Exploring the Nu Frontier with Liquid Argon Time Projection Chambers

Brooke Russell

Wright Laboratory at Yale University

Gertrude Scharff-Goldhaber Prize Seminar

Brookhaven National Laboratory

July 3rd 2019

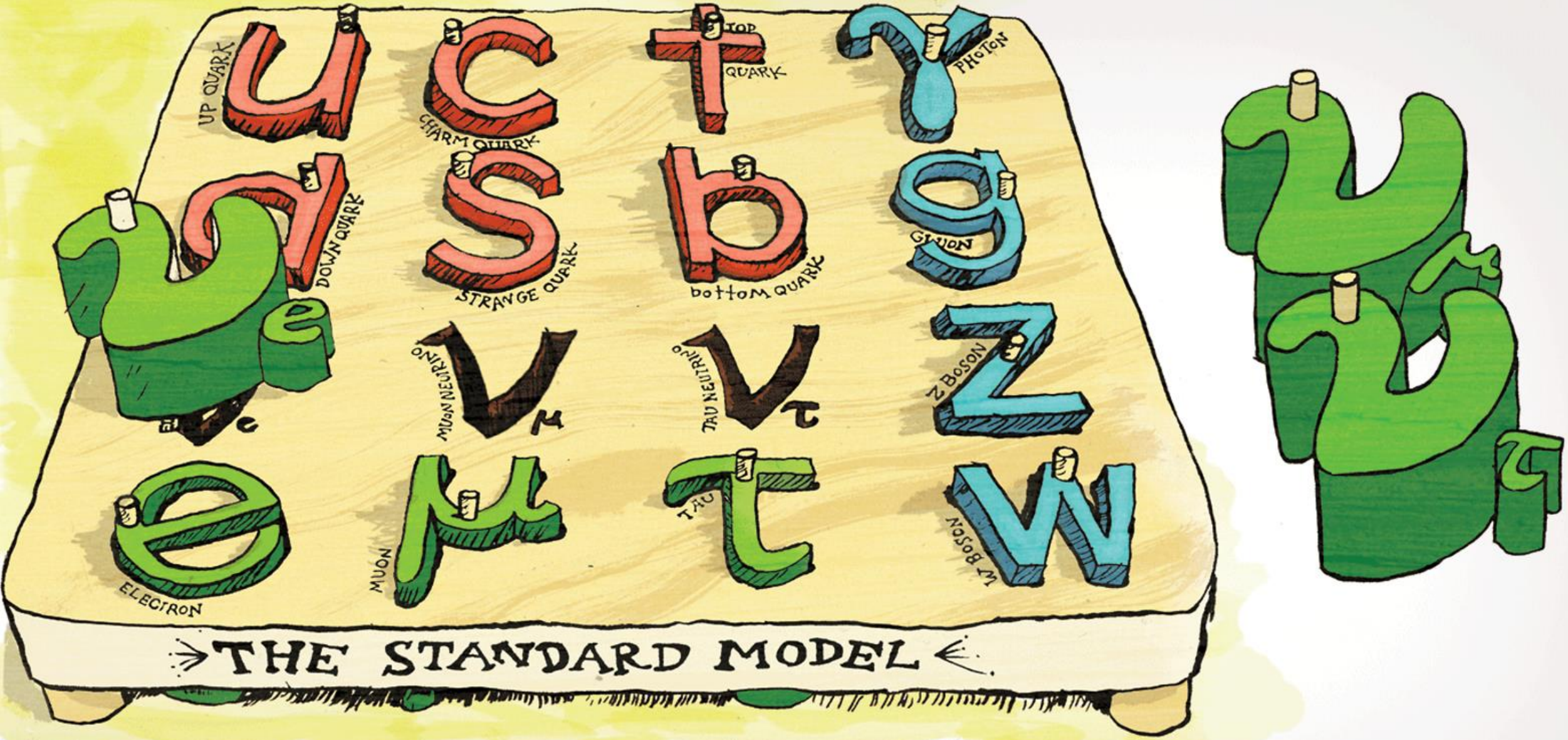


Figure credit: Symmetry magazine / Sandbox studio, Chicago

ν oscillation

Complimentary ability to explore the nature of ν oscillation physics with solar, atmospheric, reactor, and accelerator oscillation experiments

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2\ [\mathrm{eV}^2]\frac{L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}\right)$$

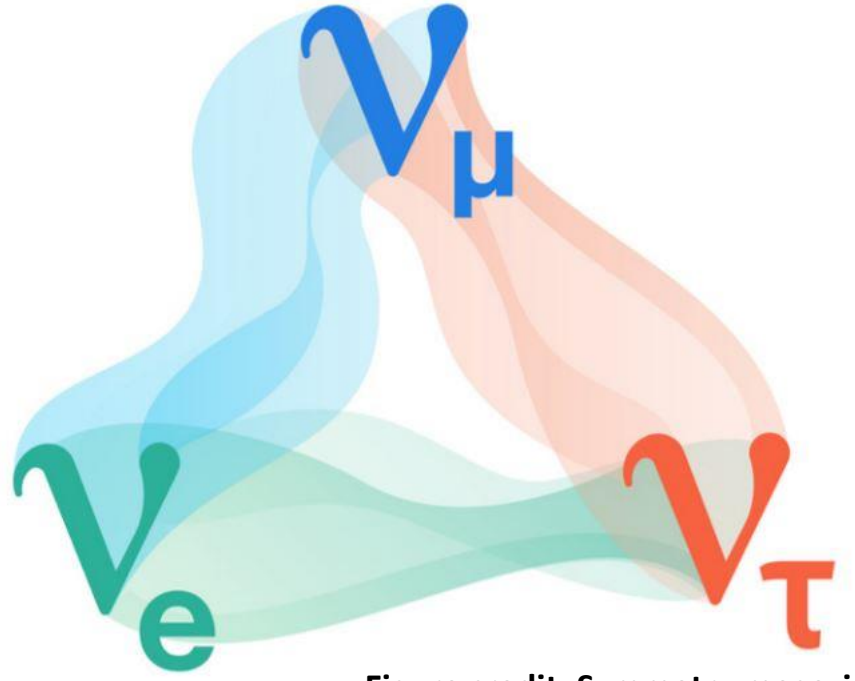


Figure credit: Symmetry magazine

Broad scientific program actively being explored:

- Precise measurement of known parameters
- Neutrino mass ordering
- Charge-parity symmetry violation in lepton sector
- Existence of sterile neutrino

