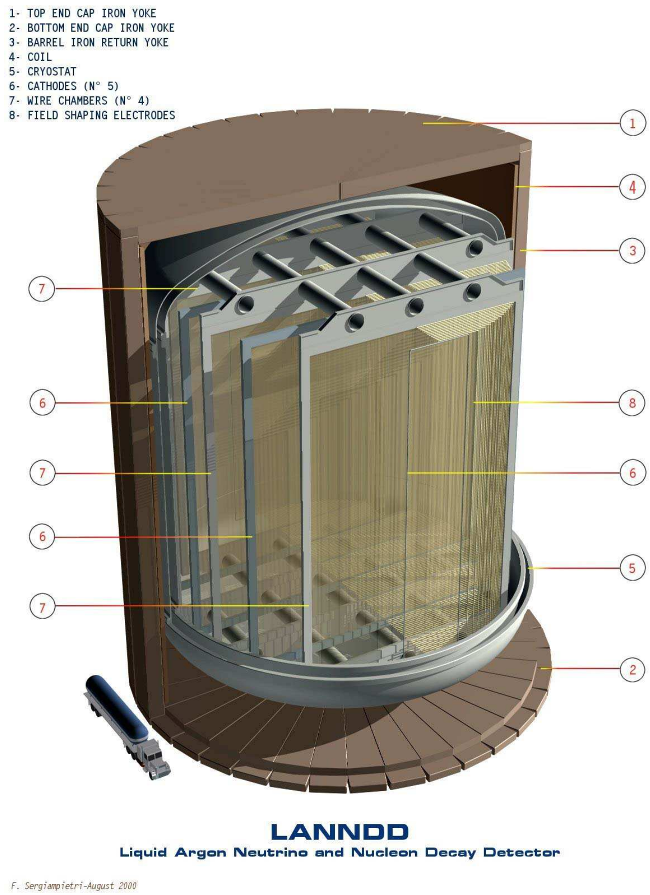
On the Feasibility of
a Very Large Liquid Argon Detector
for Neutrino Oscillation Physics



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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: $\theta_{12} \approx 30°$, $\theta_{13} < 10°$, $\theta_{23} \approx 45°$.
- A phase δ related to CP violation (unknown).

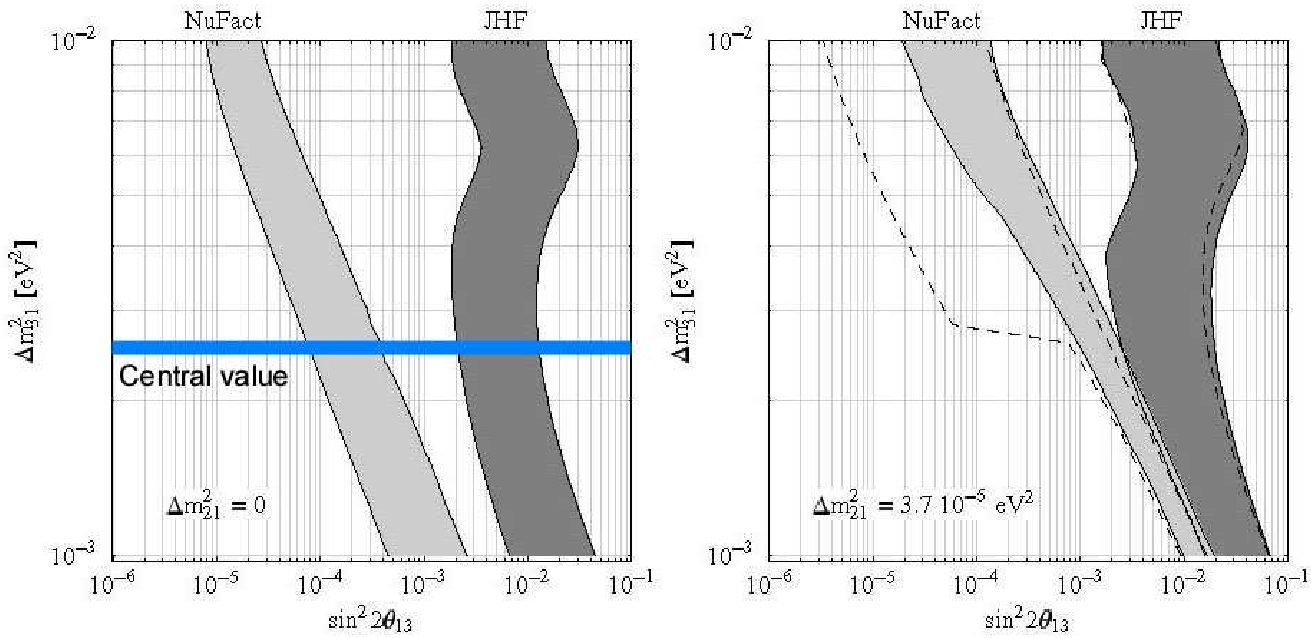
Measurement goals of new experiments:

1. $\sin^2 2\theta_{13}$.
2. Sign of Δm^2_{23}. (Sign of Δm^2_{12} known if LMA solution correct.)
3. δ_{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:

