October 22, 2018

XVIII Mexican School of Particles and Fields
2018 UNISON School of High Energy Physics

Neutrinos: An Experimental Perspective

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SNOLAB

Outline

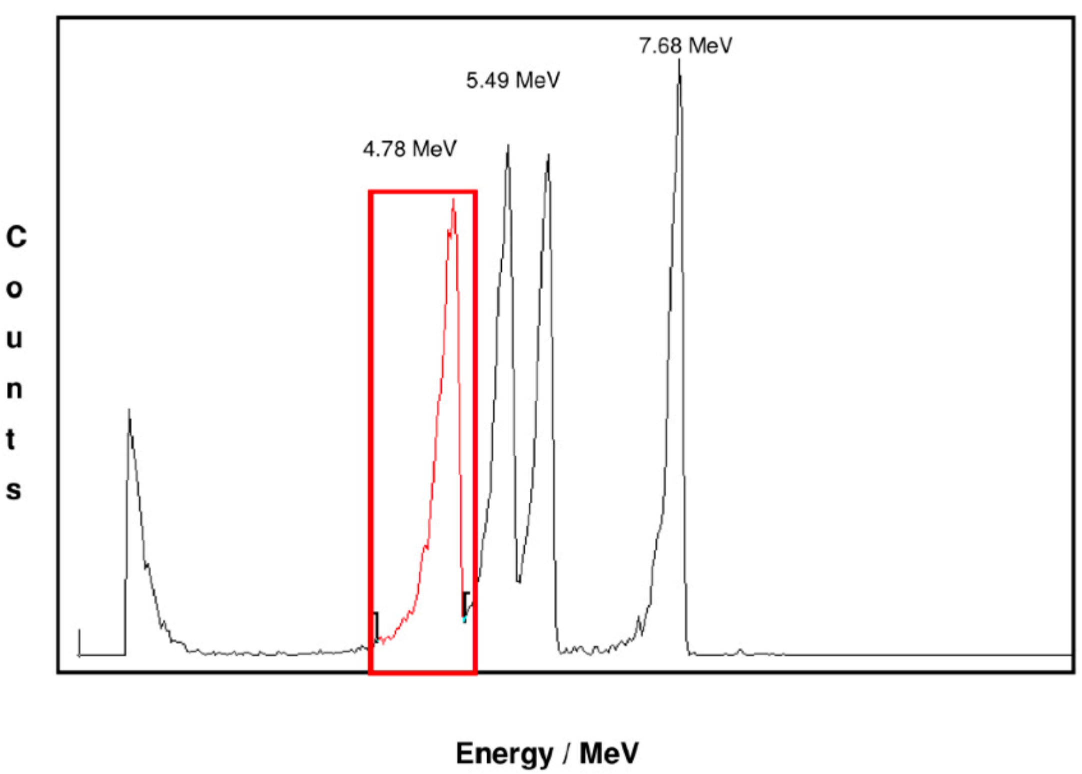
- What we ***DO*** know about neutrinos
  - How we know it
  - Why it matters
- What we still ***DON'T*** know about neutrinos
  - How we plan to find it out
  - Why it matters

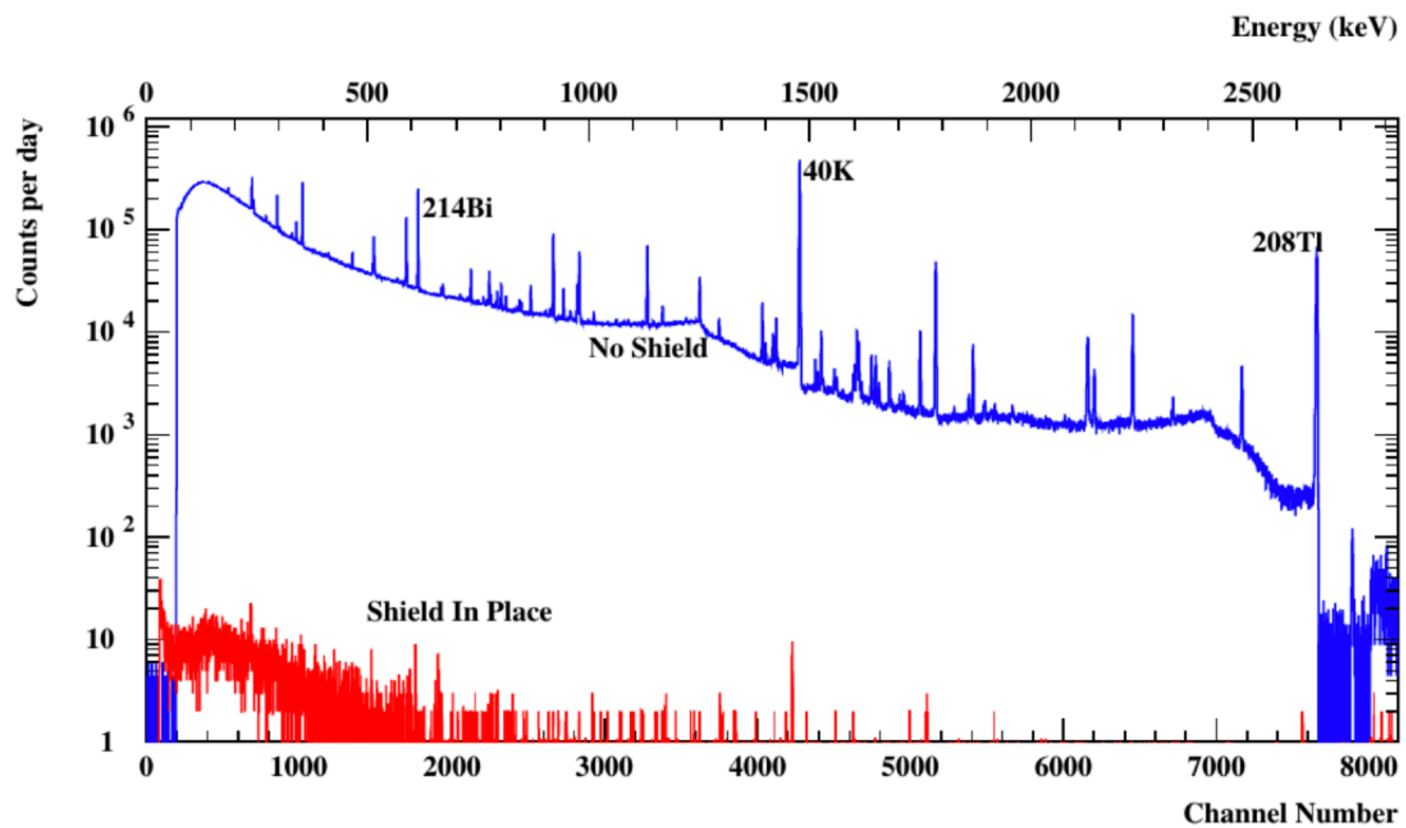
Neutrinos!

https://www.particlezoo.net/

1930: Beta Spectrum Problem

- Early particle physicists studied the energy spectra of collisions
- Alphas and gammas had sharp recognizable peaks





1930: Beta Spectrum Problem

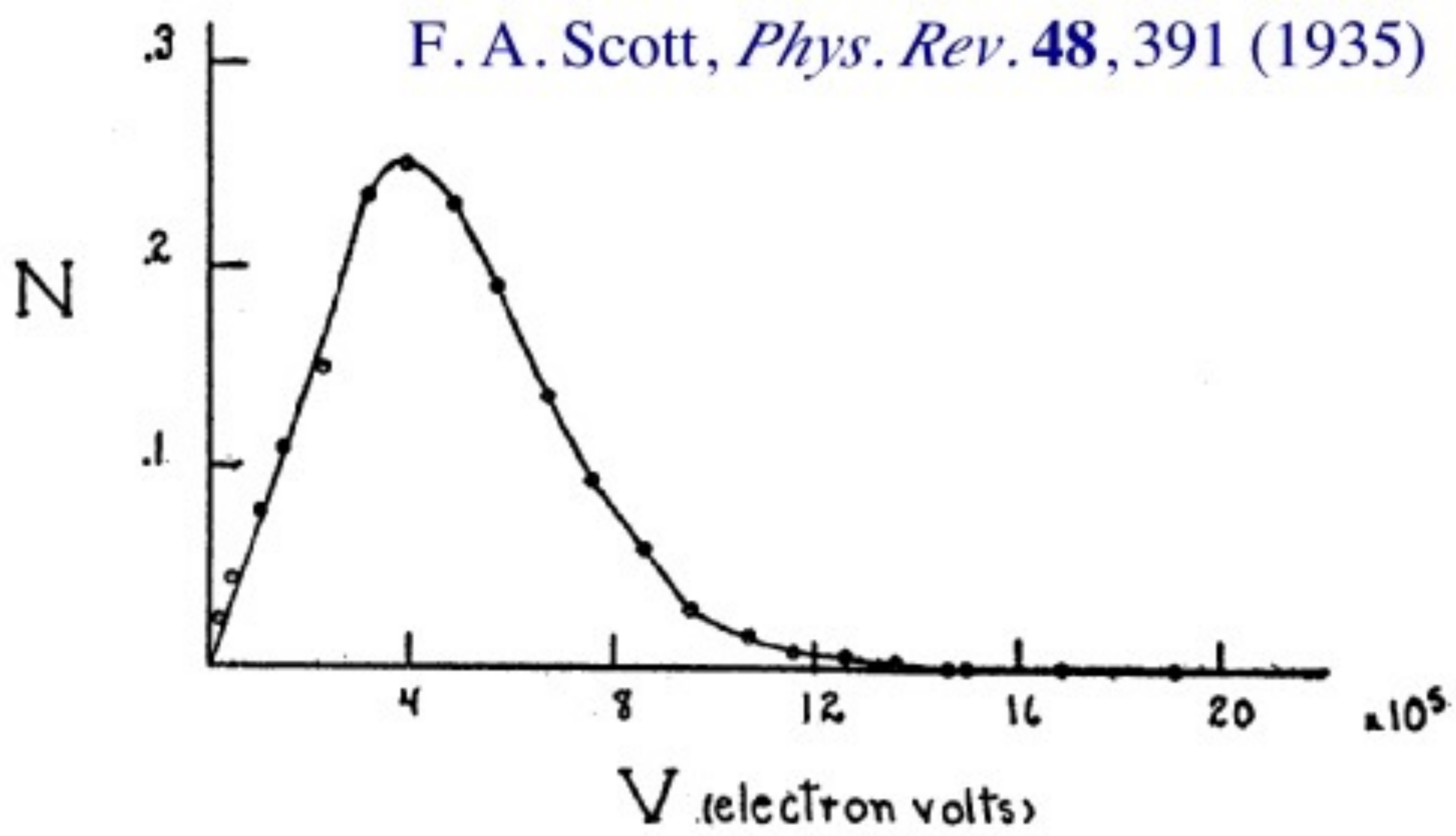
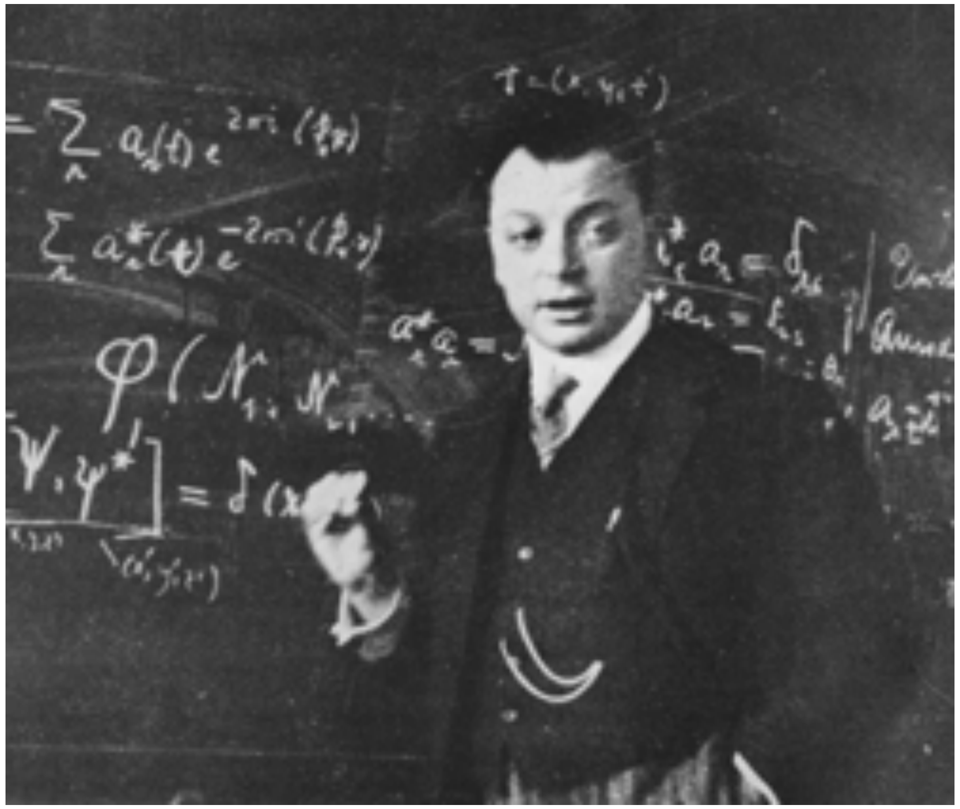


FIG. 5. Energy distribution curve of the beta-rays.

- Betas had broad spectra, which seemed to violate conservation of energy
- Reactions also violated conservation of momentum

1930: Beta Spectrum Problem



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Abschrift/15.12.56 FN

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

A Desperate Remedy

Dear Radioactive Ladies and Gentlemen

4 December 1930

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

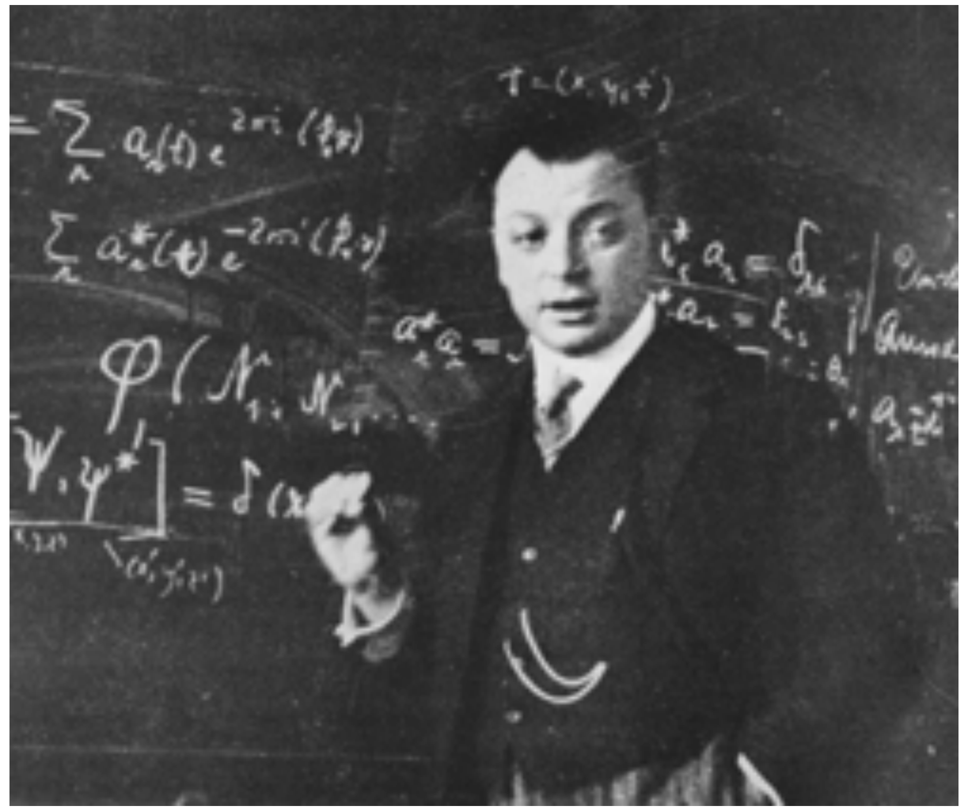
Now, the next question is what forces act upon the neutrons. The most likely model for the neutron seems to me to be, on wave mechanical grounds (more details are known by the bearer of these lines), that the neutron at rest is a magnetic dipole of a certain moment m. Experiment probably required that the ionizing effect of such a neutron should not be larger than that of a γ ray, and thus m should probably not be larger than $e^*(10^{-13}$ cm).

But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ ray.

I admit that my remedy may appear to have a small a priori probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous b-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, who told me a short while ago in Brussels, "One does best not to think about that at all, like the new taxes." Thus one should earnestly discuss every way of salvation.—So, dear radioactives, put it to test and set it right....

