Noble Liquid Based Neutrino Detector

Ana Amelia B. Machado

UNICAMP FAPESP

LIDINE 2022
LIght Detection In Noble Elements
Conference Series
21-23 September 2022
at the University of Warsaw Library

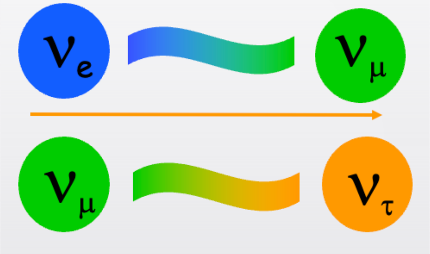
Outline

- Current Status of Neutrino Physics
- Oscillation
- Long Baseline Experiment Technologies
- Liquid Argon TPC
- DUNE - Long Baseline Experiment -
- Short Baseline Anomalies
- Short Baseline Program @ FNAL

Current Challenges in Neutrino Physics

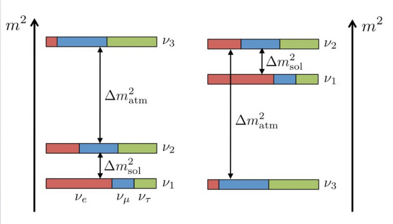
Even if neutrinos are fundamental particles which have been detected 70 years ago there **are still several open questions related to their properties**:

Oscillation



Do neutrino and anti-neutrino oscillate differently? (CP violation)

How are the **mass ordered ?** (mass hierarchy)

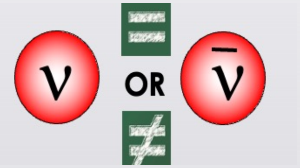


Are there other neutrino types or interactions ?

Nature

Are neutrinos their own antiparticle ?

What are the masses of neutrino?



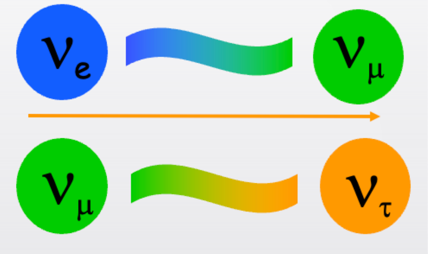
β and ββ decay experiments

Grzegorz Zuzel. (talk)

Current Challenges in Neutrino Physics

Even if neutrinos are fundamental particles which have been detected 70 years ago there **are still several open questions related to their properties**:

Oscillation



Do neutrino and anti-neutrino oscillate differently? (CP violation)

How are the mass ordered ? (mass hierarchy)

Long-Baseline

Are there other neutrino types or interactions ?

Short-Baseline

Oscillation

- PMNS mixing matrix parameters: 3 mixing angles + 1 complex phase

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

Atmospheric | Reactor & LBL | Solar

- Oscillation is a function of a mixing angle θ_{ij}, the Δm_{ij}^2, and distance L and energy E

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

- Oscillation Experiments **fix L and E** and measure the free parameters

Long Baseline Experiment Technologies

Liquid Argon based

- DUNE
- ICARUS @ LNGS

Water Cerenkov based

- T2K
- Hyper-Kamiokande

Scintillator based

- NOνA
- Minos

Photographic Emulsion

- OPERA @ LNGS

Detector need to cover these topics:

- Massive Detector
- Excellent energy resolution
- Tracking capability
- Particle identification
- Precise timing

Long Baseline Experiment Technologies

Liquid Argon based

- Perfect dielectric medium
- Drift velocity (~ 1mm/μs *@ 500 V/cm*)
- *High purification* (*<0.1 ppb O_2 equivalent*)

  Long electron *lifetimes* (*>msec*)

  drift paths (>*m*)
- High scintillation light yield (~40,000 γ/MeV)
- High *electron-ion pairs yield*

(~ *10000* e^- for 2 mm of m.i.p track)

- Density = 1.4 g/cm³ > (water density =1)
- Abundand (1% atmosphere)

Detector need to cover these topics:

- Massive Detector
- Excellent energy resolution
- Tracking capability
- Particle identification
- Precise timing

Liquid Argon TPC

Charged particles in LAr **produce** free **ionization electrons** and **scintillation light (128nm)**

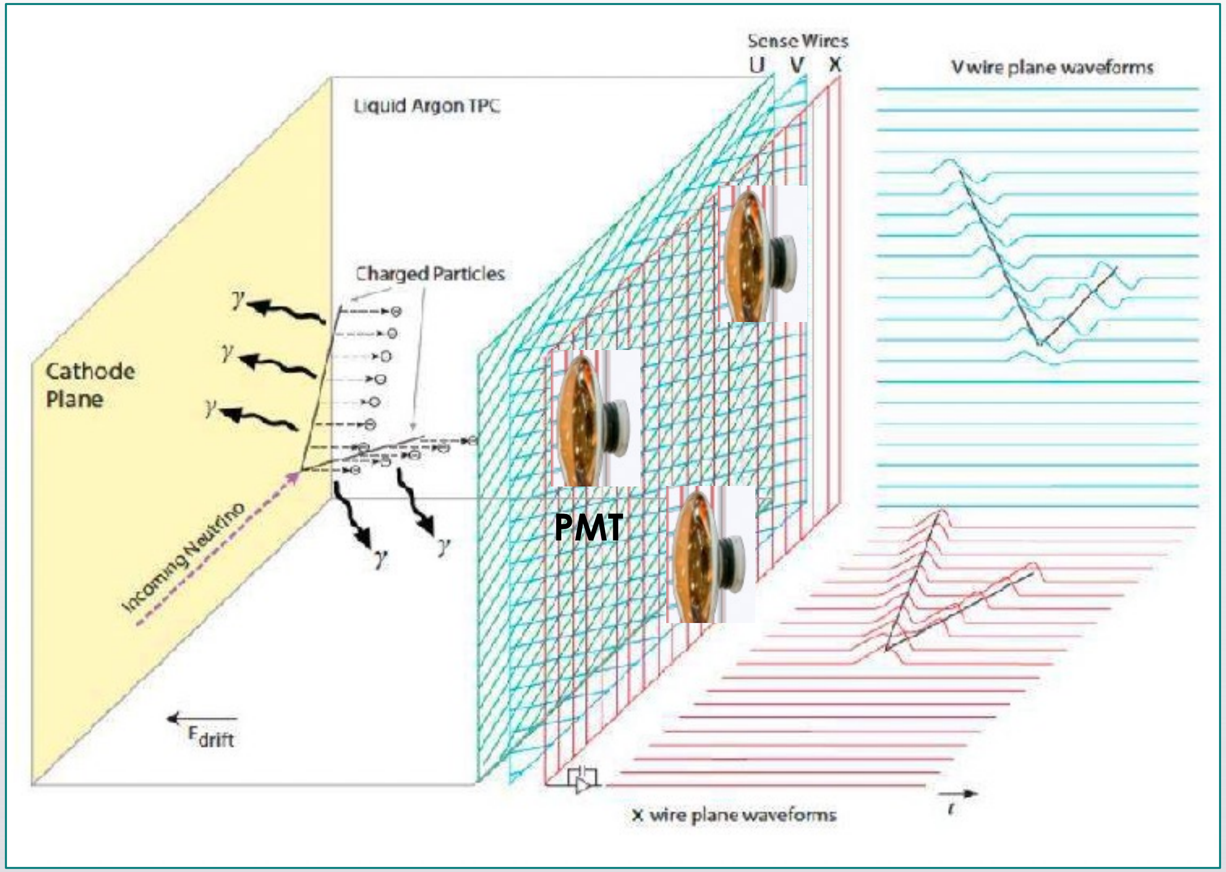
Ionization electrons drifts in a intense and uniform electric field(~500V/cm) towards the readout wire-planes

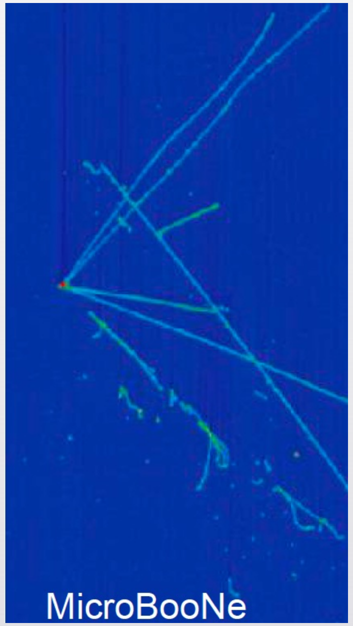
3D reconstruction
+ Calorimetric measurements

VUV photons propagate and are shifted into VIS photons

Determination of $\mathbf{t_0}$
+ Calorimetric measurements

Horizontal Drift Liquid Argon TPC





LArTPC - Original proposal

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

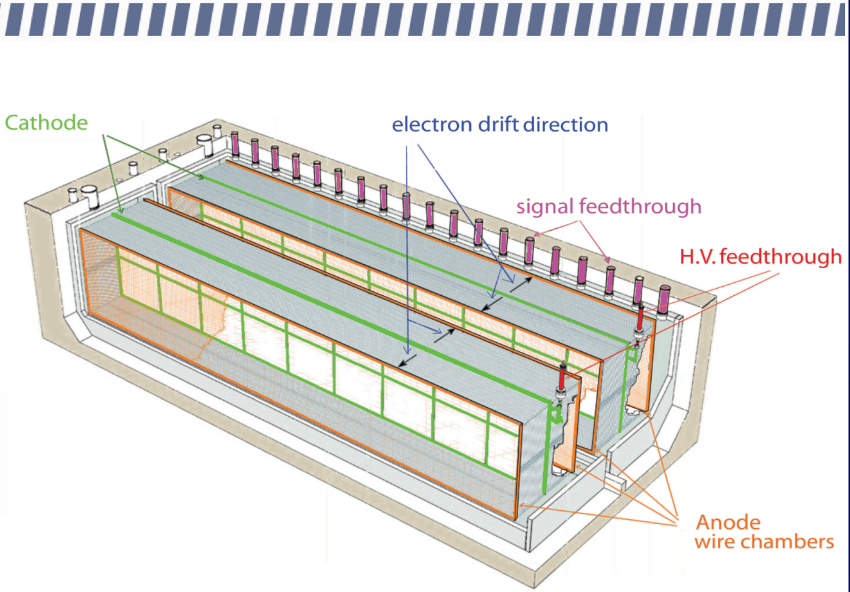
ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

First LArTPC Experiment → ICARUS @ LNGS

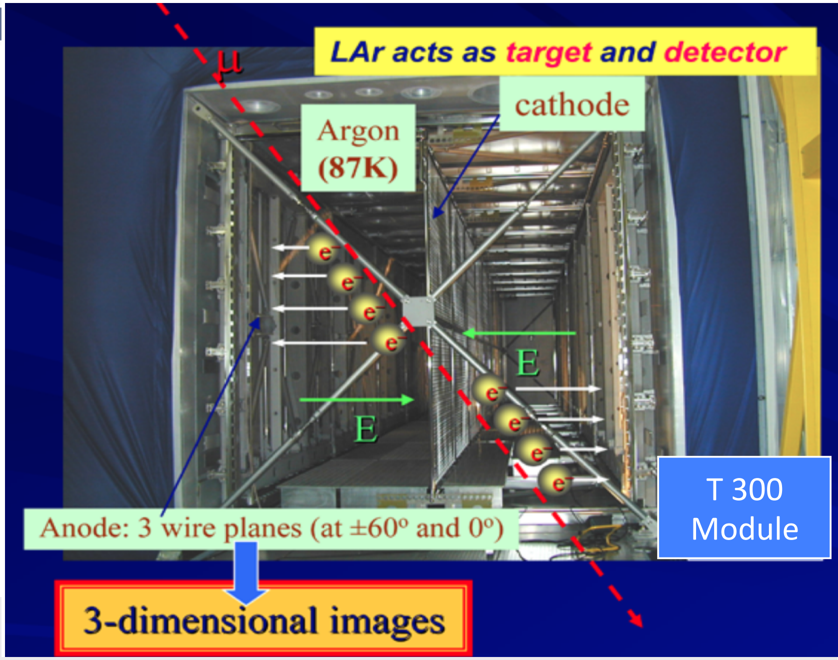
Two "T300" identical modules

- 3.6X3.9X19.6 ≅ 275 m^3 each
- Active mass 476 ton
- Drift length = 1.5 m
- E = 500V/cm   HV=-75kV



Charge Readout

- 4 wire chamber (2 chamber per module)
- 3 readout wire plane (0°, ±60°) (2 inductions + 1 collection)
- 53,248 wires, 3mm pitch, 3mm plane space

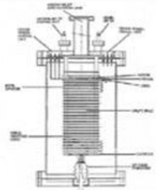


Photon Detection

- (20+54) PMTs , 8 inchs
- VUV sensitive (128nm) coated with TPB

Evolution

Credits
C. Vignoli - LNGS

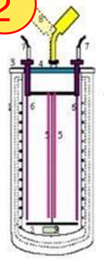


1 24 cm drift wires chamber

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

CERN

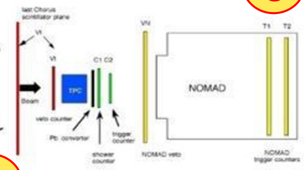
2 3 ton prototype



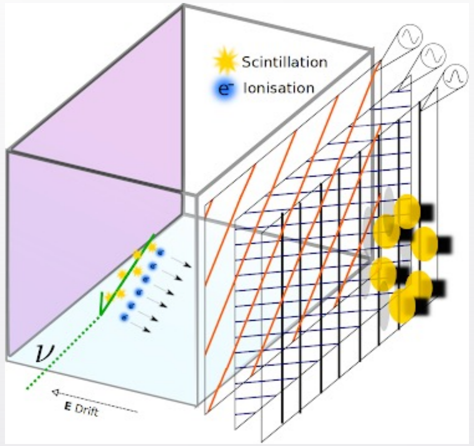
1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

CERN

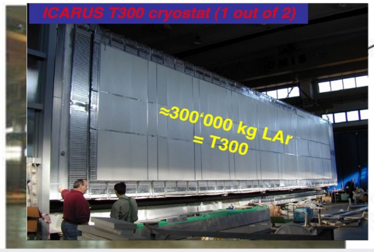
3 50 litres prototype 1.4 m drift chamber



1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.



