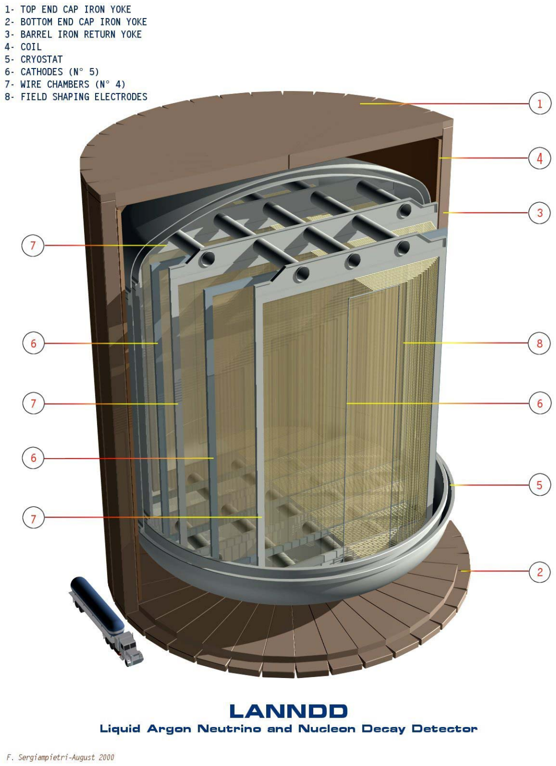
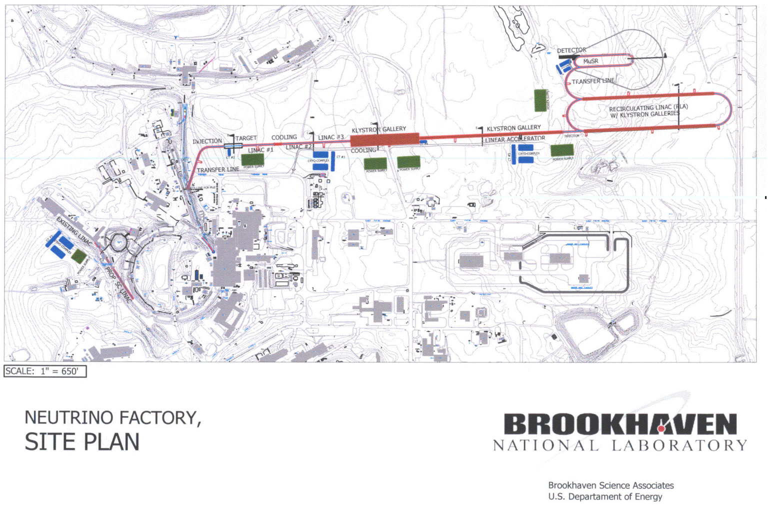
Physics with a Neutrino Superbeam





Kirk T. McDonald

Princeton U.

`mcdonald@puphep.princeton.edu`

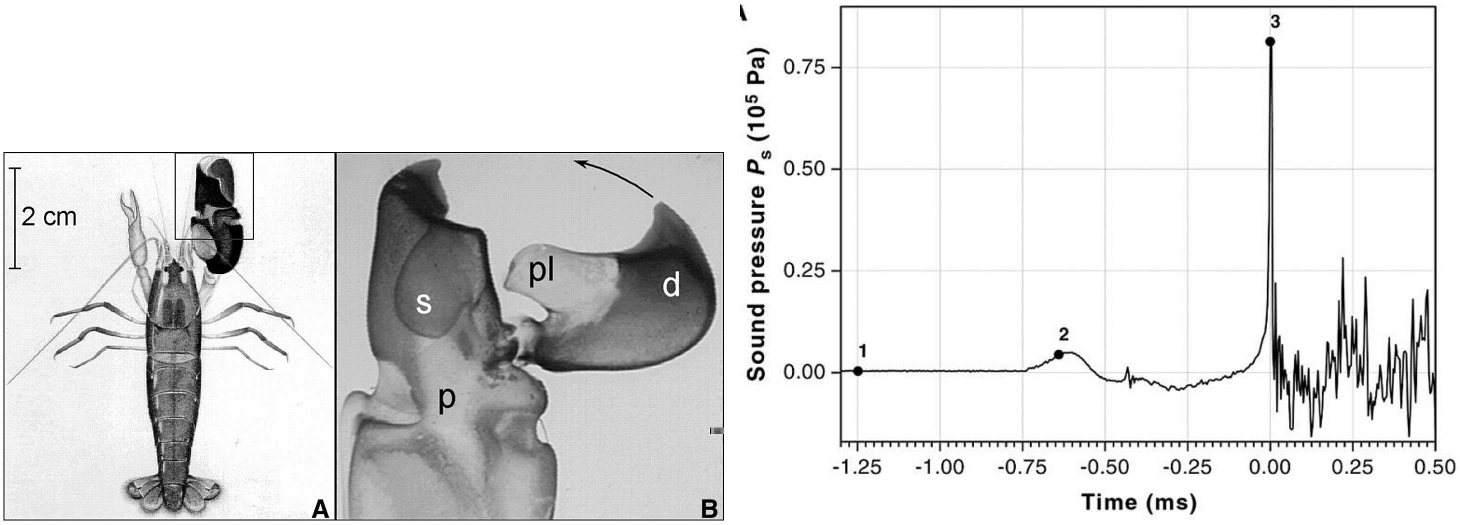
Physics Colloquium at Brookhaven National Laboratory

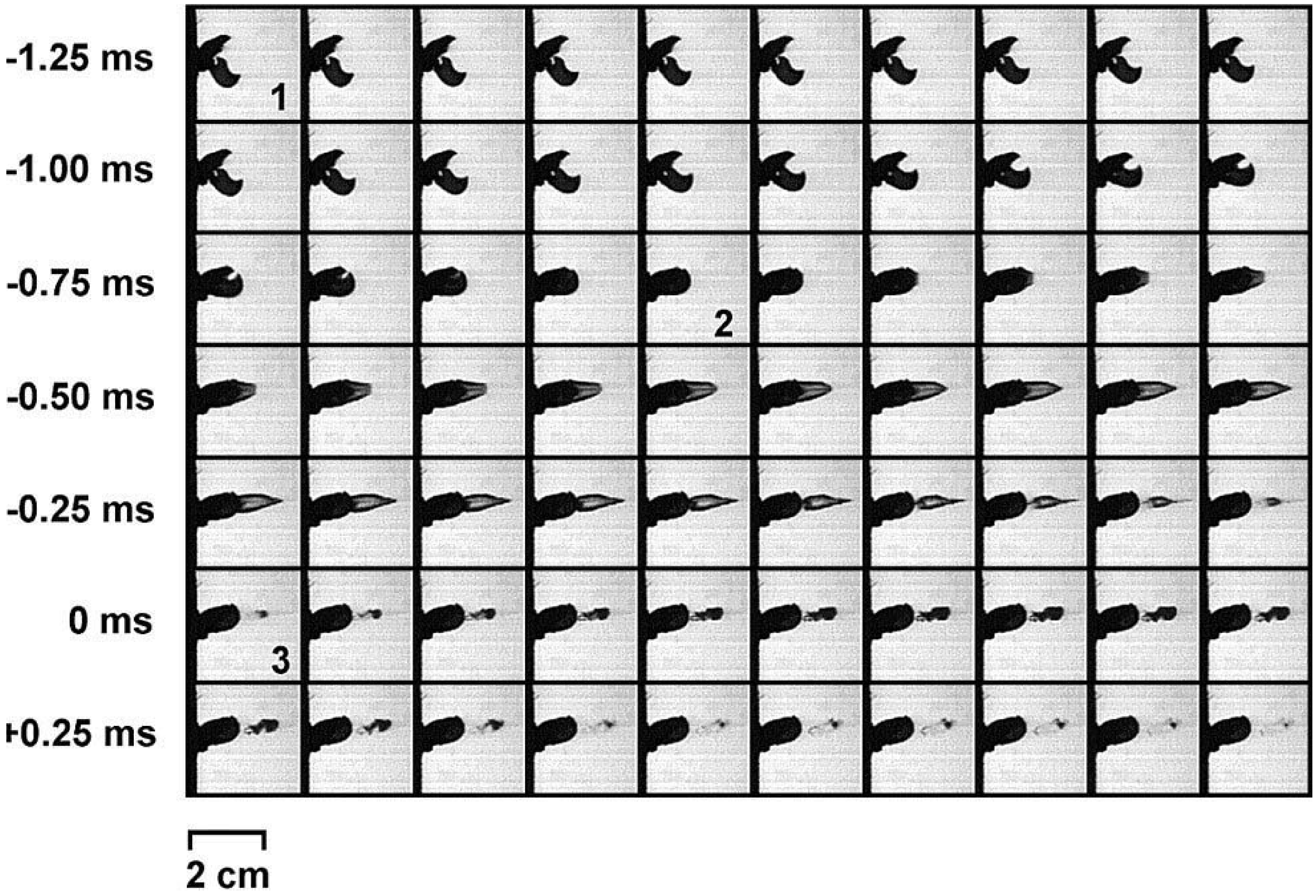
November 27, 2001

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

Snapping Shrimp Stun Their Prey with Pressure Waves from Collapsing Bubbles

M. Versluis, Science **289**, 2114 (2000).





Starting the Second Century of Neutrinos

1896 – Bequerel discovers radioactivity of uranium salts.

1899 – Rutherford identifies α and β radioactivity.

1914-1927 – Chadwick: the β energy spectrum is continuous.

1933 – Pauli: β decay involves a neutrino, $n \to p + e + \overline{\nu}_e$.

1934 – Fermi: theory of β decay with very light neutrinos.

1956 – Cowan and Reines detect the $\overline{\nu}_e$ via $\overline{\nu}_e + p \to e^+ + n$.

1957 – Pontecorvo: ν_e could oscillate into ν_μ.

1962 – Lederman, Schwartz and Steinberger detect the ν_μ.

1968 – Davis reports the first solar neutrino (ν_e) “deficit”.

1976 – Perl *et al.* discover the τ lepton; ν_τ is presumed to exist.

1990 – Γ_{Z^0} measured at LEP, ⇒ only 3 light, SM neutrinos.

1998 – Superkamiokande: ν_μ's disappear over Earth distances.

2001 – SNO: Solar neutrino deficit due to neutrino oscillations.

There are 3 known types of neutrinos, ν_e, ν_μ, and ν_τ, which are partners to the three charged leptons e, μ, and τ.

Oscillations of Massive Neutrinos

Neutrinos could have a small mass (Pauli, Fermi, Majorana, 1930's).

Massive neutrinos can mix (Pontecorvo, 1957).

In the example of only two massive neutrinos (that don't decay), with mass eigenstates ν_1 and ν_2 with mass difference Δm and mixing angle θ, the flavor eigenstates ν_a and ν_b are related by

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}.$$

The probability that a neutrino of flavor ν_a and energy E appears as flavor ν_b after traversing distance L in vacuum is

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 [\mathrm{eV}^2]\ L[\mathrm{km}]}{E[\mathrm{GeV}]} \right).$$

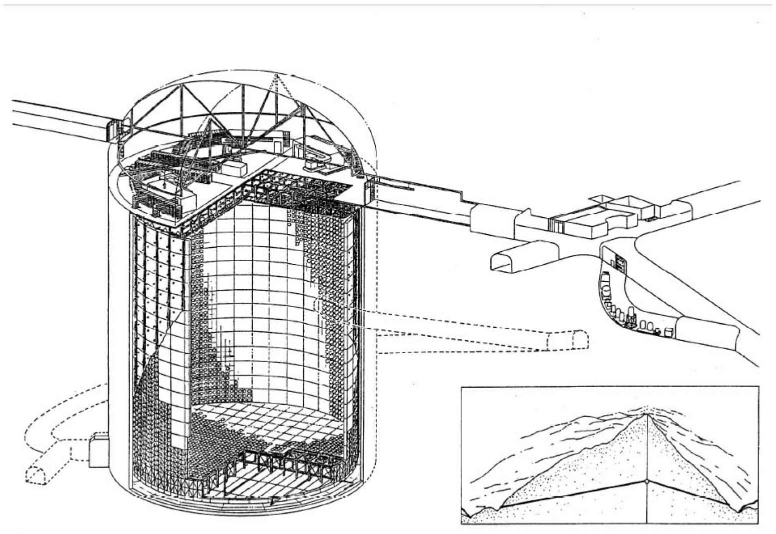
The probability that ν_a does not disappear is

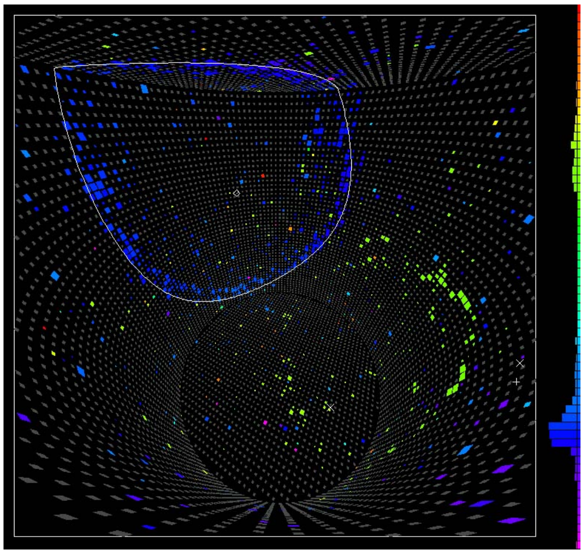
$$P(\nu_a \to \nu_a) = 1 - P(\nu_a \to \nu_b),$$

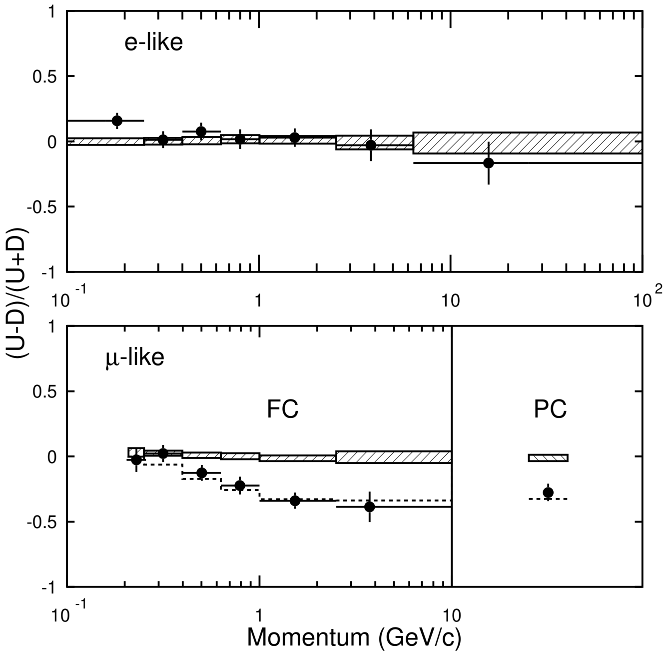
since we presume that neutrinos do not decay.

