Pushing Rare Event Search to the Limit with Machine Learning Algorithms

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CONFERENCE ON SCIENCE AT THE SANFORD UNDERGROUND RESEARCH FACILITY
South Dakota Mines campus, May 14-16, 2024

UC San Diego
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UC San Diego PHYSICS

Generated Event vs. Naturally Occurring Rare Event

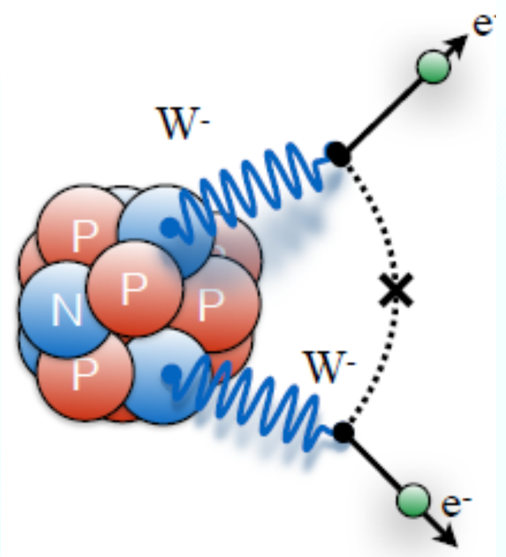
Physics Target | Detector

High-Energy Particle Beam
600 million collisions per second

ATLAS EXPERIMENT, CMS

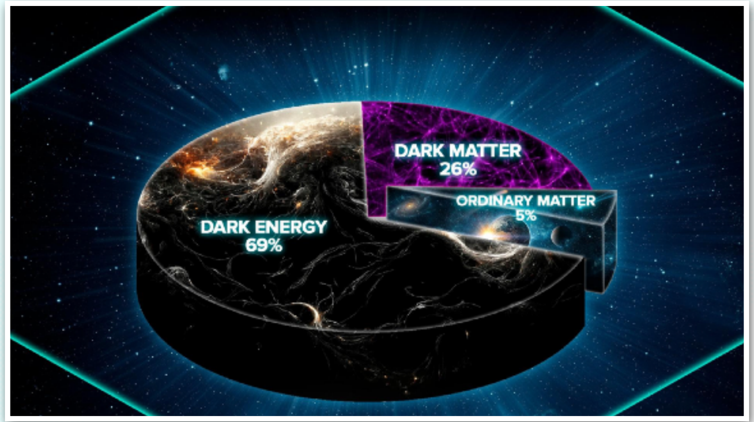
Neutrino Beam
Billions of neutrinos per second

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT, NOvA, MicroBooNE



Neutrinoless Double-Beta Decay (NLDBD)
Hypothetical radioactive decay

CUPID, LEGEND, nEXO, next, KamLAND-Zen, SNO+



Dark Matter (DM)
Constitute ~85% of mass in our universe

LZ, DARWIN, DARK MATTER RADIO, ABRACADABRA

Physics in Rare Event Search

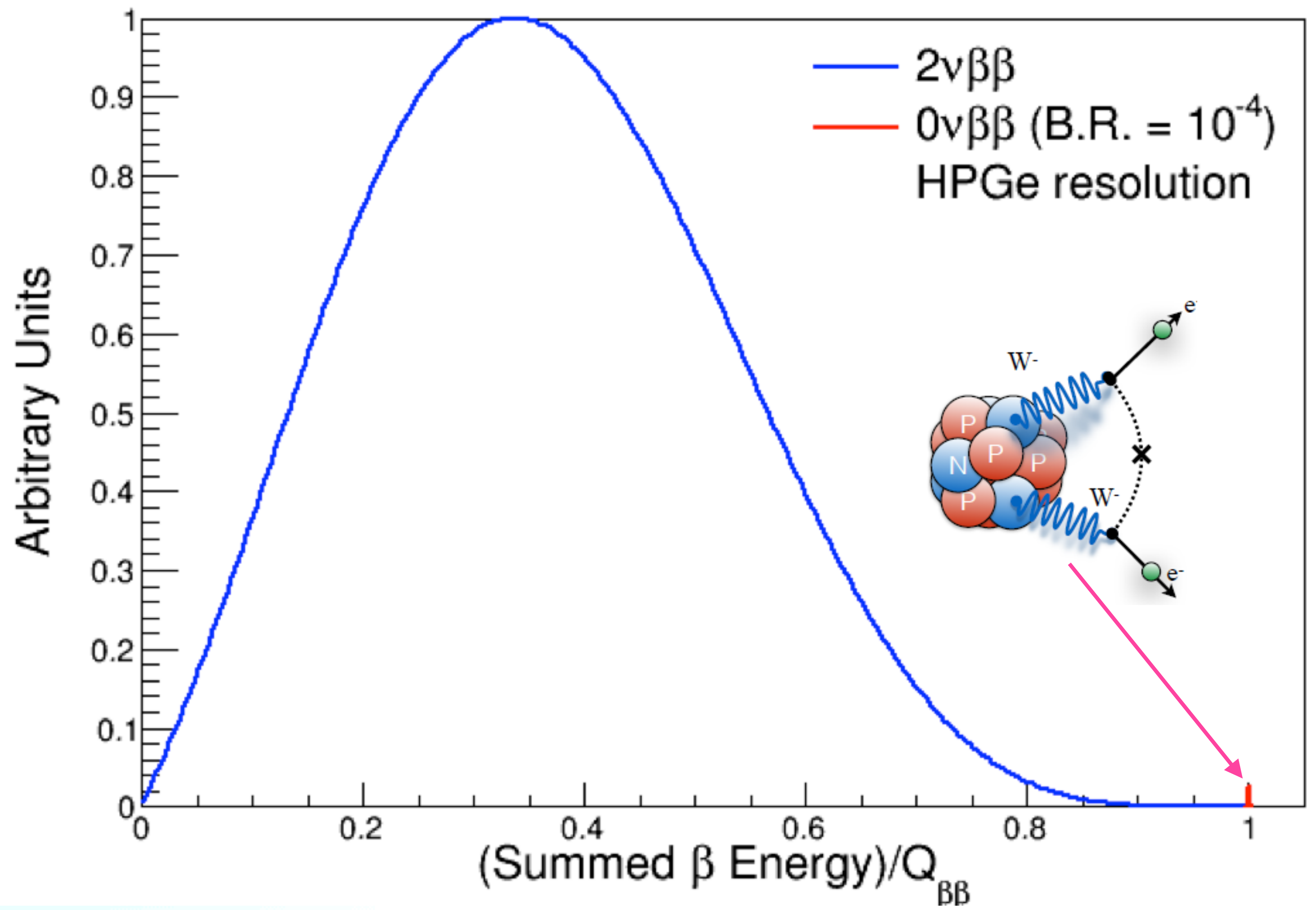
Neutrinoless Double-Beta Decay (NLDBD)

ΔL = 2 lepton number violation process

Prove that neutrinos are **Majorana particle**

Explain the **matter-antimatter asymmetry** in our universe

Has not been observed at $T_{\frac{1}{2}} > 10^{26} yrs$



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Strong astrophysical evidence, no observation on earth

We don't know which particle makes up dark matter:

- Heavy, particle-like DM candidate: **WIMP**
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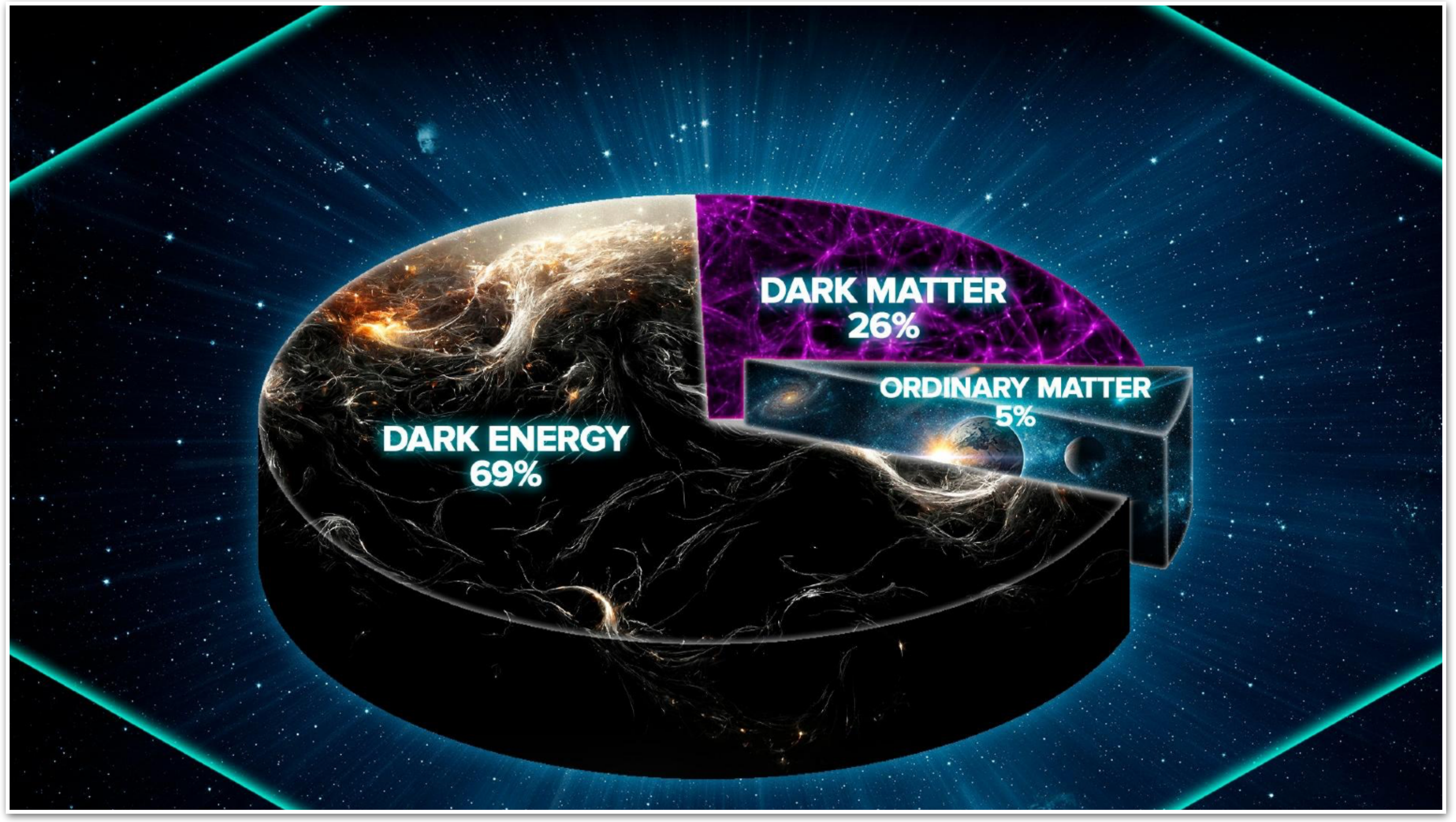
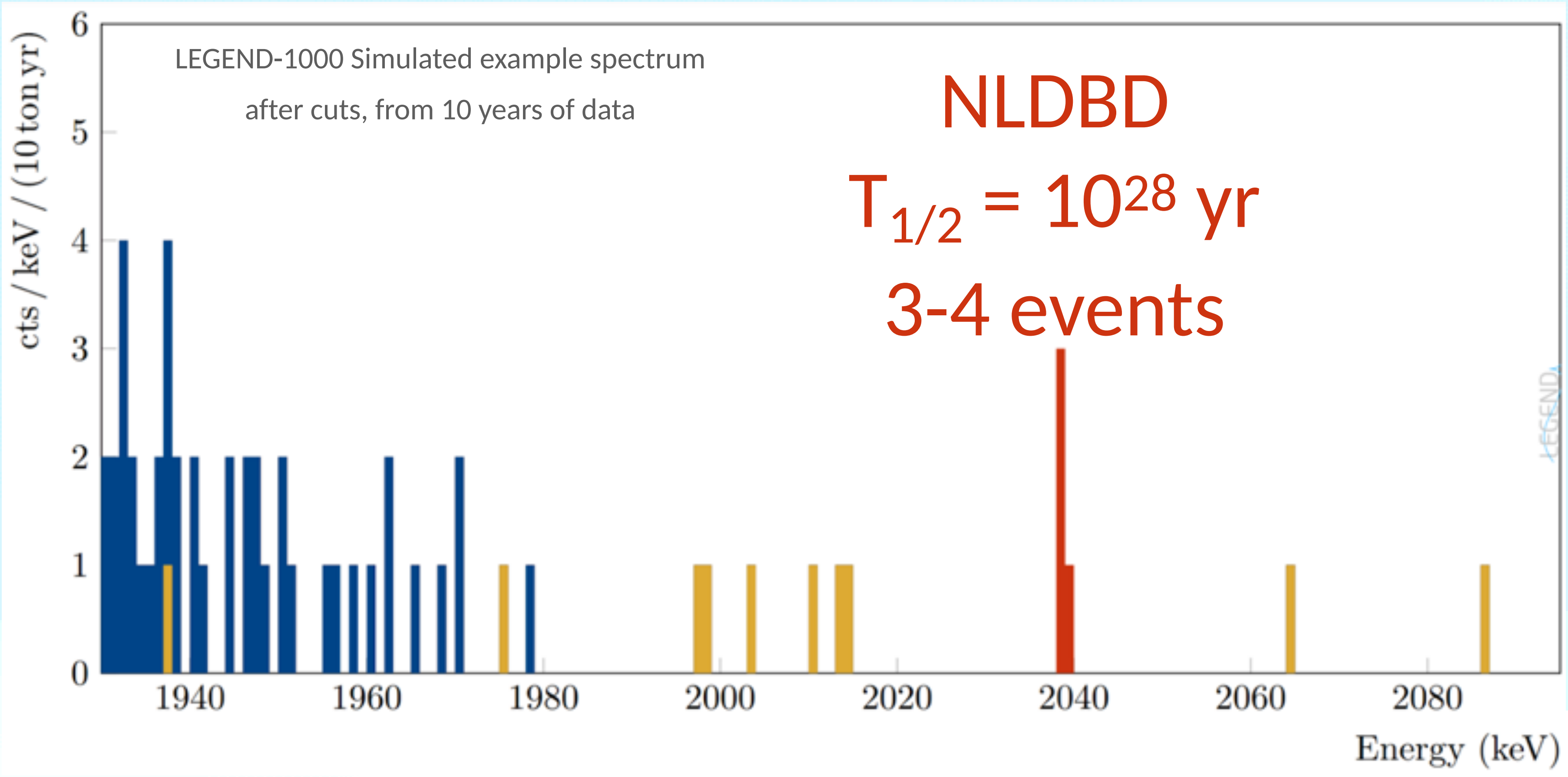
WIMP has not been observed at $\sigma < 10^{-47} cm^2$



Why hasn't we observed anything in Rare Event Search?

It is extremely rare! Using NLDBD as an example…

- We have not seen NLDBD at half life of $T_{\frac{1}{2}} > 10^{26} yrs$
- Next-generation experiments typically aims at $T_{\frac{1}{2}} > 10^{28} yrs$
- Correspond to **3-4 event** after **10 years** of data taking



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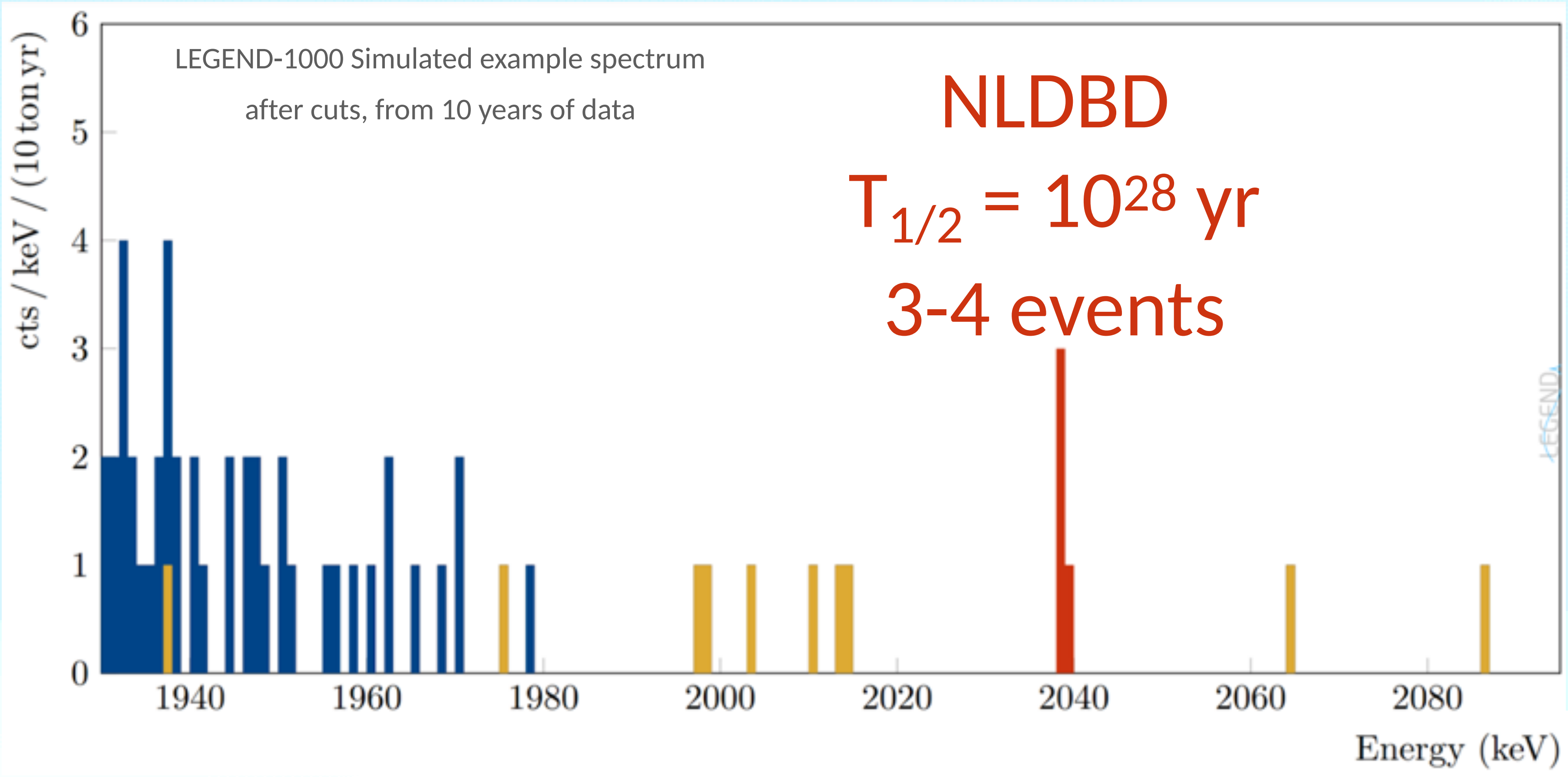
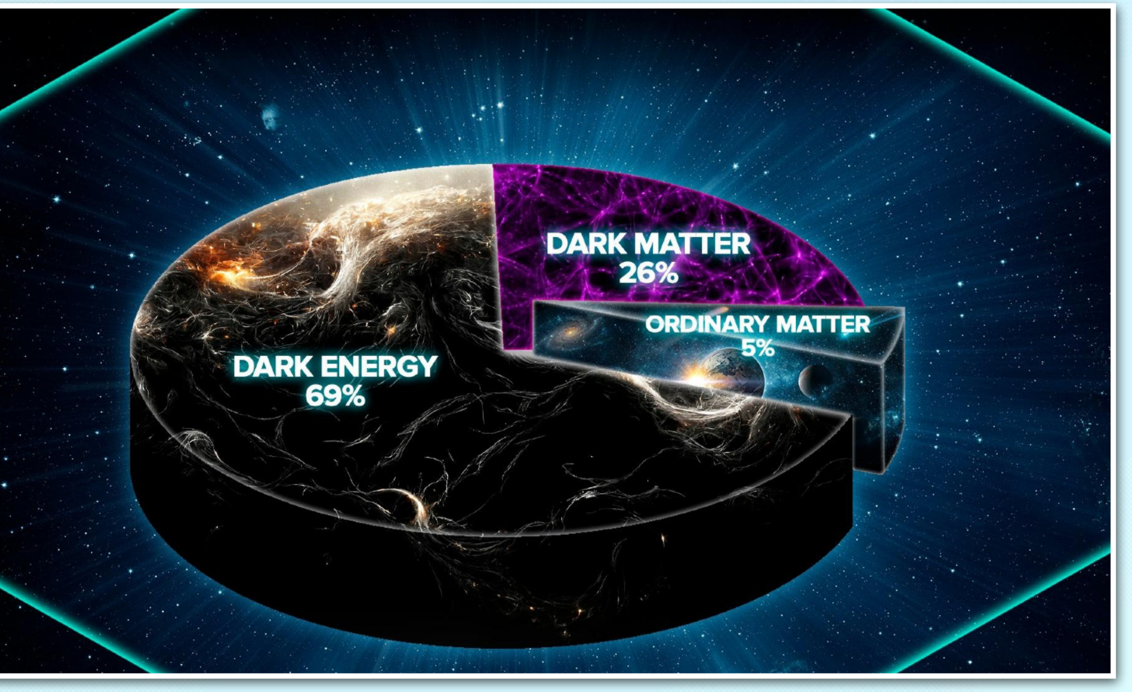
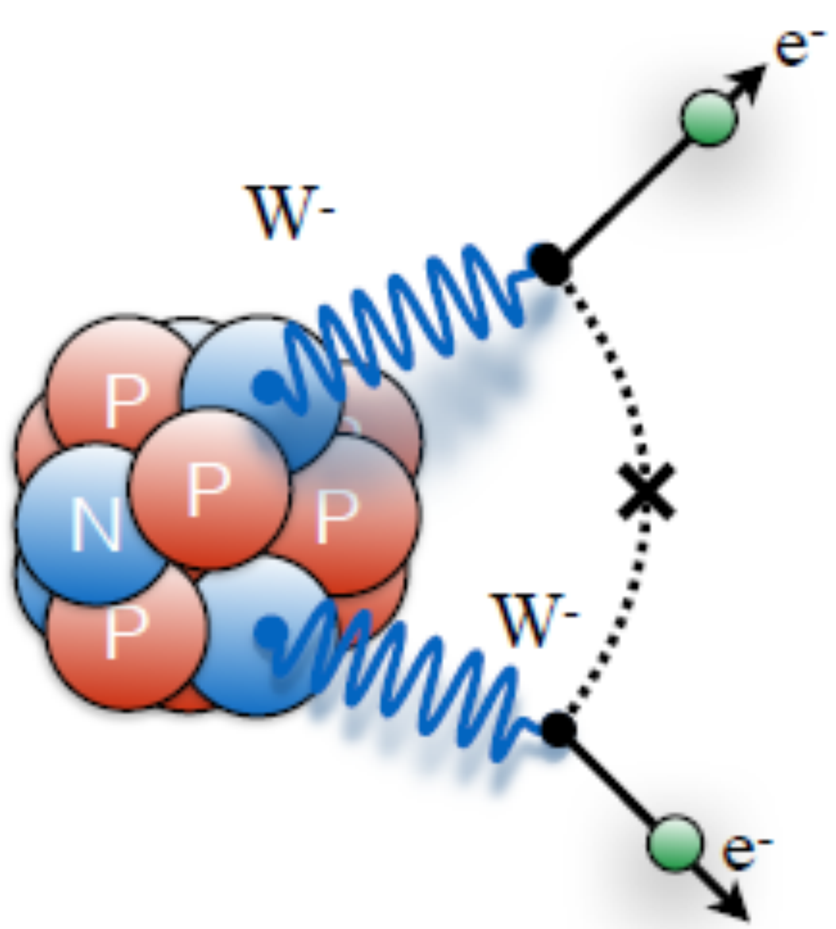


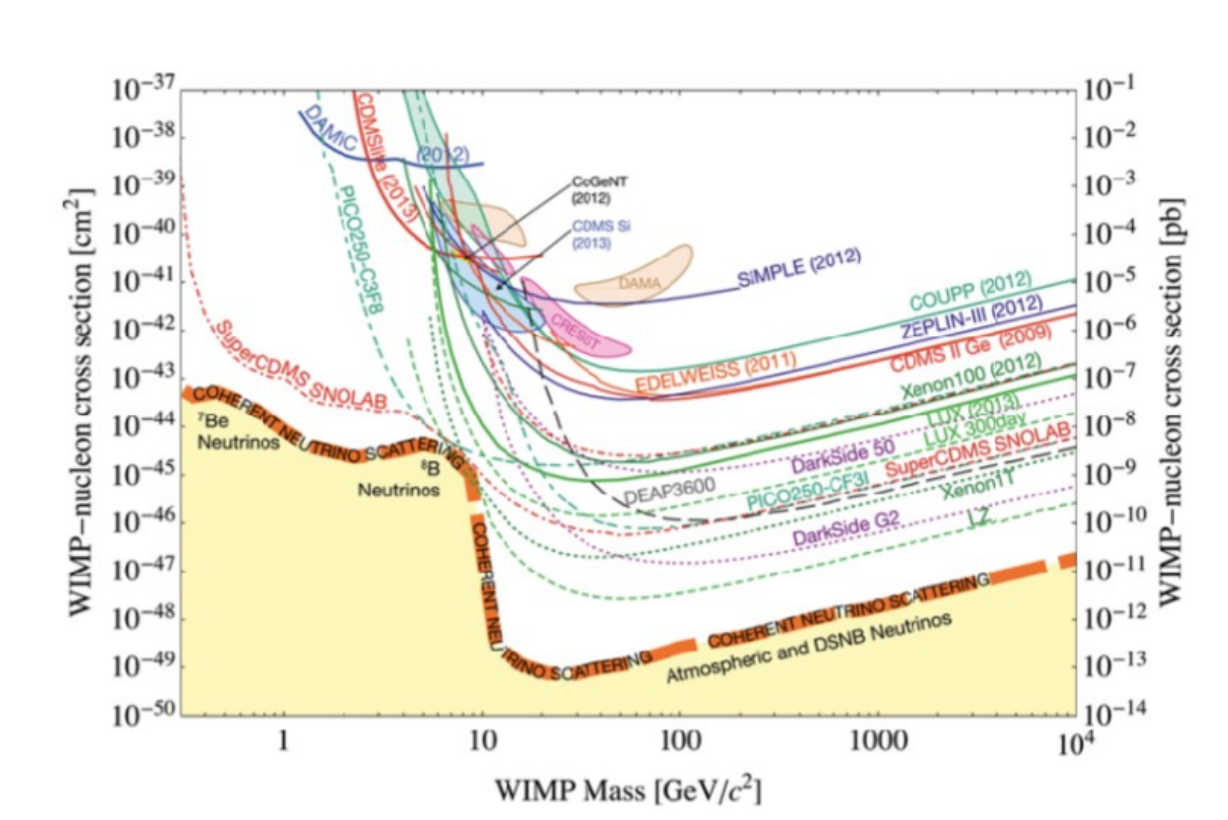
Search for needle in a haystack

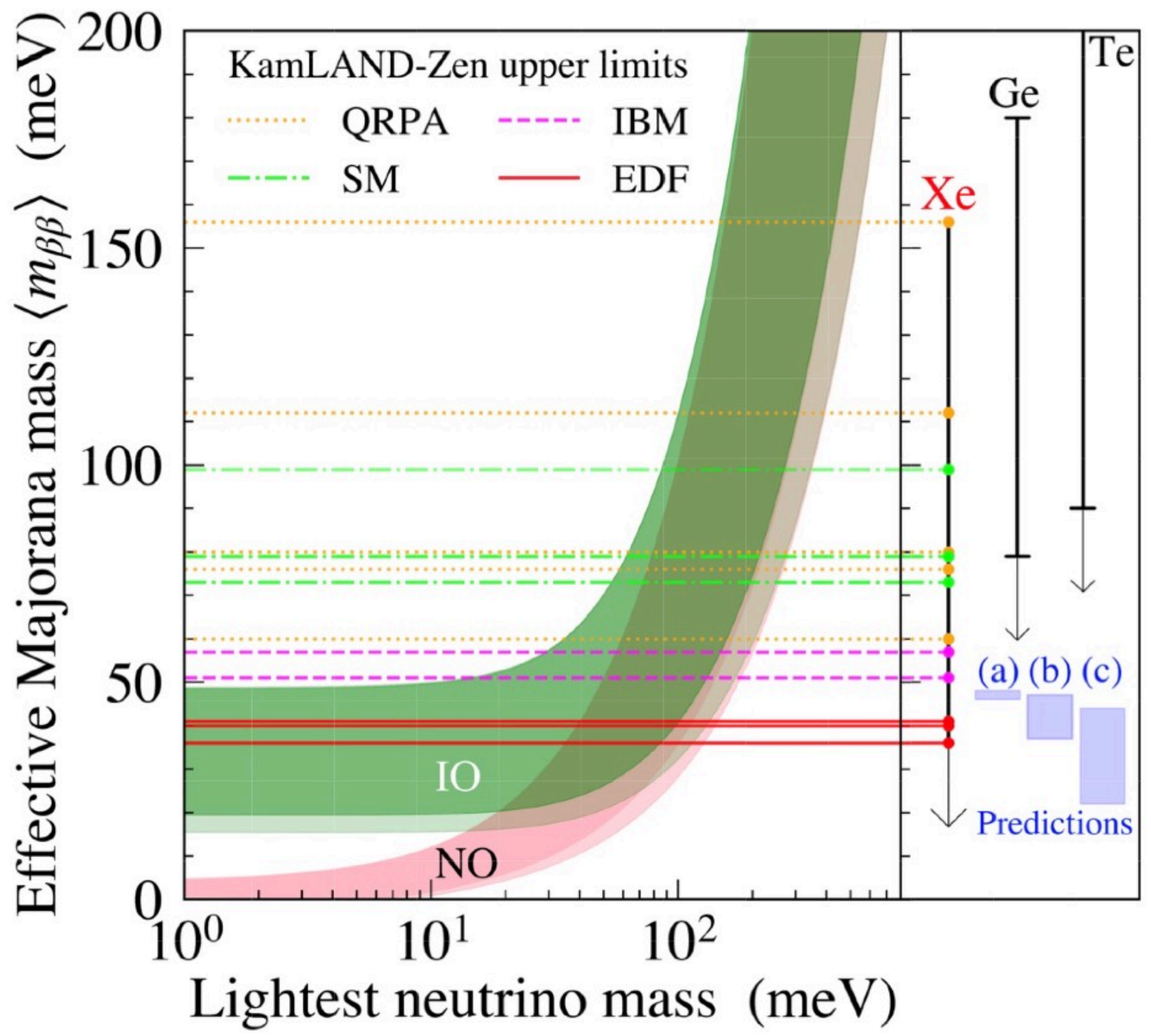
- **1 event** every **2.5-3.3 year**
- need ultra-sensitive **radiation detector** to capture every event
- As our radiation detector gets more sensitive, we inevitably collect lots of **background events**

The Rare Event Search Pipeline









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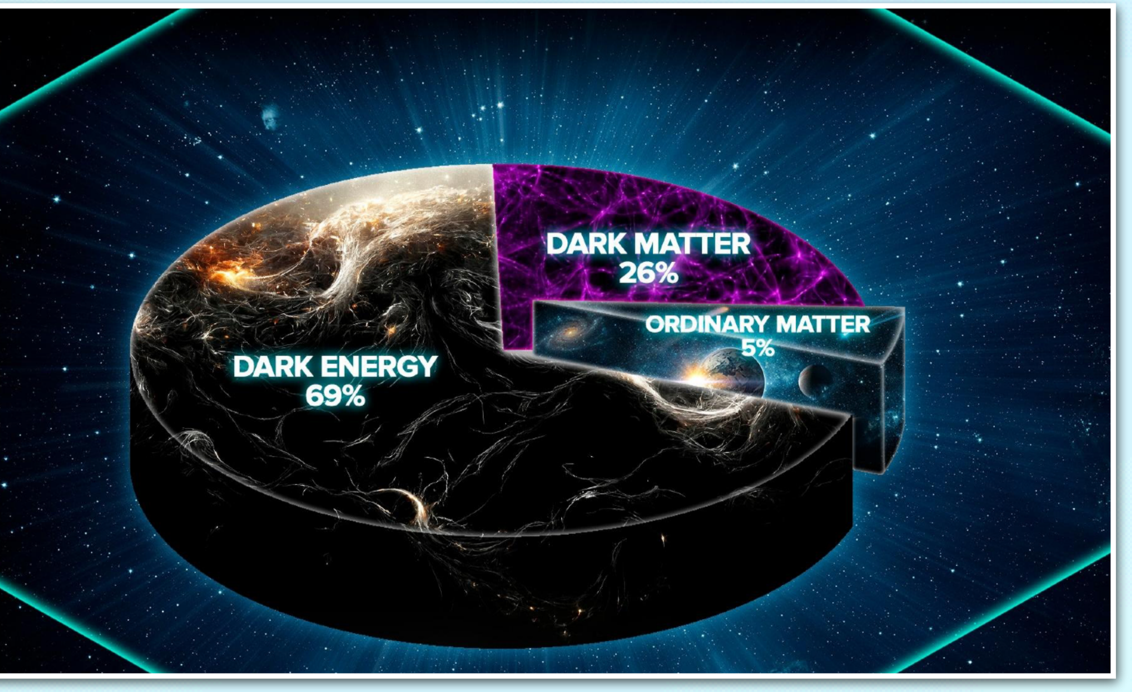
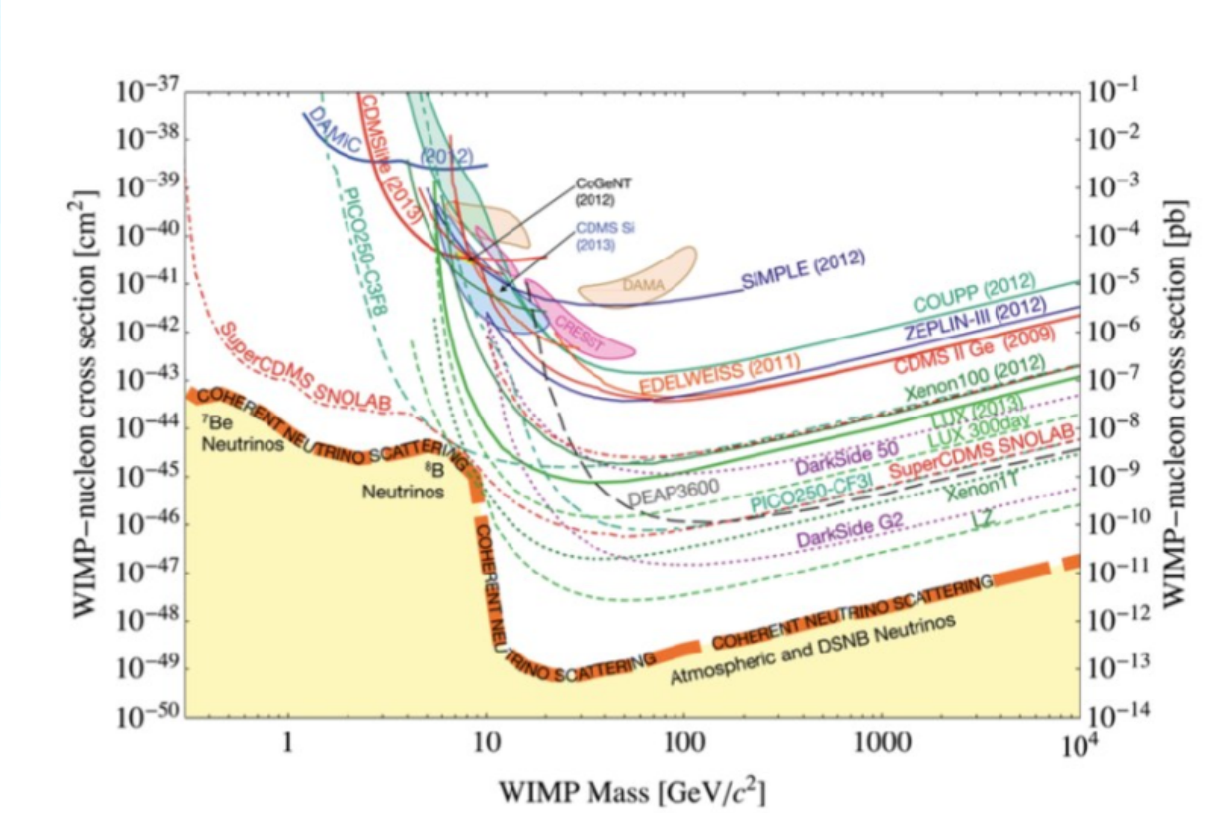
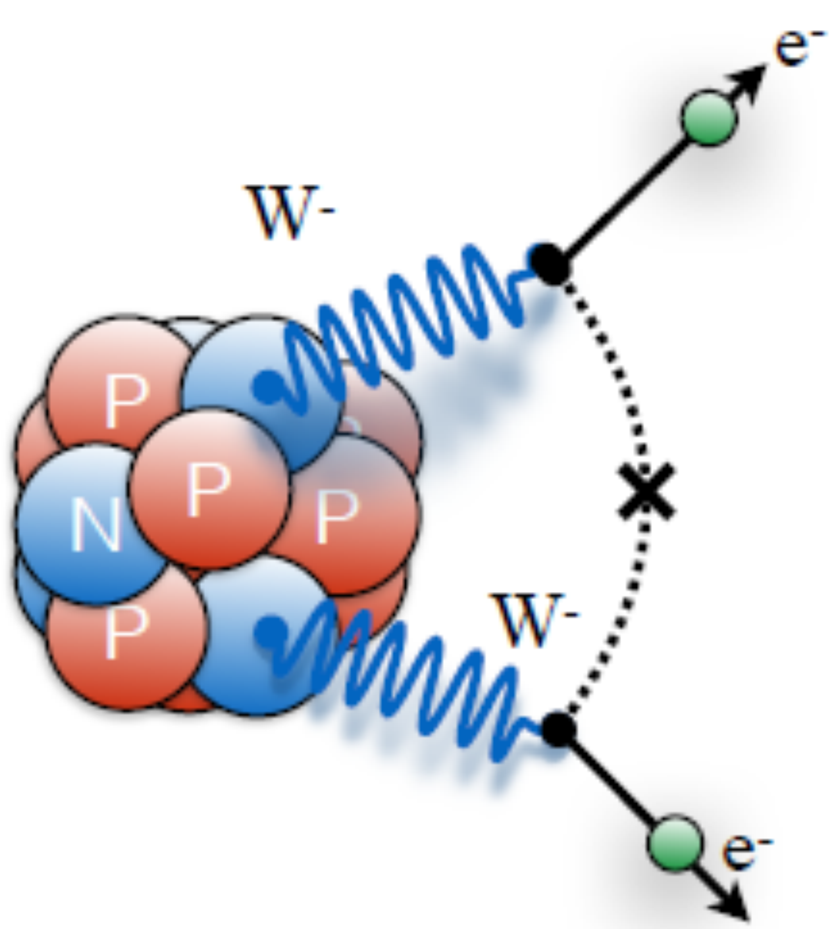
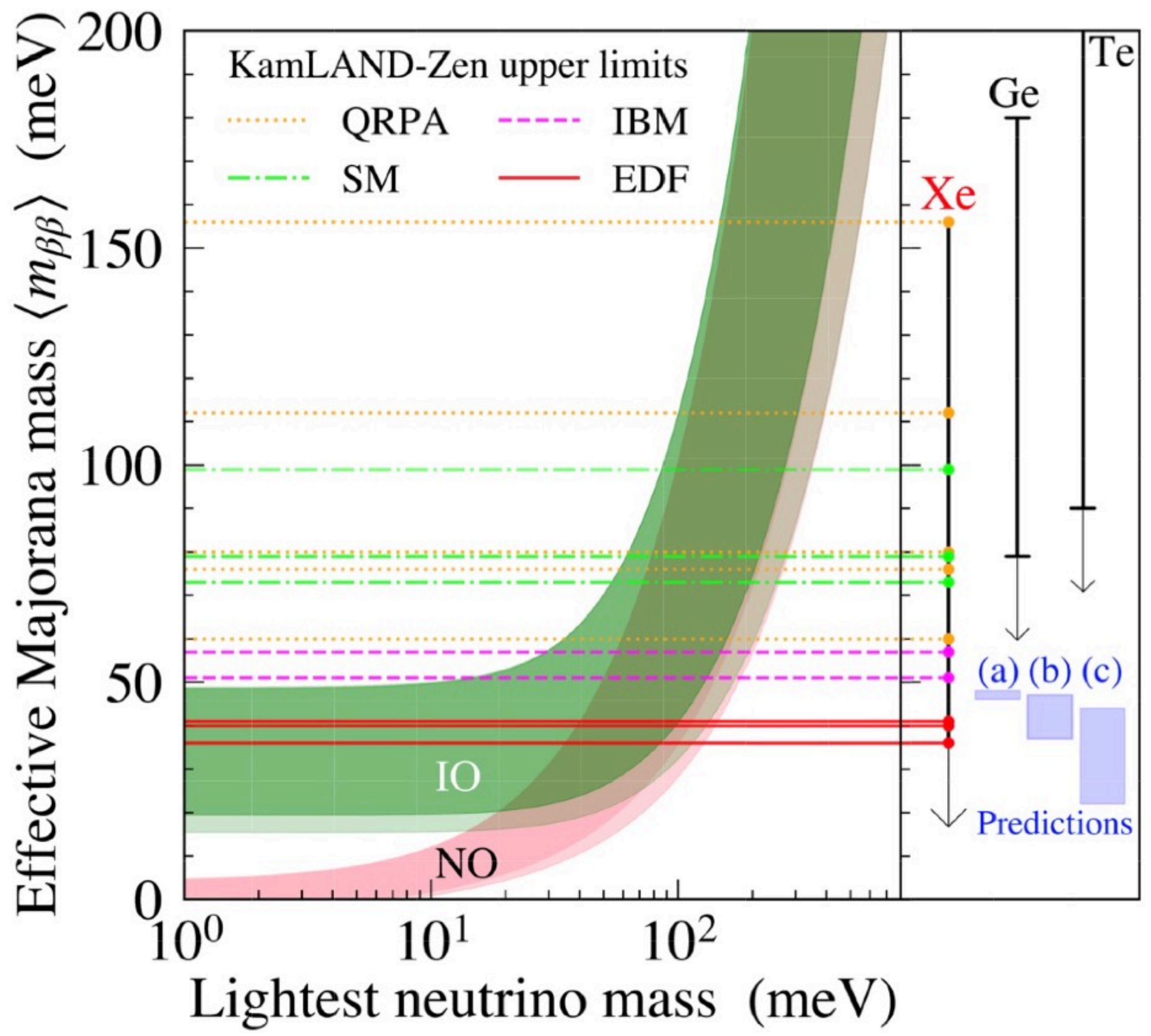


Radiation Detector

The “magnifying glass” that
help finding the needle







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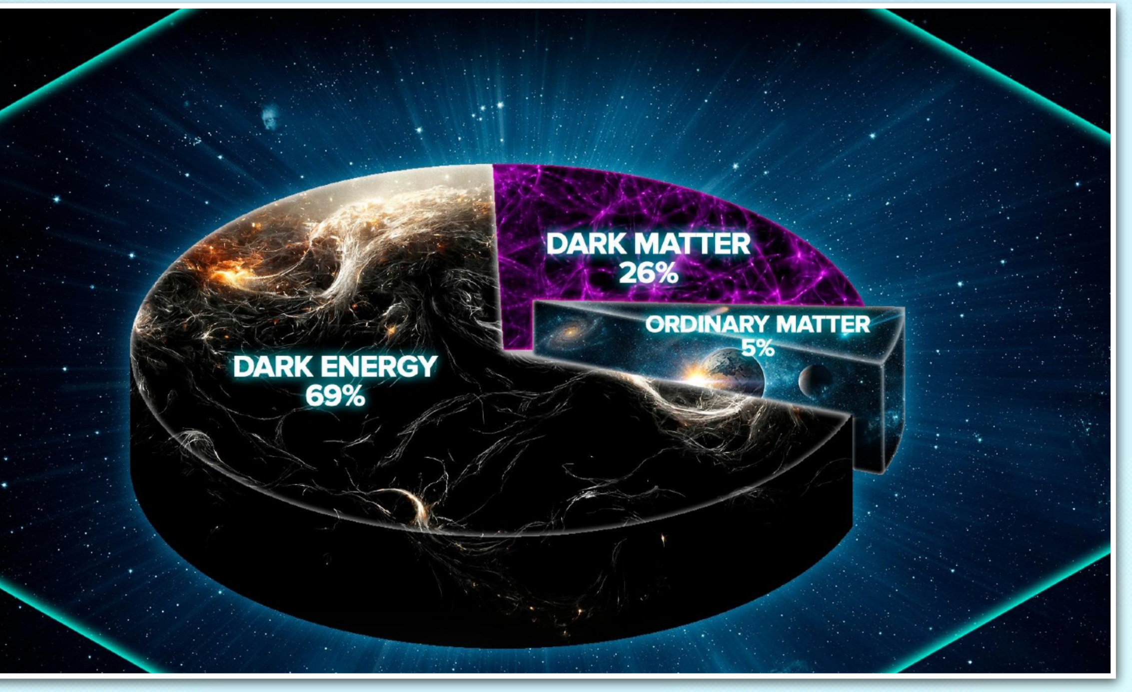
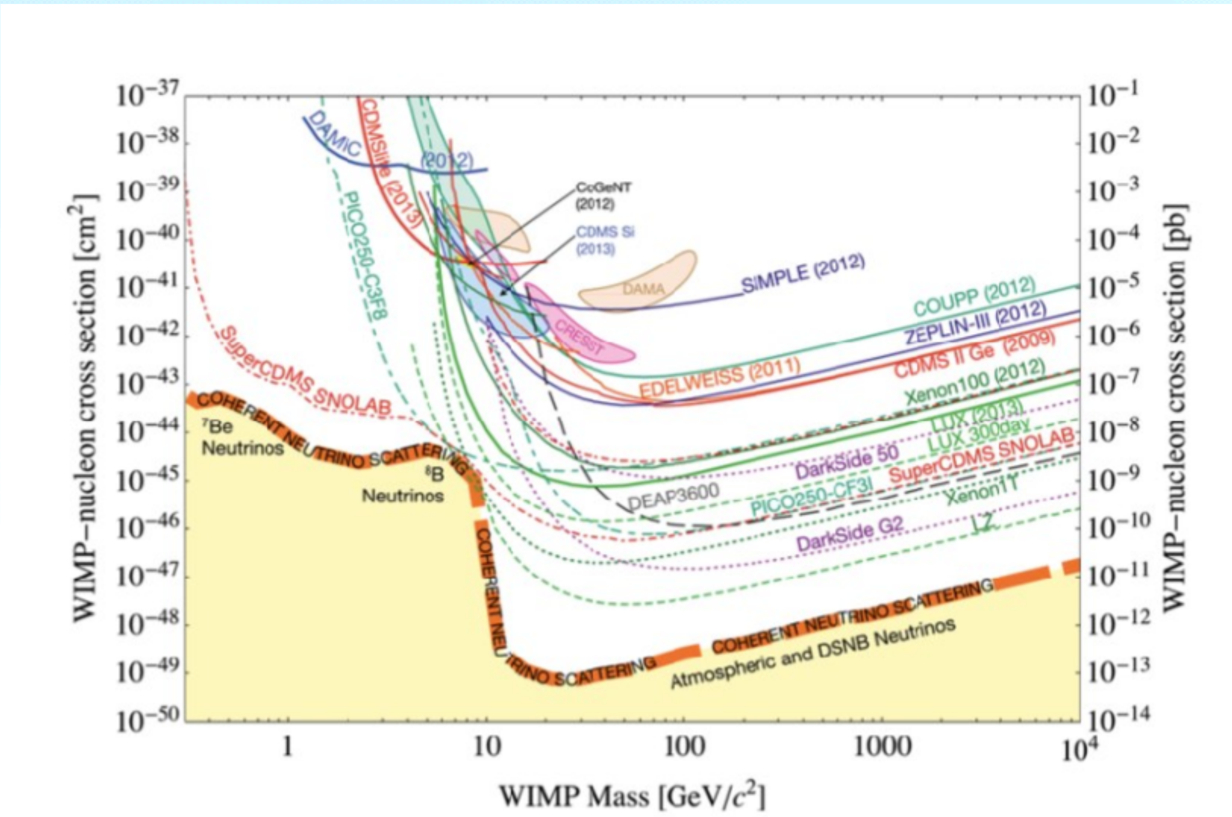


