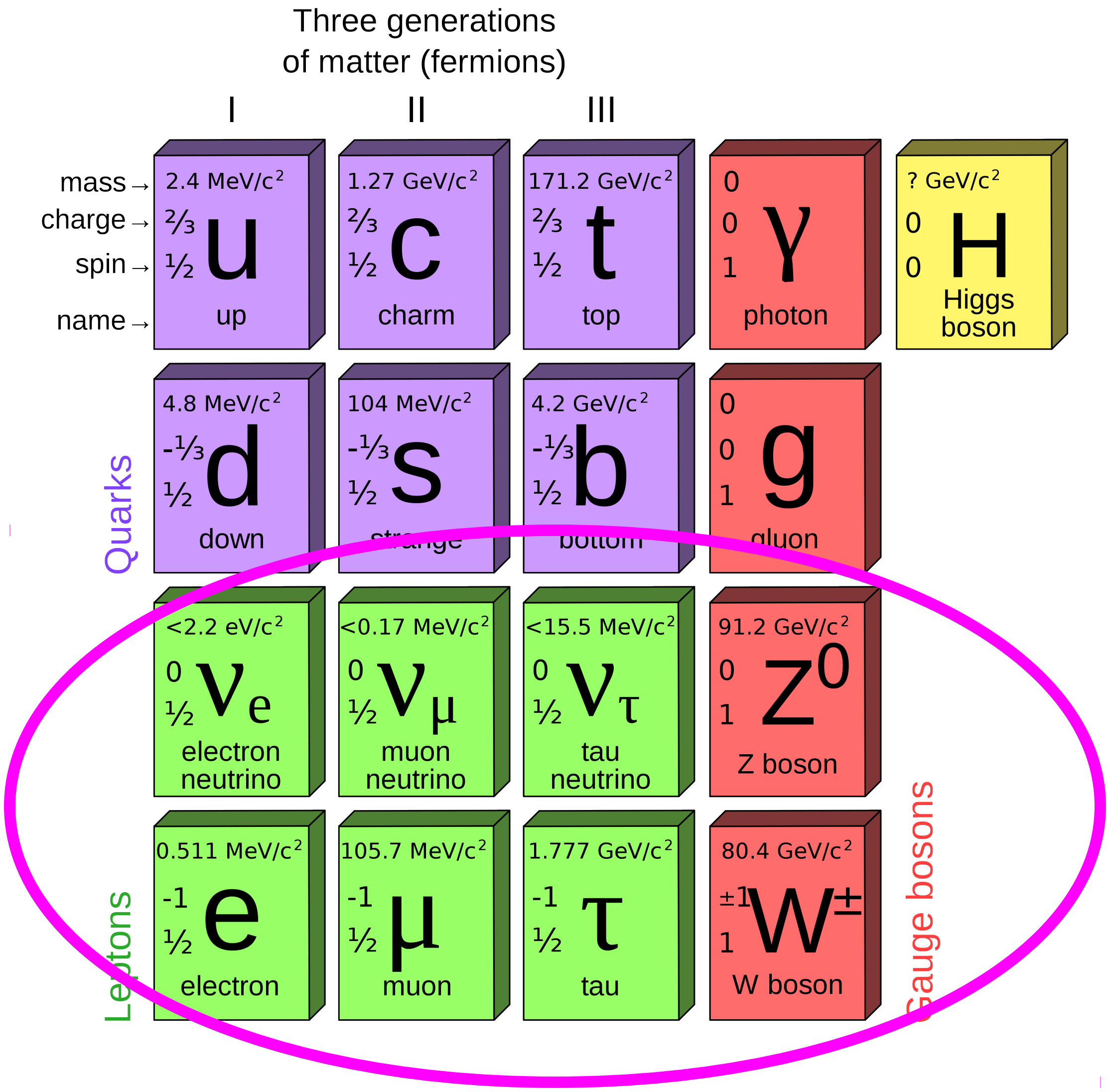
Leptons and the Weak Interaction



Question:
Do you know any weak decays?

Microscopic picture of decay

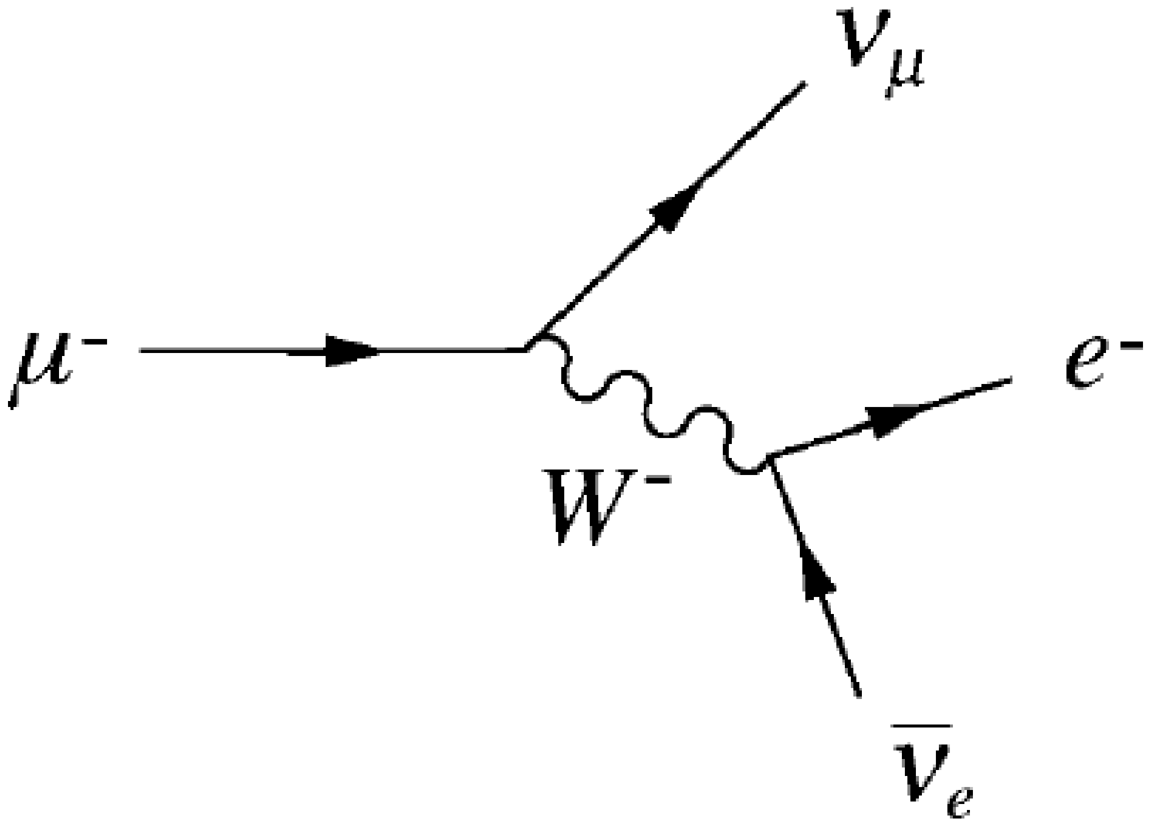


Figure 2.5 Dominant Feynman diagram for muon decay.

