Liquid Argon Detectors for Long Baseline Neutrino Oscillation Physics
Big unknowns in neutrino physics: \( \sin^2 2\theta_{13}, \text{sign}(\Delta m_{23}^2), \delta, \text{and LSND?} \)

Three Neutrino Mixing Matrix:

\[
U = \begin{pmatrix}
    c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
    -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
    s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & 23c_{13}
\end{pmatrix}
\]

Chooz limit is \( \sin^2 2\theta_{13} \sim 0.1 \)

Long Baseline measurements probe \( \delta \) and \( \theta_{13} \)

The CP Violation Parameter

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements
As well as the mass hierarchy....

\[ \Delta m^2 < 0 \quad \Delta m^2 > 0 \]

CP violation + matter effects

\[ P_{\text{osc}}(\nu_\mu \rightarrow \nu_e) \]

CP parameter

\[ P_{\text{osc}}(\nu_\mu \rightarrow \nu_e) \]
Two approaches to $\nu_\mu \to \nu_e$ long baseline searches

Off axis beams: NOvA and T2K

Beyond NOvA (NuMI Off-Axis)

T2KK

Wide Band, on axis beams: Fermilab to DUSEL

Both span the 0.5-5GeV neutrino energy range
For both: need **intense** beams, and excellent detectors.....

Detector requirements:
- maximize $\nu_e$ efficiency
- minimize backgrounds from misIDs primarily NC $\pi^0$ interactions

- **Water Cerenkov**
- **Liquid Scintillator**
- **Liquid Argon TPCs**
For both: need **intense** beams, and excellent detectors.....

Detector requirements:
- maximize $\nu_e$ efficiency
- minimize backgrounds from misIDs primarily NC $\pi^0$ interactions

- Water Cerenkov
- Liquid Scintillator
- Liquid Argon TPCs

LArTPCs by far have:
- best $\nu_e$ efficiency: 80-90%
- neutral current $\pi^0$ rejection: <0.5%
- site detector at or near surface
Liquid Argon TPCs:

passing charged particles produce 55,000 electrons/cm

Drift ionization electrons over meters of pure liquid argon to collection planes to image track

Interior of the ICARUS T300
Signals on wire chamber planes

Arrange E fields and wire spacing for total transparency for induction planes. Final plane collects charge.

Run 308 Event 7 Collection view

Run 308 Event 332 Collection view

ADC count

time sample (Δt = 400 ns)

ICARUS TM/2001-09
How does this translate into $\nu_e$ efficiency and $\pi^0$ rejection?

Multiple secondary tracks can be traced back to the same primary vertex

Each track is two electrons – 2 mip scale per hit

Use both topology and dE/dx to identify interactions
Signal efficiency and background rejection make these detectors $\sim \times 3$ more sensitive to long baseline physics. See Parke et al. hep-ph/0505202 and more recently, Barger et al. hep-ph/0610301.

"NOvA" = 100kton LAr detector at 1st osc. max
"WBB" = Wide band beam from FNAL to DUSEL
T2KK = Beam from JPARC to Kamioka and Korea

"WC": 300 kton Water Cerenkov Detector
"LAr": 100kton Liquid Argon TPC
These are great detectors, but even with excellent efficiencies they must be very large.

Can we build them?
Technical Feasibility:
History of prototype work on ICARUS


24 cm drift wires chamber

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 m³ industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.
The success of the ICARUS T600 tested above ground in Pavia in 2001 now below ground in Gran Sasso.