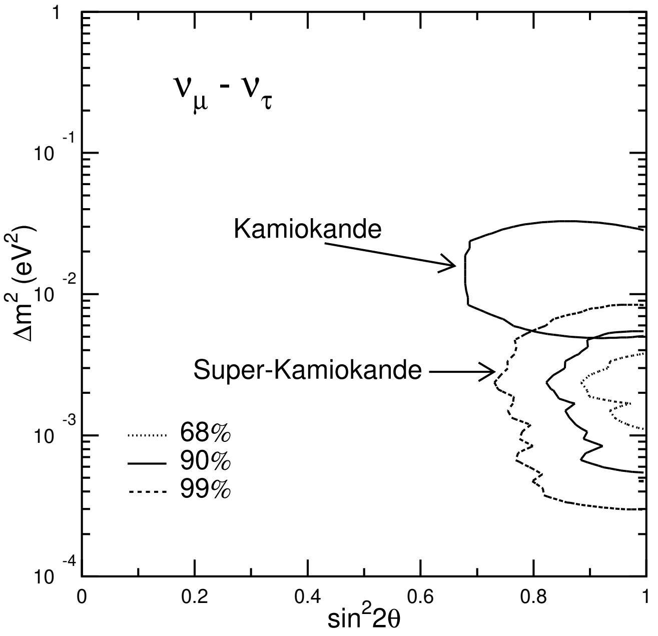
A Sketch of Current Data

- The **Atmospheric Neutrino “Anomaly”** suggests that GeV ν_μ’s (from $p+N_2 \to \pi \to \mu\nu_\mu$) disappear while traversing the Earth’s diameter, $\Rightarrow \Delta m^2 \approx 10^{-3}$ (eV)^2 for $\sin^2 2\theta \approx 1$. (Kamiokande, IMB, Soudan-2, MACRO, Super-Kamiokande)

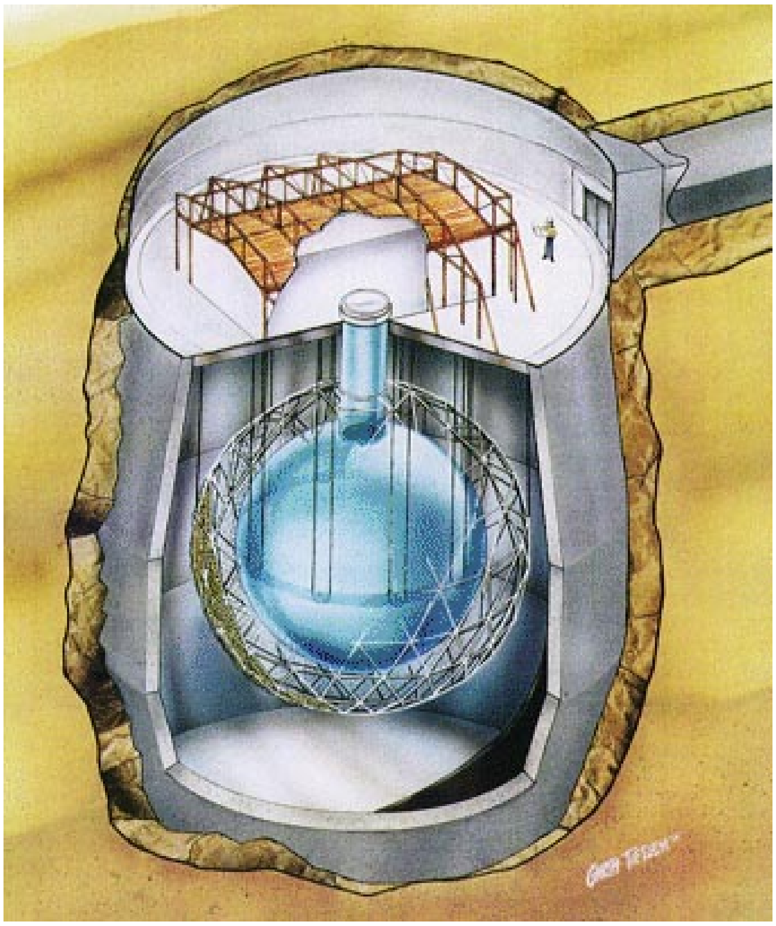


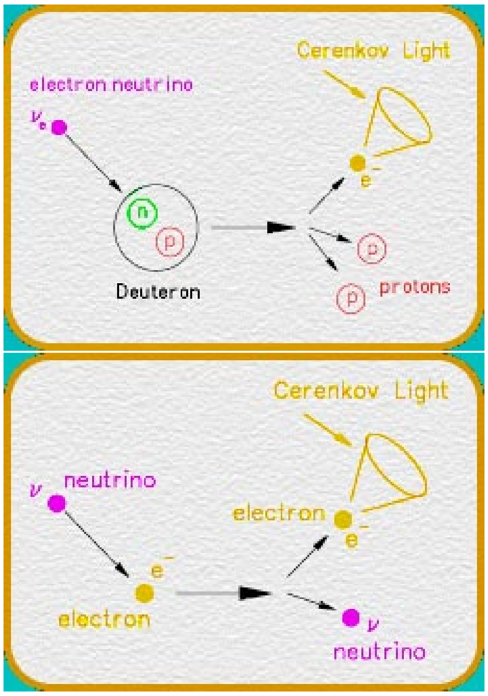






- **SNO** uses deuterium to study **Solar Neutrinos**.





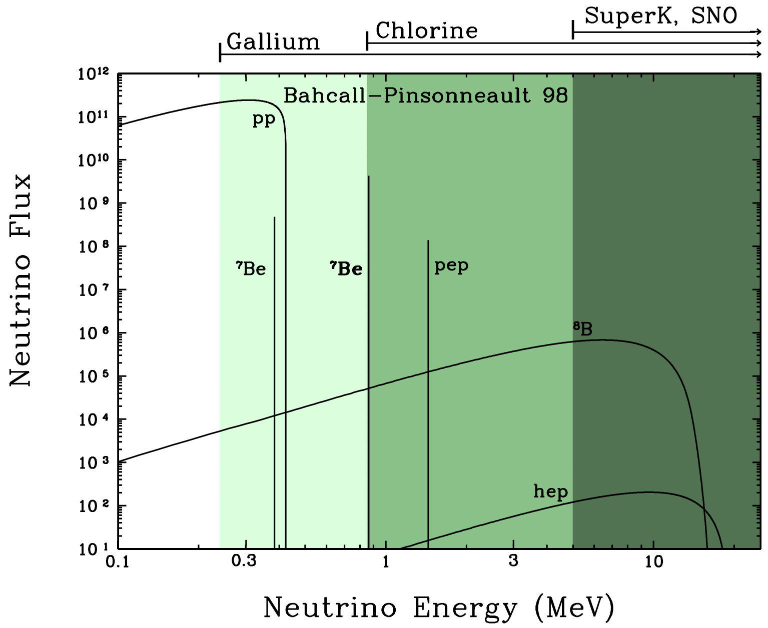
Only electron neutrinos can cause $\nu + d \to p + p + e$.

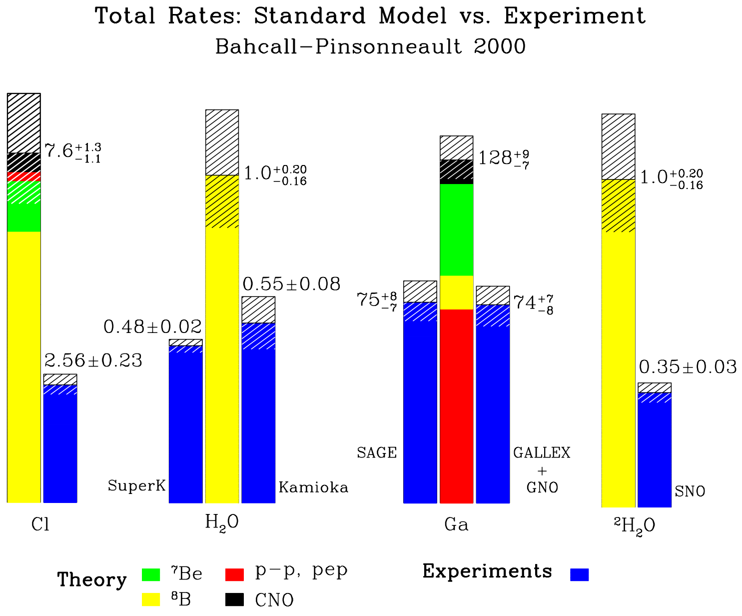
But any neutrino can cause $\nu + e \to \nu + e$.

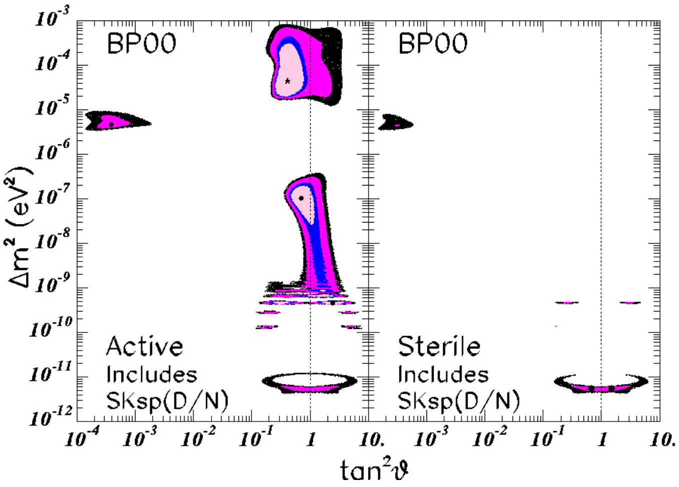
SNO observes Rate$(\nu + d \to p + p + e) \approx 0.75 \pm 0.05$ of Rate$(\nu + e \to \nu + e)$ seen by SuperK.

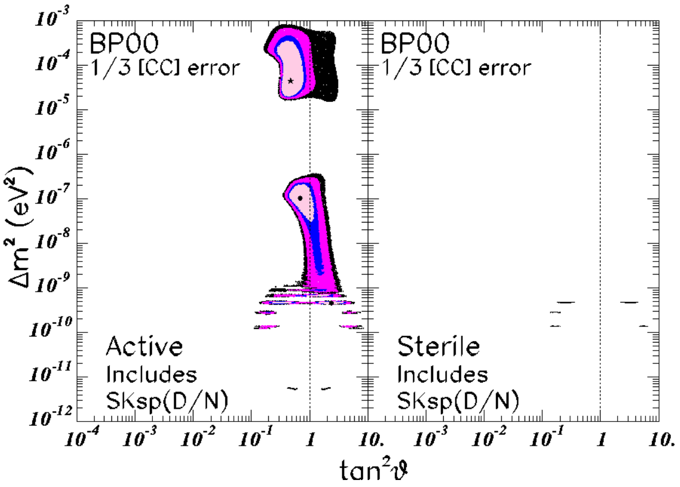
$\Rightarrow$ 25% of electron neutrinos change into another type of neutrino between the Sun and the Earth.

- The **Solar Neutrino "Deficit"** suggests that MeV ν_e's disappear between the center of the Sun and the Earth.
  $\Rightarrow \Delta m^2 \approx 10^{-10}\ (\mathrm{eV})^2$ for $\sin^2 2\theta \approx 1$, if vacuum oscillations.
  (Homestake, Super-Kamiokande, GALLEX, SAGE, SNO)







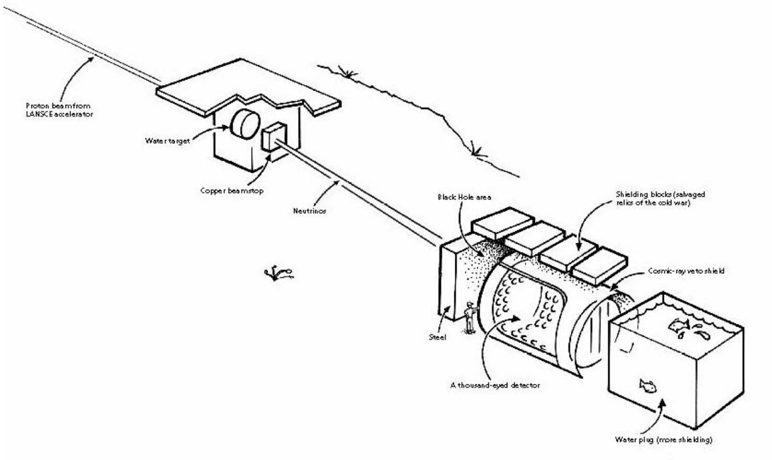


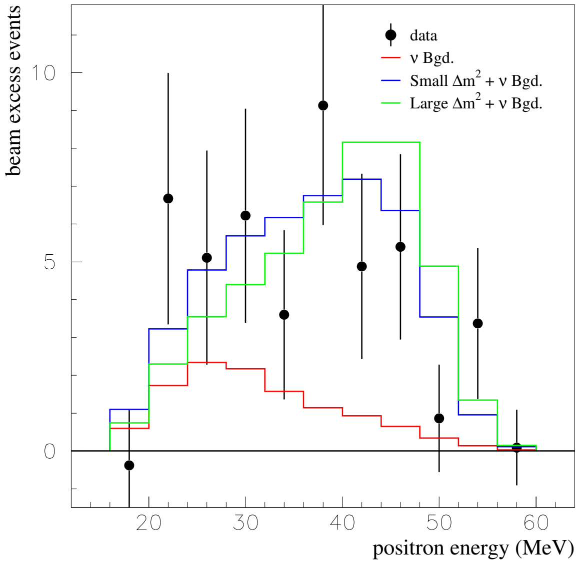
– Bahcall *et al.*, hep-ex/0106258.

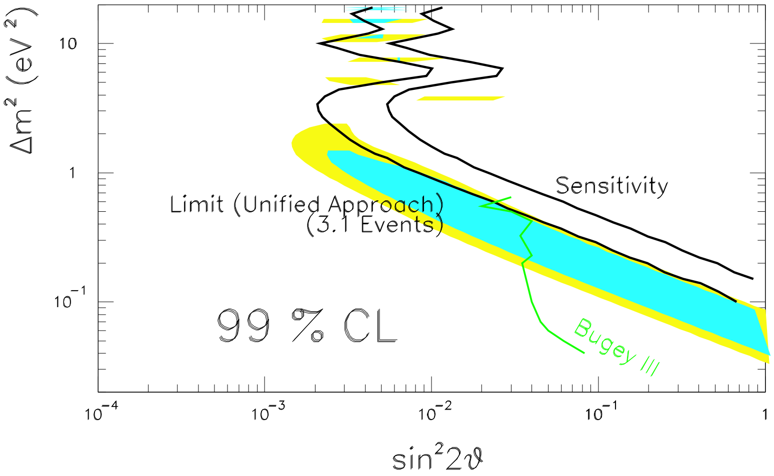
Still four solutions to the solar neutrino problem

– Though sterile neutrinos seem increasingly unlikely.

- The **LSND Experiment** suggests that 30-MeV $\overline{\nu}_\mu$'s (from $p + H_2O \to \pi^- \to \mu^- \overline{\nu}_\mu$) appear as $\overline{\nu}_e$'s after 30 m. $\Rightarrow \Delta m^2 \approx 1\ (\mathrm{eV})^2$, but reactor data requires $\sin^2 2\theta \lesssim 0.03$.







The atmospheric neutrino anomaly + the solar neutrino deficit (if both correct) require at least 3 massive neutrinos.

If LSND is correct as well, need at least 4 massive neutrinos.

The measured width of the Z^0 boson (LEP) $\Rightarrow$ only 3 Standard Model neutrinos. A 4th massive neutrino must be "sterile".

The Supersymmetric Seesaw

A provocative conjecture is that neutrino mass m_ν is coupled to two other mass scales, m_I (intermediate) and m_H (heavy), according to

$$m_\nu = \frac{M_I^2}{M_H}.$$

(Gell-Mann, Ramond, Slansky, 1979)

A particularly suggestive variant takes $m_I = \langle \phi_{\rm Higgs} \rangle = 250$ GeV; Then

$m_\nu \approx \sqrt{\Delta m^2 ({\rm atmospheric})} \approx 0.06\ {\rm eV} \Rightarrow m_H \approx 5 \times 10^{15}\ {\rm GeV}.$

This is perhaps the best experimental evidence for a grand unification scale, such as that underlying supersymmetric SO(10) models.

[Others interpret the need for a mass scale beyond the electroweak scale (≈ 1 TeV) as suggesting there exist large extra dimensions.]

Mixing of Three Neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where $c_{12} = \cos\theta_{12}$, *etc.* [Maki, Nakagawa, Sakata, 2 × 2 form, 1962; Lee & Shrock, 3 × 3 form, 1977].

Three massive neutrinos ⇒ six independent parameters:

- Two differences of the squares of the neutrino masses.
  Ex: $\Delta m^2_{12} = \Delta m^2$(solar) and $\Delta m^2_{23} = \Delta m^2$(atmospheric).
- Three mixing angles: $\theta_{12} \overset{?}{\approx} 45°$, θ_{13}, $\theta_{23} \approx 45°$,
- A phase δ related to CP violation,
- [$J_{CP} = s_{12}s_{23}s_{31}c_{12}c_{23}c^2_{31}s_\delta$ = Jarlskog invariant.]

The MNS neutrino mixing matrix is more provocative than the CKM quark matrix; if 2 of 3 mixing angles are near 45° (⇒ "bimaximal" mixing), there is likely an associated symmetry.

