The Super-Kamiokande Experiment

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The Super-Kamiokande Collaboration

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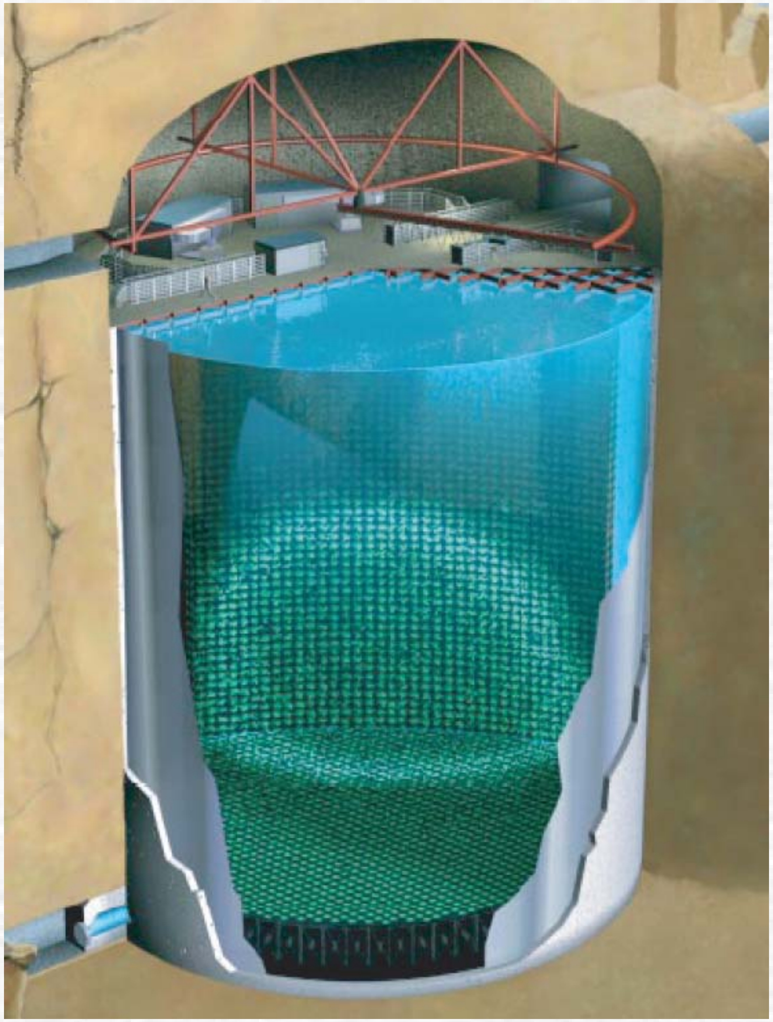
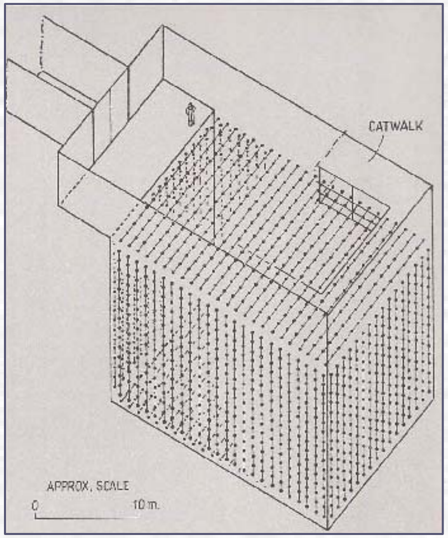


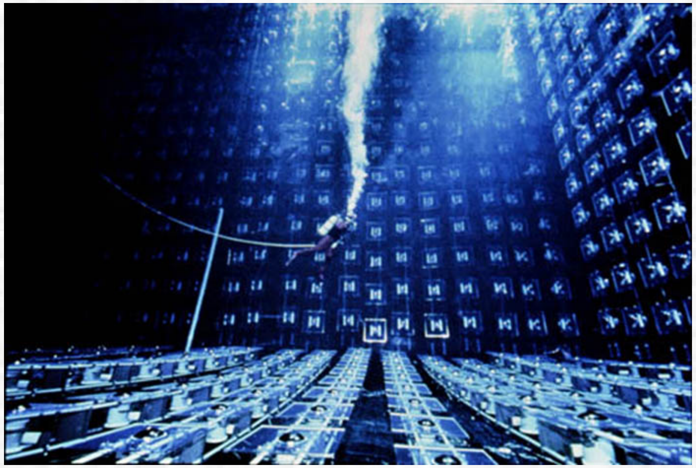
Outline

- History and Introduction
- How Super-Kamiokande Works
- Solar Neutrino Results
- Atmospheric Neutrino Results
- Proton Decay Results
- Long-Baseline Experiments and Future

A Bit of History - IMB

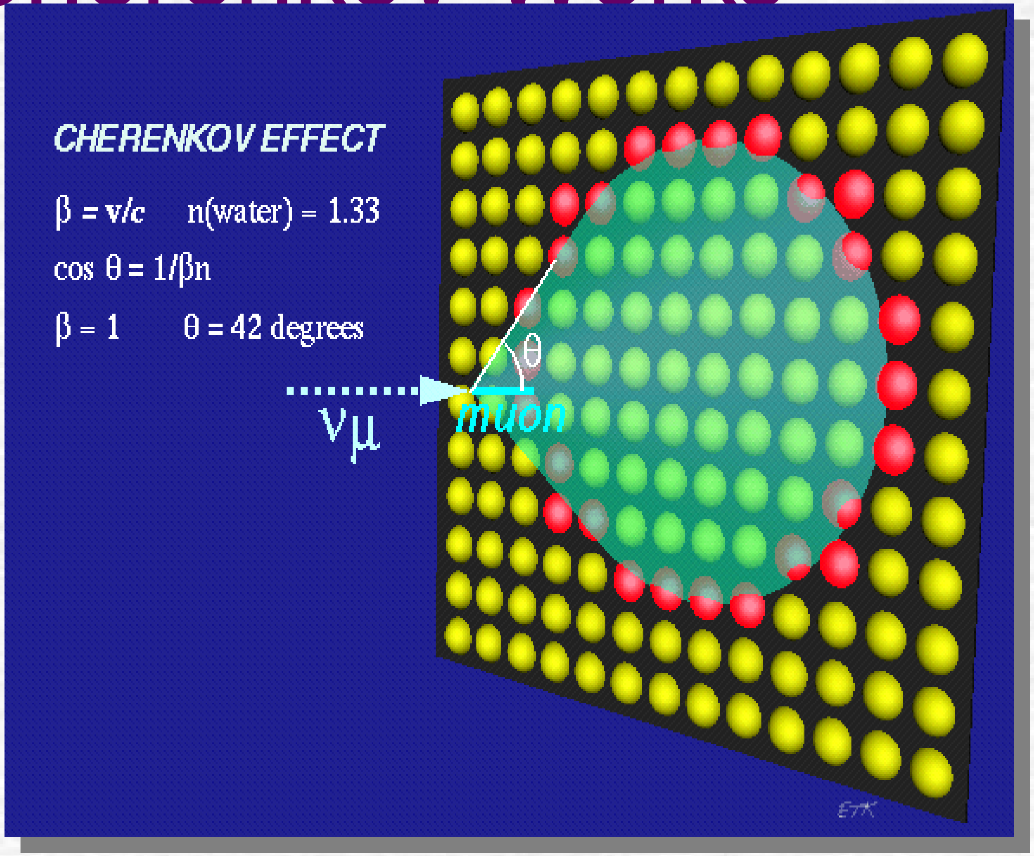


- Pioneering water Cherenkov detector
  - Data-taking 1982-1990
  - 8 kton water (3.3 fiducial)
  - 2048 5” PMTs (IMB-1)
    - Later upgraded (IMB-2,3)
- Major accomplishments:
  - Excluded minimal SU(5) grand-unified theory
  - Observation of supernova neutrinos (with Kamiokande)
  - Confirmed atmospheric muon-neutrino deficit



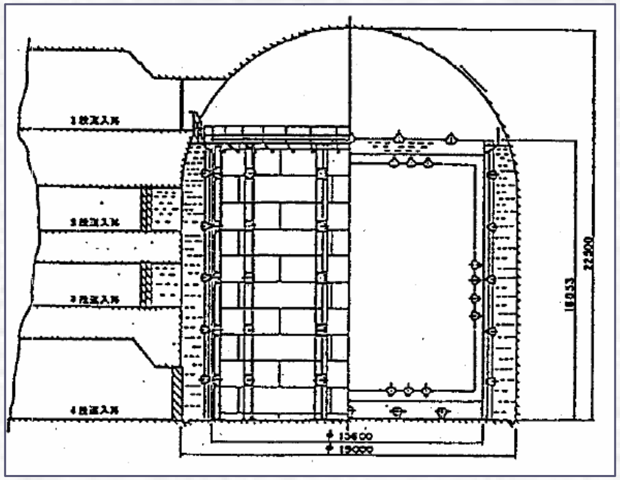
How Water Cherenkov Works

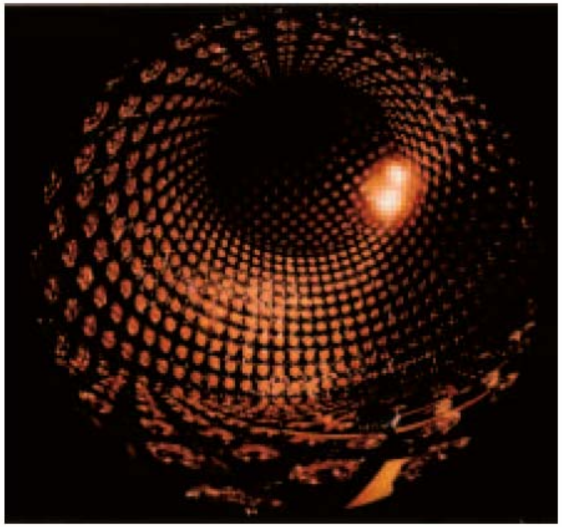
- Cheap target material
- Surface instrumentation
- Vertex from PMT timing
- Direction from ring edge
- Energy from pulse height, range and opening angle
- Particle ID from hit pattern and delayed muon decay signature
- Cherenkov threshold:
  - $\beta > 1/n \sim 0.75$



Kamiokande

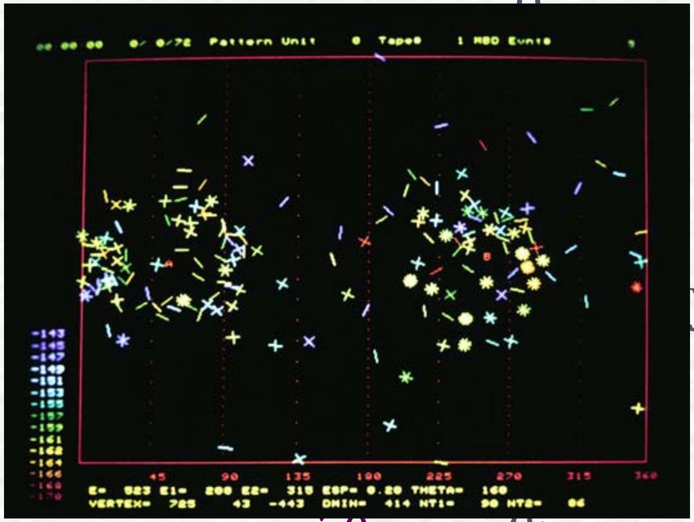
- Second kiloton water Cherenkov detector
  - Began data-taking 1983
  - Mass ~1 kton
  - 20” PMTs, 20% photocathode coverage
    - Compare to ~1% for IMB-1!
- Major accomplishments
  - Observation of neutrinos from SN1987A (with IMB-3)
  - First real-time solar neutrino measurements (M. Koshiba 2002 Nobel Prize!)
  - First clear evidence for deficit of atmospheric muon neutrinos (confirmed by IMB-3)
- Today, the same tank is used for the KAMLAND experiment

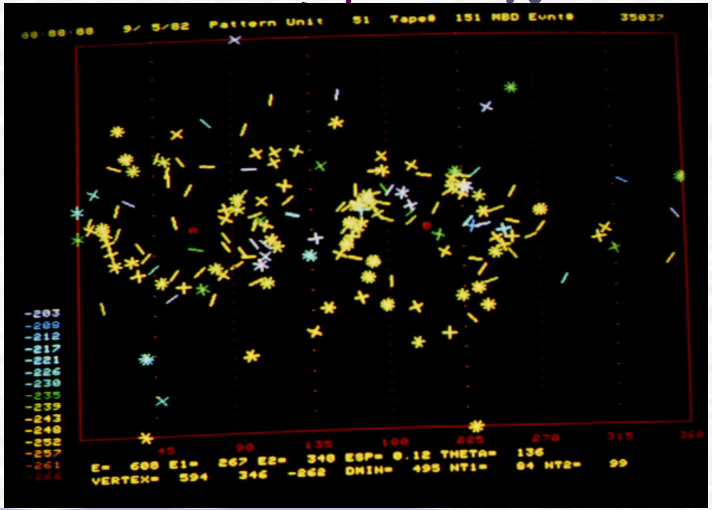




Proton Decay and Neutrinos

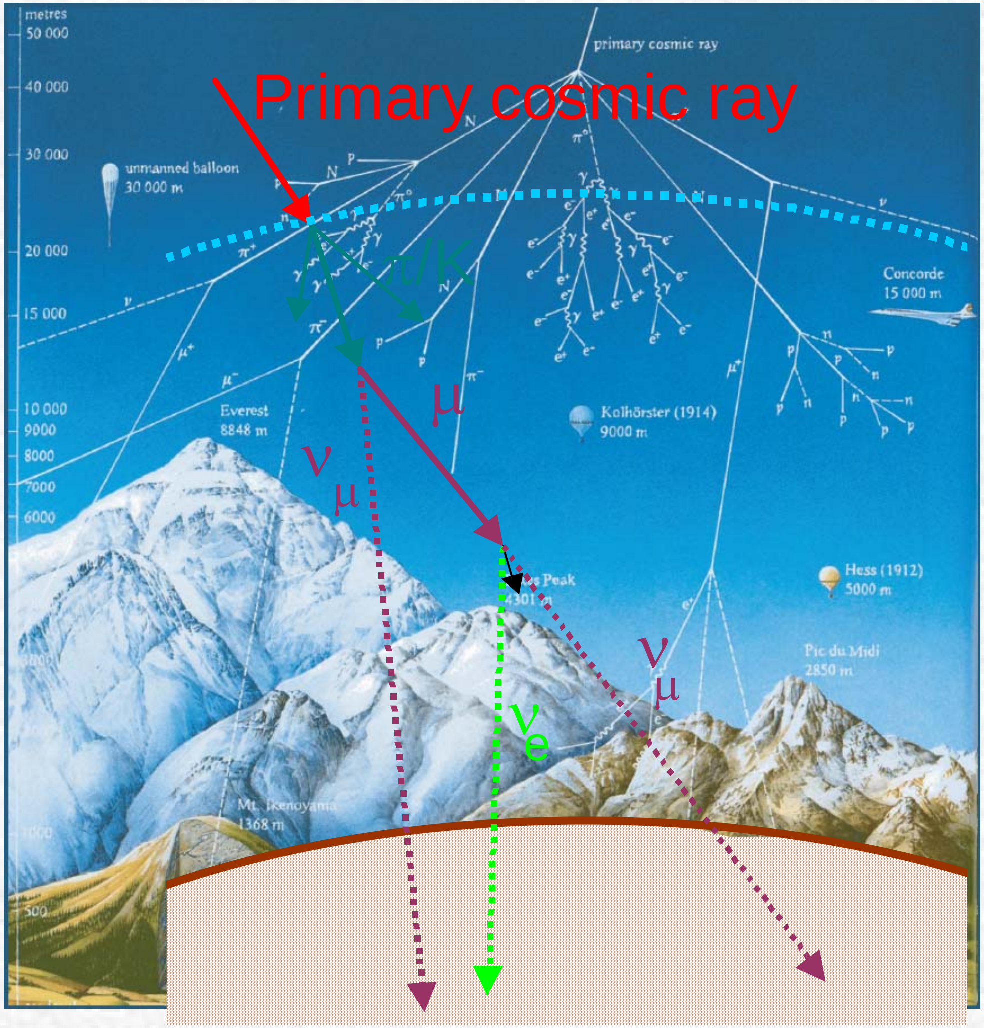
- Generic Prediction of most Grand Unified Theories
  - IMB ruled out simplest theory “SU(5)” in 1982
- Lifetime > 10^{33} yr!
  - Requires comparable number of protons
  - Colossal (kiloton) detectors
- Neutrino background proved more interesting than the (non-existent) signal!





