

The Goals of Particle Physics

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History of Elementary Particles

- Science as a field of study derives from the Western Civilization philosophy of conquering and controlling nature. *We need to know well that what we want to control.*
- Understanding involves classification of the number and types of objects, their properties and behavior under all circumstances.
- Initially, each objects (rock, tree..) was considered to be a separate entity. The system of classification started in ancient Greece. Earth, water, air and fire were the elements from which all material objects were constructed.
- From Roman times through Middle Ages alchemists discovered several “elements” which could not be decomposed or transmuted by boiling, fire, etc. These were mainly metals (gold, silver, zinc, lead etc.) and sulfur. Novel thinking, however, was not encouraged throughout Middle Ages.
- Renaissance spurred a renewed interest in understanding Nature. Many more elements were discovered. The question, whether the small amount of an element has the same properties as a big lump of it, was studied and the 5th century BC idea of “atomos” (Greek word for indivisible) –the smallest amount was re-introduced in the 19th century.

History of Elementary Particles (2)

- In second half of the 19th century about 60 elements were known and people were running out of fingers and toes to count them on. Many classification schemes were proposed to group them into manageable systems (based on names, alphabet, on colors, weight etc.). Mendeleev's system based on grouping by chemical properties and ordering by weight is called today the Periodic Table. It had a distinct feature that it not only described existing body of knowledge but also made predictions for existence of new, not yet discovered elements. The understanding of the atomic structure of elements provided additional justification in the beginning of 20th century.
- The new era started in 1895 with the discovery of electron by Thompson. His picture of an atom was similar to a raisin cake with electrons distributed uniformly within its volume. Soon after in 1907 Rutherford showed that atoms have non-uniform structure – a very dense and small nucleus. Atom is no longer indivisible but consists of a nucleus surrounded by a cloud of electrons.
- During first half of the 20th century, the fundamental structure of matter was again simple. All elements were built up from just 3 objects: proton, neutron and electron. Shell model of the atomic structure allowed to calculate and predict chemical properties.

History of Elementary Particles (3)

- First hint of troubles came from the study of beta rays from radioactive elements. The spectrum of emitted electrons suggested that something invisible is also emitted in the same process. Again, many explanations were proposed. Among them, a new neutral and very light (zero mass) particle called **neutrino**. Another, new particle called a **muon** was discovered in cosmic rays in 1937 (Anderson at Caltech) and confirmed as such only in 1947 (Piccioni). Then, in the 50th and 60th, several particle accelerators were built and several hundreds of new, short lived particles were discovered. During my college years, the feeling of analogy to 19th century chemistry was quite prevalent.
- In early 1960th we knew of about 200 elementary particles. Most common are relatively long lived **pions** and **kaons**, which live for about $10^{-8} - 10^{-10}$ of a second, but because they usually are moving very fast, the relativistic effect of time dilatation allows us to see they traces. The much more abundant are “resonances” – objects that live for a very short time – about 10^{-24} of a second and then decay into a longer lived pions and kaons. We know that they exist because the momenta and directions of the secondary decay products are correlated.

History of Elementary Particles (4)

- Again, many classification schemes of all these elementary particles were proposed . Among them, Gell-Mann and Zweig proposed in 1963 a “quark model” postulating the existence of “fundamental” constituents called **quarks** from which all elementary particles can be built-up. Protons and neutrons (and their resonances) would be made-up from 3 quarks and the other short lived particles (mesons) would be made-up from a quark-antiquark pairs. The model predicted a new, unobserved particle - Ω^- which was found few month later.
- The race to find a quark was on, but without a success. No free quarks, separated from a.g., proton have been found. The evidence for quarks is indirect. It comes from a 1969 experiment at Stanford where protons were bombarded with high energy electrons. This is an experiment similar to that of Rutherford 90 years earlier. In few instances, electrons bounced out from a very small and dense structure inside a proton. The result is consistent with existence of quarks whose dimensions are smaller than 10^{-18} m.