If four massive neutrinos, then 6 mixing angles, 3 phases, 3 independent squares of mass differences.

Matter Effects

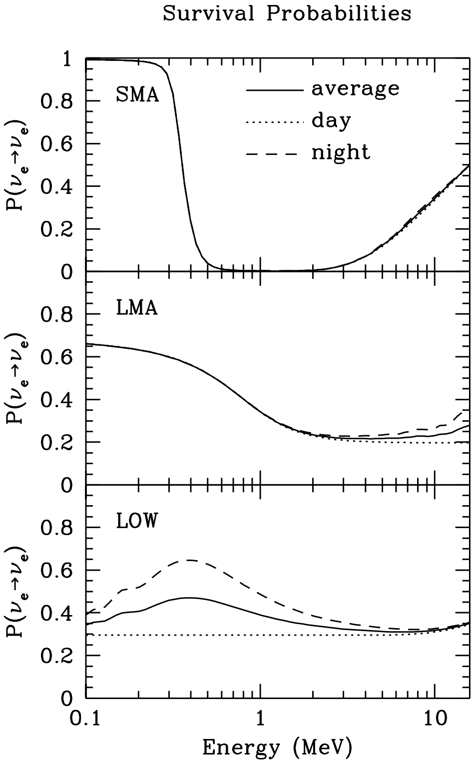
ν_e's can interact with electrons via both W and Z^0 exchanges, but other neutrinos can only interact with e's via Z^0 exchange.

$$\Rightarrow \sin^2 2\theta_{\text{matter}} = \frac{\sin^2 2\theta_{\text{vac}}}{\sin^2 2\theta_{\text{vac}} + (\cos 2\theta_{\text{vac}} - A)^2},$$

where $A = 2\sqrt{2} G_F N_e E / \Delta m^2$ depends on sign of Δm^2.

At the "resonance", $\cos 2\theta_{\text{vac}} = A$, $\sin^2 2\theta_{\text{matter}} = 1$ even if $\sin^2 2\theta_{\text{vac}}$ is small (Wolfenstein, 1978, Mikheyev, Smirnov, 1986).

$\Rightarrow$ 3 MSW solutions to the solar neutrino problem:



In any of these MSW solutions, $\Delta m^2_{\text{solar}} > 0$.

Too Many Solutions

There are 8 scenarios suggested by present data:

- Either 3 or 4 massive neutrinos.
- Four solutions to the solar neutrino problem:
  1. Vacuum oscillation (VO, or "Just So") solution;
     $\Delta m^2_{12} \approx (0.5 - 5.0) \times 10^{-10}$ eV^2, $\sin^2 2\theta_{12} \approx (0.7 - 1.0)$.
  2. Low MSW solution;
     $\Delta m^2_{12} \approx (0.5 - 2.0) \times 10^{-7}$ eV^2, $\sin^2 2\theta_{12} \approx (0.9 - 1.0)$.
  3. Small mixing angle (SMA) MSW solution;
     $\Delta m^2_{12} \approx (4.0 - 9.0) \times 10^{-6}$ eV^2, $\sin^2 2\theta_{12} \approx (0.001 - 0.01)$.
  4. **Large mixing angle (LMA) MSW solution**;
     $\Delta m^2_{12} \approx (0.2 - 2.0) \times 10^{-4}$ eV^2, $\sin^2 \theta_{12} \approx (0.65 - 0.96)$.
- Atmospheric neutrino data $\Rightarrow$ $\Delta m^2_{23} \approx (3 - 5) \times 10^{-3}$ eV^2, $\sin^2 \theta_{12} > 0.8$.
- θ_{13} very poorly known; δ completely unknown.

SO(10) Fit to CKM and MNS Matrices

[Albright and Barr, P.R. D **64**, 073010 (2001), hep-ph/0110259, Albright and Geer, hep-ph/0108070.]

12 Input parameters:

$$M_U \simeq 113 \text{ GeV}, \quad M_D \simeq 1 \text{ GeV}, \quad \Lambda_R = 2.4 \times 10^{14} \text{ GeV},$$

$$\sigma = 1.78, \qquad \epsilon = 0.145, \qquad \delta = 0.0086,$$

$$\delta' = 0.0079, \qquad \phi = 126^\circ, \qquad \eta = 8 \times 10^{-6},$$

$$1 < a' < 2.4, \qquad |\phi'| < 75^\circ, \qquad 1.8 < b = c < 5.2,$$

28 Fitted Parameters (LMA Solution):

$$m_t = 165 \text{ GeV}, \qquad m_c = 1.23 \text{ GeV}, \qquad m_u = 4.5 \text{ MeV},$$

$$m_b = 4.25 \text{ GeV}, \qquad m_s = 148 \text{ MeV}, \qquad m_d = 7.9 \text{ MeV},$$

$$V_{us} = 0.220, \qquad V_{cb} = 0.0395, \qquad |V_{ub}/V_{cb}| = 0.080,$$

$$\delta_{CP,CKM} = 64^\circ, \qquad \sin 2\beta = 0.64,$$

$$m_\tau = 1.777 \text{ GeV}, \qquad m_\mu = 105.7 \text{ MeV}, \qquad m_e = 0.511 \text{ MeV},$$

$$M_{R,1} = 2.8 \times 10^8 \text{ GeV}, \quad M_{R,2} = 2.8 \times 10^8 \text{ GeV}, \quad M_{R,3} = 2.5 \times 10^{14} \text{ GeV},$$

$$m_1 = 5.6 \times 10^{-3} \text{ eV}, \qquad m_2 = 9.8 \times 10^{-3} \text{ eV}, \qquad m_3 = 57 \times 10^{-3} \text{ eV},$$

$$\Delta m^2_{32} = 3.2 \times 10^{-3} \text{ eV}^2, \quad \Delta m^2_{21} = 0.2\text{–}2 \times 10^{-4} \text{ eV}^2, \quad |\delta_{CP,MNS}| < 50^\circ,$$

$$\sin^2 2\theta_{32} = 0.994, \qquad \sin^2 2\theta_{21} = 0.6\text{–}0.9, \qquad \sin^2 2\theta_{13} < 0.006.$$

Central values: $\sin^2 2\theta_{13} = 0.003$, $\delta_{CP,MNS} \approx 0$.

Proton Decay in SO(10) Models

[Pati, hep-ph/0106082.]

In (nonSUSY) SU(5) models, $p \to \pi^0 e^+$ is favored – but ruled out by experiment.

SUSY SU(5) has difficulty accommodating the observed data on neutrino mixing, as well as the proton decay limits.

In SUSY SO(10) models, $p \to \bar{\nu} K^+$ is favored relative to $p \to \pi^0 e^+$, with $\tau_p \approx 10^{31}$ years in MSSM, and $\tau_p \approx 10^{33-34}$ years in ESSM.

Implications for Experiment

Future studies of neutrino mixing should include good capability to study $p \to \bar{\nu} K^+$.

Studies of CP violation in neutrino mixing require lepton charge identification: both $\mu^\pm$ and $e^\pm$ desirable.

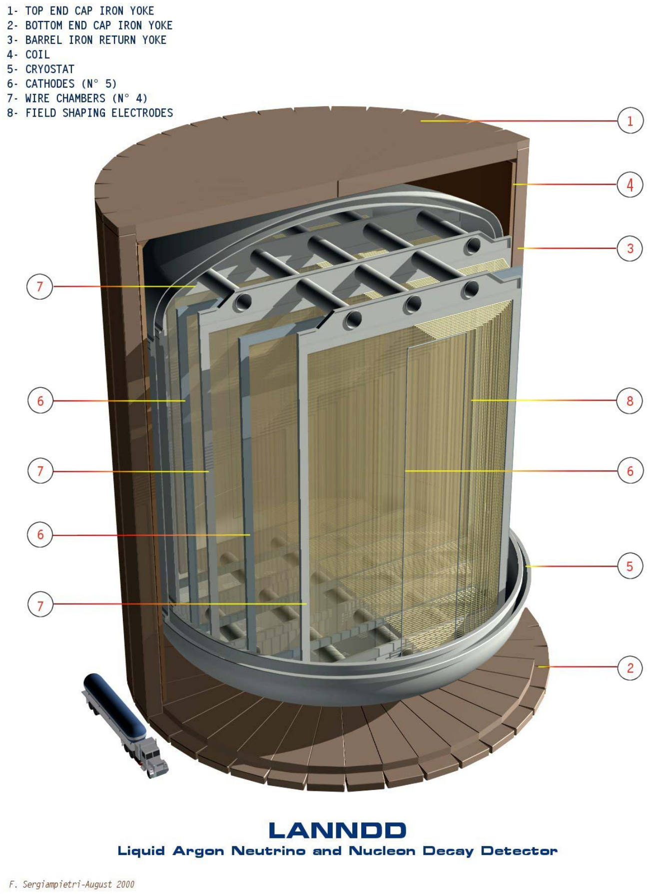
$\Rightarrow$ Water Čerenkov, Iron-Scintillator, and Liquid Scintillator detectors disfavored.

$\Rightarrow$ **Magnetized Liquid Argon** is the most flexible option.

LANNDD – A Magnetized Liquid Argon Detector

Use a magnetized detector to distinguish ν_μ from $\bar{\nu}_\mu$ via sign of $\mu^\pm$ produced.

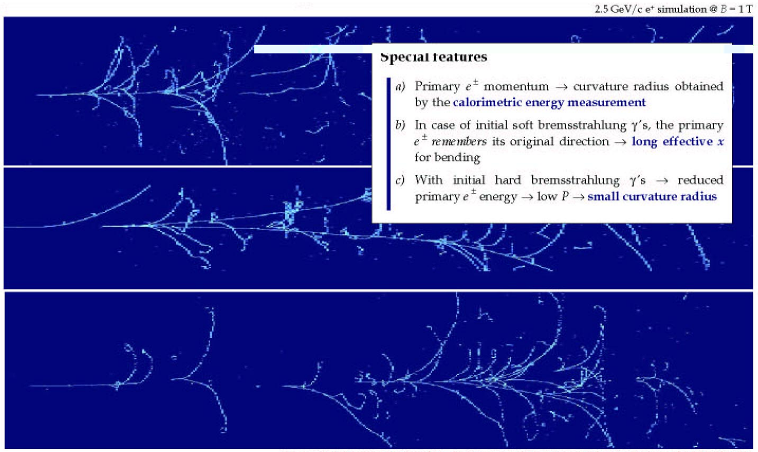
Use a magnetized liquid argon detector to distinguish ν_e from $\bar{\nu}_e$ via sign of $e^\pm$ produced.



LANNDD

Liquid Argon Neutrino and Nucleon Decay Detector

F. Sergiampietri-August 2000



Special features

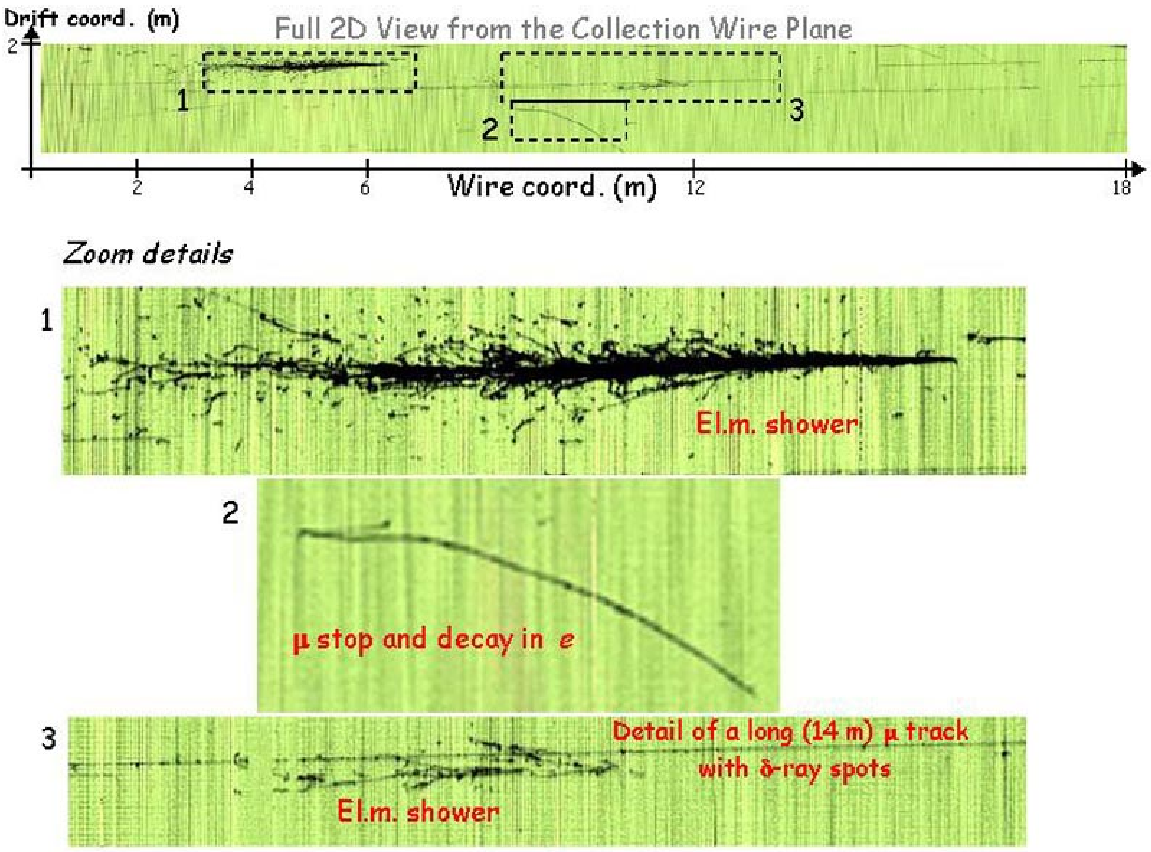
- *a)* Primary $e^\pm$ momentum → curvature radius obtained by the **calorimetric energy measurement**
- *b)* In case of initial soft bremsstrahlung γ's, the primary $e^\pm$ *remembers* its original direction → **long effective x** for bending
- *c)* With initial hard bremsstrahlung γ's → reduced primary $e^\pm$ energy → low P → **small curvature radius**

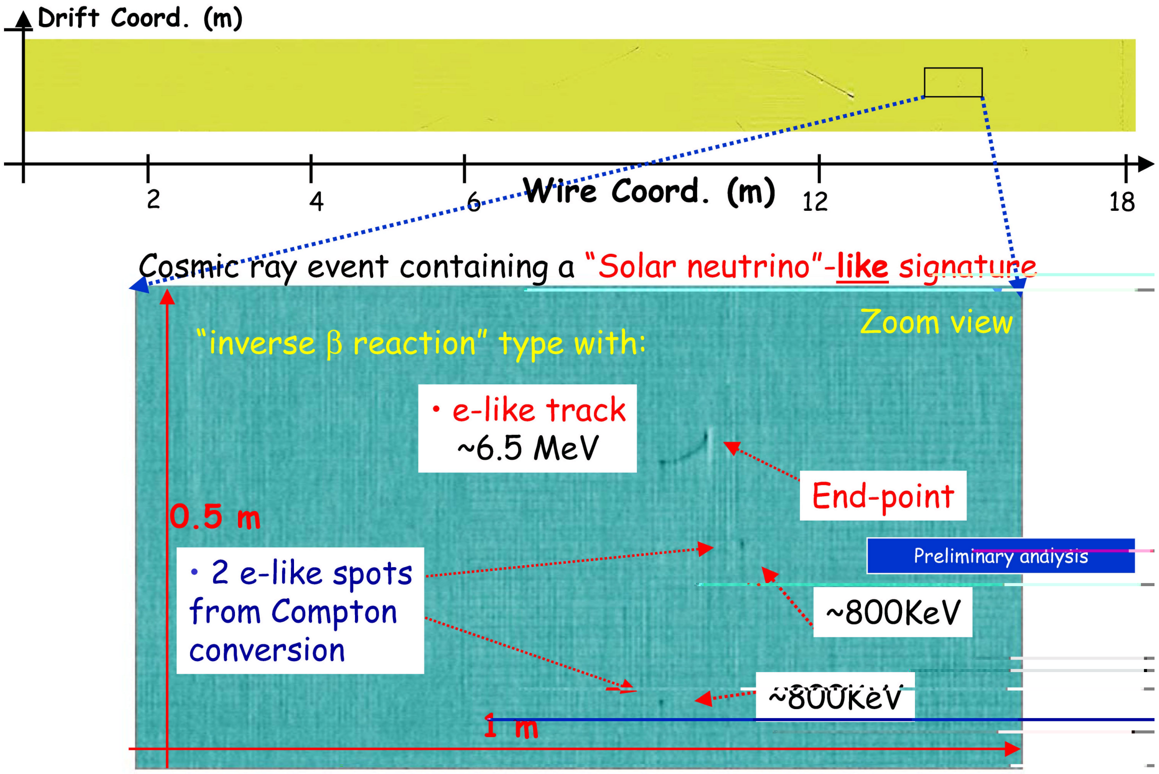
A. Bueno, M. Campanelli, A. Rubbia, *IX International Workshop on "Neutrino Telescopes"*, VENICE, 2001

Need detector mass of ≈ 100 kton for competitive neutrino physics.

