Neutrino experiments with LAr detectors

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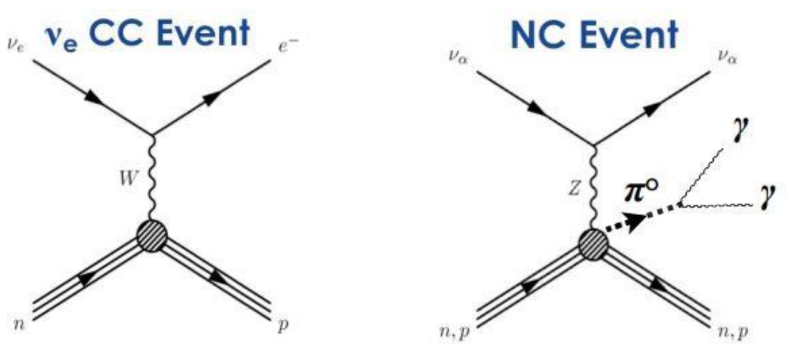
Evolution of LAr-TPC detectors

- Cherenkov detectors in water/ice and liquid scintillators have been main technology so far for neutrino and rare event physics. Unfortunately these detectors do not permit to identify unambiguously each ionizing track.

- As an alternative, the Liquid Argon Imaging technology (LAr-TPC), effectively an electronic bubble-chamber, was originally proposed by C. Rubbia in 1977 [CERN-EP/77-08]

LArTPCs for neutrinos

- Liquid argon provides a dense target for neutrino interactions, and extensive ionization/ scintillation signal for detection.
- Particle identification comes primarily from dE/dx (energy deposited) along track.
  - Wire spacing of a few millimeters combined with digital sampling provides fine-grained resolution
  - **Photons (2x mip dE/dx) and electrons (1x mip dE/dx) can be cleanly separated**
  - Topological cuts can further improve photon/electron separation
  - **Very long e-mobility**
- Ideal for ν_e appearance experiment
  - Excellent signal (ν_eCC) efficiency and background (π_0 NC) rejection

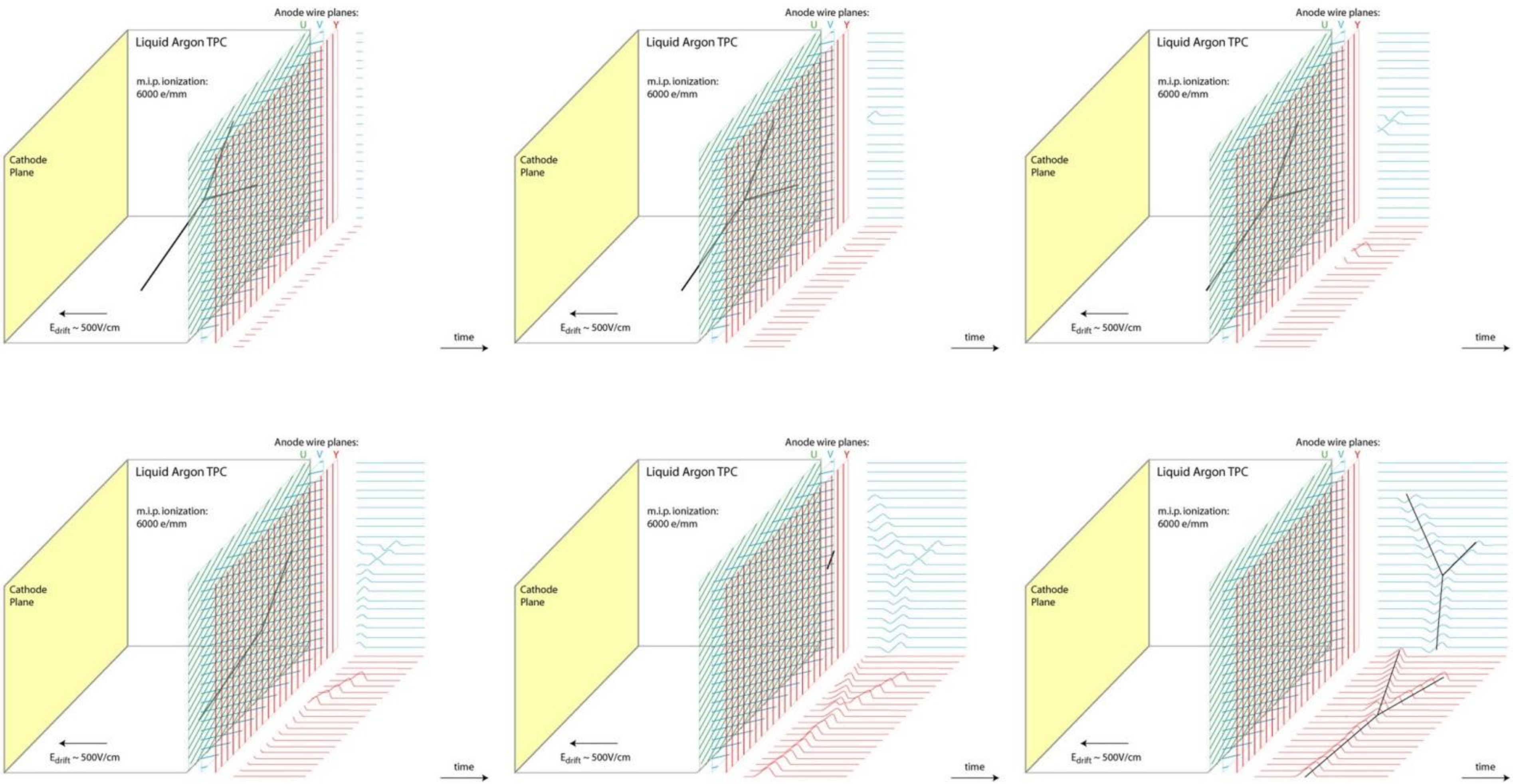


- Clean & nice, bubble-chamber like events!

LArTPC principles of detection technique

- The principle of LArTPC is quite simple:

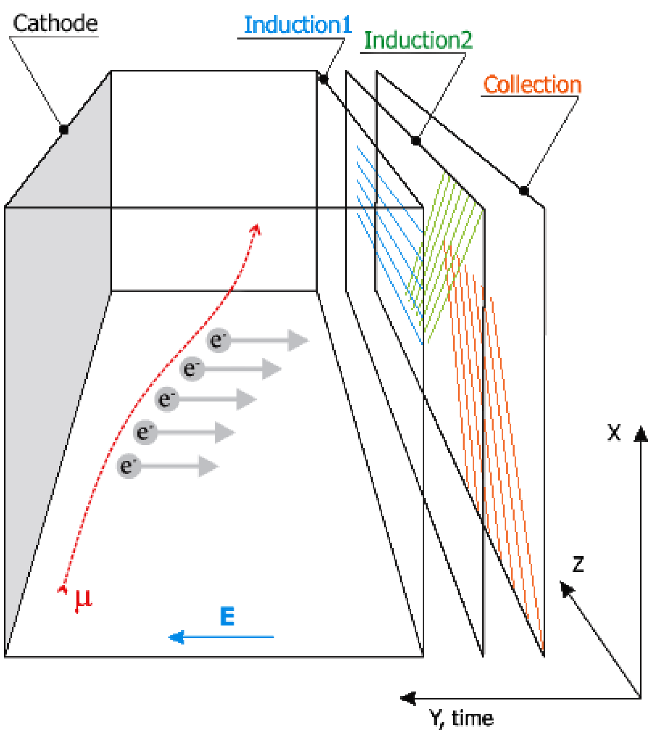
  Charged particles traversing the detector will ionize the LAr and the ionization electrons can be drifted by an applied electric field. The electrons are then collected on wire planes, which offer a 3D view of the interaction. Because of the great image resolution, the good particle ID and calorimetric reconstruction

