Studies of Neutrinos and Neutrino Oscillations

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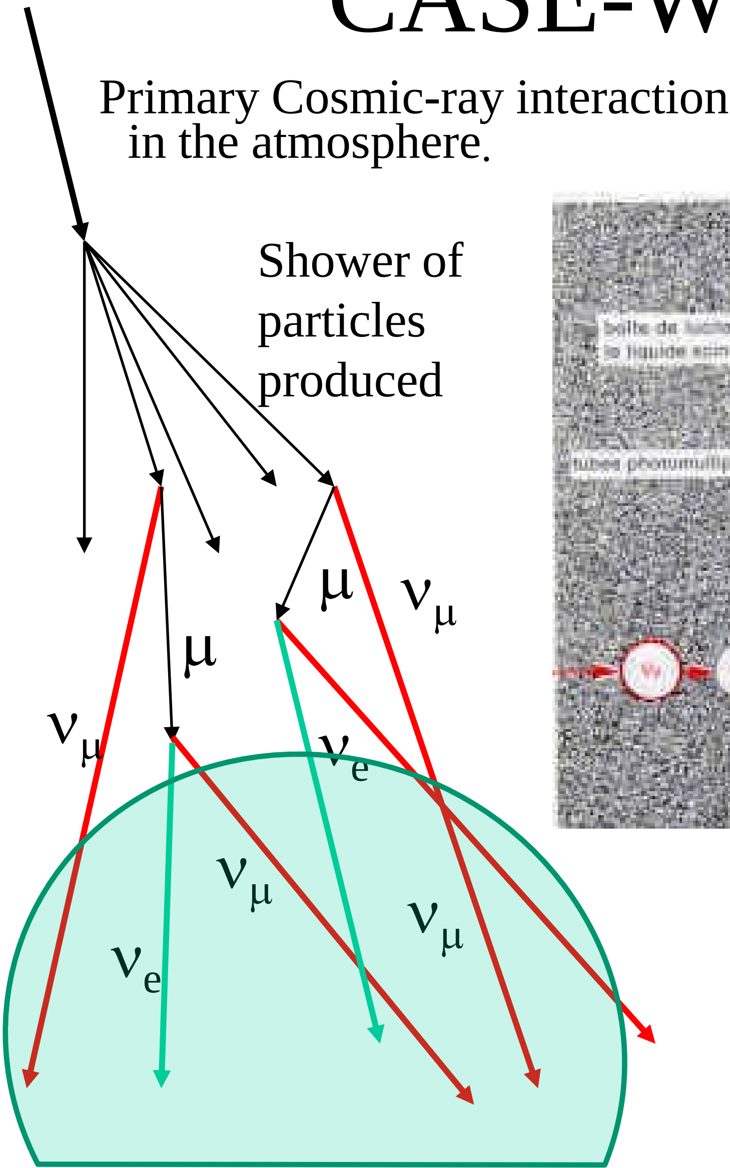
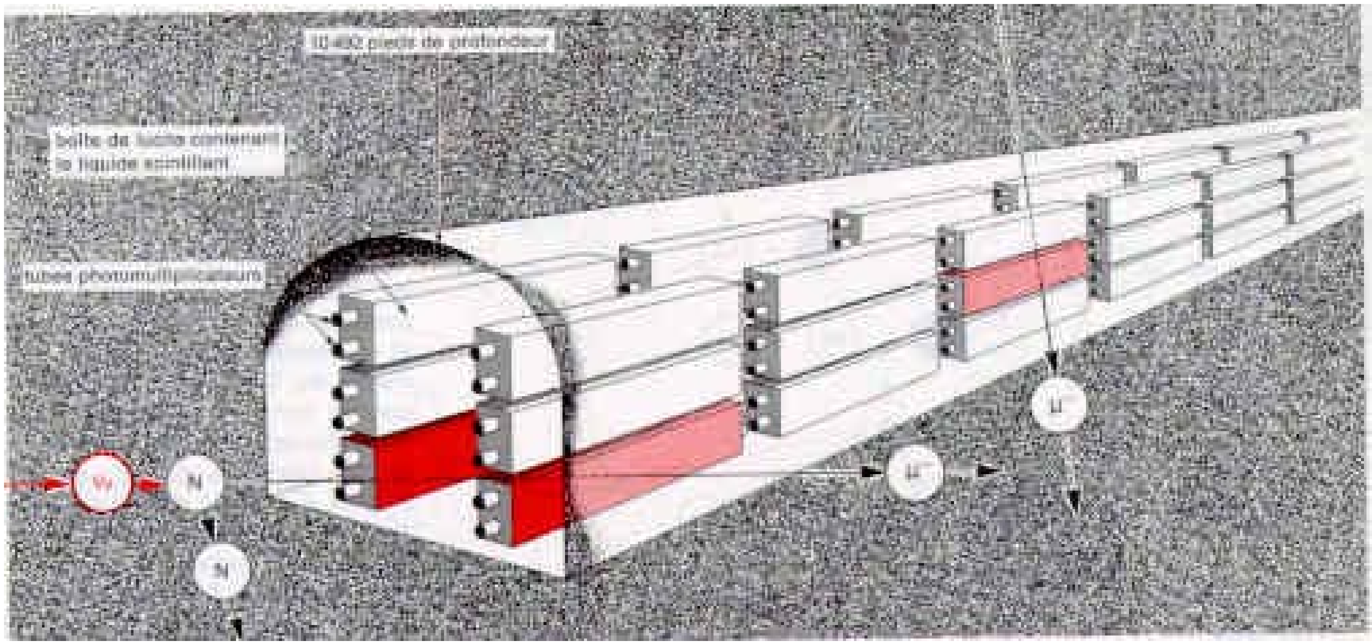
Dubna, Feb. 19, 2010

It all began for me in 1962:

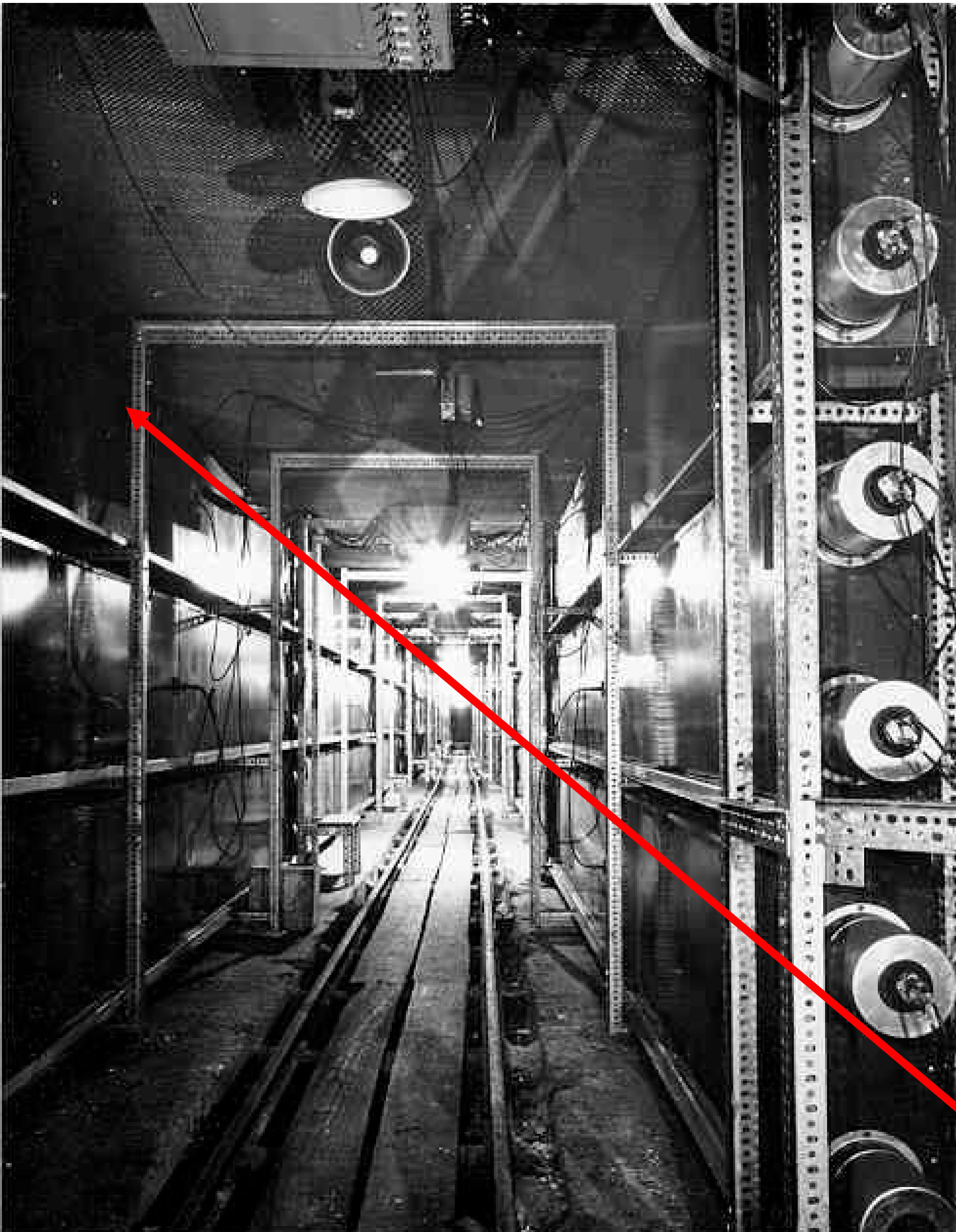
CASE-WITS (1965 - 1973)

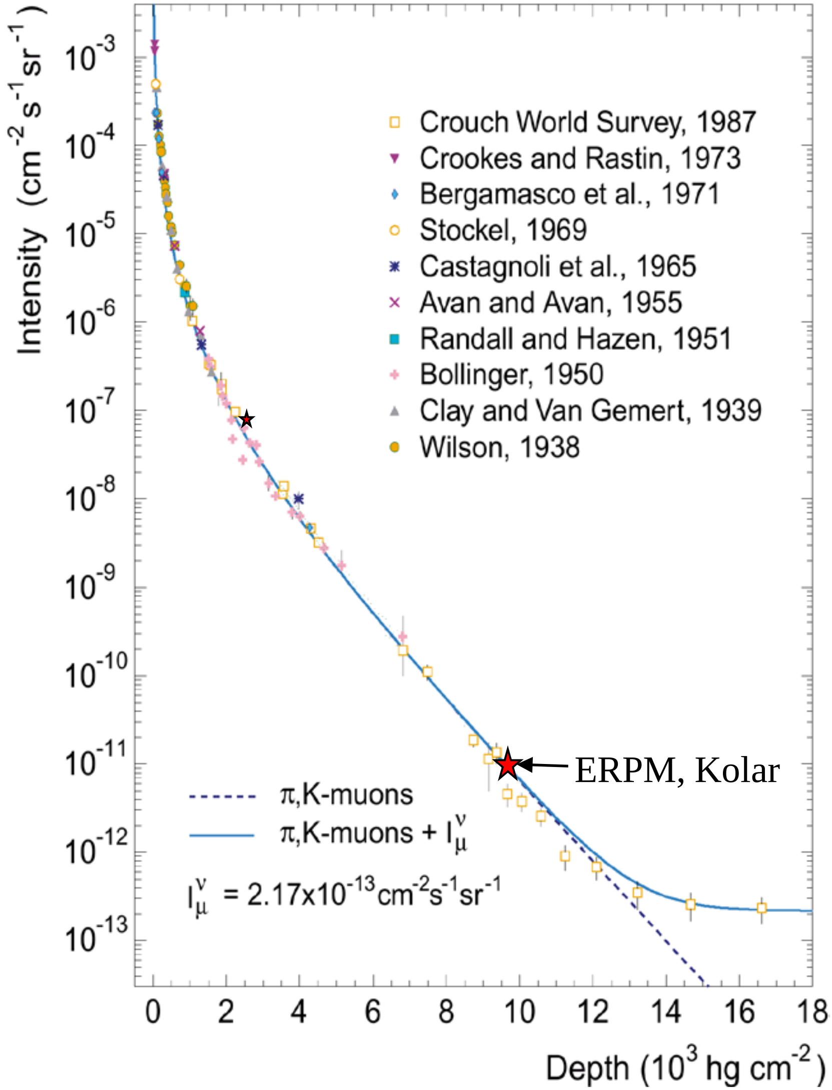




Depth of 3,200 meters in South African gold mine.

