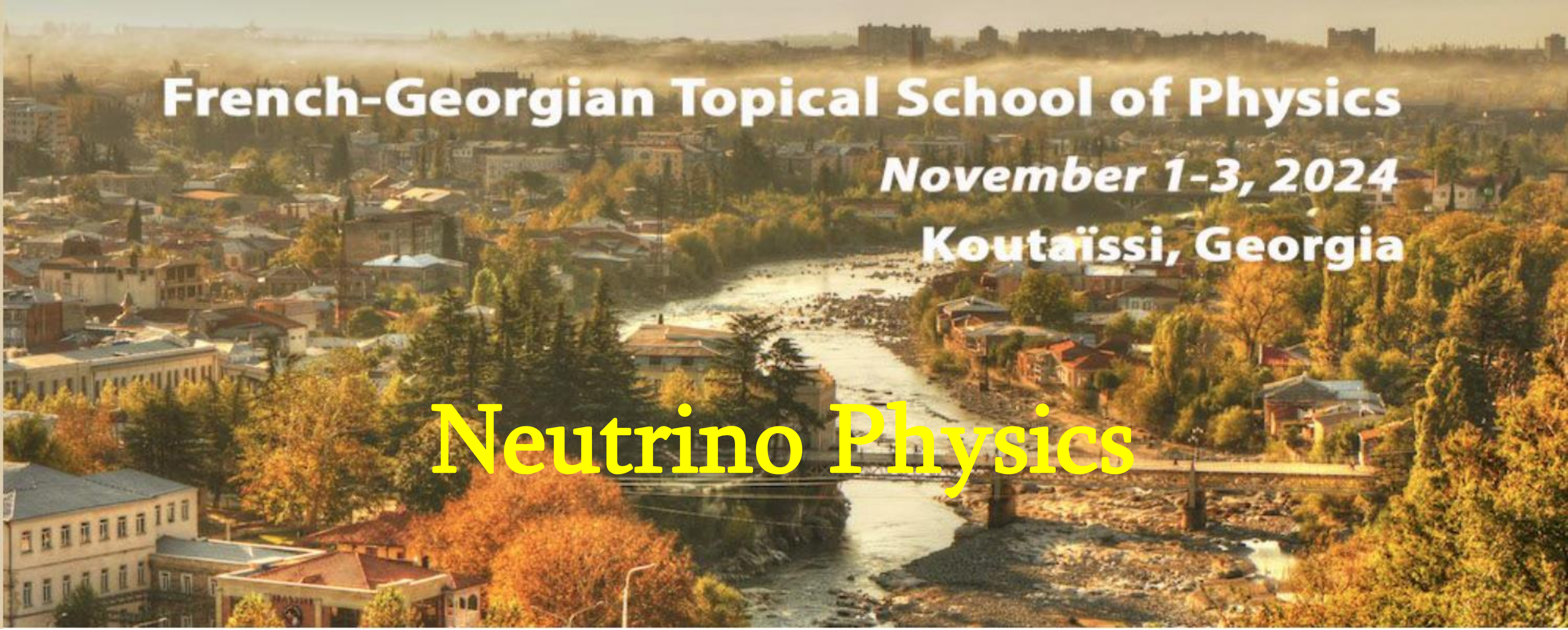
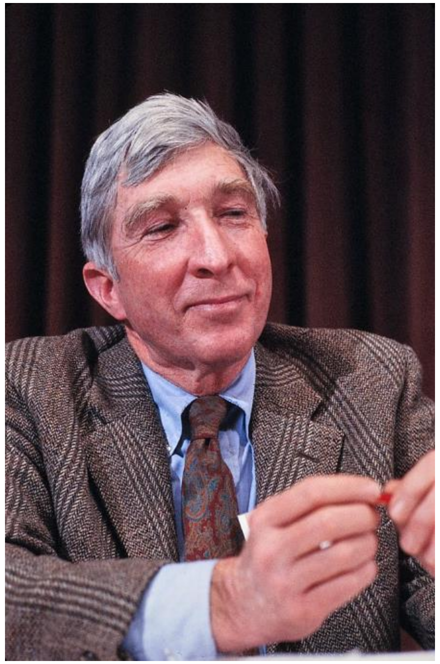


Neutrino Physics

Rezo Shanidze
Kutaisi International University
Tbilisi State University

"Neutrinos they are very small"



John Updike
1932-2009

Cosmic Gall

Neutrinos they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
. . .

http://holyjoe.org/poetry/updike.htm

Nobel Prises for Neutrino Research

1988: Leon M. Lederman, Melvin Schwartz, Jack Steinberger
"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

1995: Frederick Reines (1/2)
“for the detection of the neutrino”

2001: Raymond Davis Jr., Masatoshi Koshiba
“for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”

2015: Takaaki Kajita, Arthur B. McDonald
“for the discovery of neutrino oscillations, which shows that neutrinos have mass”

Content

- Introduction
  From Pauli and Fermi theory to discovery of neutrino.
  Neutrinos in the Standard Model

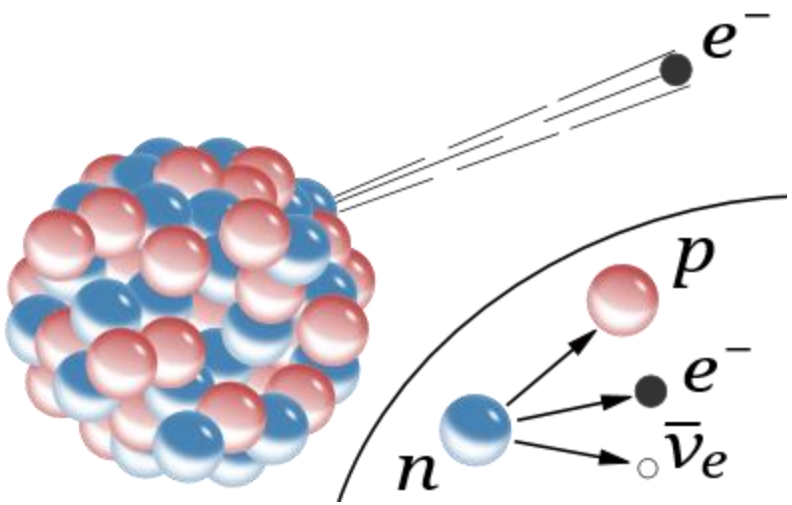
- Neutrino Oscillations
  Solar and atmospheric neutrino problem.
  Discovery of neutrino oscillations and consequences.

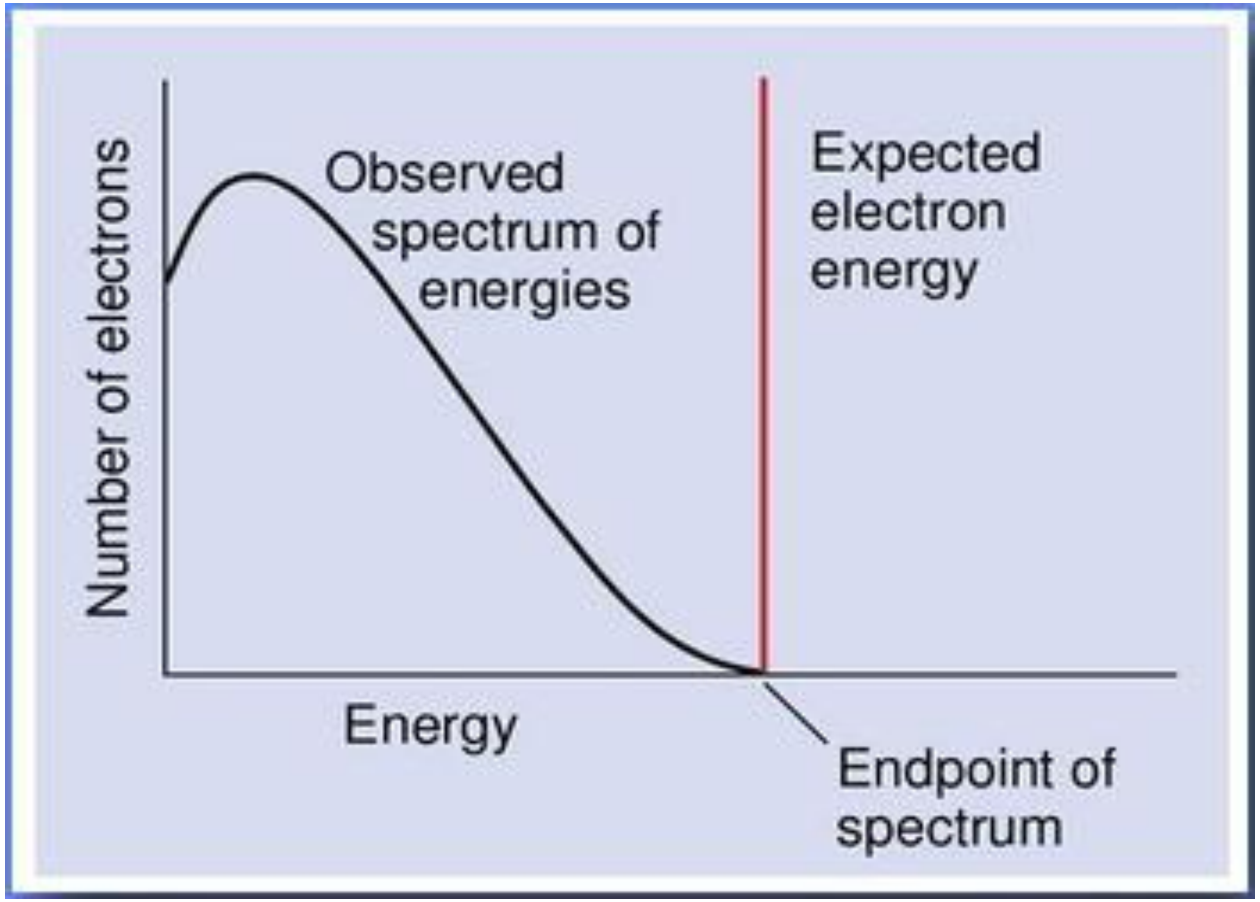
- Neutrino Astronomy/astrophysics
  Solar and Supernova neutrinos
  High Energy Neutrino Astronomy

Anomaly in β-Decay

Problems in β-decay: why electron energy in β-decay is continuous?

$\beta(1930)$: $(A,Z) \rightarrow e^- + (A,Z+1)$





Exercise:

$$p_o(m_o, 0) \rightarrow p_1(E_1,p) + p_2(E_2,-p)$$

Neutrino: "Birth Certificate" (4 December 1930)

Wolfgang Pauli
1900-1958

1945: "for the discovery of the Exclusion Principle, also called the Pauli Principle"

Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

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,

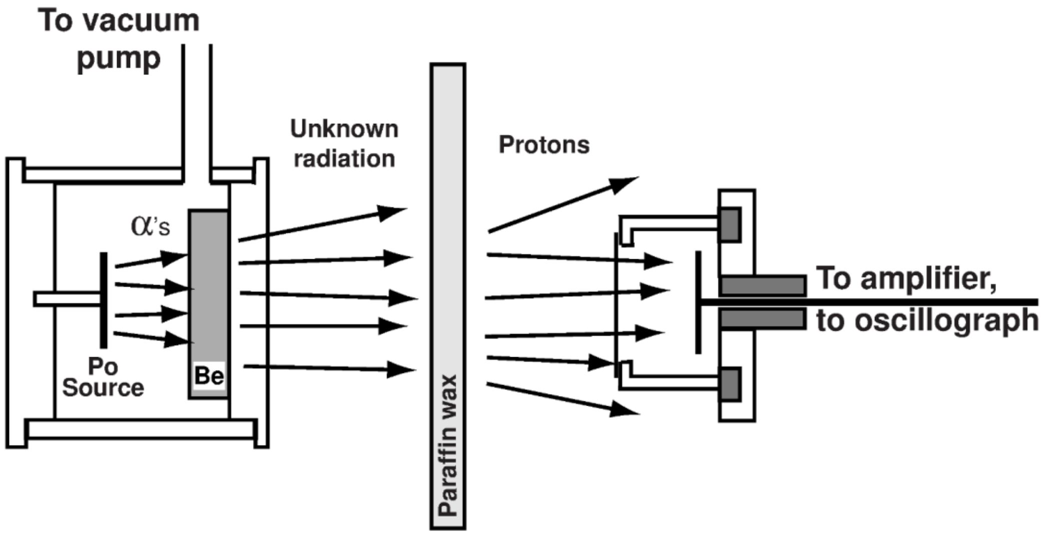
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik 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 Grössenordnung 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.

1932: Discovery Neutron and Positron

James Chadwick

(1891 – 1974)

α + 9Be   12C + n

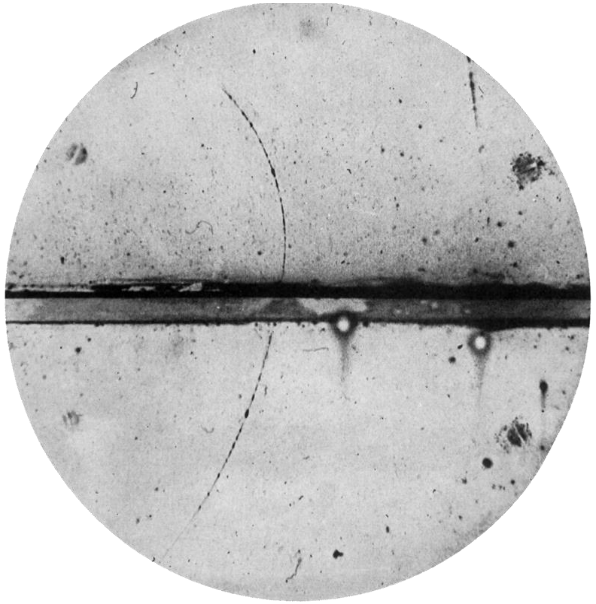


1935 For discovery of neutron

Carl Anderson

(1905 – 1981)

1936 For his discovery of positron



Fermi: Theory of β-decay

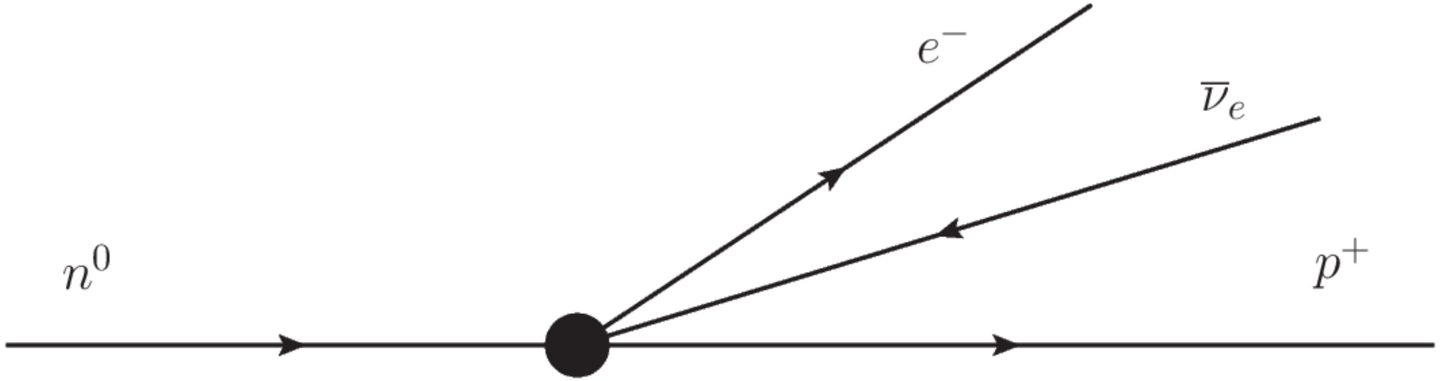
Enrico Fermi
1901-1954

1938: “for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons”

E. Fermi, Quantum Theory of Radiation,
Rev. Mod. Phys. 4(1932), 87 (published 1/01/1932)

E. Fermi. Tentativo di una Teoria Dei Raggi β,
Il Nuovo Cimento, vol. 11, issue 1, pp. 1-19

"Versuch einer Theorie der beta-Strahlen. I"
Zeitschrift für Physik, Volume 88, Issue 3-4, pp. 161-177



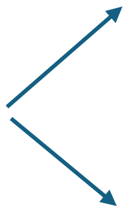
1934: Letters in Nature ("Neutrino")

Hans Bethe and Rudolf Peierls

1. The "Neutrino", Nature, 133(1934), 522
   April 7, 1934

"The possibility of creating neutrinos necessarily implies the existence of annihilation processes. "

Hans Bethe
1906-2005



$$\nu + (A,Z) \rightarrow e^- + (A,Z+1)$$

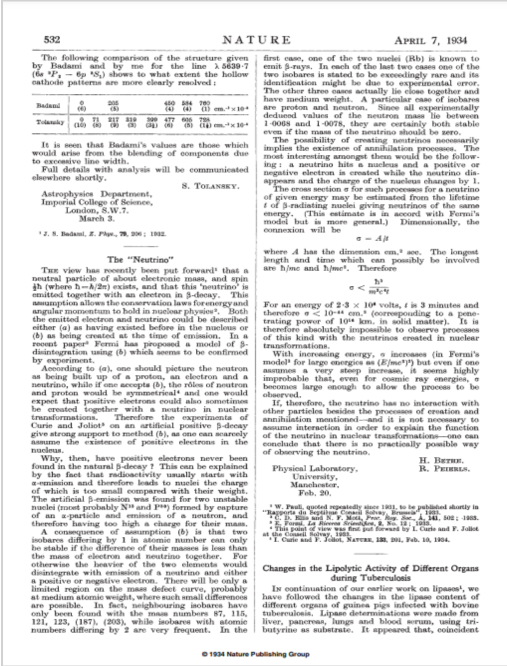
$$\nu + (A,Z) \rightarrow e^+ + (A,Z-1)$$

1967 "for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"

" .. one can conclude that there is no practically possible way of observing the neutrino."

$$\sigma < \frac{\hbar^3}{m^3 c^4 t}$$

10^{-44} cm^2 (10^{16} km)



532 NATURE APRIL 7, 1934

The following comparison of the structure given by Badami and by me for the line λ 5639·7 ($6s\ ^3P_2 - 6p\ ^3S_1$) shows to what extent the hollow cathode patterns are more clearly resolved:

Badami	0 (6)		205 (5)			450 (4)	584 (4)	760 (1)	cm.$^{-1}$ × 10^{-3}
Tolansky	0 (10)	71 (8)	217 (9)	319 (3)	399 (3½)	477 (6)	605 (5)	728 (1½)	cm.$^{-1}$ × 10^{-3}

It is seen that Badami's values are those which would arise from the blending of components due to excessive line width.

Full details with analysis will be communicated elsewhere shortly.

S. TOLANSKY.

Astrophysics Department,
Imperial College of Science,
London, S.W.7.
March 3.

[1] J. S. Badami, Z. Phys., 79, 206; 1932.

The "Neutrino"

THE view has recently been put forward[1] that a neutral particle of about electronic mass, and spin ½ħ (where ħ = h/2π) exists, and that this 'neutrino' is emitted together with an electron in β-decay. This assumption allows the conservation laws for energy and angular momentum to hold in nuclear physics[2]. Both the emitted electron and neutrino could be described either (a) as having existed before in the nucleus or (b) as being created at the time of emission. In a recent paper[3] Fermi has proposed a model of β-disintegration using (b) which seems to be confirmed by experiment.