T600 Pavia



4 10 m3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

5 LNGS Hall-B (2010-2013)

CERN

***2014-2017** Detector overhauling at*

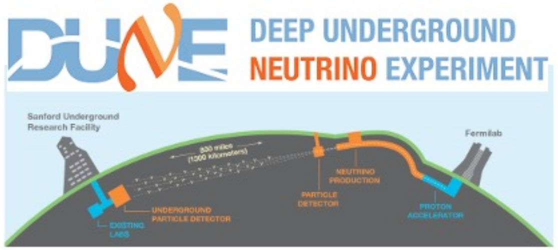
6

7

2017 Detector transportation to FNAL

T600@FNAL

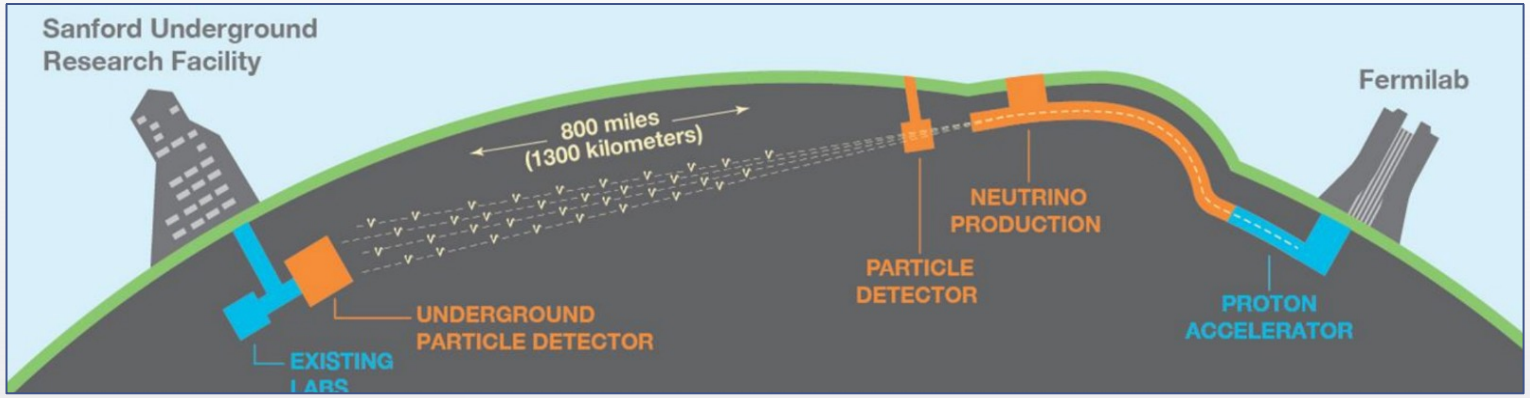
8



***2025** Multi-ktons Detectors installation at SURF*

9

DUNE – Long Baseline ν experiment



Physics goals :
- CP Violation
- Mass hierarchy
- Proton decay
- Supernova
- Solar

International Colaboration:
- 37 countries + CERN
- 233 laboratories and institutes
- ~1700 researchers

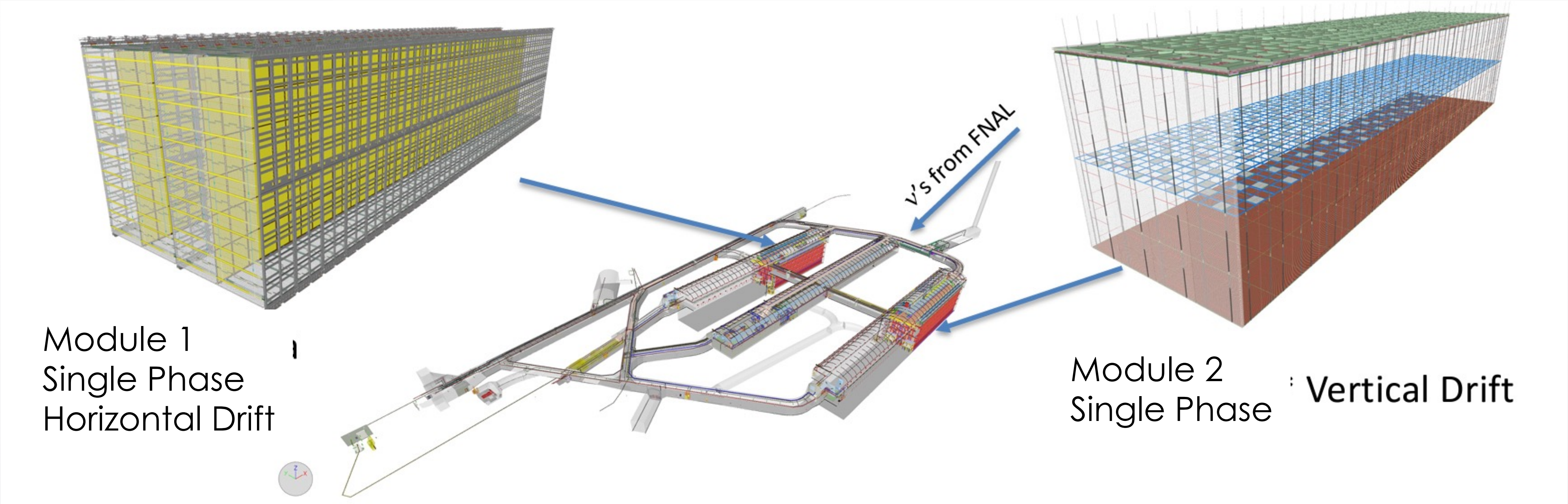
- Measure neutrino spectra at 1300Km in a wide-band beam
- High-power proton beam – 1.2MW upgradeable to 2.4MW
- Massive underground LArTPC → 4 modules - 17 kton each
- Near detector to characterize de beam (100s millions of ν interaction)

Near Detector: measurements of ν_μ **unoscillated** beam

Far Detector: measurements of **oscillated** ν_μ & ν_e spectra

then repeat for antineutrinos – and compare oscillations of neutrinos and antineutrinos

DUNE – Far Detector



- **Module 1**
  - Charge Readout. → APA Wires
  - Photon Detector → X-ARAPUCA
- **Module 2**
  - Charge readout → CRP - Charge Readout Planes
  - Photon Detector → X-ARAPUCA

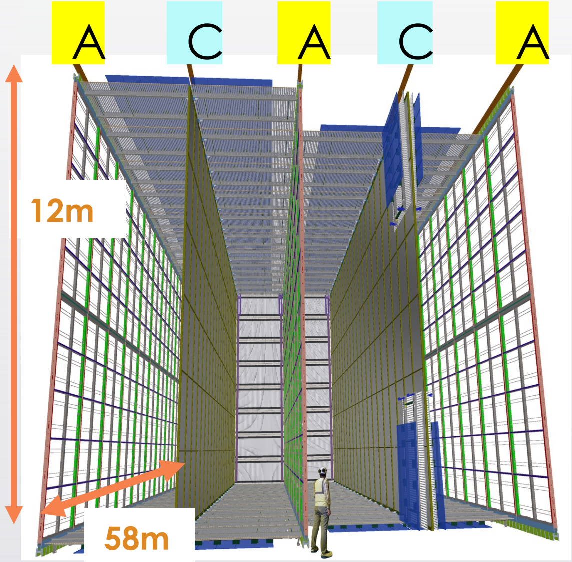
- Technologies for module 3 and 4 are not yet established

Module of Opportunity Workshop 2-4 November – Valencia, Spain

https://congresos.adeituv.es/dune_science/ficha.en.html

DUNE – Far Detector

Horizontal Drift



4 drift volumes, 3.6 m drift
Electric field = 500 V/cm
(HV = -180 kV)
High-resistivity CPA for fast discharge prevention

Anode: **150 APAs**, each with 4 wire planes (Grid, 2 x Induction, Collection)

Photon Detectors: **X-ARAPUCA**
10 modules / APA
Total of **1500 modules**

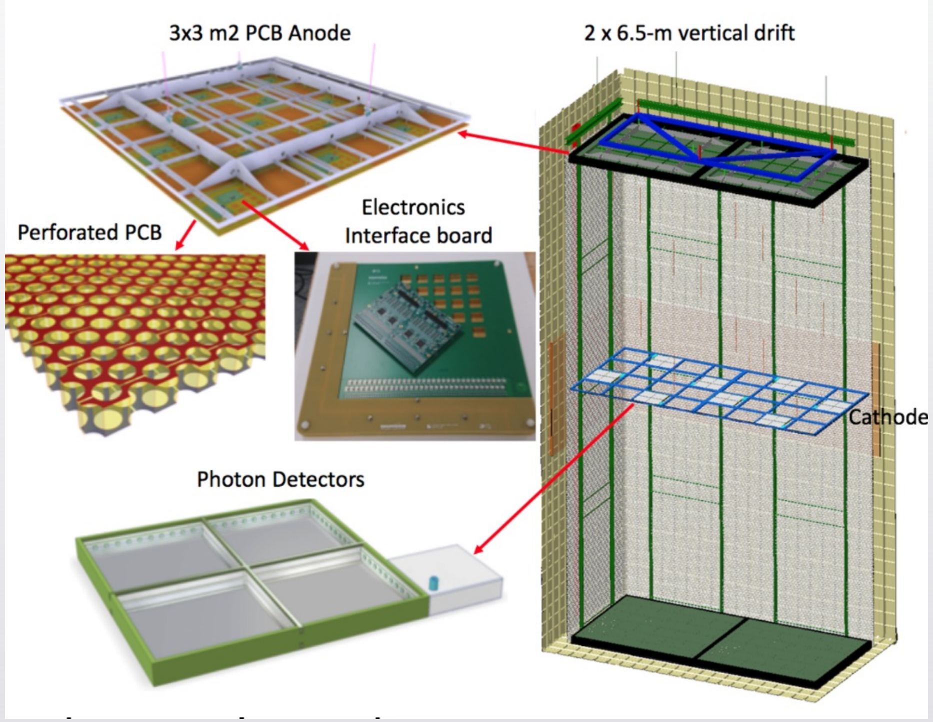
X-Arapuca module (212cm x 12cm)

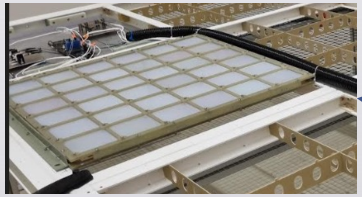
Vertical Drift

2 volumes (13.5 m x 6.5 m x 60 m) separated by a cathode plane

2 Anode planes (top & bottom)

Charge Readout via **perforated PCB anode**, fully immersed in LAr

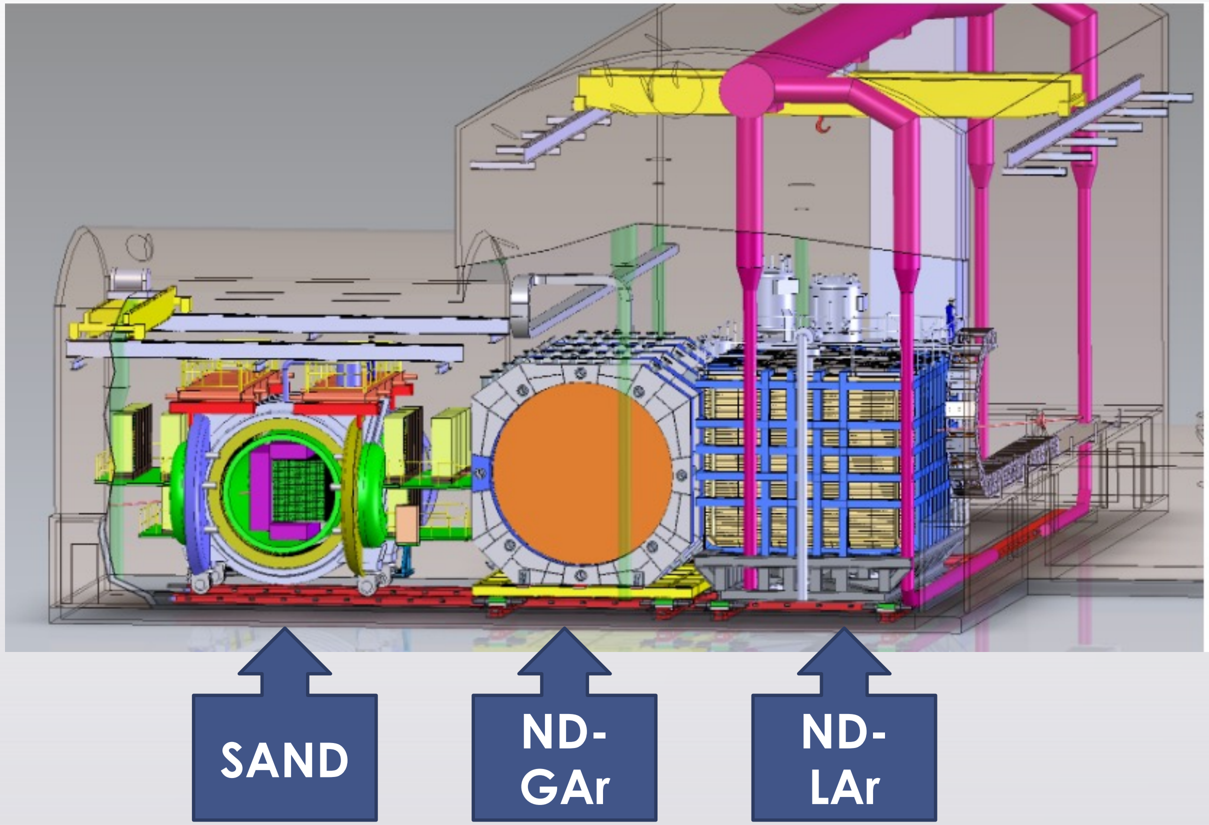




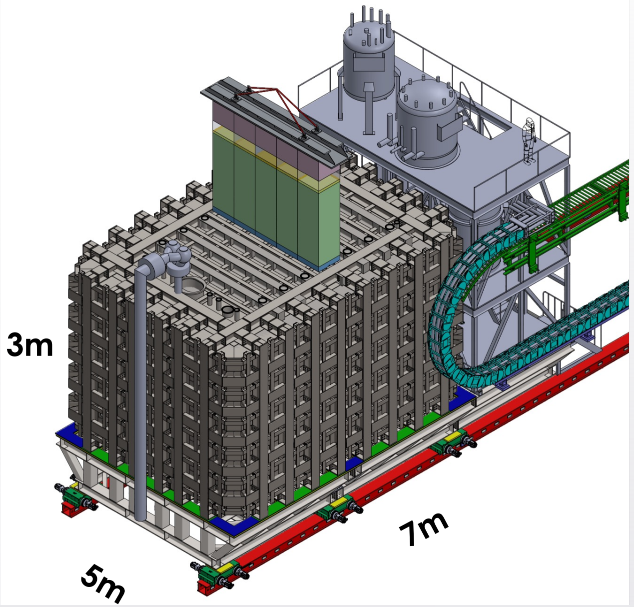
PD: Large size X-Arapuca tile (0.6 x 0.6 m^2)