First Observation of Atmospheric Neutrinos - 1965





A factor of 1.6 fewer than expected..

Muon from Neutrino interaction

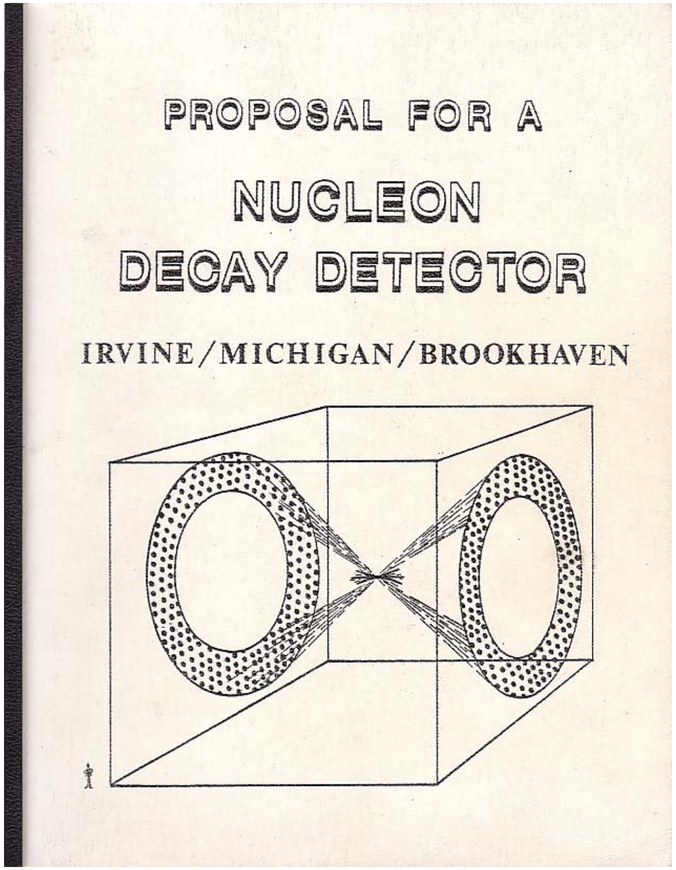
It’s interesting that the roots of the neutrino oscillation discoveries started around the same time in the mid-to-late 1960’s.

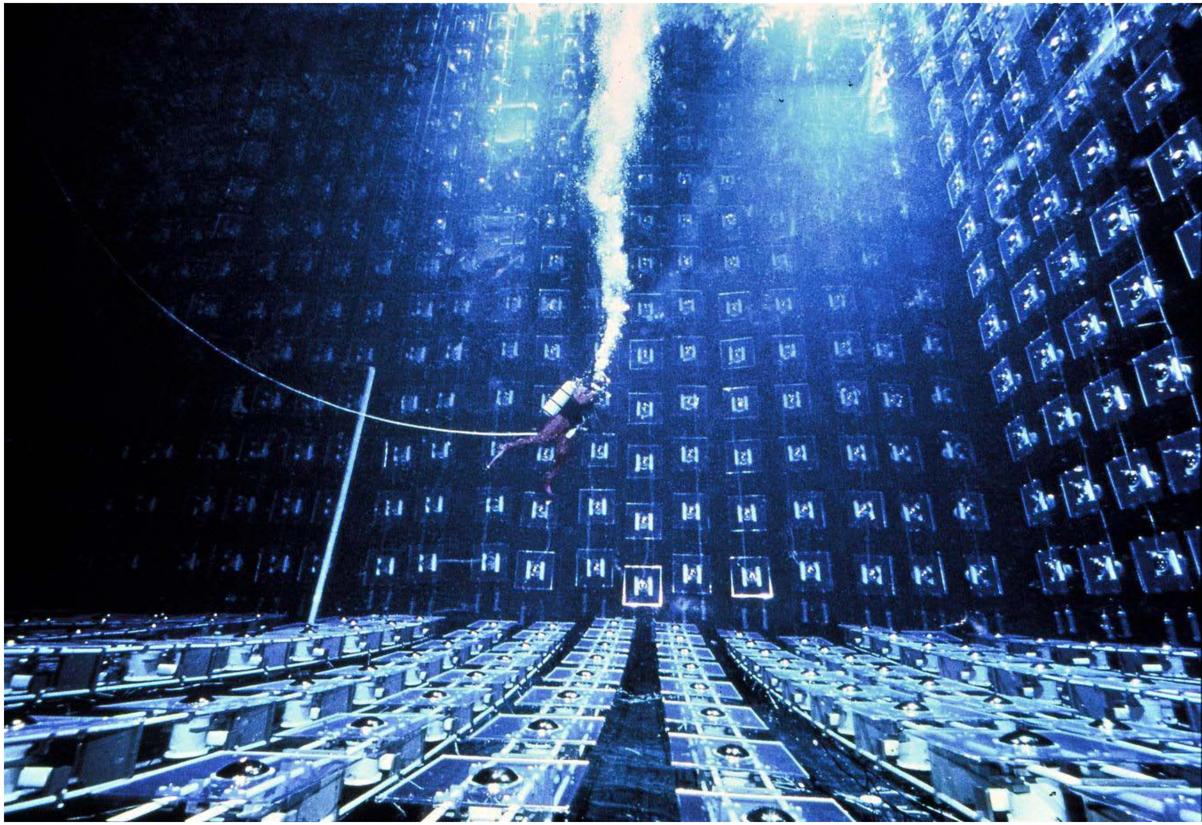
During those few years, Ray Davis observed that the solar neutrino signal was much lower than expected and the first atmospheric neutrino experiment in the South African gold mine observed fewer atmospheric neutrino events than was expected.

It’s safe to say that both of these observations were treated as errors either in the observations or in the predictions. It took over thirty years before neutrino oscillations were definitively demonstrated in atmospheric neutrinos by the Super-Kamiokande experiment and in solar neutrinos by a combination of the Super-Kamiokande and SNO experiments.

IMB (1979-1992)

(Irvine, Michigan, Brookhaven)





Proposed to observe proton decay as predicted by SU(5)

(Georgi and Glashow in 1974)

Some IMB Results

VOLUME 51, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1983

Search for Proton Decay into $e^+\pi^0$

R. M. Bionta, G. Blewitt, C. B. Bratton, B. G. Cortez,[a] S. Errede, G. W. Forster,[a] W. Gajewski, M. Goldhaber, J. Greenberg, T. J. Haines, T. W. Jones, D. Kielczewska,[b] W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, P. V. Ramana Murthy,[c] H. S. Park, F. Reines, J. Schultz, E. Shumard, D. Sinclair, D. W. Smith,[d] H. W. Sobel, J. L. Stone, L. R. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

SU(5) prediction not confirmed.

VOLUME 57, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1986

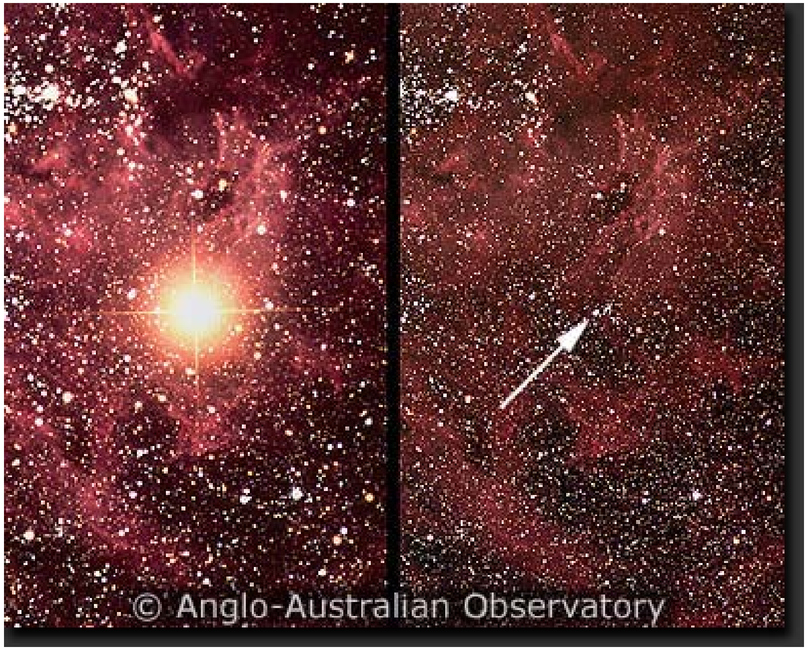
Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search

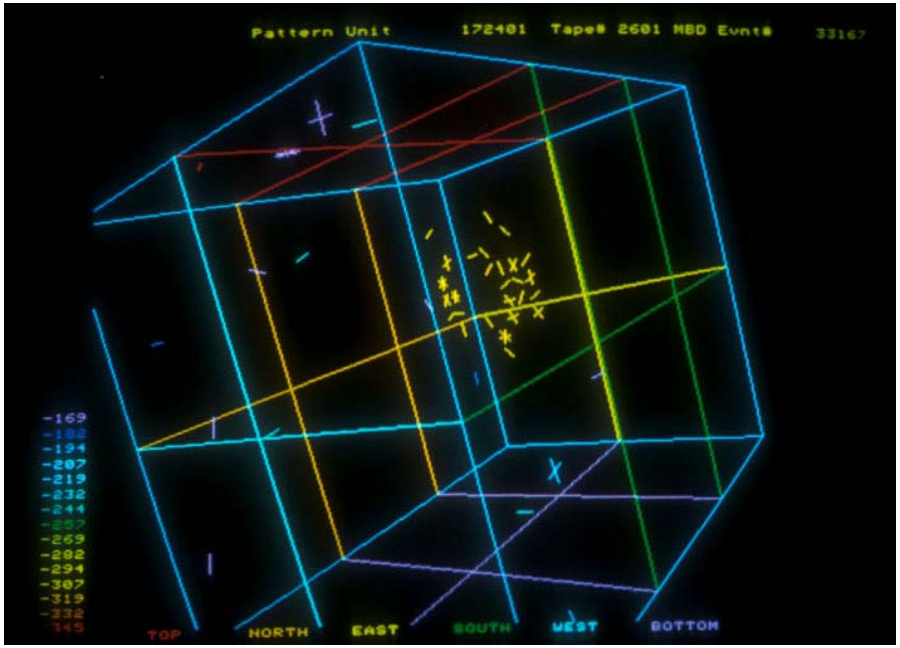
T. J. Haines, R. M. Bionta, G. Blewitt, C. B. Bratton, D. Casper, R. Claus, B. G. Cortez, S. Errede, G. W. Foster, W. Gajewski, K. S. Ganezer, M. Goldhaber, T. W. Jones, D. Kielczewska, W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, J. Matthews, H. S. Park, L. R. Price, F. Reines, J. Schultz, S. Seidel, E. Shumard, D. Sinclair, H. W. Sobel, J. L. Stone, L. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

The simulation predicts that 34% ± 1 % of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (j) an incorrect as-sumption as to the ratio of muon *v's* to electron *v's* in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) **some other as-yet-unaccounted-for physics**. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.

