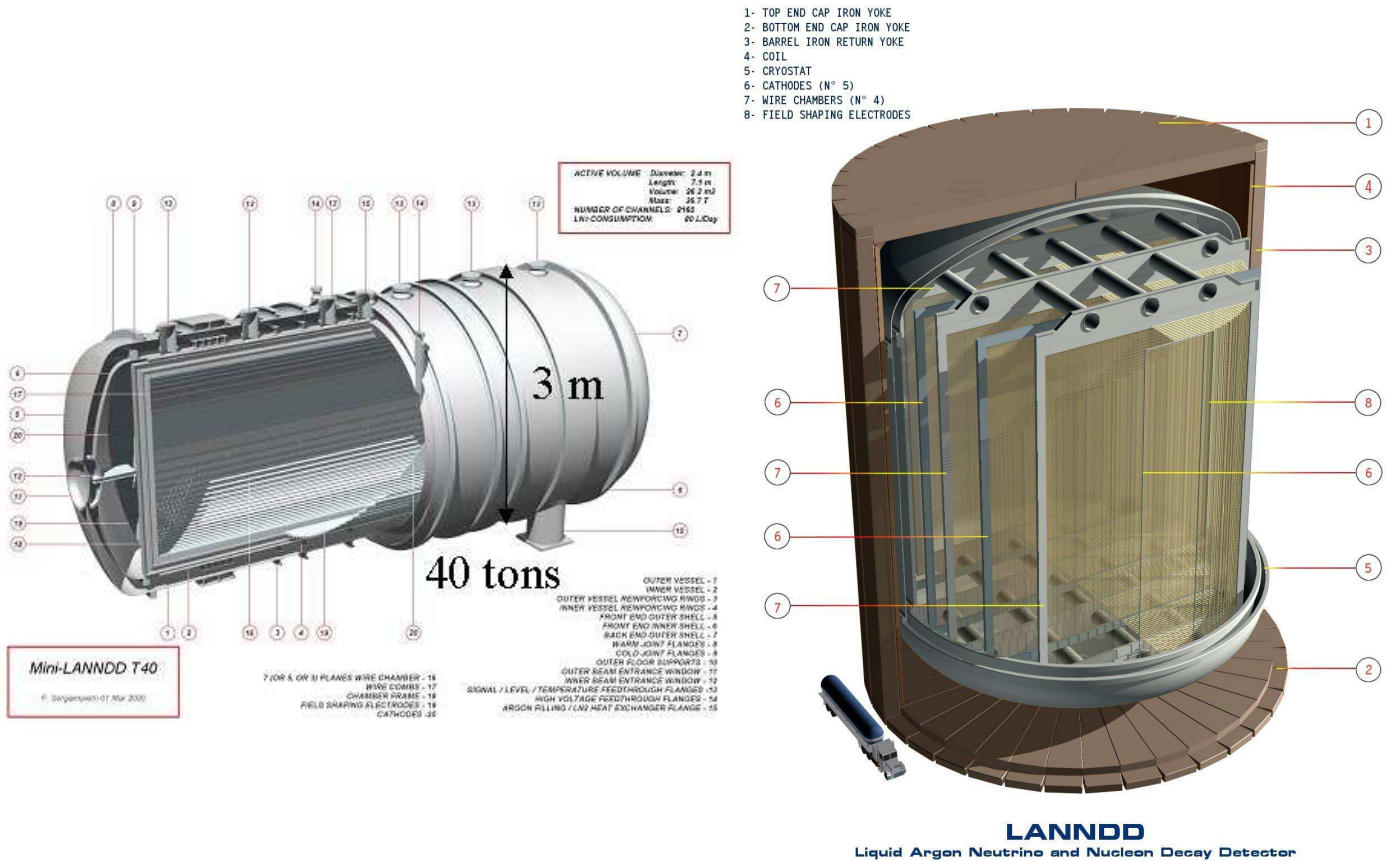


Large and Small (Far and Near) Liquid Argon Detectors for an Off-Axis NuMI Beam



Kirk T. McDonald

Princeton U.

kirkmcd@princeton.edu

NuMI Off-Axis Experiment Detector Workshop

Argonne National Laboratory, Apr. 25-27, 2003

<http://puhep1.princeton.edu/~mcdonald/nufact/>

Overview

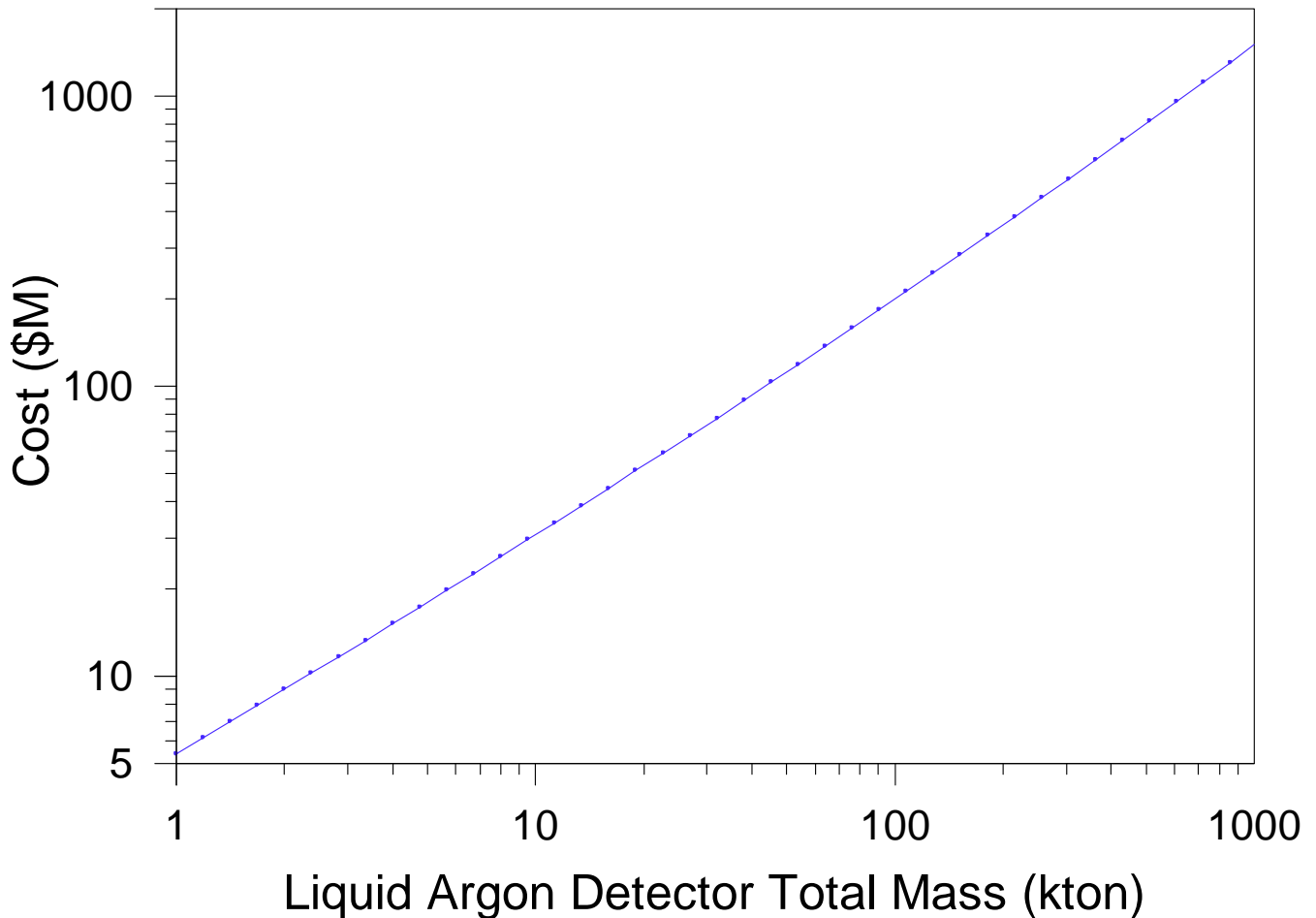
- A liquid argon time-projection chamber is a total-absorption tracking calorimeter = an electronic bubble chamber.
- It's efficiency for detection of ν_e appearance events will be greater than 90% for GeV energies. (This is 3 times the efficiency of low- Z sampling detectors.)
- A large (> 10 kton) liquid argon TPC, if in a single cryostat, will cost very nearly the same as a low- Z sampling detector of the same mass.
(There is highly competitive industry support for production, purification and storage of large quantities of liquid argon. Liquid scintillator costs 2.5 times as much as liquid argon, per unit mass.)
- The hardware of a liquid argon TPC is in a mature state, and readily scalable to large masses.
- More in need of further development is the software – in the style of bubble chambers. (Human scanning of event displays if necessary.)

