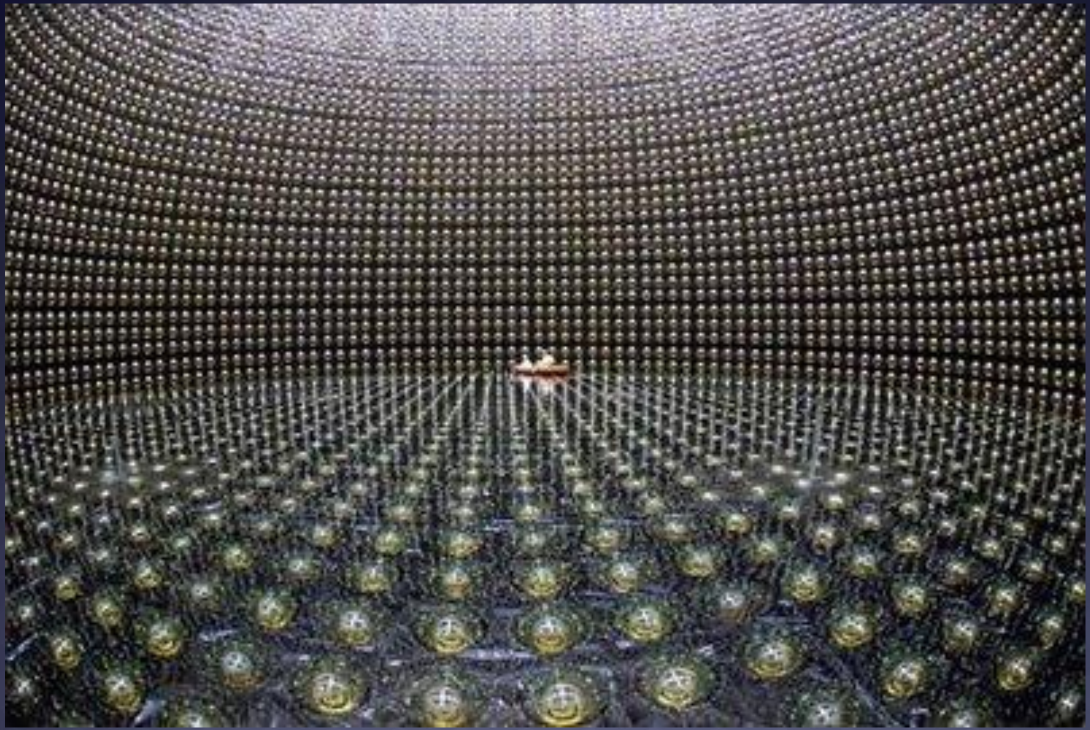

EVIDENCE FOR THE EXISTENCE OF NEUTRINOS AND NEUTRINO MASS

Amelia Perry

Advanced Particle Physics Techniques

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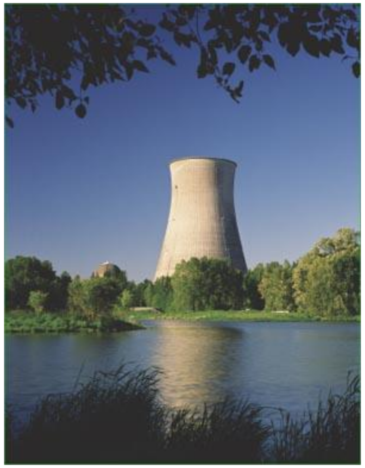
AREAS OF INTEREST

- The existence of neutrinos from theory of β decay
- Theoretical ideas:
  - Neutrino oscillation
  - Cerenkov radiation
- Experimental evidence
  - Homestake experiment
  - Super Kamiokande

