Neutrinos Underground

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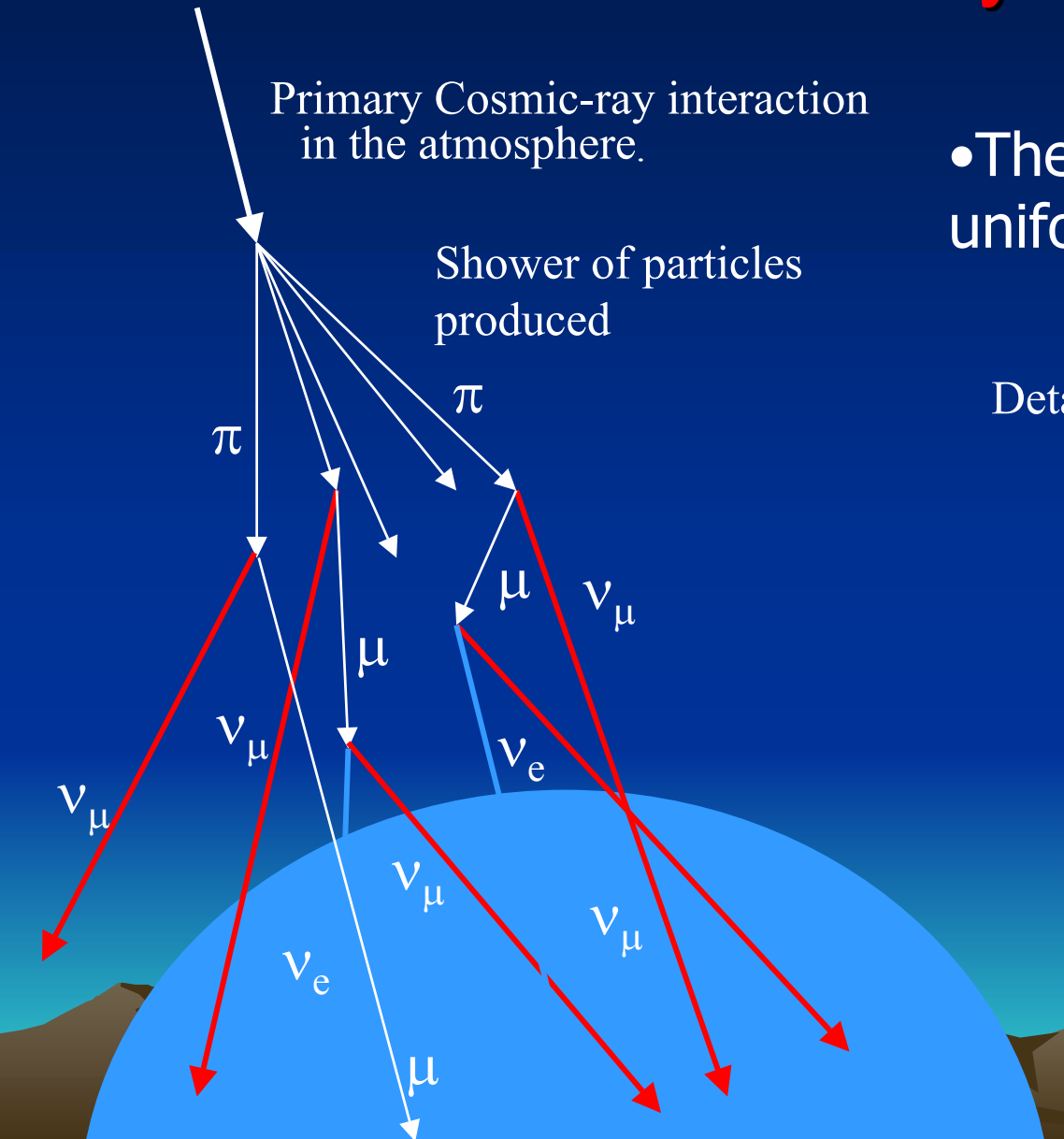
AAAS February 2004

This Talk

- Atmospheric neutrinos
- Early experiments
- First indications of the atmospheric neutrino anomaly
- The Super-Kamiokande water Cherenkov detector
- Some results
- Future plans

Cosmic-rays



- They bombard the Earth uniformly from all directions.

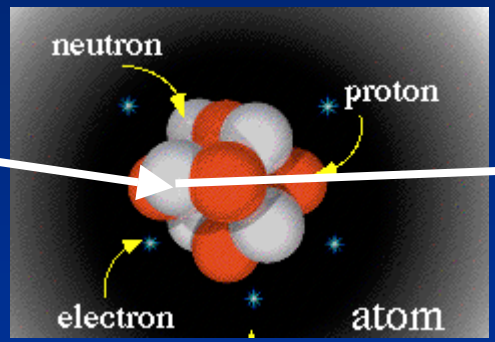
Detailed flux calculations:

Lipari
Battistoni
Gaisser, Stanev,…
Honda
Volkova
Butkevich

Indirect detection

The neutrino is observed by "seeing" the product of its interaction with matter.

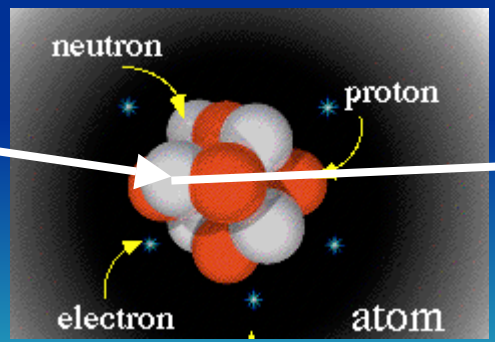
ν_e



Electron

Direction of lepton approximates neutrino direction

ν_μ



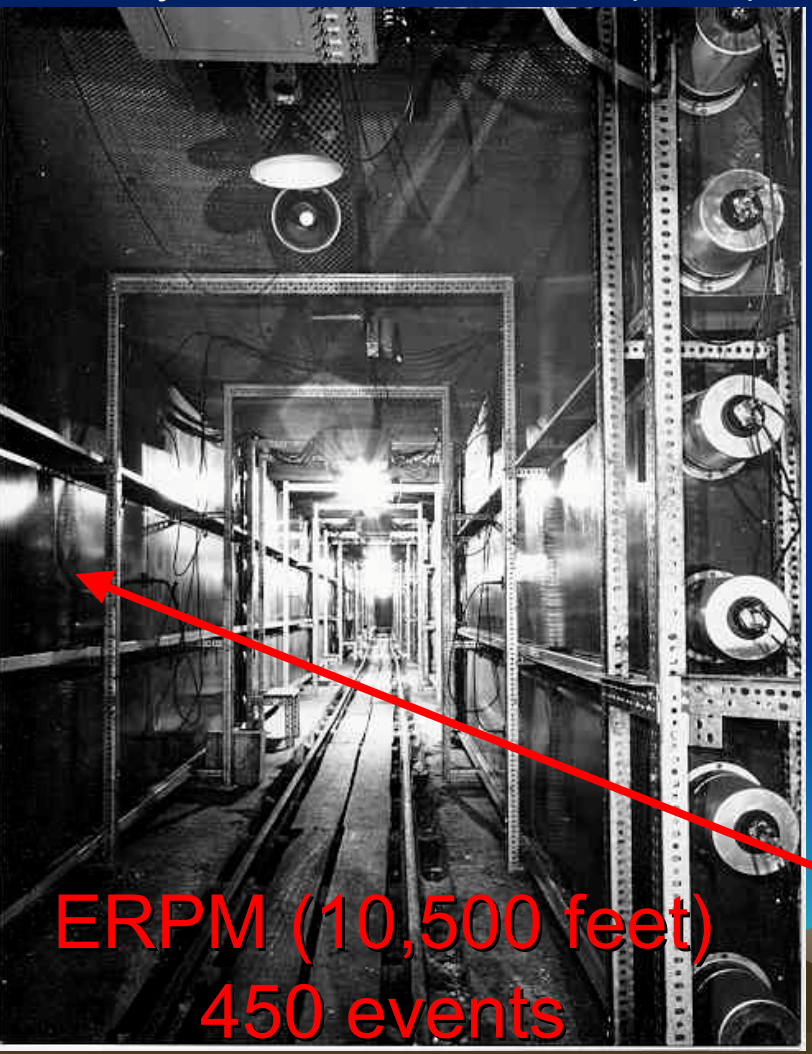
Muon

The products are charged particles.

First observations

CASE-WITS

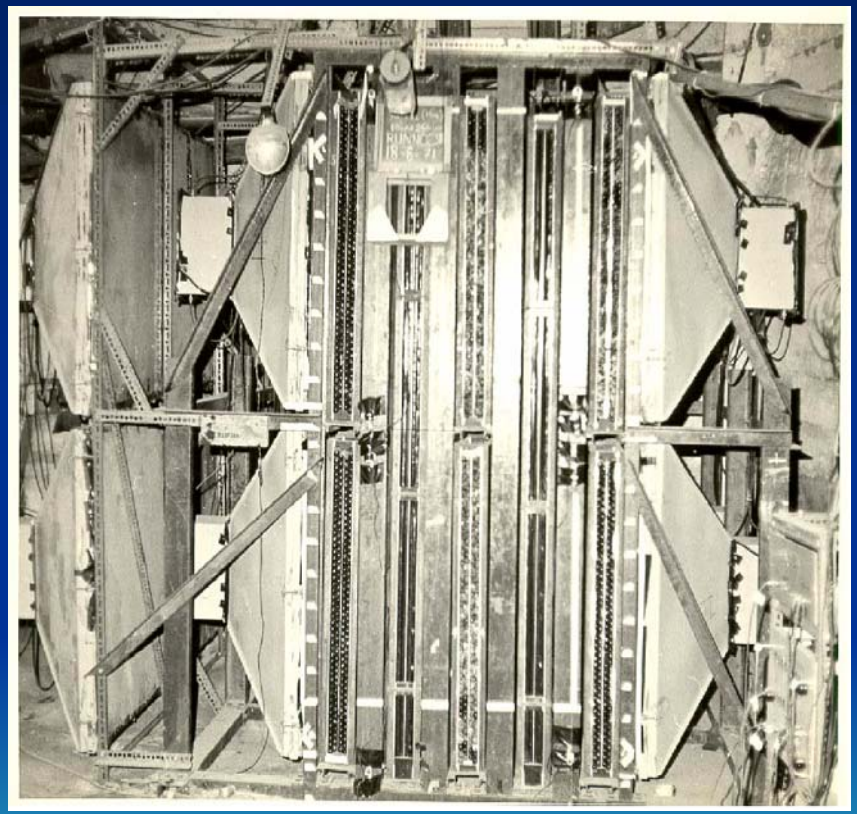
F. Reines *et al.*,
Phys. Rev. Lett. **15**, 429 (1965).



ERPM (10,500 feet)
450 events

Kolar

C.V. Achar *et al.*,
Phys. Lett. **18**, 196 and **19**, 78 (1965).

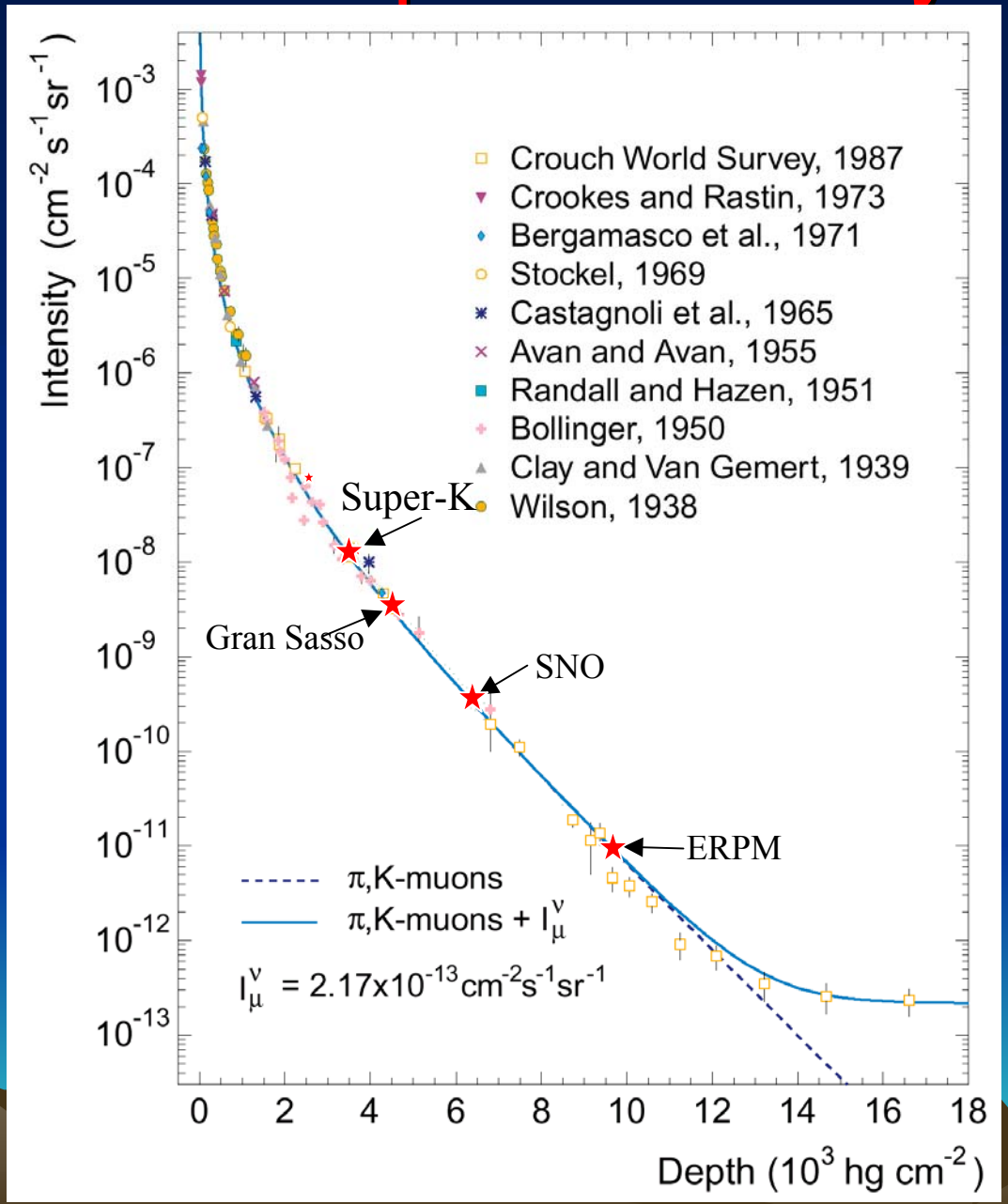


(7,500 feet)
165 events

Muon

Neutrino

Depth – Intensity



Atmospheric Neutrinos

•Interactions of atmospheric neutrinos occur in underground detectors and are dominant background for nucleon decay search.

•First significant measurements from IMB and Kamiokande nucleon decay experiments.

•Uncertainties in primary flux and hadronic interactions

Absolute numbers of ν_μ and ν_e can only be predicted to +/- 20%.

Phys. Rev. D54(1996)5578.

