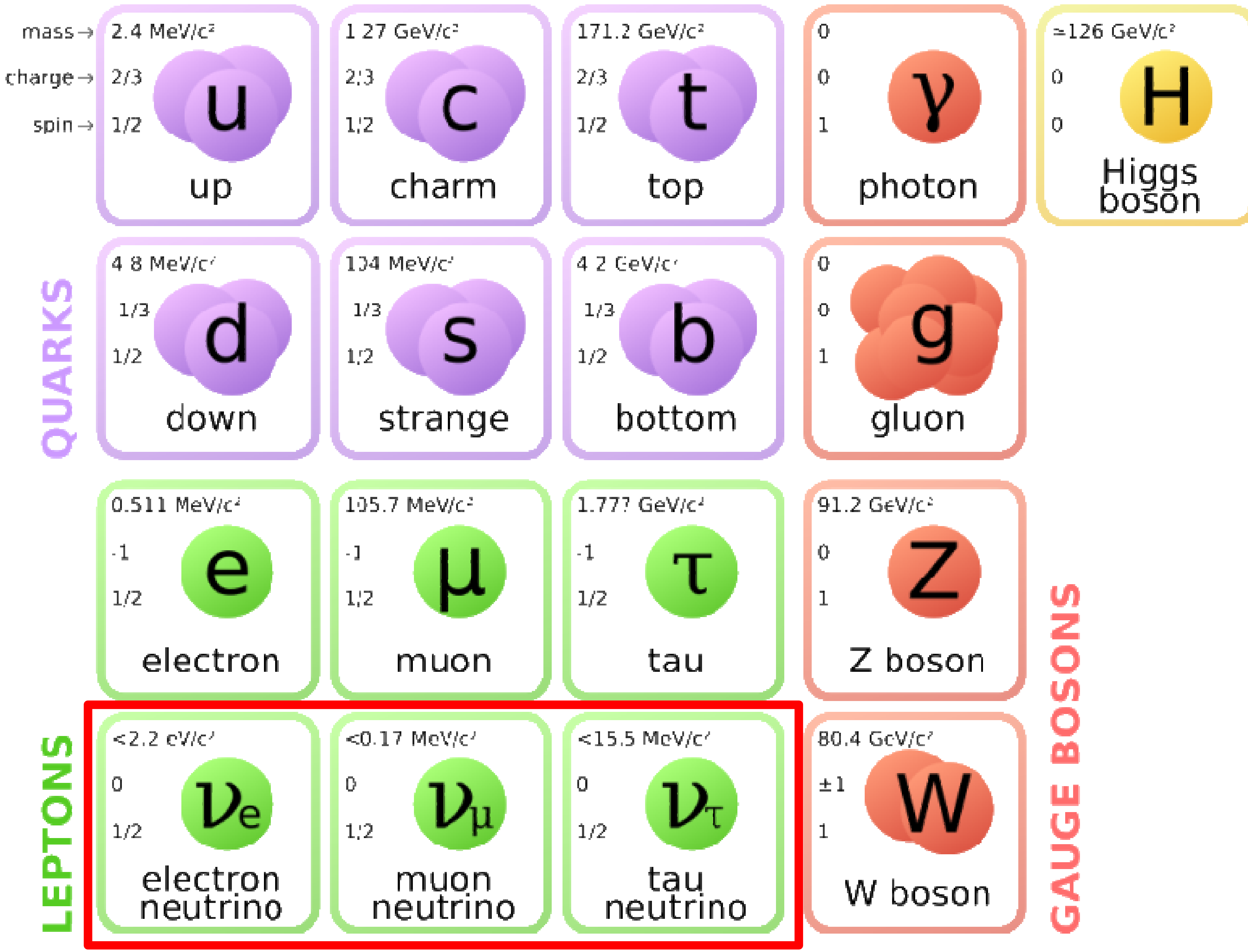
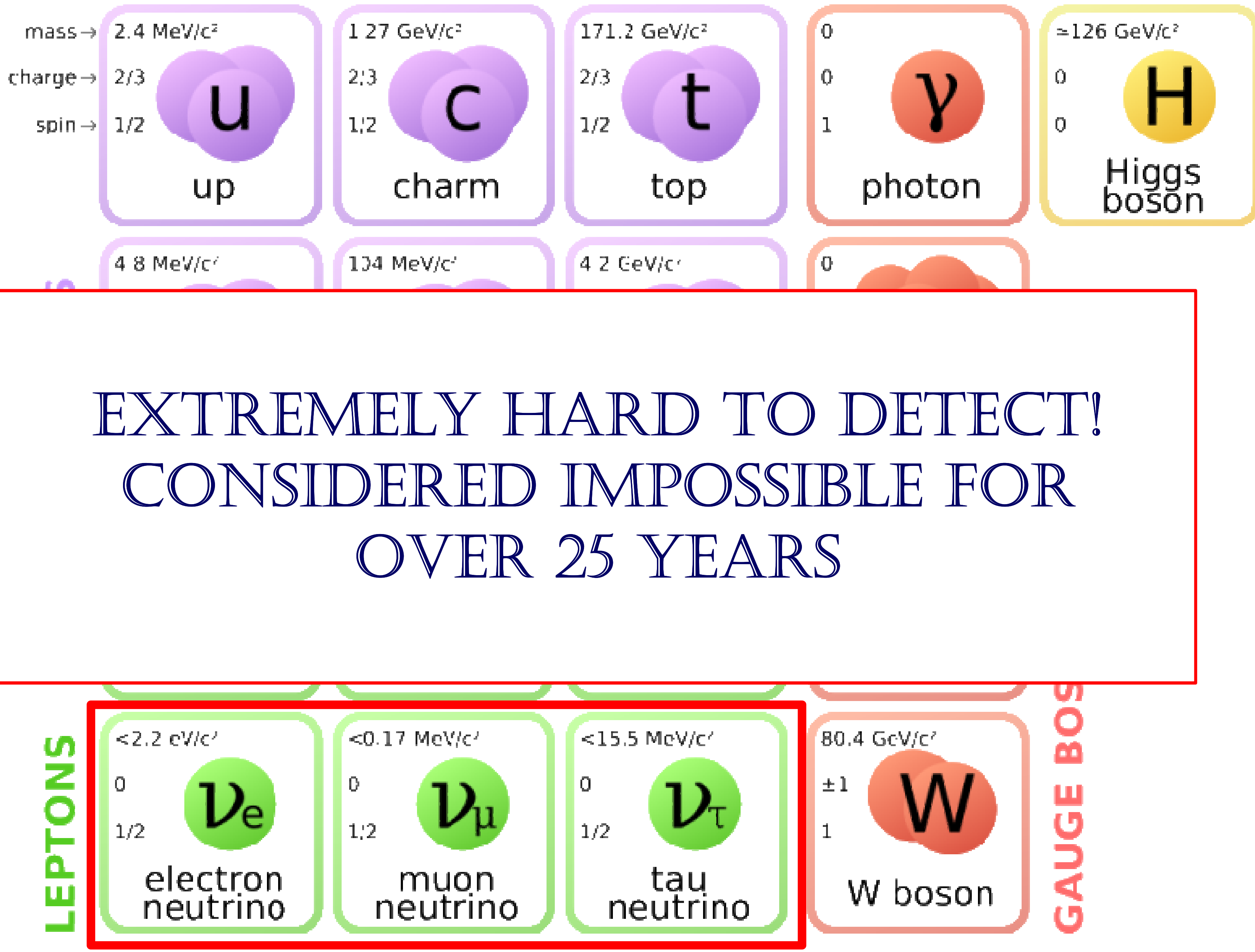
Neutrinos: the ghosts of the Universe



Credit: Wiki Commons

Neutrinos: the ghosts of the Universe



EXTREMELY HARD TO DETECT!
CONSIDERED IMPOSSIBLE FOR
OVER 25 YEARS

Credit: Wiki Commons

1953-1956

The Reines-Cowan Experiments

Detecting the Poltergeist

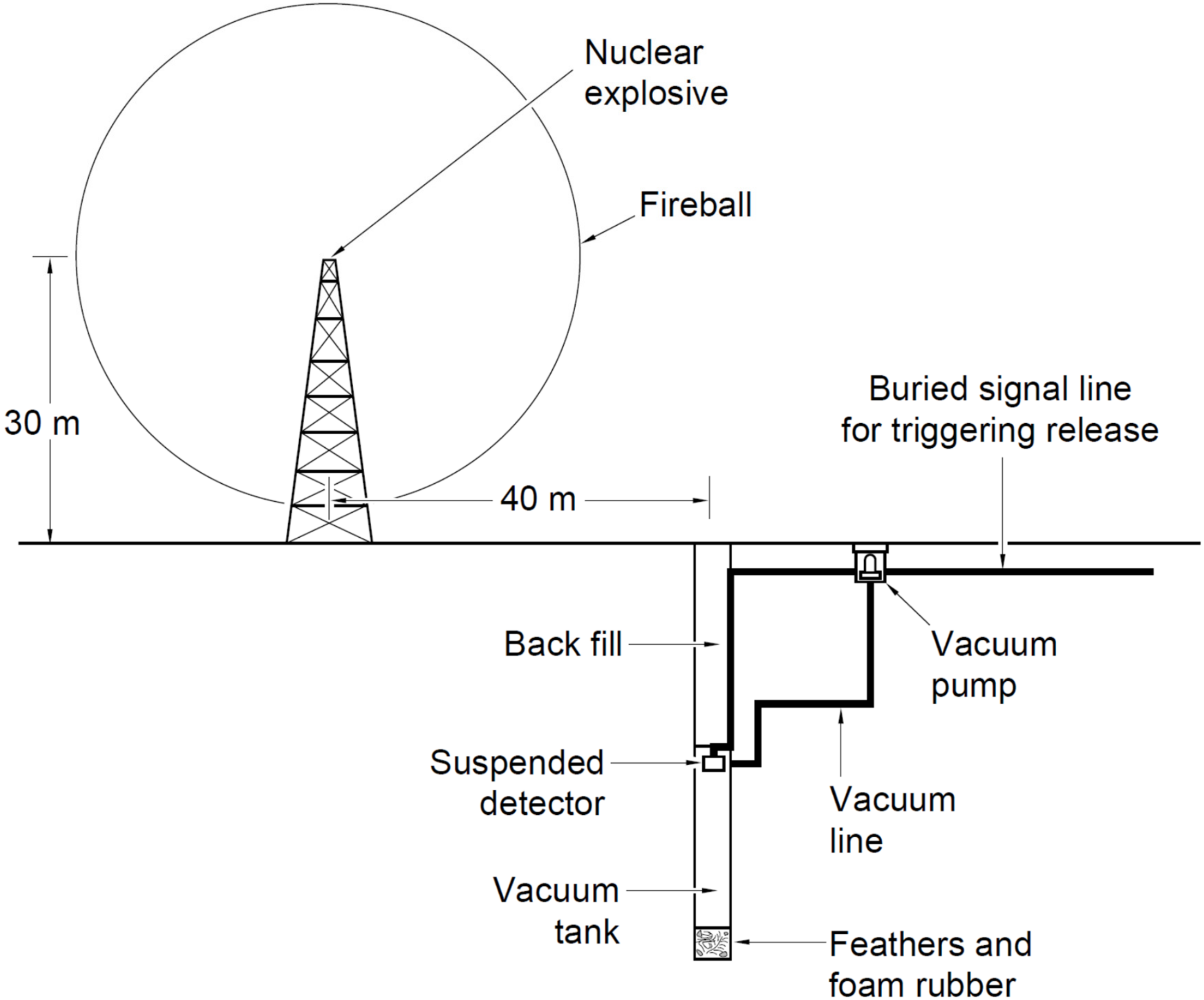
Goal: detect ANY neutrino (or antineutrino)

Why?
Because everyone said it was impossible!

