Neutrino Physics

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PIRE/GEMADARC Summer School — May 2023

1: Foundations

1897: Discovery of Electron

- J.J. Thomson, 1897
- Built on work by Perrin and Wiechert
- At time, “cathode rays” were deflected by magnetic but not electric fields.
- Thomson speculated due to bad vacuum.
  - Showed “Cathode Rays” Carried Charge
  - Measured deflection in E-field and *e/m* >> any atom
- Thomson Speculated (correctly) “corpsucles” were atomic constituents.
- First *fundamental* particle discovered.
- Took few more years for electron to be accepted -> new models of atoms.

J.J. Thomson, courtesy AIP

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

OCTOBER 1897.

XL. *Cathode Rays. By* J. J. Thomson, *M.A., F.R.S., Cavendish Professor of Experimental Physics, Cambridge**.

THE experiments† discussed in this paper were undertaken in the hope of gaining some information as to the nature of the Cathode Rays. The most diverse opinions are held as to these rays; according to the almost unanimous opinion of German physicists they are due to some process in the æther to which—inasmuch as in a uniform magnetic field their course is circular and not rectilinear—no phenomenon hitherto observed is analogous: another view of these rays is that, so far from being wholly ætherial, they are in fact wholly material, and that they mark the paths of particles of matter charged with negative electricity. It would seem at first sight that it ought not to be difficult to discriminate between views so different, yet experience shows that this is not the case, as amongst the physicists who have most deeply studied the subject can be found supporters of either theory.

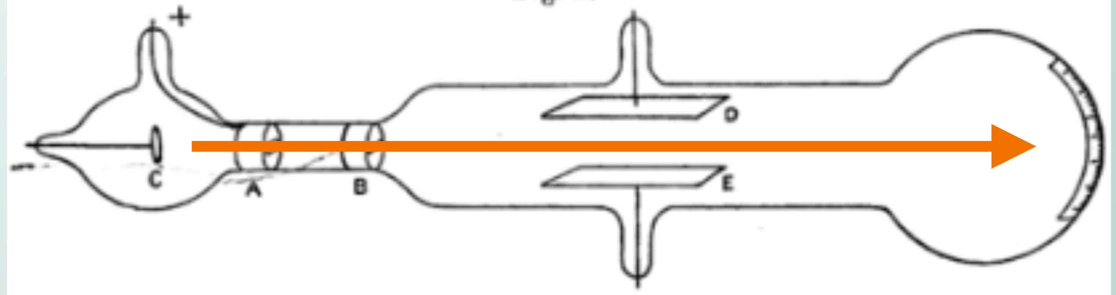
The electrified-particle theory has for purposes of research a great advantage over the ætherial theory, since it is definite and its consequences can be predicted; with the ætherial theory it is impossible to predict what will happen under any given circumstances, as on this theory we are dealing with hitherto

* Communicated by the Author.

† Some of these experiments have already been described in a paper read before the Cambridge Philosophical Society (Proceedings, vol. ix. 1897), and in a Friday Evening Discourse at the Royal Institution (‘Electrician,’ May 21, 1897).

Phil. Mag. S. 5. Vol. 44. No. 269. *Oct.* 1897. Y

Fig. 2.

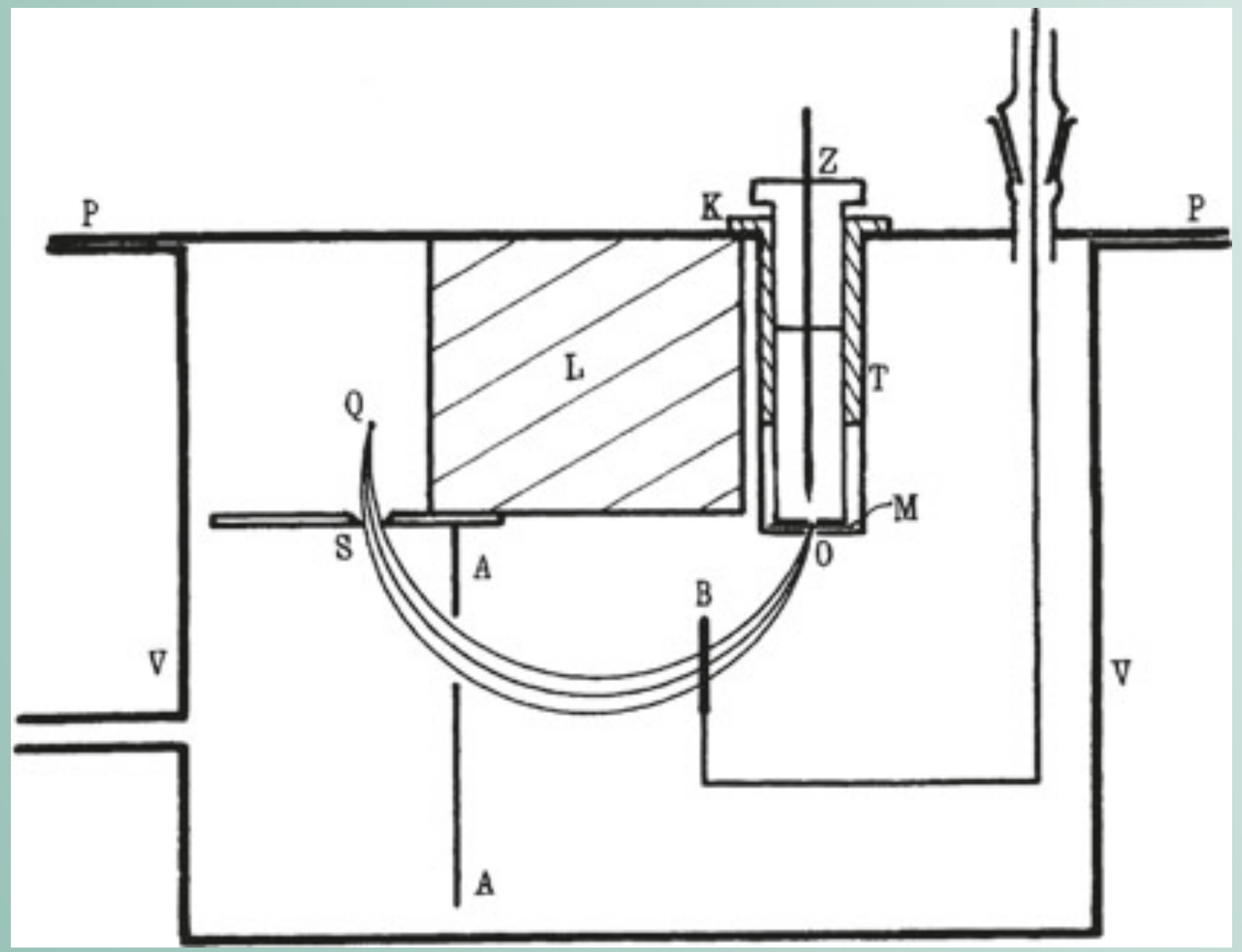


The rays from the cathode C pass through a slit in the anode A, which is a metal plug fitting tightly into the tube and connected with the earth; after passing through a second slit in another earth-connected metal plug B, they travel between two parallel aluminium plates about 5 cm. long by 2 broad and at a distance of 1·5 cm. apart; they then fall on the end of the tube and produce a narrow well-defined phosphorescent patch. A scale pasted on the outside of the tube serves to measure the deflexion of this patch.

1914: Problems in beta-decay

- 1898-99: Henri Becquerel and Marie and Pierre Curie discover radioactivity in U/Th.
- 1899: Rutherford discovers nuclear beta decay
- 1902: Becquerel shows beta rays are electrons
- Chadwick shows ^{214}Pb and ^{214}Bi beta decay spectrum is continuous using magnetic spectrometer

Verhandlungen der deutschen physikalischen Gesellschaft, 16, 383



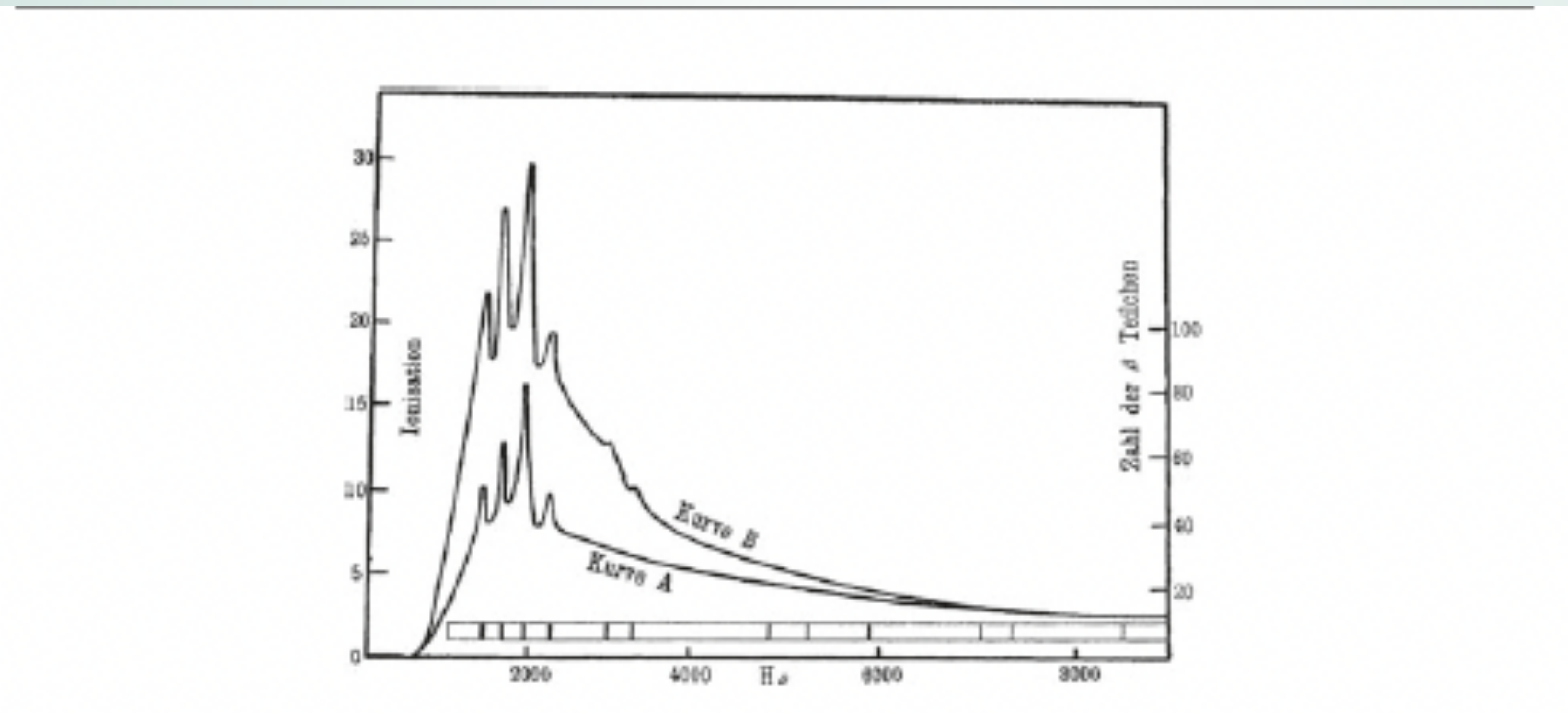
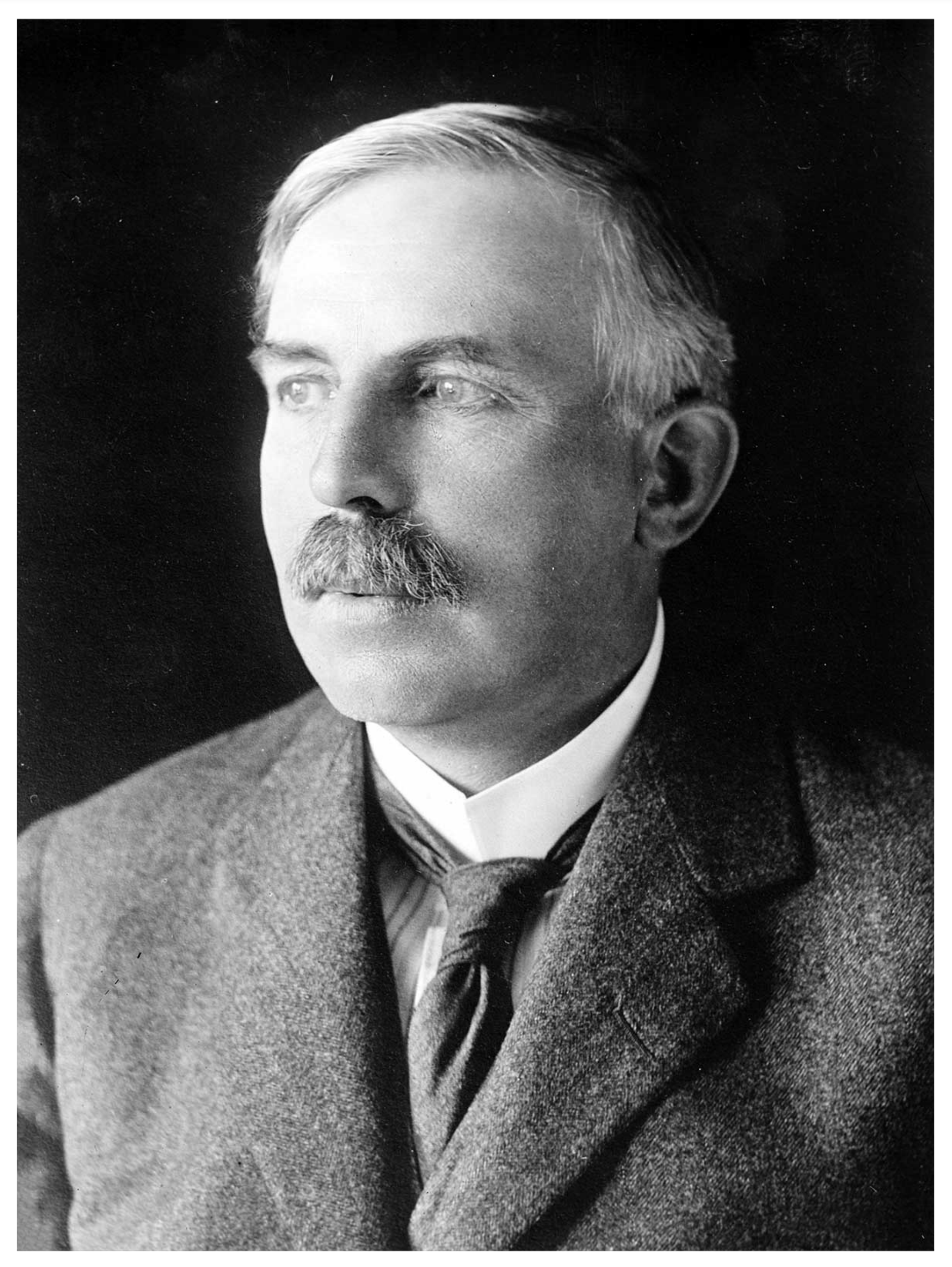


Fig. 2.20 Chadwick's beta-ray spectrum data where Curve A was obtained using Geiger's point counter, and Curve B using ionization determinations. *Source* Chadwick (1914)

tracks. As he recounted in a letter to Rutherford:

> I have not made much progress as regards definite results. We wanted to count the β particles in the various spectrum lines of RaB + C *and then to do the scattering of the strongest swift group*. I get photographs very quickly and easily, but with the counter I can't find even the ghost of a line. There is probably some silly mistake somewhere.[50]



atomicarchive.com

1930: Pauli's Solution of "Desperation"

