Status and plans of WA104/ICARUS

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(on behalf of the WA104/ICARUS Collaboration)

The ICARUS/WA104 Collaboration

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Colorado State University, USA
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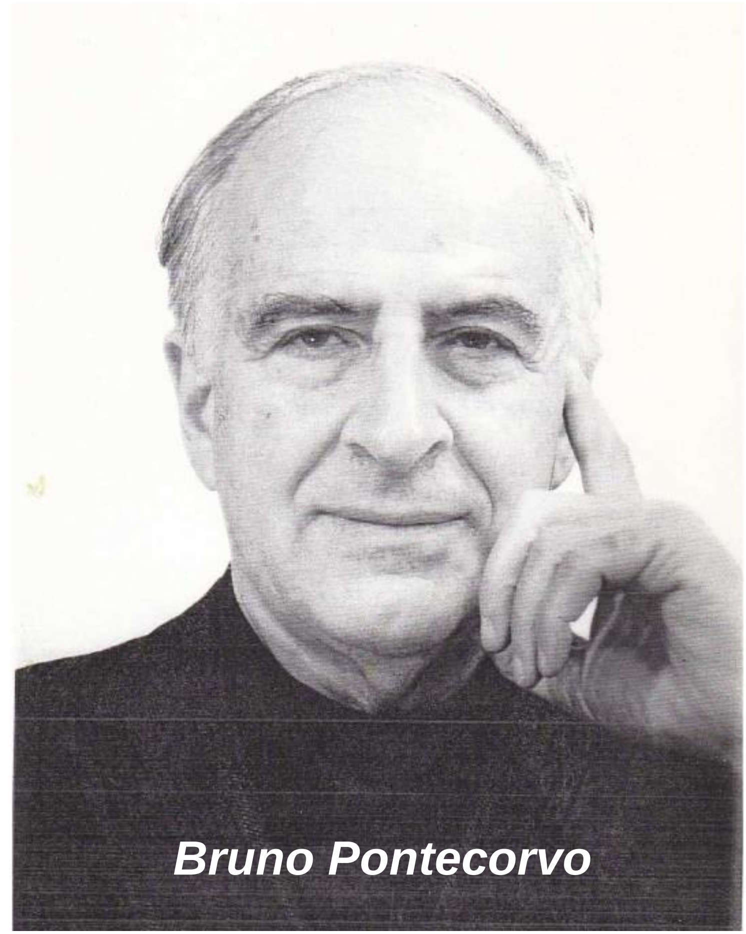
What are "sterile" neutrinos ?

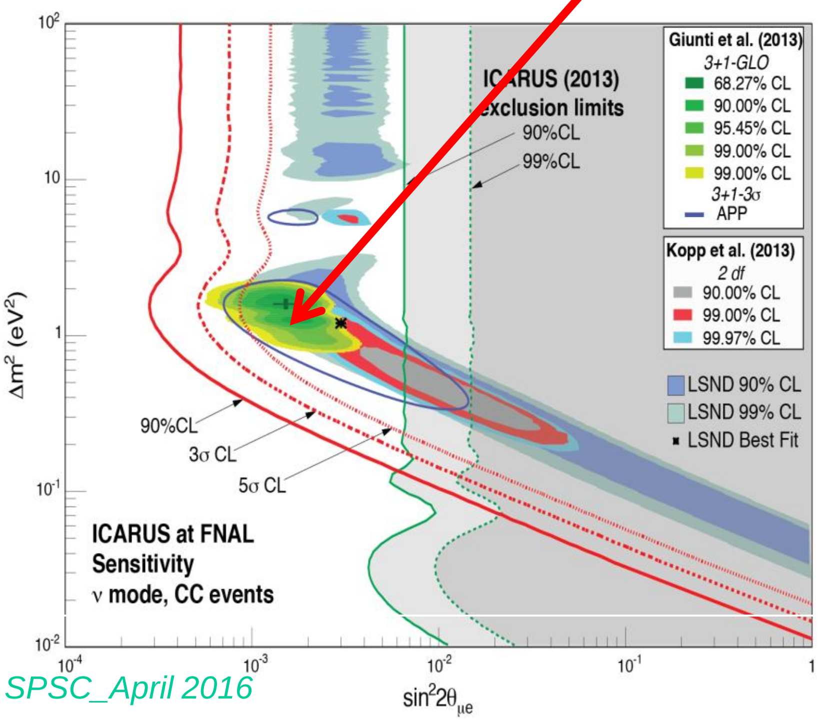
- Sterile neutrinos are a hypothetical type of neutrinos that do not interact with any of the fundamental interactions of the Standard Model except gravity.
- The name was coined in 1957 by Bruno Pontecorvo, who hypothesized their existence in a seminal paper.
- Since per se they would not interact electromagnetically, weakly, or strongly, they are extremely difficult to detect.
- If they are heavy enough, they may also contribute to cold dark matter or warm dark matter.

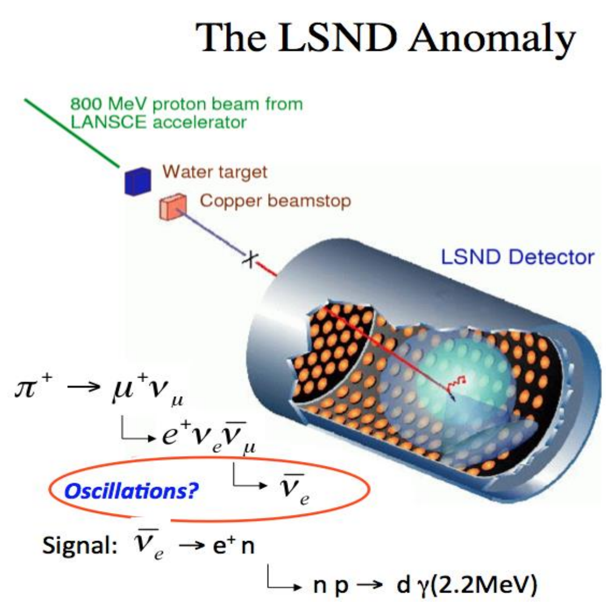


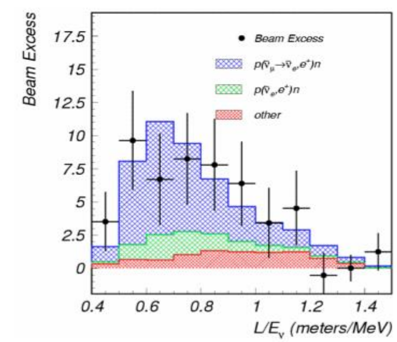
- Sterile neutrinos may mix with ordinary neutrinos via a mass term. Evidence may be building up from several experiments.

The LSND anomaly at Los Alamos (30 years ago)

- The experiment LSND at the LAMPF Neutrino Source collected data from 1993 to 1998. Cherenkov light emitted by particle interactions was detected by an array of 1220 photomultipliers.
- The more recent 2012 ICARUS experiment from CERN to LNGS and other data (KARMEN+MiniBooNE) have strongly reduced the region of LSND experimental window to a narrow region at $\Delta m_s^2 \approx 1\ eV^2$. (see f.i. Giunti et al.)





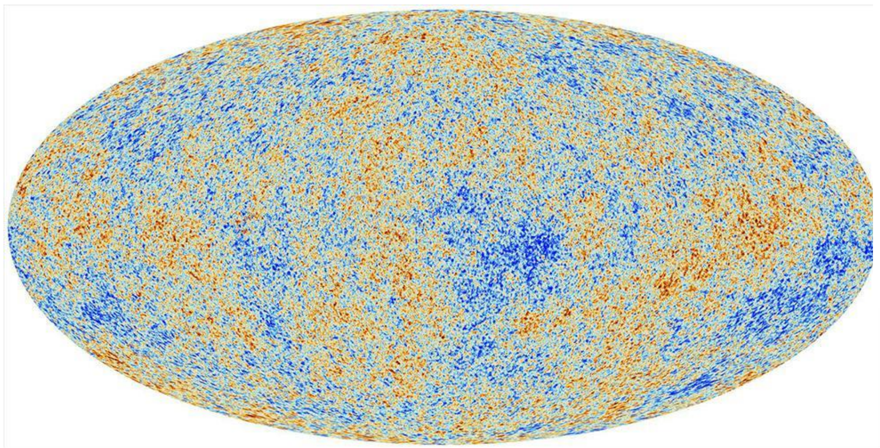


Saw an excess of $\bar{\nu}_e$:
87.9 ± 22.4 ± 6.0 events.

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

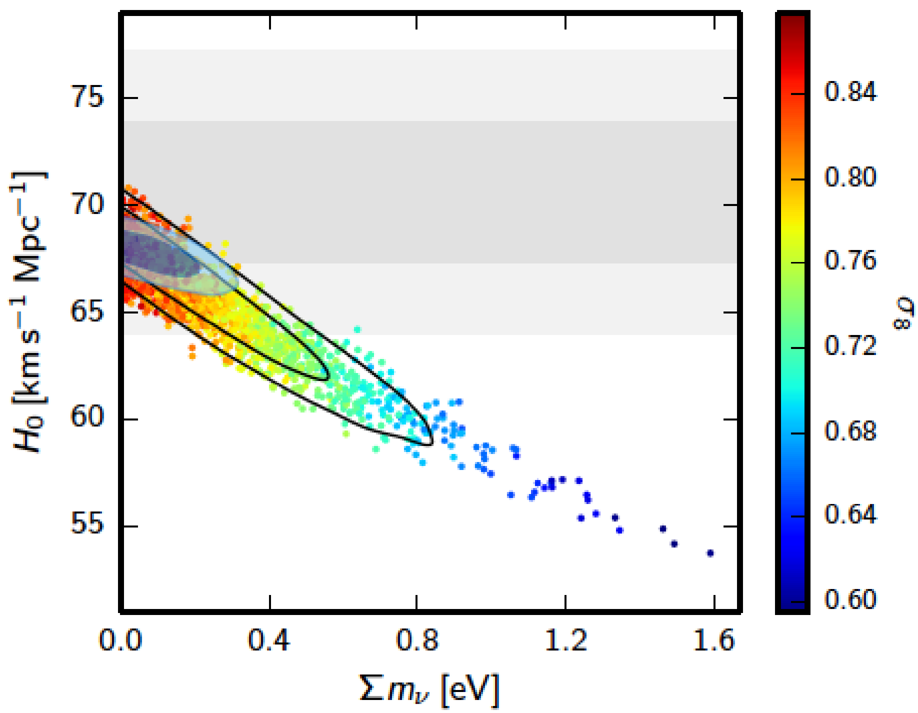
3.8 σ evidence for oscillation.

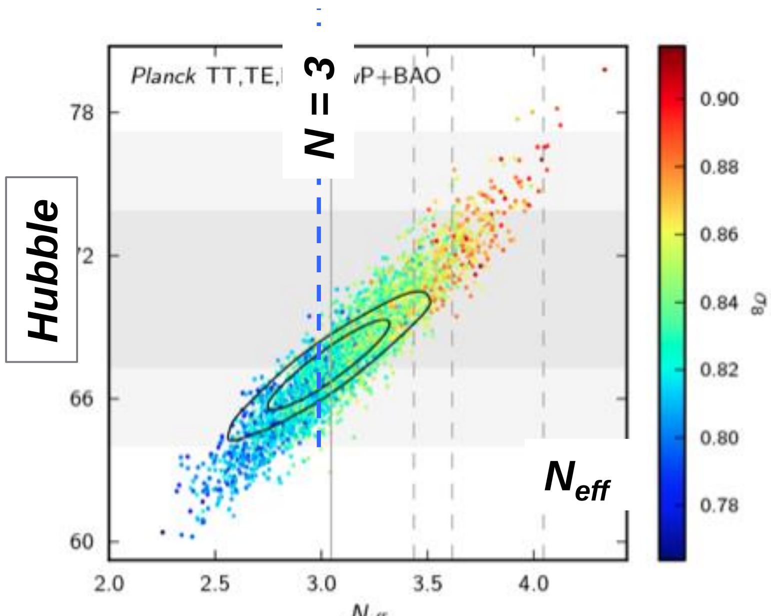
Number of neutrino families from Big Bang cosmology



$$N_{\rm eff} = 3.13 \pm 0.32 \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,;$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,;$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP}\,;$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO}$$

$$\sum m_\nu < 0.72\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,;$$
$$\sum m_\nu < 0.21\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,;$$
$$m_\nu < 0.49\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP}\,;$$
$$m_\nu < 0.17\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO}\,.$$





Comparing the LSND anomaly with cosmology

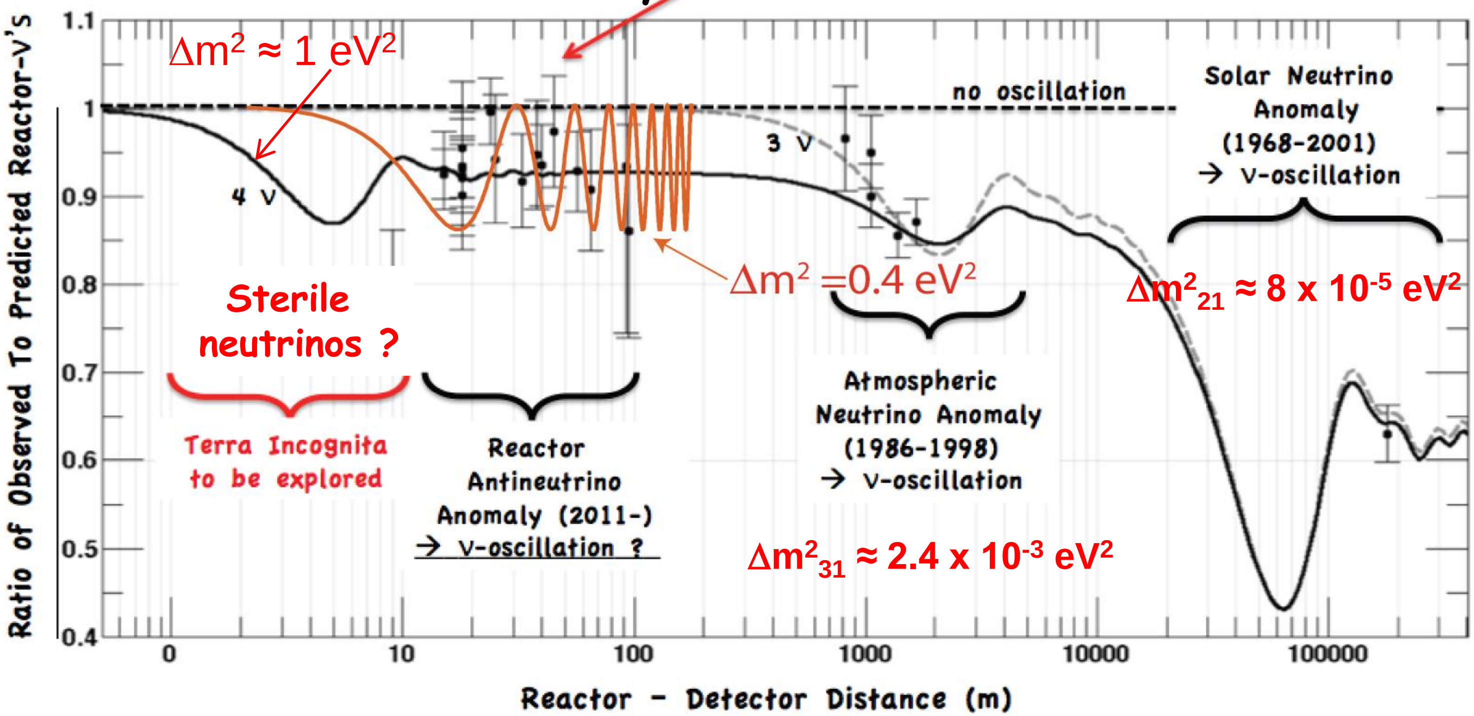
- Thirty years after its first observation, the LSND anomaly still requires a definitive experimental clarification.
- However cosmological data combining data from cosmic microwave background (CMB) experiments, large scale structure (LSS) and Lyman-a forest observations naively bind the mass limit for a 3 massless + 1 massive sterile neutrino to $m_s < 0.26$ eV (0.44 eV) at 95% (99.9%) c.l.
- This result, which implies $\Delta m_s^2 \leq (0.26 \text{ eV})^2 = 0.067 \text{ eV}^2$ should effectively exclude the sterile neutrino hypothesis as an explanation of the LSND anomaly.
- If the LSND anomaly is notwithstanding finally confirmed experimentally, cosmological data will have been proven wrong and we will need to re-examine the entire framework on which rest these very tight constraints.