Atmospheric Neutrinos

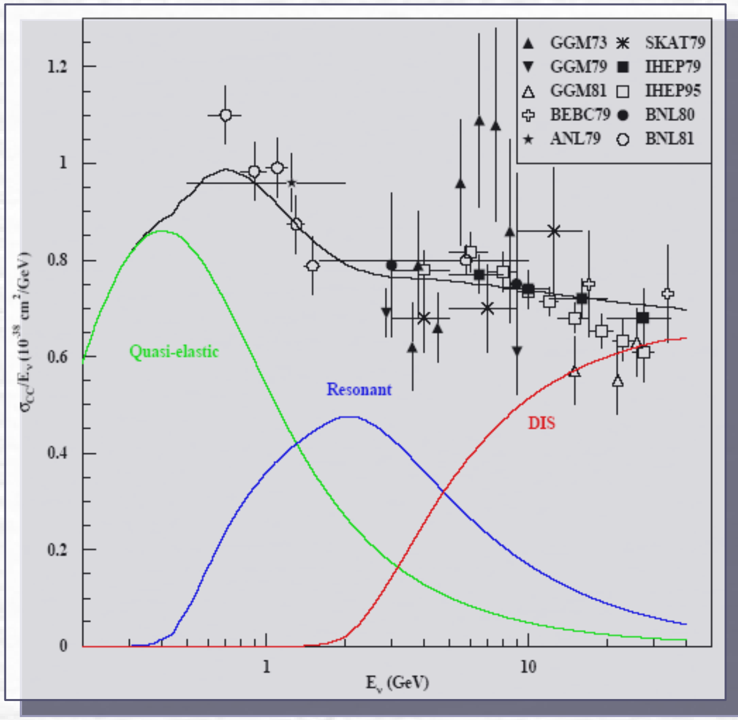
- Produced by cosmic-ray proton collisions with the upper atmosphere
  - Power-law ($\sim E^{-2.7}$) energy spectrum
    - Mean energy ~1 GeV
  - Neutrinos arrive from all directions
  - Contains muon and electron neutrinos in ~2:1 ratio
  - Absolute flux is uncertain to 10-20%



Neutrino Interactions

- Neutrino/electron scattering (e.g. $\nu + e \rightarrow \nu + e$)
  - Only relevant for lowest (solar) neutrino energies
  - Suppressed by factor $m_e/m_N \sim 2000$
  - Cross-section for ν_μ and ν_τ about 1/7 that for ν_e
- Charged-current neutrino-nucleon reactions
  - **Produces charged lepton with same flavor as neutrino**
  - Quasi-elastic (e.g. $\nu + n \rightarrow \ell^- + p$)
    - Recoil nucleon usually invisible in Cherenkov detector
  - Resonant (e.g. $\nu + N \rightarrow \ell^- + \Delta;\ \Delta \rightarrow \pi + N'$)
    - One or more pions produced in addition to charged lepton
  - Charged-current deep-inelastic scattering

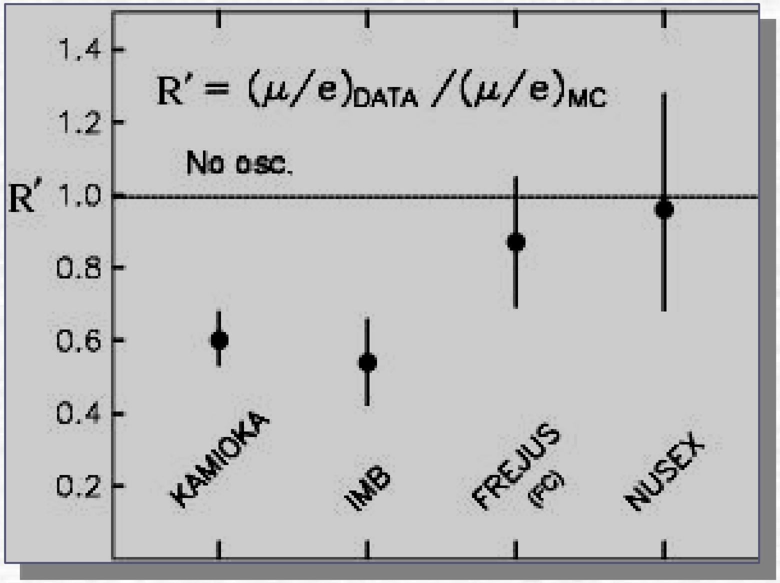
    (e.g. $\nu + q \rightarrow \ell^- + q'\ ;\ q' \rightarrow$ hadrons)
    - Multiple hadrons produced
  - Total charged-current neutrino-nucleon cross-section rises ~linearly with energy
- Neutral-current neutrino-nucleon reactions (e.g. $\nu + N \rightarrow \nu + X$)
  - No charged lepton; suppressed by a factor 2-3 compared to charged-current reactions
  - **No information about neutrino flavor**



$$\sigma(\nu + N \rightarrow \ell^- + X)/E_\nu$$

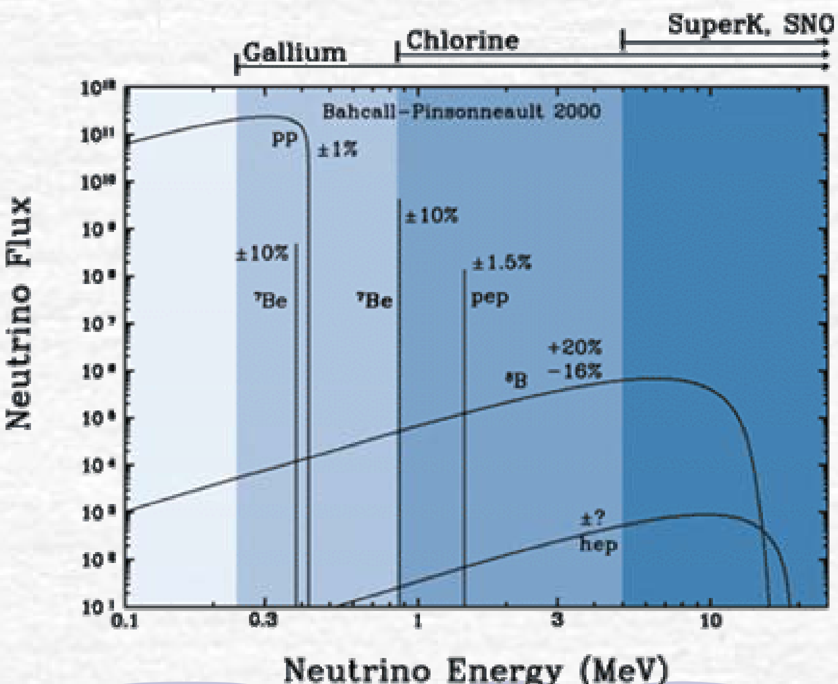
The Atmospheric Neutrino Problem

- While searching for proton-decay, IMB and Kamiokande accumulated large samples of atmospheric neutrino interactions
- Because most interactions are charged-current quasi-elastic, it was possible to study the flavor composition of the atmospheric neutrino flux
- Both found about 40% fewer ν_μ interactions than expected
  - The "atmospheric neutrino problem"
  - Kamiokande found hints of a dependence on the arrival direction
  - Two smaller detectors found no evidence of a deficit



Solar Neutrinos

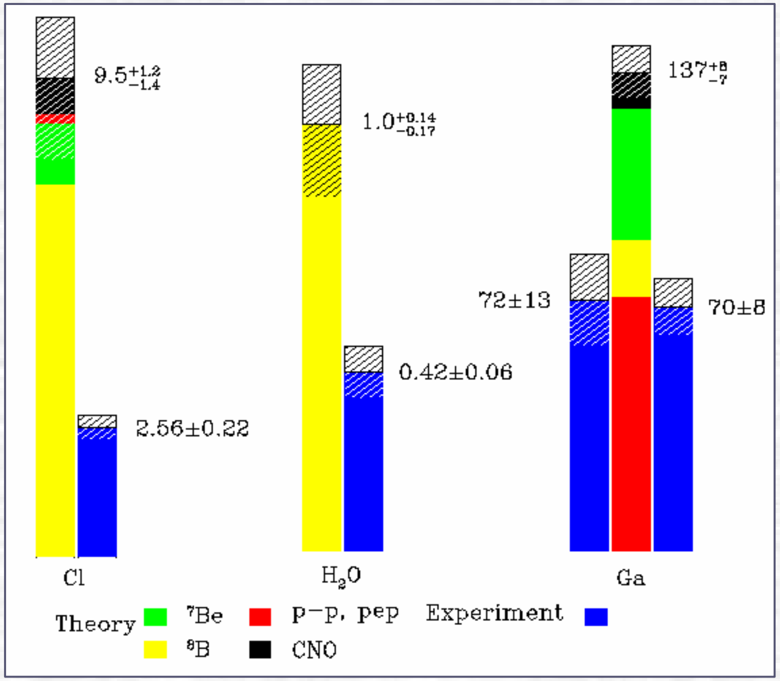
- Fusion reactions in the Sun also produce low-energy electron neutrinos
- A 20-year experiment using a tank of Chlorine found only 1/3 of the expected rate
  - Ray Davis, 2002 Nobel Prize!



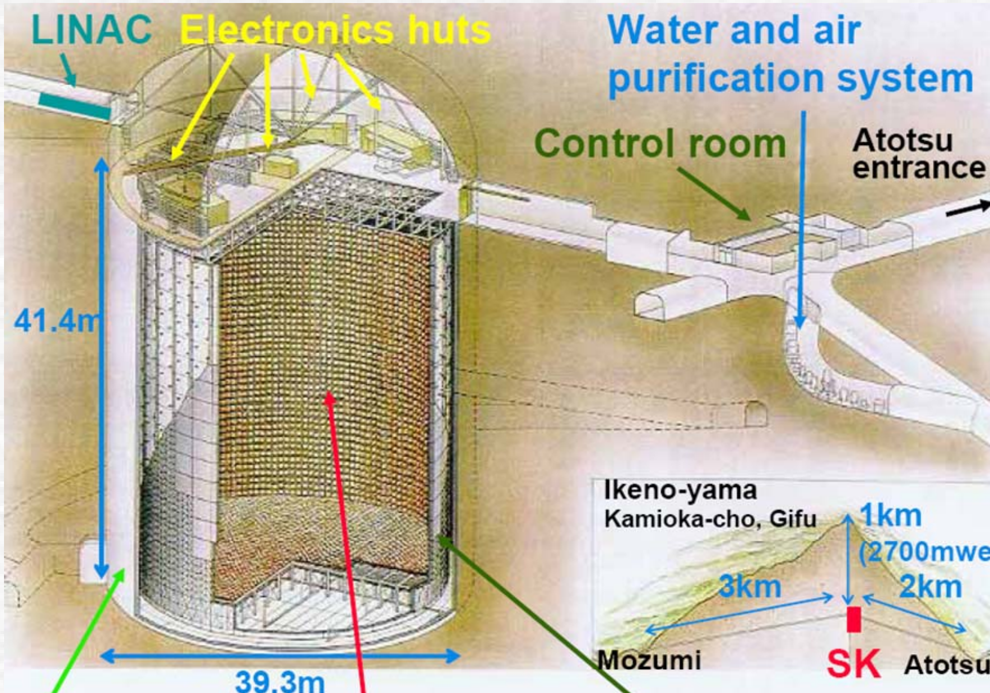
REACTION	TERM. (%)	ν ENERGY (MeV)
$p + p \rightarrow {}^2H + e^+ + \nu_e$	(99.96)	≤ 0.423
or		
$p + e^- + p \rightarrow {}^2H + \nu_e$	(0.44)	1.445
${}^2H + p \rightarrow {}^3He + \gamma$	(100)	
${}^3He + {}^3He \rightarrow \alpha + 2p$	(85)	
or		
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	(15)	
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	(15)	$\begin{cases} 0.863 & 90\% \\ 0.385 & 10\% \end{cases}$
${}^7Li + p \rightarrow 2\alpha$		
or		
${}^7Be + p \rightarrow {}^8B + \gamma$	(0.02)	
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$		< 15
${}^8Be^* \rightarrow 2\alpha$		
or		
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	(0.00003)	< 18.8

The Solar Neutrino Problem

- Kamiokande, together with two experiments using a Gallium target, confirmed this deficit of solar neutrinos
  - The “solar neutrino problem”