Liquid Argon Detector Issues for This Workshop

(as per G. Feldman)

1. **Basic design.** Unchanged in years. Based on to concept of a liquid argon detector (Alvarez) in the form of a time-projection chamber (Nygren), which combination was suggested by C. Rubbia.
2. **Construction details and issues.** Extensive industry support for large cryogenic storage tanks, and for argon purification systems.
3. **Building and infrastructure.** A cryogenic storage tank is a steel building, designed for operation in extreme climates worldwide. A “counting house” for people, computers and cryogenic diagnostic equipment would be required ($\approx 5000 \text{ ft}^2$).
4. **Need for an overburden and/or active veto.** Doubtful, in view of excellent granularity of the detector. Compare cosmic-ray tests on the surface in Pavia, Italy.

5. Cost, including building, infrastructure and operational expenses.

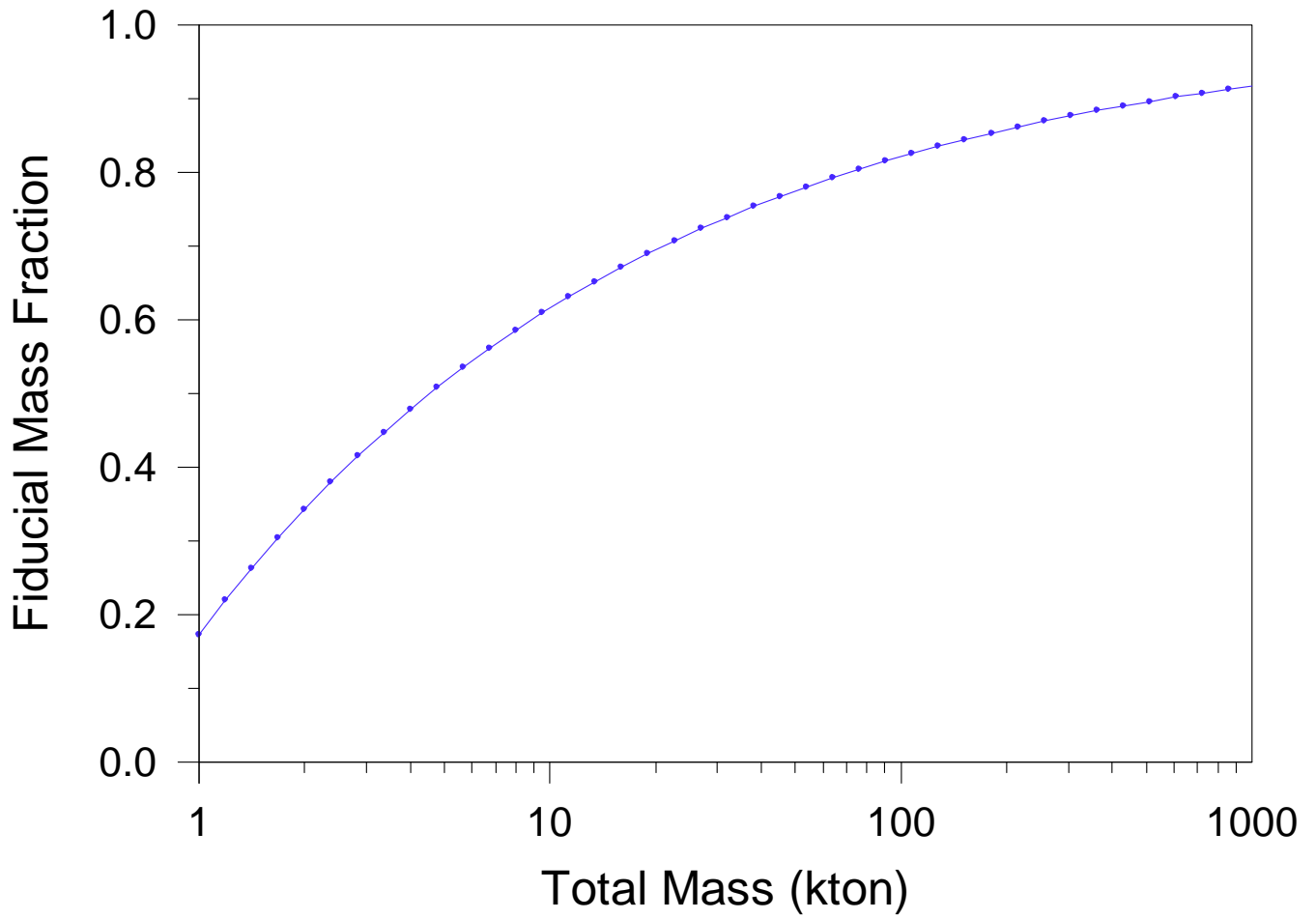


Preliminary cost estimate given on p. 19.

\$112M for a 50 kton detector (incl. 30% contingency).

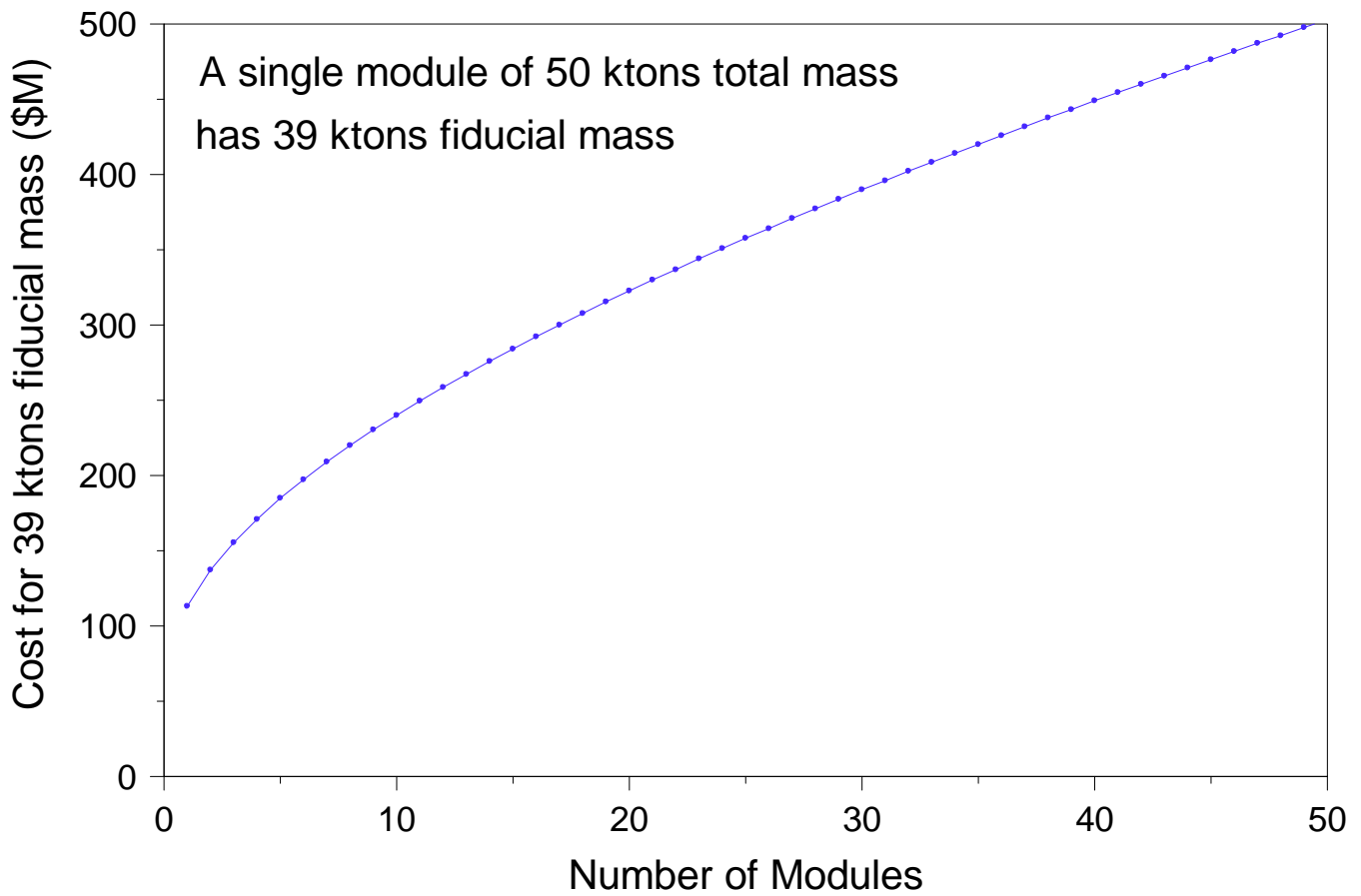
Refrigeration (100 kW @ 90K, 0.5 MW wall power) is the main operating expense.