Your humble servant,
W. Pauli

1930: Beta Spectrum Problem



"I have done a terrible thing, I have predicted a particle that can never be detected."
-Wolfgang Pauli

1953-1956: Project Poltergeist

Fred Reines

Clyde Cowan

- In 1951, Reines had the idea to detect neutrinos from the explosions of atomic bombs!
- 1 T detector needed, 10^3 bigger than anything tried before.
- Scintillator detector - new technology then

Fred Reines

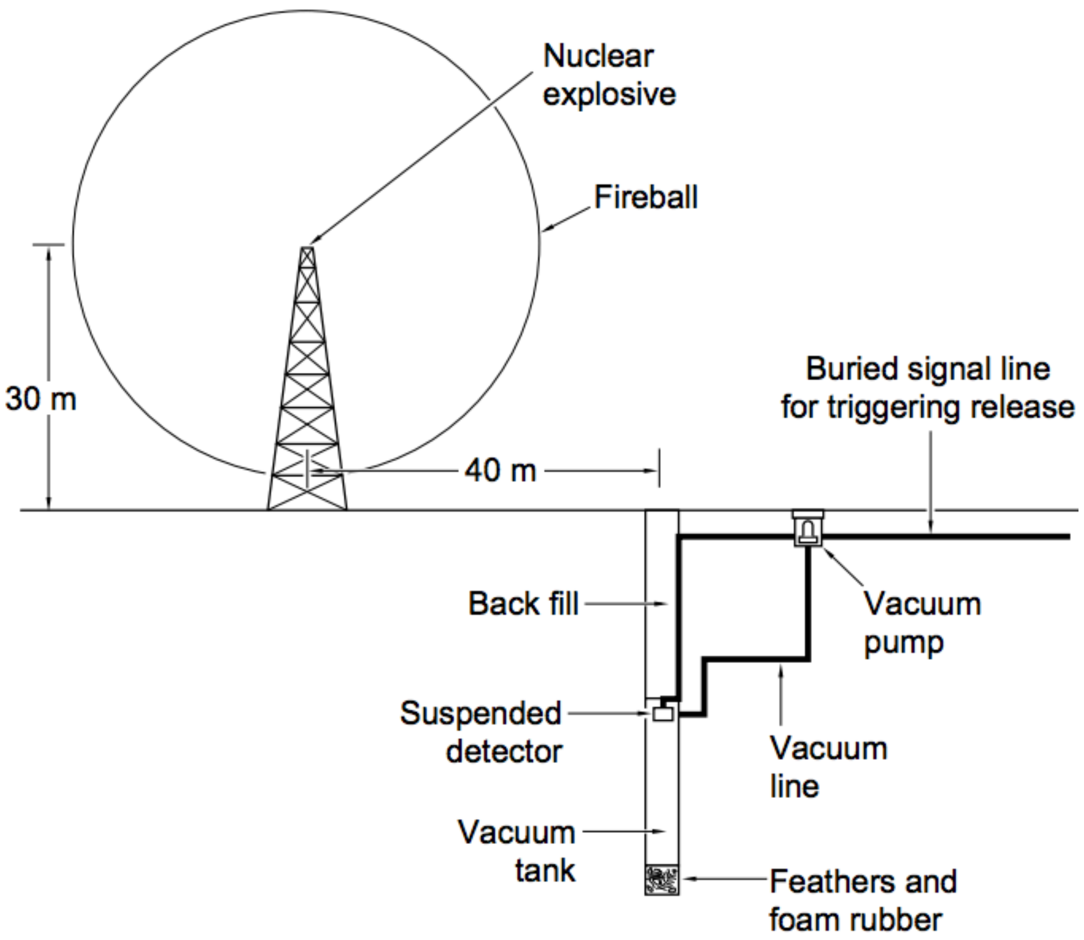
“We would dig a shaft near ‘ground zero’ about 10' in diameter and about 150' deep. We would put a tank, 10' in diameter and 75' long on end at the bottom of the shaft. We would then suspend our detector from the top of the tank, along with its recording apparatus, and back-fill the shaft above the tank. As the time for the explosion approached, we would start vacuum pumps and evacuate the tank as highly as possible. Then, when the countdown reached ‘zero,’ we would break the suspension with a small explosive, allowing the detector to fall freely in the vacuum. For about 2 seconds, the falling detector would be seeing the antineutrinos and recording the pulses from them while the earth shock [from the blast] passed harmlessly by, rattling the tank mightily but not disturbing our falling detector. When all was relatively quiet, the detector would reach the bottom of the tank, landing on a thick pile of foam rubber and feathers. We would return to the site of the shaft in a few days (when the surface radioactivity had died away sufficiently) and dig down to the tank, recover the detector, and learn the truth about neutrinos!”

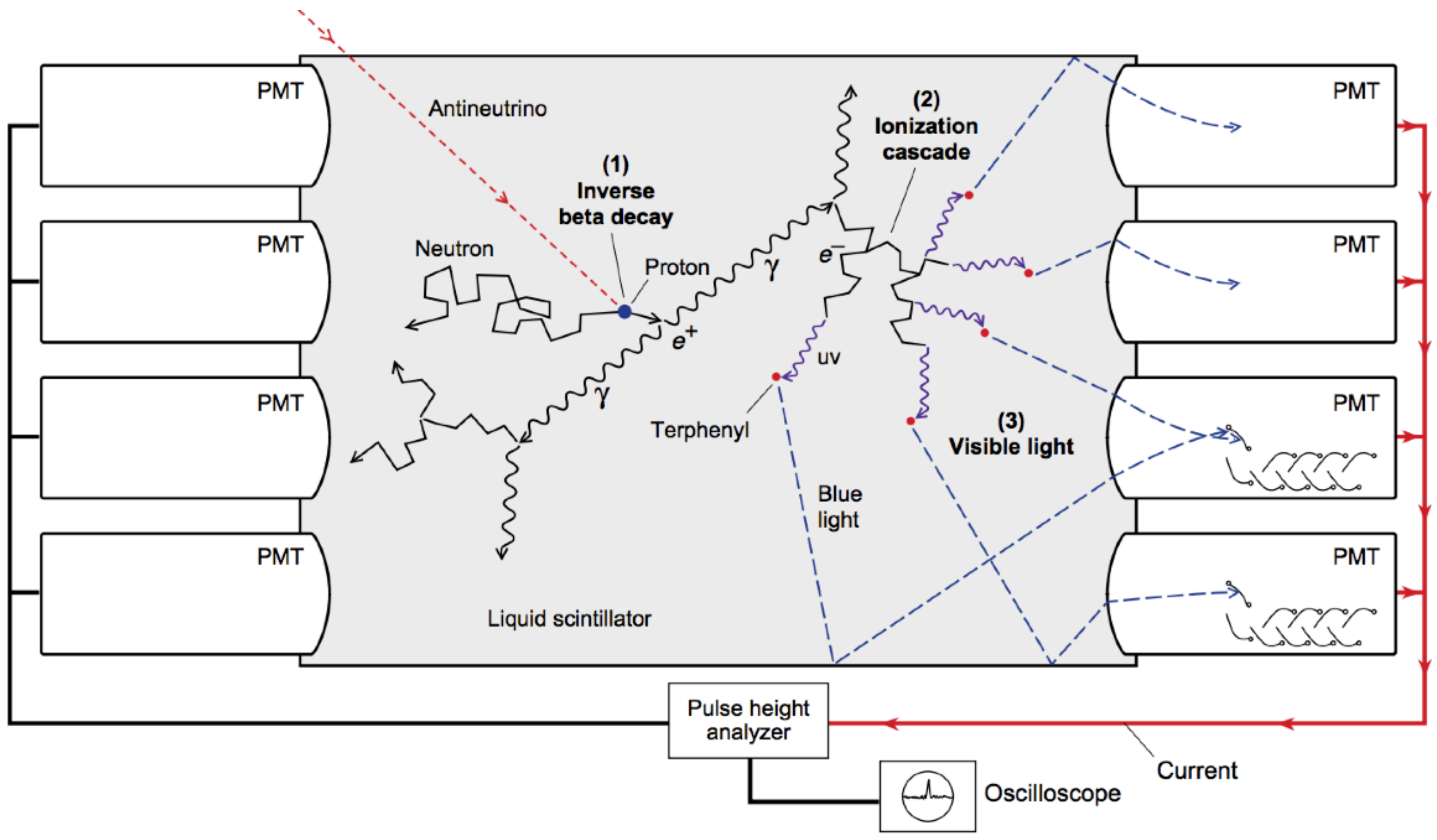
This extraordinary plan was actually granted approval by Laboratory Director Norris Bradbury.

“Life was much simpler in those days—no lengthy proposals or complex review committees."

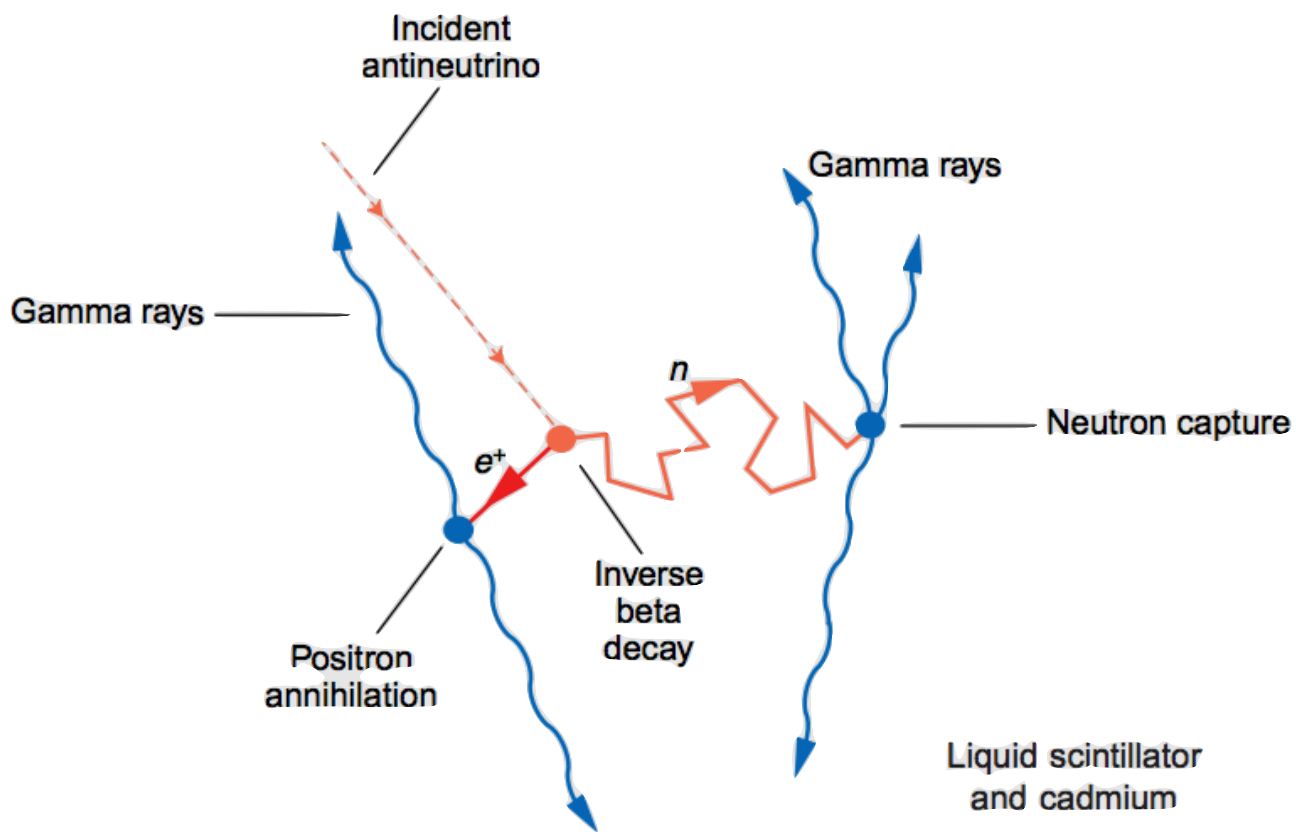
Original Reines-Cowan Experiment

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





Inverse Beta Decay

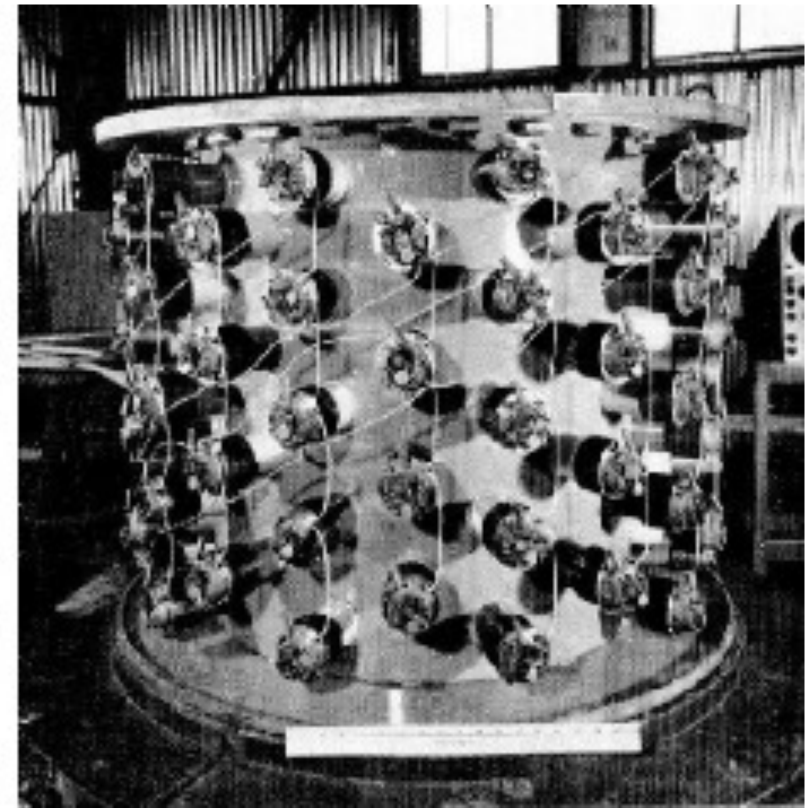


$$\bar{\nu}_e + p \rightarrow n + e^+$$

	σ [b]	E [MeV]
H	0.33	2.2
^{113}Cd	19820	9

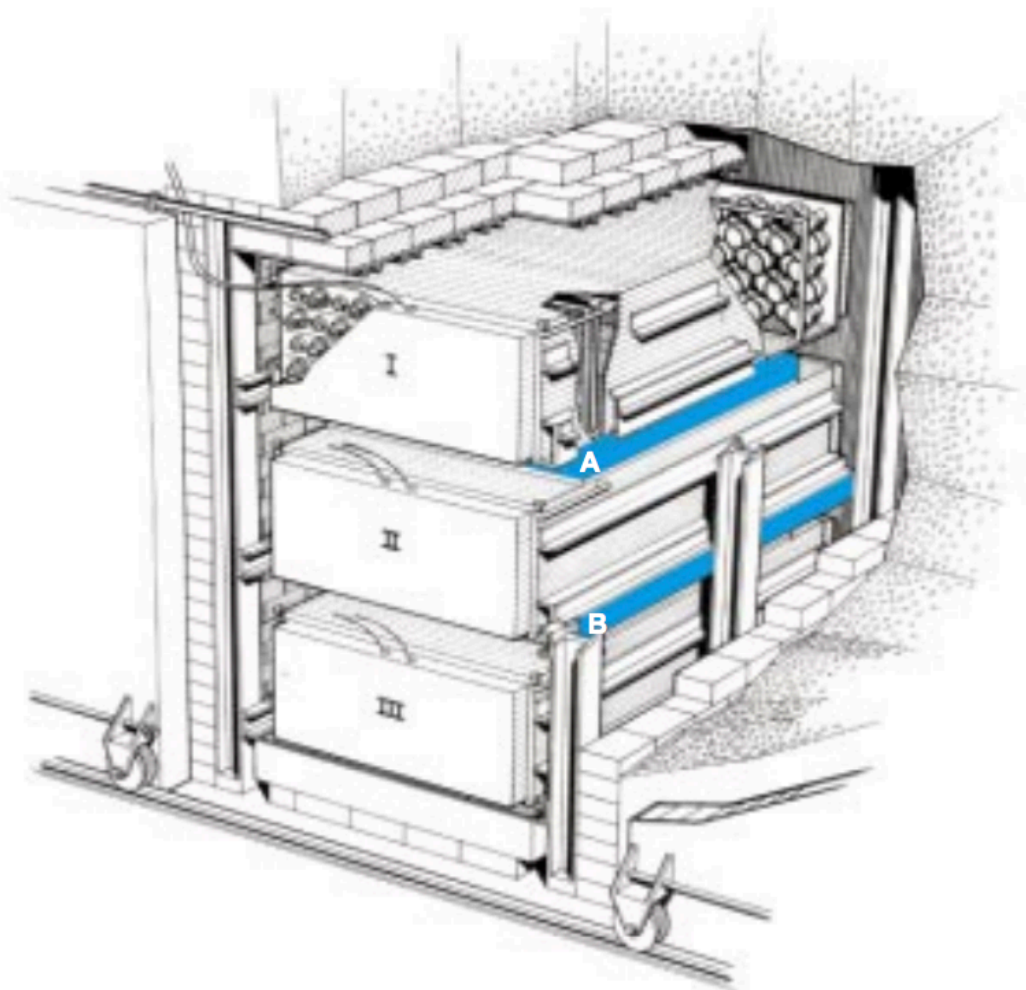
- Electronic circuits could be designed to detect this "delayed-coincidence" signature, two well defined flashes of light separated by microseconds provide a powerful means to discriminate the signature of inverse beta decay from background noise.

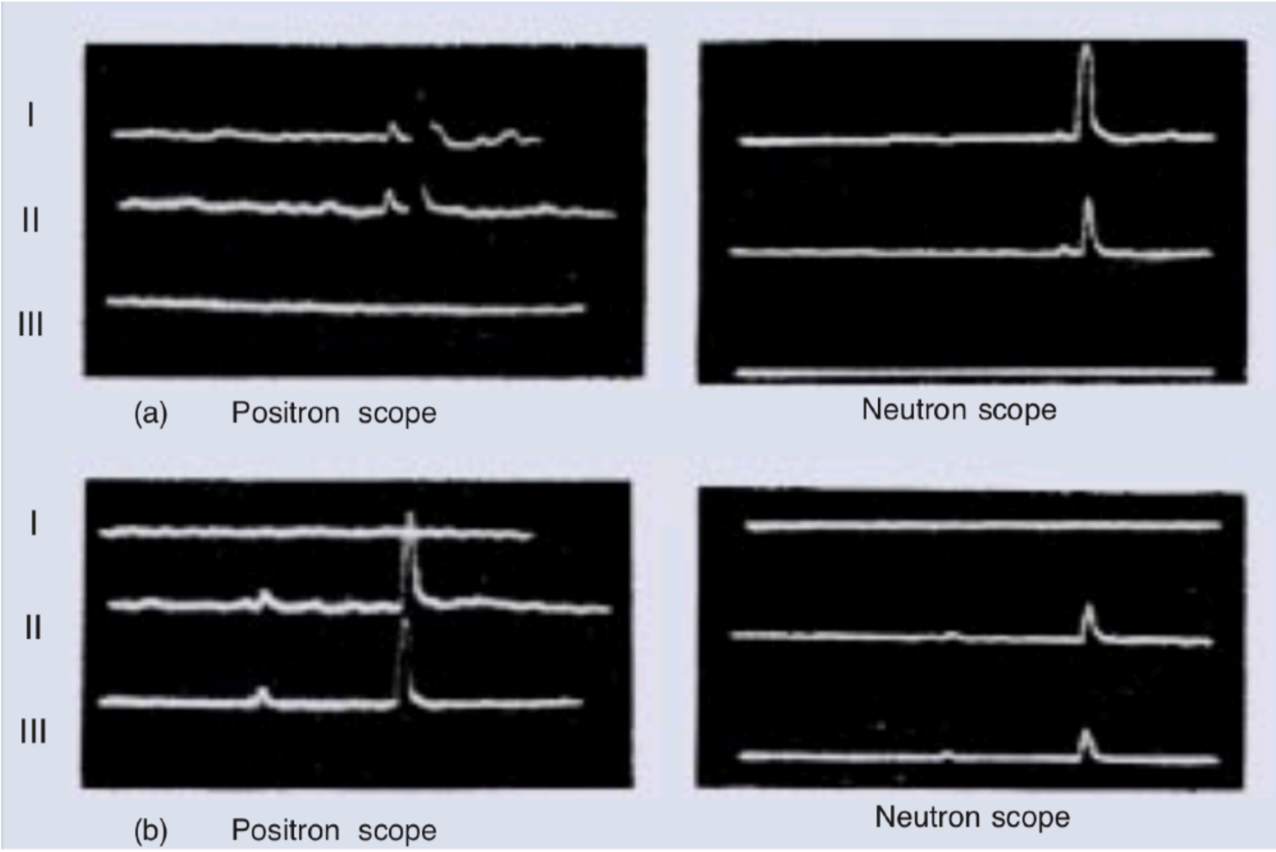
1953: Hanford Reactor



- For several months, the team stacked shielding and used various recipes for the liquid scintillator
- The delayed-coincidence background was about 5 counts per minute, much higher than the expected signal rate.
- Reines and Cowan reported a small increase in the number of delayed coincidences when the reactor was on versus when it was off
  - increase was consistent with the number expected from the estimated flux of reactor neutrinos.
- Tantalizing result but insufficient evidence that neutrino events were being detected.

