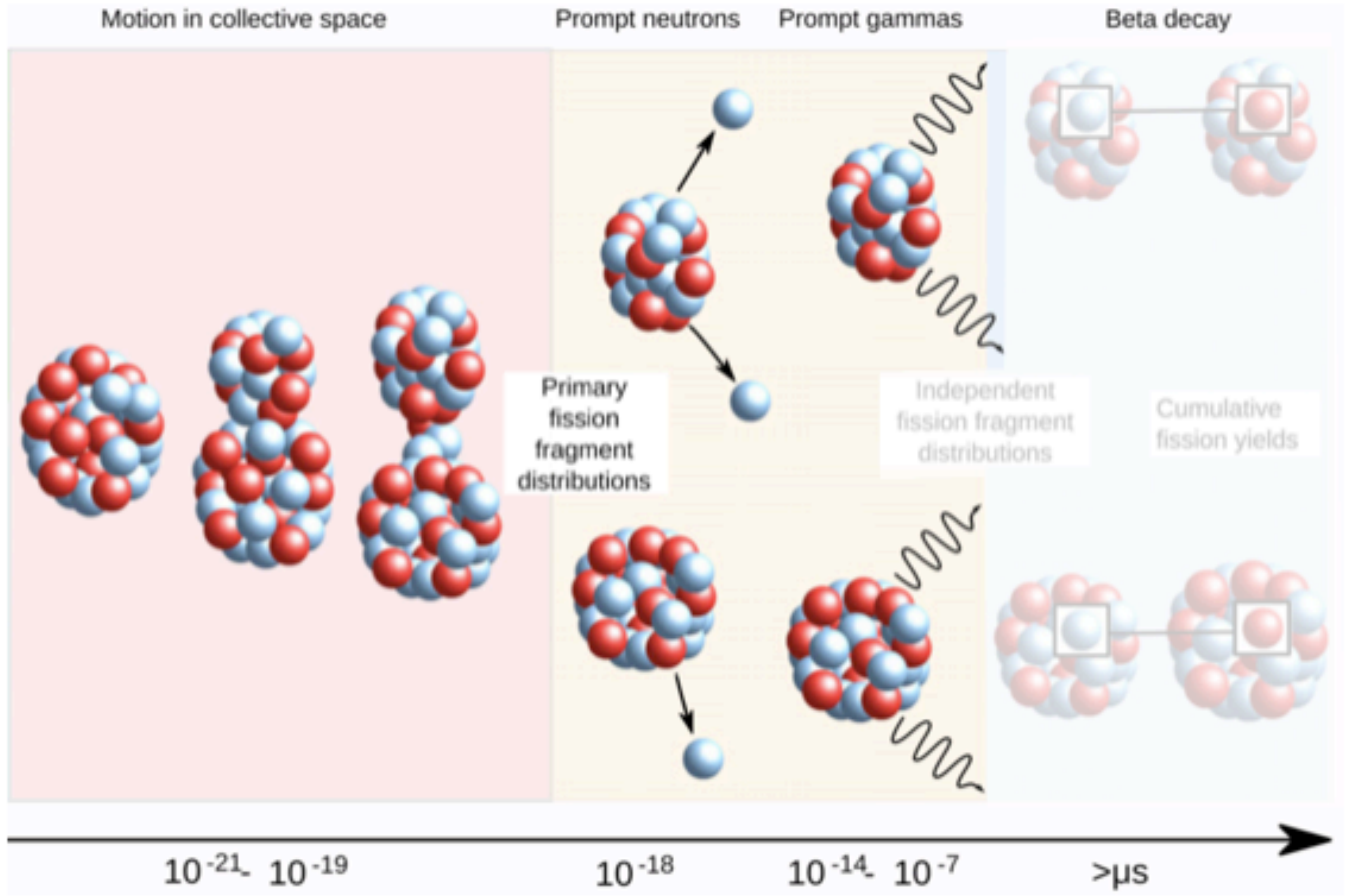
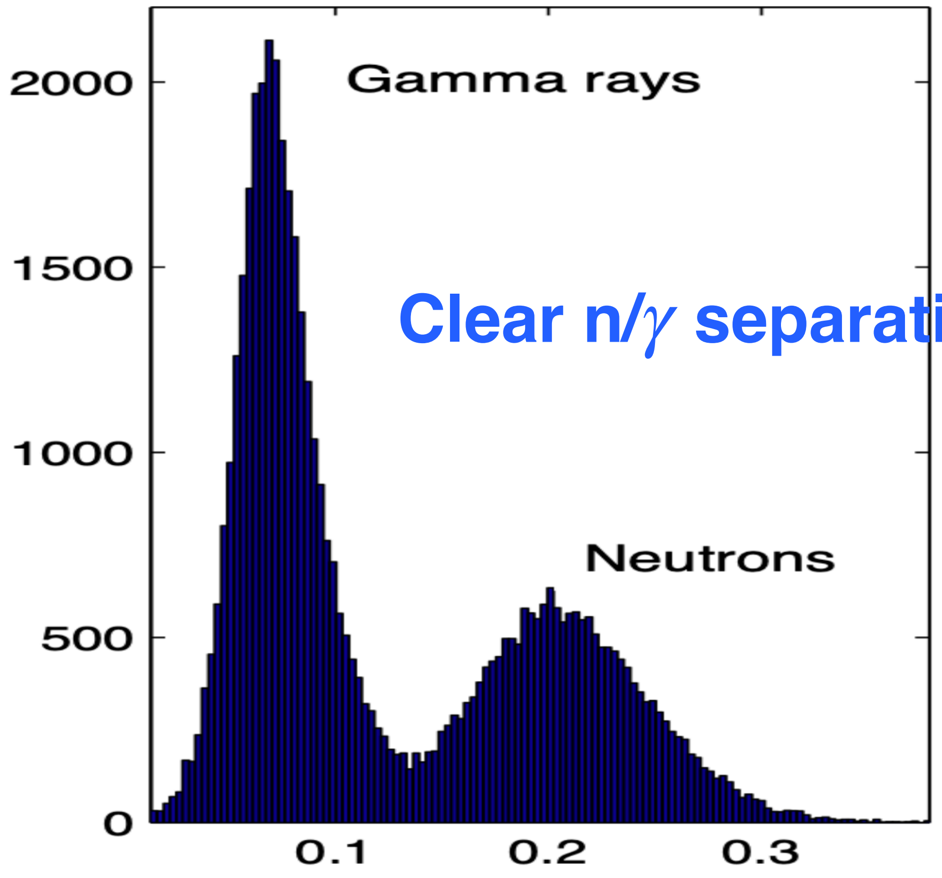


Cathode signal IC (fission trigger)

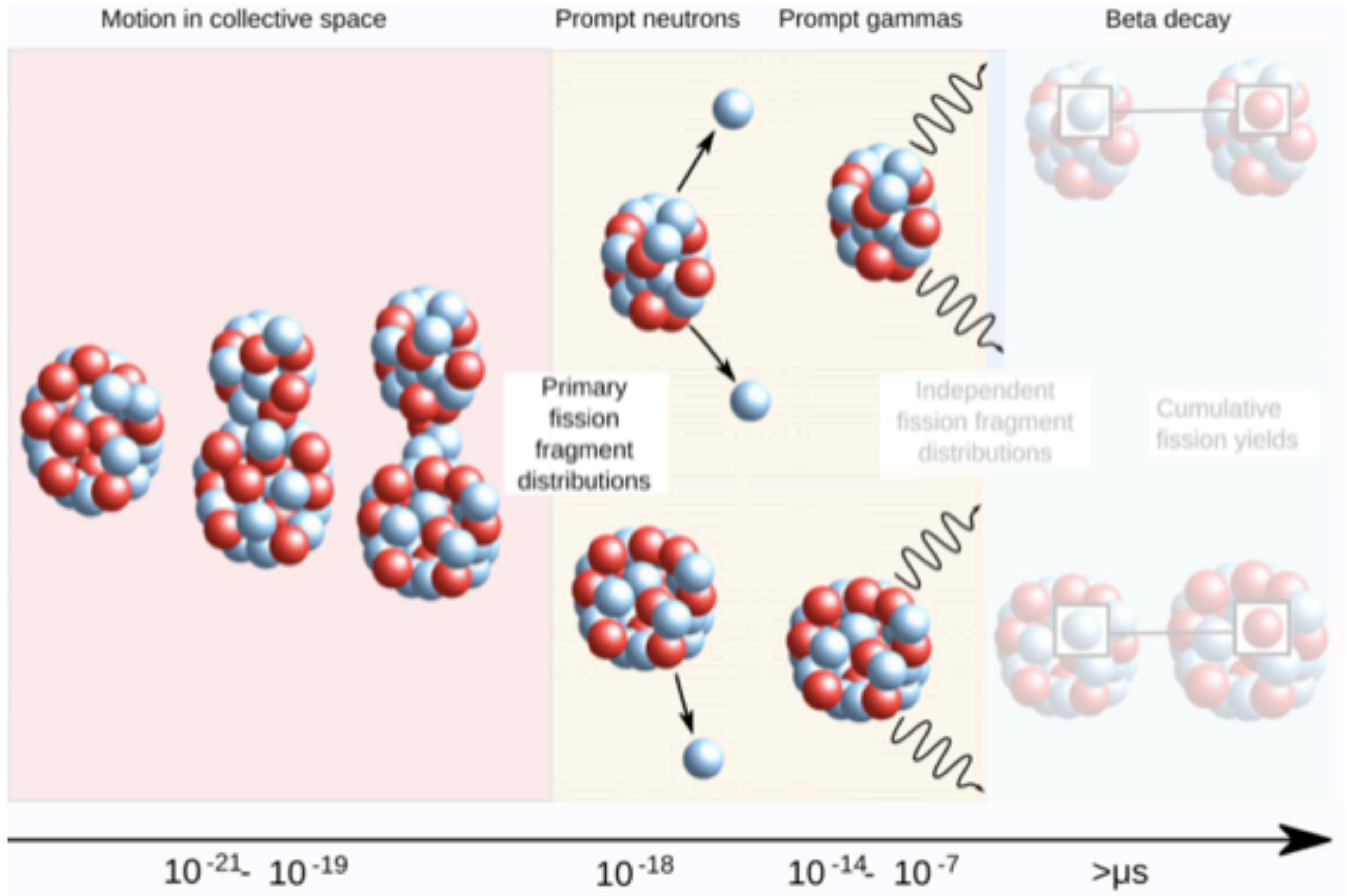
$LaBr_3$ scintillator (coincidence detector)

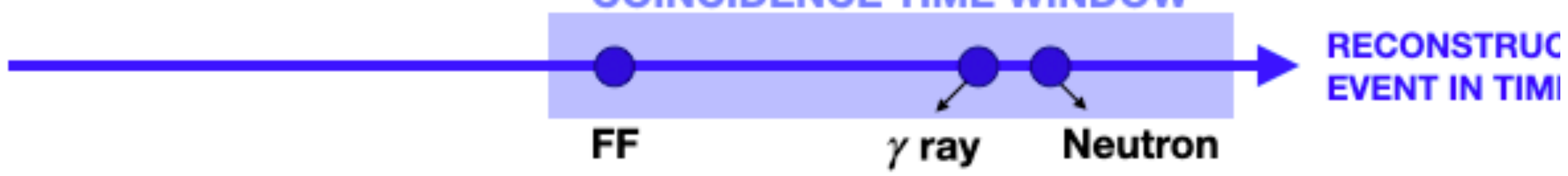
Time coincidence peak



Clear n/γ separation due to TOF

Event reconstruction





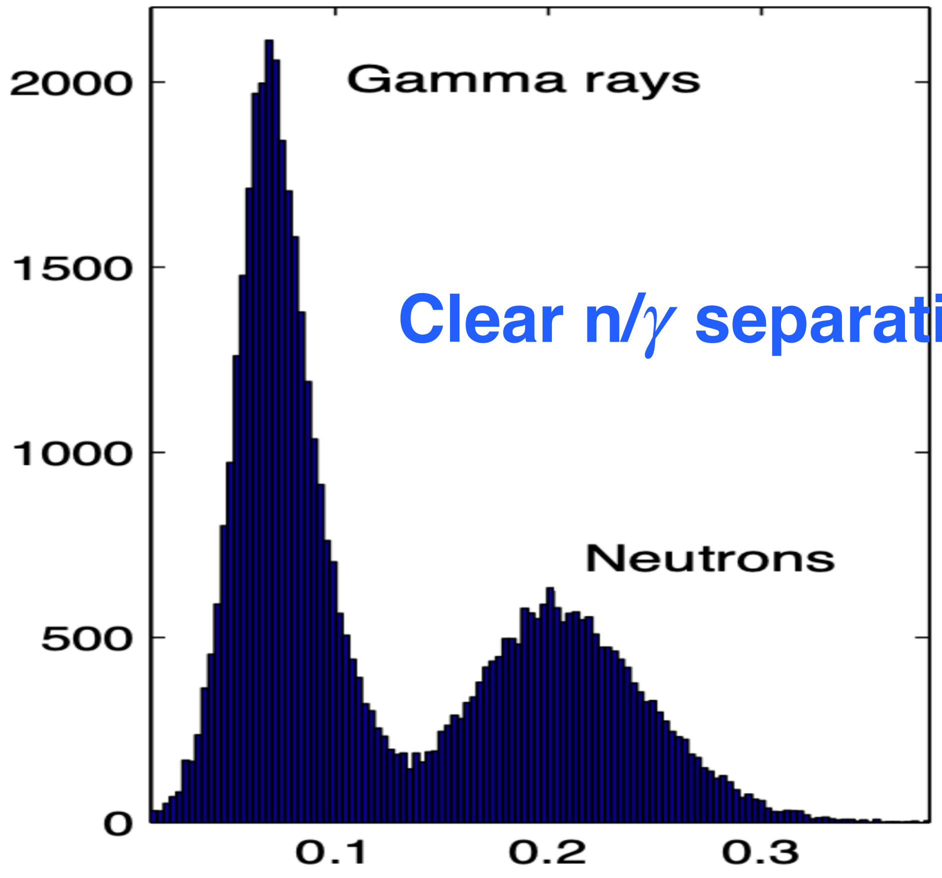
Cathode signal IC (fission trigger)

$LaBr_3$ scintillator (coincidence detector)

Triggering of signal can be optimised to 1-2% of signal rise time.

Cathode rise time ~300 ns

Time coincidence peak



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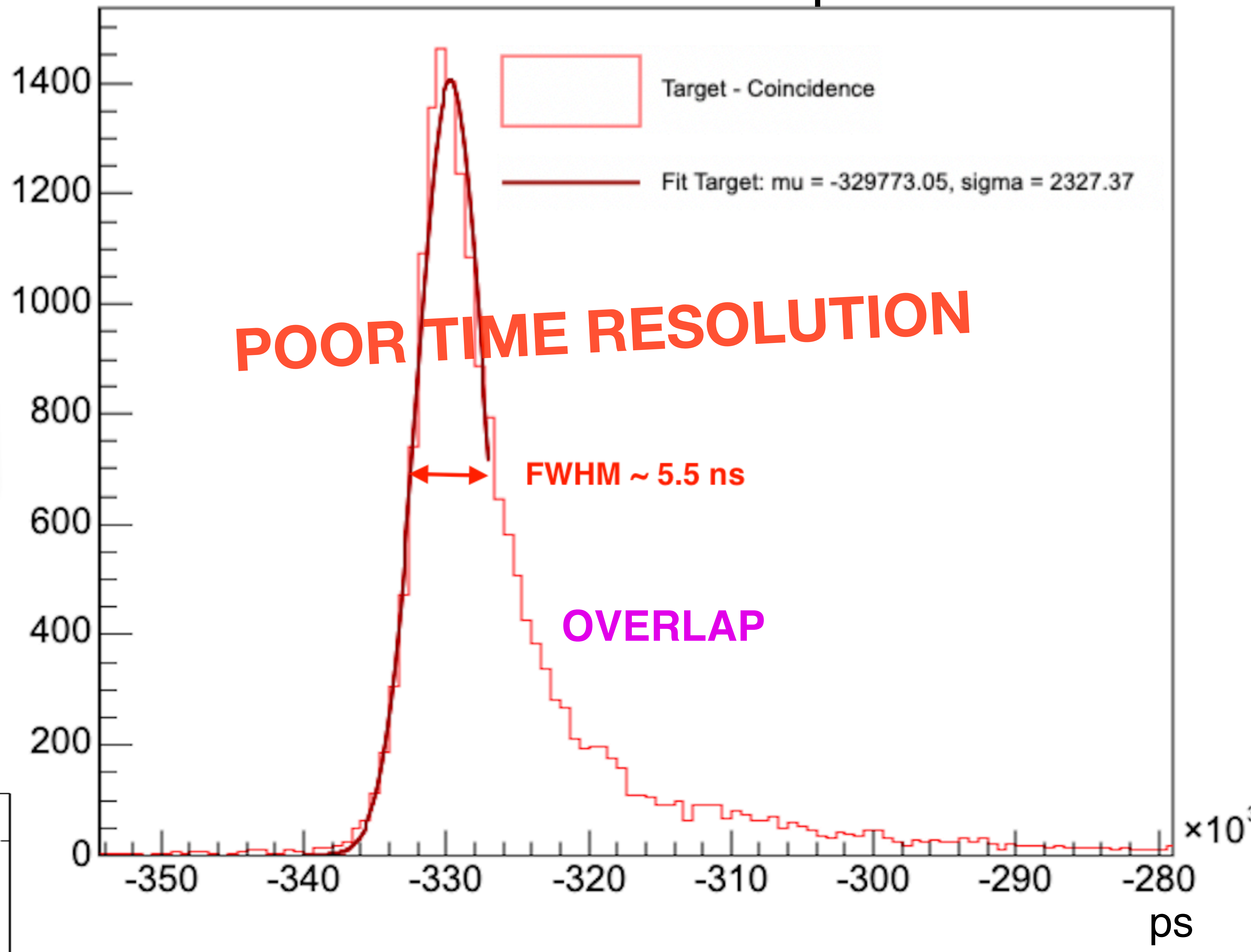

1. Time resolution is not sufficient to separate n/γ
2. Expect to obtain a resolution down to 3 ns

CONTENTS:

- Motivation for an innovative fission trigger
- Fission annotations through dFGIC analysis
- **Innovative methods based in AI**
  - **… for waveform analysis**
- Conclusion

Waveform analysis with NN - motivation

Waveform analysis through most frequently used methods

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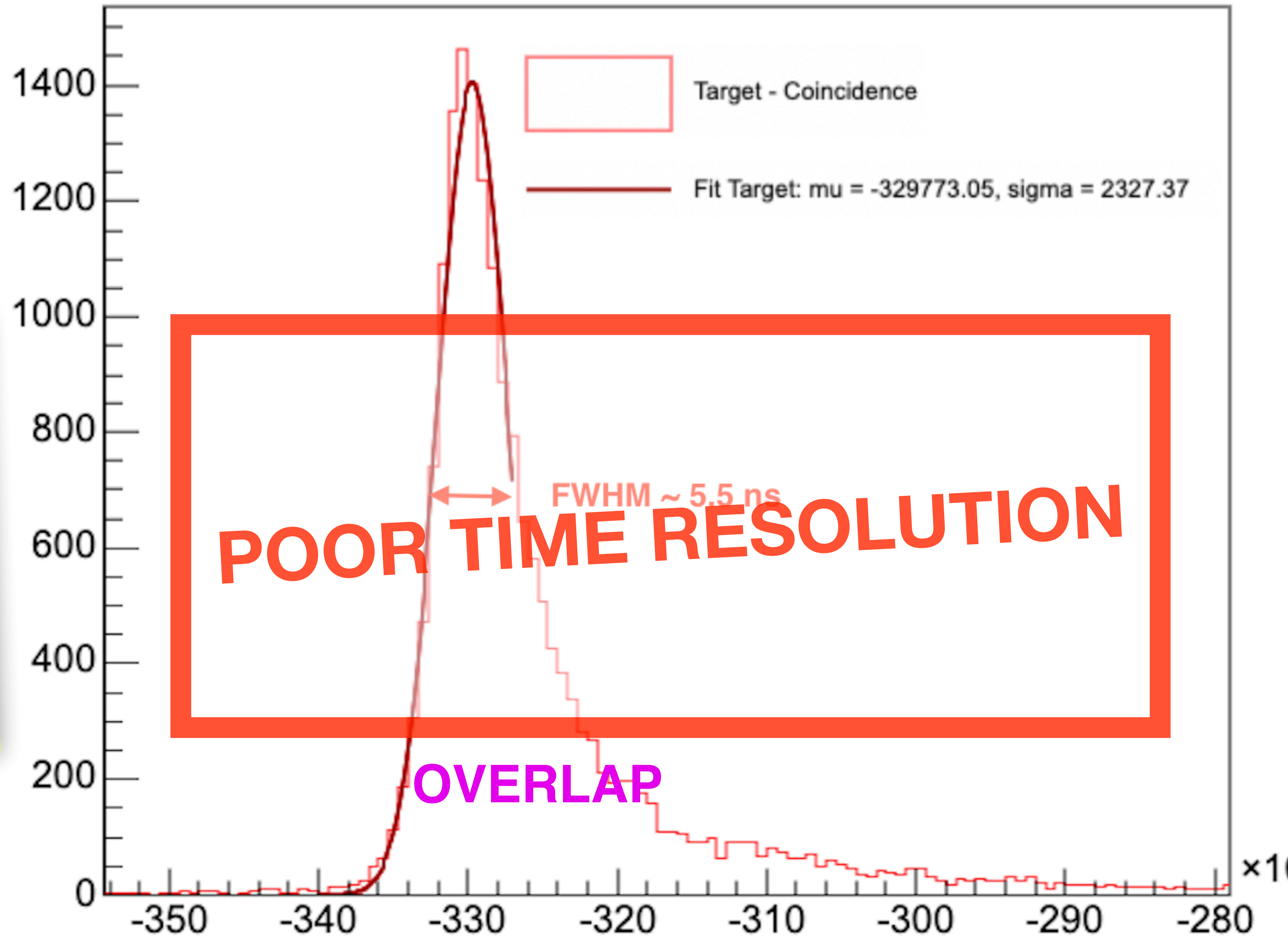
- Signal integration (deposited charge)
- Constant Fraction Discrimination (CFD)

TIME CONSUMING

Triggering of signal can be optimised to 1-2% of signal rise time.