•Ratio of two flavors is independent of cosmic-ray flux

Can be predicted to +/- 5%.

$$R = \frac{(\nu_\mu/\nu_e)_{DATA}}{(\nu_\mu/\nu_e)_{M.C.}}$$

Estimate of ν_μ/ν_e

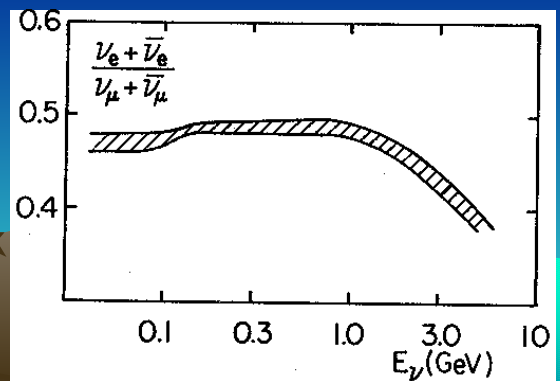
If we assume that there are no π or μ interactions, then:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- \bar{\nu}_e \nu_\mu$$

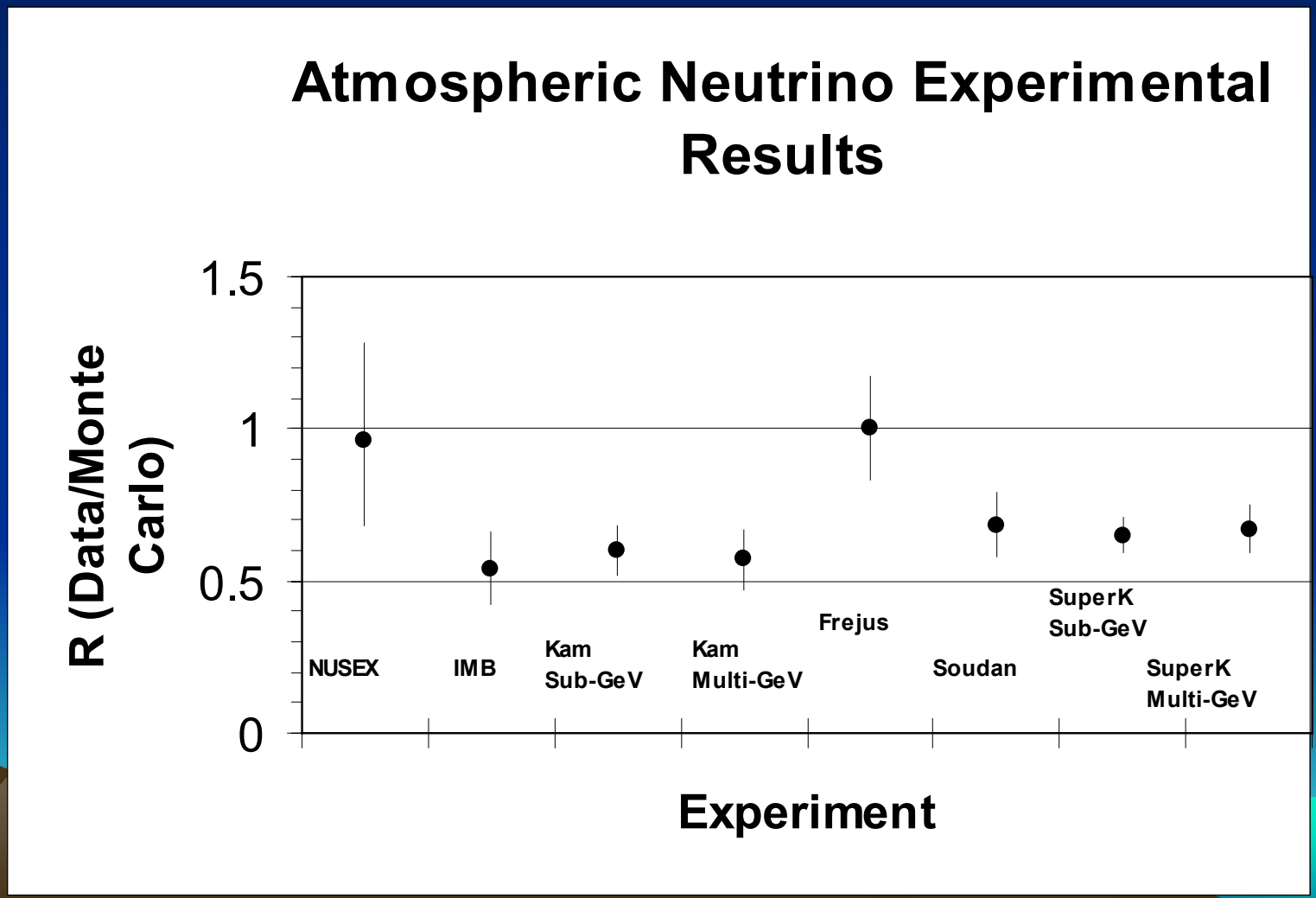
So, $$\frac{\bar{\nu}_\mu + \nu_\mu}{\bar{\nu}_e + \nu_e} = 2:1$$

ν_e / ν_μ decreases with energy above about 1 GeV.



Atmospheric neutrino measurements

$$R = \frac{(\nu_\mu/\nu_e)_{DATA}}{(\nu_\mu/\nu_e)_{M.C.}}$$



Possible Reasons for Low Value of R

- Muon deficit is really electron excess from $p \rightarrow e^+ \nu \nu$
  (Phys. Lett. B291,(1992)200.) i.e. Proton Decay background!
  Anomaly extends to beyond 1 GeV
- High energy neutron background ($\rightarrow \pi^0 \rightarrow$e-like events)
  (JETP Lett. 60,(1994)617) No evidence for this (<0.4% of total e-like events).
- Particle I.D. problems KEK beam test --- particle I.D. OK
- Detector inefficiencies favor electron detection over muon detection
  SuperK results show no problem with inefficiency.
- Something peculiar about neutrino cross section on Oxygen
  Phys. Rev. D48,(1993)3048 "...neglected physics cannot account for anomalous ratio..." "...ratio is a robust measure of the anomaly."

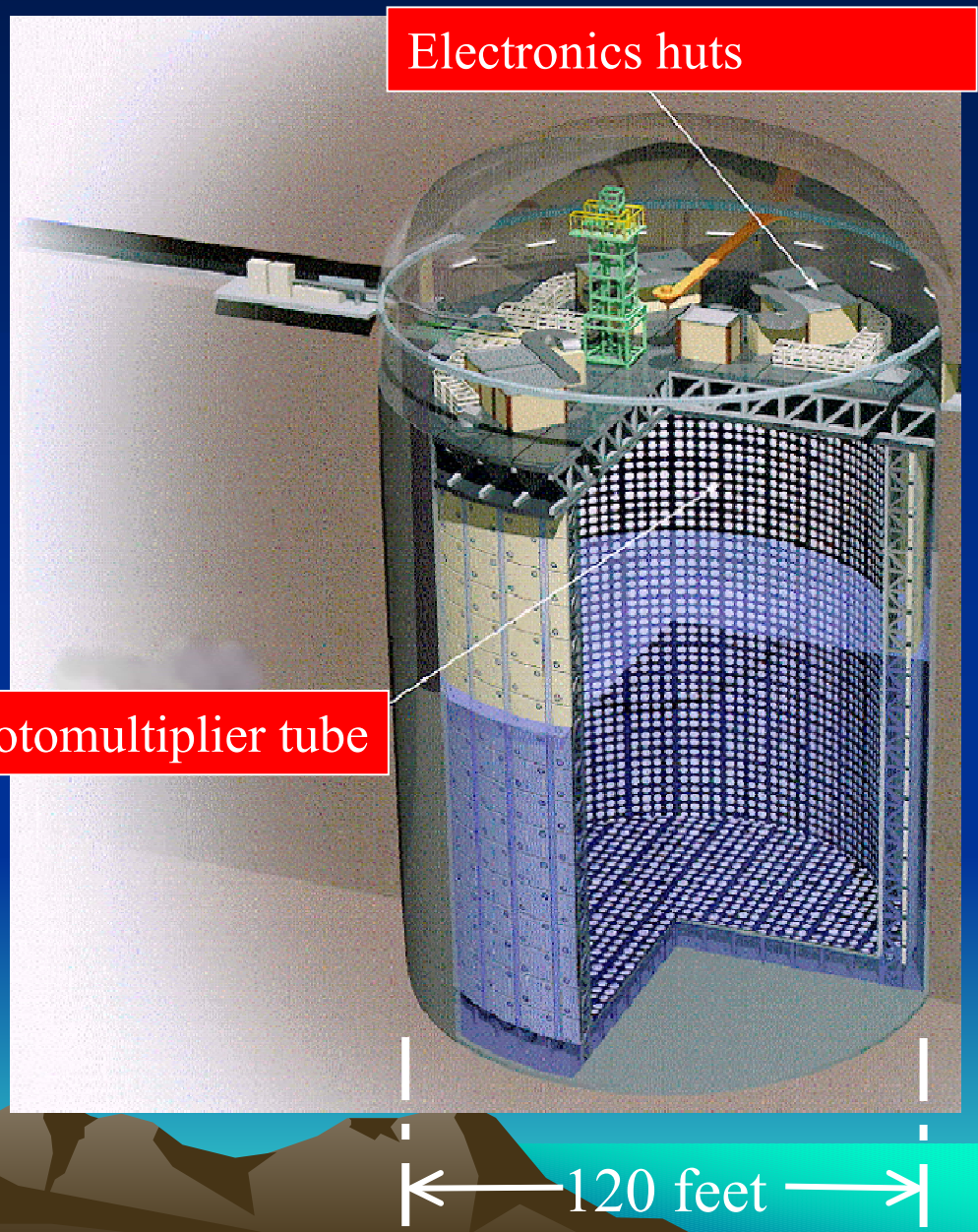
All flux calculations for ν_μ / ν_e are wrong.
Phys. Rev. D54,(1996)5578
"...we identify the major source of the difference among the calculations. We find nothing that would affect the predicted ratio of ν_μ / ν_e , which is nearly the same in all calculations."

- Neutrino Oscillations ---

BUT HOW TO PROVE THIS?

Schematic of Super-Kamiokande

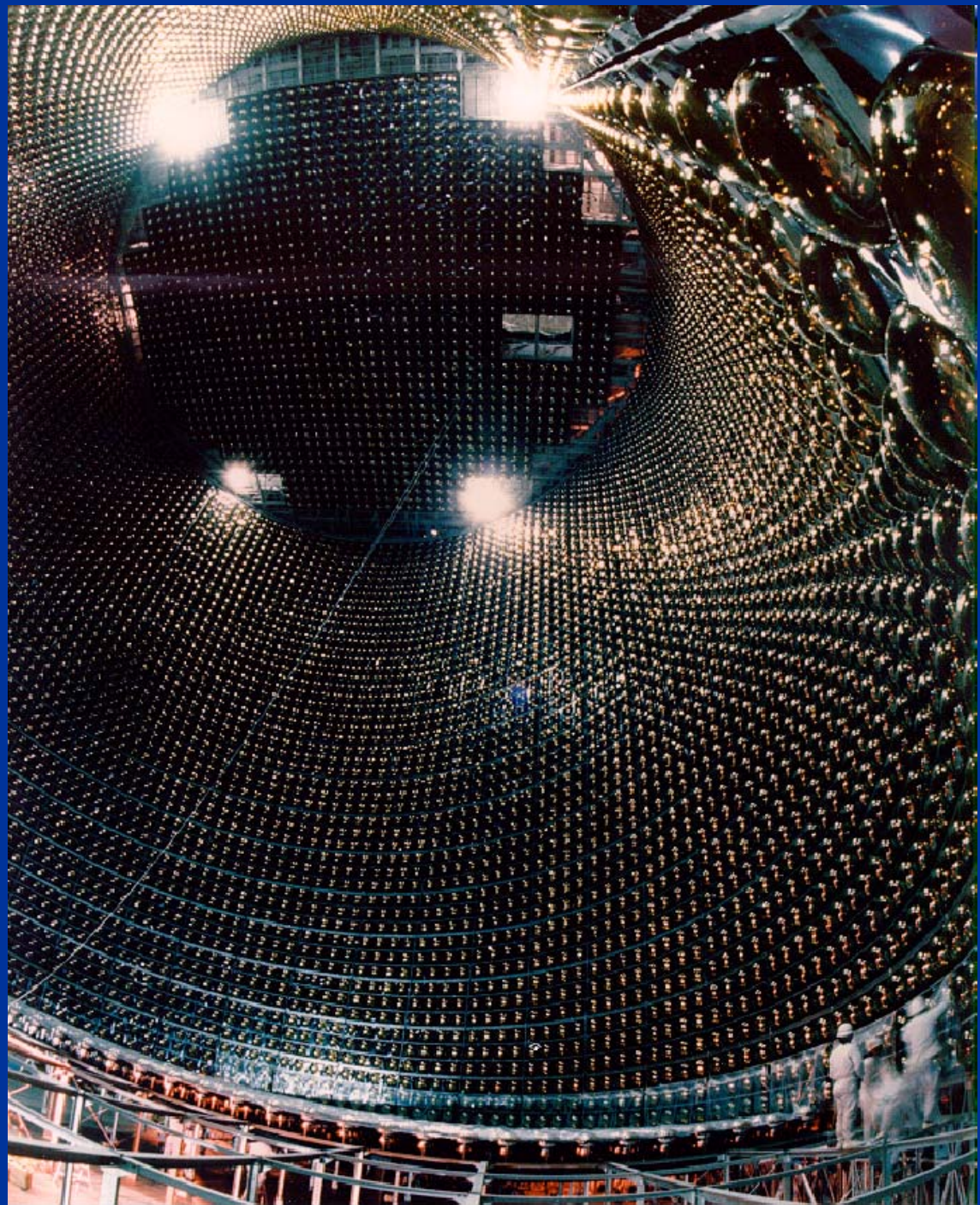
- 3000 feet underground – Japanese Alps
- 50,000 cubic meters of purified water
- 11, 200 – 20” diameter photomultiplier tubes
- 1,800 – 8” diameter photomultiplier tubes



