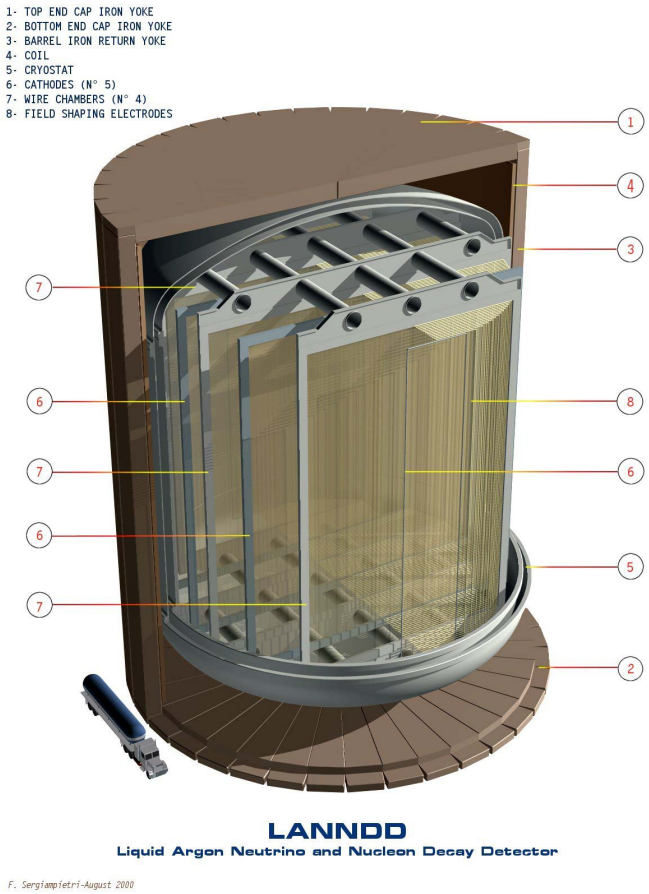
# On the Feasibility of a Very Large Liquid Argon Detector for Neutrino Oscillation Physics





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## The Opportunity for 3-Generation Neutrino Physics

Super-K $\Rightarrow$ oscillation of atmospheric neutrinos.

Super-K and SNO favor LMA solar neutrino solution, and disfavor sterile neutrinos.

$\Rightarrow$ Physics beyond the standard model, such as SO(10) SUSY.

Three massive neutrinos $\Rightarrow$ six independent parameters:

- Two differences of the squares of the neutrino masses:
  $1.6 < \Delta m^2_{23} = \Delta m^2(\text{atmos}) < 3.6 \times 10^{-3}$ eV$^2$ @ 90% c.l.
  $2 \times 10^{-5} < \Delta m^2_{12} = \Delta m^2(\text{solar}) < 1.5 \times 10^{-4}$ eV$^2$ @ 90% c.l.
- Three mixing angles: $\theta_{12} \approx 30^\circ$, $\theta_{13} < 10^\circ$, $\theta_{23} \approx 45^\circ$.
- A phase $\delta$ related to CP violation (unknown).

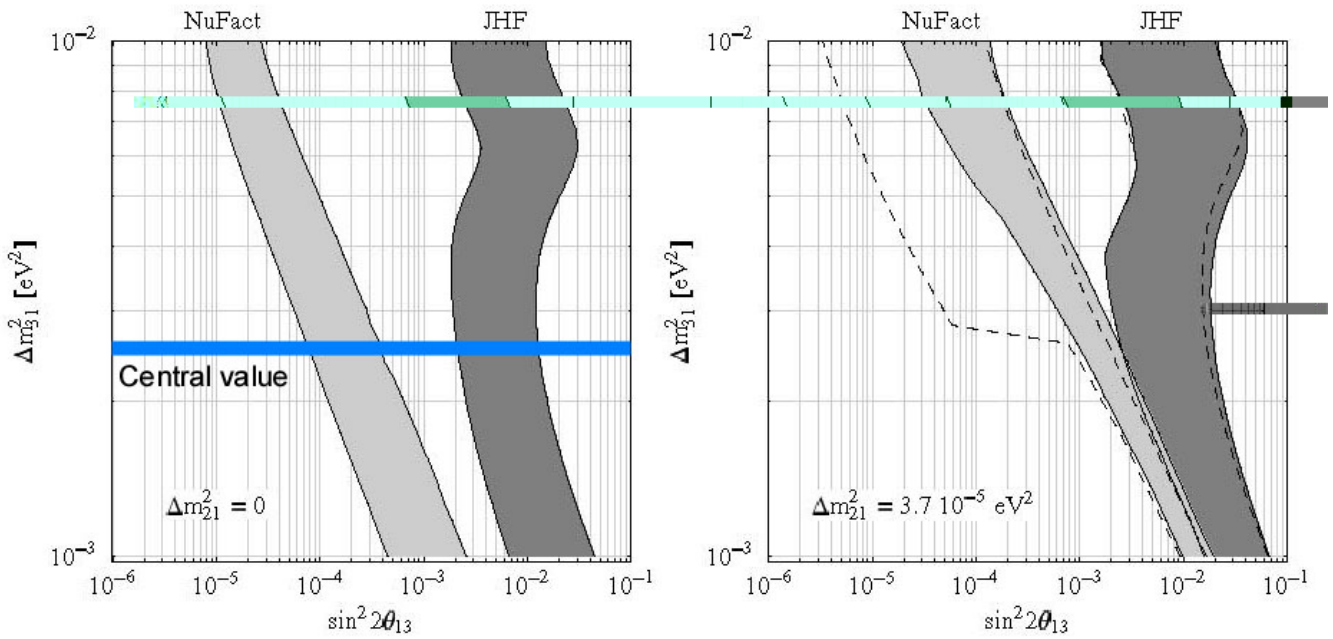
Measurement goals of new experiments:

1. $\sin^2 2\theta_{13}$.
2. Sign of $\Delta m^2_{23}$. (Sign of $\Delta m^2_{12}$ known if LMA solution correct.)
3. $\delta_{\text{CP}}$.

With conventional neutrino beams ($\pi \to \mu\nu_\mu$), all 3 measurements can be pursued via $\nu_\mu \to \nu_e$ appearance.

Best resolution if observe near first (or second) 2-3 oscillation:

$$\Rightarrow L[\text{km}] = \frac{E_\nu[\text{GeV}]}{1.27\Delta m^2_{23}[\text{eV}^2]} \approx 500 E_\nu[\text{GeV}].$$