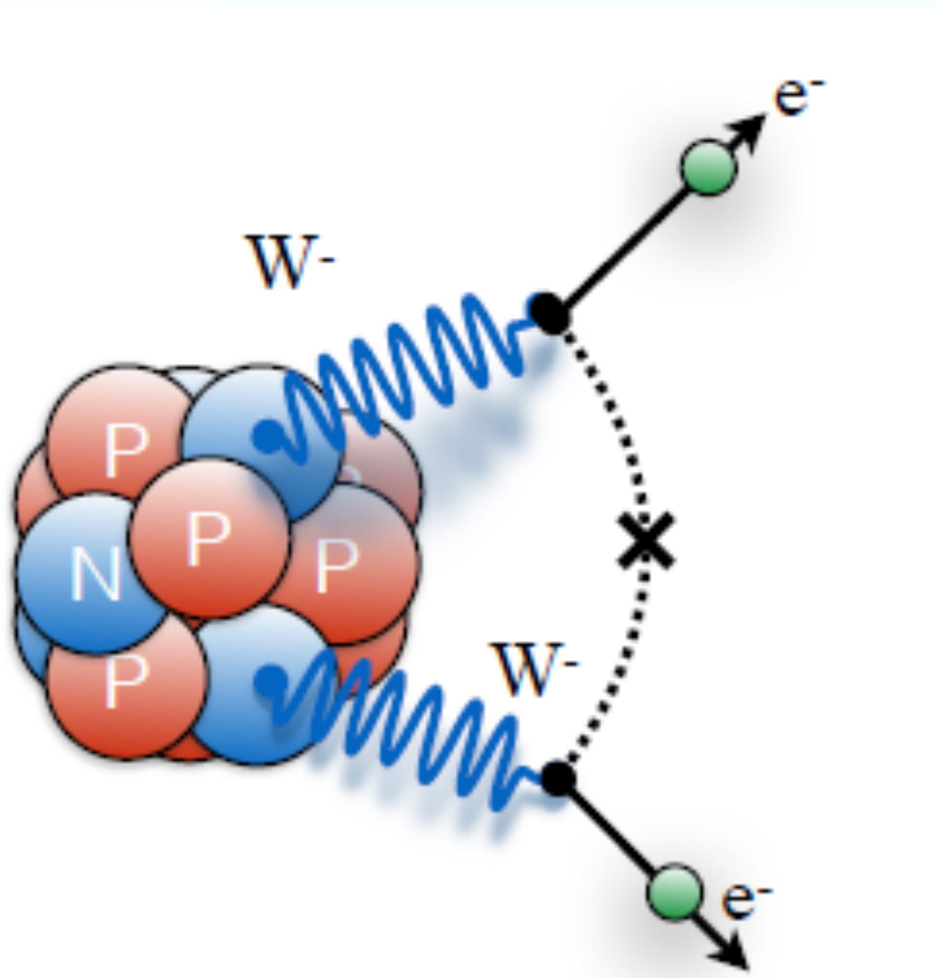
Radiation Detector

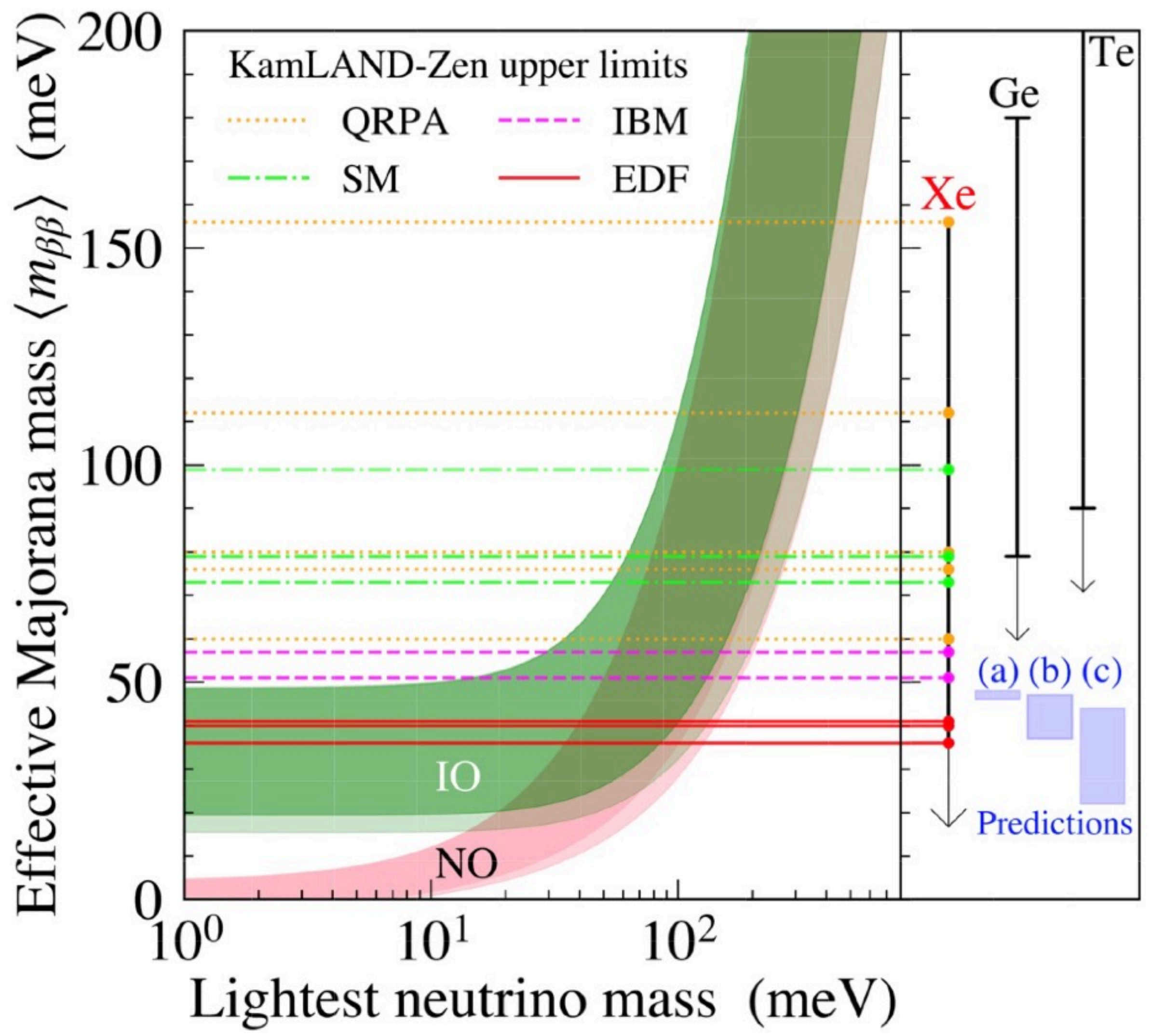
The "magnifying glass" that help finding the needle

AI/ML

The "forklift" that help removing the haystack







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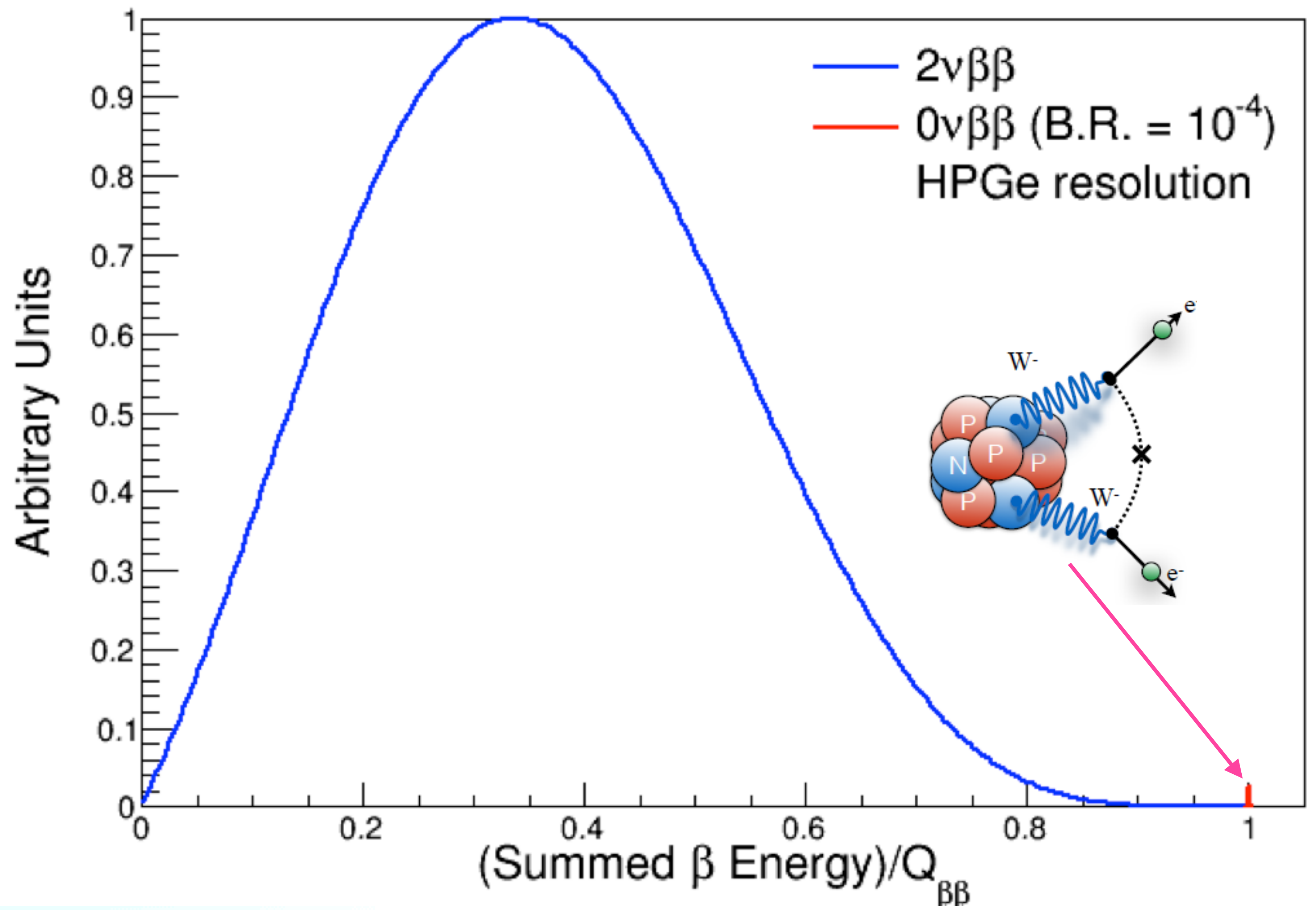

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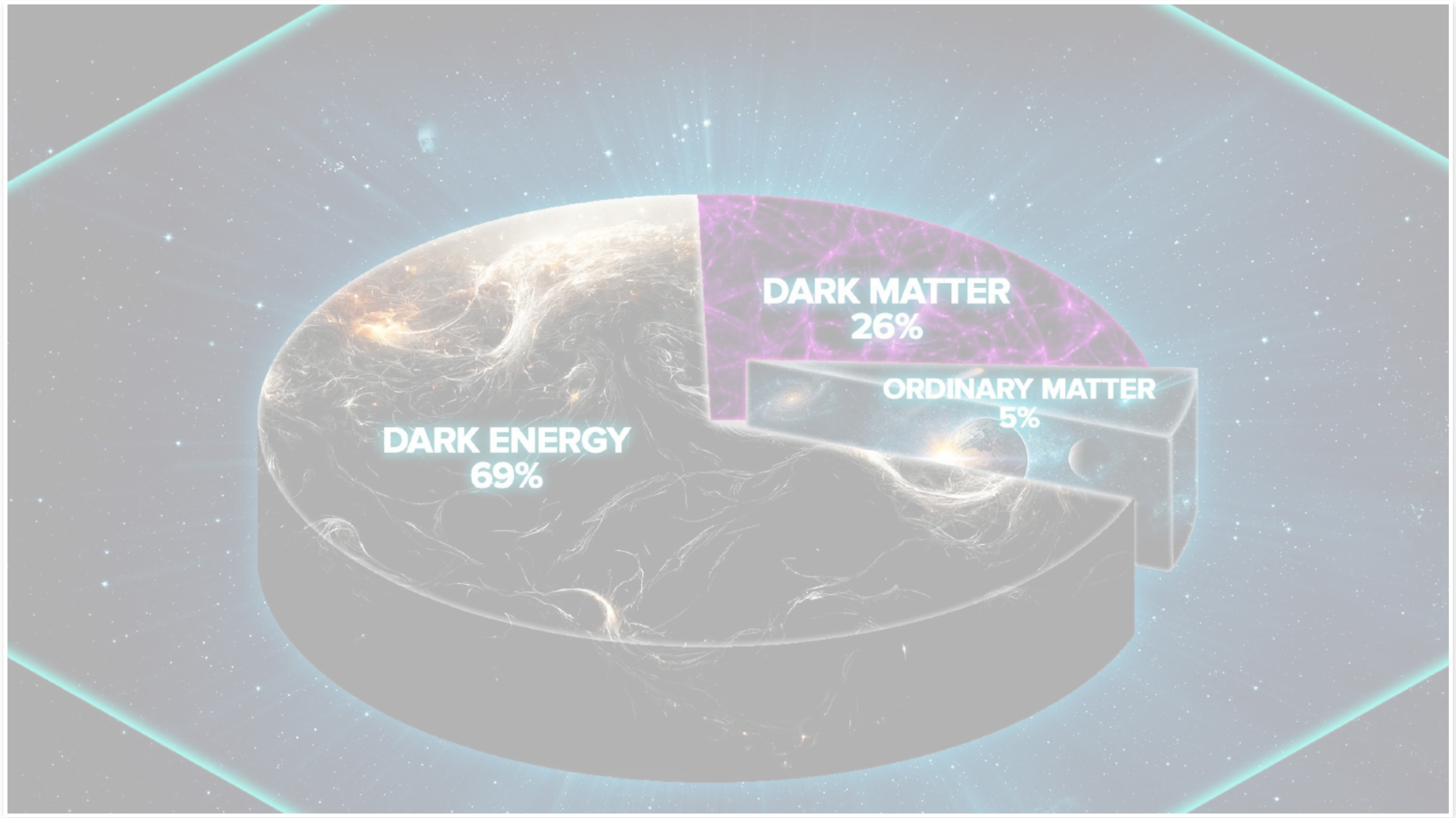
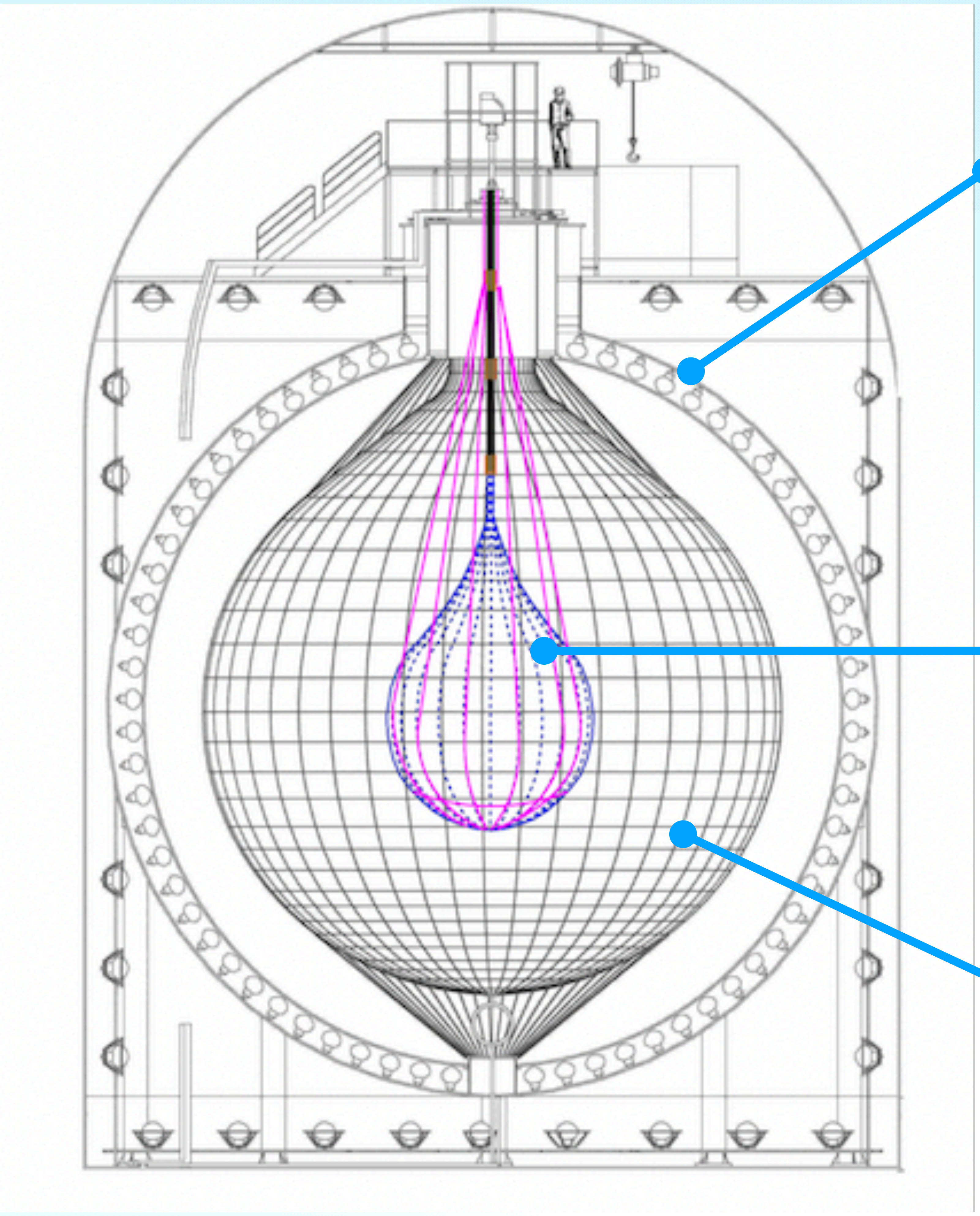
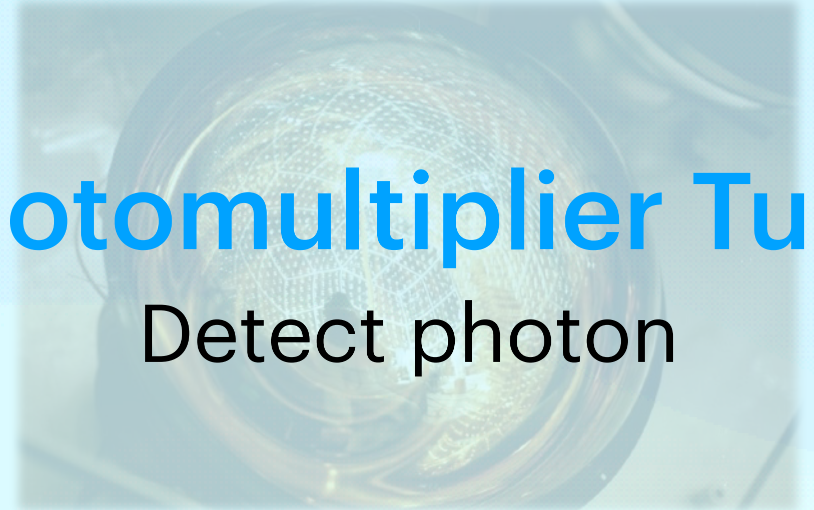


KamLAND-Zen

Monolithic Liquid Scintillator Detector for NLDBD Search





Photomultiplier Tube

Detect photon

Xenon Loading

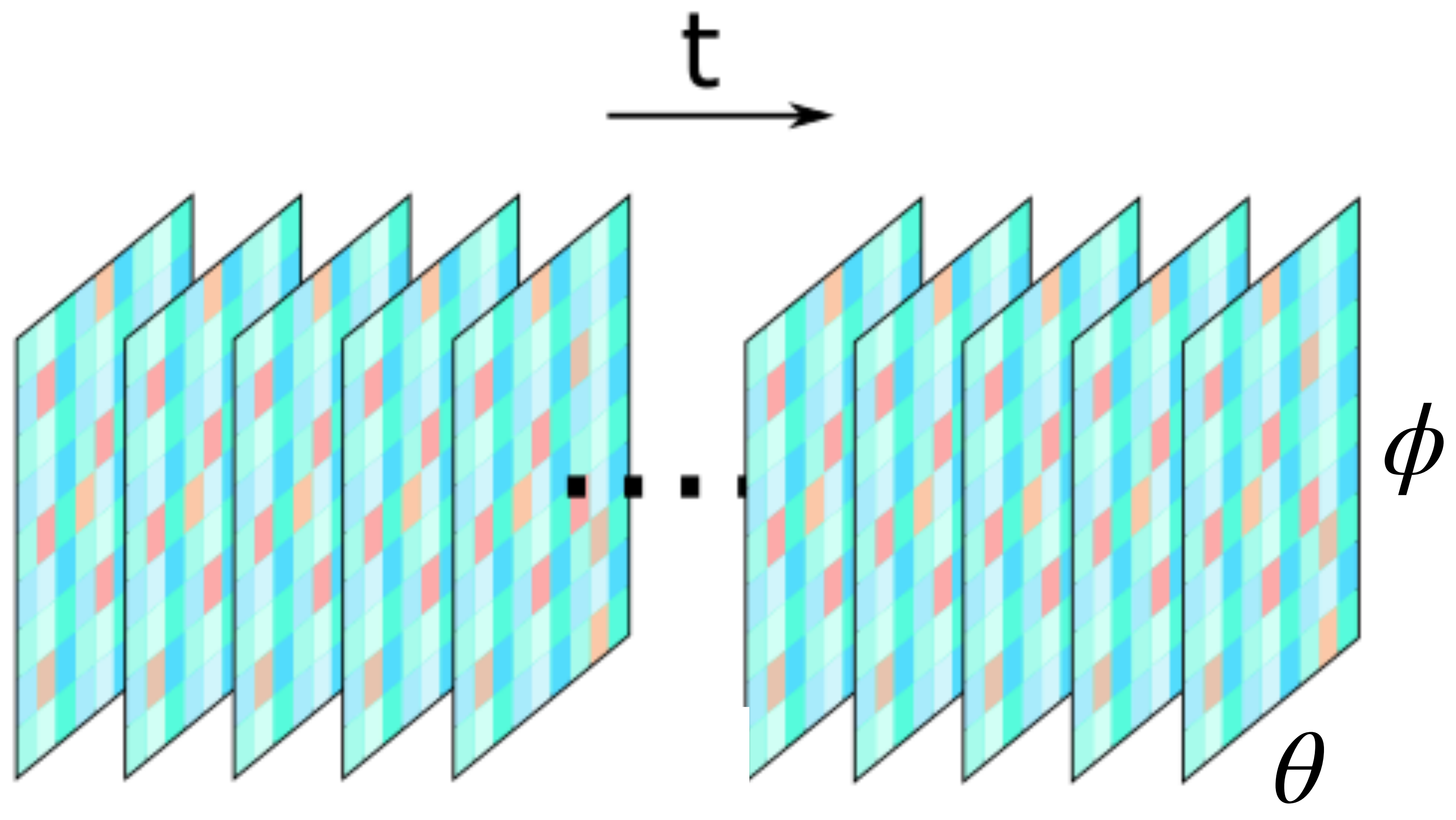
Load ^{136}Xe which could potentially undergo NLDBD

Liquid Scintillator

Generate many isotropic photon

Spatiotemporal Data

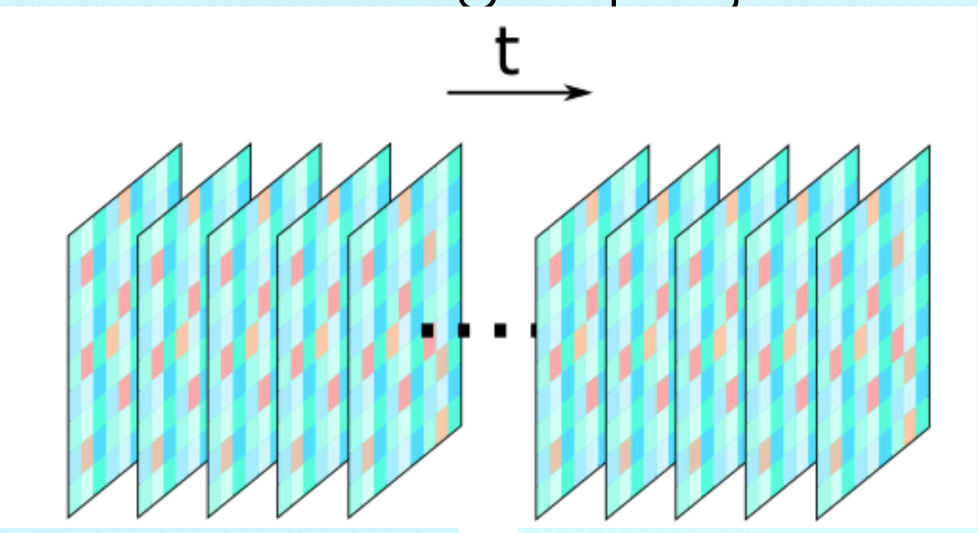
A time series of 2D images, projected onto sphere (A spherical video)



KamNet: An Integrated Spatiotemporal Neural Network

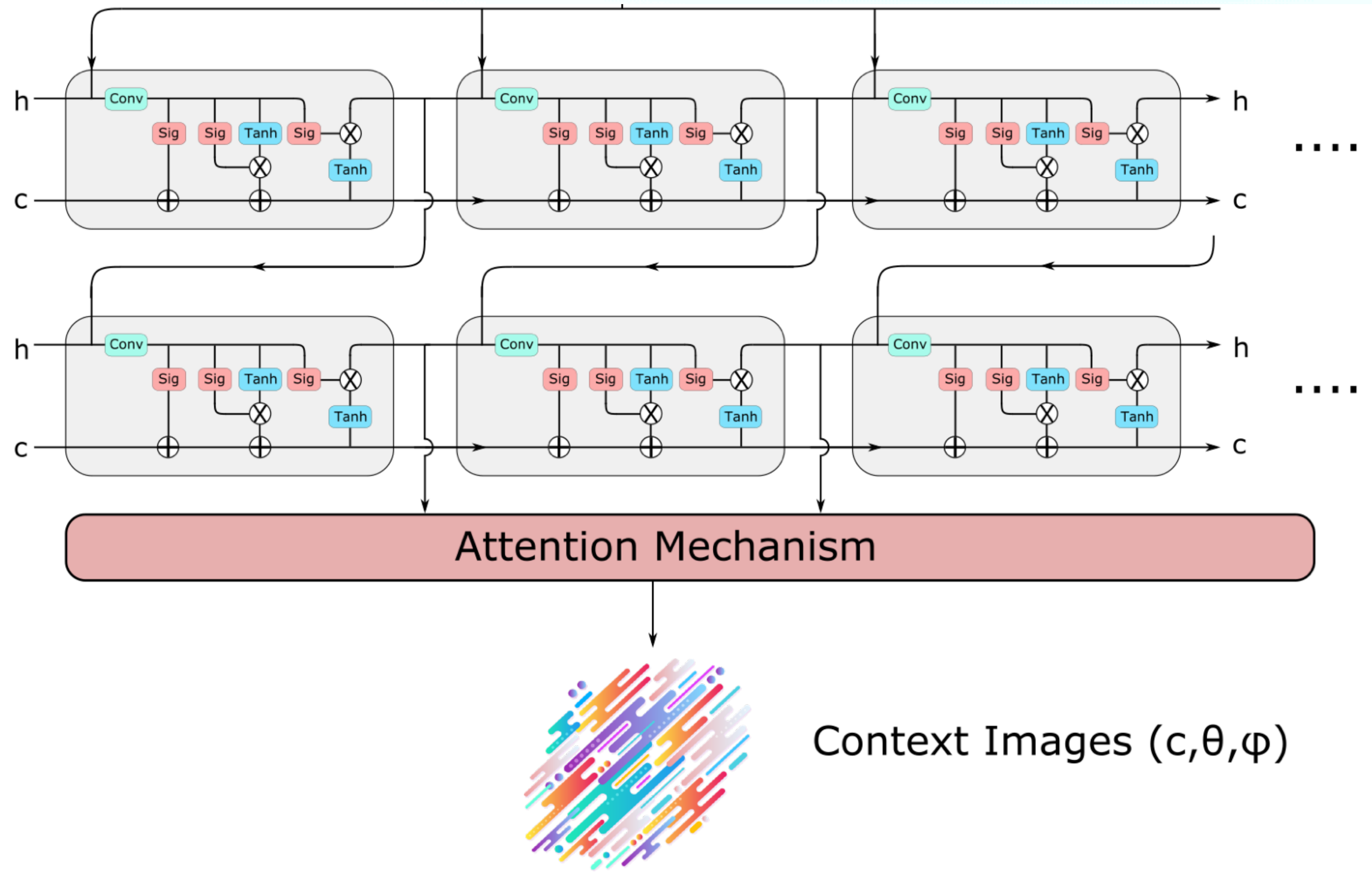
Spatiotemporal Data

A time series of images projected onto Sphere



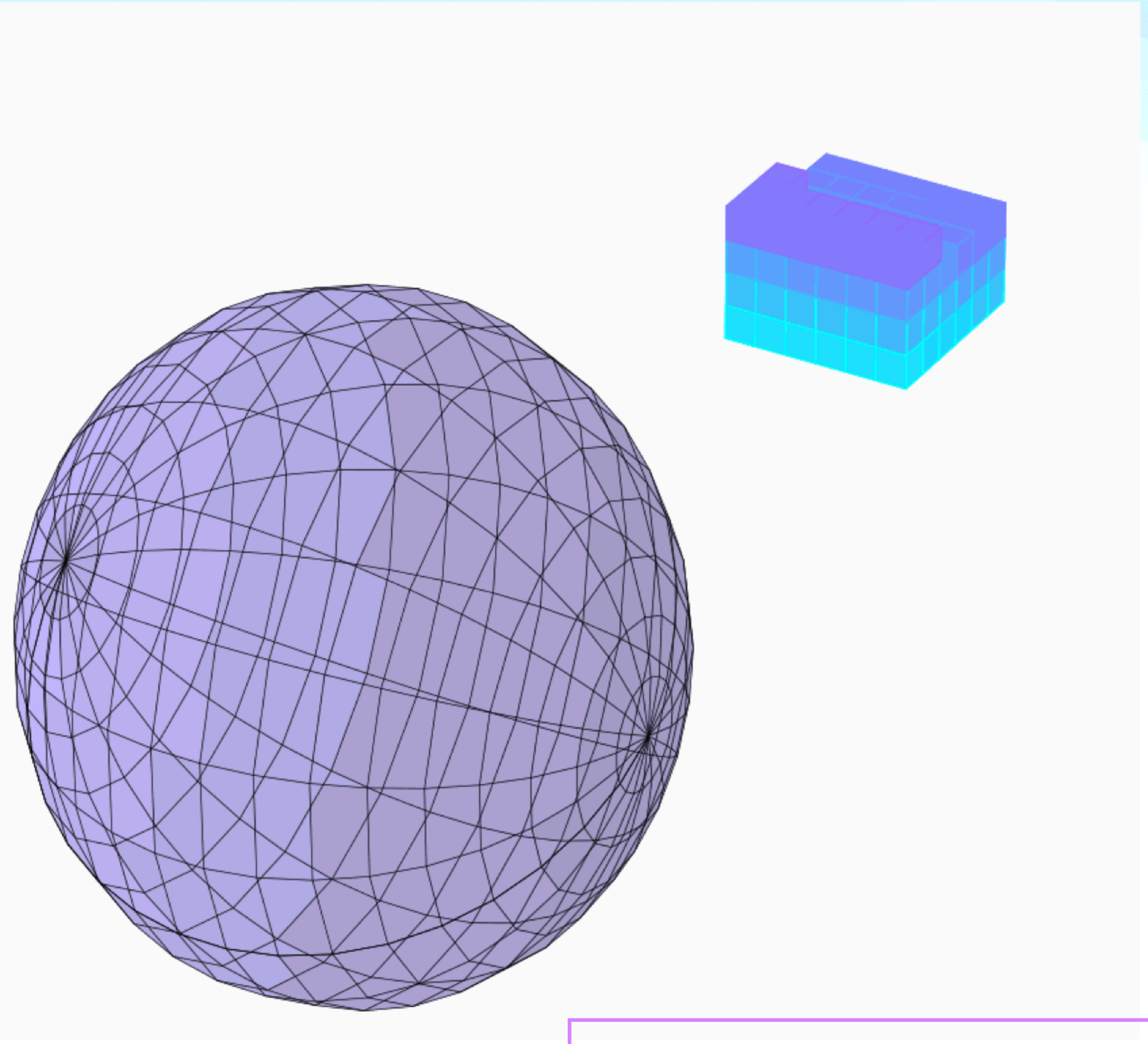
AttentionConvLSTM

for Spatiotemporal symmetry



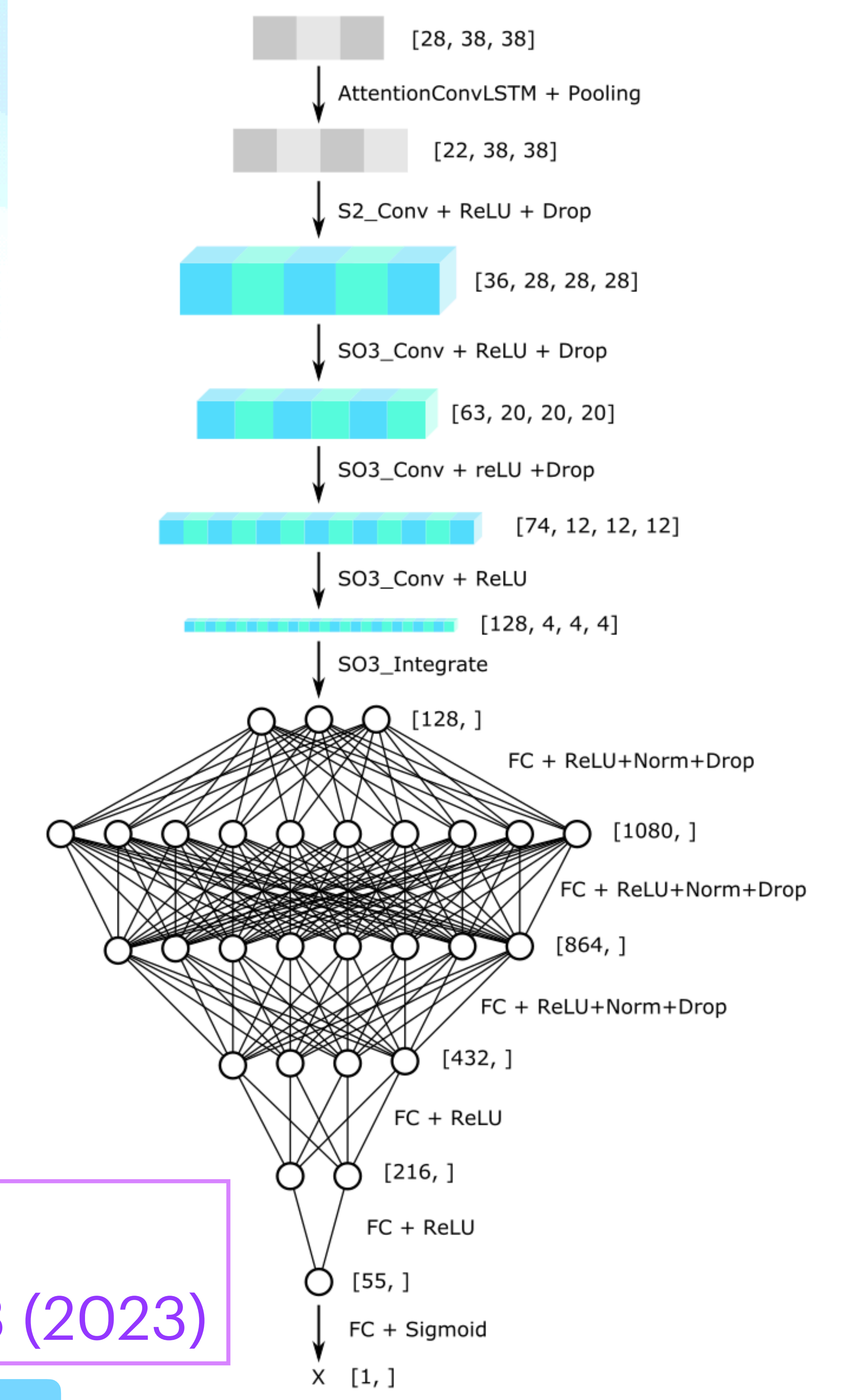
Spherical CNN

SO(3) symmetry & rotational equivariance



KamNet

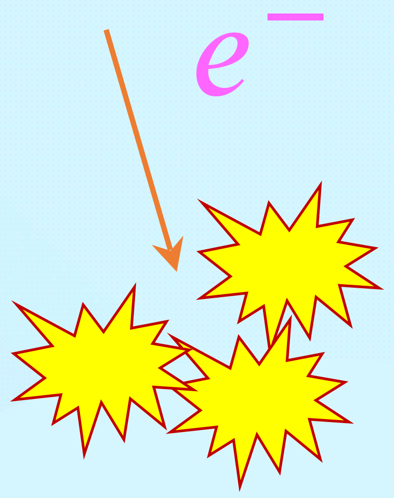
Identifying 0νββ signal in KamLAND-Zen



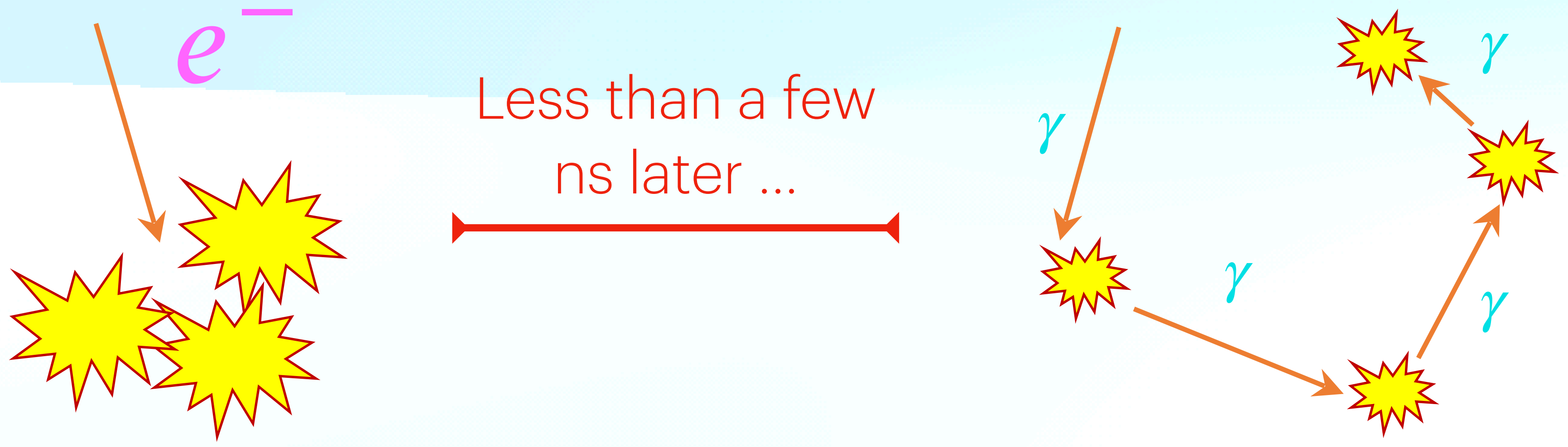
A. Li et al,
Phys. Rev. C **107**, 014323 (2023)

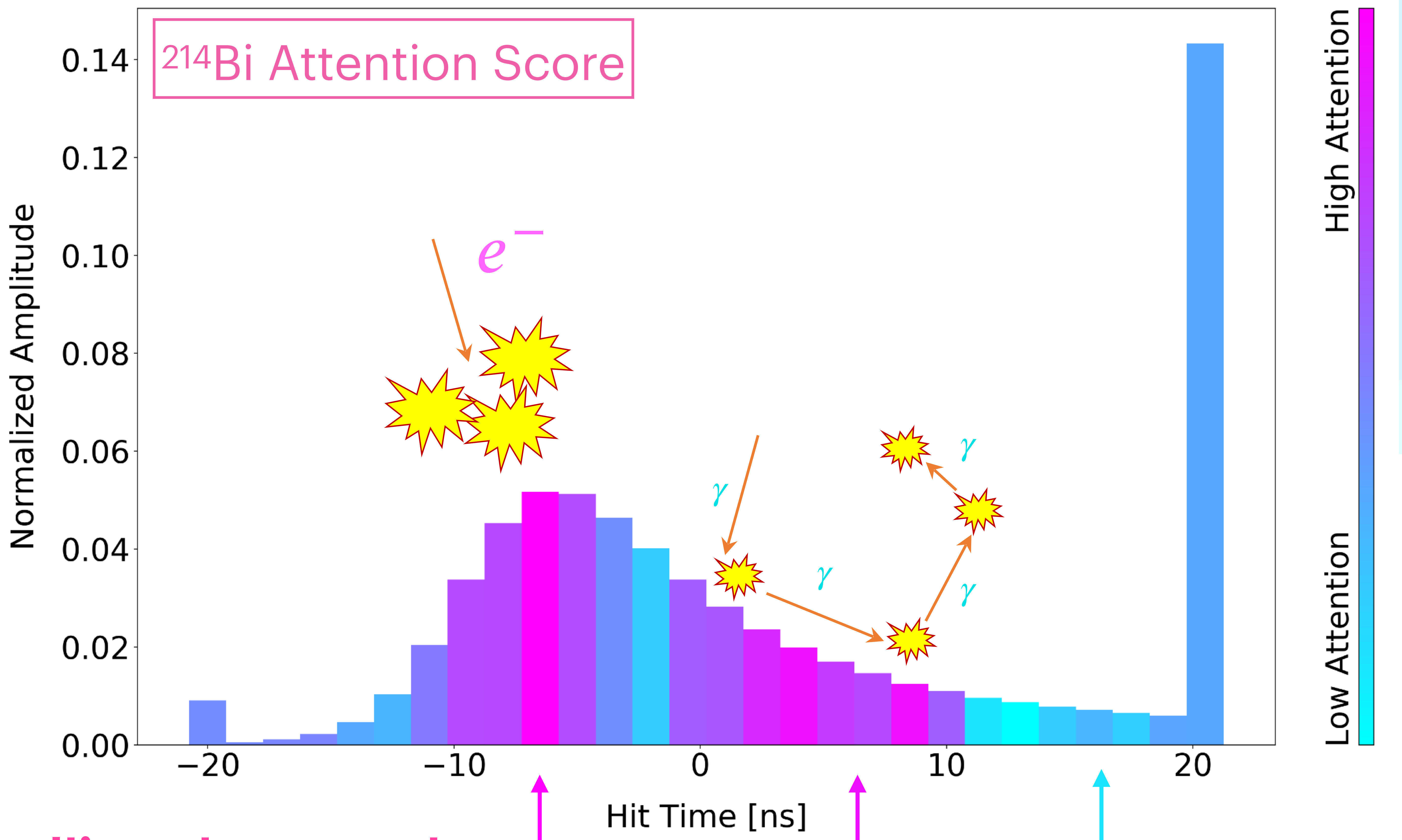
Editor's Suggestion

The Physics Behind KamNet



- Signal are strictly **single-vertex events**
  - All energy deposited almost immediately





- Most backgrounds are **closely-spaced multi-vertex events**
  - part of event energy is deposited by cascading γs that slightly alter event topology

High Attention: Important

Low Attention: Unimportant

KamNet captures this tiny alteration in event topology to efficiently reject most backgrounds in KamLAND-Zen!

KamNet-enabled New Result

KamLAND-Zen Collaboration
Phys. Rev. Lett. 130, 051801

A. Li et al,
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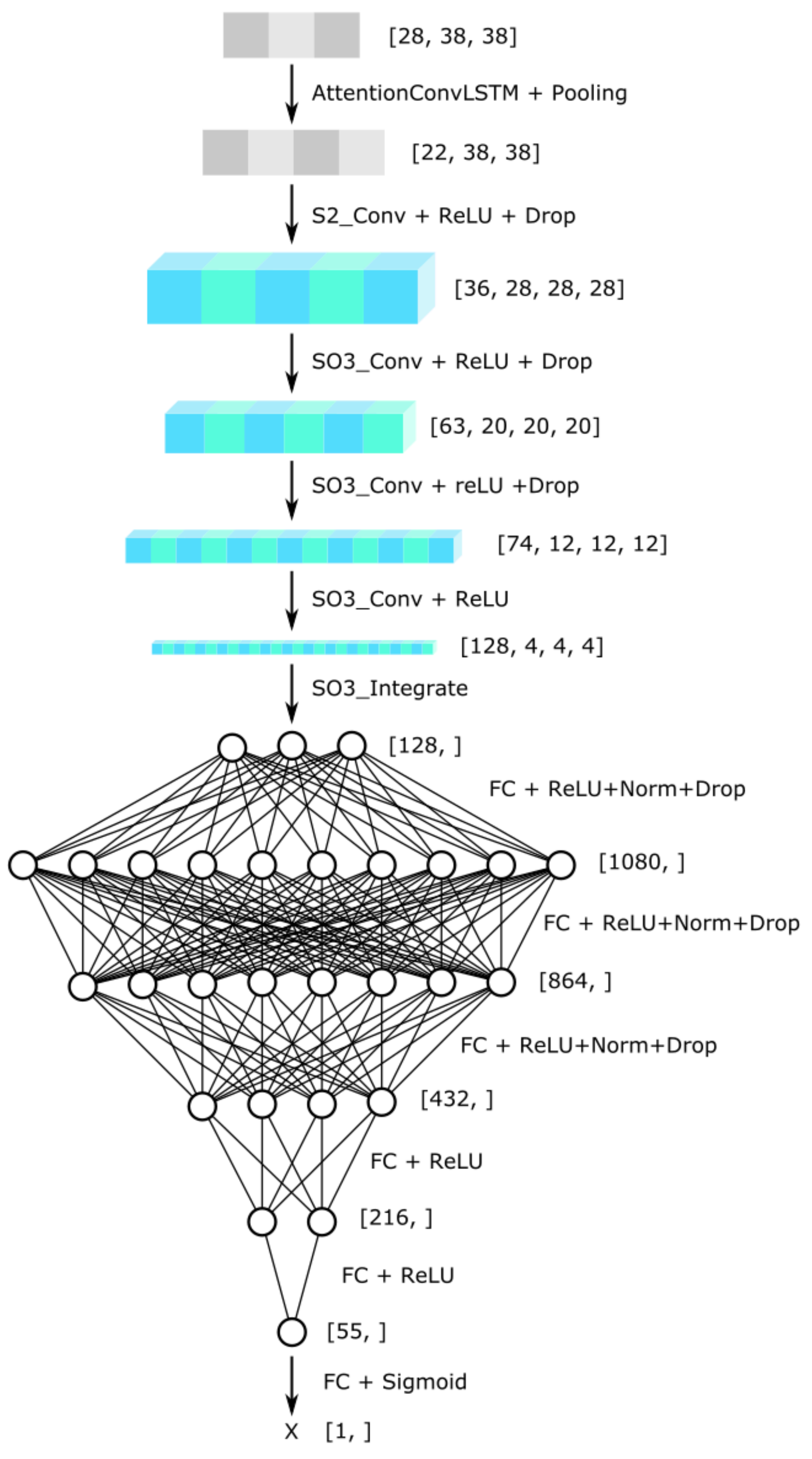
Exposure Before KamNet:

970 kg·yr

Integrated Spatiotemporal Neural Network



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+17.7%

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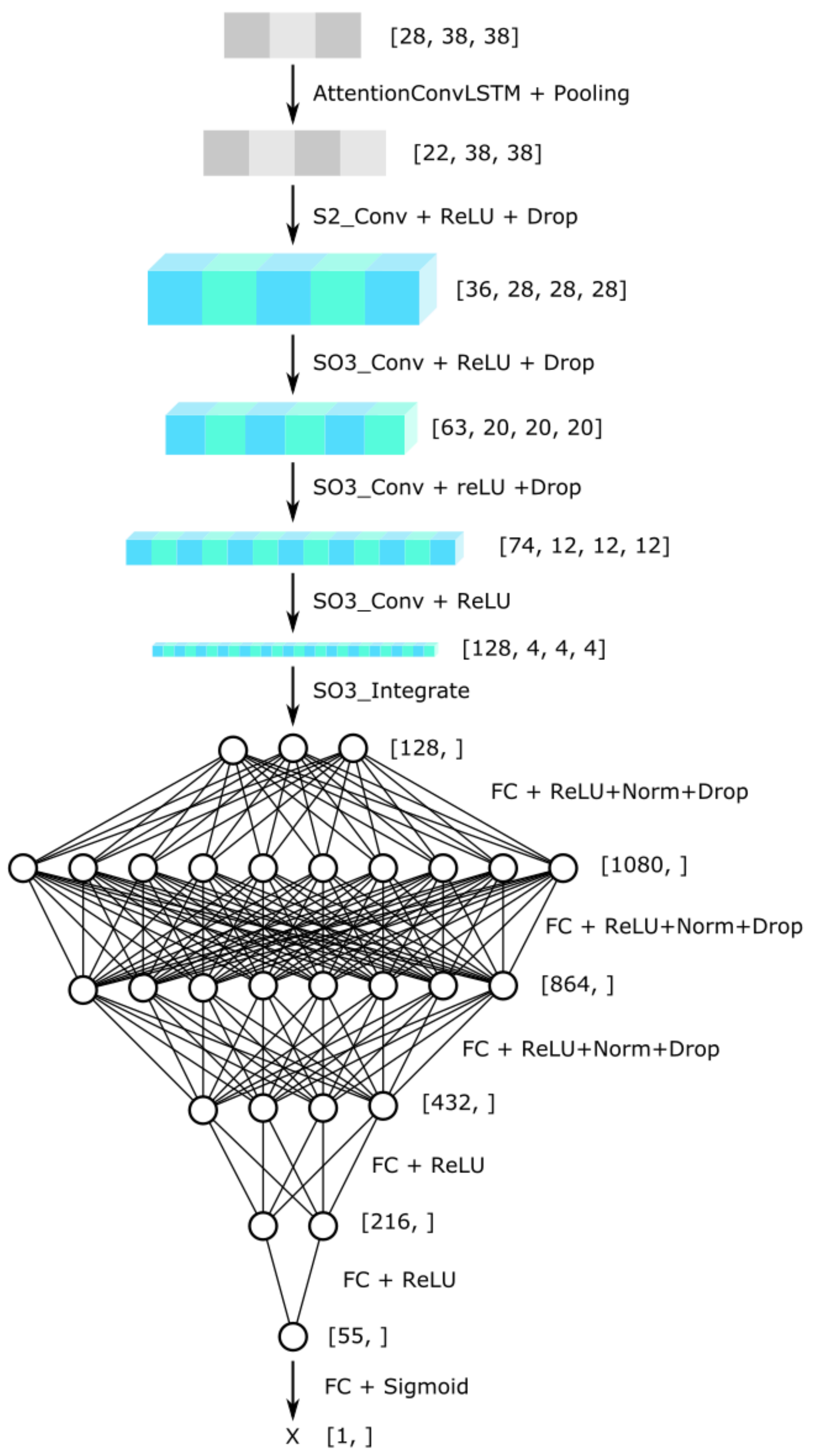

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Apply KamNet to High-Background Period Only:

- Conservative use of KamNet
- Veto critical backgrounds that passes all traditional methods

Official KamLAND-Zen 800 Limit:

$$T^{0\nu\beta\beta}_{1/2} > 2.0 \times 10^{26} \text{yr (90 \% C.L.)}$$

KLZ Combined Official Limit:

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This is the first search for Majorana neutrino in the **inverted ordering** region!

