

The 2015 Nobel Prize in Physics: Neutrinos!

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"Neutrino Physics is Largely an Art of Learning a great deal
by observing Nothing"
Haim Harari, Neutrino Physicist

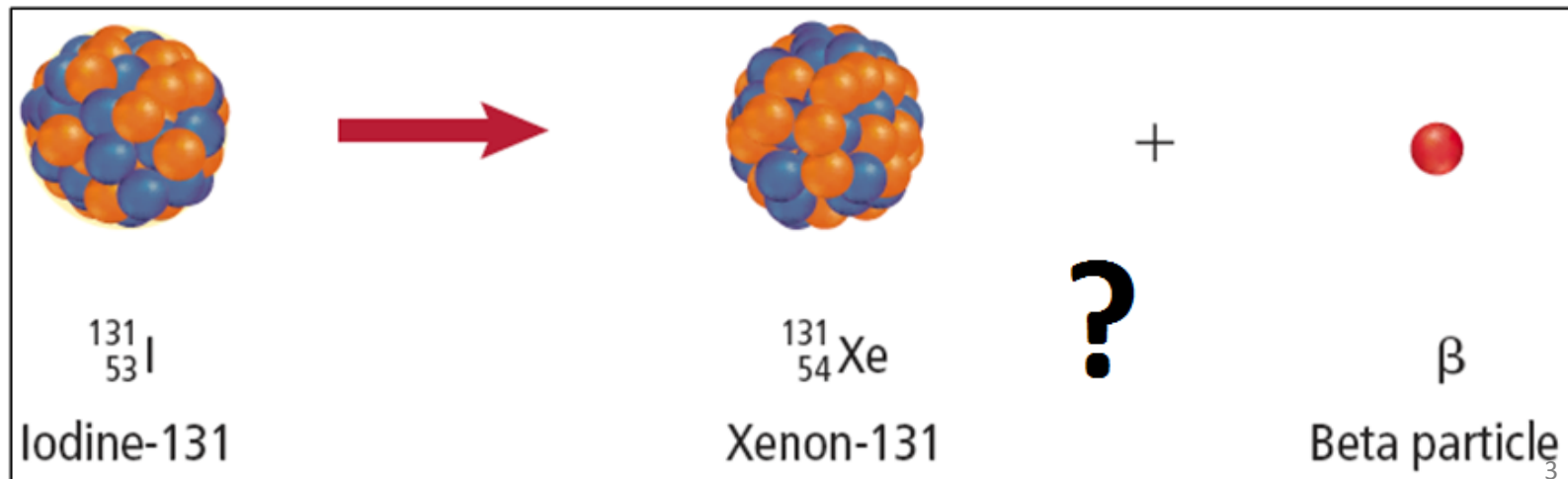
In this presentation we will follow the path of the
strangest elementary particle of Physics, the "neutrino",
from its theoretical conception in 1930 through its course
in history and contributions in science until the Physics
Nobel Prize of 2015.

How it all began

In 1914, J. Chadwick discovered the nuclear beta decay:

A nucleus decays spontaneously:

- Transmuting a neutron (proton) of the atomic nucleus to a proton (neutron)
→ A chemical element is transmuted to another with different chemical properties!
- Causing the emission of a particle which was then named: β^- (β^+) → electron (positron)



Problem

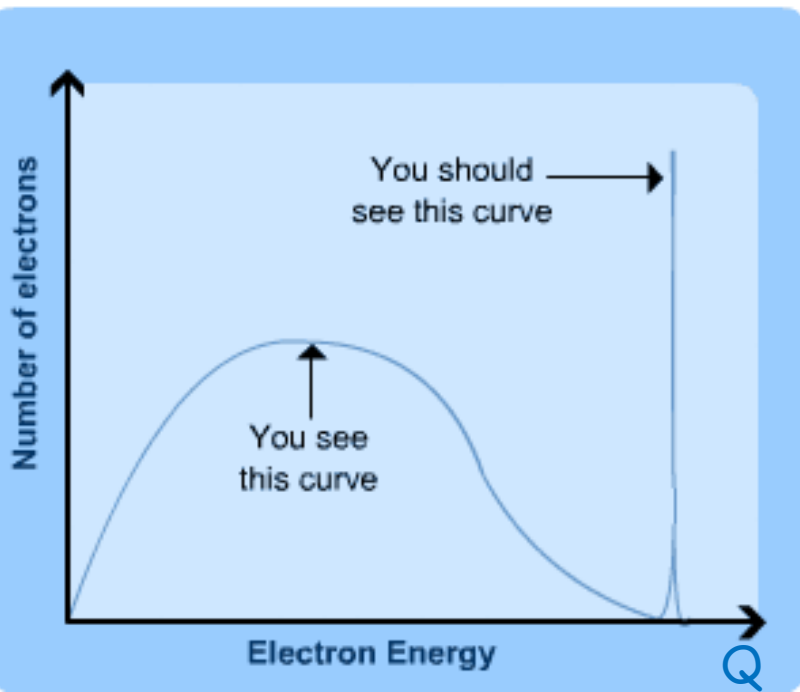
The beta decay seemed to "disrespect" the principle of conservation of energy.

During beta-decay the energy emitted is equal to:

$$Q = M_P \cdot c^2 - M_D \cdot c^2$$

(M_P, M_D : Masses of parent and daughter nucleus)

All this amount of energy should be carried by the emitted β^- (β^+)



If I measure the β^- -particle energies and plot its distribution in a histogram, I observe that most electrons have an energy less than Q !!!

What happened to the remaining energy???

Niels Bohr: « Energy is not conserved in all microscopic processes »

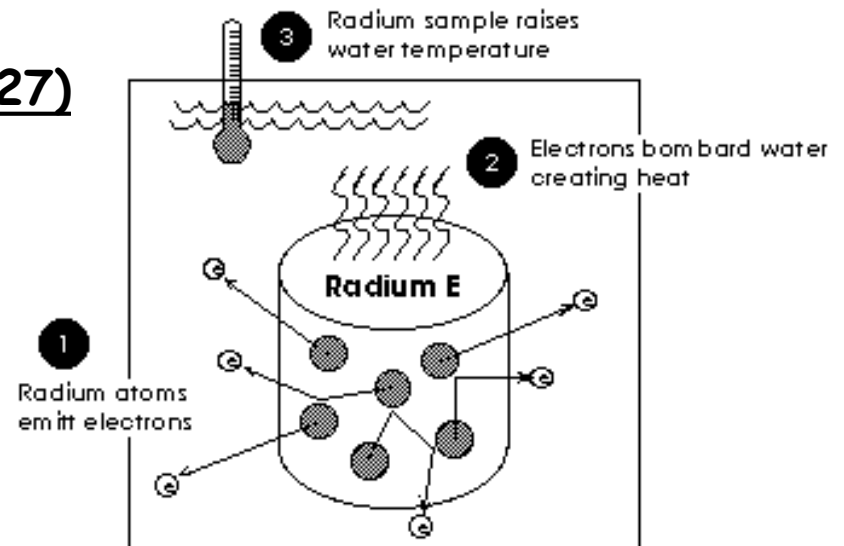
Lise Meitner:

« Electrons emitted during β -decay possess energies equal to Q but lose part of this energy because of their interaction with the material they transverse until they reach the detector»

→ The Ellis & Wooster Experiment (1927)

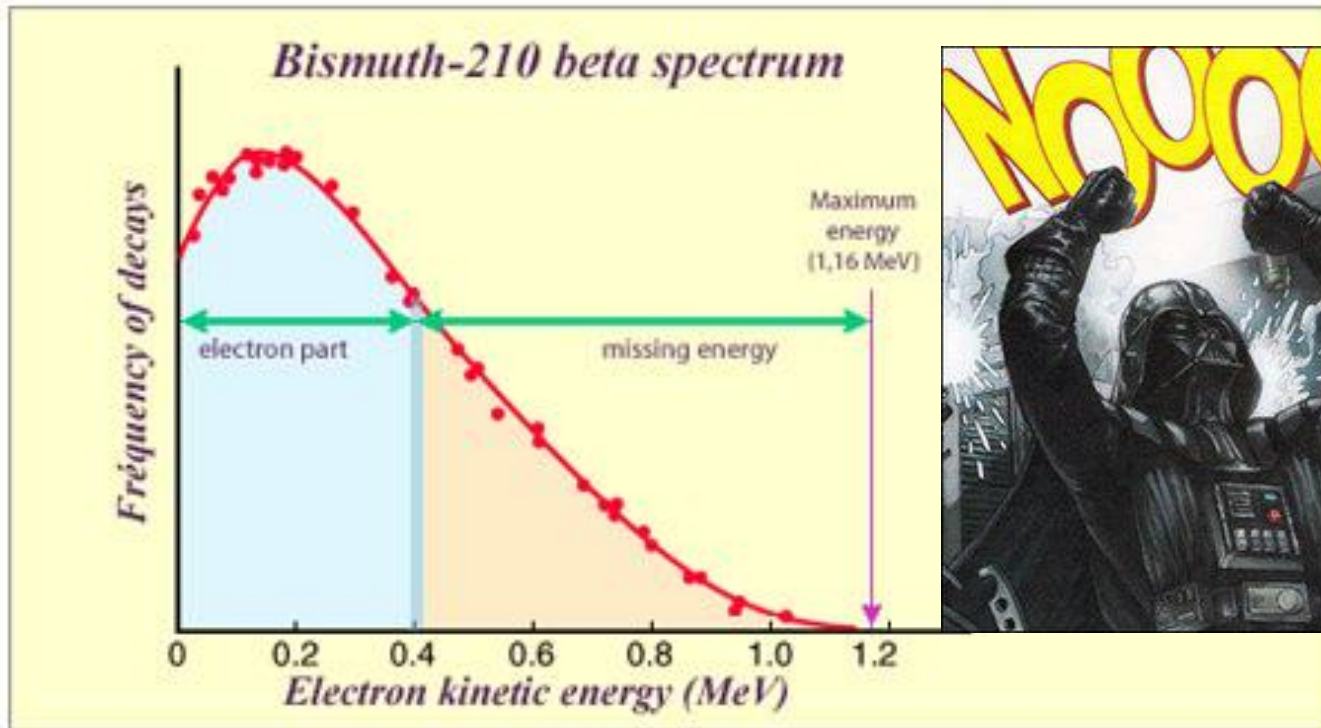
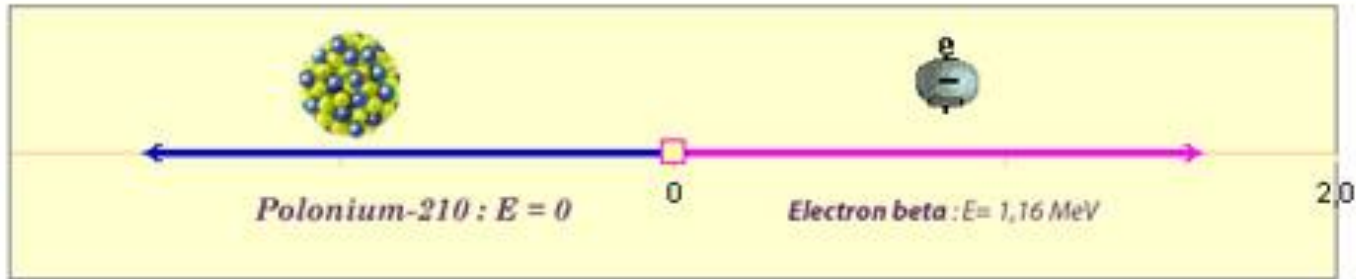
- A beta-particle source is placed in a calorimeter.
- Beta particles heat the calorimeter depositing all their energy inside it.

The Original Radium E Experiment



- Average Energy = Total Energy/Nr of Electrons
- If energy is conserved, the average energy must be equal to Q .

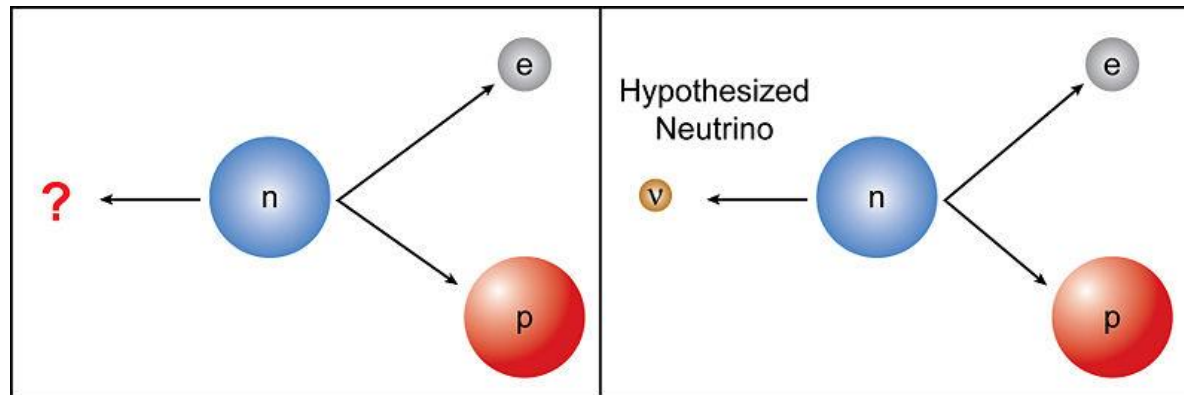
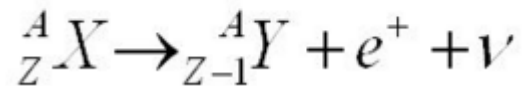
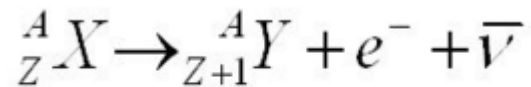
The experiment proved that the average energy is less than Q .
It either escapes detection, or ENERGY IS NOT CONSERVED!!!



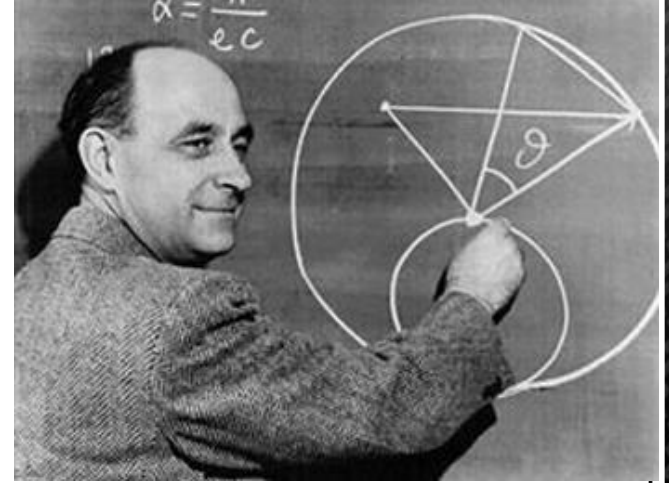
Saving the Energy-Momentum Conservation Principle.

W. Pauli (1930):

«There is one more particle produced during the nuclear beta-decay. It shares the available energy with the beta particle, its mass is almost zero and it interacts extremely weakly with matter.»



And its name: "Neutrino"!



