Long Baseline Neutrino Beams and Large Detectors

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Neutrinos

- History
  - Oscillations:
    - Atmospheric
    - Solar
    - Mixing Matrix
- New Era
  - Hierarchy, θ_{13} ,CP
  - Very Large Detector
  - Long Baseline
  - High Intensity Beams
  - Sensitivities
- Bonus:
  - Proton Decay
  - Supernova

Neutrino History

- 1930 Existence – Postulated by Pauli
- 1956 Discovered
- 1962 Two Neutrinos
- 1970-91 Solar deficiency
- 1991 Three Neutrinos
- 2000's Neutrino Oscillations
    - Kamiokande
    - Super Kamiokande
    - Sudbury
    - Kamland
    - KEK
    - Minos

and

Others

Brief review of oscillations

Assume a 2×2 neutrino mixing matrix.

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

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

Sufficient to understand most of the physics:

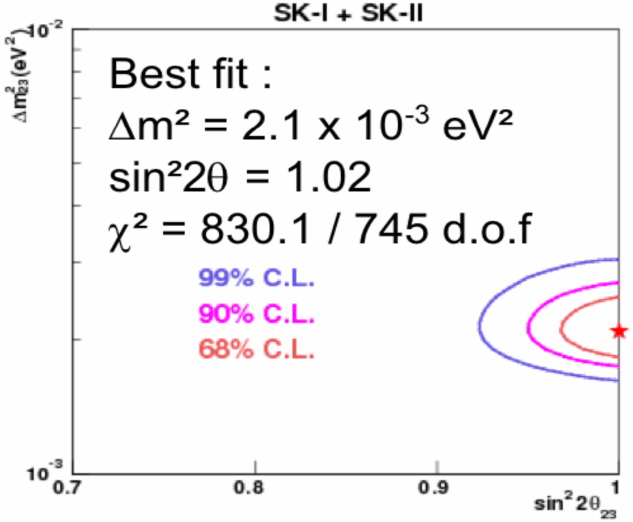
$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

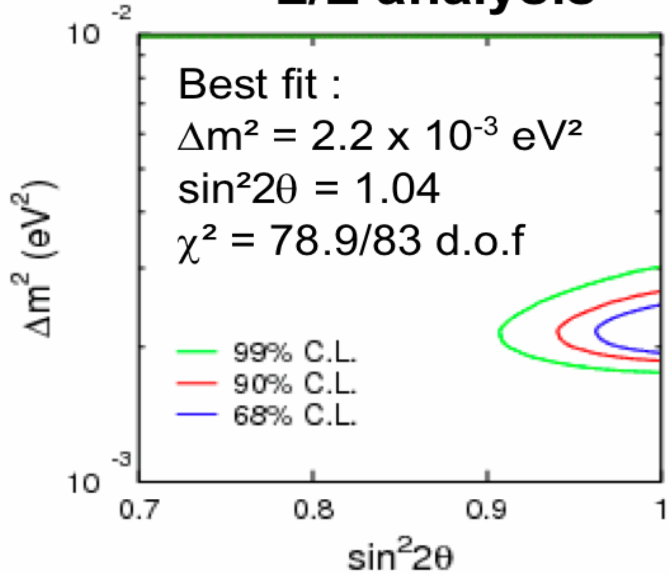
Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, ...$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1 GeV$, $L = 494 km$.

