GRASPA 2015
Summer School in Particle and Astroparticle Physics
Annecy-le-Vieux 16-22 July 2015

NEUTRINO PHYSICS
(I LECTURE)

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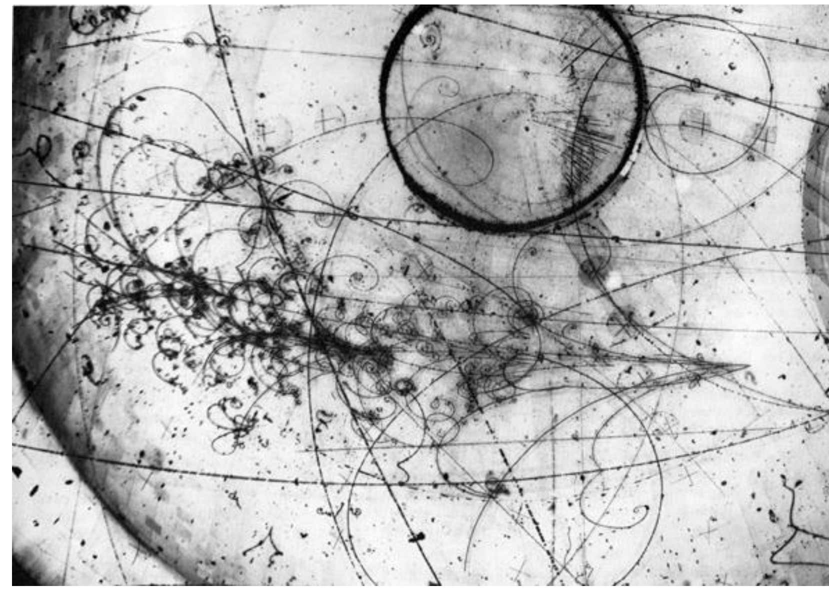
A NEUTRINO POEM

Cosmic Gall
by John Updike

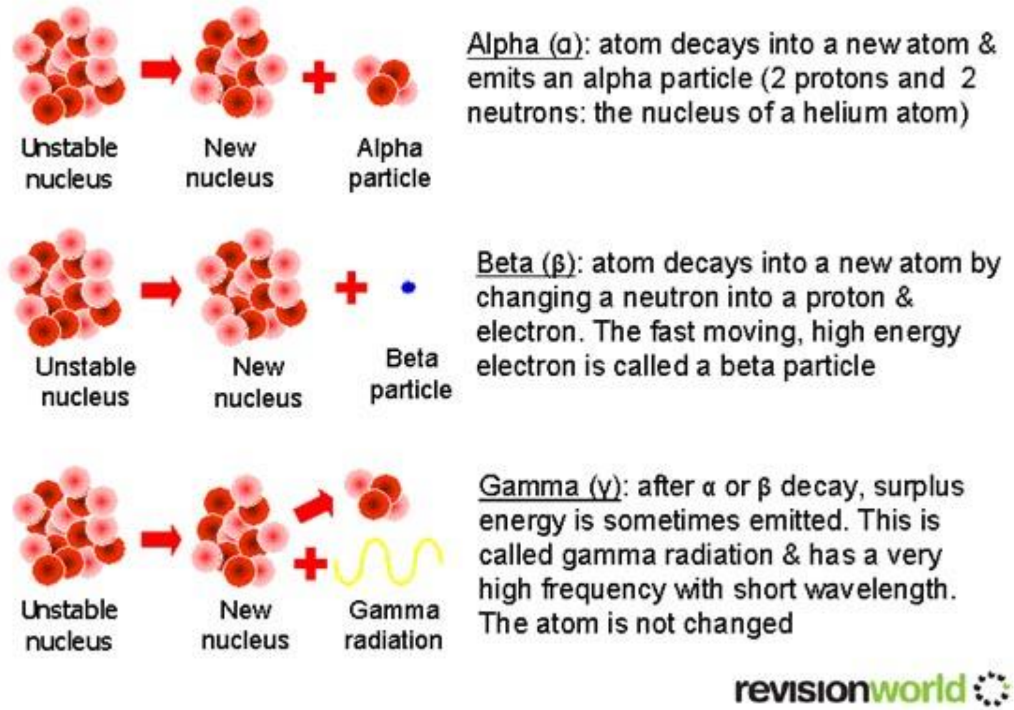
Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed—you call
It wonderful; I call it crass.



RADIOACTIVITY

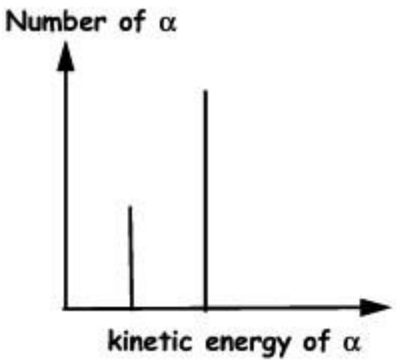
- 1896: the French scientist Henri Becquerel discovers the radioactivity, while working with phosphorescent material.

Rutherford and his student Frederick Soddy realized that many decay processes resulted in the transmutation of one element to another.



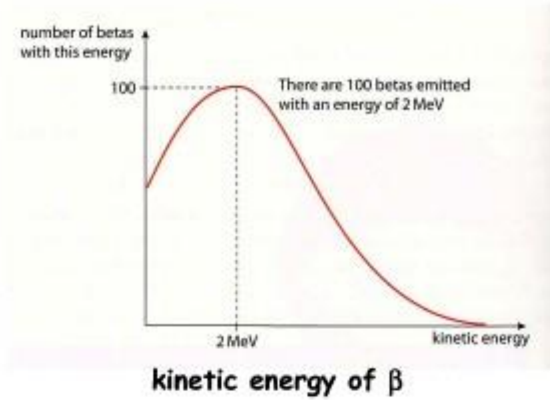
DECAY SPECTRA

α – radiation



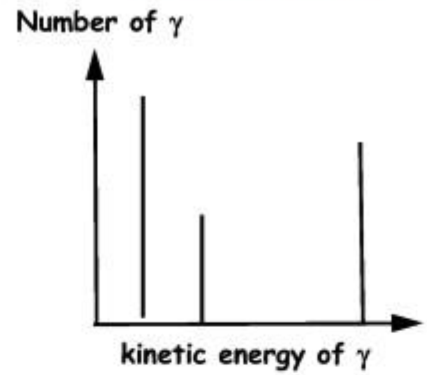
This radiation has constant energy values.

β – radiation



This radiation has not constant energy values because the kinetic energy is shared between the β and the ν.

γ – radiation



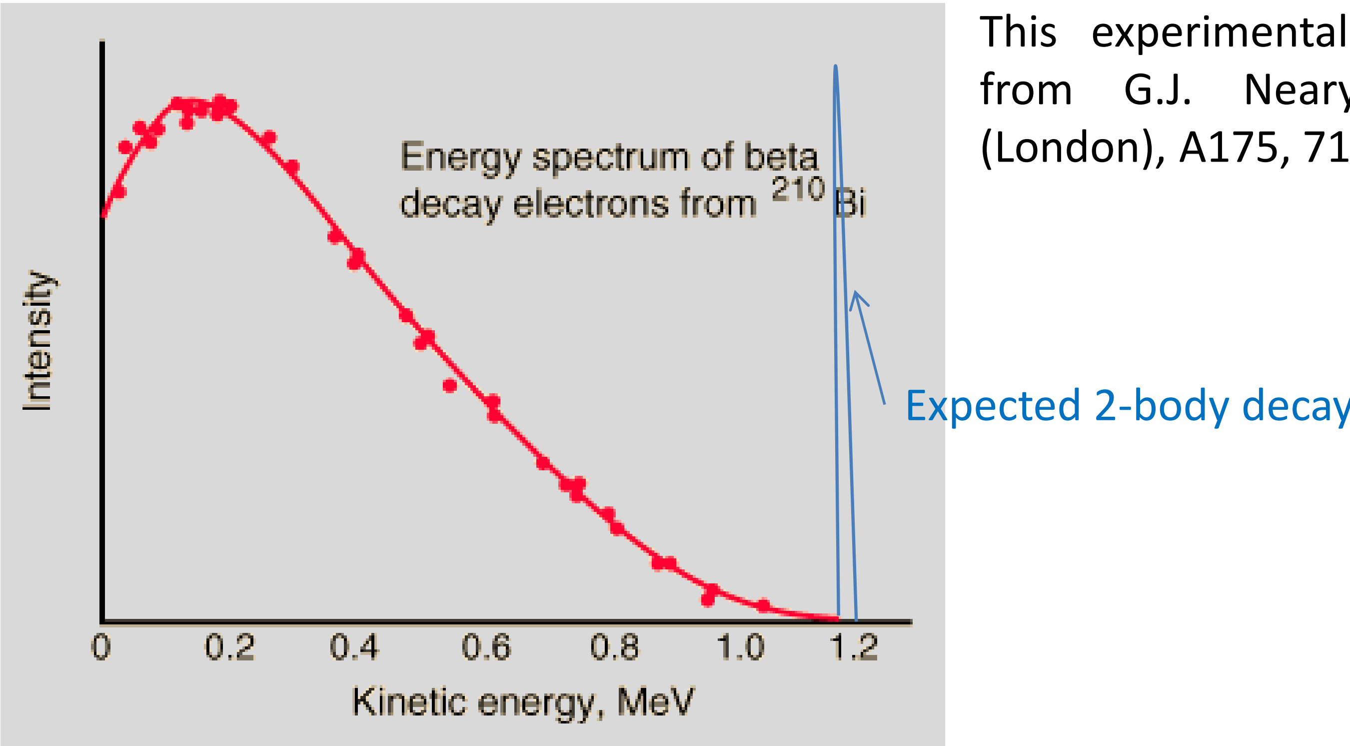
This radiation has constant energy values.

- In alpha and beta decay the energy account were straightforward. If there is only one particle emitted, energy conservation enforces a single value for the emitted energy

- 1914: James Chadwick discovered that the energy of the beta radiation varied from one measurement to the next. Instead of always having the same energy, electrons emerged with a continuous range of energies.

BETA DECAY SPECTRUM

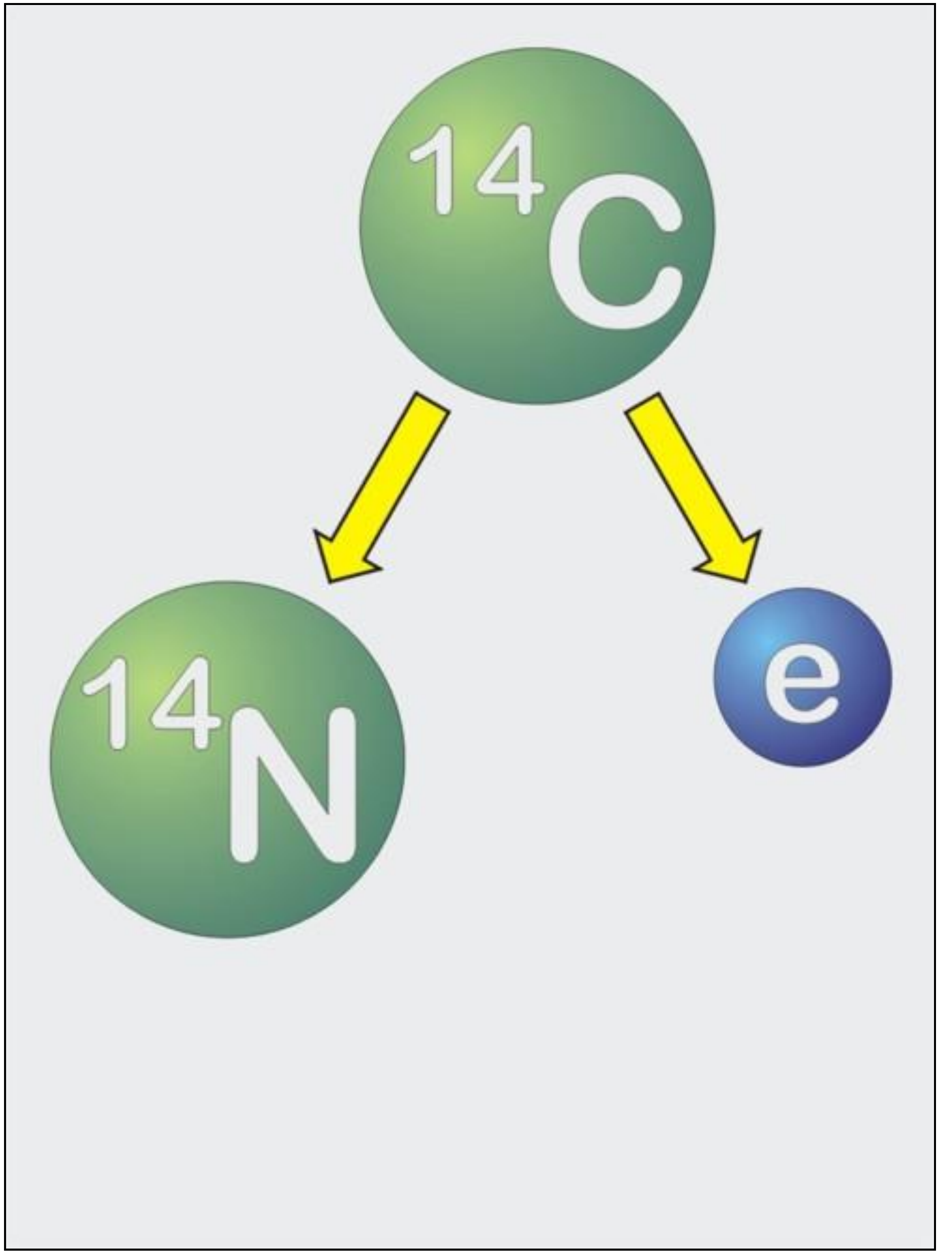
1914: discovery continuous energy spectrum of beta decay (Chadwick)

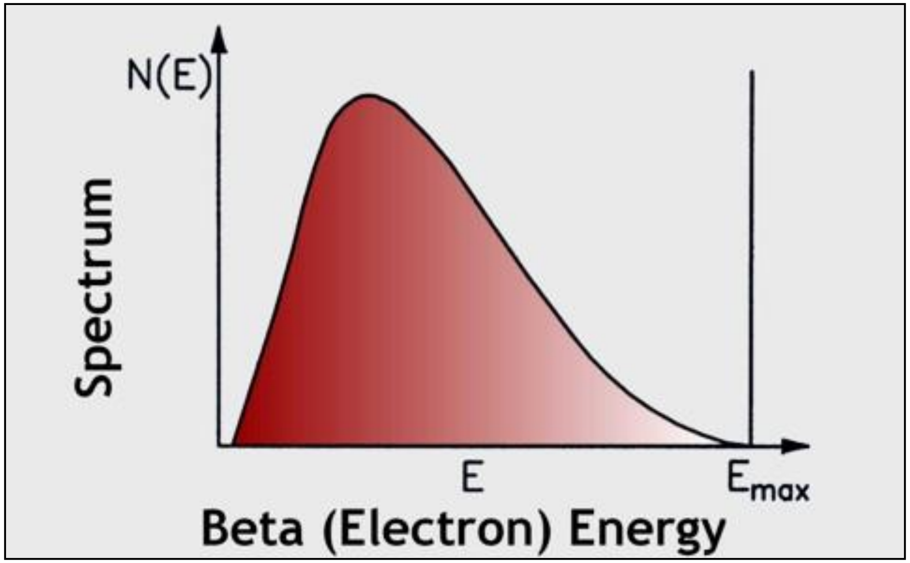


This experimental energy spectrum is from G.J. Neary, Proc. Phys. Soc. (London), A175, 71 (1940).

- **Problem:** nucleus (A,Z) thought to be A protons + (A-Z) electrons
- **Beta decay:** (A,Z) $\rightarrow$ (A, Z+1) + e- (two body decay, monoenergetic e-)

BOHR EXPLANATION OF THE BETA DECAY SPECTRUM



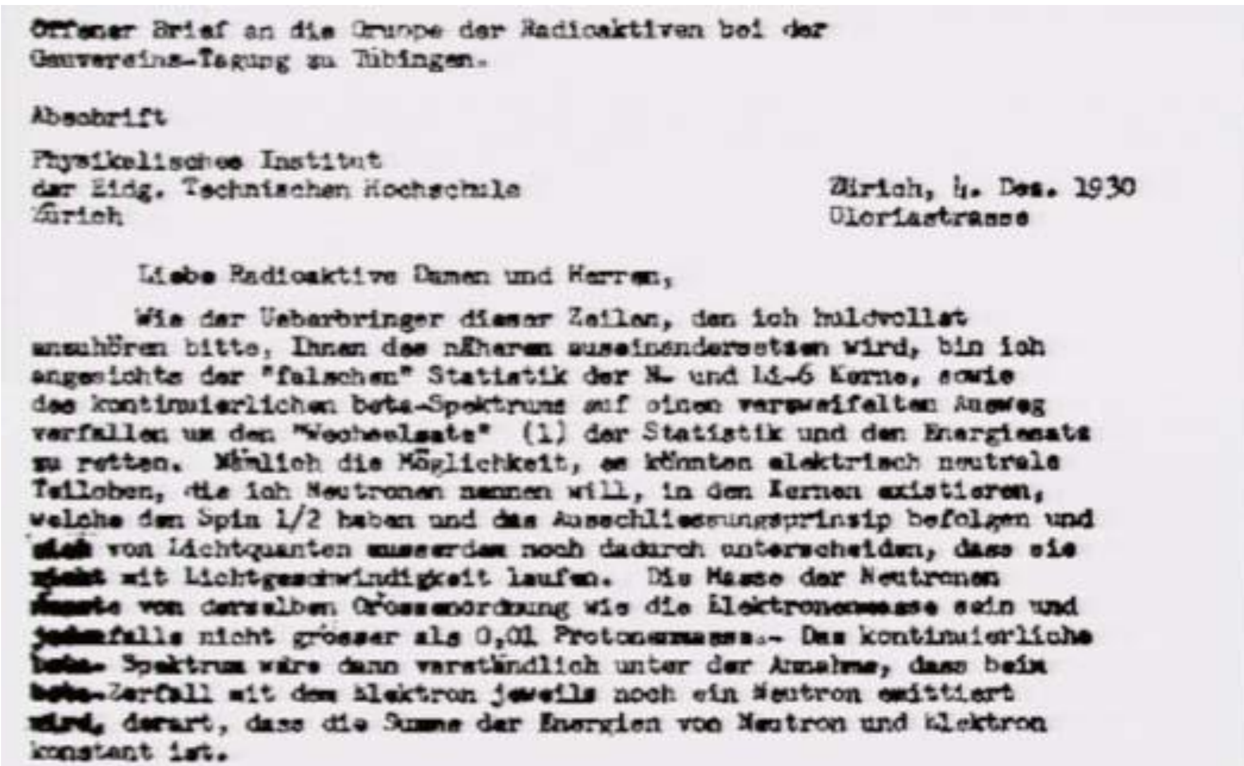


Niels Bohr:

Energy not conserved in the quantum domain?

THE BIRTH OF THE NEUTRINO

- 1930: Pauli proposes existence of "neutron" (with spin ½ and mass not more than 0.01 mass of proton) inside nucleus in a famous letter (4 December 1930):



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

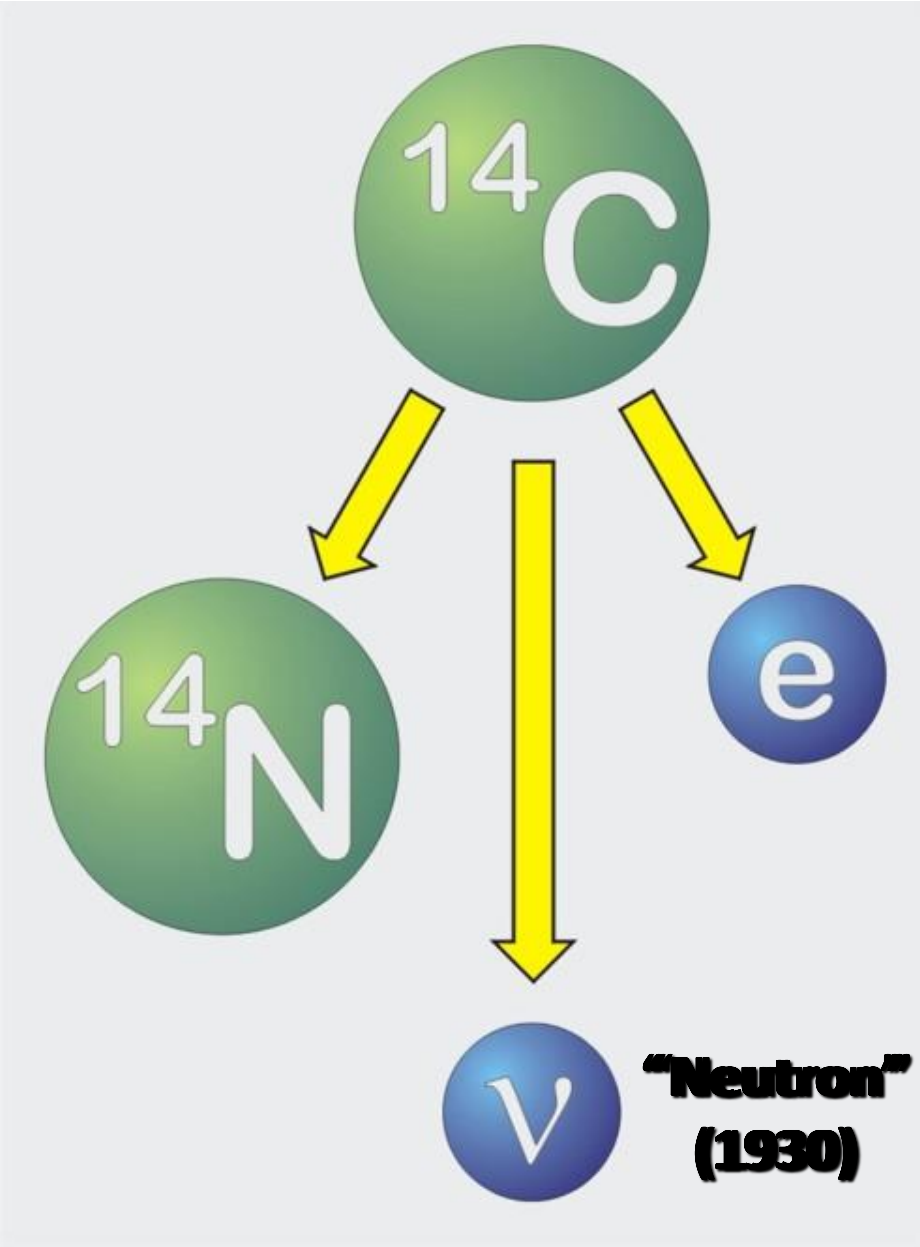
Liebe Radioaktive Damen und Herren,

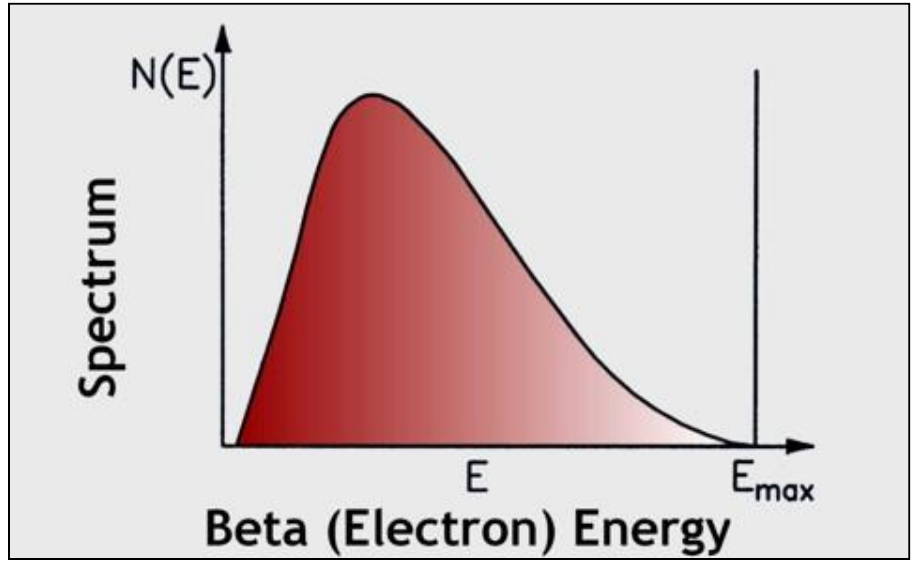
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik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

4th December 1930
Dear Radioactive Ladies and Gentlemen,
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass (and in any event not larger than 0.01 proton masses). The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...
From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately I will not be able to appear in Tübingen personally, because I am indispensable here due to a ball which will take place in Zürich during the night from December 6 to 7….
Your humble servant,
W. Pauli

Pauli also left in his diaries: "Today I have done something which no theoretical physicist should ever do in his life: I have predicted something which shall never be detected experimentally."

PAULI'S EXPLANATION OF THE BETA DECAY SPECTRUM





Wolfgang Pauli
(1900-1958)
Nobel Prize 1945

- 1932: Chadwick discovers neutron:

– Mass of neutron similar to mass of proton: not Pauli's particle!

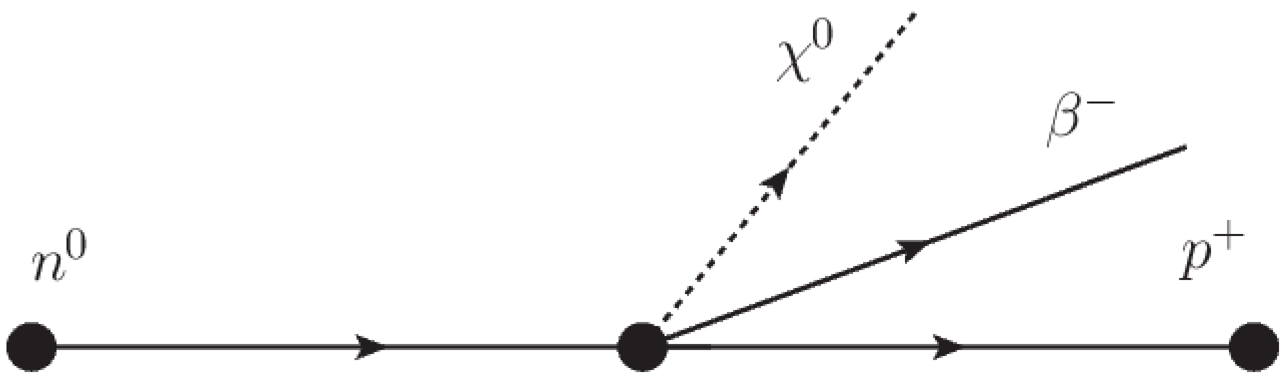
- However, the discovery of neutron has increased the number of atomic particles by 50 %! The idea of inventing further particles no longer seemed so heretical.

- 22-29 October 1933: Solvay Conference in Bruxelles to discuss about nuclear physics

FERMI'S MODEL OF BETA DECAY

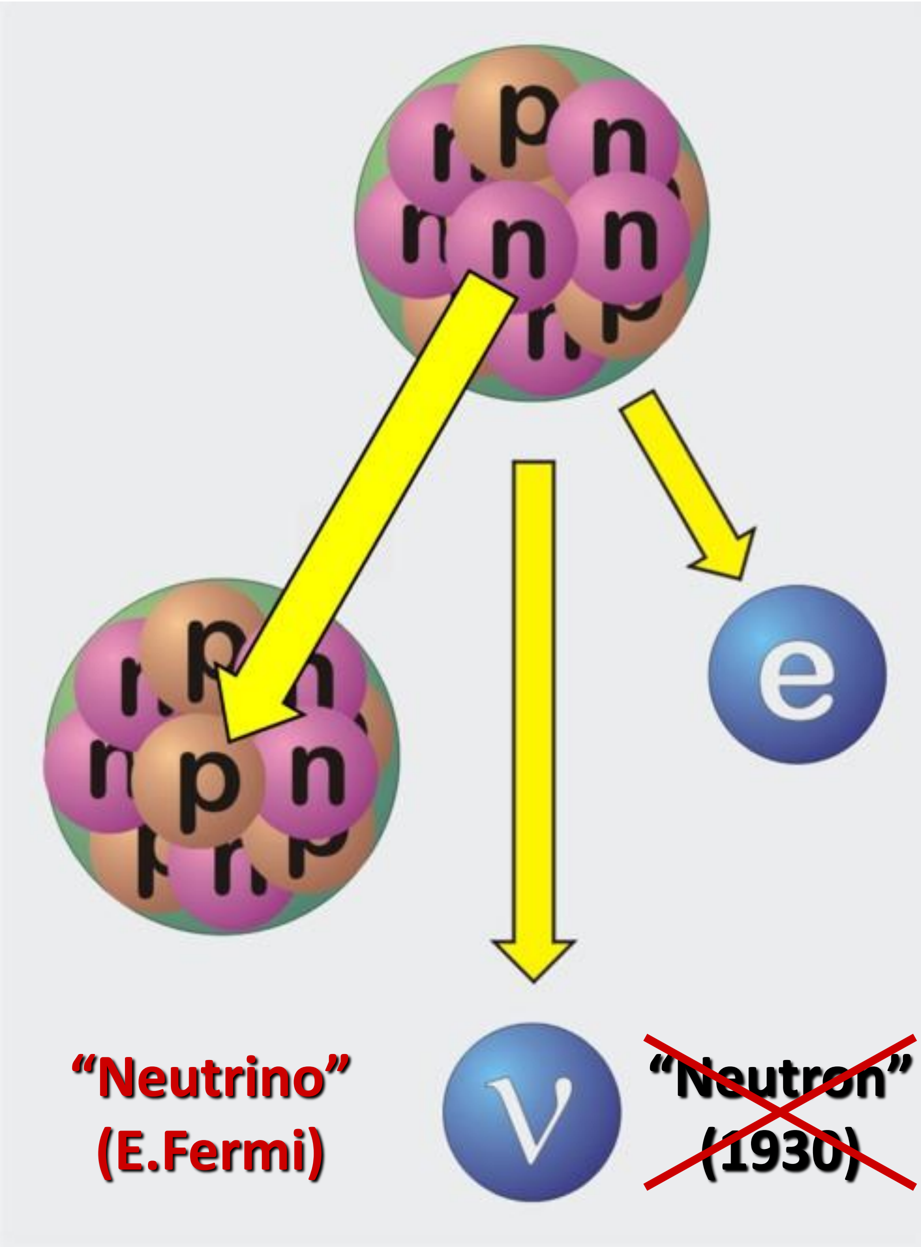
- 1934: Enrico Fermi presents his theory of the beta decay in a paper entitled 'Tentative theory of beta rays'

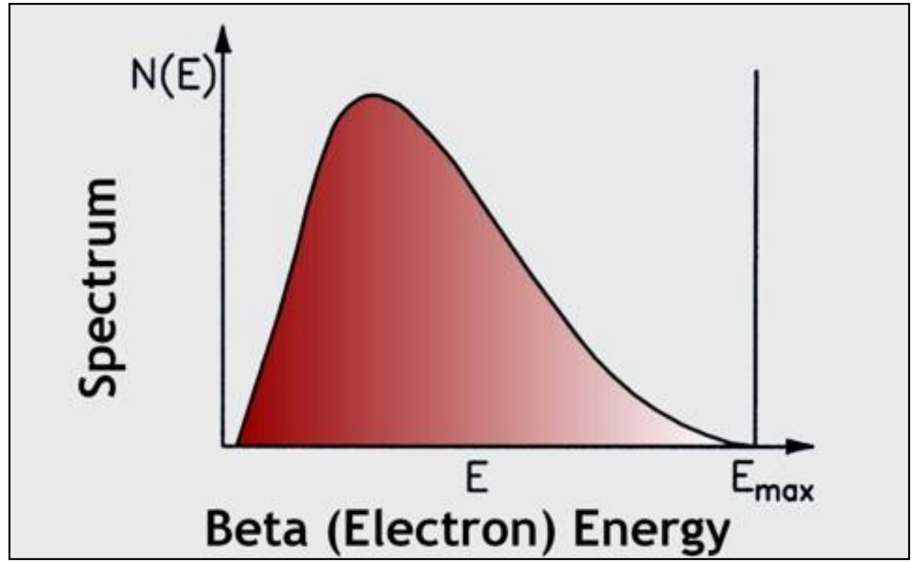
He introduces the name **"neutrino"** (ν_e), which is different to neutron, and beta decay is decay of neutron



A neutron n^0 turns into a proton p^+, electron e^- and a neutrino χ^0 in a single point of the space

FERMI EXPLANATION OF THE BETA DECAY SPECTRUM





Enrico Fermi
(1901-1954)
Nobel Prize 1938

- The paper was rejected by *Nature* since according to the editor 'contained speculations too remote from reality to be of interest to the reader'

- The paper eventually appeared in italian in *Nuovo Cimento*

ANNO IV · VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 · XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

WHO INVENTED THE NAME NEUTRINO?

