PHYS 5326 – Lecture #7

Monday, Feb. 19, 2007
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1. Neutrino Oscillation Experiments
2. Long Base Line Experiments
3. Short Base Line Experiments
4. Future Projects

Neutrino Oscillation

- First suggestion of neutrino mixing by B. Pontecorvo to explain K^0, K^0-bar mixing in 1957
- Solar neutrino deficit in 1969 by Ray Davis in Homestake Mine in SD. ➔ Called MSW (Mikheyev-Smirnov-Wolfenstein) effect
  - Describes neutrino flavor conversion in medium
- Caused by the two different eigenstates for mass and weak
- Neutrinos change their flavor as they travel ➔ Neutrino flavor mixing
- Oscillation probability depends on
  - The distance between the source and the observation point
  - The energy of the neutrinos
  - The difference in square of the masses

Oscillation Probability

- Substituting the energies into the wave function:

$$|\nu_\mu(t)\rangle = \exp\left[-it\left(p + {m_1^2}/{2E_\nu}\right)\right]\left[-\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle \exp\left[{i\Delta m^2 t}/{2E_\nu}\right]\right]$$

where $\Delta m^2 \equiv m_1^2 - m_2^2$ and $E_\nu \cong p$.

- Since the ν's move at the speed of light, t=x/c, where x is the distance to the source of ν_μ.
- The probability for ν_μ with energy E_ν oscillates to ν_e at the distance $\mathcal{L}$ from the source becomes

$$\boxed{P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)}$$

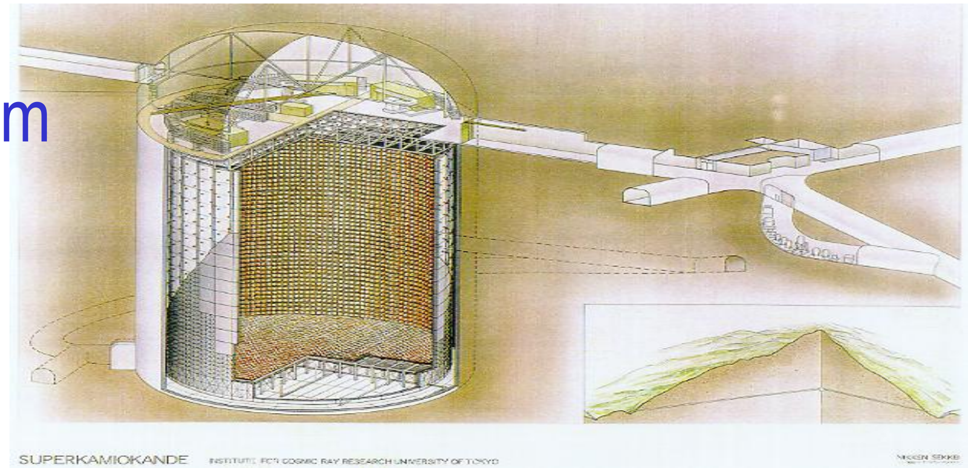
Atmospheric Neutrinos

- Neutrinos resulting from the atmospheric interactions of cosmic ray particles
  - ν_μ to ν_e is about 2 to 1
  - He, p, etc + N $\rightarrow$ π,K, etc
    - $\pi \rightarrow \mu+\nu_\mu$
    - $\mu \rightarrow e+\nu_e+\nu_\mu$
  - This reaction gives 2 ν_μ and 1 ν_e
- Expected flux ratio between ν_μ and ν_e is 2 to 1
- Form a double ratio for the measurement

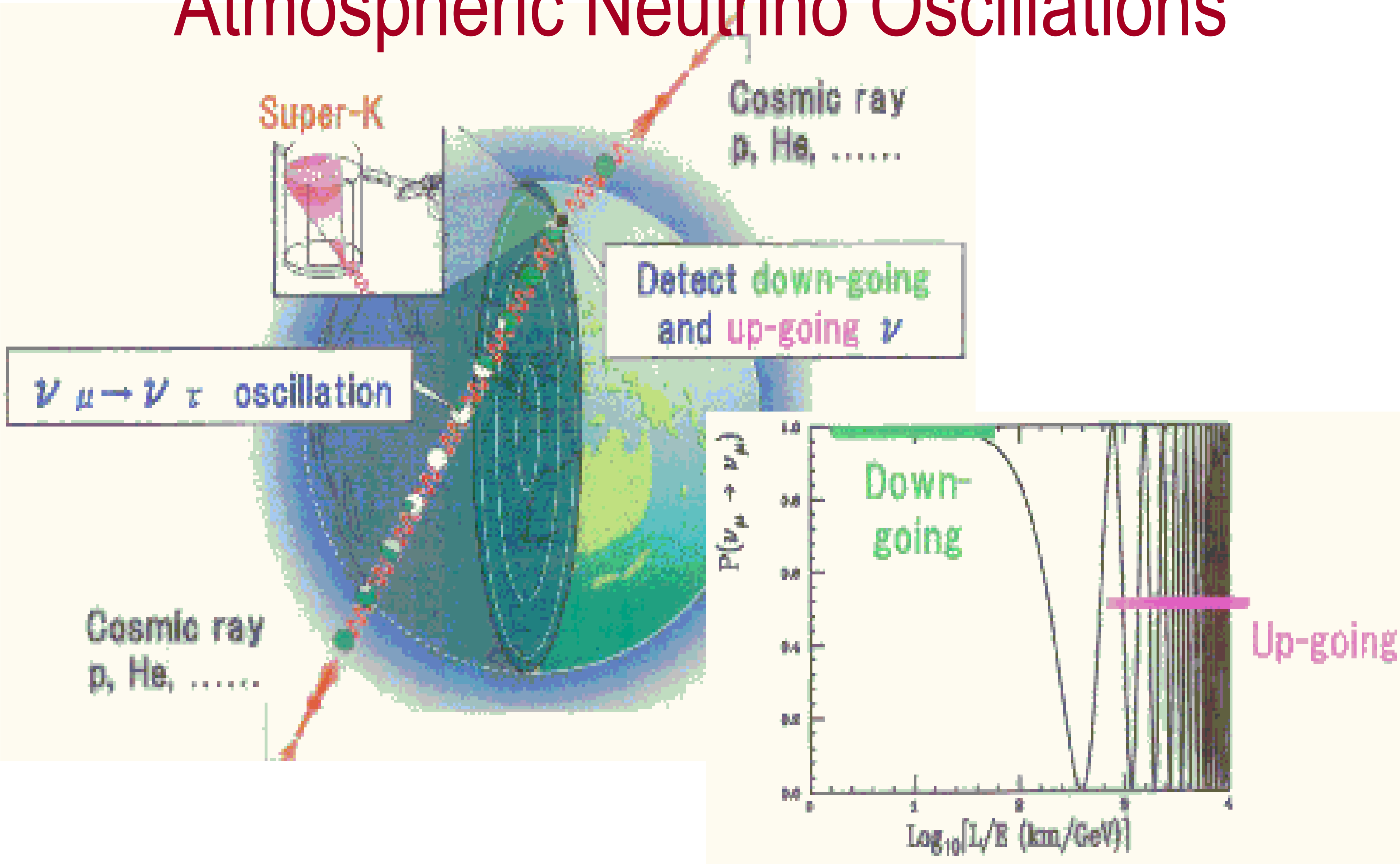
$$R \equiv \frac{\left(N_{\nu_e} / N_{\nu_\mu} \right)^{Exp}}{\left(N_{\nu_e} / N_{\nu_\mu} \right)^{The}}$$

