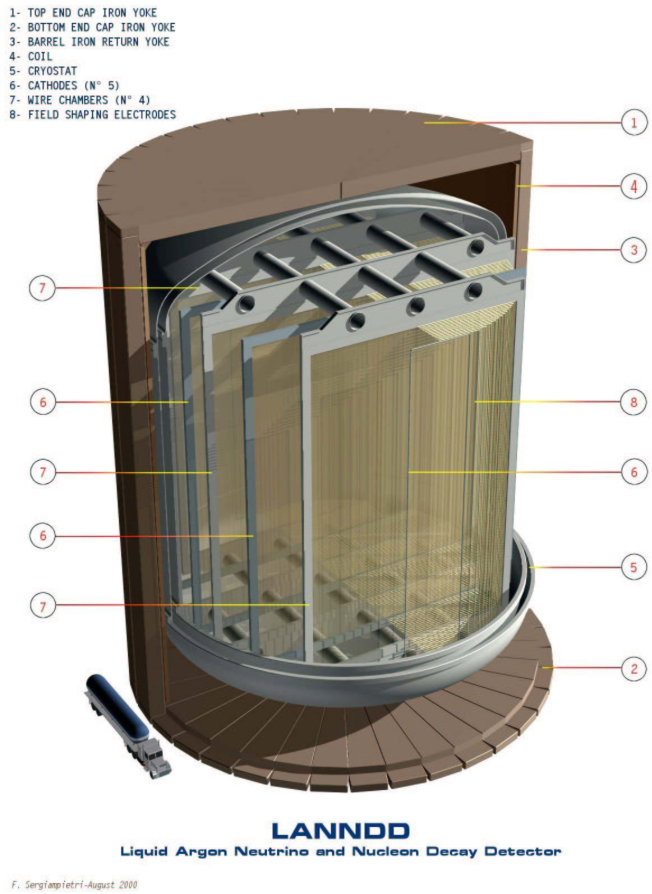
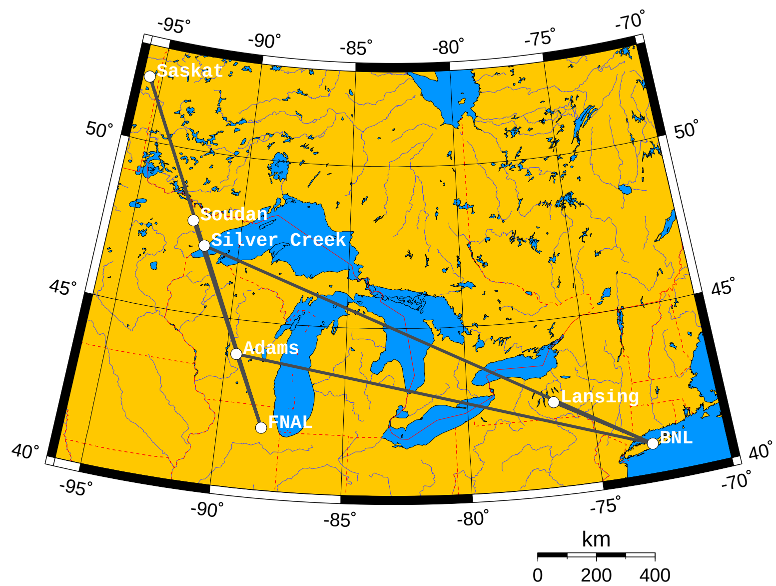
A Strategy for Accelerator-Based Neutrino Physics in the USA





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Neutrino Factory and Muon Collider Collaboration Meeting

Shelter Island, NY

May 14, 2002

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

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).

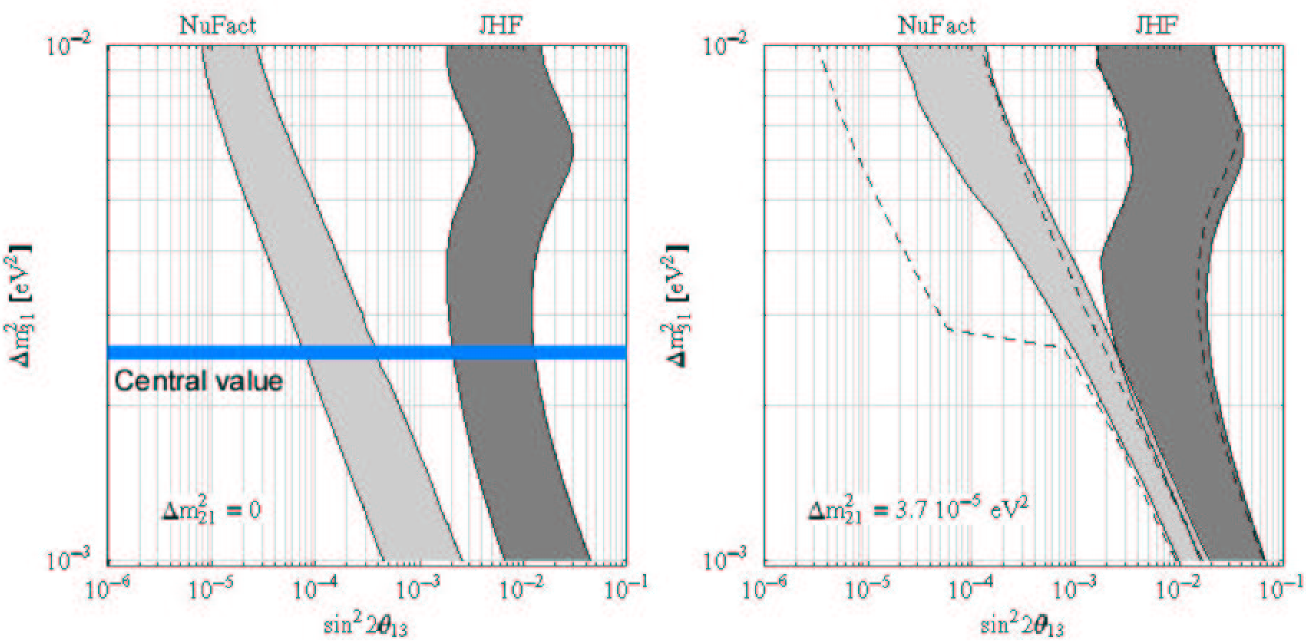
Measurement goals of new experiments:

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:

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

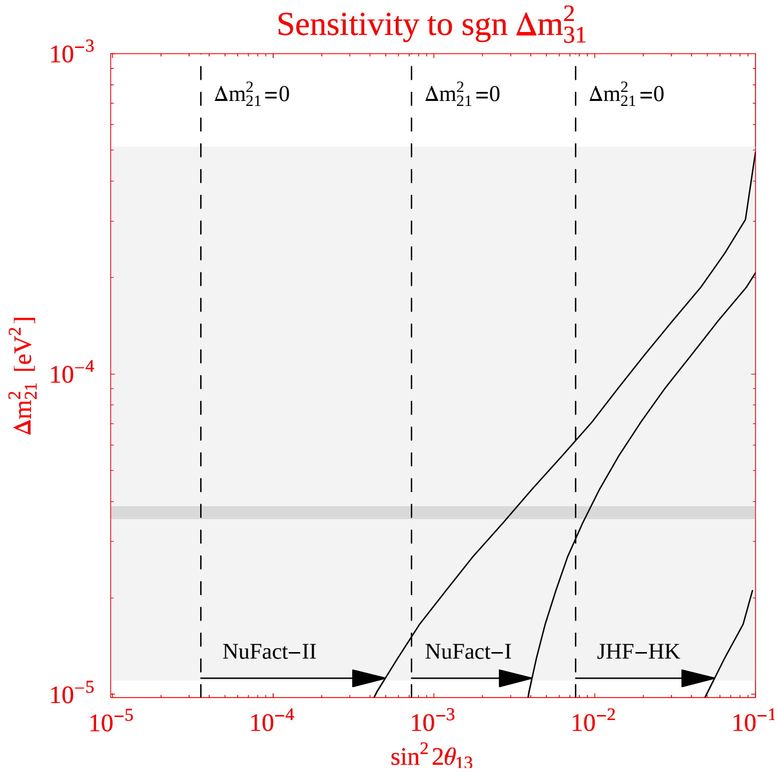


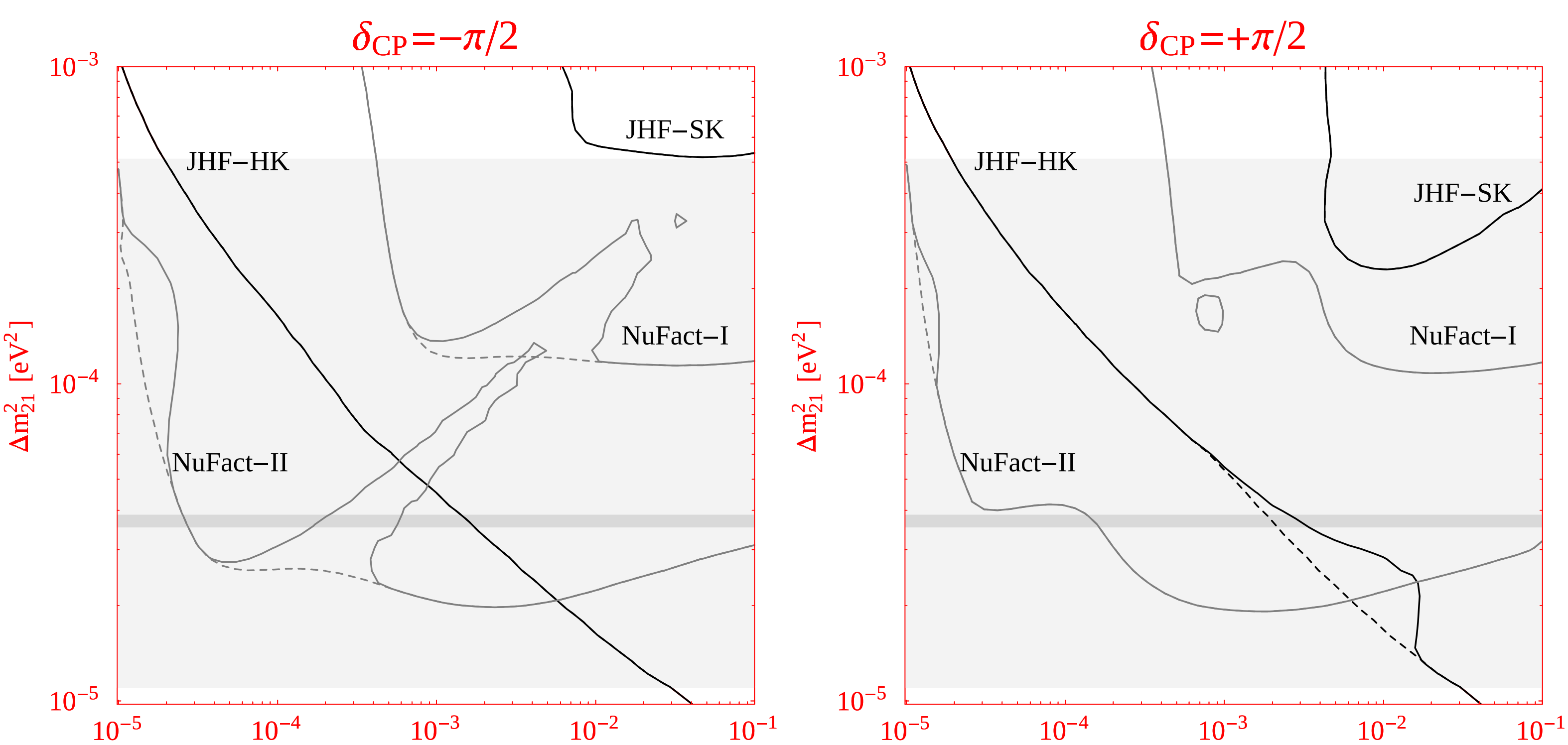
Lindner *et al.*, hep-ph/0204352

$\Rightarrow$ Can't optimize choice of L and E_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 $\delta_{\rm CP}$ is accessible.