Lifetime: 2.2 μs is very long compared to strong and EM decays

Lepton number is conserved in weak (all) interactions

$$L_e \equiv N(e^-) - N(e^+) + N(\nu_e) - N(\bar{\nu}_e)\,, \tag{2.3a}$$

And similar for Lμ and Lτ

Microscopically the picture is that:
Z does not change particle type
W works like this:
e% → ν + W%
+ “crossing”:
e% + ν-bar → W%
ν-bar → W% + e+
N-bar + W+ → e+
And so on (we return to this later)

TABLE 2.1 Examples of leptonic decays that violate conservation of lepton numbers and the experimental upper limits on their branching ratios *B*.

Decay	Violates	B
$\mu^- \to e^- + e^+ + e^-$	L_μ, L_e	$<1.0 \times 10^{-12}$
$\mu^- \to e^- + \gamma$	L_μ, L_e	$<1.2 \times 10^{-11}$
$\tau^- \to e^- + \gamma$	L_τ, L_e	$<1.1 \times 10^{-7}$
$\tau^- \to \mu^- + \gamma$	L_τ, L_μ	$<6.8 \times 10^{-8}$
$\tau^- \to e^- + \mu^+ + \mu^-$	L_τ, L_e	$<2 \times 10^{-7}$

Discovery (1/2)

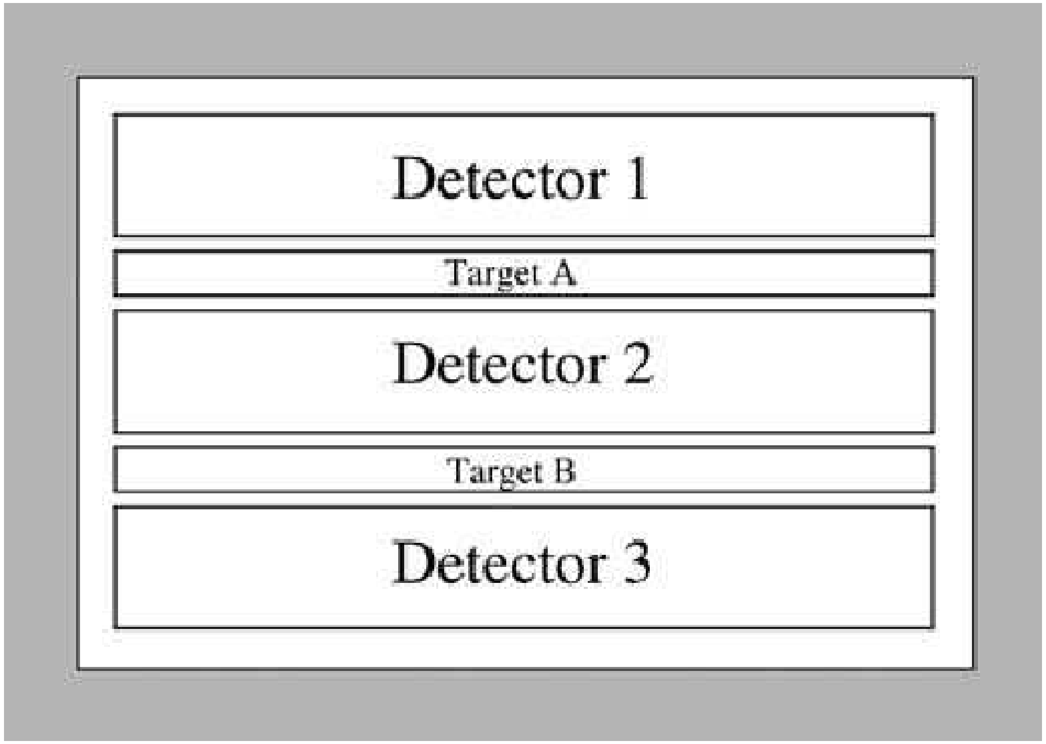


Figure 2.1 Schematic diagram of the apparatus used by Reines and Cowen to detect antineutrinos. The two target tanks, containing an aqueous solution of cadmium chloride, are sandwiched between three detector tanks of liquid scintillator. The whole apparatus is surrounded by heavy shielding to eliminate all incident particles except neutrinos and antineutrinos.

Discovery (2/2)

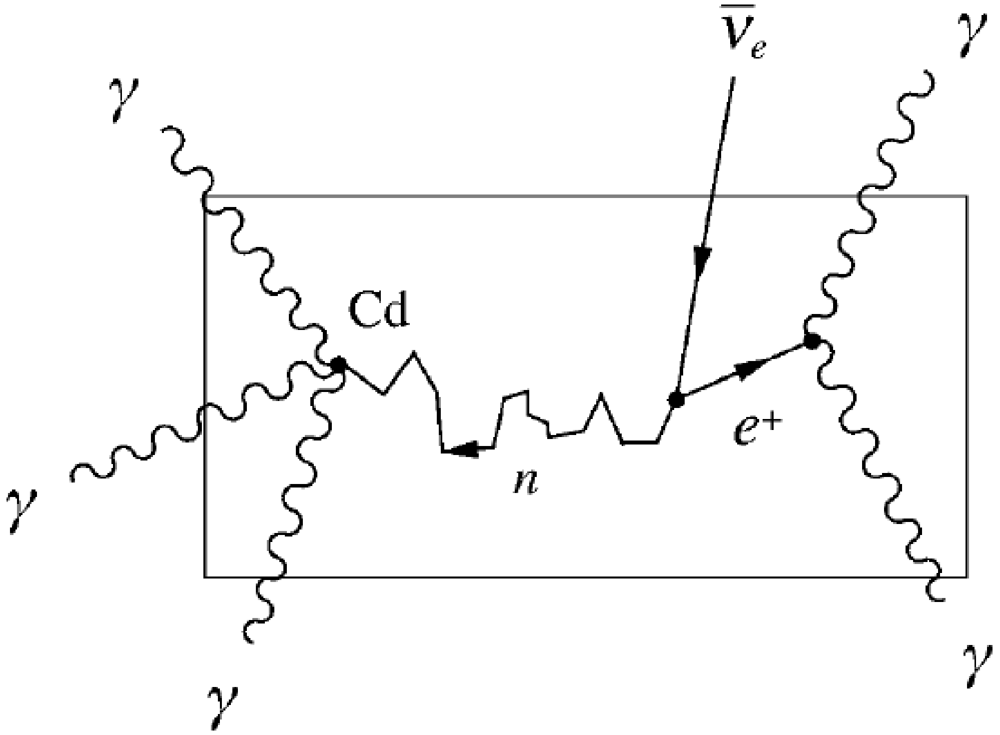


Figure 2.2 Schematic picture of an event corresponding to reaction (2.8b) in the Reines–Cowan experiment. The emitted positron rapidly annihilates with an atomic electron, and the emitted photons are detected in the adjacent tanks of scintillator as a 'prompt coincidence'. The neutron is reduced to thermal energies by repeated scattering from protons in the water before being radiatively captured by the cadmium nucleus. The emitted photons are then detected as a 'delayed coincidence' in the same pair of scintillator tanks.