6. What fraction of the detector is fiducial?



78% @ 50kton, IF build a single module.

7. Modularity. Most cost effective to build a single, large module.



For 39 kton fiducial mass (50 kton total mass if only 1 module),
Cost multiplied by 2 if build 8 modules rather than 1.
Cost multiplied by 4 if build 40 modules.

8. Resolution. Segmentation. ICARUS design with 3-d pixelation of $1 \times 3 \times 3 \text{ mm}^2$ may be finer than necessary. More on this later.
9. Maintenance and operational issues. Repairability. Failure modes and risks. The main detector is a sealed system \Rightarrow Must be well built! Primary failure modes are broken wires (more later) or O_2 poisoning of the liquid argon.
10. Near detector issues. Should build a liquid argon near detector in the NuMI beamline!
11. R&D issues. Time scale? Issues for a wire-based detector are reviewed on p. 21. Issues for a wireless system discussed on pp. 8-9.
12. Time to construct and install. Roughly 2 years to construct the storage tank, 1 year to construct the detector and (in parallel) the argon purification system, 1 year to fill the tank, \Rightarrow 4 years total construction.

Pad *vs.* Wire Readout

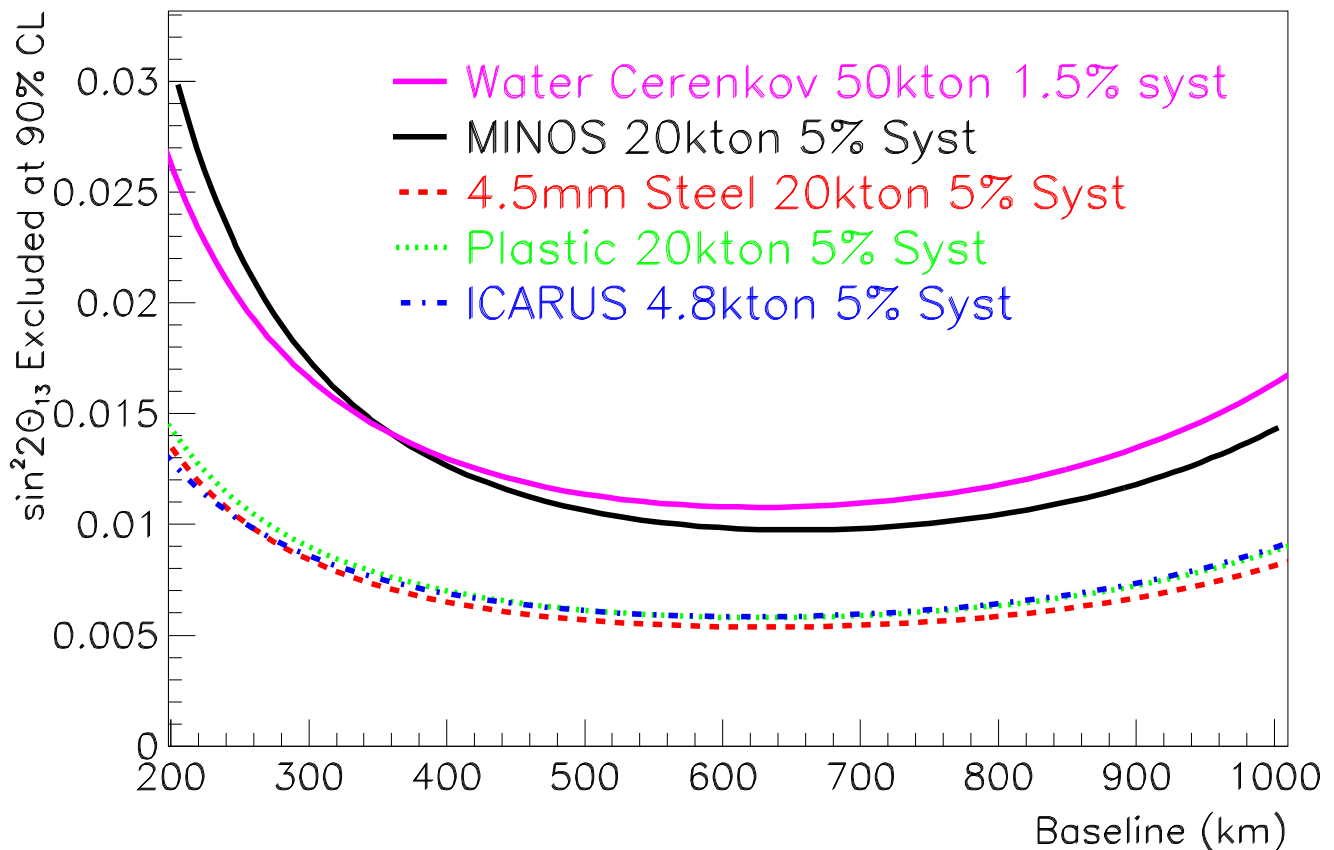
- Classic time projection chamber design is based on 2-d pixels (pads) + time sampling \Rightarrow Unambiguous 3-d pixels.
- Large channel count in large detector with tiny pixels, \Rightarrow Wire-based readout in ICARUS design.
- Wire-based readout \Rightarrow Must reconstruct 3-d pixels from 2-d projections, resolving “ghost” ambiguities, \Rightarrow Extra complexity to software.
- Wire-based readout uses collection wires + 2 planes of “induction” wires. But inductive readout is difficult when tracks lie close to the drift electric field lines, \Rightarrow Less than full solid angle can be reconstructed.
- Wire-based readout is vulnerable to wire breakage. The design based on classic method of attachment of piano wires to pegs is robust, but consequences of a wire failure system are severe.
- Wire-based readout is vulnerable to “microphonics”, \Rightarrow Differential vibration of wires at audio frequencies, \Rightarrow Baseline shifts, \Rightarrow Hard to do “zero suppression” online, \Rightarrow Much larger data flow off the detector.

Pad Readout for a Very Large Detector?