Particle Physics – Present and Future

- Standard Model – 3 families of quarks and leptons (massless neutrinos)
unified description of electromagnetic, weak and strong forces via exchange of the carriers of the force
 - photon - electromagnetic
 - W, Z - weak
 - gluons - strong
- Works great – tested at the level of 1 part in 10^{14} !!! **Incomplete.**
- Problems: all masses = 0 - need a new mechanism to generate mass in theory
 - possible solution – **Higgs** particle
 - extrapolation of theoretical calculations to higher energies gives nonsense results
 - mathematics of unification requires extrapolation over 10 orders of magnitude - pure arrogance
 - mathematics of unification neglects gravity
- Expect new physics at higher energy scale: Higgs, substructure of quarks, higher dimensions, quantum gravity.....
- Physics is an empirical science – facts select a theory.

Leptons

- The name *lepton* derives from Greek word **λεπτος** meaning “light, not heavy”. It was originally assigned to electron and neutrino.
- Standard Model: 3 families of leptons
 - electron + ν_e and corresponding antiparticles
 - muon + ν_μ “ “ “
 - tau + ν_τ “ “ “

Special rules:

lepton number conservation – each family has a characteristic “charge”
that is conserved (no good reason)

photon $\rightarrow e^+e^-$

$\mu \rightarrow e \nu_e \nu_\mu$

charged leptons –massive, neutrinos – massless

all observable properties (except mass) controlled by weak force

Muon and tau are heavy brothers of electron e.g., can form muonic/tau atoms

Astronomy Connection – Dark Matter

- Astronomical observation: spiral and disk-like galaxies (like ours) rotate and the velocity of stars does not depend on the distance from the center of the galaxy.
- That implies that mass of the ring of the galaxy grows with radius in contradiction with the observed density of stars which decrease with radius.
- Stars are visible. In our solar system almost all mass is in the sun. All planets etc contribute less than 1% . If the same is true everywhere, then we are missing about 90% of the mass.
- Either Newton's laws are wrong or there is an invisible "dark" matter in the universe (not in stars).
- Astronomical possibilities – our system is different than the rest of the universe: there may be giant planets, neutron stars, black holes...(all found but too few of them to explain more than few % of the effect)
- Particle physics possibilities – there may be particles that are remnants of the big bang that we do not see because they do not like to interact with normal matter. Candidates – neutrinos (exist), axions (speculations).....
- Big detectors : Superkamiokande, MACRO, Amanda – study neutrino astronomy.
- Byproduct – study neutrinos from the sun. Observe day/night effect.

- Rate of detection different for day and night (more during day than during night).