DUNE – Near Detector

- Allows for high statistic measurements of the initial neutrino flux
- **High Statisitc measurement of neutrino-nucleus** interaction with the same target as the Far Detectors
- Constraints systematic uncertainties due to flux, cross sections, and detector response ➔ fundamental to achieve δ_{CP} sensitivity goals

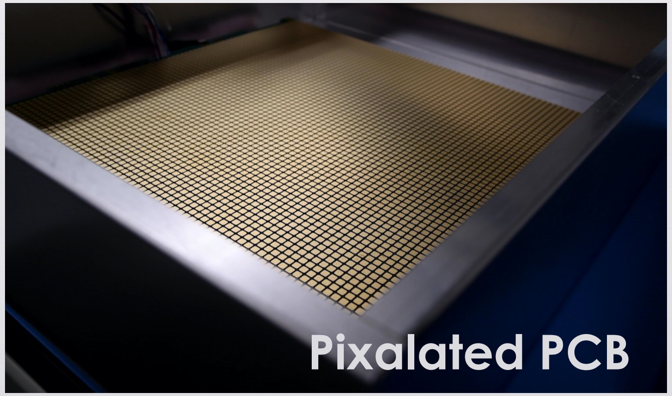


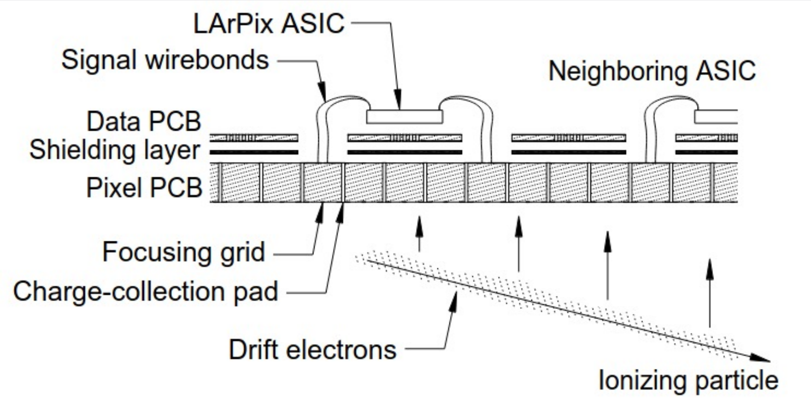
ND-LAr DUNE – Near Detector

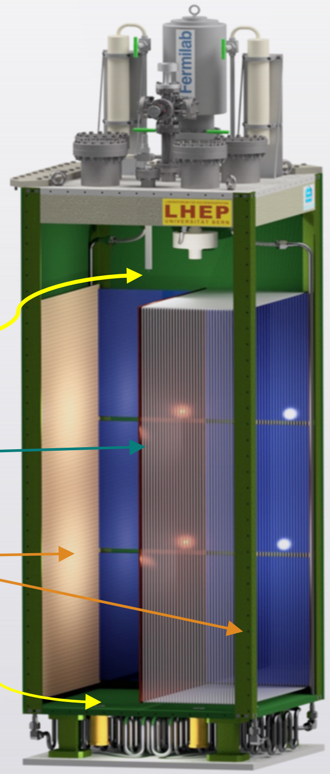


- Modular design: 35 modules with 1m×1m×3 m
- **Two TPCs** per module (50 cm drift)
- Charge: **LArPix pixel readout** for direct-to-3D charge information
- Light: High (~40%) detector coverage with ns-scale timing and cm-scale position

Anja Gauch & **Jan Kunzmann** Talk on Light and charge readout section

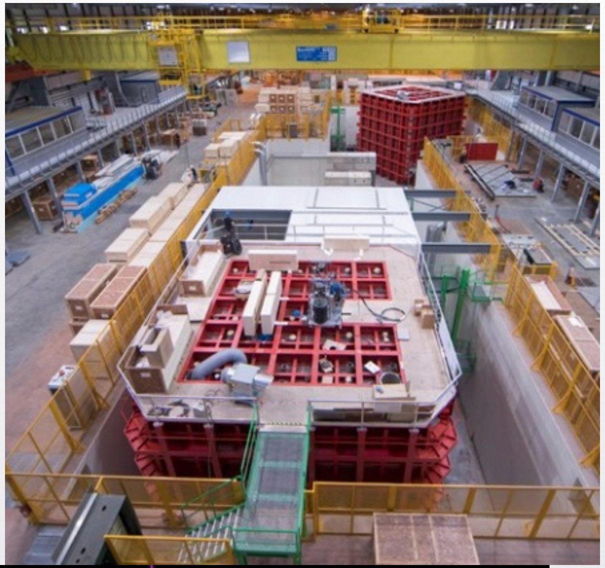


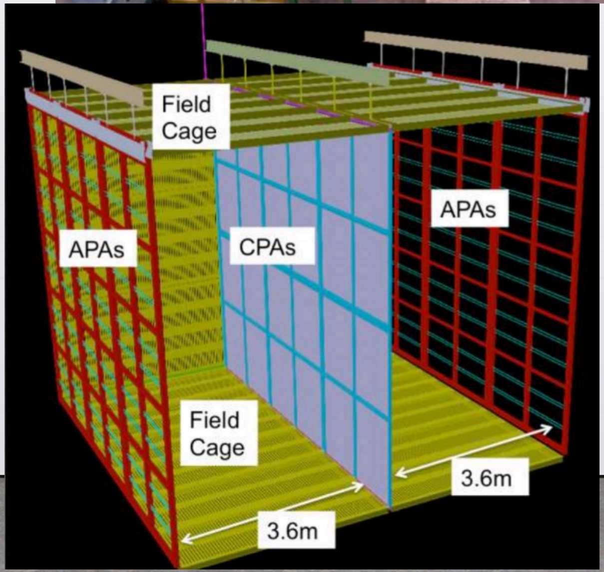


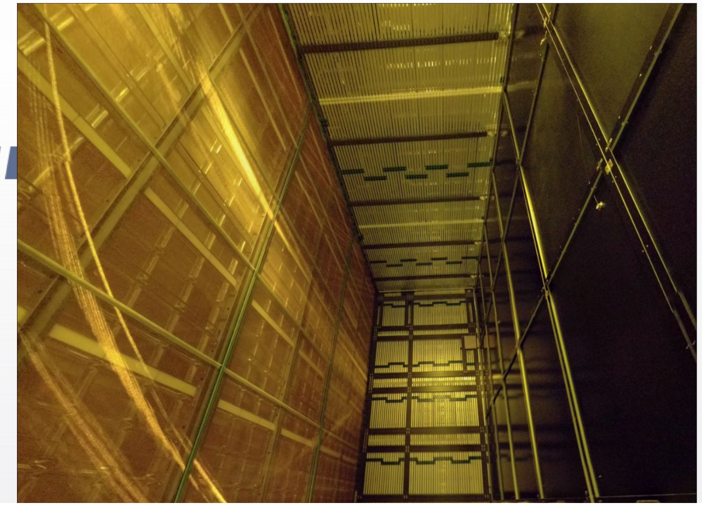


protoDUNE – Single Phase

- Active Volume **419ton LAr**
- 2 Drift Volumes
- Max **drift length 3,6m**
- Run1 – 2018 to 2020 at CERN
- Beam of charged particles: pions,kaons, protons, muons and electrons with momenta in a range 0.3 GeV/c to 7 GeV/c
- **PS system:** ARAPUCA, waveshifting light guides and double shift light guide

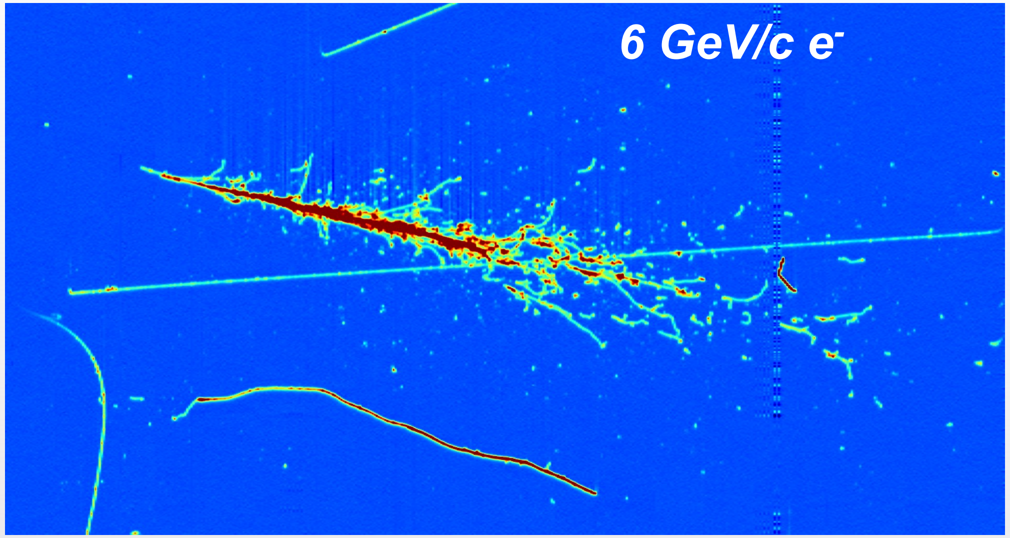


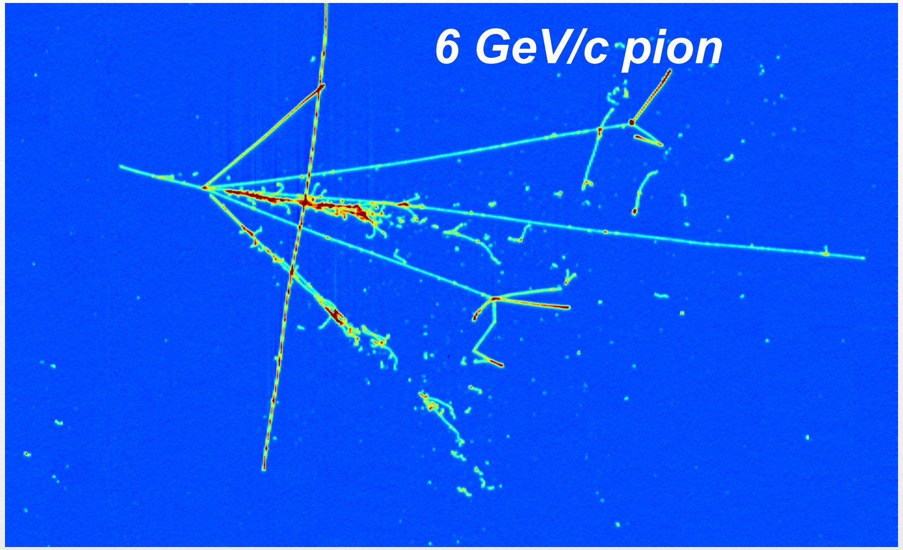


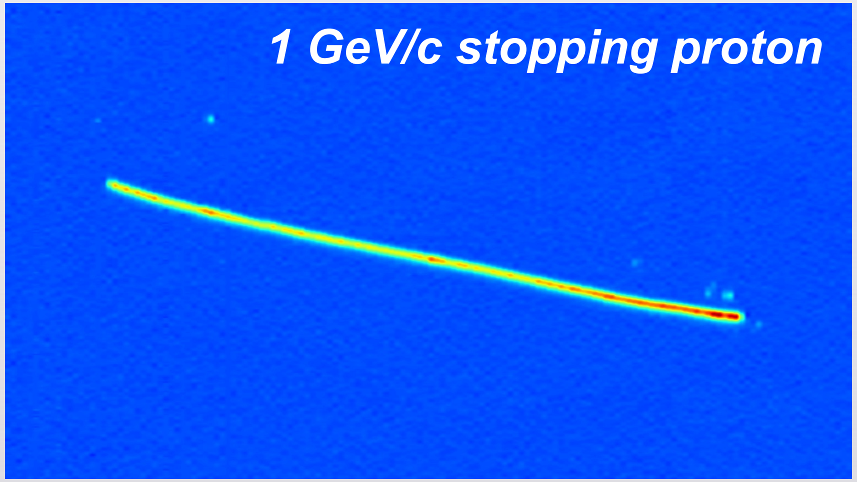


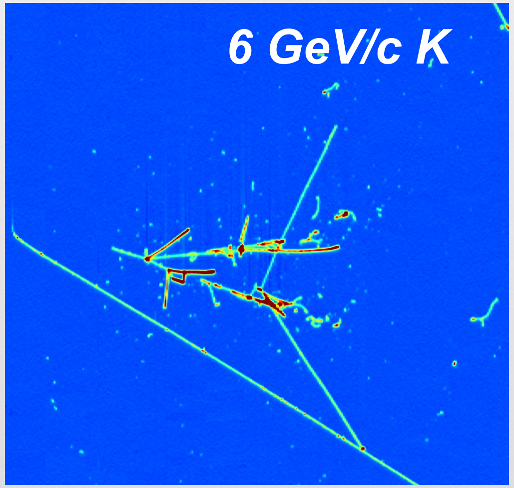
TPC configuration	Anode-Cathode-Anode (2 active volumes)
TPC dimensions (active volumes)	6.086 (h) × 3.597 (w) × 7.045 (l) m^3
(instrumented volumes)	5.984 (h) × 3.597 (w) × 6.944 (l) m^3
Total active volume (nominal, at room T)	2 ×154 m^3
Total instrumented LAr mass (87.65 K)	419 t
Number of TPC wire planes	4 (G, U, V, X)
Number of wires (total)	15360 (instrumented)
G: Grid plane	2 × 2880 (non-instrumented)
U: 1^{st} induction plane	2 × 2400 (instrumented, wrapped)
V: 2^{nd} induction plane	2 × 2400 (instrumented, wrapped)
Z: TPC-side collection plane	2 × 1440 (instrumented)
C: Cryostat-side collection plane	2 × 1440 (instrumented)
Wire orientation (w.r.t. vertical)	G: 0°, U: +35.7°, V: −35.7°, X: 0°
Wire pitch (normal to wire direction)	4.79 mm (G, X); 4.67 mm (U, V)
Wire type	Cu-Be Alloy #25, diam. 150 μm
Gap width between planes	4.75 mm
E-Field (nominal) in drift volume	500 V/cm
Cathode plane voltage	−180 kV
Anode plane bias voltages	G: -665 V, U: -370 V, V: 0 V, X: +820 V
Ground mesh	0 V
Max. drift length (Cathode-to-G-plane distance at 87.65 K)	3572 mm
Drift velocity (nominal field, 87.65 K)	1.59 mm/μs
Max. drift time (nominal field, 87.65 K)	2.25 ms

