Neutrino experiments at LNGS

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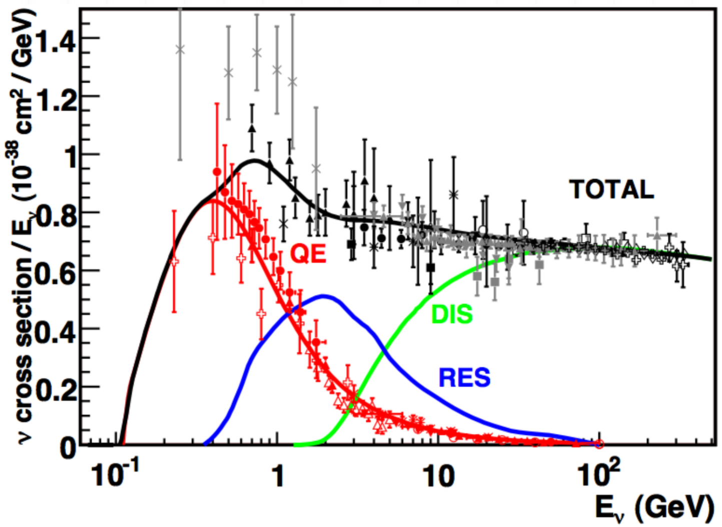
EDIT
International School

Neutrino Properties

- lepton -> no strong force
- no charge -> no electromagnetic force
- spin ½
- 3 lepton flavors: e, μ, τ
- 3 mass eigenstates



Neutrinos can only interact with weak force (and gravity)

the cross section is very small in the order of 10^{-38} cm^2 at 1 GeV

Neutrino Sources

✧ **Universe**
- from astrophysical processes (up to 10^{15} eV)

✧ **Stars**
- Sun radiates us with $7 \cdot 10^{10}$ $\nu/cm^2/s$ with energy up to ~15 MeV
- supernova collapse can produce a burst of ~10^{65} eV in neutrinos with energy ~30 MeV

✧ **Atmospheric** neutrinos produced in collision of cosmic rays with upper atmosphere (energy range ~GeV)

✧ **Artificial**
- Reactor neutrinos produced in the U and Th fission (energy few MeV)
- Accelerator can produce neutrinos with energies up to 50 GeV

✧ **Geoneutrinos** produced in the U and Th fission (few MeV)

Neutrino Propagation

http://www.nobelprize.org

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

1957 Bruno Pontecorvo

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) **Matrix**

if PMNS is not diagonal

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

Atmospheric neutrinos
K2K, MINOS, T2K, OPERA

Chooz, DayaBay, RENO, T2K, MINOS, NOνA, …

Solar neutrinos
Borex, SuperK, SNO, KamLAND

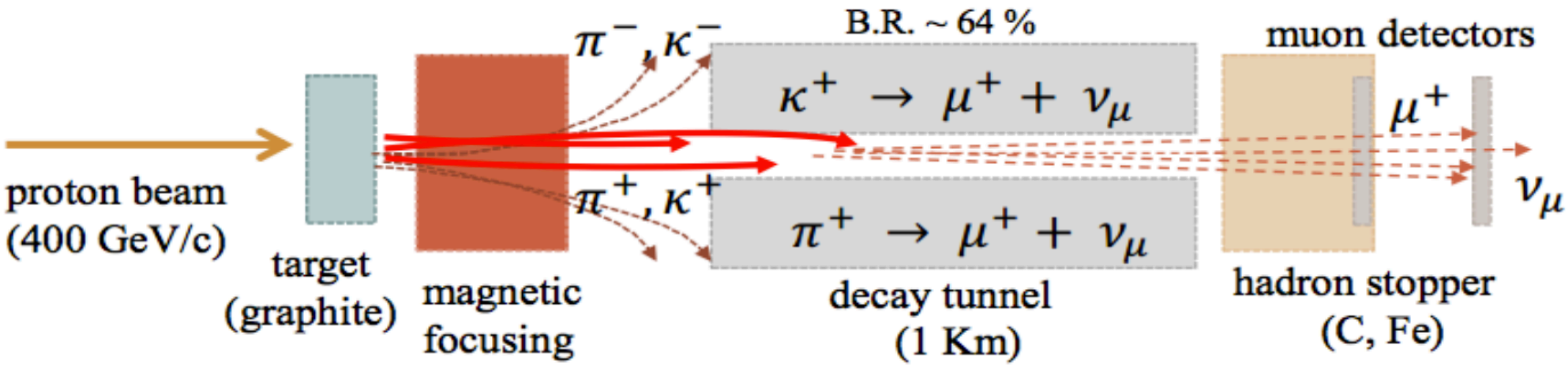
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Δm^2_{32} = (2.44±0.06)10^{-3} eV^2
θ_{32} = (45.5±3.2)°

θ_{13} = (8.88±0.39)°

Δm^2_{21} = (7.53±0.18)10^{-5} eV^2
θ_{12} = (33.4±0.85)°

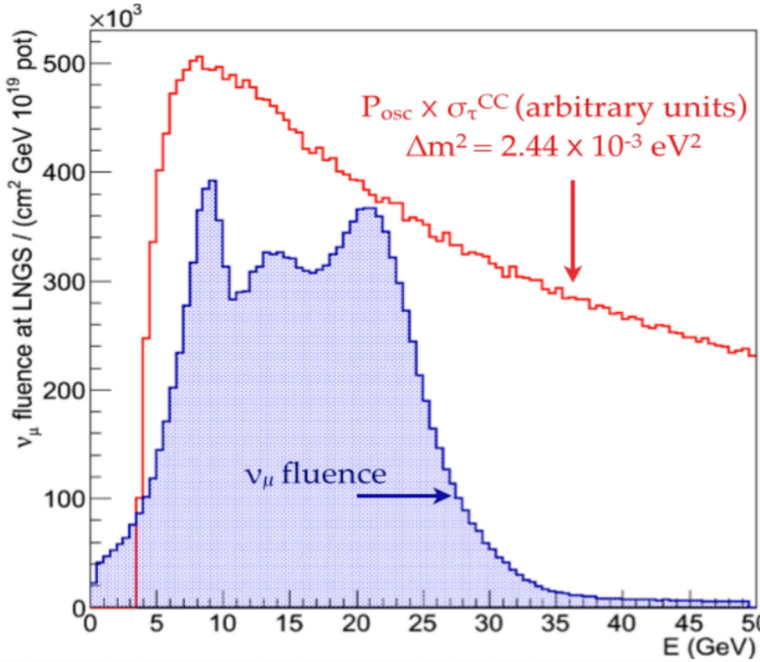
CERN Neutrinos to Gran Sasso



CNGS ν beam

$E_{\nu\mu}$	17 GeV
distance	732 km
(anti-νe + νe) / νμ	0.8 % *
anti-νμ / νμ	2.0 % *
ντ prompt	negligible *

