The Neutrino Long Baseline Project Preparation: challenges and ongoing R&D and tests at LBNF-FNAL, USA

Ettore Segreto

segreto@ifi.unicamp.br

UNICAMP - DRCC

The need of visual detectors of high target density

- The success of the bubble chamber as a main tool in high energy fixed target physics is due to two main characteristics:
  - ✓ It provides a massive target, of substantial density
  - ✓ It provides complete imaging and reconstruction of the events in it
- This technology has permitted in the past very substantial advances based on :
  - ✓ Single events with complete reconstruction (e.g. discovery of Ω^-)
  - ✓ Surprise events, i.e. topologies not a priori expected (e.g. Gargamelle neutral currents)
- Technology is costly and complicated
  - ✓ It requires high pressures and mechanical expansion
  - ✓ Its sensitivity is limited to about a few milliseconds
  - ✓ Optics limits viewing of large volumes
- These limitations make the bubble chamber technology ***inapplicable*** to ***modern needs*** (e.g. neutrino physics)

Early attempts to produce an "electronic image"

- The possibility to extract an "electronic image" of a noble liquid (Xenon) has been explored by Luis Alvarez in Berkley in the seventies, *drifting the electrons to a collecting structure*
  - ✓ This provide an "image" only in one view
  - ✓ Drift can be fairly long, due to small capture probability in a *sufficiently pure liquid*.

- His technique failed because of the ***tiny signal***, which he tried to multiply at the collection point in a liquid with a very high local electric field.

- Further developments have been based on methods with ***no multiplication***, using very low noise, charge sensitive amplifiers.

Take for instance a minimum ionizing track in ***Liquid Argon*** (LAr): about 8800 ionization pairs (electron + ion) for each millimeter are produced. Local recombination reduces typically this number to about 5500/mm

The LAr Time Projection Chamber was born with this CERN internal note by C. Rubbia

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

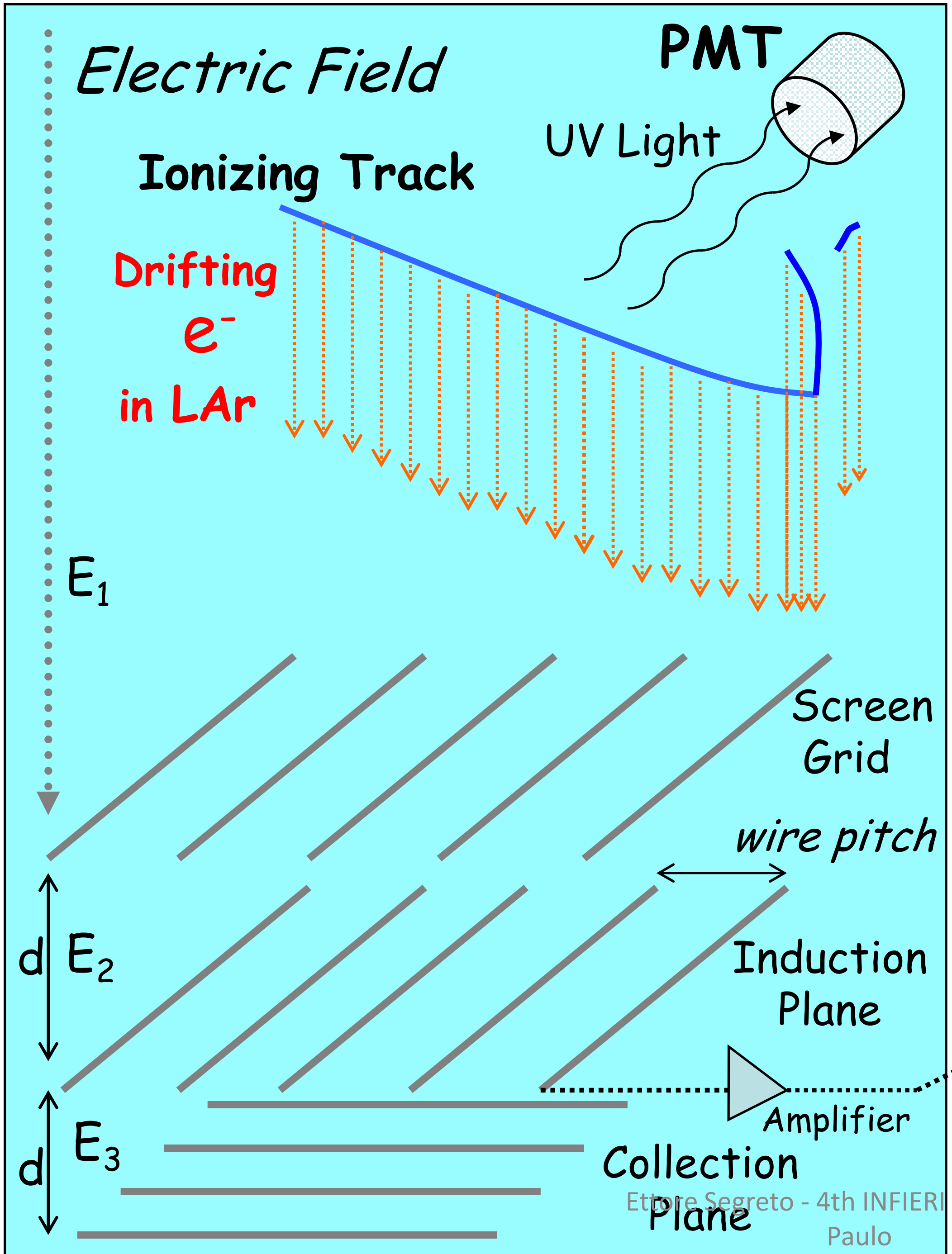
EP Internal Report 77-8
16 May 1977

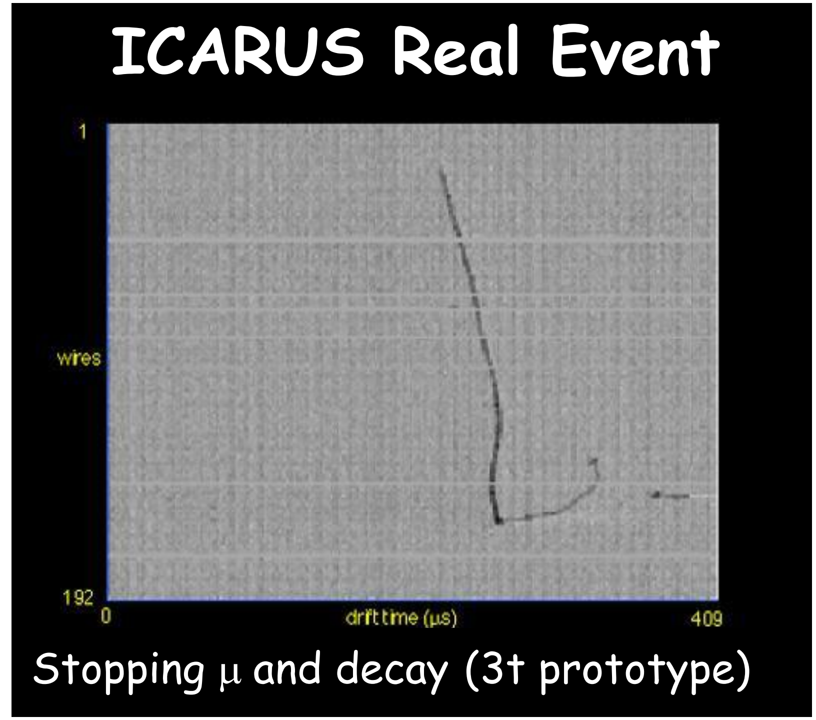
THE LIQUID-ARGON TIME PROJECTION CHAMBER: A NEW CONCEPT FOR NEUTRINO DETECTORS

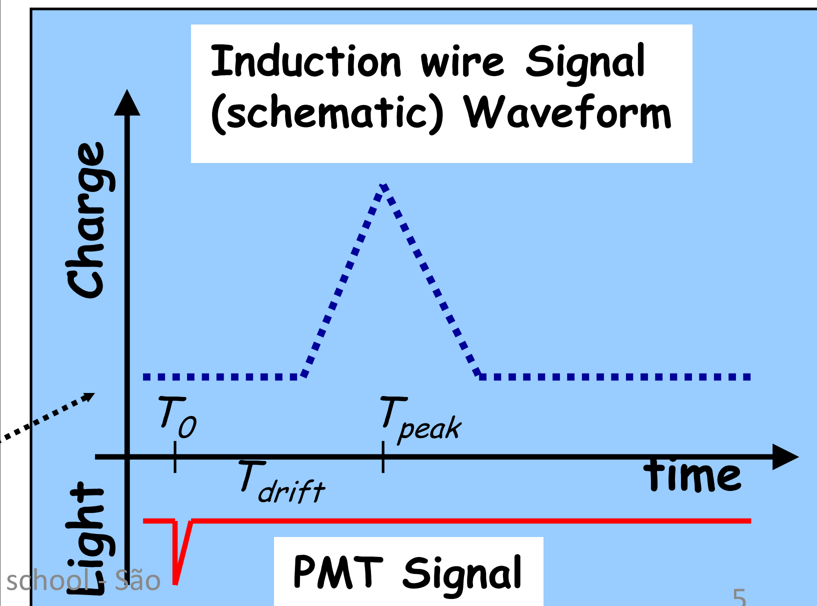
C. Rubbia

ABSTRACT

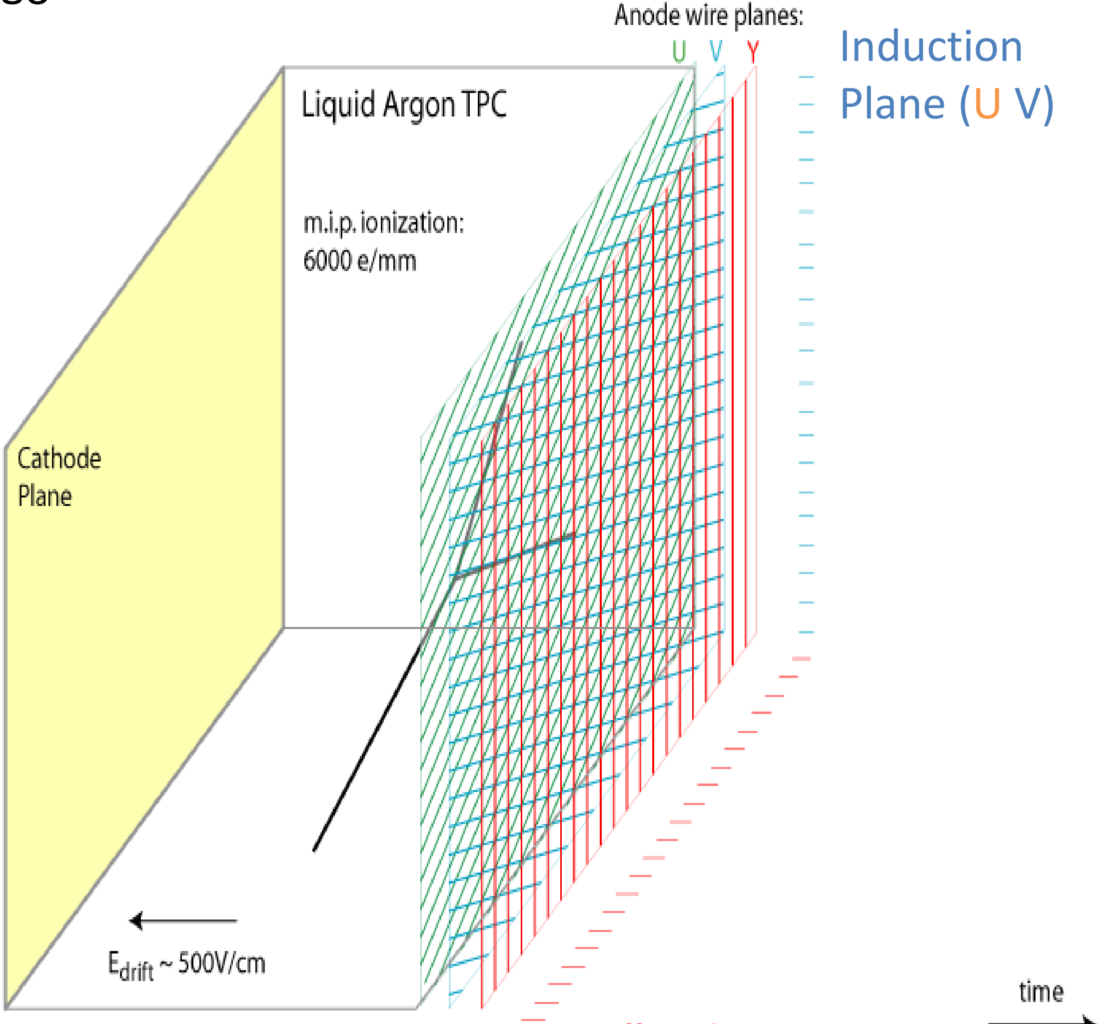
It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple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


Electric Field
PMT
UV Light
Ionizing Track
Drifting
e⁻
in LAr
E1
Screen Grid
wire pitch
d
E2
Induction Plane
Amplifier
d
E3
Collection Plane


ICARUS Real Event
1
wires
192
0
drift time (μs)
409
Stopping μ and decay (3t prototype)

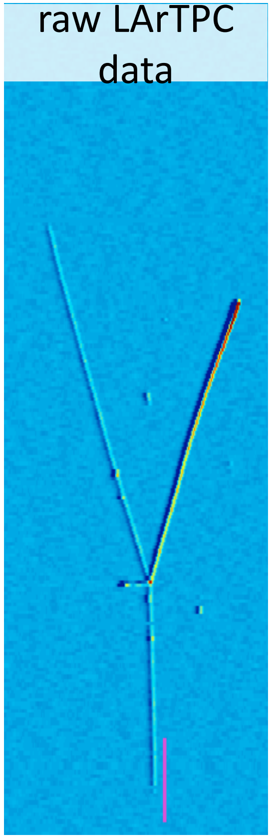

Induction wire Signal (schematic) Waveform
Charge
T0
Tpeak
Tdrift
time
Light
PMT Signal

V. Radeka
G.Valdiviesso



Induction Plane (U V)

Collection Plane (Y)



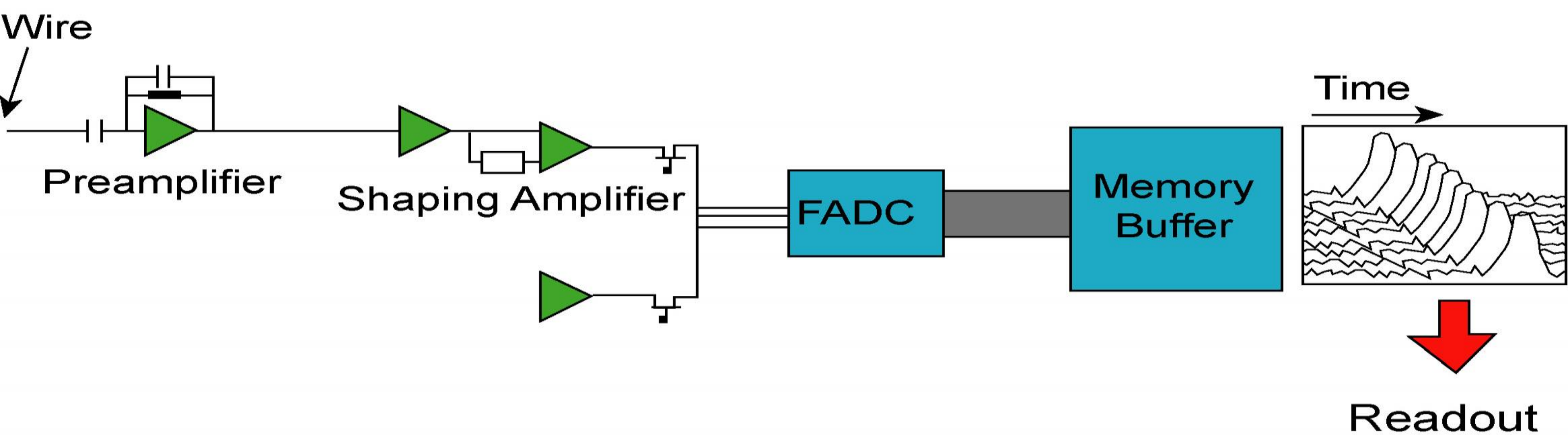
Why Liquid Argon?

- Perfect dielectric medium
- High ***electron mobility*** (*~ 500* $cm^2V^{-1}s^{-1}$)
- Possibility of ***high purification*** (*<0.1 ppb* O_2 *equivalent*)
  - ✓Long electron ***lifetimes*** (›*msec*) and ***drift paths*** (›*m*)
- High ***electron-ion pairs yield*** (*~ 10000* e^- for 2 mm of m.i.p track)
- Reasonably ***cheap*** and available in ***large quantities*** (*GAr ~ 0.9% of air*)

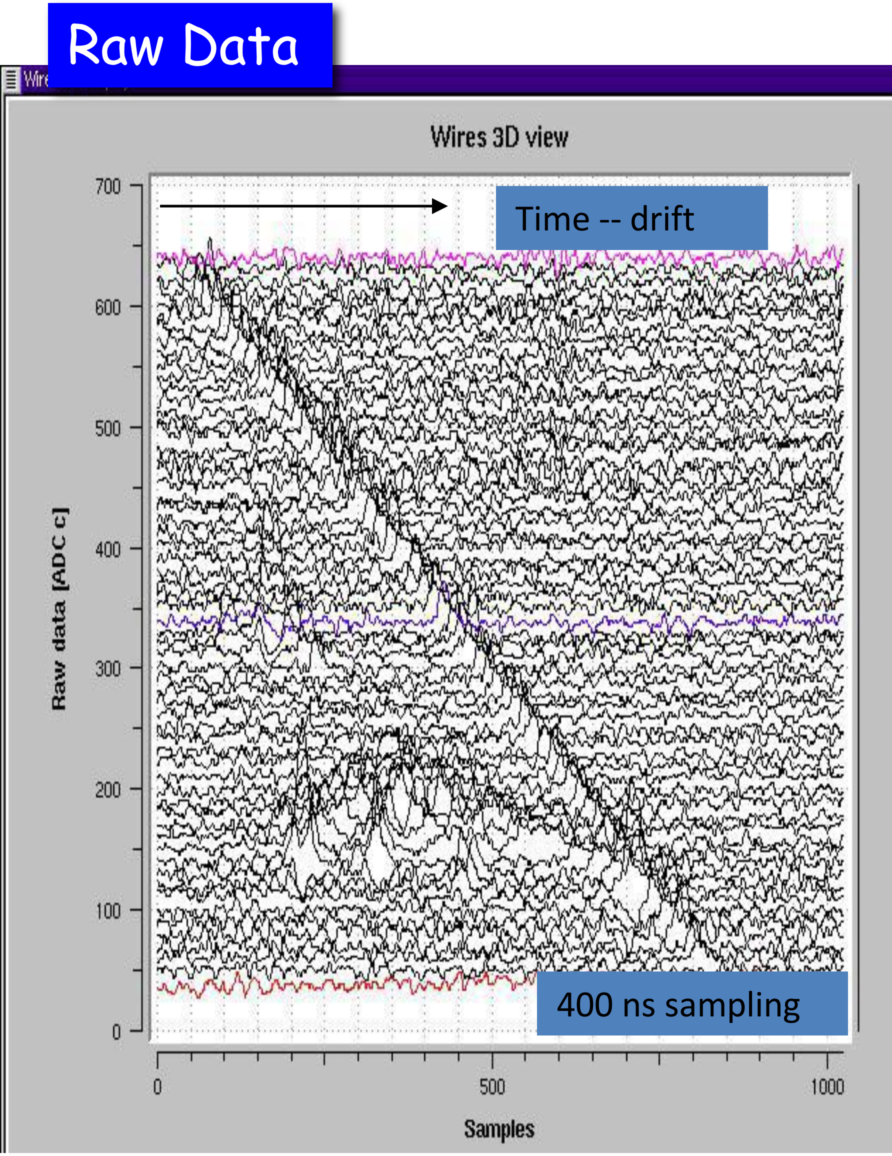
Other Lar characteristics:	
Density =	1.4 g/cm^3
Radiation length =	14.0 cm
Collision length =	54.8 cm
dE/dx =	2.1 MeV/cm

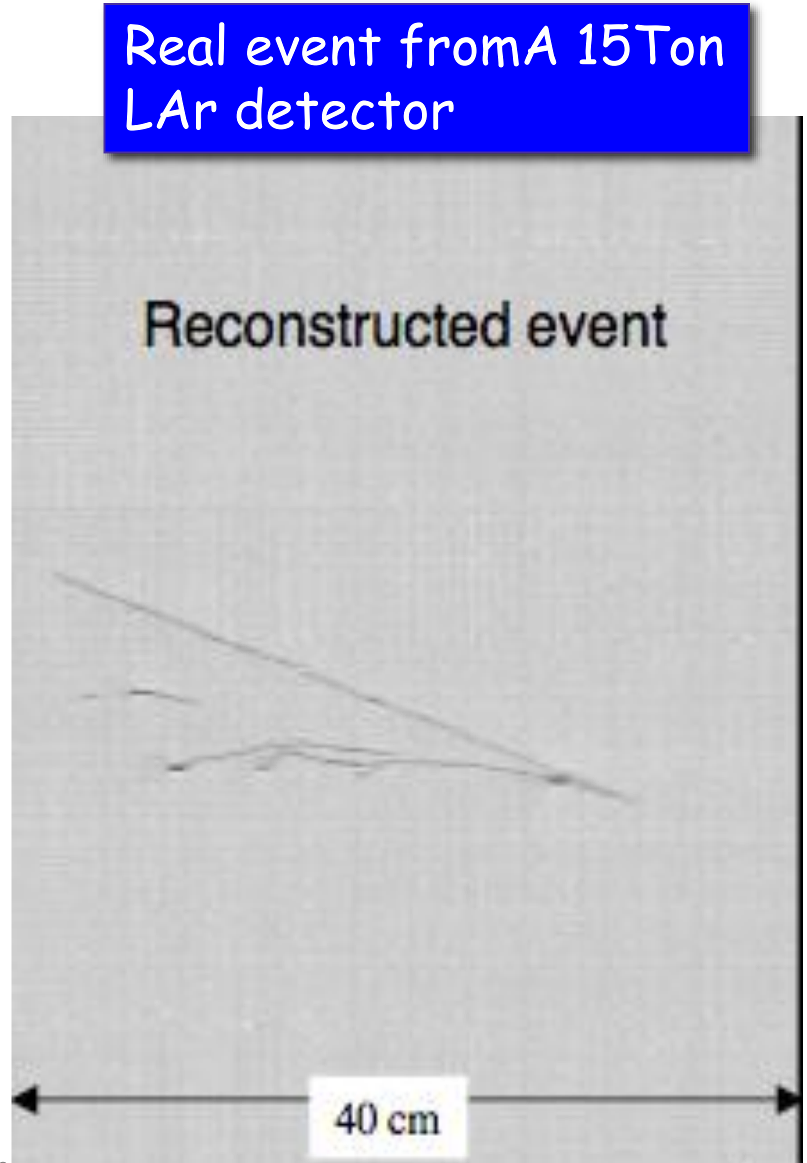
Principle of signal recording

- The *collected charge* is sensed by a ***ultra low noise***, FET charge sensitive pre amplifier
- The signal waveform from individual wires, after being further amplified, filtered and digitized, is continuously stored on a circular memory buffer.
  - ✓The chamber is ***continuously sensitive***.
  - ✓The event is contained in a time window, equal to the maximum drift time



Principle of signal recording II





Ionization electron attachment

- The main limitation for a full collection of the free electron charge in LAr is due to the residual concentration of electro-negative molecules

- The free electron concentration decreases as:

$$\frac{d\left[e^-\right]}{dt} = -k_e\left[O_2\right]\left[e^-\right] \quad \Longrightarrow \quad \left[e^-\right](t) = \left[e^-\right](0)\exp(-t/\tau)$$

- Where the electron lifetime τ_e is:

$$\frac{1}{\tau_e} = k_e\left[O_2\right]$$

- Where the reaction rate $k_e = 1.9\ \mathrm{ppm}^{-1}\ \mu\mathrm{s}^{-1}$

- To reach drift lengths of 1 m, that corresponds to drift time of 1 msec => $[O_2] < 1$ ppb

Scintillation light in Liquid Argon (I)

• The interactions of ionizing particles in LAr cause the formation of both electron-hole (ion) pairs e^--Ar^+ and excited atoms Ar^+ ($Ar^*/Ar^+ \sim 0.21$).

• Both states lead to the formation (with times of the order of tens of picoseconds) of the excited dimer Ar_2^* ($^1\Sigma_u$ singlet state and $^3\Sigma_u$ triplet state)

• The de-excitation of the excited dimer: $Ar_2^* \rightarrow 2Ar + \gamma$ produces a Vacuum Ultra Violet (VUV) photon with $\lambda = 128$ nm ($\sigma \sim 3$ nm) .

• The absolute photon yield depends on the type of ionizing radiation and on its Liner Energy Transfer (LET). For minimum ionizing particles (mip) the photon yield has been measured to be $\sim 4\text{x}10^4\ \gamma$/MeV.

Scintillation light in Liquid Argon (II)

- Time dependence of the scintillation light emission of **pure LAr**:

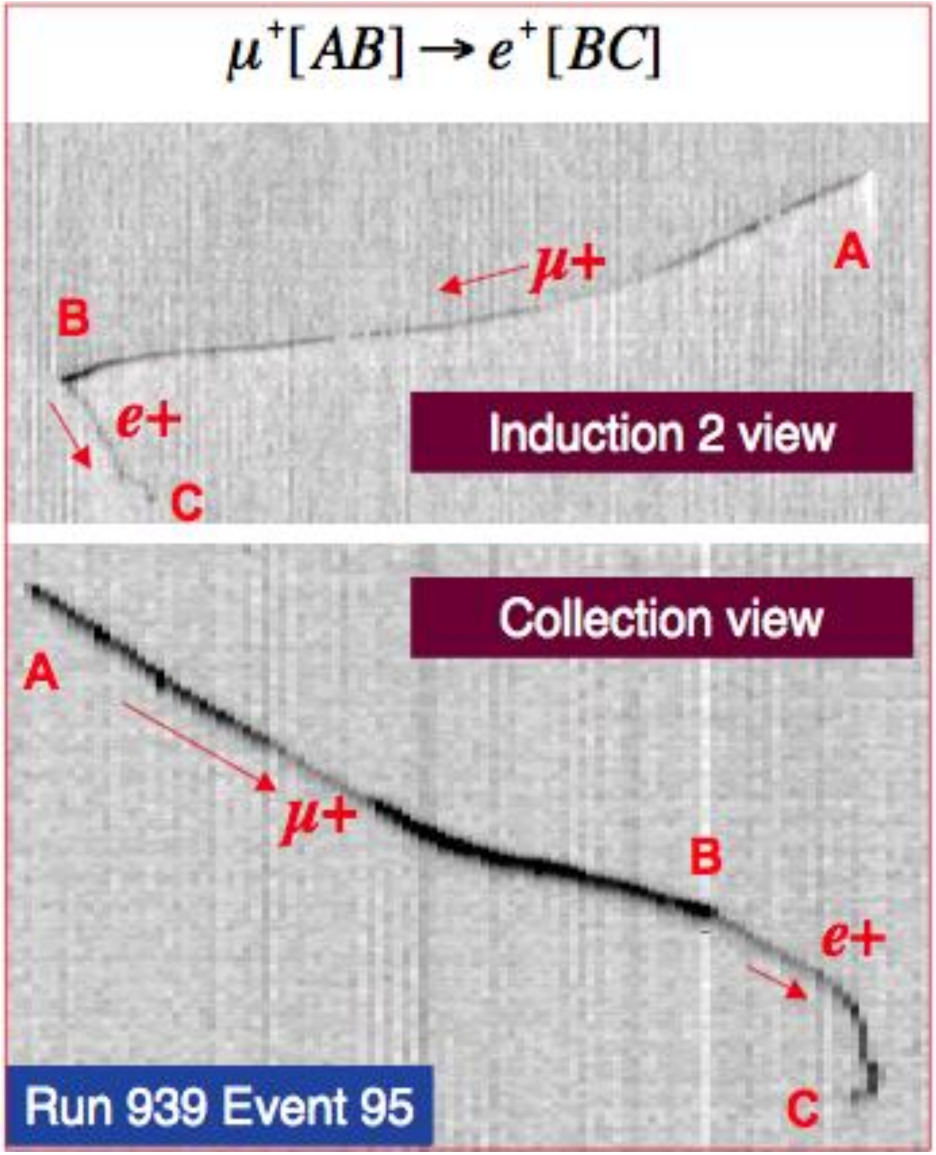
$$\ell(t) = \frac{A_S}{\tau_S}\exp\left(\frac{t}{\tau_S}\right) + \frac{A_T}{\tau_T}\exp\left(\frac{t}{\tau_T}\right)$$

$\tau_s(^1\Sigma_u)$ = 2 - 6 nsec
$\tau_T(^3\Sigma_u)$ = 1100 - 1600 nsec

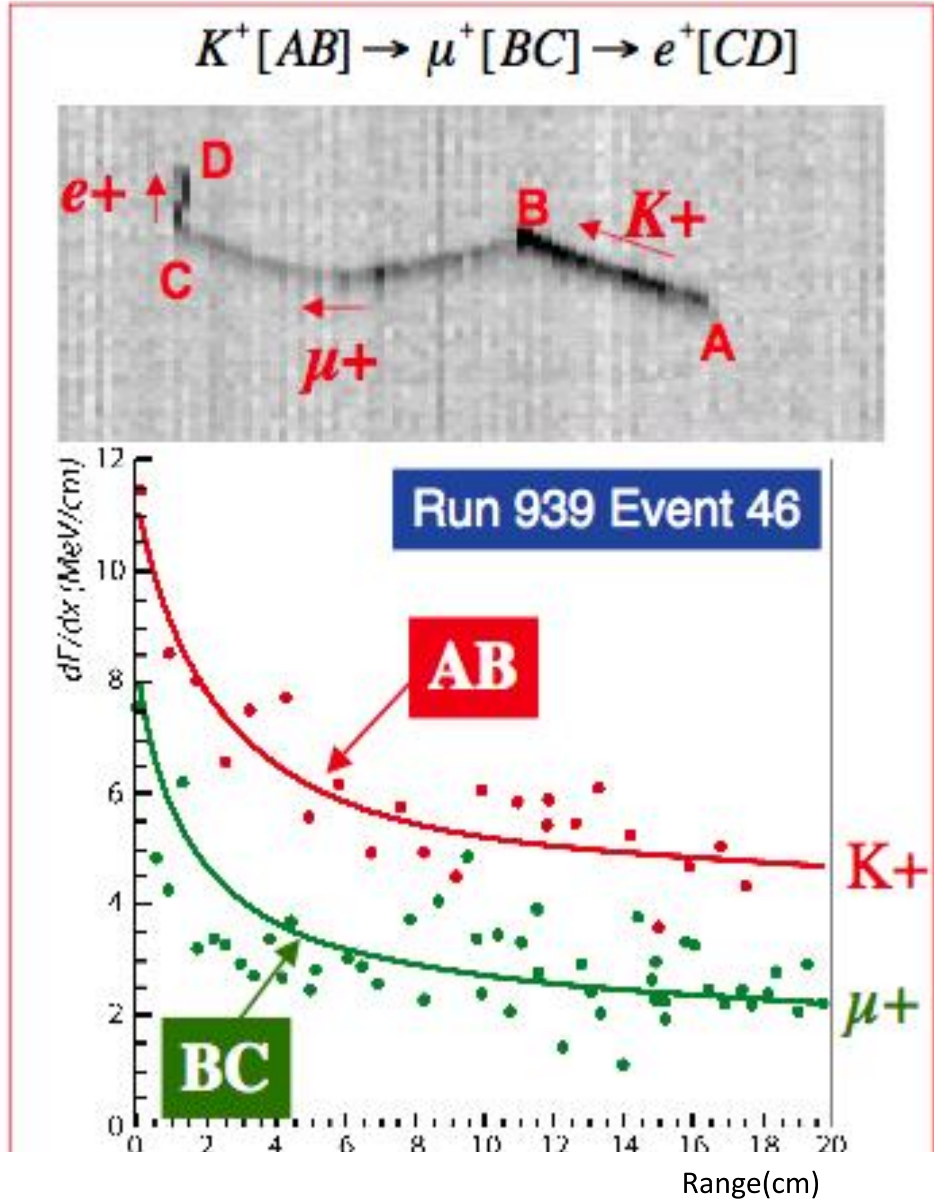
$\int l(t)dt = A_S + A_t = 1$
A_S/A_T depends on ionizing radiation => Used to discriminate different particles

- LAr scintillation photons are in the Vacuum Ultra Violet and need to be shifted to be detected by common photo-sensitive devices
- Scintillation light is shifted by **TetraPhenyl Butadiene** (TPB) that absorbs VUV scintillation light and re-emits it around **430 nm**
- It can be used for triggering and T_0 determination purposes
- It can significantly improve the performance of the TPC in terms of energy resolution and particle discrimination

Particle ID



$\mu^+[AB] \rightarrow e^+[BC]$
A
B
C
μ+
e+
Induction 2 view
Collection view
Run 939 Event 95

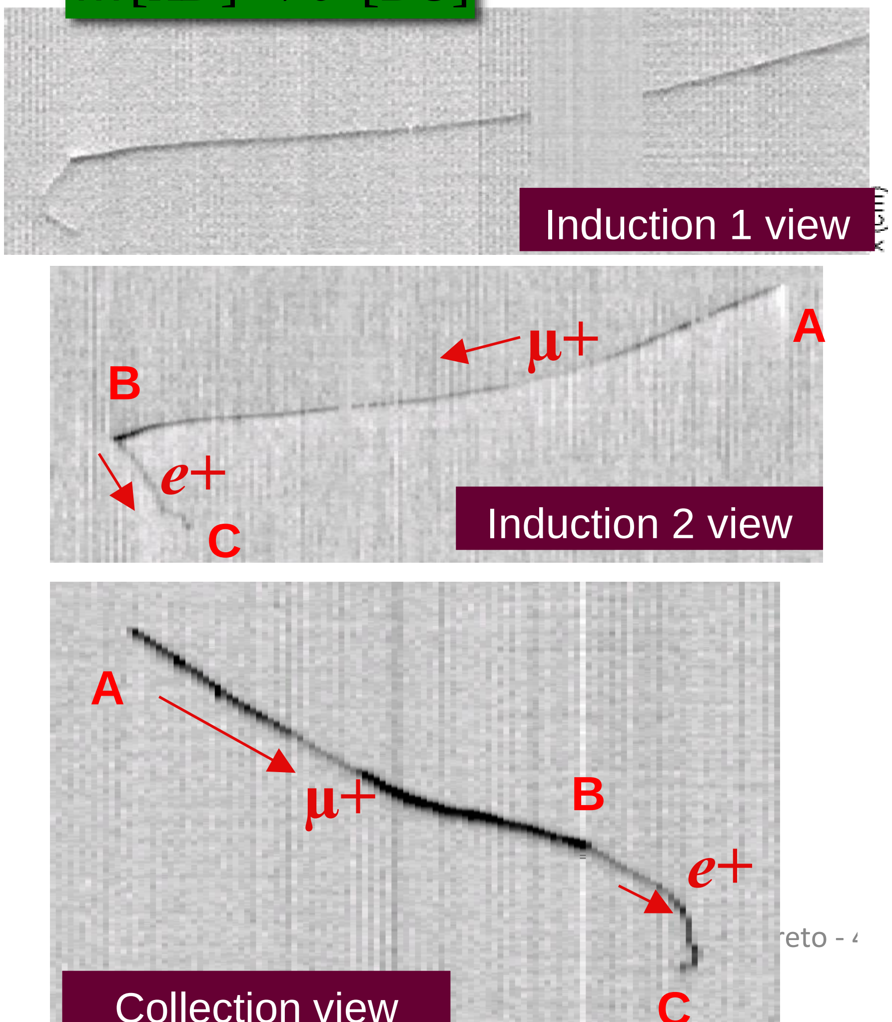


$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$
A
B
C
D
K+
μ+
e+
Run 939 Event 46
dE/dx (MeV/cm)
AB
BC
K+
μ+
0
2
4
6
8
10
12
14
16
18
20
Range(cm)