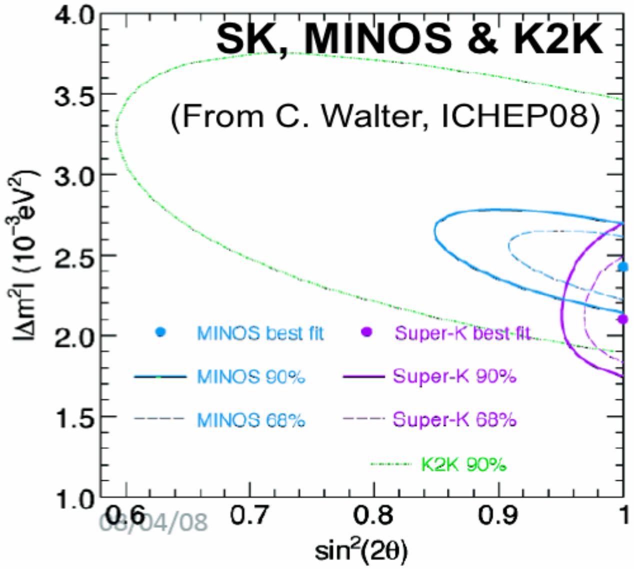
Allowed regions

Zenith angle analysis

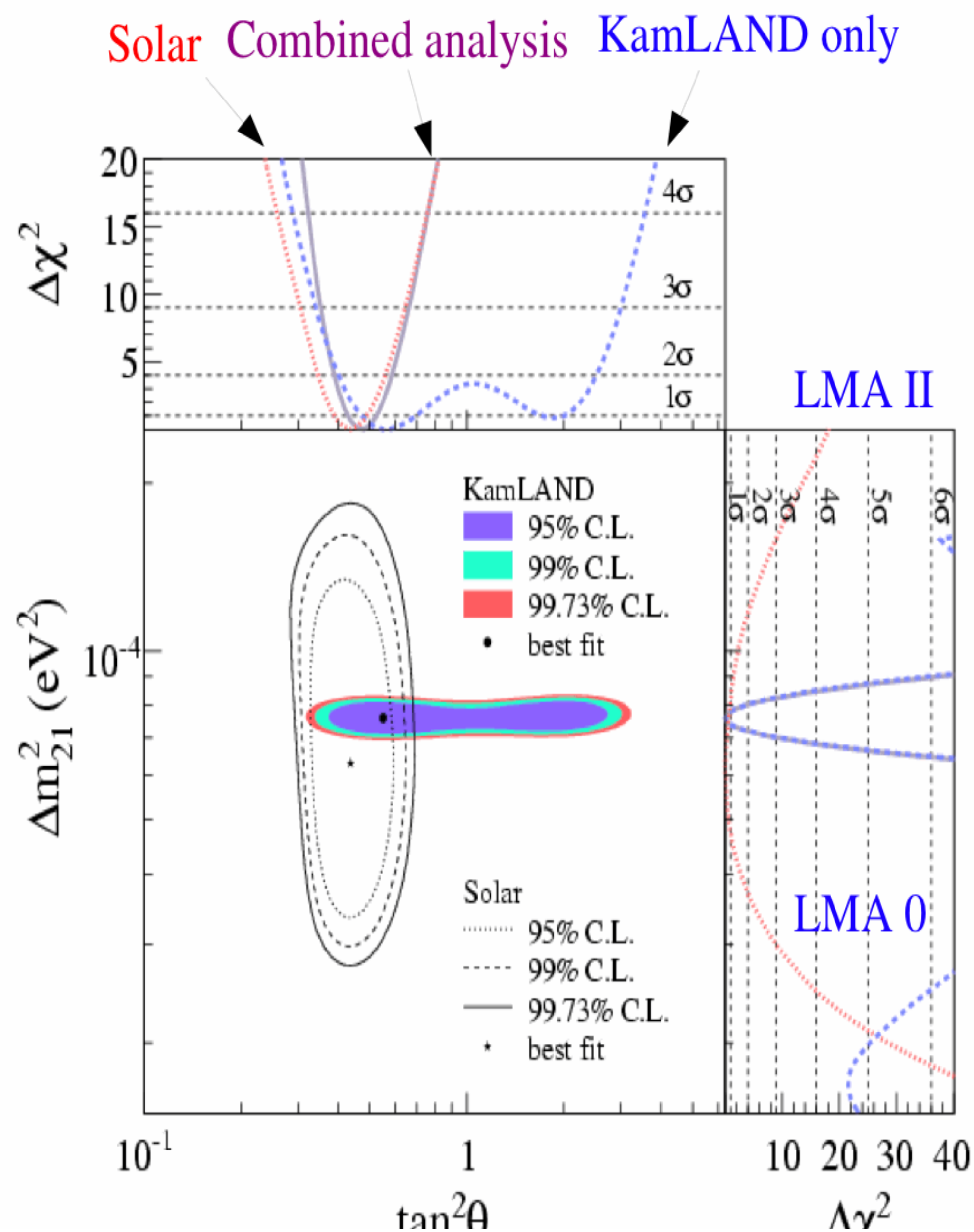


L/E analysis





Current best measurement of θ_{23} :
~ 45±4° (10% accuracy)



KamLAND only:

$\Delta m^2 = 7.58^{+0.14}_{-0.13}(st) \pm 0.15(syst) \times 10^{-5}\ (eV^2)$

$\tan^2\theta = 0.56^{+0.10}_{-0.07}(st)^{+0.1}_{-0.06}(syst)$

KamLAND+solar:

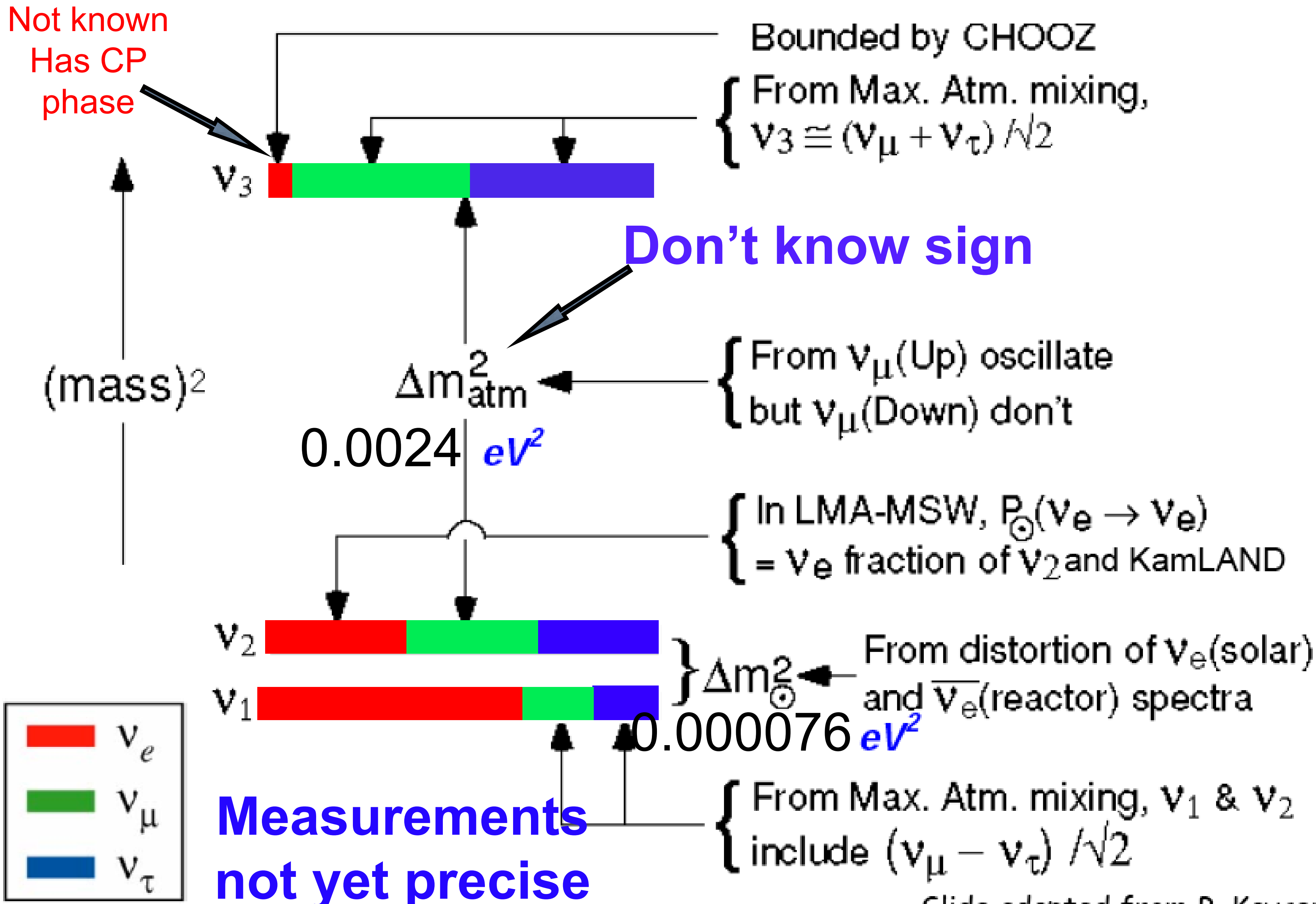
$\Delta m^2 = 7.59 \pm 0.21 \times 10^{-5} (eV^2)$

$\tan^2\theta = 0.47^{+0.06}_{-0.05}$

Only the LMA I solution remains

KamLAND improved result for mixing angle and Δm^2. Solar data have no effect on the Δm^2 measurement.

What do we know and how do we know it



Slide adapted from B. Kayser

Current Neutrino Mixing Parameters

- $\Delta m_{32}{}^2 = m_3{}^2 - m_2{}^2 = \pm\ 2.3(2)\times 10\text{-}3\ eV^2$
- $\Delta m_{21}{}^2 = m_2{}^2 - m_1{}^2 = +7.6(2)\times 10^{-5}\ eV^2$

(Recent very precise KamLAND Measurement)

$\Delta m_{21}{}^2/\Delta m_{32}{}^2 \approx 1/30$

Hierarchy m_3>m1(normal) or m_3<m1(inverted)

$\theta_{23} \sim 45°\ \sin^2 2\theta_{23} = 1.0$

$\theta_{12} \sim 34°\ \sin^2 2\theta_{12} = 0.87$

$\theta_{13} \leq 11°\ \sin^2 2\theta_{13} \leq 0.15$

$0 \leq \delta \leq 360°$?