Something wrong with atmospheric neutrinos?

Detection of SN1987a





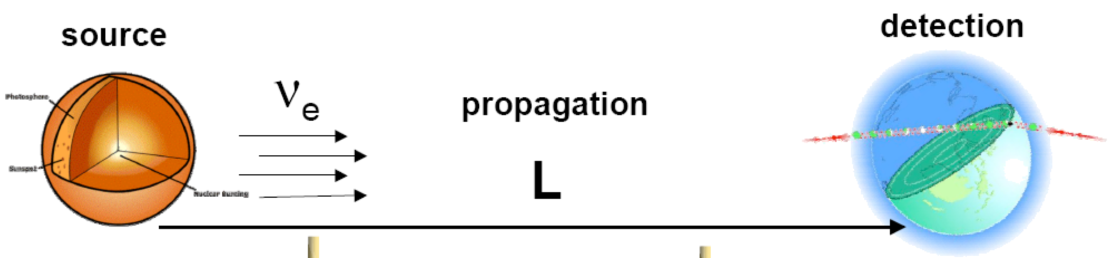
VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud

R. M. Bionta,[12] G. Blewitt,[4] C. B. Bratton,[5] D. Casper,[2,14] A. Ciocio,[14] R. Claus,[14] B. Cortez,[16] M. Crouch,[9] S. T. Dye,[6] S. Errede,[10] G. W. Foster,[15] W. Gajewski,[1] K. S. Ganezer,[1] M. Goldhaber,[3] T. J. Haines,[1] T. W. Jones,[7] D. Kielczewska,[1,8] W. R. Kropp,[1] J. G. Learned,[6] J. M. LoSecco,[13] J. Matthews,[2] R. Miller,[1] M. S. Mudan,[7] H. S. Park,[11] L. R. Price,[1] F. Reines,[1] J. Schultz,[1] S. Seidel,[2,14] E. Shumard,[16] D. Sinclair,[2] H. W. Sobel,[1] J. L. Stone,[14] L. R. Sulak,[14] R. Svoboda,[1] G. Thornton,[2] J. C. van der Velde,[2] and C. Wuest[12]

Since both IMB and the original Kamiokande detector both saw a deficit in atmospheric neutrinos, and Ray Davis continued to see a deficit in solar neutrinos…the community started to think seriously about neutrino oscillations…but it still was only one of several explanations for the deficits.

Neutrino Oscillation



$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \, \sin^2(\Delta m^2 L/E)$

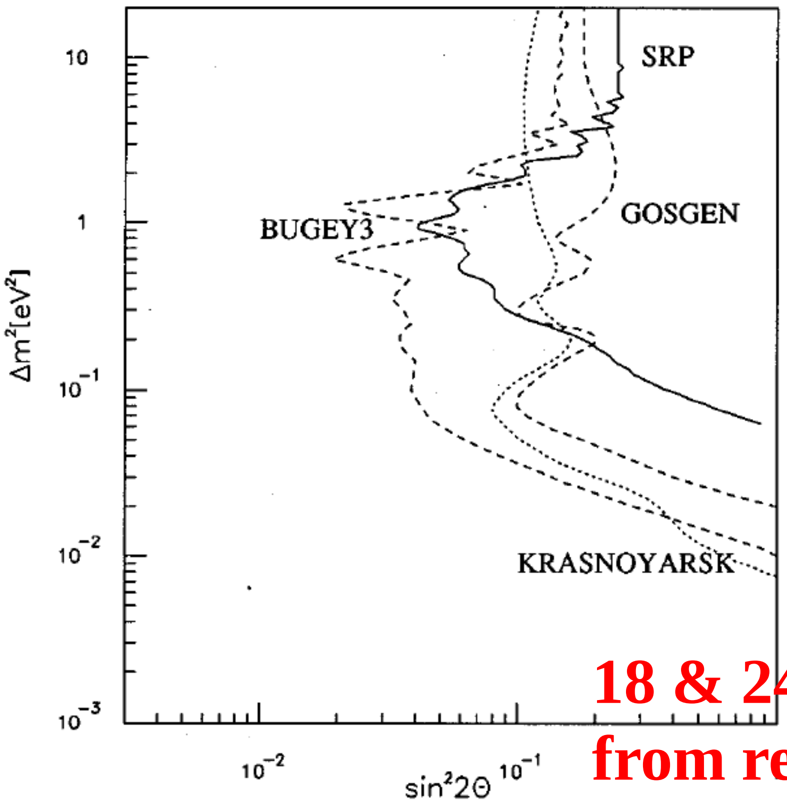
- If neutrinos have mass and mix, then a state which begins as purely one flavor can change over time.
- The components (with different masses) propagate with a different quantum mechanical time dependence
- Similar to a "beat frequency" between two sound waves
  - For sound: $f_{beat} \sim |f_1 - f_2| = \Delta f$
  - For neutrinos: $f_{osc} \sim m_1^2 - m_2^2 = \Delta m^2$

Reactor Neutrino Oscillation Searches

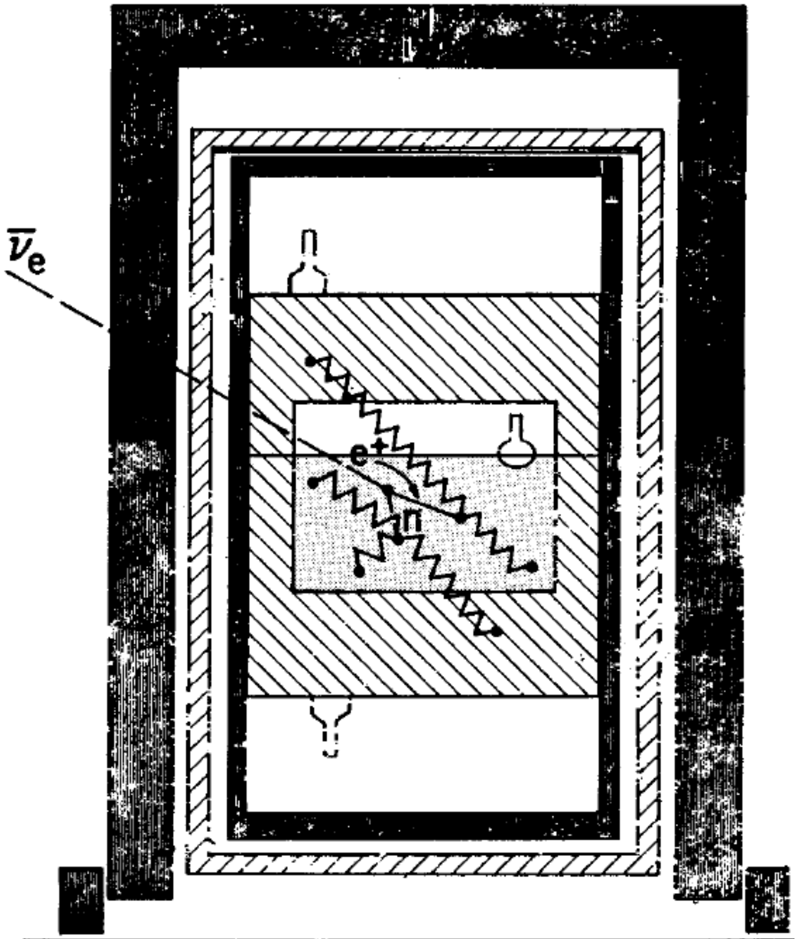
- 1979 "Detection of Weak Neutral Current Using Fission anti-ν_e on Deuterons".

$(\overline{\nu}_e d \rightarrow \overline{\nu}_e p n$ and $\overline{\nu}_e d \rightarrow e^+ n n)$ **Became basis for SNO experiment**

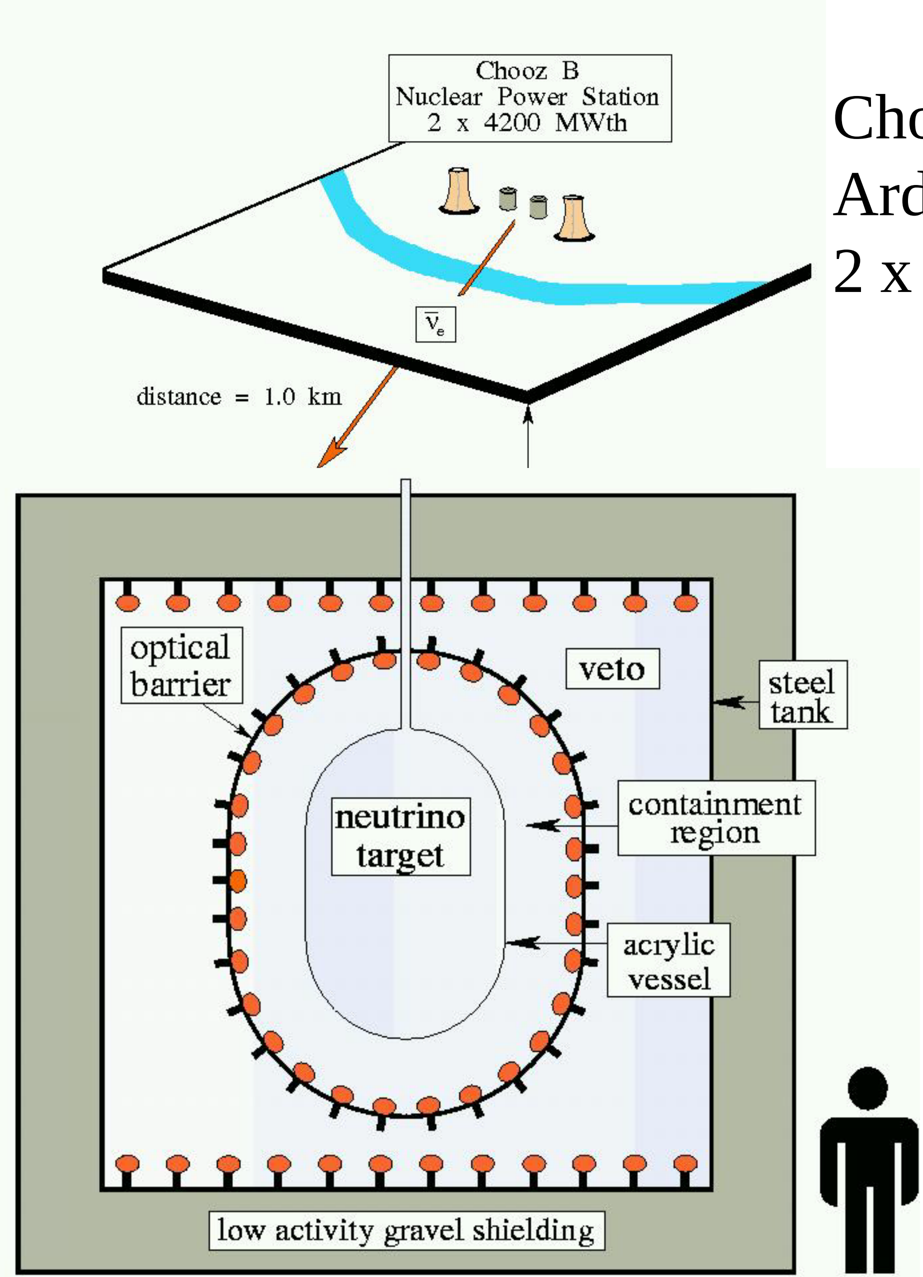
- 1996 "Results of a Two-Position Reactor-Neutrino Oscillation Experiment".