→ Employ LArTPC technology to investigate

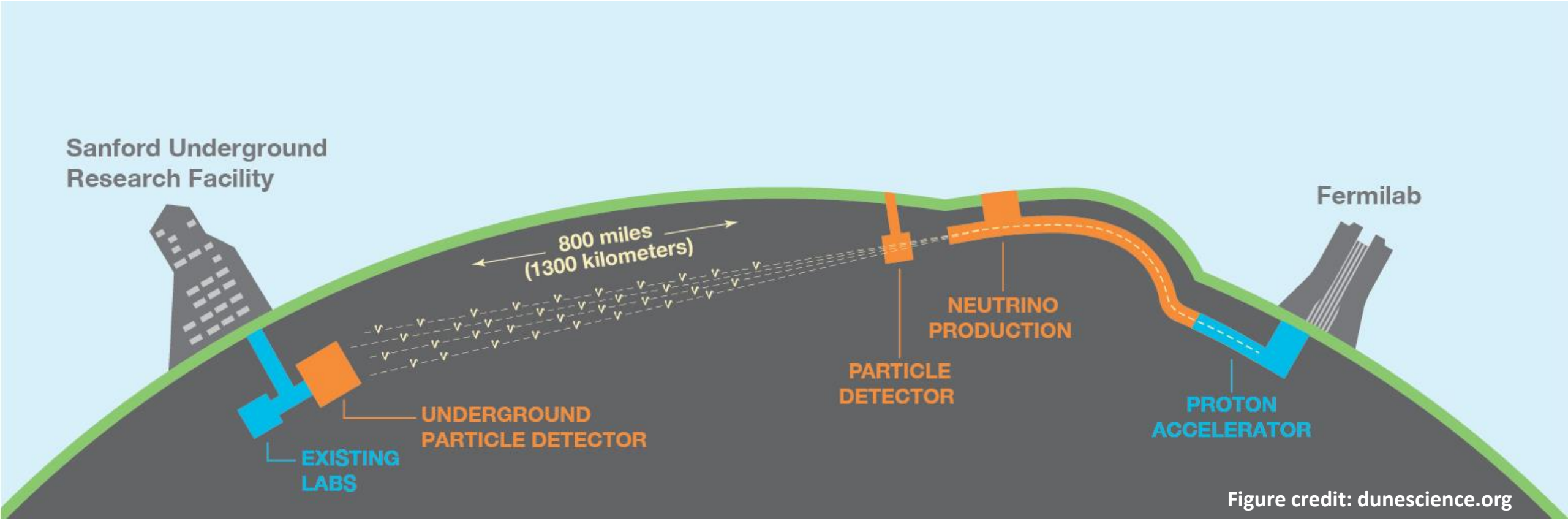
Is charge parity invariance (CP) violated in neutrino oscillations?

Ramifications for whether neutrinos are responsible for the matter-antimatter asymmetry in the universe

Compare $P(\nu_\mu \rightarrow \nu_e)$ versus $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ to study CP-violation

Figure credit: Symmetry magazine

Deep Underground Neutrino Experiment (DUNE)



- Search for CP violation in the leptonic sector
- Resolve the neutrino mass hierarchy
- Test grand unified theories (GUTs) with the detection of proton decay
- Observe neutrinos from core collapse super nova

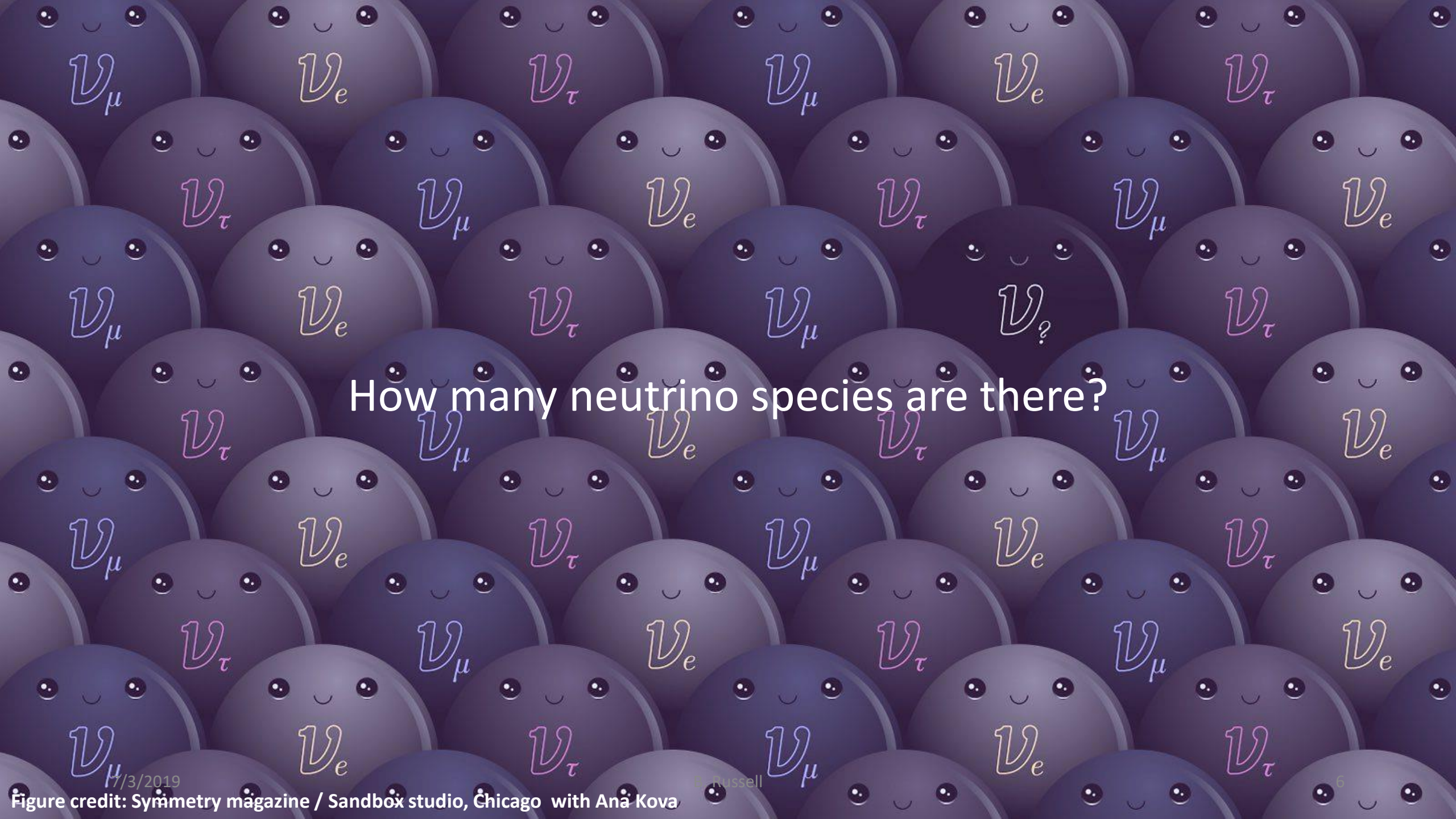
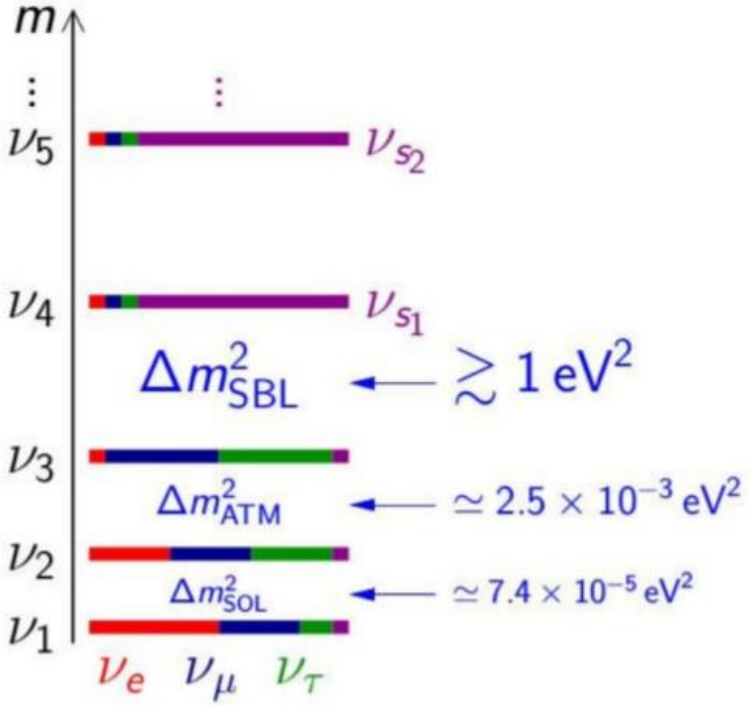