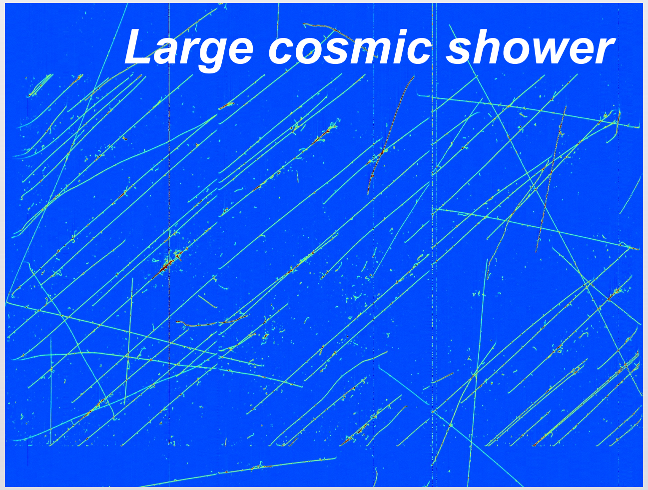
protoDUNE run 1 - events



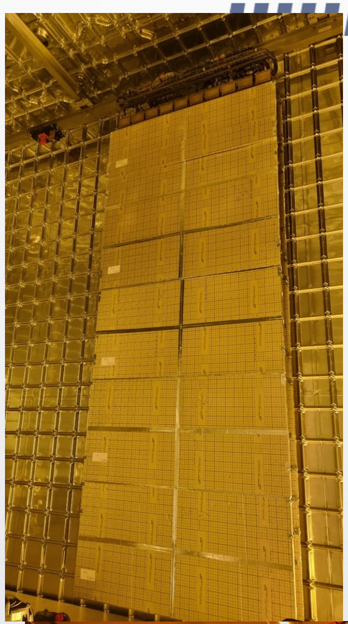




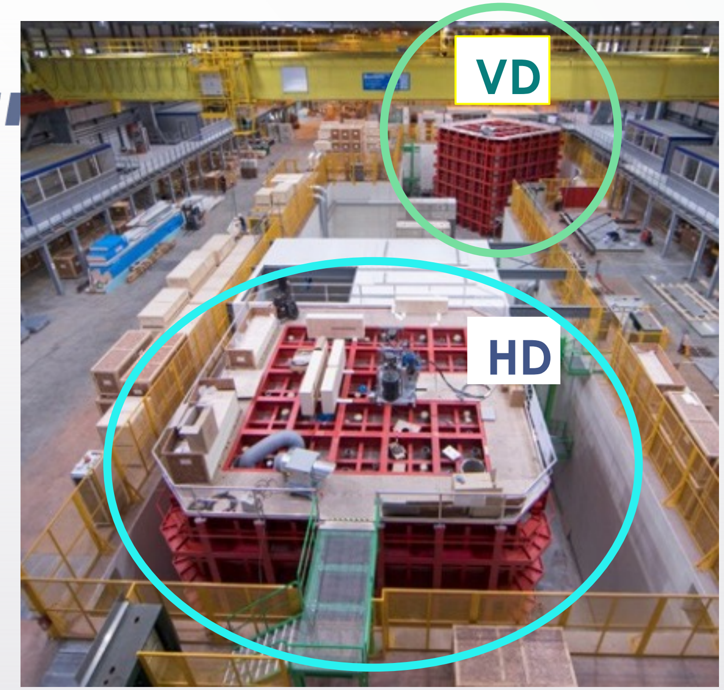




protoDUNE run2 → 2023

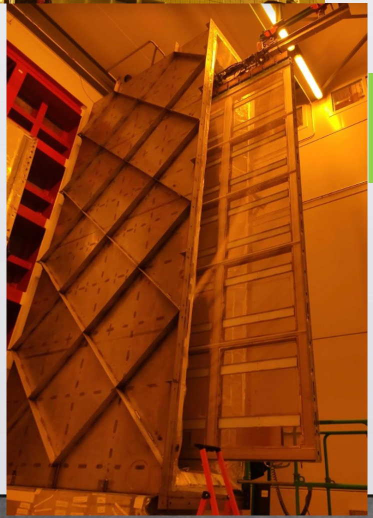


We are preparing the run of protoDUNE to test the final components of Horizontal Drift and Vertical Drift far detector

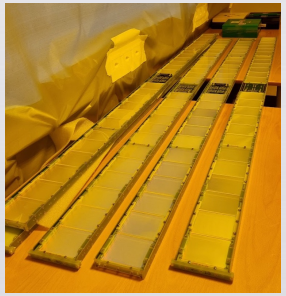


Horizontal Drift

- DUNE APA 2 top and 2 botom
- Photon Detection few different options are being evaluated
  - Two different SiPM type (Hamamatsu and FBK)
  - Two different light guide (ELJEN and GlastoPower)
  - Test of the electronics readout (DAPHNE)



Carmen Palomares talk
Applications section



Carlos Benitez Montiel
poster section

Henrique Souza' talk
Light and charge readout section

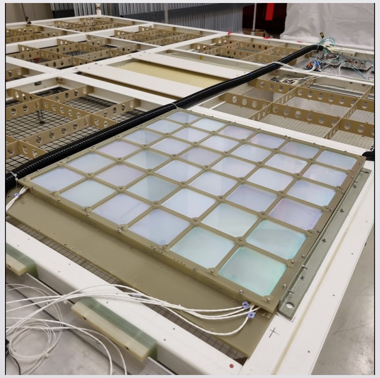
Vertical Drift

PDS

- New X-ARAPUCA modules

8 on the cathode (Power of Fiber)

8 on the membrane



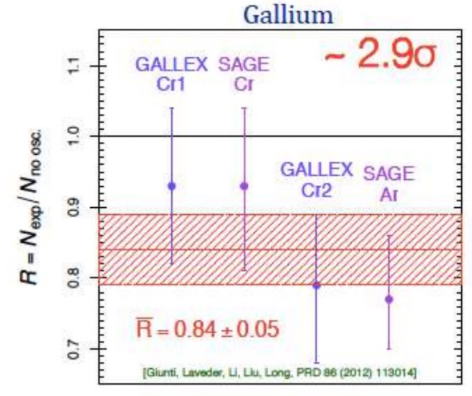
ν oscillation - Short Baseline Anomalies

- **Disappearance** of anti-ν_e in the low energy ν from nuclear reactors;

Reactor Anomaly

- **Disappearance** of ν_e from intense calibration sources in solar ν experiments;

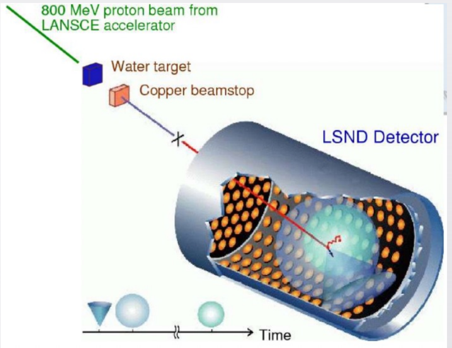
Gallium Anomaly - GALLEX/SAGE



- **Appearance** of ν_e /anti-ν_e in ν_μ /anti-ν_μ beams at particle accelerators.

LSND (Liquid Scintillator Neutrino Detector)

MiniBooNE



No one of these anomalies can be explained through 3 neutrino flavors models

A nonstandard **"sterile" neutrino** state(s) driving oscillations at $\Delta m^2_{new} \approx 1$ eV^2 and small $\sin^2(2\theta_{new})$, could be an answer

ν oscillation - Short Baseline Anomalies

- LSND

Low energy **anti-ν_μ** beam from a decay-at-rest pion beam (Los Alamos)

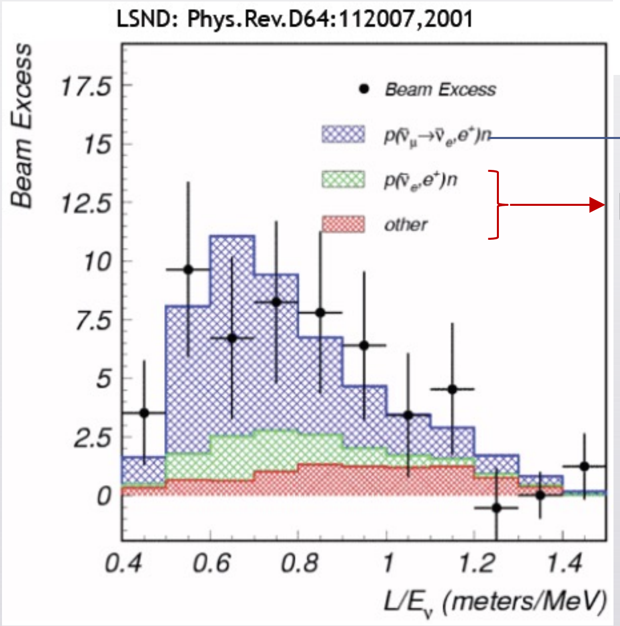
Intense proton beam

$$p + X \to \pi^+ + X'$$
$$\hookrightarrow \mu^+ \nu_\mu \text{ (DAR)}$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

Baseline 30m
E=(20-50)MeV
L/E ~1m/MeV
167ton of Liq Scint

Observed 87.9 ± 22.4 ± 6.0 events above background
Oscillation Probability: 0.26%

Consistent with a Δm^2 on the order of 1 eV^2 (not consistent with 3 flavor picture)



Signal

Bkg

Detected an excess in the appearance of **anti-ν_e**, corresponding to 3.8 σ evidence for
anti-ν_μ → anti-ν_e oscillation occurring at $\Delta m^2 \simeq 1$ eV^2

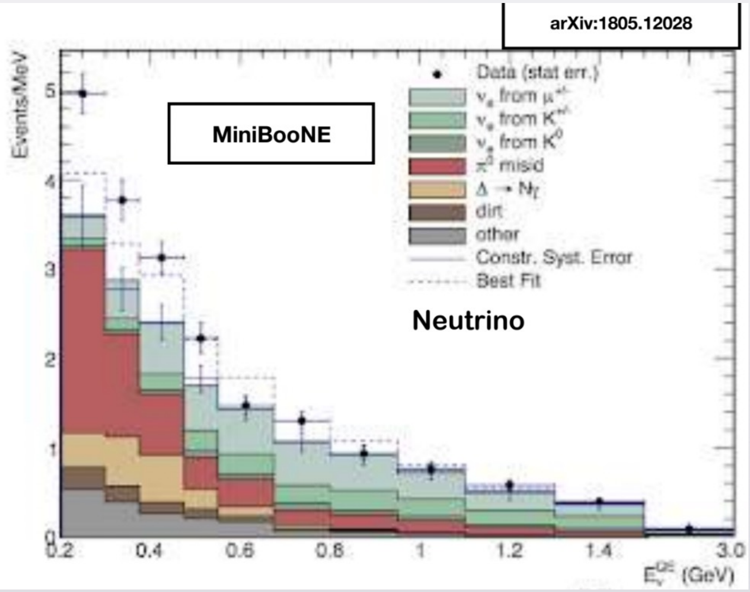
- MiniBOONE

Booster Neutrino Beam - BNB (FERMILAB)

Baseline 540m
E=(0-2)GeV
L/E ~1m/MeV
800ton of Mineral Oil

Intense proton beam

$$p + X \to \pi^+, \pi^-, \cdots + X'$$
$$\hookrightarrow \mu^+ \nu_\mu$$



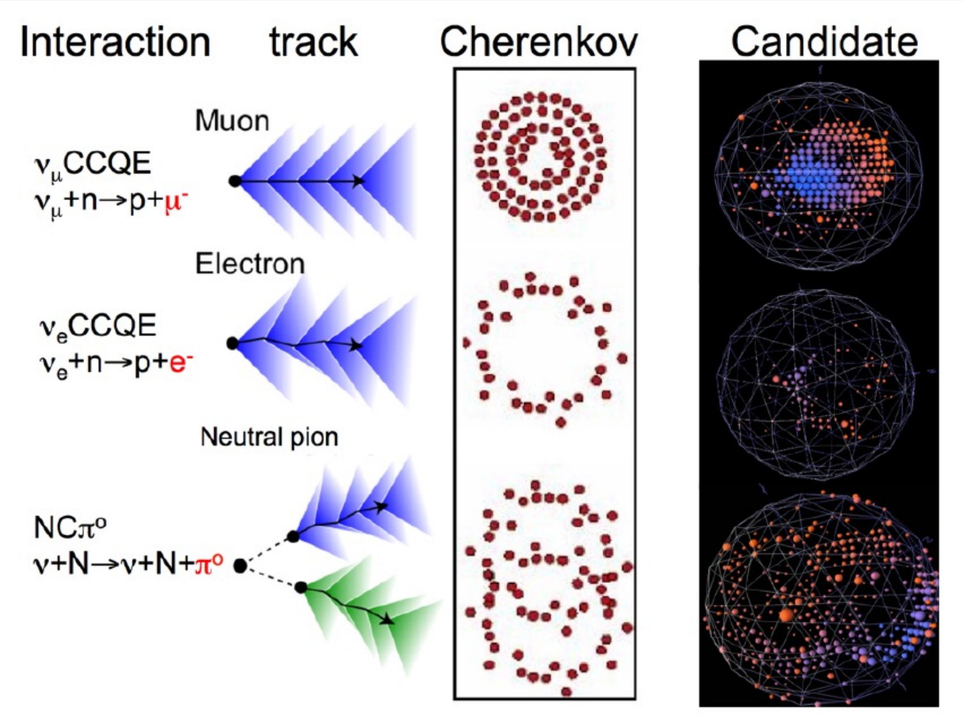
$\nu_\mu \to \nu_e$ 4.5 σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ 2.8 σ