Super Kamiokande

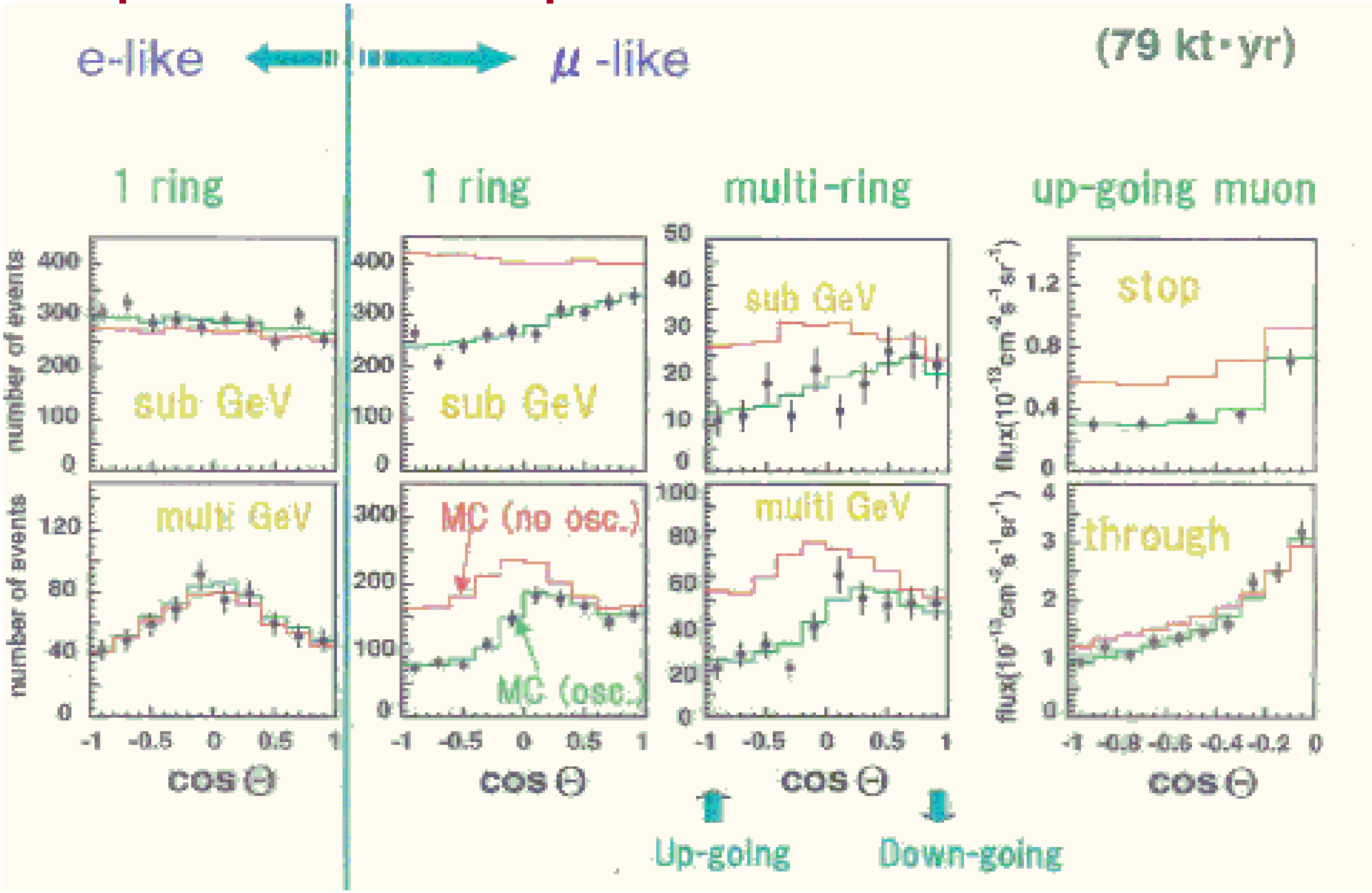
- Kamioka zinc mine, Japan
- 1000m underground
- 40 m (d) x 40m(h) SS
- 50,000 tons of ultra pure H_2O
- 11200(inner)+1800(outer) 50cm PMT's
- Originally for proton decay experiment
- Accident in Nov. 2001, destroyed 7000 PMT's
  - Virtually all PMT's below the surface of the water
- Dec. 2002 resumed data taking