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

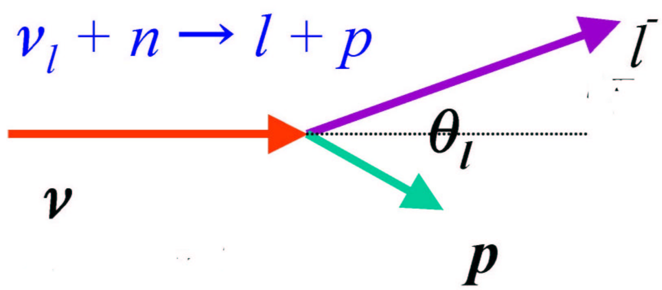


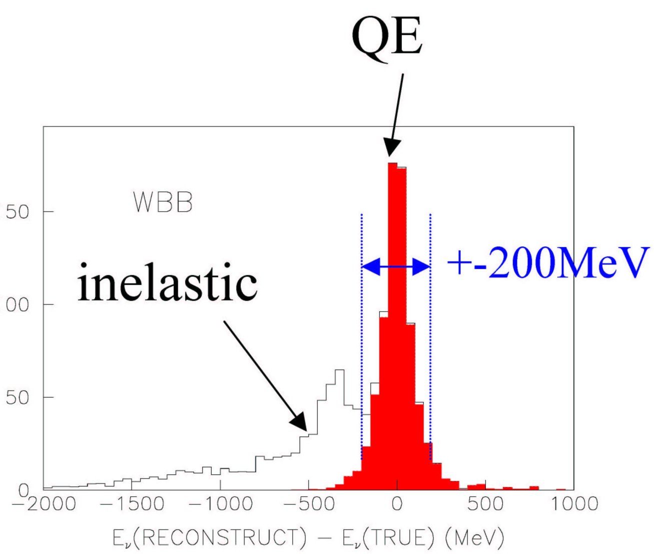


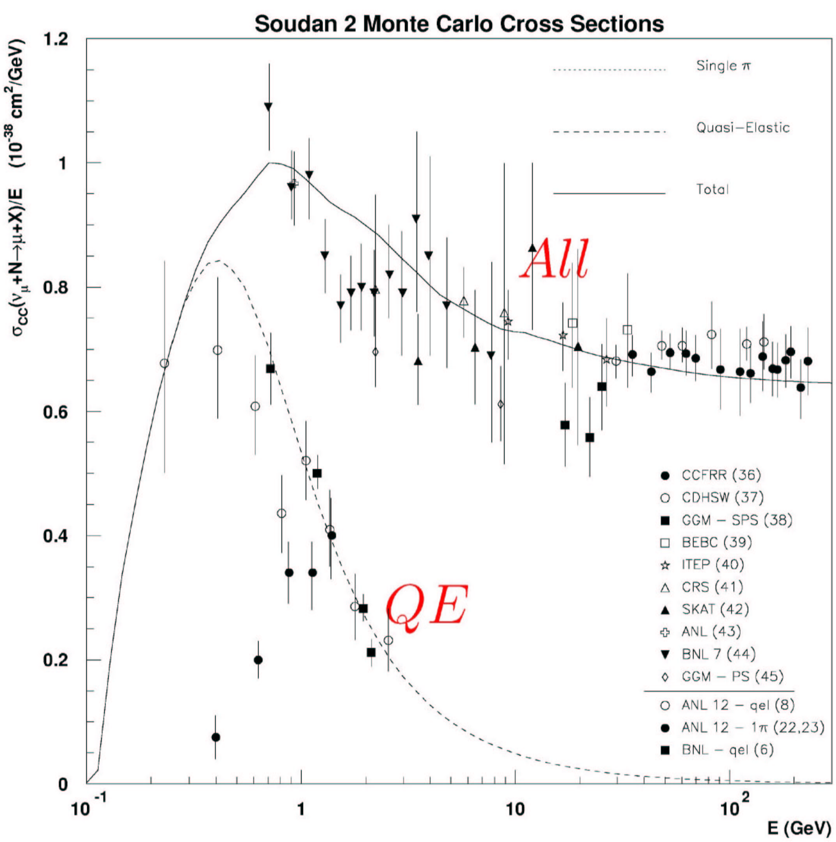
Use ≈ 1 GeV Neutrinos

Production rate is high.

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



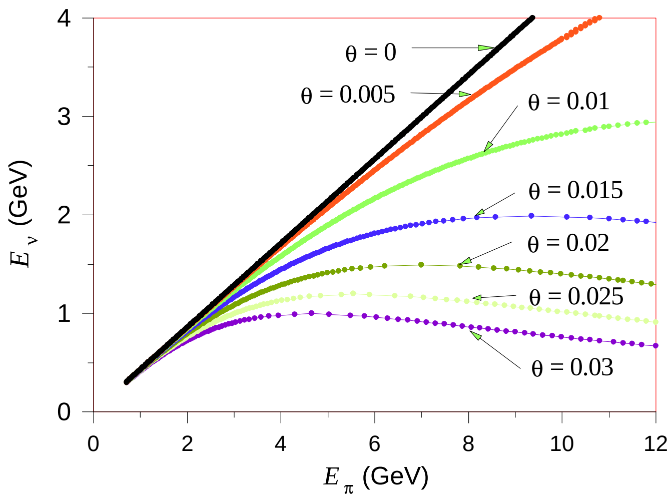


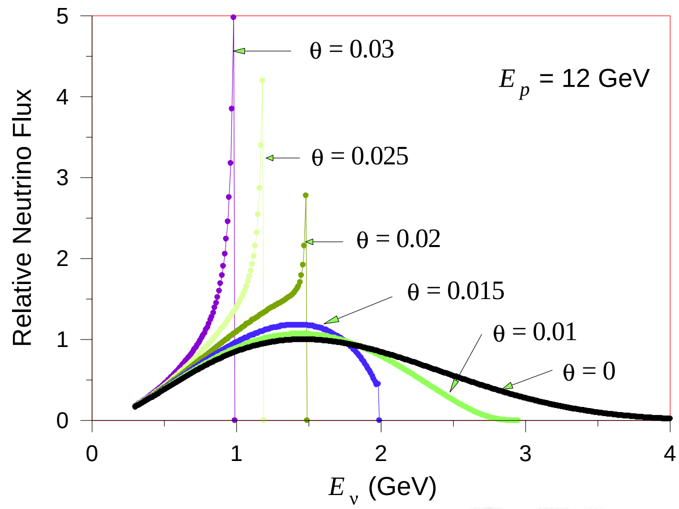


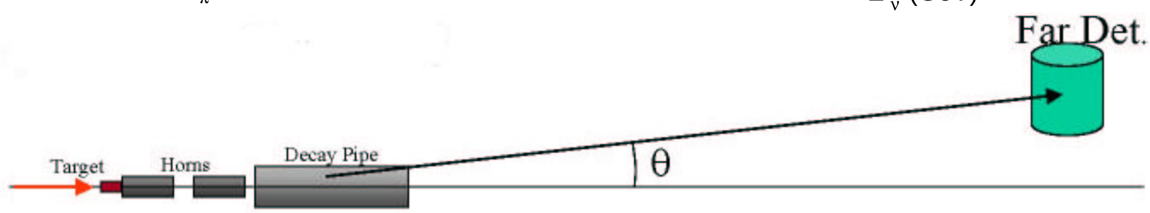
Use an Off-Axis Neutrino Beam (BNL E-889)

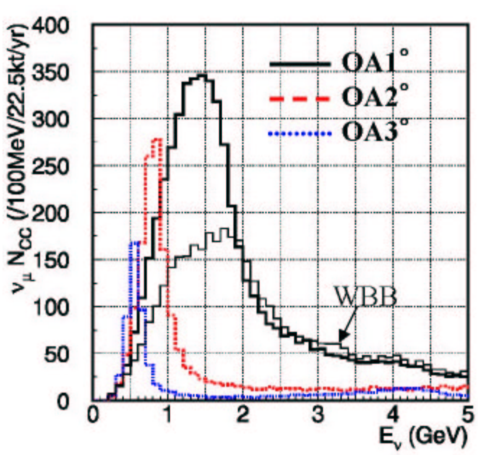
$\pi \to \mu\nu$ decay kinematics has a Jacobian peak: $\theta \approx 2^\circ$ / GeV.