$J_{CP} \cong 0.11 \sin 2\theta_{13} \sin\delta$

Oscillations: 3 Flavors

Mixing between flavors and mass states

Quark Sector

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = U \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Lepton Sector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U' \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U, U' unitary 3 x 3 matrix 3 mixing angles, one phase

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{13}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = cos_{ij} \qquad s_{ij} = sin_{ij}$$

$$J_{CP\ Jarlskog} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \sin \delta$$

Oscillations: 3 Flavors

Quark Sector CKM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} .97 & .23 & (2-3i)10^{-3} \\ -.23 & .97 & .04 \\ (7-3i)10^{-3} & -.04 & .99 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$J = 3.1 \times 10^{-5} \qquad \delta = 57^{o}$$

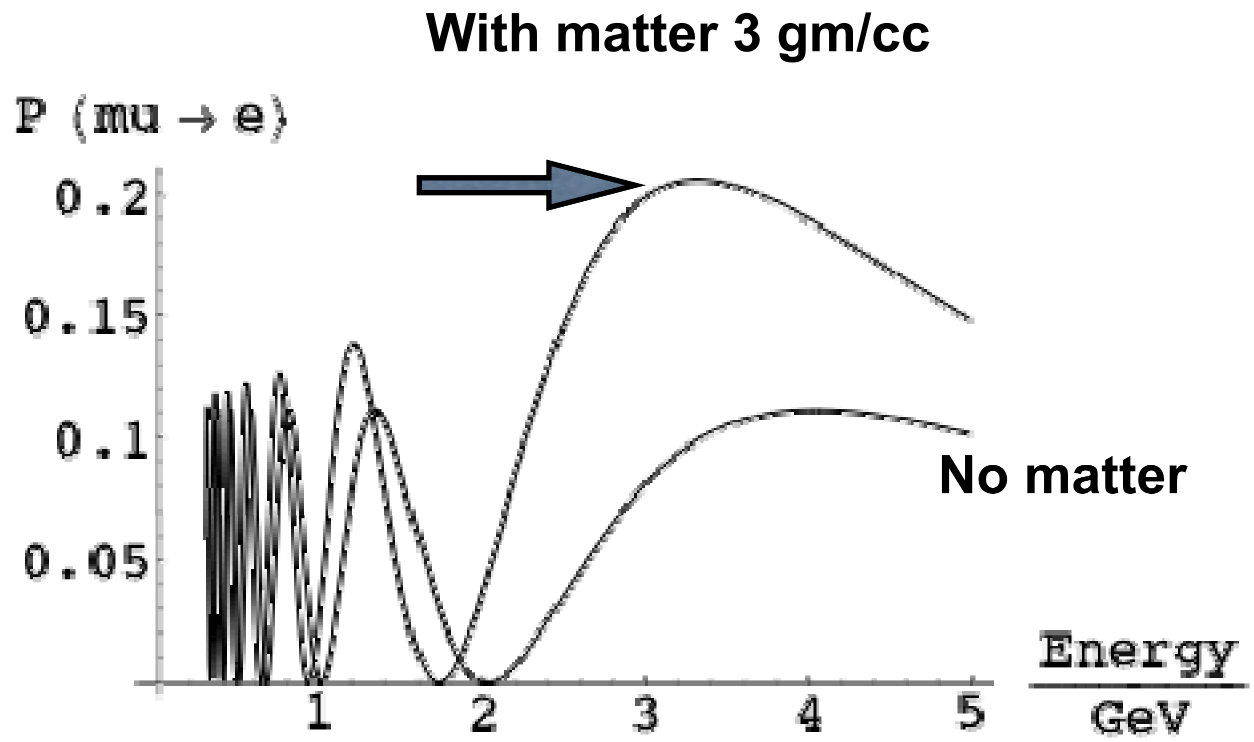
Lepton Sector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} .81 & .51 & s_{13}e^{-i\delta} \\ -.4 - .6\, s_{13}e^{i\delta} & .6 - .4\, s_{13}e^{i\delta} & .7 \\ .4 - .6\, s_{13}e^{i\delta} & -.6 - .4\, s_{13}e^{i\delta} & .7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$s_{13} \equiv \sin\theta_{13} \quad \leq 0.2$$

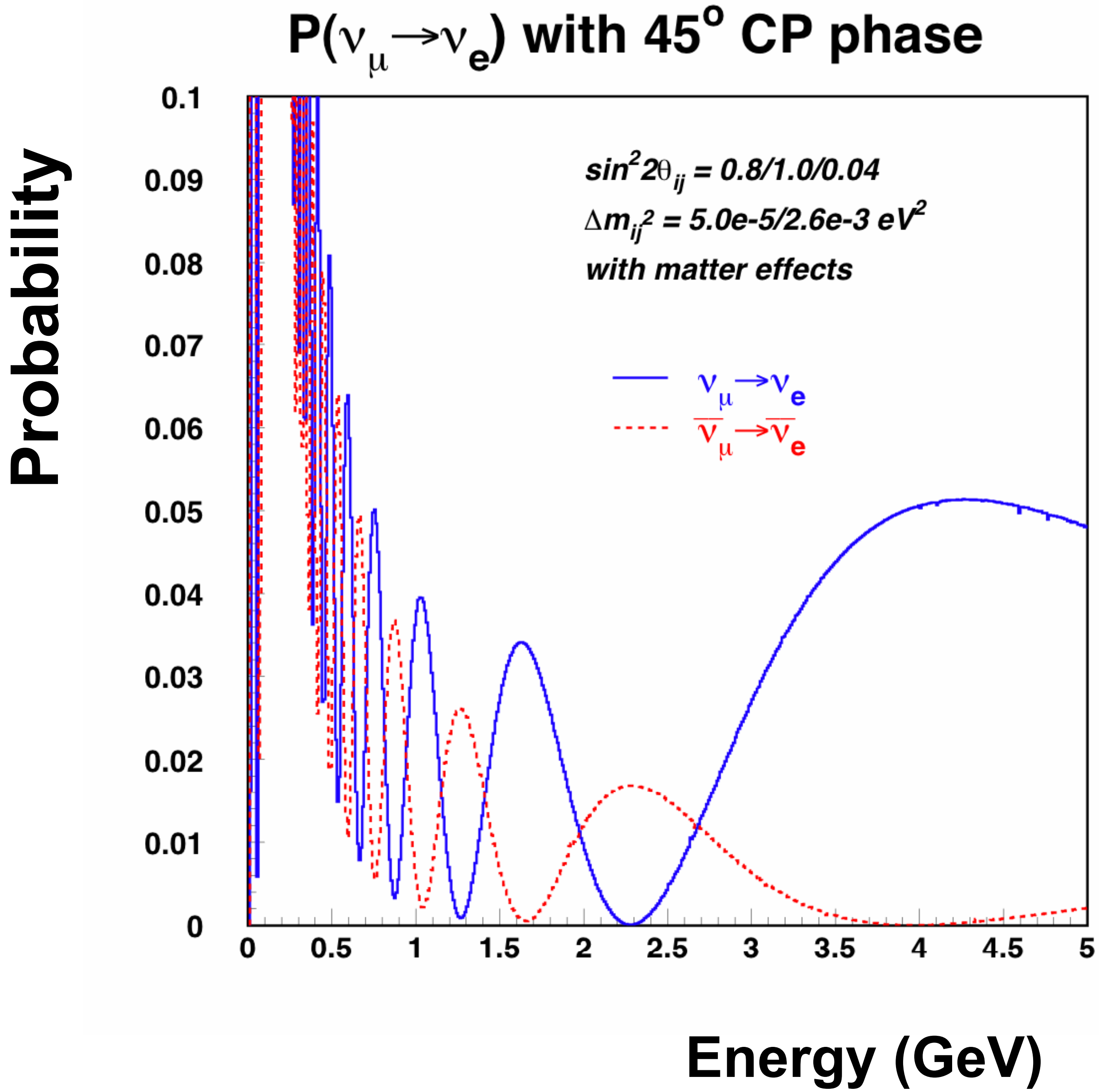
$$J = .11 \sin 2\theta_{13} \, \sin\delta$$