A liquid argon detector has good sensitivity to $p \to \nu K^+$ $\Rightarrow$ 100 kton of LAr is competitive with 1 Mton of water for proton decay.

ICARUS – 300 Ton Liquid Argon Module





Cosmic ray event containing a "Solar neutrino"-like signature

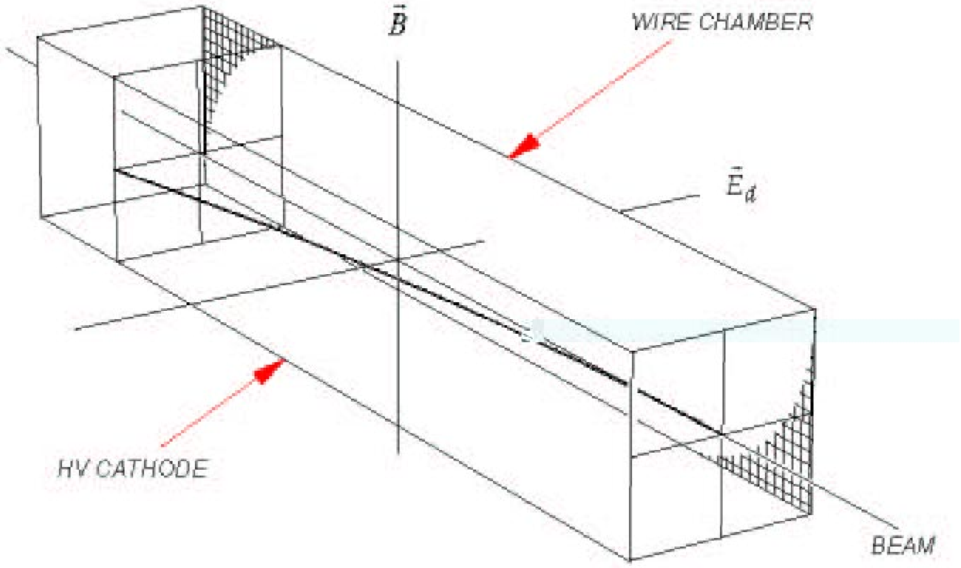
"inverse β reaction" type with:

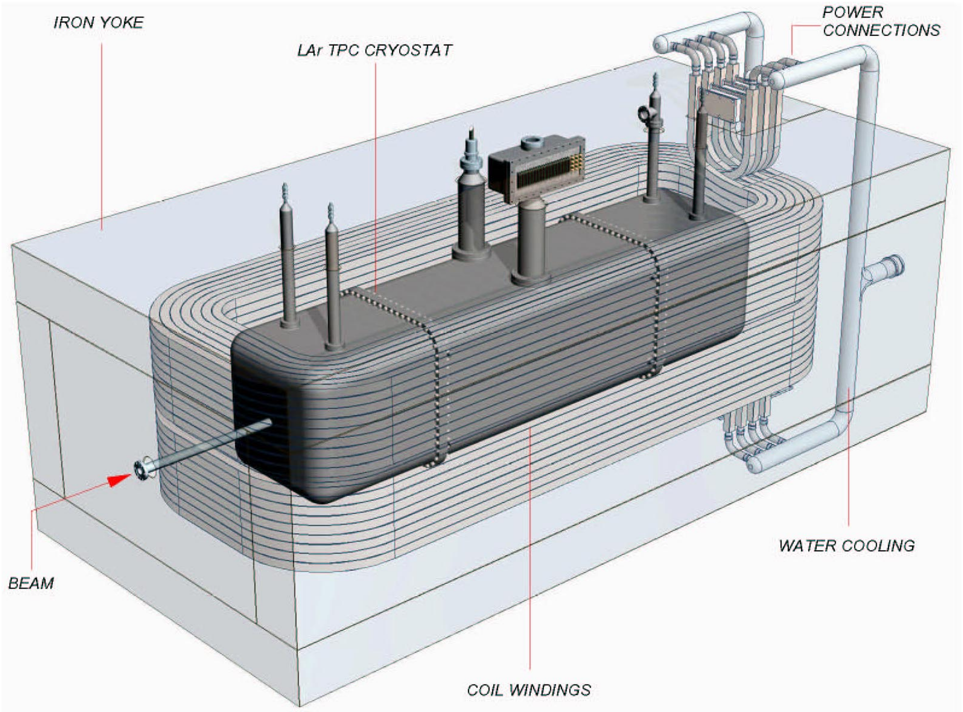
- e-like track ~6.5 MeV
- 2 e-like spots from Compton conversion

T600 test @ Pv: Run 785 - Evt 4 (July 22nd, 2001)

Demonstration of Electron Sign Determination

Study electromagnetic showers or 0.5-10 GeV in a liquid argon TPC 6 rad. lengths deep, ±1 rad. length wide, in magnetic field up to 1 T.





The BNL A3 line (Neutrino Factory Test Beam) is well suited to such a study.

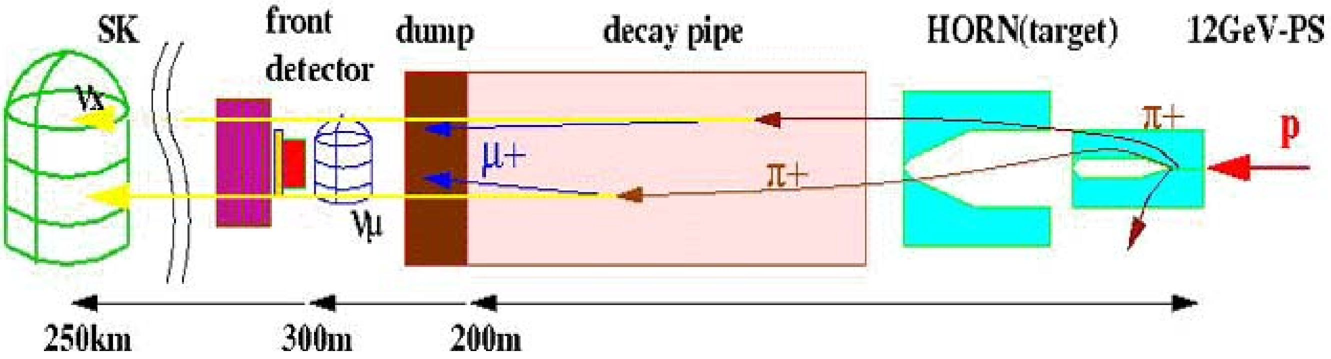
The Next Generation of Neutrino Experiments

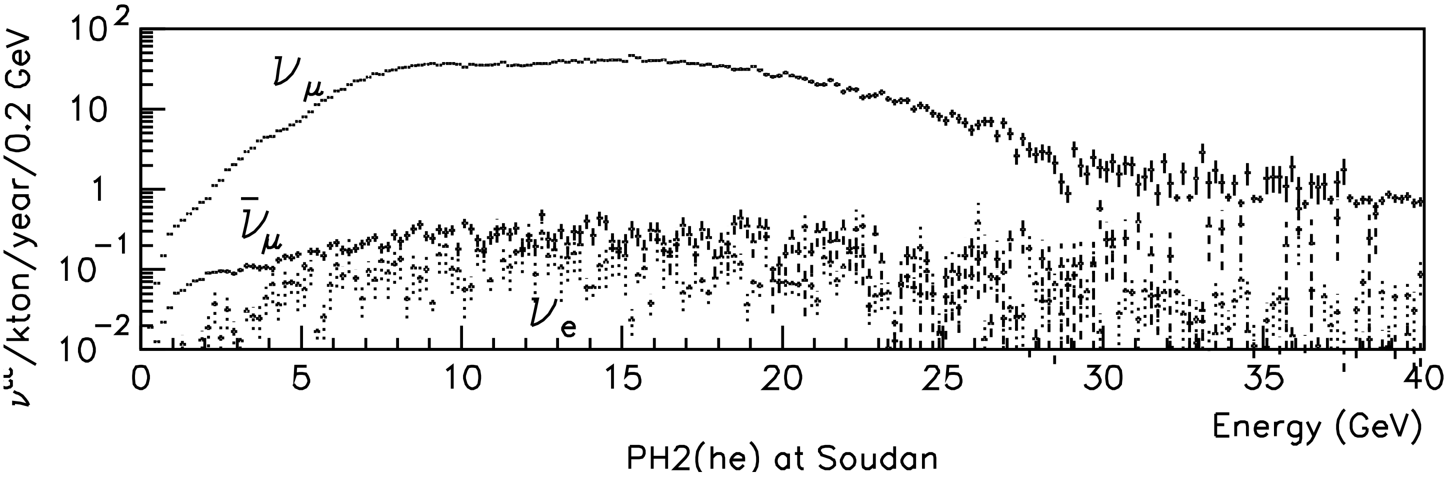
- Short baseline accelerator experiments (miniBoone, CERN) will likely clarify the LSND result.
- Super-Kamiokande + new long baseline accelerator experiments (K2K, Minos, NGS) will firm up measurements of θ_{23} and Δm^2_{23}, but will provide little information on θ_{13} and δ.
- New solar neutrino experiments (BOREXino, HELLAZ, HERON) will explore different portions of the energy spectrum, and clarify possible pathlength-dependent effects.

  SNO should also provide independent confirmation of neutrino oscillations via comparison of reactions
  $\nu + {}^2\mathrm{H} \to p + p + e$ and $\nu + {}^2\mathrm{H} \to p + n + \nu$.
- Reactor experiments such as KamLAND can help clarify whether the LMA solar neutrino solution is correct.
- Each of these experiments studies oscillations of only a single pair of neutrinos.
- The continued search for the neutrinoless double-beta decay ${}^{78}\mathrm{Ge} \to {}^{78}\mathrm{Se} + 2e^-$ will improve the mass limits on Majorana neutrinos to perhaps as low as 0.01 eV (hep-ex/9907040).

The Opportunity for a Neutrino Factory

- Many of the neutrino oscillation solutions permit study of the couplings between 2, 3, and 4 neutrinos in accelerator based experiments.
- More neutrinos are needed!
- Present neutrino beams come from $\pi, K \to \mu\nu_\mu$ with small admixtures of $\overline{\nu}_\mu$ and ν_e from μ and $K \to 3\pi$ decays.

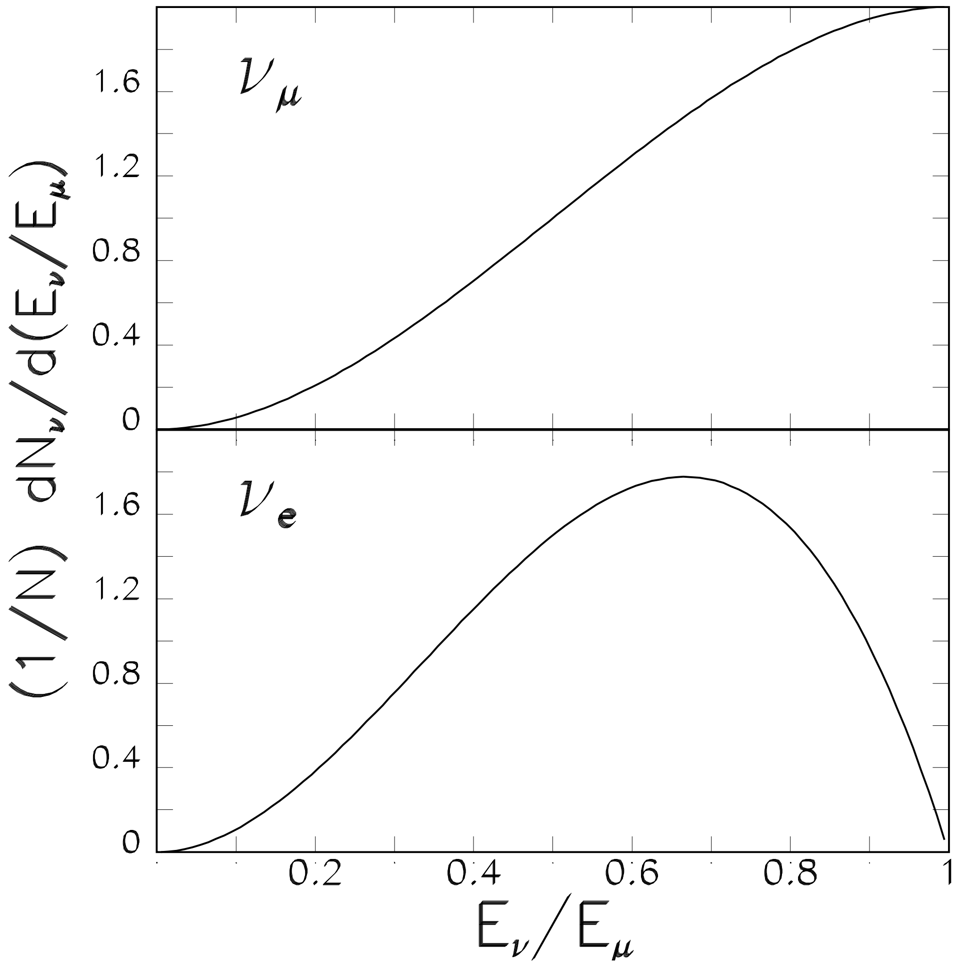




- Cleaner spectra and comparable fluxes of ν_e and ν_μ desirable.

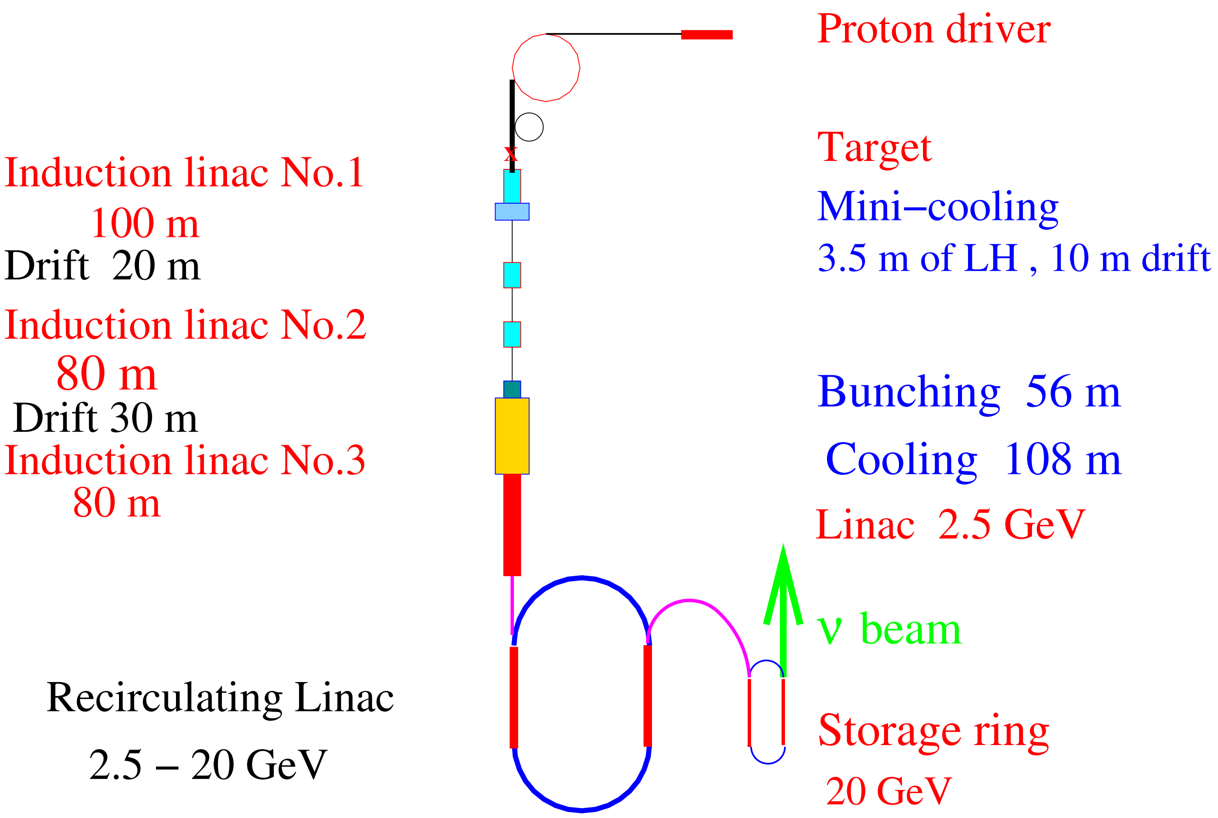
A Neutrino Factory based on a Muon Storage Ring

- Higher (per proton beam power) and better characterized, neutrino fluxes are obtained from μ decay.
- Collect low-energy μ's from π decay,
  Cool the muon bunch,
  Accelerate the μ's to the desired energy,
  Store them in a ring while they decay via $\mu^- \to e^-\nu_\mu\overline{\nu}_e$.
  [Of course, can use μ^+ also.]