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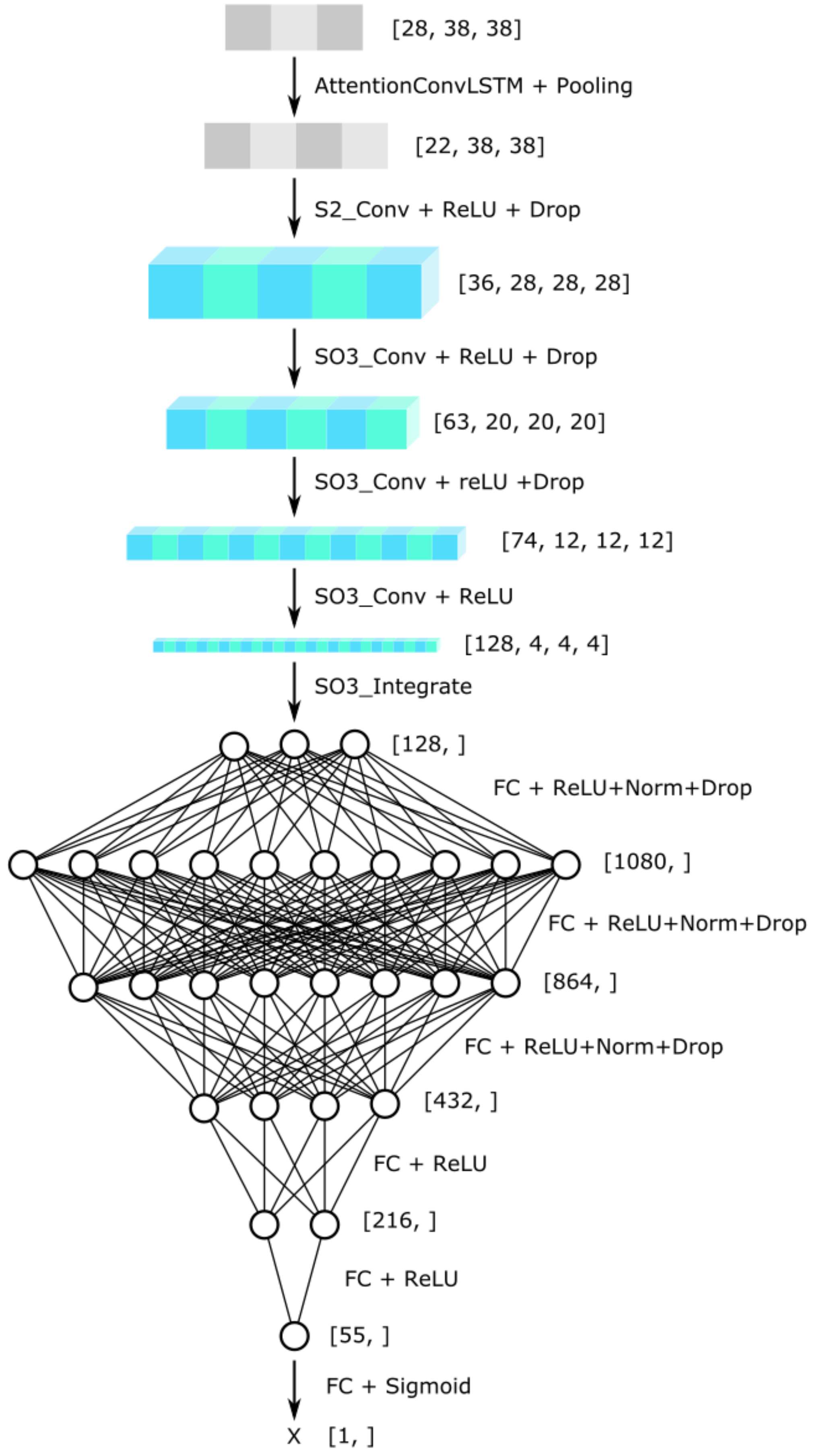

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Apply KamNet to All Data:

$$T^{0\nu\beta\beta}_{1/2} > 2.7 \times 10^{26}\text{yr (90 \% C.L.)}$$ +35%

LEGEND

D. Radford
Thursday Plenary: Advanced Materials, Geology, Advanced Data Analysis

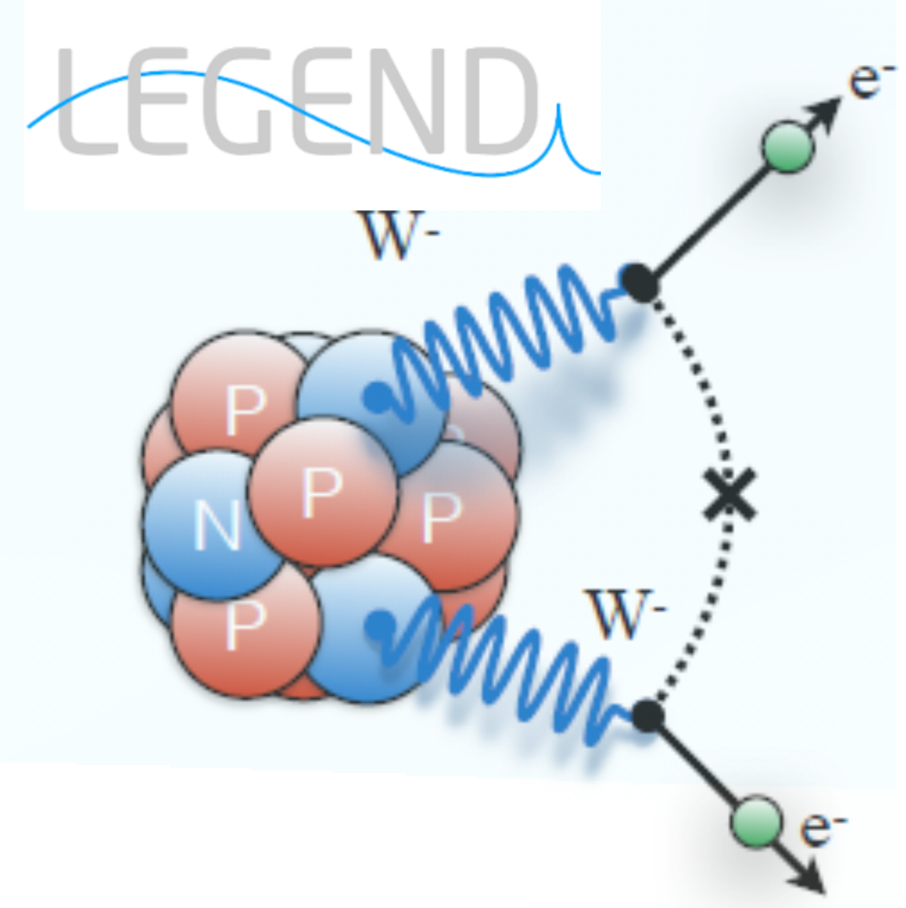
B. Bos
Double Beta Decay Parallel Session

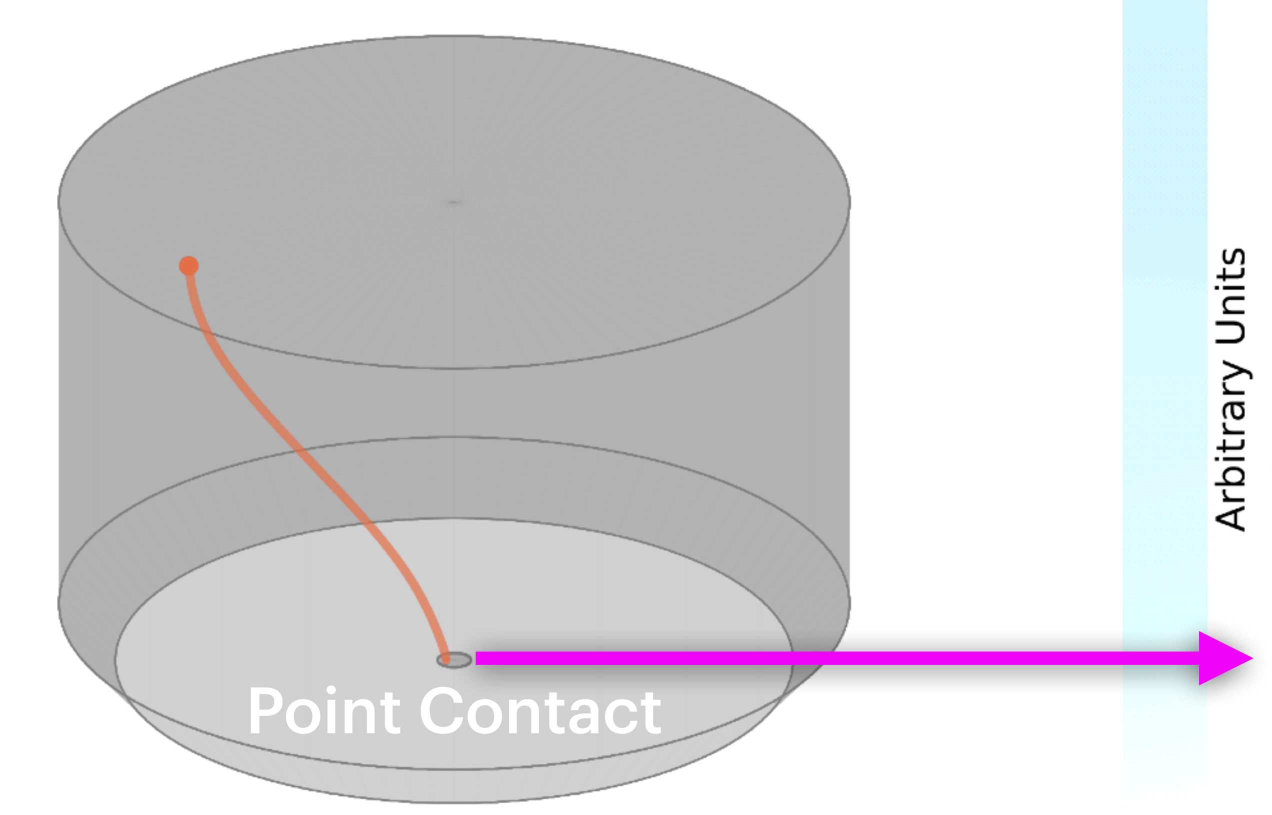
Tonne-Scale Germanium Detector Experiment for NLDBD Search

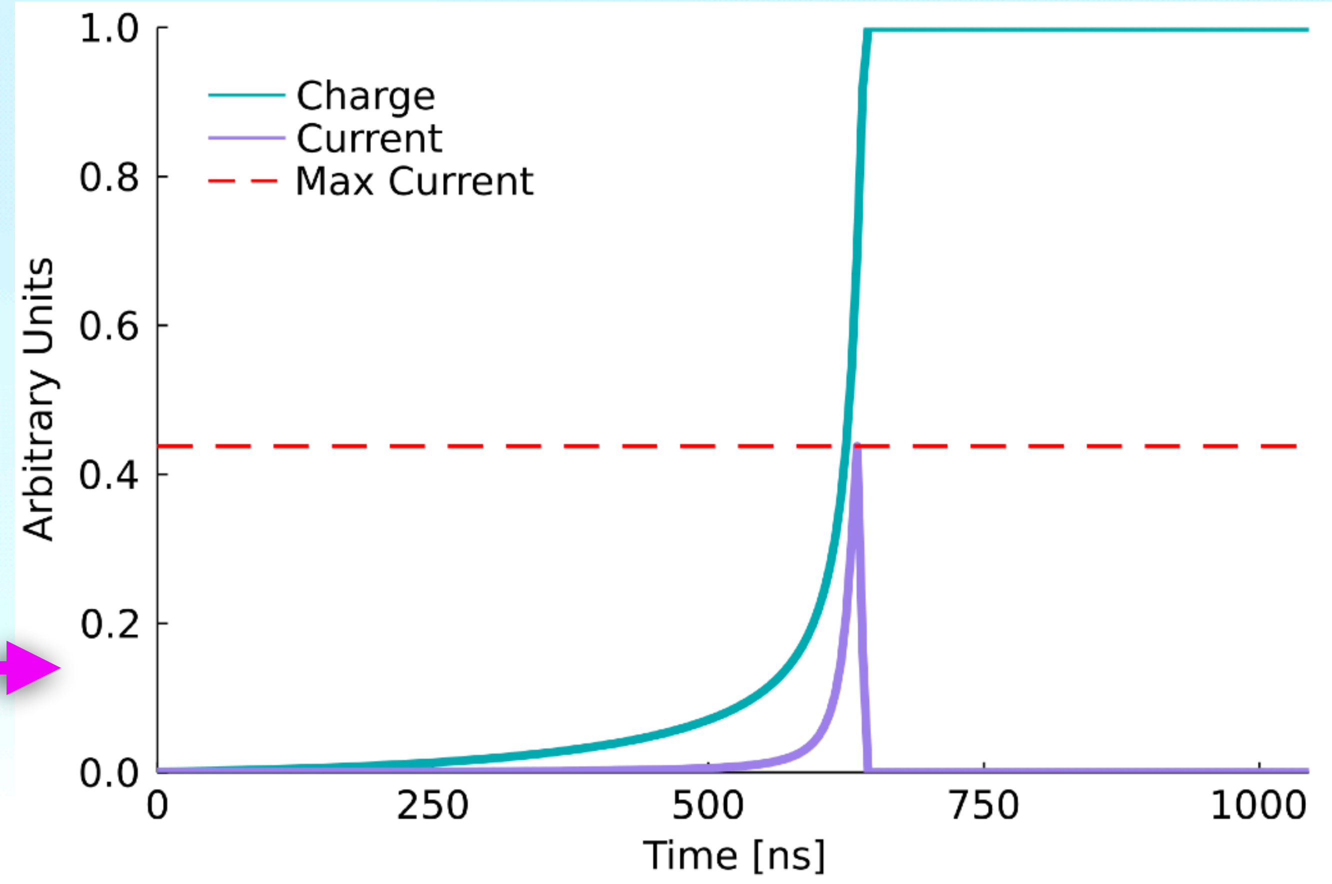
Semiconductor Detector made with ^{76}Ge

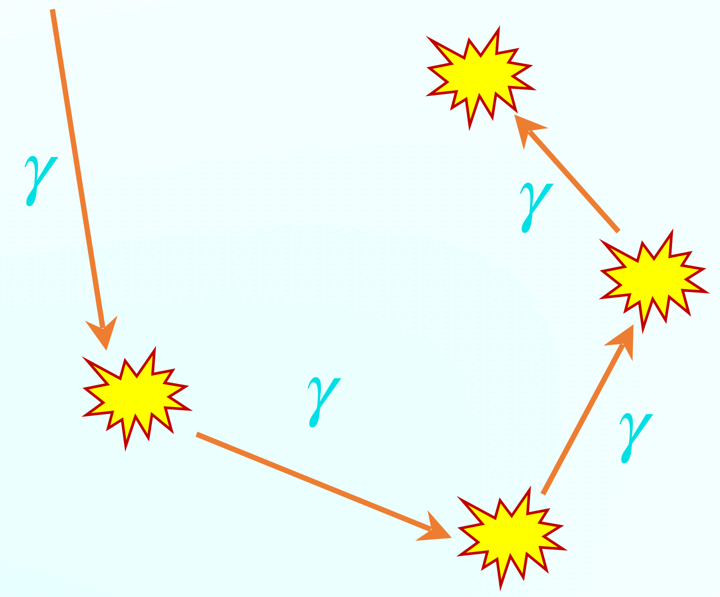
Waveform

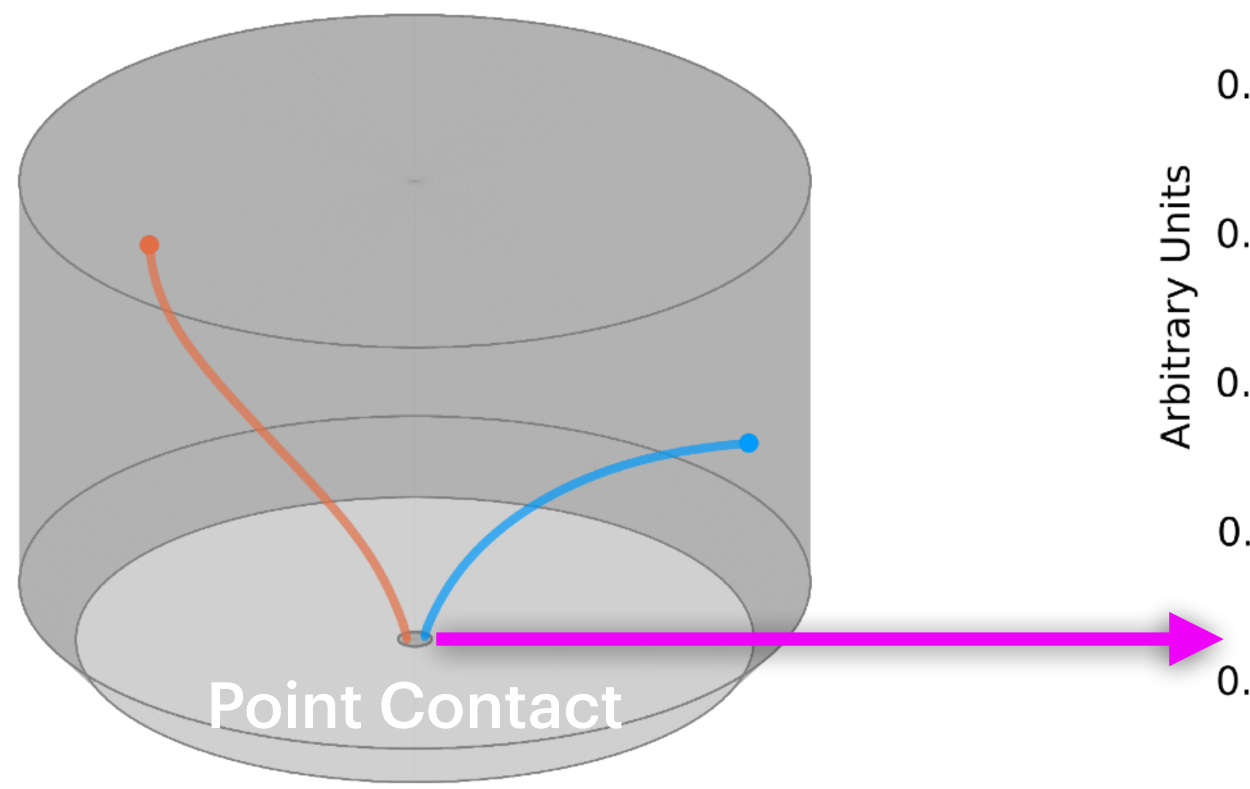
Pulse Shape Parameter

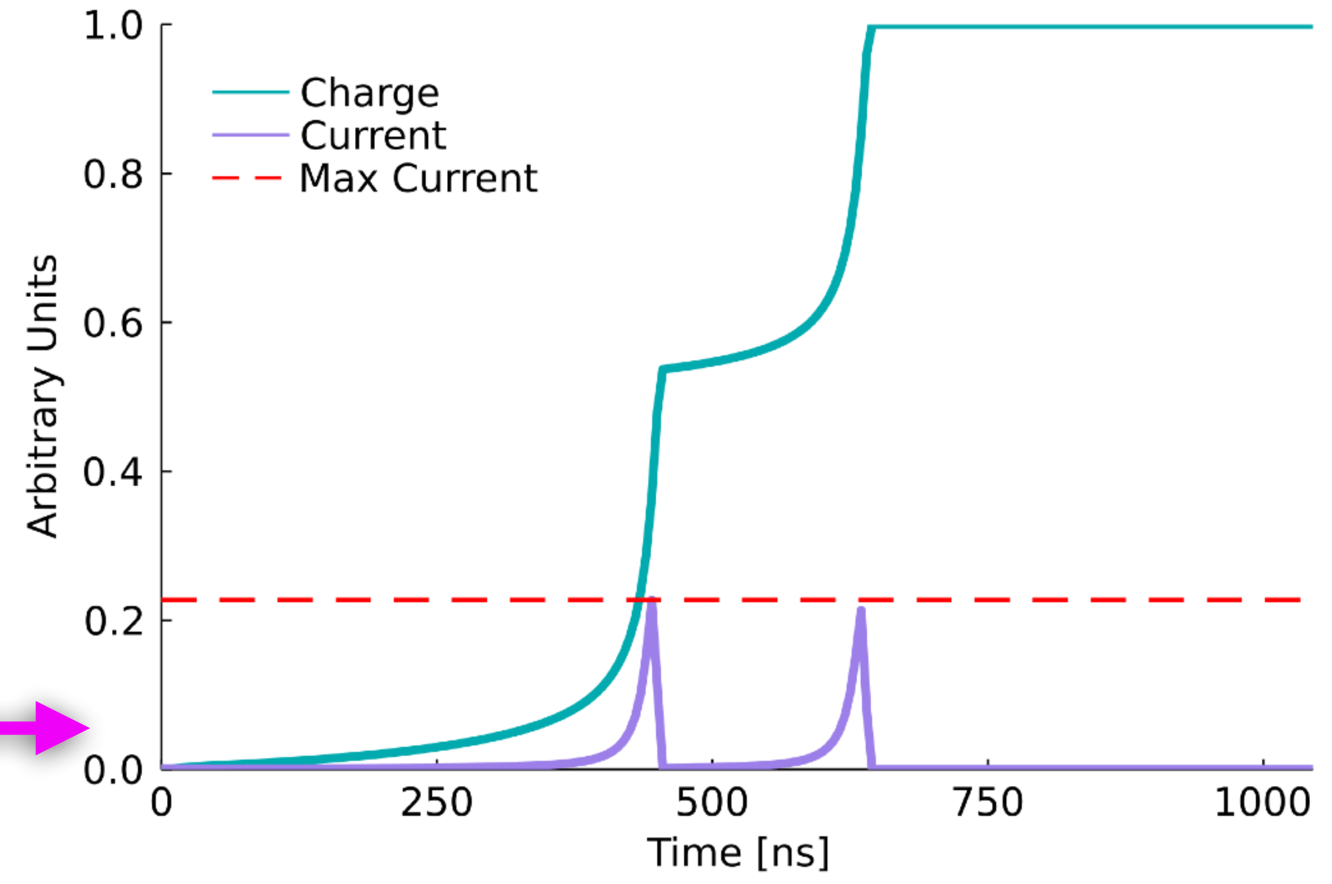












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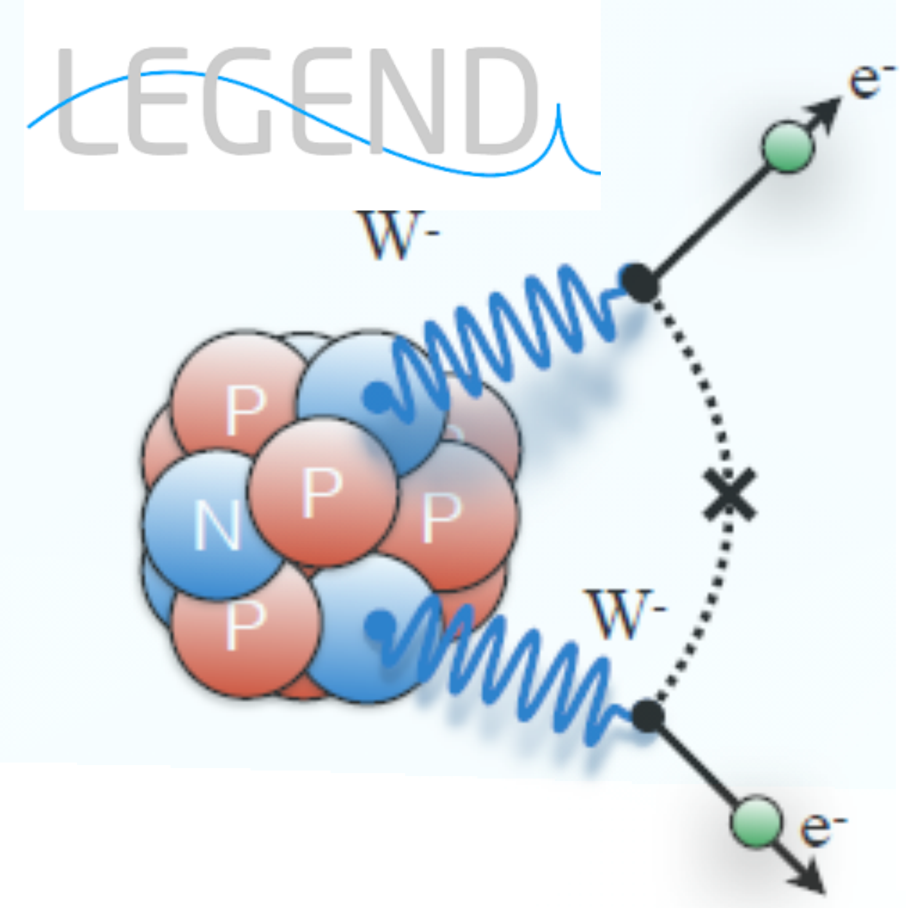

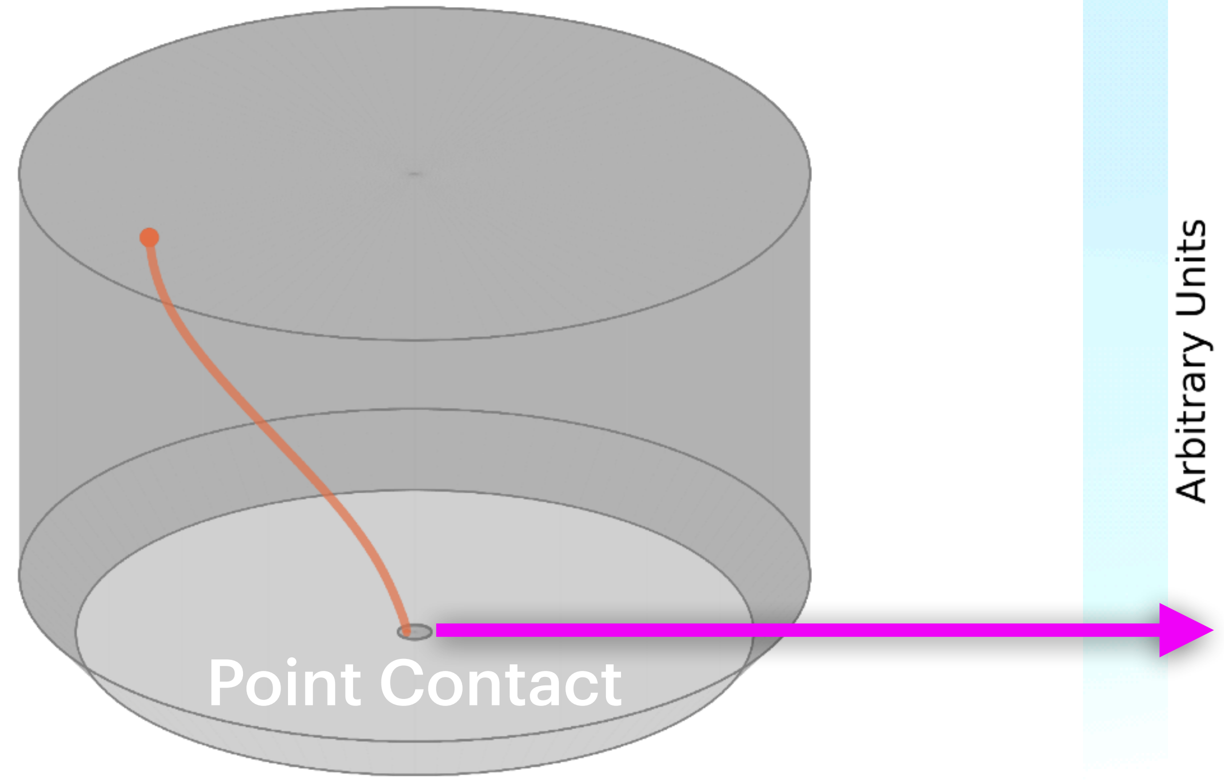

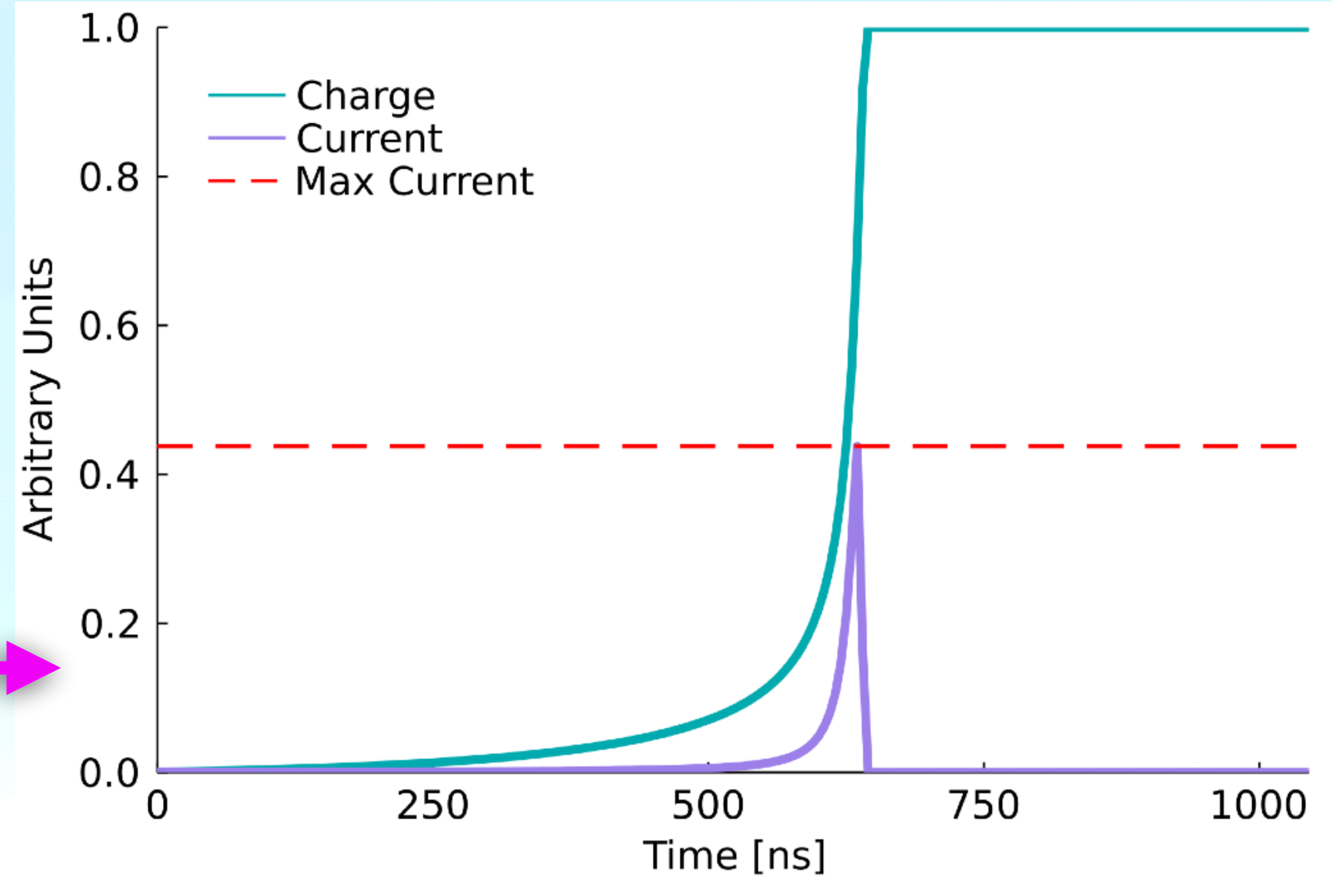

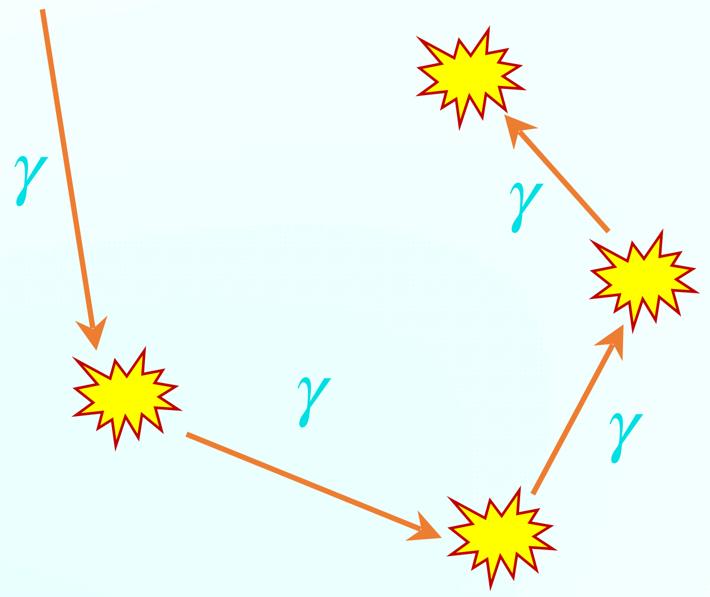

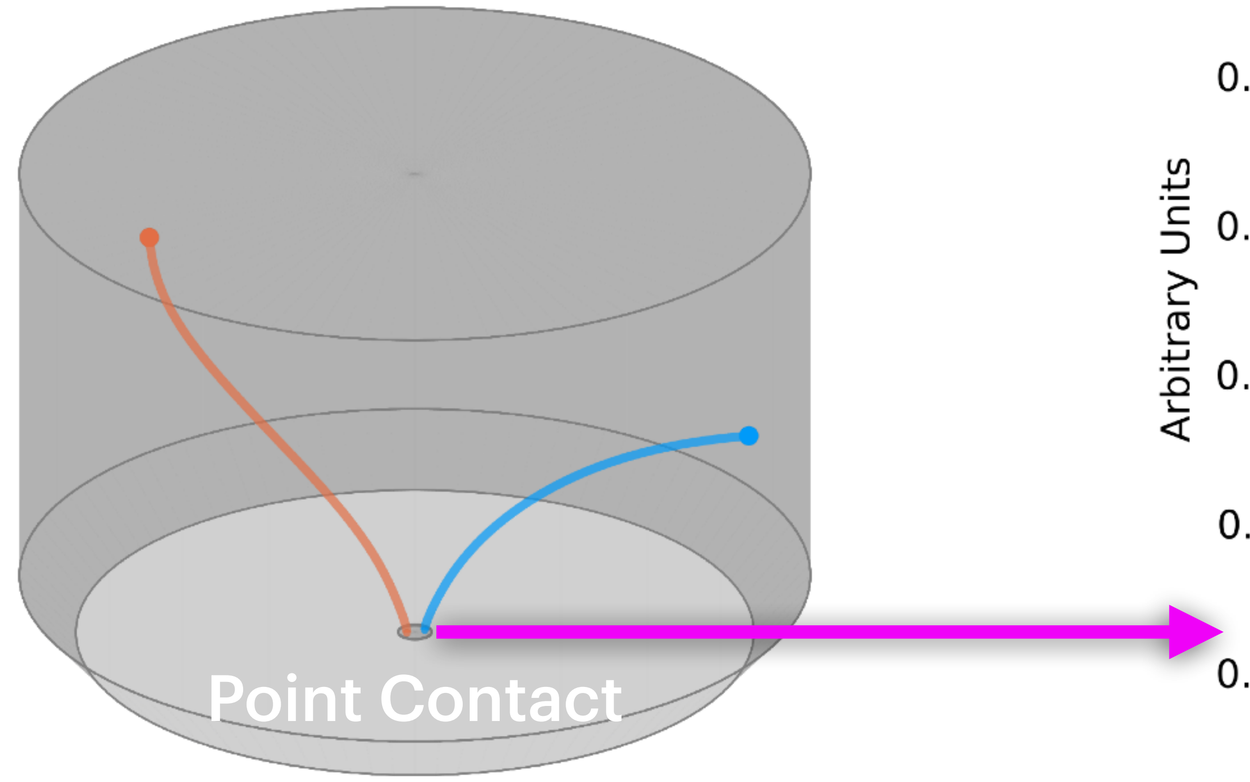

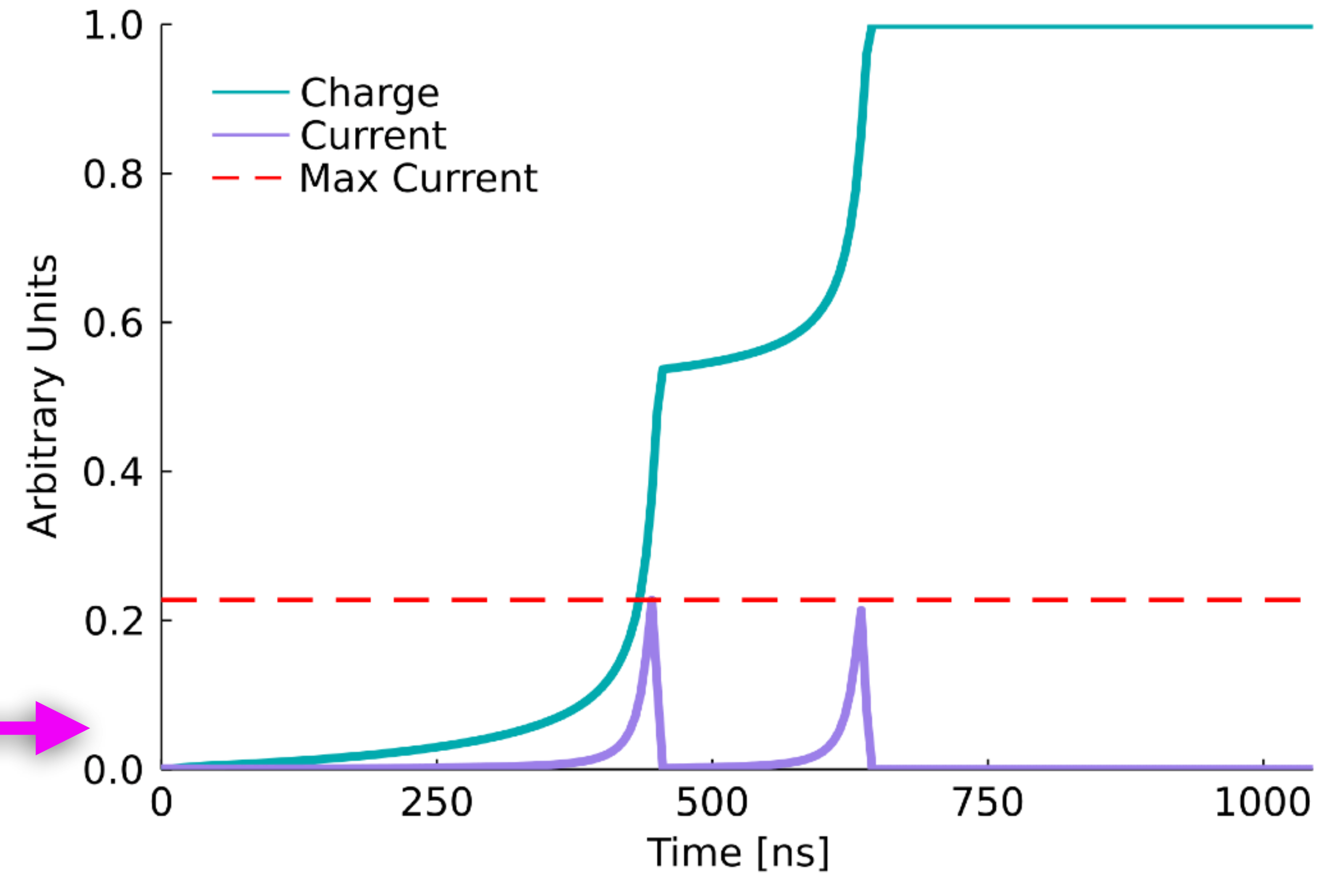

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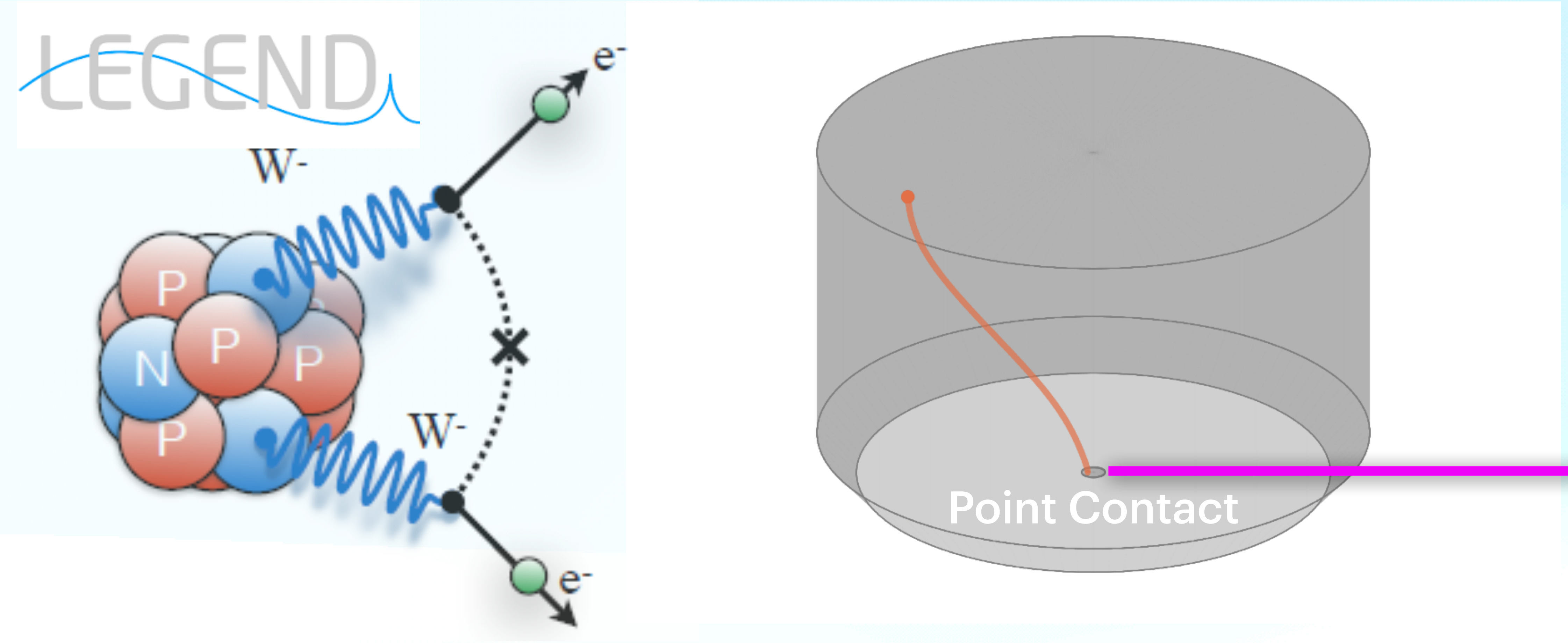
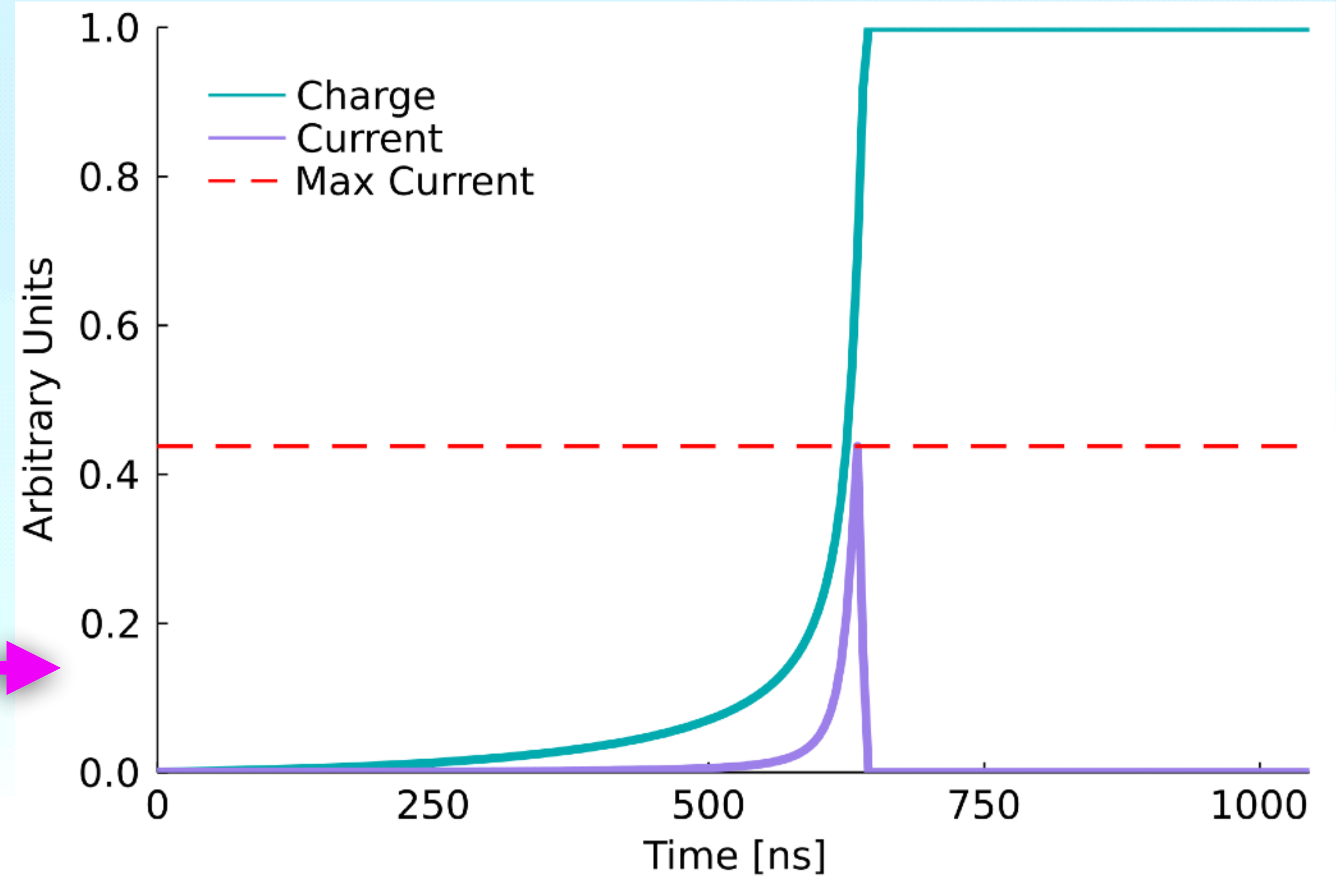
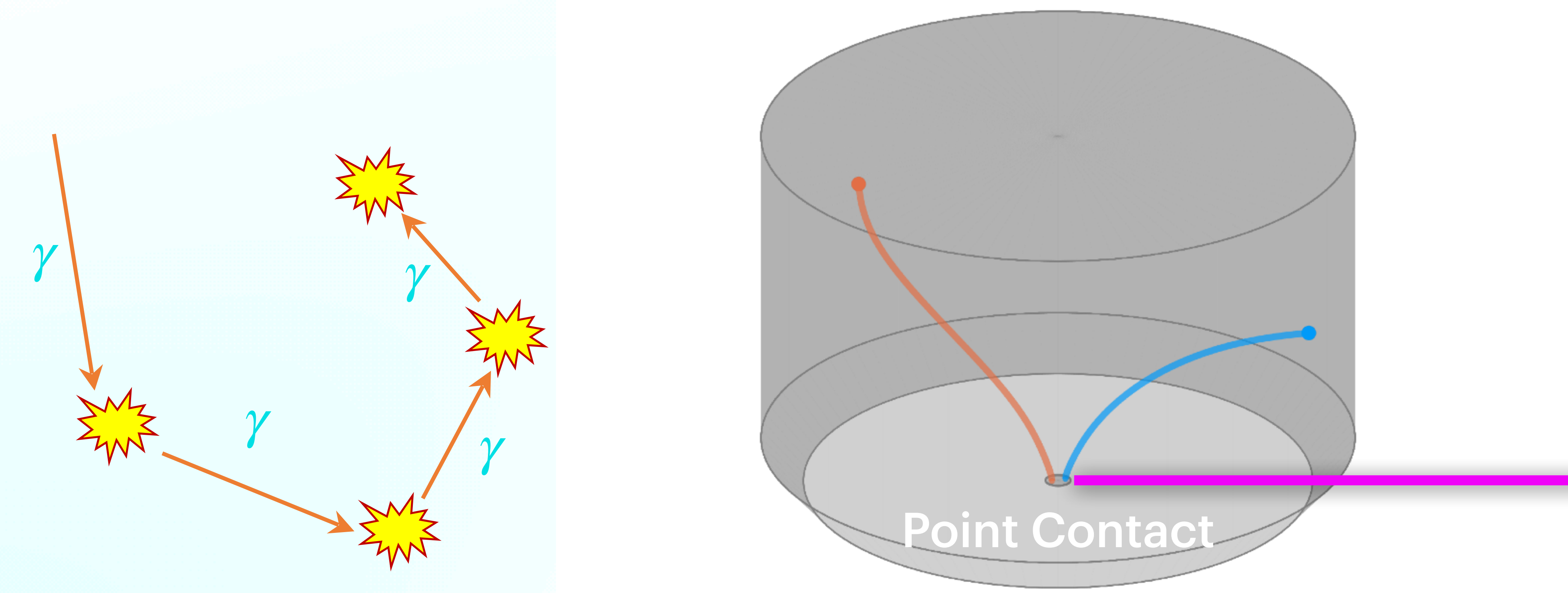
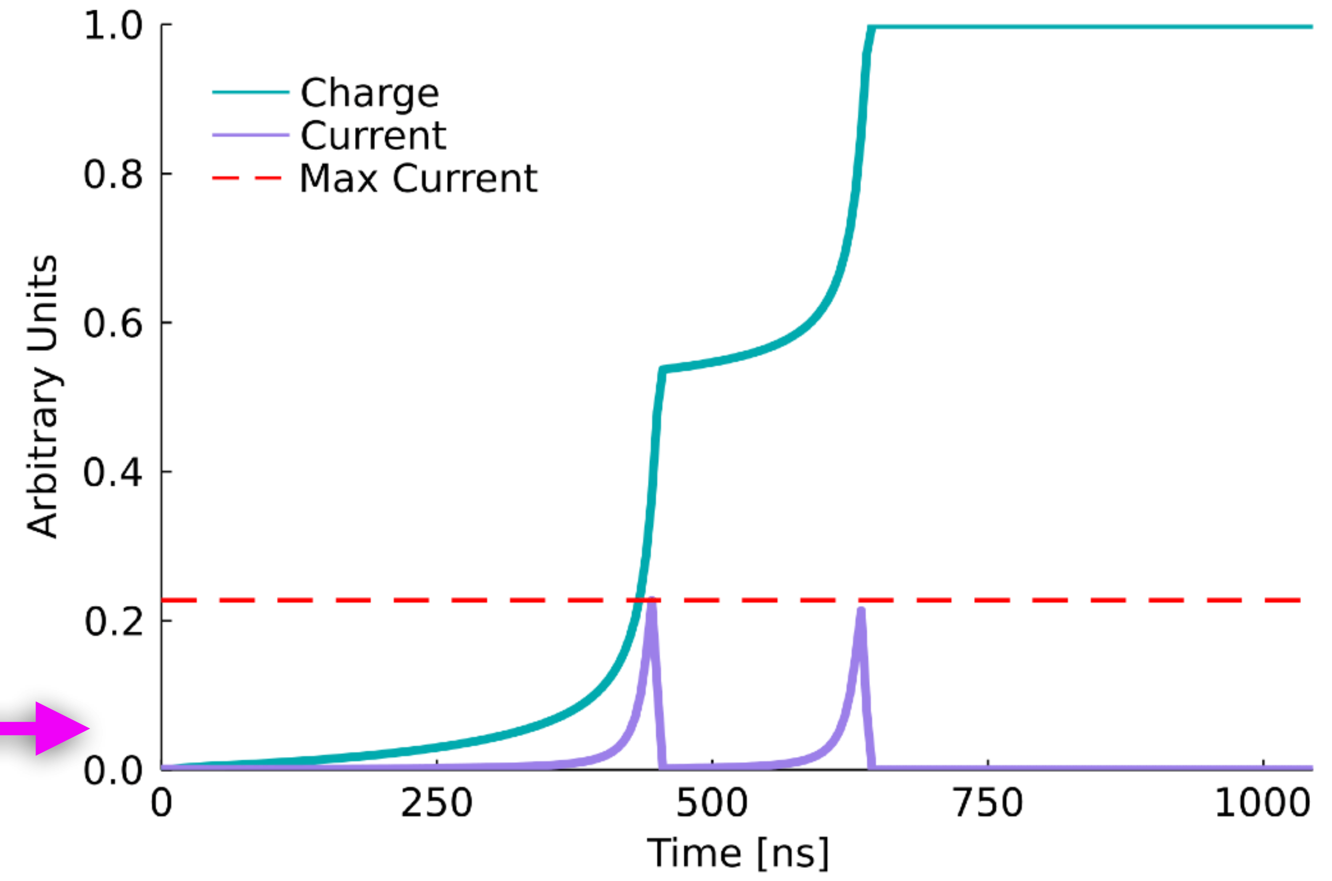
Semiconductor Detector made with ^{76}Ge | **Waveform** | **Pulse Shape Parameter**