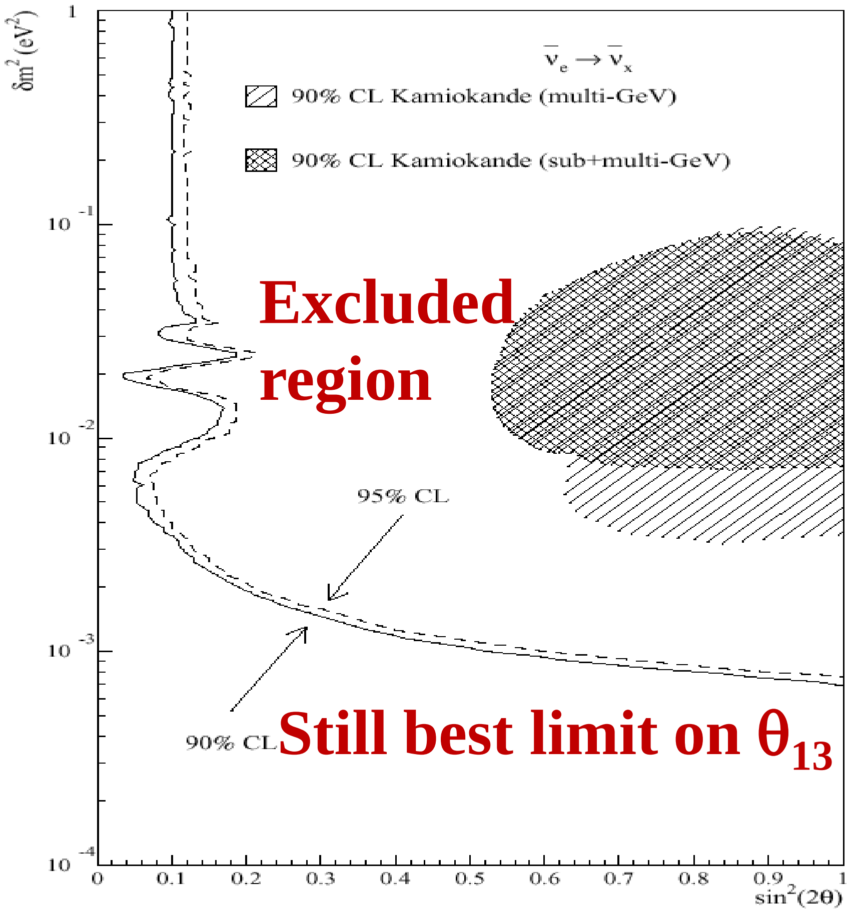
18 & 24 meters from reactor



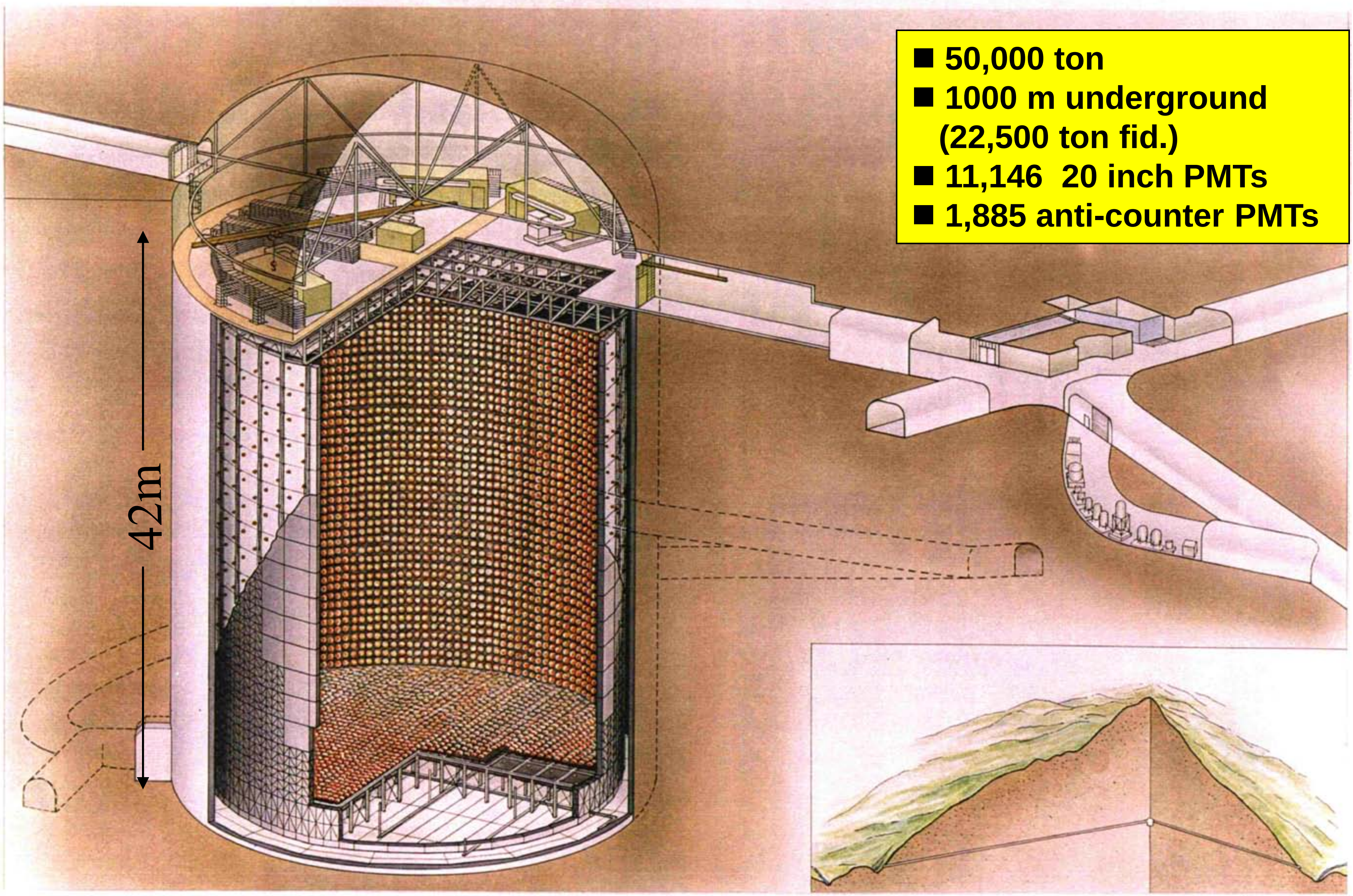
1999 - Chooz Reactor Search



Chooz Underground Laboratory,
Ardennes, France
2 x 4200 MWth reactors – 1 km distant