The Super-Kamiokande Detector

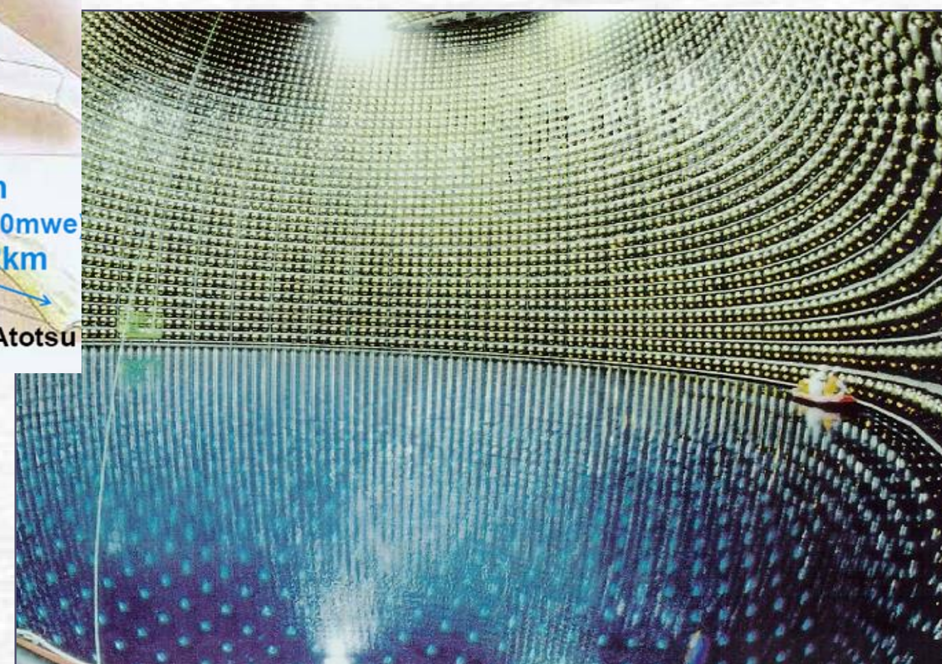


- In the mid-1990's, Super-Kamiokande was built to study all three puzzles:
  - Nucleon decay
  - Solar neutrinos
  - Atmospheric neutrinos

50,000 ton total mass (22,500 ton fiducial)

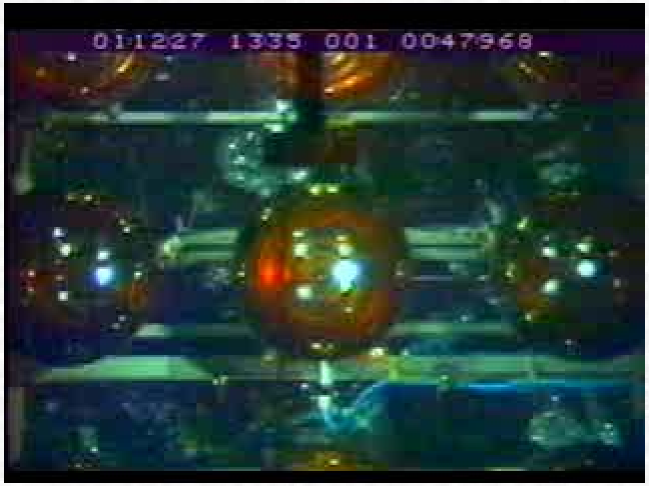
Inner detector: 11,186 20" PMTs (40% coverage)

Outer detector: 1885 8" PMTs (veto)



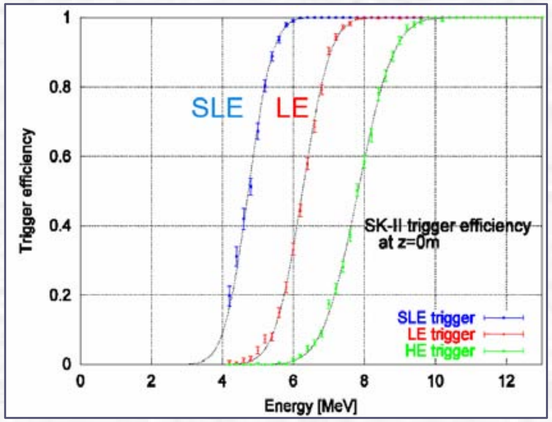
Super-Kamiokande Milestones

- April 1996: Data-taking begins
- June 1998: Evidence for atmospheric oscillation announced
- Spring 1999: K2K long-baseline experiment begins
- June 2001: Detector shutdown for PMT maintenance
- August 2001: Refilling of detector begins
- November 2001: Implosion disaster; end of SK-I
- December 2002: SK-II phase begins with half PMT coverage and acrylic housings
- Summer 2005: K2K long-baseline experiment ends
- Fall 2005: Restoration of full PMT coverage (SK-III) begins
- 2008?: Start of T2K long-baseline experiment



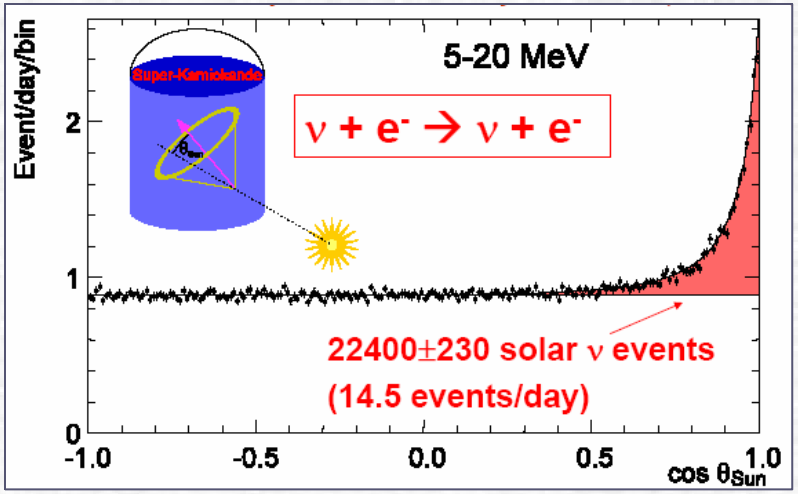
Solar Neutrino Rate

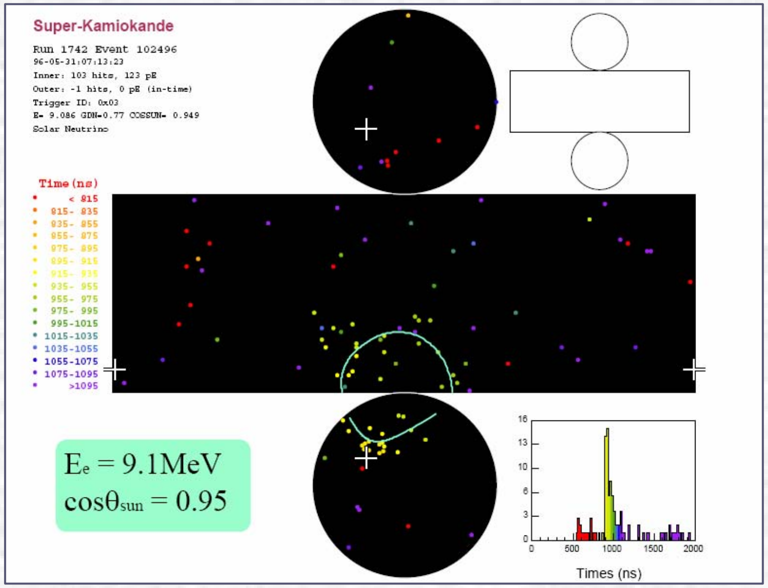
- SK observes a clear excess of electrons pointing from the direction of the Sun
- Principal solar neutrino backgrounds come from Radon, spallation products, and radioactivity
- Only about 40% of the expected interaction rate is observed:



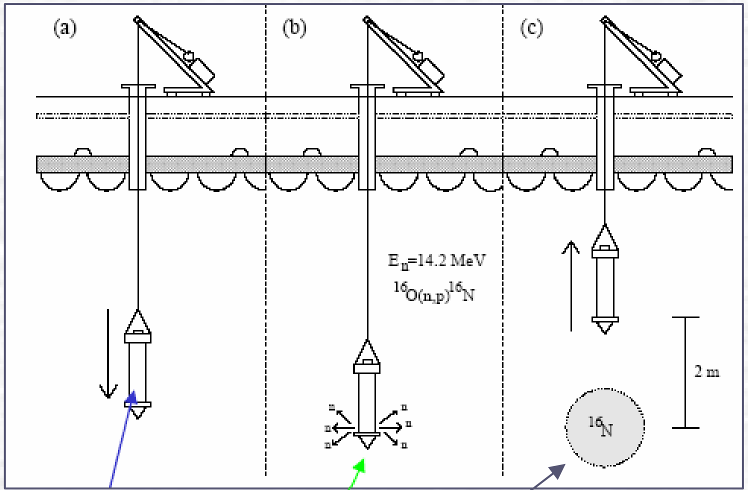
^{8}B flux = 2.35 ± 0.02 ± 0.08 [x10^{6}/cm^{2}/s]

Data / SSM_{BP2004} = 0.406 ±0.004(stat.) +0.014 -0.013 (syst.)

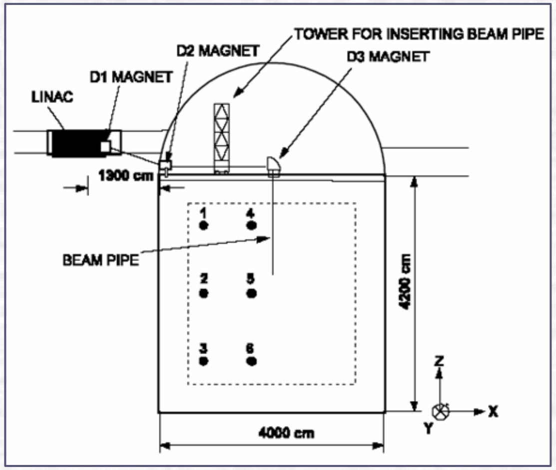




Low Energy Calibrations



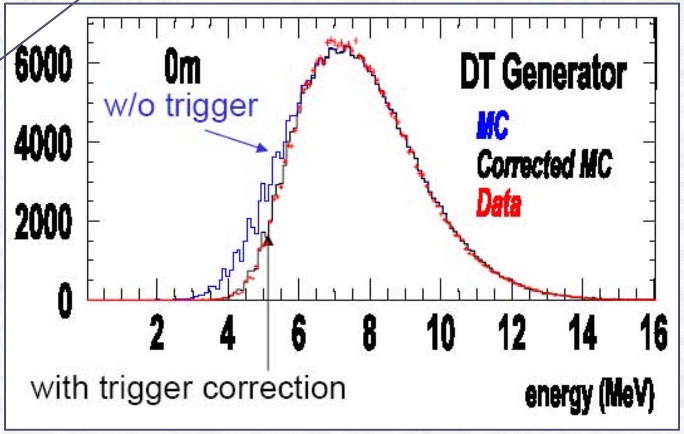
- At low-energy, SK is calibrated using:
  - lasers,
  - radioactive sources,
  - a "DT" generator,
  - and its own LINAC

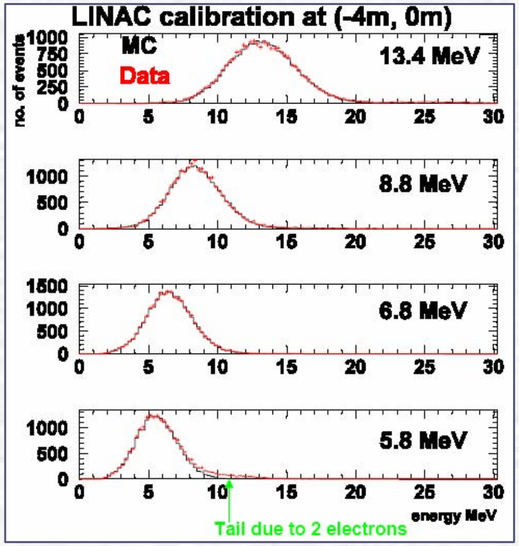


D+T→He + n

n + ^{16}O→p+^{16}N

^{16}N→^{16}O+e^{-}+ν



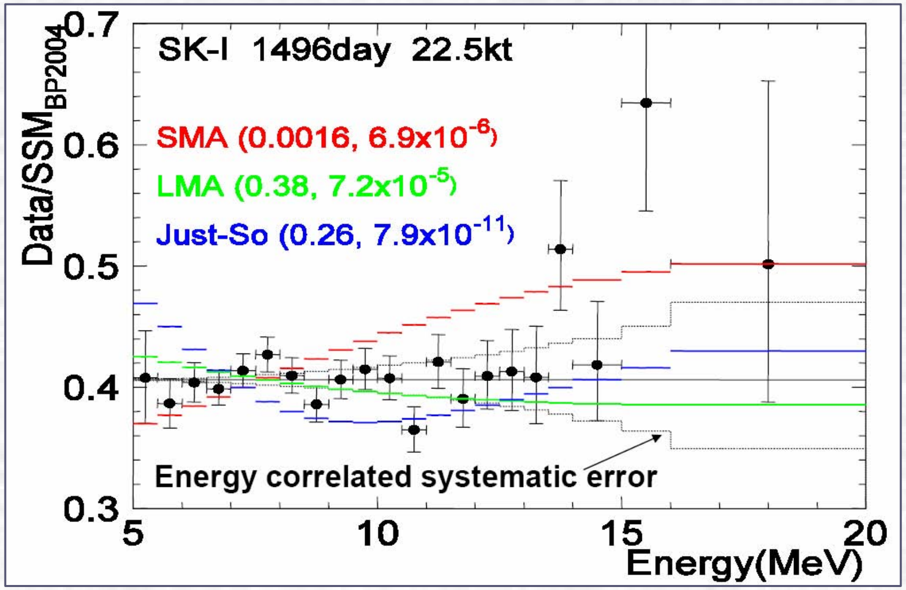


Probing Solar Neutrino Oscillation

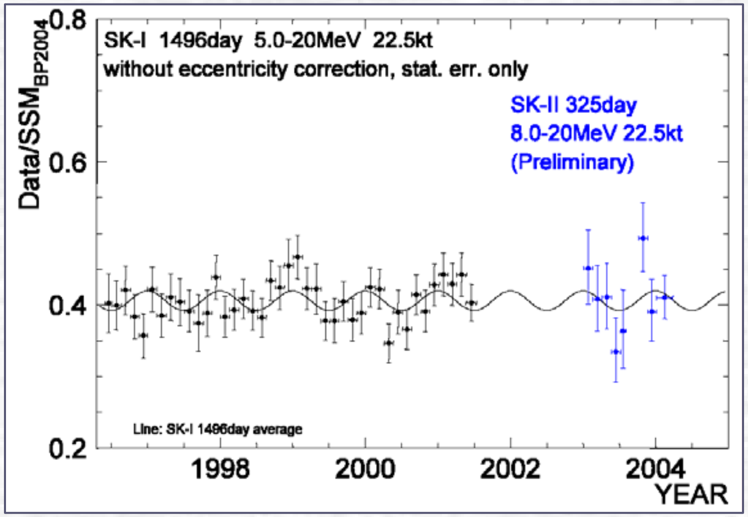
- If ν_e from the Sun oscillate to other flavors, the observed rate will be suppressed because ν_μ and ν_τ have a much smaller cross-section than ν_e
- In addition to the rate, SK can look for:
  - Distortions of the neutrino energy spectrum
    - SMA and Vacuum (“Just-So”) solutions
  - Day/Night Time Variations
    - Lower part of LMA solution and upper part of LOW solution
  - Seasonal Variations
    - Vacuum solution
- The predicted ^{8}B flux from solar models, and/or data from other experiments, can be used as additional constraints