Figure credit: Symmetry magazine / Sandbox studio, Chicago with Ana Kova

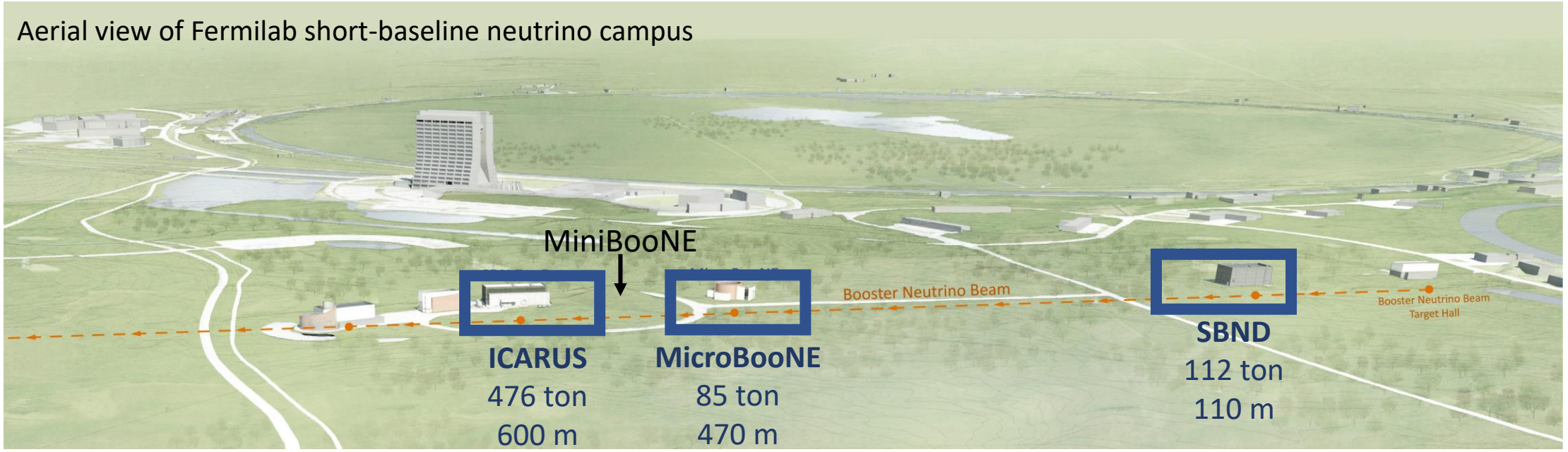
Sterile ν landscape

- Three flavor neutrino states are well established
- However, there exist a number of ***hints*** of additional neutrino states with masses at the eV scale
  - *LSND and MiniBooNE anomalies*
  - *Gallium anomaly*
  - *Reactor antineutrino anomaly*
- Do sterile neutrinos exist?
  - Disappearance: $P(\nu_\mu \rightarrow \nu_\mu)$ or $P(\nu_e \rightarrow \nu_e)$
  - Appearance: $P(\nu_\mu \rightarrow \nu_e)$



Short-**B**aseline **N**eutrino (SBN) Program

Staged approach to address short baseline anomalies
Phase 1: MicroBooNE – definitive test of the MiniBooNE low energy excess
Phase 2: SBND + MicroBooNE + ICARUS – ν_e appearance and ν_μ disappearance searches



- Reduce statistical uncertainties with *large mass* far detector
- Reduce systematic uncertainties with *same detector technology*

Single-Phase Liquid Argon Time Projection Chamber (LArTPC)

- *Massive* - fully active multi-ton target volume
- *Topology* - fine-grained 3D tracking
- *Calorimetry* - local dE/dx information

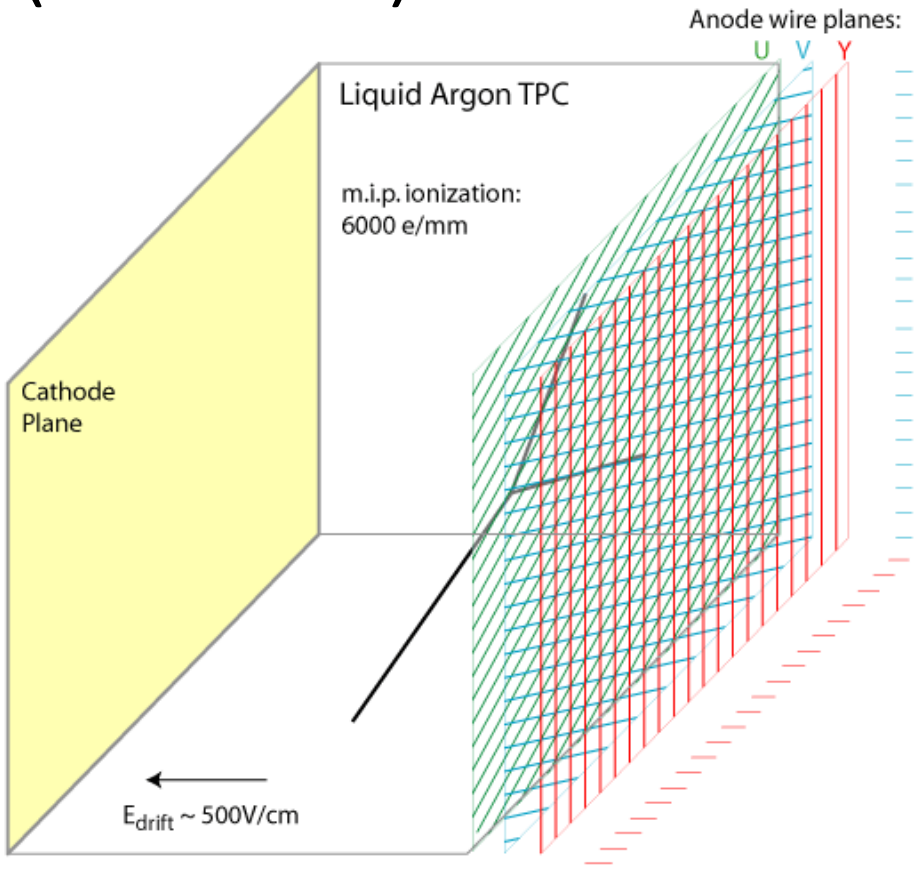
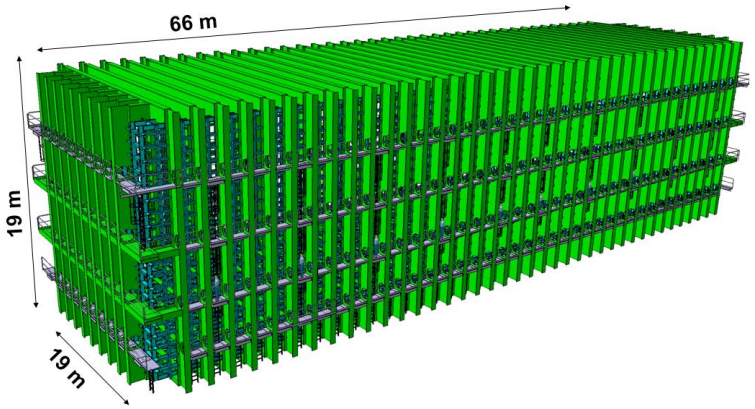


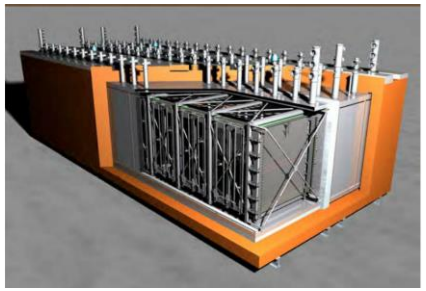
Figure from Bo Yu (BNL)