Persisting other anomalies in the neutrino sector

- In addition to the observation of presumed *excess signals* of ν_e electrons from muon neutrinos from particle accelerators (the LSND effect) additional classes of anomalies have been reported, namely the apparent *disappearance signal* in the anti-ν_e events:
  - (1) missing fraction from near-by nuclear reactors and
  - (2) from Mega-Curie k-capture calibration sources in the experiments to detect solar ν_e,
- The most popular direction is the one of of "sterile neutrinos" although also other alternatives are possible
- These independent signals may all point out to the possible existence of at least a fourth non standard and heavier neutrino state driving oscillations at near distances, with Δm^2_{new} of the order of ≈ 1 eV^2 and relatively small $\sin^2(2\theta_{new})$ mixing angles.

1.-The reactor (anti)-neutrino disappearance anomaly

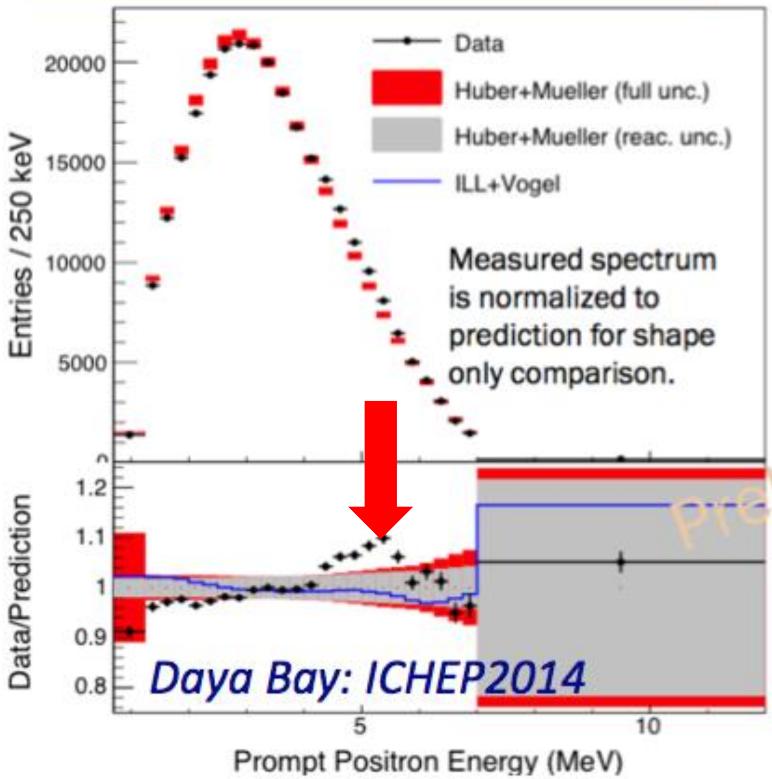
- A recent re-evaluation of the reactor antineutrino spectra has introduced changes in the expected flux. With such new evaluation, the ratio R between the observed and predicted rates of experiments is significantly less than 1.
- However all reactor experiments rely on a common prediction on fission cross-sections and R = 0.938 ± 0.023, leading to a deviation of 2.7 σ from unity

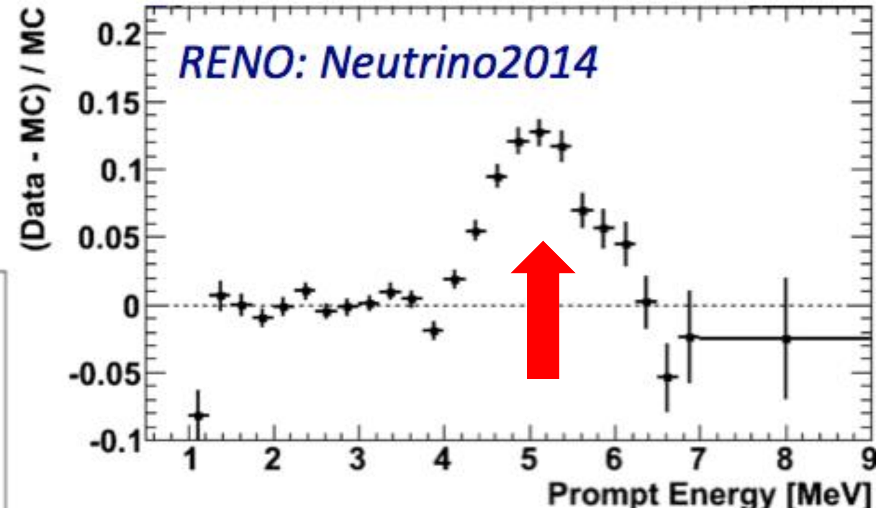


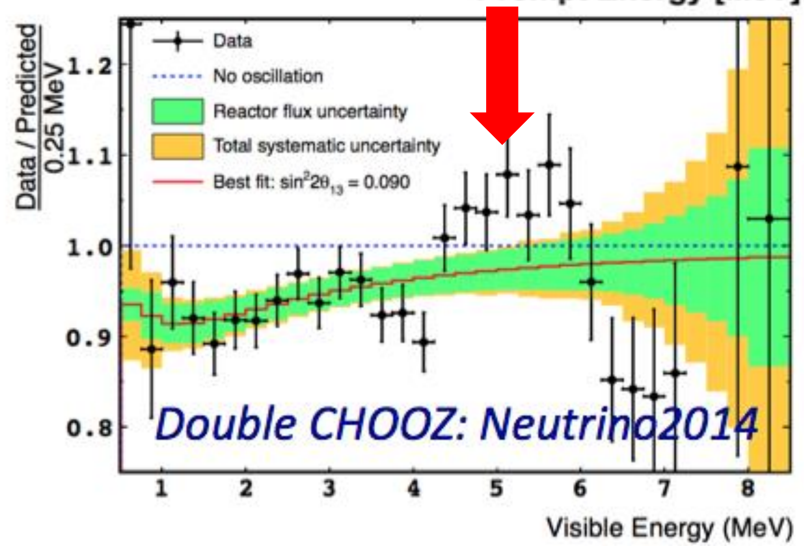
Experimental data from reactors are not in perfect agreement

- A rate excess is observed over Montecarlo flux predictions at about 5 MeV

Recent $\overline{\nu}_e$ measurements also disagree with BILL-derived spectra.



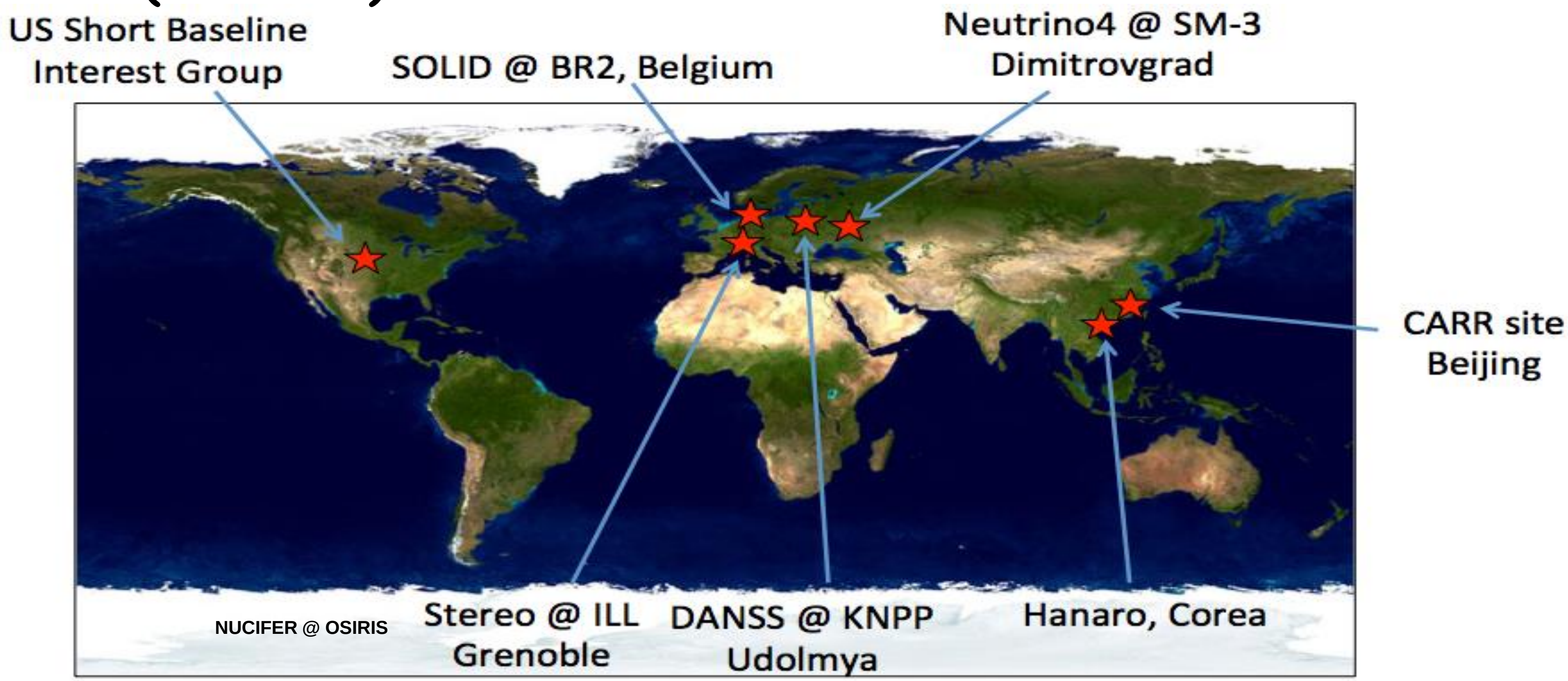




Several future, very short baseline reactor experiments

- Compact, intense sources and very short baselines are used in order to determine oscillation patterns within the detector
- High statistics ~100 evts/day/t
- Challenging reactor-induced backgrounds (©and n)

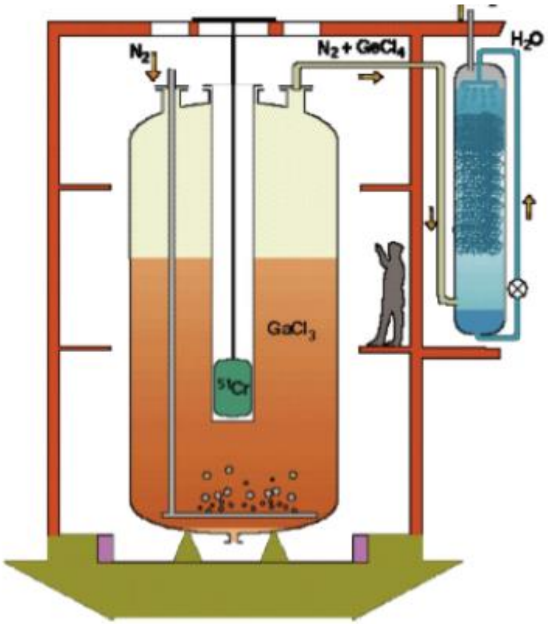
Projects	Ref	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)
Nucifer	[22]	70	0.75	7	13
Stereo	[23]	50	1.75	[8.8-11.2]	18
Neutrino 4	[24]	100	2.2	[6-12]	few
DANSS	[25]	3	0.9	[9.7-12.2]	50
Solid	[26]	[45-80]	3	[6-8]	10
Hanaro		30	0.5	6	few
US project	[27]	20-120	1 & 10	4 & 18	few
CARR	[28]	60	-	7 & 15	few



2.-The Gallium disappearance anomaly

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

- SAGE and GALLEX experiments recorded the calibration signal produced by intense artificial k-capture sources of ^{51}Cr and ^{37}Ar.
- The averaged result of the ratio R between the source detected and predicted neutrino rates are consistent with each other, giving R=(0.86 ± 0.05), about 2.7σ from unity



30.3 tons of Gallium
in an aqueous solution : $GaCl_3$ + HCl

- These best fitted values may favour the existence of an undetected sterile neutrino with an evidence of 2.3σ and a broad range of values centred around $\Delta m^2_{new} \approx 2\ eV^2$ and $\sin^2(2\theta_{new}) \approx 0.3$.

Future experiments

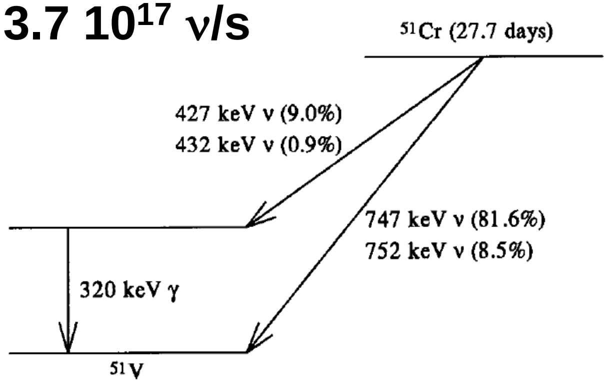
- Aiming at recording the L/E oscillation pattern within the detector using an intense ν source:
  - Existing (Borexino, KamLAND, Daya-Bay) or future (SNO+, LENS, JUNO) liquid scintillator detectors;
  - Future experiments based on other techniques (RICOCHET, BEST)

First data available by 2016 ?

Many processes have been studied

^{51}Cr: 750 KeV ν; 40 d

3.7 10^{17} ν/s

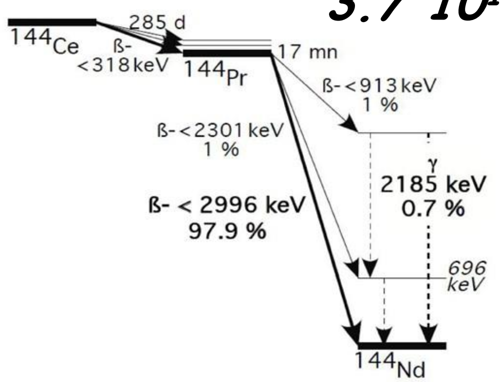


Decay scheme of ^{51}Cr to ^{51}V through electron capture.