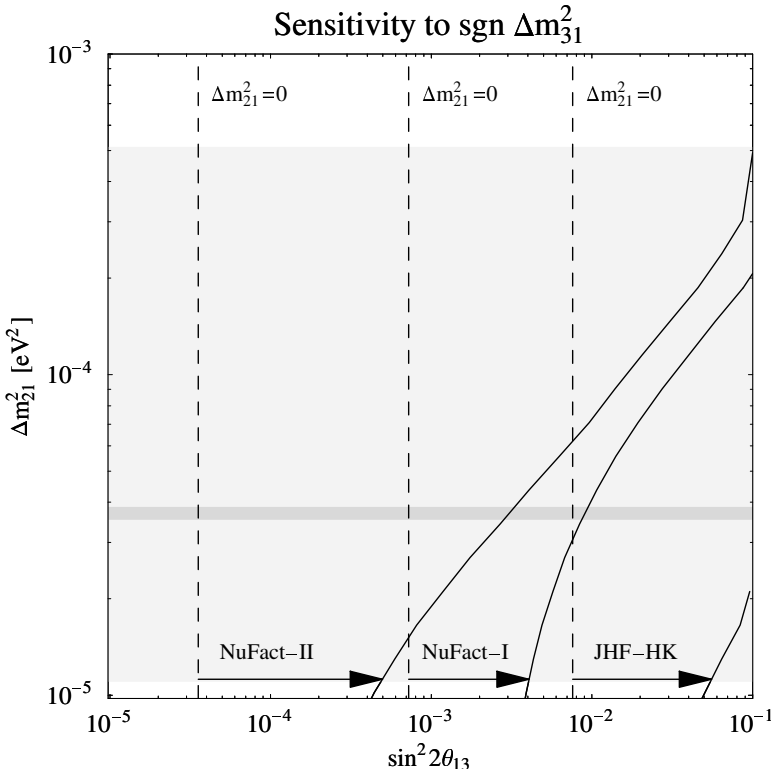


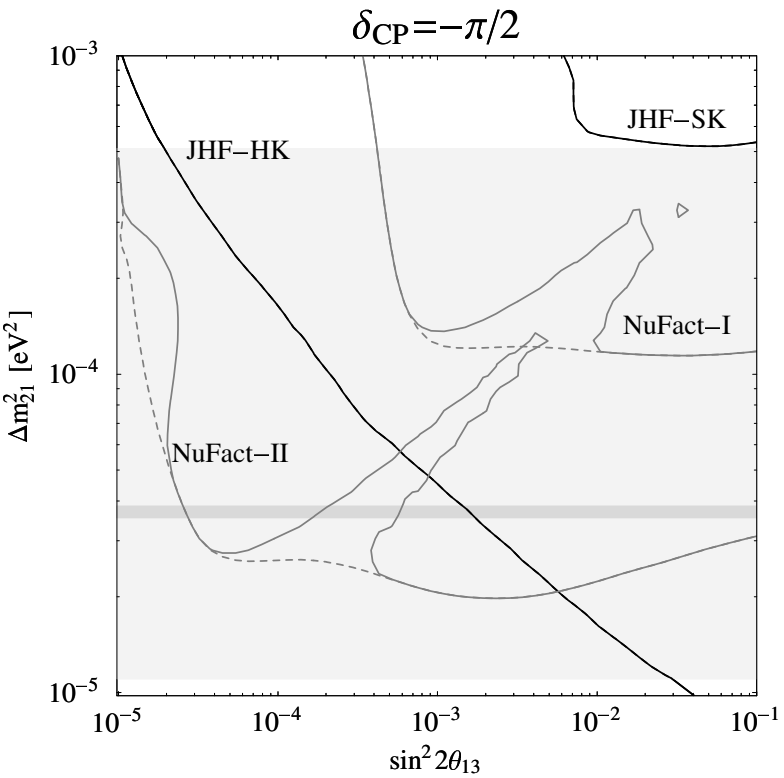

Lindner *et al.*, hep-ph/0204352

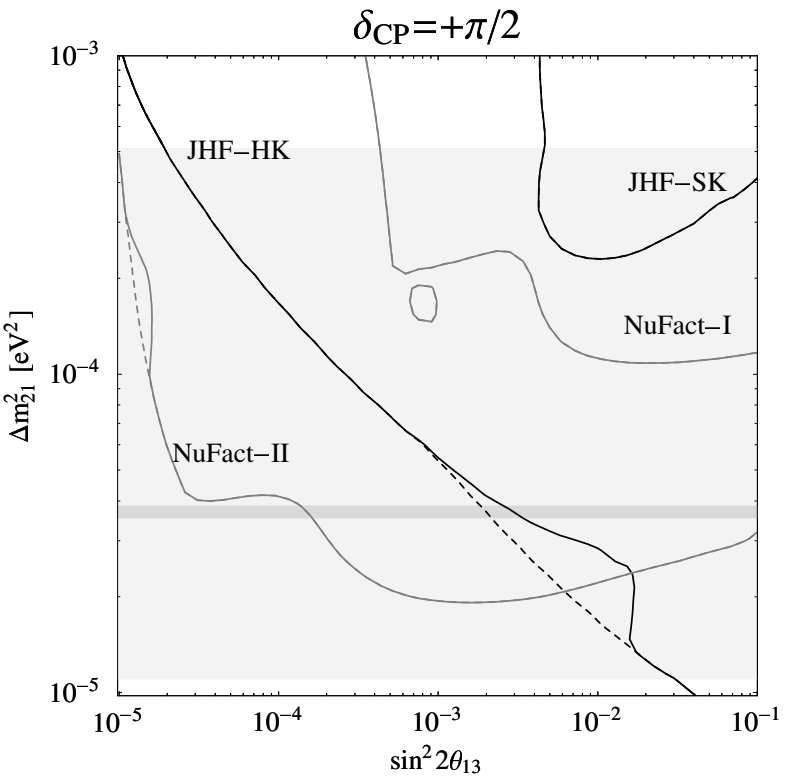
$\Rightarrow$ Can't optimize choice of $L$ and $E_\nu$ until $\Delta m^2_{23}$ known to $\pm 20\%$. (One year of MINOS in nominal NUMI beam.)

Can't justify "prime time" effort until know that $\sin^2 2\theta_{13}$ is large enough that $\delta_{\text{CP}}$ is accessible.

Quality of measurement of $\delta_{\rm CP}$ and sign of $\Delta m^2_{23}$ also affected by value of $\Delta m^2_{12}$.



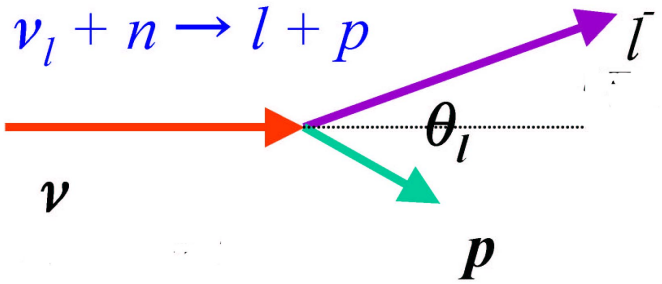



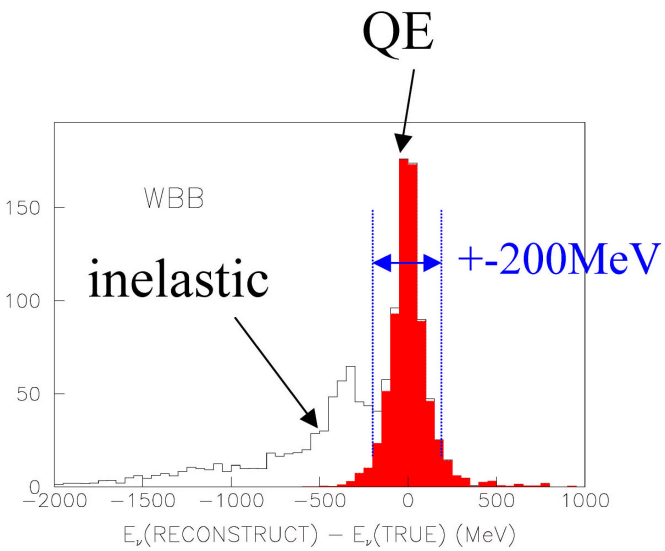



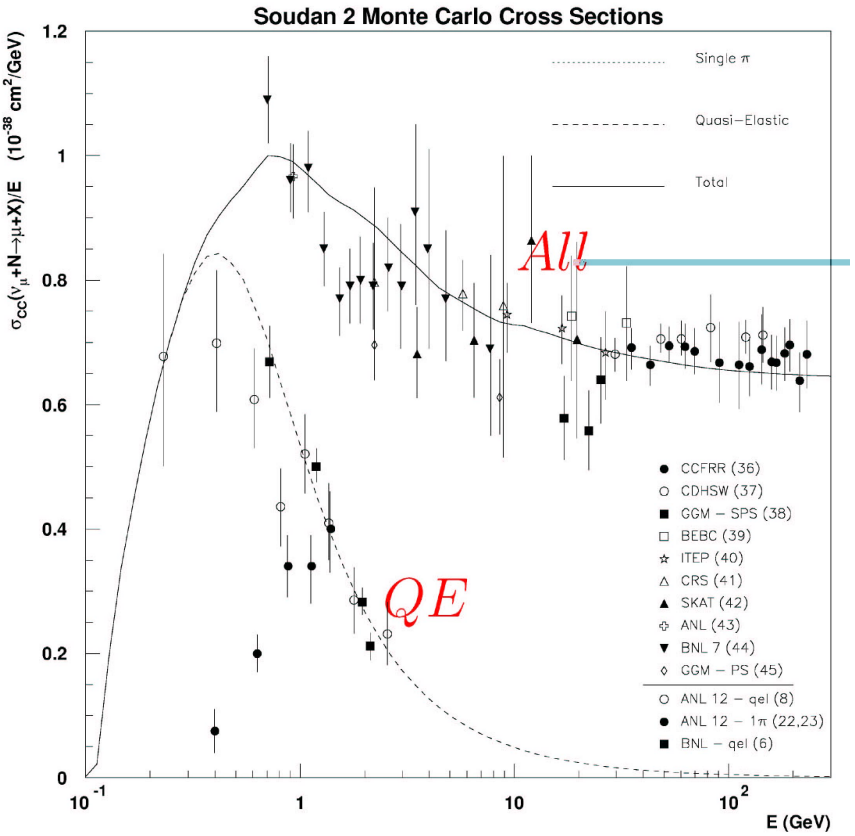
# Use $\approx 1$ GeV Neutrinos

Production rate is high.