According to (a), one should picture the neutron as being built up of a proton, an electron and a neutrino, while if one accepts (b), the rôles of neutron and proton would be symmetrical[4] and one would expect that positive electrons could also sometimes be created together with a neutrino in nuclear transformations. Therefore the experiments of Curie and Joliot[5] on an artificial positive β-decay give strong support to method (b), as one can scarcely assume the existence of positive electrons in the nucleus.

Why, then, have positive electrons never been found in the natural β-decay? This can be explained by the fact that radioactivity usually starts with α-emission and therefore leads to nuclei the charge of which is too small compared with their weight. The artificial β-emission was found for two unstable nuclei (most probably N^{13} and P^{30}) formed by capture of an α-particle and emission of a neutron, and therefore having too high a charge for their mass.

A consequence of assumption (b) is that two isobares differing by 1 in atomic number can only be stable if the difference of their masses is less than the mass of electron and neutrino together. For otherwise the heavier of the two elements would disintegrate with emission of a neutrino and either a positive or negative electron. There will be only a limited region on the mass defect curve, probably at medium atomic weight, where such small differences are possible. In fact, neighbouring isobares have only been found with the mass numbers 87, 115, 121, 123, (187), (203), while isobares with atomic numbers differing by 2 are very frequent. In the first case, one of the two nuclei (Rb) is known to emit β-rays. In each of the last two cases one of the two isobares is stated to be exceedingly rare and its identification might be due to experimental error. The other three cases actually lie close together and have medium weight. A particular case of isobares are proton and neutron. Since all experimentally deduced values of the neutron mass lie between 1·0068 and 1·0078, they are certainly both stable even if the mass of the neutrino should be zero.

The possibility of creating neutrinos necessarily implies the existence of annihilation processes. The most interesting amongst them would be the following: a neutrino hits a nucleus and a positive or negative electron is created while the neutrino disappears and the charge of the nucleus changes by 1.

The cross section σ for such processes for a neutrino of given energy may be estimated from the lifetime t of β-radiating nuclei giving neutrinos of the same energy. (This estimate is in accord with Fermi's model but is more general.) Dimensionally, the connexion will be

$$\sigma = A/t$$

where A has the dimension cm.^{2} sec. The longest length and time which can possibly be involved are $\hbar/mc$ and $\hbar/mc^2$. Therefore

$$\sigma < \frac{\hbar^3}{m^3 c^4 t}$$

For an energy of $2{\cdot}3 \times 10^6$ volts, t is 3 minutes and therefore $\sigma < 10^{-44}$ cm.^{2} (corresponding to a penetrating power of 10^{16} km. in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.

With increasing energy, σ increases (in Fermi's model[3] for large energies as $(E/mc^2)^2$) but even if one assumes a very steep increase, it seems highly improbable that, even for cosmic ray energies, σ becomes large enough to allow the process to be observed.

If, therefore, the neutrino has no interaction with other particles besides the processes of creation and annihilation mentioned—and it is not necessary to assume interaction in order to explain the function of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

H. BETHE.
R. PEIERLS.

Physical Laboratory,
University,
Manchester.
Feb. 20.

[1] W. Pauli, quoted repeatedly since 1931, to be published shortly in "Rapports du Septième Conseil Solvay, Brussels", 1933.
[2] C. D. Ellis and N. F. Mott, Proc. Roy. Soc., A, 141, 502; 1933.
[3] E. Fermi, La Ricerca Scientifica, 2, No. 12; 1933.
[4] This point of view was first put forward by I. Curie and F. Joliot at the Conseil Solvay, 1933.
[5] I. Curie and F. Joliot, NATURE, 133, 201, Feb. 10, 1934.

Changes in the Lipolytic Activity of Different Organs during Tuberculosis

IN continuation of our earlier work on lipases[1], we have followed the changes in the lipase content of different organs of guinea pigs infected with bovine tuberculosis. Lipase determinations were made from liver, pancreas, lungs and blood serum, using tributyrine as substrate. It appeared that, coincident

How to Detect Neutrino

Bruno Pontecorvo
(1913-1993)

Radio-chemical method (B. Pontecorvo)

$$\nu + (A,Z) \rightarrow e^- + (A,Z+1)$$

Cl-Ar method:

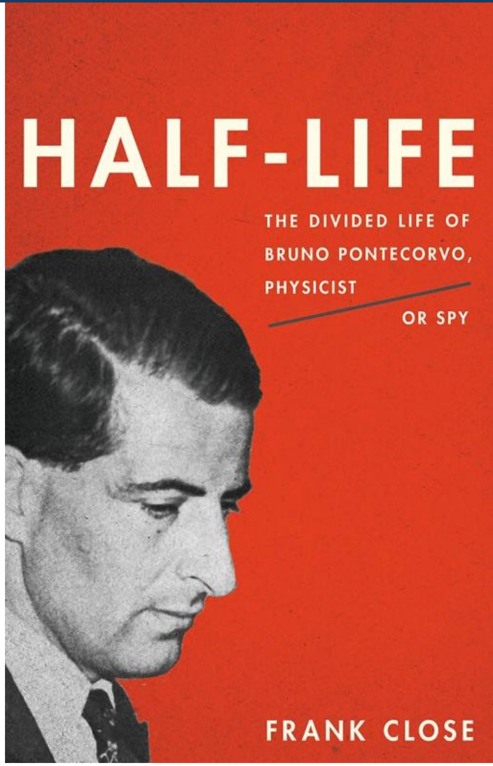
$$\nu + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

Stable isotopes of Clorine: ${}^{35}Cl$ (76%), ${}^{37}Cl$(24%)

Neutrino energy $E_\nu > 0.814$ MeV

${}^{37}Ar$ half-life: 35 days (decay mode: EC)

$$\nu + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$



How to Detect Neutrino: Inverse beta Decay

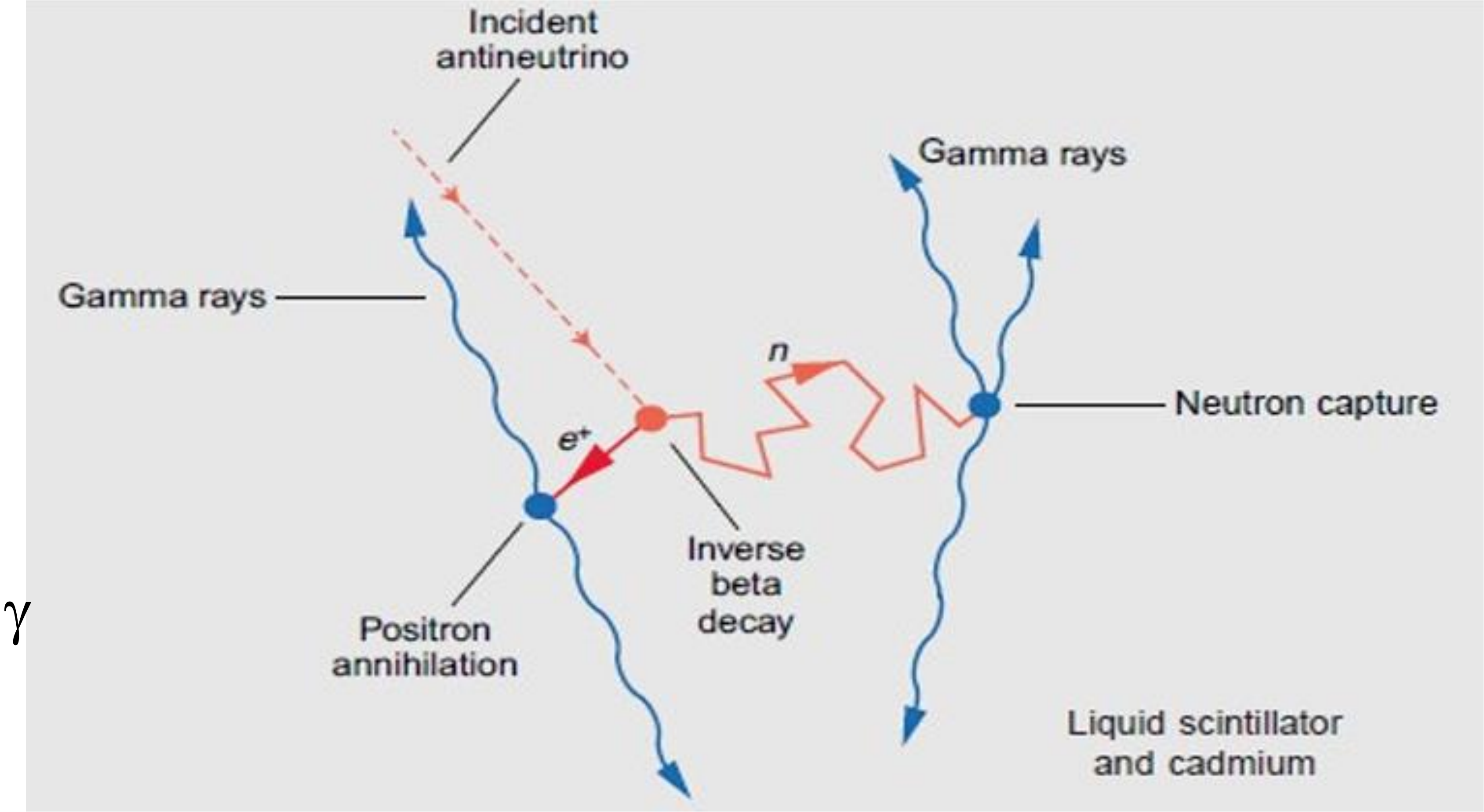
Inverse beta decay

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

$$e^{+} + e^{-} \rightarrow \gamma + \gamma$$

Neutron capture reaction:

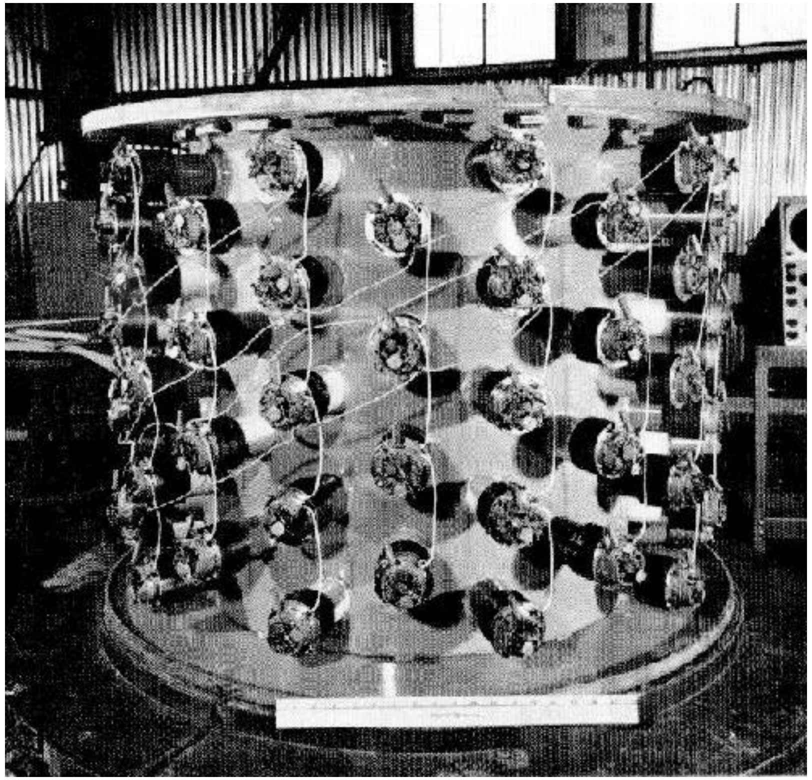
$$n + Cd \rightarrow Cd^{*} \rightarrow Cd + \gamma$$



Project "Poltergeist"

Cowan and Reines experiments for neutrino detection (1951-1956)

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



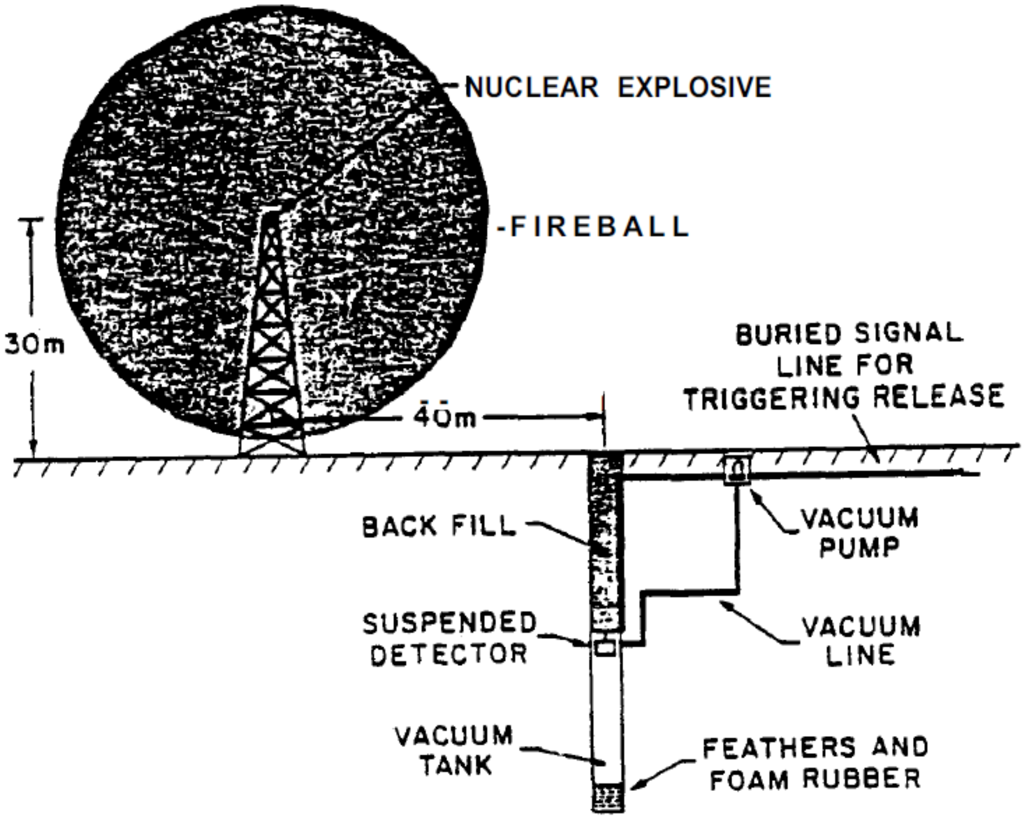
Liquid scintillator detector with 90 PMTs.

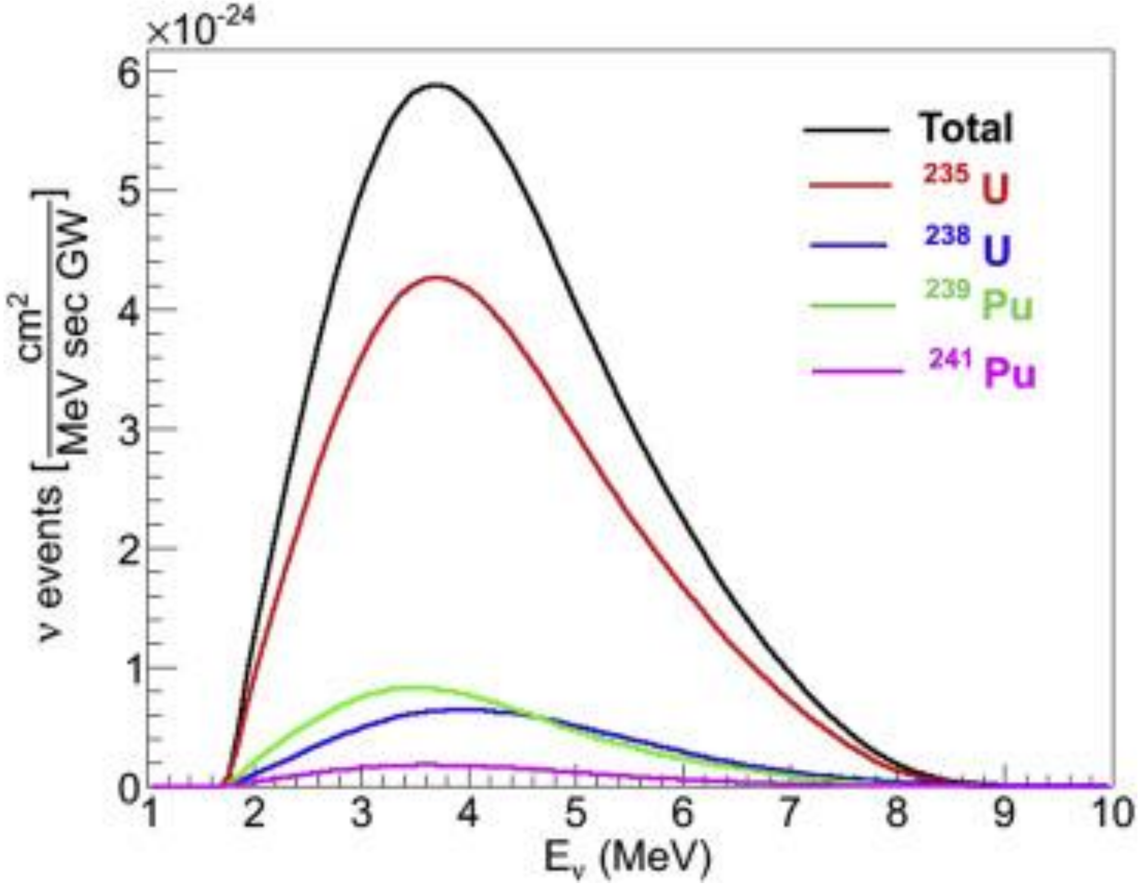
Considered sources of neutrinos:

a) Nuclear bomb explosion (20kt)

b) Nuclear reactor flux (about 10^{-13} cm^{-2} s^{-1})

