Physics and Computing with DUNE

Aaron Higuera

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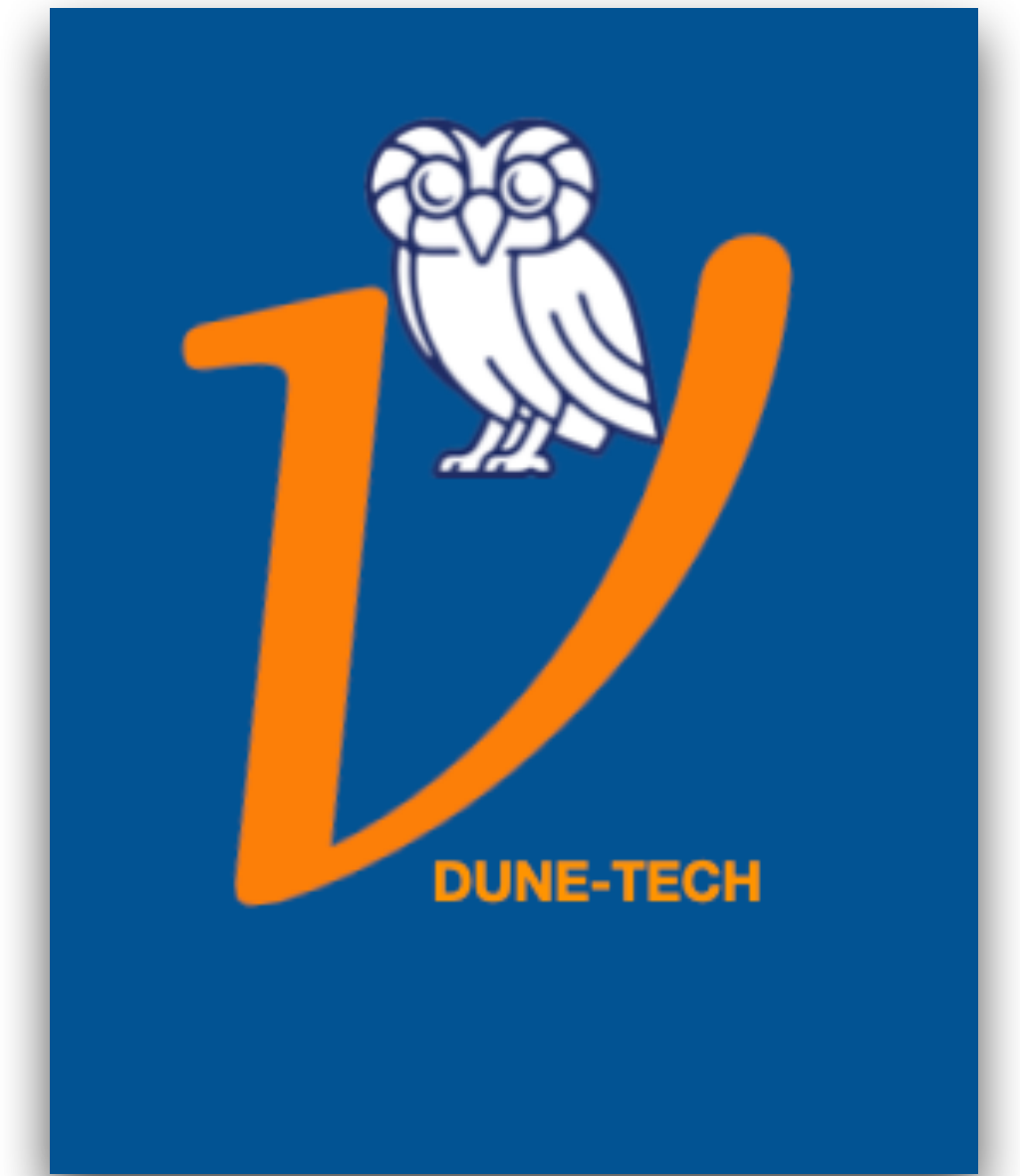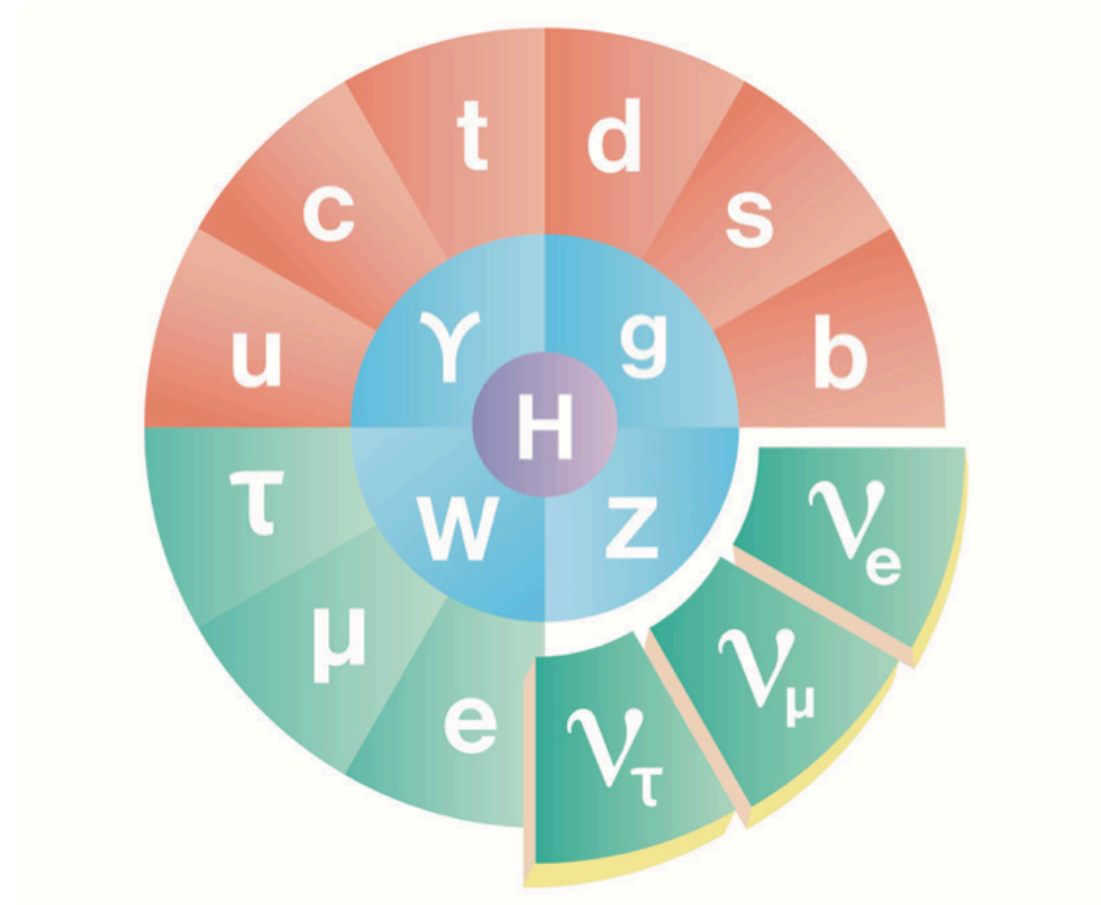
Aaron Higuera

Rice University

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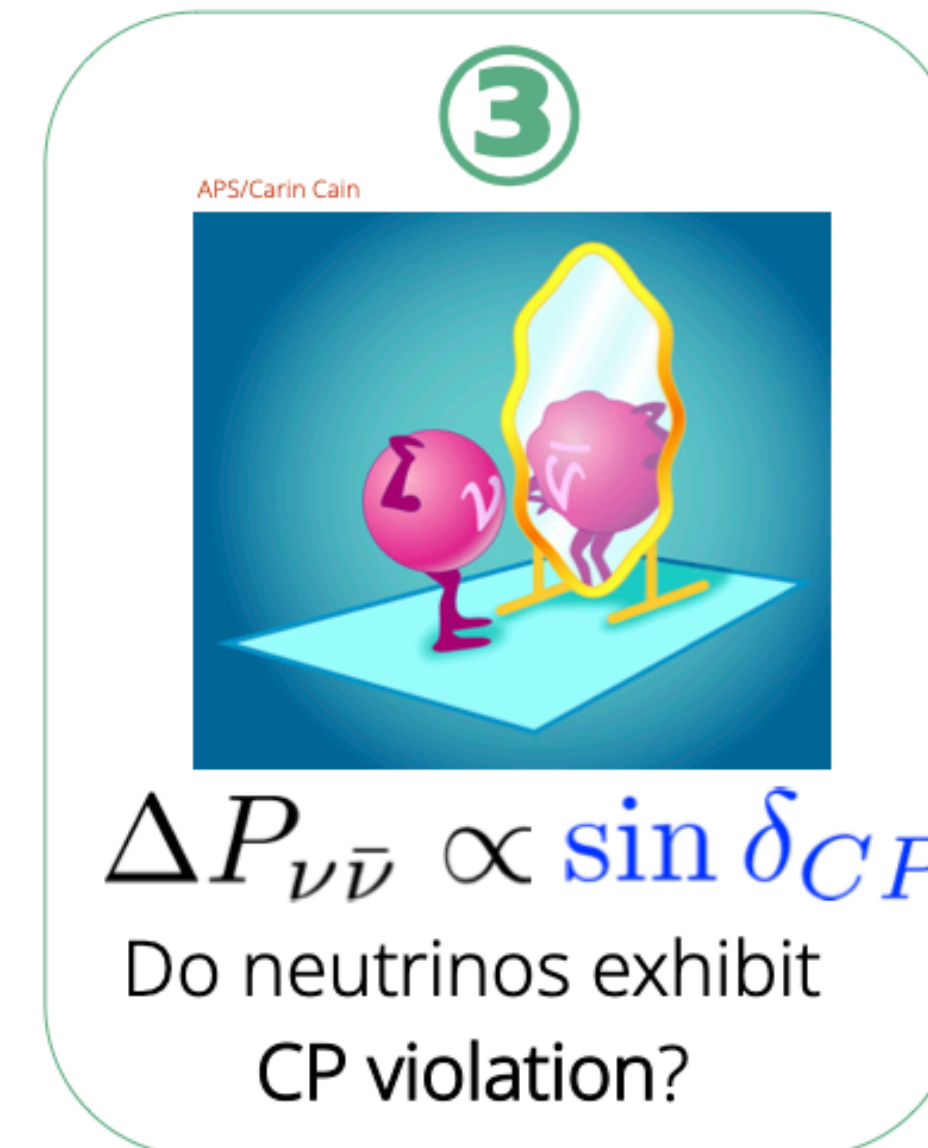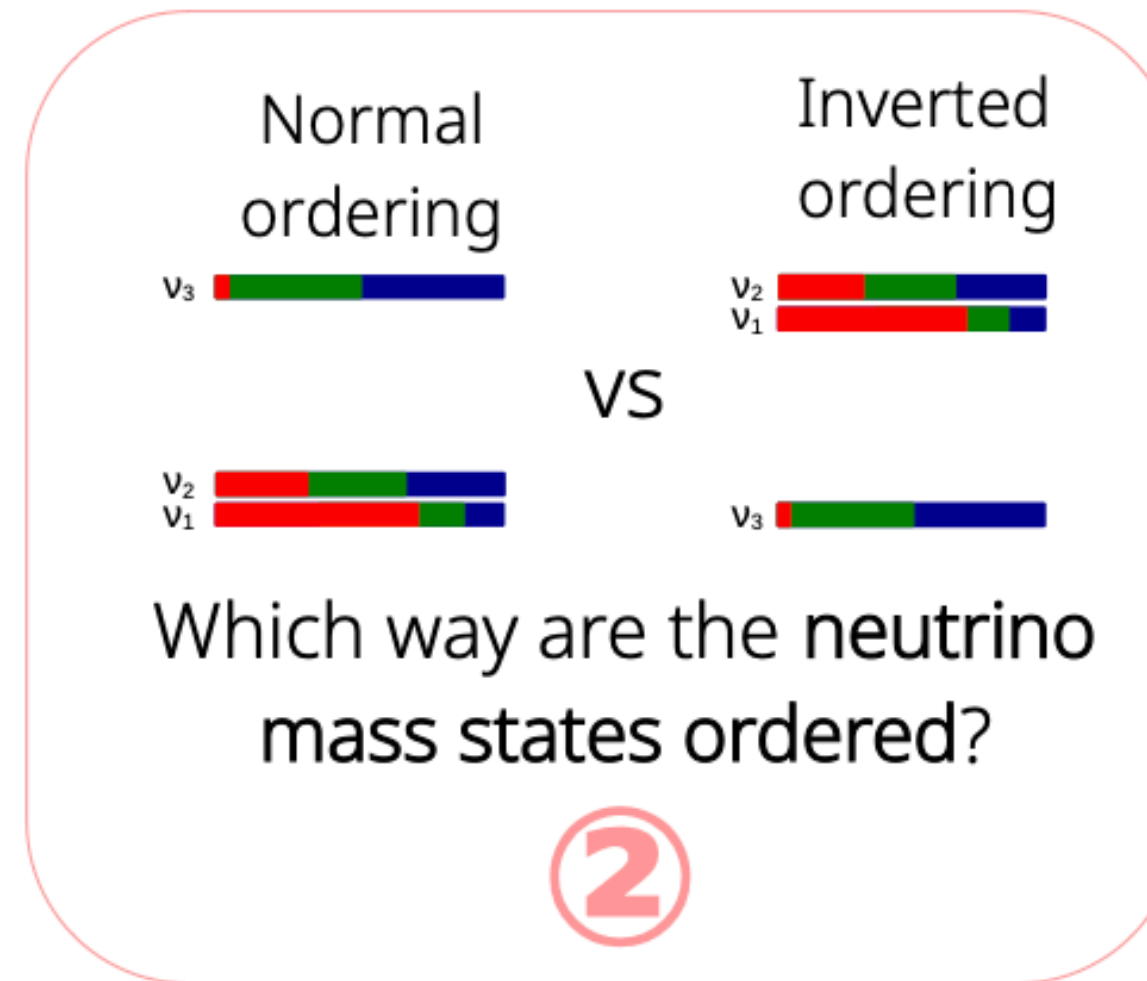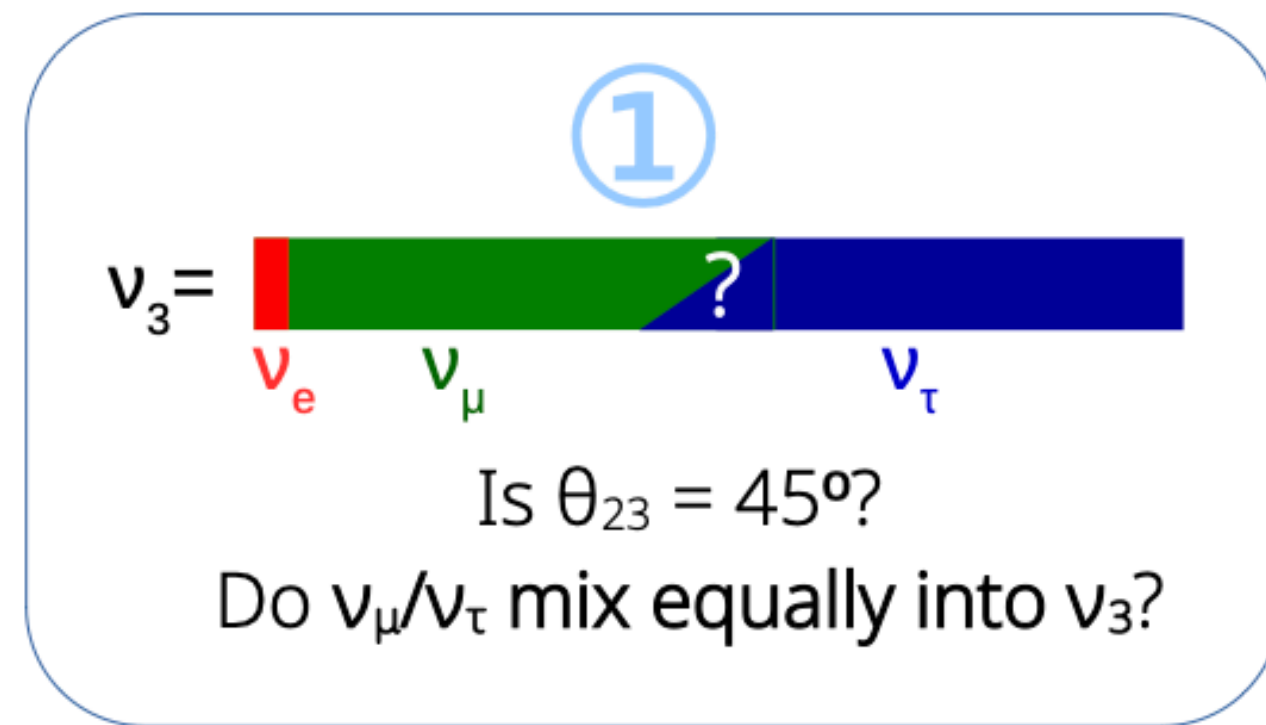# Why do we care about neutrinos?

- What are neutrinos?

FUNDAMENTAL

ABUNDANT

ELUSIVE

Image credit neutrinos.fnal.gov

Why do we care about neutrinos?

①

$$\nu_3 =$$

ν_e $\quad$ ν_μ $\quad\quad$ ν_τ

Is $\theta_{23} = 45°$?
Do ν_μ/ν_τ mix equally into ν_3?

Normal ordering	Inverted ordering
ν_3	ν_2 ν_1
VS	
ν_2 ν_1	ν_3

Which way are the **neutrino** mass states ordered?

②

③

APS/Carin Cain
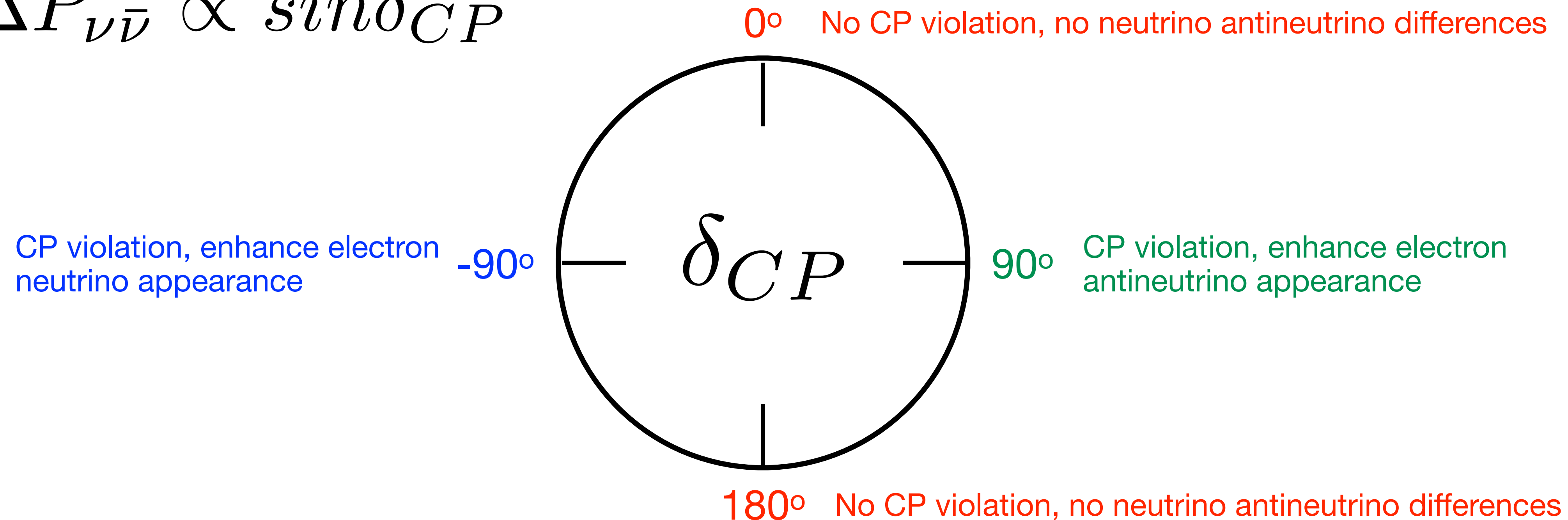
$$\Delta P_{\nu\bar\nu} \propto \sin \delta_{CP}$$

Do neutrinos exhibit
CP violation?

$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} =
\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}
\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix}
\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}
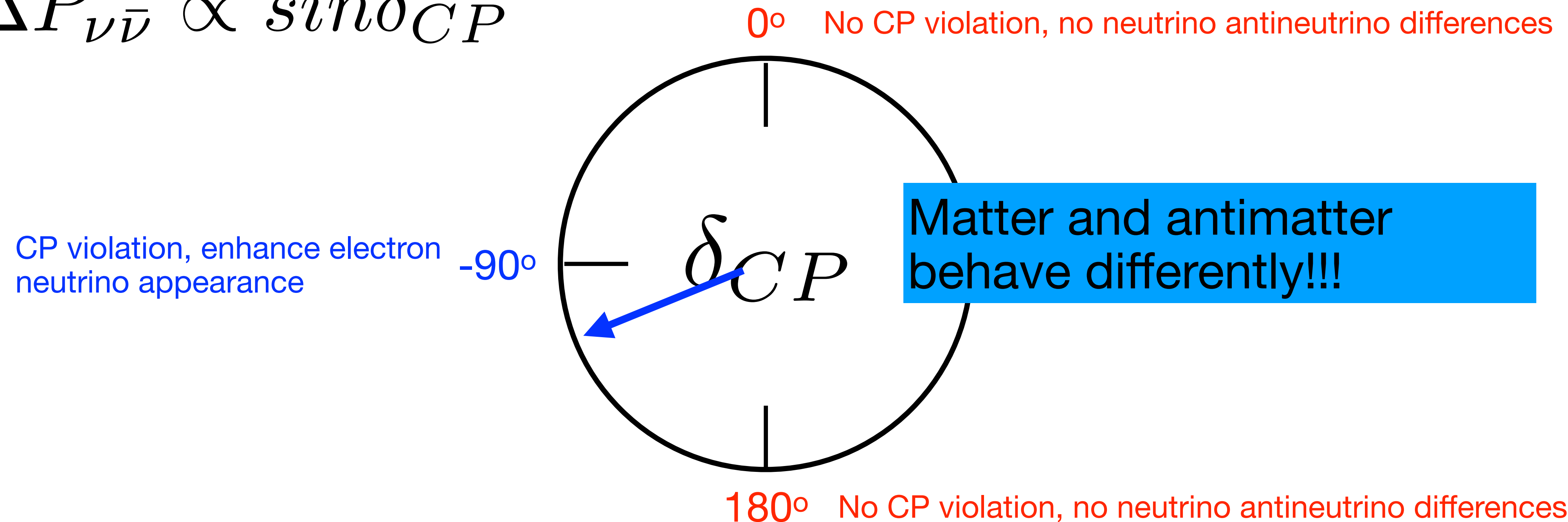\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
$$

Neutrino Oscillation Phenomenon

$$\Delta P_{\nu\bar{\nu}} \propto sin\delta_{CP}$$

0° No CP violation, no neutrino antineutrino differences

CP violation, enhance electron neutrino appearance -90°

δ_{CP}

90° CP violation, enhance electron antineutrino appearance

180° No CP violation, no neutrino antineutrino differences

Neutrino Oscillation Phenomenon

$$\Delta P_{\nu\bar{\nu}} \propto sin\delta_{CP}$$

0° No CP violation, no neutrino antineutrino differences

CP violation, enhance electron neutrino appearance

-90°

δ_{CP}

Matter and antimatter behave differently!!!