Sketch of a Neutrino Factory

[S. Ozaki *et al.*, Neutrino Factory Feasibility Study-2 (4/01)]



Proton driver

Target

Mini−cooling

3.5 m of LH , 10 m drift

Induction linac No.1

100 m

Drift 20 m

Induction linac No.2

80 m

Drift 30 m

Induction linac No.3

80 m

Bunching 56 m

Cooling 108 m

Linac 2.5 GeV

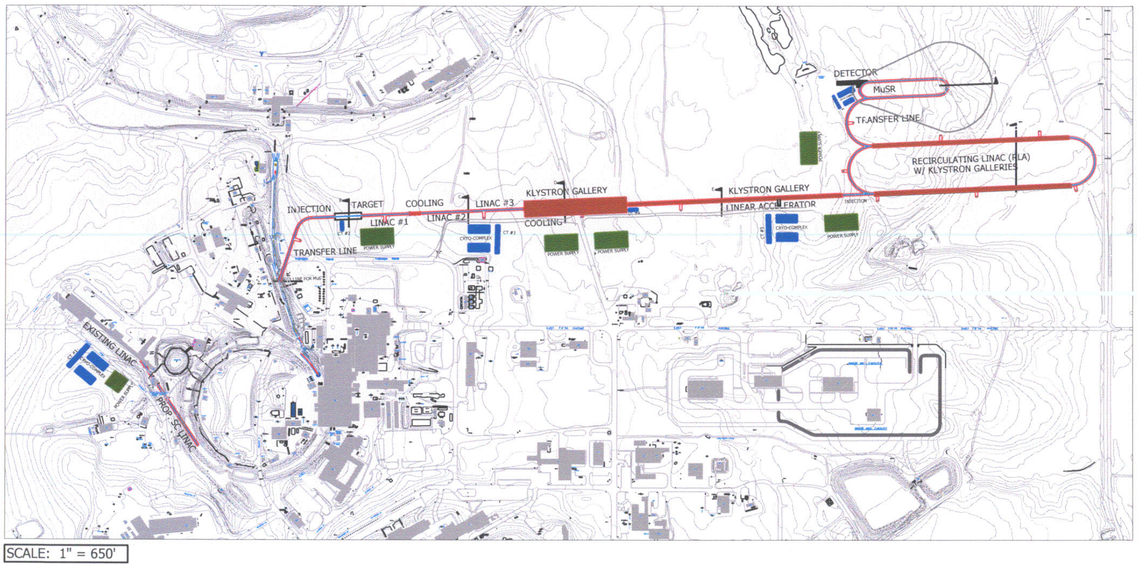
ν beam

Recirculating Linac

2.5 – 20 GeV

Storage ring

20 GeV



NEUTRINO FACTORY,
SITE PLAN

BROOKHAVEN
NATIONAL LABORATORY

Brookhaven Science Associates
U.S. Departament of Energy

6 Classes of Experiments at a Neutrino Factory

$$\nu_\mu \to \nu_e \to e^- \qquad \text{(appearance)}, \tag{1}$$

$$\nu_\mu \to \nu_\mu \to \mu^- \qquad \text{(disappearance)}, \tag{2}$$

$$\nu_\mu \to \nu_\tau \to \tau^- \qquad \text{(appearance)}, \tag{3}$$

$$\overline{\nu}_e \to \overline{\nu}_e \to e^+ \qquad \text{(disappearance)}, \tag{4}$$

$$\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+ \qquad \text{(appearance)}, \tag{5}$$

$$\overline{\nu}_e \to \overline{\nu}_\tau \to \tau^+ \qquad \text{(appearance)}. \tag{6}$$

[Plus 6 corresponding processes for $\overline{\nu}_\mu$ from μ^+ decay.]

Processes (2) and (5) are easiest to detect, via the final state μ.

Process (5) is noteworthy for having a "wrong-sign" μ.

Processes (3) and (6) with a final state τ require μ's of 10's of GeV.

Processes (1) and (4) with a final state electron are difficult to distinguish – unless use magnetized liquid argon.

Magnetic detectors of 10's of kilotons will be required, with fine segmentation if τ's are to be measured.

The Rates are High at a Neutrino Factory

Charged current event rates per kton-yr.

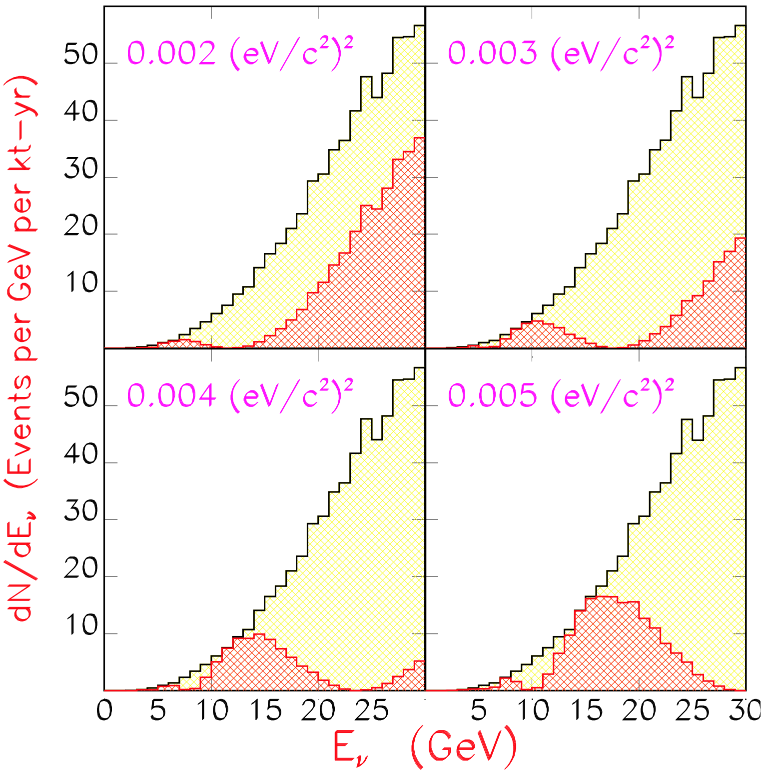
($L = 732$ km)	ν_μ	$\overline{\nu}_e$
Neutrino Factory	(2×10^{20} ν_μ/yr)	
10 GeV	2200	1300
20 GeV	18,000	11,000
50 GeV	2.9×10^5	1.8×10^5
250 GeV	3.6×10^7	2.3×10^7
MINOS (WBB)		
Low energy	460	1.3
Medium energy	1440	0.9
High energy	3200	0.9

Even a low-energy neutrino factory has high rates of electron neutrino interactions.

A neutrino factory with $E_\mu \gtrsim 20$ GeV is competitive for muon neutrino interactions.

$\nu_\mu \to \ \nu_\mu \to \mu^-$ **Disappearance**

$$P(\overline{\nu}_e \to \overline{\nu}_\mu) = (\sin^2 2\theta_{23} \cos^2 \theta_{13} + \sin^2 2\theta_{13} \sin^4 \theta_{23}) \sin^2 \frac{1.27\Delta m^2_{23} L}{E_\nu}$$



(hep-ph/9906487)

$E_\mu = 30$ GeV,
2×10^{20} μ decays,
$L = 7000$ km,
$\sin^2 2\theta_{23} \approx 1 \approx \cos^2 \theta_{13}$.

Δm^2_{23} (eV^2)	Events (per 10 kton-yr)
0.002	2800
0.003	1200
0.004	900
0.005	1700
No Osc.	6200

$\nu_\mu \to \ \nu_\tau \to \tau^-$ **Appearance**

Δm^2_{23} (eV^2)	Events (per 10 kton-yr)
0.002	1200
0.003	1900
0.004	2000
0.005	1800

For conditions as above.

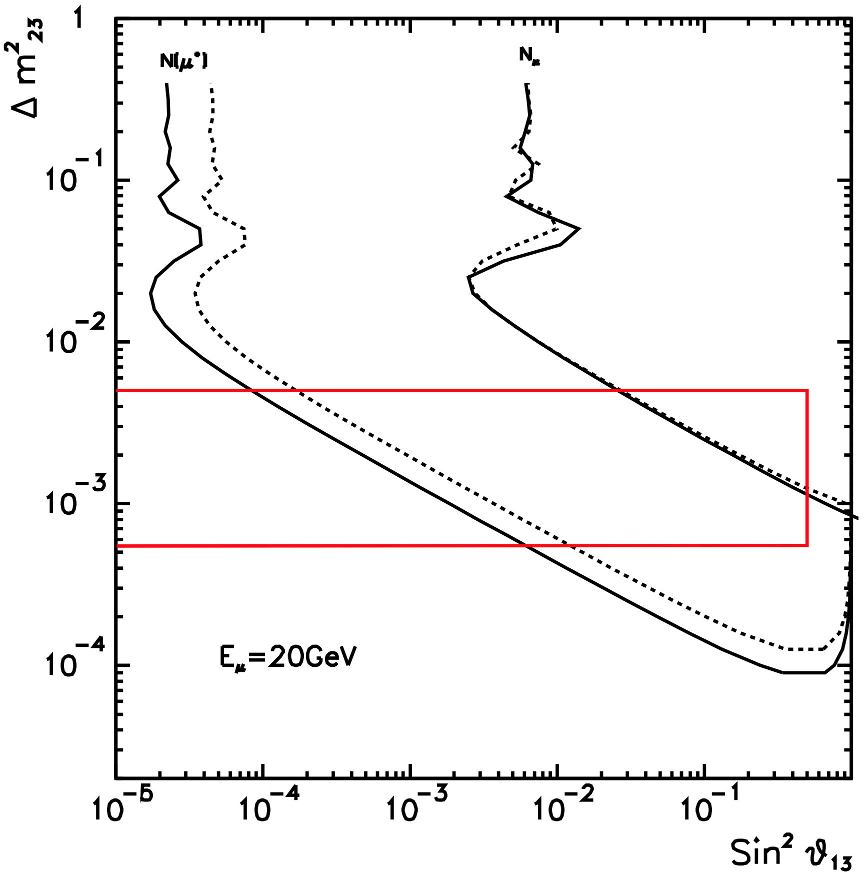
Measuring θ_{13}

Many ways:

$$P(\overline{\nu}_e \to \overline{\nu}_\mu) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{1.27 \Delta m^2_{23} L}{E_\nu},$$

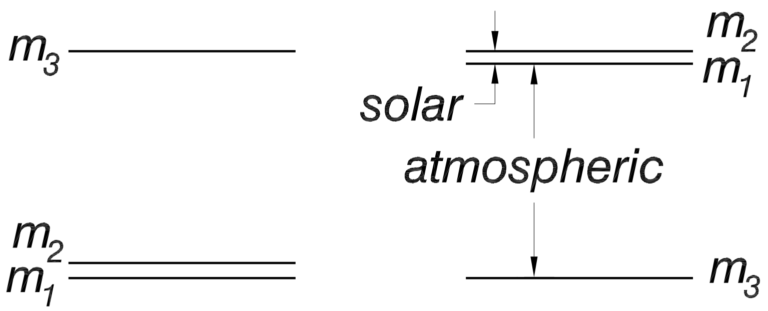
$$P(\overline{\nu}_e \to \overline{\nu}_\tau) = \sin^2 2\theta_{13} \cos^2 \theta_{23} \sin^2 \frac{1.27 \Delta m^2_{23} L}{E_\nu},$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{1.27 \Delta m^2_{23} L}{E_\nu}.$$



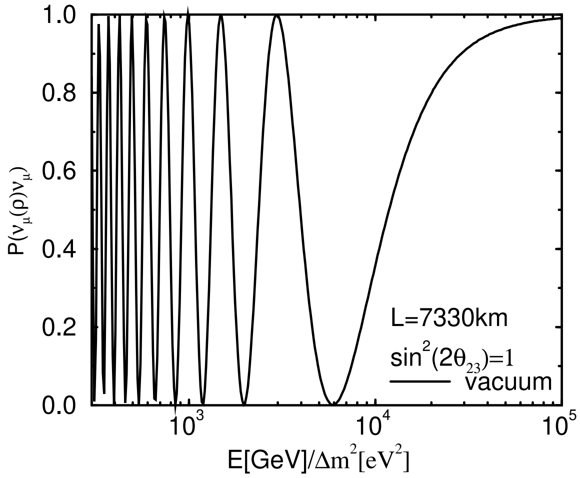
10 kton detector,
$E_\mu = 20$ GeV,
2×10^{20} μ decays,
$L = 732$ km,
$\sin^2 2\theta_{23} = 1$,
Left: $\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$,
Right: $\nu_\mu \to \nu_\mu \to \mu^-$,
Box = presently allowed.
(hep-ph/9811390).

Measuring the Sign of Δm^2_{23} via Matter Effects

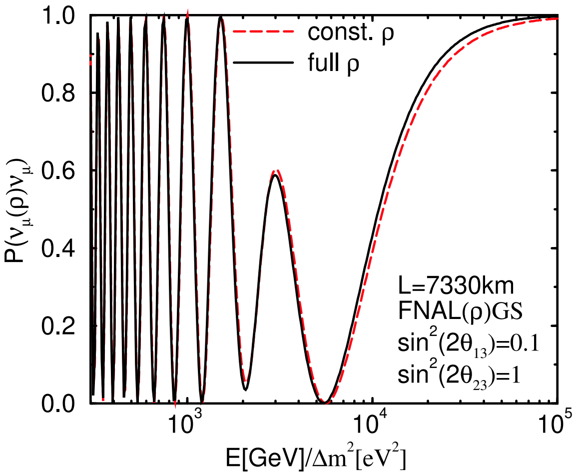


The matter effect resonance depends on the sign of Δm^2 (p. 11).

Large effect of Δm^2_{23} in ν_μ (disappearance) if $\sin^2 2\theta_{13} \approx 0.1$.

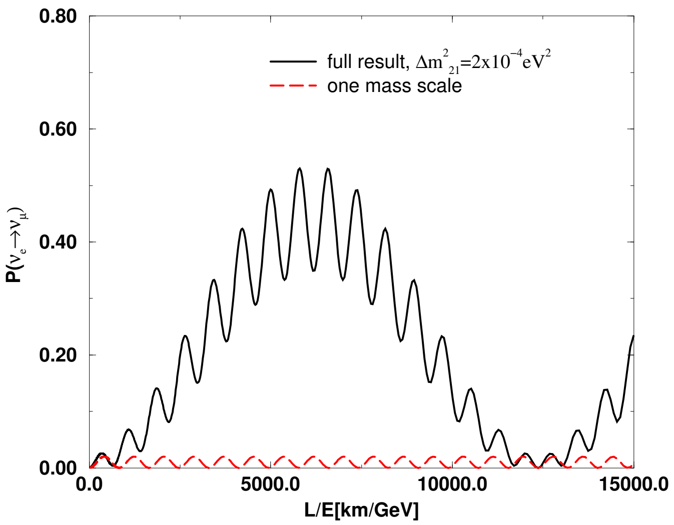


(hep-ph/ 9910554)



For smaller $\sin^2 2\theta_{13}$, may be better to use $\overline{\nu}_e \to \overline{\nu}_\mu$ (appearance).