Detector technology for **DUNE** & **SBN** experiments

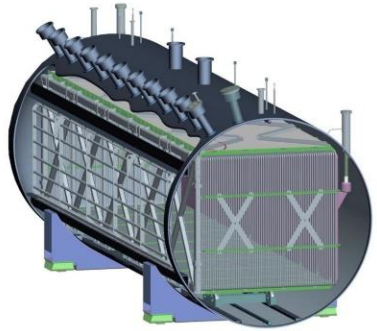
DUNE FD 10kt module



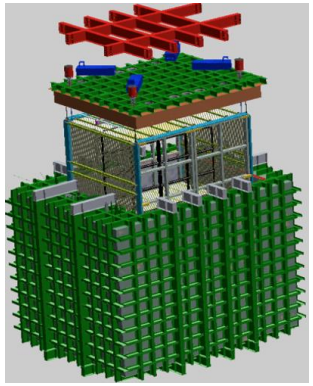
Icarus



MicroBooNE



SBND



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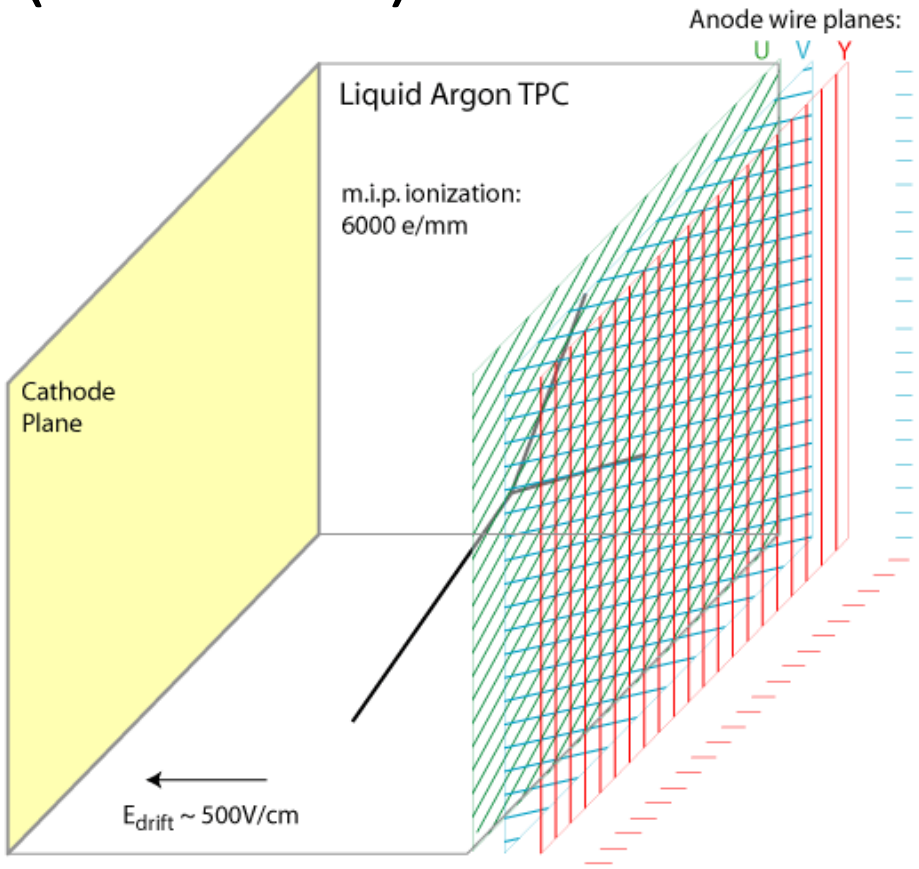

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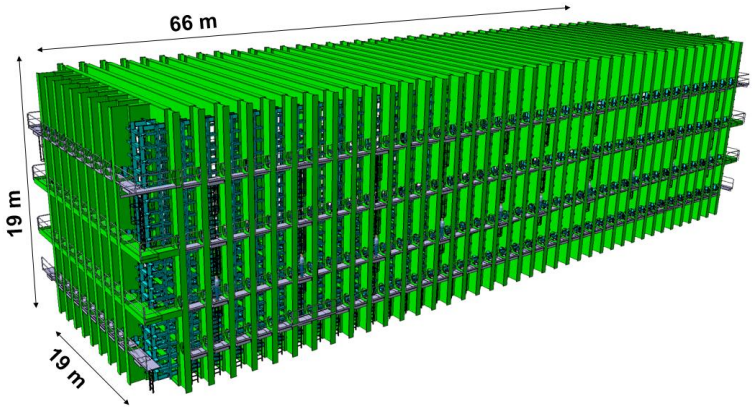

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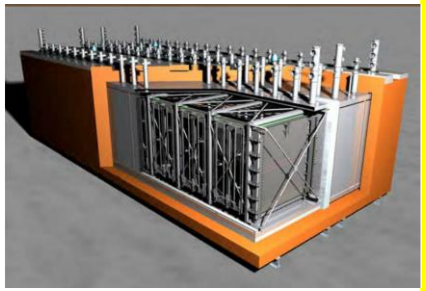
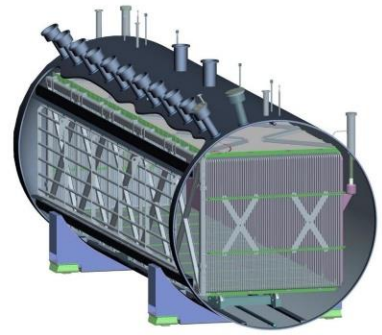
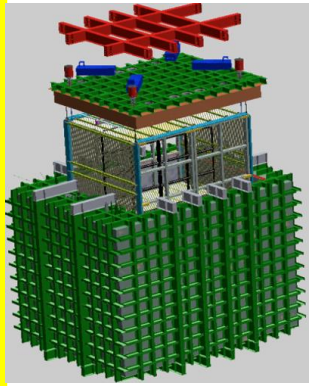


MicroBooNE



SBND



BNL MicroBooNE group

With MicroBooNE data, work to bring to fruition LArTPC capability for near-term and long-term neutrino oscillation physics