Interactions are simple $\leftrightarrow$ quasielastic (no pions).

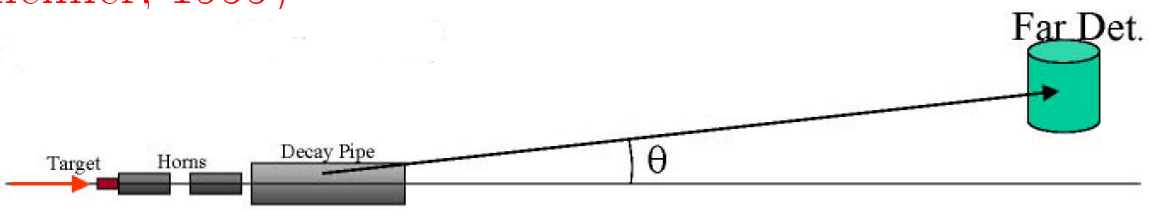


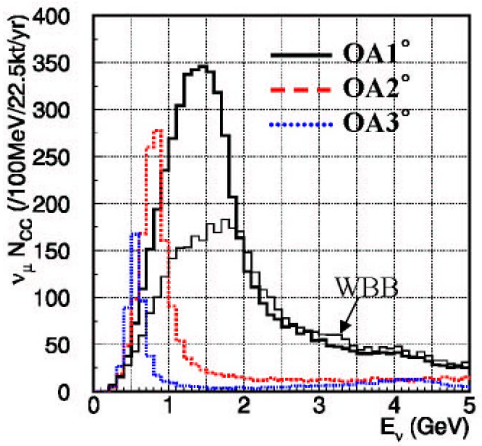



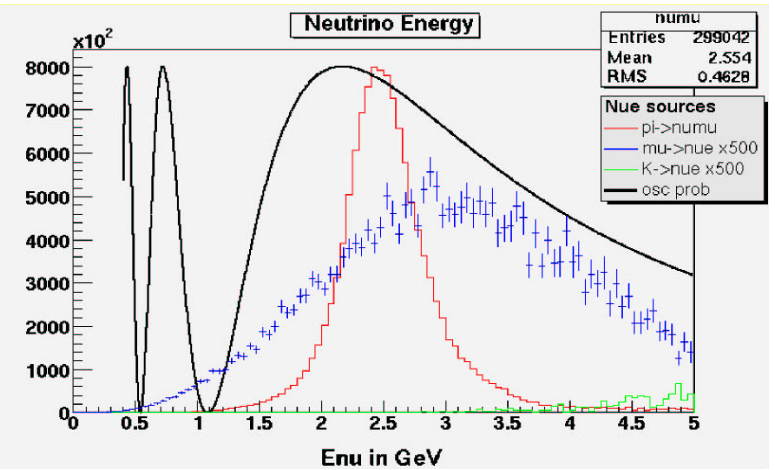



# Use an Off-Axis Neutrino Beam (BNL E-889)

$\pi \to \mu\nu$ decay kinematics has a Jacobian peak: $\theta \approx 2^\circ$ / GeV. (Sternheimer, 1955)

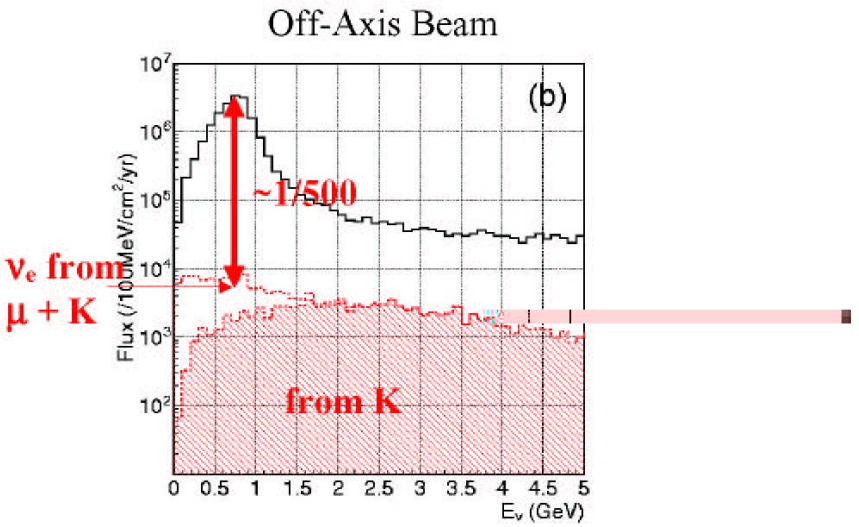



J2K (Kobayashi) NUMI (Wojcicki)

## $\nu_e$ contamination in the beam




Intrinsic background: $\nu_e$ /$\nu_\mu$ (peak) ~ 0.002 (0.005 for $\sin^2 2\theta_{13}$)

## Can Study CP Violation at $L/E = (2n+1)500$ km/GeV

[Marciano, hep-ph/0108181]

The $n$th maximum of $\nu_2$-$\nu_3$ oscillations occurs at $L/E \approx (2n+1)500$ km/GeV.

The CP asymmetry grows with distance:

$$A = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \approx \frac{2 s_{12} c_{12} c_{23} \sin\delta}{s_{23} s_{13}} \left(\frac{\Delta m^2_{12}}{\Delta m^2_{23}}\right) \frac{\Delta m^2_{23} L}{4 E_\nu}$$

$$\Rightarrow \frac{\delta A}{A} \approx \frac{1}{A\sqrt{N}} \propto \frac{E_\nu}{L\sqrt{N}} \approx \text{ independent of } L \text{ at fixed } E_\nu.$$

$N_{\text{events}} \propto 1/L^2$, $\Rightarrow$ Hard to make other measurements at large $L$.

Low $E_\nu$ favorable for CP violation measurements.

But since need to disentangle matter effects from CP asymmetries, this suggests use of 2 detectors at oscillation maxima $n = 0$ and $n = 1$ or 2, $\Rightarrow R = L'/L = 3$ or 5.

Small $s_{13} = \sin\theta_{13} \Rightarrow$ large CP asymmetry, but low rates.

$\Rightarrow$ May be difficult to untangle $\sin\delta$ and $s_{13}$.

## Strategy Overview

- Phase I: New search for $\sin^2 2\theta_{13}$ with sensitivity better than MINOS/NUMI, Super-K/J2K, ICARUS/CNGS.
- Phase II: If $\sin^2 2\theta_{13}$ large enough, upgrade (or new) beam and detector to study CP violation and measure sign of $\Delta m^2_{23}$.
- Combine neutrino oscillation physics with nucleon decay measurement.
- Phase I: Use a 1° off-axis NUMI beam at $\approx$ 2 GeV with a 20-30 kton liquid argon detector sited under a bluff at Silver Creek, MN, 640 km from FNAL, 1640 km from BNL.
  $\Rightarrow \sin^2 2\theta_{13}$ to 0.003, $\tau/B(p \to K^+\bar{\nu})$ to $10^{34}$ year.
- Phase II, Option A:
  1. Build 100-200 kton liquid argon detector near Adams, WI, 260 km from FNAL, 1410 km from BNL.
  2. Upgrade FNAL beam with a 4-MW, 8-GeV proton driver.
  3. New $\nu$ beam at BNL with a 1-4 MW proton driver.