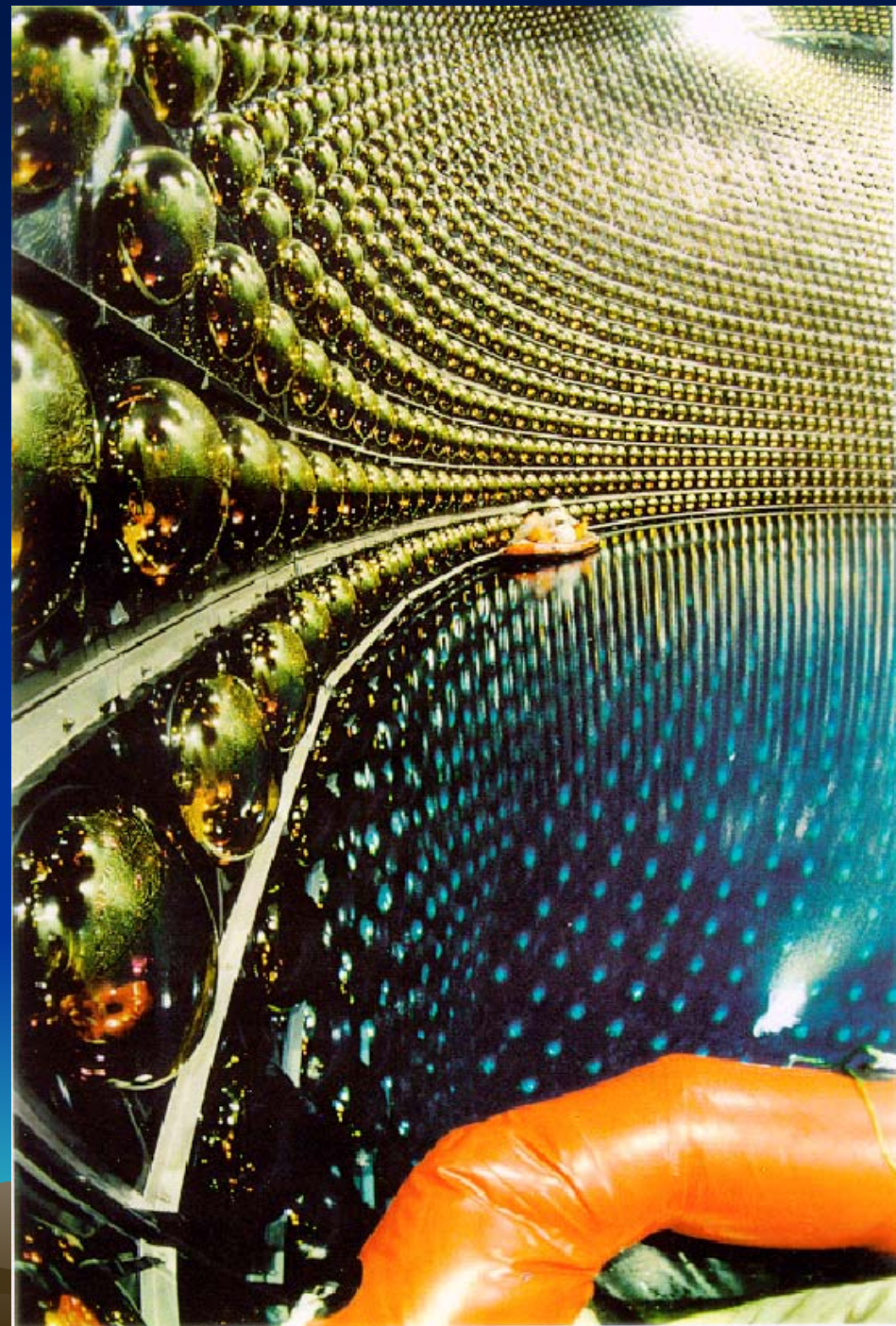
SK-I: Apr 1996 – Jul 2001

↓

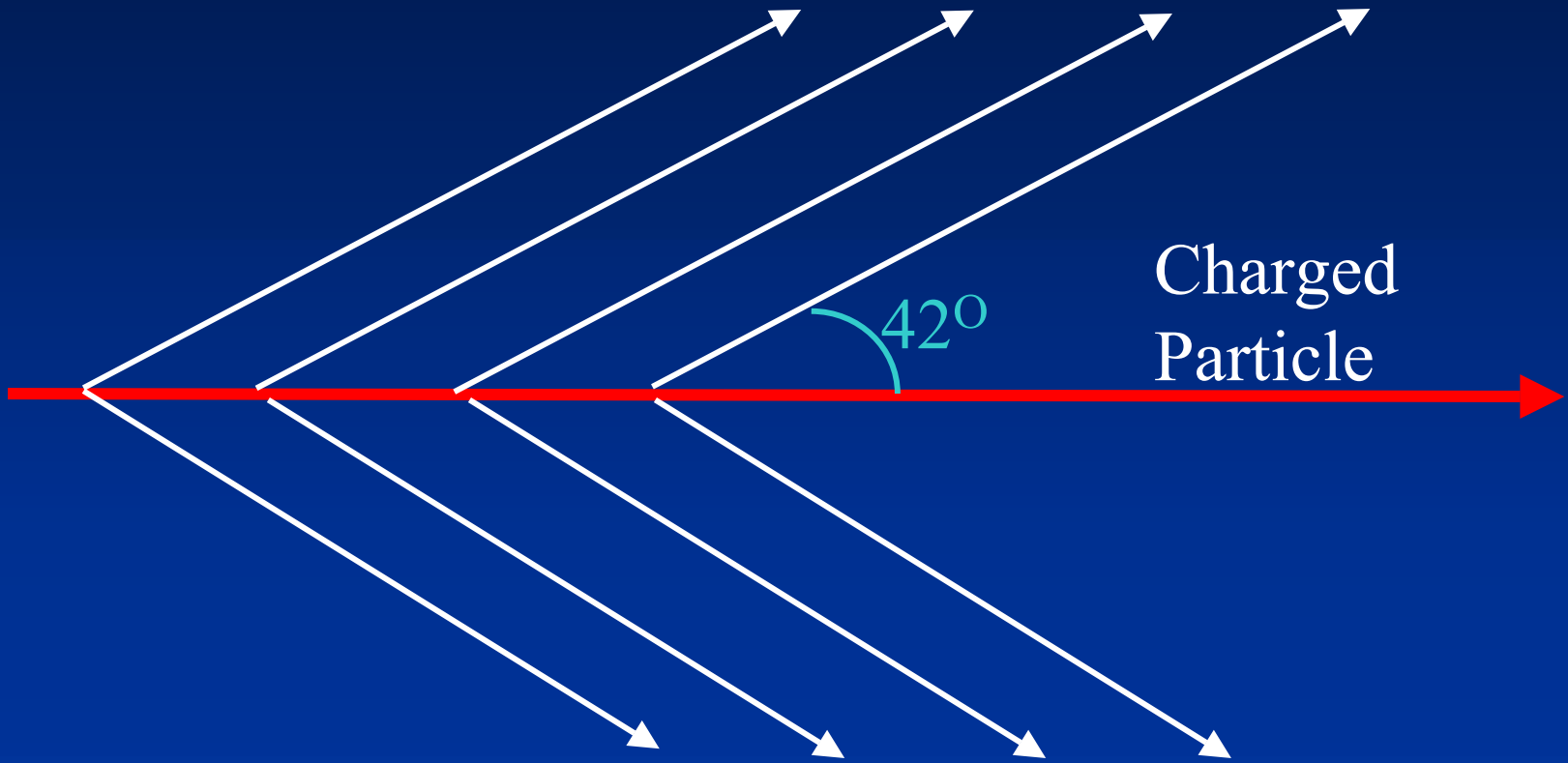
SK – II now running



Filling the Detector



Cherenkov Radiation

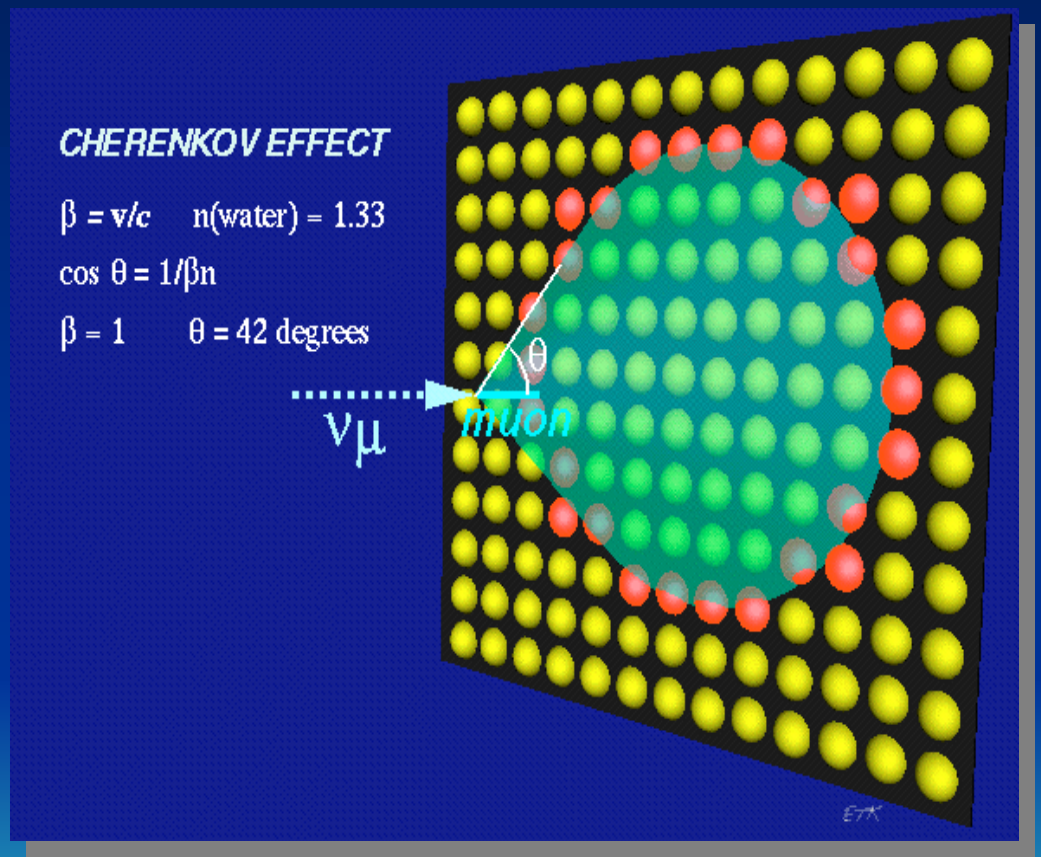


Fixed angle of light to track

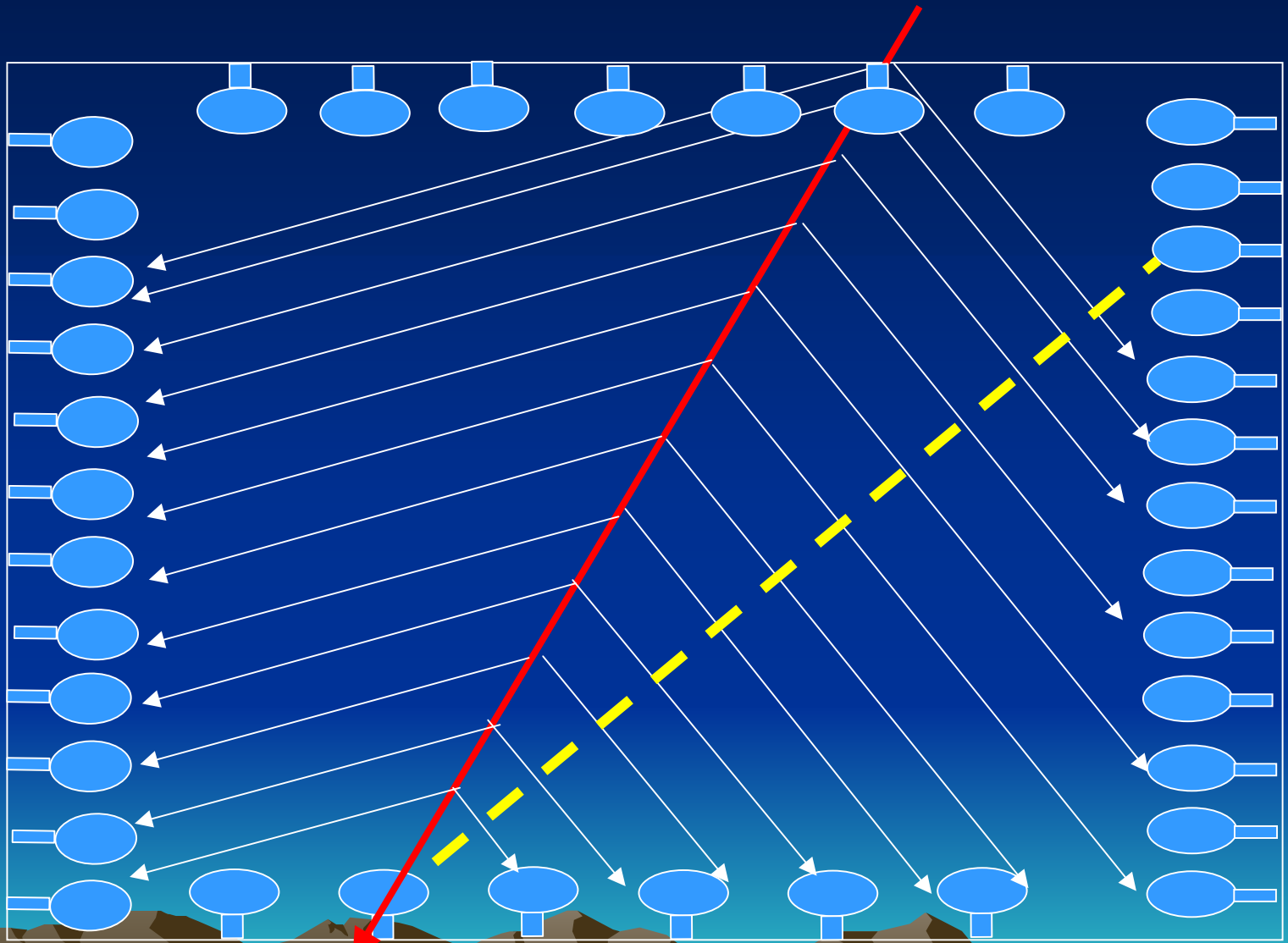
About 42 degrees for particle in water

Water Cherenkov

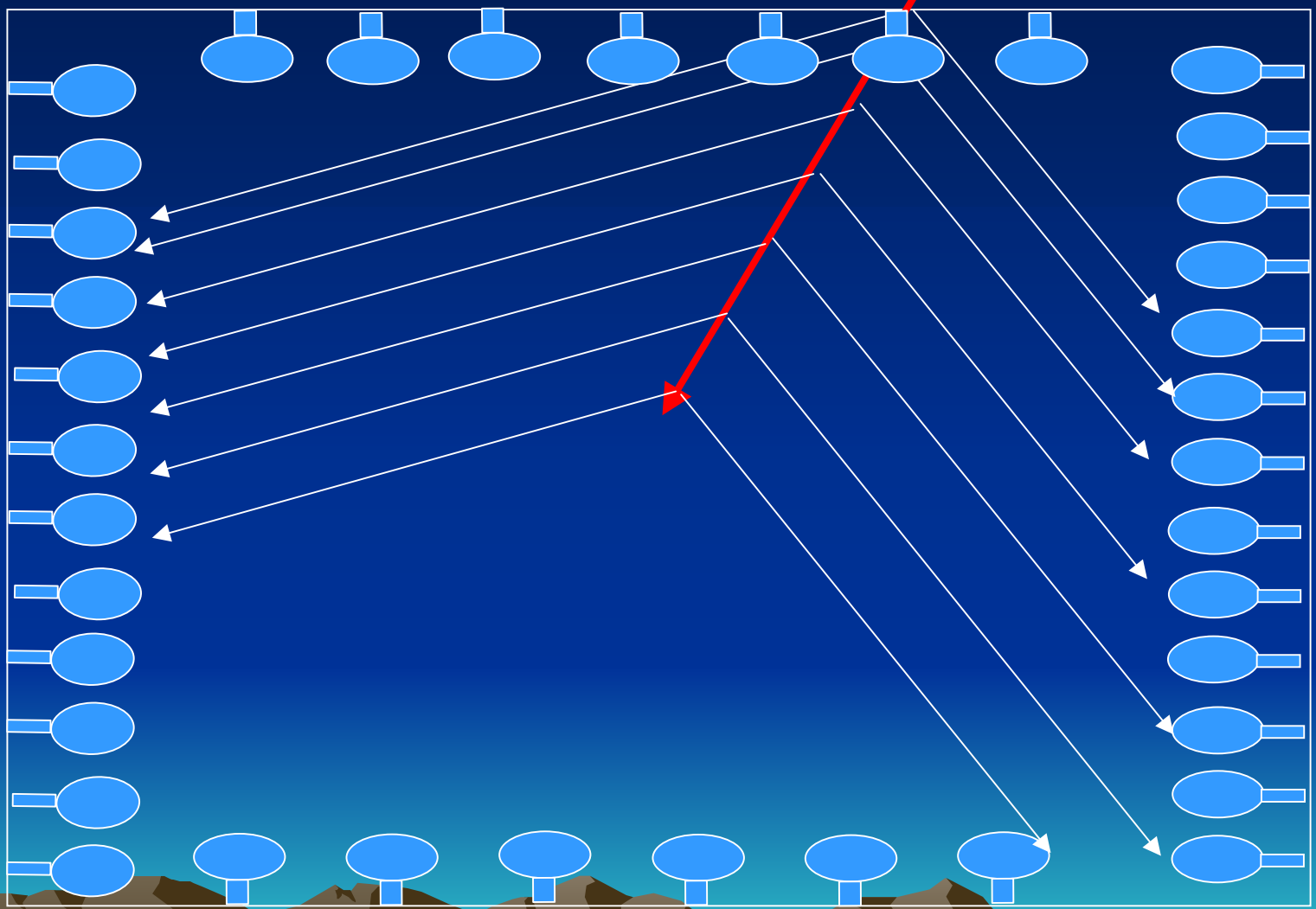
- Cheap target material
- Surface instrumentation
- Vertex from timing
- Direction from ring edge
- Energy from pulse height, range and opening angle
- Particle ID from hit pattern and muon decay