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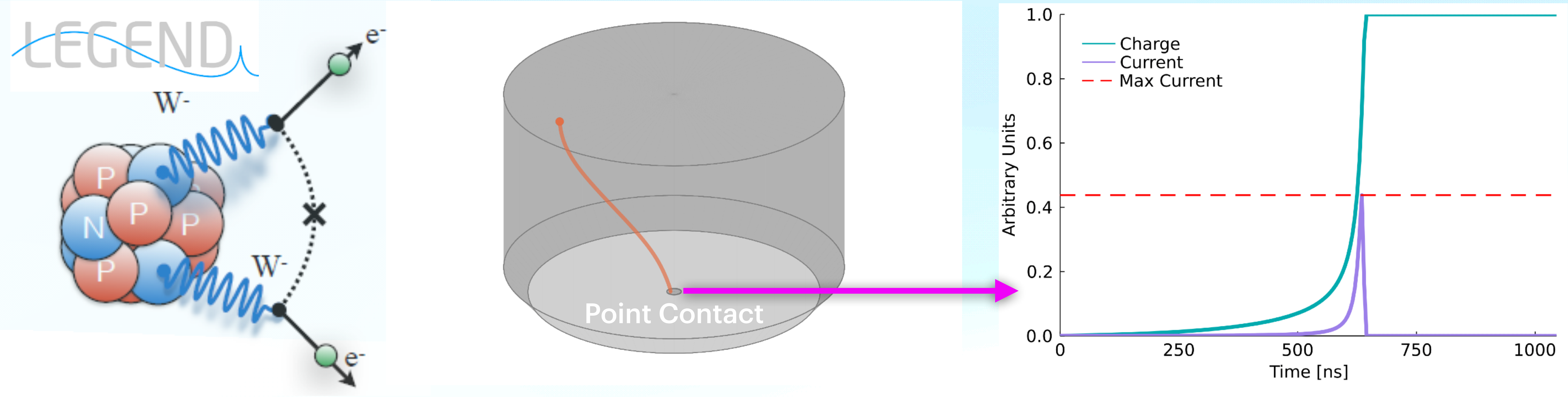

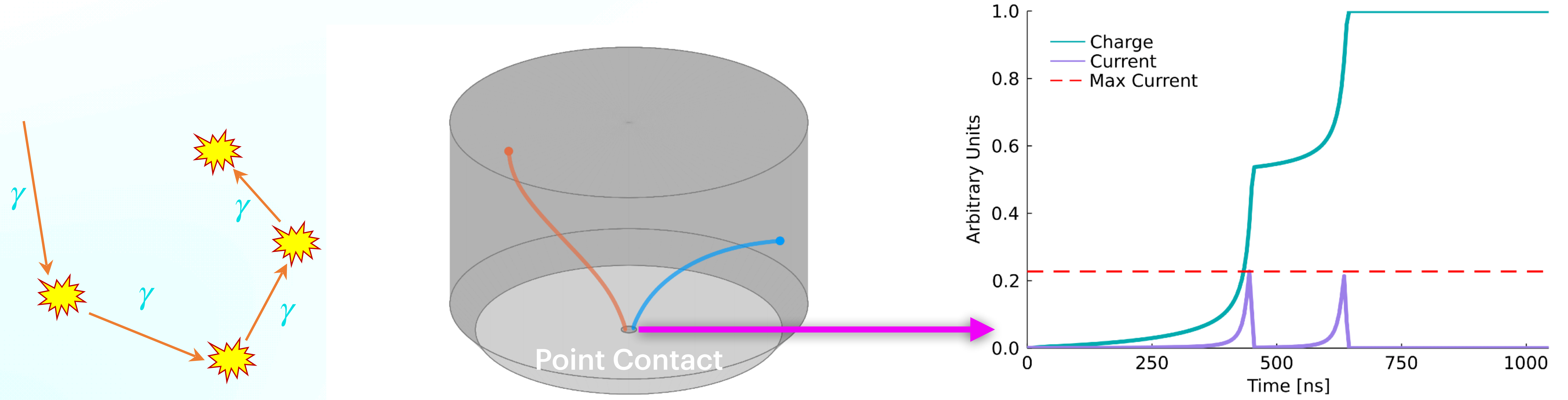

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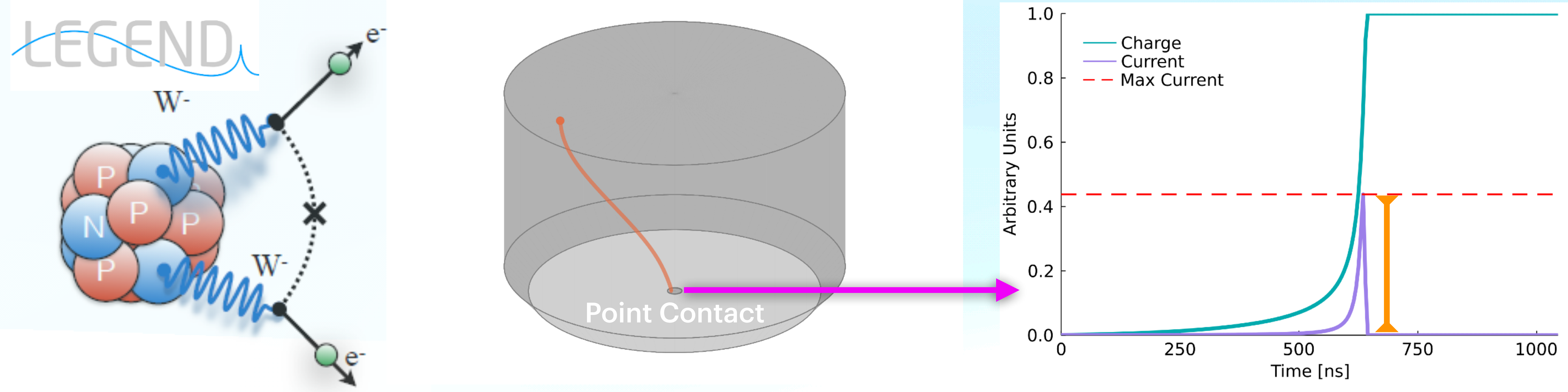

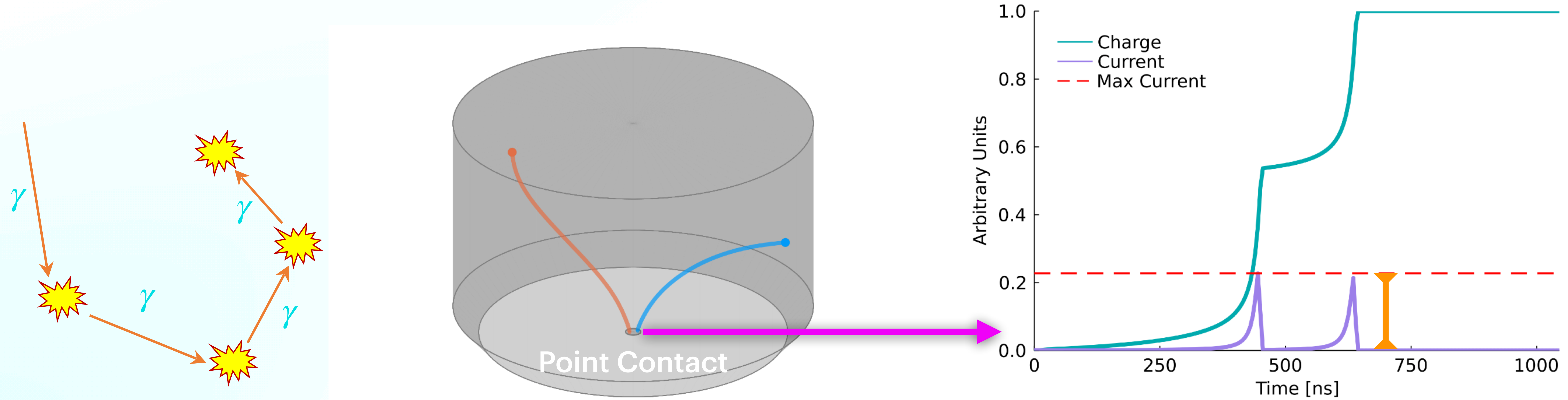

Maximal Current Amplitude

For **multi-site background** rejection

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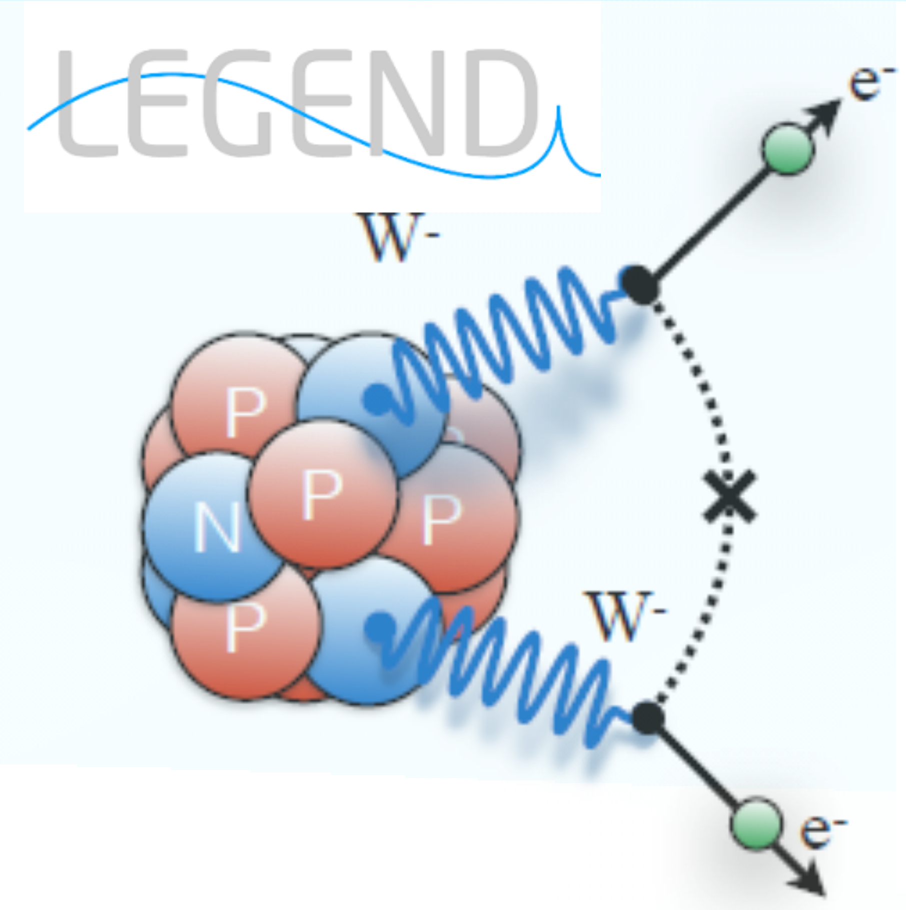
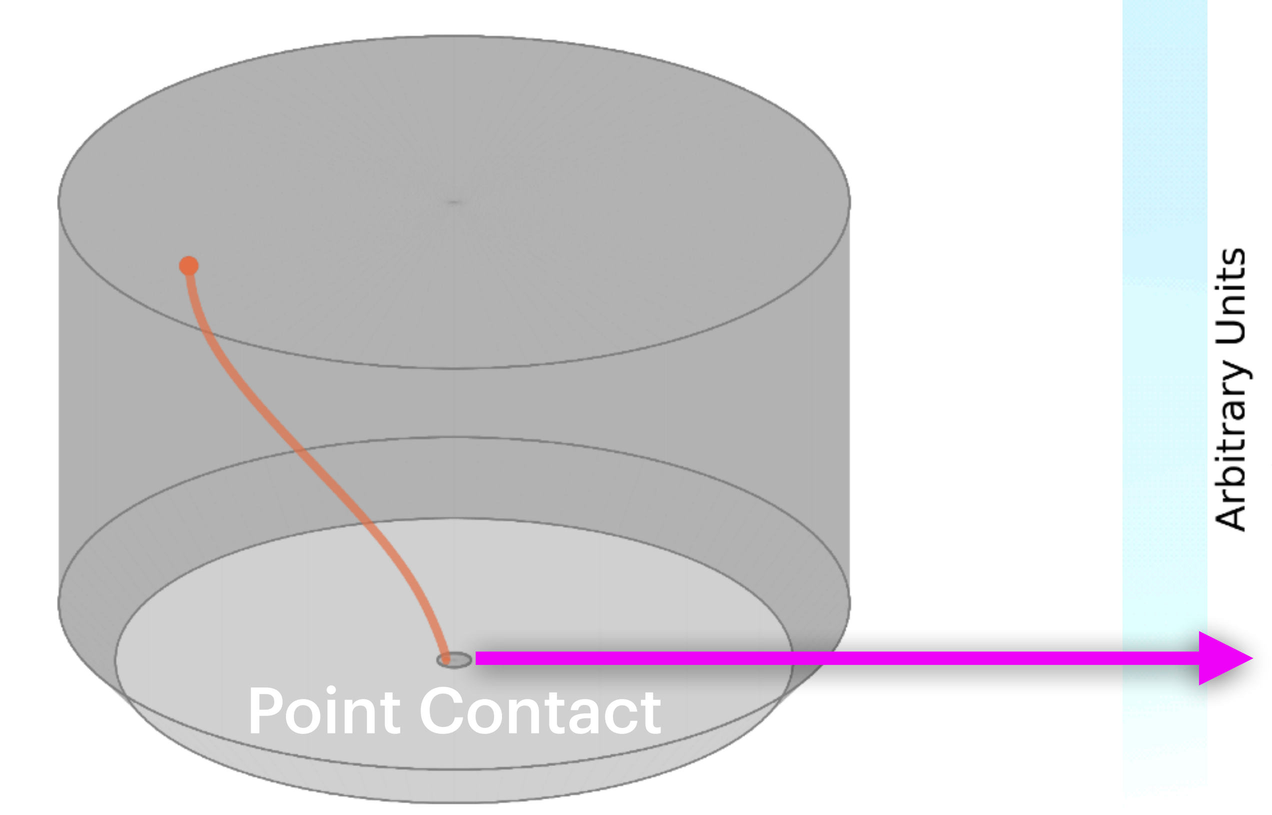
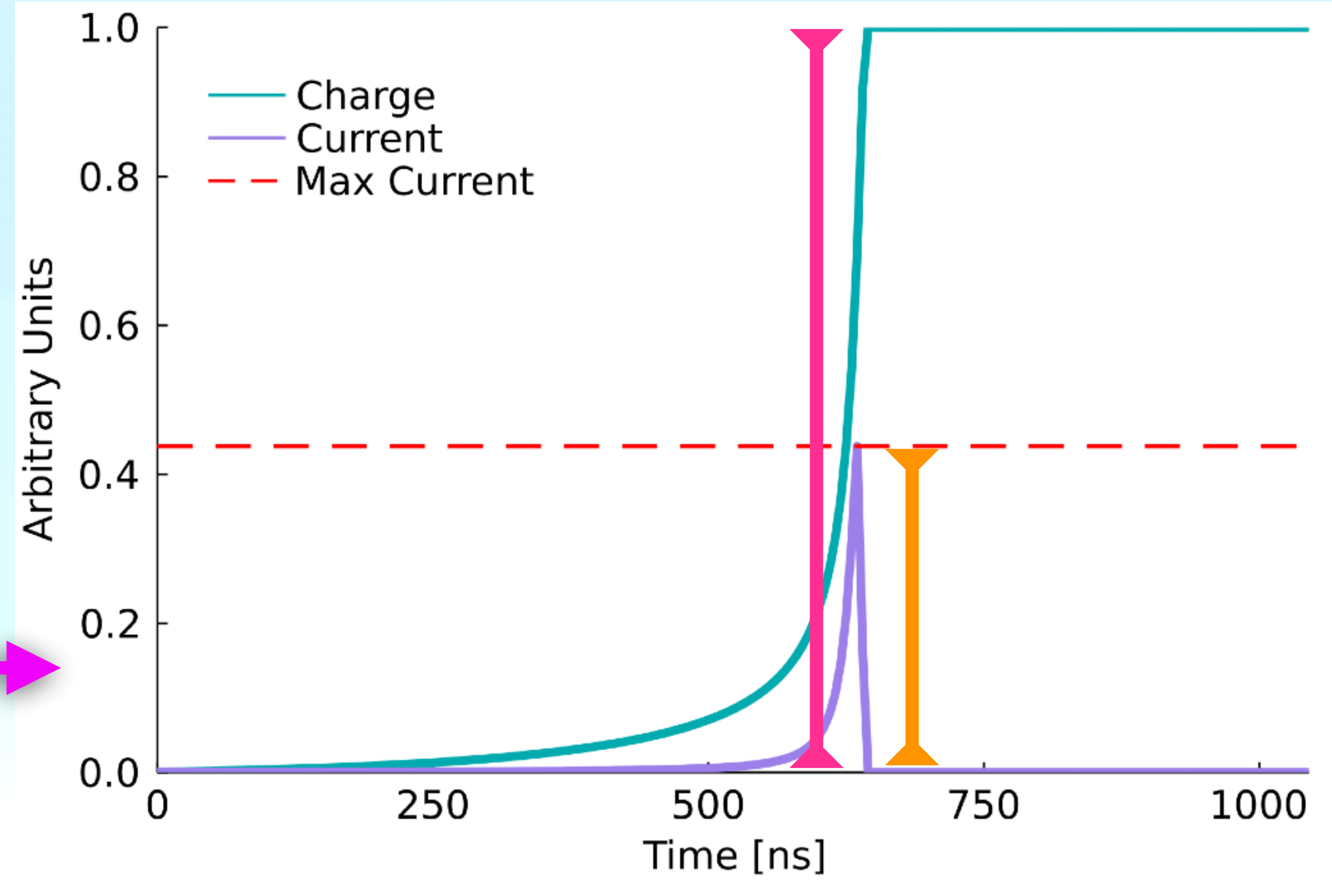


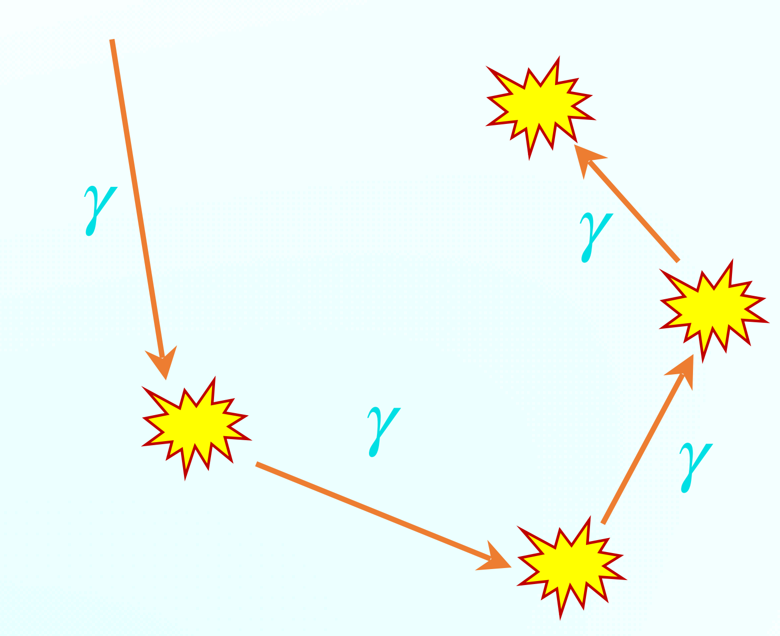


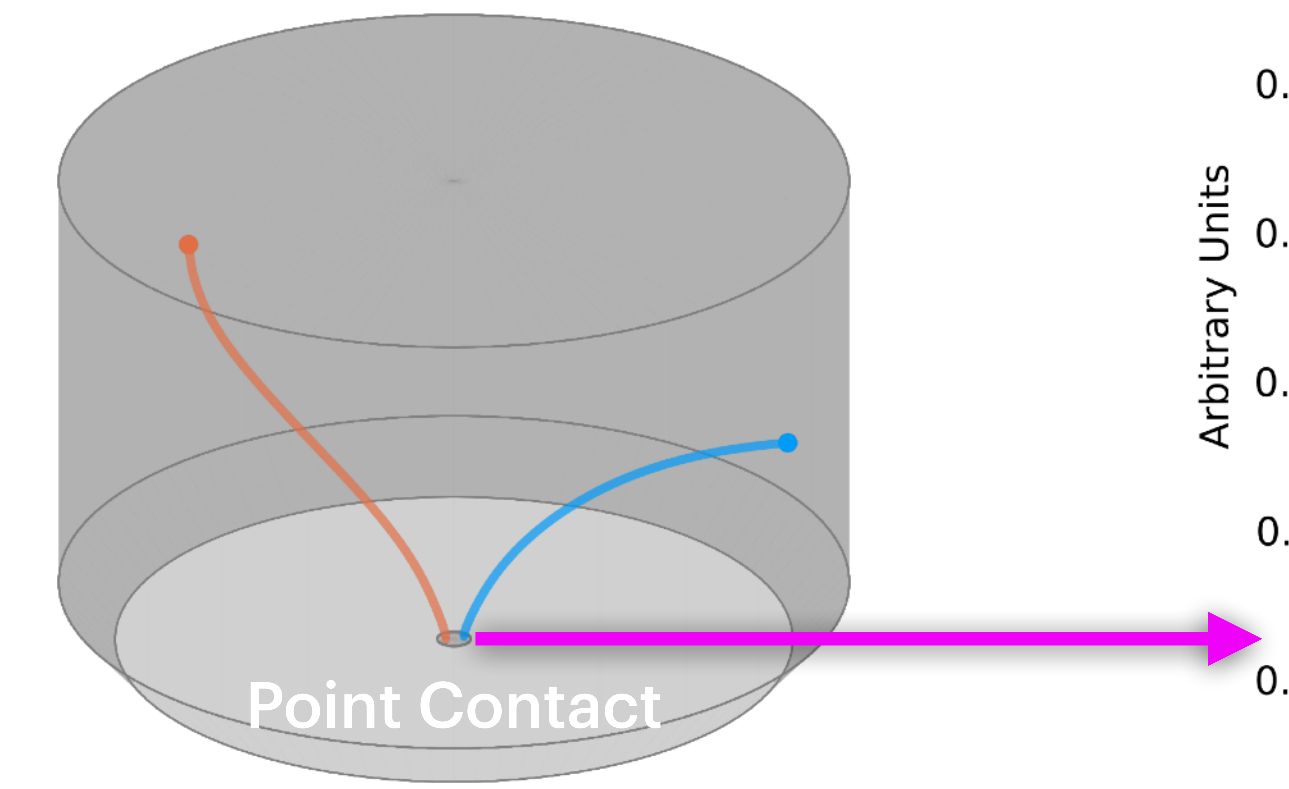
Waveform

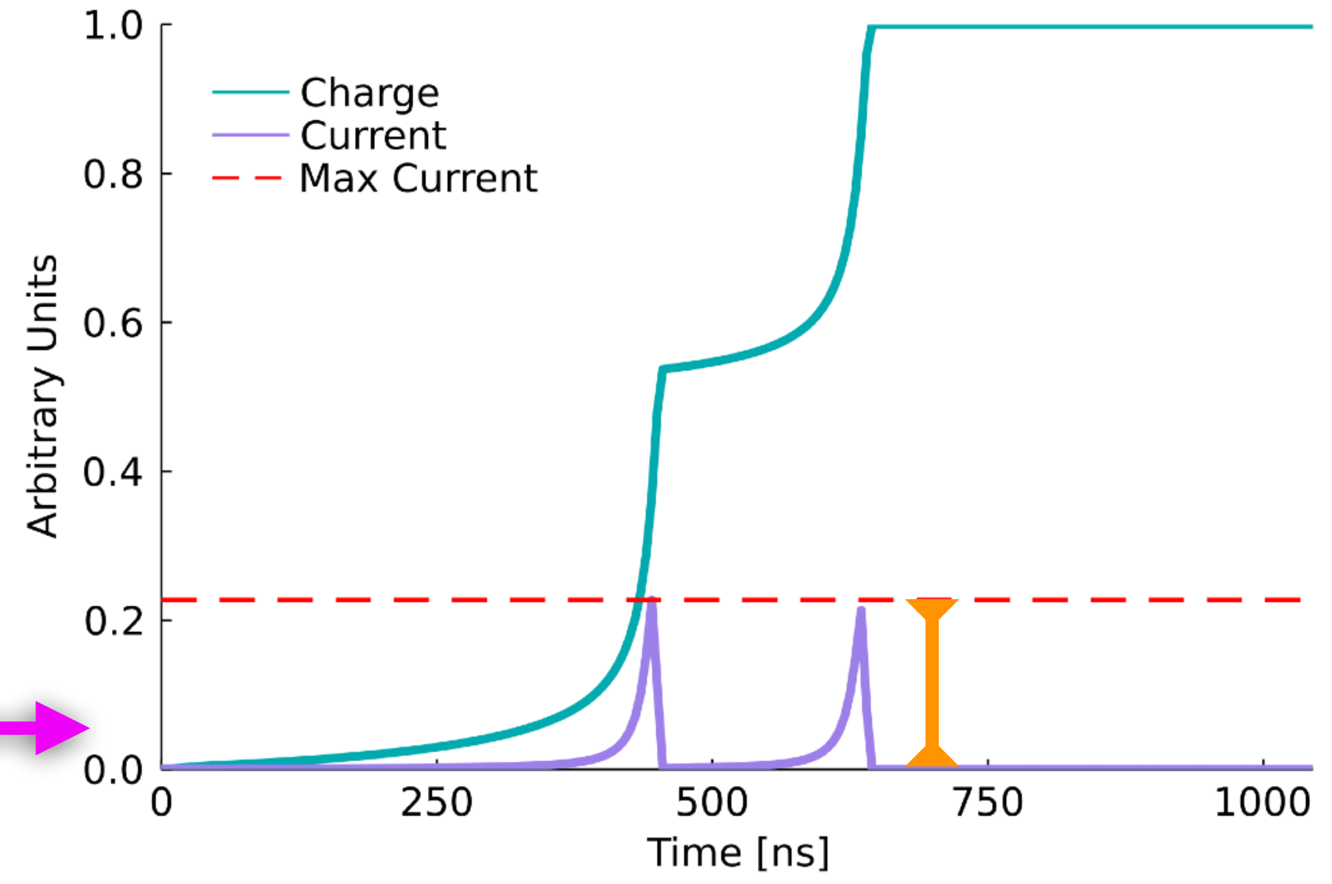


Pulse Shape Parameter

Energy







Maximal Current Amplitude

For **multi-site background** rejection

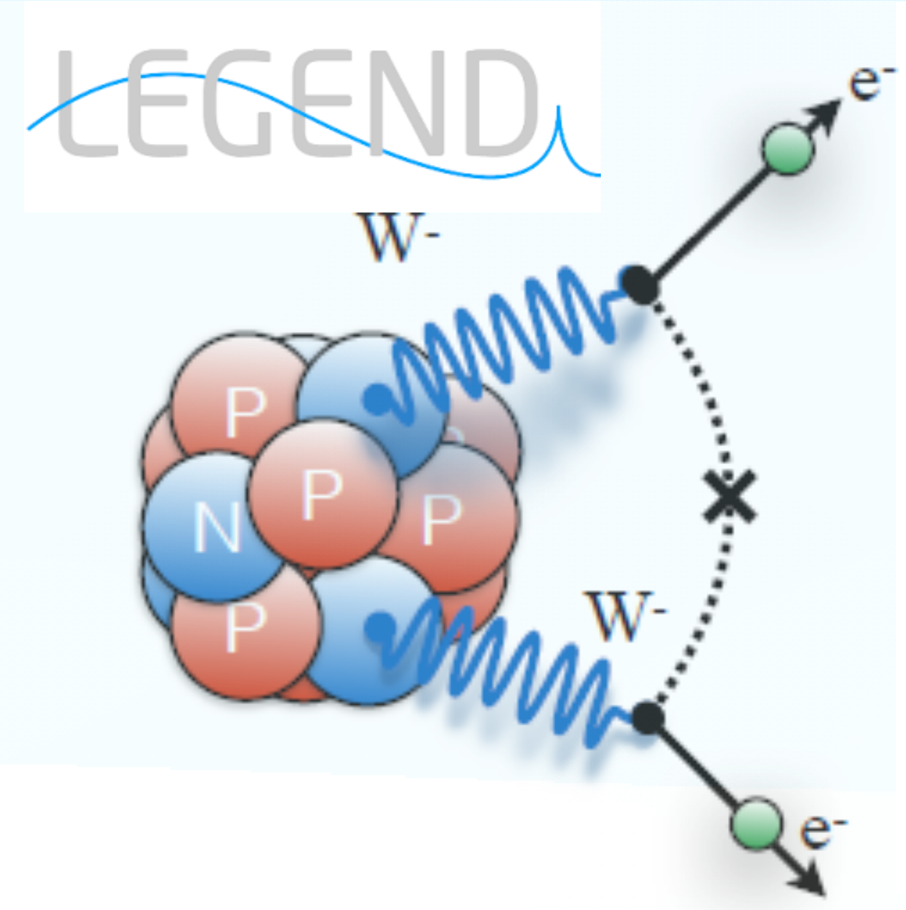
D. Radford
Thursday Plenary: Advanced Materials, Geology, Advanced Data Analysis

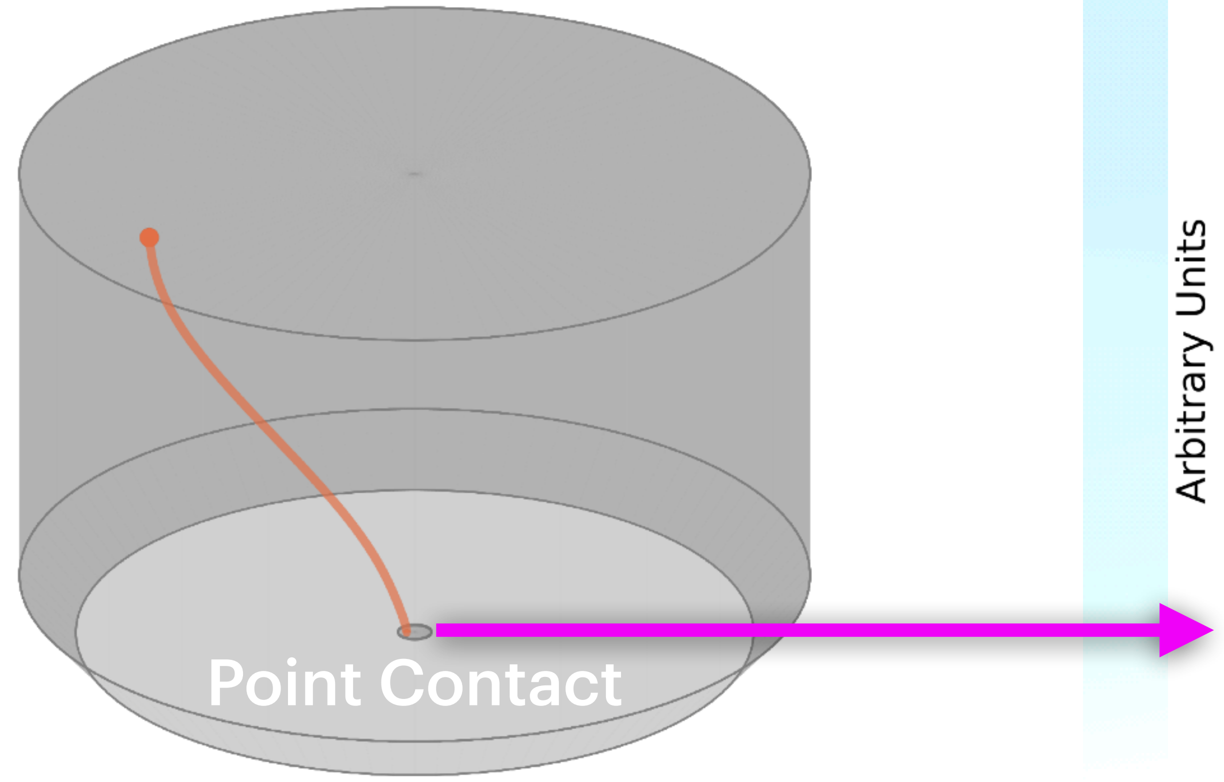
B. Bos
Double Beta Decay Parallel Session

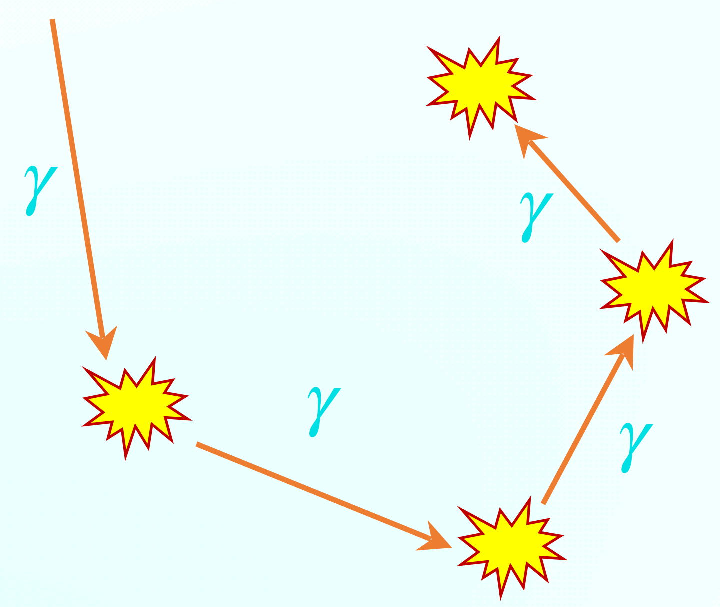
LEGEND

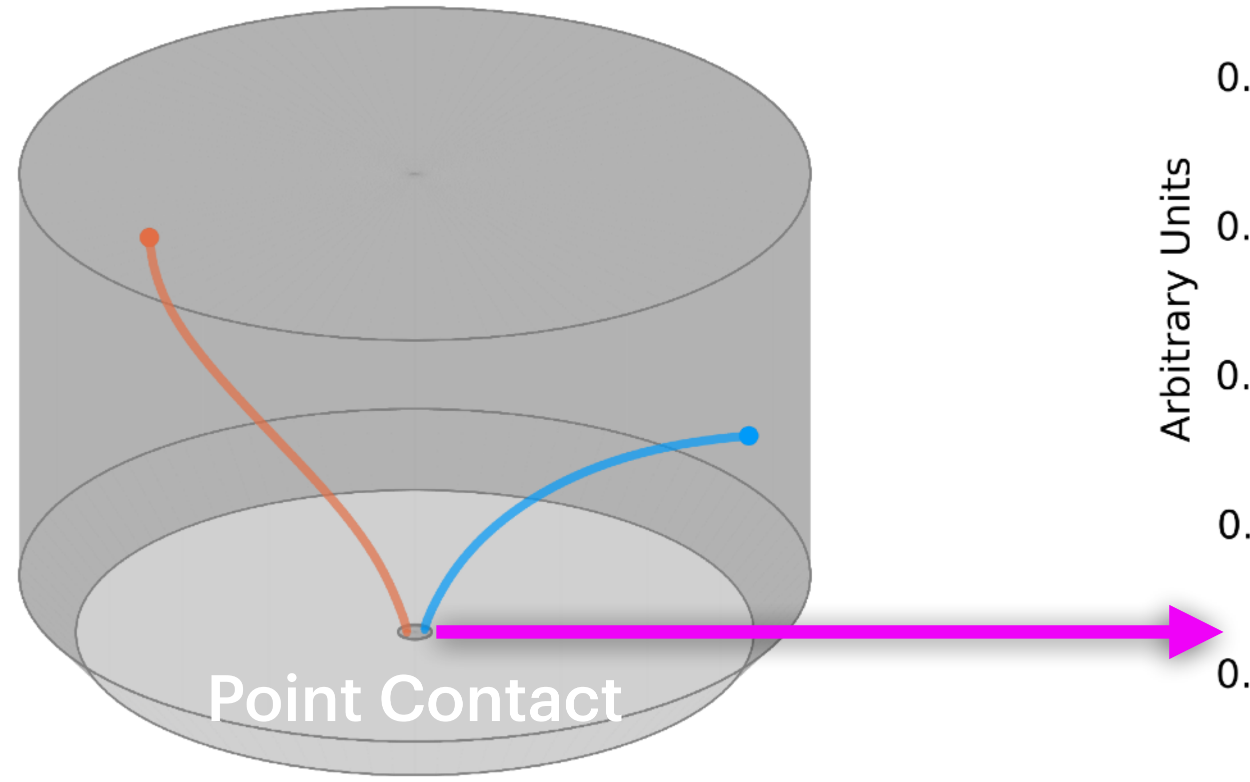
Tonne-Scale Germanium Detector Experiment for NLDBD Search