Effect of Δm^2_{12} can be prominent in some cases. (hep-ph/0106139)



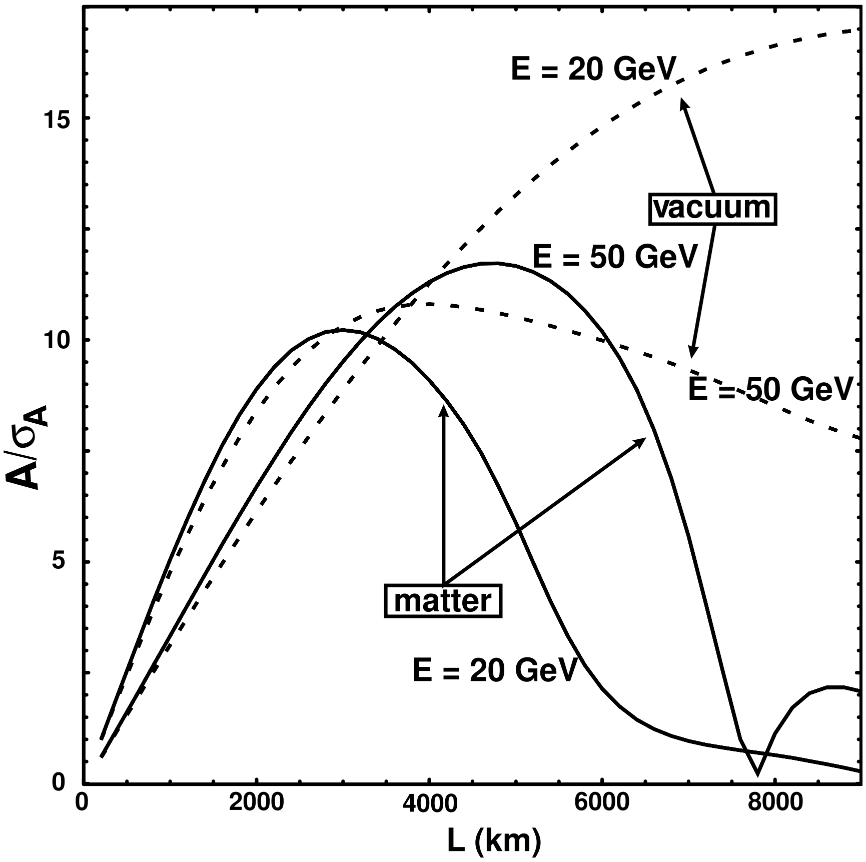
Measuring δ via CP Violation

The phase δ is accessible to terrestrial experiment in the large mixing angle (LMA) solution to the solar neutrino problem
(or if there are 4 massive neutrinos).

CP violation:

$$A_{\mathrm{CP}} = \frac{P(\nu_e \to \ \nu_\mu) - P(\overline{\nu}_e \to \ \overline{\nu}_\mu)}{P(\nu_e \to \ \nu_\mu) + P(\overline{\nu}_e \to \ \overline{\nu}_\mu)} \approx \left| \frac{2\sin\delta}{\sin 2\theta_{13}} \sin \frac{1.27\Delta m^2_{12} L}{E} \right| ,$$

assuming $\sin^2 2\theta_{12} \approx \sin^2 2\theta_{23} \approx 1$ (LMA).



10 kton detector,
2×10^{21} muon decays,
Large angle MSW:
$\Delta m^2_{12} = 10^{-4}$ eV^2,
$\Delta m^2_{23} = 2.8 \times 10^{-3}$ eV^2,
$\theta_{12} = 22.5°$,
$\theta_{13} = 13°$,
$\theta_{23} = 45°$,
$\delta = -90°$.
(hep-ph/9909254)

Matter effects dominate the asymmetry for $L > 1000$ km.

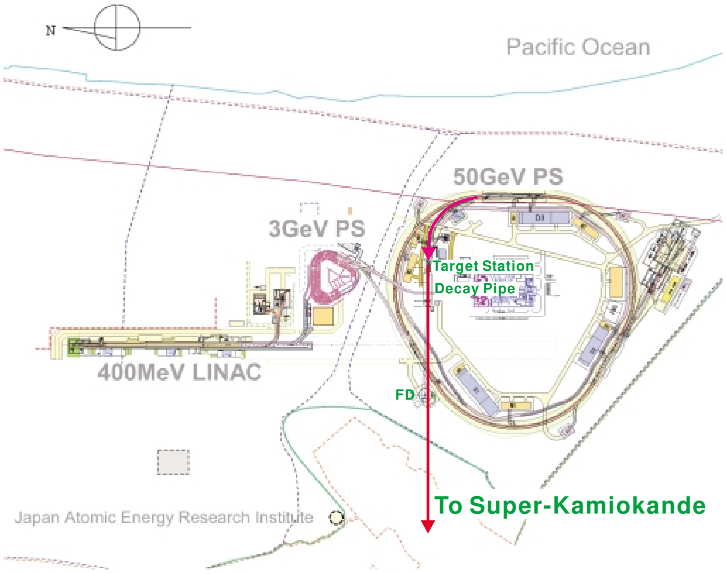
Before a Neutrino Factory – a Neutrino Superbeam

Many technical challenges remain for a neutrino factory
⇒ Costly in both money and time.

Results of neutrino factory R&D strongly encourage use of 1-4 MW target stations to produce future neutrino (and muon) beams.

Success of the SuperK detector encourages construction of neutrino detectors of ≈ 100 kton mass.

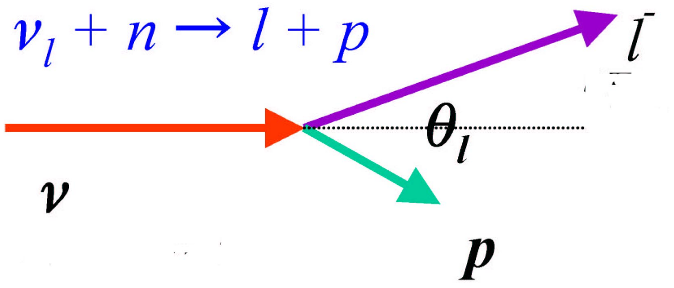
The Japanese are well positioned to follow this path, using SuperK + a neutrino beam from the JHF 0.7-MW, 50-GeV proton source recently approved (hep-ex/0106019).



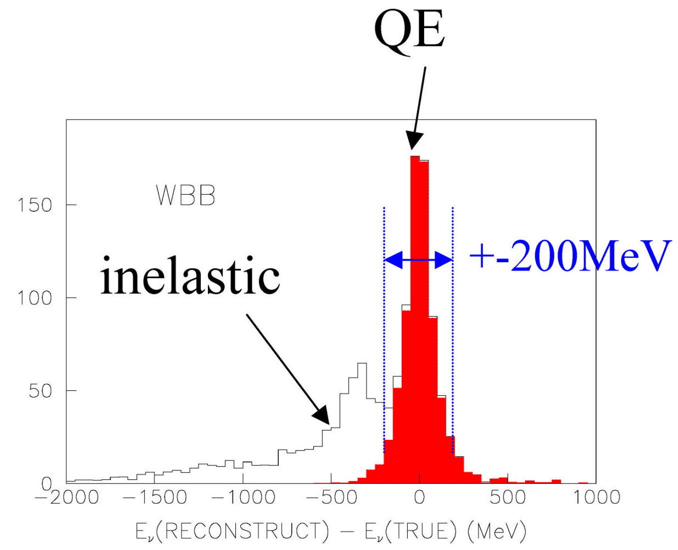
Superbeam Strategy, I

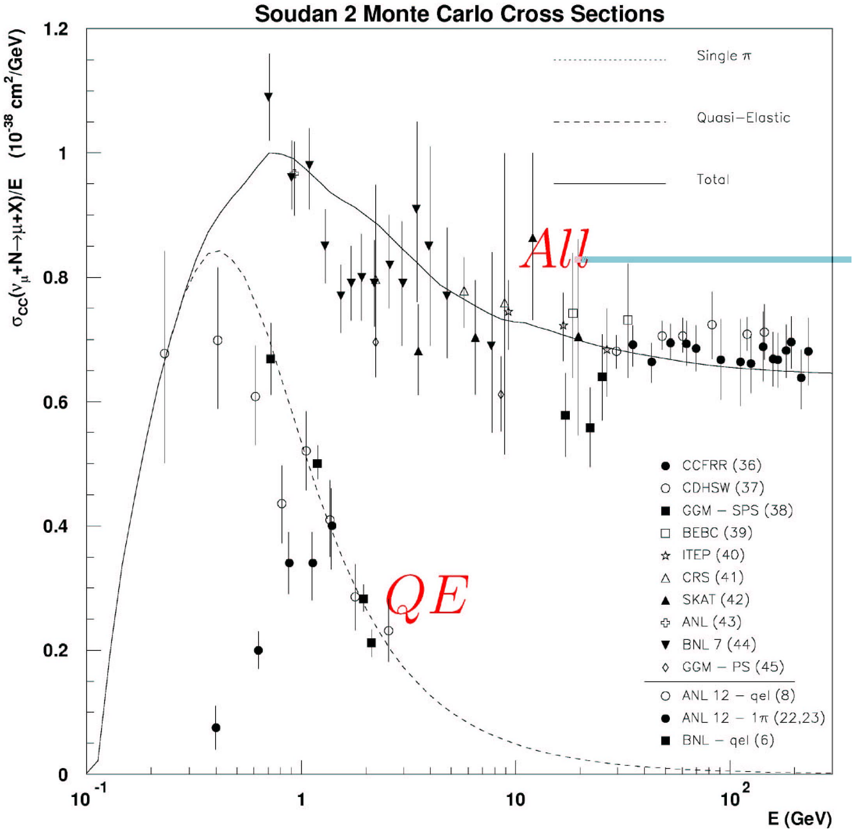
Use ≈ 1 GeV neutrinos: Production rate is high;

Interactions are simple ↔ quasielastic (no pions).



$\nu_l + n \rightarrow l + p$



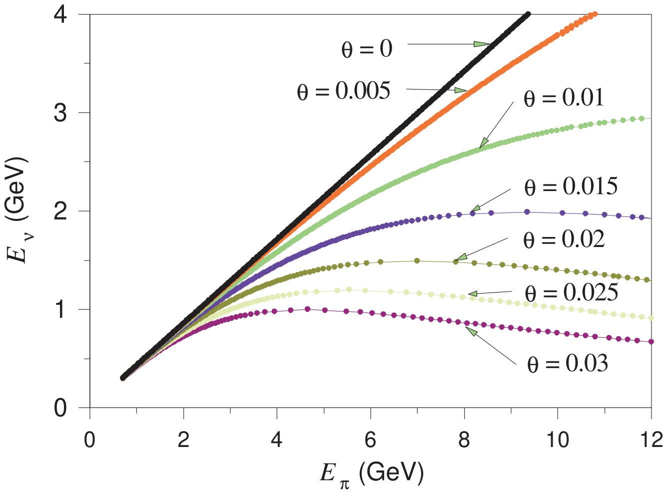


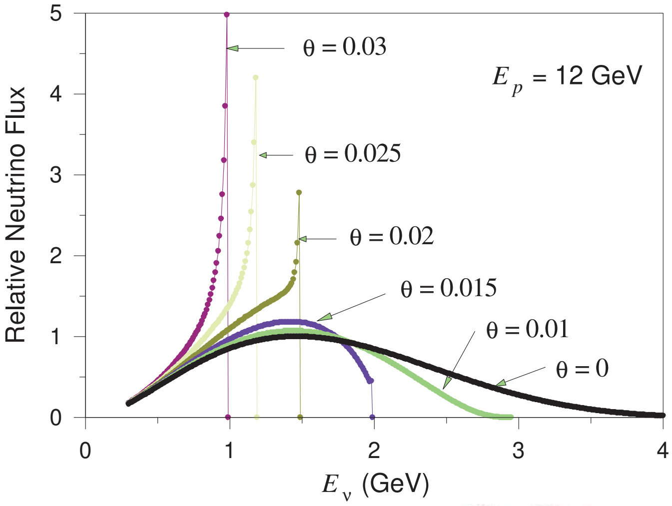
Superbeam Strategy, II

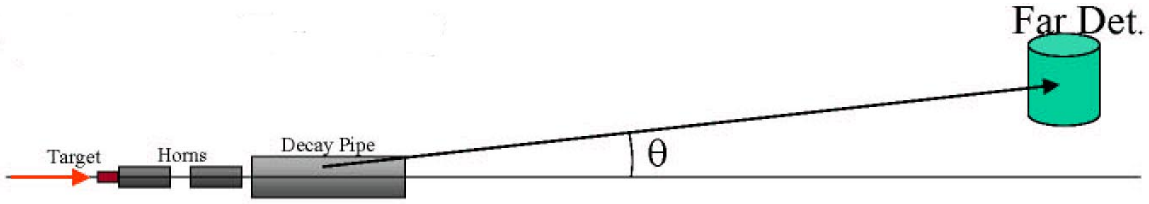
Use an **off-axis** neutrino beam (BNL E-889).

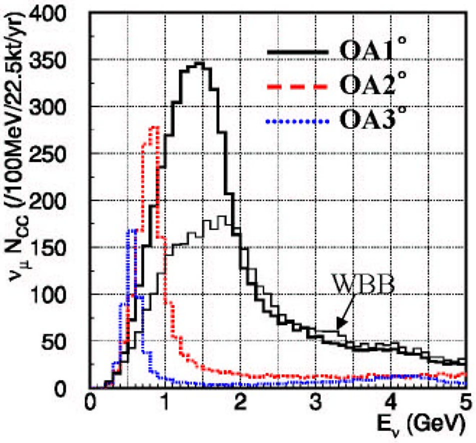
$\pi \to \mu\nu$ decay kinematics has a Jacobian peak.

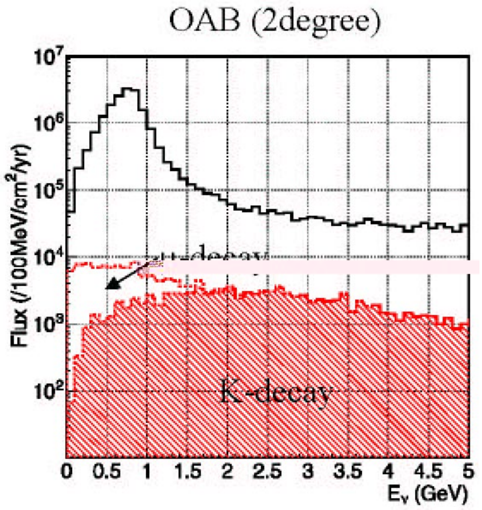
(Sternheimer, 1955)







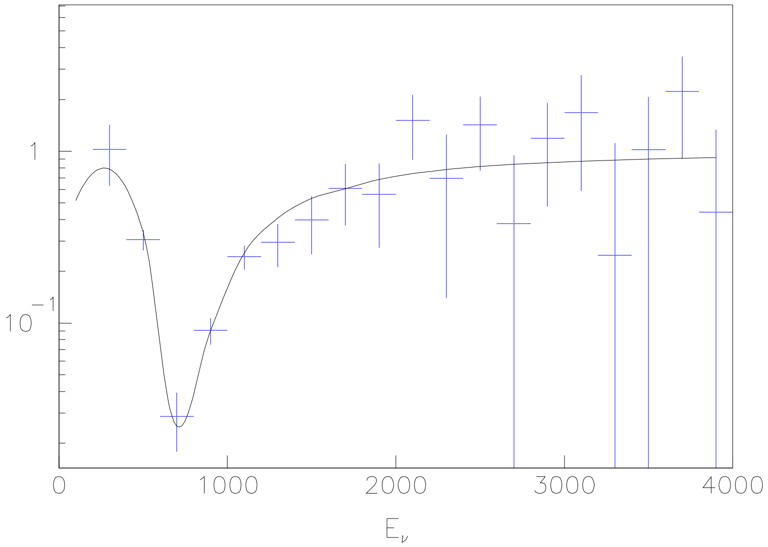




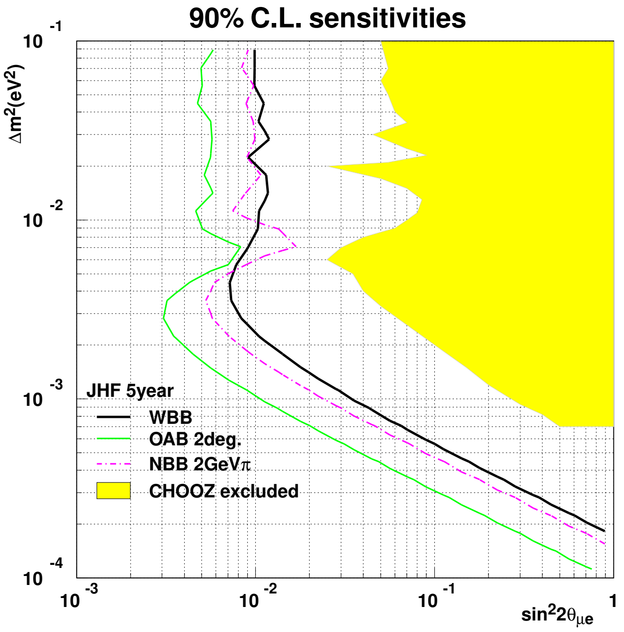
Superbeam Strategy, III

Choose detector distance L to match first maximum of ν_2-ν_3 oscillations: $L/E \approx 400$ km/GeV.