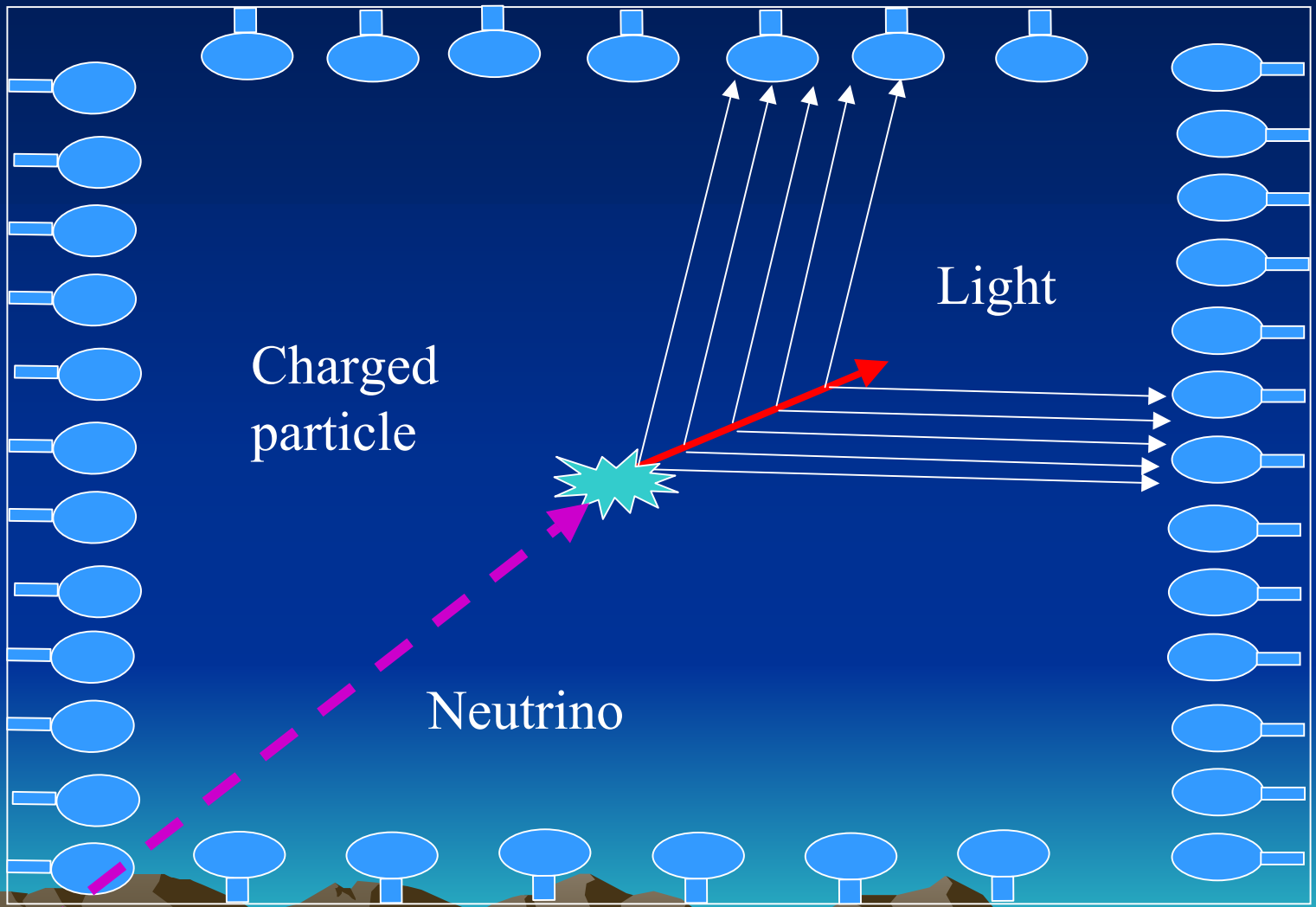
Long Track

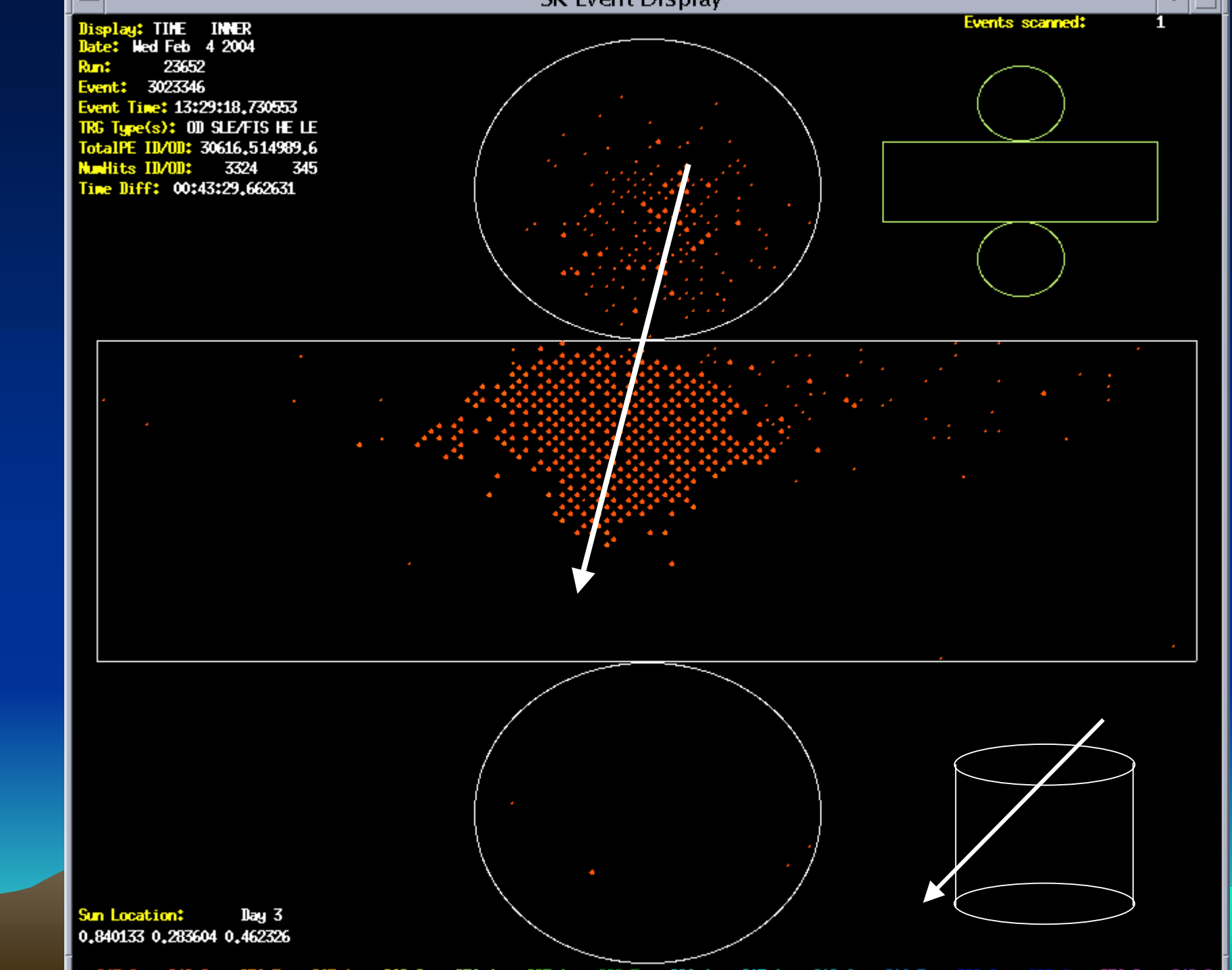


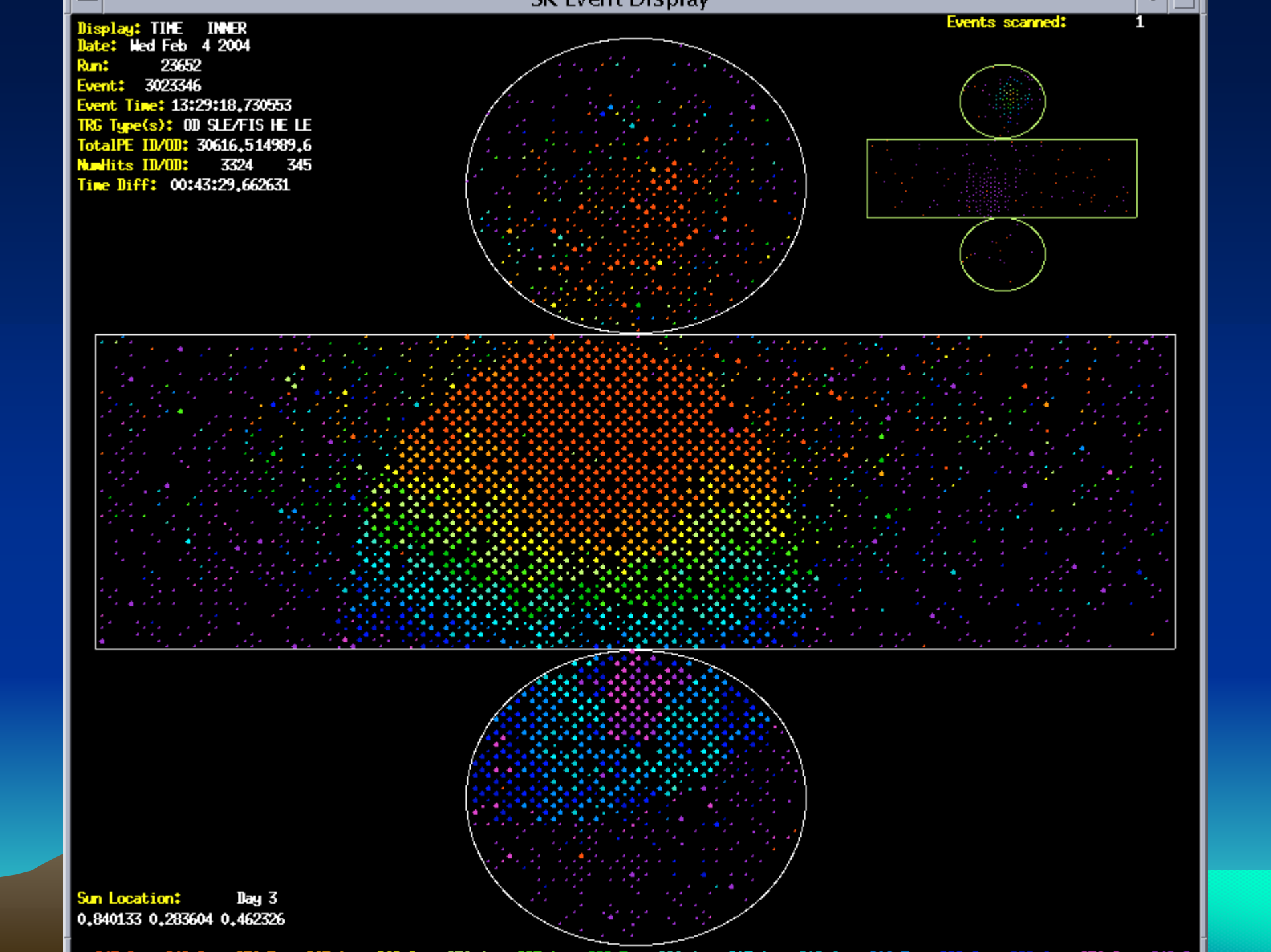
Stopping Track



Neutrino




SK Event Display
Display: TIME INNER
Date: Wed Feb 4 2004
Run: 23652
Event: 3023346
Event Time: 13:29:18.730553
TRG Type(s): OD SLE/FIS HE LE
TotalPE ID/OD: 30616.514989.6
NumHits ID/OD: 3324 345
Time Diff: 00:43:29.662631
Events scanned: 1
Sun Location: Day 3
0.840133 0.283604 0.462326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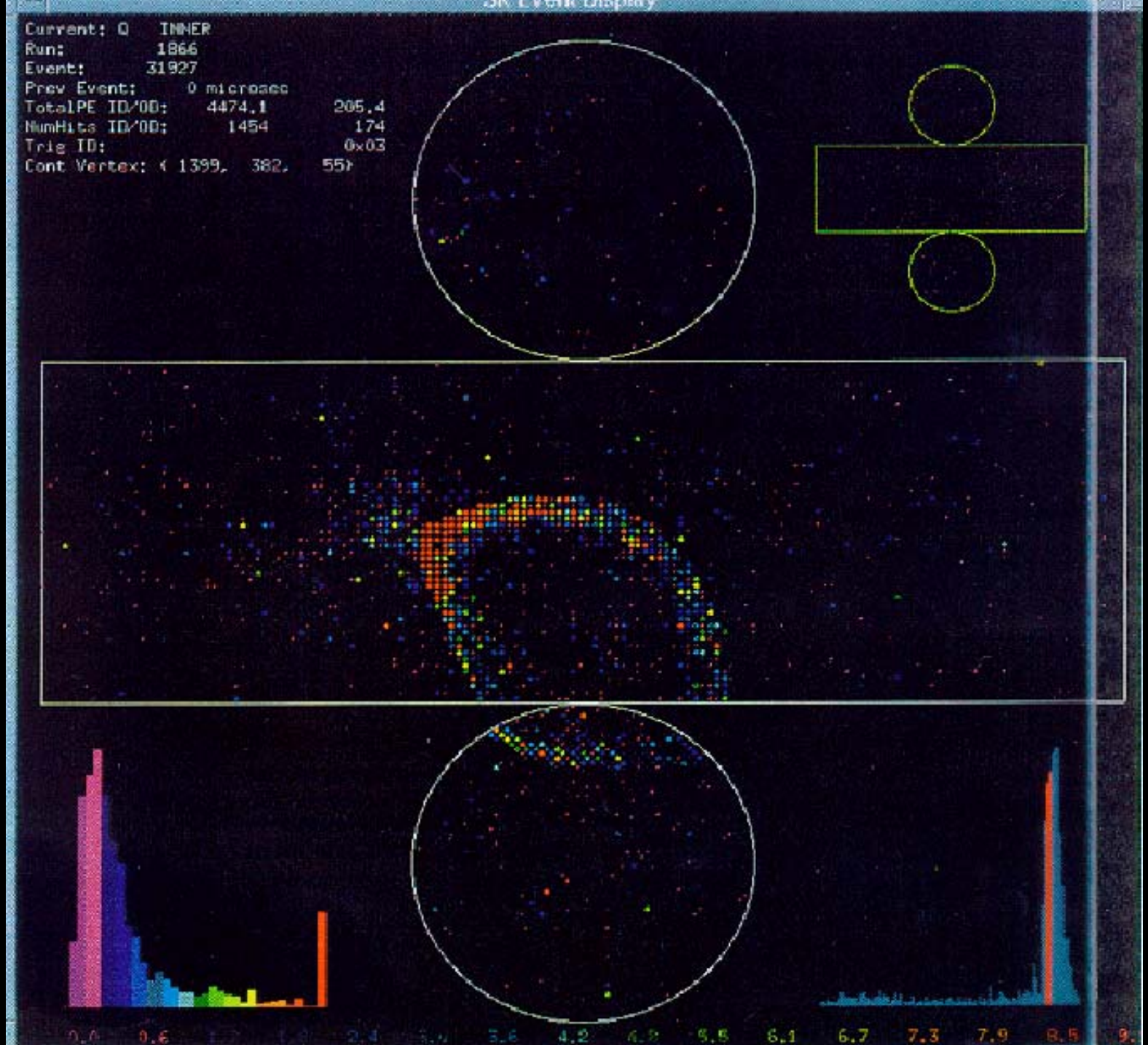
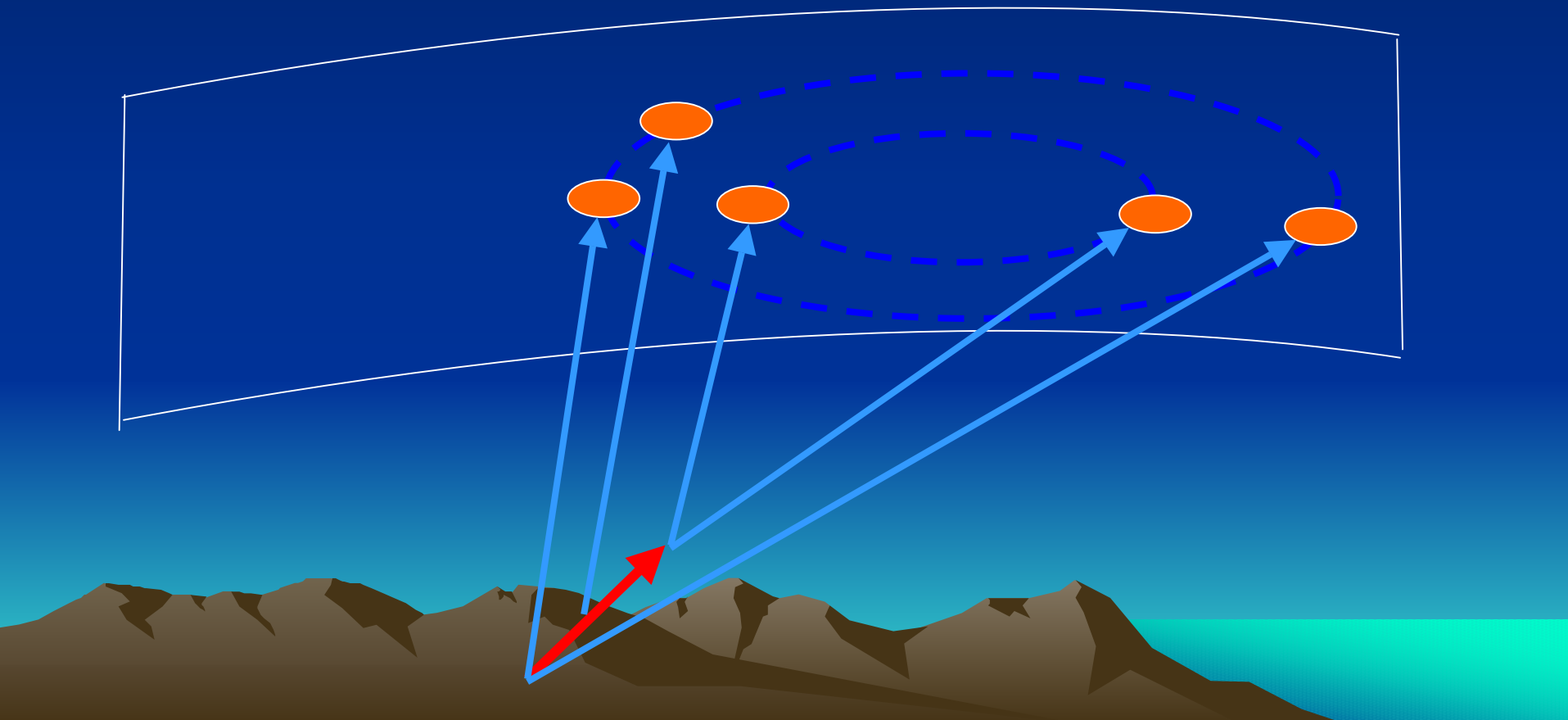
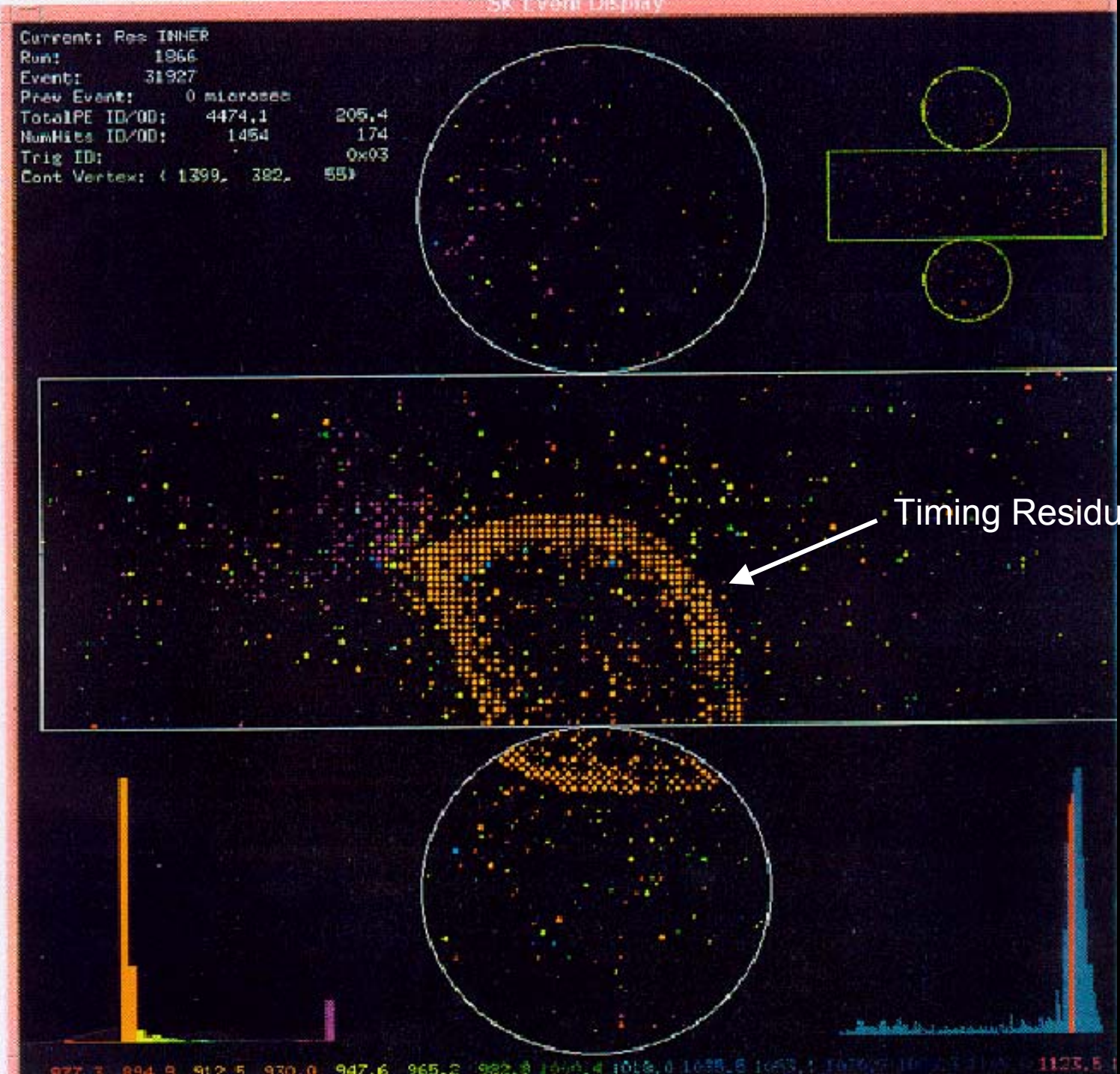
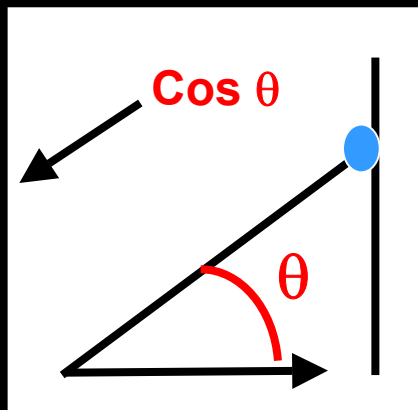

