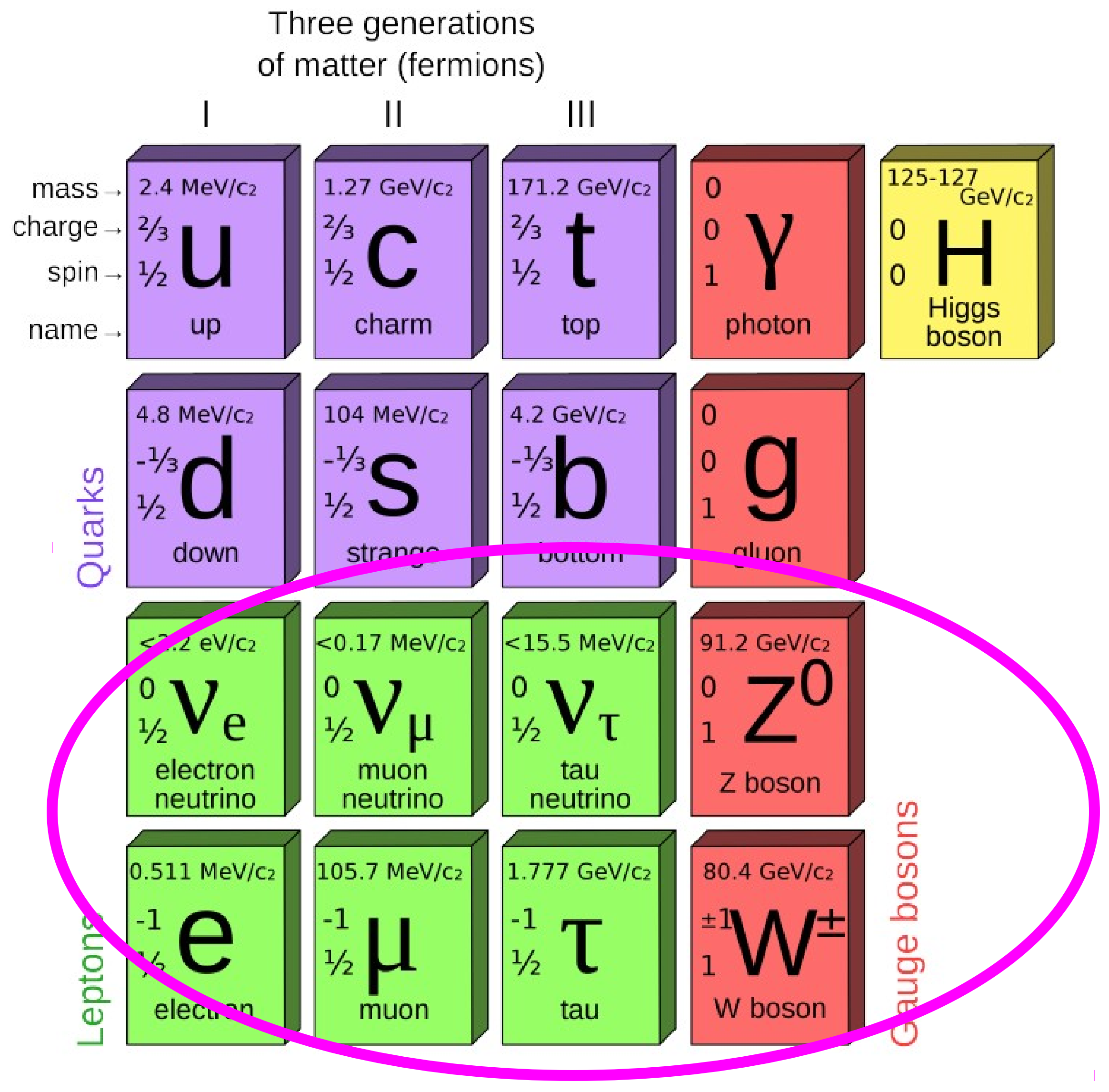
Leptons and the Weak Interaction



Question:
Do you know any weak decays?

Microscopic picture of decay

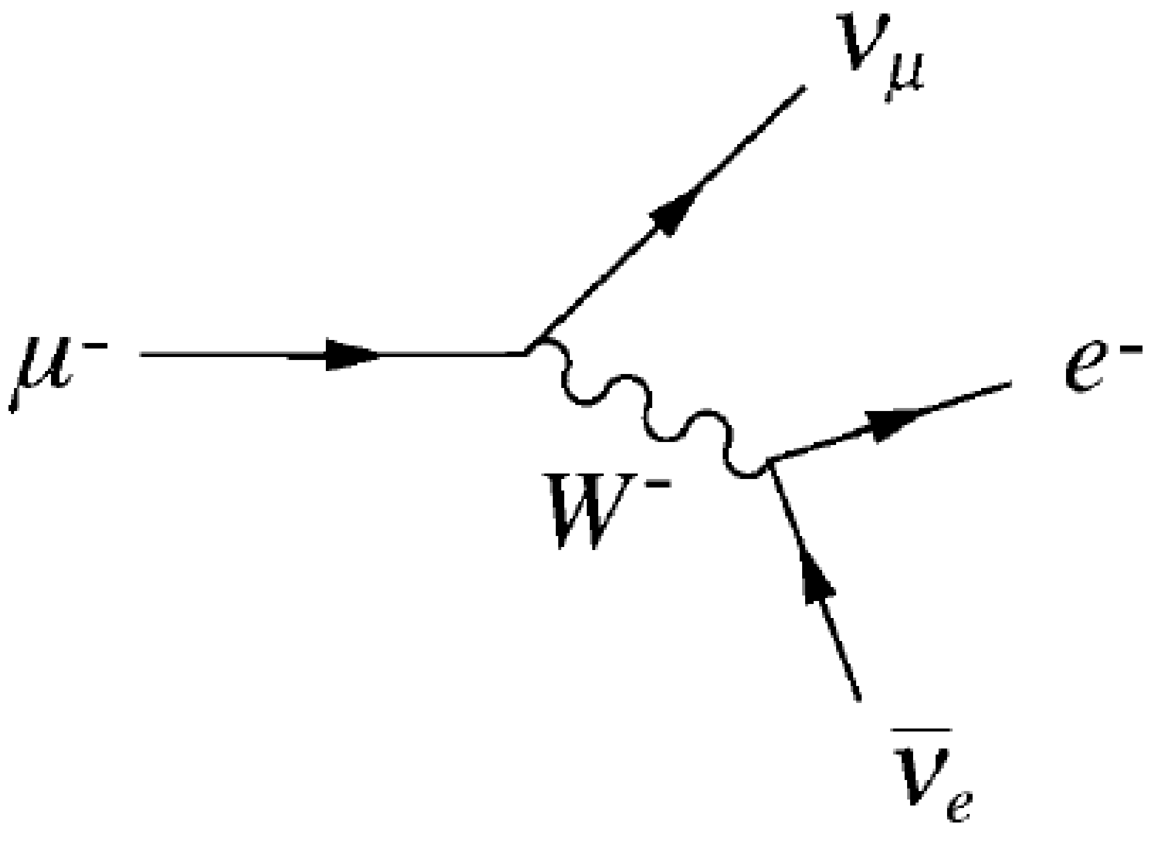


Figure 2.5 Dominant Feynman diagram for muon decay.

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

Lepton number is conserved in weak (all) interactions

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

And similar for Lμ and Lτ

Microscopically the picture is that:
Z does not change particle type
W works like this:

$$e^- \rightarrow \nu_e + W^-$$

+ "crossing" gives:

$$e^- + \bar{\nu}_e \rightarrow W^-$$

$$\bar{\nu}_e \rightarrow W^- + e^+$$

$$\bar{\nu}_e + W^+ \rightarrow e^+$$

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 of the neutrino (1/2)