[5]The "neutrino," a funny and grammatically incorrect contraction of "little neutron" (in Italian neutronino), entered the international vocabulary through Fermi, who used it sometime between the conference in Paris in July 1932 and the Solvay Conference in October 1933, where Pauli used it. The word arose in a humorous conversation at the Istituto di via Panisperna. Fermi, Amaldi, and a few others were present and Fermi was explaining Pauli's hypothesis about his "light neutron." To distinguish this particle from the Chadwick neutron, Amaldi jokingly used this funny name. Quoted by Ugo Amaldi in the preface to *20th Century Physics: Essays and Recollections. A Selection of Historical Writings by Edoardo Amaldi*, edited by G. Battimelli and G. Paoloni (World Scientific, Singapore, 1998).

From L. Bonolis "Bruno Pontecorvo. From slow neutrons to oscillating neutrinos" AJP 73(6): 487 (2005)

CONSEQUENCES OF FERMI'S THEORY FOR NEUTRINOS

- Fermi theory implied that neutrino could bump into a neutron and convert it into a proton and an electron.

- Neutrino ceases to be a shorthand for 'lost energy'. It carries energy along with it until it hits something.

Neutrino can be revealed !!

- 1934: Bethe and Pierls calculate from the Fermi's theory the probability of interactions between neutrinos and matter. They found it to be incredibly small. The interaction become known as weak interaction. Neutrinos could travel through the Earth without interruption 'like a bullet through a bank of fog ' They concluded:

There is no practically possible way of observing the neutrino

BRUNO PONTECORVO'S IDEA

- 1946: Bruno Pontecorvo comes with an idea to capture a neutrino (seminal report at Chalk River Laboratory in Canada).
  Nuclear power in uranium reactor should also produce 10 million billion neutrinos each second!
  With right detector it would be possible to capture a few

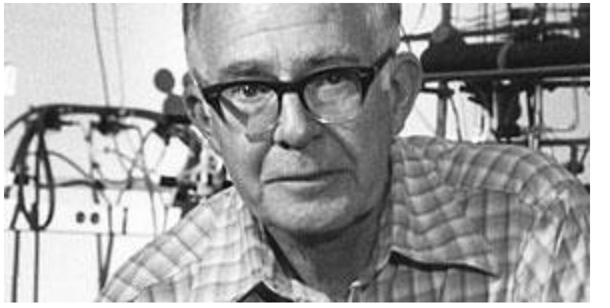
Pontecorvo's idea: a huge vat of chlorine (hundreds of tons). If neutrino hits Cl atoms, it is transformed in Argon

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

Ar is radioactive and decays. Its radiation can be detected.

ENTER RAY DAVIS

- 1955: Ray Davis realized an experiment (based on the Pontecorvo idea) in the Savannah river nuclear reactor in South Carolina



Result: Nothing!

Reactor were producing <u>antineutrinos</u> and not neutrinos. Chlorine would have been fine to detect neutrinos !!
By seeing nothing- Davis implicitly proved that neutrinos are different from antineutrinos

DETECTING NEUTRINOS FROM A NUCLEAR EXPLOSION

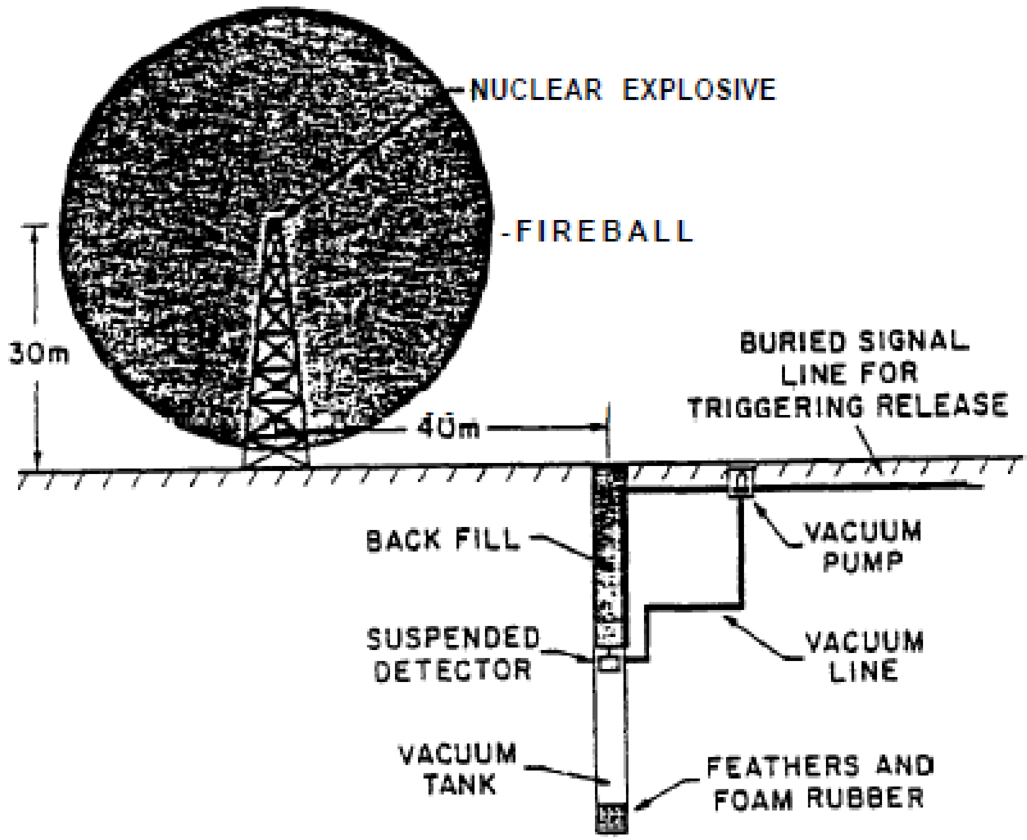
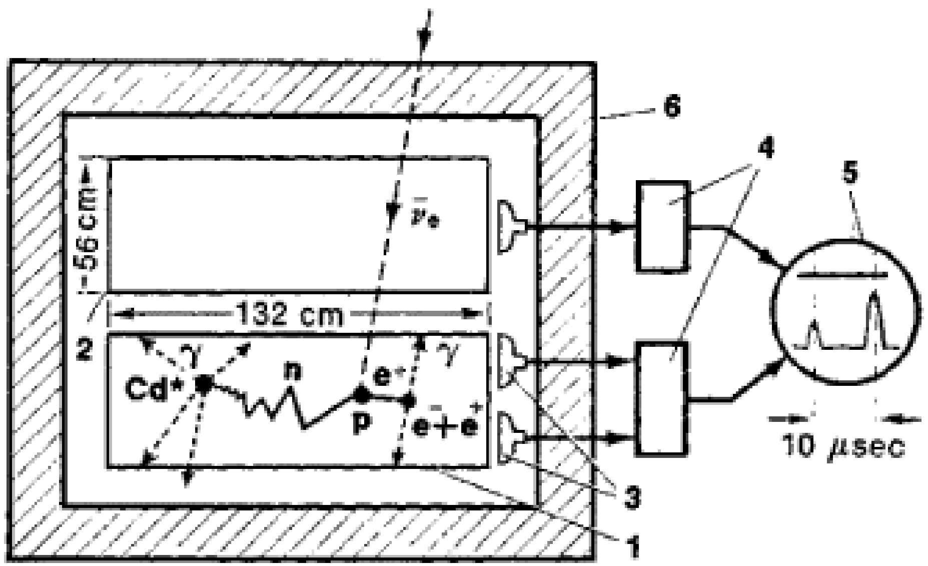


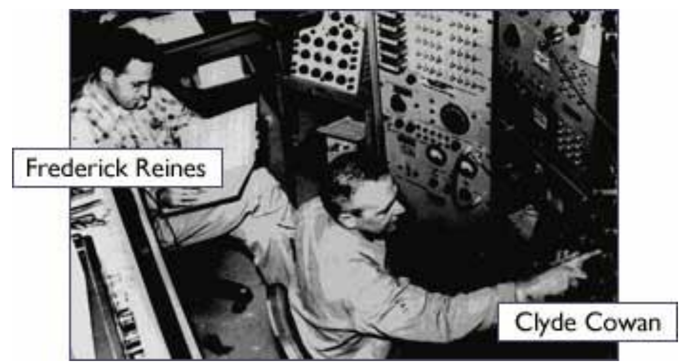
Figure 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor.

Reines and Cowan project 1st idea. However they realized that there is a better way to realize the experiment….

PROJECT POLTERGEIST

- 1953-56: Reines and Cowan experiment. target made of 400 liters of a mixture of water and cadmium chloride. The anti-neutrino coming from the nuclear reactor interacts with a proton of the target matter, giving a positron and a neutron. The positron annihilates with an electron of the surrounding material, giving two simultaneous photons and the neutron slows down until it is eventually captured by a cadmium nucleus, implying the emission of photons some 15 microseconds after those of the positron annihilation. All those photons are detected and the 15 microseconds identify the neutrino interaction.

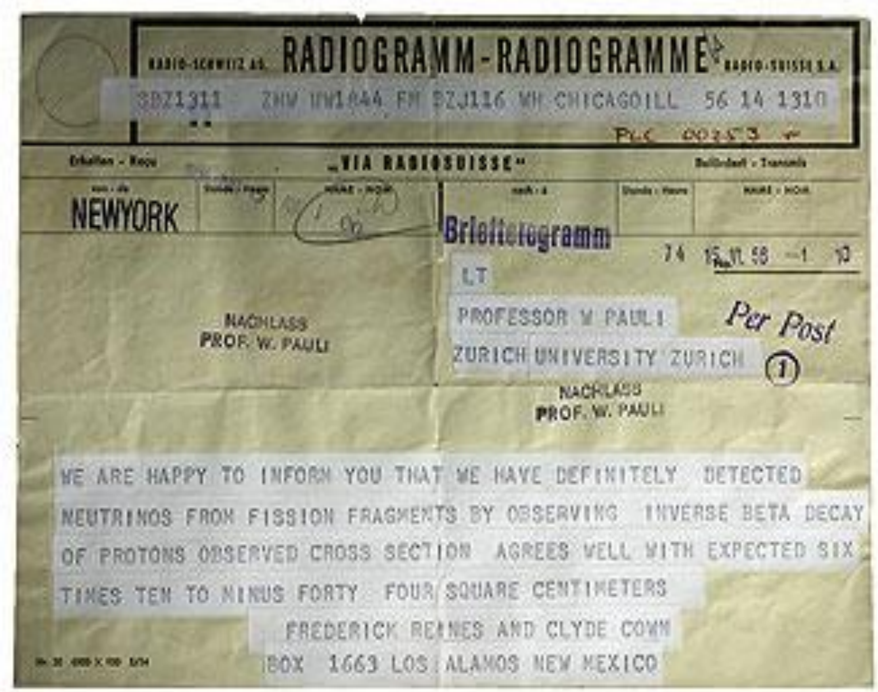




- 1955: The detector was taken to Savannah River 12 meter underground to shield it from cosmic rays

1956: NEUTRINO DISCOVERY

- Summer 1956: Poltergeist recorded gamma-rays separated by 5.5 μs.



RADIOGRAMM - RADIOGRAMME

SBZ1311 ZHW UW1844 FN PZJ116 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

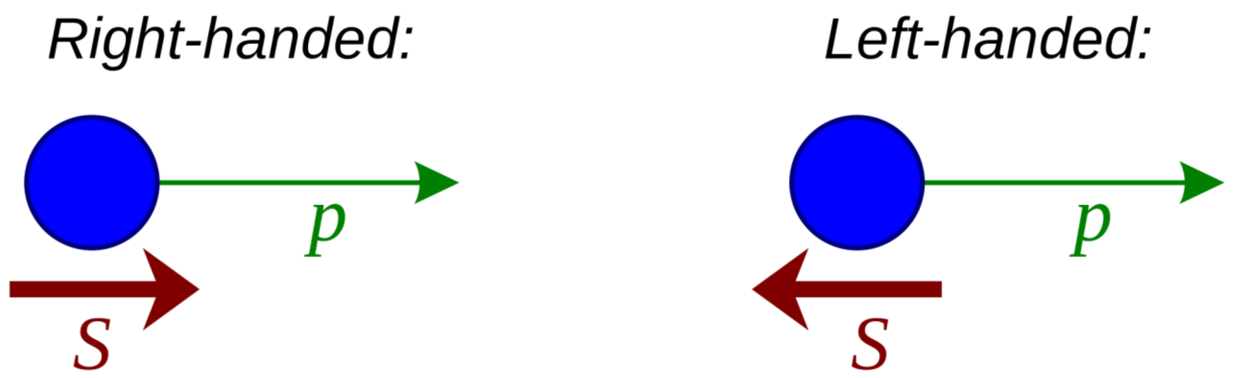
FREDERICK REINES AND CLYDE COWAN

BOX 1663 LOS ALAMOS NEW MEXICO

On 14 June, Cowan & Reines sent Pauli a telegram announcing that they found the neutrino he invented a quarter of century earlier.

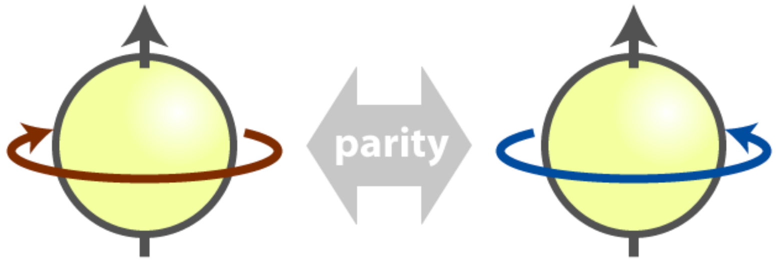
HELICITY

- Helicity: projection of the particle spin along the direction of motion



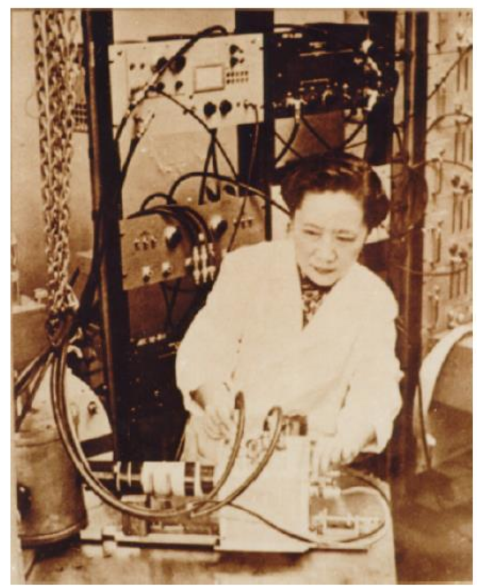
- For massive particles it depends on the reference frame.

PARITY VIOLATION IN THE WEAK INTERACTIONS



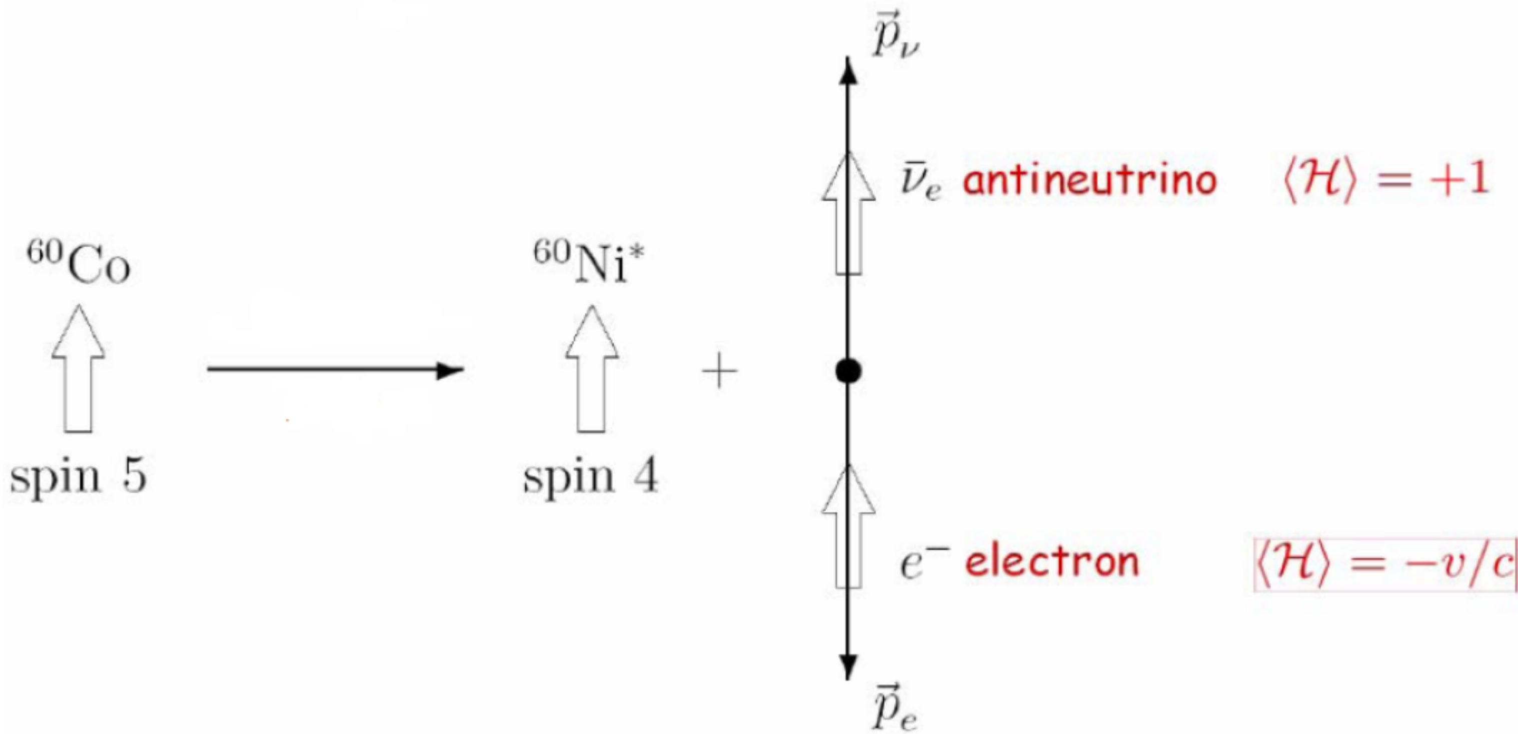
First hints that there are only LH neutrinos and RH antineutrinos

1956: T. D. Lee and C. N. Yang predict P violation

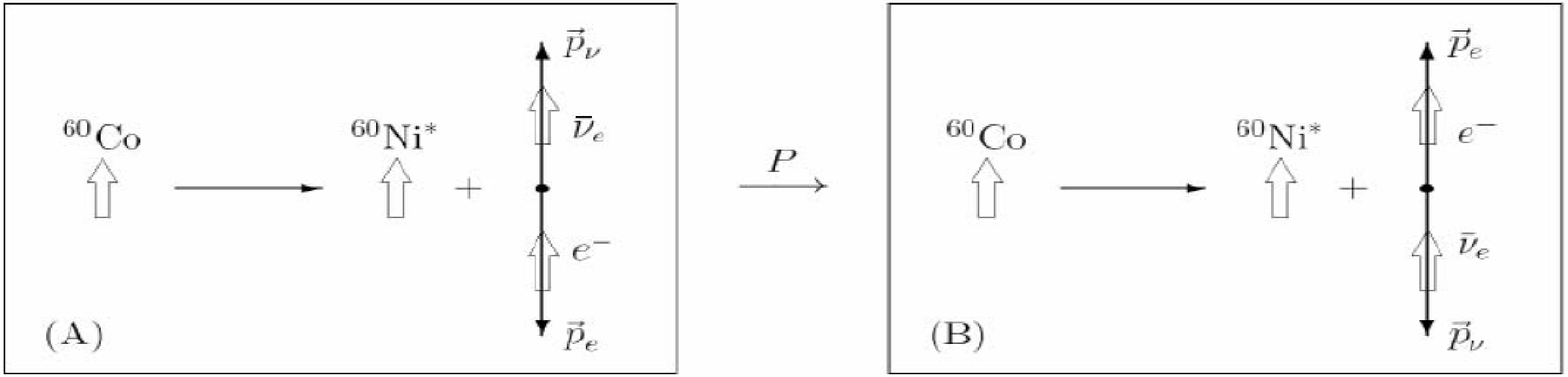


1957: Wu et al. observed maximum P violation

WU EXPERIMENT



Helicity: $\mathcal{H} = \dfrac{\vec{s}\cdot\vec{p}}{|\vec{p}|}$



parity transformation:

- polar vectors change sign: $\vec{p} \to -\vec{p}$
- axial vectors don't change sign: $\vec{s} \to \vec{s}$

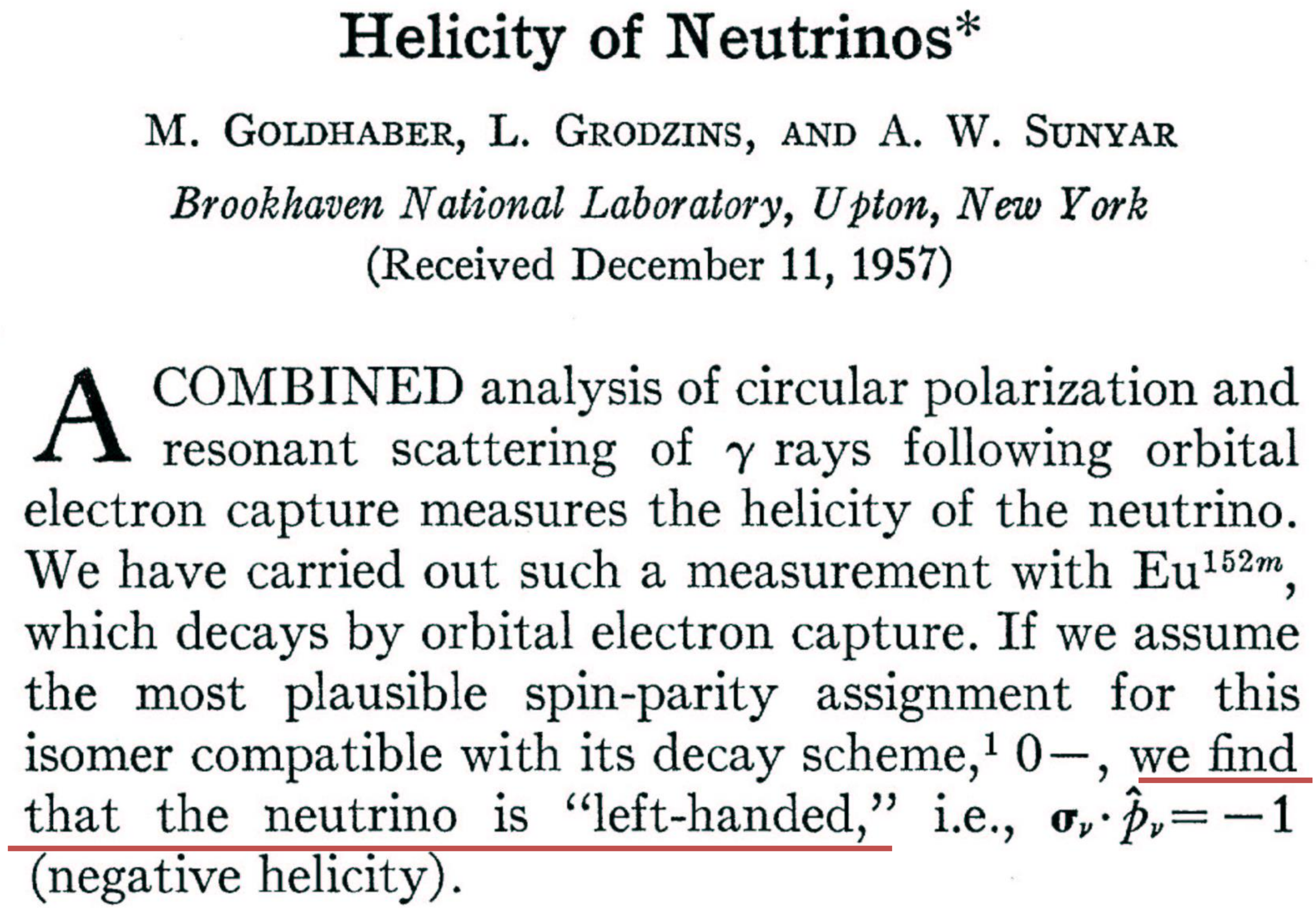
experiment:

- nuclear spins are aligned through magnetic field, measurement of the electrons
- reverse magnetic field for other scenario

result:

beta emisssion is preferentially in the direction opposite to the nuclear spin $\Rightarrow$ parity is violated

Neutrinos are Left-handed



Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR

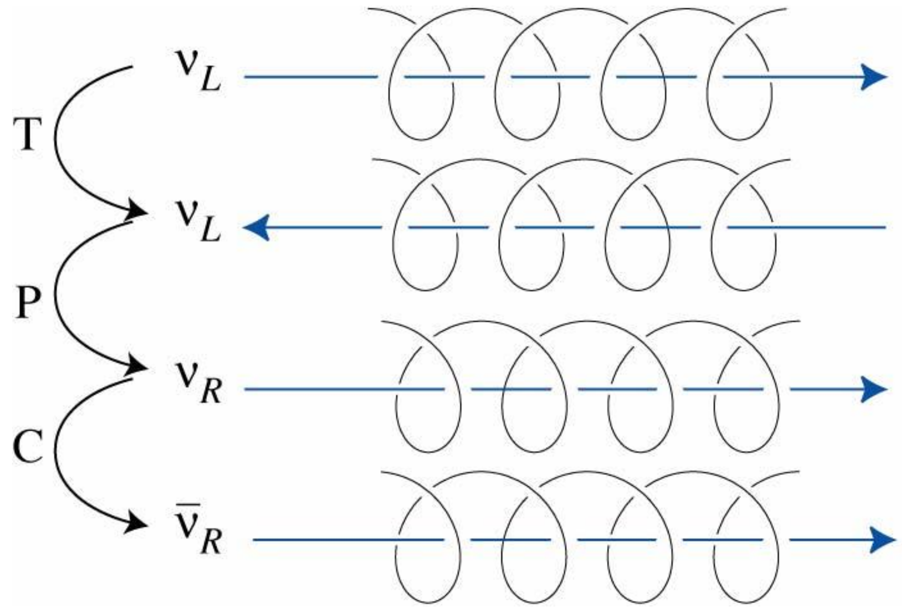
Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Anti-Neutrinos are Right-handed

- CPT theorem in quantum field theory
  - C: interchange particles & anti-particles
  - P: parity
  - T: time-reversal
- State obtained by CPT from ν_L must exist: $\overline{\nu}_R$



HOW SUN SHINES?

This question challenged scientists for a hundred and fifty years, beginning in the middle of the nineteenth century. Theoretical physicists battled geologists and evolutionary biologists in a heated controversy over who had the correct answer.

- 1939: Hans Bethe published his paper 'Energy Production in Stars' where he worked out the basic nuclear processes by which hydrogen is burned into helium in stellar interiors.

Bethe's Classic Paper on Nuclear Reactions in Stars

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5-6) that *no elements heavier than He^4 can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. Introduction

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \qquad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^+ \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^+ \\ N^{15}+H=C^{12}+He^4. & \end{array} \qquad (2)$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

No neutrinos
from nuclear reactions
in 1938 ...