$$\overline{\nu}_e + p \rightarrow n + e^+$$

Hanford Team 1953

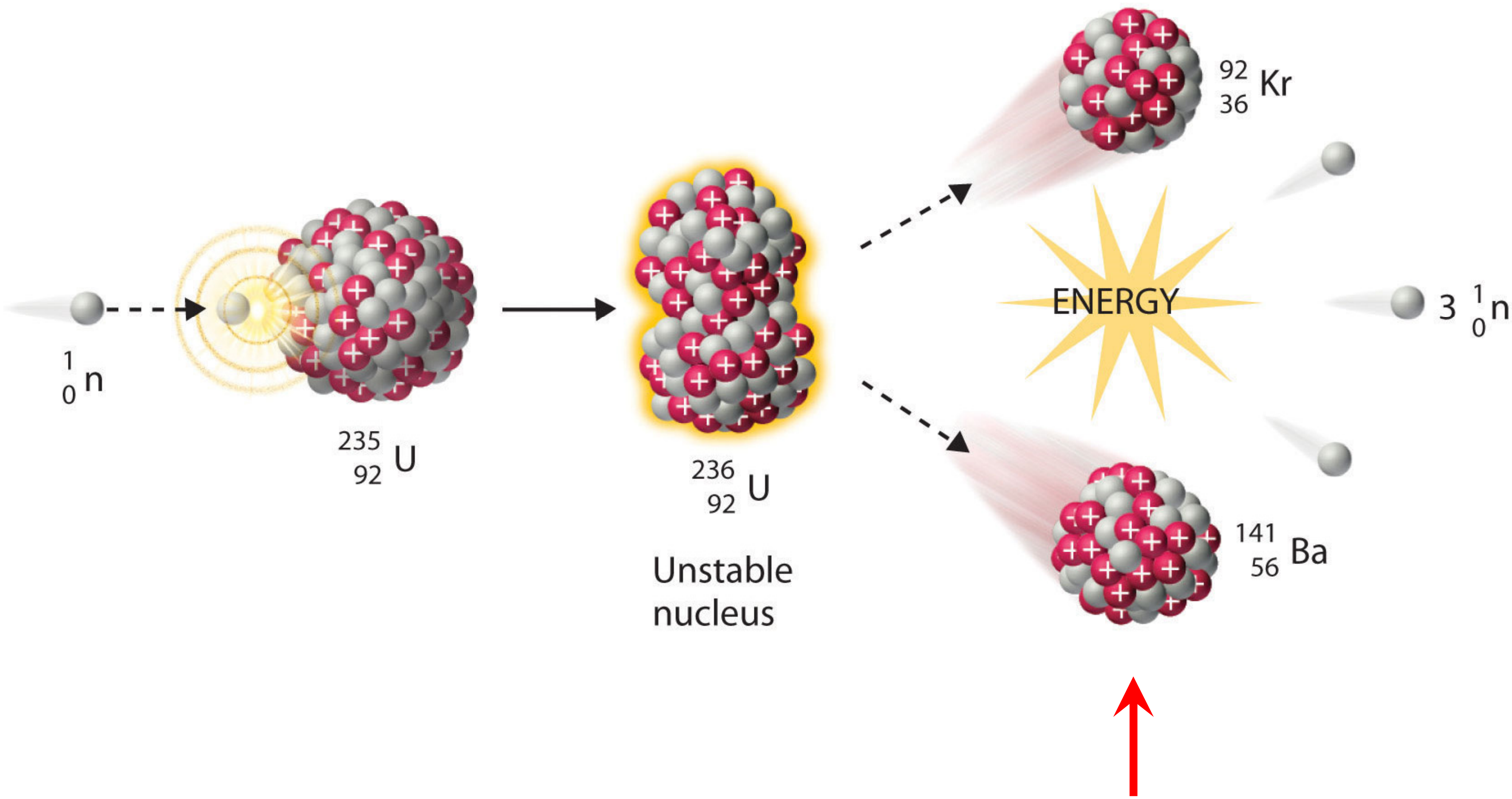
http://library.lanl.gov/cgi-bin/getfile?00326606.pdf



Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superseded by the approach which used a fission reactor.

http://library.lanl.gov/cgi-bin/getfile?00326606.pdf

Nuclear fission reactor as (anti)neutrino source



$$n \rightarrow p + e^{-} + \overline{\nu_e}$$

Resulting fission fragment nuclei have too many neutrons, so are highly unstable and β-decay, emitting (anti)neutrinos

Basic idea of (anti)neutrino detection

Build a large trap

$$\overline{\nu}_e + p \rightarrow n + e^+$$

Need to detect neutron and positron (anti-electron) which will be emitted as a result

(anti)neutrinos will occasionally interact with protons in nuclei

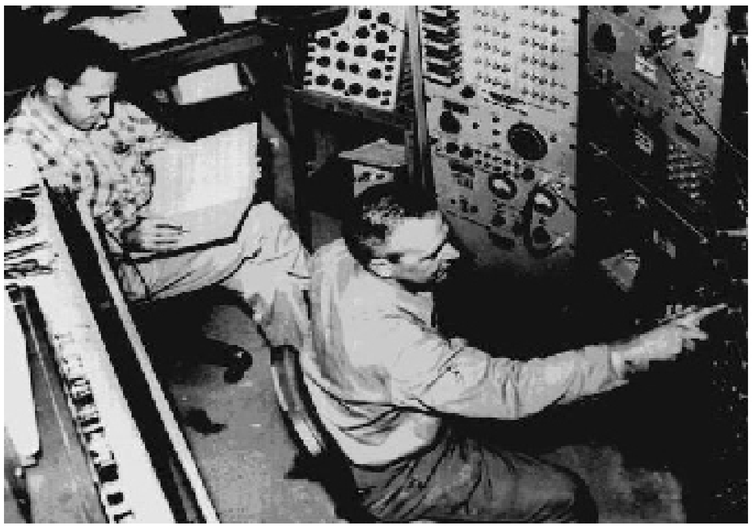
http://library.lanl.gov/cgi-bin/getfile?00326606.pdf

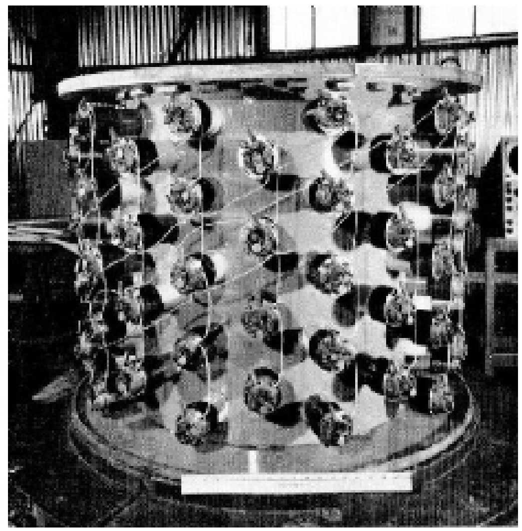
Basic idea of (anti)neutrino detection

$$\overline{\nu}_e + p \rightarrow n + e^+$$

Build a large trap

Savannah river neutrino detection experiment

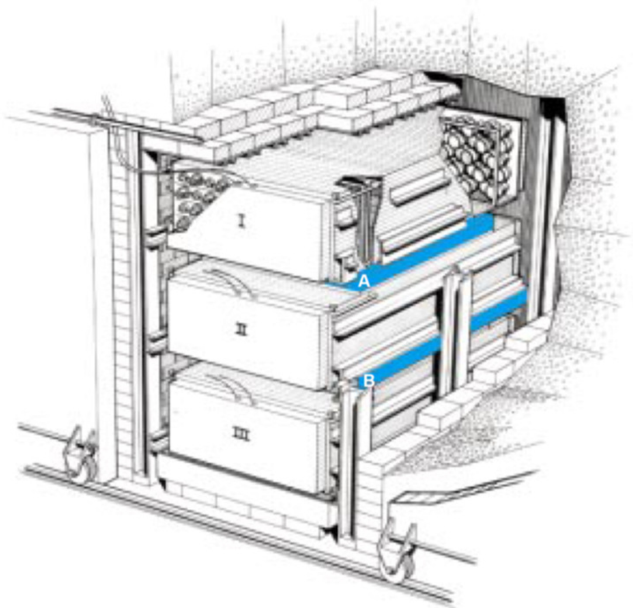




The neutrino detector is inside its lead shield.

Each of two large, flat plastic tanks (pictured in light blue and labeled A and B) was filled with 200 liters of water.

The **protons in the water** provided the target for inverse beta decay.



10 ton without lead shielding

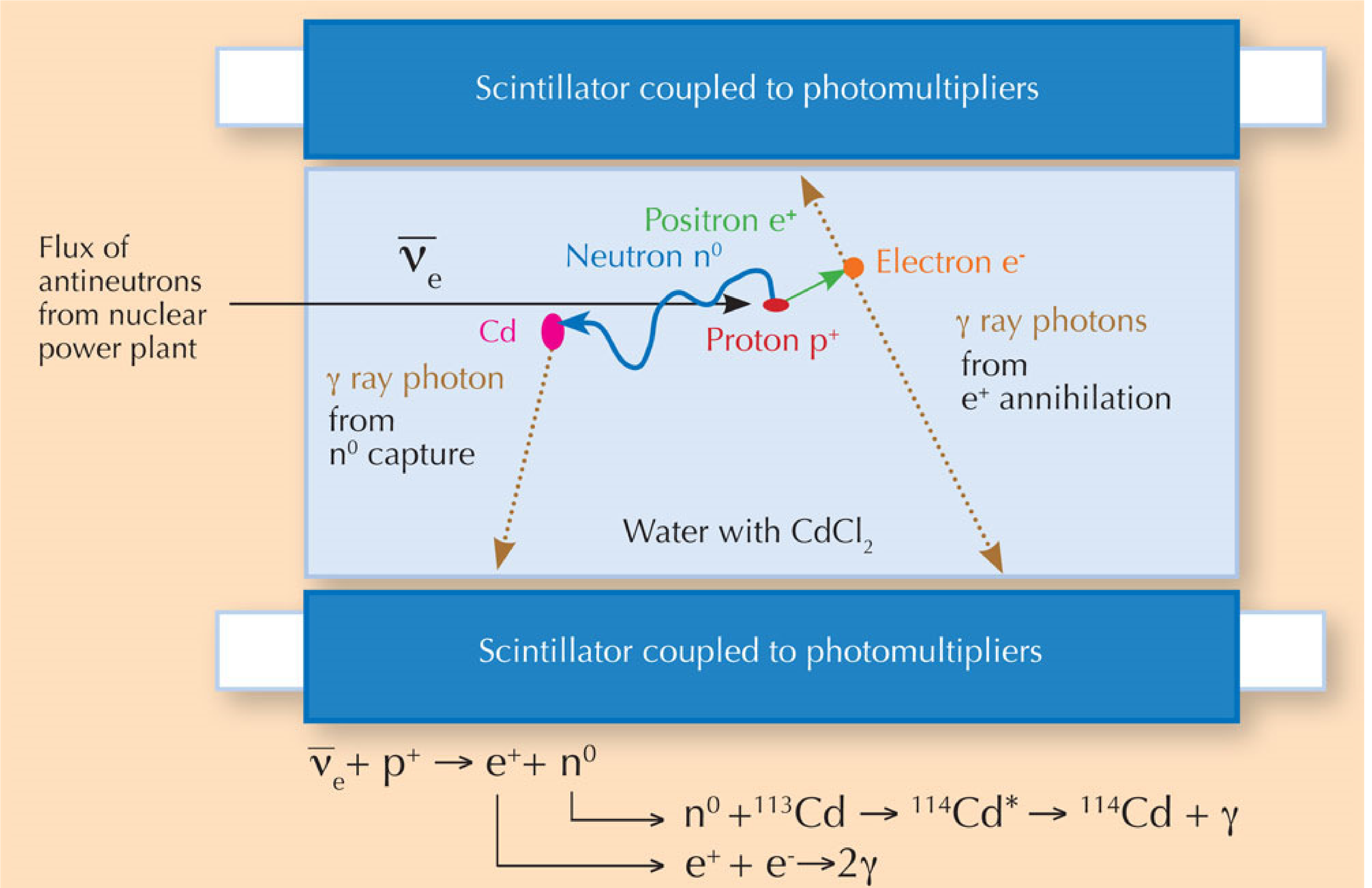
Cadmium chloride dissolved in the water provided the cadmium nuclei that would **capture the neutrons.**

The target tanks were sandwiched between three scintillation detectors (I, II, and III).

Each detector contained 1,400 liters of liquid scintillator that was viewed by 110 photomultiplier tubes.

http://library.lanl.gov/cgi-bin/getfile?00326606.pdf

Savannah river neutrino detection experiment

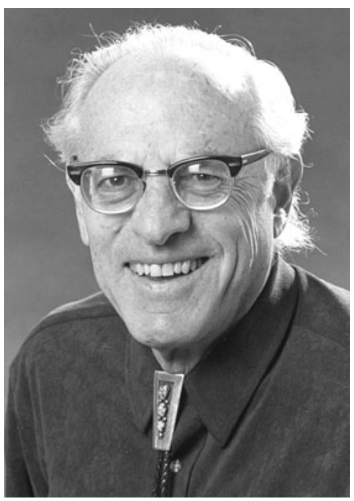


http://www.scienceinschool.org/2011/issue19/neutrinos

1956: Neutrino detected!
3.0±0.2 events per hour were observed

Telegram to Pauli (who first suggested neutrino)

"We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters."