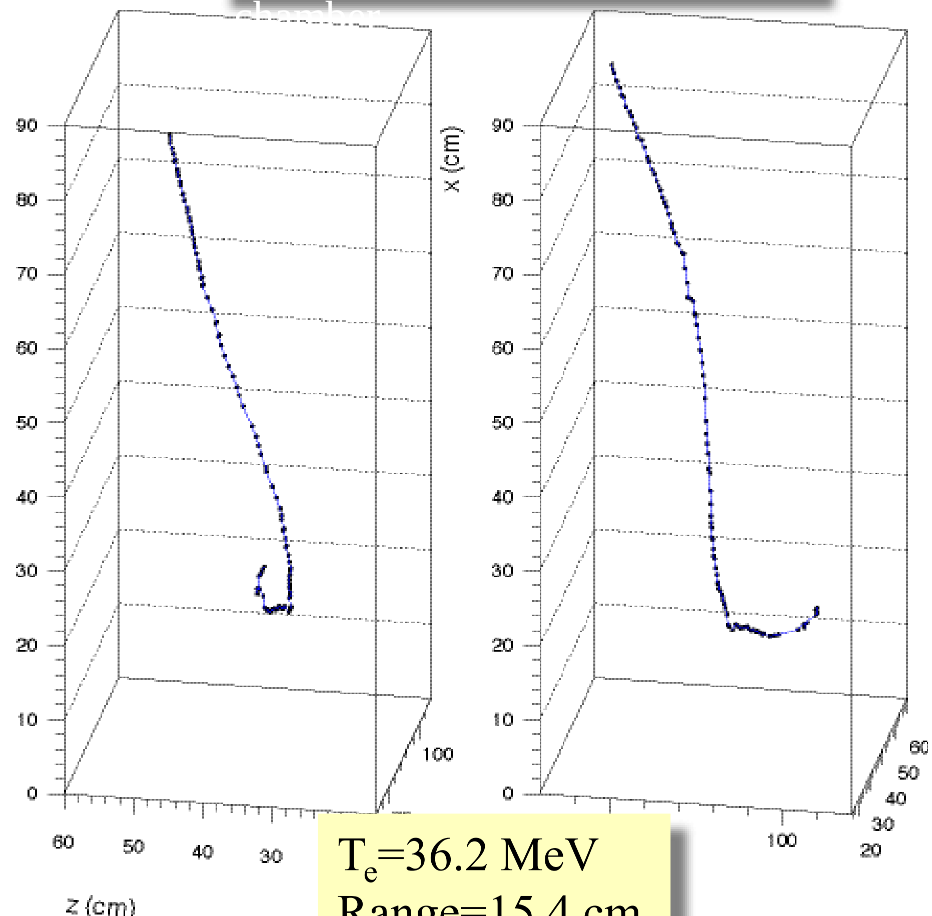
3d recontruction

Detector with ***three view 60° apart*** --> it is possible to ***reconstruct the events in space***, using the redundancy of coordinates

$m^{+}[AB] \rightarrow e^{+}[BC]$

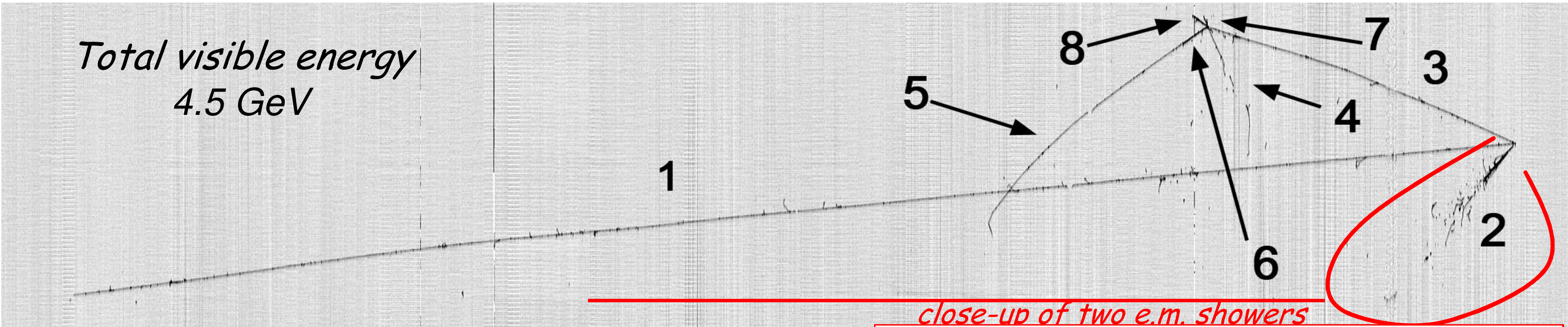


Run 939 Event 95 Right chamber



T_e=36.2 MeV
Range=15.4 cm

A neutrino event



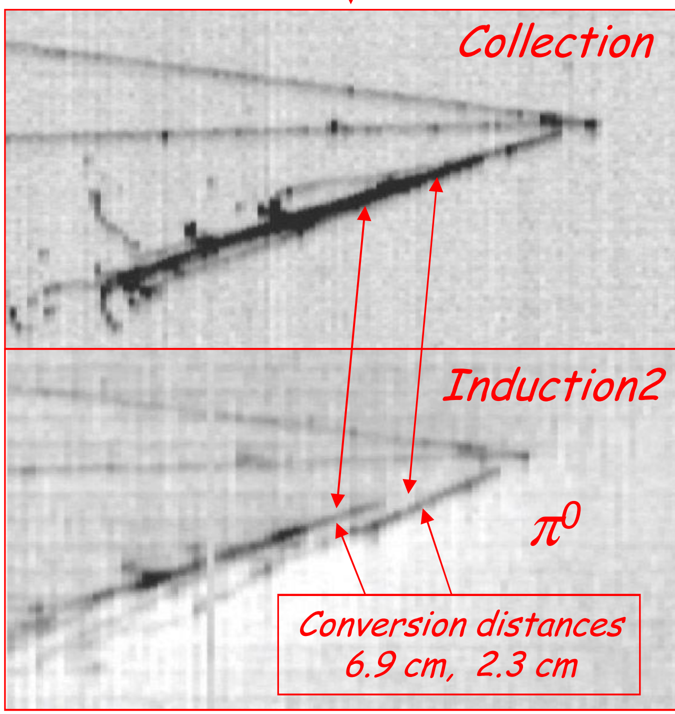
Primary vertex (A):

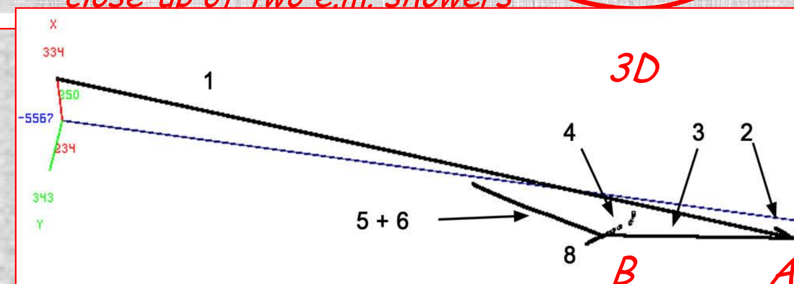
very long (1), e.m. cascades (2), pion (3)

Secondary vertex (B):

*The longest track (5) is a μ coming from stopping **k** (6).*

μ decay is observed





Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2	520.82	0.054	-0.420	-0.906
3 (p)	514.04	-0.001	0.137	-0.991
Sec. vtx.	797			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

The DUNE Collaboration

As of today:

60 % non-US

945 collaborators from 161 institutions in 30 nations

Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, **UK**, Ukraine, USA

DUNE has broad international support and is growing

Continued Progress…

DUNE experiment: science program

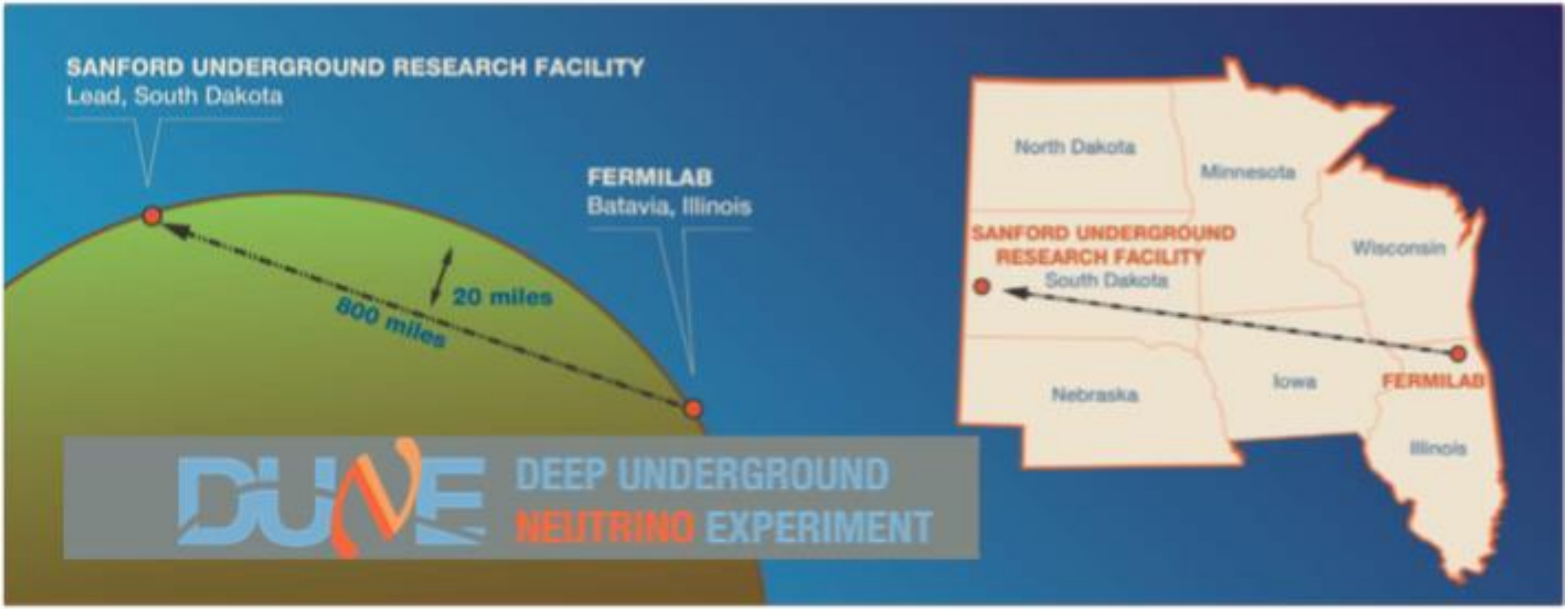
Fundamental open questions in particle and astroparticle physics:

- Neutrino oscillation physics
  - ✓ CP violation in the leptonic sector
  - ✓ Mass hierarchy
  - ✓ Precision oscillation physics to test the 3-flavour paradigm

- Nucleon decay
  - ✓ Predicted in beyond the Standard Model theories [but not yet seen]
  - ✓ e.g. the SUSY favored mode: $p \rightarrow K^{+}\overline{n}$

- Supernova burst physics and astrophysics
  - ✓ Galactic core collapse Supernova, unique sensitivity to ν_e

DUNE/LBNF: the Long Baseline Neutrino program



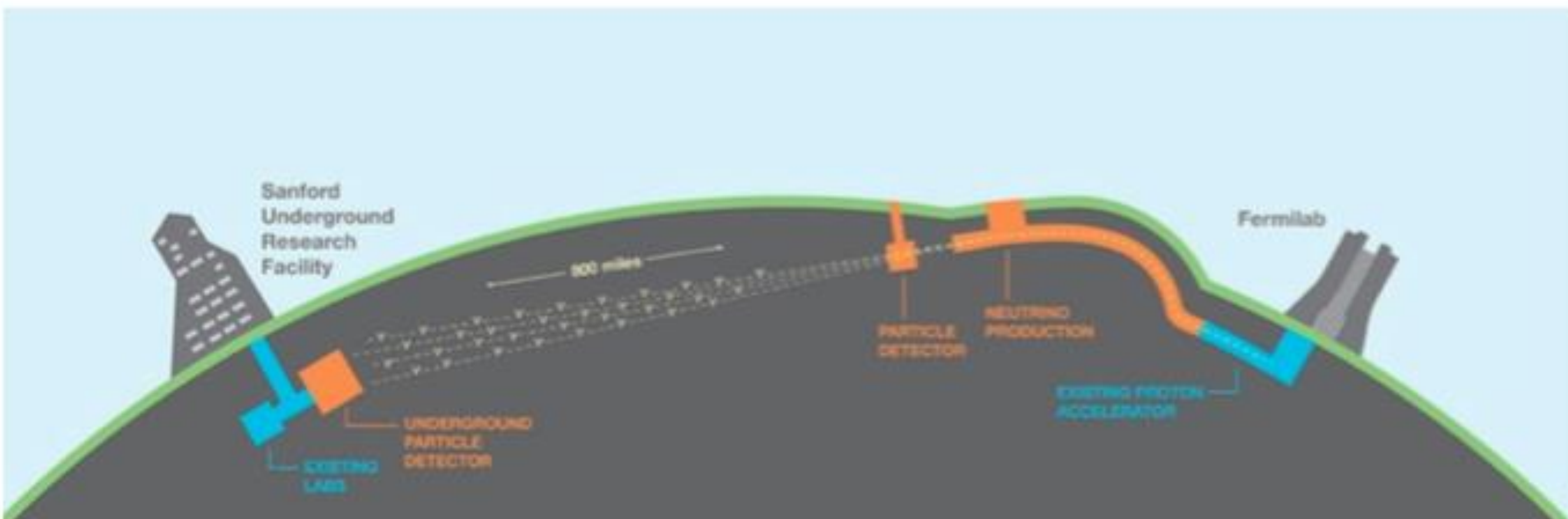
DUNE/LBNF: the Long Baseline Neutrino program

- **LBNF:** The Long-Baseline Neutrino Facility will build the infrastructure necessary to send a powerful beam of neutrinos 800 miles straight through the earth, and measure them deep underground at South Dakota's Sanford Underground Research Facility.
- LBNF supports **DUNE,** the Deep Underground Neutrino Experiment. The international DUNE scientific collaboration will construct and operate massive neutrino measurement apparatus at Fermilab and in South Dakota.
- The DUNE/LBNF project will be the first internationally conceived, constructed and operated mega-science project hosted by the Department of Energy in the United States.

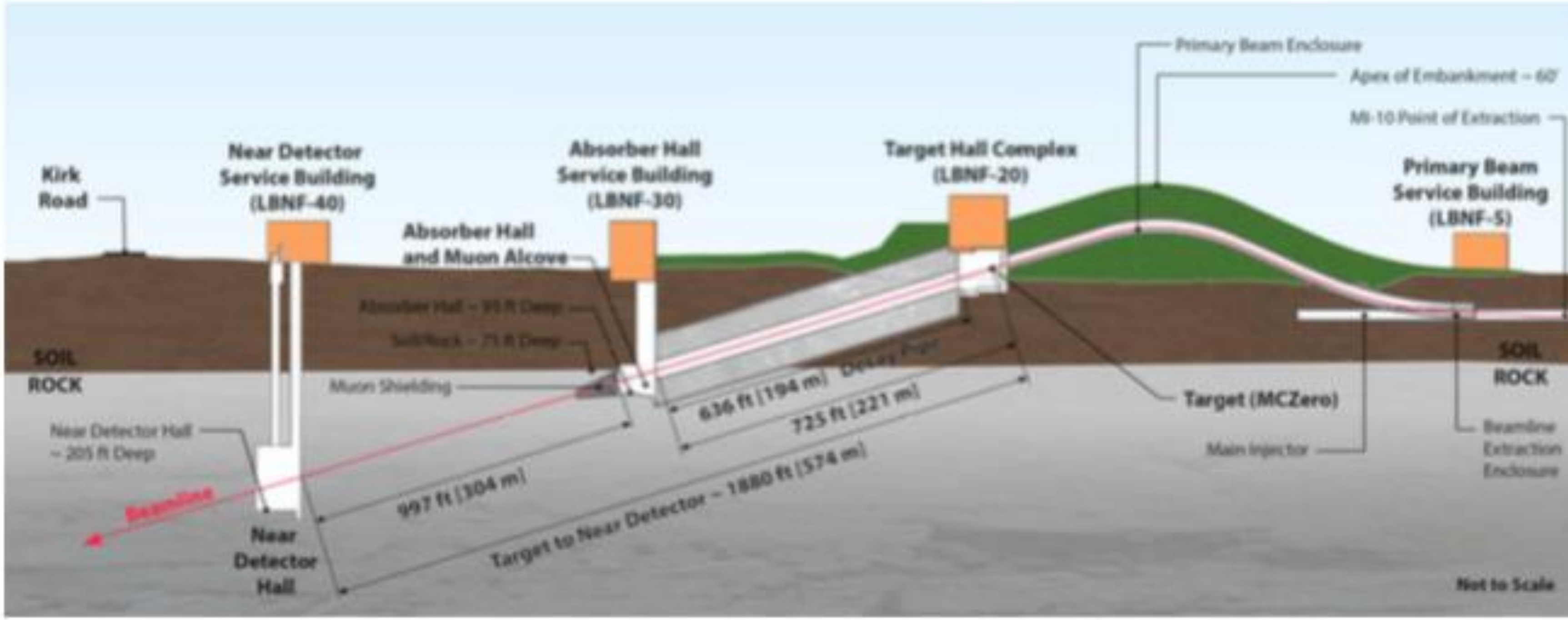
LBNF will drive neutrino science forward the way CERN's Large Hadron Collider drove ATLAS/CMS Higgs discovery.

LBNF:
The Long-Baseline Neutrino Facility in Illinois and South Dakota

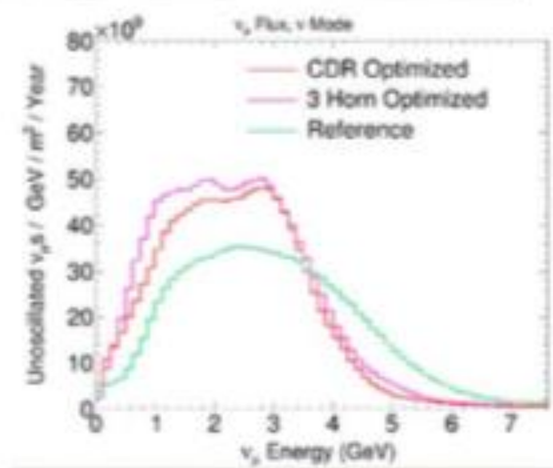
- Fermilab, host laboratory for DUNE/LBNF, will house the particle accelerators to create the neutrinos, and apparatus to measure them as they leave the site.
- The Sanford Underground Research Facility in Lead, SD will house the massive detectors one mile underground in the former Homestake gold mine to catch the neutrinos when arriving at the far site.



"Near Site" - LBNF at Fermilab, Batavia, IL

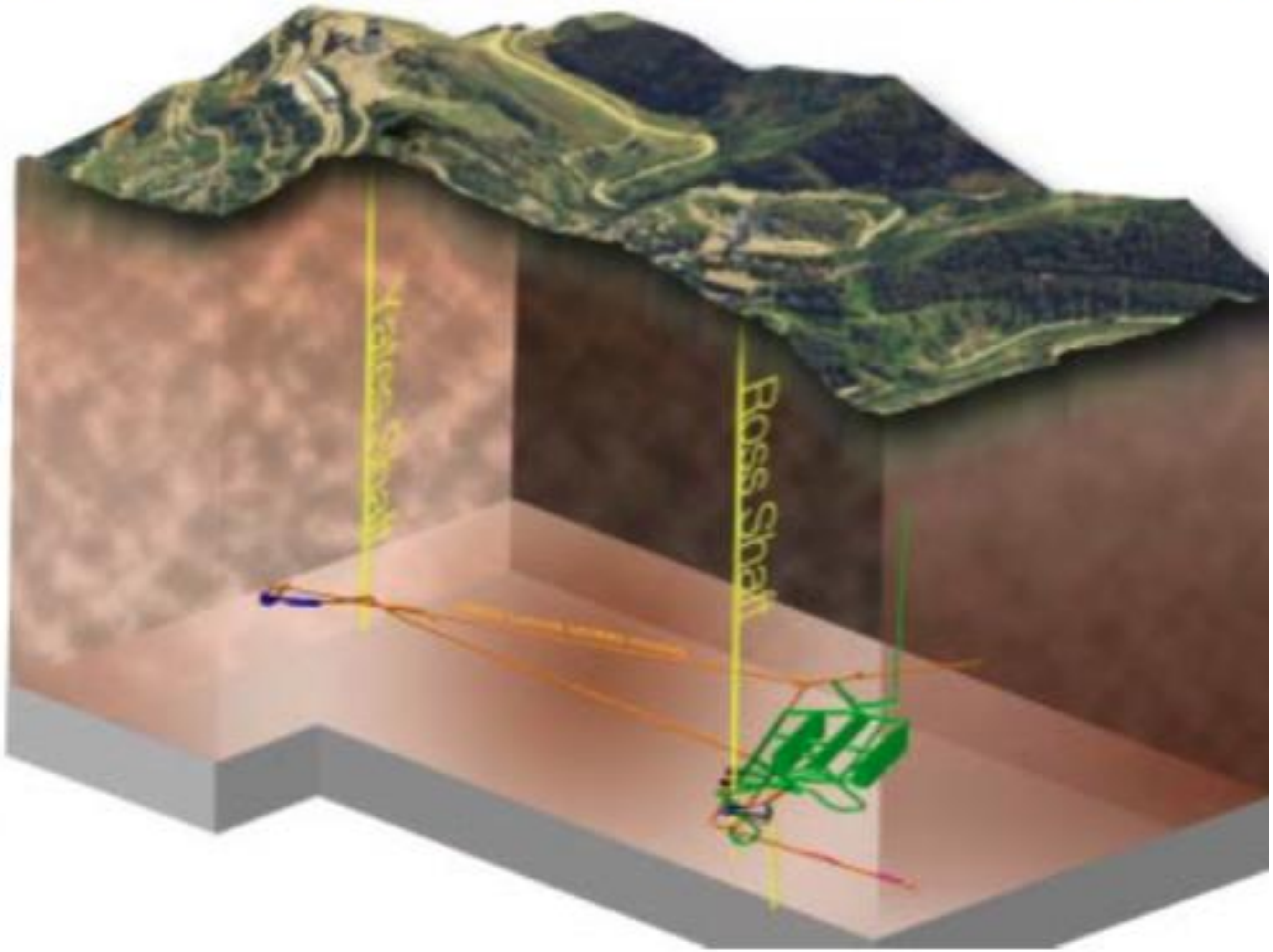


- Lab already home to world's most powerful neutrino beams
- LBNF will use primary protons 60-120 GeV from Main Injector utilizing improvements from PIP-II with 1.2 MW beam power upgradable to 2.4 MW
- Beamline aimed at South Dakota planned for completion in 2025



"Far Site" – LBNF at Sanford Lab, Lead, SD

- Major underground excavation removing ~800,000 tons of rock
- Two massive caverns at 4850L housing four membrane cryostats each 62m(L) x 14m(w) x 15m(h) and a central utility space
- 70,000 tons of cryogenic liquid argon to fill the cryostats
- "Ship in a bottle" detector construction 1 mile underground using existing, refurbished mine shaft

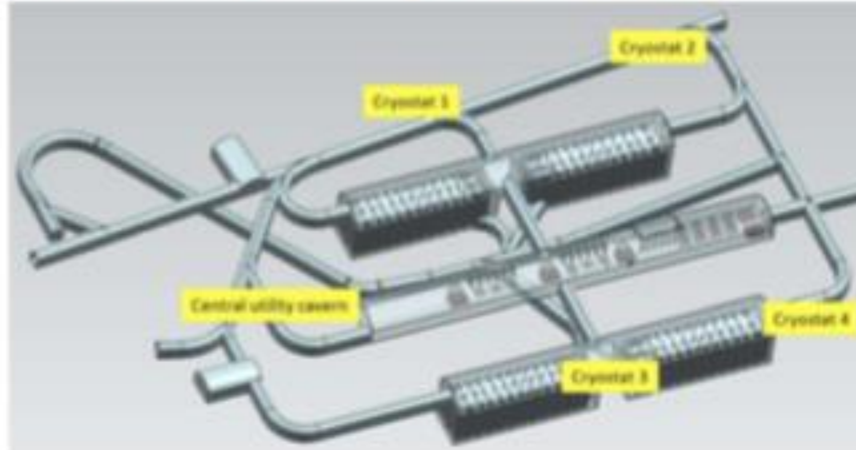


US President Budget includes budget for LBNF pre-excavation work in FY2017 (starts October 2016) - US Congress authorises start of construction

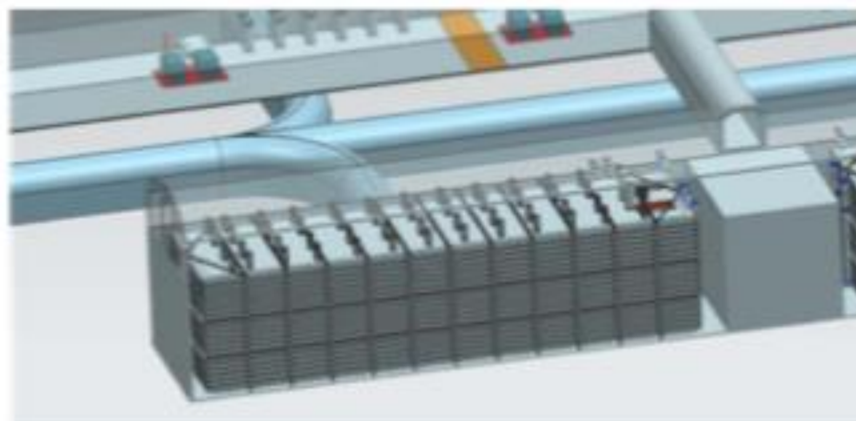
"Far Site" – LBNF/DUNE at Sanford Lab, Lead, SD

- **Conventional Facilities**:
  - Surface and shaft Infrastructure including utilities
  - Central utility cavern for conventional and cryogenic equipment
- **Cryogenic Systems**:
  - LN2 refrigeration system for cooling and re-condensing gaseous Argon
  - Systems for purification and recirculation of LAr
- **Cryostats**:
  - Four membrane cryostats supported by external steel frames