$\Rightarrow$ ν_μ disappearance is dramatic.



$\Rightarrow$ Sensitivity to $\sin^2\theta_{\mu e} \approx \sin^2\theta_{13}$ down to a 10^{-3} with 4 MW beam and 100 kton fiducial volume detector.



Can Study CP Violation at $L/E = (2n+1)400$ **km/GeV**

[Marciano, hep-ph/0108181]

The nth maximum of ν_2-ν_3 oscillations occurs at $L/E \approx (2n+1)400$ km/GeV.

The CP asymmetry grows with distance:

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

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

Of course, since $N_{\text{events}} \propto 1/L^2$, hard to make other measurements at large L.

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.

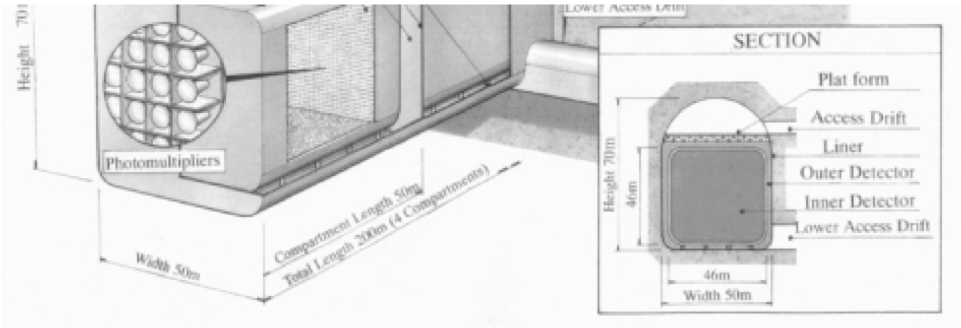
Note also that small $s_{13} = \sin\theta_{13} \Rightarrow$ large CP asymmetry, but low rates.

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

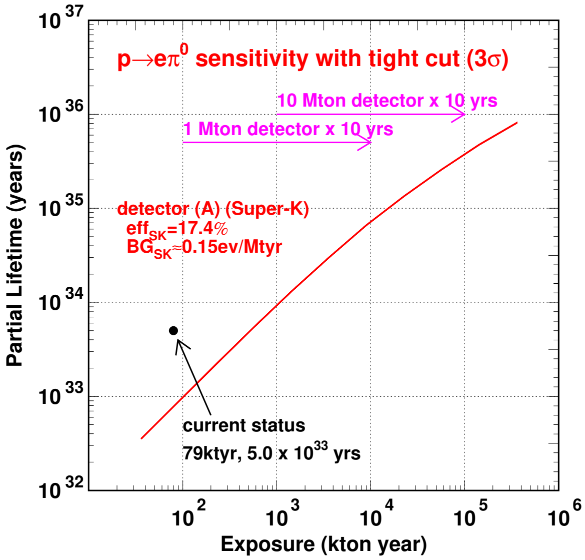
Possible Upgrades in Japan

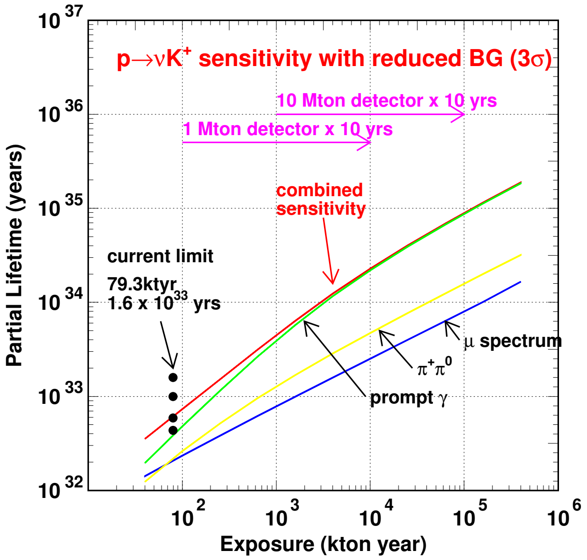
Raise proton beam power to 4 MW.

Construct a 1 Mton water Čerenkov detector (HyperK).



HyperK would improve proton lifetime limits by 10.

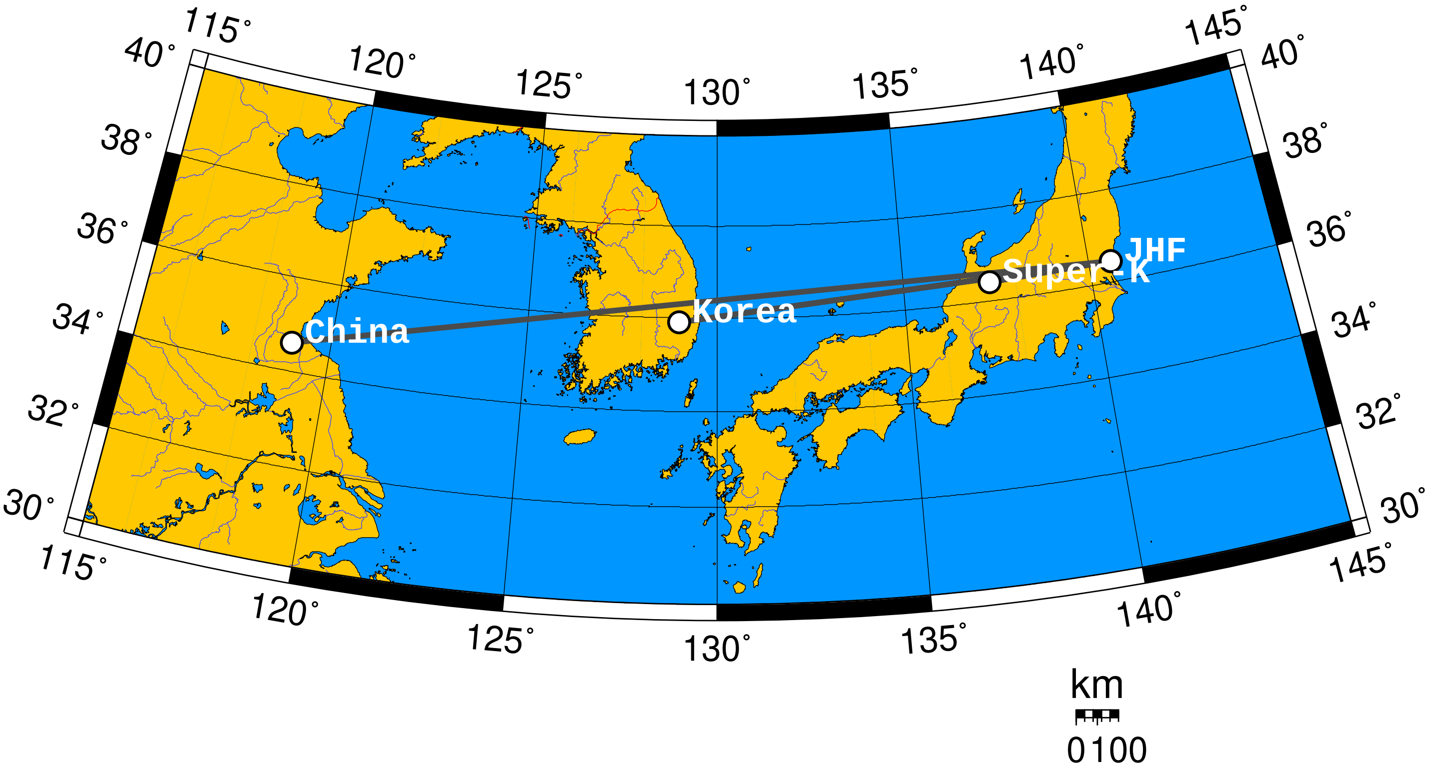




Off-Axis Beam to Two Detectors

Detectors 400 and 1200 km from source are 4° apart.

Aim neutrino beam halfway between, ⇒ 2° off-axis beam to each.



JHF – Super-K = 295 km.

JHF – Korea ≈ 1040 km ($R \approx 3.5$).

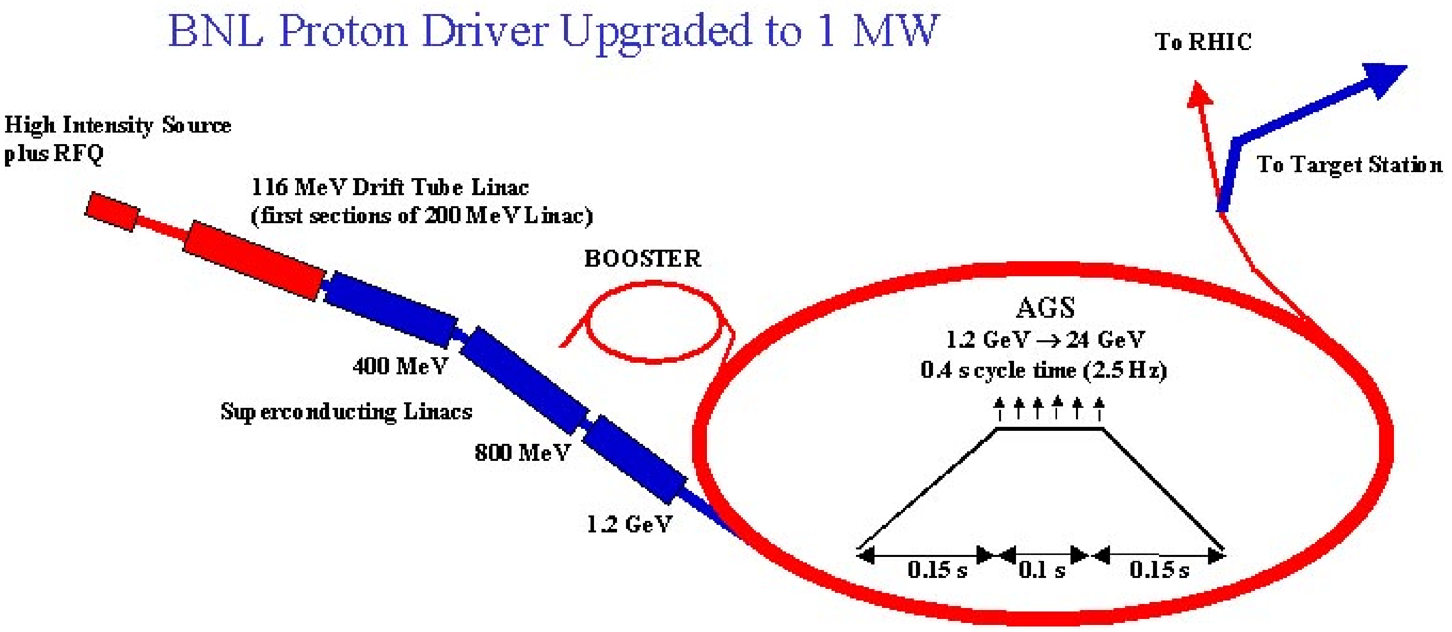
$\angle$(Super-K – JHF – Korea) = 3.4°.

⇒ Could locate magnetized liquid argon detector in Korea.

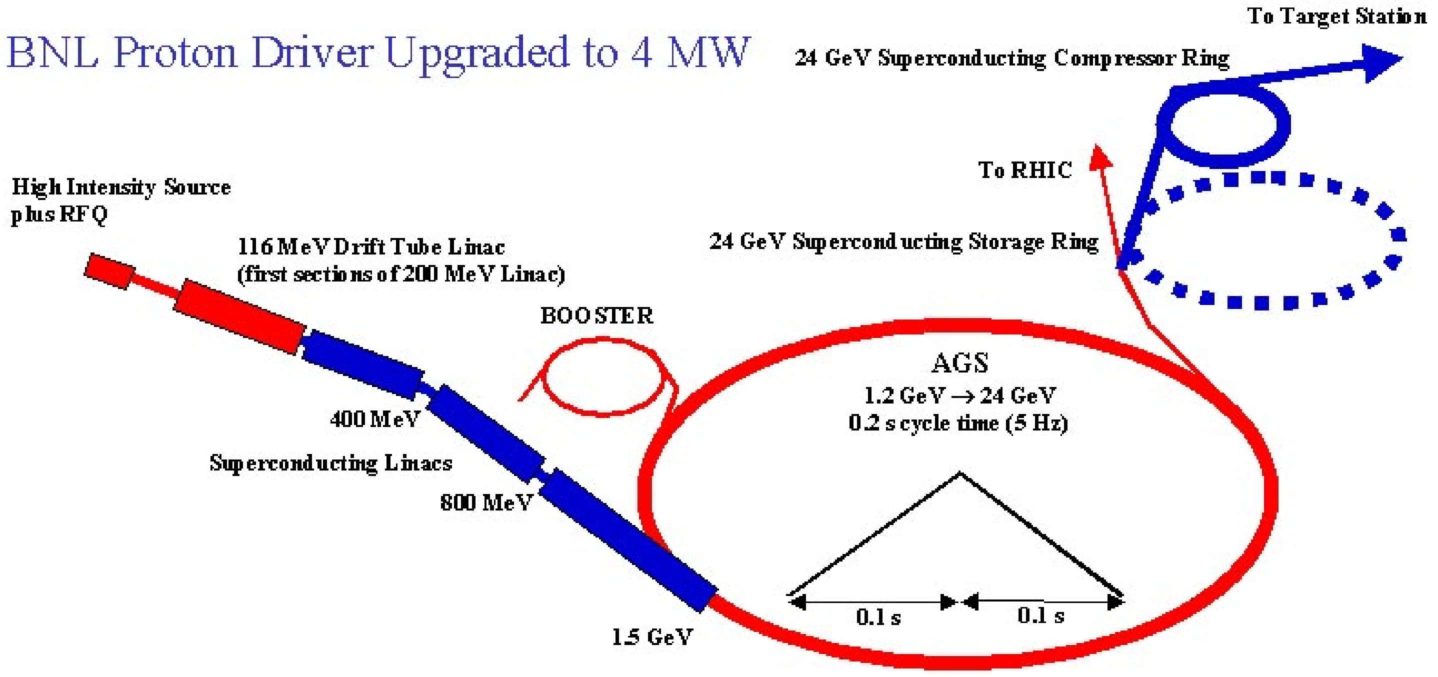
[China is too far away for the double off-axis beam method.]

A Strategy for the Western Hemisphere, I

Upgrade the **BNL** (or FNAL) proton driver to **4 MW**.