Solar Neutrino Energy Spectrum

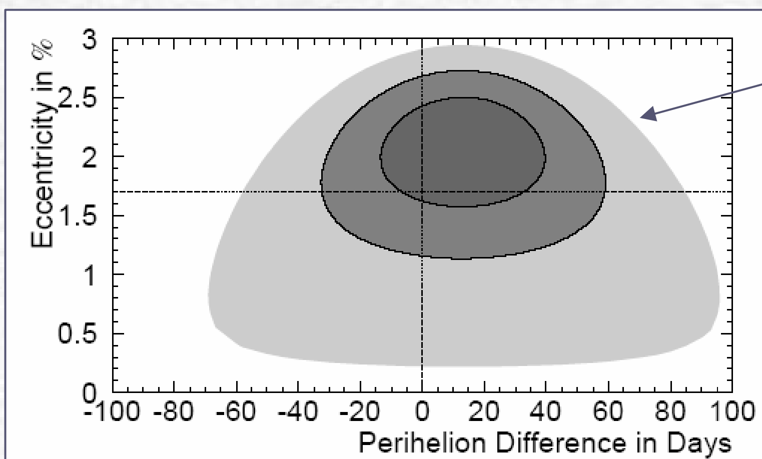
- Absence of large spectral distortions allowed Super-K to rule out the SMA and "Just-So" (Vacuum) at 95% confidence level solutions prior to the results from SNO and and KAMLAND
  - SK data alone allows only solutions with large mixing



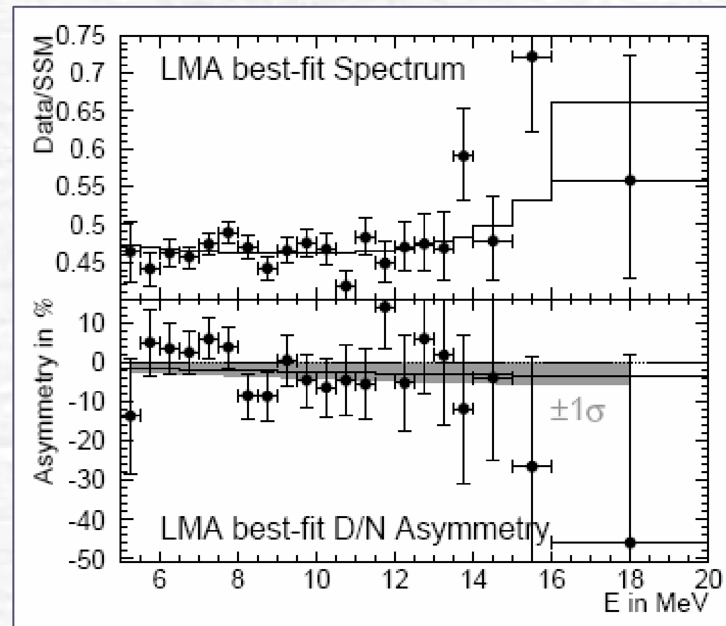
Solar Neutrino Time Variation



- Absence of seasonal variation (apart from $1/r^2$ variation due to eccentricity of the Earth's orbit) also excludes the "Just-So" region
- Day/Night variation is also consistent with zero, excluding a significant portion of the LMA solution

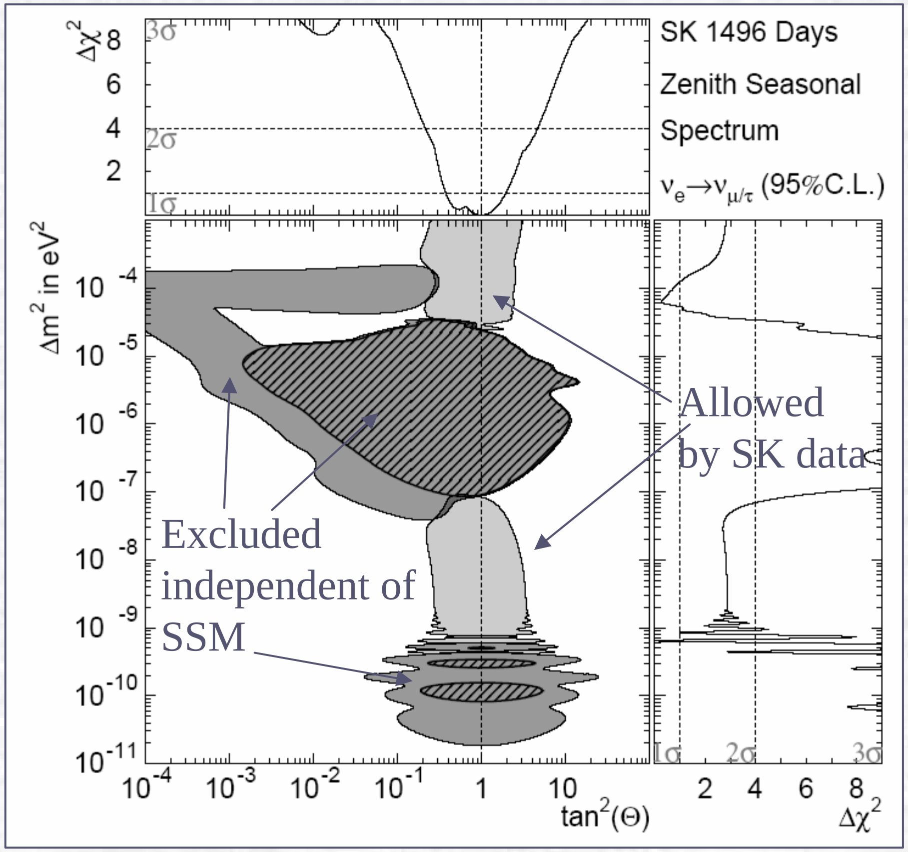


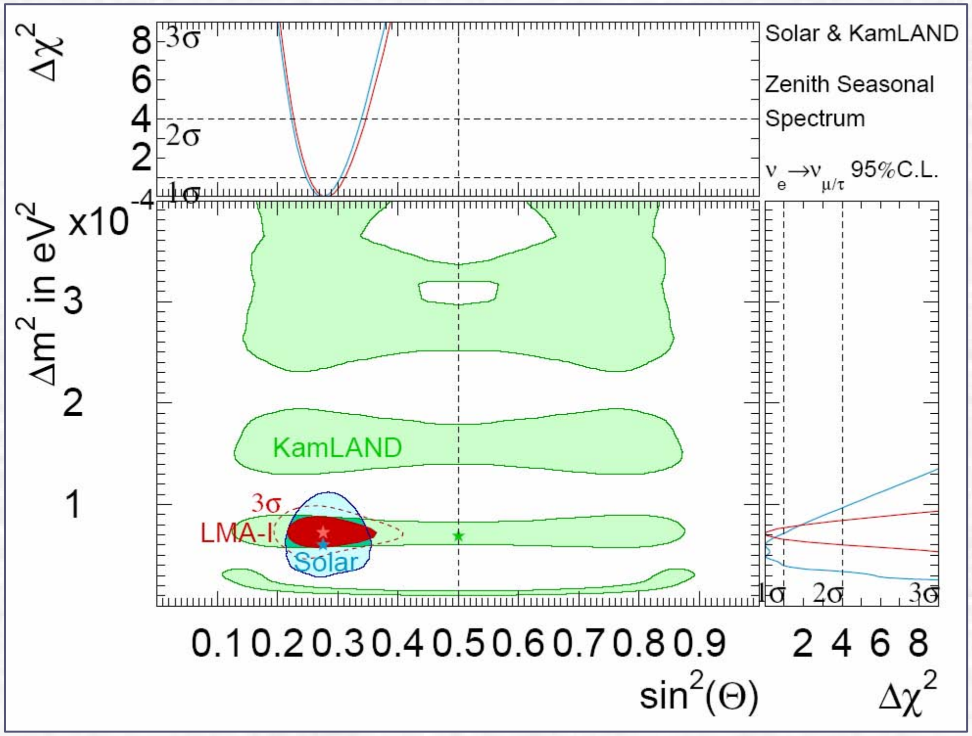
Measurement of Earth's orbital parameters with neutrinos!



$A_{DN}=-1.8\pm1.6\,^{+1.3}_{-1.2}\,\%$

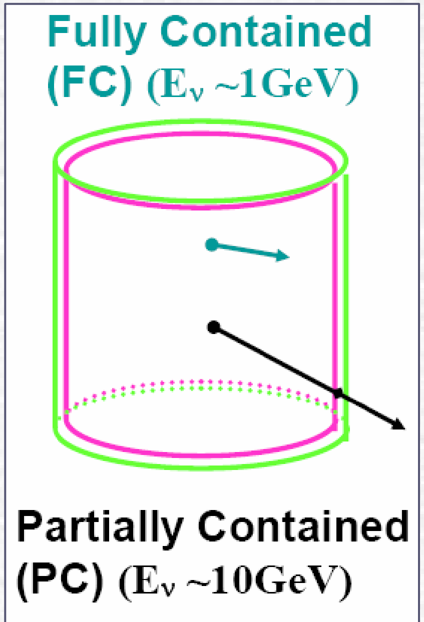
Summary of Solar Neutrinos





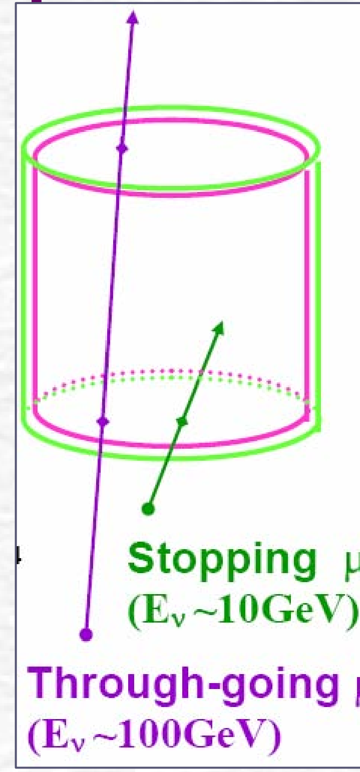
Combining Solar neutrino and KAMLAND results

Atmospheric Neutrinos in Super-K



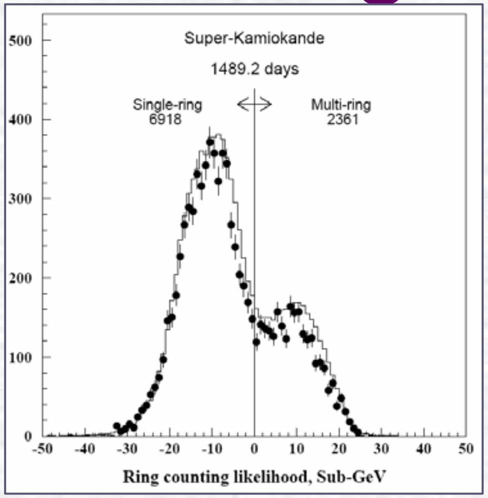
- Atmospheric neutrino data is classified by topology and energy into a variety of categories
- About 80% of the total atmospheric data sample is used in the oscillation analysis

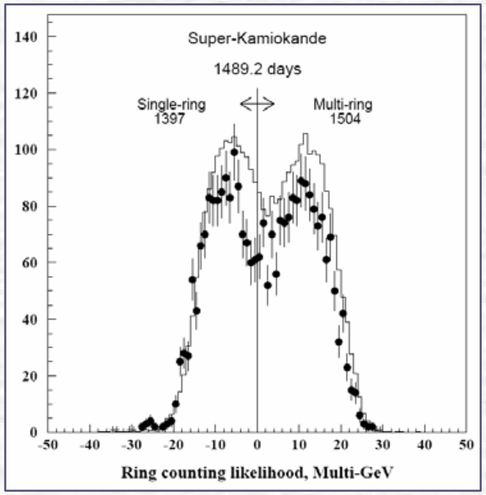
	DATA	MC	C.C. Purity
Sub-GeV 1-ring e-like	3353	2978.8	88.0%
Multi-GeV 1-ring e-like	746	680.5	82.6%
Sub-GeV 1-ring μ-like	3227	4212.8	94.5%
Sub-GeV Multiring μ-like	208	322.6	90.5%
Multi-GeV 1-ring μ-like	651	899.9	99.4%
Multi-GeV Multiring μ-like	439	711.9	95.0%
Partially Contained μ	647	1034.5	97.3%
Stopping Upward μ	417.7	721.4	~100%
Throughgoing Upward μ	1841.6	1684.4	~100%



Data Reduction and Ring Counting

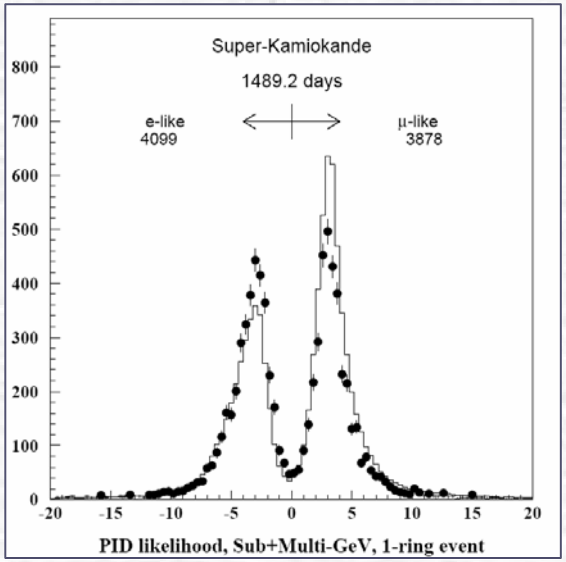
- Fully-contained events are selected by requiring no activity in the outer detector
- Partially-contained and upward-muon events are selected by reconstructing the vertex and direction
- Contained events are required to originate at least 2m from the walls
  - Vertex resolution is about 25 cm
- A maximum likelihood algorithm automatically identifies Cherenkov rings

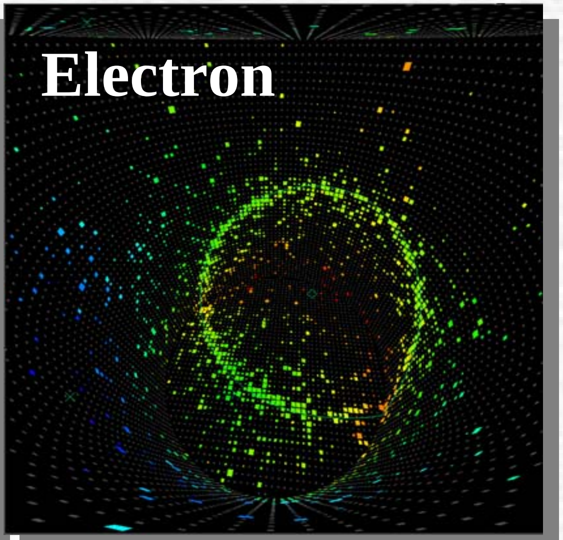




Particle Identification

- Single-ring events are identified as e-like or μ-like, based on the geometry of the Cherenkov cone
  - e-like events shower
  - μ-like events have a sharp ring edge