* interaction rate @ LNGS



Oscillation **P**roject with **E**mulsion-t**R**acking **A**pparatus

OPERA

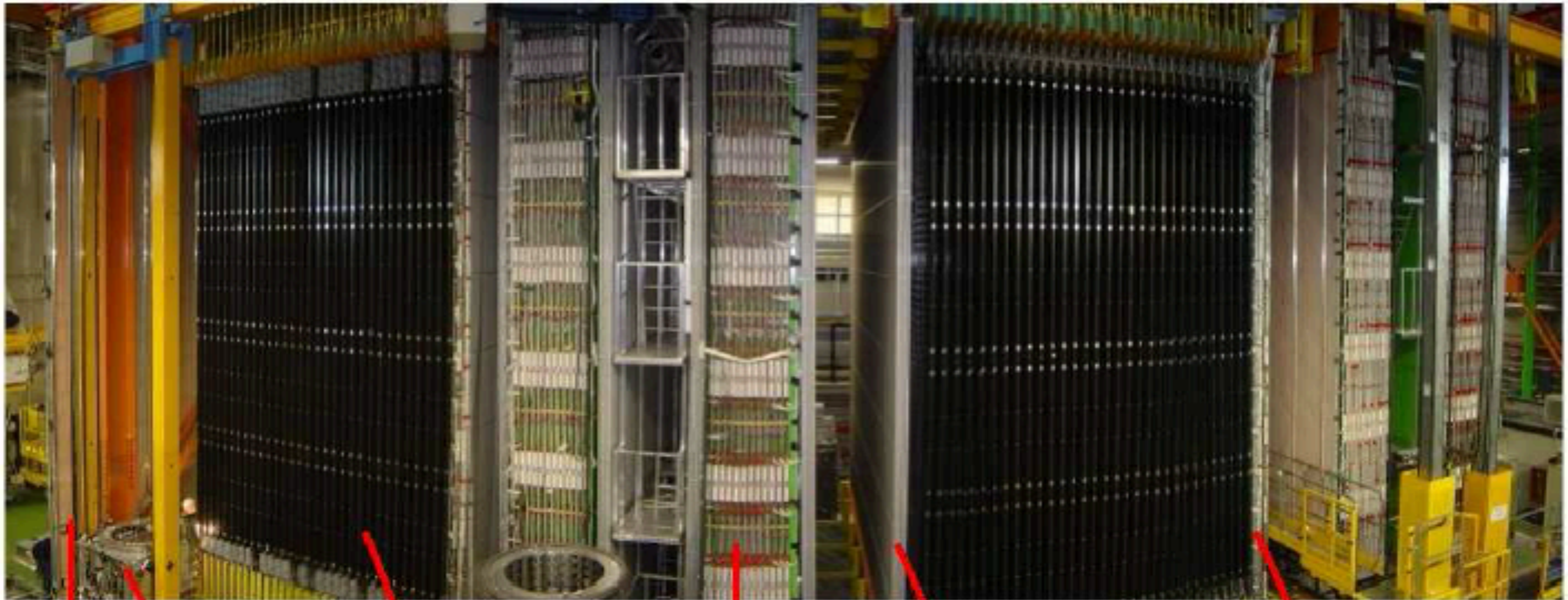
1. Direct observation of ν_τ appearance from $\nu_\mu \rightarrow \nu_\tau$ oscillation

τ decay channel	**br [%]**
$\tau \rightarrow \mu$	17.7
$\tau \rightarrow e$	17.8
$\tau \rightarrow h$	49.5
$\tau \rightarrow 3h$	15.0

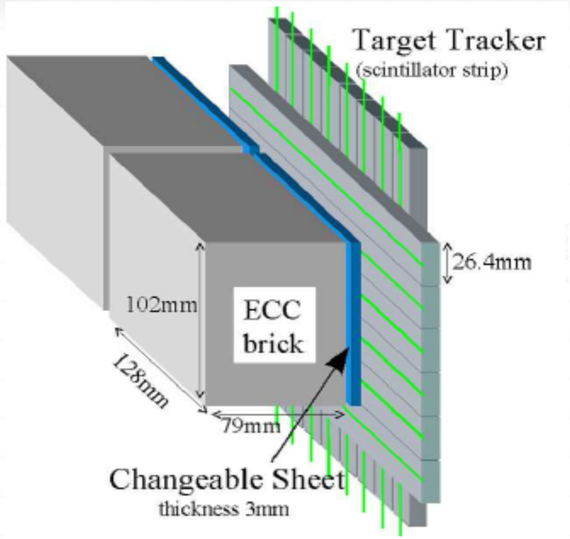
2. Search for non-standard oscillations at large Δm^2 values
   OPERA limit: $\sin^2(2\theta_{new}) < 7.2 \cdot 10^{-3}$ (Bayesian)

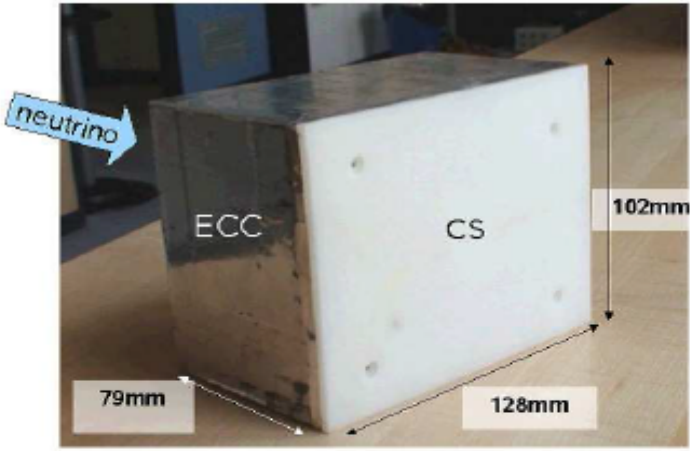
Hybrid detector with modular structure

target + spectrometer



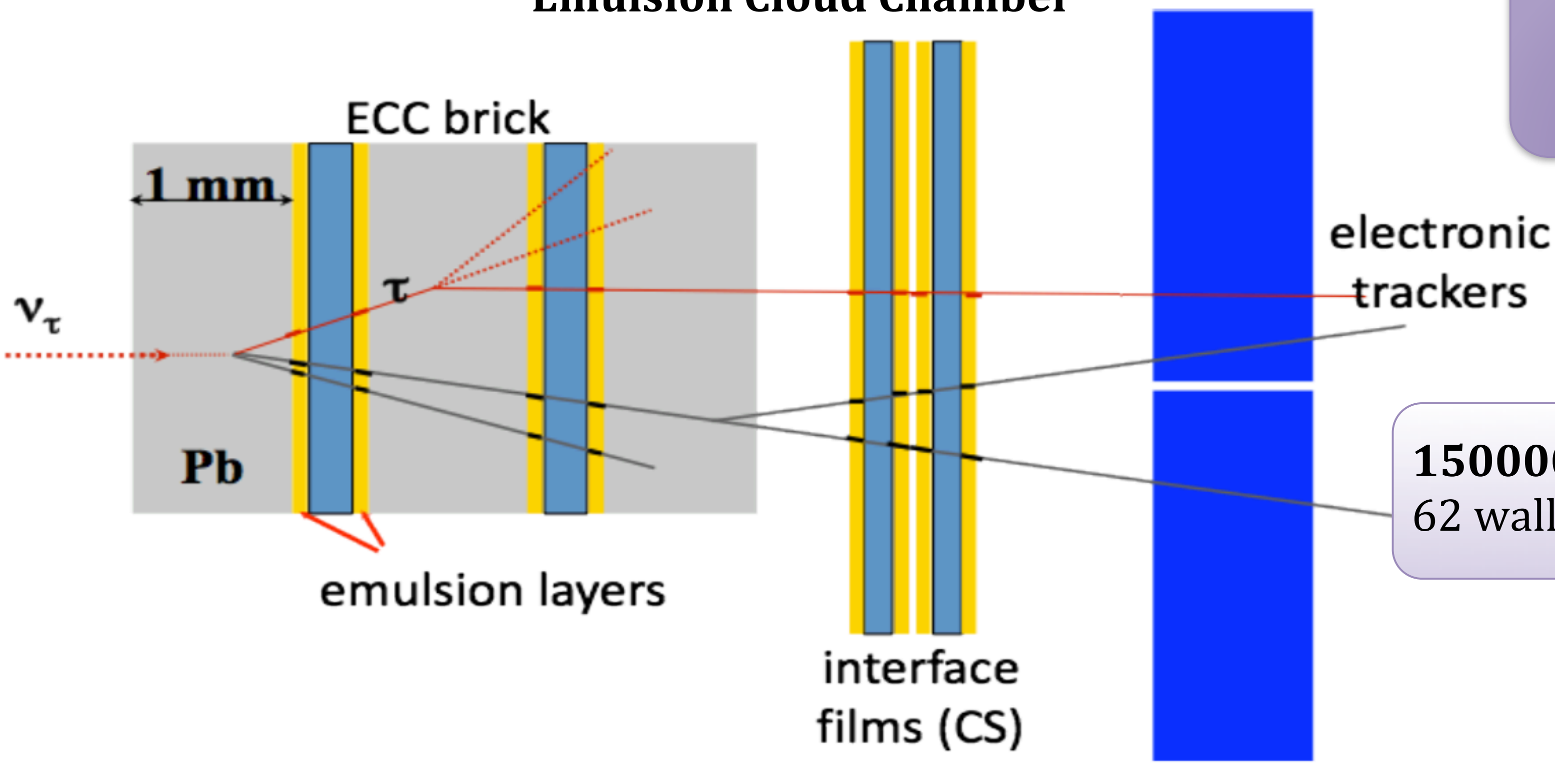
6.7 x 6.7 m^2 -> 10 x 10 x 20 m^3 -> 4kt