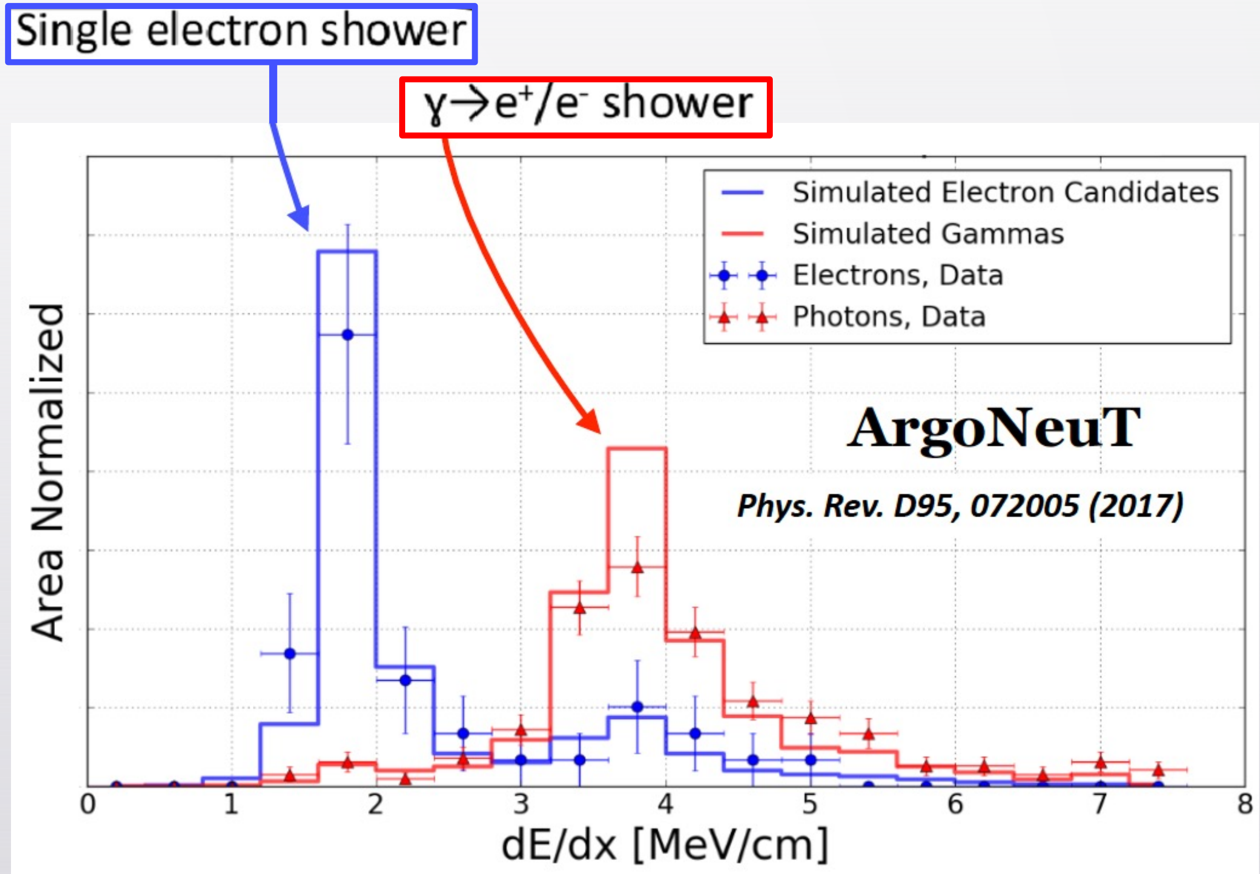
The significance of the combined LSND and MiniBooNE excesses is 6.0 σ

LArTPC Advantages also in short baseline experiments

At MiniBooNE low energy, γ was the biggest background, which was hard to **distinguish** from **e**$^-$ in Cherenkov detector



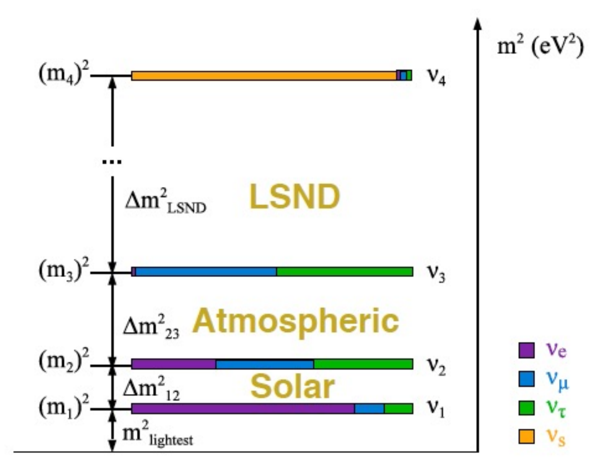
Capability in discriminating electron and gamma showers



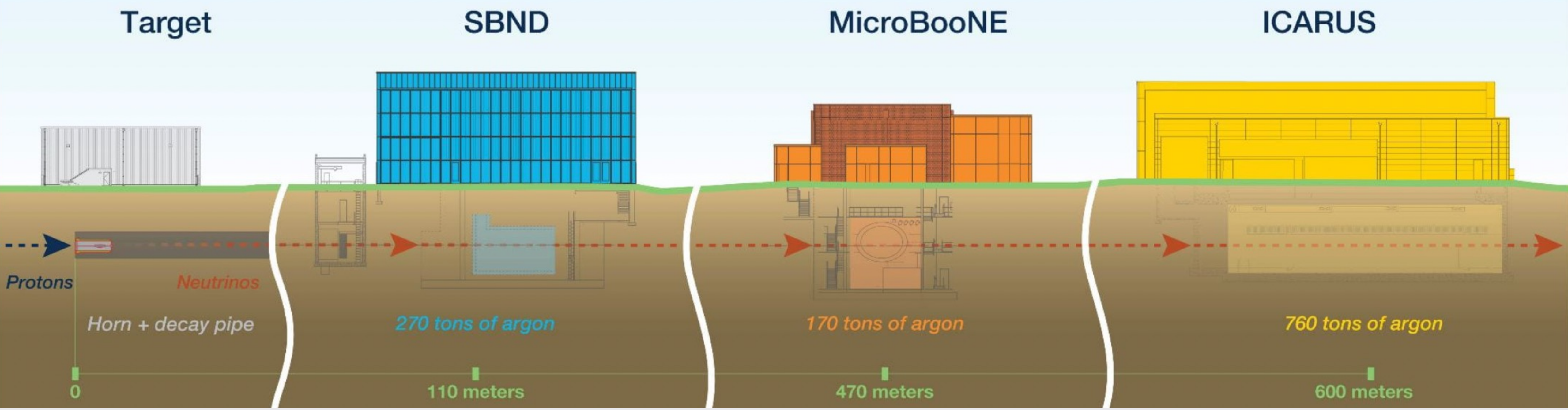
Short Baseline Neutrino Program Science

The SBN program at Fermilab it is using LAr-TPC detectors for:

- **Verify** the "low-energy excess" anomaly
  - Investigate the excess of ν_ε observed by MiniBooNE experiments, using LArTPC
- **Search for** Sterile Neutrino
  - Discover or Exclusion of 1 eV-scale sterile neutrino mass region suggested by LSND and MiniBooNE results
- **Measurements** of neutrino–argon cross section
  - Millions of ν_μ and thousands of ν_e from two neutrino beams
- **Beyond** Standard Model Physics
- **R&D** for DUNE
  - Test new technologies that can be used in long baseline LArTPC

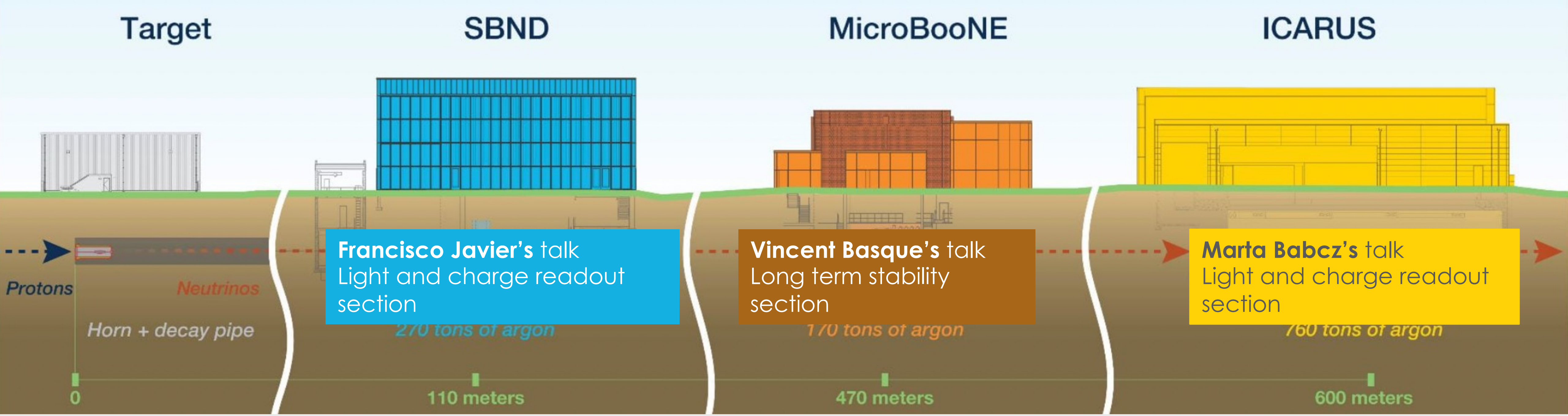


Short-Baseline Neutrino Program at Fermilab



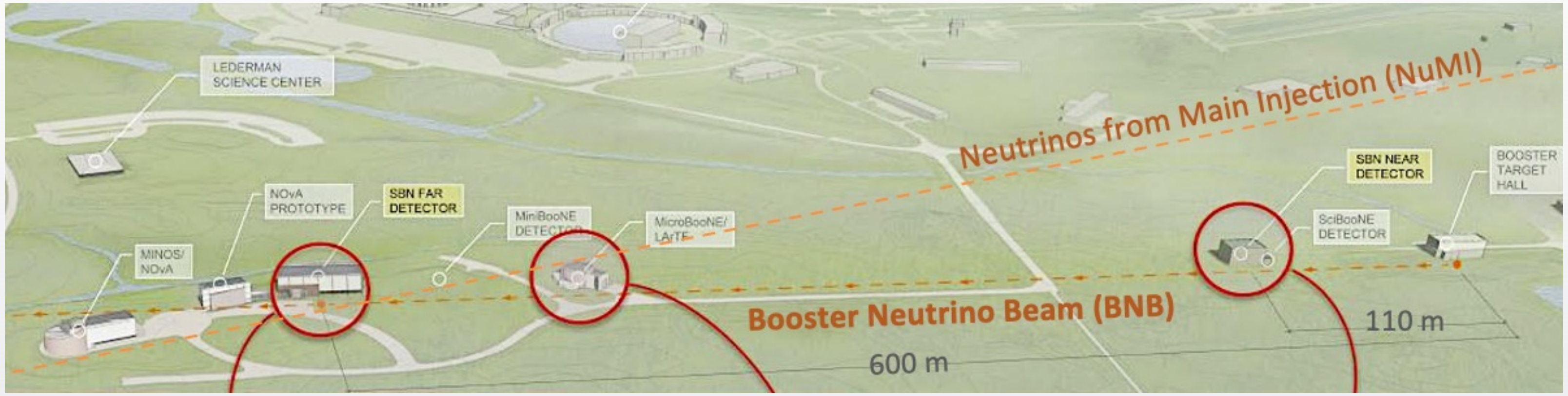
- Three Liquid Argon TPC detector along of BNB to study short range neutrino oscillation
- eV-scale sterile neutrinos
- Neutrino argon interactions at GeV energy scale
- Search for rare physics process in the neutrino sector

Short-Baseline Neutrino Program at Fermilab



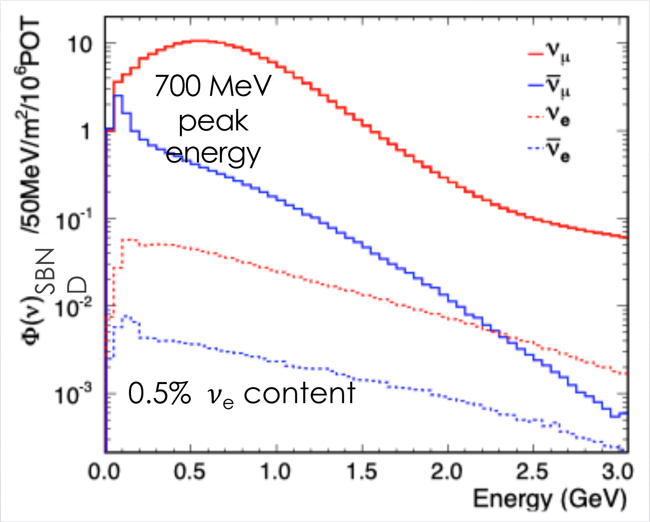
- Three Liquid Argon TPC detector along of BNB to study short range neutrino oscillation
- eV-scale sterile neutrinos
- Neutrino argon interactions at GeV energy scale
- Search for rare physics process in the neutrino sector