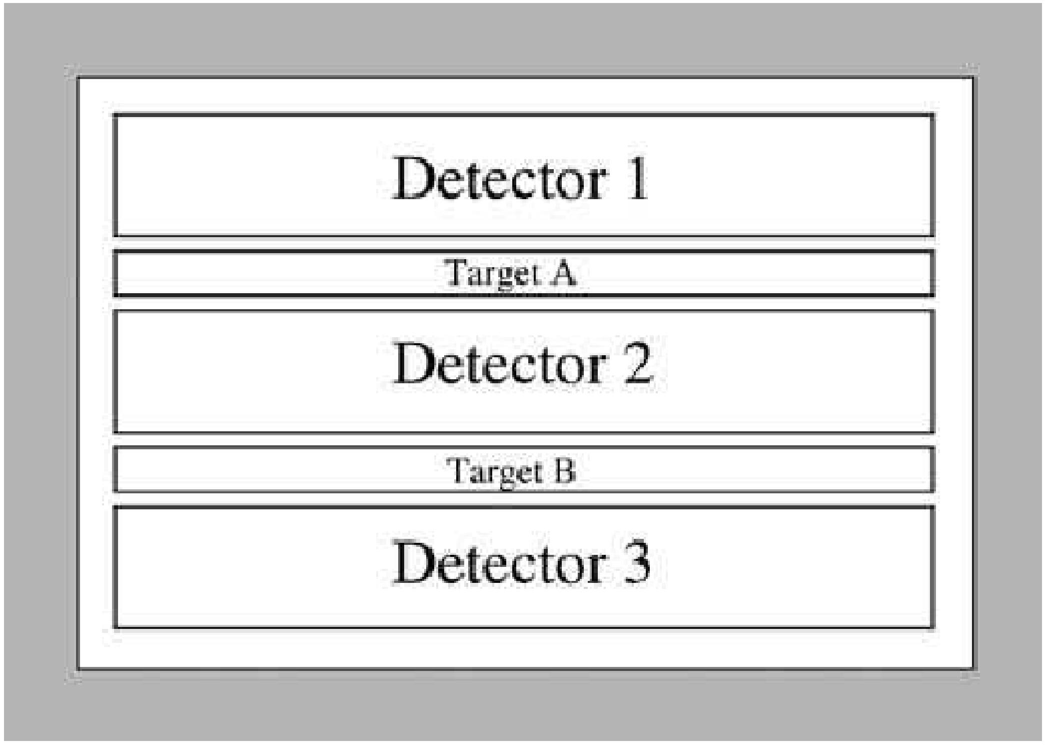


Figure 2.1 Schematic diagram of the apparatus used by Reines and Cowen to detect anti-neutrinos. The two target tanks, containing an aqueous solution of cadmium chloride, are sandwiched between three detector tanks of liquid scintillator. The whole apparatus is surrounded by heavy shielding to eliminate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

Discovery of the neutrino (2/2)

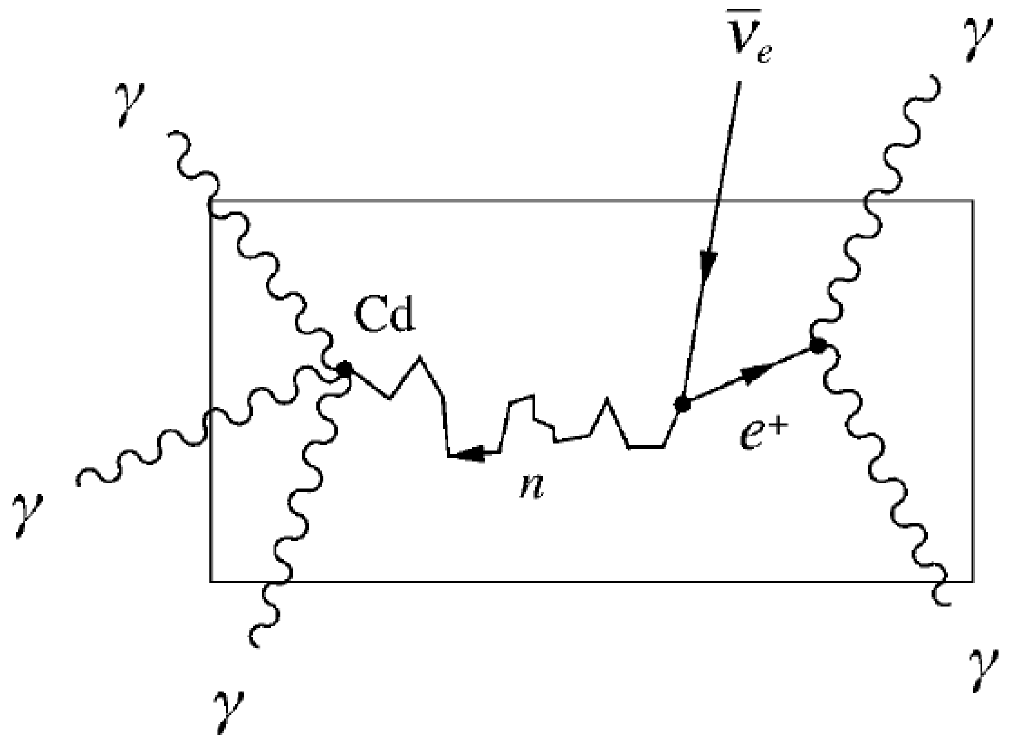


Figure 2.2 Schematic picture of an event corresponding to reaction (2.8b) in the Reines–Cowan experiment. The emitted positron rapidly annihilates with an atomic electron, and the emitted photons are detected in the adjacent tanks of scintillator as a 'prompt coincidence'. The neutron is reduced to thermal 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?

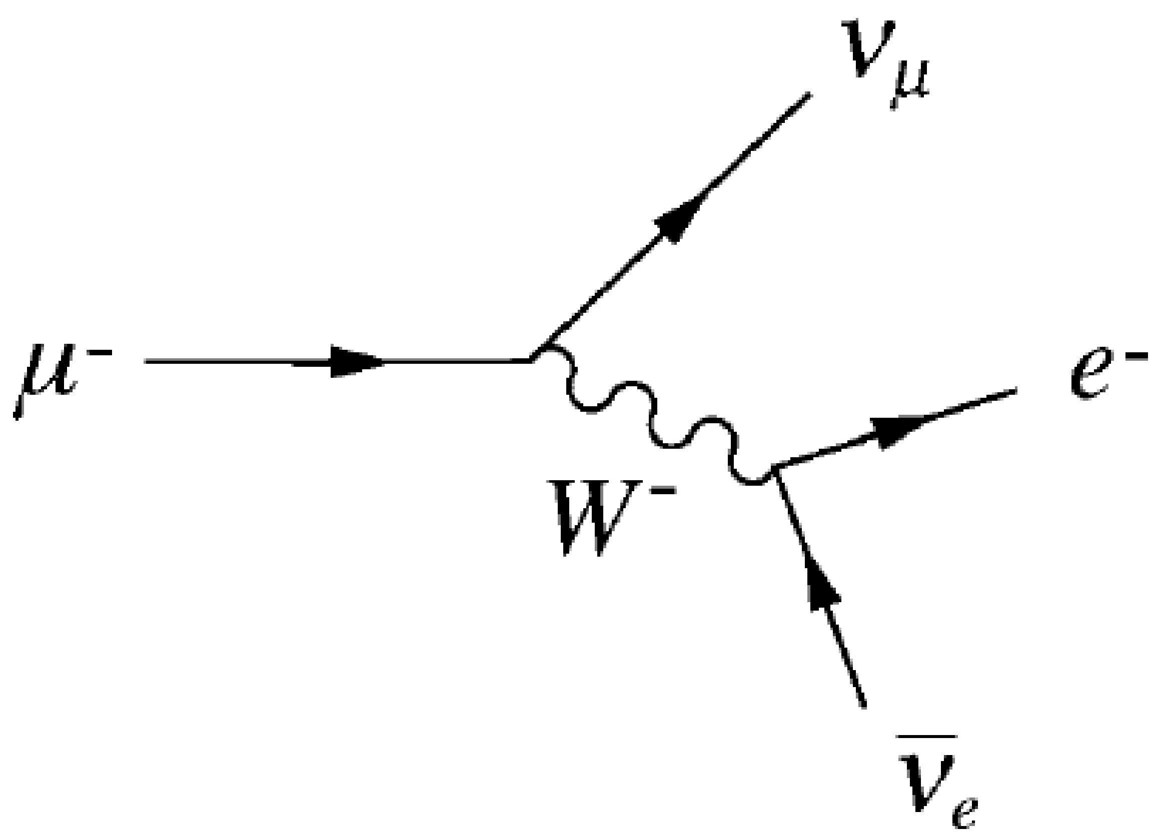


Figure 2.5 Dominant Feynman diagram for muon decay.

Propagator is very small!