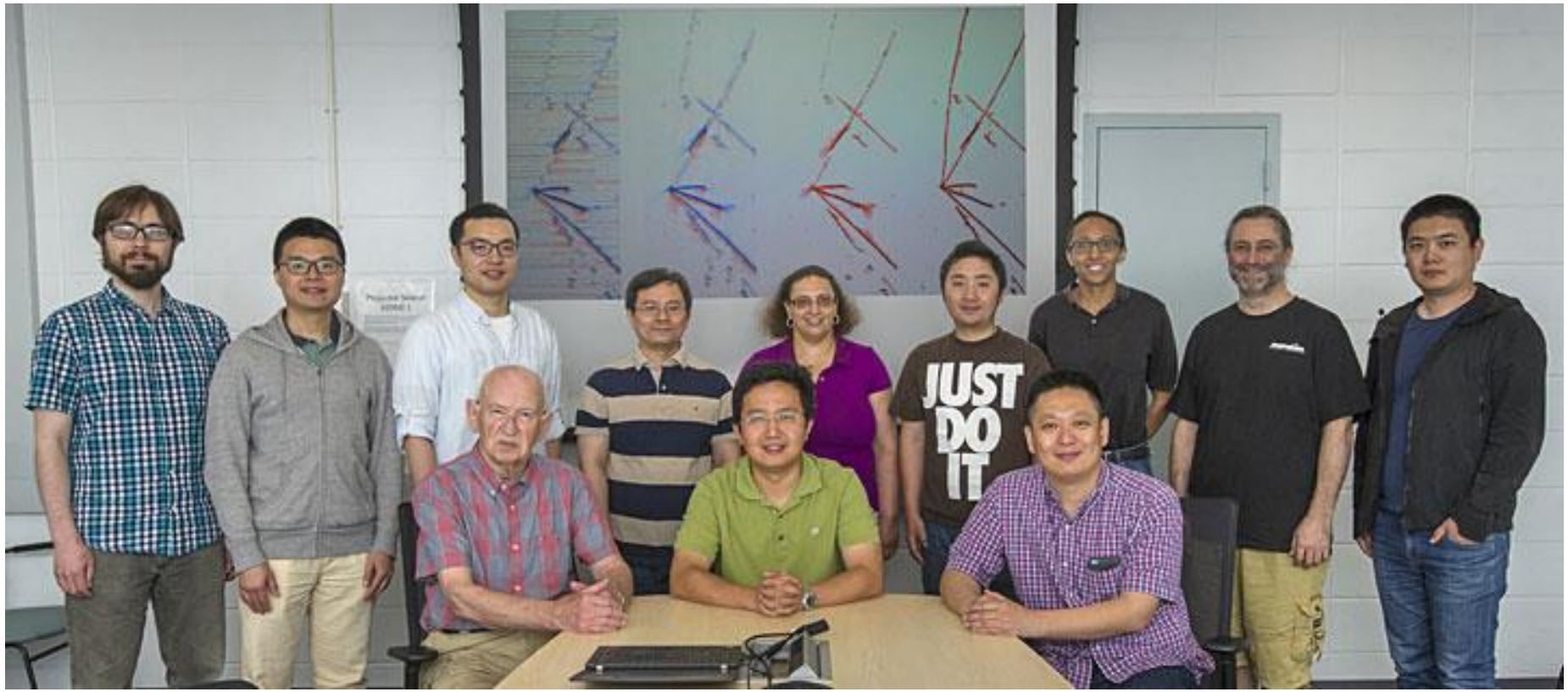


Photo from BNL press release: *"Extracting Signals of Elusive Particles from Giant Chambers Filled with Liquefied Argon"*

LAr as total absorption calorimeter

1974

NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

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and

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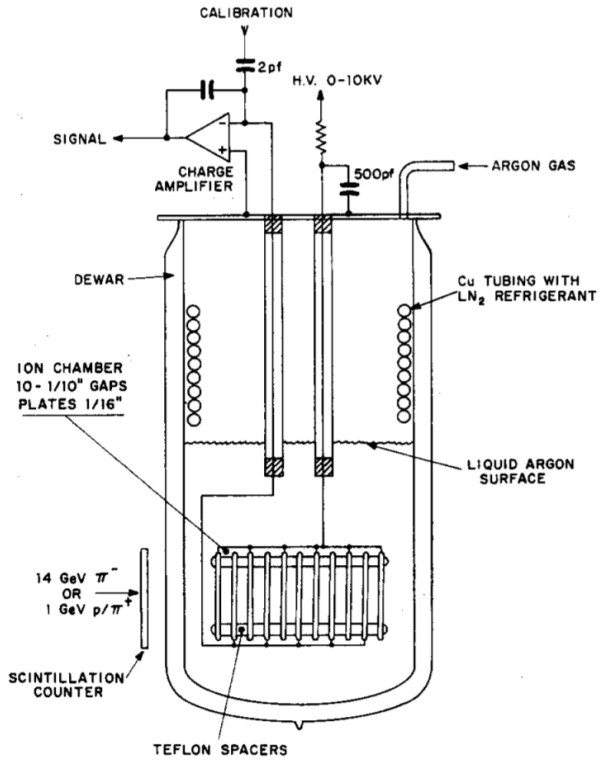
Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

Received 14 May 1974



In anticipation of scaling LAr ionization chambers to large detectors, emphasized early on that *capacitance matching of the detector and the amplifier is essential* to reach the fundamental lower limit of noise (higher signal-to-noise ratio)

LAr is an attractive active target medium:

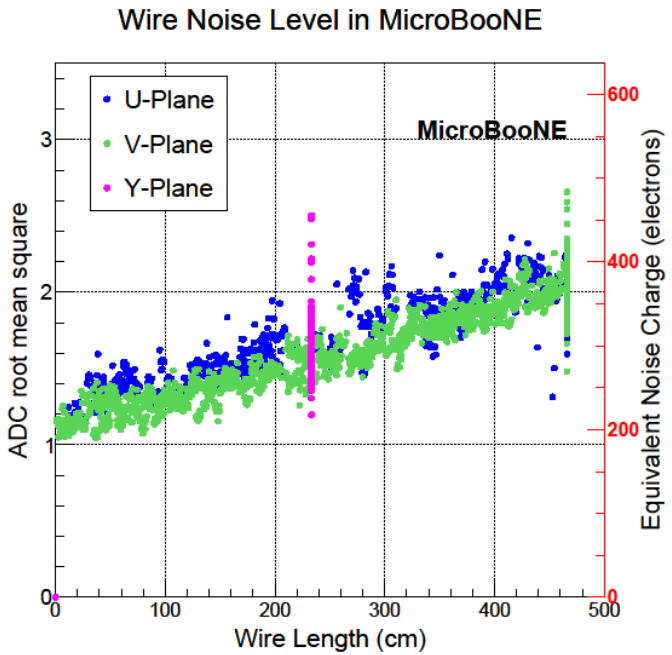
- High electron mobility
- Cheap
- Abundant
- Inert
- Many nucleons

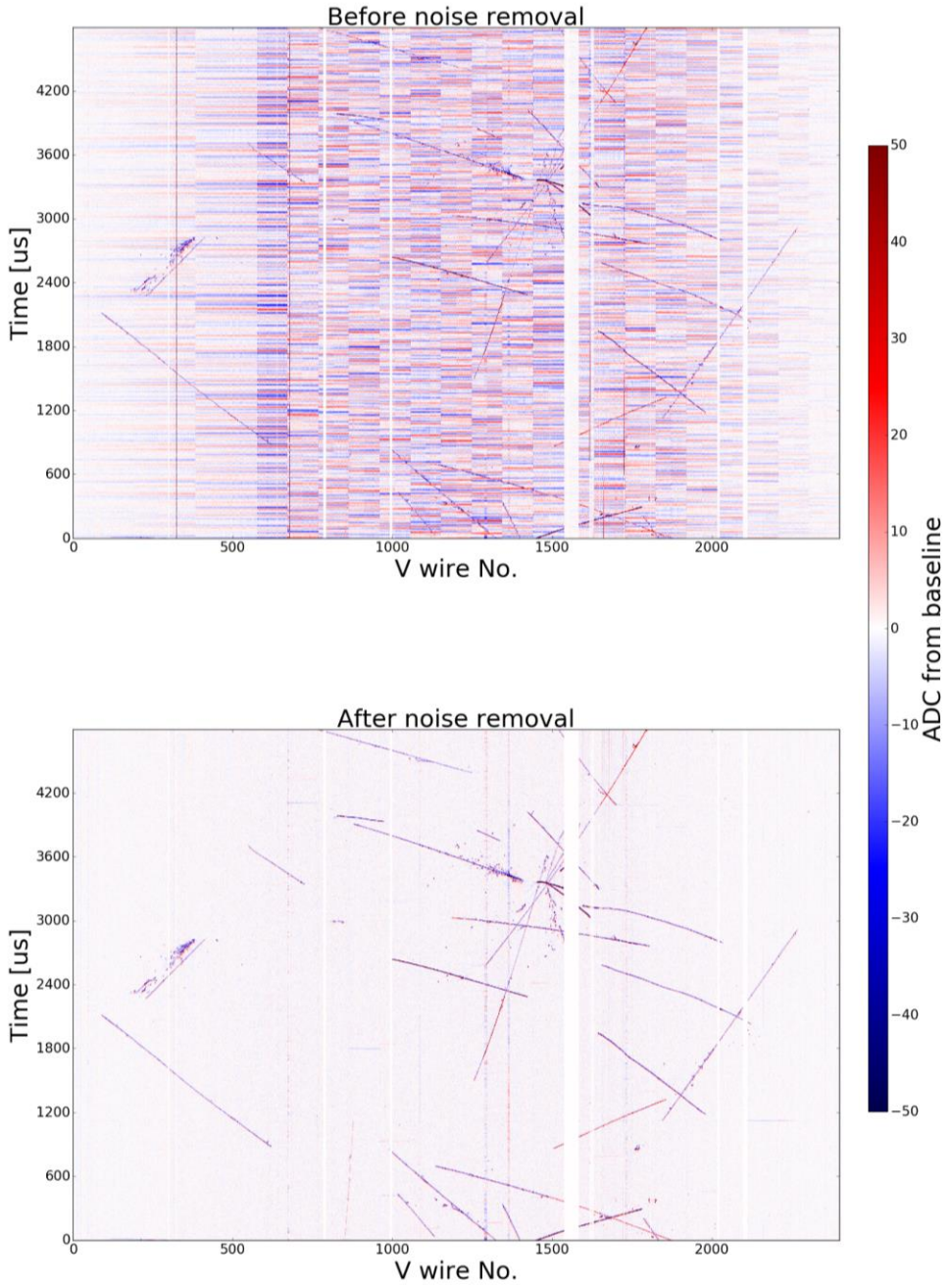
✓Mitigate excess noise

✓Low inherent electronics noise

Lessons learned from MicroBooNE have led to improvements in cold ASIC design for SBND & DUNE, *imperative for scaling to O(kt) masses*