Matter effect with 2-neutrinos



Osc. probability: 0.0025 eV^2, L= 2000 km, Theta=10deg

Example of oscillation probability with matter effects
L=2540 km



$\nu_\mu \to \nu_e$ with matter effect

Approximate formula (M. Freund)

matter effect ~E

~7500 km
no CPV.
magic bln

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$
$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$
$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

CPV term
approximate
dependence
~L/E

solar term

linear dep.

$$J_{CP} = 1/8\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$
$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31}L/4E$$
$$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \text{ For Earth's crust.}$$

CP asymmetry grows
as θ13 becomes
smaller

Implications

Have some knowledge of

Theta 23 , Theta 12, and Squares of 12, and 32 mass differences

Require More Precise values of above and
Theta 13, sign of 32 mass difference and CP violation

New Era

Very Large Detectors

Long Baseline

High Intensity Beams

First Proposed (2003)

Very Long Baseline Neutrino Oscillation

Experiment for Precise Measurement of mixing Parameters and CP Violating Effects

M. Diwan et. al.

Phys. Rev. D 68, 12002 (2003)

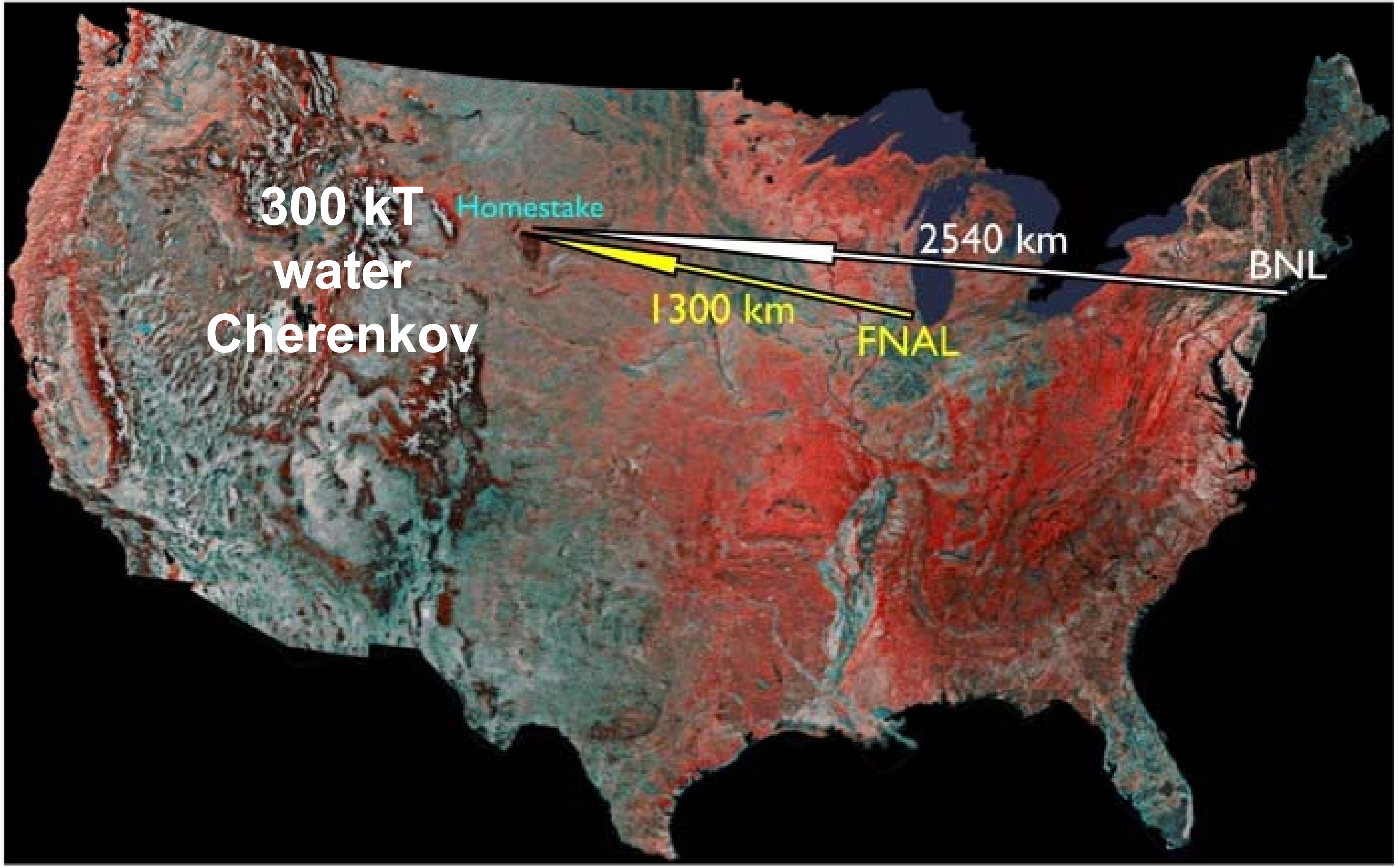
Key Experimental Factors

Large Detectors
– >> 100 ktons

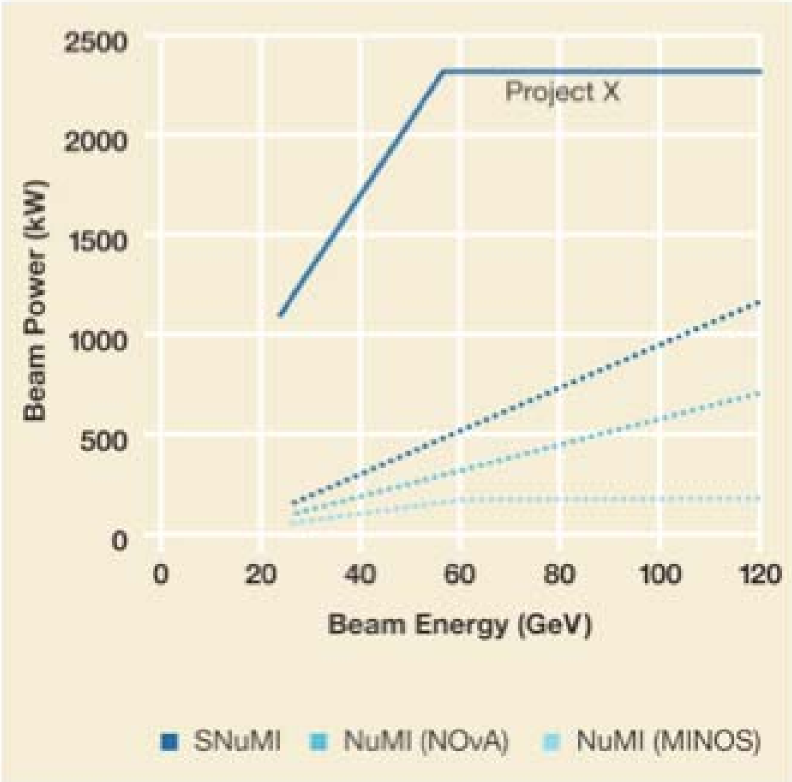
- Water Cerenkov 300 Ktons (50kt)
- Liquid Argon TPC 100 Ktons (.6 kt)
- Liquid Scintillator 50 Ktons (1 kt)
- High Proton Beam Intensities
  - 1 Mwatt
  - 60 GeV on axis
  - 120 GeV slightly off axis
- Long Neutrino Flight Paths
  - L > 1,000 km
  - 1,300 km Fermilab – Homestake
  - Neutrino Energies 0.5 – 10 GeV
- Being Pursued
  - US
  - Europe
  - Japan