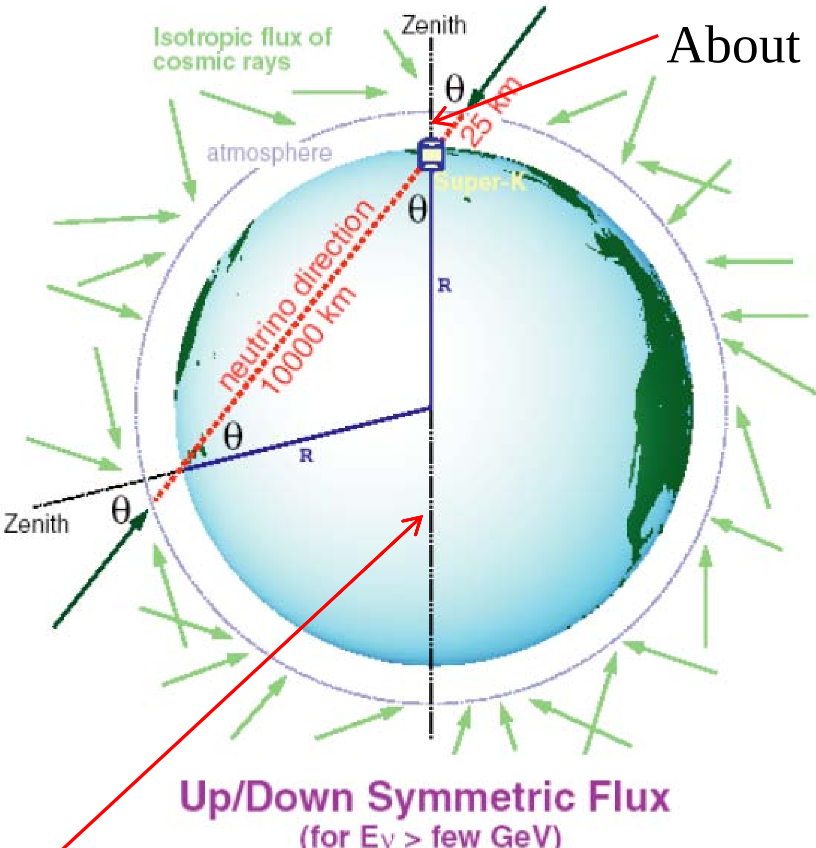
1996 - The Super-Kamiokande detector




A Cathedral for Neutrinos

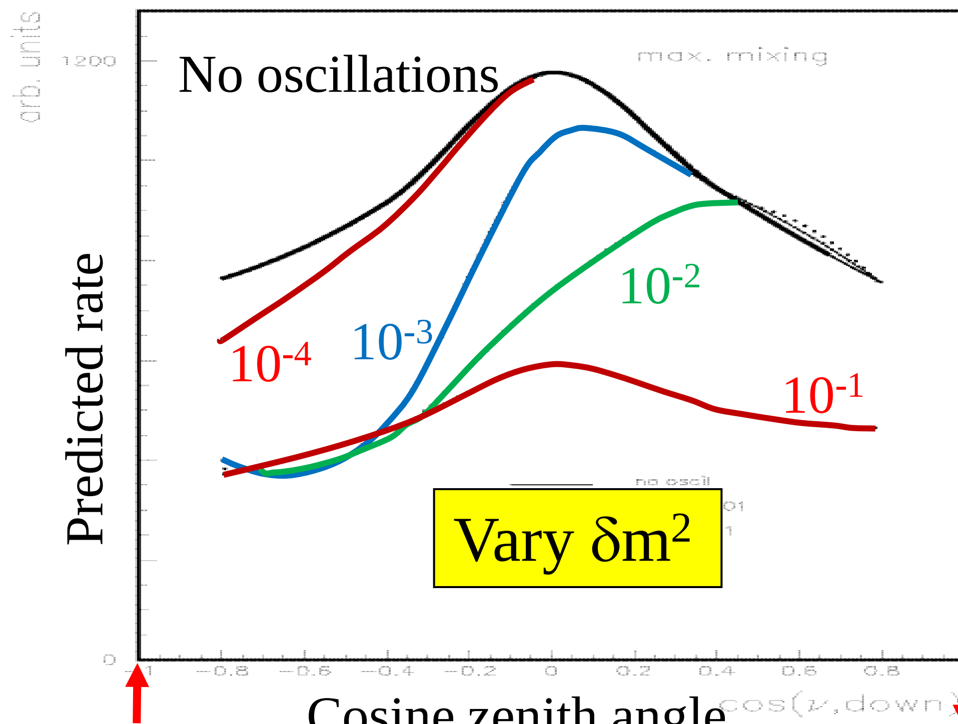
Atmospheric Neutrinos

About 15 km



About 13,000 km

$L \sim E_\nu / \delta m^2$

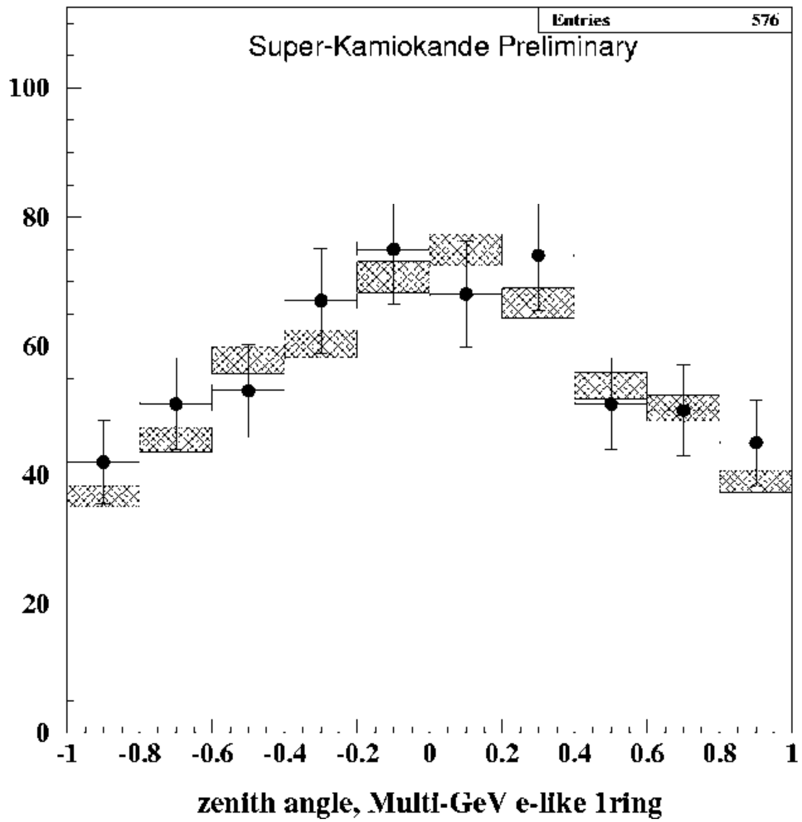


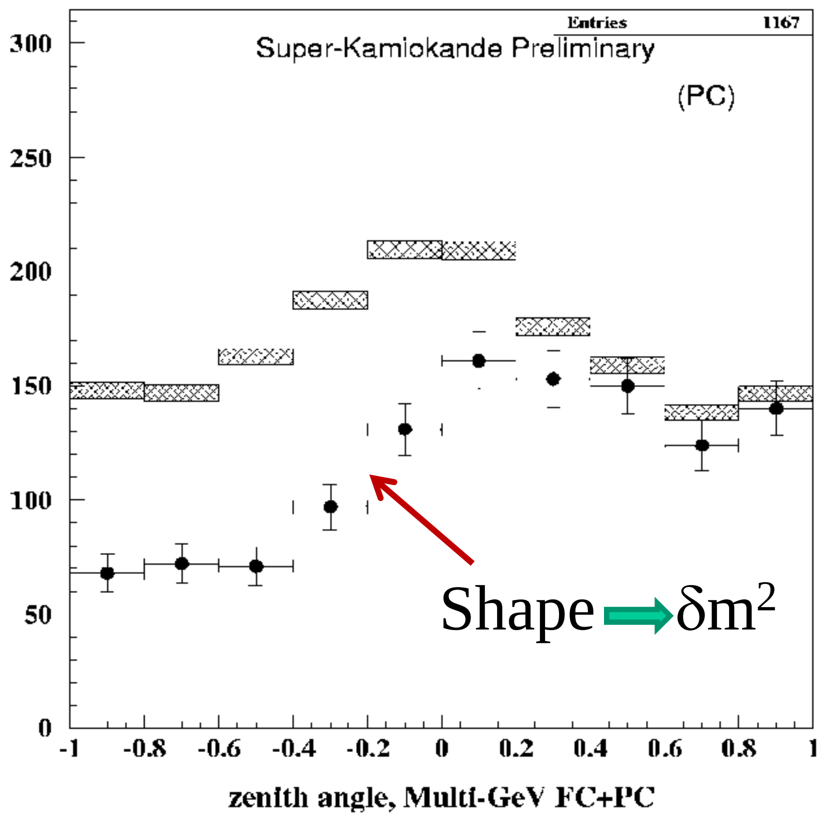
From other side of Earth

From above

Sensitivity from ~10^{-4} to 10^{-1} eV^2

The Earth is Just the Right Size…





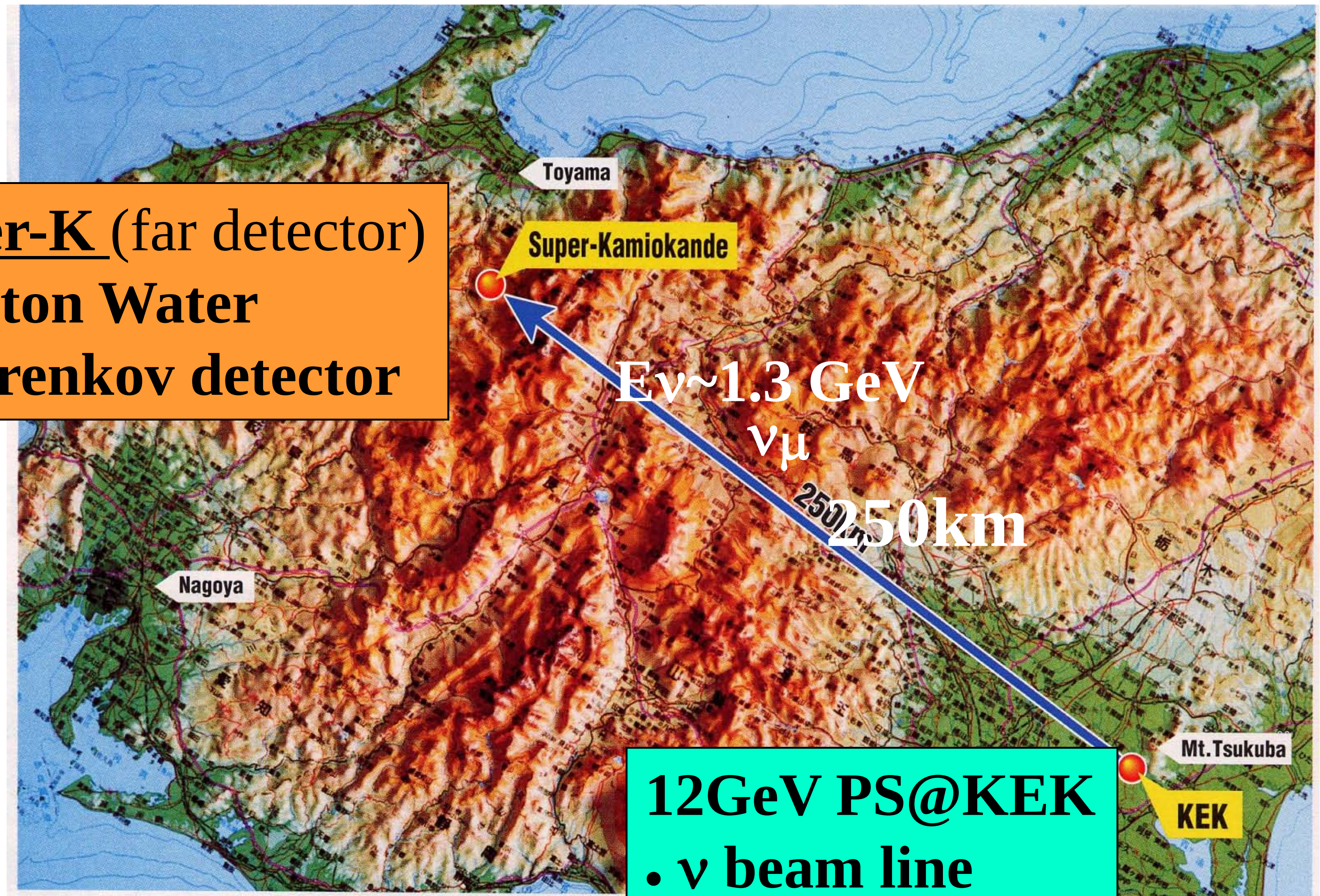
Electron Neutrinos as Expected

1998 announcement

Upward-going Muon Neutrinos Missing

KEK to Kamioka Neutrino Oscillation Experiment

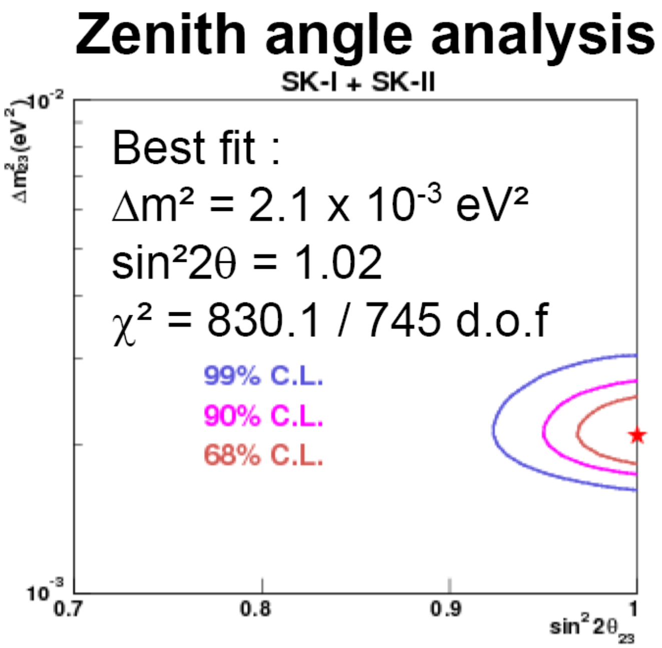
Followed in 2000



Super-K (far detector)
50 kton Water Cherenkov detector

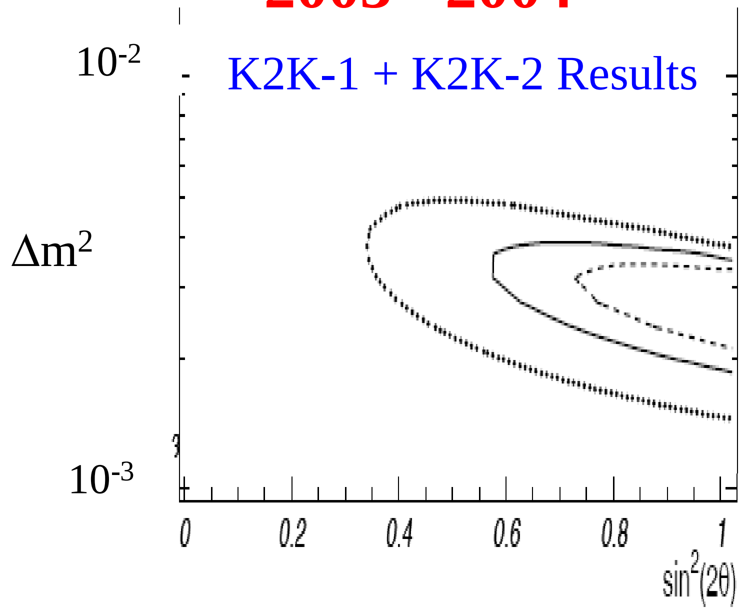
12GeV PS@KEK
- **ν beam line**
- **Beam monitor**
- **Near detectors**