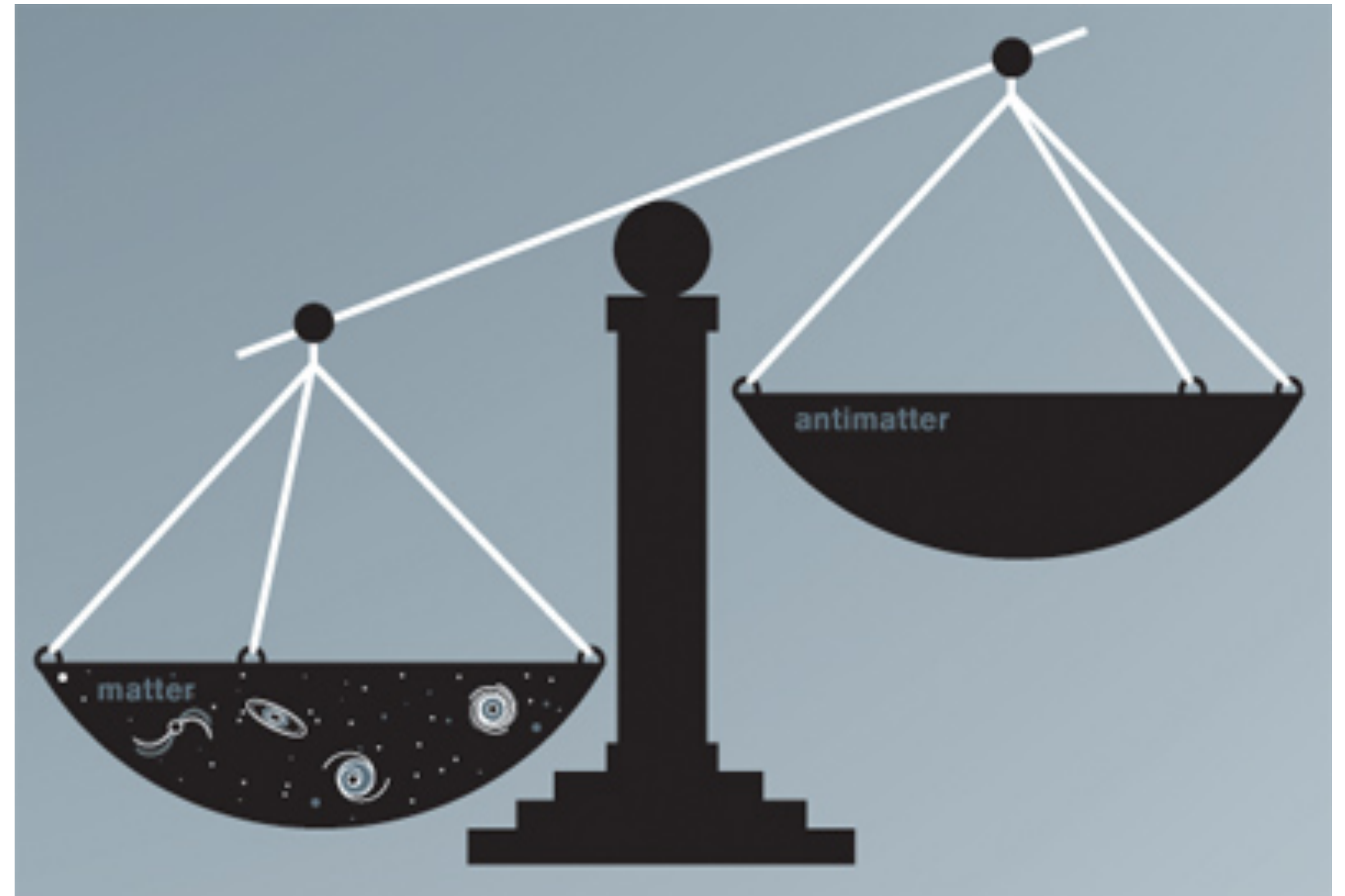180° No CP violation, no neutrino antineutrino differences
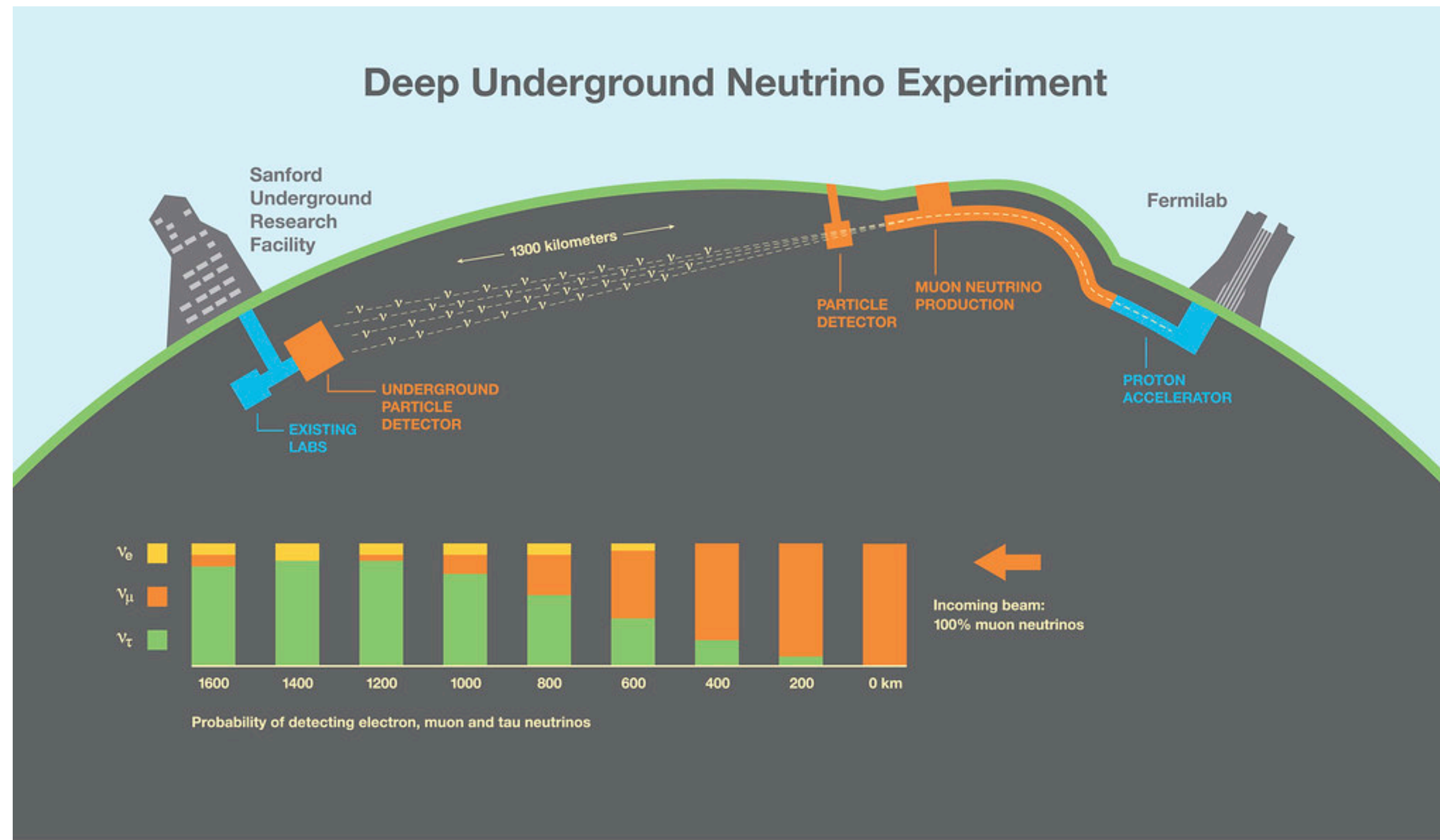
Why do we care about neutrinos?

$$\Delta P_{\nu\bar{\nu}} \propto sin\delta_{CP}$$

- According to the Big Bang theory, the same amount of matter and antimatter should have been created

- If there is CP violation in the neutrino sector, this can help us to understand the matter-antimatter asymmetry in the universe

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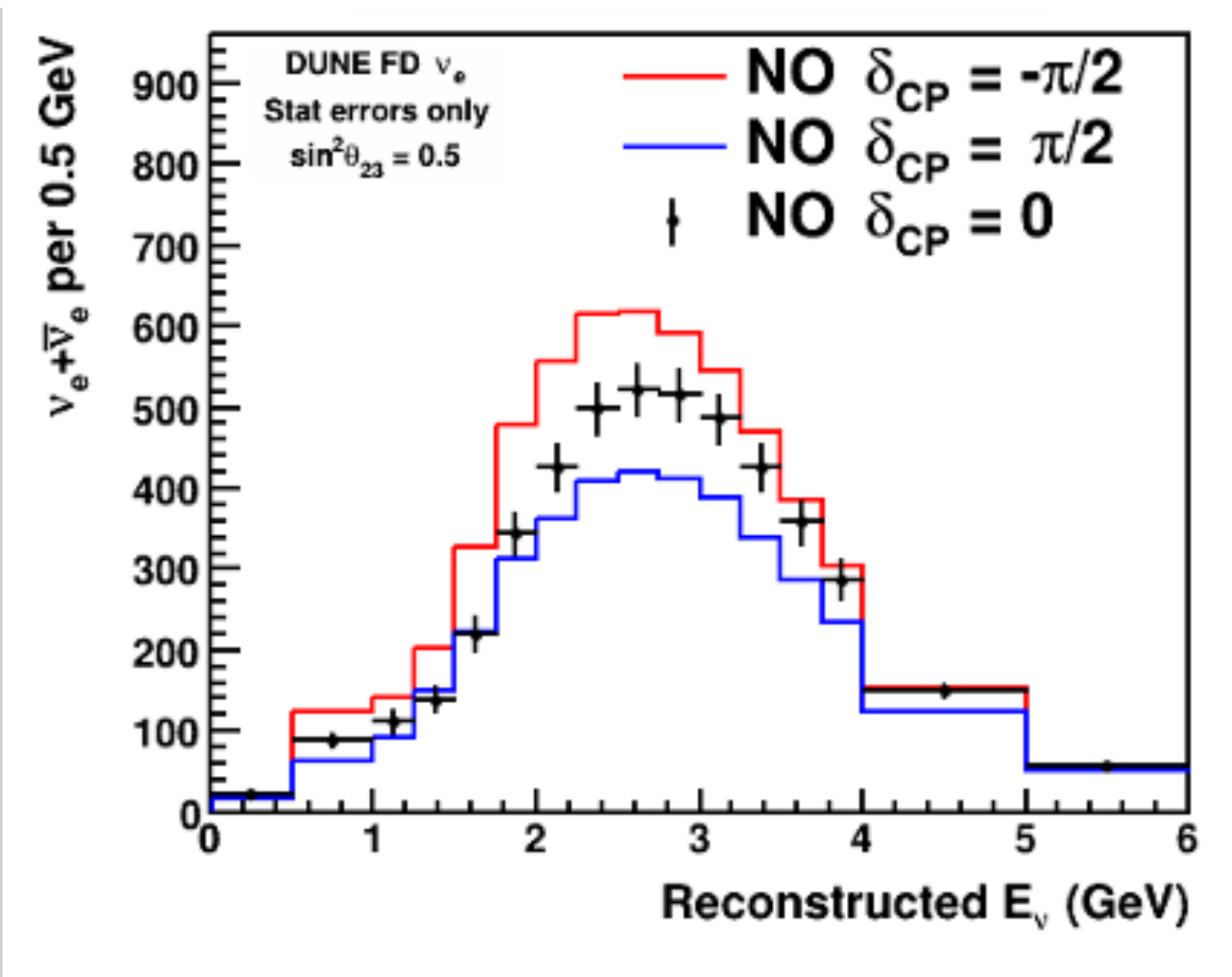
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Deep Underground Neutrino Experiment (DUNE)

- Measure ∂_{CP} and determine if CP is violated

- Determine the neutrino mass ordering

- Non-beam physics (supernova, atmospheric neutrinos, etc)

  - Sensitive large underground detector

  - Intense neutrino beam

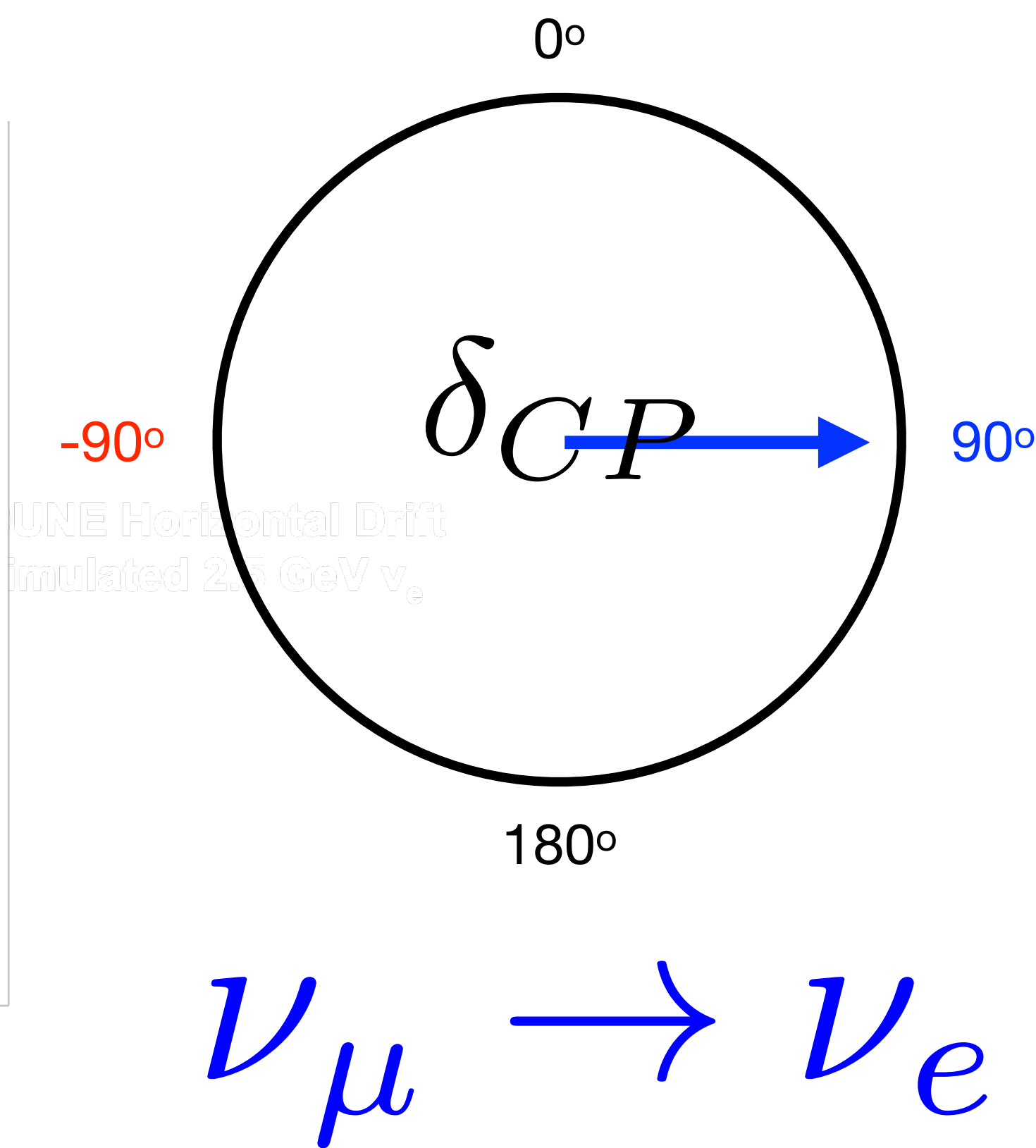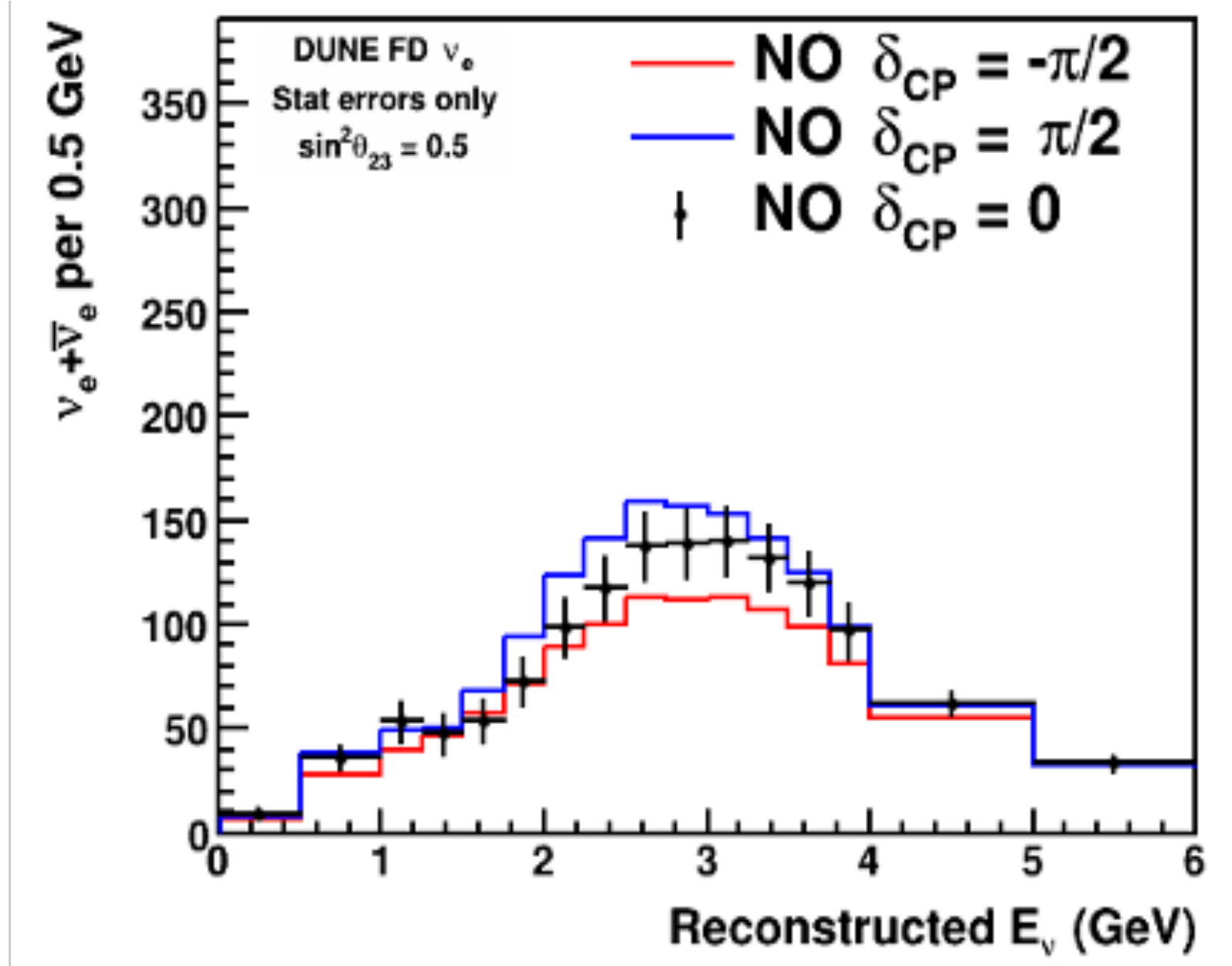 - Near detector for systematics constraints

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Deep Underground Neutrino Experiment (DUNE)

Neutrinos

DUNE FD ν_e
Stat errors only
$\sin^2\theta_{23} = 0.5$

NO $\delta_{CP} = -\pi/2$
NO $\delta_{CP} = \pi/2$
NO $\delta_{CP} = 0$

Antineutrinos

DUNE FD ν_e
Stat errors only
$\sin^2\theta_{23} = 0.5$

NO $\delta_{CP} = -\pi/2$
NO $\delta_{CP} = \pi/2$
NO $\delta_{CP} = 0$

$\nu_e + \overline{\nu}_e$ per 0.5 GeV

Reconstructed E_ν (GeV)

0°

-90° δ_{CP} 90°

180°

$\nu_\mu \rightarrow \nu_e$

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Deep Underground Neutrino Experiment (DUNE)

Eur. Phys. J. C 80, 978 (2020)

$$\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$$

Do neutrinos exhibit CP violation?

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How do we go from sensitivity plots to physics?

Eur. Phys. J. C 80, 978 (2020)

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How do we go from sensitivity plots to physics?

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How do we go from sensitivity plots to physics?

How do we go from data to physics?
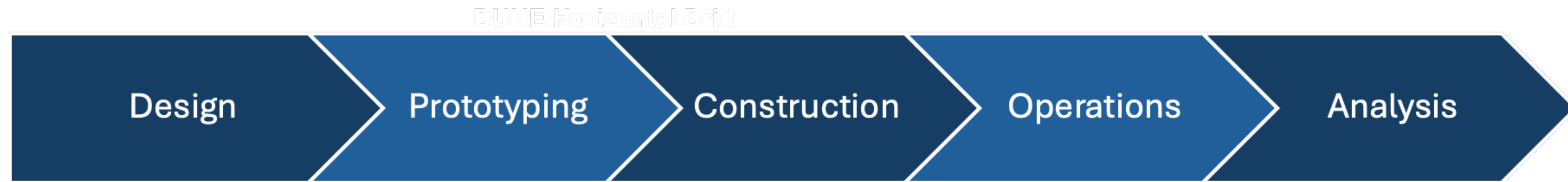
Computing & Data!

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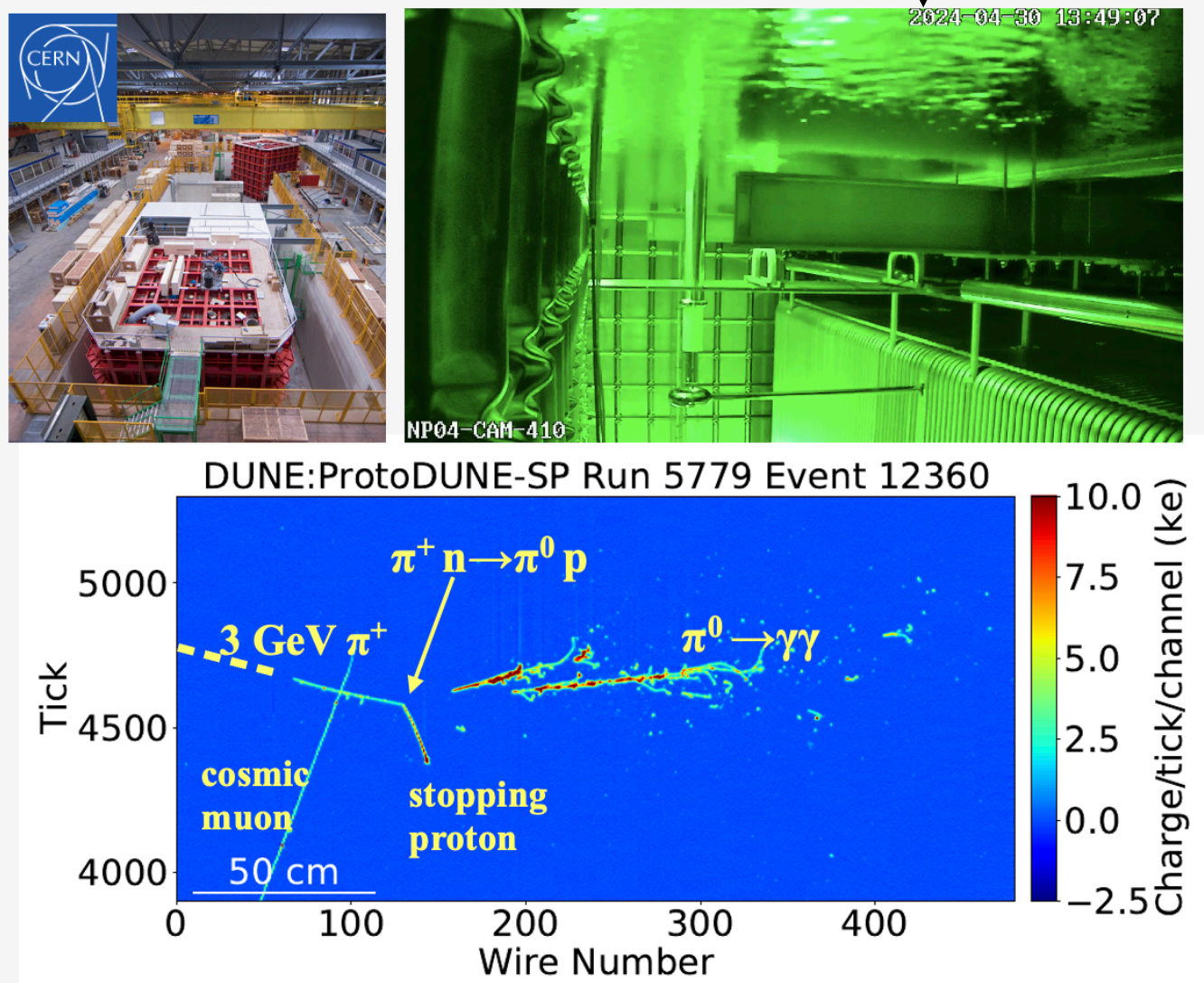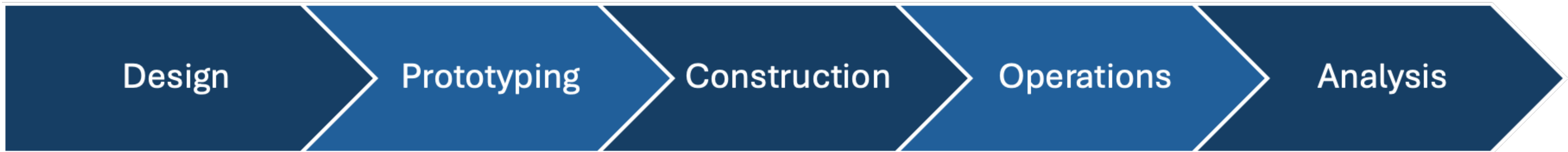
How do we go from data to physics?