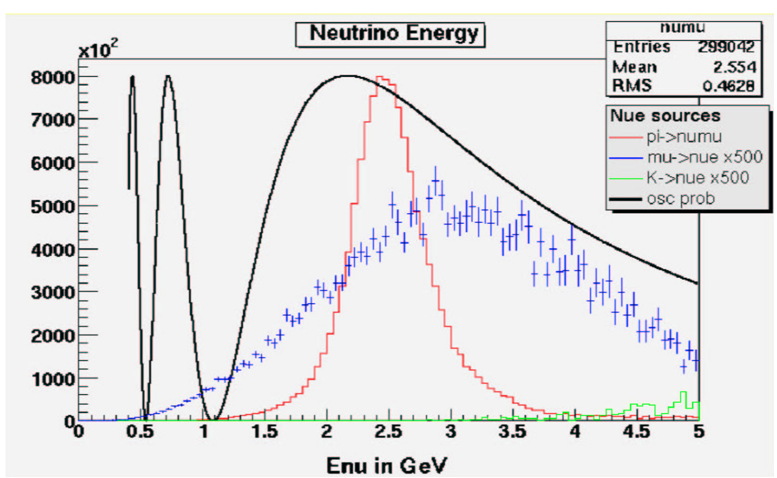
(Sternheimer, 1955)











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:

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

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

$N_{\rm events} \propto 1/L^2$, $\Rightarrow$ 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.

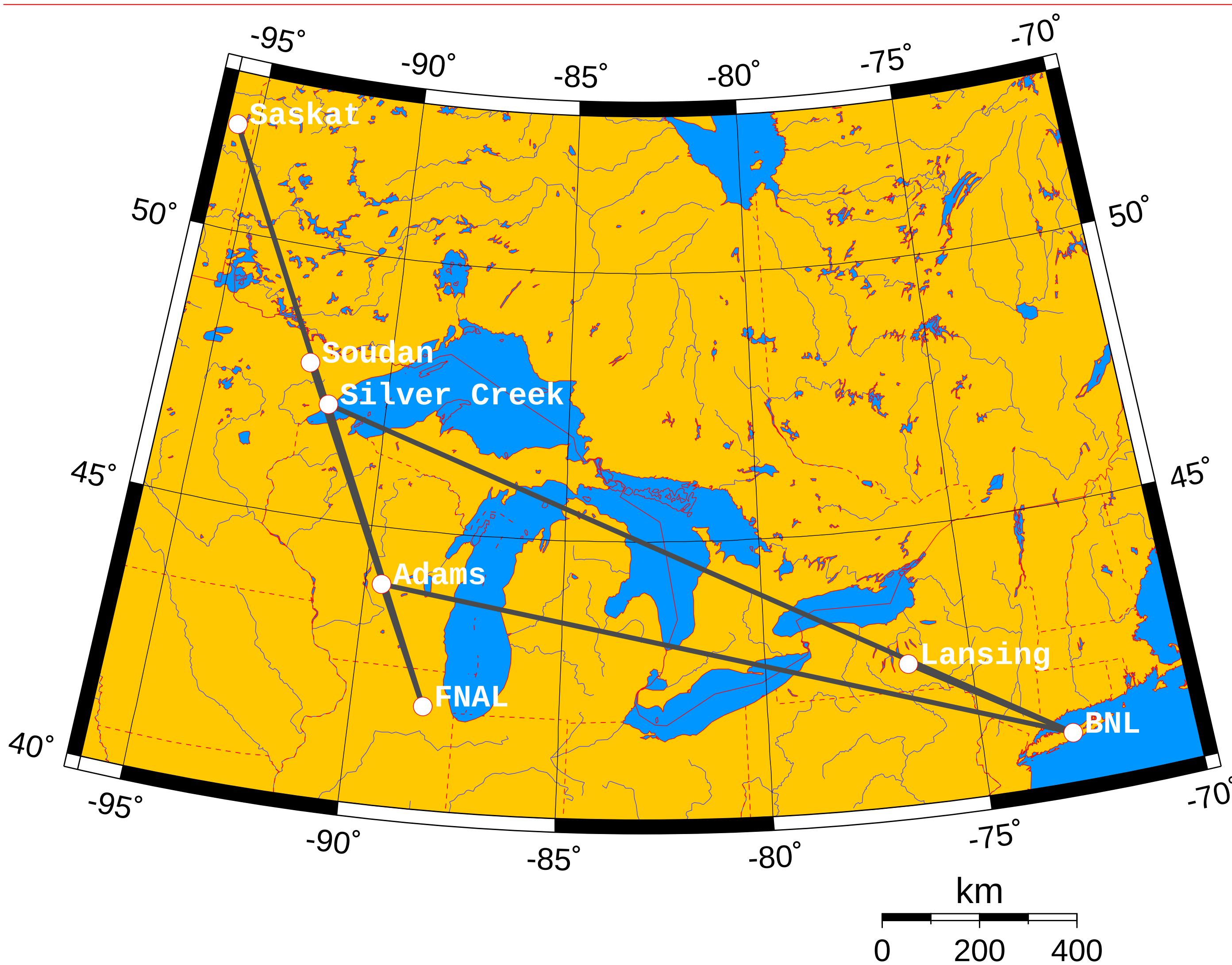
  $\Rightarrow \sin^2 2\theta_{13}$ to 0.0003, $\tau/B(p \to K^+\bar{\nu})$ to 10^{35} year, search for CP violation and measurement of sign of Δm^2_{23}.