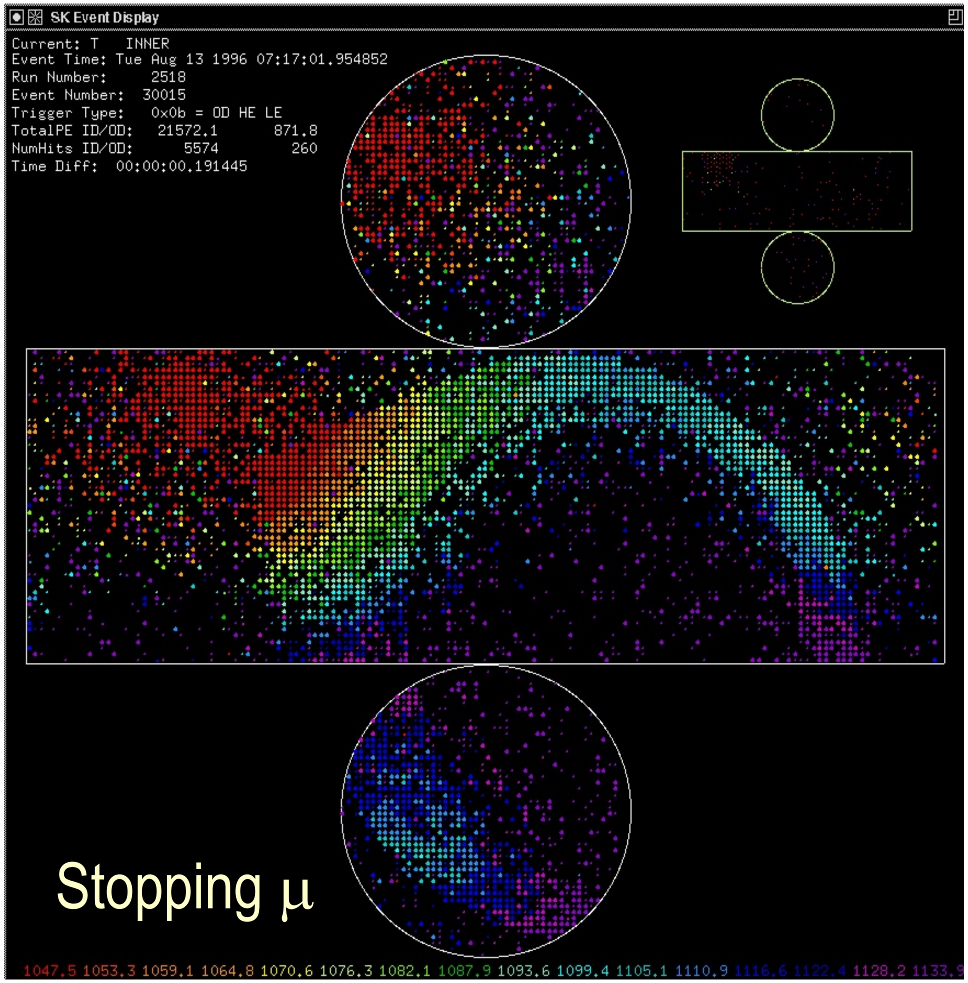
Atmospheric Neutrino Oscillations

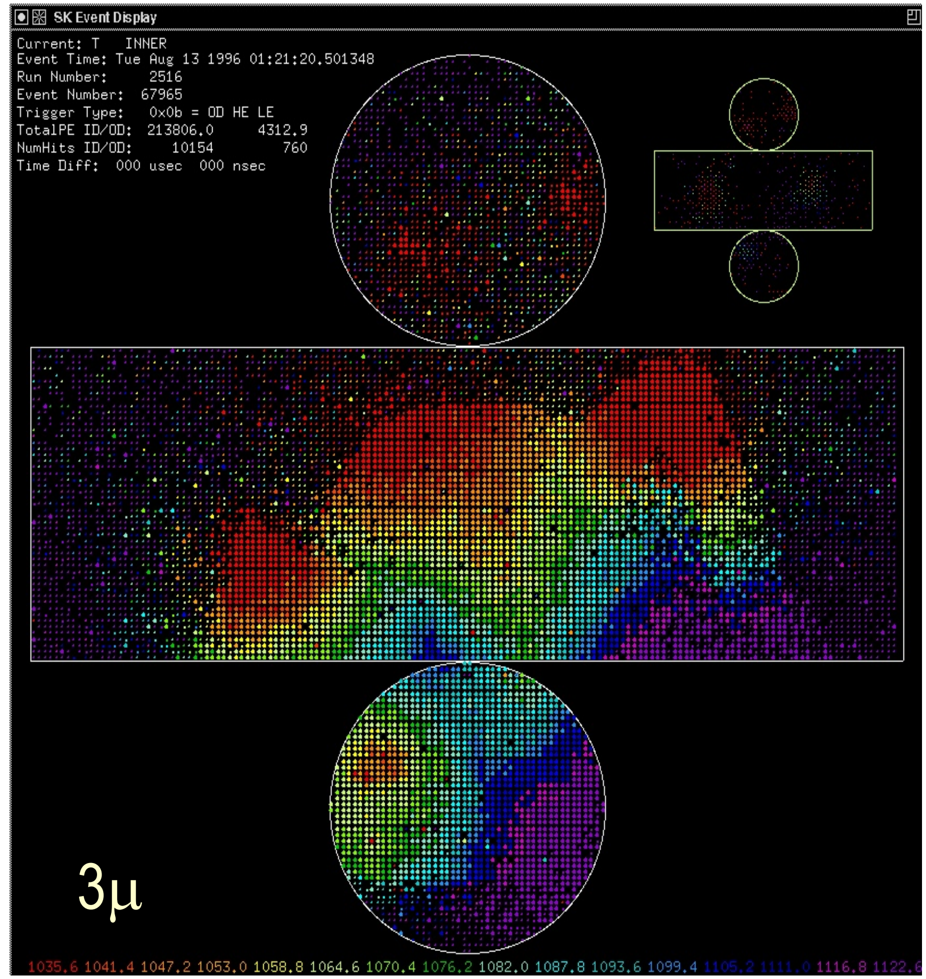


Super-K Atmospheric Neutrino Results

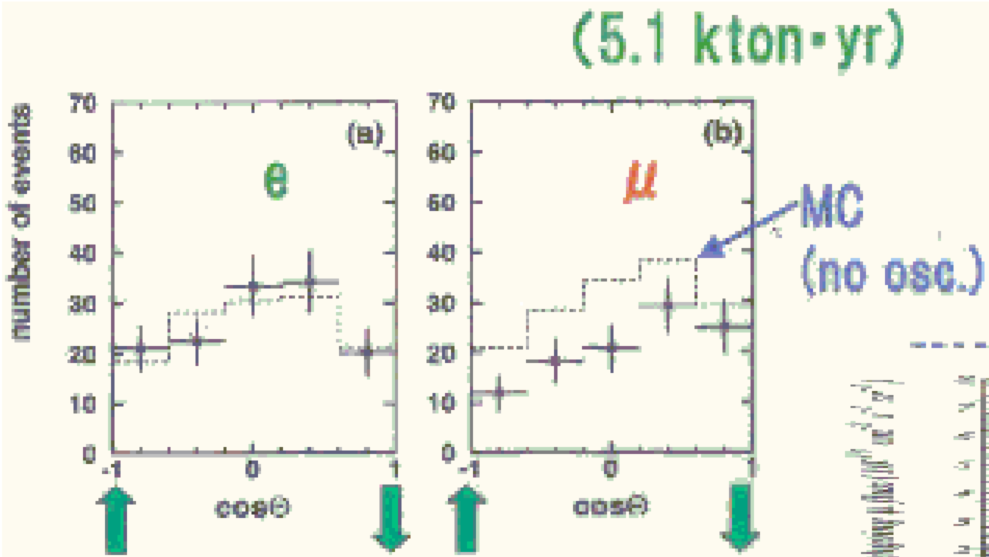


Super-K Event Displays



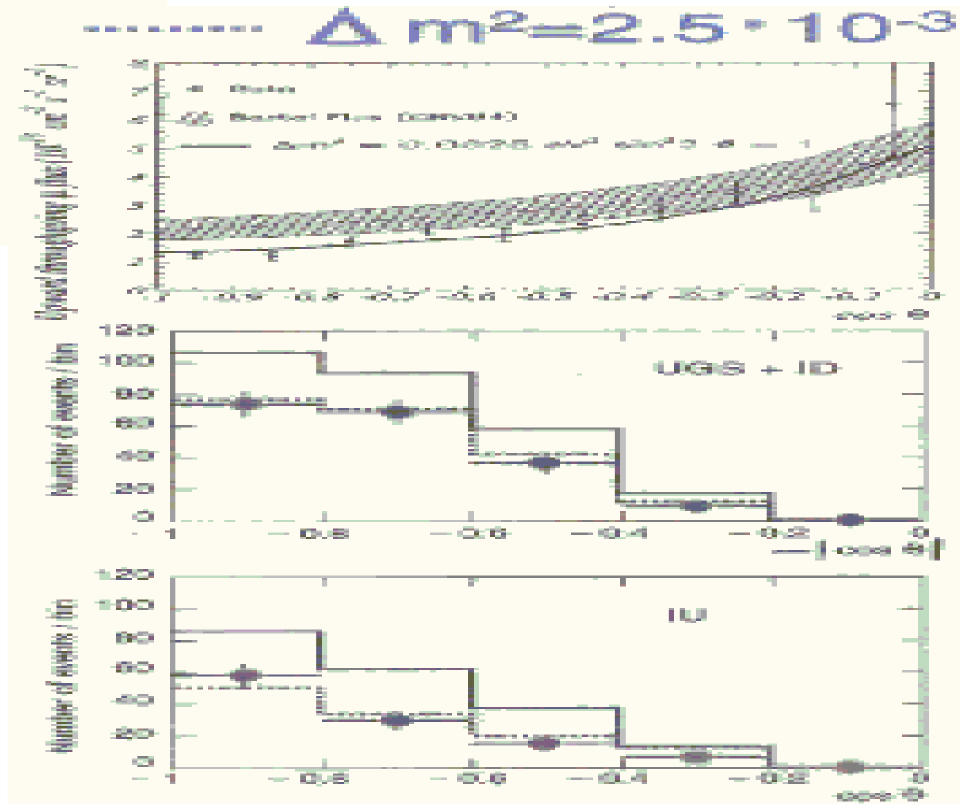


Other Experimental Results



Soudan 2 experiment

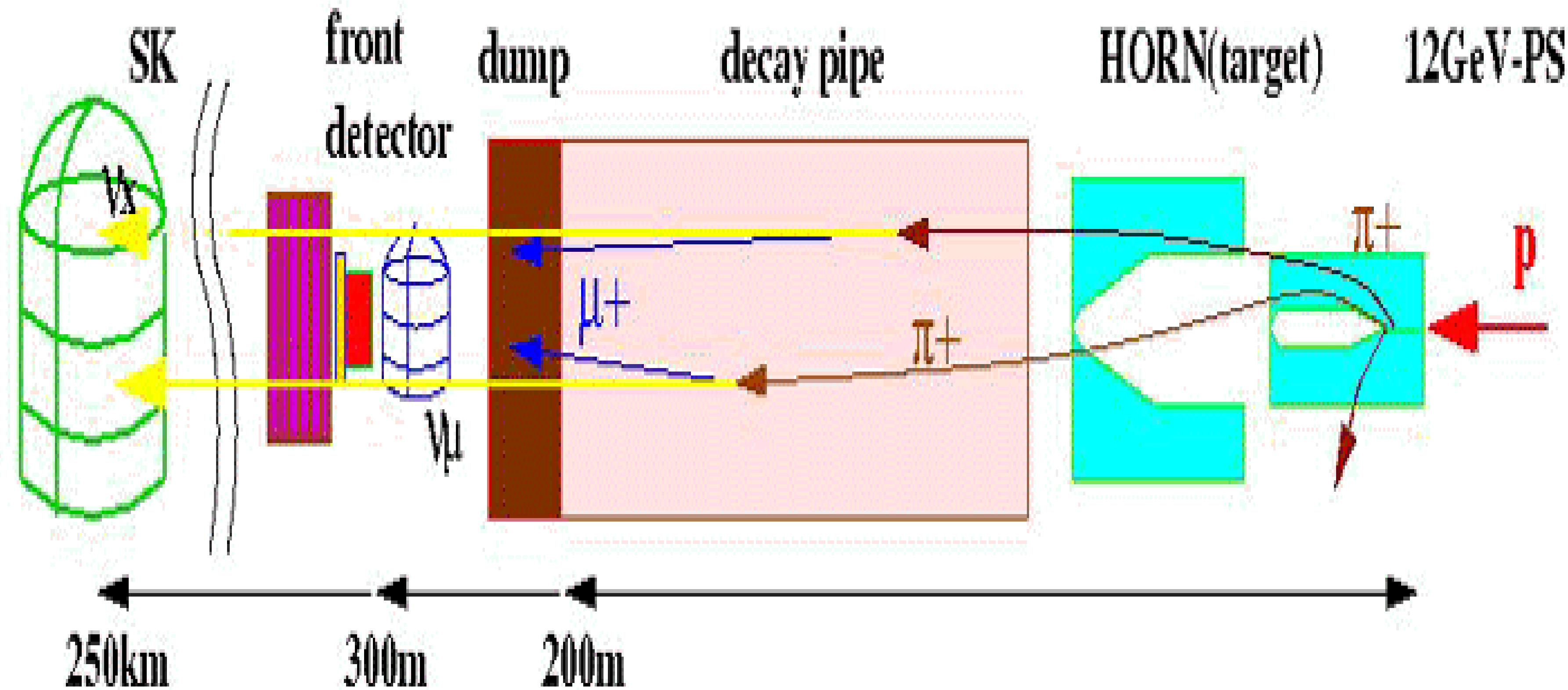