The combination of four p[...] and two electrons can occur essentially o[...] two ways. The first mechanism starts with [...]ombination of two protons to form a deuter[...] with positron emission, *viz.*

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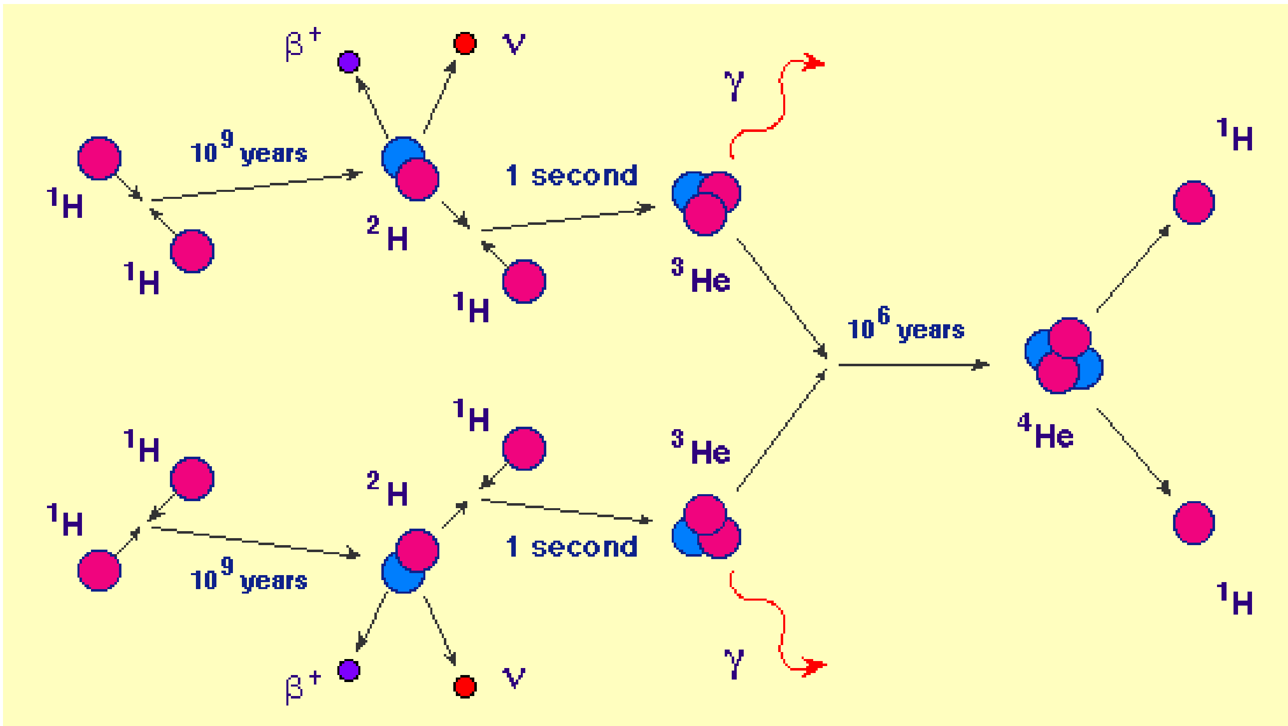
THE p-p CHAIN IN THE SUN

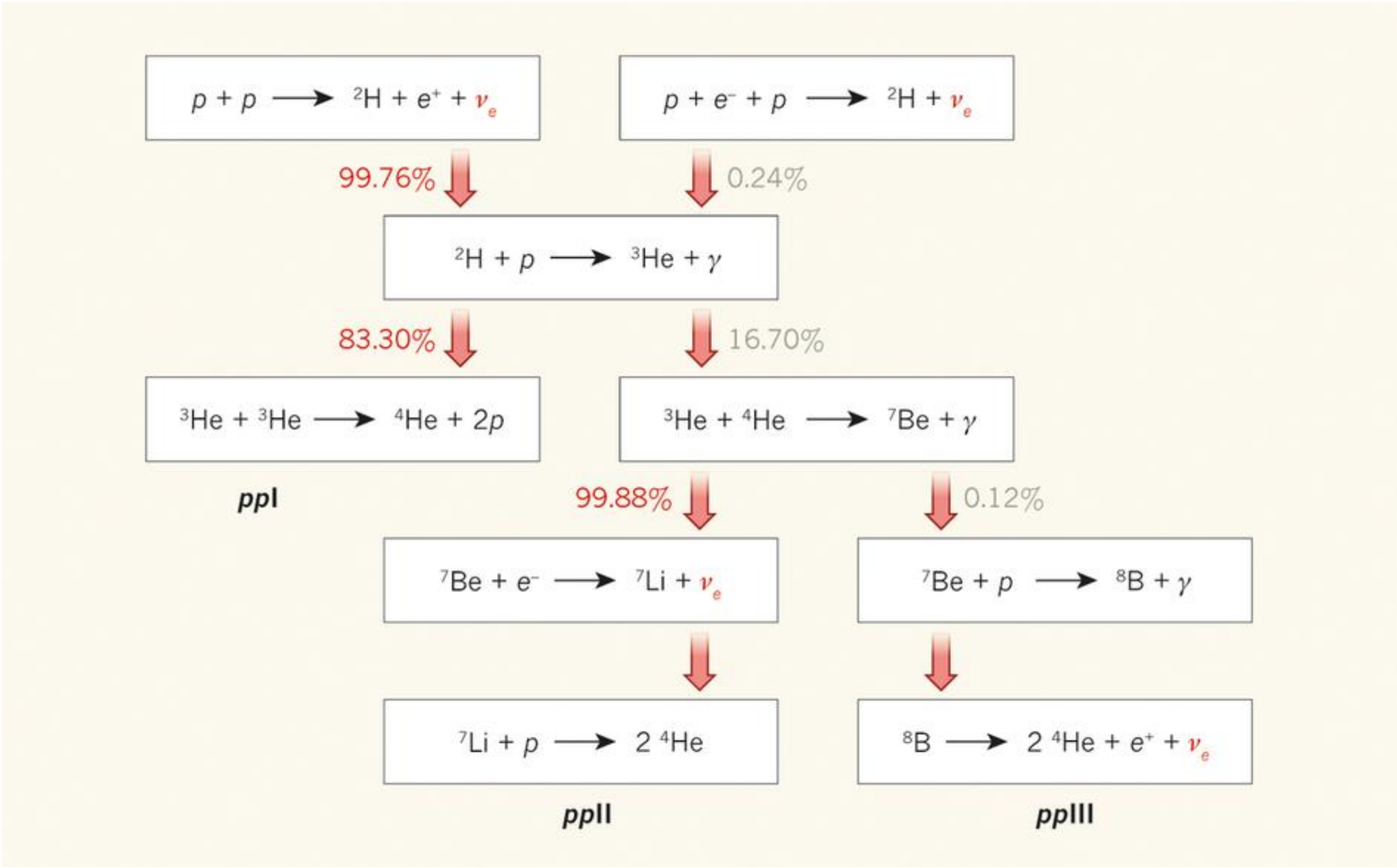


The *pp* neutrino energy is less than half than required to affect chlorine.

- 1955: Davis finds no evidence of solar neutrinos

A GLIMMER OF HOPE

- 1958: Bethe realized that production of Be can happen, but only rarely. If Be-7 was produced it could bump into one of the solar proton, fusing togheter to make B-8.



Neutrino can have energy as high as 15 MeV that Davis'experiment could detect!!

ENTER JOHN BAHCALL

- 1962: John Bahcall wrote a paper pointing out that the rates for beta decay processes in stars would differ from those being used by astrophysicists

- February 1962: Davis wrote an historical letter to Bachall asking about the specific process involving Be-7 and B-8 and producing neutrinos.

- 1963: Bahcall first attempt was complete.
  However, it did not give too much encouragement:
  4000 liter tank would capture only one neutrino event every 100 days !

(Further calculations by Bahcall improved by a factor 20 the rates)

Davis was eager to build a 400,000 litres experiments. However, the venture was considered high risk.

HOMESTAKE MINE EXPERIMENT

- 1965: Excavation started in Homestake Gold Mine, South Dakota

- End summer 1966: the experiment was ready to begin

- How many solar neutrinos could Davis hope to capture?

Bahcall calculated that a neutrino born along with B-8 would have a chance of

10^{-36}/sec $\equiv$ 1 SNU (1 Solar Neutrino Unit)

to hit a single atom of Cl-37.
Given a capture rate of 1 SNU it would be an average waiting time of six days for a single capture.

Using the best models for solar interior and data on various nuclear reactions Bahcall predicted a rate of

7.5 ± 3 SNU

- 1968: Davis announced his first result. If the experiment was observing solar neutrinos the rate was at most

3 SNU

in tension with Bahcall predictions

SOLAR NEUTRINO PROBLEM

SOLAR NEUTRINO PROBLEM

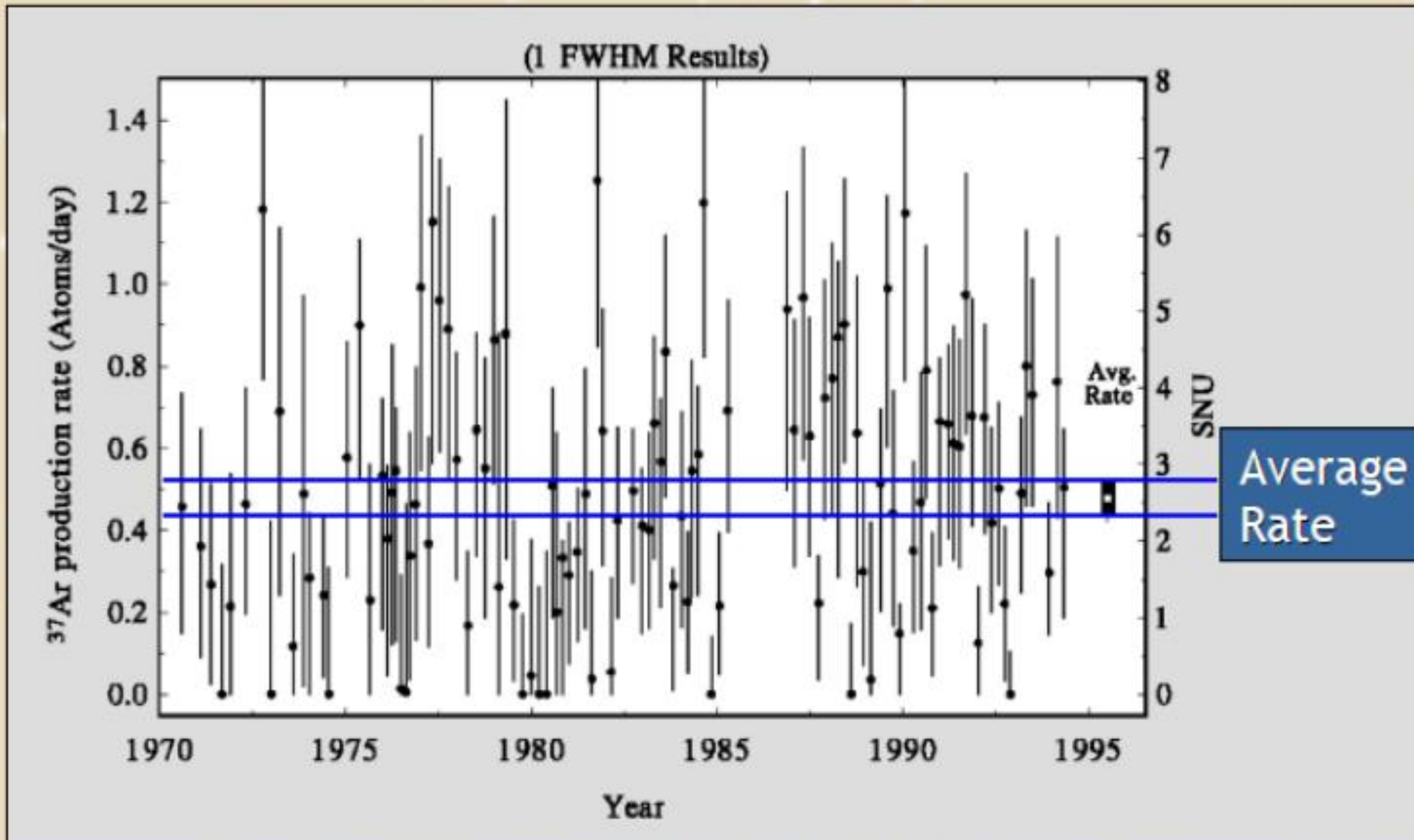
- 1978: After ten years from the first data Davis continued to improve his experiments and Bahcall had improved and refined his calculations. However, the disagreement still remained.

  Pontecorvo wrote to Bahcall:

  "It starts to be really interesting! It would be nice if all this ends with something unexpected from the point of view of [neutrinos]. Unfortunately it will not be easy to demonstrate this even if nature works that way."

- 1988: Still very few people worked on solar neutrinos. Davis's chlorine experiments was the only one recording data for two decades. Bahcall summed the situation: "All the people working steadily on solar neutrinos, theorists and experimentalists, could (and often did) fit confortably into the front seat of Ray Davis's car ".

Results of Chlorine Experiment



Average (1970–1994) $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ **SNU**

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

Theoretical Prediction 6–9 SNU

"Solar Neutrino Problem" since 1968

MUONS AND PIONS

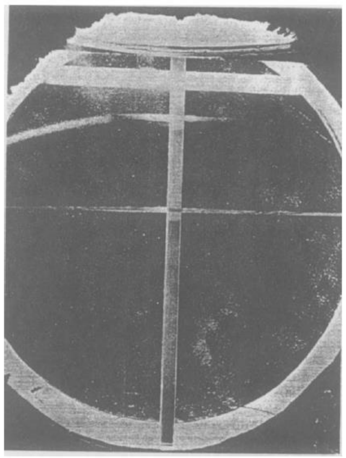
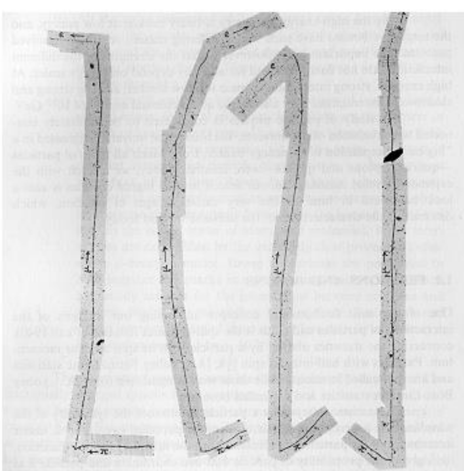


Figure 6. Stopping muon. First photograph of a muon travelling slowly enough to allow measurement of its ionization and momentum. From these quantities Sfreet and Stevenson deduced the muon mass: $M_\mu \sim 130\ M_e$
Source: Harvard Physics Department photo archives. A detail from this picture appeared in Street and Stevenson, "New Evidence", (Ref. 138).

In the 1940s, cosmic radiation revealed new particles

- 1937: Discovery of muon μ. Mass ~ 105 MeV/c^2 , Spin 1/2



- 1947: Discovery of pion π. Mass ~ 139 MeV/c^2 , Spin 0

MUONS AND NEUTRINOS

- 1947: Pontecorvo proposed compelling evidences that the muon was not the carrier of the nuclear force, but a heavy version of the electron.

If that was the hole story a muon should produce an electron and a neutrino

$$\mu \to e\gamma$$

However, a young physicist Jack Steinberger, was about to show that this is not the case, uncovering a great mistery

- 1947: Steinberger concluded his experiments. The result was that muon decays into an electron accompanied by two further particles, not one. Everything was consistent with the idea that it consisted of two neutrinos, that escaped the detection

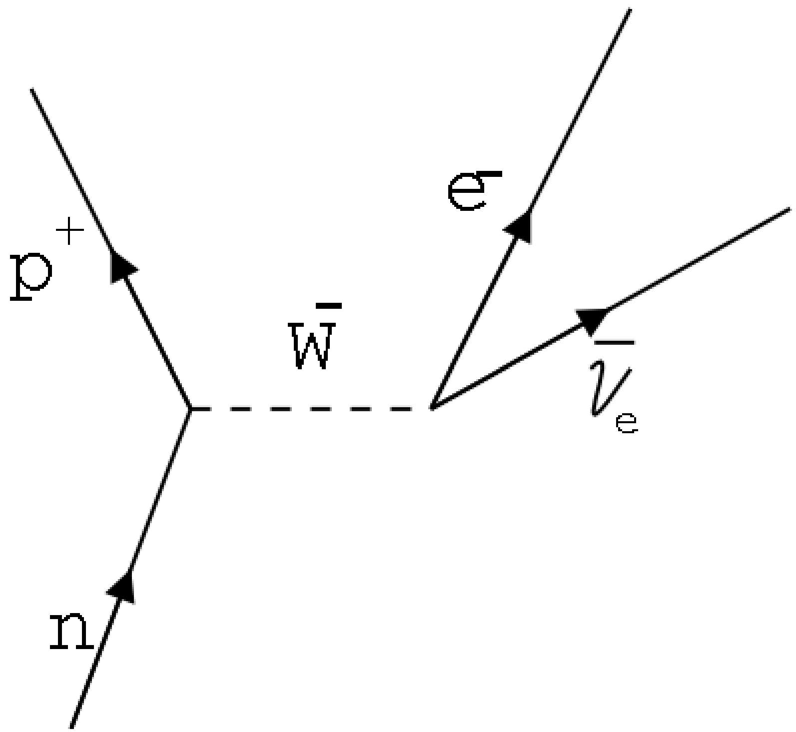
- 1958: Steinberger studying the decay of pions produced by accelarators in muons and neutrinos, found a ratio consinstent with parity violation

Bruno Pontecorvo started wondering: Are the neutrinos produced when a pion decays into a muon, the same as those emitted in conventional beta decays?

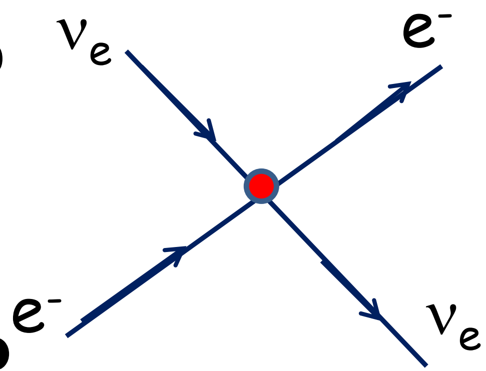
W BOSON

The theory of Fermi of the weak interactions implied that the chances of neutrinos reacting grew with energy. However, this had absurd implications: With increasing energy this cross section grows without limit!

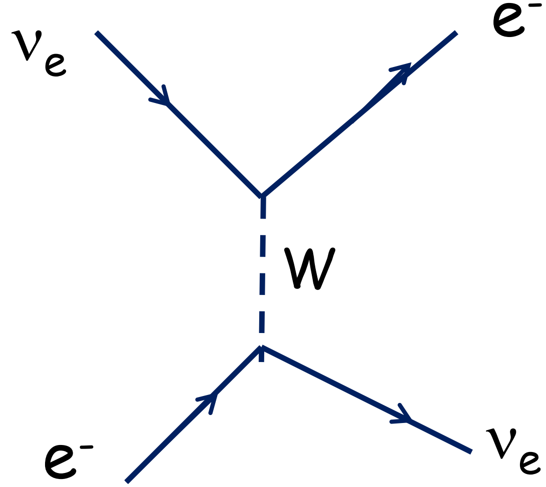
The solution was to abandon the idea that particles all met in a single point. Like e.m. forces are carried by photons, weak forces are carried by an agent, W boson.



The introduction of a finite-mass W boson removes the divergence of ν_e e scattering

σ [

] $= \dfrac{G_F^2 s}{\pi} \xrightarrow[s\to\infty]{} \infty$

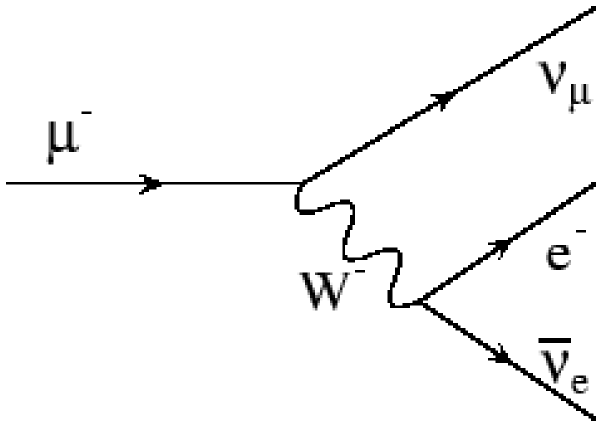
σ [

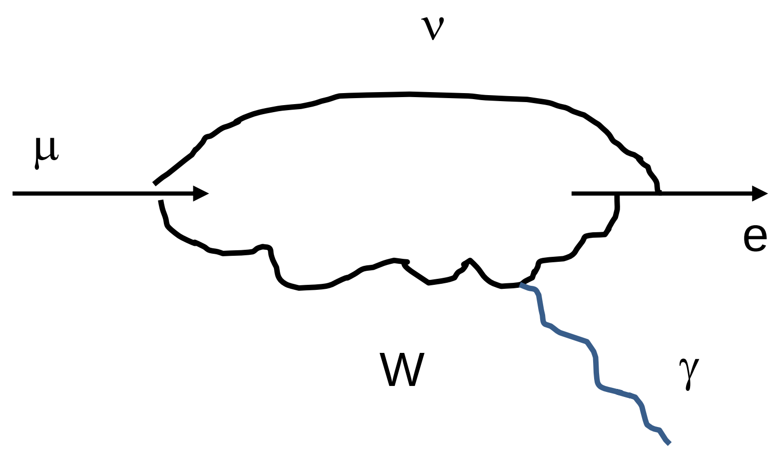
] $\xrightarrow[s\to\infty]{} \dfrac{G_F^2 M_W^2}{\pi}$

Finite!

MUON DECAYS AND W BOSON

Muon decay





If the two neutrinos are the same (nu_e = nu_mu) it would be possible for a muon to convert into an electron through the intermediate W

- Pontecorvo was the first to propose that the muon is more than just an heavy electron: it has a special "muon-ness". Today we call it flavor. Pontecorvo extended its idea also to neutrinos. Symmetry among particles.
  Electron and its sibling neutrino in one pair, muon and its sibling neutrino in another pair

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \qquad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$$

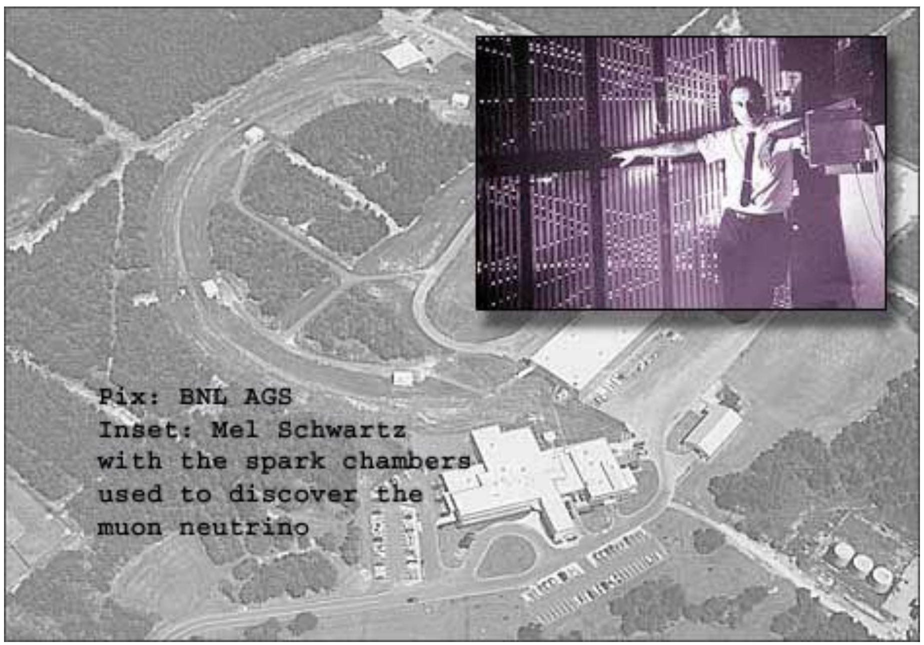
  Neutrinos carry memory of their provenance.

- How to probe it?

  Pontecorvo's idea was to make a large number of pions by smashing a beam of high-energy protons into a target. Pions decay into muons and neutrinos. A steel shield will absorbe muons, but is transparent to neutrinos. Several meter further another target acts as detector. It all neutrinos are alike, the number of electron and muon produced will be similar. However, if only muons appear, electron neutrino differs from muon neutrinos.

DISCOVERY OF MUON NEUTRINOS

- 1962: Leon Lederman, Mel Schwartz, Jack Steinberger and colleagues at the accelerator of Brookhaven National Laboratories realized an experiment based on Pontecorvo's idea. They prove that nu_mu are different from nu_e.



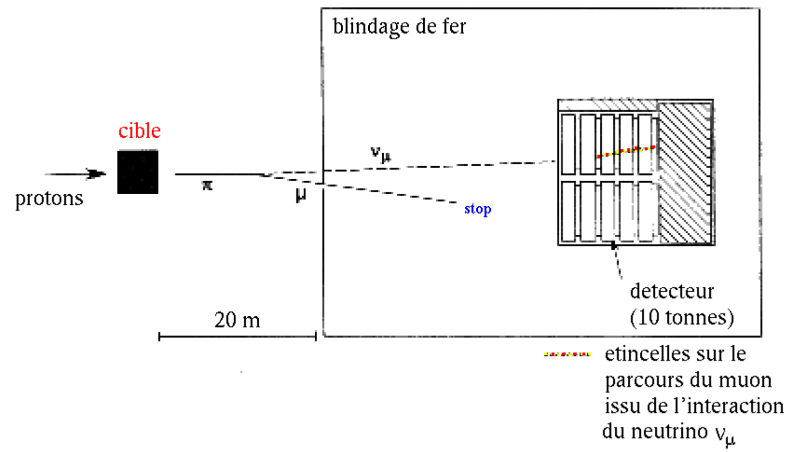
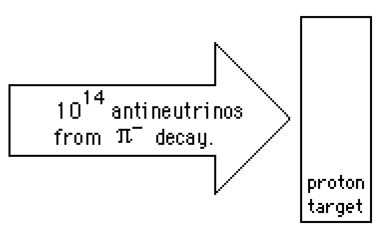


Schéma de l'appareillage utilisé par Schwartz, Lederman et Steinberger pour mettre en évidence la deuxième famille de neutrinos, les ν_μ. Les protons issus de l'accélérateur interagissent avec une cible en émettant des pions. Ces pions se désintègrent en muons et neutrinos ν_μ. Les muons s'arrêtent dans le blindage de fer. Les neutrinos interagissent dans le détecteur en produisant des muons qui laissent une trace dans les chambres à étincelles.



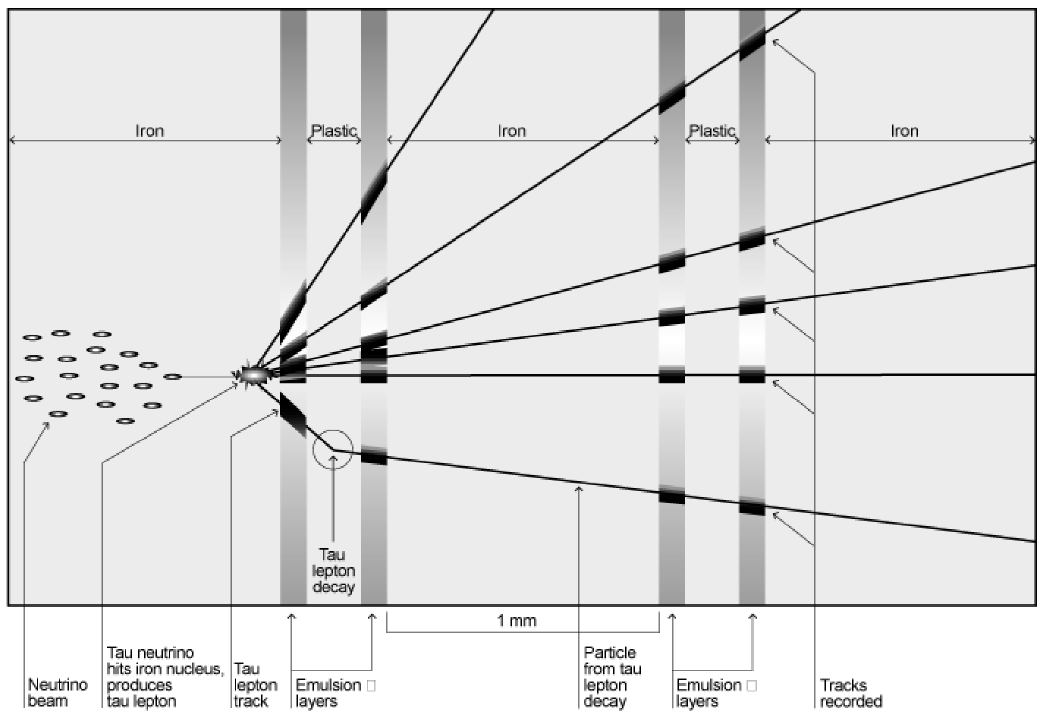
Reaction	Number observed
$\bar{\nu}_\mu + p^+ \rightarrow \mu^+ + n$	29
$\bar{\nu}_\mu + p^+ \rightarrow e^+ + n$	0

THREE NEUTRINOS

- 1976: the tau lepton was discovered….A third type of neutrinos, associated with the lepton, was required.

- 2000: DONUT experiment (Direct Observation of 'Nu-Tau') at Fermilab, Chicago discovers nu_tau

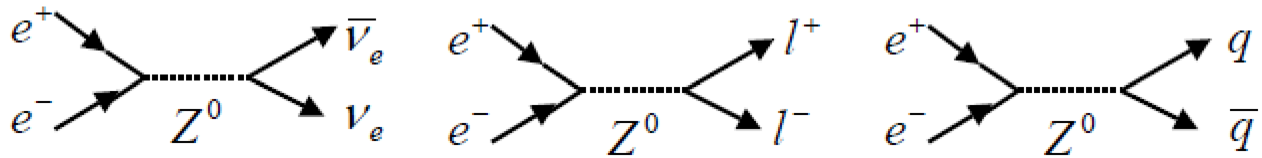
Detecting a Tau Neutrino



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

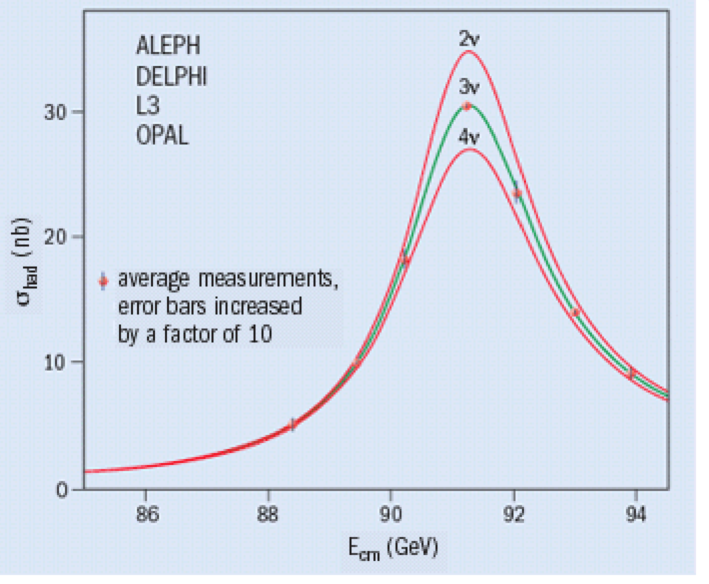
NUMBER OF LIGHT NEUTRINOS FROM COLLIDER EXPERIMENTS

The most precise measurements of the number of light neutrino types, Nν, come from studies of Z production in e+e− collisions. The invisible partial width, Γ_{inv}, is determined by subtracting the measured visible partial widths, corresponding to Z decays into quarks and charged leptons, from the total Z width. The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model.



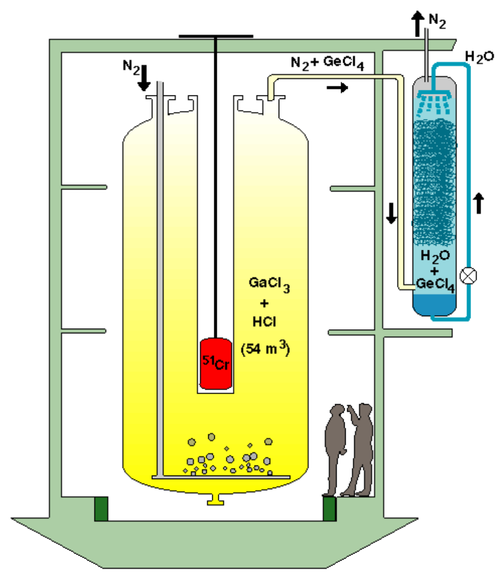
$$N_\nu = 2.9841 \pm 0.0083$$

Only 3 neutrinos with mass less than the Z mass



BACK TO SOLAR NEUTRINO PROBLEM

- In order to solve the solar netrino problem Bahcall proposed an experiment sensitive to pp neutrinos. A Gallium experiment was proposed, since it has a lower threshold than a chlorine one. One would have sensitivity to the whole neutrino spectrum with good intensity.
  In 1990s the stage was set for two experiments with this technique, GALLEX in LNGS (Italy) and SAGE in URSS.

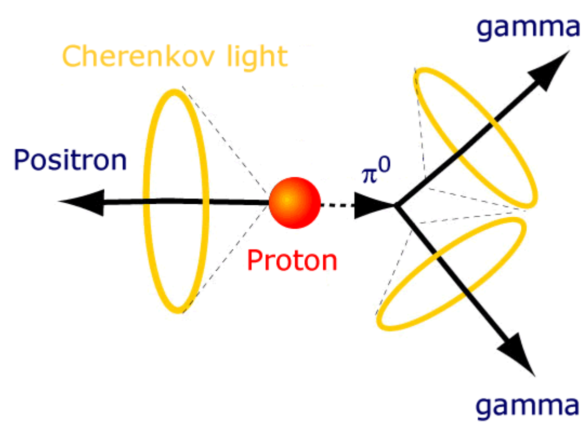


But even before these experiments a new way of detecting solar neutrinos was being born...