1956: Savannah River Reactor

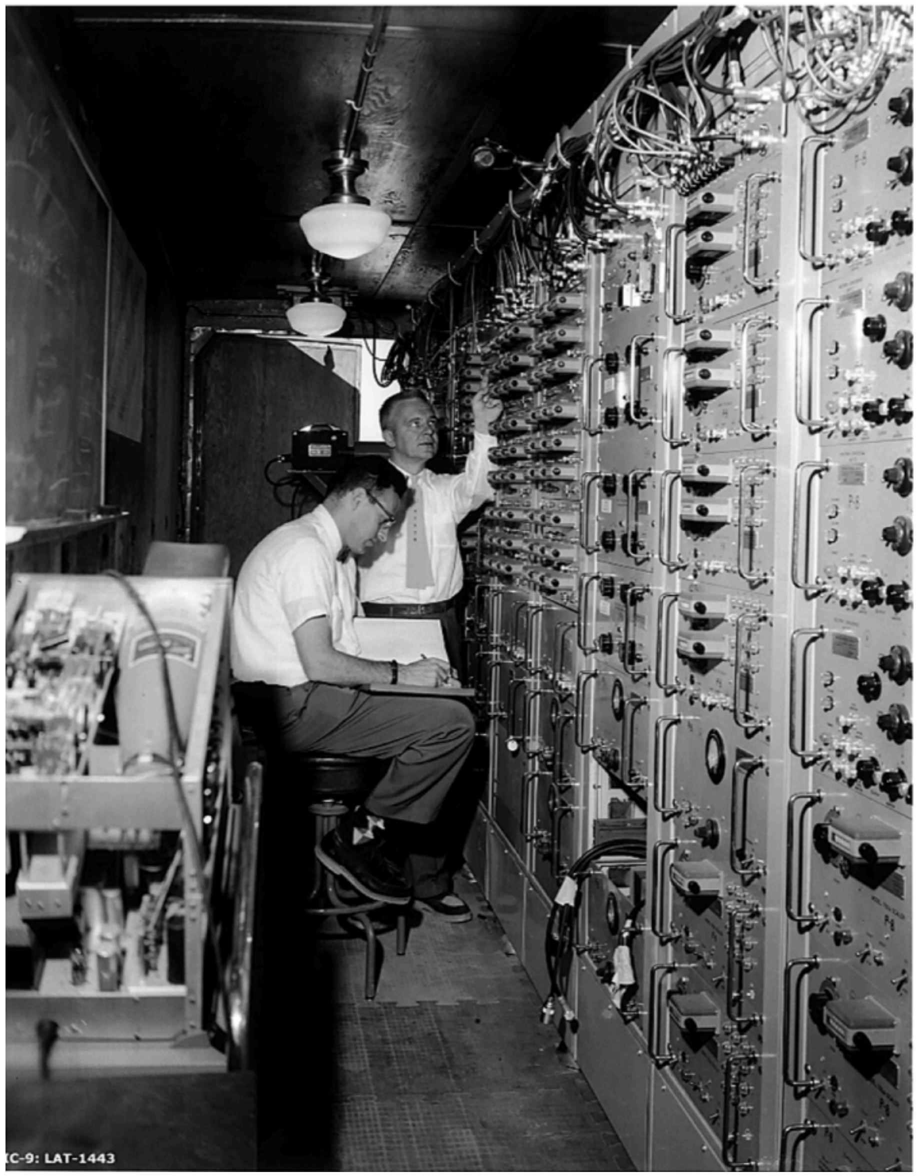




- Two large, flat plastic tanks filled with H2O as target for inverse beta decay C
- Cd2Cl4 dissolved in the water for neutron capture
- The target tanks were sandwiched between three large scintillation detectors with 110 photomultiplier tubes to collect scintillation light

- Signal 5 times greater than when reactor on vs off, ~1 reactor-associated event per hour.

1956: Savannah River Reactor

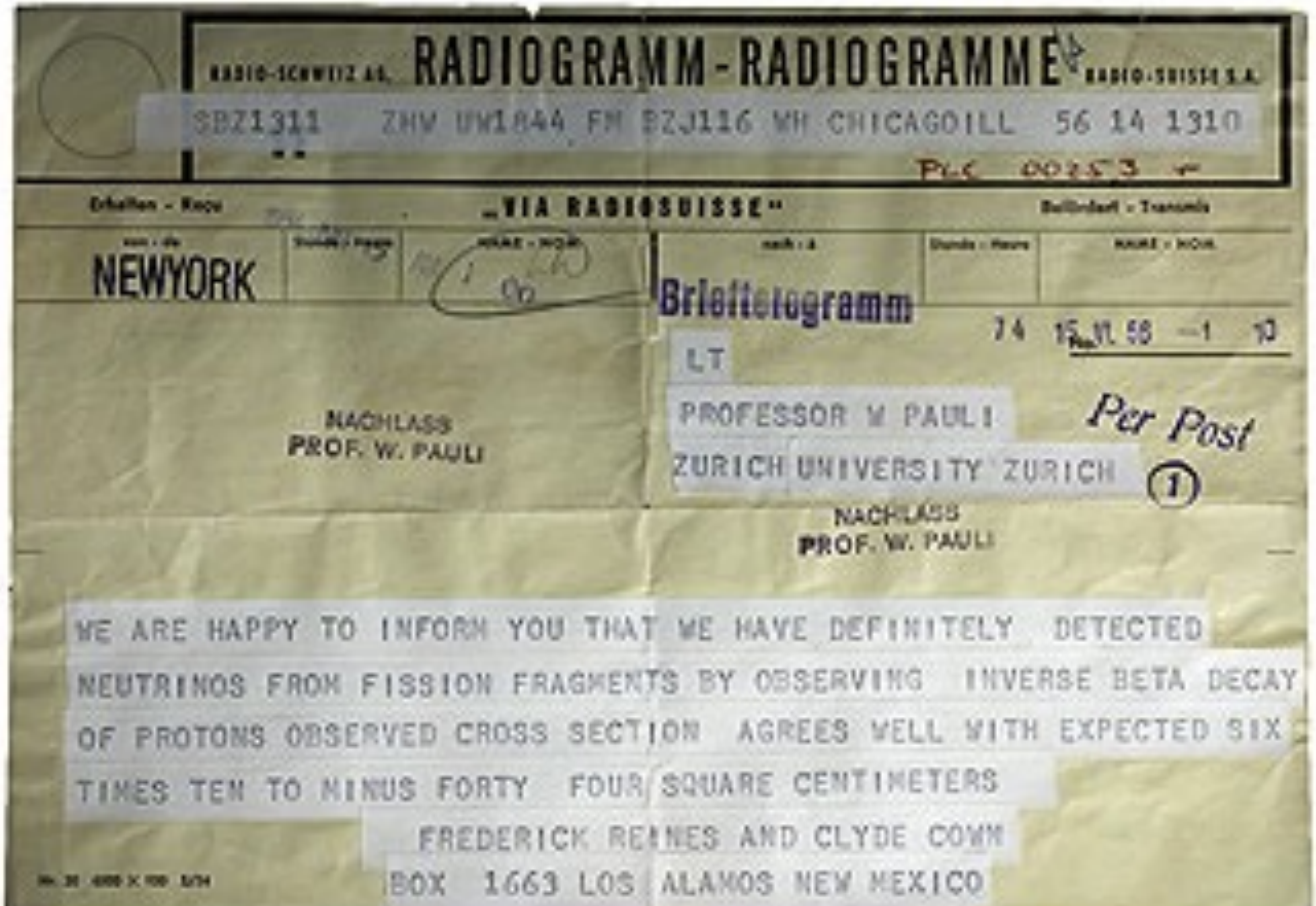


Experimentalists check their signal!

- Are coincidences from positron annihilation and neutron capture, rather than other processes?
  - Dissolve ^{64}Co in the water to understand what positrons look like
  - Doubled Cd_2Cl_4 in the water to watch the coincidence time decrease
- Does signal strength vary with number of protons?
  - Filled half of tanks with heavy water, decreased IBD cross section on deuterium
- Is signal really cosmic rays & reactor backgrounds?
  - varied the thickness and type of shielding

This and all other tests confirmed that the signal was indeed inverse beta decay of reactor antineutrinos!

1956: Discovery!



RADIO-SCHWEIZ AG. RADIOGRAMM - RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

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 AND CLYDE COWAN

BOX 1663 LOS ALAMOS NEW MEXICO

Muon Neutrino Discovery

- In 1962, Lederman, Steinberger, & Schwartz's group discovered the muon neutrino

Pions produced

Spark Chamber to detect neutrinos

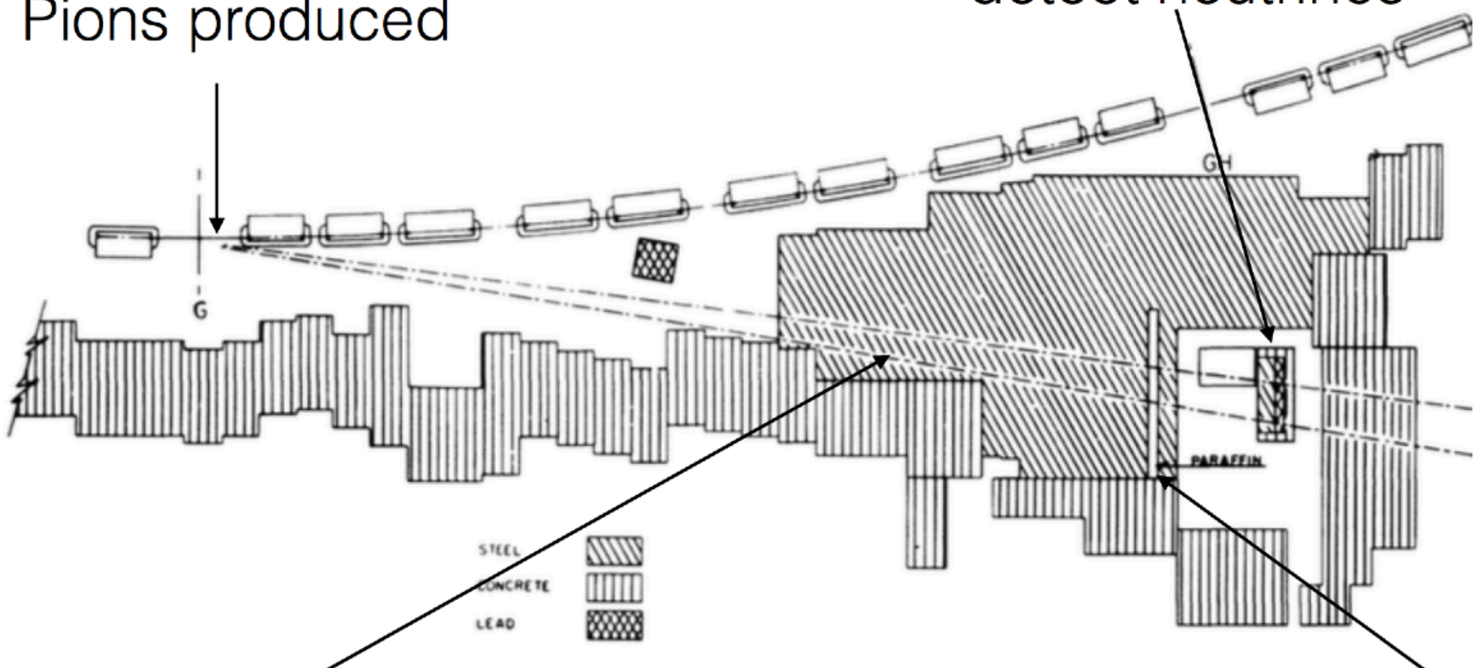


FIG. 1. Plan view of AGS neutrino experiment.

Steel shield stops strongly interacting particles

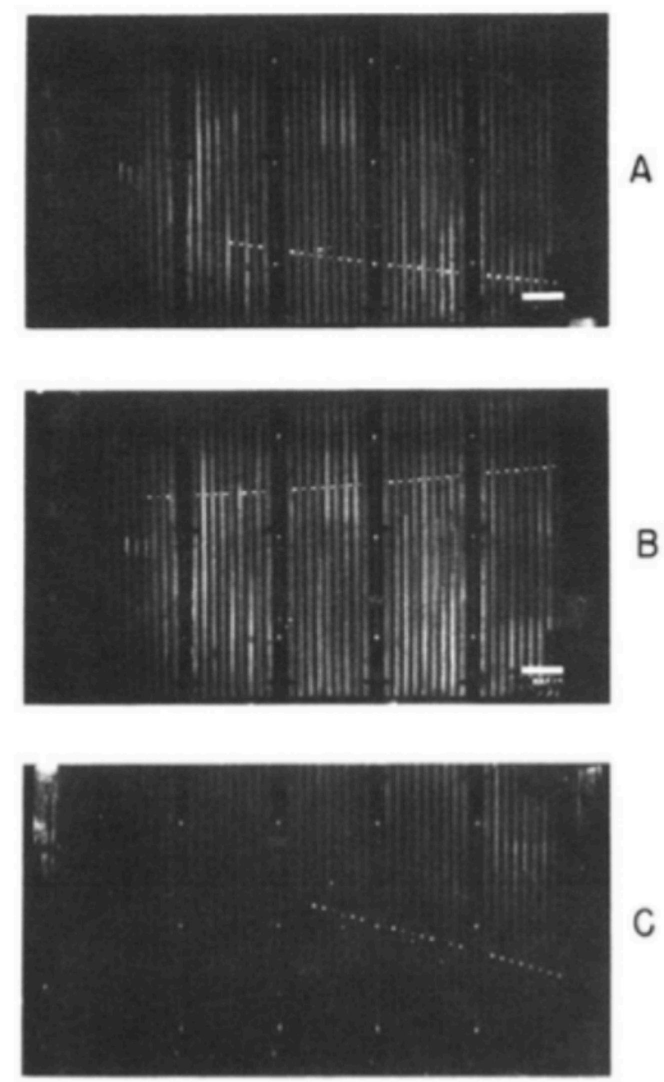
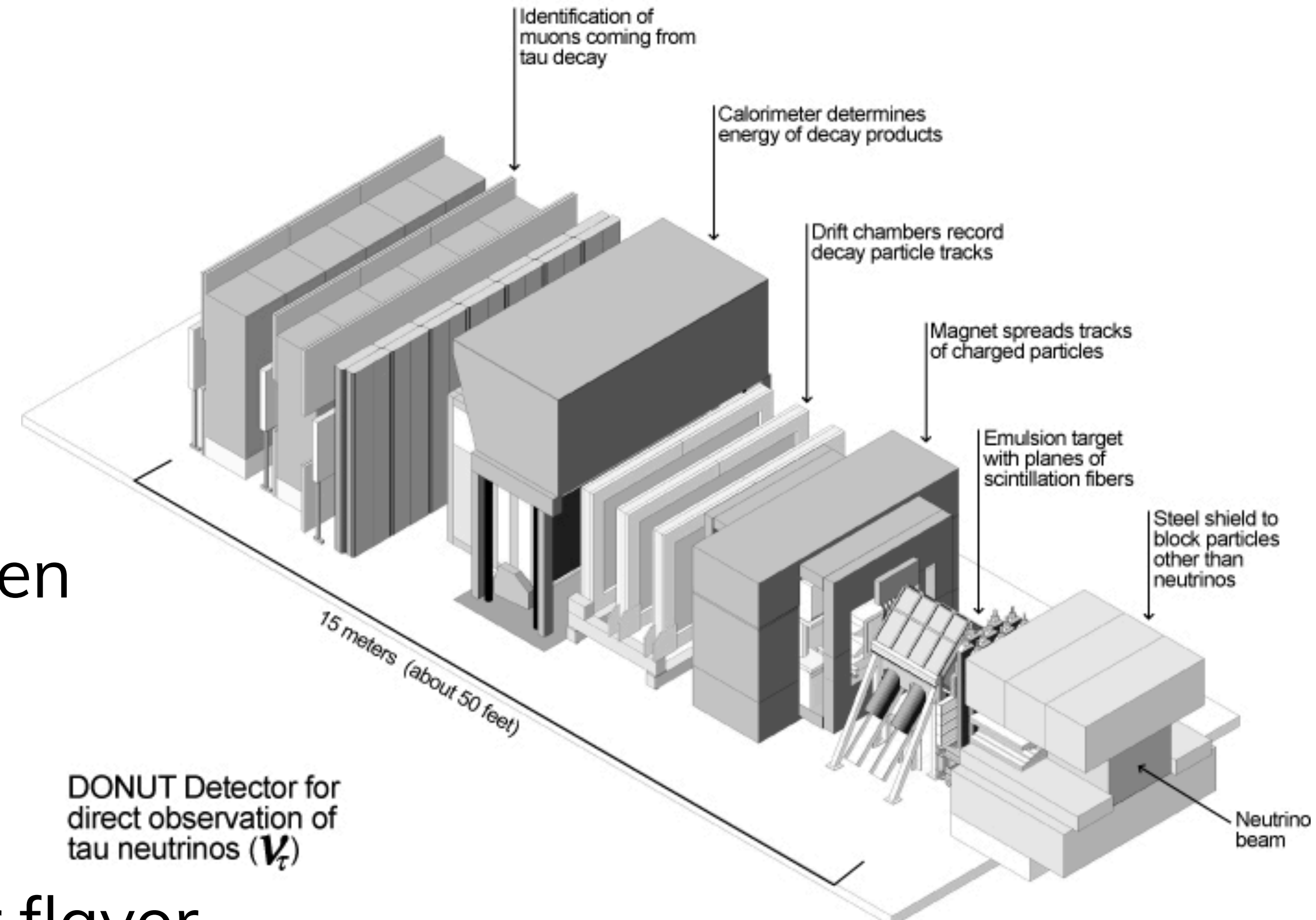


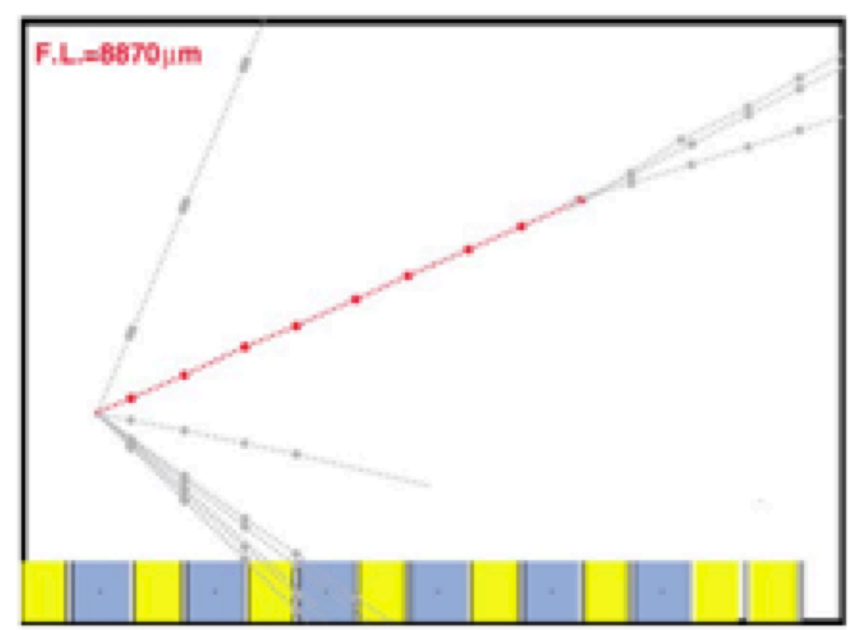
FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

- 34 muon tracks, 6 electrons showers
- They're different particles!

