The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA International Atomic Energy Agency

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Summer School on Particle Physics

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Neutrino Physics - II

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Neutrino Physics
Past, “Present” and Future
“Puzzle Solving”

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ICTP Lecture #3 & 4

Trieste, Italy

June, 2011

BROOKHAVEN
NATIONAL LABORATORY

OUTLINE

1.) ***Early History*** (1931- 1973) the first 42 years

2.) ***Weak Neutral Currents***: $SU(2)_L xU(1)_Y$ confirmation

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3.) ***Neutrino Oscillations***: Reactor, Solar, Atmospheric

*4.) ***Neutrino Masses, Mixing, & Matter***

5.) ***Leptogenesis***: Matter-Antimatter Asymmetry (Universe)

6.***)*** ***Neutrinoless Double Beta Decay*** (Dirac vs Majorana)

7.) ***Leptonic CP Violation*** (neutrino vs antineutrino)

Requirements~300kton H_2O, 1-2MW protons,

8.) ***Future Neutrino Physics*** ➔ **Muon Collider**

9.) ***Outlook & Speculation***

3.) ***Neutrino Oscillations*: Reactor, Solar, Atmospheric…**

- If states are nearly degenerate & mix, quantum oscillations are possible. Produce a state that is not a Hamiltonian eigenstate, but a linear combination of several. Each will evolve separately in time and overall oscillations will occur.

Examples: ***K^0-K^0bar, B^0-B^0bar etc max mixing 45^o***

$K^0(t=0)$➔K^0bar➔K^0… (modulo decay)

Neutrinos similar but different (Fundamental point particles) not bound states

Non zero (but small) neutrino masses➔oscillations

Or oscillations➔neutrino masses & mixing

Blackboard Discussion of Neutrino Mass

4. Neutrino Masses, Mixing and Matter

- 1969-90s Ray Davis Measures Solar ν_e Flux at Homestake Deep Underground Mine ~1/3 Expected!

  Gallex, Sage, SuperK, SNO, Kamland (Reactor)

  Interpretation: solar $\nu_e \rightarrow 1/3\ \nu_e + 1/3 \nu_\mu + 1/3 \nu_\tau$ (roughly)

- 1980s IMB, Kamioka, measure atm. ν_μ flux, less than expected (Also observe supernova 1987a neutrinos!)

  SuperK; K2K, MINOS (Accelerators)

  Interpretation: atm. $\nu_\mu \rightarrow 1/2 \nu_\mu + 1/2 \nu_\tau$ (near maximal!)

Neutrino Oscillations Established → Neutrino Masses & Mixing Measured (Great Progress!)

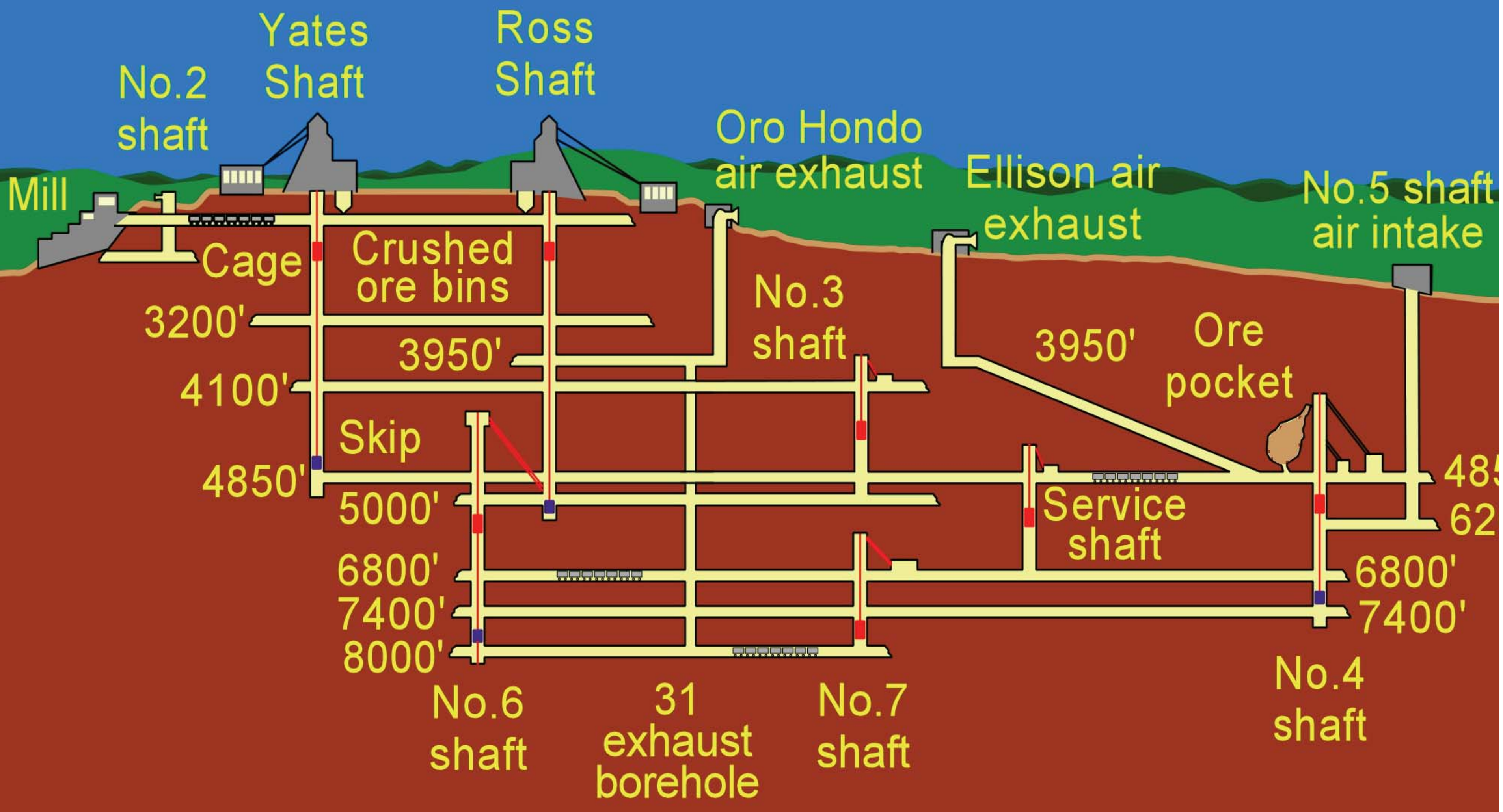
Katrin Spectrometer for $H^3 \rightarrow He^3 + e^- + \text{anti-}\nu_e$ (to 0.2eV!)

After the leak tests the tank was ready to be shipped. There is a slight problem of transportability from Deggendorf to Karlsruhe: The tank is too big for motorways, and the canal between the rivers Rhine and Danube has to be ruled out, too. Thus, instead of a journey of about 400 km, the spectrometer has to travel nearly 9000 km as indicated in the map.