Semiconductor Detector made with ^{76}Ge

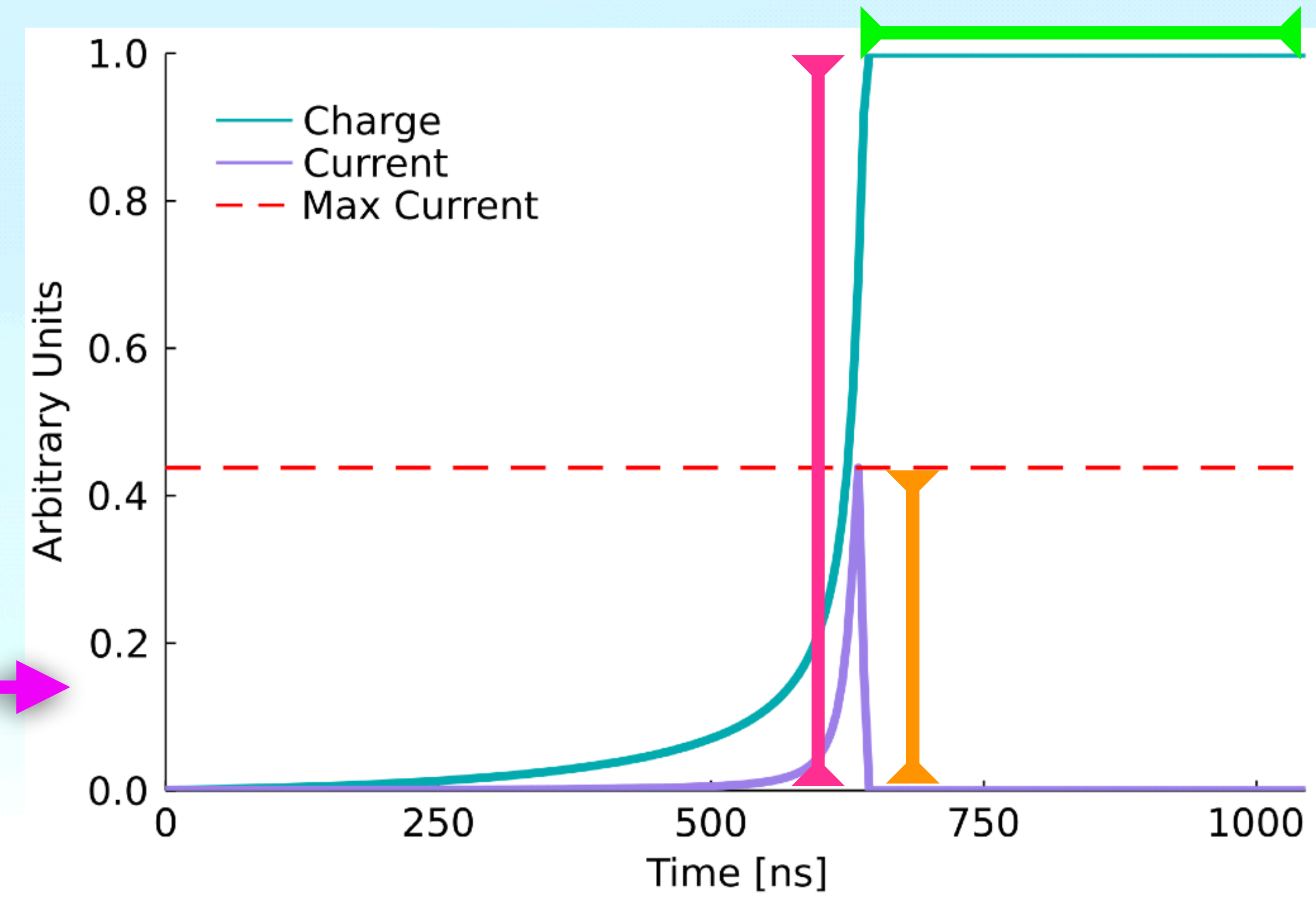


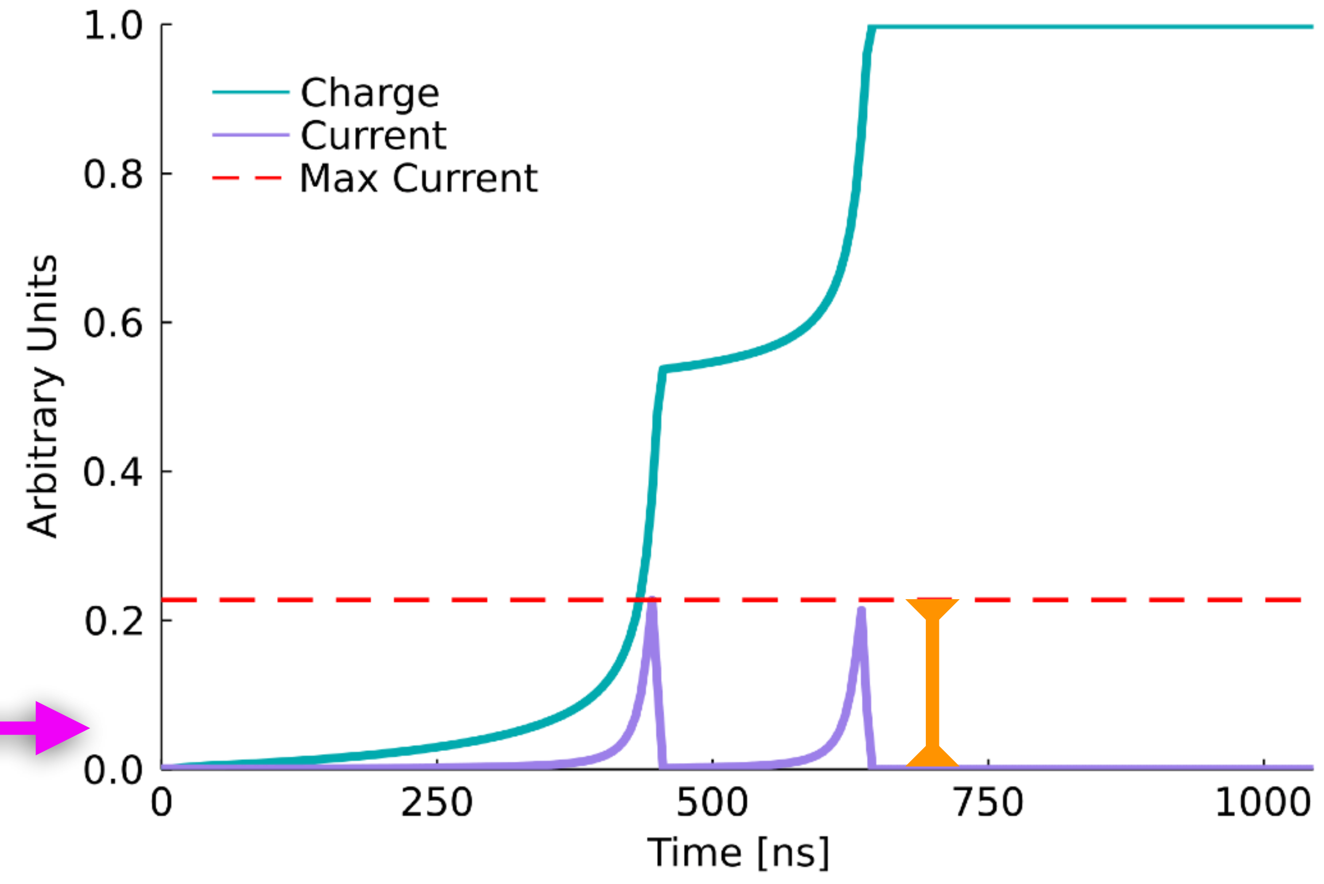






Waveform





Pulse Shape Parameter

Tail Slope

For **surface background** rejection

Energy

Maximal Current Amplitude

For **multi-site background** rejection

LEGEND

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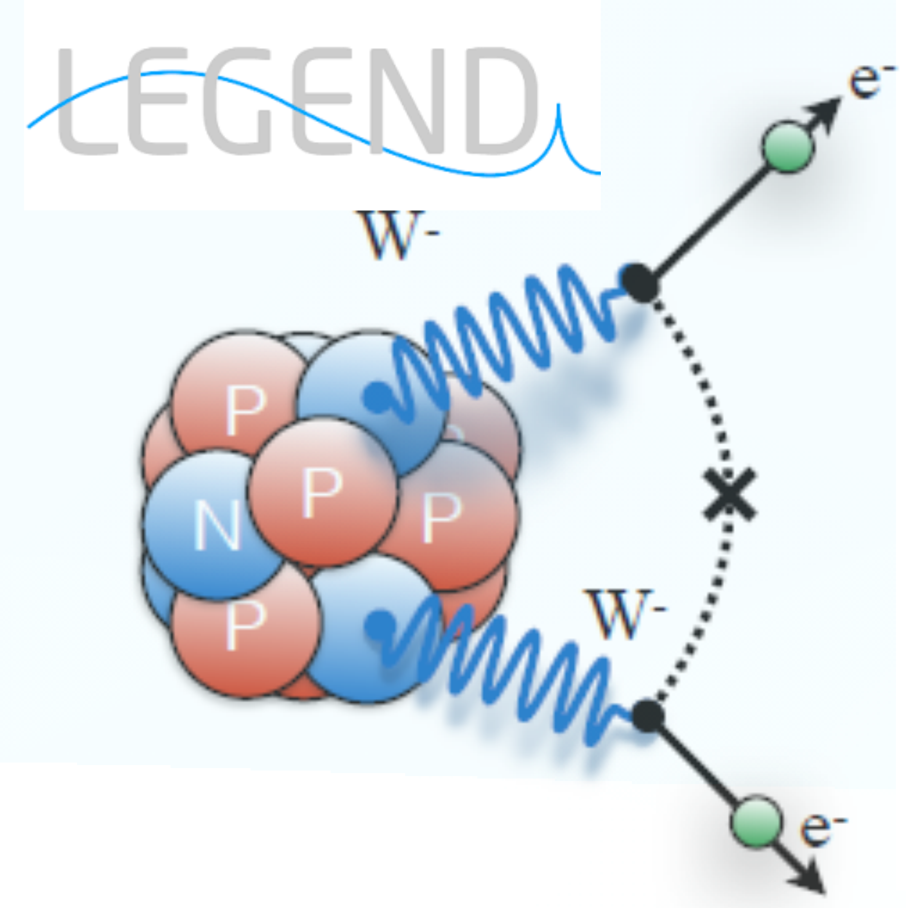
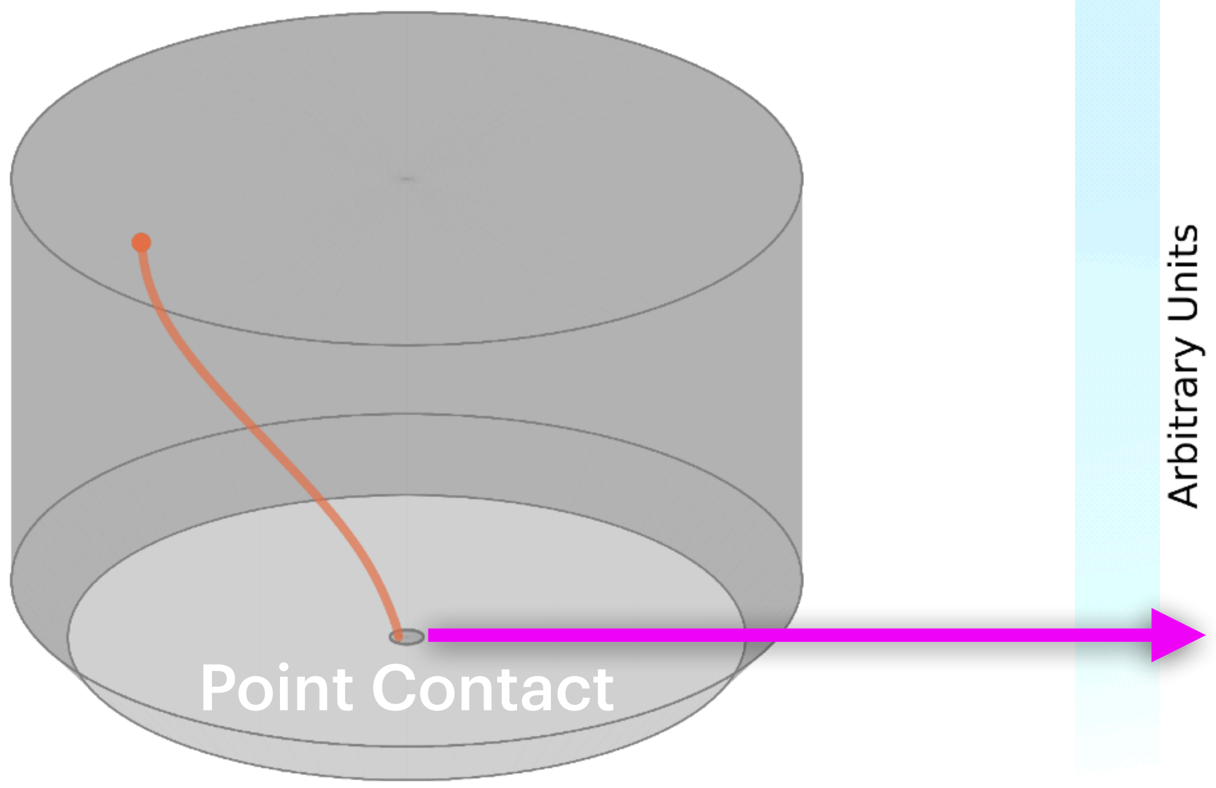
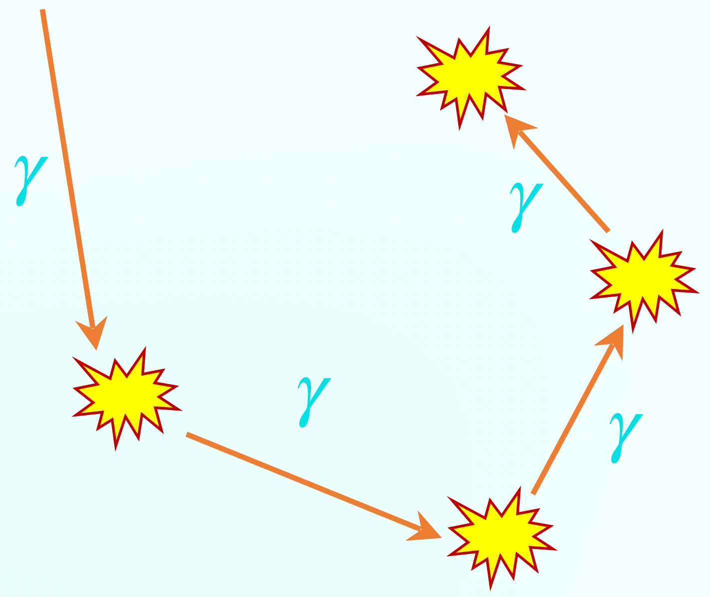
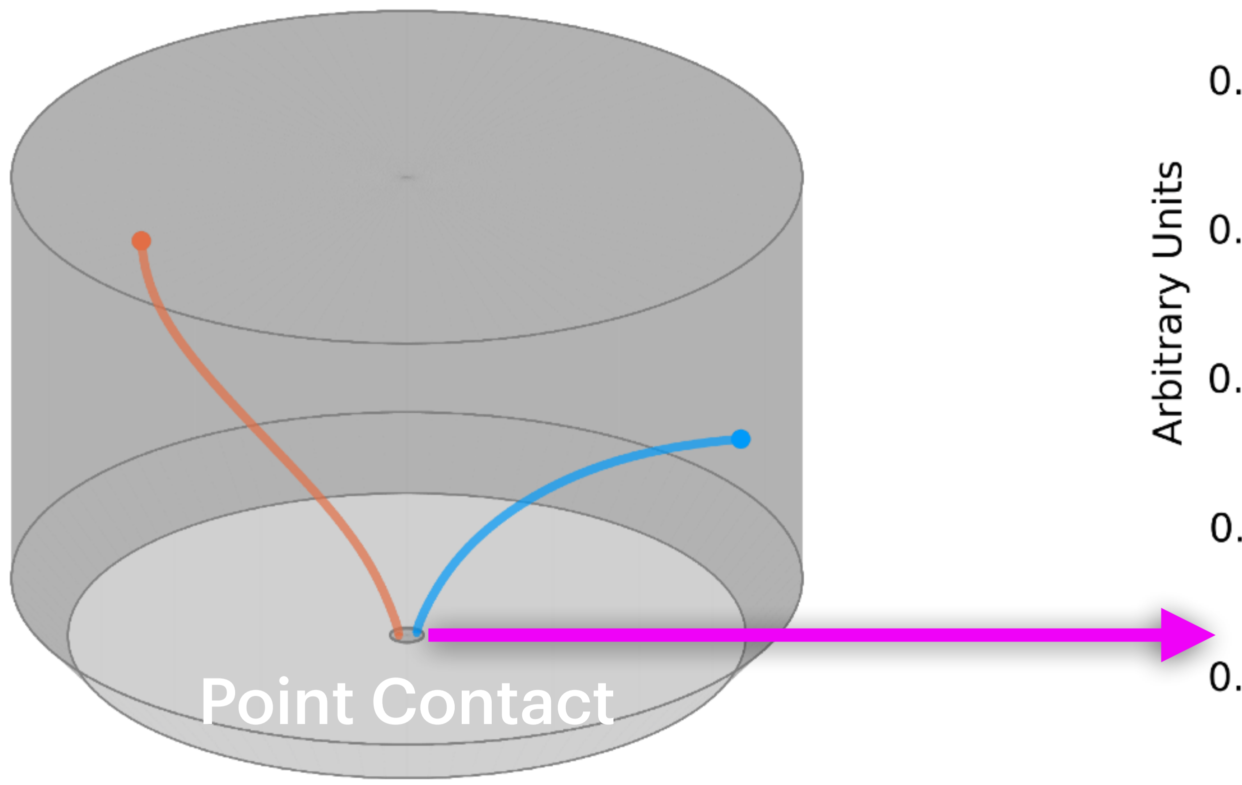
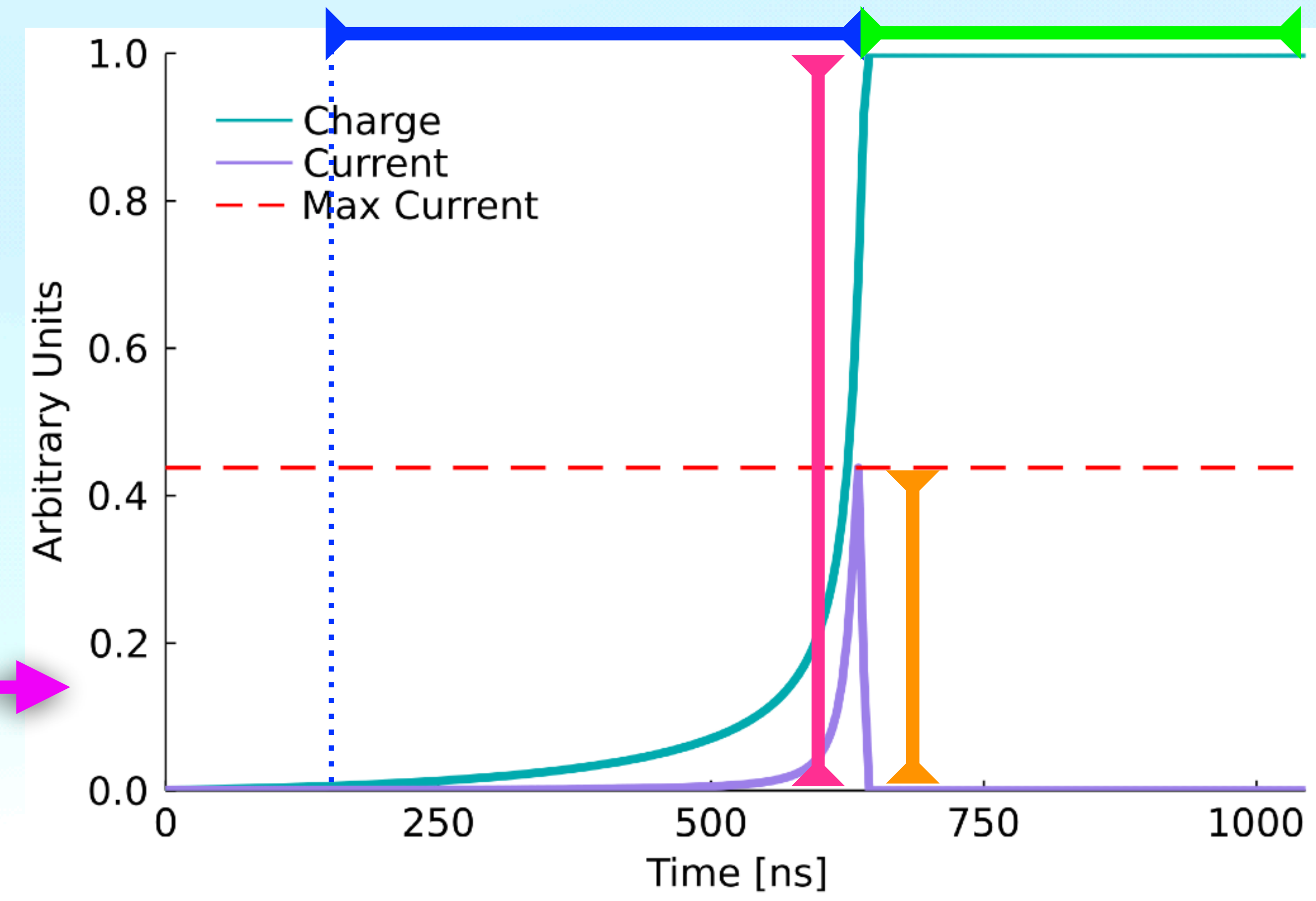


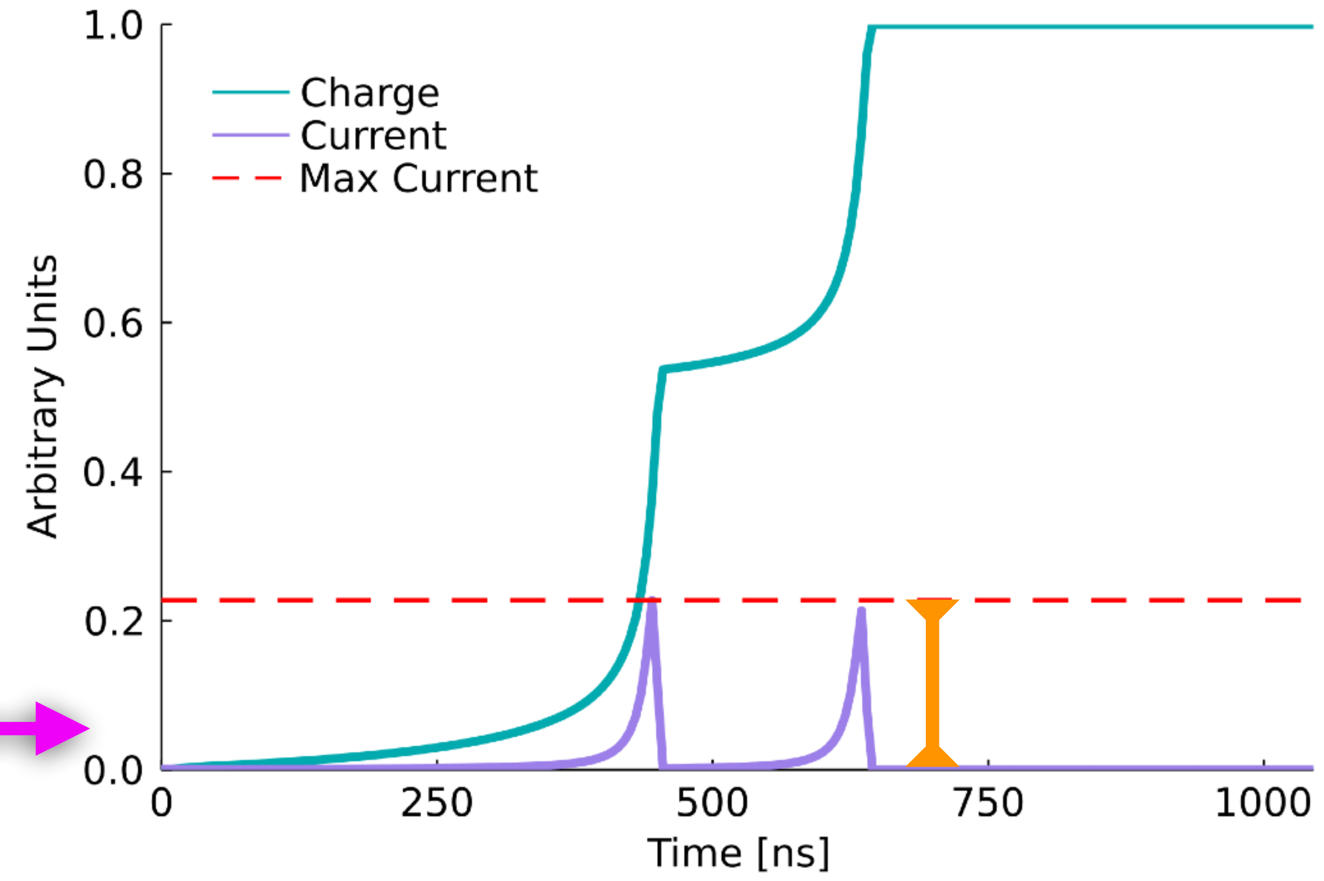






Waveform





Pulse Shape Parameter

Tail Slope

For **surface background** rejection

Energy

Maximal Current Amplitude

For **multi-site background** rejection

Drift Time

Reflect the location of incident particle

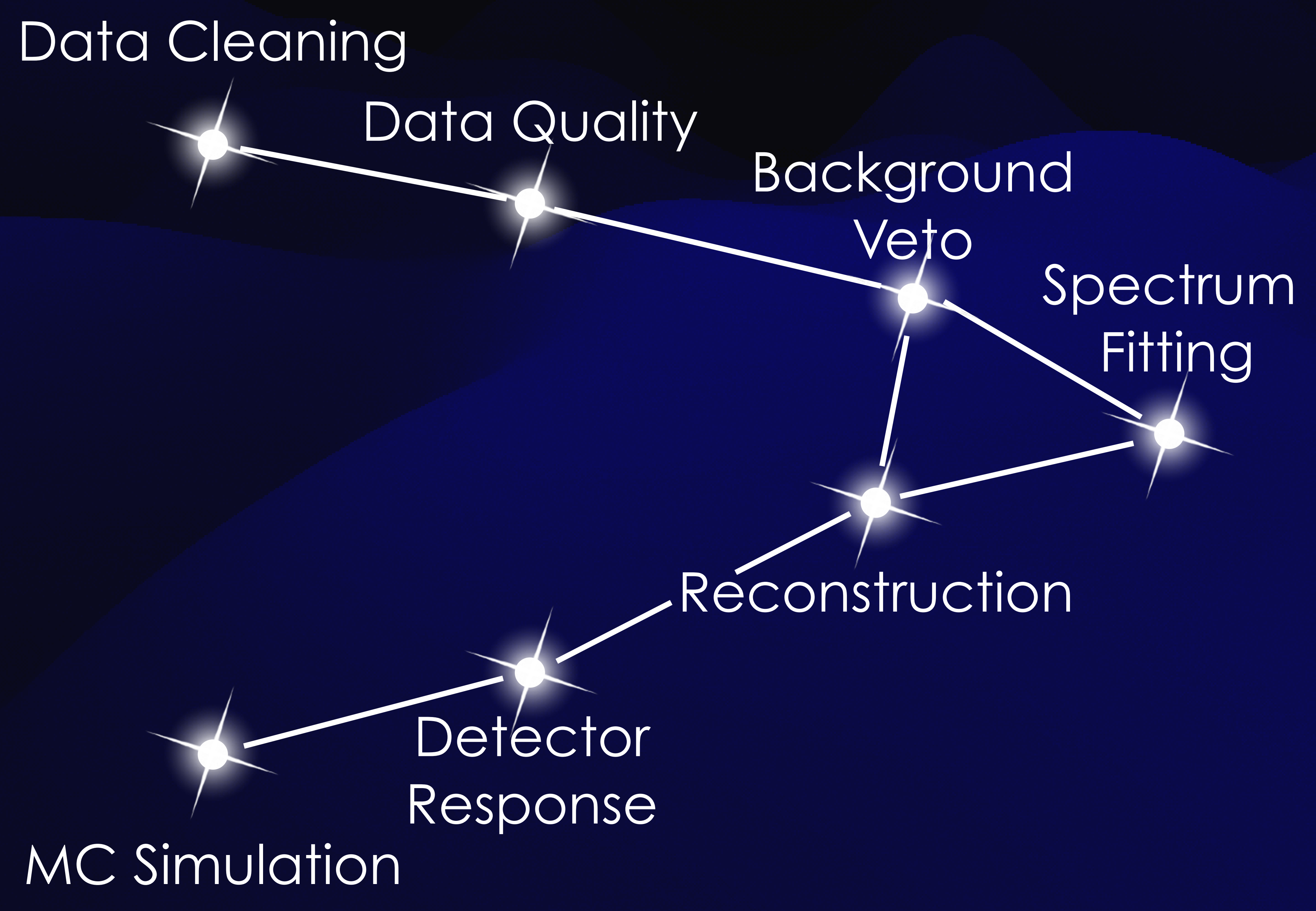
Germanium Machine Learning (GeM) Group

Leverage efficient and interpretable AI to aid all aspects of LEGEND analysis and simulation

Leverage resources to educate domestic and international collaborators to gain AI experience

Completed Project

Ongoing/Future Project



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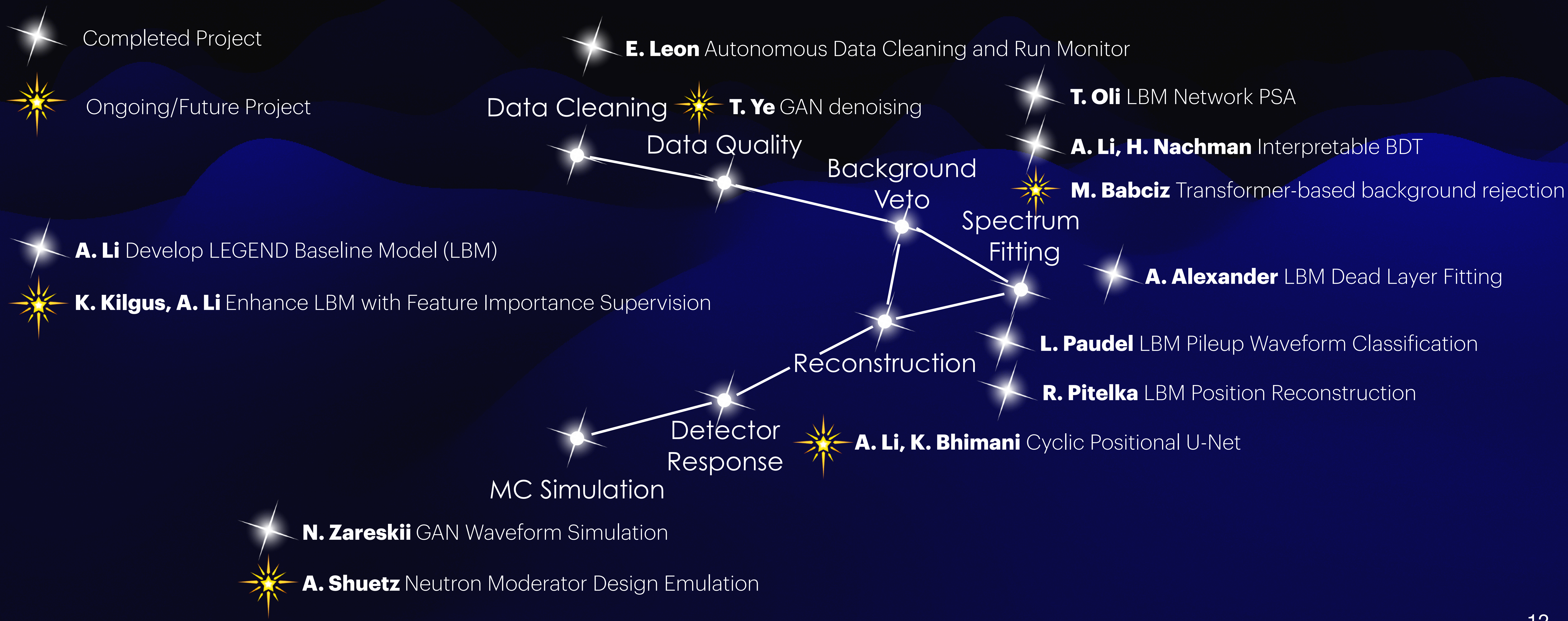
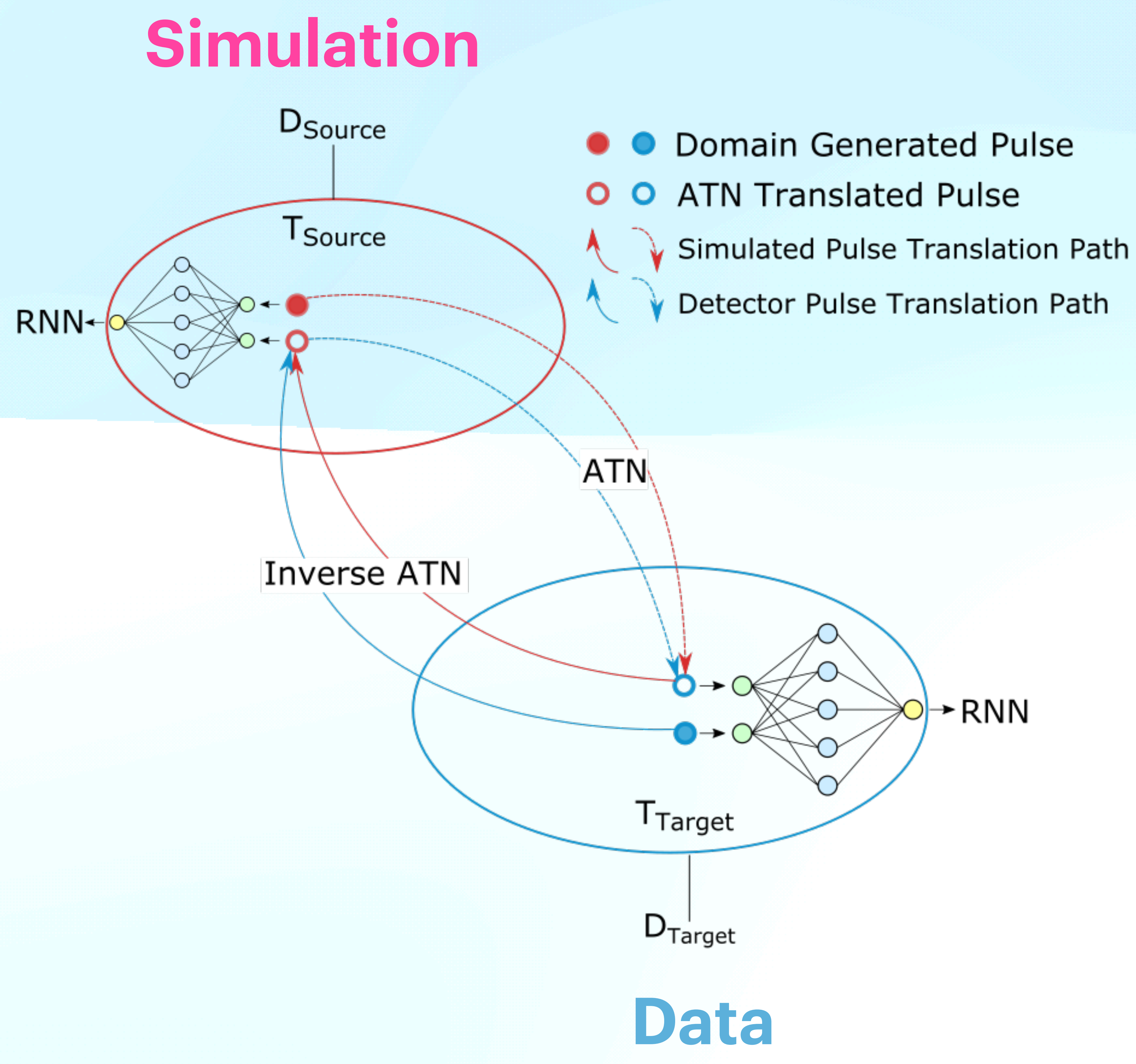
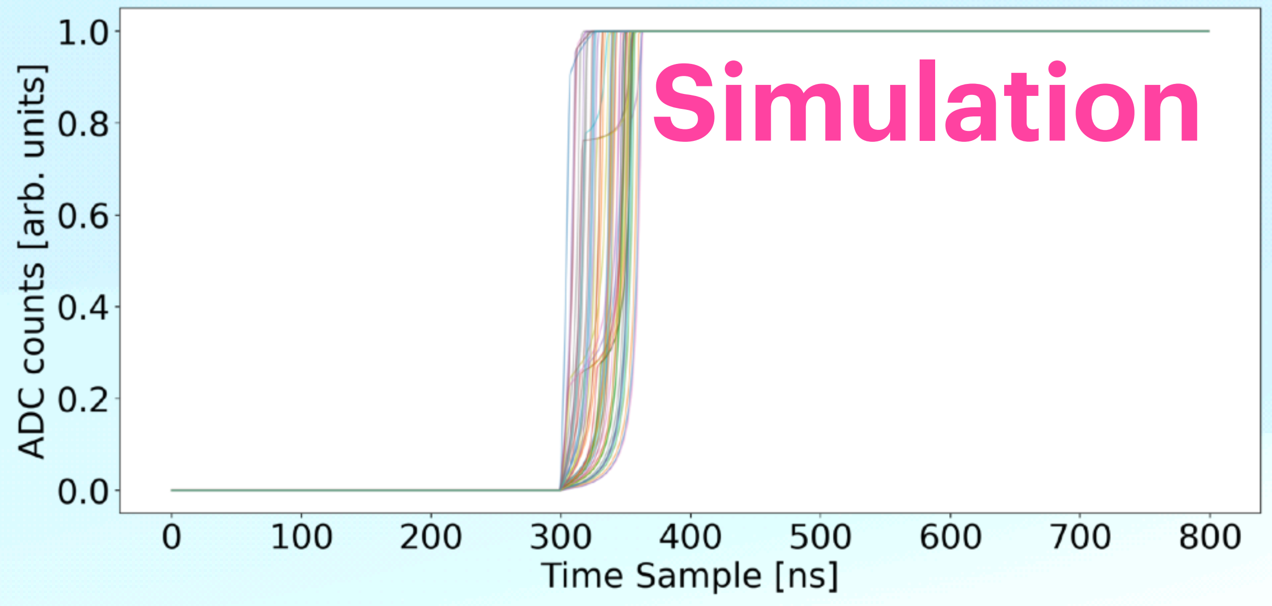


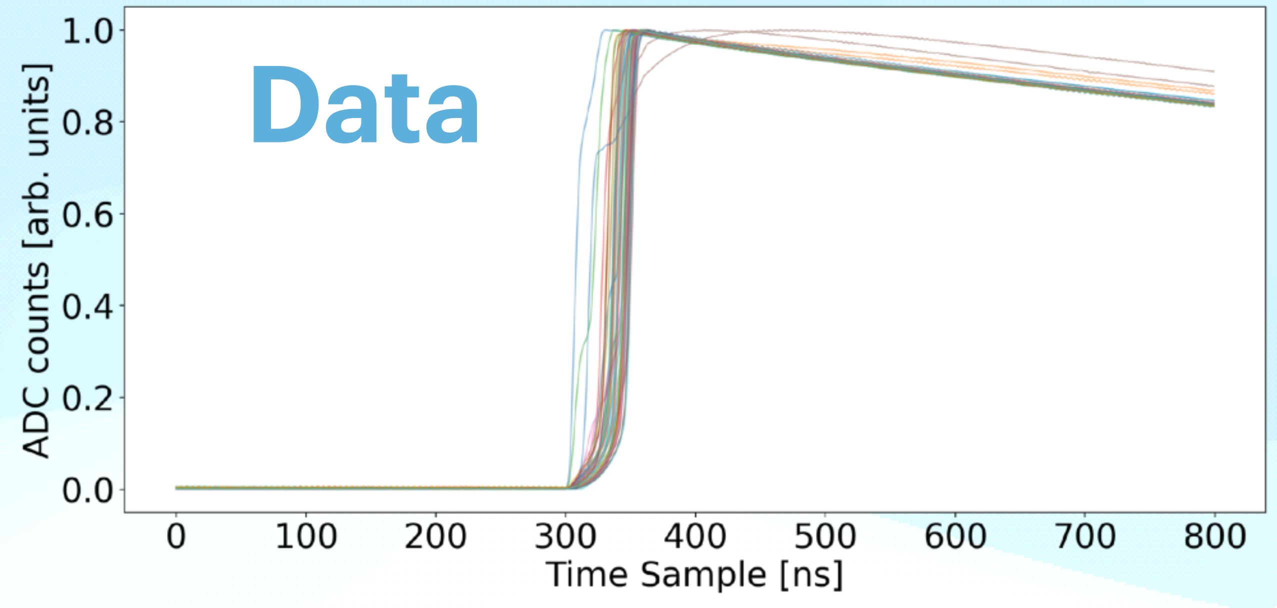
CPU-Net: Translate Simulation to Data

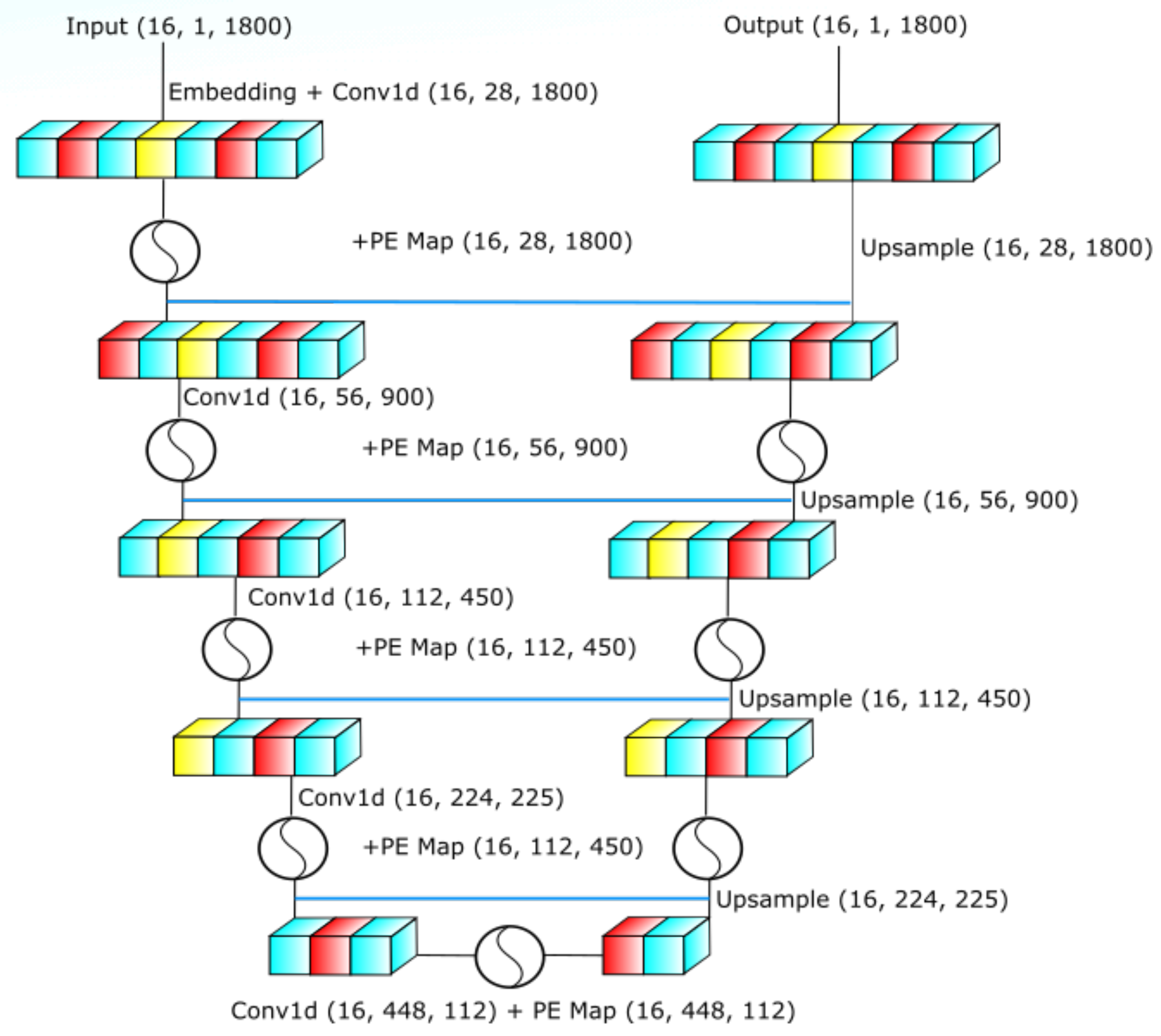
Unpaired Translation with CycleGAN

Ad-hoc Pulse Shape Simulation using Cyclic Positional U-Net
A. Li et al. NeurIPS 22 ML4PS Workshop Outstanding Paper
Updated Manuscript Under Preparation









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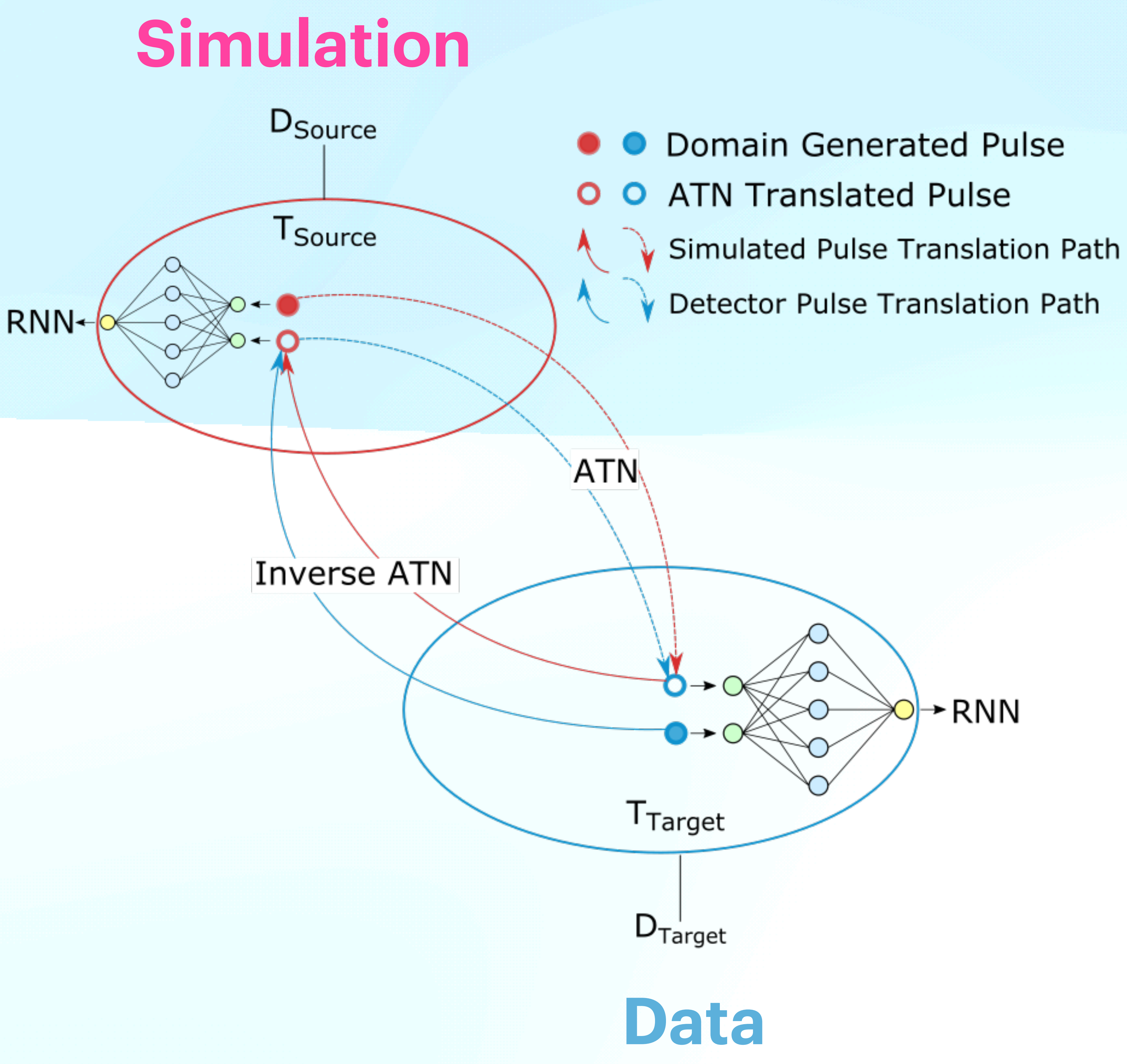
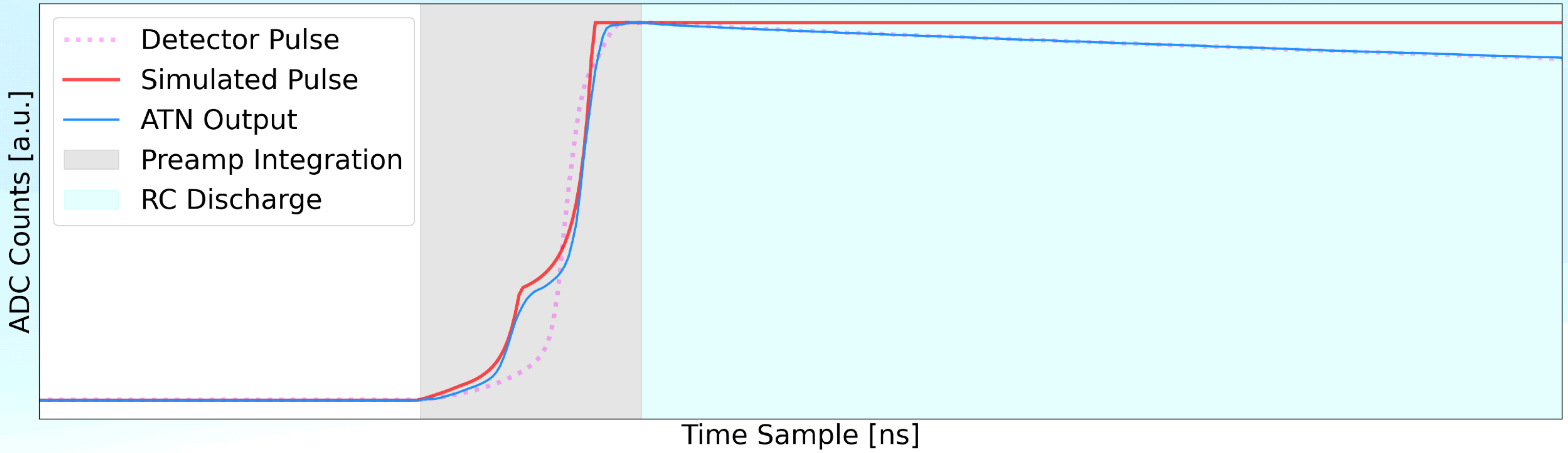
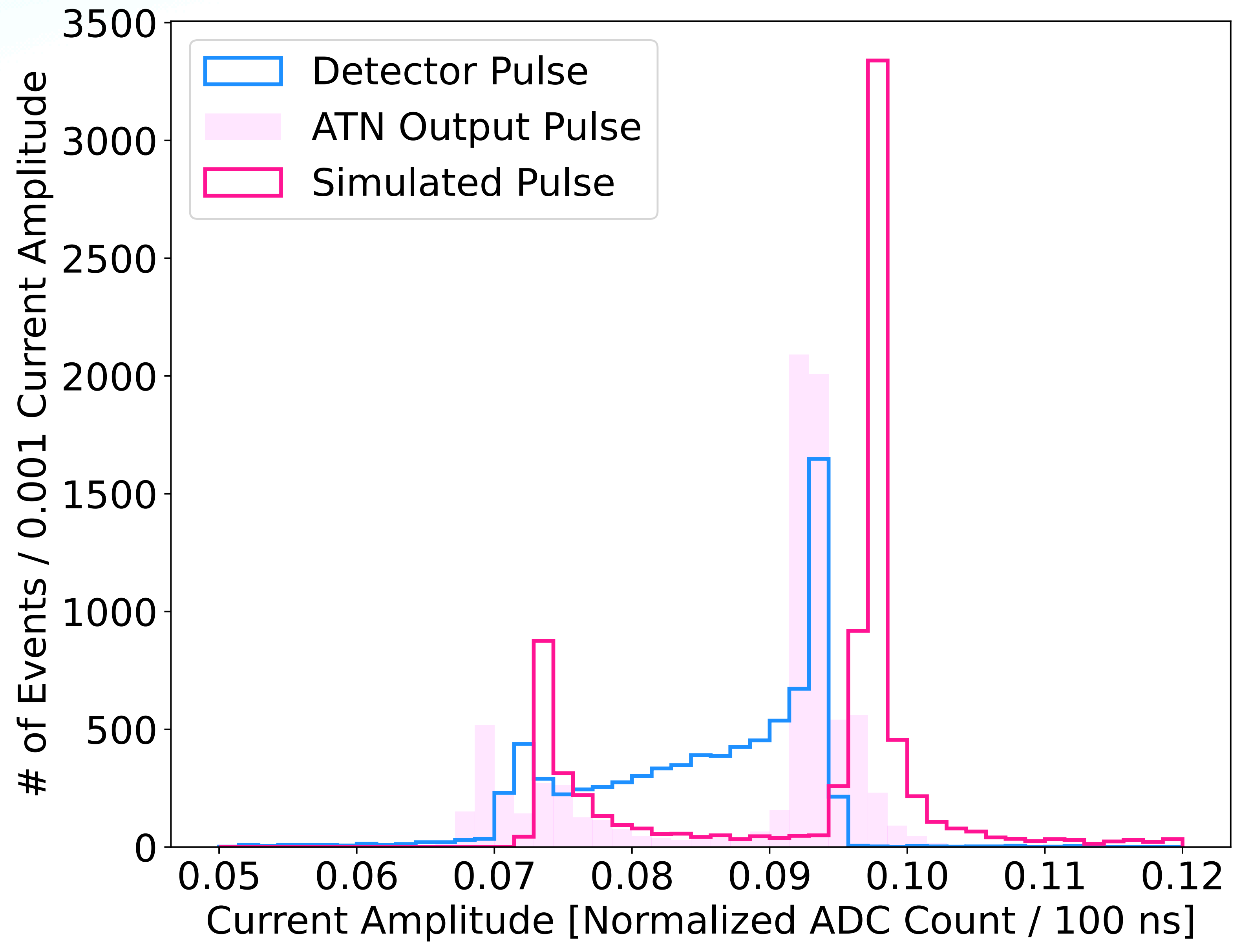
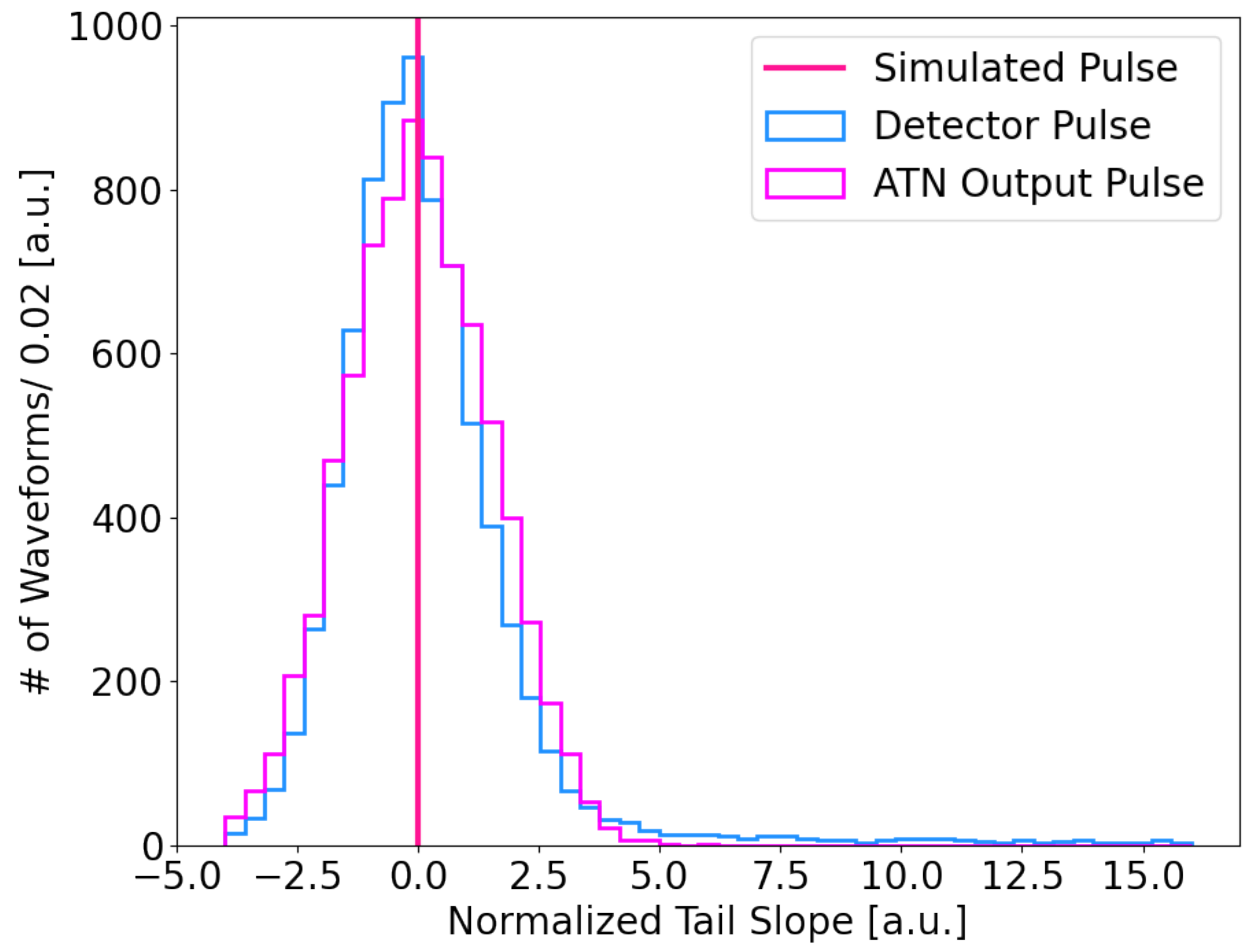