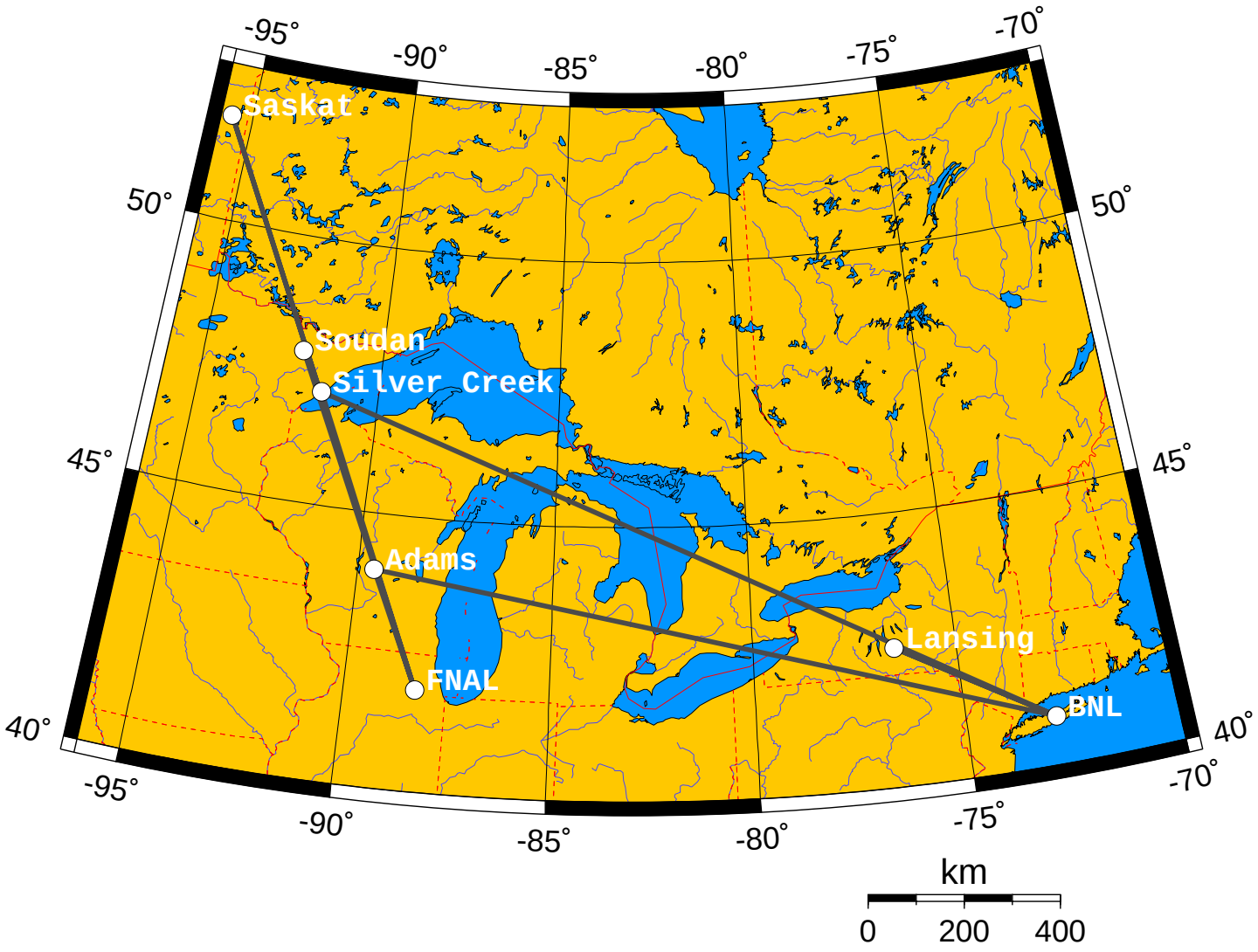
  $\Rightarrow \sin^2 2\theta_{13}$ to 0.0003, $\tau/B(p \to K^+\bar{\nu})$ to $10^{35}$ year, search for CP violation and measurement of sign of $\Delta m^2_{23}$.

## Overview, cont'd

- Phase II, Option B:
  1. Build 100-200 kton liquid argon detector near Adams, WI, 260 km from FNAL, 1410 km from BNL.
  2. Upgrade FNAL beam with a 4-MW, 8-GeV proton driver.
  3. Build new detector in Saskatchewan, 1200 km from FNAL.
- Phase II, Option C:
  1. Build 100-200 kton liquid argon detector near Lansing, NY, 350 km from BNL.
  2. New $\nu$ beam at BNL with a 4 MW proton driver.
- Phase II, Option C cheaper than Option A, but must study CP violation with Lansing detector during separate runs from measurement of sign of $\Delta m^2_{23}$ with Silver Creek detector.
- Phase II, Option B may be cheapest of all, but baseline to far detector only $\approx$ 1200 km.

# Off-Axis Neutrino Beams from BNL and FNAL

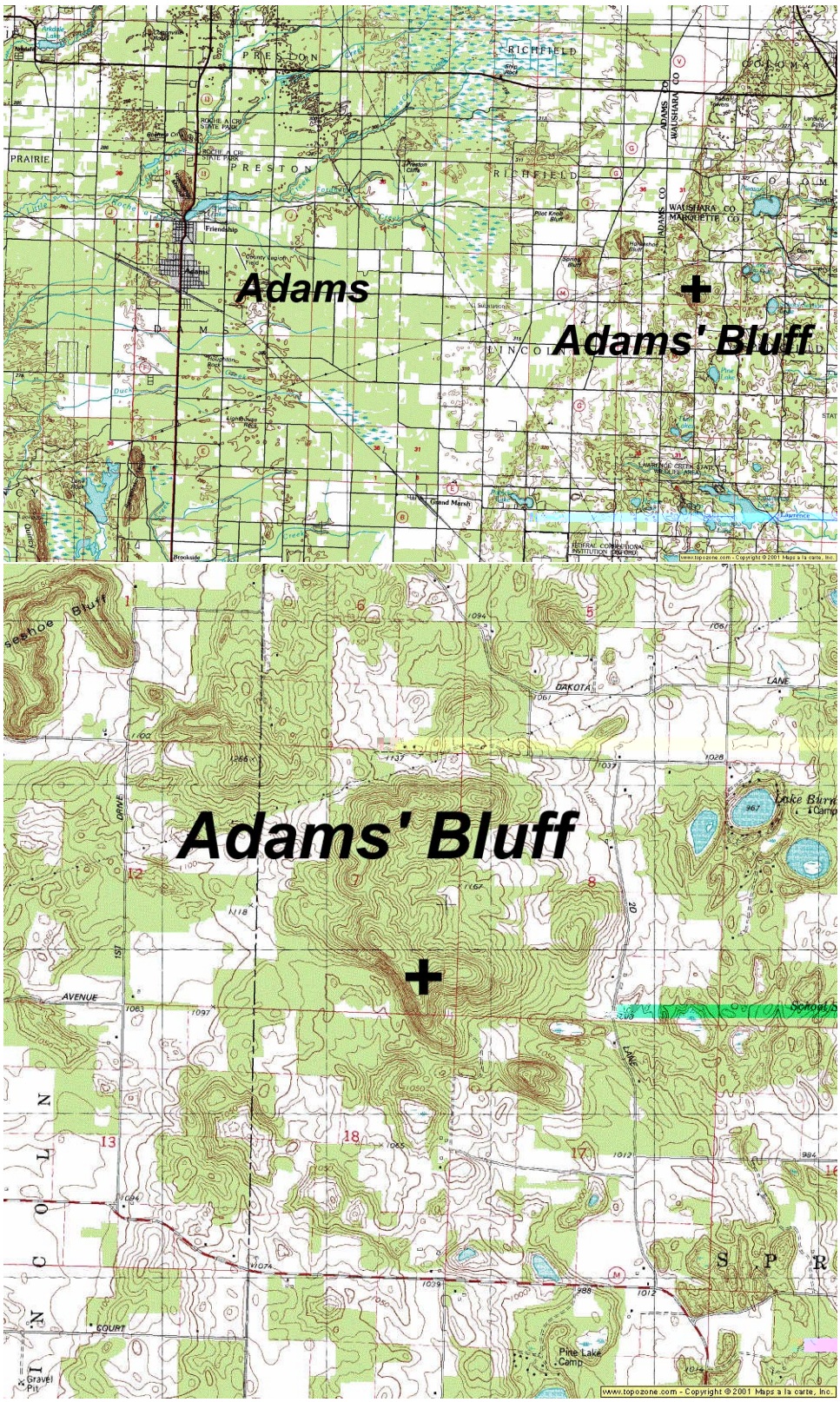
| Site | Dist. (km) to BNL | Dist. (km) to FNAL | Lat. | Long. | $\angle_{\text{FNAL}}$ to Soudan |
|---|---|---|---|---|---|
| Soudan | 1710 | 735 | 47.82° | -92.24° | – |
| Silver Creek | 1640 | 640 | 47.11° | -91.59° | 0.9° |
| Adams' Bluff | 1410 | 260 | 43.95° | -89.59° | 2.2° |
| Saskatchewan | 2110 | 1260 | 52.0° | -95.65° | 2.4° |
| Lansing | 350 | 970 | 42.51° | -76.52° | – |



## Silver Creek, MN, lat. 47.11°, long. −91.58°

500′ overburden with horizontal tunnel.