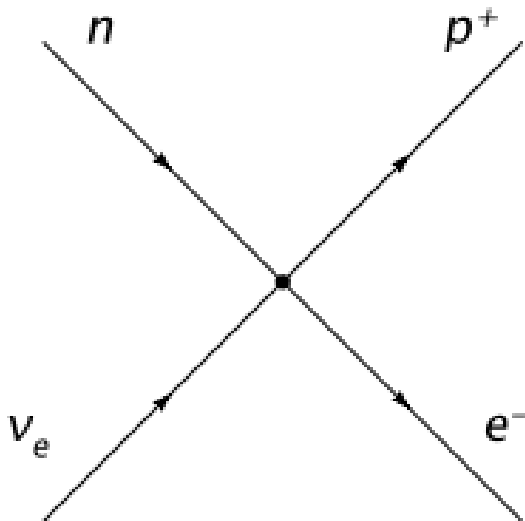
In 1934, Enrico Fermi developed the first theory of the Weak Interaction.

This Interaction is responsible for the beta decay.

For the theory to be complete,

Pauli's hypothesized particle is a necessary ingredient.

Fermi baptized the new particle: "Neutrino" (the little neutral one in Italian).



A neutron interacts with a neutrino resulting in the production of a proton and an electron.

The range of the interaction $\rightarrow 0$

To interact via weak interactions, the particles must be essentially in the same position in space.

Some Useful Conclusions

According to Fermi's Theory:

- The interaction probability of a neutrino with another particle is minuscule! A 1 MeV neutrino will transverse 50 light years in water until it interacts !!
(MeV: Unit of energy in the microcosm. It is equal to the energy that an electron will obtain if it is accelerated by a voltage equal to 1 MV)

→ Neutrino detection is extremely difficult

- The neutrino interaction probability is proportional to the neutrino energy!

$$\sigma(n + \nu \rightarrow e^- + p^+) \sim E_\nu (\text{MeV}) \cdot 10^{-43} (\text{cm}^2)$$

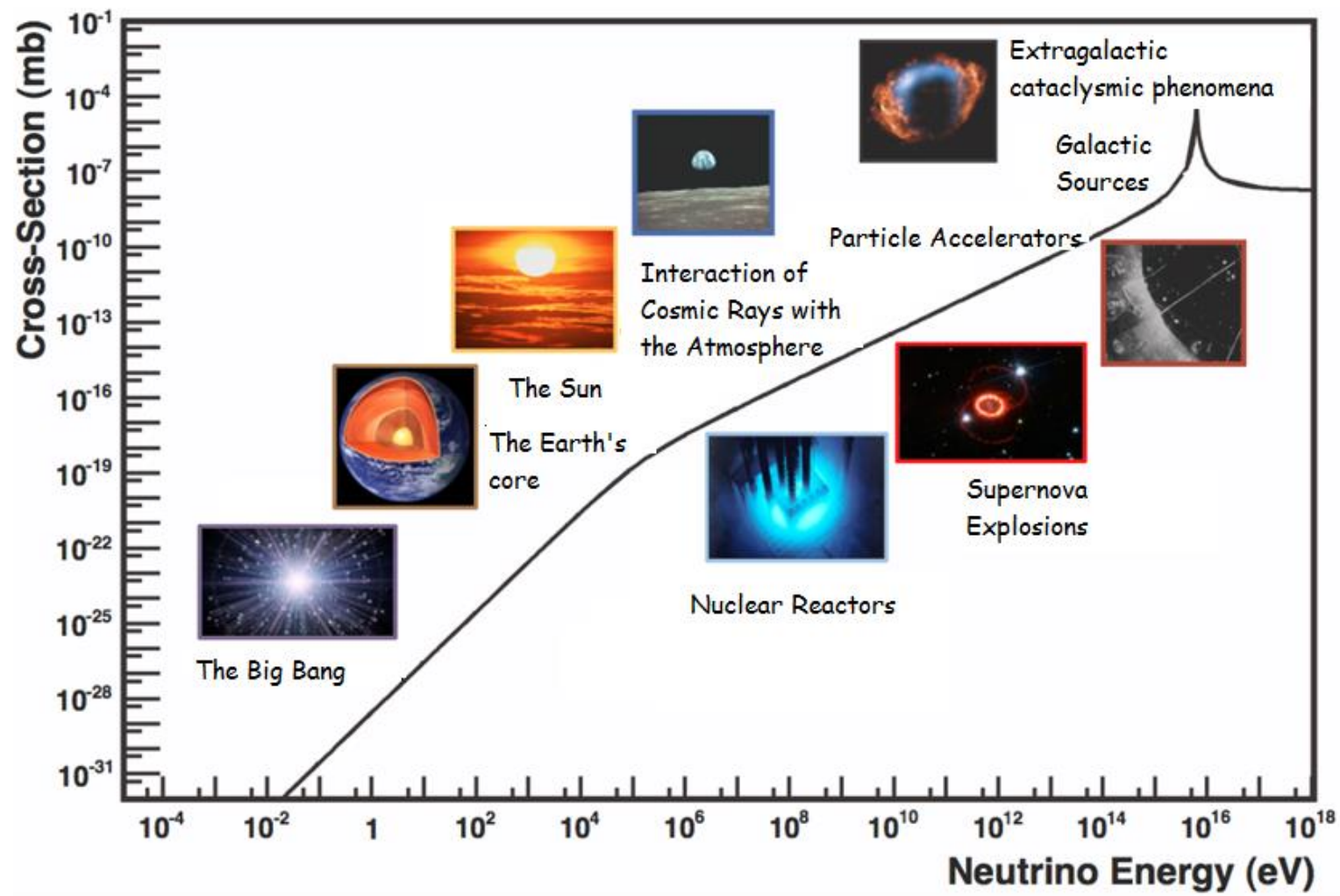
- **The neutrino interacts only via the weak (and the gravitational) interaction.**



Searching for the Ghost Particle

Where can we search for neutrinos?

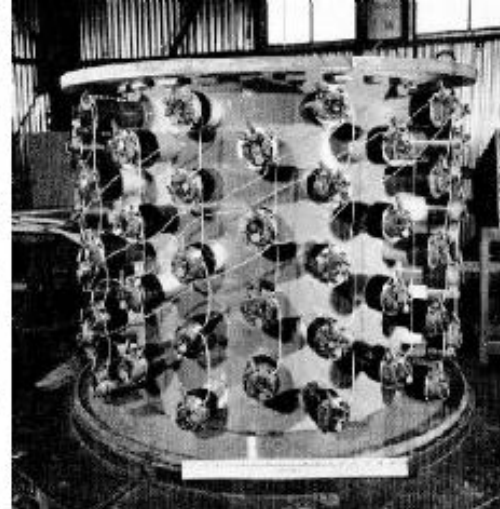
We will search for violent natural processes during which weak interactions take place!



The Neutrino is Finally Detected

26 years passed from the theoretical conception of the neutrino until its detection by C. Cowan and F. Reines in 1956

Remember! **Neutrinos interact very rarely. To detect a neutrino, we need a "source" emitting many neutrinos, a big detector with enough targets to maximize interaction probability, optimized detectors and loads of patience.**



Reines & Cowan used the Savannah River nuclear reactor in S. Carolina as a neutrino source. They placed their detector 11m away from the reactor in 12m depth from the Earth's surface.

Neutrino: How many of them?

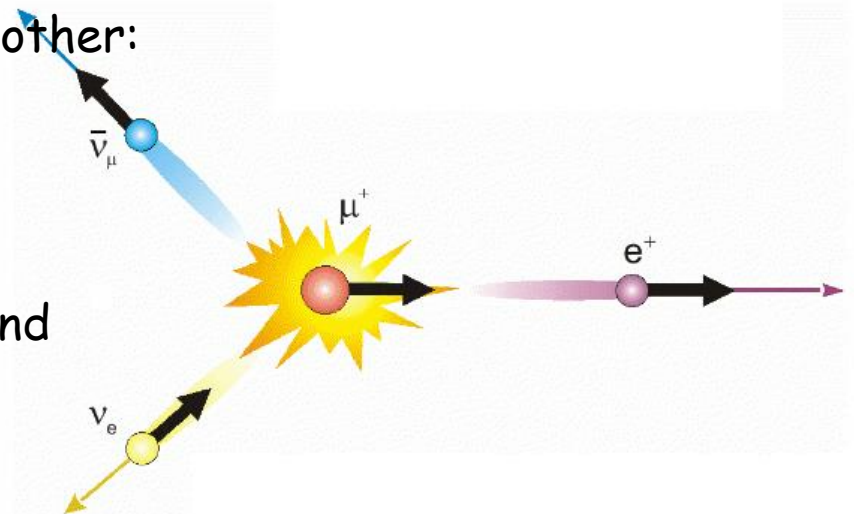
In the meantime, Particle Physics was flourishing due to the development of the particle accelerator tool. Many new particles had been discovered. Among these new particles was the muon, a heavy version of the electron (~200 times more massive), which lives only for two millionths of a second.

After this fraction of a second has passed, the muon decays producing an electron.

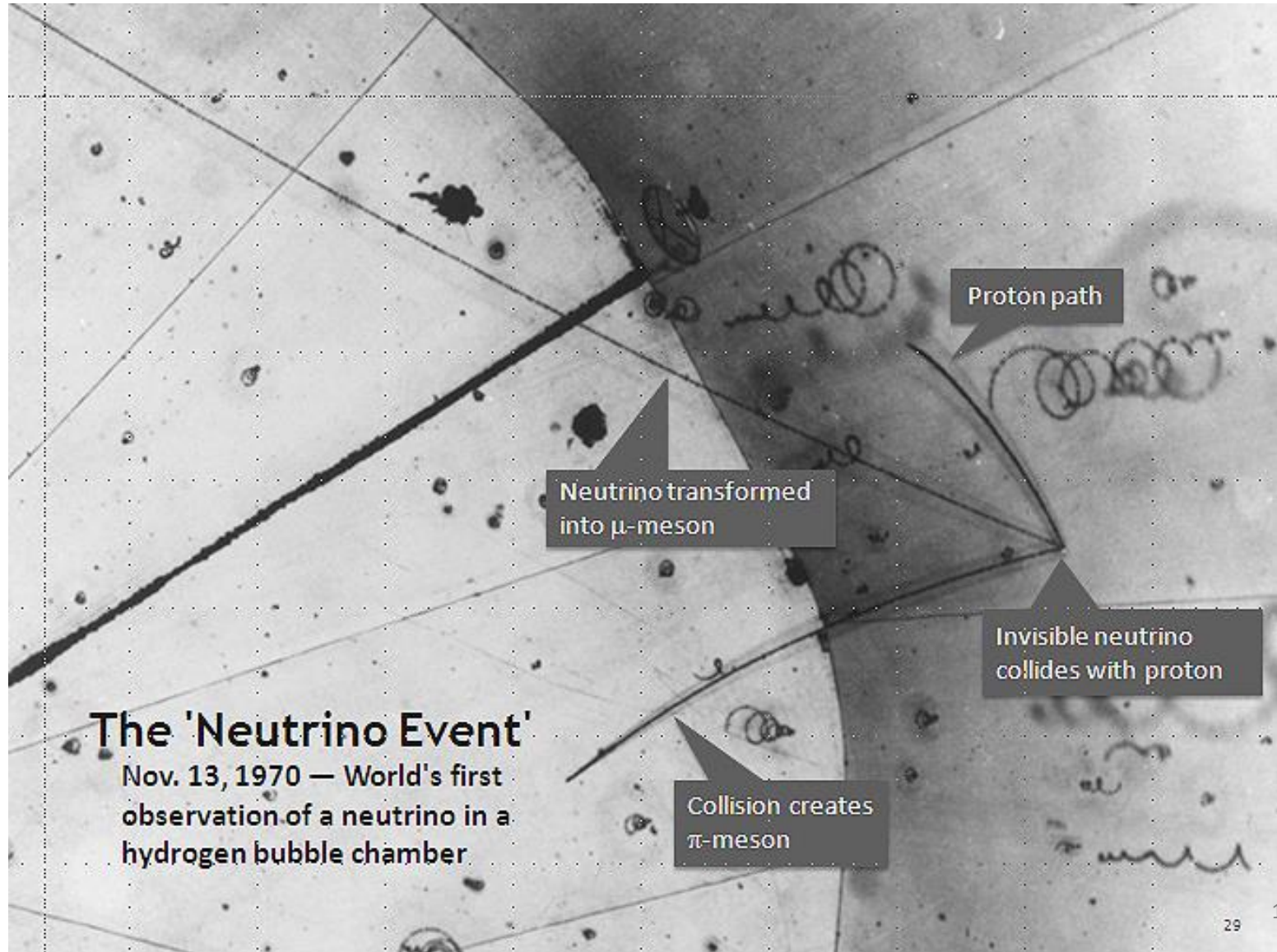
The energy distribution of the produced electrons resembled heavily this of the beta decay. This fact persuaded the physicists that one or more neutrinos are produced during muon decay!

These neutrinos need not be similar to each other:
One of them would interact with matter and produce electrons in the final state.
This is the electron neutrino.

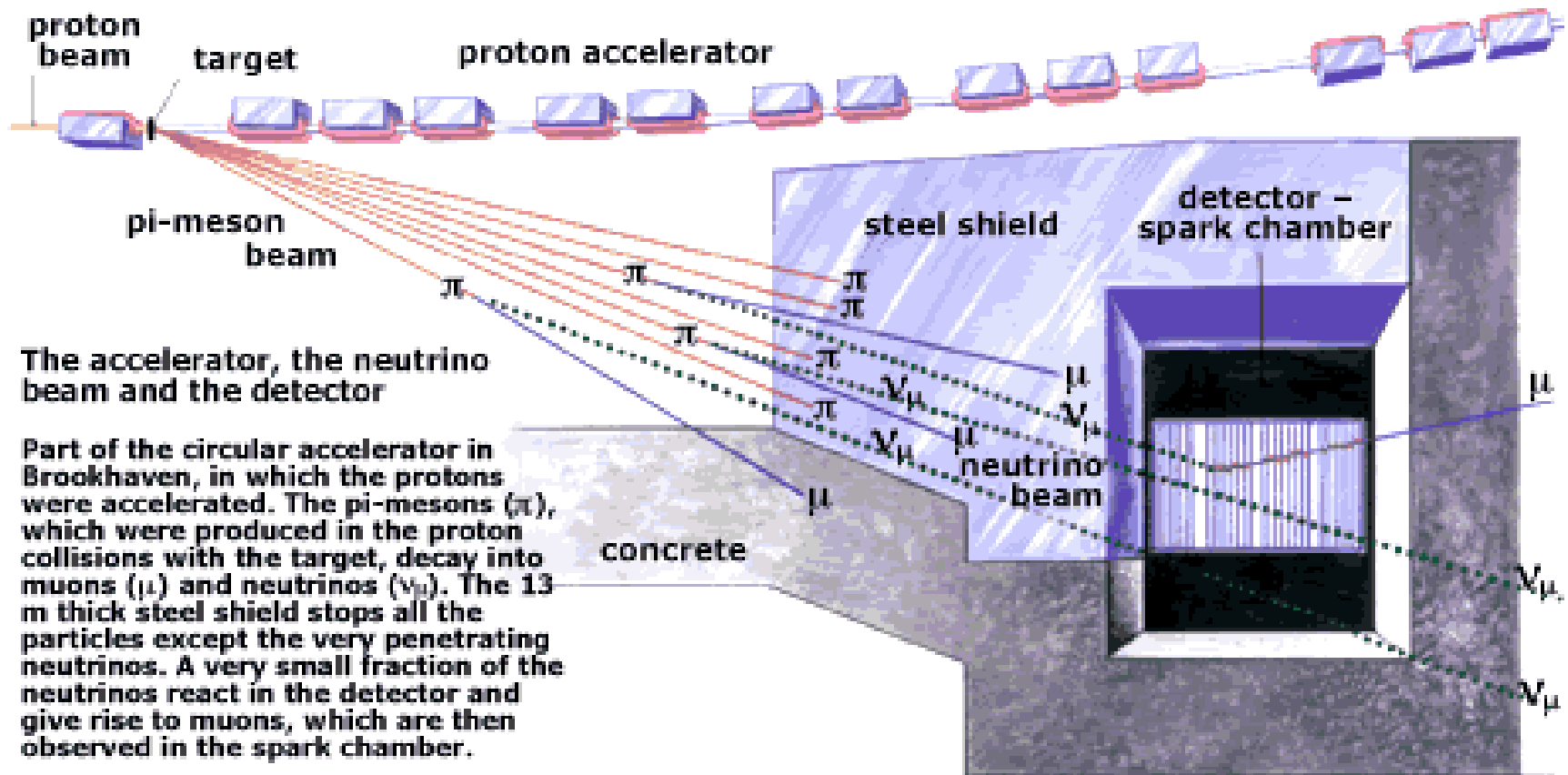
The other kind would interact with matter and produce muons in the final state.
This is the muon neutrino.