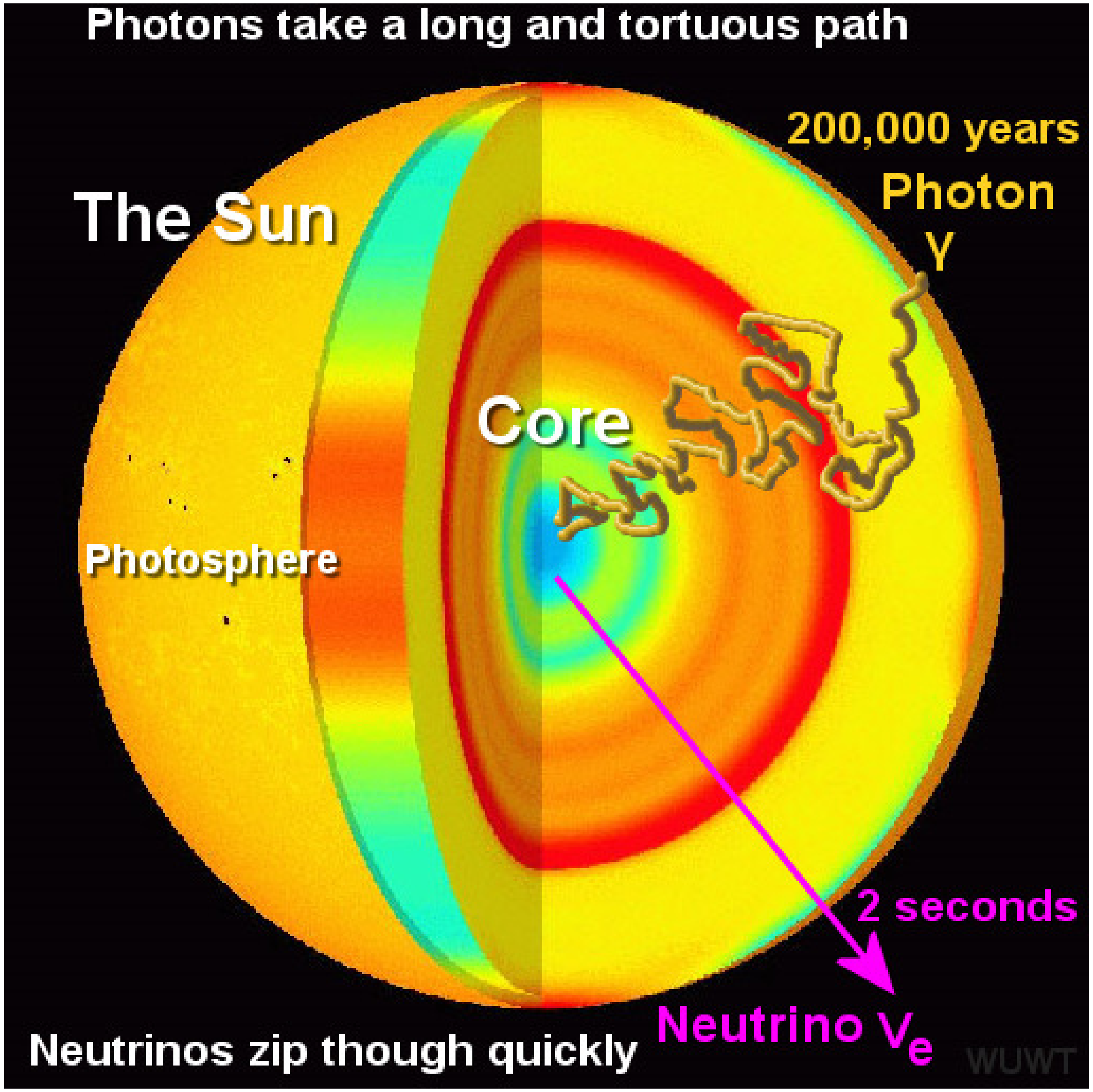
Frederick Reines

The Nobel Prize in Physics 1995

"for pioneering experimental contributions to lepton physics"

Frederick Reines
"for the detection of the neutrino"

The puzzle of missing solar neutrinos



http://wattsupwiththat.com/2010/08/27/follow-up-on-the-solar-neutrinos-radioactive-decay-story/

The story of Raymond Davis

or how to catch neutrinos in a gold mine

Raymond Davis
2002 Nobel Prize

"When I joined the Chemistry Department at Brookhaven, I asked the chairman, Richard Dodson, what he wanted me to do.

To my surprise and delight, he told me to go to the library and find something interesting to work on.

I found a stimulating review on neutrinos (Crane, 1948). "

Fast forward to 1960s:

Brookhaven National Laboratory, with support from the chemistry office of the Atomic Energy Commission, approved building a **100,000-gallon chlorine-argon neutrino detector** in the Homestake Gold Mine, in Lead, South Dakota.

http://www.nobelprize.org/nobel_prizes/physics/laureates/2002/davis-lecture.pdf

Detecting solar neutrinos

Main idea: $\nu_e + {}^{37}Cl \mapsto {}^{37}Ar + e^-$

17 protons	18 protons
20 neutrons	19 neutrons

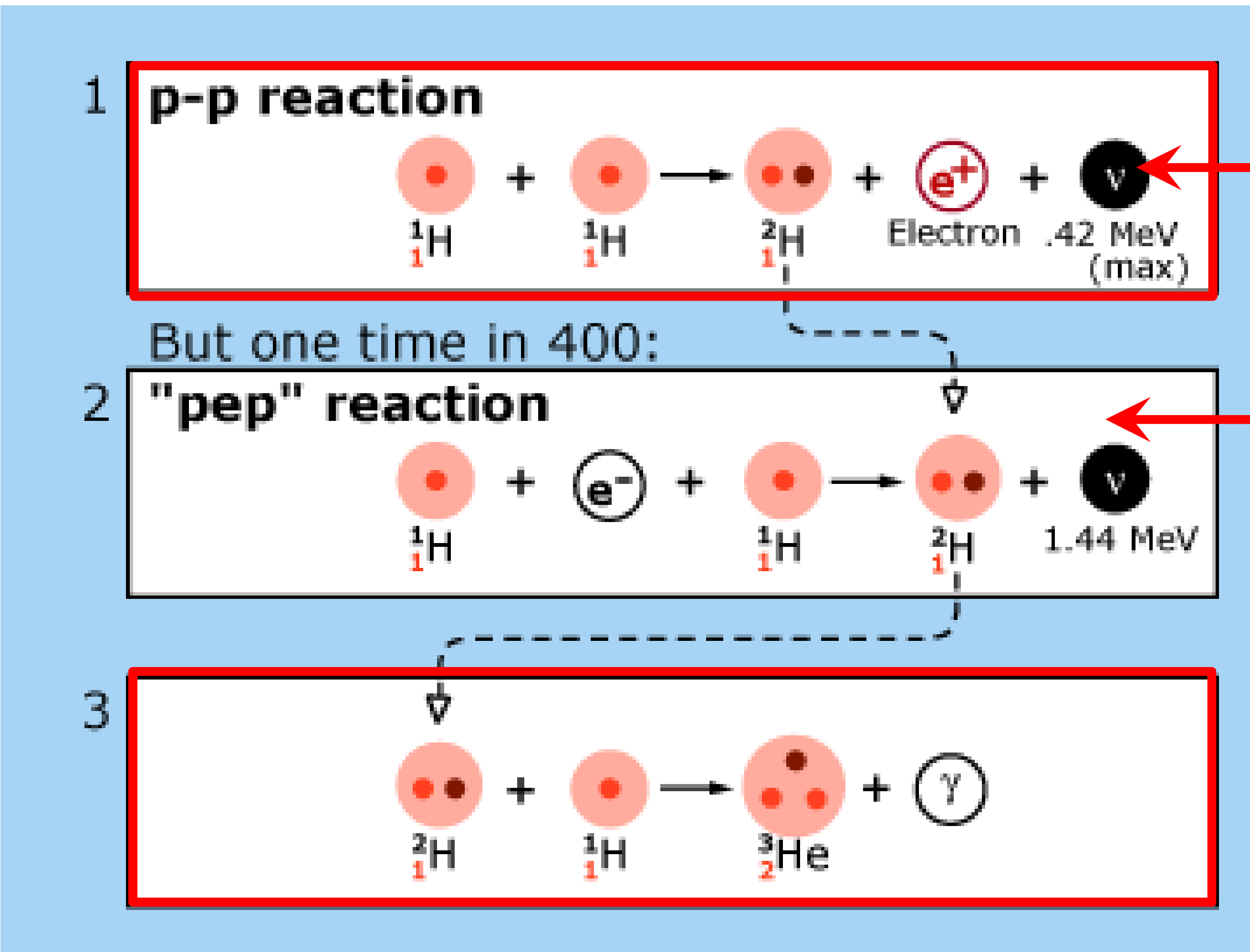
Problem: energy threshold for the capture reaction is 0.814 MeV, so need neutrinos with energies higher than 0.814 MeV.

Let's look at the energies of neutrino's coming from the sun.