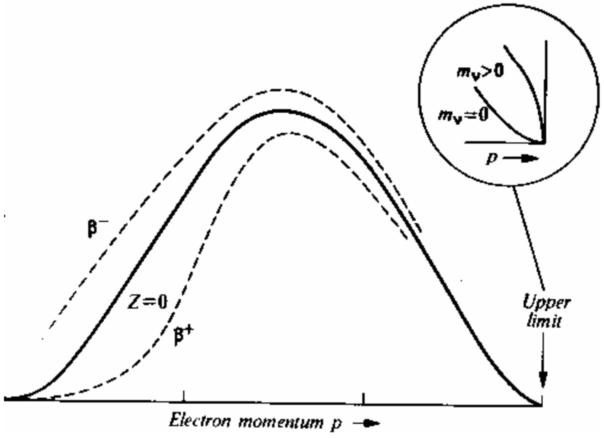
SOURCES OF NEUTRINOS

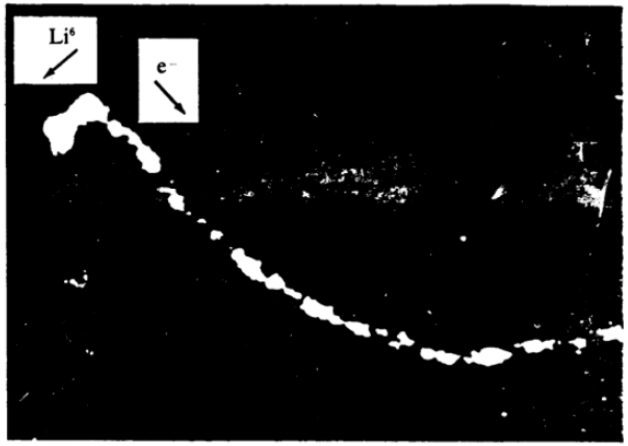
- Solar neutrinos
- Neutrinos formed in supernovae
- Reactor neutrinos
- Atmospheric neutrinos
- Geological Neutrinos
- Cosmic background neutrinos



BETA DECAY

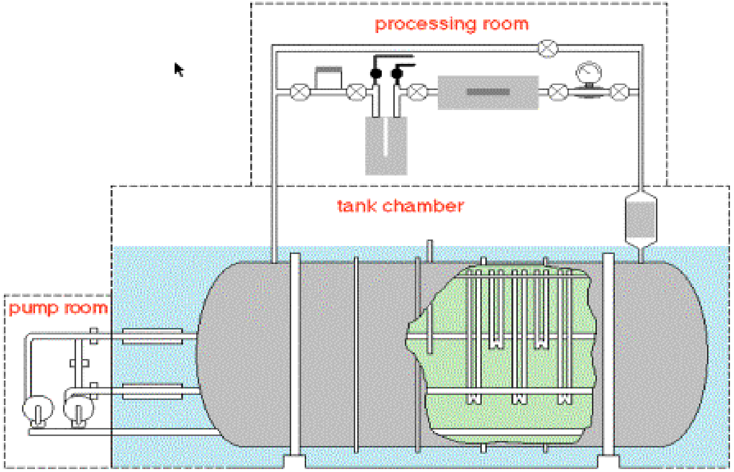
- Existence of neutrino first predicted by Pauli in 1931 when looking at plots for beta decay
- There are issues with the plots which break conservation laws:
  - Expect a unique value for energy released in beta decay, instead see a range of energies
  - In the absence of a neutrino, angular momentum is not conserved
  - Also, images from cloud chambers showed that linear momentum was not conserved
- Therefore the properties of the neutrino were chosen to remove these problems
- It was initially suggested that the neutrino has zero mass (But later found to be incorrect)
- It can be seen from these results that amendments needed to be made to theory