We CANNOT observe neutrinos themselves, only the results of their interactions! Observe below a real image of a neutrino interaction taking place in a bubble chamber. Can you determine the neutrino's direction?



In 1962, L. Lederman's team discovered the muon- neutrino experimenting on the Brookhaven Laboratory's accelerator.

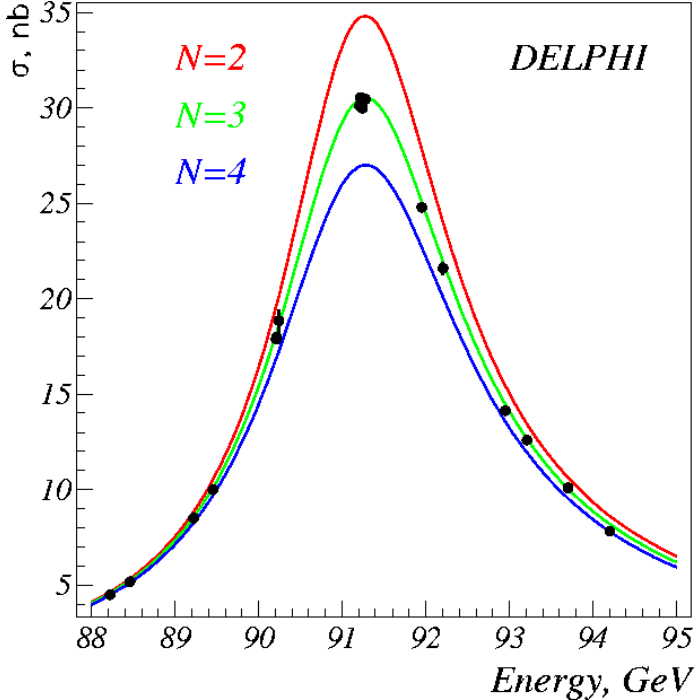
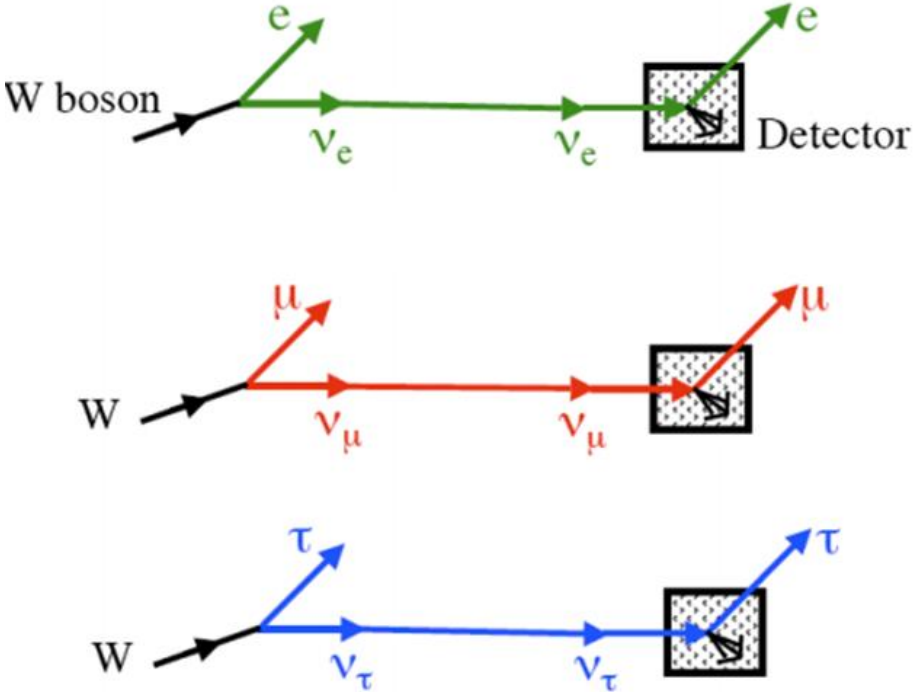


The accelerator, the neutrino beam and the detector

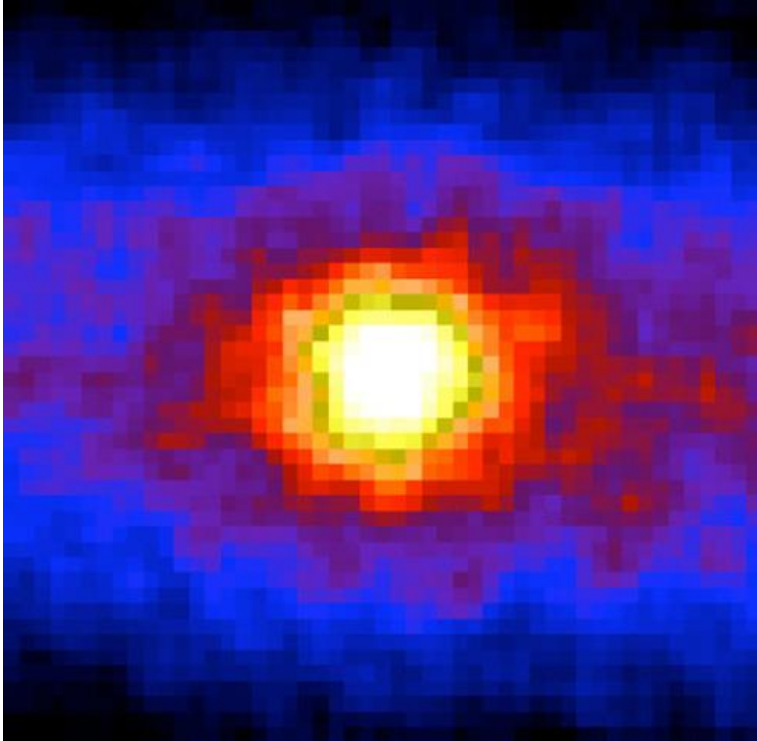
Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.

Nowadays, we know that the electron (e^-) has two heavier "cousins": the muon (μ^-) and the tau (τ^-). Therefore, the neutrino should also have three "versions" or "flavors": The electron neutrino (ν_e), the muon neutrino (ν_μ) and the tau neutrino (ν_τ). These six particles are called "Leptons".



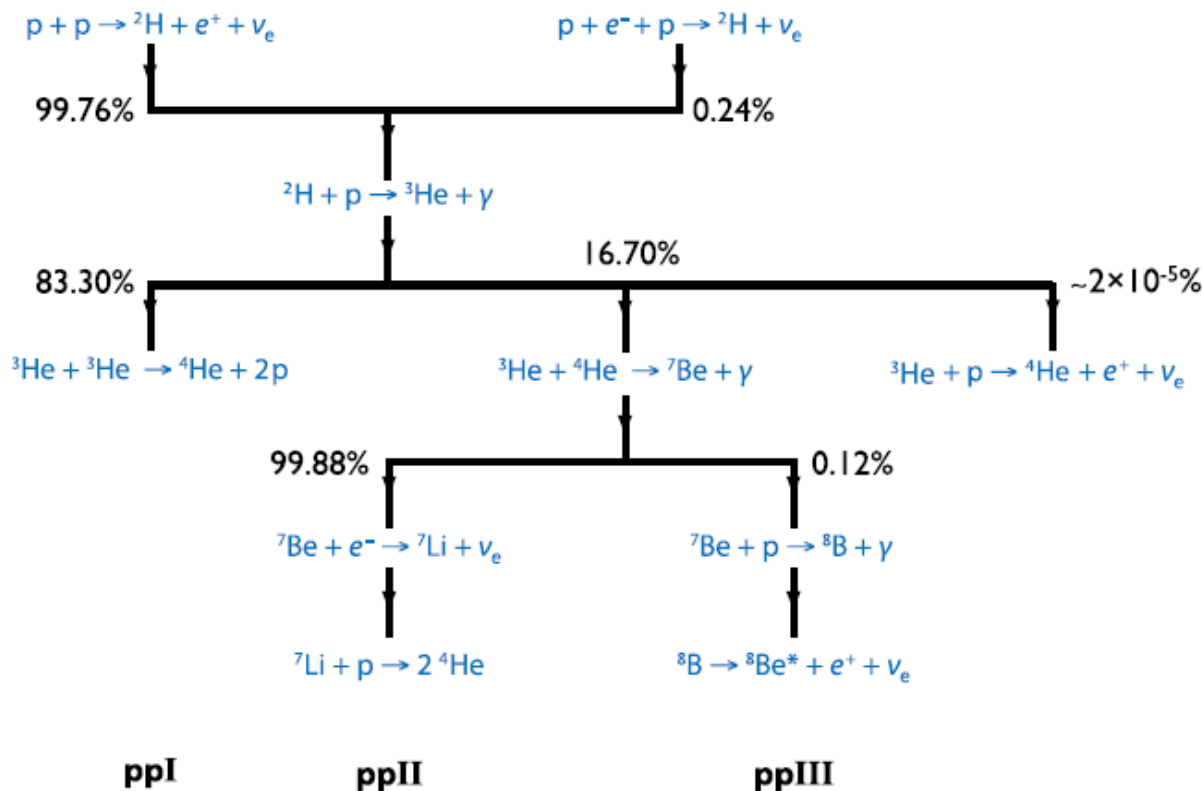
The tau neutrino was discovered by the DONuT collaboration in Fermilab, USA in 2000.



Did You know that you can observe the Sun at night?

Solar Neutrinos

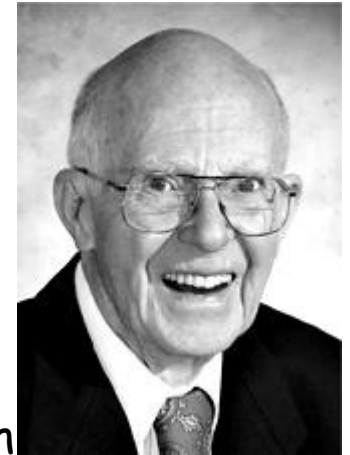
- The energy produced by the sun comes from the nuclear reactions taking place in its interior.
- These nuclear reactions produce electron neutrinos (ν_e)!
- The Solar Model (by John Bahcall) describing the nuclear reactions in the sun is so successful that can predict the value of the Solar Constant: The solar energy reaching a square meter of the earth every second!!



Did you know that every second, about 65 million solar neutrinos pass through our thumb??

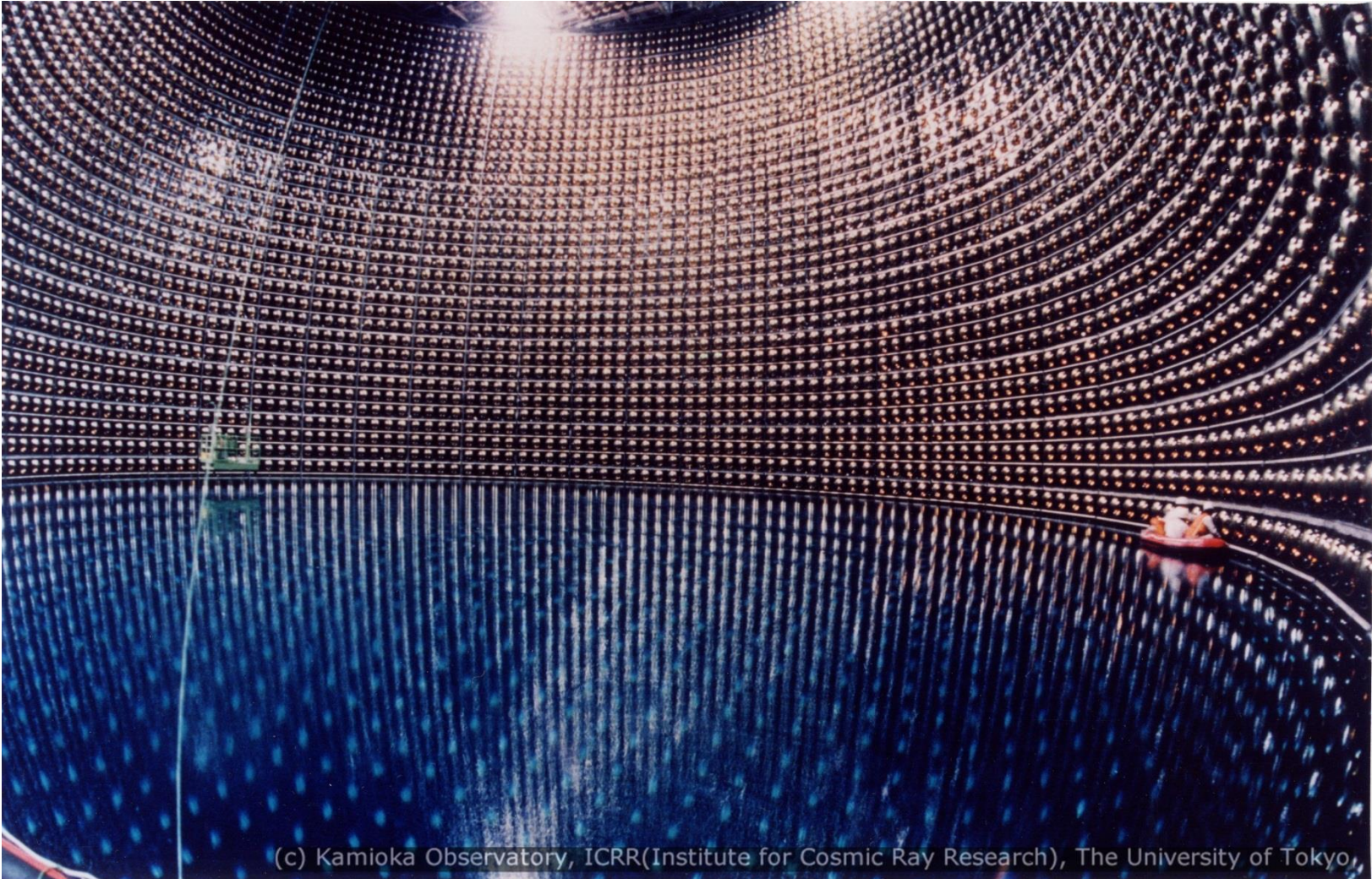


The Solar Neutrino Experiment (Ray Davies)