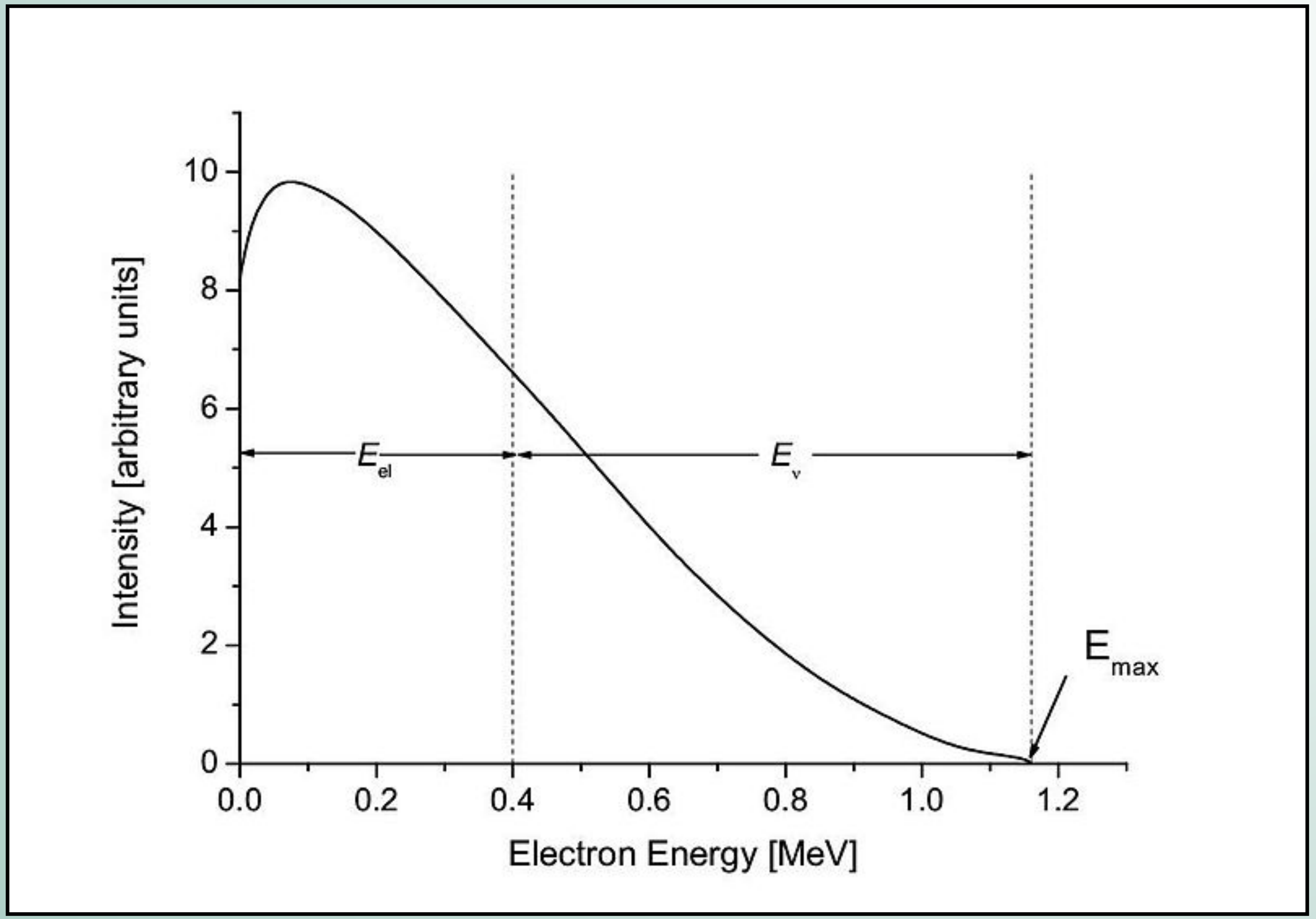
- Bohr: Energy Conservation is Violated
- Pauli wrote famous "dear radioactive ladies and gentlemen" letter to experimental physicists meeting at Tubingen:

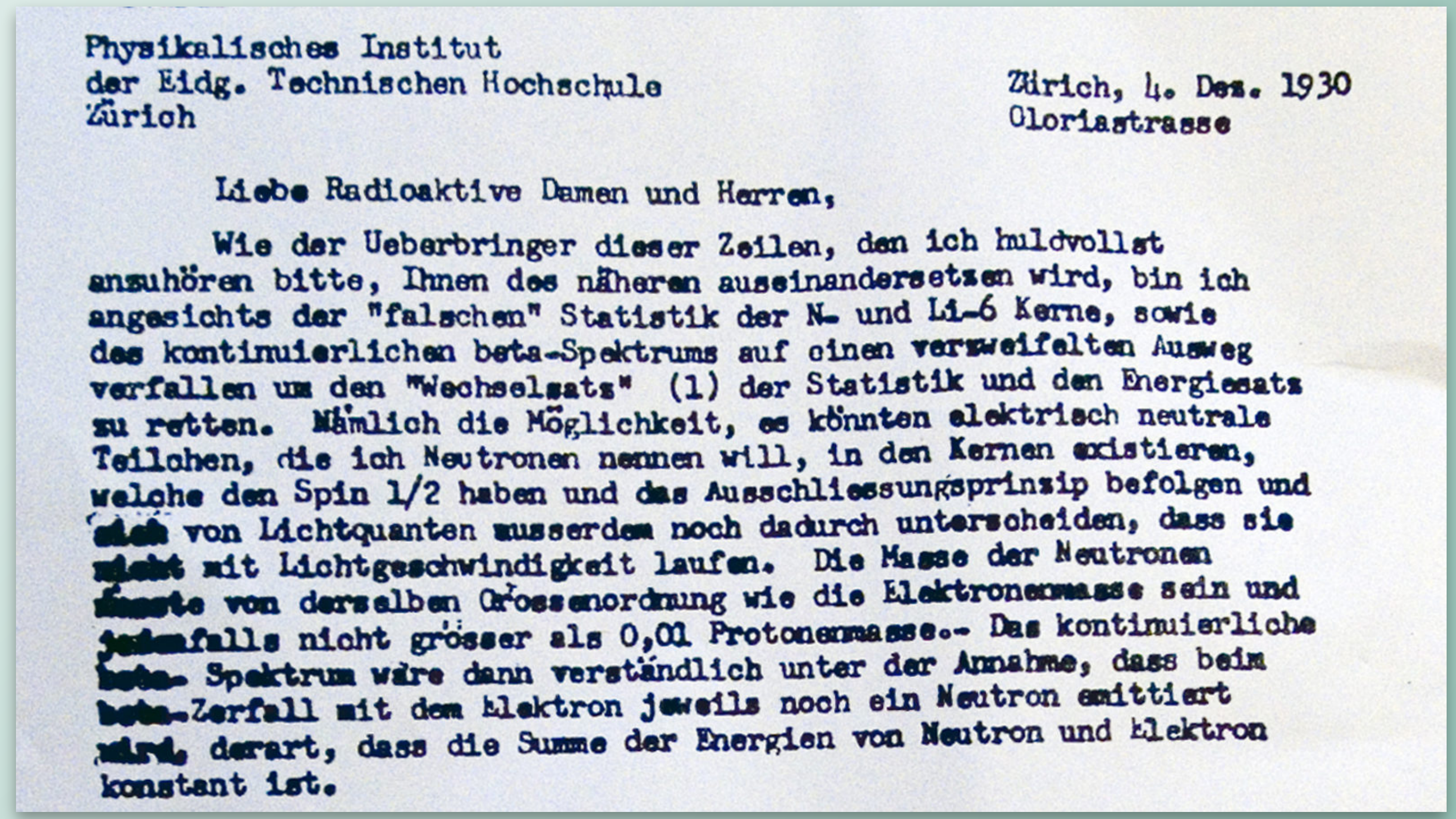
"I have hit upon a desperate remedy to save…the law of conservation of energy."

"…there could exist electrically neutral particles, which I will call **neutrons**, in the nuclei…"

"But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive ones, with the question of how likely it is to find experimental evidence for such a neutron…"

"I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained…"





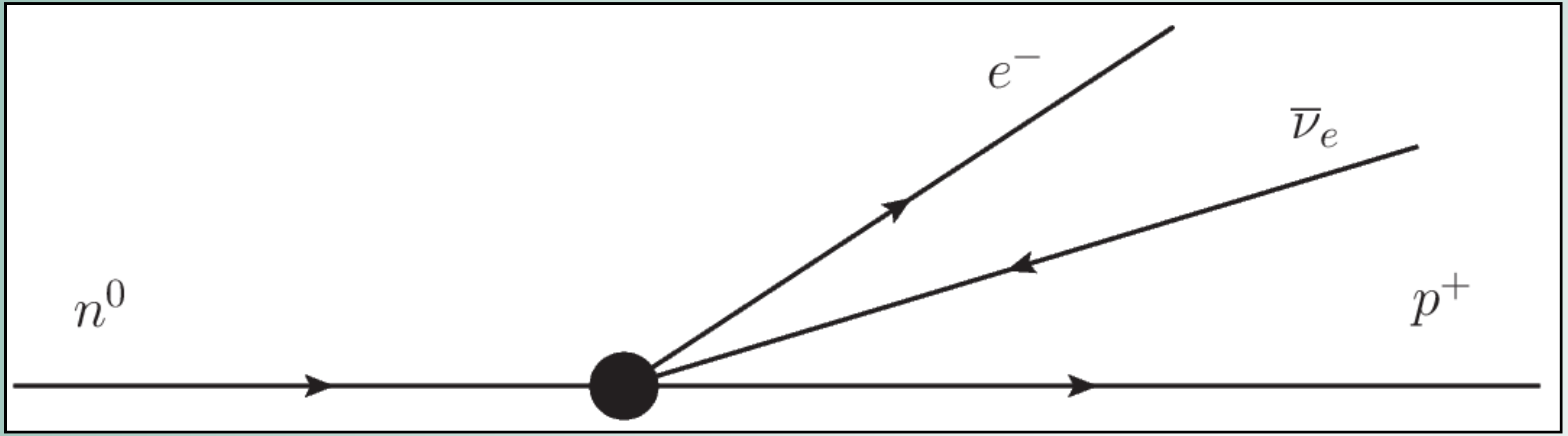
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

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.

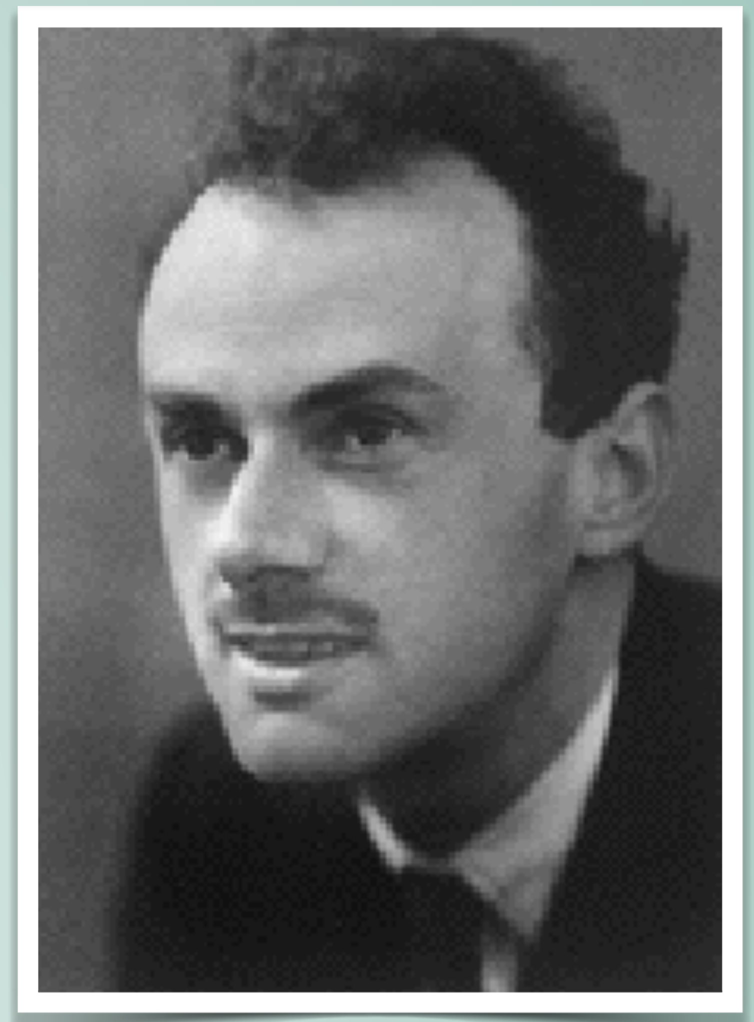
1934: Fermi's Theory of Beta Decay



Mondari Portfolio

- 1932: Chadwick discovers neutron. Too heavy to explain beta decay
- 1932-1934 : Fermi uses "neutrino" at conferences, meaning "weak little one"
- 1934: Fermi Interaction Theory: *Zeitschrift für Physik* 88 (3–4): 16, *Il Nuovo Cimento.* 11 (1): 1
  - Built on models of photon emission from atoms
  - First successful model of interaction that created/annihilated particles
  - Also saved angular momentum conservation
  - Laid groundwork for modeling interactions in Standard Model.
  - Fermi submitted to *Nature*, rejected as too speculative. Later acknowledged as greatest editorial blunder in its history
  - Rejection made Fermi switch to experimental physics and eventually work on Manhattan project.

1937: Majorana Fermions Proposed

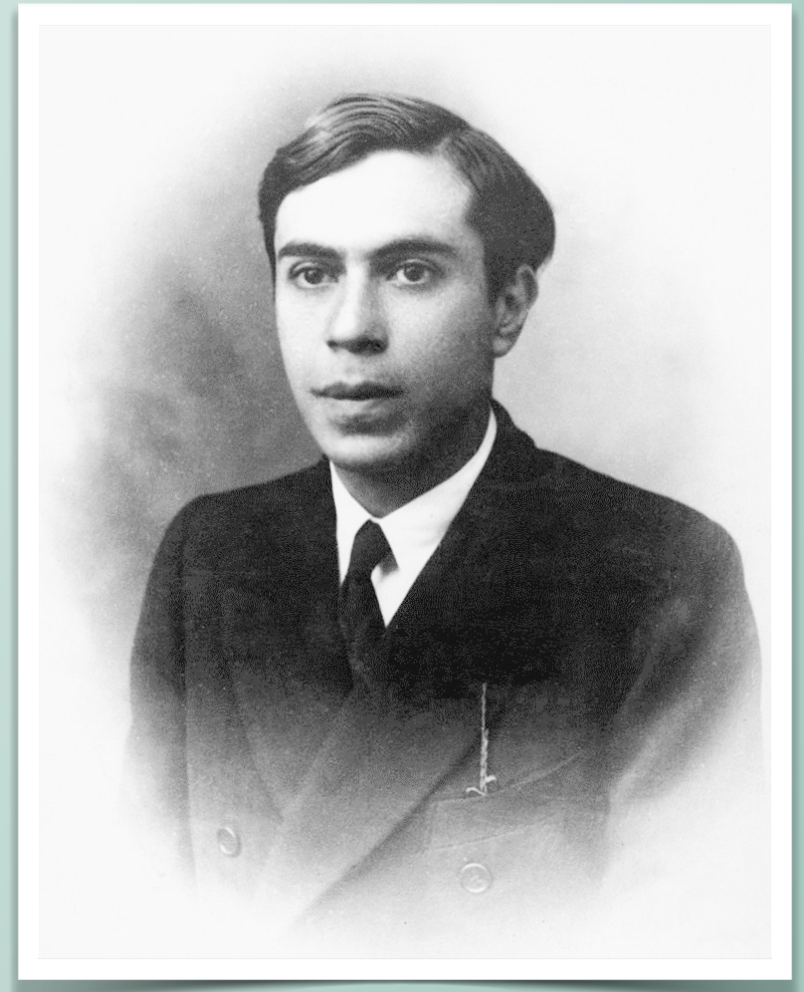


- 1929: Paul Dirac publishes Dirac equation

Proceedings of the Royal Society of London (1905-1934) **117**, 610

$$(i\hbar\gamma^{\mu} - mc)\psi = 0$$

  - Relativistic wave equations for spin-1/2 fermions
  - Implied existence of antimatter
  - Naturally explained spin
  - 4 solutions: “2 spin states x particle/anti-particle”
  - **Dirac Fermions**



- 1937: Ettore Majorana found solutions to Dirac equations where particle and anti-particle states are the same
  - 2 solutions: “2 spin states”
  - **Majorana Fermions**
  - Mentions Neutrinos as candidates

Nuovo Cimento **14** (1937) 171

TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di Ettore Majorana

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* Dirac *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di «antiparticelle» corrispondenti ai «vuoti» di energia negativa.*