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

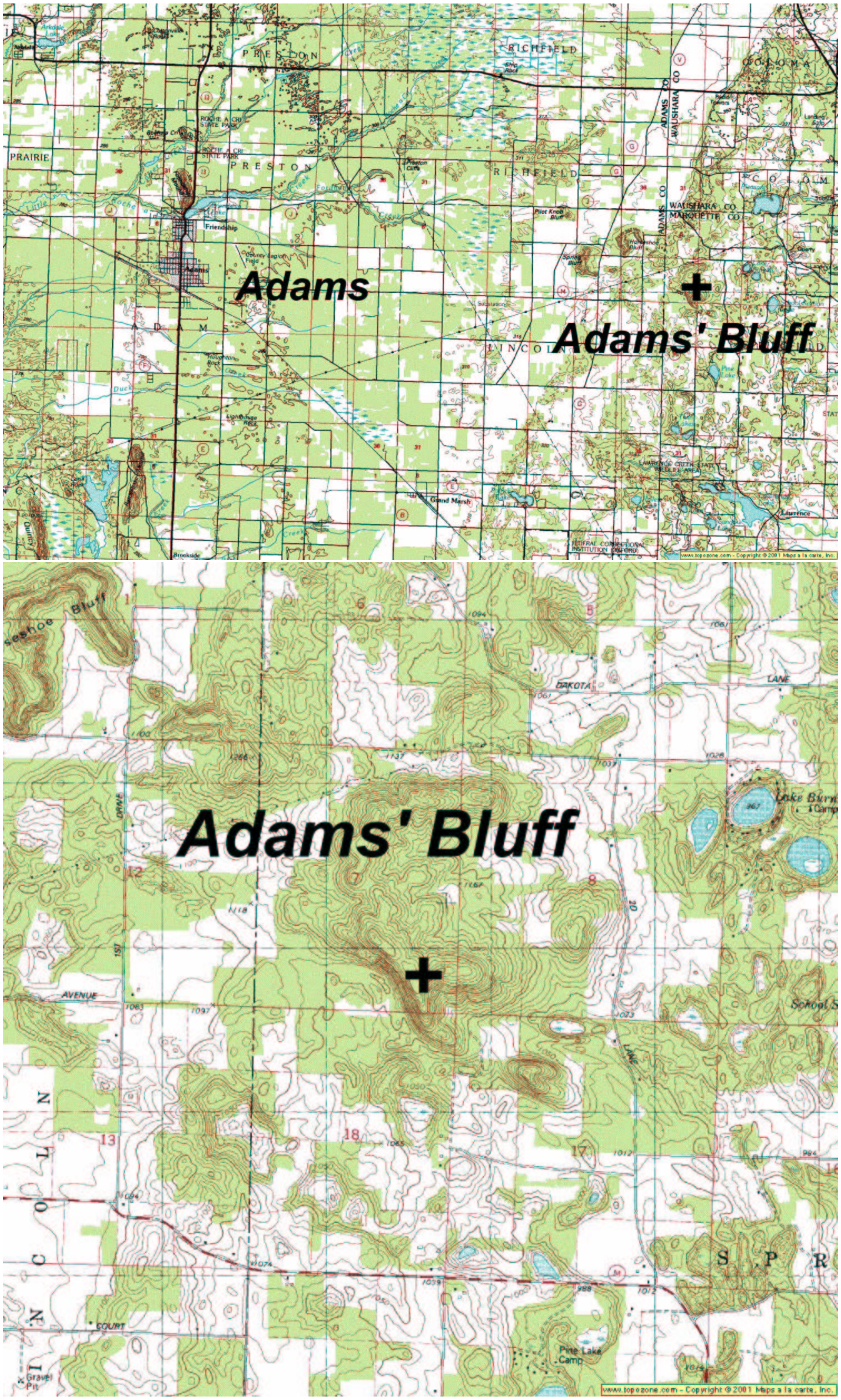
Site	Dist. (km) to BNL	Dist. (km) to FNAL	Lat.	Long.	$\angle_{\rm FNAL}$ to Soudan
Soudan	1710	735	47.82°	-92.24°	–
Silver Creek	1640	640	47.11°	-91.59°	0.9°
Adams' Bluff	1410	260	43.95°	-89.59°	2.2°
Saskatchewan	2110	1260	52.0°	-95.65°	2.4°
Lansing	350	970	42.51°	-76.52°	–



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

500′ overburden with horizontal tunnel.

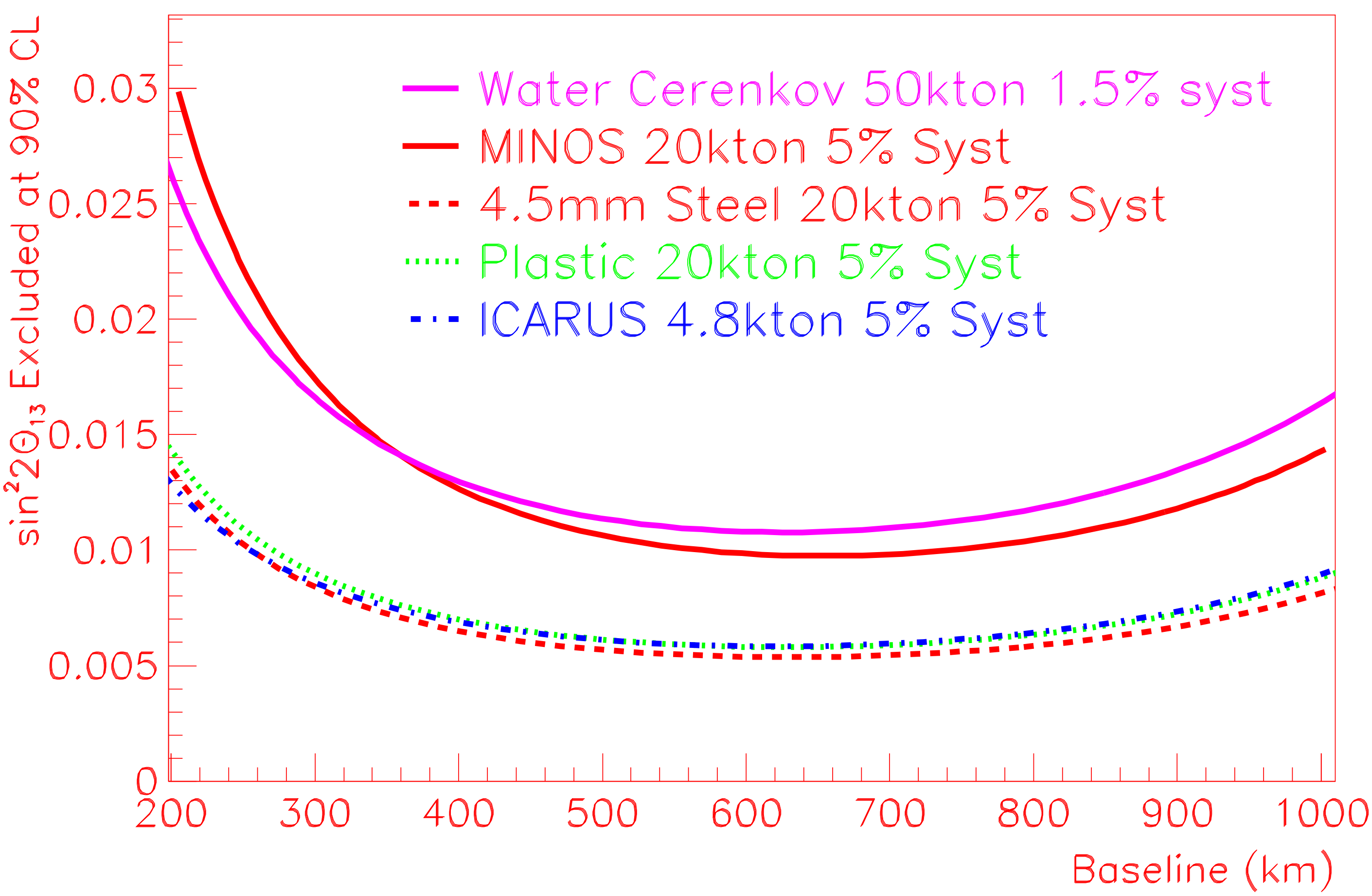
Adam's Bluff, WI, lat. 43.95°, long. −89.59°