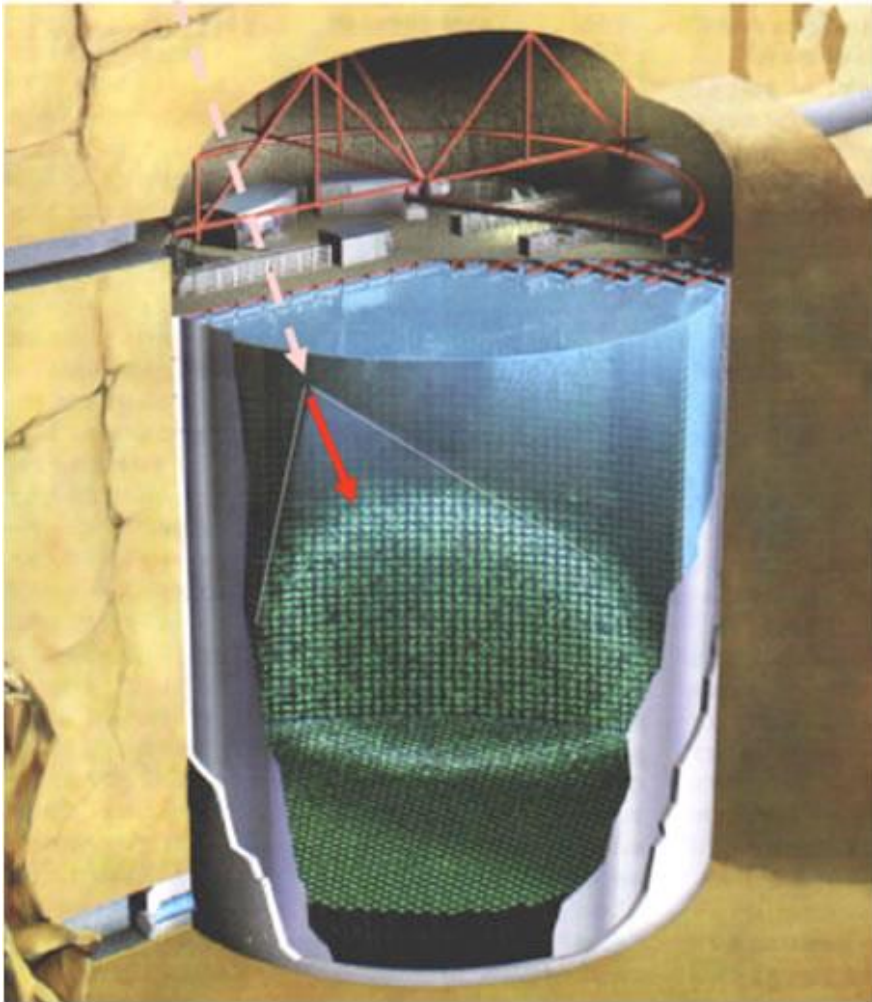
- Took place by the end of the 60's.
- A 380 cubic meters container with chlorine was placed 1480m below the surface of the Earth at the Homestake Mine in California.
- Neutrinos from the Sun interacted with Chlorine and produced an Argon nucleus.
- Argon was pumped from the container using radiochemical methods.
- **This experiment showed that neutrinos coming from the sun were 1/3 from what the Solar Model predicted.**

The Super Kamiokande Detector in Japan



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo,

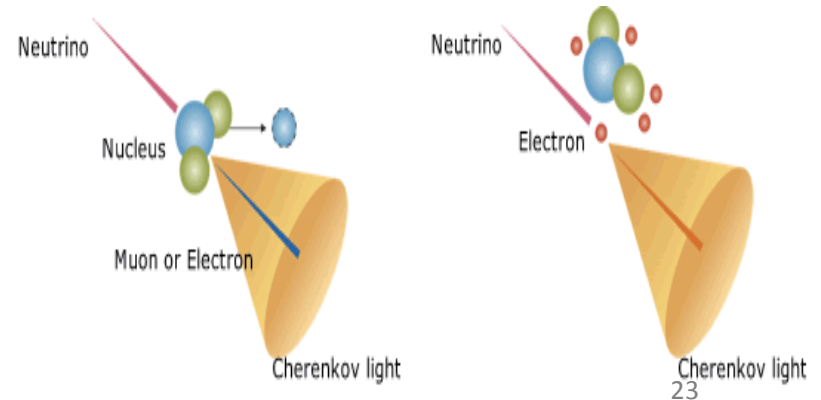
Super –K detection principle



Neutrinos interact with the nucleons (or the electrons) of the water inside the detector.

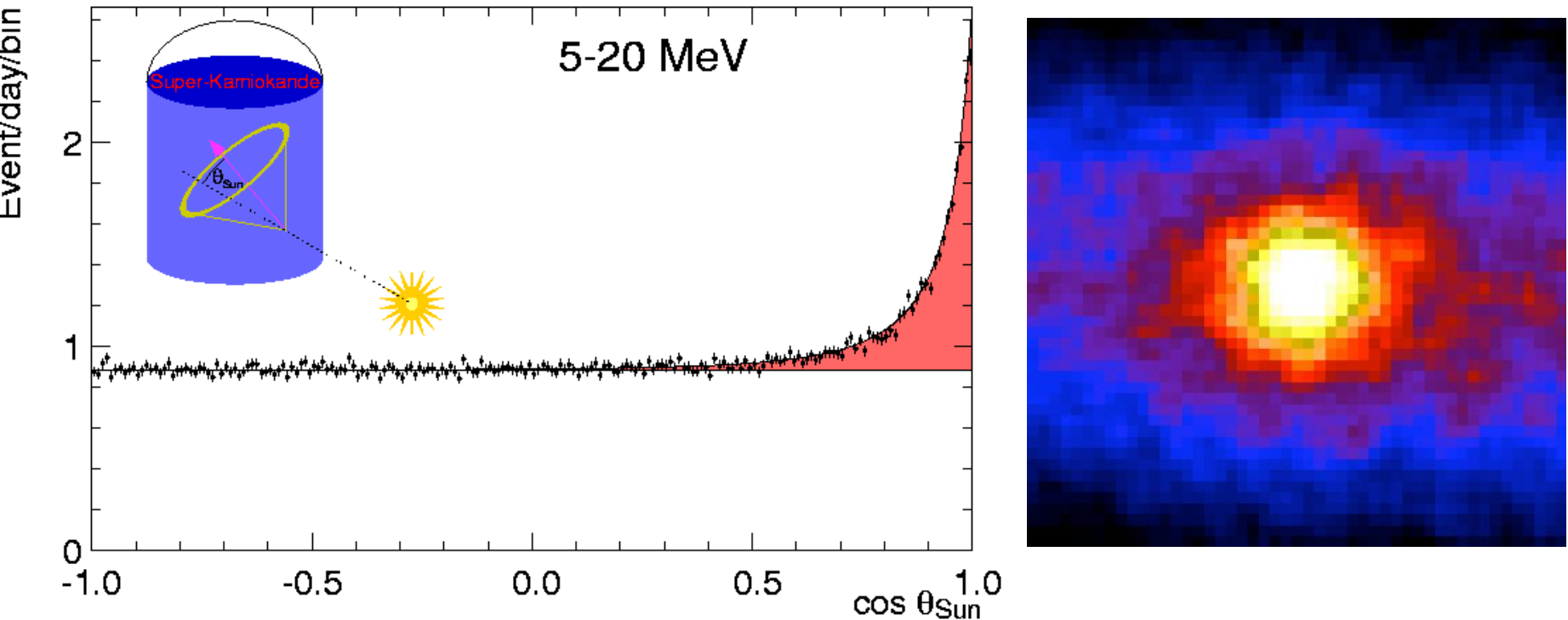
The charged particle produced moves faster than the speed of light in water: A bluish light, Cherenkov radiation, is produced and detected by the Photomultipliers (The “eyes” of the detector) placed on the walls of the detector.

The radiation pattern can be used to infer the neutrino interaction.



The generated charged particle emits the Cherenkov light.

Monitoring the Sun with neutrinos on a 24-hr basis.



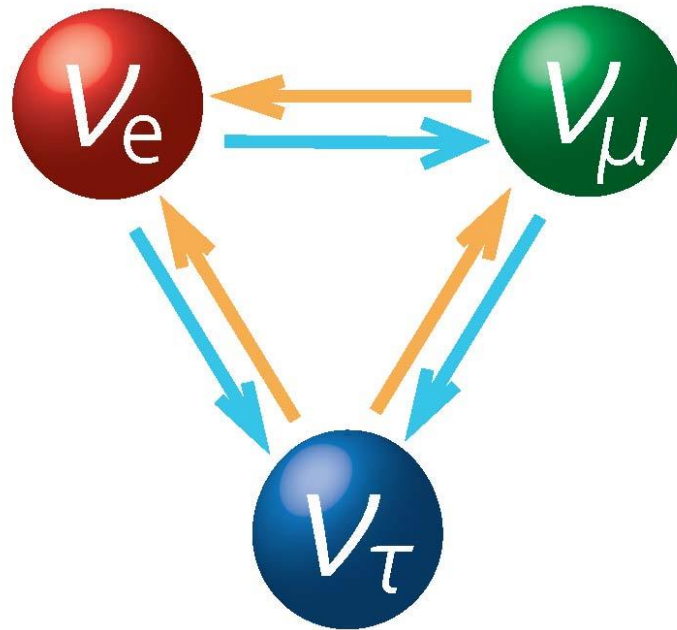
The measurements of Kamiokande and of the new generation version of it, Super Kamiokande confirmed Davies's results.

The neutrinos detected are three times less than predicted by theory.

The Solar Theory has been confirmed by helioseismological and other observations. Thus we somehow miss the majority of neutrinos that the sun sends us.

Where are they???

Neutrino Oscillations

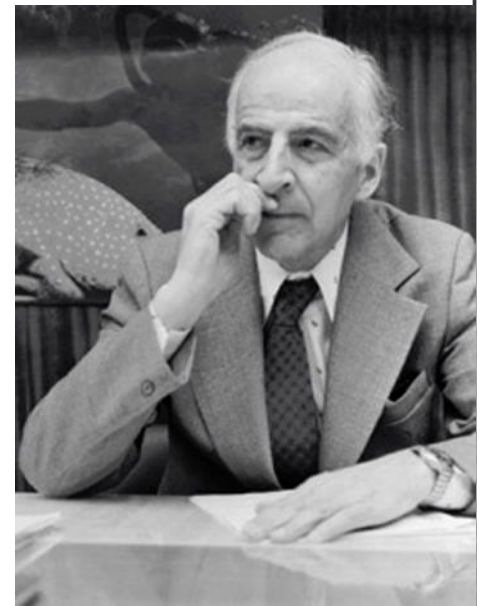


What have we learnt so far:

- Neutrinos come in three flavors : electron neutrinos (ν_e), muon neutrinos (ν_μ) and tau neutrinos (ν_τ).
- Each type of neutrino will react and produce the corresponding charged lepton.
- Solar neutrinos are electron neutrinos according to the theory: When they interact, they will produce electrons in our detector which we can measure.
- The neutrino flux we detect on earth is $\sim 1/3$ of the flux predicted by the successful solar model.

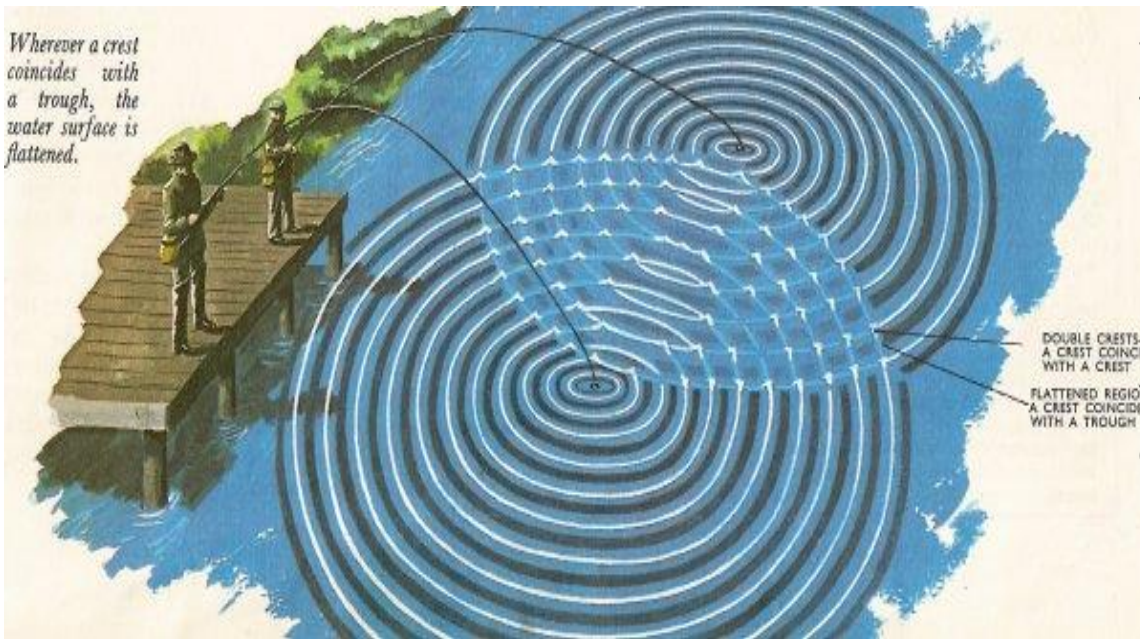
→ Conclusion: Either the Solar Model is Wrong (Hint: Not Likely), or something happens to the neutrinos in their path from their creation to their detection that doesn't allow us to count them all!

- During the '60, Physicist Bruno Pontecorvo proposed a new effect : The Neutrino Oscillations.
- According to this effect, when a neutrino is produced during a physical process, and we consider that neutrino is massive, then its "flavor" will change!
A neutrino may start as a muon neutrino and after some distance to "oscillate " into a tau or electron neutrino!!!



Bruno Pontecorvo

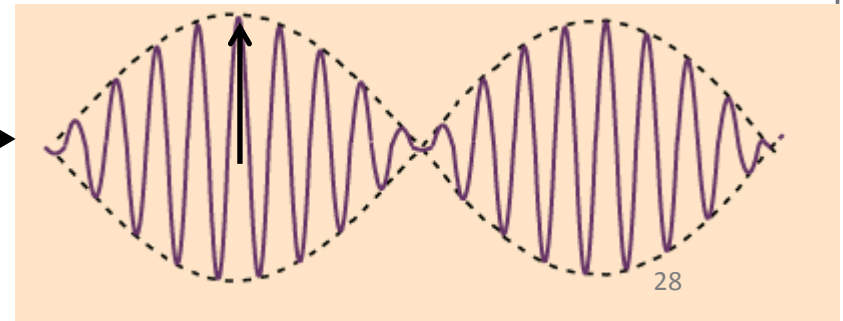
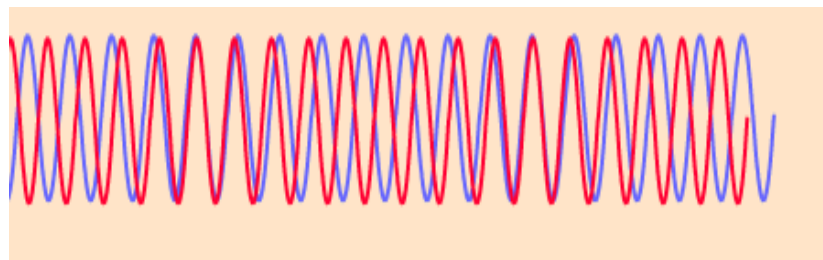
A Classical Physics Analogy



2 waves with slightly different frequencies start transversing the same medium simultaneously.

The points at which the waves interfere have amplitude which depends on the distance from their sources and the difference of their frequencies.

→ Beats in waves!