SK Event Display
Current: 0 INNER
Run: 1866
Event: 31927
Prev Event: 0 microsec
TotalPE ID/OD: 4474.1 205.4
NumHits ID/OD: 1454 174
Trig ID: 0x03
Cont Vertex: (1399, 382, 55)
0.0 0.6 1.2 1.8 2.4 3.0 3.6 4.2 4.8 5.5 6.1 6.7 7.3 7.9 8.5 9.

Track Reconstruction

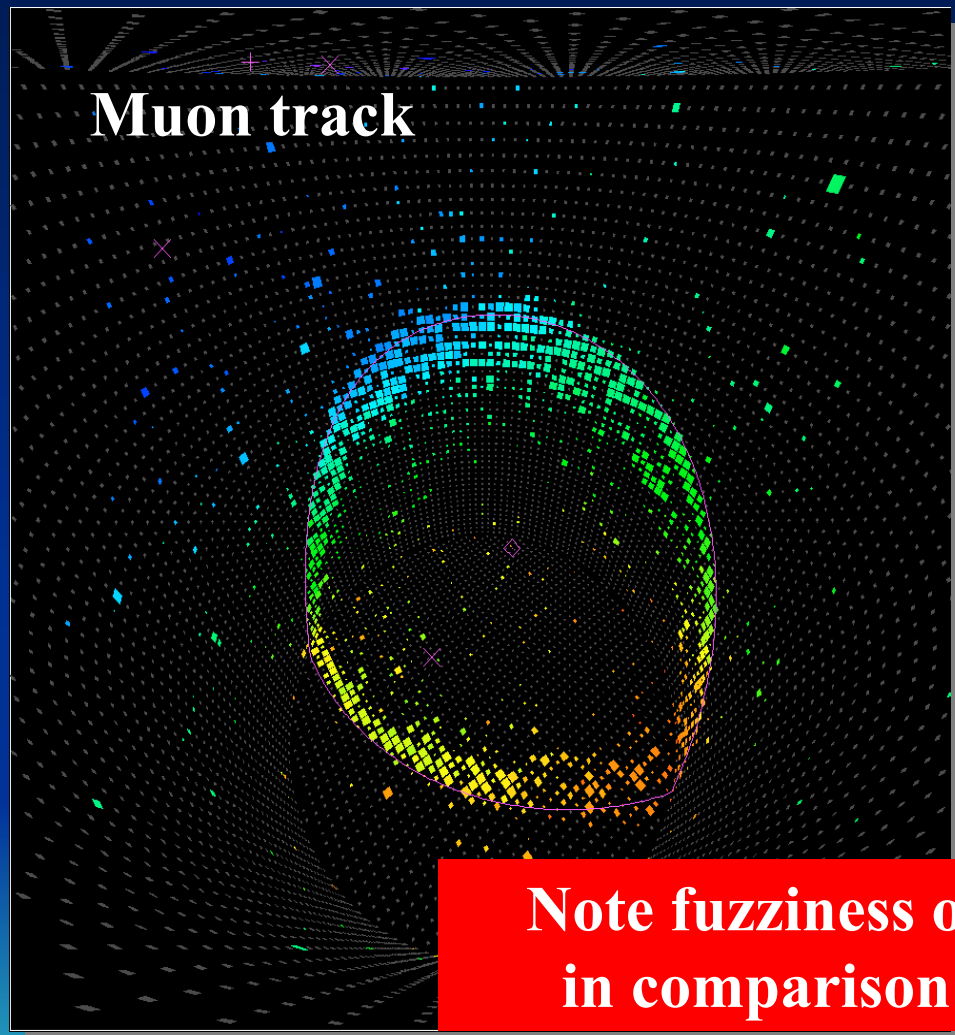
- Calculate difference between observed time of hit and calculated time.
- Adjust track to minimize.

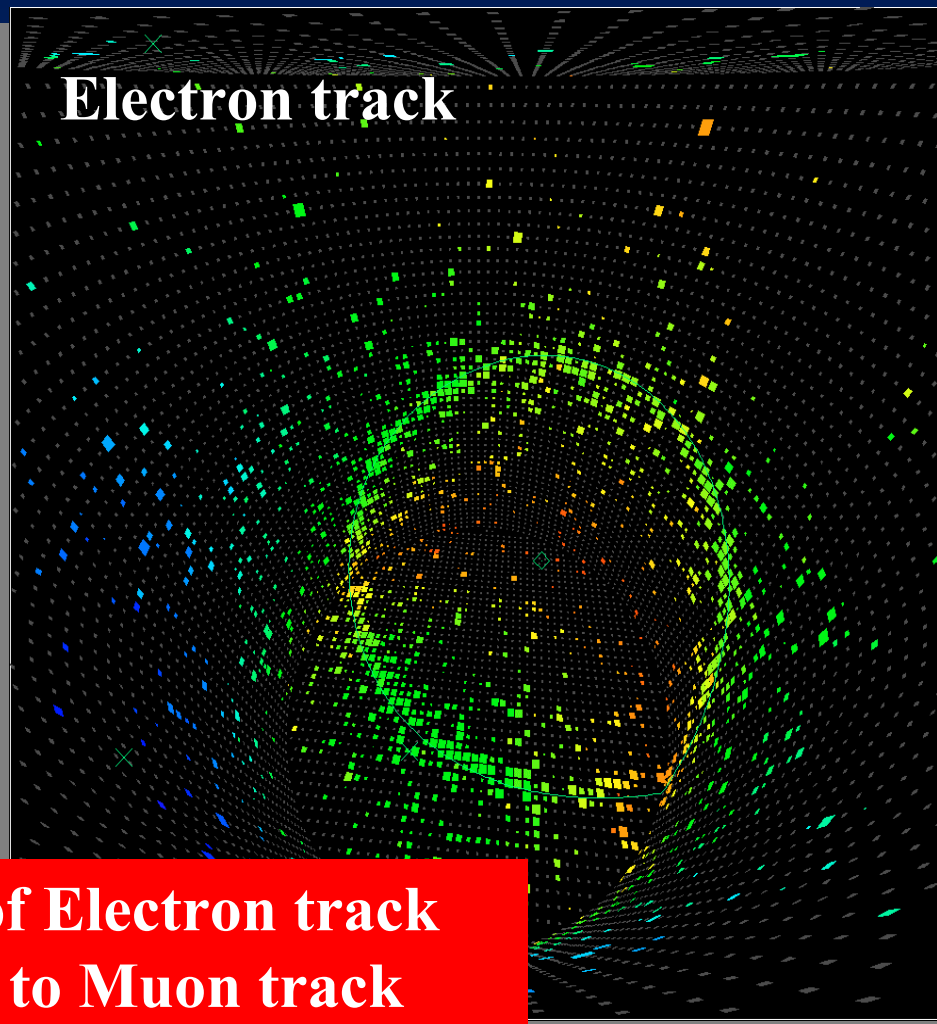



SK Event Display
Current: Res INNER
Run: 1866
Event: 31927
Prev Event: 0 microsec
TotalPE ID/OD: 4474.1 205.4
NumHits ID/OD: 1454 174
Trig ID: 0x03
Cont Vertex: (1399. 382. 55)
Timing Residuals