- Production: **thermal neutrons on ^{50}Cr; n-capture x-sect ~17 b**
- **Advantages: 320 KeV γ emitted by the source not difficult to handle; Enriched Cr still available from Gallex.**
- **Disadvantages: radioctivity is a serious bkg for ν+e→ν+e- detection.**

^{144}Ce: <2.99 MeV $\bar{\nu}$; 411 d

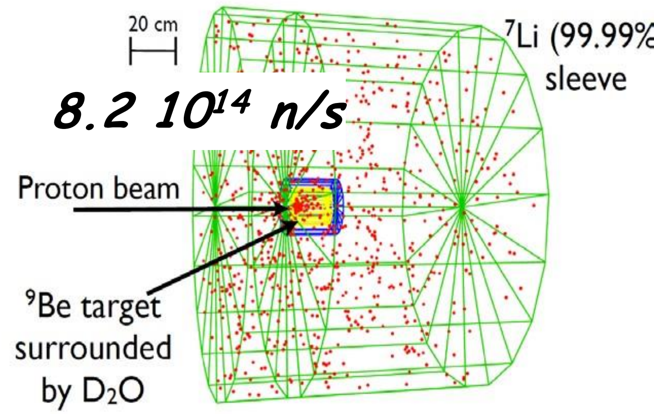
3.7 10^{15} n/s



- Production: **extracted from exhausted nuclear fuel (Russia)**
- **Advantages: detecting reaction anti-□+p->n+e+ has very little bkg; long source lifetime.**
- **Disadvantages: □s (E=2.2 MeV) emitted by the source are difficult to handle.**

^{8}Li: <13 MeV $\bar{\nu}$; 868 ms

8.2 10^{14} n/s



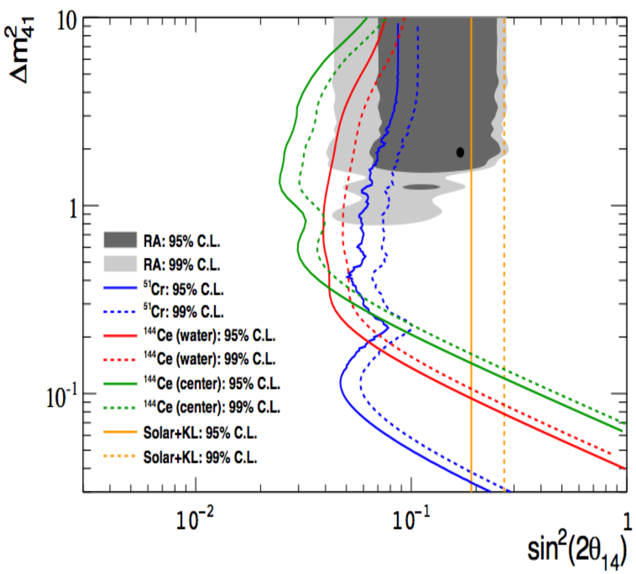
- **Production: IsoDAR, Isotropic Decay At Rest (prototype by 2016): 60 MeV p on ^{9}Be tgt -> n moderated and multiplied by D_2O shield -> ^{8}Li produced in surrounding sleeve of ^{7}Li**
- **Advantages: long data taking possible; high Eν.**
- **Disadvantages: flux known at ~5%; Prod. of ^{8}Li not point-like (~150 cm).**

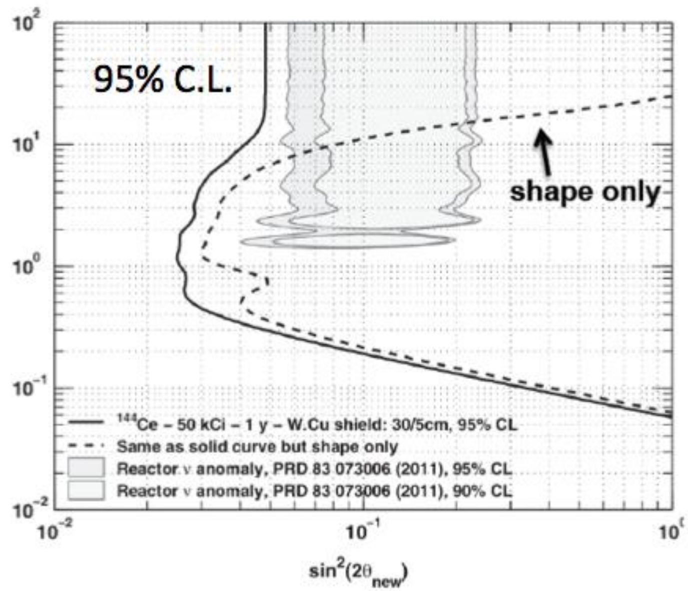
Some examples of different detectors

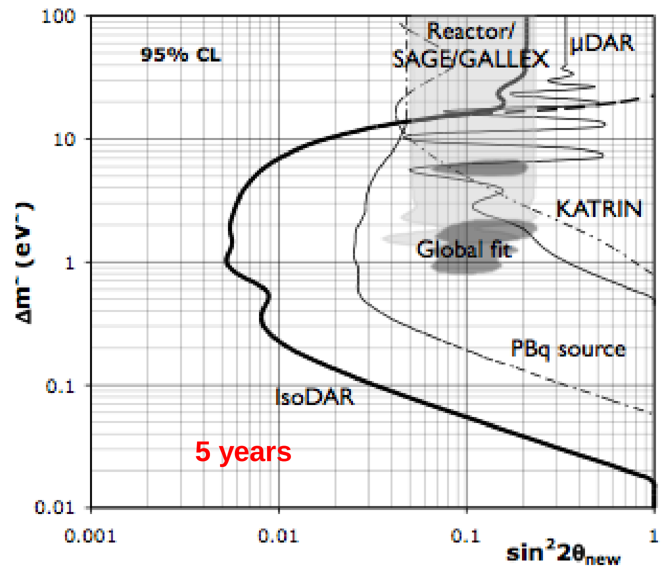
Borexino detector:
SOX
75 kCi ^{144}Ce and 10MCi ^{51}Cr placed outside/
in water tank/
in inner Scintill.:

Kamland:
CeLAND
Phase 1 (2015): 75 kCi ^{144}Ce in outer detector
Phase 2 (2016, if feasible): 50 kCi ^{144}Ce at center of LS

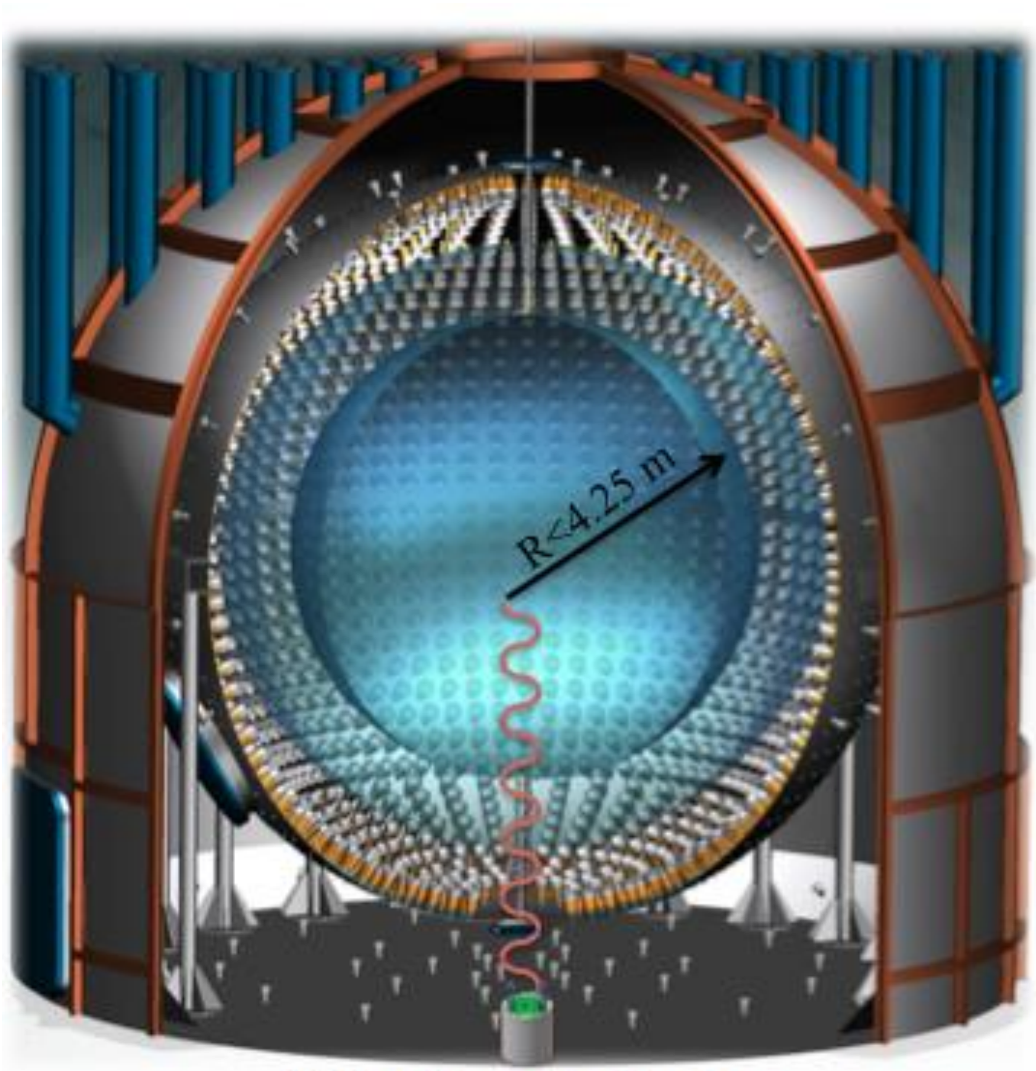
IsoDAR:
R&D proposal to place high-power low-energy cyclotron (DAEdALUS project) in the Kamioka mine to search for an oscillation pattern in Kamland



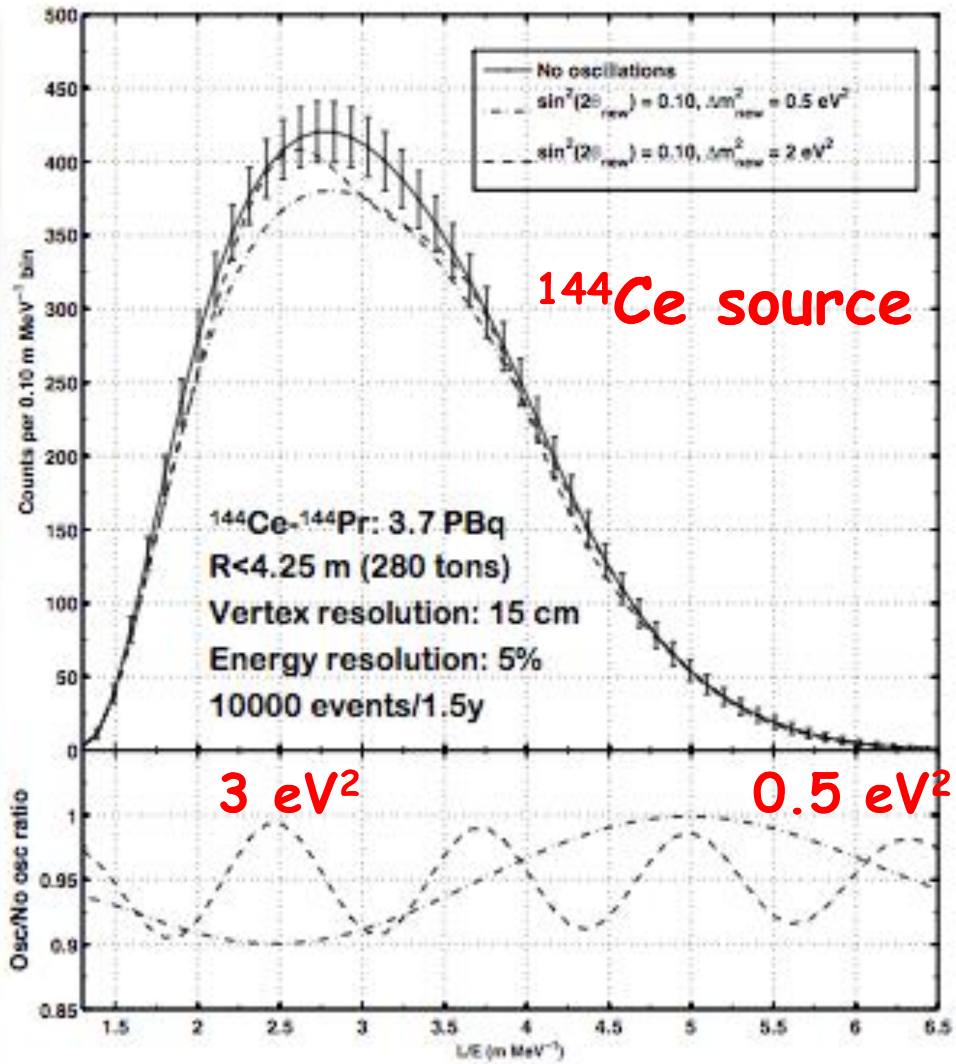




An example:Borexino experiment at LNGS



8.3 m from Bx Center



Transport of the ^{144}Ce source from Russia to LNGS

- IAEA Regulations for the Safe Transport of Radioactive Material
- Train / Dedicated Boat/ Truck: 3 weeks (5% activity loss)

A definitve clarification of these "anomalies" at FNAL

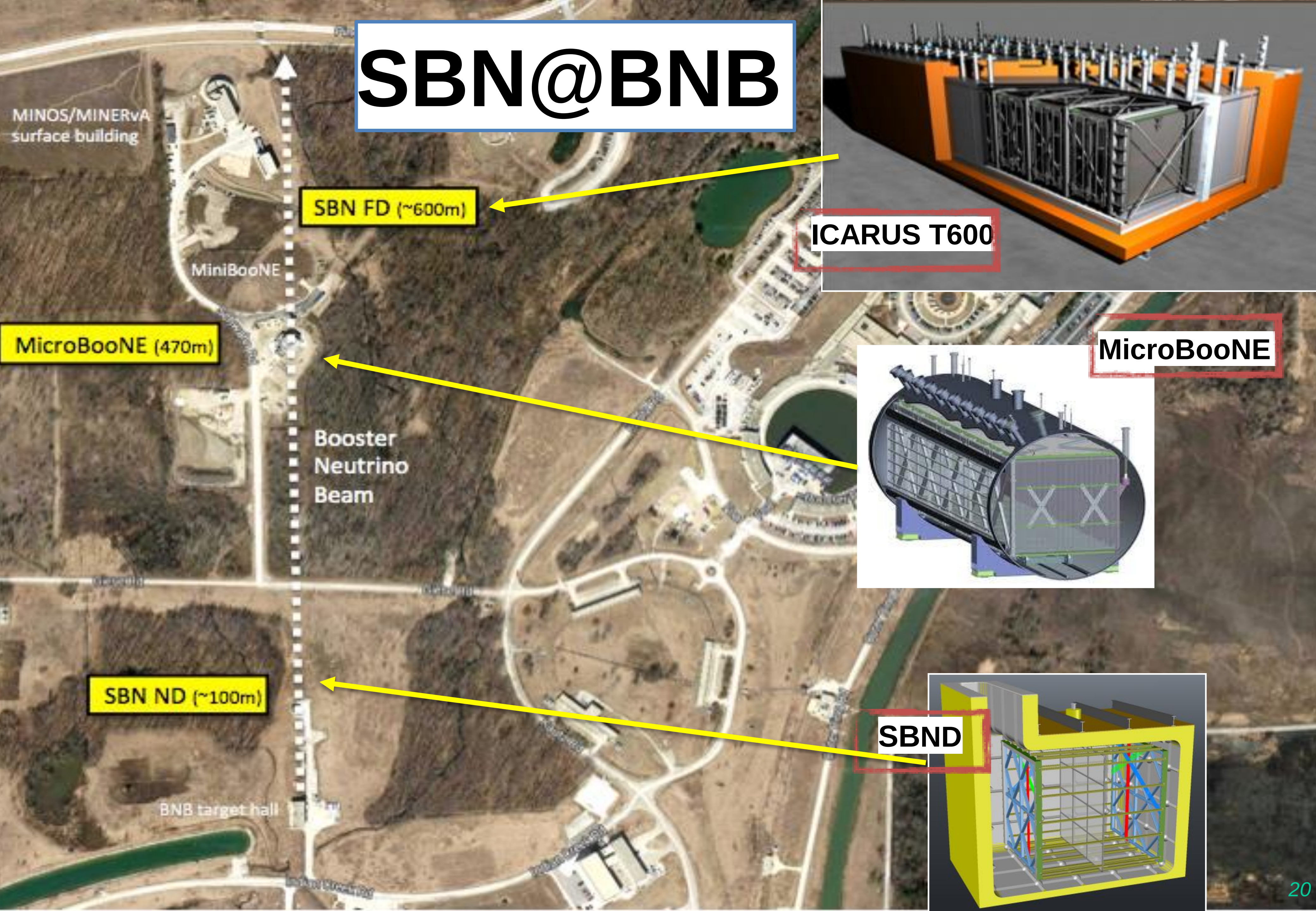
- A single experiment capable to clarify all these anomalies at the appropriate > 5 sigma level is therefore highly desirable.
- Our experiment at FNAL is based on two main, innovative concepts and a low energy ν and anti-ν from a proton accelerator.
  - The first new concept is the comparison for spectral differences of two (or more) identical detectors located at two different distances. In the case of absence of "anomalies", the two distributions will be a precise copy of each other, without any Monte Carlo comparison.
  - The second new concept is the novel, now fully operational large mass (0.7 k ton) Liquid LAr-TPC detector developed by the ICARUS collaboration. The detector offers a "bubble chamber like" continuous sampling, homogeneous calorimeter with excellent accuracies and the total energy reconstruction of the event from charge integration.