Physics of Neutrino Oscillations

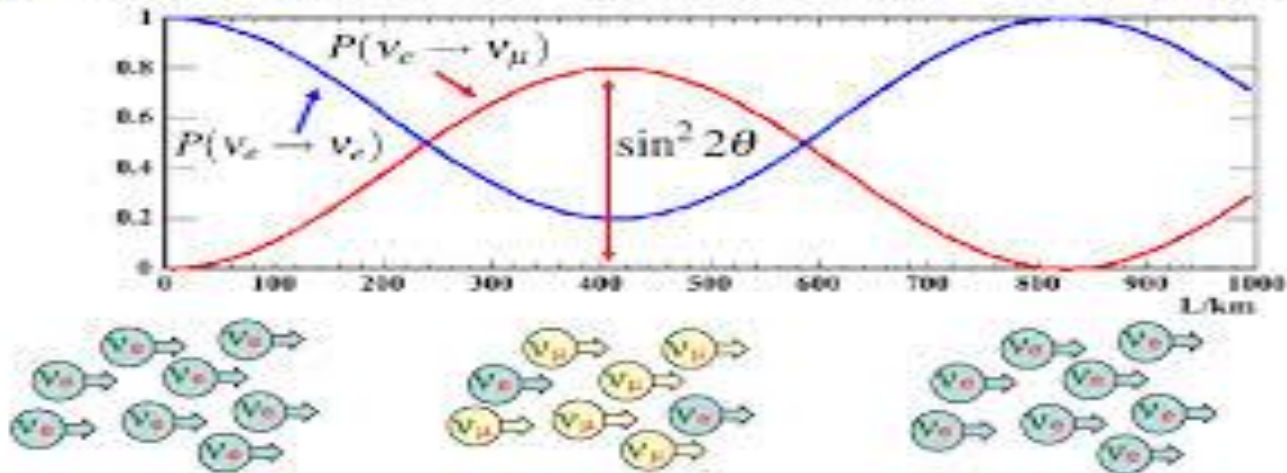
Likewise, we can consider the neutrino oscillations:

A muon neutrino starts propagating from point A. We can consider the muon neutrino as a mixture of two other waves (mass eigenstates) with slightly different (masses) frequencies.

These waves with different frequencies mix up to "cook" a muon neutrinos. The muon neutrino amplitude gives us the probability to observe a muon neutrino in position X.

As the neutrino travels, the probability to observe a muon neutrino changes: Neutrinos oscillate from one flavor to another.

e.g. $\Delta m^2 = 0.003 \text{ eV}^2$, $\sin^2 2\theta = 0.8$, $E_\nu = 1 \text{ GeV}$



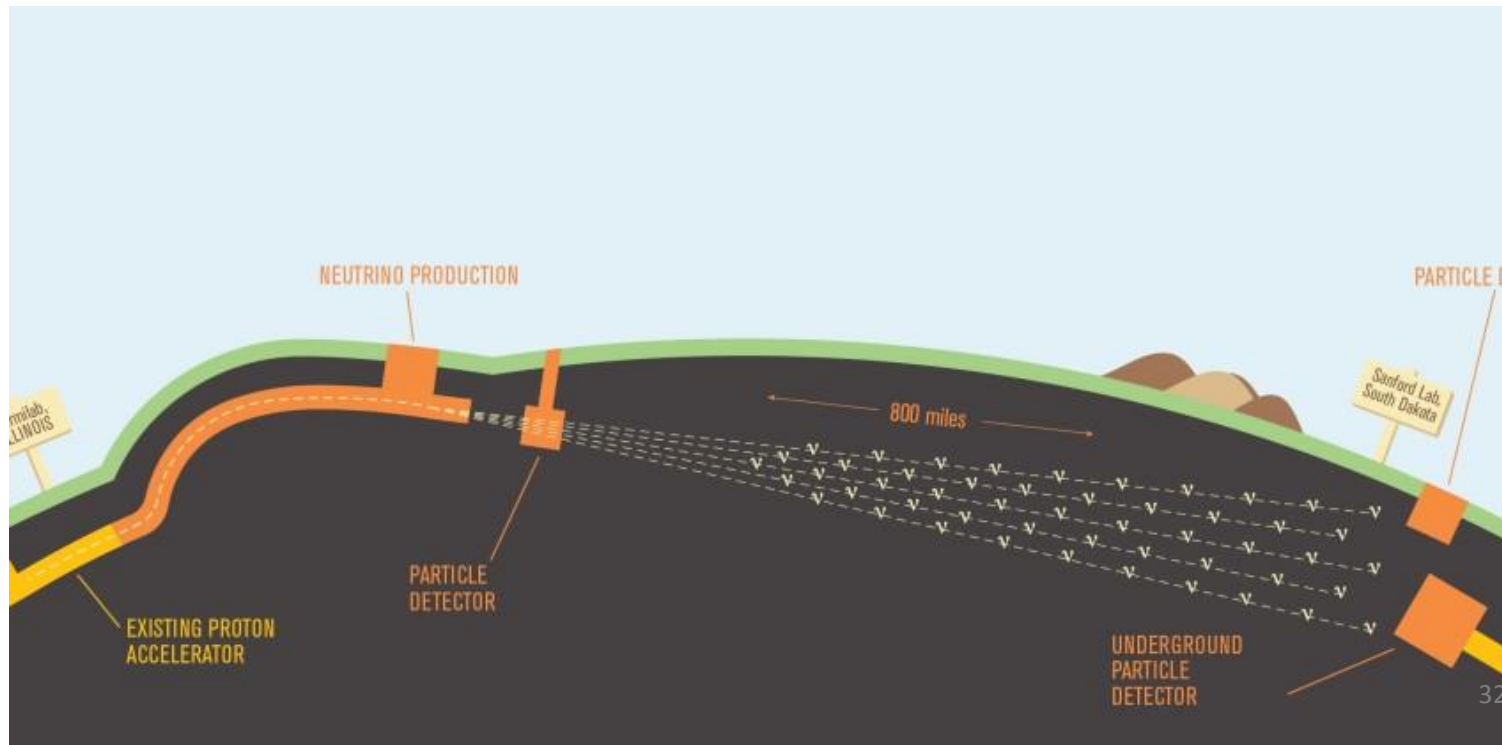
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E_\nu} \right)$$

Neutrino Oscillations in Accelerator Experiments

Disappearance experiments

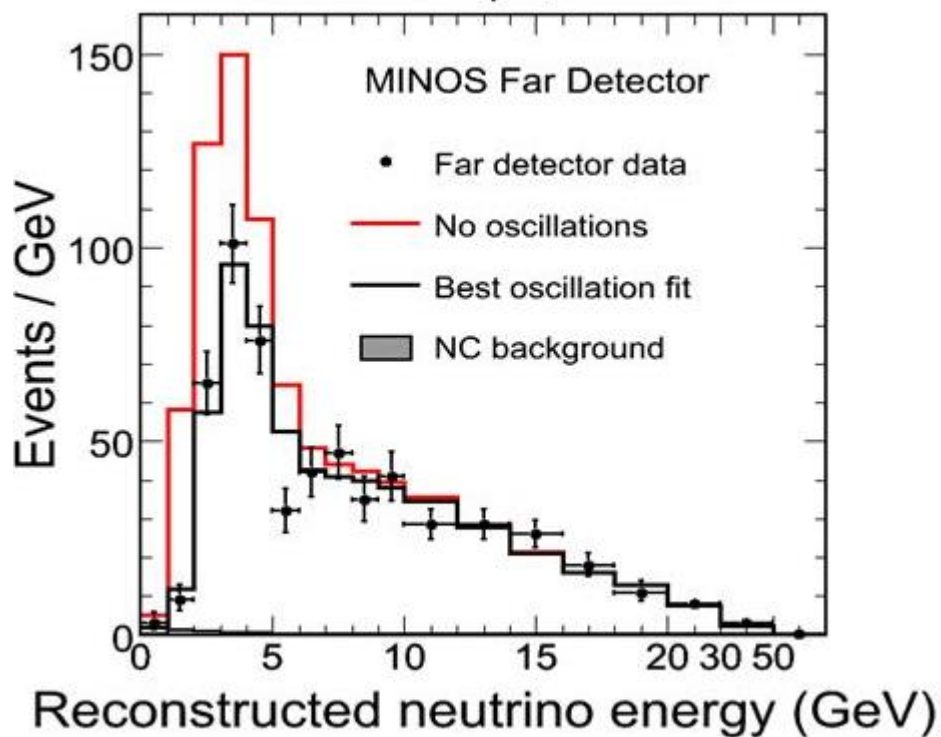
- Protons are accelerated and collide with a stationary target.
- Muon Neutrinos are produced.
- Muon Neutrinos travel towards a dedicated near detector and their energy spectrum is measured .
- Neutrinos keep travelling through the earth (distances up to 700 km) until they reach a similar far detector where their spectrum is measured again.

By comparing the near and far spectra, we observe that if neutrinos have oscillated, the far detector will measure less muon neutrinos than the near one in some energy bins determined by the physics of oscillations. Thus, muon neutrinos will disappear.

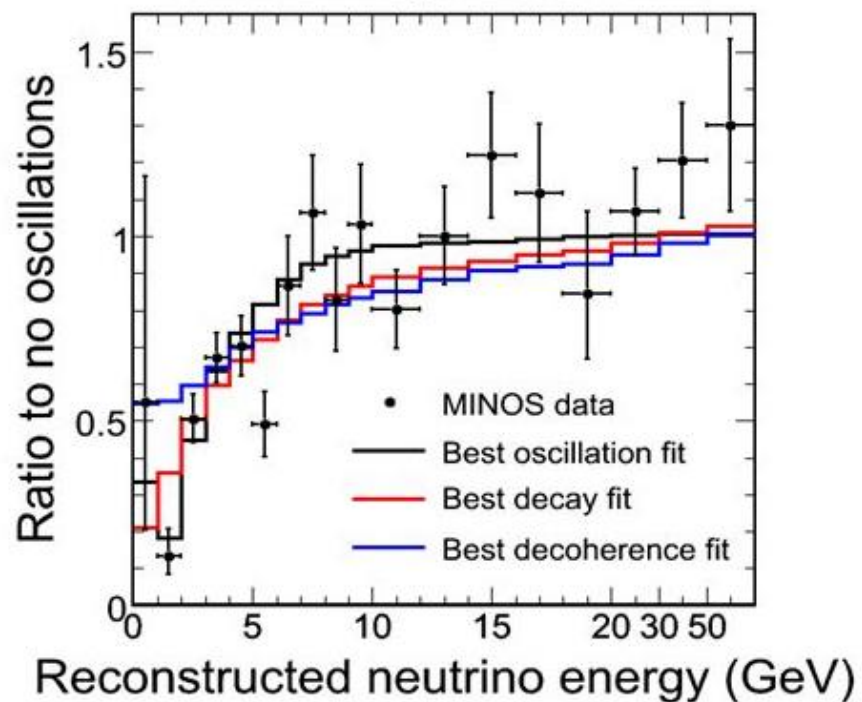


Results from the MINOS experiment in USA:

observed ν_μ spectrum



observed spectrum ratio

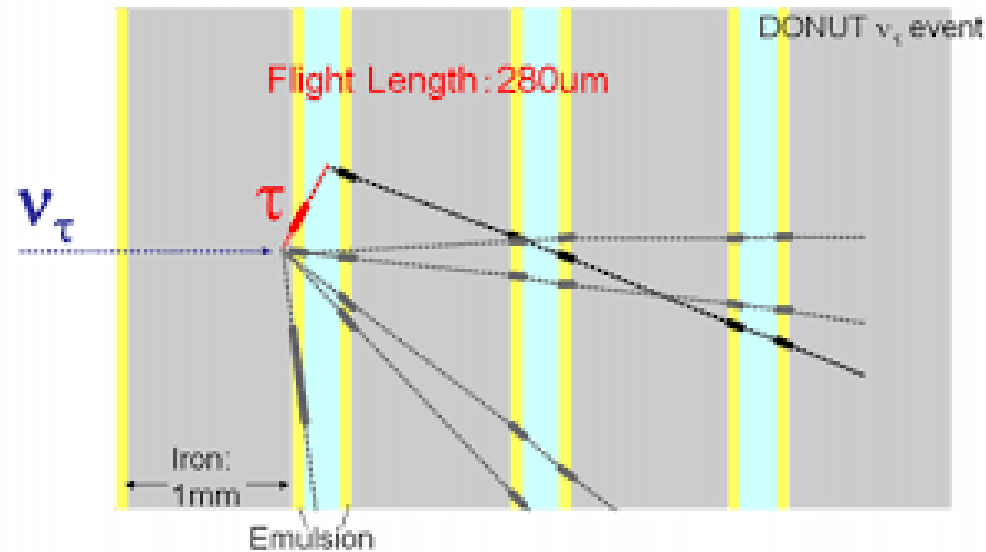
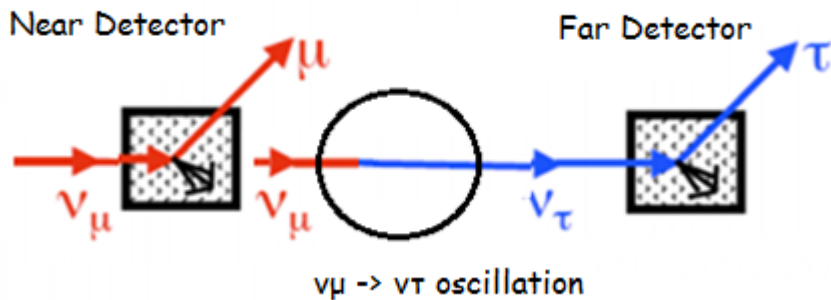


Neutrino Appearance Experiments

Similar approach to the disappearance experiments:

We study the neutrinos interacting with the near detector.

We measure the neutrinos in the far detector and check if we observe any neutrino "flavor" that didn't exist in the near detector measurement.



Let's check the following app:

http://www.learner.org/courses/physics/interactive/lab_interactives/subatomic.html

- Could the neutrino oscillation effect explain the "Solar Neutrino Deficit" ?

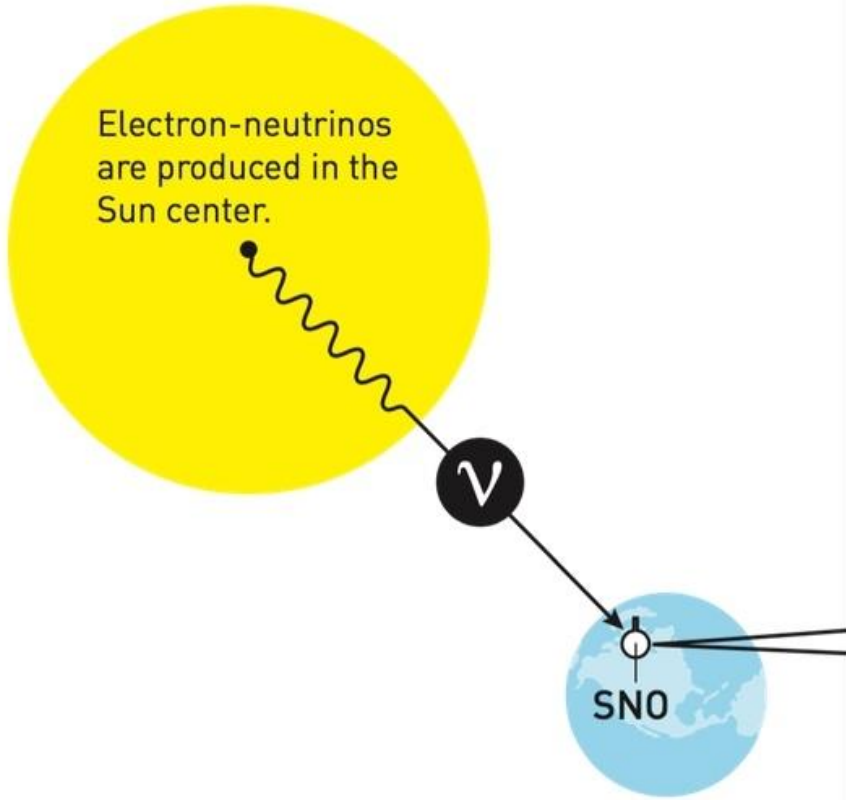
Consider this: If we could somehow count all the neutrinos coming from the sun without focusing on a particular flavor, and compared with the number of electron neutrinos coming from the sun, if neutrino oscillations were true we would measure different numbers! The neutrinos would flip identities while travelling towards us!!