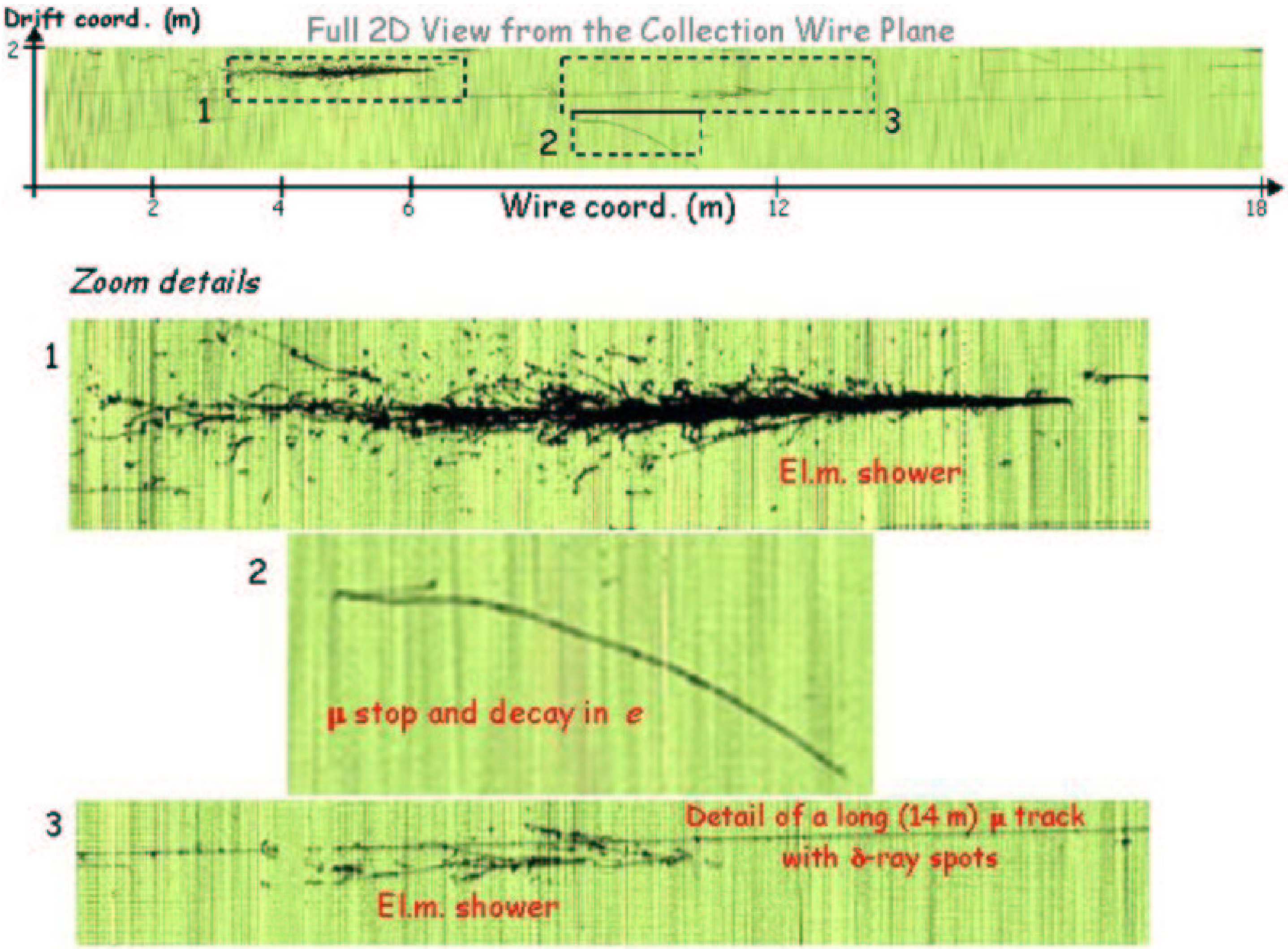
300′ overburden with horizontal tunnel.

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).