K2K Confirms Super-K Results

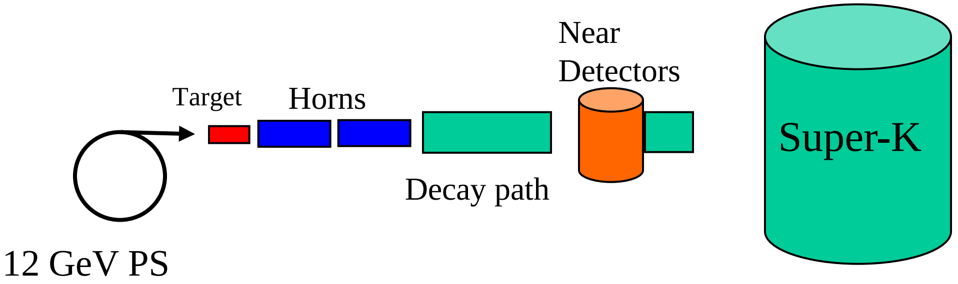


Atmospheric Neutrinos

2003 - 2004

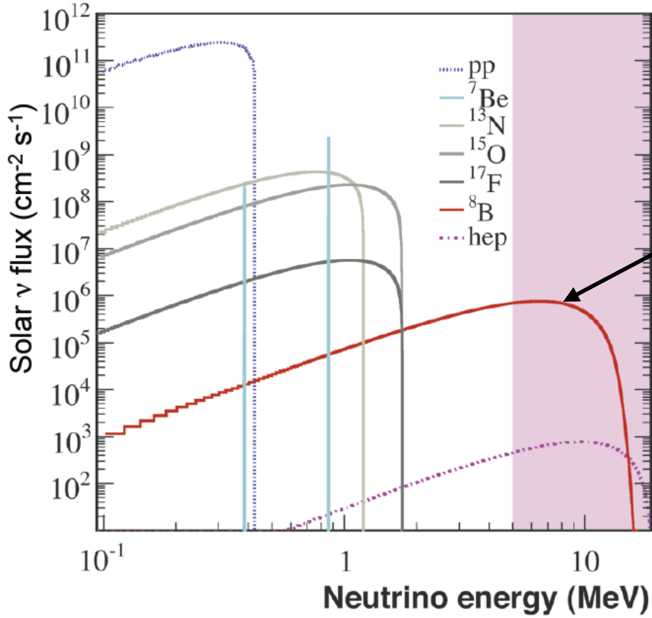


Accelerator Neutrinos



Now also confirmed by MINOS

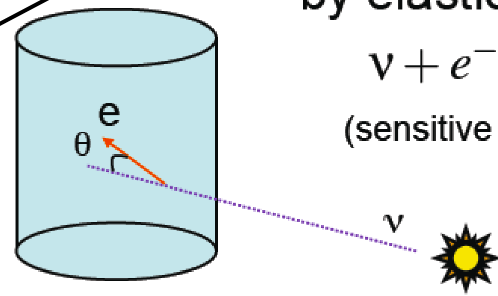
SK Solar Neutrinos



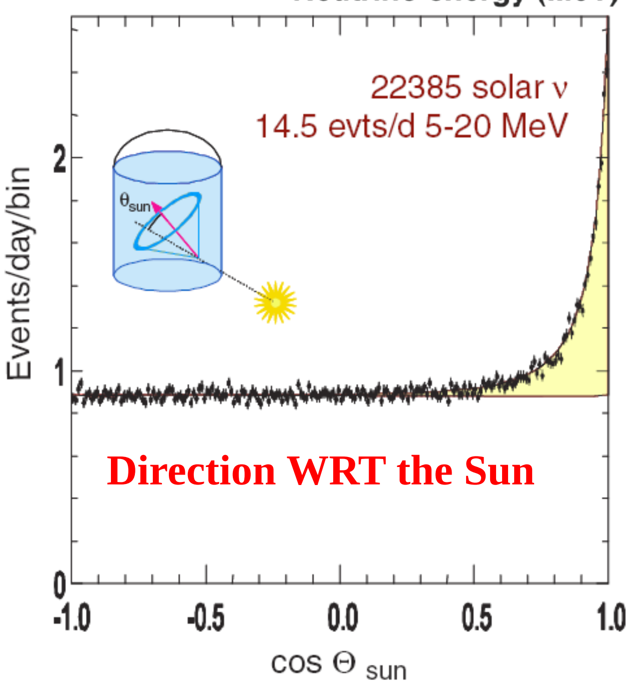
^{8}B neutrino measurement by elastic scattering:

$$\nu + e^- \rightarrow \nu + e^-$$

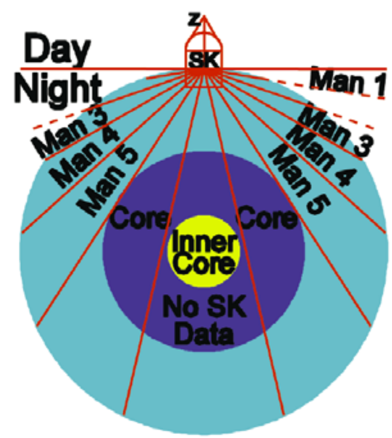
(sensitive to all ν flavors)



Collected ~33,000 events ~5.0< E< 20 MeV



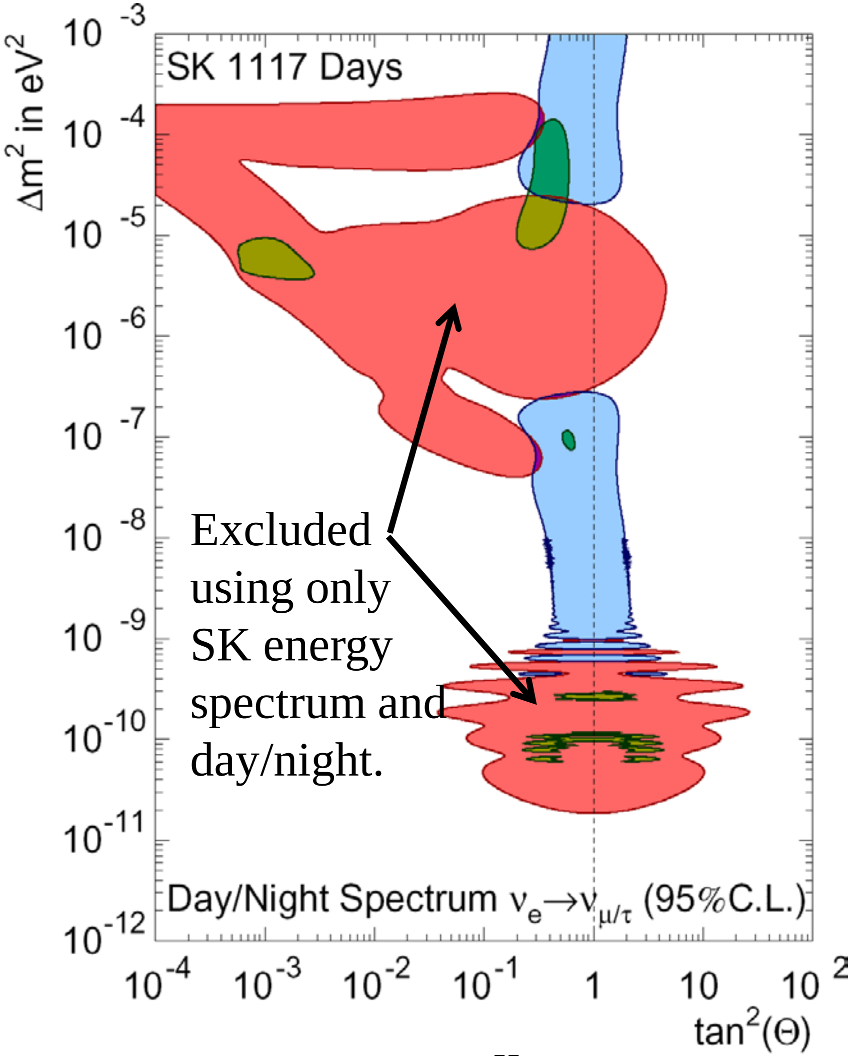
Direction WRT the Sun



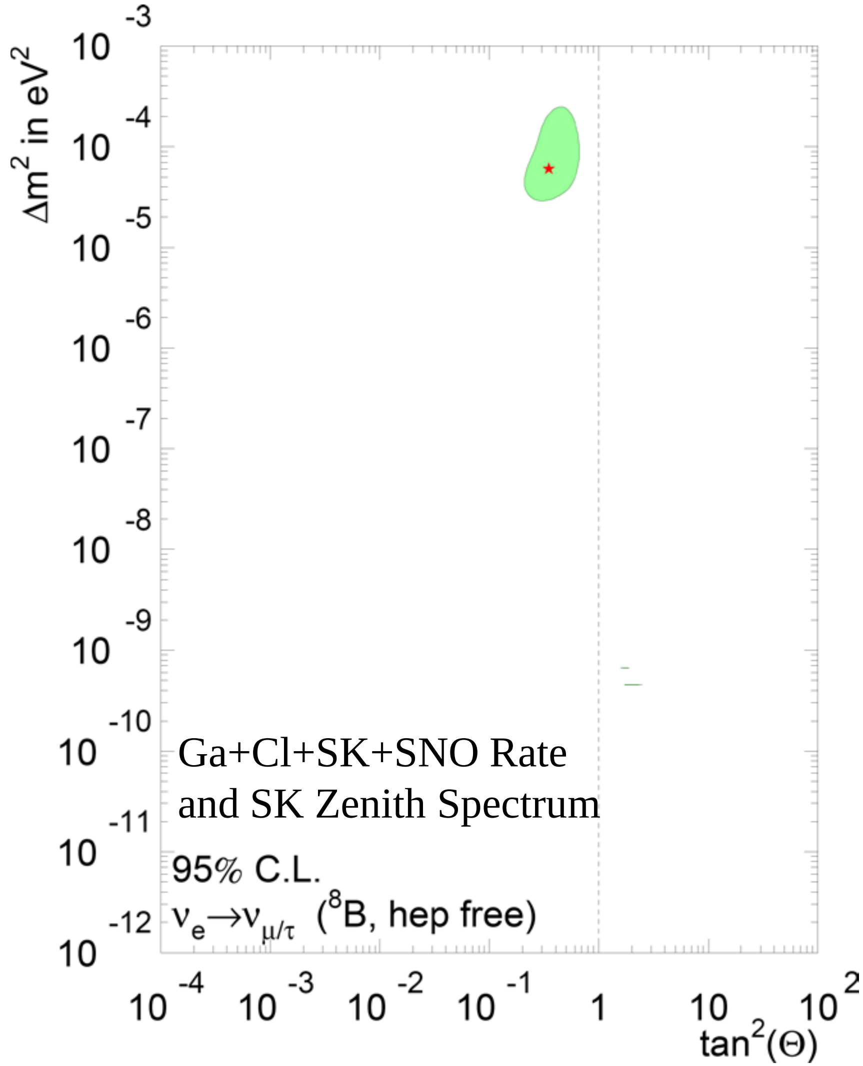
Day/Night asymmetry

- Determine:
- Direction WRT Sun
- Energy spectrum
- Time variation of flux
- Correlation with Solar Activity
- Day/Night asymmetry