Computing & a lot of data!

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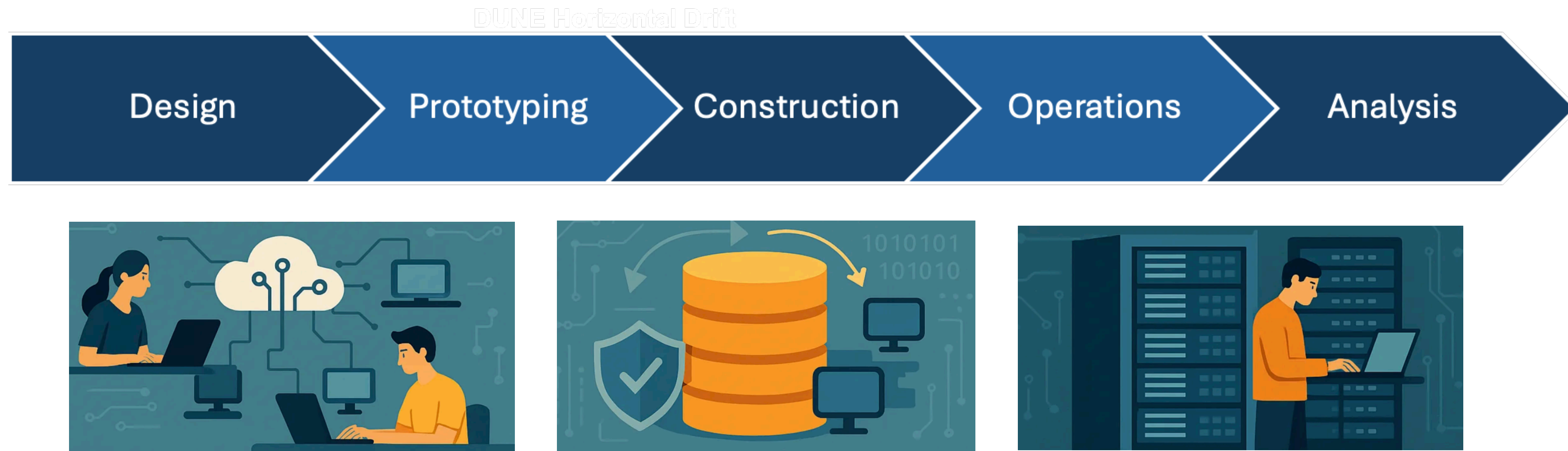
How much data is out there?

- Neutrinos rarely interact with matter

- The expected rate at DUNE is 10PB/year per module

- Assume that the streaming rate on Spotify is~160kbps (20KB/sec)

- A 3.5 mins song would be ~4.2 MB

- If the experiment runs for 10 years, it will collect 100PB/module (400PB in total)

- The equivalent amount of songs given the data collected would be **~96 billion songs**!!!

- You will need ~**640,000 years** to play every song!!!
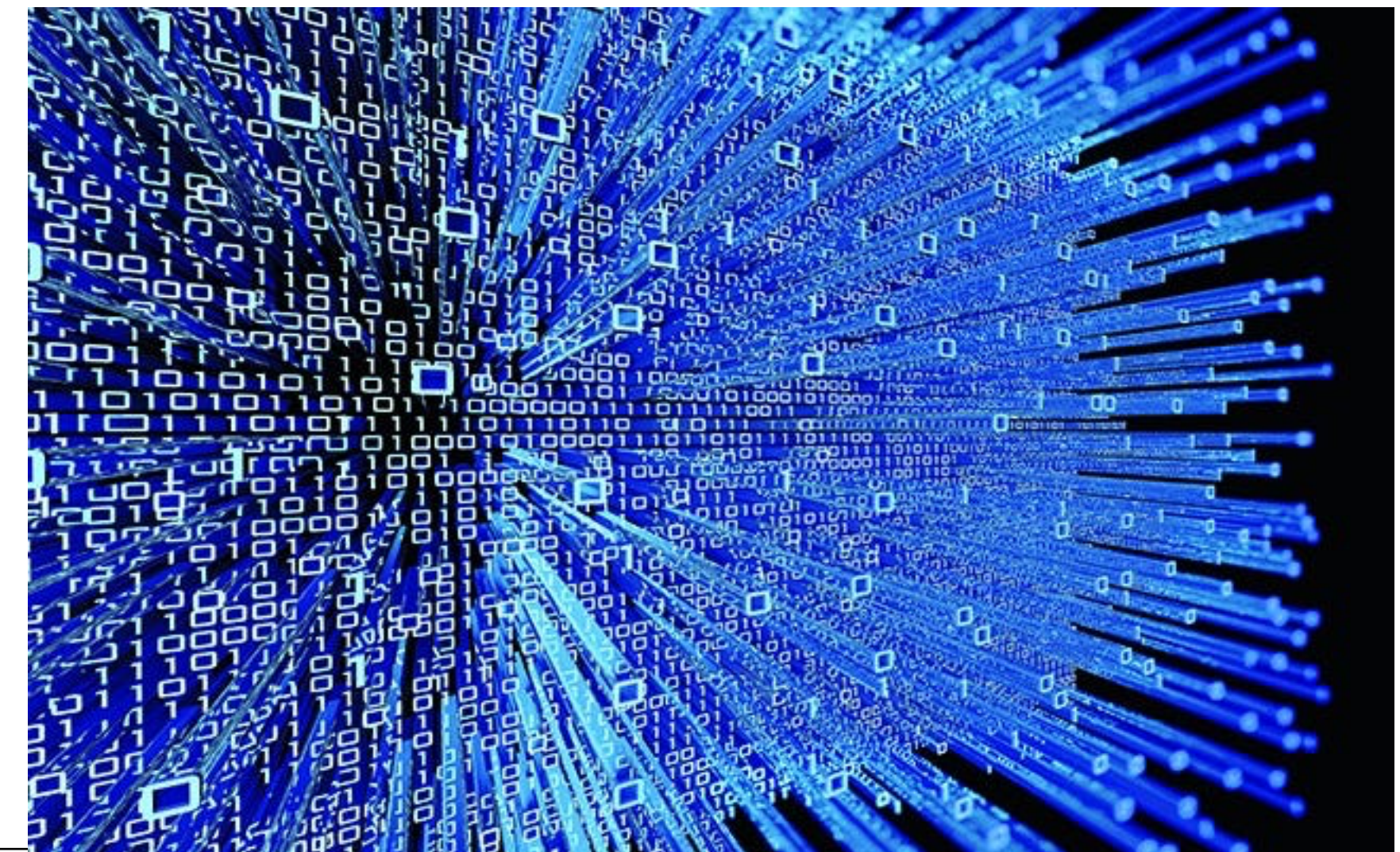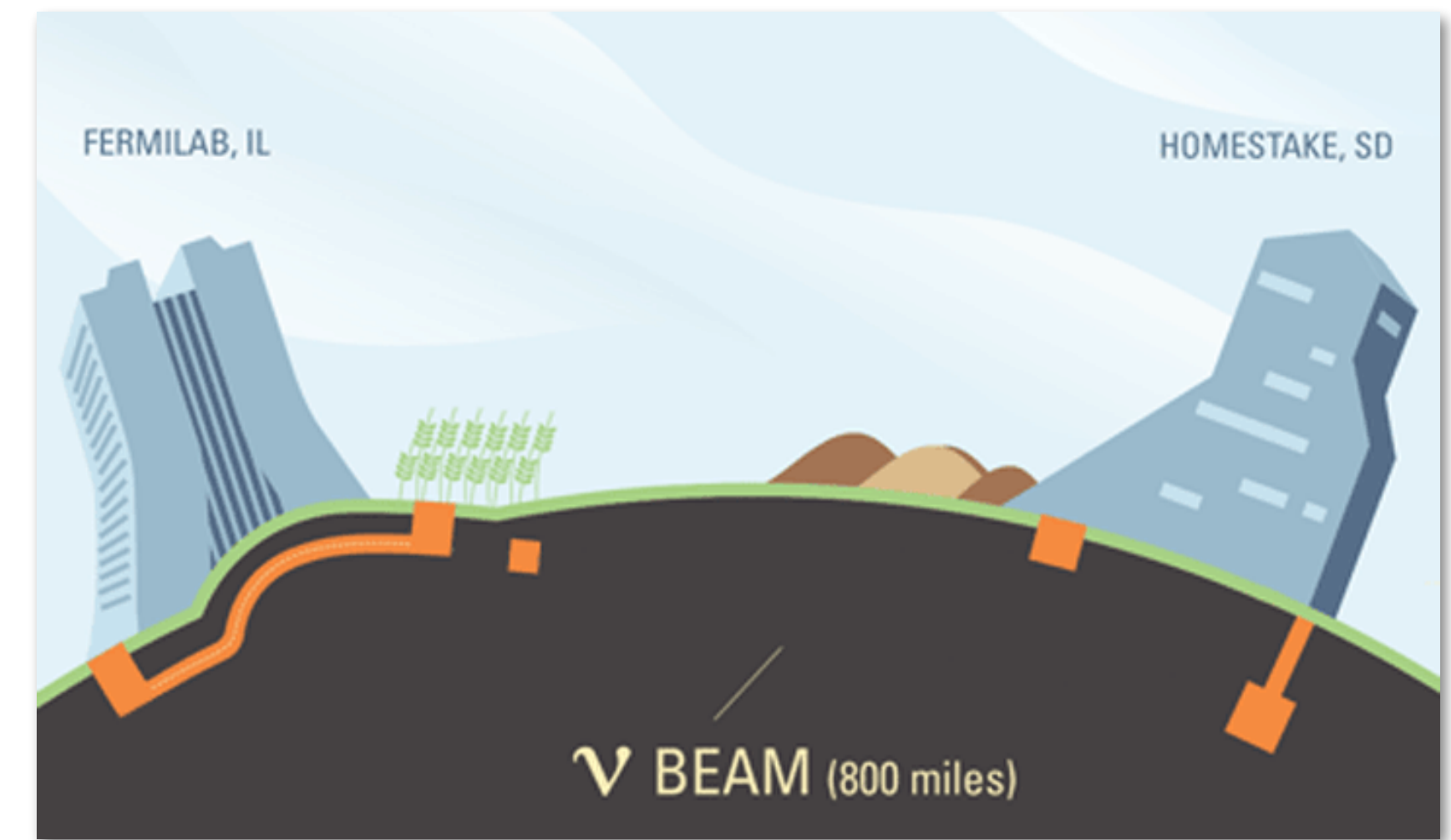
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How do we manage that amount of data?

- If you would like to play **~96 billion songs** simultaneously, you will need **~10 billion laptops**

- **How do we solve this computing problem?**

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How do we manage that amount of data?

- If you would like to play **~96 billion songs** simultaneously, you will need **~10 billion laptops**

- **How do we solve this computing problem?**

  - The data amount increases with time

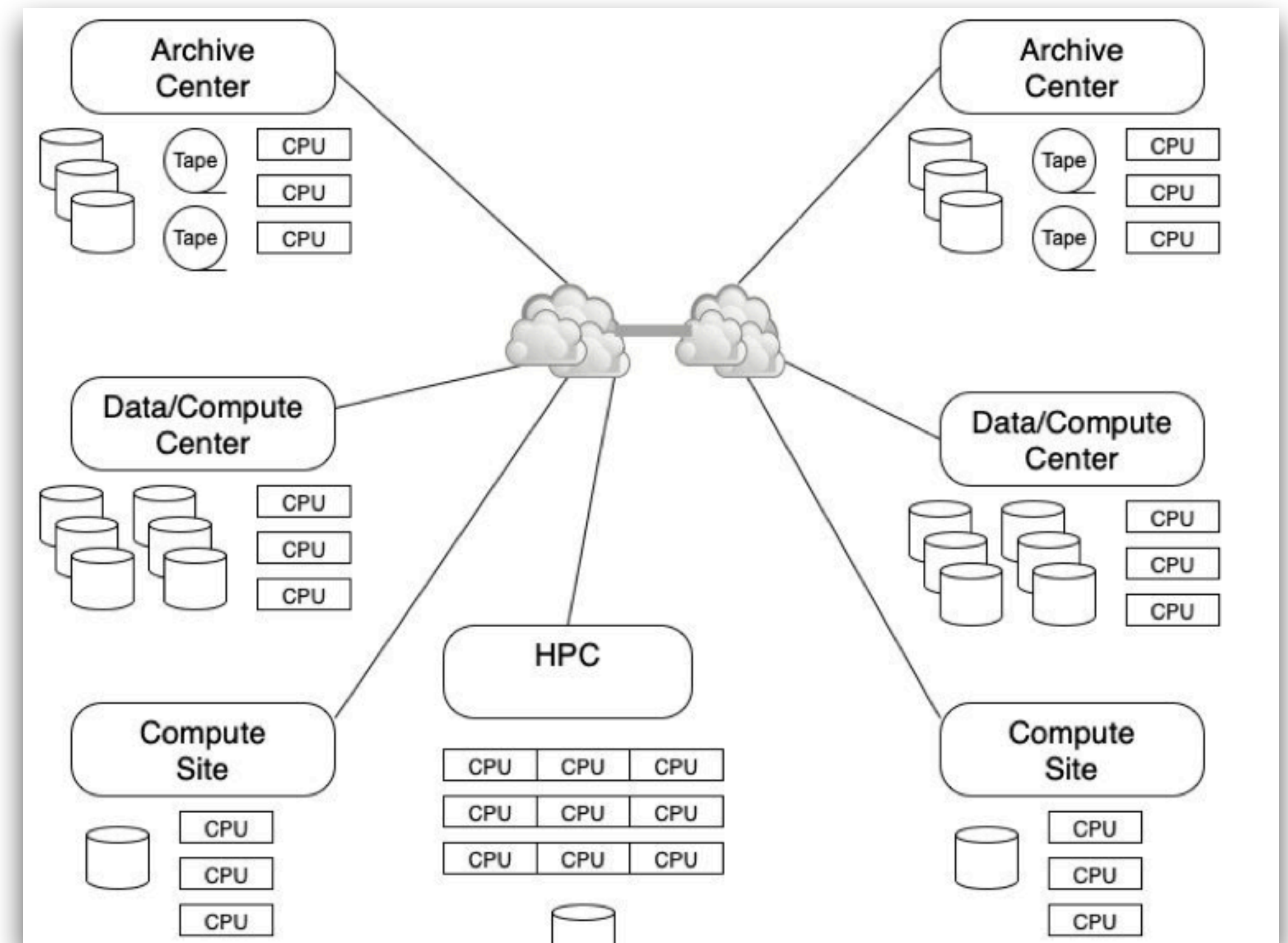 - Once data collection ends, in most cases, a final analysis will include *all* data

Solving the computing problem

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Solving the computing problem

- **Distributed computing**: this involves using multiple resources to work together, sharing workload and resources to achieve a common goal

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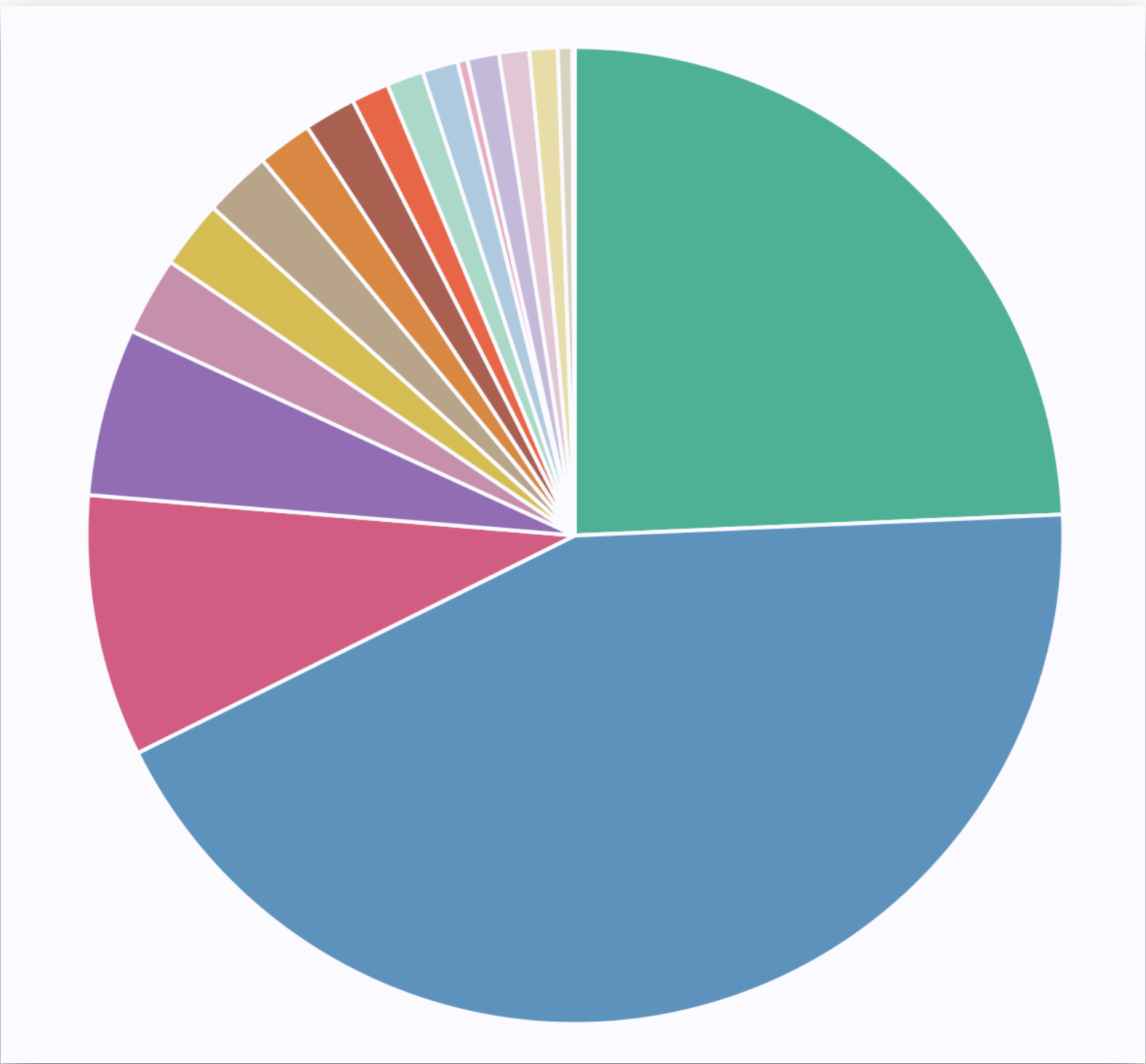The Inaugural Workshop of Exploring the Frontiers of Nuclear, Particle, and Astrophysics, TSU, April 9-11, 2025

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Solving the computing problem

- Storage

  - To retrieve any data, metadata is crucial

  - What is metadata?