LBNF facilities will support the DUNE experiment



4850L cavern and drift layout

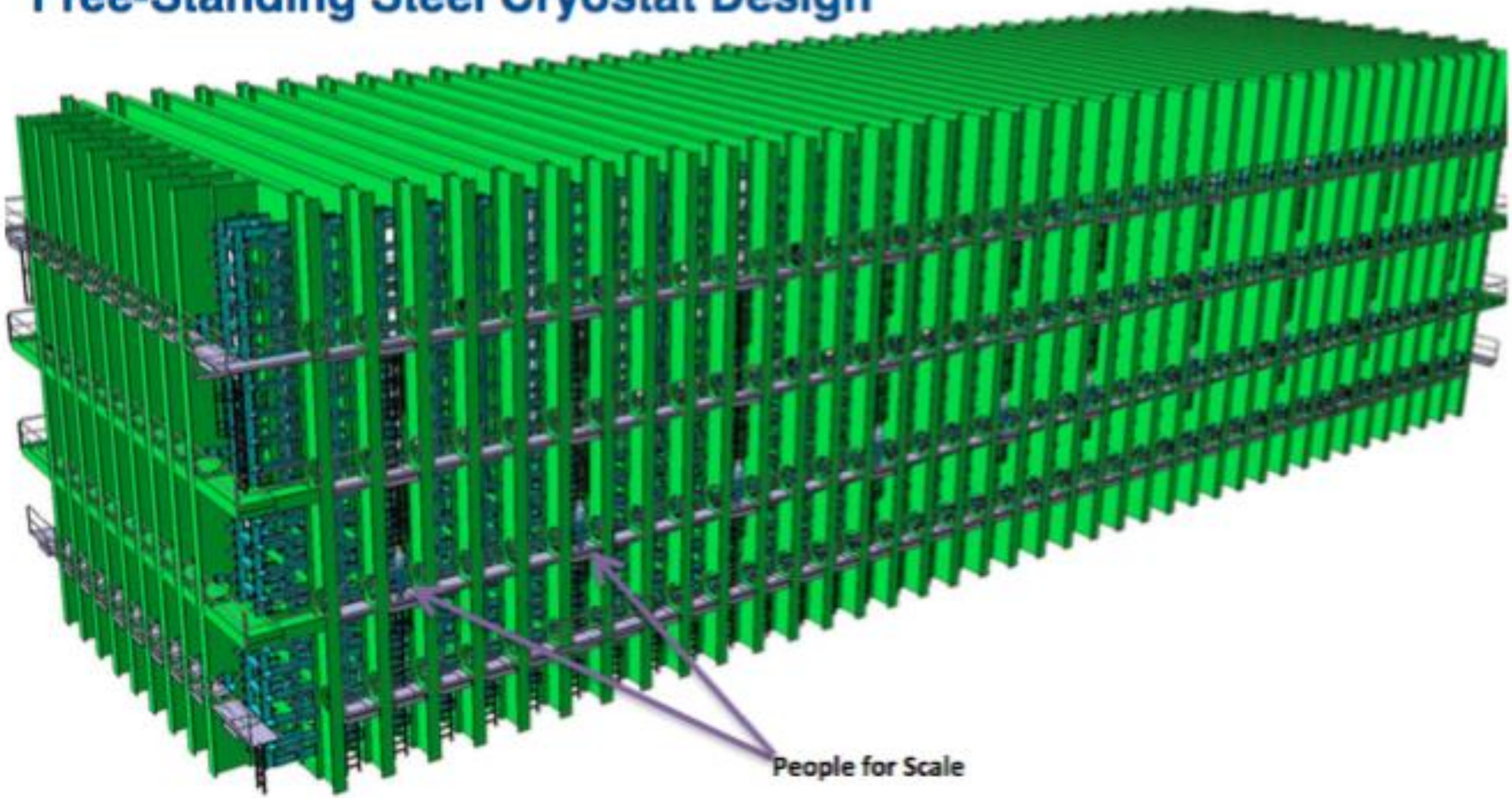


Single cryostat

- **DUNE LAr-TPC Detectors inside cryostats (4 x 10kt LAr active mass)**

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

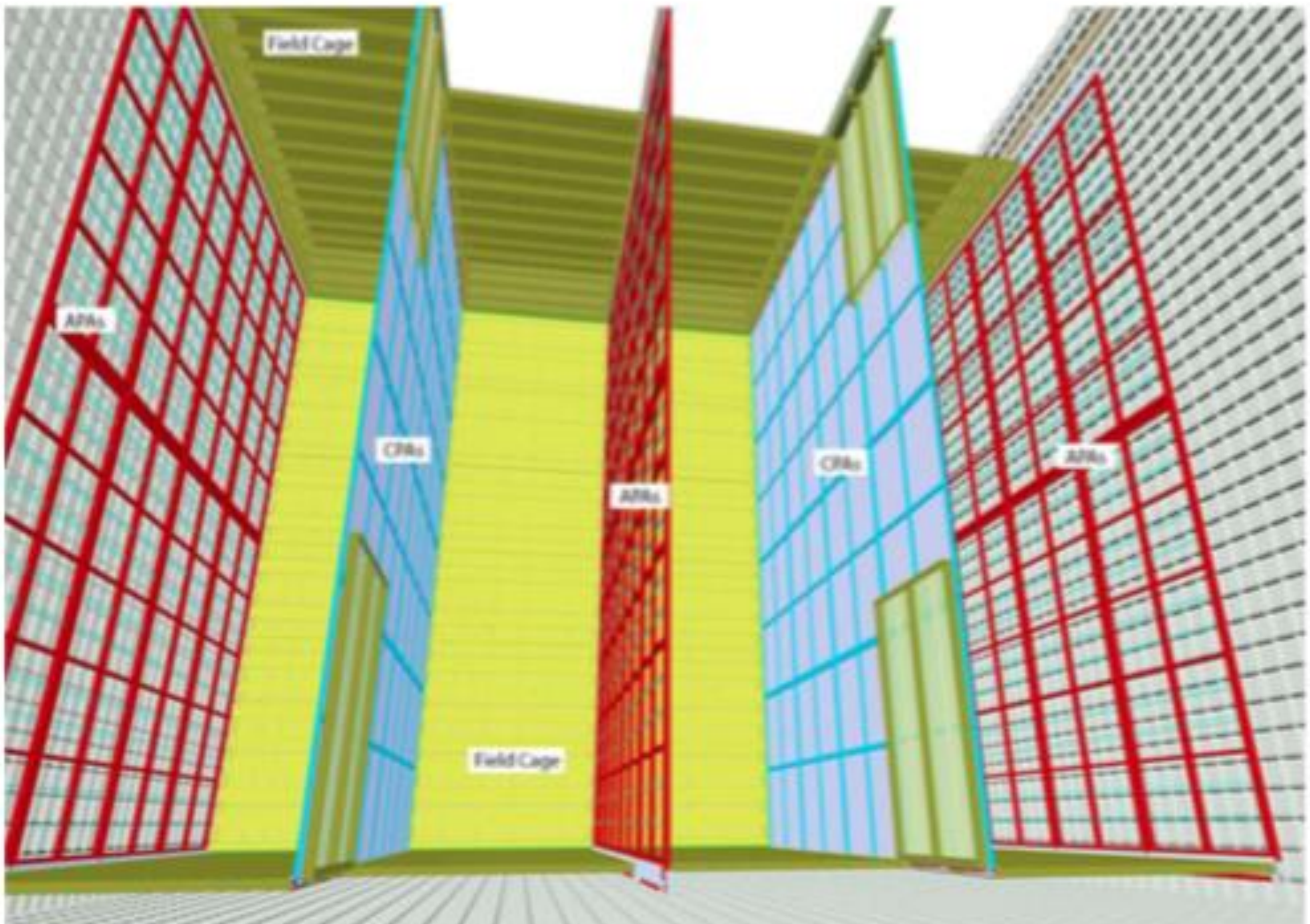
Free-Standing Steel Cryostat Design

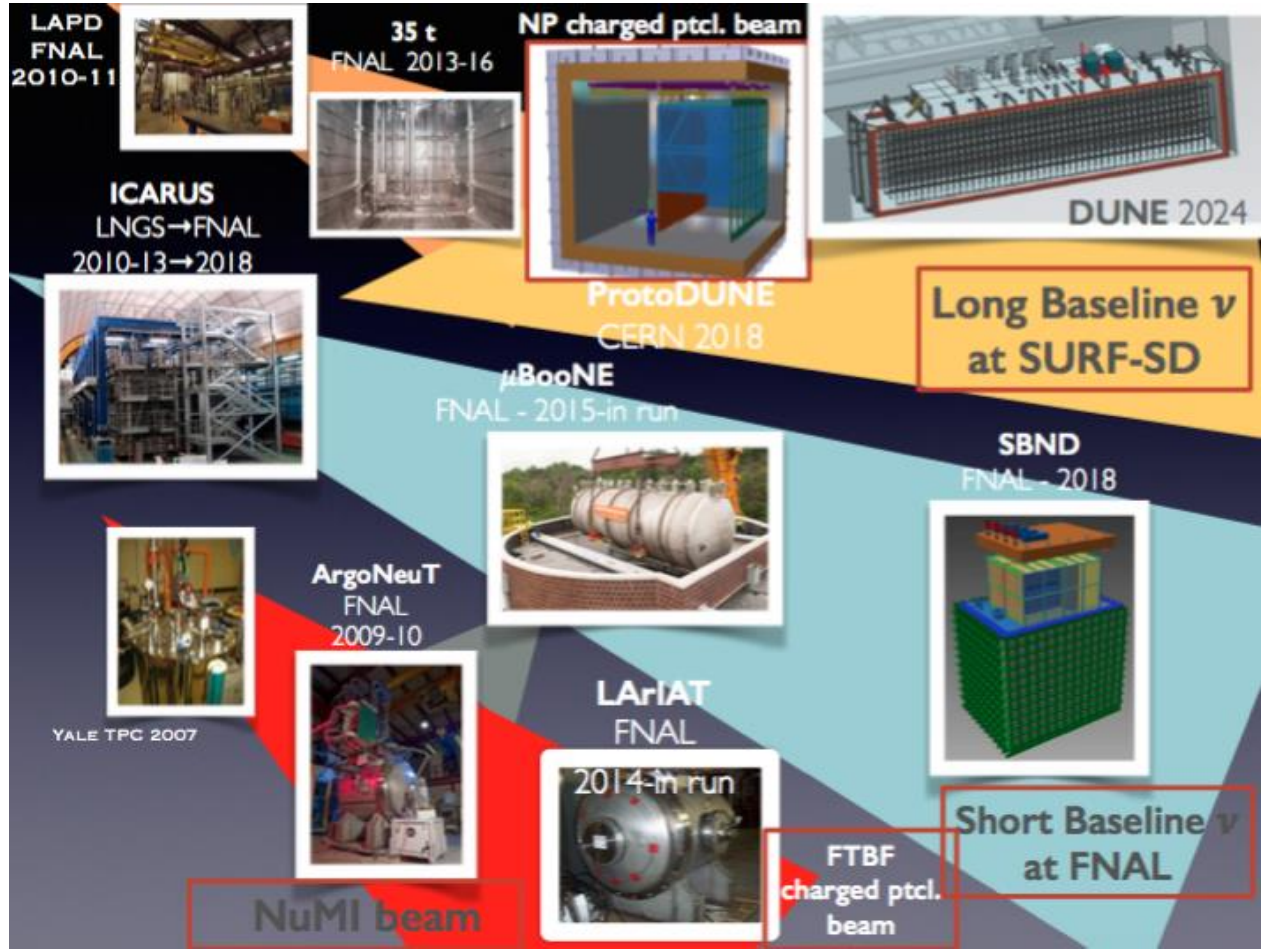


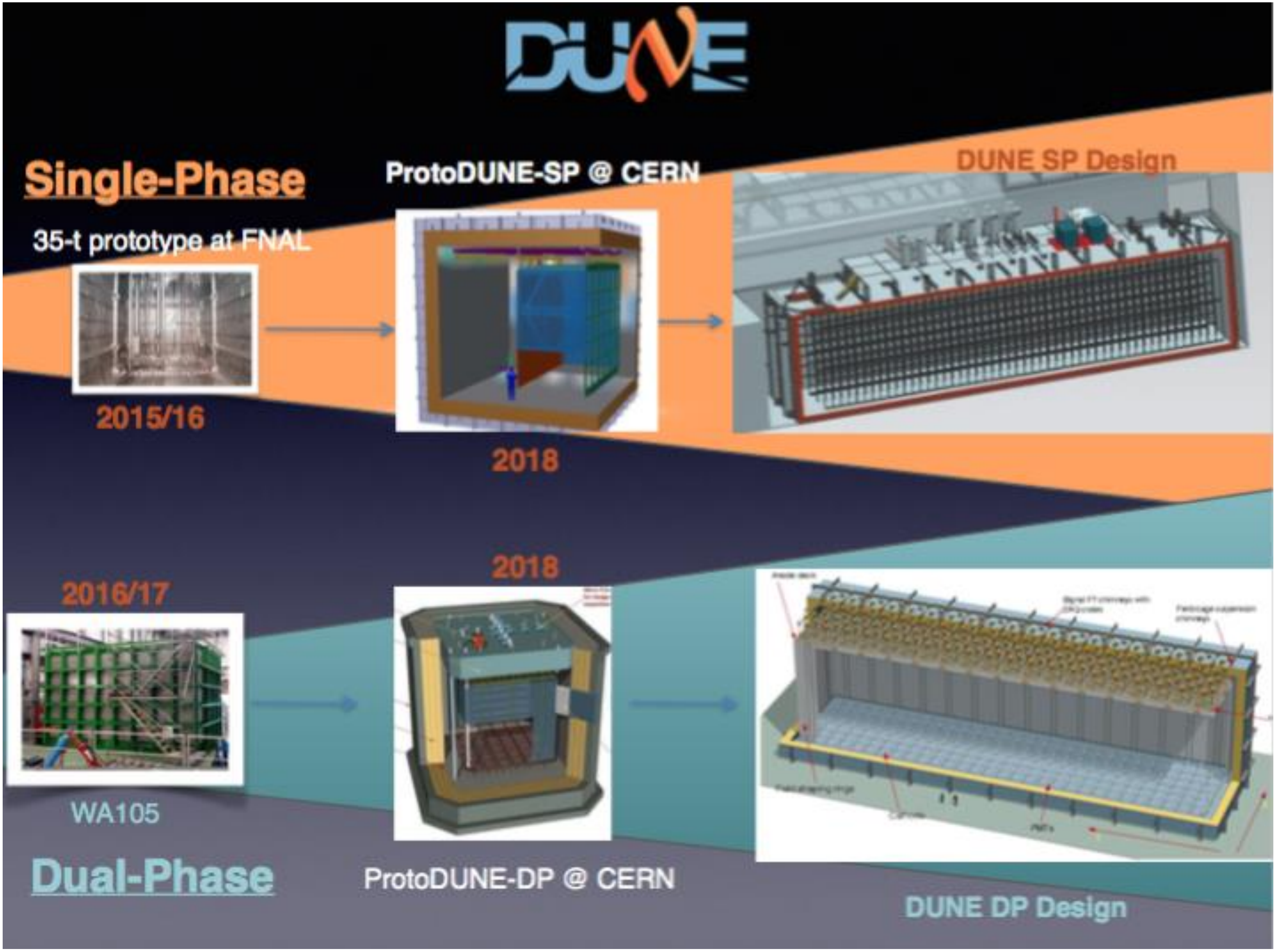
External (Internal) Dimensions
19.1m (15.1m) W x 18.0m (14.0m) H x 66.0m (62.0m) L

DEEP UNDERGROUND NEUTRINO EXPERIMENT .. LArTPC inside cryostat

The TPC for a single 10kTon detector consists of three rows of anode planes, 2
high and 25 planes long (150 APAs total)




LAPD
FNAL
2010-11
35 t
FNAL 2013-16
NP charged ptcl. beam
DUNE 2024
ICARUS
LNGS→FNAL
2010-13→2018
ProtoDUNE
CERN 2018
Long Baseline ν
at SURF-SD
μBooNE
FNAL - 2015-in run
SBND
FNAL - 2018
ArgoNeuT
FNAL
2009-10
Yale TPC 2007
LArIAT
FNAL
2014-in run
FTBF
charged ptcl.
beam
Short Baseline ν
at FNAL
NuMI beam


DUNE
Single-Phase
35-t prototype at FNAL
2015/16
ProtoDUNE-SP @ CERN
2018
DUNE SP Design
2016/17
WA105
2018
ProtoDUNE-DP @ CERN
DUNE DP Design
Dual-Phase

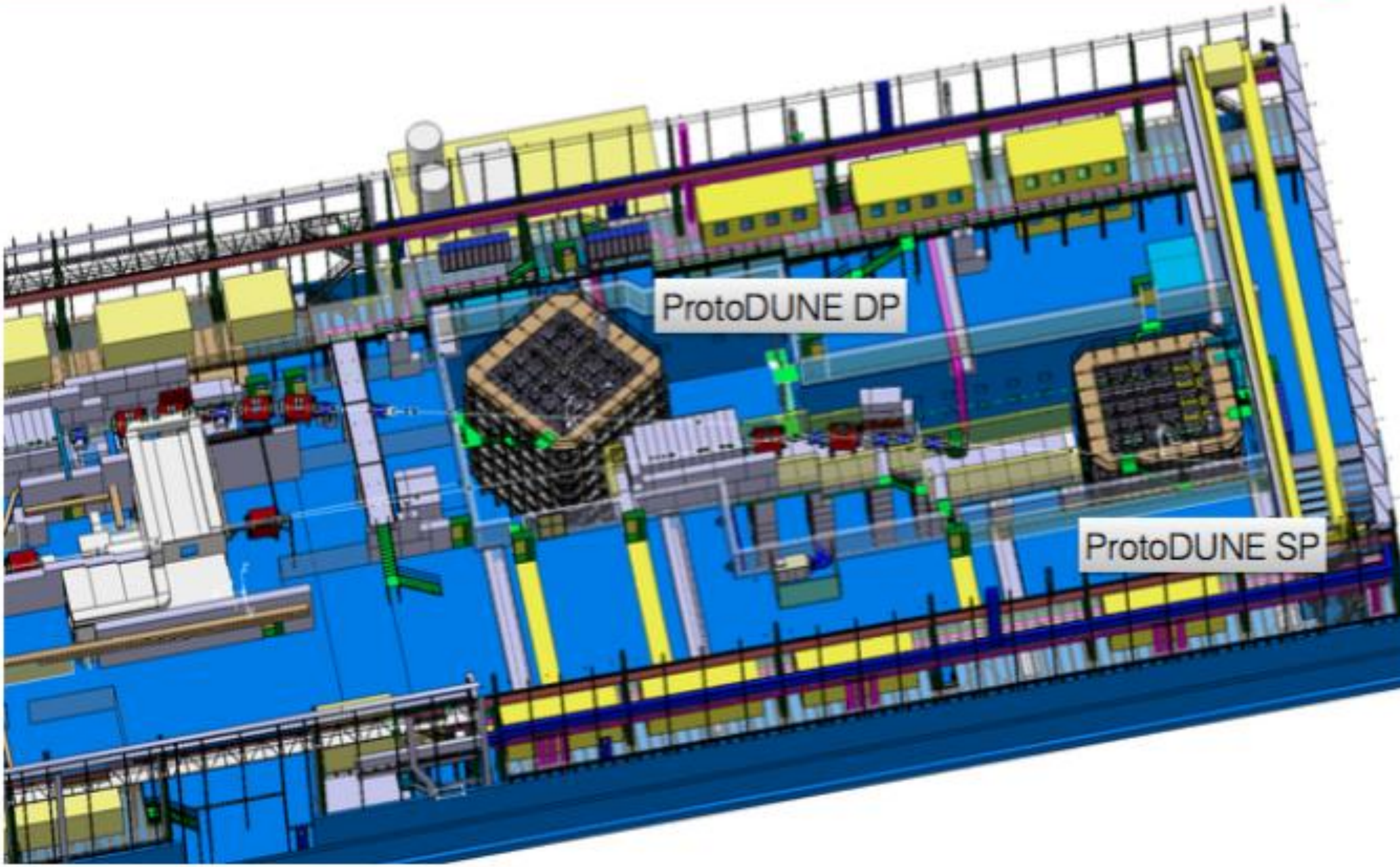
ProtoDUNE within DUNE

ProtoDUNE is a central part of the DUNE strategy for construction of the Far Detector

- *Production*: stress testing of the production and quality assurance processes of the detector components will mitigate the associated risks for the far detector.
- *Installation*: test of the interfaces between the different elements and will mitigate the associated risks for the far detector.
- *Operation* (cosmic-ray data): provide validation of the design and performance.
- *Test beam* (data analysis): essential detector and physics calibration benchmarks.

Prototyping, Risk Mitigation & Essential Calibration Data

Large prototype(s) for LBNF/DUNE at the new CERN Neutrino Platform



ProtoDUNE SP at CERN:

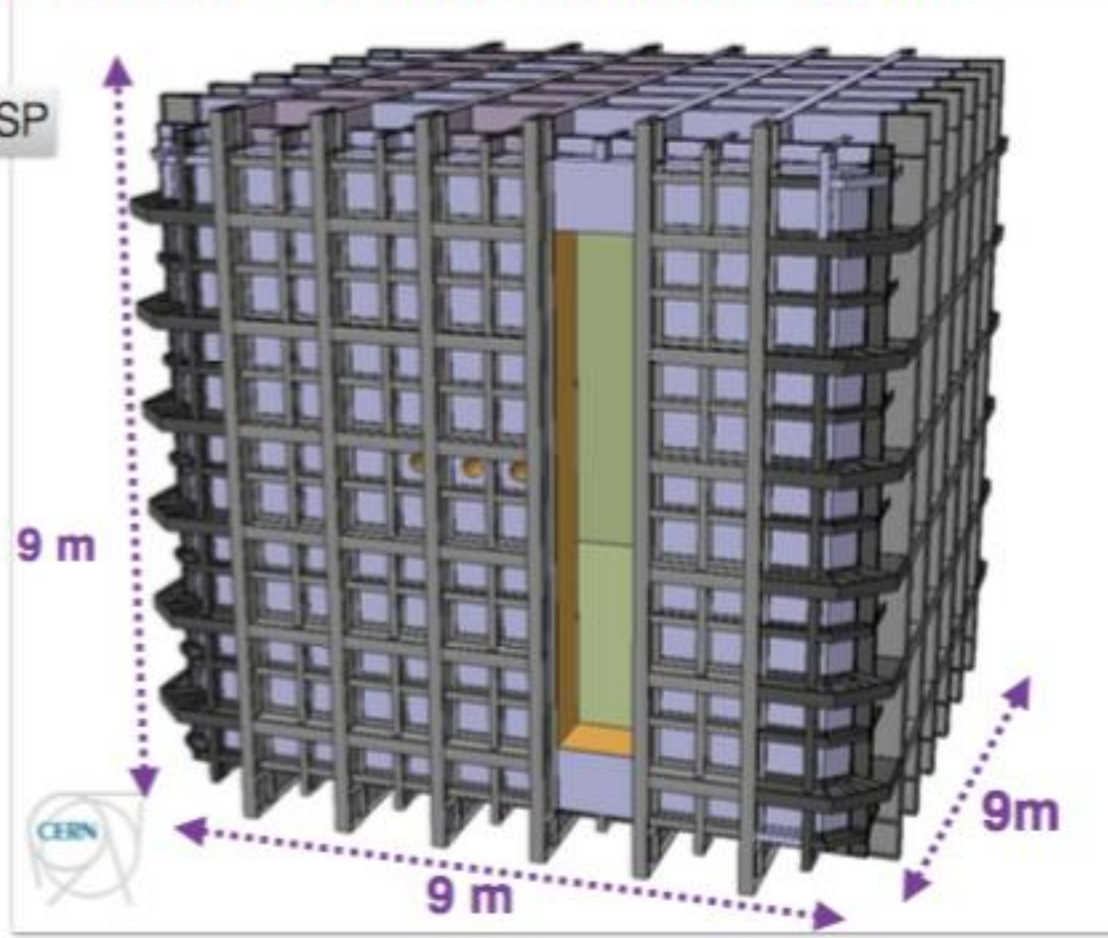
DEEP UNDERGROUND NEUTRINO EXPERIMENT

the ProtoDUNE cryostat at the Neutrino-Platform - update

ProtoDUNE SP

Membrane Cryostat: major contribution by CERN

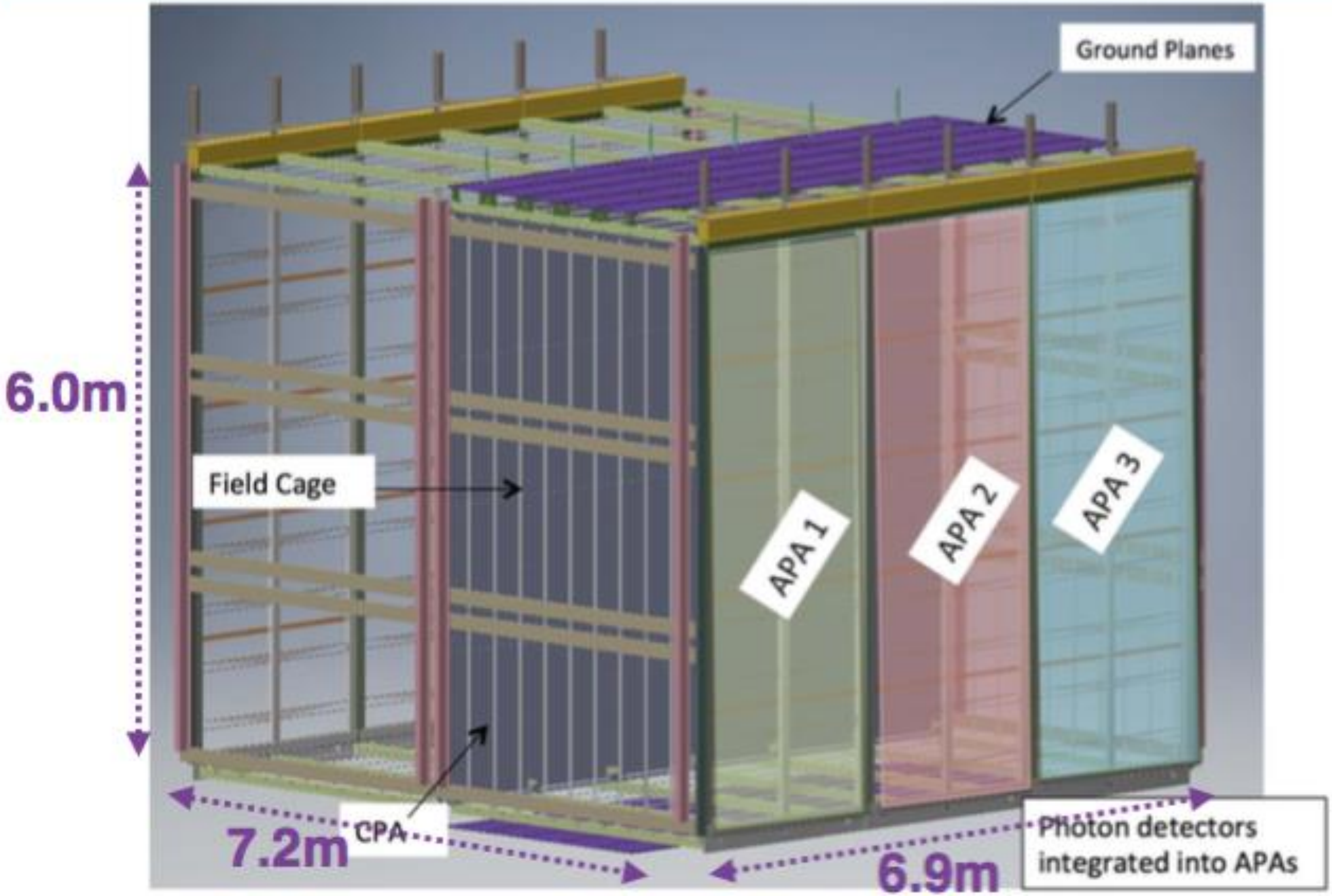
- **Goal: cryostat ready by spring 2017**

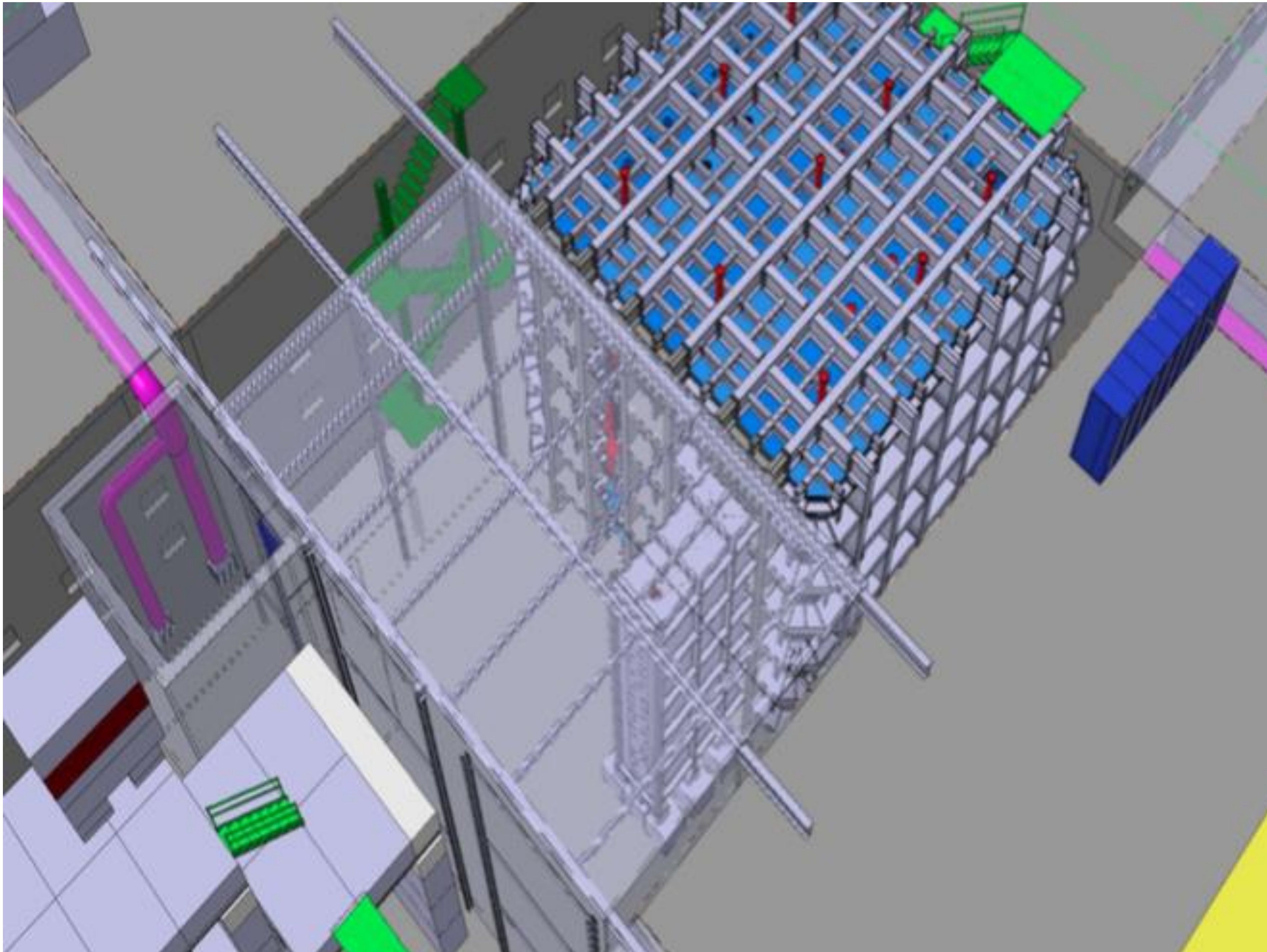


TEMPORARY CONSTRUCTION OPENING

ProtoDUNE SP

The LAr-TPC detector



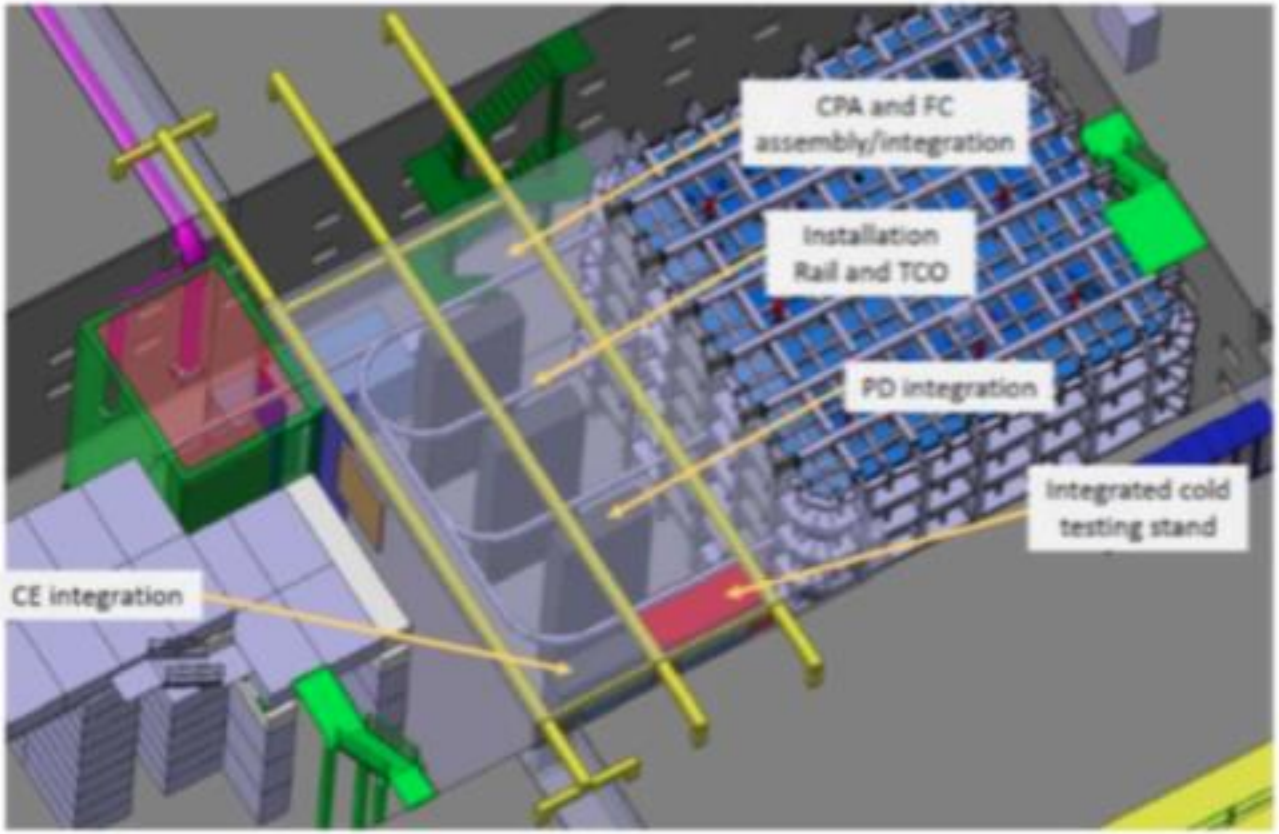


ProtoDUNE SP at CERN:

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Detector integration and installation - update

Conceptual view of installation area in Pit B EHN1



ProtoDUNE SP

“Sterile” neutrinos ?

- Sterile neutrinos are a hypothetical type of neutrino that *does not interact via any of the fundamental interactions* of the Standard Model except gravity.

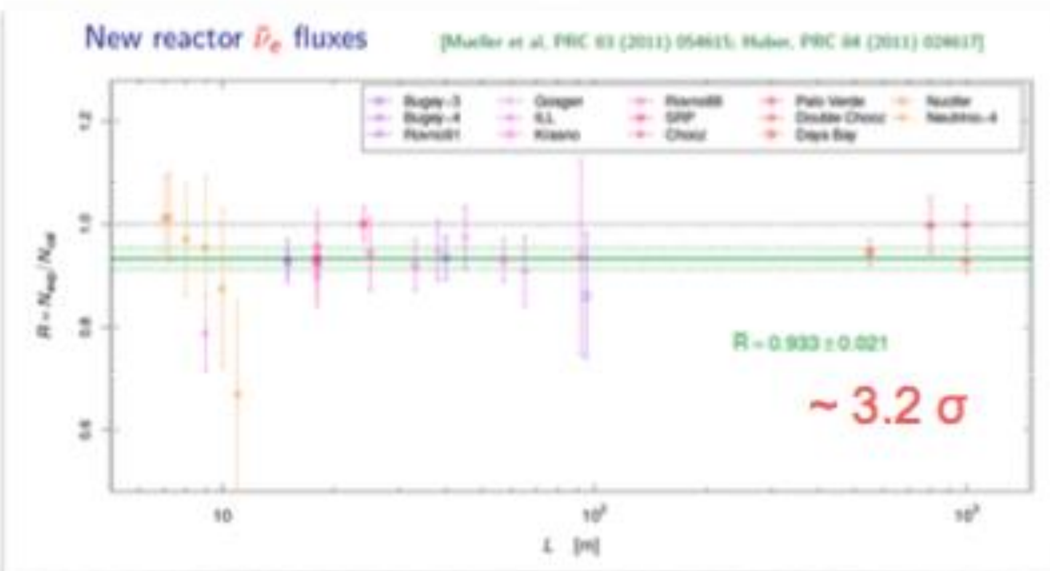
- Since per se they may not interact directly, they are extremely difficult to detect. If they are heavy enough, they may also contribute to dark matter.

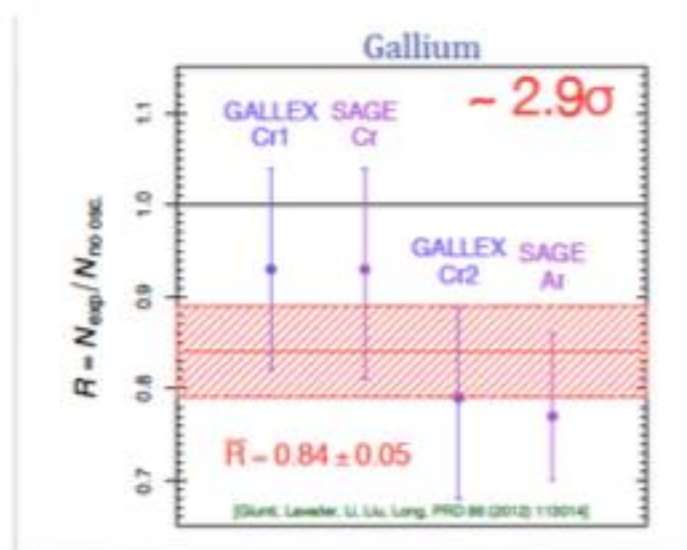
- Sterile neutrinos may mix with ordinary neutrinos via a mass term. Evidence may be building up by ***“anomalies”*** observed by several neutrino experiments:
  - ✓ sterile neutrino(s) with $\Delta m^2 \approx 10^{-2}$ — 1 eV^2 from ν_e observation in ν_μ *accelerator experiments* (LNSD anomaly).
  - ✓ Neutrino disappearance may have been observed in *nuclear reactors* and very intense (megacurie) *electron conversion neutrino sources* with maybe comparable mass differences

Short-Baseline Neutrino Anomalies (I)

In recent years, two classes of experimental “neutrino anomalies” have been reported from measurement at short-baseline:

(I) An apparent ν_e disappearance signal in the low energy anti-neutrinos from nuclear reactors (“reactor anomaly”) and from radioactive neutrino sources in the Gallium experiments (“Gallium anomaly”)

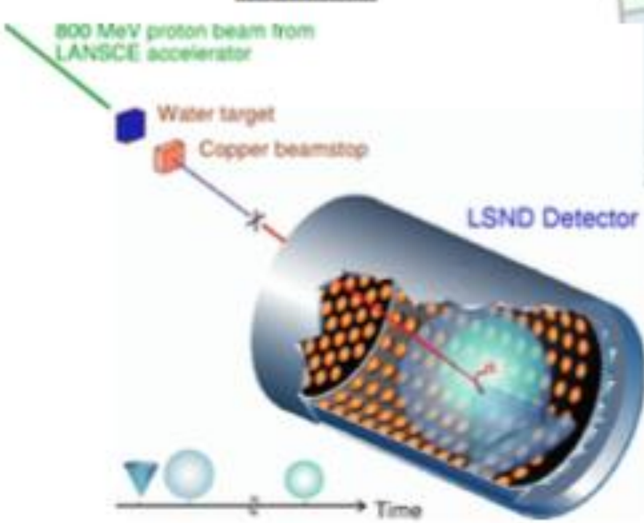




Short-Baseline Neutrino Anomalies (II)

(II) Evidence for an electron-like excess from neutrinos from particle accelerators (the "LSND and Mini-BooNE anomalies")

LSND



MiniBooNE

Short-Baseline Accelerator Anomalies

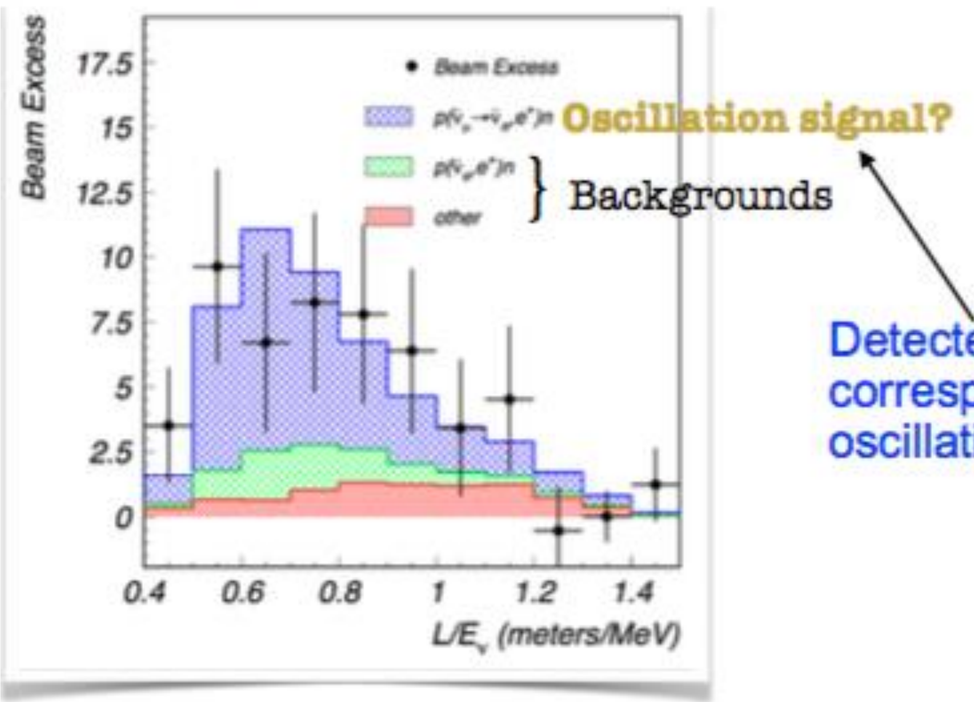
LSND

Baseline 30 m
E= [20 – 50] MeV
L/E ≈ 1 m/MeV

Low energy $\overline{\nu}_\mu$ beam from a decay-at-rest pion beam (Los Alamos)