Solar Results

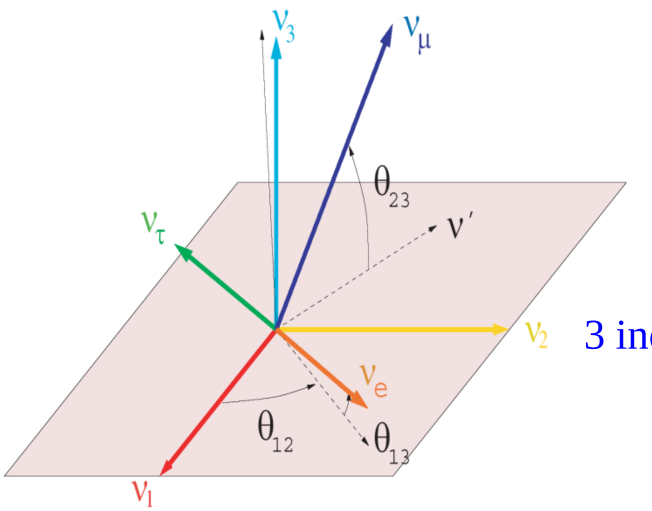


June 2000, Sudbury
Large angle
Not VAV, SMA



December 2001, Kashiwa
Not Low
Really Osc – with SNO

Current Three Neutrino Picture

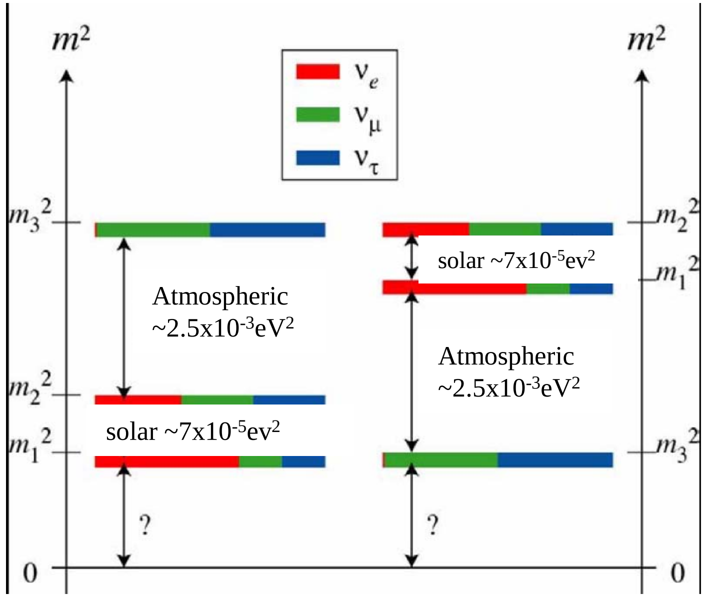


Flavor Eigenstates	MNS Maki-Nakagawa-Sakata mixing matrix	Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 independent parameters + 1 complex phase (+ Majorana phase)

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$



θ_{12} , $\delta m_{12}{}^2$ Solar + KamLAND

θ_{23} , $\delta m_{23}{}^2$ Atmospheric + accelerator

θ_{13} Limit from Chooz reactor

Remaining Questions:

- Measurement of θ_{13}
  - Precision measurements of other quantities
- What is the value of Dirac CP phase δ?
- What is the mass hierarchy?
- What is the mass of the lightest neutrino?
- Are neutrinos Majorana particles?
  - If so what are Majorana phases?

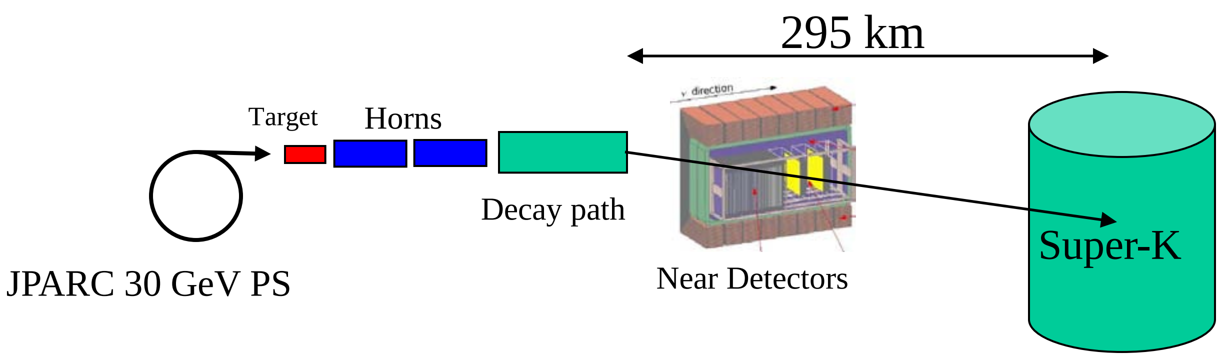
CP Violation

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) = 16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$

$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- Possible only if:
  - $\Delta m_{12}{}^2$, s_{12} large enough (LMA) **- Ok**
  - θ_{13} large enough **- ???**
- Can we see CP violation?

T2K Experiment



Narrow band off-axis beam
Neutrino energy peaked 600-700 MeV

Starting now

Phase I - Initial Goals

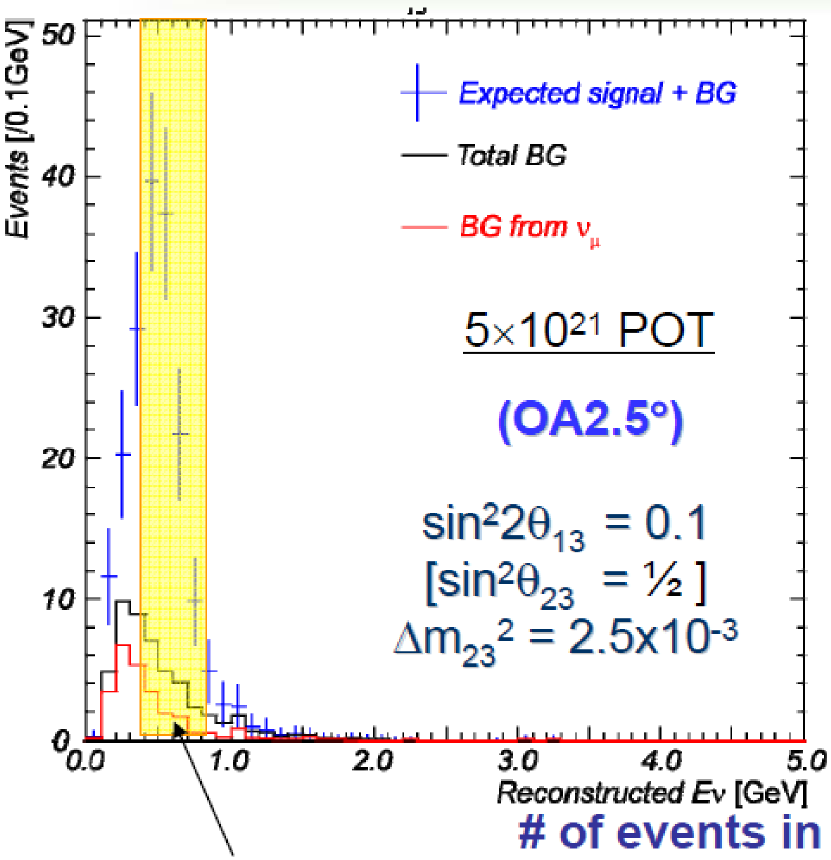
- Discover if θ_{13} is non-zero by observing ν_e appearance
- Attempt to resolve if θ_{23} is non-maximal.
- Precisely determine δm^2_{23} ($\sim 10^{-4}$ eV^2)