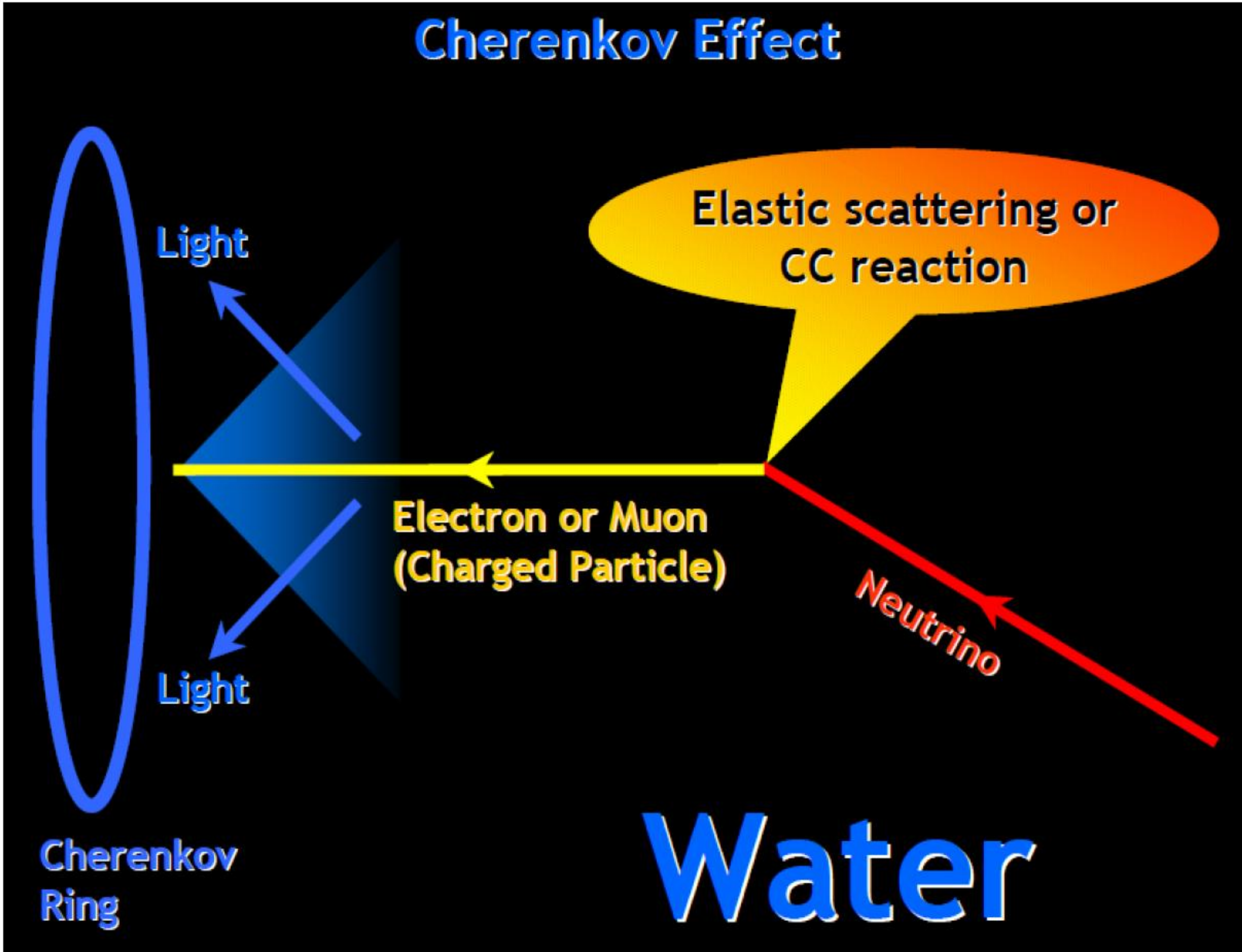
WATER CHERENKOV DETECTORS

- 1976: Designs for a new generation neutrino detectors made at Hawaii workshop, subsequently leading to IMB, HPW and Kamioka detectors.

- 1980-90: The IMB, the first massive underground nucleon decay search instrument and neutrino detector is built in a 2000' deep Morton Salt mine near Cleveland, Ohio. The Kamioka experiment is built in a zinc mine in Japan.

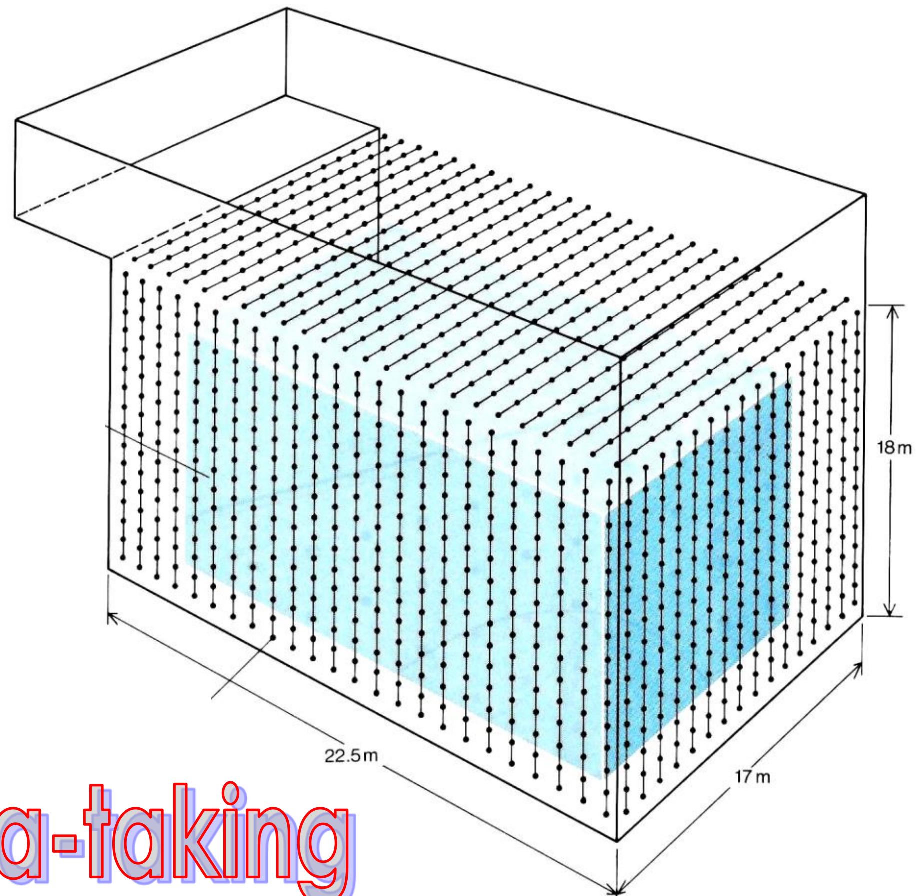


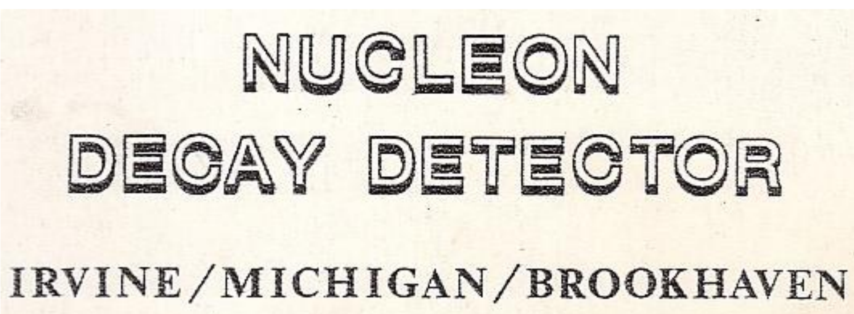
Proton decay is predicted in theories that attempt to unify the forces of nature


Cherenkov Effect
Elastic scattering or
CC reaction
Light
Light
Electron or Muon
(Charged Particle)
Neutrino
Cherenkov
Ring
Water

IMB: 8000 ton Water Cherenkov Detector

2400 x 5" PMTs



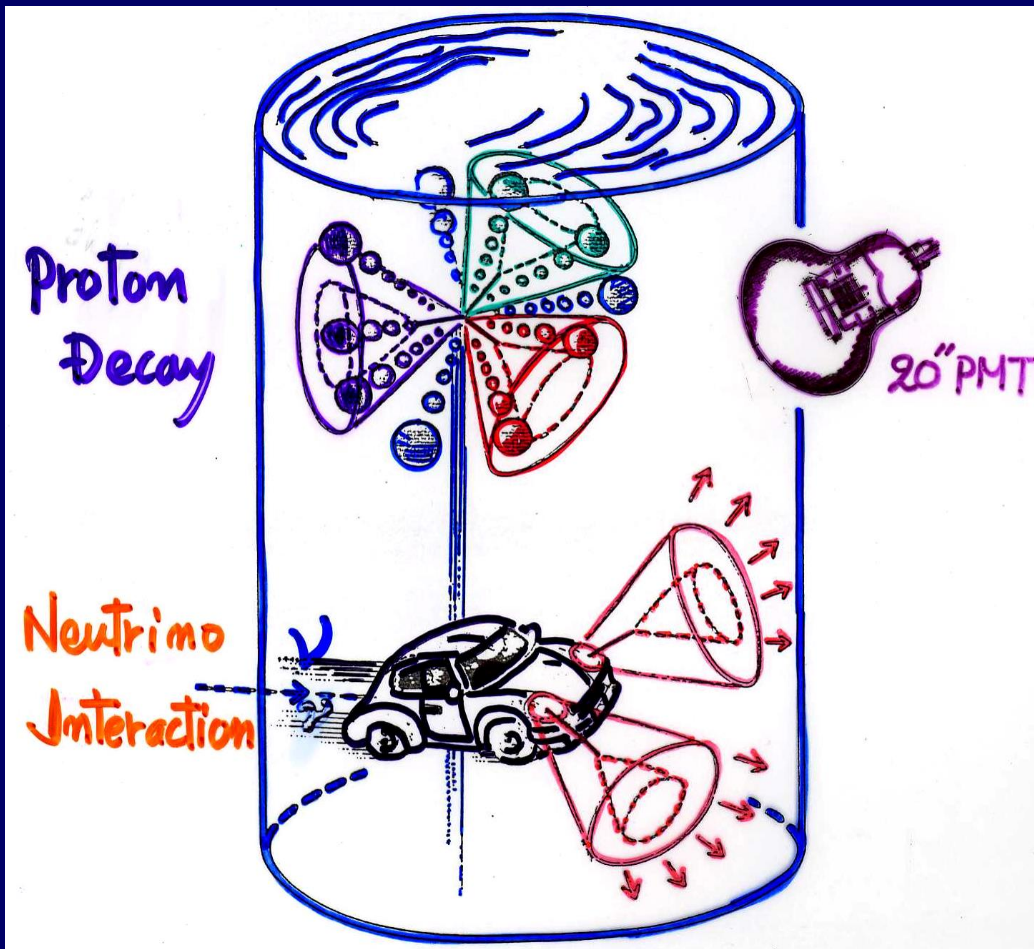


July 31, 1982 : data-taking

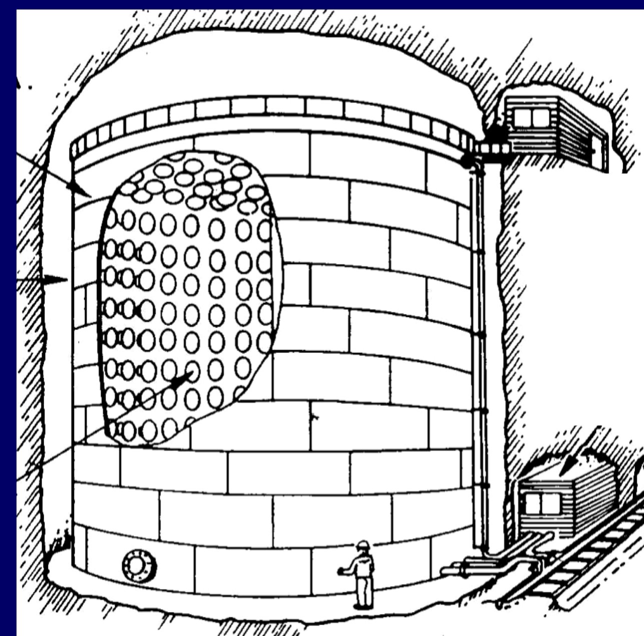
Kamiokande-I

Kamiokande : Kamioka Nucleon Decay Experiment

3000-ton Imaging Water Cerenkov Detector



July 6, 1983



January '83

First public report:

80 days of live time

No candidates for $P \longrightarrow e^{+} \pi^{0}$

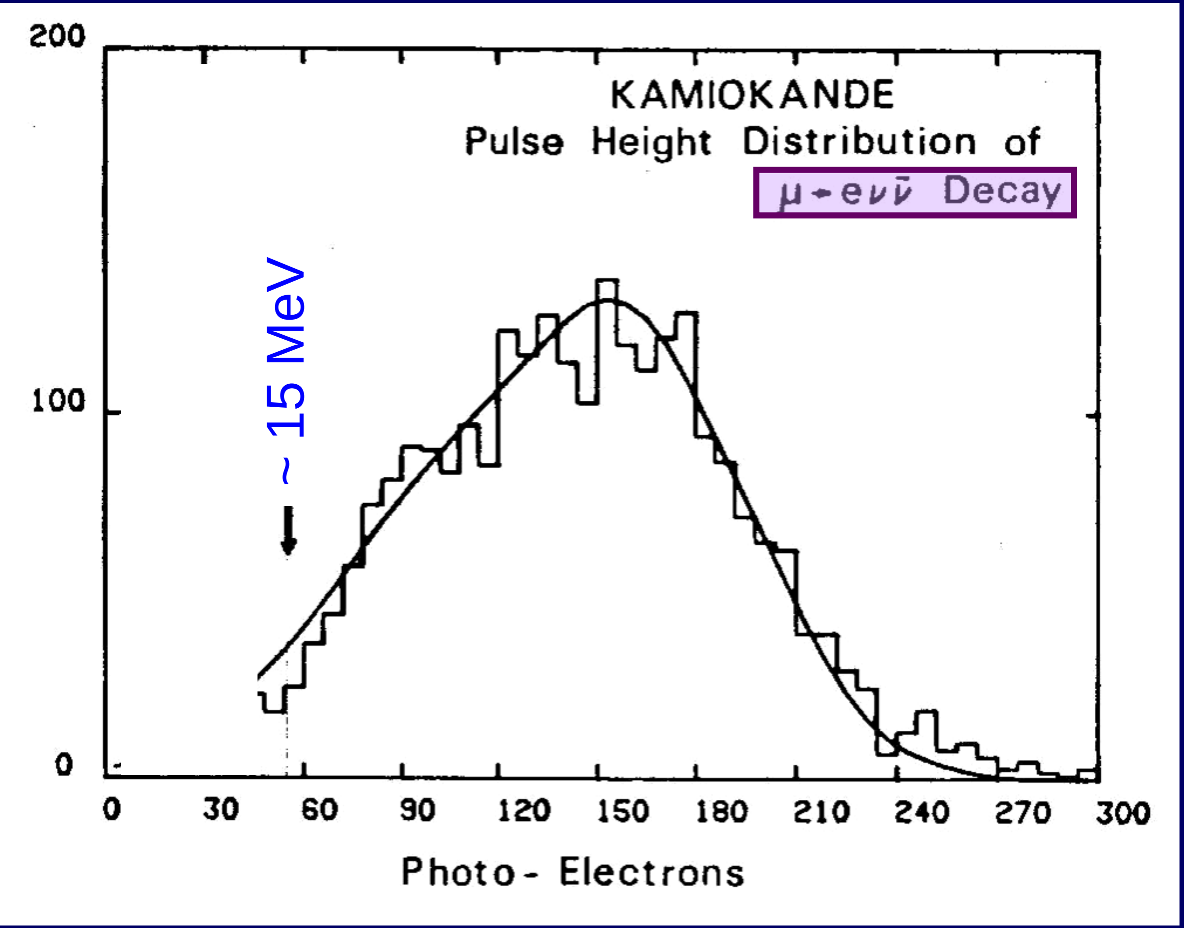
$t/b \geq 5 \times 10^{31}$ yr

May '83…. Kamiokande taking data

We need more light collection !

G: Uhhhh…. No kidding !

What invented Kamiokande-II ?

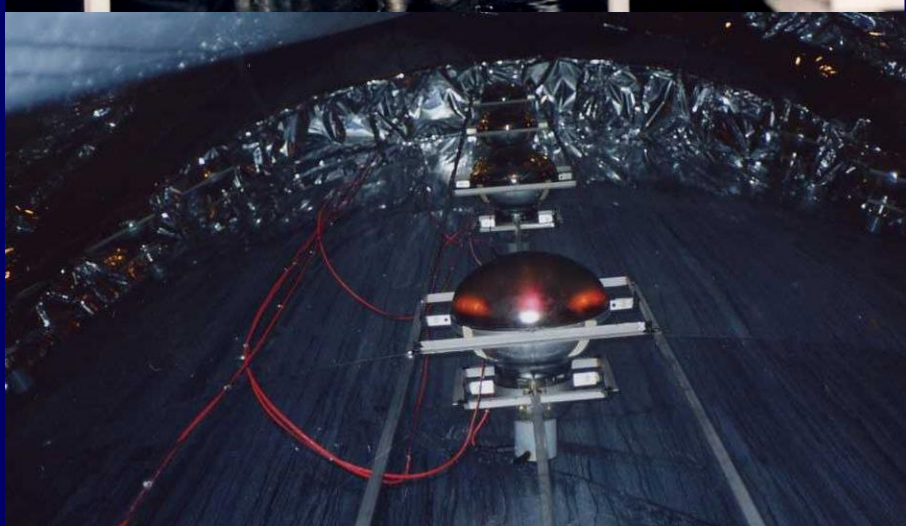


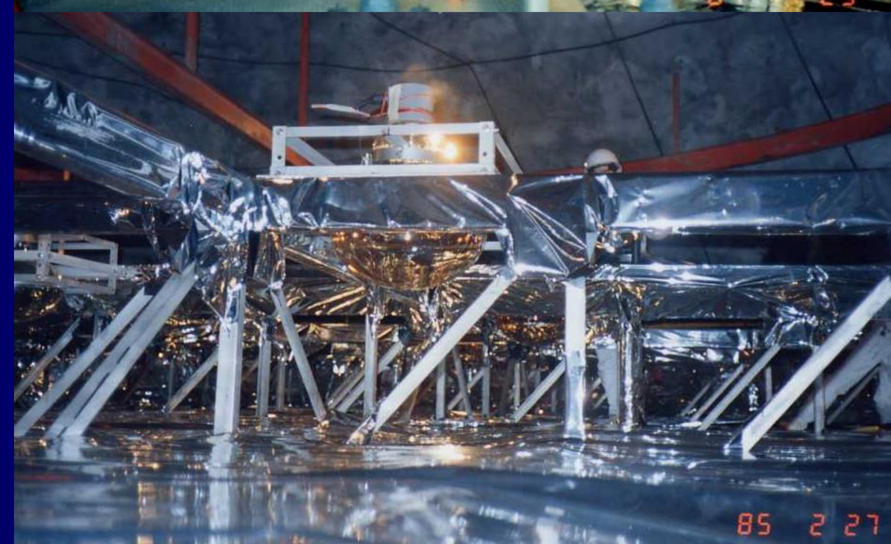
Masatoshi Koshiba: "Why not lower E_{th} down to 10 MeV to detect ^{8}B solar ν's!"
(1983)

Kamiokande-II

Kamiokande-II Construction

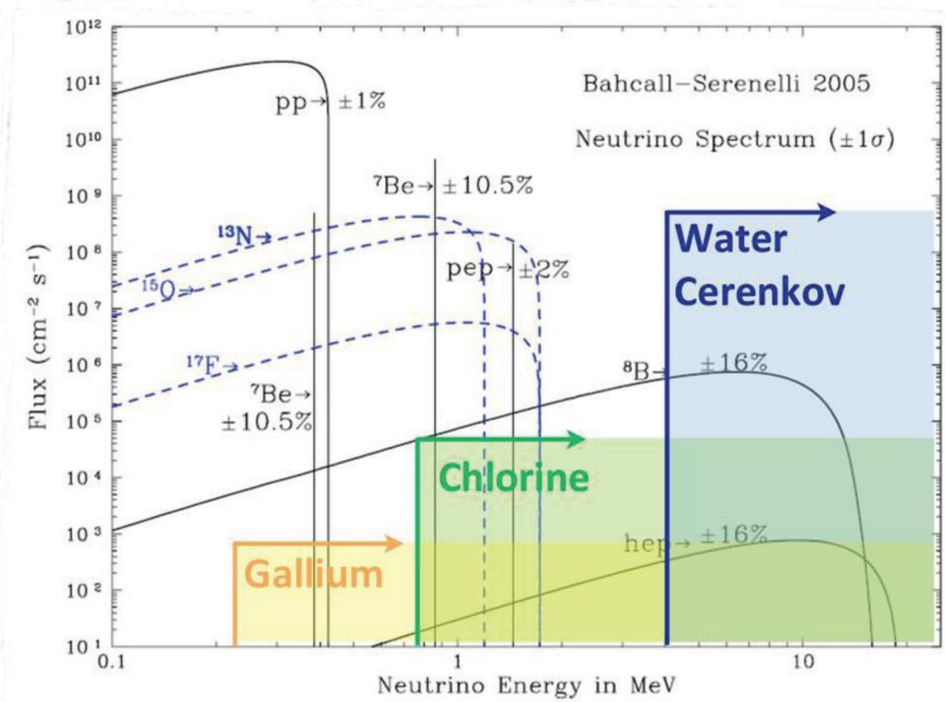
(September, 1984 ~)





- 1986: Kamiokande group makes first directional counting observation of solar neutrinos and confirms deficit.

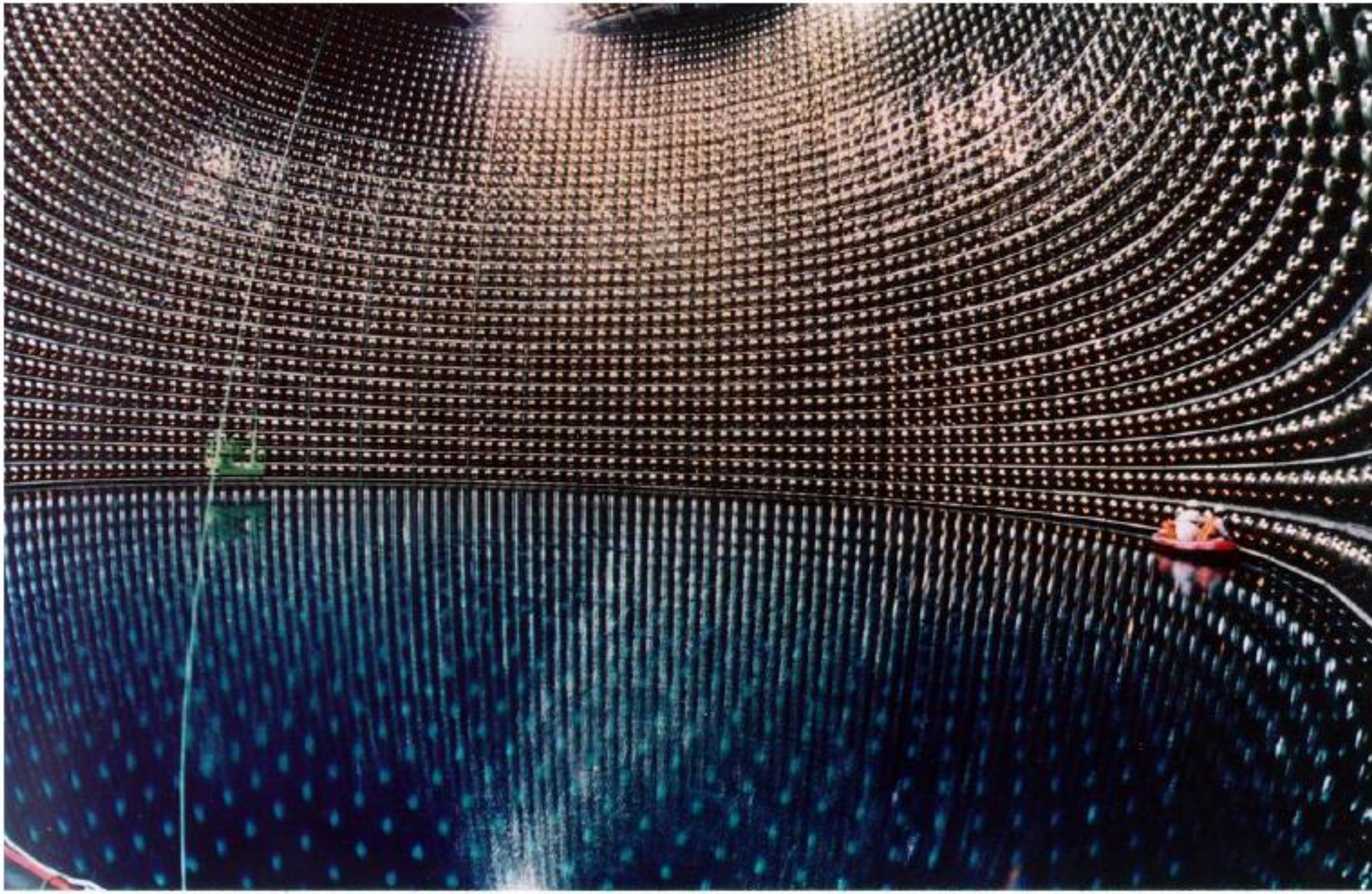
- 1991-2: SAGE (in Russia) and GALLEX (in Italy) confirm the solar neutrino deficit in radiochemical experiments.



In all energies it seemed that the number of neutrinos detected was only about one-half of the predicted by the solar models!

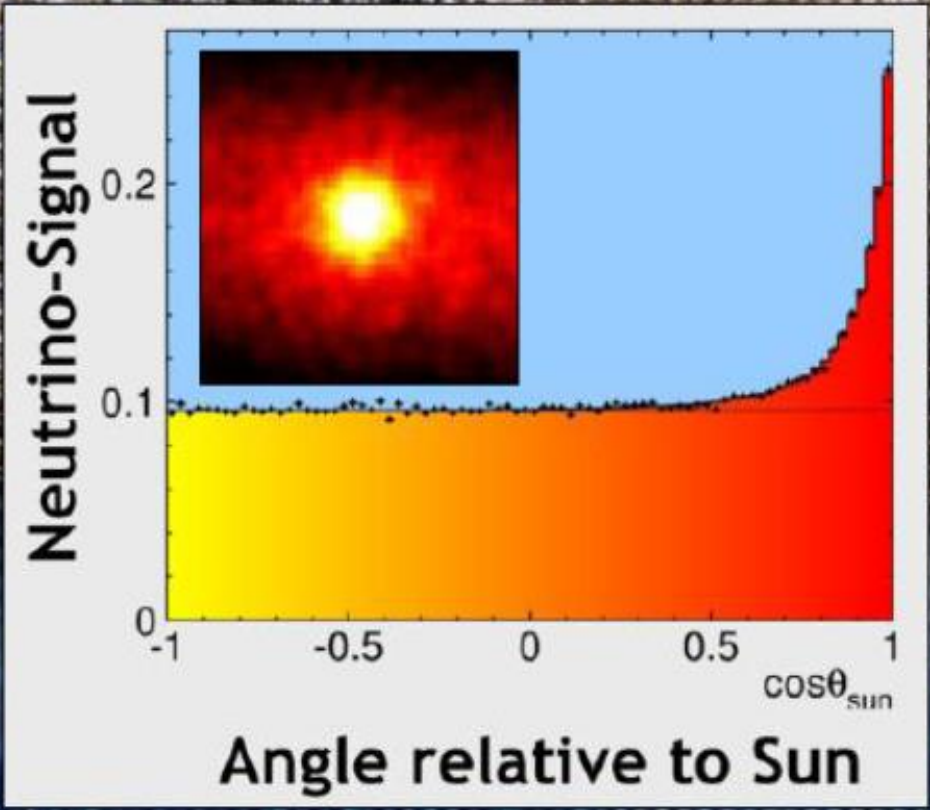
- 1996: Kamiokande is ready for more work. With ten times more water and PMT than Kamiokande, the detector was named Super-Kamiokande (SK)

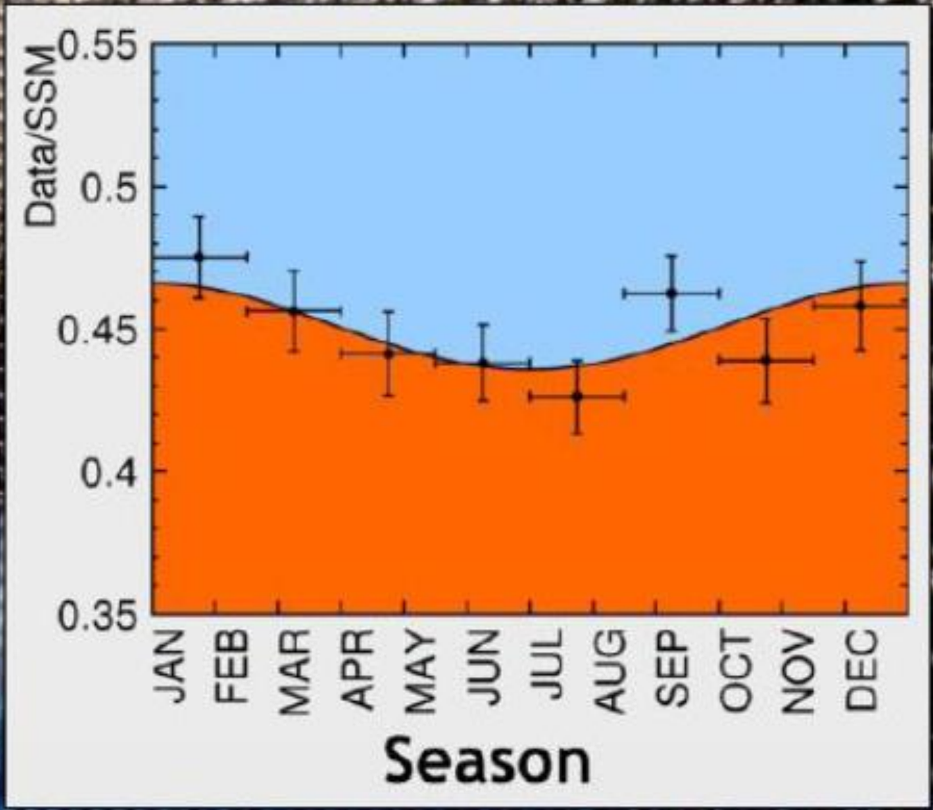
SUPER-KAMIOKANDE DETECTOR



SK is a cylindrical tank containing 50000 ton of light water surrounded by photomultipliers, located underground in the Kamioka mine in Japan.