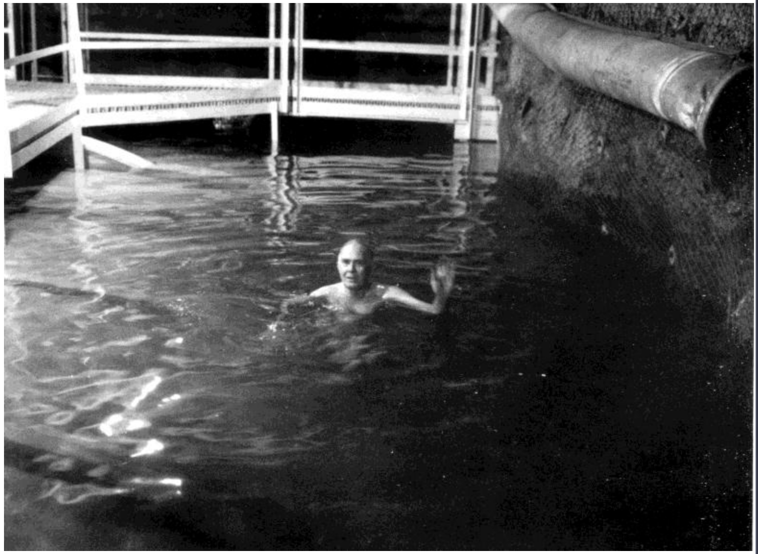




SOLAR NEUTRINO PROBLEM AND THE HOMESTAKE EXPERIMENT

- The Homestake experiment was performed in the late 1960s by Ray Davis and John N. Bahcall and used a detector filled with a chlorine-based compound which measured solar neutrino flux
  - $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
- The detector was situated in the Homestake Gold Mine in South Dakota
- It could be seen that there was a discrepancy in the number of neutrinos detected (about ⅓ to ½) compared to that predicted by the solar model
- The suggested theory to solve this problem, known as the solar neutrino problem, was the idea of neutrino oscillations, with the concepts of both neutrino flavour and neutrino mass being introduced





NEUTRINO OSCILLATIONS

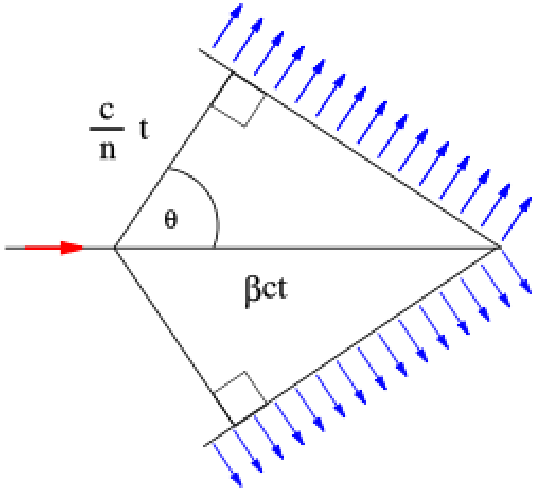
- Neutrinos can have one of three "flavours":
  - Electron neutrinos v_e (as emitted by sun and detected in Homestake experiment)
  - Muon neutrinos v_μ
  - Tau neutrinos v_τ
- It was proposed that if neutrinos had mass, they could change flavour whilst travelling through space, and v_e not detected in the Homestake experiment could be existing as other flavours
- Mathematics behind flavour oscillations is complicated, but the results show the following result for probability of a neutrino changing flavour:
  - $P(v_\mu \rightarrow v_e) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$
  - $\Delta m^2 = m_\mu^2 - m_e^2$
- Shows that neutrinos must have mass to change flavour, and that different neutrino flavours must have different mass