Need high-energy neutrinos to detect
Al least above 0.814 MeV

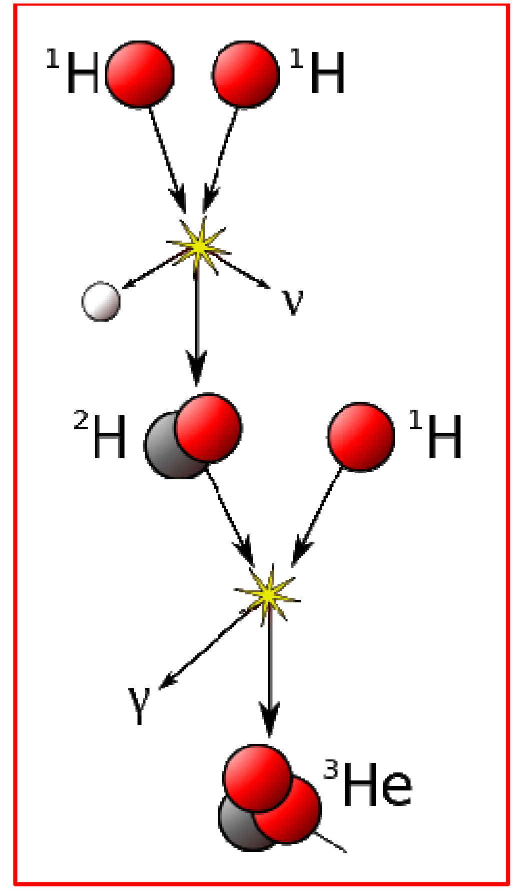
The p—p Chain Reaction

$$p \rightarrow n + e^{+} + \nu_{e}$$



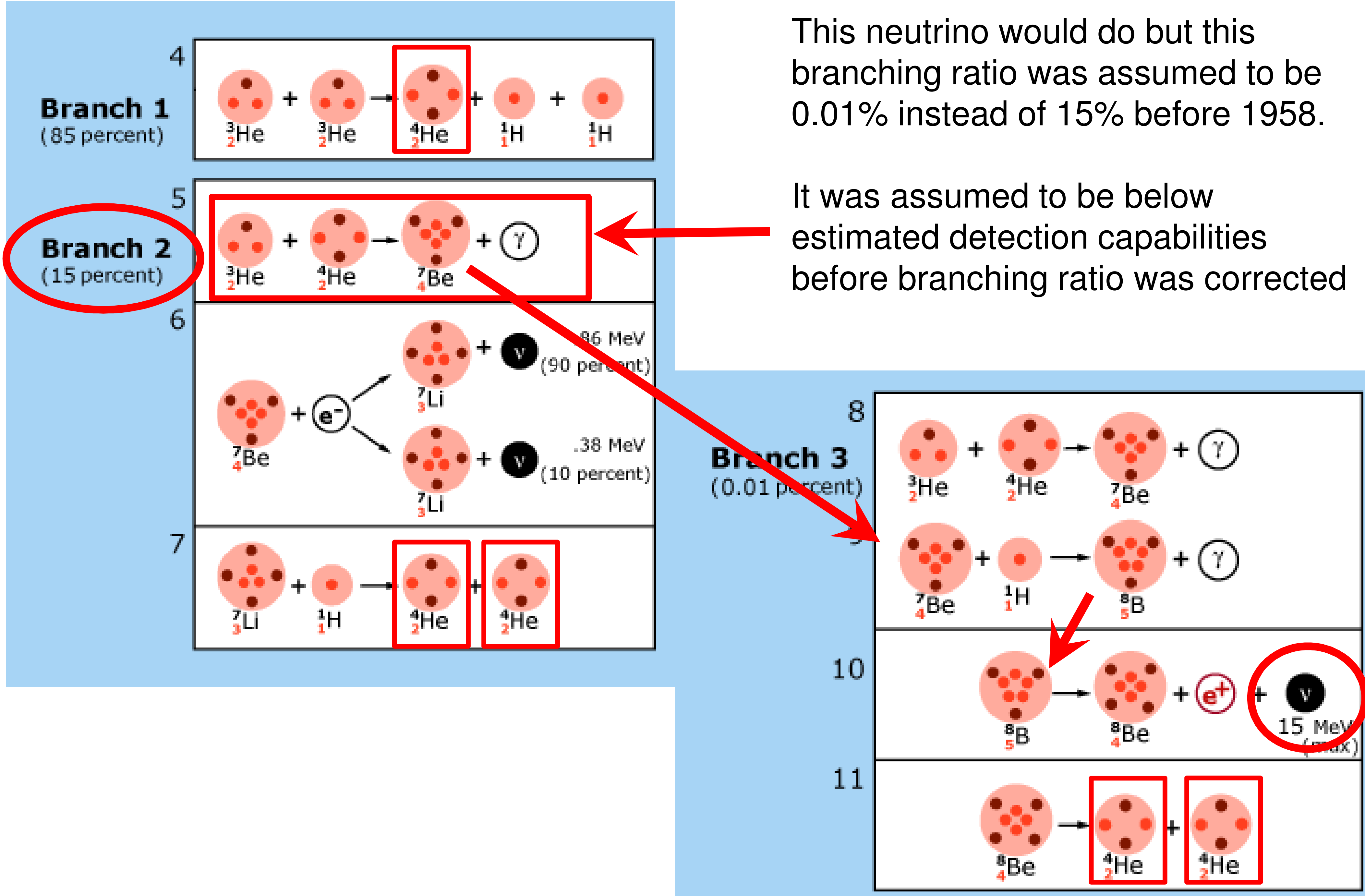
Too low energy

Too rare – not enough to detect



http://www.nobelprize.org/nobel_prizes/themes/physics/fusion/

The p—p Chain Reaction cont.



This neutrino would do but this branching ratio was assumed to be 0.01% instead of 15% before 1958.

It was assumed to be below estimated detection capabilities before branching ratio was corrected

Detecting solar neutrinos

Main idea: $\nu_e + {}^{37}Cl \mapsto {}^{37}Ar + e^-$

	${}^{37}Cl$	${}^{37}Ar$
	17 protons	18 protons
	20 neutrons	19 neutrons

(1) Estimates showed that one needed a very large detector: Estimates gave 4 to 11 37Ar atoms per day for 100 000 gallons of perchloroethylene (dry-cleaning fluid).

(2) Need the 300,000 gallons of water surrounding the tank to reduce background radiation which could interfere with counting.

(2) Needed to be very deep underground to get rid of cosmic-ray muon background: 4,900 feet below ground surface.
Note: 90 degree heat 1 mile underground.


Construction of the
Homestake Mine tank
20 feet in diameter
48 feet long
https://www.bnl.gov/bnlweb/raydavis/pictures.htm


https://www.bnl.gov/bnlweb/raydavis/pictures.htm

1967: First results from Homestake mine experiment

Letter to Willy Fowler:

Dear Willy,

I do have a preliminary result from our first good run. The sample was taken June 22nd and counting has continued until today … The background for this counter run just before the sample is shown also on the enclosed sheet. Comparing these we can obtain the following results: …

$$\phi B^8 \leq 0.5 \times 10^7\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$$

This limit is quite low, but according to the latest opus from Bahcall and Shaviv the B^8 flux is $1.4\,(1 \pm 0.6) \times 10^7\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$

Please regard these results as very preliminary. There are several points that must be checked before we are certain this is a bonafide observation.
I will collect another sample in September – ***we are ready now, turn on the sun…***

1967: SOLAR NEUTRINO PUZZLE WAS BORN

1967-2002: SOLAR NEUTRINO PUZZLE

Collection of nearly 30 years of data and 30 years of refinement of the standard solar model have greatly improved precision.

Over a period of 25 years, Homestake chlorine experiment counted a total of 2200 ^{37}Ar atoms and obtained a solar neutrino flux of
2.56 ± 0.16 (statistical error) ± 0.16 (systematic error) SNU.
The 2001 prediction of the standard solar model is **7.6 ±1.3** SNU.

The solar neutrino unit, or SNU, is defined as 10^{-36} captures per target atom per second.

The numbers haven't changed much: the Sun produces one-third as many neutrinos as expected.

SOLAR NEUTRINO PUZZLE

About the same from other (very different) neutrino detection experiments

Solar Neutrino Fluxes		
Experiment	**Measured / Predicted**	Year
Homestake Mine	0.273 (0.021)	1967 - 1994
SAGE	0.526 (0.089)	1989 - 2007 data
GALLEX	0.509 (0.089)	1991 - 1997
Super-Kamiokande	0.379 (0.034)	1996 - present

SOLAR NEUTRINO PUZZLE

Possible explanations

1. Something is wrong with neutrino detection experiment
   Numerous tests were conducted to rule out various sources of error and to test the detector capabilities.
   Other later experiments were showing similar results.

2. Something is wrong with theory calculating neutrino flux from the Sun
   Calculations were redone and improved over the years.
   relevant nuclear reactions were studied experimentally.

3. Something is wrong with the Sun or basic idea of solar energy source

4. Something is wrong with neutrinos

SOLAR NEUTRINO PUZZLE

Possible explanations

3. Something is wrong with the Sun or basic idea of solar energy source

Fowler (1968, 1972) and Sheldon (1969) suggested that there was an instability in energy production in the center of the Sun. Since light takes about 10 million years to reach the surface of the Sun, while neutrinos sample the core eight minutes ago, the energy production could be low at the present time.

Libby and Thomas (1969) and Salpeter (1970) suggested that quark catalysis could play a role.

Kocharov and Starbunov (1970) suggested that there was an overabundance of ^3He in the present Sun.

Demarque *et al.* (1973) suggested that the solar interior rotated rapidly, lowering the central pressure and temperature.

SOLAR NEUTRINO PUZZLE

Possible explanations

3. Something is wrong with the Sun or basic idea of solar energy source contd.

Prentice (1973) proposed that the Sun was in a later stage of stellar evolution, such that hydrogen was burned out and the core was made of helium.

Clayton *et al.* (1975) proposed that the Sun's energy did not come from fusion, rather from release of energy from accretion onto a black hole at the center of the Sun.

4. Something is wrong with neutrinos

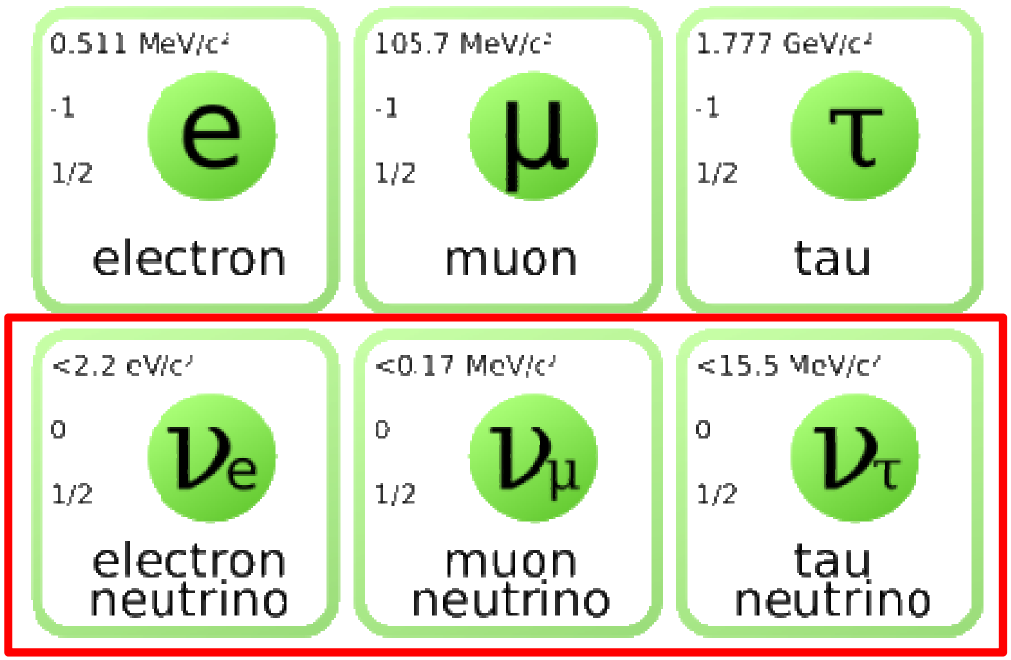
Cisneros (1969) proposed that the neutrino had a significant magnetic moment.

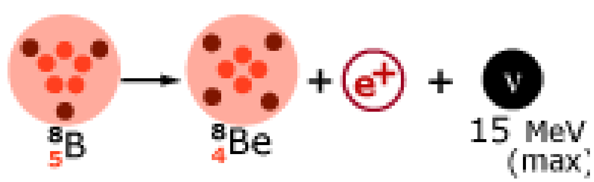
Bahcall *et al.* (1972) suggested that neutrinos might decay.

SOLAR NEUTRINO PUZZLE

4. Something is wrong with neutrinos

Neutrino oscillations were suggested by Gribov and Pontecorvo (1969) and Wolfenstein (1978) and the theory was further developed by Mikheyev and Smirnov (1985) into what is now known as the MSW effect

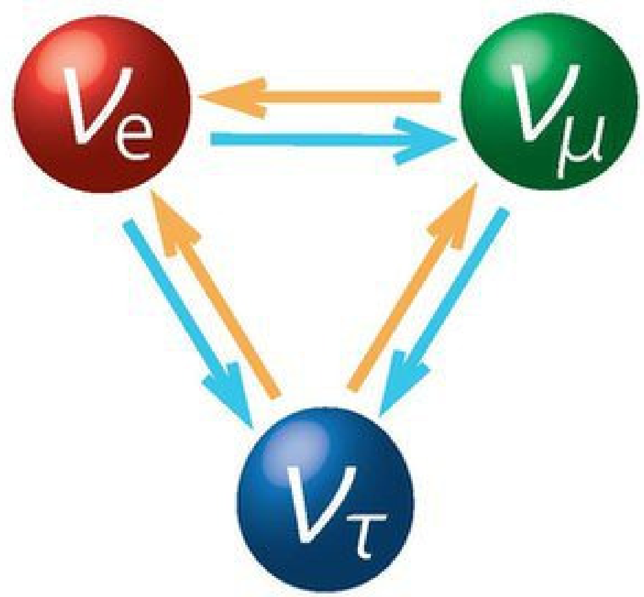


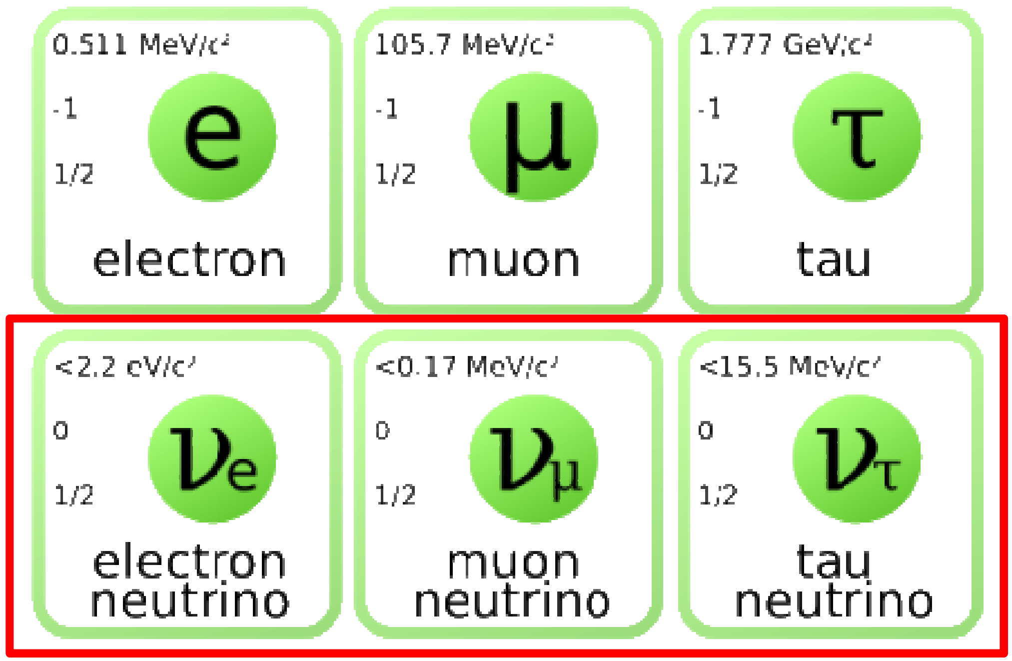


Sun produces only electron neutrinos

$\nu_e + {}^{37}\mathrm{Cl} \mapsto {}^{37}\mathrm{Ar} + e^-$ Detects only electron neutrinos