Physics in Rare Event Search

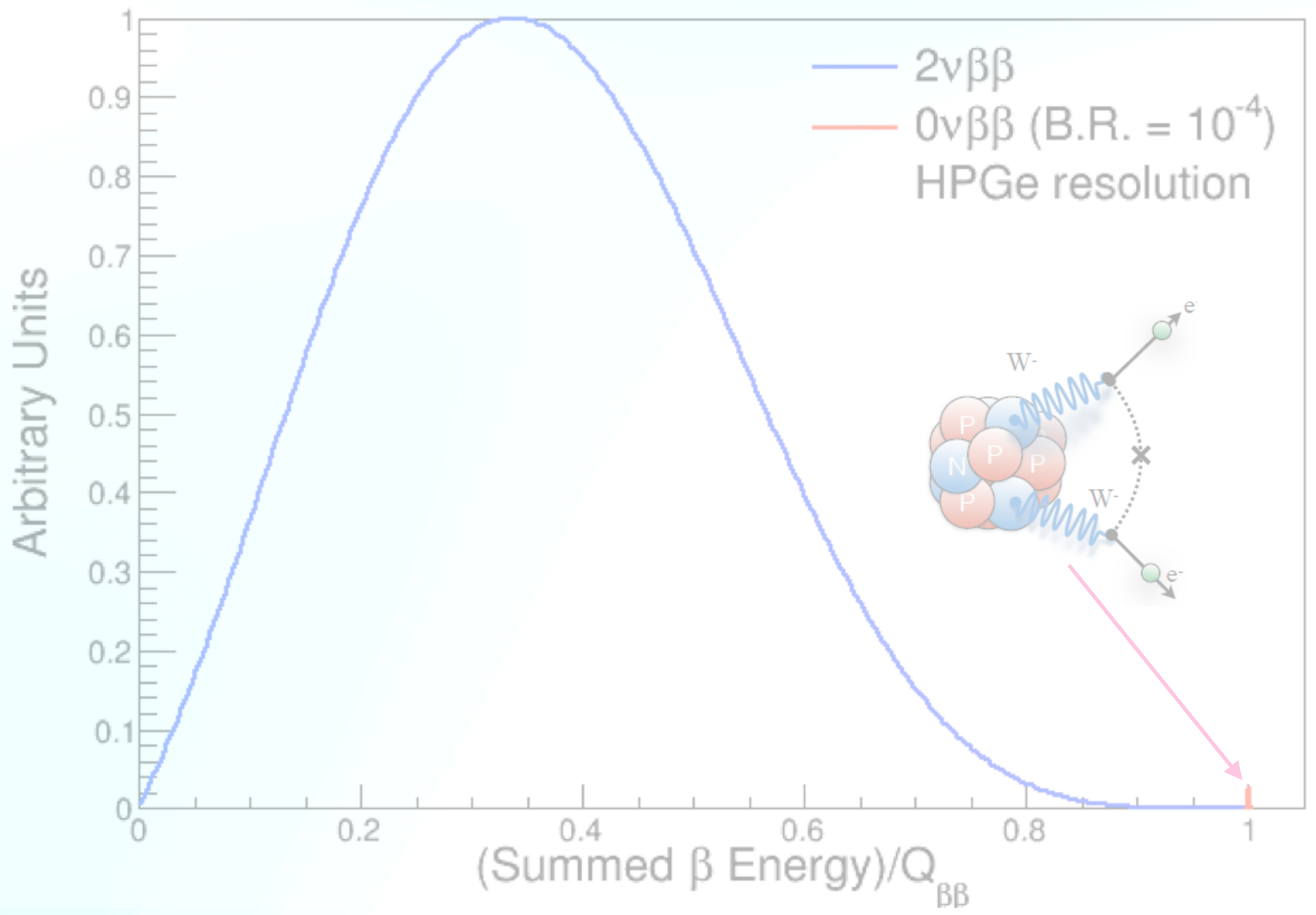
Neutrinoless Double-Beta Decay (NLDBD)

ΔL = 2 lepton number violation process

Prove that neutrinos are **Majorana particle**

Explain the **matter-antimatter asymmetry** in our universe

Has not been observed at $T_{\frac{1}{2}} > 10^{26} yrs$



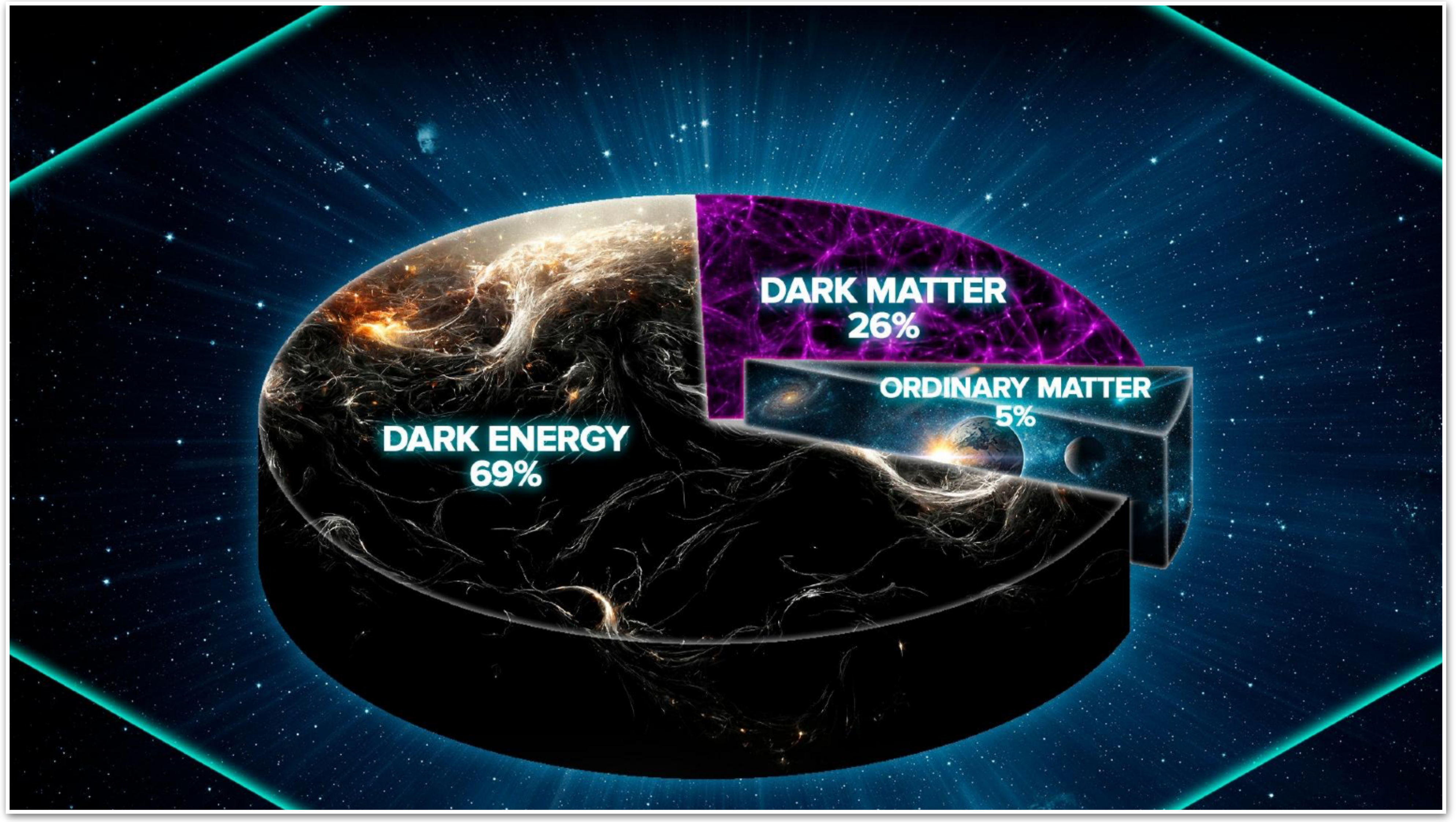
Dark Matter (DM)

Strong astrophysical evidence, no observation on earth

We don't know which particle makes up dark matter:

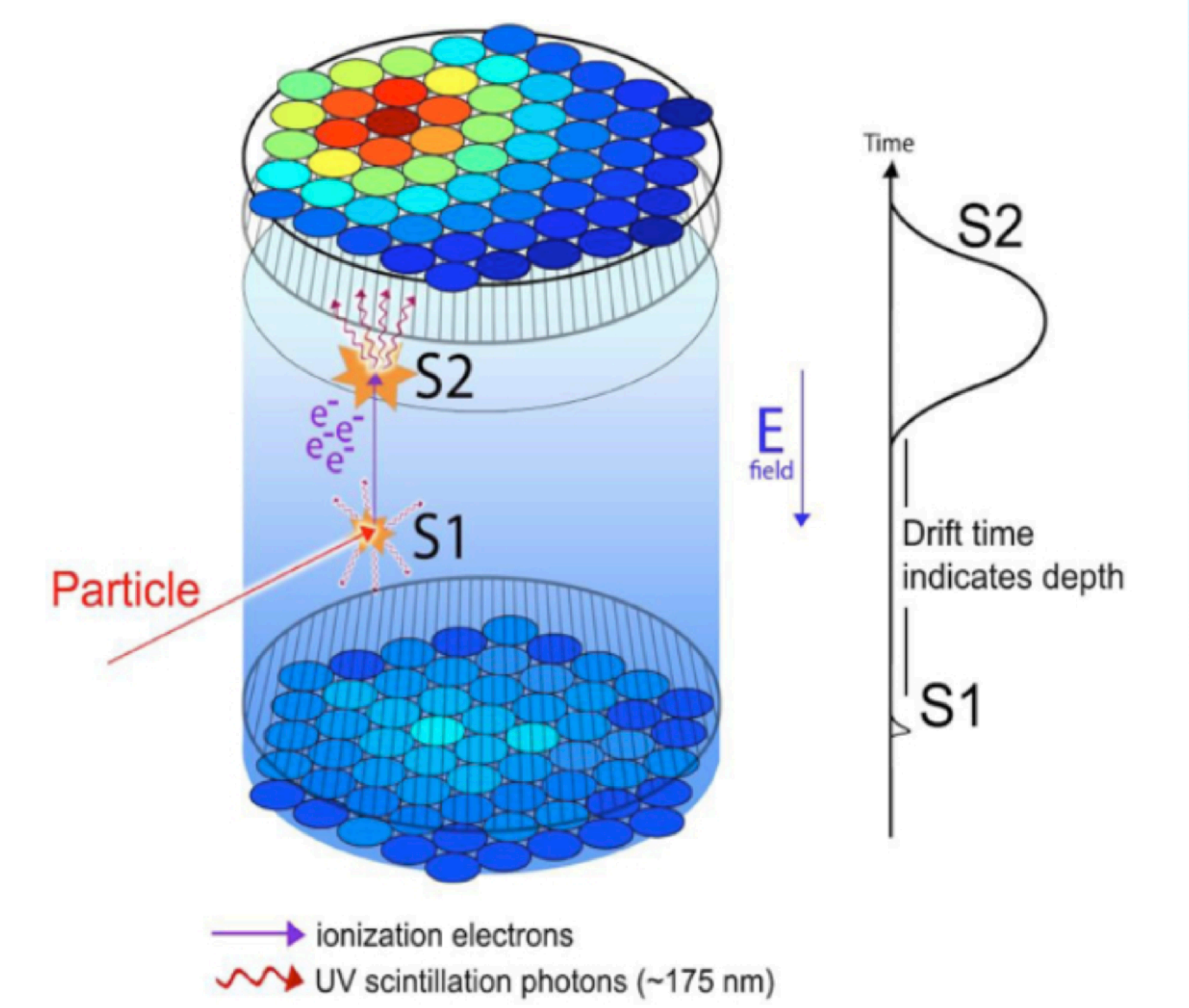
- Heavy, particle-like DM candidate: **WIMP**
- Light, wave-like DM candidate: **Axion**

WIMP has not been observed at $\sigma < 10^{-47} cm^2$



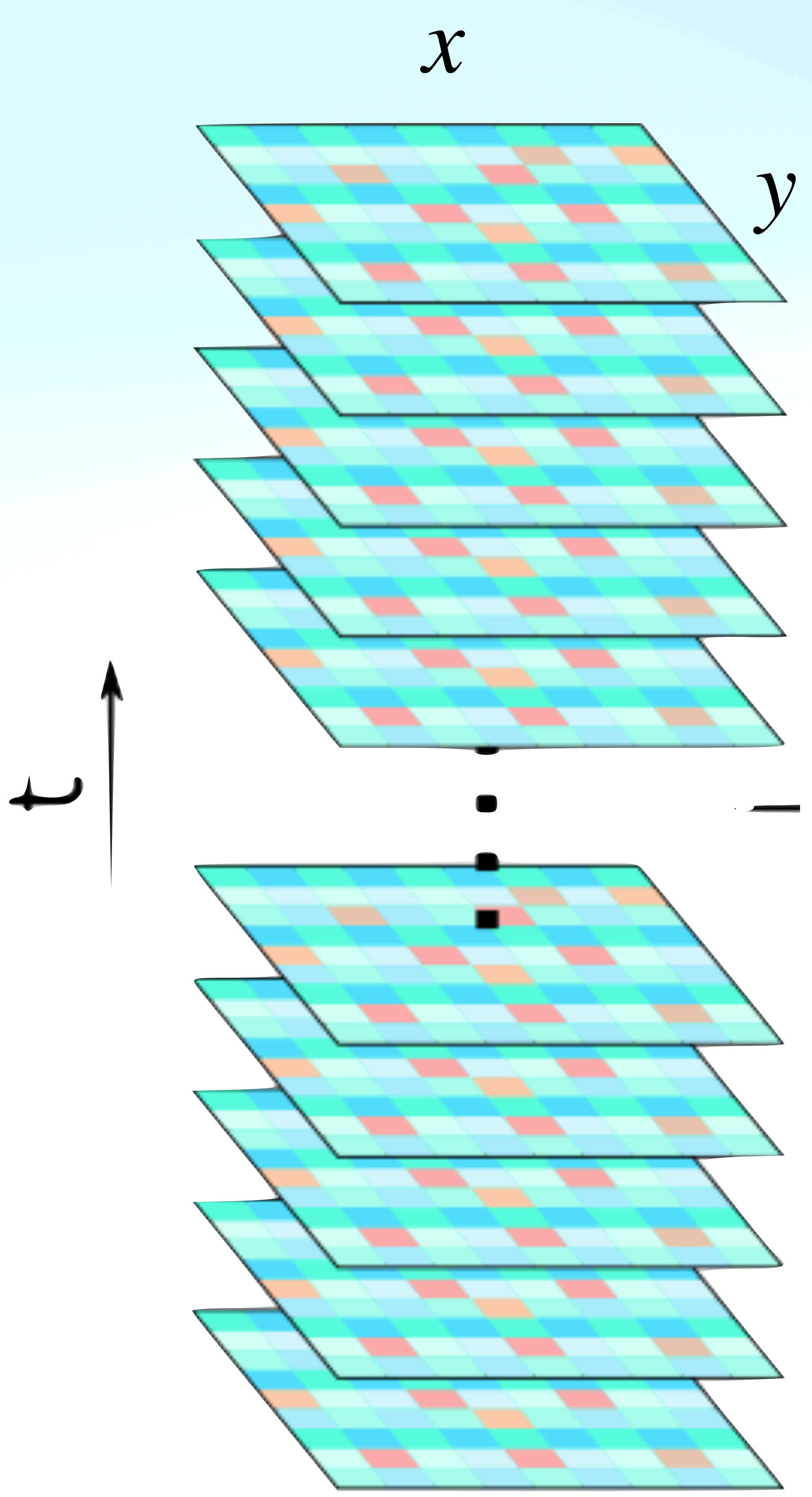
XENONnT

2-Phase Liquid Xenon Time Projection Chamber for WIMP DM Search



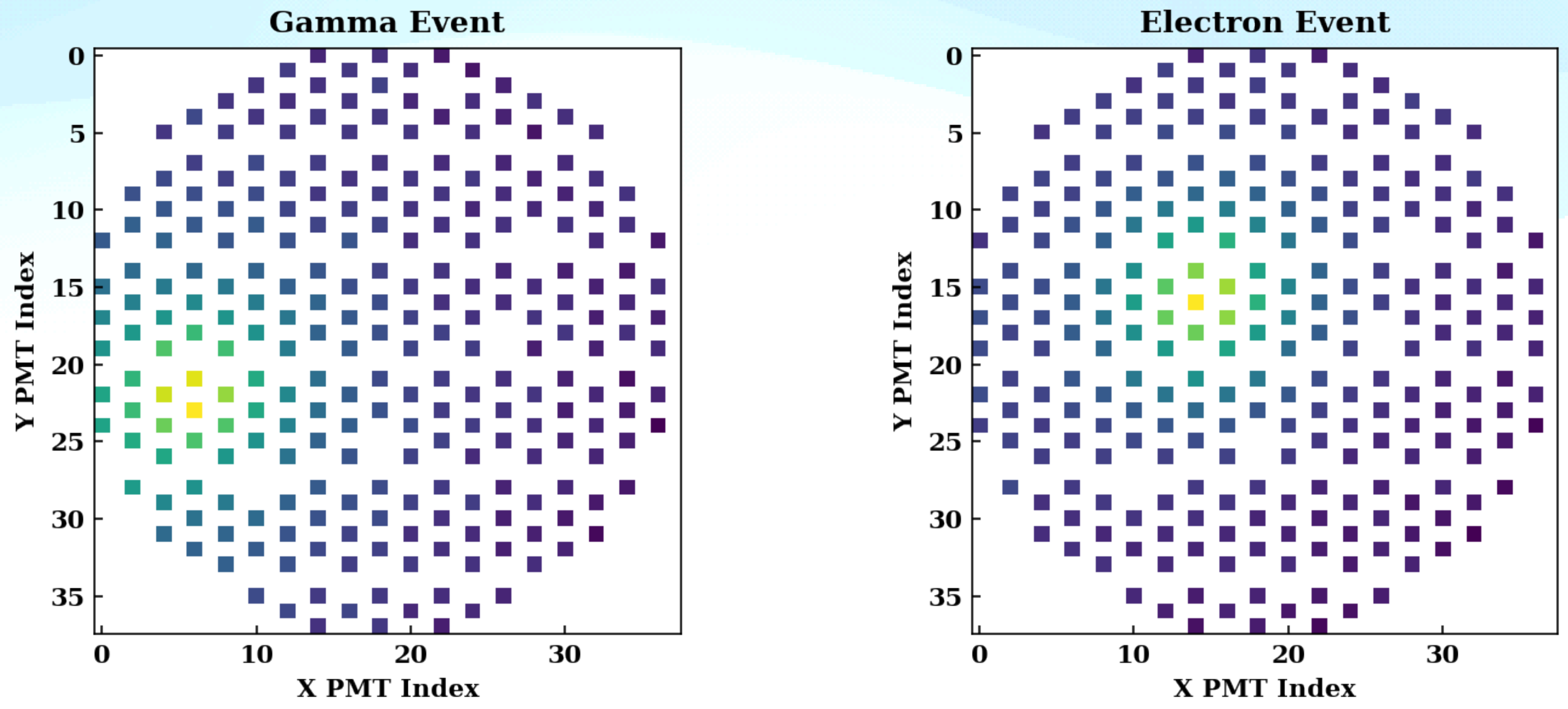
Spatiotemporal Data

A 2D flat video



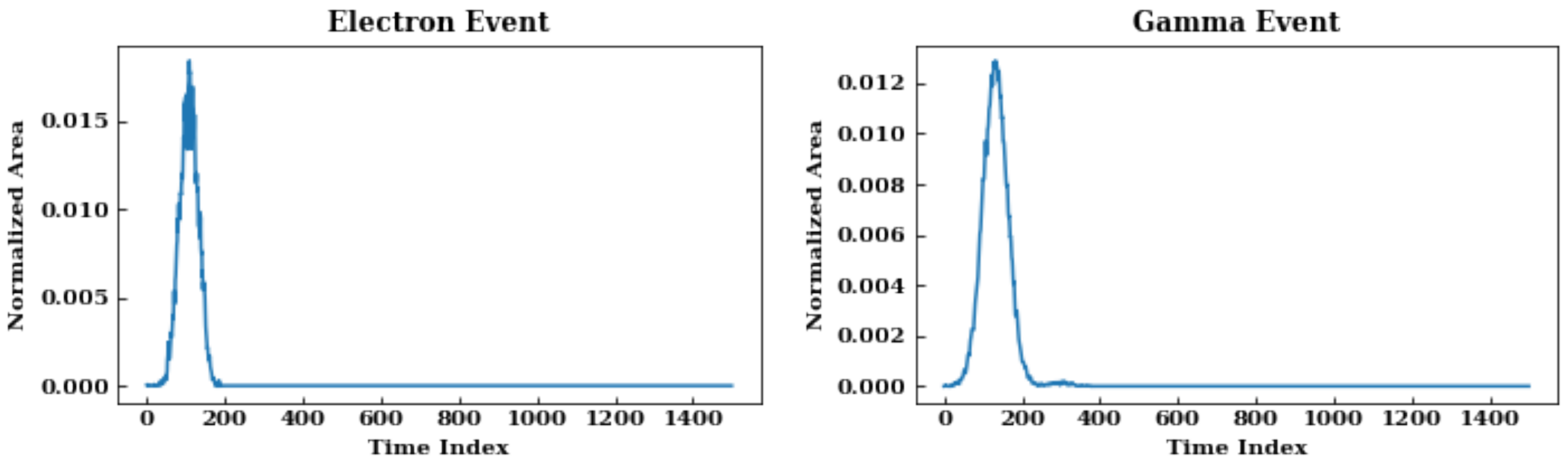
Hit Pattern

2D Image



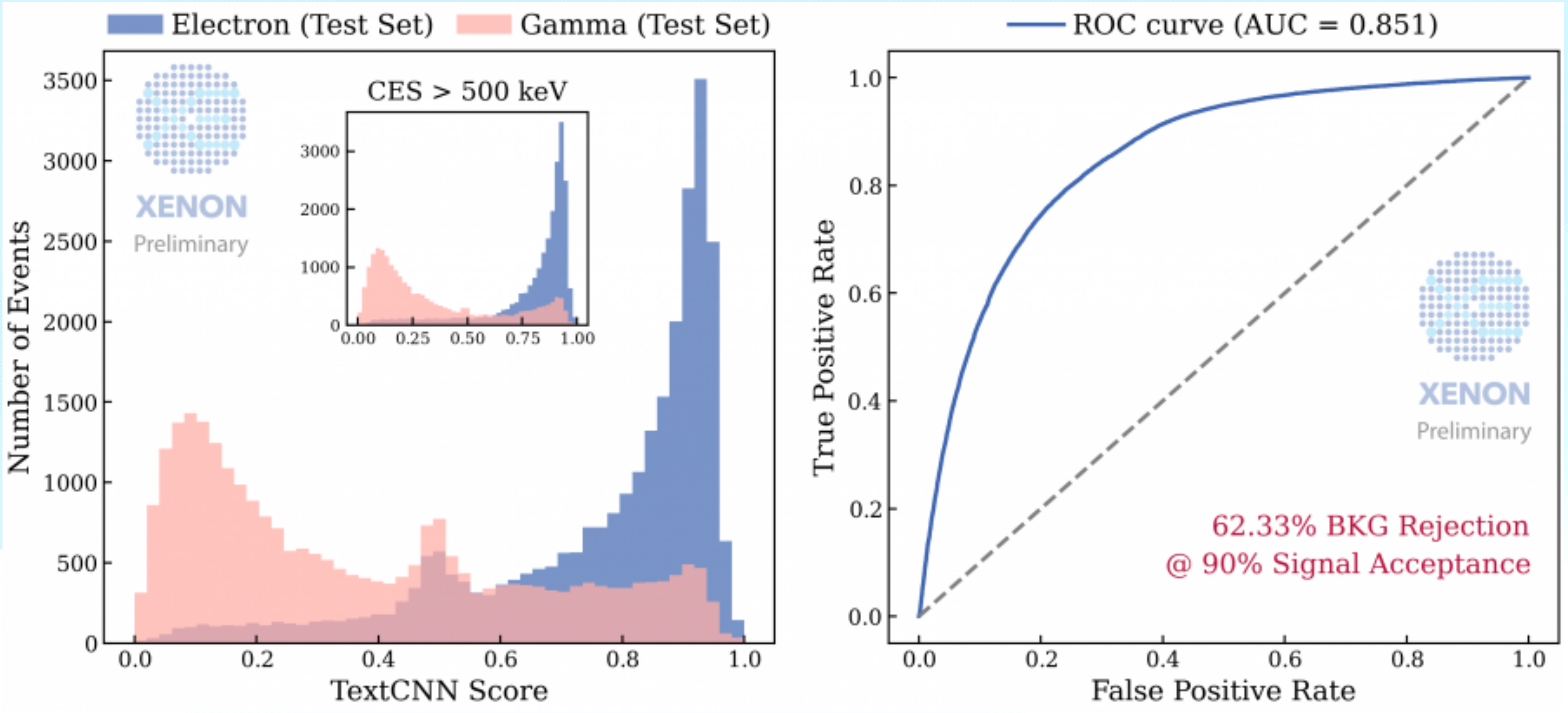
Waveform

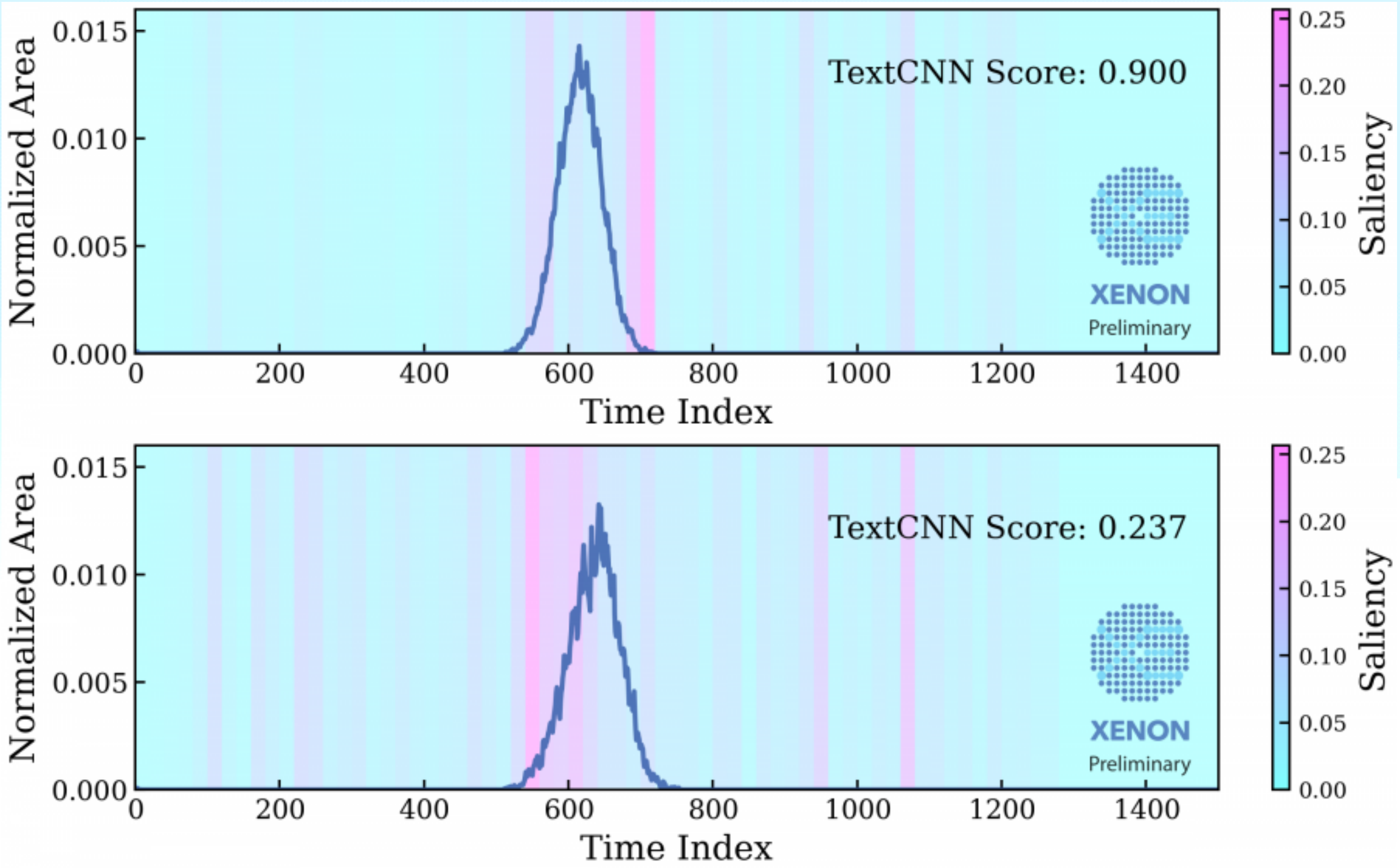
1D Time Series



TextCNN for High Energy Background Rejection

Background rejection based solely on the waveforms





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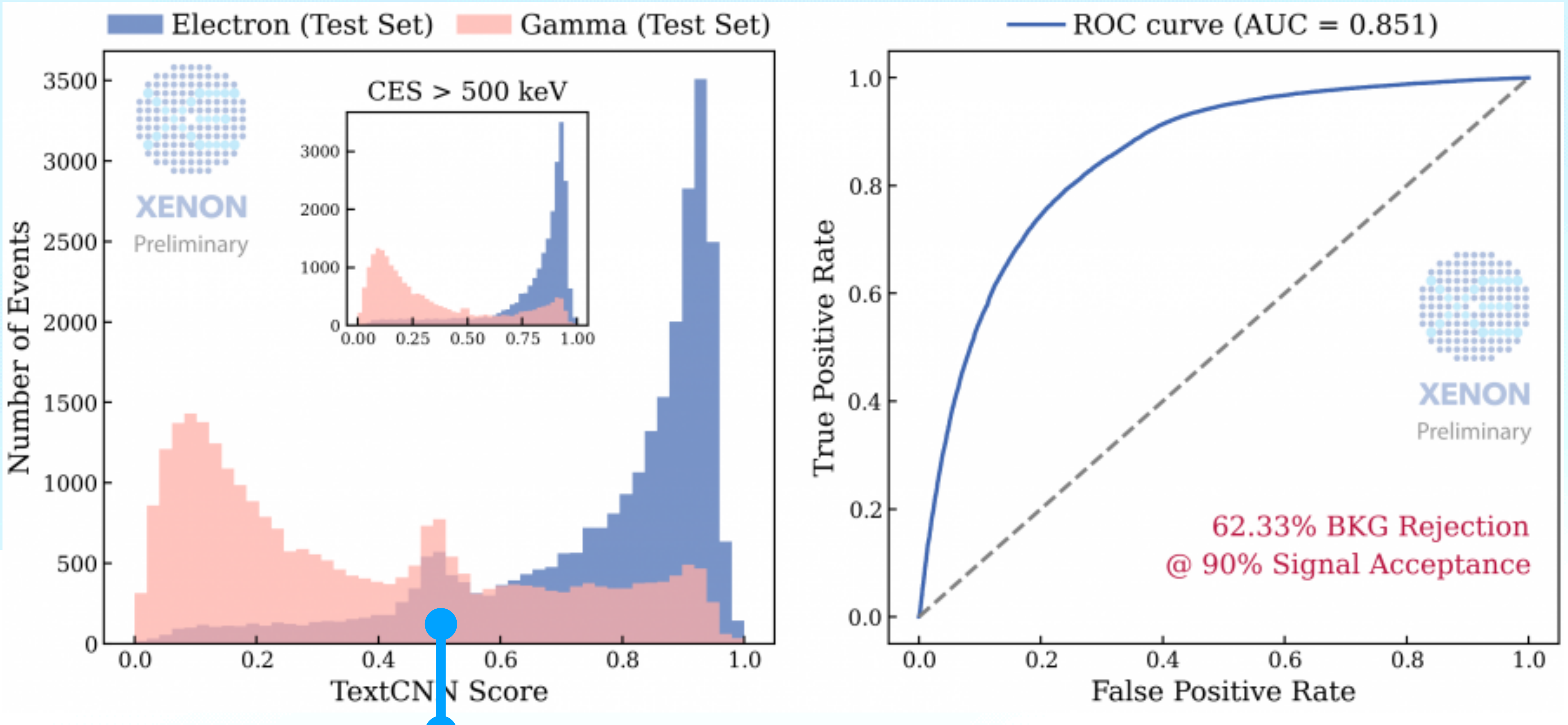
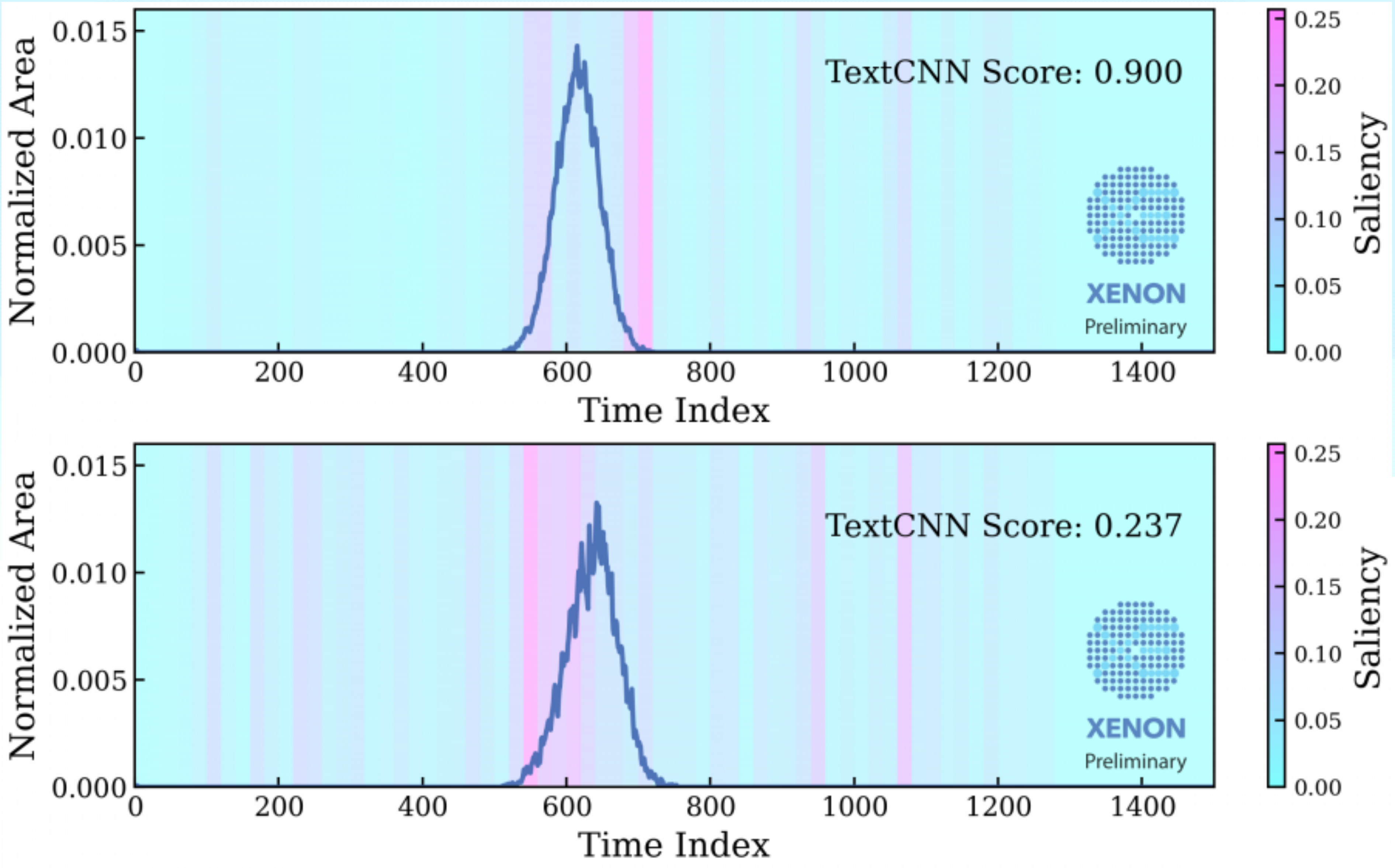


Faithful Decision

Assign score of 0.5 when encounter hard-to-classify low energy events



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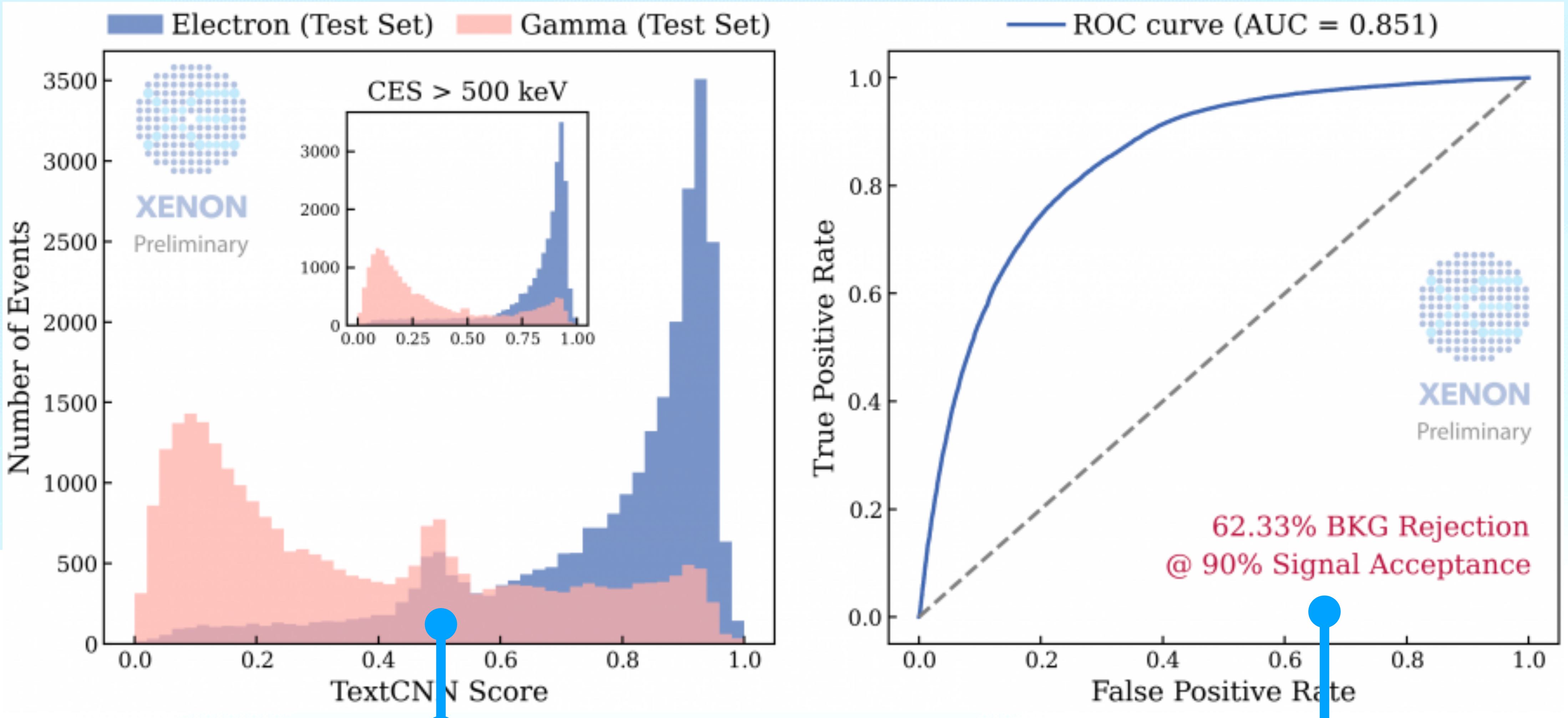

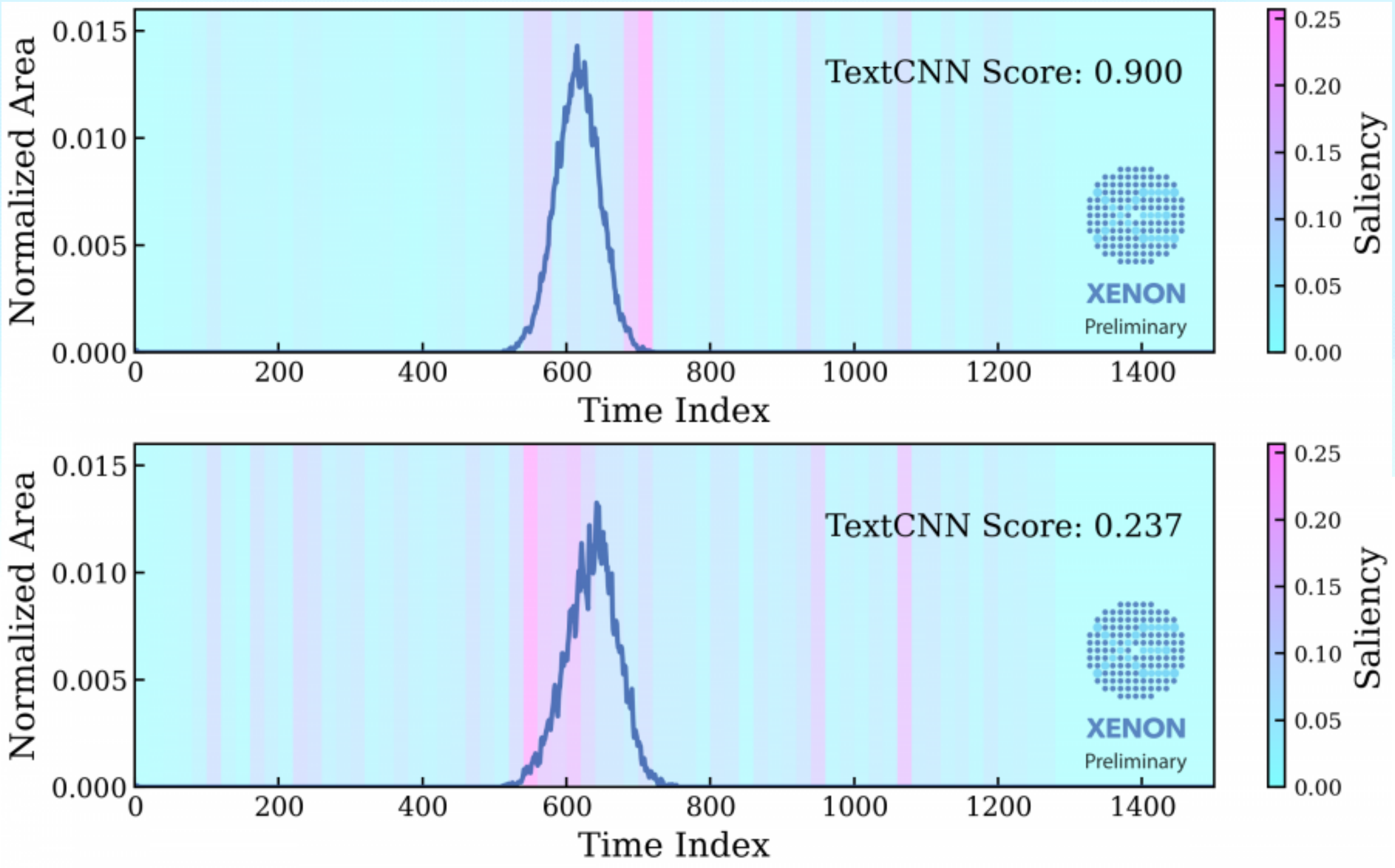

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Powerful Background Suppression

Generalizable to multiple background types based on KamLAND-Zen's experience

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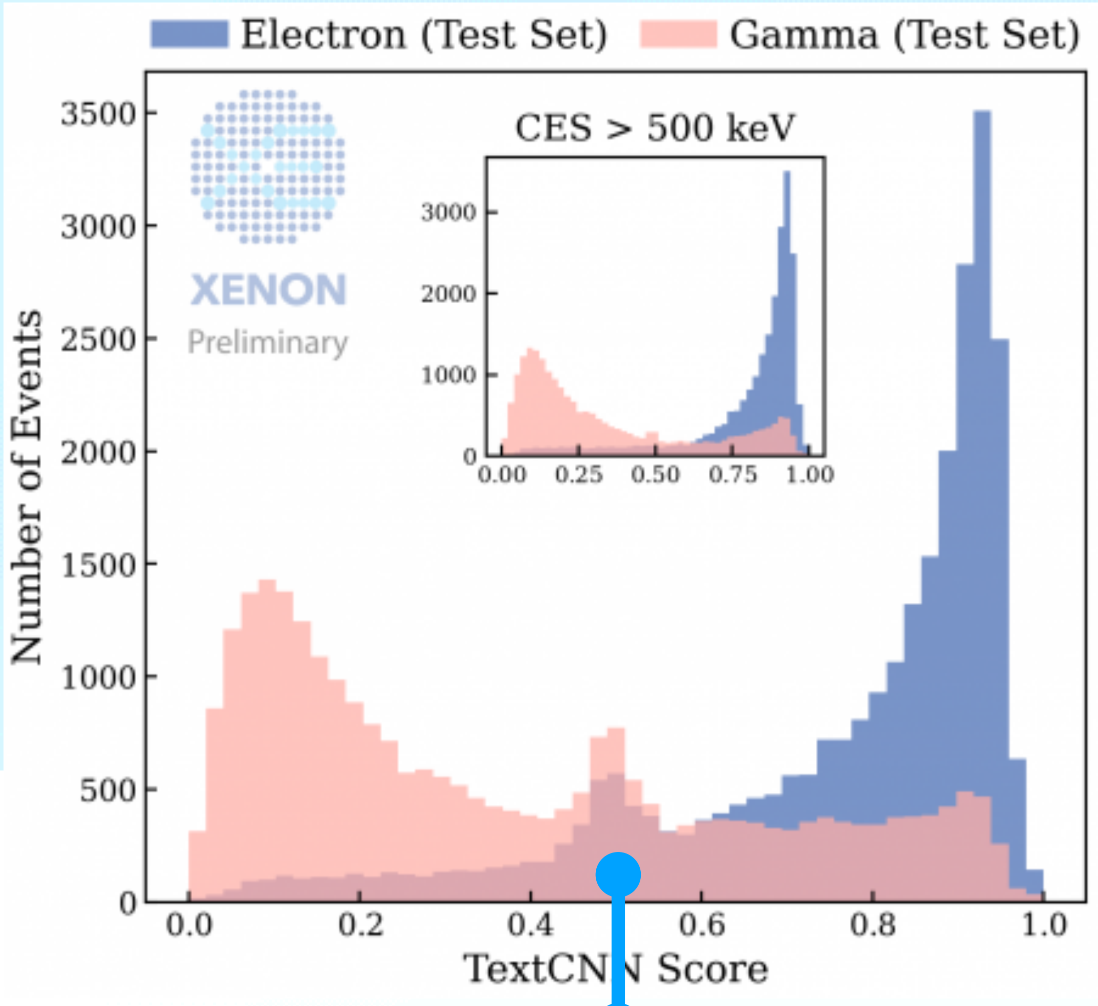