Cathode rise time ~300 ns

Time coincidence peak



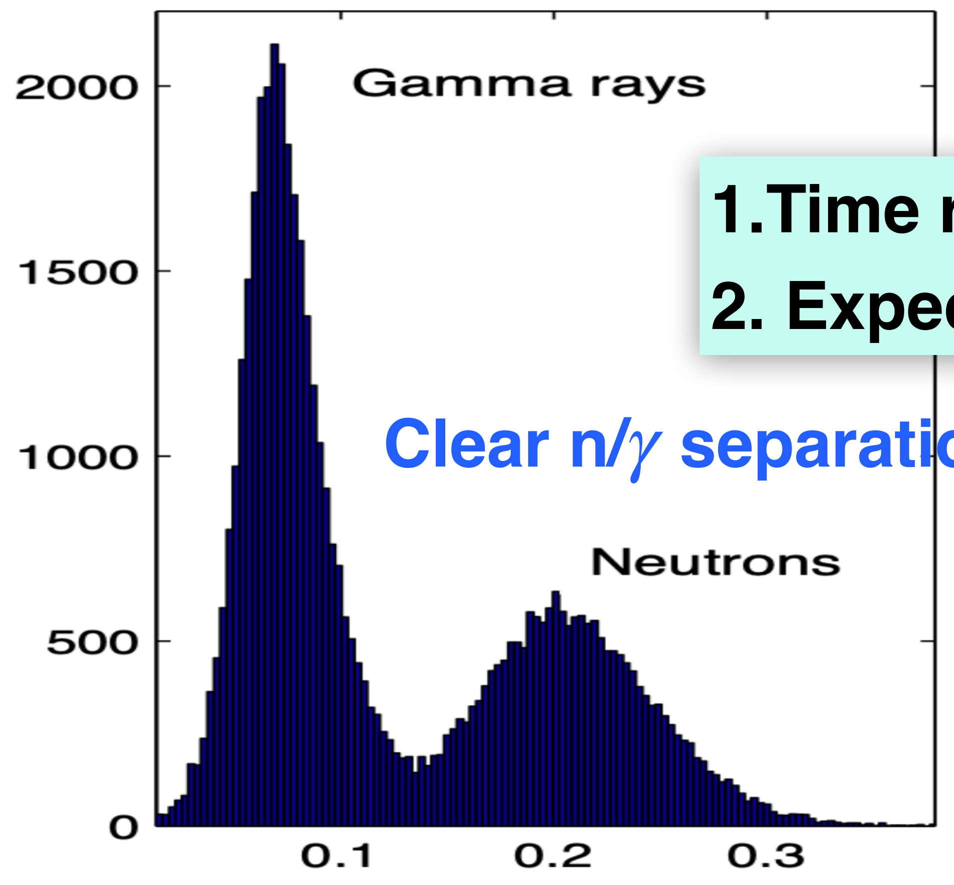
CFD on cathode signals requires ~15000 FLOP per signal

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

3 weeks of data acquisition -> 600M events

300 h or 13 days to process the waveforms

Time coincidence peak



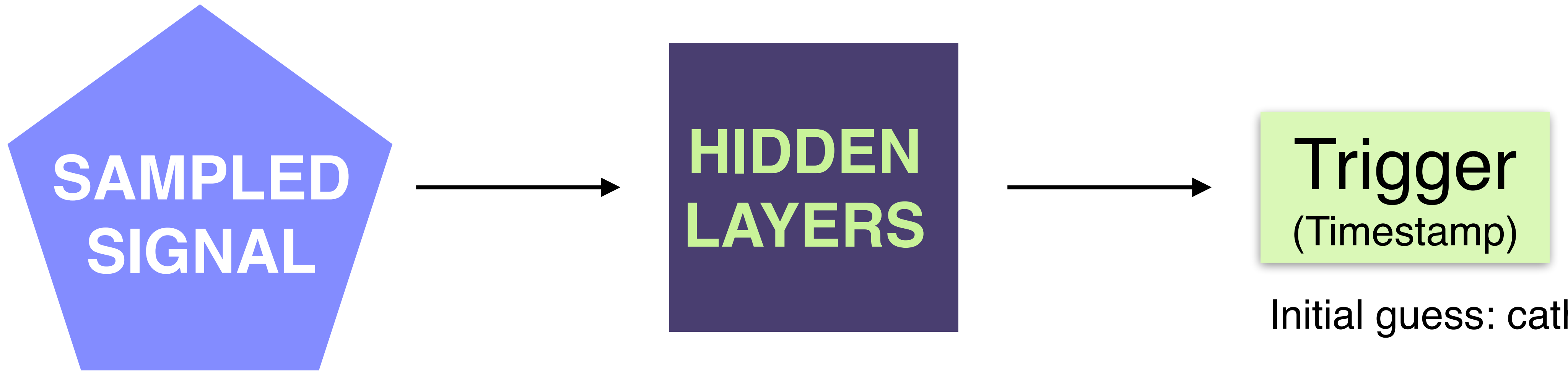
1.Time resolution is not sufficient to separate n/γ

2. Expect to obtain a resolution down to 3 ns

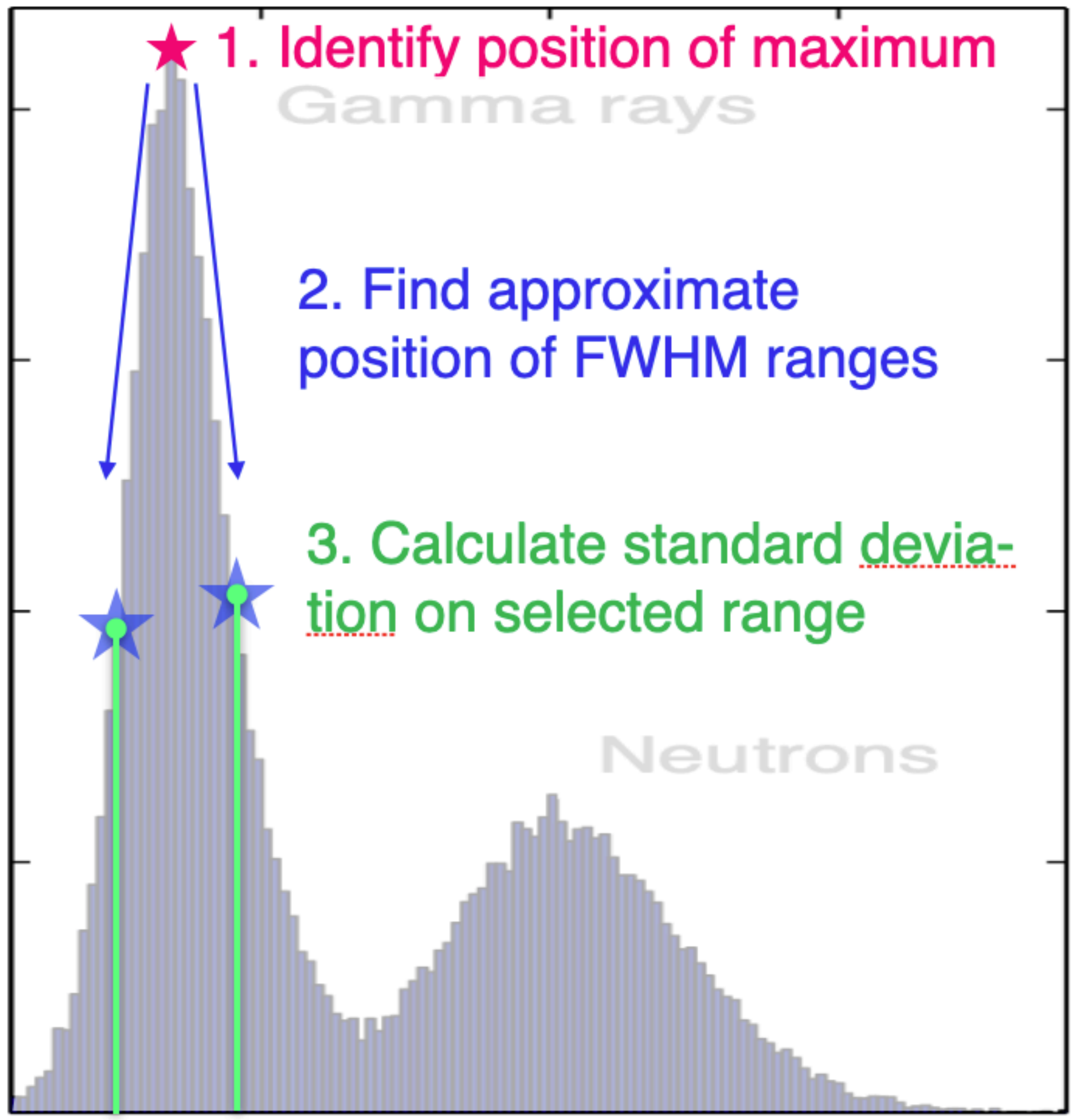
Clear n/γ separation due to TOF

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

Loss function for time resolution improvement

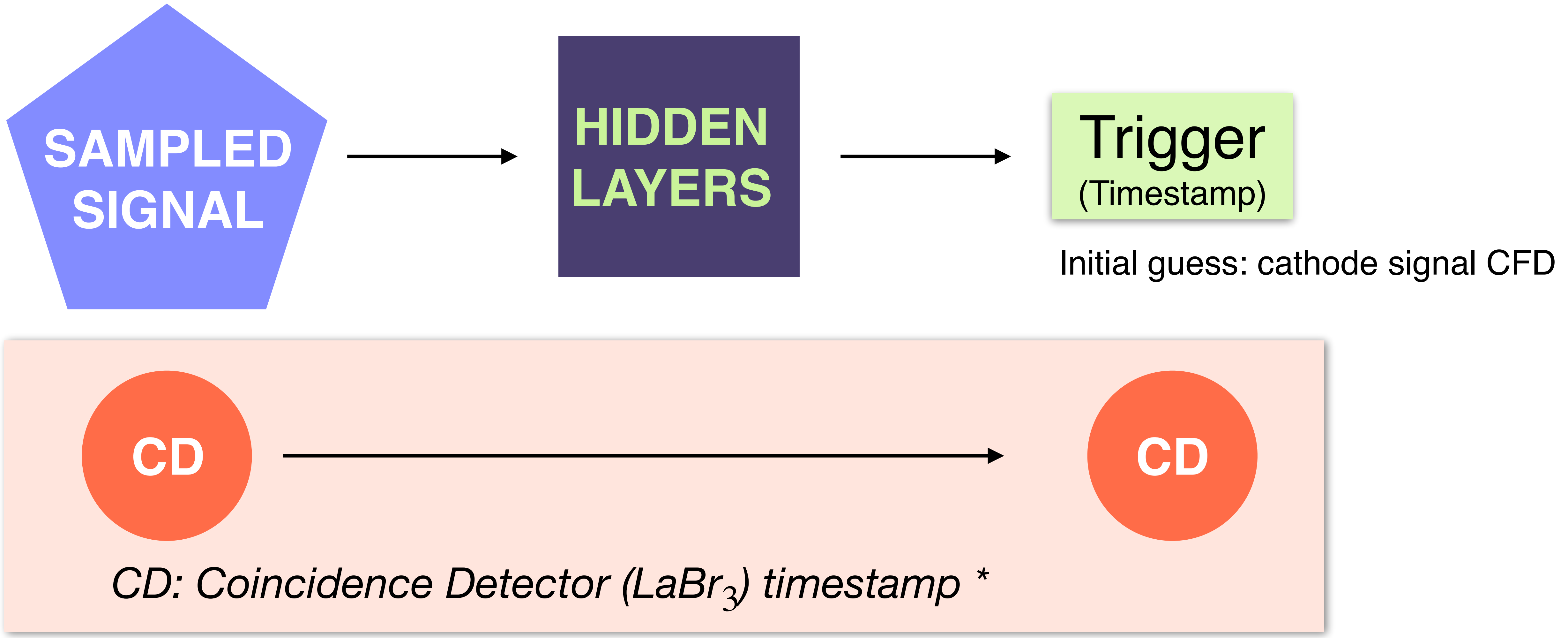


Initial guess: cathode signal CFD



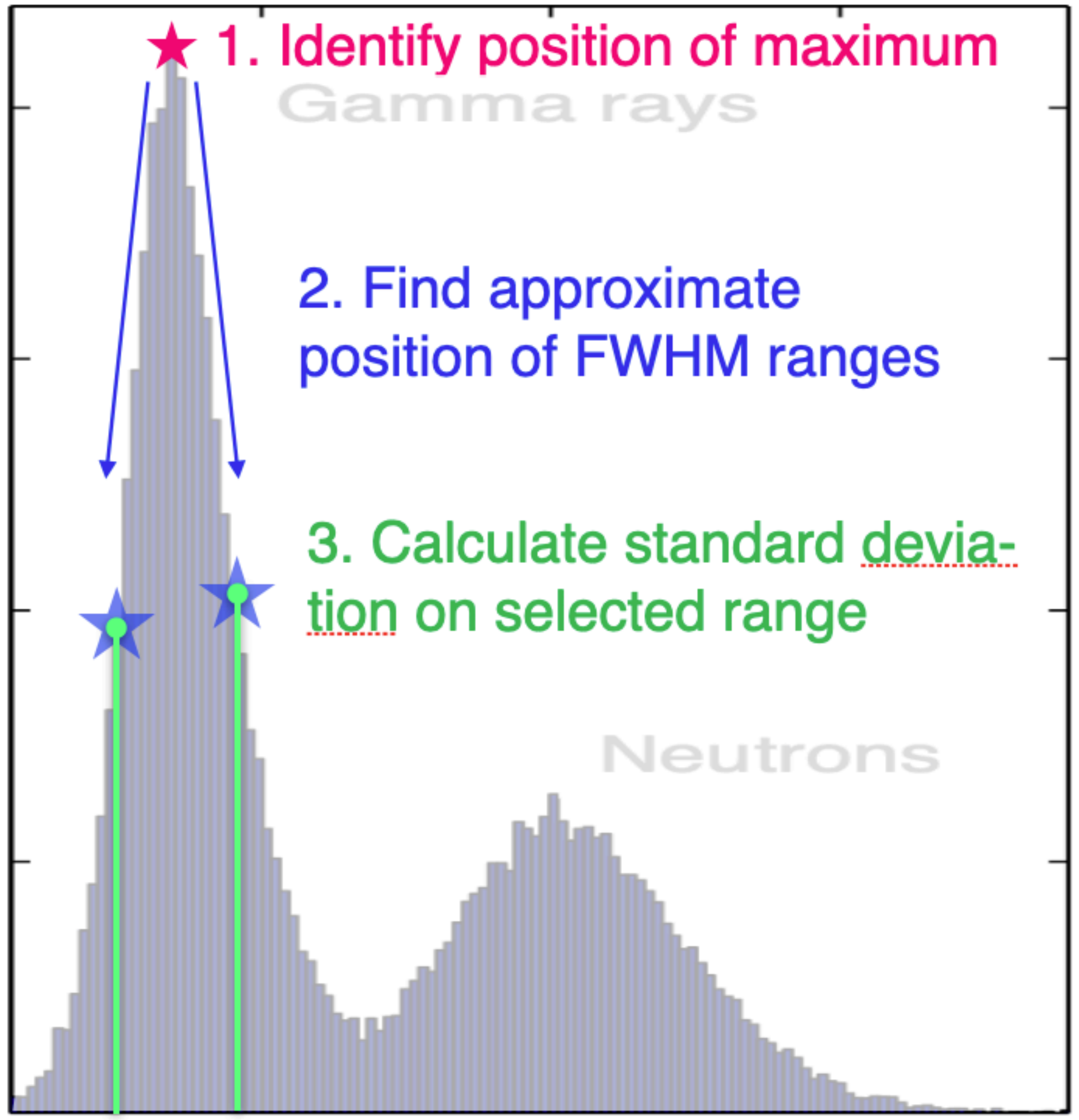
By batch

Loss function for time resolution improvement



NO CONNECTION BETWEEN CD NEURON AND ANY OTHER LAYER IN NN ARCHITECTURE.

USED ONLY FOR LOSS ESTIMATION.



By batch

Layer complexity

CFD on cathode signals requires ~15000 FLOP per signal

3.1.1. Fully connected neural network (FCNN)

$$\mathrm{FLOP}_{\mathrm{FCNN}} = 2 \times L_{in} \times L_{out} + b \tag{1}$$

3.1.2. Convolutional neural network (CNN) - one dimension

$$\mathrm{FLOP}_{\mathrm{CNN}} = 2 \times L_{in} \times L_{out} \times F \times K + b \tag{2}$$

$$L_{out} = \left\lfloor \frac{L_{in} - K + 2P}{S} \right\rfloor + 1 \tag{3}$$

Where F is the number of filters and K is the kernel size, P is the padding option, S is the stride, and b is the bias term.

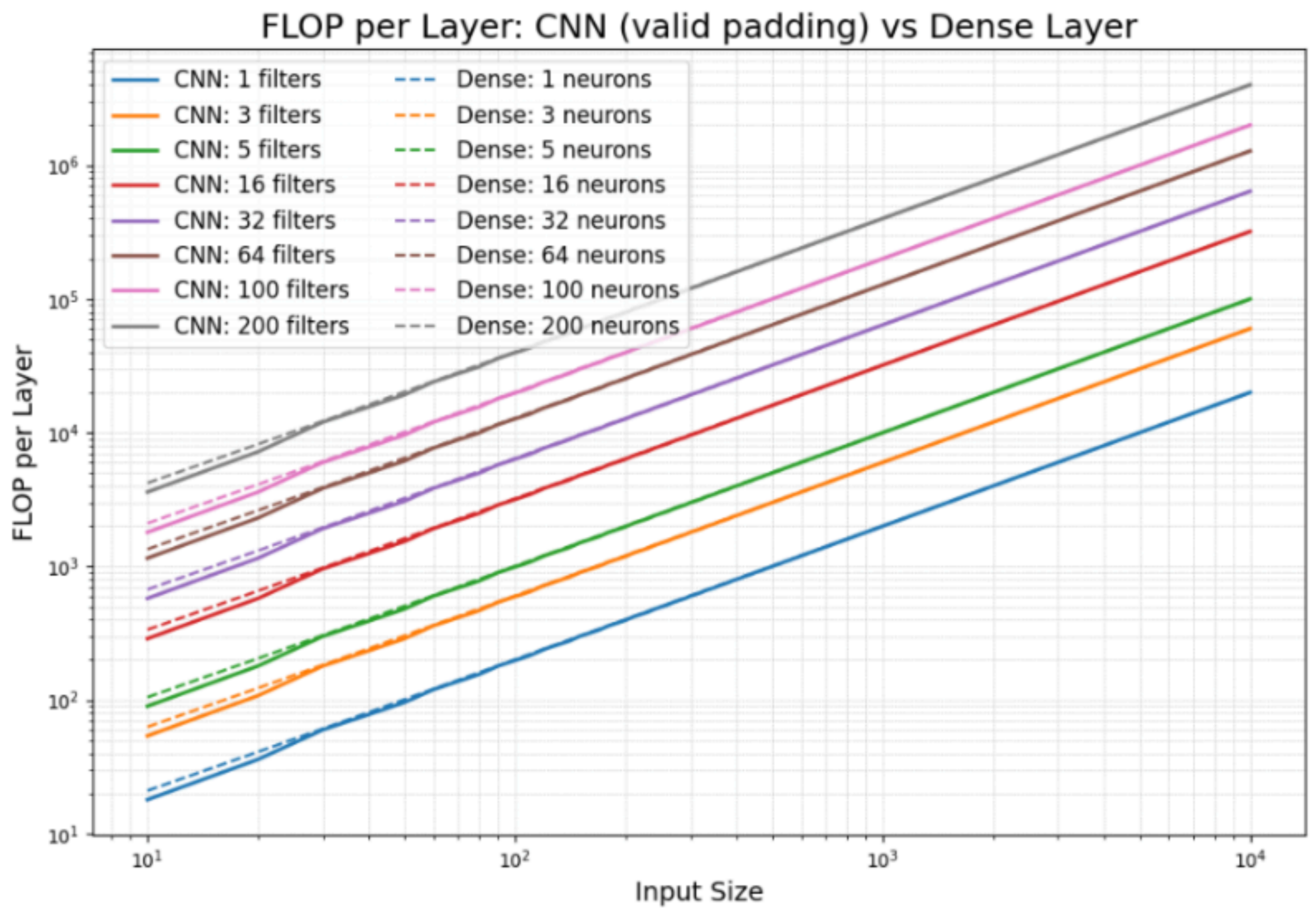


Figure 5: Comparison of total computational cost (FLOP) per layer for 1D convolutional layers (CNN) and fully connected (dense) layers as a function of input size. Fluctuations in convolutional model comes from valid padding (or no padding), not recommended if border information is crucial. Solid lines represent CNNs, and dashed lines represent dense layers. Both axes are on logarithmic scales.

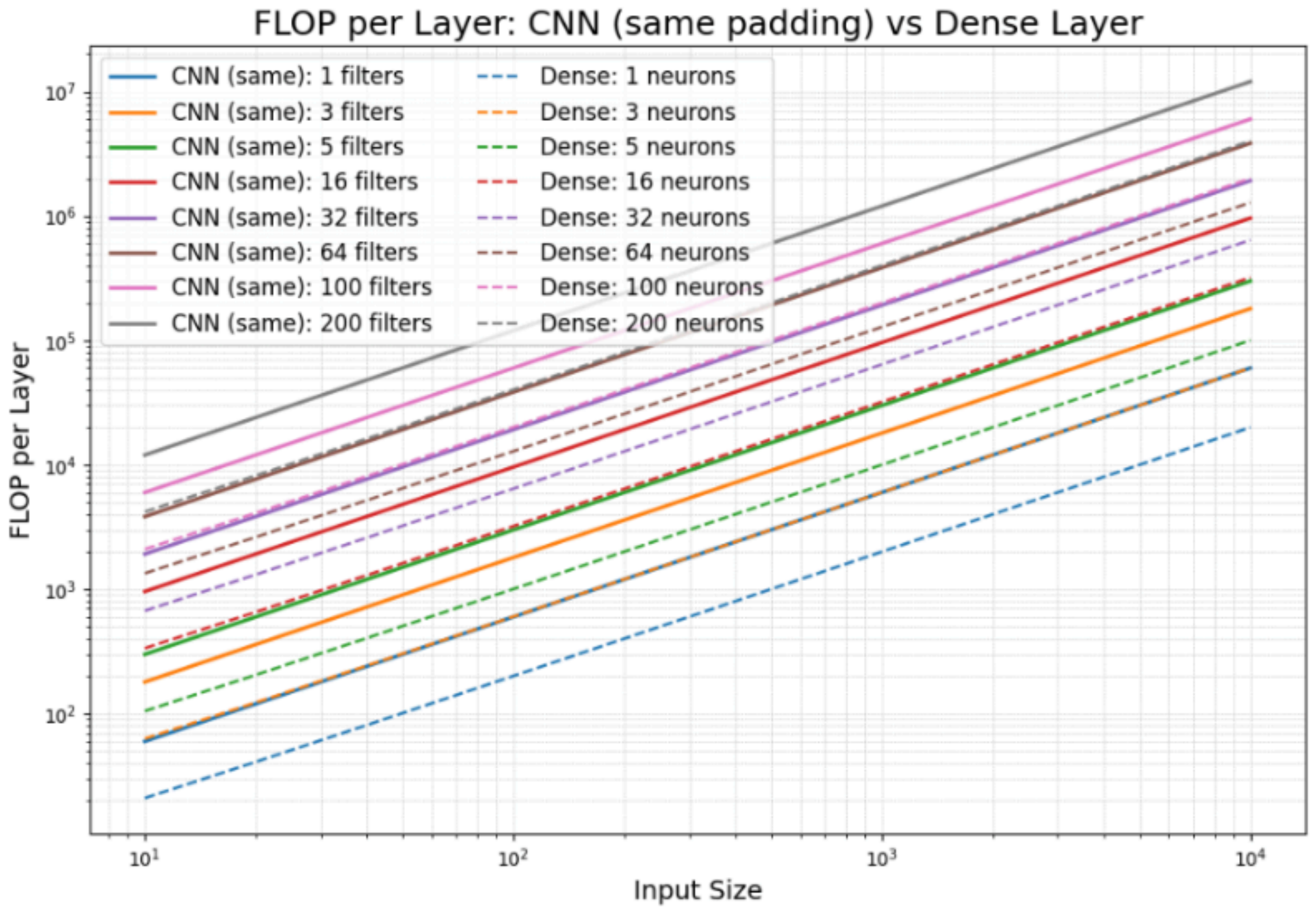


Figure 6: Comparison of total computational cost (FLOP) per layer for 1D convolutional layers (CNN) and fully connected (dense) layers as a function of input size. Case for layers designed with "same" padding, which preserves border information. In this situation, convolutional layers conserve their dimensions, hence the higher complexity.