Why is the interaction weak?
Do you recall?

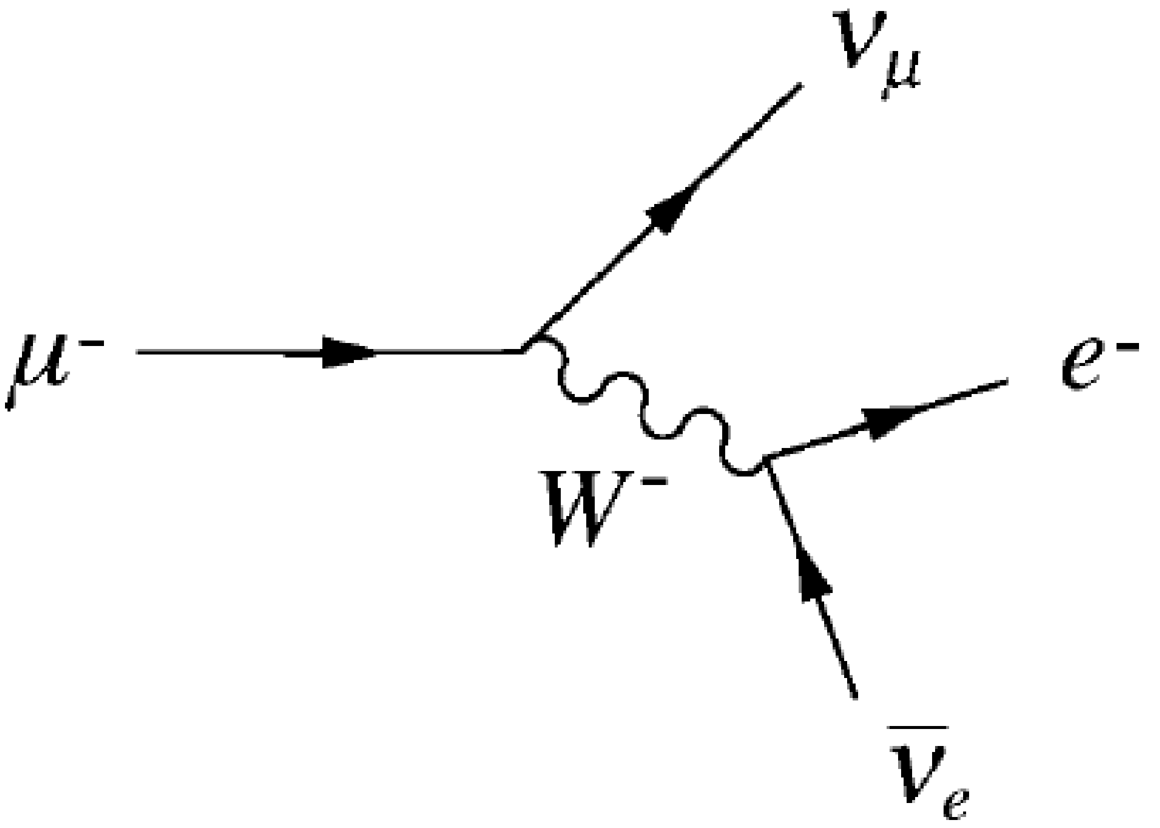
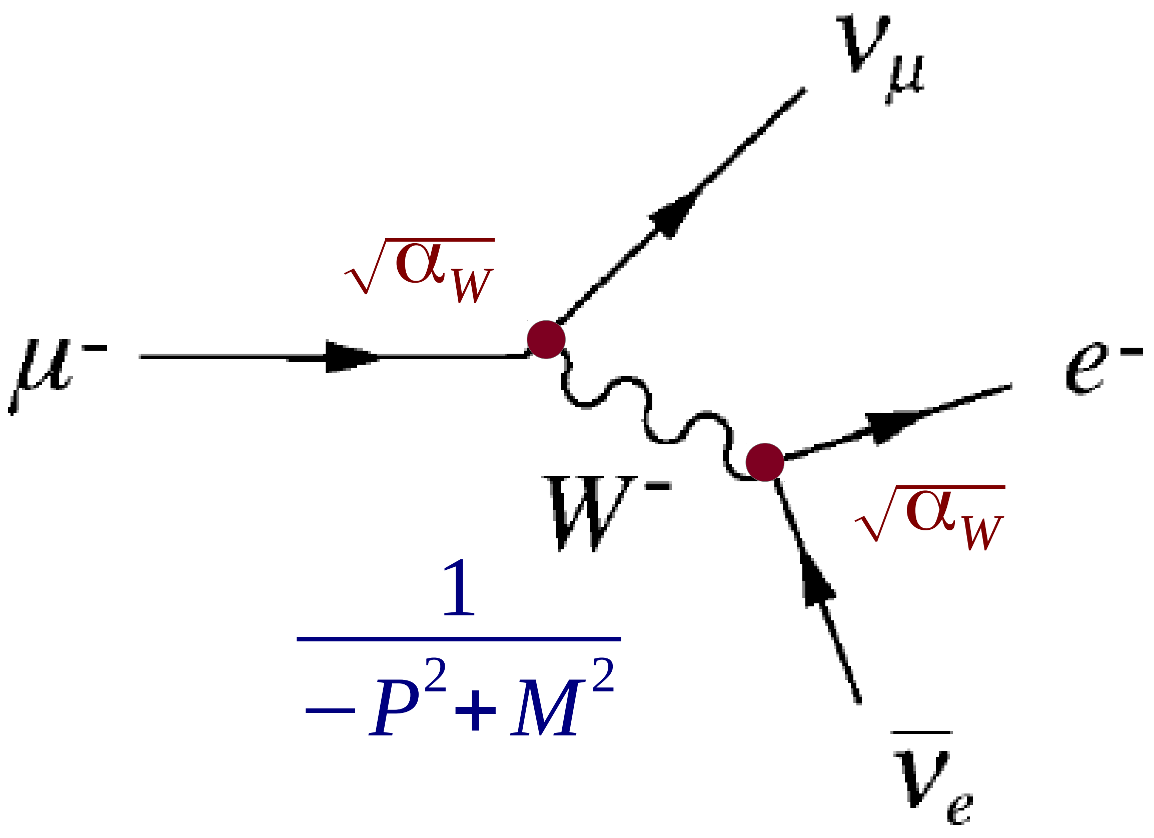


Figure 2.5 Dominant Feynman diagram for muon decay.