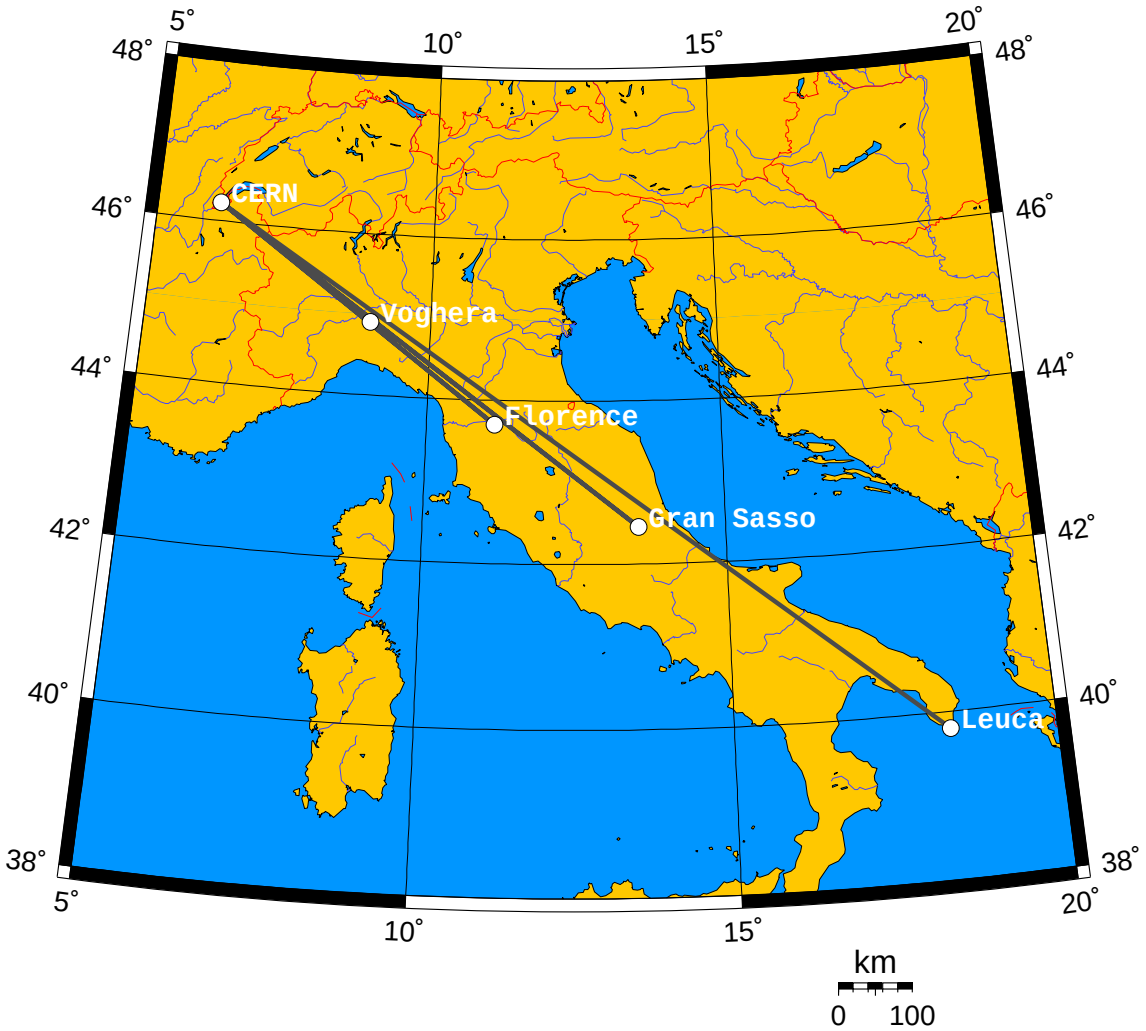
## Adam's Bluff, WI, lat. 43.95°, long. −89.59°




300′ overburden with horizontal tunnel.

# Off-Axis Neutrino Beams from CERN

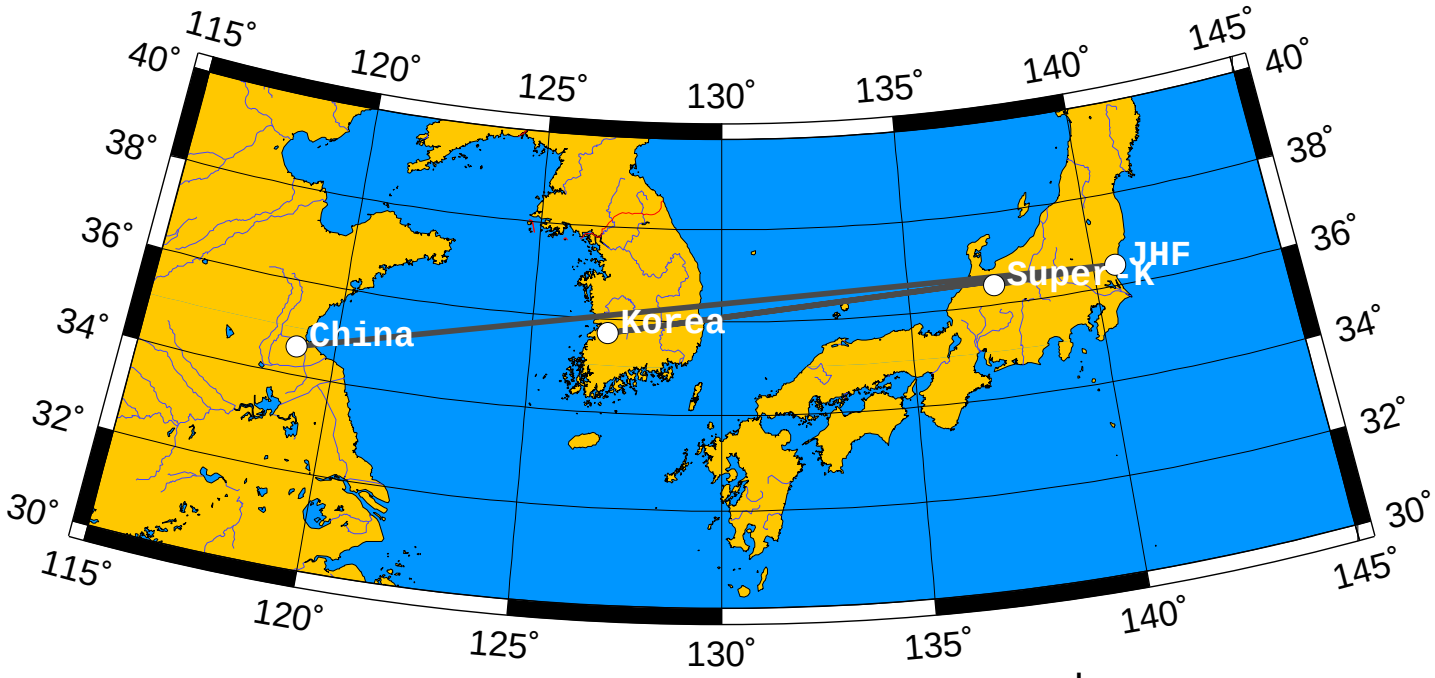
| Site | Distance to CERN (km) | Lat. | Long. | $\angle_{\text{CERN}}$ to Leuca |
|---|---|---|---|---|
| Voghera | 270 | 44.9° | 8.95° | 4.4° |
| Florence | 490 | 43.7° | 11.15° | 3.9° |
| Gran Sasso | 730 | 42.45° | 13.57° | 2.5° |
| Leuca | 1225 | 39.8° | 18.35° | – |




Could also use converted LNG tanker in the Gulf of Taranto.