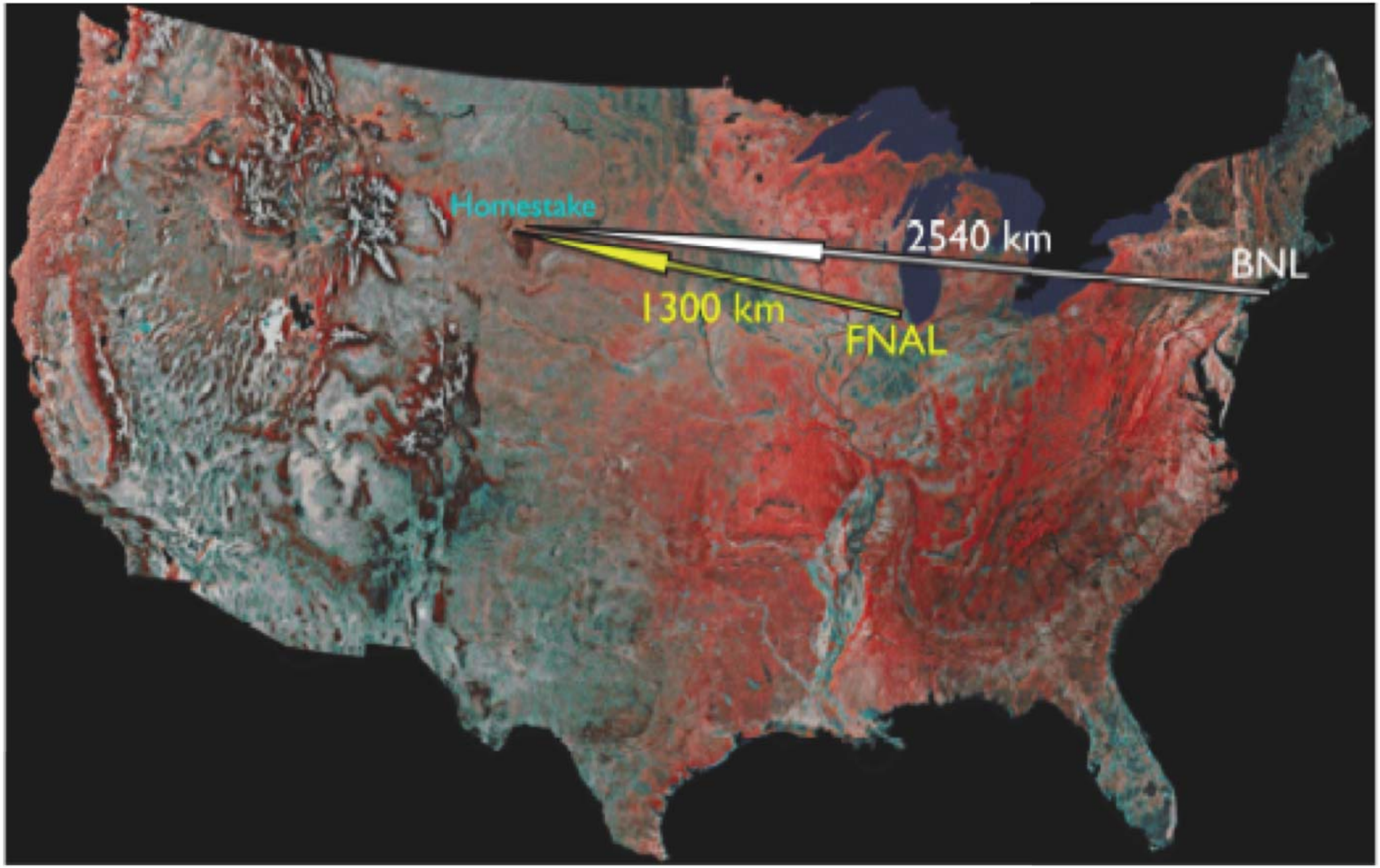
Fig. 5*): Journey of main spectrometer from Deggendorf (river Danube) to Leopoldshafen nr FZK (river Rhine)

*) Map courtesy of the University of Texas Libraries, The University of Texas at Austin.

General Homestake Mine Development



Very Long Baseline Neutrino Oscillations
(Fermilab or BNL- Homestake)



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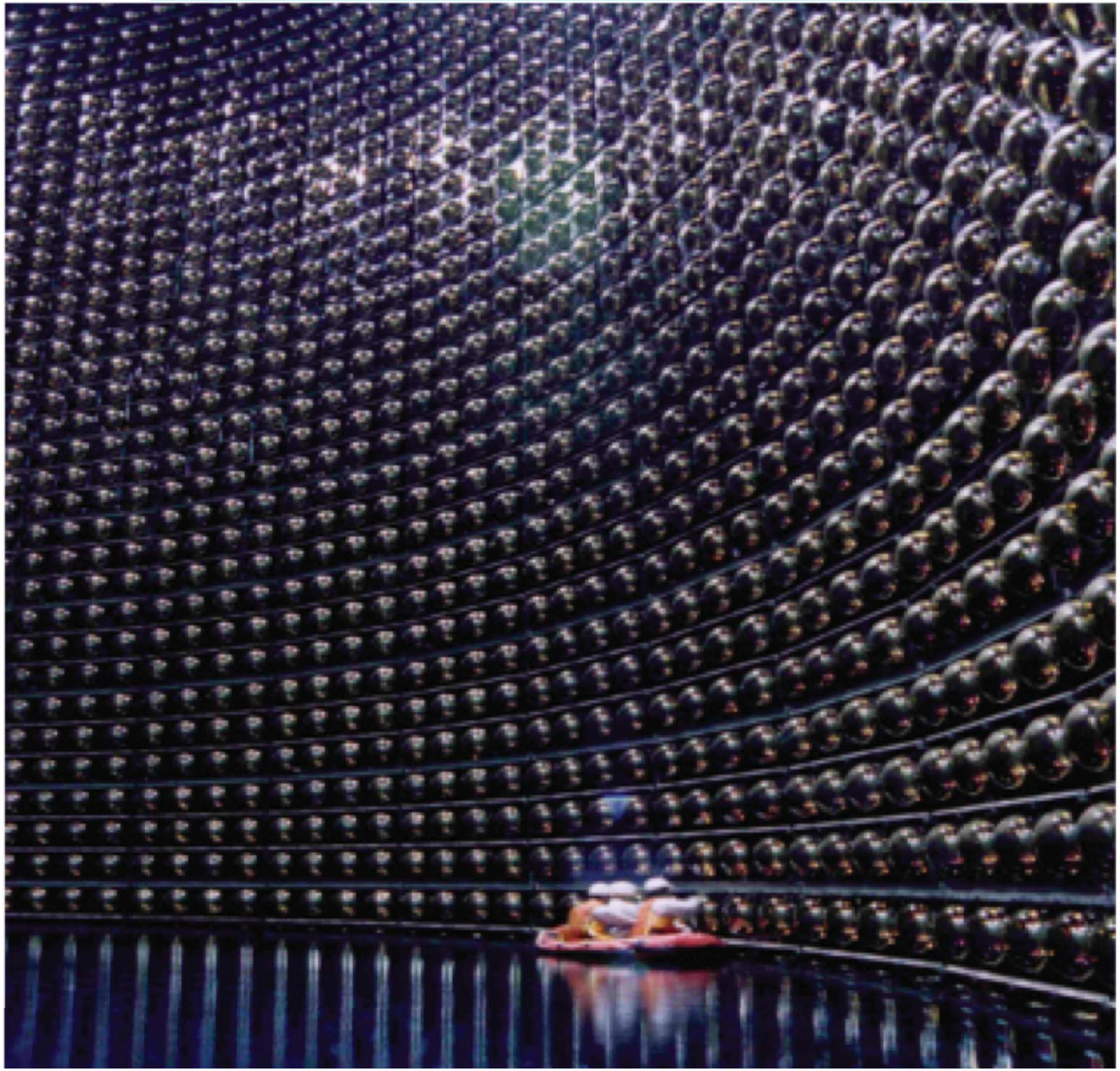