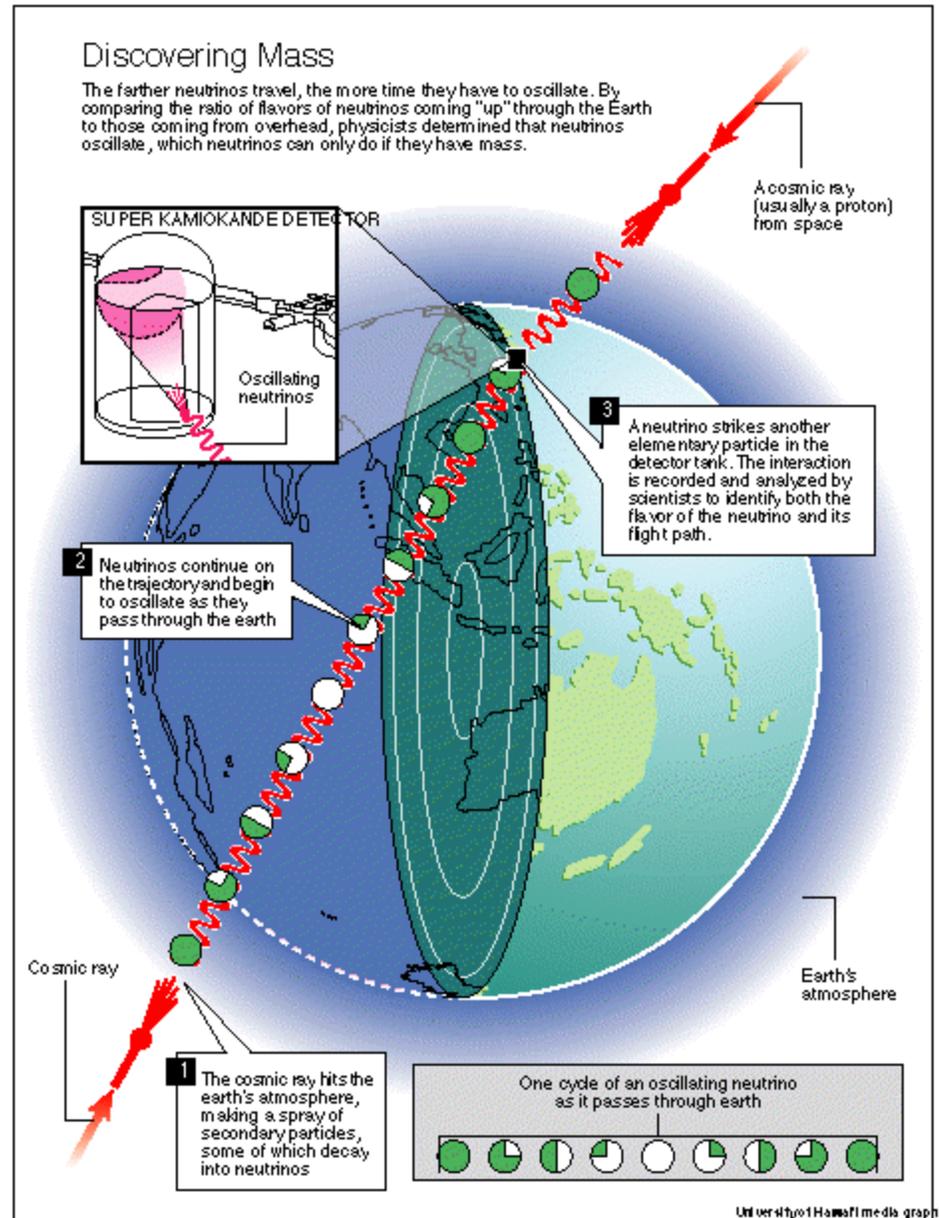
- Neutrino absorption by Earth – negligibly small.