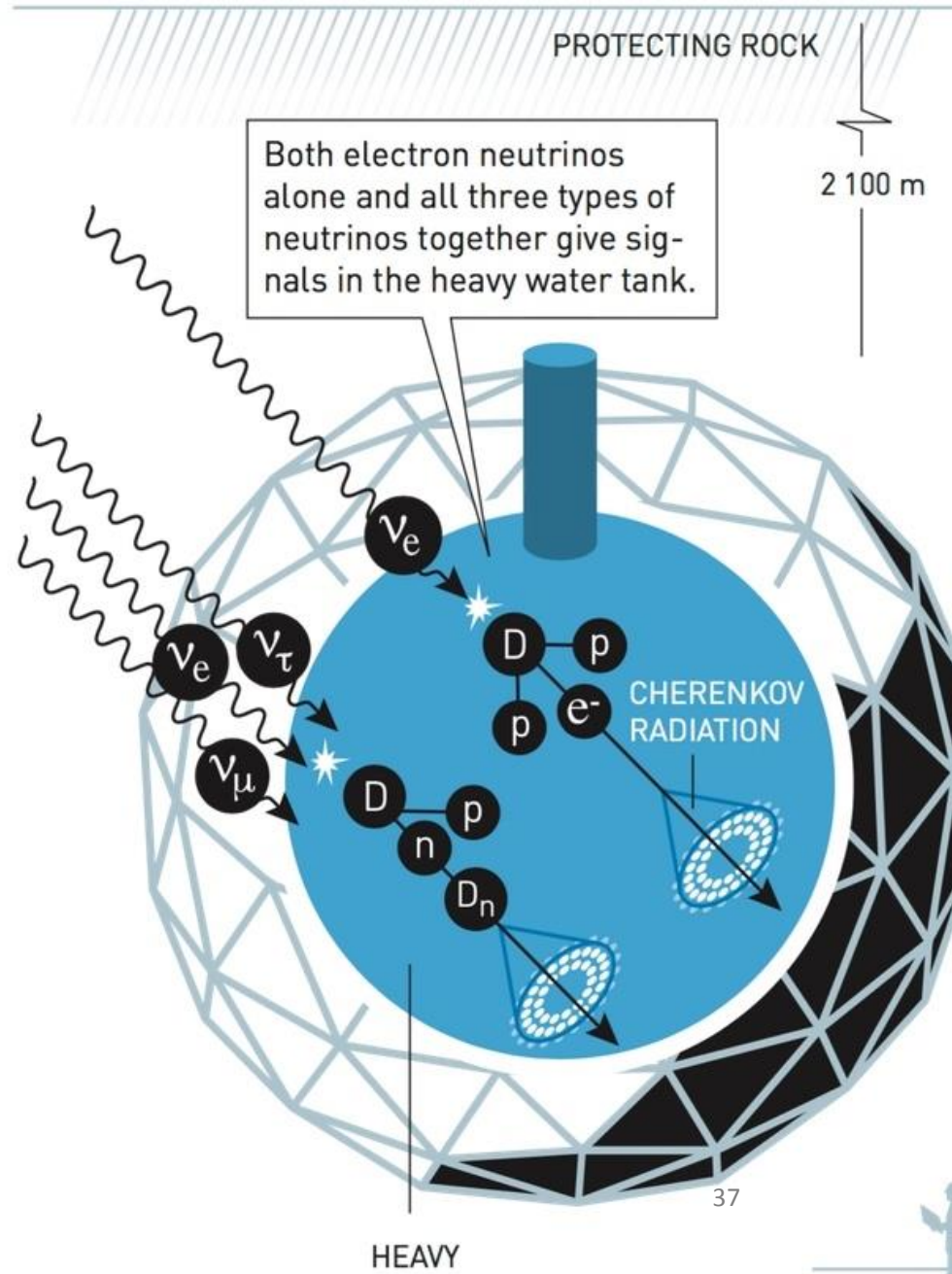
The SNO Detector

NEUTRINOS FROM THE SUN

Electron-neutrinos are produced in the Sun center.



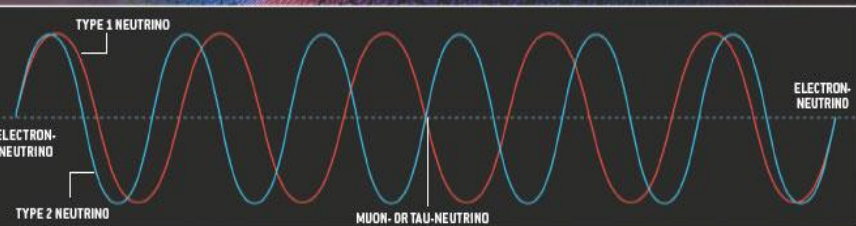
SUDBURY NEUTRINO OBSERVATORY (SNO) ONTARIO, CANADA



DETECTING FICKLE NEUTRINOS

HOW NEUTRINOS OSCILLATE

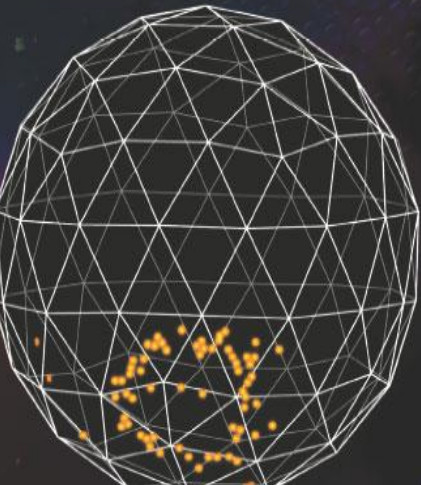
An electron-neutrino (*left*) is actually a superposition of a type 1 and a type 2 neutrino with their quantum waves in phase. Because the type 1 and type 2 waves have different wavelengths, after traveling a distance they go out of phase, making a muon- or a tau-neutrino (*center*). With further travel the neutrino oscillates back to being an electron-neutrino (*right*).



WHERE NEUTRINOS OSCILLATE

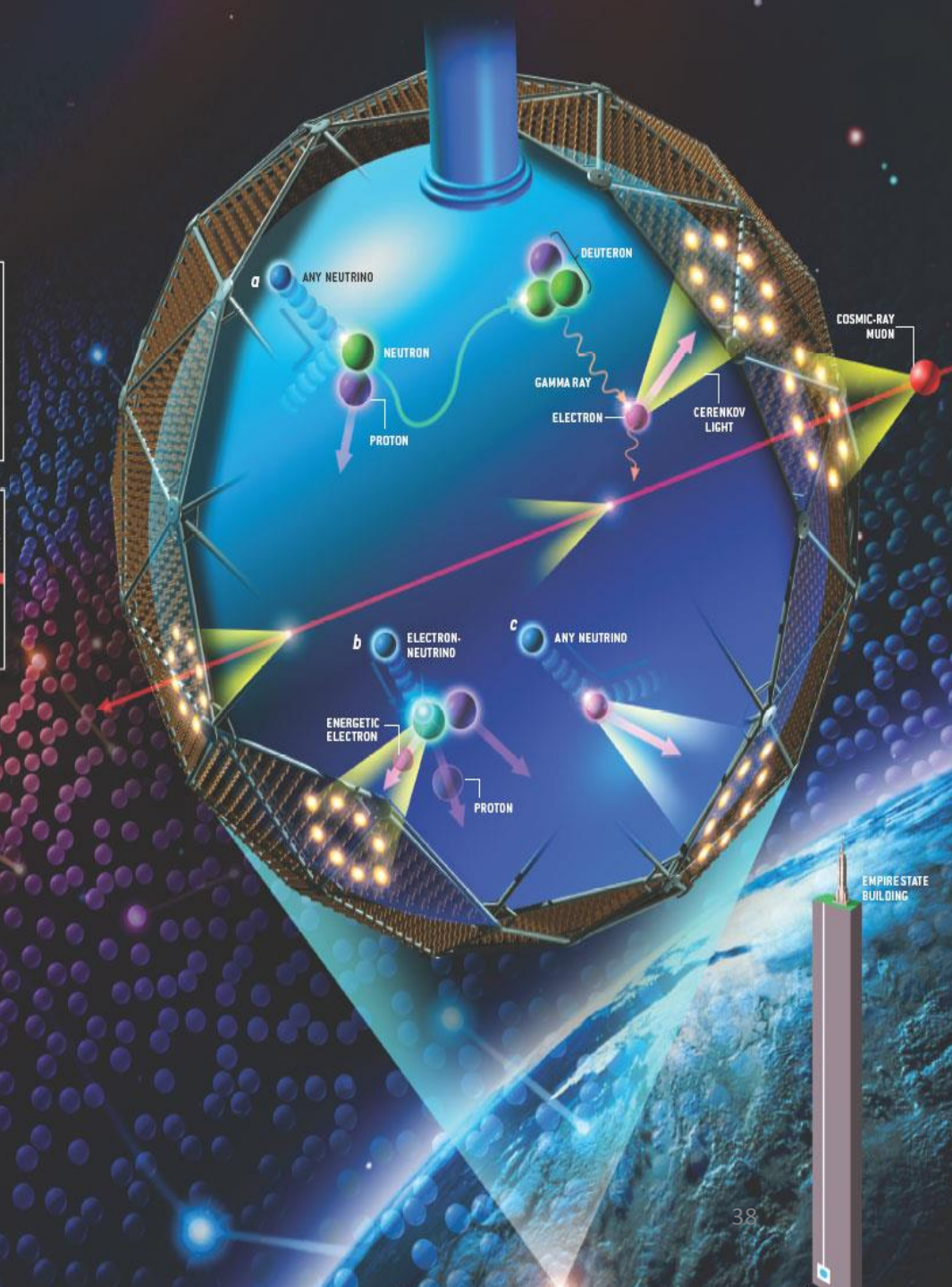
The electron-neutrinos produced at the center of the sun may oscillate while they are still inside the sun or after they emerge on their eight-minute journey to the earth. Which oscillation occurs depends on details such as the mass differences and the intrinsic degree of mixing of type 1 and 2 neutrinos. Extra oscillation may also occur inside the earth, which manifests as a difference between daytime and nighttime results.

ACTUAL DATA OF A CANDIDATE NEUTRINO EVENT

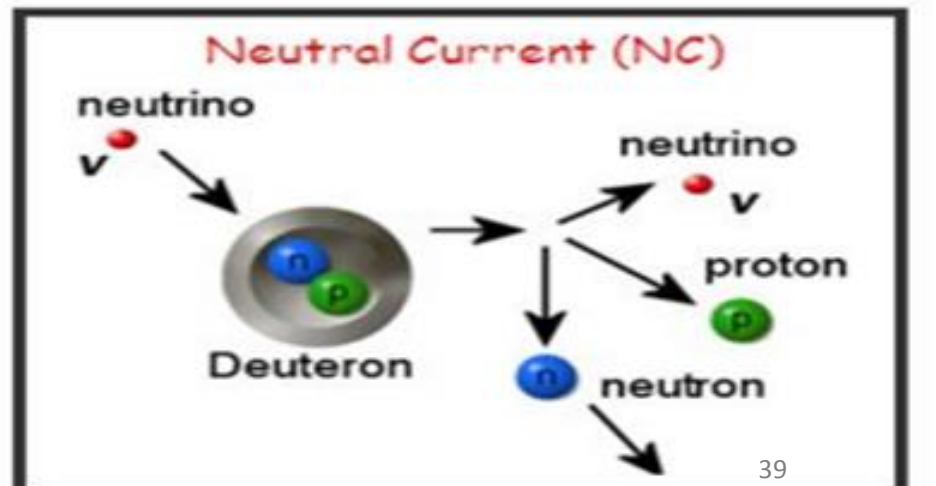
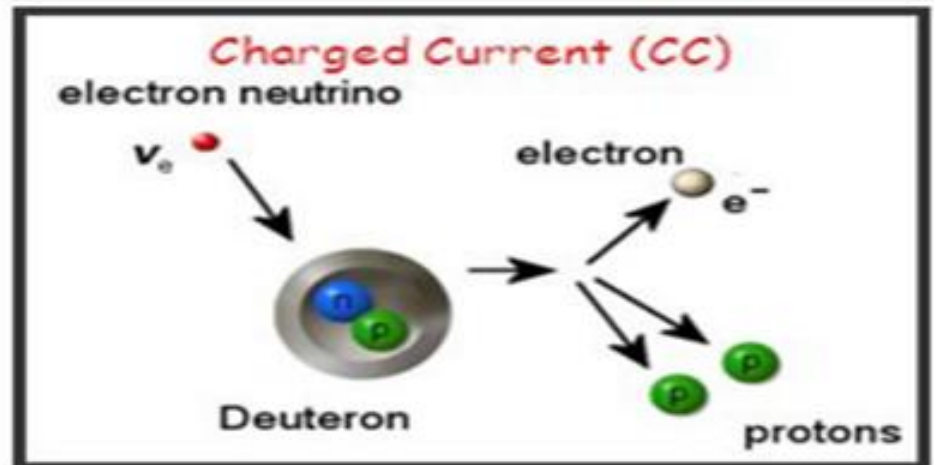
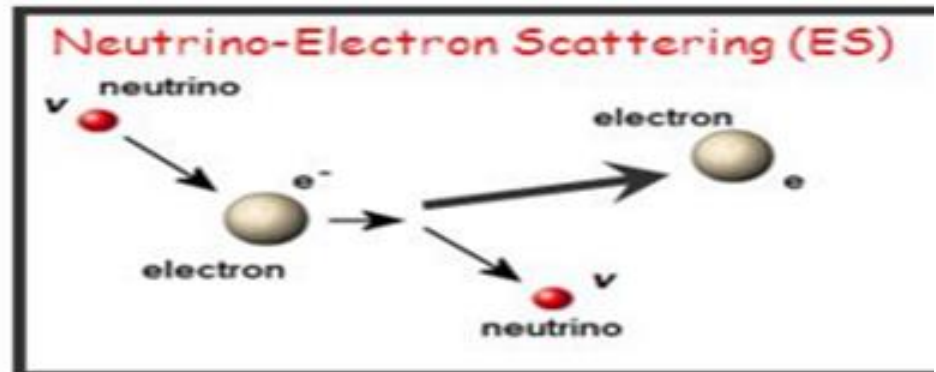


HOW SNO DETECTS NEUTRINOS

The Sudbury Neutrino Observatory, or SNO (*opposite page*), detects a neutrino by seeing a characteristic ring of Cerenkov light emitted by a high-speed electron. The neutrino produces the energetic electron in SNO's heavy water (*large blue sphere*) in one of three ways. In deuterium breakup (*a*), the neutrino (*blue*) splits a deuterium nucleus into its component proton (*purple*) and neutron (*green*). The neutron eventually combines with another deuterium, releasing a gamma ray (*wavy line*), which in turn knocks free an electron (*pink*) whose Cerenkov light (*yellow*) is detected. In neutrino absorption (*b*), a neutron absorbs the neutrino and is thereby turned into a proton and an energetic electron. Only electron-neutrinos can be absorbed in this way. Less often the neutrino may collide directly with an electron (*c*). Cosmic-ray muons (*red*) are distinguished from neutrinos by the amount of Cerenkov light they produce and where they produce it—outside the detector as well as inside. The number of muons is reduced to manageable levels by positioning the detector two kilometers underground.