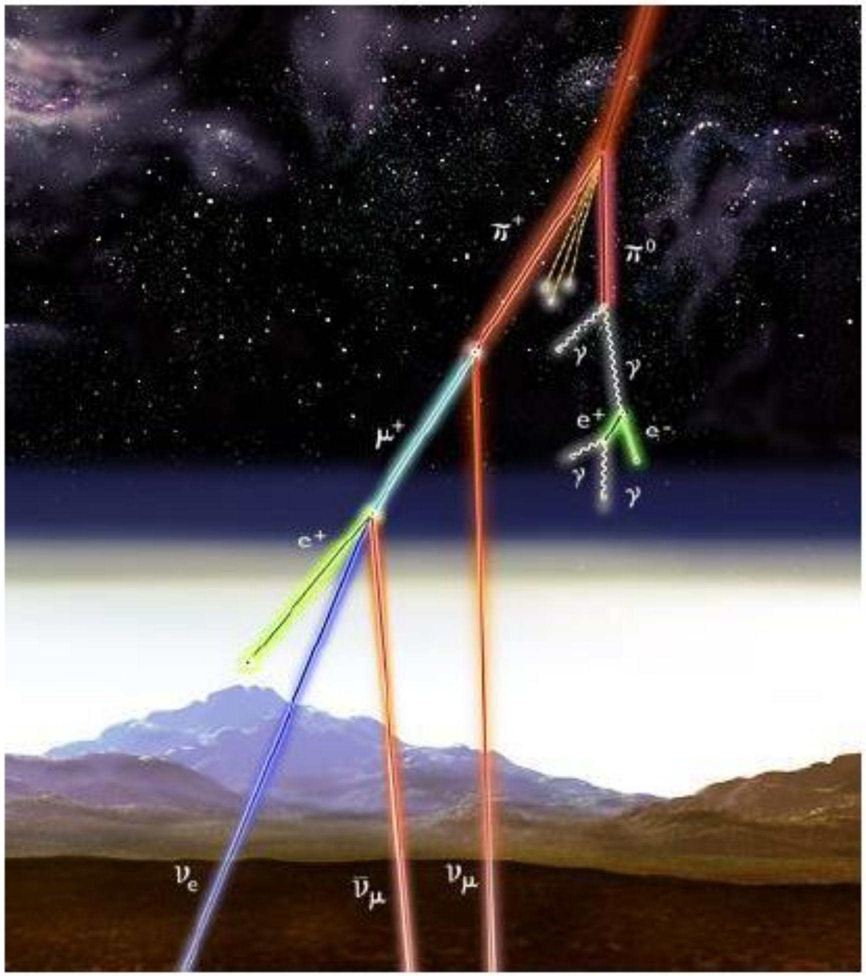
Super-Kamiokande: Sun in the Light of Neutrinos





ATMOSPHERIC NEUTRINOS

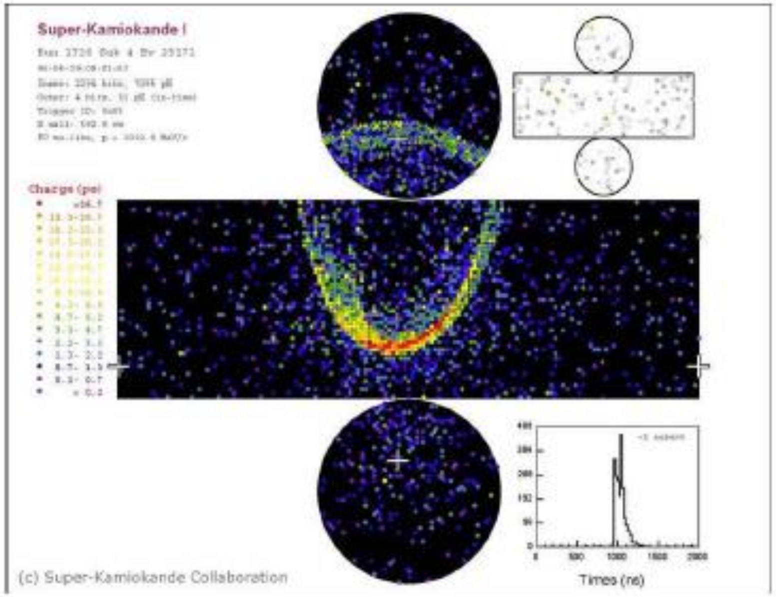
When cosmic rays, i.e. protons and heavier nuclei interact with the Earth's atmosphere they produce kaons and pions, which in turn decay into muons, electrons and neutrinos.



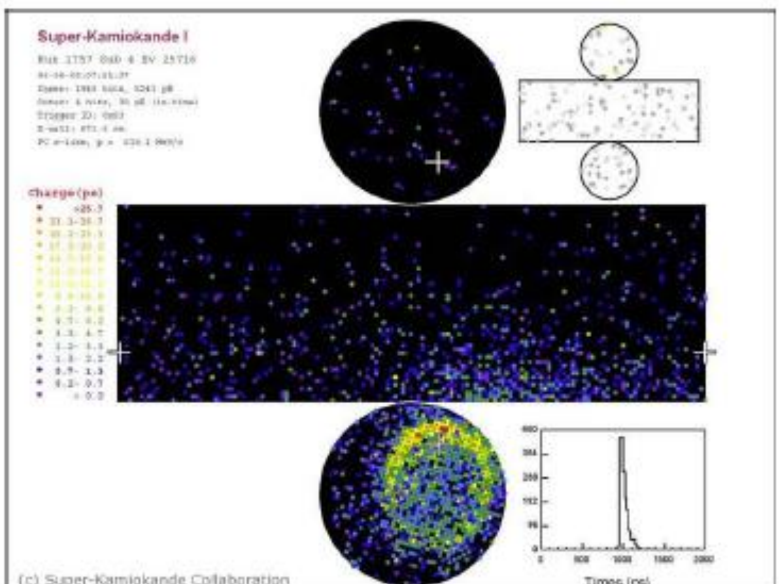
The flavor can be very well measured; from the simple production mechanism one expects

$$N(\nu_\mu) : N(\nu_e) = 2 : 1.$$

This ratio depends on the energy of the measured neutrinos since the lifetime of high energy muons is increased by their Lorentz factor so that they may hit the ground before decaying (at energies > few GeV).



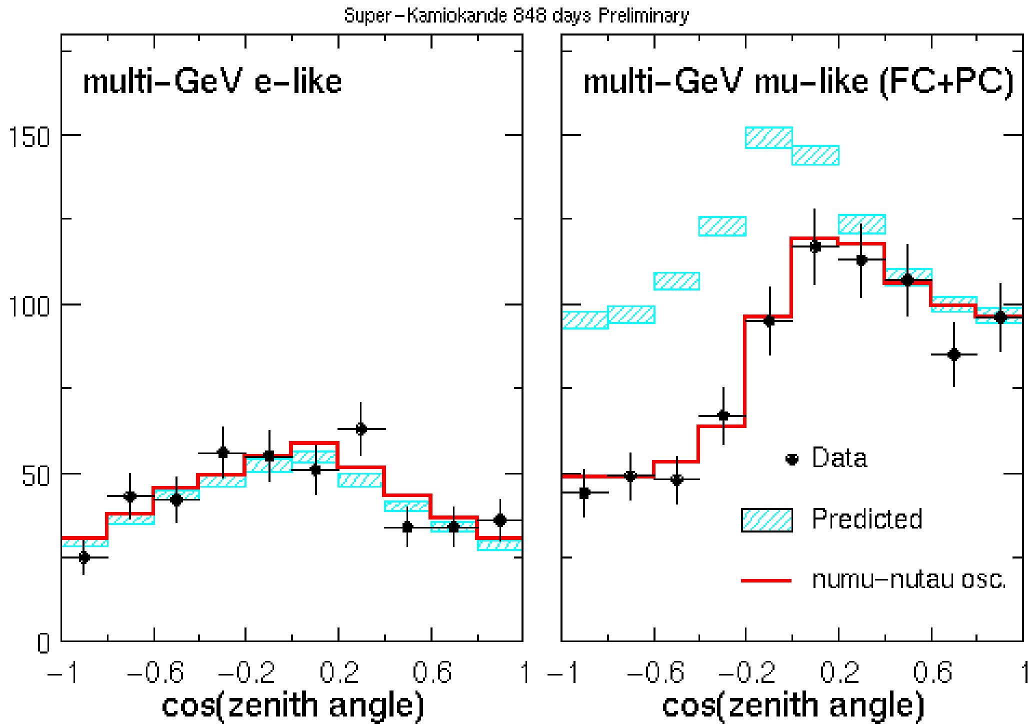
A Cherenkov ring occured by a muon neutrino. A muon neutrino interacts with a nucleon in water and transforms to a muon.

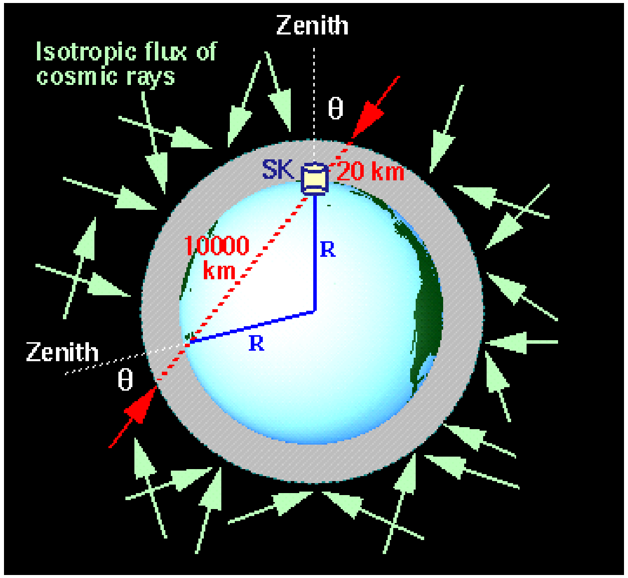


An electron neutrino event. An electron neutrino scatters an electron in water. The emitted electron generates a electromagnetic shower, leading to the fuzzy edge of the Cherenkov ring.

- 1985: Hints in both Kamiokande and IMB that the ratio of nu_mu to nu_e coming from the atmosphere was closer to 1 than to 2. The anomaly is at first believed to be an artifact of detector inefficiencies.

- Super-Kamiokande detection of atmospheric neutrinos





Muon data show an anomaly (clearly asymmetric distribution). Electron samples are compatible with the predicitons.

The flux of up-ward going muons (↑) is about two times lower than the flux of down-ward muons (↓).

COULD NEUTRINO DISAPPEAR IN FLIGHT, NOT JUST MUON-NEUTRINOS FROM THE ATMOSPHERIC ANOMALY, BUT ELECTRON NEUTRINOS TOO?

OSCILLATING NEUTRINOS

- 1957: Bruno Pontecorvo proposes neutrino-antineutrino ocillations analogously to K0-antiK0, leading to what is later called oscillations into sterile states.

- 1962: Ziro Maki, Masami Nakagawa and Sakata introduce neutrino flavor mixing and flavor oscillations.

- 1969: Gribov and Pontecorvo published their theory on neutrino oscillations based on the hypotheses that there are two varieties of neutrinos with different masses. They realized that laws of quantum mechanics allow neutrinos to oscillate back and forth between one state to another, but only if they have some (even tiny) mass.

$$\nu_{eL} = \cos\theta\,\nu_{1L} + \sin\theta\,\nu_{2L}$$

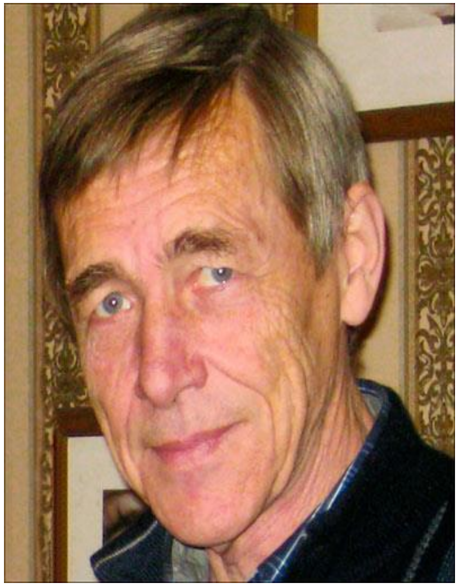
$$\nu_{\mu L} = -\sin\theta\,\nu_{1L} + \cos\theta\,\nu_{2L}$$

In Pontecorvo's original theory, electron neutrinos that had been created in the center of the Sun could convert into muon or tau neutrinos, being invisible to Davis's experiment.

Figure 3: Dubna 1988. Neutrino oscillations.

However, this idea was considered more as a mathematical curiosity. Large mixing angle was required to have significant conversions.

MSW EFFECT



Mikheyev (1985)

Smirnov (1985)

Wolfenstein (1978)

Opinions start to change when three theorists discovered a novel implication of the oscillation idea, known as MSW effect: As neutrino passed through the layers of the Sun, the presence of matter could amplify the likelihood that neutrinos oscillate. Even a small mixing angle would be enough.

Largely because the elegance of the theory, around 1990, physicists began to take idea of neutrino oscillations seriously.

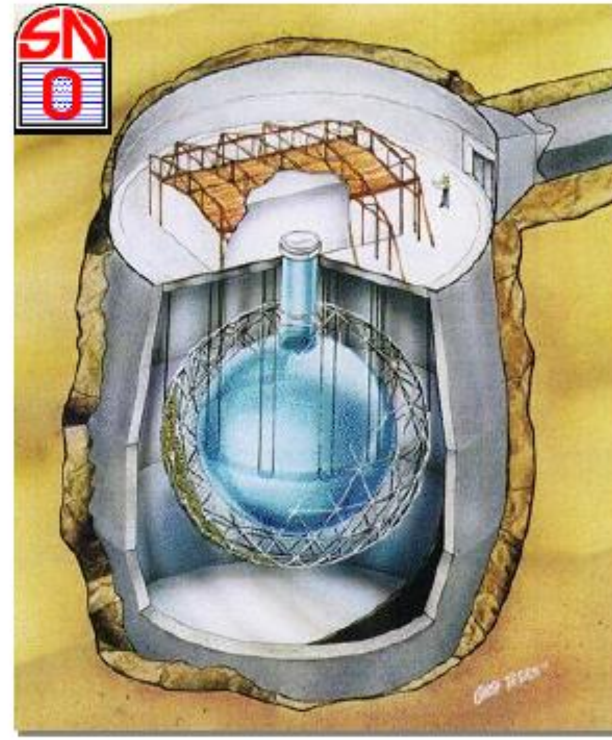
- 1998: After analyzing more than 500 days of data, the Super-Kamiokande team reports finding oscillations and, thus, mass in muon neutrinos. After several years these results are widely accepted and the paper becomes the top cited experimental particle physics paper ever.

Evidence for oscillation of atmospheric neutrinos

The Super-Kamiokande Collaboration

Y.Fukuda[a], T.Hayakawa[a], E.Ichihara[a], K.Inoue[a], K.Ishihara[a], H.Ishino[a], Y.Itow[a], T.Kajita[a], J.Kameda[a], S.Kasuga[a], K.Kobayashi[a], Y.Kobayashi[a], Y.Koshio[a], M.Miura[a], M.Nakahata[a], S.Nakayama[a], A.Okada[a], K.Okumura[a], N.Sakurai[a], M.Shiozawa[a], Y.Suzuki[a], Y.Takeuchi[a], Y.Totsuka[a], S.Yamada[a], M.Earl[b], A.Habig[b], E.Kearns[b], M.D.Messier[b], K.Scholberg[b], J.L.Stone[b], L.R.Sulak[b], C.W.Walter[b], M.Goldhaber[c], T.Barszczak[d], D.Casper[d], W.Gajewski[d], P.G.Halverson[d,*], J.Hsu[d], W.R.Kropp[d], L.R. Price[d], F.Reines[d], M.Smy[d], H.W.Sobel[d], M.R.Vagins[d], K.S.Ganezer[e], W.E.Keig[e], R.W.Ellsworth[f], S.Tasaka[g], J.W.Flanagan[h,†] A.Kibayashi[h], J.G.Learned[h], S.Matsuno[h], V.J.Stenger[h], D.Takemori[h], T.Ishii[i], J.Kanzaki[i], T.Kobayashi[i], S.Mine[i], K.Nakamura[i], K.Nishikawa[i], Y.Oyama[i], A.Sakai[i], M.Sakuda[i], O.Sasaki[i], S.Echigo[j], M.Kohama[j], A.T.Suzuki[j], T.J.Haines[k,d] E.Blaufuss[l], B.K.Kim[l], R.Sanford[l], R.Svoboda[l], M.L.Chen[m], Z.Conner[m,‡] J.A.Goodman[m], G.W.Sullivan[m], J.Hill[n], C.K.Jung[n], K.Martens[n], C.Mauger[n], C.McGrew[n], E.Sharkey[n], B.Viren[n], C.Yanagisawa[n], W.Doki[o], K.Miyano[o], H.Okazawa[o], C.Saji[o], M.Takahata[o], Y.Nagashima[p], M.Takita[p], T.Yamaguchi[p], M.Yoshida[p], S.B.Kim[q], M.Etoh[r], K.Fujita[r], A.Hasegawa[r], T.Hasegawa[r], S.Hatakeyama[r], T.Iwamoto[r], M.Koga[r], T.Maruyama[r], H.Ogawa[r], J.Shirai[r], A.Suzuki[r], F.Tsushima[r], M.Koshiba[s], M.Nemoto[t], K.Nishijima[t], T.Futagami[u], Y.Hayato[u,§], Y.Kanaya[u], K.Kaneyuki[u], Y.Watanabe[u], D.Kielczewska[v,d], R.A.Doyle[w], J.S.George[w], A.L.Stachyra[w], L.L.Wai[w,**], R.J.Wilkes[w], K.K.Young[w]

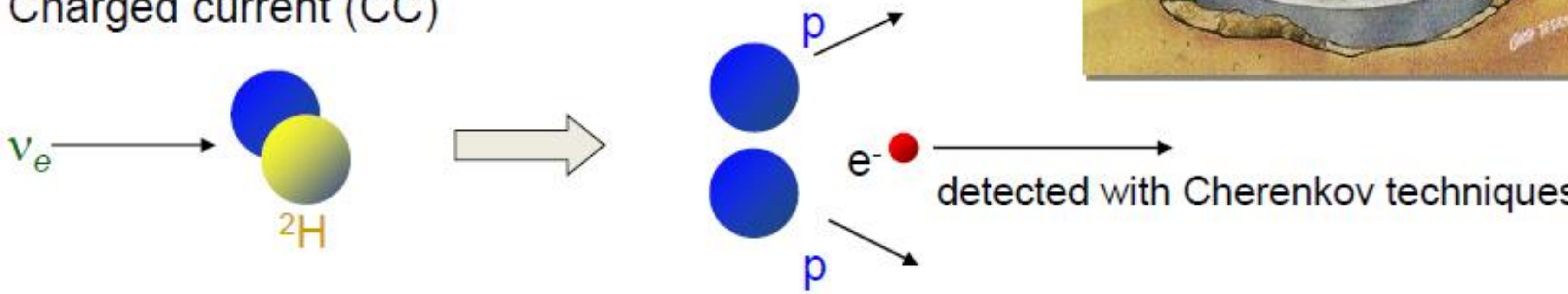
Subdury Neutrino Observatory (SNO)



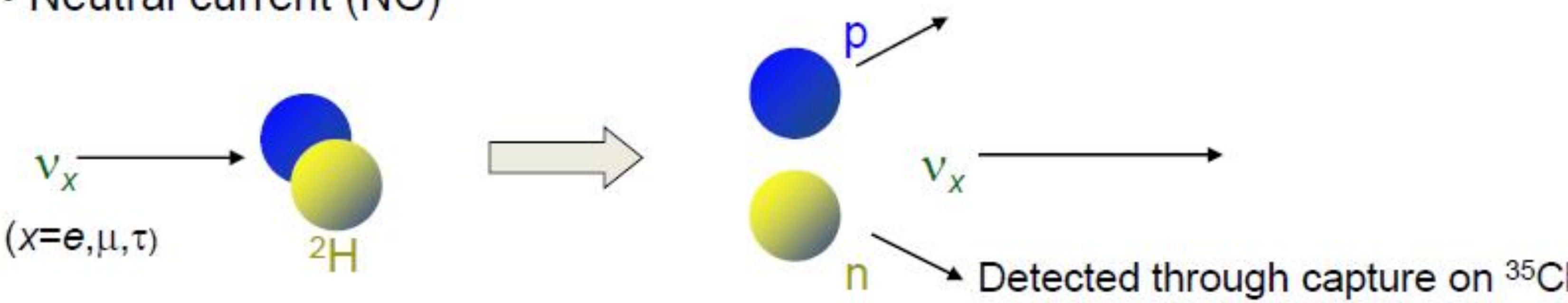
1000 tons di D_2O

The breakthrough: in deuterium one can separate CC events (induced by ν_e only) from NC events (induced by ν_e, ν_μ, ν_τ), and double check via Elastic Scattering events (due to both NC and CC)

- Charged current (CC)



- Neutral current (NC)



- 2001-2: SNO announces observation of neutral currents from solar neutrinos, along with charged currents and elastic scatters, providing convincing evidence that neutrino oscillations are the cause of the solar neutrino problem.

Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory

Q.R. Ahmad,[17] R.C. Allen,[4] T.C. Andersen,[6] J.D. Anglin,[10] J.C. Barton,[11,*] E.W. Beier,[12] M. Bercovitch,[10] J. Bigu,[7] S.D. Biller,[11] R.A. Black,[11] I. Blevis,[5] R.J. Boardman,[11] J. Boger,[3] E. Bonvin,[14] M.G. Boulay,[9,14] M.G. Bowler,[11] T.J. Bowles,[9] S.J. Brice,[9,11] M.C. Browne,[17,9] T.V. Bullard,[17] G. Bühler,[4] J. Cameron,[11] Y.D. Chan,[8] H.H. Chen,[4,†] M. Chen,[14] X. Chen,[8,11] B.T. Cleveland,[11] E.T.H. Clifford,[14] J.H.M. Cowan,[7] D.F. Cowen,[12] G.A. Cox,[17] X. Dai,[11] F. Dalnoki-Veress,[5] W.F. Davidson,[10] P.J. Doe,[17,9,4] G. Doucas,[11] M.R. Dragowsky,[9,8] C.A. Duba,[17] F.A. Duncan,[14] M. Dunford,[12] J.A. Dunmore,[11] E.D. Earle,[14,1] S.R. Elliott,[17,9] H.C. Evans,[14] G.T. Ewan,[14] J. Farine,[7,5] H. Fergani,[11] A.P. Ferraris,[11] R.J. Ford,[14] J.A. Formaggio,[17] M.M. Fowler,[9] K. Frame,[11] E.D. Frank,[12] W. Frati,[12] N. Gagnon,[11,9,8,17] J.V. Germani,[17] S. Gil,[2] K. Graham,[14] D.R. Grant,[5] R.L. Hahn,[3] A.L. Hallin,[14] E.D. Hallman,[7] A.S. Hamer,[9,14] A.A. Hamian,[17] W.B. Handler,[14] R.U. Haq,[7] C.K. Hargrove,[5] P.J. Harvey,[14] R. Hazama,[17] K.M. Heeger,[17] W.J. Heintzelman,[12] J. Heise,[2,9] R.L. Helmer,[16,2] J.D. Hepburn,[14] H. Heron,[11] J. Hewett,[7] A. Hime,[9] M. Howe,[17] J.G. Hykawy,[7] M.C.P. Isaac,[8]

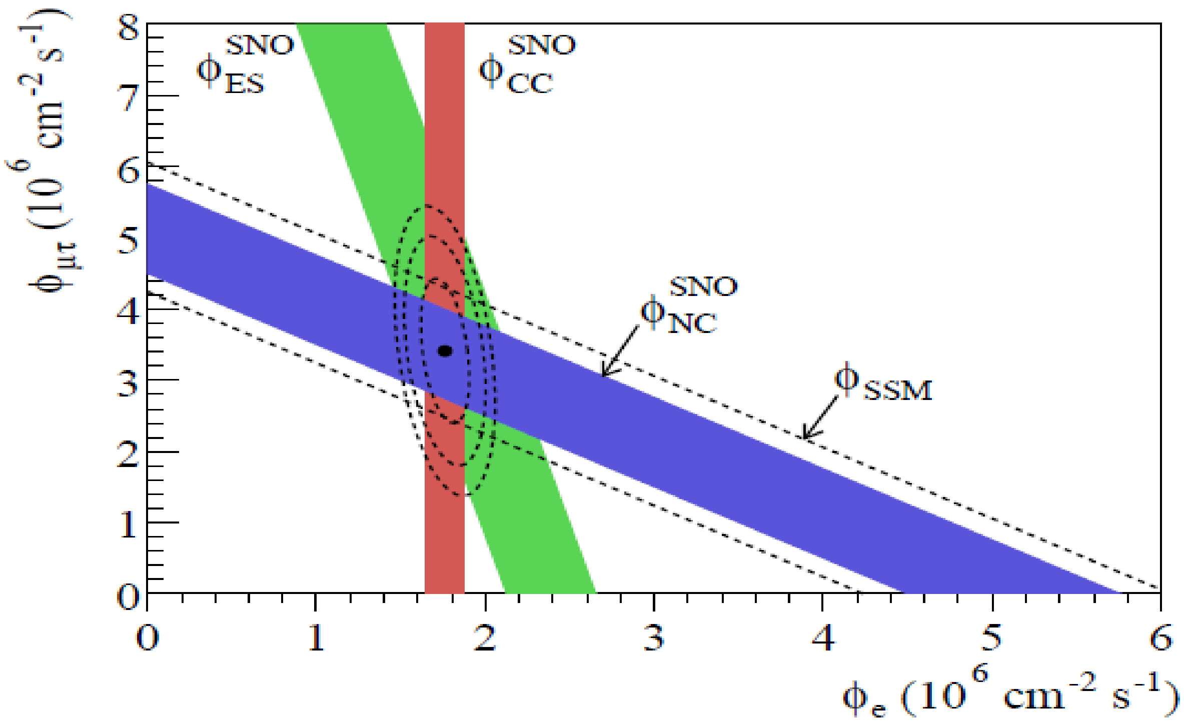


FIG. 3: Flux of ^{8}B solar neutrinos which are μ or τ flavor vs flux of electron neutrinos deduced from the three neutrino reactions in SNO. The diagonal bands show the total ^{8}B flux as predicted by the SSM [11] (dashed lines) and that measured with the NC reaction in SNO (solid band). The intercepts of these bands with the axes represent the $\pm 1\sigma$ errors. The bands intersect at the fit values for ϕ_e and $\phi_{\mu\tau}$, indicating that the combined flux results are consistent with neutrino flavor transformation assuming no distortion in the ^{8}B neutrino energy spectrum.

On receiving the news Bahcall commented: ‘I feel like dancing, I am so happy’

KamLAND experiment

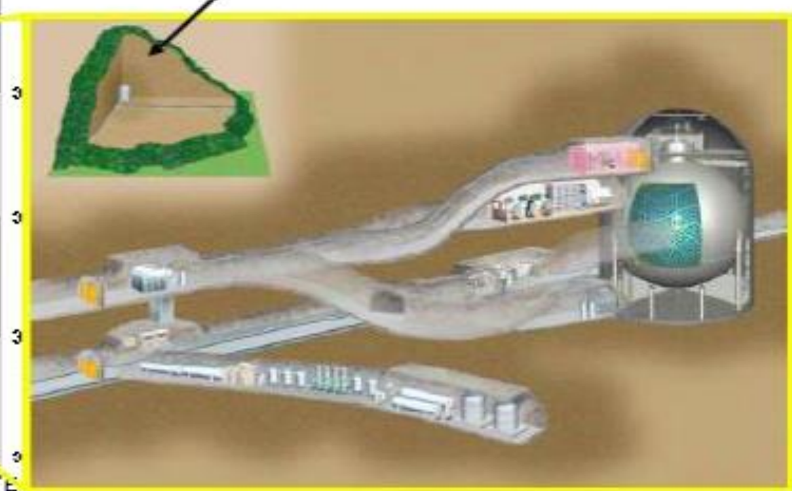
Also in 2002... KamLAND: 1000 ton mineral oil detector, "surrounded" by nuclear reactors producing anti-ν_e. Characteristics:

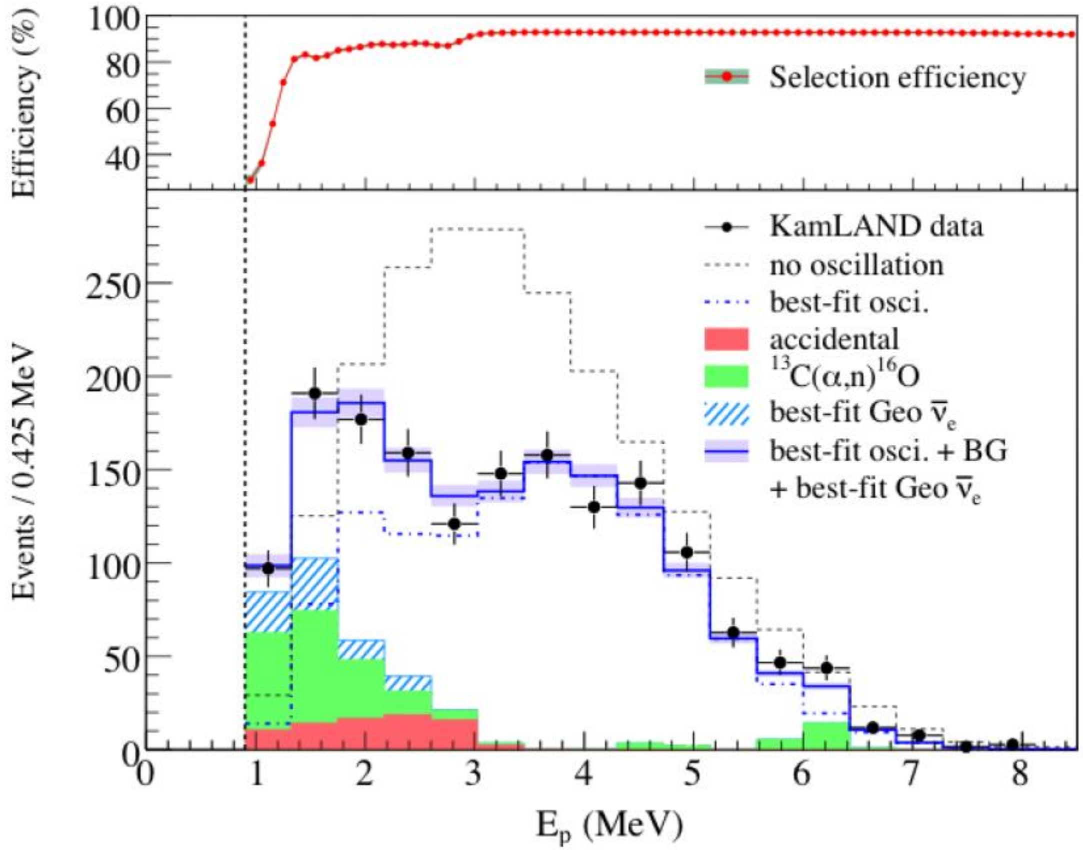
$A/\delta m^2 \ll 1$ in Earth crust (vacuum approxim. OK)
L~100-200 km
E_ν ~ few MeV

⇨ With previous $(\delta m^2,\theta)$ parameters it is $(\delta m^2 L/4E) \sim O(1)$ and reactor neutrinos should oscillate with large amplitude (large θ)

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

~1 km high
Mt Ikenoyama

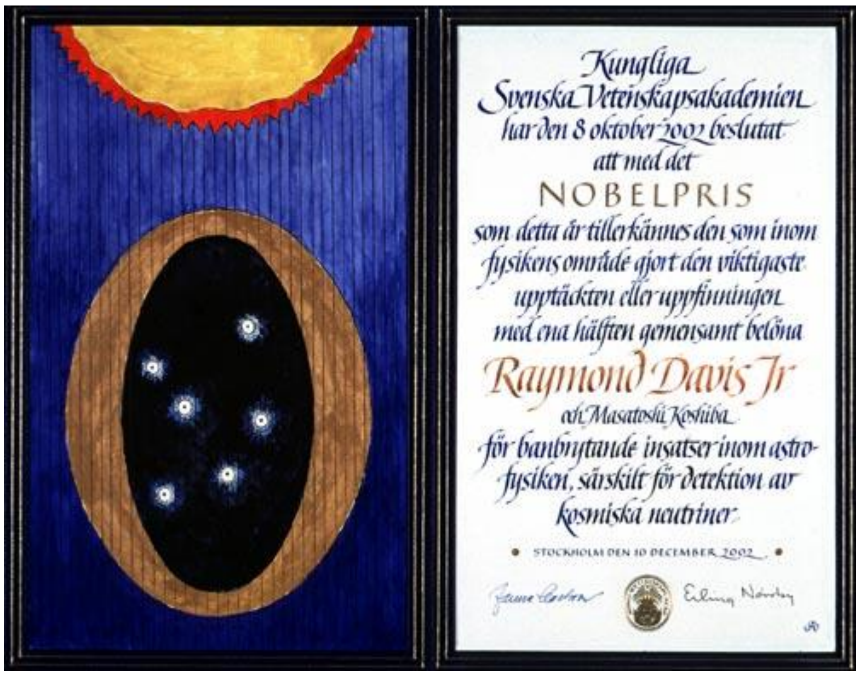




KamLAND finds that on average about 40% of the anticipated number of antineutrinos has disappeared. It shows that neutrino oscillates with the same parameters indicated by the solution of the solar problem.