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

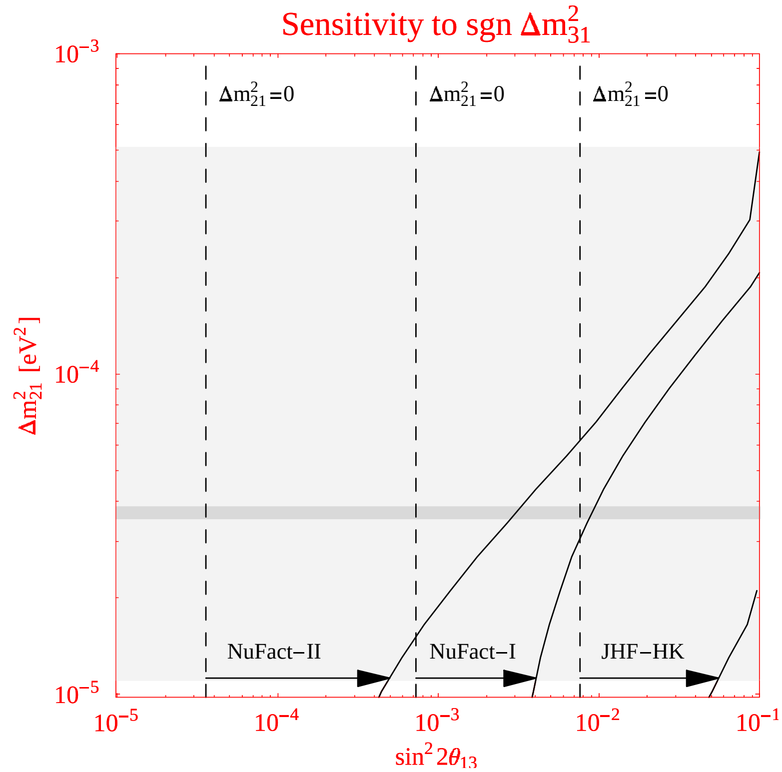


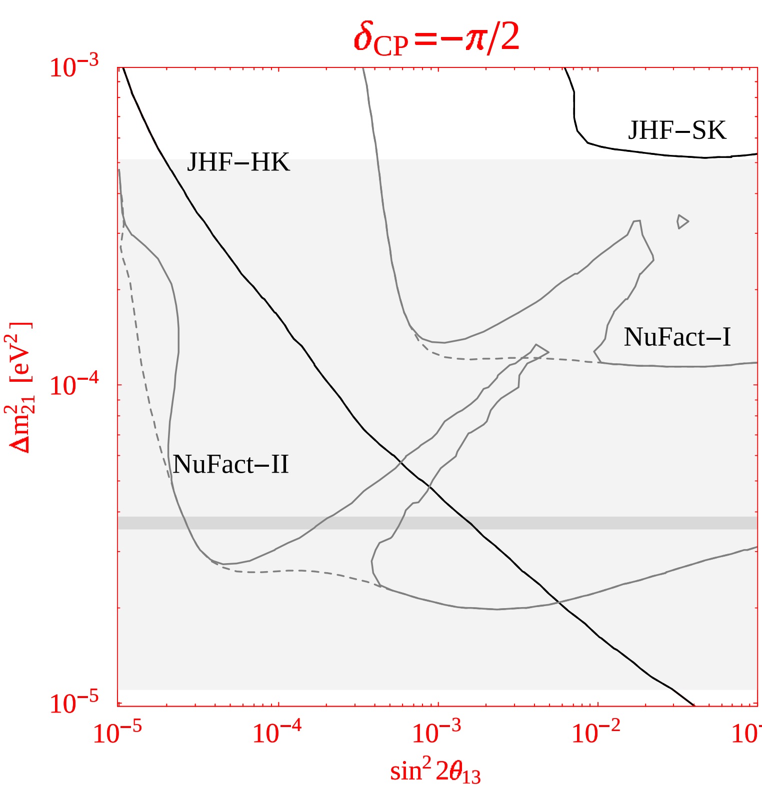
Lindner *et al.*, hep-ph/0204352

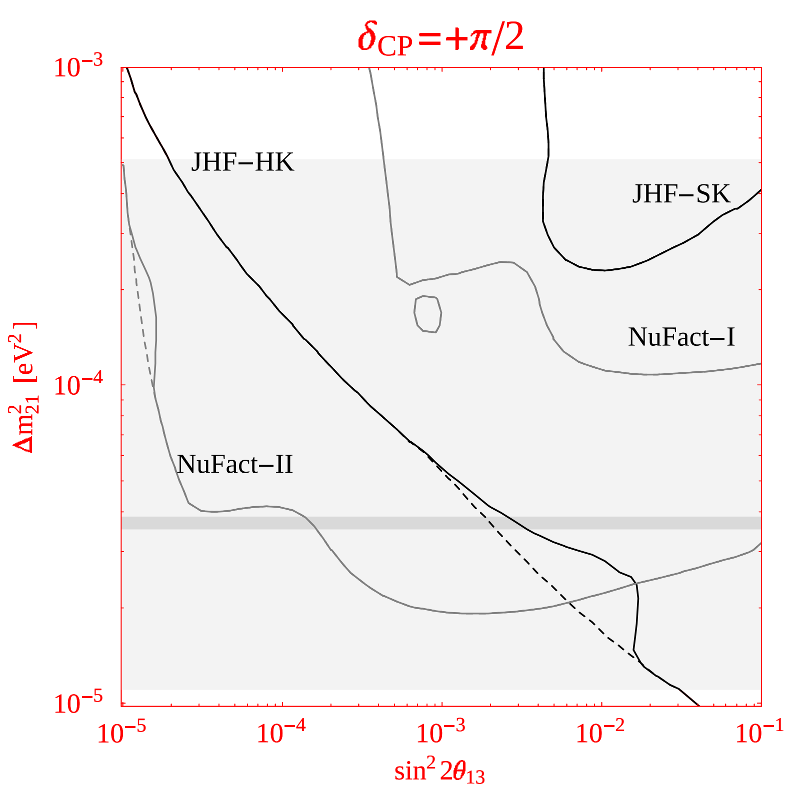
$\Rightarrow$ Can't optimize choice of L and E_ν until Δm^2_{23} known to $\pm 20\%$. (One year of MINOS in nominal NUMI beam.)

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

Quality of measurement of δ_{CP} and sign of Δm^2_{23} also affected by value of Δm^2_{12}.



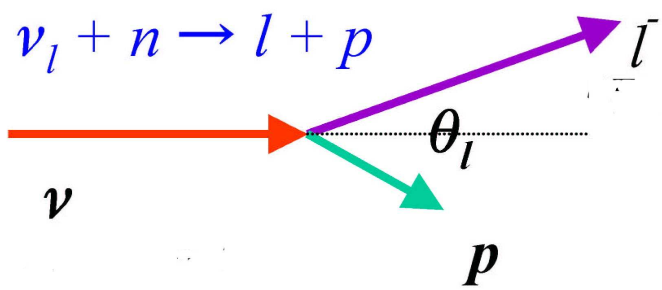


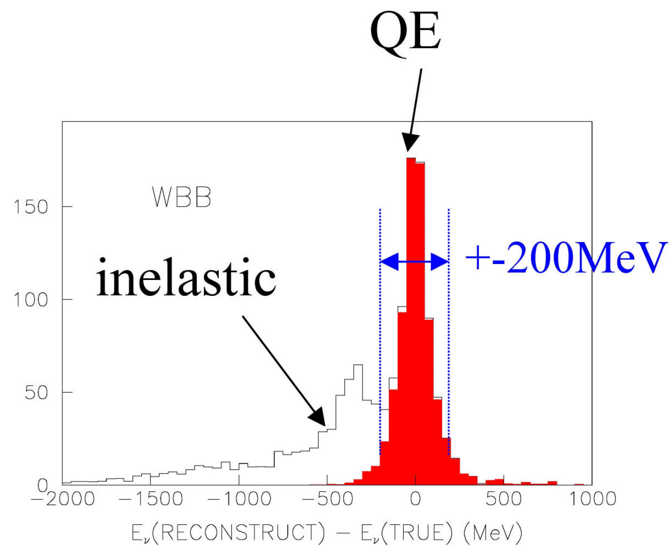


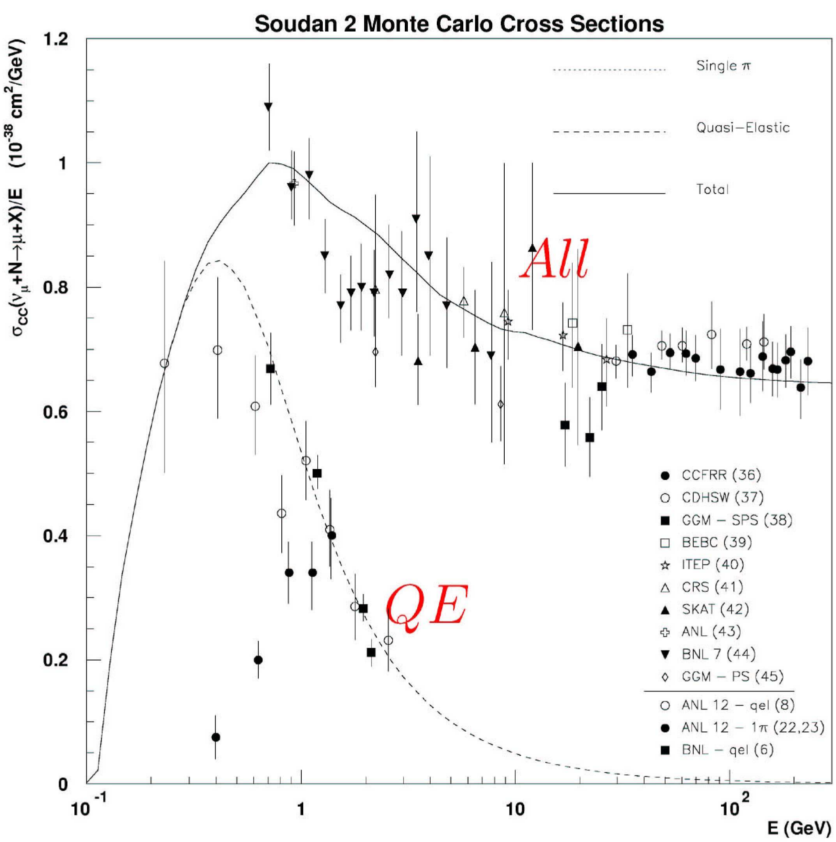
Use ≈ 1 GeV Neutrinos

Production rate is high.