    - Is data about the data

    - Crucial for data cataloging

    - This allows to comply with **FAIR** principles

    - Findable, Accessible, Interoperable, and Reproducible

Solving the computing problem

- Storage

  - Disk and Tape

Legend:
- DUNE_CERN_EOS
- DUNE_US_FNA...
- DUNE_ES_PIC
- PRAGUE
- NIKHEF
- DUNE_FR_CCIN...
- RAL_ECHO
- QMUL
- DUNE_UK_MAN...
- SURFSARA
- CERN_PDUNE_...
- RAL-PP
- DUNE_UK_GLA...
- DUNE_UK_LAN...
- DUNE_US_BNL...
- IMPERIAL
- DUNE_IT_INFN...
- LANCASTER
- DUNE_CA_SFU
- DUNE_FR_CCIN...
- DUNE_FR_CCIN...
- DUNE_FR_CCIN...
- T3_US_NERSC

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Solving the computing problem

- Software and software distribution

  - Version control (Git, GitLab, GitHub)

  - Software distributions:

    - An ad-doc tool was developed at CERN called CERN Virtual Machine File System (CVMFS) to distribute and manage software environments

    - Container-based software distribution (Docker, Singularity, etc)

  - Clouds Systems
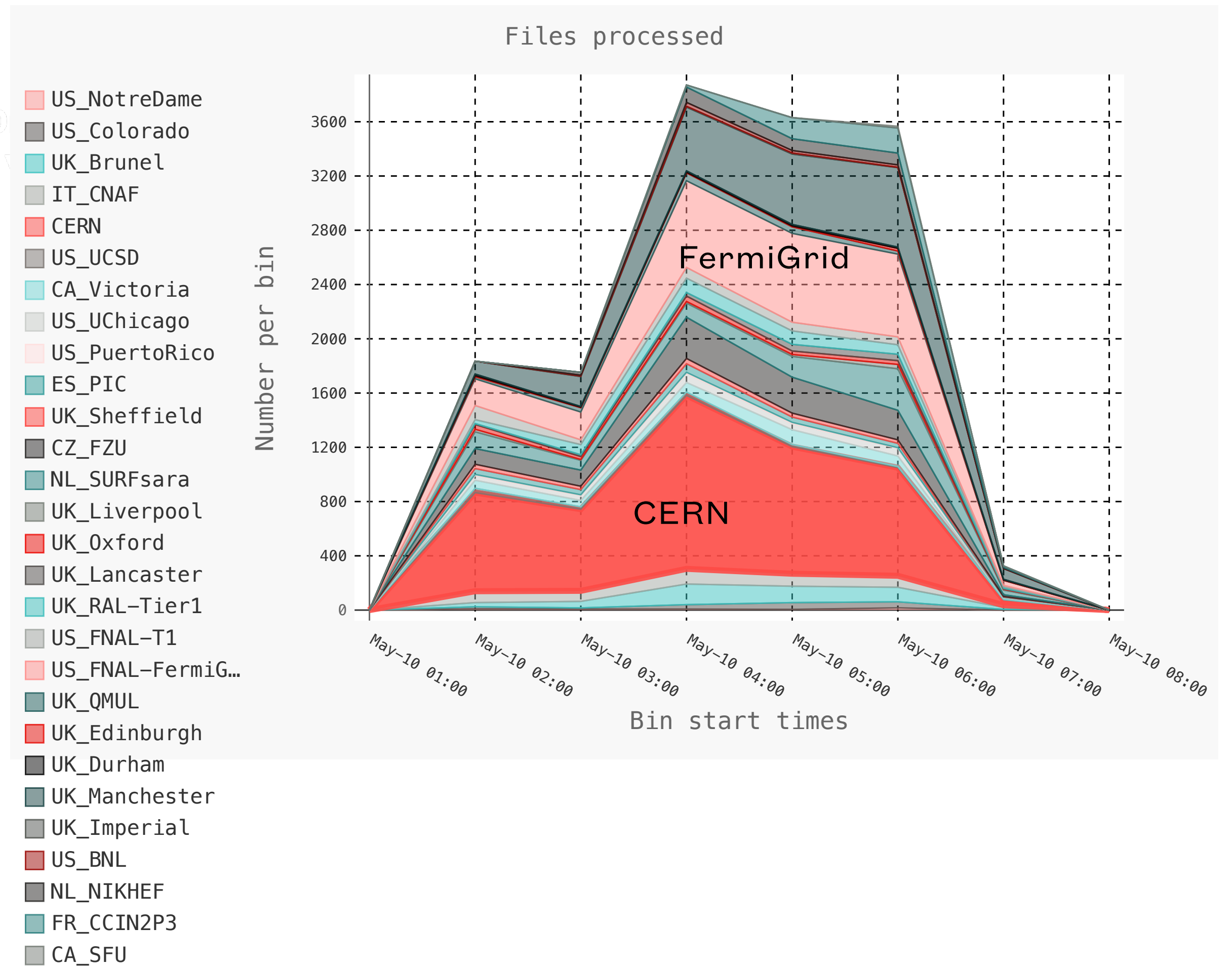
Solving the computing problem

- Workflow Management

- JustIN: manages DUNE workflows on the grid. It allows the experiment to produce MC and process datasets registered in DUNE's data catalogs

  - It relies on a software distribution service, e.g. CVMFS

  - Based on data location, optimize CPU usages

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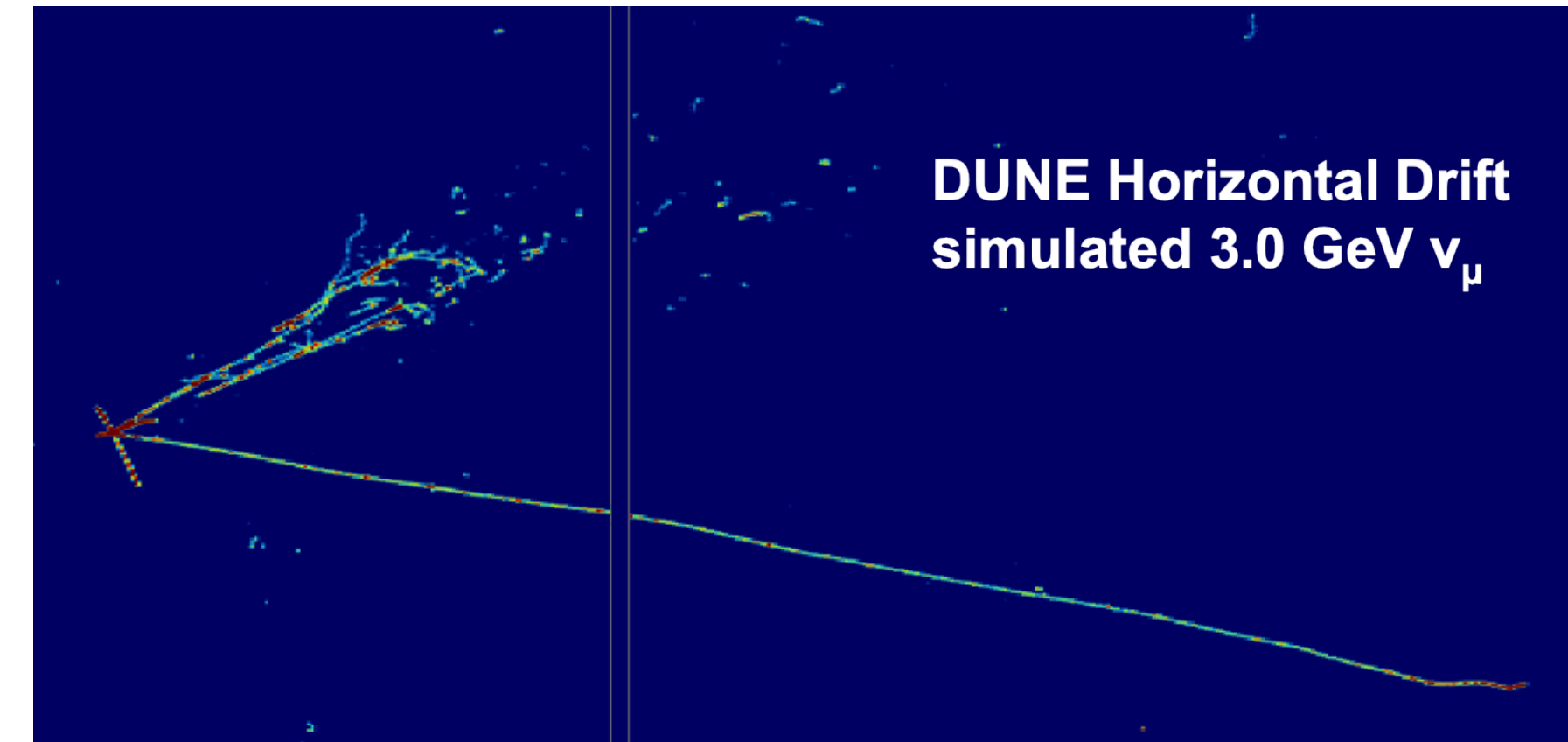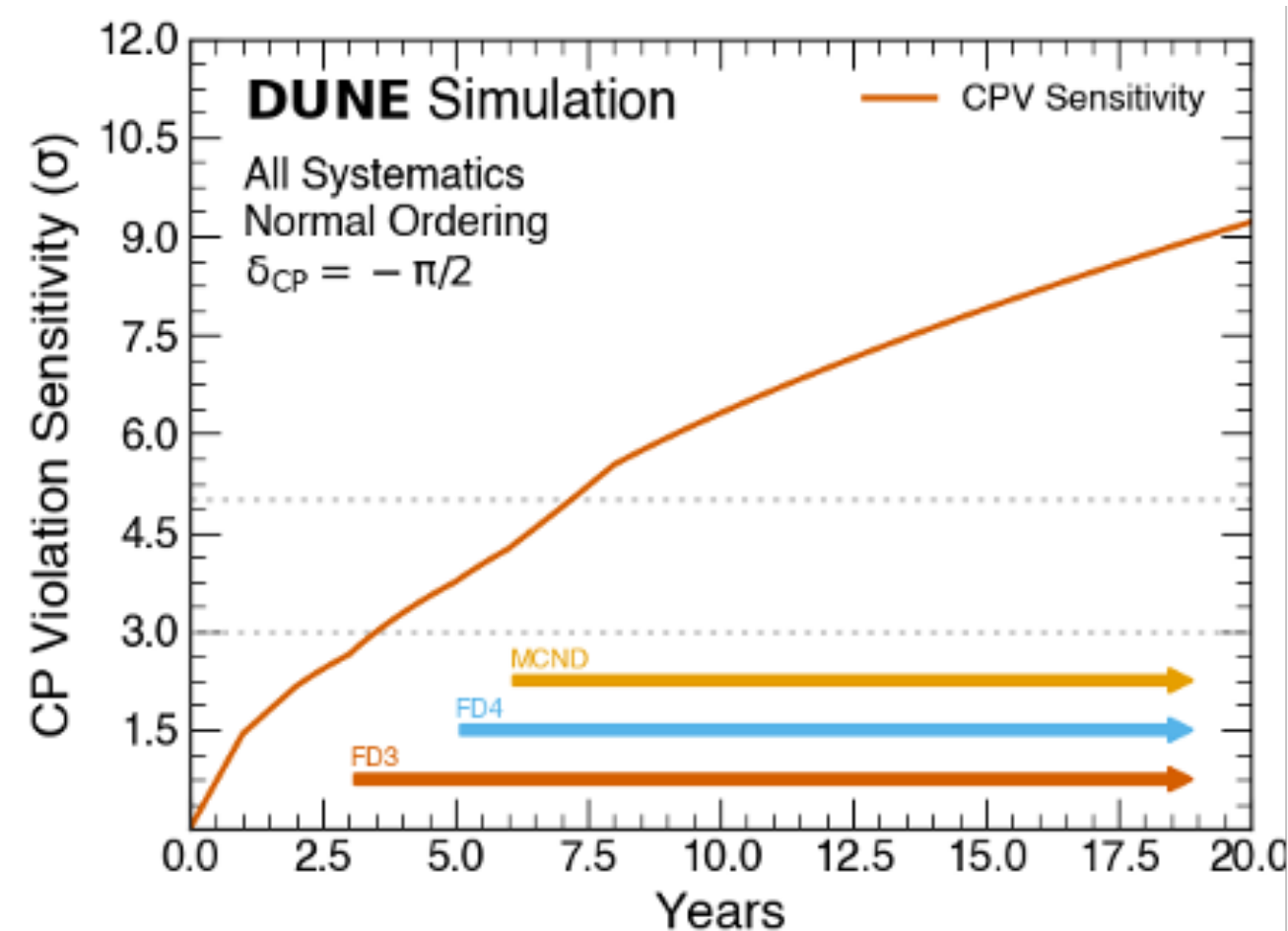The Inaugural Workshop of Exploring the Frontiers of Nuclear, Particle, and Astrophysics, TSU, April 9-11, 2025
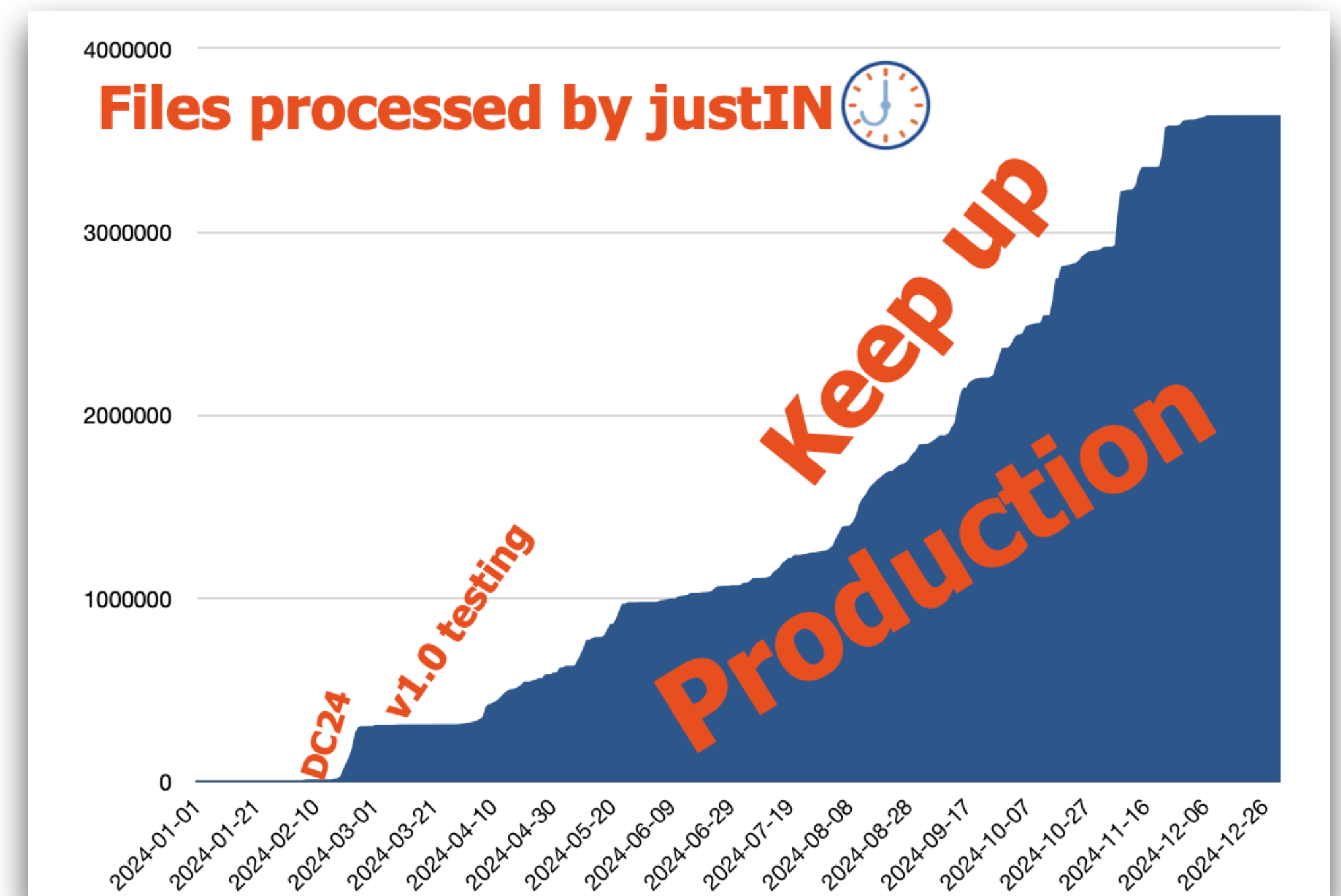
Solving the computing problem

- A MC campaing

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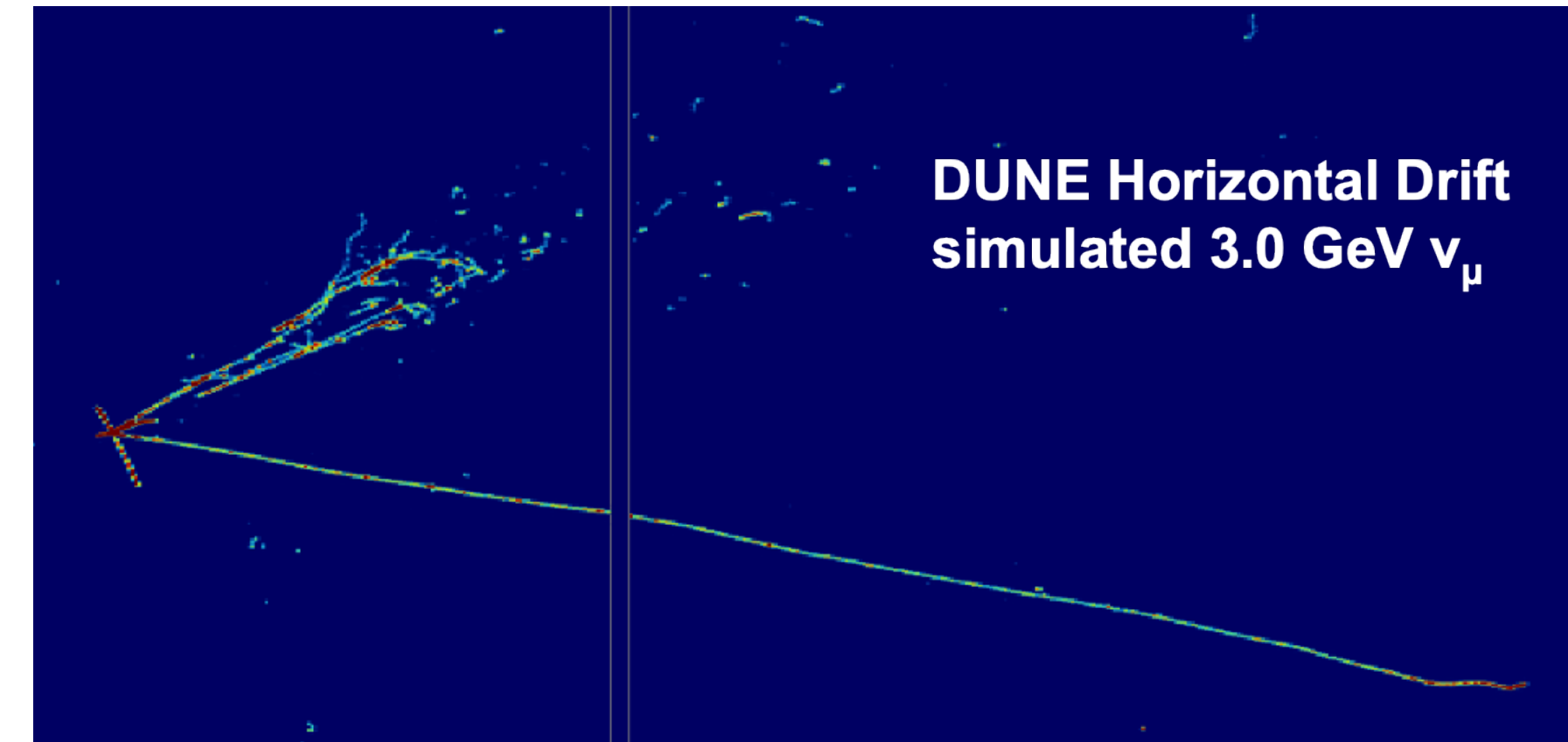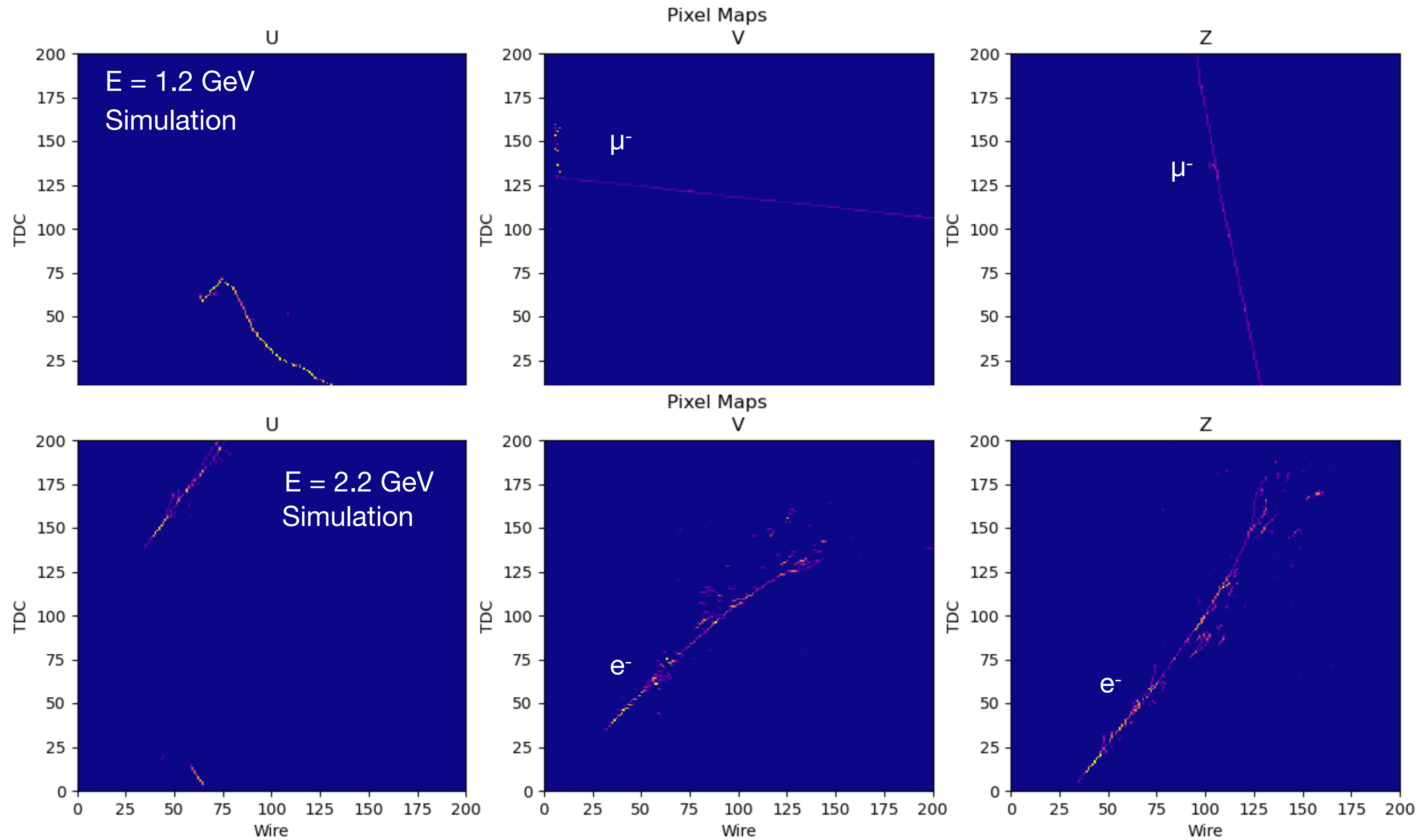
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DUNE and ML

- How do we enable DUNE's physics program?

  - The experiment has created the cyberinfrastructure to do that

  - Innovative research

DUNE Horizontal Drift
simulated 3.0 GeV ν_μ

DUNE Horizontal Drift
simulated 2.5 GeV ν_e

DUNE Simulation
CPV Sensitivity
All Systematics
Normal Ordering
$\delta_{CP} = -\pi/2$

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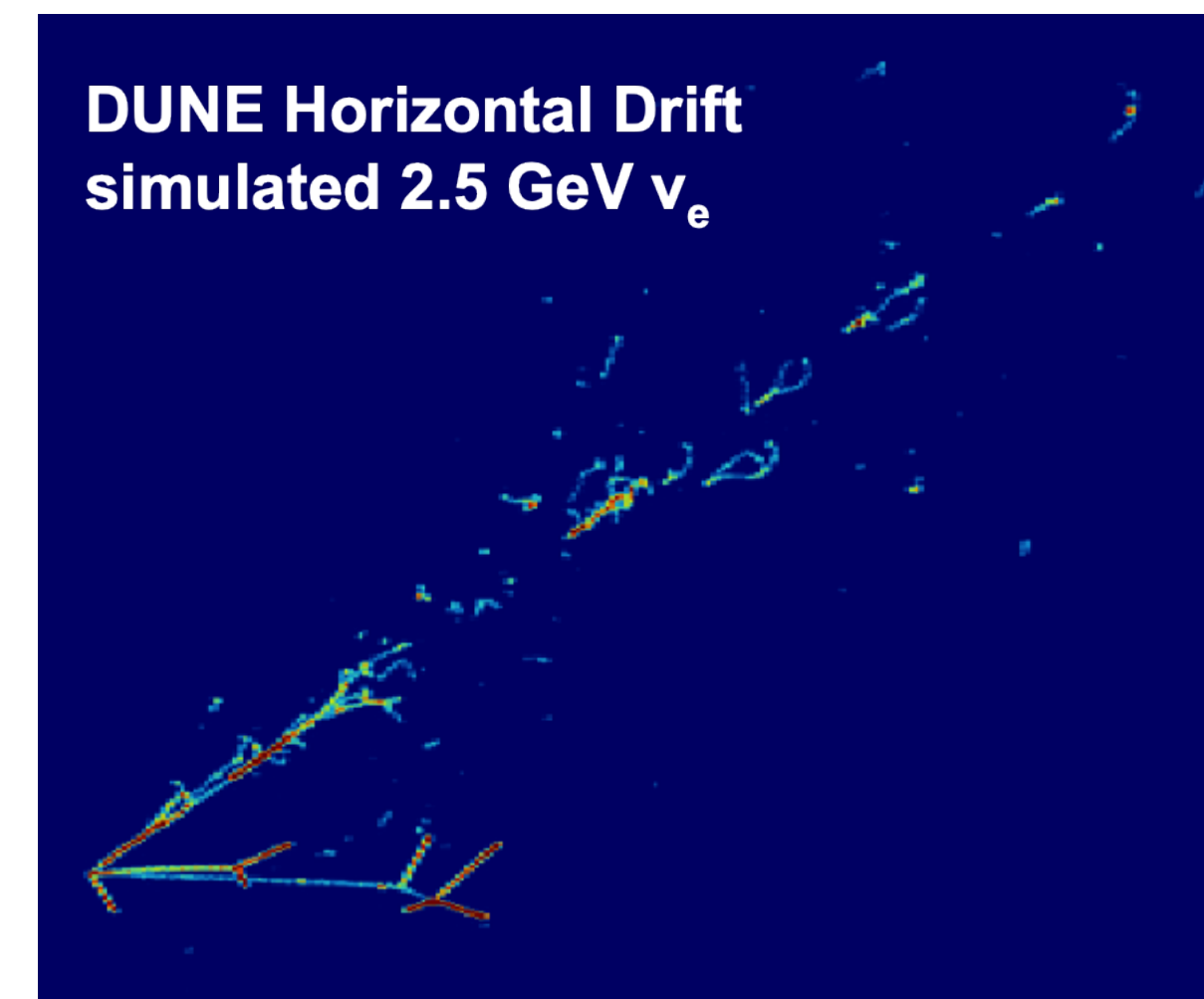
DUNE and ML

- How do we enable DUNE's physics program?