The ICARUS LAr-TPC invention by INFN

- The ICARUS T600 detector, ~500 ton of sensitive mass, has already concluded in 2013 a long duration experiment with LNGS underground lab taking data both of CNGS ν beam and c-rays.
- The detector demonstrated the performance as tracking device (~1 mm^3 spatial resolution) and as homogenous calorimeter measuring the total energy with excellent accuracy for contained events. Remarkable particle identification capabilities have been determined exploiting the measurement of dE/dx vs. range.
- Reconstruction of the neutrino interaction vertex, measurements of e.m. showers generated by primary electrons and invariant mass of photon pairs allow to reject to unprecedented level backgrounds in the study of $\nu\mu \rightarrow \nu e$ f.i. in LSND like transitions.
- Momentum of non-contained muons can be determined via multiple Coulomb scattering with $\Delta p/p$ ~15% in the 0.4-4 GeV/c range.

ICARUS physics at FNAL

- The ICARUS Collaboration at FNAL has been enlarged by a number of US teams: Arlington University, ANL, BNL, Colorado State University, FNAL, LANL, Pittsburg University and SLAC) .
- ICARUS detector will be soon moved to the US and exposed to the ≈ 0.8 GeV ν beam from the Booster at 600 m from target, in the framework of the SBN program. The neutrino oscillations are searched comparing the measured spectra with the un-oscillated ones at the nearer sites of MicroBooNE(400 m) and SBND(130 m).
- At shallow depths, a large background of uncorrelated cosmic rays will occur during the 1 ms long the LAr-TPC readout and each triggering event: ~ 11 muon uncorrelated tracks per drift in were measured on surface in Pavia 2001.
- ICARUS will also collect simultaneously a large sample of ve events with the NUMI Off-Axis beam at ~ 2 GeV in preparation to the future DUNE project.



SBN@BNB
MINOS/MINERvA surface building
SBN FD (~600m)
ICARUS T600
MiniBooNE
MicroBooNE (470m)
MicroBooNE
Booster Neutrino Beam
SBN ND (~100m)
SBND
BNB target hall

Far Detector building at FNAL

- Engineering design of the infrastructures (Far Detector building and services) to host the T600 plant at FNAL has been completed in July 2015. Groundbreaking has started in August 2015.

T600 transport and Far Detector building

- According to schedule, the two T300 modules will be ready for shipment to the US by the end of 2016, which is compatible with the foreseen beneficial occupancy of the Far Detector building in beginning 2017.

Ground level walls under construction and preparatory work for the loading dock (front)
April 7, 2016

A new building

- Transverse section of the FNAL building for T600

A “naïve expectation” for the short baseline FNAL program

- Let us combine the appearance (LSND) and the disappearances (neglecting oscillations into ν_τ and direct *$\nu\mu \leftrightarrow \nu e$)* as coming from an unique sterile neutrino signature with a 4 x 4 matrix U_{ik}.
- The general formula in the (3+1) model is then:

$$P_{\nu a \to \nu b} = \delta_{ab} - 4|U_{a4}|^2 \left(\delta_{ab} - |U_{b4}|^2\right) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

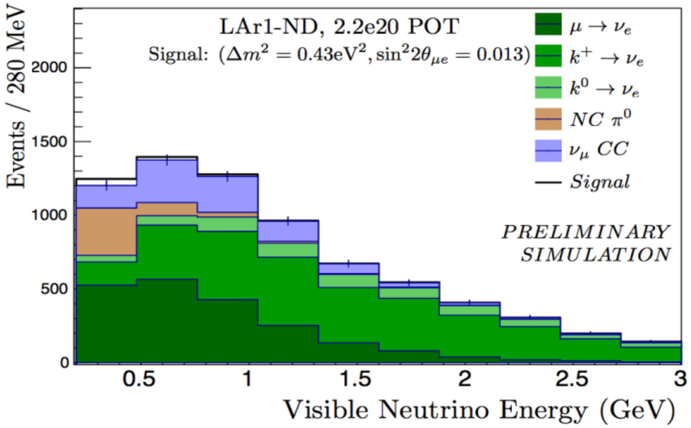
where Δm_{41}^2 is the squared mass difference with respect to the fourth heavier neutrino

- Let us take LSND with $\sin^2(2\theta_{e\mu}) = 4|U_{e4}|^2|U_{\mu4}|^2 \approx 1.5\ 10^{-3}$
- This implies disappearances of both νe and νμ, since $\sin^2(2\theta_{ee}) = 4|U_{e4}|^2 (1-|U_{e4}|^2)$ and $\sin^2(2\theta_{\mu\mu}) = 4|U_{\mu4}|^2 (1-|U_{\mu4}|^2)$.
- Reactors may claim $\sin^2(2\theta_{ee}) \approx 0.12$, hence $|U_{e4}|^2 = 0.03$.
- Let us assume in addition also muon-electron Universality, such that νe and νμ disappearances are identical.
- Then we expect $\sin^2(2\theta_{ee}) = \sin^2(2\theta_{\mu\mu}) \approx 0.08$, still in reasonable agreement within present observations.

Appearances and disappearances

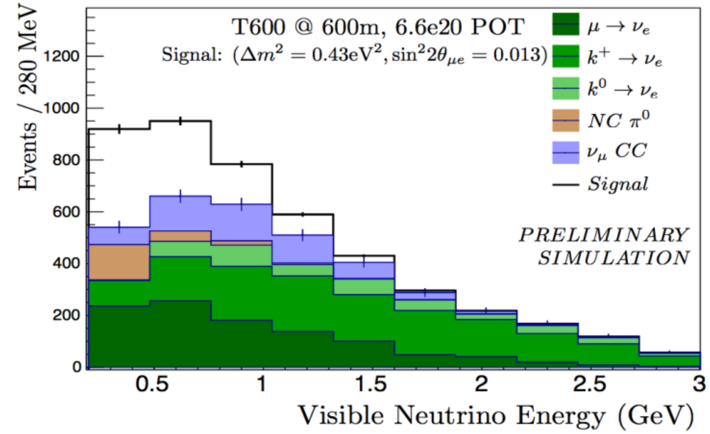
ND @ 120 m

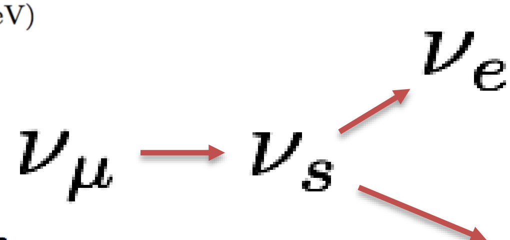
ICARUS T600 @ 600 m

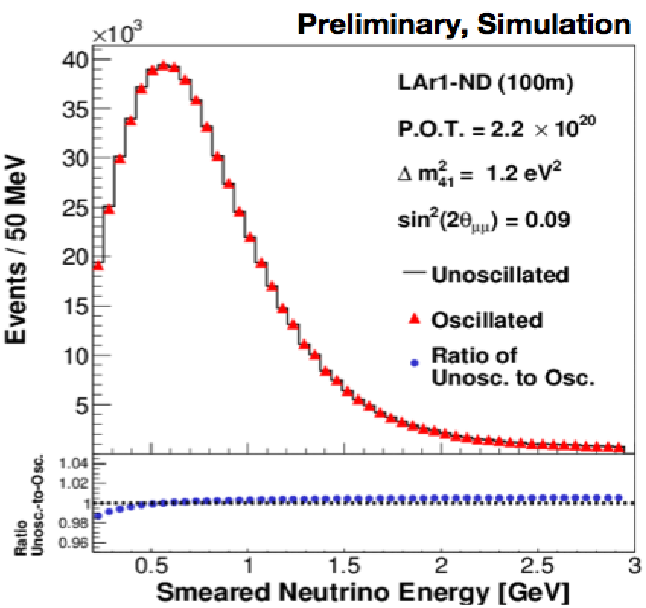


Δm² = 0.4 eV²

e Appearance

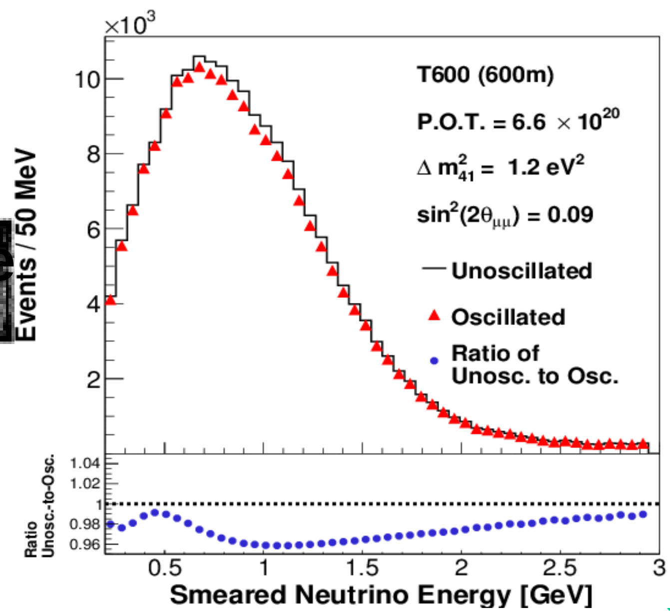






Δm² = 1.2 eV²

Disappearance



Cancellations between disappearance and appearance

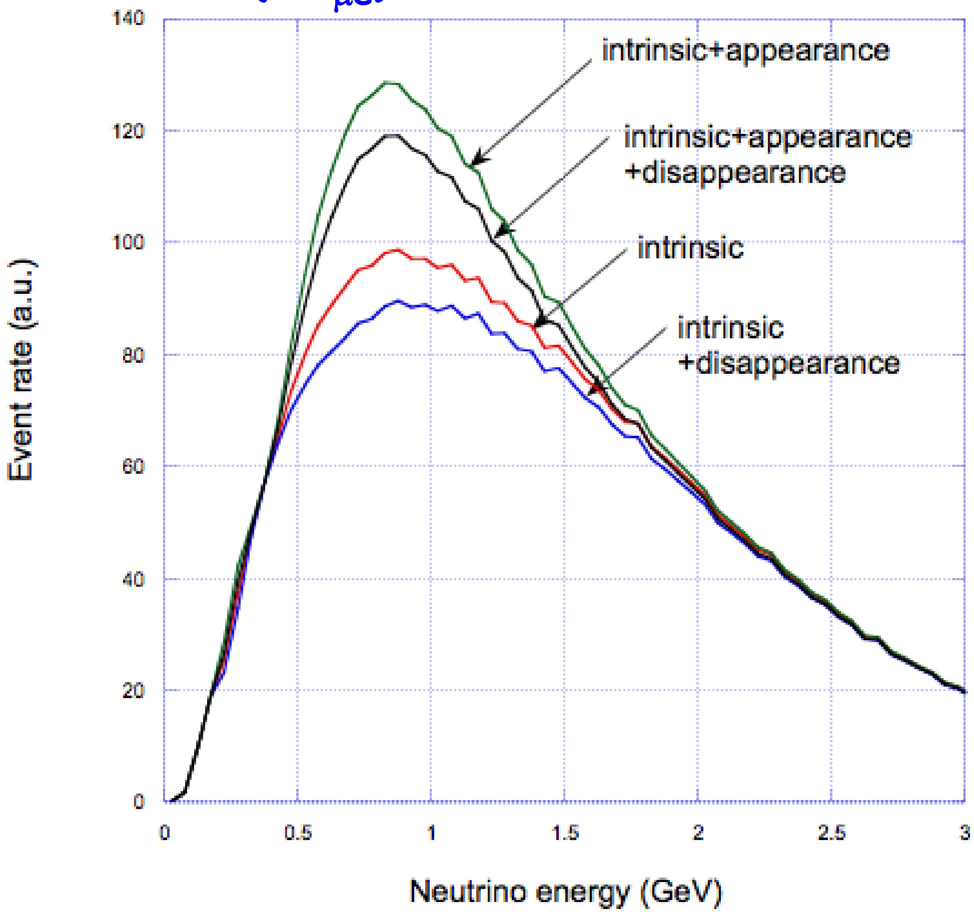
- There is an important difference between the original LSND and the future FermiLab programs.
- This is due to the fact that νe events are now produced both from $R_{\nu e}(E)$, the "intrinsic" νe source at about 0.5% of the muon rate and $R_{\nu\mu}(E)$ and from a potential LSND $\nu\mu \to \nu e$ effect.
- Therefore cancellation between these two contributions is expected in the detected νe signal $S_{\nu e}$:

$$S_{\nu e} = [R_{\nu\mu}(E)\sin^2(2\theta_{e\mu}) - R_{\nu e}(E)\sin^2(2\theta_{ee})]\sin^2(1.27\,\Delta m_{41}^2\, L/E)$$

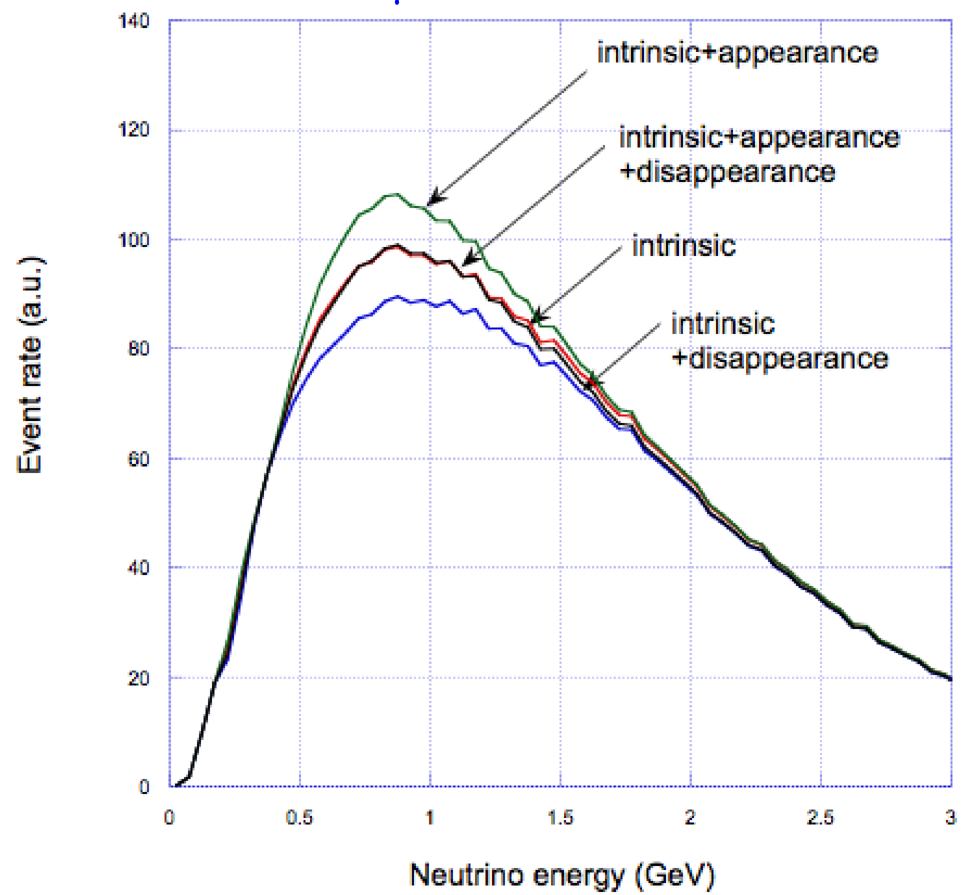
- Δm_{41}^2 ,the squared mass difference with respect to the fourth heavier neutrino is a common factor as a function of mass difference and L/E.