Layer complexity

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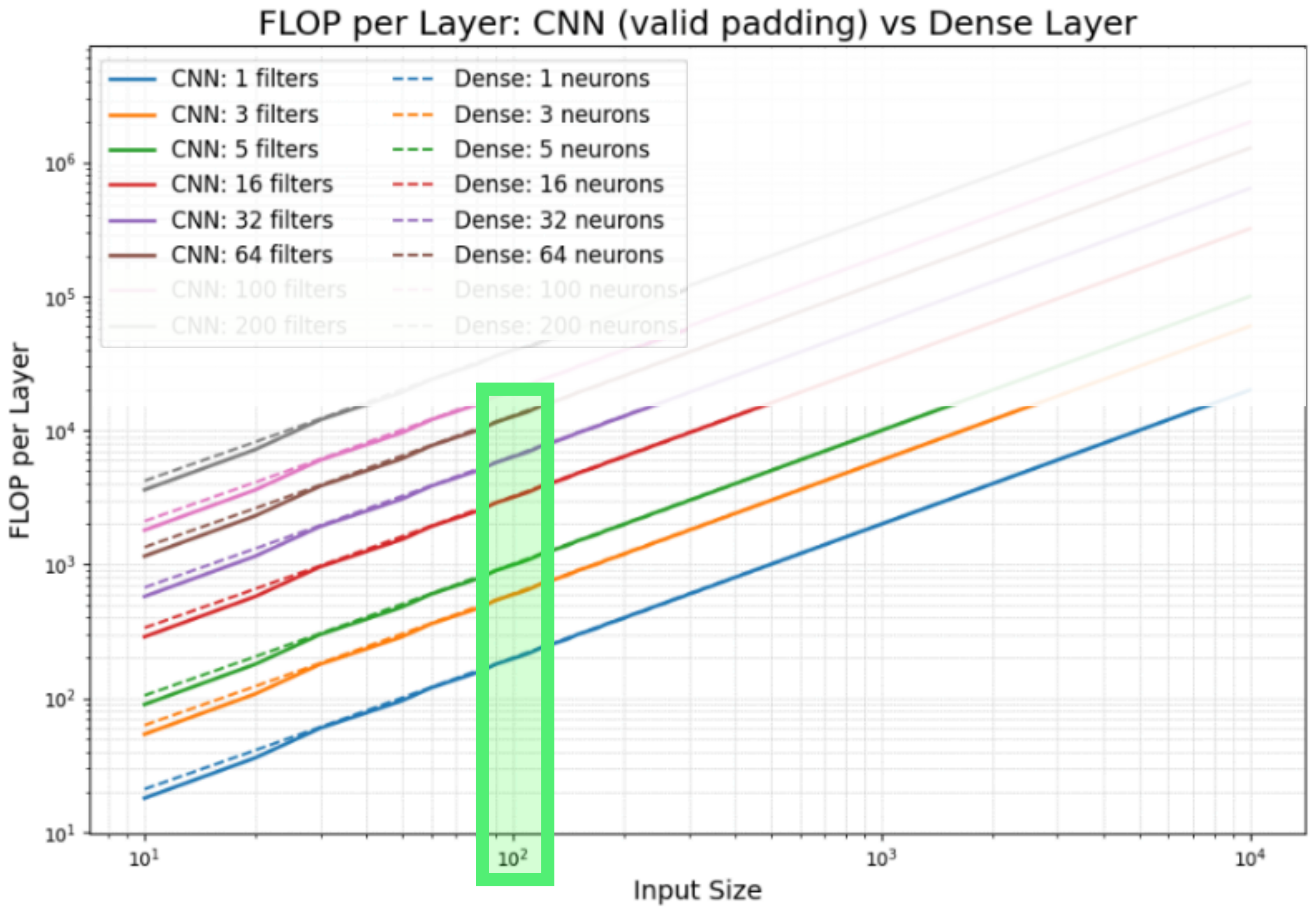

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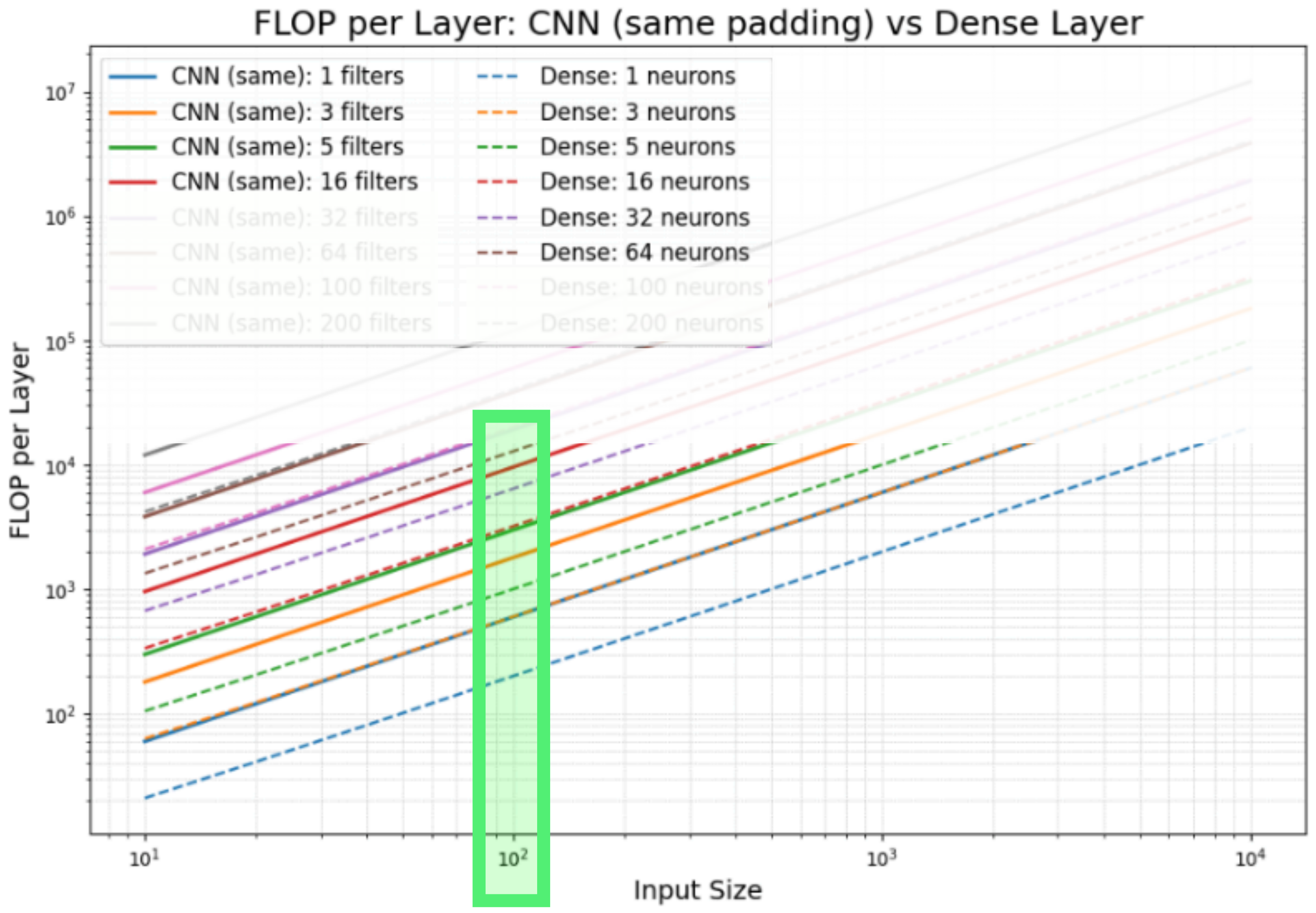

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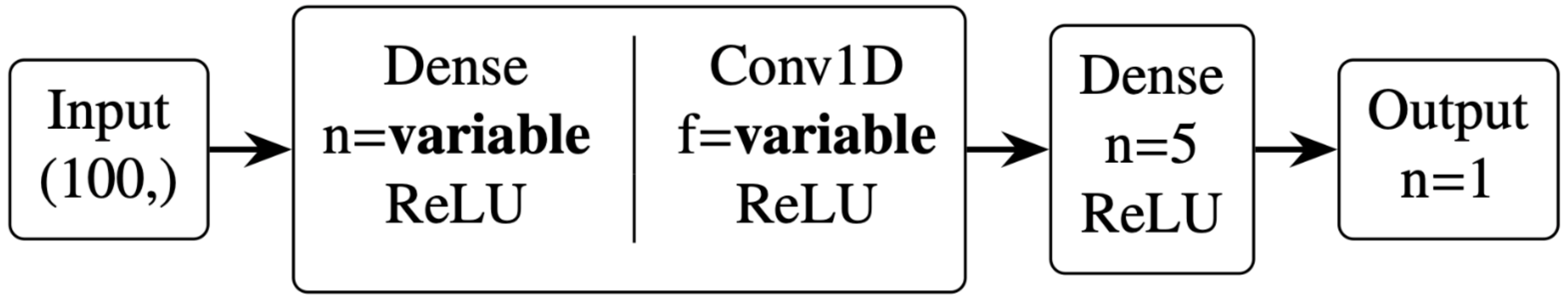
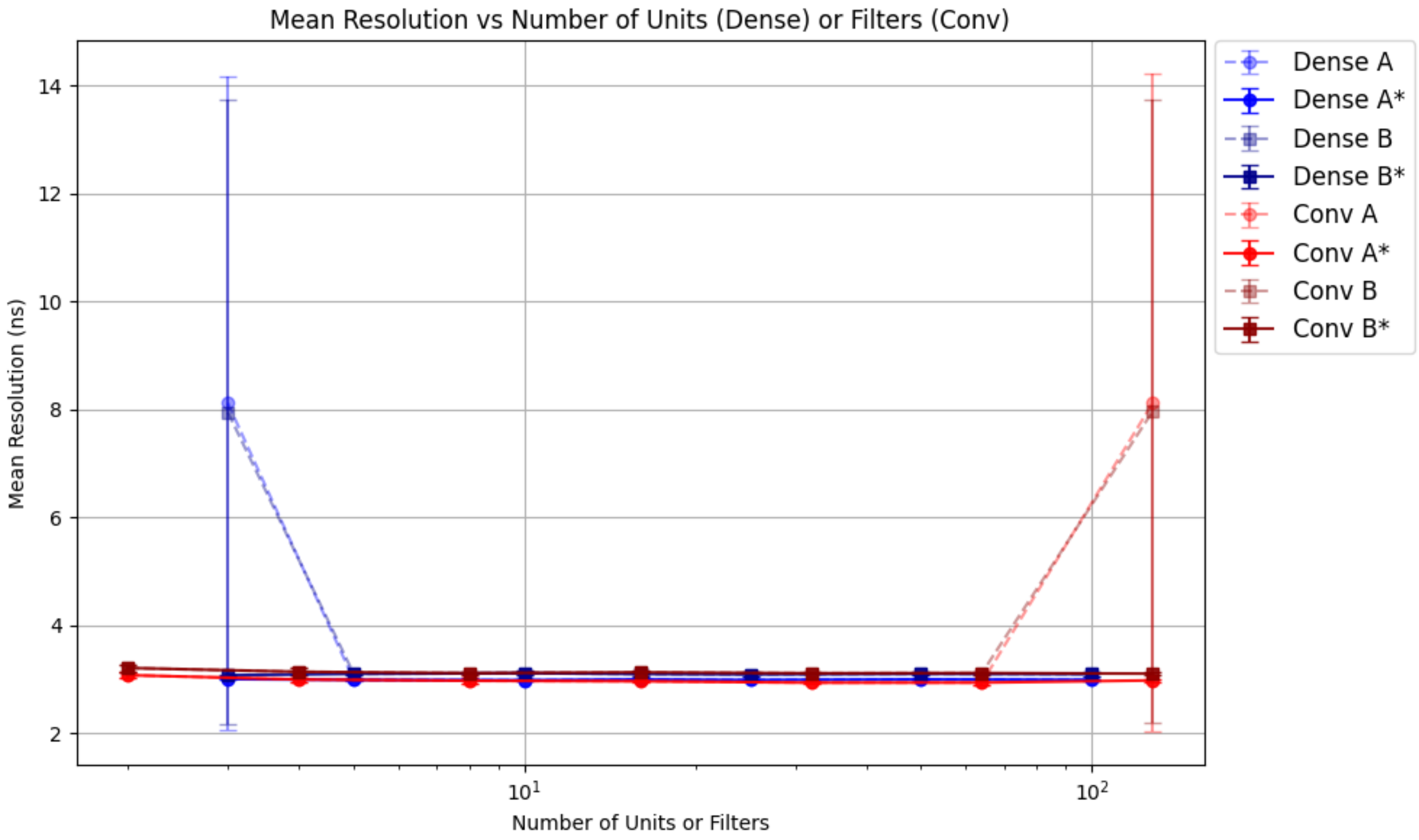
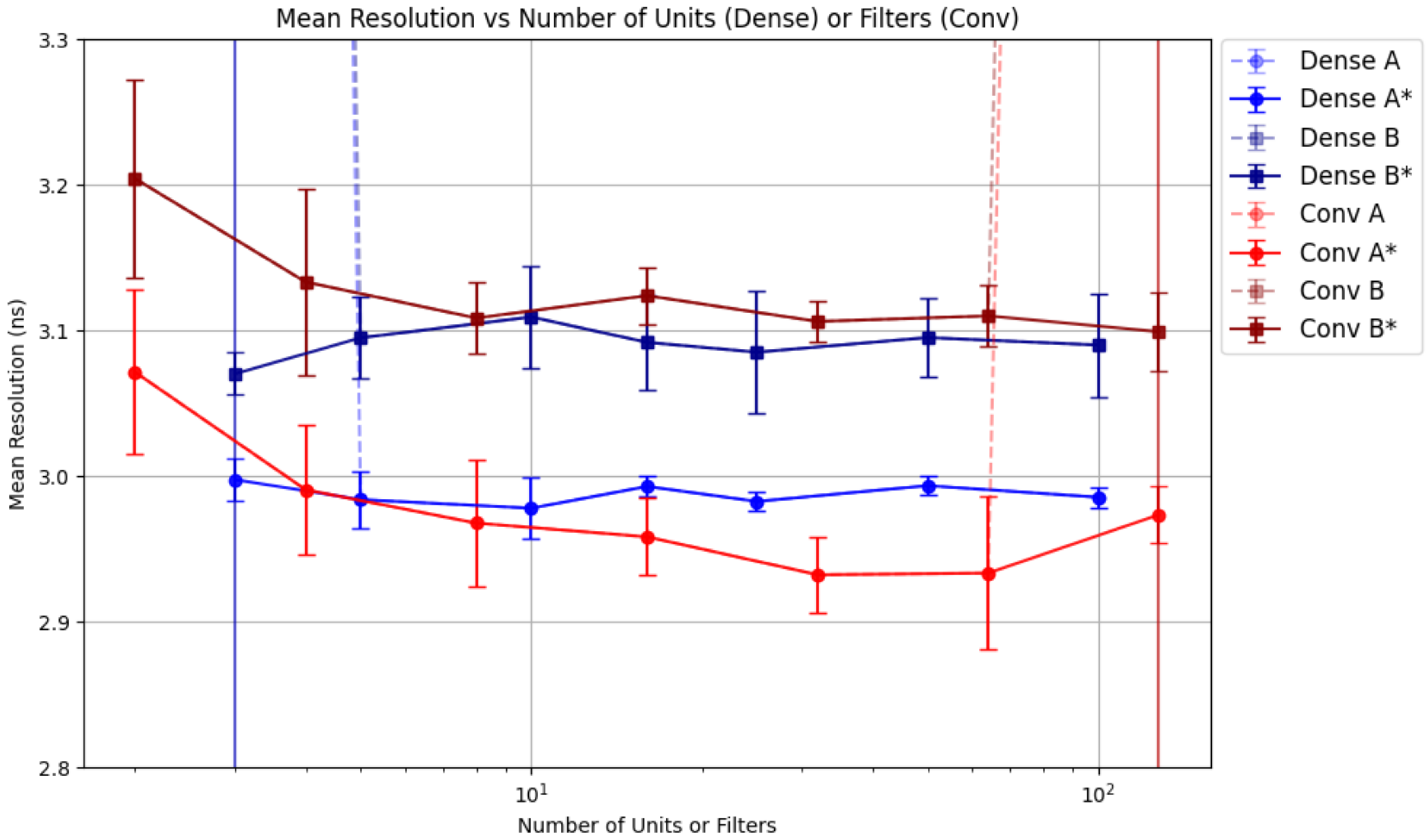
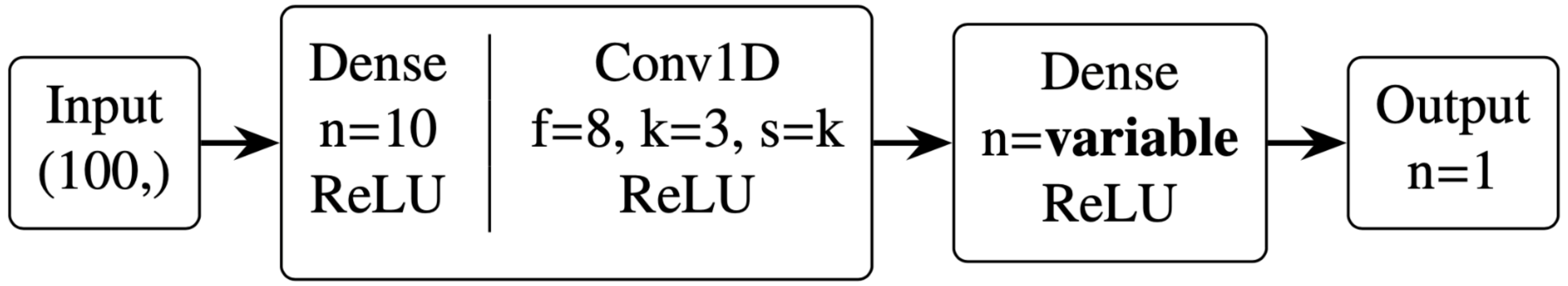
Model tuning - first hidden layer

