Fermilab

ML4FE Workshop 2025 @Hawaii

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Smart TPC

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References

- “Anomaly Detection & Smart TPC” **S. H. Seo** @DUNE AI/ML Workshop, Fermilab, April 2025
- “Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics” S. Ashai, …, **S. H. Seo** et al, arXiv:2407.19716 (P5 2023 report)
- “DUNE: Science & Status” C. Marshall @Neutrino, Milano, June 2024
- “Status & Prospects of the DUNE Experiment” W. Shi @DPF-PHENO, Pittsburg, May 2024
- “Overview and Status of the 2x2 NDLAr Demonstrator: A Pixel-Based LArTPC Prototype for the DUNE Near Detector” K. Wresilo @ICHEP 2024
- “Capabilities of the DUNE Near Detector Complex” T. Mohayai @NuTel, Feb 2021

Intensity Frontier

Big Questions

- Is CP violated in the leptonic sector?
- ν mass ordering (is ν_3 heaviest or lightest?)
- Sterile ν?

ν oscillation

- Nature of ν (Majorana or Dirac?)
- What's the absolute mass of ν?
- What are the sources of highest energy ν in cosmos?

ν Oscillation

- **3 mixing angles**
  (θ_{12}, θ_{23}, θ_{13})
- **2 mass square diff.**
  (Δm^2_{21}, Δm^2_{31})
- δ_{CP}
- **Mass ordering**

Weak Eigen state **Mass Eigen state**

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \boxed{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

PMNS matrix

in 1962

- **P**ontecorvo
- **M**aki
- **N**akagawa
- **S**akata

$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{"CP" sector}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}} \underbrace{\begin{bmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Majorana}}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

$\theta_{23} \approx 45°$ $\theta_{13} = 9°$ $\theta_{12} \approx 34°$

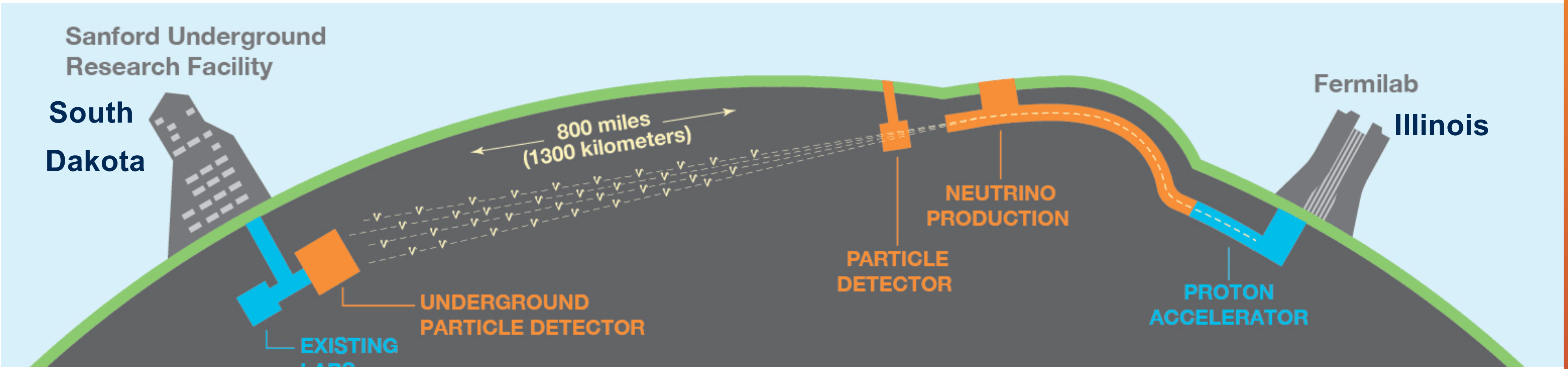
$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}\ \mathrm{eV}^2$ $\Delta m^2_{21} \approx 7.6 \times 10^{-5}\ \mathrm{eV}^2$

Atmos. (ν_μ, $\overline{\nu}_\mu$ deficit)
Long baseline (ν_μ deficit)

Reactor ($\overline{\nu}_e$ deficit)
Long baseline ($\nu_\mu \rightarrow \nu_e$)

Solar (ν_e deficit)
Reactor ($\overline{\nu}_e$deficit)