Propagator is very small!



$$\frac{1}{-P^2+M^2}$$

Figure 2.5 Dominant Feynman diagram for muon decay.

Almost constant

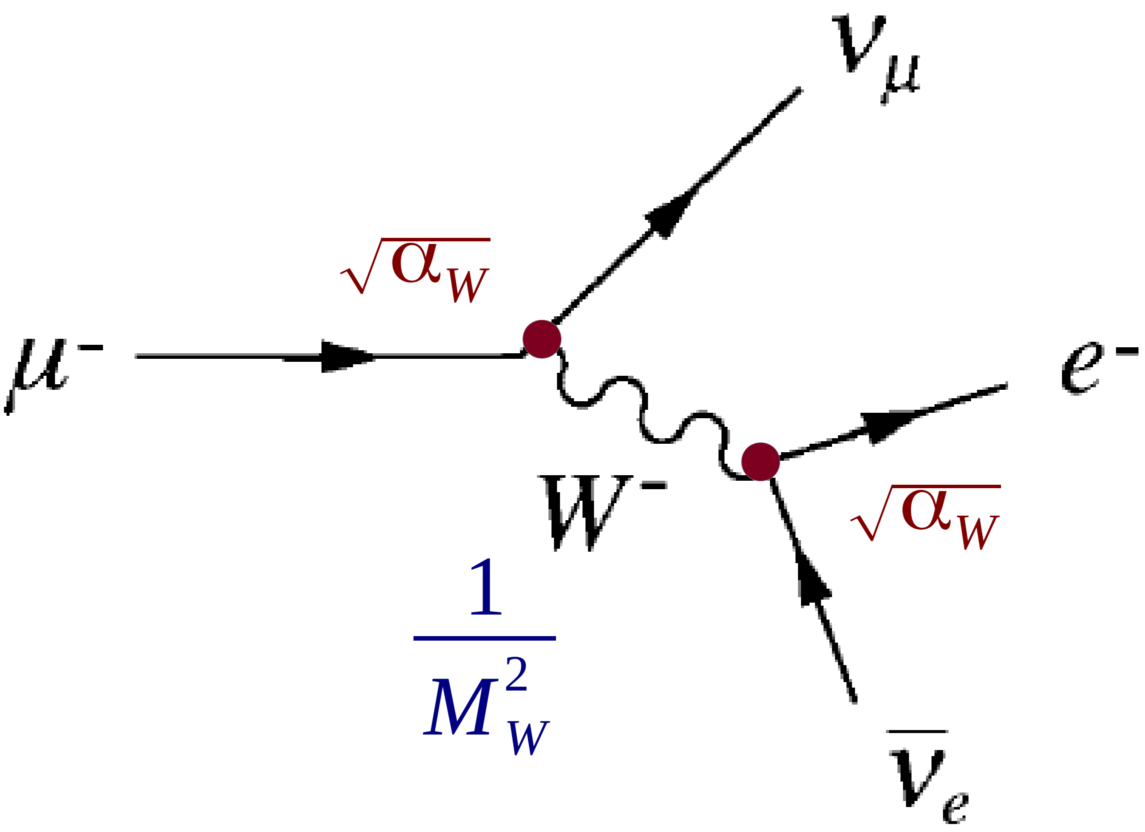


Figure 2.5 Dominant Feynman diagram for muon decay.

Good approximation: point interaction!

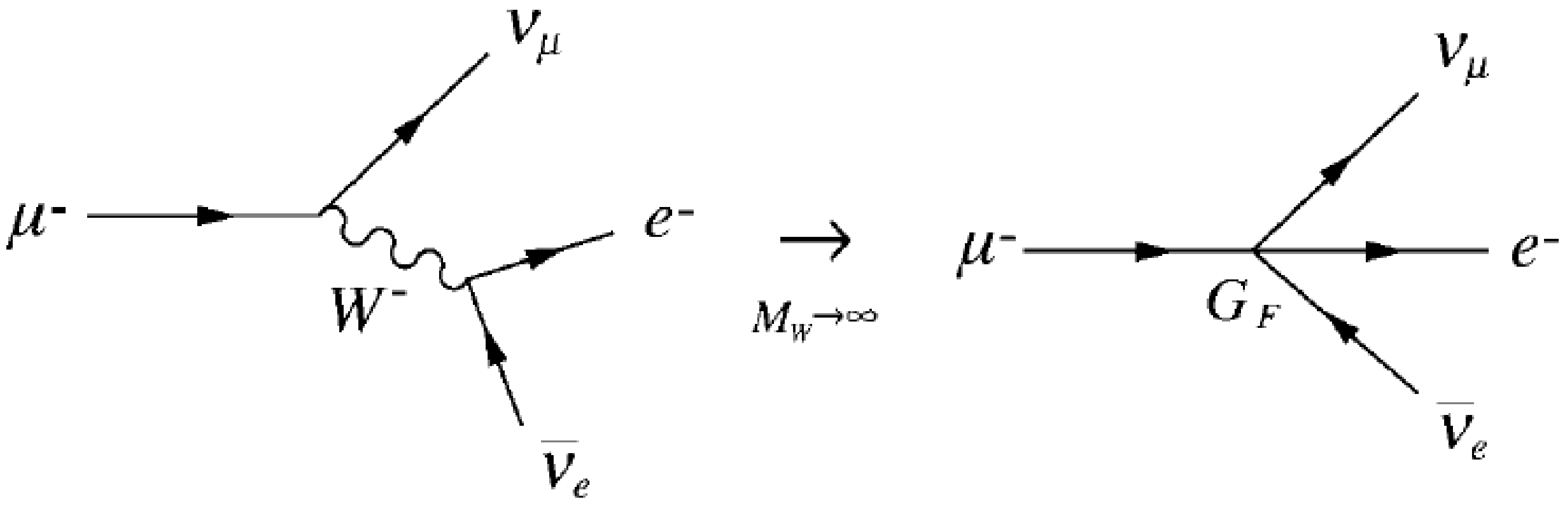


Figure 2.8 Origin of the low-energy zero-range interaction in muon decay (2.10).