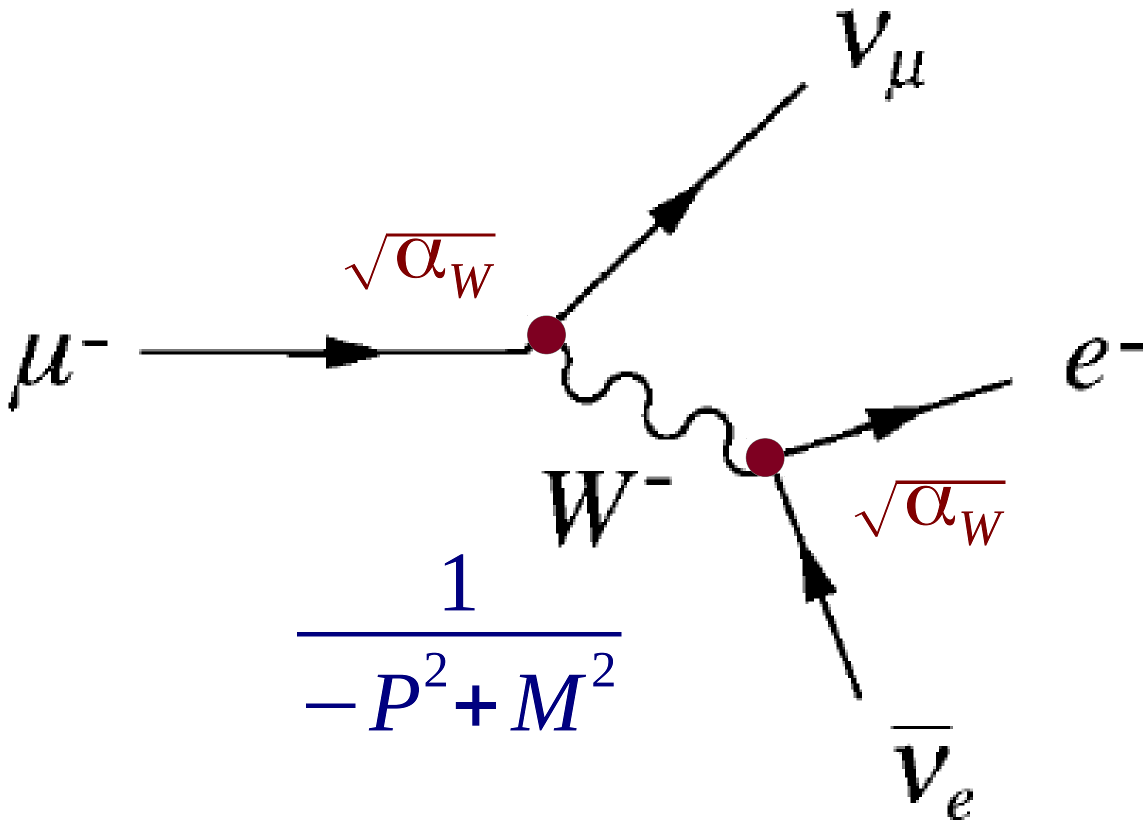


Figure 2.5 Dominant Feynman diagram for muon decay.

Almost constant

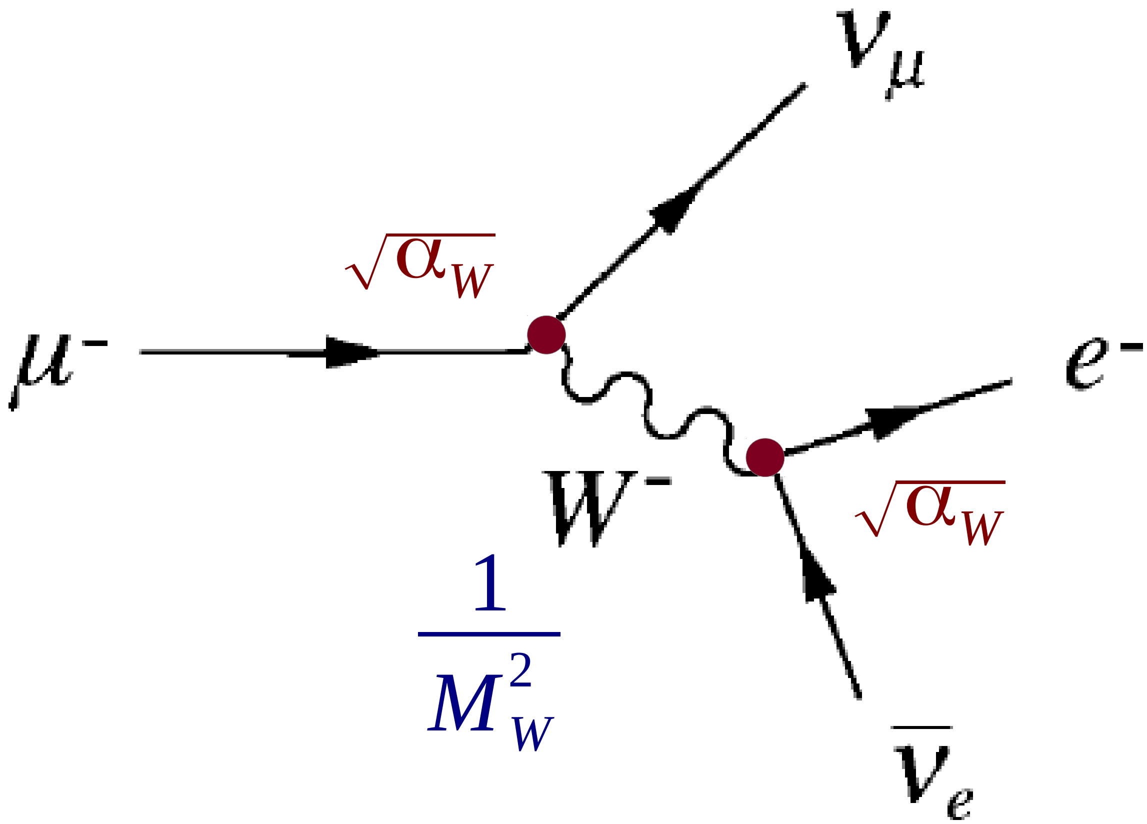
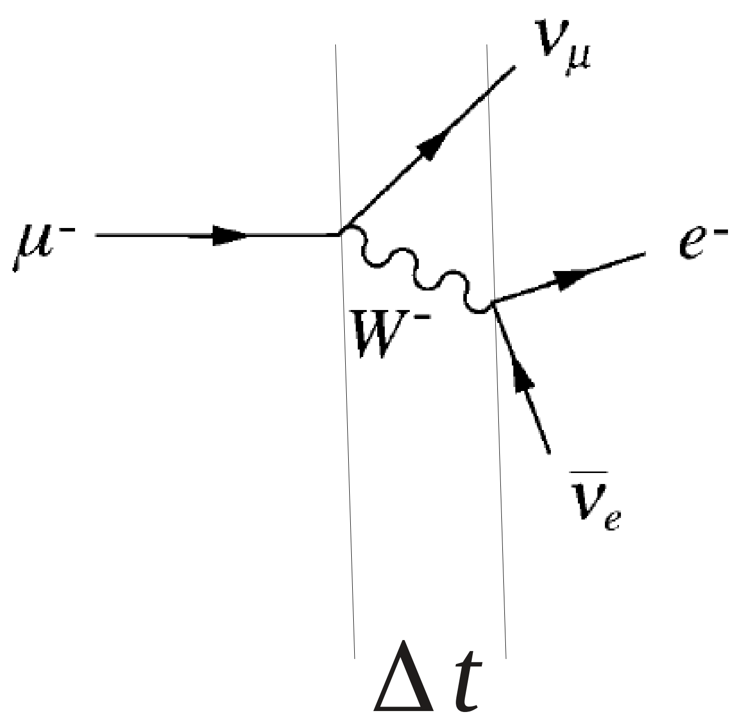


Figure 2.5 Dominant Feynman diagram for muon decay.

Recall why it is so



- The strength of the interaction goes as Δt^2
- And since W is so massive

$$\Delta t \sim \frac{\hbar}{\Delta E} \sim \frac{\hbar}{M_W}$$

Good approximation: point interaction!