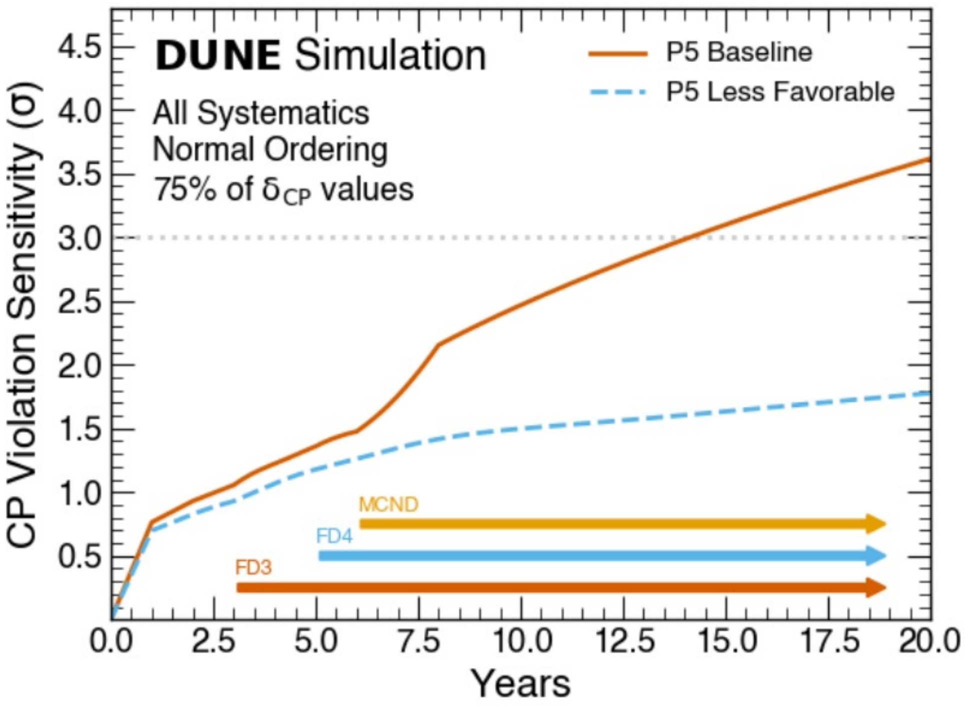
Deep Underground Neutrino Exp. (DUNE)



- ❑ Neutrino Source: 1 ~ 2 MW neutrino (ν_μ) beam produced at LBNF, Fermilab (**L**ong **B**aseline **N**eutrino **F**acility)
- ❑ Neutrino Detections:
  - Far Detector: (3+1) x 17 kton Liquid Argon TPC at SURF (1300 km)
  - Near Detector: Liquid Argon TPC at Fermilab (500 m)

DUNE Physics Program

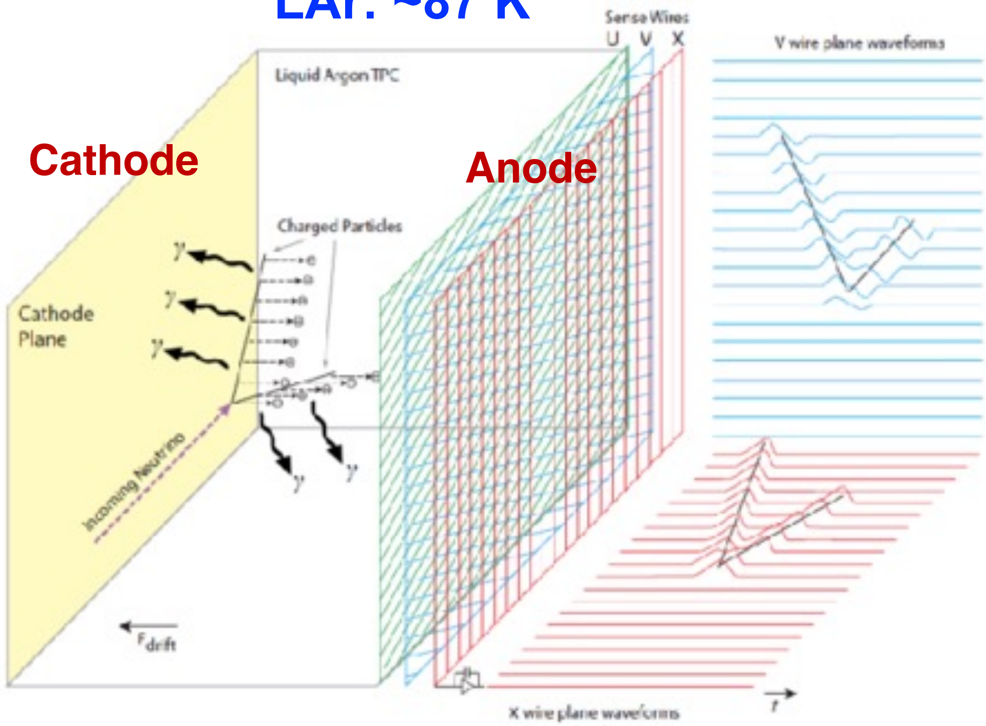
- ❑ CP Violation or Conservation?
  if violated, how much?
- ❑ Neutrino Mass Ordering (5σ , ~4yr)
  is ν_3 the heaviest or lightest?
- ❑ Proton decays?
- ❑ Atmospheric ν: θ_{23}
- ❑ Supernova Burst ν
- ❑ Solar ν: ^8B, *hep* ν, θ_{12}, Δm^2_{21}
- ❑ BSM physics, etc…