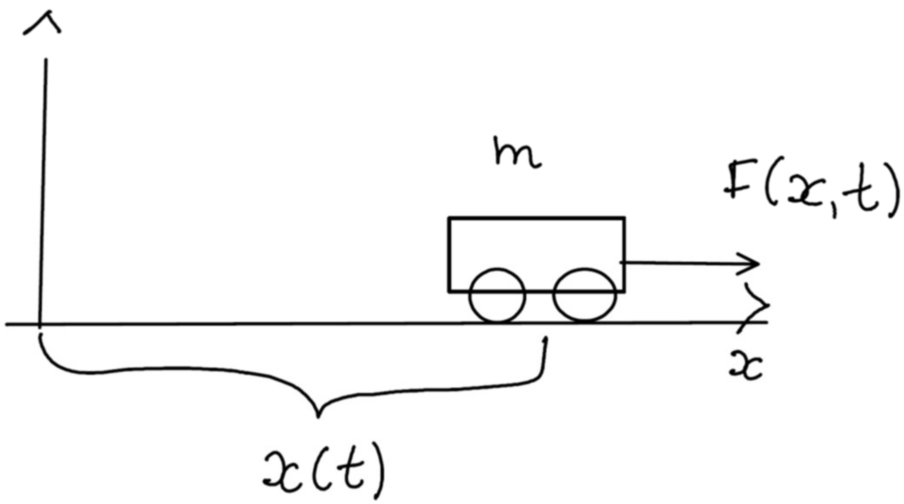
Neutrino oscillation hypothesis





A very brief introduction into quantum mechanics

Classical mechanics (in one dimension):



Particle of mass m, constrained to move along x-axis, subject to some force F(x,t).

Task of classical mechanics: find x(t). If we find x(t), we can find velocity $v = dx/dt$,

momentum p=mv, kinetic energy $T = \frac{1}{2}mv^2$, an so on.

How do we determine x(t)? Use second Newton's law $F_x = ma_x$.

For conservative forces $F_x = -\frac{\partial V}{\partial x}$ $\Rightarrow$

$$F_x = ma_x \Rightarrow m\frac{d^2x}{dt^2} = -\frac{\partial V}{\partial x}$$

+ initial conditions (generally position and velocity at t = 0).

A very brief introduction into quantum mechanics

Quantum mechanics (in one dimension)

Task: we want to determine particle's wave function Ψ.

To do so we use Schrödinger equation:

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V\Psi \quad + \text{initial conditions}$$

$\hbar$ is a Plank's constant divided by 2π

$$\hbar = \frac{h}{2\pi} = 1.054572 \times 10^{-34} \text{ Js.}$$

Note: wave function is complex, but $\Psi^*\Psi$ is real and nonnegative. Ψ^* is a complex conjugate of Ψ. So,we can find the wave function.

A very brief introduction into quantum mechanics

What is the wave function?

Born's statistical interpretation of the wave function:

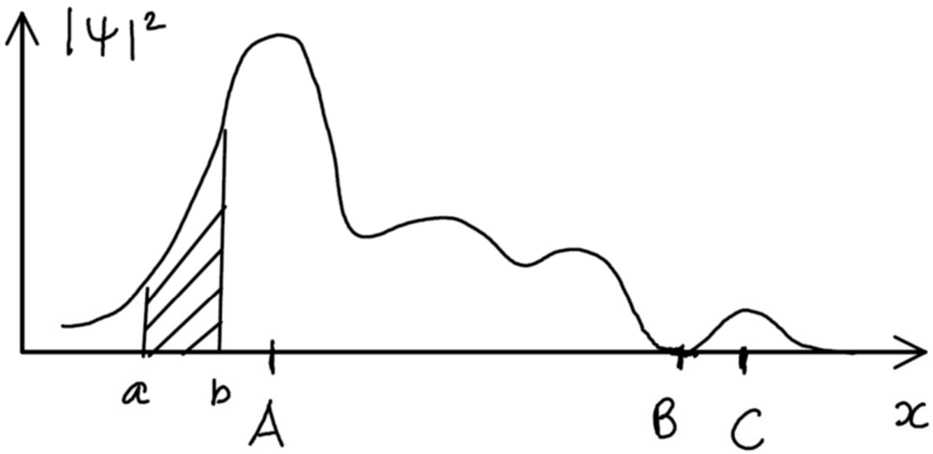
$|\Psi(x,t)|^2$ gives the probability of finding the particle at the point x at time t. More precisely,

$$\int_a^b |\Psi(x,t)|^2 dx = \left\{ \begin{array}{c} \text{probability of finding} \\ \text{a and b, at time t} \end{array} \right\}$$

Problem: indeterminacy of the quantum mechanics. Even if you know everything that theory (i.e. quantum mechanics) has to tell you about the particle (i.e. wave function), you can not predict with certainty where this particle is going to be found by the experiment.

Quantum mechanics provides statistical information about possible results.

A very brief introduction into quantum mechanics



Example: particle is likely to be found in the vicinity of A and is unlikely to be found in the vicinity of B.

Now, suppose we make a measurement and find particle at C.

<u>Question: where was the particle just before the measurement ?</u>

Question: where was the particle just before the measurement ?

Answer # 1. Realist position.

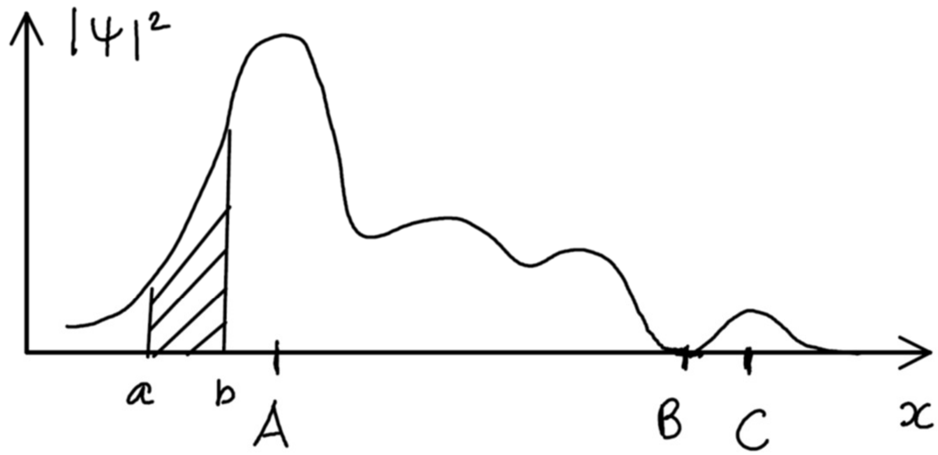
It was at C. That means quantum mechanics is incomplete theory. Why? Well, the particle was at C, but quantum mechanics could not predict it. Therefore, Ψ does not give the whole story and we need additional information (hidden variables) to provide a complete description of the particle.

Answer #2. The orthodox position.

The particle was not really anywhere. It was an act of measurement that forced particle to "take a stand". We still have no idea why it "decided" on point C. Note: there is something very strange about concept of measurement.

Answer #3. The agnostic position.

Refuse to answer. Since the only way to know if you were right is to make a measurement, you no longer get "before the measurement". Therefore, it can not be tested.

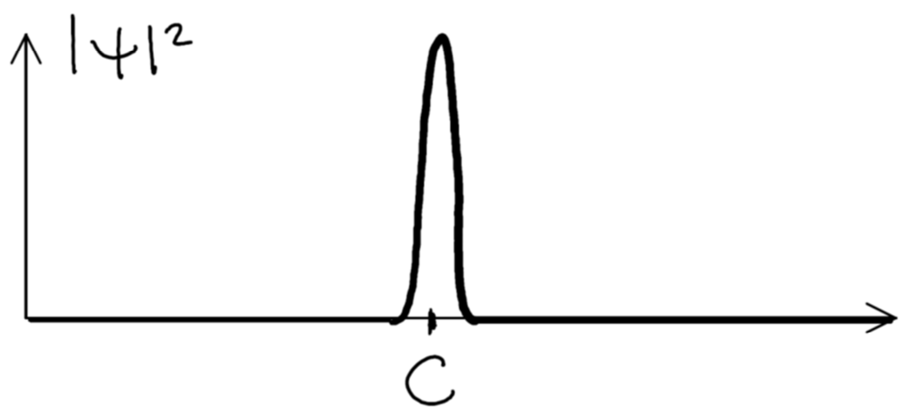


Example: particle is likely to be found in the vicinity of A and is unlikely to be found in the vicinity of B.

Now, suppose we make a measurement and find particle at C.

What if we make a second measurement after the first?

Repeated measurement returns the same value.



The first measurement alters the wave function and it collapses to a spike at C. After that, it will start evolving according to Schrödinger equation.

One of the biggest difference between classical and quantum physics: superposition

If your quantum system (particle) has three possible

states, $|\psi_1\rangle, |\psi_2\rangle, \text{and} |\psi_3\rangle$

it may be in superposition of these three states

$$|\psi\rangle = a_1|\psi_1\rangle + a_2|\psi_2\rangle + a_3|\psi_3\rangle$$

If you make a measure the wave function will collapse to "eigenstate"

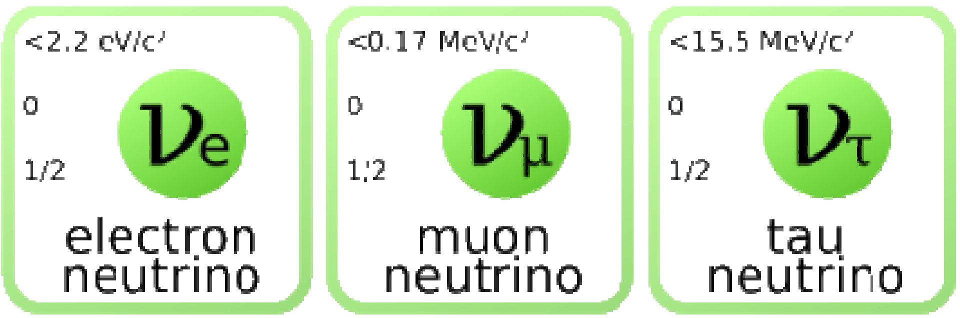
$$|\psi_1\rangle, |\psi_2\rangle, \text{and} |\psi_3\rangle$$

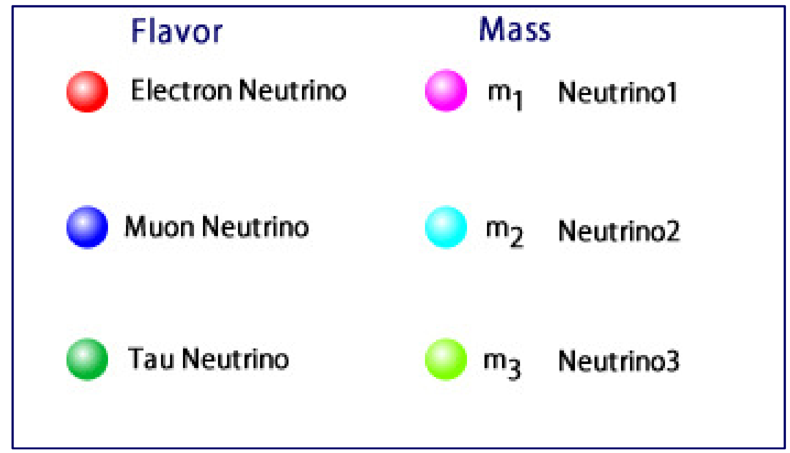
The probability to "catch" particle in state 1 is $|a_1|^2$.