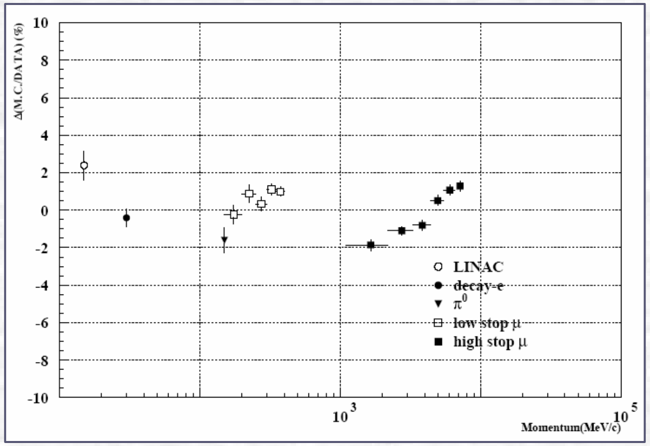


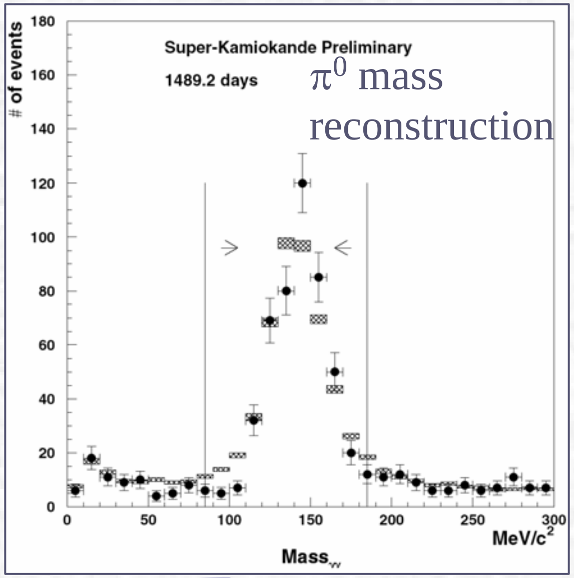


- Particle ID perfomance can be tested on cosmic-ray muons, muon-decay electrons, π^0. It has also been verified in a test beam

High-Energy Calibration

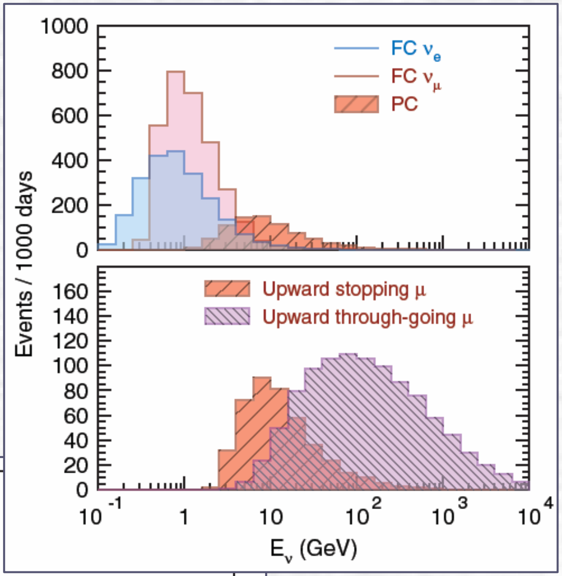
- For high-energy events, the energy scale is calibrated using:
  - Through-going cosmic-ray muons
  - Stopping cosmic-ray muons
  - Electrons from muon decay
  - Reconstructed π^0 from neutral-current interactions
- The energy scale for all types of events agrees to within about 2%

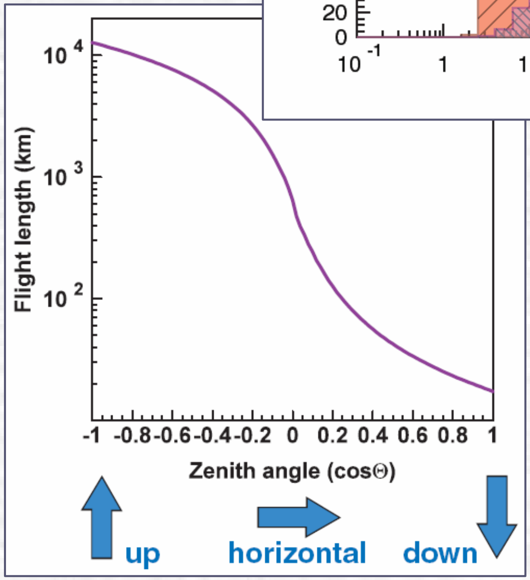




Atmospheric Neutrino Oscillation

- In the simplest, two-flavor, oscillation case, the survival probability depends on $\Delta m^2 \times L/E_\nu$
  - The various atmospheric neutrino sub-samples span a range of five decades in neutrino energy E_ν
    - From ~100 MeV to 10 TeV
  - Depending on the neutrino's arrival direction, L spans a range of three decades
    - From ~15 km to 13000 km
- Broad Δm^2 sensitivity





Two-Flavor Oscillation Analysis

- We study $\sin^2 2\theta$ and Δm^2 by binning our real and simulated data in $\cos\theta_z$ and p, then minimizing χ^2 to find the best-fit values
- Since there are many sources of systematic uncertainty, we also include many "systematic" terms in the χ^2
  - If some combination of systematic effects can account for the features of the data, oscillation will not be necessary

number of p, Θ bins

number of sys. effects (normalization is free)

$$\chi^2 = \sum_{i=1}^{180} \frac{\left(N_i^{obs} - N_i^{\exp}\left(1 + \sum_{j=1}^{39} f_j^i \cdot \varepsilon_j\right)\right)^2}{\sigma_i^2} + \sum_{j=1}^{38}\left(\frac{\varepsilon_j}{\sigma_j}\right)^2$$

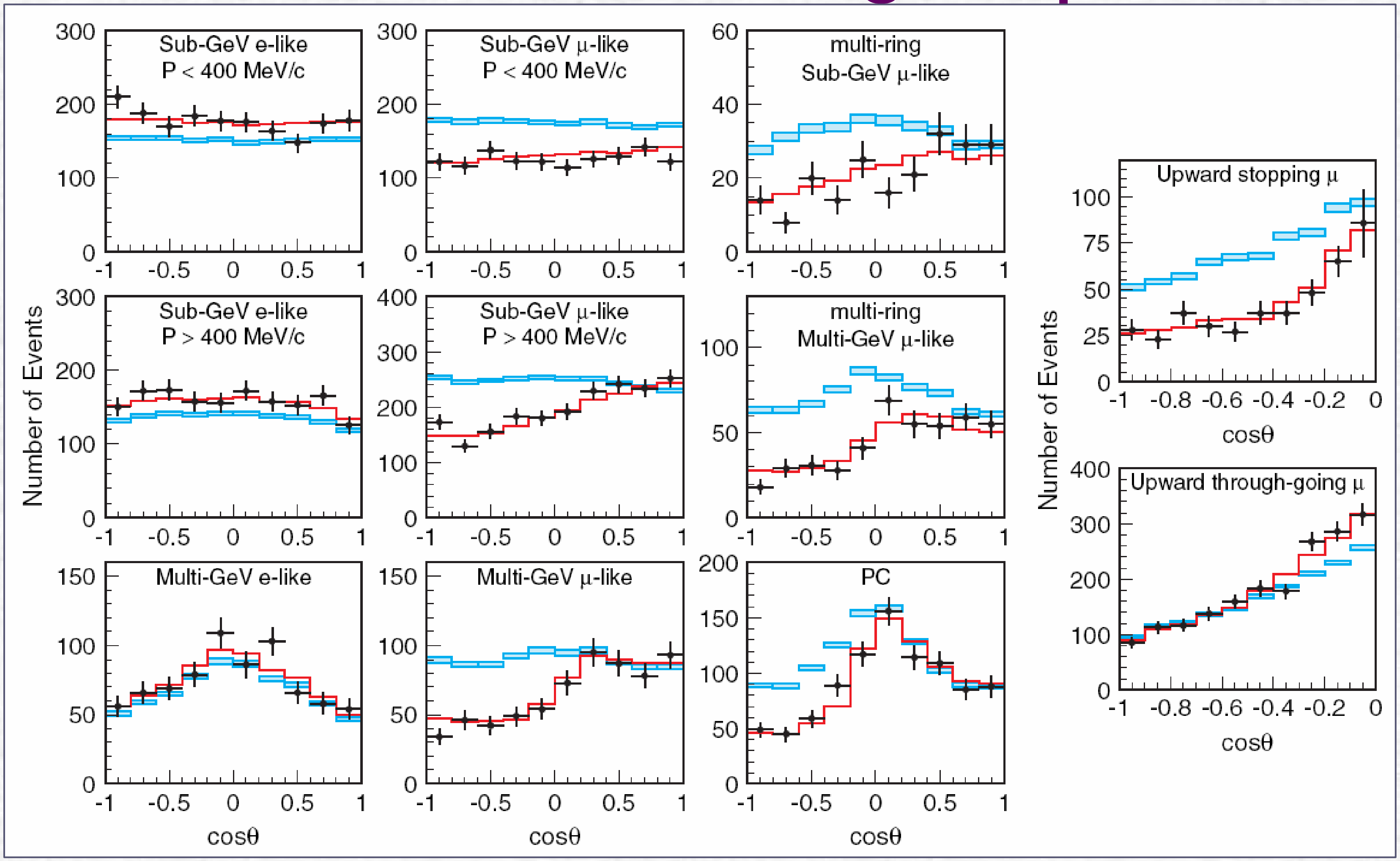
$$N_i^{\exp} = N_i^0 \cdot P(\nu_\alpha \to \nu_\beta) \cdot \left(1 + \sum_{j=1}^{39} f_j^i \cdot \varepsilon_j\right)$$

fractional change in predicted event rate due to variation in systematic parameter ε

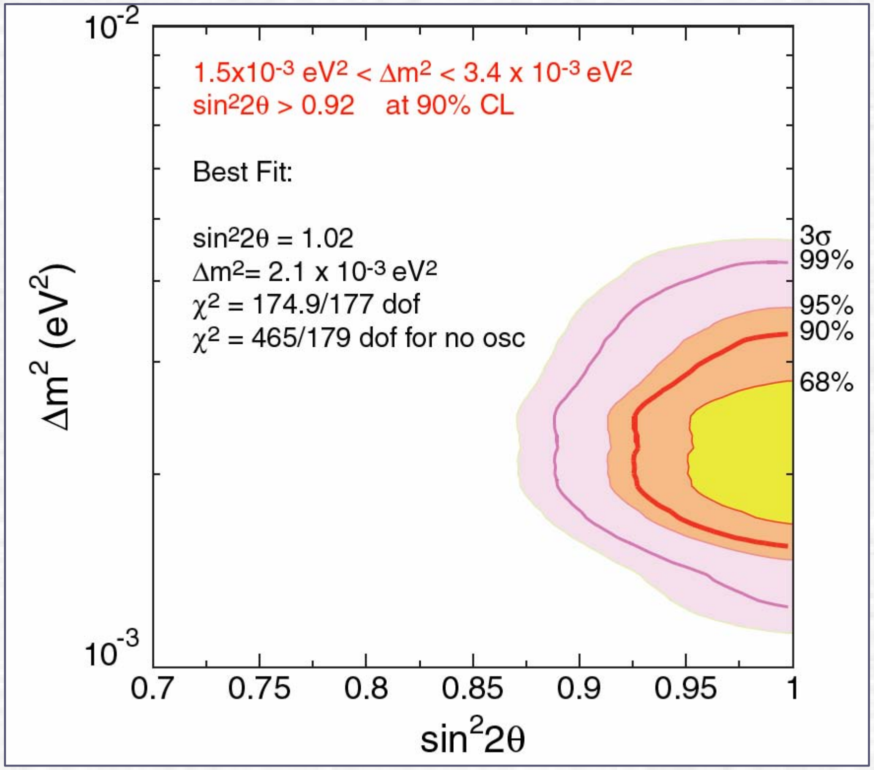
solve set of linear equations:

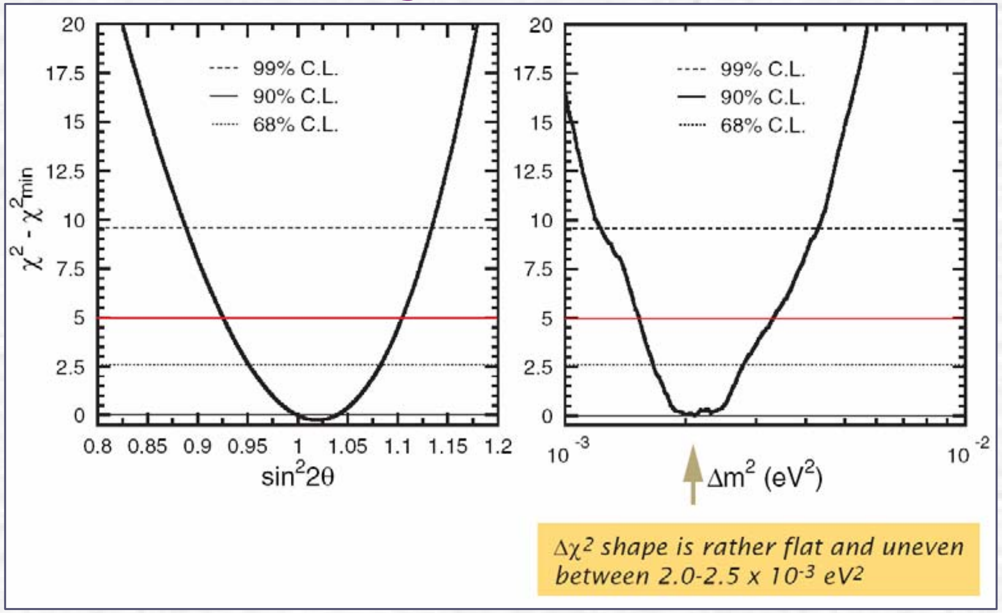
$$\sum_{j=1}^{38}\left[\frac{1}{\sigma_j^2}\delta_{jk} + \sum_{i=1}^{180}\left(\frac{N_i^{\exp} \cdot N_i^{\exp} \cdot f_j^i \cdot f_k^i}{\sigma_i^2}\right)\right] \cdot \varepsilon_k = \sum_{i=1}^{180} \frac{\left(N_i^{obs} - N_i^{\exp}\right) \cdot N_i^{\exp} \cdot f_k^i}{\sigma_i^2}$$