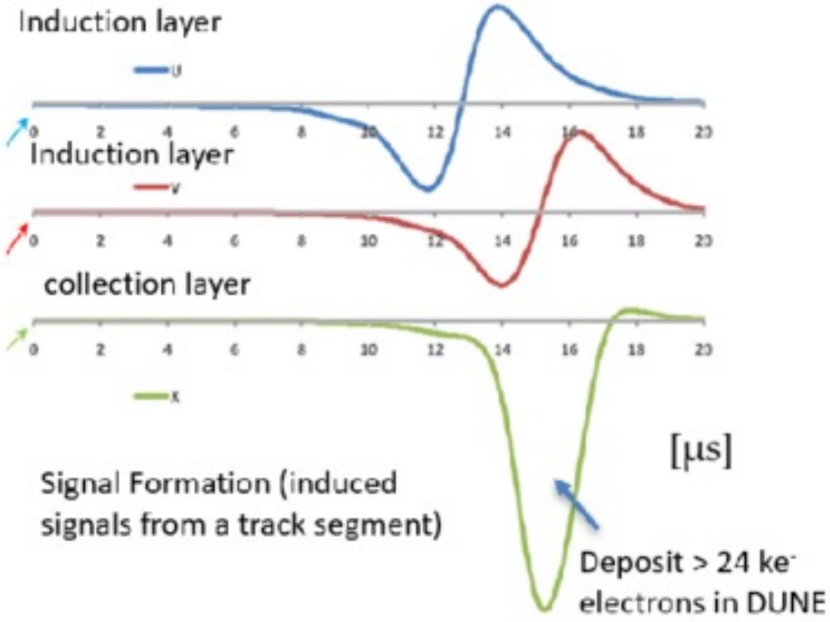


→ DUNE will be the only exp. which can measure all PMNS params precisely.