One of the two T300 modules technically feasible on “small” scales (600 tons).
Several design ideas in moving beyond T600 to very massive detectors

**LArTPC:** Modularized drift regions in one large (10-50kton) tank

**GLACIER:** Combination of charge and light collection, single large large drift area

**LAANDD:** Modularized evacuated vessels
Many large LNG tanks in service

Excellent safety record
Last failure in 1940 understood
LArTPC: Modularized drift regions inside tank

- 6 Wire Sectors, each containing 6 Wire Planes
- 7 Cathode Planes
- Active volume: Diameter: 40m, Height: 30m
- Scalable: 15-50 kTons, 4 - 6 wire planes
- Trusses (schematic)
Challenges for massive “multi-drift region” detector

**Purity:**
3 m drift in LAr
- purification - starting from atmosphere (cannot evacuate detector tank)
  - effect of tank walls & non-clean-room assembly process

**Wire-planes:**
- long wires - mechanical robustness, tensioning, assembly, breakage/failure

**Signal processing:**
- electronics - noise due to long wire and connection cables (large capacitance)
  - surface detector - data rates,
    - automated cosmic ray rejection
    - automated event recognition and reconstruction
R&D path in scaling to 10-50 kton

**Physics Development using existing technology**
- Record complete neutrino interactions: ($\nu_e$ & $\nu_\mu$)
- Establish Physics Collaboration
- Develop Event Identification,
- Develop Reconstruction,
- Develop Analysis,
- Establish successful Technology transfer

**Engineering Development:**
- Construction of Tank
- Argon Purity
- Mechanical Integrity of TPC
- Readout S/N
- Microphonics due to Argon Flow

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Long drift test studies using Materials Test Stand at FNAL:
- Trigon filter, developed at FNAL
  → regenerated in line
- measure purity via ICARUS style purity monitor
  50 cm long drift

S. Pordes, FNAL
a 5.7 millisecond drift with the long PrM

Lifetime Measurements:
> 8ms lifetimes achieved.
Example here: 5.7ms drift

Next step:
Implement the Materials test station..
(new closed system cryostat)
Developing in-cryostat thermal pump

T. Tope
S. Pordes, FNAL
Test of purging a volume from atmosphere:

insert Argon gas at bottom of tank over large area at low velocity;
the Argon introduced being heavier than air will act as a piston and drive the air out of the tank at the top;
fewer volume changes than simple mixing model will achieve a given reduction in air concentration.

tank volume = 157 cf
tank cross section = 19 sf
flow rate ~ 73.2 cf/h (reading for air was 86 scfh)
climb rate ~ 3.8 f/h

S. Pordes, FNAL
to 100 ppm (reduction of 2,000) takes 6 hrs = 2.6 volume changes
(cf simple mixing, which predicts ln(2000) = 7.6 volume changes)
Cellular design for detector wire planes
Seeing tracks: small TPC prototypes at Yale and FNAL

Yale Prototype TPC

Larger version of this -> expose to NuMI beam

300 liter TPC (~175 liter active volume) exposed to on-axis NuMI beam:
~175K neutrino interactions/year

5m drift TPC test program starting up at FNAL as well!
LArTPC’s report to NuSAG*

www-lartpc.fnal.gov

Fermilab Note: FN-0776-E

A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-Axis Neutrino Oscillation Physics with the NuMI Beam

Submission to NuSAG

September 15, 2005

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A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-Axis Neutrino Oscillation Physics with the NuMI Beam
Submission to NuSAG

“Promising emergent technology for the detection of neutrino appearance is the Liquid Argon Time Projection Chamber.”

One of top three recommendations for US accelerator program:
The US R&D program in Liquid Argon TPC’s should be supported at a level that can establish if the technology is scalable to the 10-30 kiloton range. If workable, this technology will come into its own in the later phases of the long-baseline program.

Growing collaboration of Fermilab scientists, University groups (Michigan State, Princeton, Tufts, UCLA, Yale, York)

growing interest from INFN groups
Various considered options along the JPARC neutrino beam...

- Korea > 100 kton
- SK cavern ≈ 30 kton

2km ≈ 100 tons
280m ≈ 3 tons?
Summary

Liquid Argon TPCs are the best detectors for long baseline oscillation physics (as well as for nucleon decay, supernova detection....etc)

Challenging to construct on massive scales

R&D program towards achieving this both in the US, and in Europe and Japan

Growing interest in realizing these detectors!
Physics R&D: develop fully automated reconstruction....

Reconstruct primary and secondary vertex and muon track to within 2 deg.

*work in progress*