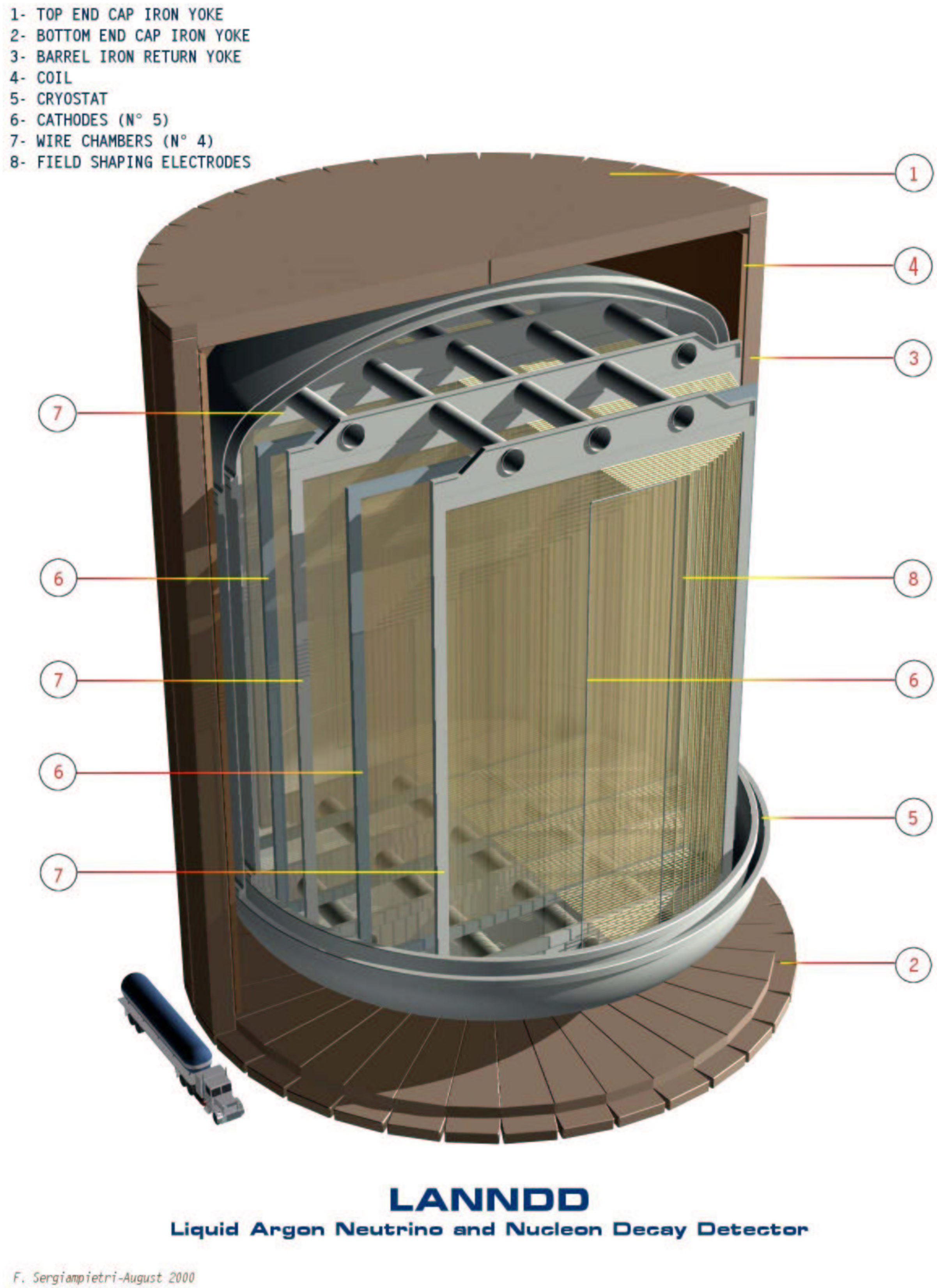


ICARUS – a Working Liquid Argon Detector



- Operates at the Earth's surface with near zero overlap of cosmic ray events.
- Operates with deadtimeless, selftriggering electronics.
- Liquid argon costs $\approx \$1M/\mathrm{kton}$.
- Minimize cost of a large detector by building a single module.

LANNDD – Liquid Argon Neutrino and Nucleon Decay Detector



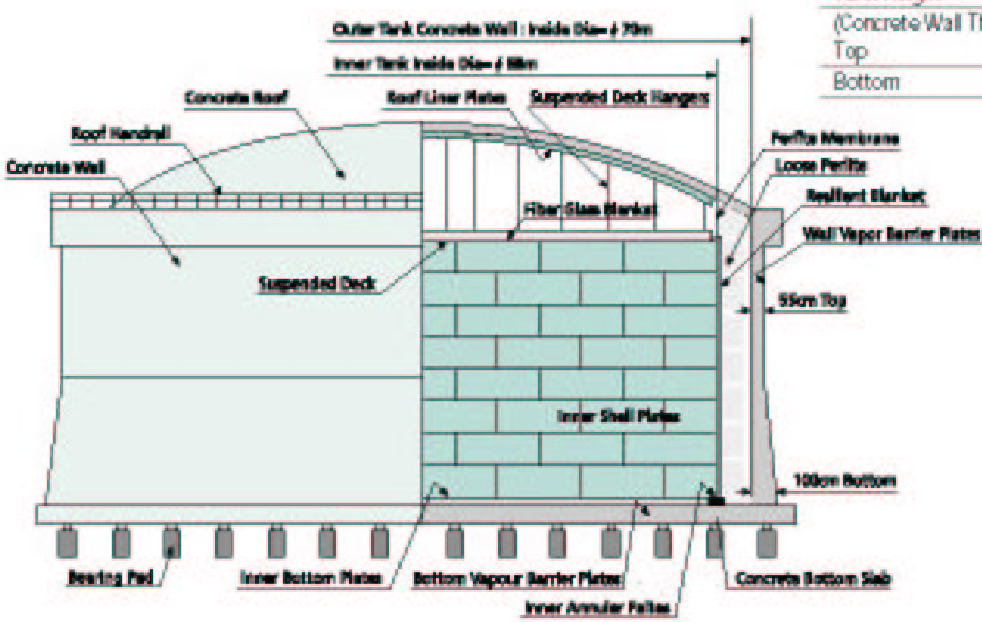
200-kton Cryogenic Tanks Used for LNG Storage

7. LNG Storage Tank

KOGAS

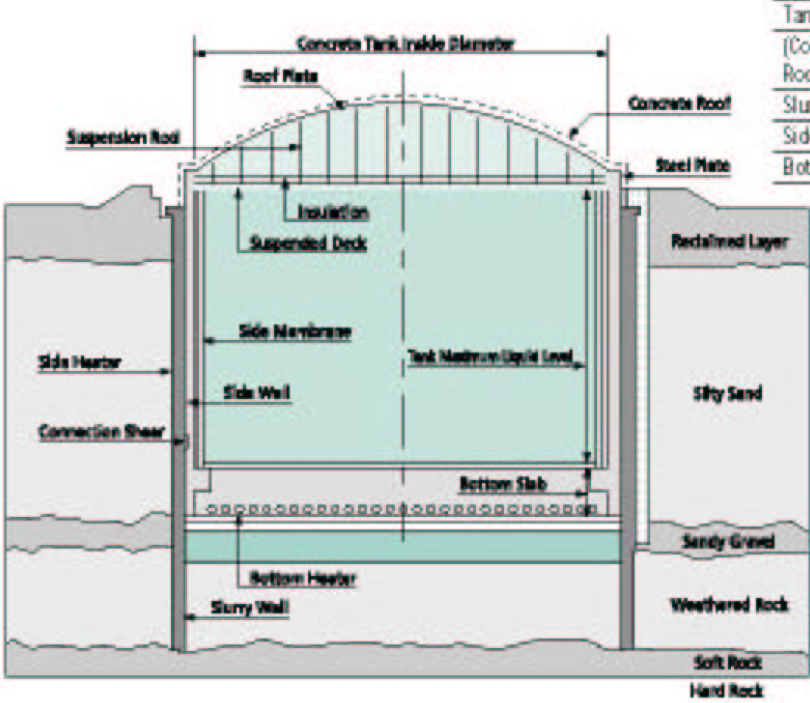
- •Above-ground LNG tank: 100,000m^3

Concrete Tank I· D	· 70m
9%Ni steel Tank I· D	· 68m
Tank Height	46m
(Concrete Wall Thickness) Top	55cm
Bottom	100cm



- •In-ground LNG tank: 140,000m^3(a), 200,000m^3(b)

	a	b
Concrete Tank I· D	· 64m	· 72m
Tank Maximum Liquid Level	43.65m	49.2m
(Concrete Thickness) Roof	0.6~1.3m	0.6~1.4m
Slurry Wall	1.5m	1.7m
Side Wall	2.5m	3.0m
Bottom Slab	7.7m	9.0m