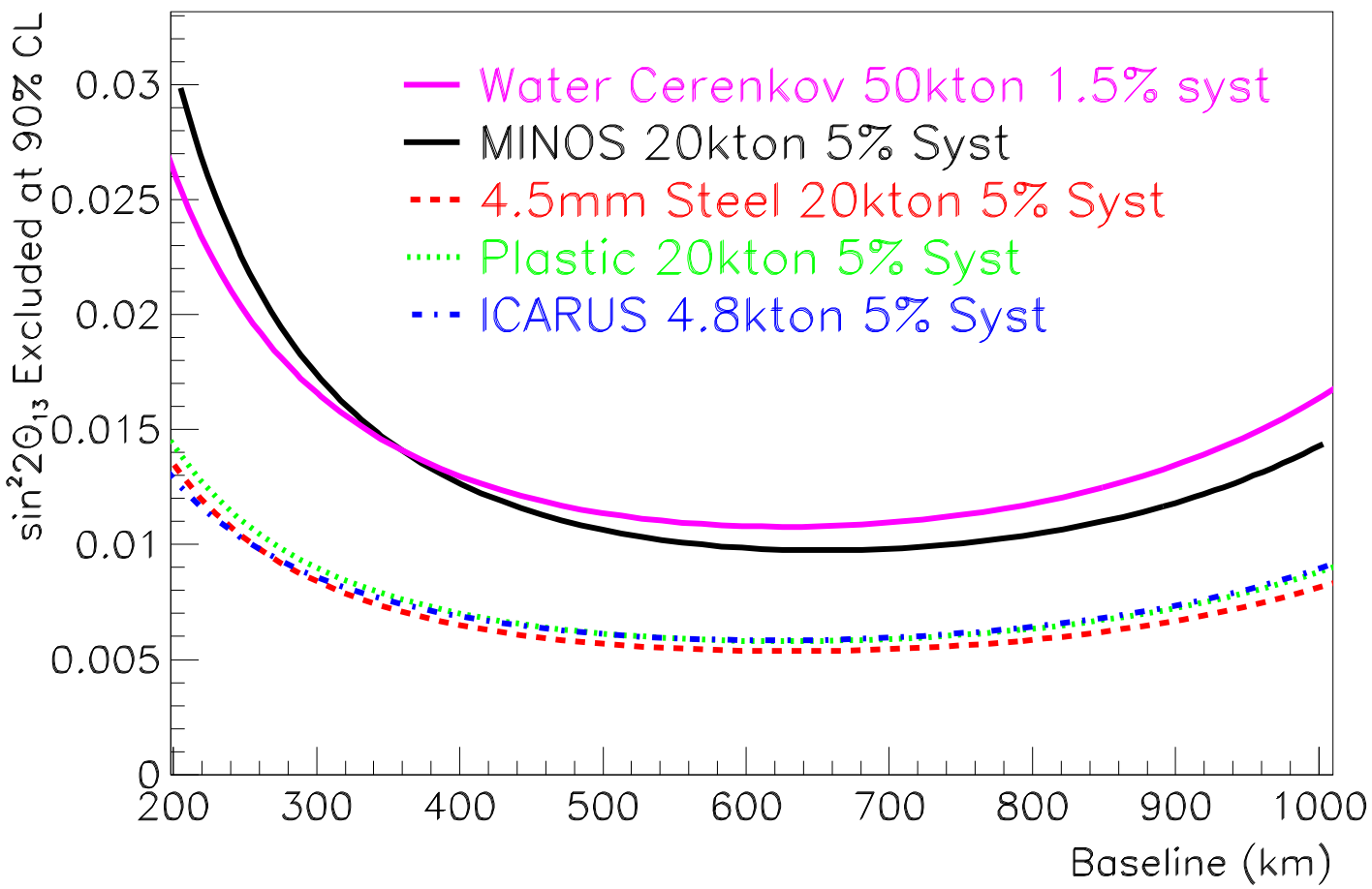
# Off-Axis Neutrino Beams from JHF

| Site | Distance to JHF (km) | Lat. | Long. | $\angle_{\mathrm{JHF}}$ to Super-K |
|---|---|---|---|---|
| Super-K | 295 | 36.42° | 137.31° | – |
| Korea | 1220 | 35.7° | 127.0° | 4.2° |
| China | 1955 | 34.6° | 119.0° | 7.5° |

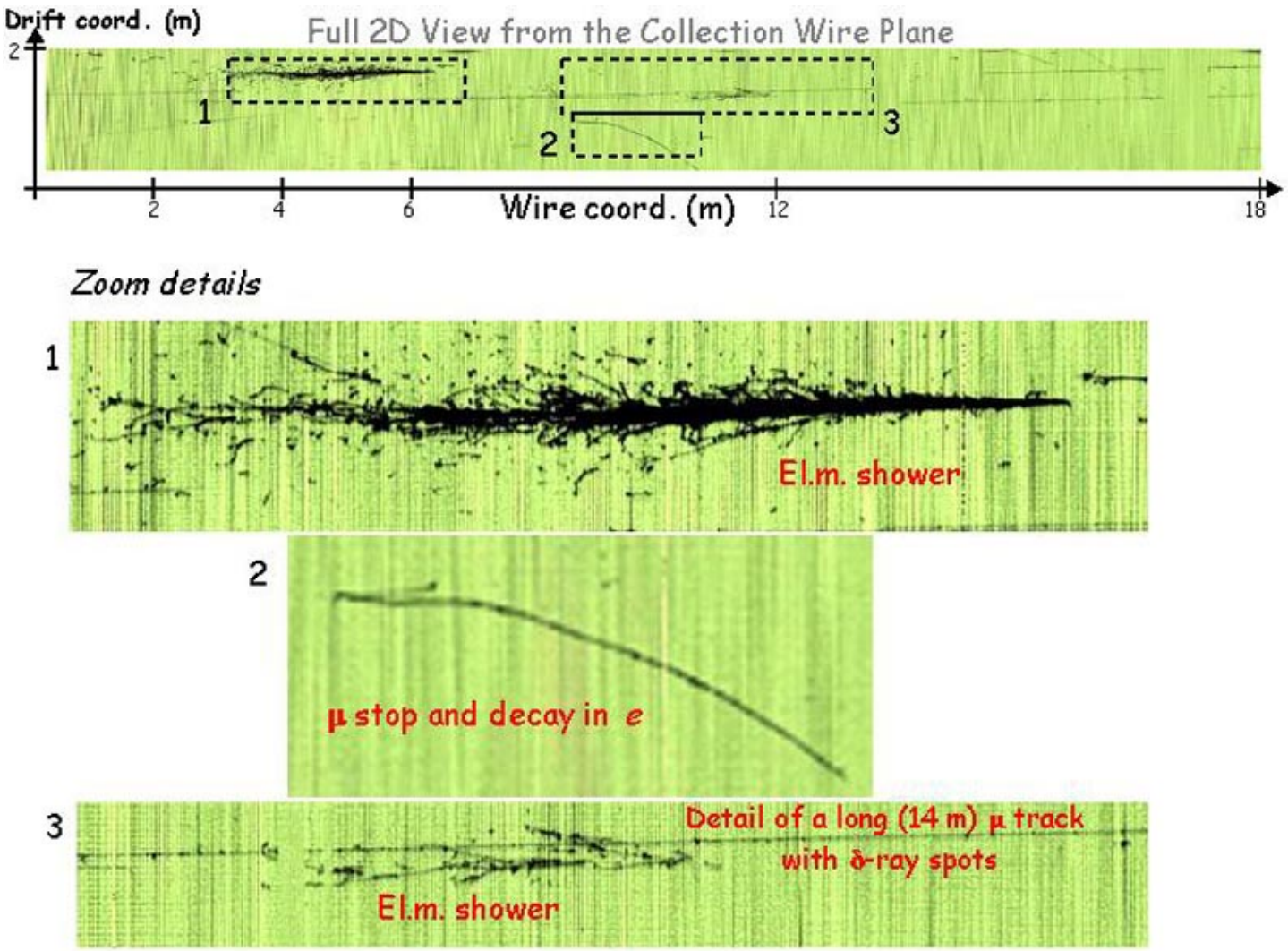


## Liquid Argon is the Best Detector Choice

- Density = 1.4; $X_0 = 14$ cm; can drift electrons 2-4 m.
- 100% sampling tracking and calorimetry.
- Construction is simplest of large neutrino detector options.
- Best rejection of neutral current backgrounds, including soft $\pi^0$'s.
- 10 times better per kton than water Čerenkov for $\nu_\mu \rightarrow \nu_e$ appearance (Harris).