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

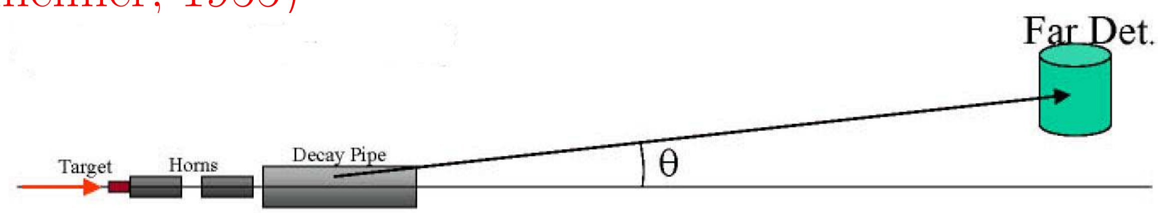


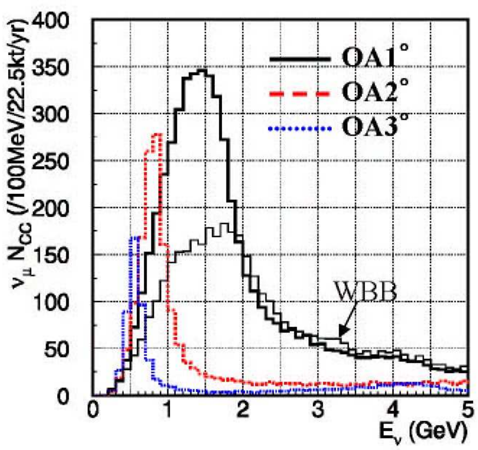


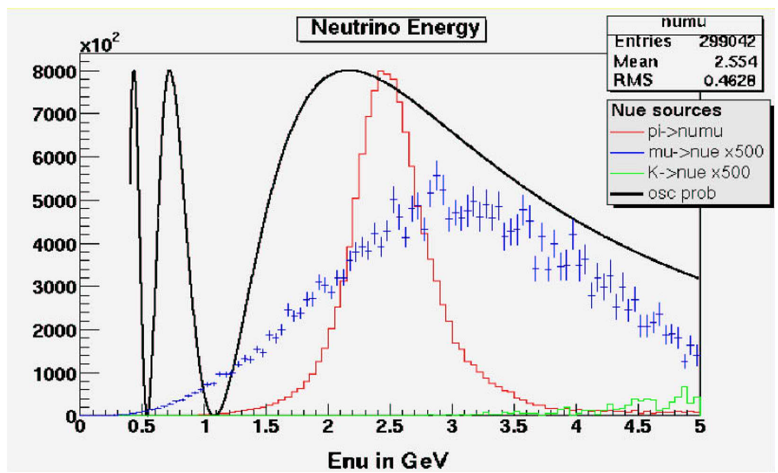


Use an Off-Axis Neutrino Beam (BNL E-889)

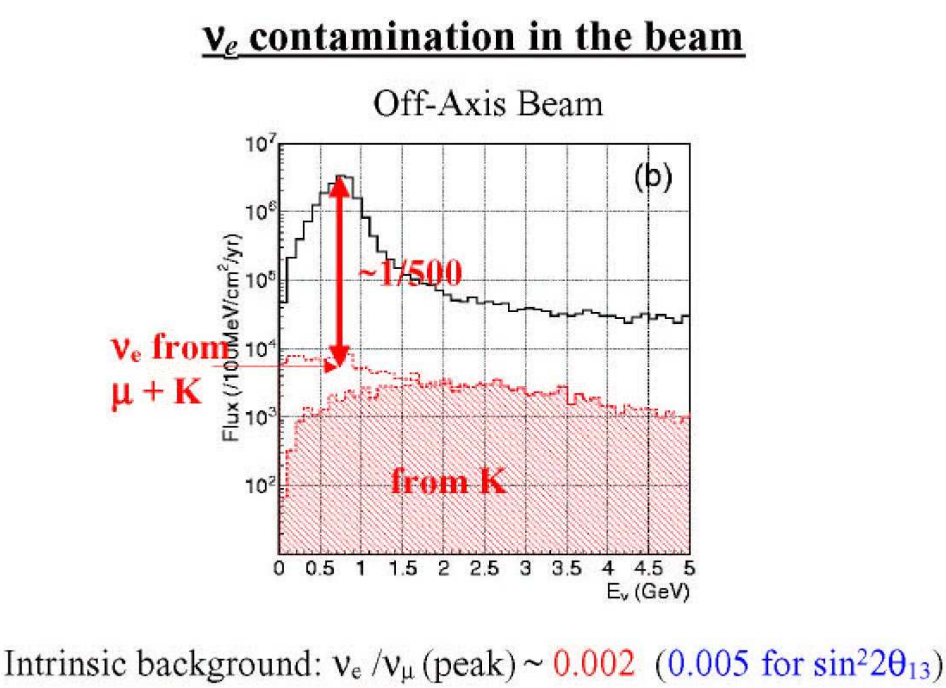
$\pi \to \mu\nu$ decay kinematics has a Jacobian peak: $\theta \approx 2^\circ$ / GeV.
(Sternheimer, 1955)







J2K (Kobayashi) NUMI (Wojcicki)



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

[Marciano, hep-ph/0108181]

The nth maximum of ν_2-ν_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_ν 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 Δm^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 ν beam at BNL with a 1-4 MW proton driver.

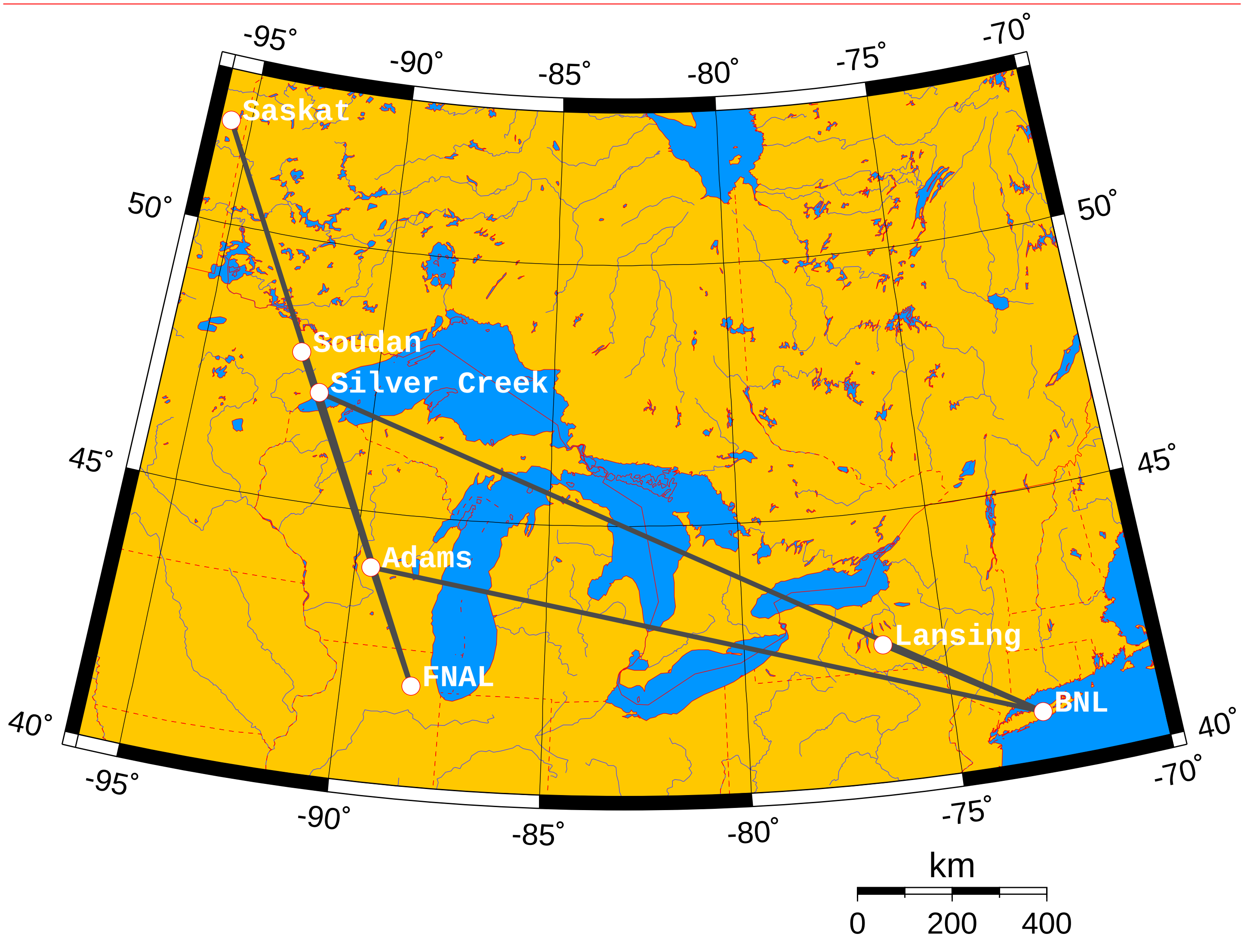
  $\Rightarrow \sin^2 2\theta_{13}$ to 0.0003, $\tau/B(p \to K^+\bar{\nu})$ to 10^{35} year, search for CP violation and measurement of sign of Δm^2_{23}.