167 tons liquid scintillator

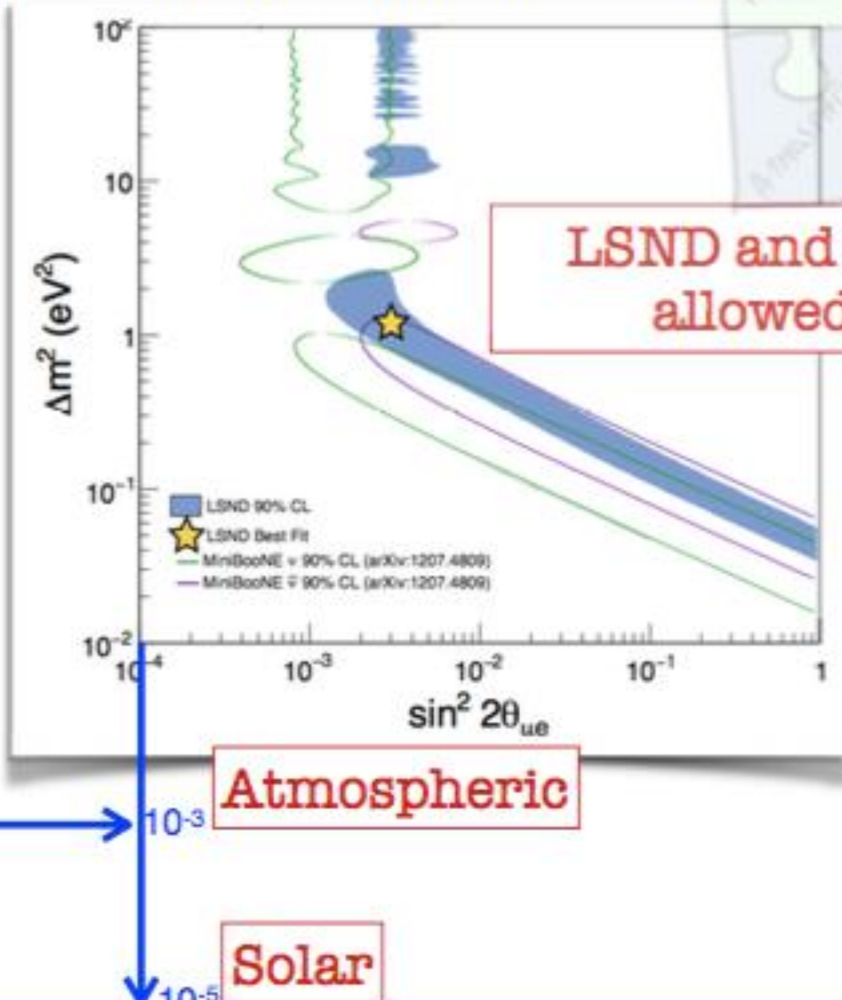
PRD 64 (2001) 112007



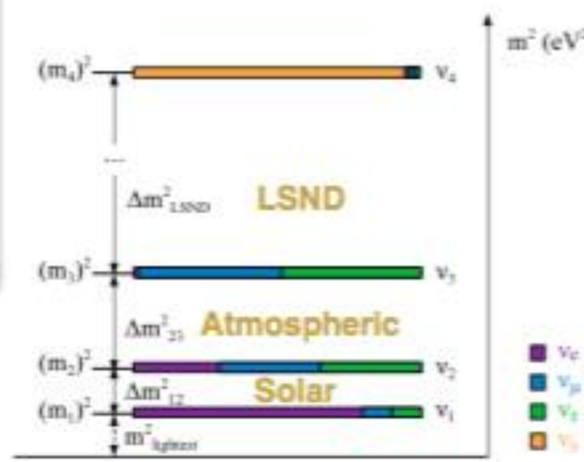
Detected an excess in the appearance of $\overline{\nu}_e$, corresponding to a 3.8 σ evidence for $\nu_\mu \rightarrow \nu_e$ oscillation occurring at $\Delta m^2 \simeq 1$ eV^2

Hints at new physics

None of the SBL neutrino anomalies can be described by oscillations between the three Standard Model neutrinos



The standard active neutrino mass splittings are way down here at 10^{-3} and 10^{-5} eV^2



Short Baseline Neutrino Program @ FNAL

- The future short-baseline experimental configuration is proposed to include three Liquid Argon Time Projection Chamber detectors (LAr-TPCs) located on-axis in the Booster Neutrino Beam (BNB)

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

- The near detector (SBND – formerly LAr1-ND) will be located in a new building directly downstream of the existing SciBooNE enclosure 110 m from the BNB target,

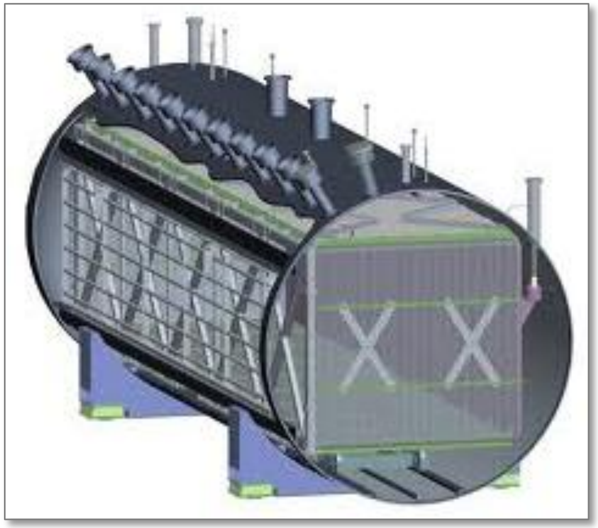
- The MicroBooNE detector, which is actually already in operation, is located in the Liquid Argon Test Facility (LArTF) at 470 m

- The far detector (the improved ICARUS- T600) will be located in a new building 600 m from the BNB target and between MiniBooNE and the NOvA near detector surface building

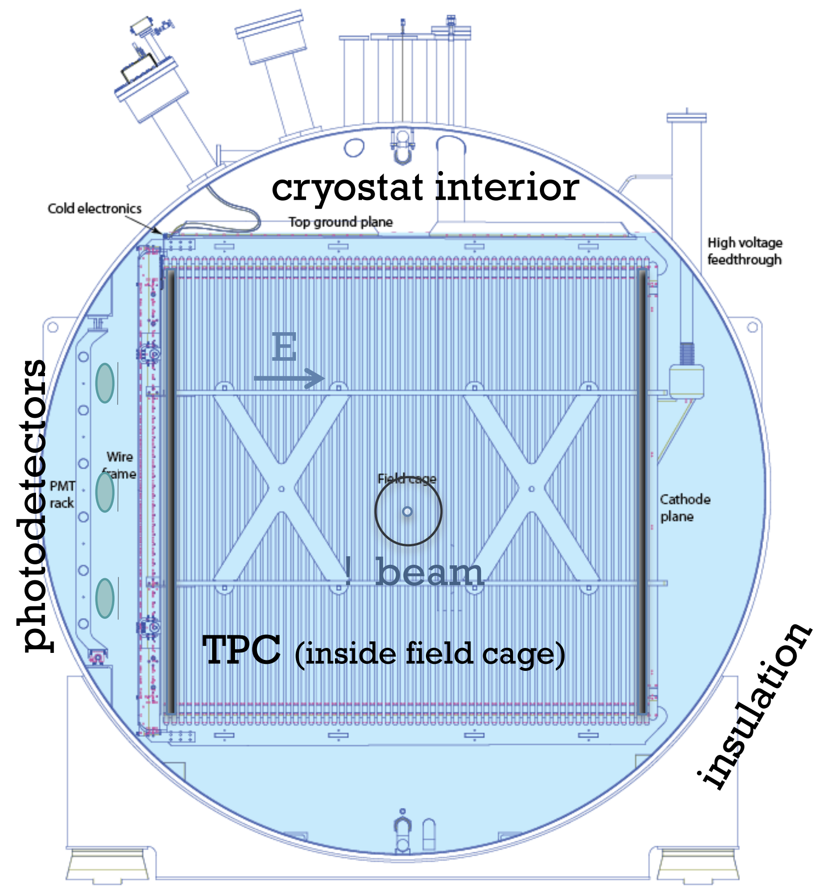
- The detector locations were chosen to optimize sensitivity to neutrino oscillations and minimize the impact of flux systematic uncertainties


MINOS
NOvA
600m – Far Detector
ICARUS/T600
MiniBooNE
MicroBooNE
110m - Near Detector
SciBooNE
LAr1-ND
BNB Target

MicroBooNE



Cross section of detector:

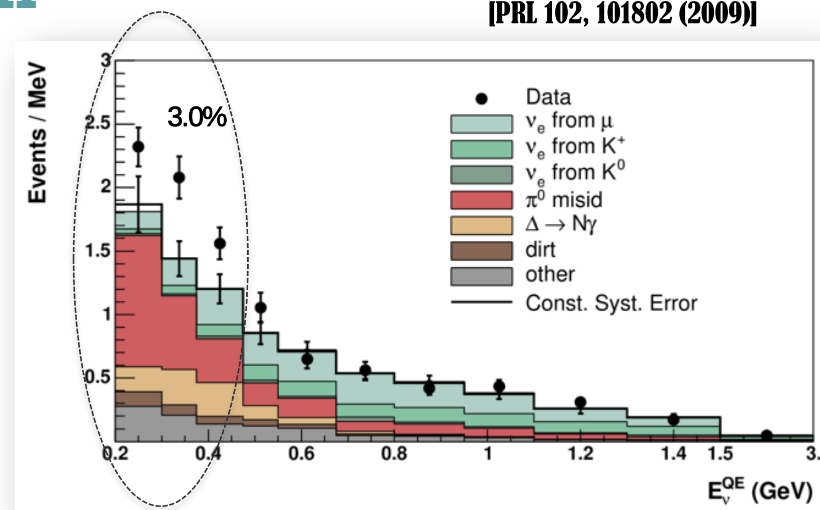


- Detector parameters:
  - 2.5 m x 2.3 m x 10.2 m TPC
  - 2.5 m drift length
  - 170 (60) tons total (fiducial) mass
  - 3 wire planes, 0,±60° from vertical, 3 mm wire separation
  - 8256 wires
  - 32 PMT's for t_0, drift coordinate, and triggering for empty beam spill rejection

MicroBooNE

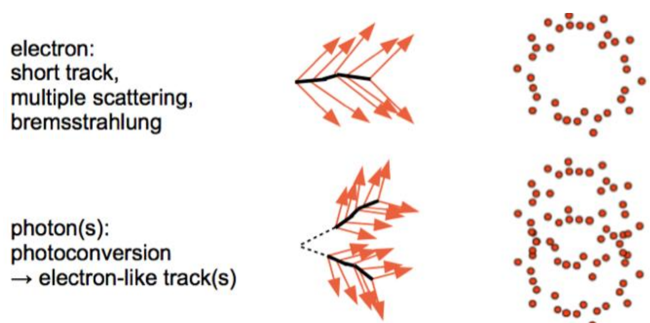
Primary physics goal

MiniBooNE unexplained "low energy excess"
[PRL 102, 101802 (2009)]



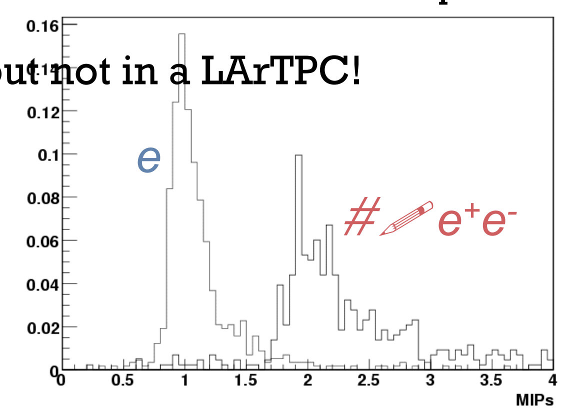
- Investigate the nature of the MiniBooNE low energy excess
- Is the excess due to e or)?

Single e and single)
are indistinguishable in a cherenkov detector…



Energy loss in first 24mm of track:
250 MeV electron vs. 250 MeV photon

…but not in a LArTPC!



SBND

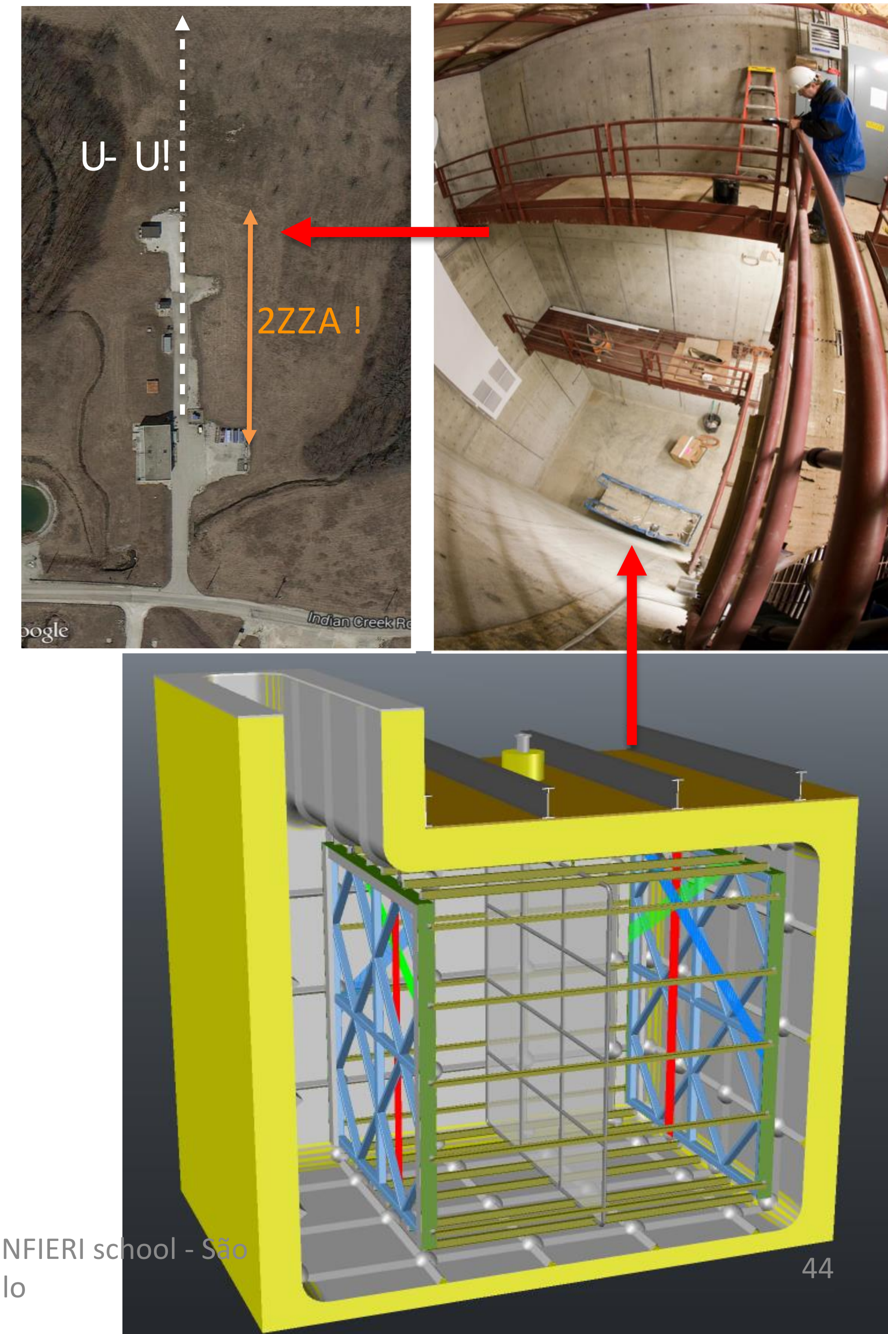
- The active TPC volume is 4.0 m (width) × 4.0 m (height) × 5.0 m (length, beam direction), containing 112 tons of liquid argon

- ***LAr TPC exploiting as many design elements developed for DUNE***

- High statistics measurement of intrinsic BNB content: sensitive oscillation searches in combination with downstream detectors

- With MicroBooNE and ICARUS, provide full interpretation of the MiniBooNE excess.

- *Side results: reconstruction development and GeV ν,Ar cross sections*



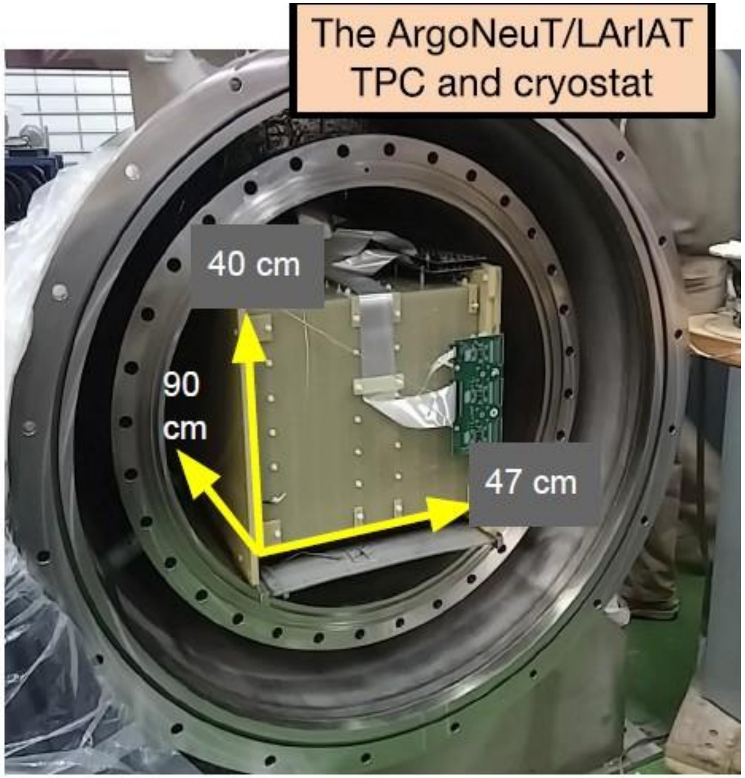
LArIAT experiment and its goals (1)

•Small by size (a “table-top” 170L TPC refurbished from ArgoNeuT) but important **part of the US-based neutrino program**

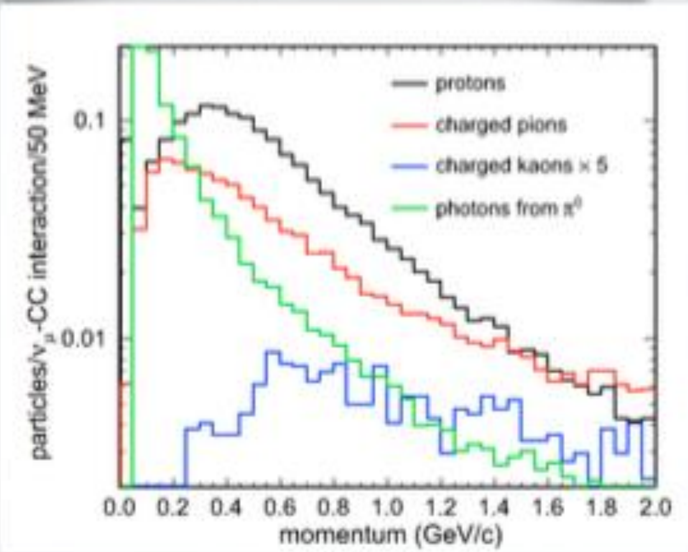
•Succesfuly completed first run (April 30th-July 3rd)

•Goals:

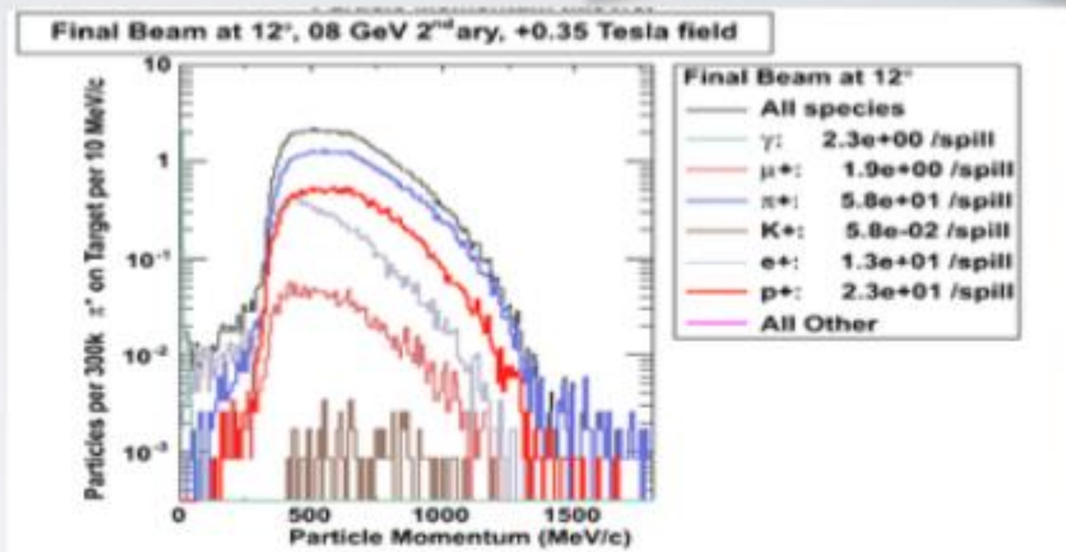
- Physics
- R&D



MOTIVATION — LARIAT — METHOD



NuMI LE on-axis Beam
M. Kordoski



LArIAT Test Beam

Study in LArTPC Particles emerging from ν Interactions (in the energy range relevant for SBN & LBN)

→

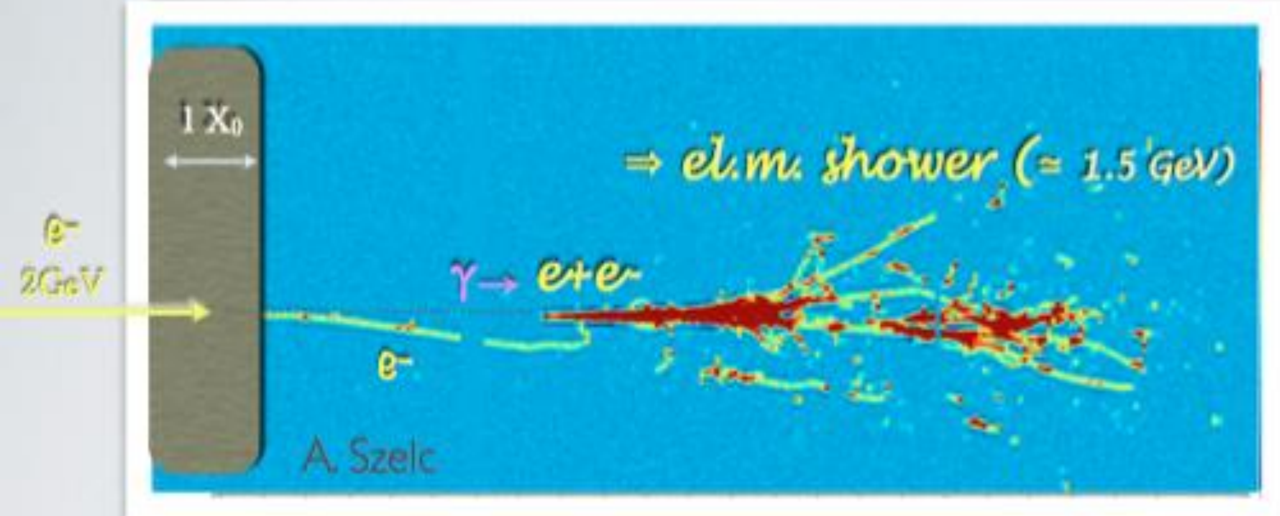
Study in LArTPC Particles emerging from a suitably designed Beam-line with appropriate momentum range

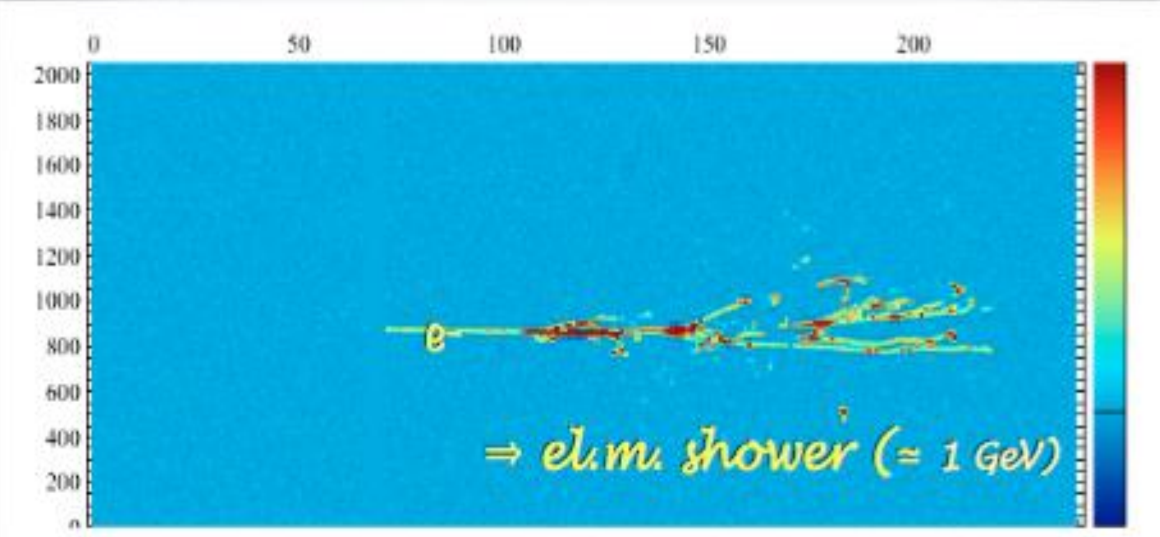
LArIAT experiment and its goals (2)

LArIAT goals

Physics	R&D
• π-Ar interactions in the energy range relevant to neutrino experiments • E/γ shower ID • μ-Ar capture • Non – magnetic charge determination • Kaon studies • Geant 4 validation	• Optimizing PID algorithms • Calorimetry with charge and light • 2D/3D event reconstruction • Will test a possibility of applying Pulse Shape Discrimination methods in neutrino physics • Important development platform for software used in US neutrino program

ELECTRON VS PHOTON SHOWER DISCRIMINATION





Bremsstrahlung from upstream radiator plate

Tagged with incoming electron PID in beamline + deviated track + gap.

MUON SIGN DETERMINATION (W/OUT MAGNETIC FIELD)

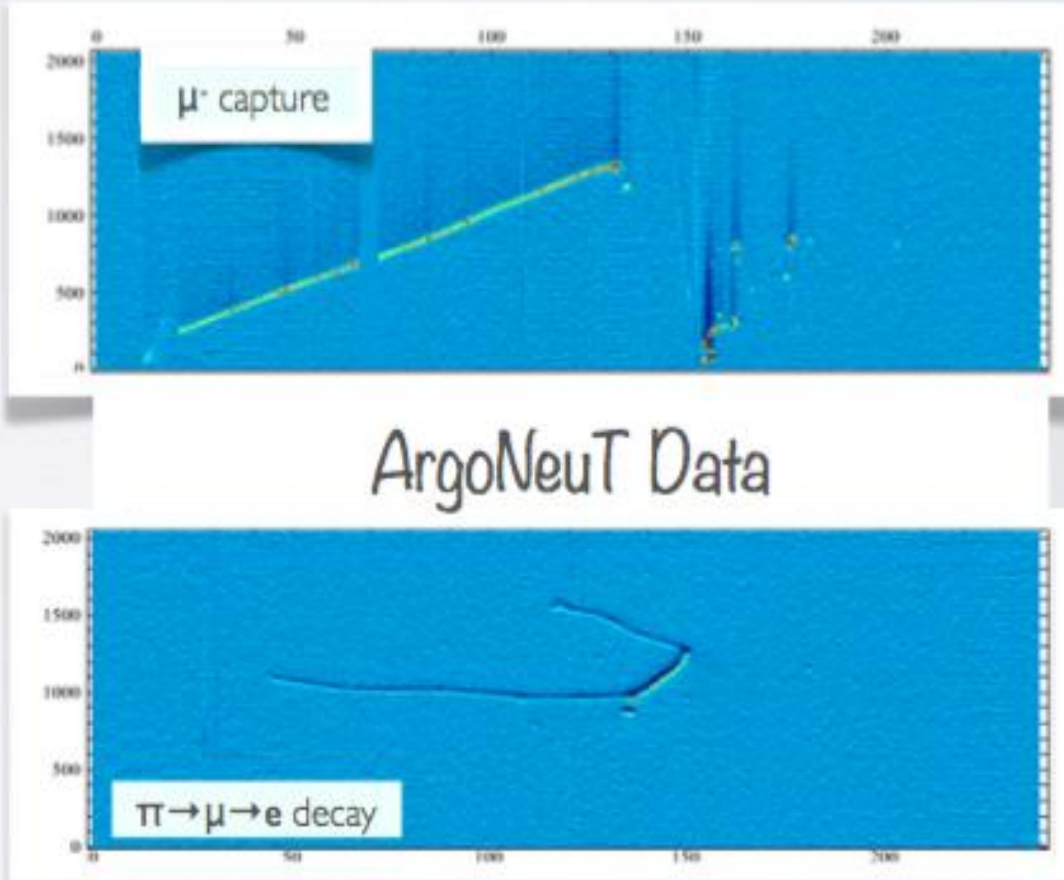
Charge sign determination (w/o magnetic field) for fully contained muons using statistical analysis :

- μ^+ decay rate with e^+ emission of a known energy spectrum = 100 %

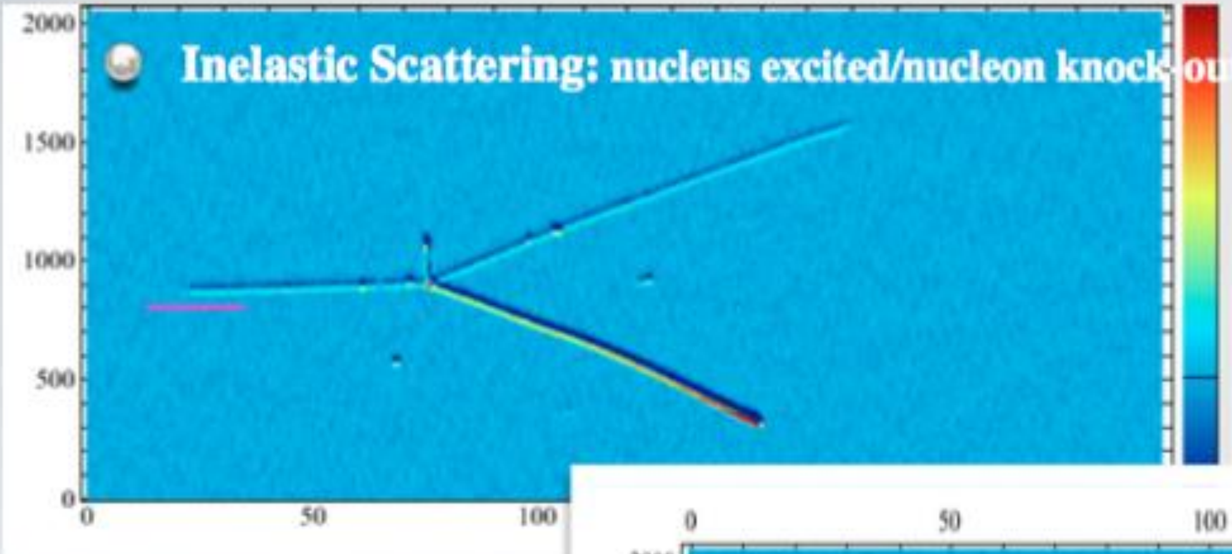
- μ^- capture on nuclei rate followed by γ / n emission ~ 75% vs decay rate ~25%

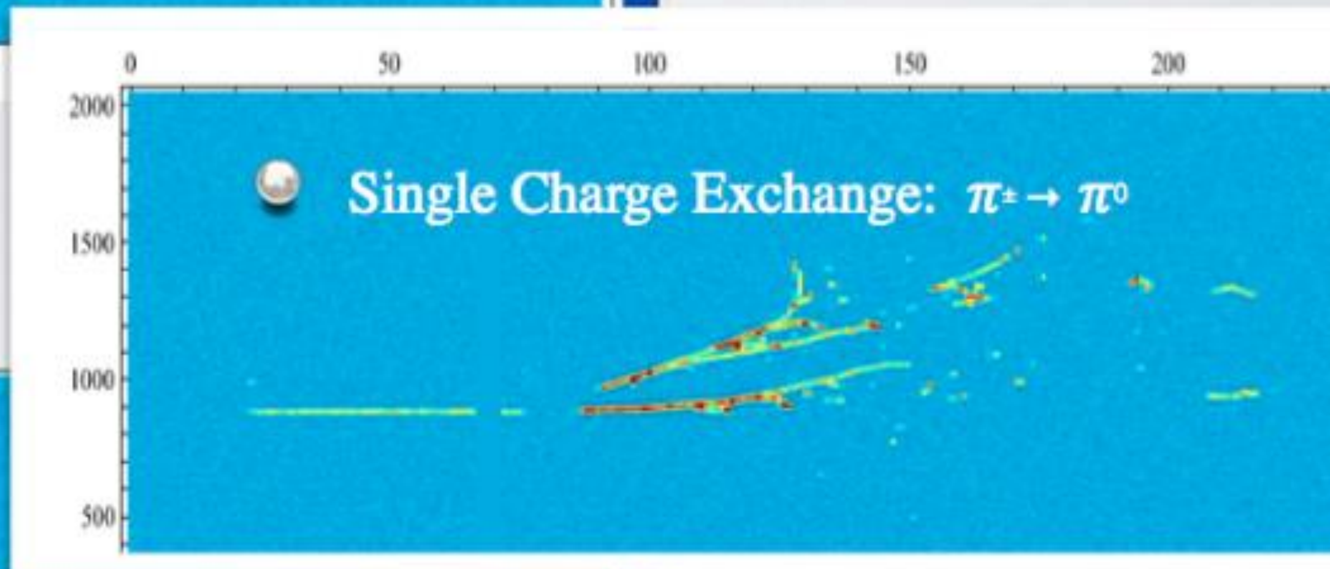
→ capture rate higher in Ar than in lighter elements

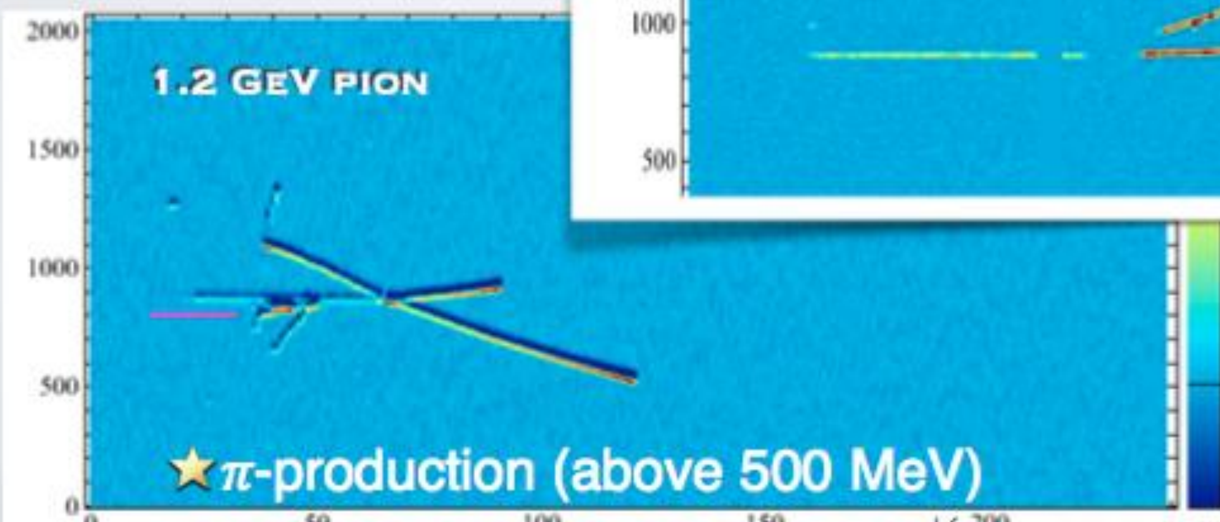
- Beam tunable polarity will provide data for direct measurement of the sign separation efficiency and purity for muons (might be possible for pions)



Charged π's in LAr







(A.Szelc-Yale)

LAr program @ UNICAMP

TPB is still a bit unknown object

- The TetraPhenyl Butadiene (TPB) is the most common wavelength shifter used in combination with LAr

- The conversion efficiency and the spectral properties have been recently measured very precisely

- But there is not an exact knowledge of its response function in time

- It is usually assumed as good the one measured with near UV radiation (λ ~ 350 nm), that is a fast decaying exponential. It is compatible with the photo-excitation of highly excited singlet states of the TPB molecule (S_n). They decay very fast (< 1 ns) non-radiatively to the lowest lying singlet state (S_1) whose de-excitation to the ground state produces the shifted light - around 430 ns

- Does it hold at any wavelength?