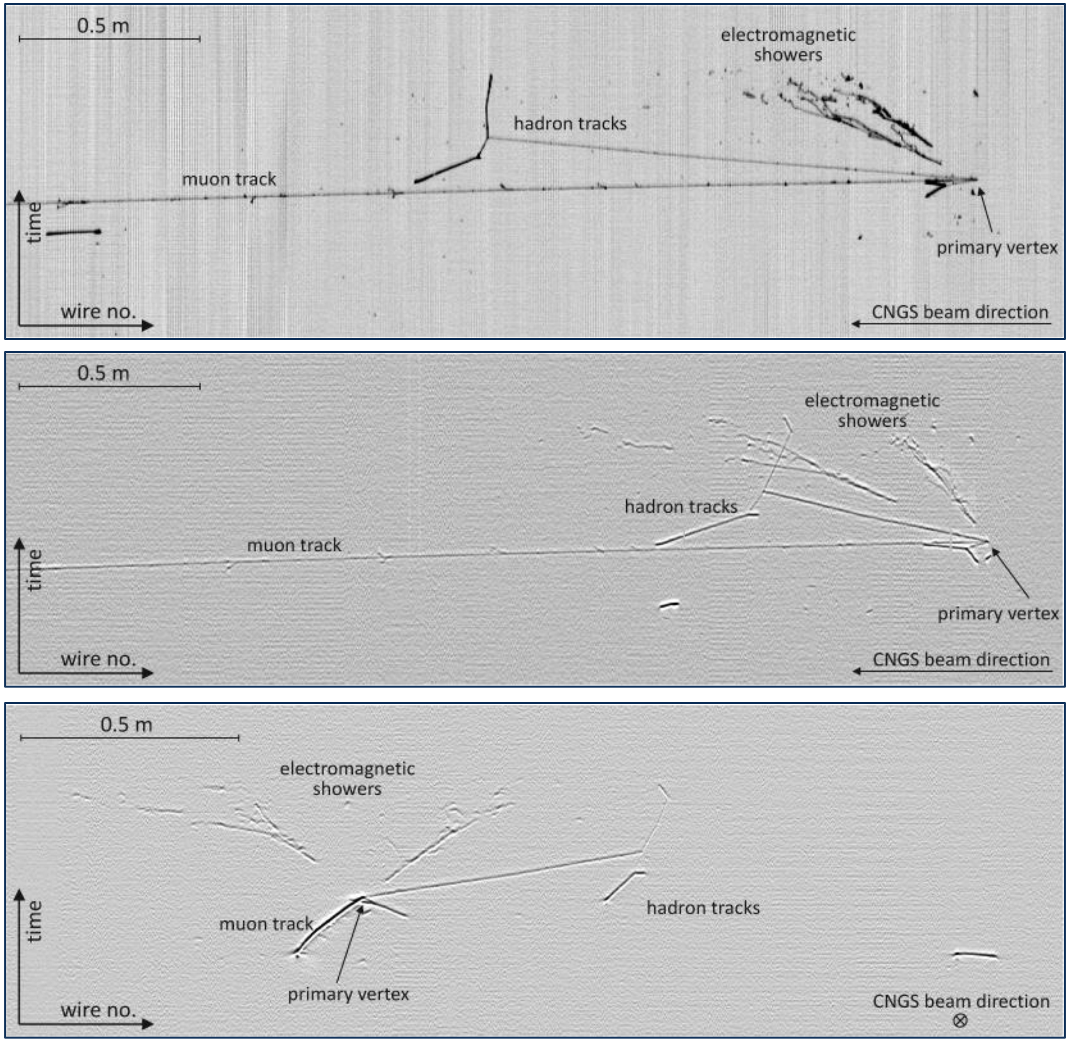


http://www.phy.bnl.gov/wire-cell/

LArTPC principles of detection technique (ICARUS – T600)

- 2D projection for each of 3 wire planes per TPC
- 3D spatial reconstruction from stereoscopic 2D projections
- charge measurement from Collection plane signals
- Absolute drift time from scintillation light collection



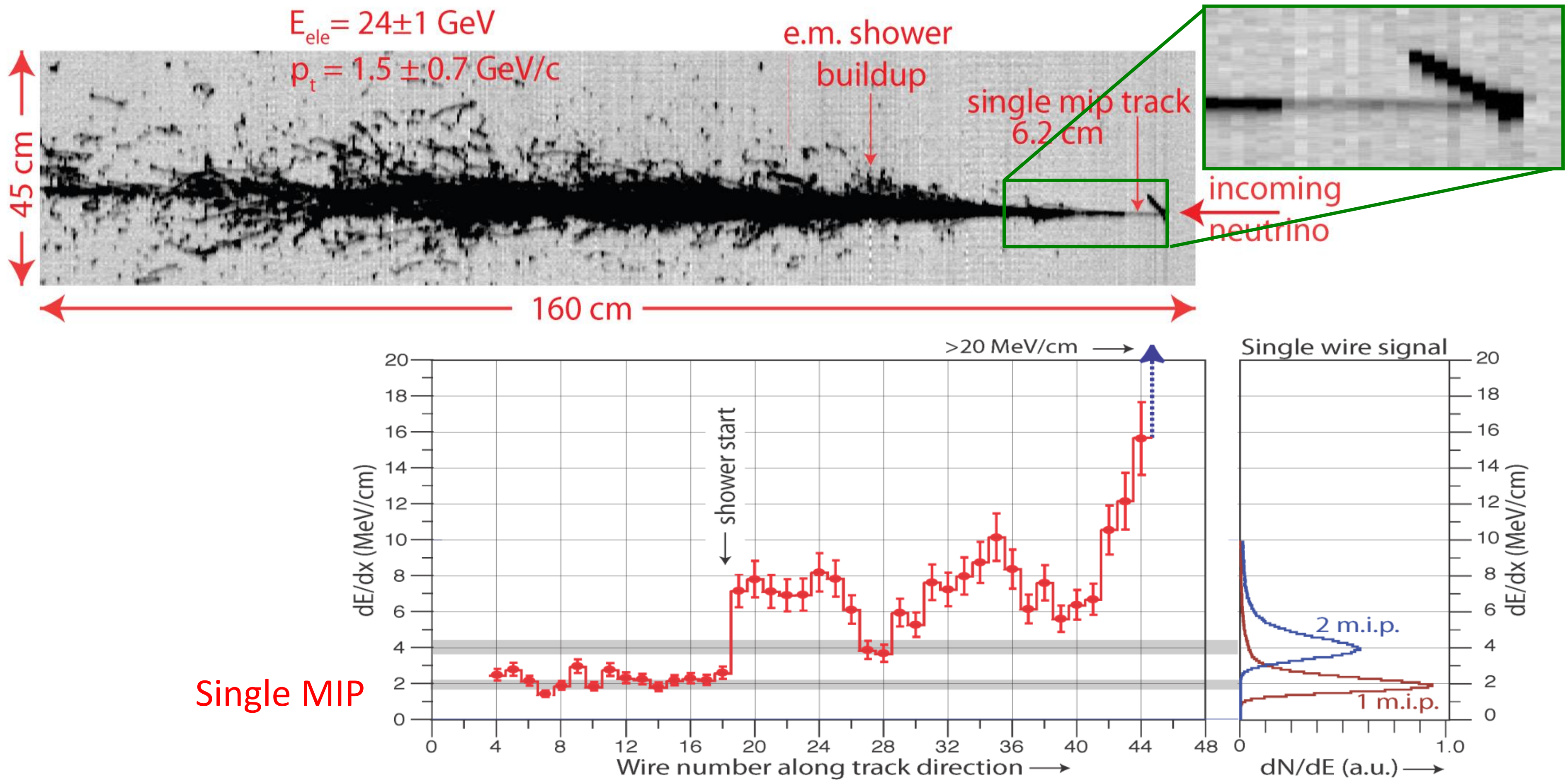


CNGS ν_μ charge current interaction one of TPC's shown

- **Photons (2x MIP dE/dx) and electrons (1x MIP dE/dx) can be cleanly separated**

Example event with a clear electron signature

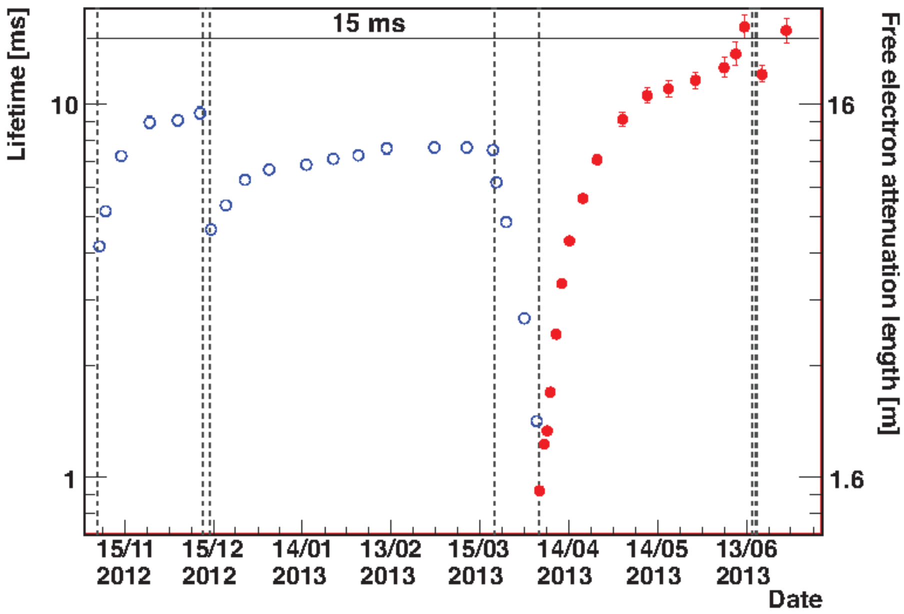
The evolution of the actual dE/dx from a single track to an e.m. shower is clearly visible.

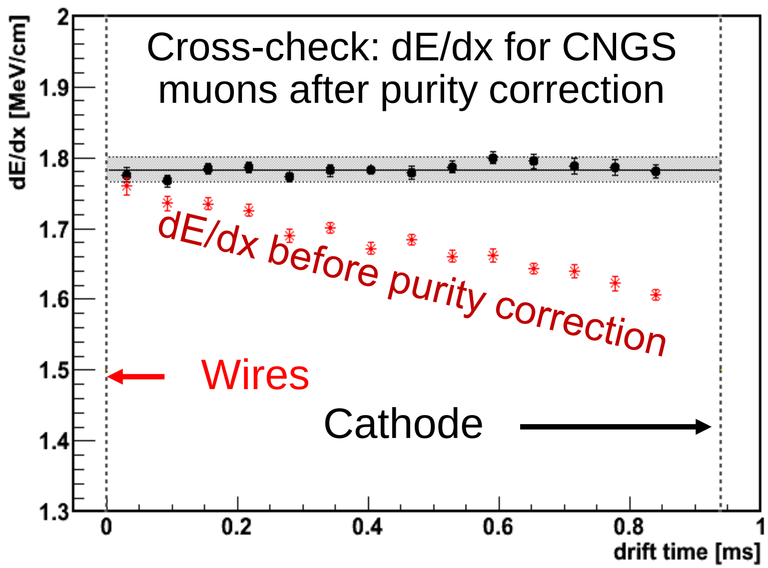


Key features of Single Phase LAr imaging

- **Very long e-mobility**

- Level of electronegative impurities in LAr must be kept exceptionally low to ensure ~m long drift path of ionization e^- without attenuation.
- New industrial purification methods developed to continuously filter and re-circulate both in liquid (100 Nm^3/day) and gas (2.5 m^3/hour) phases.
- Electron lifetime measured during ICARUS run at LNGS with cosmic m's: t_{ele} >15 ms (~40 p.p.t. [O_2] eq) →12% max. charge attenuation.