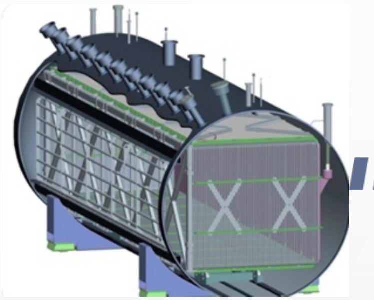
Booster Neutrino Beam (BNB)



ICARUS MIicroBooNE SBND

- **8 GeV** protons from Booster
  - Up to 5 Hz and 5 x 10^{12} protons per pulse, 1.6 μs spill
- SBN Detector interaction rates
  - SBND: 0.25 Hz ν, 0.03 Hz cosmic
  - ICARUS: 0.03 Hz ν, 0.14 Hz cosmic
    + NuMI: 0.014 Hz ν, 0.08 Hz cosmic)

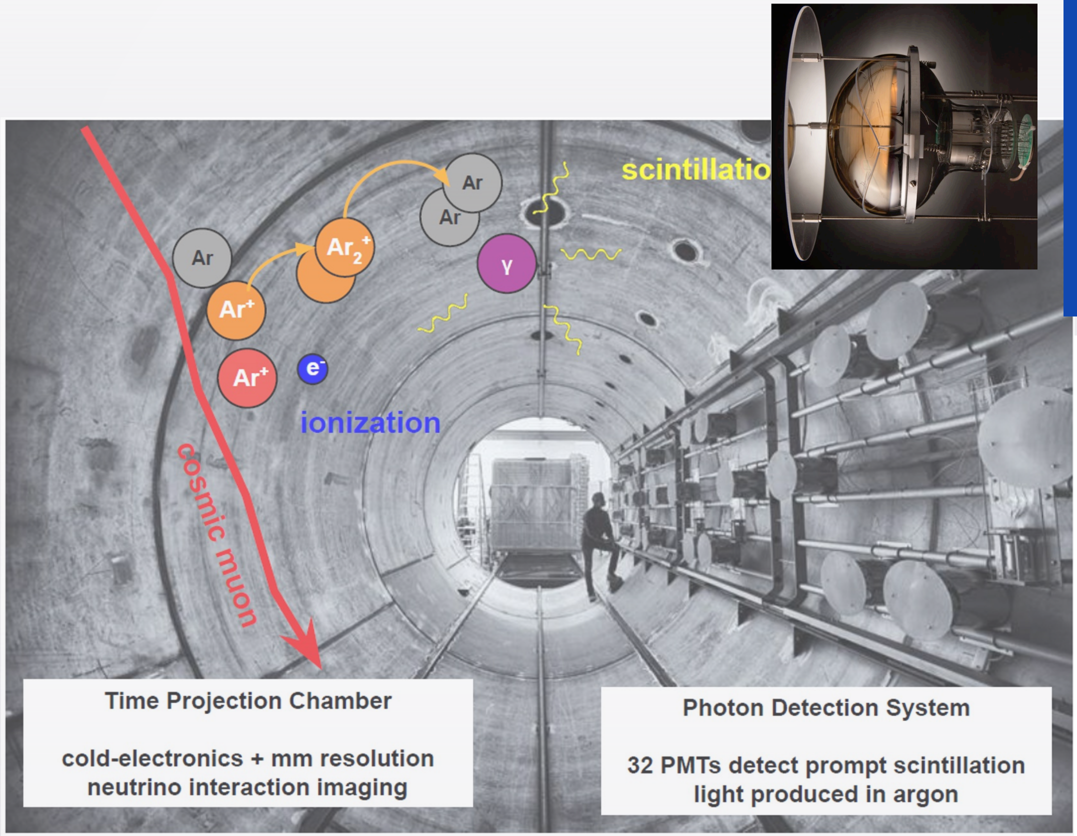


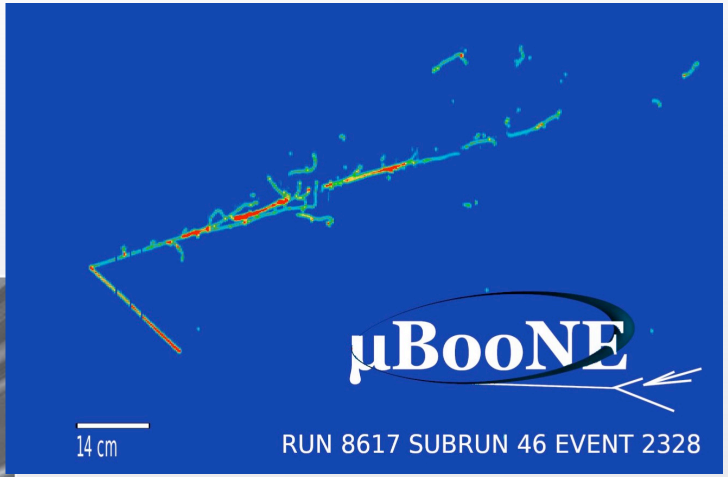


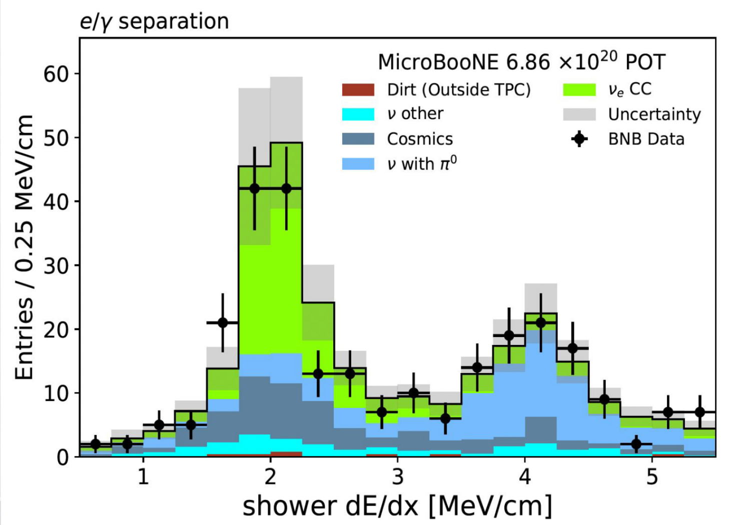
MicroBooNE

Understand the nature of the **MiniBooNE** “low energy” excess anomaly, using the **same beam**.

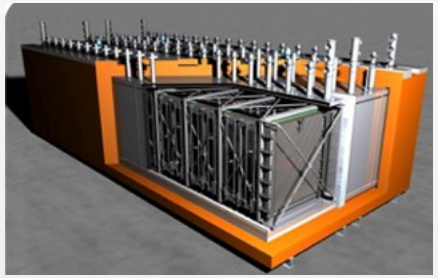
- LArTPC of 170 ton (**87ton active**)
- **470m** from target
- **1 TPC** with **2.5m drift**
- **32 8”PMT** on acrylic support TPB coated
- Top and side **CRT**
- The experiment **first started** collecting neutrino data in **October 2015**
- Longest running large scale LArTPC to date
- About **500k ν interactions** collected







ICARUS @ Fermilab



- 760 ton of LArTPC (**460ton active**)
- 600m from target
- 4 TPC with 1.5m drift length
- **360** 8''PMT TPB coated

Aug. 2020: start of TPC/PMT operation

Dec. 2021: CRT installation complete

June 2022: overburden complete

Credits R.Wilson

*Steady data taking **with BNB, NuMI beams** since March 2021, in parallel with commissioning activities. Cosmics, ν_μ, and ν_e samples collected for trigger/calibration/reconstruction studies.*

Data taking for Physics with BNB and NuMI beams 9 June 2022

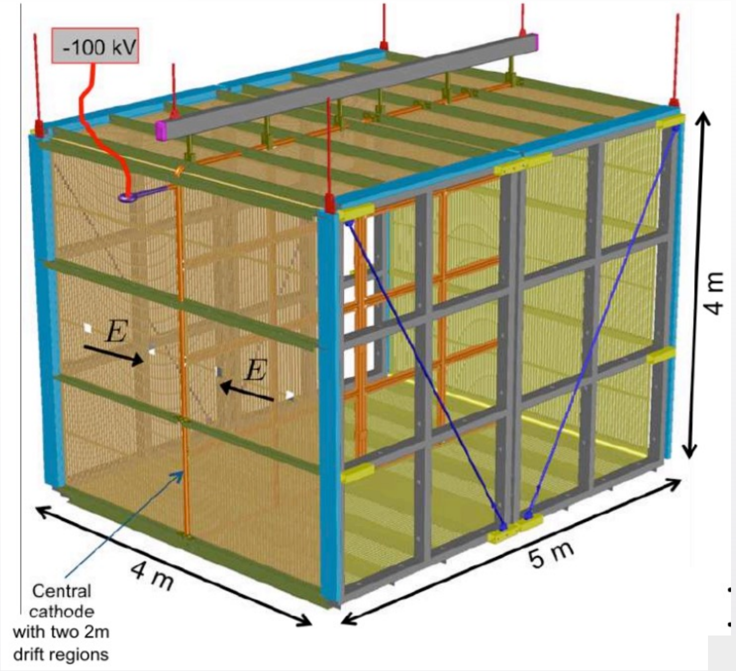
SBND

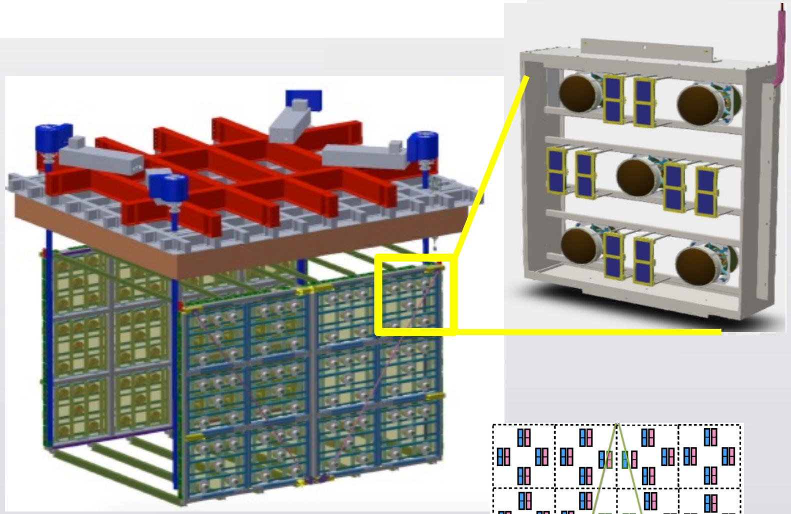
- **112-ton active** LAr volume
- **2 TPC** - 2m drift length - 1,28ms drift time at E = 500V/cm
- Cathode Plane Assembles (**CPA**) – **middle**
- Anode Plane Assembles (**APA**) – at the ends
- APA has 3 wire planes with 3mm pitch and spacing: vertical (y) and ± 60° (U&V)
- Photon Detection system – 24 PD BOX

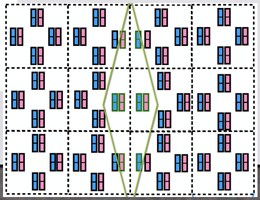
120 8”PMTs (96 coated with TPB)

192 X-ARAPUCA modules (VIS and VUV)

TPB coated reflector foils on the cathode

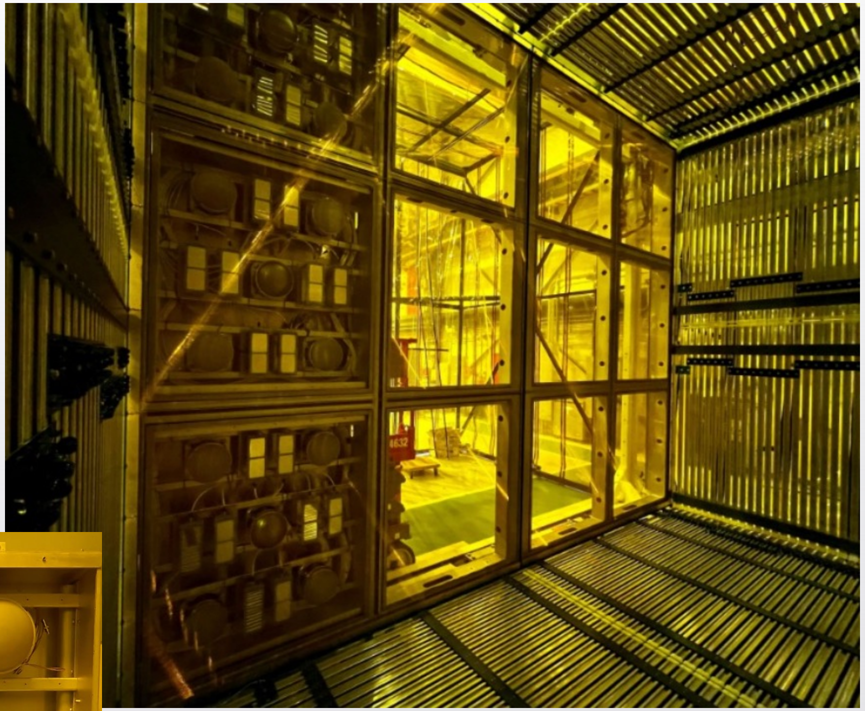




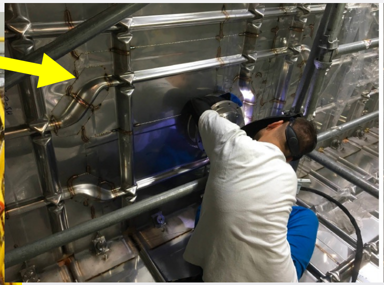


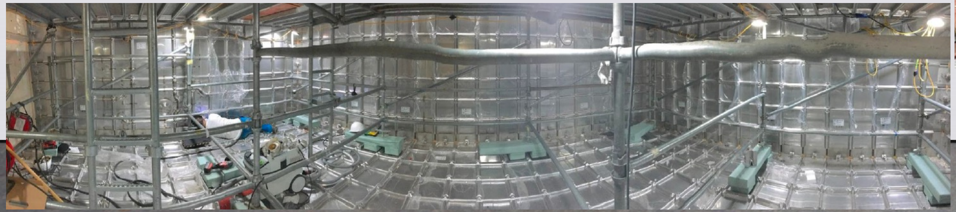
SBND

TPC Assembly
PDS box assembly, cable routing & termination **completed**
Planning the detector move from DAB to SBND



Cryostat installation phase 3 is **completed**
all primary insulation panels and steel membrane panels installed & welded





Pictures: A. Schukraft

R&D from SBND → DUNE

SBND gave a huge contribution with R&D for **DUNE** far detector, mainly for the **Photon Detection System**.