3 Generation Mixing Formalism & Status)

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = U \begin{pmatrix} |\nu_1> \\ |\nu_2> \\ |\nu_3> \end{pmatrix} \qquad (1)$$

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

$$c_{ij} = \cos\theta_{ij} \quad , \quad s_{ij} = \sin\theta_{ij}$$

$$J_{CP} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta. \qquad (2)$$

Current Neutrino Mass & Mixing Parameters

- $\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm\ 2.4(1) \times 10^{-3}\ \mathrm{eV}^2$ (atmospheric)
- $\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.6(2) \times 10^{-5}\ \mathrm{eV}^2$ (solar)

(Very precise Minos & KamLAND Measurements)

$|\Delta m_{21}^2/\Delta m_{32}^2 \approx 1/30| \rightarrow$ CP Violation Exp Doable!

Hierarchy $m_3 > m_1 \& m_2$ (normal) or $m_3 < m_1 \& m_2$ (inverted)?

Large Mixing!

$\theta_{23} \sim 45°$ $\sin^2 2\theta_{23} = 1.0$ (θ_{23} or $90° - \theta_{23}$) (atm.)

$\theta_{12} \sim 34°$ $\sin^2 2\theta_{12} = 0.87(3)$ (solar)

$\theta_{13} \leq 11°$ $\sin^2 2\theta_{13} \leq 0.15$ (How Small?)

$0 \leq \delta \leq 360°$?

$J_{CP} \cong 0.11 \sin 2\theta_{13} \sin\delta$ (potentially large!)

What do we still need to learn?

- 1. **Value of θ_{13}?** (Reactors: $\sin^2 2\theta_{13} \to 0.01$)
  (Long Baseline $\nu_\mu \to \nu_e$ 0.003)

- 2. **Sgn Δm_{32}^2?** (Important for Neutrinoless $\beta\beta$ Decay)

- 3. **Value of** δ?, J_{CP}?, CP Violation? ***(Holy Grail)***

- 4. **Precision** Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12} (better than 1%!)

- 5. **"New Physics"** - Sterile ν, ***Very Weak*** Long Distance Physics (*The Dark World*)…

Leptogenesis: Matter-Antimatter Asymmetry

- **More baryons than antibaryons in our Universe**
- Leptogenesis Scenario:

1. Heavy Majorana Neutrinos Created and Decay

   $N \rightarrow H^{-}e^{+}$, $H^{0}\nu$bar (***L & CP VIOLATION***)

   Leads to antilepton (excess)-lepton Asymmetry

2. Electroweak Phase Transition (250GeV) (Baryogenesis)

   't Hooft Mechanism B-L Conserved (B&L Violated)

   antilepton excess$\rightarrow$baryon (quark) excess by 1 in 10^{9}

Is L Violated in Nature? ***(Neutrinoless ββ Decay)***

Is there Leptonic CP Violation? ***(ν oscillations)***

Indirect evidence for Leptogenesis (Best we can do.)

The Fundamental Importance of Neutrinos

Neutrino Physics May Be Responsible For Our Existence! (baryons & electrons)!

They help power the Sun (nuclear Reactions)

They Allow R Process in Supernova

(Supernova - Heavy Elements)

We are the remnants of Supernovae

7. Leptonic CP Violation

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e)$$

$$+ \ \text{matter} \ + \text{smaller terms}$$

$$\mathbf{P}_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)$$

$$\mathbf{P}_{II}(\nu_\mu \to \nu_e) = \frac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$

$$\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right) \times \left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right.$$

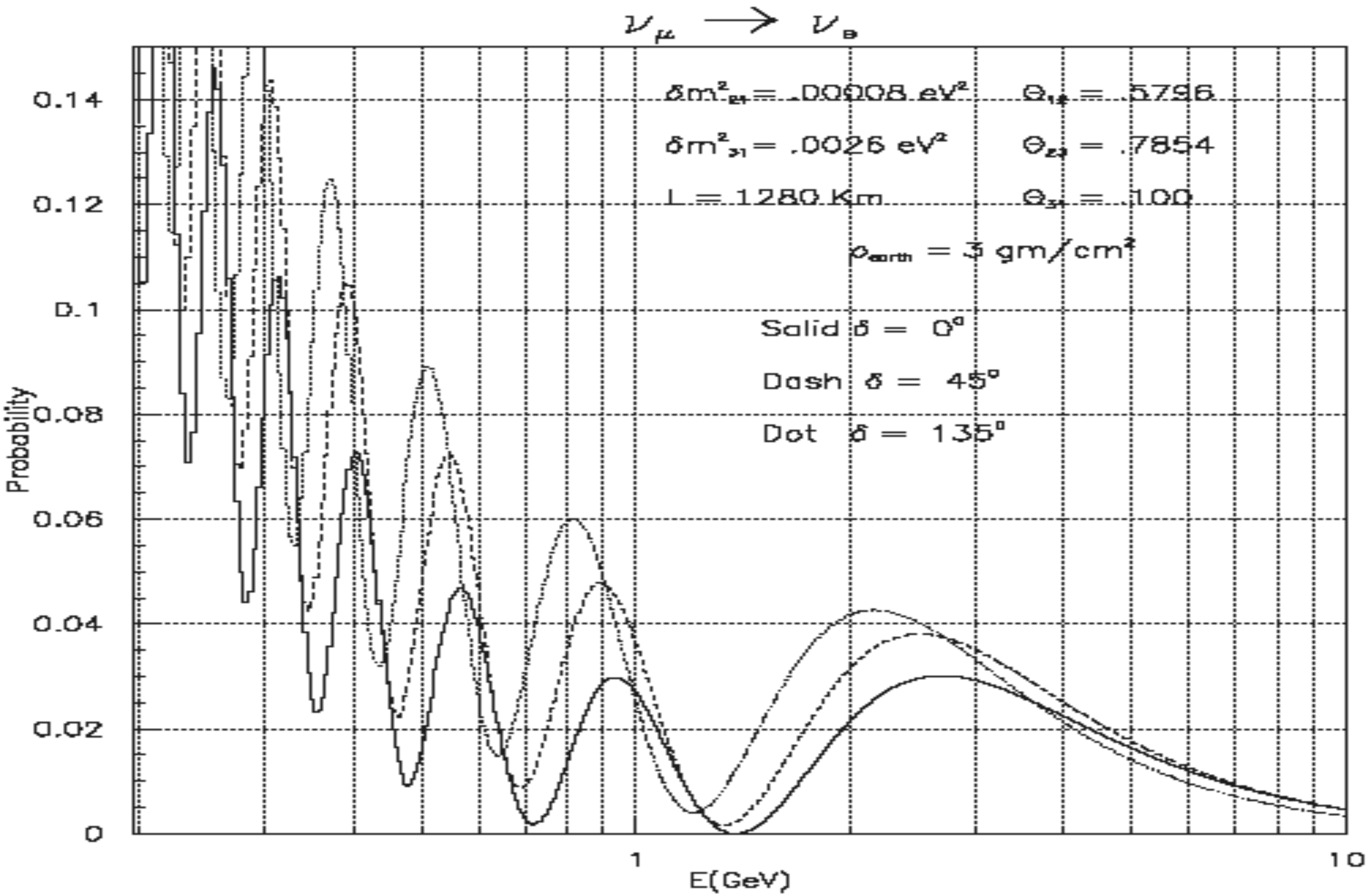
$$\left. + \cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right]$$

$$\mathbf{P}_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

For antineutrinos, $\delta \to -\delta$ and opposite matter effect.