Best-Fit Zenith Angle Spectra



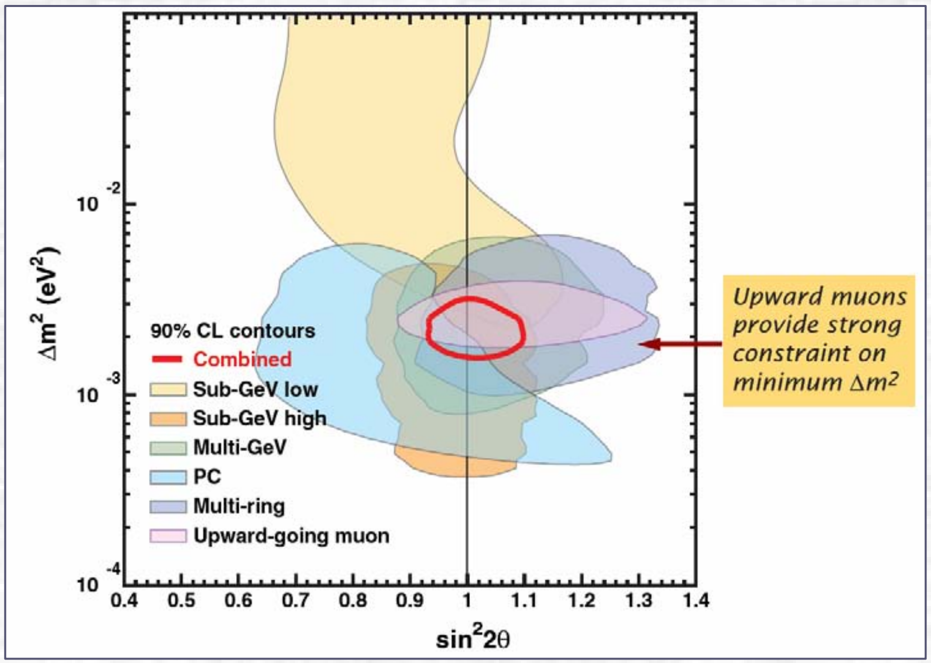
Combined Oscillation Analysis Results





- Two-flavor $\nu_\mu \rightarrow \nu_\tau$ oscillation gives an excellent fit to the data
- Even allowing for systematic uncertainties, the no-oscillation hypothesis is statistically ruled out

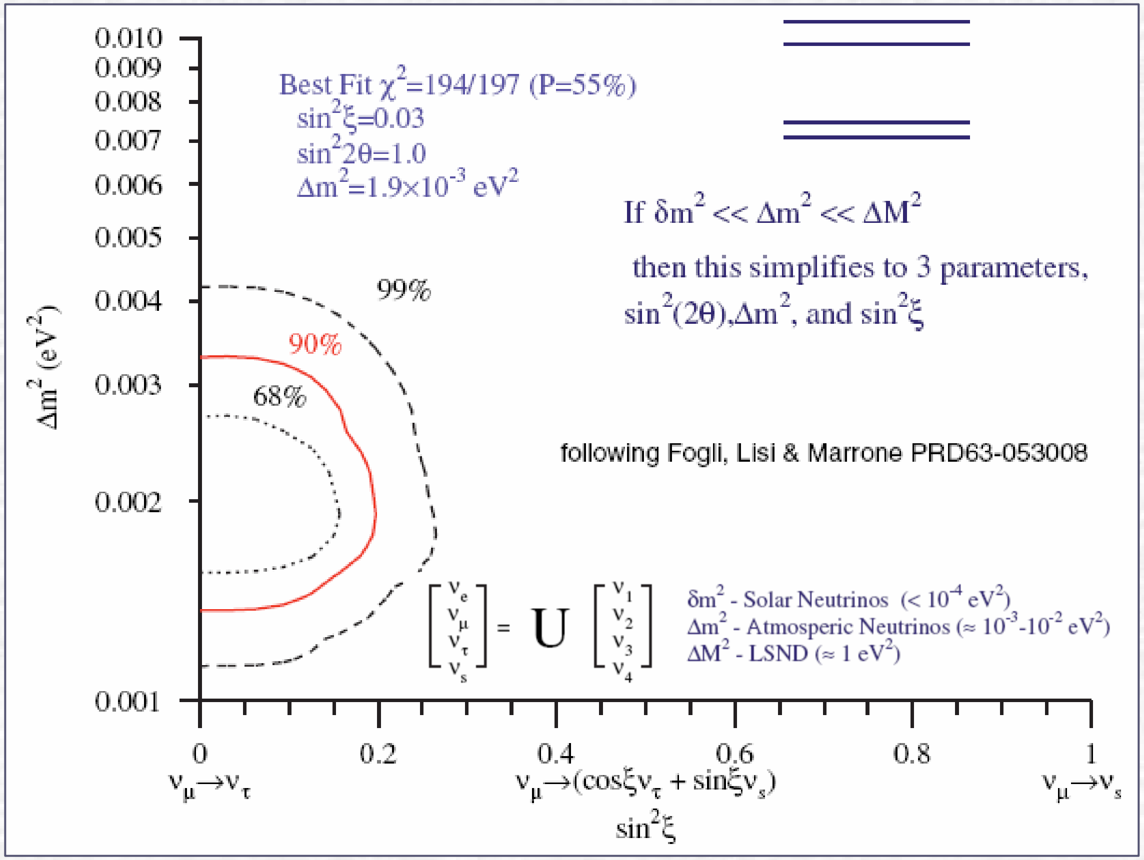
Atmospheric Neutrino Sub-Samples



- Each sub-sample looks at different ranges of neutrino energy, so they individually allow quite different regions
  - All sub-samples are consistent with the global best-fit region

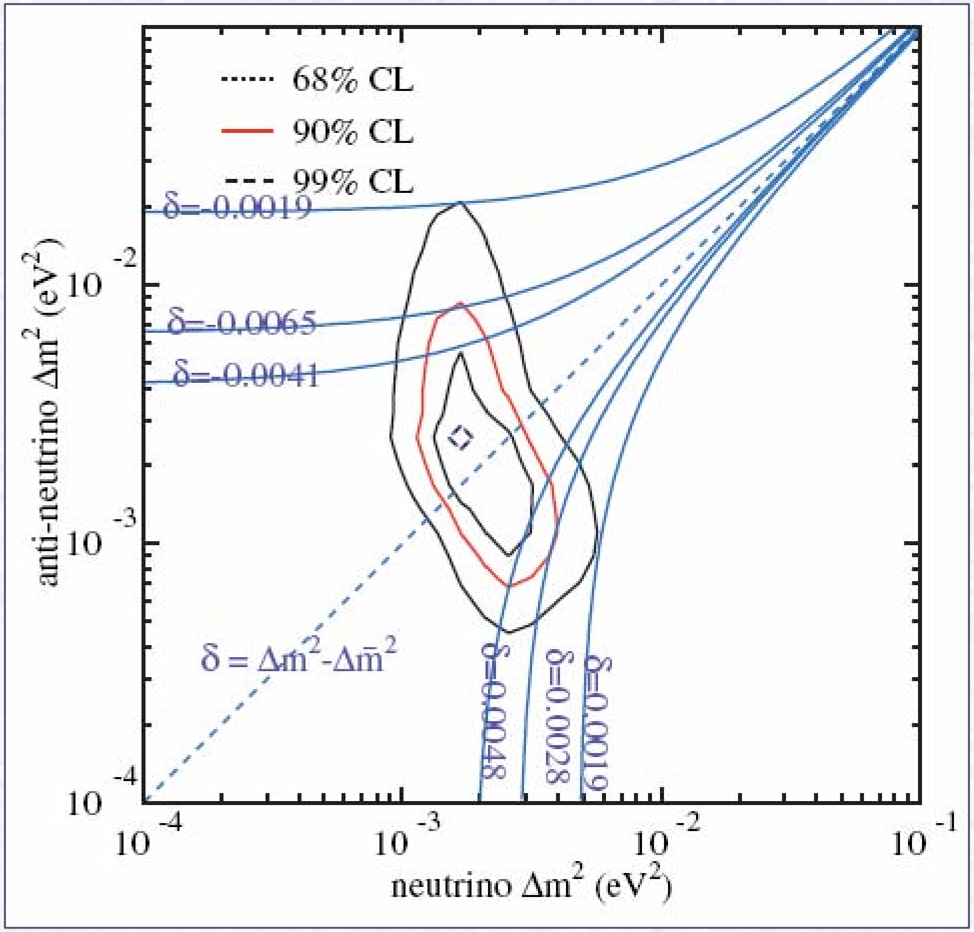
$\nu_\mu \rightarrow \nu_\tau$ and/or $\nu_\mu \rightarrow \nu_{sterile}$?

- Matter effects discriminate between oscillation into active and sterile neutrinos
  - Only a small admixture of sterile neutrino oscillation is allowed

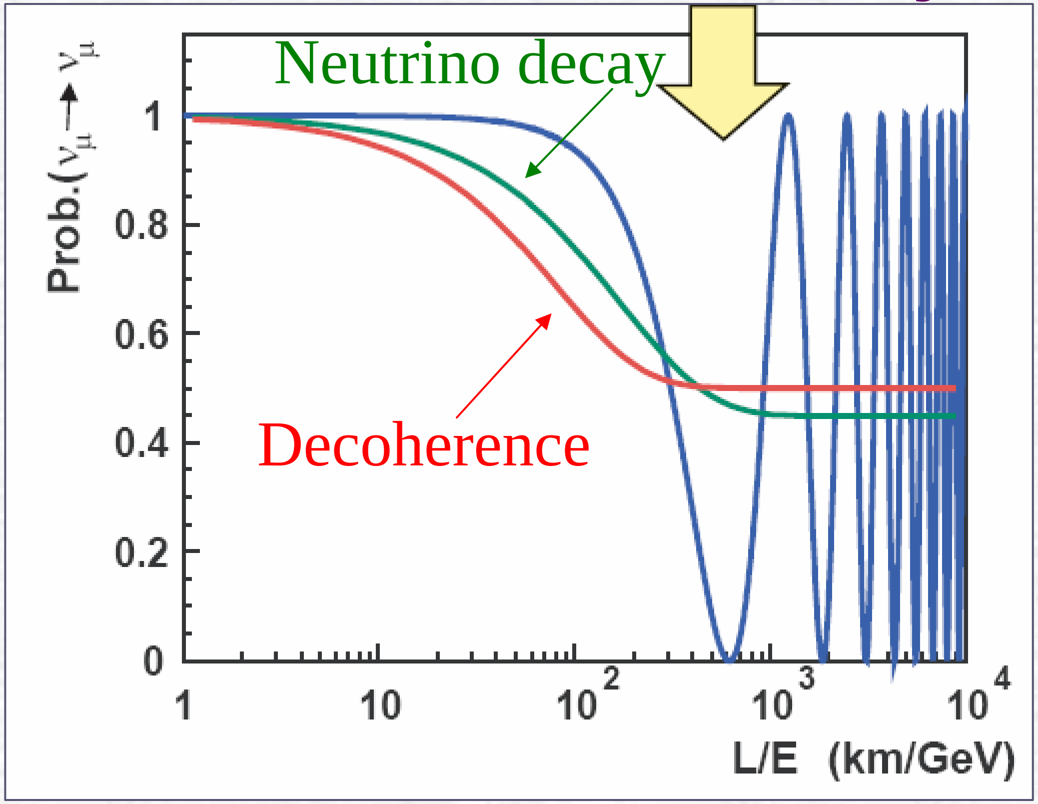


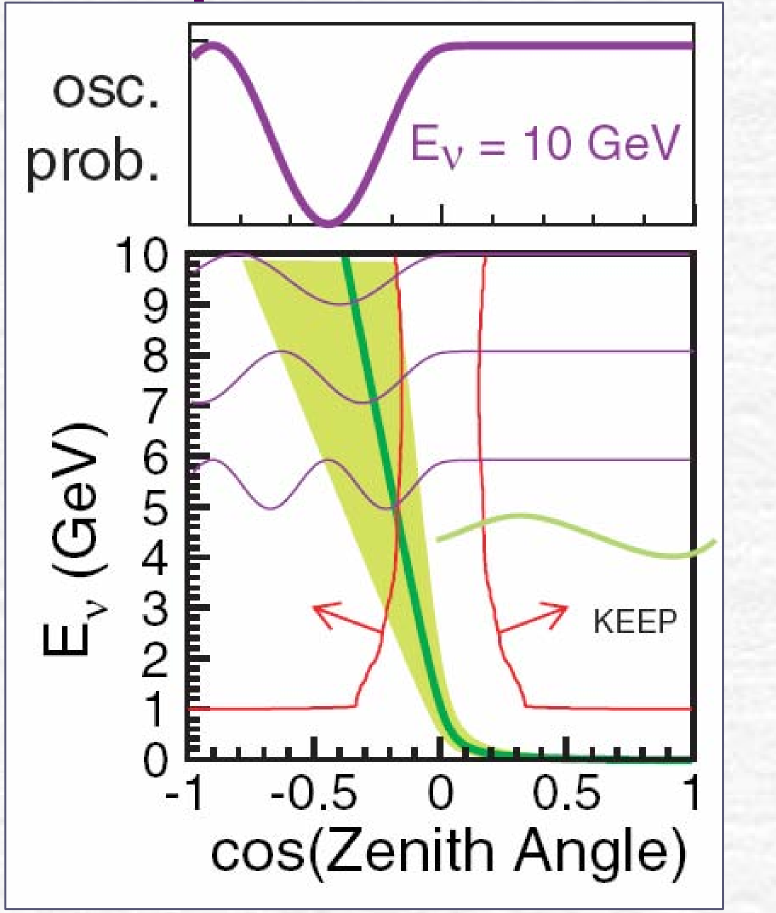
Exotic Explanations

- LSND can be reconciled with solar and atmospheric mixing if CPT symmetry is violated
  - Neutrinos and anti-neutrinos have different masses
- Our data strongly disfavors this scenario