Examples of electron neutrino spectra

Giunti Laveder best fit:
$\Delta m^2 \sim 1.5\ eV^2$;
$\sin^2(2\theta_{\mu\mu}) = 0.05$;
$\sin^2(2\theta_{ee}) = 0.1$;
$\sin^2(2\theta_{\mu e}) = 1.25 \times 10^{-3}$



Extreme case of full cancellation
$\Delta m^2 \sim 1.5\ eV^2$;
$\sin^2(2\theta_{\mu\mu}) = 0.016$;
$\sin^2(2\theta_{ee}) = 0.1$;
$\sin^2(2\theta_{\mu e}) = 0.4 \times 10^{-3}$

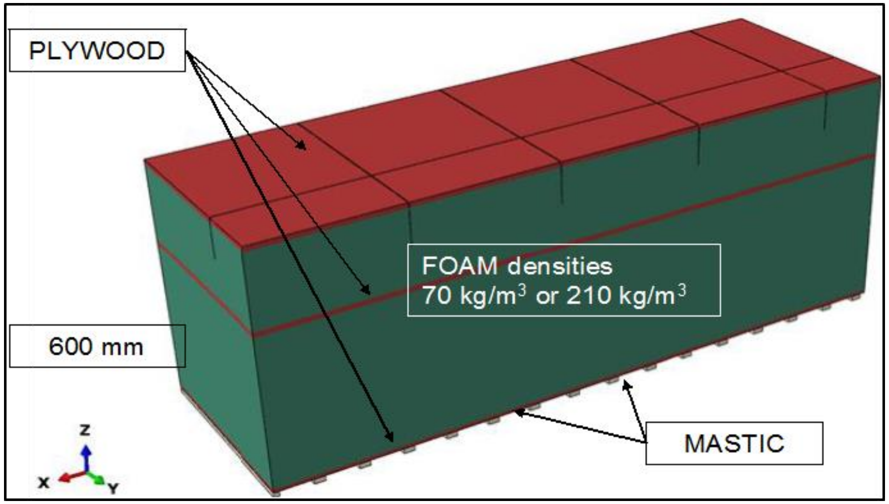


A brief description of the activities of WA104/ICARUS

- The WA104/ICARUS program is devoted to "*Improving the ICARUS T600 Liquid Argon Time Projection Chamber (LAr TPC) in order to prepare for its operation at shallow depths*",
- The overhauling activities on the T600 at CERN are progressing, to be completed by end of 2016 and include amongst others:
  - new purely passive insulation (1a) and new cold vessels (1b)
  - a renovated purification systems (2a) and cryogenics (2b) ,
  - inner detectors with better planarity (3)
  - an improved scintillation system(4a) and its electronics(4b)
  - A faster, higher-performance wire read-out electronics (5)
  - Experimental observation of cosmic ray shower events (6)
- At FNAL's shallow depth, the T600 will require two additions:
  - 3 m concrete overburden to mitigate the c. rays background,
  - Particles entering the detector must be removed with a Cosmic Rays Tagging (CRT) around the full LAr volume

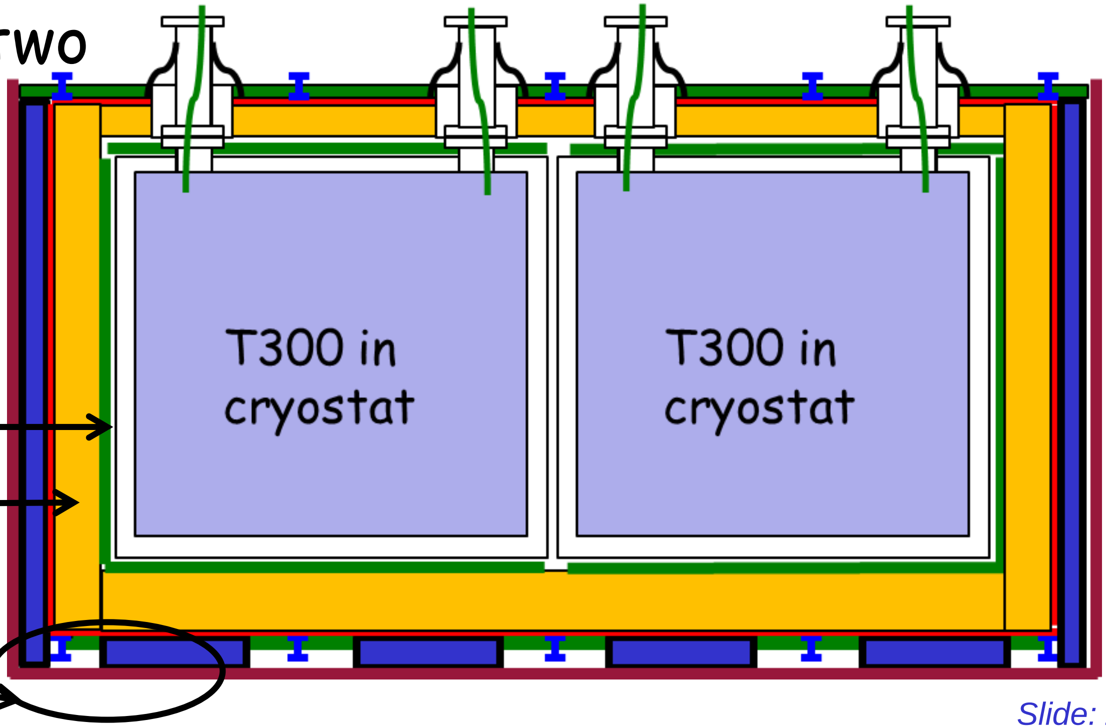
1a.- New purely passive insulation

- Purely passive insulation (right), and two-phase N_2 cooling shield.
- Insulation technique developed with membrane for LNG transport ships. Expected heat loss through insulation: ≈ 6.6 kW (10-15 W/m²).
- Preliminary design of the insulation 2 years ago by GTT: to be refined and integrated in the next two months.



Simplified front view in the installed ICARUS detector:

- N_2 cooling shield;
- thermal insulation;
- external warm vessel (see next slide).



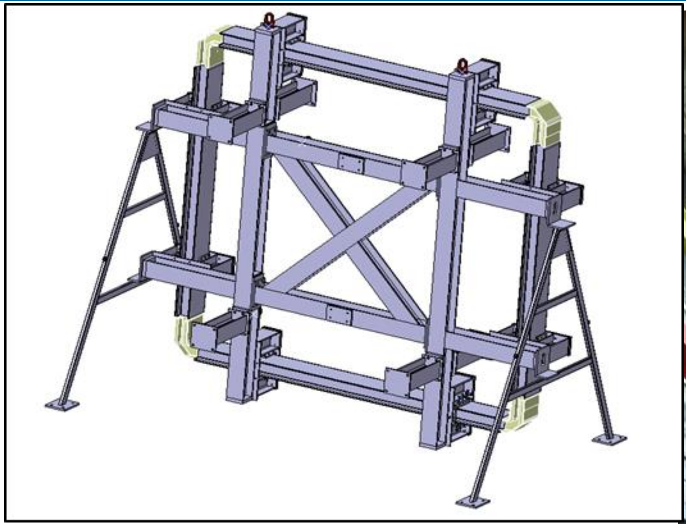
1b.- New cold vessels

- The new cold vessels are being assembled at CERN. The production and delivery of the pre-assembled aluminum profiles (orders sent out in 2015) is on schedule.
- CERN Main Workshop is proceeding with the stiffening frames, special profiles that will stand the LAr mass. All the pieces (angular and "I" profiles) have been delivered at CERN.
- The 1st module is being assembled in bdg. 156 and will be completed in June 2016.
- The 2nd will be ready in October 2016: it will be built in bdg. 185, to allow operation in parallel

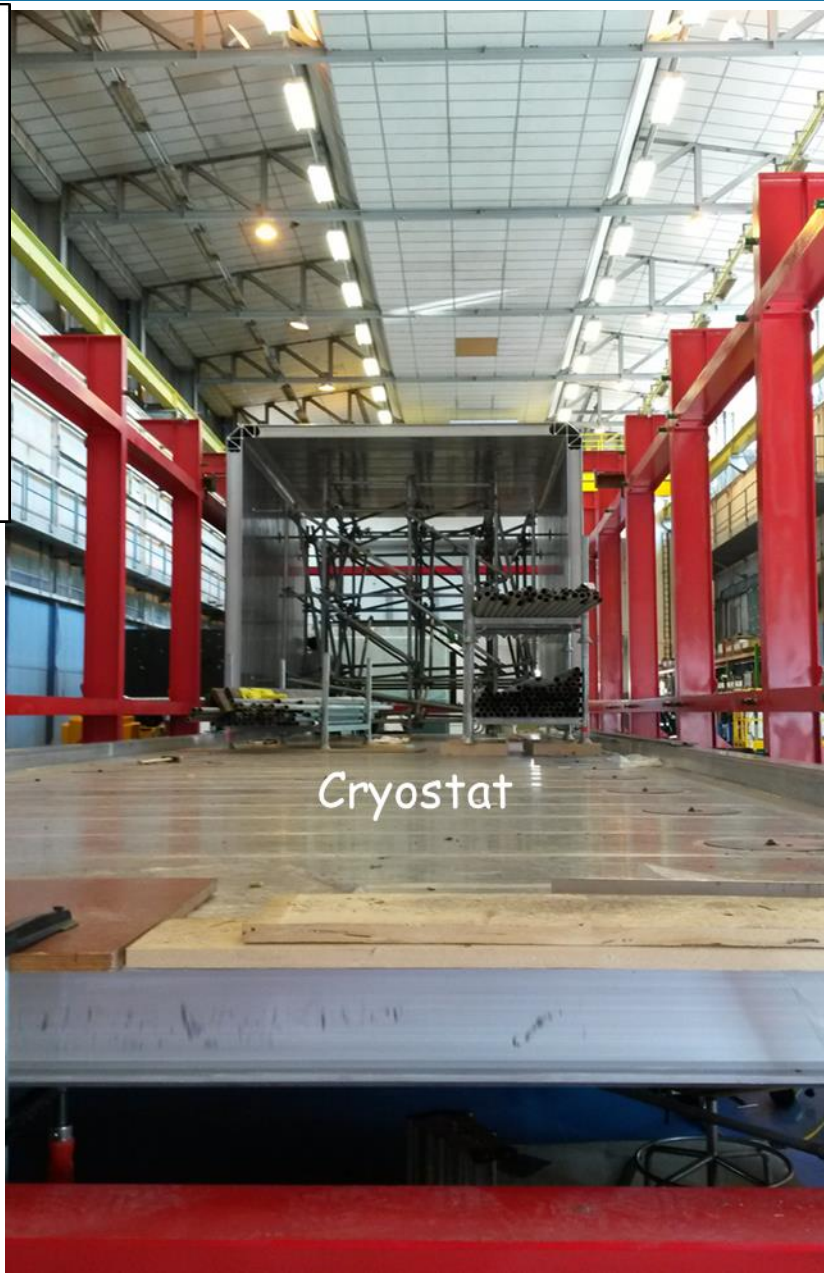
Roof pre-assembly

New cold vessels (cont)

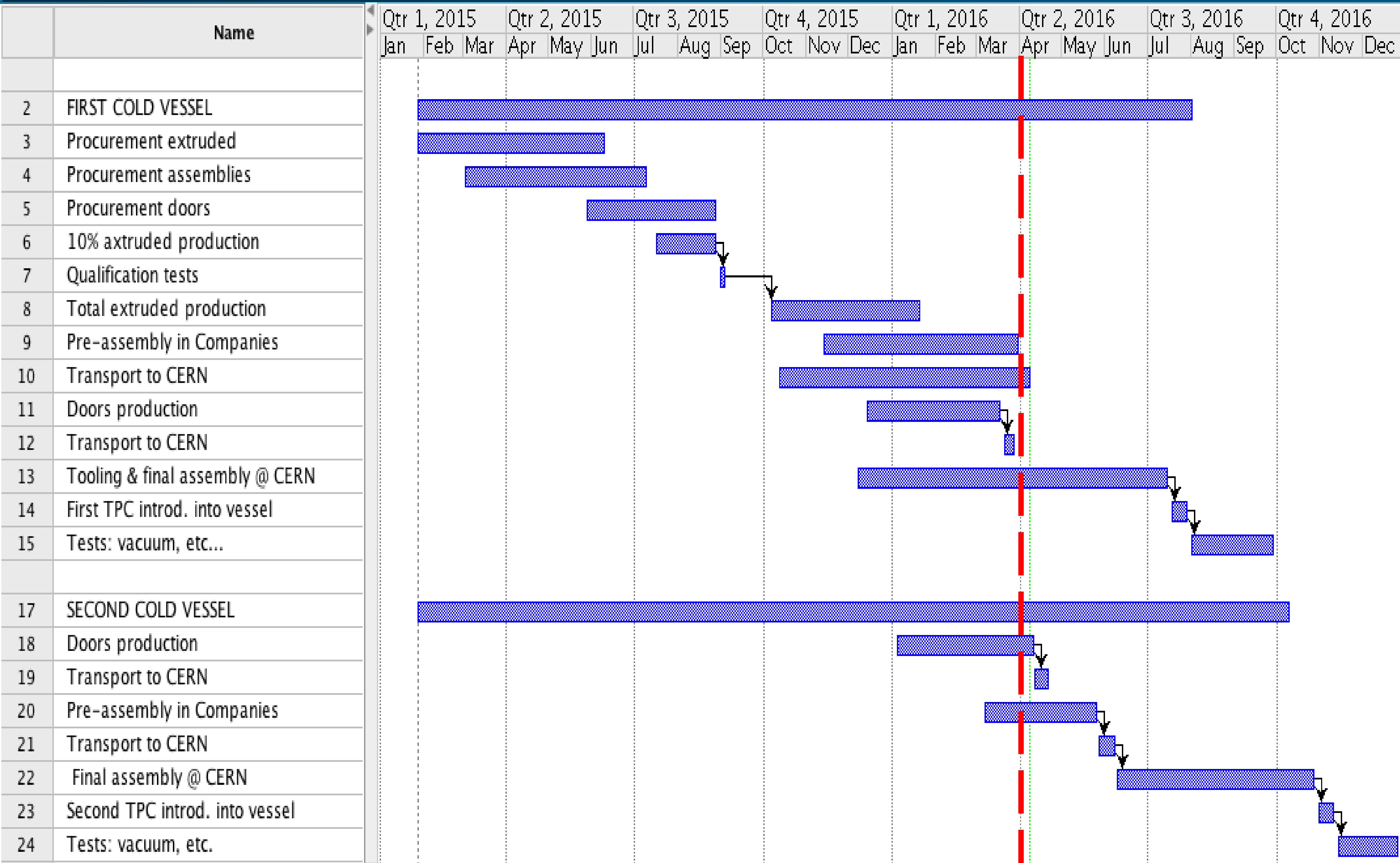
- A dedicated tool has been built for the assembly of stiffening of frames at CERN.