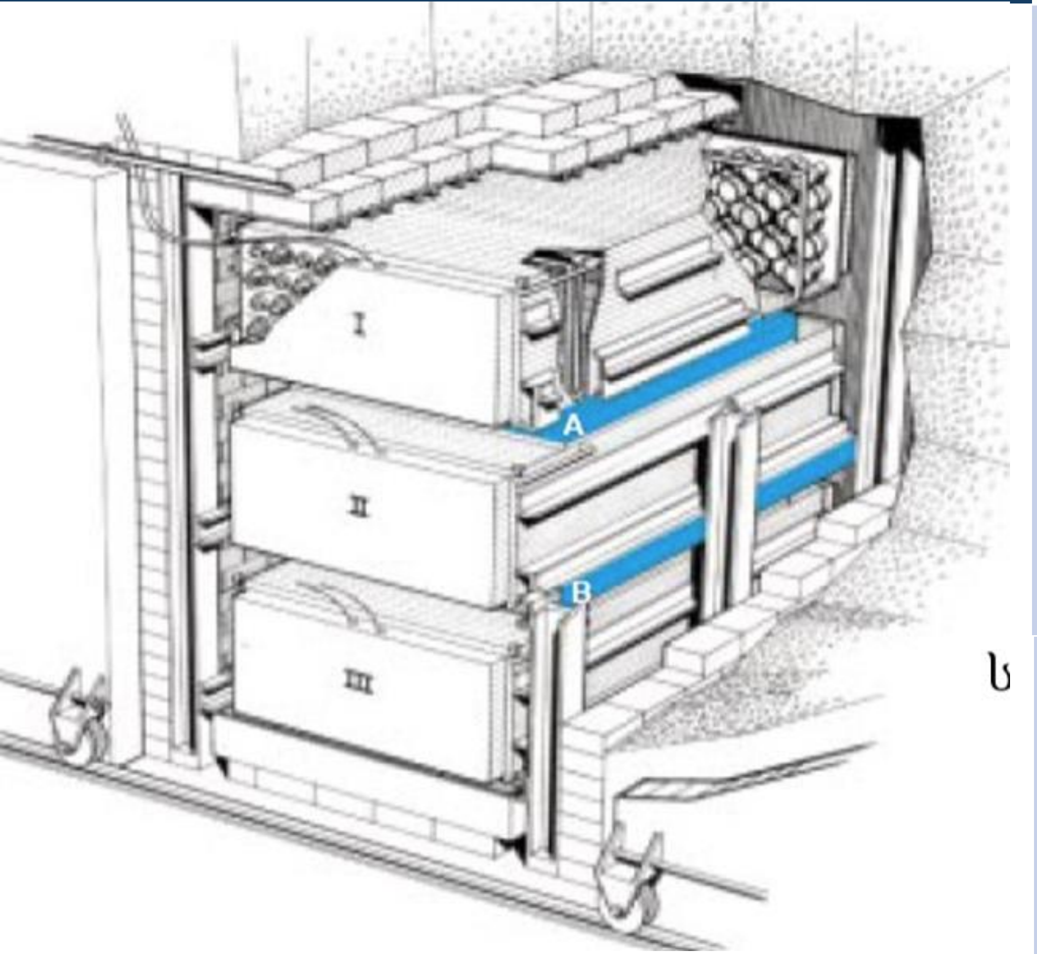
1945-1960: Neutrino Fluxes for Neutrino Detection



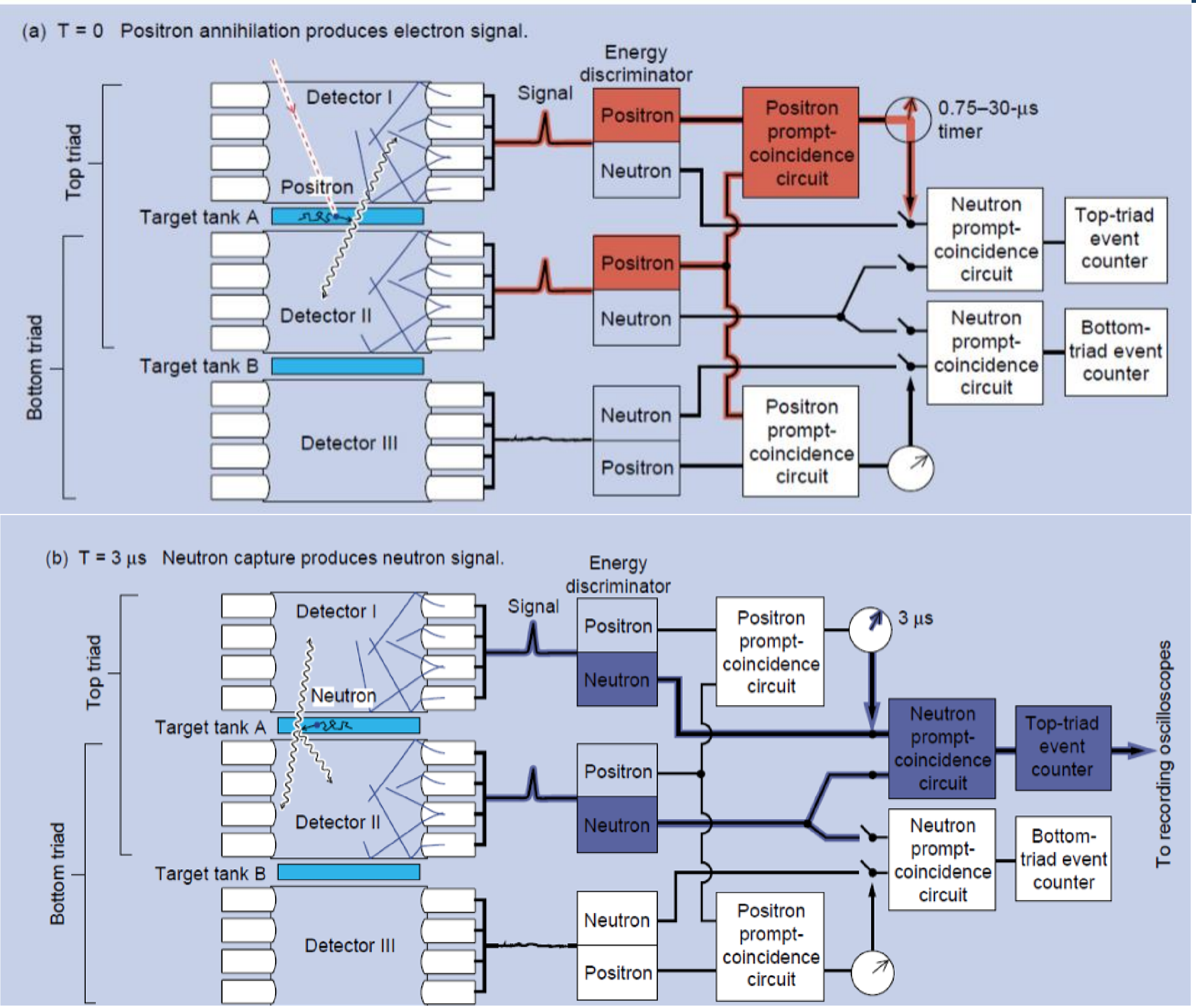


proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved but was superceded by the approach which used a fission reactor.

Detection of Neutrino



The Savannah River Experiment



Detection of Neutrino

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

SB71311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

"VIA RADIOSUISSE"

NEWYORK

Briefltelegramm

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

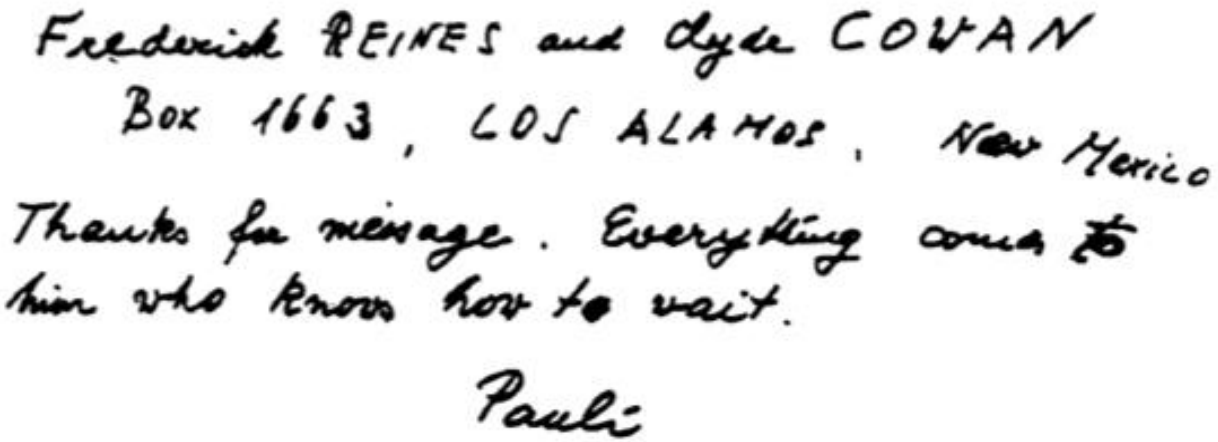
BOX 1663 LOS ALAMOS NEW MEXICO

Telegram set on June 14, 1954 by Cowen and Reines to Wolfgang Pauli

Neutrino flux: 2 x 10^{13} $cm^{-2}s^{-1}$

200 L H_2O + 40 kg $CdCl_2$

3.0 ± 0.2 events/hour



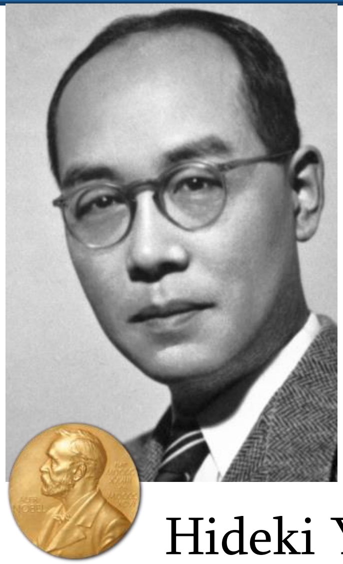
Frederick REINES and Clyde COWAN

Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

Pions, Muon and Muon Neutrino



Hideki Yukawa
1949 1907-1981

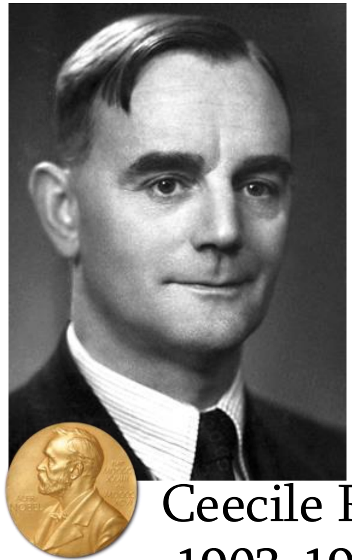
Meson (or π-meson) was introduced by Hideki Yukawa 1939 □

$\pi^+ \longrightarrow \mu^+ + \nu_\mu$ □

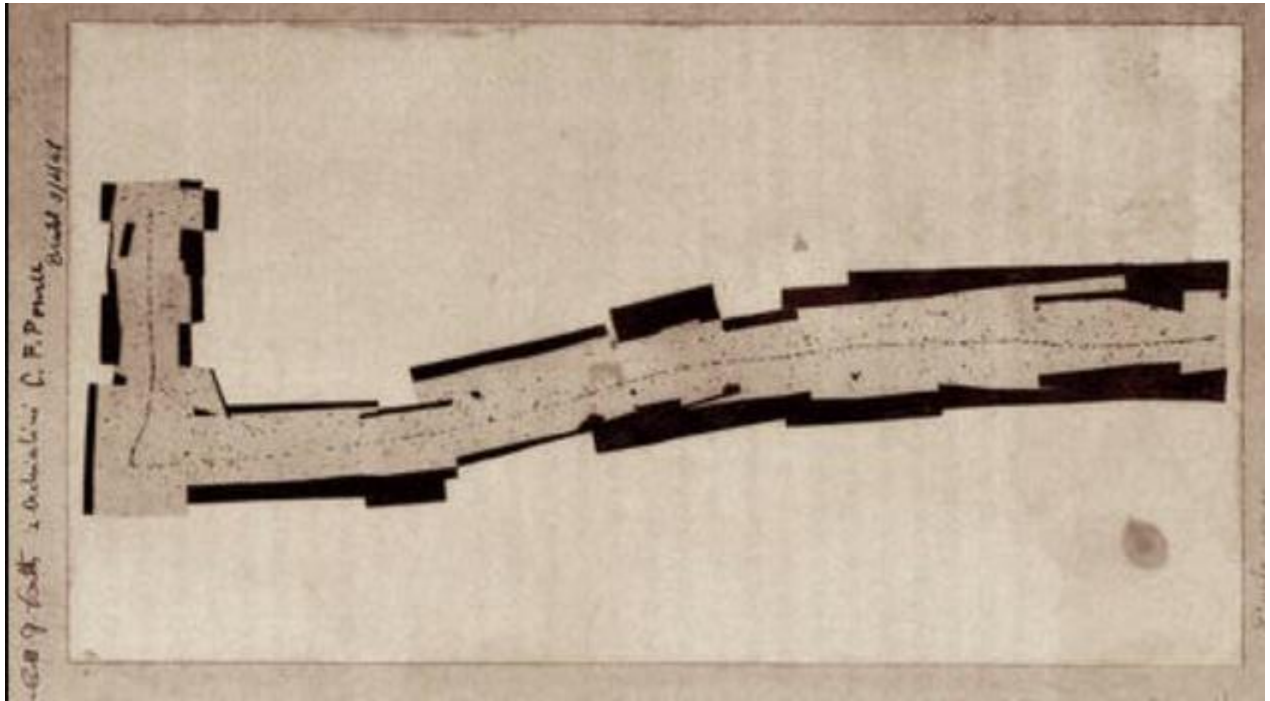
❖ Lightest hadrons, with isospin 1: π^+, π^o, π^-

$\mu^+ \longrightarrow e^+ + \nu + \nu$ □

Discovered by
Ceccile Pawell □



Ceecile Powell
1947 1903-1969



Two Types of Neutrinos

Neutrino physics at proton accelerators:

Secondary beams of selected particles: – including neutrino beams.

$p + A \longrightarrow \pi^+/\pi^- + X$ $\pi^+ \longrightarrow \mu^+ + \nu_\mu$ $\nu_e = \nu_\mu$□ ?

First neutrino beam at particle accelerator:

$\nu_\mu + A \longrightarrow \mu^- + X$

Alternating Gradient Synchrotron (1960-present)

$\nu_e + A \longrightarrow e^- + X$

Accelerator Neutrinos and Discovery of Muon Neutrino

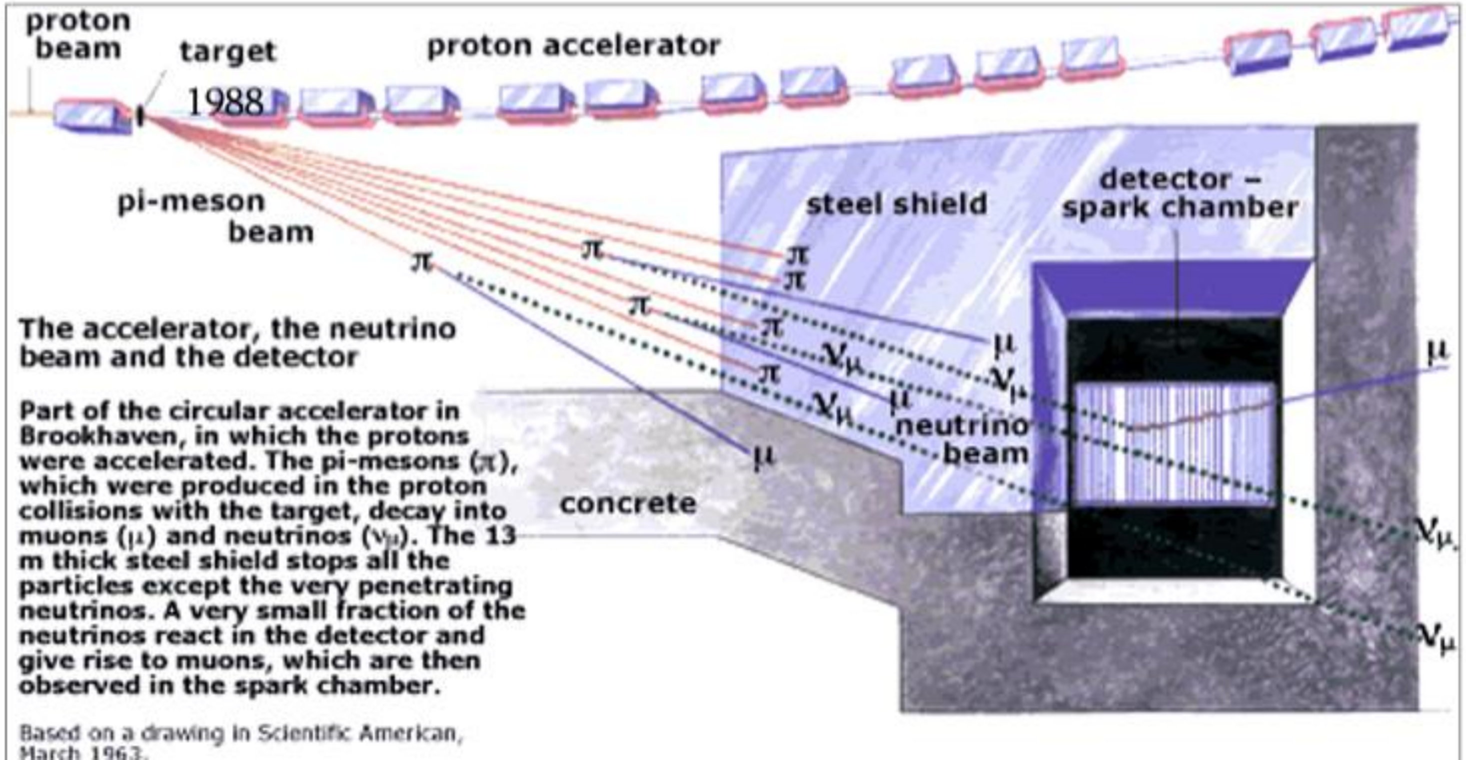
L. M. Lederman (1922-2018), M. Schwartz (1932-2006) ,
J. Steinberger (1921)

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

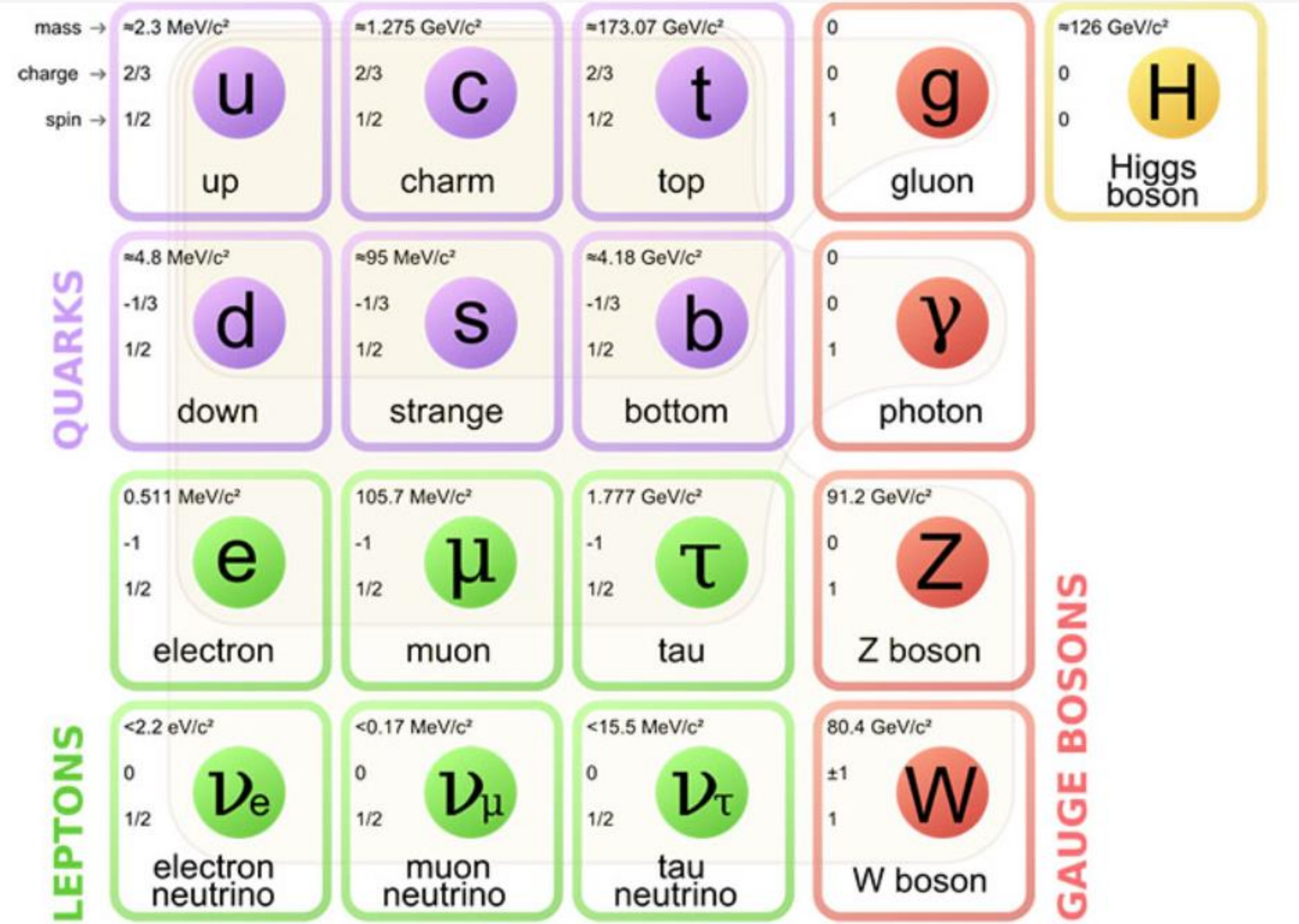
$p + Be \rightarrow \pi + X$ $\quad \pi \rightarrow \mu + \nu_\mu$