LArTPC Principle

LAr: ~87 K



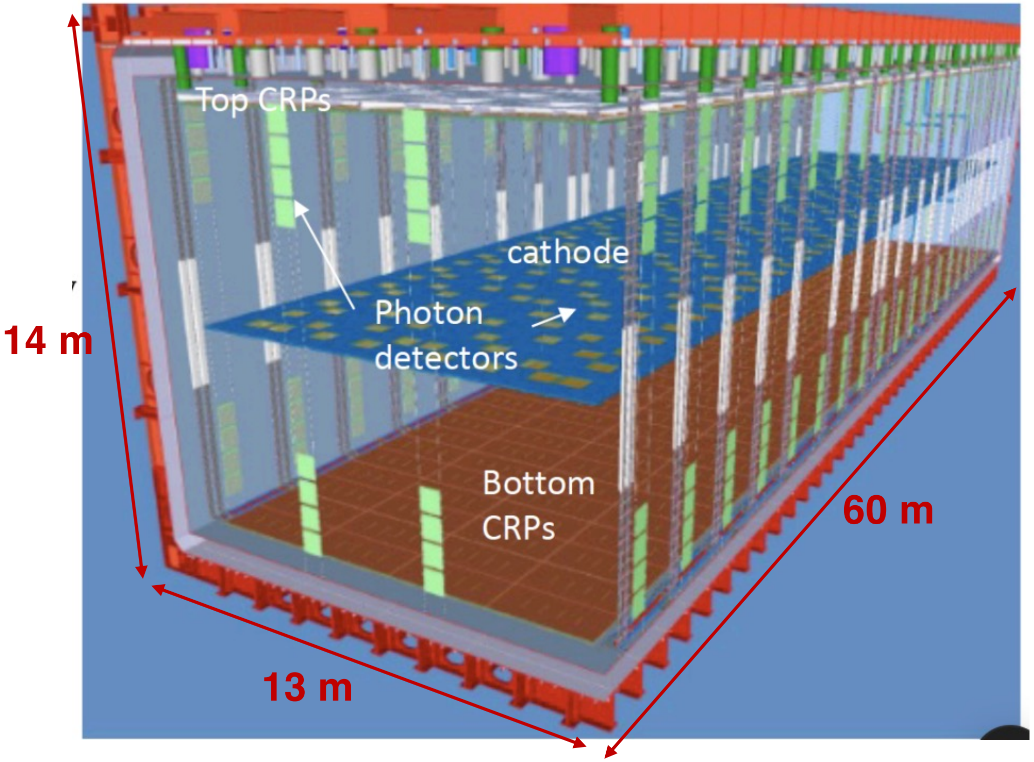


E field: ~500 V/cm

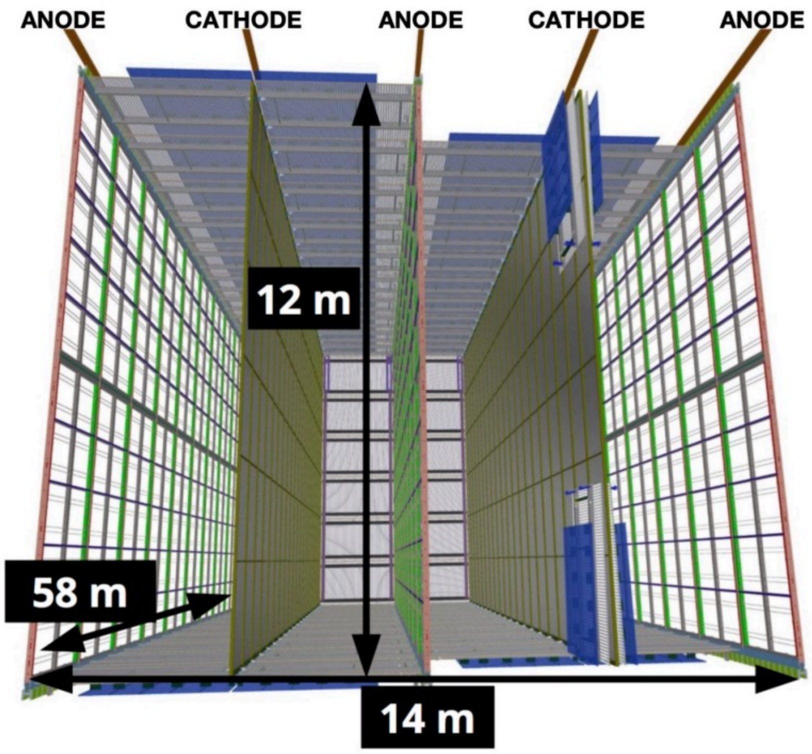
DUNE Far Detector (FD)

FD – Vertical Drift (VD)

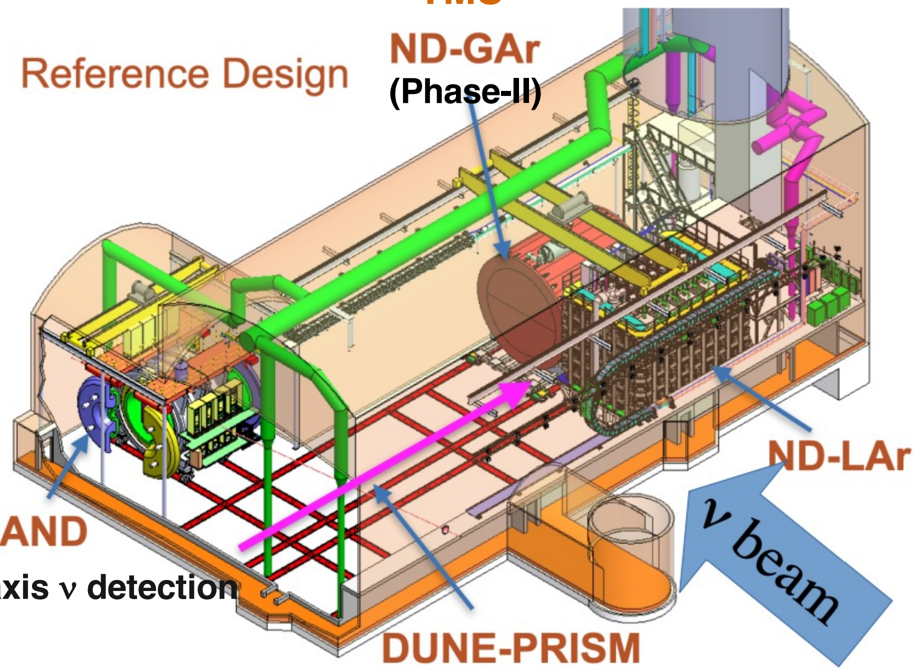
- Simpler
- More robust



FD – Horizontal Drift (HD)

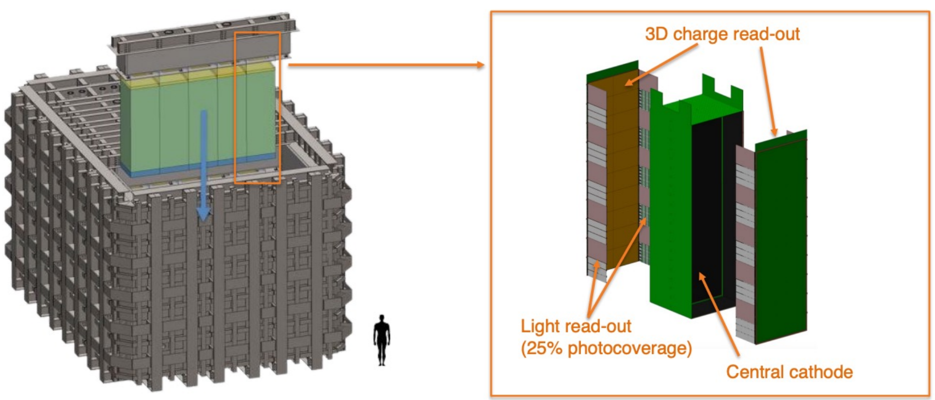


DUNE Near Detector Complex

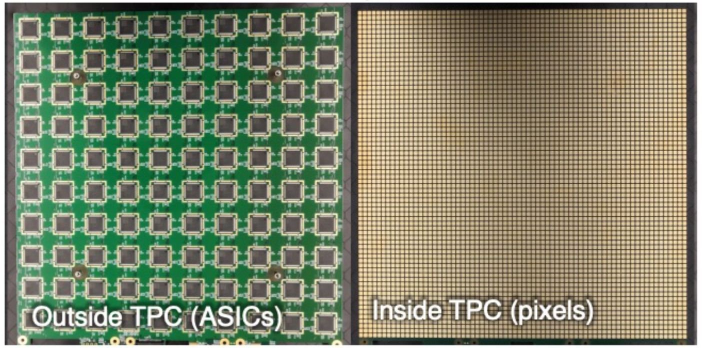


ND-LAr

35x2 TPCs optically isolated



LArPix anode tile (prototype dimensions)