FNAL to DUSEL long baseline experiment

Beam requirement: >1 MW, 1000 to 2000 km



- 60 -120 GeV protons from the Main Injector fed by Project X



20-40x10^{20} POT/yr

10×10^{20} POT/yr

6×10^{20} POT/yr

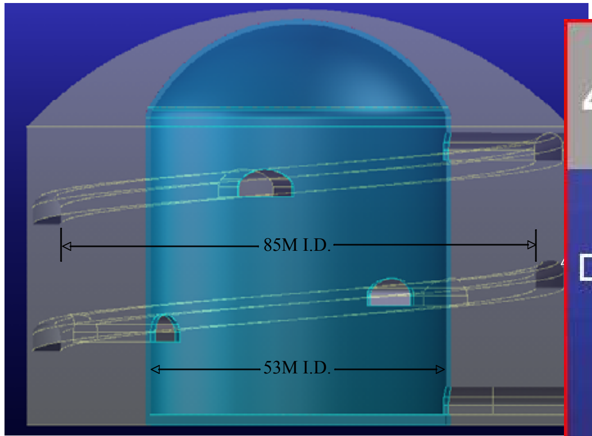
3×10^{20} POT/yr

Recent sensitivity studies are being done for 120×10^{20} POT each ν and $\bar{\nu}$ (120 GeV)

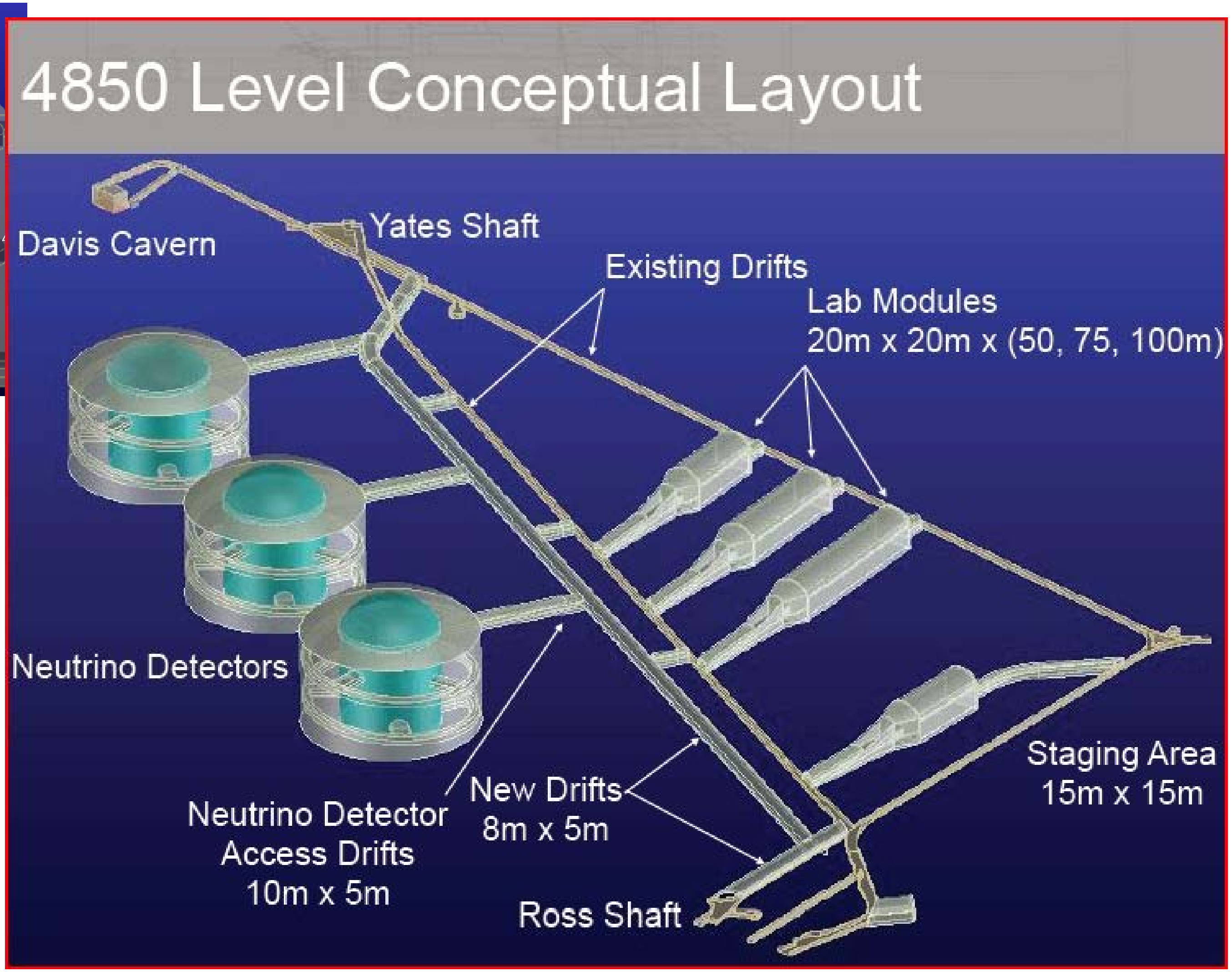
$$POT(10^{20}) = \frac{1000 \times BeamPower(MW) \times T(10^7 s)}{1.602 \times E_p(GeV)}$$

5.2 10^{20} POT for 1 MW and 10^7 sec

Water Cherenkov Detector



1 module fid:
100 kT



300 kT

Studies:

- Baseline: 1300km
  Fermilab – Homestake
- Detector: 300 Kton Water Cerenkov
  100 Kton Liquid Ar TPC

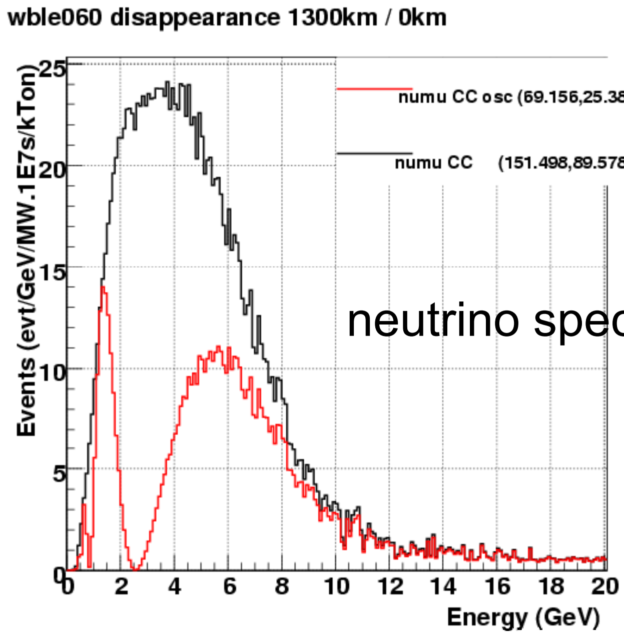
- Beam: 60 GeV, O^{o}
  120 GeV, 0.5^{o}
- Intensity: 7 x 10^{13} ppp/ 4/3 sec. rep rate
  2 x 10^{7} sec/yr
  10 x 10^{20} POT/yr