TPB ionization

- Probably, a less known information is that the ionization potential of TPB is quite low. It should be between 5 and 6 eV
- This is higher than the energy of LAr scintillation photons – 9.7 eV
- TPB molecules are ionized and electrons have enough energy to excite some of the surrounding molecules
- Both singlet and triplet states are formed (also in the electron-ion recombination)
- Singlet states decay very fast to the ground state emitting a prompt shifted photon
- Triplet states are responsible of a delayed scintillation through the triplet-triplet interaction: $T_1+T_1 \rightarrow S_1+S_0$ and a photon is emitted with the same wavelength of the prompt component
- We should expect a delayed scintillation in TPB excited by VUV photons – as already observed for sodium-salycilate and p-terphenyl

PHYSICAL REVIEW C **91**, 035503 (2015)

Evidence of delayed light emission of tetraphenyl-butadiene excited by liquid-argon scintillation light

E. Segreto*,†

Instituto de Física "Gleb Wataghin" Universidade Estadual de Campinas - Unicamp Rua Sérgio Buarque de Holanda, No 777, CEP 13083-859 Campinas, São Paulo, Brazil

(Received 26 November 2014; revised manuscript received 1 February 2015; published 12 March 2015)

Tetraphenyl-butadiene is the wavelength shifter most widely used in combination with liquid argon. The latter emits scintillation photons with a wavelength of 127 nm that need to be downshifted to be detected by photomultipliers with glass or quartz windows. Tetraphenyl-butadiene has been demonstrated to have an extremely high conversion efficiency, possibly higher than 100% for 127 nm photons, while there is no precise information about the time dependence of its emission. It is usually assumed to be exponentially decaying with a characteristic time of the order of one ns, as an extrapolation from measurements with exciting radiation in the near UV. This work shows that tetraphenyl-butadiene, when excited by 127 nm photons, re-emits photons not only with a very short decay time, but also with slower ones due to triplet states de-excitations. This fact can strongly contribute to clarifying the anomalies in liquid-argon scintillation light reported in the literature since the 1970s, namely, the inconsistency in the measured values of the long decay time constant and the appearance of an intermediate component. Similar effects should be also expected when the TPB is used in combination with helium and neon, which emit scintillation photons with wavelengths shorter than 127 nm.

DOI: 10.1103/PhysRevC.91.035503 PACS number(s): 29.40.Mc, 33.50.Dq, 33.80.Eh, 61.25.Bi

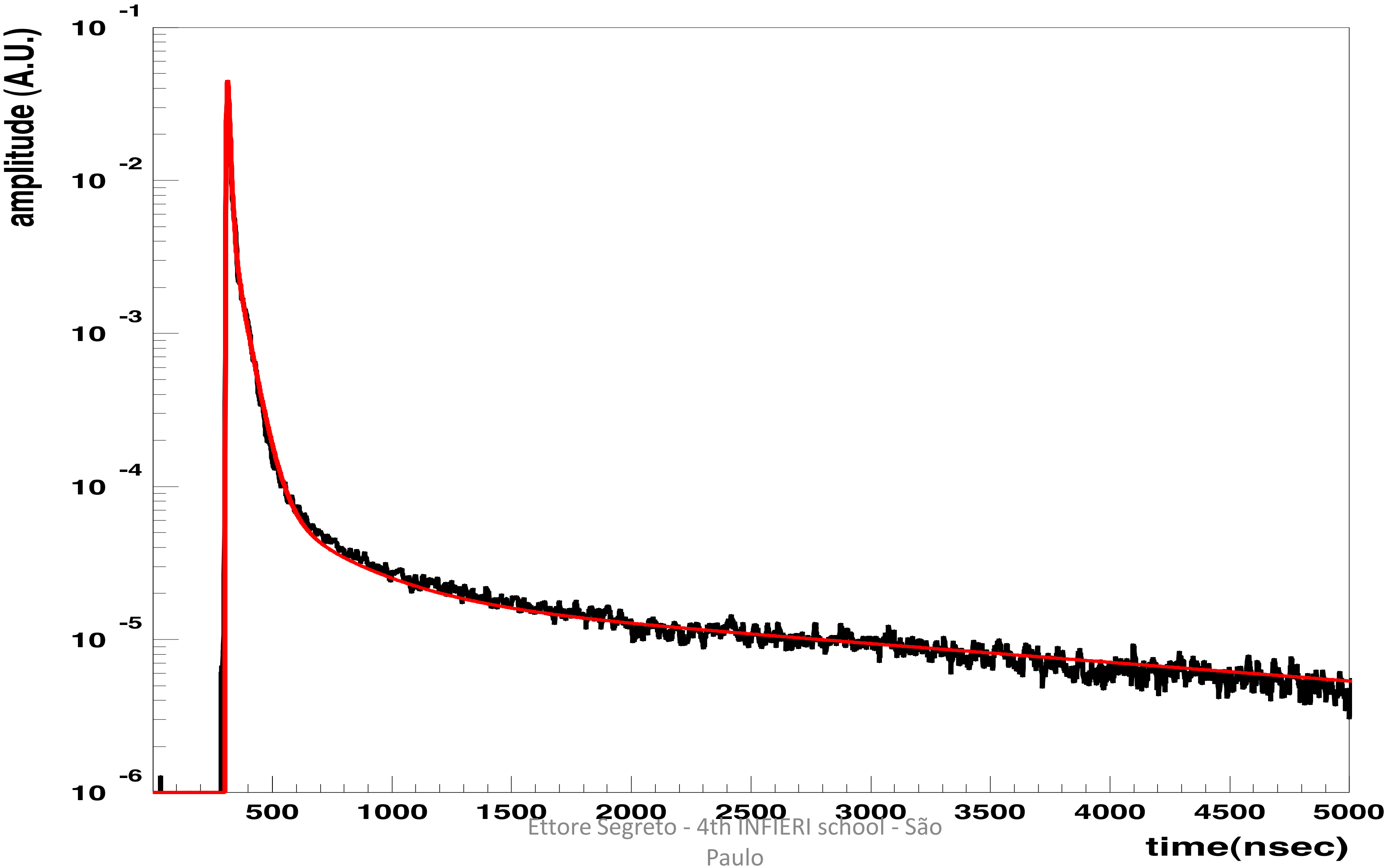
I. INTRODUCTION

Liquid argon (LAr) is a widely used active medium in particle detectors, especially in the fields of neutrino physics and dark matter direct search [1–4]. It is often used in scintillation detectors thanks to its high photon yield (~40 000 photons/MeV at null electric field for minimum ionizing particles) and to the possibility of discriminating different

which typically has a characteristic time of the order of 1 ns [12–14].

The point never considered up to now is that VUV scintillation photon energy (9.7 eV) could very likely exceed the ionization potential of TPB. Actually there are no available data in the literature, but a calculation leads to a value of 5.4 eV [15]. This could appear an extremely low energy, but it

TPB response function to 127 nm photons



Wavelength-shifter program

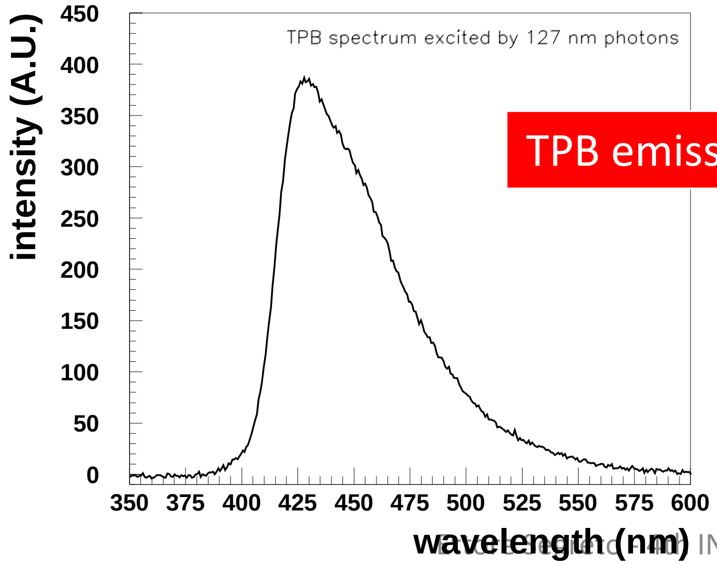
- Precision measurements of TPB time characteristics. Same measurements for other shifters
- Measurements performed in Campinas (Brazil) at the Brazilian Synchrotron Light Laboratory (LNLS)
- The Brazilian Synchrotron Light Laboratory (LNLS) in operation since 1997 is a second generation electron storage ring with a synchrotron source of 1.37 GeV. Actually there are 15 beam-lines in operation.
- The Toroidal Grating Monochromator (TGM) beamline provides monochromatic photons with energy tunable between 3eV up to 330eV. 127 nm photons (9.7 eV) are easily available with a resolution of ~0.1 eV.
- The synchrotron can produce also pulsed light with sub-nanosecond width. Ideal to study the time response of shifters


D05A - TGM
Monocromador de Grade
Toroidal
D03A - DFE

Current status

- Photo-emission and photo-luminescence spectra of many different commonly used wavelength shifters (TPB, p-therphenyl - pTP, p-bis-(o-methylstyryl)-benzene - bis-MSB, 2,5-diphenyloxazole – PPO) measured with multi-bunch beam (continuous flux of light)
  - ✓ Data analysis ongoing

- Time response of the same sample of shifters measured with the single bunch beam (pulsed beam – pulse duration ~ hundreds of picoseconds)
  - ✓ Data analysis ongoing



TPB emission spectrum

ARAPUCA

- We want to develop a new concept of photo-sensitive device for LAr time projection chambers

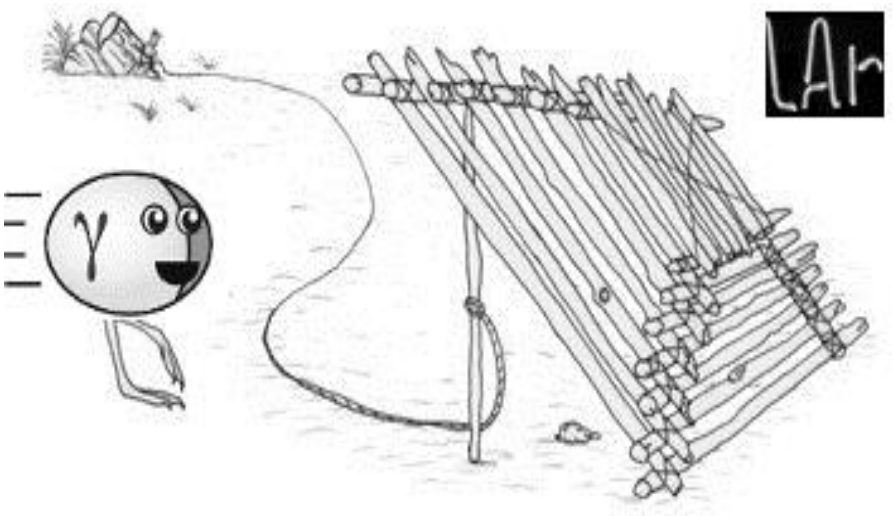
- The idea is to combine an ***high efficiency light collector*** with ***silicon devices (SiPM)*** to obtain good detection efficiency on ***large areas*** even with ***a limited use of photo-sensitive devices***

- The total efficiency of the device ***can be tuned***, depending on the application, ***changing the active photo sensitive coverage***

Idea

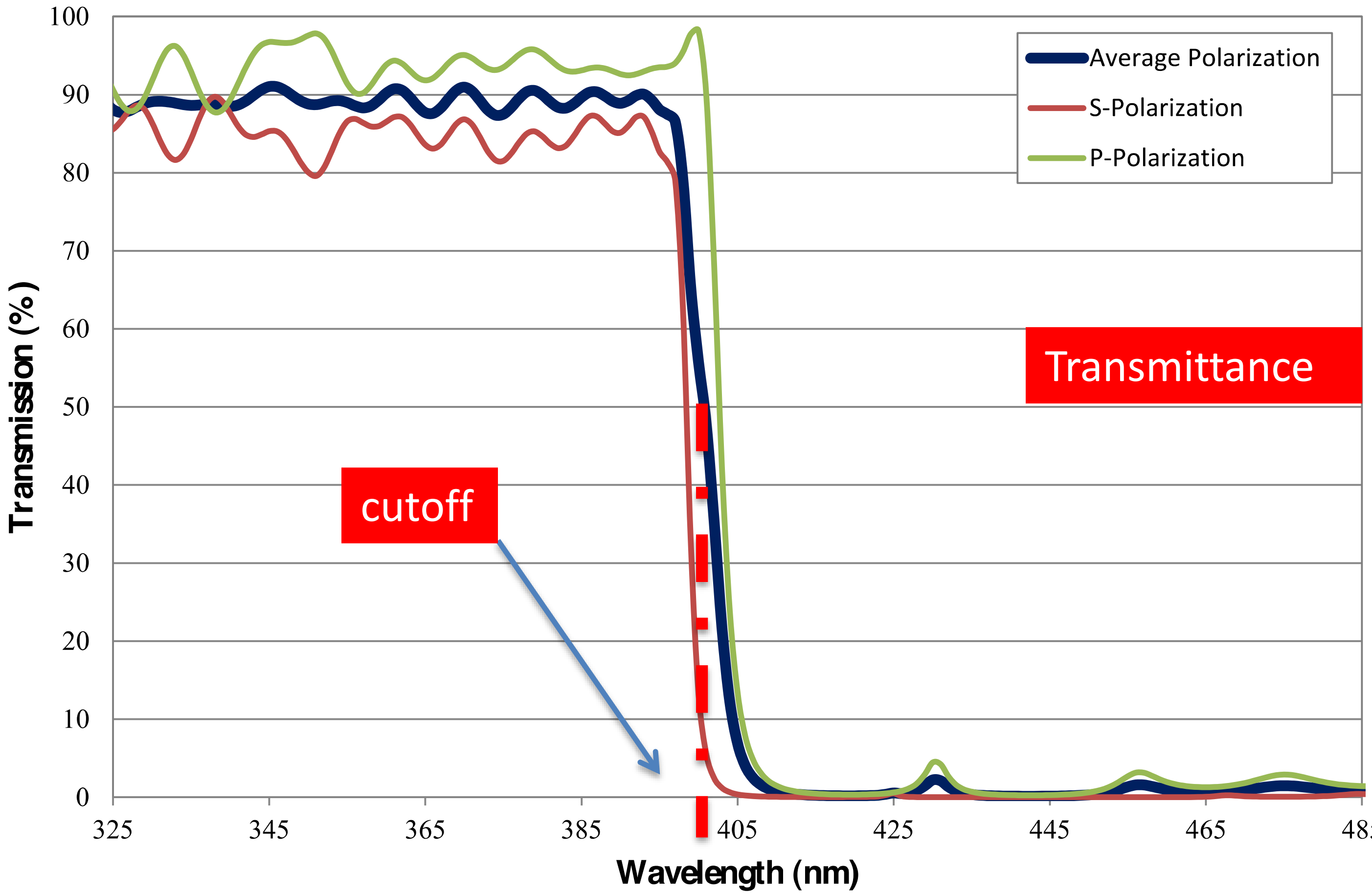
- **ARAPUCA** (**A**rgon **R**&D **A**dvanced **P**rogram @ **U**ni**CA**mp) in the language of *native Brazilian* means ***trap*** to catch birds

- The idea at the basis of the ARAPUCA is to ***trap photons*** inside a *box with highly reflective internal surfaces*, so that the detection efficiency of trapped photons is high *even with a limited active coverage of its internal surface*

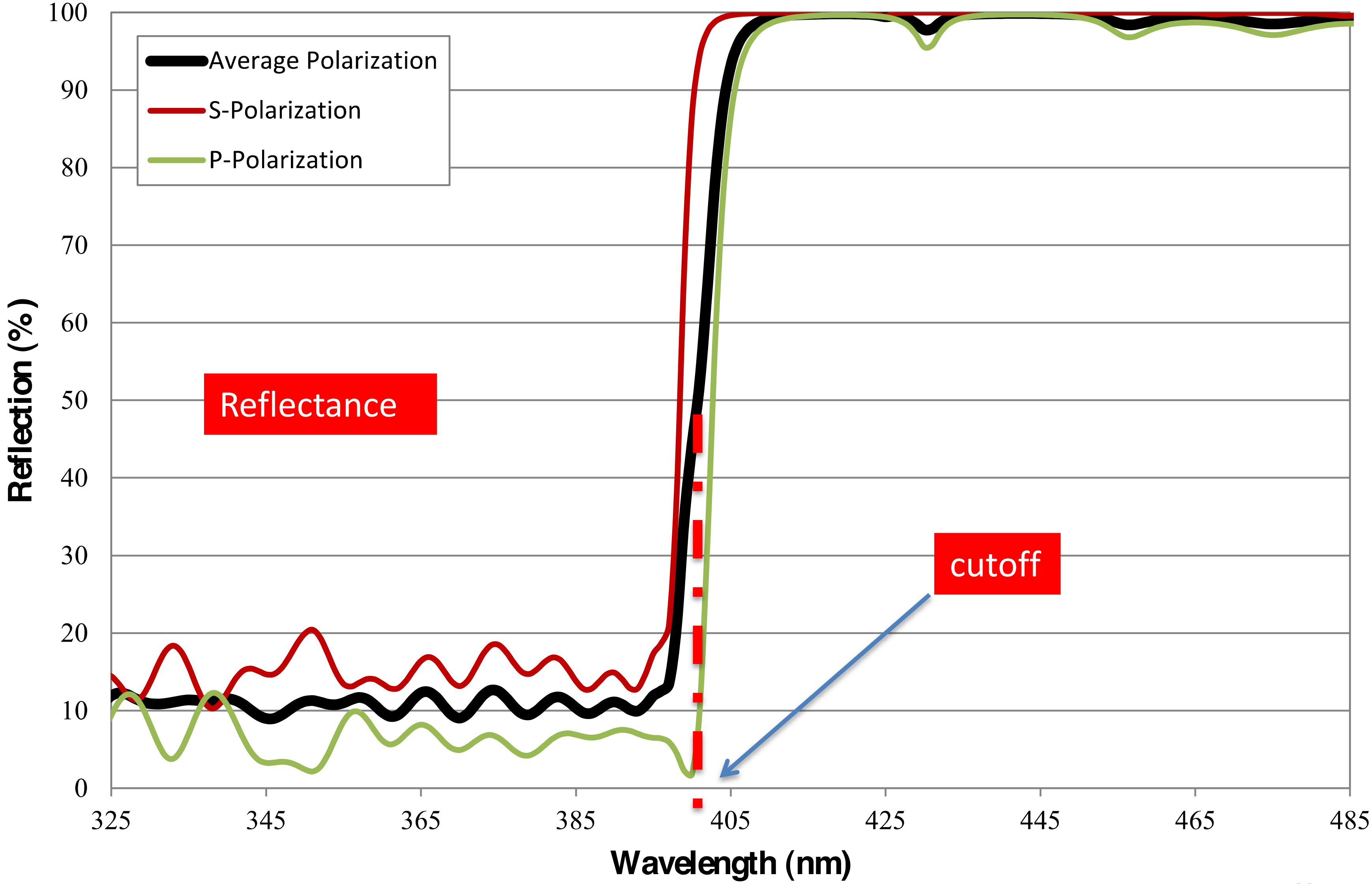


The dichroic filter I

- The core of the device is a ***dichroic filter***. It is a **multilayer acrylic film** - *same technology used to produce reflective plastic foils like 3M VIKUITI or VM2000*.
- It has the property of being **highly transparent** for wavelength **below a cutoff** and **highly reflective above it.**

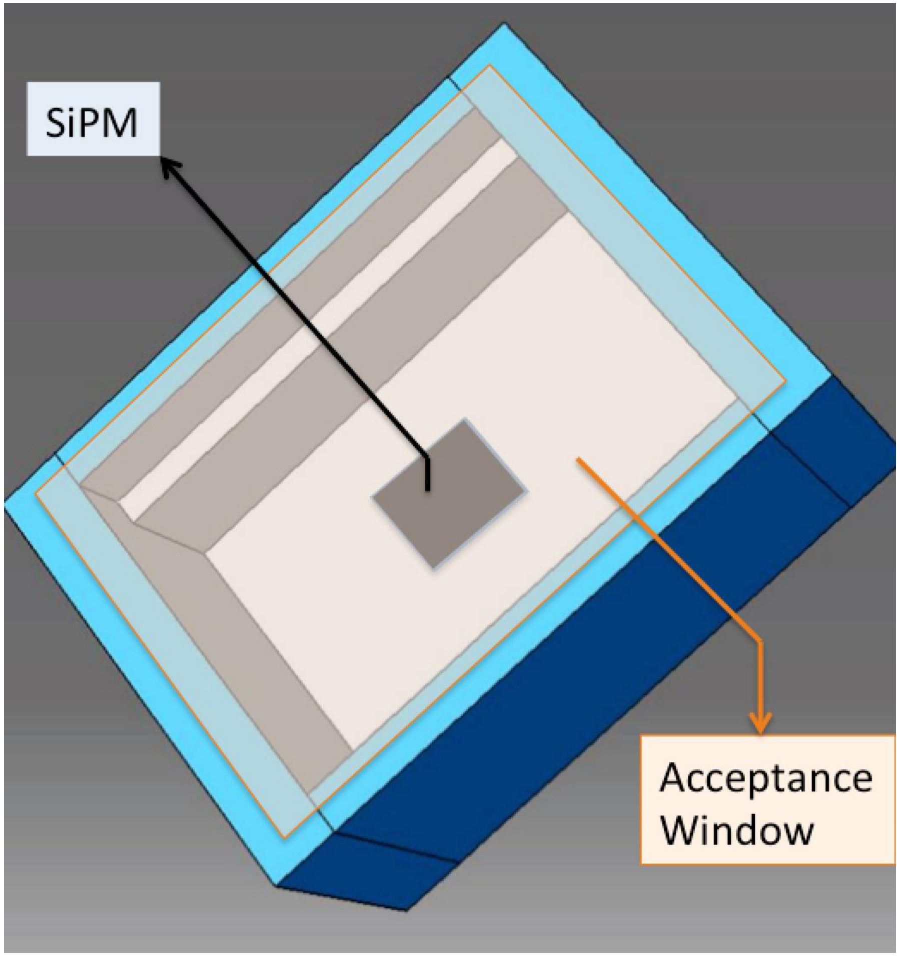


The dichroic filter II



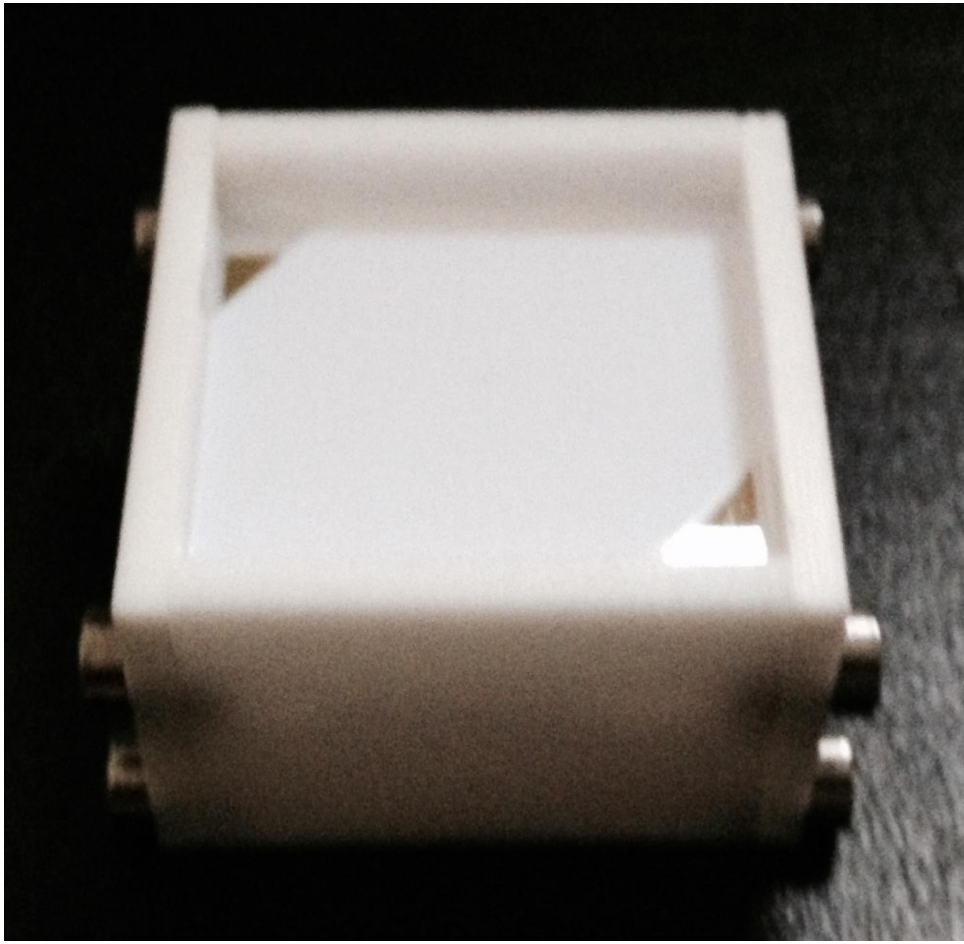
Operating principle I

- The ARAPUCA is a ***flattened box*** with *highly reflective internal surfaces* (teflon or anything covered by VIKUITI, ...) and with an open side.
- ***The open side hosts the dichroic*** filter that represents the **entrance window of the device**
- The filter is deposited with **TWO SHIFTERS** – **one on each side**
- The shifter on the **external side**, S1, converts LAr scintillation light to a wavelength L1, with **L1 < cutoff**
- The shifter on the **internal side**, S2, converts S1 shifted photons to a wavelength L2, **with L2 > cutoff**
- **The internal surface** of the ARAPUCA is observed by ***one or more SiPM***

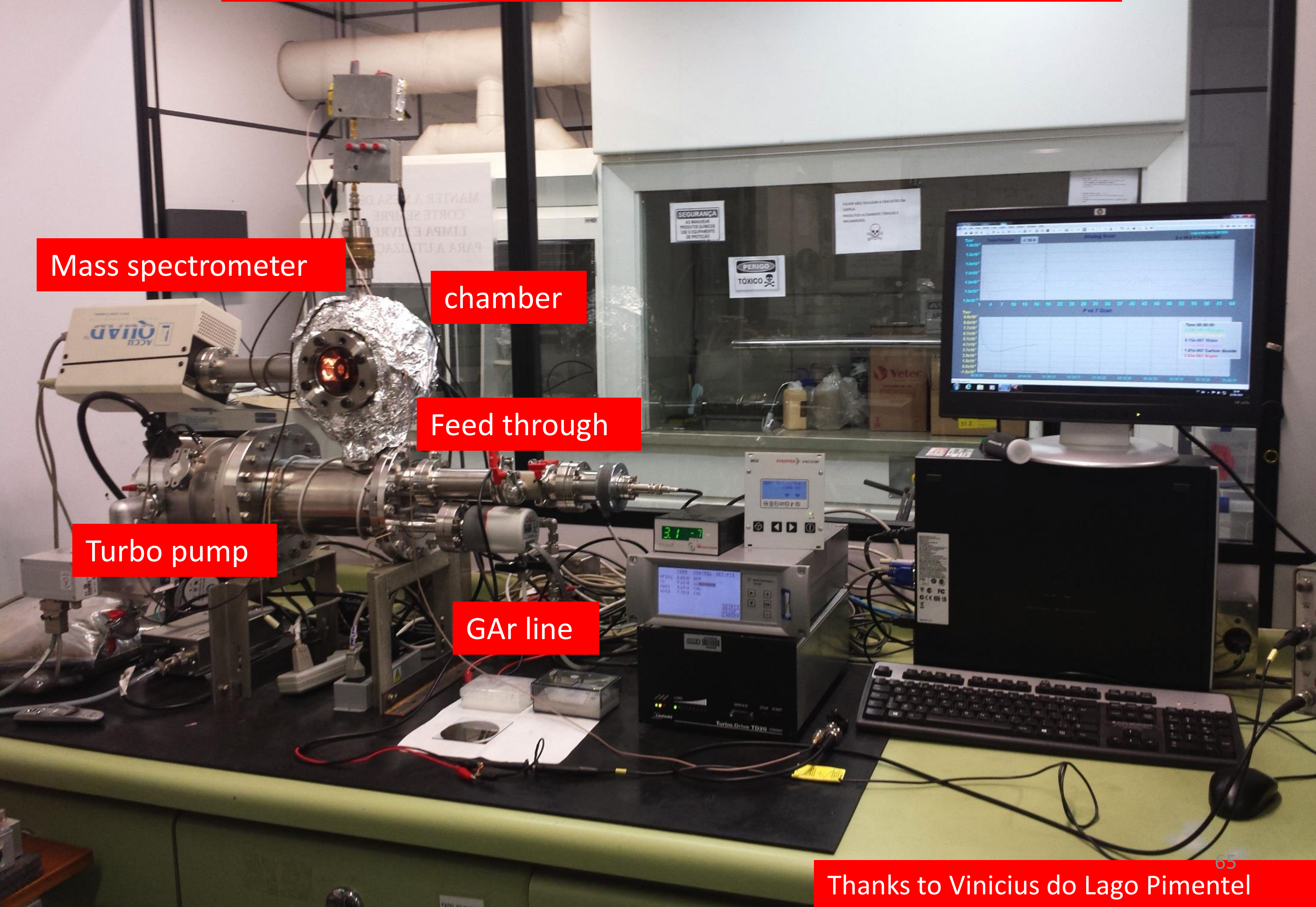


The first Prototype

- We realized a ***small prototype*** of ARAPUCA with a window of **3.5 cm x 2.3 cm**
- The box is made of **teflon** and has an internal height of **1 cm**
- The *dichroic filter* has a ***cutoff of 400 nm***
- We used as shifters ***P-Terphenyl*** **(λ ~ 350 nm**) for the *external side* and ***TPB*** (λ **~ 430 nm**) for the *internal one.*
- A **3x3 mm^2** SiPM for detecting trapped light.
- We expect a **total detection efficiency** for 127 nm photons ***around 2%*** (evaluated with analytical calculation)



Test Chamber @ CTI - Campinas



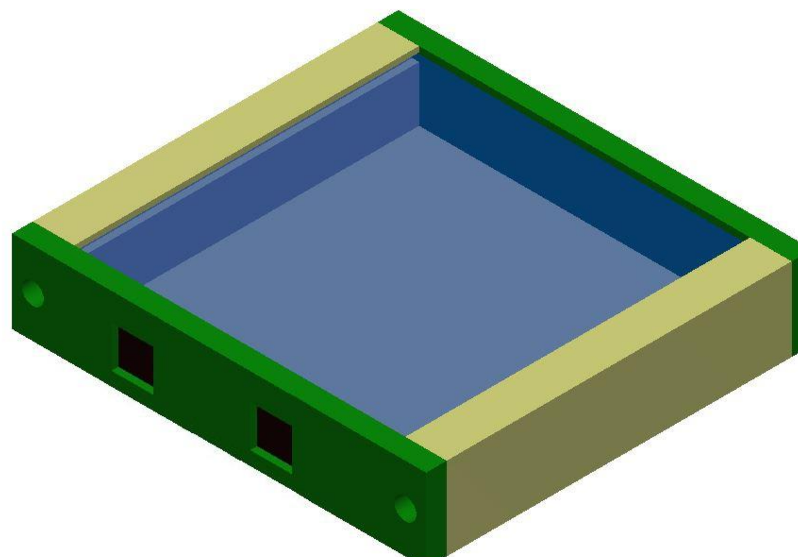
Thanks to Vinicius do Lago Pimentel

Test in LAr @ FERMILAB (I)

- Arapuca with **5x5 cm^2** acceptance window;
- **Box** with dimensions **5x5x0.6 cm^3**
- Read-out by **2 SiPM** 0.6cm X 0.6cm active area each

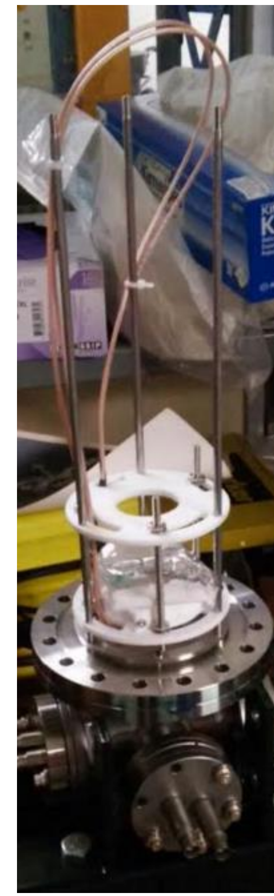
SensL MicroFC-60035-SMT (courtesy of **Cormac Campbell** - SensL Technologies Ltd.)