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  - Innovative research

$$P(\nu_\mu \to \nu_e)$$

DUNE Horizontal Drift
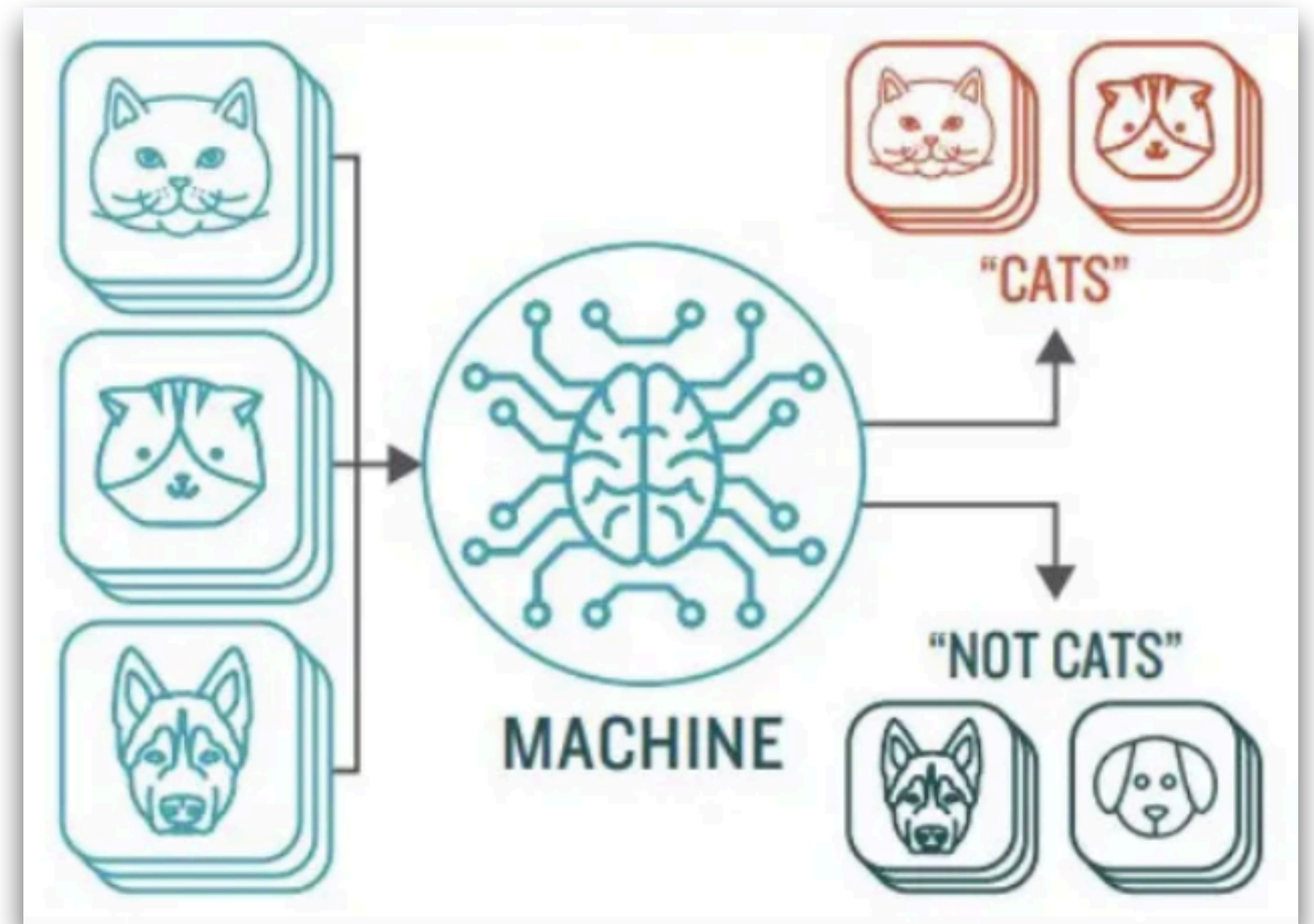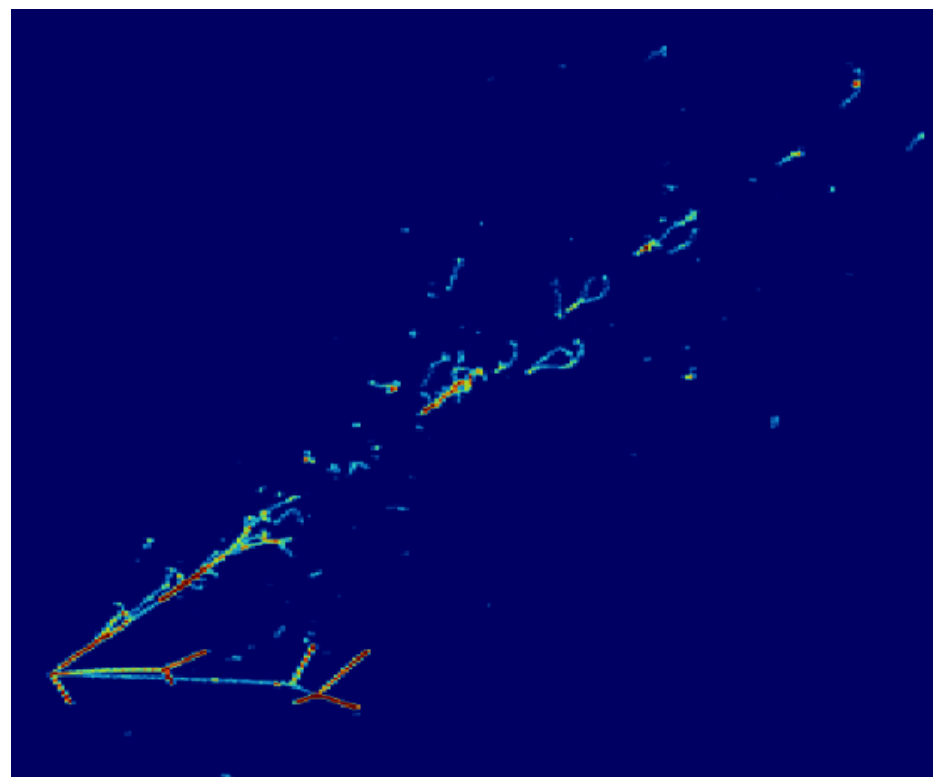simulated 3.0 GeV ν_μ

DUNE Horizontal Drift
simulated 2.5 GeV ν_e

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DUNE and ML

$$P(\nu_\mu \rightarrow \nu_e)$$

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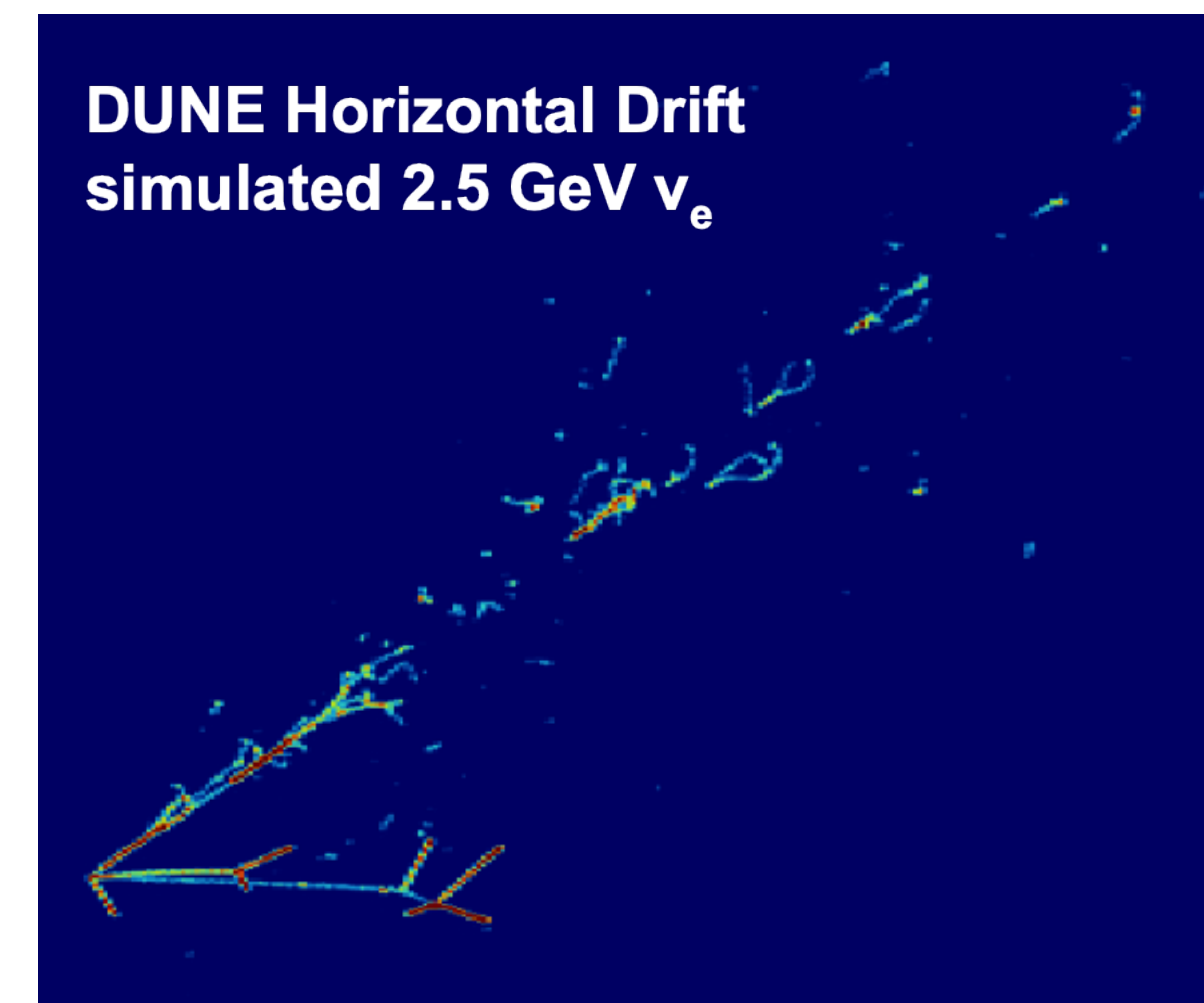
DUNE and ML

- How do we enable DUNE's physics program?

  - The experiment has created the cyberinfrastructure to do that

 - Innovative research: **supervised ML**

    - Image recognition

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DUNE and ML

- How to enable DUNE's physics program: supervised ML and CNNs

Feature maps

f.maps

f.maps

Output

Convolutions   Subsampling   Convolutions   Subsampling   Fully connected
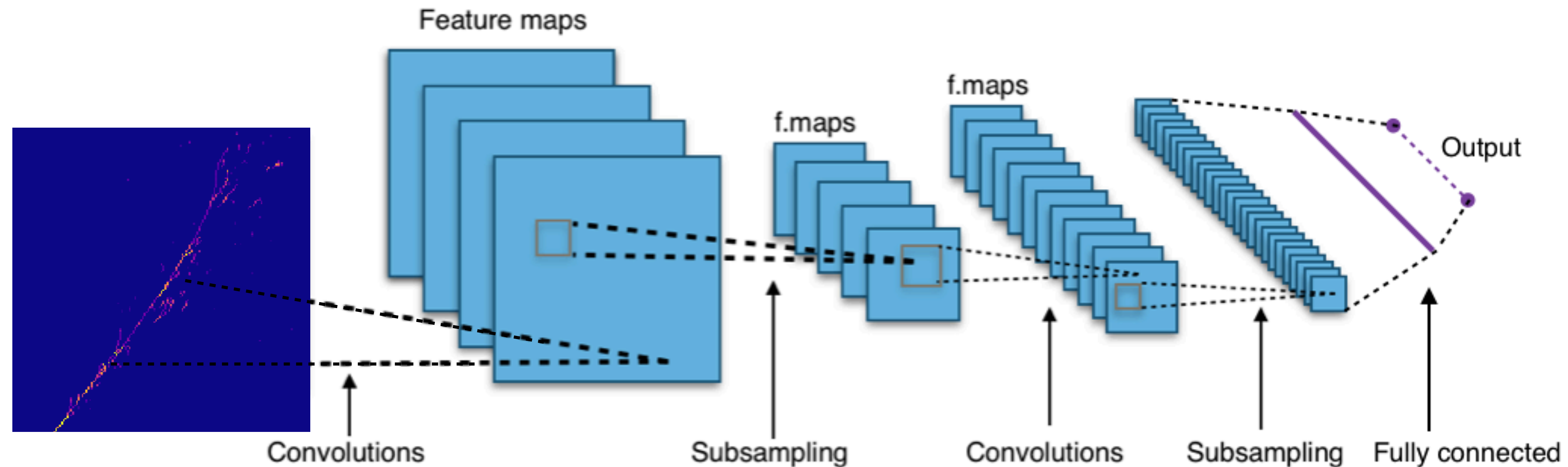
CNNs primarily focus on the topological representation of an image, which includes the shapes, patterns, and spatial relationships within the image
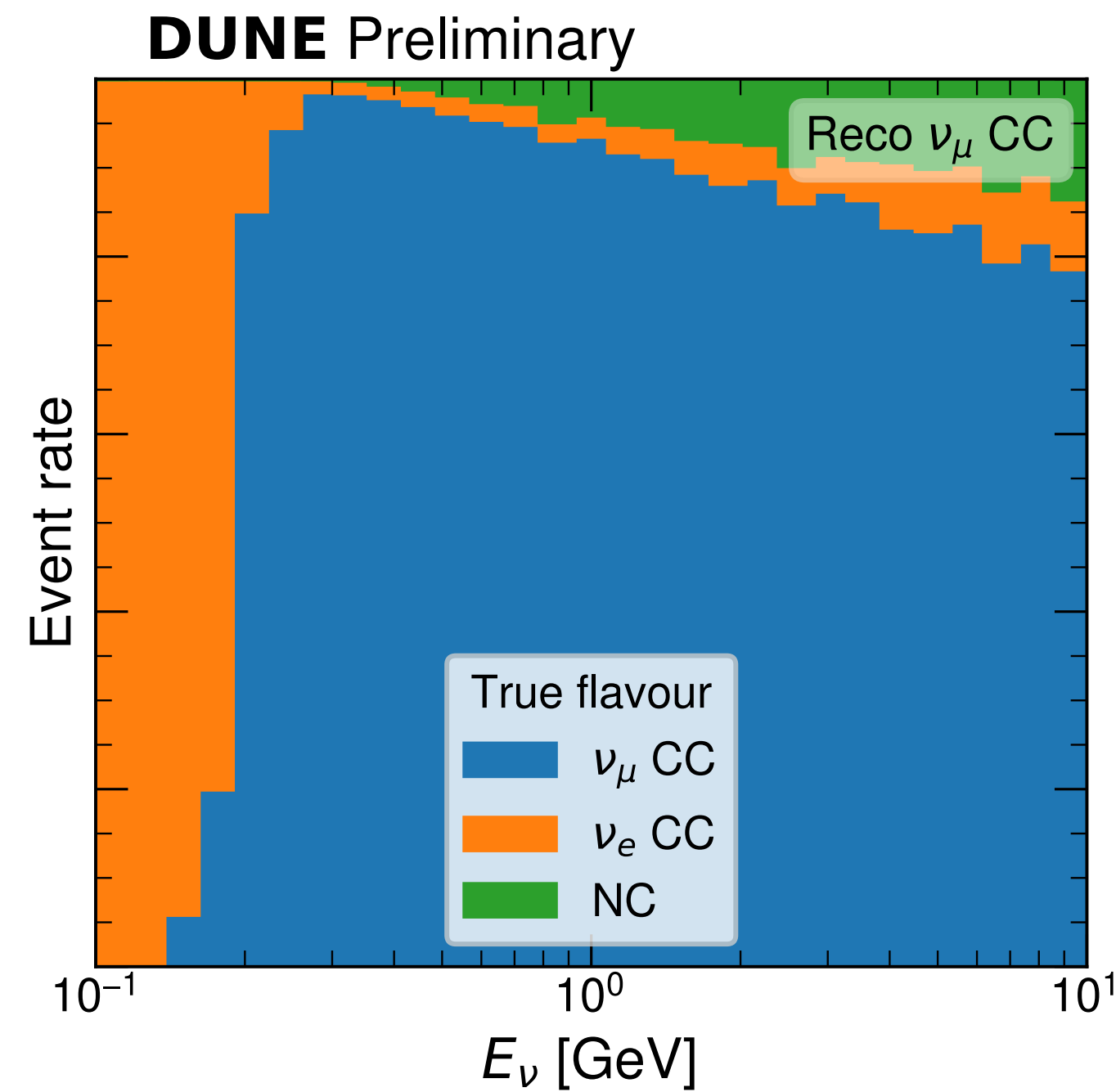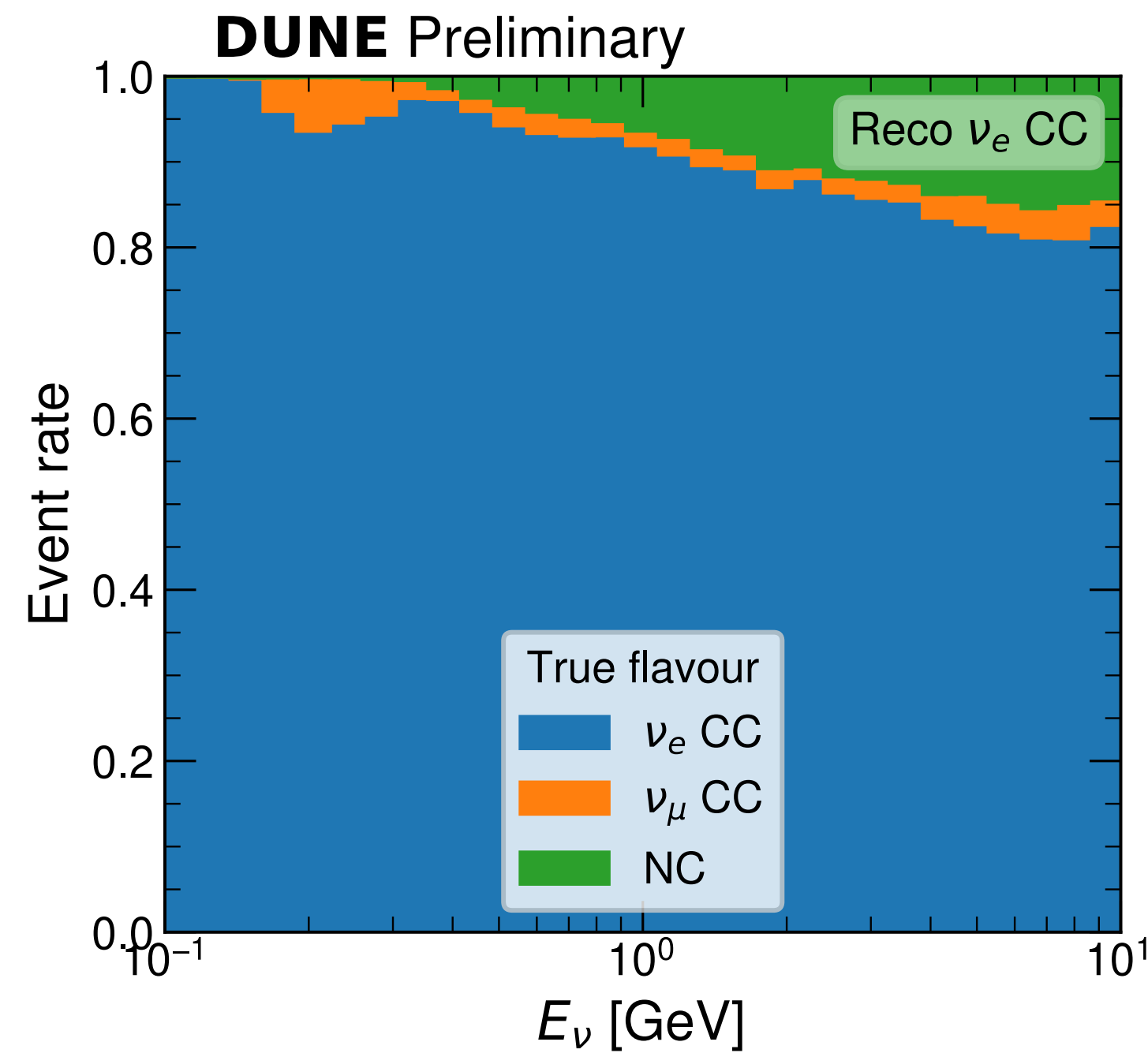
DUNE and ML
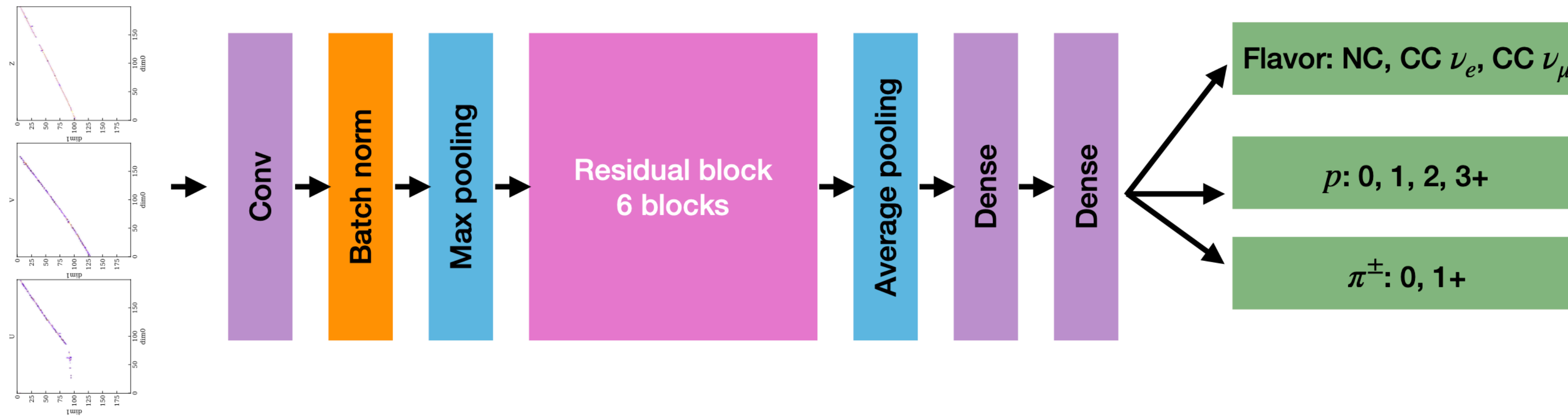
- Usages case: flavor discrimination for atmospheric neutrinos

- 5M trainable parameters

- 1M of pixel maps used for training

- Each output uses a weighted sparse categorical cross-entropy loss function, with pre-computed class weights to improve the handling of imbalanced datasets