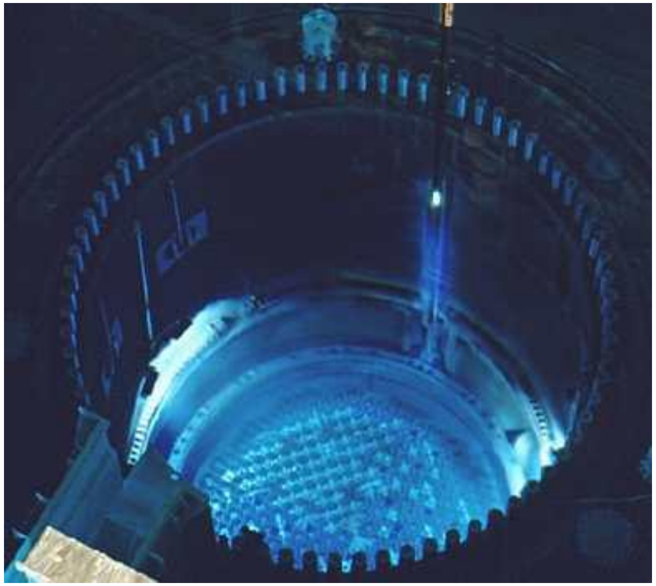
Neutrino Detectors

- Fall into two general categories
  - Radiochemical (e.g. Homestake)
  - Cerenkov (e.g. Super Kamiokande)
- They are very large to capture neutrinos which are weakly interacting
- They are placed underground for shielding, often in mines, and often surrounded by water for further shielding
- Radiochemical detectors were mainly used in early neutrino experiments
- Cerenkov detectors are lined with photomultiplier tubes to detect Cerenkov light

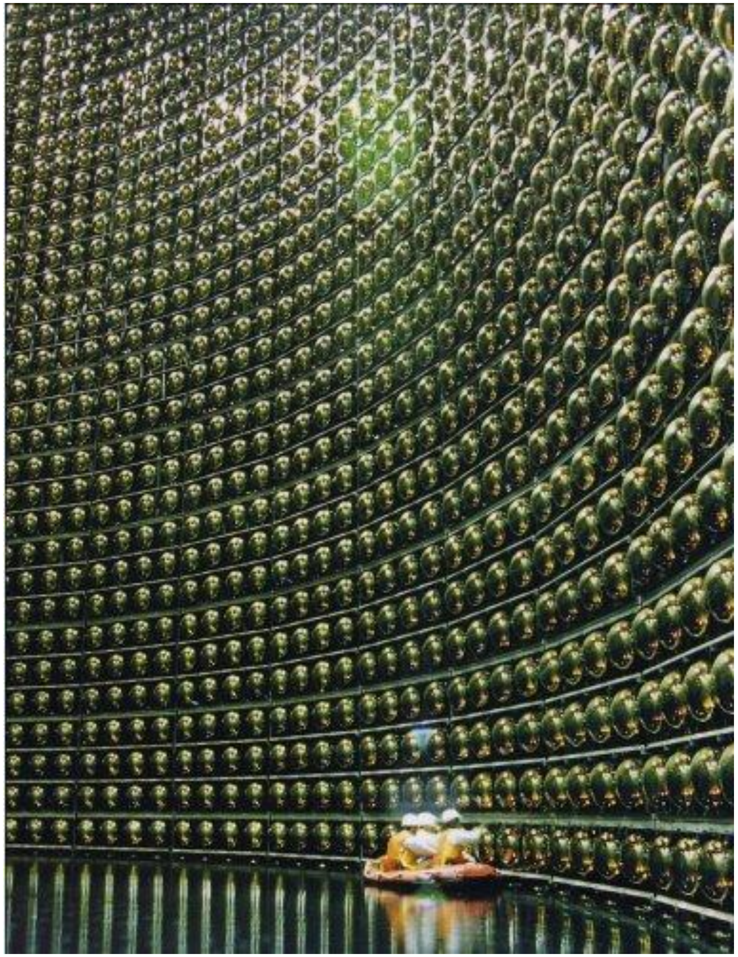
CERENKOV RADIATION

- Cerenkov radiation is emitted by charged particles when they travel through a medium faster than light speed in that medium
  - v > c/n
- It is emitted in a cone at a constant angle from a particle's track
  - cosθ = 1/nβ
- Causes a wavefront (shock) of light
- The cone is seen as a ring in detectors such as Super K