Liquid argon boiling point -186℃

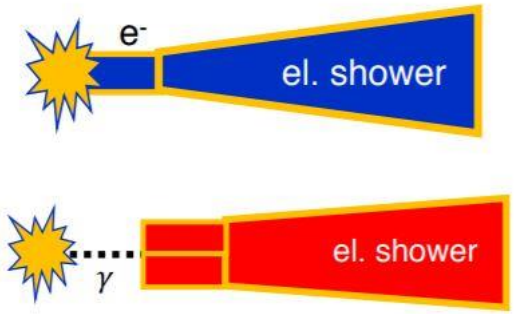


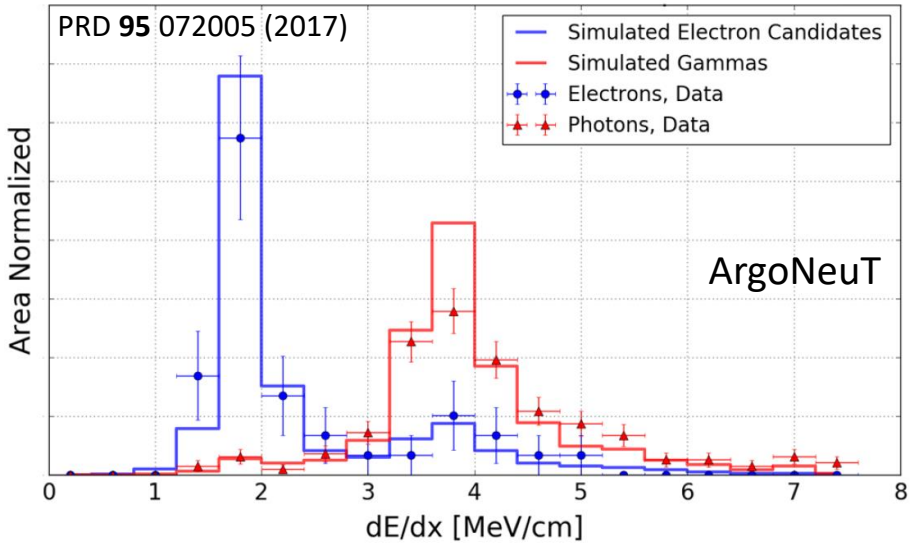


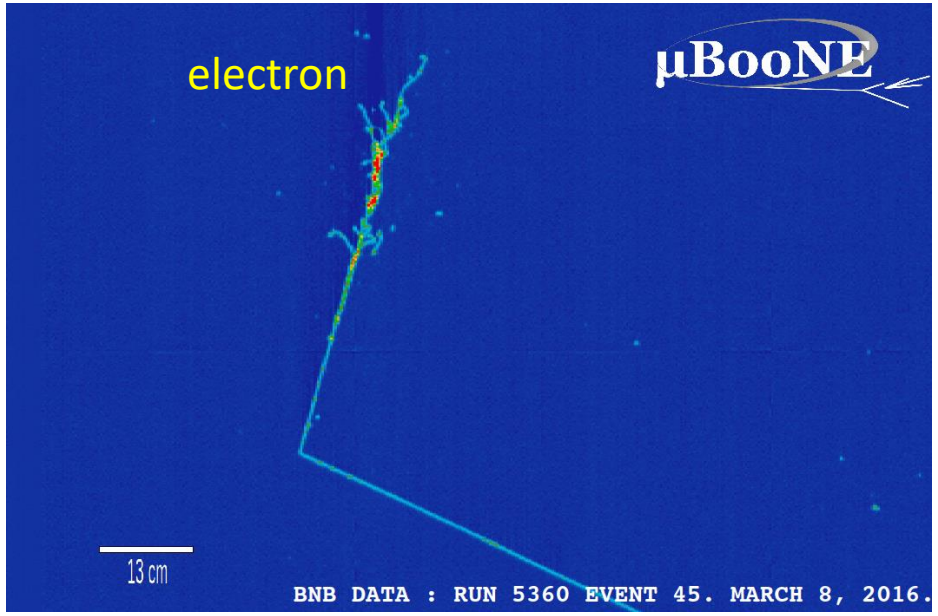
JINST **12** P08003 (2017)