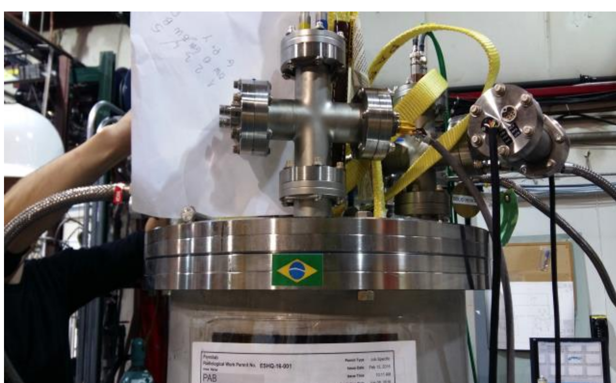
- **Dichroic filter** (Quantum Design- cutoff @ 400 nm – substrate fused silica)

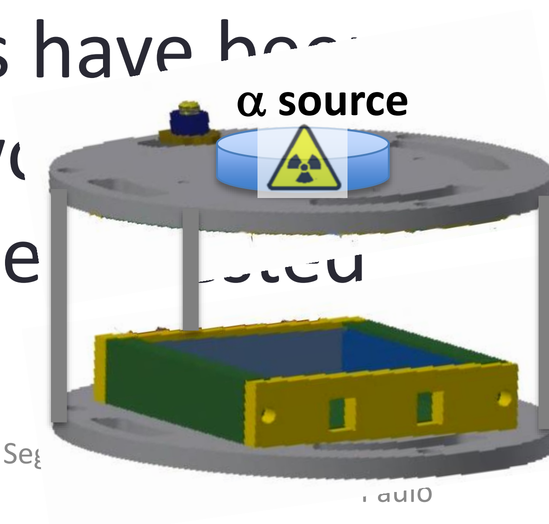


Test in LAr @ FERMILAB (II)

- The device has been installed inside a **liquid argon cryostat** and exposed to an alpha source.
- Alpha source is ^{241}**Am** that produces 5.4 MeV monochromatic particles
- Two different runs have bee… tw… -out …e be… …ted



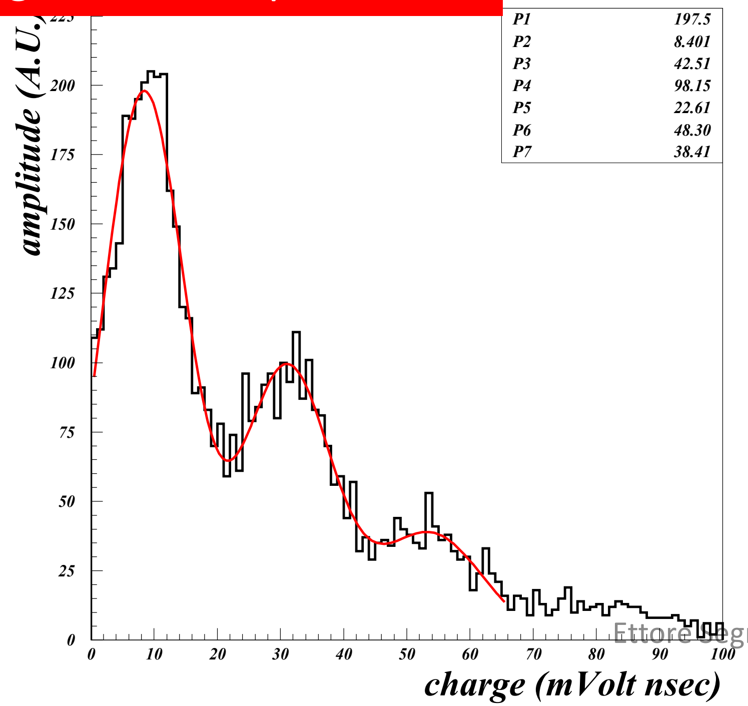




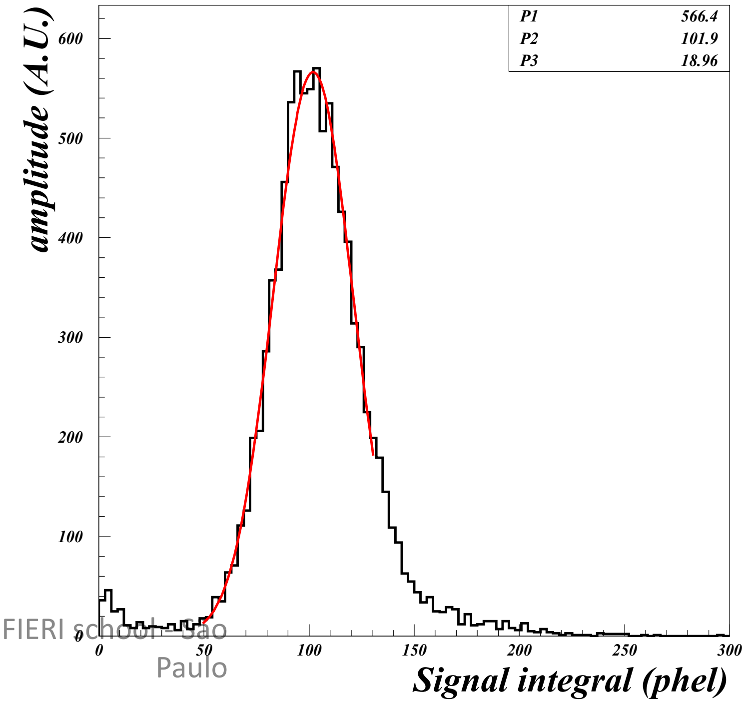
Test in LAr @ FERMILAB (III)

- Encouraging results: we measured an efficiency of ~1% (S_{eq} ~ 0.25 cm^2) in this first test
- It can be significantly improved considering that:
  - ✓ Low quality of the evaporations
  - ✓ Thicknesses of the films non-optimized
  - ✓ Internal reflectivity probably not at its maximum (cleanliness, quality of the material, thickness of the box walls)

Single electron spectrum



Source spectrum



ARAPUCA current status

- ARAPUCA approved for being installed inside protoDUNE
- ARAPUCA approved for being installed inside SBND and LArIAT
- Small prototype (**3.5 cm x 2.3 cm**) tested in LAr at the LNLS (first LAr measurement performed in South America)
- An array of 7 ARAPUCAs is being tested at Fermilab in order to optimize the design of the devices which will be installed in protoDUNE.
- The ARAPUCA and wavelength shifter programs is funded by FAPESP under the project number: 2016/01106-5

Conclusions

- LAr technology resulted to be extremely powerful and has become the paradigm detector for next generation neutrino experiment
- A strong short baseline program is being developed in the US
- A mega-science program is being prepared, actually involving 800 researchers
- Brazilian experimental physicists should profit of the chance of joining this experimental effort from the beginning, to have a significant role in future developments
- Experimental activity related to LAr at UNICAMP has started
- Precision measurements of TPB time emission features
- ARAPUCA development as a new concept for scintillation light detection in big LAr TPC

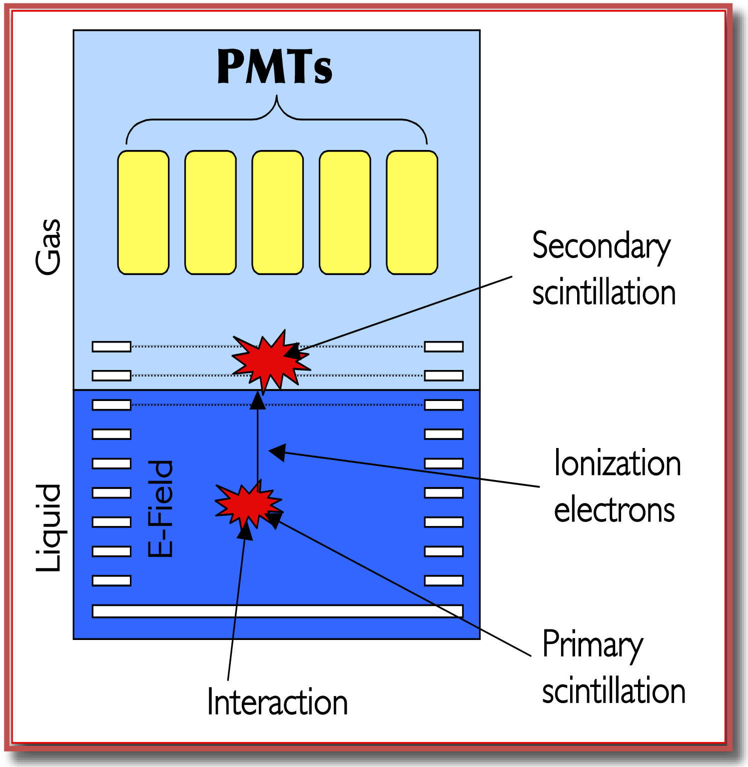
WIMP Detection in LAr

- **Three simultaneous criteria to discriminate potential WIMP recoils from backgrounds**:
  1 Simultaneous detection of **prompt scintillation and drift time-delayed ionisation in Liquid Argon**:
  - pulse height ratio strongly dependent from columnar recombination of ionizing tracks.
  - 3D reconstruction of event position.

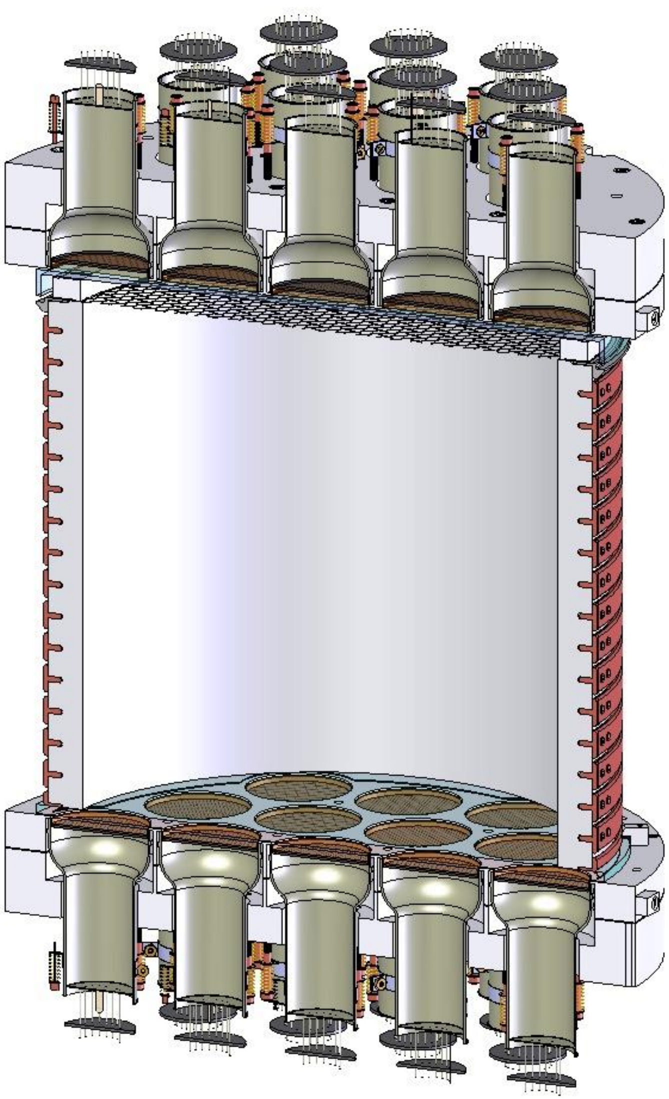
  2 **Pulse shape discrimination of primary scintillation**:
  - wide separation in rise times between fast (≈ 10 ns) and slow (≈ 1.6 μs) components of the emitted UV light.

  3 **Precise 3D reconstruction of event position**:
  - Precise definition of fiducial volume; additional rejection of multiple neutron recoils and gamma background

Double Phase Argon Chamber

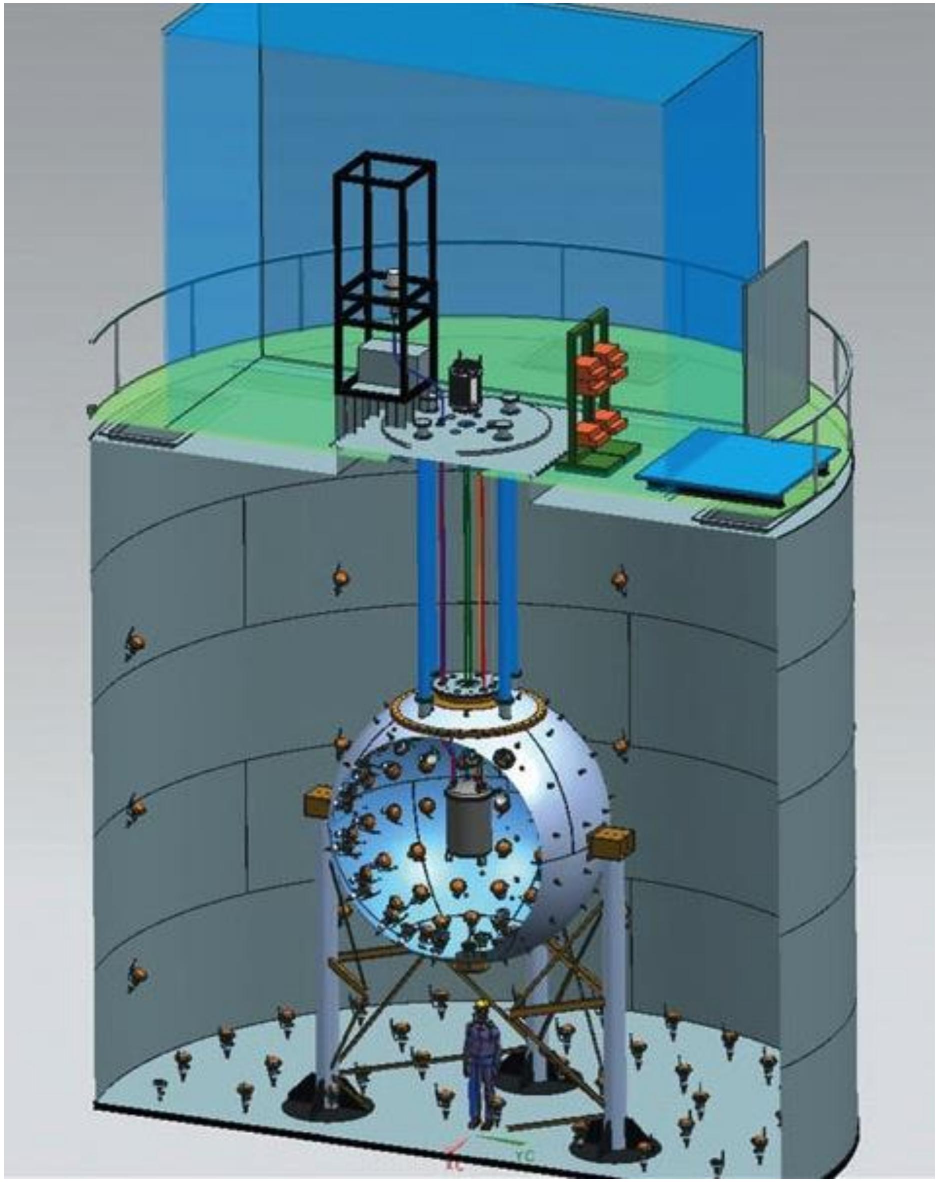


DarkSide-50 detector: TPC



- 46 kg active volume
- 36 cm diameter, 36 cm height
- 38 R11065 3” PMTs
- 38 cold preamplifiers on PMTs
- High reflectivity PTFE walls
- Fused silica anode and cathode windows coated with ITO
- All inner surfaces coated with TPB
- 2 cm gas pocket
- 0.2 kV/cm drift & 2.8 kV/cm extraction electric fields
- Electron drift lifetime > 5 ms (max. drift time of ~ 375 μs)
- Electron drift speed = 0.93 ± 0.01 mm/μs

DarkSide-50 detector: Vetoes



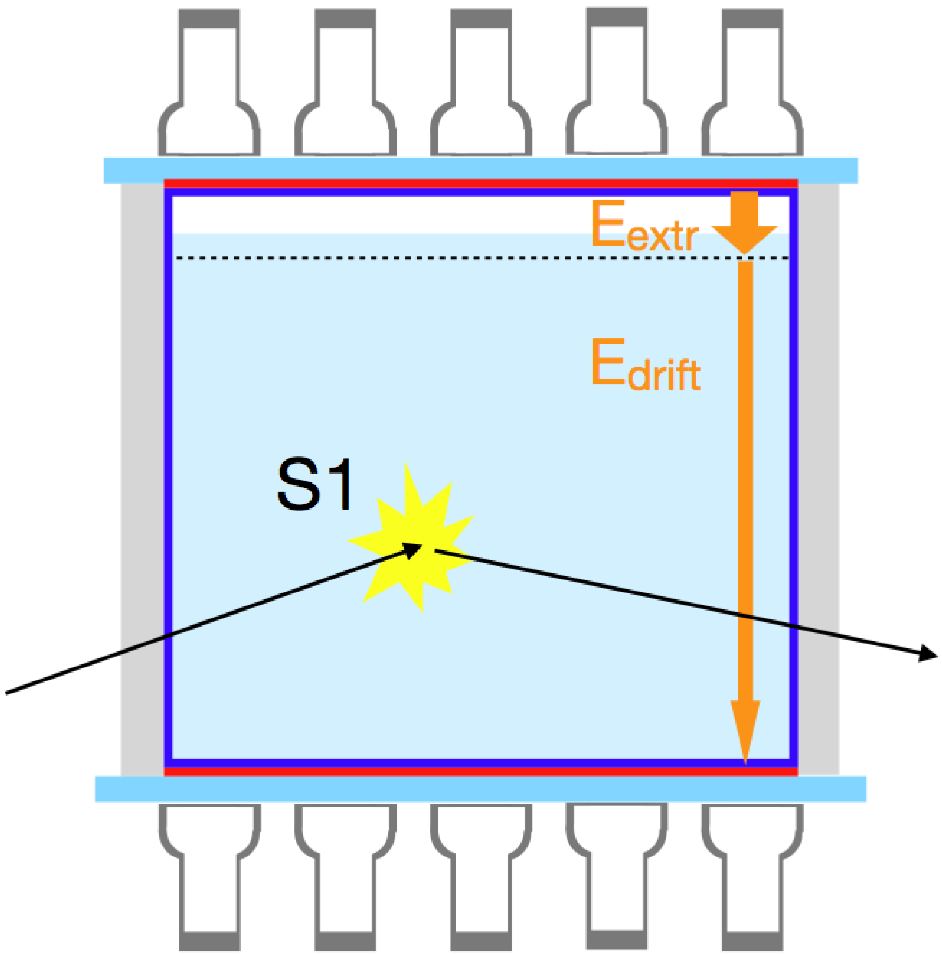
- **Liquid Scintillator Veto**

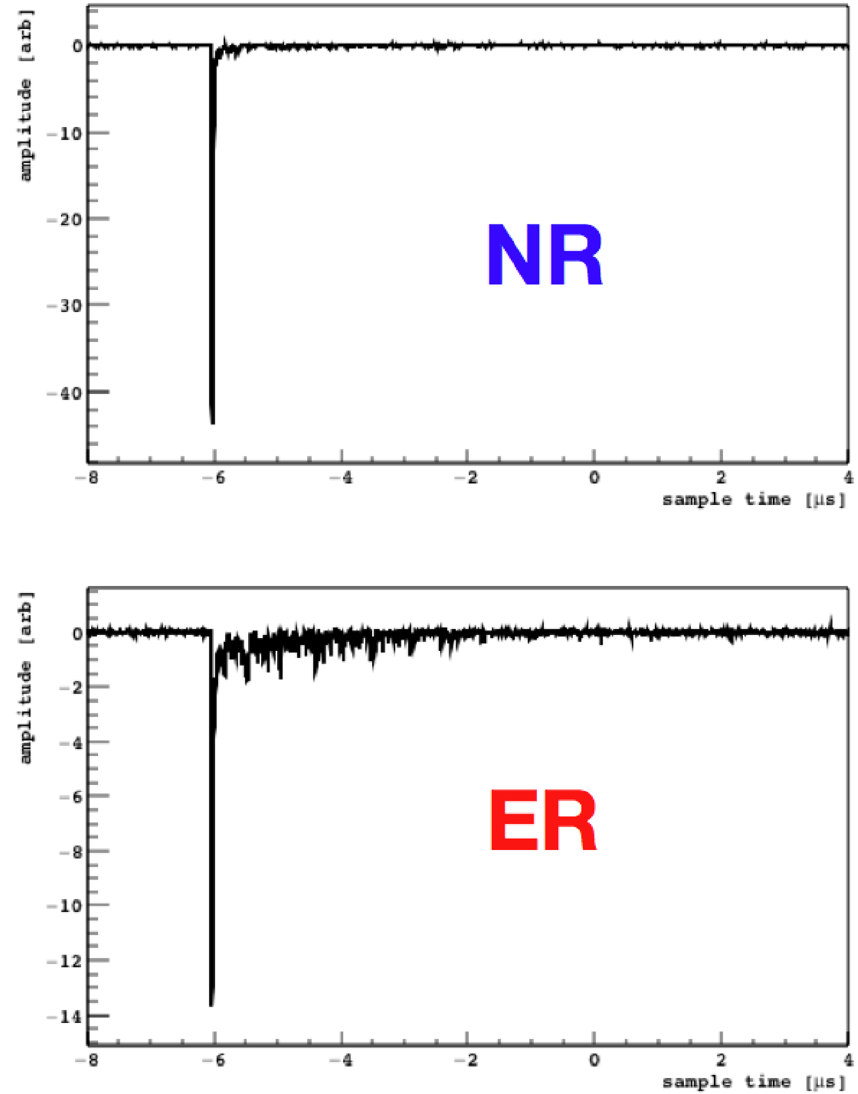
- 4 m diameter sphere
- Boron-loaded: PC + TMB
- 110 8” PMTs
- Active neutron veto
  - tag neutrons in TPC
  - in situ measurement of neutron BG
- Neutron and gamma shielding

- **Water Tank**

- 11 m diameter x 10 m high
- Existing Borexino CTF tank
- 80 PMTs
- Active muon veto
  - tag cosmogenic neutrons
- Neutron and gamma shielding

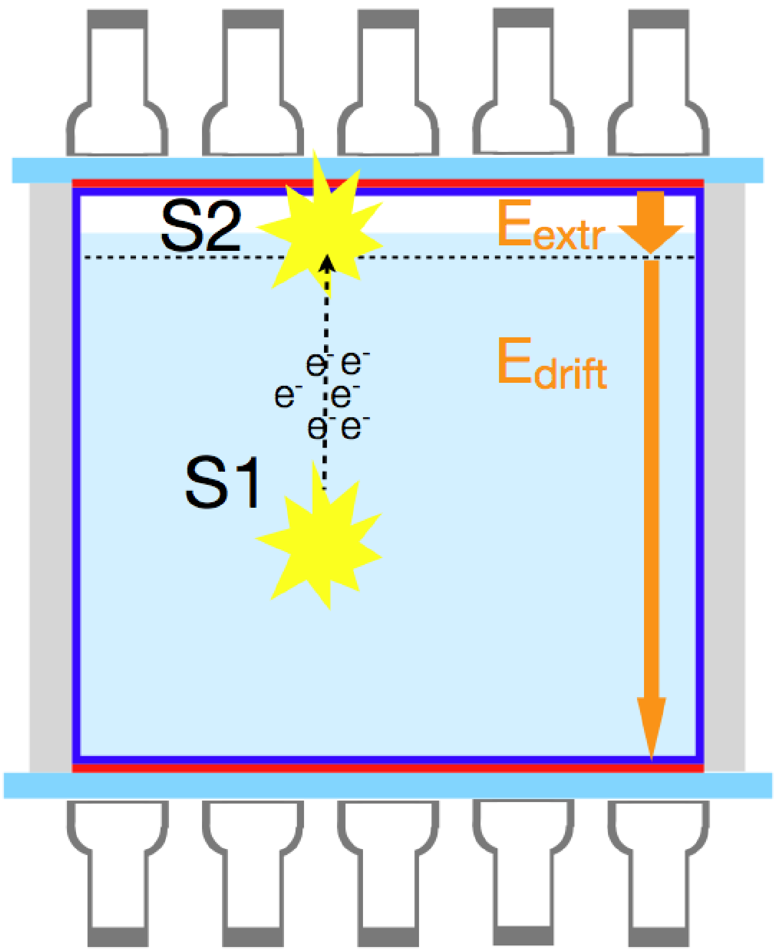
78&96#: %3FD*PQG*a +&9#' ; *S&#' =#5 @%' g*
>-09 ' -V#310' . ((' . *" #(0B&+#

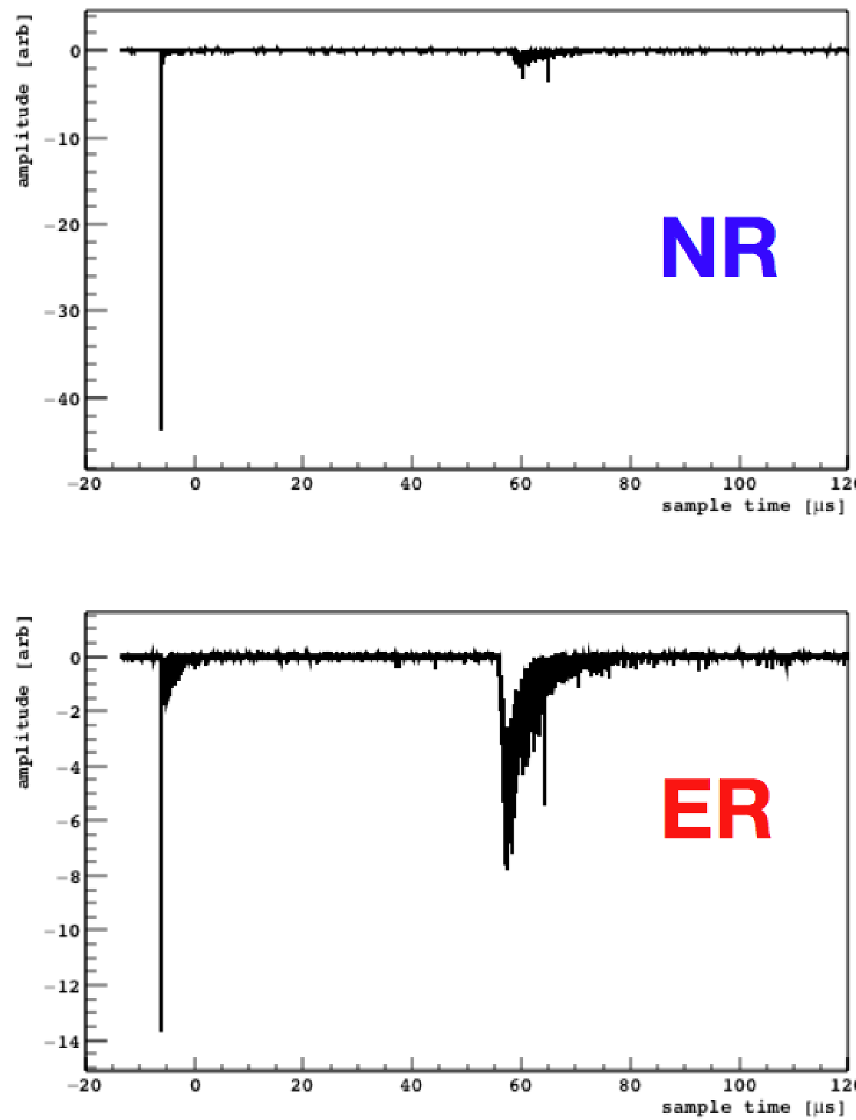




78896#: %3FD*PQG*a +89#' ; *S 8#' =#5 @%' g*

3%1*" 2' -V#%(%1+-*(<9 0' %31%' 1%#(0B&+#

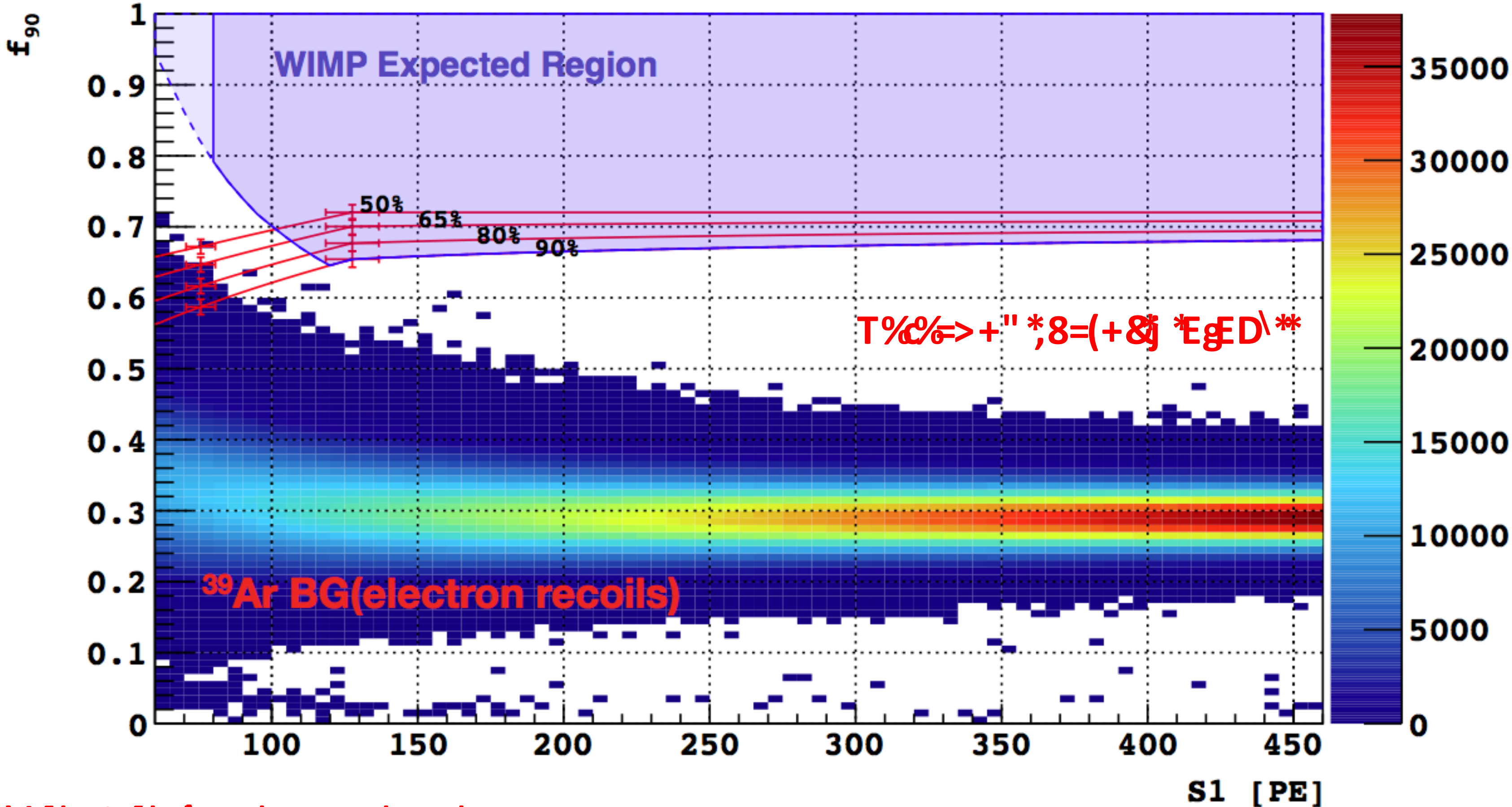




763FDg*2#&(*Q<)'#='*T%.@*

;'18B-*<"2#j-%%#%\>*3<-%#*)#PXOO## #^i #3Bt2'V##

No background events in nuclear recoil (WIMP) region!



Q<)'[*4%i [*U*\WK*MDEFOWFY*#

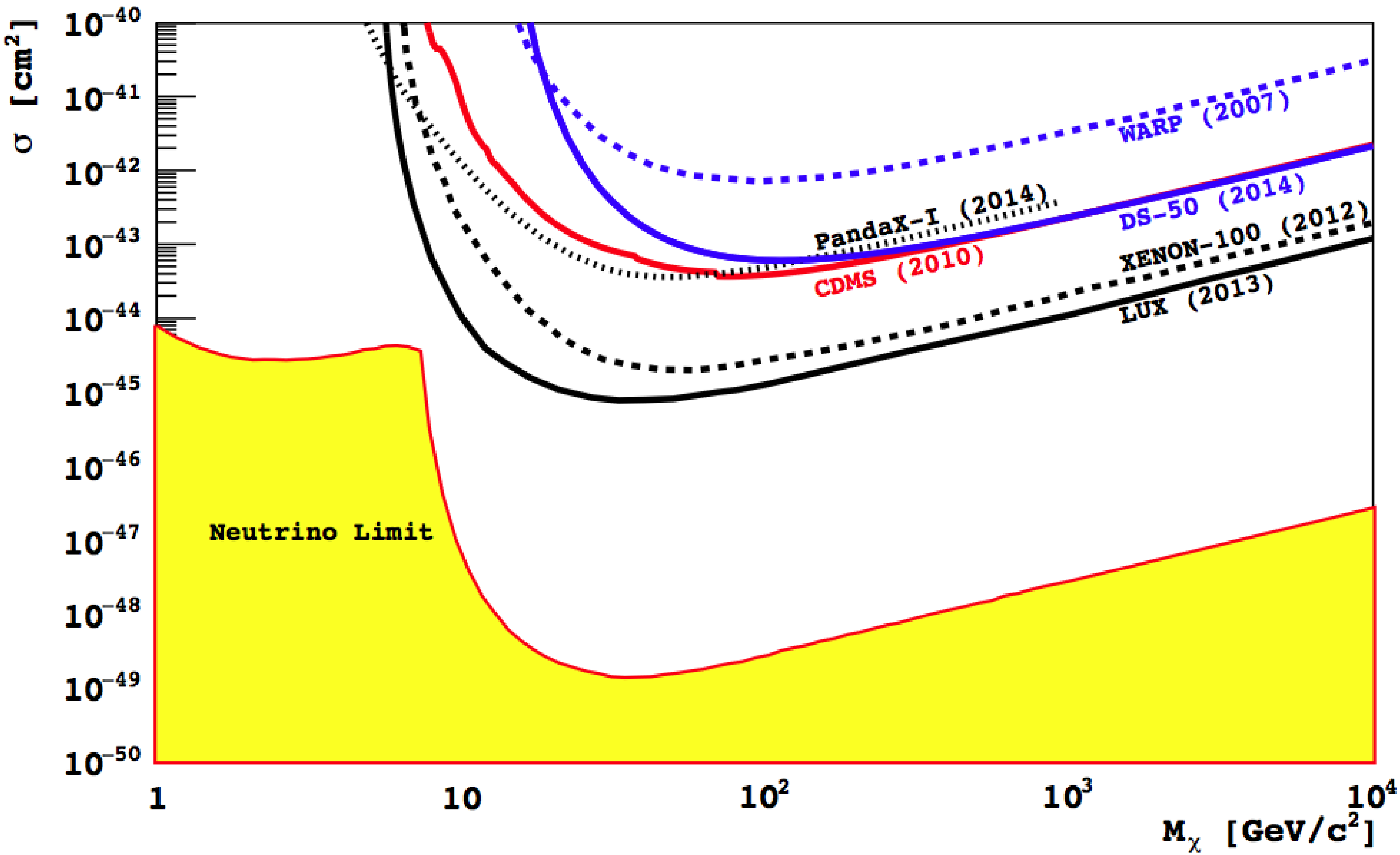
,*--%3>*"23#*#uOY#V-#%\>*3<-%#*)#/K=`Y#H0+&#GA-#

K%(%1+%2#*"(V#30'B(%=&0+#0'+%'1.*"3#0'#+&%#C7,#a2<10`(#R*(<9%#EQ^dT#3BF#H0+&#"*#%'%BV#2%>*30*"#0'#+&%#R%+*#

7 63FDg*Af =@' #+" *Q@(*

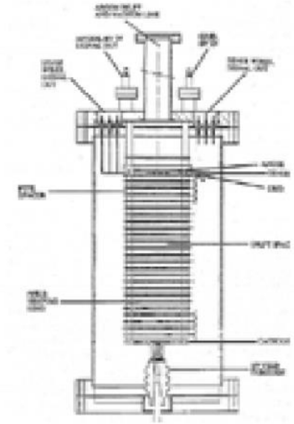
- C&%#9 *3+#3%' 30 R%#2' -8#9 ' : % #3% -1&#>%)*-9 %2#H0&# "#8&+" *' -B%#
- C&0-2#$%3+#4 56 7#2' -8#9 ' : % #(09 0# +#&0B&#9 ' 33%3##
- C&%#4 56 7=" <1(%*" #3>0' =0' 2%>%' 2%' +#1-*33#3%1. *" #3#Y[EkED' ****19 º#)*-# #6 $_4$ kPYY#J %ZN1º#

#



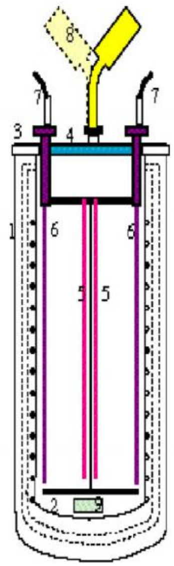
Milestones: LAr imaging

24 cm drift wires chamber



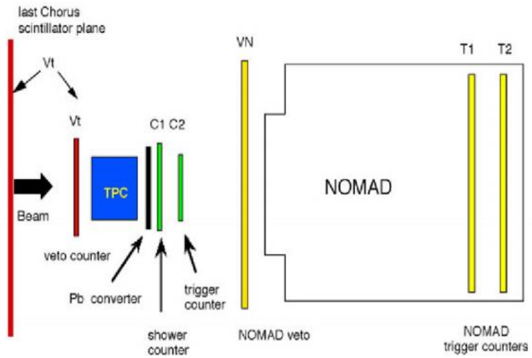
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

3 ton prototype



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

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.