brick
- 56 plates
- 8.3 kg

Emulsion Cloud Chamber

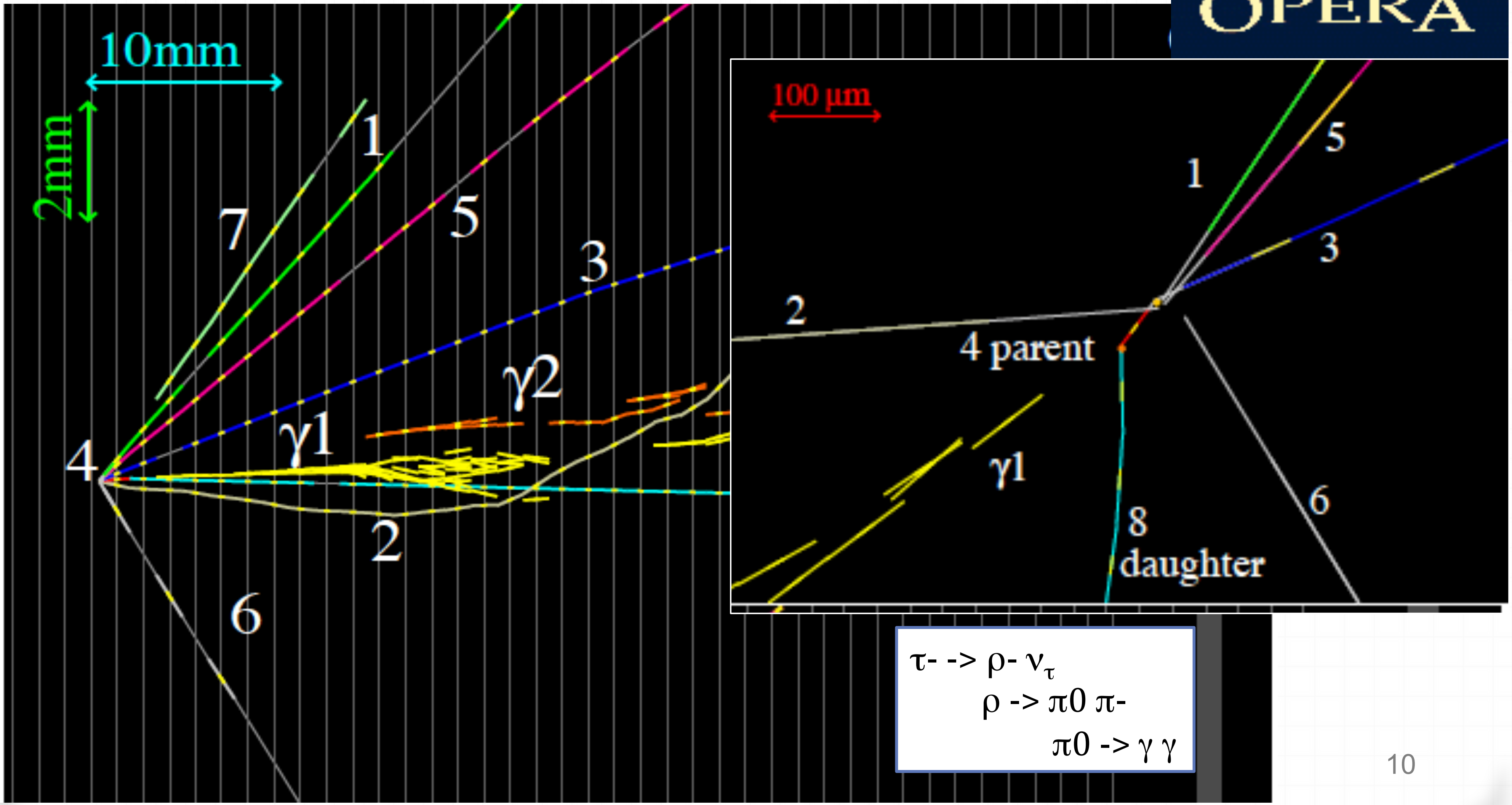


150000 bricks = **1.25 kt**
62 walls = 2 x 2912 bricks

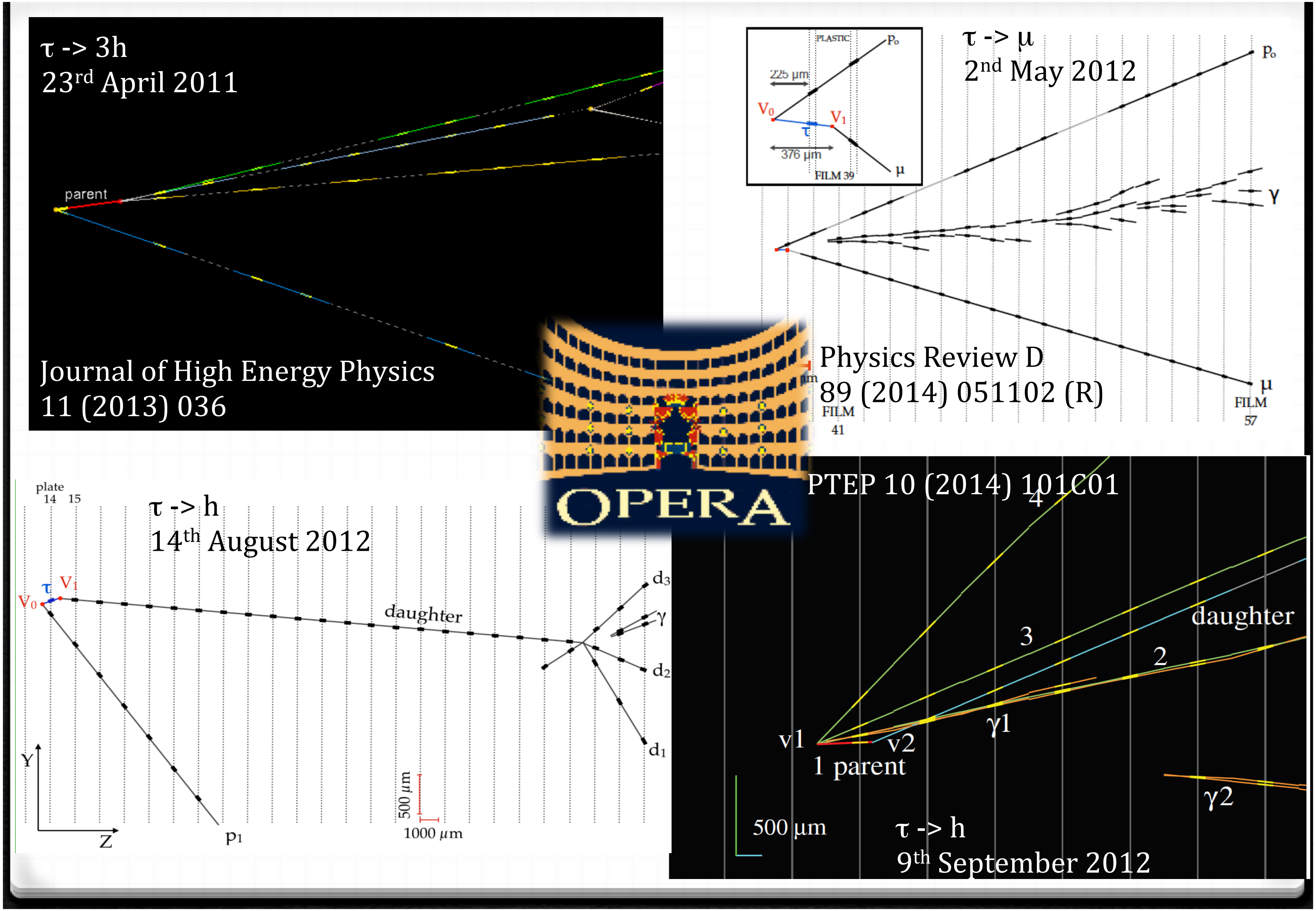
1^{st} ν_τ candidate

Physics Letters B 691 (2010) 138

τ -> h
22 August 2009



τ^- -> ρ^- ν_τ
ρ -> π0 π-
π0 -> γ γ


τ -> 3h
23rd April 2011
parent
Journal of High Energy Physics
11 (2013) 036
τ -> μ
2nd May 2012
PLASTIC
225 μm
376 μm
FILM 39
Physics Review D
89 (2014) 051102 (R)
FILM 41
FILM 57
OPERA
τ -> h
14th August 2012
plate
14 15
daughter
500 μm
1000 μm
PTEP 10 (2014) 101C01
daughter
1 parent
500 μm
τ -> h
9th September 2012

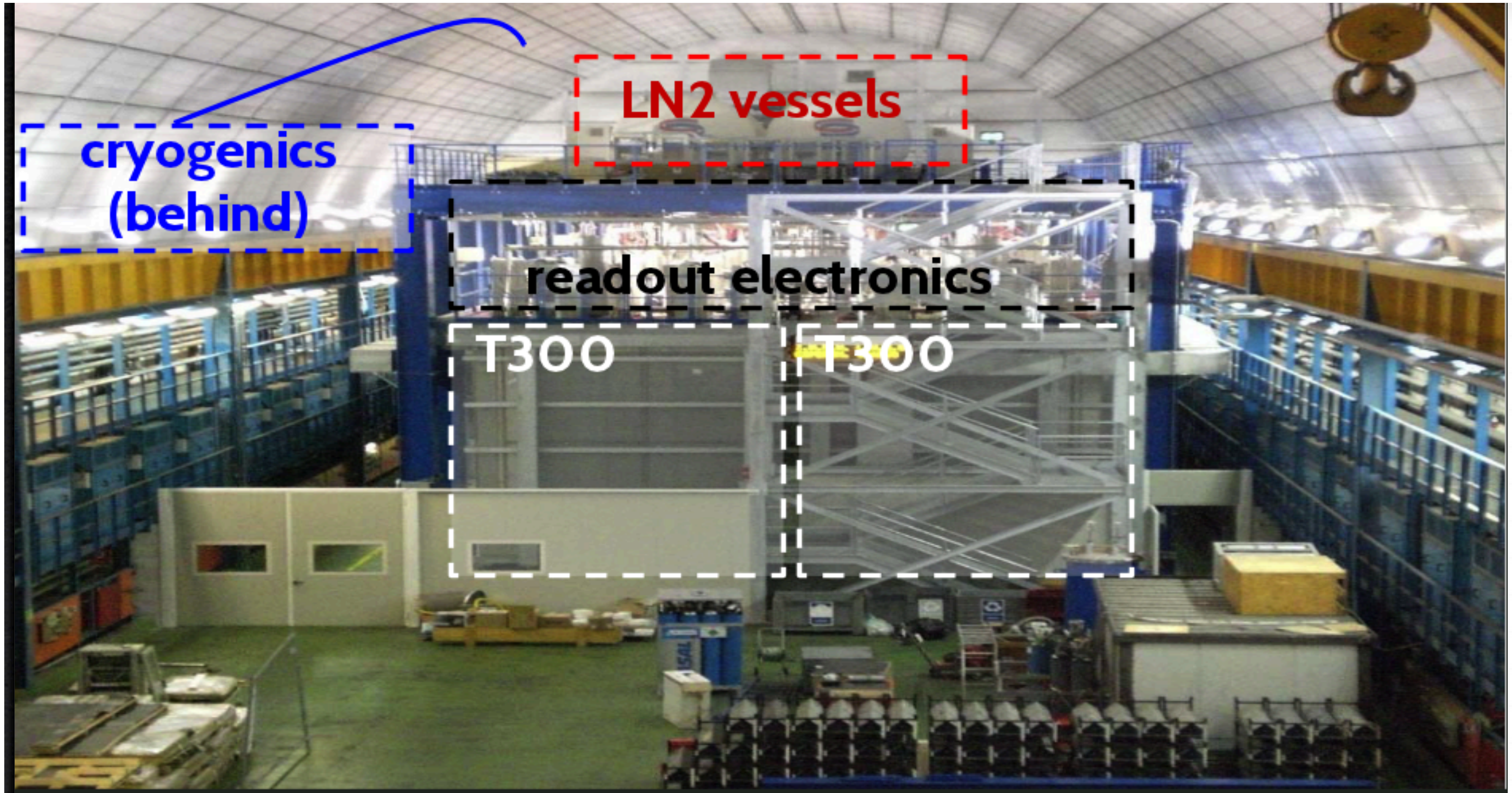
Imaging Cosmic And Rare Underground Signals

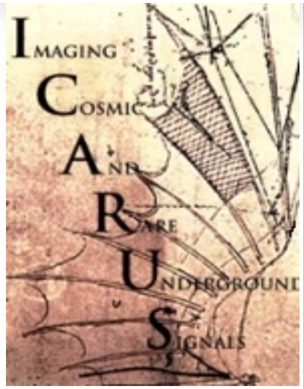
1. Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations
2. Search for sterile neutrinos
3. Atmospheric neutrinos
4. Nucleon decay
5. Supernovae neutrinos

"Precise 3D track reconstruction algorithm for the ICARUS T600 liquid argon time projection chamber detector",
Advances in High Energy Physics, AHEP, Volume 2013, Article ID 260820, 2013

"Experimental search for the 'LSND anomaly' with the ICARUS LAr-TPC detector in the CNGS beam",
Eur. Phys. J. C 73:2345, 2013

"Search for anomalies in the ν_e appearance from a ν_μ beam",
Eur. Phys. J. C 73:2599, 2013





1977 Carlo Rubbia

Two identical modules, T300

- 3.6 x 3.9 x 19.6 ~ 275 m^3 each
- LAr active mass: 476 t
- drift length: 1.5 m (1 ms)
- E = 0.5 kV/cm
- sampling time: 0.4 μs

Four wire chambers

- 2 Induction + 1 Collection
- ~ 54000 wires, 3 mm pitch and plane spacing oriented at 0°, ±60°
- spatial reconstruction + calorimetric measurement