Effectiveness of single phase LArTPC technique, paving the way to huge detectors ~5 m drift as required for LBNF/DUNE project was demonstrated by ICARUS

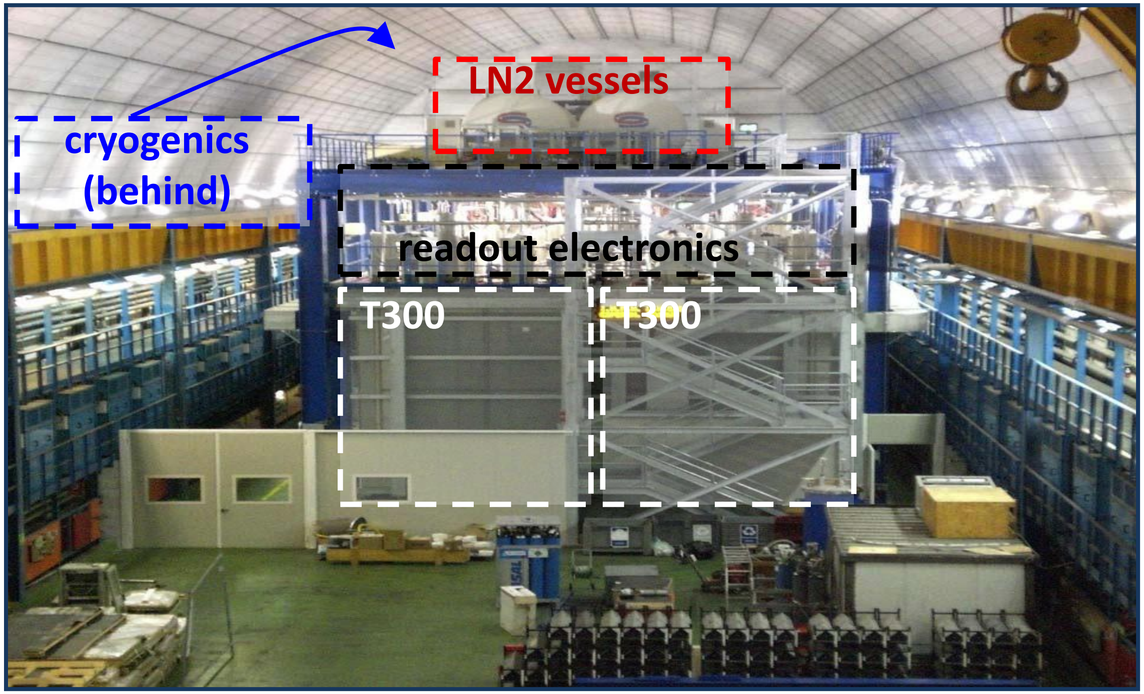
LAr experiments

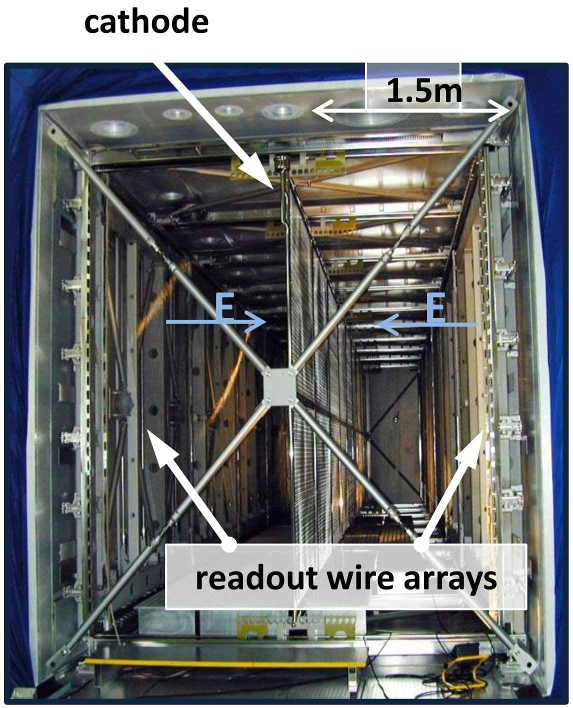
Experiment	LAr mass	Physics goals	Baselines (km)	E_ν (GeV)	Detector location	Current status
ArgoNeuT	175 l	R&D, cross section Accelerator ν	1	~0.1 – 10	Fermilab NuMI beam)	Completed (2010) Data under analysis
LArIAT	550 l	Study of charge particle interaction in LAr	Dedicated tertiary charged beam line (e, mu, pi, K, p)	0.2 – 1.2	Fermilab	Running since 2015.04
MicroBooNE	170 t (86 t - active)	Sterile neutrinos, R&D, short baseline	0.470	~0.1 – 3	Fermilab (BNB)	2015.07: filled with LAr 2015.08.06: First tracks in the TPC
CAPTAIN	(2 t - prototype) 10 t	Neutrino interaction,		< 0.05, 1.5 - 5	LANL, Fermilab	
SBND (LAr1-ND)	220 t (112 t - active)	Sterile neutrinos, Short baseline	0.110	~0.800	Fermilab (BNB)	Design phase, begin operation in 2018
ICARUS	600 t (476 t - active)	R&D, long baseline (single detector)	732 (0.600 for SBNE)	~5 - 25	Gran Sasso (CNGS beam), Fermilab	Past & under development
MODULAr	5 kt	Long baseline (shallow depth)	730	~5 - 25	Gran Sasso	Proposed
GLADE	5-10 kt	Long baseline	810	~0.5 – 2	NuMi off-axis	Letter of Intent (2012)
DUNE (LBNE) (ProtoDUNE)	68 kt (4x17 kt)	Long baseline	1300	~0.5 – 5	SURF - Fermilab	Planned, installation ~2021
LAGUNA/LBNO	20 kt	Long baseline (underground FD	2300	~few	Europe (new CERN beam)	R&D, future
ArgonCube	2.8 t/module DUNE ND: 39 t		Short		CERN	R&D

ICARUS T600

Imaging **C**osmic **A**nd **R**are **U**nderground **S**ignals

ICARUS – T600 at LNGS laboratory





Two identical modules

- $3.6 \times 3.9 \times 19.6 \sim 275\ m^3$ each
- LAr active mass: 476 t
- Drift length: 1.5 m (1 ms)
- E=0.5 kV/cm, $v_{drift} \sim 1.5$ mm/μs
- Sampling time 0.4μs (sub-mm resolution in drift direction)

Four wire chambers:

- 2 chambers/ module
- 3 readout wire planes per chamber: 2 Induction + 1 Collection; ~54 000 wires, 3 mm pitch and plane spacing, oriented at 0°,±60°;
- Charge measurement on last Collection plane

20+54 PMTs,8" Ø, for scintillation light detection:

- VUV sensitive (128nm) with TPB wave shifter

ICARUS

- **Operational technics**
  - LAr purification method → very long e-mobility,
  - 3D track reconstruction + particle identification,
  - e/γ separation and π^0 reconstruction,
  - determination of muon momentum via multiple scattering ($\Delta p/p$ ~15% in 0.4-4 GeV/c range)

- **Physics results:**
  - Refuted superluminal ν (OPERA),
  - Sterile neutrino searches (LSND anomaly)

MicroBooNE

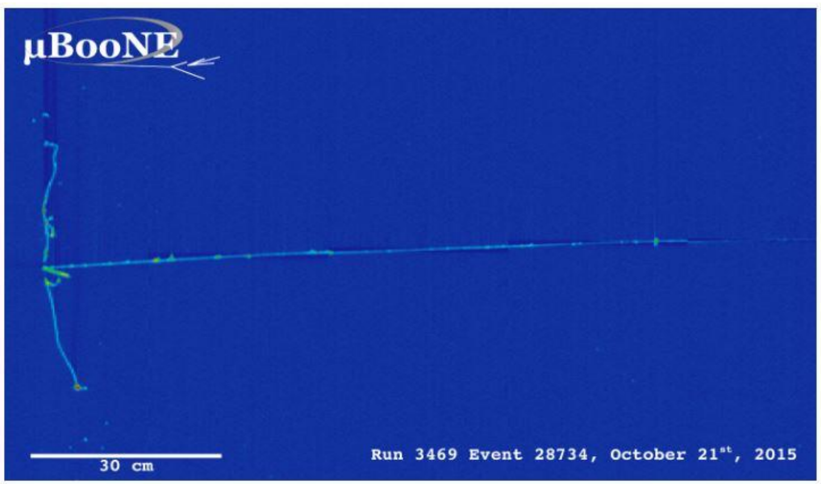
Micro **Boo**ster **NE**utrino

MicroBooNE

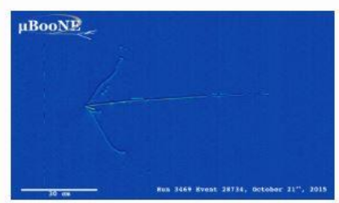
Located at Fermilab, the experiment will build and operate a large 170 ton Liquid Argon Time Projection Chamber (LArTPC) located along the Booster neutrino beam line. The experiment will measure low energy neutrino cross sections and investigate the low energy excess events observed by the MiniBooNE experiment.