10 m^3 industrial prototype

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

Non destructive charge read-out: imaging

- A non destructive read-out can be done by replacing the anodic plane with a sequence of wire planes, that are highly transparent to the ionization charge of the event

- To reach the total transparency the electric field in front of the plane and behind it, need to satisfy:

$$\frac{E_2}{E_1} > \frac{1+\rho}{1-\rho}$$

Where $\rho = 2\pi r/p$ with r -> radius of the wire and p -> distance between wires (pitch)

- This condition has to be balanced with the condition that each wire plane needs to act as an electric shield for the wire planes behind it:

$$\sigma = \frac{p}{2\pi d}\log\left(\frac{1}{\rho}\right)$$

σ is the screening power and d the distance between planes

Non destructive charge read-out: imaging

- Typical values for a TPC are: pitch = 3 mm, wire radius 0.15 mm, distance between planes = 3 mmm, ratio between electric fields E_2/E_1 = 2
- Drifting electrons can cross a succession of wire planes, when the above conditions are matched
- The electrons induce a signal on the wire towards which they are drifting. When drifting away they induce a current of opposite sign.
- Integrating the signal give an almost triangular signal in shape, with a limited duration given the shielding effect of the other planes.
- Each wire plane gives a 2D representation of the event: one coordinate is the wire position, the other coordinate is the drift (drift time proportional to distance travelled, assuming to know t_0 of the event – the start time)
- The combination of 2 or more 2D view of the same event, with a common coordinate – the drift- allows for complete 3D reconstruction
- The spatial resolution is given by the wire pitch and by the resolution in the measurement of the drift time => typical 'bubble size' 1.5 x 1.5 x 0.1 mm^3

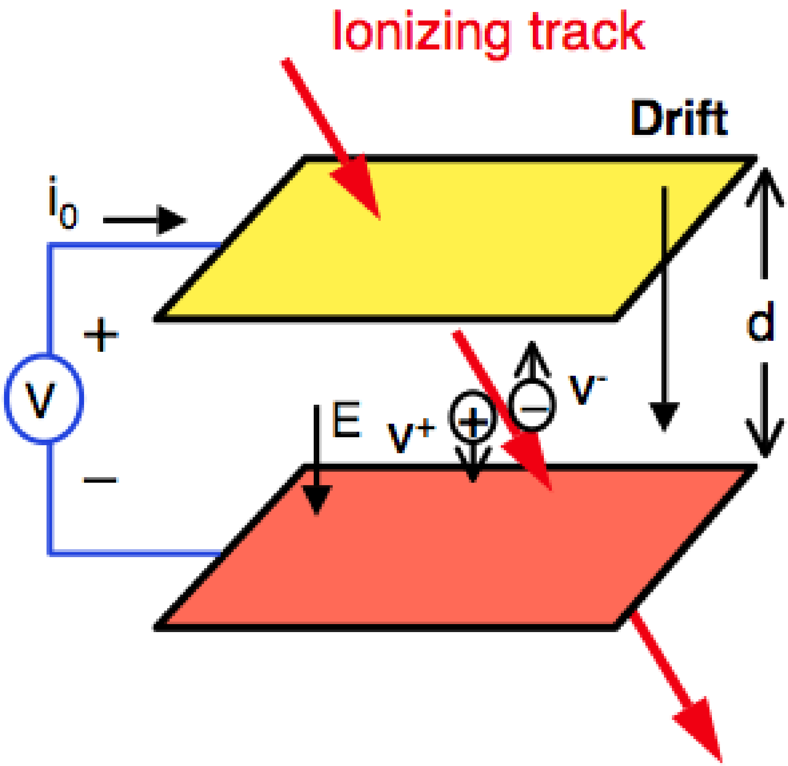
Detector's performances

- Self triggering
- Continuously sensitive
- High granularity: wire pich 3 mm:
  - ✓ Space resolution: $\sigma_{xy} \approx 1$mm; along the drift coordinate: $\sigma_z \approx 150\mu$m
  - ✓ Highly accurate measurement of range, angles, multiplicity …
- Measurement of local energy deposition
  - ✓ Electron/gamma separation (3mm)
  - ✓ Particle id by means dE/dx vs range measurement
- Total energy reconstruction of the event from *charge integration*. ***Excellent calorimeter*** with high accuracy for contained events

RESOLUTIONS:

Low energy electrons:	$\sigma(E)/E = 7\,\% / (E[MeV])^{1/2}$
Electromagnetic showers:	$\sigma(E)/E = 3\% / (E[GeV])^{1/2}$
Hadronic showers:	$\sigma(E)/E = 16\% / (E[GeV])^{1/2} + 1\%$

Signals in a non-multiplying medium



The "work" performed by the power supply which puts electrons and ions in movement is given by:

$$dW = eE(v^+ + v^-)dt = Vi_0dt$$

from wich the current and charge are:

$$i_0 = e\,(v^+ + v^-)/d$$

since $v^- \gg v^+$, *electron current is dominant*.

$$Q^- = e\,(d-x)/d$$

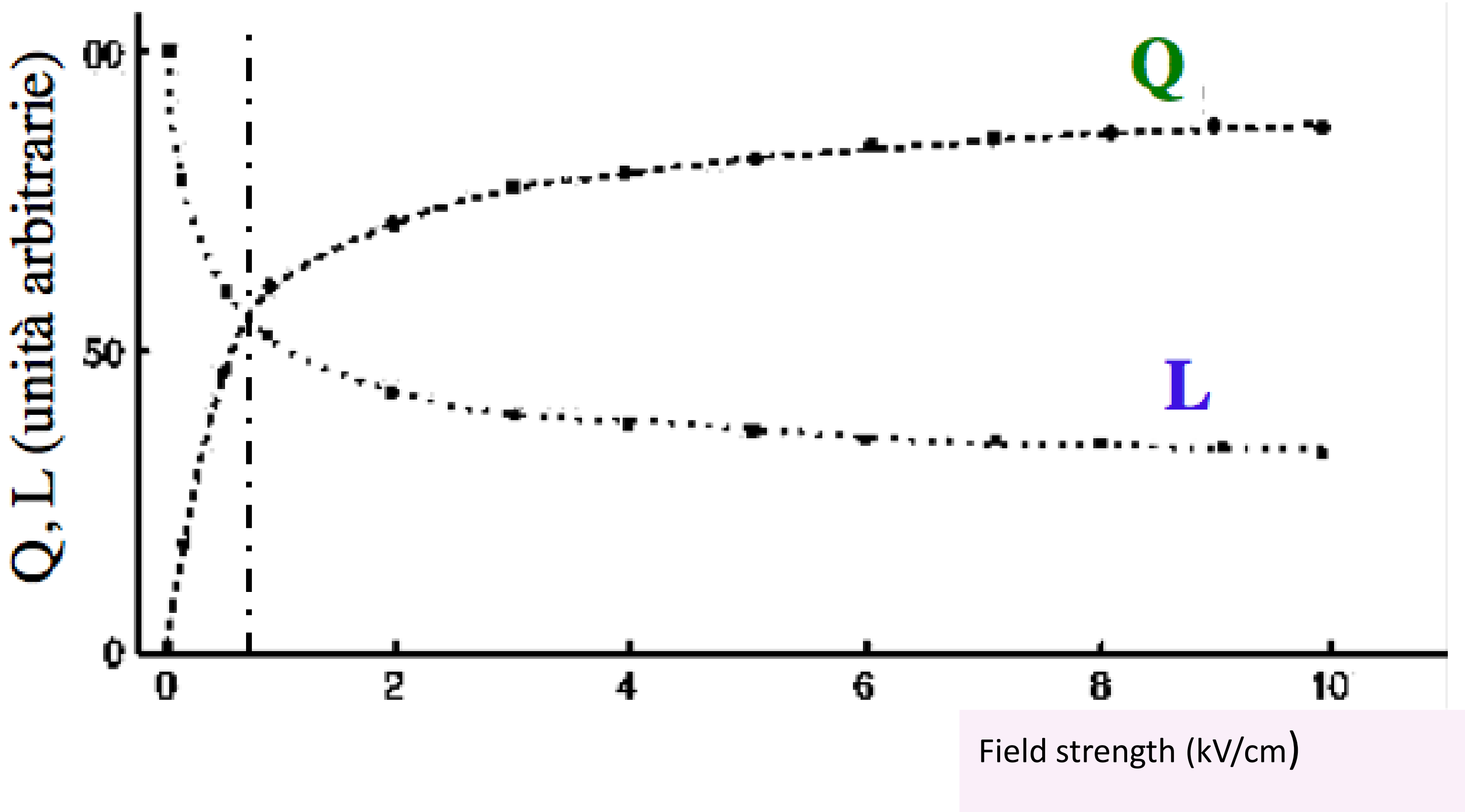
- Signals are very small: for 10000 electrons $\boldsymbol{i_0 = 0.24/d[cm]\ nA}$ ($v^- = 1.5 \times 10^3$ m/sec @ E ≈ 500 V/cm)
- LAr must be ultra pure – better than 1 ppb of electronegative impurities

Non destructive charge read-out: imaging

- A non destructive read-out can be done by replacing the anodic plane with a sequence of wire planes, that are highly transparent to the ionization charge of the event
- For a typical TPC: distance between wires = 3 mm, wire radius 0.15 mm, distance between planes = 3 mmm – the total transparency is obtained for $E_2/E_1 > 2$
- Drifting electrons can cross a succession of wire planes
- Each wire plane gives a 2D representation of the event: one coordinate is the wire position, the other coordinate is the drift (drift time proportional to distance travelled, assuming to know t_0 of the event – the start time)
- The combination of 2 or more 2D view of the same event, with a common coordinate – the drift- allows for complete 3D reconstruction

T=0 time mark

For *fully contained events,* the longitudinal position measurement requires the *time of arrival* of the event. This is called ***t=0***. It can be determined by ***collecting the scintillation light*** naturally occurring in LAr



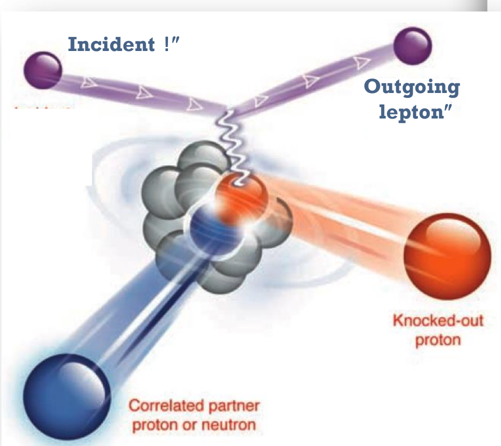
MicroBooNE

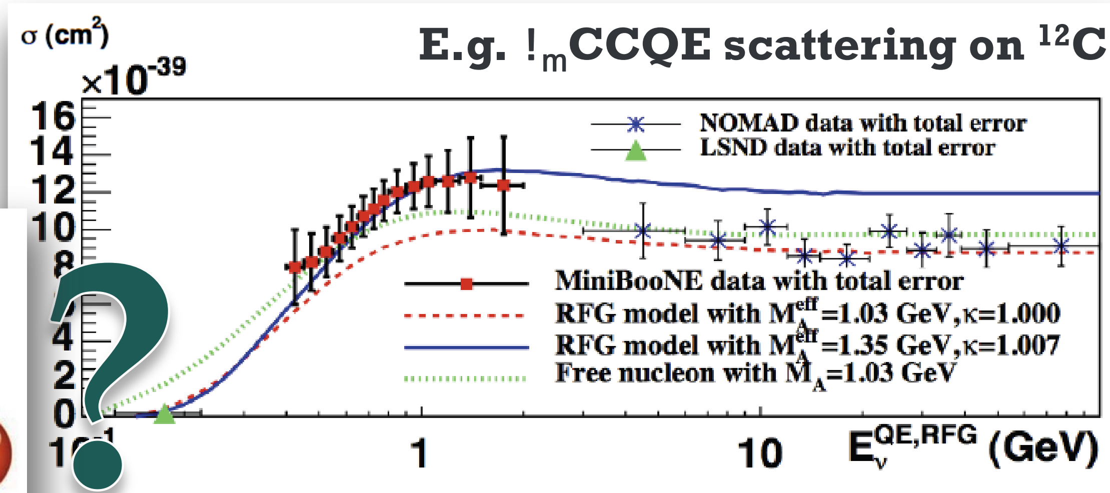
Additional physics goal

measure neutrino cross sections around 1 GeV

- Past cross section measurements (from K2K, MiniBooNE, SciBooNE, MINOS, NOMAD) have revealed limitations in our understanding of neutrino interactions

Hadronic effects must play a critical role!





Phys. Rev. D81, 092005 (2010)

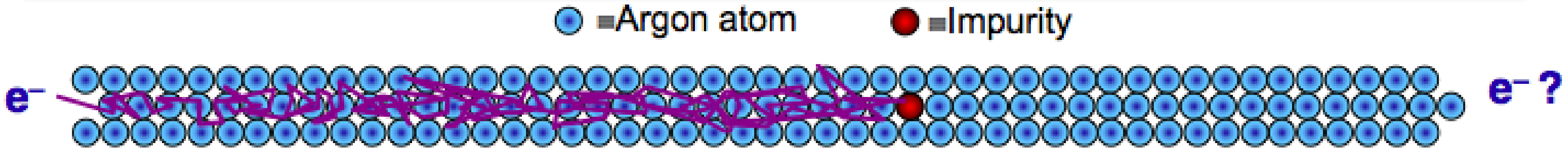
The relevance of drift length

The complexity of the detector is strictly linked to the *number of wire planes*. For this reason the distance over which electrons are made to drift should be *as long as possible*. Several limitations come into play:

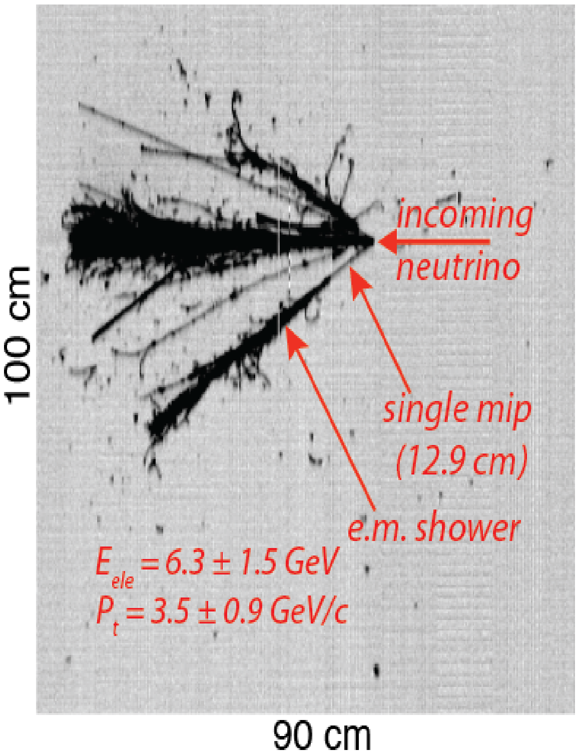
- The value of ***high voltage***. For a drift field of 500 V/cm, in order to drift over 3 meters, it requires 150 kVolt. The drift time over this distance is 1.85 msec.

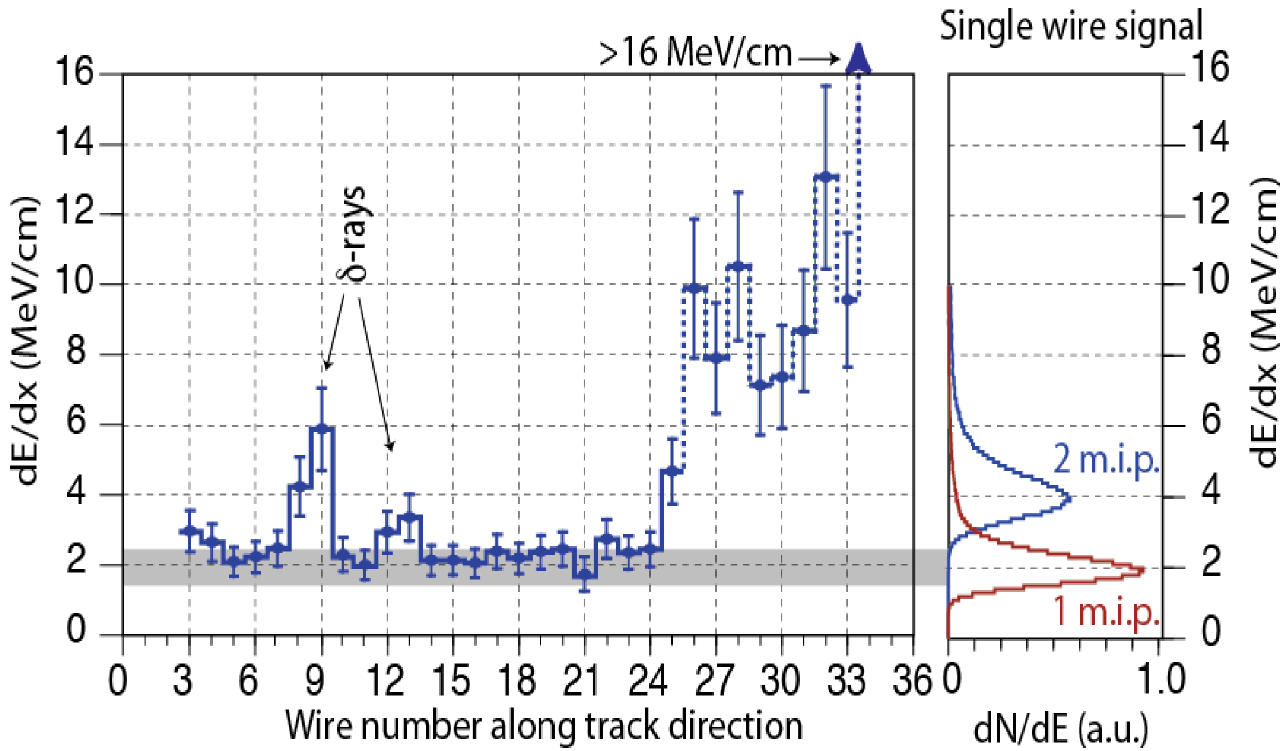
- The ***diffusion of electrons***, which slightly blur the image, transforming a delta function into an approximately gaussian distribution:
  $\sigma(t) = (2Dt)^{1/2}$ $D=4.8\pm0.2\ cm^2sec^{-1}$

- The ***electron attachment probability***. In order to drift over macroscopic distances (meters) LAr must be *extremely pure*, because free electrons can attach electronegative impurities like O_2.

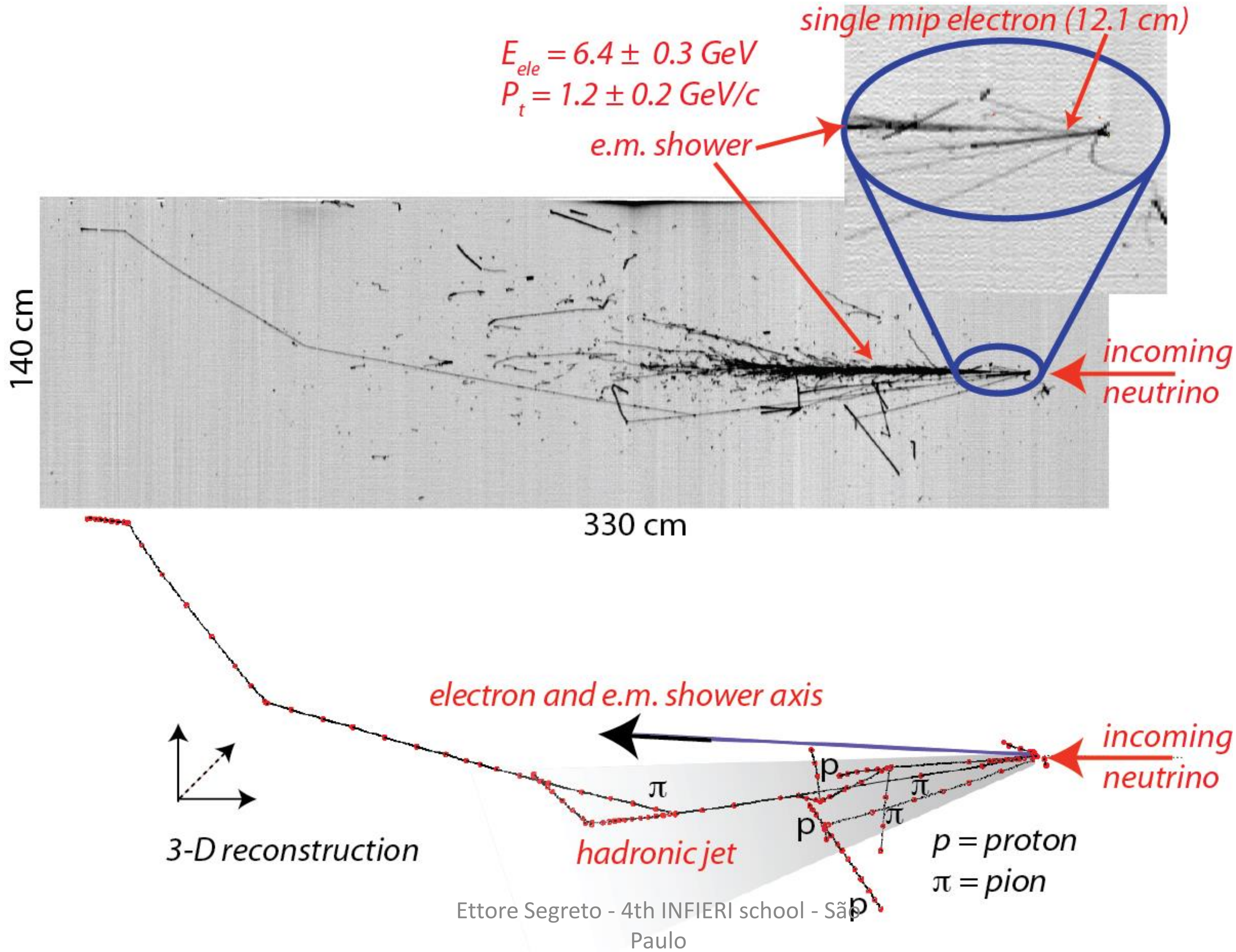


3rd event


incoming neutrino
single mip
(12.9 cm)
e.m. shower
$E_{ele} = 6.3 \pm 1.5$ GeV
$P_t = 3.5 \pm 0.9$ GeV/c
100 cm
90 cm


>16 MeV/cm
Single wire signal
δ-rays
dE/dx (MeV/cm)
Wire number along track direction
2 m.i.p.
1 m.i.p.
dN/dE (a.u.)
dE/dx (MeV/cm)

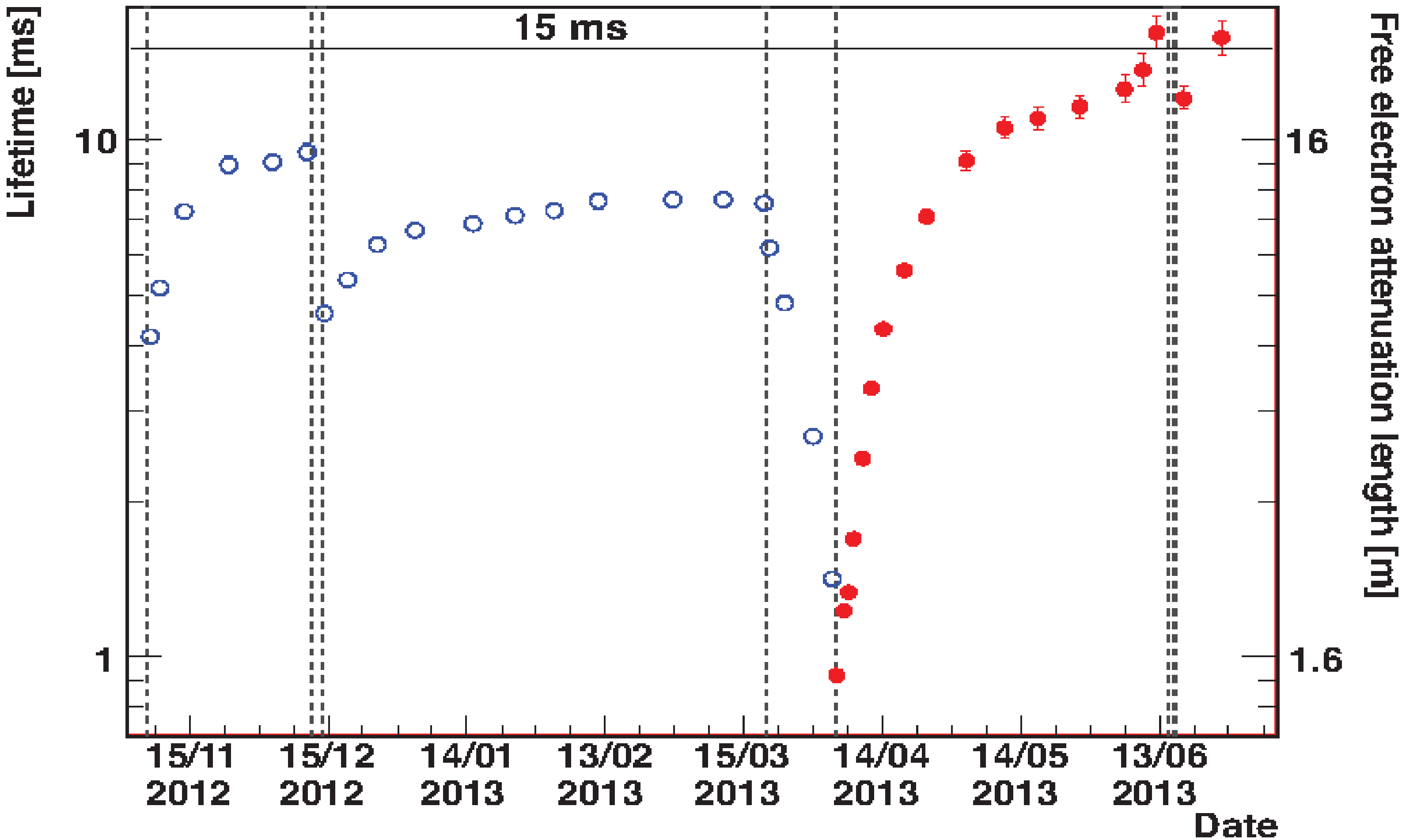
4th event


single mip electron (12.1 cm)
$E_{ele} = 6.4 \pm 0.3$ GeV
$P_t = 1.2 \pm 0.2$ GeV/c
e.m. shower
140 cm
incoming neutrino
330 cm
electron and e.m. shower axis
incoming neutrino
p
π
π
p
π
3-D reconstruction
hadronic jet
p = proton
π = pion
p

ICARUS T600 @ LNGS

- ICARUS T600 has been continuously operating at Gran Sasso National Laboratory from 2010 to 2013
- Major milestone towards *multi-kton high performance LAr detectors*
- Many relevant technical achievements, mainly in the field of LAr purity. An electron lifetime of 15 msec has been reached at the end of the Run with a new concept of LAr recirculation
- It has been exposed to the CNGS beam (CERN Neutrino to Gran Sass and a total sample of 2650 ν interactions, corresponding to 7.93 10^{19} over 8.6 10^{19} pot collected
- Performed studies on the neutrino velocity after the OPERA claim
- Searches for sterile neutrinos

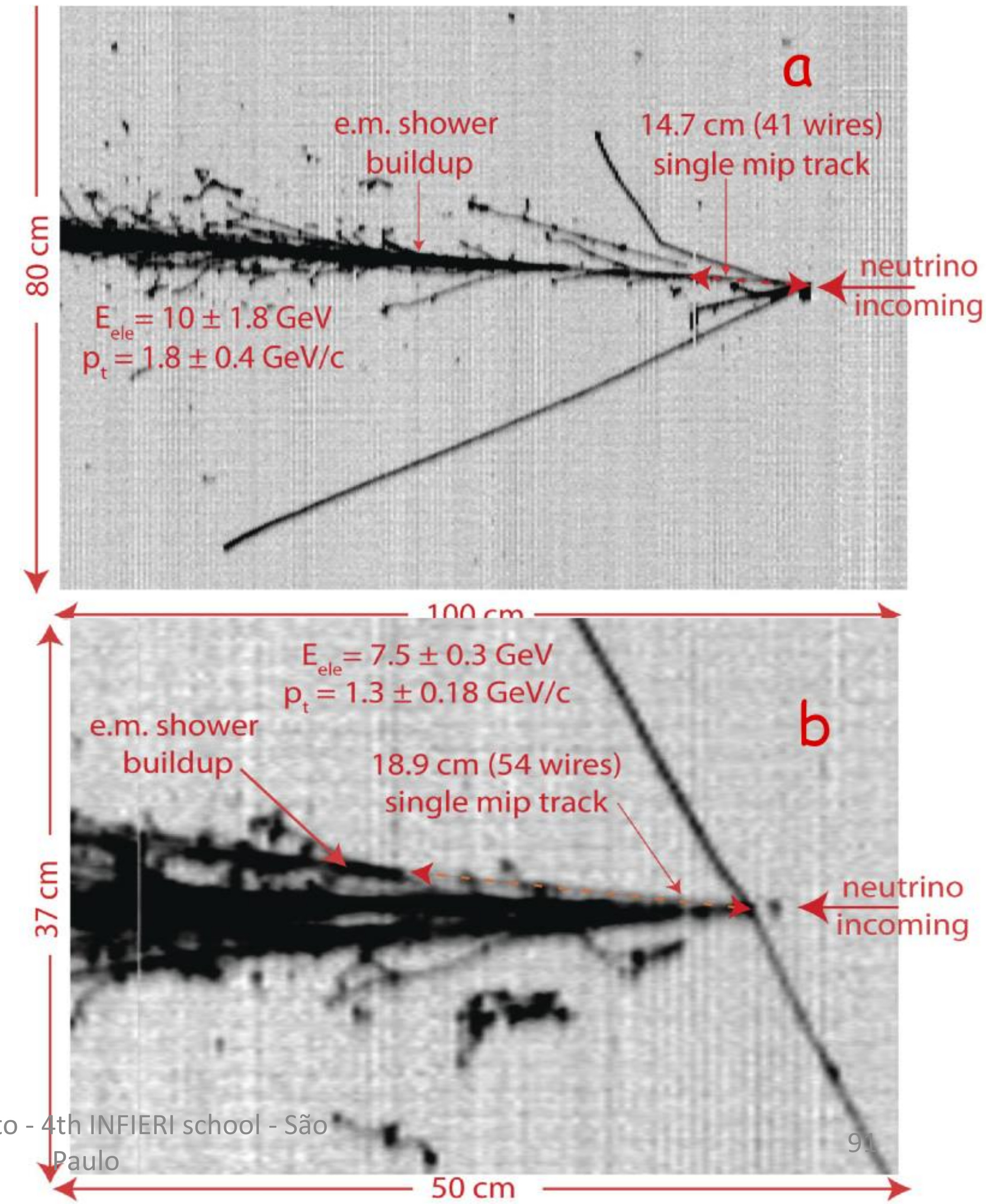
ICARUS T600 @ LNGS – e^- lifetime



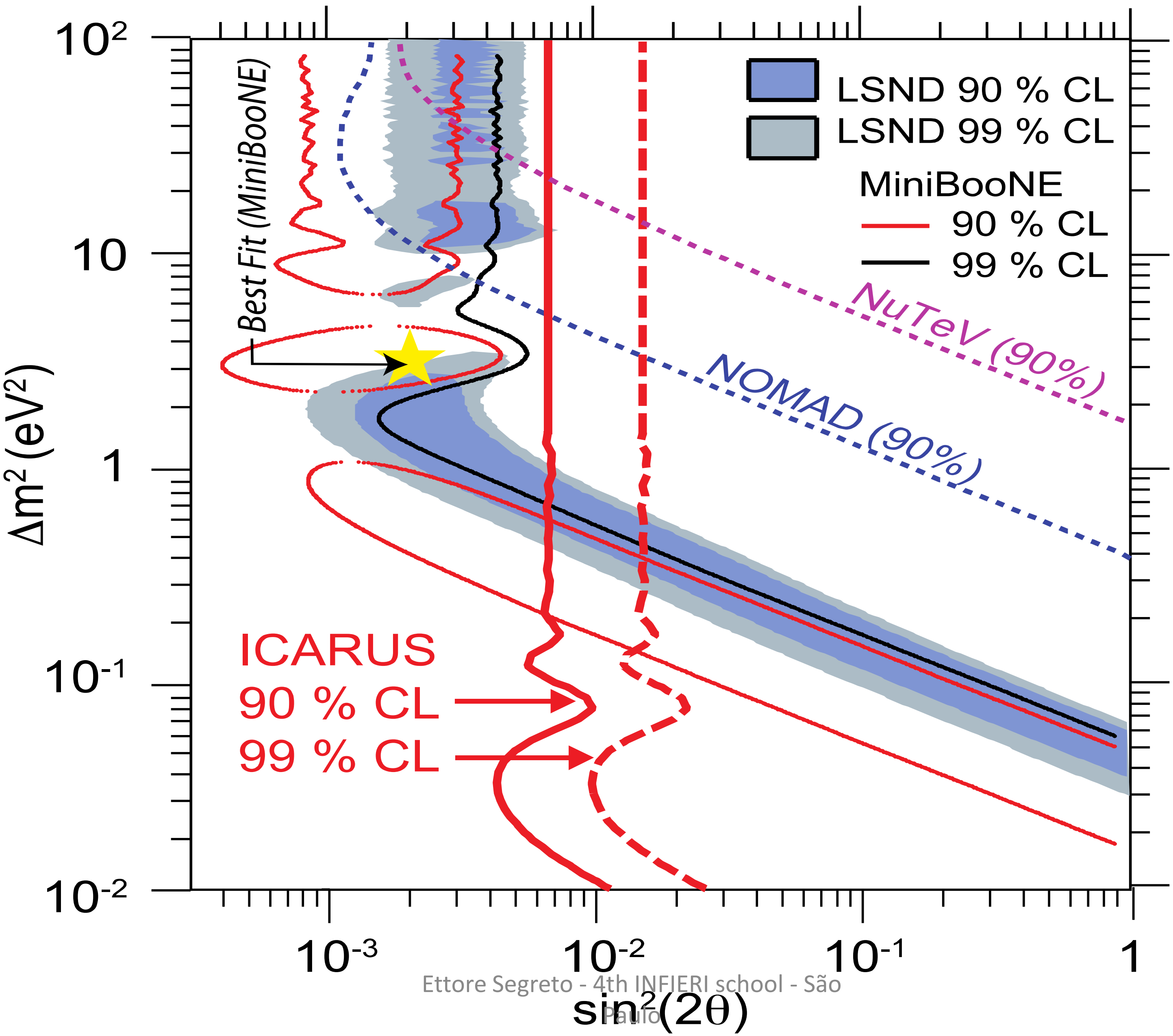
Exceptionally high electron lifetime

Events in the data

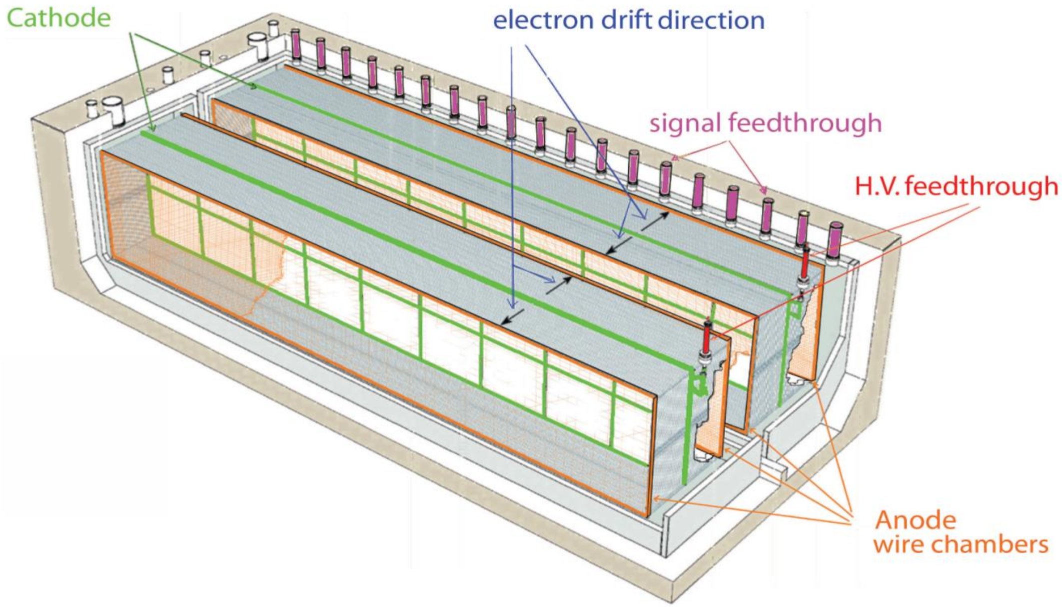
- ***Four CC events in the data***
- Compatible with the expected background of 6.4 ± 0.9 events due to: intrinsic beam contamination, $\nu_\mu \rightarrow \nu_e$ oscillations from $\sin^2(\theta_{13})$, ν_τ with $\tau \rightarrow e$ events from the three neutrino mixing standard model predictions,