Cos θ
θ

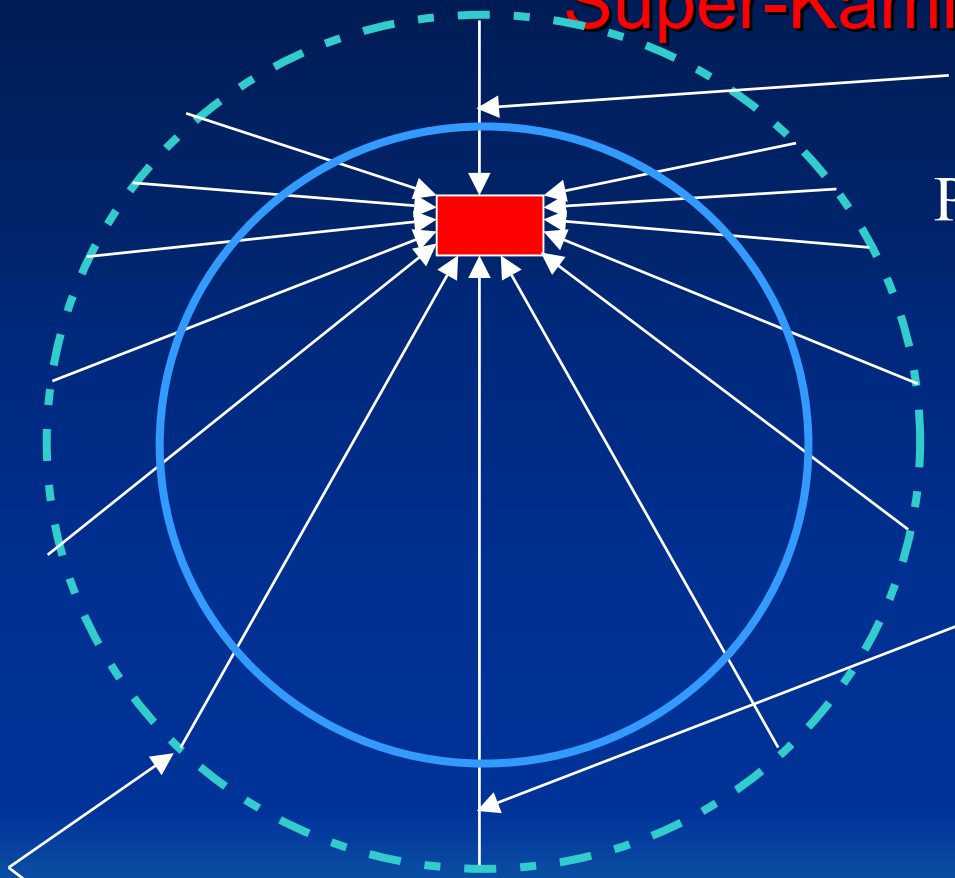
Particle Identification





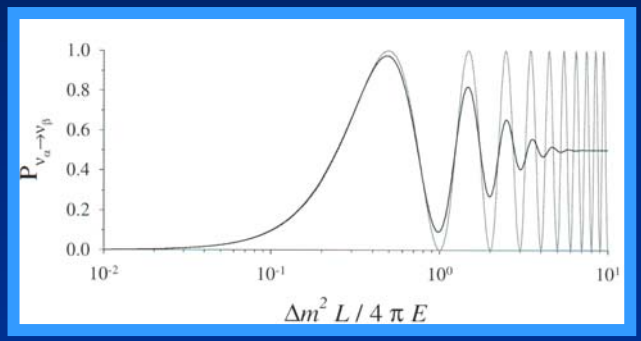
Note fuzziness of Electron track in comparison to Muon track

Study Angular Distributions of ν_μ and ν_e with Super-Kamiokande



About 15 km

$P_{\nu\nu'} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$



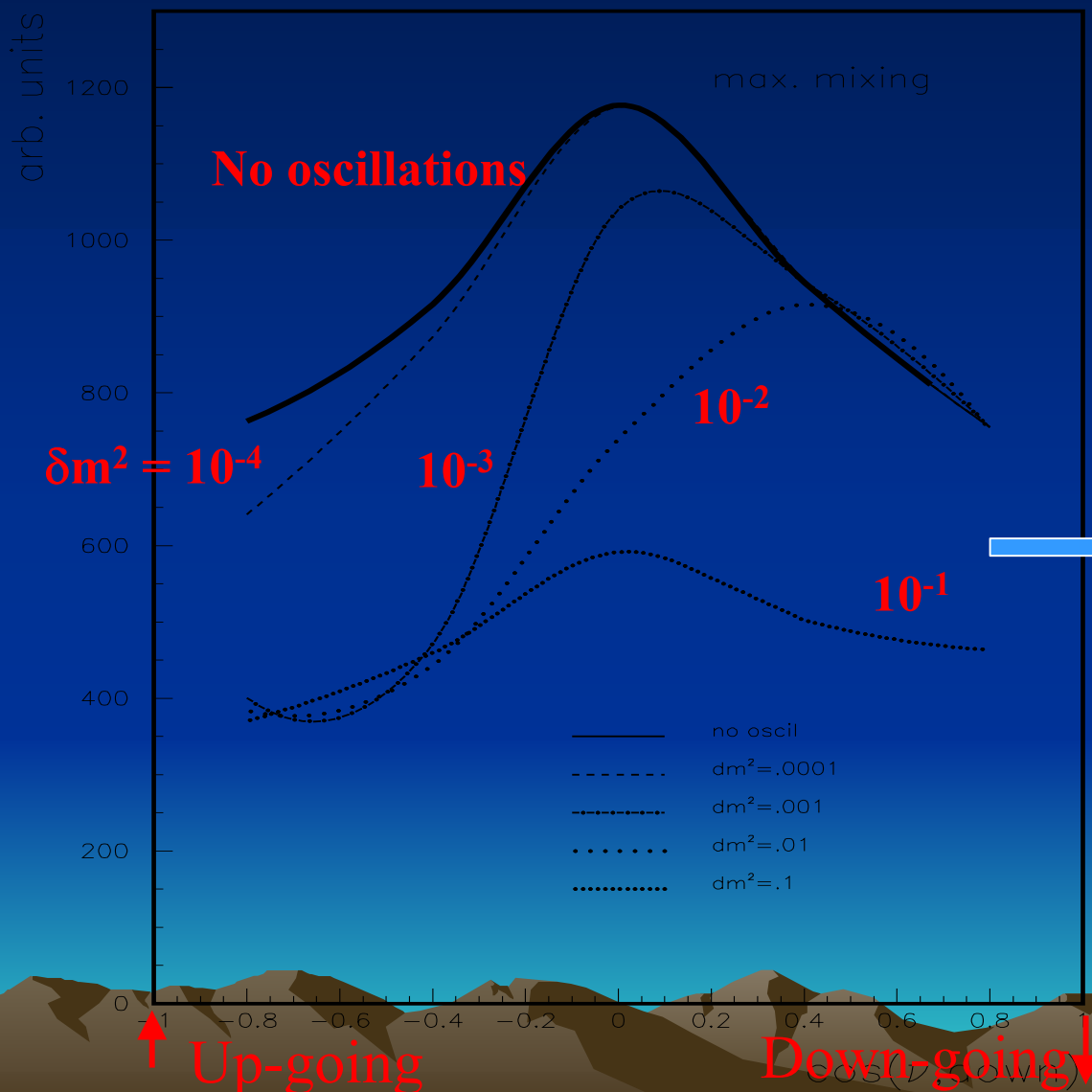
About 13,000 km

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

Neutrinos produced in the atmosphere at ~15 km altitude...

travel through the earth and interact in the detector.

Sensitivity of angular distribution to neutrino oscillations

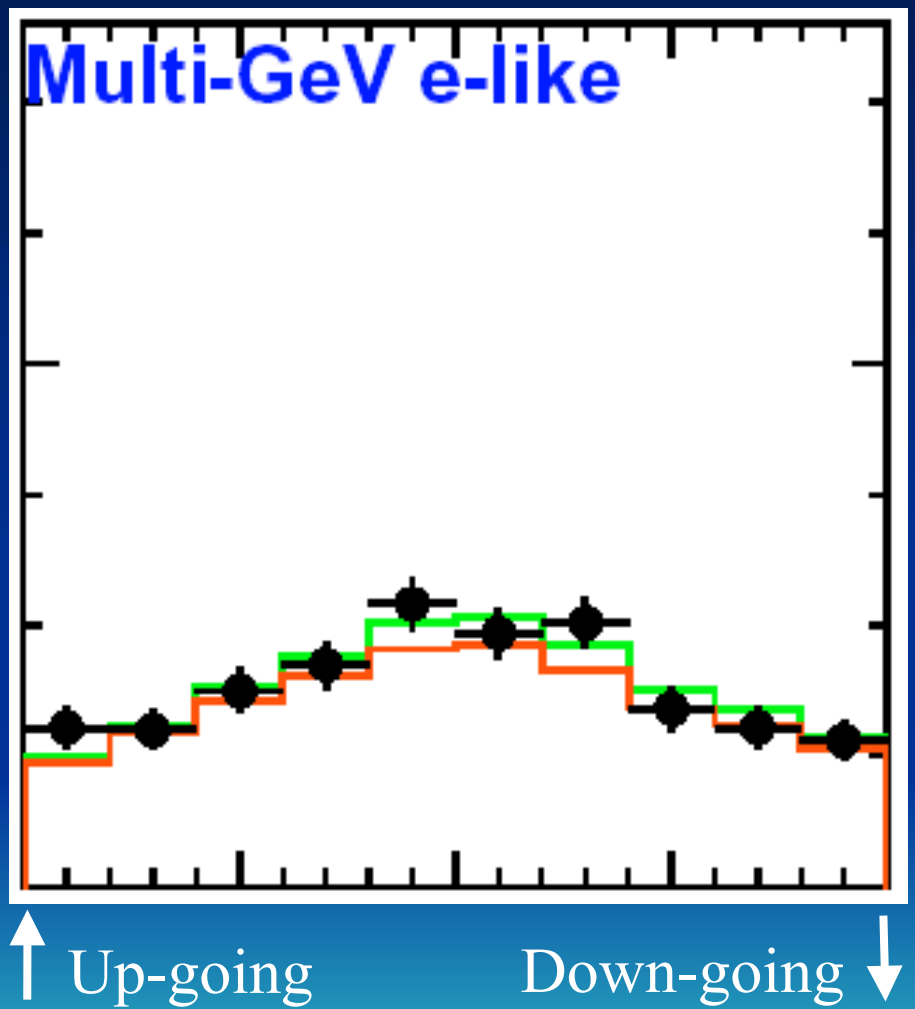


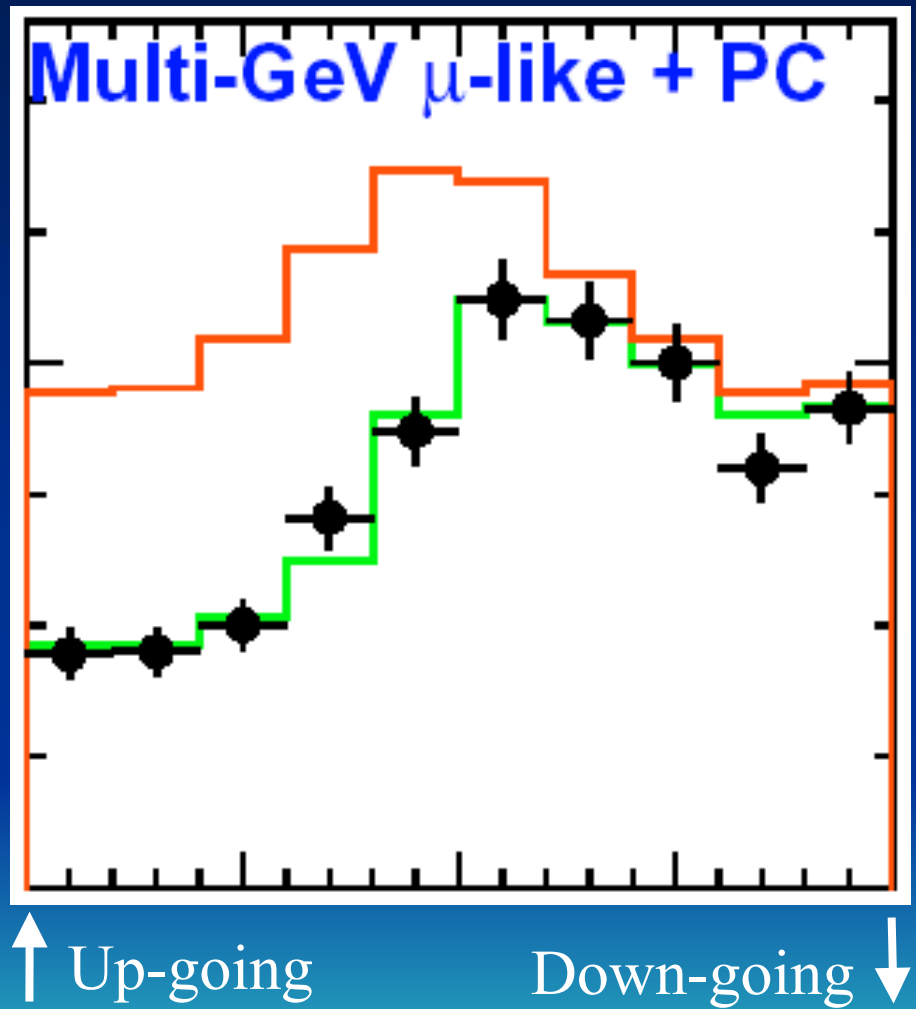
Vary δm^2

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

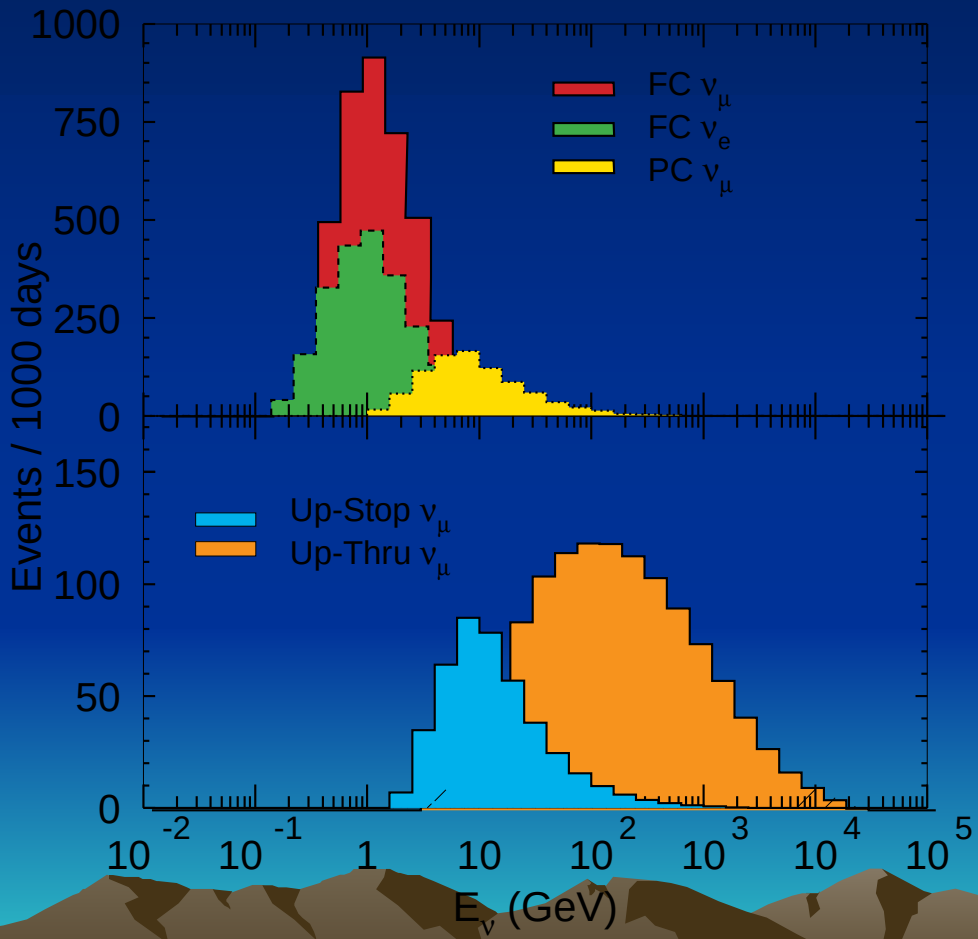
Sensitivity from ~10^{-4} to 10^{-1} eV^2

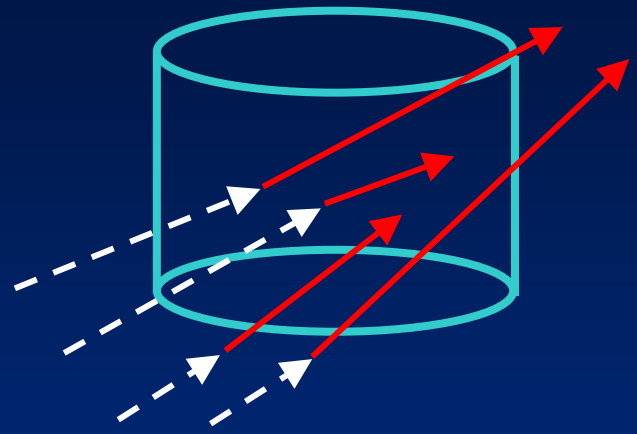
What is seen?