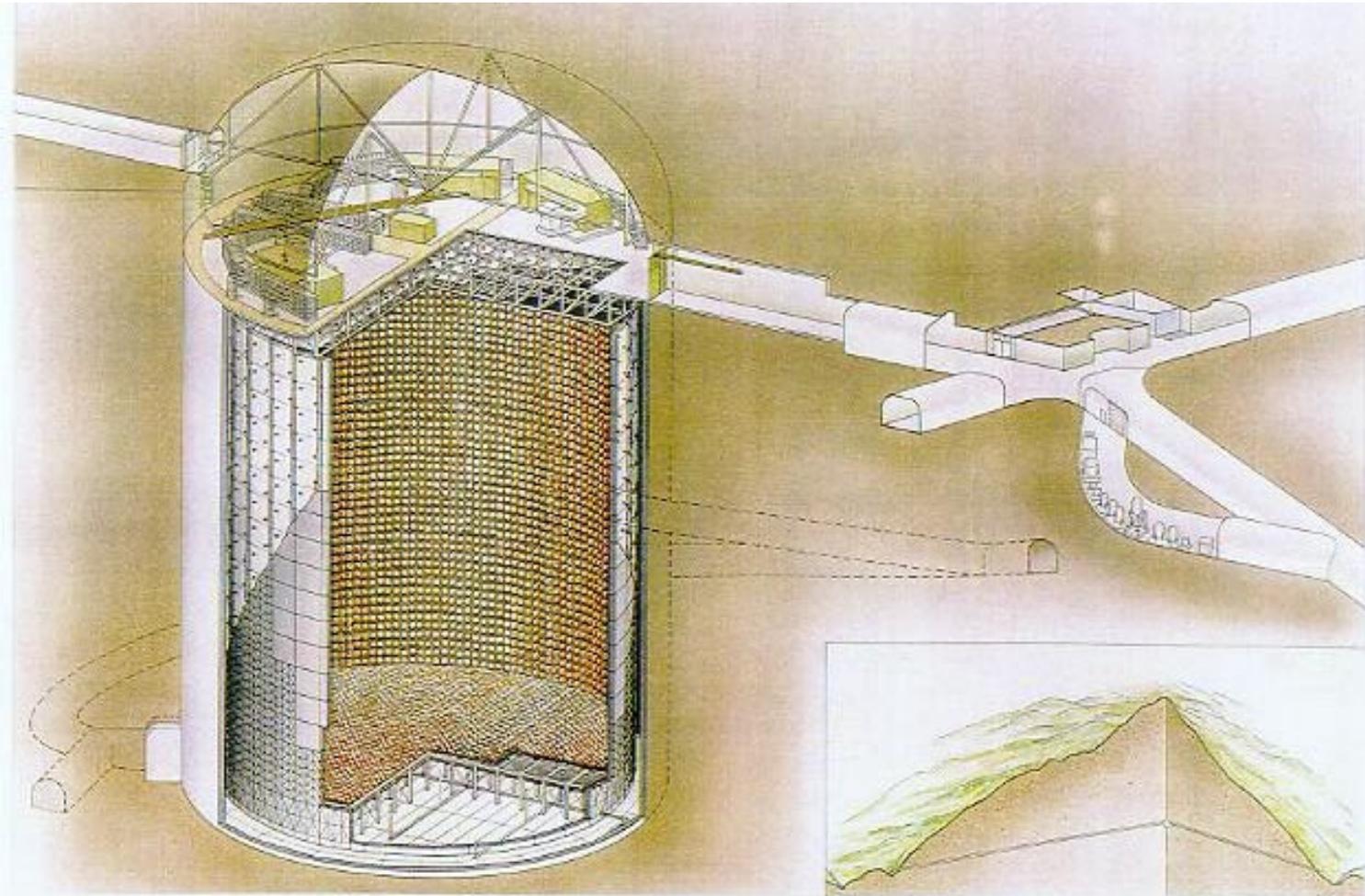
- During passage through Earth neutrino must change into something that is not detected.

- Since only electron neutrino can be detected – the electron neutrino must oscillate into either muon or tau neutrino.

Oscillations are possible only if neutrino has a non-zero mass.