Main assembly structure



Cold Vessels Time Schedule



2a.- Purification systems

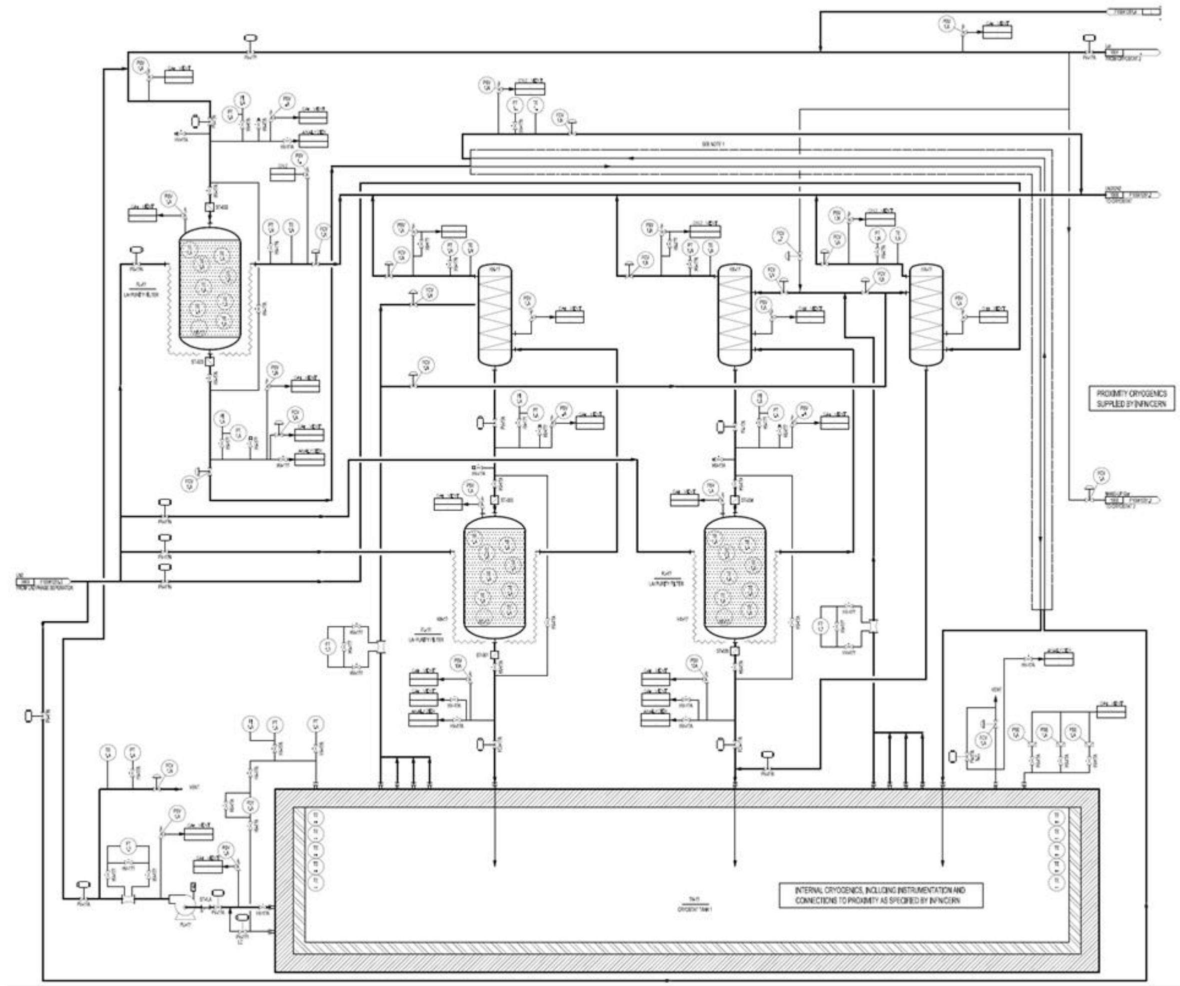
- Selection of parts to be recovered for operations at FNAL is underway, with the help of CERN Cryolab group.
- Tests of the new, dual-phase N2 cold shield have been done in 2015. Lab. measurements confirm the numerical model, and technical drawings now are being prepared.
- Oxysorb/Hydrosorb filters used in the previous ICARUS experience allowed reaching extremely high purity results (electron lifetime $\tau_e > 16$ ms), but their content of hexavalent Chromium has raised safety issues for use in US laboratories.
- A search for chemical residuals of Chromium was performed at CERN on the T600 detector in 2015, yielding negative results.
- Filters based on Copper, have been proposed by FNAL. Such purifiers were developed by the lab. personnel, carrying out regeneration in house. The filters are made of alumina pellets with Copper deposited on them (10% mass of Cu). Copper surface is rough, in order to increase active adsorption area

Characterization of copper filters

- A small, 50 liters TPC at CERN is presently used to characterize these Copper filters.
- Results with gas circulation show that purification capability is compatible with ICARUS needs: easily reached $\tau_e > 10$ ms, above the sensitivity of the 50 l chamber.
- Measured adsorption capacity in gas is of 5 g of O_2 per kg of filtering material. Further tests for purification in liquid phase are being prepared.
- According to experience from US colleagues, a factor 5-10 decrease in adsorption capacity is expected at cryogenic temperatures.
- The final choice is still under discussion between the Oxysorb commercial solution widely used in Europe (ICARUS, ATLAS), and copper purifiers.

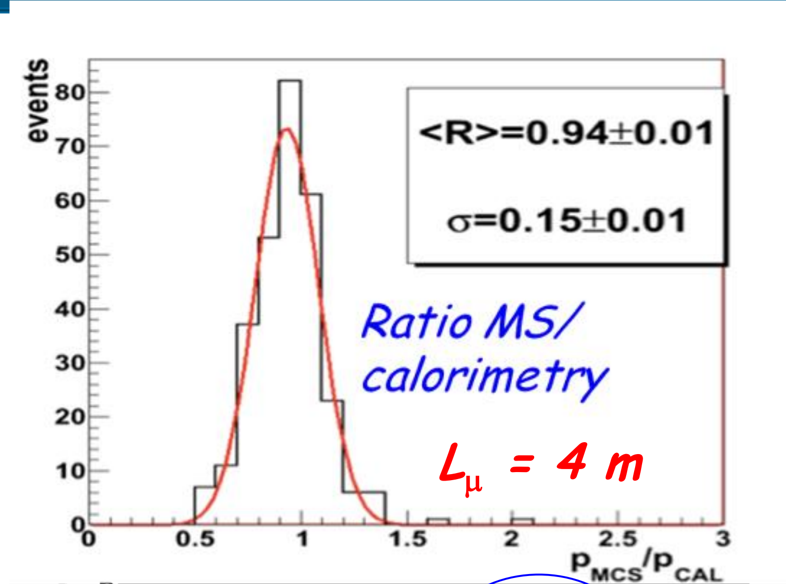
2b.- Cryogenics specifications

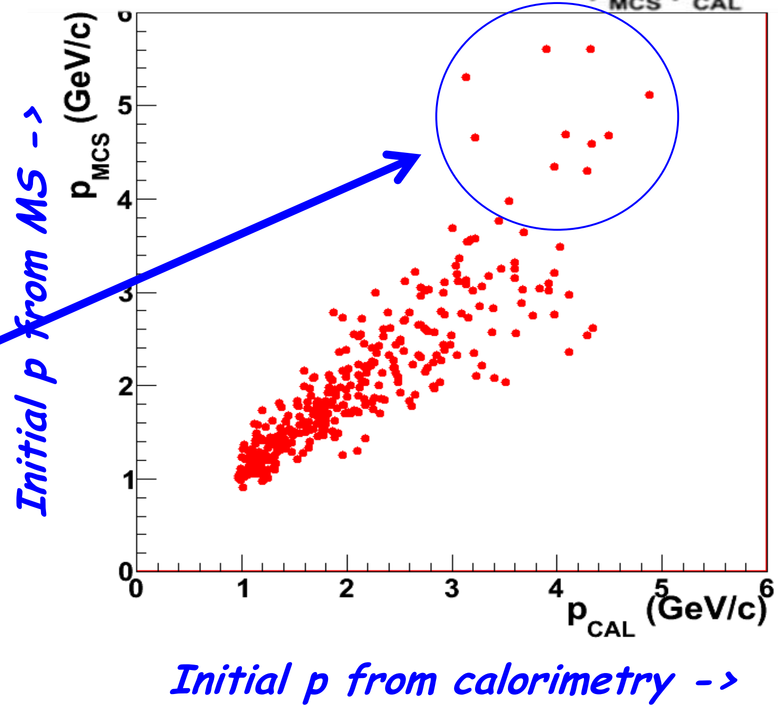
- Example of Process and Instrumentation diagram (P&ID) for the T600 @ FNAL, developed in collaboration between ICARUS and CERN Cryolab group.
- Drawings and technical specs for the ICARUS detector are being finalized, and a tendering document is in preparation.
- Tender opening is foreseen for June 2016.
- The tender concerns the proximity cryogenics of all the Argon detectors included in the Neutrino Platform.



3a.-Inner detectors with better planarity

- Muon momentum measurements by Multiple Coulomb Scattering (MCS) has been demonstrated at the CNGS experiment with $\Delta p/p \sim 15\%$ in the few-GeV region and $L_\mu \approx 4$ m.
- Unexpected deviations for p > 3 GeV/c have been observed for tracks travelling at d < 50 cm from the cathode, caused to a non-perfect planarity of TPC cathode panels.
- The consequent apparent deviations of tracks would mimic a larger MCS, resulting in an underestimation of the momentum.





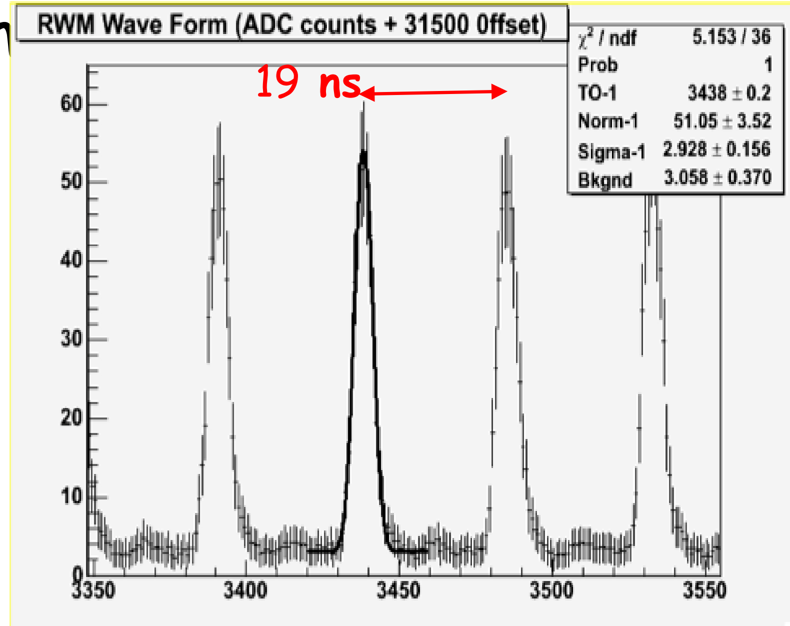
3b.-Refurbishing of the cathode panels at CERN

- A thermal treatment, including local heating and pressing was applied to the panels of the first T300 module in September 2015. The intervention, performed by CERN Main Workshop, was successful in reducing the non-planarity to within few mm.
- Panels have been reinstalled in the detector after cleaning and electro-polishing.
- The TPC cathode of the second T300 module will be treated during this summer.

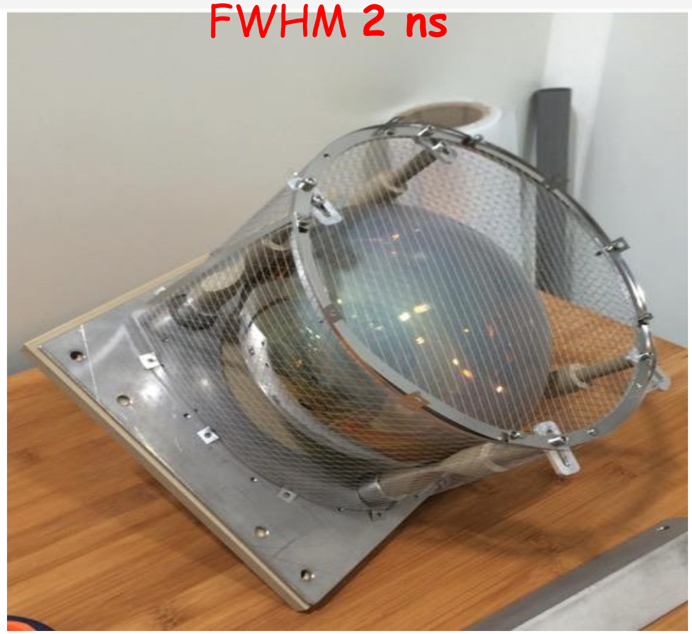
These interventions will improve the event imaging and track reconstruction for the future of ICARUS T600.

4a.-The new T600 light detection system

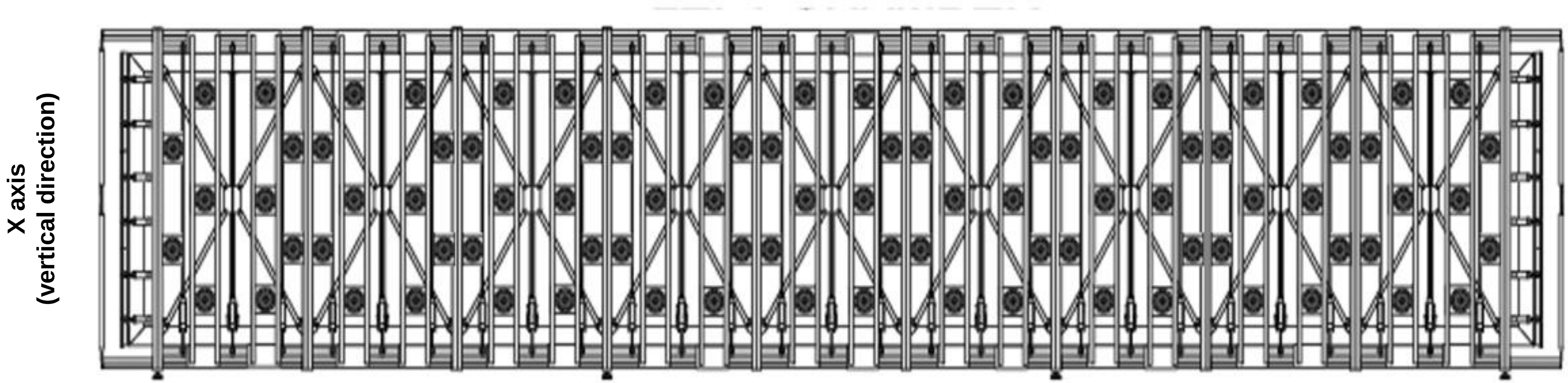
- The improved light detection system has been designed to ensure:
  - The generation of a more sophisticated light based trigger signal;
  - The identification of the time of occurrence (t_0) with high temporal precision of ≈ 1 ns, to exploit the available 2ns/19ns bunched beam structure of the FNAL Booster.
  - An initial identification of the various event topologies.
  - New shielded mechanical supports which prevent the induction of PMT signals to the collection planes.