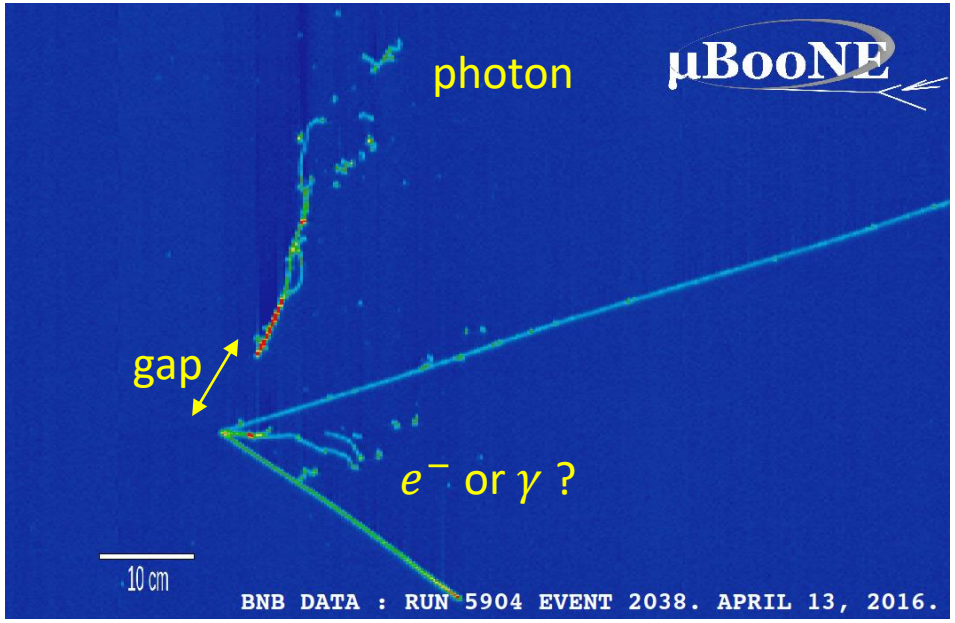
e^-/γ discrimination

critical for $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ measurements



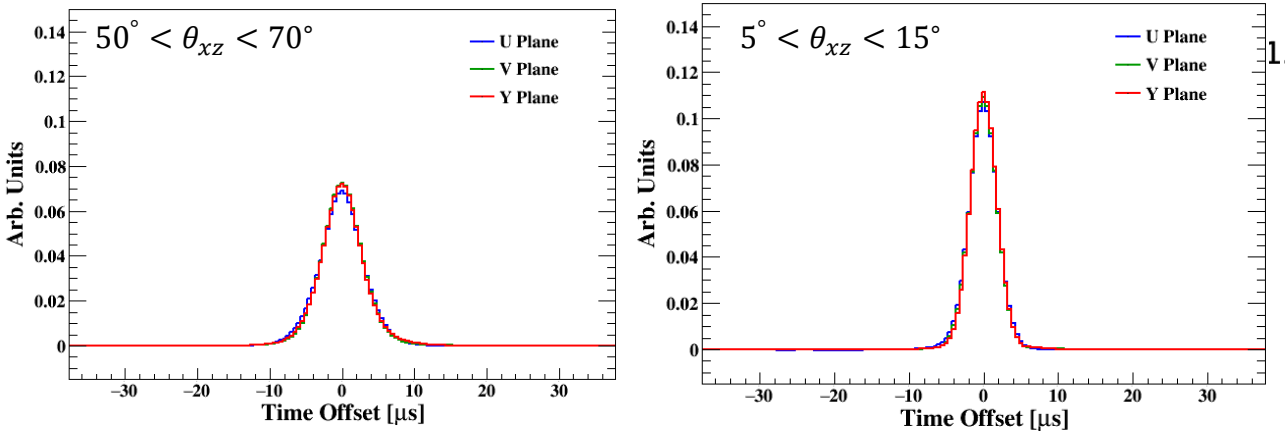




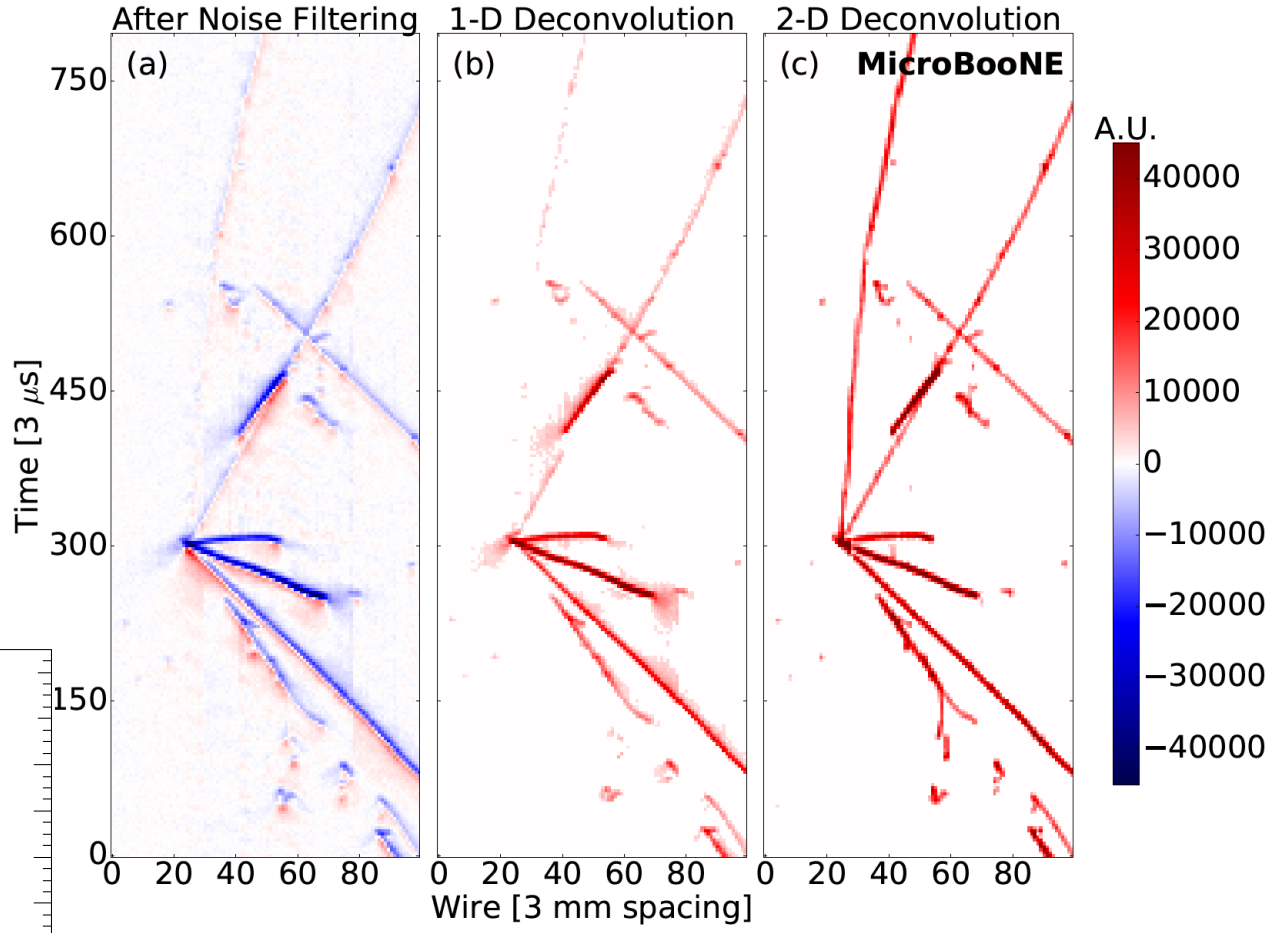


✓Careful signal extraction

Pioneered novel signal processing techniques for single-phase LArTPCs, *critical for topology agnostic reconstruction of neutrino final states*



JINST **13** P07007 (2018)



JINST **13** P07006 (2018)

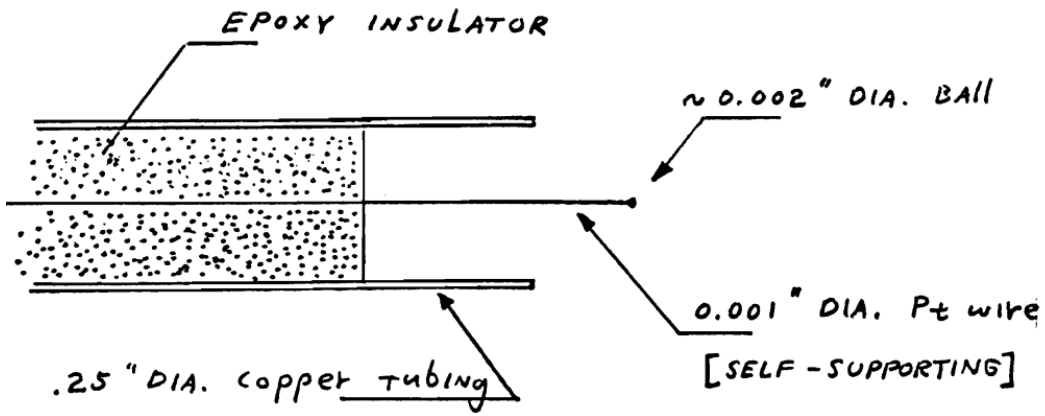
TPC as 4π charged particle detector

1976

The Time-Projection Chamber
- A new 4π detector for charged particles

David R. Nygren

Lawrence Berkeley Laboratory
Berkeley, California 97420



"The absence of the ambiguities associated with spatial projections should have an enormously beneficial impact on the problem of pattern recognition in high multiplicity events."