MACRO experiment



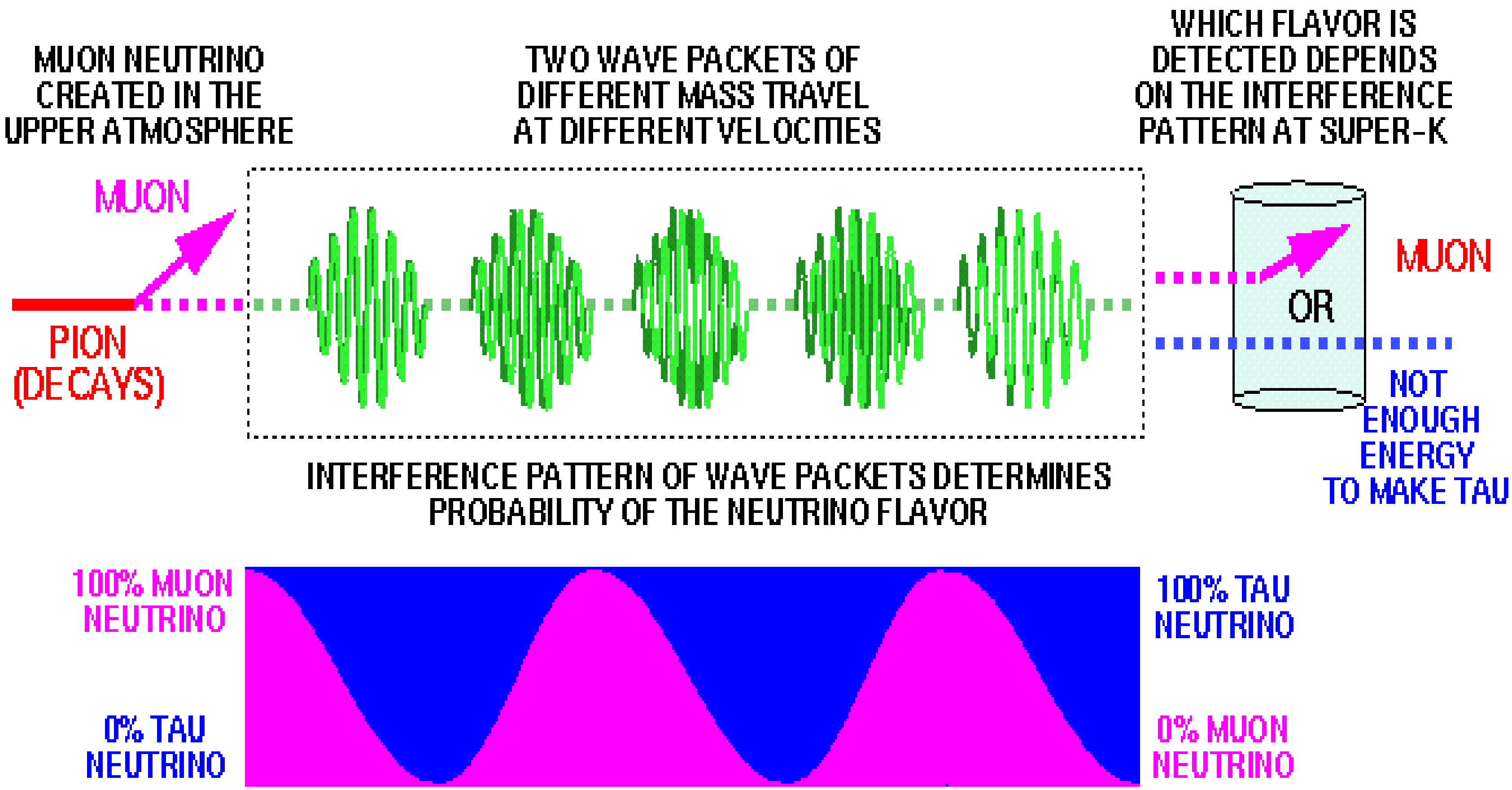
Accelerator Based Experiments

- Mostly ν_μ from accelerators
- Long and Short baseline experiments
  - Long baseline: Detectors located far away from the source, assisted by a similar detector at a very short distance (eg. MINOS: 730km, K2K: 250km, etc)
    - Compare the flux measured in the near detector with that