Overview, cont'd

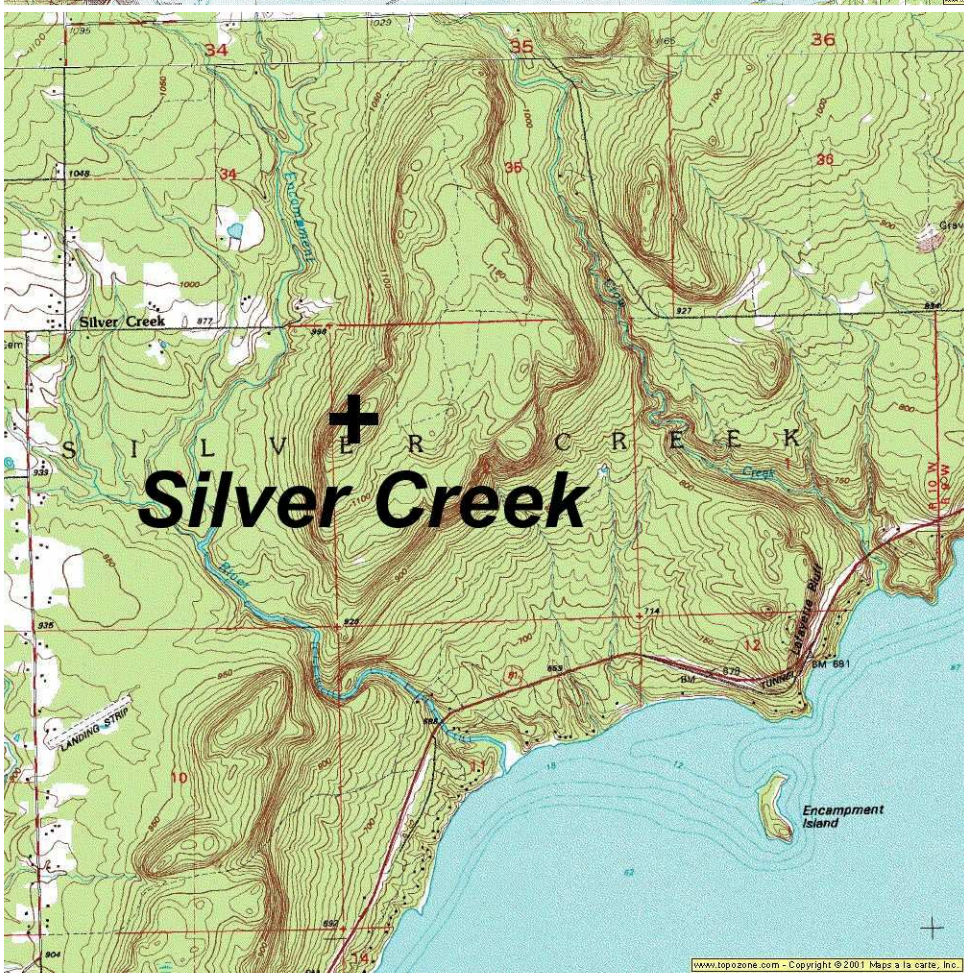
- Phase II, Option B:
  1. Build 100-200 kton liquid argon detector near Adams, WI, 260 km from FNAL, 1410 km from BNL.
  2. Upgrade FNAL beam with a 4-MW, 8-GeV proton driver.
  3. Build new detector in Saskatchewan, 1200 km from FNAL.
- Phase II, Option C:
  1. Build 100-200 kton liquid argon detector near Lansing, NY, 350 km from BNL.
  2. New ν 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 Δm^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.	$\angle_{\rm FNAL}$ 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°	–