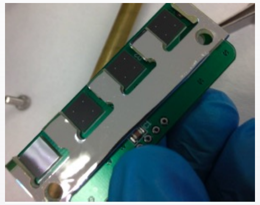
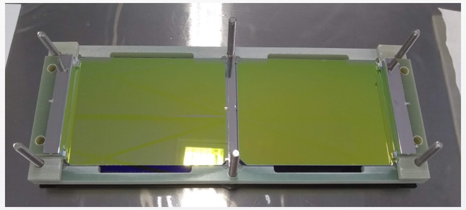
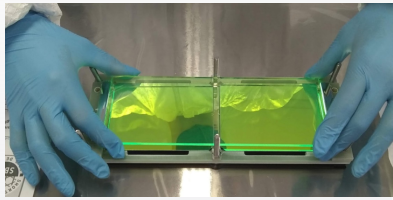
- Will be the first experiment to detect neutrinos using the ARAPUCA device
- Optimization of the WLS evaporation on dichroic filters
- A fraction of the X-ARAPUCAs has the same Hamamatsu SiPMs we are using in protoDUNE X-ARAPUCA modules
- It is the only detector to have X-ARAPUCA sensitive to visible light
- The readout electronics (DAPHNE) represented the starting point for DUNE PD readout electronics

R&D from SBND → DUNE

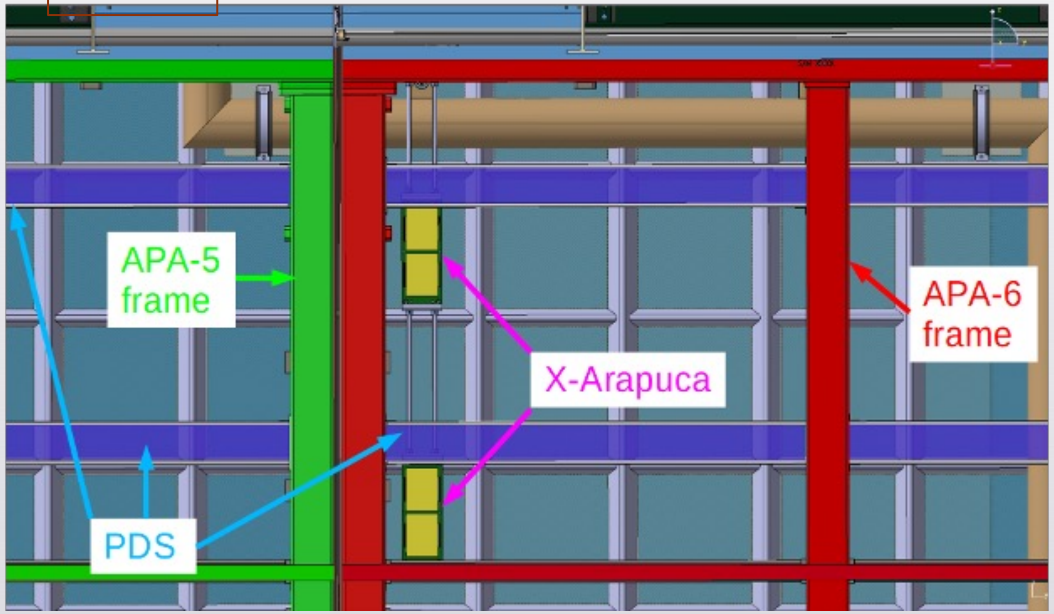
SBND X-ARAPUCA modules are used in **DUNE** for:

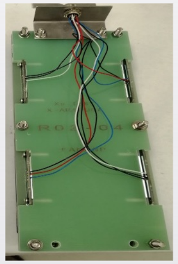
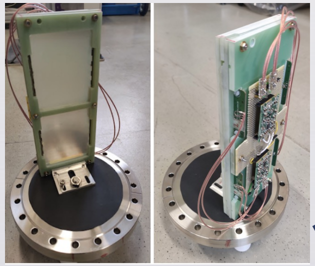
- Measuring the detection eficiency
- Testing the long term stability
- Performing the measurement with Xe doping LAr at protoDUNE SP

Dedicated paper in preparation

CERN

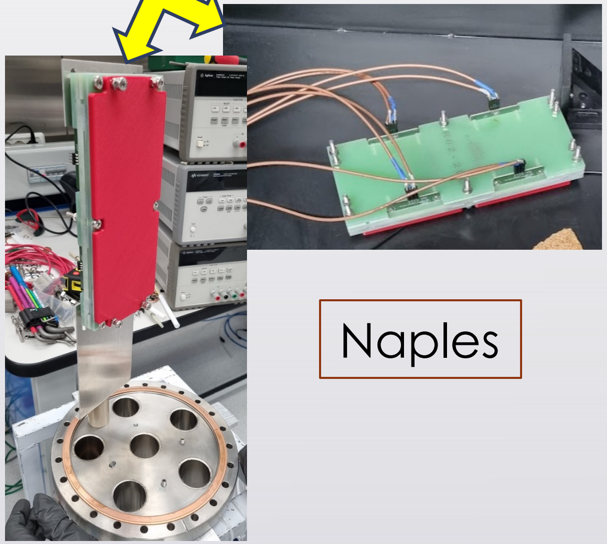



MIB

https://arxiv.org/abs/2104.07548

Francesco Di Capua's talk
Long term stability section

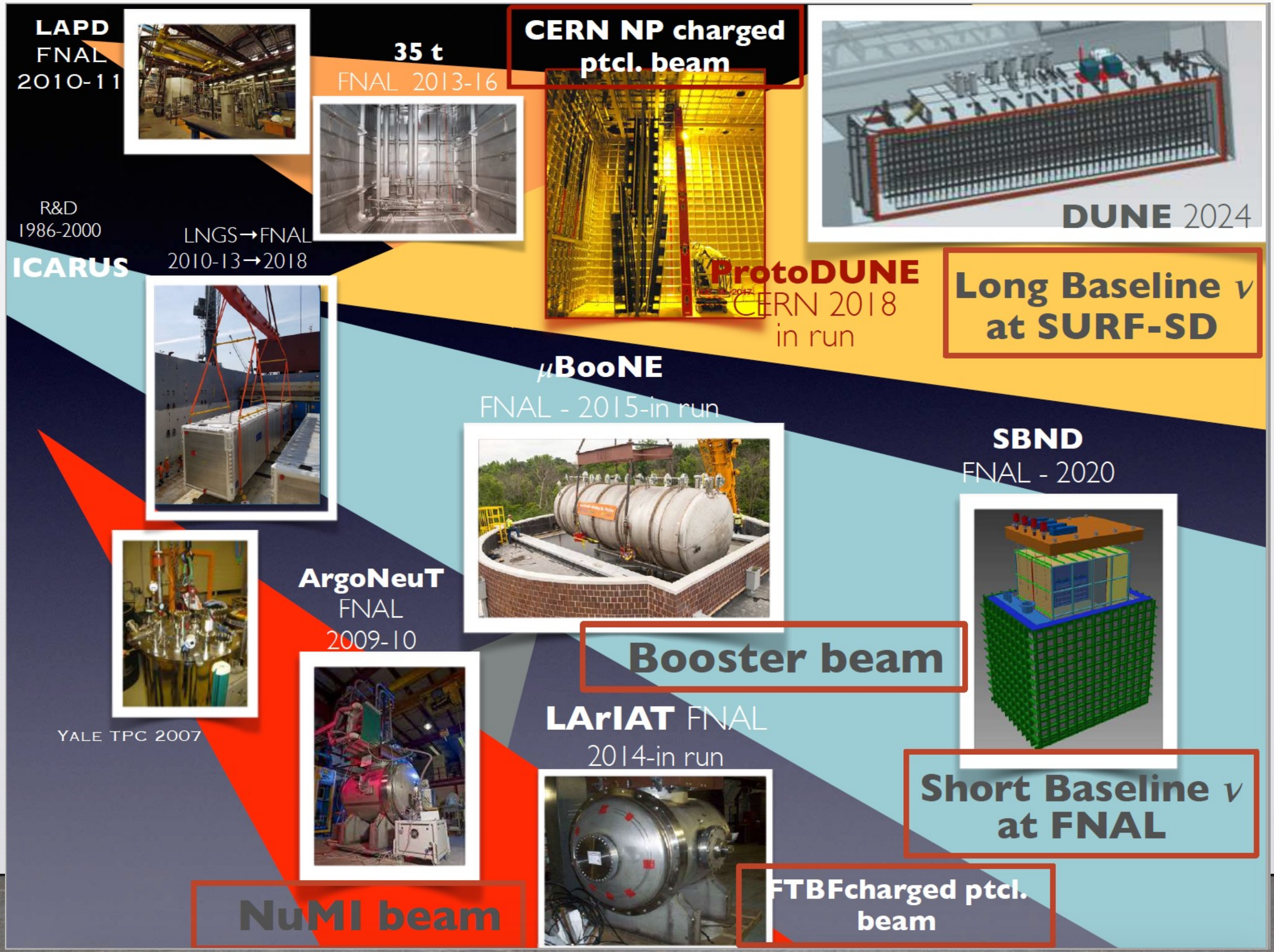


Naples

Dziękuję

Backup

LAr-TPC at Fermilab



Slide
O. Palamara

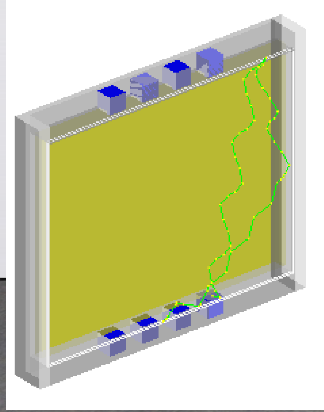
Fermilab Neutrino Experiments

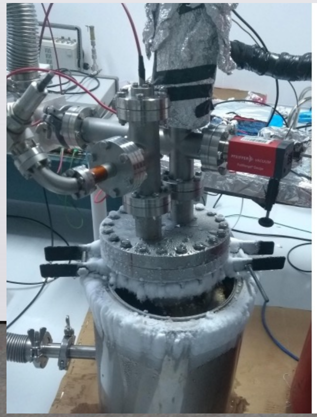
Experiment	**Goal**	**Techniques**
ArgoNeut	R&D	LArTPC
MiniBooNE	oscillation	Scintillation
LArIAT	R&D	LArTPC
MicroBoone	Anomaly	LArTPC
MINERvA	ν reaction with 5 different nuclei	Plastic scintillators
MINOS	ν oscillations	Plastic scintillators
NOvA	$\nu_\mu \rightarrow \nu_e$	Plastic filled with liquid scintillator
DUNE	CP Violation – SN - p+ decay	LArTPC
SBND	Anomaly	LArTPC
ICARUS	Anomaly	LArTPC

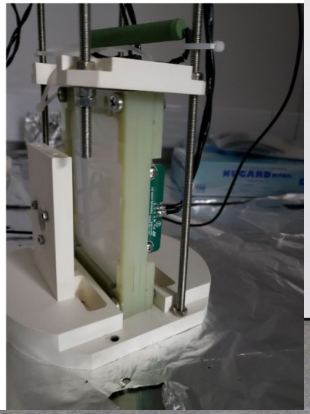
X-ARAPUCA →Efficiency Expected

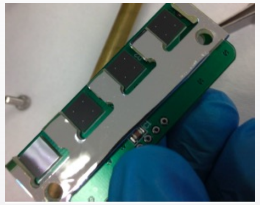
- UNICAMP- Half SBND module was used for measurement of its efficiency in LAr.
- https://arxiv.org/abs/2106.04505

Eljen Bars	→	$2.2 \pm 0.5\%$



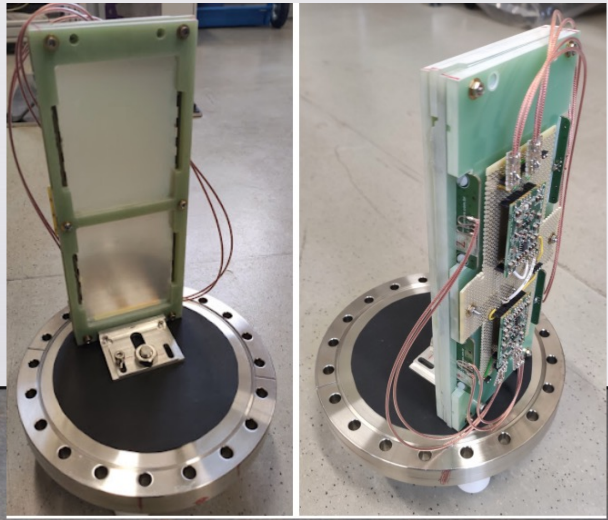




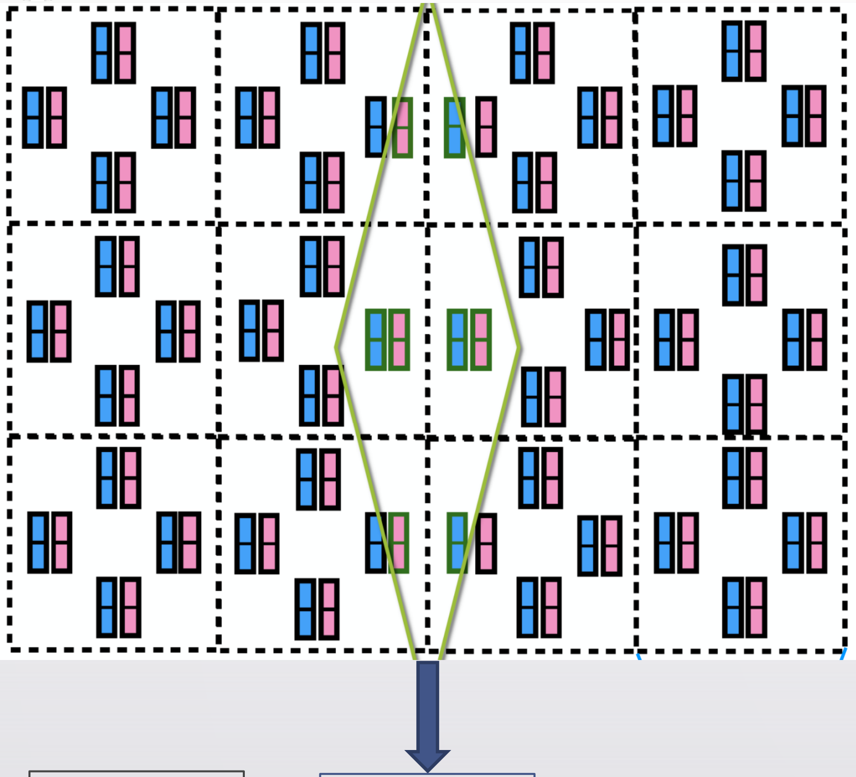


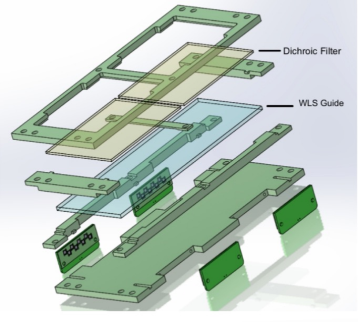
- Milano Biccoca group working on X-ARAPUCA for DUNE experiment.
- The Unicamp group provided the X-ARAPUCA module which is an SBND one
- https://arxiv.org/abs/2104.07548