Tau Neutrino Discovery

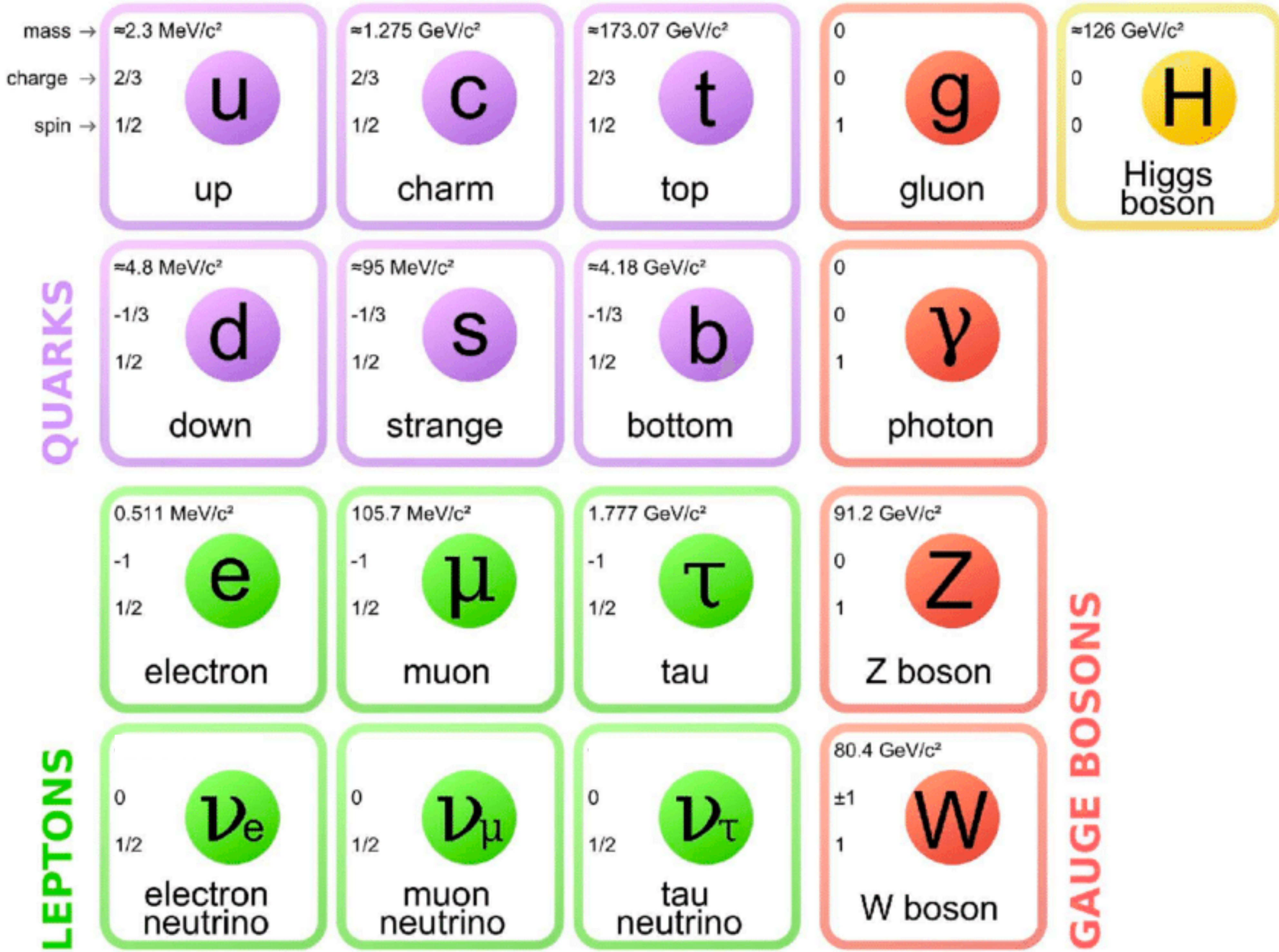
- In 2000 the DOnuT collaboration discovered the tau neutrino
- The neutrino source was the tungsten beam dump behind the Tevatron.
- Only 36 feet from source to target.
  - This did not allow enough time for flavor oscillations.
- The target was made of emulsion sheets, which was used as an electromagnetic calorimeter in some cases.
- 4 Tracks observed! (bkg < 0.2)



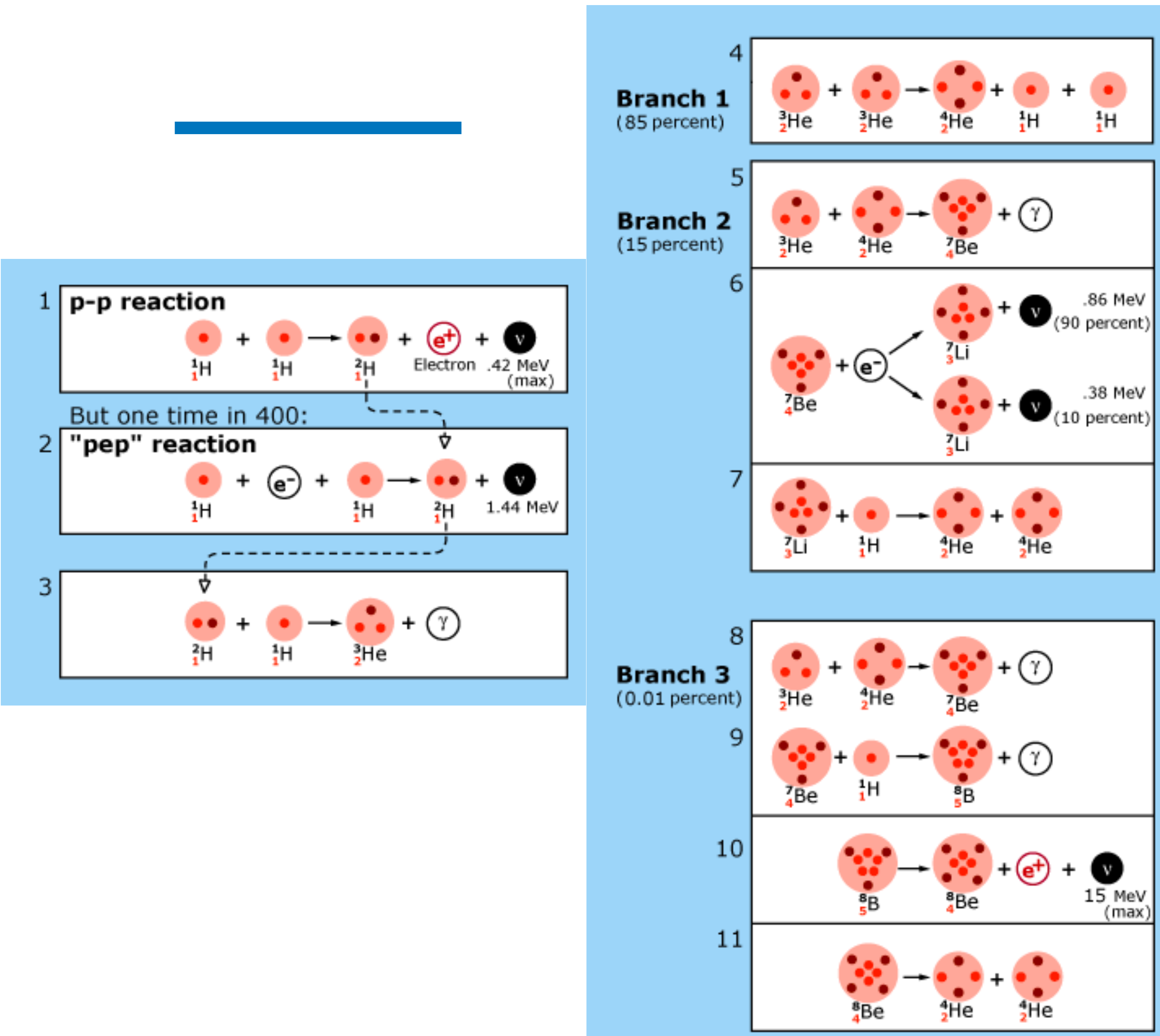


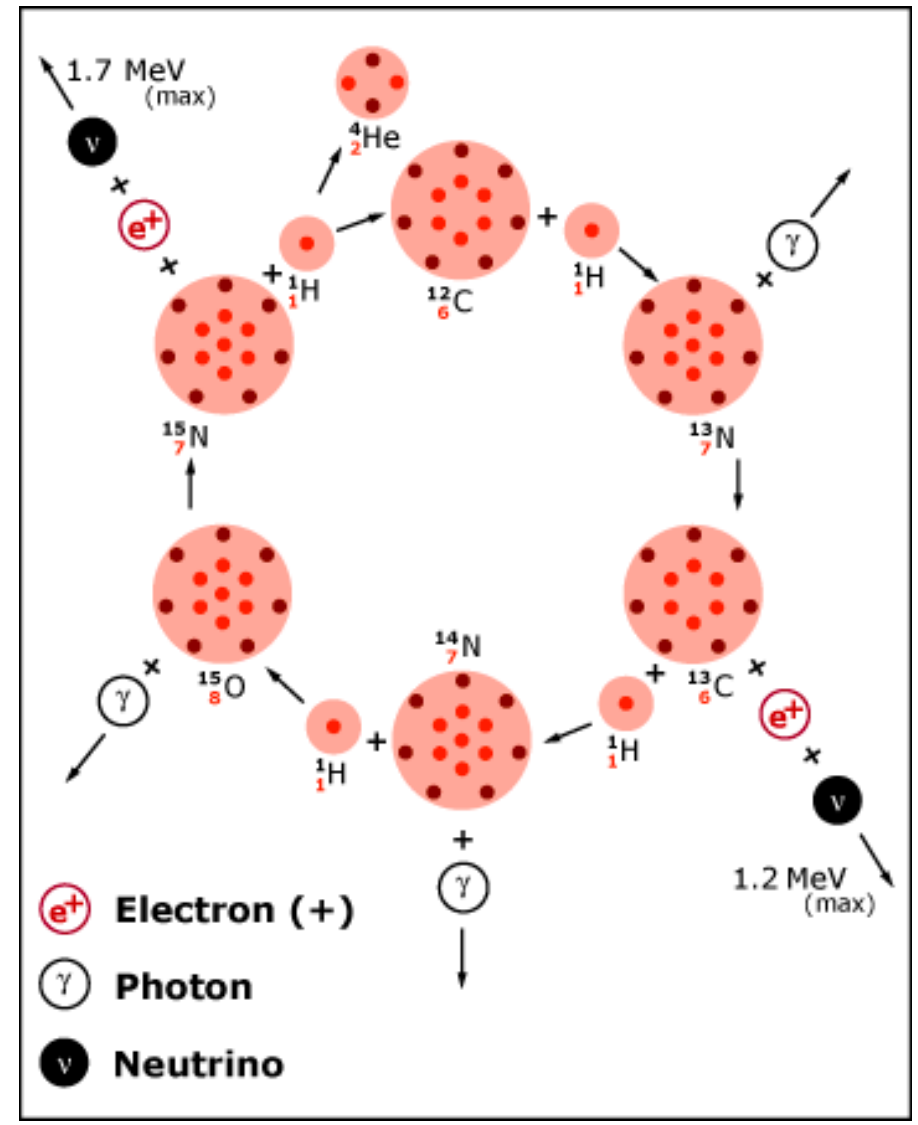
The Standard Model

The Standard Model



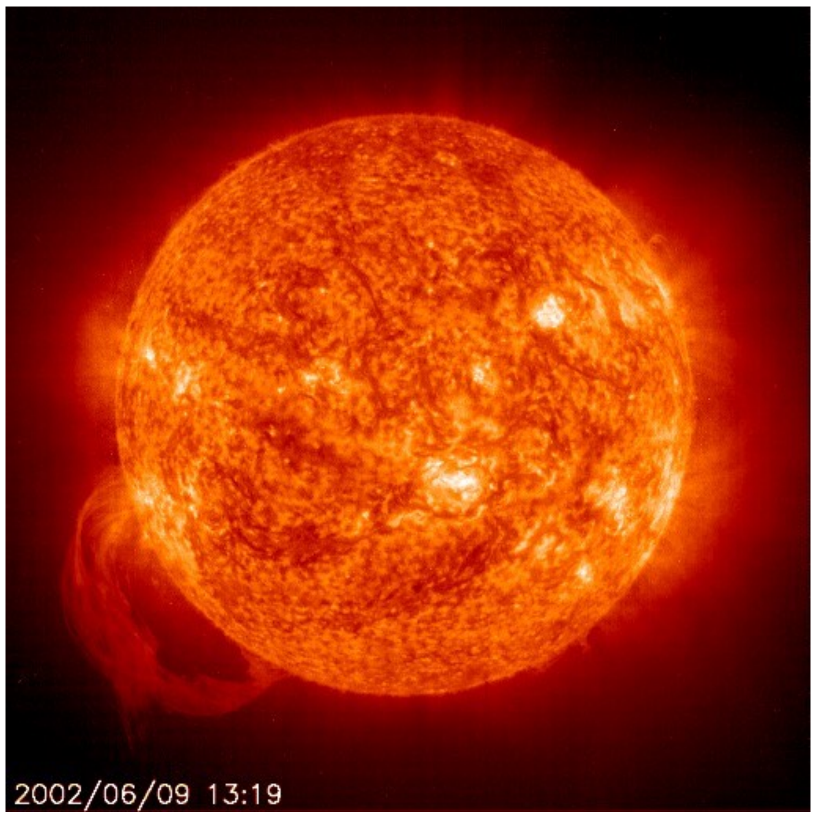
The Standard Model





$$\Phi_{\nu_e} = 10^{11}/cm^2/s$$

Solar Neutrinos!