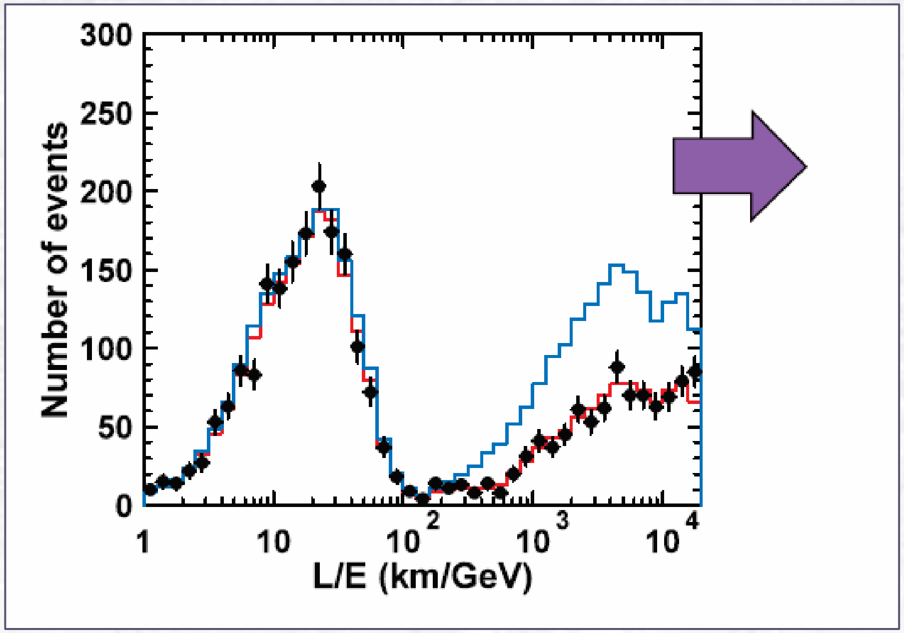
Search Oscillatory L/E dependence

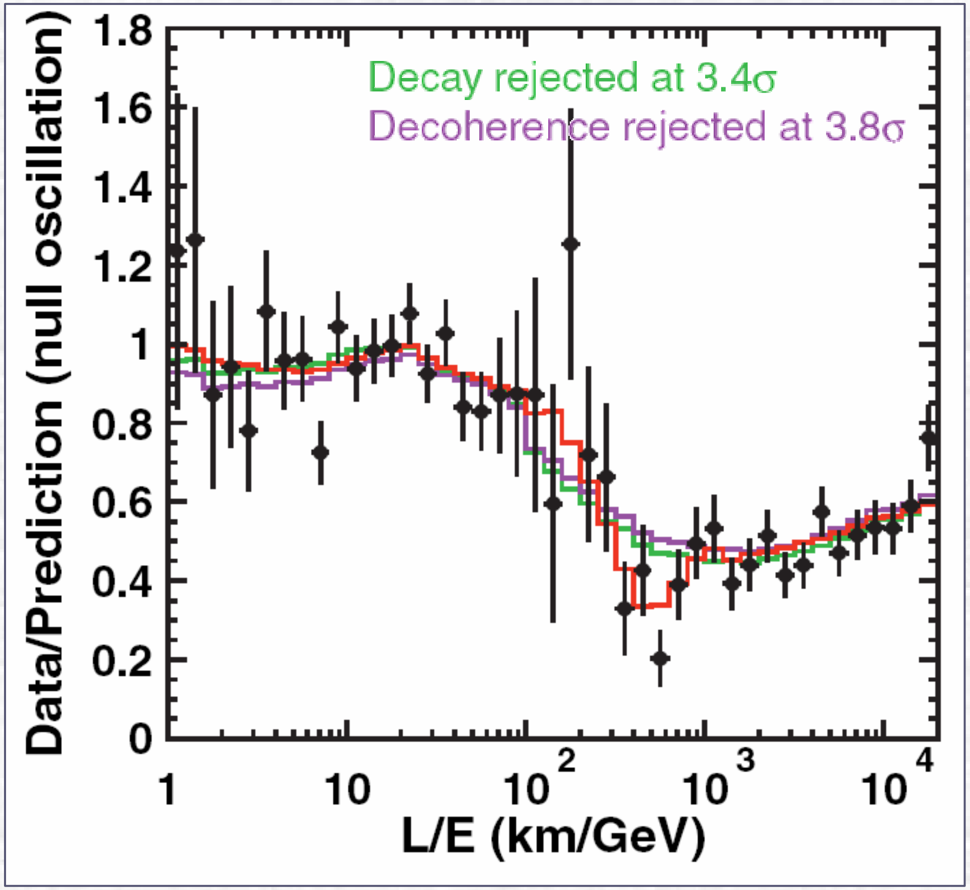




- Search for direct oscillatory dependence on L/E requires using a high-L/E resolution sub-sample

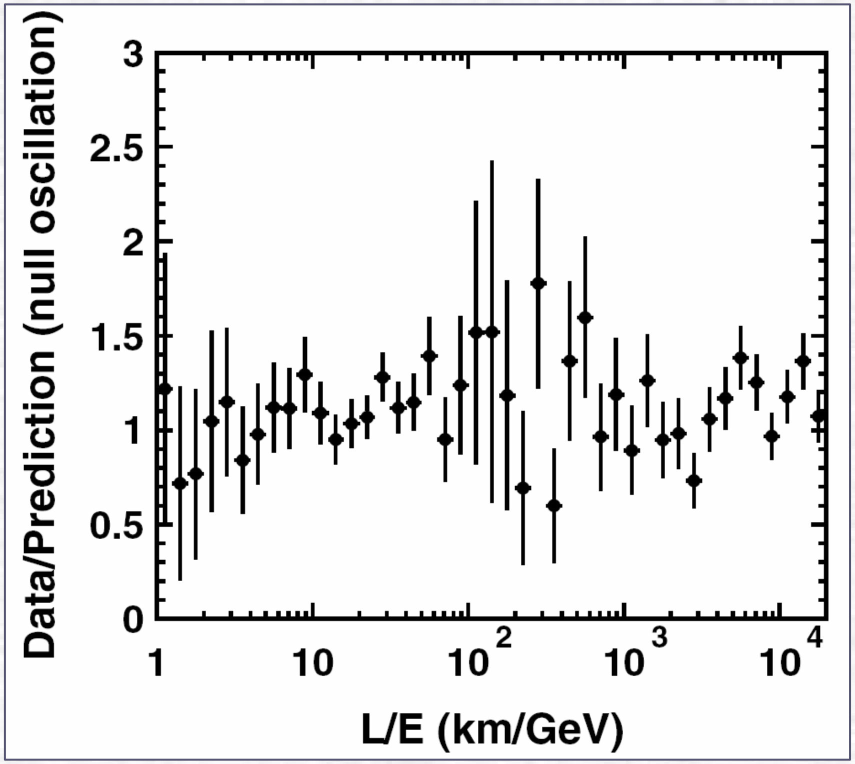
“Direct” Evidence for Oscillation



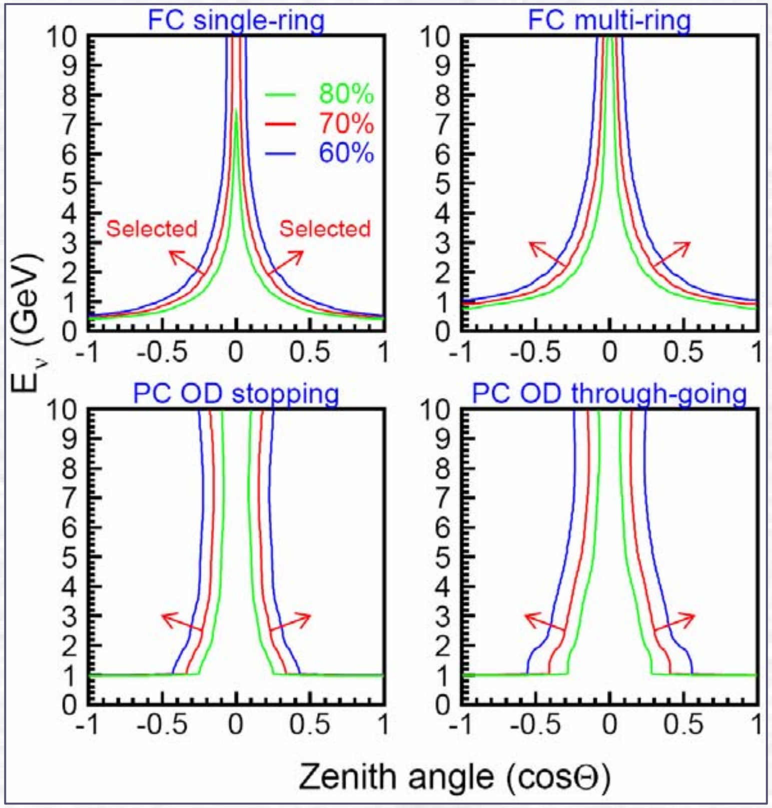


High L/E-resolution μ-like data sample

Checks on L/E Analysis



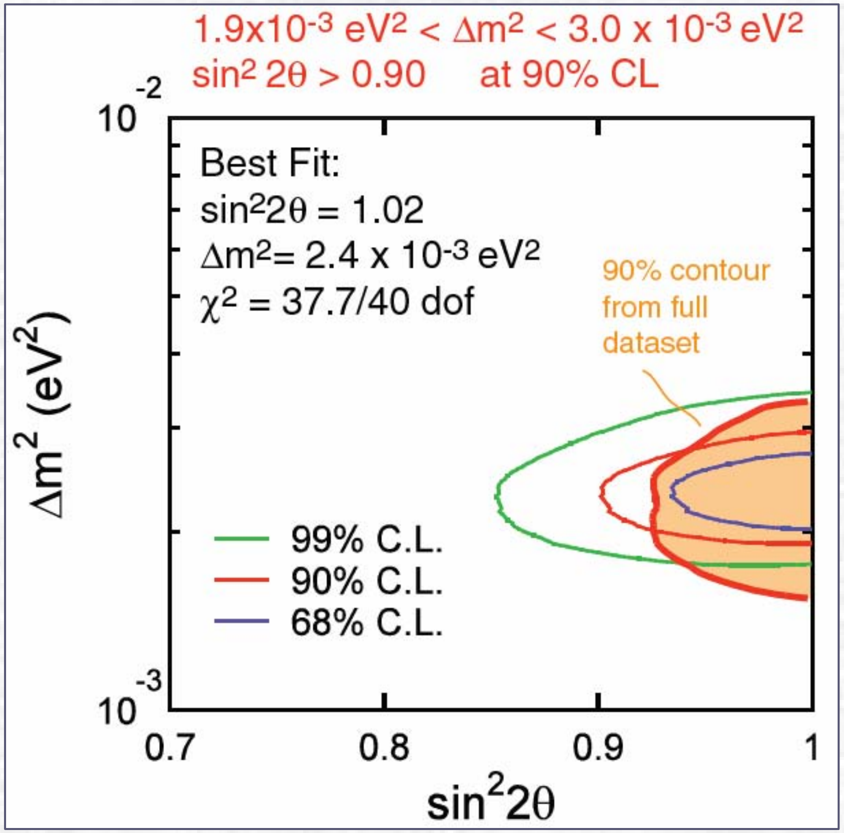
No “dip” seen in high-L/E resolution e-like data



Vary the L/E resolution cut from 60-80%

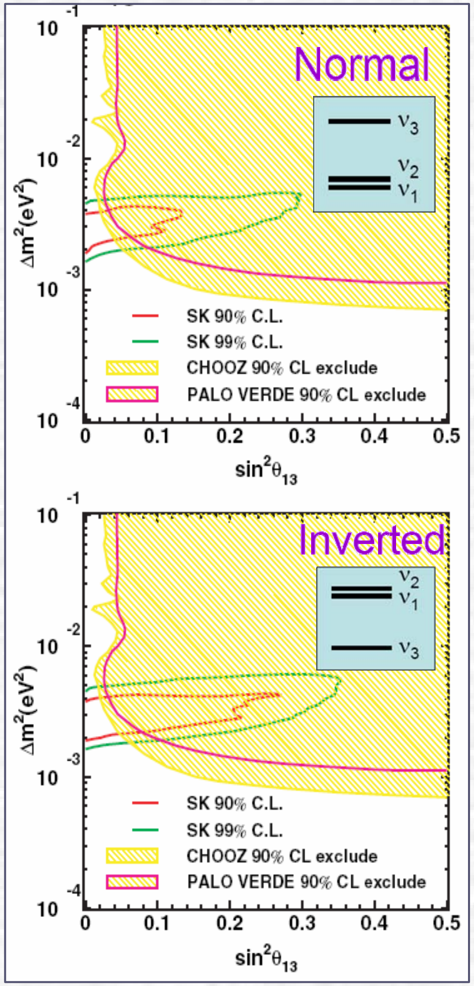
L/E Analysis Results

- A fit to the high-L/E resolution sample gives results consistent with the global (non-L/E) analysis
  - Note samples are not independent
  - Slightly better constraint on minimum value of Δm^2



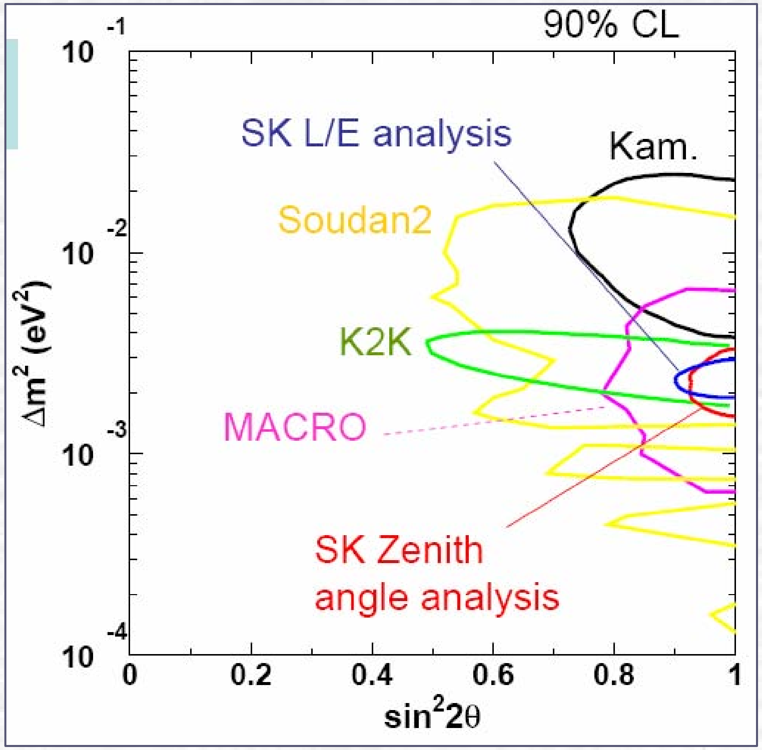
Three-Flavor Analysis

- We can also do a full three-flavor oscillation analysis, and search for ν_e appearance
  - Indicator of non-zero θ_{13}
- Our current limits do not improve on those set by the CHOOZ experiment



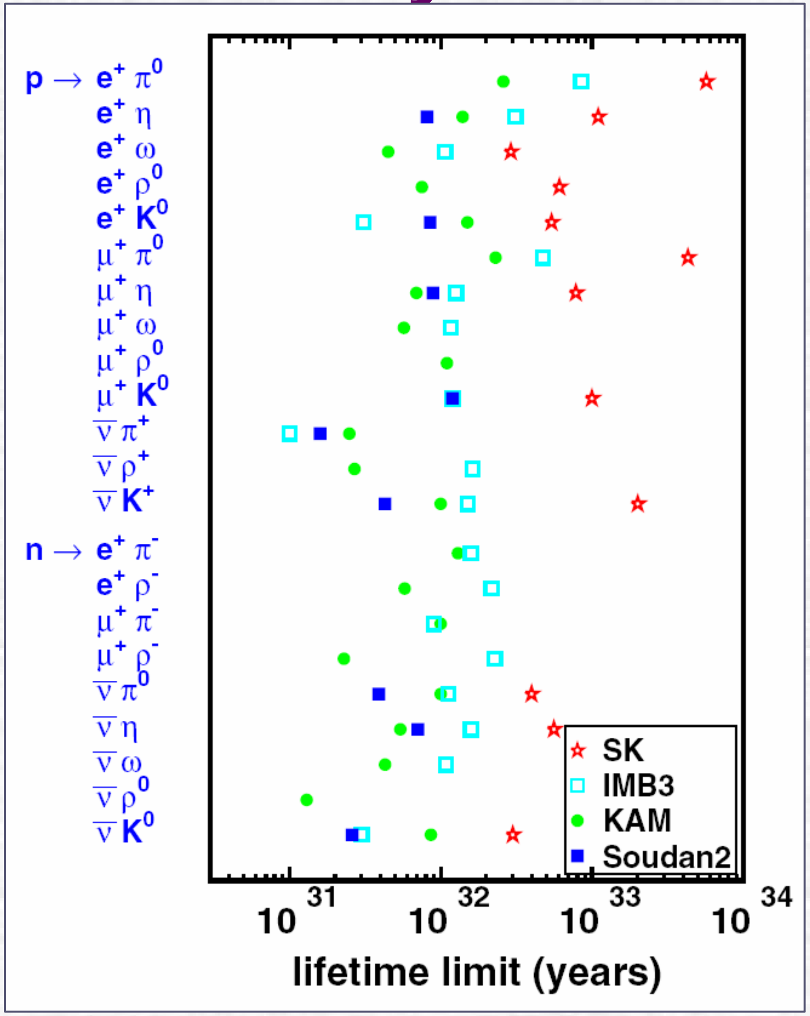
Atmospheric Neutrino Summary

- Super-K atmospheric neutrino data show strong evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillation, with near-maximal mixing and $\Delta m^2_{23} \sim (2\text{-}3)\times 10^{-3}\ \mathrm{eV}^2$