Zohreh Parsa, BNL

FNAL



CP Violation Asymmetry

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \tag{3}$$

To leading order in Δm^2_{21} ($\sin^2 2\theta_{13}$ is not too small):

$$A_{CP} \simeq \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects} \tag{4}$$

$$F.O.M. = \left(\frac{\delta A_{CP}}{A_{CP}}\right)^{-2} = \frac{A^2_{CP} N}{1 - A^2_{CP}} \tag{5}$$

N is the total number of $\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$ events.Since N falls (roughly) as $\sin^2\theta_{13}$ and $A^2_{CP} \sim 1/\sin^2\theta_{13}$, to a first approximation the F.O.M.is independent of $\sin\theta_{13}$. Similarly, given E_ν the neutrino flux and consequently N falls as $1/L^2$ but that is canceled by L^2 in A^2_{CP}.

i) CP Violation Insensitivities

- To a very good approx., our statistical ability to determine δ or A_{cp} is **independent** of $\sin^2 2\theta_{13}$ (down to ~ 0.003) and the detector distance L (for long distance).

ii) CP Violation Requirements

- Pick any reasonable θ_{13} (eg $\sin^2 2\theta_{13}=0.04$)
- What does it take to measure δ to $\pm 15°$ in about 5×10^7 sec?

Answer (Approx.): 300kton Water Cerenkov Detector

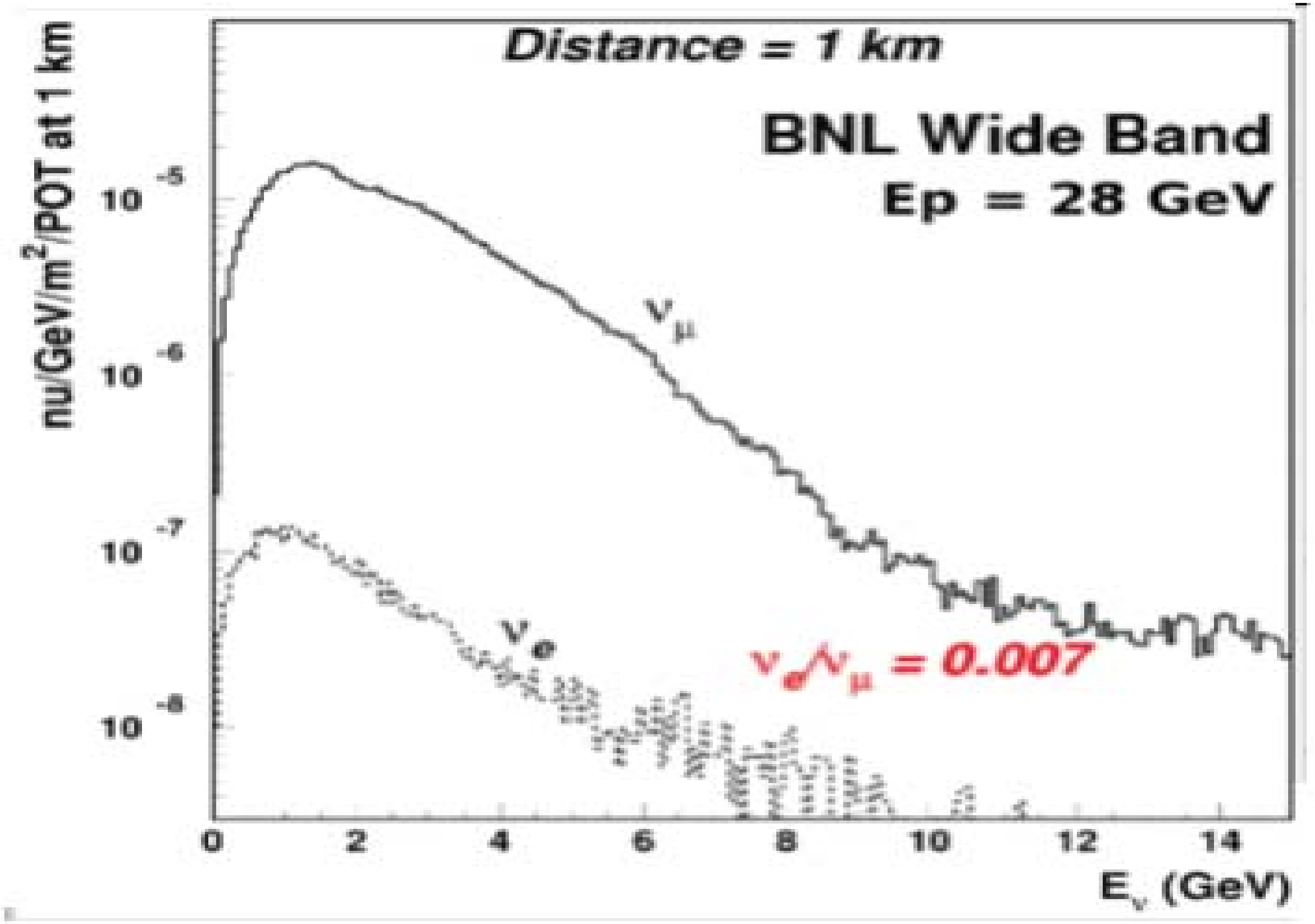
Approx 20% Acceptance,

50 kton LArgon 90% Acceptance

or Hybrid combination

+ Traditional Horn Focused ν WBB powered by 1-2MW proton accelerator (egs. Project X at FNAL)