The detector serves as a next step in a phased program towards the construction of massive kiloton scale LArTPC detectors.

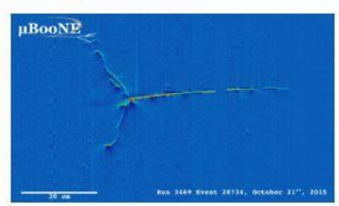
- **November 2, 2015: First neutrino event candidates**
- October 15, 2015: first neutrino beam
- August 6, 2015: First tracks in the TPC!
- July 9, 2015: Detector filled with liquid argon (170 tons)
- June 17, 2015: End of detector cooldown and start of liquid argon fill
- April 21, 2015: Start of gaseous argon purge

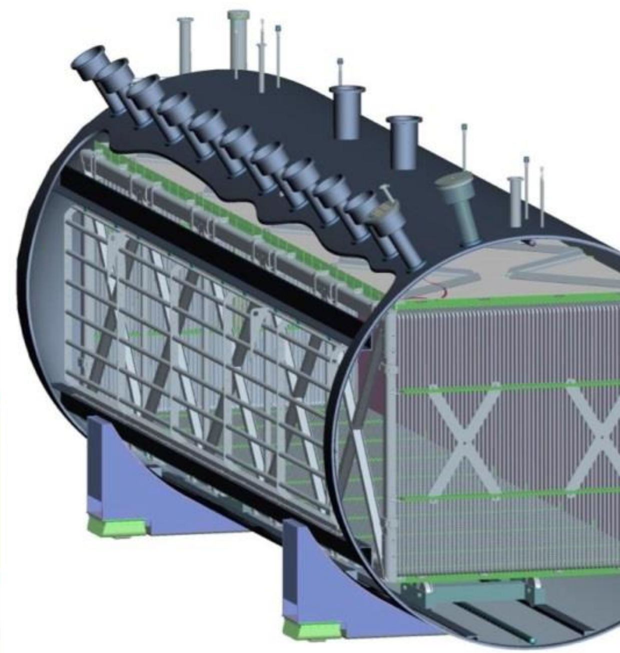


induction plane 1:



induction plane 2:



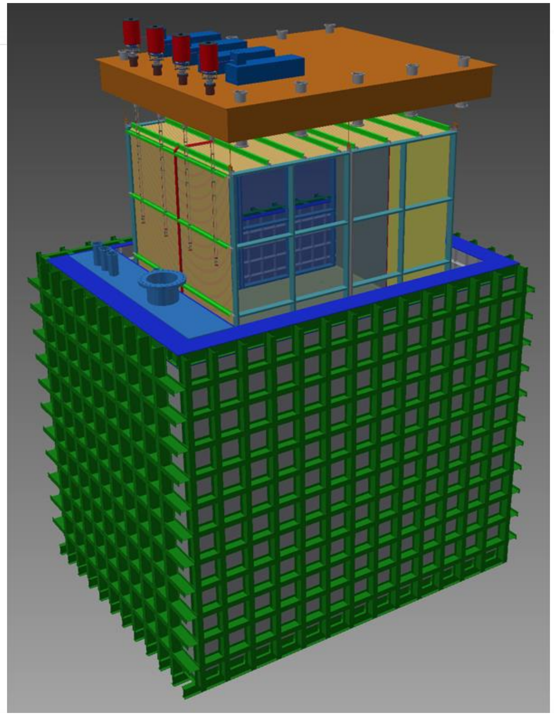


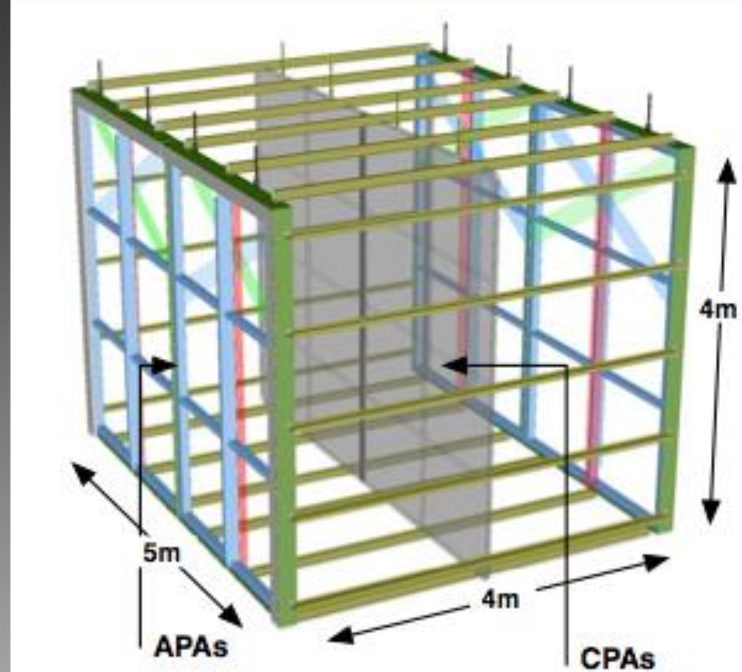
SBND

Short **B**aseline **N**ear **D**etector

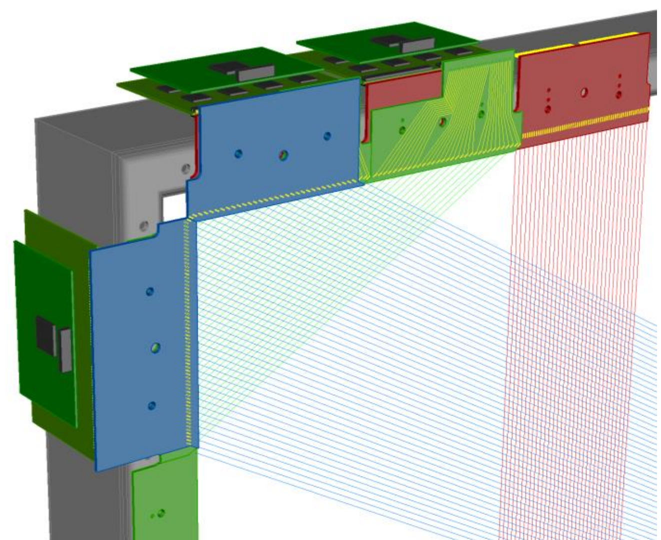
SBND

TPC dimensions:
- 4 m long x 4 m tall x 5 m wide
- Active volume: 112 t of LAr





- The 4 APAs hold 3 planes of wires with 3 mm wire spacing
- Drift distance: 2 m
- UV laser-based calibration system
- Light collection system for the detection of scintillation light
- External cosmic ray tagging system

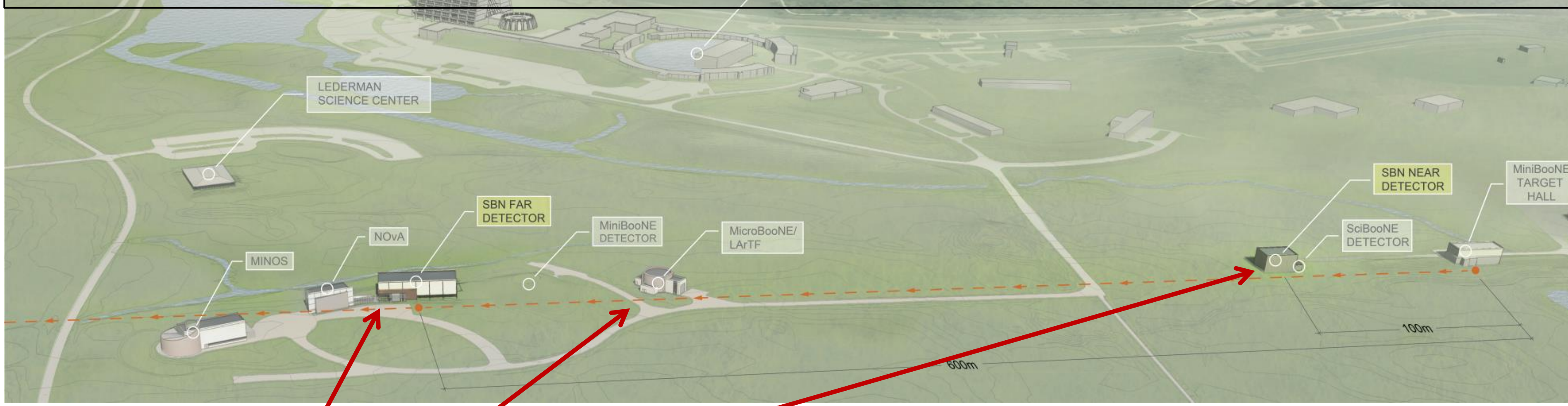


Layout of three LArTPCs at FNAL

The future short-baseline experimental configuration is proposed to include <u>three LArTPCs</u> located <u>on-axis in the BNB.</u>