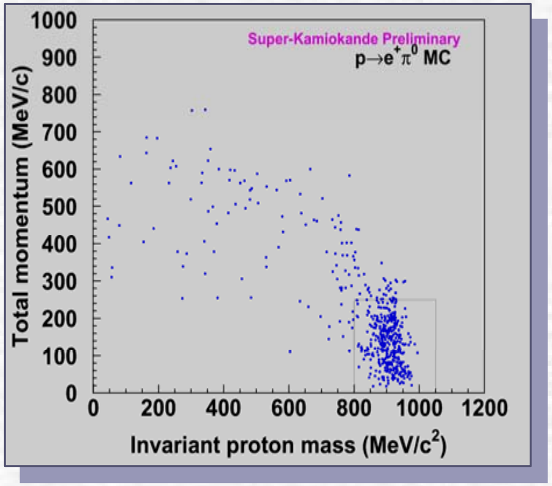


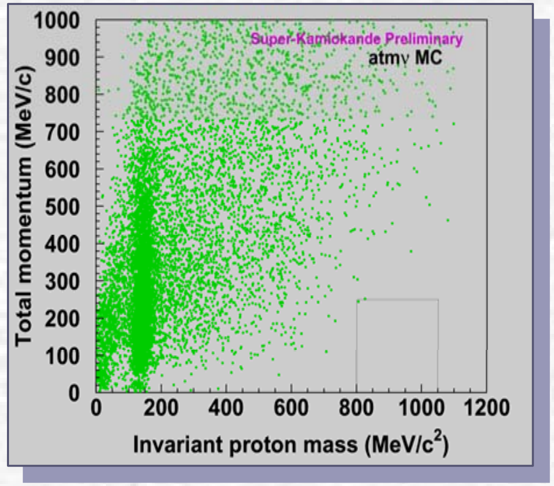
Search for Proton Decay

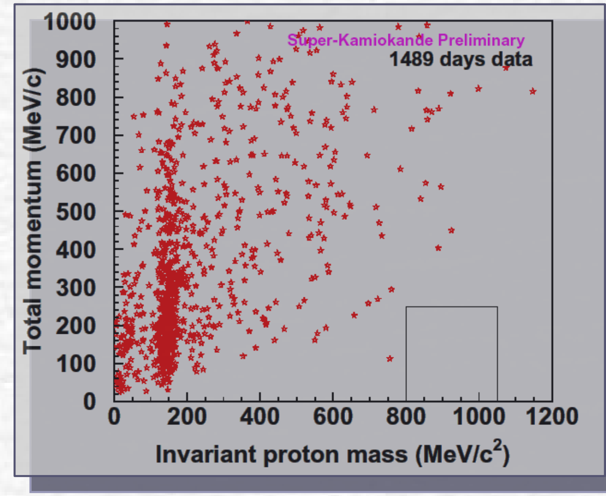
- Proton decay remains a high priority, as no known symmetry requires the proton to be stable
  - No evidence of a nucleon decay signal has appeared
  - SuperK has set limits on a wide range of possible decay modes



SuperK I: $p \rightarrow e^+\pi^0$ Results



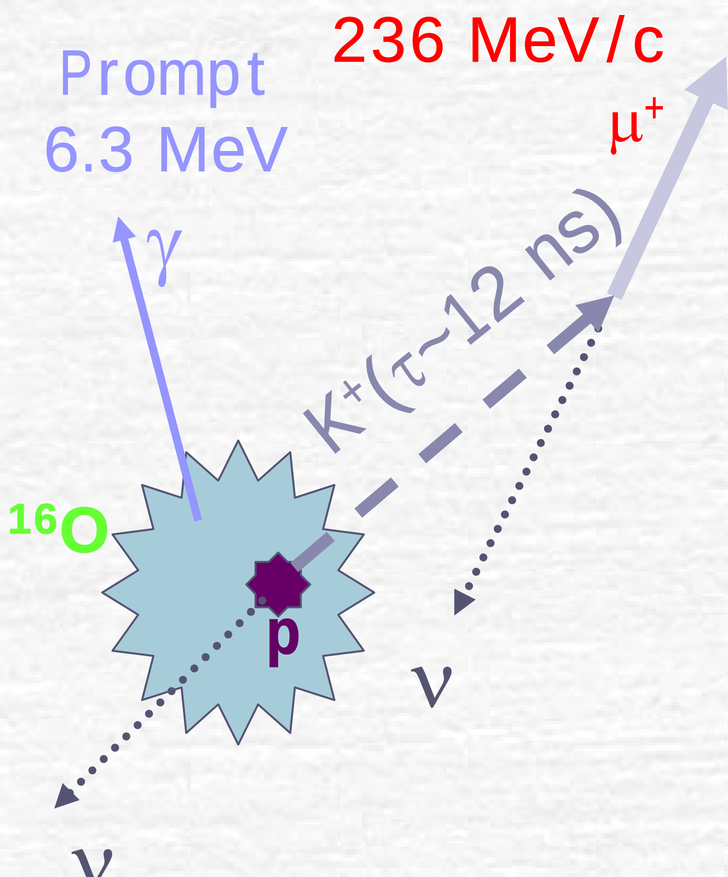


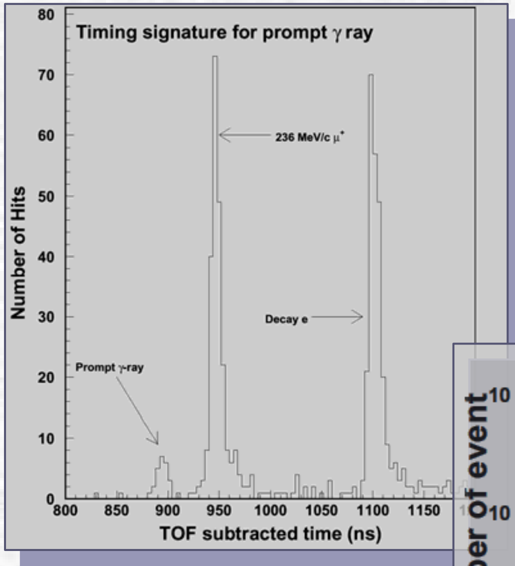


- Require 2-3 showering rings, 0 $\mu \rightarrow e$
- π^0 mass cut if 3 rings
- Overall Detection Efficiency: 43%
- No candidates
- $\tau/\beta > 5.7 \times 10^{33}$ yrs (90% CL)

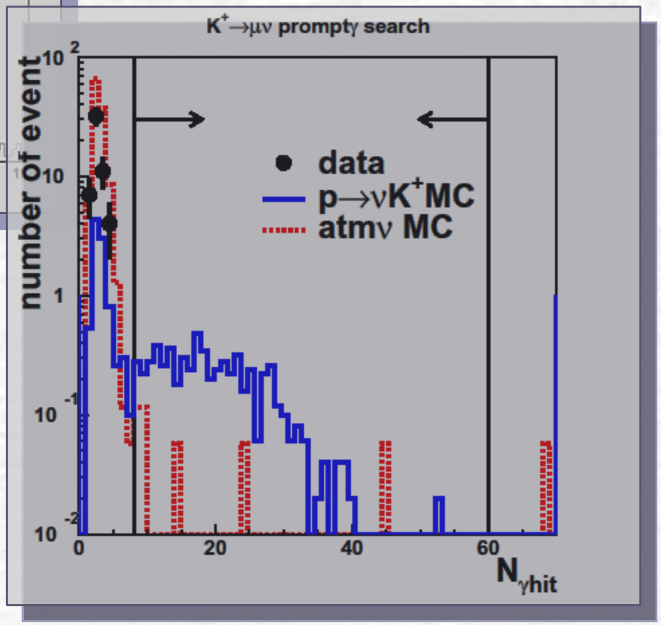
SuperK I:
1489 days = 0.091 Mty

SuperK I: $^{16}O \rightarrow {}^{15}N^* + \nu K^+ (K^+ \rightarrow \mu^+ \nu)$





No candidates



SuperK I: $p \to \nu K^+$ Summary

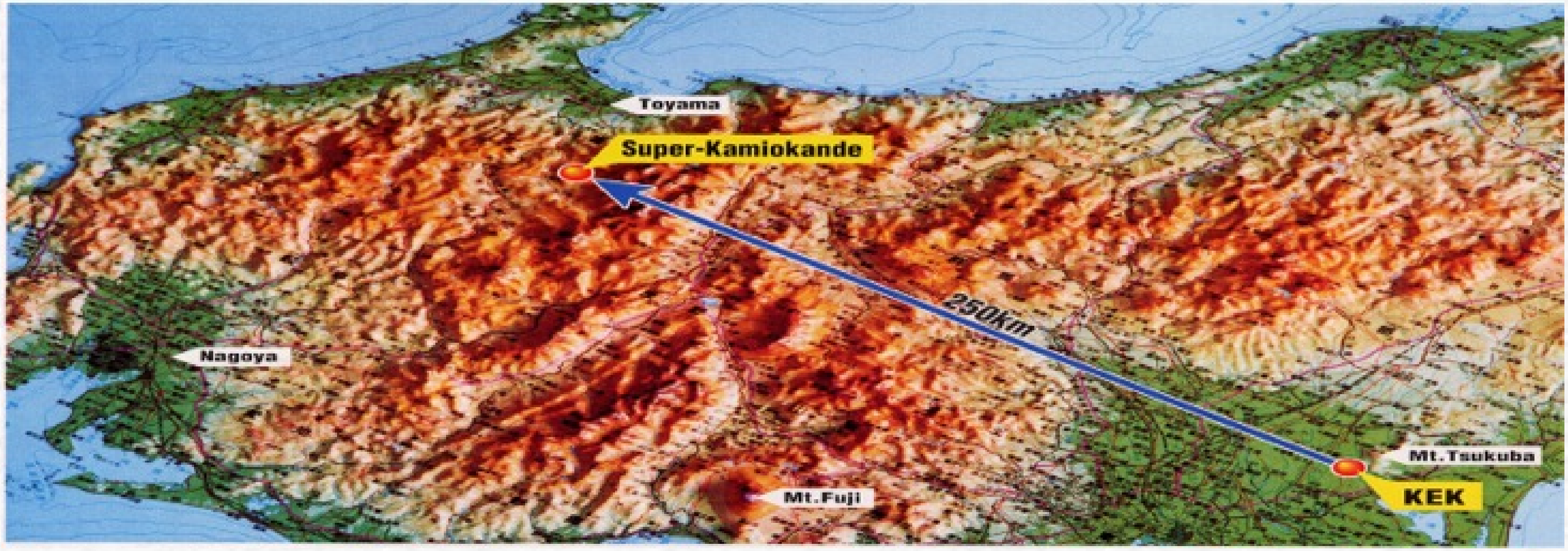
mode	efficiency	background	data	limit (10^{32} yr)
prompt γ	8.8→8.7%	0.5 → 0.3	0	11.5
spectrum fit	33%	---	---	5.5
$\pi^+ \pi^0$	6.8→ 6.5%	1.7→ 0.9	1 → 0	5.9 → 8.6

Combined Limit: 1.6 →2.0×10^{33} years

Particle Astrophysics

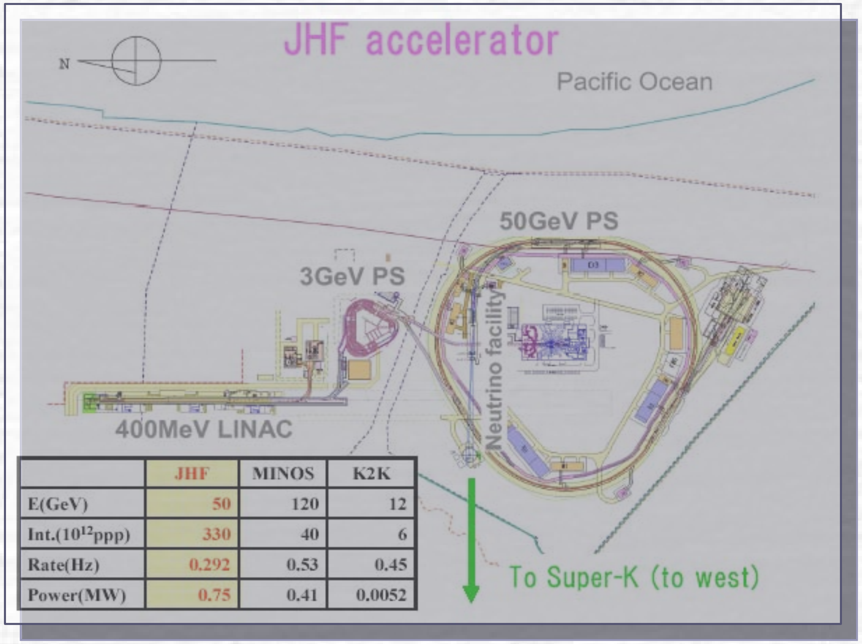
- Diverse studies of particle astrophysics, including:
  - Supernova watch
  - Search for relic supernova neutrinos
  - Search for neutrinos from gamma-ray bursts
  - Searches for point-sources of neutrinos
  - Searches for neutrinos from dark-matter (WIMP) annihilation in the Sun and Earth

The K2K Long-Baseline Experiment



The Future: T2K Long-baseline

- Use 0.75 MW, 50-GeV proton synchrotron for 295km neutrino beam to Super-K
- Factor 20 improvement in θ_{13} sensitivity over CHOOZ
- Measure $\sin^2 2\theta_{23}$ to 1%
- Measure Δm_{23}^2 to few %
- CPV search in phase 2



	JHF	MINOS	K2K
E(GeV)	50	120	12
Int.(10^{12}ppp)	330	40	6
Rate(Hz)	0.292	0.53	0.45
Power(MW)	0.75	0.41	0.0052