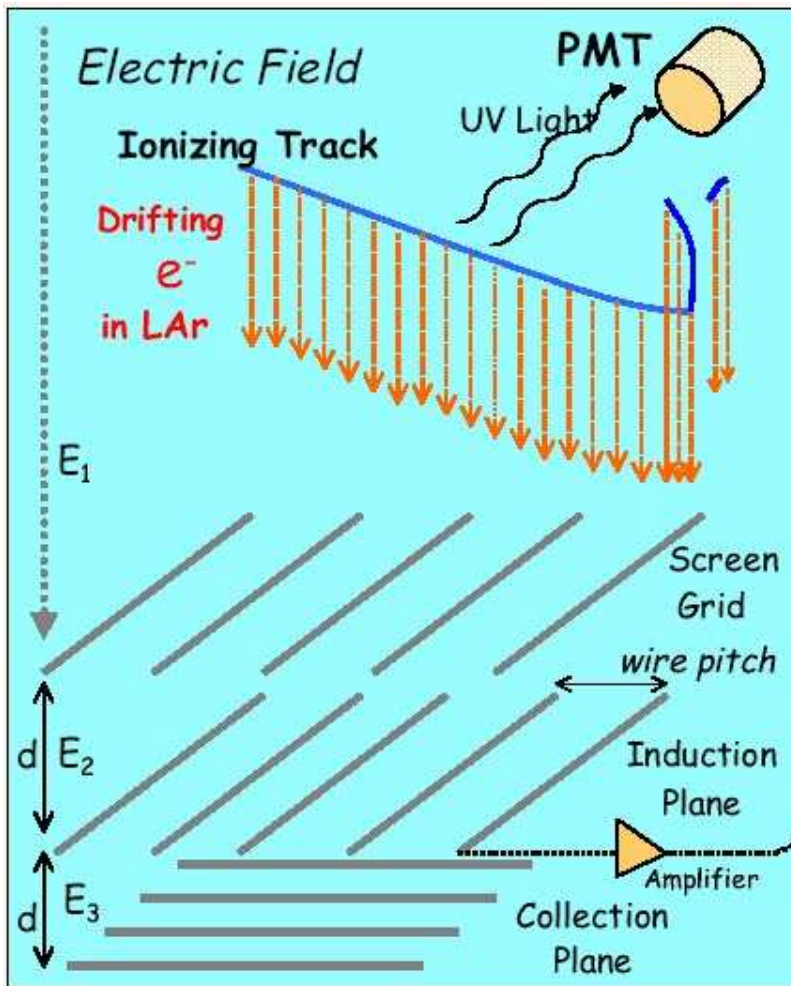
- Lower the channel count by coarser pixelation.
Ex: $1 \times 1 \times 1 \text{ cm}^3$ pixels (recall that $X_0 = 14 \text{ cm}$ in LAr),
 $\Rightarrow 10,000 \text{ ch/m}^2$ with 512-deep time-sampling over a 5-m drift.
- Take further advantage of large-scale integration of front-end electronics. (STAR TPC uses 16-ch/chip.)
 - Feature width of 0.2 mm/ch of analog electronics probably can't be reduced, but if arrange channels in 2 rows, could put 256 ch on a $20 \times 40 \text{ mm}^2$ die.
 - Cost of \$100 per 256-ch readout chip (\$0.40/ch)
 \Rightarrow \$4k/m² of readout area.
 - 30 kton detector ($h = 2r = 30 \text{ m}$) would have 3,000 m² of readout, \Rightarrow \$12M readout cost.
(Same as for wire-based readout with ICARUS pixel size.)
- New R&D Topics:
 - Simulations to study effect of pixel size.
 - Development of larger-scale front-end readout chips.
 - Verify operation of front-end electronics in liquid argon.
(1 mW/ch \Rightarrow 30 kW additional heat load.)

Liquid Argon the Best Detector to Study $\sin^2 2\theta_{13}$ in the NUMI Beamline

- ≈ 10 times better per kton than water Čerenkov for $\nu_\mu \rightarrow \nu_e$ appearance at 1-2 GeV (Harris).

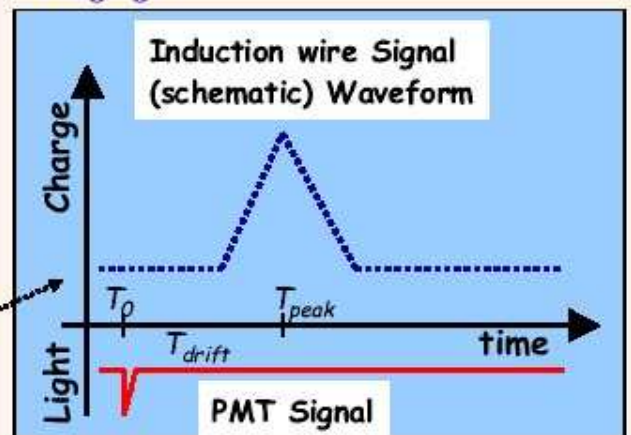


- Density = 1.4; $X_0 = 14$ cm; can drift electrons 3-5 m.
- 100% sampling tracking and calorimetry.
- Construction is simplest of large neutrino detector options.
- Best rejection of neutral current backgrounds, including soft π^0 's.



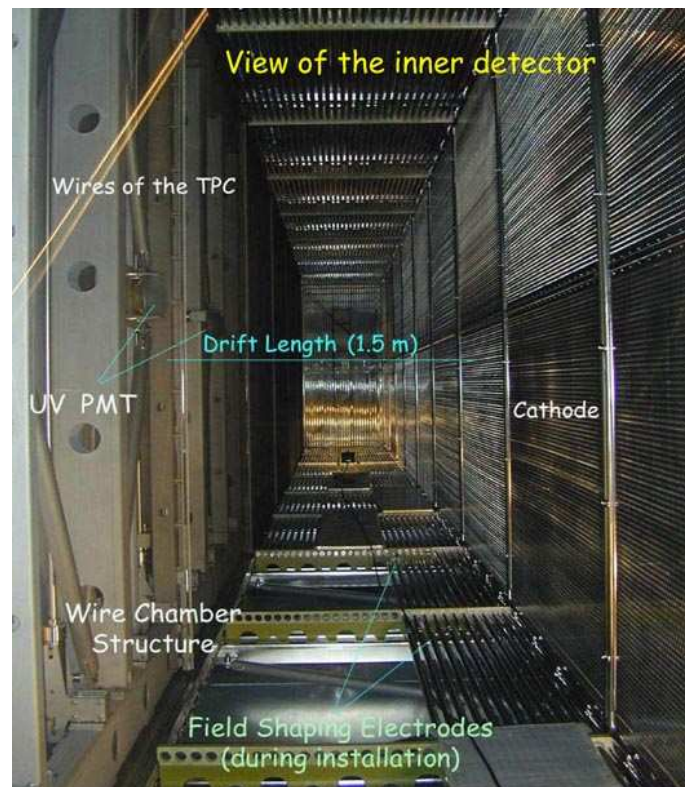
ICARUS Liquid Argon TPC

The LAr TPC technique is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of fine pitch wire grids) it is possible to realize a massive "electronic bubble chamber", with superb 3-D imaging.



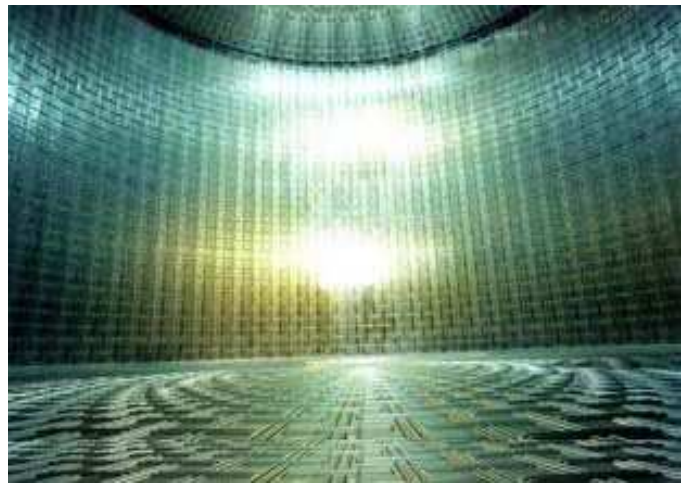
Liquid argon time projection chamber conceived by C. Rubbia (1977).