Blackboard Time

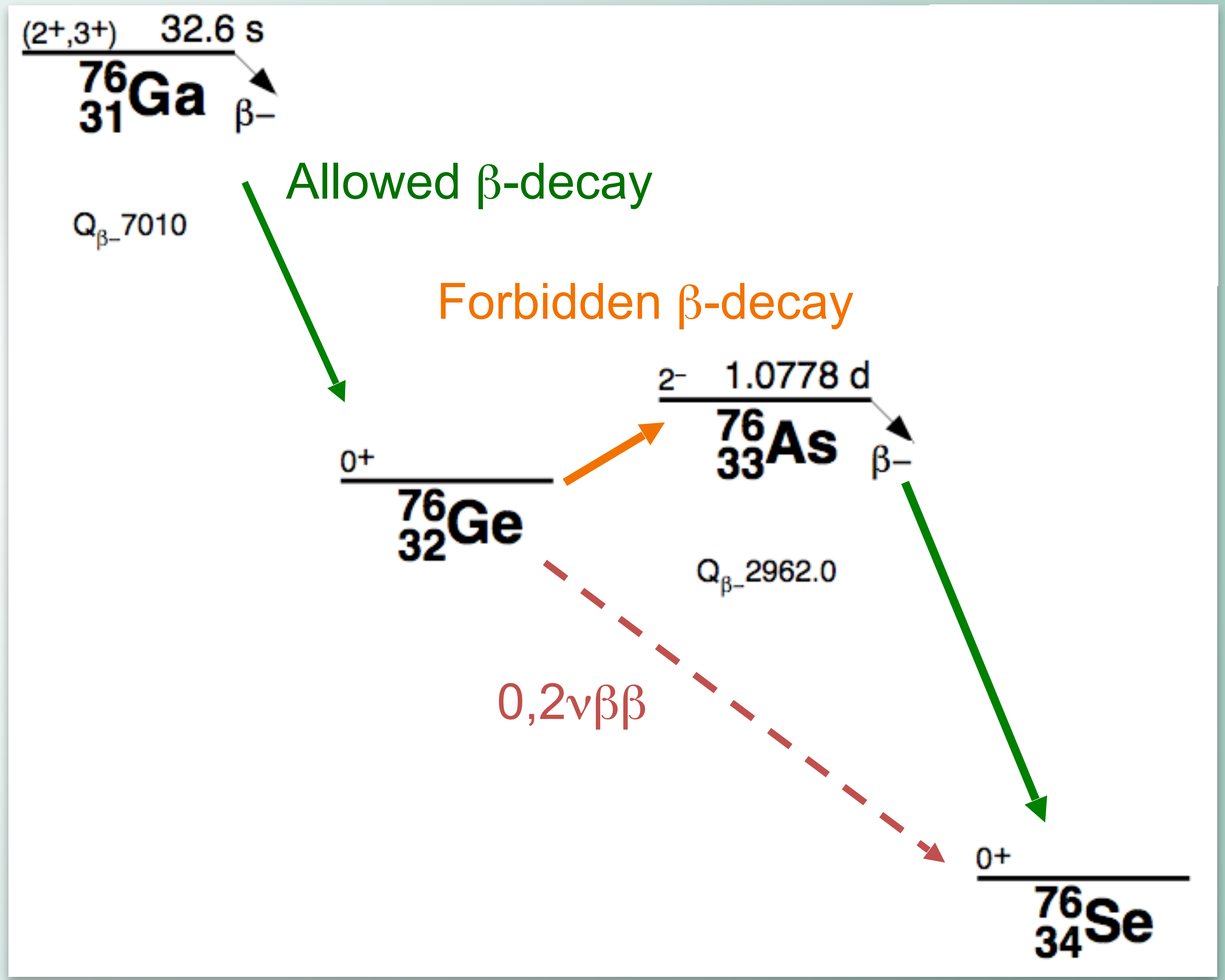
Segue: Neutrinoless double-beta decay

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-}$$

- Energetically allowed in many nuclei.
- Prefer nuclei stable against β-decay (about 30)

2υββ: Observed 2nd order weak process.

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-} + 2\overline{\nu}_{\epsilon}$$



1935: Double Beta Decay Proposed

SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. Goeppert-Mayer, *The Johns Hopkins University*

(Received May 20, 1935)

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

AIP

1. Introduction

In a table showing the existing atomic nuclei it is observed that many groups of isobars occur, the term isobar referring to nuclei of the same atomic weight but different atomic number. It is unreasonable to assume that all isobars have exactly the same energy; one of them therefore will have the lowest energy, the others are unstable. The question arises why the unstable nuclei are in reality metastable, that is, why, in geologic time, they have not all been transformed into the most stable isobar by consecutive β-disintegrations.

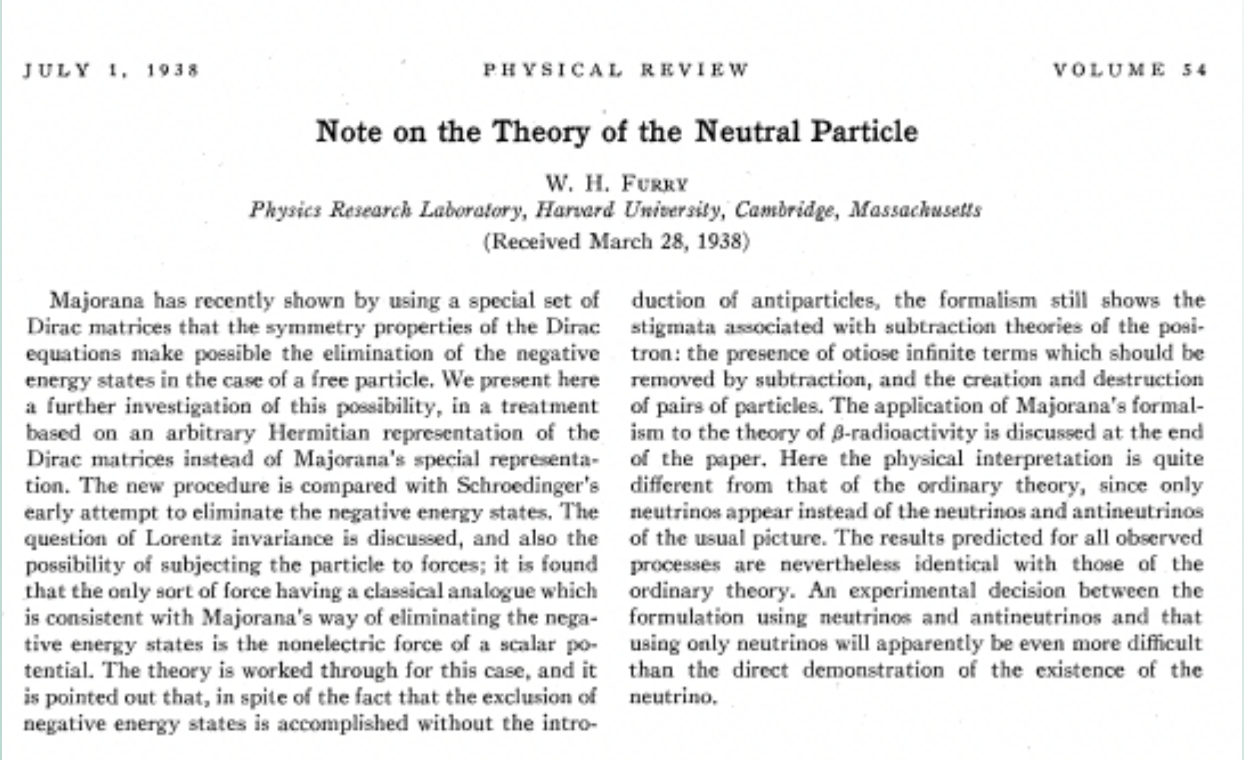
- **1935:** Double beta decay postulated by Maria Goeppert-Mayer Phys. Rev. 48 (1935) 512
- Applied Fermi's Theory to two simultaneous beta-decays.
- Estimated Half-life

1937-1938: DBD and Neutrinos

- **1937:** Giulio Racah showed that symmetry between ν and $\bar{\nu}$ requires new Fermi theory
  - If $\nu = \bar{\nu}$ then Majorana's formalism applies

- **1938**: Wendell Furry: Determining Majorana or Dirac Nature of ν will be difficult

gf.org

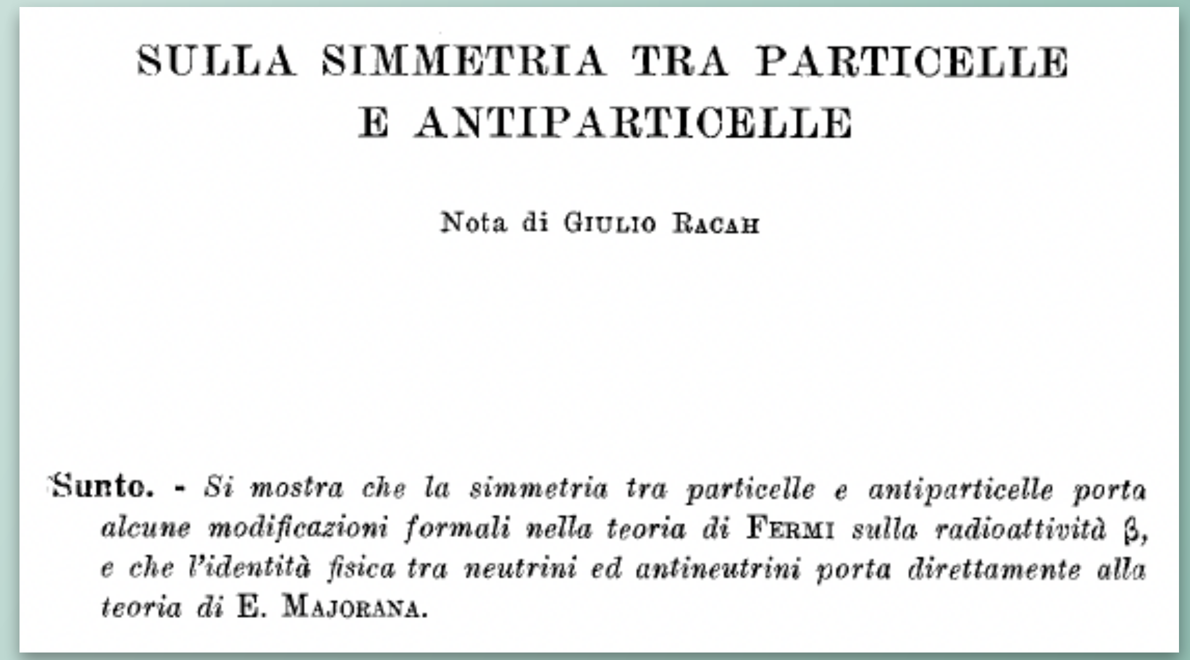


JULY 1, 1938 PHYSICAL REVIEW VOLUME 54

Note on the Theory of the Neutral Particle

W. H. Furry
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received March 28, 1938)

Majorana has recently shown by using a special set of Dirac matrices that the symmetry properties of the Dirac equations make possible the elimination of the negative energy states in the case of a free particle. We present here a further investigation of this possibility, in a treatment based on an arbitrary Hermitian representation of the Dirac matrices instead of Majorana's special representation. The new procedure is compared with Schroedinger's early attempt to eliminate the negative energy states. The question of Lorentz invariance is discussed, and also the possibility of subjecting the particle to forces; it is found that the only sort of force having a classical analogue which is consistent with Majorana's way of eliminating the negative energy states is the nonelectric force of a scalar potential. The theory is worked through for this case, and it is pointed out that, in spite of the fact that the exclusion of negative energy states is accomplished without the introduction of antiparticles, the formalism still shows the stigmata associated with subtraction theories of the positron: the presence of otiose infinite terms which should be removed by subtraction, and the creation and destruction of pairs of particles. The application of Majorana's formalism to the theory of β-radioactivity is discussed at the end of the paper. Here the physical interpretation is quite different from that of the ordinary theory, since only neutrinos appear instead of the neutrinos and antineutrinos of the usual picture. The results predicted for all observed processes are nevertheless identical with those of the ordinary theory. An experimental decision between the formulation using neutrinos and antineutrinos and that using only neutrinos will apparently be even more difficult than the direct demonstration of the existence of the neutrino.



SULLA SIMMETRIA TRA PARTICELLE E ANTIPARTICELLE

Nota di Giulio Racah

Sunto. - *Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di* Fermi *sulla radioattività* β, *e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di* E. Majorana.

1939: The Big Enchilada

- *Furry shows that emission and absorption of Majorana neutrino can mediate 0νββ decay.*

- Possible if MJ neutrinos massless (Fermi-Racah interaction only)
  - V-A nature of weak force unknown at time.
- Predicted half-lives of ~10^{15} years for scalar interaction.
- Led to initial experimental searches.

DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received October 16, 1939)

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with $\Delta i = \pm 1, 0$. The results obtained with the Majorana theory indicate that it is not at all certain that double β-disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ($\epsilon \gtrsim 20$, $\Delta M \gtrsim 0.01$ unit).

gf.org

First Experimental Search for DBD Decay

Phys. Rev. 74 (1948) 1248 (conference proceedings)

Artificial Radioactive Substances

T1. Double Beta Decay.* E. FIREMAN, *Princeton University.*—There exist a number of stable isobaric nuclei that differ by two in charge and may differ by several Mev in mass. The heavier should decay into the lighter with simultaneous emission of two electrons. The decay probability depends markedly upon whether or not the two electrons are accompanied by two neutrinos. No neutrinos are emitted if they obey the Majorana equation or if the interaction is composed of linear combinations of the usual interactions. Furry's calculations using Majorana wave functions have been extended to linear combinations that arise from symmetry considerations and meson theories. Isobars belonging to a triple set are the most promising for double beta decay since the middle one is near the minimum of the isobaric mass defect curve. Therefore, ${}_{40}Zr^{96}$ and ${}_{50}Sn^{124}$ were investigated with a Geiger counter coincidence arrangement. Their activity was compared with elements that are stable against all types of decay. No difference was detected. On the basis of these measurements and the assumption of two-Mev mass difference, the lifetime of ${}_{50}Sn^{124}$ is greater than $3 \cdot 10^{15}$ years. This result rules out the polar vector, axial vector, and tensor interactions with Majorana wave functions and the more important linear combinations.

* This work was supported in part by Navy contract.

This is the whole paper!

Searched for coincident betas from target materials using Geiger tubes

Followed by Discovery!

Phys. Rev. 75 (1949) 323

A Measurement of the Half-Life of Double Beta-Decay from $_{50}Sn^{124}$ *

E. L. FIREMAN
Department of Physics, Princeton University, Princeton, New Jersey
November 29, 1948

In all situations specimen *A* gives 2 coincidence counts/hr. more than specimen *B*. By repeating this type of measurement with Al absorbers over one side of each specimen an absorption curve is obtained. This absorption curve is similar to that of electrons from a spectrum with an energy end point between 1.0 Mev and 1.5 Mev. The single counts from specimens *A* and *B* both give 6.5 ± 0.3 counts/min. If one interprets this effect as double beta-decay from Sn^{124}, one obtains a half-life between $0.4 \cdot 10^{16}$ yr. and $0.9 \cdot 10^{16}$ yr. Other alternative explanations for these observations have been considered but none have been found to be plausible. This result would indicate that double beta-decay is unaccompanied by neutrinos. A further consequence of these results pointed out to the author by Professor J. R. Oppenheimer is that the neutron-proton charge difference is exactly equal to the electron charge.