Multi-GeV e-like
Up-going
Down-going


Multi-GeV μ-like + PC
Up-going
Down-going

Data Samples

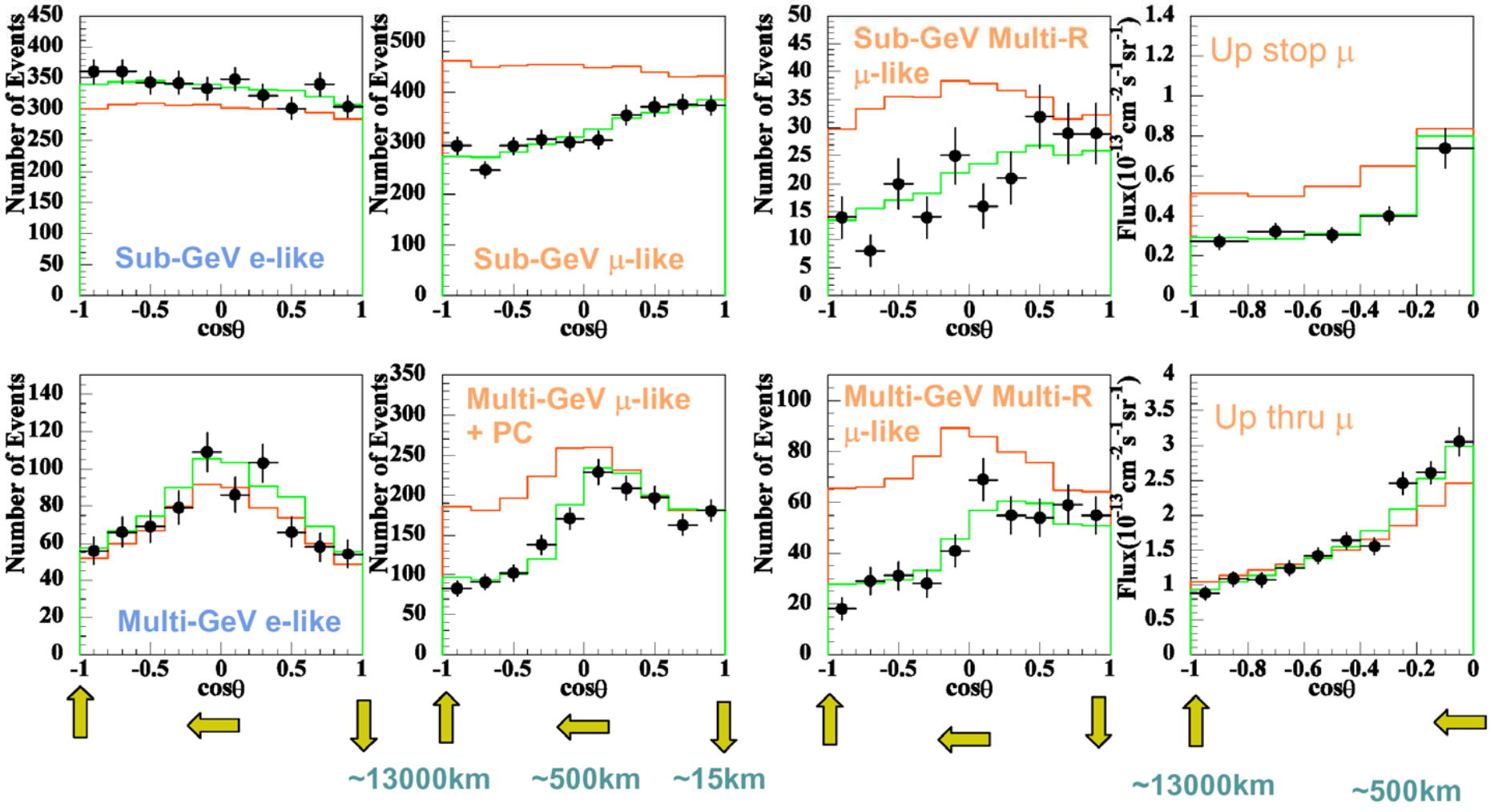




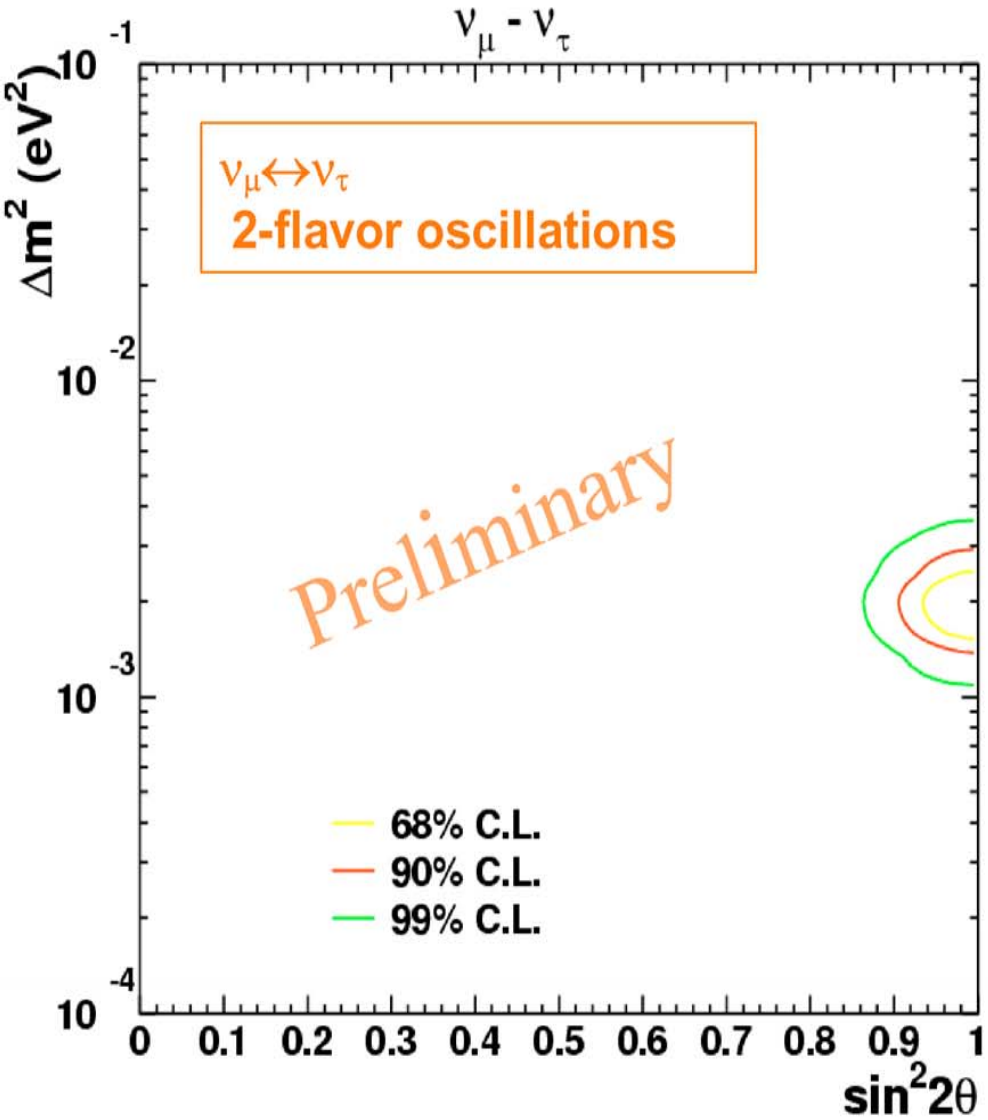
- Fully-contained events
- Partially-contained events
- Upward-going neutrino induced muons.
  - Those that enter and exit the detector.
  - Those that stop in the detector.

Different systematics
Different energy ranges

Zenith distributions with combined fit



Results of combined fit FC+PC+Up-m+Multi-ring



- **Best fit:**

  $\sin^2 2\theta = 1.0$

  $\Delta m^2 = 2.0 \times 10^{-3}$ eV^2

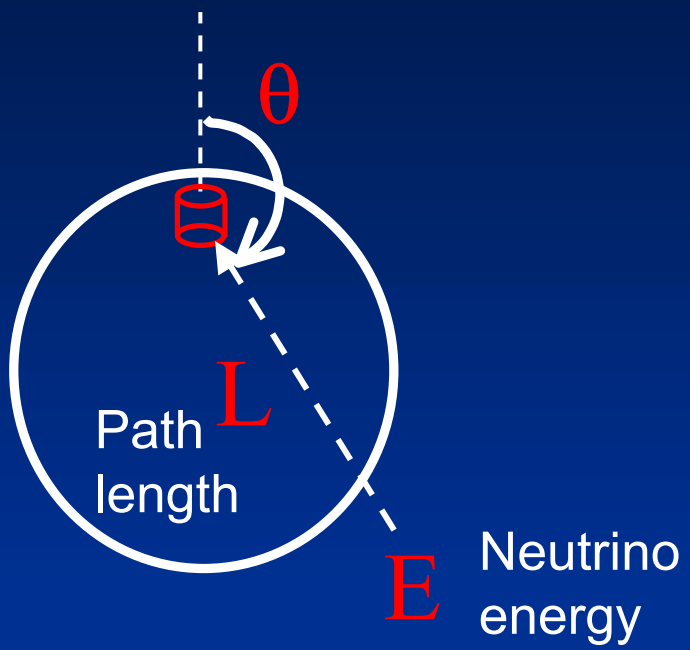
  $\chi^2 = 170.8/170$ dof

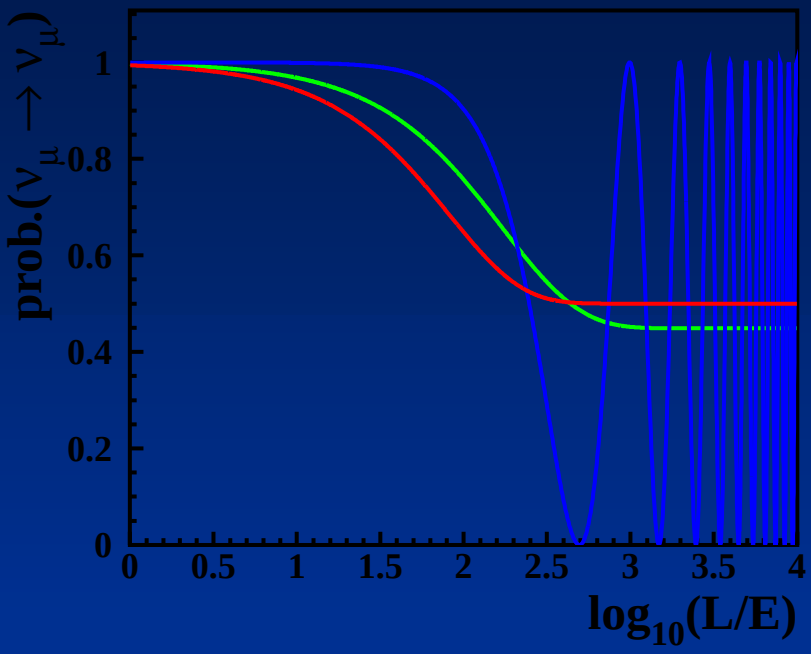
- **90% C.L. region:**

  $\sin^2 2\theta > 0.90$

  $1.3 < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2

Search for oscillation pattern (L/E)





Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

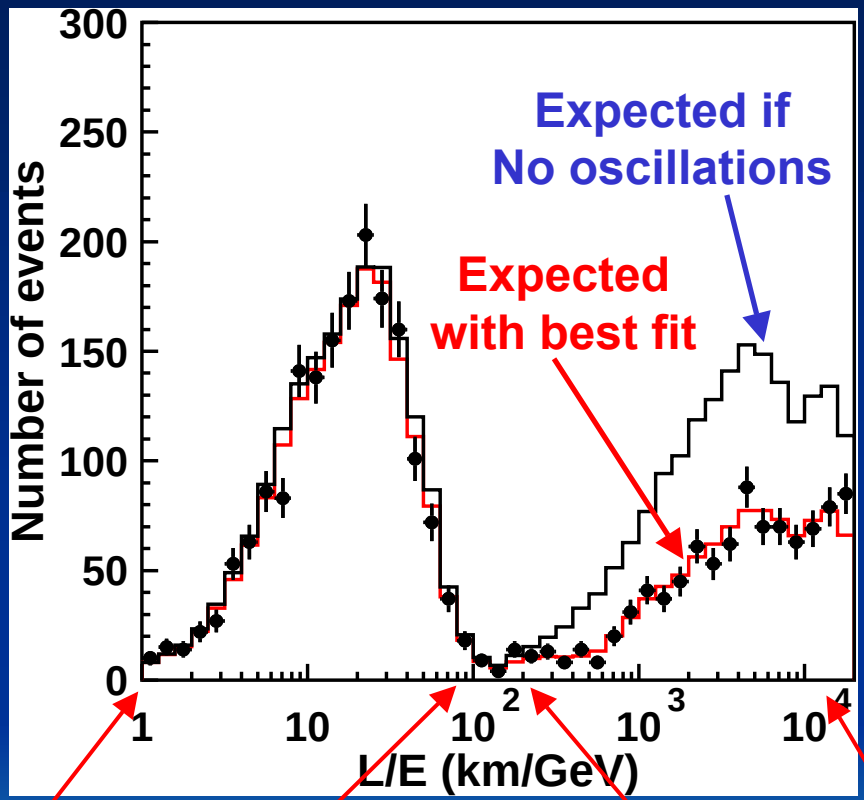
Neutrino decay : $P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \times \exp(-\frac{m_3}{2\tau_3}\frac{L}{E}))^2$