Horn Focused Neutrino Beam



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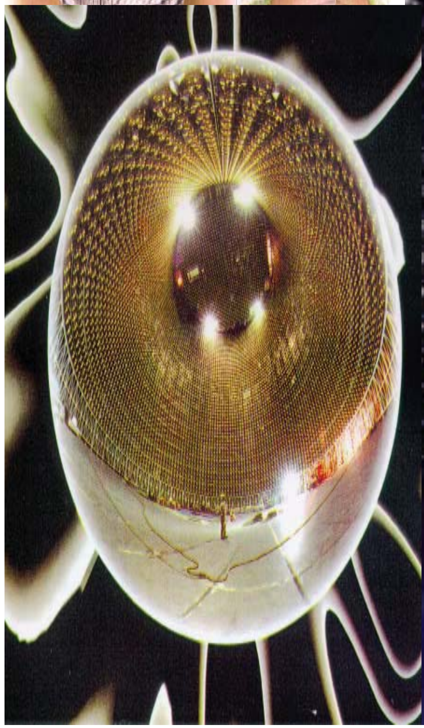
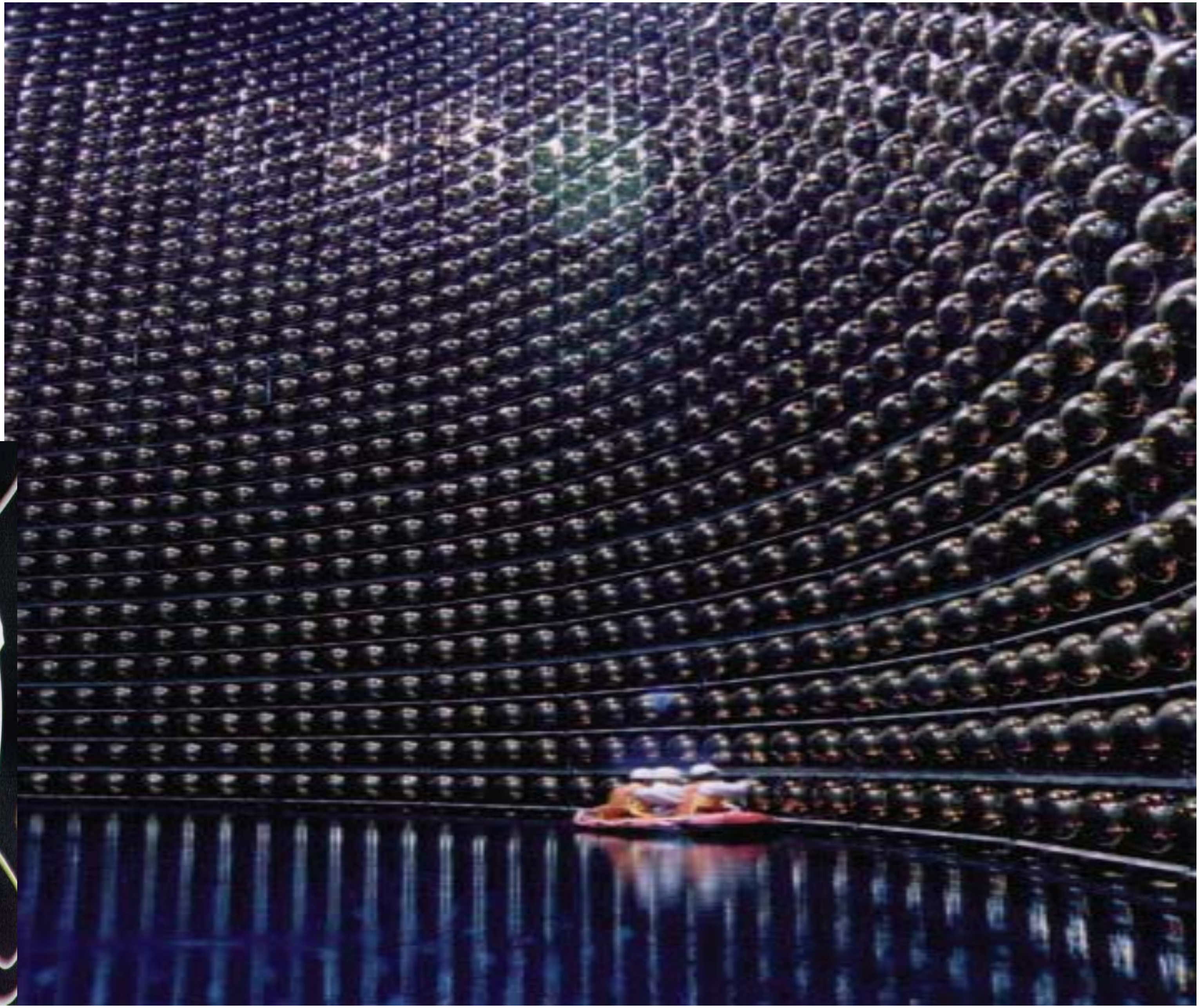
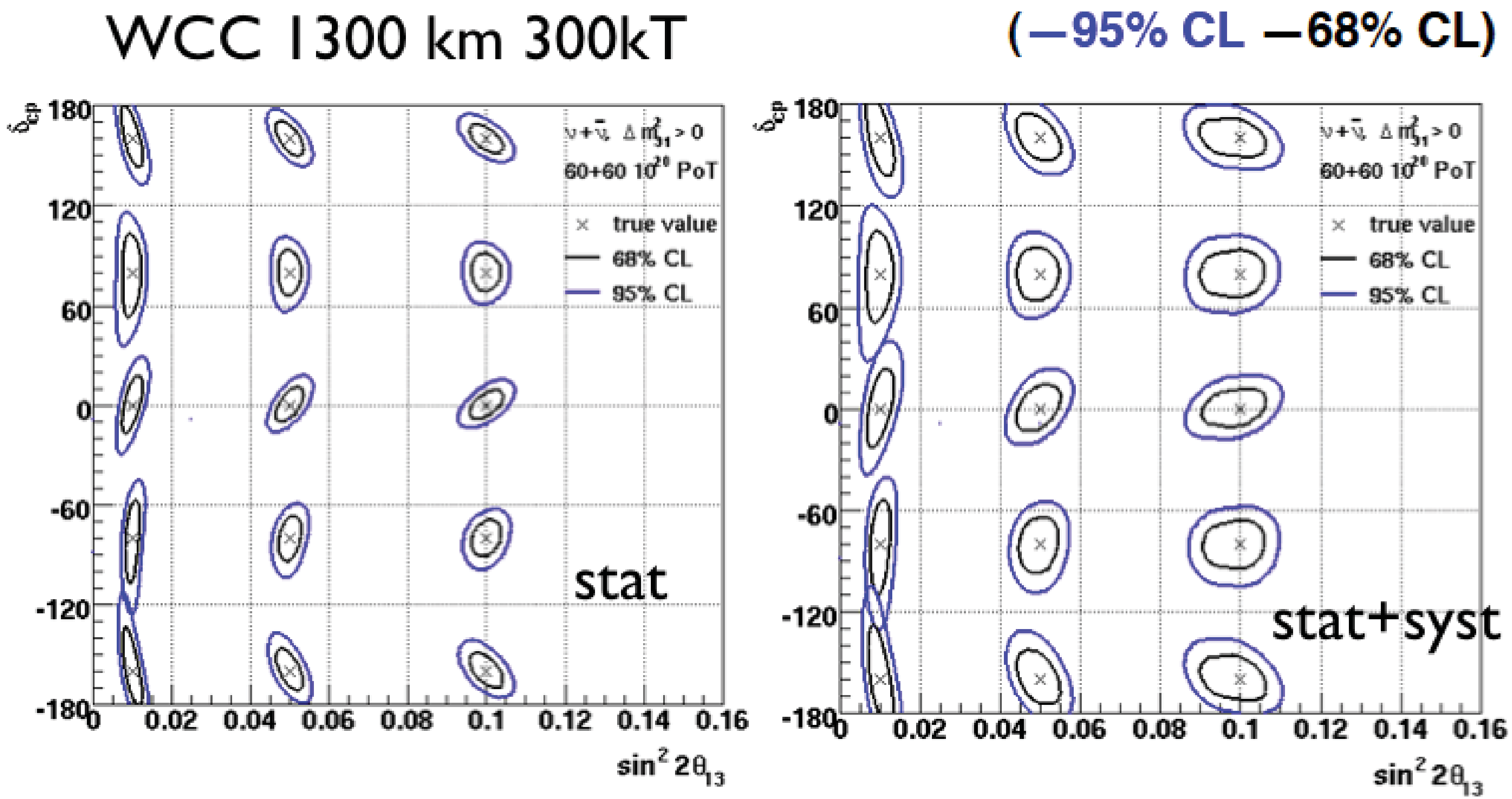




CP Phase Insensitivity to θ_{13} Value



4. "New Physics" search via ν_μ & ν_μ disappearance

Disappearance at MINOS $\nu_\mu \rightarrow \nu_\mu$ & anti-$\nu_\mu \rightarrow$anti-ν_μ show differences?