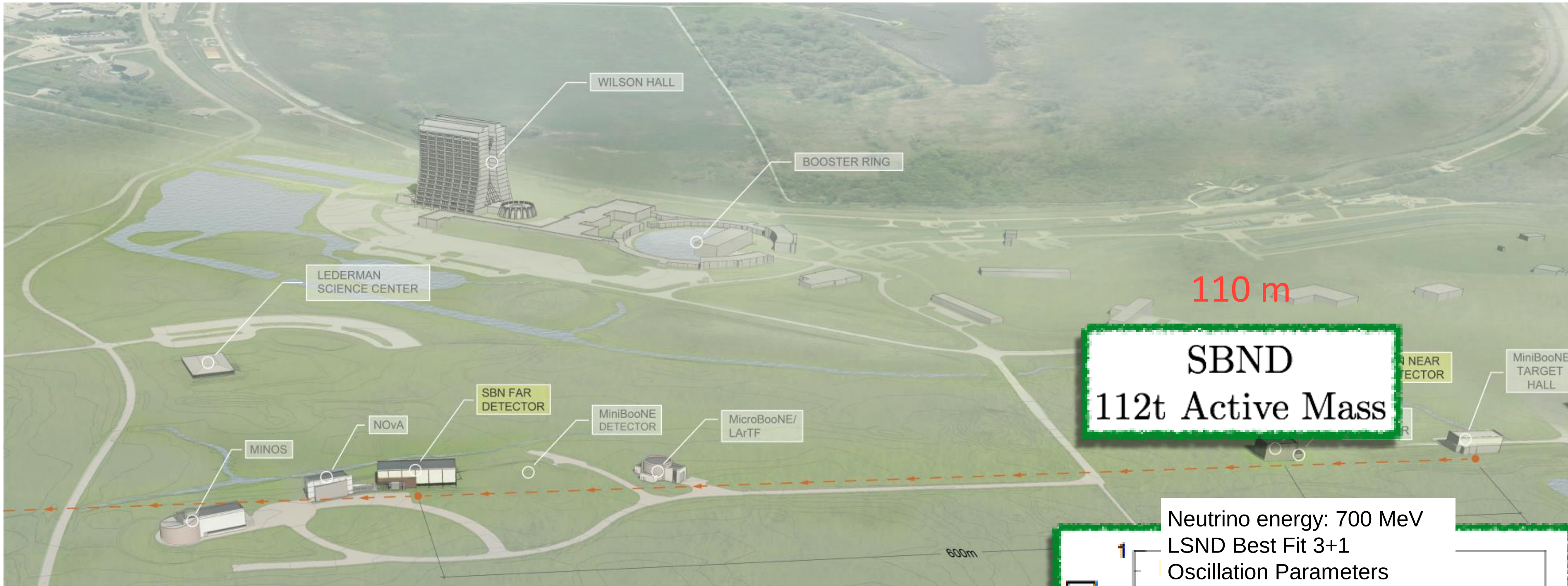
Multiple detectors very valuable for reducing systematic uncertainties.

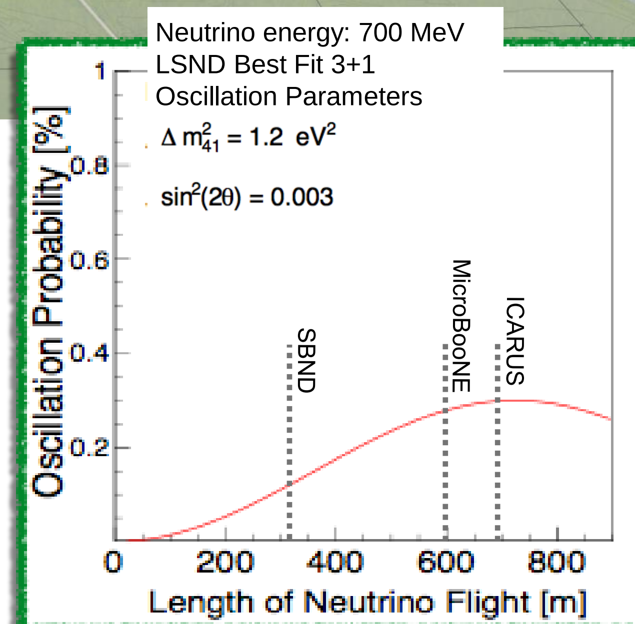
- SBN can clarify the issue with a single experiment, exploiting similar LArTPCs at different distances from the target.
- It will confirm or reject the LSND signal at the 5σ level, both in the appearance and disappearance channels.



Detector	Distance from BNB Target	LAr Total Mass	LAr Active Mass
LAr1-ND	110 m	220 t	112 t
MicroBooNE	470 m	170 t	89 t
ICARUS T600	600 m	760 t	476 t

SBND (LAr1-ND)





- **SBND will provide a detailed characterization of the beam before oscillations can occur**

- This allows for the cancelation of many of the dominant systematics

Toward future of LArTPC detectors

1st LArTPC division

Modular

- **ModulAr**
  structure with several separated vessels
- **ArgonCube**
  as alternative design (magnetized) DUNE Near Detector

Large scale

- **LBNO**
  Double Phase
- **DUNE**
  ProtoDune
  (NP04) Single or Dual phase (NP02)

2nd LArTPC division

Single phase

- **ICARUS**
- **SBND**
- **ProtoDUNE** (NP04)
- …

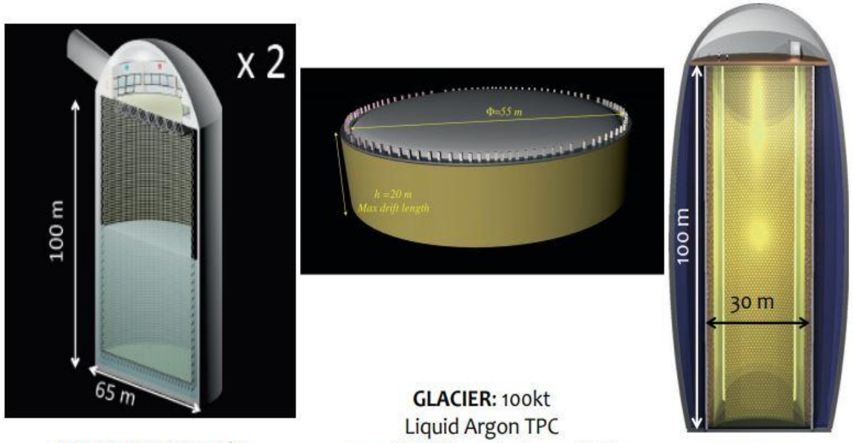
Dual phase

- **LBNO (GLACIER)**
- **ProtoDUNE** (NP02)
- DarkSide-20k

LAGUNA-LBNO

Large **A**pparatus studying **G**rand **U**nification and **N**eutrino **A**strophysics
for **L**ong **B**aseline **N**eutrino **O**scillation

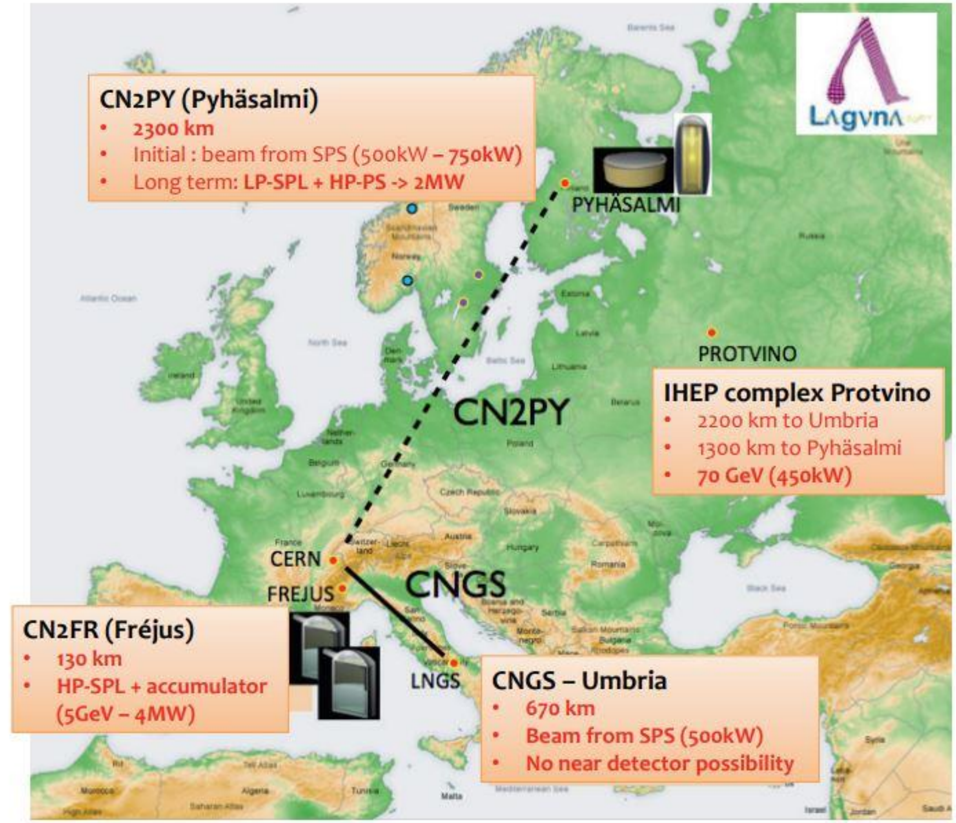
- **Three detector considered:**



MEMPHYS: 2 x 330 kt
Water Cherenkov
130000 12" PMTs

GLACIER: 100kt
Liquid Argon TPC
1000 8" WLS-coated cryo PMTs
27000 cryogenic PMTs

LENA: 50 kt
Liquid Scintillator
30000 12" PMTs



Pan-European infrastructure addresses the feasibility of a new European research infrastructure hosting a deep underground neutrino detector, much larger and more sensitive than those presently in operation, **for fundamental research in astrophysics** and particle physics