$E_p = 15$ GeV $\quad \nu_\mu + A \rightarrow \mu + X$

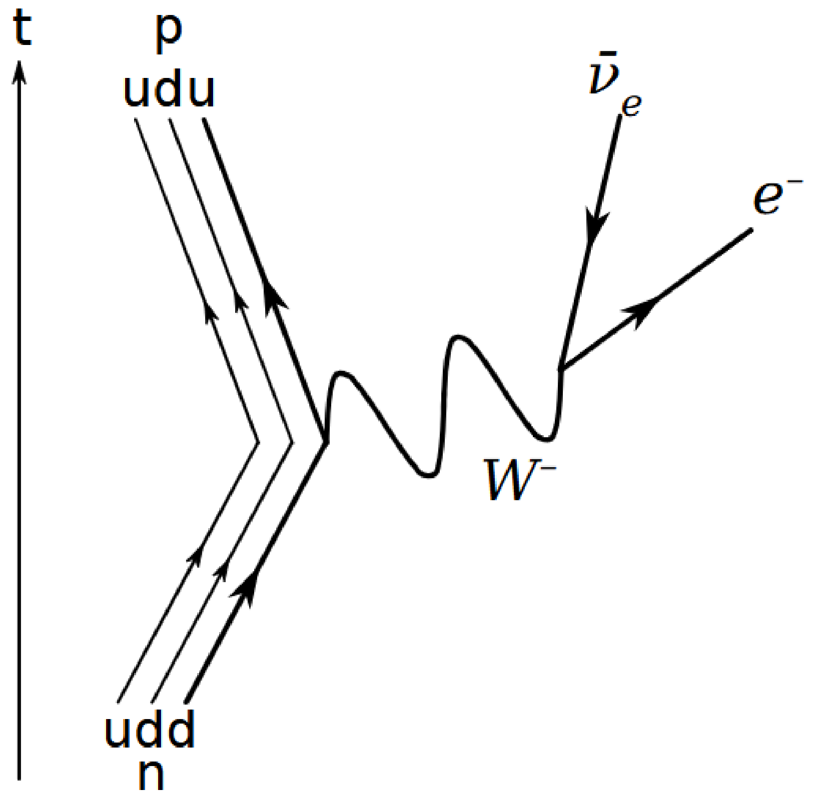


Standard Model of Particle Physics

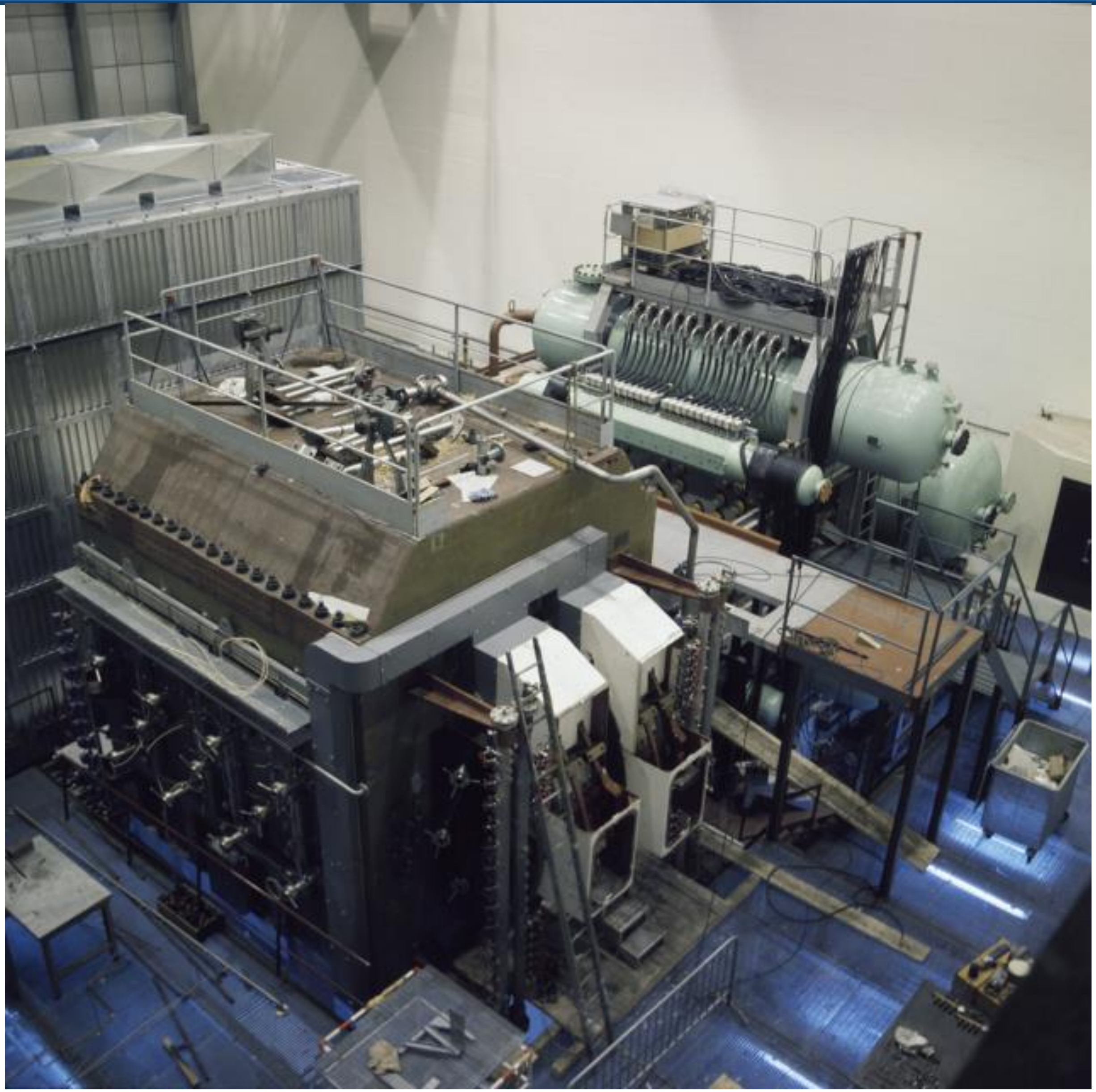
Steven Weinberger, "Model of Leptons", Phys. Rev. Lett 19 (1987) 1264



Gauge bosons of weak interaction: W and Z

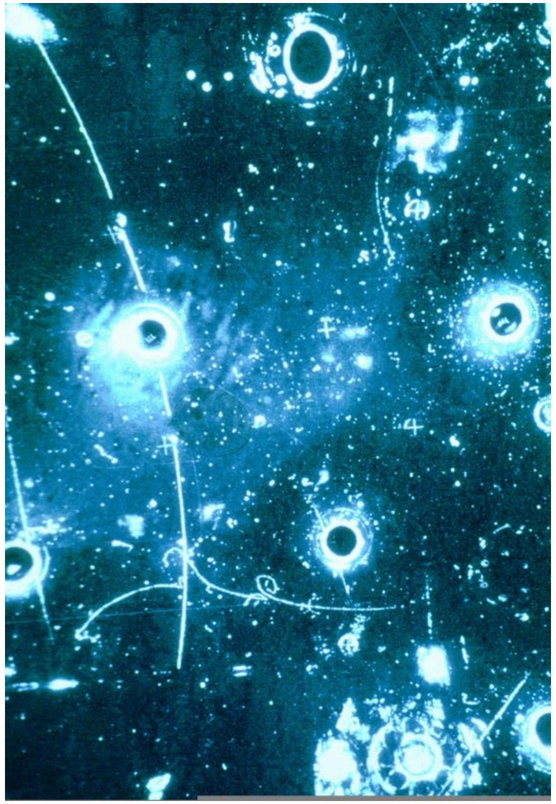


Gargamelle Experiment at CERN

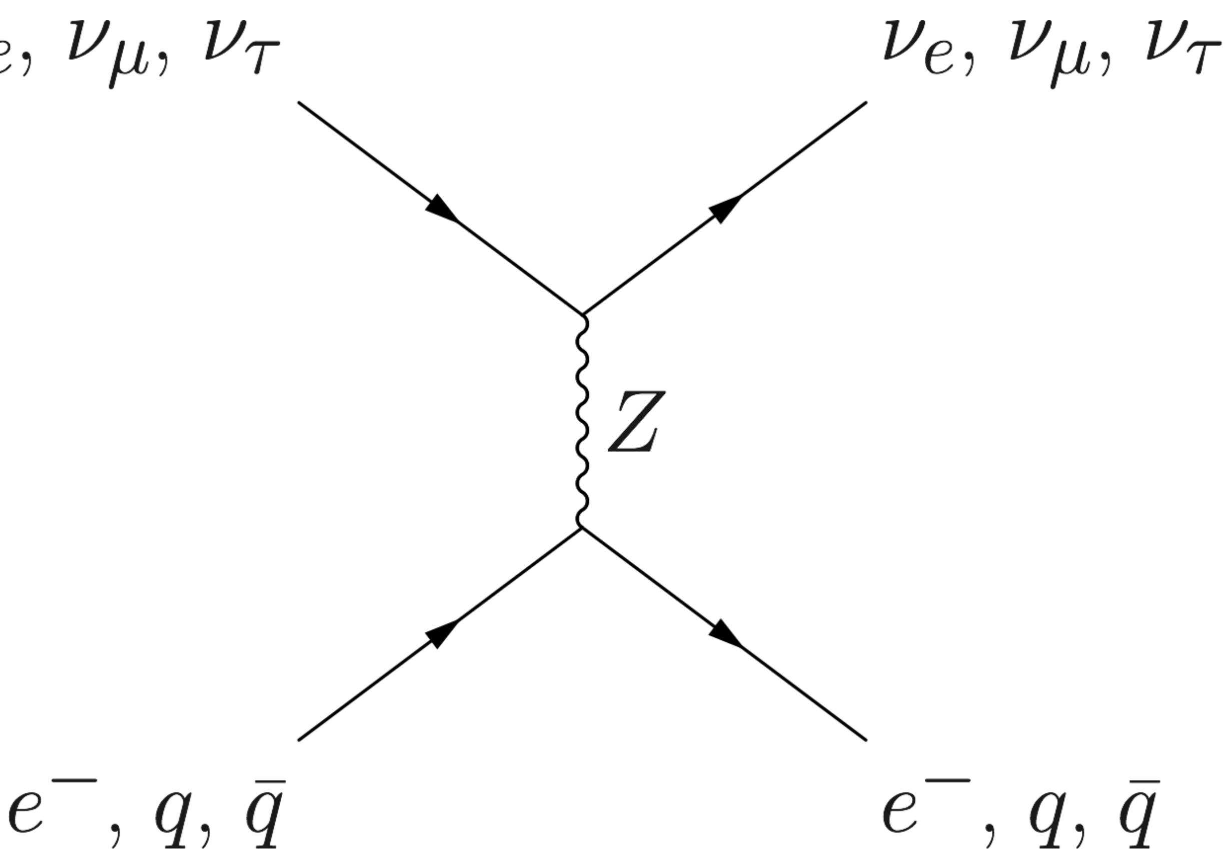


Gargamelle – bubble chamber

4.8 m long and 2 m in diameter, filled with 12 m^3 of heavy liquid Freon. Operated in a 2 Tesla field.



Discovery of Neutral Currents

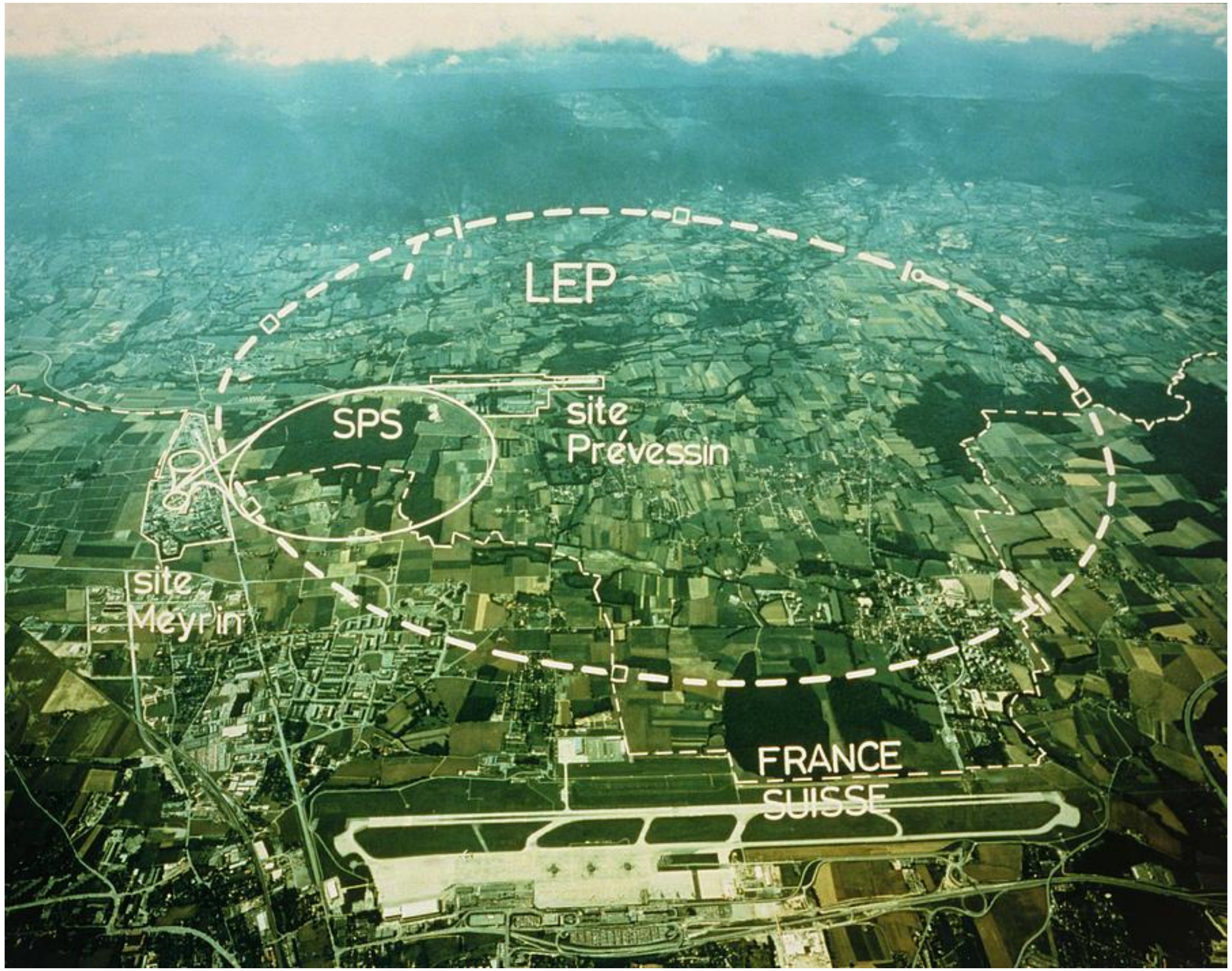


F.J Hasert et al., Search for elastic muon-neutrino electron scattering
Phys. Lett. 46 (1973) 121

F.J Hasert et al., Observation of neutrino-like interactions without muon or electron in the gargamelle neutrino experiment
Phys. Lett. 46 (1973) 138

LEP – Collider to study the Standard Model

The Large Electron–Positron Collider (LEP)



1983–1988, the largest civil engineering project in Europe.