in the far detector, taking into account angular dispersion
  - Short baseline: Detectors located at a close distance to the source
    - Need to know beam flux well
      - Better if only one neutrino species are contained in the beam
      - Neutrinos from reactors are good candidates

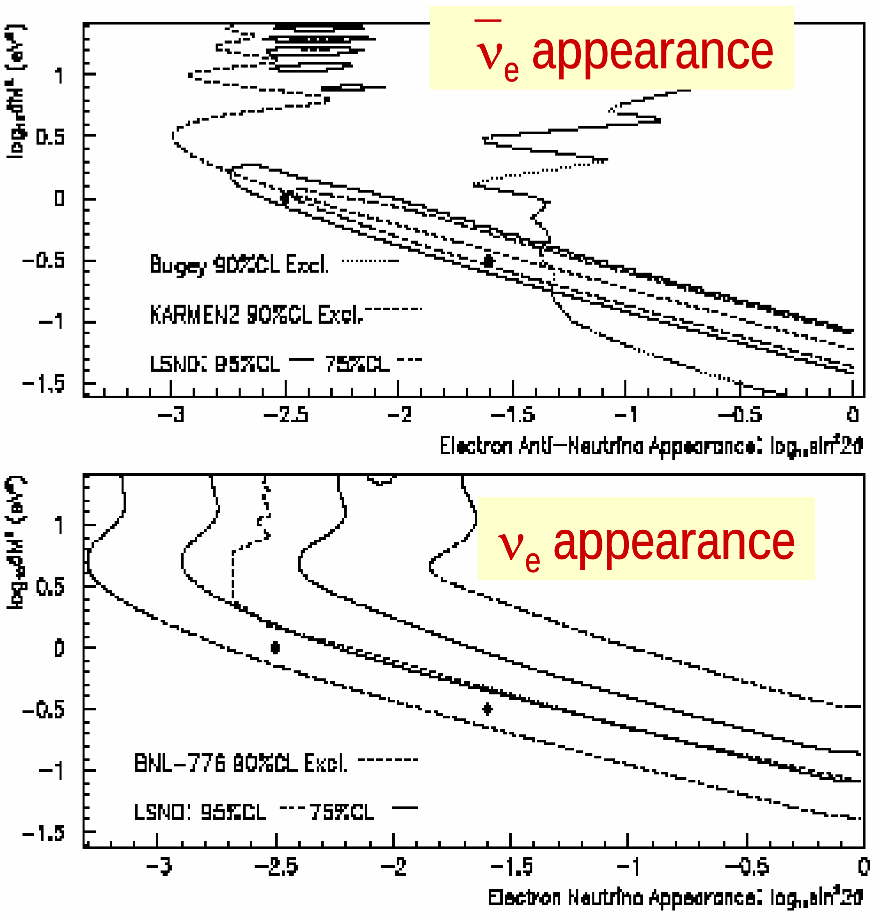
Long Baseline Experiment Concept (K2K)