DUNE Phase I → II

Phase I:

- Beam: 1.2 MW
- FD1: VD (strips)
- FD2: HD (3 wire planes)
- ND: Liquid Argon (pixel)

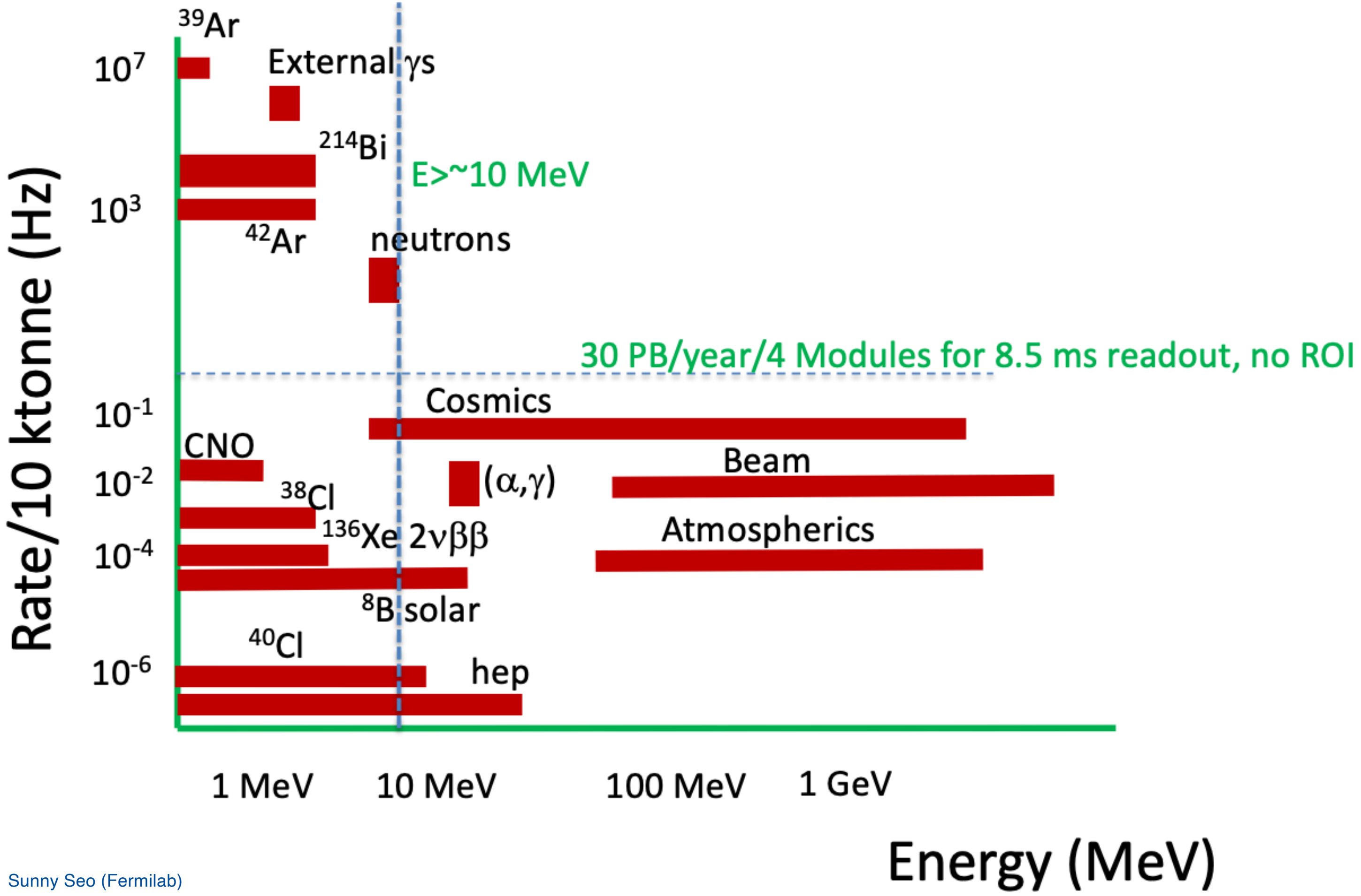
Phase II:

- Beam: 2.1 MW
- FD3: VD (strips or pixel)
- FD4? → module of opportunity (pixel?)
- ND: TMS -> Gas Argon (pixel)