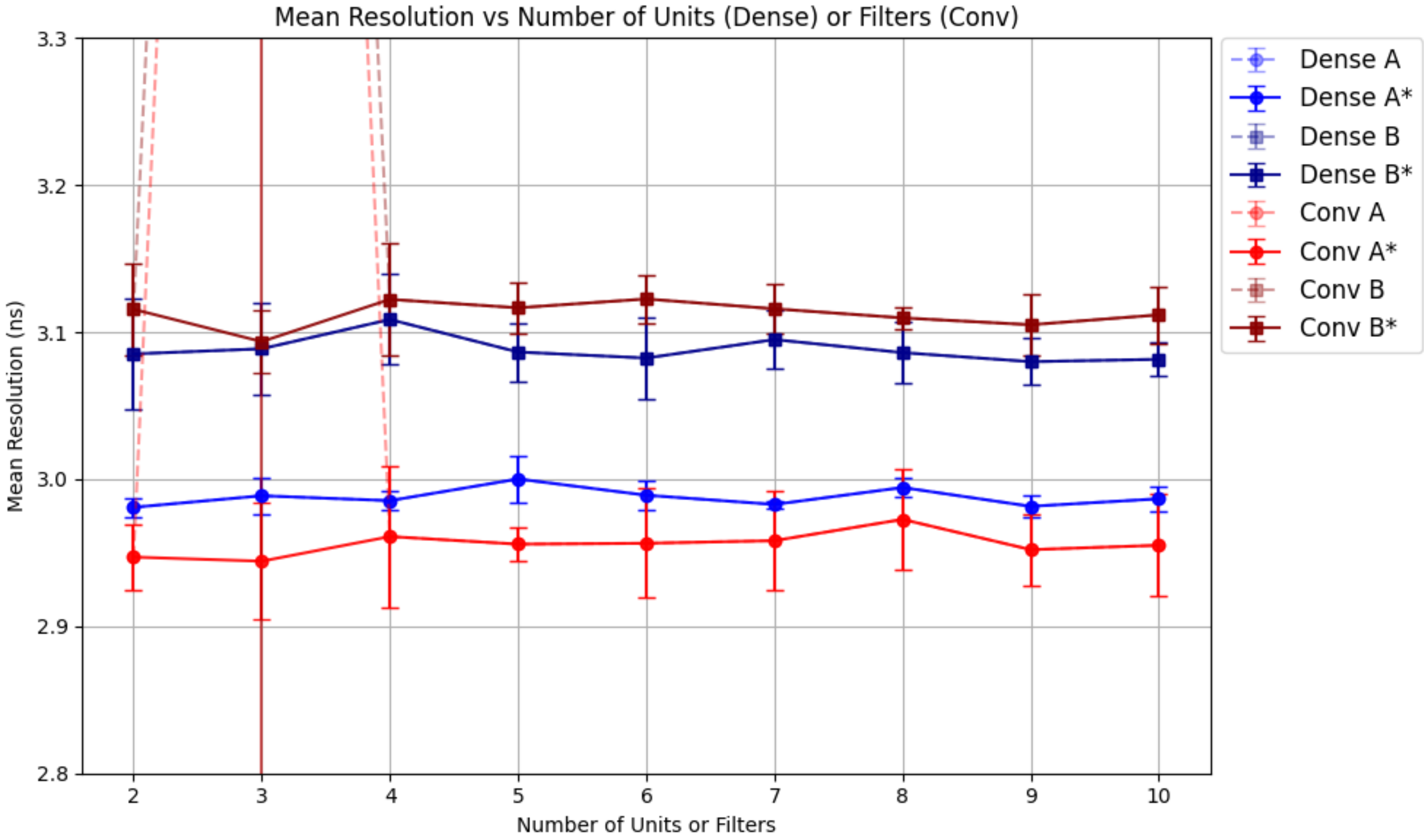




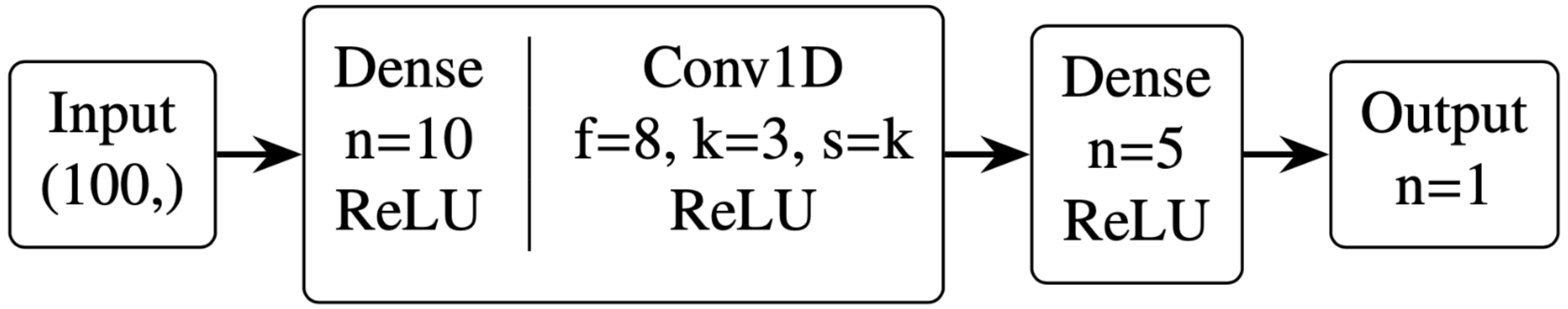


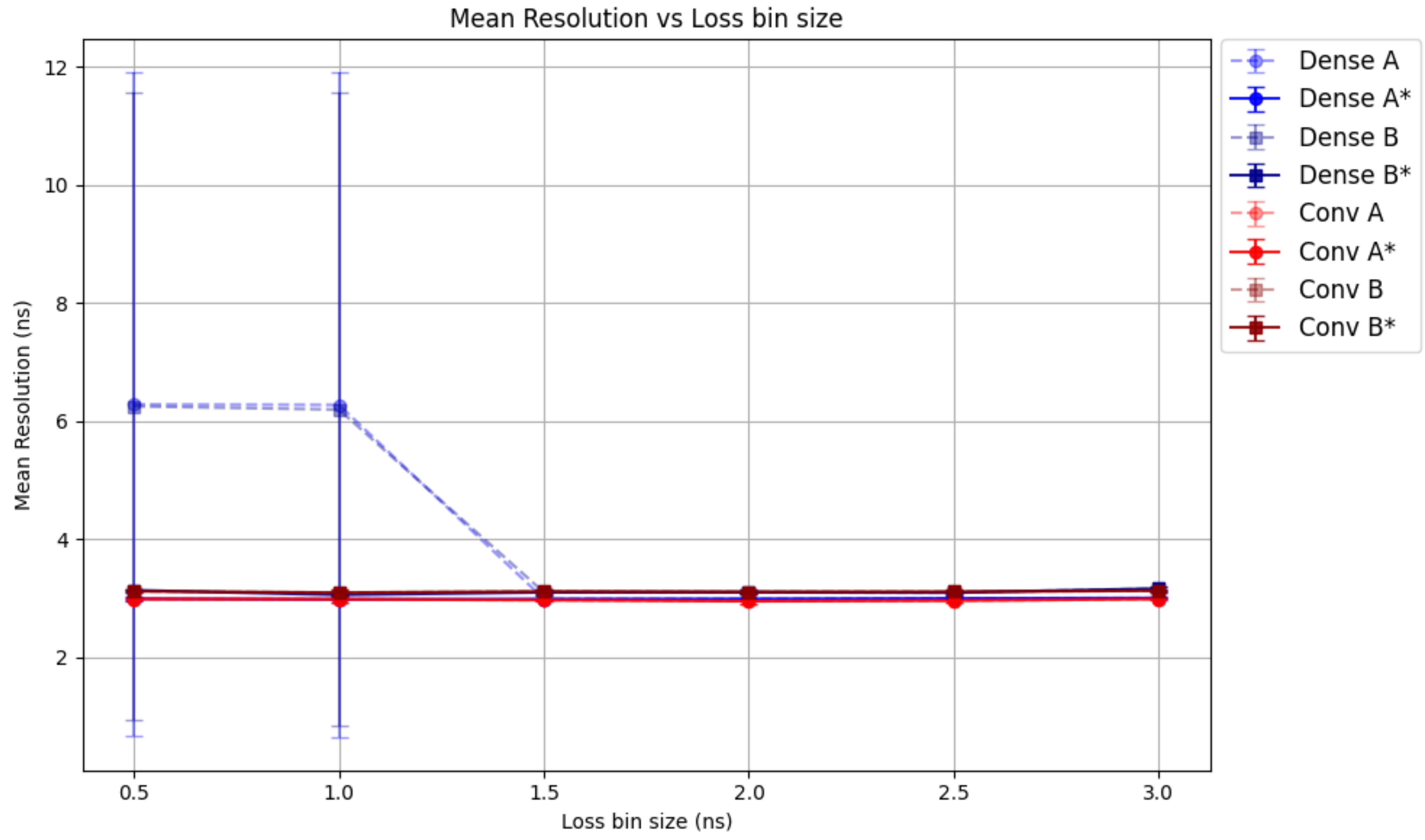
Model tuning - second hidden layer

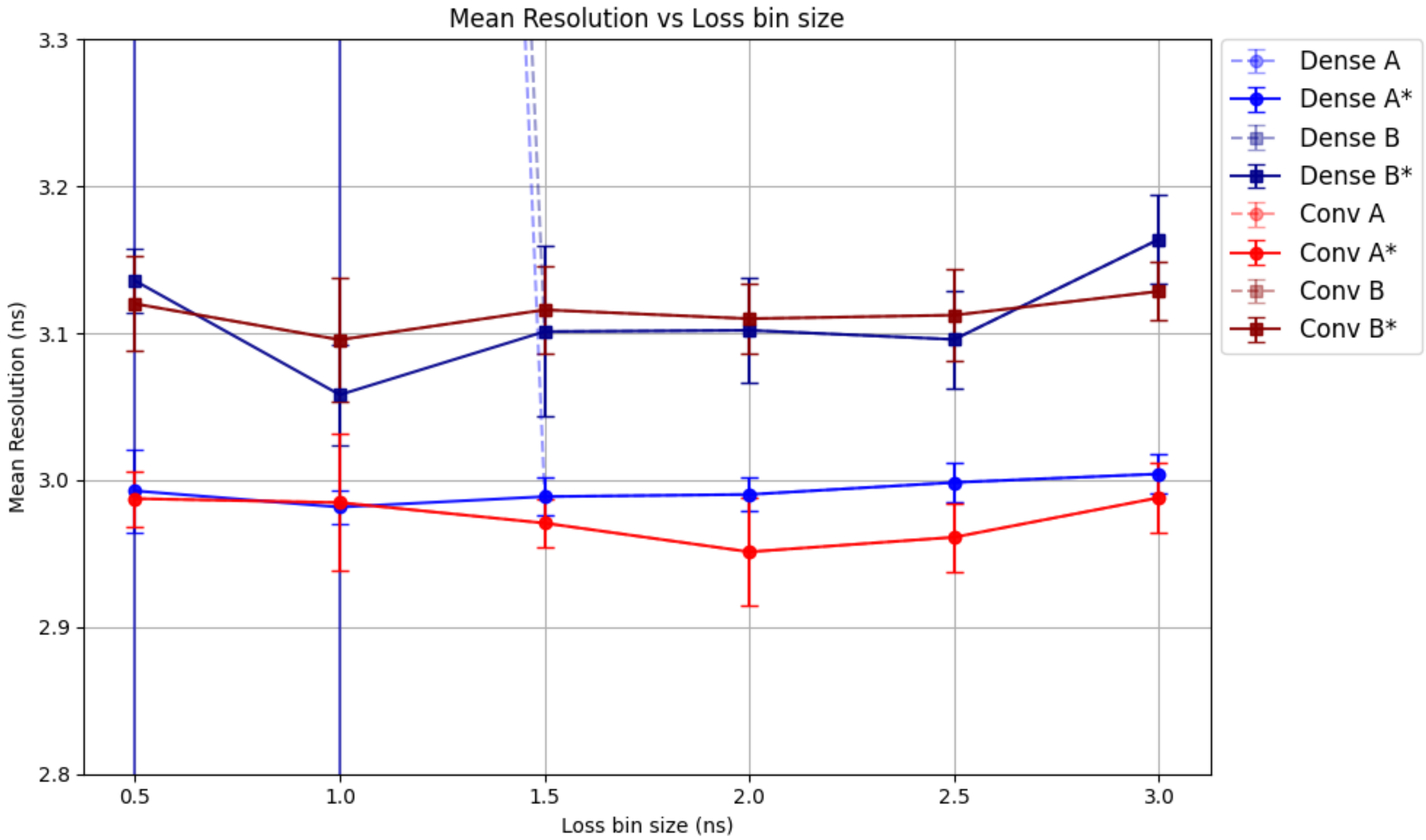




Model tuning - loss function bin size

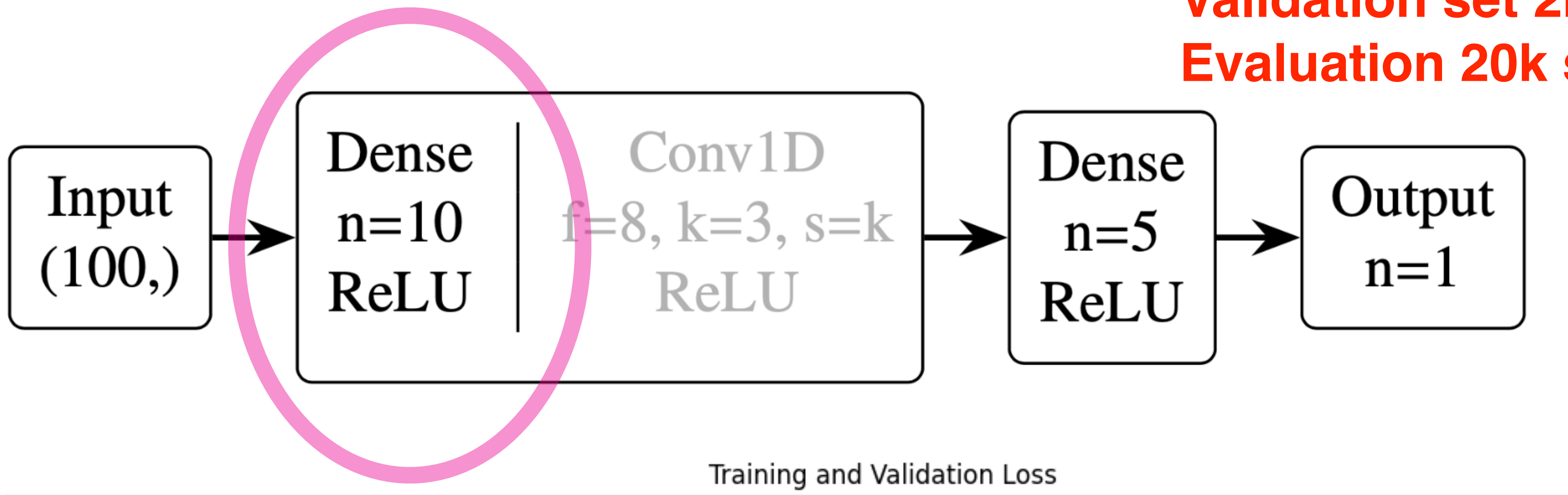






Final Model

Training set 10k signals
Validation set 2k signals
Evaluation 20k signals

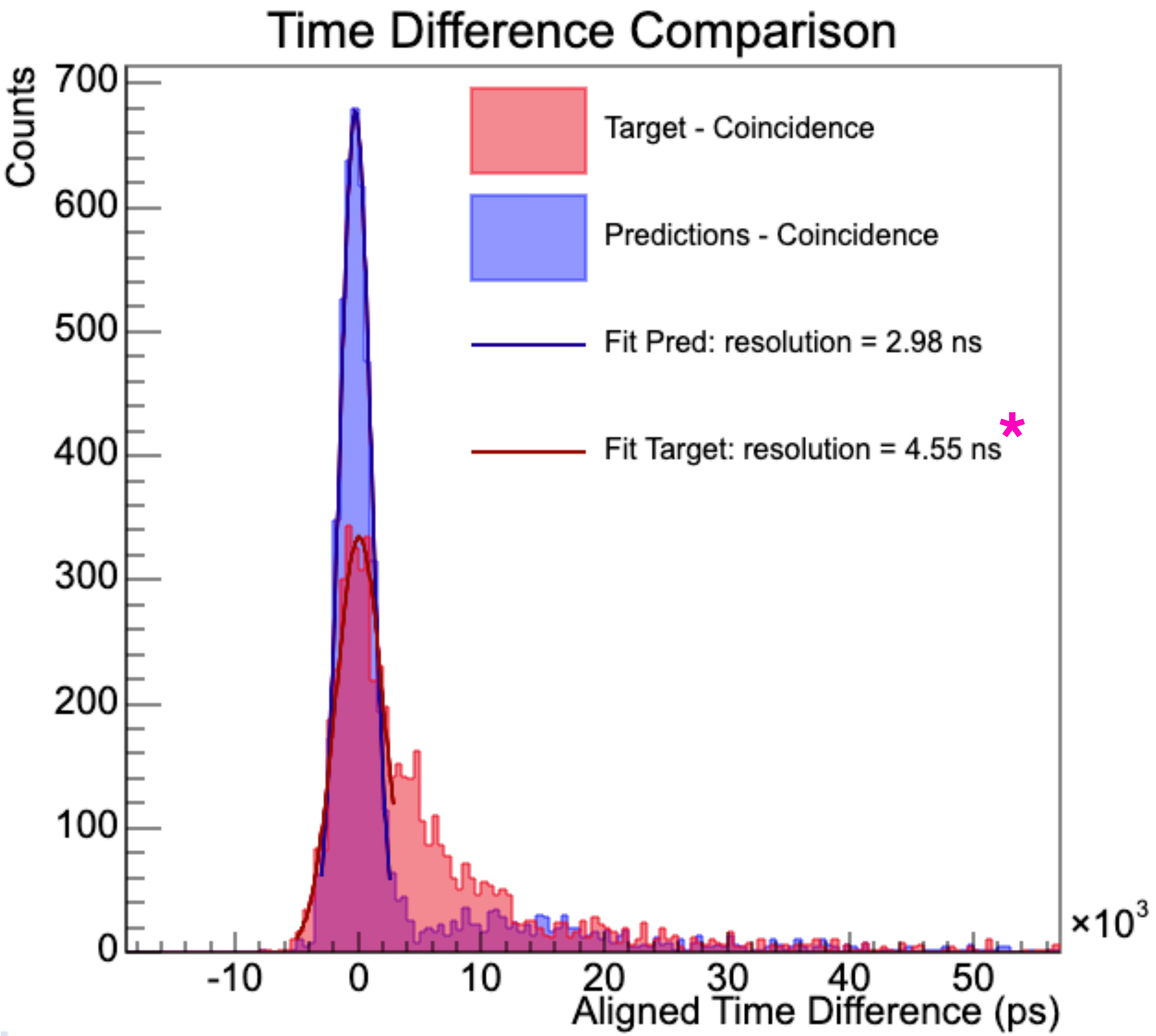


The model can be loaded in c++ script with Tensorflow API and it was directly implemented in our raw data conversion code to ROOT format, replacing the CFD algorithm.

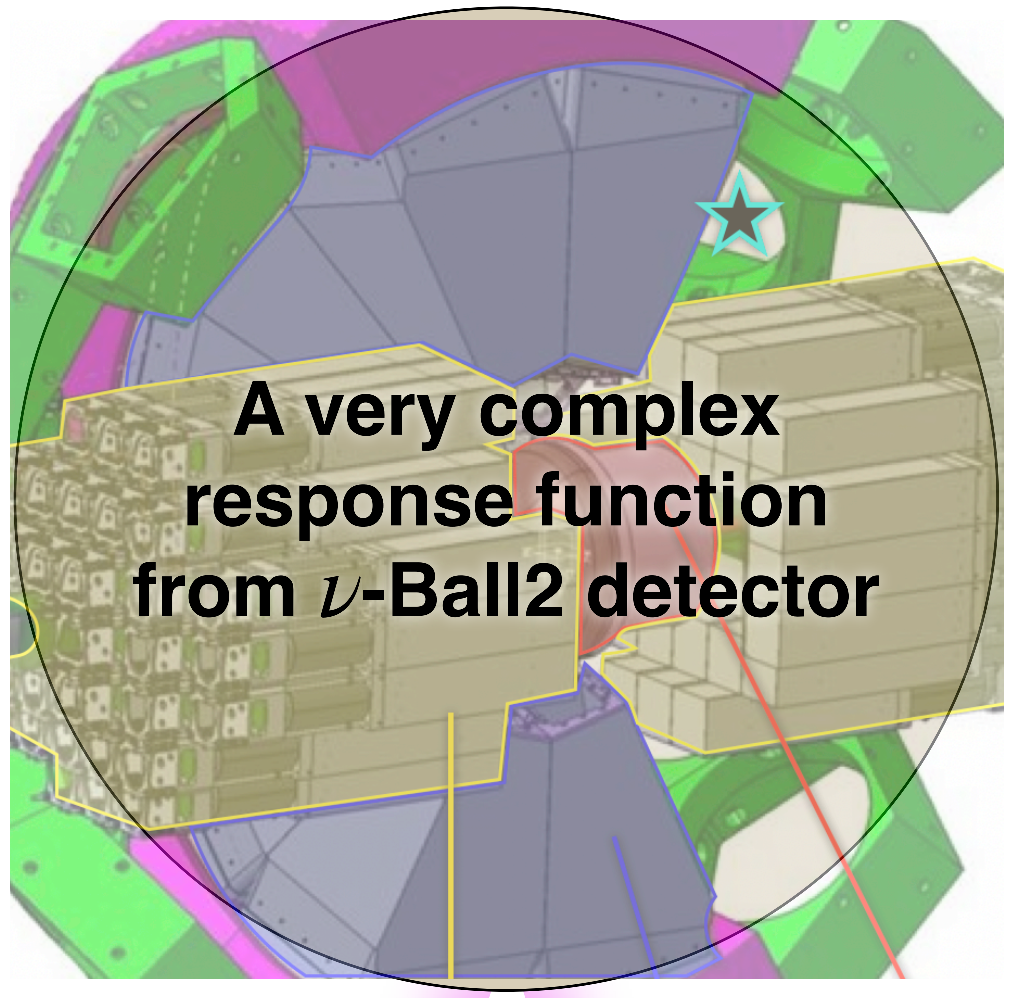
Our final model has **1065 parameters** and requires 2110 FLOP per signal entry, with **total FLOP 2910 per signal.**

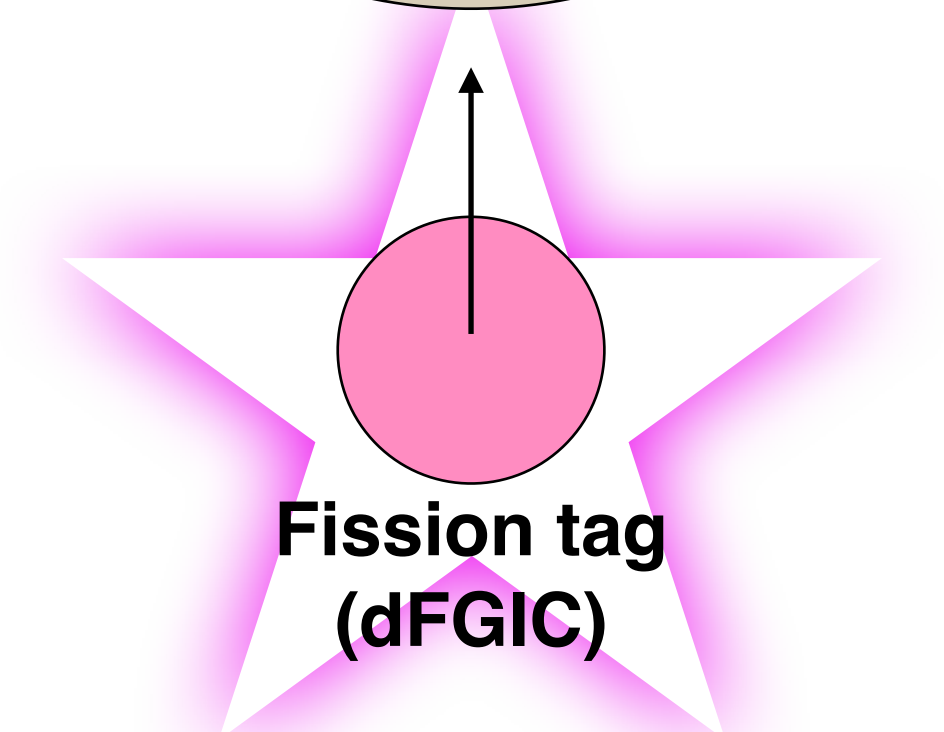
The total number of operations already takes into account signal downsampling (600 + 100 FLOP) and rescaling (100 FLOP).

This represents a computational cost 5 times smaller than CFD algorithm with a time resolution at least 34% better * .