Estimate α_W from G_F

- $G_F = 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$
- Relation:

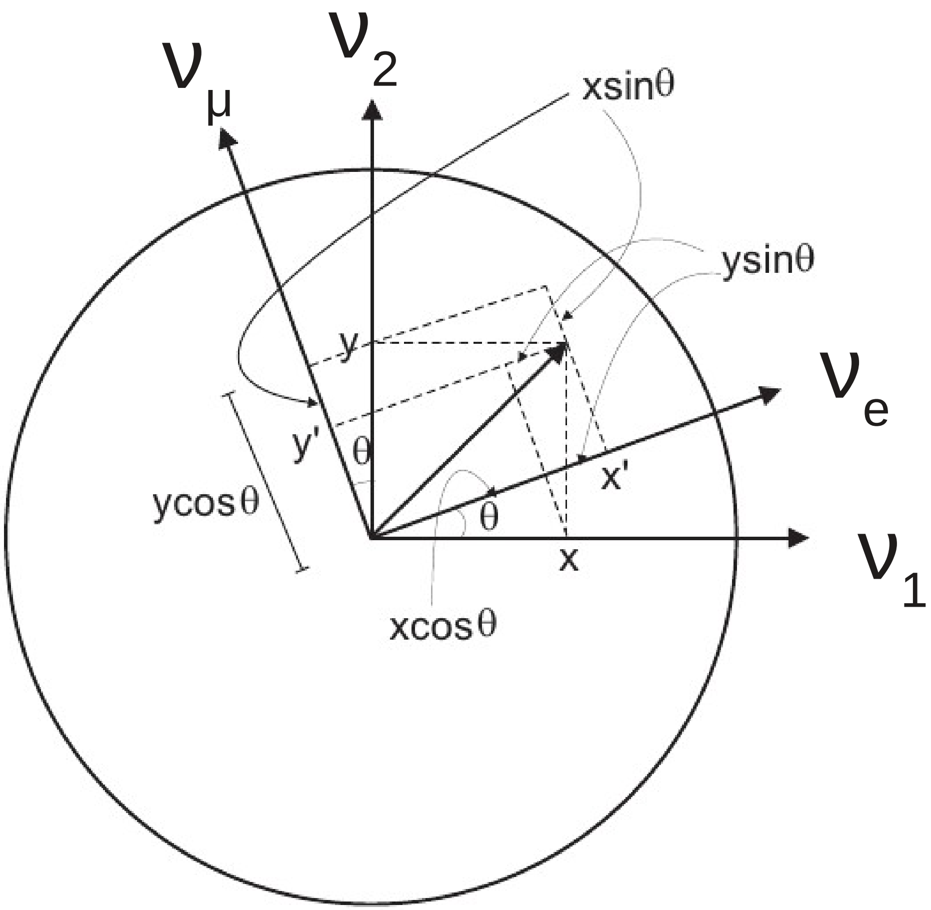
$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{M_W^2} = \frac{4\pi\alpha_W}{M_W^2} \qquad (2.17)$$

Neutrino oscillations

- An electron neutrino can be observed later as a muon neutrino
  - Very small violation of lepton number and in general negligible (see also book)
- Current understanding:
  - Neutrinos in particle zoo are not mass eignestates = free particles
  - They are interaction eigenstates = the particles the W couple too!

Neutrino oscillations

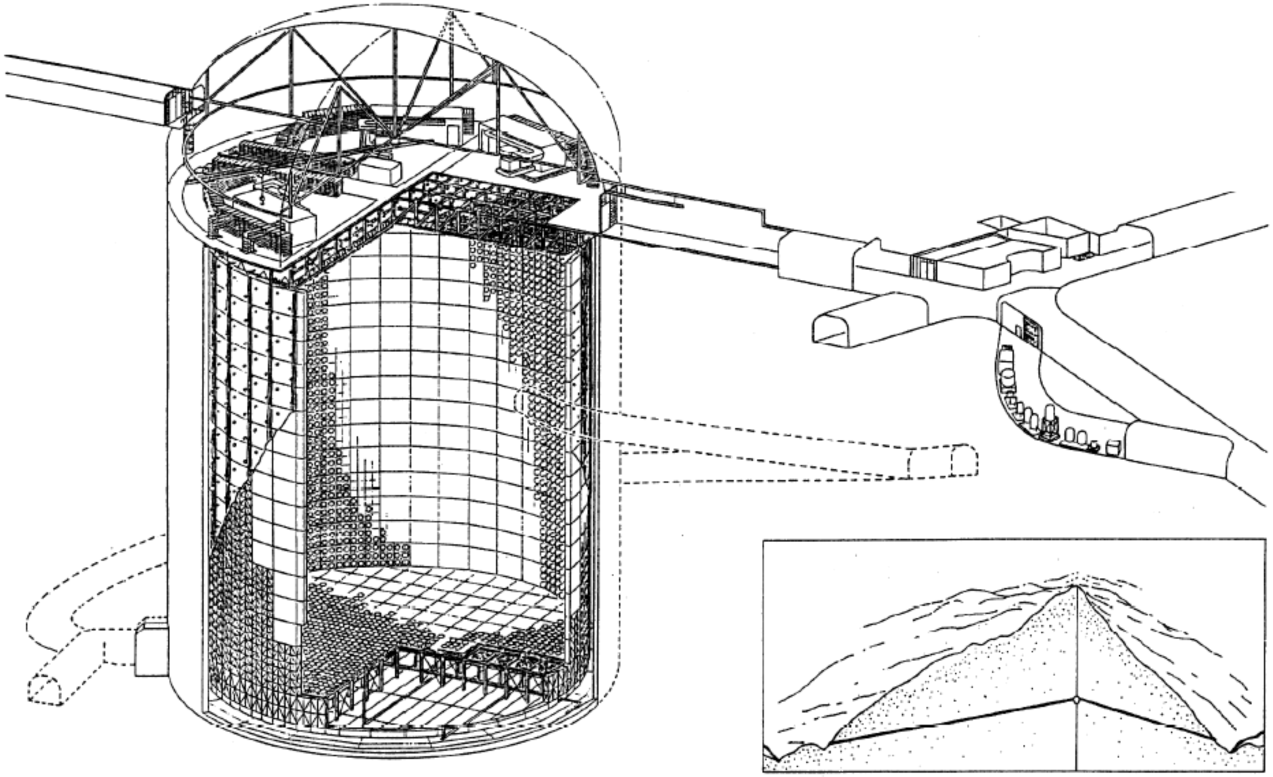
(considering only 2 states for simplicity)