Eljen Bars	→	$(1.8 \pm 0.1)\%$
Glass to Power	→	$(2.9 \pm 0.1)\%$



X-ARAPUCA System Overview





192 modules

- **176 DAPHNE** readout (SensL SiPM)
  - 88 VUV light (Even)
    - 400nm cutoff pTP coating EJ286
  - 88 Visible light (Odd)
    - 450nm cutoff EJ280
- **16 APSAIA** readout (Hamamatsu SiPM)
  - 8 VUV light (Even)
    - 400nm cutoff pTP coating Glass to Power Blu
  - 8 Visible light (Odd)
    - 450nm cutoff Glass to Power Green

DAPHNE System Modules

Labels: **020-195**

APSAIA System Module

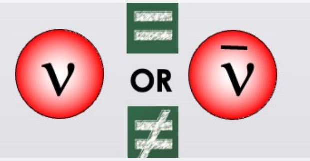
Labels: **001-016**

Current Challenges in Neutrino Physics

Even if neutrinos are fundamental particles which have been detected 70 years ago there **are still several open questions related to their properties**:

- **Nature** → Are neutrinos their own antiparticle ?

  What are the masses of neutrino?



} β and ββ decay experiments { Grzegorz Zuzel. (talk)

- **Oscillation** → Do neutrino and ant… …illate differently? (CP violation)

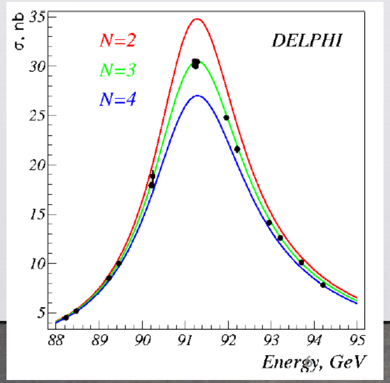
  How ar… …ed ? (mass hierarchy)

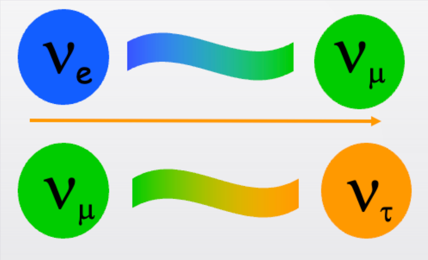
  Are there other … interactions ?

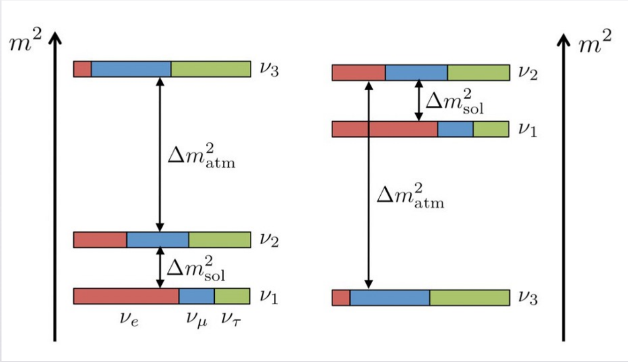
Long-Baseline

Short-Baseline

LEP →three flavours of neutrinos (ν_e, ν_μ, ν_τ)



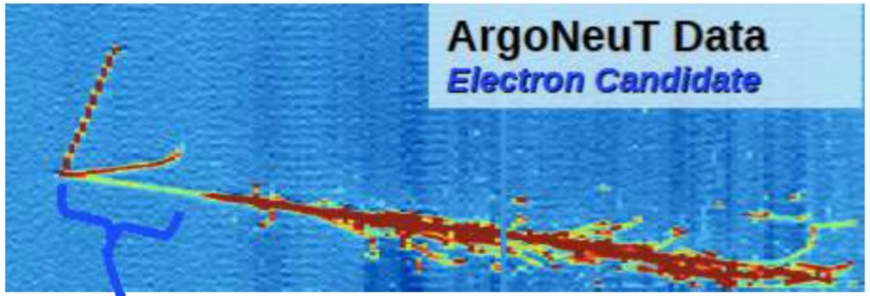


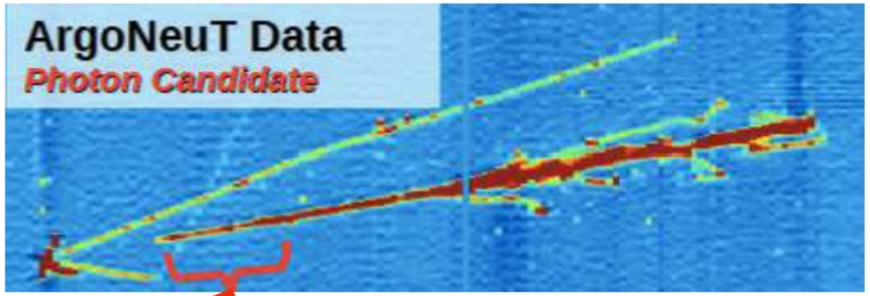


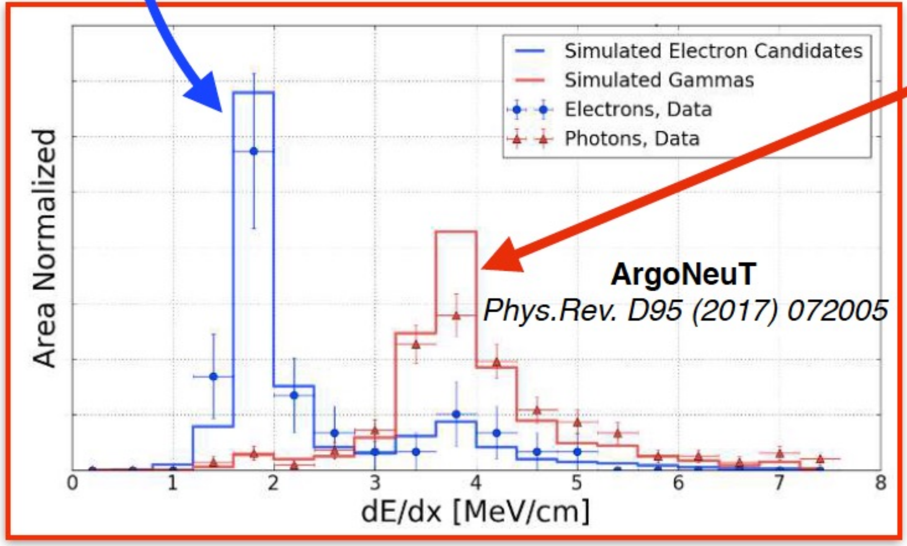
Why LAr ?

- ***Massive detector*** -> LAr is a dense medium (1.4 g/cm^3)
- ***Imaging detector*** -> allows for a 3 dimensional reconstruction of the interaction with extremely high resolution (below 1 mm)
- ***Precise calorimetric reconstruction*** -> allows to measure the energy of the incoming particle and of all the charged particles produced by its interaction with Argon.
- ***Particle discrimination*** -> allows to identify the type of the charged particles that are detected

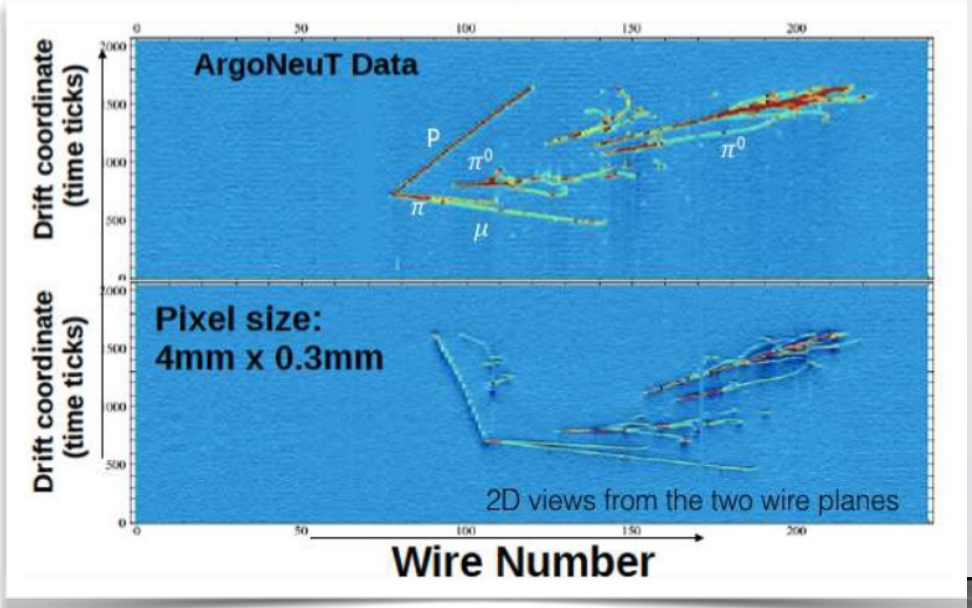
Electron-γ separation in LAr







Analyzing topology and dE/dx

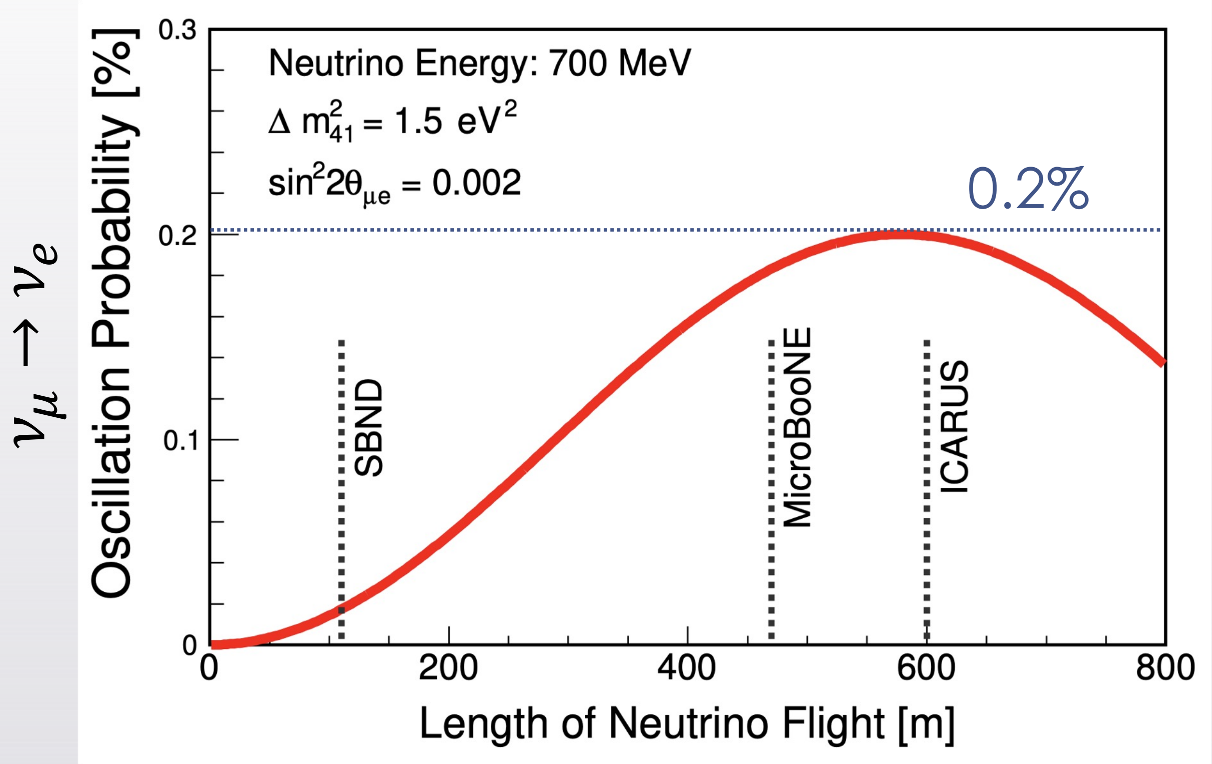


LAr TPC offers incredible fine tracking and calorimetry, along with electron/photon separation

O.Palamara Slide

SBN Oscillation Sensitivity

Example oscillation at BNB peak energy



P. Machado et al., arXiv:1903.04608V11
https://doi.org/10.1146/annurev-nucl-101917-020949

- Multiple detectors using the same technology enables sensitive searches for ν_e appearance and ν_μ disappearance within the same experiment