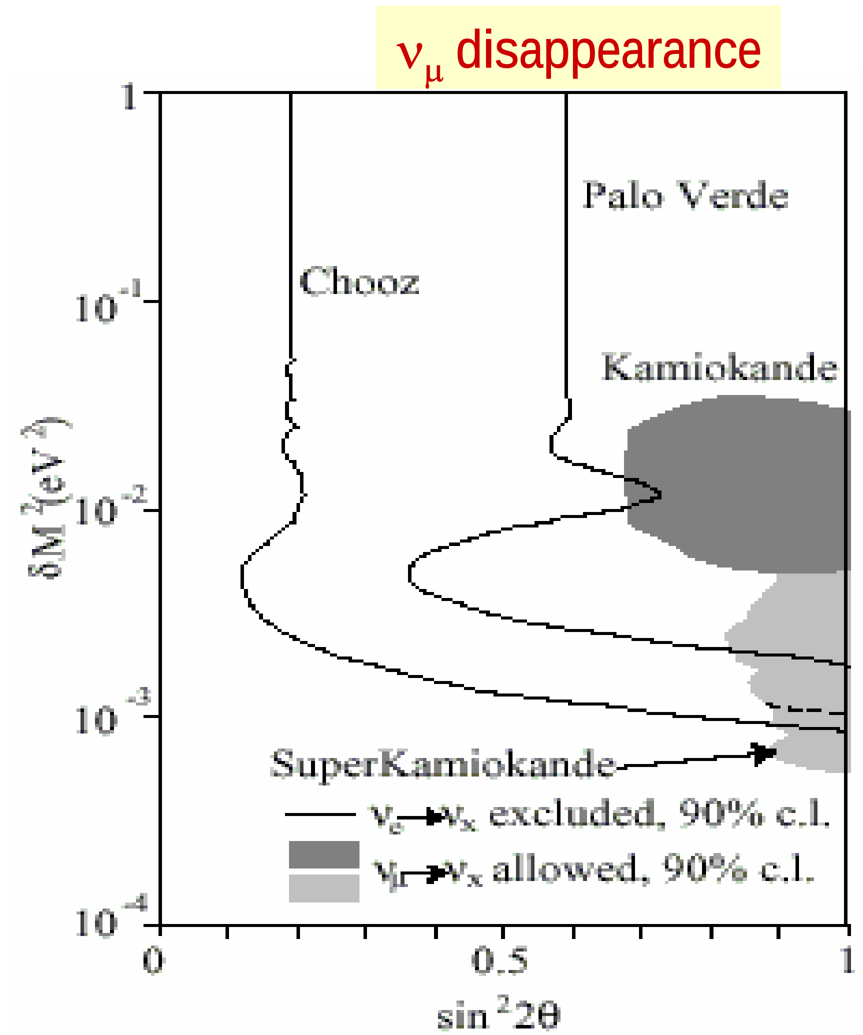


Different Neutrino Oscillation Strategies



Exclusion Plots

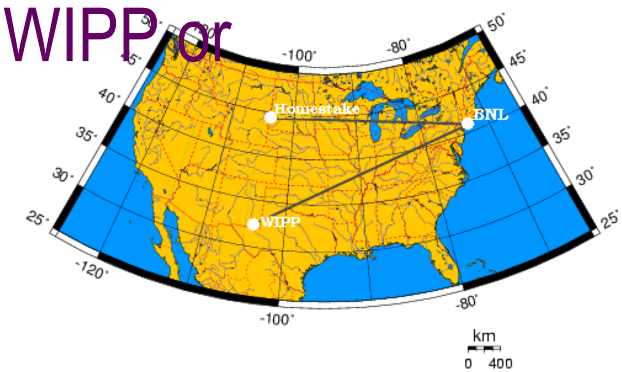




Long Baseline Experiments

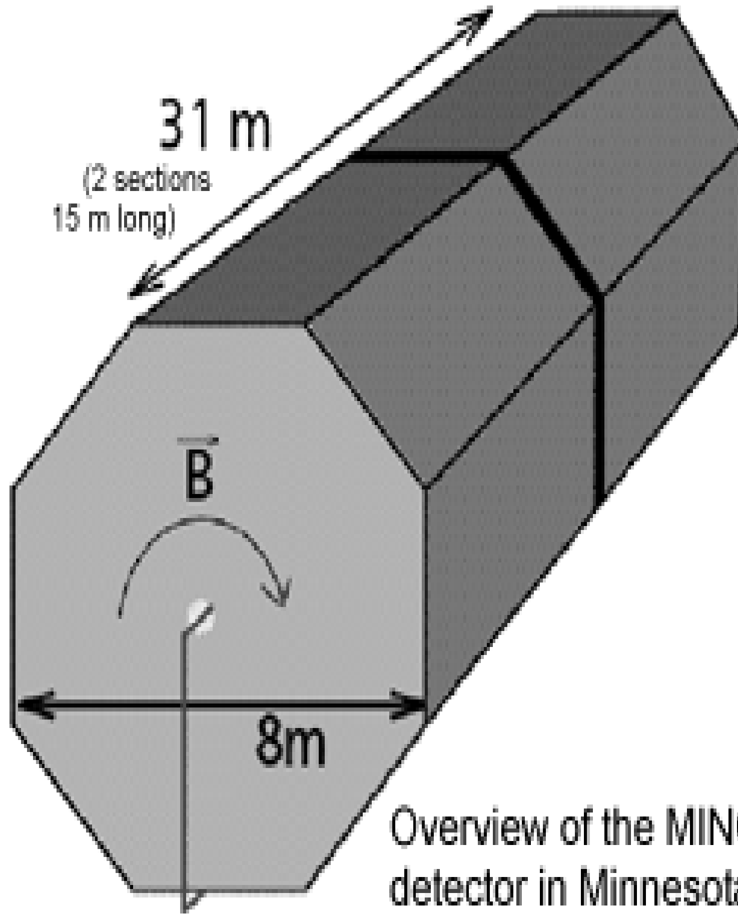
- Baseline length over a few hundred km
- Neutrino energies can be high
- Experiments and Facilities
  - Fermilab (to Soudan Underground Facility):
    - MINOS: Main Injector Neutrino Oscillation Search (L=730km)
    - Nova: Off axis neutrino appearance experiment ($\nu_\mu \longrightarrow \nu_e$)
    - New Neutrino Oscillation Experiment at Soudan (Emulsion+iron) ➔ Tau appearance
  - BNL: A proposal to shoot neutrinos to WIPP or Homestake

$$P\left(\nu_\mu \to \nu_e\right) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$



MINOS (Main Injector Neutrino Oscillation Search)

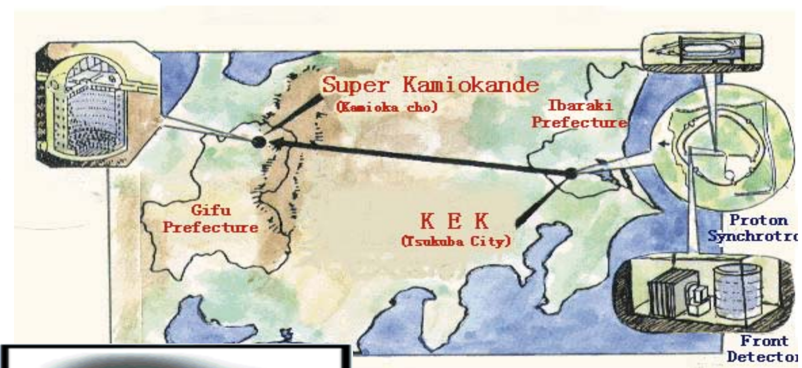
- Receives beam from NuMI (Neutrino at Main Injector) facility
- Located in the Soudan mine in Minnesota, 800m underground
- Detector consists of iron and scintillation counters, weighing a total of 5400 tons
- 9000 neutrino events/year expected

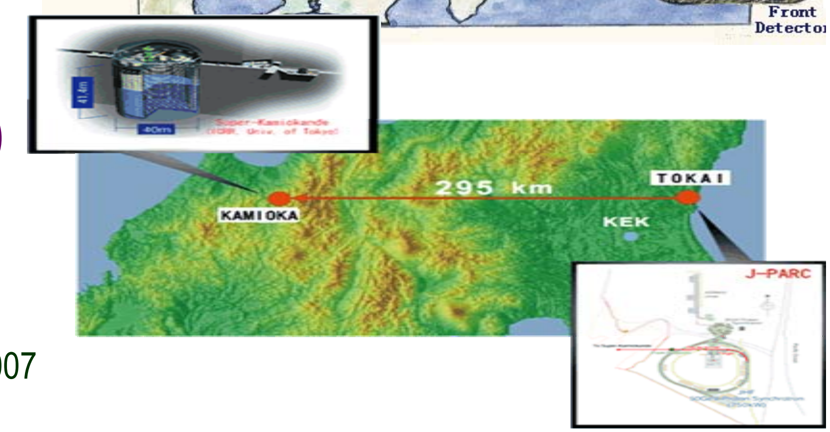


Overview of the MINOS detector in Minnesota.