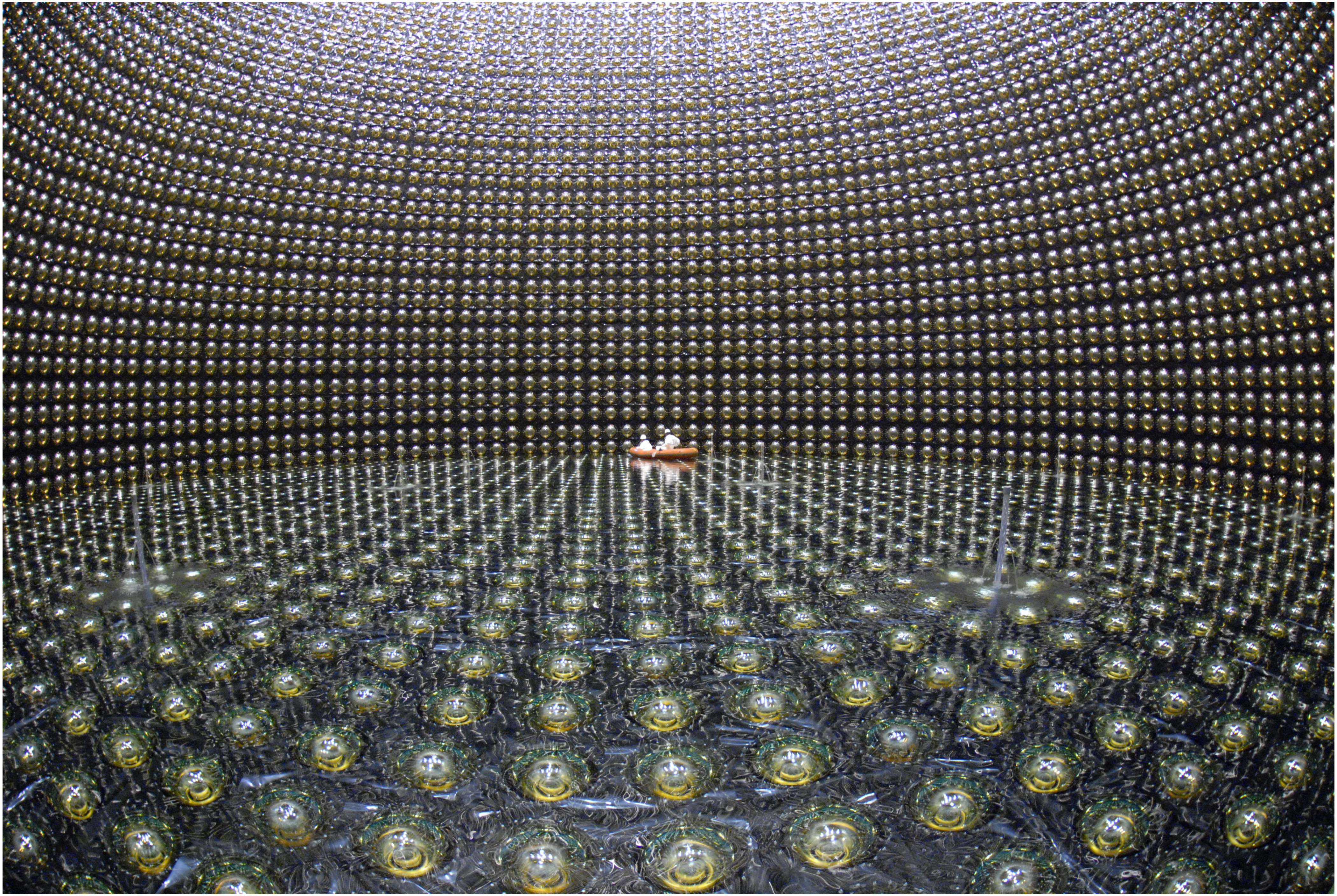


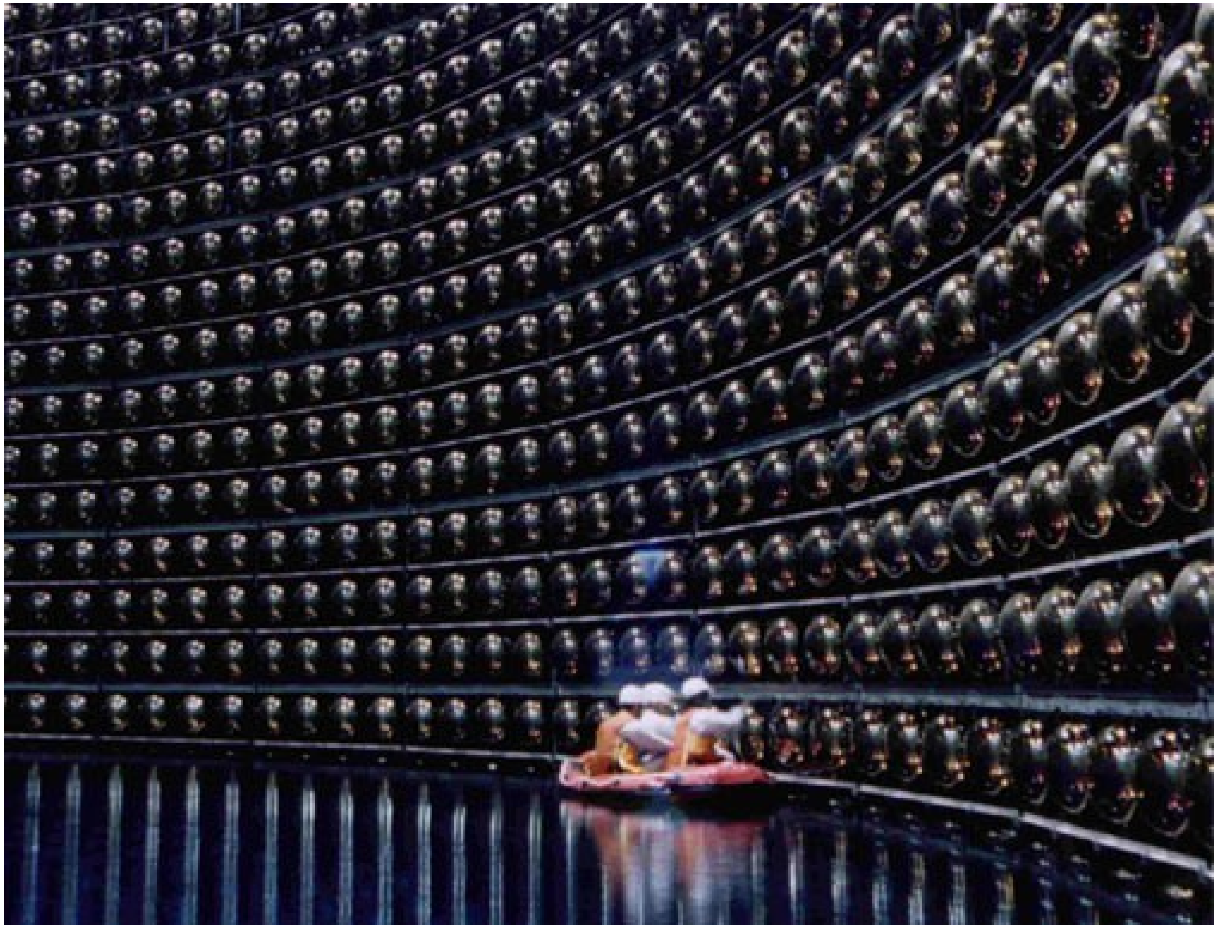
$$x' = x\cos\theta + y\sin\theta$$