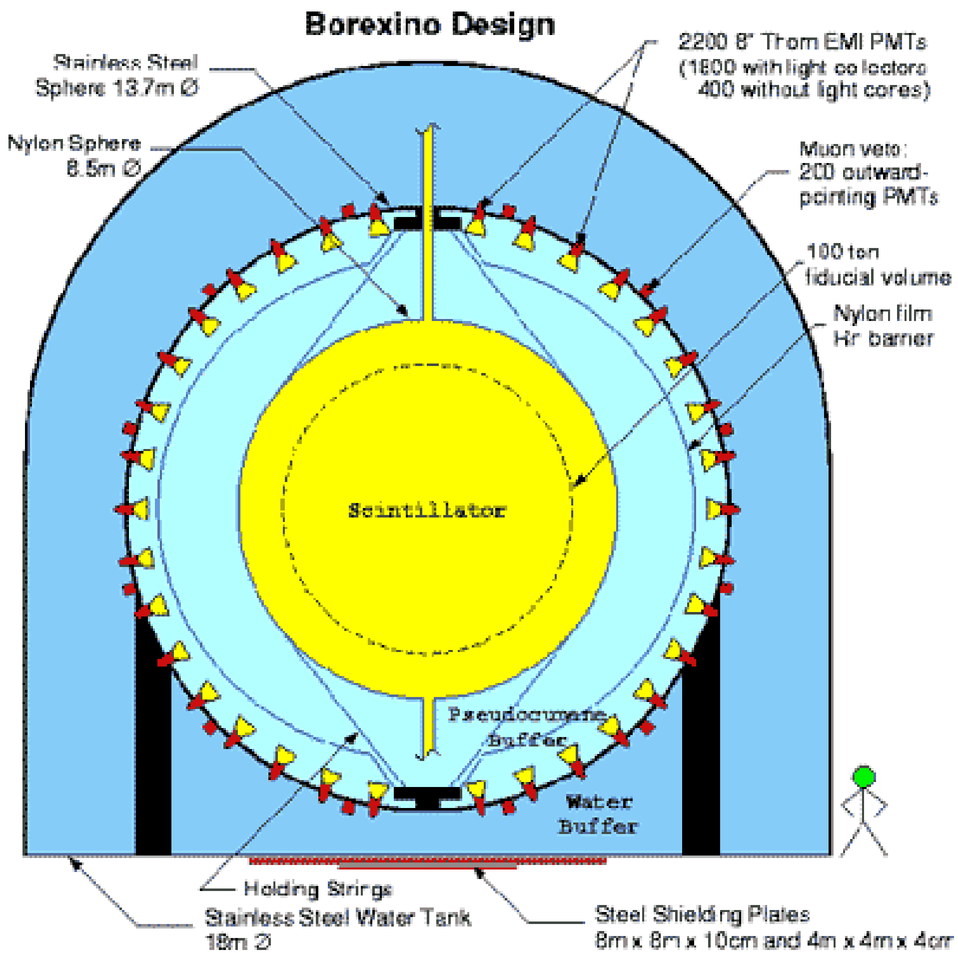
NEUTRINOS:...ANNUS MIRABILIS

- December 10, 2002: The ceremony of the Nobel Prize award: R. Davis Jr. and M. Koshiba: "... for pioneering contribution to astrophysics, in particular for the detection of cosmic neutrinos"



BOREXINO

Real time ν detector with liquid scintillator



- ν detection: elastic scattering on electrons

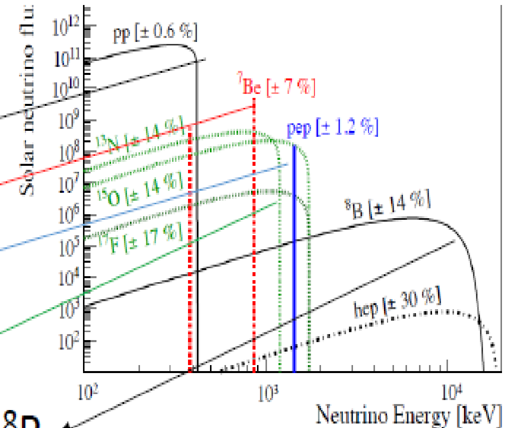
$$\nu_x + e^- \to \nu_x + e^-$$

- Very low threshold (~240 keV due to ^{14}C bkg)
- Unique possibility to probe the solar ν spectrum in the sub-MeV regime

Fiducial mass: 75 ton

(Slide from G. Testera)

Real time solar ν detection



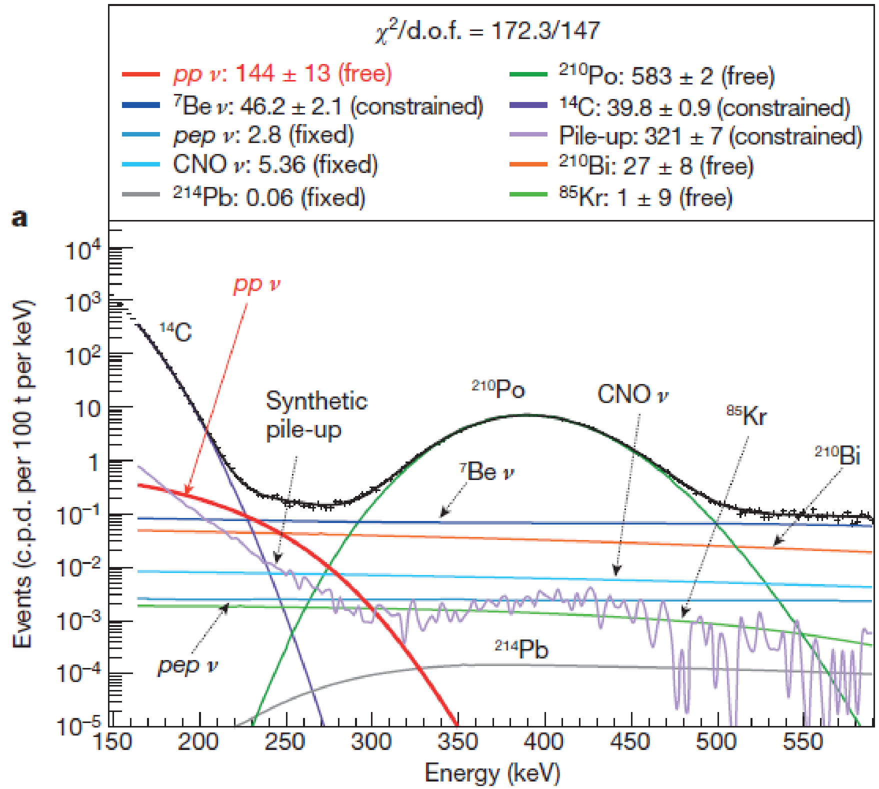
	pp (10^{10} cm^{-2} s^{-1})	^{7}Be (10^9 cm^{-2} s^{-1})	pep (10^8 cm^{-2} s^{-1})	CNO (10^8 cm^{-2} s^{-1})	^{8}B (10^6 cm^{-2} s^{-1})	^{8}B detect en. thres. (Lowest)
SK					2.344 ± 0.034 ν_e equiv.[1] (1.4%)	3.5 MeV
SNO					$5.25 \pm 0.16^{+0.11}_{-0.13}$ Total active[2] ν (3.8%)	3.5 MeV
Kamland		3.26 ± 0.5 (15%) ν_e equiv[8]			$2.77 \pm 0.26 \pm 0.32$ ν_e equiv.[3] (15%)	5.5 MeV
Borexino	6.6 ± 0.7 (10.6%) LMA-MSW included[7]	3.10 ± 0.15 (5%) ν_e equiv[6]	1.6 ± 0.3 (19%) LMA-MSW included[5]	< 7.7 LMA-MSW included[5]	$2.4 \pm 0.4 \pm 0.1$ ν_e equiv.[4] (17%)	3. MeV

1) Y. Koshio (SK Coll.) Neutrino 2014 talk
2) B. Aharmim et al (SNO Coll.) Phys. Rev. C 88 025501 (2013)
3) S. Abe et al (Kamland Collaboration) Phys. Rev. C 84 035804 (2011)
4) G. Bellini et al (Borexino Collaboration) Phys. Rev. D 82, 3 (033006) 2010
5) G. Bellini et al., (Borexino Collaboration) Phys. Rev. Lett. 108 (2012) 051302..
6) G. Bellini et al., (Borexino Collaboration) Phys. Rev. Lett. 107 (2011) 141362.
7) G. Bellini et al. (Borexino Collaboration) Nature 512 383 (2014)
8) A. Gando et al. (Kamland Collaboration) arxiv:1405.6190v1 (May2014)

DISCOVERY OF pp NEUTRINOS

[Borexino Collaboration, Nature 512 , 383 (2014)]

The $p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ reaction occurs 99.76 % of the time



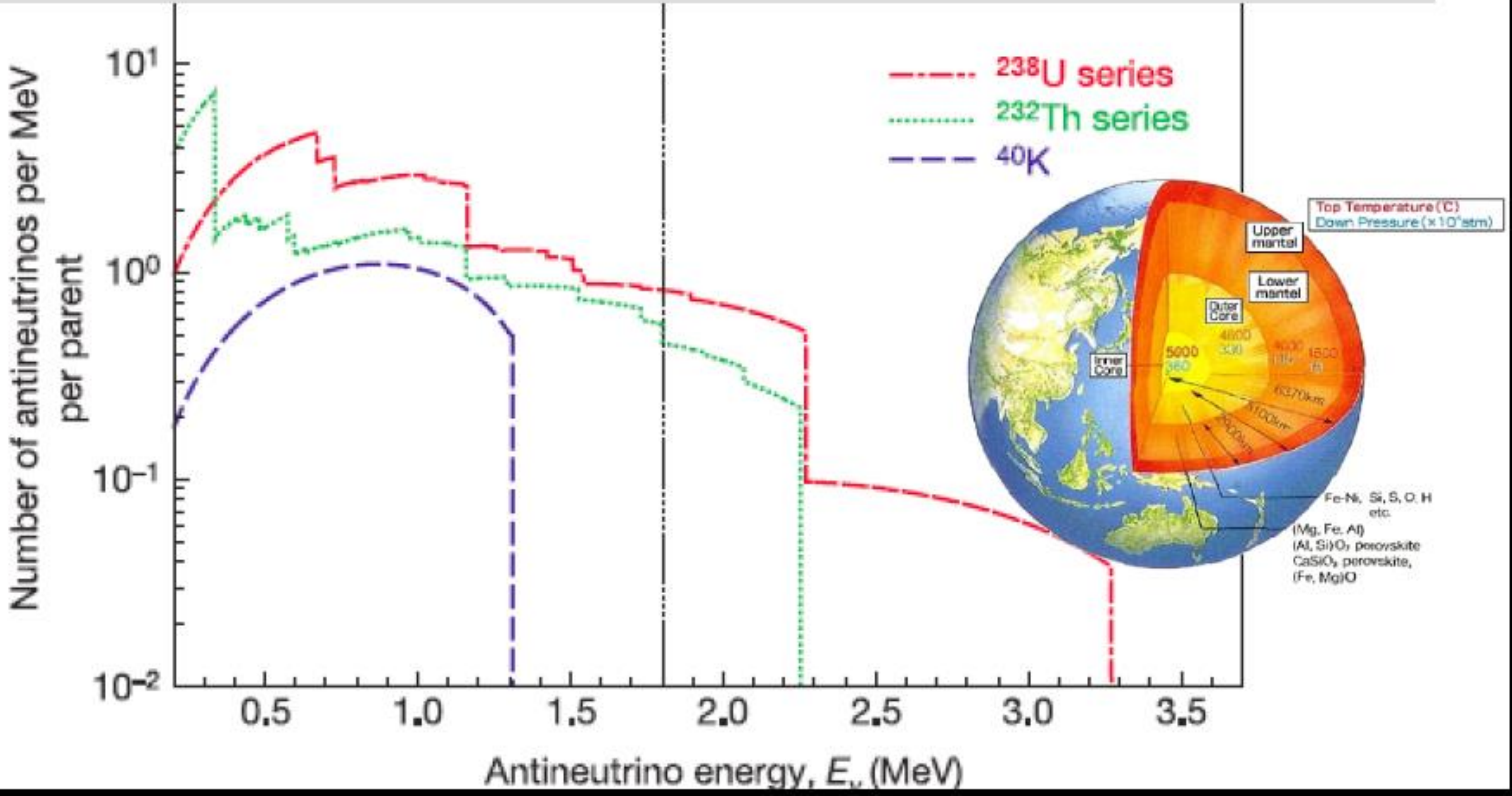
- Unprecedent low level of radioactivity inside the detector. Measured pp neutrino flux $(6.6 \pm 0.7) \times 10^{10}$ cm^{-2} s^{-1} in agreement wit SSM + oscillations. Accuracy ~10% vs 0.6% SSM.

- ν flux consistent with solar luminosity → The Sun has been in thermodynamic equilibrium at least over a timescale of 10^5 years

GEONEUTRINOS

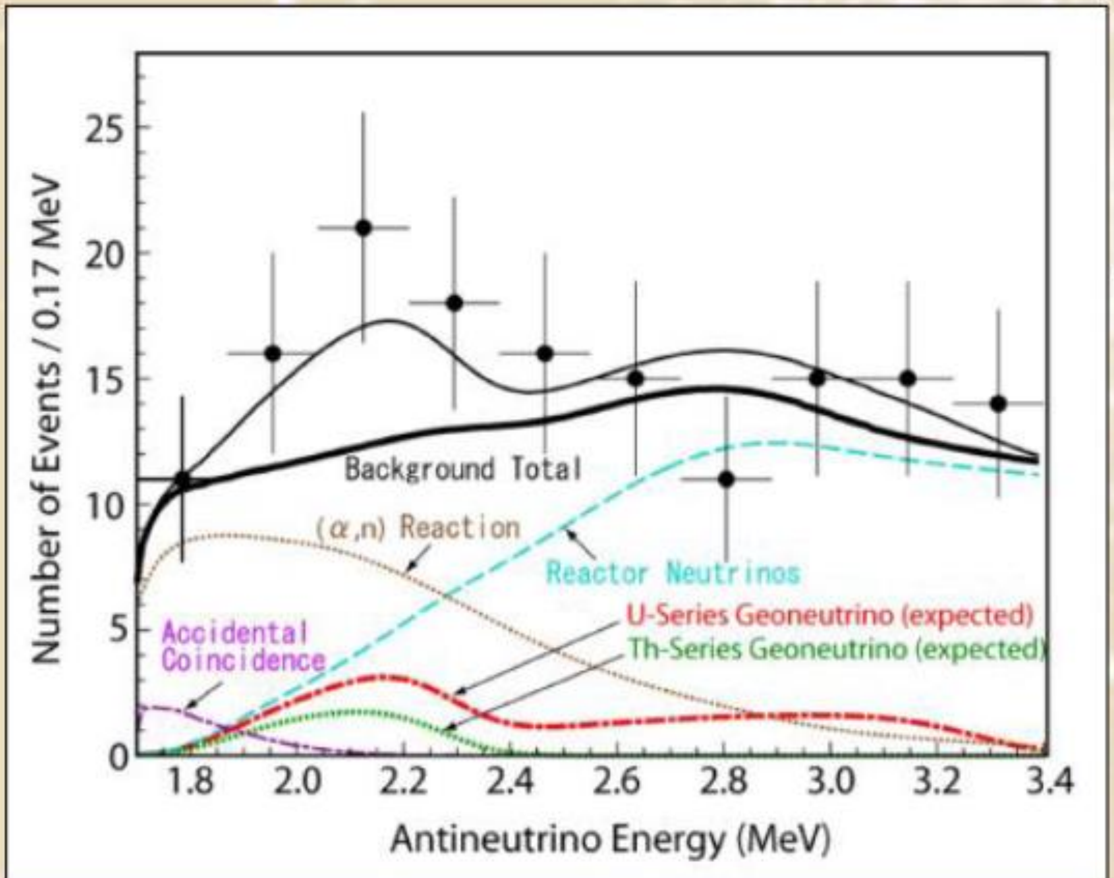
Earth as "antineutrinos star" due to radiactive decays of U, Th e ^{40}K in the crust and the mantle (~40TW).

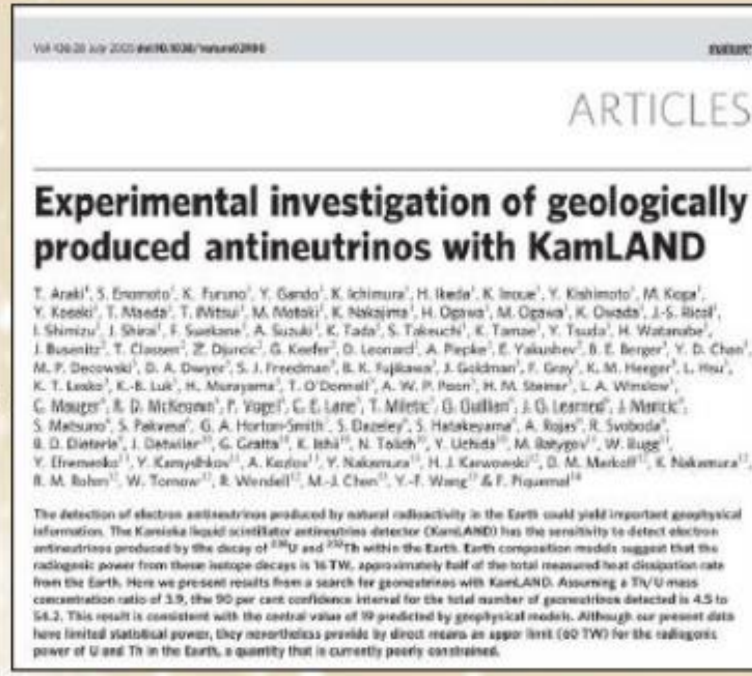
- Neutrinos escape freely
- Carry information about chemical composition, radioactive heat production, or even a putative natural reactor at the core



Kamland Observation of Geoneutrinos

- First tentative observation of geoneutrinos at Kamland in 2005 (~ 2 sigma effect)
- Very difficult because of large background of reactor neutrinos (is main purpose for neutrino oscillations)

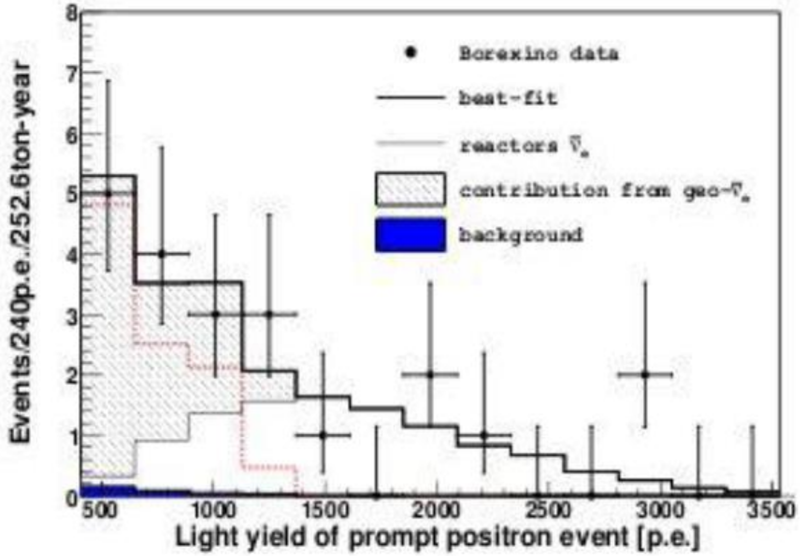



ARTICLES

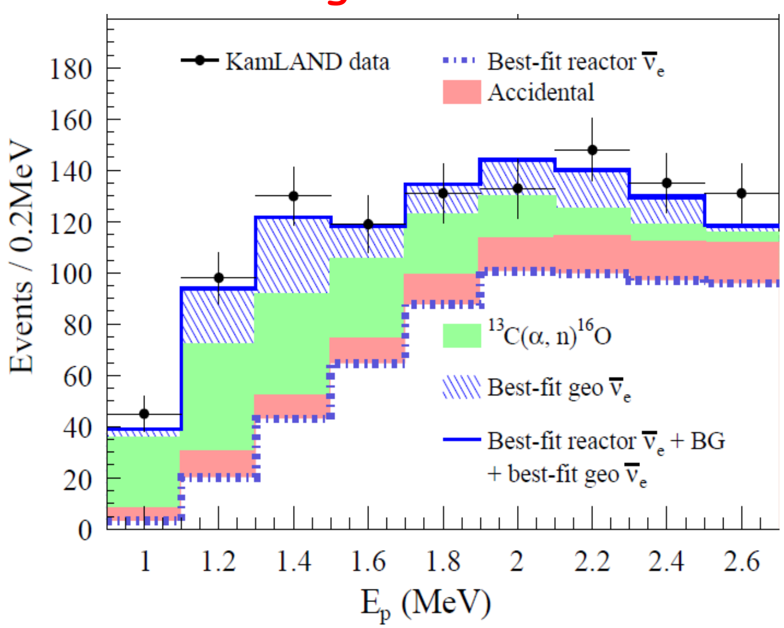
Experimental investigation of geologically produced antineutrinos with KamLAND

The detection of electron antineutrinos produced by natural radioactivity in the Earth could yield important geophysical information. The Kamioka liquid scintillator antineutrino detector (KamLAND) has the sensitivity to detect electron antineutrinos produced by the decay of ^{238}U and ^{232}Th within the Earth. Earth composition models suggest that the radiogenic power from these isotope decays is 16 TW, approximately half of the total measured heat dissipation rate from the Earth. Here we present results from a search for geoneutrinos with KamLAND. Assuming a Th/U mass concentration ratio of 3.9, the 90 per cent confidence interval for the total number of geoneutrinos detected is 4.5 to 54.2. This result is consistent with the central value of 19 predicted by geophysical models. Although our present data have limited statistical power, they nevertheless provide by direct means an upper limit (60 TW) for the radiogenic power of U and Th in the Earth, a quantity that is currently poorly constrained.

2010: Also Borexino observes geoneutrinos !



2013: KamLand geo-neutrino flux



116^{+28}_{-27} geo-neutrino events

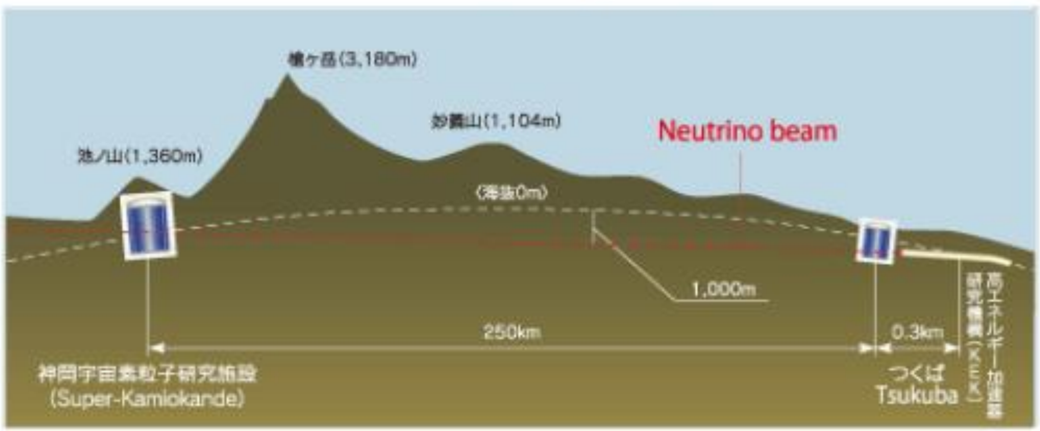
Separately free fitting:
U 116 events
Th 8 events

Beginning of neutrino geophysics !

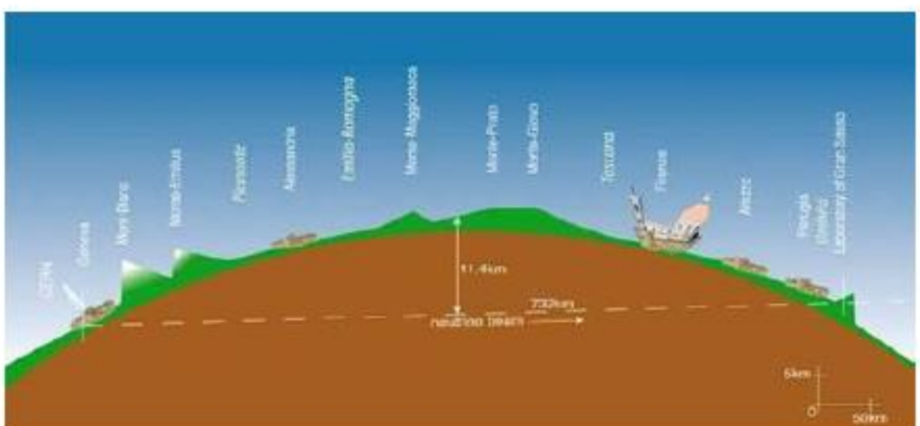
LONG-BASELINE EXPERIMENTS

Reproducing atmospheric ν_μ physics in controlled conditions

K2K (Japan)



MINOS (USA)

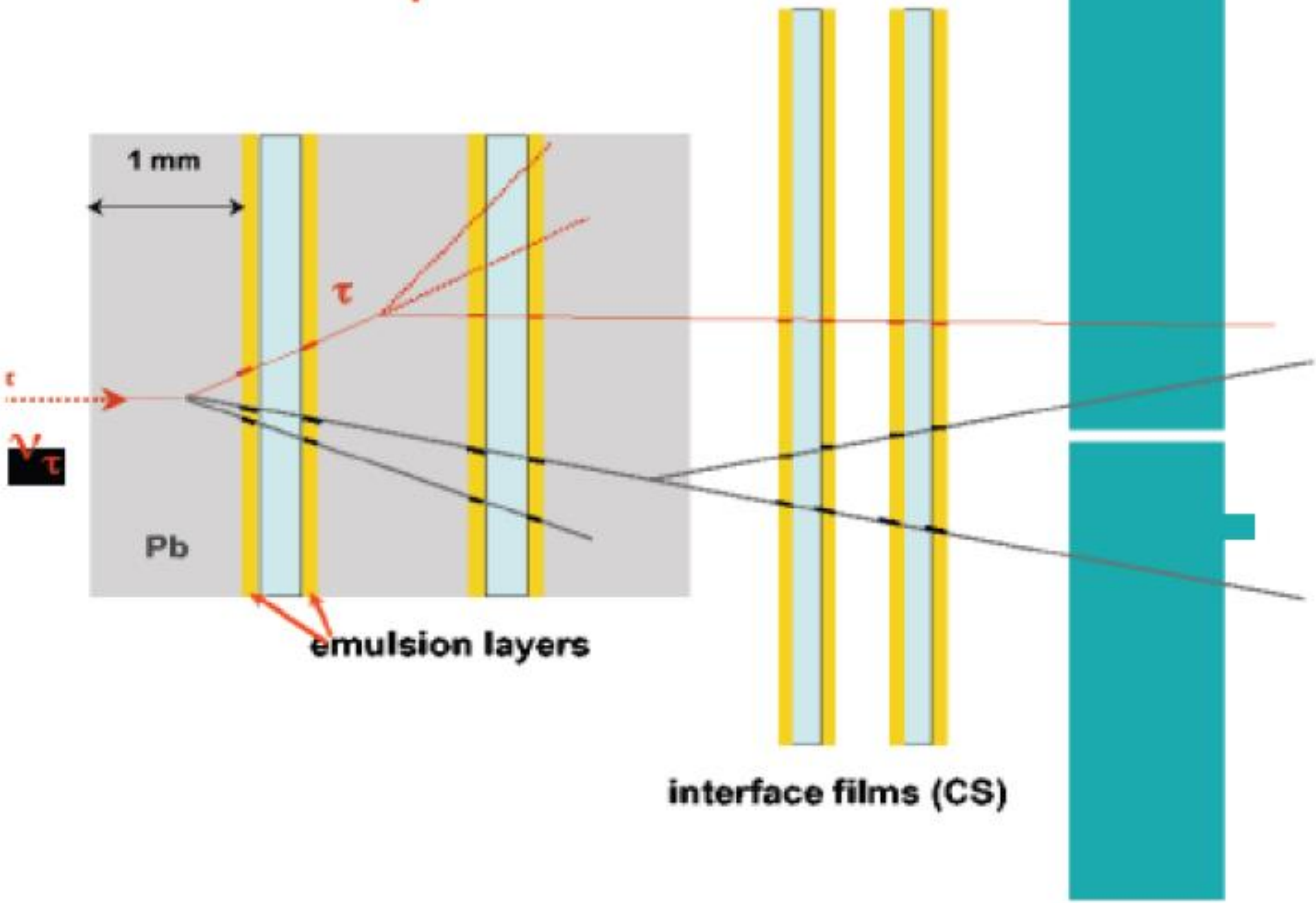


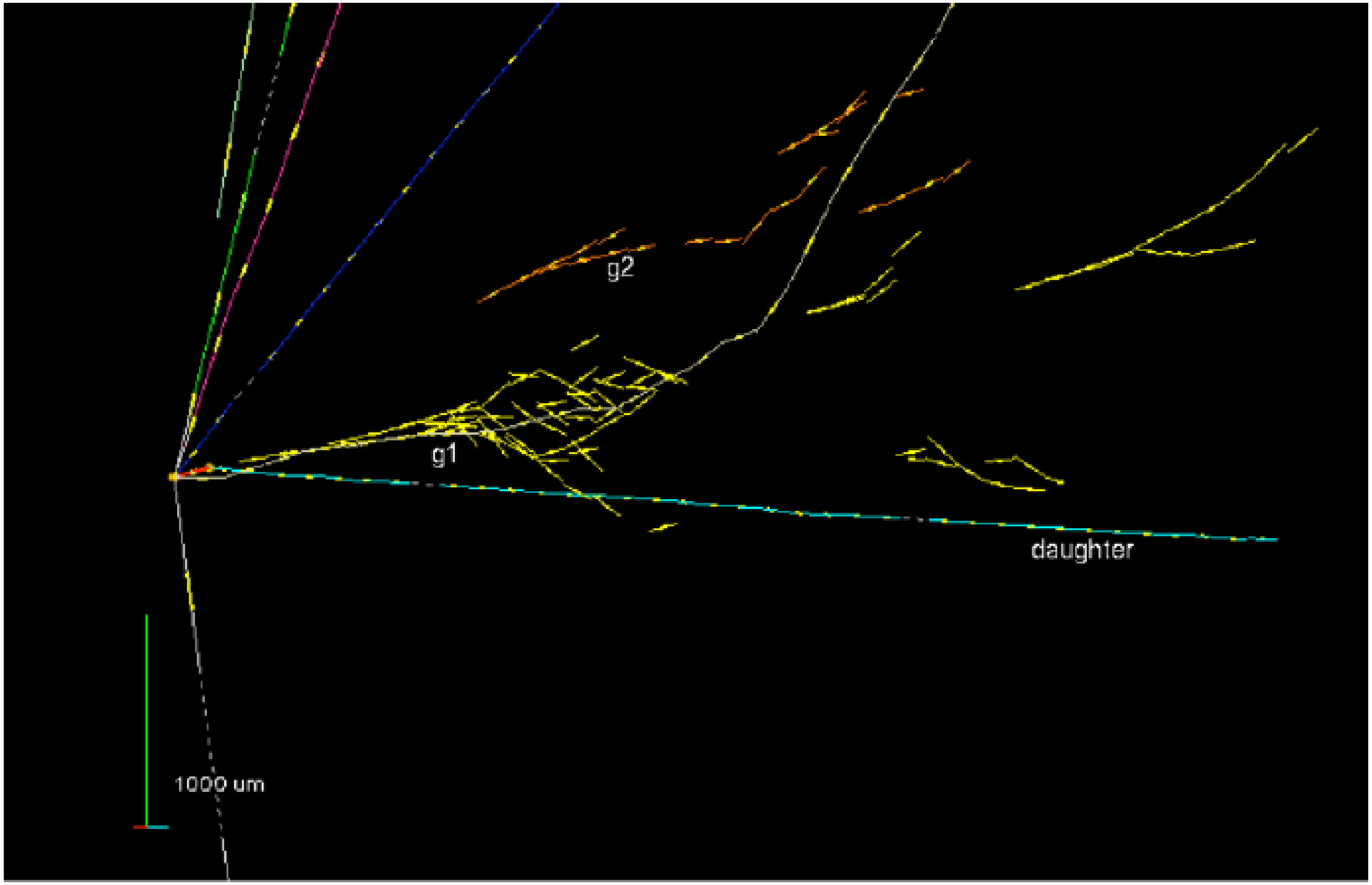
OPERA (Europe)

OPERA (CERN-LNGS)

CNGS project employs a higher E (at the price of a lower oscillation probability), somewhat above the $\nu_\tau \to \tau$ production threshold, with the goal of directly confirming the $\nu_\mu \to \nu_\tau$ character of atmospheric oscillations by detecting a few appearance events. The experimental signal of a is a `kink' i.e. two vertices separated by a distance comparable to τ_τ = 0.086mm (long-lived particles like K and π produce a background), that could be directly seen with a fine-graned emulsion detector. In practice the detector OPERA is built by alternating emulsion with some cheaper material (lead), that constitutes most of the detector mass, such that in most events one infers the presence of two separated vertices from the observed tracks.