2.6 sigma effect

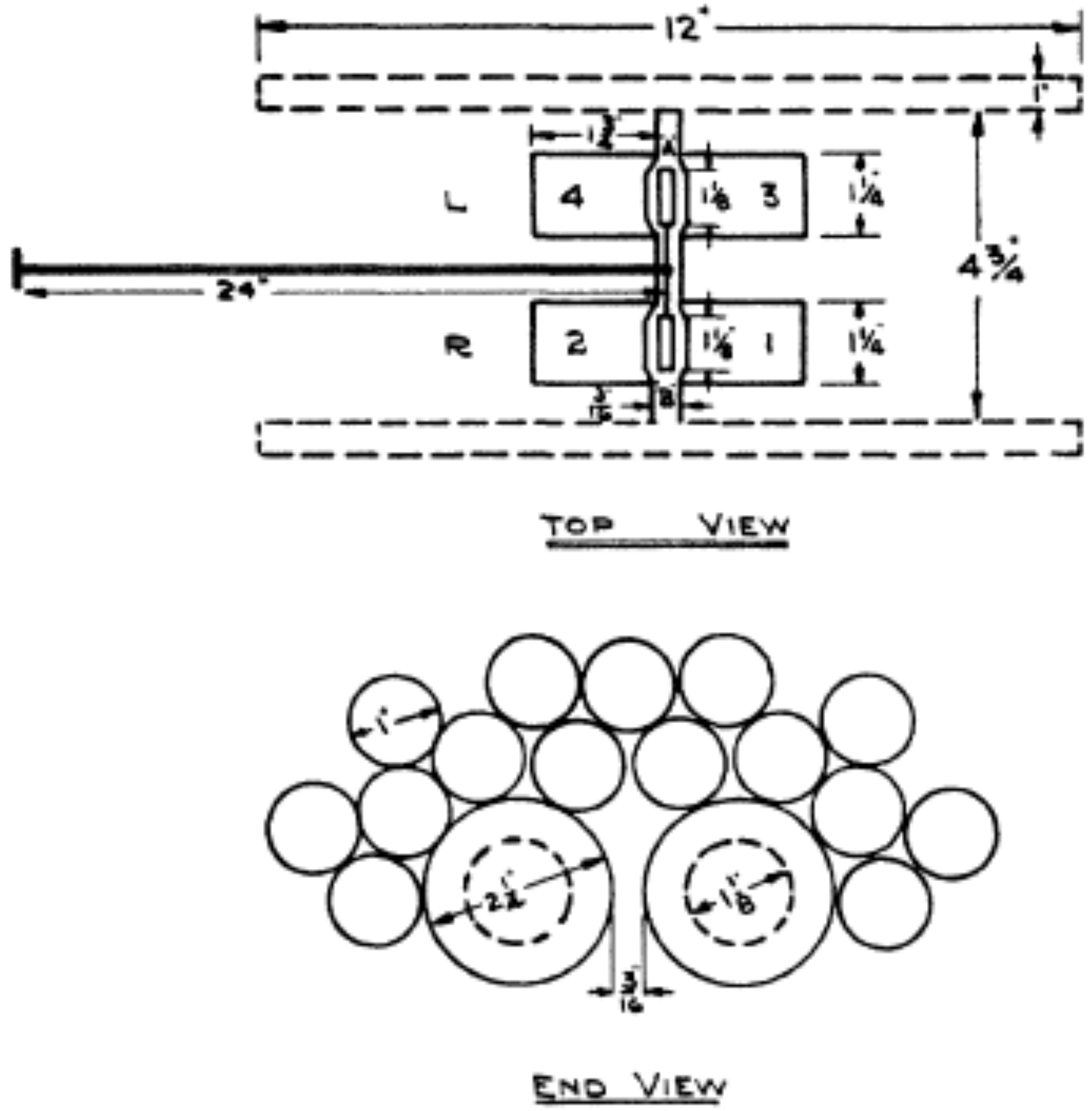


FIG. 1. Experimental arrangement.

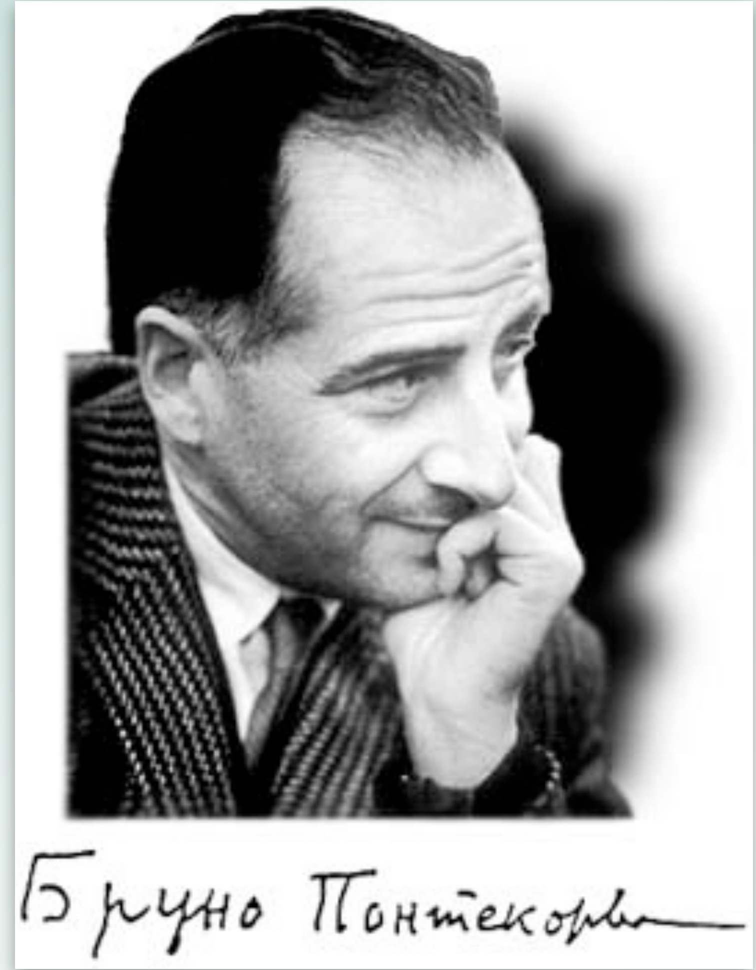
Discussion

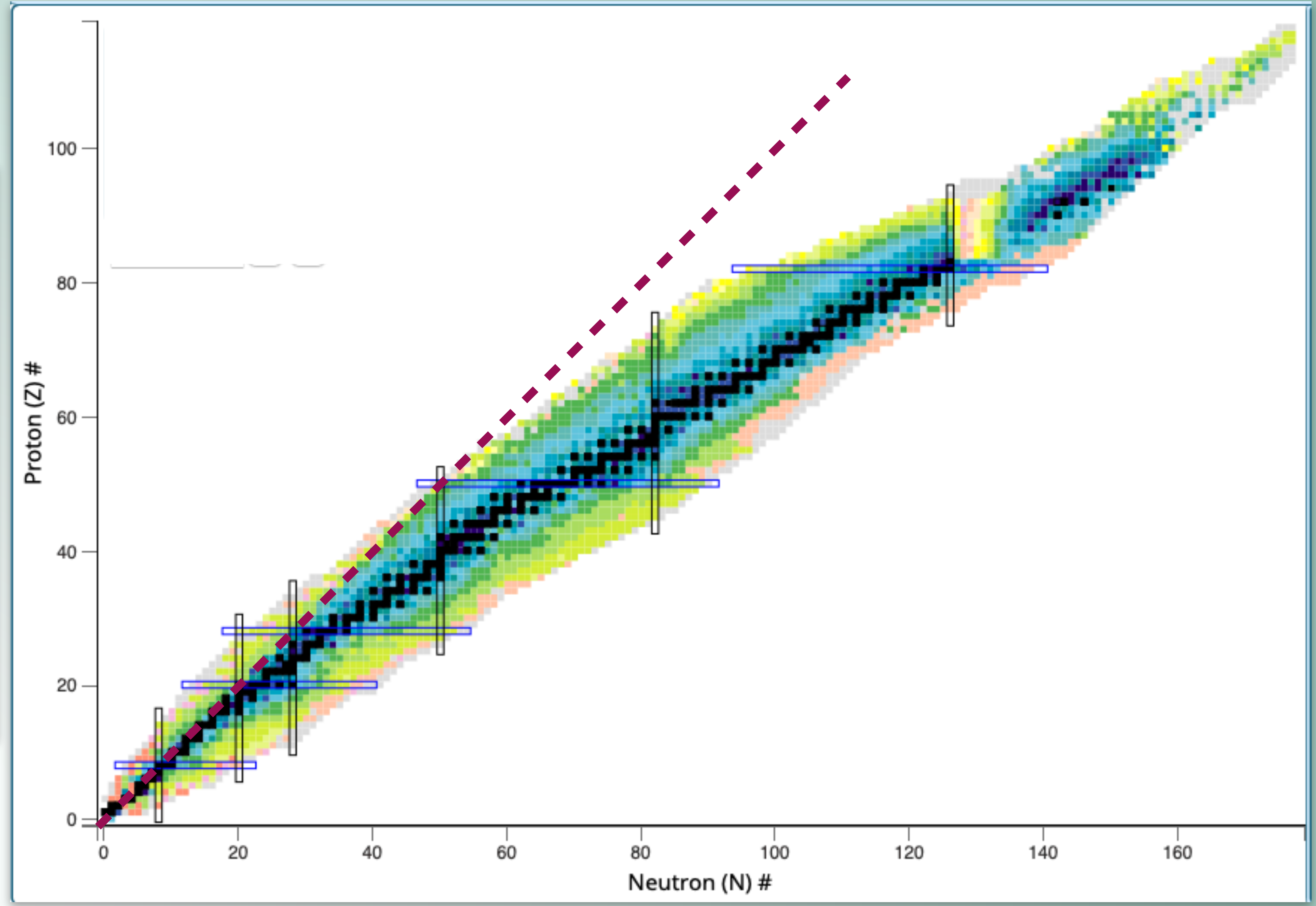
- Ruled out by subsequent measurements, though (Astropart. Phys. 31 (2009) 412) $T_{1/2}(^{124}Sn, 0n) > 2.0 \times 10^{19}$ yr)
- Likely due to radioactive contamination, uncontrolled systematics (no discussion of calibrations), sample thickness
- Limited handles on data
- About dozen "claims" in literature, all debunked
- Three explanations:
  - Unknown backgrounds
  - Statistical fluctuations
  - Systematics / unknown detector response
- **These are hard experiments**

2: Discovery

Reactor Neutrinos

- Beta decay emits antineutrinos – find good source of beta decays
- B. Pontecorvo proposes reactors as (anti)neutrino source.*
- Nuclear fission releases energy by breaking up heavy nuclei
- *N/Z* increases with Z for stable nuclei
- Evident in U/Th decay chains (alpha/beta)





Fission results in excess neutrons + energy

Fission Neutrons

Beta-decaying nuclei

$\overline{\nu_e}$

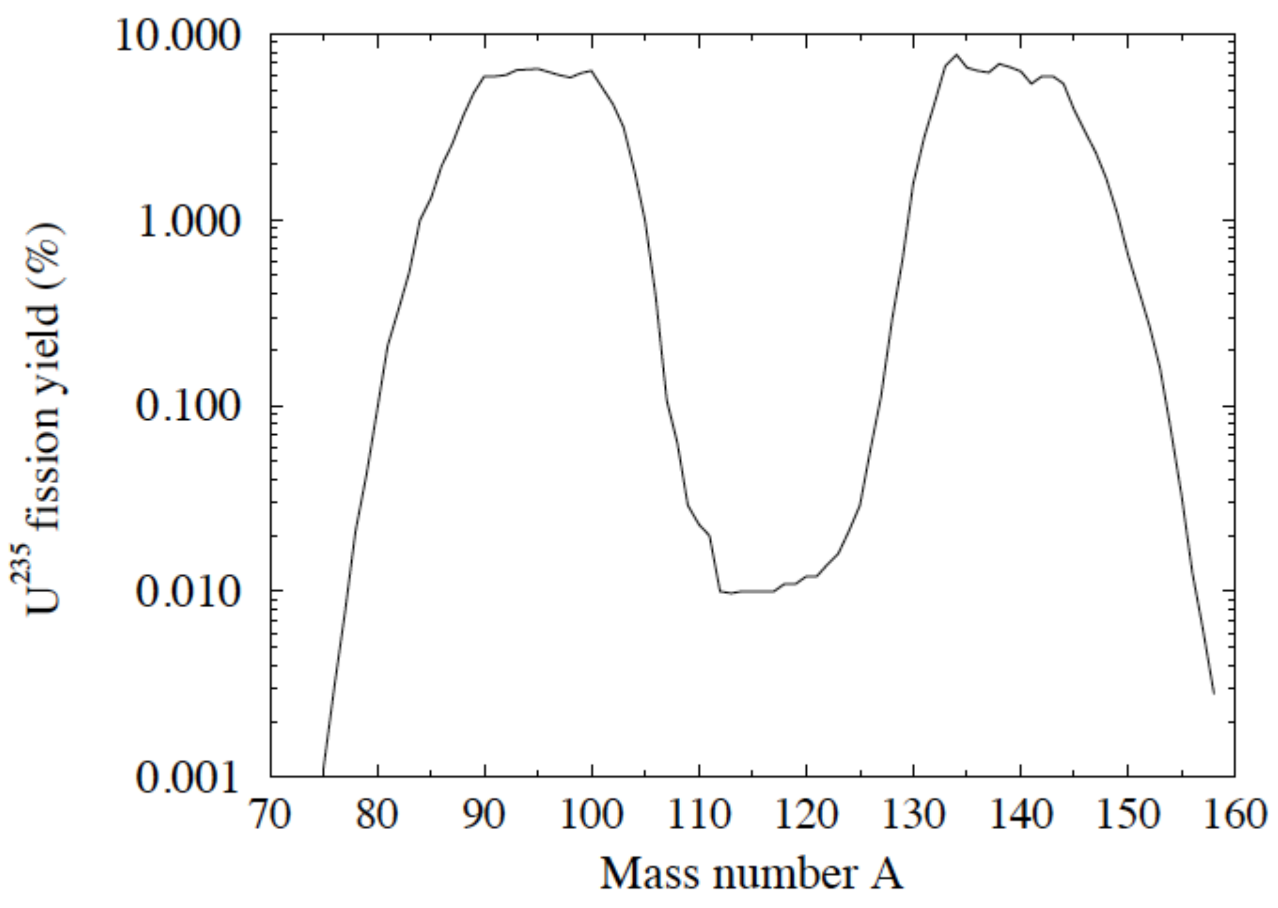
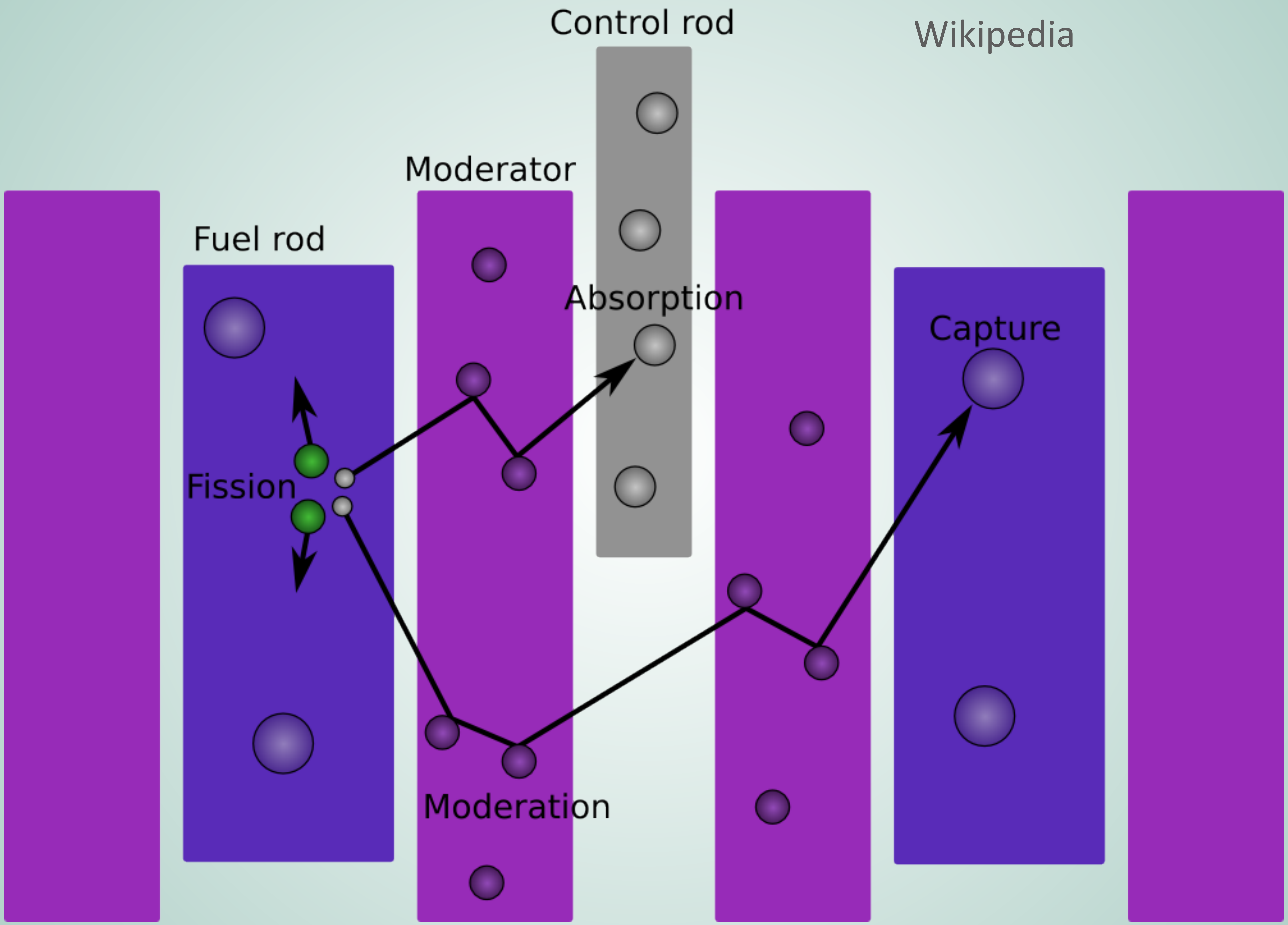