$$\Phi_{\nu_e} = 10^{11}/cm^2/s$$

378 tonnes of C_2Cl_4

^{37}Cl is 25% of nat Cl

$$\nu_e +^{37} Cl \rightarrow^{37} Ar + e^-$$

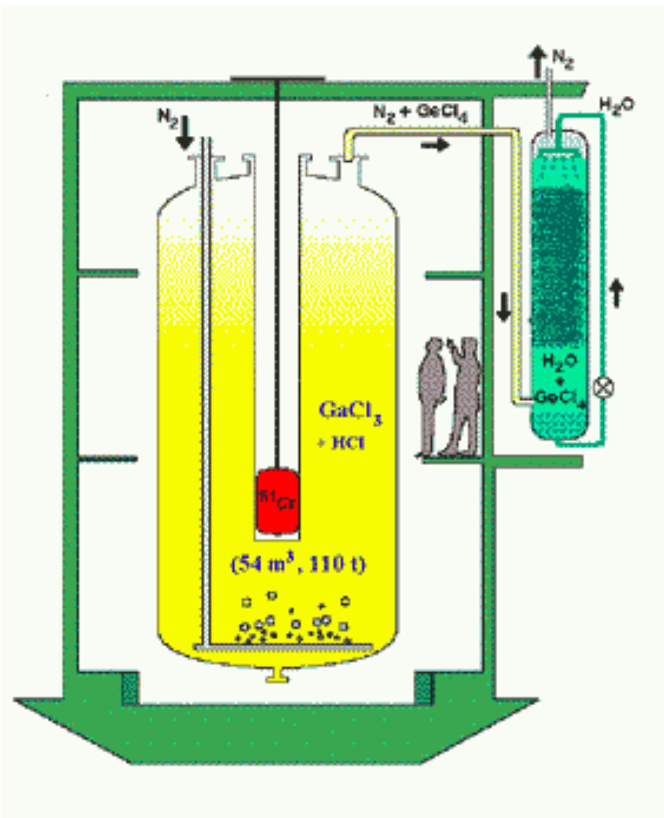
Homestake Experiment

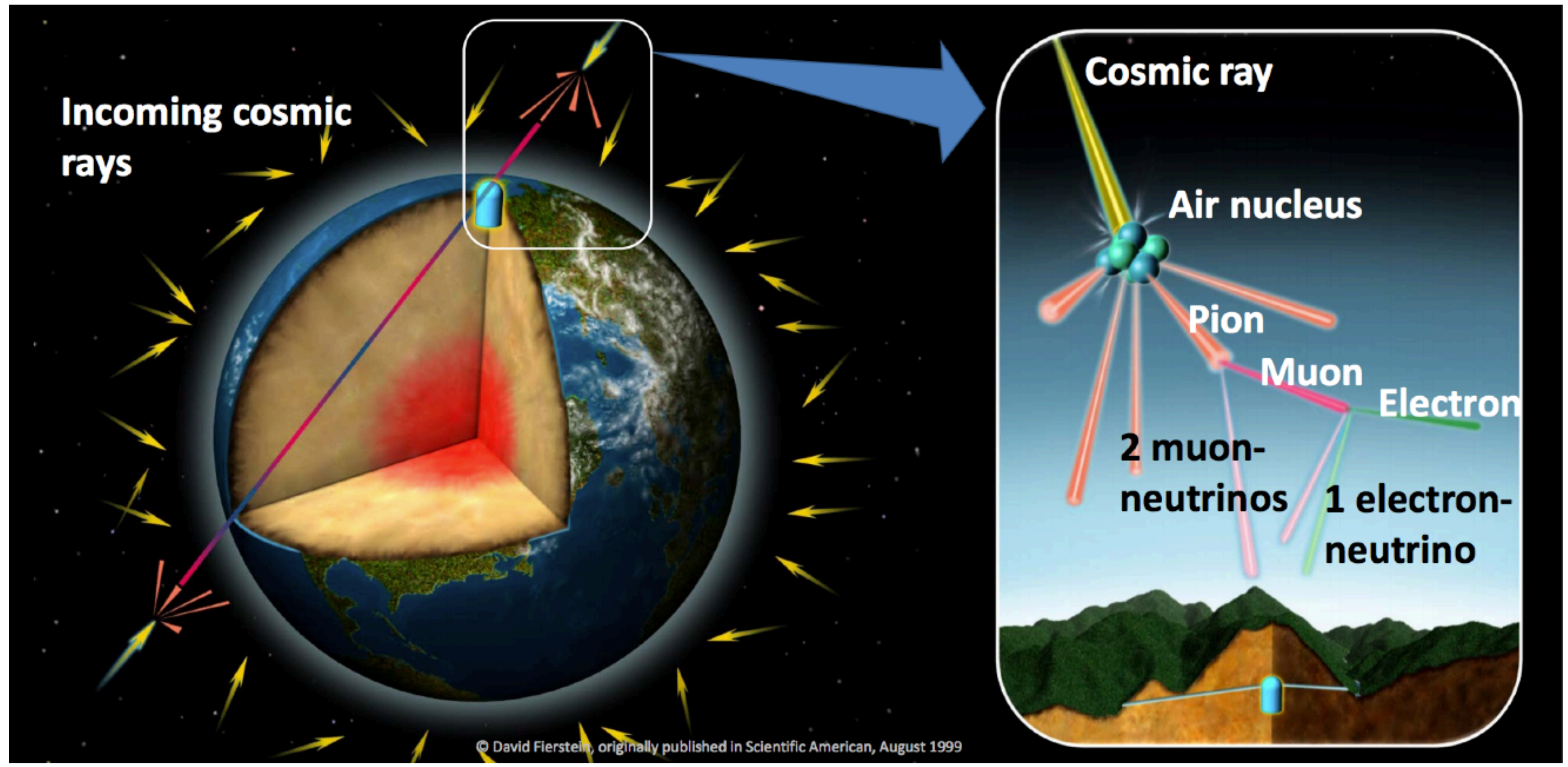
- The ^{37}Ar formed by neutrino capture is then removed from the bulk of the liquid by bubbling 280 lpm of helium gas through the system.
- After the sample of argon is purified chemically it is placed in a small counter holding about .5 ml of gas.
- The ^{37}Ar is unstable and reverts to ^{37}Cl by capturing one of its own orbital electrons. The decay releases a low-energy electron from the Ar, which is detected

- Bahcall: "Ray Davis tells me that the experiment is simple ('Only plumbing') and that the chemistry is 'standard.' The total number of atoms in the big tank is about 10^{30}. He is able to find and extract from the tank the few dozen atoms of ^{37}Ar that may be produced inside by the capture of solar neutrinos. **This makes looking for a needle in a haystack seem easy.**"

Only detected 1/3 of predicted flux

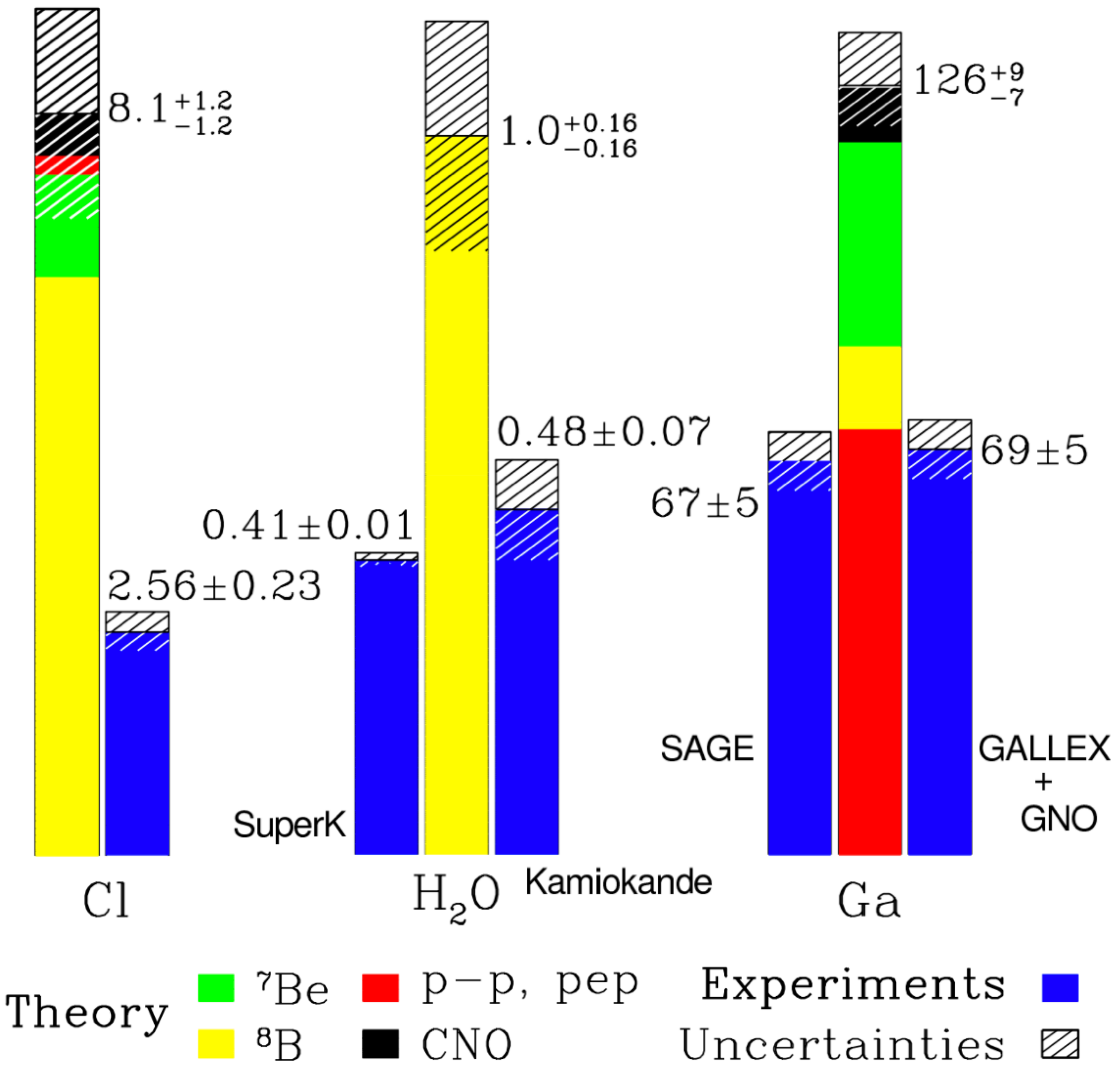
Neutrino Anomaly?



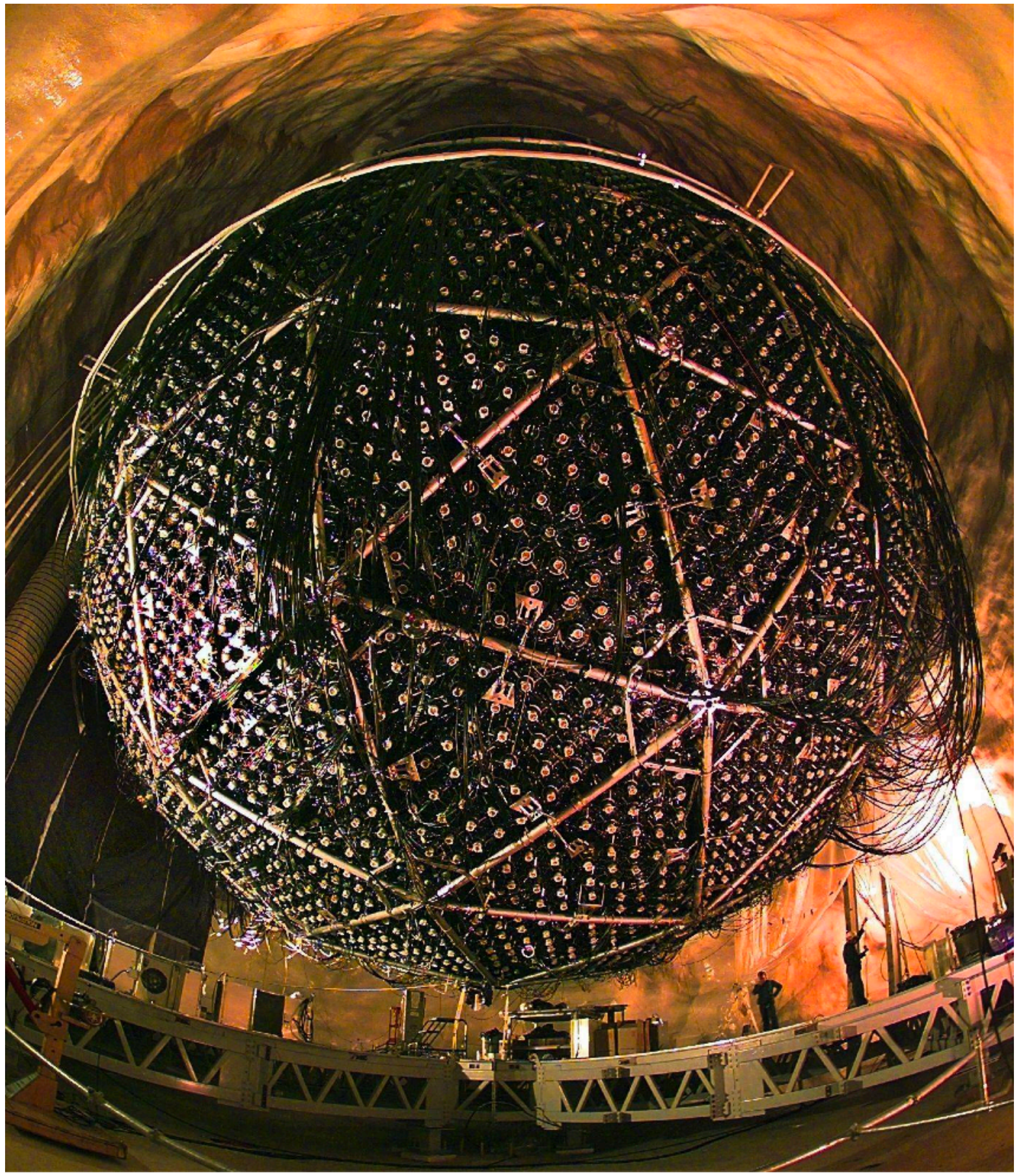


- Gallium Experiments looking for lower energy solar nus
  - $\nu_e +^{71} Ga \rightarrow^{71} Ge + e^-$
- KamiokaNDE, MACRO, IMB looking for nucleon decay, observed atmospheric nus
  - Saw half of expected rate

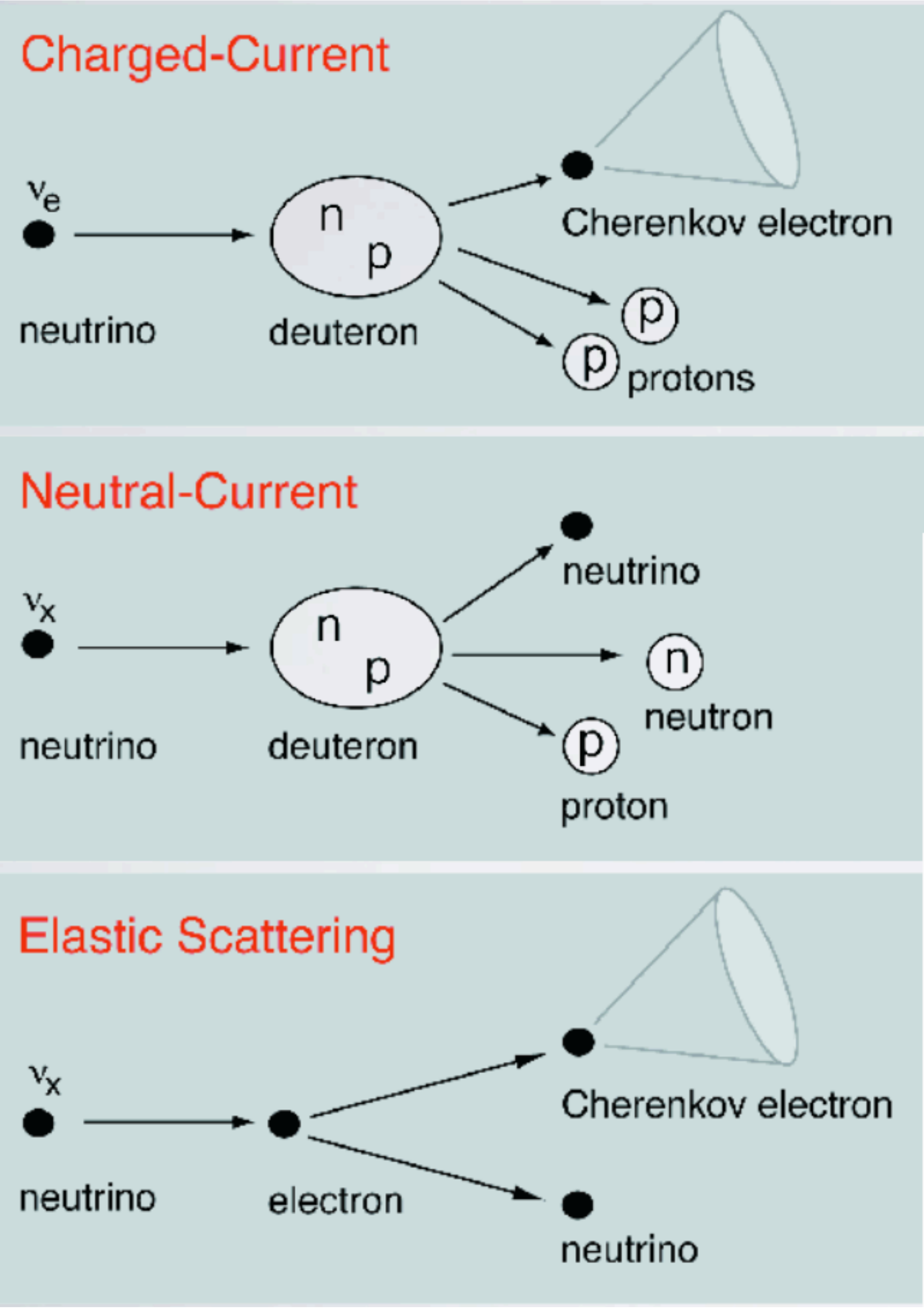
Standard Model Rates vs Expt



SNO



- 1 kT Heavy Water
- 2km underground in active mine
- Incredible cleanliness constraints