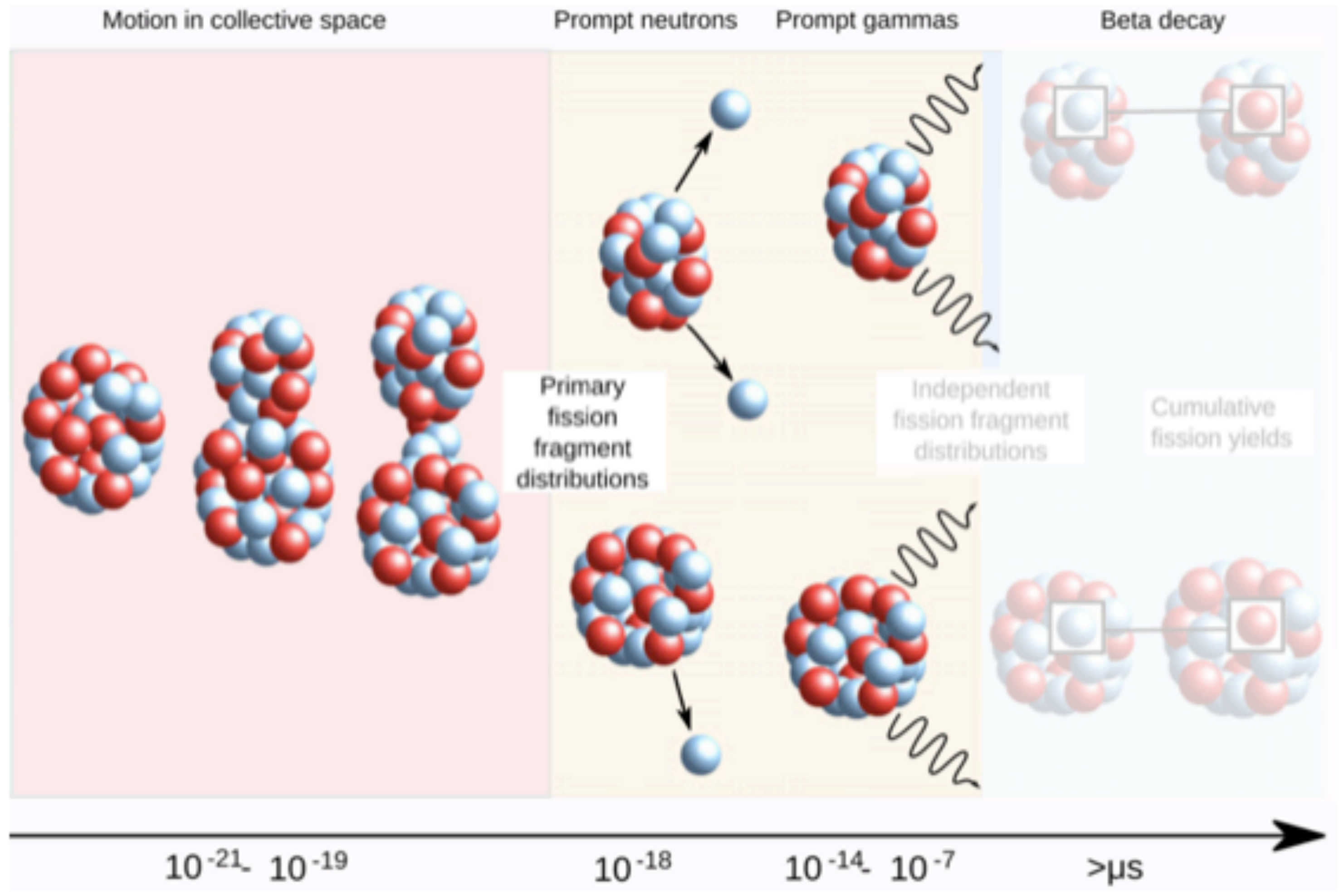


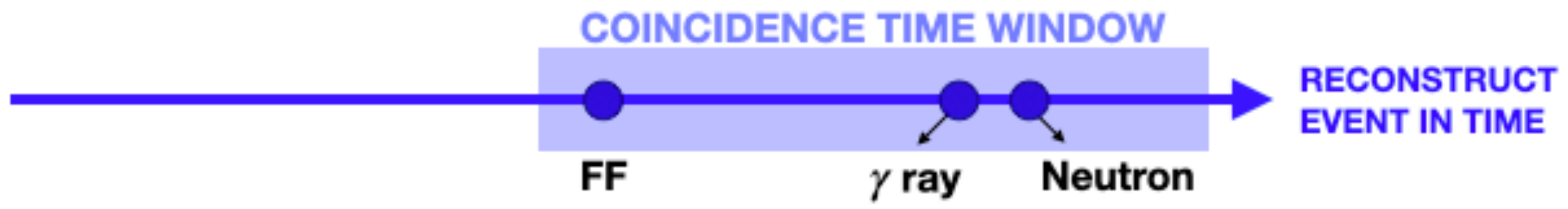
CONTENTS:

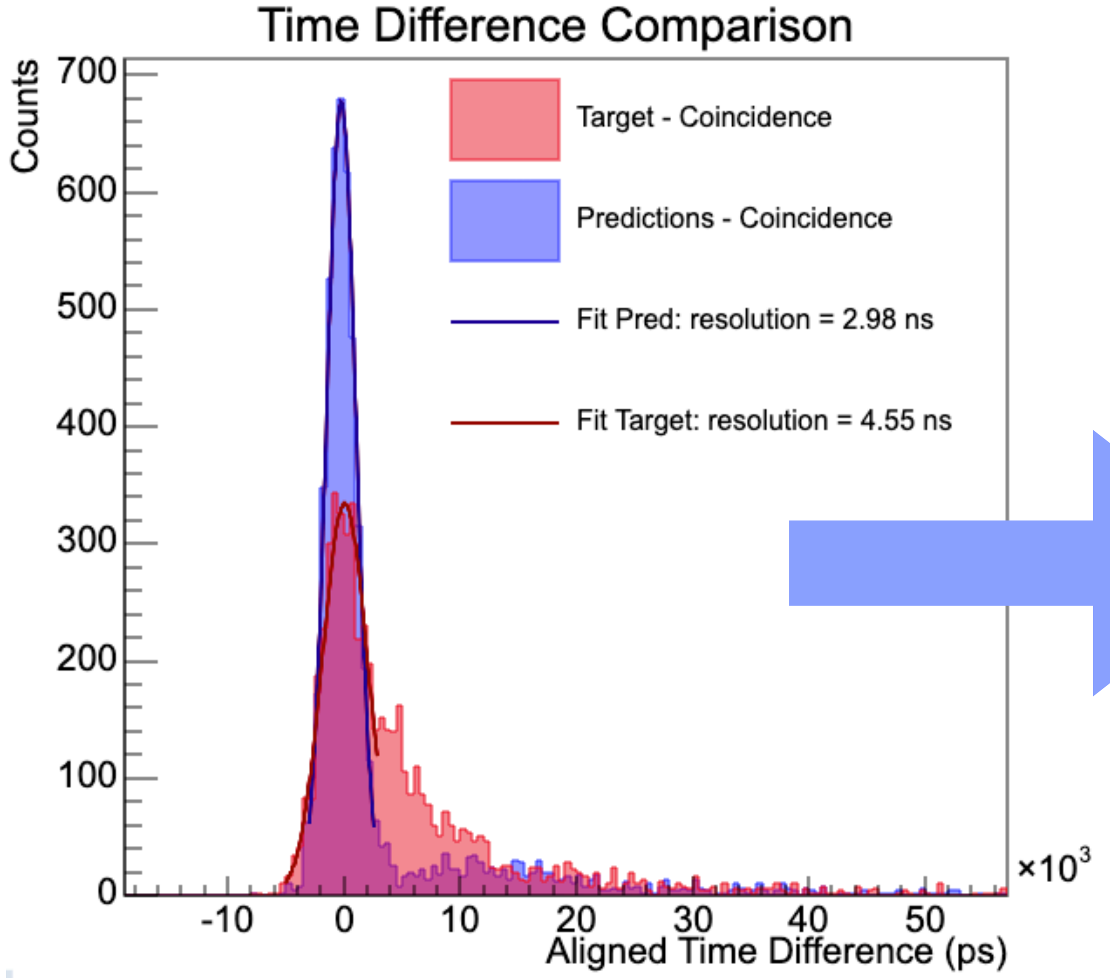




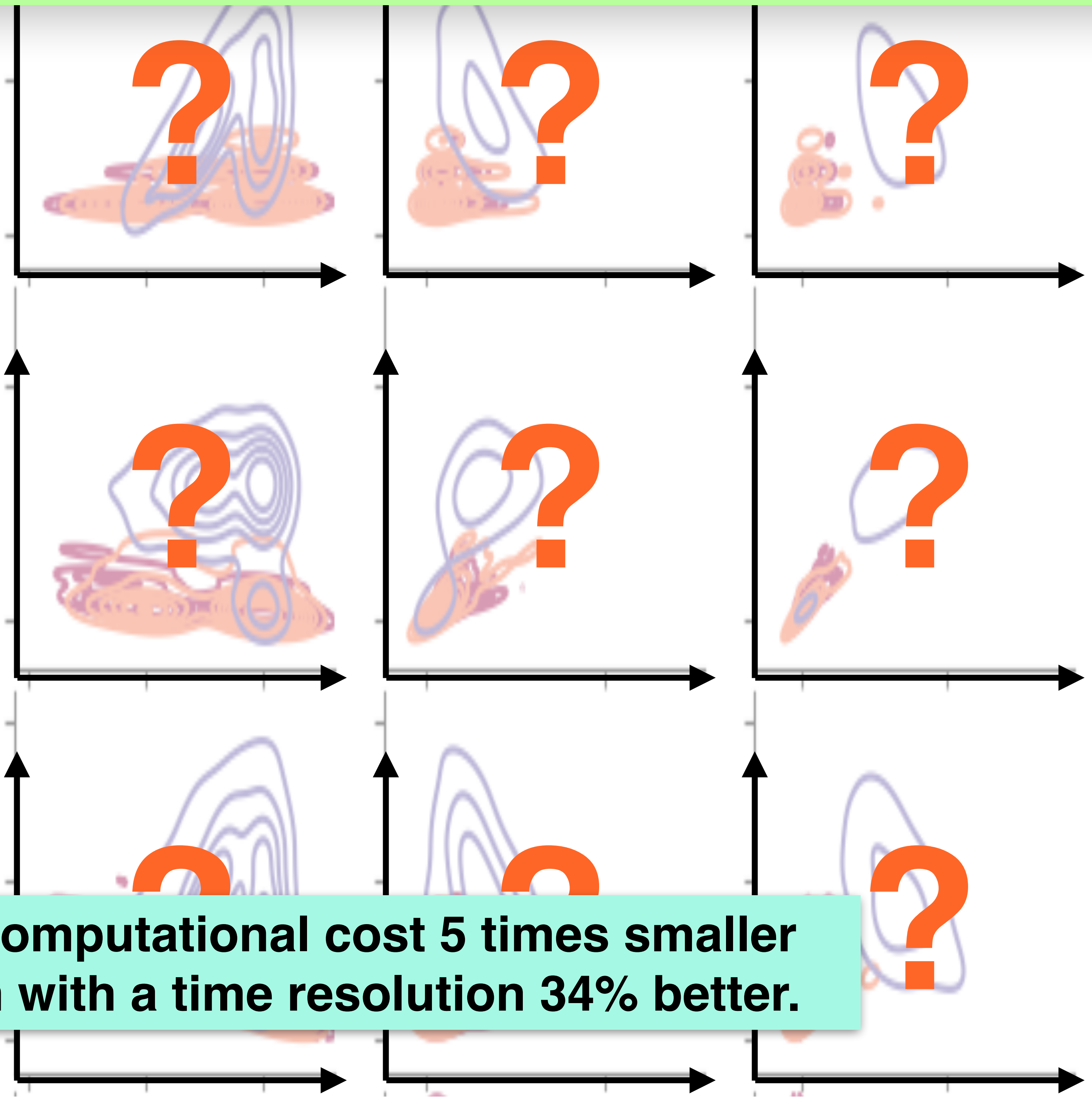
Classification labels







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



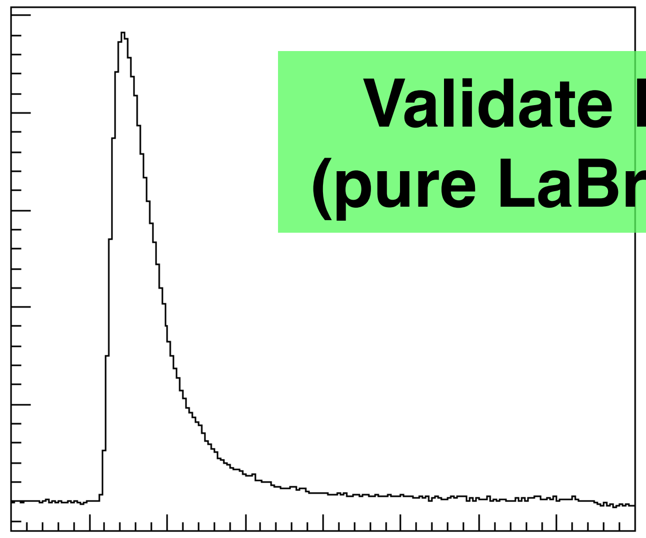
Improvement of fission trigger annotations

This represents a computational cost 5 times smaller than CFD algorithm with a time resolution 34% better.

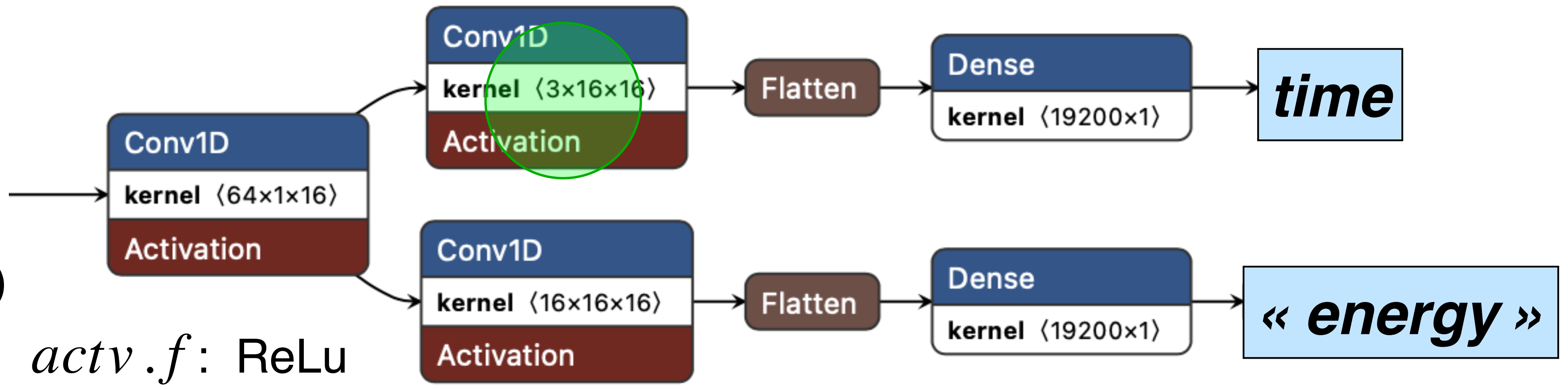
Supervised regression model for signal trigger

Validate NN for THALIA (pure LaBr3) signal trigger

BENCHMARK



Input: sampled signal (P,dt)



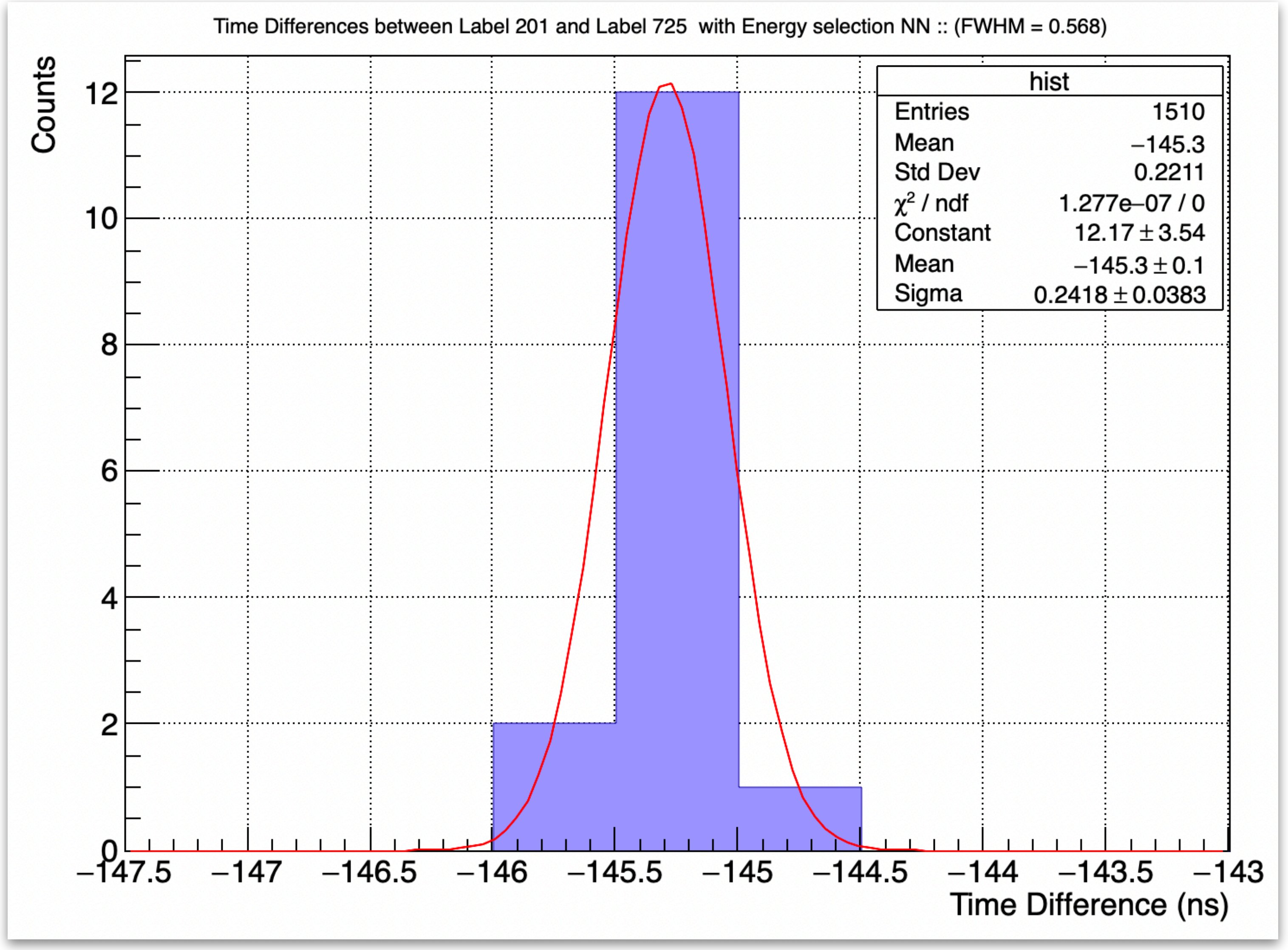
$actv.f$: ReLu

Model evaluation:

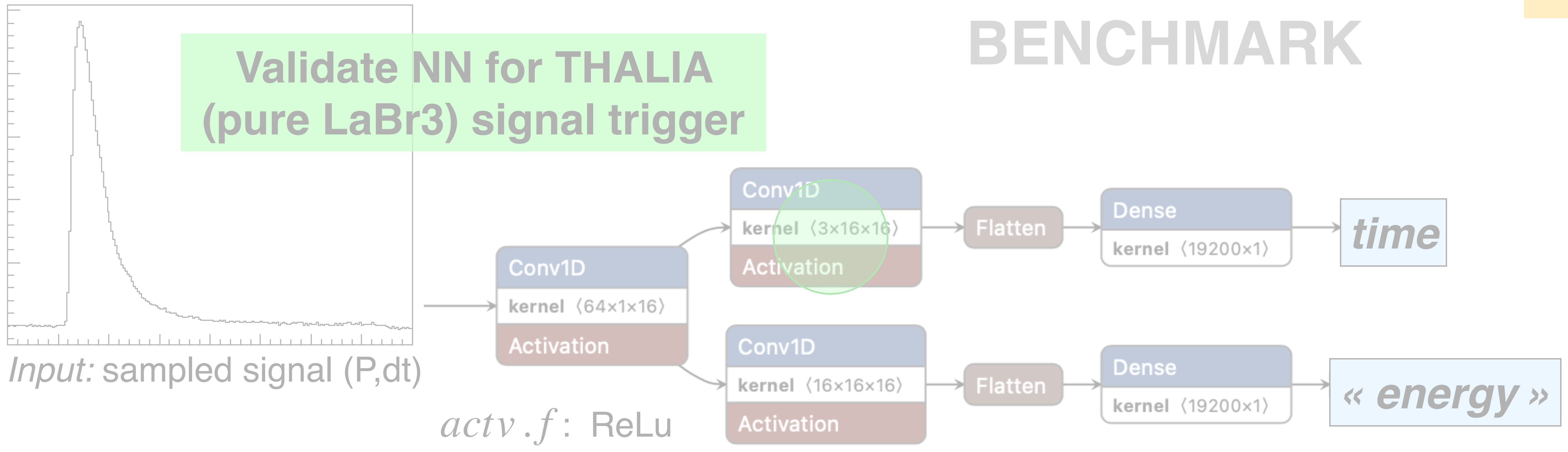
*** Loss: MSE**

3,6 % @ 661,7 keV
$R(t)$ = 569 ps

With NN:
5,6% @ 661,7 keV
$R(t)$ = 568 ps



Supervised regression model for signal trigger



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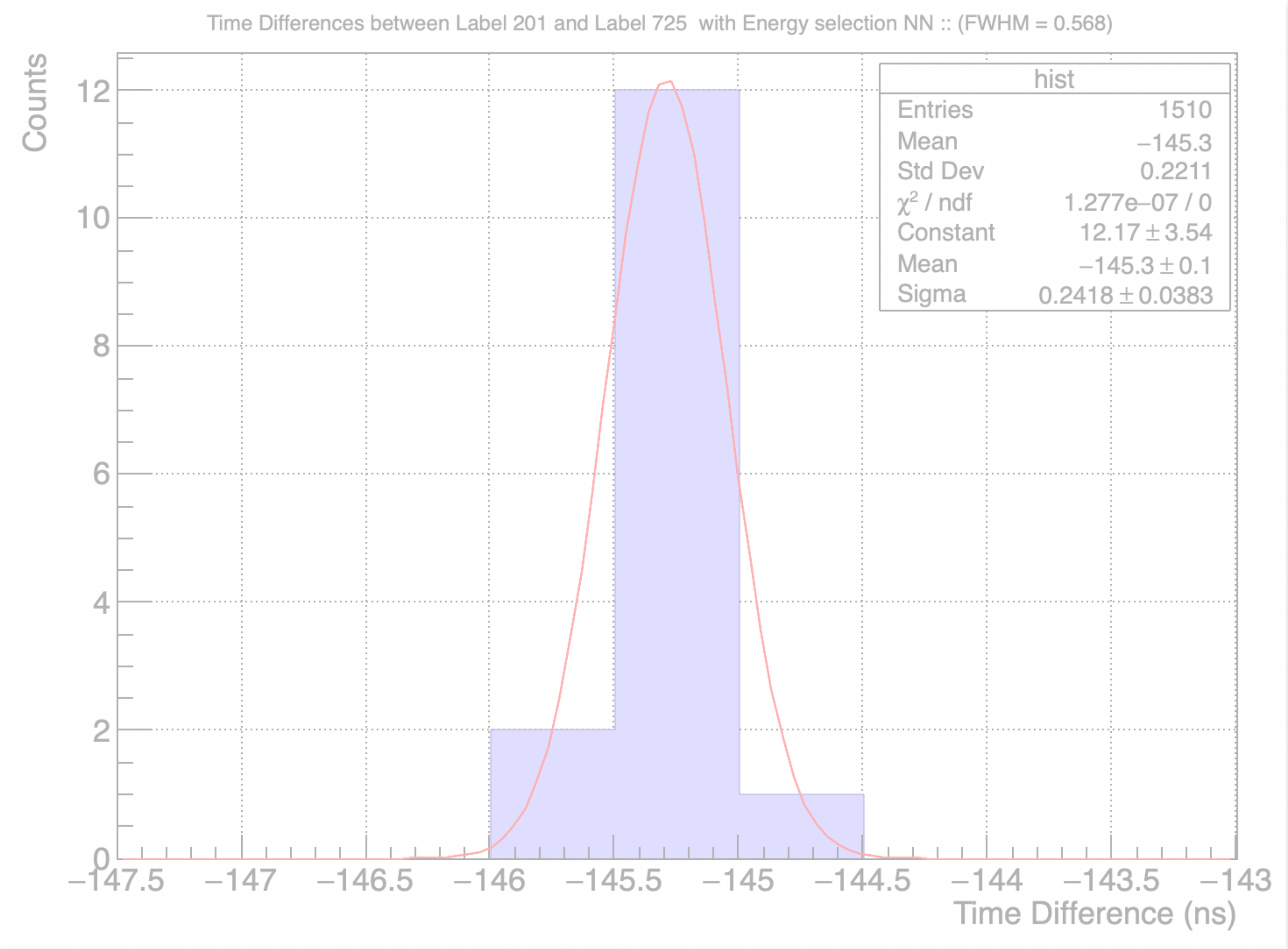
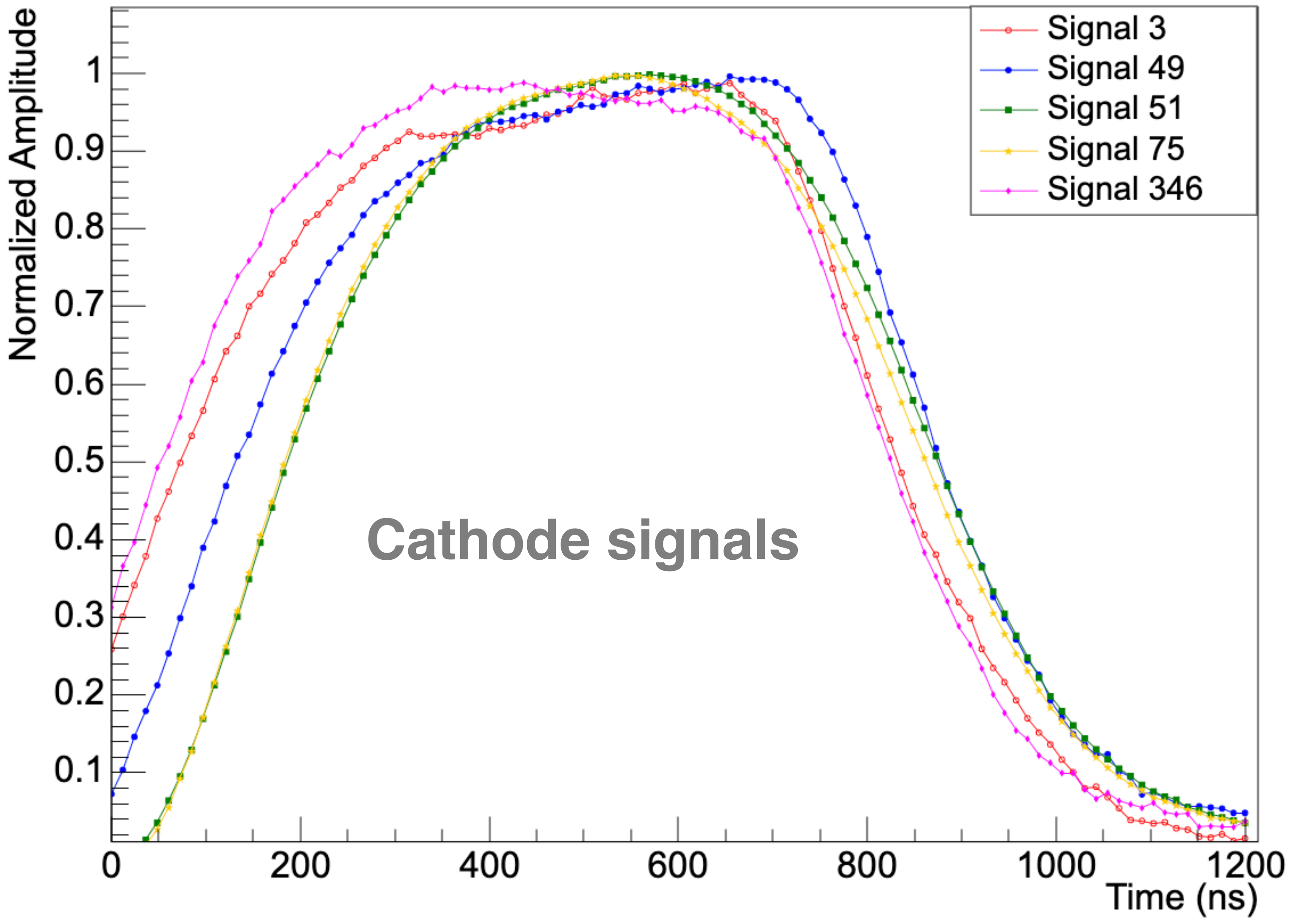




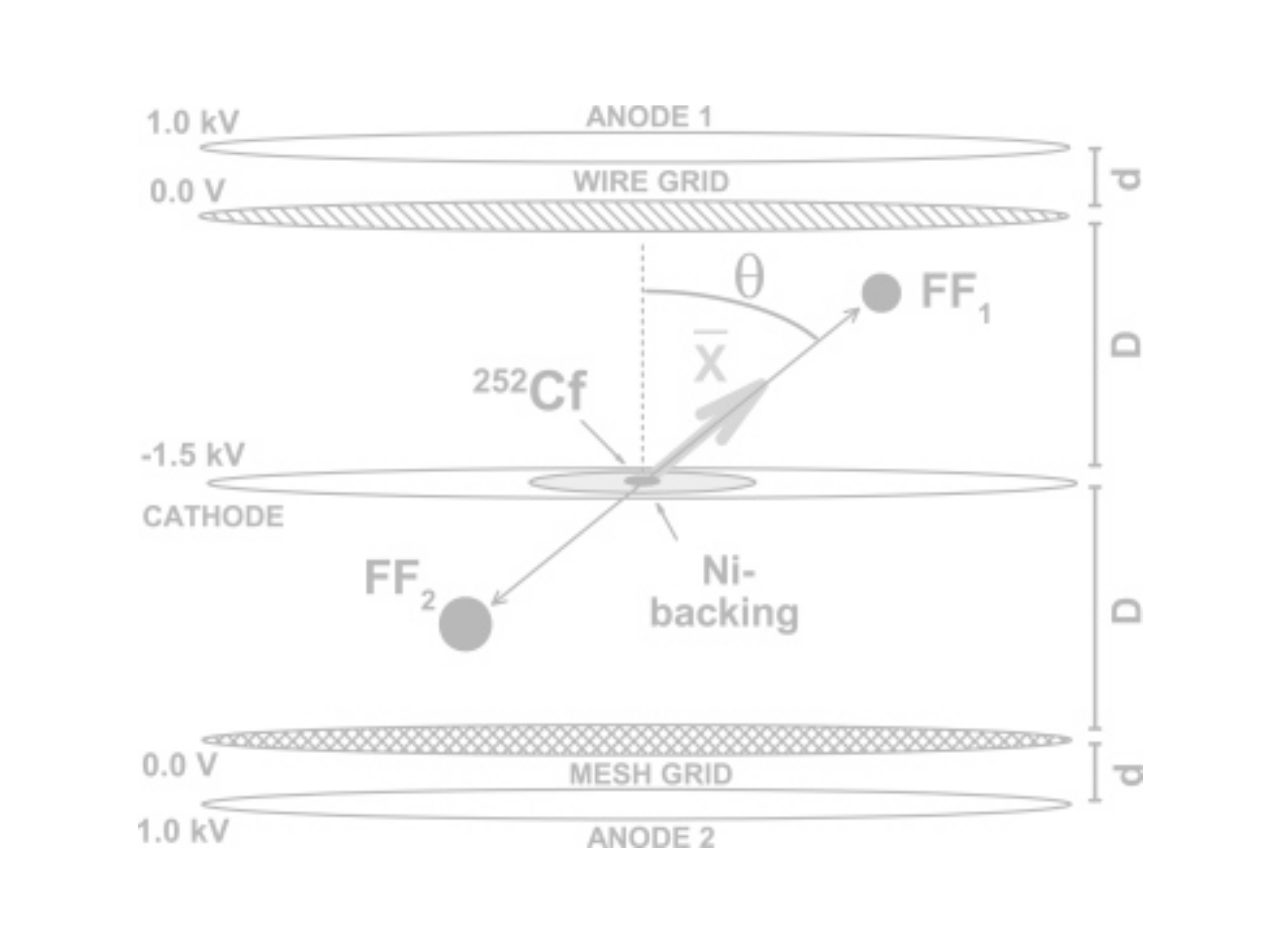
Adapt and apply to dFGIC cathode signals

- **Model fails to improve time resolution**

  CAUSE: degraded resolution in target data (cathode signal CFD trigger)

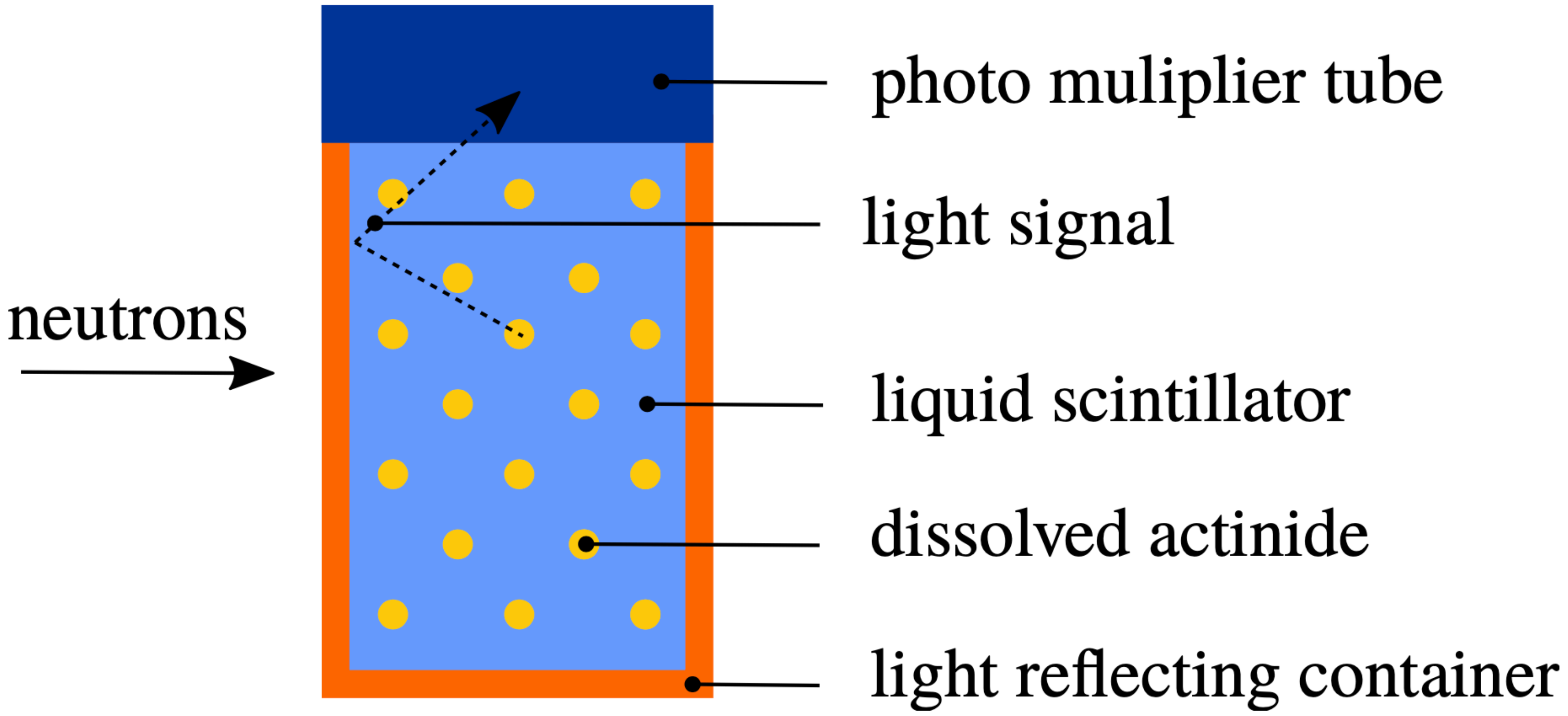
Dedicated detector:

…such as an ionisation chamber



Taken from: L. Bardelli et al., Nucl. Instrum. Methods Phys. Res. A, vol. 654, pp. 272-278, 2011.

…such as an active target



PhD thesis: Dennis Wilmsen. Nuclear structure studies with neutron-induced reactions : fission fragments in the N=50-60 region, a fission tagger for FIPPS, and production of the isomer Pt-195m. Physics [physics]. Normandie Université, 2017. English. <NNT : 2017NORMC269>. <tel-01768580>

Fission Tagging

Dedicated detector:

…such

Taken from: L. Bardelli

Eur. Phys. J. A (2020) 56:207

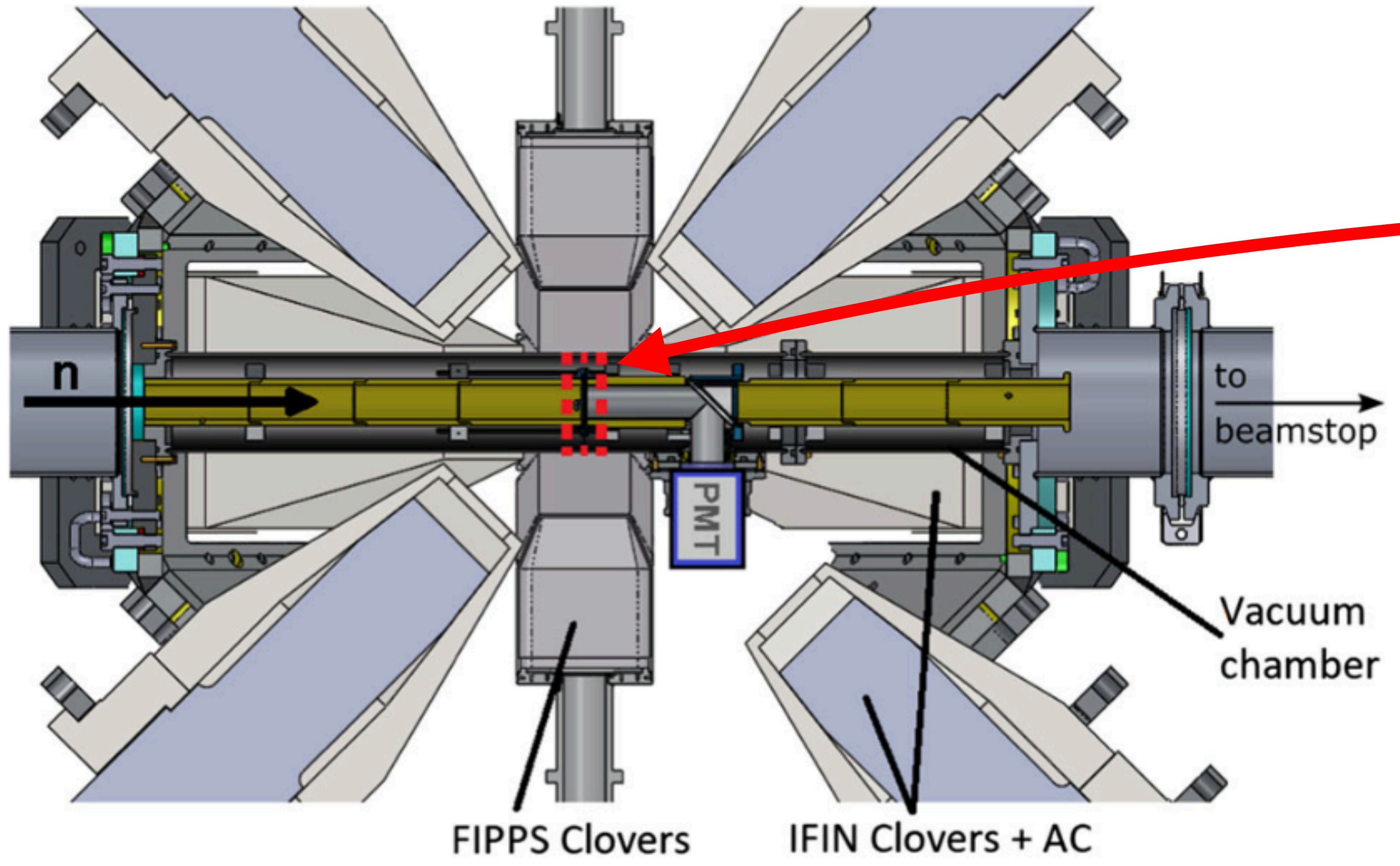
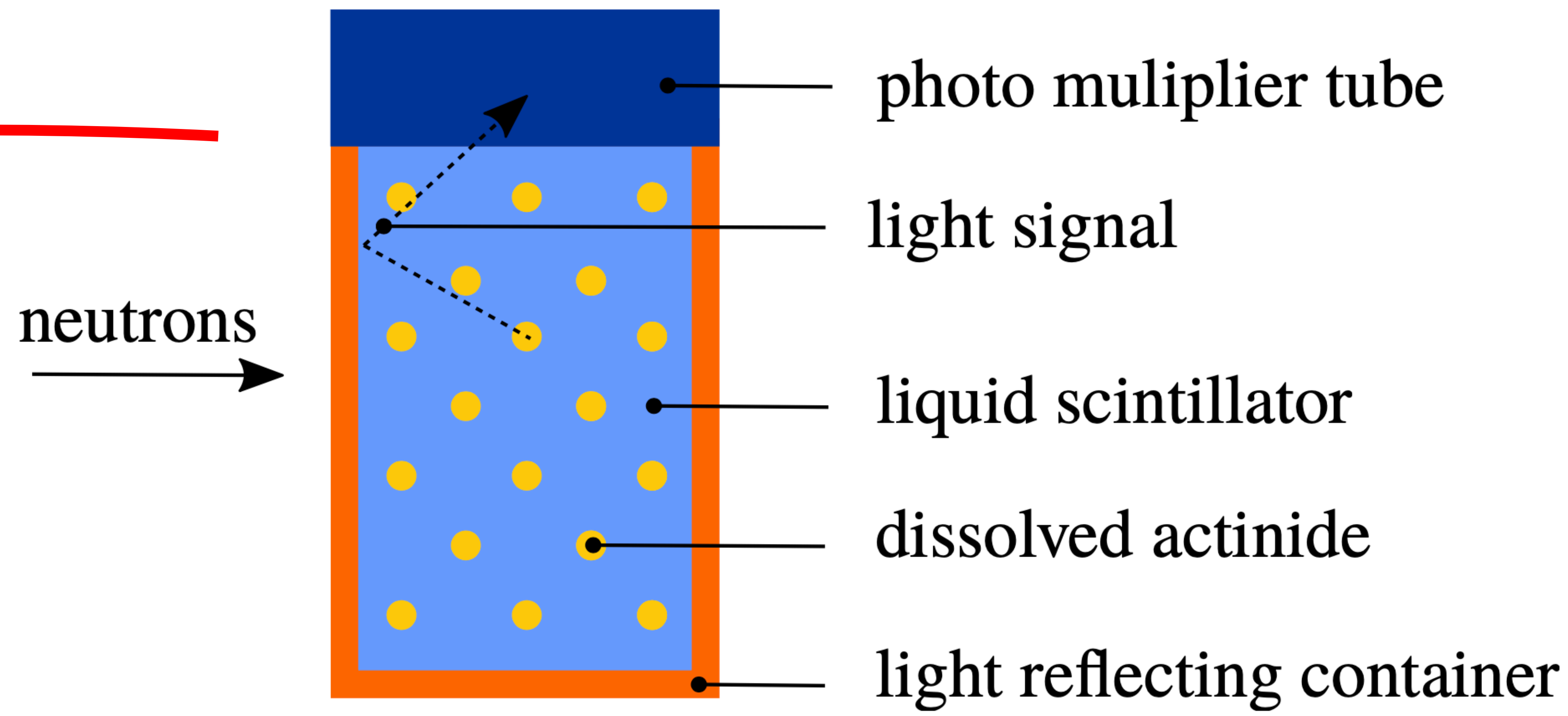


Fig. 1 Section view of the active target setup at the FIPPS instrument. The direction of the collimated, thermal neutron beam (left-to-right) is indicated by an arrow. Eight germanium clover detectors are arranged in the plane perpendicular to the neutron beam at the target position. Eight additional clover detectors with their anti-Compton (AC) shields (loan from IFIN-HH [17]) are mounted in horizontal and vertical 45deg positions with respect to this plane. The active target cell is mounted at target position (red dashed lines). It is optically connected to the PMT by a light guiding system, both are also shown. ^{6}Li-loaded cylinders (represented in yellow) mounted around the neutron beam all along the vacuum chamber are used to absorb scattered neutrons, thus minimizing the γ-ray background