- determination of the neutrino mass pattern,
- the understanding the origin of matter dominance in the Universe
- searches for new physics at the energies beyond the reach of the LHC at CERN

From Physics Procedia 61 (2015) 524 – 533

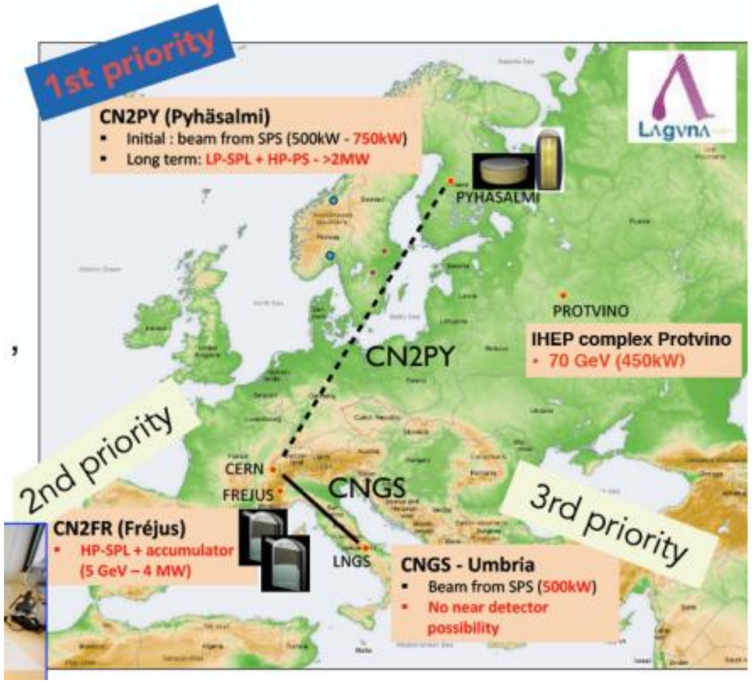
The LAGUNA-LBNO project

LAGUNA EU FP7 Design Study 2008-11

- 3 detector technologies, 7 sites (130-2300 km)
- ~100 members, 10 countries

LAGUNA-LBNO EU FP7 D.S. 2011-14

- prioritzaton of sites and detectors (3 det, 2 possible sites)
  - **Liquid Argon Double-Phase TPC GLACIER (20-70kt) @Pyhäsalmi**
  - Water-Cherenkov detector MEMPHYS (500 kt) @Fréjus
  - Liquid ScinJllator LENA (50 kt) @Pyhäsalmi
- fully engineered detector designs for 20/50 kt DLAr, 50 kt LSc, 540 kt WCD
- underground facility constructon and costing (Pyhäsalmi, Fréjus and Umbria)
- extended site investgaton at Pyhäsalmi mine
- ~300 members, 14 countries + CERN



LBNO (CERN SPSC-EOI-007 for a very long baseline ν oscillaton experiment, 2012)

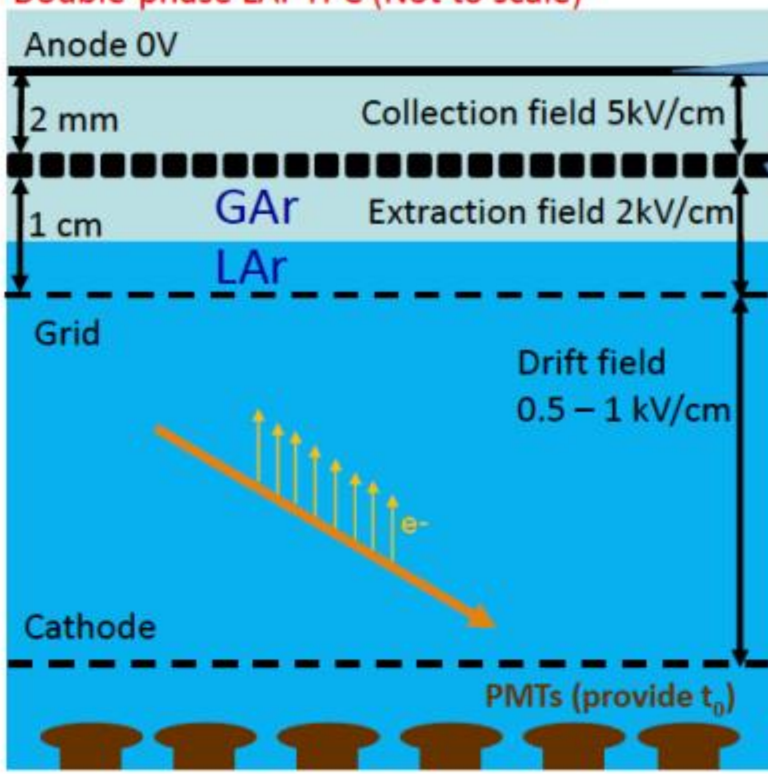
- incremental approach for a large neutrino observatory with excitng physics from phase 1
- ~230 authors, 51 instutons

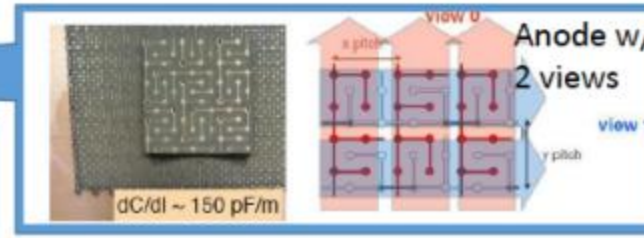
LBNO-DEMO WA105 1:20 scale demonstrator for DLAr TPC detector @ CERN

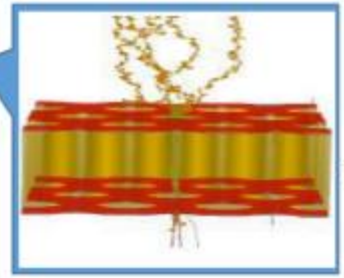
Detector technology

GLACIER (**G**iant **L**iquid **A**rgon **C**harge **I**maging **E**xpe**R**iment) concept
A. Rubbia hep-ph/0402110

Double-phase LAr TPC (Not to scale)







LEM (Large Electron Multiplier):
w=1mm, 25-35 kV/cm

- Single cryo-tank based on LNG technologies
- Double-phase → charge amplification and readout in gas phase
  - Large drift distances
  - Low energy detection threshold

Full engineering solution is now available for 20/50 kton detectors from LAGUNA-LBNO DS

02/07/2014 LAGUNA/LBNO - V. Galymov ICHEP2014 5

ModulAr

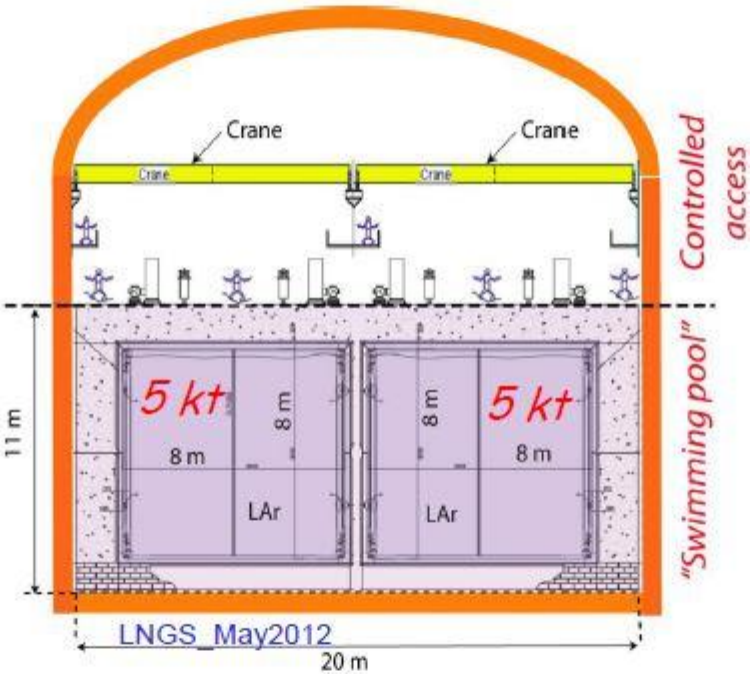
ModulAr – structure with several separated vessels

From C. Rubbia, NuTown2012

- The most naive design would **assume a single** (may be ≈100 kton) **LAr container of a huge size**. But the dimensions of most events under study (beam-ν, cosmic ray-ν, proton decays) are of much smaller dimensions.

- For instance, the whole volume of ultra-pure **LAr will be totally contaminated even by a tiny accidental leak** (ppb). A spare container vessel for ≈100 kton are unrealistic.

- Fortunately **increasing the size** of a single container does **not introduce significant physics arguments** in its favour.