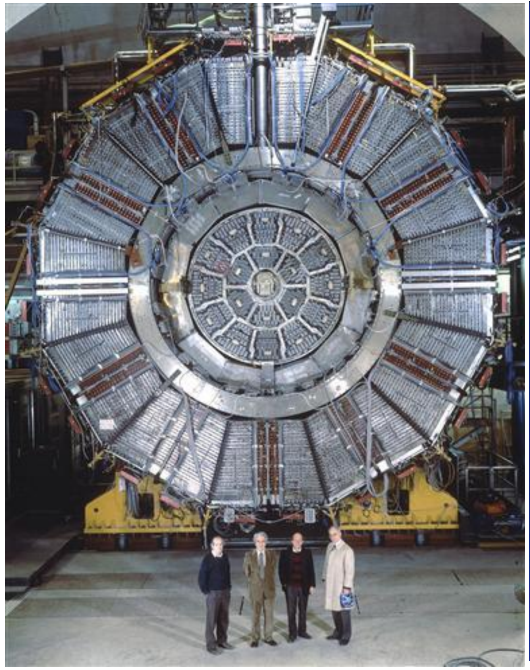
26659 m length tunnel for electron Positron beams

e+e- collider, E_c = 91, 209 GeV

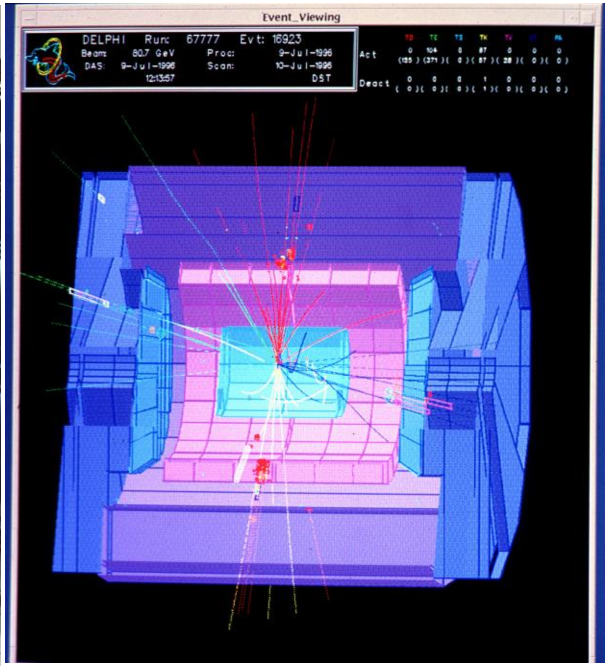
Data taking: 1989-2000

Current collider: LHC

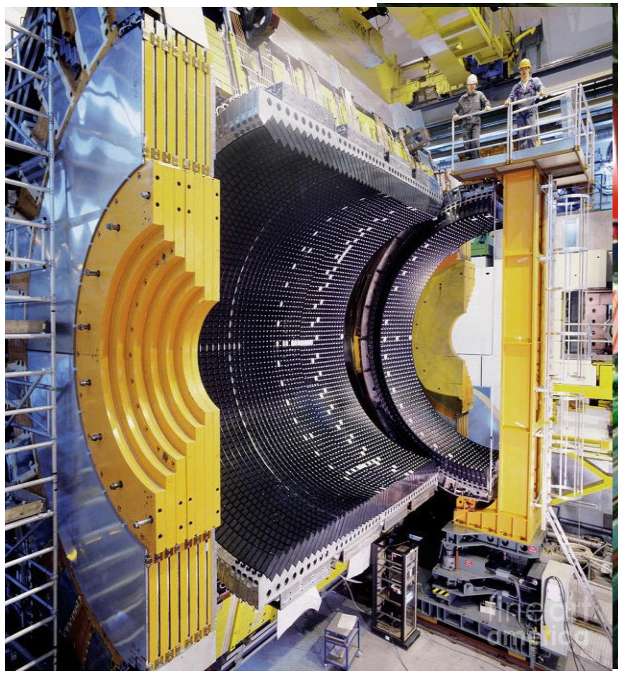
LEP Detectors



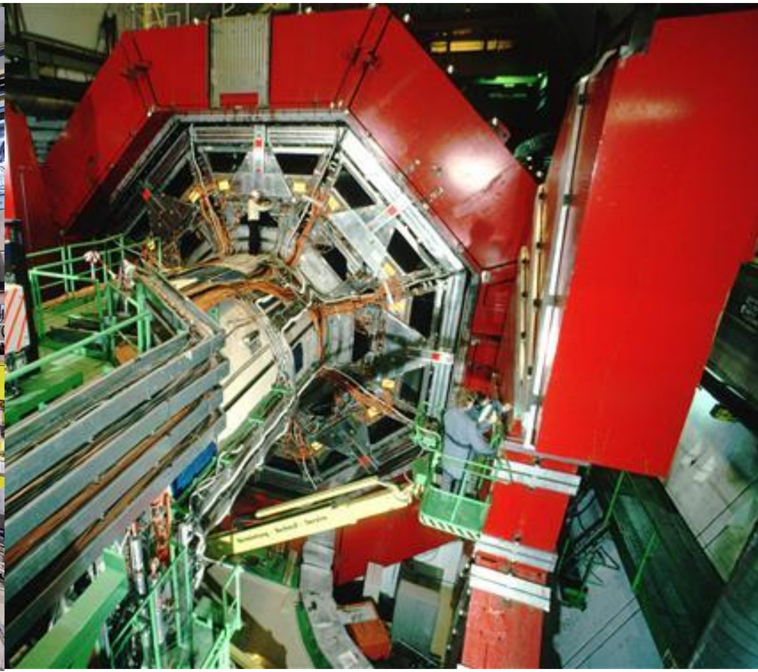
ALEPH



DELPHI



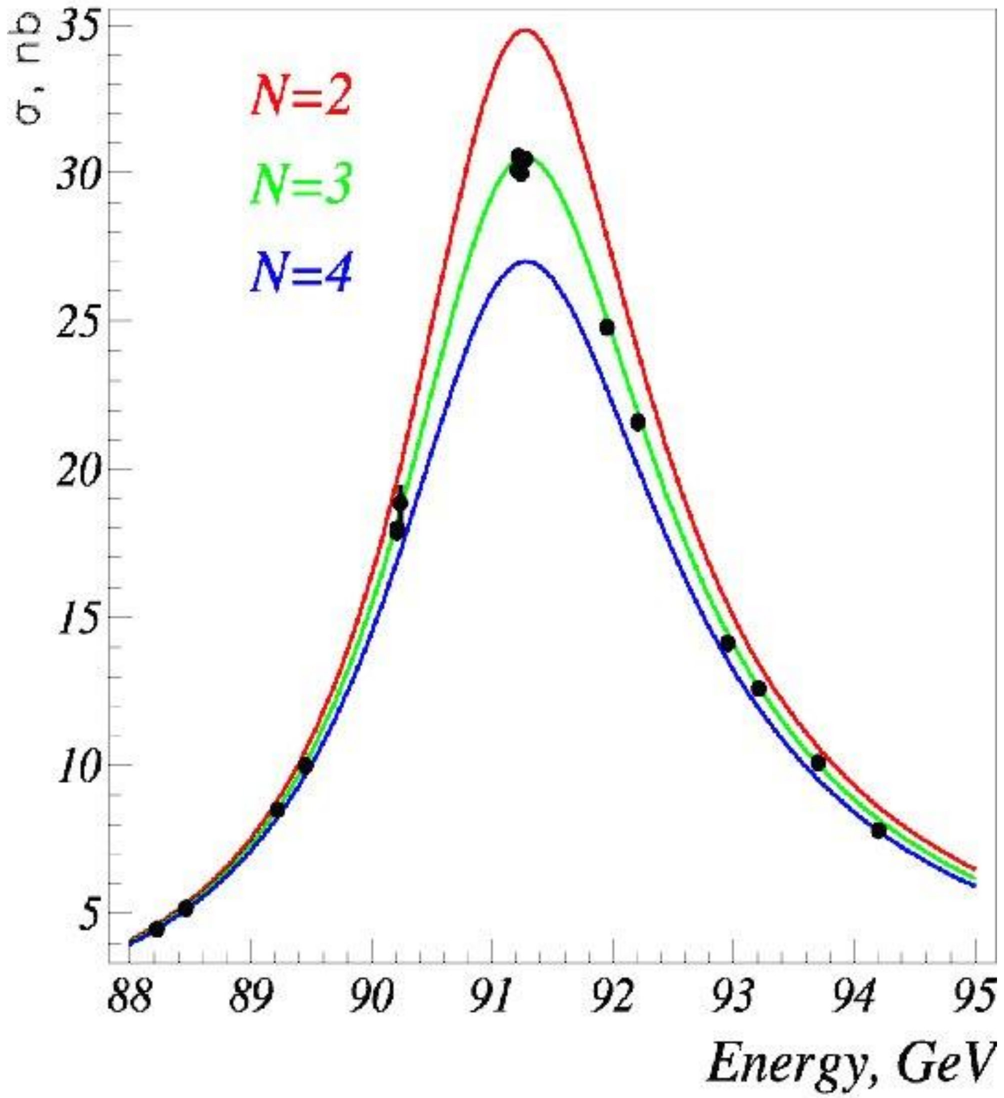
OPAL

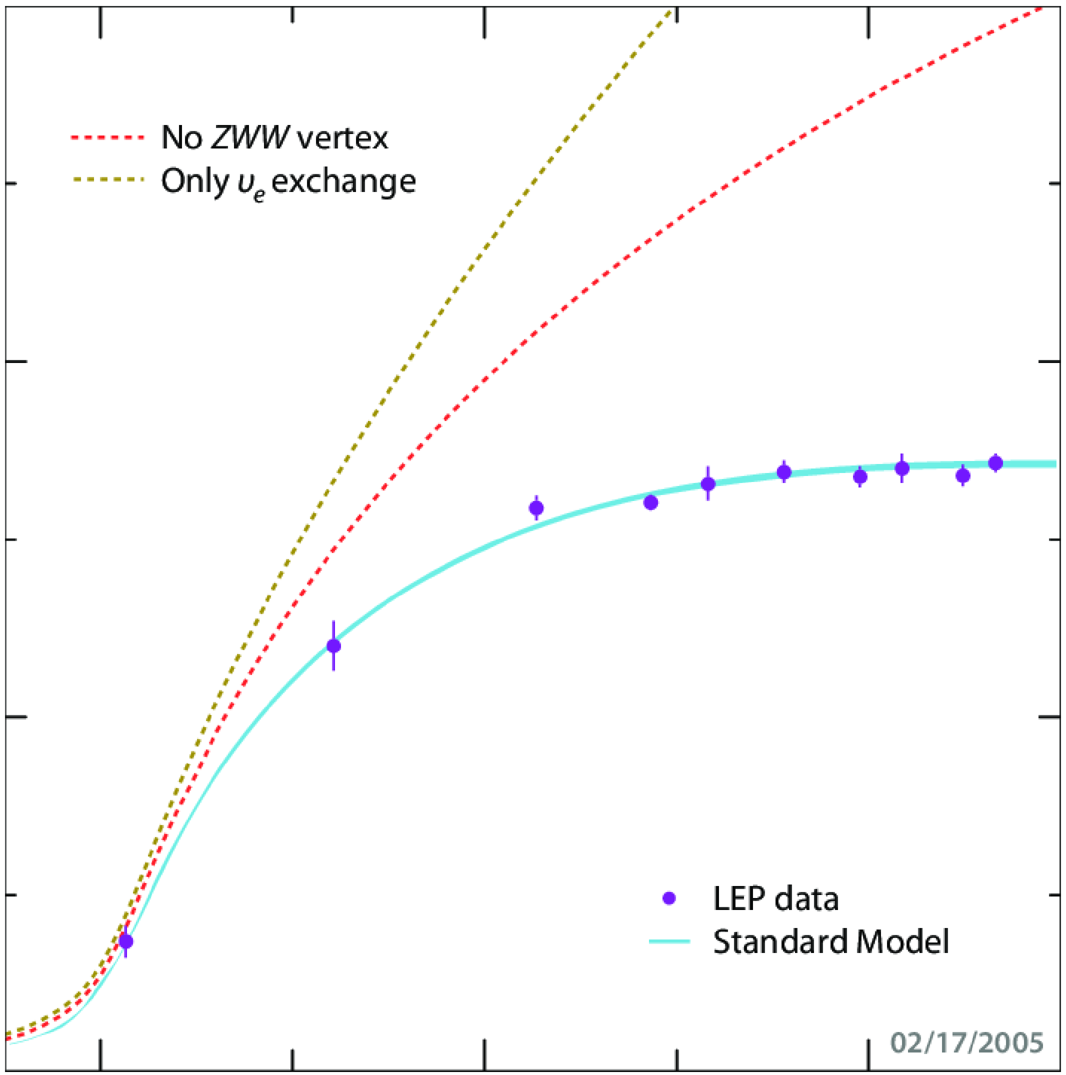


L3

4 large detectors at LEP

Number of Light Neutrinos and Test of SM



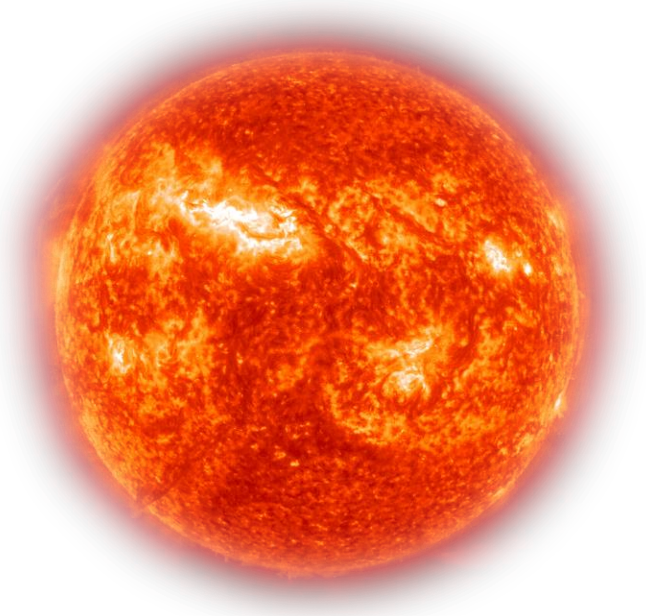


Neutrino Oscillations

Solar and atmospheric neutrino problems

Discovery of neutrino oscillations and consequences

Solar Neutrinos



Distance from Earth (mean): 149,600,000 km (1 A.U.)

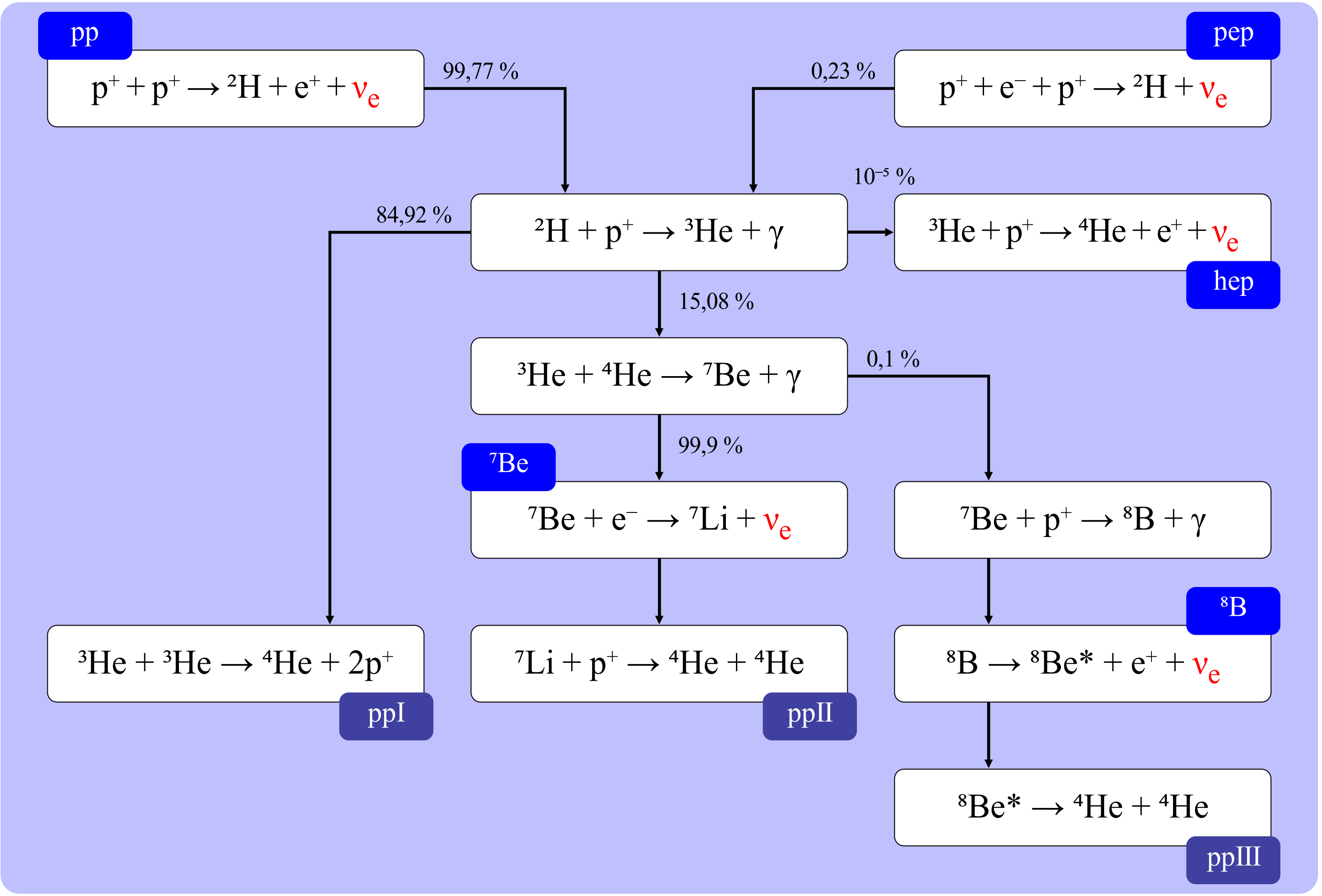
Luminosity: 3.828 10^{26} W

Energy production by nuclear reactions[1]:

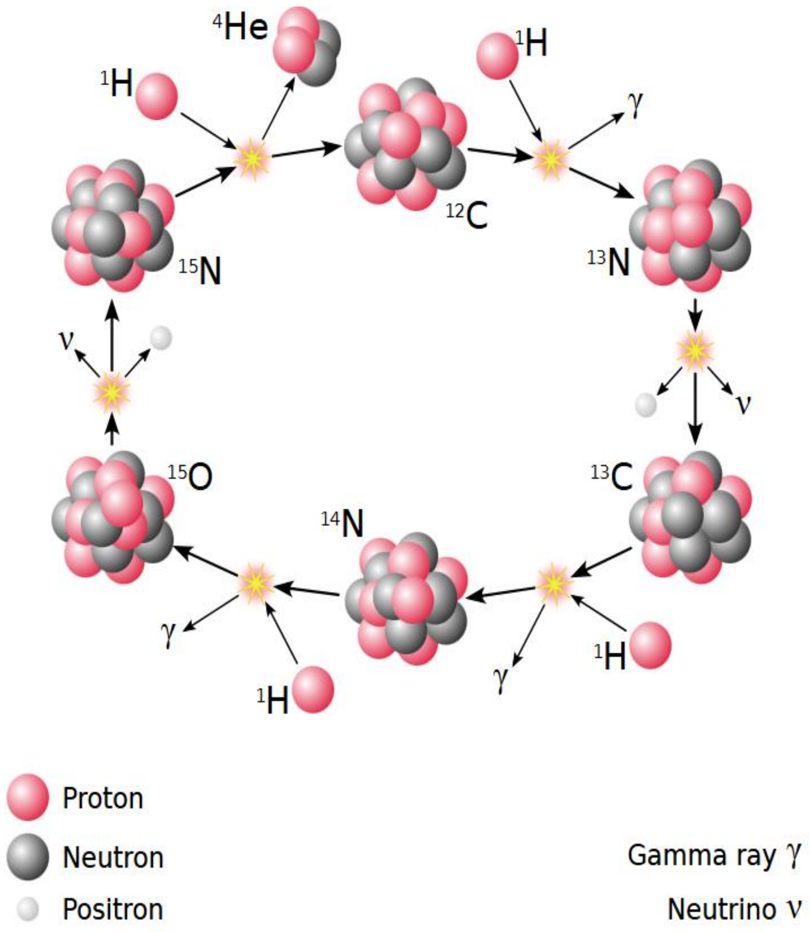
$$4\,p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e$$