FIG. 5. Yields (in %) for ^{235}U thermal neutron fission (normalized to 2 for the two fragments)

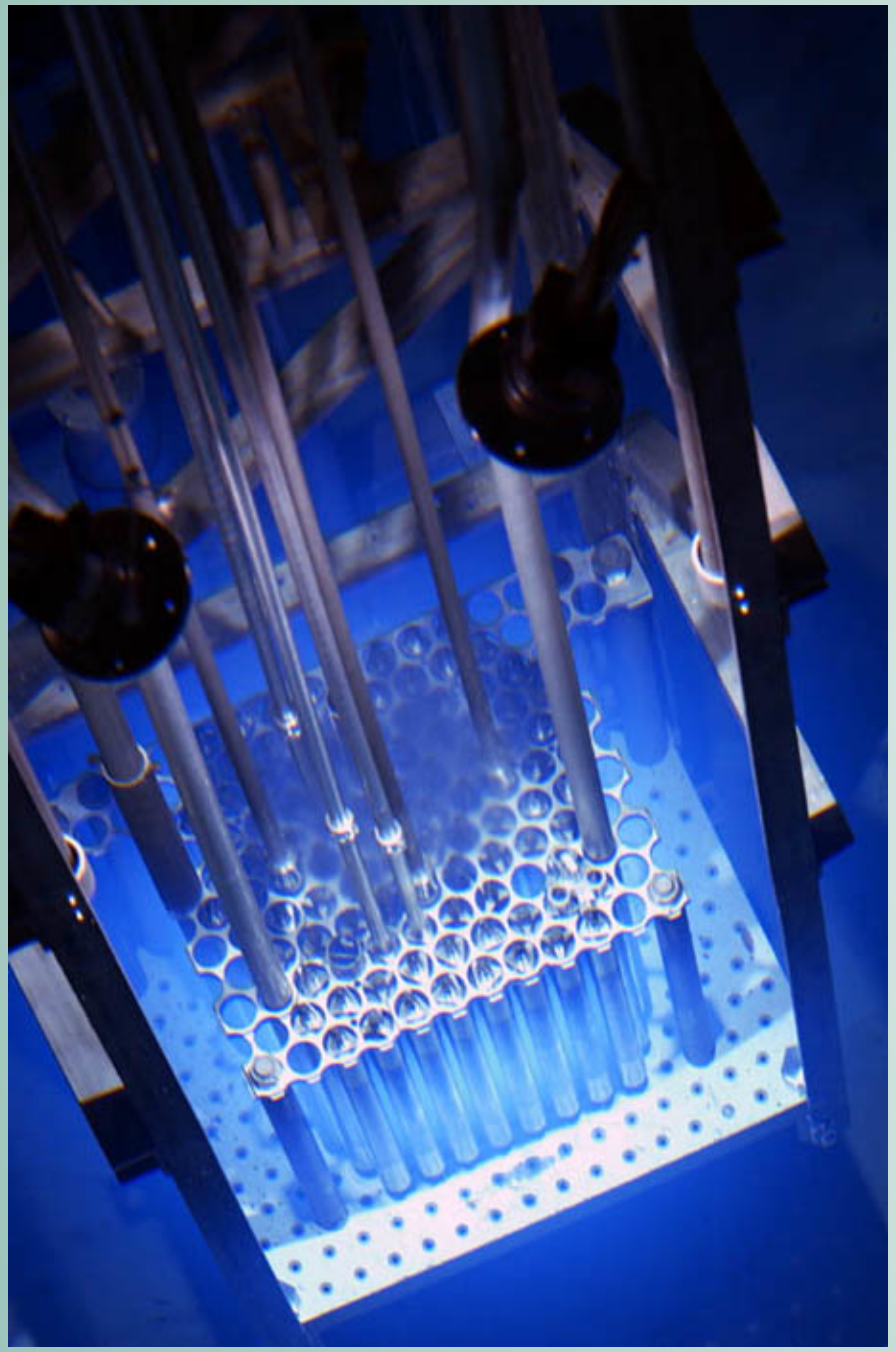
*B. Pontecorvo Natl.Res. Council Canada Rep. (1946) 205, Helv.Phys.Acta.Suppl. 3 (1950) 97

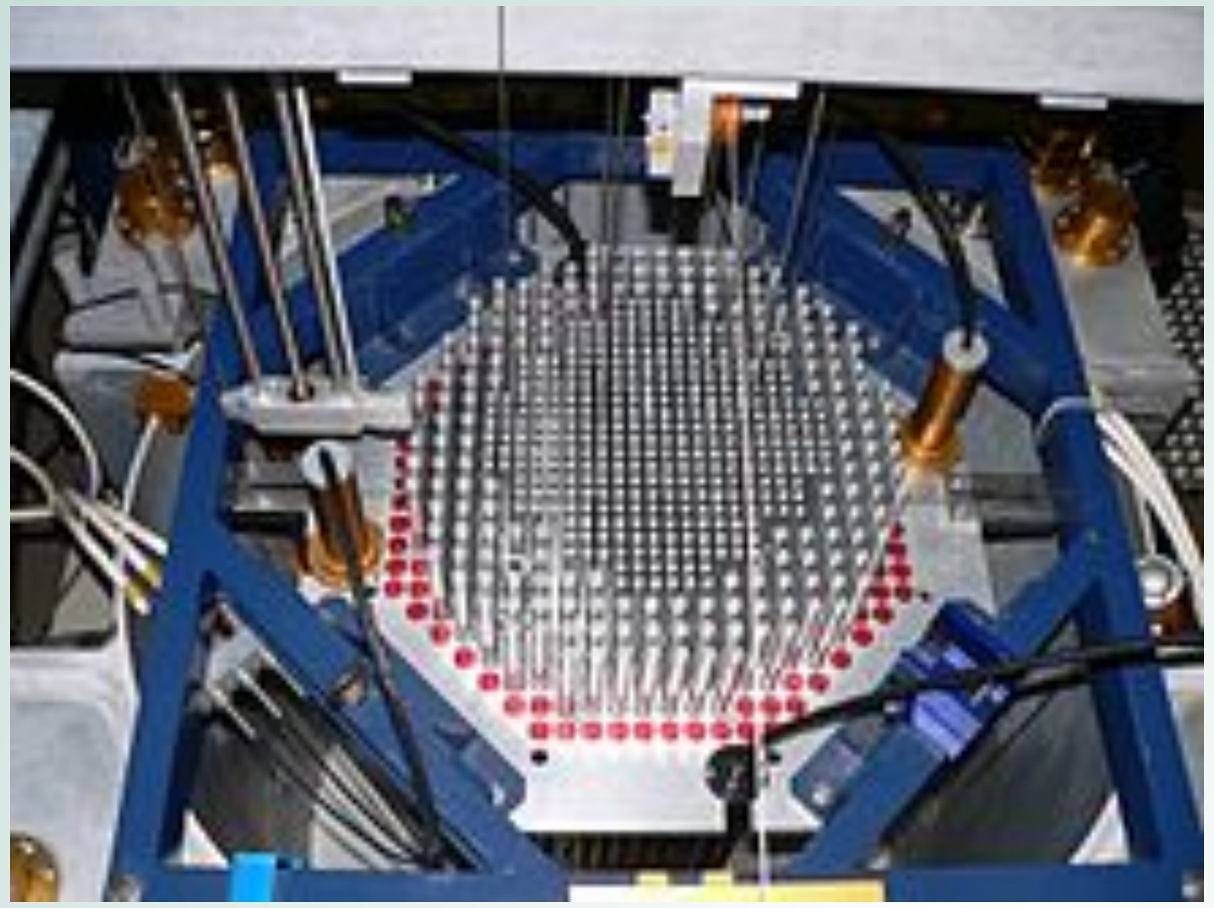
Thermal Reactor Principle



Wikipedia

Nuclear Reactors





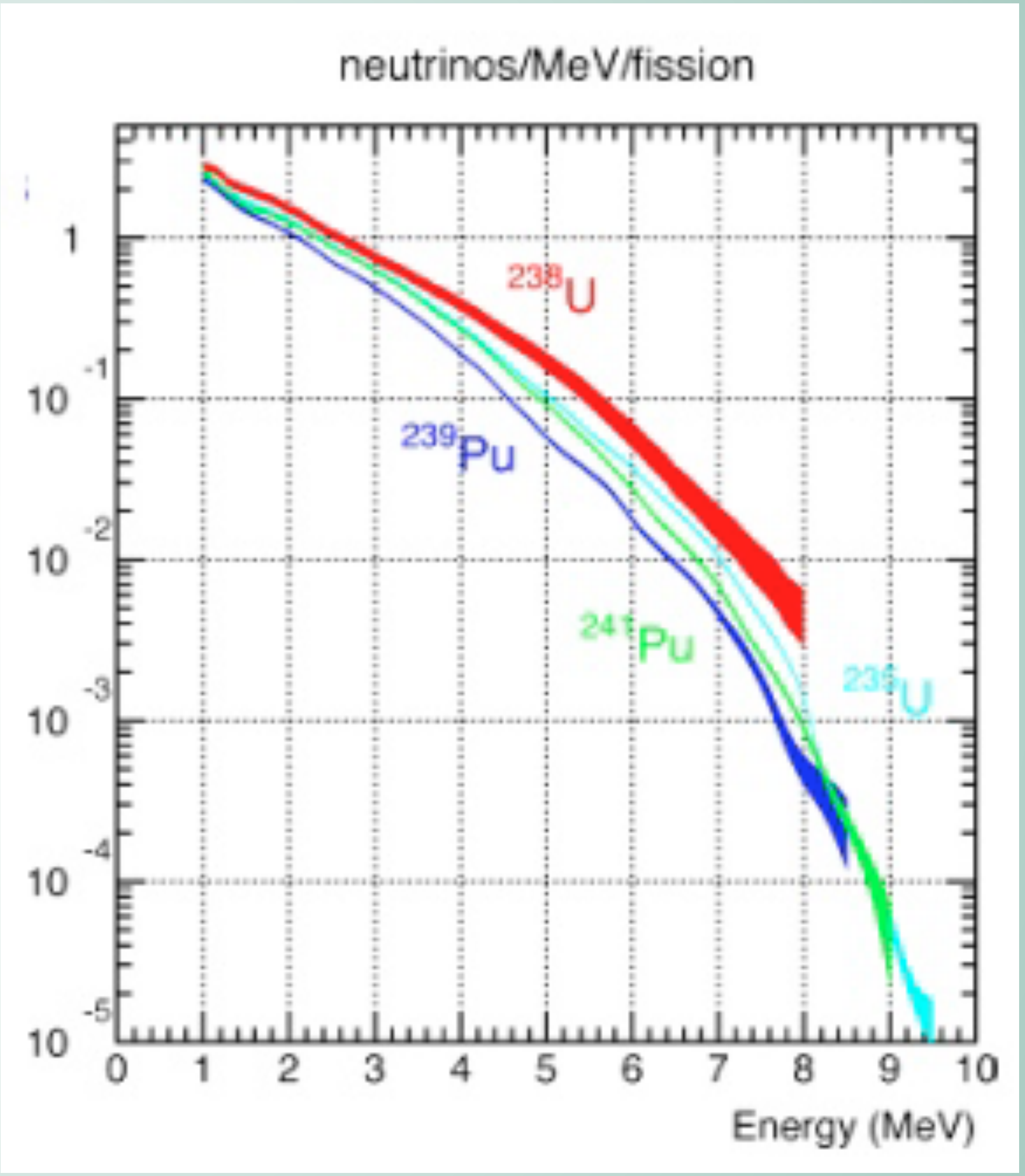
Crocus

Daya Bay

NC State

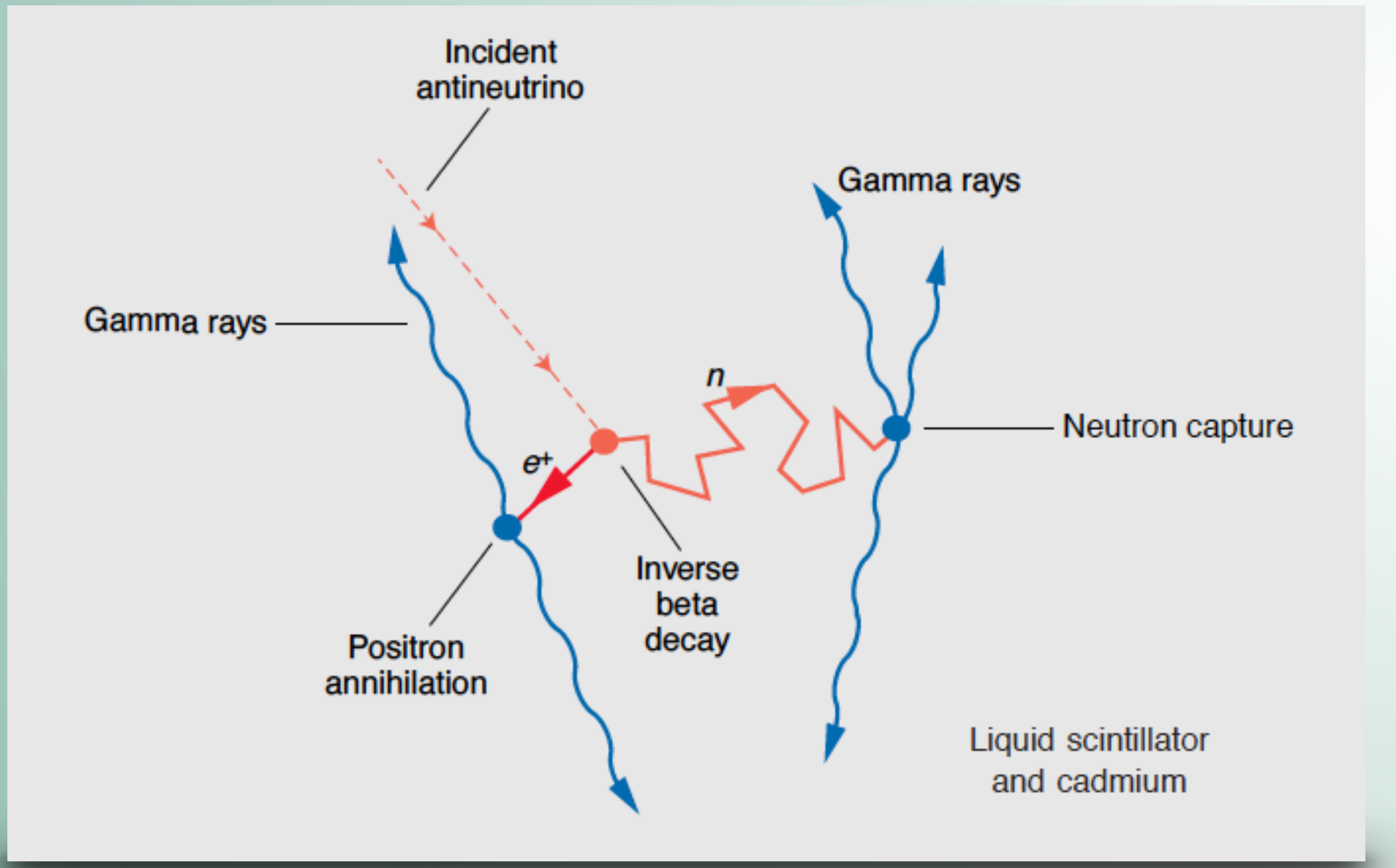
Neutrinos from reactors

- Huge flux
- Spectrum complex
  - Many isotopes involved
  - Fuel composition
  - Fuel age
  - Neutron flux
  - Example: ^{235}U:
    - 6 ν_e per fission
    - ~$2x10^{20}$ ν_e per GWth



Detector Signal

- Inverse Beta-decay
- Can be computed using Fermi Theory
- $p + \bar{\nu}_e \rightarrow n + e^+$ E_{th} = 1.8 MeV