- Disappearance: $\upsilon_{\mu} \rightarrow \upsilon_{\mu}$
- Appearance: $\upsilon_{\mu} \rightarrow \upsilon_{e}$

Event rate

Evt rate: 1 MW for 3 yrs ★

Event type	300kT, 120 GeV 0.5 deg.	300kT, 60 GeV 0 deg.
Numu CC no osc	161820	272693
Numu CC with osc	68220	124479

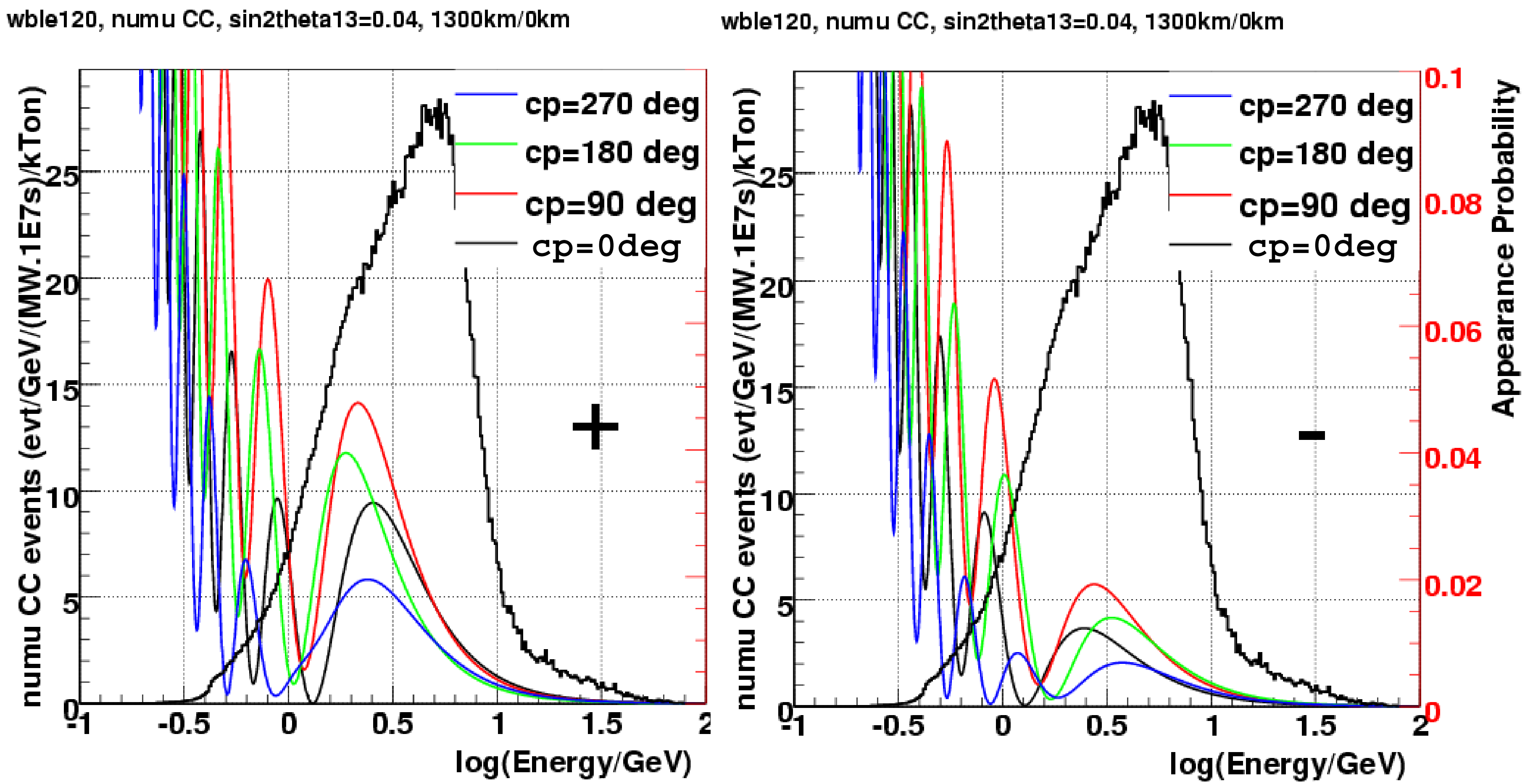


High precision $\sin^2 2\theta_{23}$, Δm^2_{31}

- **Important (esp. θ23 ~ 45 deg.) with possibility of new physics.**
- **Either 120 GeV or 60 GeV beam can be used: two oscillation nodes.**
- **Measurement dominated by systematics (see hep/0407047) (~1%)**

★ **yr~2x10^7 sec**

$\nu_\mu \rightarrow \nu_e$ Probability (for some CP angles and the mass ordering) superimposed on charged current ν_μ rate