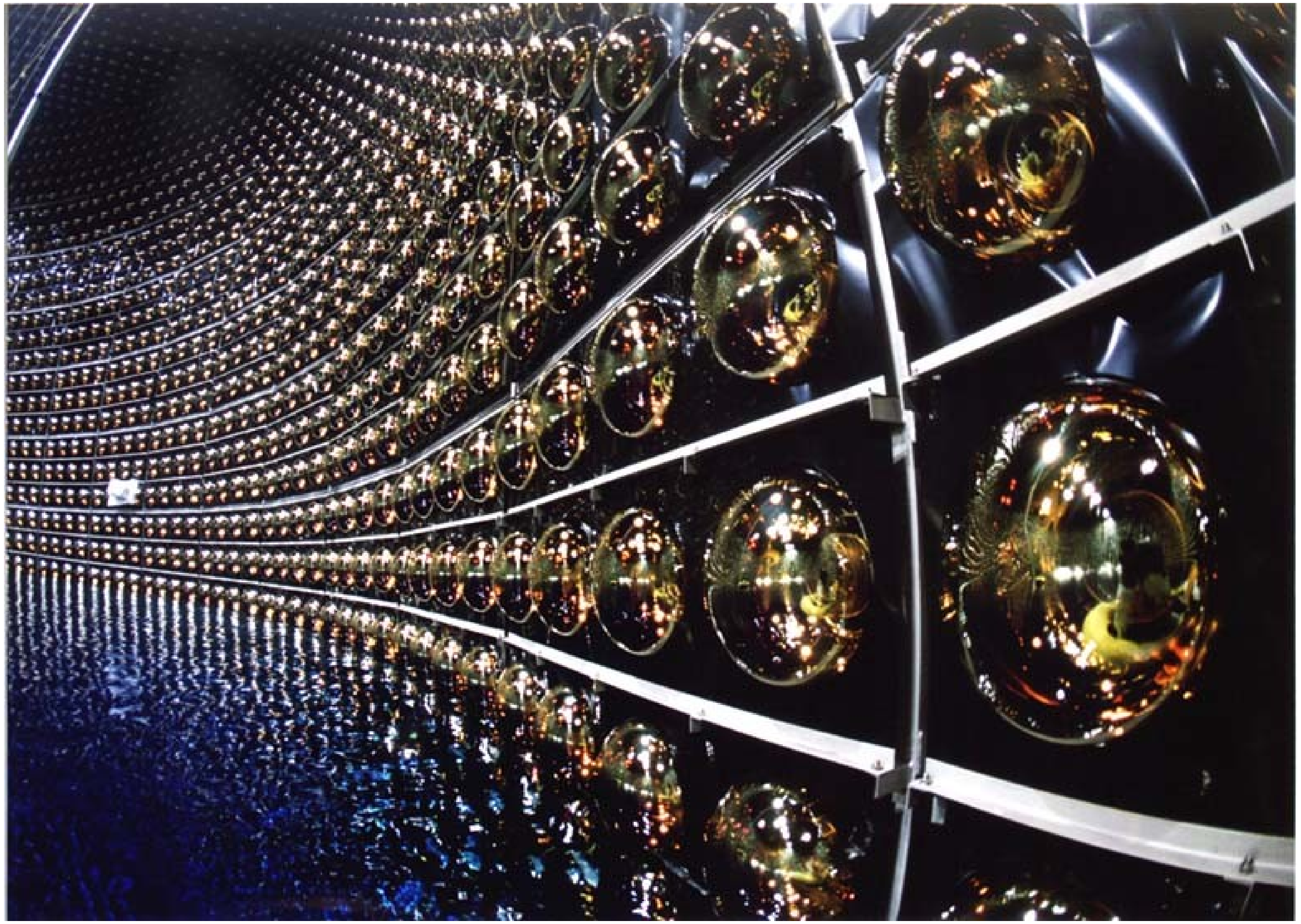
$$y' = y\cos\theta - x\sin\theta$$

Super Kamiokande (Kamioka Nucleon Decay Experiment)