1H. A Bethe, Energy production in stars, Phys.Rev, 55(1939), 434

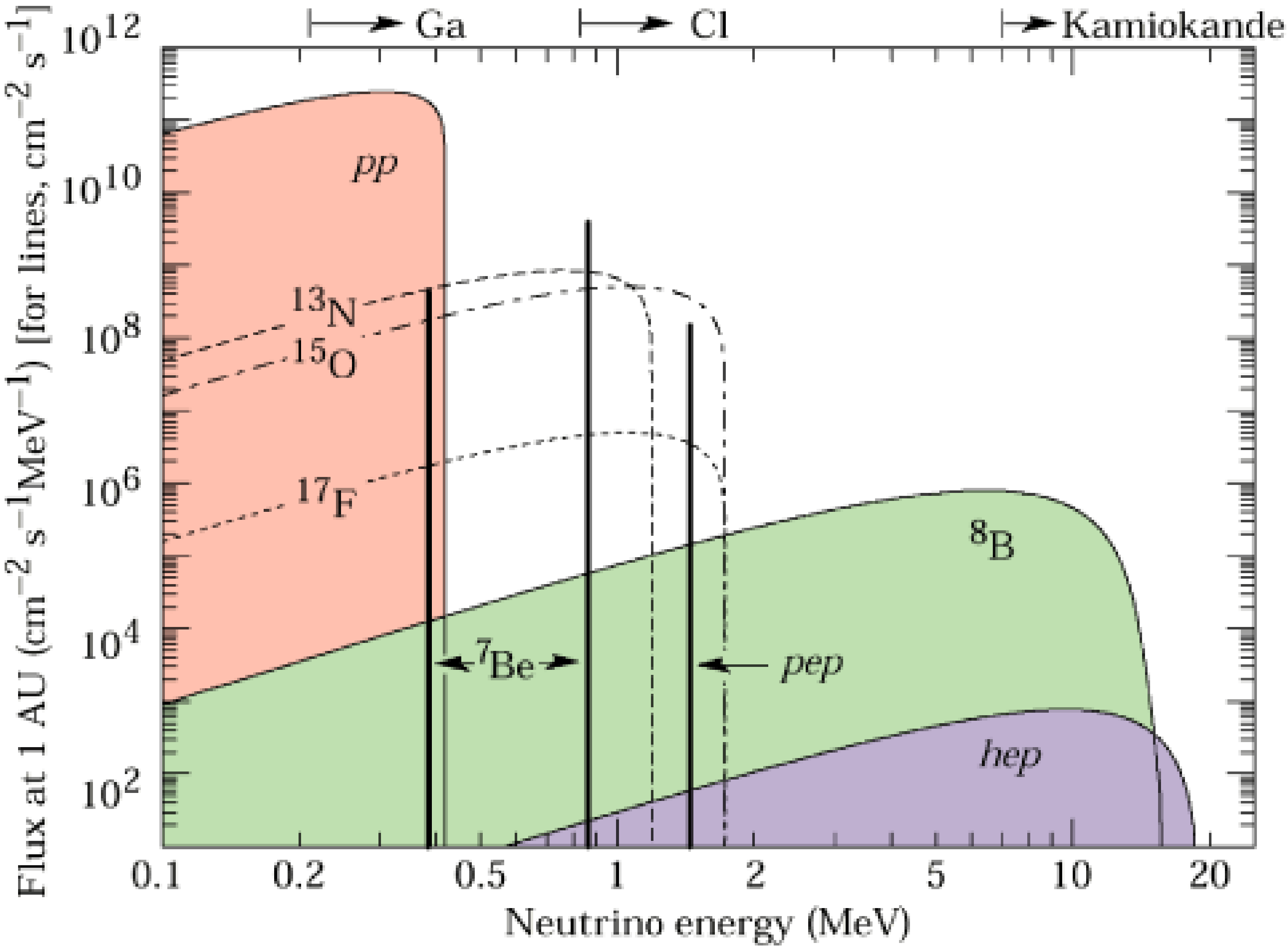
Solar Neutrinos: pp-Chain and CNO-cycle



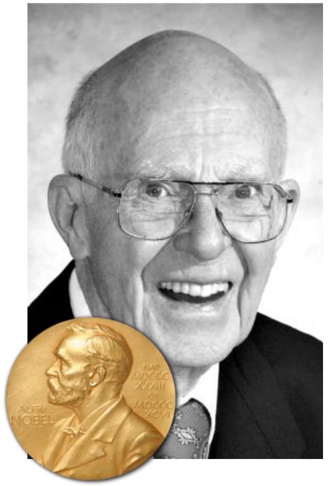
99% of Sun's energy



Solar Neutrino Fluxes



Homestake Solar Neutrino Experiment



Raymod Devis Jr.
1914- 2006

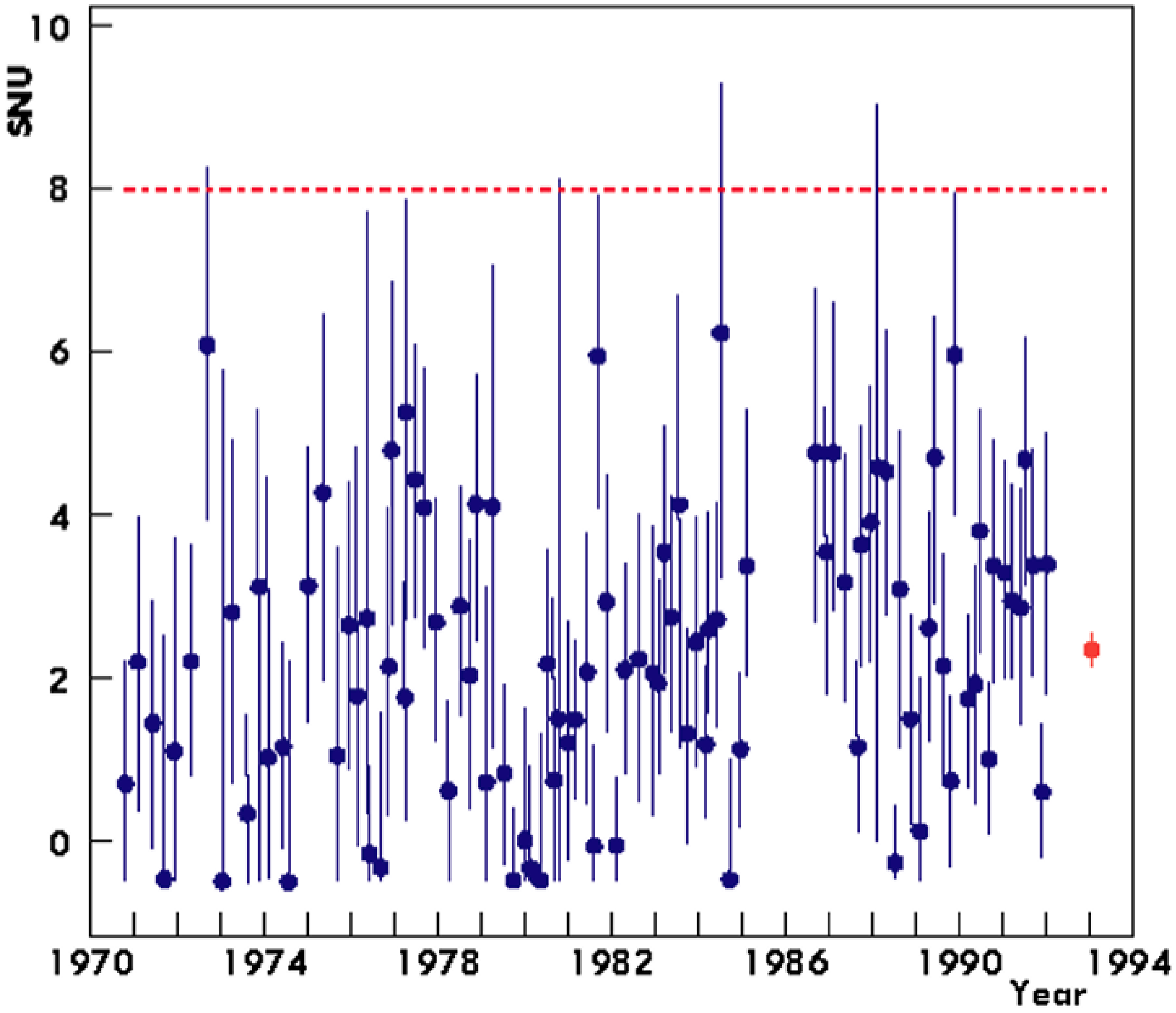
Devis (Bahcall-Devis) experiment
1970-1994

In the Homestake Mine, South Dacota

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

380 m^3 (100,000 gallon) tank filled with tetrachloroethylene (C_2Cl_4)

Solar Neutrino Problem

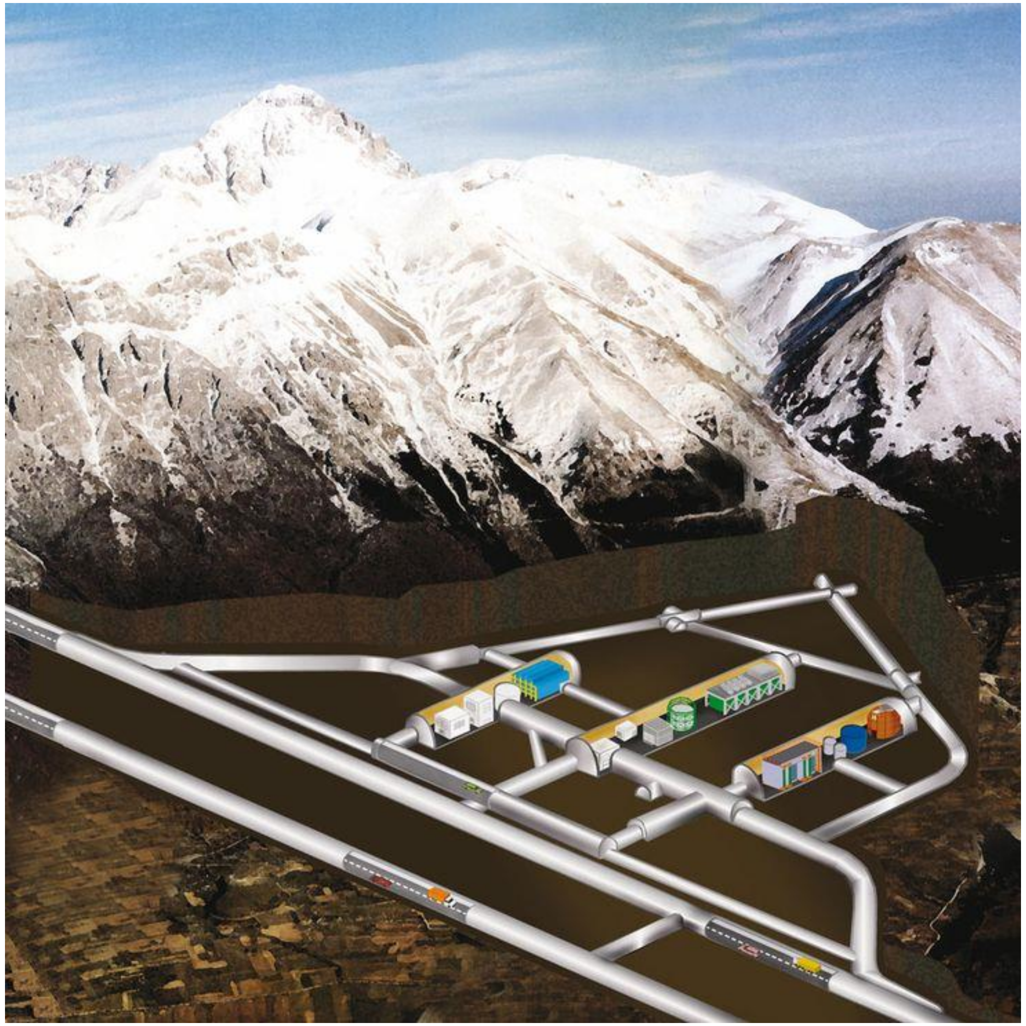


Gallium Experiments

$$\nu + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

$E_\nu > 0.233$ MeV

$T({}^{71}Ge) = 11.2$ d



Solar Neutrino experiments in LNGS:

1991-1997 GALLEX
Gallium Experiment

1998-2003 GNO
Gallium Neutrino Observatory

Solar Neutrino experiment in Baskan (BNO)

1991- SAGE
Soviet(Russian)–American Gallium Experiment

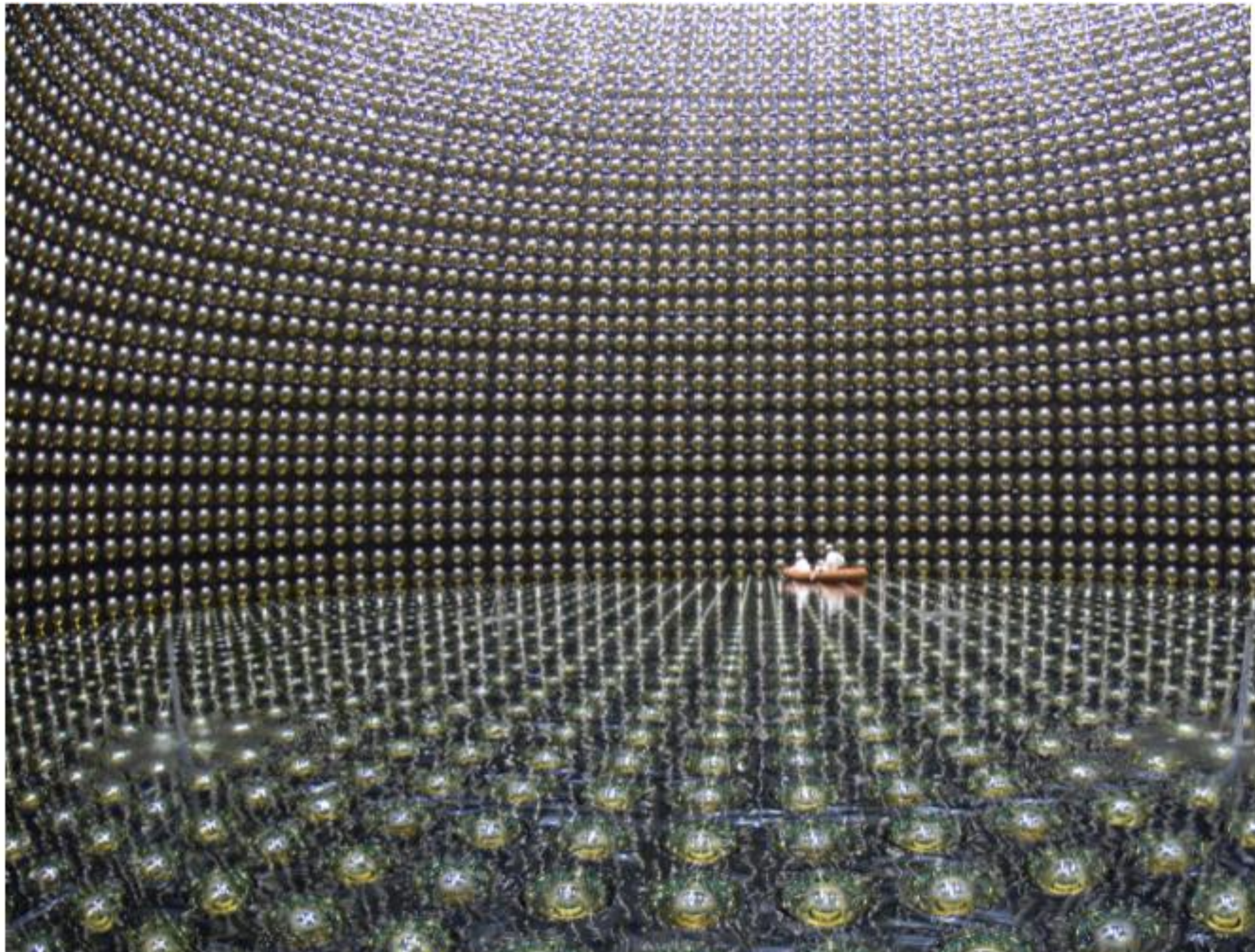
Cherenkov Detectors: Super-Kamiokande

1926-2020

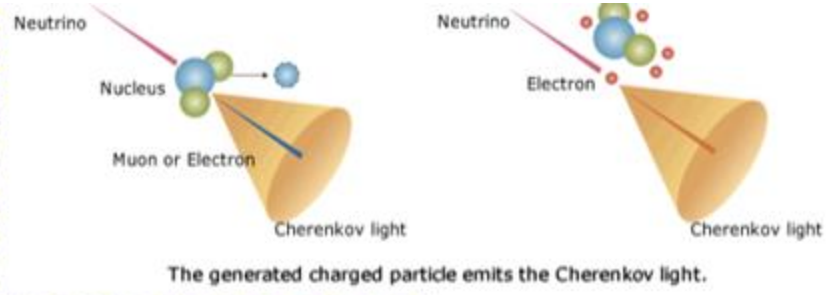
Masatoshi Koshiba

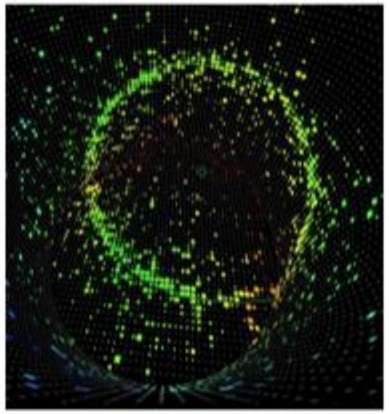
2002

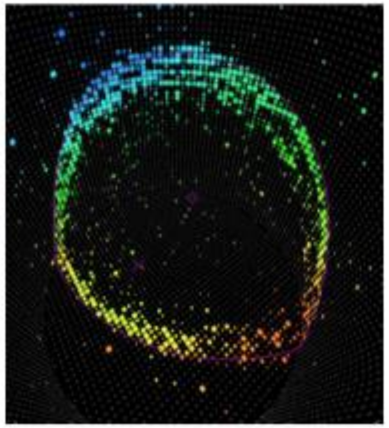
1983-1986
Kamiokande-I
1996:
Super-Kamiokande
(59kton, 13000 PMT)