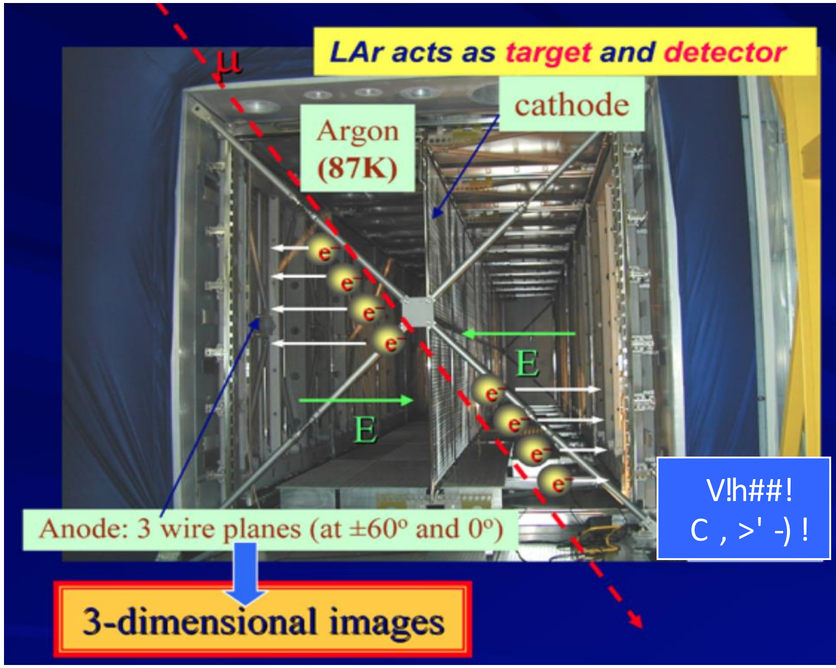


ICARUS result



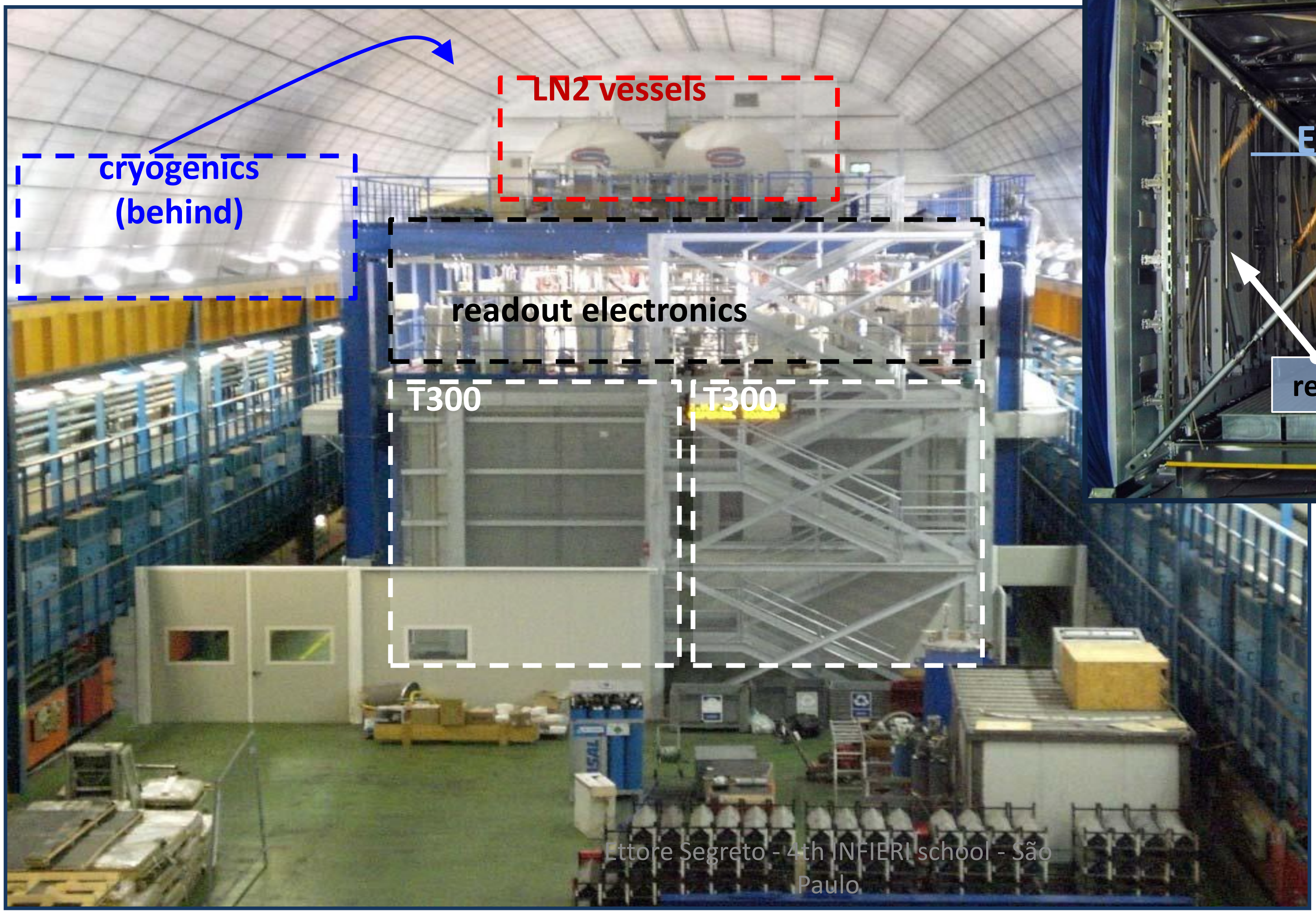
The ICARUS T600 Detector

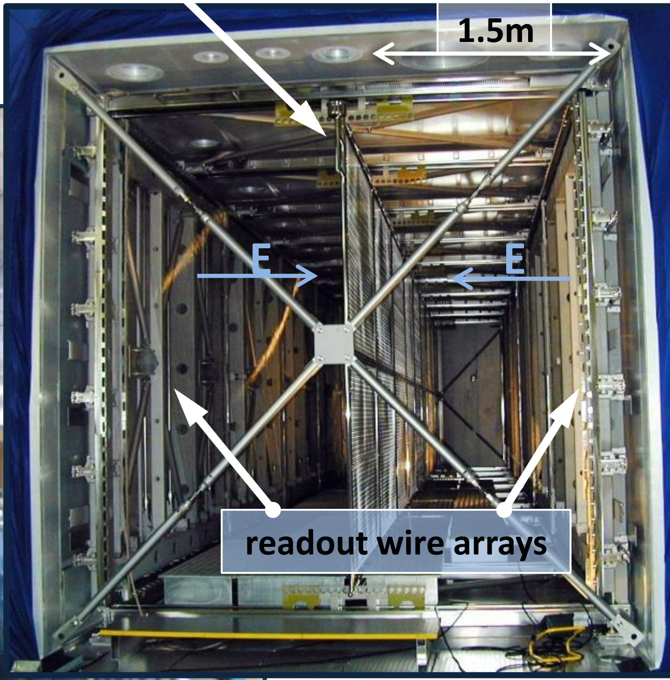




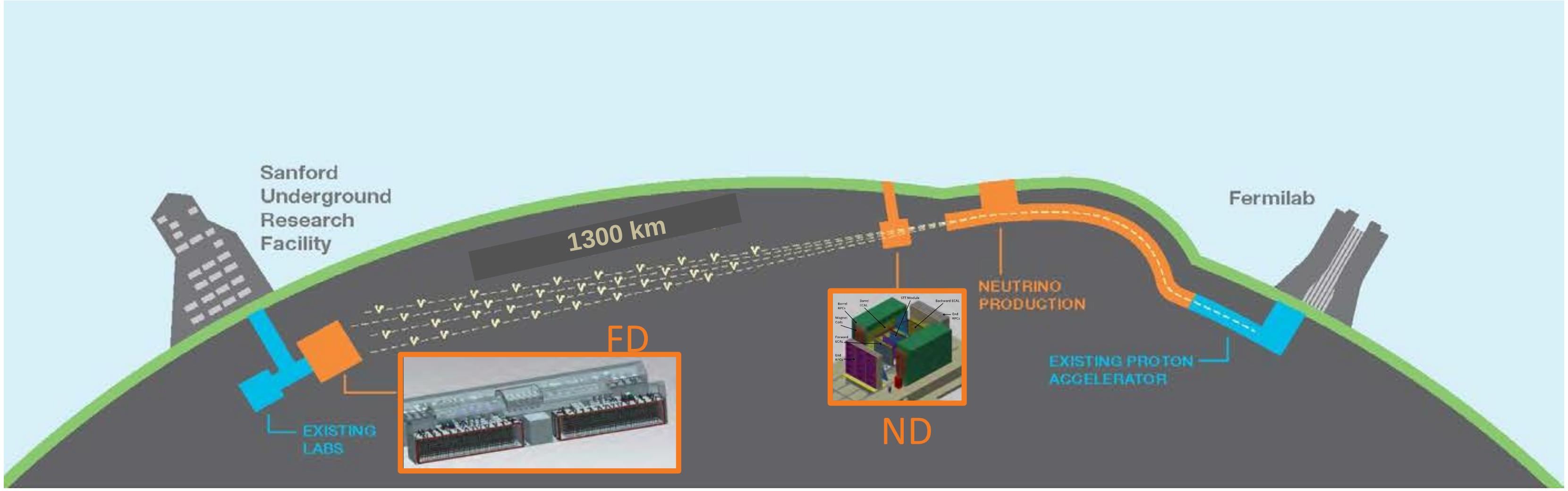
- VO, !i Vh##j !3>) (\ 81-!/ , >' -) @
  - hD%!m!hDc !m!" c D%!!p!*` f !/ h!) 18A!
  - <3P' 3>!E 2!18\ I) !/ 1@@!p!q` %!6!
  - N23h !!-) (L6A!s !" D !/ !
  - S W!s !$ f !MW!!!K!s !#D !MW_8/ !!
  - I >23h !s !" D f !/ / _y @
- q!O 32) !8A1/ 0) 2@!!
  - * !8A1/ 0) 2@G) 2!/ , >' -) !!
  - h!2) 1>, ' 6!O 32) !G-1( ) @G) 2!8A1/ 0) 24!O 32) @16!#~4!%#~!!!!!!
  - p!f h###!O 32) @4h!/ / !G368A4h!/ / !G-1( ) !@G183(L!
- FC V!B, 2!@83(\ –1\ , (!-3LA6"!!
  - b*#xf qd!FC V@4!a" !Ä !!!
  - Wg W!@(@\ I) !b" a(/ d!O 36A!O 1I) !@A3h) 2!bVFHd!

ICARUS T600 @ LNGS





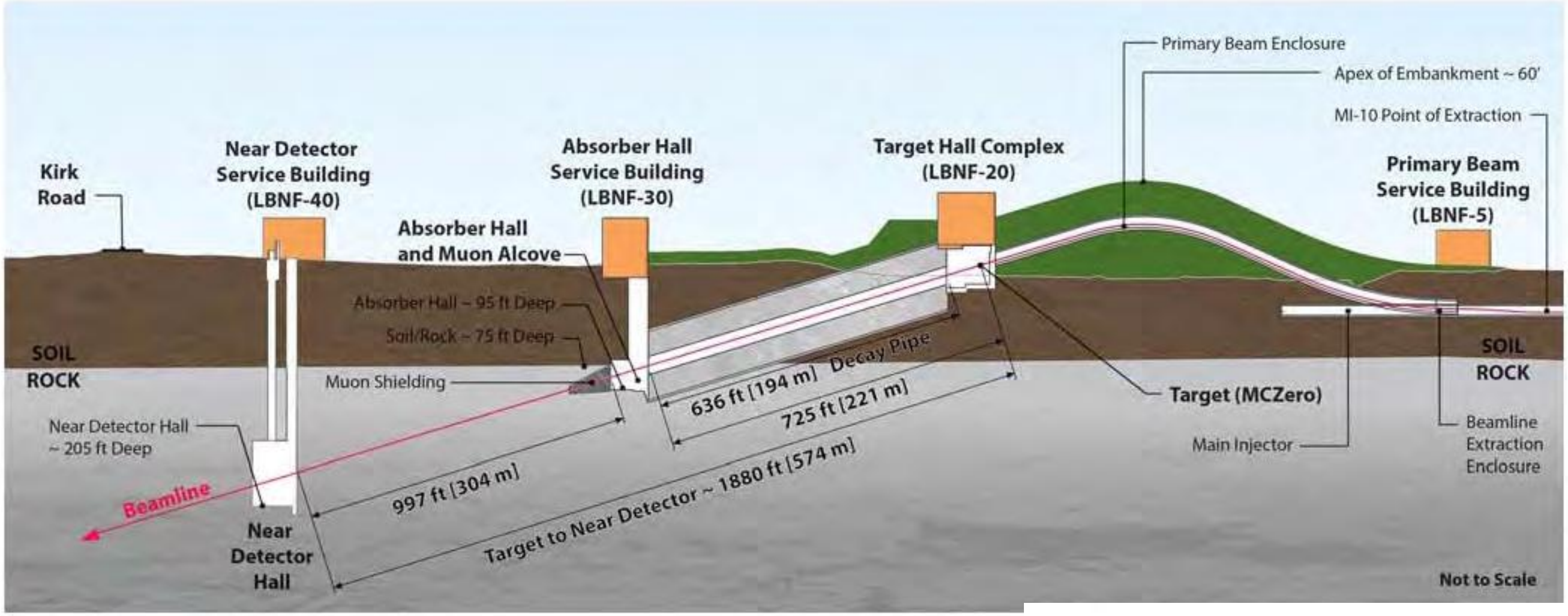
DUNE EXPERIMENT



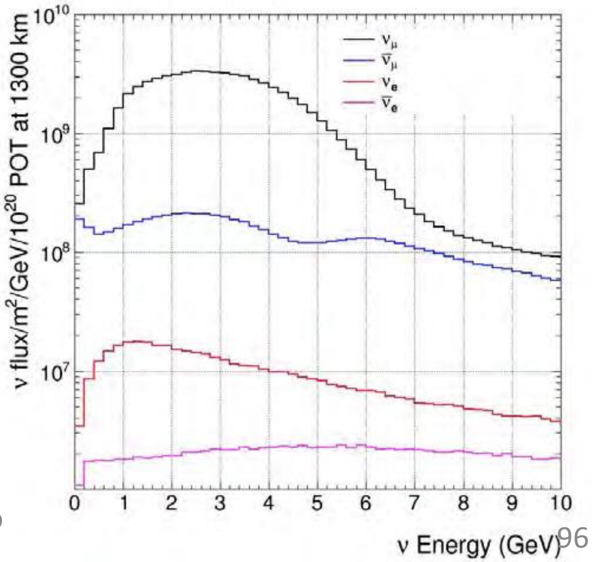
Key DUNE features:

- High-intensity wide-band neutrino beam originating at FNAL
  - 1.2 MW proton beam upgradable to 2.4 MW
- Highly capable near detector to measure the neutrino flux
- A ~40 kt fiducial mass liquid argon far detector
  - Located 1300 km baseline at SURF's 4850 ft level (2,300 mwe)
  - Staged construction of four ~10 kt detector modules. First module installation starting in 2021.

LBNF/DUNE Neutrino Beam



- 60 – 120 GeV Proton beam energy
- Initial power 1.2 MW upgradable to 2.4 MW
  - PIP II complete before start of data taking
- 10^{21} protons on target per year
- Large ν flux 1 to 5 GeV

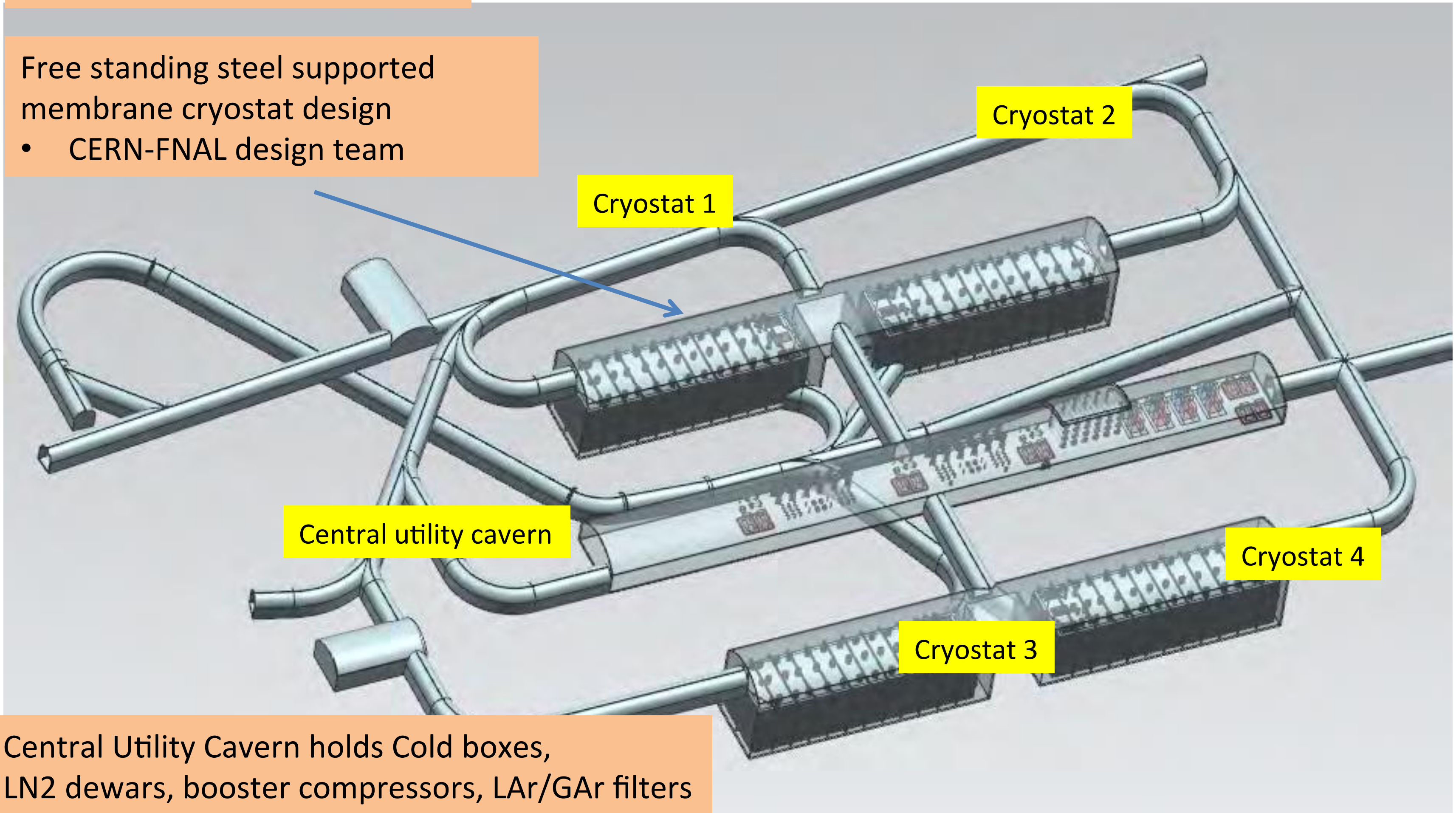


Far Detector – Cryostat / Cryogenic Systems Layout

Each Cryostat holds 17.1kt LAr

Free standing steel supported membrane cryostat design

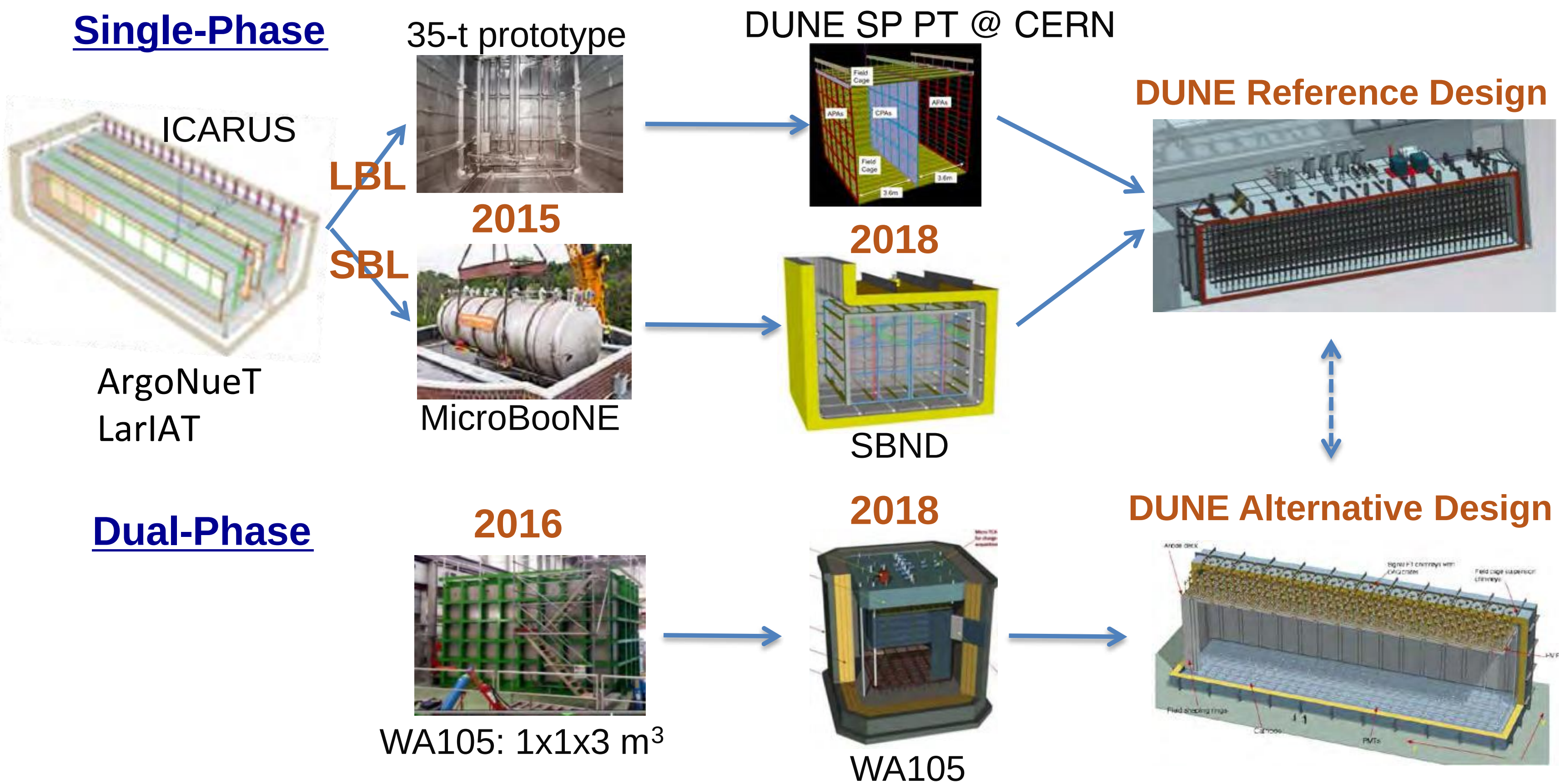
- CERN-FNAL design team



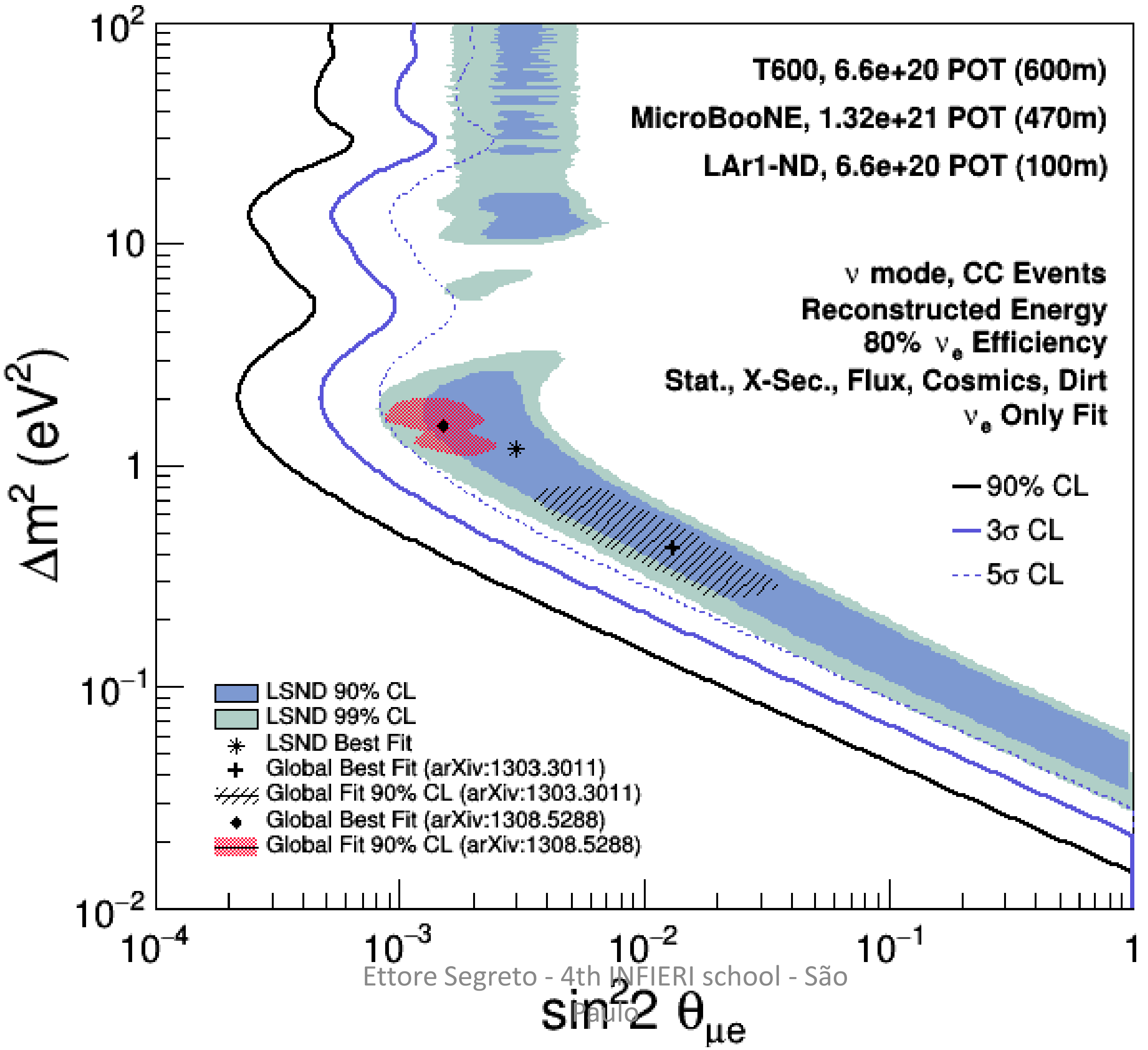
Central Utility Cavern holds Cold boxes,
LN2 dewars, booster compressors, LAr/GAr filters

LArTPC Development Path

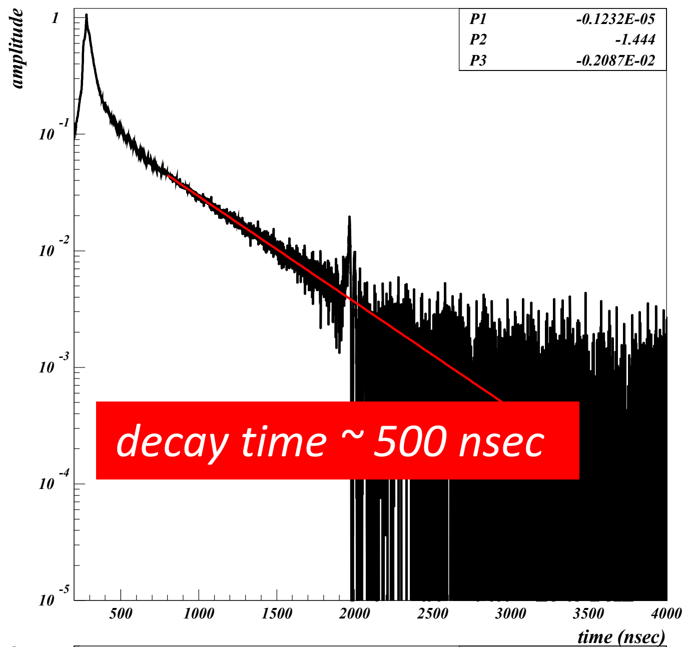
Fermilab SBN and CERN neutrino platform provide a strong LArTPC development and prototyping program



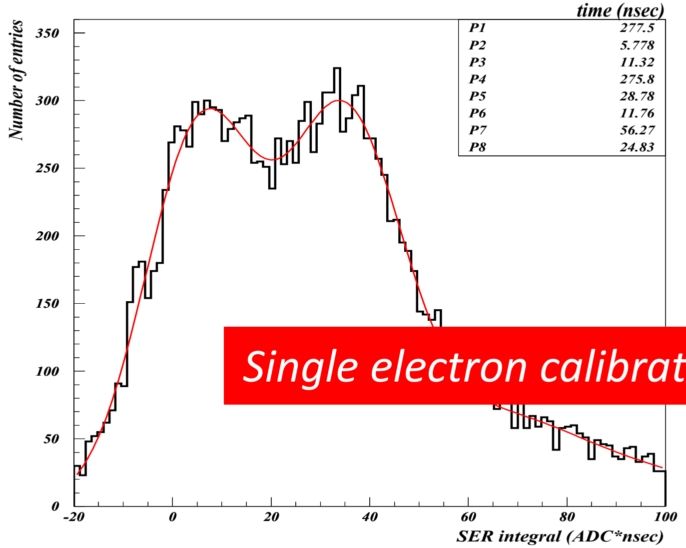
$\nu_\mu => \nu_e$ appearance sensitivity



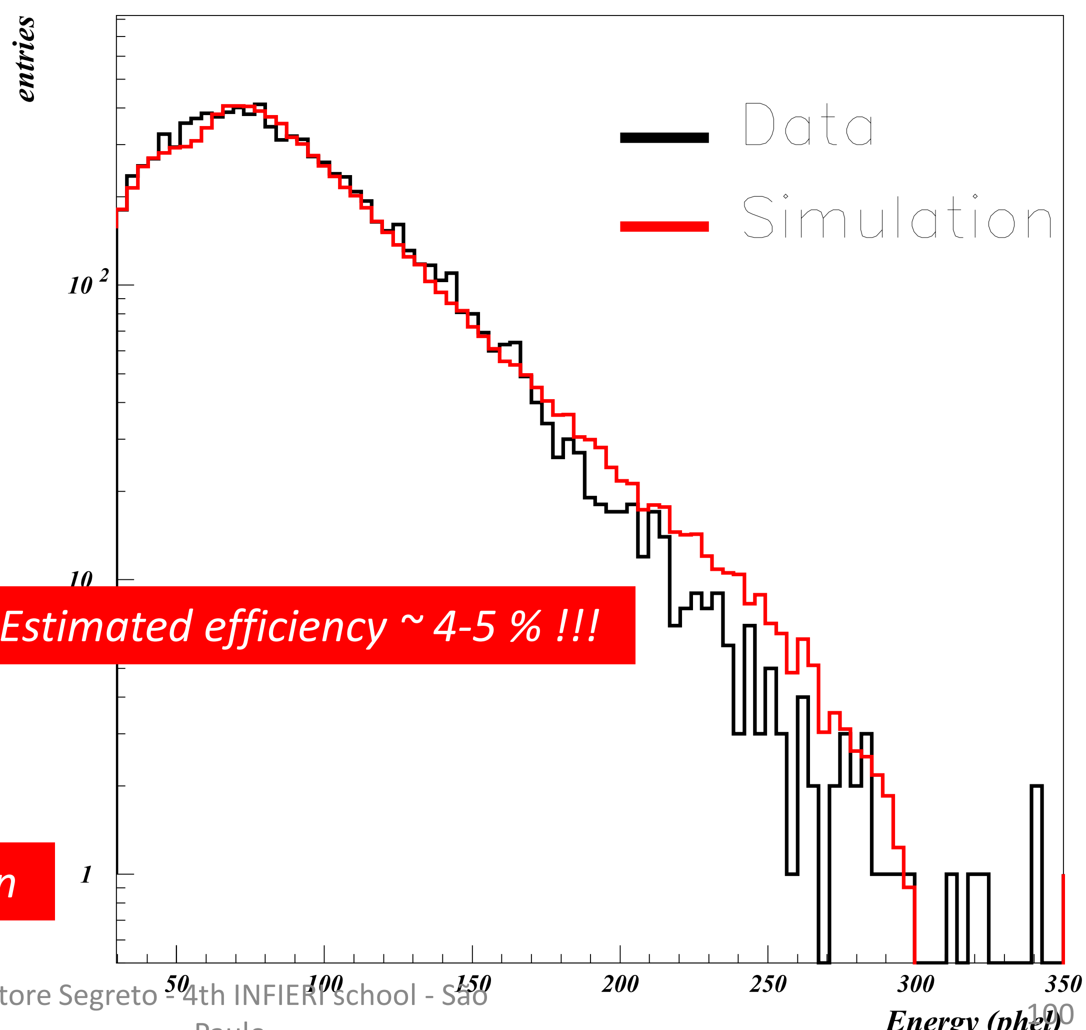
Preliminary results



decay time ~ 500 nsec



Single electron calibration



Estimated efficiency ~ 4-5 % !!!