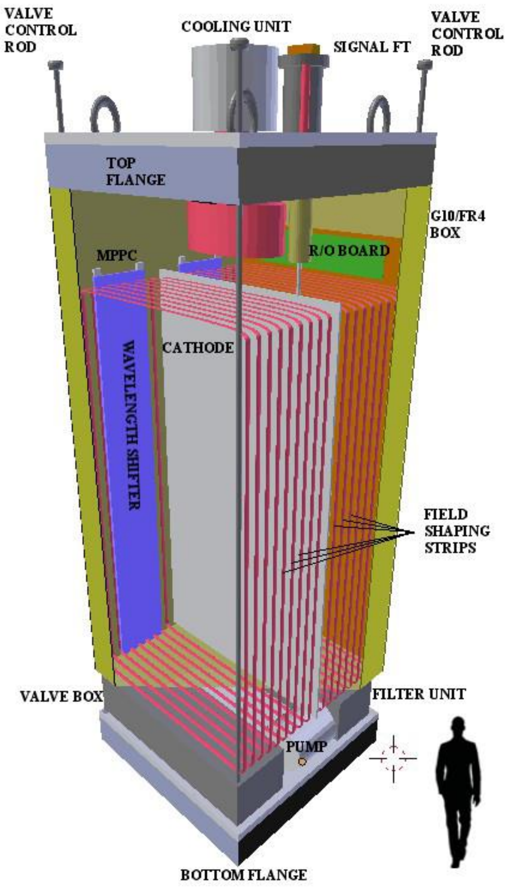
- A reasonable single volume unit could be of 8 x 8 m^2 cross section, a drift gap of 4 m and a length of about 60 m, corresponding to 3840 m^3 of liquid or 5370 t of LAr.

- Two units should be located side to side with 10 kt mass.

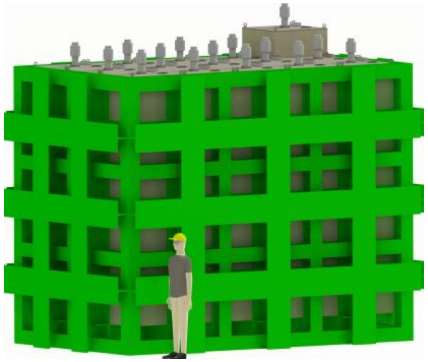
ArgonCube

ArgonCube

- Proposal (Bern) as alternative design for (Magnetized) DUNE Near Detector:
  - Shorter drij-times - Less stringent purity, less pileup & lower voltage
  - Light contained - Less optical pileup, accurate trigger & veto
  - Pixel readout - Live 3D reconstruction with reduced ambiguites
  - Several modules sharing the same LAr bath
- Modular prototype under construction:
  - Containing 4 modules:
    - 1 x Reference wire readout (Sheffield)
    - 3 x Pixel readout (Bern, CERN)
  - Engineering (Bern, CERN)
  - First TPC tests in the fall of 2016. Using pixel demonstrator TPC



DUNE Near Detector
- Total argon volume split by ~1-10 ton modules
- Cryostat dimensions: 5x7x4 m^3
- 15 modules
- Argon mass: ~2.8 t/module
- Total active mass: 39 t



One Module:
- 2 m x 2 m x 3 m
- 1 m drift length

DUNE

Deep **U**nderground **N**eutrino **E**xperiment

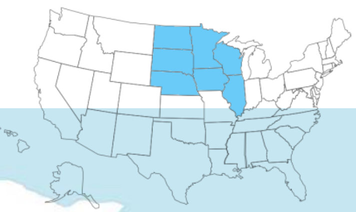
ProtoDUNE

single-phase (NP04), dual-phase (NP02) LArTPC detectors

DUNE

- DUNE will be dual-site experiment focused around three central components:
  - a high intensity neutron source
  - two detectors spaced apart about 1300 km
    - first detector serves as near detector located in Fermilab
    - **second as far massive LArTPC detector deep underground at the SURF**

- DUNE far detector will be more than ten times the volume of the largest past operating (ICARUS)
  - 68 kt LAr (4x17 kt)

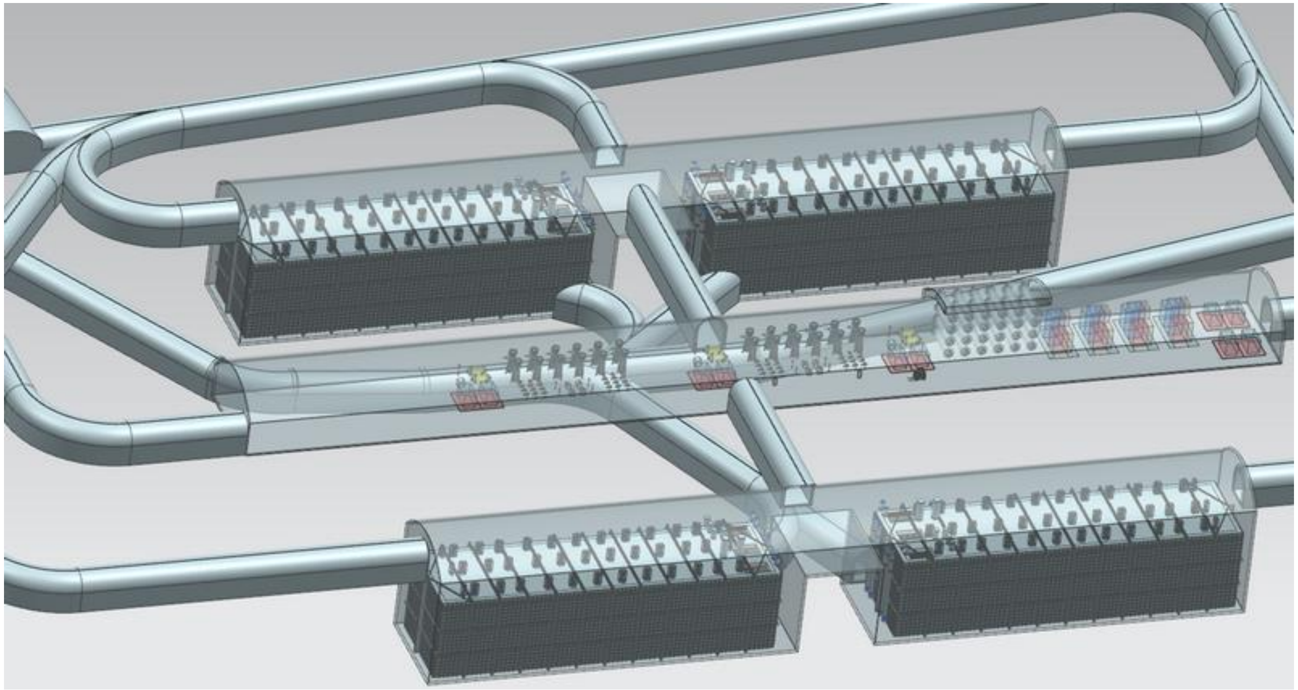


Sanford Underground Research Facility (SURF): site of the former Homestake Mine in Lead, South Dakota

DUNE

- DUNE will be dual-site experiment focused around three central components:
  - a high intensity neutrino source
  - two detectors spaced apart about 1300 km
    - first detector serves as near detector located in Fermilab
    - **second as far massive LArTPC detector deep underground at the SURF**

- DUNE facts:
  - 68 kt LAr (4x17 kt),
  - 1475 m underground



ProtoDUNE – before DUNE will born

- The protoDUNE experimental program is designed to test and validate the technologies and design that will be applied to the construction of the DUNE
  - single-phase (NP04) and dual-phase (NP02) LArTPC detectors (assembly and readlines for cooling down by summer 2016)
- Detectors will be run in a dedicated beam line at the CERN SPS accelerator complex
  - which provides a mixture of electrons, muons, pions, kaons and protons at a selected (within 5-7%) momentum in the range 0.5-7 GeV

- **ProtoDUNE is not a neutrino experiment in itself!**

  Goals:
  - prototype the production and installation procedures for the single-phase far detector design;
  - validate the design from the perspective of basic detector performance—this can be achieved with cosmic-ray data;
  - accumulate large samples of test-beam data to understand/calibrate the response of the detector to different particle species;
  - demonstrate the long-term operational stability of the detector as part of the risk mitigation program ahead of the construction of the first 10-kt far detector module.

Conclusions

Advantages

- mature technology
- high precision and low energy threshold
- complete 3D imaging
- relatively cheap

Disadvantages:

- cannot be made anywhere near as large as water Cherenkov detectors
  (DUNE far detector will be only about one-tenth the mass of Hyper-Kamiokande, when both are complete)
- require high purity LAr → but exist Dual Phase LArTP!
- require voltages in the hundred of kV range but also uniform electric field

Backup

LArIAT

LAr TPC **I**n **A** **T**estbeam

LArIAT

Status:

Physics Run 1 **completed**

- Data collected from April 30 to July 8 2015.
- Analysis ongoing

Physics Run 2

- Fall 2015

Goal:

Characterize LArTPC performance in the range of energies relevant to upcoming short- and long-baseline experiments for neutrino physics and for proton decay searches.