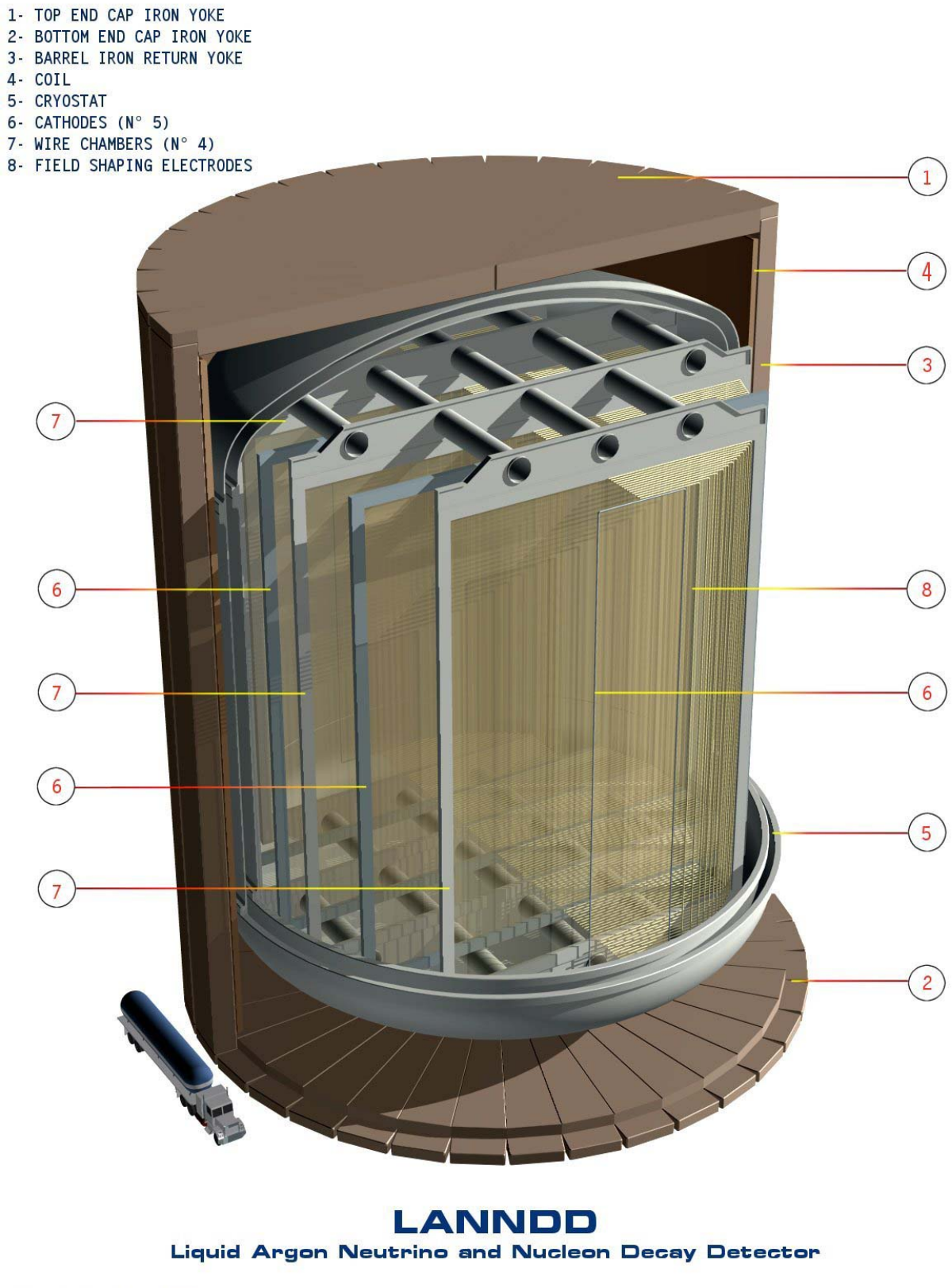


# ICARUS – a Working Liquid Argon Detector




- Operates at the Earth's surface with near zero overlap of cosmic ray events.
- Operates with deadtimeless, selftriggering electronics.
- Liquid argon costs $\approx$ \$0.7M/kton.
- Minimize cost of a large detector by building a single module.

# LANNDD – Liquid Argon Neutrino and Nucleon Decay Detector



## Is a 100-kton Liquid Argon Detector Feasible?

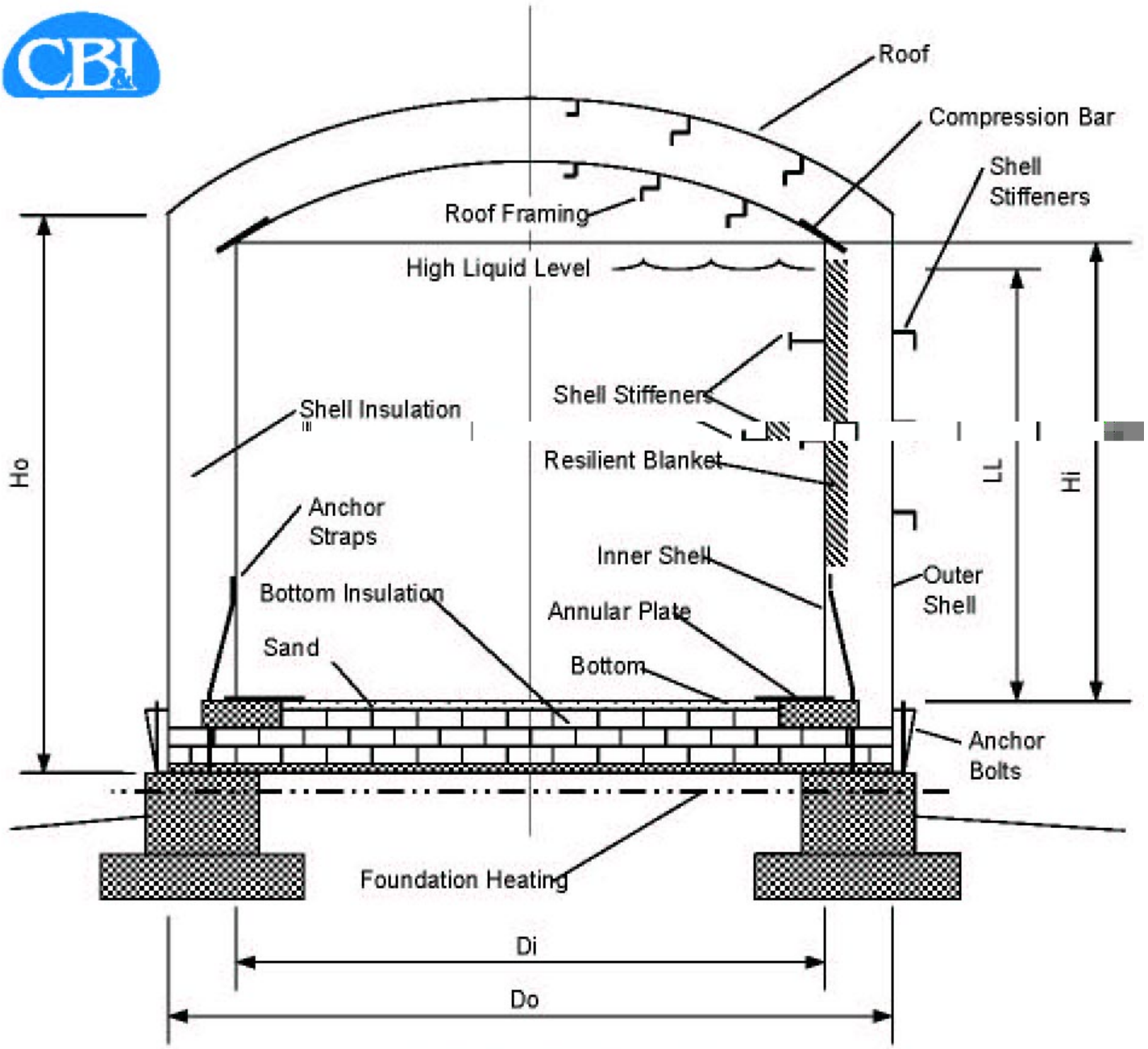
- Use mature, low-cost technology of liquid methane storage tanks (up to 300 kton based on existing structures).
  Preliminary budget estimate from industry of $<$ \$20M for a 100-kton tank, IF built on the SURFACE.