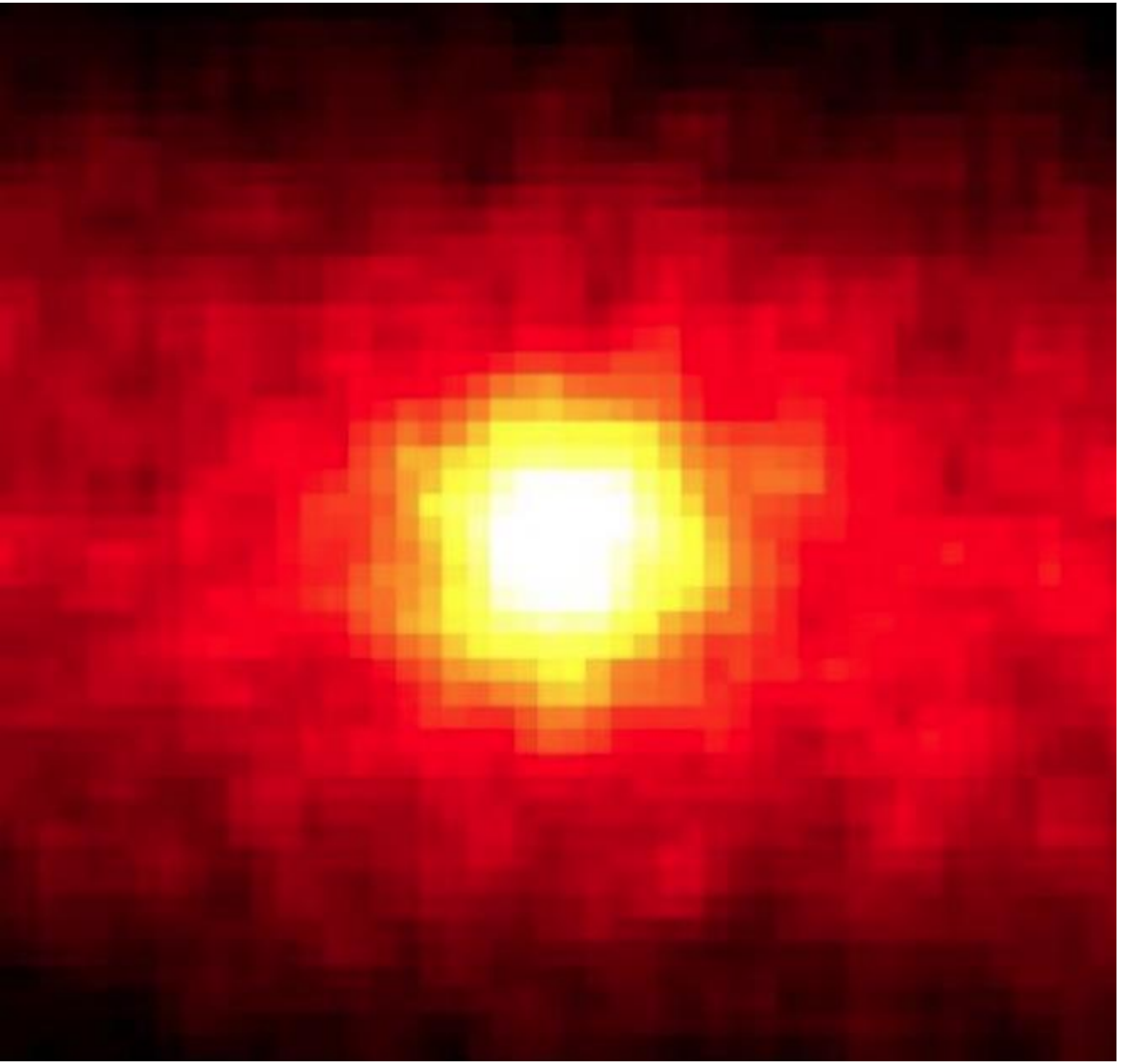
Super-Kamiokande: is the world's largest underground Cherenkov detector. (D:39.3m ,H:41.4m)







Sun in the Super-Kamiokande

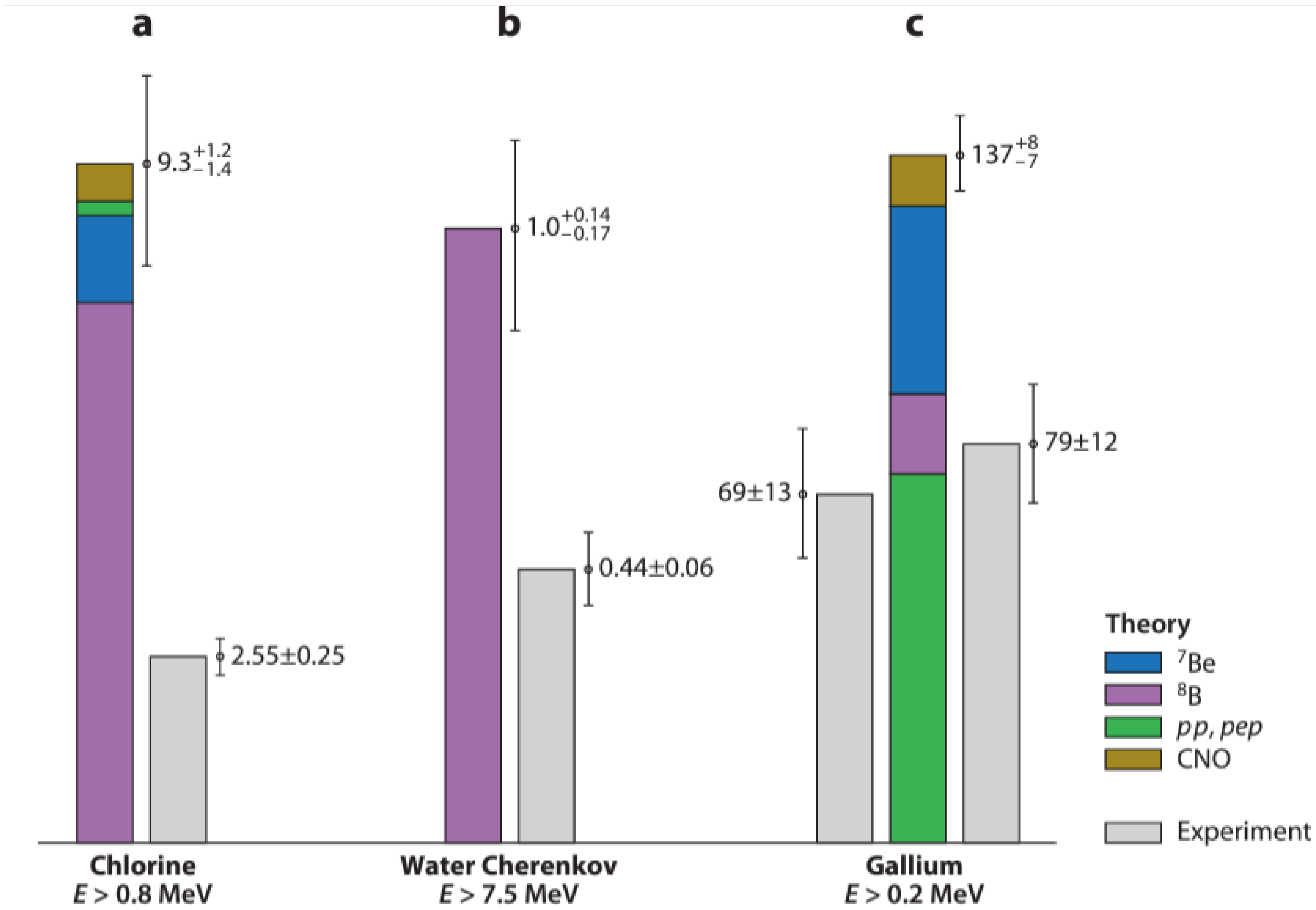


Neutrino image of the Sun - 500 days worth of data was needed from Super-K to detect this image. Centered on the Suns position, the picture covers a significant fraction of the sky (90x90 degrees in R.A. and Dec.). Brighter colors represent a larger flux of neutrinos.

https://apod.nasa.gov/apod/ap980605.html

Astronomy picture of the day,

Solar Neutrino Problem



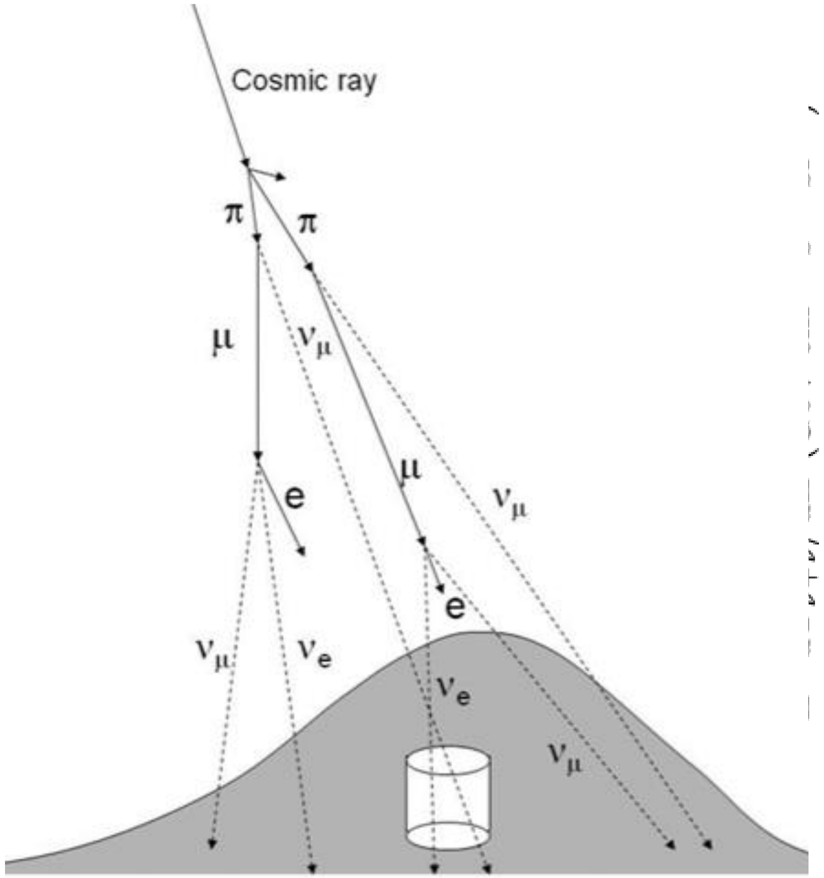
Comparison of the measured rates with the Standard Solar Model predictions for the solar Neutrino experiments:

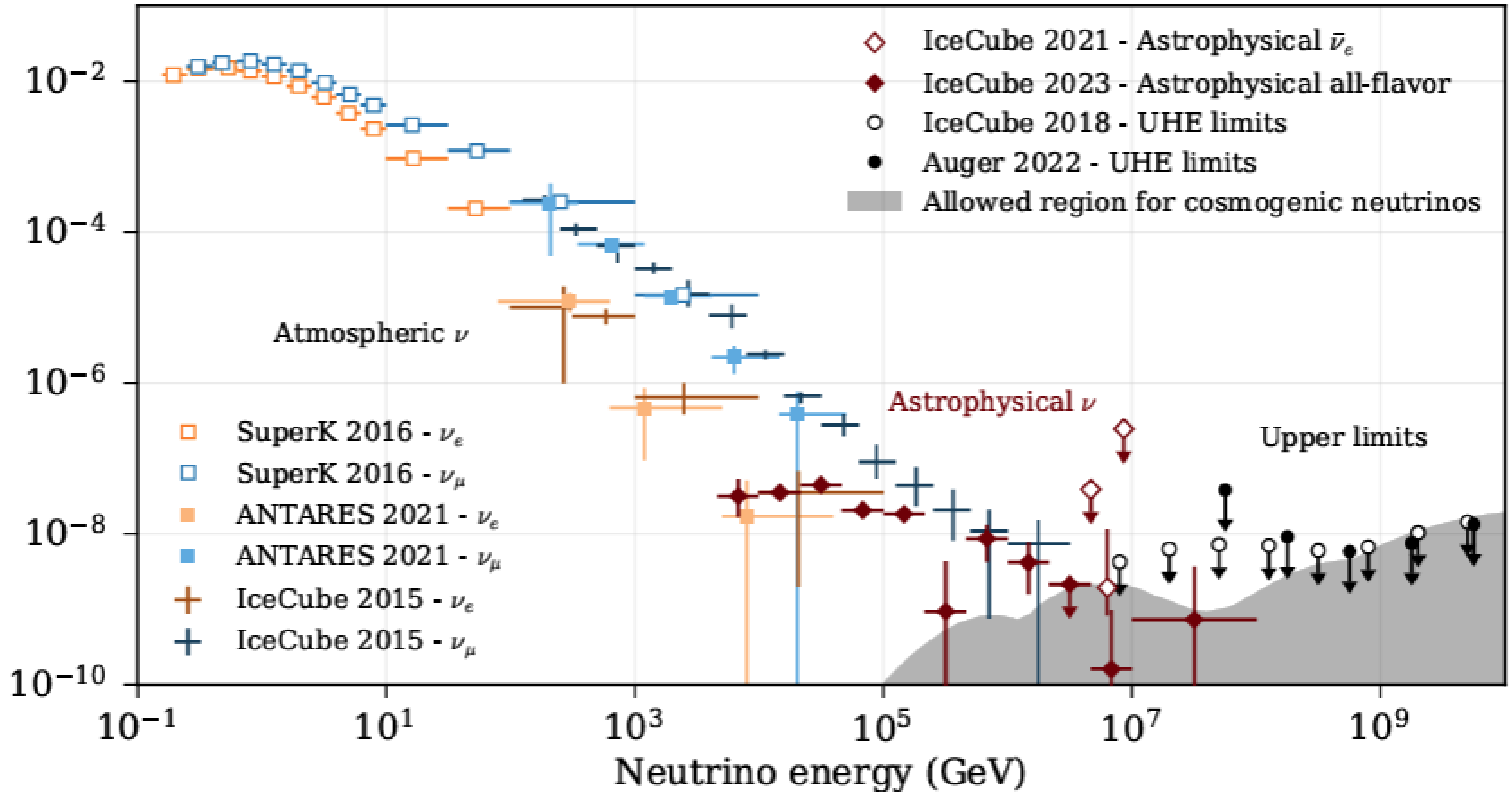
(a) chlorine

(b) water Cherenkov

(c) gallium

Atmospheric Neutrinos

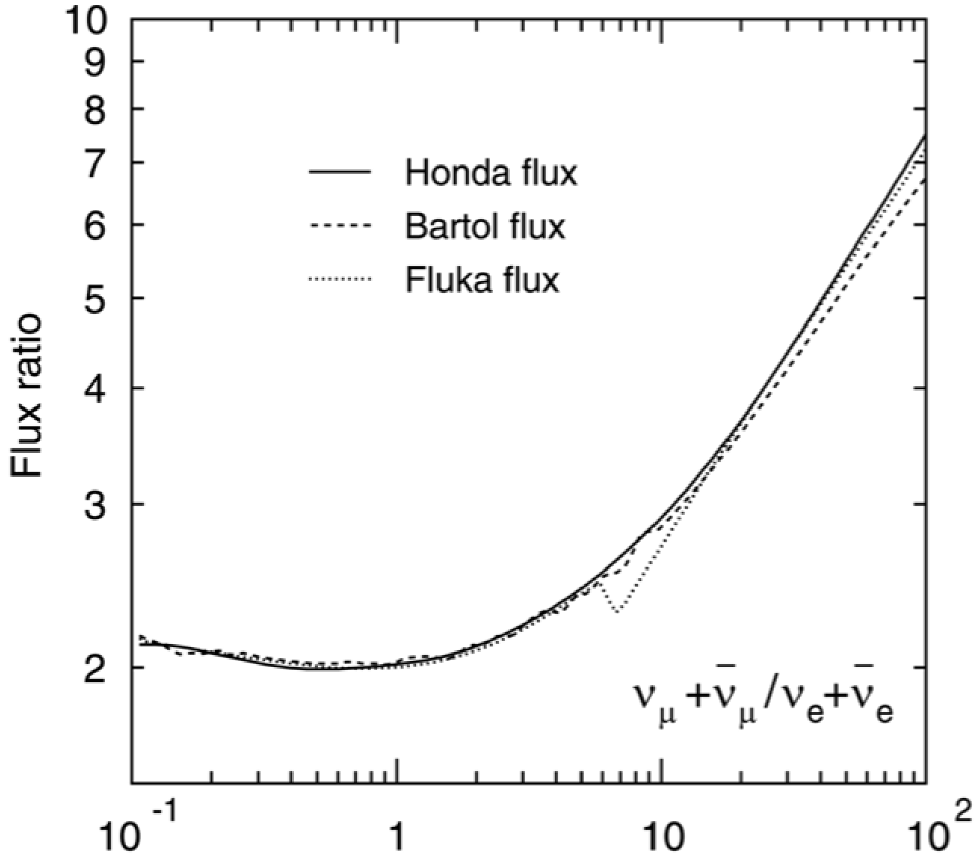




Atmospheric neutrinos are produced from the cosmic ray interactions in the atmosphere - (weak decays of hadrons)

Atmospheric Neutrino Anomaly

the μ^-/e ratio of atmospheric neutrino interactions with energies of about 1 GeV (or less) was significantly smaller than expected.

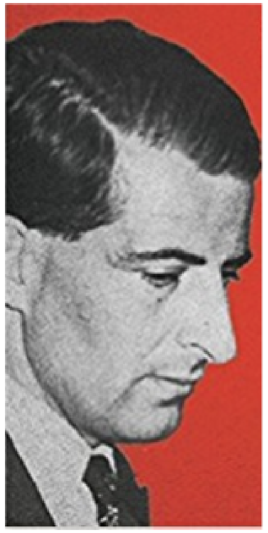


ratio of the atmospheric neutrino by three independent groups

	Data	Monte Carlo Prediction
e-like events	93 ± 9.6	88.5
μ-like events	85 ± 9.2	144.0

The numbers of e-like and μ-like events observed in Kamiokande in 1988, compared with the prediction (without neutrino oscillations.23).