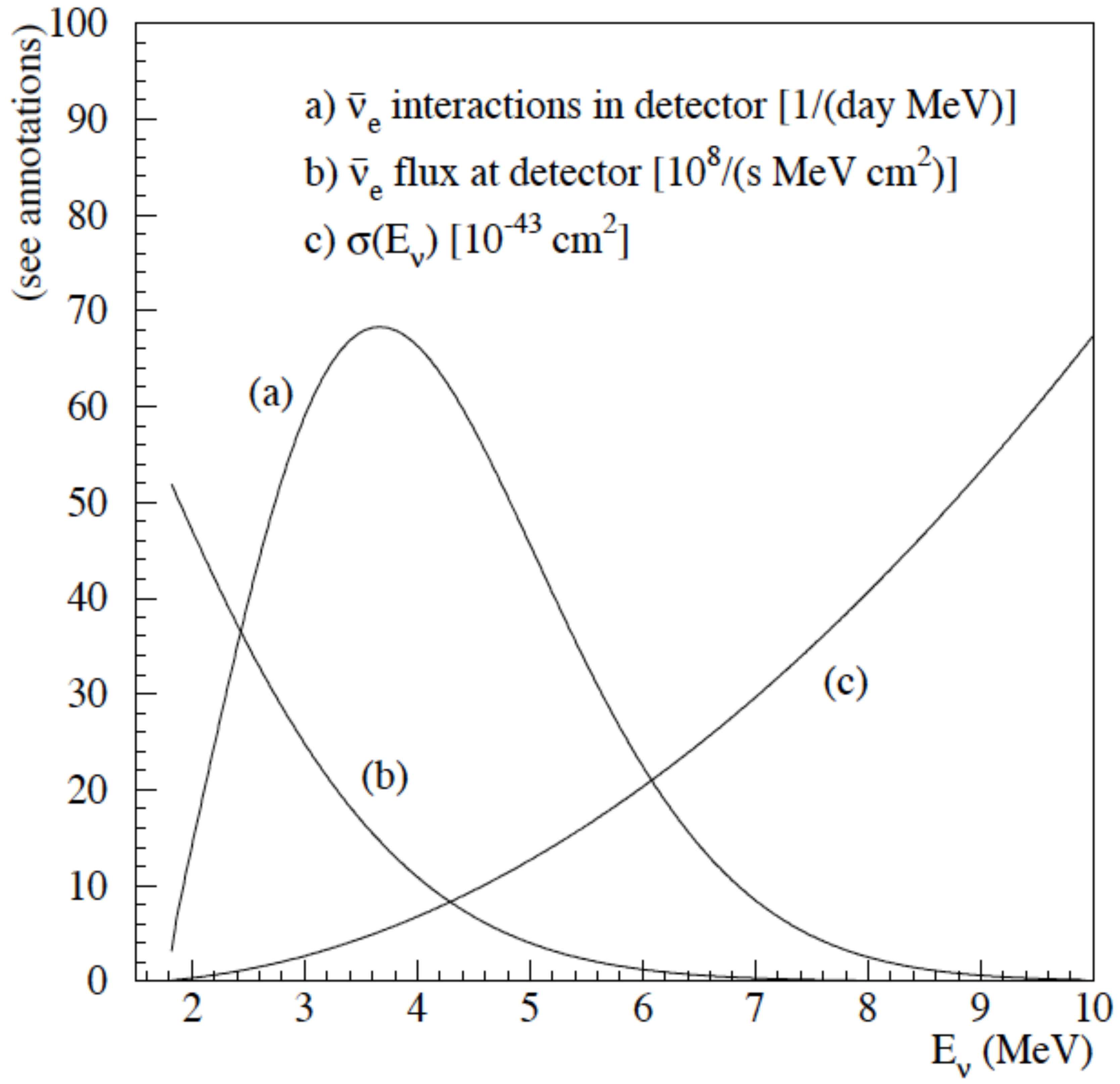
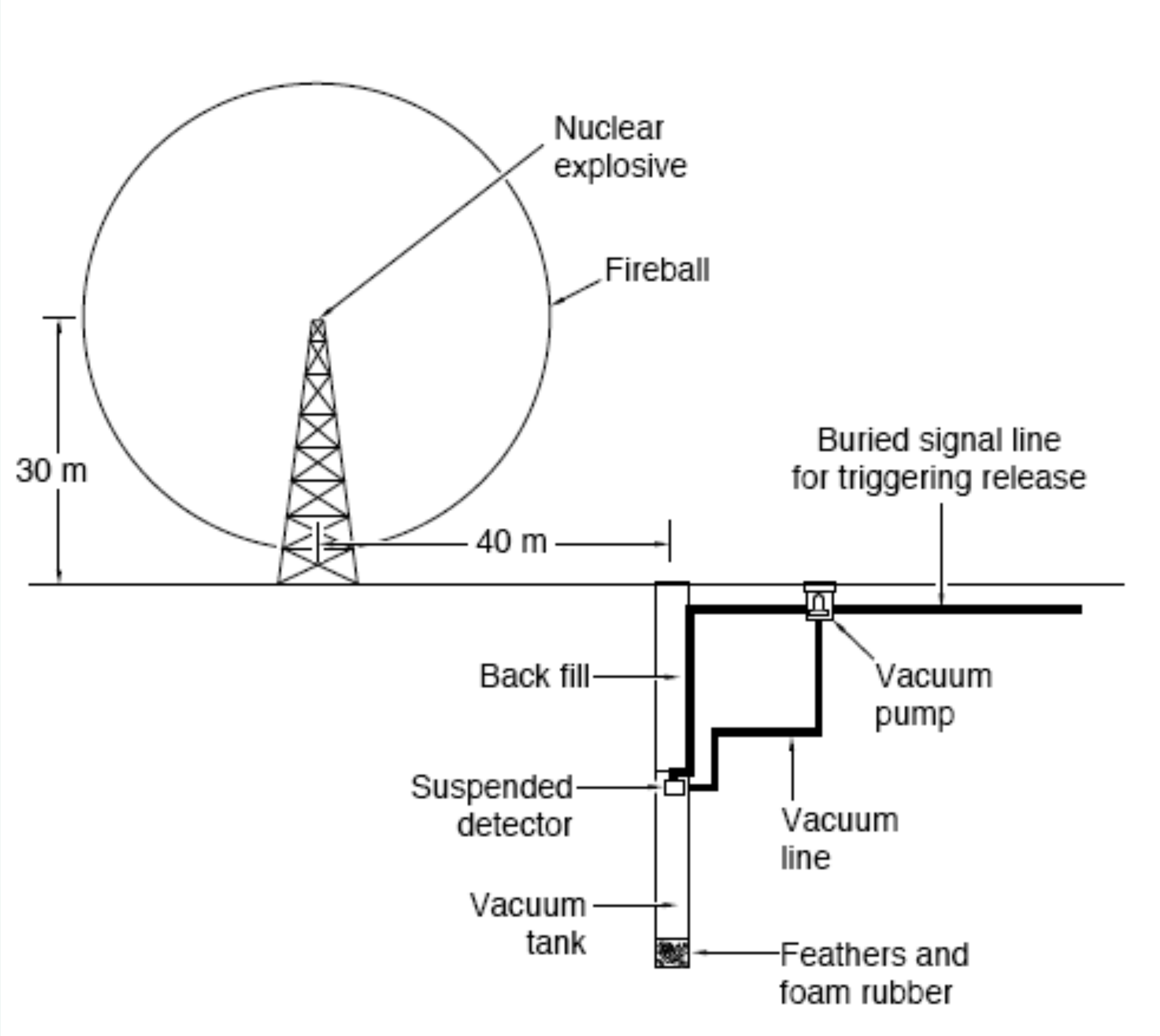


FIG. 2. Reactor $\bar{\nu}_e$ flux, inverse beta decay cross section, and $\bar{\nu}_e$ interaction spectrum at a detector based on such reaction.

Aside: A (Very) Prompt Neutrino Source



1956: Discovery of the $\overline{\nu}$

The Savannah River Experiment (1956)

Los Alamos Science 25 (1997)

The Savannah River Experiment

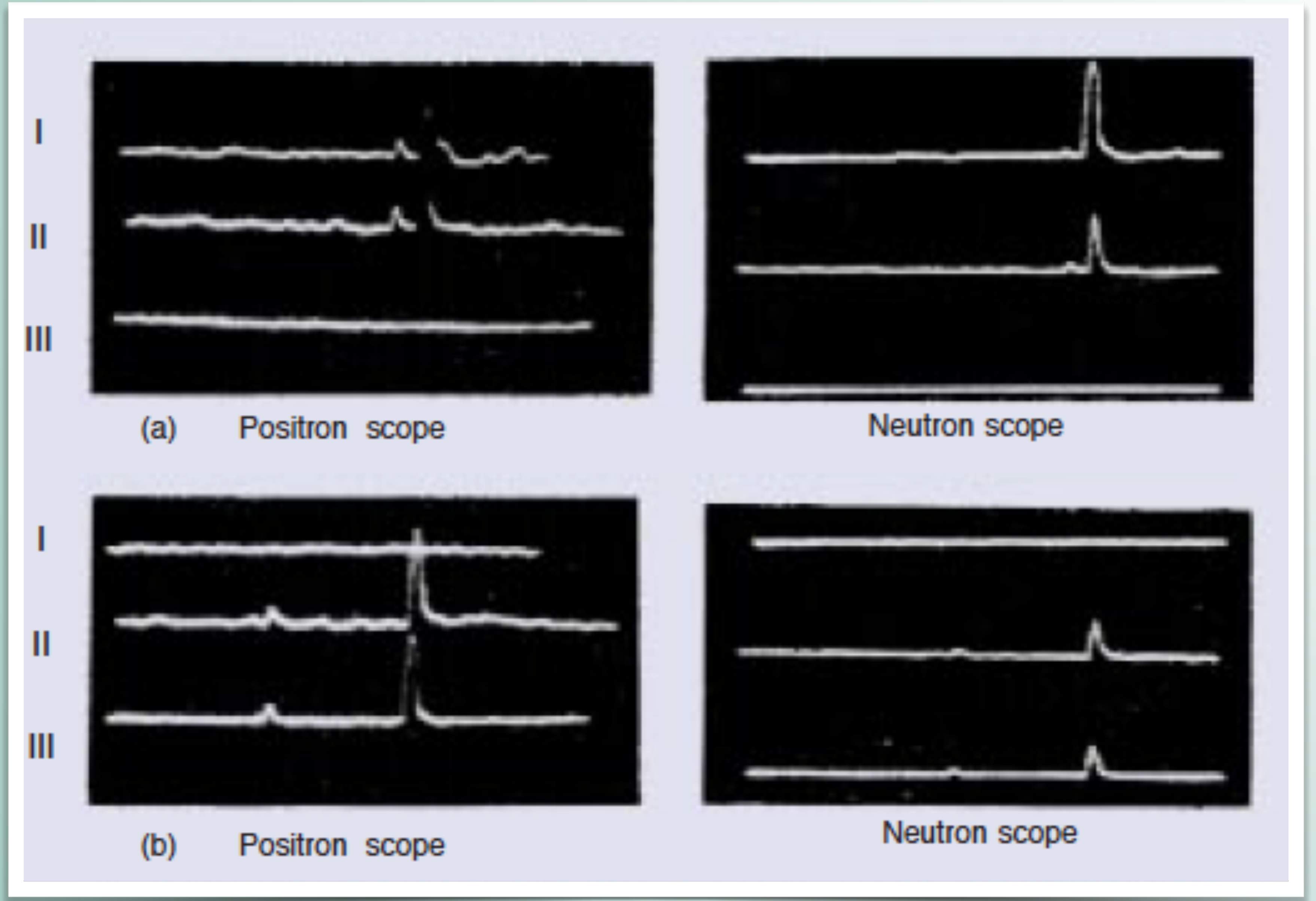
Sequel to previous experiments at Hanford

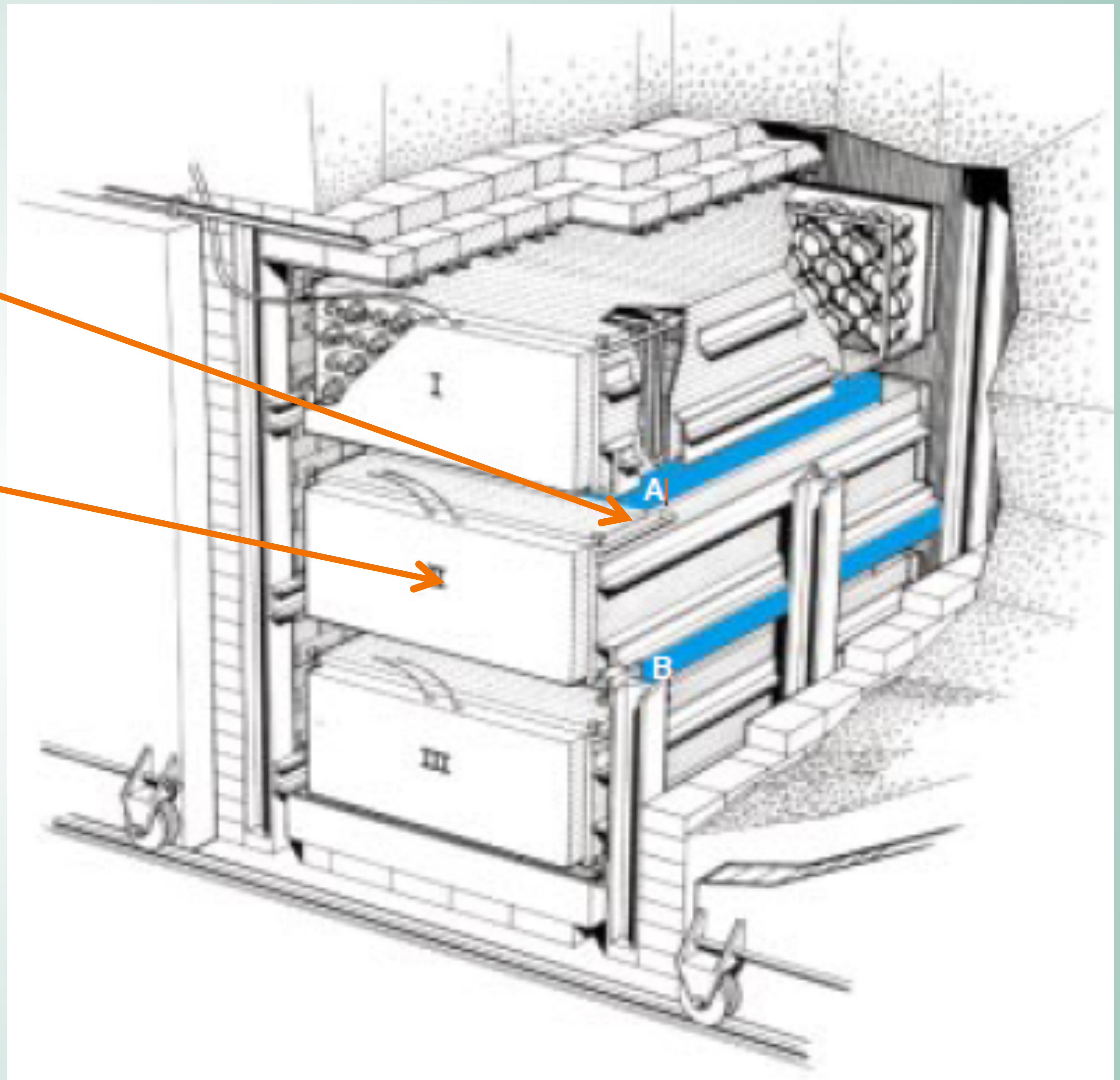
10m from core

200 kg Water (proton targets)

Cadmium Chloride (delayed neutrons)