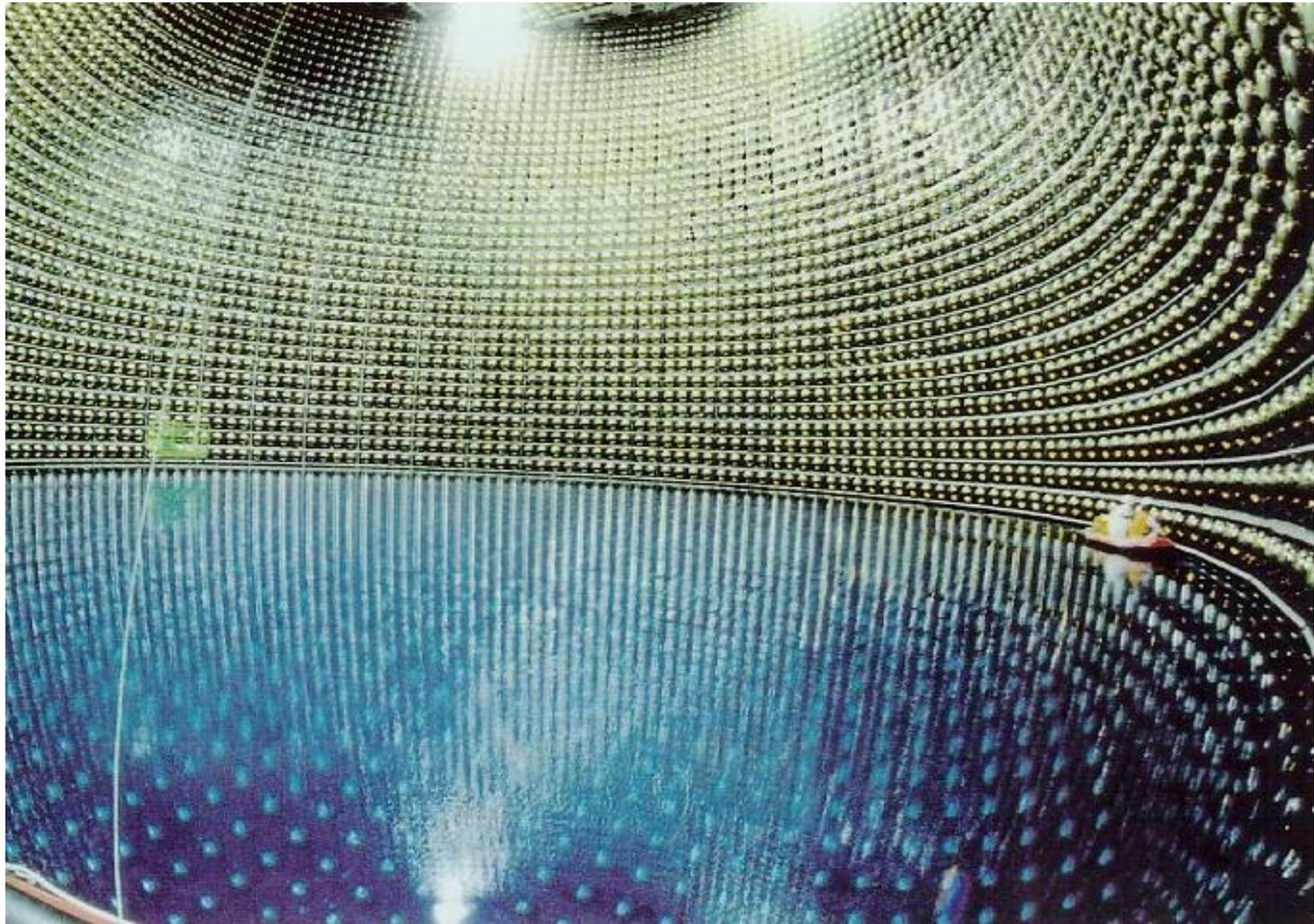
Superkamiokande



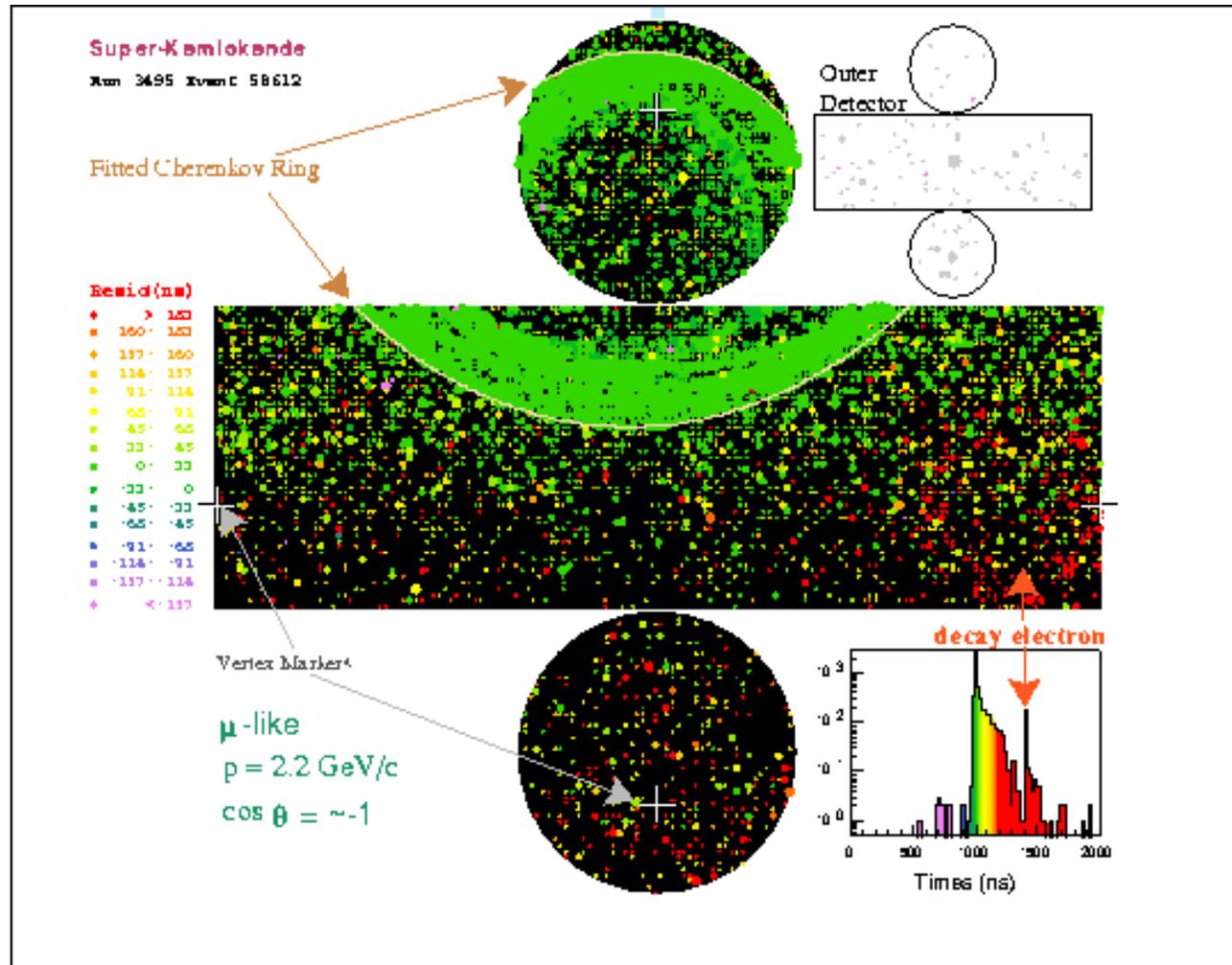
SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

MIKEN SEKKE
ARCHITECTS

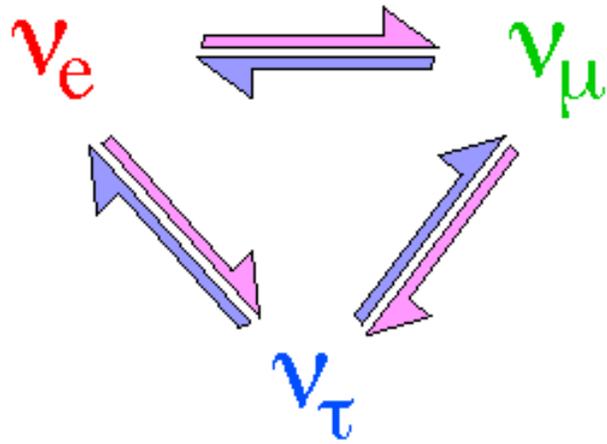
Superkamiokande – half filled with water