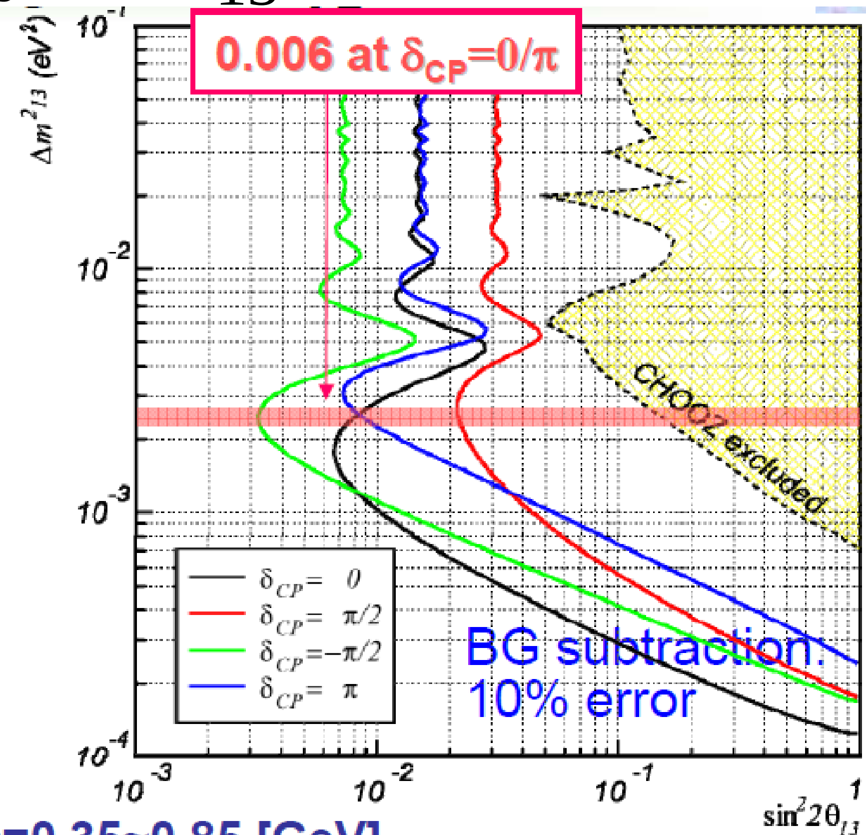
Phase II

- Discovery of non-zero CP phase
- Determination of mass hierarchy

New, far detector required

Sensitivity to θ_{13}

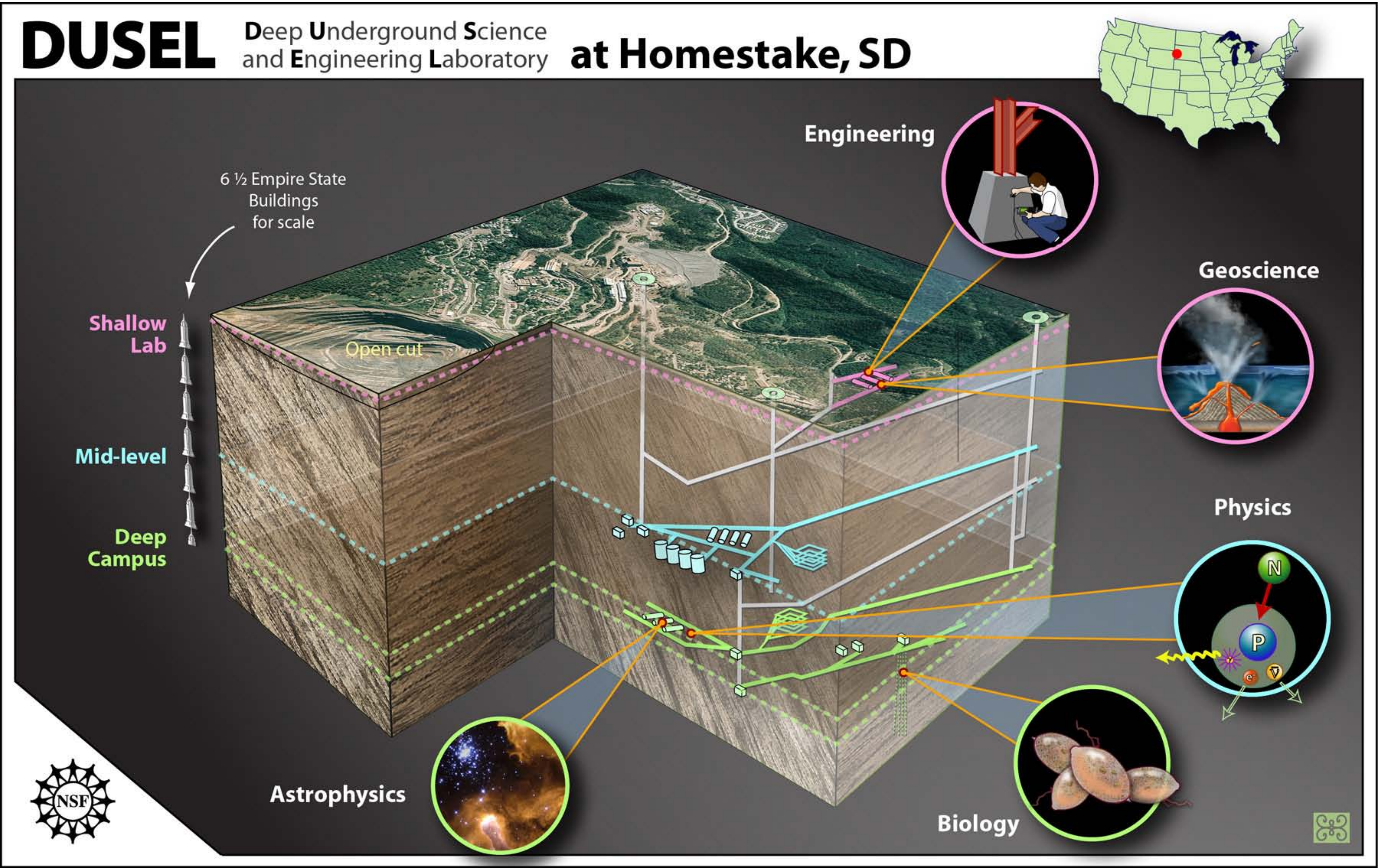




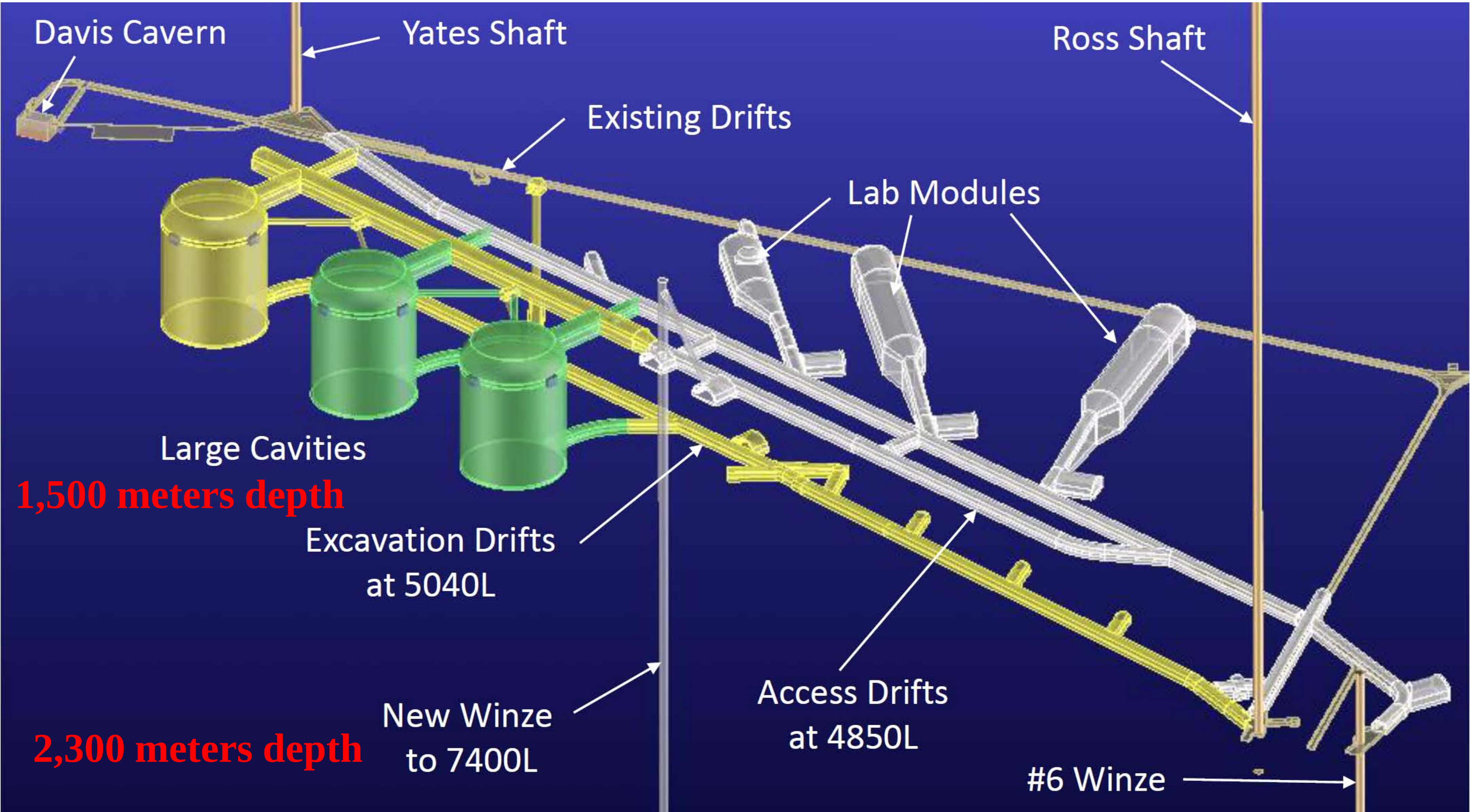
# of events in Eνrec=0.35~0.85 [GeV]

$\sin^2 2\theta_{13}$	Background in Super-K			Signal [~40% eff]	Signal + BG
	ν_μ	ν_e	total		
0.1	10	13	23	103	126
0.01				10	33

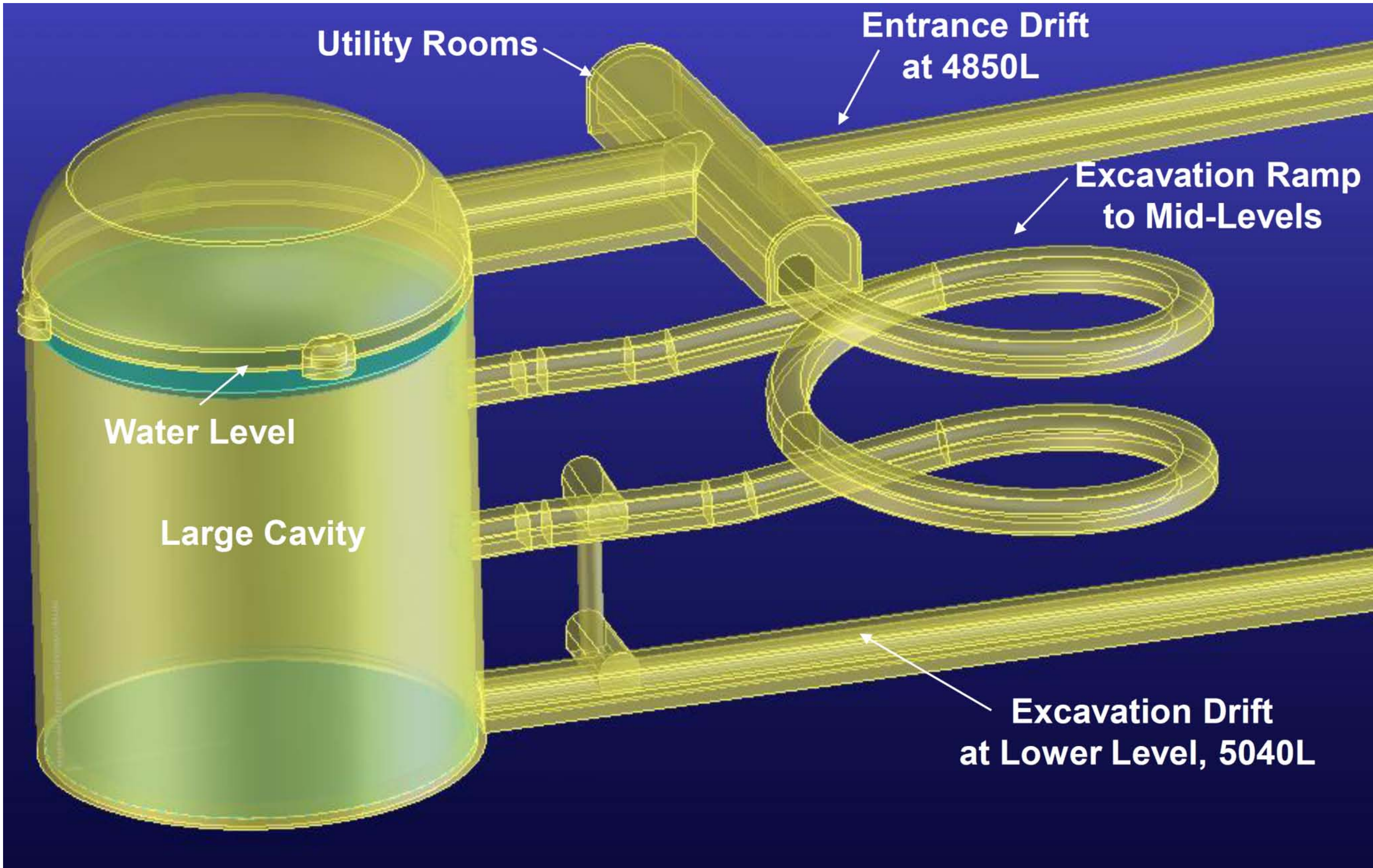
Detector at DUSEL – New Beam from Fermilab



Plans anticipate DUSEL Construction Start FY2013



Each Module 100 to 150kt Fiducial Volume



Summary, Outlook

- The tiny neutrino mass, as demonstrated by observing neutrino oscillations, is the first evidence for ***incompleteness of Minimal Standard Model.***
- The future is bright for neutrino physics with many new experiments building and starting shortly.