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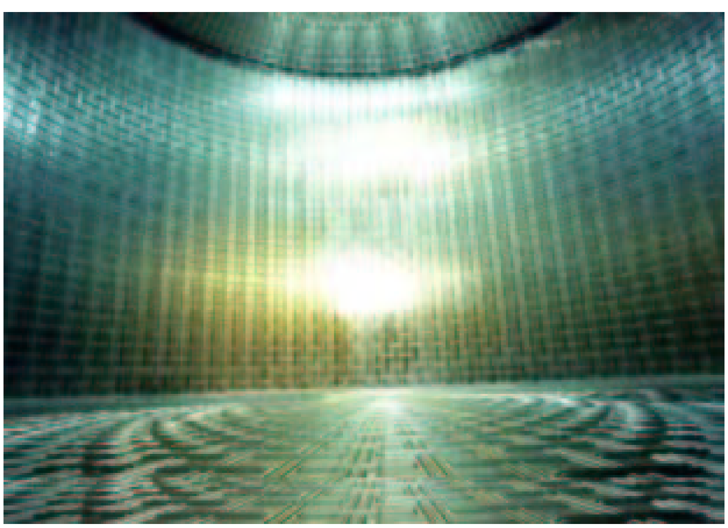
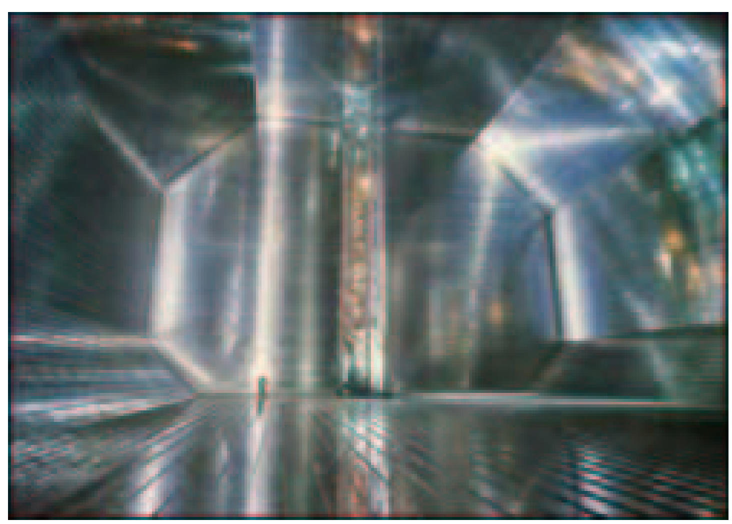
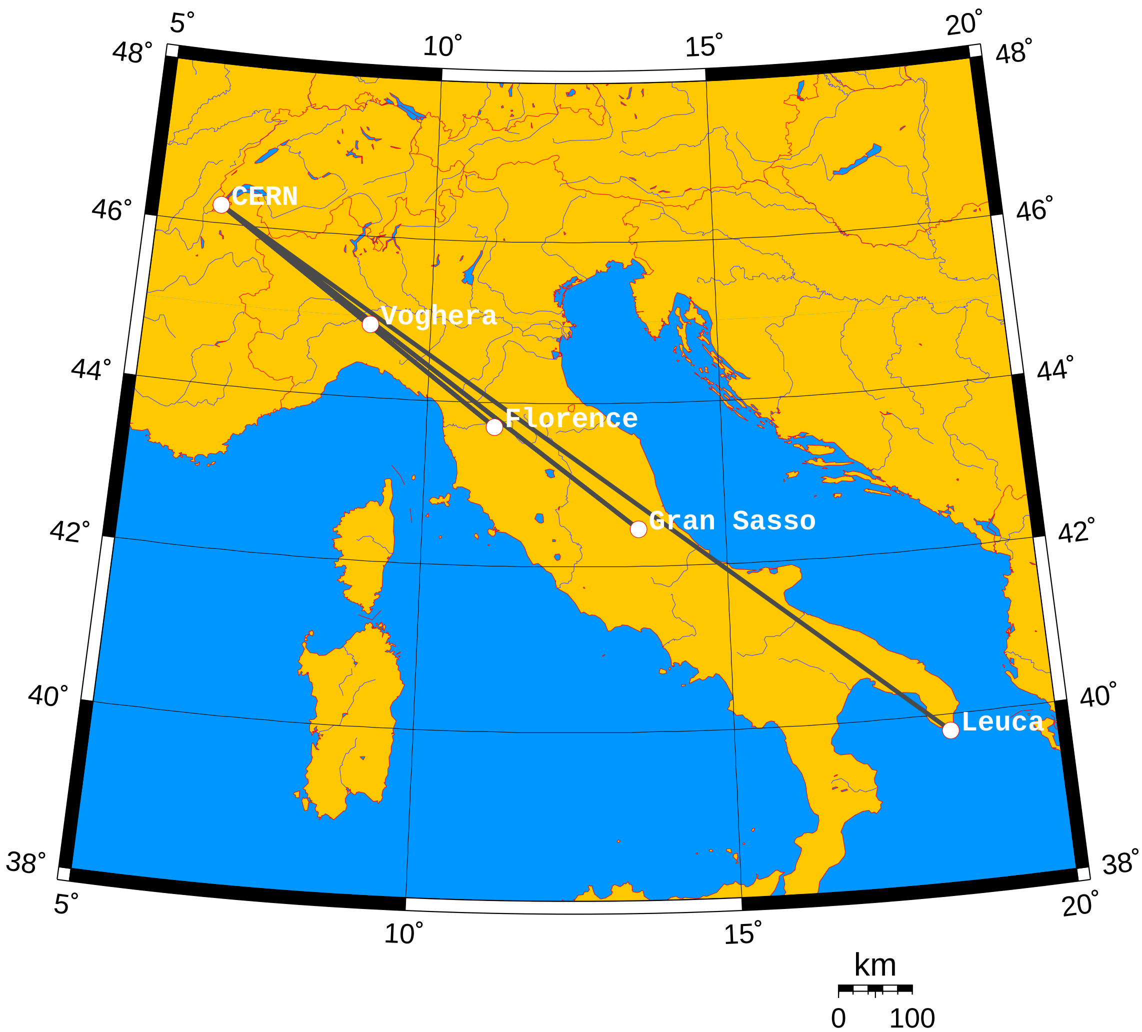
Cryogenic LNG Storage Tanks





Off-Axis Neutrino Beams from CERN

Site	Distance to CERN (km)	Lat.	Long.	$\angle_{\rm CERN}$ 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.	$\angle_{\rm JHF}$ 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°