Long Baseline Experiment Cont'd

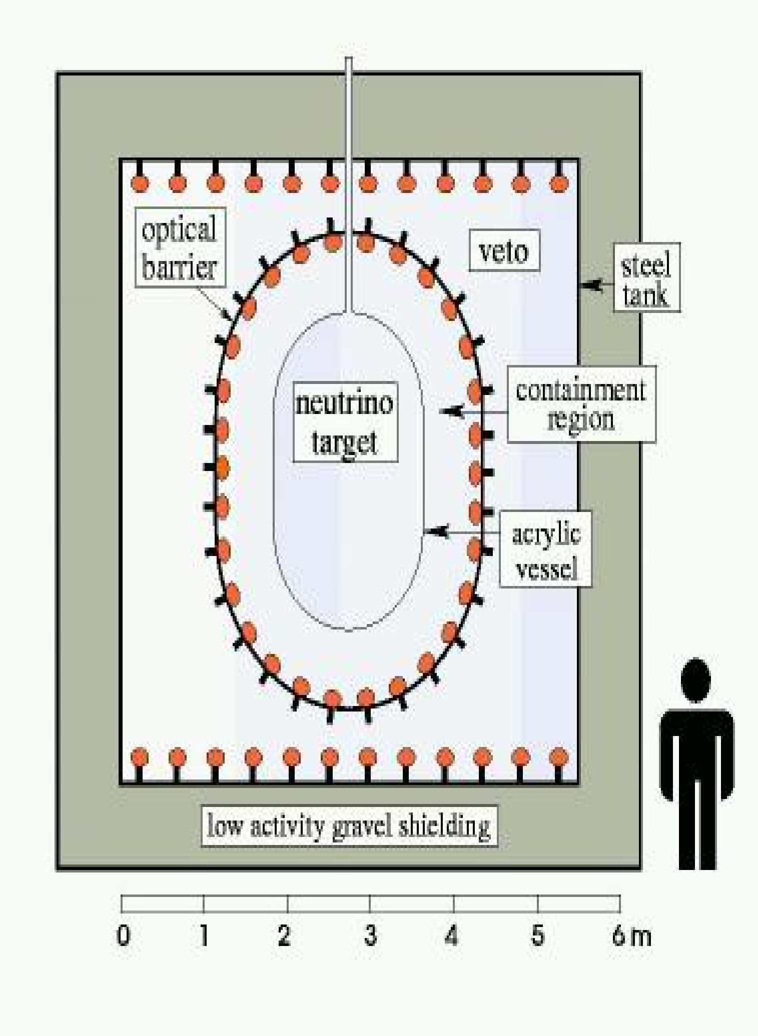
- CERN (CNGS, CERN Neutrinos to Grand Sasso):
  - Baseline length, L=730km
  - ICANOE (Ring Imaging Cerenkov Detector)
  - ICARUS (LAr Cerenkov detector)
    - $\nu_\mu \rightarrow \nu_\tau; \quad \nu_\mu \rightarrow \nu_e$
  - OPERA ($\nu_\mu \rightarrow \nu_\tau$): Lead+Emulsion, start taking data in Aug. 2006
  - NOE (Neutrino Oscillation Experiment)
- Japan:
  - K2K: KEK to Kamioka Mine (L=250km)
  - T2K: J-PARC at Tokai to Kamioka (L=295km)





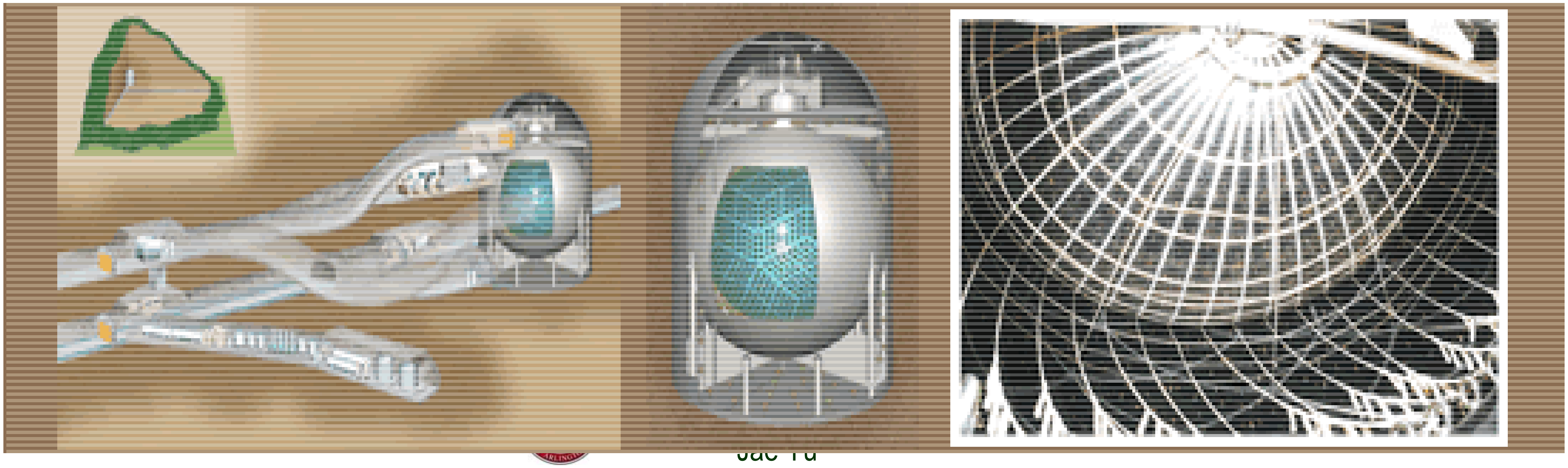
Chooz

- Nuclear reactor Long Base Line experiment
- Look for neutrino oscillation from the disappearance in $\bar{\nu}_e \rightarrow \bar{\nu}_e$
- The detector used Cerenkov light in liquid scintillator (mineral oil)
- The experiment is completed
- The final paper published in 1999
- Will continue with mixing angle measurement experiment at Double-Chooz



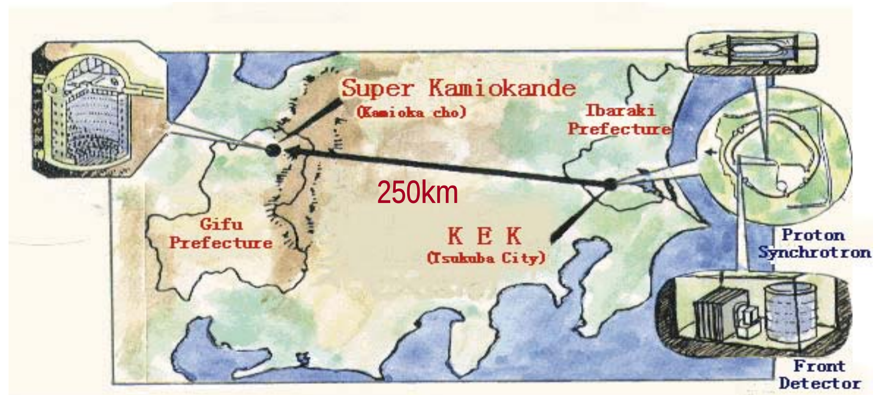
KamLAND – Kamioka Liquid scintillator Anti - Neutrino Detector