20+54, 8” **PMTs** for scintillation light detection

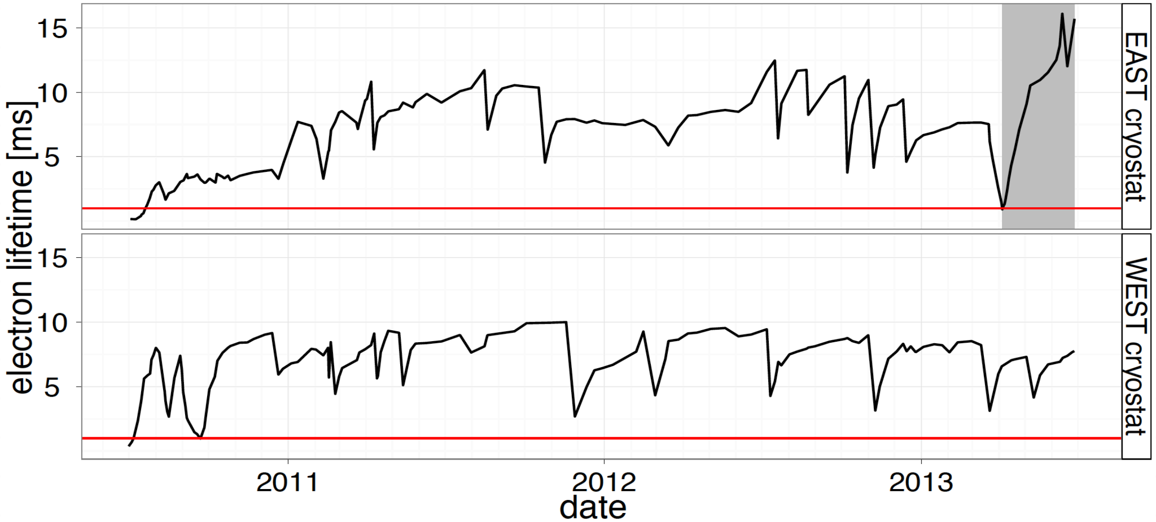
- VUV sensitive (128 nm) with TPB wave shifter
- trigger and t_0 assignation

Extremely high electron lifetime

very long electron-mobility

Level of electronegative impurities in LAr must be kept exceptionally low to ensure long drift path of ionization electrons without attenuation

New industrial purification methods developed to continuously filter and re-circulate both in liquid and gas phases

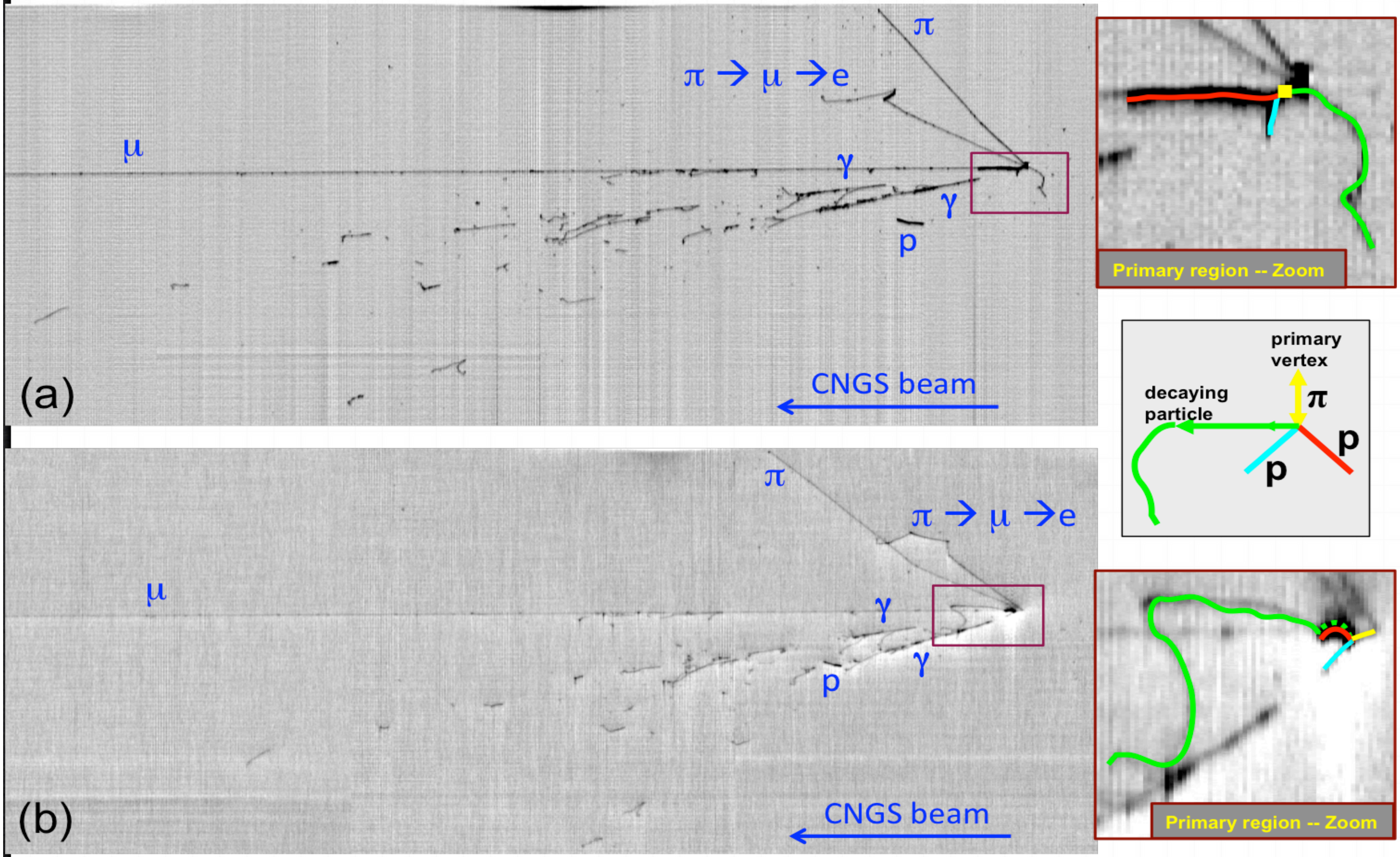


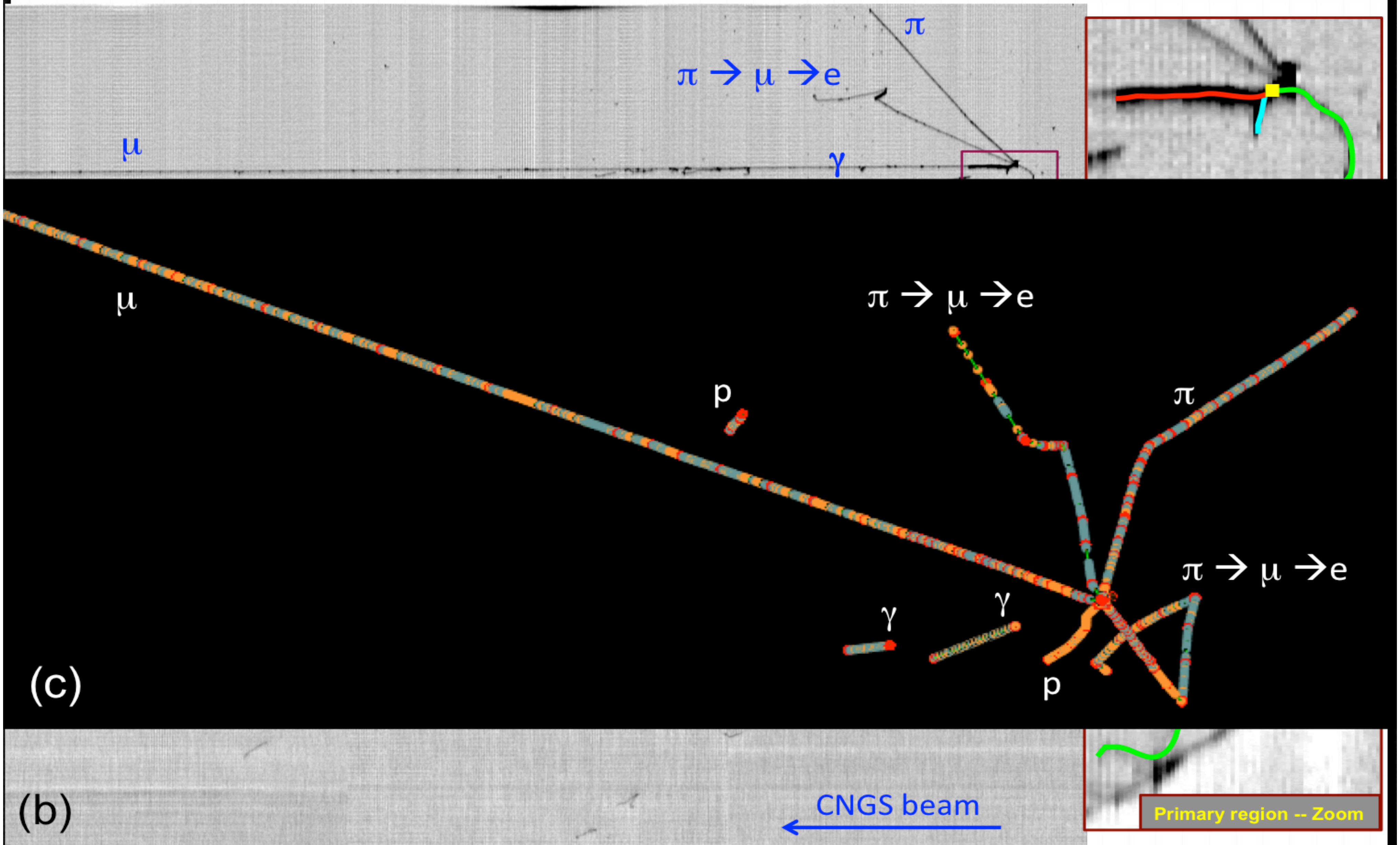
Electron lifetime measured during ICARUS run at LNGS with cosmic μ's:

τ_{ele} > 7 ms

New pump installed on East cryostat since 14/04/2013:

τ_{ele} > 15 ms


π
π → μ → e
μ
γ
γ
p
(a)
CNGS beam
Primary region -- Zoom
primary vertex
π
decaying particle
p
p
π
π → μ → e
μ
γ
γ
p
(b)
CNGS beam
Primary region -- Zoom


π
π → μ → e
μ
γ
μ
π → μ → e
p
π
π → μ → e
γ
γ
p
(c)
(b)
CNGS beam
Primary region -- Zoom

neutrino "anomalies"

hint at additional 4th (sterile) neutrino
with $\Delta m^2_{new} \sim 1\ eV^2$, small $\sin^2 2\theta_{new}$

excess of e-like events

'LSND anomaly'
observation of $\nu_\mu \rightarrow \nu_e$ excess signals from LSND, MiniBooNE at accelerators

disappearance of anti-ν_e

'Gallium anomaly'
deficit of anti-ν_e events from Mega-Curie calibration sources in solar ν_e experiments

'reactor anomaly'
deficit of anti-ν_e events, detected from near-by nuclear reactors,

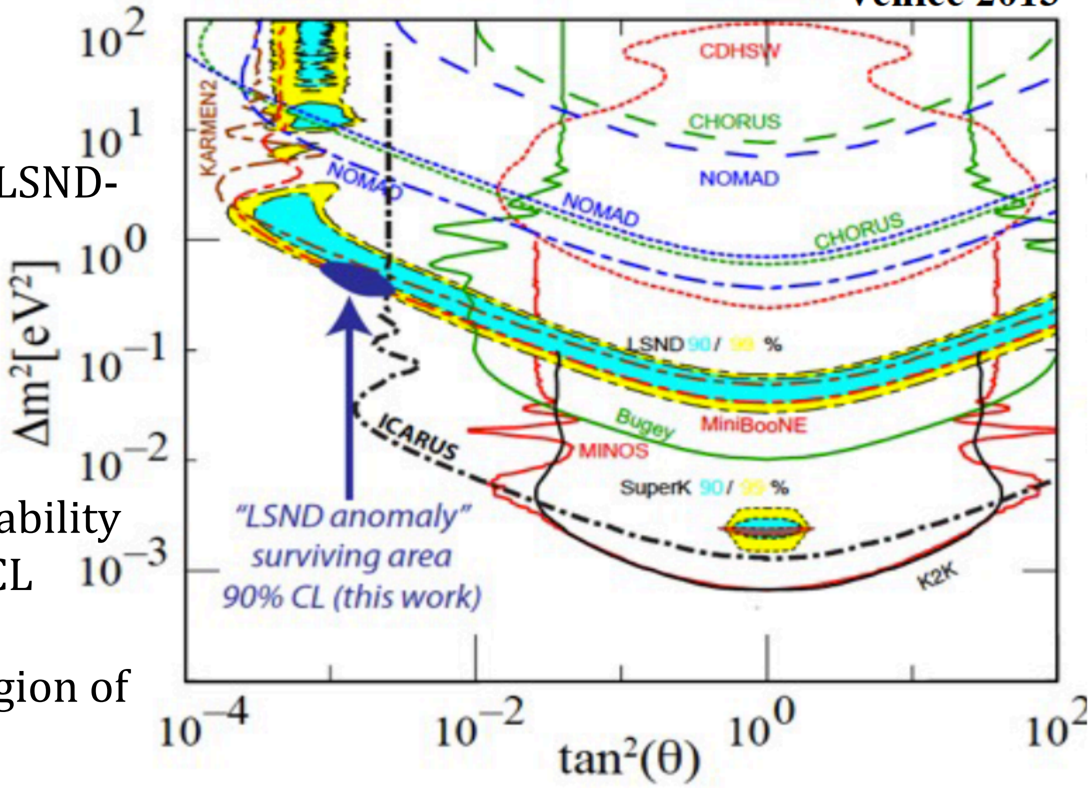
Search for LSND-like anomaly

Venice 2013

- ✓ ICARUS searched for ν_e excess related to LSND-like anomaly on the CNGS ν_μ beam
  ~ 1% intrinsic ν_e contamination,
  $L/E_\nu \sim 36.5$ m/MeV

- ✓ analysis on $7.23 \cdot 10^{19}$ pot event sample provided the limit on the oscillation probability $P(\nu_\mu \to \nu_e) \leq 3.85\ (7.60) \cdot 10^{-3}$ at 90(99)% CL

- ✓ ICARUS result indicates a very narrow region of parameter space,
  $\Delta m^2 \sim 0.5$ eV^2, $\sin^2 2\theta \sim 0.005$,
  where all experimental results can be accommodated at 90% CL



Borexino

Large volume ultra-pure liquid scintillator detector aimed for low energy neutrino detection