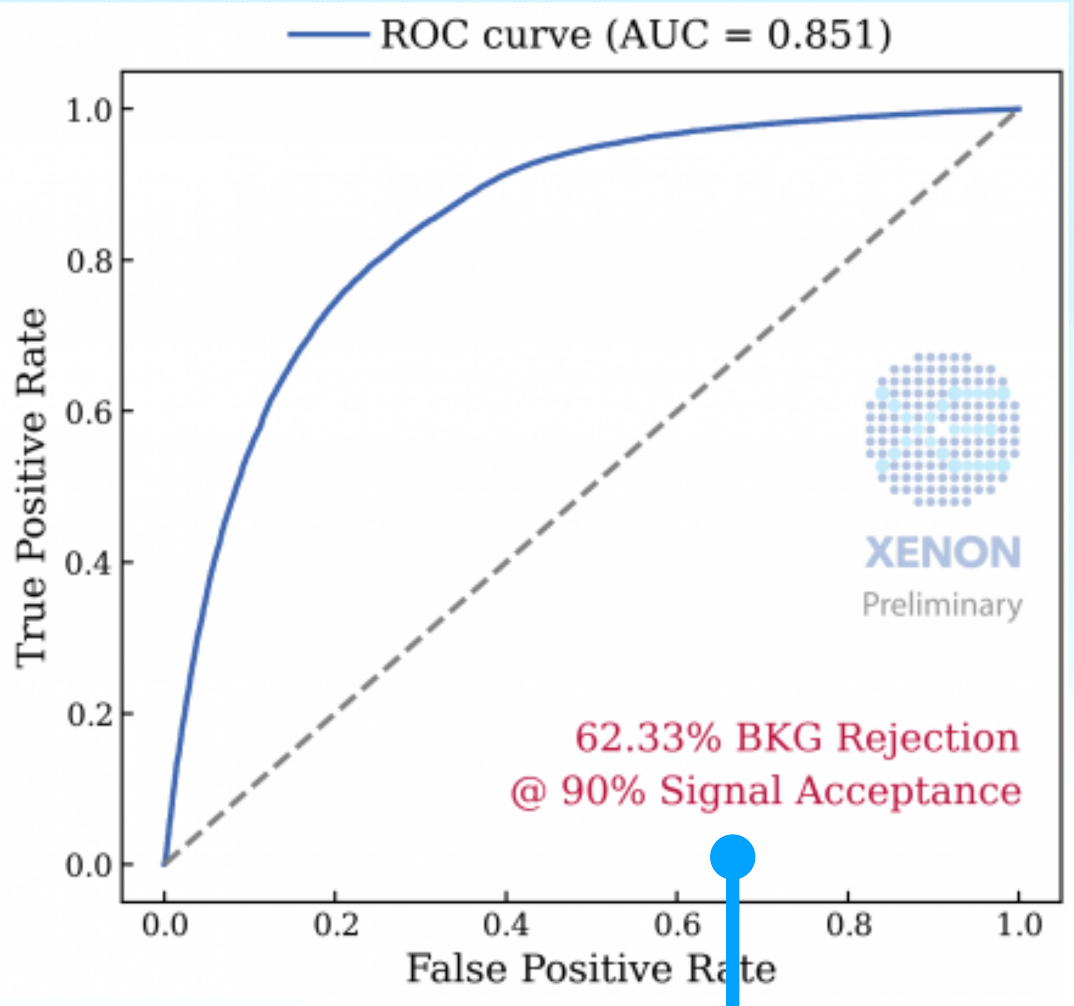

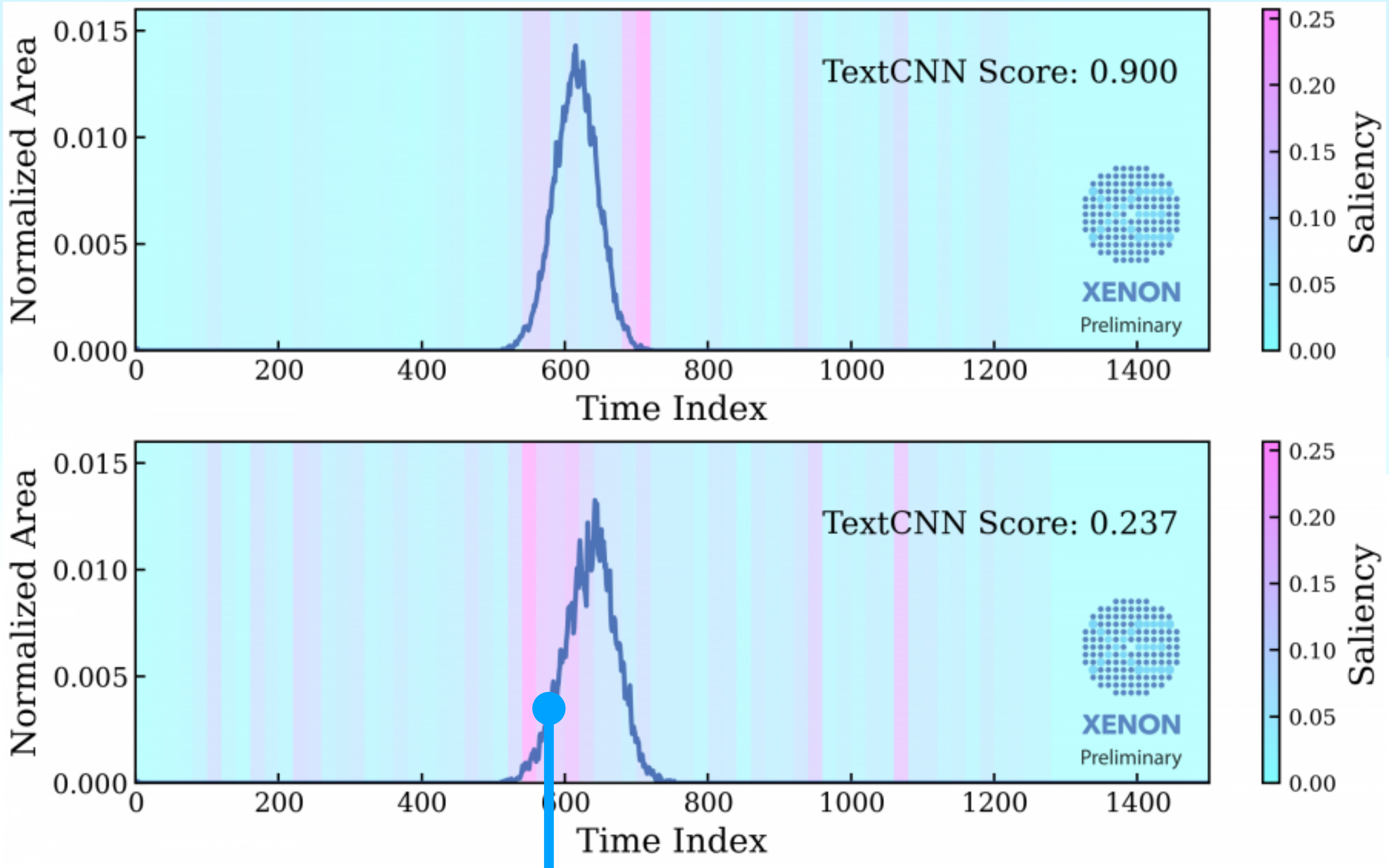

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Interpretability Study

Saliency map shows that TexCNN mostly look at rising/falling edge

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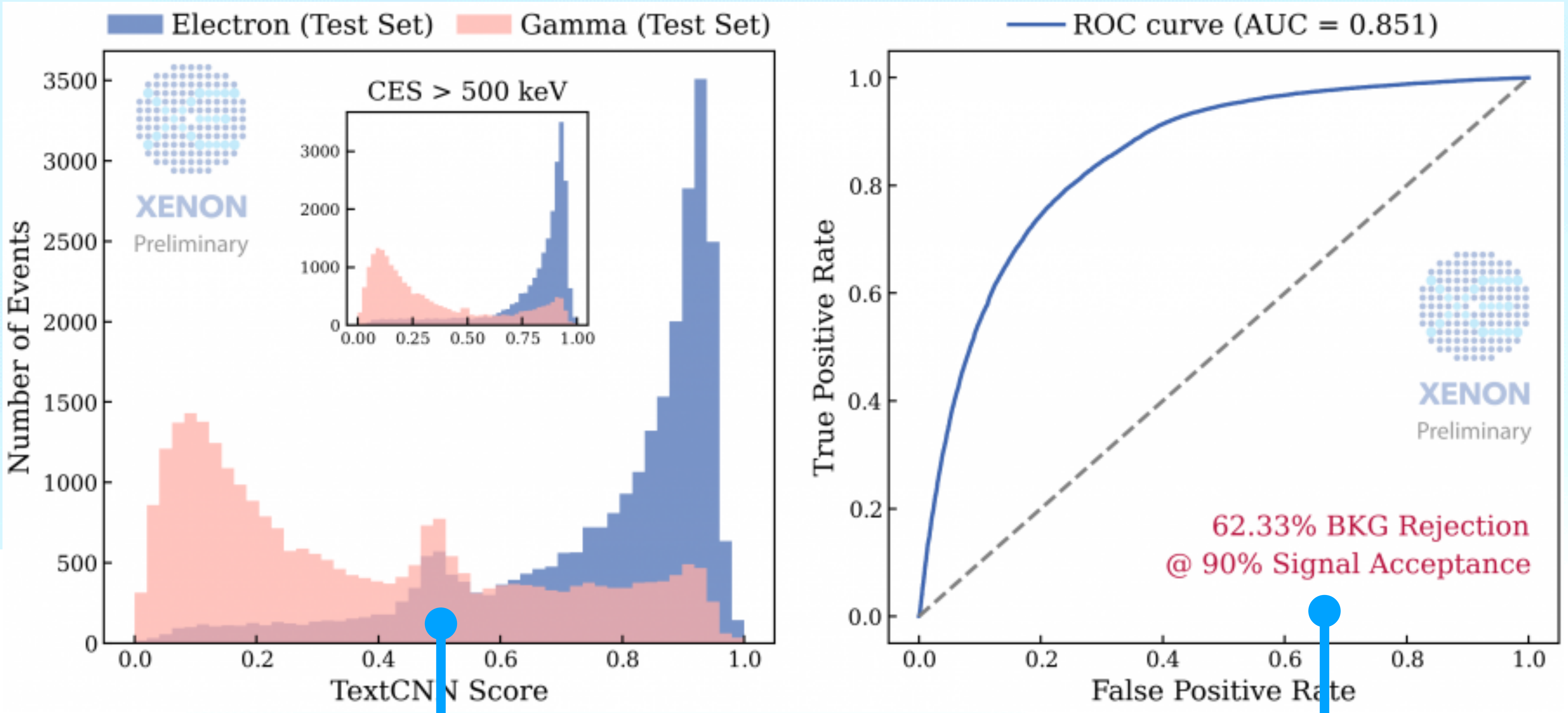

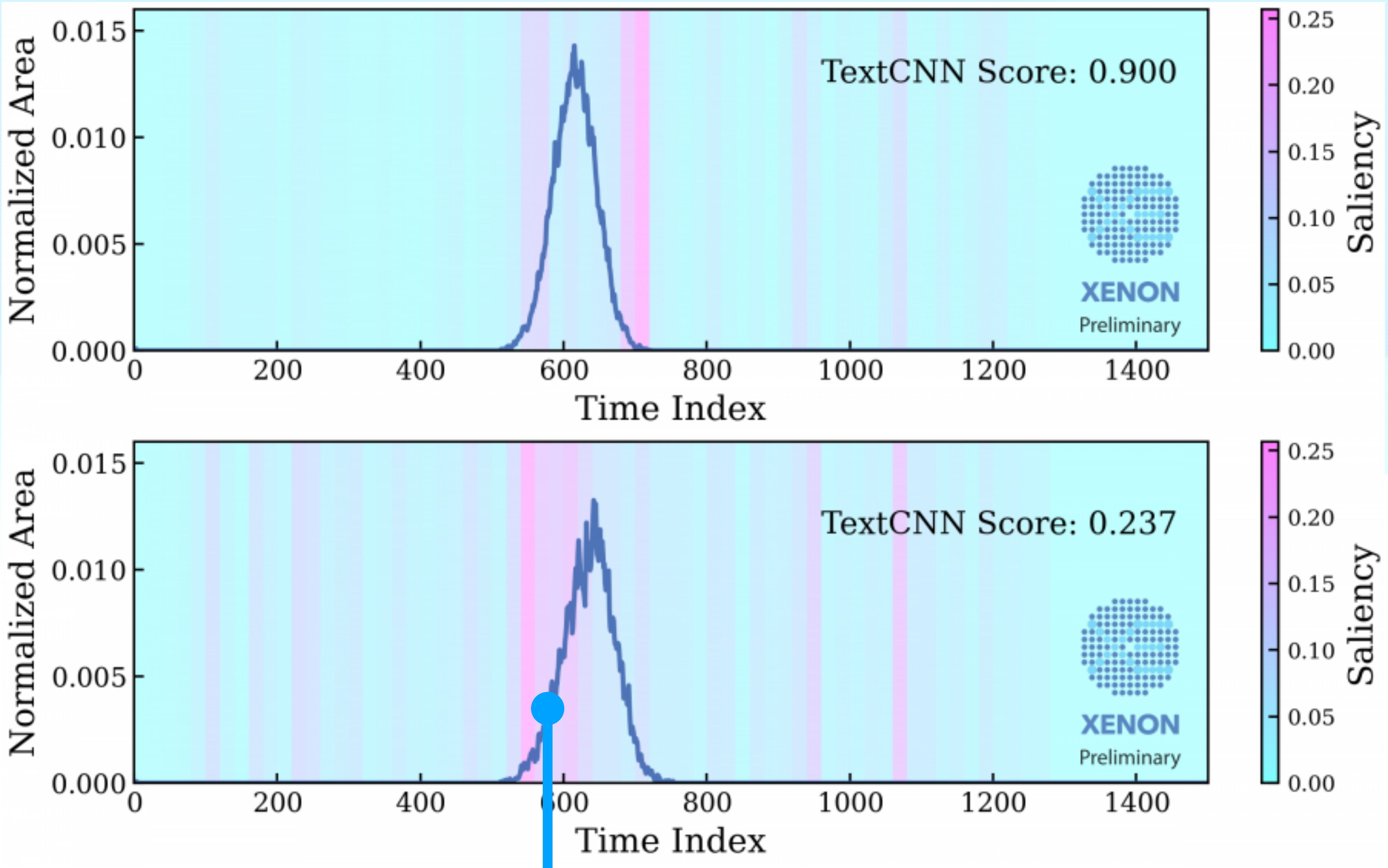

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M. Zhong: Enhancing XENONnT's Sensitivity to Neutrinoless Double-beta Decay with TextCNN

Double Beta Decay Parallel Session

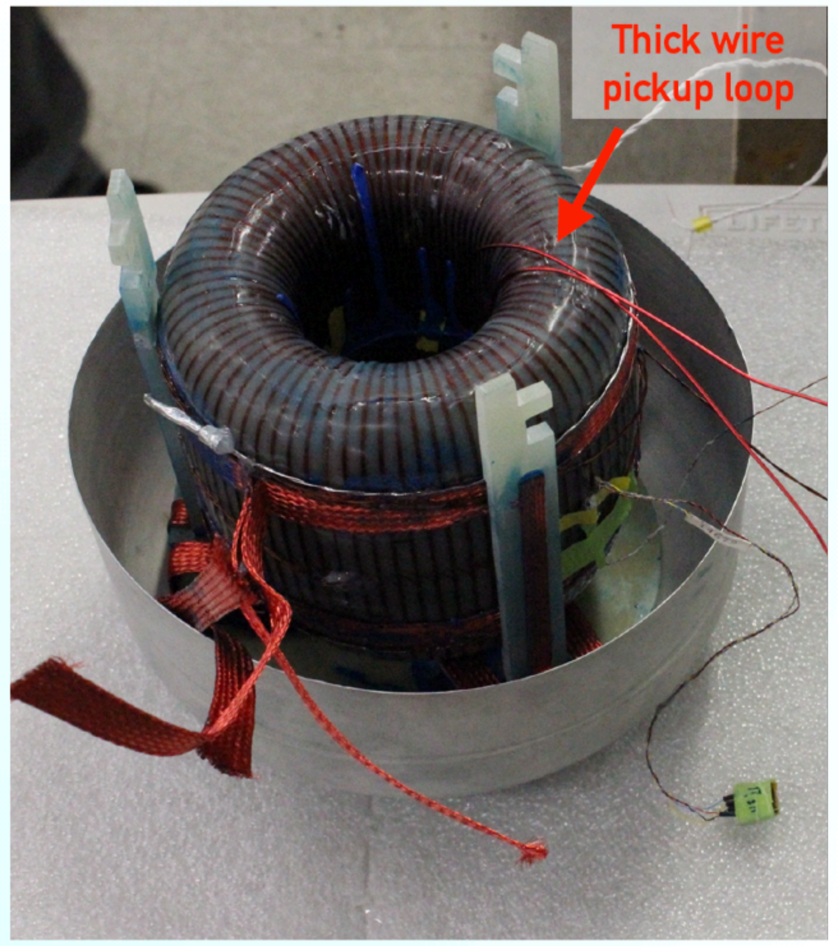
ABRACADABRA

Y. Kahn, B. R. Safdi, and J. Thaler, Phys. Rev. Lett. 117, 141801

J. L. Ouellet et al. Phys. Rev. Lett. 122, 121802 (2019)

C. P. Salemi et al. Phys. Rev. Lett. 127, 081801 (2021)

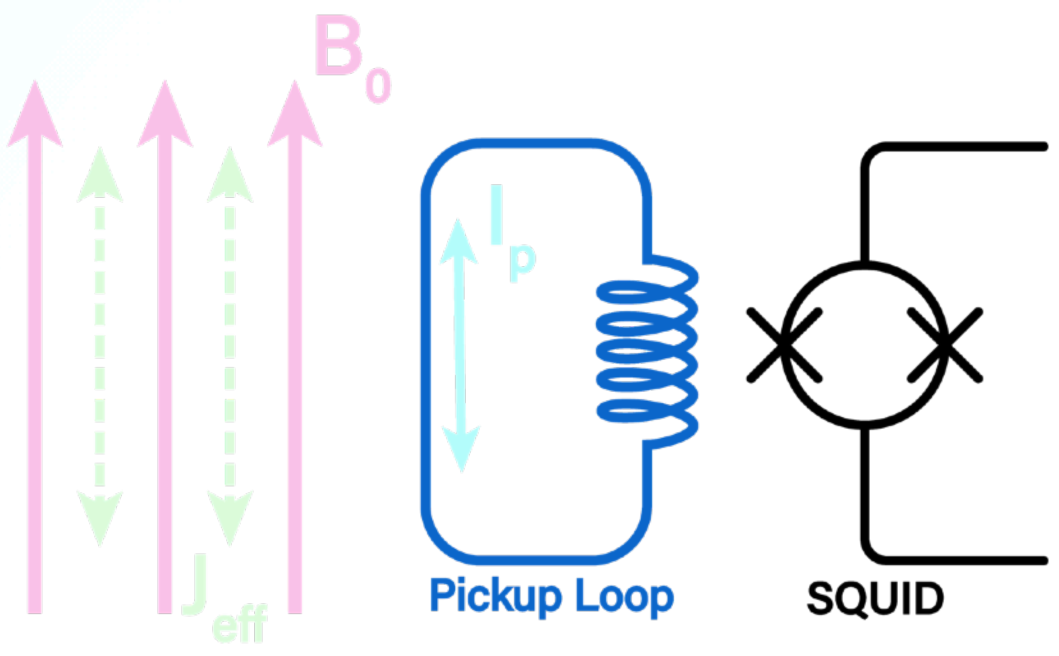
Broadband Axion Dark Matter Search with Toroidal Magnet



Axion-Modified Maxwell's Equation:

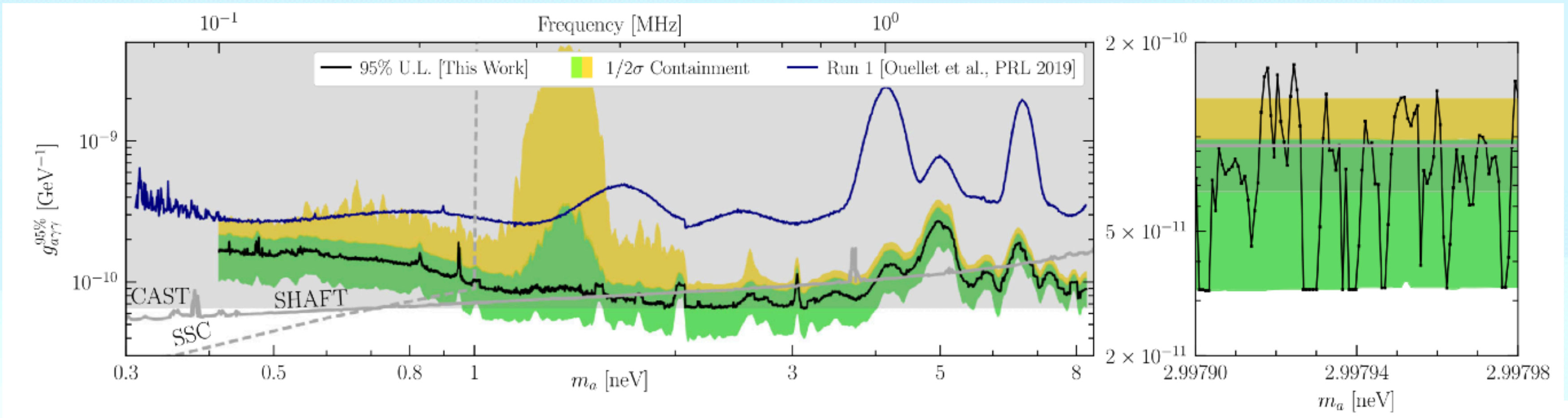
$$\nabla \times B = \frac{\partial E}{\partial t} - g_{a\gamma\gamma}(E \times \nabla a - \frac{\partial a}{\partial t} B)$$

$$J_{eff} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}} cos(m_a t) B$$



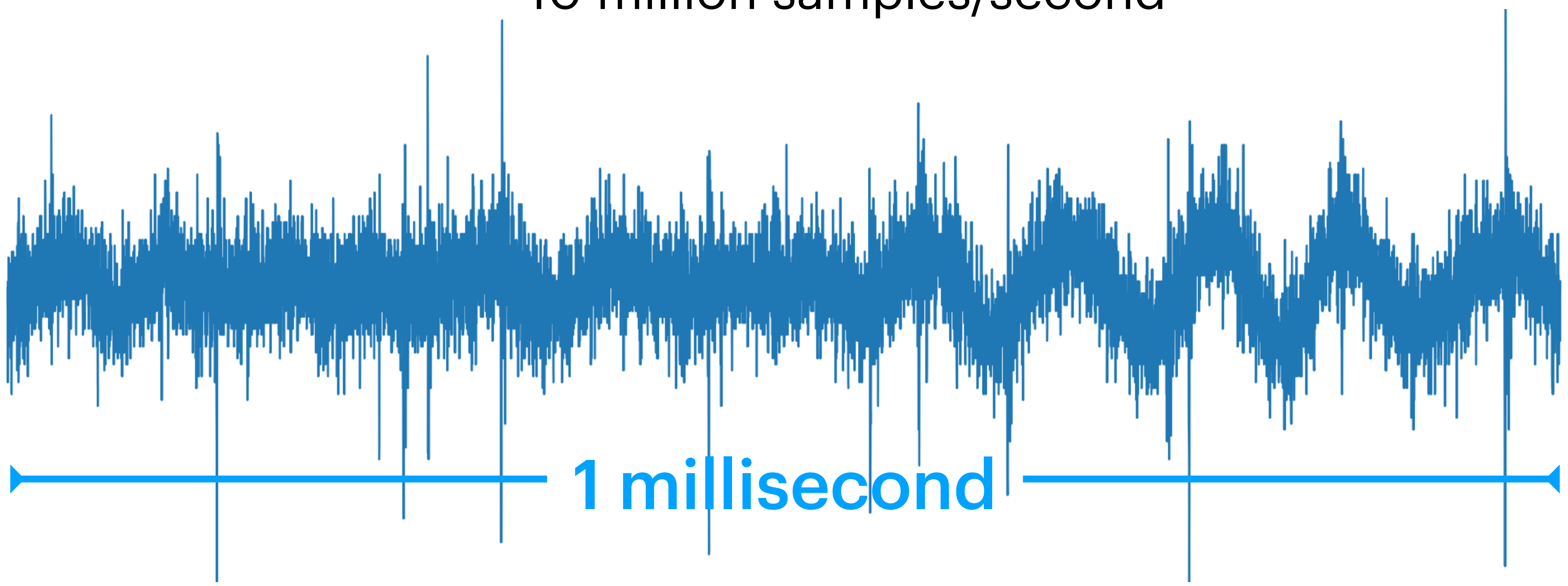
Frequency Spectrum

Broadband search for axion DM



Ultra-long Time Series

10 million samples/second



Experimental Apparatus Constructed by Winslow Lab at MIT

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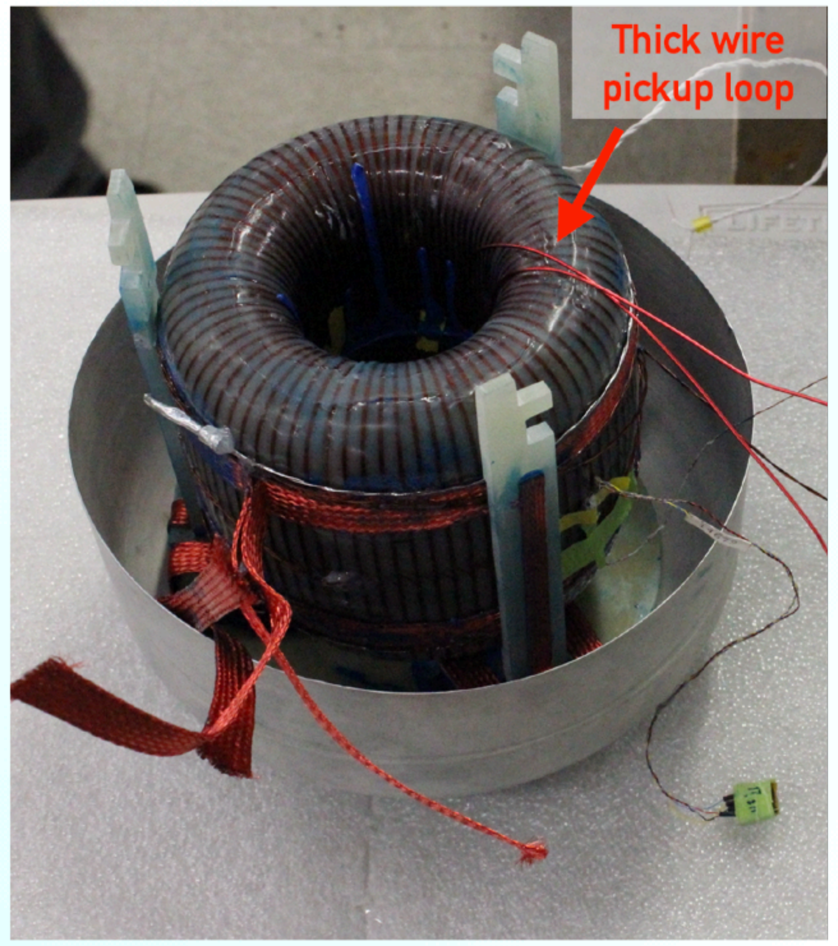

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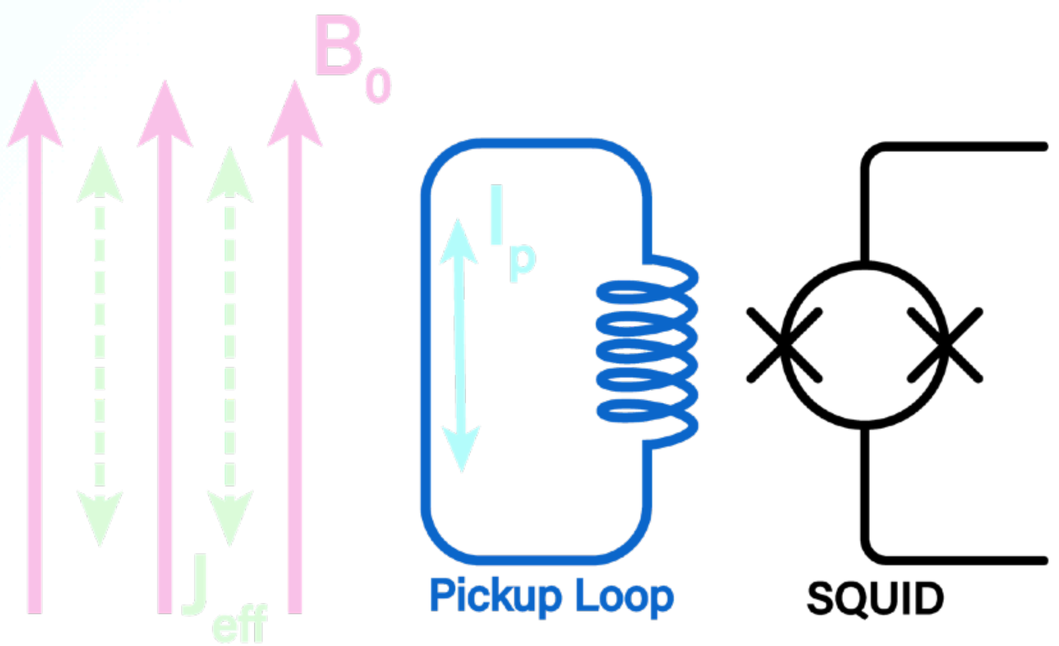

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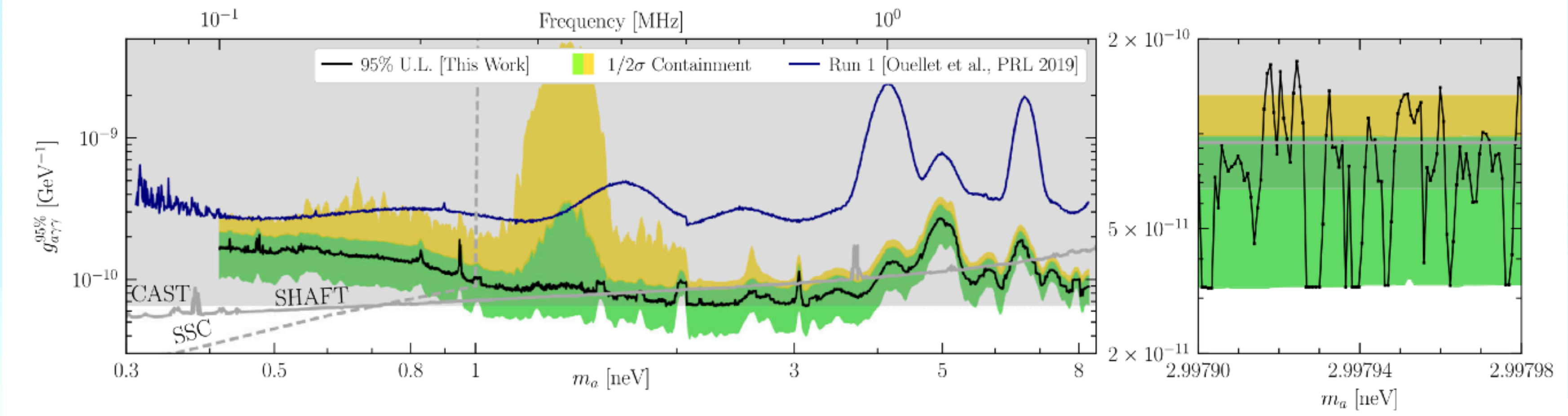

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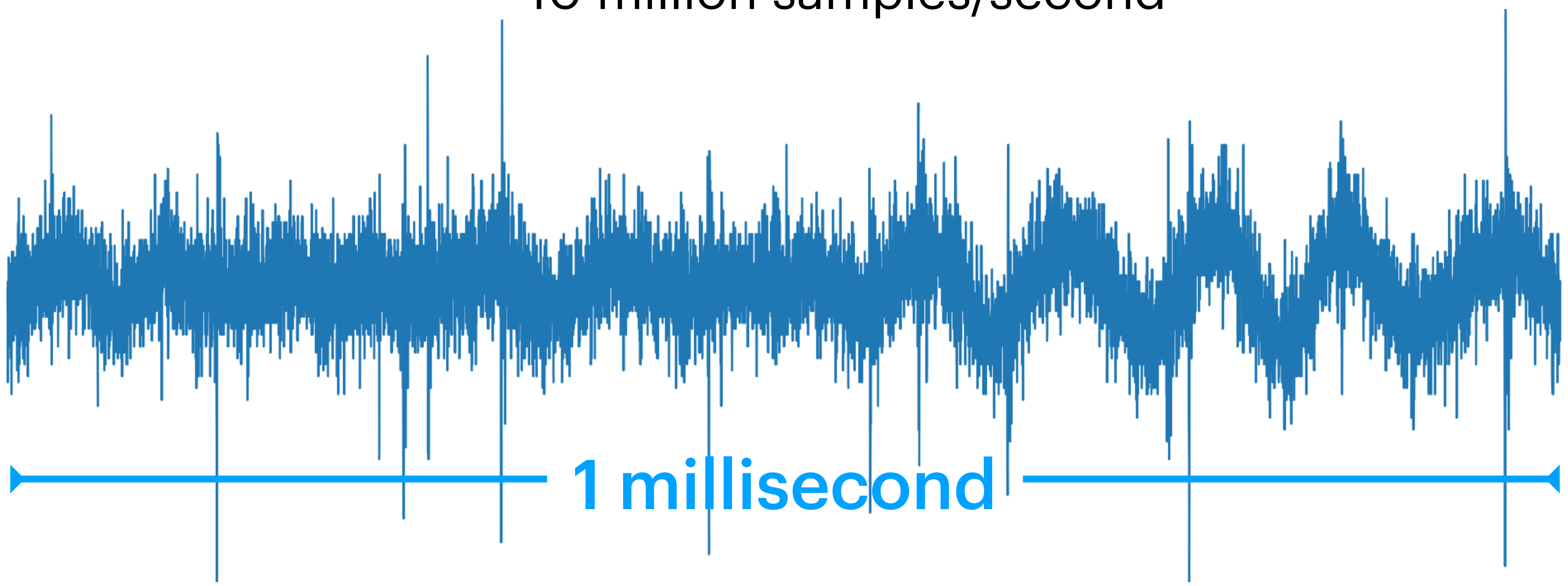
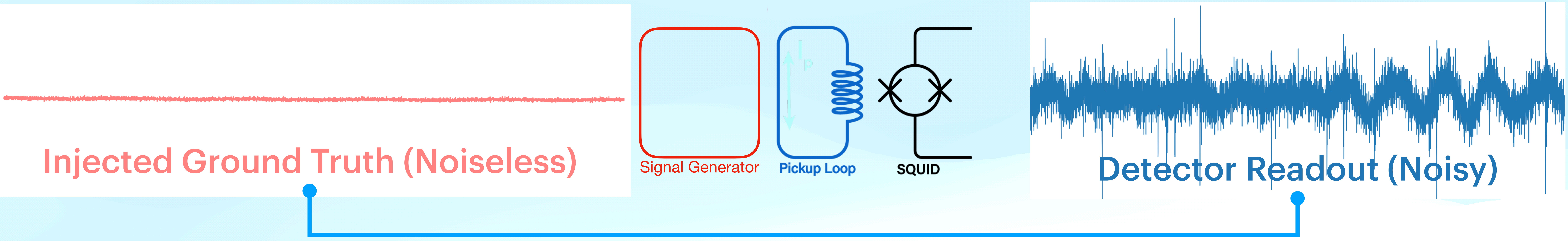


Experimental Apparatus Constructed by Winslow Lab at MIT

AI for ABRACADABRA

ABRACADABRA Data Release

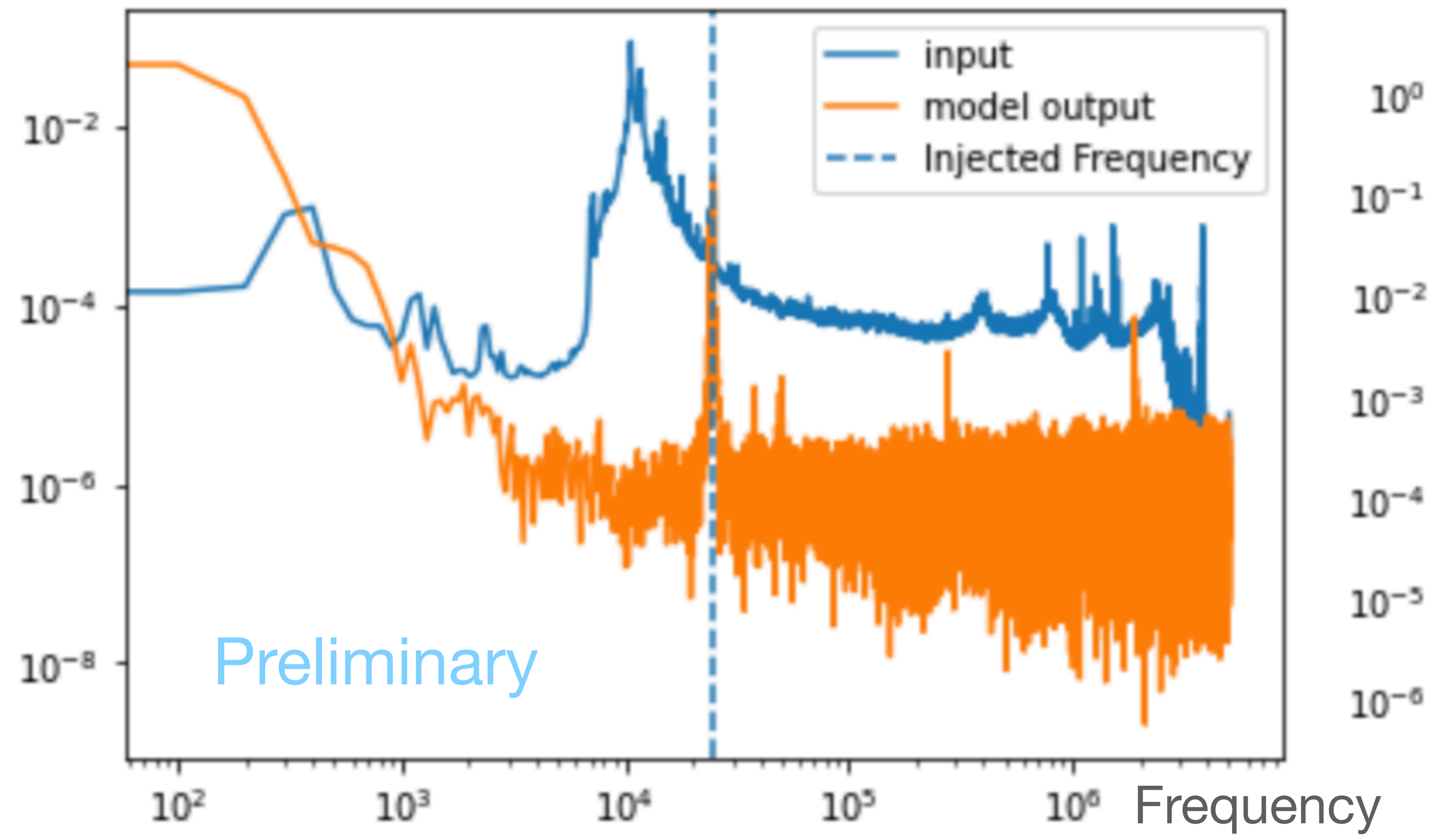
Long Time Series Data Release from Broadband Axion Dark Matter Experiment
J. T. Fry et al, NeurIPS 2023 ML4PS
New Manuscript Under Preparation



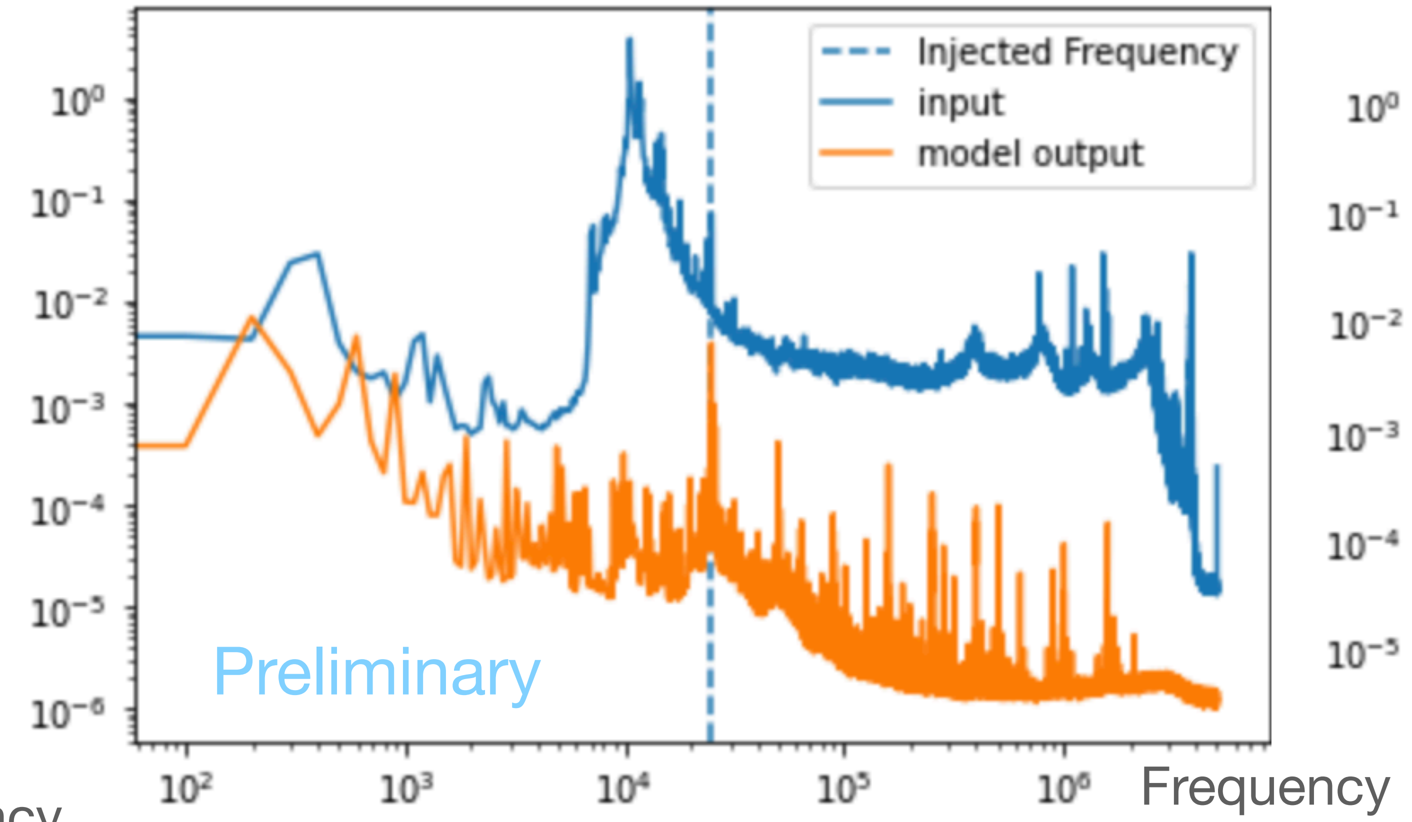
Denoising ABRA Time Series

AI Denoising

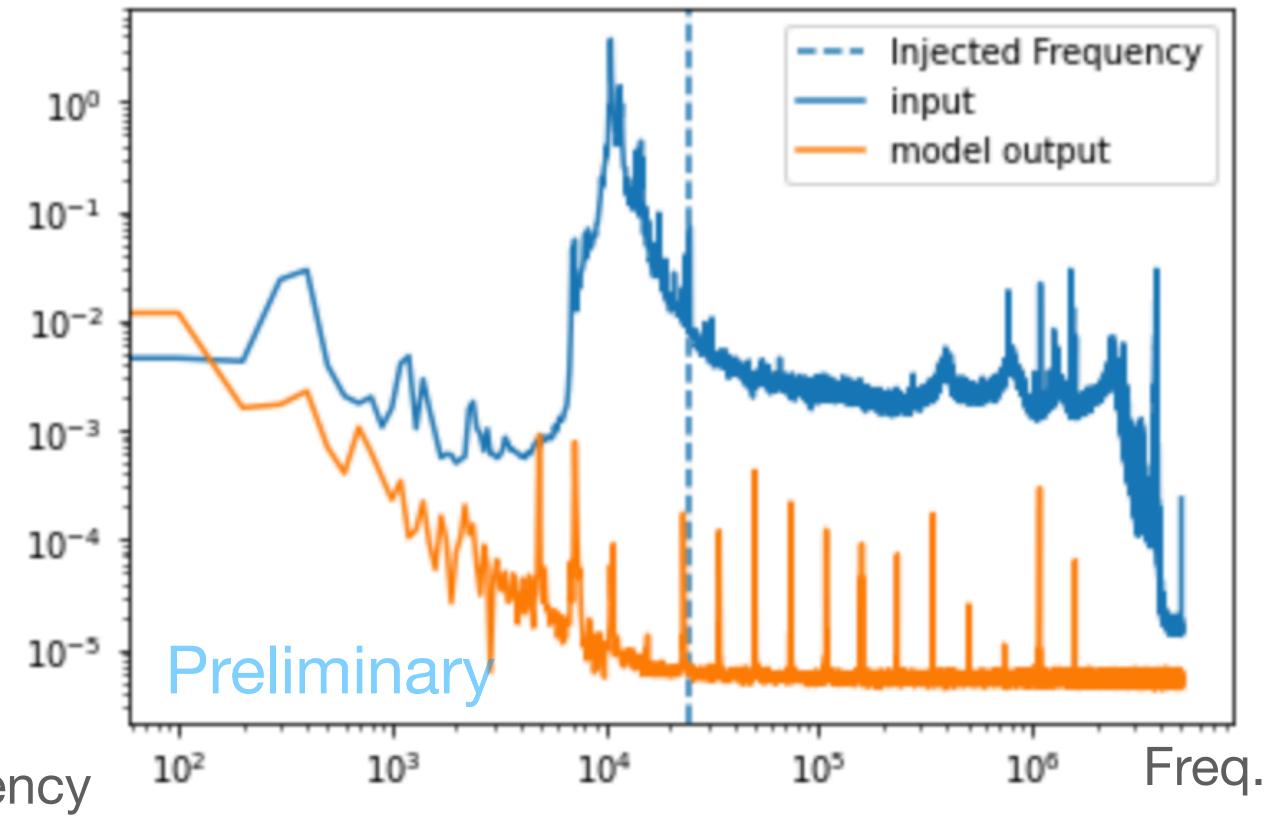
Recover injected peaks in frequency spectrum



Fully Connected NN



Positional U-Net



Transformer

How Could AI Shape the Future of Rare Event Search?

Experimental Data Release

Your data is valuable even outside physics!

Self-Supervised Learning

Don’t teach physics to the machine, let physics reveal itself!

Fast Machine Learning at Edge

Pushing AI to your DAQ board for real-time physics information!

Rare Event Search Data Release

MAJORANA DEMONSTRATOR

Release calibration data and analysis label for AI/ML Benchmarking and training students

Majorana Demonstrator Data Release for AI/ML Applications

I.J. Arnquist, F.T. Avignone III, A.S. Barabash, C.J. Barton, K.H. Bhimani, E. Blalock, B. Bos, M. Busch, M. Buuck, T.S. Caldwell, Y.-D. Chan, C.D. Christofferson, P.-H. Chu, M.L. Clark, C. Cuesta, J.A. Detwiler, Yu. Efremenko, H. Ejiri, S.R. Elliott, N. Fuad, G.K. Giovanetti, M.P. Green, J. Gruszko, I.S Guinn, V.E. Guiseppe, C.R. Haufe, R. Henning, D. Hervas Aguilar, E.W. Hoppe, A. Hostiuc, M.F. Kidd, I. Kim, R.T. Kouzes, T.E. Lannen V, A. Li, J.M. Lopez-Castano, R.D. Martin, R. Massarczyk, S.J. Meijer, S. Mertens, T.K. Oli, L.S. Paudel, W. Pettus, A.W.P. Poon, B. Quenallata, D.C. Radford, A.L. Reine, K. Rielage, N.W. Ruof, D.C. Schaper, S.J. Schleich, D. Tedeschi, R.L. Varner, S. Vasilyev, S.L. Watkins, J.F. Wilkerson, C. Wiseman, W. Xu, C.-H. Yu, B.X. Zhu

The enclosed data release consists of a subset of the calibration data from the Majorana Demonstrator experiment. Each Majorana event is accompanied by raw Germanium detector waveforms, pulse shape discrimination cuts, and calibrated final energies, all shared in an HDF5 file format along with relevant metadata. This release is specifically designed to support the training and testing of Artificial Intelligence (AI) and Machine Learning (ML) algorithms upon our data. This document is structured as follows. Section I provides an overview of the dataset's content and format; Section II outlines the location of this dataset and the method for accessing it; Section III presents the NPML Machine Learning Challenge associated with this dataset; Section IV contains a disclaimer from the Majorana collaboration regarding the use of this dataset; Appendix A contains technical details of this data release. Please direct questions about the material provided within this release to liaobo77@ucsd.edu (A. Li).

MAJORANA Collaboration, ArXiv: 2308.10856

Rare Event Search Data Release

MAJORANA DEMONSTRATOR

Release calibration data and analysis label for AI/ML Benchmarking and training students

Majorana Demonstrator Data Release for AI/ML Applications

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ABRACADABRA

Release data and analysis pipeline to allow direct production of Axion DM search result.