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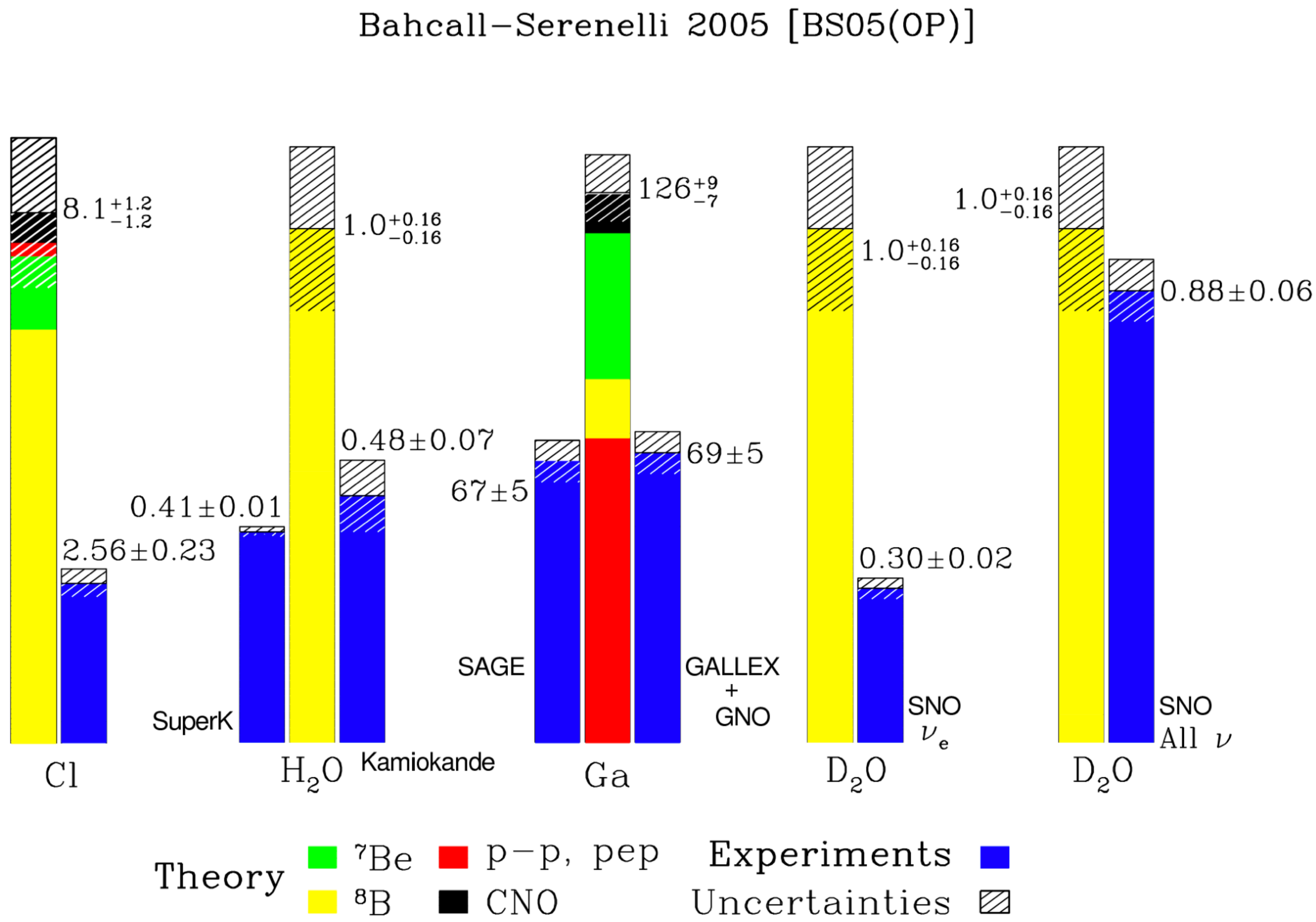
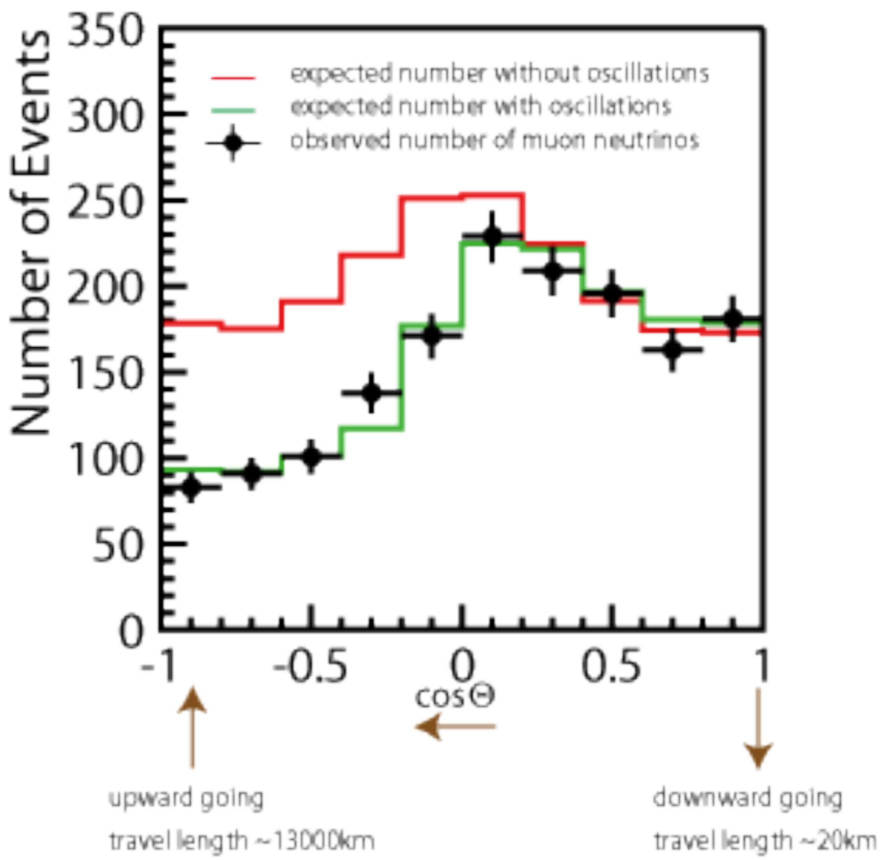
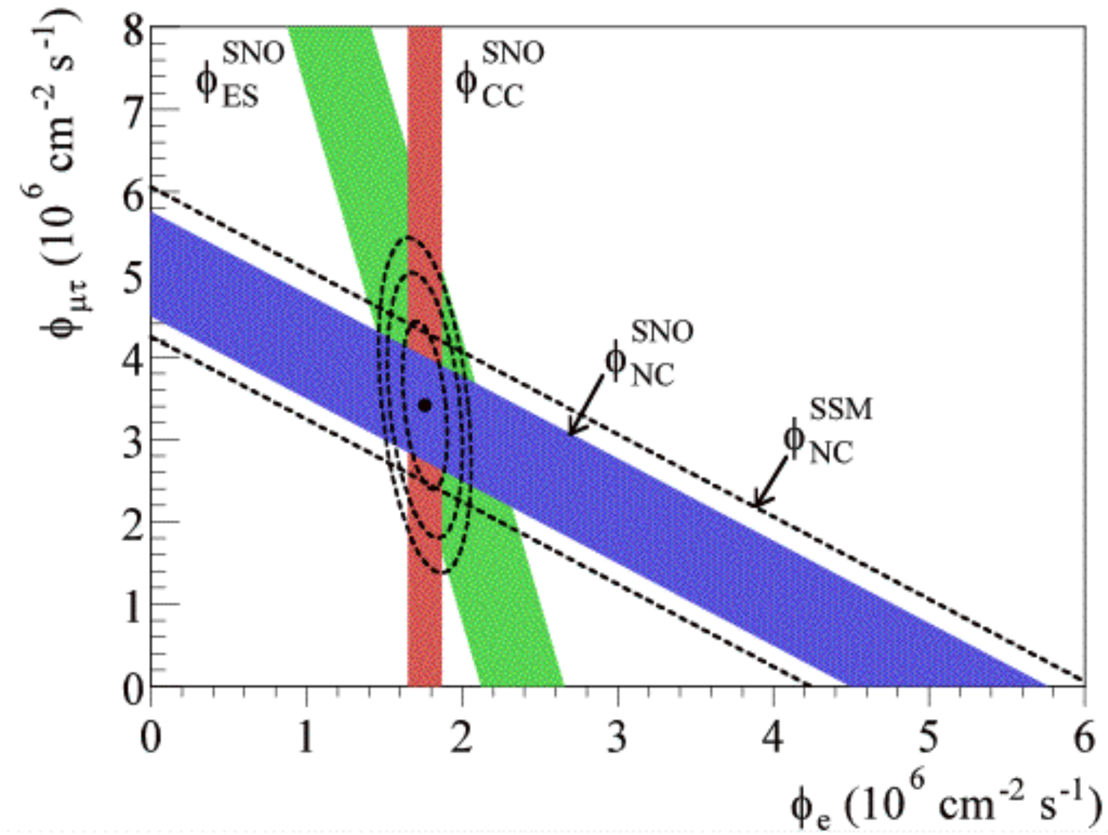
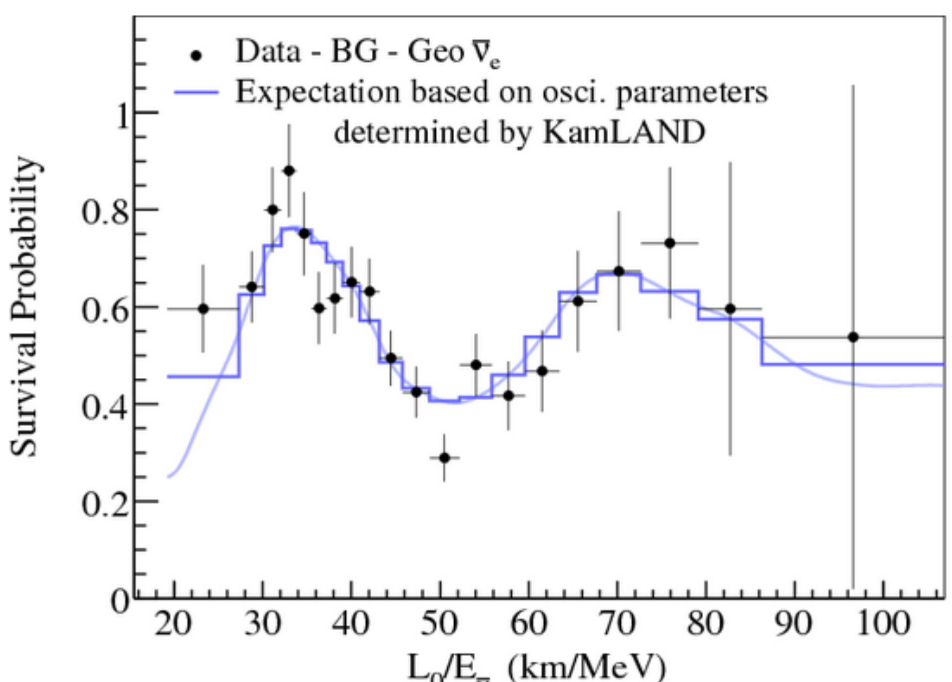
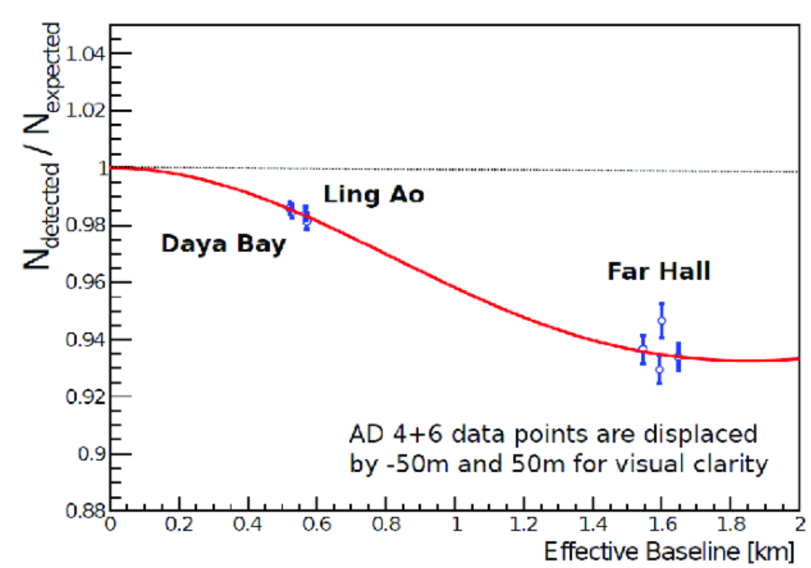


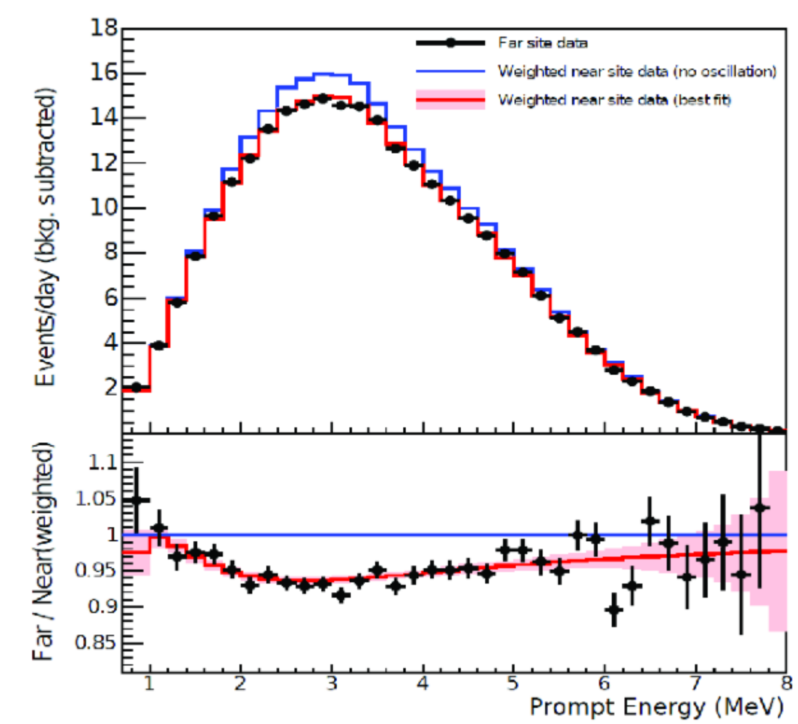
Neutrino Oscillations











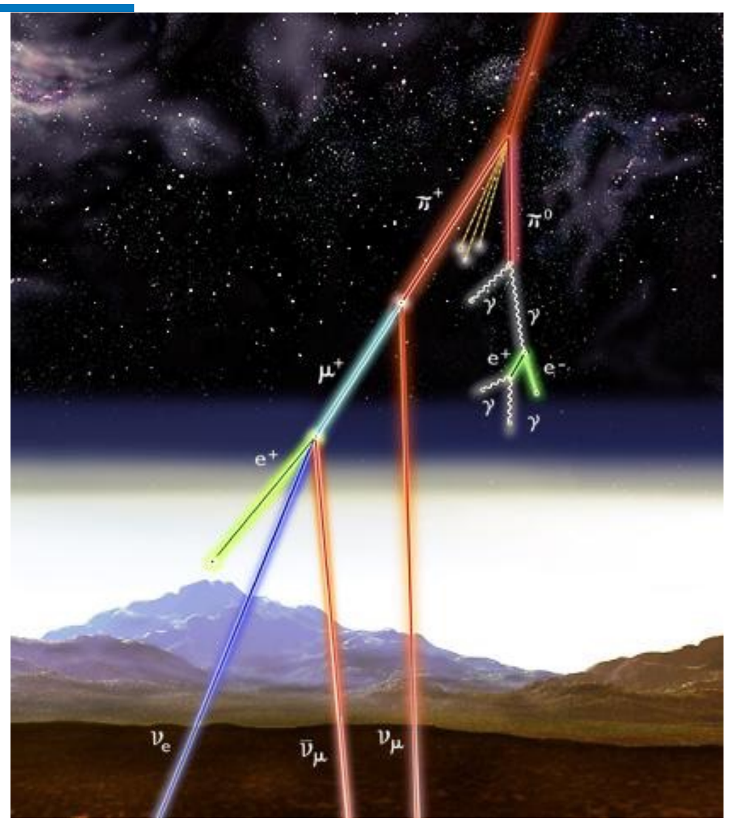
http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/atmnu-e.html

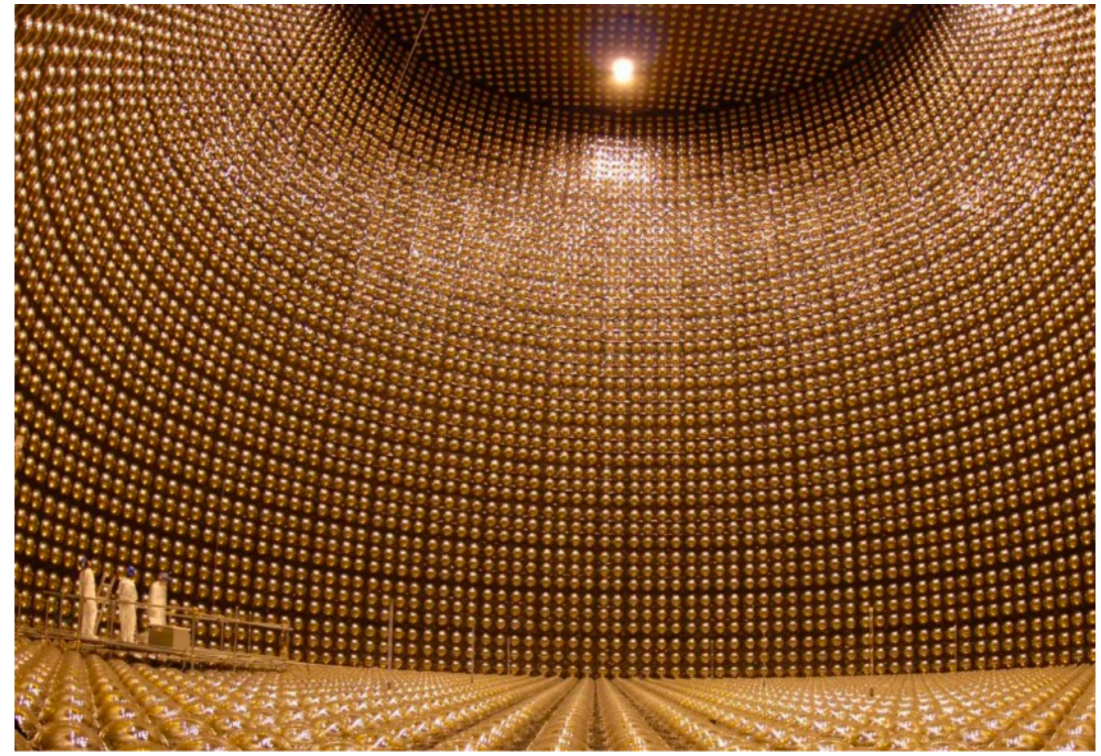
http://kamland.lbl.gov/research-projects/kamland/physics-impact

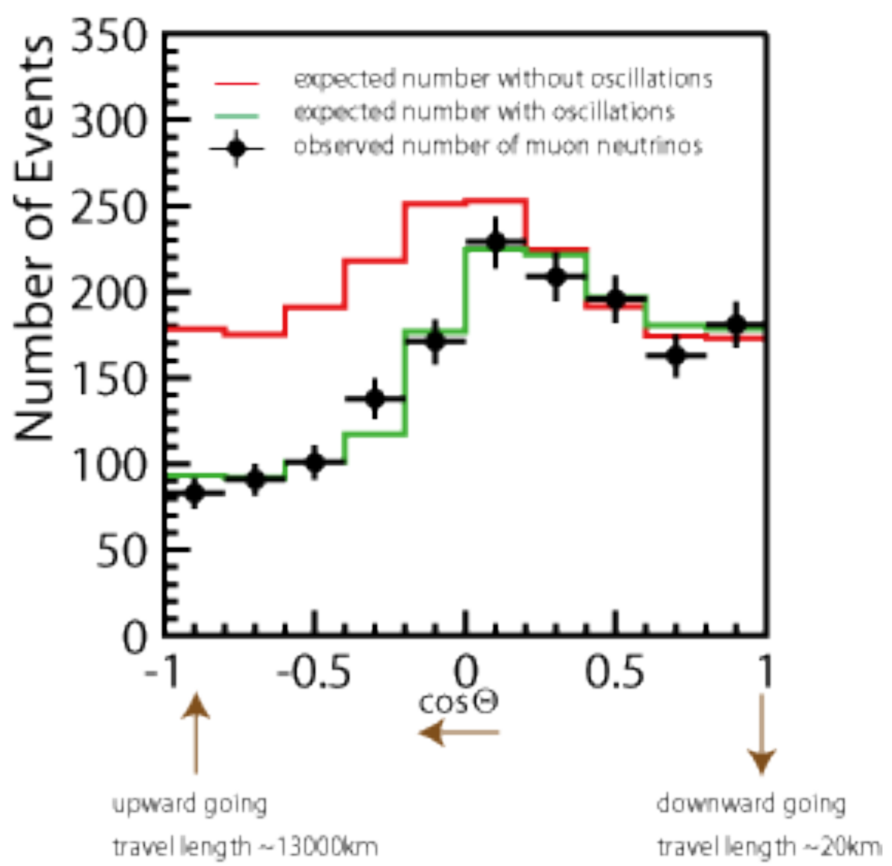
https://www.aps.org/units/dnp/research/sno.cfm