Borexino performed a full solar neutrino spectroscopy

- pp
- ^{7}Be
- pep
- ^{8}B

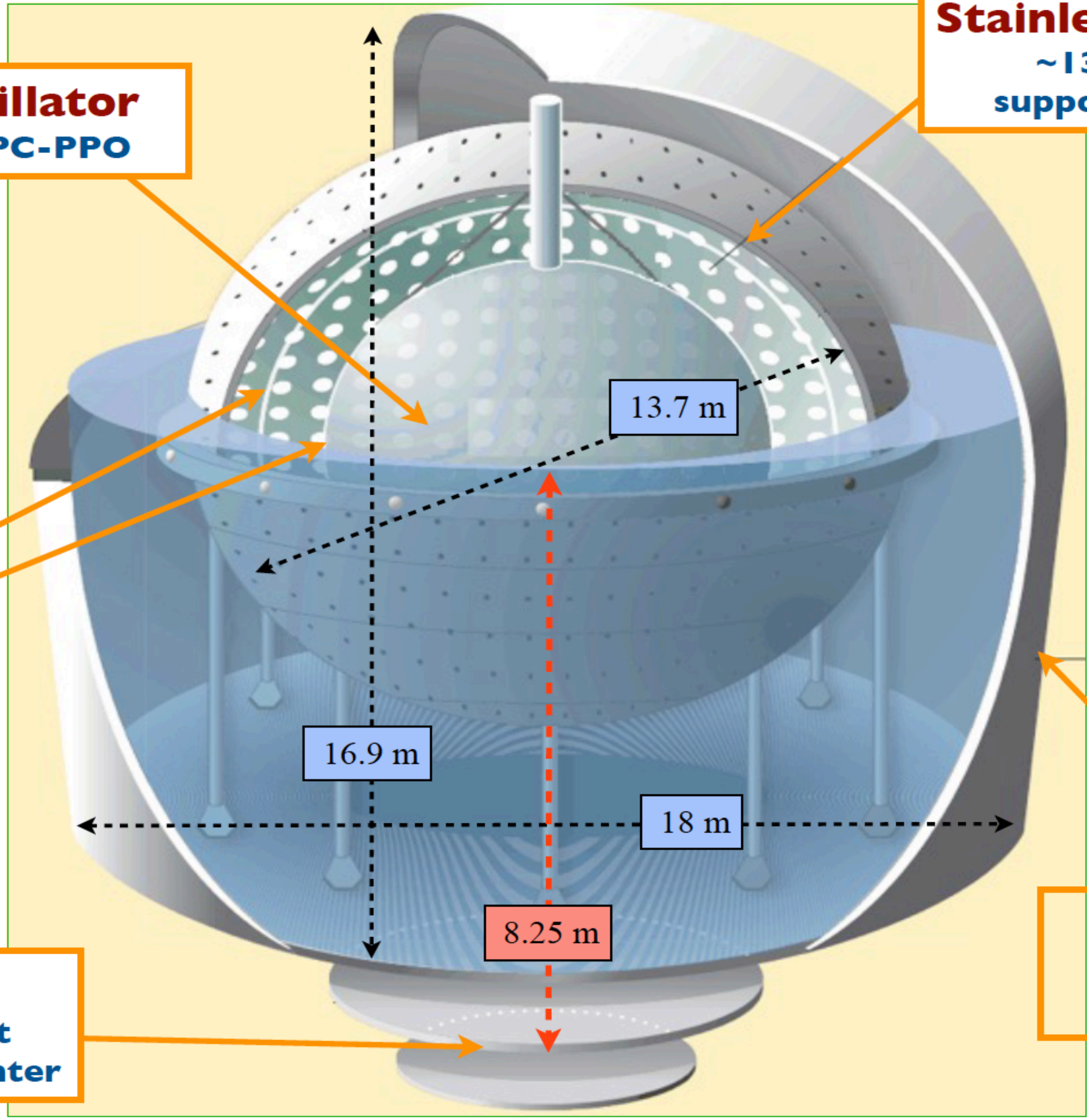
Borexino performed the first un-ambiguous detection of geophysical anti-ν_e

BOREXINO

Scintillator
270 t PC-PPO

Stainless Steel Sphere
~1300 m³ of liquid
support for 2214 PMTs

R=6.85 m



Nylon Vessels
internal: R=4.25 m
external: R=5.50 m

barrier against radon and outer contamination

Principle:
"graded shielding".

Pure and pure materials toward the center of the detector

PIT
~ 1 m³ available at
8.25 cm from the center

Tank
3300 m³ of water
210 PMTs Cherenkov

R=9 m, 16.9 m

Short distance ν_e Oscillations with BoreXino

Motivations:

- Search for sterile neutrinos or other short distance effects on P_{ee}
- Measurement of neutrino magnetic moment (A)
- Check of g_V and g_A at low energy (A + C)

To test the existence of low L/E ν_e and/or anti-ν_e anomalies by placing well known artificial sources close to or inside Borexino:

- SOX-A - ^{51}Cr external (chromium neutrino source)
- **SOX-B - ^{144}Ce external** (cerium antineutrino source)
- SOX-C - ^{144}Ce internal

Neutrino program in US

short-baseline **SBN**	long-baseline **DUNE\LBNE**
✓sensitive search for sterile neutrinos at the eV mass-scale	✓measurement of the value of the unknown CP-violation phase
✓explanation of LSND and MiniBooNE anomalies	✓determination of the neutrino mass hierarchy
✓study of neutrino-nucleus cross sections ✓ν_μ-Ar and ν_e-Ar scattering measurement	✓precise determination of proton decay lifetime limits
	✓neutrino flux from potential core-collapse SN

Fermilab

Short Baseline Neutrino Program

MicroBooNE

- ✓ **470 m** from the BNB target
- ✓ 2.33 x 2.56 x 10.37 m
- ✓ **170 t** total mass (**89 t** active mass) LAr TPC
- ✓ drift path of **2.56 m**
- ✓ 3 read-out planes (wires at 0, ±60°), spaced by 3 mm
- ✓ 32 PMTs behind the wire planes

SBND

- ✓ **110 m** from the BNB target
- ✓ 4.0 x 4.0 x 5.0 m
- ✓ **112 t** of liquid argon TPC
- ✓ drift path of **2 m**
- ✓ 3 planes of wires with 3 mm spacing

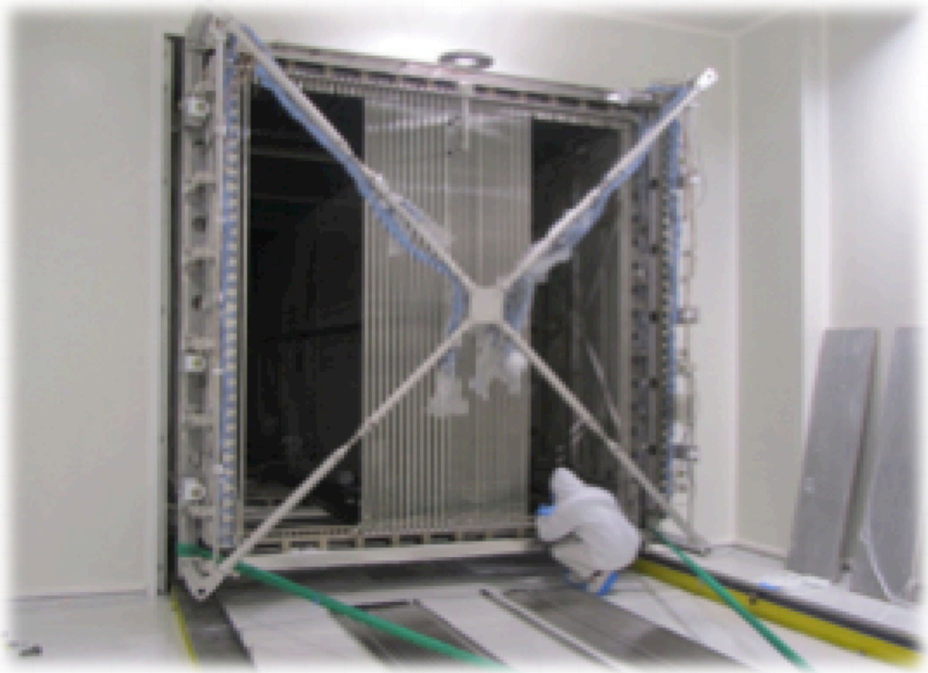
http://sbn-nd.fnal.gov
http://arxiv.org/abs/1503.01520

BNB = Booster Neutrino Beamline
- ✓ 8 GeV protons on beryllium target

WA104 program: overhauling of T600

The T600 was moved to CERN in December 2014 and is being upgraded, by introducing technology developments

- new cold vessels and purely passive insulation
- refurbishing of the cryostat and purification equipment
- existing cathode panels flattened to provide improved planarity
- new faster, higher performance read-out electronics
- upgrade of the light collection system (trigger)