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DUNE and ML

- First neutrino data will come from atmospheric neutrinos

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DUNE and ML

- First neutrino data will come from atmospheric neutrinos

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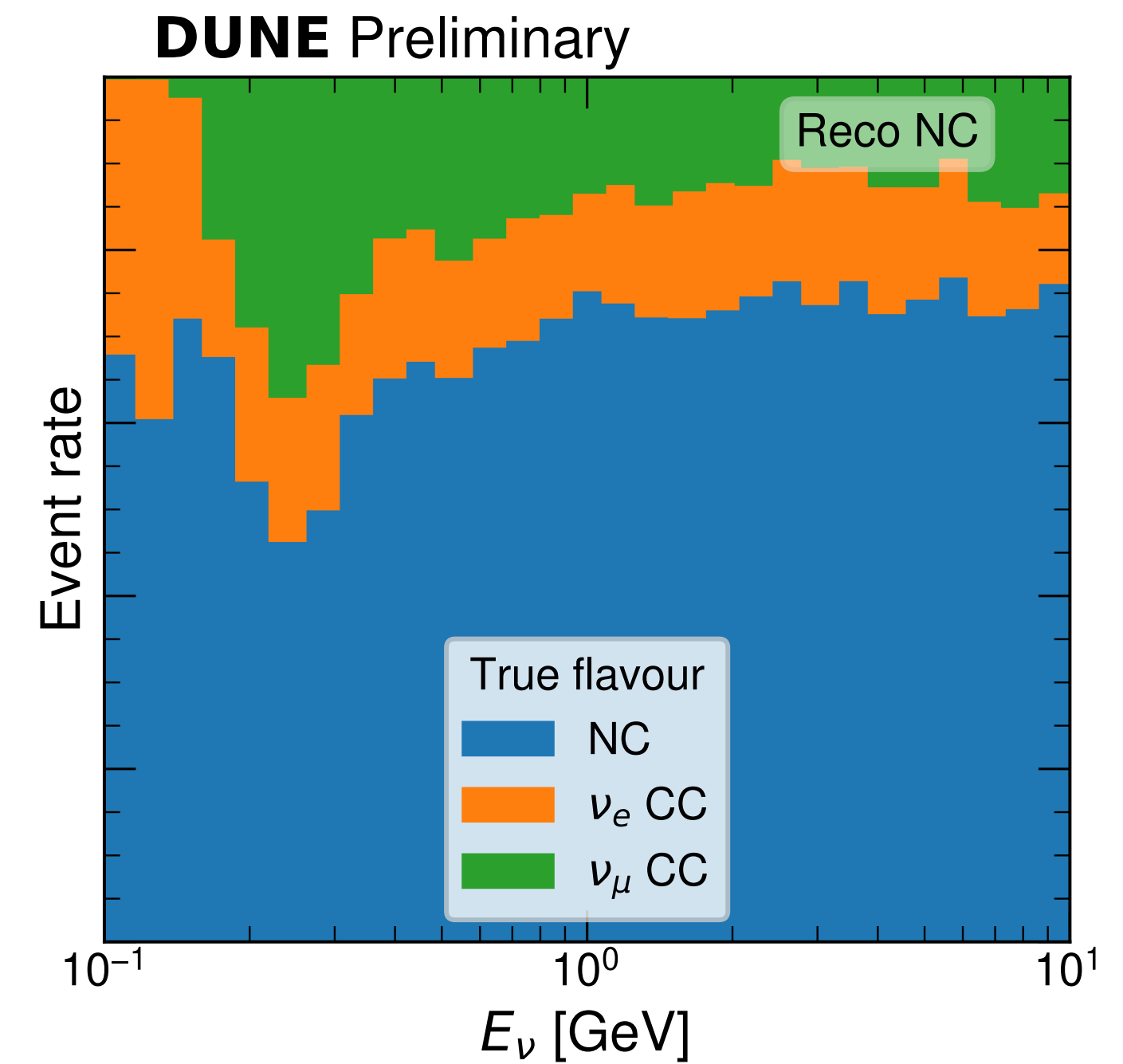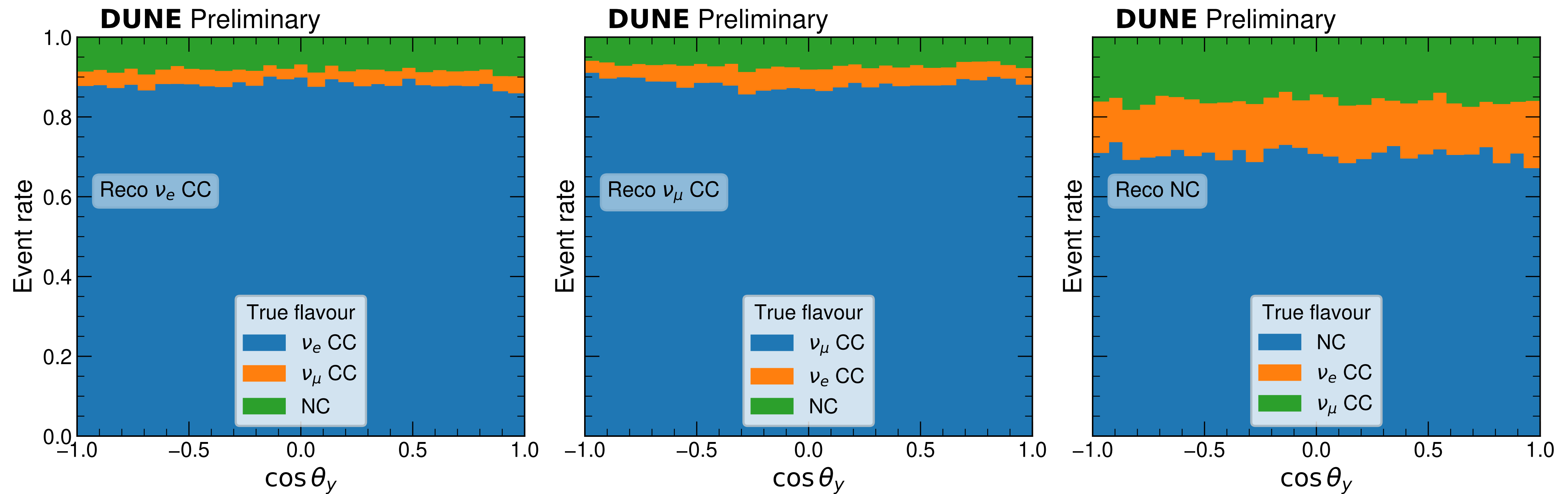
DUNE and ML

- Vertex reconstruction with Pandora deep learning: 2502.06637 (DUNE Pandora)

(a)

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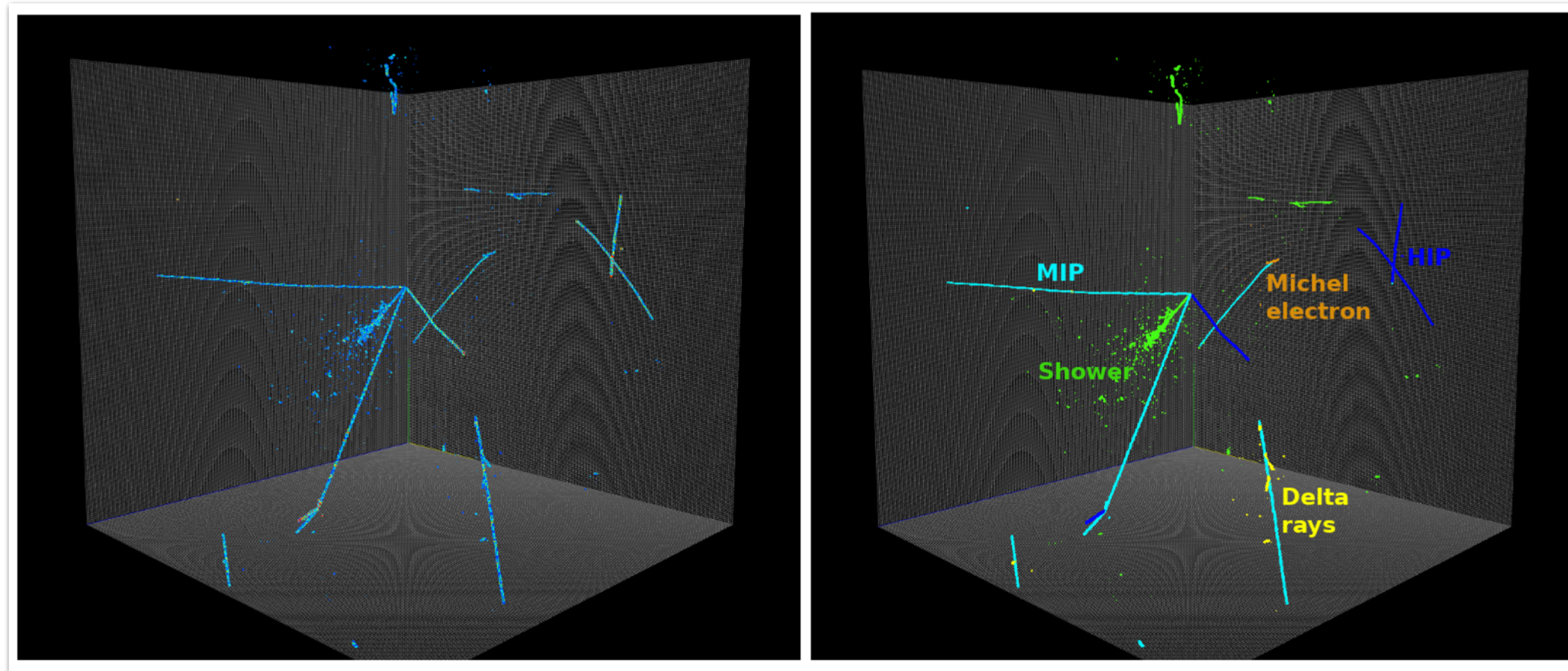
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DUNE and ML

Pixel Maps
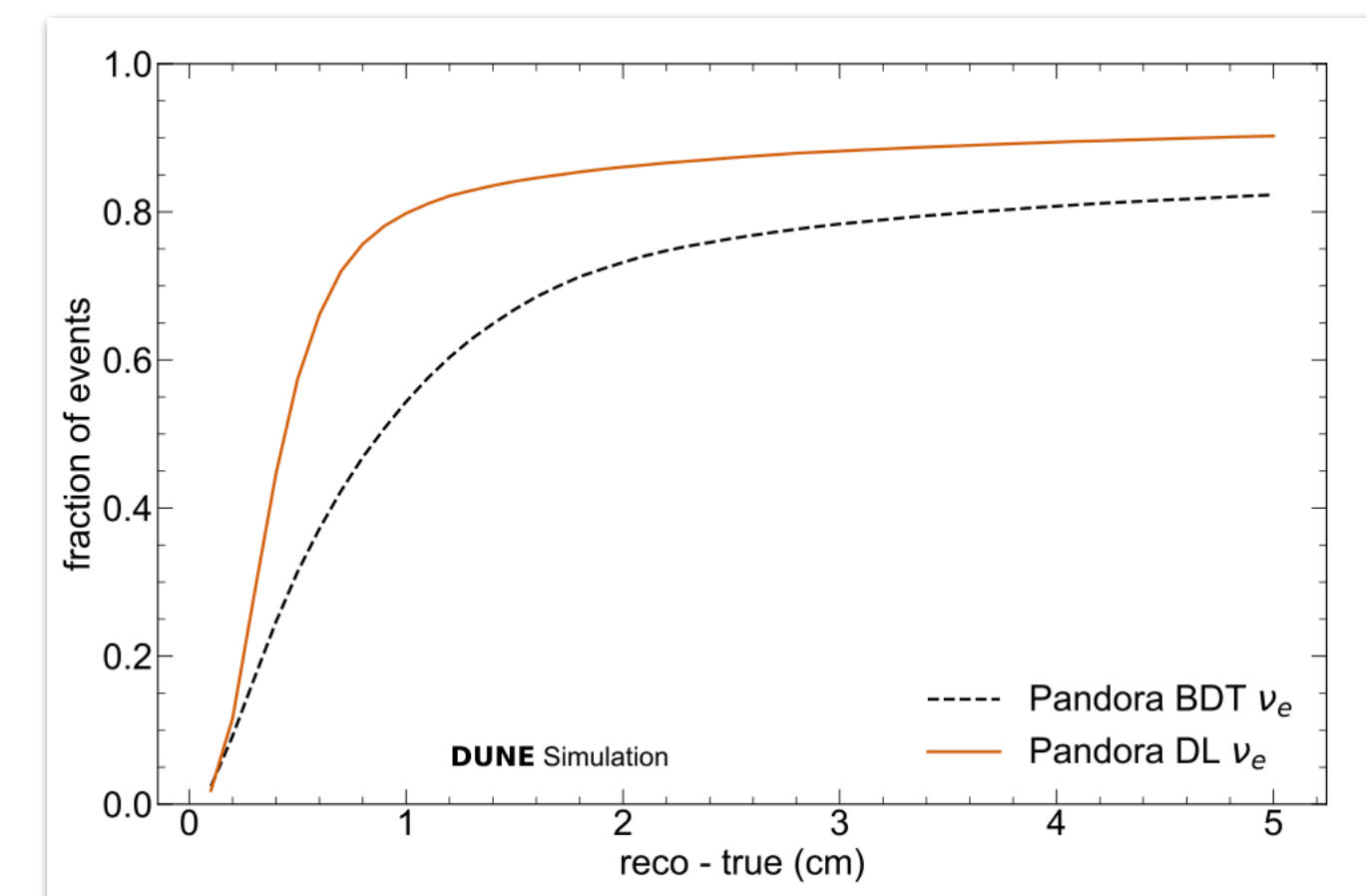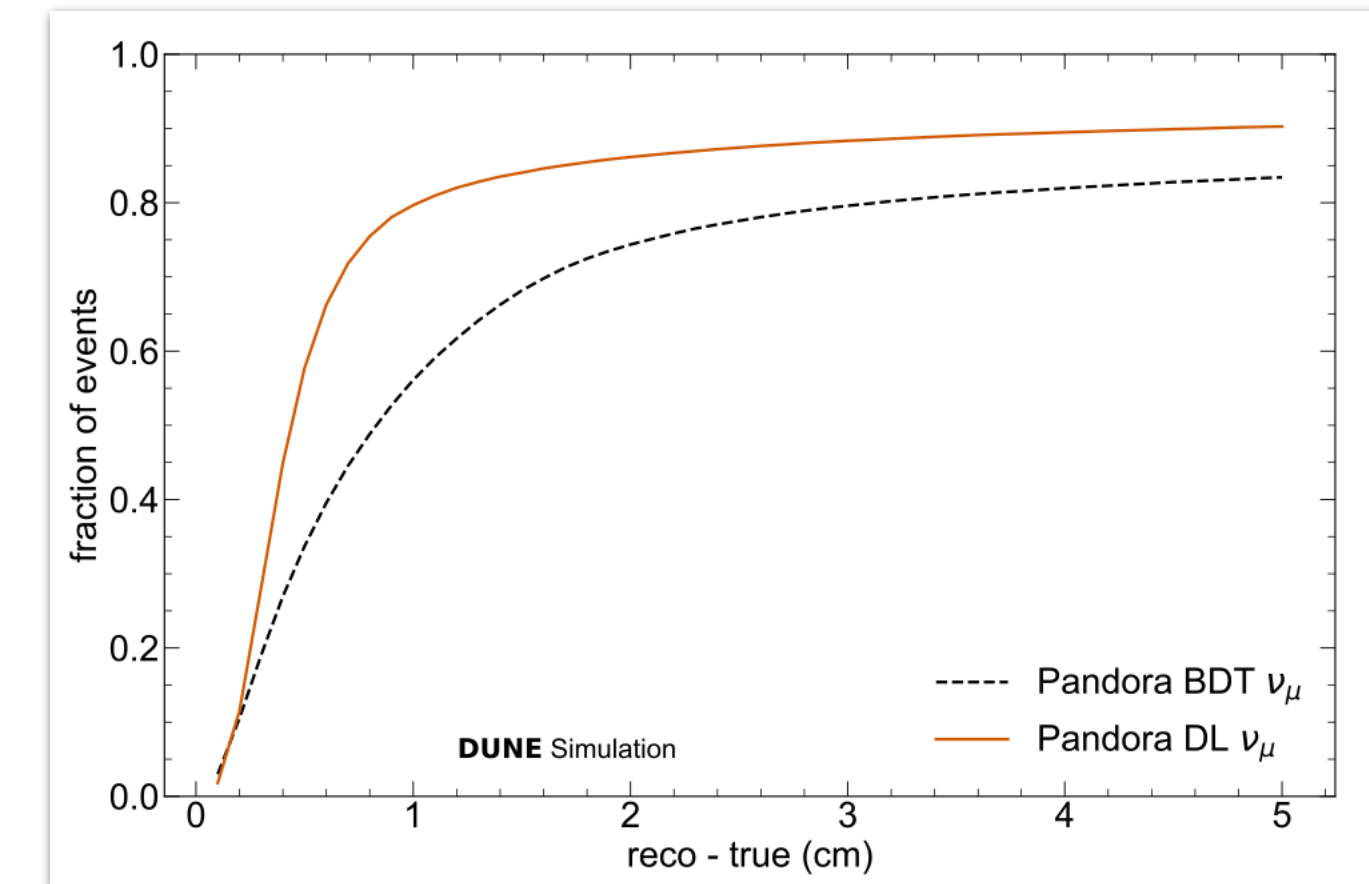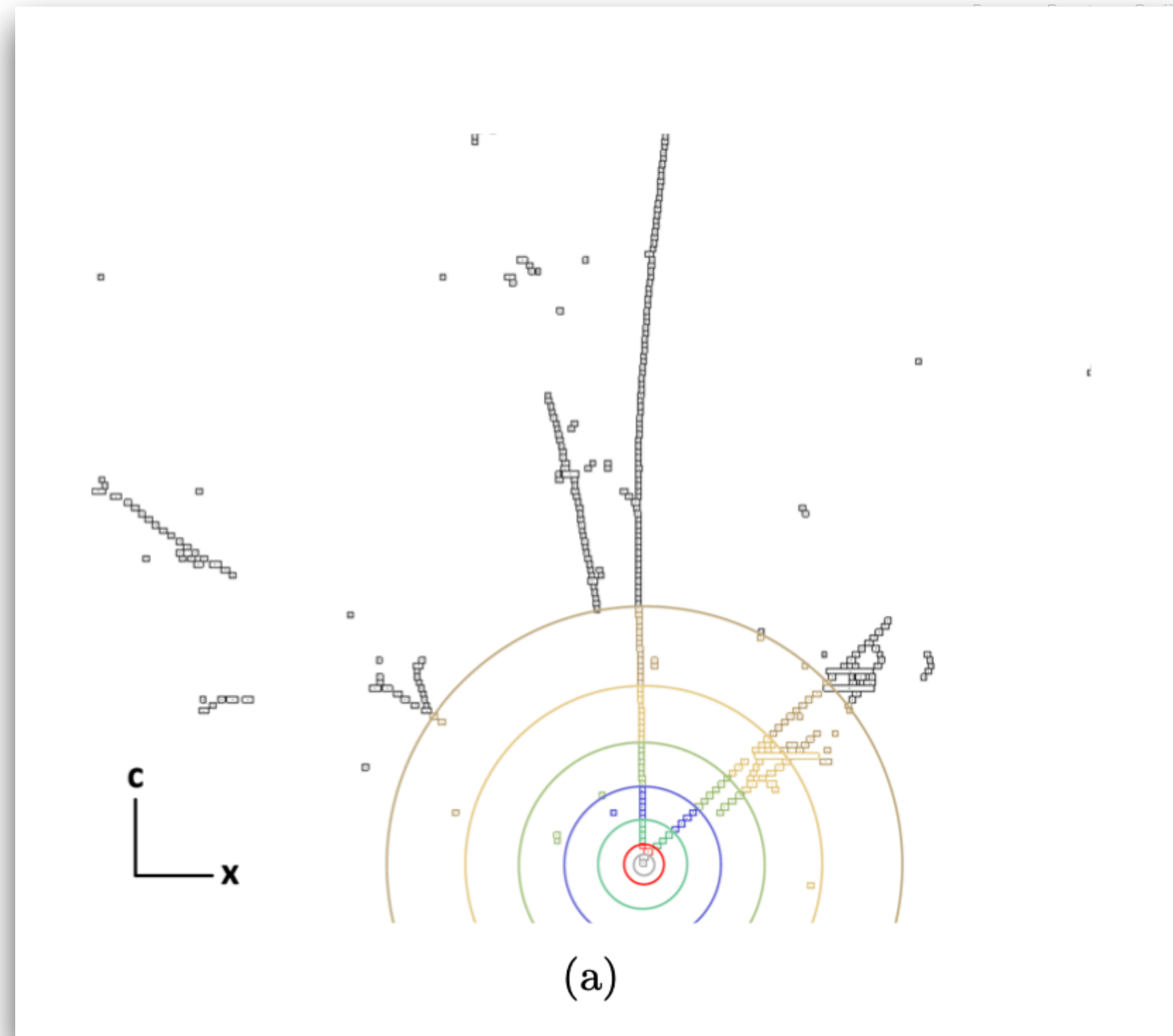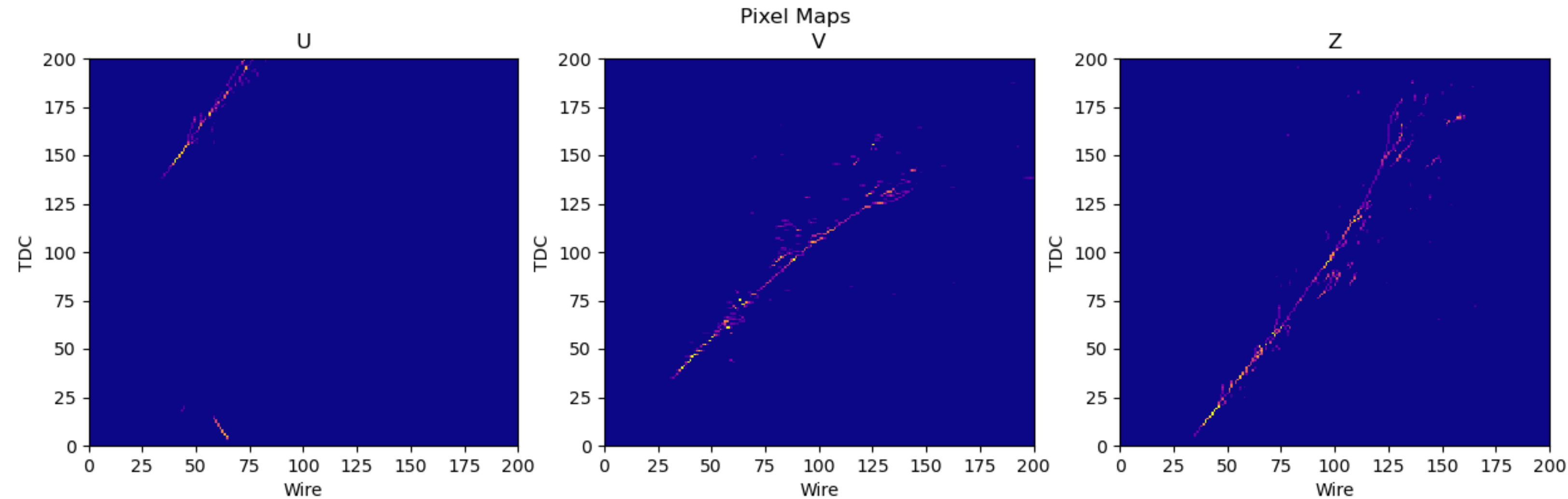
- Most of the work done is by looking at the 2D image from different views

- What if you use 3D?