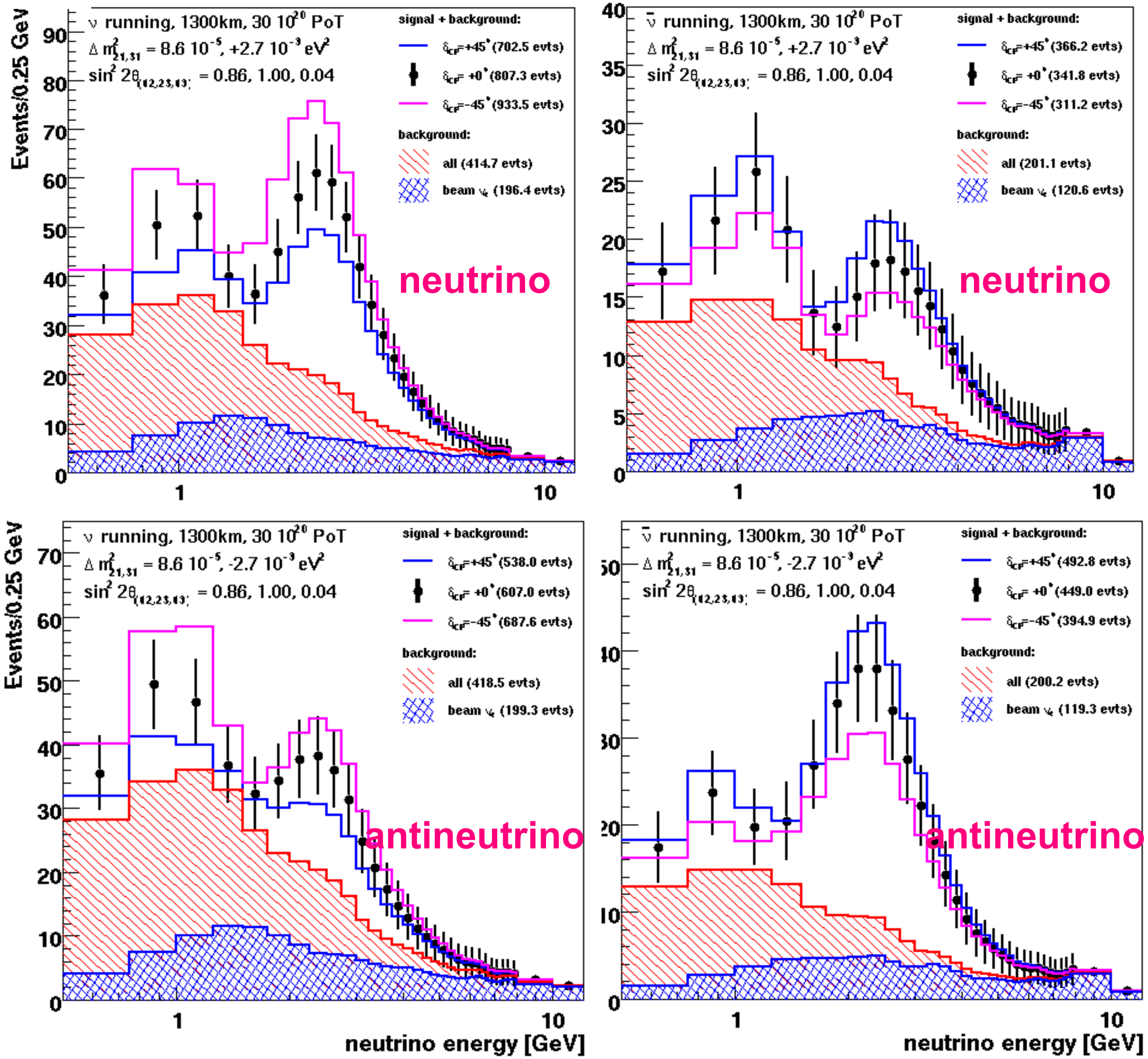
Electron neutrino appearance spectra

$\sin^2 2\theta_{13} = 0.04$, 300kT WCe. , WBLE 120 GeV, 1300km, 30E20 POT.

$(-\ \delta_{cp} = -45°,\ -\ \delta_{cp} = +45°)$

Normal Reversed

- All background sources are included.
- S/B ~ 2 in peak.
- NC background about same as beam nue backg.
- For normal hierarchy sensitivity will be from neutrino running.
- For reversed hierarchy anti-neutrino running essential.
- Better efficiency at low energies expected with higher PMT counts.



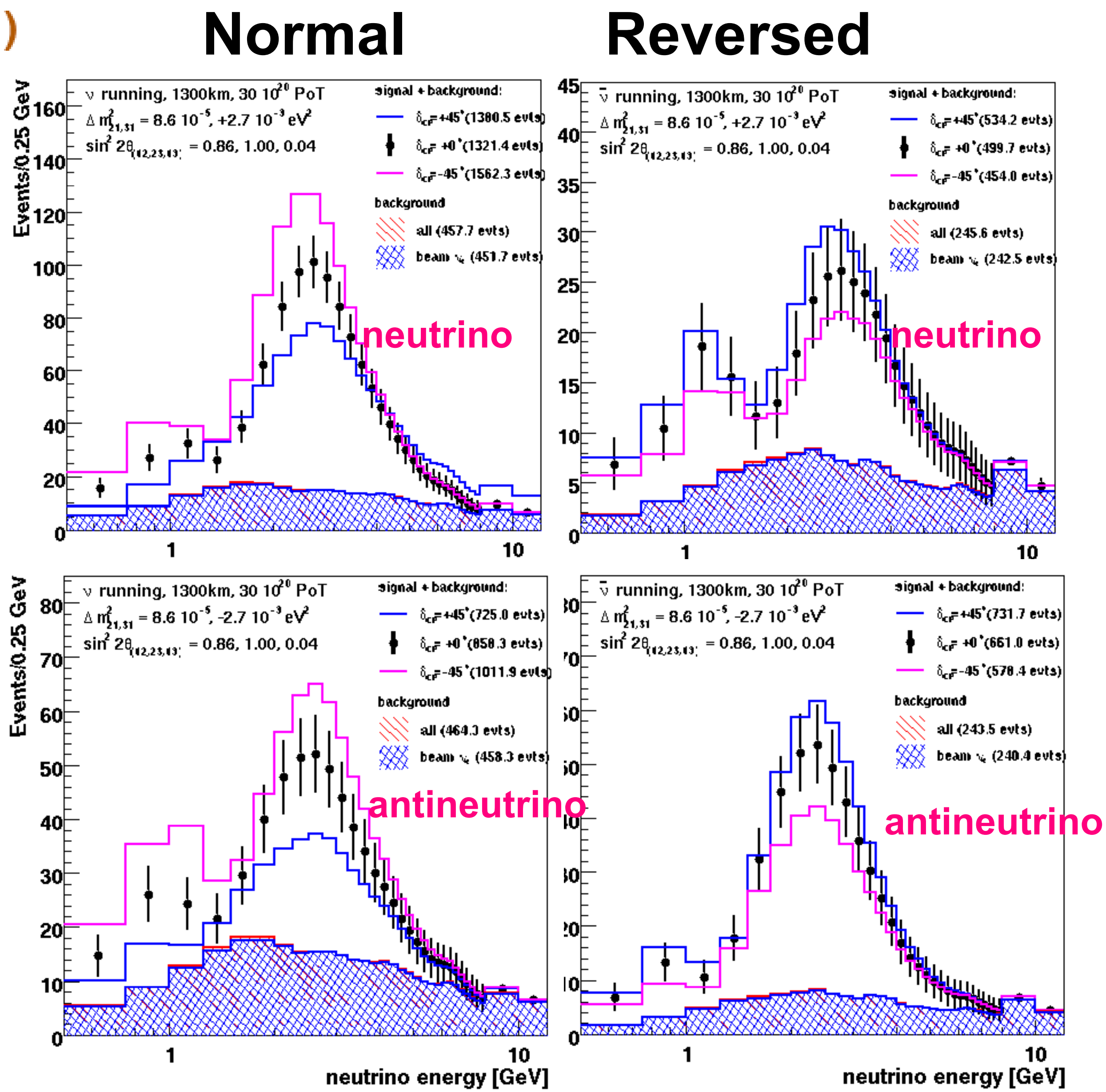
Electron neutrino appearance spectra

$\sin^2 2\theta_{13} = 0.04$, 100kT LAr. , WBLE 120 GeV, 1300km, 30E20 POT.

$(-\ \delta_{cp} = -45°,\ -\ \delta_{cp} = +45°)$

- LAR assumptions
- 80% efficiency on electron neutrino CC events.
- sig(E)/E = 5%/sqrt(E) on quasielastics
- sig(E)/E = 20%/sqrt(E) on other CC events

Spectra and sensitivity is the work of M. Bishai, Mark Dierckxsens, Patrick Huber + many helpers