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2(\Delta m^2_{32} L/4E_\nu)$$

$\nu_\mu \rightarrow \nu_\mu$: $\Delta m^2_{32} = 2.35(11) \times 10^{-3} eV^2$ $\sin^2 2\theta_{32} \sim 1$ (>0.91)

anti-$\nu_\mu \rightarrow$antiν_μ: $\Delta m^2_{32} = 3.36(45) \times 10^{-3} eV^2$, $\sin^2 2\theta_{32} = 0.86(11)$

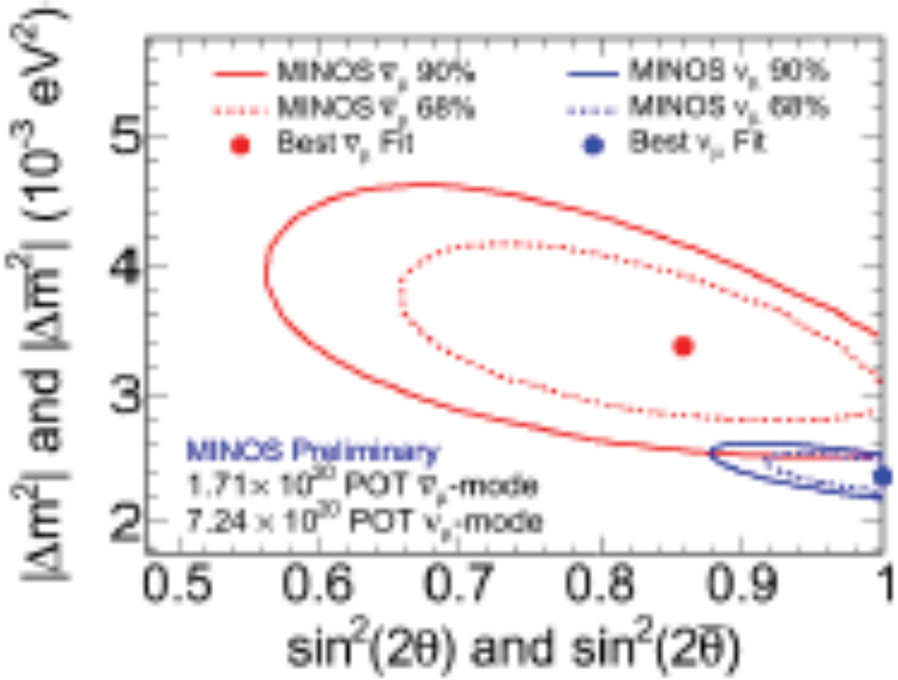
2σ difference? 30%?

(Collaboration does not claim discrepancy!)

But good motivation to examine "New Physics" effects in neutrino oscillation experiments, since in the future one might expect better than 1% measurements!

Anticipate Surprises!

$\bar{\nu}_\mu$ oscillation parameters



- Contours include the effects of systematic uncertainties

ν_μ Disappearance

Very easy to get this effect
Does not need extensive pattern recognition. Can enhance the seco
minimum by background subtracti

Neutrino Running

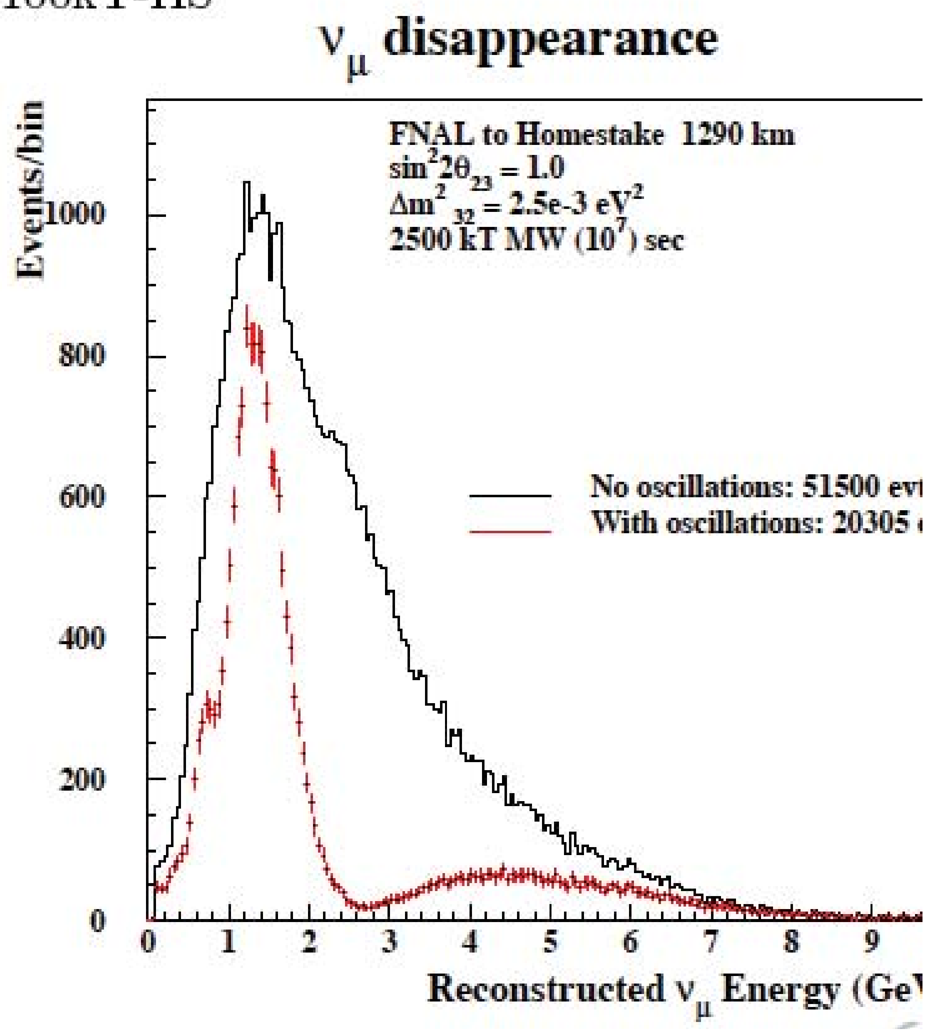
- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

Measurements

- 1% determination of Δm^2_{32}
- 1% determination of $\sin^2 2\theta_{23}$
- Most likely systematics limited.

$\bar{\nu}$ running

- Need twice the exposure for similar size data set.
- very precise CPT test possible.



Δm^2_{32} and $\sin^2 2\theta_{32}$ can be measured in long baselines as functions of E_ν (also obtained from atmospheric ν).