Neutrino Oscillations



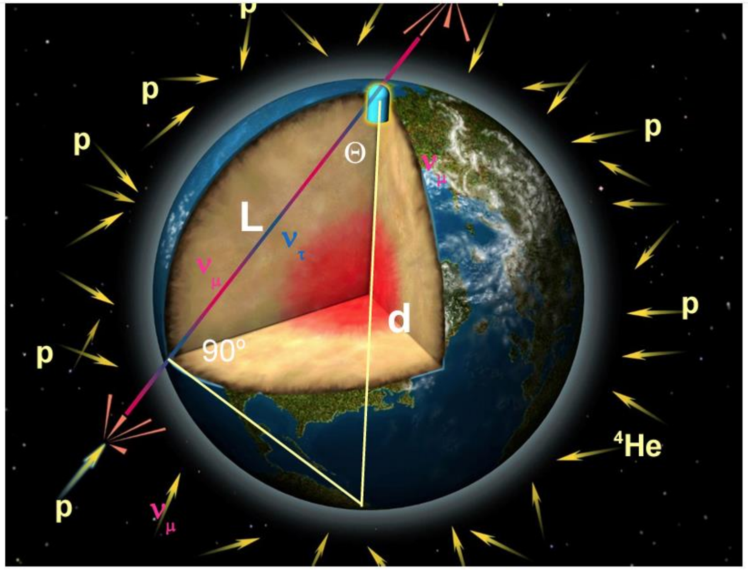
Bruno Pontekorvo

2ν – mixing:

Mixing of flavor neutrinos (ν_α, ν_β) with massive neutrino states (ν_1, ν_2)

$$\nu_\alpha = u_{\alpha i}\nu_i \qquad \alpha = e, \mu \qquad i = 1,2$$

$$u_{\alpha i} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad \nu_\alpha(x) = \cos\Theta\,\nu_1(x) + \sin\Theta\,\nu_2(x)$$



Neutrino propagation: $P_{\alpha\alpha} + P_{\alpha\beta} = 1$

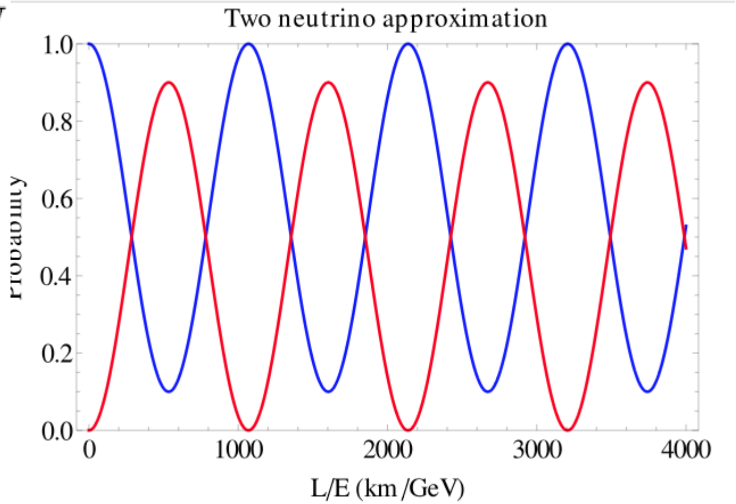
$P_{\alpha\alpha}$ - survival(disappearance) probability

$P_{\alpha\beta}$ - appearance probability

$$P_{\alpha\beta}(\theta, \Delta m^2_{21}, L, E_\nu) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{12} L}{4 E_\nu}\right)$$

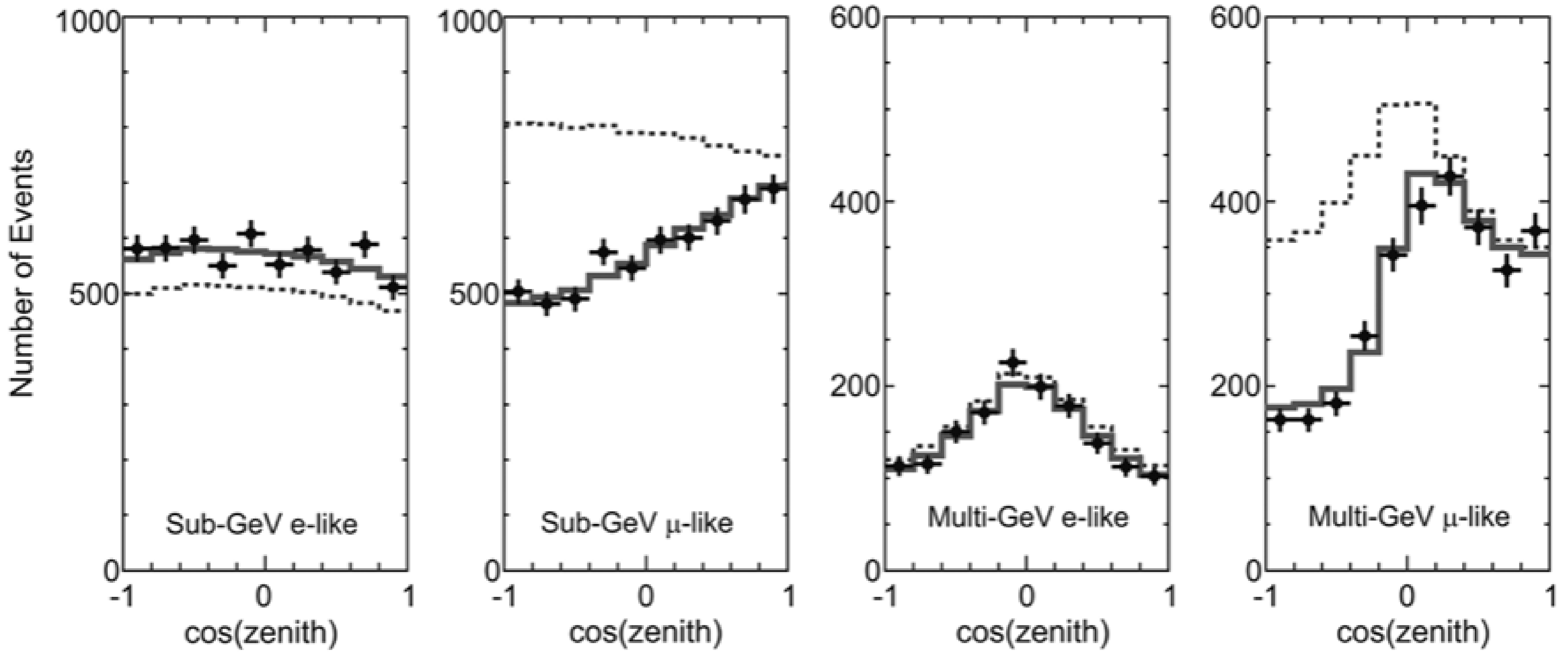
Oscillation parameters: $\theta, \Delta m^2_{21}$

Conditions: $\begin{cases} \theta \neq 0 \\ \Delta m^2_{21} = m^2_2 - m^2_1 \neq 0 \end{cases}$



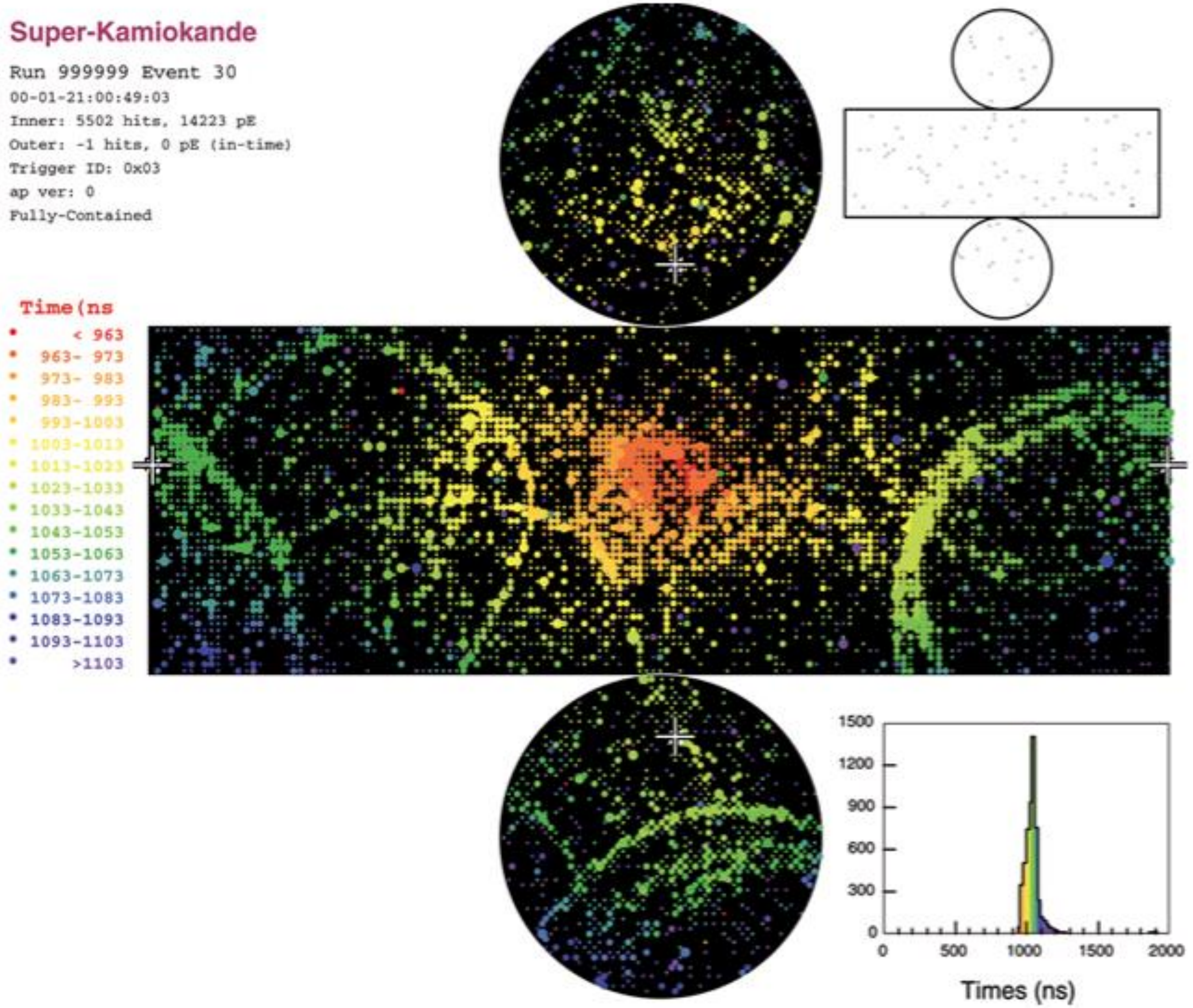
Oscillation of Atmospheric Neutrinos

Super-Kamiokande Collaboration (Y. Fukuda et al.), Phys,. Rev. Lett., 81 (1998) 1562-1567



Zenith angle distributions observed in SK (2,806 days exposure). Sub- and multi-GeV events are defined to have the visible energy below and above 1.33 GeV, respectively. The dotted and solid histograms show the un-oscillated and best- fit oscillated Monte Carlo distributions.

Tau Neutrinos in Syper-Kamiokande



A simulated charged-current ν_τ interaction in the Super-Kamiokande detector.

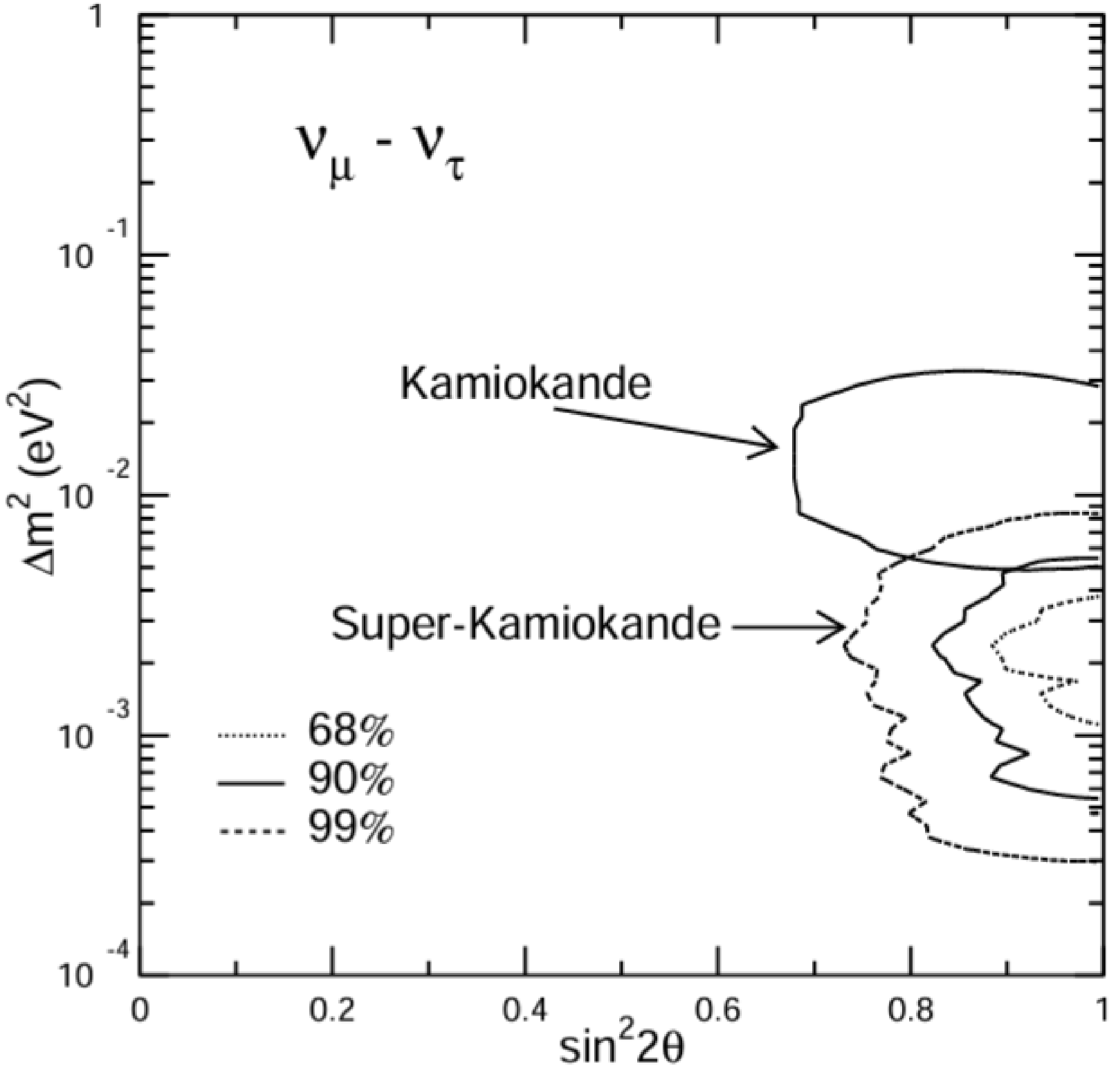
$$\nu_\tau + p \rightarrow \tau^+ + n$$

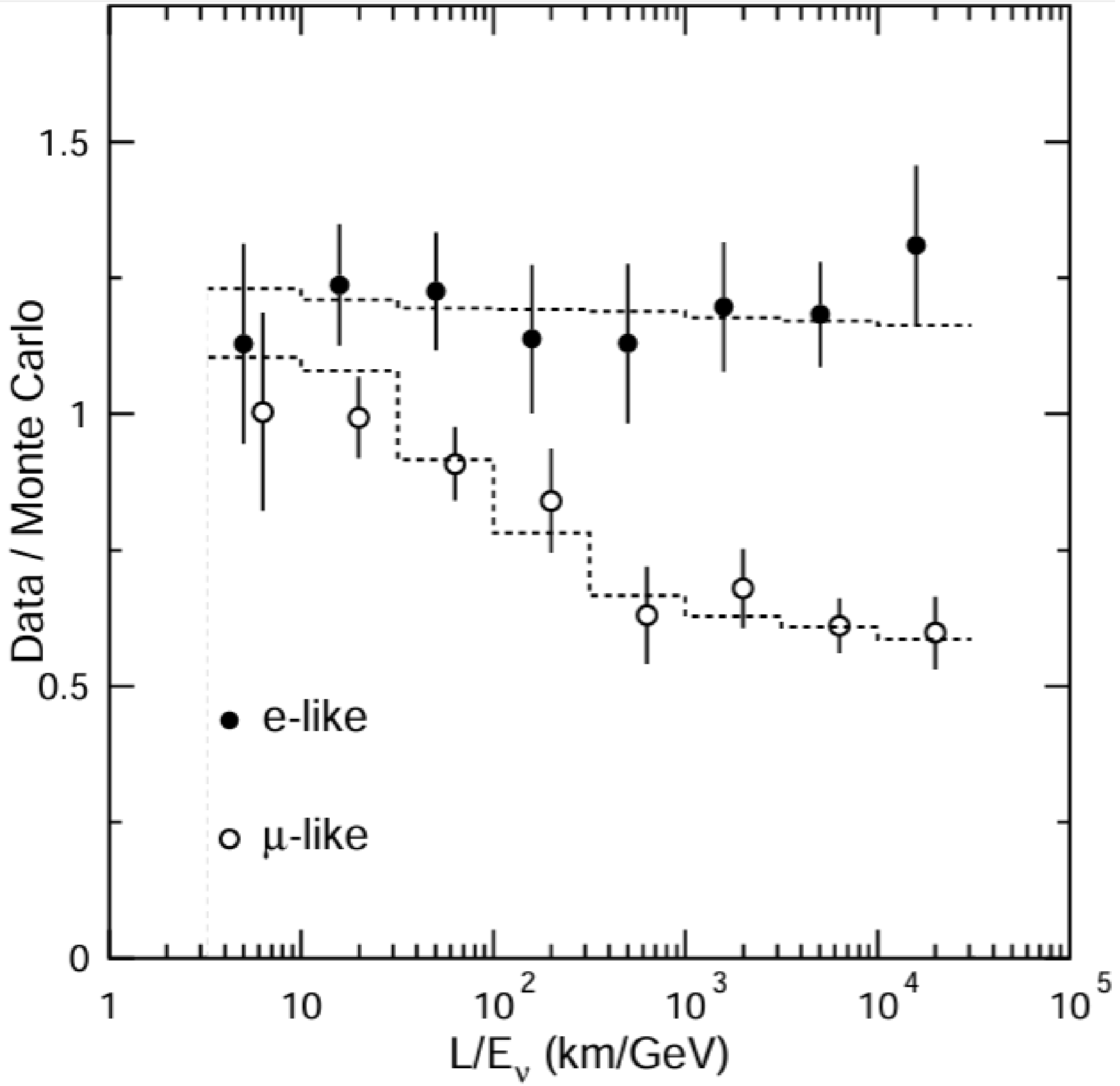
Due to the heavy tau mass (1.78 GeV/c^2), the is about 3.5 GeV.

With lifetime is 2.9 10^{-13} sec.
τ almost immediately decays into many hadrons.
Difficult to select over large background from MC events.

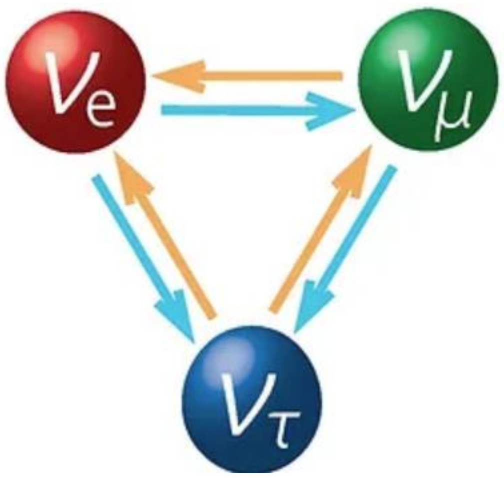
Neutrino Oscillations

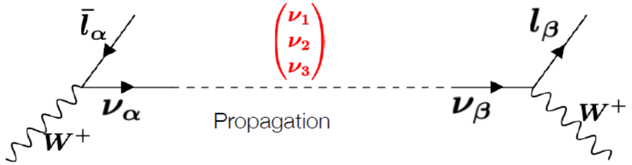
Super-Kamiokande Collaboration (Y. Fukuda et al.), Phys,. Rev. Lett., 81 (1998) 1562-1567





Neutrino Oscillations





3 neutrino case:

$$\nu_\alpha = u_{\alpha i}\nu_i \qquad \alpha = e, \mu, \tau \quad i = 1,2,3$$

$$u_{\alpha i} = U_{PMNS}$$

PMNS matrix (Pontecorvo–Maki–Nakagawa Sakata)

$$U_{PMNS} = \begin{pmatrix} u_{e1} & u_{e2} & u_{e3} \\ u_{\mu 1} & u_{\mu 2} & u_{\mu 3} \\ u_{\tau 1} & u_{\tau 2} & u_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & e^{i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = \cos\Theta_{ij} \qquad s_{ij} = \sin\Theta_{ij}$$

Oscillation parameters: $\begin{cases} \Theta_{23}, \ \Theta_{13}, \ \Theta_{12}, \ \delta_{CP} \\ \Delta m^2_{32}, \ \Delta m^2_{31}, \ \Delta m^2_{21} \end{cases}$

$$\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21}$$

$$\pm\Delta m^2_{32} = m^2_3 - m^2_2$$

(Neutrino Mass Hierarchy, NMH)

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23})\cos^4(\theta_{13})\sin^2(\Delta m^2_{32} L_\nu / 4E_\nu)$$

(ignoring Δm^2_{21}, δ and matter effects)

End of Lecture I