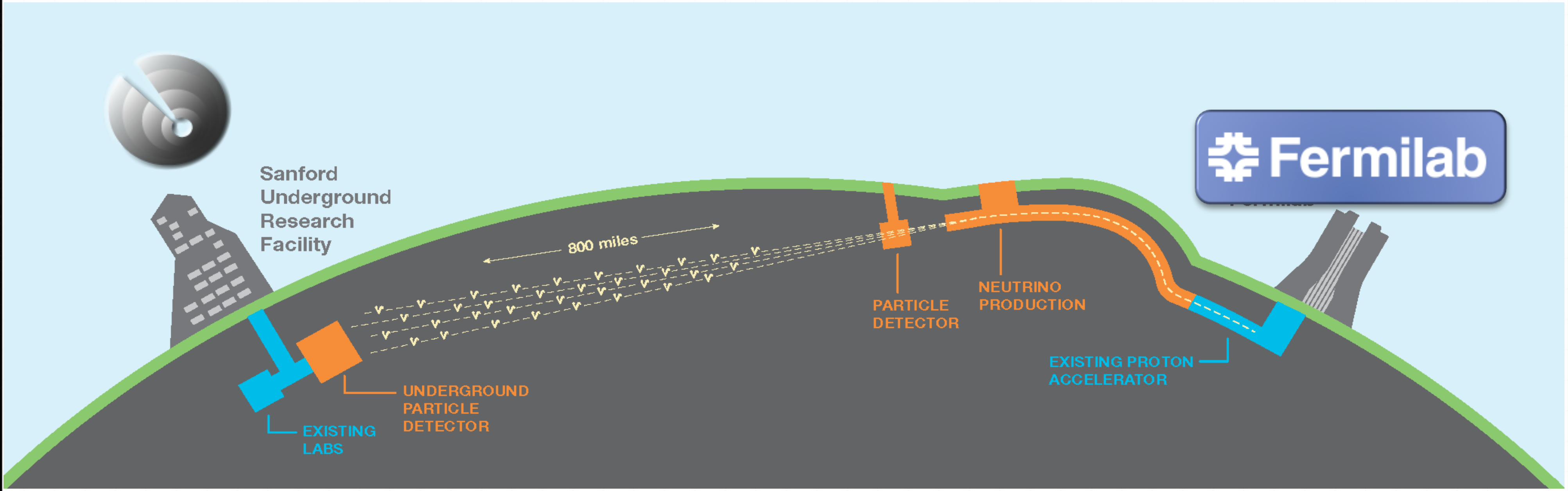


The detector is expected to **be transferred to FNAL before the end of 2016** for installation, commissioning and start of data taking (end of 2017)

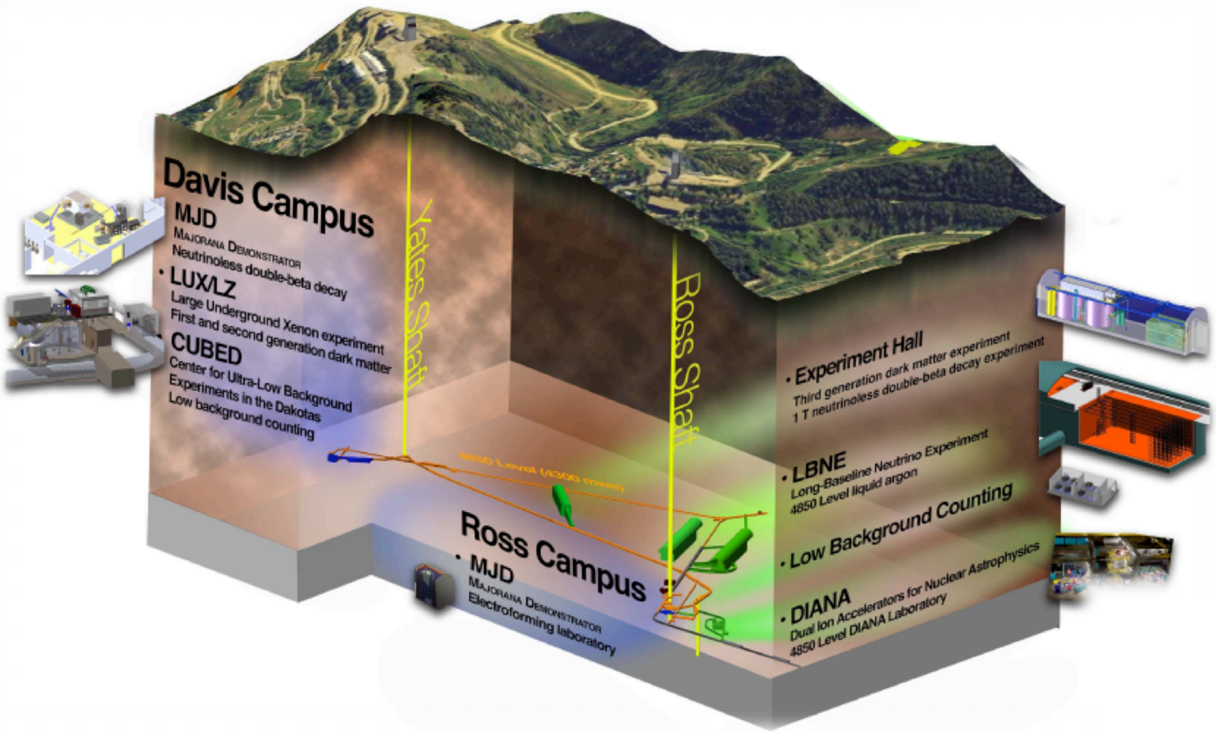
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

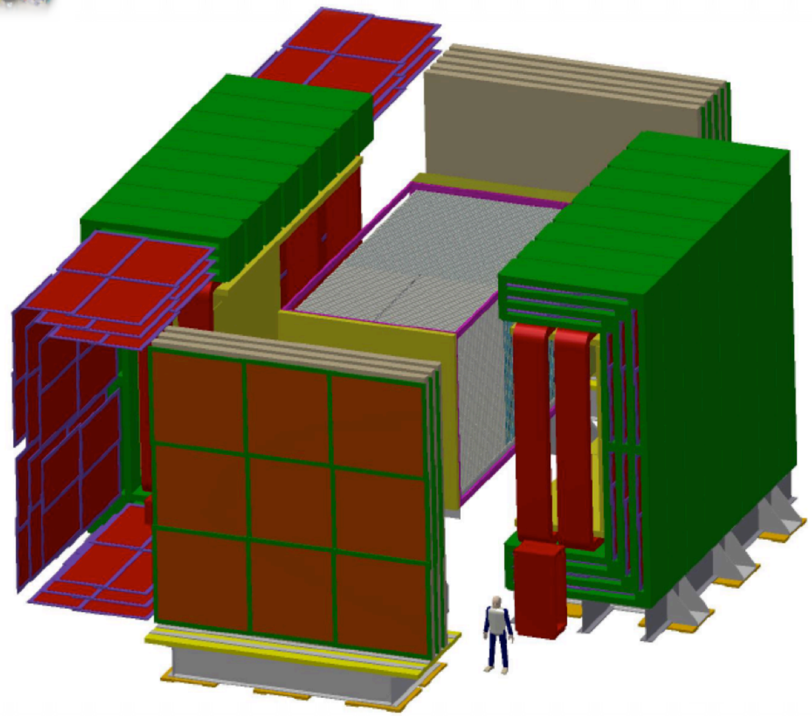
Near Site
- <u>beamline</u>
  - 2.5 GeV high-purity ν_μ beam
- <u>near detector</u>
  - 500 m downstream
  - 3 x 3 x 7 m^3 tracking detector with ECAL, magnet, RPC

Far Site
- <u>far detector</u>
  - 4850 feet depth
  - LAr TPC of **34 kt** fiducial mass
  - modular design



http://www.dunescience.org


Davis Campus
MJD
Majorana Demonstrator
Neutrinoless double-beta decay
• LUX/LZ
Large Underground Xenon experiment
First and second generation dark matter
• CUBED
Center for Ultra-Low Background
Experiments in the Dakotas
Low background counting
Yates Shaft
Ross Shaft
Ross Campus
• MJD
Majorana Demonstrator
Electroforming laboratory
• Experiment Hall
Third generation dark matter experiment
1 T neutrinoless double-beta decay experiment
• LBNE
Long-Baseline Neutrino Experiment
4850 Level liquid argon
• Low Background Counting
• DIANA
Dual Ion Accelerators for Nuclear Astrophysics
4850 Level DIANA Laboratory



Thank you