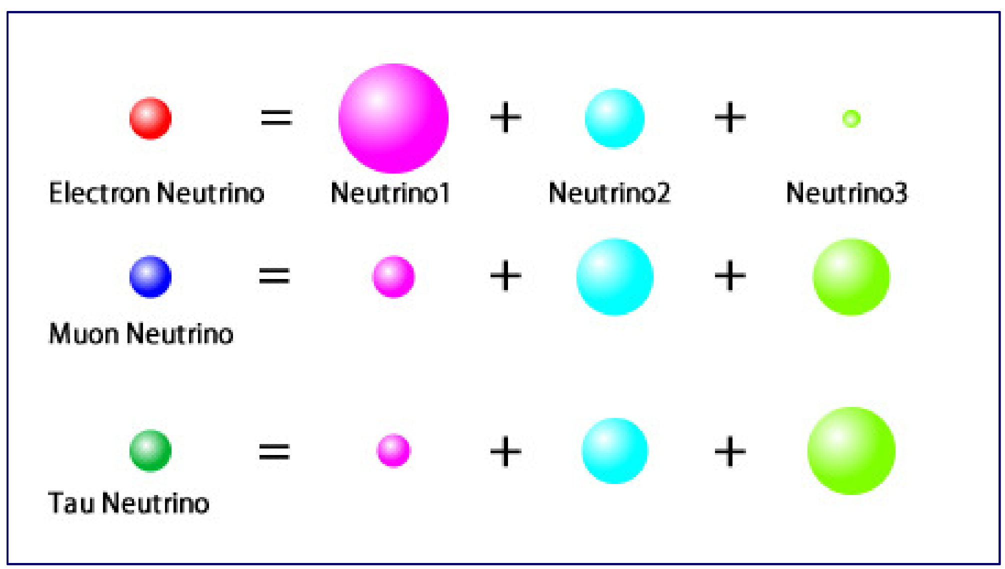
The probability to "catch" particle in state 2 is $|a_2|^2$.

The probability to "catch" particle in state 3 is $|a_3|^2$.

Neutrino oscillation hypothesis







Neutrinos are mixing between flavor classification and mass classification.

www-sk.icrr.u-tokyo.ac.jp

Neutrino oscillation hypothesis

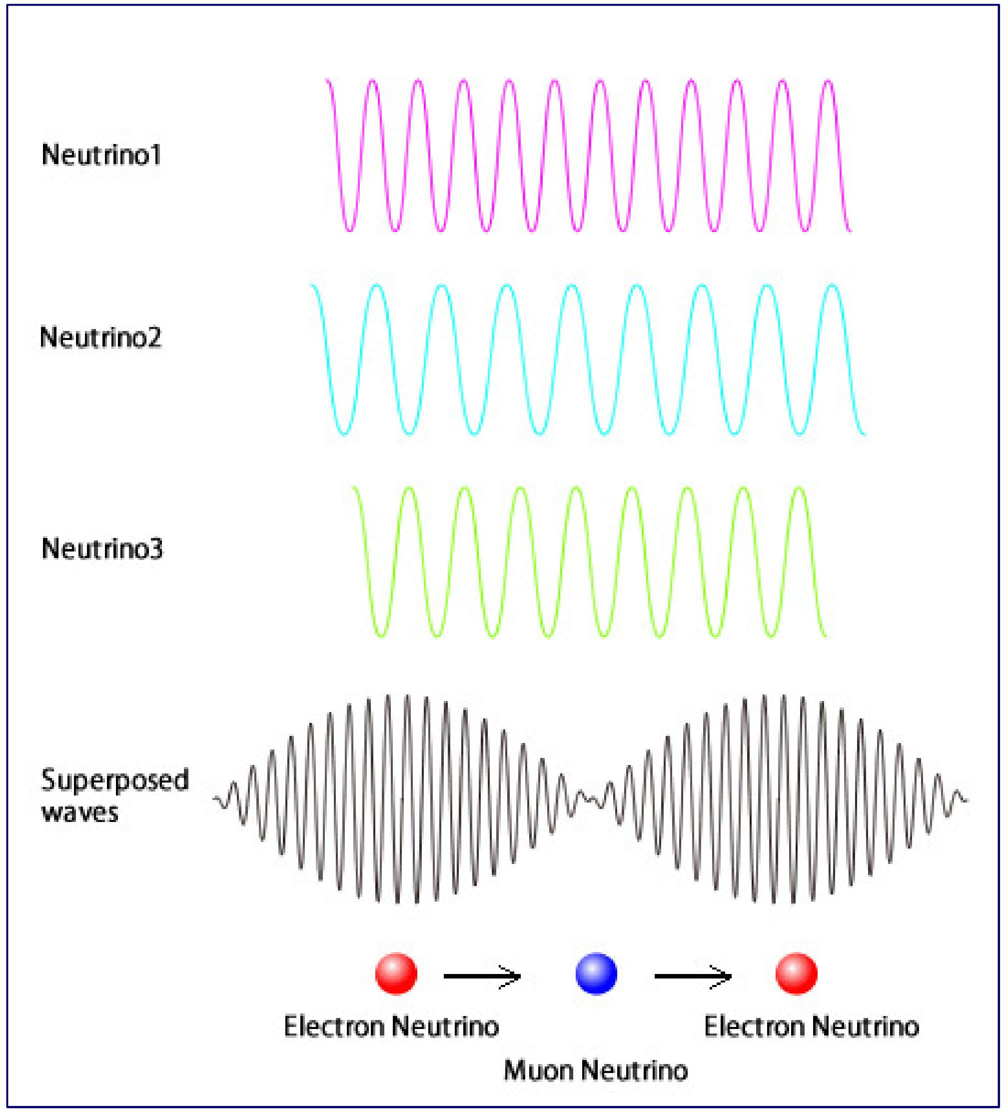
Neutrinos exhibit the properties of a particle as well as a wave.

Therefore, neutrino-1, neutrino-2 and neutrino-3, each with different mass eigenstates, travel through space as waves that have a different frequency.

The flavor of a neutrino is determined as a superposition of the mass eigenstates.

The type of the flavor oscillates, because the phase of the wave changes (see the right figure).

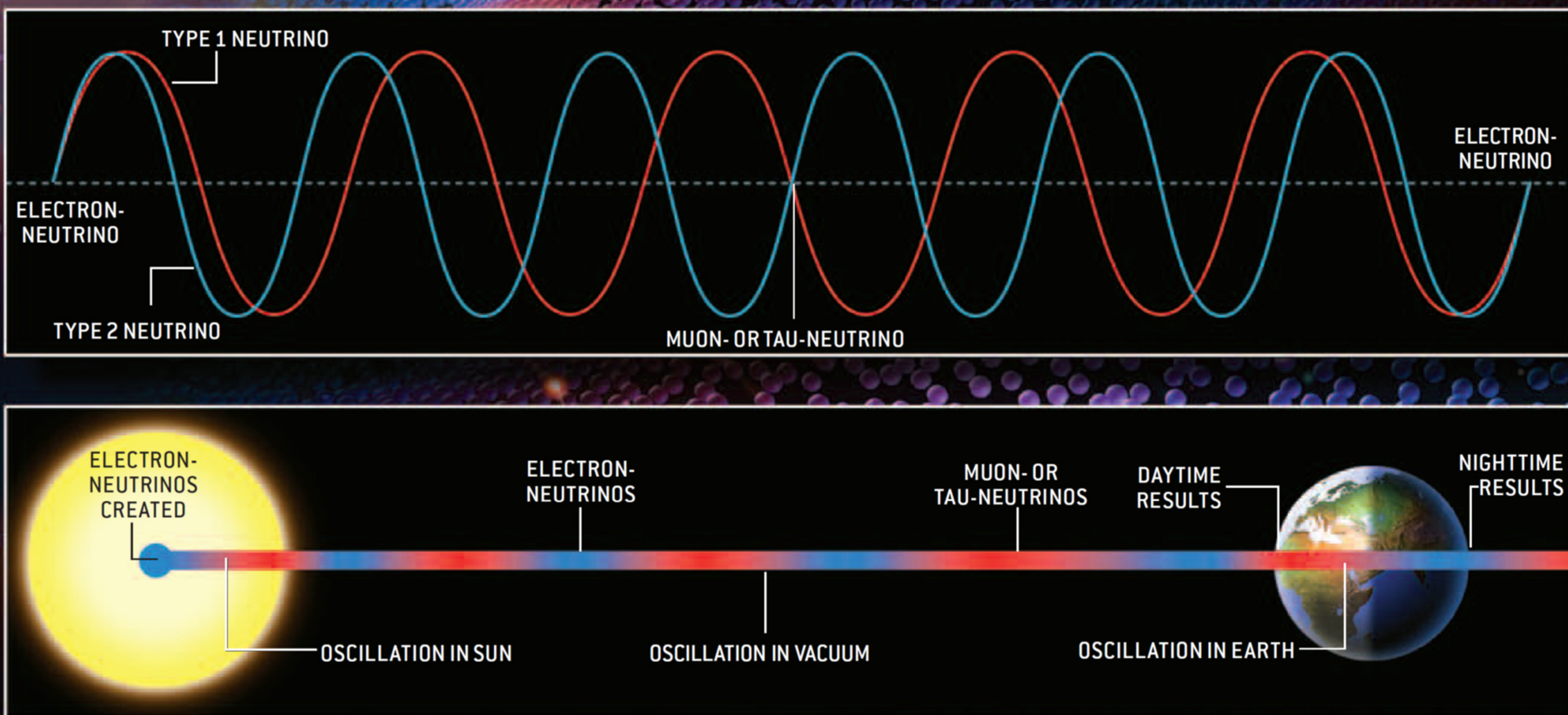
This phenomenon is called neutrino oscillation.



www-sk.icrr.u-tokyo.ac.jp

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*).



Scientific American 15, 22 (2006)

Sudbury Neutrino Observatory (SNO)

Neutrinos are very difficult to detect so our detector had to be very big with low radioactivity, deep underground.

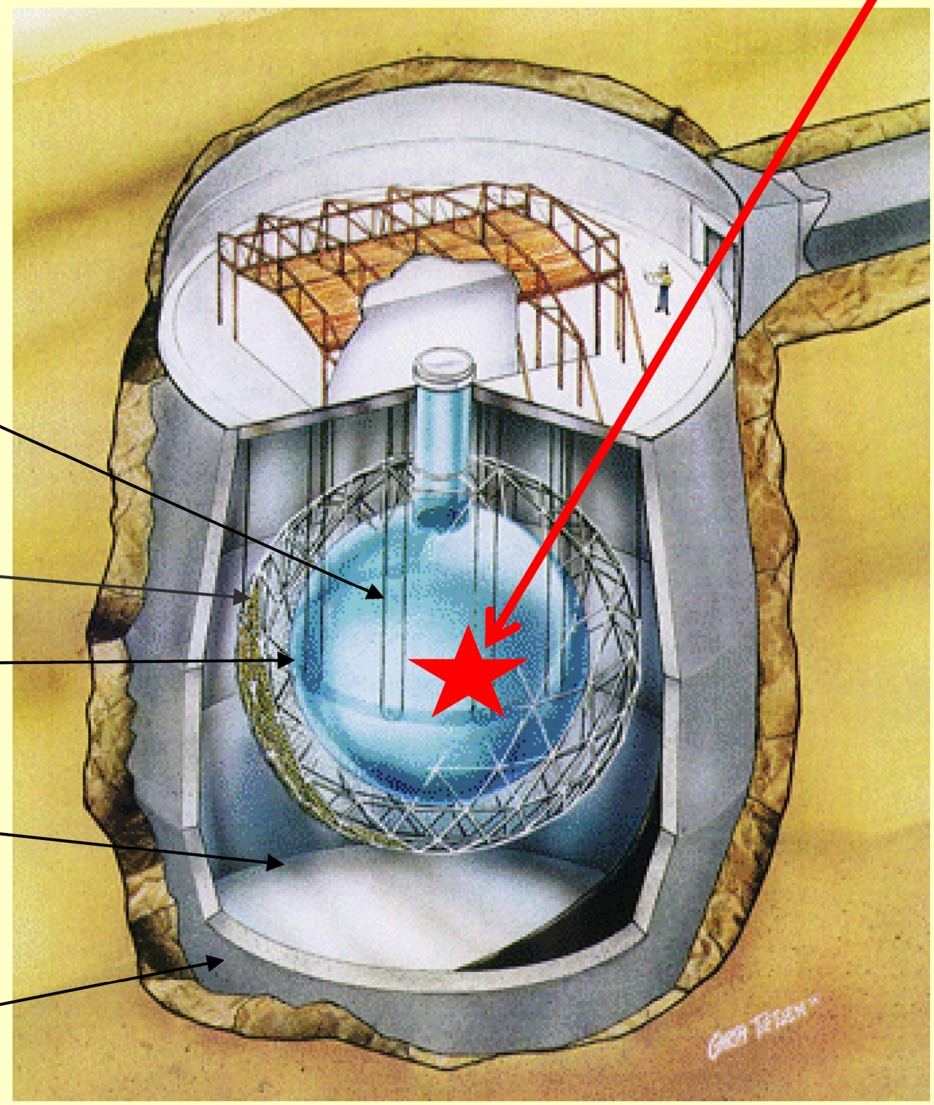
1000 tonnes of heavy water: D_2O
\$ 300 million on Loan for \$1.00

9500 light sensors

12 m Diameter Acrylic Container

Ultra-pure Water: H_2O.