Scintillator Photon Detectors



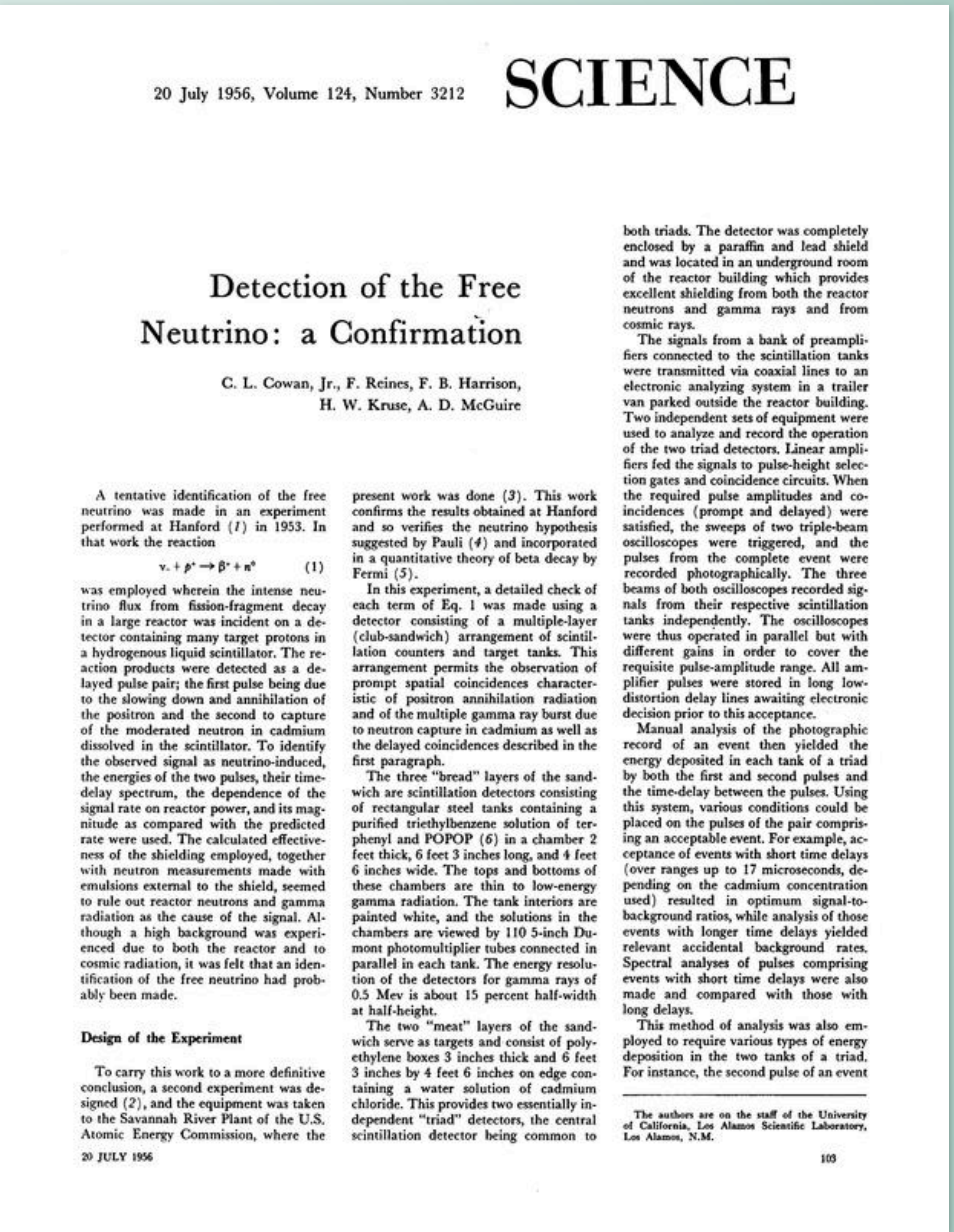


Water + Cadmium Chloride

Fame and Fortune

Reines et al, Science 124, 103 (1956).
Reines and Cowan, , Nature 178, 446 (1956)
"Neutrino Physics", Frederick Reines and Clyde L. Cowan, Jr., Physics Today 10, no. 8, p.12 (1957).

1995



20 July 1956, Volume 124, Number 3212 SCIENCE

Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

A tentative identification of the free neutrino was made in an experiment performed at Hanford (1) in 1953. In that work the reaction

$$\nu_- + p^+ \rightarrow \beta^+ + n^0 \quad (1)$$

was employed wherein the intense neutrino flux from fission-fragment decay in a large reactor was incident on a detector containing many target protons in a hydrogenous liquid scintillator. The reaction products were detected as a delayed pulse pair; the first pulse being due to the slowing down and annihilation of the positron and the second to capture of the moderated neutron in cadmium dissolved in the scintillator. To identify the observed signal as neutrino-induced, the energies of the two pulses, their time-delay spectrum, the dependence of the signal rate on reactor power, and its magnitude as compared with the predicted rate were used. The calculated effectiveness of the shielding employed, together with neutron measurements made with emulsions external to the shield, seemed to rule out reactor neutrons and gamma radiation as the cause of the signal. Although a high background was experienced due to both the reactor and to cosmic radiation, it was felt that an identification of the free neutrino had probably been made.

Design of the Experiment

To carry this work to a more definitive conclusion, a second experiment was designed (2), and the equipment was taken to the Savannah River Plant of the U.S. Atomic Energy Commission, where the present work was done (3). This work confirms the results obtained at Hanford and so verifies the neutrino hypothesis suggested by Pauli (4) and incorporated in a quantitative theory of beta decay by Fermi (5).

In this experiment, a detailed check of each term of Eq. 1 was made using a detector consisting of a multiple-layer (club-sandwich) arrangement of scintillation counters and target tanks. This arrangement permits the observation of prompt spatial coincidences characteristic of positron annihilation radiation and of the multiple gamma ray burst due to neutron capture in cadmium as well as the delayed coincidences described in the first paragraph.

The three "bread" layers of the sandwich are scintillation detectors consisting of rectangular steel tanks containing a purified triethylbenzene solution of terphenyl and POPOP (6) in a chamber 2 feet thick, 6 feet 3 inches long, and 4 feet 6 inches wide. The tops and bottoms of these chambers are thin to low-energy gamma radiation. The tank interiors are painted white, and the solutions in the chambers are viewed by 110 5-inch Dumont photomultiplier tubes connected in parallel in each tank. The energy resolution of the detectors for gamma rays of 0.5 Mev is about 15 percent half-width at half-height.

The two "meat" layers of the sandwich serve as targets and consist of polyethylene boxes 3 inches thick and 6 feet 3 inches by 4 feet 6 inches on edge containing a water solution of cadmium chloride. This provides two essentially independent "triad" detectors, the central scintillation detector being common to both triads. The detector was completely enclosed by a paraffin and lead shield and was located in an underground room of the reactor building which provides excellent shielding from both the reactor neutrons and gamma rays and from cosmic rays.

The signals from a bank of preamplifiers connected to the scintillation tanks were transmitted via coaxial lines to an electronic analyzing system in a trailer van parked outside the reactor building. Two independent sets of equipment were used to analyze and record the operation of the two triad detectors. Linear amplifiers fed the signals to pulse-height selection gates and coincidence circuits. When the required pulse amplitudes and coincidences (prompt and delayed) were satisfied, the sweeps of two triple-beam oscilloscopes were triggered, and the pulses from the complete event were recorded photographically. The three beams of both oscilloscopes recorded signals from their respective scintillation tanks independently. The oscilloscopes were thus operated in parallel but with different gains in order to cover the requisite pulse-amplitude range. All amplifier pulses were stored in long low-distortion delay lines awaiting electronic decision prior to this acceptance.

Manual analysis of the photographic record of an event then yielded the energy deposited in each tank of a triad by both the first and second pulses and the time-delay between the pulses. Using this system, various conditions could be placed on the pulses of the pair comprising an acceptable event. For example, acceptance of events with short time delays (over ranges up to 17 microseconds, depending on the cadmium concentration used) resulted in optimum signal-to-background ratios, while analysis of those events with longer time delays yielded relevant accidental background rates. Spectral analyses of pulses comprising events with short time delays were also made and compared with those with long delays.

This method of analysis was also employed to require various types of energy deposition in the two tanks of a triad. For instance, the second pulse of an event

The authors are on the staff of the University of California, Los Alamos Scientific Laboratory, Los Alamos, N.M.

3: Breaking Things

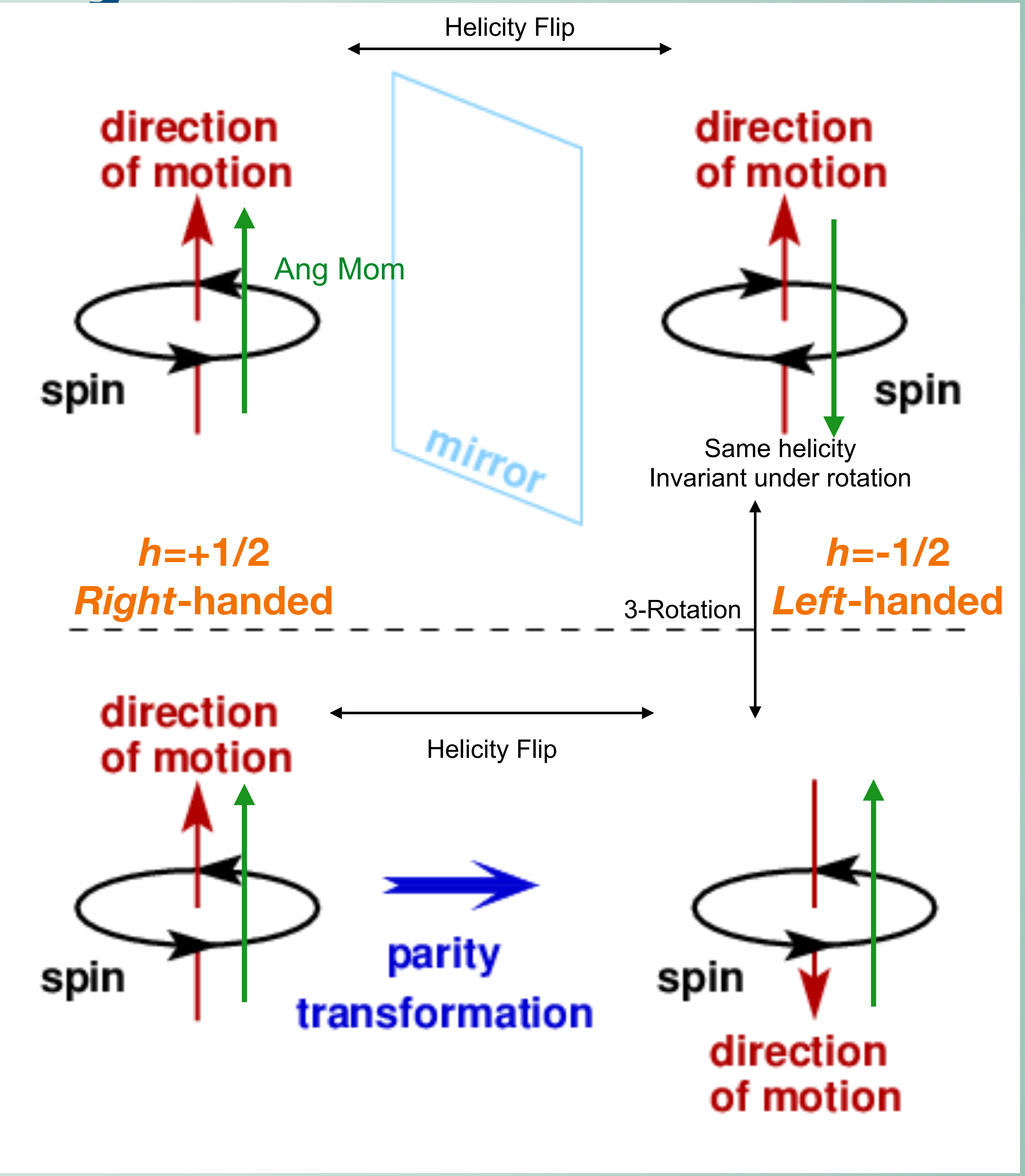
Seque: Parity and Helicity

- "Symmetries" play key role in physics
- Lead to conservation laws:
  - Translational — Conservation of Linear Momentum
  - Rotational —Conservation of Angular Momentum
  - U(1) Gauge — Conservations of Electric Charge
  - Lorentz Invariance
  - …
- 1950's — Physicists believe all physical processes invariant under *parity*:

$$\psi(\mathbf{x}) \leftrightarrow \psi(-\mathbf{x})$$

- Parity state of system can be determined by *helicity* of constituents:

$$h = \frac{\mathbf{S} \cdot \mathbf{p}}{p}$$



1957: Neutrino Helicity Measured

Phys Rev. 109 (1957) 1015

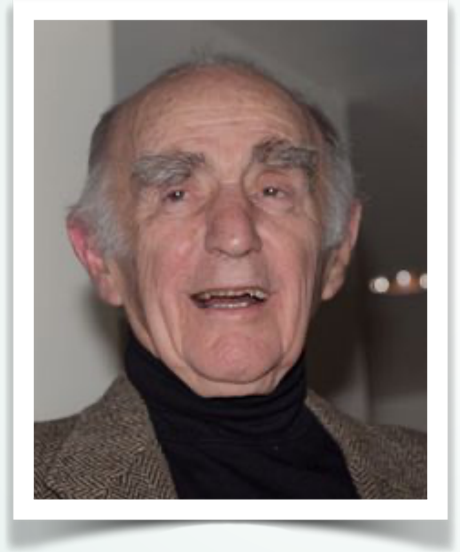
Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

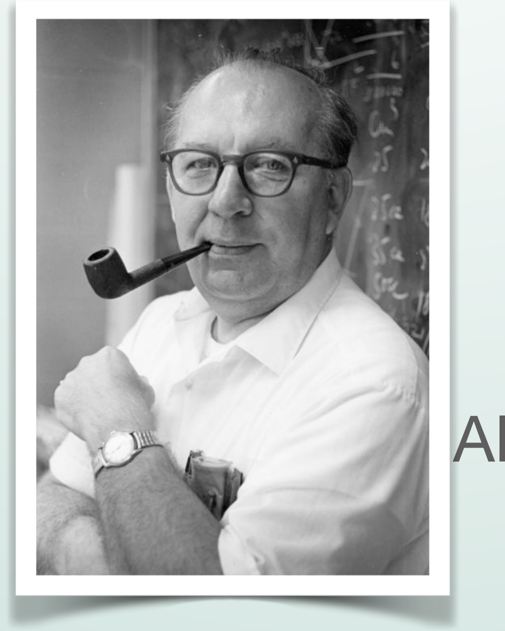
isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

Thus, a measurement of the circular polarization of the γ rays which are resonant-scattered by the nucleus B, yields directly the helicity of the neutrino, if one assumes only the well-established conservation laws of momentum and angular momentum.

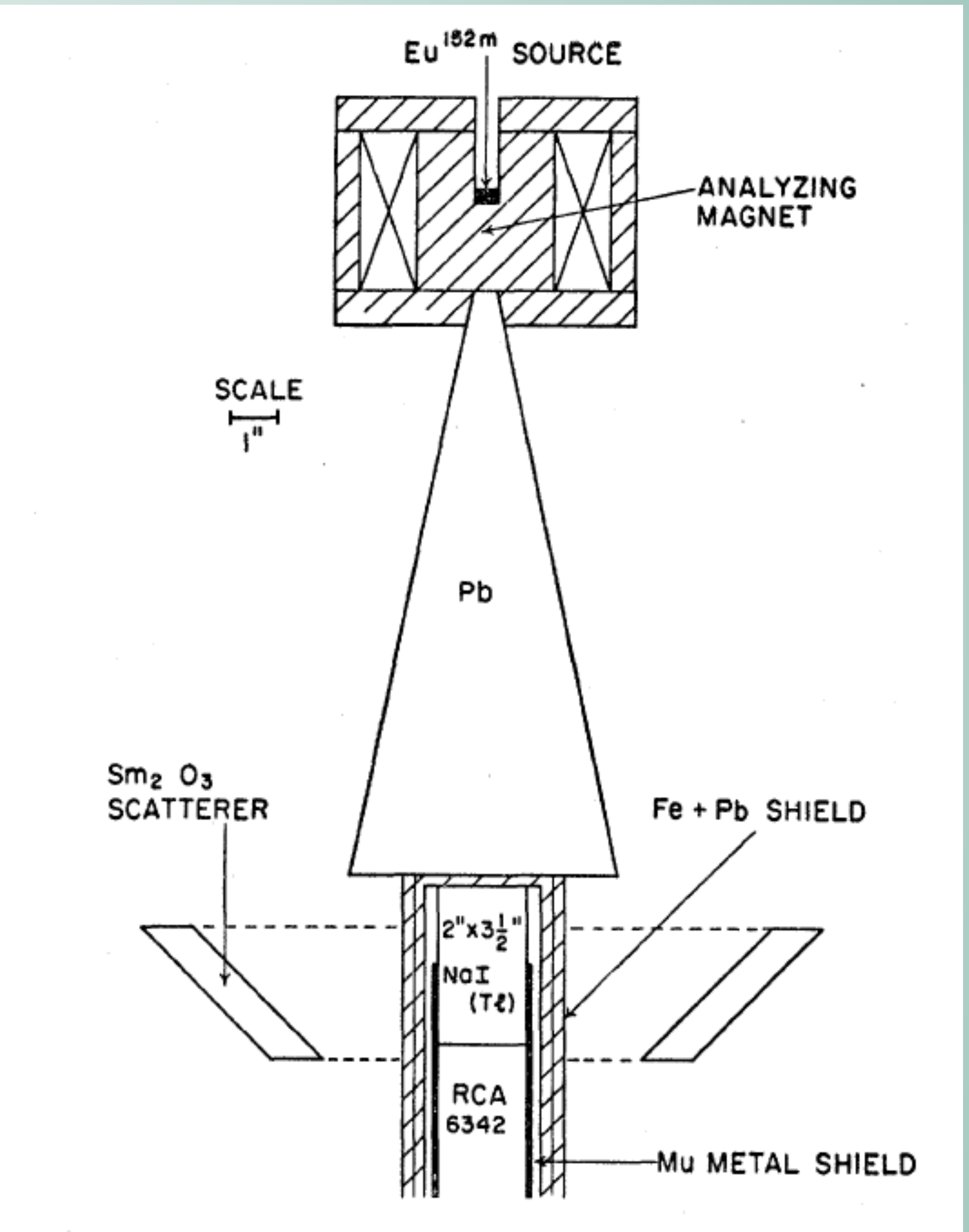
Wikipedia



Wikipedia



AIP



- Inferred Neutrino Helicity before Neutrinos were detected!