…such as an active target



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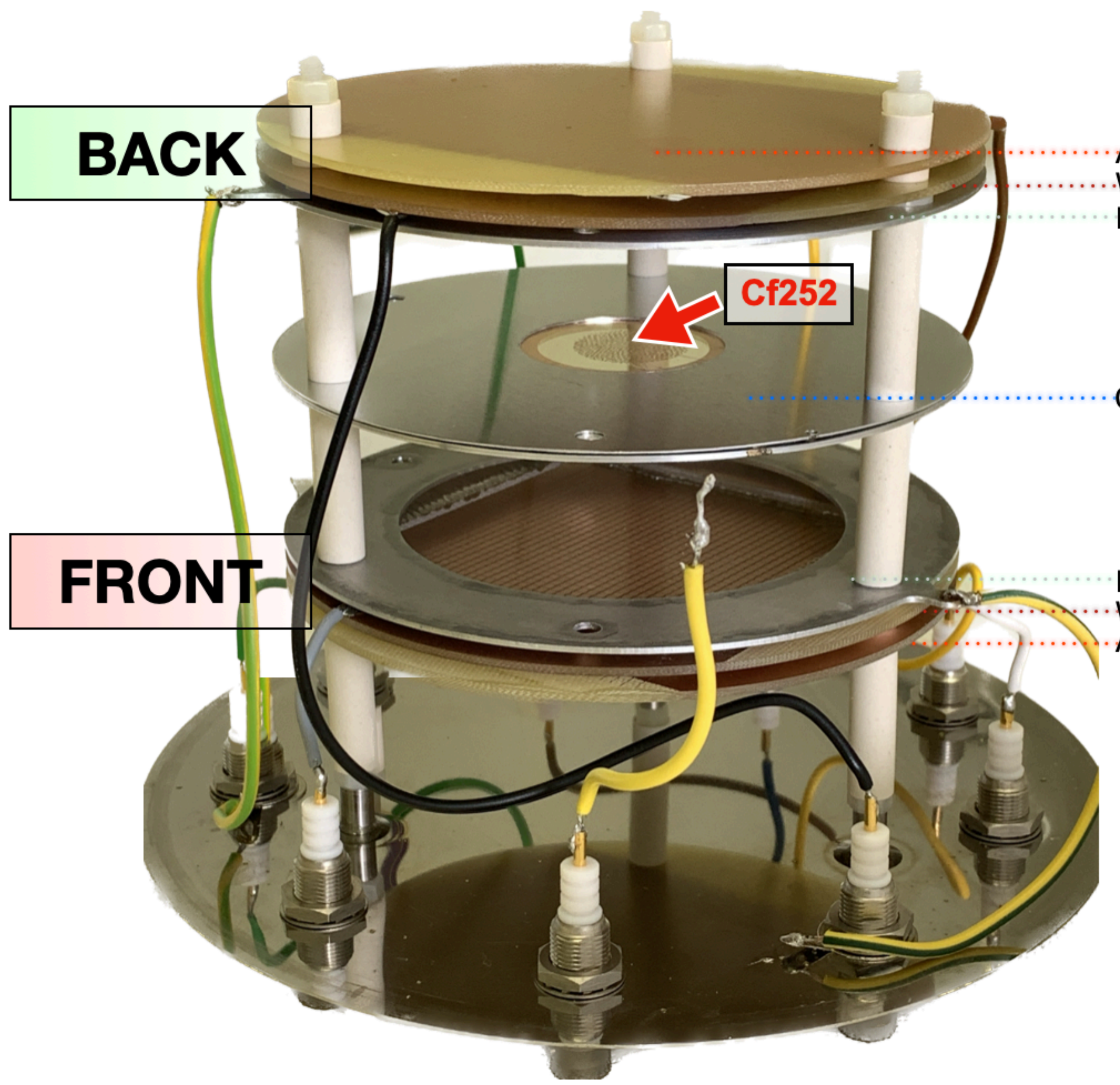
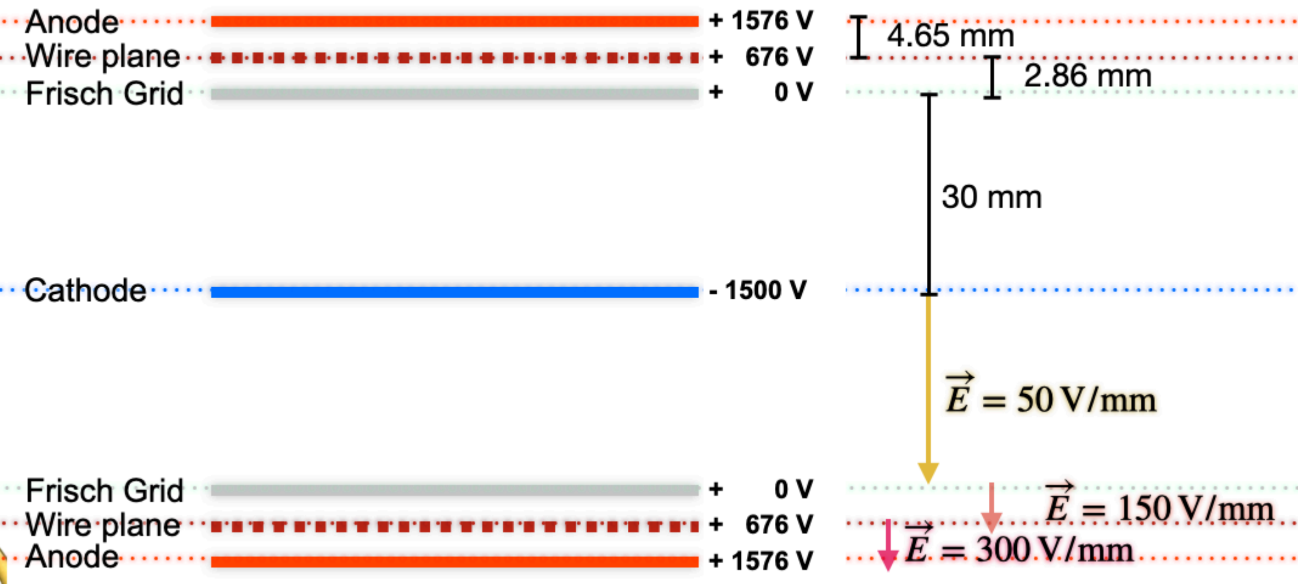
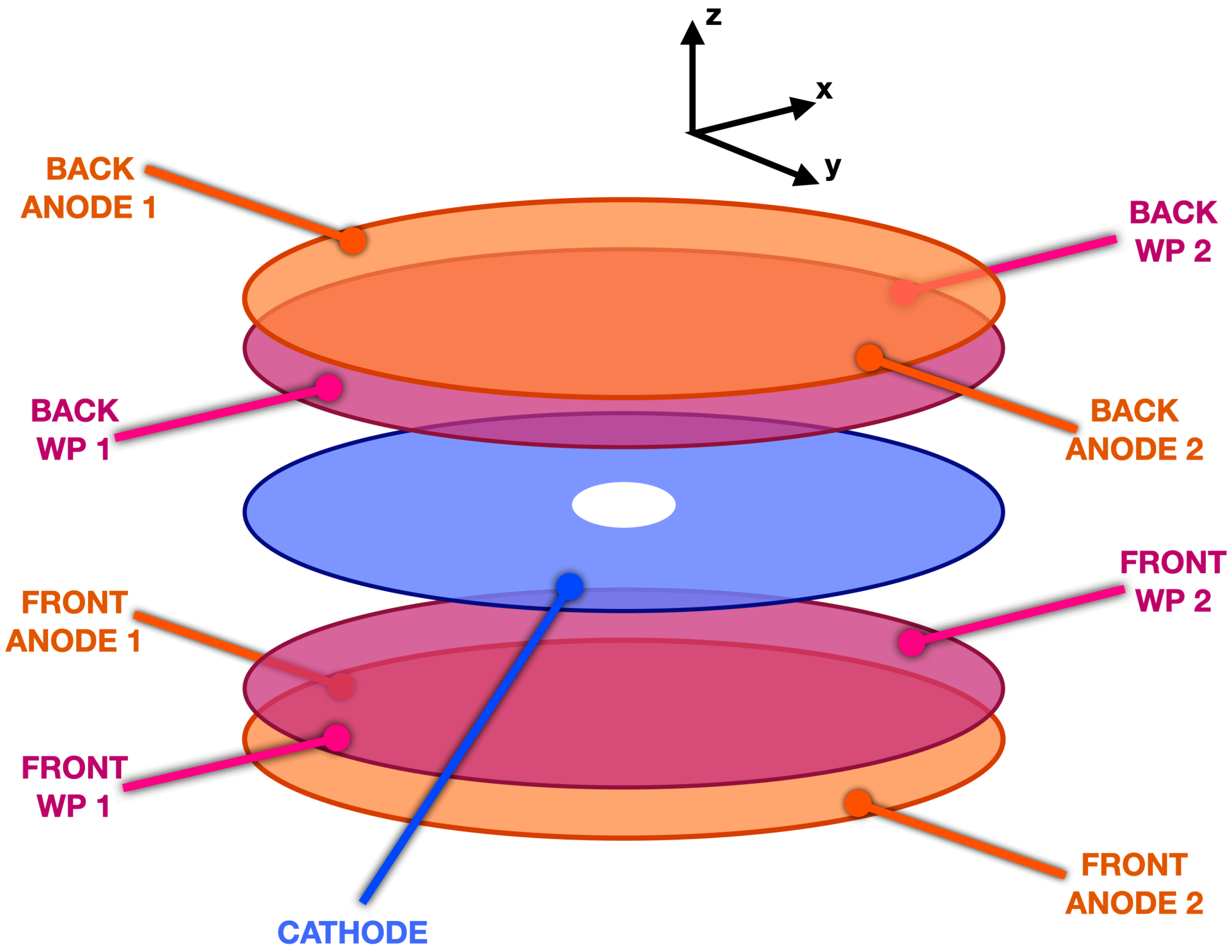
Fission tagging efficiency of 97.8 (25)% for $^{233,235}U$
This fission tag gives a gain in statistics up to a factor of 10

Constraints:
- Suitable for dissolvable actinides;
- Target mass density.

Double Frisch-Grid Ionisation Chamber (dFGIC)







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

calibration constants

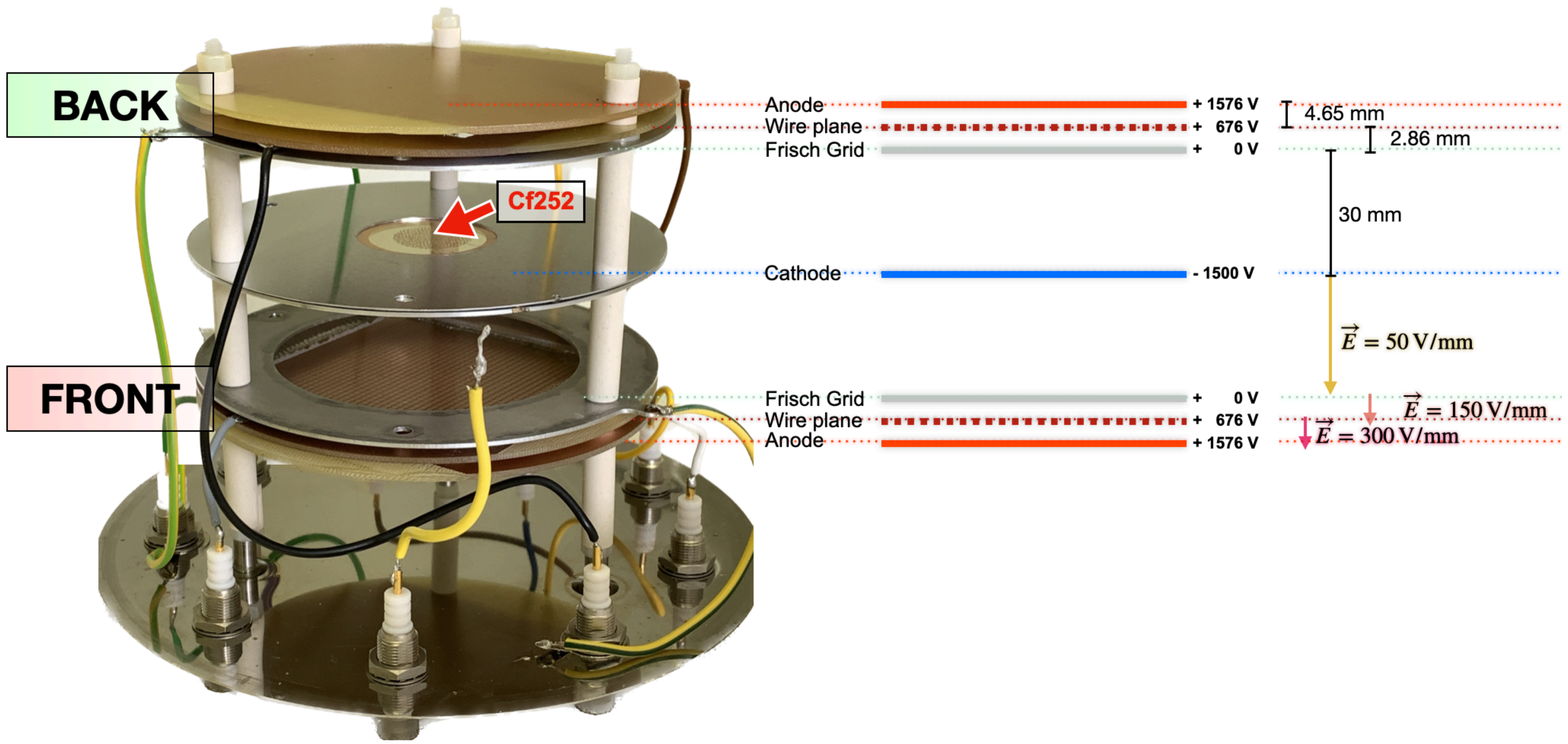
$$\bar{z} = v_d \left(\bar{t}_{\theta_{max}} - \bar{t}_{1,2} \right)$$

average electron drift time

electron drift velocity

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.

Double Frisch-Grid Ionisation Chamber (dFGIC)



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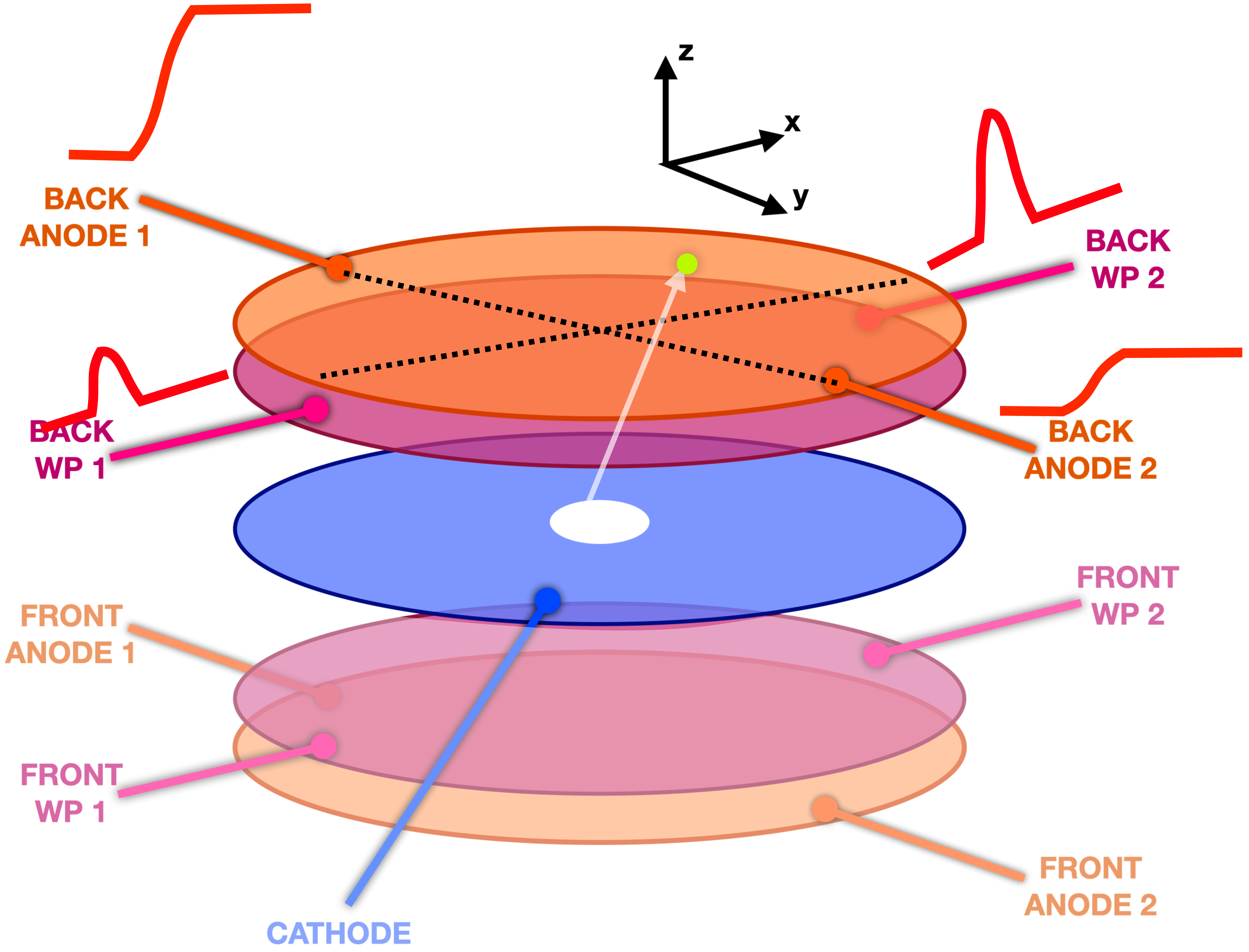

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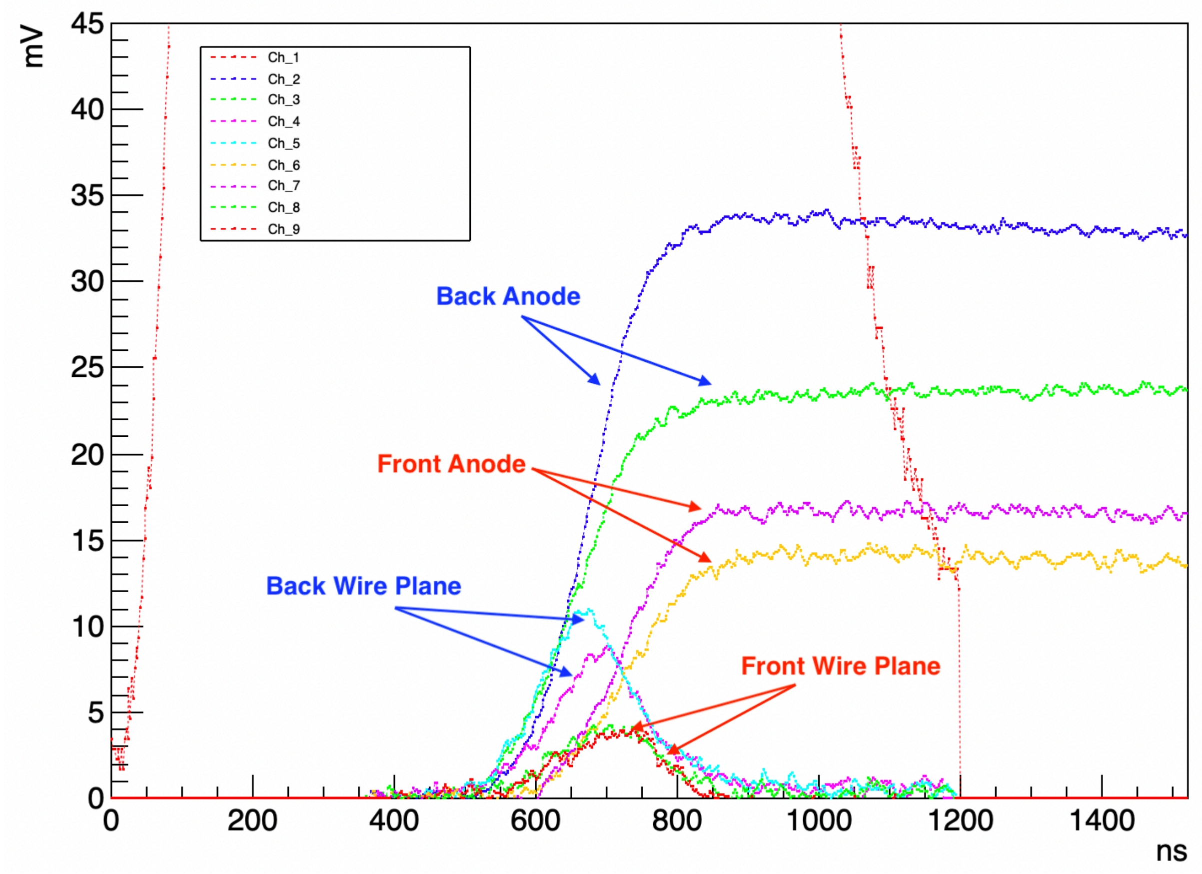
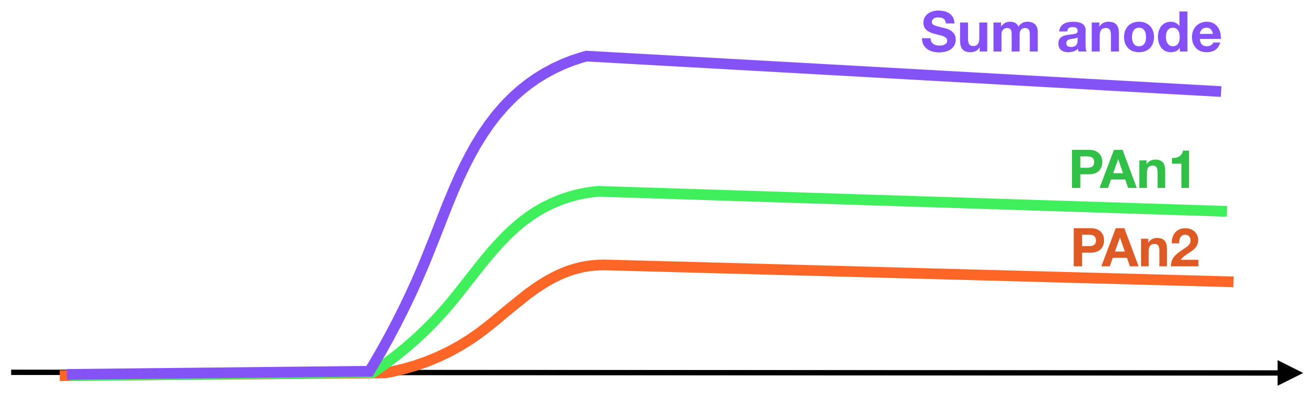
Waveform analysis through most frequently used methods



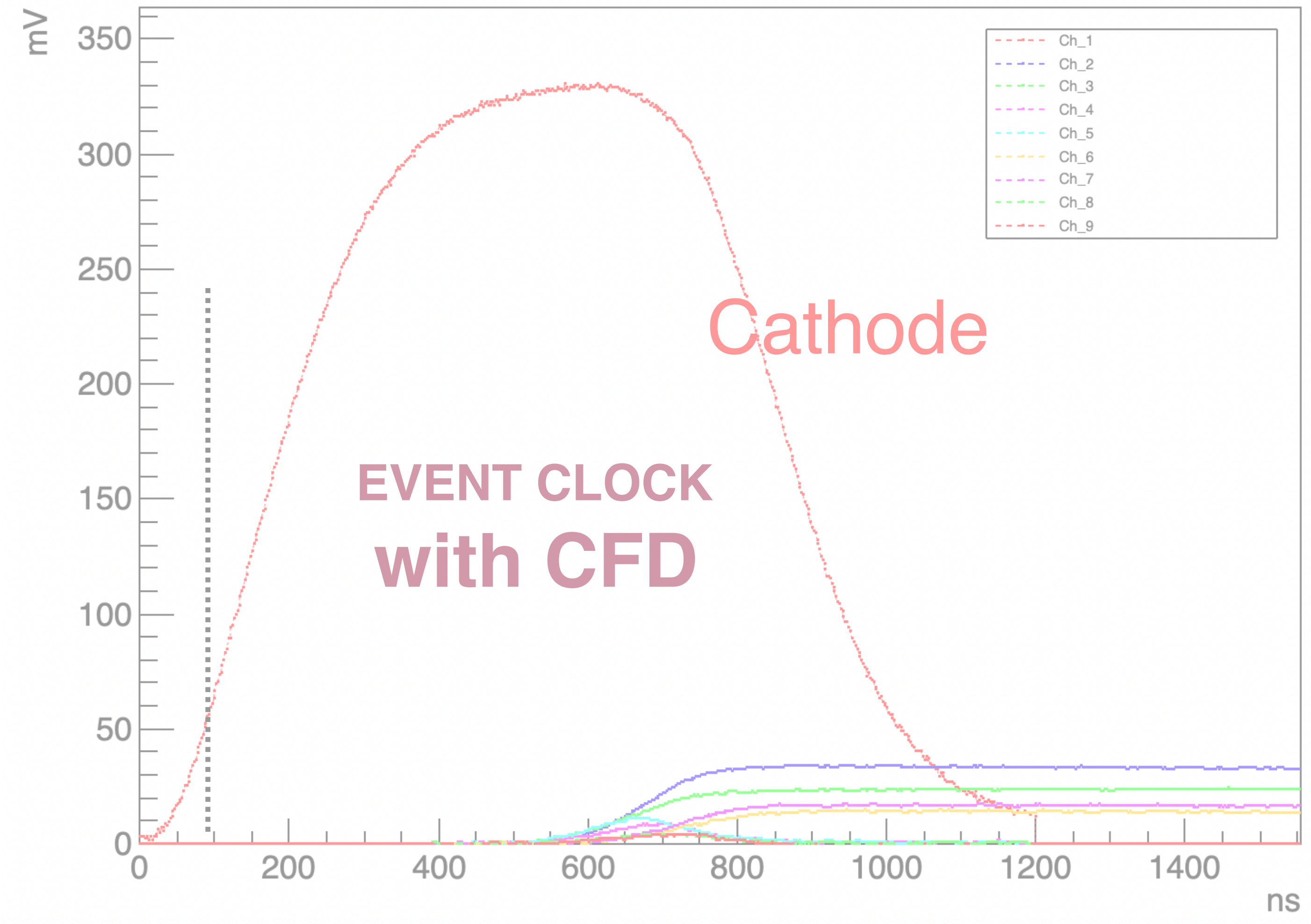


- Perform CFD in all anode signals
- Select first anode signal output for each side as reference. Align and sum samples for both sides