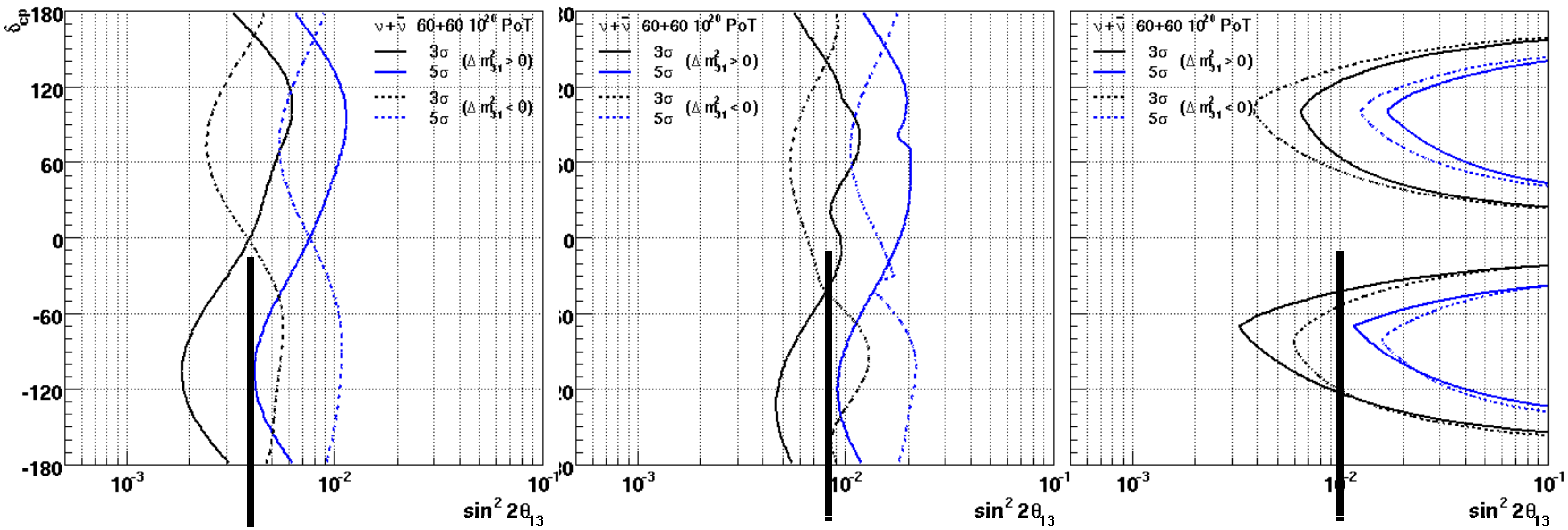


WBLE to DUSEL(1300km) 3sig, 5sig discovery regions.

60 10^20 POT for each nu and anu

300 kT WCh

Stat+syst th13 | mass ordering | CP violation

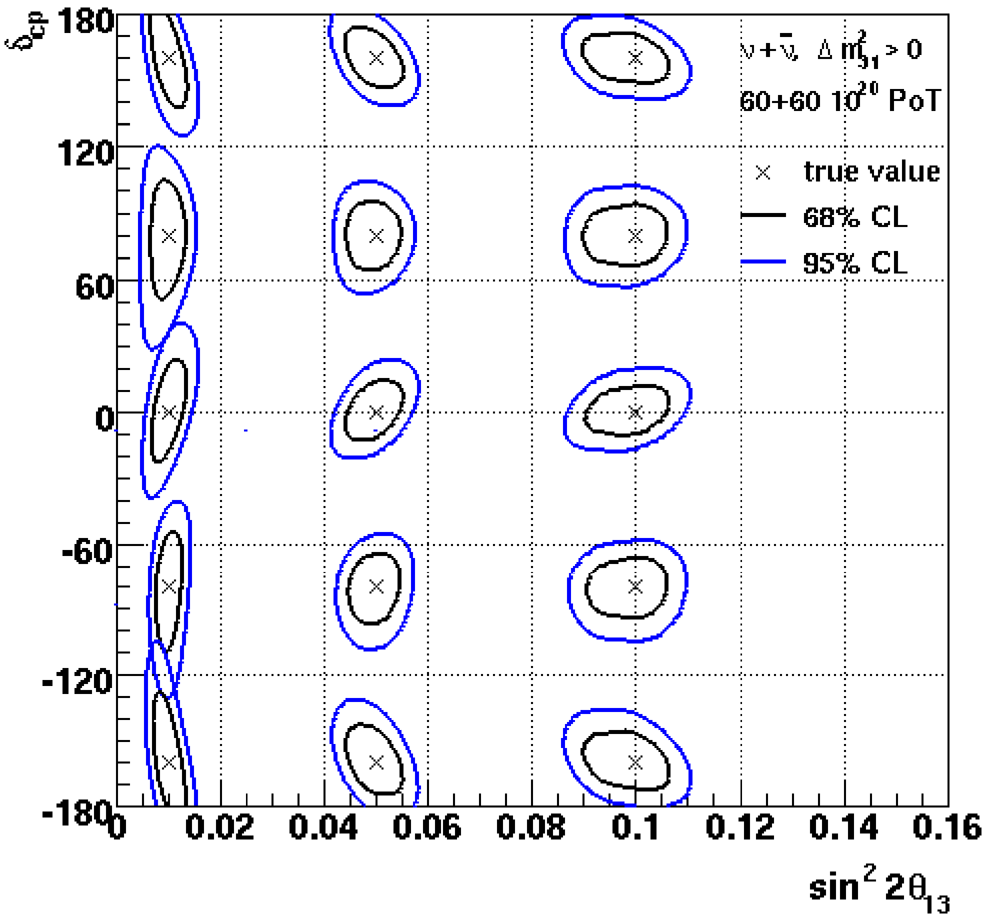


0.004 | 0.008 | 0.01

CP Fraction: Fraction of the CP phase (0-2pi) covered at a particular confidence level.

Report the value of th13 at the 50% CP fraction.

- **Program should lead to measurement of 3-generation parameters without ambiguities.**
- **CP measurement is approximately independent of θ13 if not background limited. Need large detector independent of θ13 value.**



300 kT water Cherenkov detector @DUSEL Measurement of CP phase and Sin²2θ13 at several points. All ambiguities and mass hierarchy are resolved.

Deductions

$\nu + \overline{\nu' s}$

$60 \times 10^{20} POT$
6 – 12 yrs

3 – 5 σ effects

$Sin^2 2\theta_{13} \sim .004$

Mass Hierarchy if $Sin^2 2\theta_{13} > .008$

CP violation if $Sin^2 2\theta_{13} > .01$

Programs:

Fermilab – Homestake
JPARC – SuperK/Island/South Korea
CERN-Finland/Great Britain

Proton Decay

Early Experiments

IMB, Kolar Gold Mine, Homestake, Soudan, Frejus

Recent Experiments

Kameokande, Superkameokande

	$p \to e^{+}\pi^{o}$	$p \to k^{+}\nu$
Theory:		
SU(5) Minimal	**10^{29}-10^{30} yrs**	**10^{28}-10^{30} yrs**
SUSY GUT		
SU(5)		
SO(10)	**2 x 10^{35} yrs**	**10^{34}yrs**
Exp. Limits	**8.2 x 10^{33}yrs**	**>1.6x 10^{33}yrs**

SuperK 141 kton yrs

Next Order of Magnitude

Again Need very large detectors

Supernova Neutrinos

SN87A IMB
Kameokande 19 Events

Core of Supernova
Supernova Hydrodynamics
Fundamental Neutrino Properties

Galactic Supernovae
~ 40 years $(\bar{\upsilon} + p \rightarrow n + e^{+})$
~ 100,000 events in 10 kpc

Diffuse (Relic) Supernova
Close to present limits

Measure Neutrino
Number
Energy
Time

Need many Large Detectors

Conclusions

New Era:

- **Large Scale detectors**
- **Intense Beams**
- **Long distances**

Grand opportunity:

- **Greatly improve accuracy of**
  - **atmospheric and solar neutrino parameters**
- **Resolve value of Theta 13, mass hierarchy and possibly observe CP violation**
- **Observe Supernova**
- **Possibly observe proton decay**