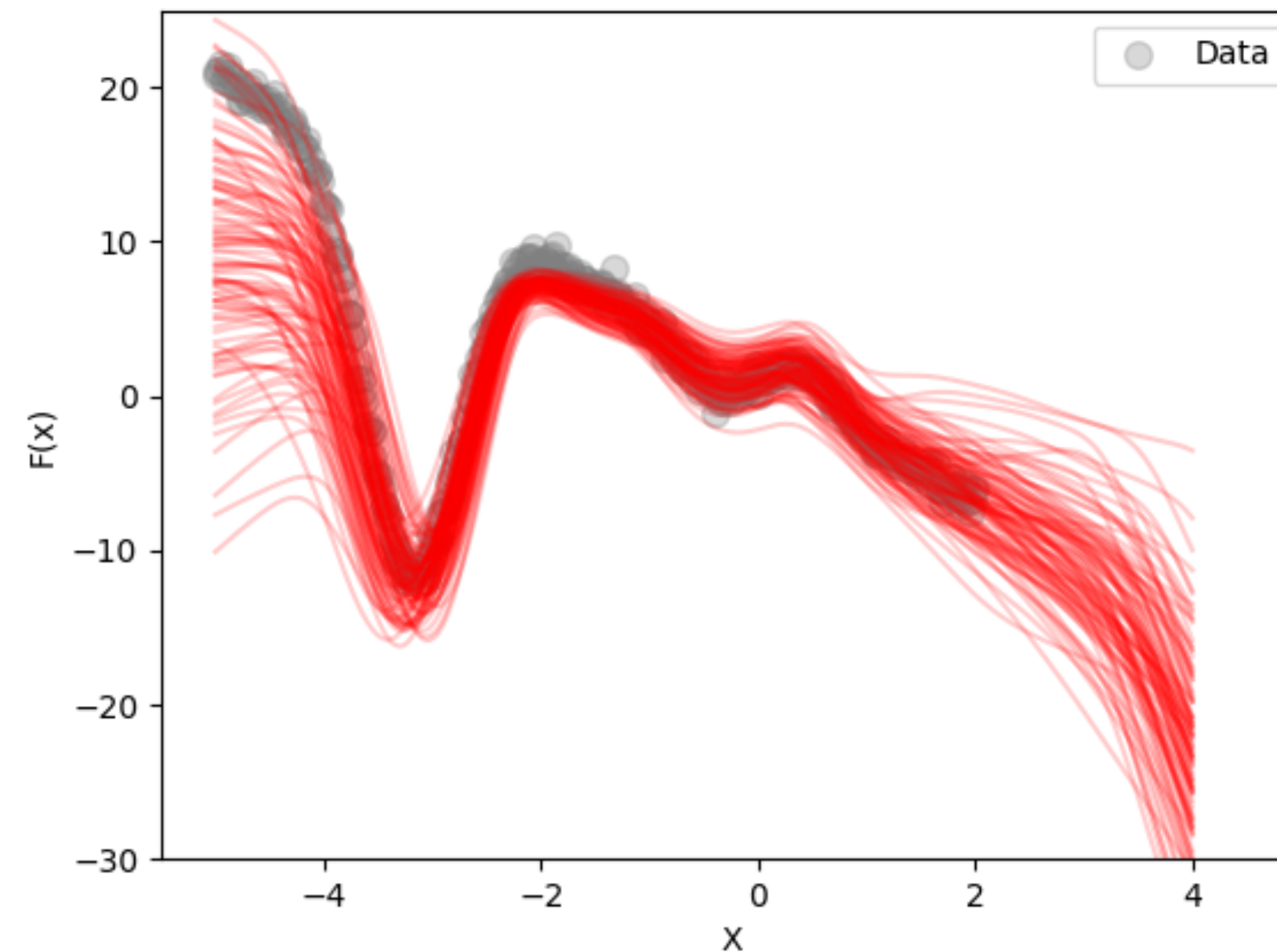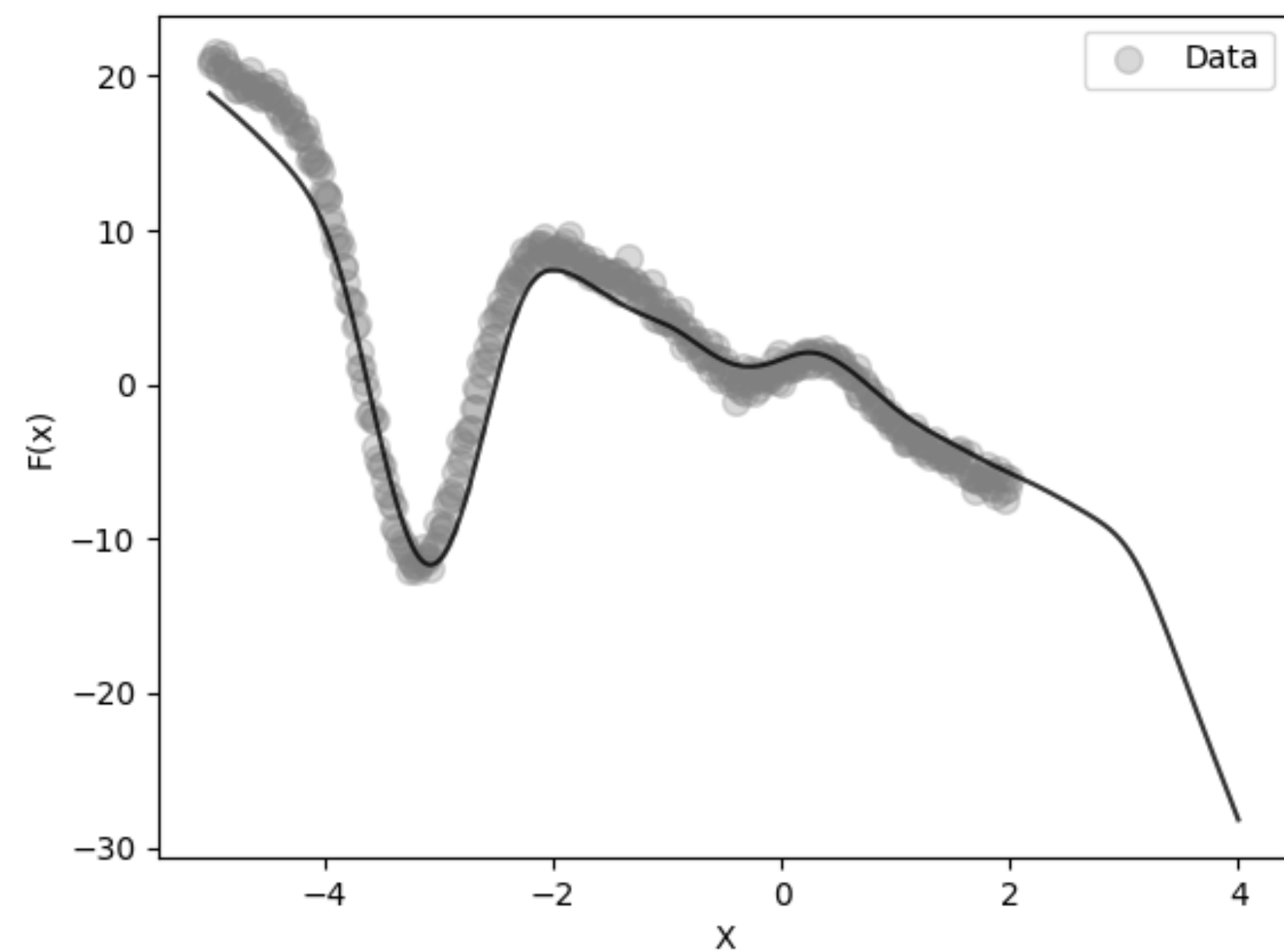- Also, there is a lot of empty space (sparse data), are the current approaches memory efficient?

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DUNE and ML

- Scalable deep convolutional neural networks for sparse, locally dense liquid argon time projection chamber data: PhysRevD.102.012005 (L. Domine and K. Terao)

- By using submanifold sparse convolutional networks (SSCNs) the computational memory and wall-time cost for inference is reduced by a factor of 364 and 33 respectevely

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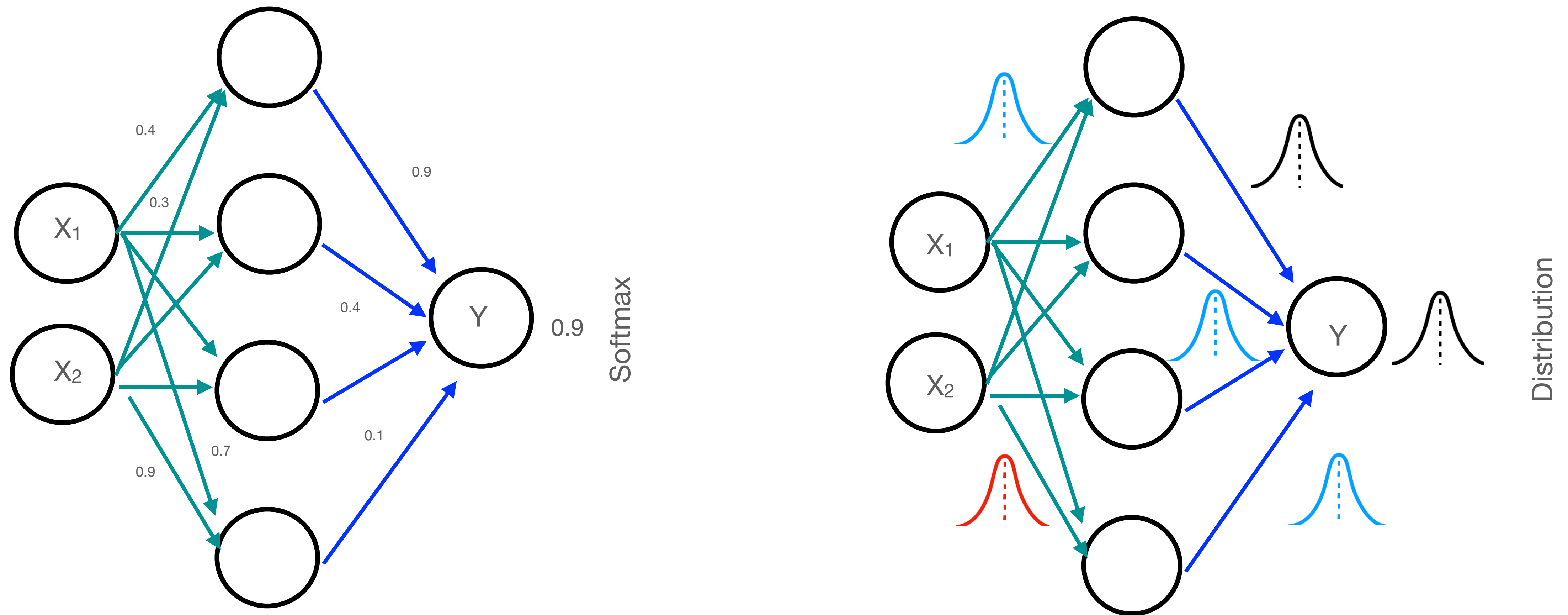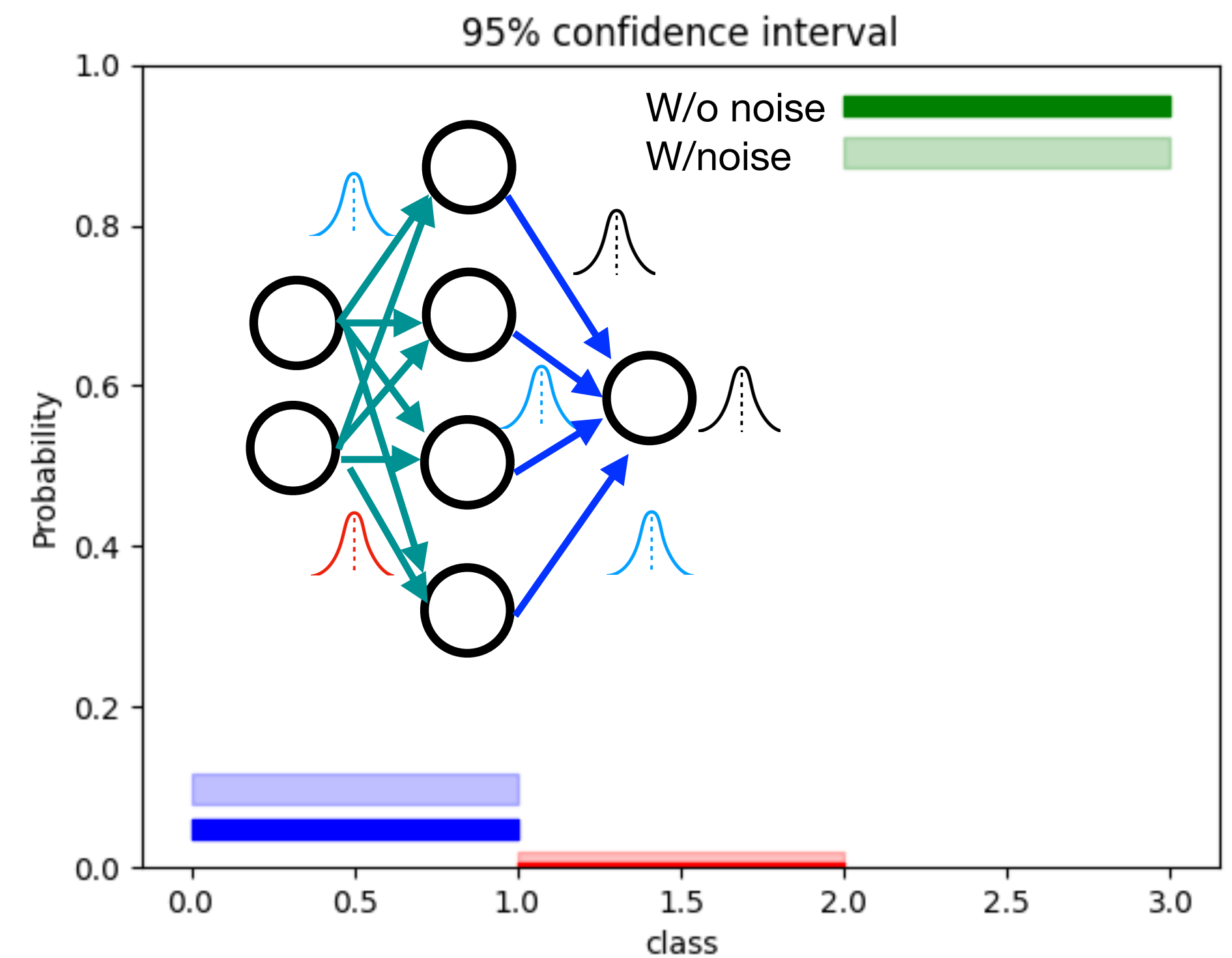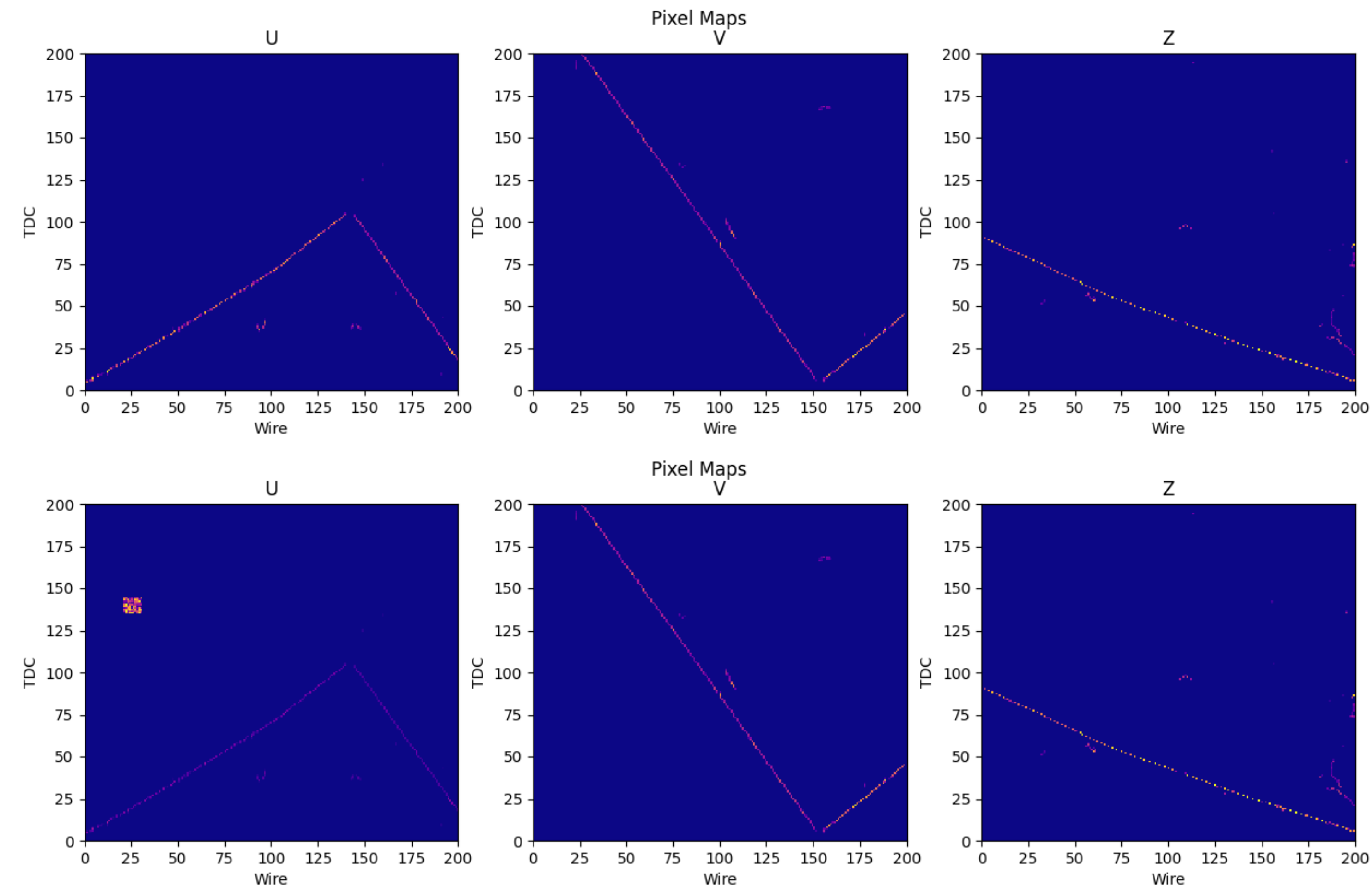
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Uncertainty quantification in ML

- Any ML is as good as the training data; most of the time, the training data is incomplete and model-dependent; how can we account for that?
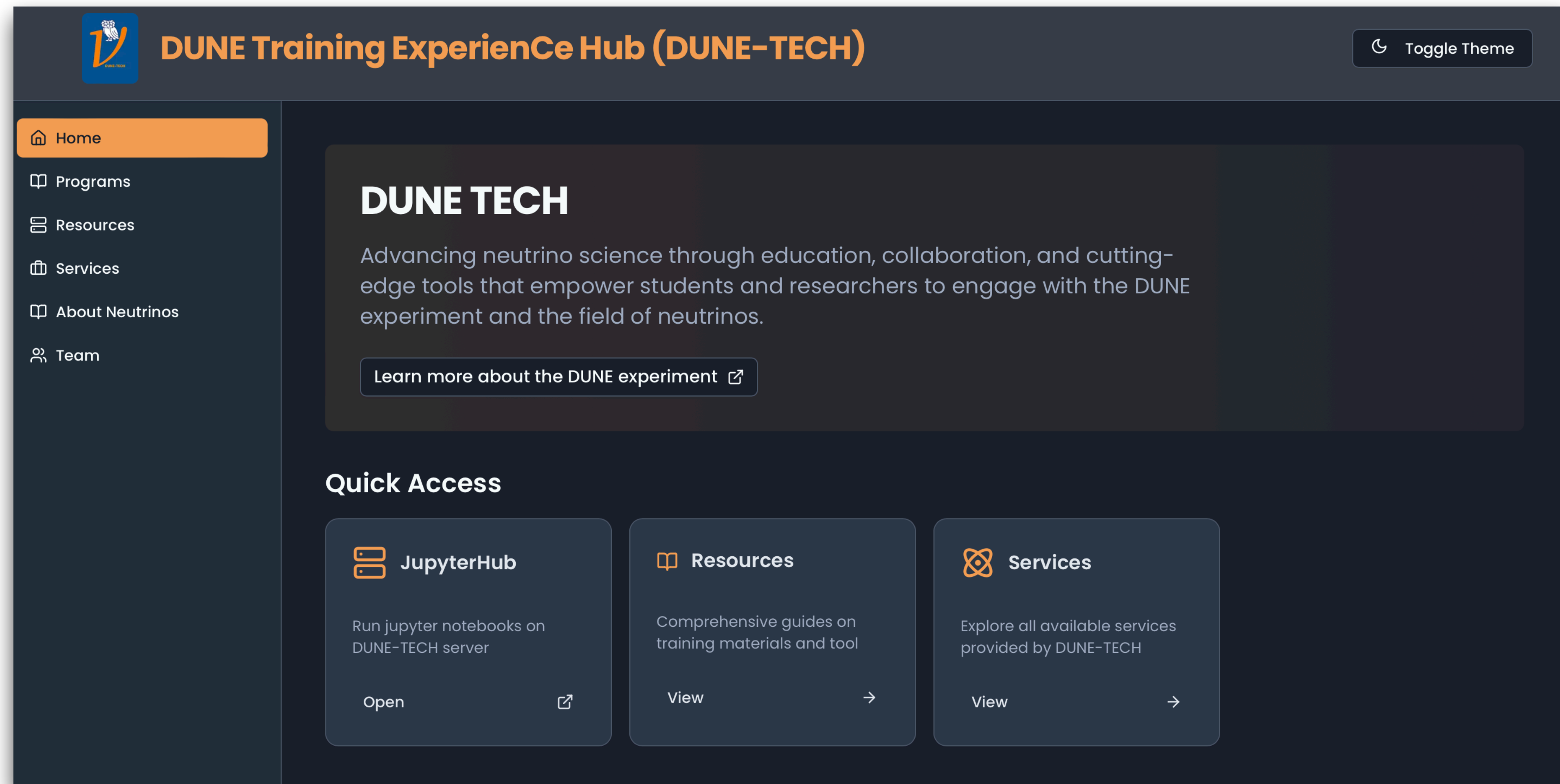
Uncertainty quantification with BNNs

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Uncertainty quantification in ML

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https://dune-tech.rice.edu/

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https://dune-tech.rice.edu/

DUNE-TECH Programs

Workforce and career development programs

DUNE Undergraduate Program

This is a unique opportunity where student-faculty pairs work together throughout the spring semester, followed by a 10-week summer research program, which includes a one-week school at Rice University. During the spring semester, the emphasis will be on preparing the student for research, focusing on foundational computational training and basic particle physics concepts. This training can be conducted through coursework or independent study directed by the faculty. Students are expected to dedicate 8 hours per week to this preparation and will receive financial compensation for their time.

Apply ⧉

DUNE Early-career Researcher Program

This program is designed to provide support to early-career researchers, including graduate students and postdocs, to participate in in-person activities that contribute to their career development and align with current or future projects within the Core Software and Computing Consortium.