FWHM 2 ns



The new T600 light detection system



- The new light collection system consists of 90 PMTs 8" HAMAMATSU R5912-MOD for TPC, installed behind each wire chamber (360 PMTs in the whole T600). About 200 $\mu g/cm^2$ of wavelength shifter is deposited on each PMT window. The photo-cathode coverage corresponds to 5% of the wire plane area.
- The number of photo-electrons collected per MeV of deposited energy in a single TPC is ~ 15 phe/MeV (9 phe/MeV for events close to the cathode) allowing the possibility to trigger low energy (100 MeV) events with fairly high threshold and multiplicity.

Present PMT activities at CERN

Activities on the PMTs are organized at CERN in three different areas:

Room temperature tests
IdeaSquare building 3179

Tests can be carried out in consecutive bunches of 16 samples.

Cold tests
building 182

A cryogenic facility allows the simultaneous measurement of 10 PMTs in a LAr bath.

TPB deposition
TE-Laboratory hall (B169)

The facility allows the production of ~5 coatings per day.

4b.- PMT electronics and calibration system

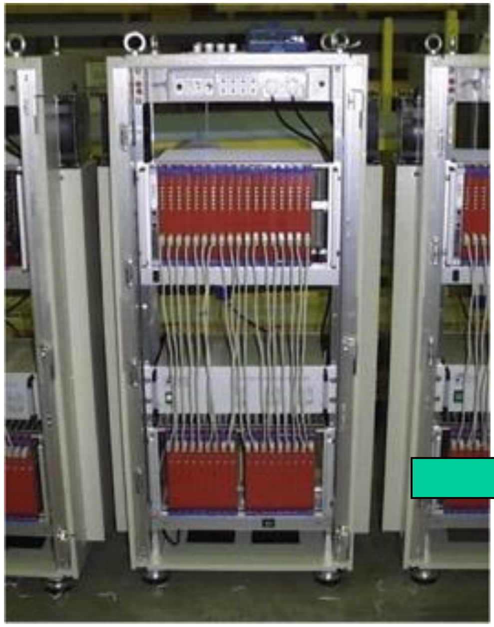
- The electronics for PMT signals must offer recording of the fast component of the scintillation light and, at the same time recording of the photons of the slow LAr component (1.6 μs).
- The ADC sampling frequency should be sufficiently high, in order to allow a time resolution of 1 ns, with a buffer size sufficient to collect all events occurring during the 1 ms LAr-TPC acquisition windows. Possible acquisition boards will be tested in the next months.
- To obtain a 1 ns timing, equalization of all the channels will be performed with the help of a signal of a fast LASER.
- The system will be made by fused fiber splitters, optical switches and optical patch-cords. The fibers to be inserted in the detector have been selected for LAr temperature endurance and have been commissioned. Each element of the system will be tested for installation and functionality.

5.-A new, higher-performance read-out electronics

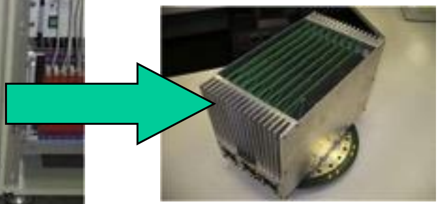
- ICARUS-T600 electronics was organized in sets of 32 *low noise amplifiers*, a tree of 8 analog multiplexers, of 4 10-bit ADCs, of 2 digital multiplexers, that result in a 2.5 MHz AD conversion (400 ns sampling). A digital VME module provides storage, data compression & trigger information.
- Some limitations, due to the technology when electronics was first conceived, can be now overcome. Improvements concern:
  - adoption of *serial synchronous ADCs*, one per channel;
  - housing and *integration of electronics* on detector flanges;
  - adoption of a *modern serial bus architecture* (instead of VME) with optical links for faster transmission rate (Gbit/s).
- The imaging "quality" of a LAr TPC is fully based on *mechanical accuracy, LAr purity, and electronics* that treat the signal.
- In the following we show that we *don't need to change our basic architecture, but only adopt more modern components.*

A new simplified/compact design

- Adoption of single ADCs (12 bits, one per channel) in place of the multiplexed arrangement used in T600 al LNGS.
- Sampling of channels (400 ns/s) of the whole detector are now *synchronous*, improving for instance the μ momentum of MCS with < 4 GeV/c and 4 m length to $\Delta p/p$ to 12%.
- The digital part is contained in a *single high performance* FPGA in each board, handling signal filtering and the information of ADCs.
- The new compact design allows the hosting of both analogue and digital electronics directly on the flanges.
- Prototype boards are under test at INFN-LNL and CERN.

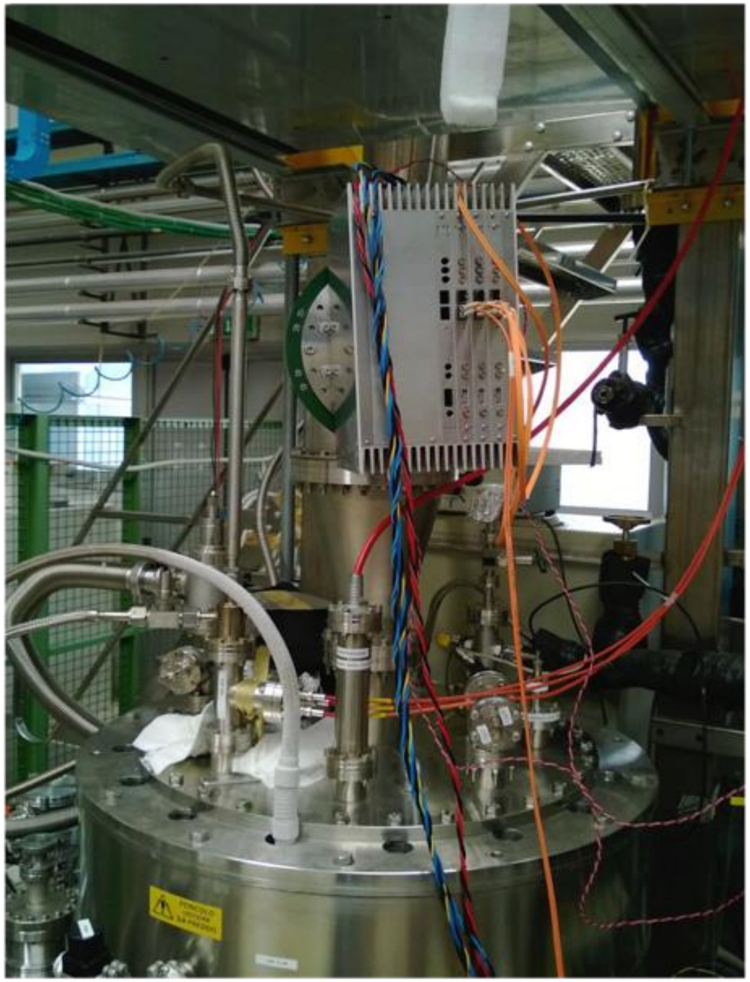


From 595 to 10 liters



Electronics optimization

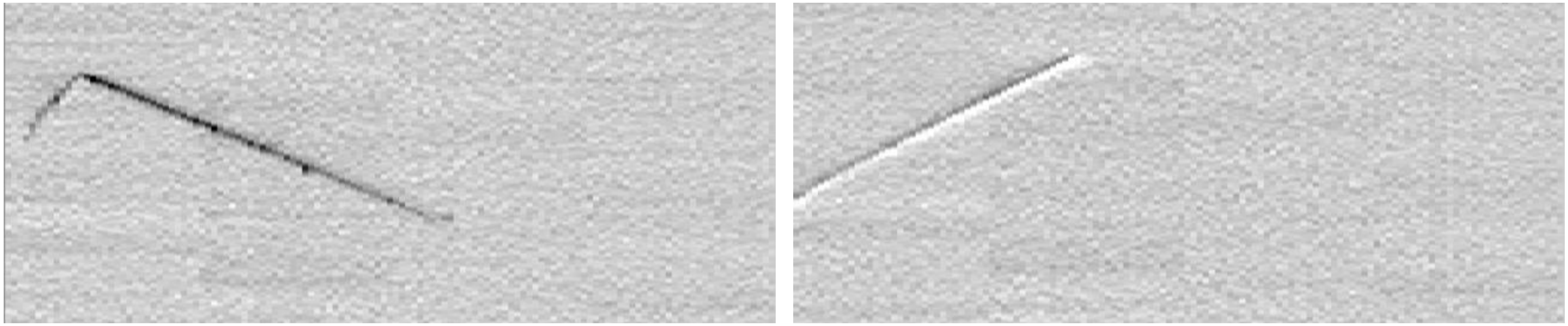
- The new electronics response is designed to be faster without undershoot with optimized shaping. So far the approach is:
  - signal integration by pre-amplifier (long shaping time) followed by zero-pole cancellation circuit;
  - short shaping time preserves bipolar signals in induction planes allowing for numerical integration of the digitized output.
- Ongoing tests at Lar TPC facility in CERN and LNL facilities.
- Significant improvement on the Induction wire planes is obtained.
- New cables have been selected. First delivery is expected in April.



Test set-up on ICARINO at LNL

Cosmics test @ CERN LAr TPC facility

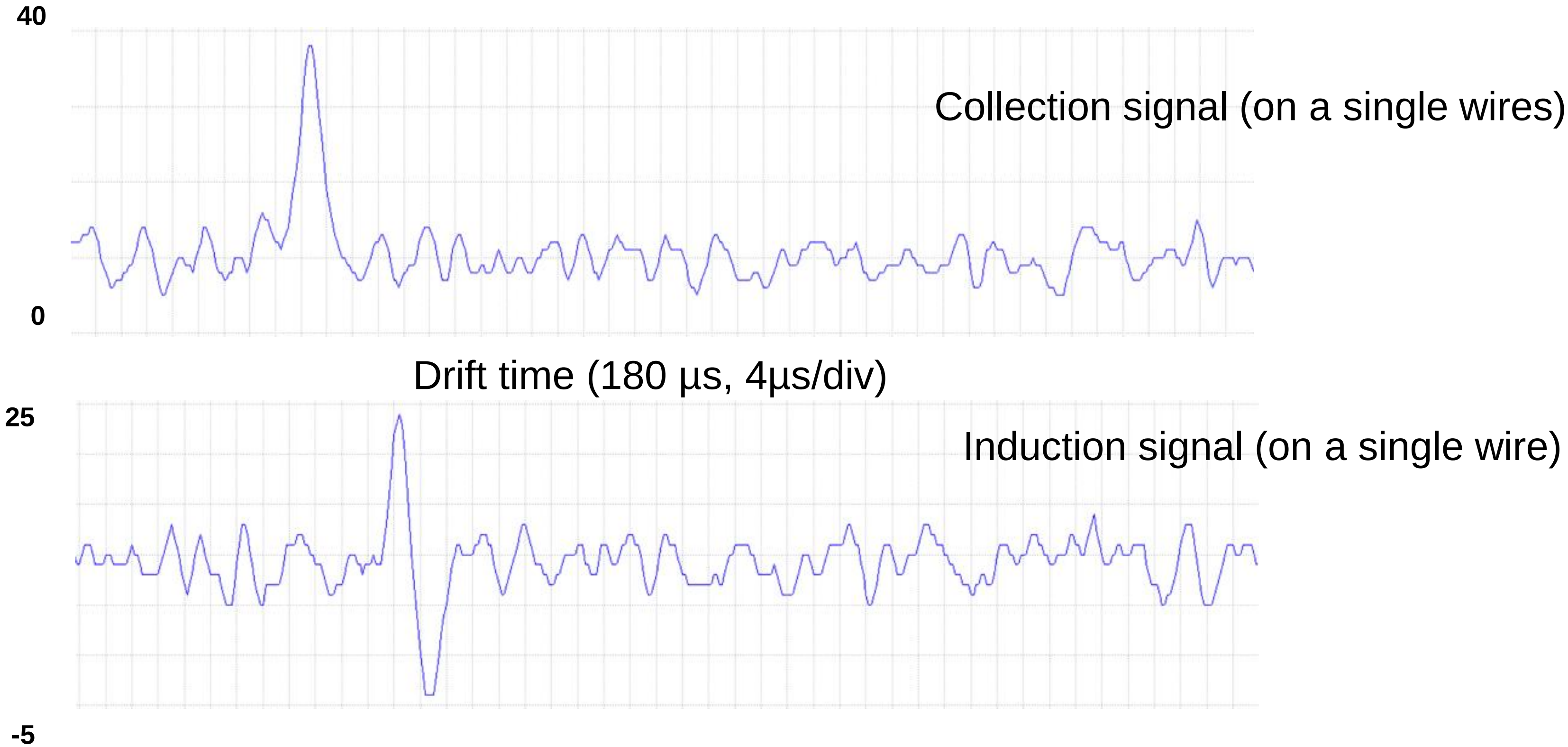
180 μs (280 mm)
Drift velocity 1.5mm/μs



128 collection wires (325 mm)

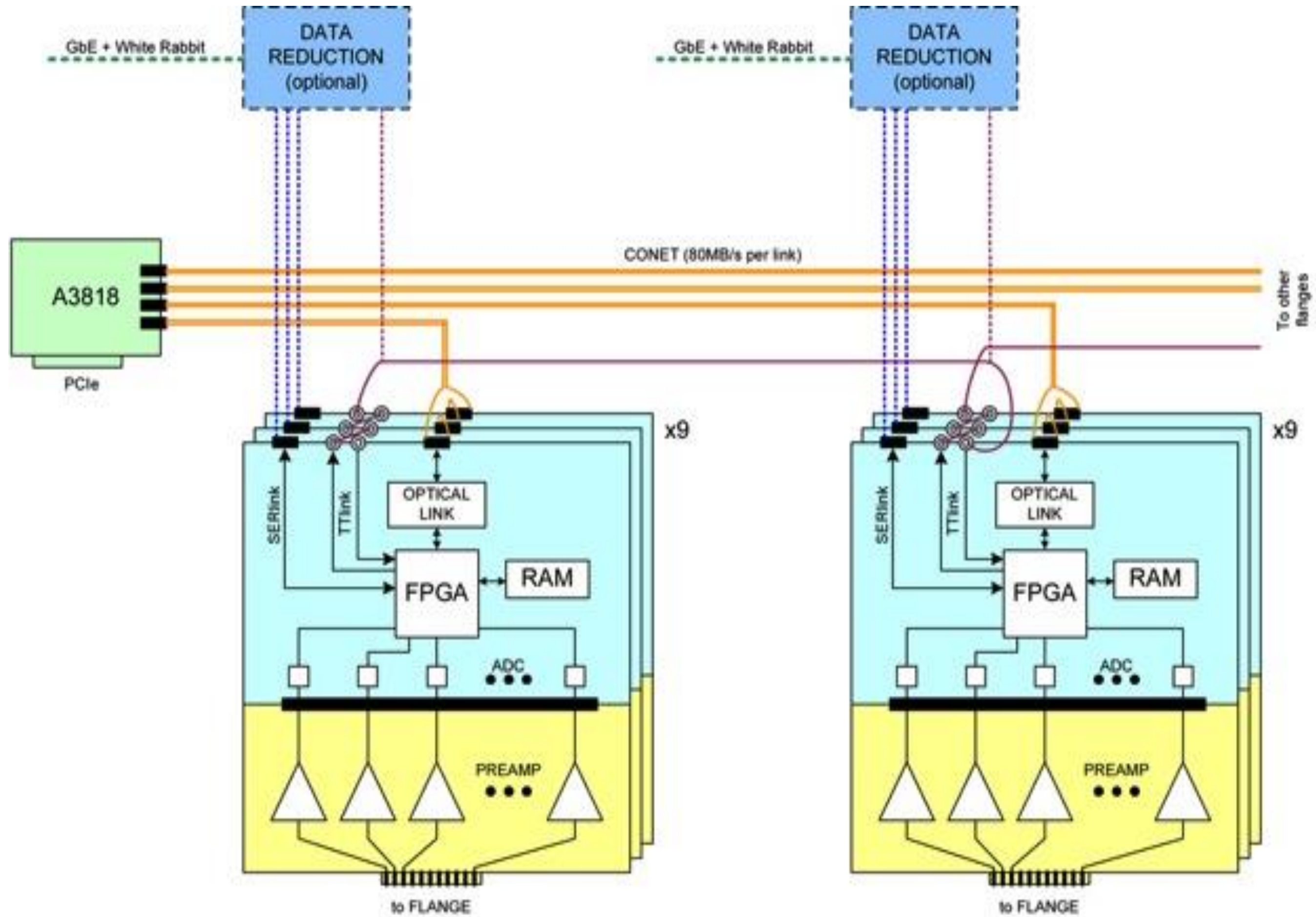
128 induction wires (325 mm)

Pulse height in units of~400 el/count



DAQ architecture

- Prototypes under development use CONET-2 (by CAEN) transfer protocol (80 MB/s) and a A3818 controller. The system will guarantee the full TPC drift data recording even in case of a Booster repetition rate of 15 Hz (47 MB/s).