Largest implementation to date is the ICARUS T600 (600 ton) module, on the surface in Pavia, Italy.
<http://www.aquila.infn.it/icarus/>



Liquid Argon TPC Properties

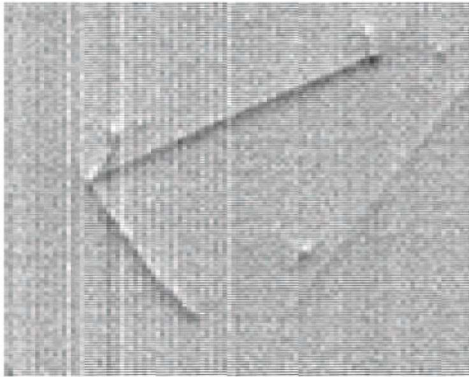
- 3D tracking + total-absorption calorimetry.
- Pixel size: 3 mm \times 3 mm (wire planes) \times 0.6 mm (via 400 ns time sampling).
- $\rho = 1.4 \text{ g/cm}^3$, $T = 89\text{K}$ at 1 atm., $X_0 = 14 \text{ cm}$, $\lambda_{\text{int}} = 80 \text{ cm}$.
- A minimum ionizing particle yields 50,000 e/cm .
- Drift velocity of 1.5 m/msec at 500 V/cm \Rightarrow 5 m drift in 3 msec.
- Diffusion coef. $D = 6 \text{ cm}^2/\text{s} \Rightarrow \sigma = 1.3 \text{ mm}$ after 3 msec.
- Can have only 0.1 ppb of O_2 for a 5 m drift,
 \Rightarrow Purify with Oxisorb.
- Liquid argon costs \$0.7M/kton – and is “stored” not “used”.
- Large modules ($\gtrsim 100 \text{ kton}$) can be built using technology of liquid methane storage. (Total cost of a 100-kton detector is estimated to be \$200M.)



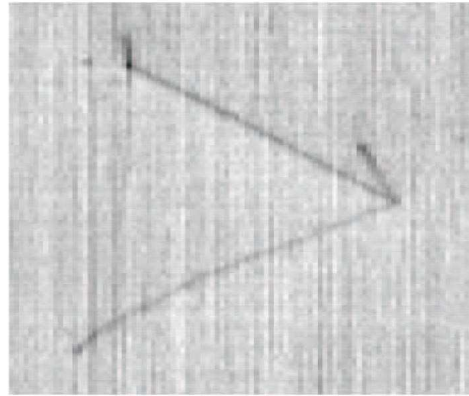
- Detector is continuously “live” and can be “self-triggered” using pipelined, zero-suppression electronics.
- Operates at the Earth’s surface with near zero overlap of cosmic ray events.
- Detector is compatible with operation in a magnetic field.

Events from the ICARUS T300 Cosmic Ray Test

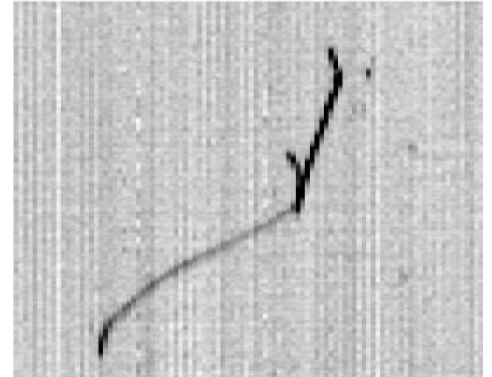
Induction I



Induction II

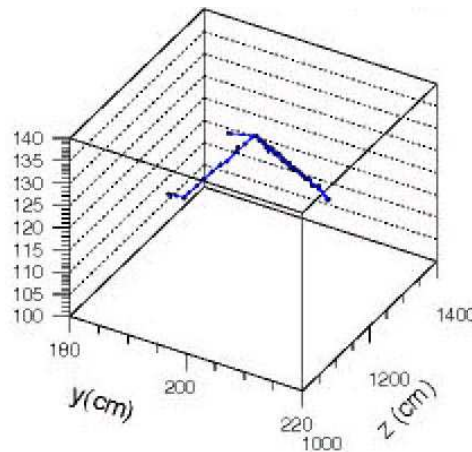


Collection

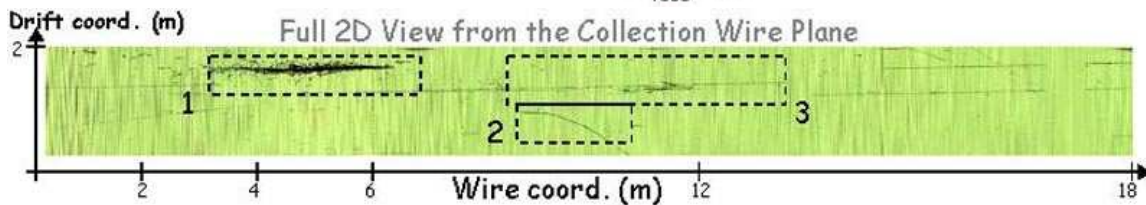


Above: 3 views of a low-energy hadronic interaction.

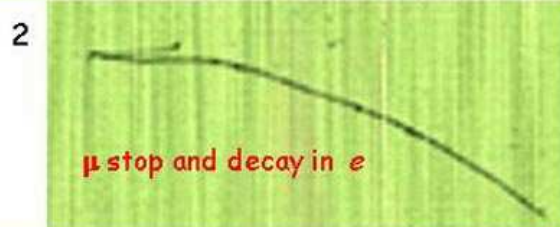
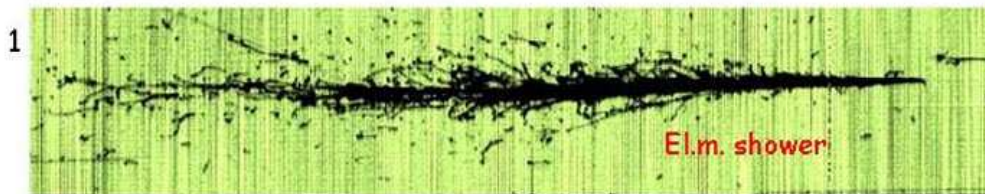
Right: Computer reconstruction.



Below: Cosmic ray shower that includes a muon with a δ -ray, a stopping muon, and an electromagnetic shower.