Urylon Liner and Radon Seal



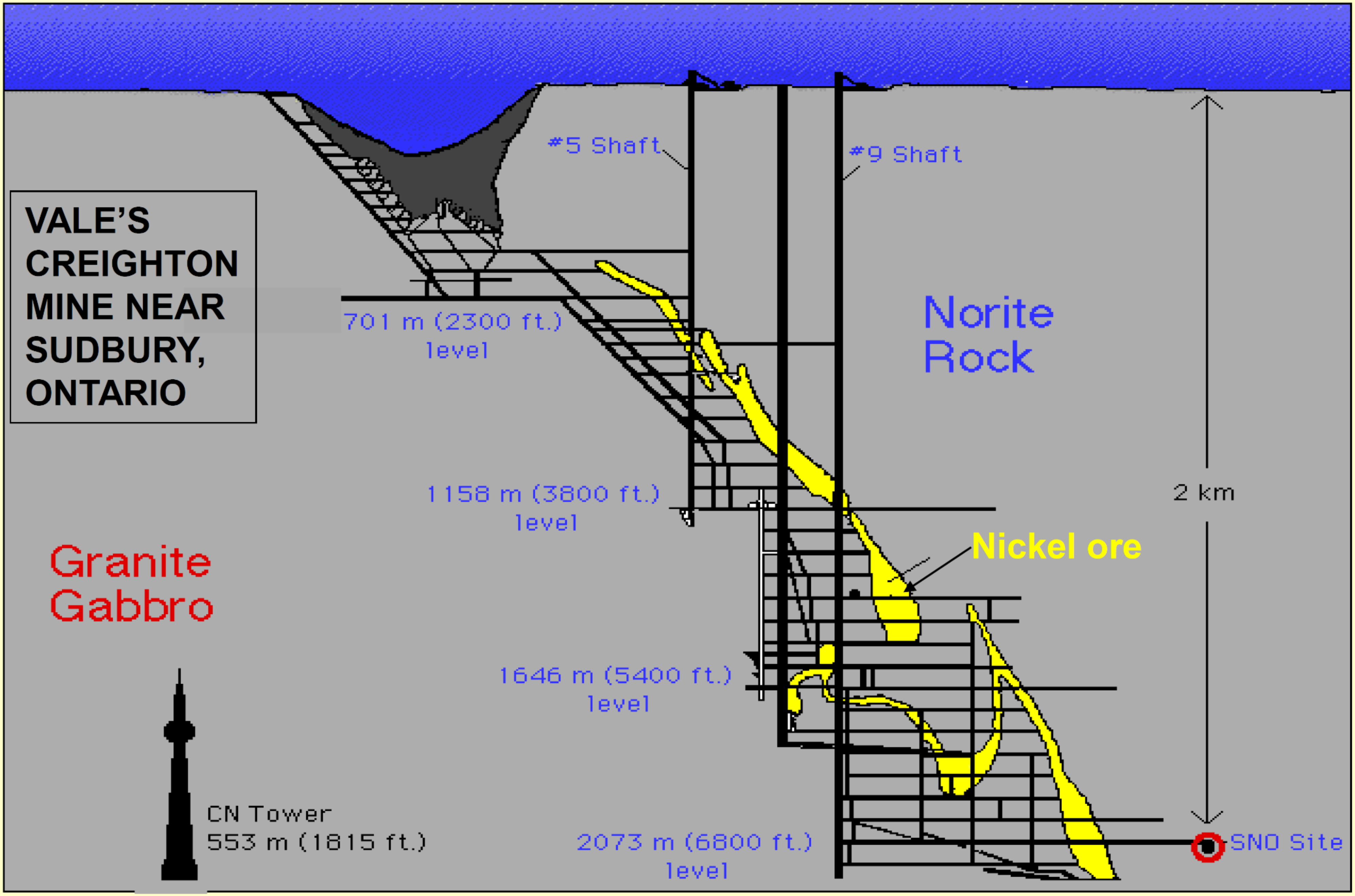
NEUTRINO

34 m or ~ Ten Stories High!

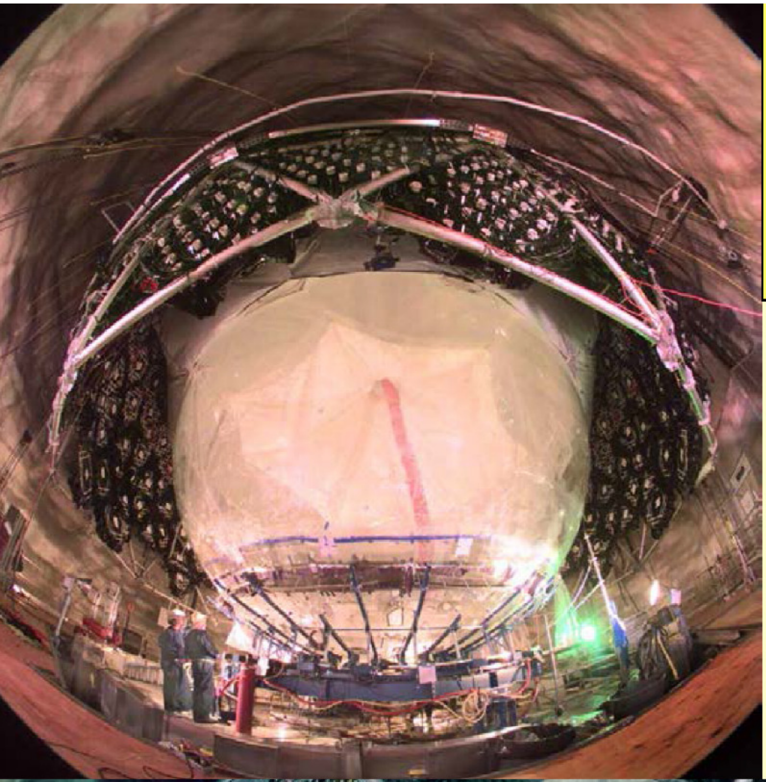
2 km below the ground

http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/mcdonald-lecture-slides.pdf

To study Neutrinos with little radioactive background, we went 2 km underground to reduce cosmic rays and built an ultra-clean detector: SNO

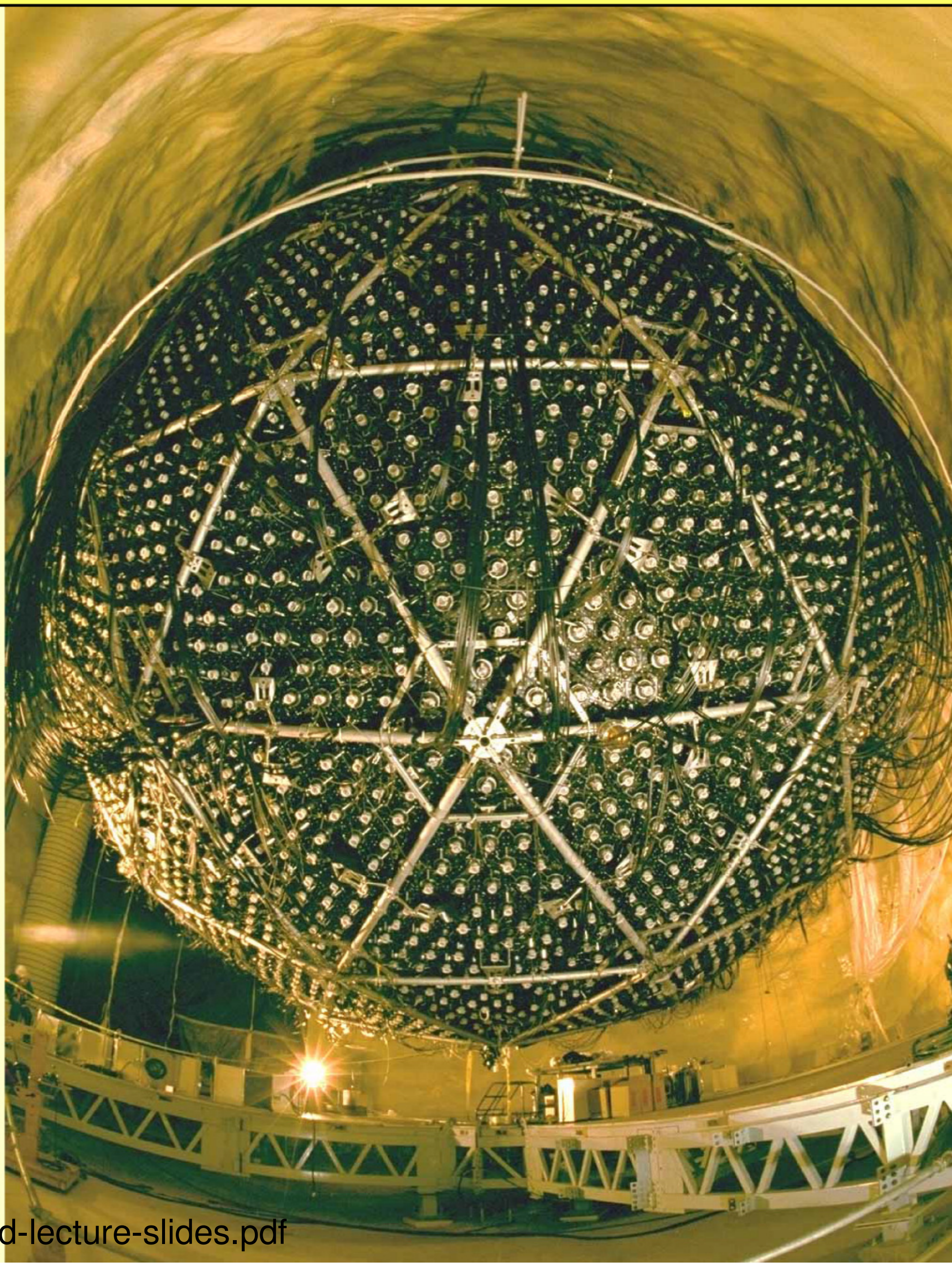


http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/mcdonald-lecture-slides.pdf



SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

70,000 showers during the course of the SNO project



http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/mcdonald-lecture-slides.pdf

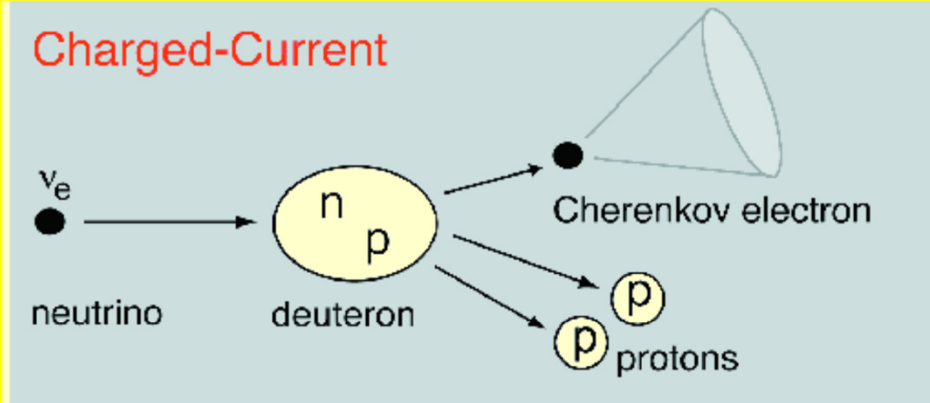
Unique Signatures in SNO (D_2O)

(1 in 6400 molecules in ordinary water are D_2O. We used >99.75% D_2O)

Electron Neutrinos (CC)

$\nu_e + d \rightarrow e^- + p + p$

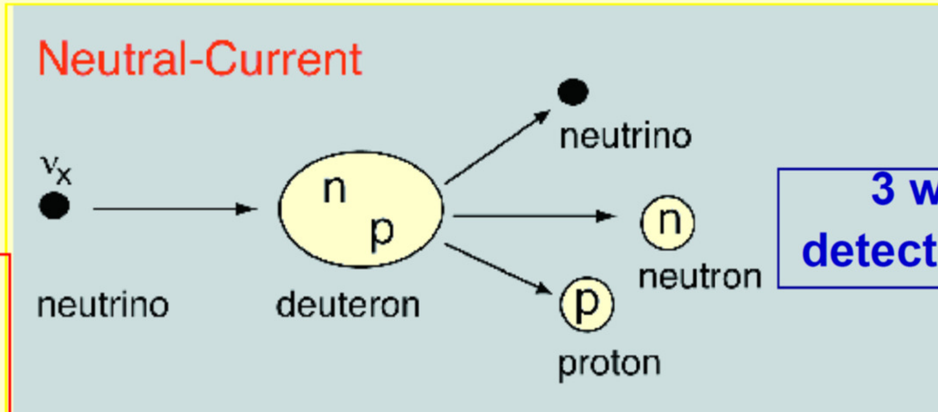
$E_{thresh} = 1.4$ MeV



Equal Sensitivity All Types (NC)