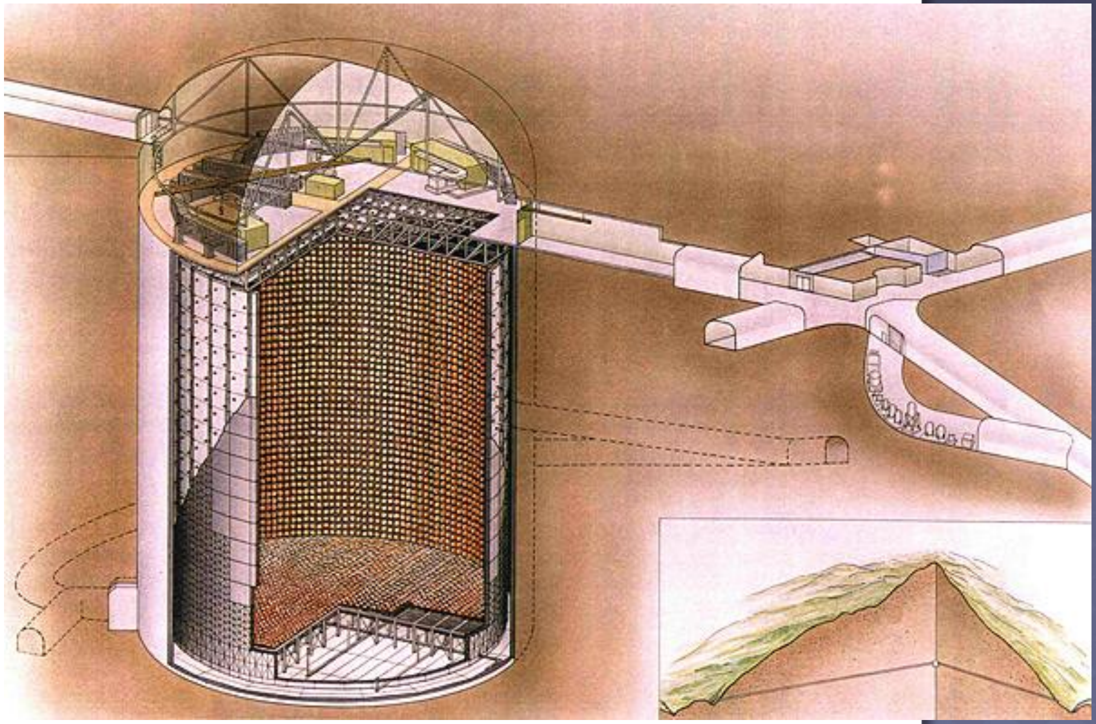




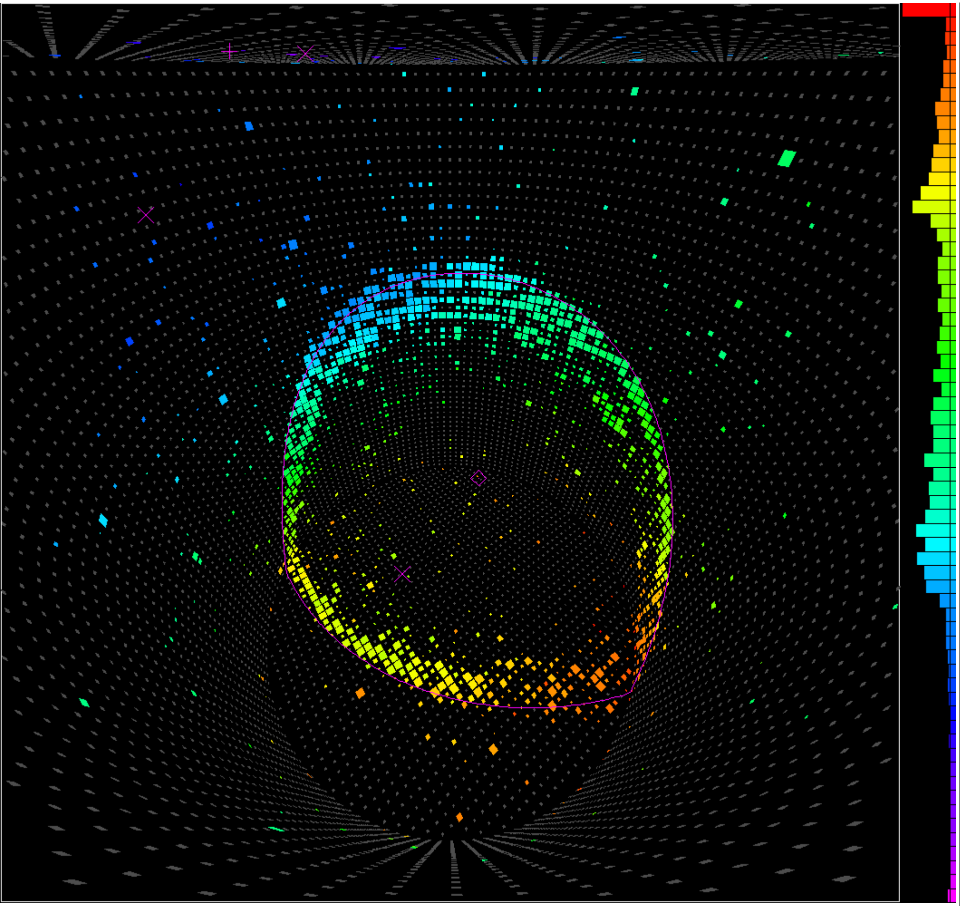
SUPER KAMIOKANDE (SUPER K)



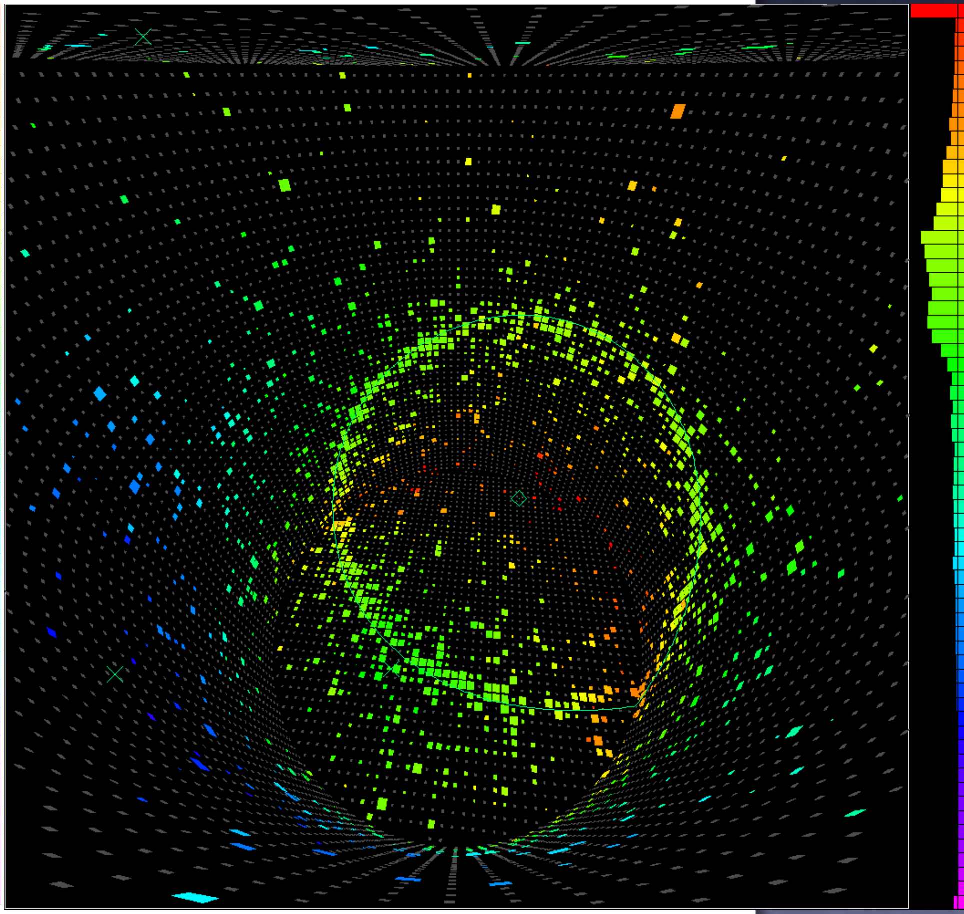
- Situated in Kamioka mine, Japan
- 41.4m tall cylindrical tank
- Contains 50,000 tonnes pure water
- 11,146 PMTs in inner detector