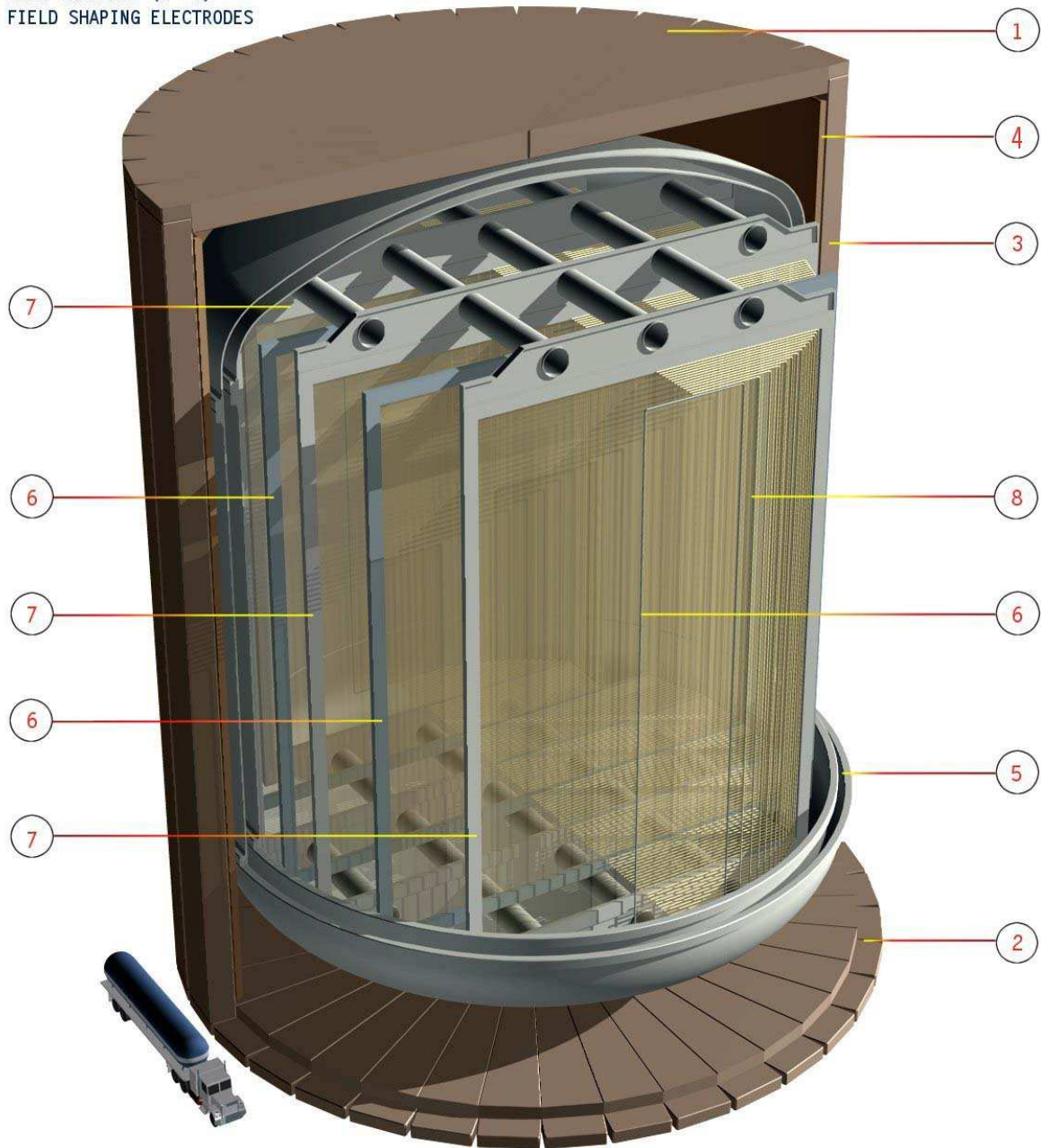


Zoom details



LANNDD – 100 kton Liquid Argon Neutrino and Nucleon Decay Detector

- 1- TOP END CAP IRON YOKE
- 2- BOTTOM END CAP IRON YOKE
- 3- BARREL IRON RETURN YOKE
- 4- COIL
- 5- CRYOSTAT
- 6- CATHODES (N° 5)
- 7- WIRE CHAMBERS (N° 4)
- 8- FIELD SHAPING ELECTRODES

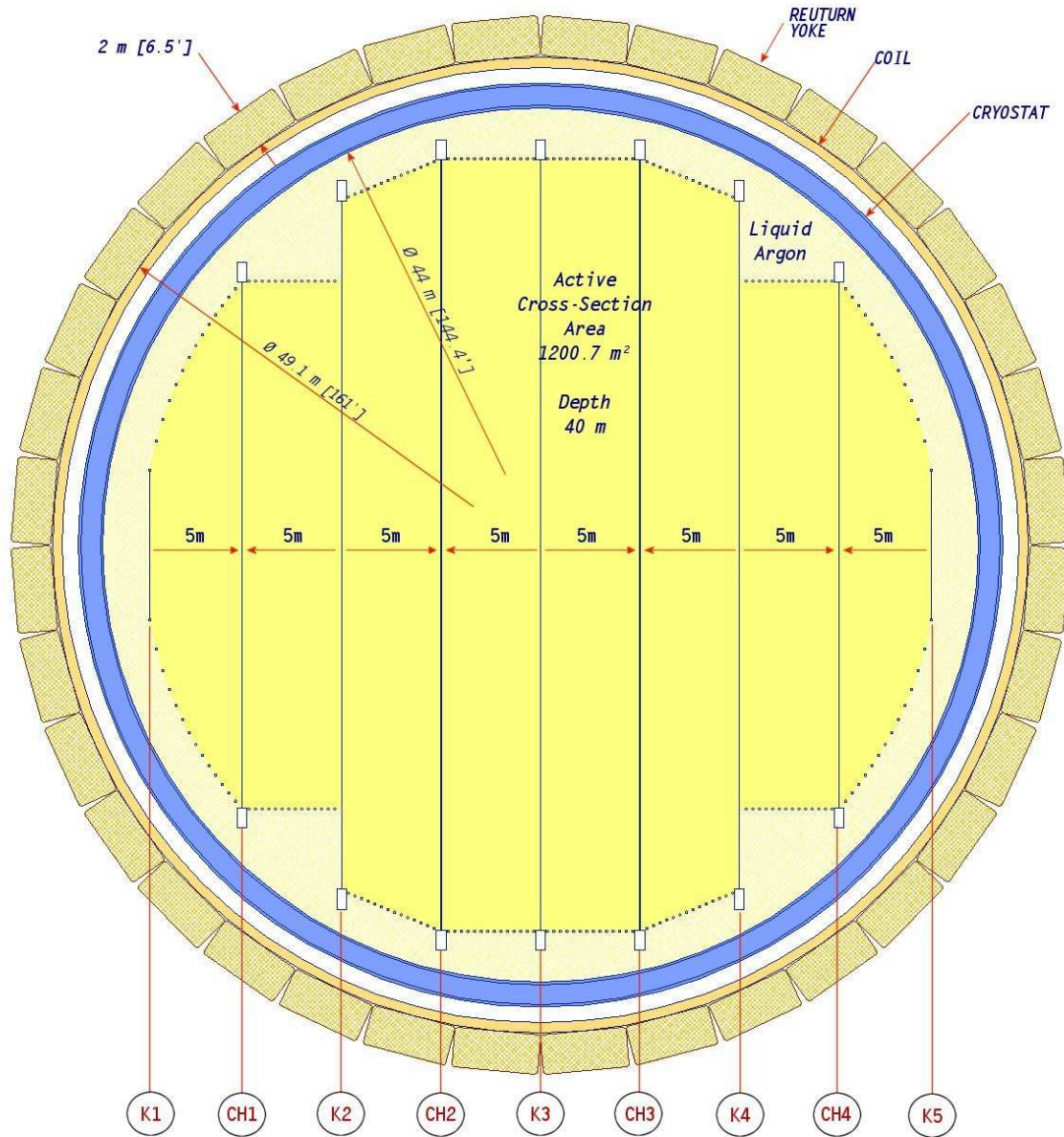


LANNDD
Liquid Argon Neutrino and Nucleon Decay Detector

F. Sergiampietri-August 2000

LANNDD Top View

N°OF WIRE CHAMBERS	4	ACTIVE VOLUME	48'000 m ³
WIRE CHAMBER CH1, CH4	W=26.46m H=40m	ACTIVE MASS	67 kT
CH2, CH3	W=38.73m H=40m	N°OF CATHODE PLANES	5
READOUT PLANES/CHAMBER	4 [2 at +45°, 2 at -45°]	MAXIMUM DRIFT	5 m
SCREEN-GRID PLANES/CHAMBER	3	MAXIMUM HIGH VOLTAGE	250 kV
N°OF WIRES-CHANNELS/PLANE	CH1, CH4 8x15'664=125'312	REQUIRED PURITY LIFETIME	15+20 ms
	CH2, CH3 8x18'557=148'455		
TOTAL N°OF WIRES-CHANNELS	273'767		