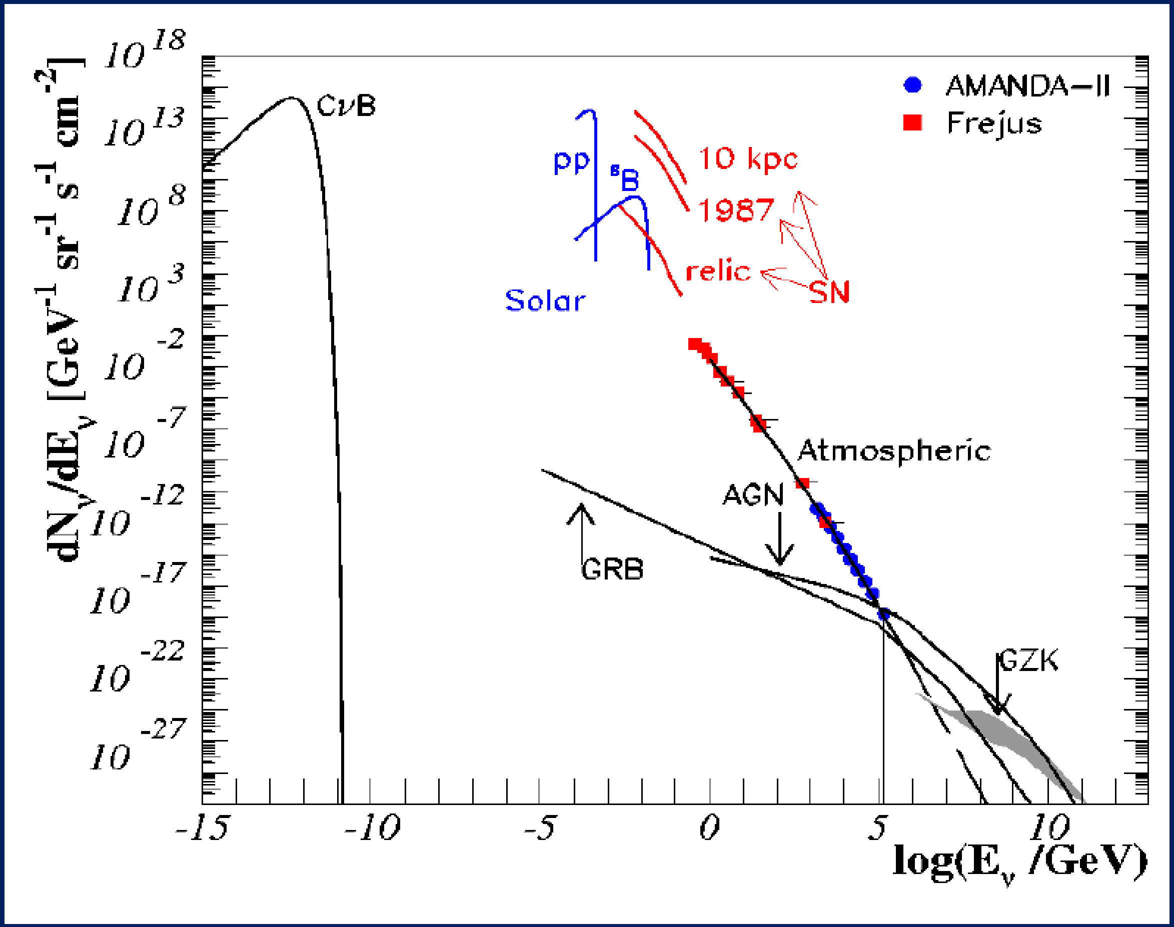
• the OPERA hybrid detector

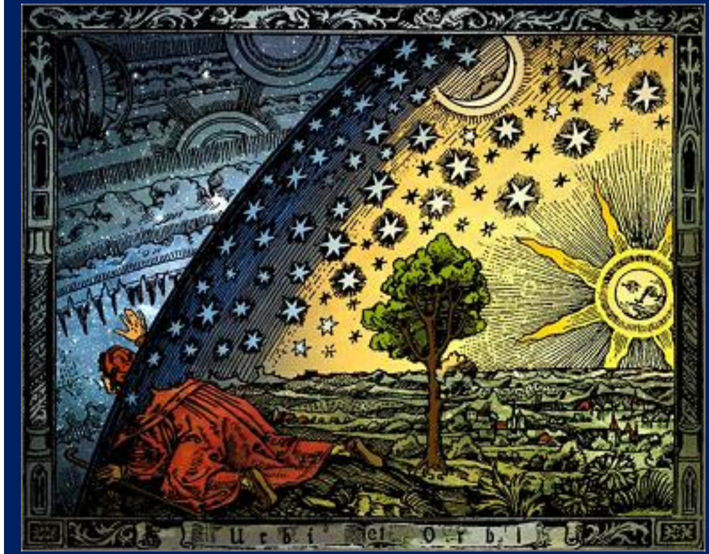




Computer reconstruction of the tau candidate event detected in the OPERA experiment. The light blue track is the one likely induced by the decay of a tau-lepton produced by a tau-neutrino.

THE COSMIC-NEUTRINO SKY





Through Neutrino Eyes: Ghostly Particles Become Astronomical Tools

SUPERNOVA NEUTRINOS

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

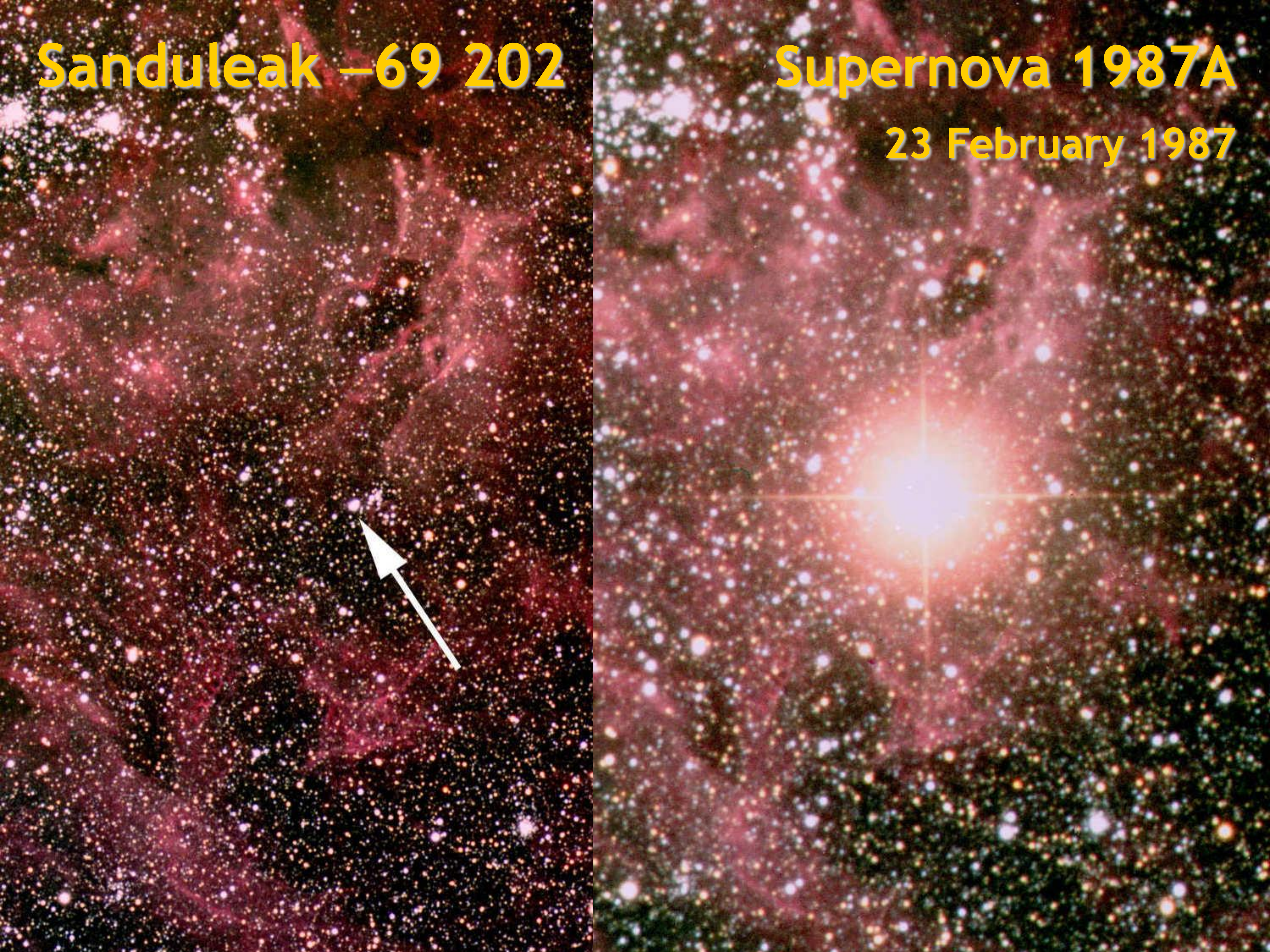
- **ENERGY SCALES:** 99% of the released energy

  ($L\nu \sim 10^{53}$ erg/3sec= $3 \times 10^{19}\ L_{sun}$)

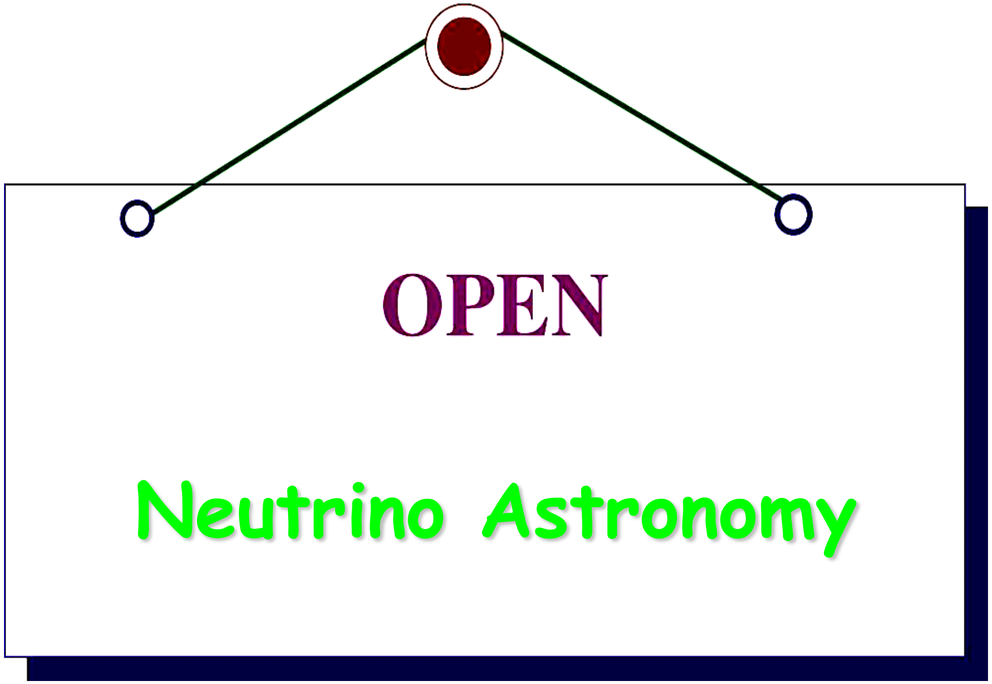
  is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies $E \sim O(15\ \text{MeV})$.

- **TIME SCALES:** Neutrino emission lasts **~10 s**

- **EXPECTED:** **1-3 SN/century** in our galaxy ($d \approx O(10)$ kpc).


Sanduleak −69 202
Supernova 1987A
23 February 1987

Neutrino Burst Observation :
First verification of stellar evolution mechanism



25 February 1987

SN1987A neutrino drama in Kamioka was raised.

Fax from Sid Bludman to E. Beier

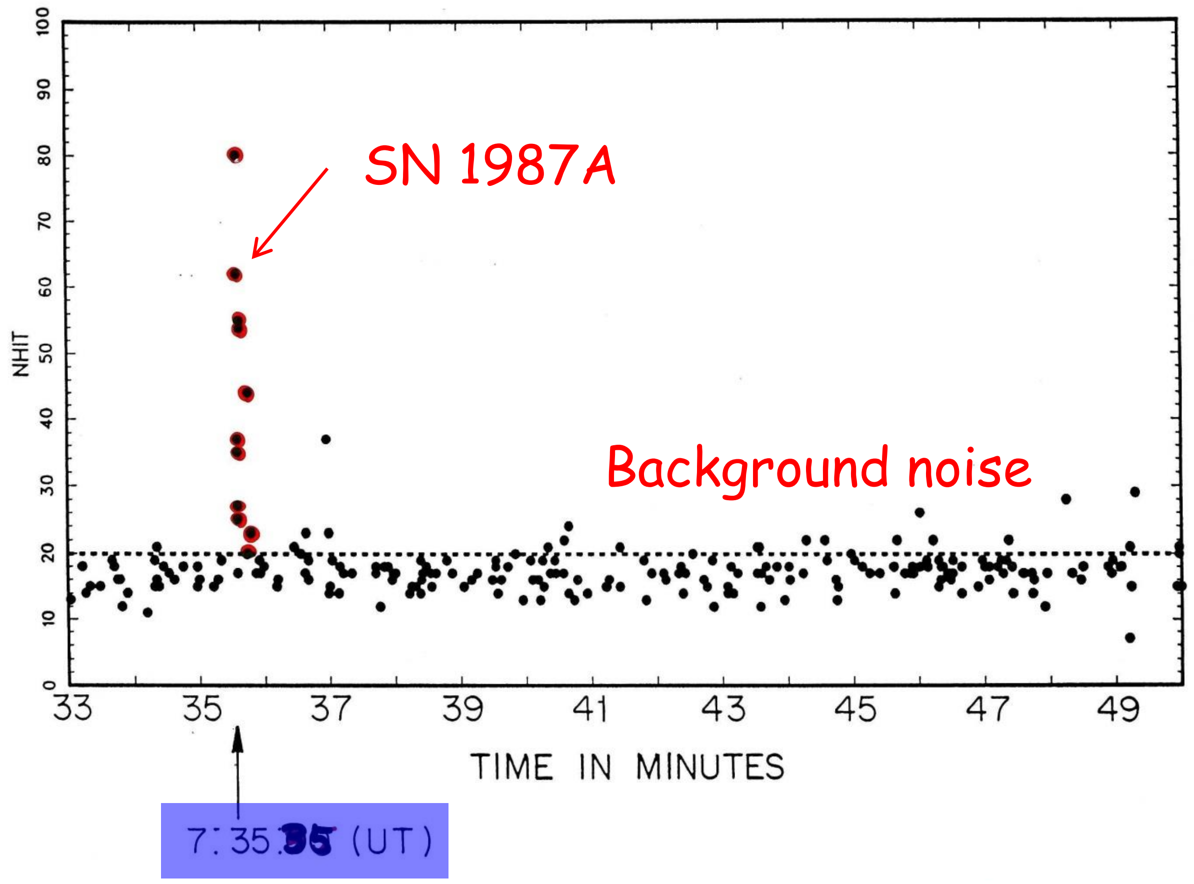
UNIV OF PENN – DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF
4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC
AWAY. NOW VISIBLE MAGNITUDE 4NS, WILL
REACH MAXIMUM MAGNITUDE (~1~0) IN A WEEK.
CAN YOU SEE IT? THIS IS WHAT WE HAVE
BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083

NEUTRINO SIGNAL OF SN 1987A IN KAMIOKANDE



6 April 1987

Kamiokande & IMB in *PRL*

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst from the Supernova SN1987A

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E. W. Beier, L. R. Feldscher, S. B. Kim, A. K. Mann, F. M. Newcomer, R. Van Berg, and W. Zhang
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and

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California Institute of Technology, Pasadena, California 91125
(Received 10 March 1987)

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud

R. M. Bionta,[12] G. Blewitt,[4] C. B. Bratton,[5] D. Casper,[2,14] A. Ciocio,[14] R. Claus,[14] B. Cortez,[16] M. Crouch,[9] S. T. Dye,[6] S. Errede,[10] G. W. Foster,[15] W. Gajewski,[1] K. S. Ganezer,[1] M. Goldhaber,[3] T. J. Haines,[1] T. W. Jones,[7] D. Kielczewska,[1,8] W. R. Kropp,[1] J. G. Learned,[6] J. M. LoSecco,[13] J. Matthews,[2] R. Miller,[1] M. S. Mudan,[7] H. S. Park,[11] L. R. Price,[1] F. Reines,[1] J. Schultz,[1] S. Seidel,[2,14] E. Shumard,[16] D. Sinclair,[2] H. W. Sobel,[1] J. L. Stone,[14] L. R. Sulak,[14] R. Svoboda,[1] G. Thornton,[2] J. C. van der Velde,[2] and C. Wuest[12]

[1] *The University of California, Irvine, Irvine, California 92717*
[2] *The University of Michigan, Ann Arbor, Michigan 48109*
[3] *Brookhaven National Laboratory, Upton, New York 11973*
[4] *California Institute of Technology, Jet Propulsion Laboratory, Pasadena, California 91109*
[5] *Cleveland State University, Cleveland, Ohio 44115*
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[10] *The University of Illinois, Urbana, Illinois 61801*
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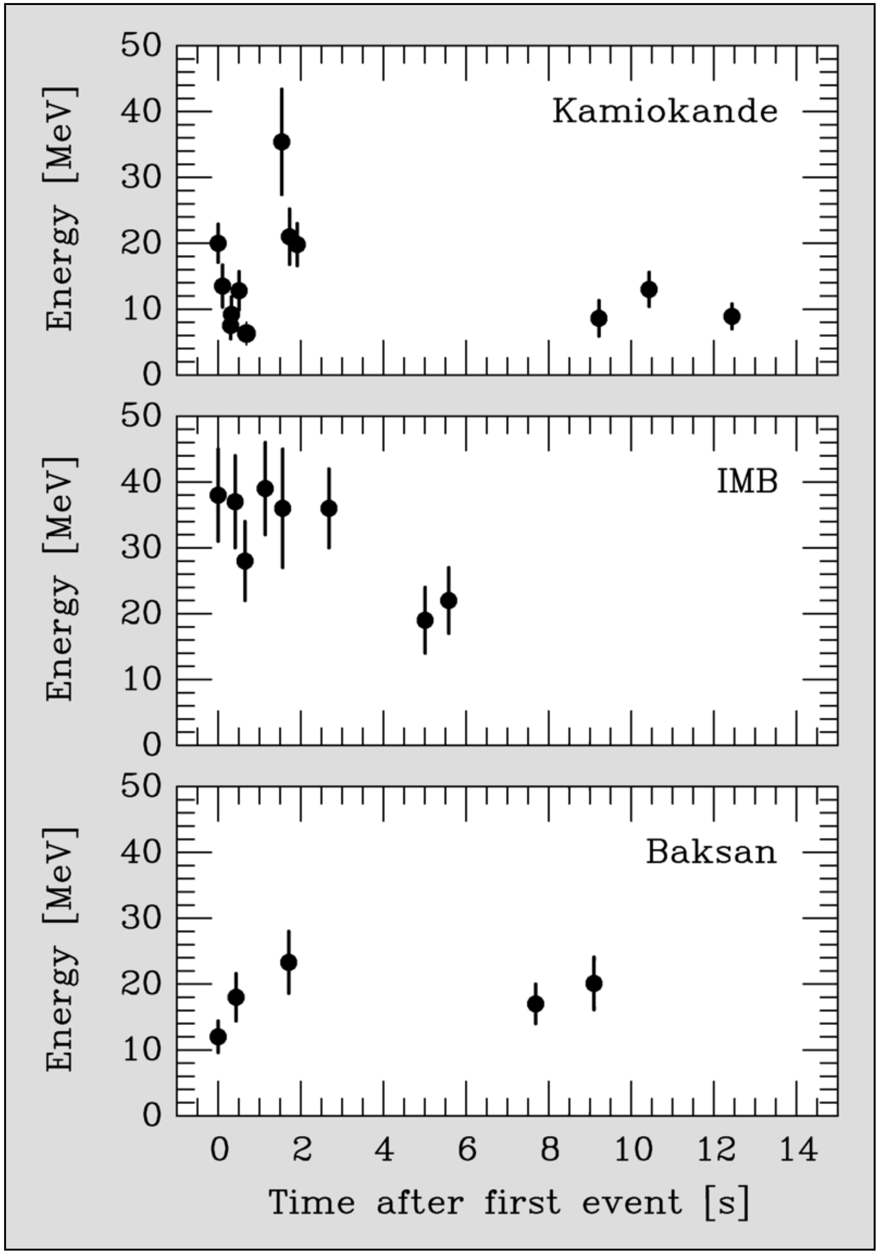
[12] *Lawrence Livermore National Laboratory, Livermore, California 94550*
[13] *The University of Notre Dame, Notre Dame, Indiana 46556*
[14] *Boston University, Boston, Massachusetts 02215*
[15] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[16] *AT&T Bell Laboratories, Summit, New Jersey 07910*
(Received 13 March 1987)

NEUTRINO SIGNAL OF SUPERNOVA 1987A



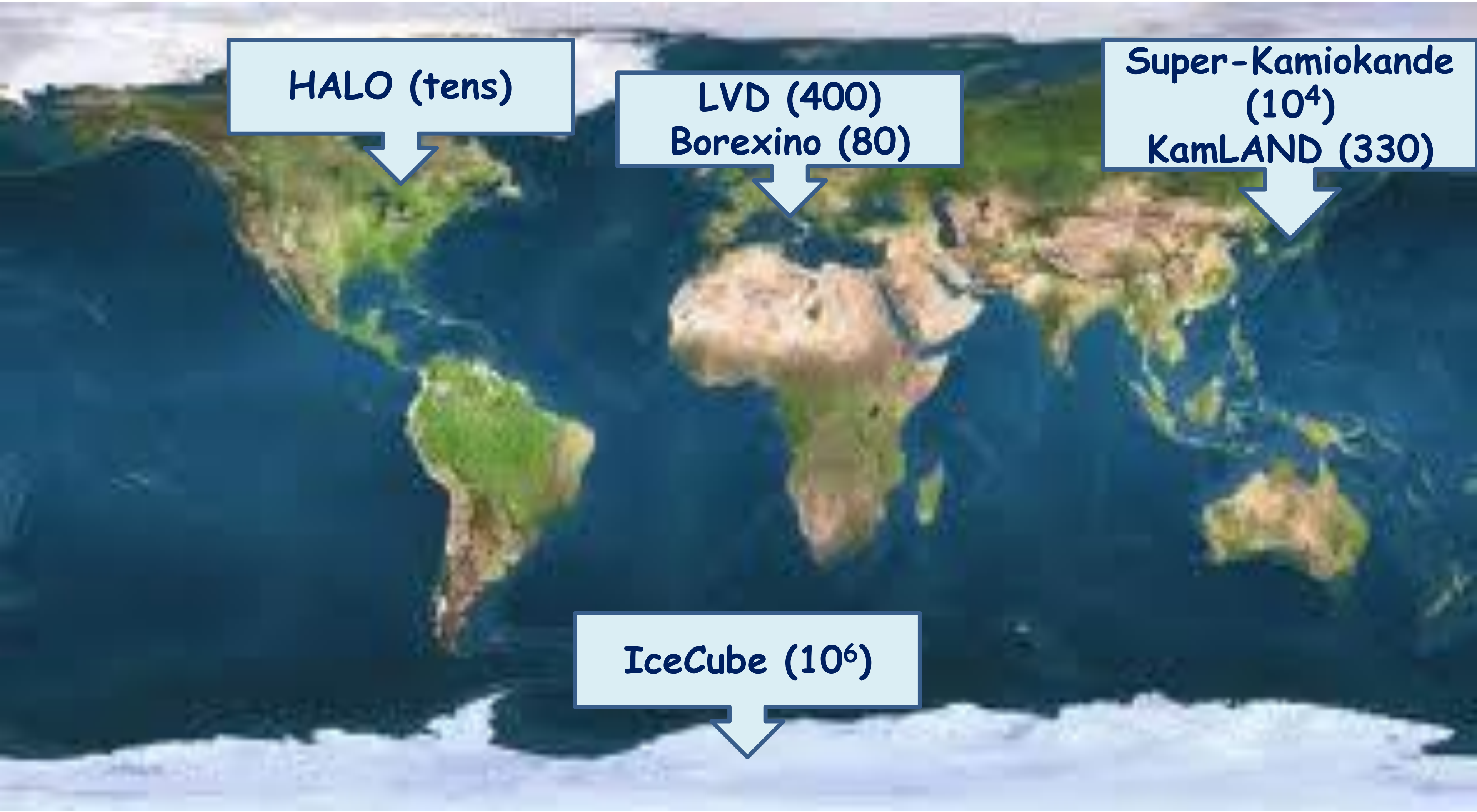
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty $\pm$1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty $\pm$50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

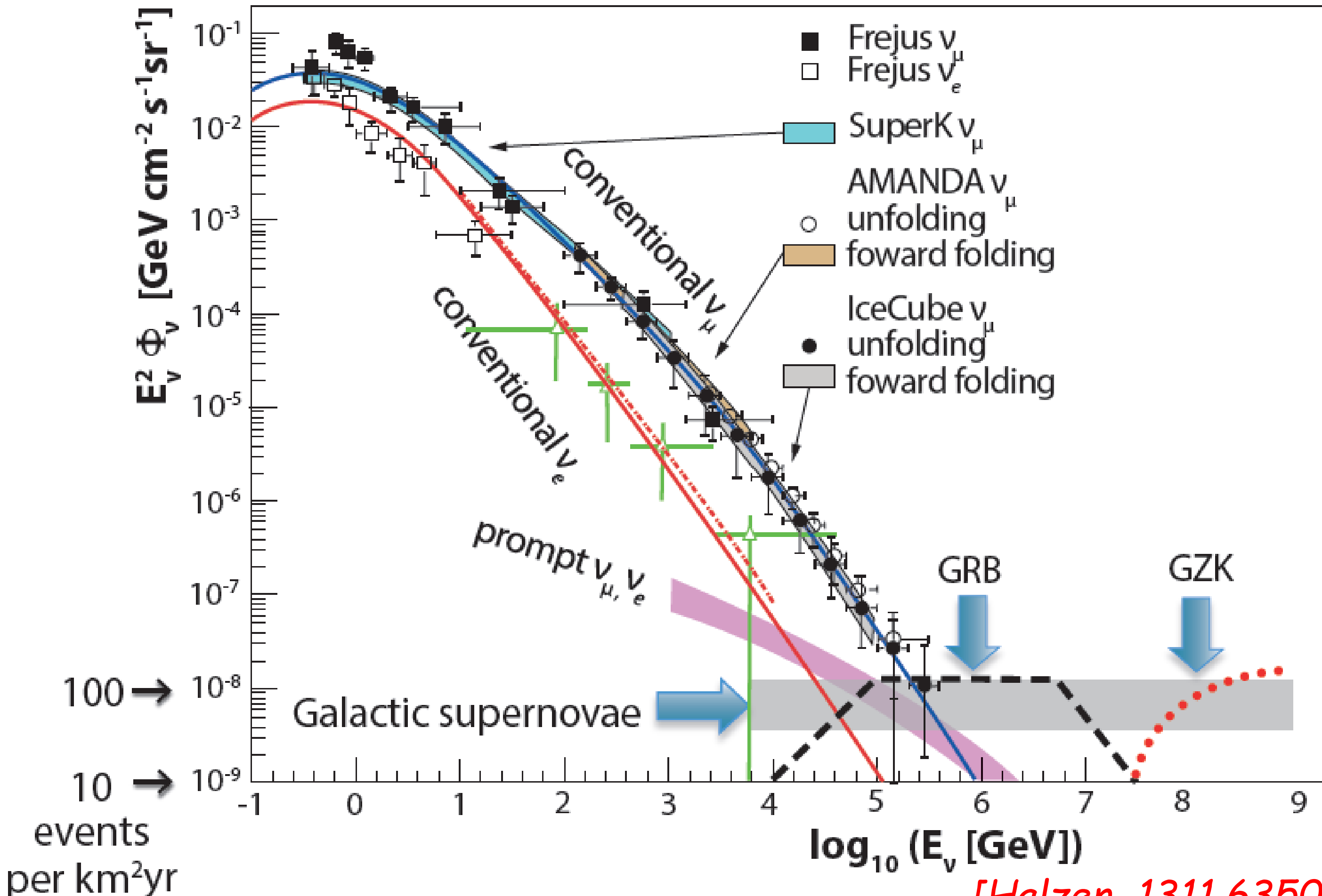
Within clock uncertainties,
signals are contemporaneous