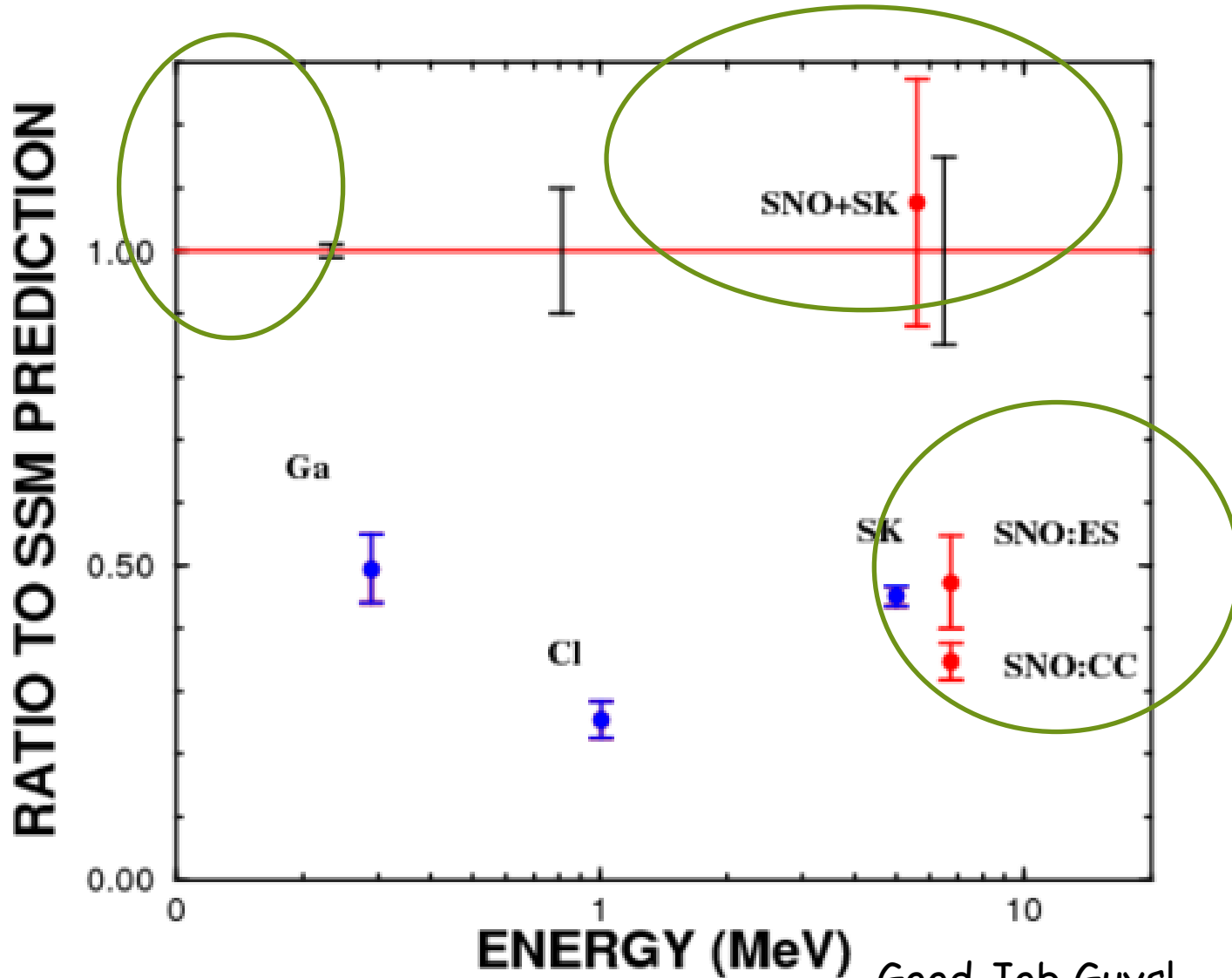


- The SNO detector can measure electron neutrinos independently (by measuring the Cherenkov radiation from electrons in the final state as well as the two protons produced when an electron neutrino strikes a deuteron nucleus).
- The SNO detector can measure Neutral Current neutrino scattering, in which a neutrino strikes a deuteron nucleus and recoils producing a proton and a neutron in the final state. Neutral current scattering is the same for ALL neutrino flavours.
- By comparing the electron neutrino interactions with the neutral current interactions, SNO scientists can determine if the two types of interaction have the same frequency. If not, then neutrino oscillations will be taking place.

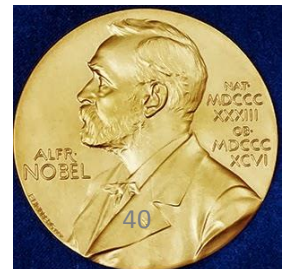


SNO results (2001): electron neutrinos are proven to be 1/3 of the total neutrino flux from the sun!!

The Solar Model is Correct and Neutrinos DO oscillate



Good Job Guys!



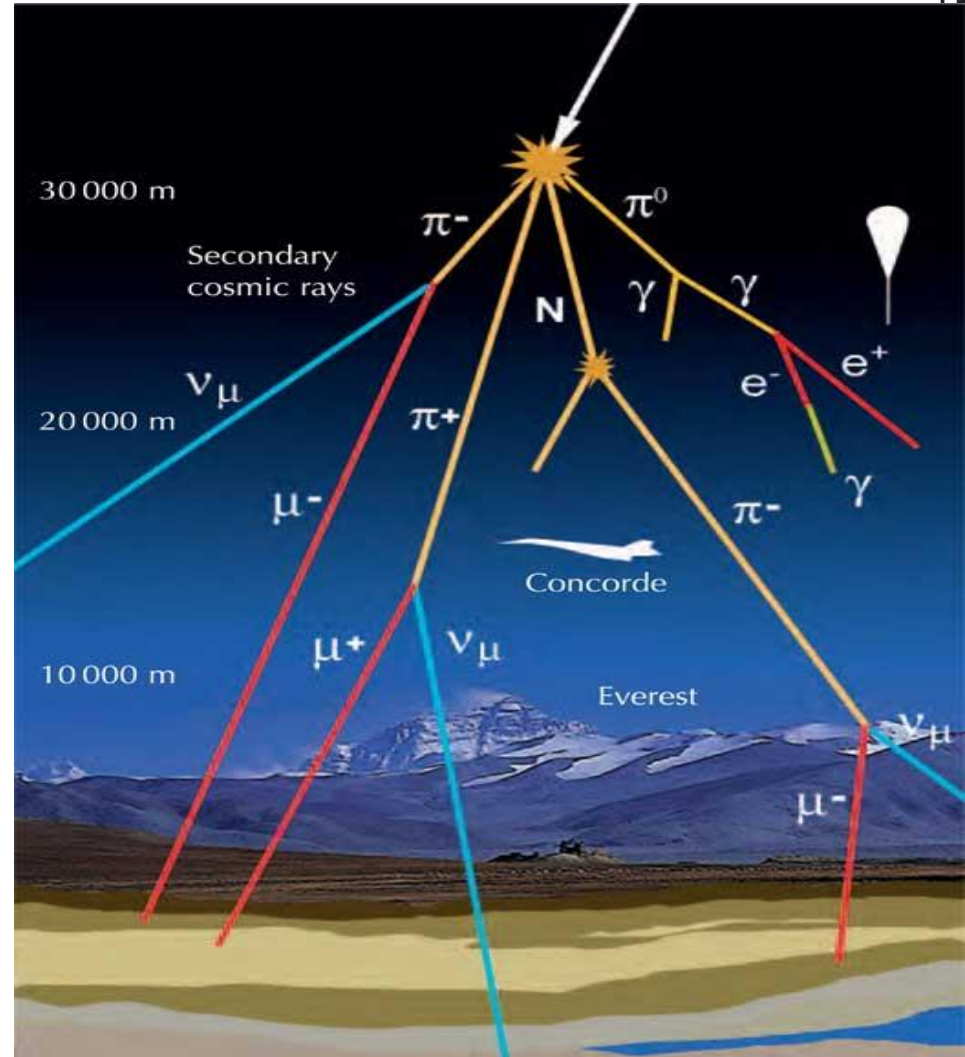
And Now WHAT?



The atmosphere is constantly bombarded by cosmic radiation:

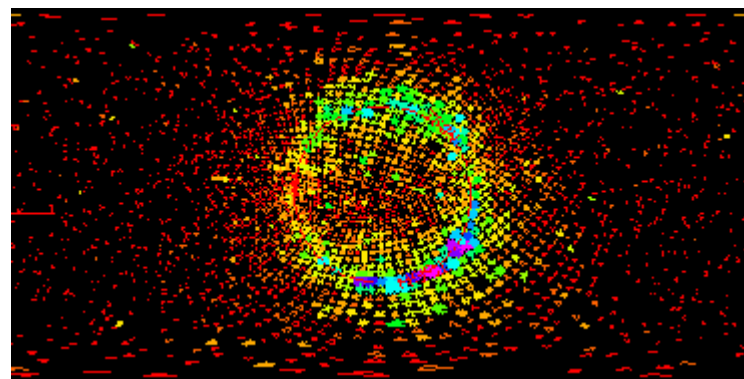
Energetic particles (mainly protons) coming from outer space interact with molecules in the atmosphere. These reactions produce neutrinos!

Do atmospheric neutrinos exhibit oscillation effects??

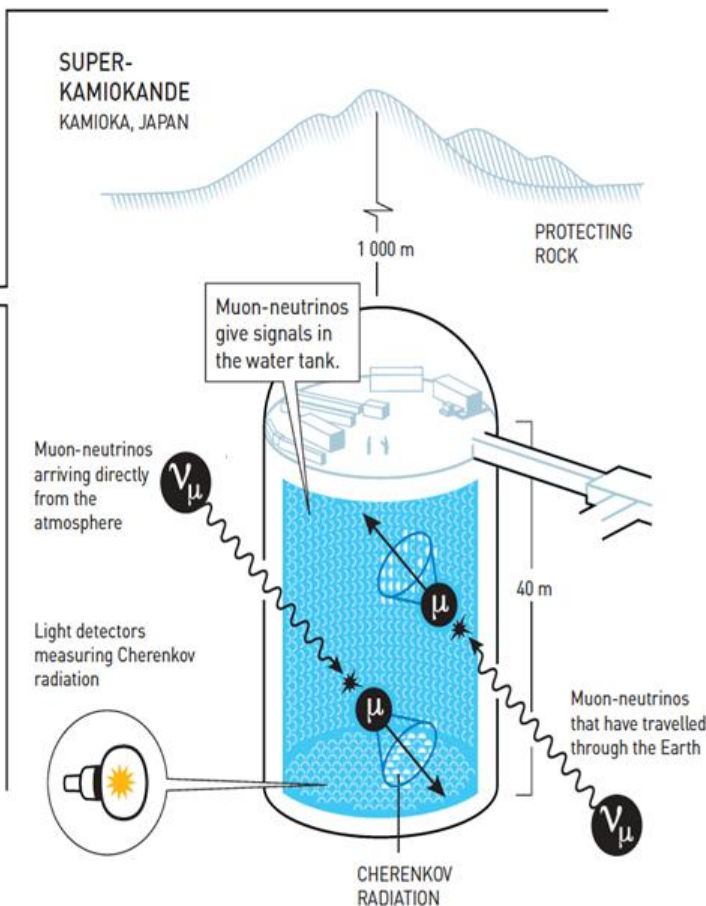
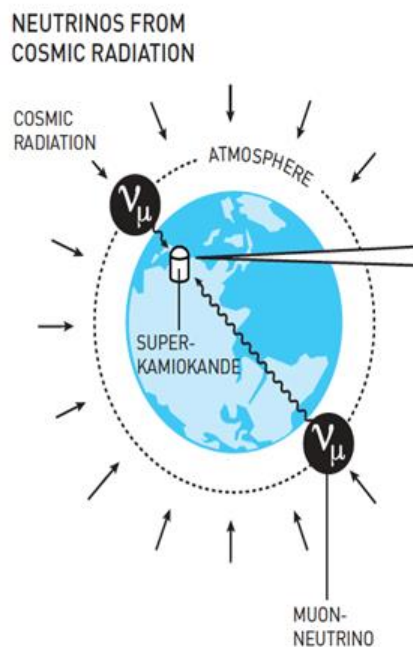
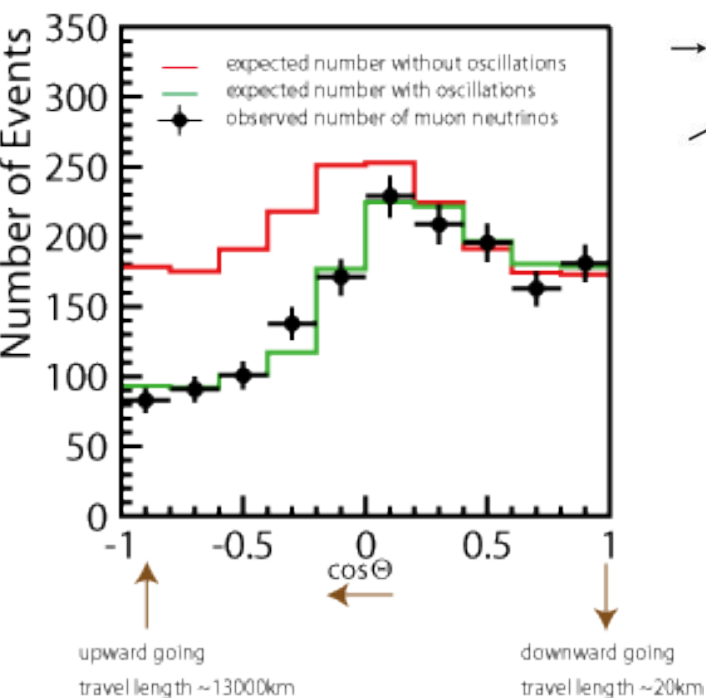




That makes 2 out of 2!
Good job Super Kamiokande.



(Super-K, 1998)



Oscillations in atmospheric neutrinos!!!



Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2



Photo: K. MacFarlane,
Queen's University
/SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015

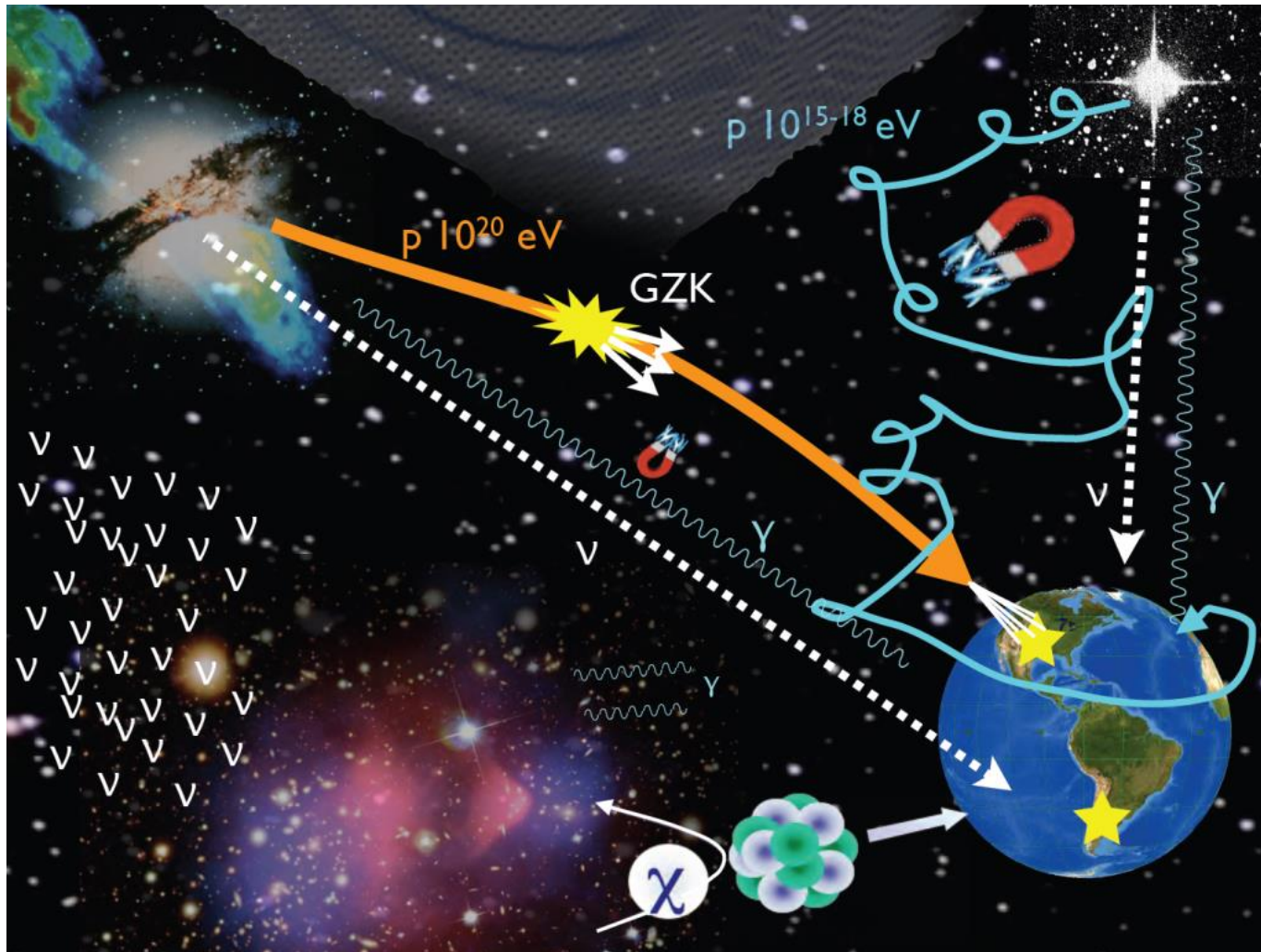
- ▶ **Takaaki Kajita**
- ▶ **Arthur B. McDonald**

**"for the discovery of
neutrino oscillations"**

What else can we learn from Neutrinos?

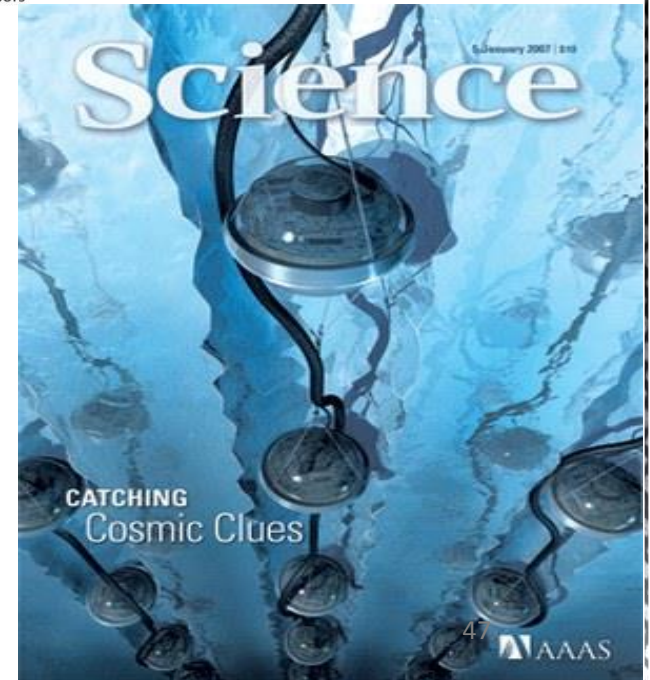
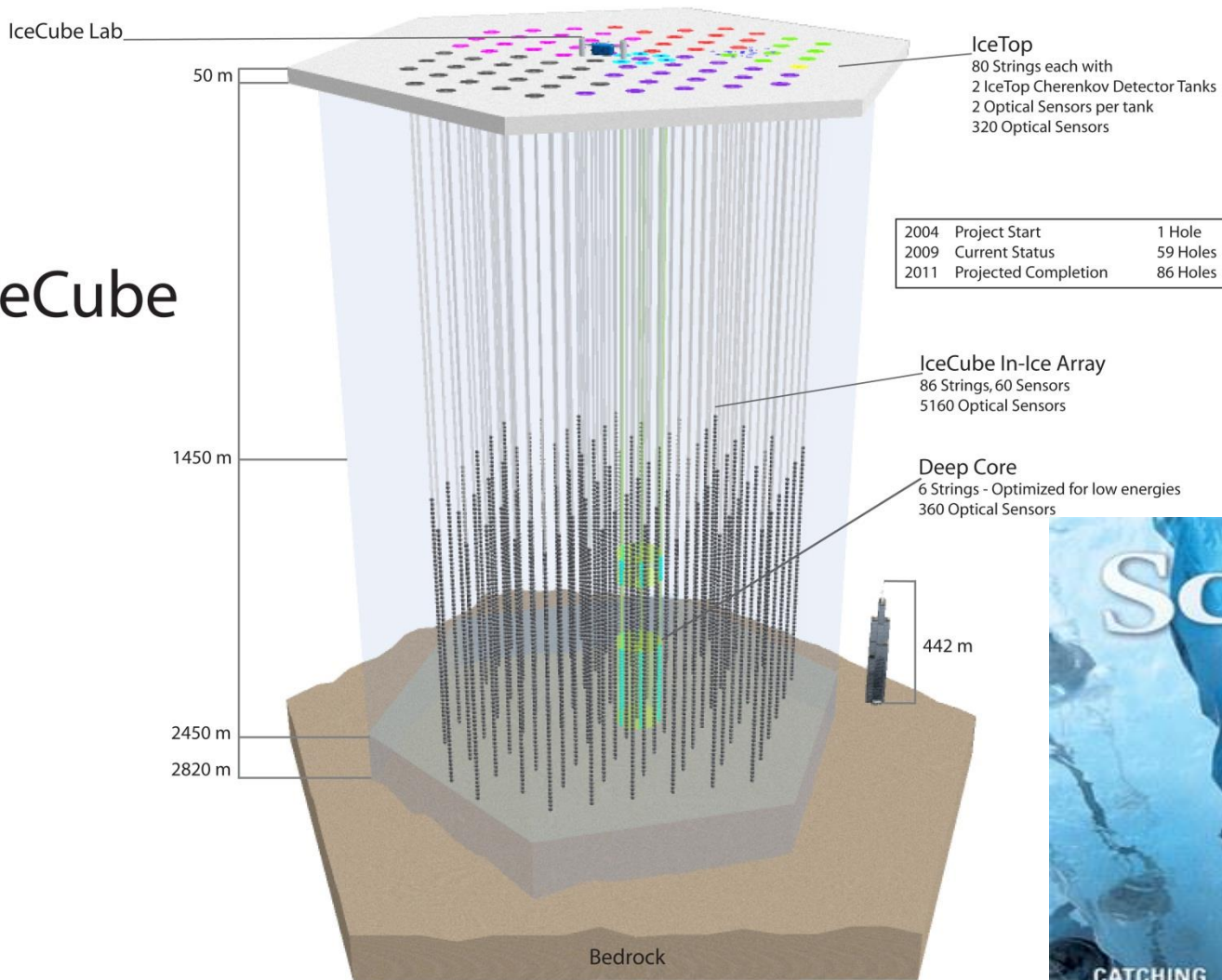
Neutrino Astronomy

- Neutrinos interact very rarely: They can travel vast distances in the Universe without interacting and be detected on earth!!
By detecting such "cosmic neutrinos" we can get information on the violent astrophysical events that created them.

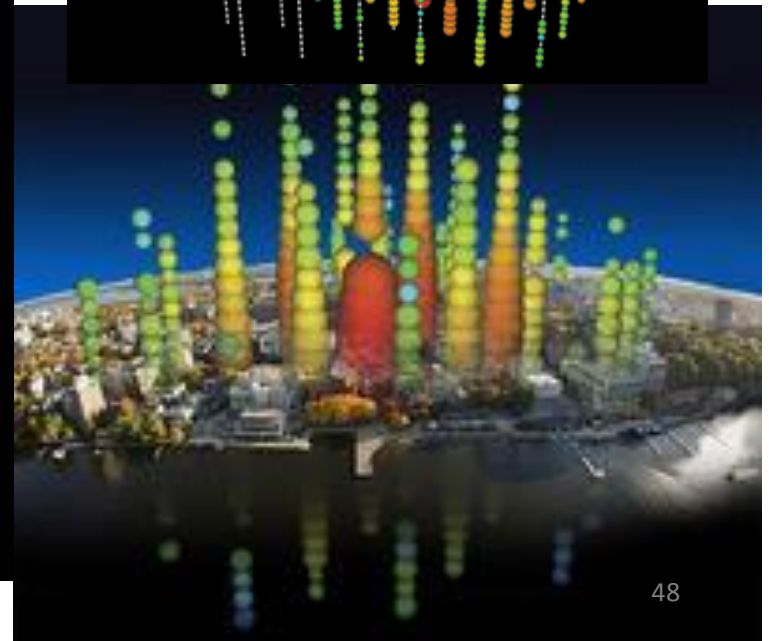
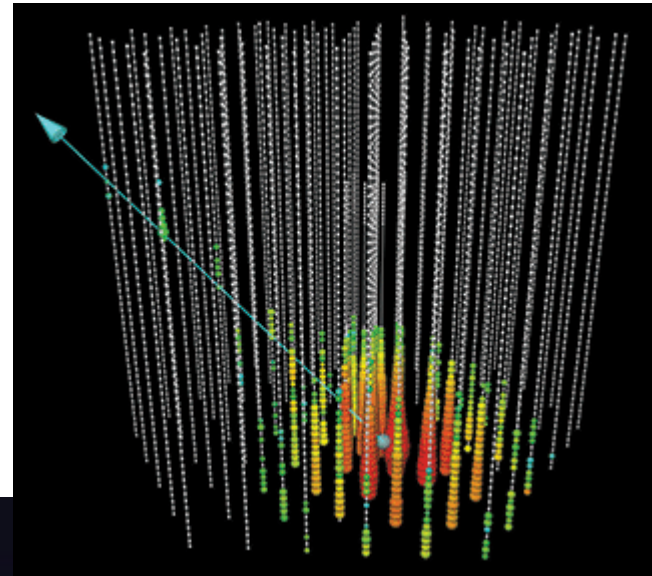
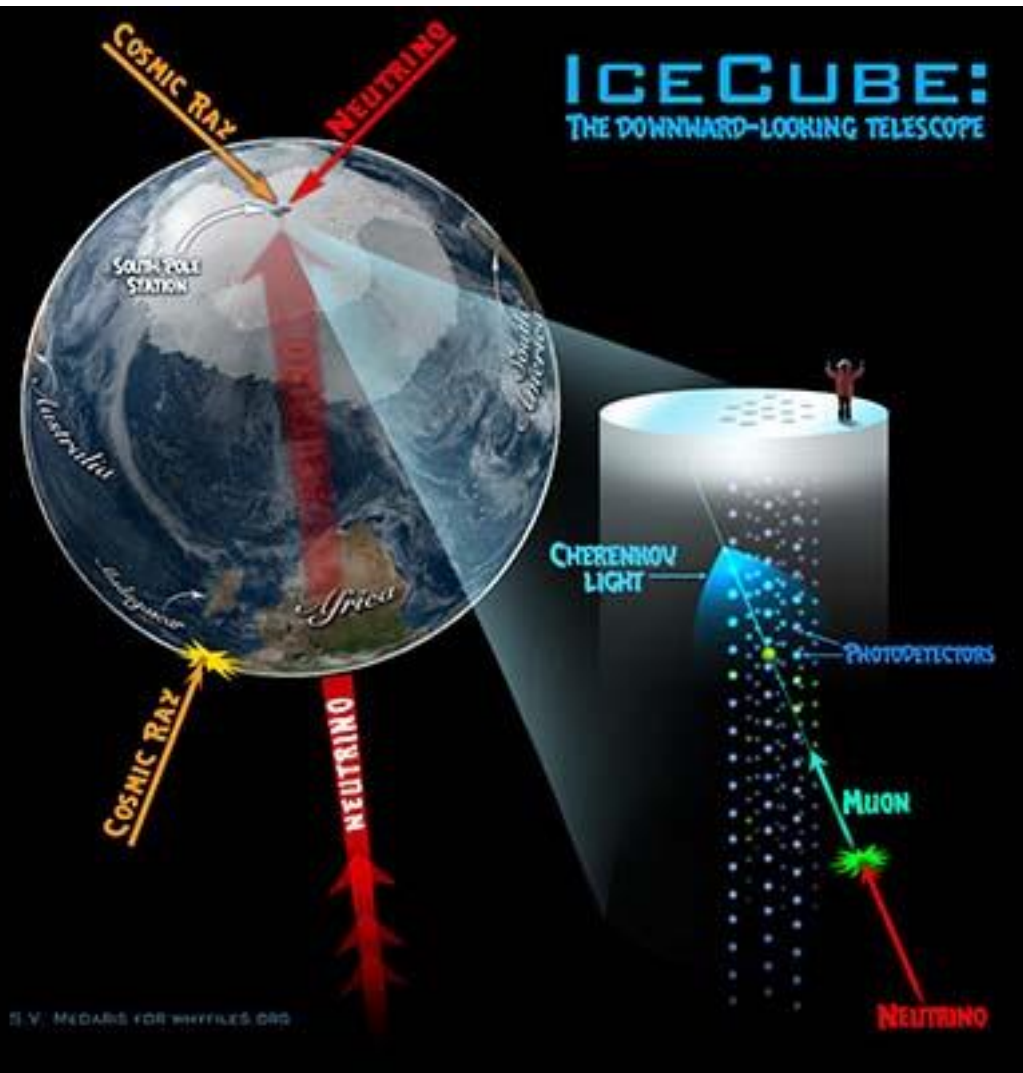


The IceCube experiment

IceCube



Achievement of Year 2013! Detection of the first ultra high energy cosmic neutrinos from the IceCube experiment!!



CONCLUSION:

- Neutrinos come in three flavors : electron neutrinos (ν_e), muon neutrinos (ν_μ) and tau neutrinos (ν_τ).
- Each type of neutrino will react and produce the corresponding charged lepton.
- Neutrinos coming from the sun, the atmosphere, accelerators and other sources exhibit the "Oscillation Effect" in which they can morph from one "flavor" to the other as they travel from their source to the detector. The verification of this effect resulted in the 2015 Nobel Prize in Physics!
- Neutrinos interact rarely. Thus, to detect them we need large fluxes of them, big detectors and lots of patience.
- The neutrinos can be used as probes for the Cosmos: "Neutrino Astronomy" has been born!