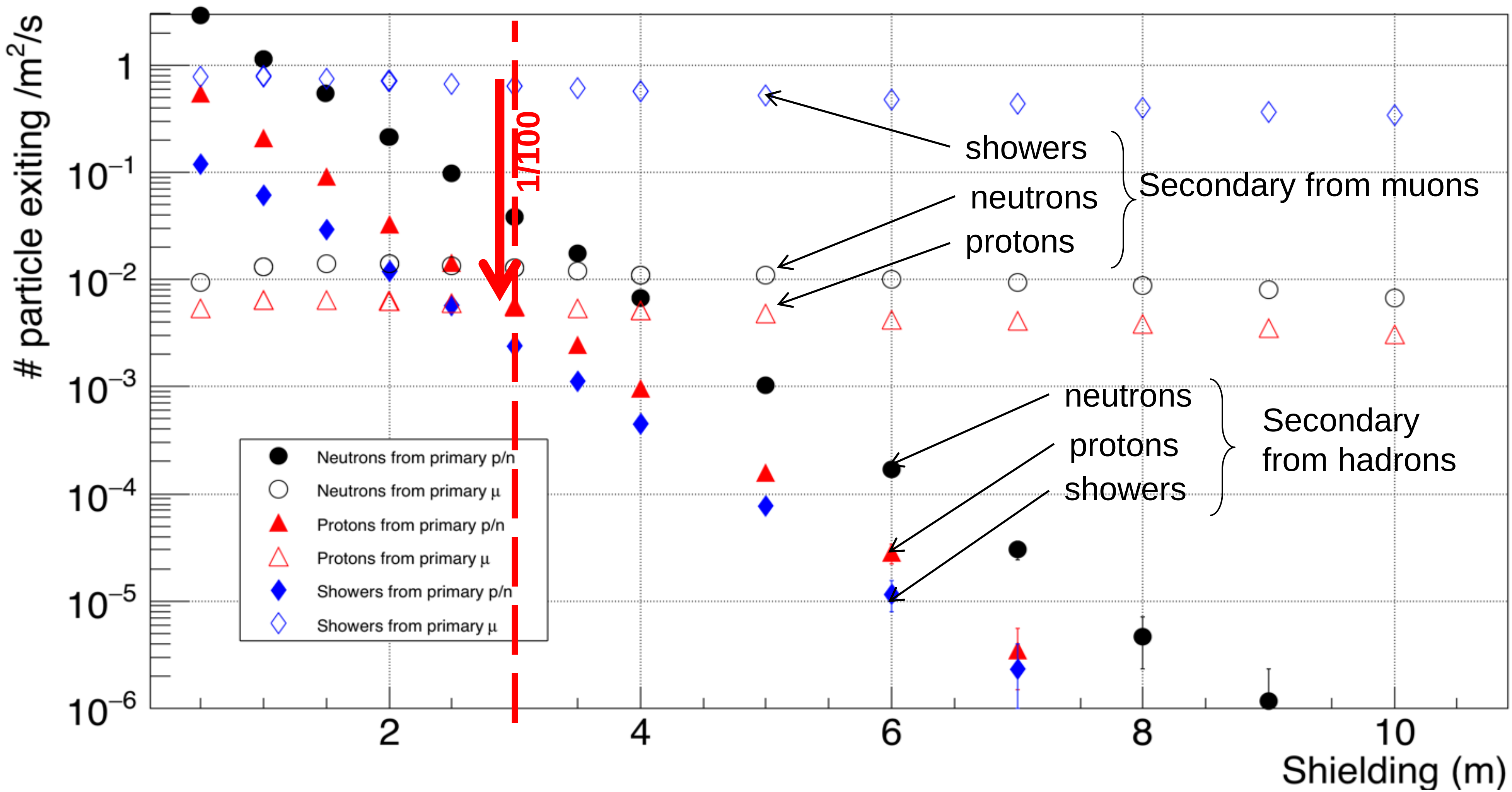


- A DAQ demonstrator of the basic functionality has been setup at LNL and CERN for integrating the synchronization and readout of multiple TPC front-end units with the PMT system.

6.- Simulation of cosmic ray (νe) events

- *Primary* cosmic rays electrons and hadrons are are strongly attenuated by an heavy concrete shield. However, *secondary* interactions may enter the T600 and be confused with νe events.
- The propagation of the cosmic primary flux, predicted by CRY through the overburden with GEANT4 and FLUKA codes shows comparable and substantial differences especially in the rates of hadrons passing through the concrete shielding (up to a factor 4).
- Therefore, an experimental verification in comparison with the simulation is required and it will be performed at CERN with the much smaller WARP detector, already operated extensively at LNGS, which offers the opportunity to provide experimentally crucial information on cosmic ray induced background events.
- the apparatus is also configured to ensure convincing proof on a relatively smaller verification of several technologies required for the T600 upgrade at CERN before going to FNAL.

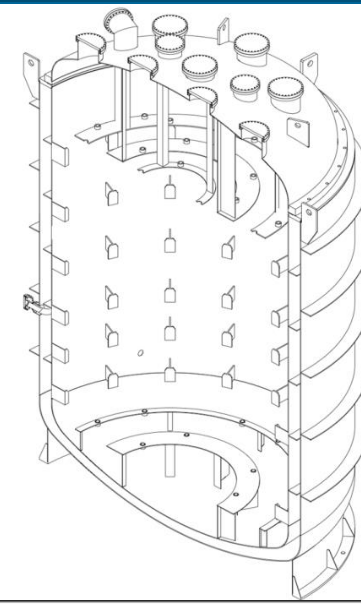
Comparison in T600 of penetrated particles from n+p and μ



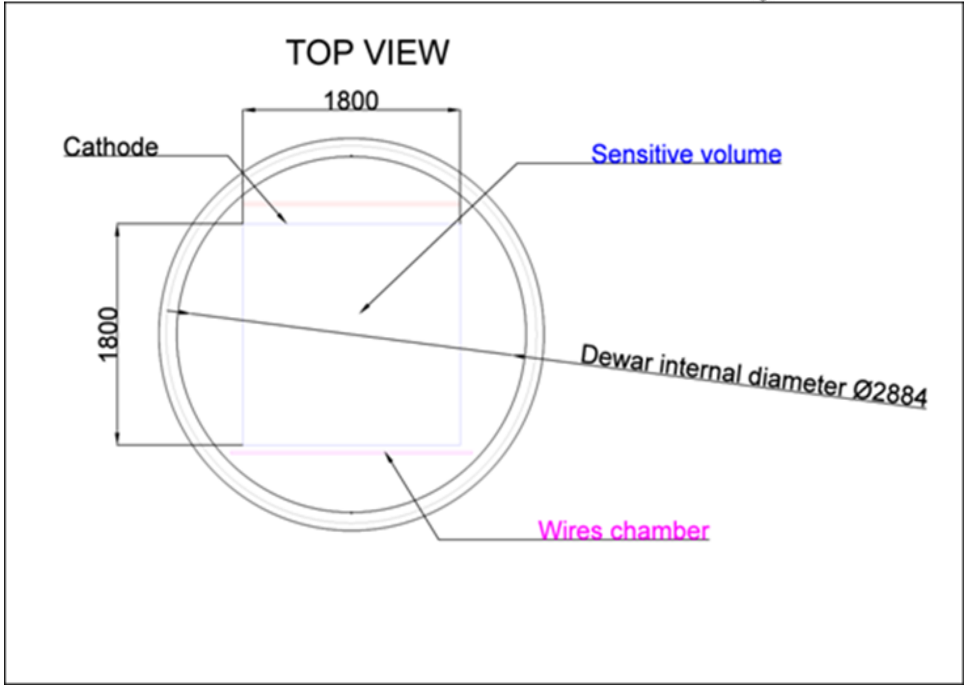
- Kinetic energy threshold for the particles exiting: T > 200 MeV.
- While only ≈ 1% of muon induced showers may show no presence of the visible μ, showers from hadrons remain mostly unaccompanied.

The ICARUS – WARP cosmic ray facility

- The apparatus consists of a LAr-TPC - *1.8 m width x 1.8 m length x 3.2 m height* - inserted in the existing WARP cryostat, a cylinder of 3 m diameter and 6 m of height and ~15 t active LAr mass, surrounded by a 4π CRT.



- The chamber is composed of 3500 wires organized in 3 planes, with 3 mm pitch/plane spacing oriented at 0^0,+/- 60^0 w.r.t. horizontal direction. A 500 V/cm electric field is applied over 1.8 m drift distance.
- Scintillation light will be collected by 10 PMT 8" Hamamatsu coated with TPB wave-shifting, located behind the TPC wire planes.

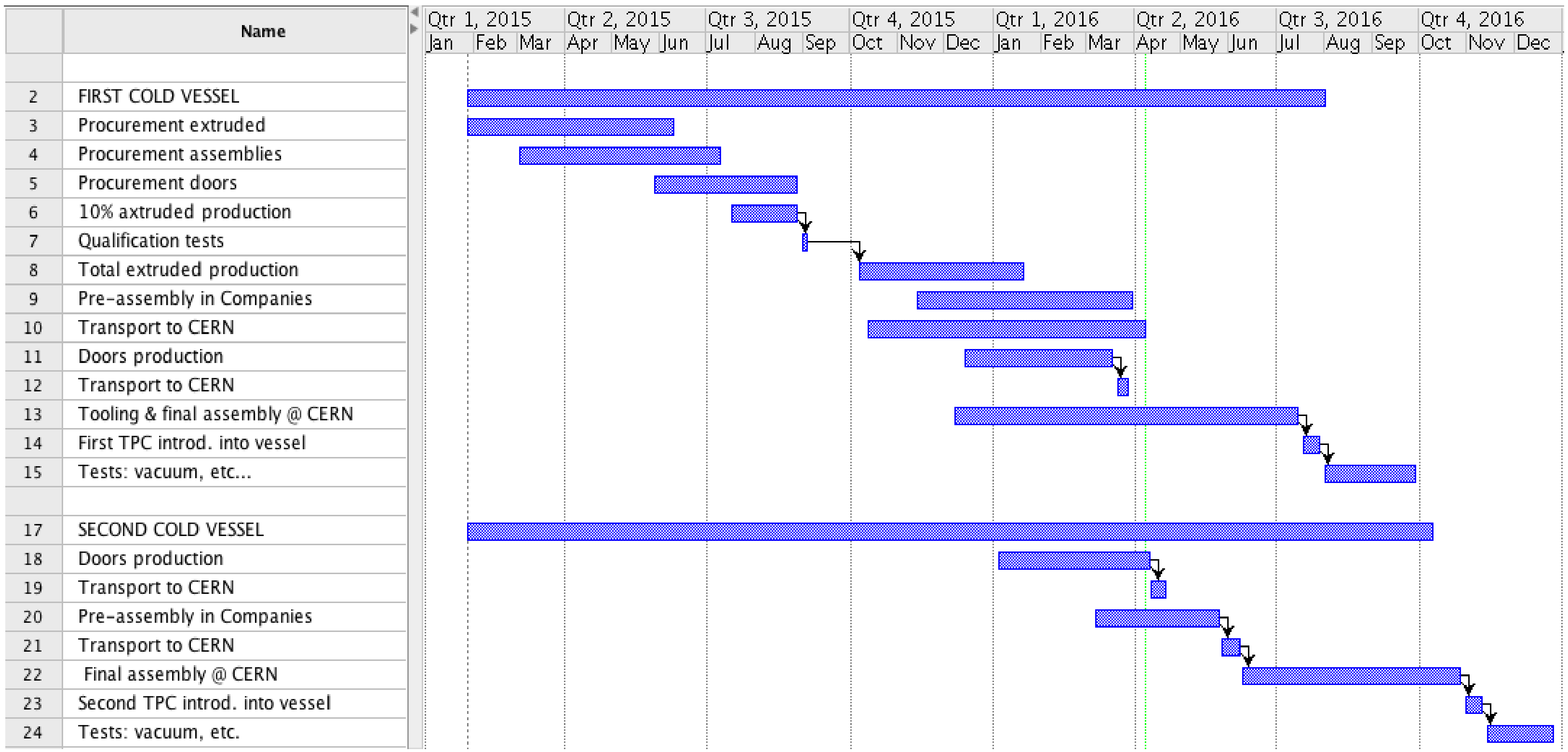


Cosmic Rays induced background measurement

- The proposed facility will be exposed, below a 3 m overburden, at an estimated rate of ~ 460 ev/s with mostly cosmic μ□s giving a LAr signal E >100 MeV in the TPC.
- A first mandatory reduction is provided by the 4π CRT with an estimated anti-coincidence rate of 98%, leading to a ~9.2 ev/s rate.
- The integrated c-ray active time of the ICARUS-T600 has been estimated to be 211 s during the 3 years of beam exposure with FNAL neutrino beam.
- The equivalent c-ray dose can be collected with WARP in ~ 55 hours of active time (200'000 triggers), at the limited rate of 1 ev/s. Therefore it should be possible to record in a reasonable time several relevant data samples with different conditions.
- The first step of data reduction would consist of selecting events requiring the presence of an e.m. shower, expected in ~1% of the cases, leading to a more reasonable number of events to be studied with the LAr-TPC.

Conclusions and moving to FNAL

- We expect that the two T300 modules will be ready for transportation at the end of 2016, in correspondence with the beneficial occupancy of the Far Detector building at FNAL.
- The transport of the equipment to the US will require about 2 months, funded by CERN for an estimated amount of 1 Million SF.



Thank you !