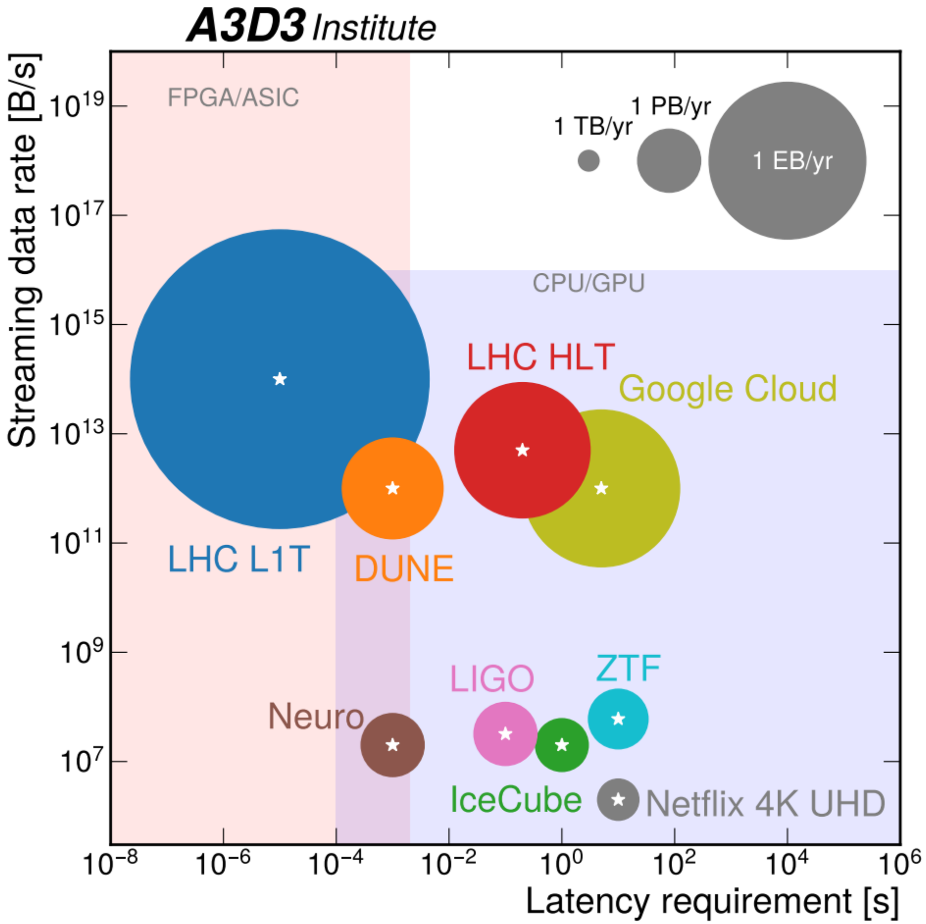
P5-2023 Baseline Scope

Trigger Design Constraints

Rates and Energy Threshold



Motivation for Data Volume Reduction



→ We expect high raw data volumes for (HL-)LHC and DUNE.

❑ DUNE: arXiv:2203.16255

- ~ TB/sec → ~32 EB/year
- 100 % livetime (for Supernova)
- > ~ 20 years of operation

❑ DUNE's cap for computing: ~ 30 PB/year

→ 3 orders of magnitude reduction is needed.

Proposed Solution

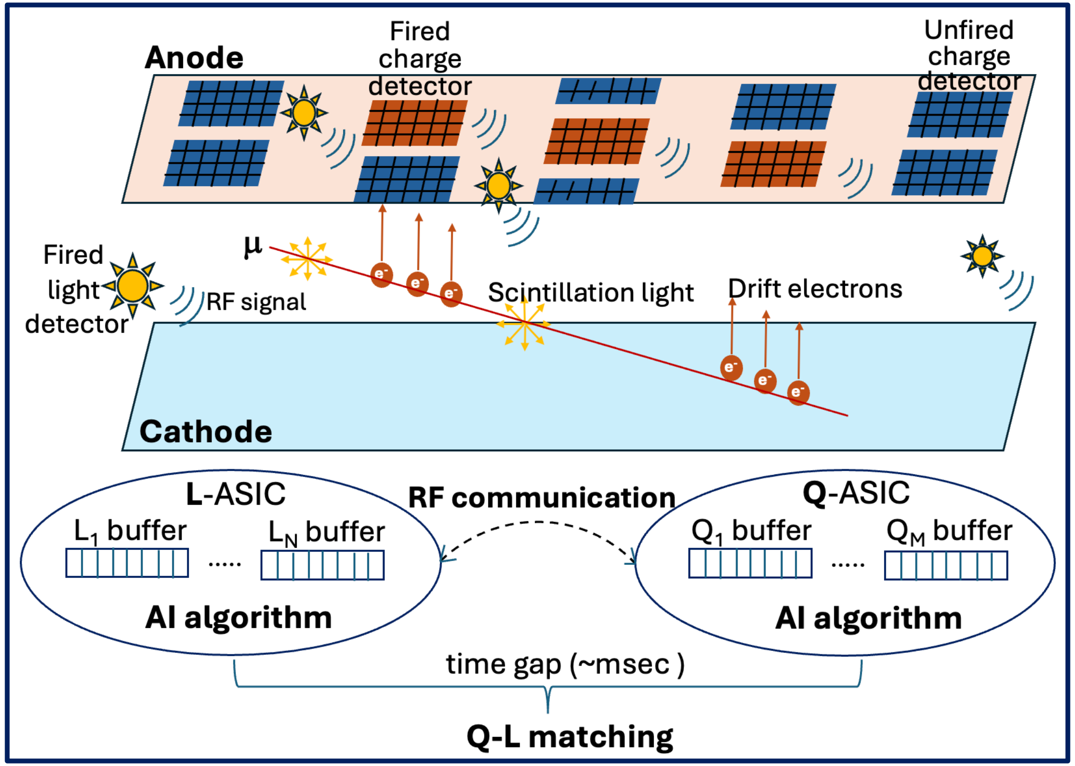
- ❑ Apply AI/ML "*in-situ*"
  - Q-L matching & pattern recognition "*in-situ*"
  - Increase S/B ratio "*in-situ*"
- ❑ Employ RF network
  - Essential for subdetector communication for Q-L matching
  - Additional benefit:

    a cable-free detector

→ Advanced technologies can reduce data volume & budget.

Smart TPC: AI/ML "*in-situ*" in LArTPC

Smart TPC



- ❑ Q-L matching "*in-situ*"
- ❑ Pattern recognition "*in-situ*"
  - Time
  - Space
  - Deposited charge & light
  - **Could add new physics trigger!**

→ RF network among all subdetector components are essential.

Test of RF Device(s) at LAr

❑ RF communication between Q & L detectors is essential for raw data reduction.

- We can start with a commercial RF device(s) to test it at LArTPC.
  ex) LoRa
  low power, cheap

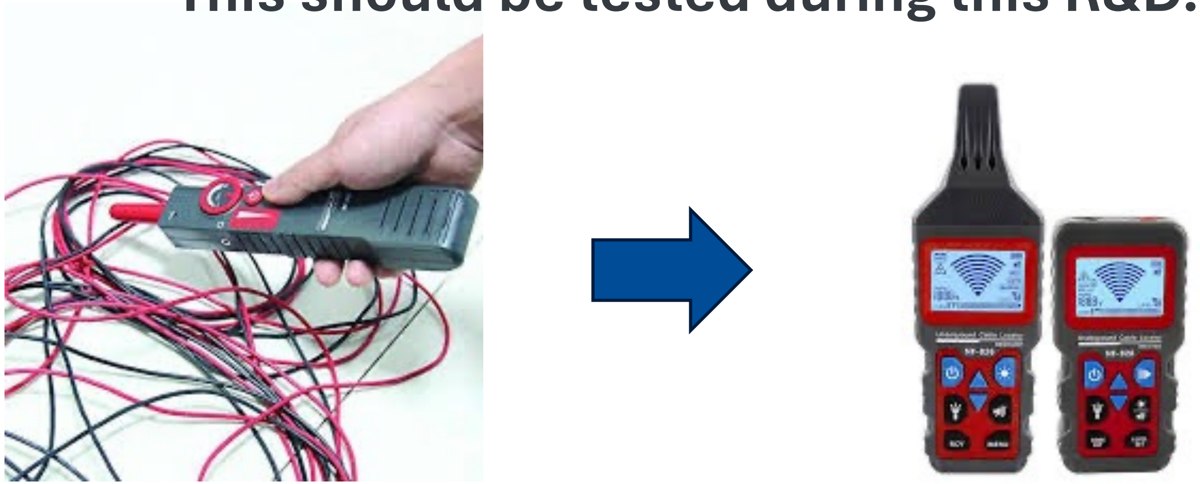
- Through tests in LAr,
  the device could be optimized to work properly in Cryo temperature.

RF Communication

❑ Not only RF communication between sub-detectors, we can consider sending out raw data over RF network.

→ This will allow us to build a cable-free detector.

This should be tested during this R&D.



Here, imagine DUNE detector w/ & w/o cables.

Alternative Light Pixel Detector

SPAD: Single Photon Avalanche Diode

- ❑ Cryo dSiPM

→ Currently under-development by Fermilab, EPFL, and Global Foundry

- Pros:
  -- Cheaper (~10% of commercial SiPMs)

- Cons:
  -- High dark count rate (→ need to measure it in LAr)
  -- Need VUV wavelength shifter

Key Technologies in this R&D

- **AI/ML on Chips (ASIC/FPGA)**
  → Reduce raw data volume, special trigger "*in-situ*"
- **RF Network**
  -- Communication between Q & L detector
  → essential for Q-L matching "*in-situ*"
  -- Raw Data transfer
  → cable-free detector
- **Digital CryoSPAD**
  -- Alternative to commercial SiPMs
  -- not required for this R&D (but helps reduce budget)

This has applications to any other experiments.

Fermilab has experts in these areas, but we need more humanpower!