$\nu_\mu \rightarrow \nu_\mu$ & anti-$\nu_\mu \rightarrow$ anti-ν_μ Comparison

Usually phrased as a test of CPT (true in vacuum)

Apparent CPT violation $\rightarrow$ "New Physics" in ν interactions

(in matter or) $\varepsilon\sqrt{2}G_F \nu\gamma_\mu\nu' f\gamma^\mu f$, f=e, u, d

long range interactions Potential changes sign $\nu_\mu \rightarrow$ anti-ν_μ

Sterile Neutrinos? etc

"General bounds on non-standard neutrino interactions" by Biggio, Blennow and Fernandez-Martinez (2009)

Using solar and atmosheric oscillation data in $\nu_e\,\nu_\mu\,\nu_\tau$ space

From Solar and Atmospheric.

$$
|\varepsilon| < \begin{array}{cccc} \nu_e & \nu_\mu & \nu_\tau & \\ 2.5 & 0.21 & 1.7 & \nu_e \\ 0.21 & 0.046 & 0.21 & \nu_\mu \\ 1.7 & 0.21 & 9.0 & \nu_\tau \end{array}
$$

(Bounds being updated-Take with a grain of salt)

ε represents the size of the "New Physics" potential relative to MSW potential (Weak Strength $\sqrt{2}G_F\nu_e\gamma_\mu\nu_e e\gamma^\mu e$)

Some Interesting Recent $\varepsilon \neq 0$ Examples

Engelhardt, Nelson and Walsh: sterile neutrinos & gauge B-L
new long distance physics
weakly coupled

Heeck and Rodejohann: gauge L_μ-L_τ (violate e-μ-τ universality)
very long range interaction, $m_V < 10^{-18}$eV!

Earlier: *Joshipura &Mohanty* Gauged L_e-L_μ, L_e-L_τ, L_μ-L_τ
Fifth Force: $\alpha' \approx 10^{-52}$!

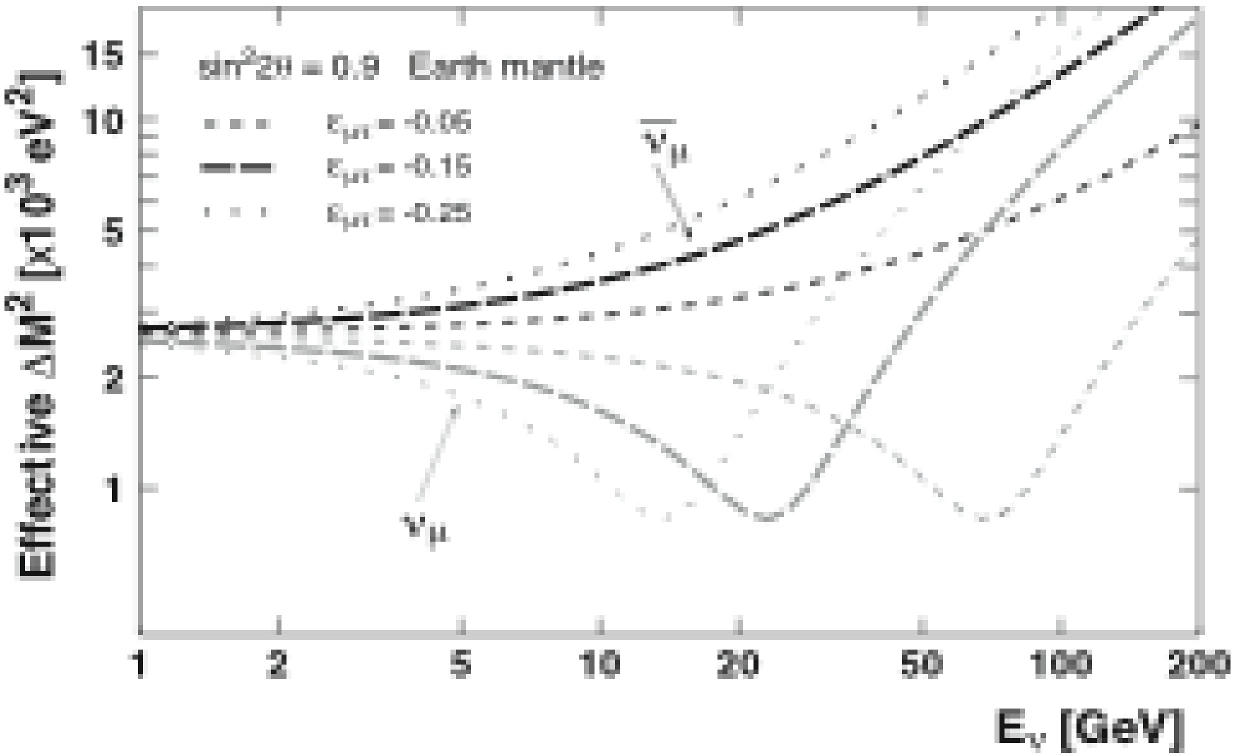
Mann et al.: New $\nu_\mu \rightarrow \nu_\tau$ Interaction $\varepsilon_{\mu\tau} \sim -0.1$ (see figure, some generic features)

Either $O(\alpha/\Lambda^2)$ Λ large or $O(\alpha'/m^2)$ *α' and m small* (long distance)
Effective potential changes sign for $\nu_\mu \rightarrow$ anti-ν_μ

All lead to different ν_μ and anti-ν_μ oscillations (in matter)

E_ν Dependence of Oscillation Parameters

From Mann, Cherdack, Musial and Kafka (Example)



$\nu_\mu \rightarrow \nu_\mu$ and anti-ν_μ $\rightarrow$anti-ν_μ disappearance

- $$i\,d/dt \begin{vmatrix}\nu_\mu(t)\\ \nu_\tau(t)\end{vmatrix} = \begin{vmatrix}\Delta m^2_{32}s^2/2p_\nu & \Delta m^2_{32}sc/2p_\nu \\ \Delta m^2_{32}sc/2p_\nu & \Delta m^2_{32}c^2/2p_\nu - p_\nu(n_{\nu\tau}-n_{\nu\mu})\end{vmatrix} \begin{vmatrix}\nu_\mu(t)\\ \nu_\tau(t)\end{vmatrix}$$

  $s=\sin\theta_V$ $c=\cos\theta_V$

  Could also be off diagonal matter effects, eg Mann et al

  $L_V=2(2p_\nu/\Delta m^2_{32})\sim1000(E_\nu/1\text{GeV})$km

  $L_0=2\pi/p_\nu(n_{\nu\tau}-n_{\nu\mu})\sim5000/\varepsilon$km Refraction index length

  $y=L_V/L_0\sim E_\nu\varepsilon/5$GeV (Big Effects For $y\sim O(1)$)

  $P(\nu_\mu\rightarrow\nu_\mu)=1-\sin^2 2\theta_m \sin^2(\pi x/L_m)$ disappearance

(Suggests studies at high energies & long distances)

$E_\nu>5\text{GeV}/\varepsilon$ Atmospheric & Very Long Baseline

Best Bet – Deep Core in Ice Cube E≈ 20GeV

$\sin^2 2\theta_m = \sin^2 2\theta_V / (1 \pm 2y\cos 2\theta_V + y^2)$

$L_m = L_v / (1 \pm 2y\cos 2\theta_V + y^2)^{1/2}$

$y = L_v / L_0 \sim E_\nu \varepsilon / 5\text{GeV}$

for 3 gm/cm^3

$\Delta m^2_{32}(\text{matter}) = \Delta m^2_{32}(1 \pm 2y\cos 2\theta_V + y^2)^{1/2}$

for $y >> 1$ oscillations highly suppressed $L_m \sim L_0$

for $y << 1$ matter effects very small

Resonance $y = \cos 2\theta_V \rightarrow \theta_m = 45°$, minimum $\Delta m^2_{32}(\text{matter}) =$

$\Delta m^2_{32} \sin 2\theta_V$

No resonance for maximal vacuum mixing $\theta_V = 45°$ (our world)

No Δm^2_{32} difference in **ν_μ vs anti-ν_μ** for $\theta_V = 45°$ (but depends on E_ν)

Note high E_ν more sensitive to matter!