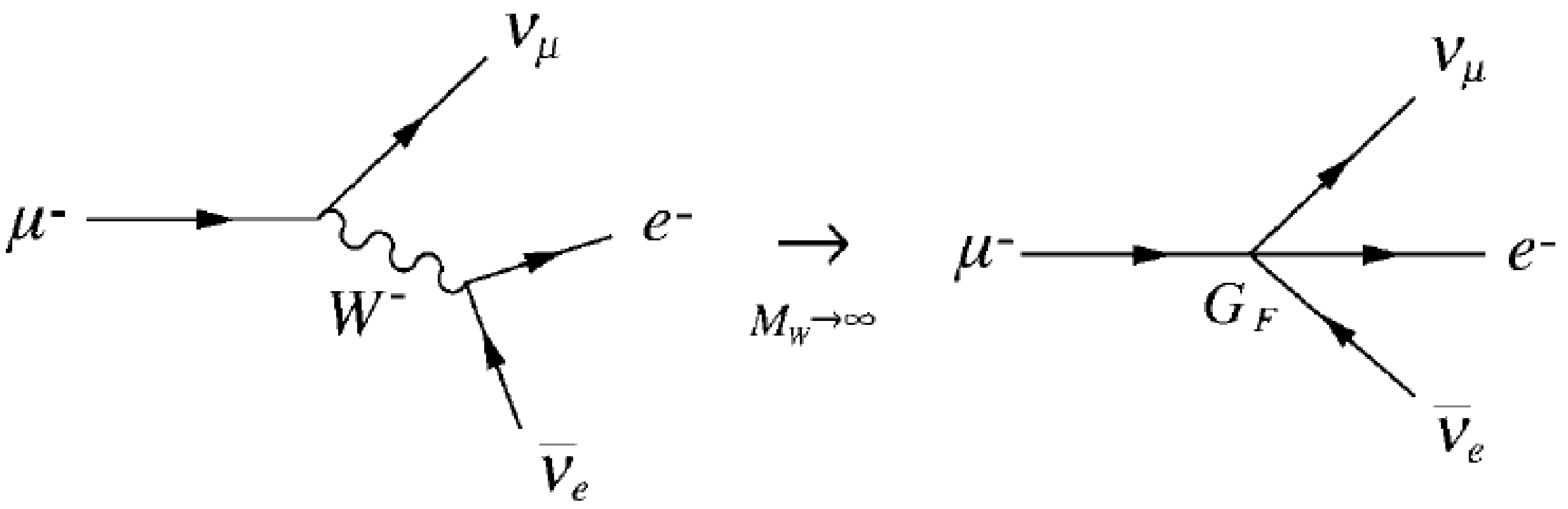


Figure 2.8 Origin of the low-energy zero-range interaction in muon decay (2.10).

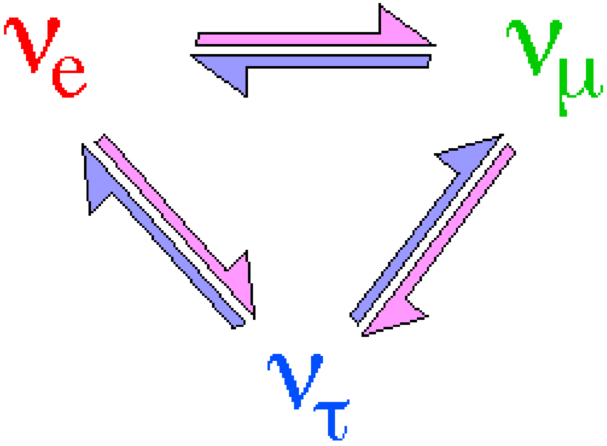
Estimate α_W from G_F

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

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

Look at exercise 1.2, 1.3 & 1.6

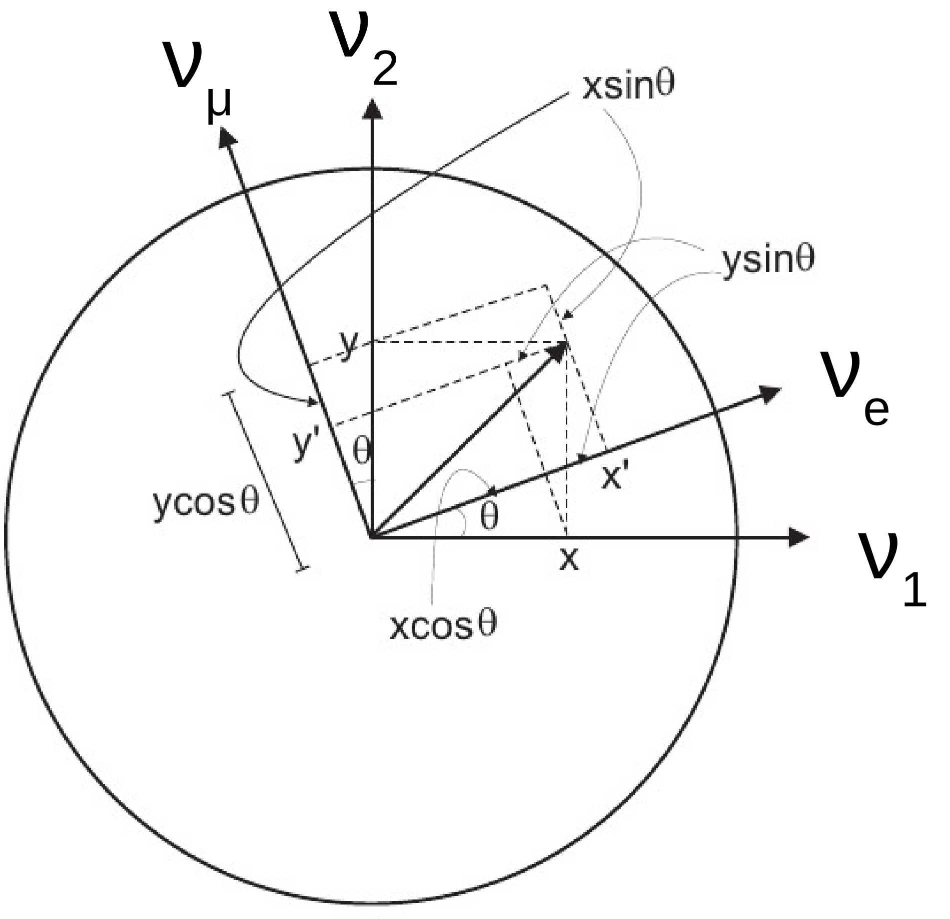
Neutrino oscillations



Neutrino oscillations

- Proposed as solution to solar neutrino problem
- 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!

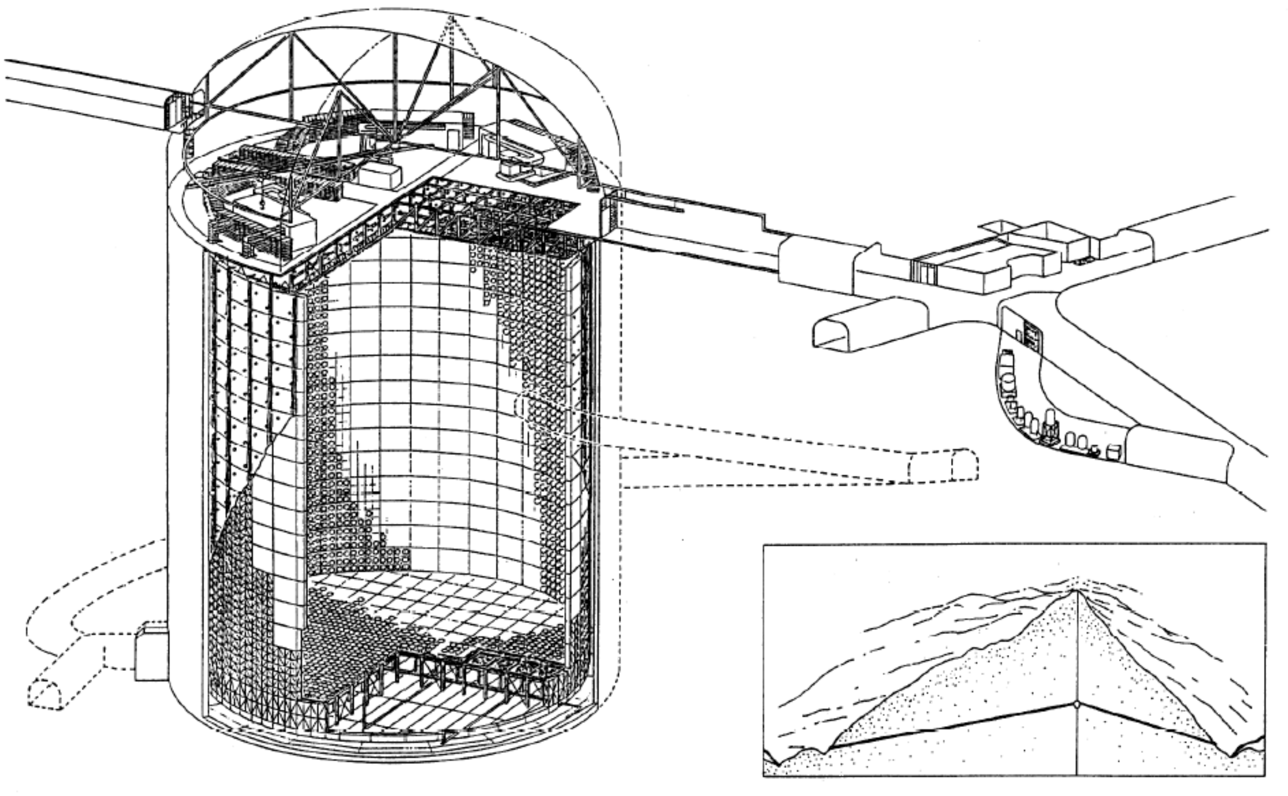
Neutrino oscillations
(considering only 2 states for simplicity)