BNL Proton Driver Upgraded to 1 MW



BNL Proton Driver Upgraded to 4 MW

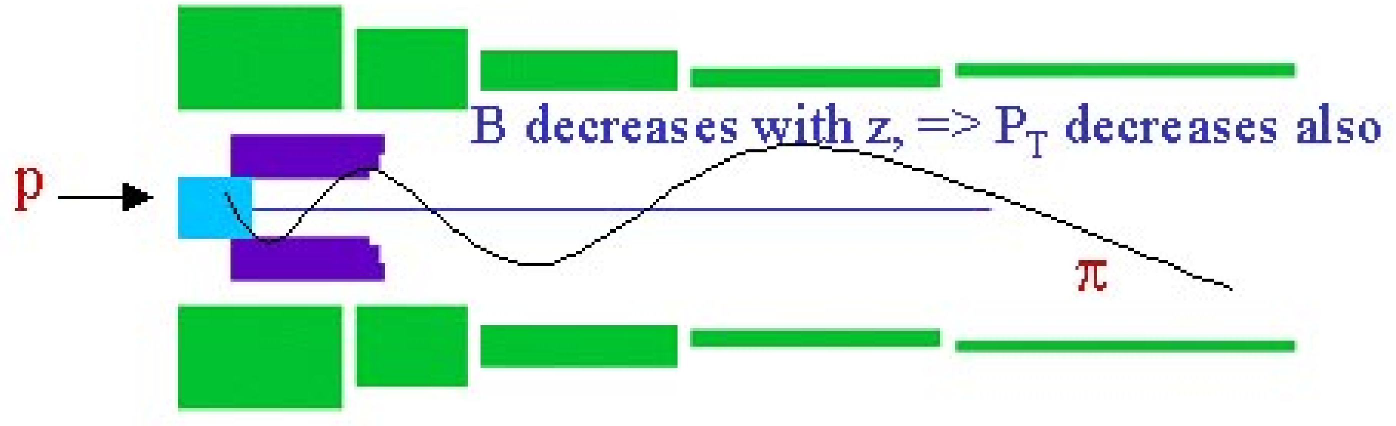
Upgrade in 2 stages: 1 MW, then 4 MW.

[T. Roser *et al.*, Snowmass'01]

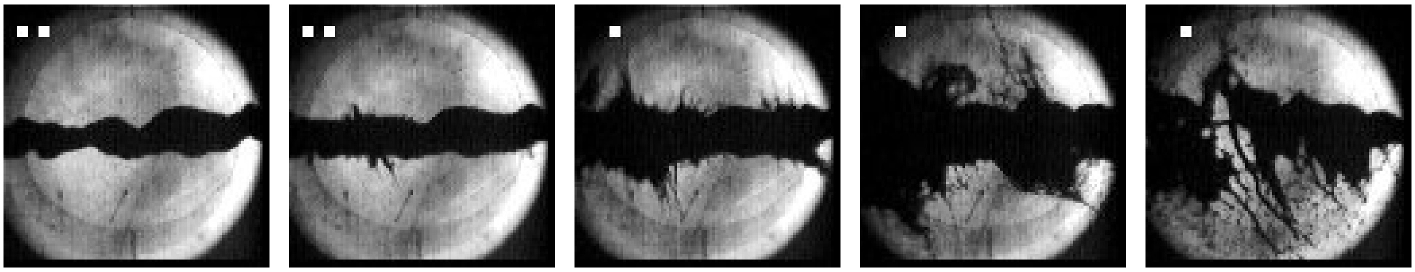
A Strategy for the Western Hemisphere, II

To run at 4 MW, use a mercury jet target inside a solenoid "horn".

This is a DC device, with coil outside high radiation area.



Interaction of 24 GeV proton beam with a mercury jet studied in BNL E951: 2×10^{12} protons + 1-cm-diameter mercury jet at $t = 0$, 0.75, 2, 7, 18 ms:



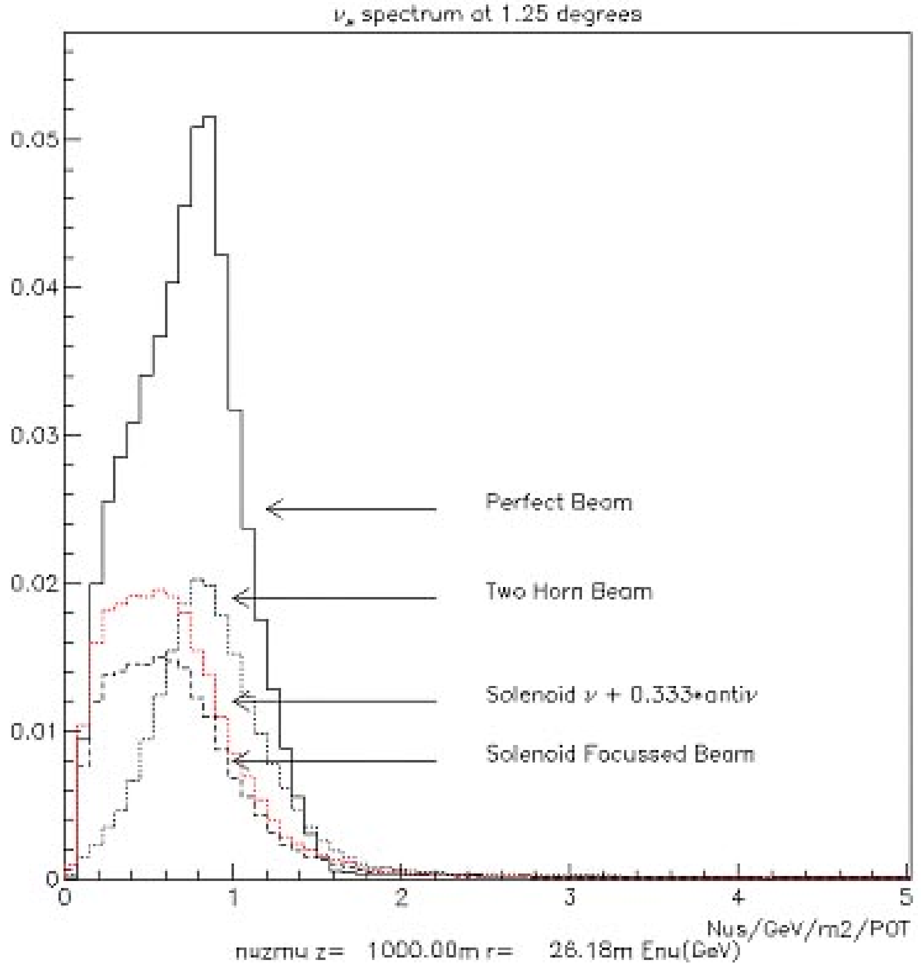
The beam disperses the jet over the interaction region, with velocity ≈ 50 m/s.

$V \approx 20$ m/s replaces the jet between proton pulses.

A Strategy for the Western Hemisphere, III

Use an off-axis beam – which will contain both ν and $\bar{\nu}$.

S. Kahn:



Decay pions not sign selected ⇒ detector must identify sign of muons (and electrons).

Solenoid horn is very effective at capturing soft muons,

⇒ ν_e Backgrounds from μ decay,

⇒ Further study needed to “detune” the horn for soft μ’s.

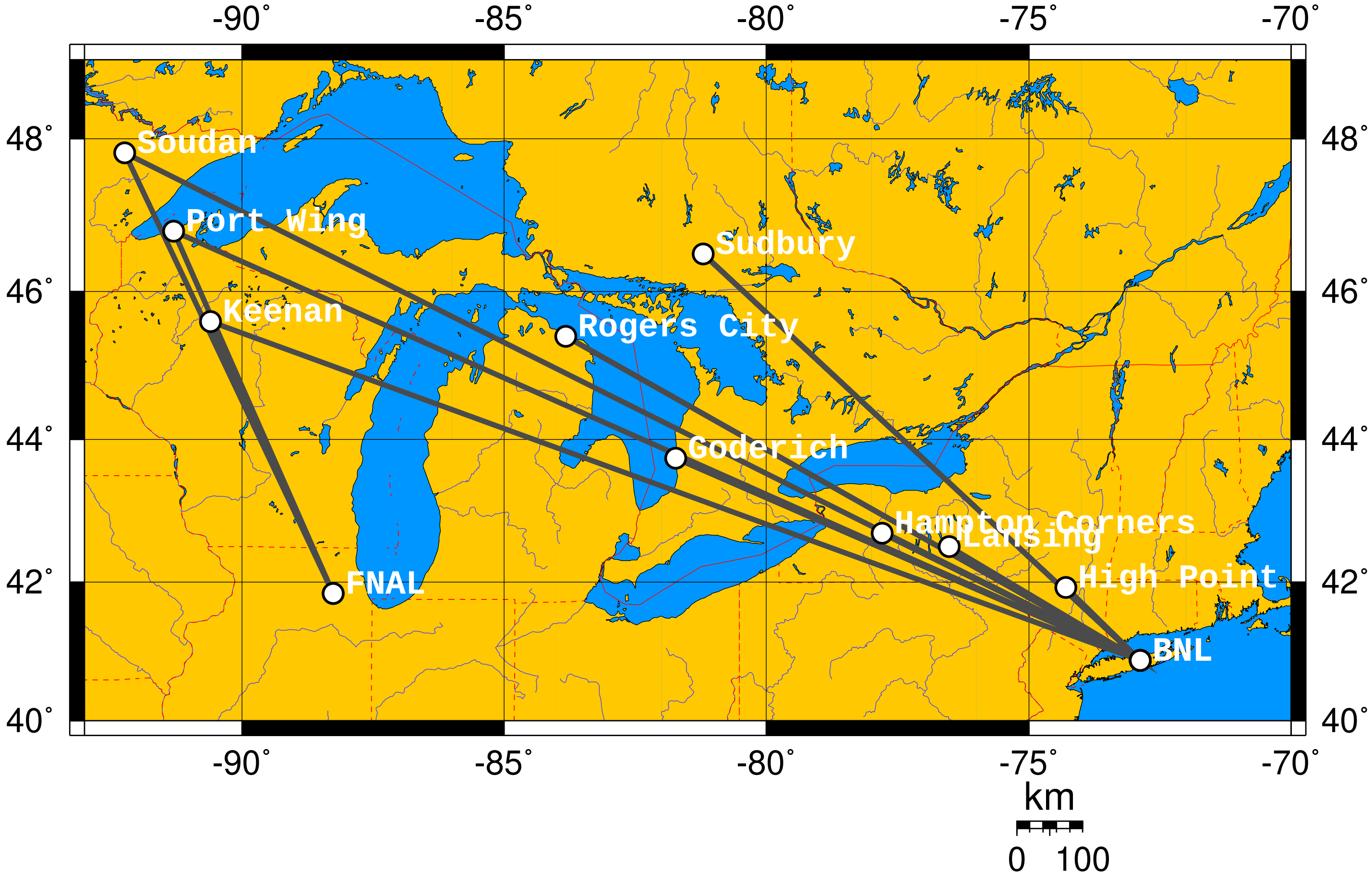
1 Beam + 2 Detectors, or 2 Beams + 1 Detector?

When studying CP violation, we must distinguish the asymmetry for ν and $\bar{\nu}$ due to matter effects from that due to intrinsic CP violation.

Matter effects are hard to study unless $L > 1000$ km.

But, rates fall off as $1/L^2$, $\Rightarrow$ need both near and far detectors.

$\Rightarrow$ Use off-axis beam + 2 detectors



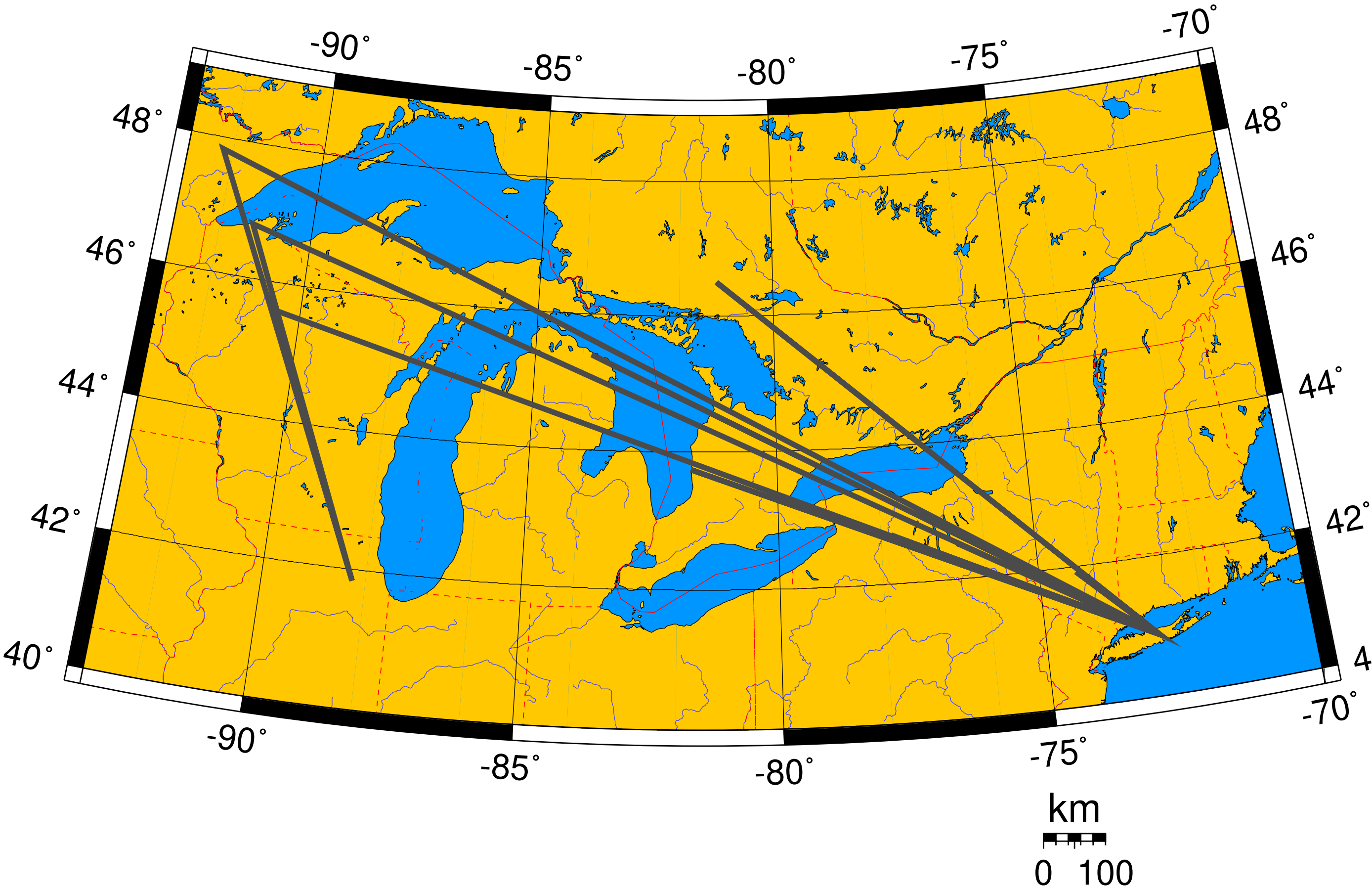
[Mercator projection distorts angles!]

Example Scenarios of Detector Siting

1. Detectors at Lansing (Ithaca), NY (350 km) and Rogers City, MI (1020 km, $R = 2.9$). $\angle$(Lansing – BNL – Rogers City) = 3.2°. Note: $\angle$(Lansing – BNL – Soudan) = 6.2°.

2. Detectors at Hampton Corners, NY (455 km) and Goderich, ON (795 km, $R = 1.75$). $\angle$(Hampton – BNL – Goderich) = 2.1°.

3. Detectors at High Point, NY (167 km) and Sudbury, ON (920 km, $R = 5.5$). $\angle$(High Point – BNL – Sudbury) = 3.4°.



[Polar sterographic projection is conformal.]

Summary

The discovery of neutrino oscillations in astrophysical experiments provides a rich opportunity for neutrino detectors + accelerater-based neutrino beams.

The desire for intense, clean neutrino beams leads to the challenge of a neutrino factory based on a muon storage ring.

On the path to a neutrino factory is a neutrino superbeam using a 1-4 MW proton source and a solenoid-horn target station.

An off-axis beam can fed both a near and far detector.

The most flexible and precise neutrino detector is magnetized liquid argon, which should be implemented at the 100 kton level.

The physics program will encompass proton decay, neutrino astrophysics as well as detailed measurement of the neutrino mixing matrix.

The accelerator technology is a step towards an energy frontier muon collider.