VIEWING CERENKOV LIGHT CONES IN SUPER K



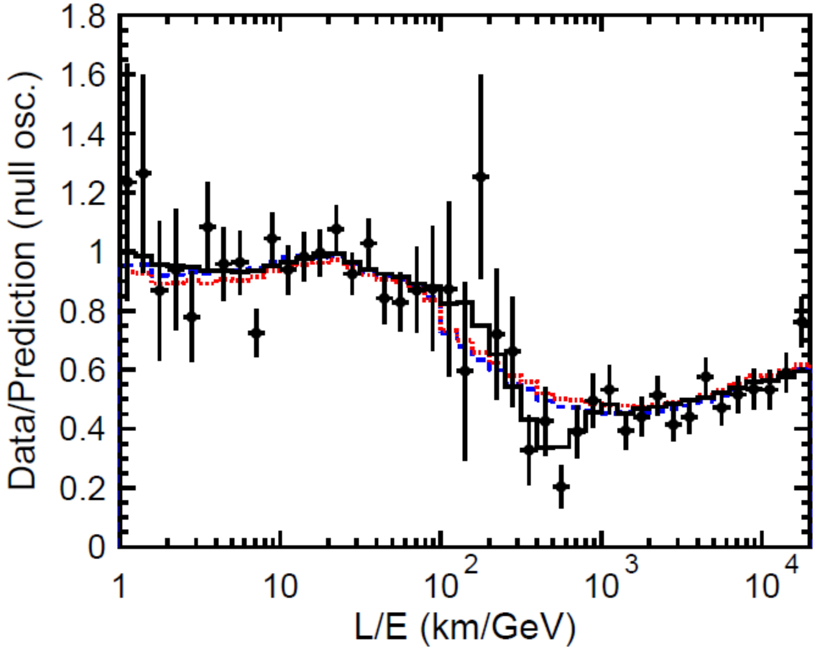
Muon with momentum 603 MeV
Shows sharp, defined edges