LANNDD
Liquid Argon Neutrino and Nucleon Decay Detector
Horizontal Cross-Section

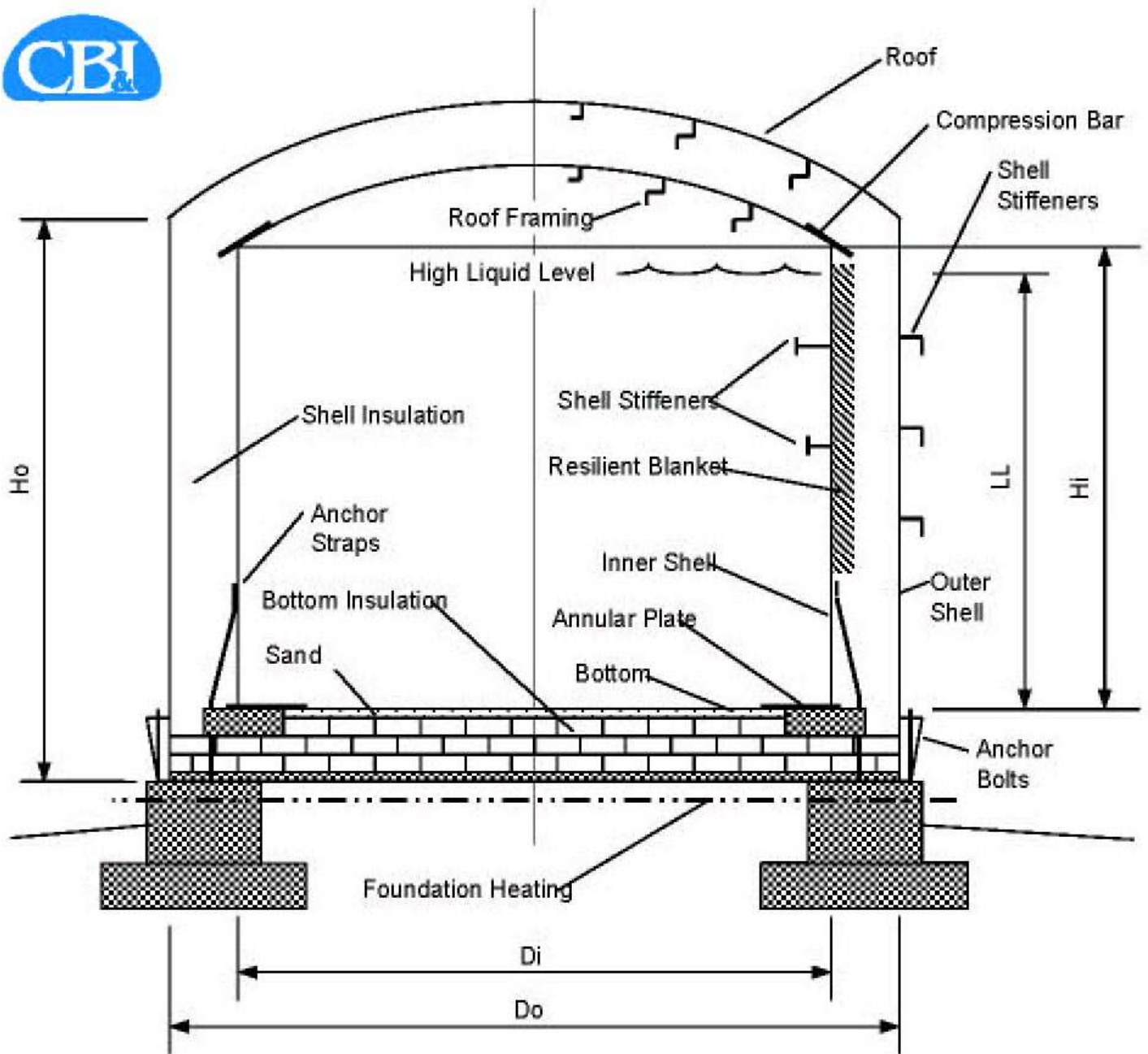
F. Sergiampietri-August 2000

Max drift length of 5 m (limited by O₂ purity),
 ⇒ Several drift cells.

Is a 100-kton Liquid Argon Detector Feasible?

- Use mature, low-cost technology of liquid methane storage tanks (up to 300 kton based on existing structures).
Preliminary budget estimate from industry of $< \$20\text{M}$ for a 100-kton tank, IF built on the SURFACE.
- 100 kton of liquid argon = 10% of USA annual production.
 \Rightarrow Deliver one trailer-load every 2 hours from Chicago,....
Only 5 ppm O_2 grade available in large quantities,
 \Rightarrow On-site liquid-phase purification via Oxisorb (MG).
Raw material, delivery + purification \Rightarrow $\$0.8\text{M}/\text{kton}$.
- ICARUS electronics from CAEN @ $\$100/\text{channel}$.
3 mm wire spacing \Rightarrow 300k ch \Rightarrow $\$30\text{M}$.
9 mm wire spacing \Rightarrow 100k ch \Rightarrow $\$10\text{M}$.
High capacity of long wires \Rightarrow signal may be too weak to use 3 mm spacing.
- With neutrino beam, record every pulse (10^{-3} duty factor).
Cosmic rays occupy $\approx 10^{-3}$ of active volume,
 \Rightarrow ≈ 10 MB data per trigger.
 \Rightarrow Modest ($< \$10\text{M}$) DAQ/computer system.

200-kton Cryogenic Tanks Used for LNG Storage



Double Wall & Double Roof Tank

	Feet
Di =	165
Hi =	117.9803
LL =	117.7303
Do =	173
Ho =	118.0443

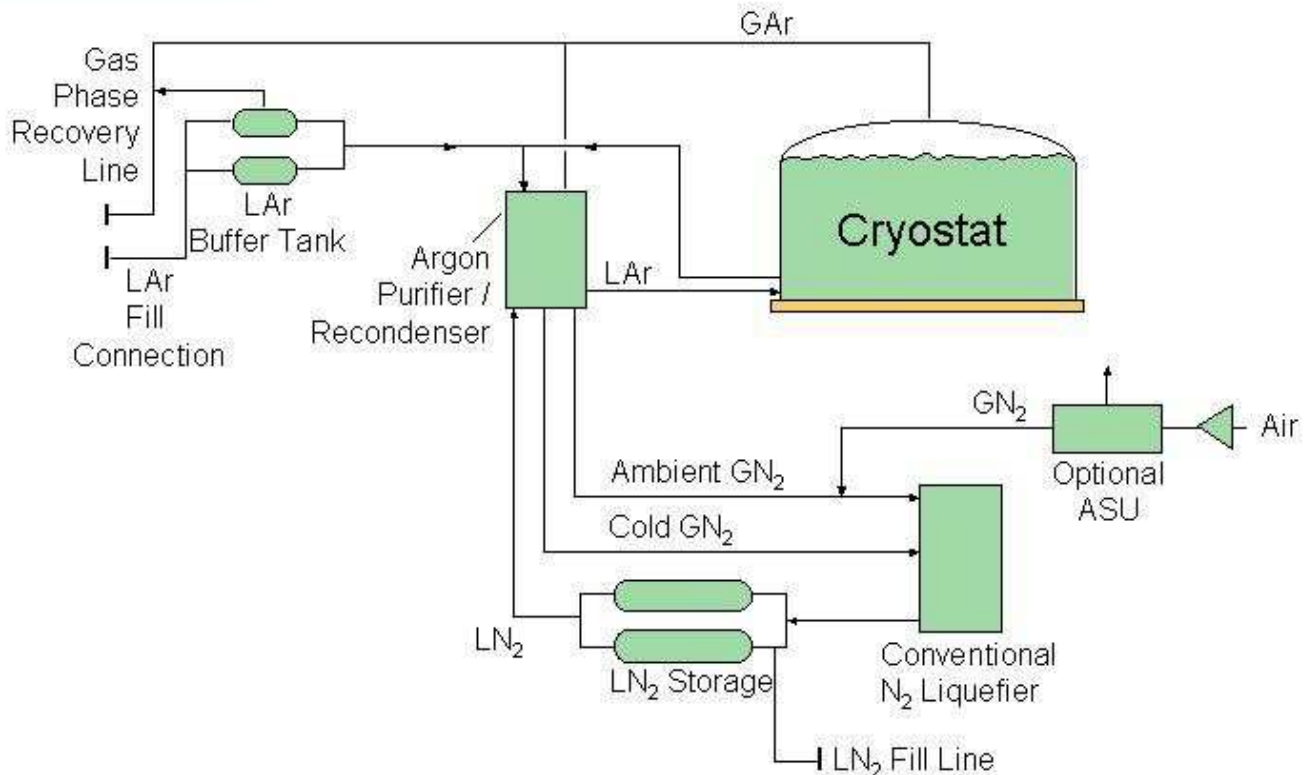
Chicago Bridge & Iron: can build 100-kton LAr tank for < \$20M.

Strong Interest by Praxair

Praxair is the leading USA vendor of liquid argon.

The Praxair R&D Lab in Tonawanda, NY is same Union Carbide lab that provided the expertise to build the Oak Ridge gaseous diffusion plant in the 1940's.