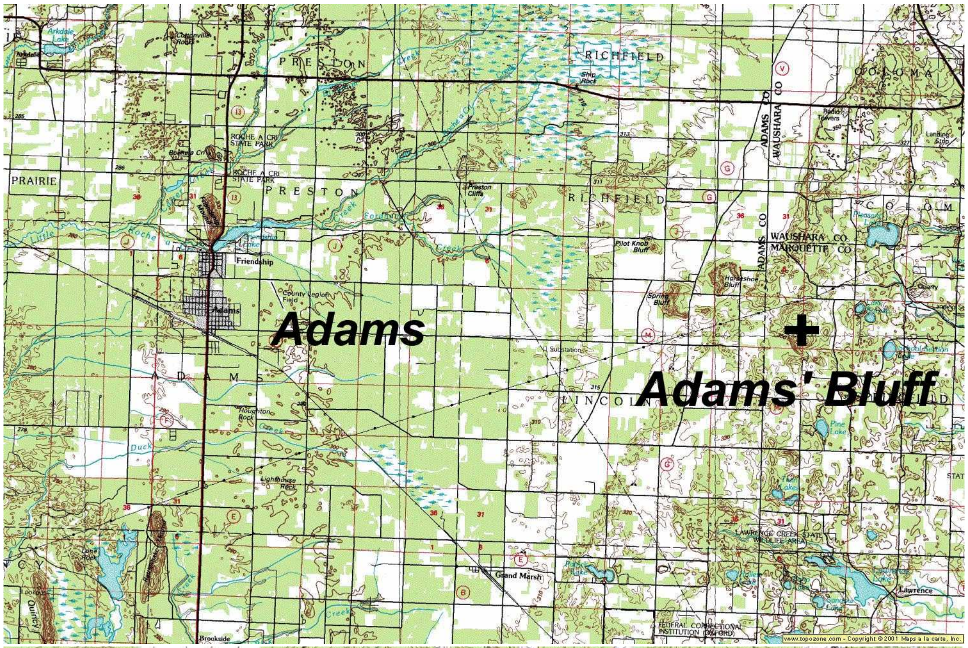


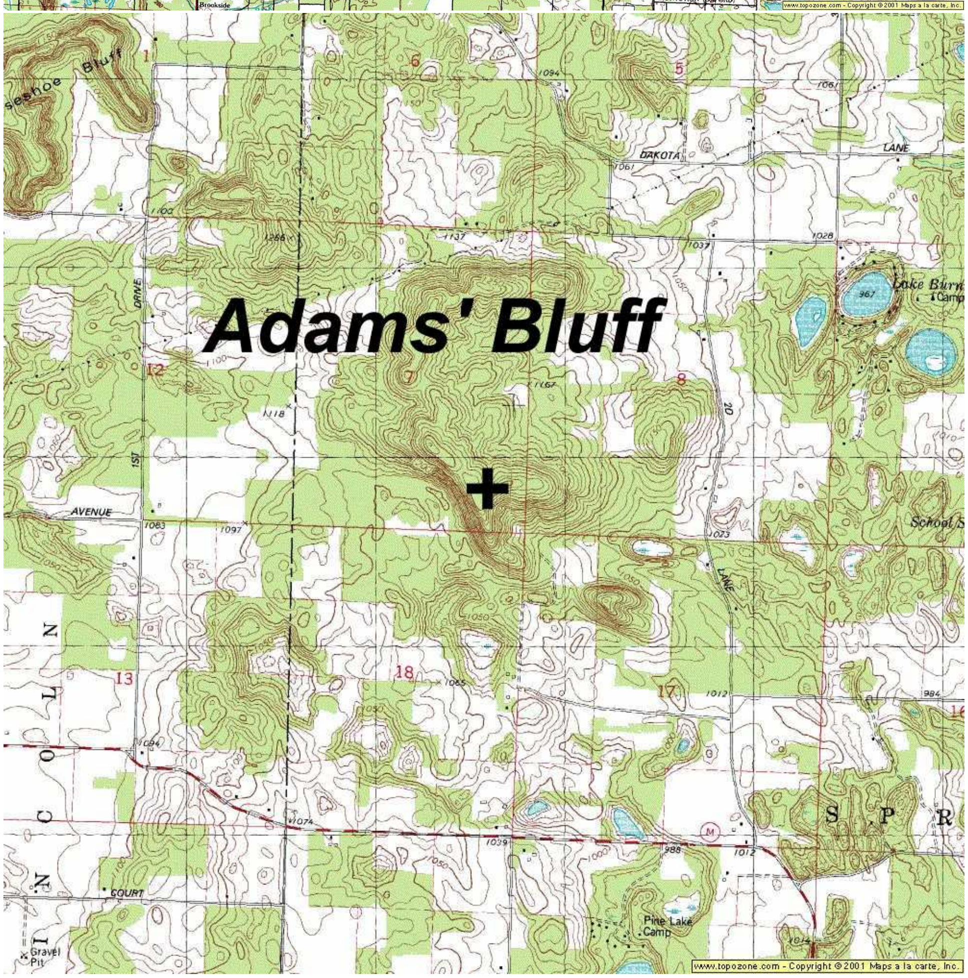
Silver Creek, MN, lat. $47.11°$, long. $-91.58°$



500′ overburden with horizontal tunnel.

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

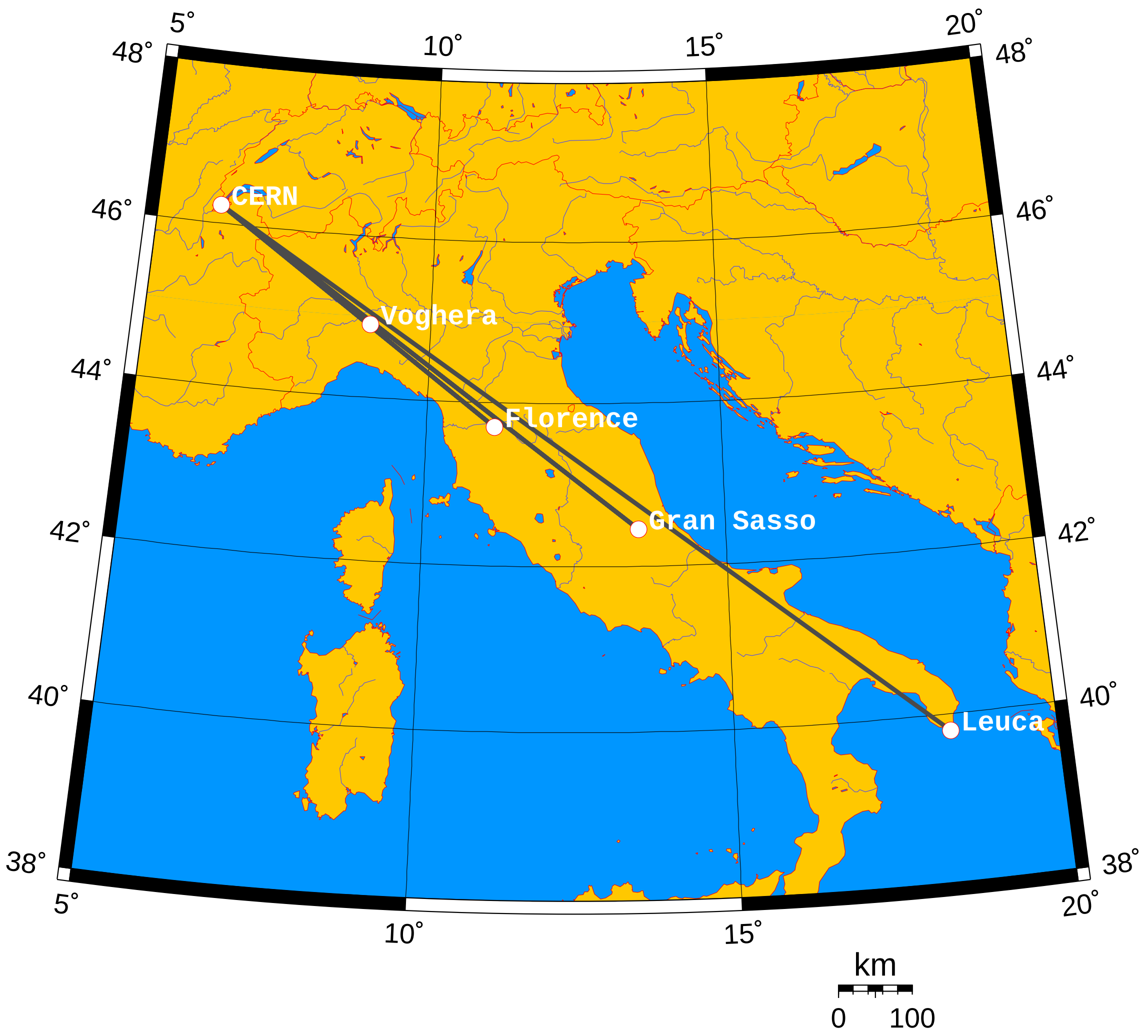




300′ overburden with horizontal tunnel.