Large Detectors for Supernova Neutrinos



In brackets events for a “fiducial SN” at distance 10 kpc

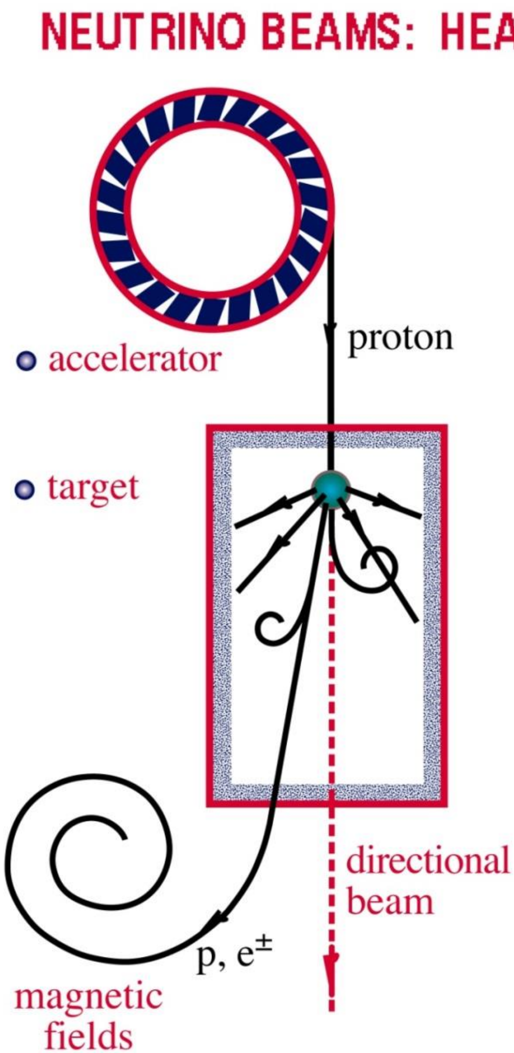
COSMIC-NEUTRINO FLUXES @ E > 100 TeV

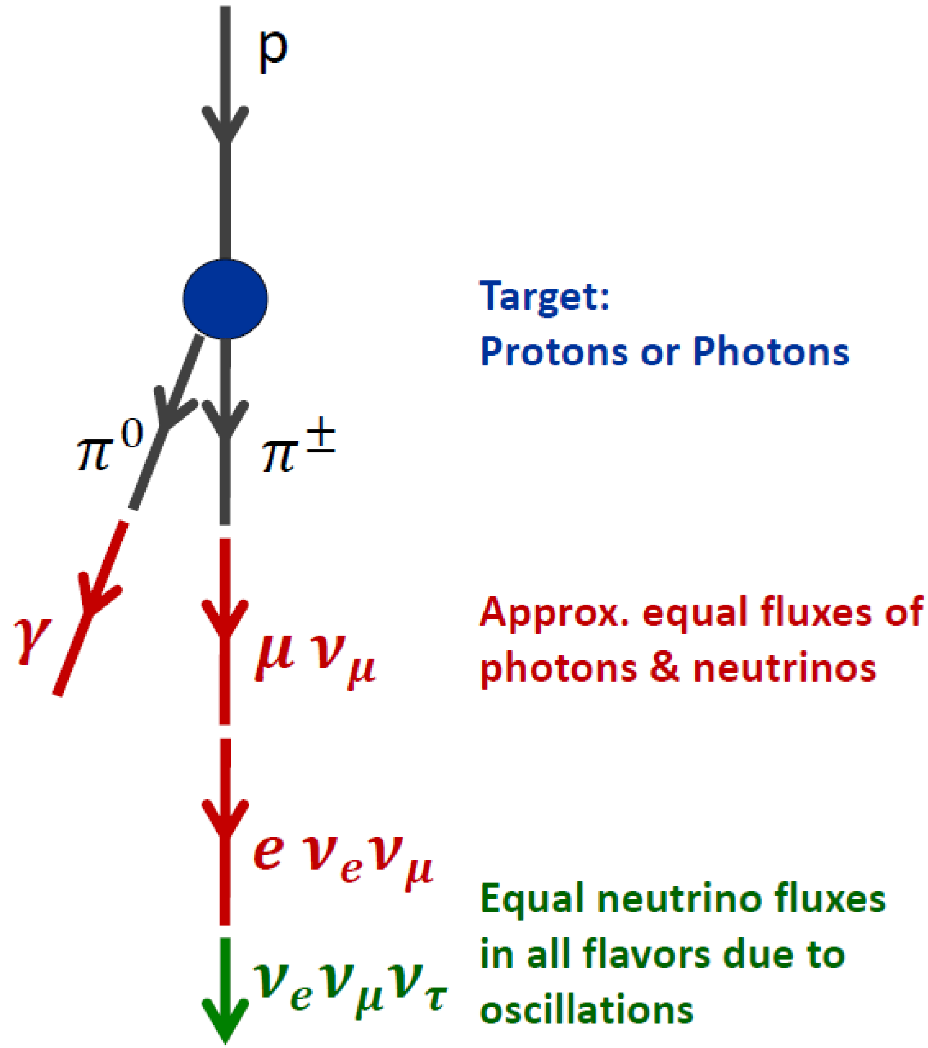


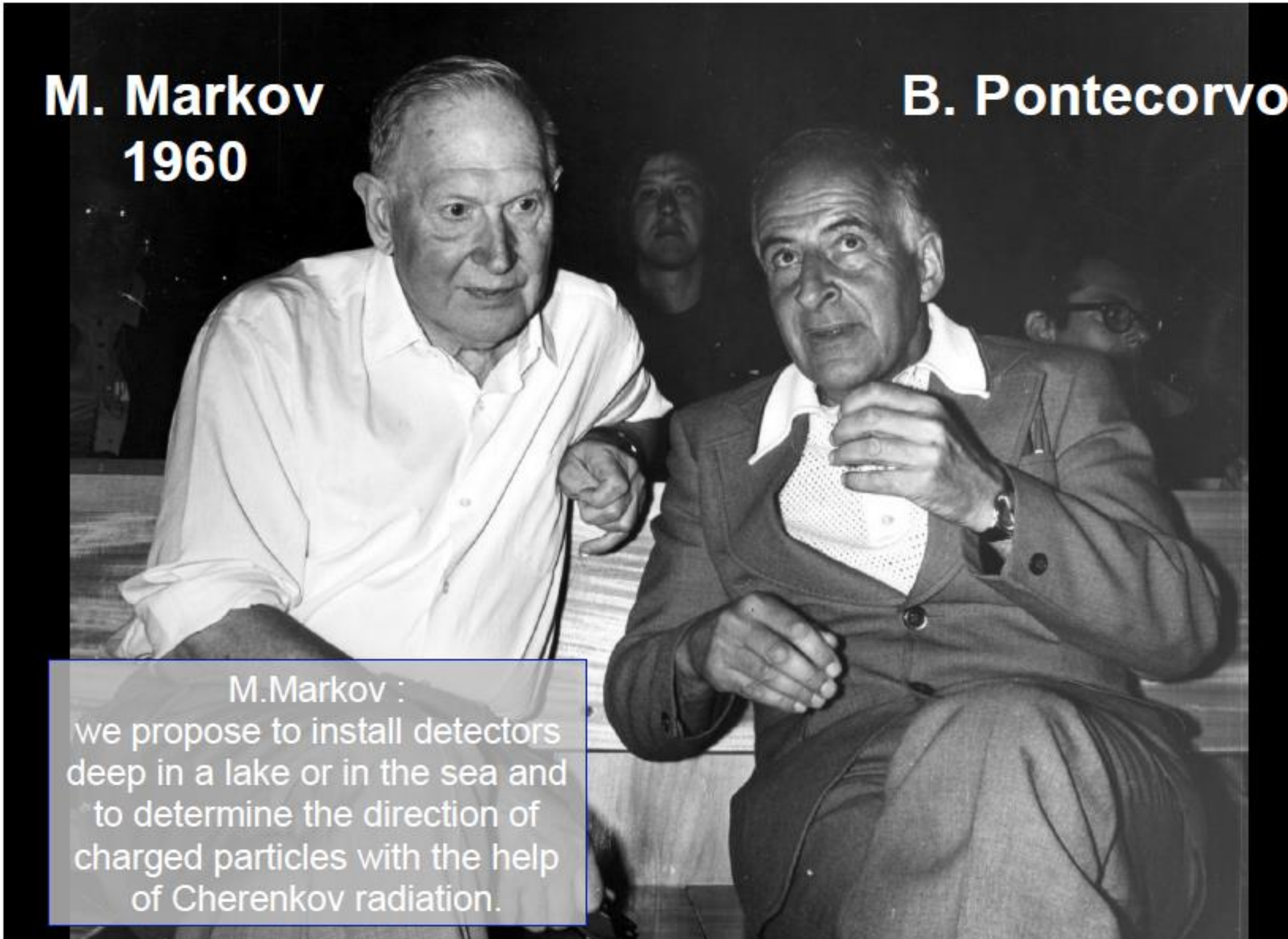
[Halzen, 1311.6350]

At E > 100 TeV cosmic-neutrino fluxes (produced by SNR & GRB) exceed the atmospheric neutrino flux

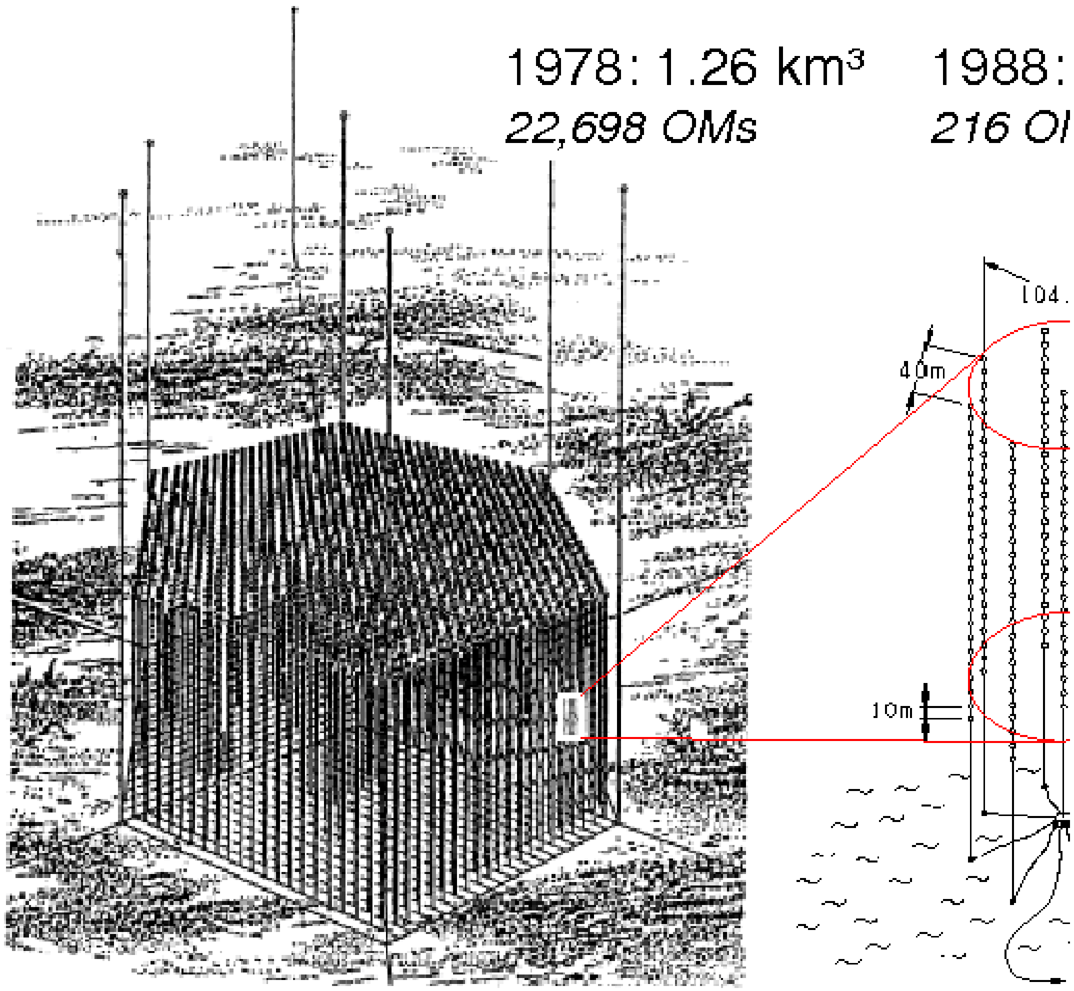
NEUTRINO BEAM DUMP





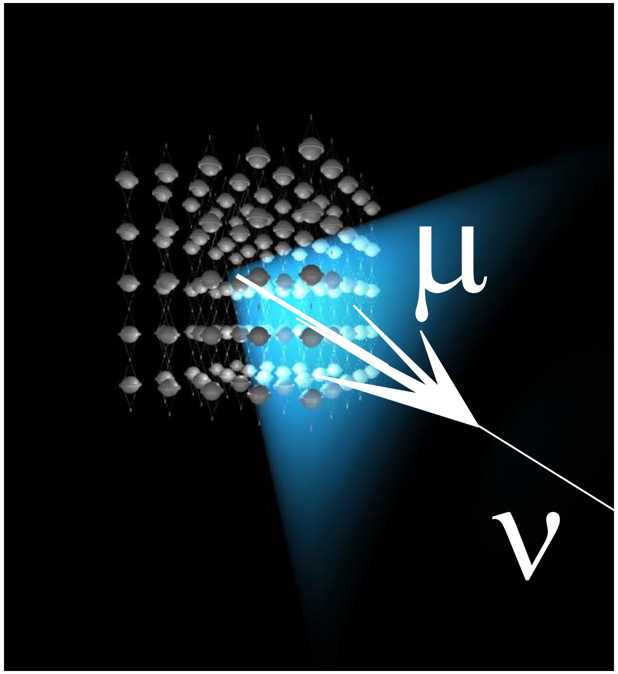

M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

A CUBIC KILOMETER DETECTOR: FROM DREAM....

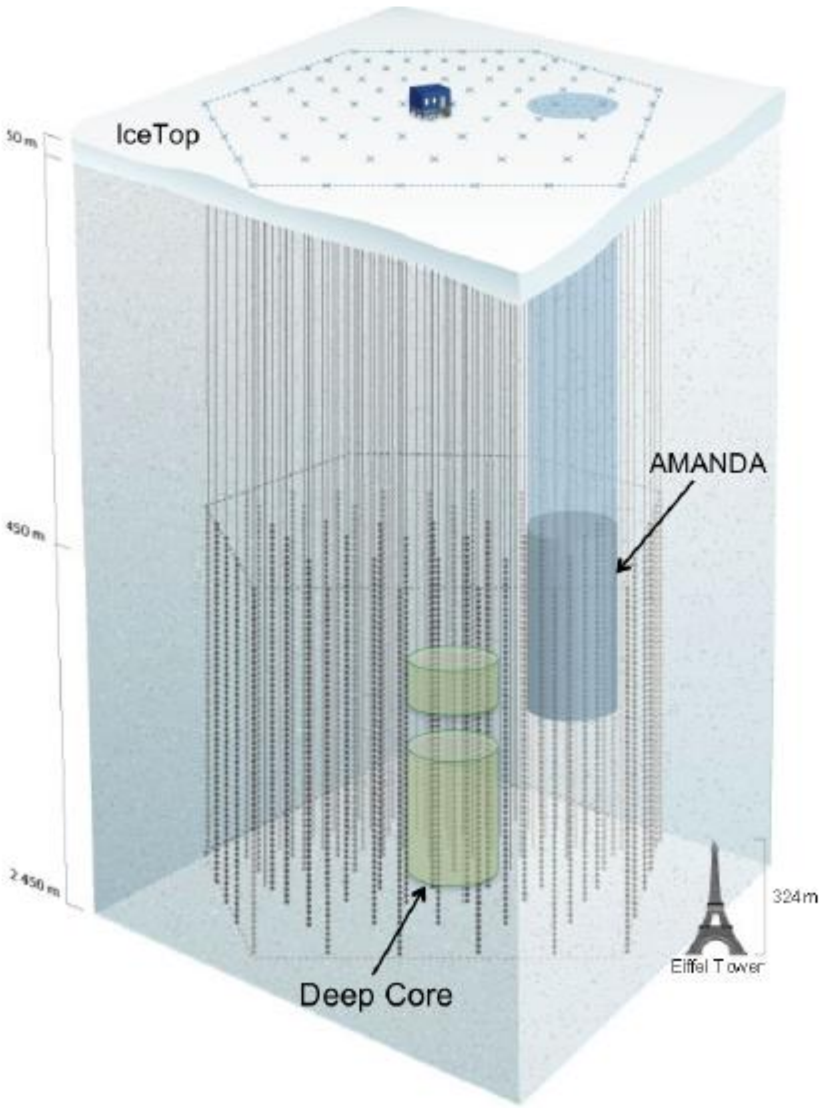


- ICRC 1973: first discussion of DUMAND (Deep Underwater Muon and Neutrino Detector) to be built in the sea off the main island of Hawaii.

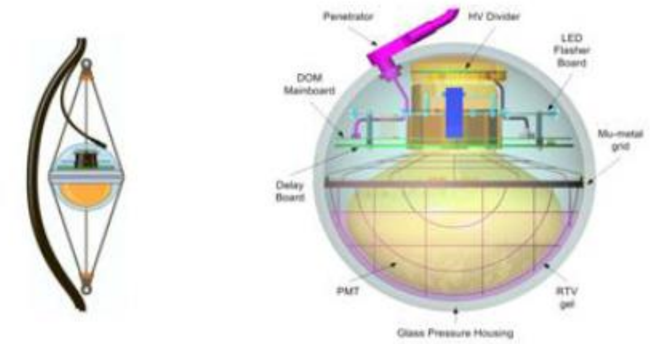
Cherenkov light



.... TO REALITY: ICECUBE NEUTRINO TELESCOPE AT SOUTH POLE

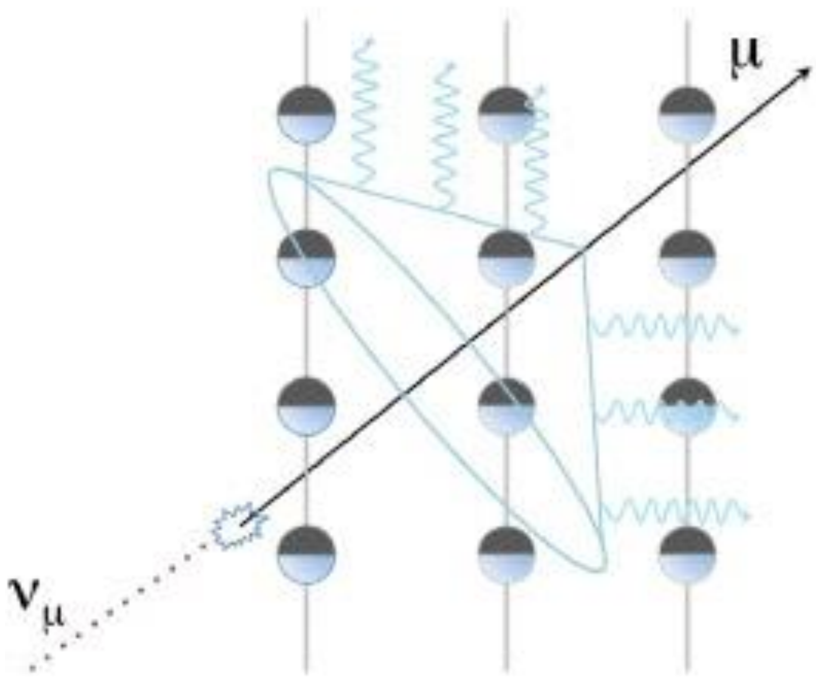


Instrumentation of 1 km^3 antartic ice with ~5000 photomultipliers
Completed December 2010



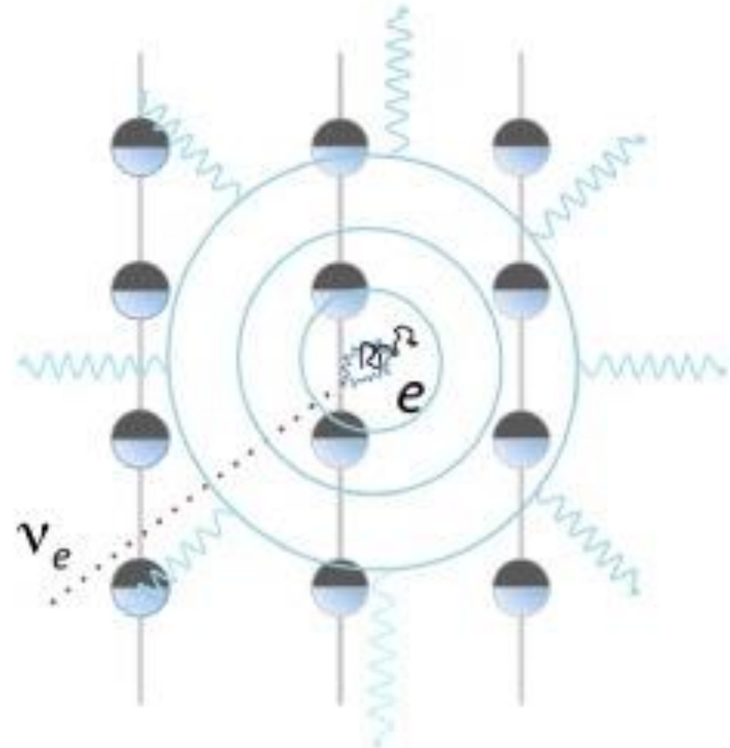
DETECTION OF ν_e , ν_μ , ν_τ

O(km) long muon tracks



~ 15 km

Electromagnetic and hadronic cascades



~ 5 m

THE TWO PeV NEUTRINO EVENTS IN ICECUBE

[Icecube Collaboration, 1304.5356, PRL 111, 021103 (2013)]

THE TWO PeV NEUTRINO EVENTS IN ICECUBE

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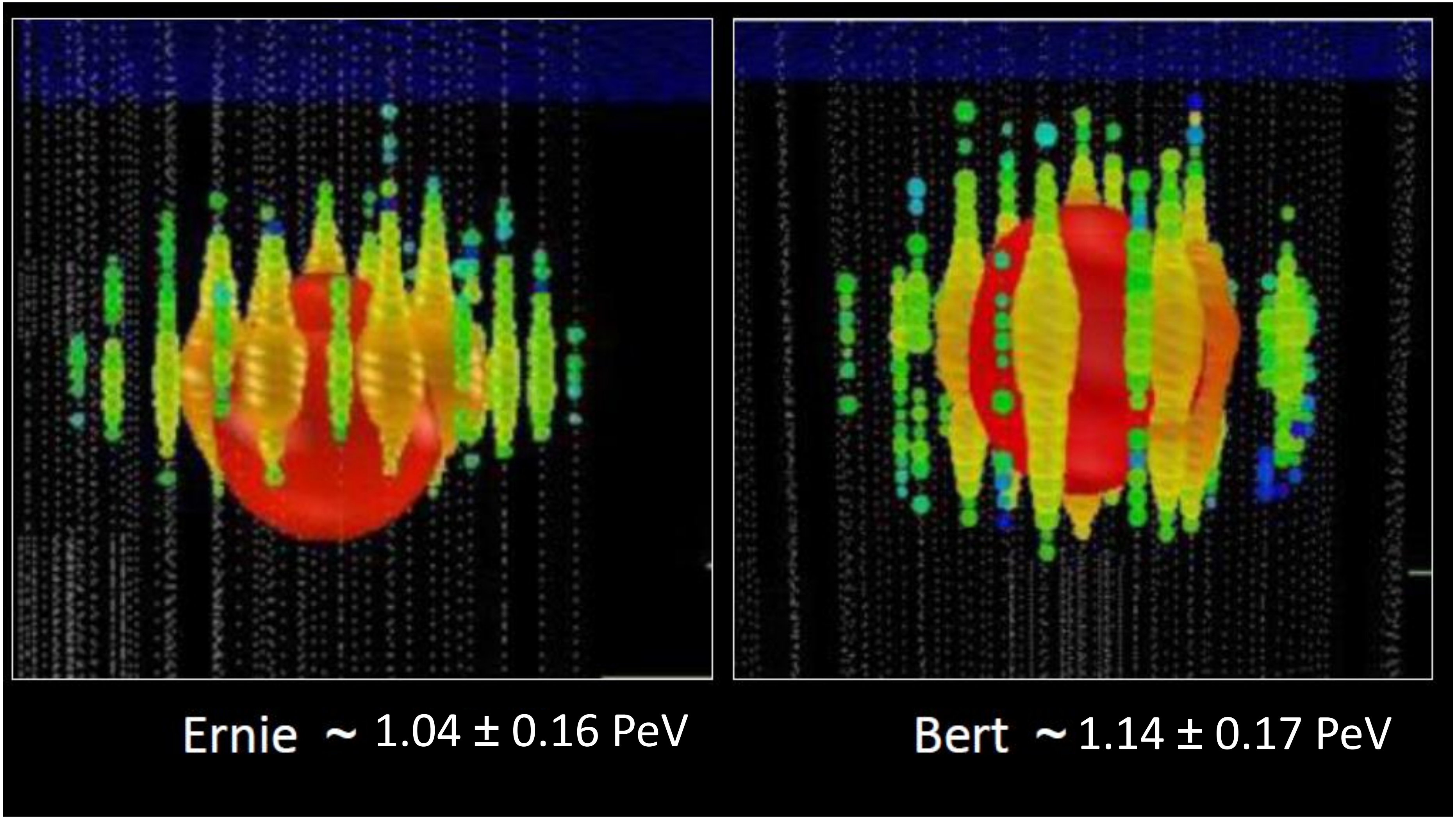
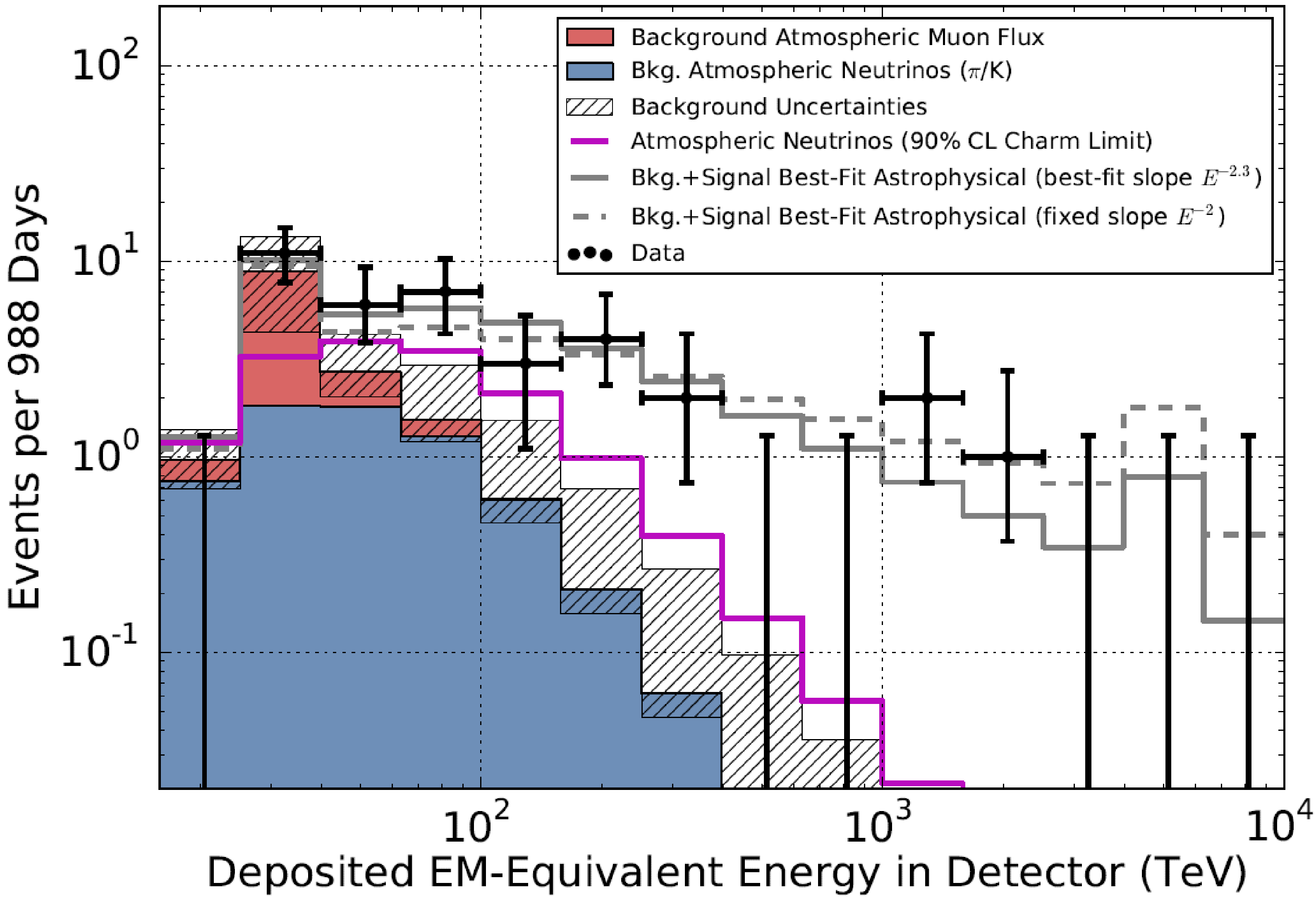


HIGH-ENERGY NEUTRINO ENERGY SPECTRUM

[Icecube Collaboration, 1405.5303, PRL 113, 101101 (2014)]



Conservative analysis: 37 candidates, ~15 background, 5.7σ rejection of pure atmospheric neutrino flux

SUMMARY

Understanding neutrino internal properties — a mature field

- Neutrino mixing parameters:Matrix well known from astro and lab evidence
- New experiments for missing parameters in the making
- Absolute masses yet to be determined (KATRIN, cosmology)

Neutrinos as astrophysical messengers

- Detailed measurement of solar nus (ca 60,000 events in Super-K)
- First geo-neutrinos (ca 116 events in KamLAND)
- SN 1987A (ca 20 events)
- First high-E events in IceCube (Ernie, Bert, and 35 others)

"If you can measure something accurately enough, you have a chance of discovering something of important. The history of astronomy shows that it is very likely that what you discover will not be what you were looking for...It helps to be lucky" (J. Bahcall)

FURTHER READING