Apply ⧉

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https://indico.fnal.gov/event/69074/

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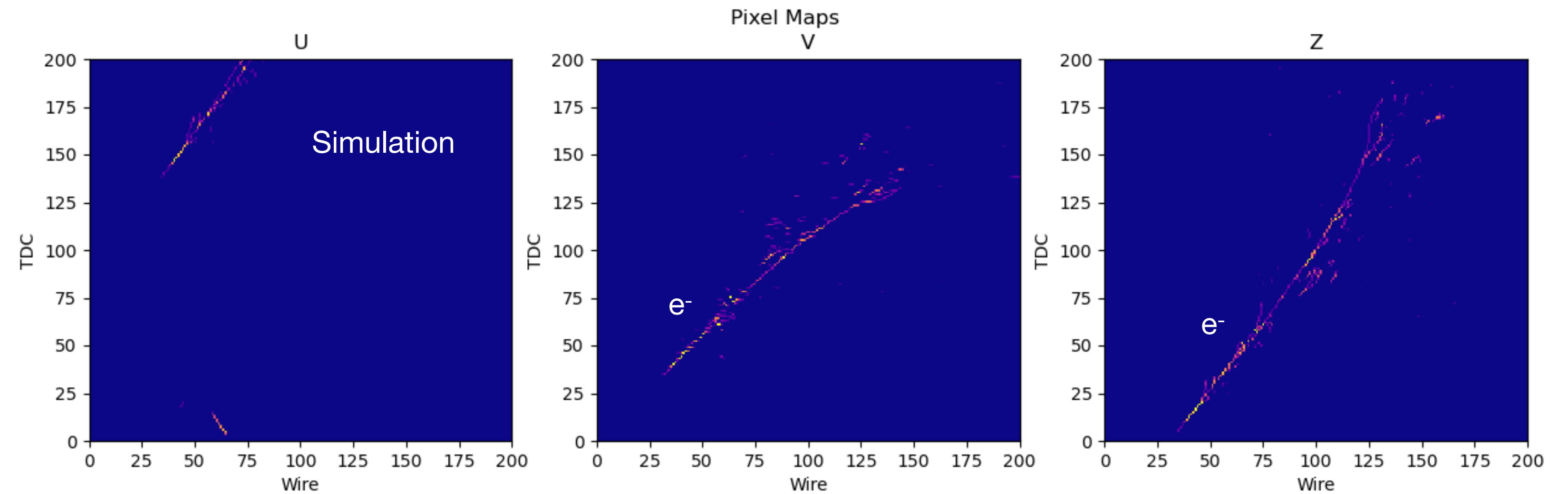
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Comments

- DUNE is a cutting-edge neutrino experiment and the most significant neutrino endeavor in the US

- Neutrino science is a vibrant field with a lot of interesting things going on

- Plenty of opportunities for the new generation of scientist

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Thanks for listening

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We have self-driving cars, right?

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We have self-driving cars, right?

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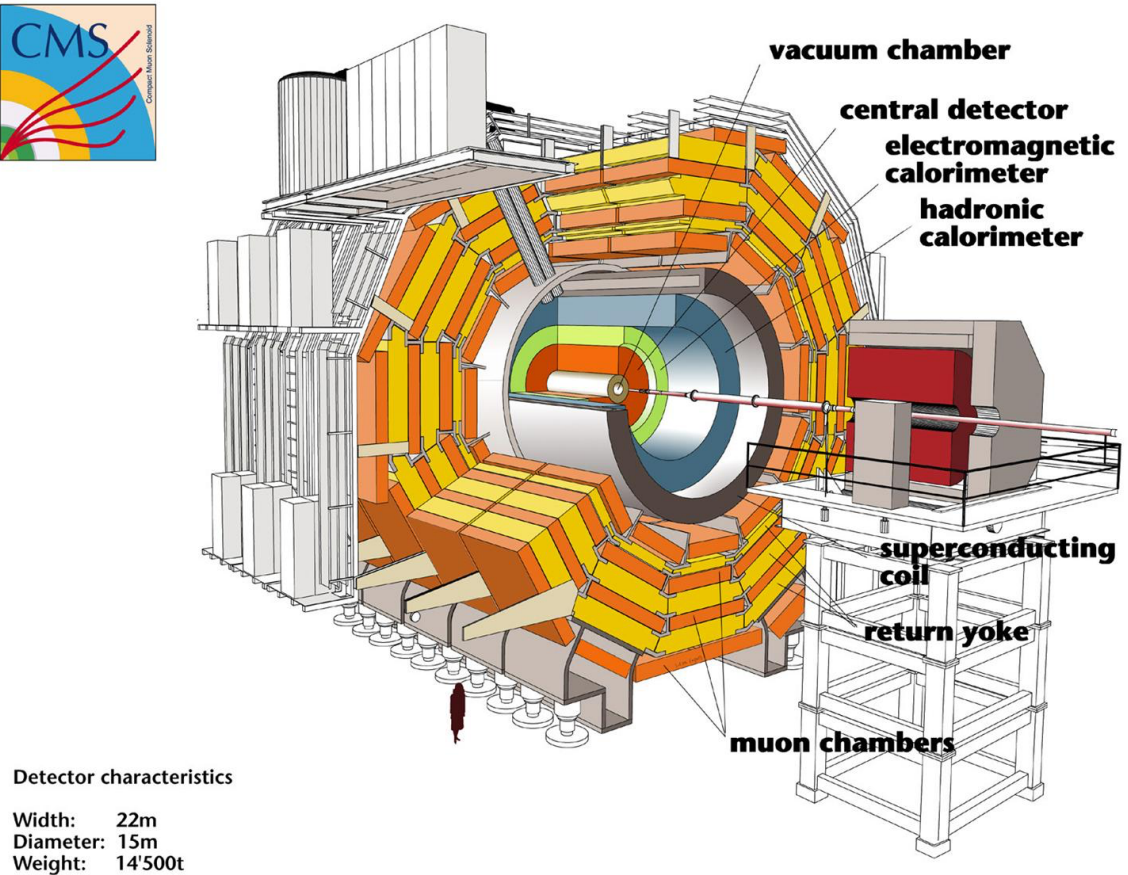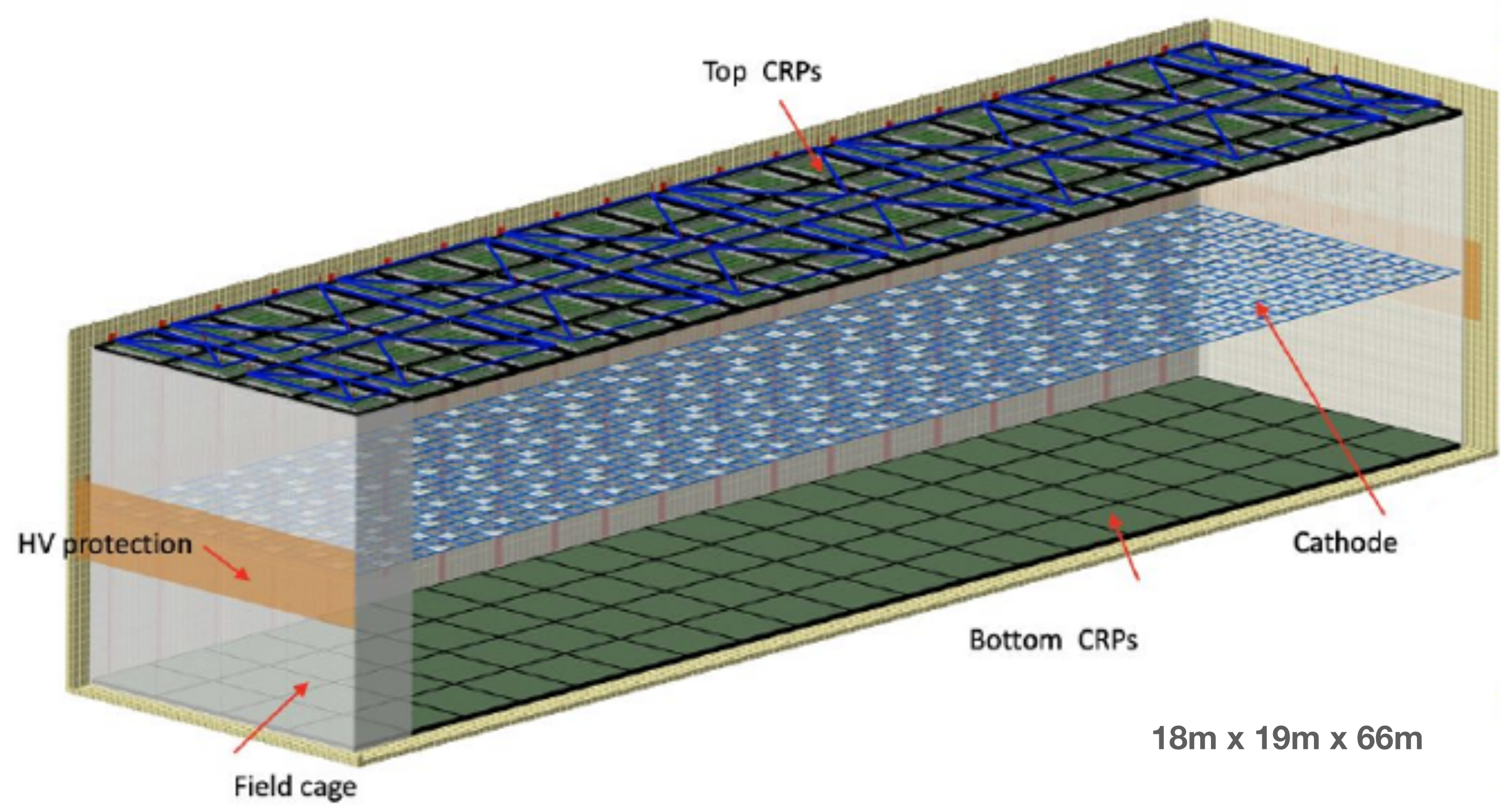
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There are many challenges
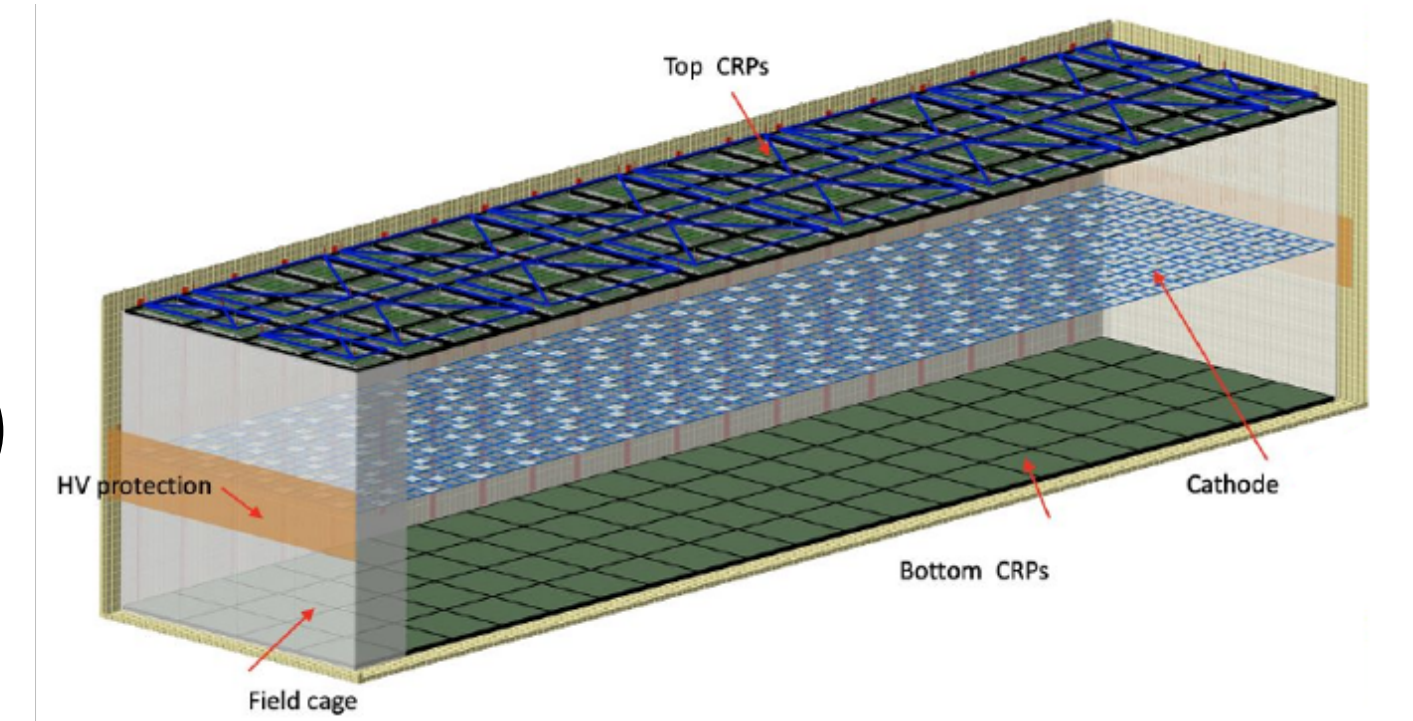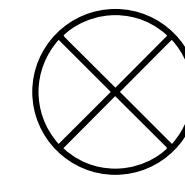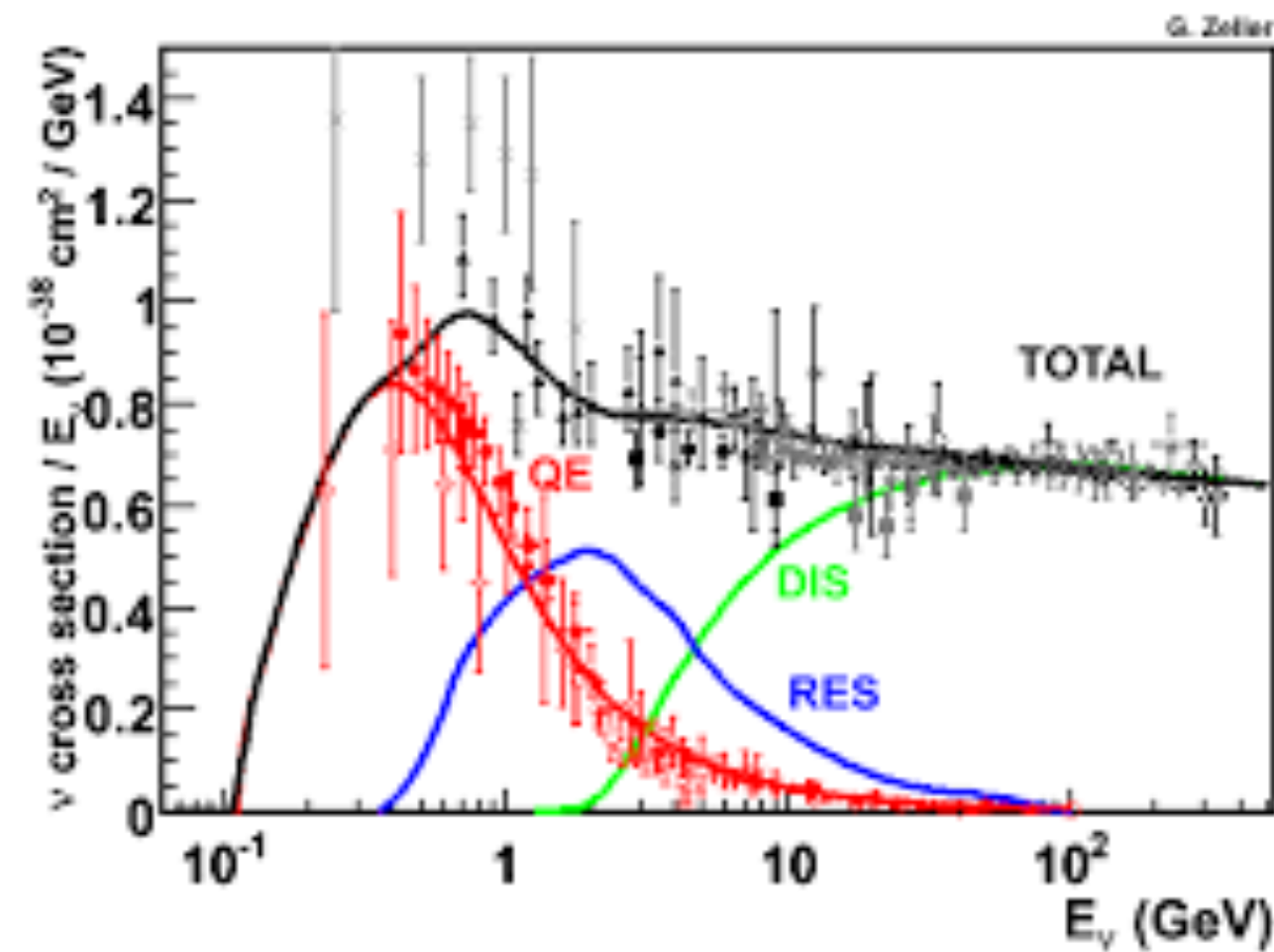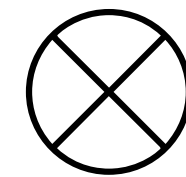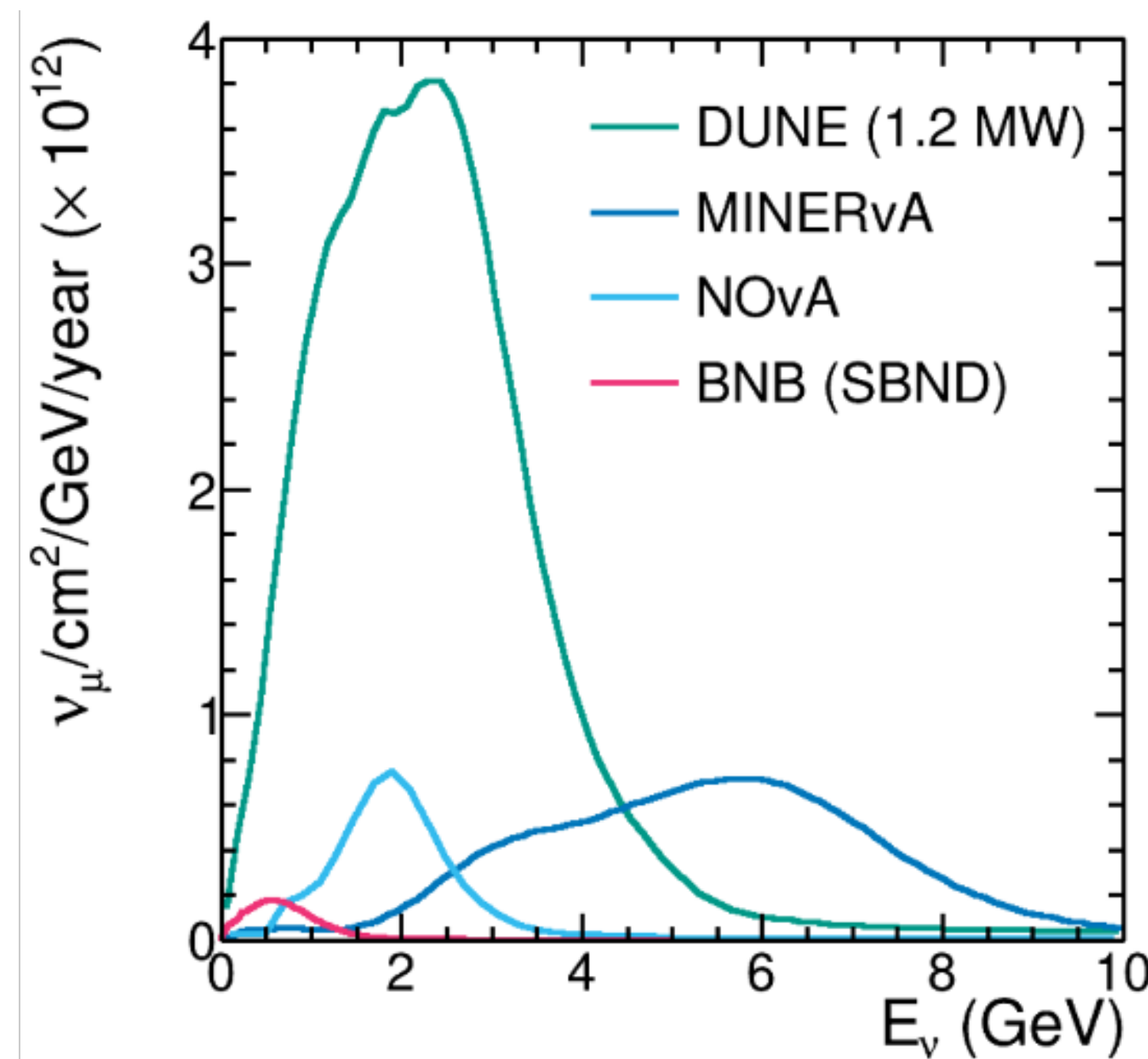
- Neutrino interactions are a very convoluted process where everything is energy-dependent
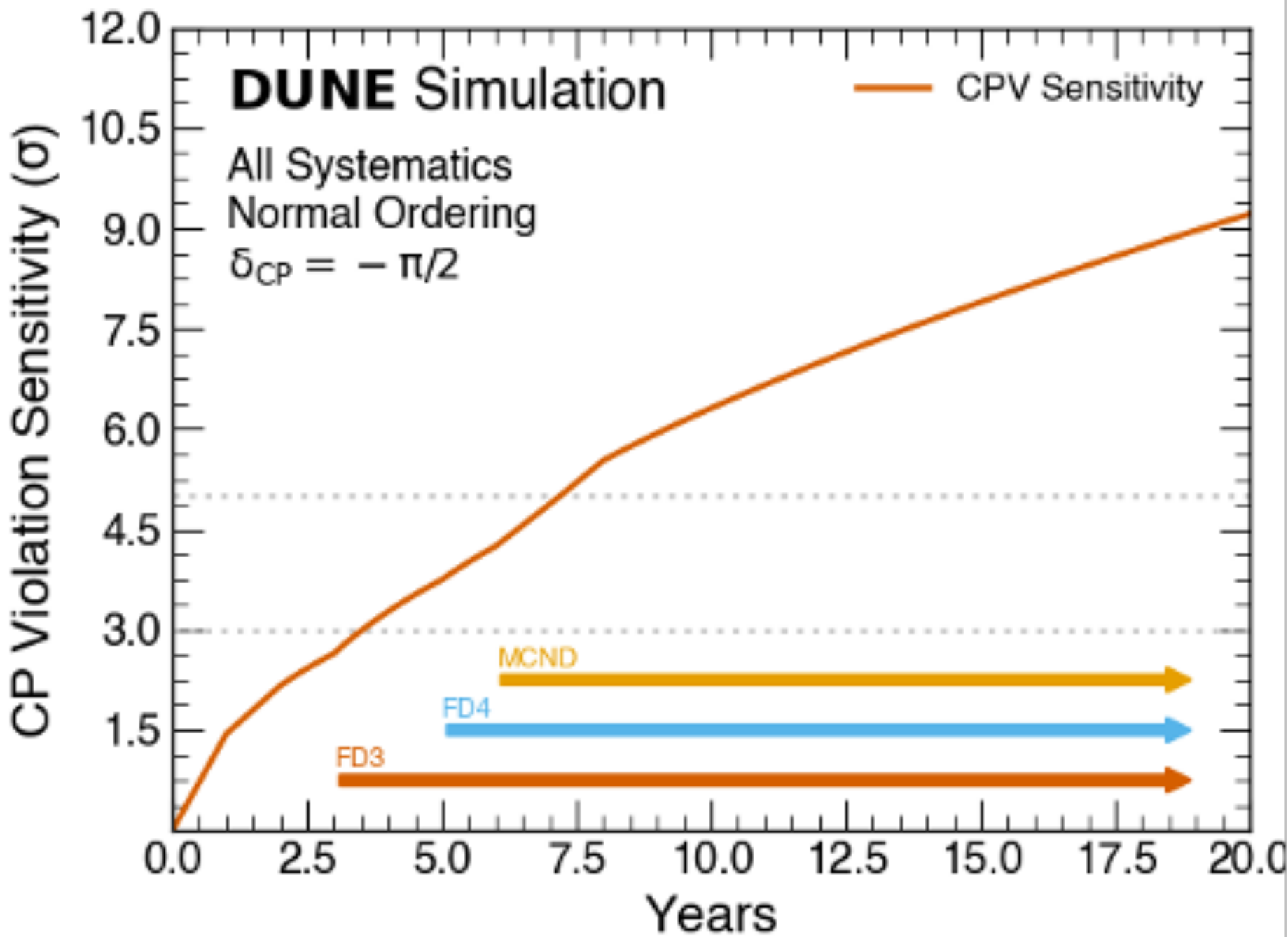- Stop, light signs, etc, are the same across the world

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Deep Underground Neutrino Experiment (DUNE)

CMS

vacuum chamber
central detector
electromagnetic calorimeter
hadronic calorimeter
superconducting coil
return yoke
muon chambers

Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

Top CRPs

Cathode

HV protection

Bottom CRPs

Field cage

18m x 19m x 66m

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DUNE' Sensitivities

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