Off-Axis Neutrino Beams from CERN

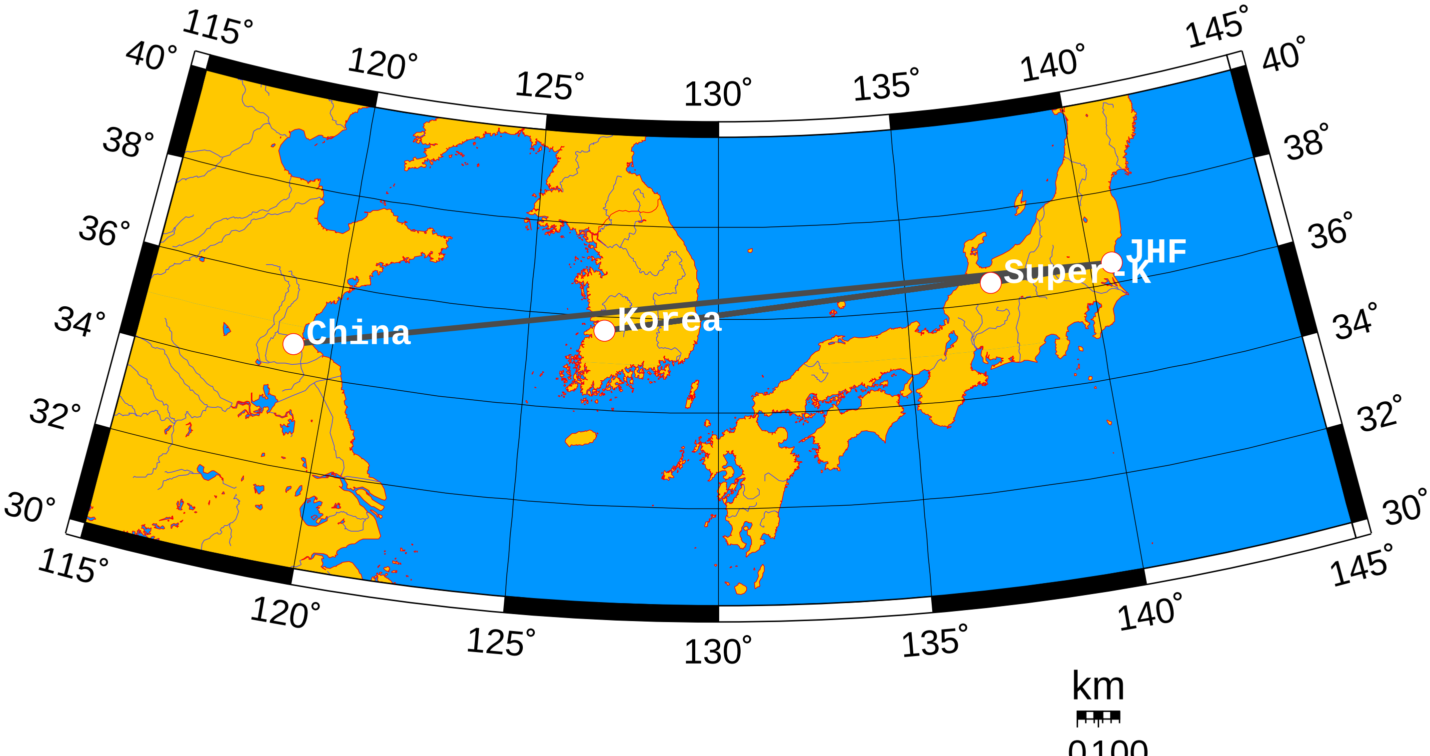
Site	Distance to CERN (km)	Lat.	Long.	$\angle_{\mathrm{CERN}}$ to Leuca
Voghera	270	44.9°	8.95°	4.4°
Florence	490	43.7°	11.15°	3.9°
Gran Sasso	730	42.45°	13.57°	2.5°
Leuca	1225	39.8°	18.35°	–