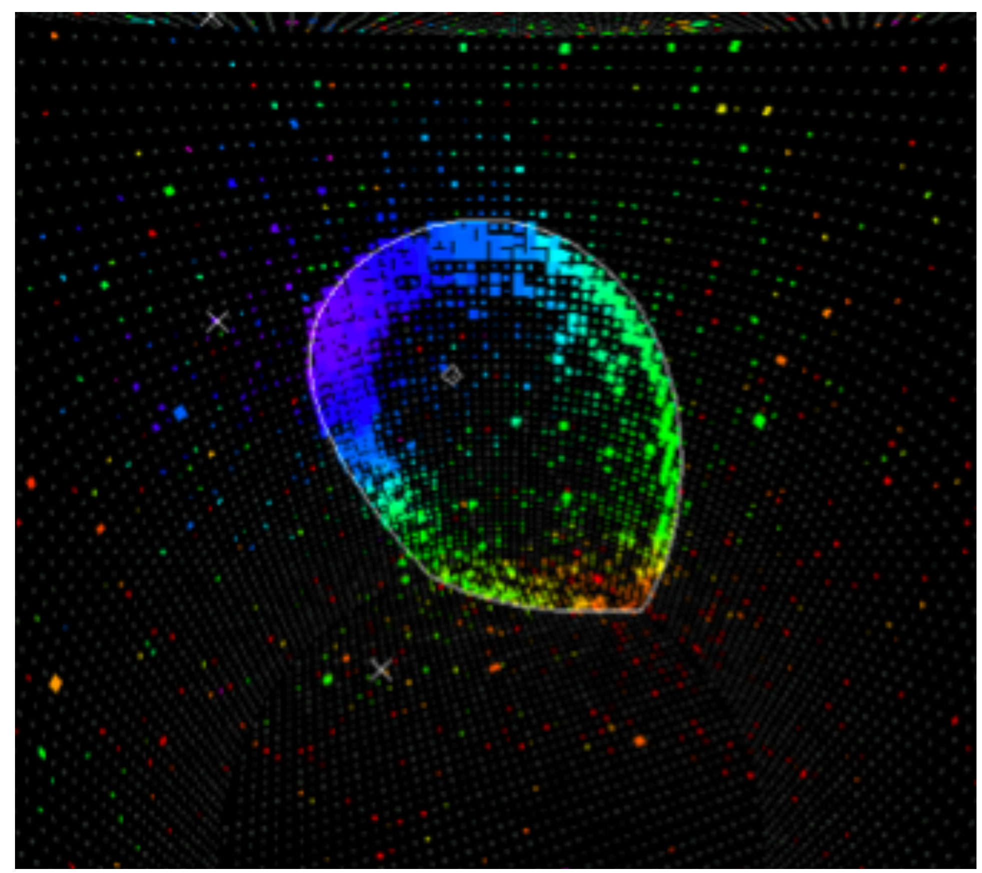
https://inspirehep.net/record/1332512/plots