$\nu_x + d \rightarrow \nu_x + n + p$

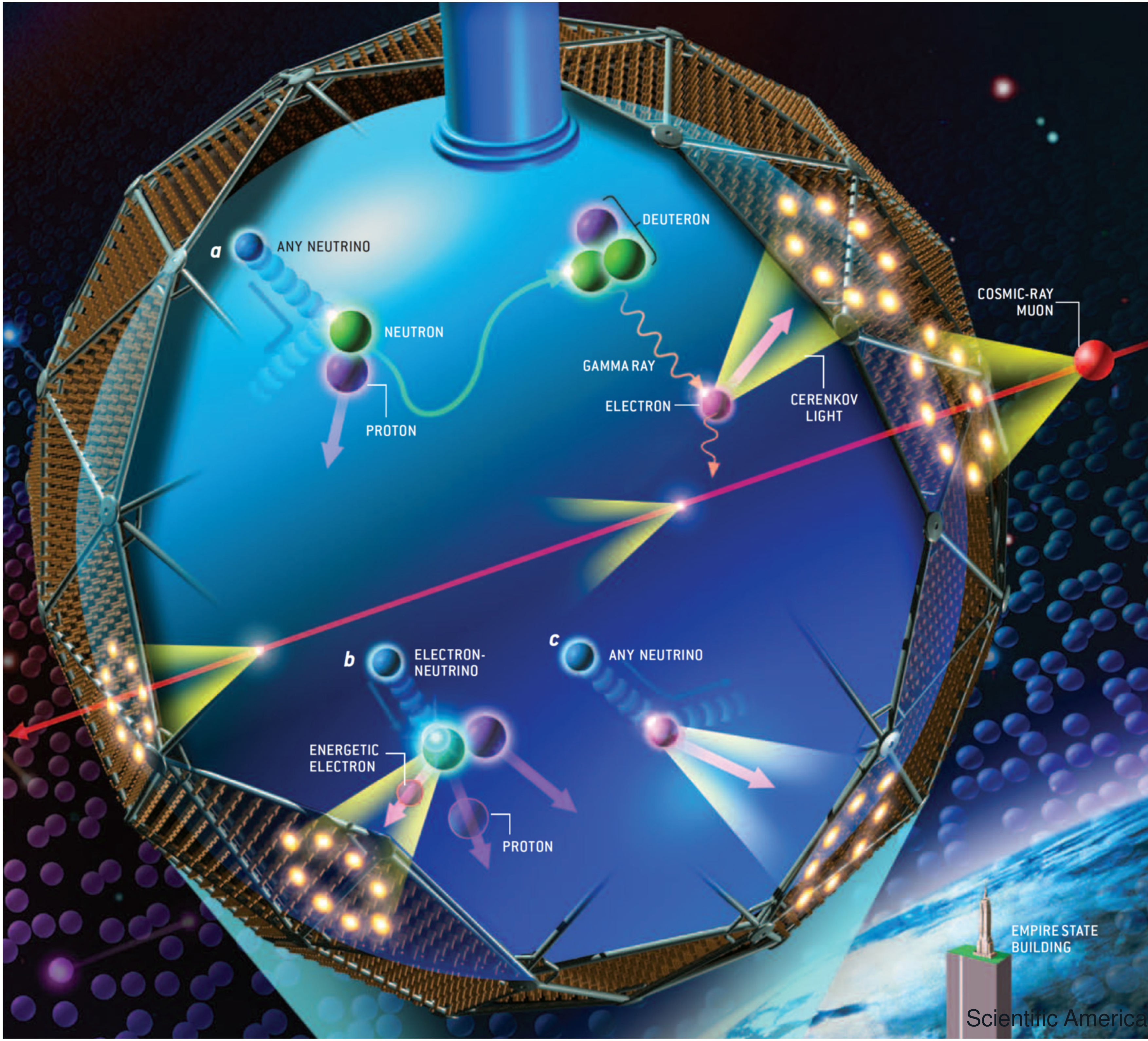
$E_{thresh} = 2.2$ MeV



3 ways to detect neutrons

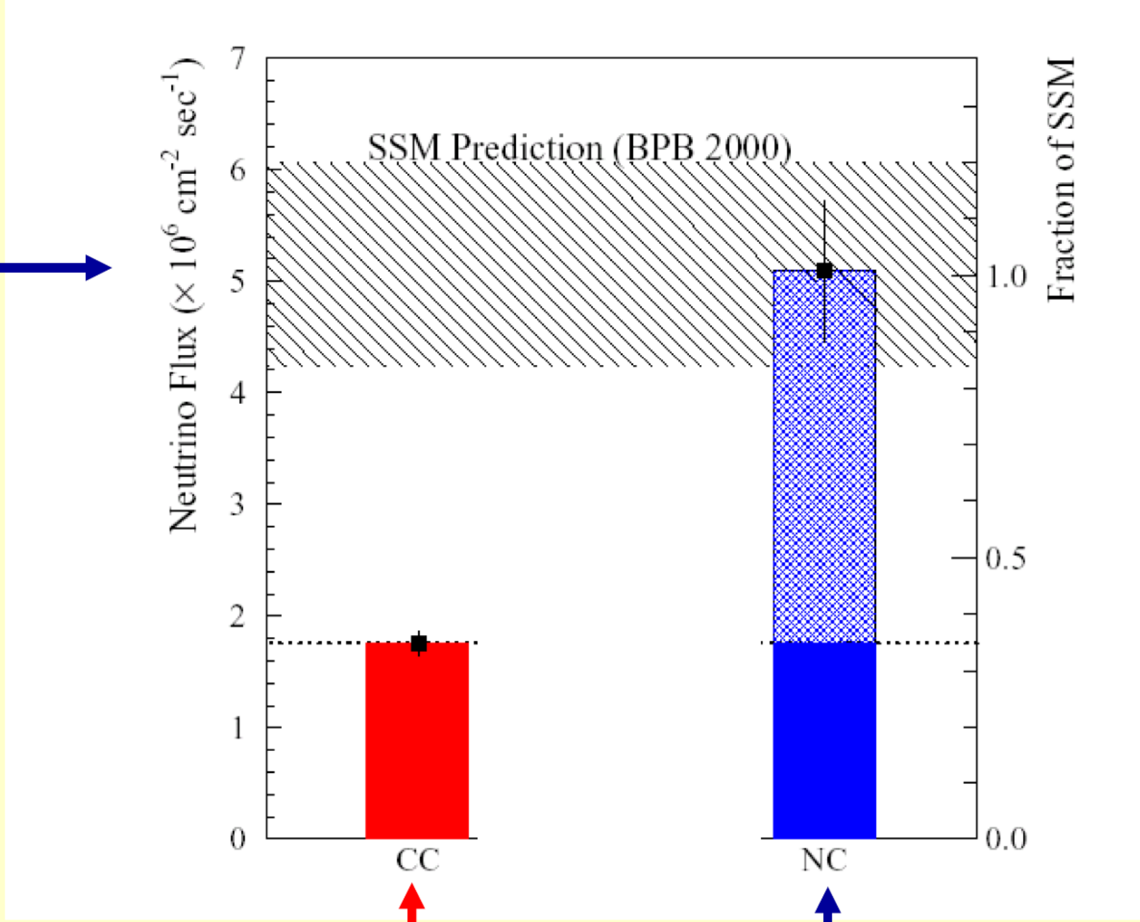
Comparing these two reactions tells if electron neutrinos have changed their type.

http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/mcdonald-lecture-slides.pdf



Scientific American 15, 22 (2006)

SOLAR MODEL



Excellent Agreement With the Solar Model Calculations

SNO USED HEAVY WATER TO MEASURE TWO SEPARATE THINGS

LESS THAN ONE CHANCE IN 10 MILLION FOR "NO CHANGE IN NEUTRINO TYPE"

ELECTRON NEUTRINOS

ALL NEUTRINO TYPES

A CLEAR DEMONSTRATION NEUTRINOS CHANGE THEIR TYPE: 2/3 OF THE ELECTRON NEUTRINOS HAVE CHANGED TO MU, TAU NEUTRINOS ON THE WAY FROM THE SOLAR CORE TO EARTH. THIS REQUIRES THAT THEY HAVE A FINITE MASS.

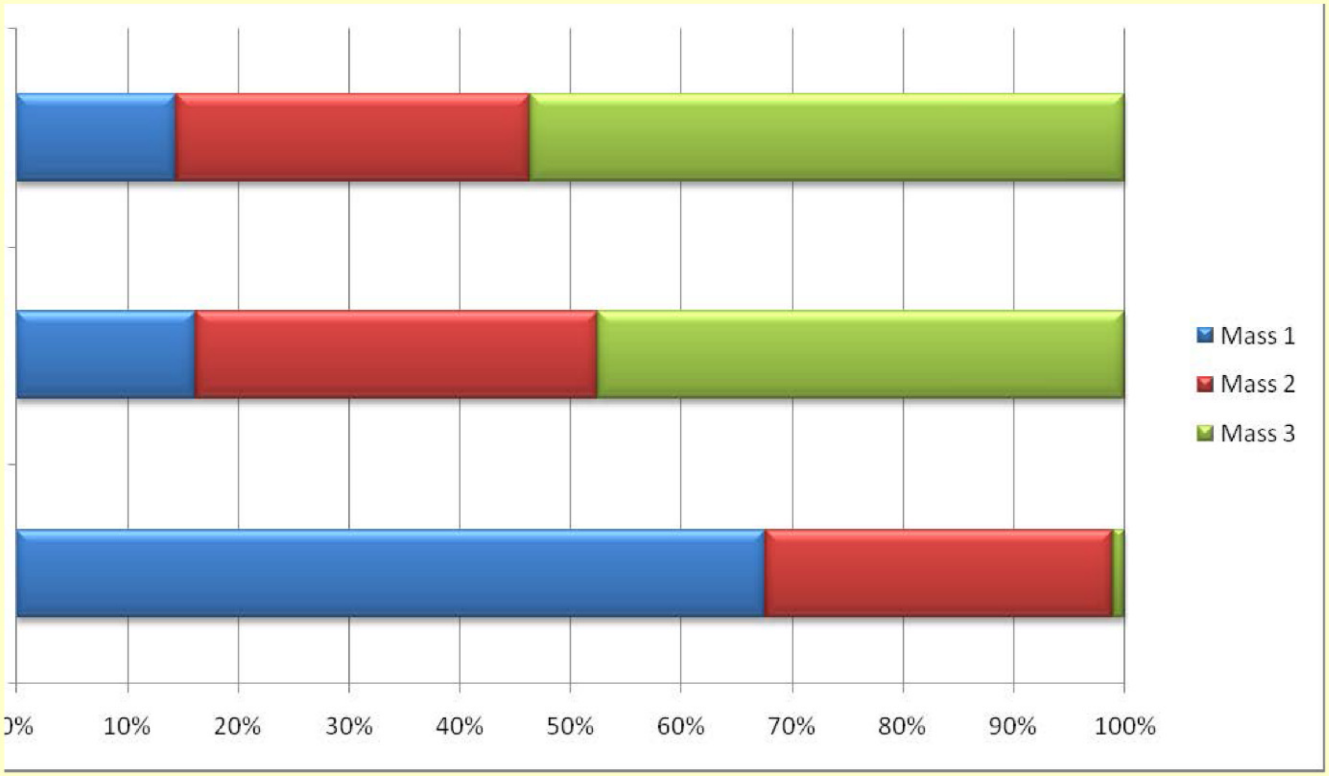
NEUTRINO OSCILLATIONS AND NEUTRINO MASS

Neutrino Flavors (Electron, Muon, Tau) can be expressed as combinations of Masses (1,2,3)

Tau Neutrino

Muon Neutrino

Electron Neutrino



Quantum mechanics states

Created in a unique Flavor State

The mass fractions change as the neutrino travels

After traveling there is a finite probability to be detected as a different flavor type

http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/mcdonald-lecture-slides.pdf

The Nobel Prize in Physics 2015

Takaaki Kajita

Arthur B. McDonald

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass“.*

http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/