Physics

- Charged pion interaction cross section measurements
- Optimize pion and kaon ID
- Experimentally measure e/γ separation capabilities
- Develop criteria for muon charge sign determination w/out magnetic field
- Study Energy Resolution and Particle Identification improvement by combining information from scintillation light and ionization charge signals

R&D

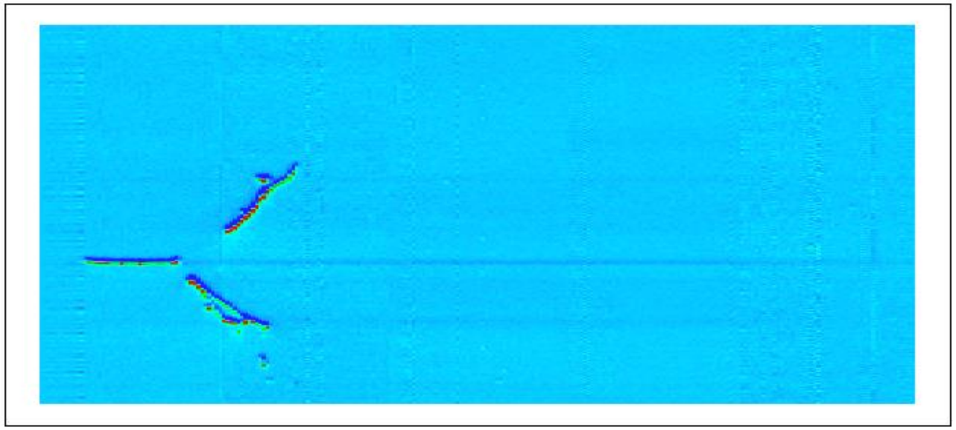
- Development of innovative, augmented performance Scintillation Light detection Systems for Liquid Argon Detectors *(*Yale/Wright Lab*)*

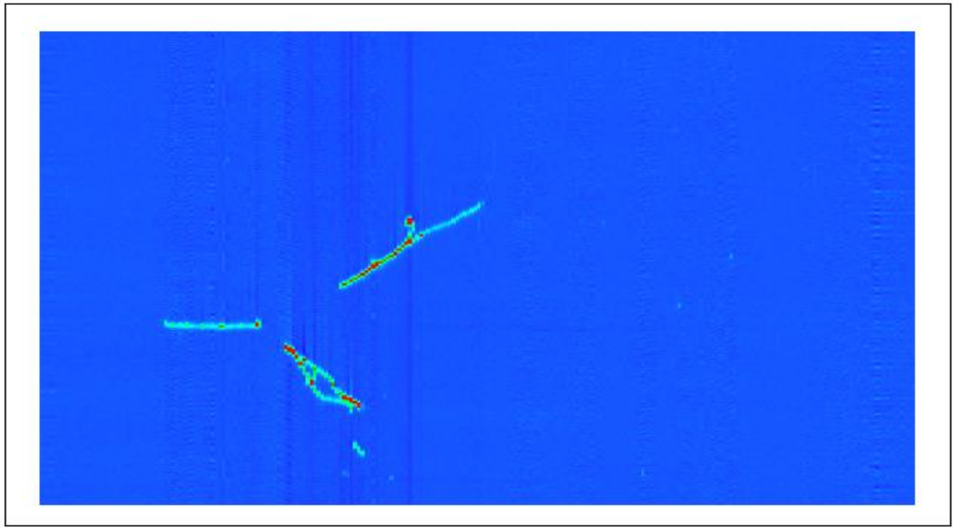
Slide: thanks to Flavio Cavanna

Pion beam

Pion exchange

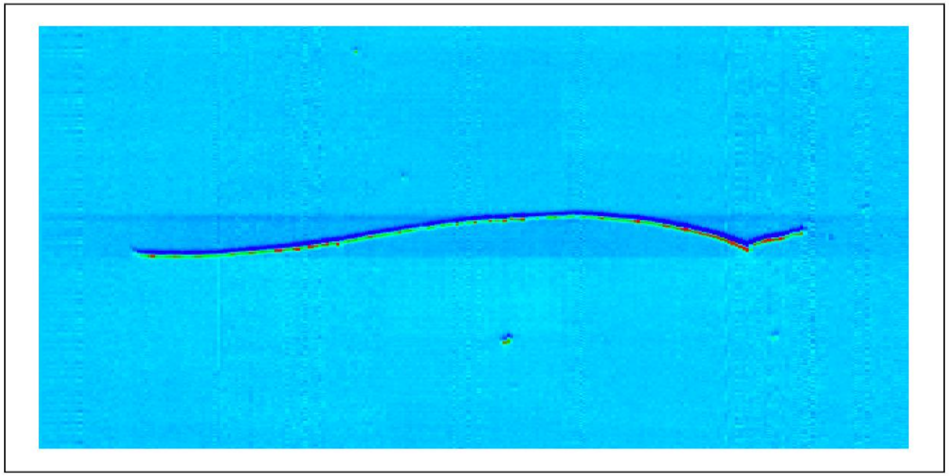
$\pi^- + p\ (\rightarrow\ \Delta^0\ ) \rightarrow\ \pi^0 + n$

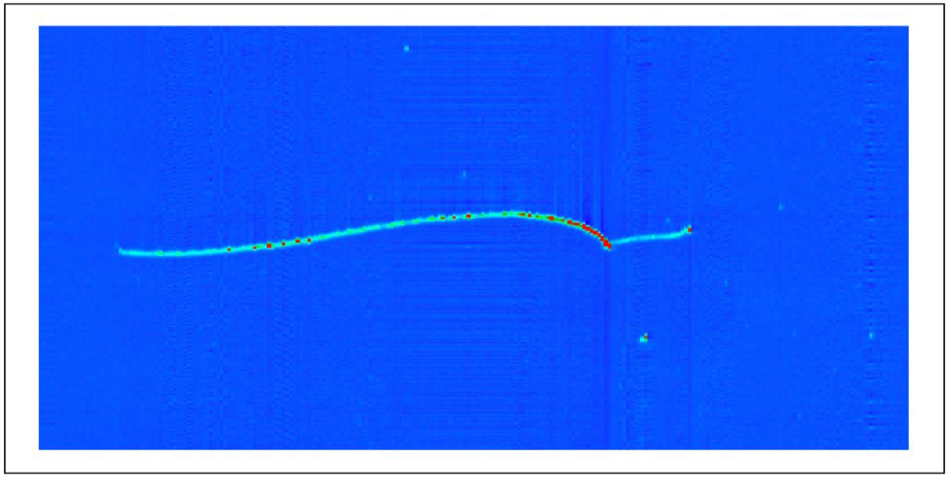




Pion decay at rest

$\pi+ \rightarrow \mu+ \rightarrow e+$

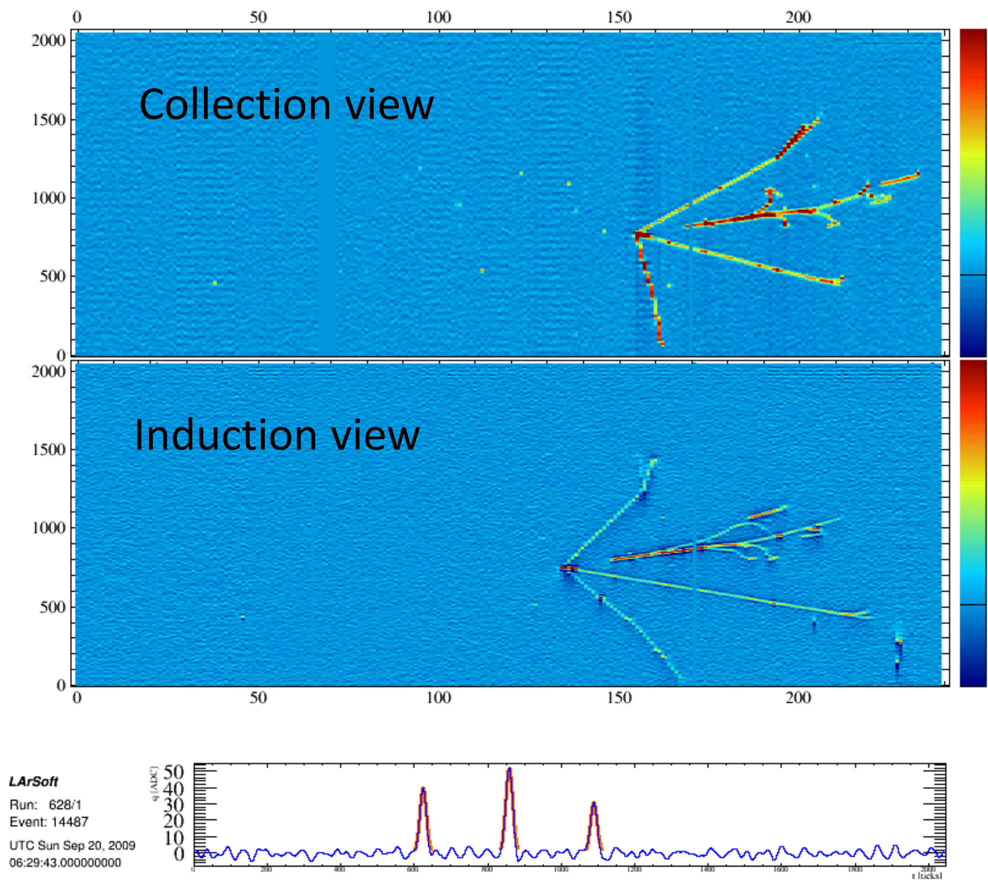




ArgoNeuT

ArgoNeuT

- ArgoNeuT is a R&D project at Fermilab to expose a **small-scale** LArTPC to the NuMI neutrino beam
  - Three main systems in ArgoNeuT:
    - time projection chamber
    - purity system
    - recirculation system
- Data-taking concluded in March 2010, and analysis is ongoing



The horizontal axis corresponds to the wire number within a plane, while the vertical axis corresponds to the sampling time (which is equivalent to the distance along the drift direction). The color-scale depicts the amplitude of the ADC pulse on a wire.

Physics goals

- Search of CP violation
- Determination of the neutrino mass hierarchy
- ν_e and anitν_e appearance
- Searches for rare events, including proton decay and baryon number violating processes, SuperNova core collapse neutrinos, and, potentially diffuse SuperNova neutrino background detection
- Whether sterile neutrino oscillations take place at short baselines,
- Whether and how well we understand inclusive and exclusive neutrino cross sections, and in particular nuclear effects and final state interactions in neutrino-nucleus scattering

Liquid Argon

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ /MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

(By Mitch Soderberg)

- Dense: 40% more dense than water
- Abundant: 0,9% of the atmosphere
- Ionizes easily: 89 000 pairs electron-ion / cm