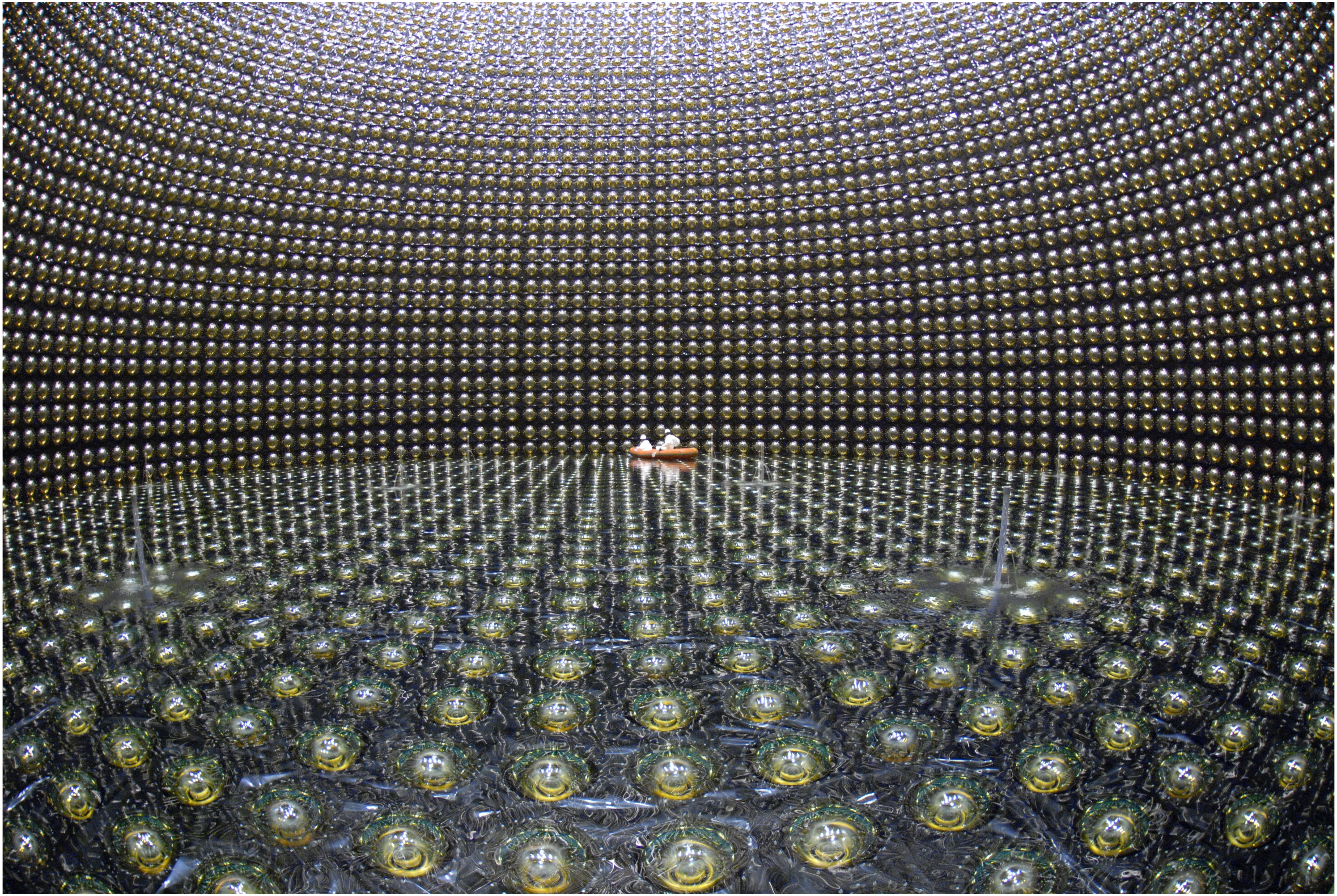


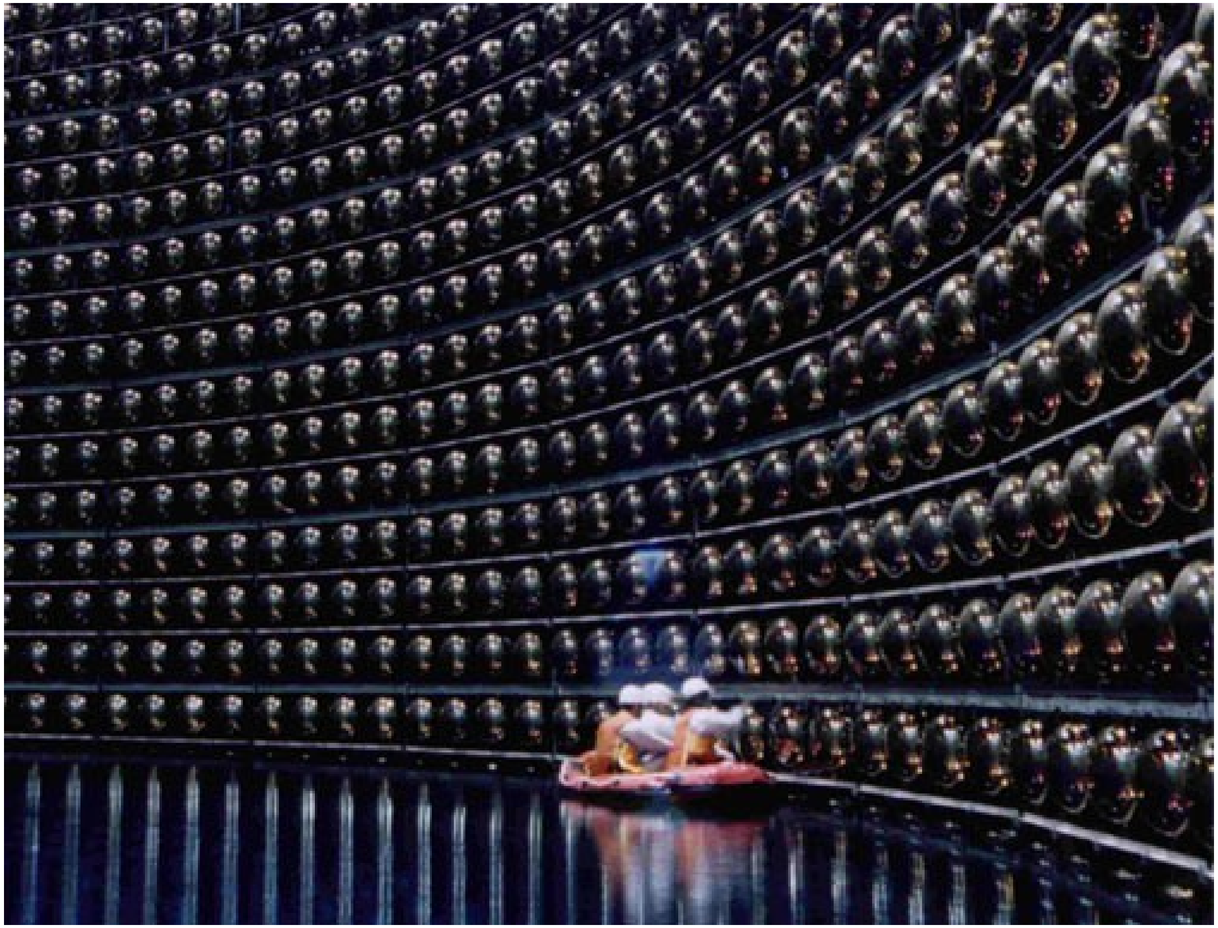
$$x' = x\cos\theta + y\sin\theta$$

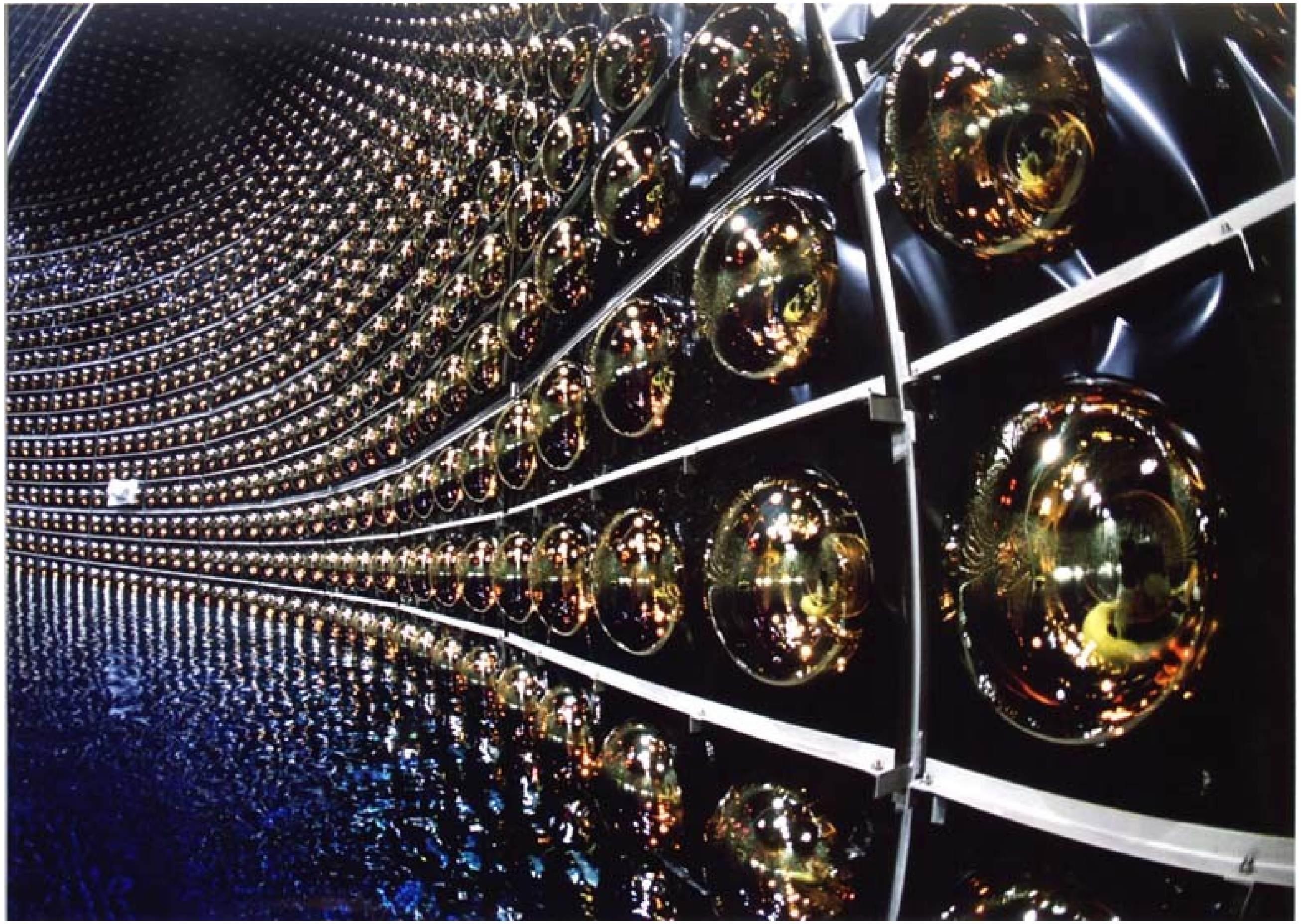
$$y' = y\cos\theta - x\sin\theta$$

Super Kamiokande (Kamioka Nucleon Decay Experiment)



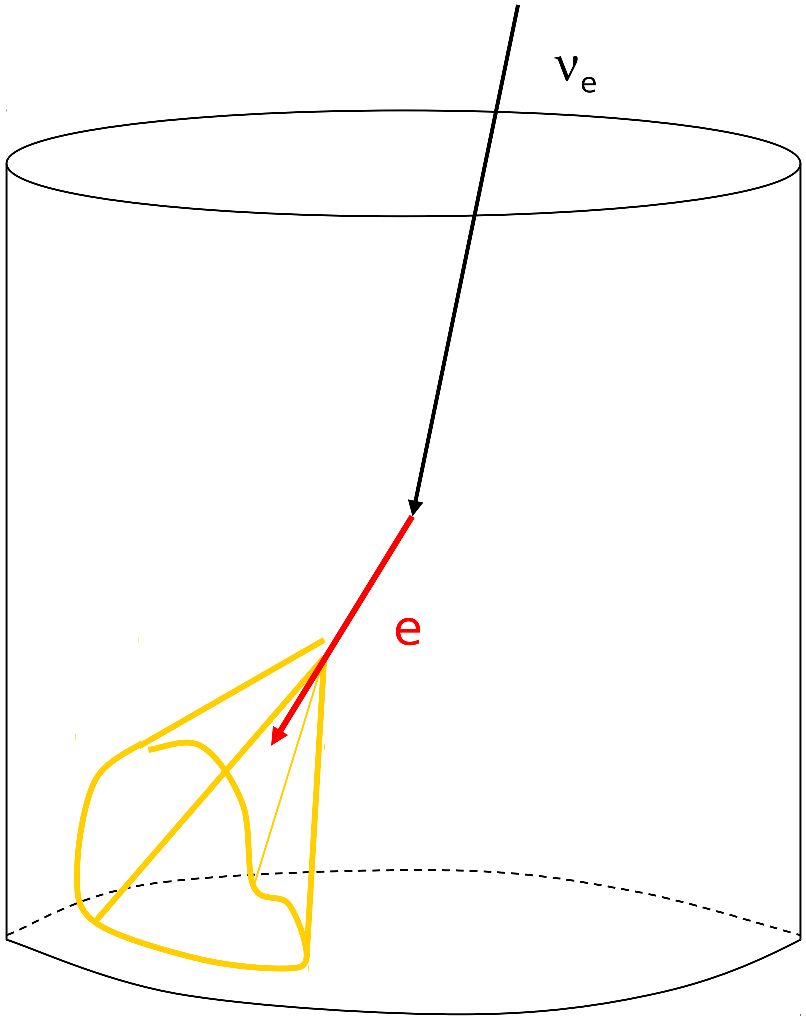




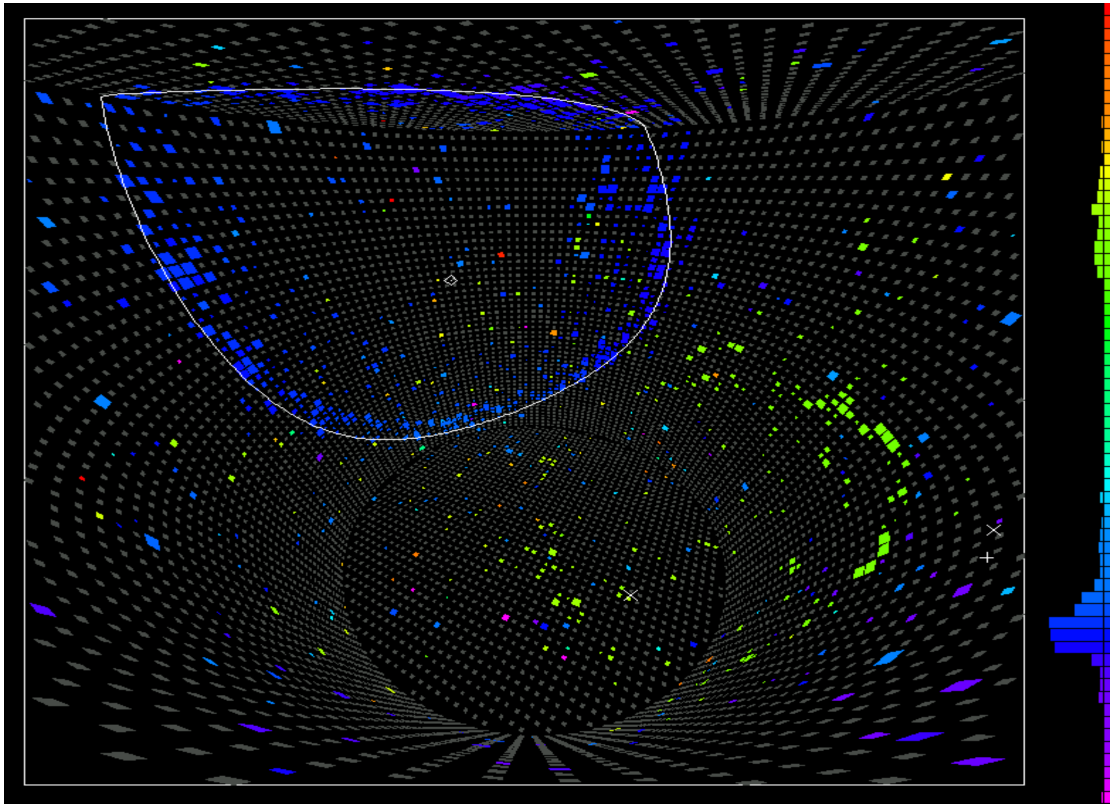


2001 accident during cleaning
Implosion of most PMTs

Overview



Works by Cherenkov light



The picture 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
  - It is possible to search for day/night or seasonal variations
- The time of the neutrino's arrival can be determined
  - One can provide solid evidence that the neutrinos are actually coming from the sun
- The energy of the electron gives a rough estimate of the neutrino energy
  - It is possible to distinguish neutrinos from different reaction chains in the sun