- 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 $\Rightarrow$ \$0.8M/kton.

- ICARUS electronics from CAEN @ \$100/channel.
  3 mm wire spacing $\Rightarrow$ 300k ch $\Rightarrow$ \$30M.
  9 mm wire spacing $\Rightarrow$ 100k ch $\Rightarrow$ \$10M.
  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,
  $\Rightarrow$ $\approx$ 10 MB data per trigger.
  $\Rightarrow$ Modest ($<$ \$10M) DAQ/computer system.

# 200-kton Cryogenic Tanks Used for LNG Storage

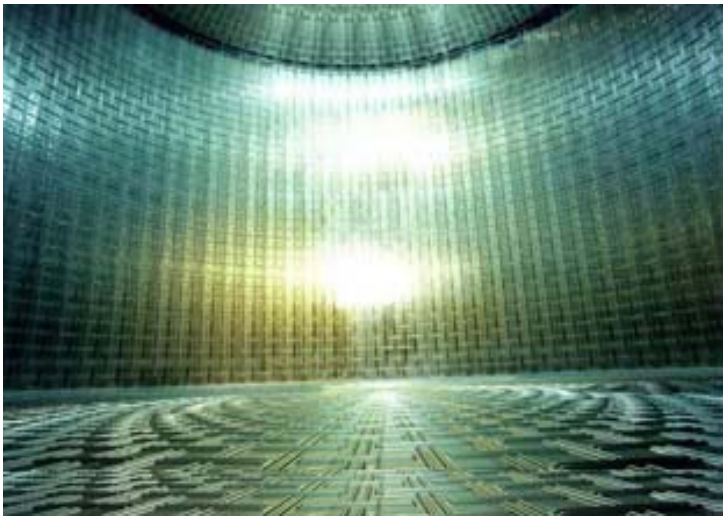


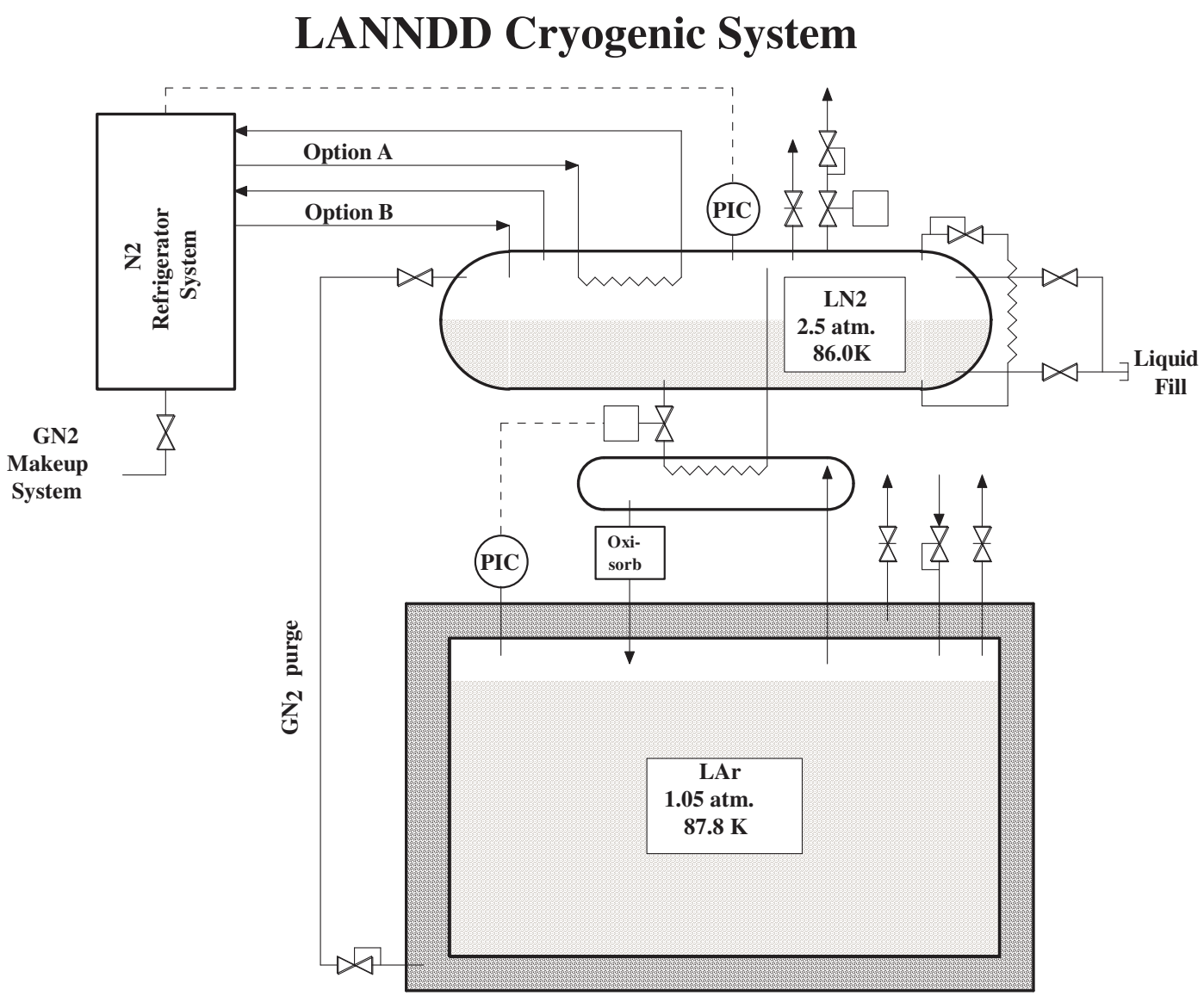

**Double Wall & Double Roof Tank**

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

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

# Cryogenic LNG Storage Tanks






– Applied Cryogenic Technology + Cosmodyne.

## Can a Proton Decay Search Be Done at the Surface?

- The signature of the decay $p \to K^+\overline{\nu}$ is particularly clean: $K^+ \to \pi^+ \to \mu^+ \to e^+$.
  $\Rightarrow$ Maybe "no background" to $10^{35}$ year even at surface.
- Need 100% duty factor for proton decay search.
  $\Rightarrow \approx$ 10 GB/sec data rate at surface.
- May need to go underground (100 m?) to suppress the data rate.
  $\Rightarrow$ Additional \$100M to site detector underground.
- Cheaper to buy a big DAQ system and operate at the surface – if backgrounds are OK there.

## Budget Estimate (Very Rough)

For a 100-kton detector at the surface:

1. Liquid argon (industrial grade) ..... $70M
2. Cryogenic storage tank ..... $20M
3. Surface site preparation ..... $10M
4. Cryo plant, including Oxisorb purifiers ..... $10M
5. Electronics (200k channels) ..... $20M
6. Computer systems ..... $10M
7. Subtotal ..... $140M
8. Contingency ..... $60M
9. Total ..... $200M

Cost Scaling: Argon $\propto$ mass; rest $\propto$ mass$^{2/3}$.

25-kton detector ..... $70M

5-kton detector ..... $20M

## R&D Topics

- Liquid-phase purification of industrial grade argon via Oxisorb.
- Mechanics and electronics of wires up to 60-m long.
- Cryogenic feedthroughs, possibly including buffer volume at 150K for low-noise FET's.
- Verify operation of a liquid argon TPC at 10 atmospheres (as at bottom of a 100-kton tank).
- For eventual use at a neutrino factor, verify operation of a liquid argon TPC in a magnetic field (proposals submitted to BNL, CERN).

## Simulation Studies

- What is maximum wire spacing consistent with good background rejection of neutral current events, good $\pi^0$ identification?
- What is shallowest depth at which proton decay search can be performed to $10^{35}$ year for $p \to e^+\pi^0$ and $p \to K^+\bar{\nu}$?