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AI/ML Model to Hardware

Model Building	HW-Aware Test	Model Translation	HW Implementation
	To optimize the model for given HW constraints (memory, speed, power,..)	**Co-design model** (physicist, AI expert, HW engineer)	
AI/ML model	Model Optimization (for resources)	HLS4ML (SW → HW)	AI/ML on FPGA, ASIC
+ Simulated data	+ Quantization + Pruning	+ Optimization + Profiling + Tuning	

HLS =high level synthesis

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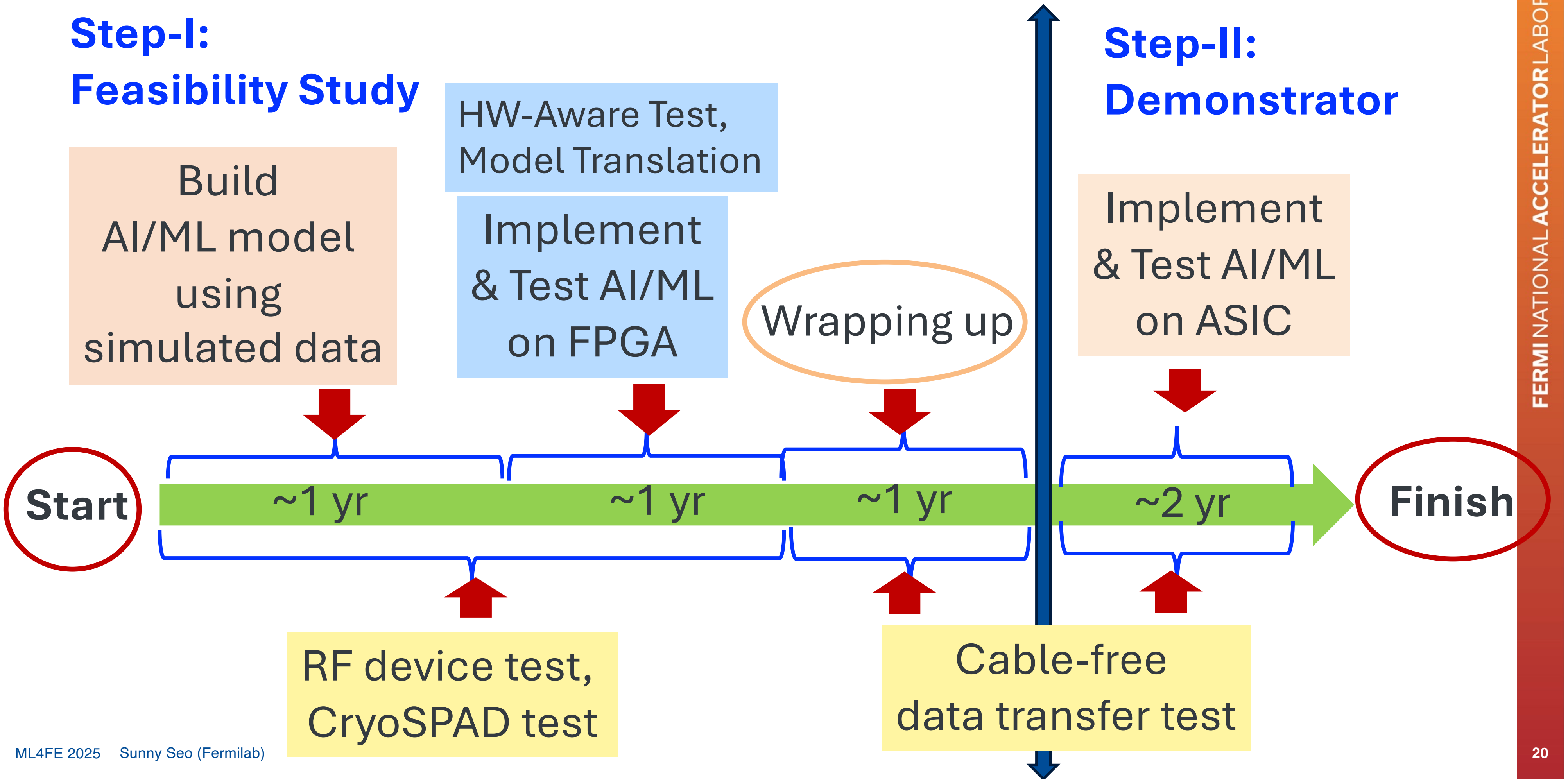
Rough Timeline of “Smart TPC” R&D



Summary & Conclusion

- ❑ Smart TPC is to apply AI/ML in real-time to reduce data volume by implementing AI/ML model to ASICs in TPC detector.
- ❑ DUNE, as an imaging detector, is the best place to apply AI/ML, and by employing Smart TPC, DUNE could reduce data volume.
- ❑ Even though DUNE Phase-I is not a pixel detector, Smart TPC still can be applied (by FPGA implementation).
- ❑ Smart TPC actually can be applied to any TPC experiment.

→ If you are interested in this Smart TPC, let's work together.
Let me know! shseo@fnal.gov