Neutrino Oscillations - SuperK

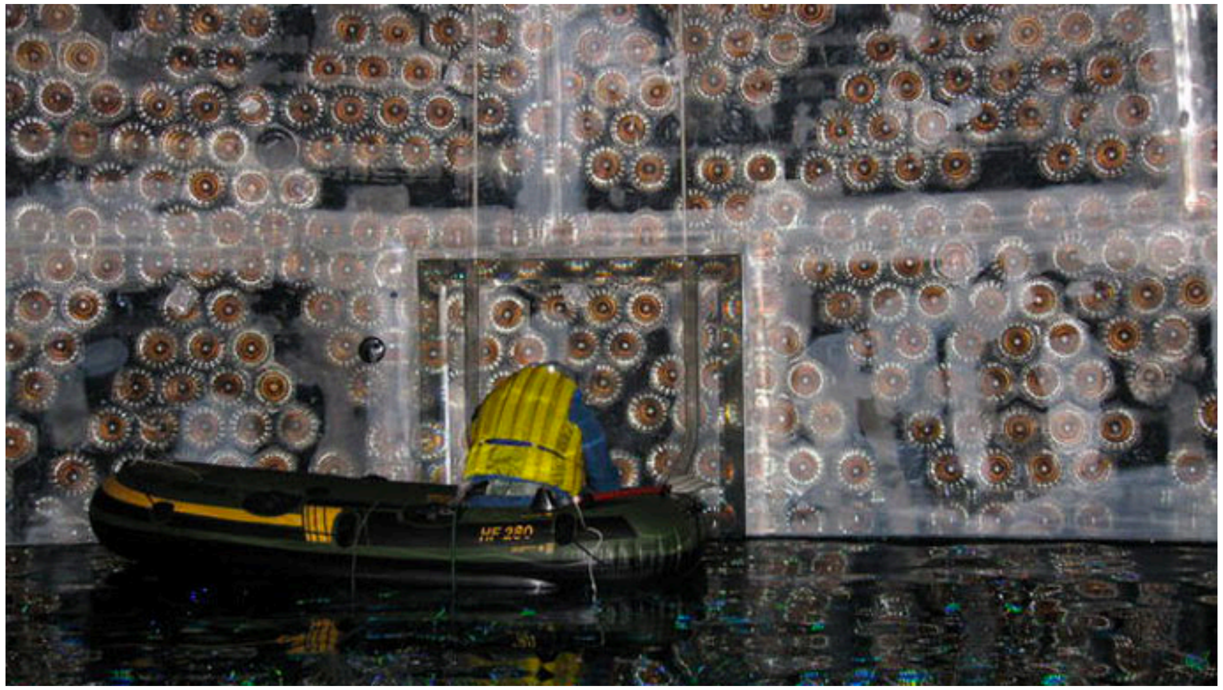


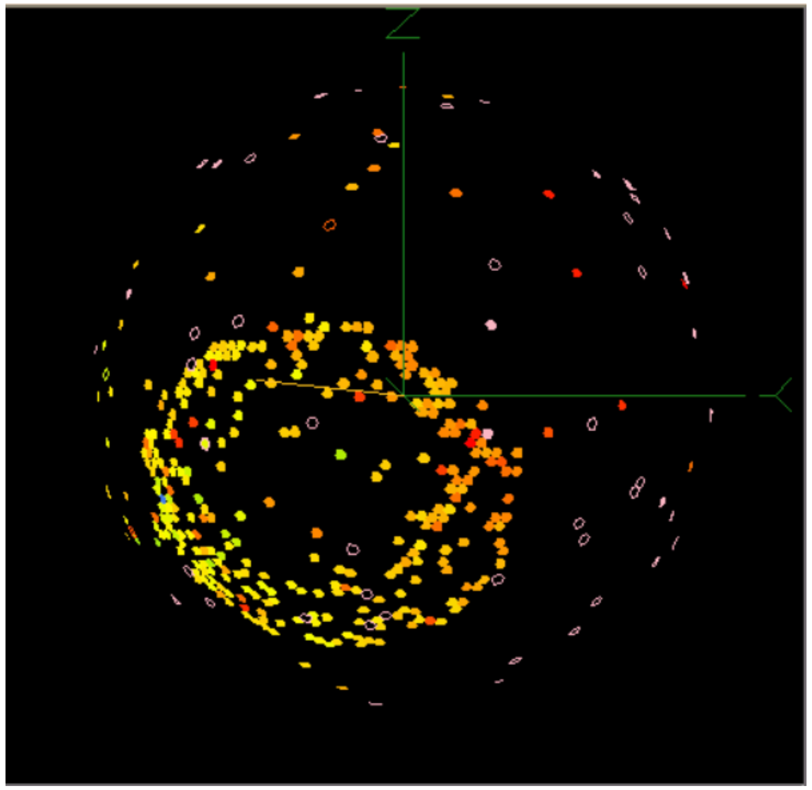


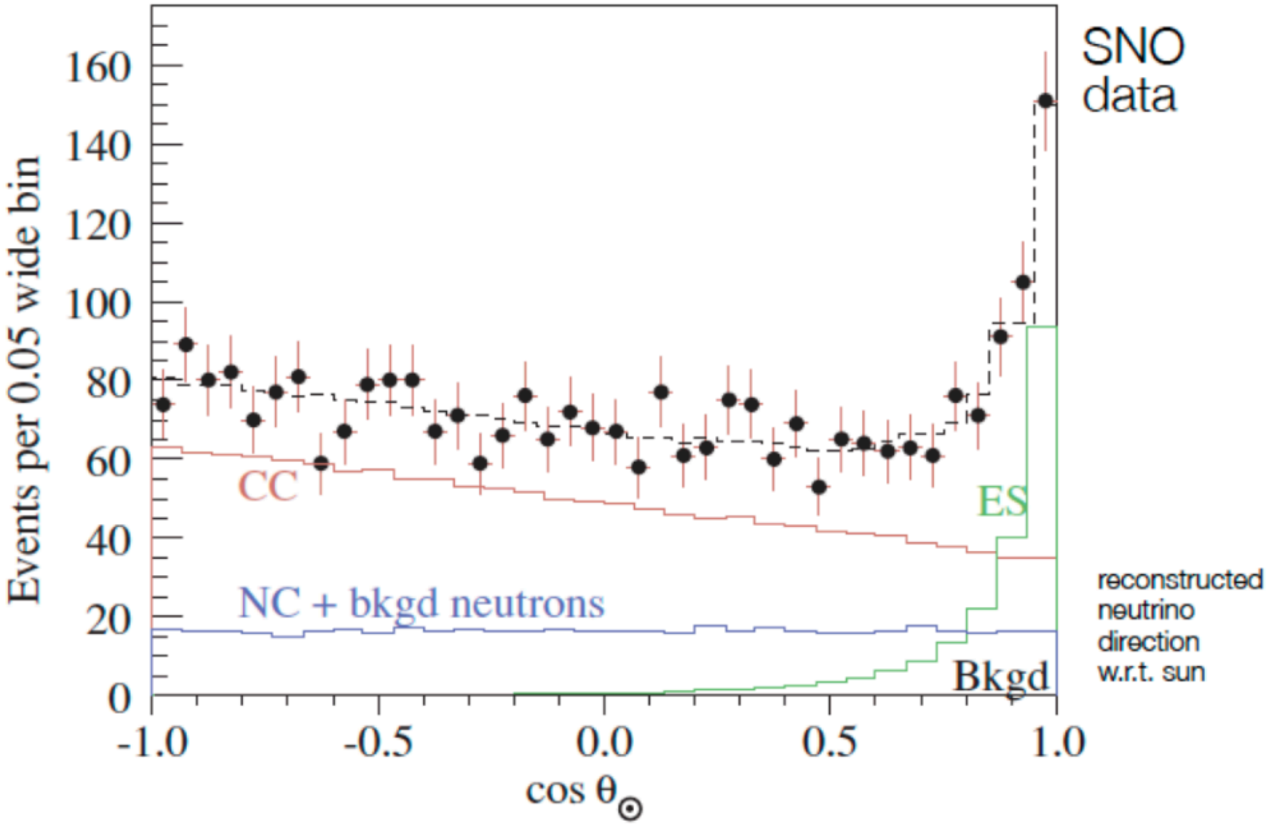


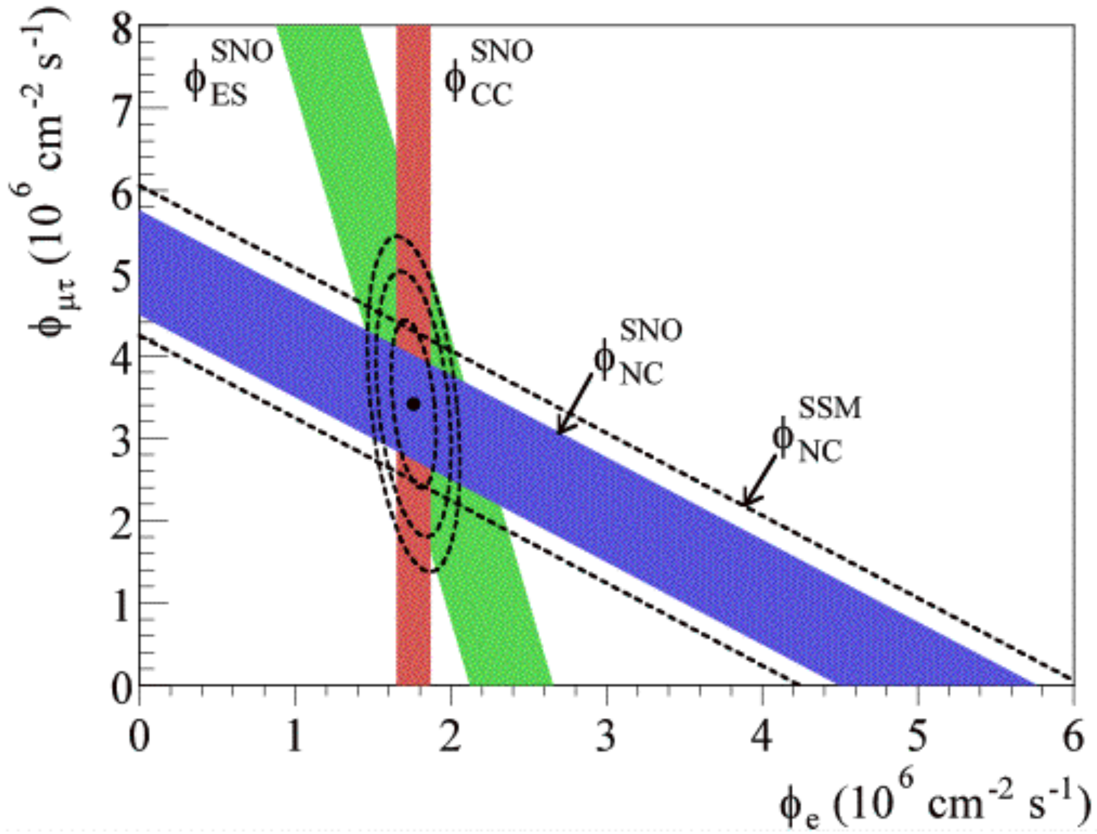


Neutrino Oscillations - SNO

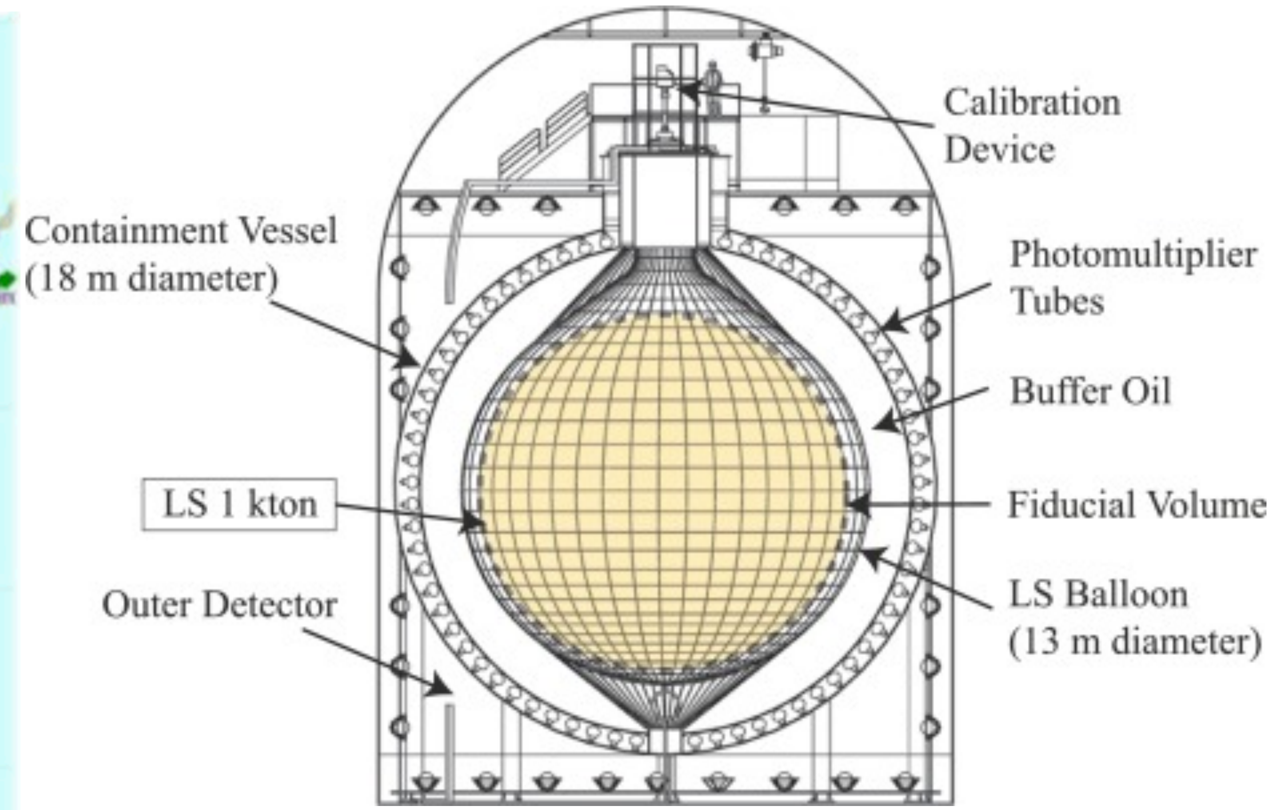


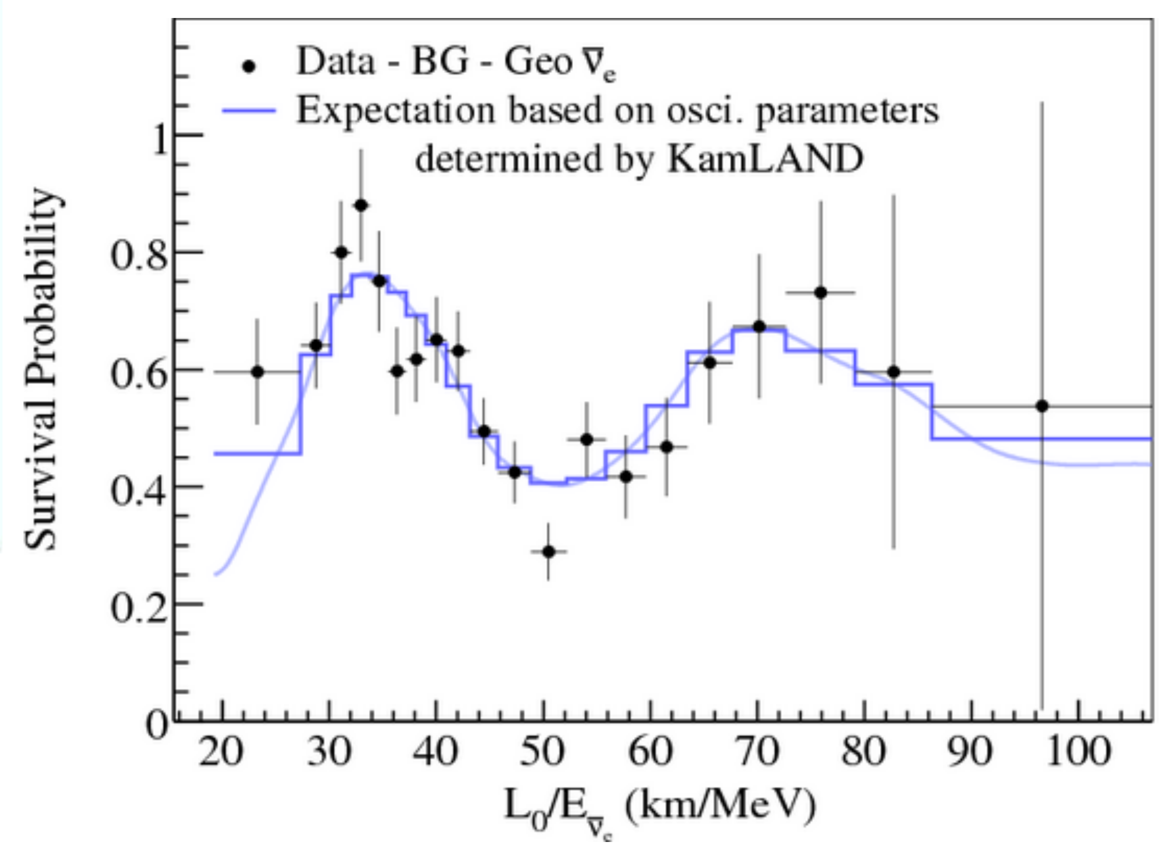






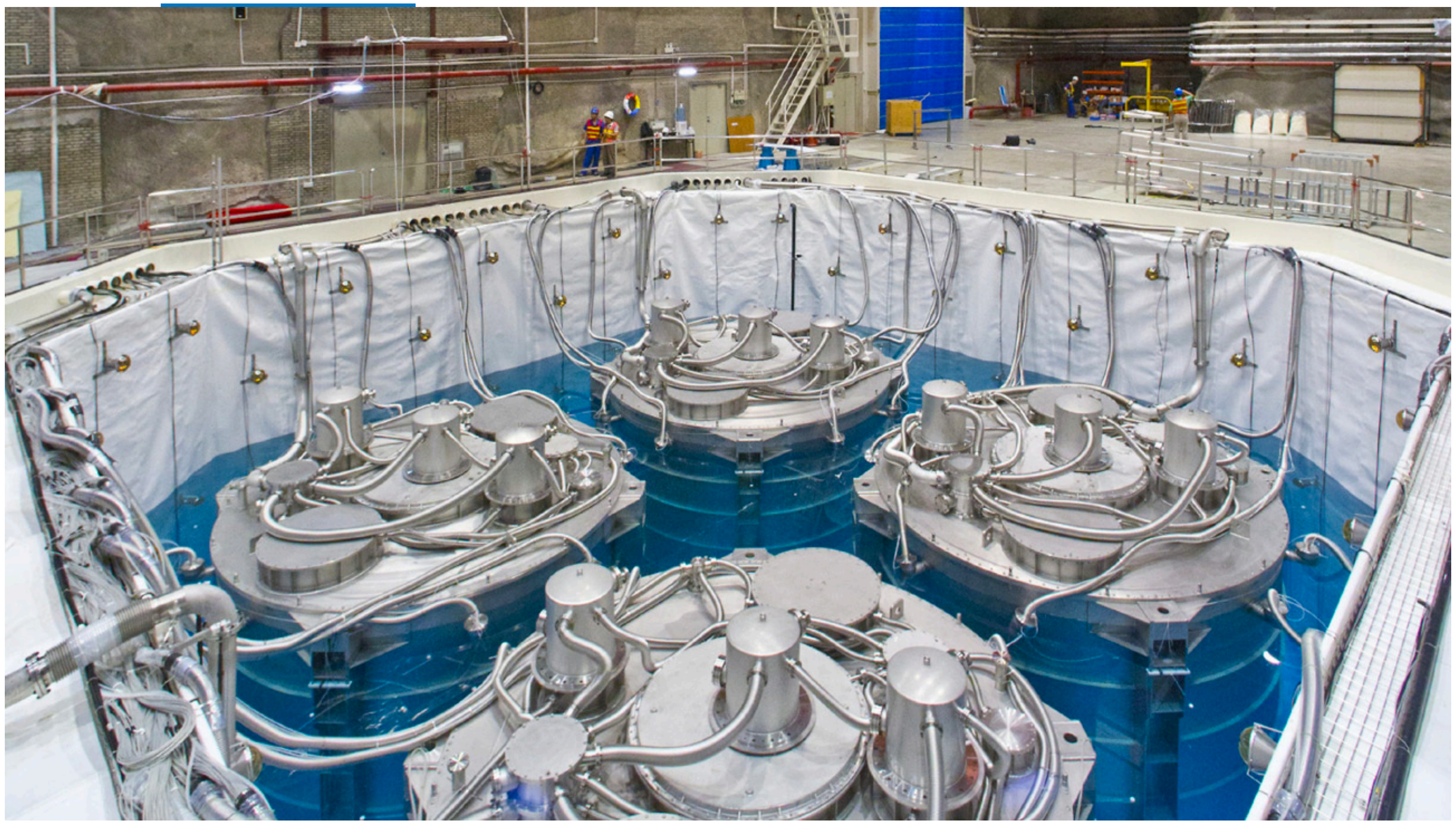
Neutrino Oscillations - KamLAND

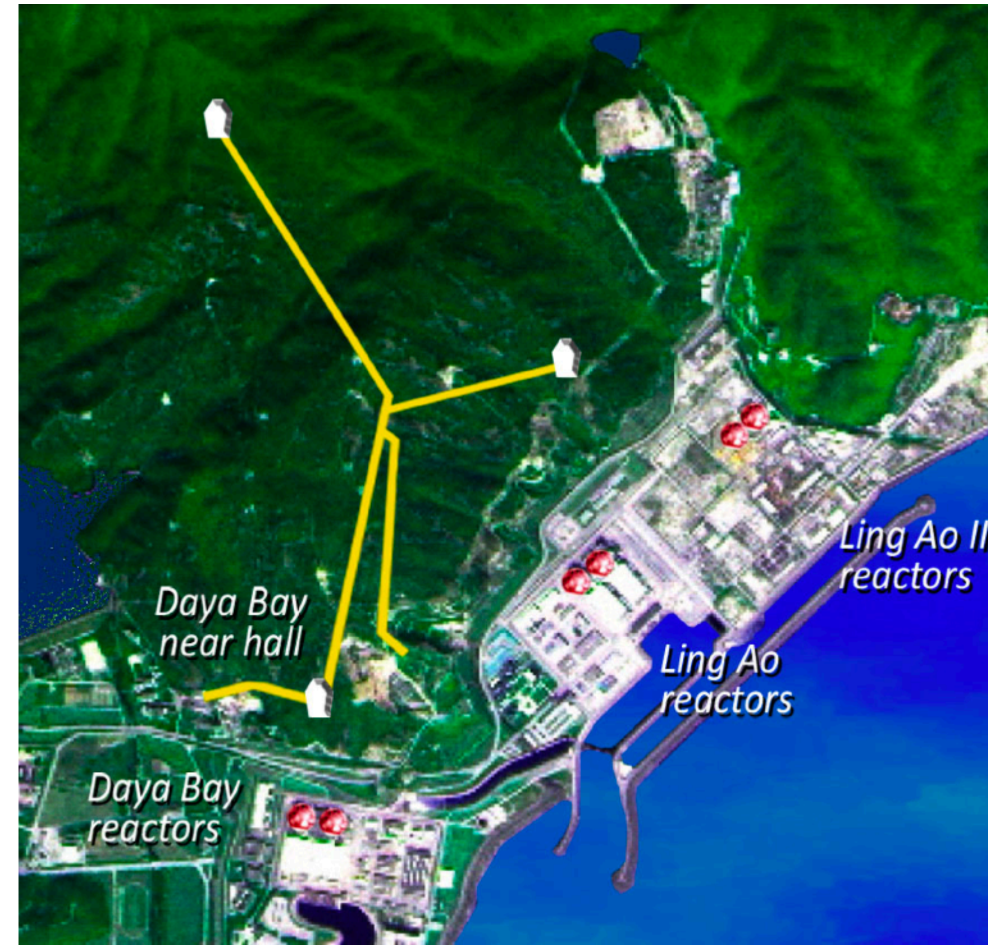


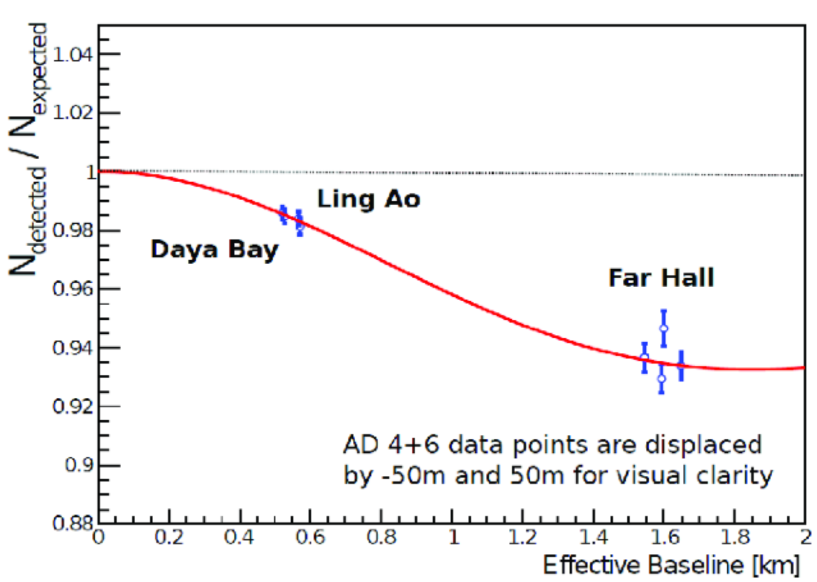


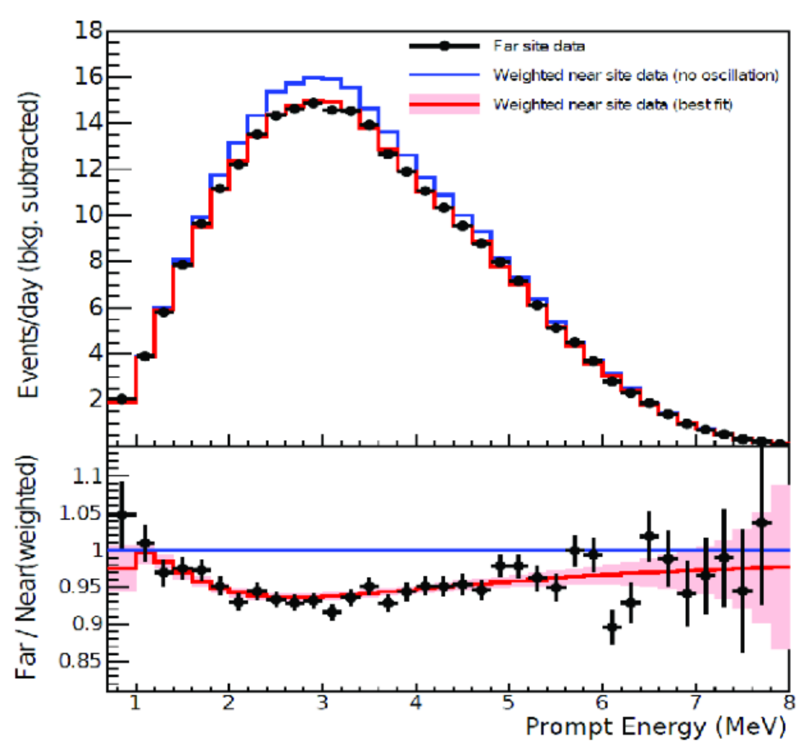
$$\bar{\nu}_e + p \to n + e^+$$

Neutrino Oscillations - Daya Bay









$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$e^+ + e^- \rightarrow \ \sim few\ MeV$$
$$n + Gd \rightarrow \ \sim 8\ MeV$$

Oscillations

$|\nu_\alpha\rangle$ is a neutrino with definite flavor α = e, μ, τ

$|\nu_i\rangle$ is a neutrino with definite mass m_i, i = 1, 2, 3

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i}\,|\nu_\alpha\rangle$$

$$P_{\alpha\to\beta} = |\langle\nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

$$U_{\alpha i} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}$$

Atmospheric, Accelerator $\theta \sim 45°$

Reactor, Accelerator $\theta \sim 9°$

Solar, Reactor $\theta \sim 32°$

$0\nu\beta\beta$

What we DO know about neutrinos

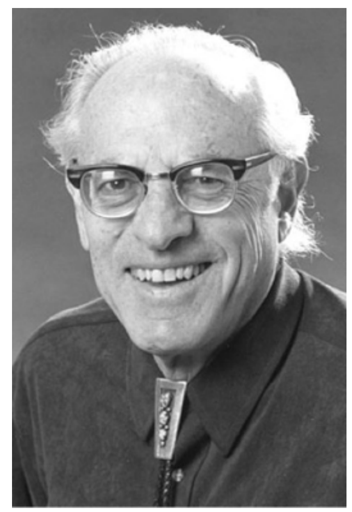
- Fermion: spin 1/2, electrically neutral
- Only experience the weak force, rarely interacting with anything
- They come in three flavors associated with three other fundamental particles (the electron, muon and tau)
- They change, or oscillate, from one type to another
- Most abundant massive particles in the universe, 340/cm^3

Neutrino Nobel Prizes:

1988

"neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino."

1995

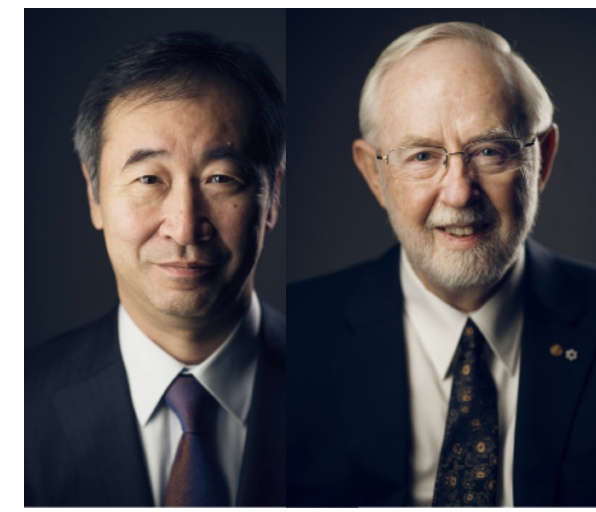


"detection of the neutrino."

2002

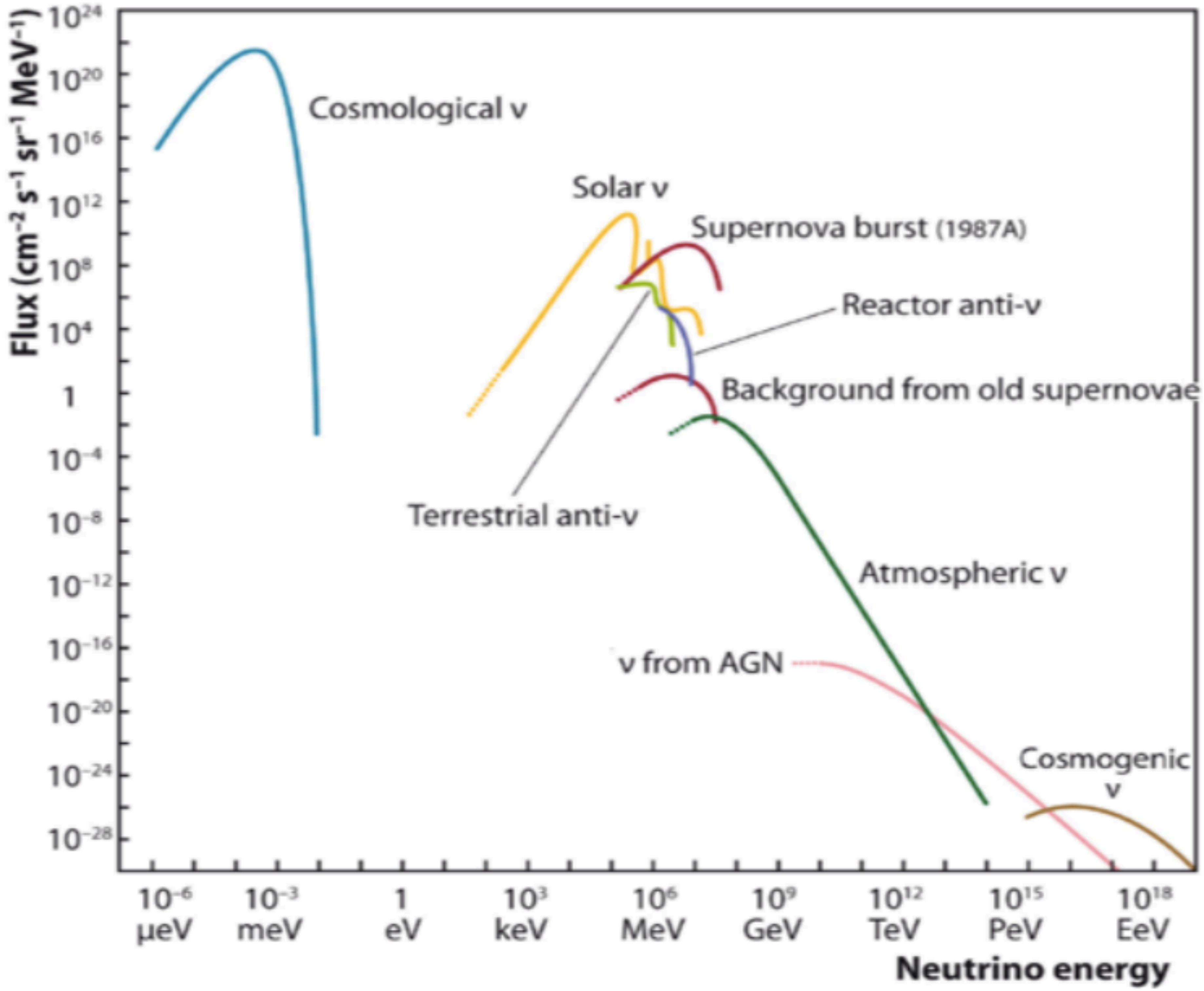
"pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."

2015



"discovery of neutrino oscillations, which shows that neutrinos have mass."

Neutrino Sources



What we still don't know!

- What is the absolute mass of the neutrino?
- Which neutrino is the heaviest?
- Are there more than three types of neutrinos?
- Do neutrinos and antineutrinos behave differently?
- What is the quantum nature of the neutrino – Dirac or Majorana?
- Is our picture of neutrinos correct?

References

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