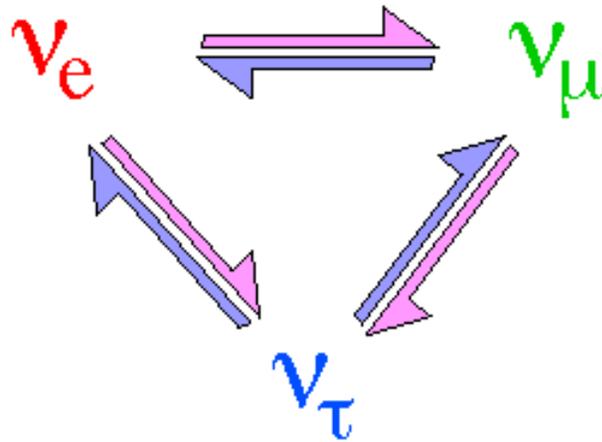
Neutrino Event



Neutrino Oscillations



Neutrino Oscillations



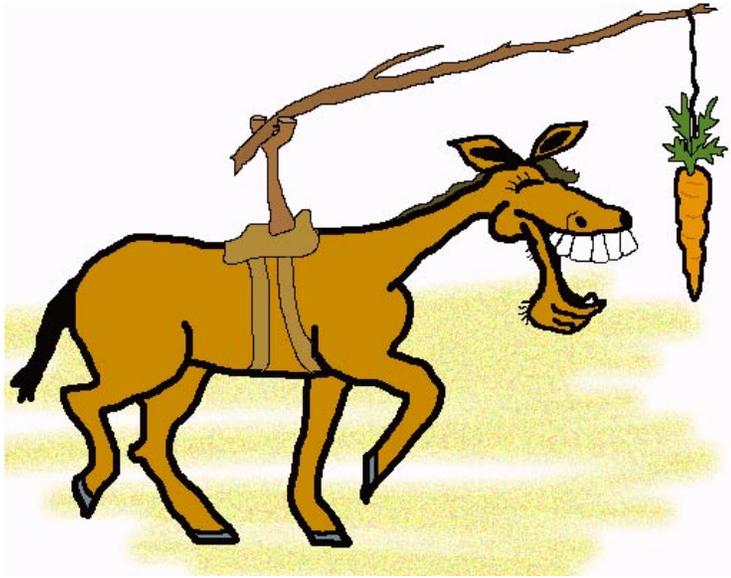
$$\nu_e p \rightarrow e + X$$

$$\nu_\mu p \rightarrow \mu + X$$

$$\nu_\tau p \rightarrow \tau + X$$

To be detected, neutrino has to have enough energy to produce the corresponding lepton

Principle of Acceleration Technique



Symmetries and Conservation Laws

- General Assumptions in Physics

- 1) Continuous symmetries:

- Space is homogeneous (uniform) → conservation of momentum and energy
- Space is isotropic (no preferred direction) → conservation of angular momentum
- Properties of space do not depend on the observer → special relativity

- 2) Discrete symmetries:

Space reflection (mirror symmetry) → parity conservation, P

Particle-antiparticle symmetry → charge conjugation, C

Time reversal → T

True for strong, electromagnetic, violated in weak interactions.

Conservation of C, P and T → matter-antimatter symmetry

Symmetries and Conservation Laws

- CPT believed to be always conserved
- Parity violations – radioactive ^{60}Co decay
- CP conservation – good until 1964 (Cronin+Fitch)
 - Small effect for s quark decays $\sim 1/1000$
 - Time reversal violated in weak decays

Observation – Universe is mostly matter (no evidence for electron-positron annihilation lines in cosmic ray photon spectrum)

Open question – since Big Bang is believed to be matter-antimatter symmetric, what is responsible for the disappearance of antimatter
→ search for CP violation in b quark decays