LANNDD Cryogenic System



PRAXAIR BUSINESS CONFIDENTIAL

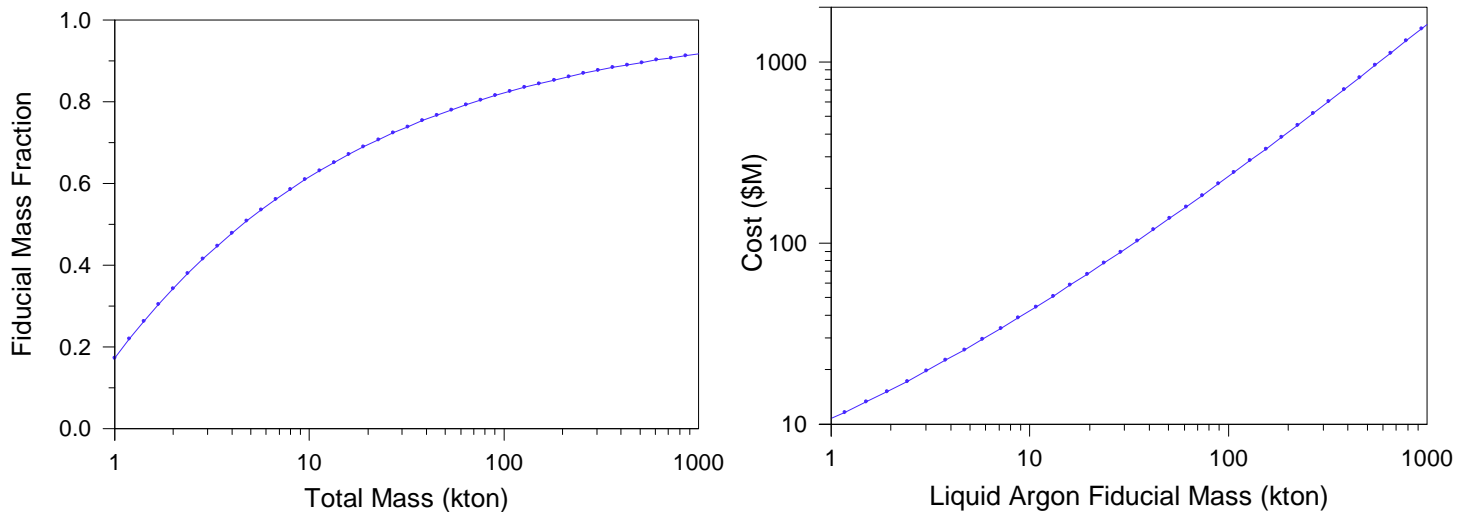
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Extrapolation to Very Large Modules

Preliminary cost estimate for a liquid argon detector of 100 kton **total** mass.

Component	Scaling	Cost
Liquid argon (industrial grade)	M	\$70M
Cryo plant, including Oxisorb purifiers	M	\$10M
Surface site preparation	$M^{2/3}$	\$10M
Cryogenic storage tank	$M^{2/3}$	\$20M
Electronics (300k channels)	$M^{2/3}$	\$30M
Computer systems	$M^{2/3}$	\$10M
Subtotal		\$150M
Contingency		\$50M
Total		\$200M

Fiducial mass is for ν_e appearance events \Rightarrow contain EM showers.



Cost scaling = $1.33 [\$80M (M/100 \text{ kton}) + \$70M (M/100 \text{ kton})^{2/3}]$.

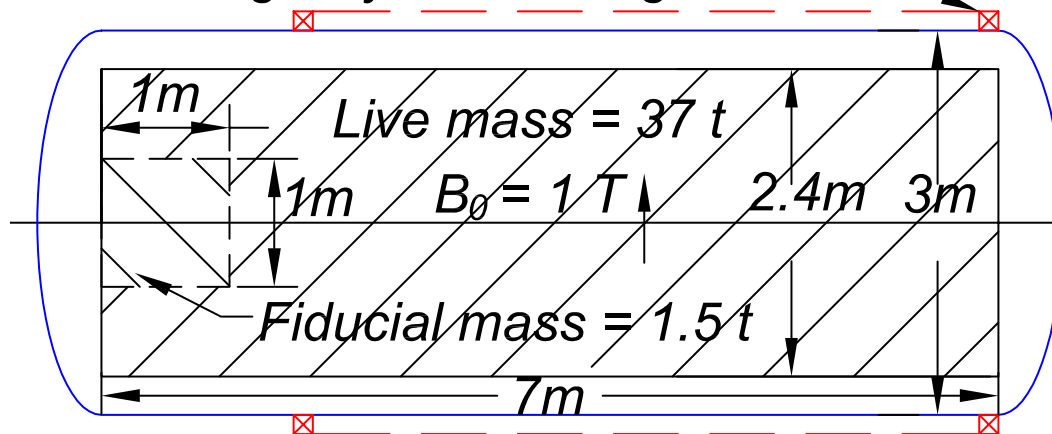
Next Steps

- 40-ton near detector (1.5-ton fid. mass) in off-axis NUMI beam.



- Add Chicago Cyclotron Magnet coils to give $B \approx 1$ T over downstream (or upstream) 2/3 of detector.

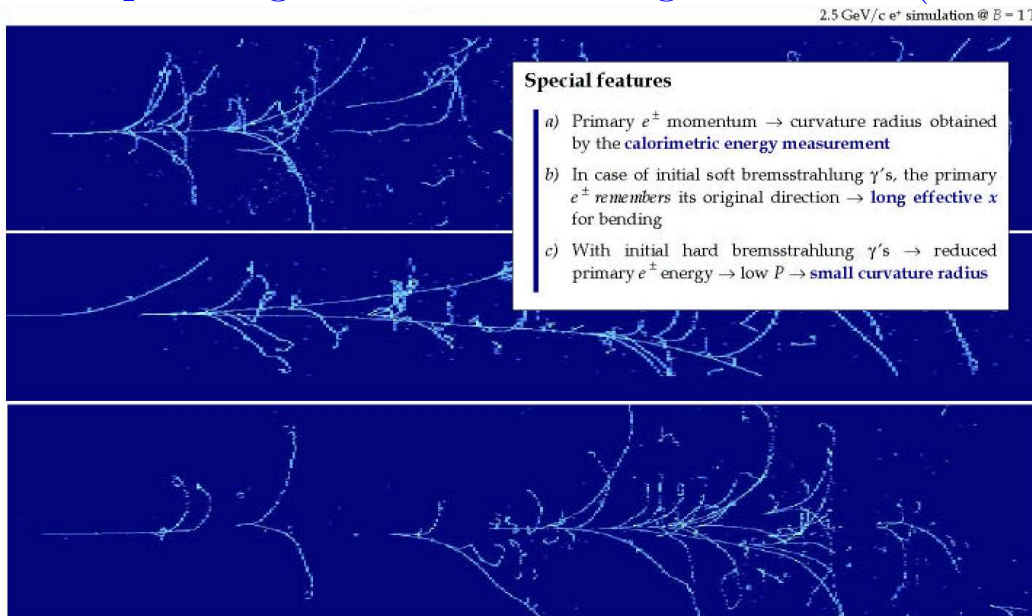
Chicago Cyclotron Magnet coil



$\Rightarrow 10^5$ CC ν_μ interactions/year.

R&D (see NuMI-PUB-GEN-0880)

- Liquid-phase purification of industrial grade argon via Oxisorb or equivalent (Praxair).
- Verification of 5-m drift with good signal collection.
- Mechanics and electronics of wires up to 60-m long.
- Cryogenic feedthroughs, possibly including buffer volume at 150K for low-noise FET's.
- Verification of operation of a liquid argon TPC at 10 atmospheres (as at bottom of a 100-kton tank).
- Study of liquid argon TPC in a magnetic field (BNL P-965).



A. Bueno, M. Campanelli, A. Rubbia, IX International Workshop on "Neutrino Telescopes", VENICE, 2001

Should identify sign of e^\pm up to ≈ 3 GeV in a 0.5-T field.