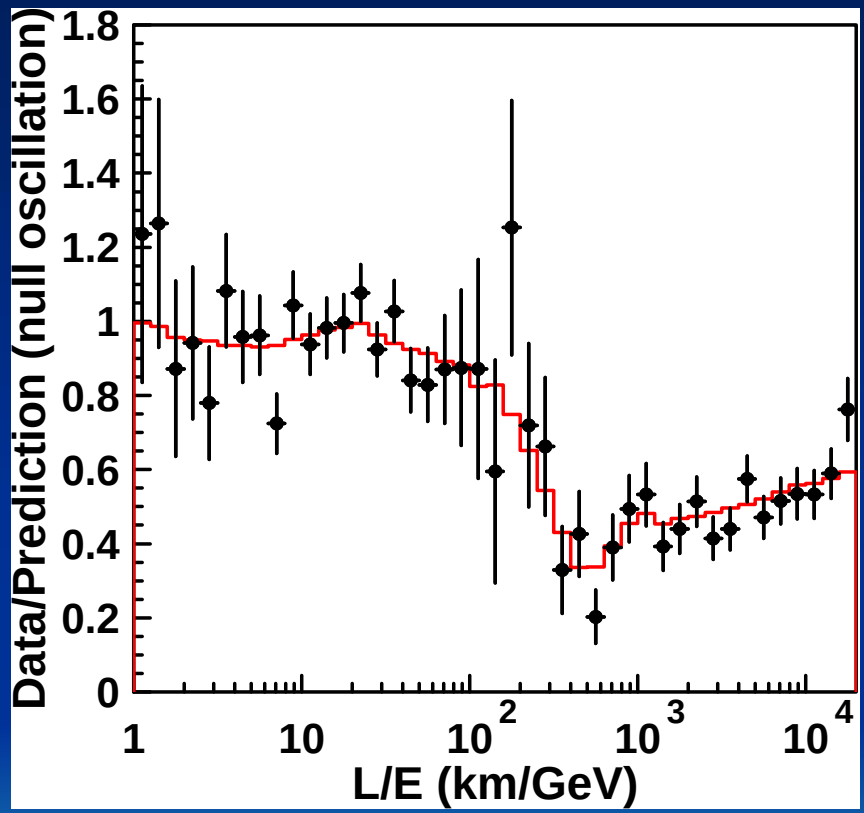
Decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \sin^2(1 - e^{-\gamma x})$

Select high resolution L/E events → **Search for first dip**

L/E distribution

1489.2 days FC+PC





Large E
Small L

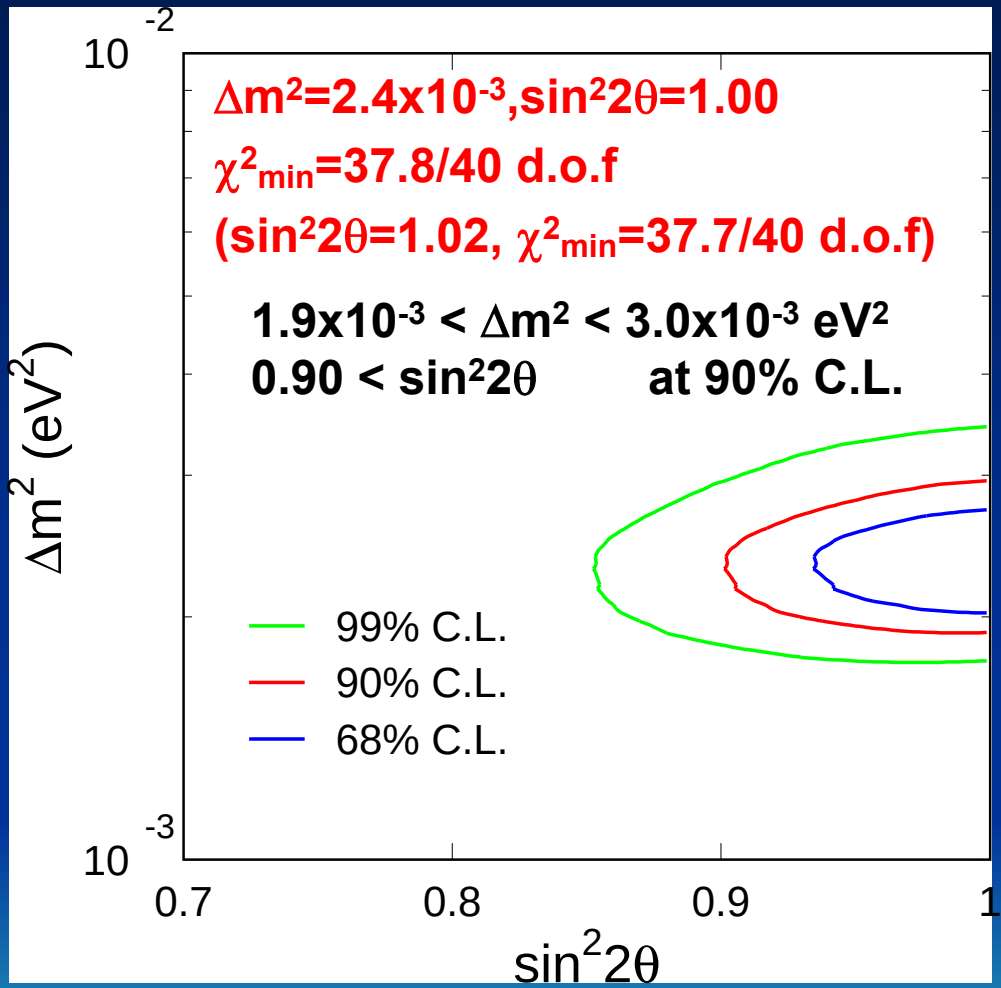
Small E
Small L

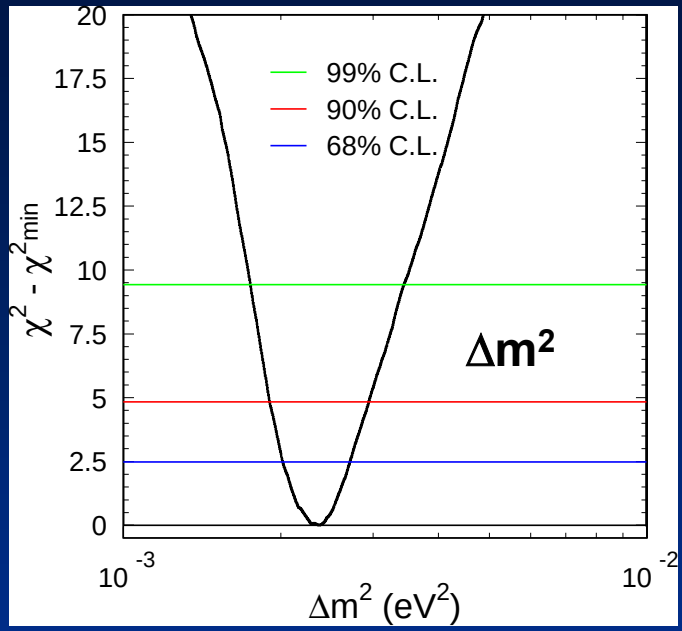
Large E
Large L

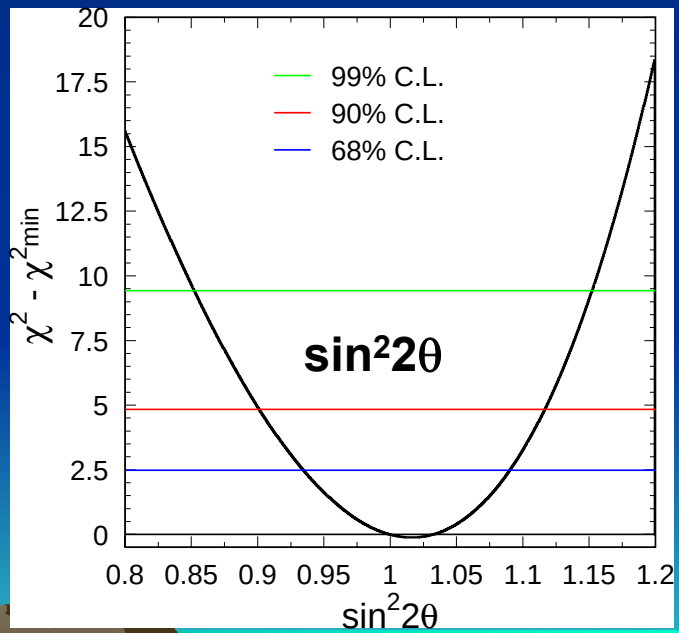
Small E
Large L

First dip observed

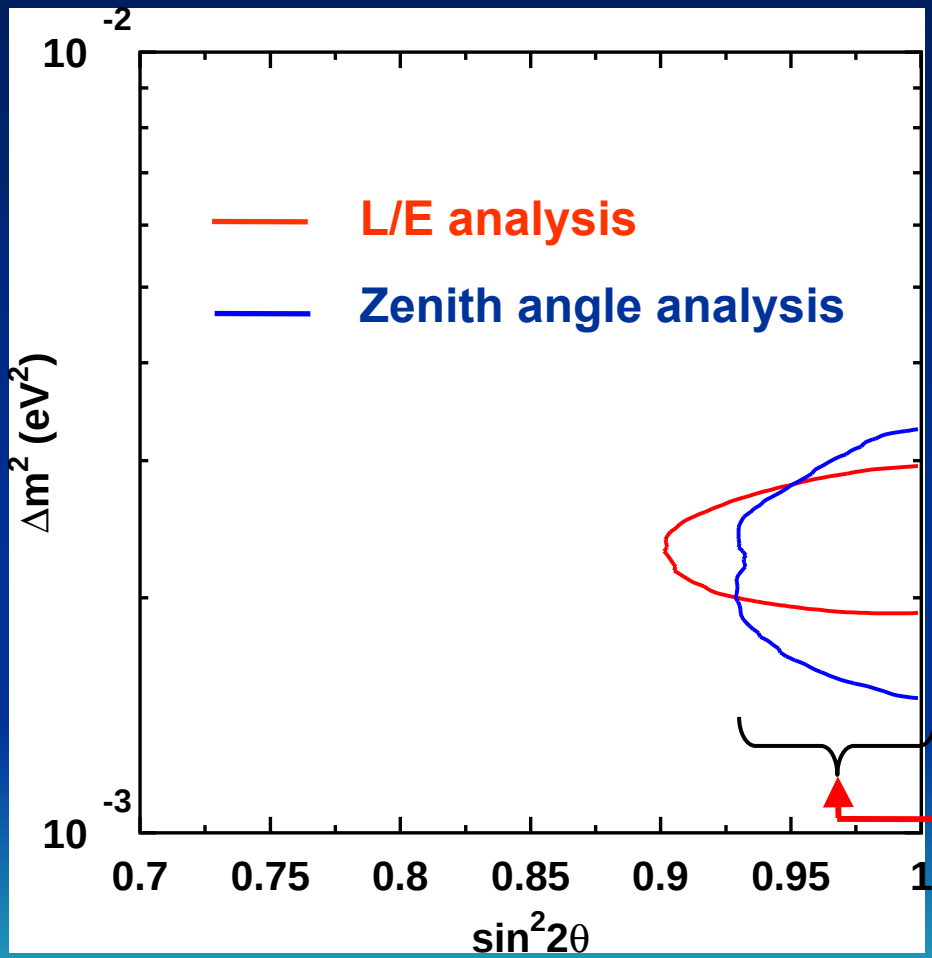
Neutrino oscillation analysis







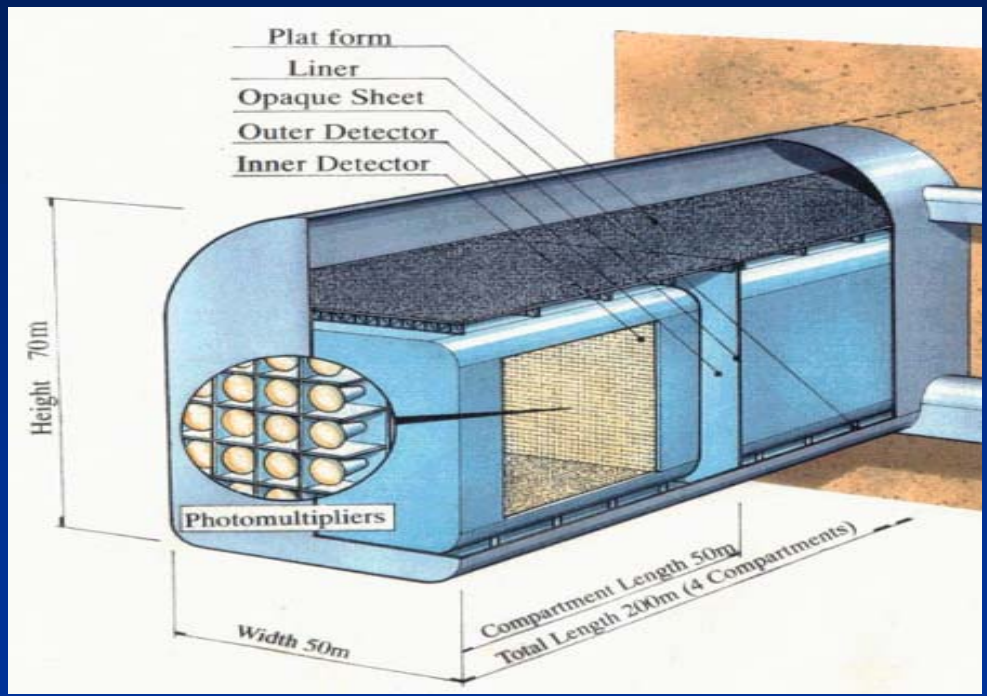
Comparison of the allowed parameter regions between zenith angle analysis and L/E analysis

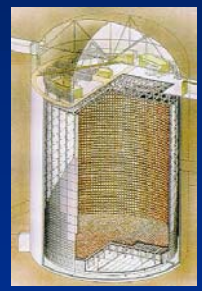


Allowed δm^2 region will get smaller as sqrt(exposure)

Allowed $\sin^2 2\theta_{23}$ region will get smaller as sqrt(exposure)

New Proposed Detectors
10 to 20 Times Super-K





Super-K

Hyper-K

Associated with second phase
of new long baseline experiment

Summary

- Atmospheric ν_μ are disappearing
  - Oscillations $\nu_\mu \rightarrow \nu_\tau$ are dominant (99% c.l.)
    - $\sin^2 2\theta > 0.9$; $\Delta m^2 = 1.3 \sim 3.0 \times 10^{-3}\ eV^2$ @ 90% confidence level
  - L/E oscillation pattern observed
  - Small contribution of $\nu_\mu \rightarrow \nu_e$ oscillations is not excluded
    - $\mathrm{Sin}^2 2\theta_{13} < 0.15$ @90% CL
  - Pure oscillations $\nu_\mu \rightarrow \nu_s$ are excluded at 99% CL
    - Admixture < 0.19 @90%CL
  - ν_τ appearance needs more statistics…now ~ 2.5 σ

Comparison to other models

Oscillation χ^2_{min}=37.8/40 d.o.f

Decay χ^2_{min}=49.2/40 d.o.f → $\Delta\chi^2$ =11.4 (3.4σ)

Decoherence χ^2_{min}=52.4/40 d.o.f → $\Delta\chi^2$ =14.6 (3.8σ)