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

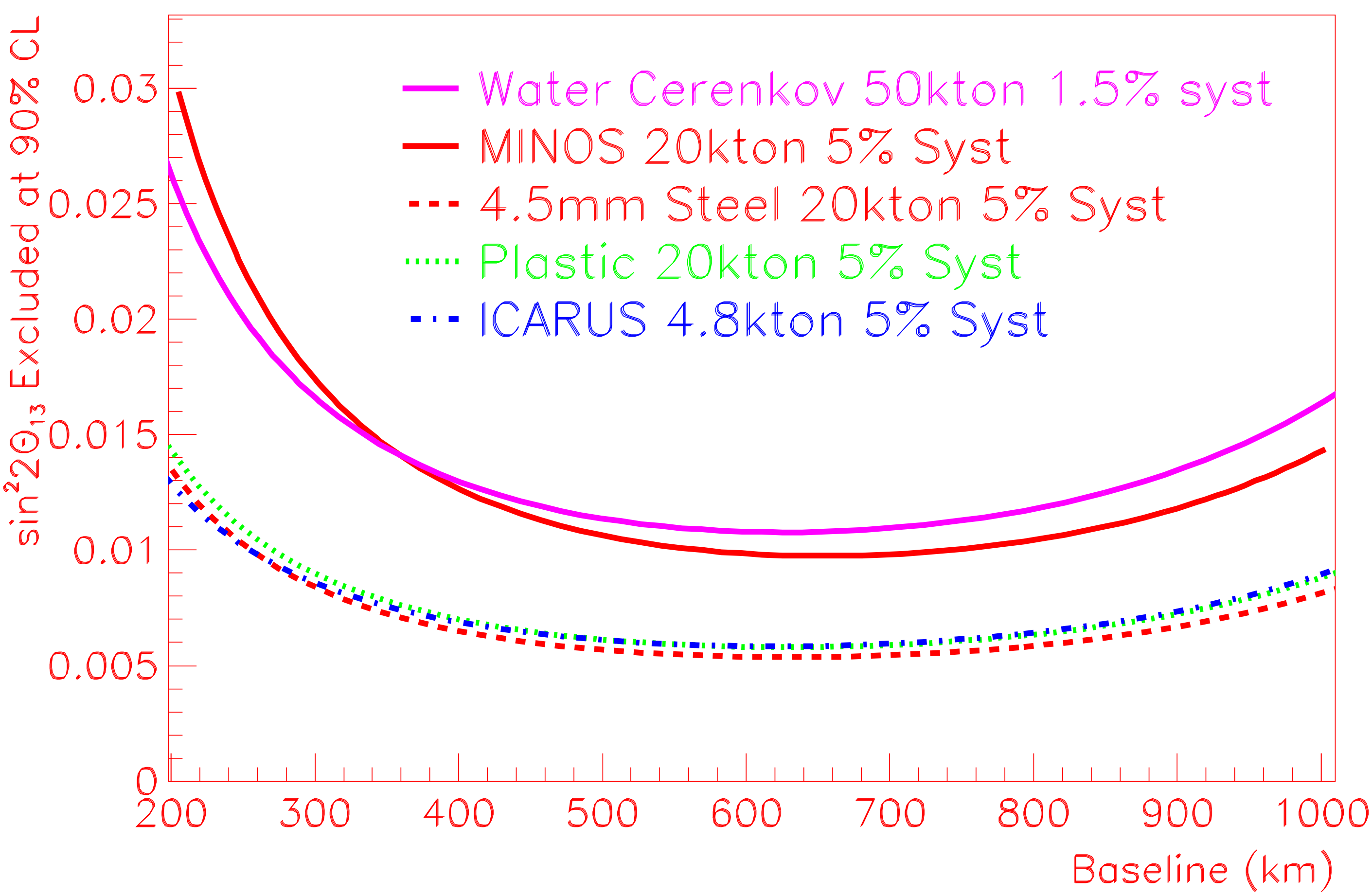
Off-Axis Neutrino Beams from JHF

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°

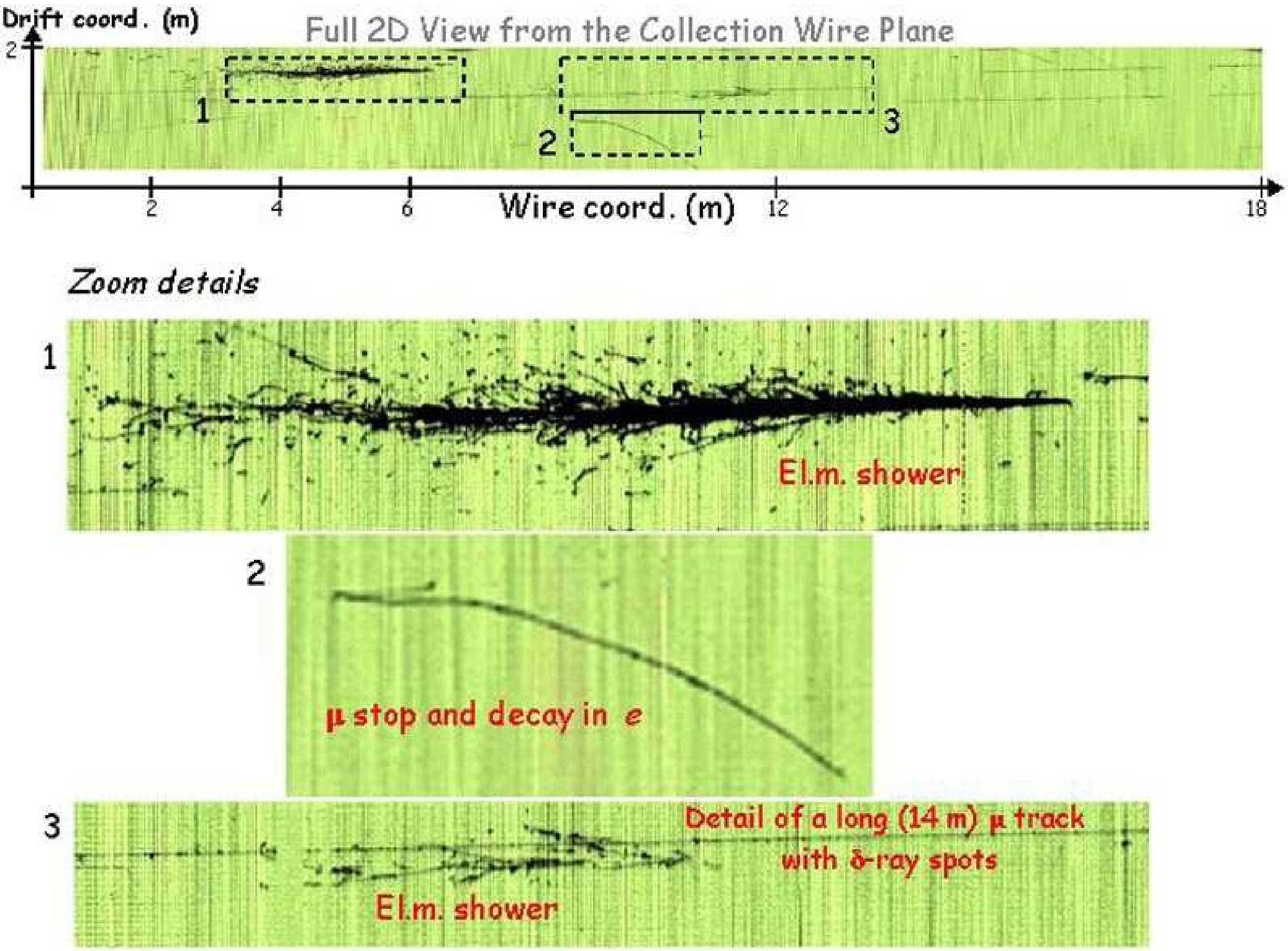


Liquid Argon is the Best Detector Choice

- 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 π^0's.
- 10 times better per kton than water Čerenkov for $\nu_\mu \rightarrow \nu_e$ appearance (Harris).