Oscillations

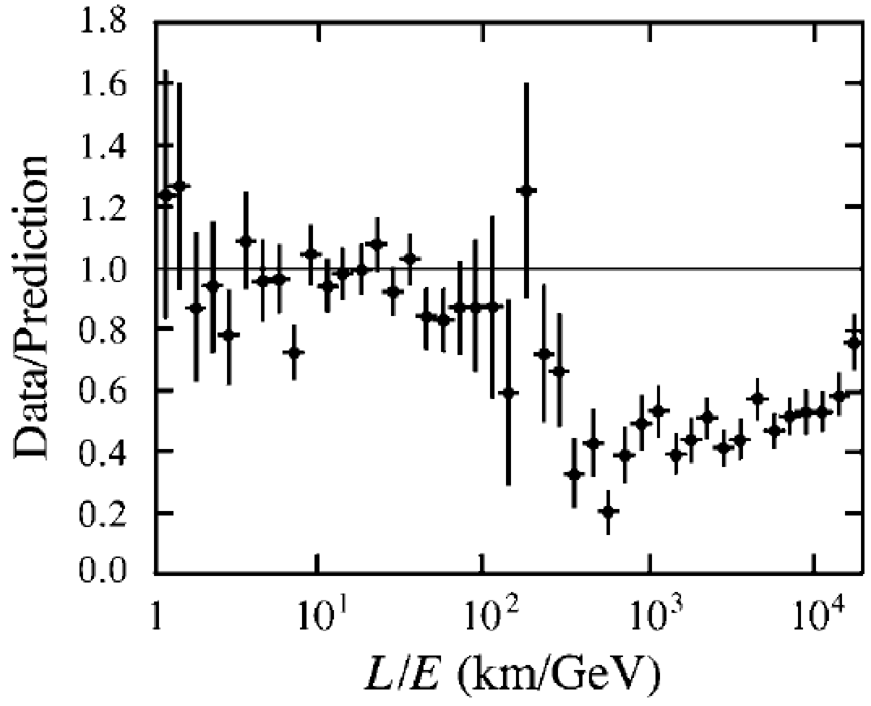


Figure 2.10 Data from the SuperKamiokande detector showing evidence for neutrino oscillations in atmospheric neutrinos. See text for details. (Reprinted Figure 4 with permission from Y. Ashie *et al.*, *Phys. Rev. Lett.*, **93**, 101801. Copyright 2004 American Physical Society.)

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!

ESSνSB Project for Leptonic CP Violation Discovery based on the European Spallation Source Linac (status)

Marcos DRACOS

IPHC-IN2P3/CNRS Université de Strasbourg

ESS Neutrino Super Beam (ESSνSB)

A Very Intense Neutrino Super Beam Experiment for Leptonic CP Violation Discovery based on the European Spallation Source Linac: A Snowmass 2013 White Paper

arXiv:1212.5048
arXiv:1309.7022

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14 participating institutes from 10 different countries, among them ESS and CERN

CP Violating Observables (and MH)

$$P_{\nu_\mu\to\nu_e(\bar\nu_\mu\to\bar\nu_e)} = s_{23}^2 \sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{\tilde B_\mp}\right)^2 \sin^2\left(\frac{\tilde B_\mp L}{2}\right)$$

atmospheric

Non-CP terms

$$+c_{23}^2 \sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$

solar

$$+\tilde J \frac{\Delta_{12}}{A}\frac{\Delta_{13}}{\tilde B_\mp}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde B_\mp L}{2}\right)\cos\left(\pm\delta_{CP}-\frac{\Delta_{13}L}{2}\right)$$

interference

CP violating

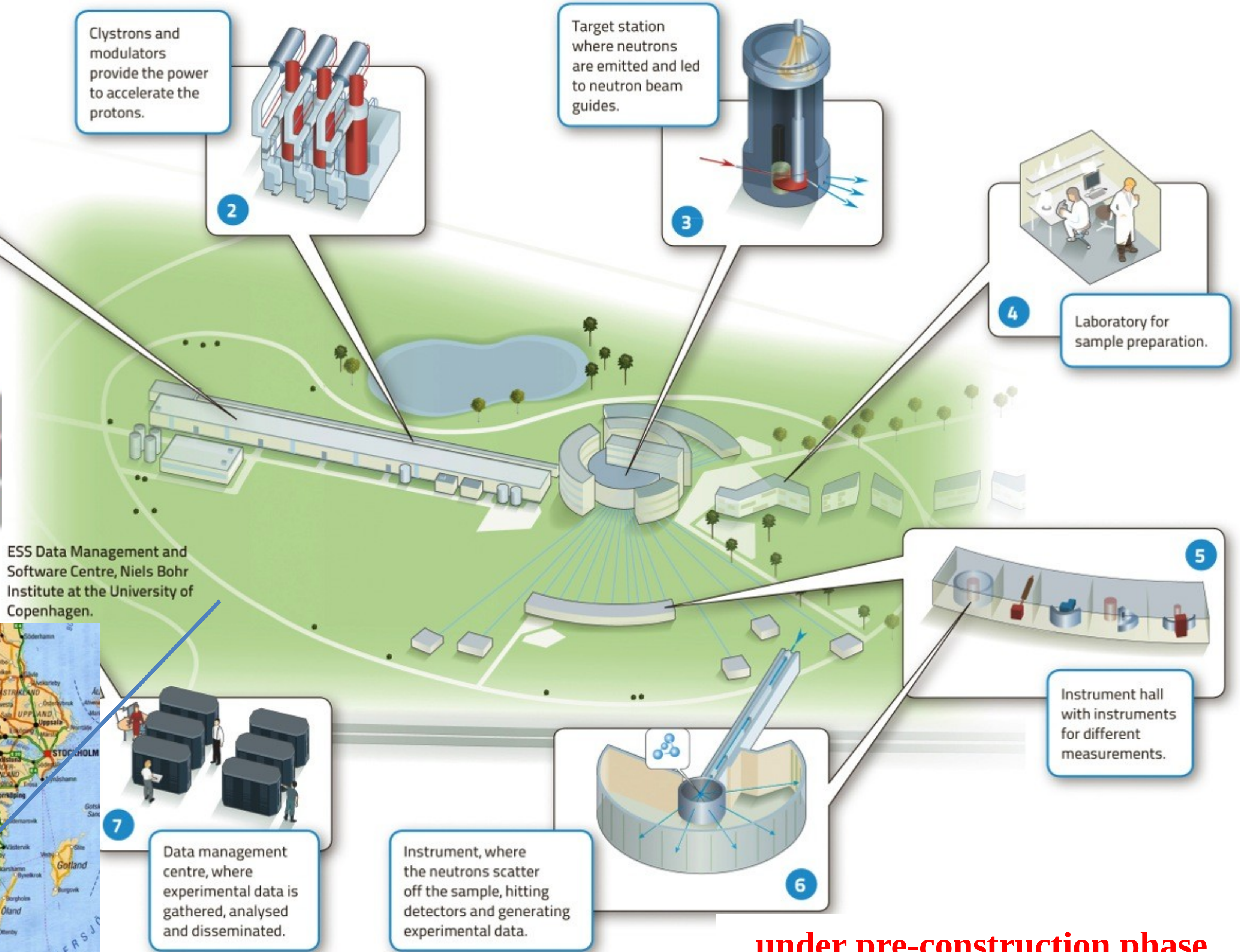
$$\tilde J \equiv c_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13},\ \Delta_{ij}\equiv\frac{\Delta m_{ij}^2}{2E_\nu},\ \tilde B_\mp \equiv \left|A\mp\Delta_{13}\right|,\ \ A=\sqrt{2}G_F N_e$$

matter effect
⇒ accessibility to mass hierarchy
⇒ long baseline

$$\mathcal{A} = \frac{P_{\nu_\mu\to\nu_e} - P_{\bar\nu_\mu\to\bar\nu_e}}{P_{\nu_\mu\to\nu_e} + P_{\bar\nu_\mu\to\bar\nu_e}}$$