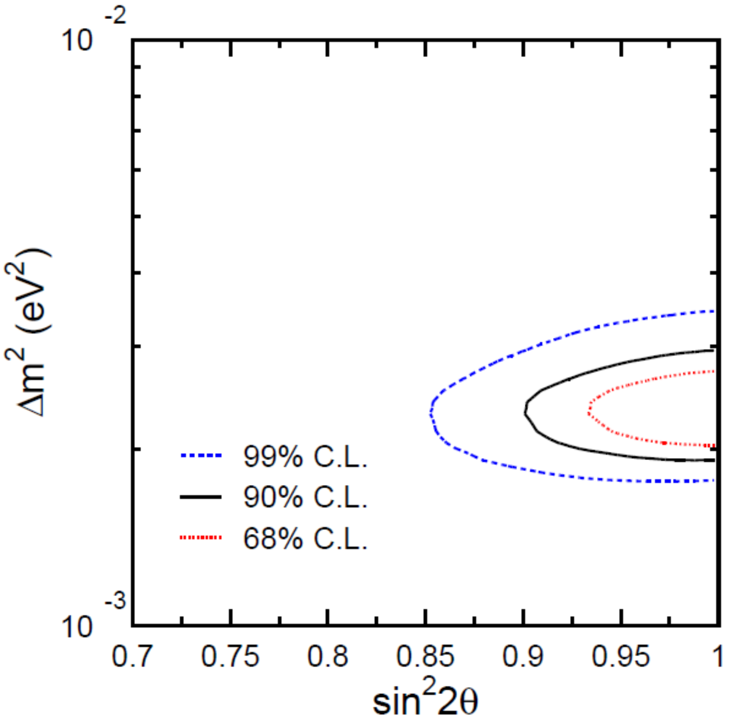


Electron with momentum 492 MeV
Shows fuzzier, less well defined edges due to electron showers

SUPER K RESULTS

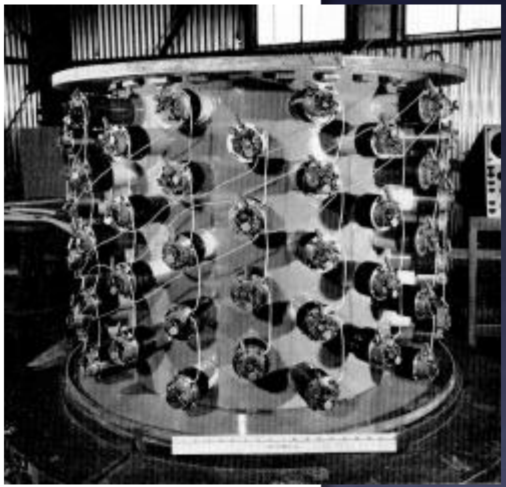
- $\Delta m^2 = 2.4 \times 10^{-3}\ eV^2$
- $\sin^2 2\theta = 1.0$

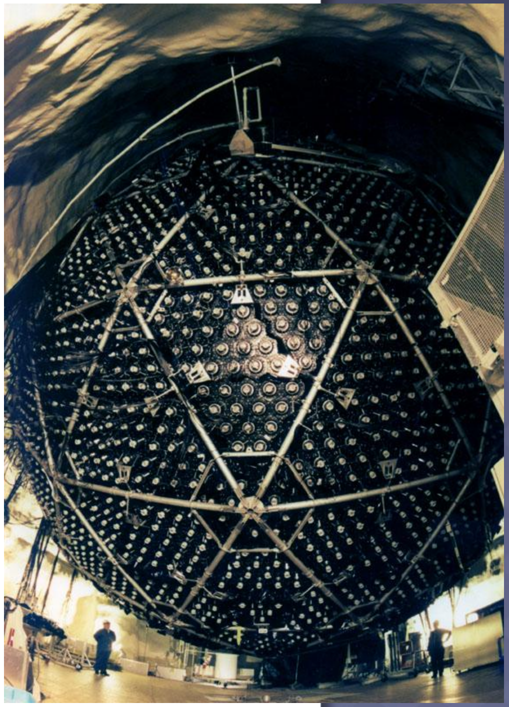




OTHER EXPERIMENTS

- Neutrino Experiment – very early experiment (in 1956) which confirmed existence of antineutrinos
- Sudbury Neutrino Observatory (SNO) – Also provided evidence for neutrino oscillations, spherical tank containing D_2O
- KamLAND – in Kamioka mine, to detect neutrinos created in nuclear reactors (53 of which surround the site)
- KATRIN – predicted to begin in 2009, and measure the mass of the electron neutrino
- IceCube – neutrino observatory in the Antarctic, to detect high energy neutrinos at high resolution (installation precticted to be finished in 2011)





THANK YOU FOR LISTENING

- For more information, see:
  - Official Japanese Super K site: http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html
  - US Super K site: http://neutrino.phys.washington.edu/~superk/
  - Official SNO site: http://www.sno.phy.queensu.ca/
  - Official IceCube site: http://icecube.wisc.edu/
  - Official KamLAND site: http://www.awa.tohoku.ac.jp/KamLAND/
  - Official KATRIN site: http://www-ik.fzk.de/tritium/