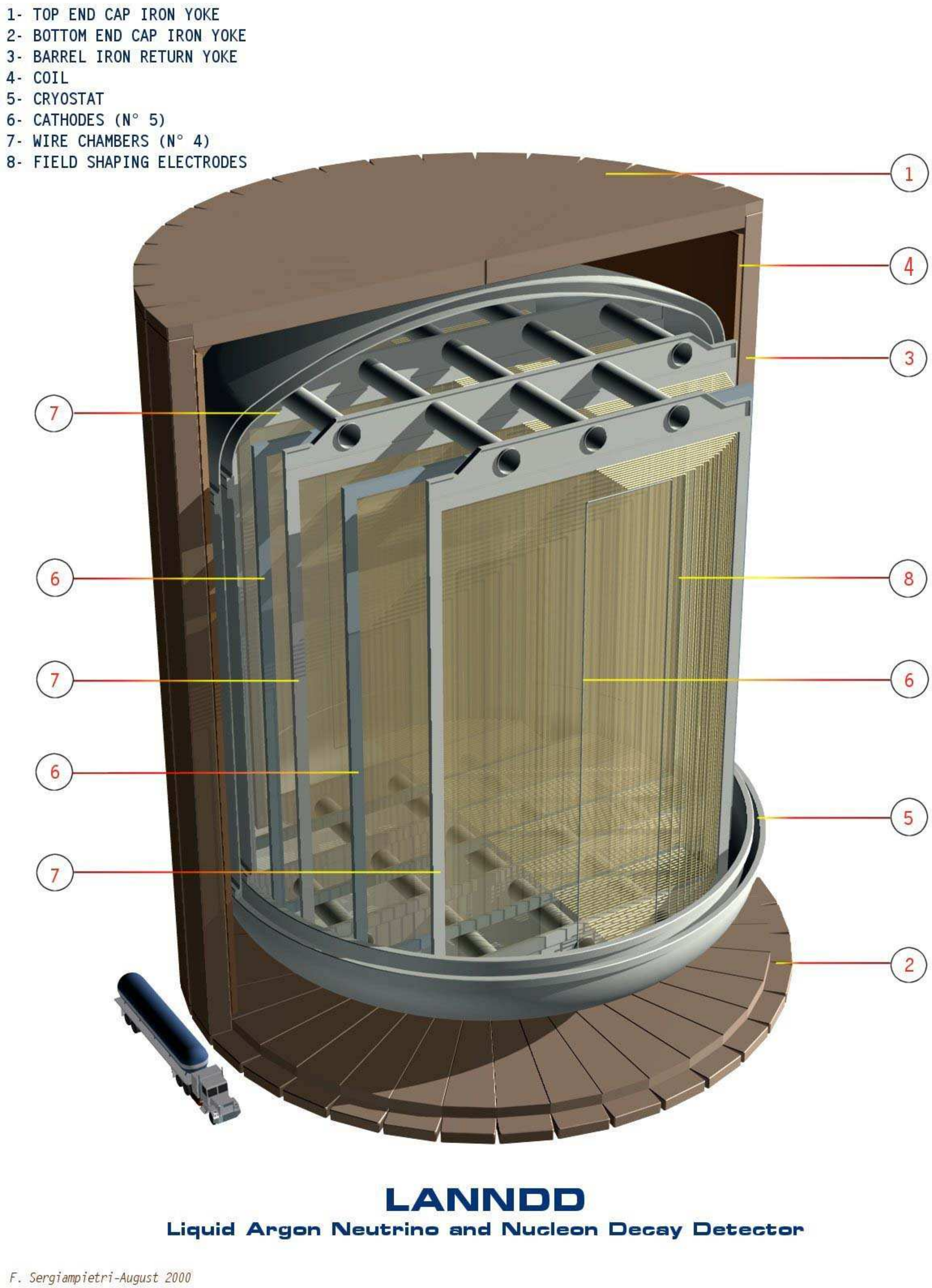


ICARUS – a Working Liquid Argon Detector



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

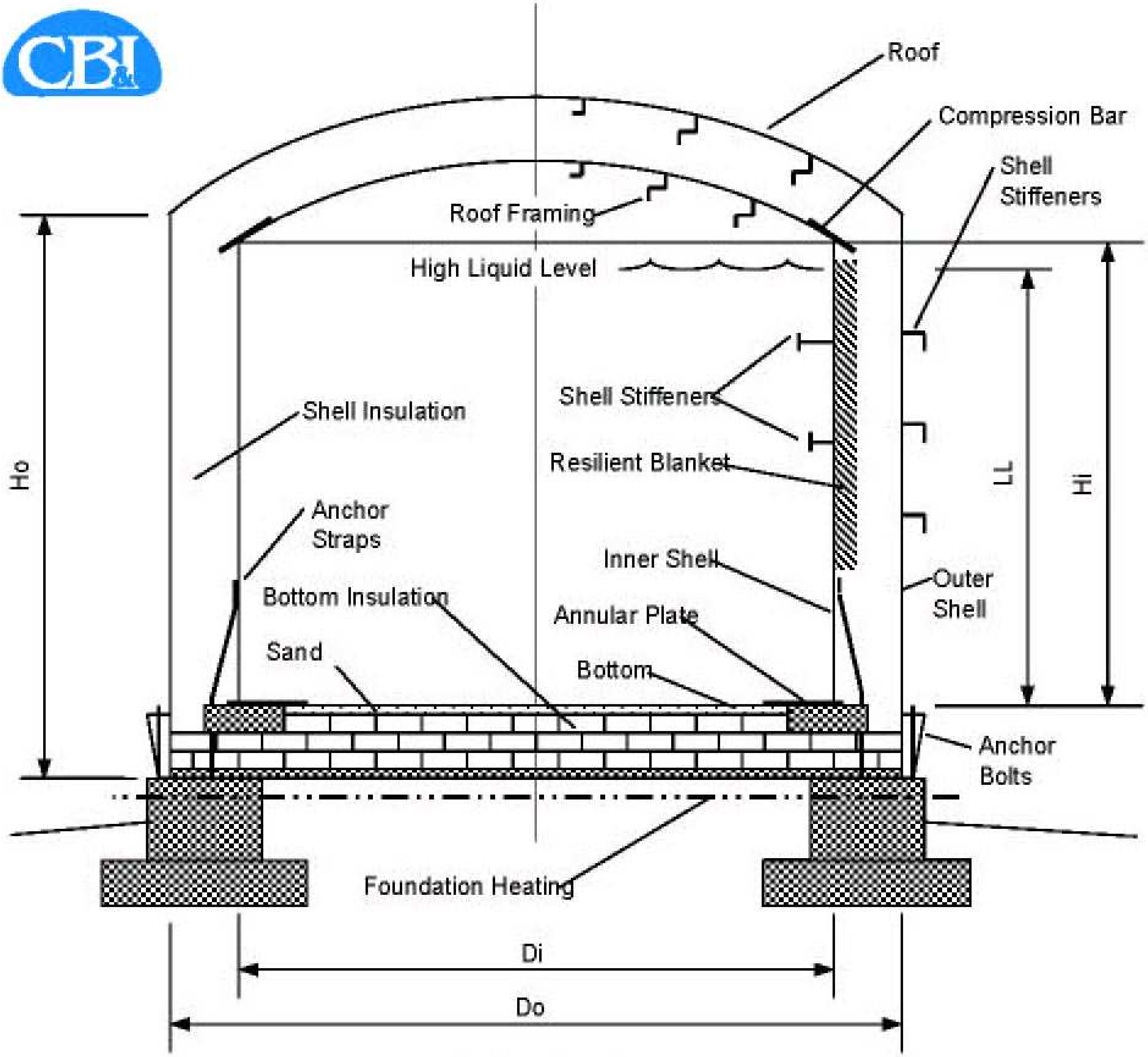
LANNDD – Liquid Argon Neutrino and Nucleon Decay Detector



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

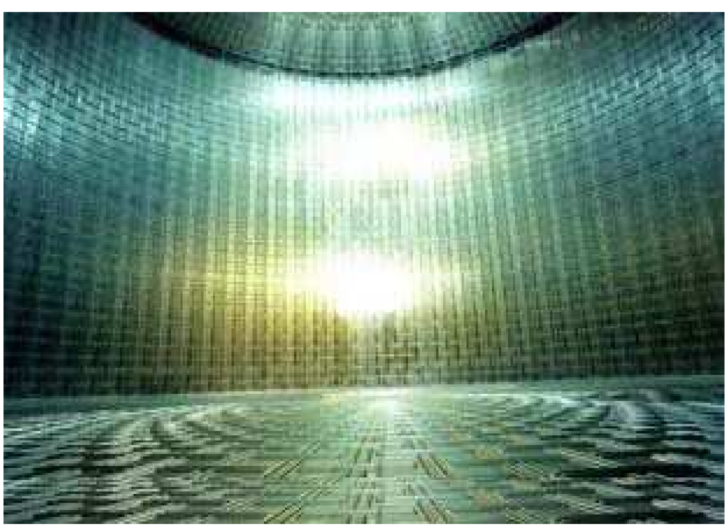


Double Wall & Double Roof Tank

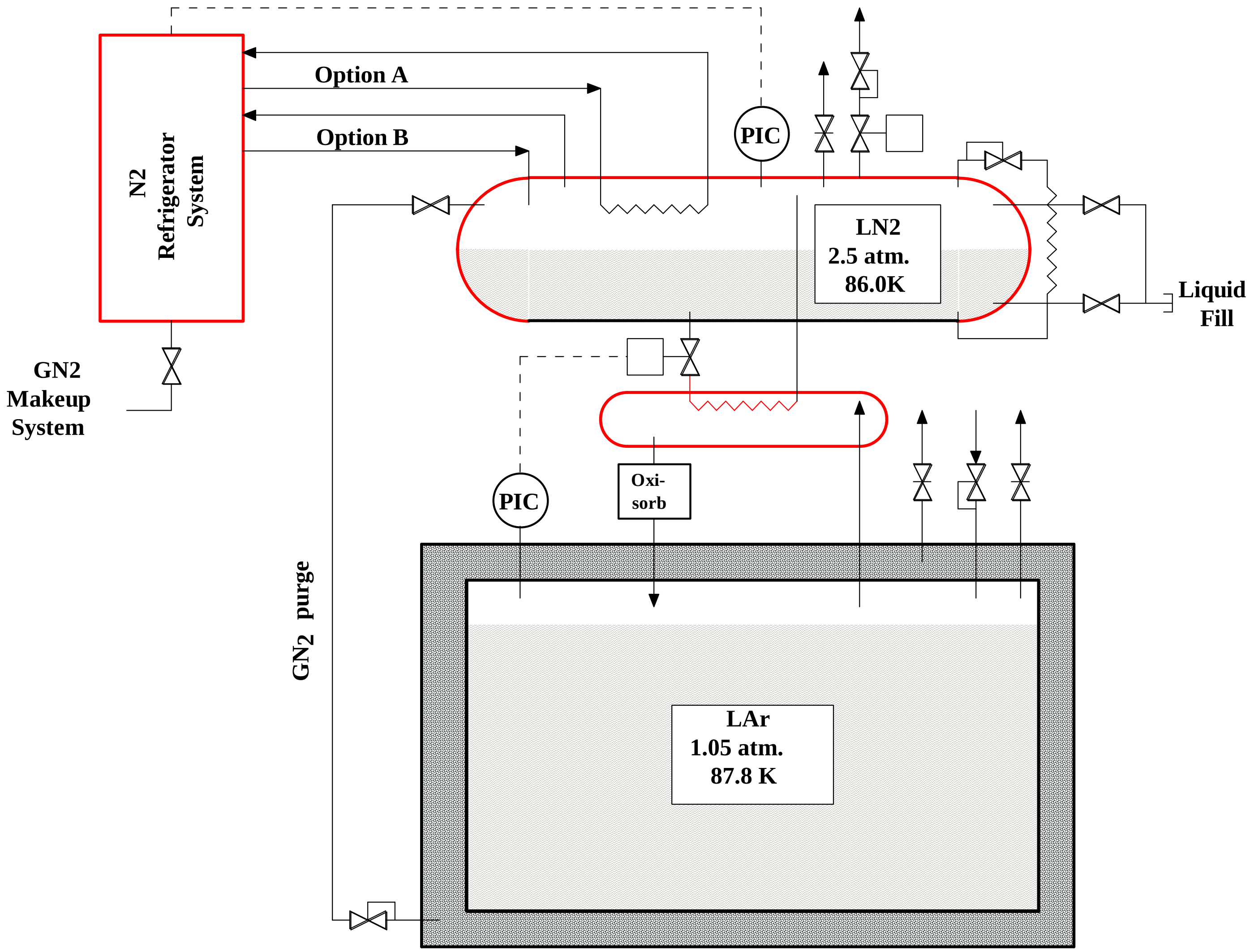
	Feet
Di =	165
Hi =	117.9803
LL =	117.7303
Do =	173
Ho =	118.0443

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

Cryogenic LNG Storage Tanks



LANNDD Cryogenic System



June 13, 2002 ***ACT***

– Applied Cryogenic Technology + Cosmodyne.

Can a Proton Decay Search Be Done at the Surface?

- The signature of the decay $p \rightarrow K^+\overline{\nu}$ is particularly clean:
  $K^+ \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$.
  $\Rightarrow$ 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 π^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 $p \to K^+\bar{\nu}$?