≠0 ⇒ CP Violation
be careful, matter effects also create asymmetry

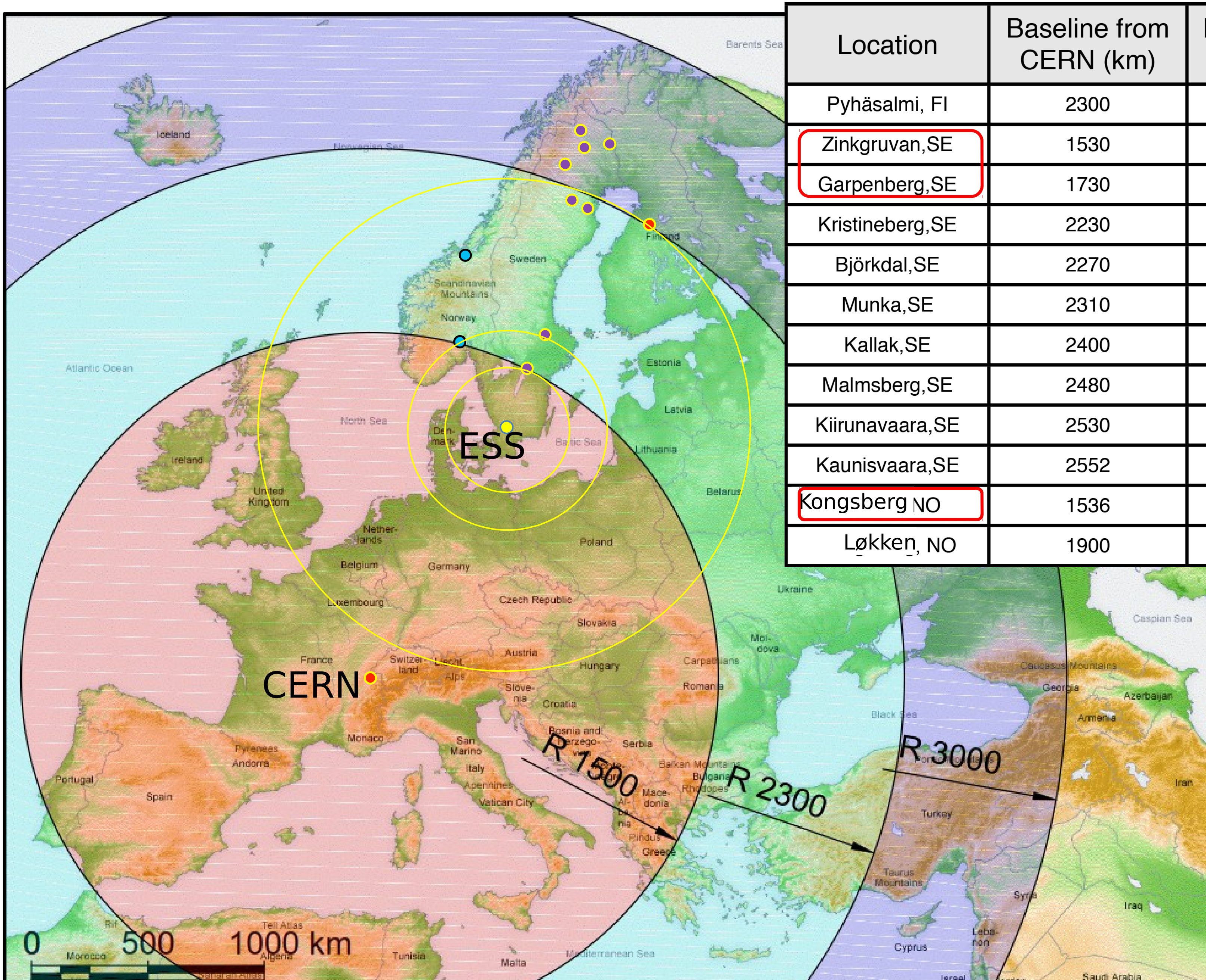
European Spallation Source



ESS Data Management and Software Centre, Niels Bohr Institute at the University of Copenhagen.

under pre-construction phase (~1.8 B€ facility)

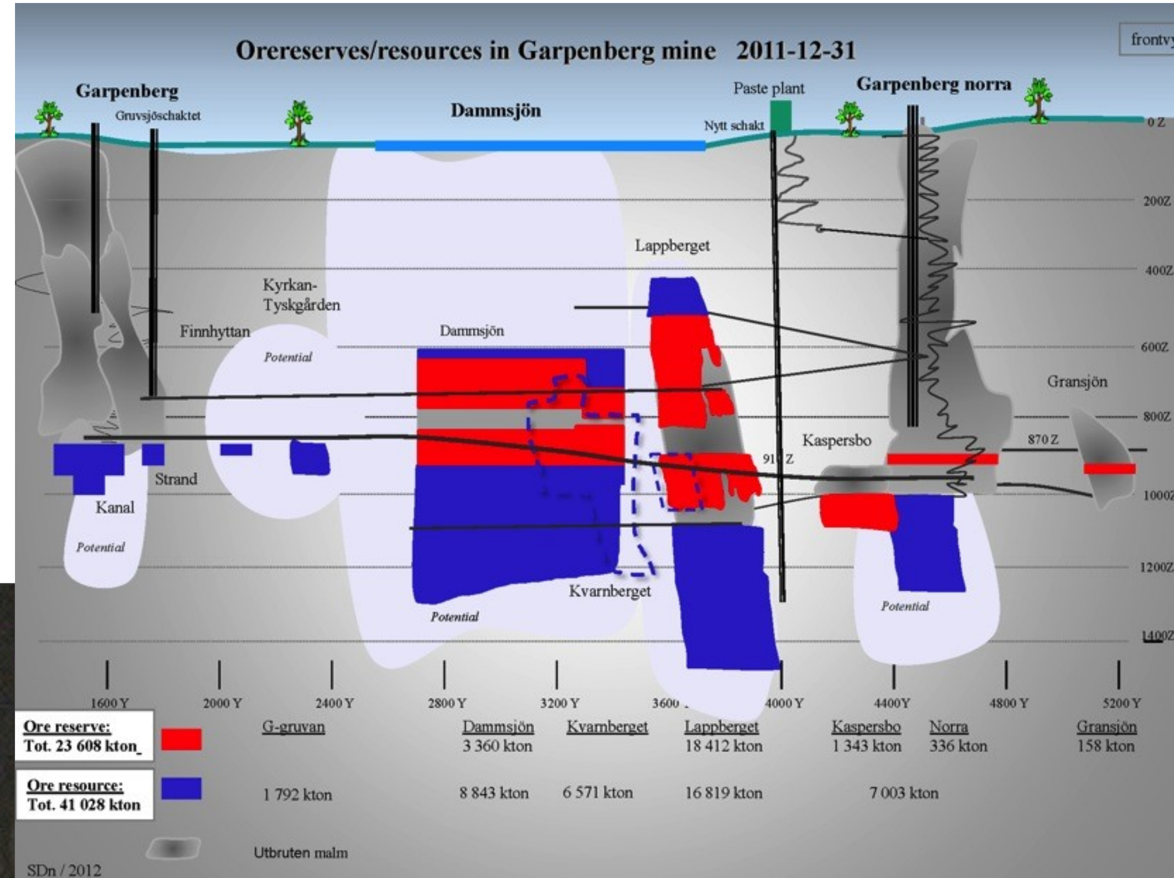
WC detector possible locations



Location	Baseline from CERN (km)	Baseline from Protvino (km)	Baseline from ESS (km)
Pyhäsalmi, FI	2300	1160	1140
Zinkgruvan,SE	1530	1420	360
Garpenberg,SE	1730	1300	540
Kristineberg,SE	2230	1530	1080
Björkdal,SE	2270	1450	1100
Munka,SE	2310	1620	1160
Kallak,SE	2400	1700	1260
Malmsberg,SE	2480	1620	1320
Kiirunavaara,SE	2530	1700	1380
Kaunisvaara,SE	2552	1580	1390
Kongsberg NO	1536	1740	500
Løkken, NO	1900	1800	840

Garpenberg Mine (Boliden)

- Distance from ESS: 540 km
- Depth: 1232 m
- Truck access tunnels
- Two ore hoist shafts
- A new ore hoist shaft is planned to be ready in 3 years, leaving the two existing shafts free for other uses



Granite drill cores around a candidate position

δCP, not just one more parameter to measure…

- **Why is the universe as we know it made of matter, with no antimatter present?**
- **What is the origin of this matter-antimatter asymmetry?**
- **Are neutrinos connected to the matter-antimatter asymmetry, and if so, how?**
- **If neutrinos exhibit CPV, is it related to the CPV observed in quark interactions?**
    - **Already observed CPV in the hadronic sector is not enough to explain the matter-antimatter asymmetry (even if CPV in QCD).**
    - **CPV in leptonic sector could be enough to explain matter-antimatter asymmetry if $|\sin\theta_{13}\sin\delta_{CP}|\gtrsim 0.11$ (hep-ph/0611338) $\Rightarrow$ $|\sin\delta_{CP}|\gtrsim 0.7$ ($45^{o}\lesssim\delta_{CP}\lesssim 135^{o}$ or $225^{o}\lesssim\delta_{CP}\lesssim 315^{o}$).**
- **Are neutrinos their own antiparticles (do we need Majorana phases)?**
- **What role did neutrinos play in the evolution of the universe?**