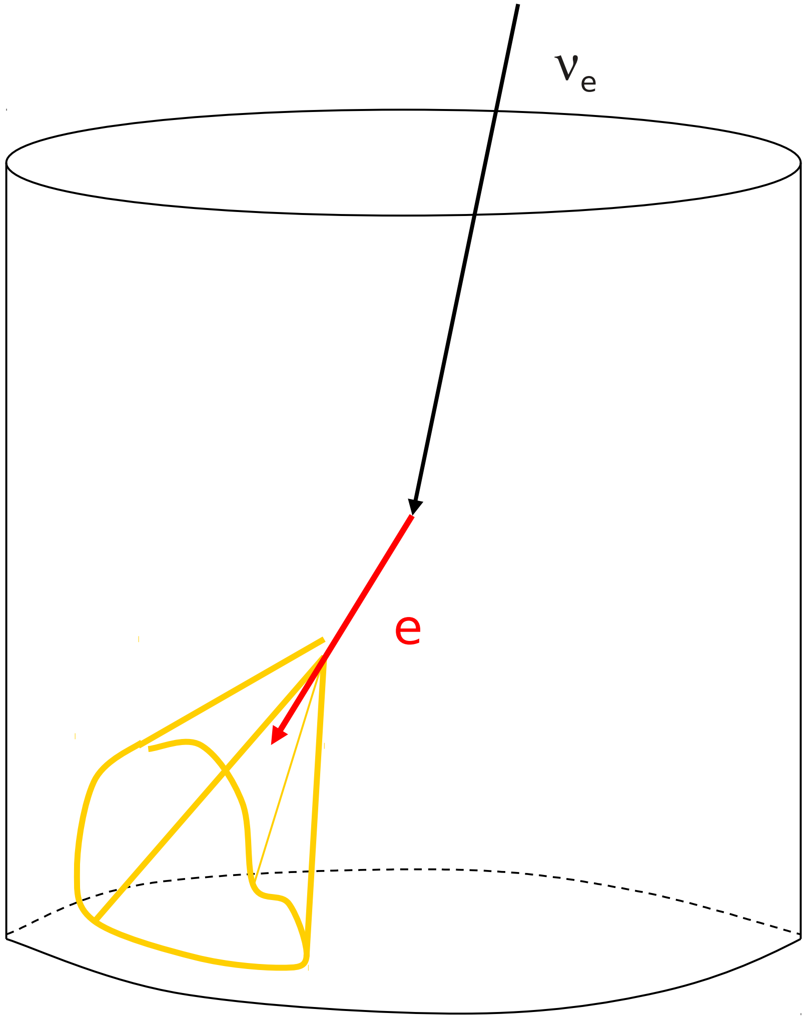




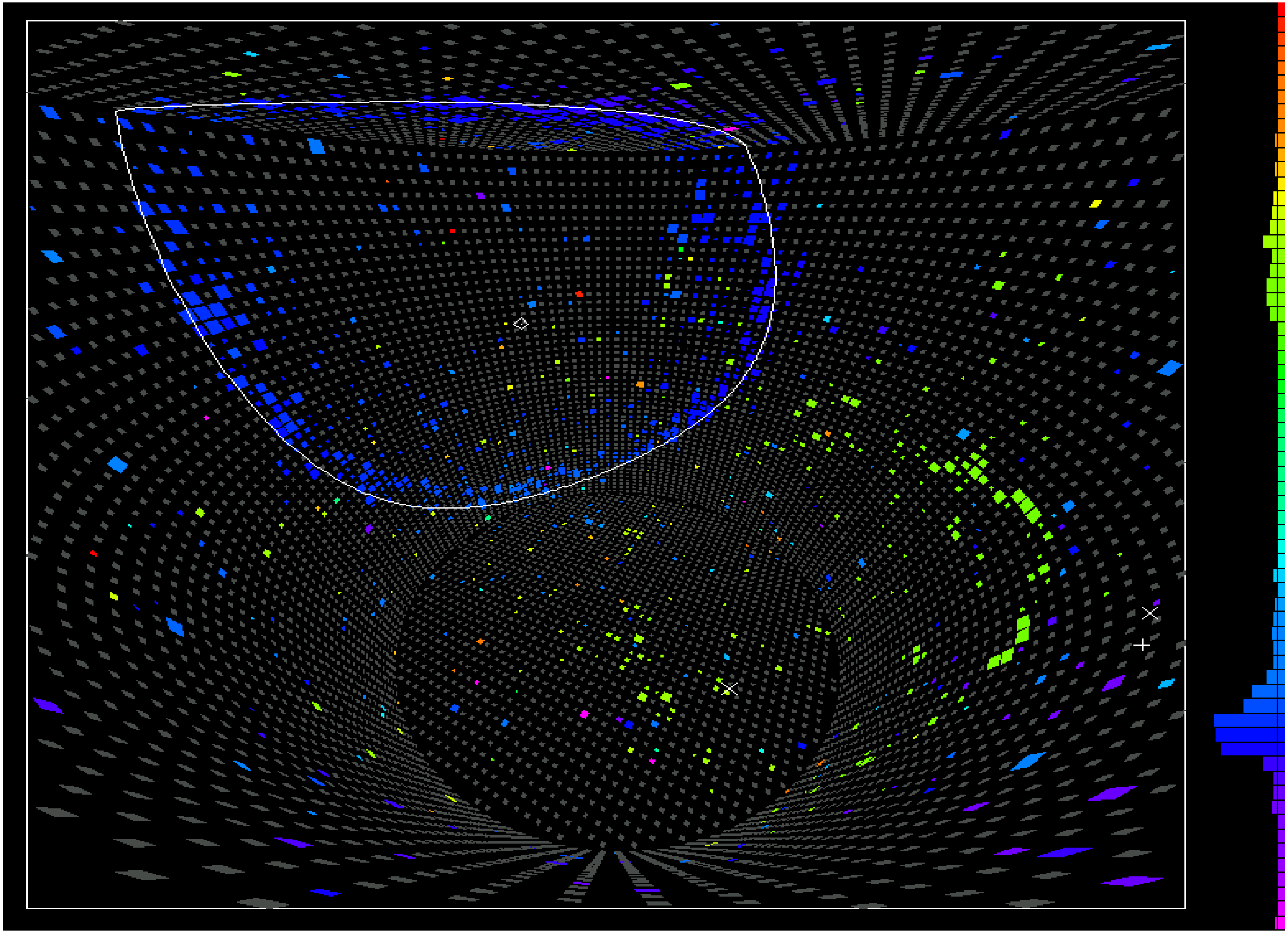
2001 accident during cleaning
Implosion of most PMTs

SUPER-KAMIOKANDE

Overview



Works by Cherenkov light



The picture before shows an incoming 1063 MeV neutrino which strikes a free proton at rest and produces a 1032 MeV muon. Different colors are related to time, blue shows the muon, green the electron of the muon decay.

Advantages of Super Kamiokande

- The direction the neutrino came from can be determined
- The time of the neutrino’s arrival can be determined
- The energy of the electron gives a rough estimate of the neutrino energy

Time of neutrino’s arrival

- It is possible to search for day/night or seasonal variations

Direction of neutrino

- One can provide solid evidence that the neutrinos are actually coming from the sun

Estimate of neutrino Energy

It is possible to distinguish neutrinos from different reaction chains in the sun

Oscillations

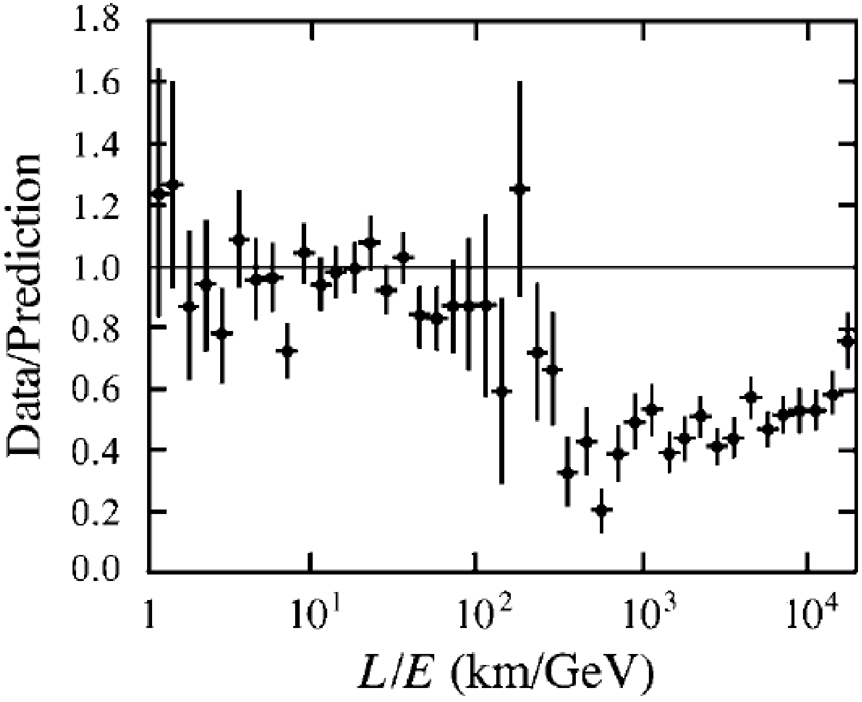


Figure 2.10 Data from the SuperKamiokande detector showing evidence for neutrino oscillations in atmospheric neutrinos. See text for details. (Reprinted Figure 4 with permission from Y. Ashie *et* al., *Phys. Rev. Lett.*, **93**, 101801. Copyright 2004 American Physical Society.)

Summary

- Neutrino interaction eigenstates: ν_e, ν_μ, ν_τ are not mass eigenstates: ν_1, ν_2, ν_3
- If the mass eigenstates have different masses their phases evolves asynchronous in time
- This gives rise to neutrino oscillations in the interaction states, e.g., $\nu_e \leftrightarrow \nu_\mu$ that have been measured experimentally (indirectly = disappearance)
- There are ideas to also make neutrino experiments at ESS!