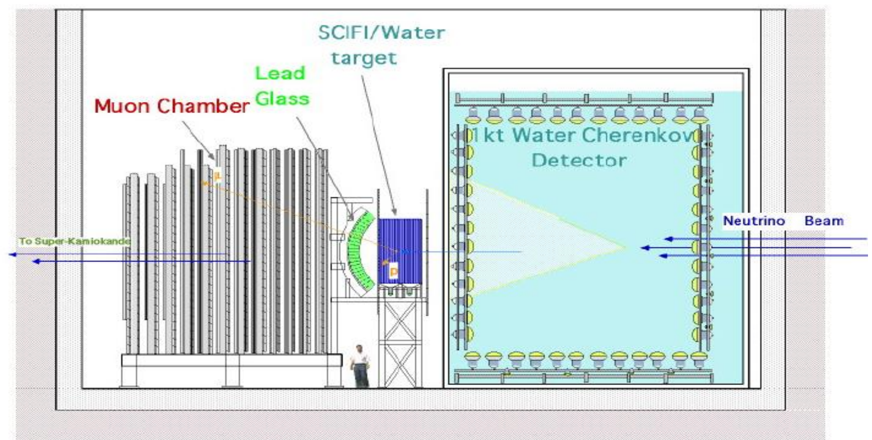
- Reactor and solar neutrino long baseline experiment
- Located in the old Kamiokande detector cavern 1000m underground
- 1000 ton liquid scintillator detector w/ good $\bar{\nu}_e$ detection.
- The experiment is completed
- Taking data

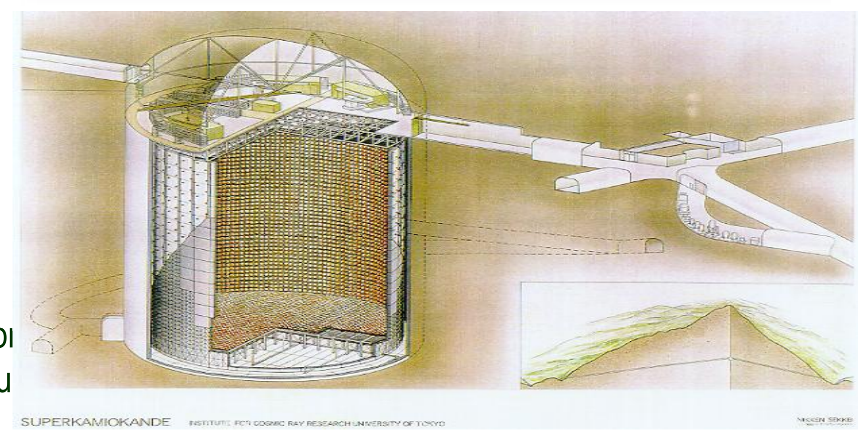


K2K – KEK to Kamioka

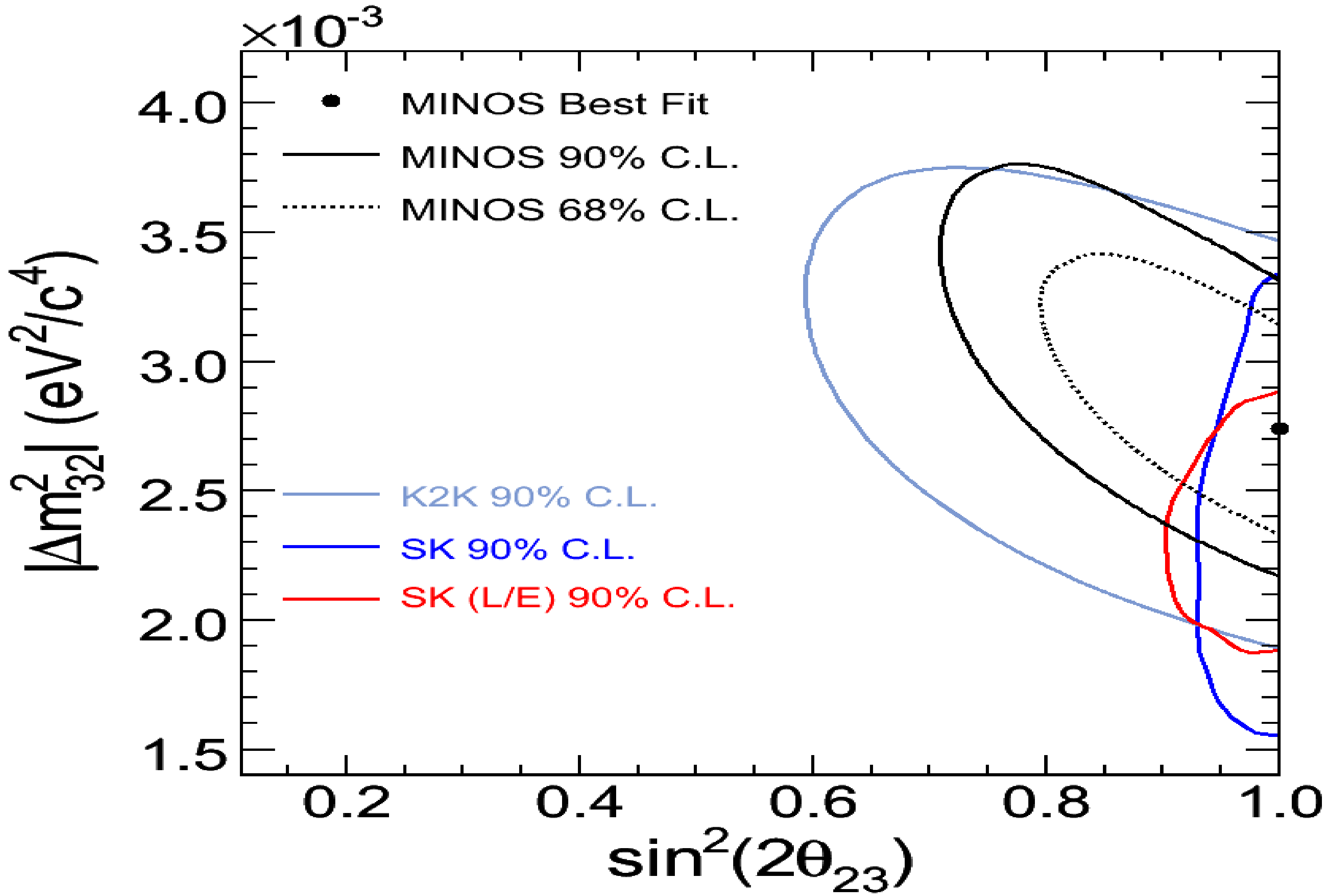
- Send neutrino beam from KEK’s proton synchrotron to Super-Kamiokande detector
- What are they looking for?
  - ν_μ disappearance
  - ν_e appearance
- K2K-II started data taking in Jan. 2004
- Based line length: 250km
- Compare measured flux at the near detector with that measured at the far detector
- Crucial to know the beam flux







Latest ν Oscillation Results From K2K and MINOS



Useful Links for Neutrinos Oscillations

- General summary: http://www.nu.to.infn.it/
- http://www.hep.anl.gov/ndk/hypertext/nuindustry.html
- http://www.ps.uci.edu/~superk/oscillation.html
- http://wwwlapp.in2p3.fr/neutrinos/ankes.html

Homework Assignments

- Complete the derivation of the probability for ν_μ of energy E_ν to oscillate to ν_e at the distance $\mathcal{L}$ away from the source of ν_μ.
- Draw the oscillation probability distributions as a function of
  - Distance $\mathcal{L}$ for a fixed neutrino beam energy E_ν (=5, 50, 150 GeV)
  - E_ν for a detector at a distance $\mathcal{L}$ (=1.5, 735, 2200km) away from the source
- Due Wednesday, Feb. 21