I TIME AND « ENERGY
SUREMENTS

« ENERGY » MEASUREMENTS

TIME MEASUREMENTS



Waveform analysis

Waveform analysis through most frequently used methods

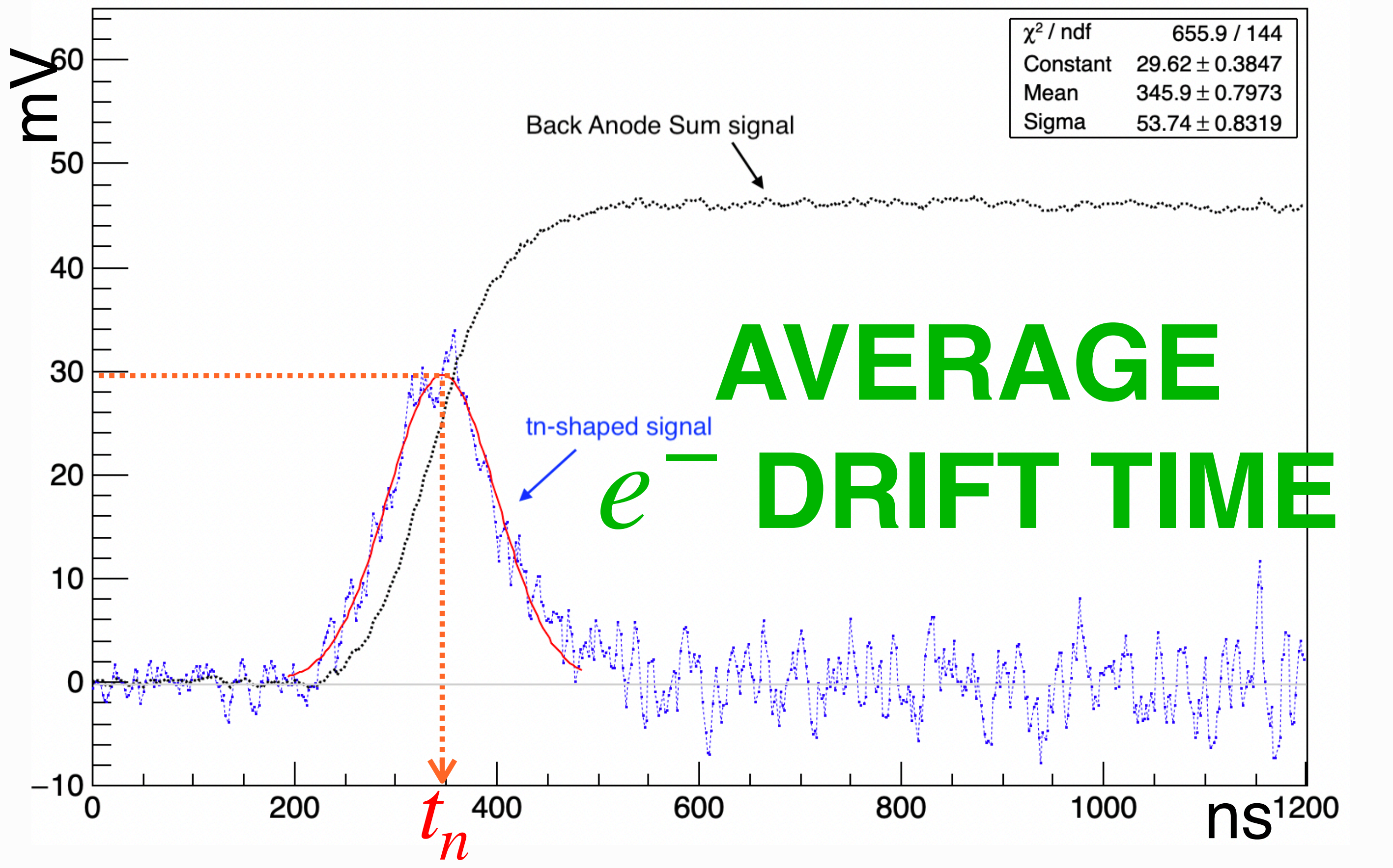
- Moving average algorithm;
- RC filter;
- Signal baseline correction;

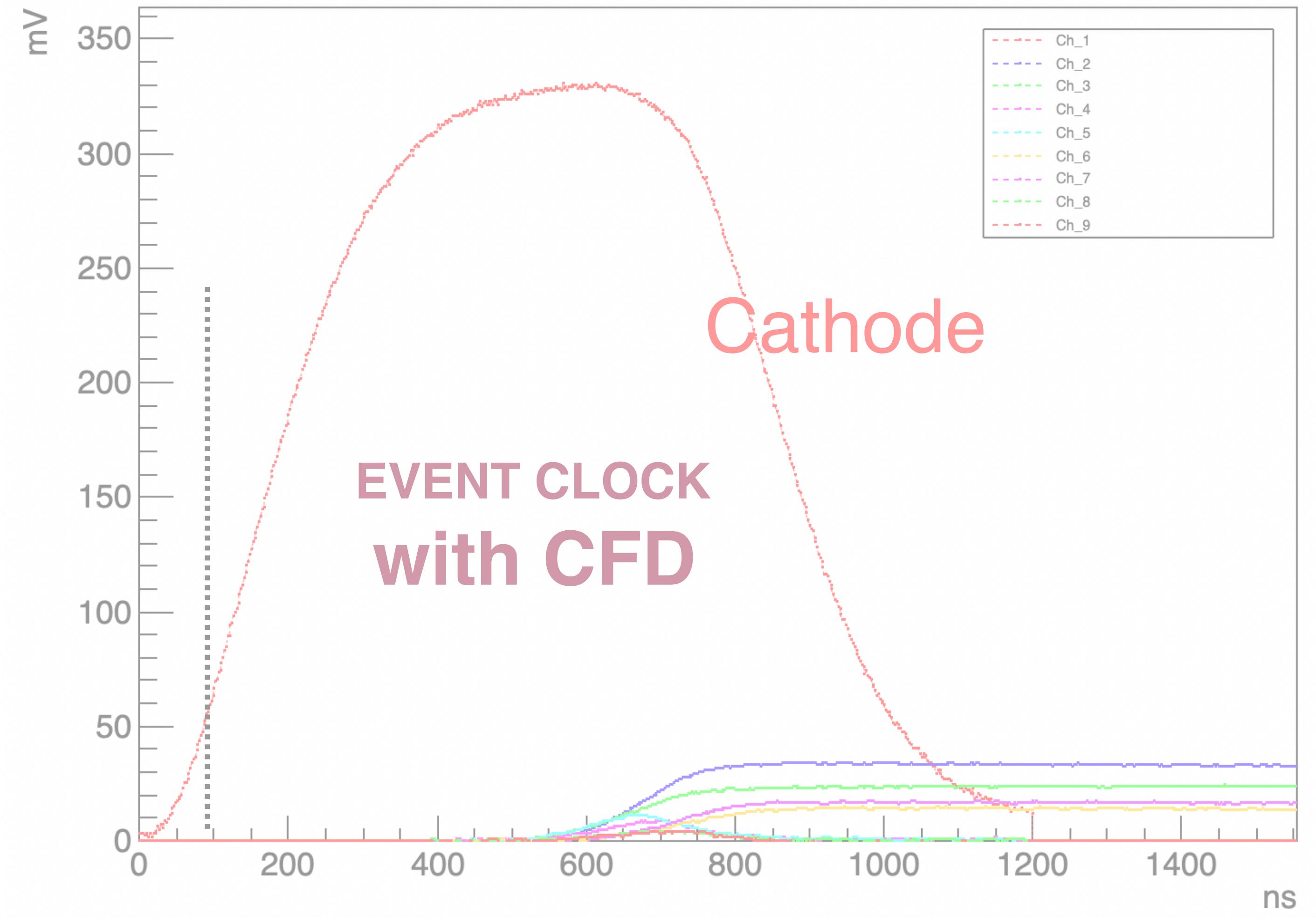
→ **BOTH TIME AND « ENERGY MEASUREMENTS**

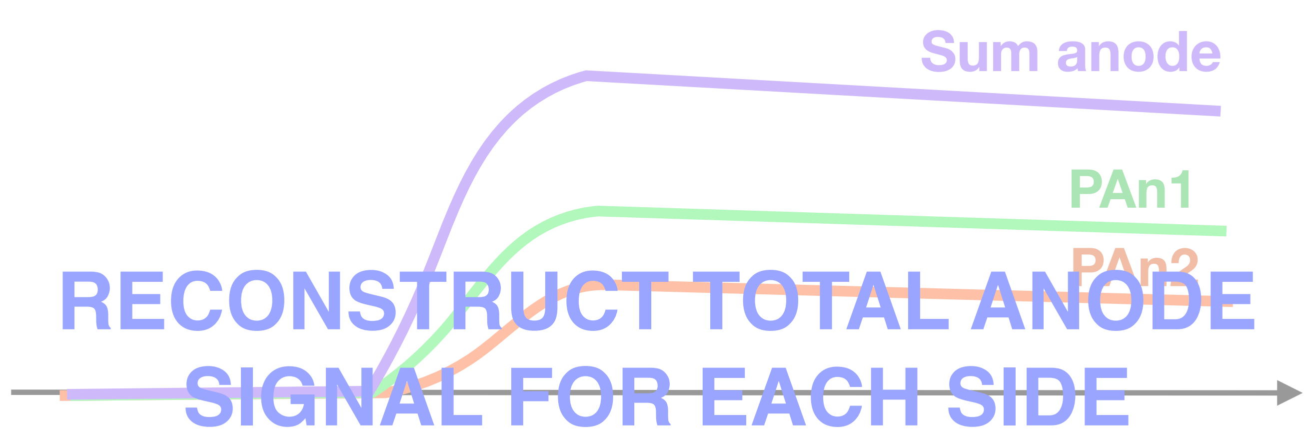
- CR-RC and CR-RC4 shaping filters;
- Trapezoidal shaping filter;
- Signal integration (deposited charge)
- Constant Fraction Discrimination (CFD)

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

e.g. Waveform analysis for average electron drift time calculation:







RECONSTRUCT TOTAL ANODE SIGNAL FOR EACH SIDE

- Perform CFD in all anode signals
- Select first anode signal output for each side as reference. Align and sum samples for both sides

Waveform analysis

Waveform analysis through most frequently used methods

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

→ **BOTH TIME AND « ENERGY MEASUREMENTS**

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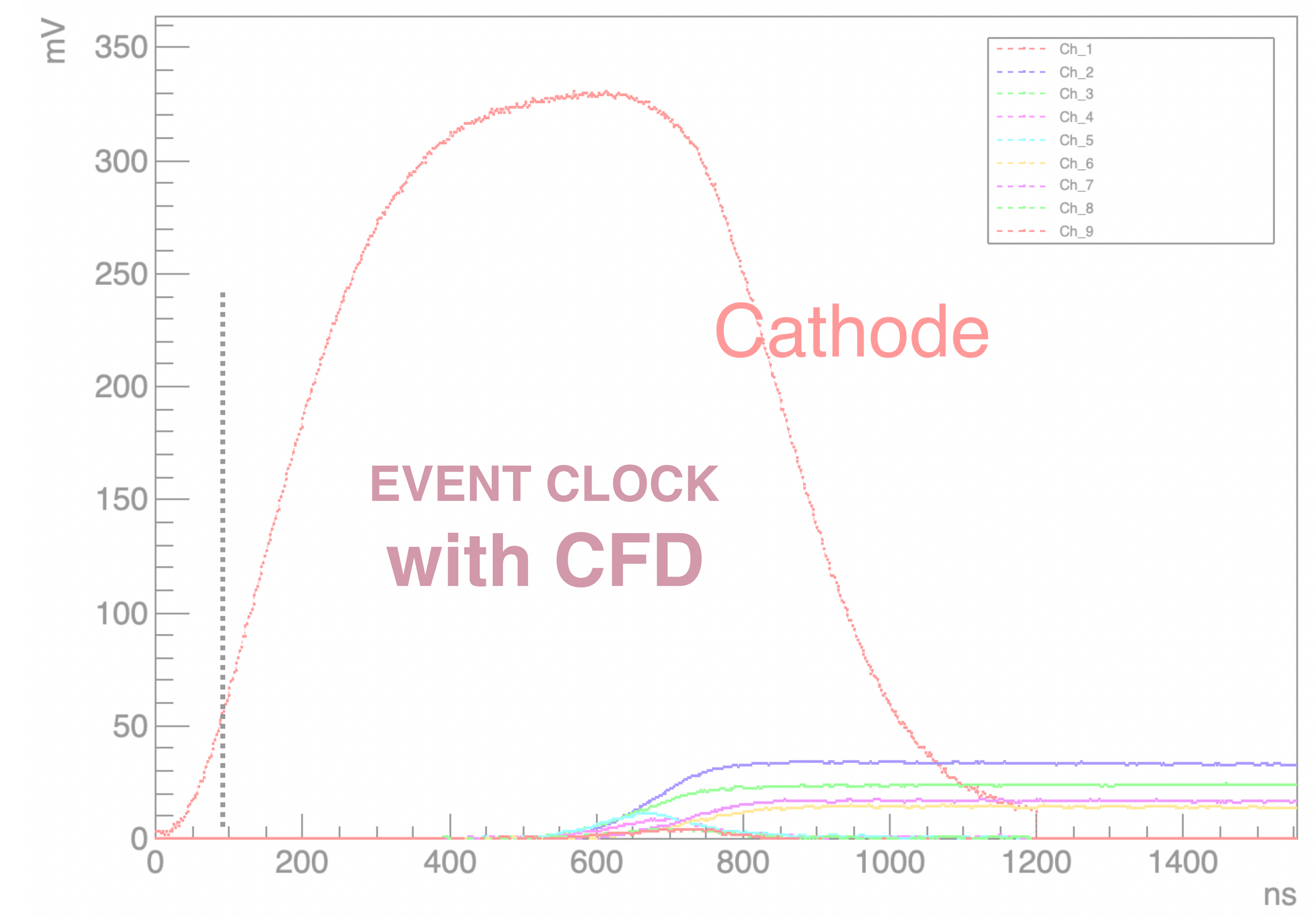
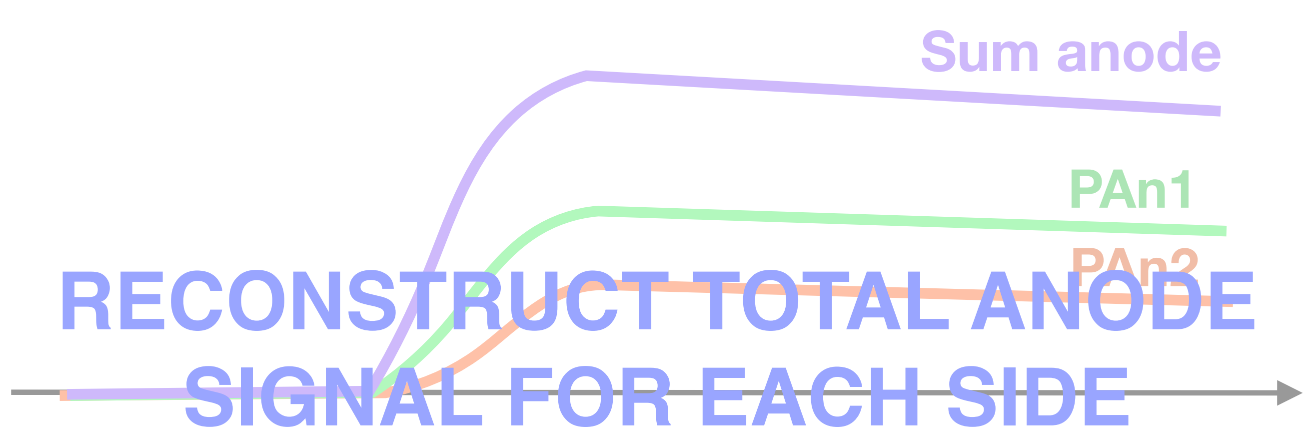
→ **« ENERGY » MEASUREMENTS**

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





- Perform CFD in all anode signals
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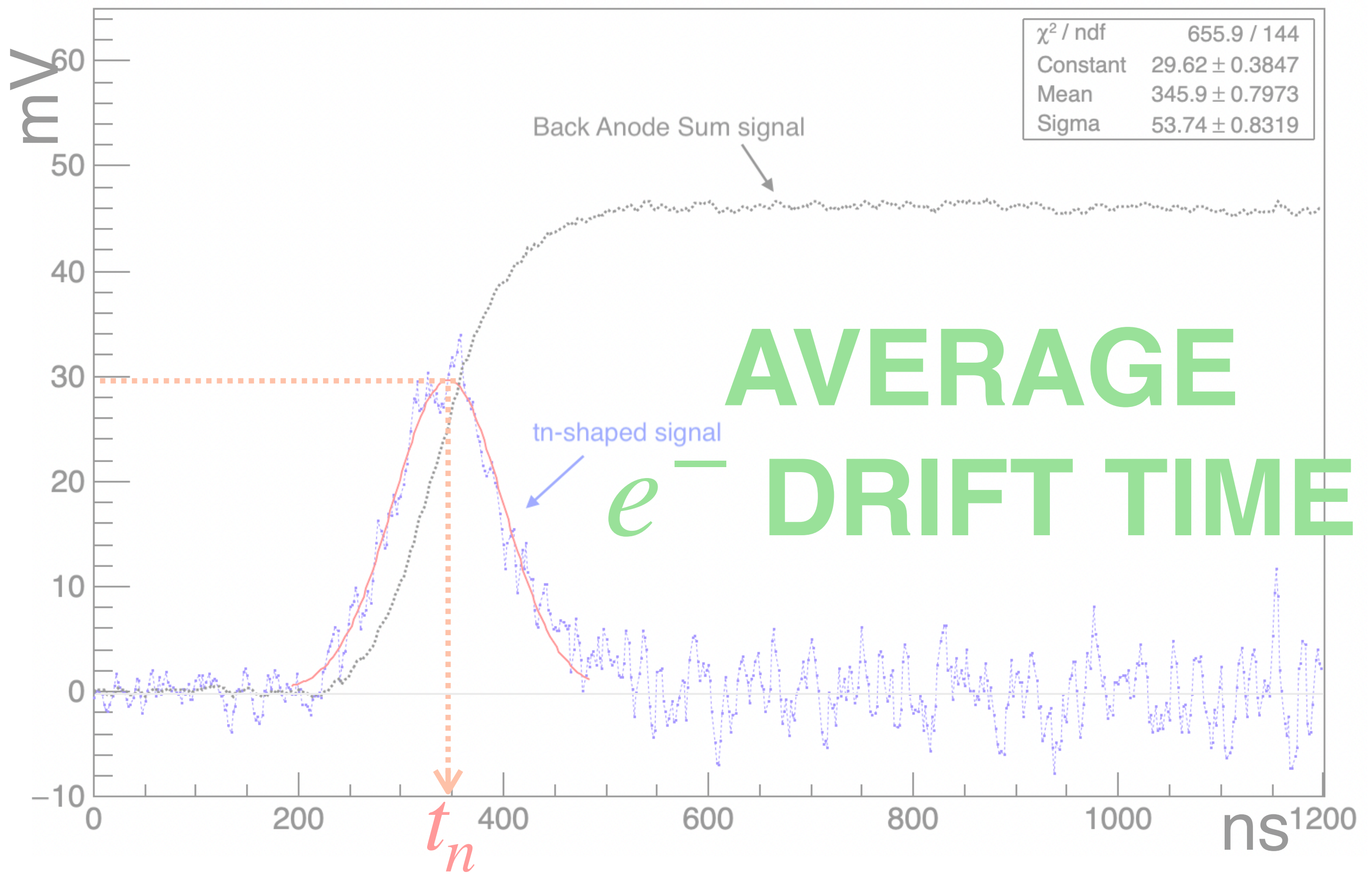
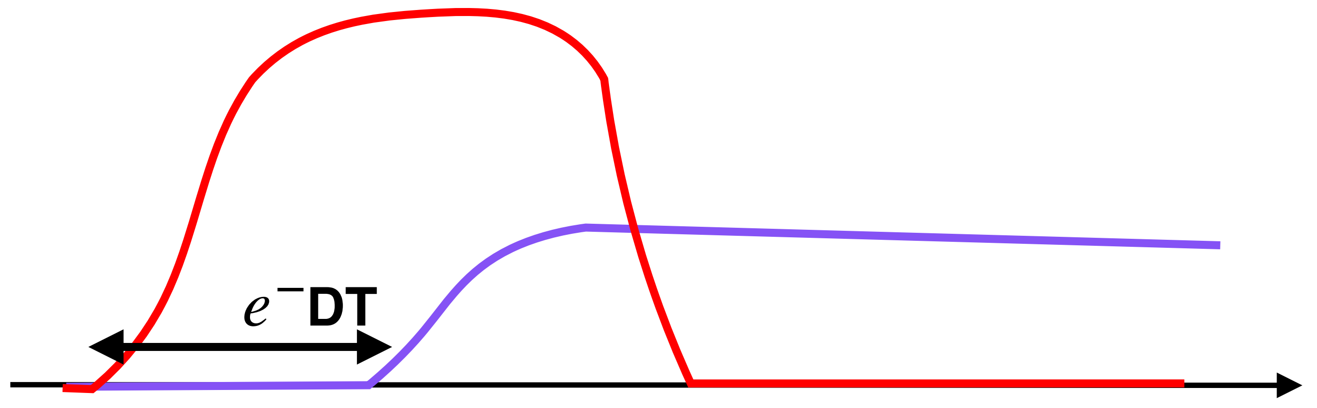
e.g. Waveform analysis for average electron drift time calculation:





- e^- drift time is the time difference between cathode and sum anode calculated timestamps (with CFD)
- Apply shaping filters to measure « energy » for all channels