Anticipate possible differences in ν_μ and □ν_μ effective energy dependent mixing angles and Δm^2_{32} in matter

Future experiments will measure those parameters with very high precision! Atmospheric as well as Long Baseline ν_μ and □ν_μ disappearance will be very powerful probes of non standard (long and short distance) neutrino interactions!

Note, *$\nu_\mu \rightarrow \nu_\tau$ and anti-$\nu_\mu \rightarrow$ anti-ν_τ appearance potentially very interesting*

***Moral:* Neutrino ν_μ and anti-ν_μ Osc in Matter provides a potentially powerful probe of (weakly coupled) light and heavy "New Physics". Particularly light $\varepsilon \sim \alpha'/G_F m^2$**

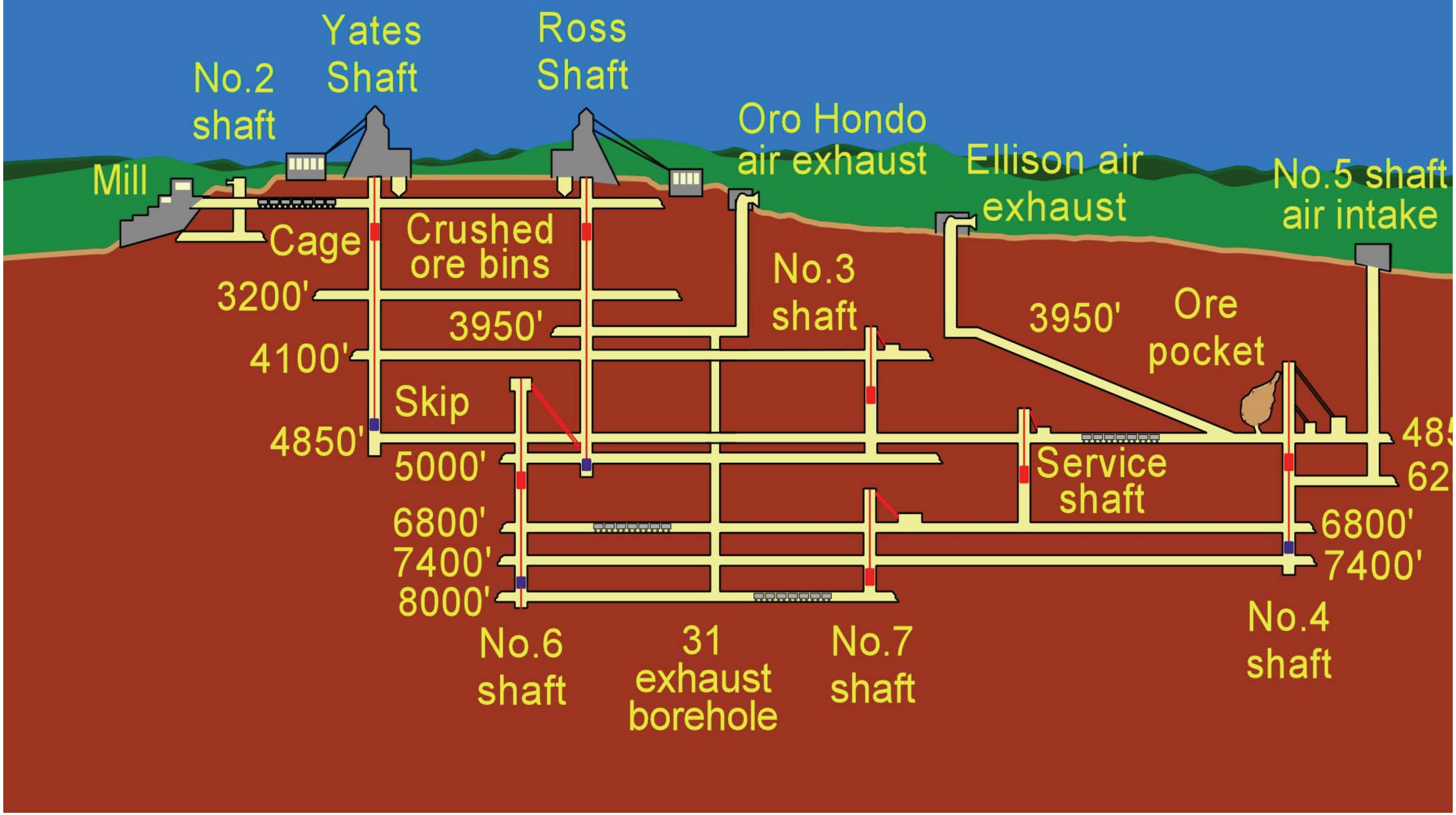
(Does not depend sensitively on $\sin^2 2\theta_{13}$ value!)

5. Outlook

- Neutrino exps will advance: θ_{13} Mass Hierarchy, ν CP Violation … via LBNE Requires Big Detector: 300kton H_2O or equivalent
  2MW Accelerator wide band neutrino beam
- ***Also***
- Atmospheric & Solar ν
- 100,000 supernova ν events (if in our galaxy)!
- Observe relic supernova ν (universe history)!
- ***"New Physics"***: sterile ν, extra dim. dark energy…
- Proton decay, n-anti-n osc.,…magnetic monopoles

The potential for major discoveries & surprises is great!

General Homestake Mine Development



Supernova Neutrinos

- SN 1987A: 19 events observed by Kamiokande & IMB
  anti-$\nu_e p \rightarrow e^+ n$ Great Discovery - Confirmed SN Models
  A SN in our galaxy (every ~ 40yr) at typical10kpc would
  lead to about 100,000 anti-$\nu_e p \rightarrow e^+ n$ events/300kton H_2O
  Also, $\nu e \rightarrow \nu e$, ($\nu = \nu_e, \nu_\mu, \nu_\tau$,+antineutrinos) ~ 1000events
  We would like to see $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$ (initial burst)
  ~250 events/kton LArgon
  Neutrino Spectrum $\rightarrow$ SN Dynamics & Oscillations
  Extremely Rich Discovery Possible
  We must have as many detectors as possible online
  Relic SN Neutrinos (10-40MeV) S/B/yr ~10/10

Fermilab Activities

- What does Fermilab do after the LHC starts?
- (Great Hope - ILC e^+e^- Collider ($\mu^+\mu^-$ Collider?))

In the meantime? New Working Group Report

Project X Option- 2MW 8GeV proton linac (ILC R&D)

8GeV fixed target program (eg. $\mu N \rightarrow eN$…)

+ Main Injector 30-120GeV (also at 2MW)

2MW at 50GeV provides nice neutrino beam for FNAL-Homestake (Cost ?) Total Project ≈$1-2 Billion

Doable! Must Do!

(START AS SOON AS POSSIBLE!)