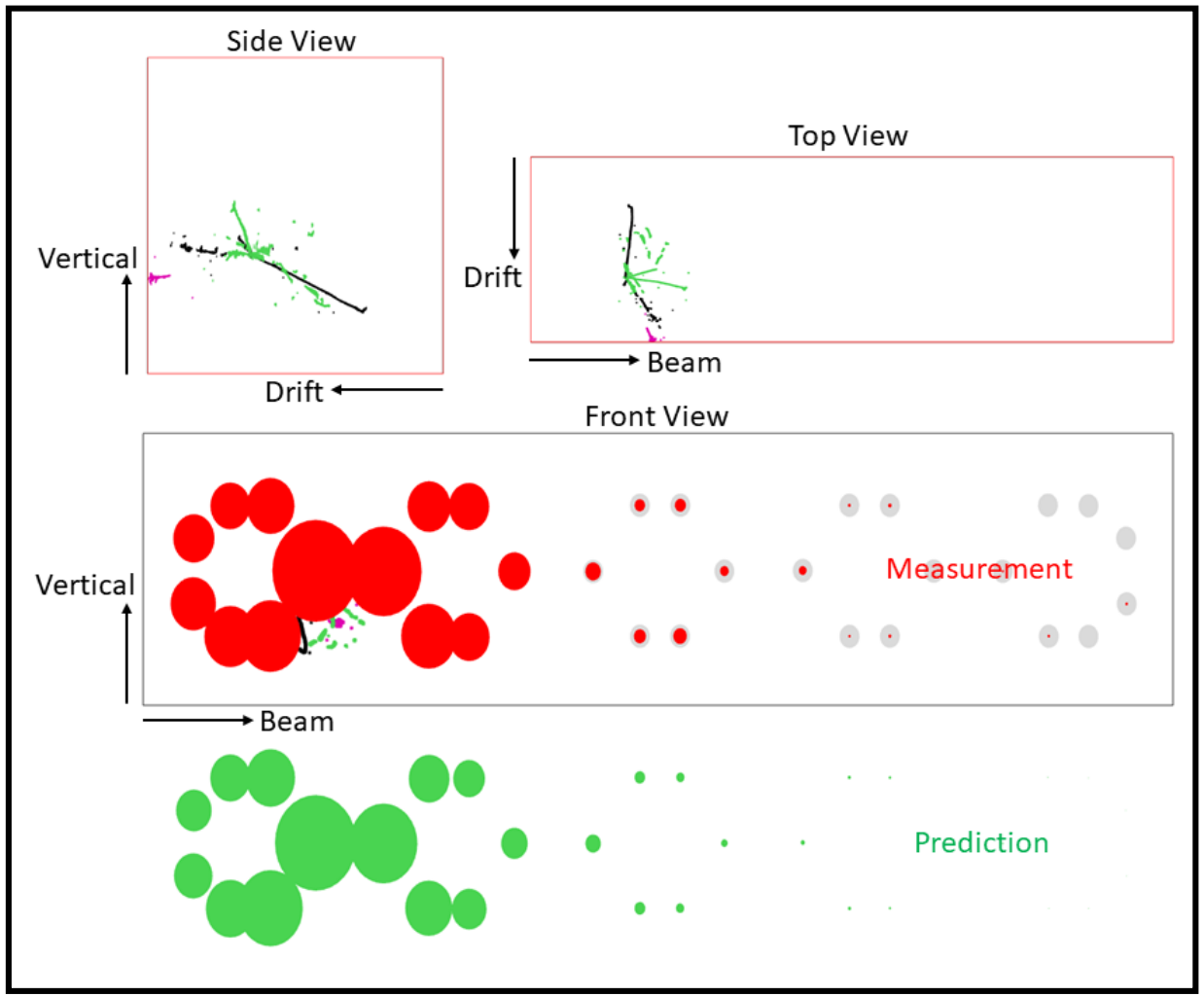
Ubiquitous application in modern experimental physics

- Neutrino-less double beta decay
- Dark matter direct detection
- Etc.

Wire-Cell tomographic event reconstruction

X. Qian, C. Zhang, B. Viren, M. Diwan
JINST **13** P05032 (2018).

ν candidate with 3 π^0s



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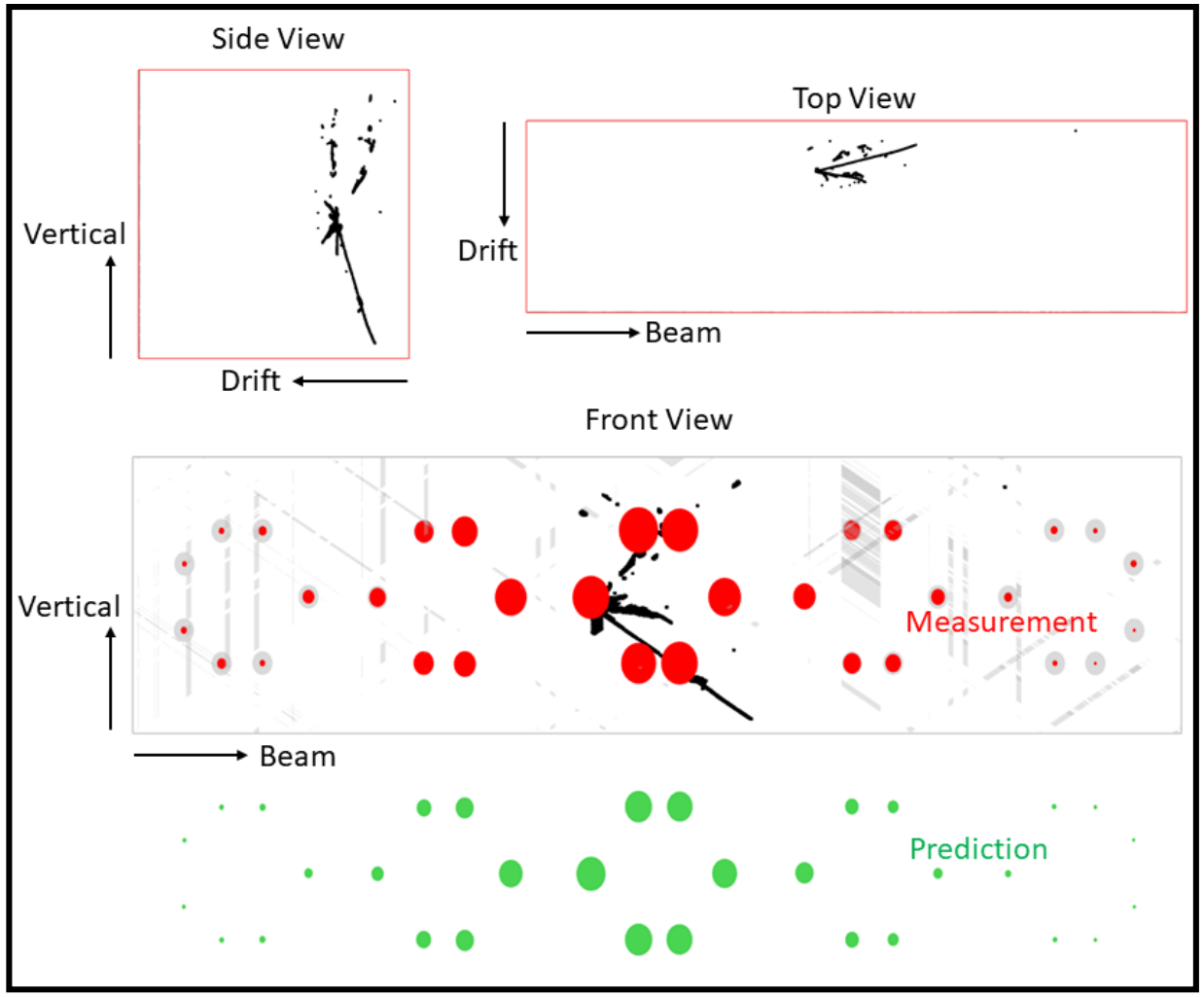

Bringing to fruition LArTPC capability for ν oscillation physics

Employ LArTPCs to answer critical questions in neutrino physics

- CP violation in lepton sector?
- Existence of sterile neutrino?

In the era of precision ν oscillation physics, MicroBooNE is blazing the trail

- Near term SBN program seeds the success for flagship long baseline DUNE experiment
- Demanding technical requirements are needed to make these ambitious measurements