Long Time Series Data Release from Broadband Axion Dark Matter Experiment

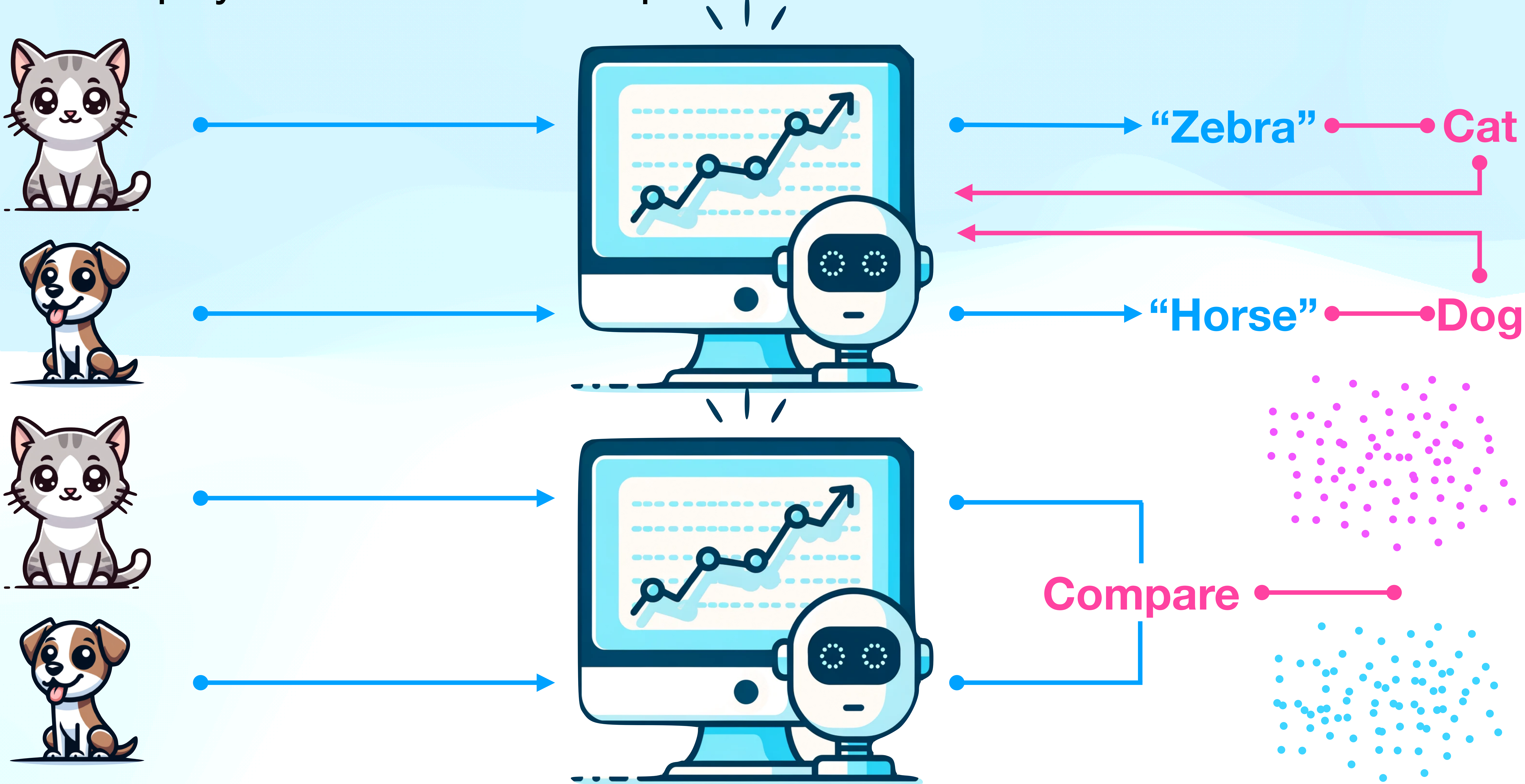
Long Time Series Data Release from Broadband Axion Dark Matter Experiment
J. T. Fry et al, NeurIPS 2023 ML4PS
New Manuscript Under Preparation

Self-Supervised Learning

Learn a physics-embedded representation without label

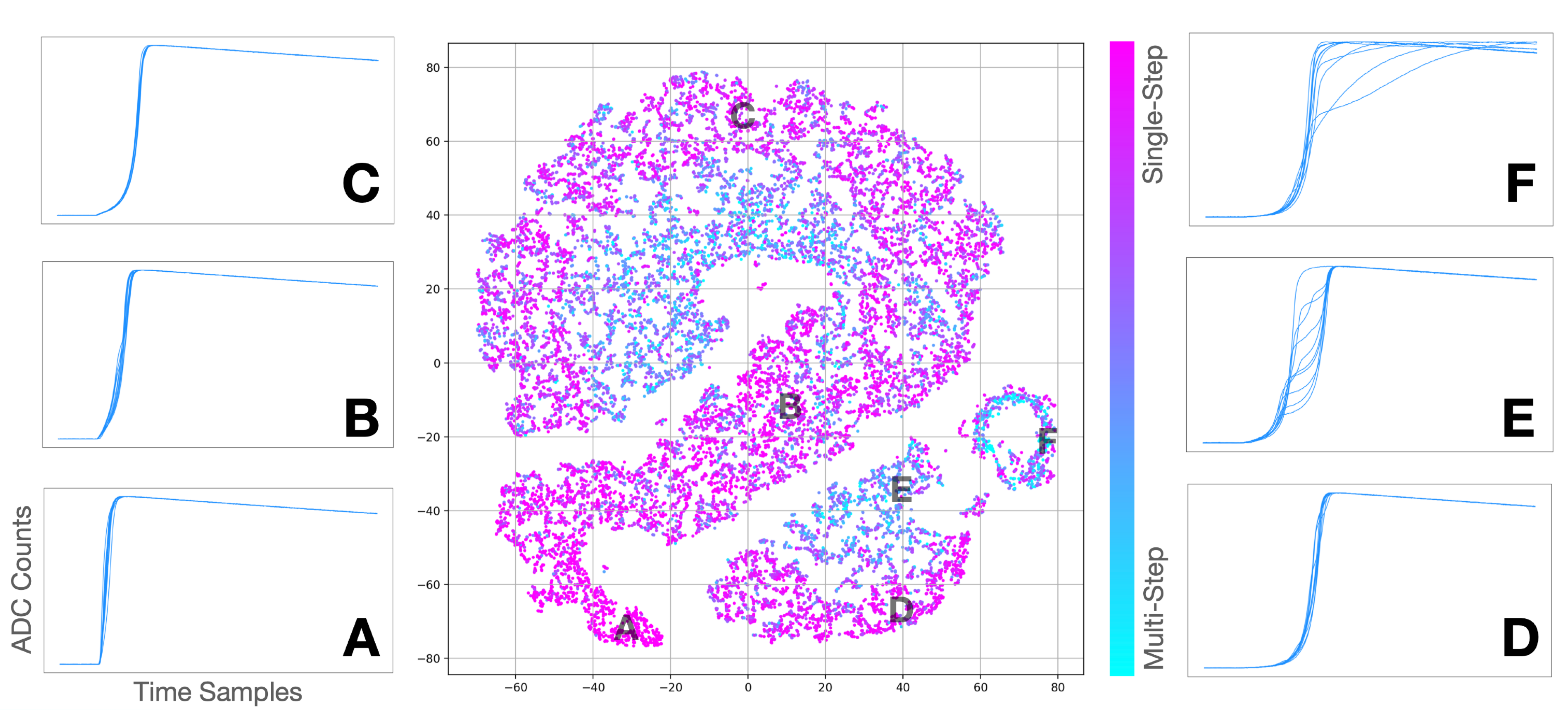
Self-Supervised Learning

Learn a physics-embedded representation without label



Self-Supervised Learning for LEGEND

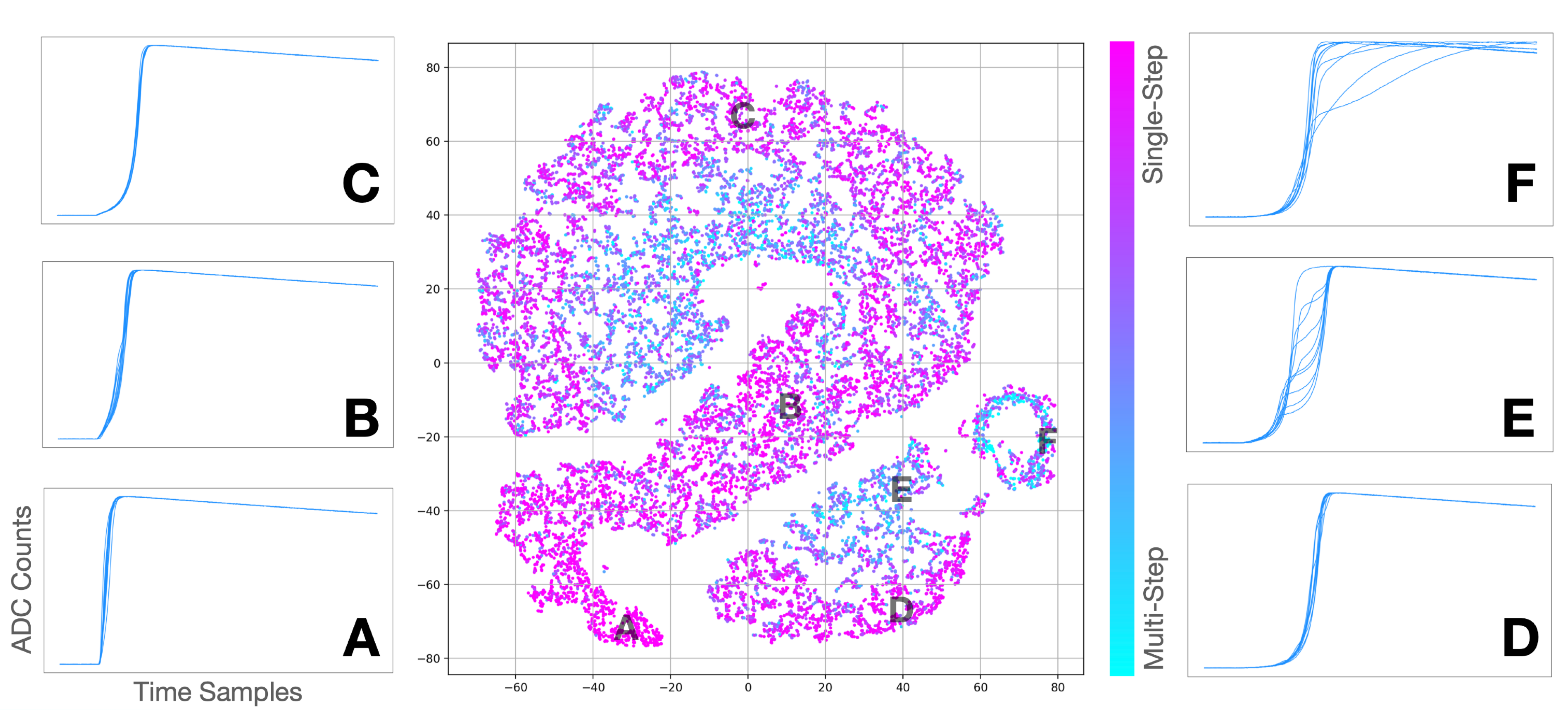
Learn a physics-embedded representation without label



Self-Supervised Learning for LEGEND

Learn a physics-embedded representation without label

Fig. A→D: the length of the “band” is the time it takes for waveforms to reach maximum

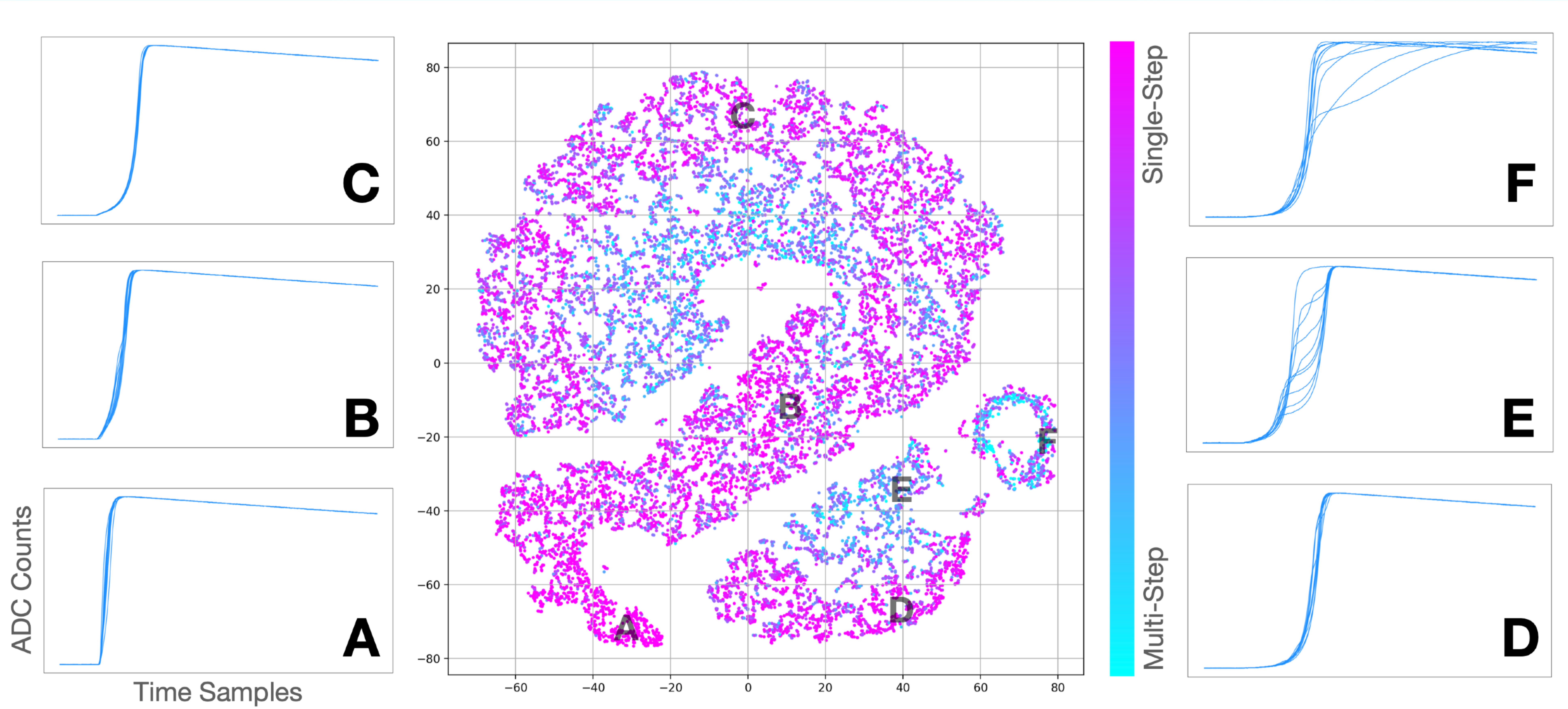


Self-Supervised Learning for LEGEND

Learn a physics-embedded representation without label

Fig. A→D: the length of the "band" is the time it takes for waveforms to reach maximum

Fig. D vs. Fig E: the width of the "band" represents the number of steps in waveforms



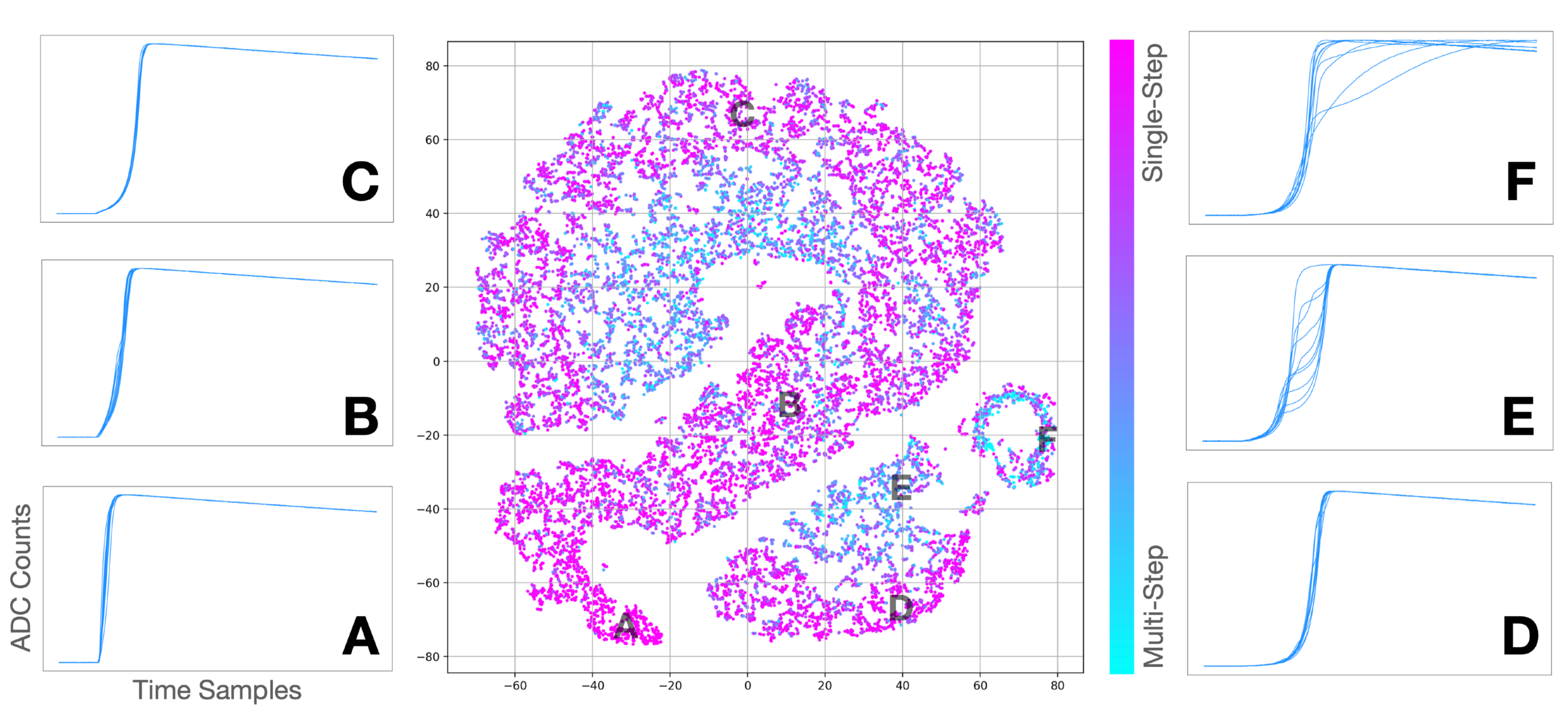
Self-Supervised Learning for LEGEND

Learn a physics-embedded representation without label

Fig. A→D: the length of the "band" is the time it takes for waveforms to reach maximum

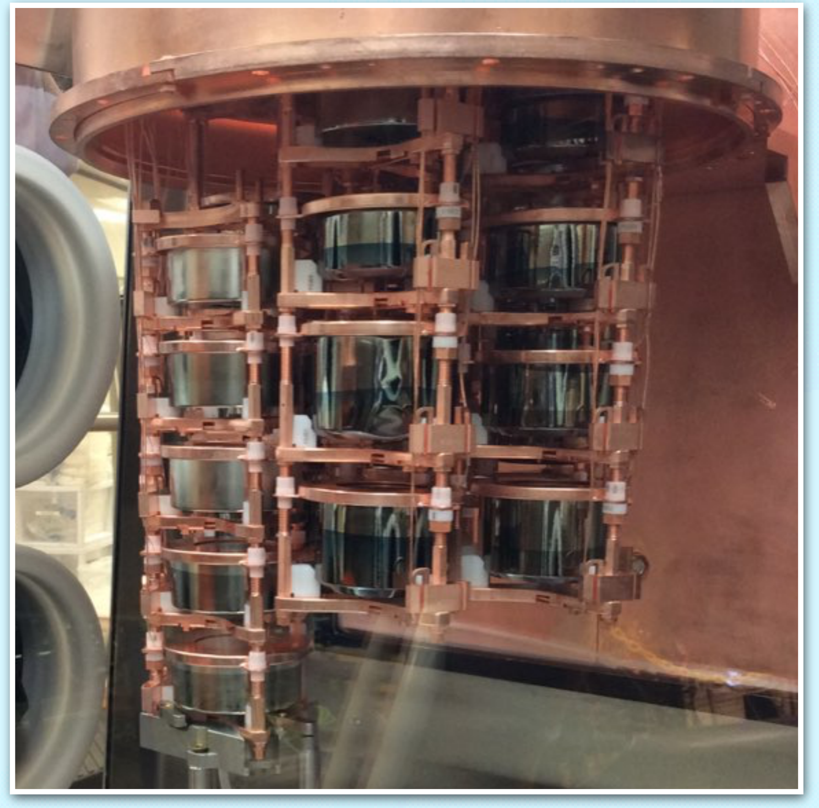
Fig. D vs. Fig E: the width of the "band" represents the number of steps in waveforms

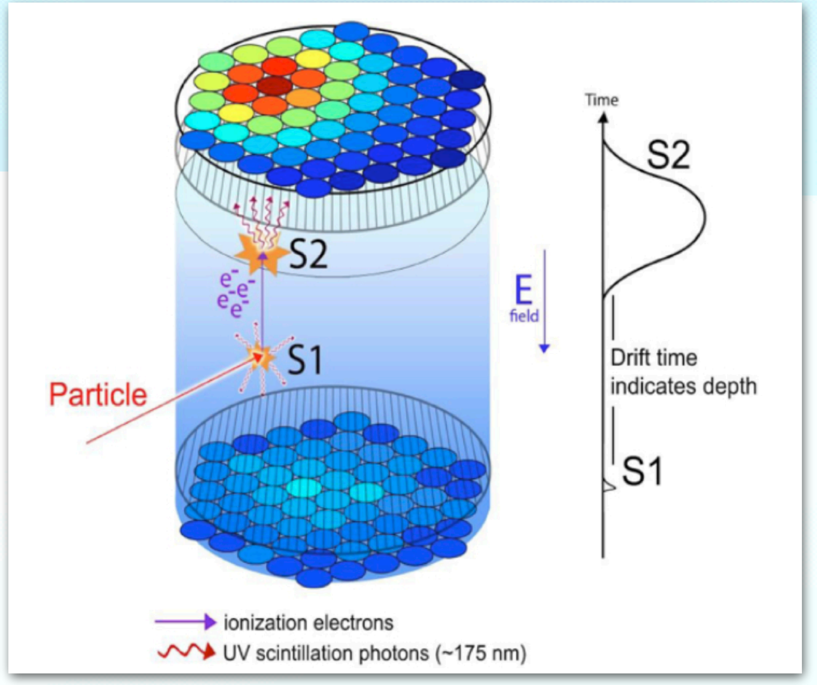
Fig. F: the "ring island" are slow-rounded-top waveforms caused by passivated surface

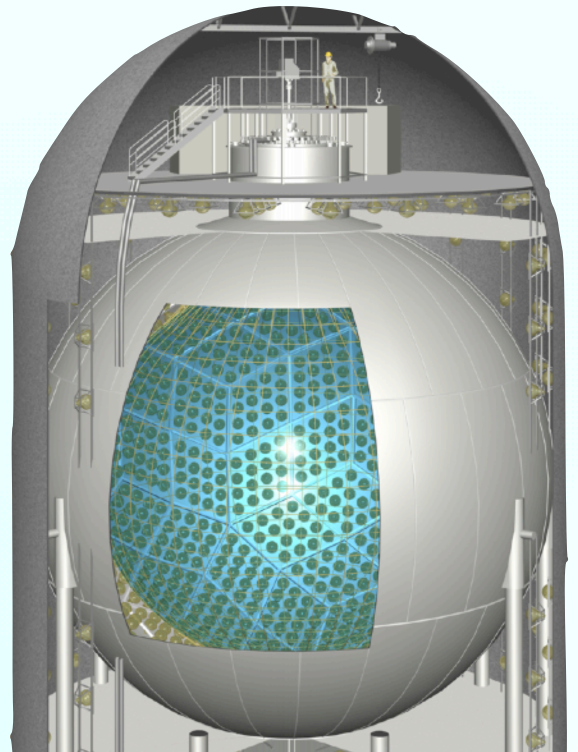


Fast Machine Learning at Edge

Widely adopted in LHC, new to rare event search experiments







Data Stream

Offline Analysis

Energy

Position

Particle Type

Detector Response

Fast Machine Learning at Edge

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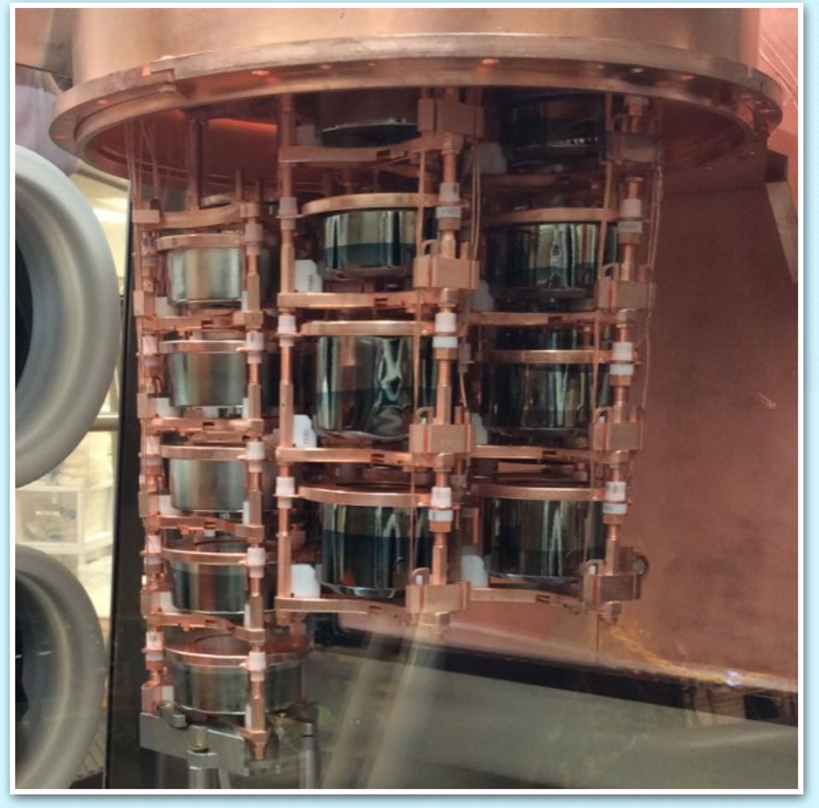

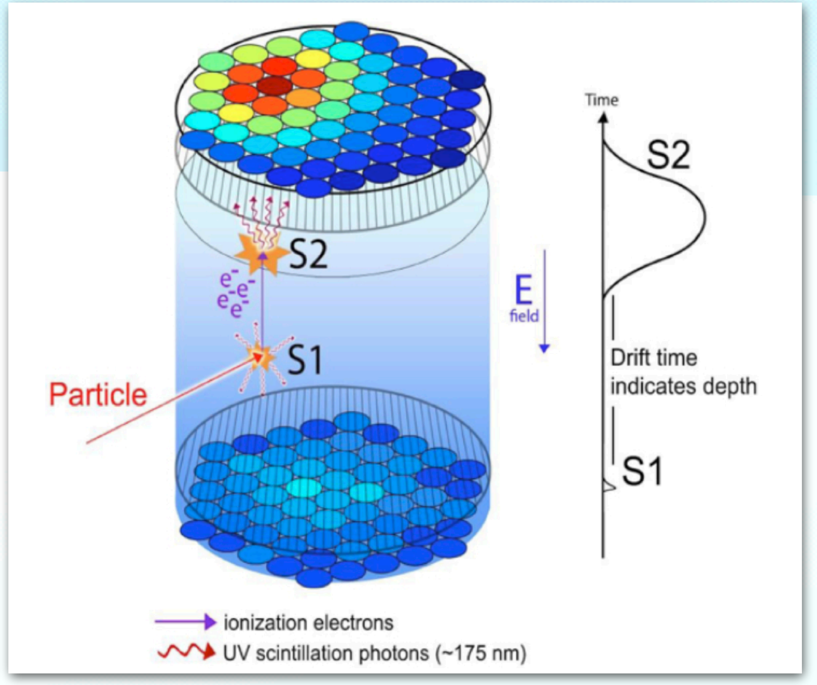

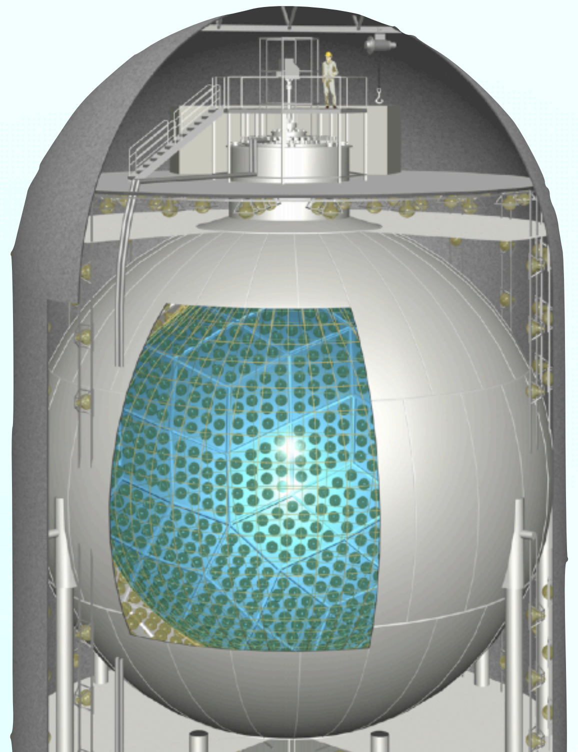

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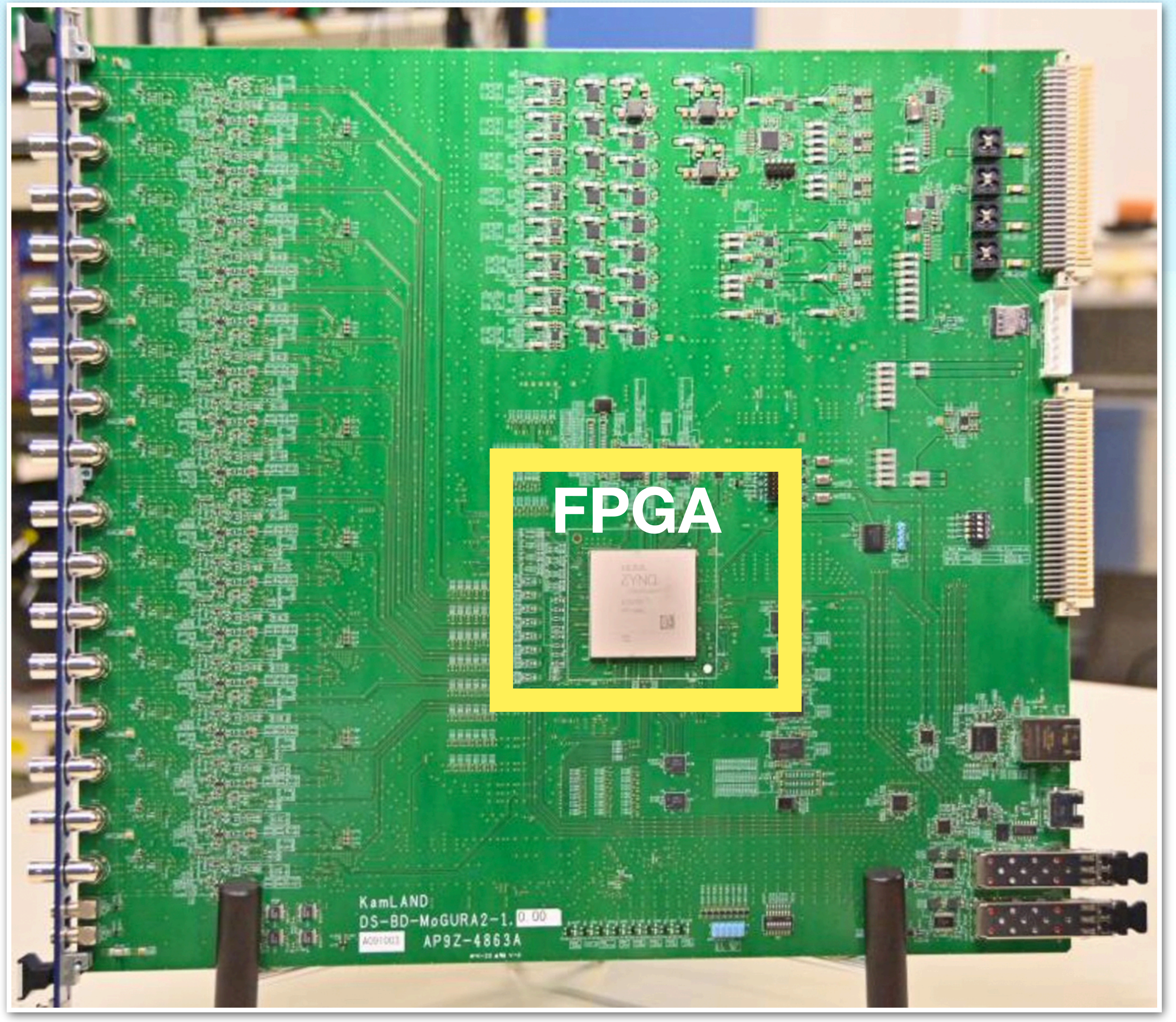

Offline Analysis

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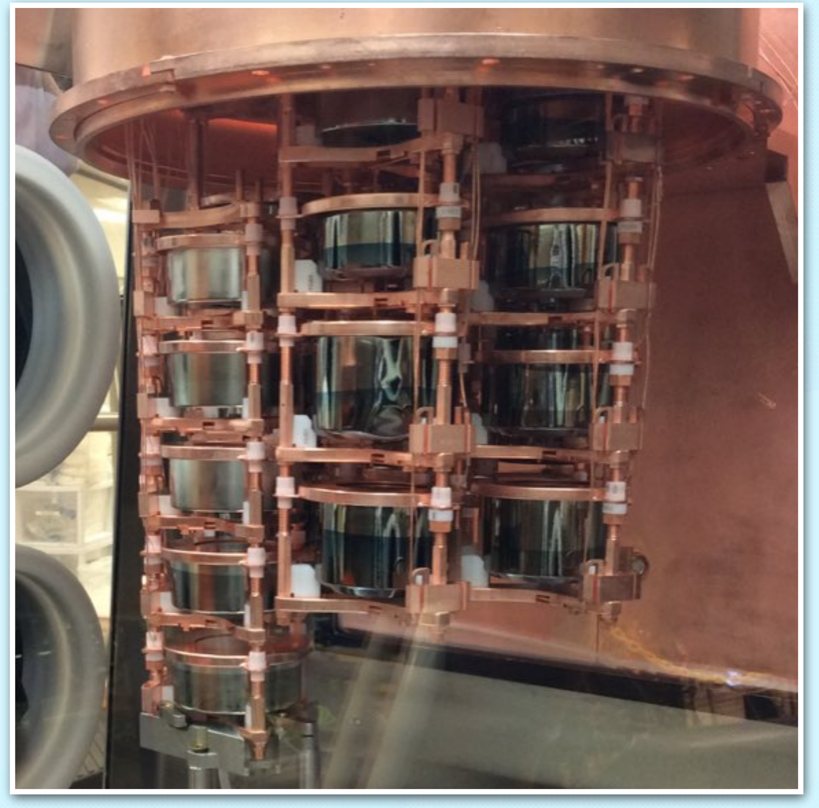

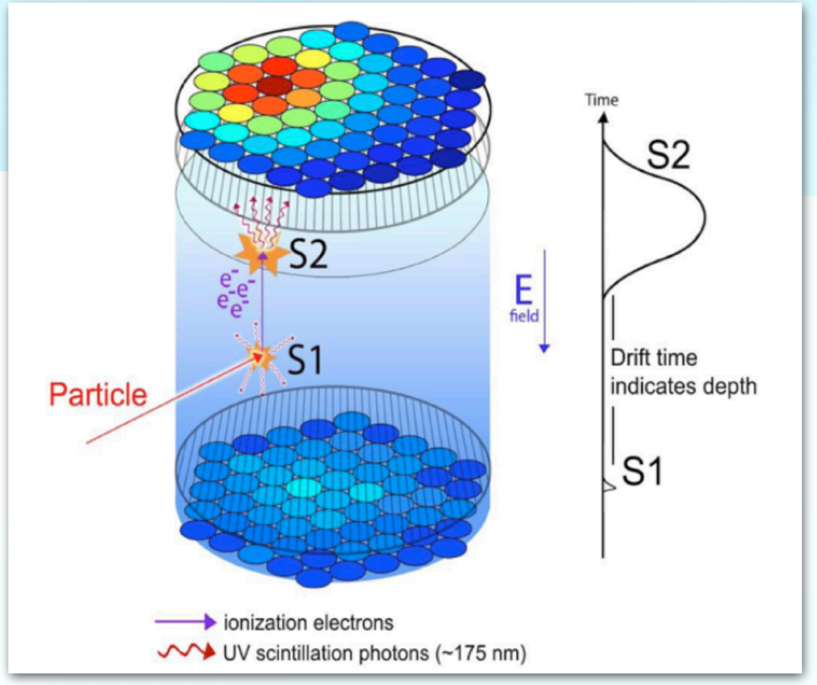

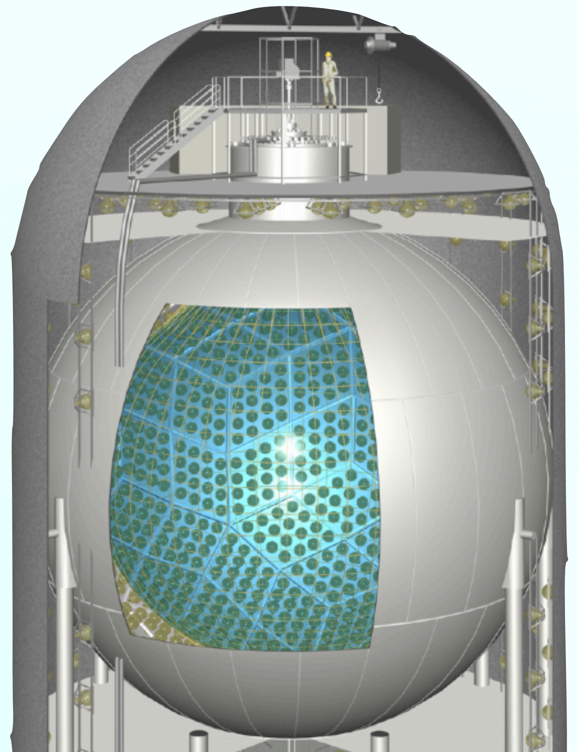

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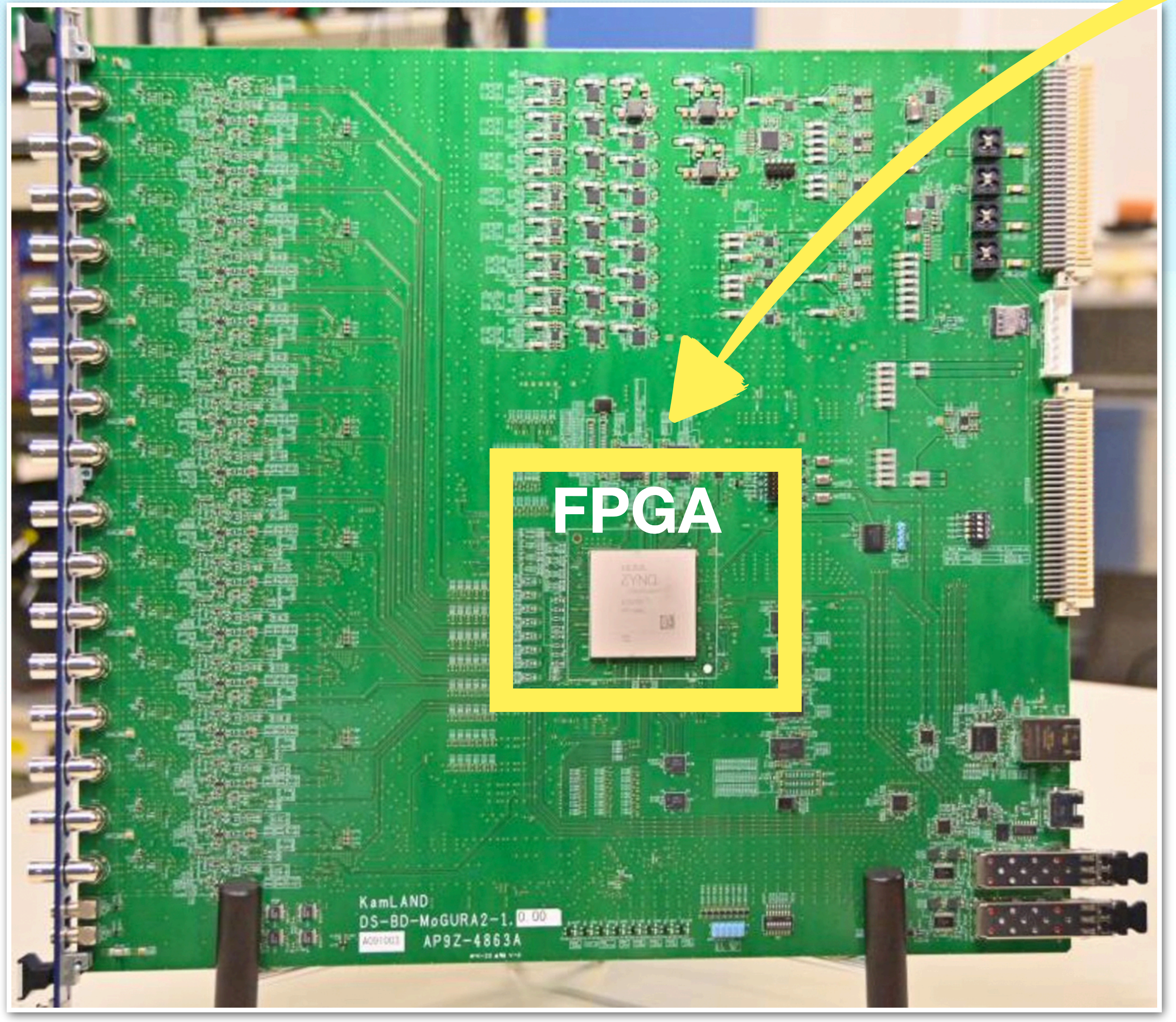


Deploy ML model onto FPGA
to produce these in real-time

Offline Analysis

Energy

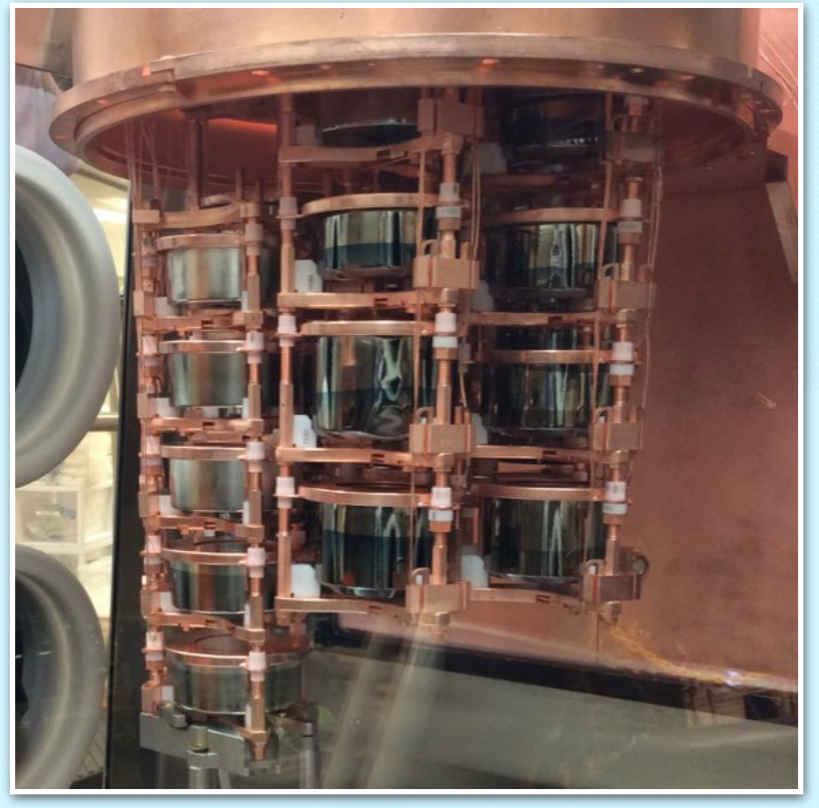
Position

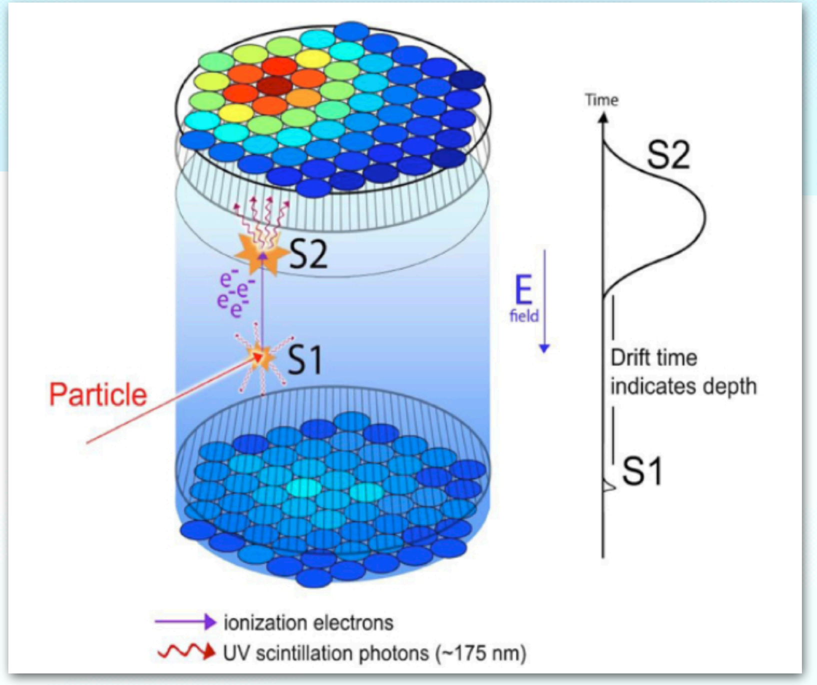
Particle Type

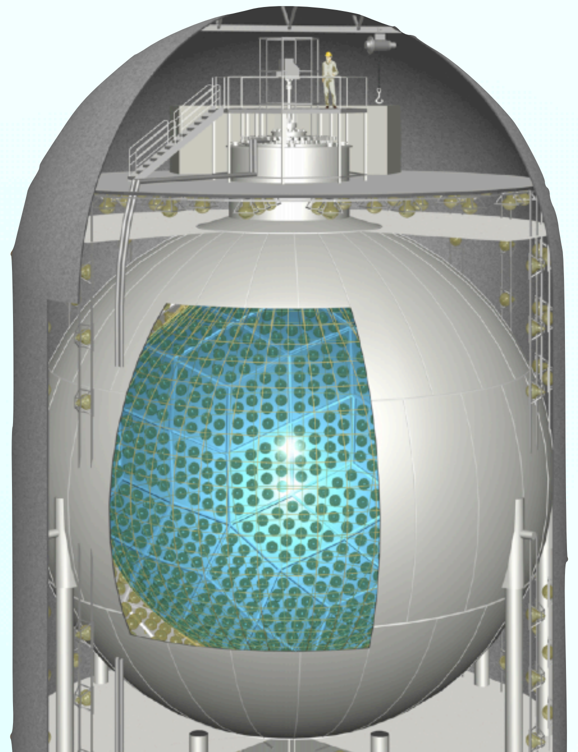
Detector Response

Fast Machine Learning at Edge

Widely adopted in LHC, new to rare event search experiments







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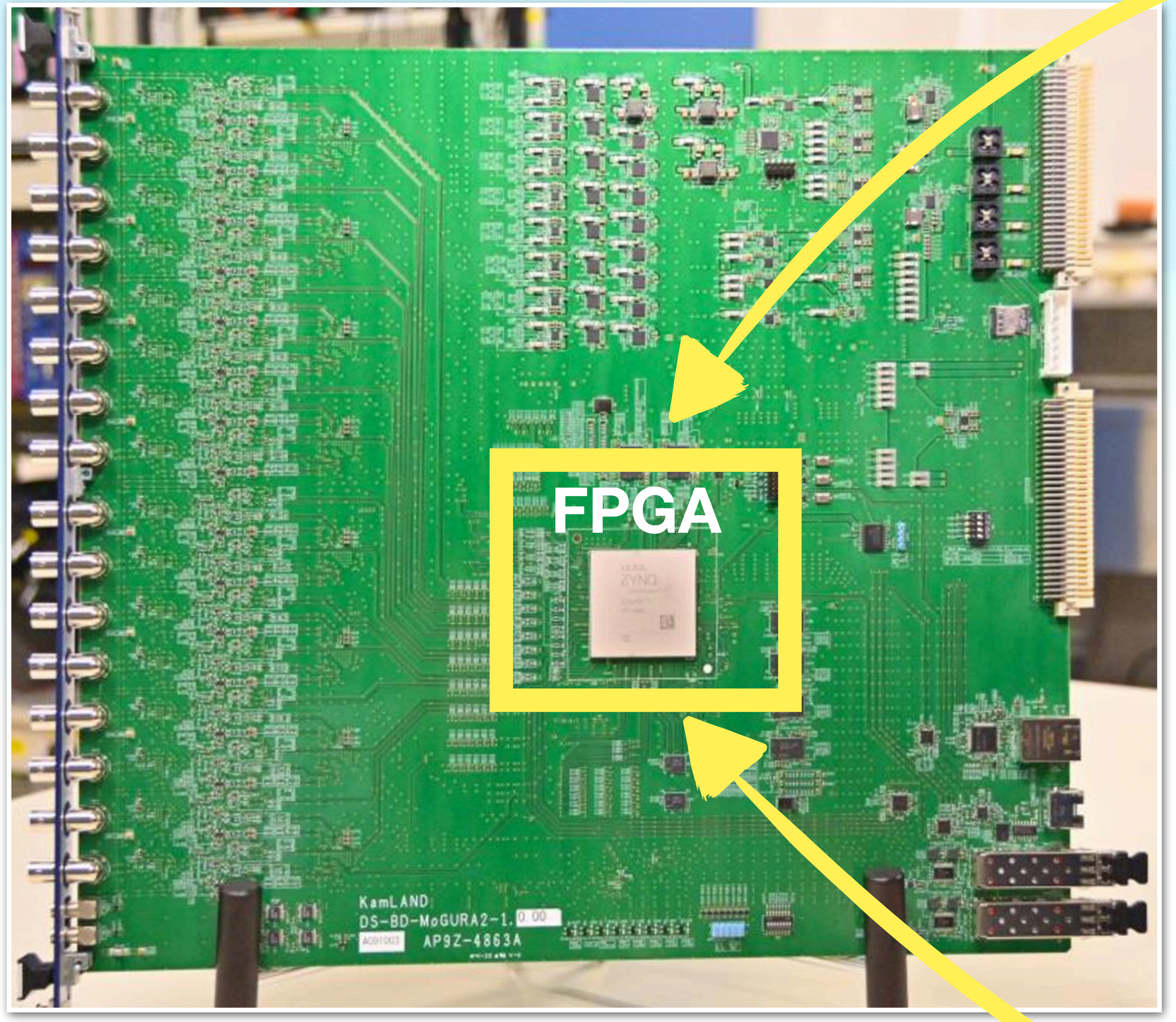

Offline Analysis

Energy

Position

Particle Type

Detector
Response

Online model update to account
for detector status change

Summary

"AI/ML has shaped rare event search, it's an accelerator for new physics results."

- KamLAND-Zen: KamNet
- LEGEND: Germanium Machine Learning
- XENONnT: TextCNN for Background Rejection
- ABRACADABRA: Time Series Denoising

"It will continue to evolve and foster discovery in next-generation experiments"

- Experimental Data Release
- Self-Supervised Learning
- Fast Machine Learning at Edge

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