1956: Evidence of Parity Conservation Evaluated

- "Tau-theta" puzzle — same particle appeared to decay into different parity states.
- Lee and Yang found no existing experimental evidence for parity consideration in Weak interaction.
- Many skeptics:
  - Pauli "Ich glaube aber nicht, daß der Herrgott ein schwacher Linkshänder ist." (I do not believe that the Lord is a weak left-hander.)
- Proposed several test, including using nuclear beta decay
- Yang in his Nobel acceptance speech: "This prospect did not appeal to us. Rather we were, so to speak, driven to it through frustration."

The Nobel Prize in Physics 1957

Photo from the Nobel Foundation archive.

Chen Ning Yang

Prize share: 1/2

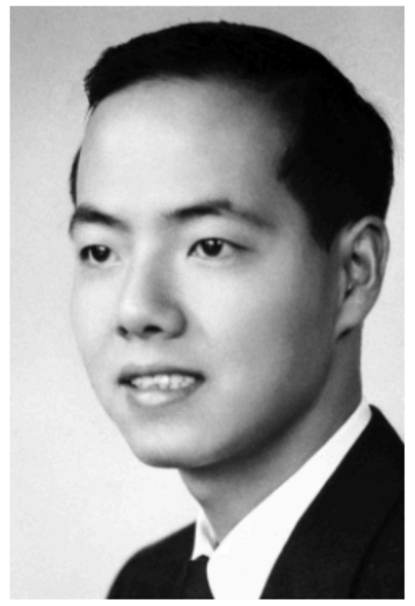


Photo from the Nobel Foundation archive.

Tsung-Dao (T.D.) Lee

Prize share: 1/2

The Nobel Prize in Physics 1957 was awarded jointly to Chen Ning Yang and Tsung-Dao (T.D.) Lee "for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles."

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

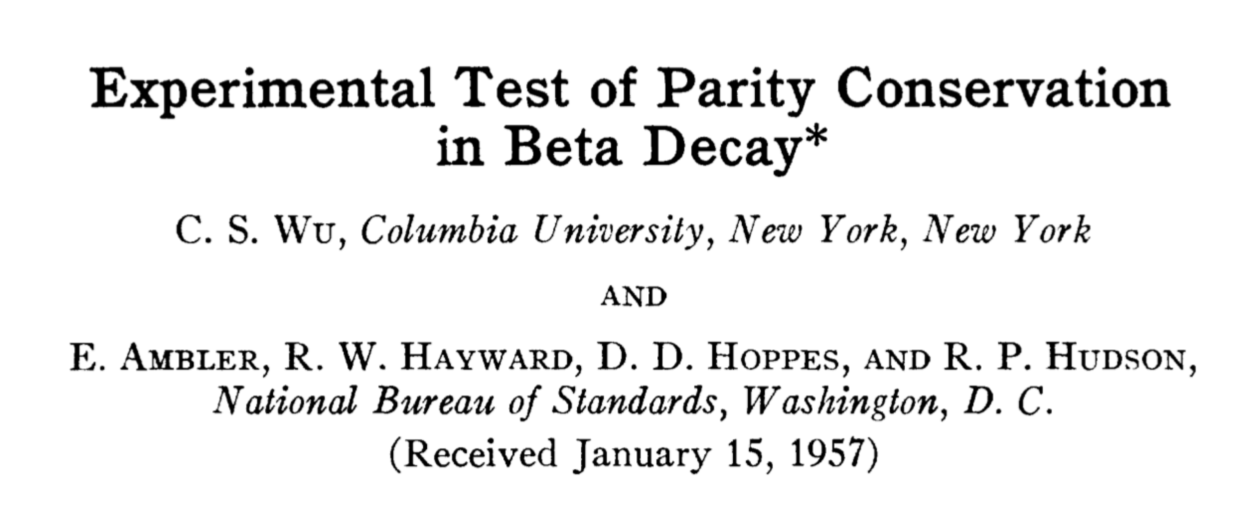
C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

1957: “Wu” Experiment Confirms Parity Violation

- $^{60}\mathrm{Co} \rightarrow ^{60}\mathrm{Ni} + e^- + \bar{\nu}_e + 2\gamma$
- Polarized spin of ^{60}Co nucleus using magnet and low temperatures.
- Gamma-rays served as control
- “A large beta asymmetry was observed.”
- Later found to be *maximal*
  - Weak interaction only “sees” LH nu’s and RH anti-nu’s



Experimental Test of Parity Conservation in Beta Decay*

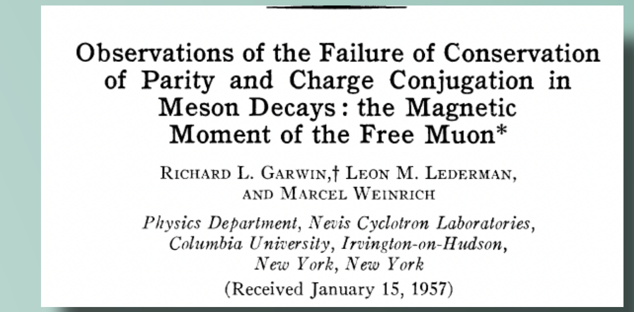
C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

Next Paper in Journal

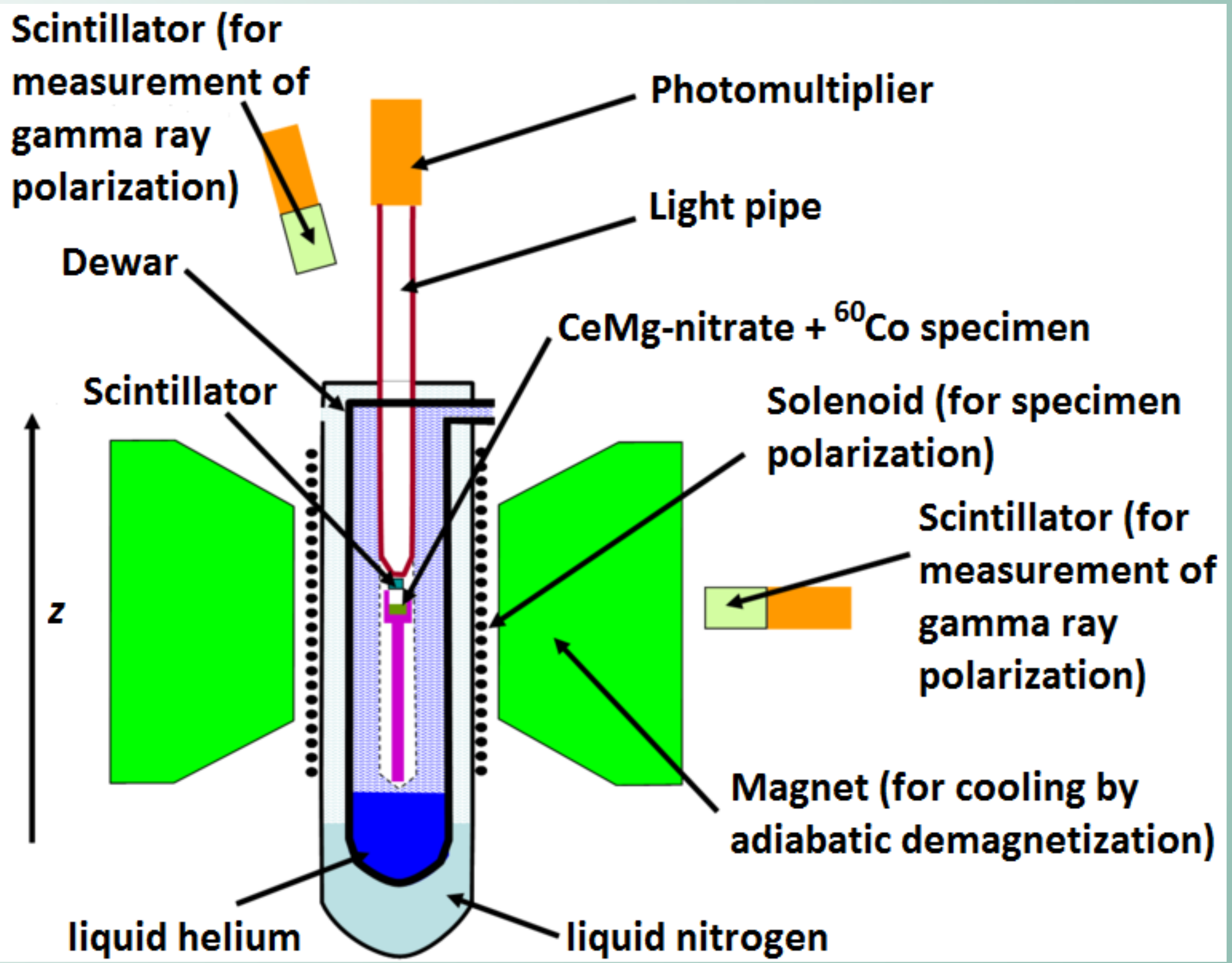


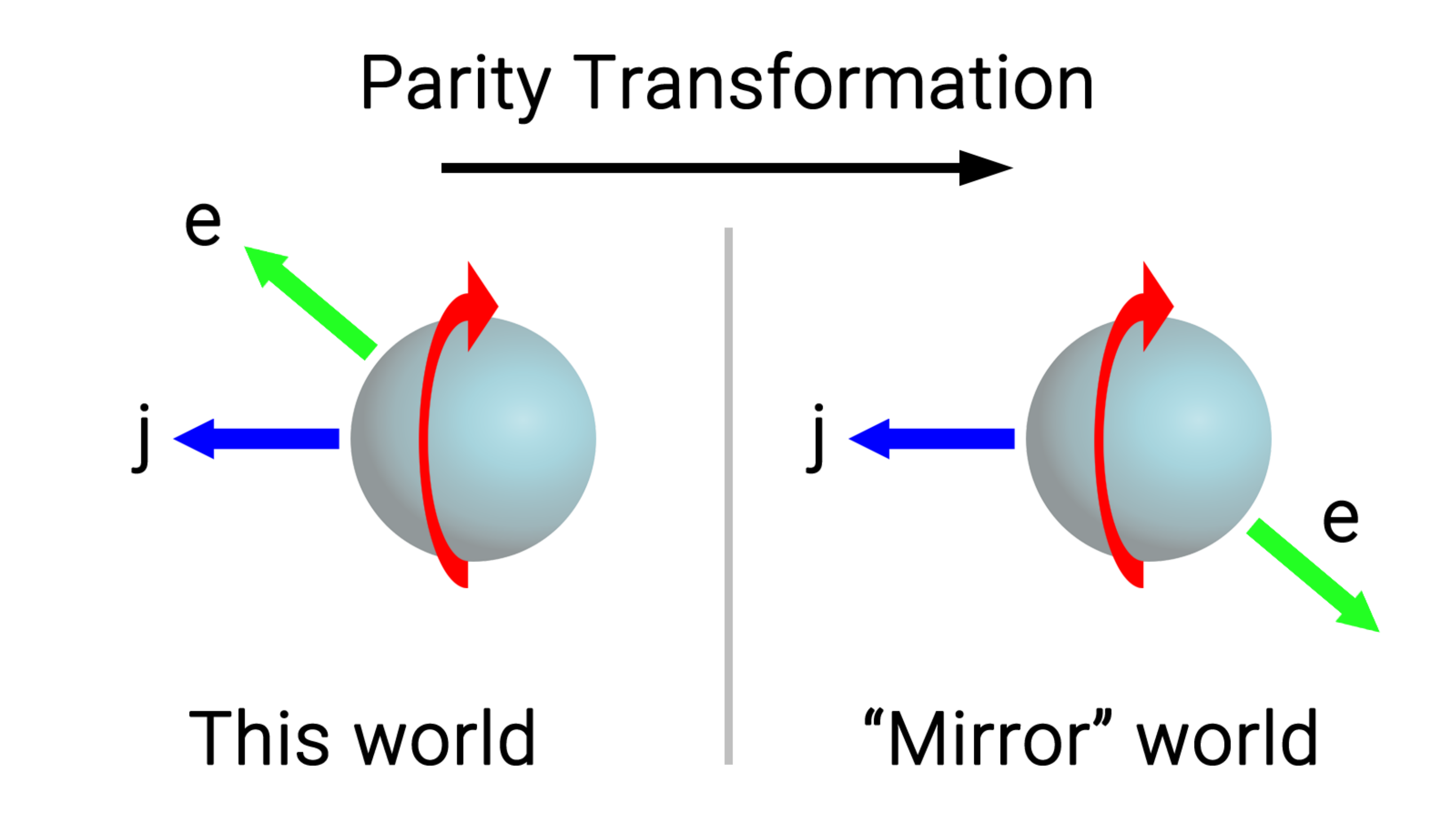
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

Richard L. Garwin,† Leon M. Lederman, and Marcel Weinrich

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

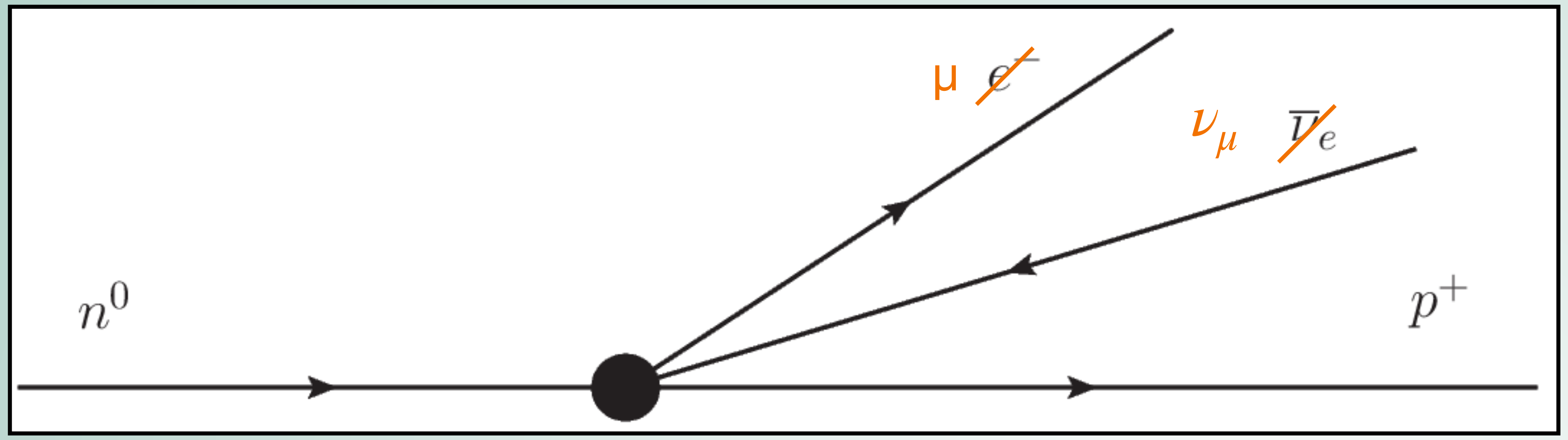


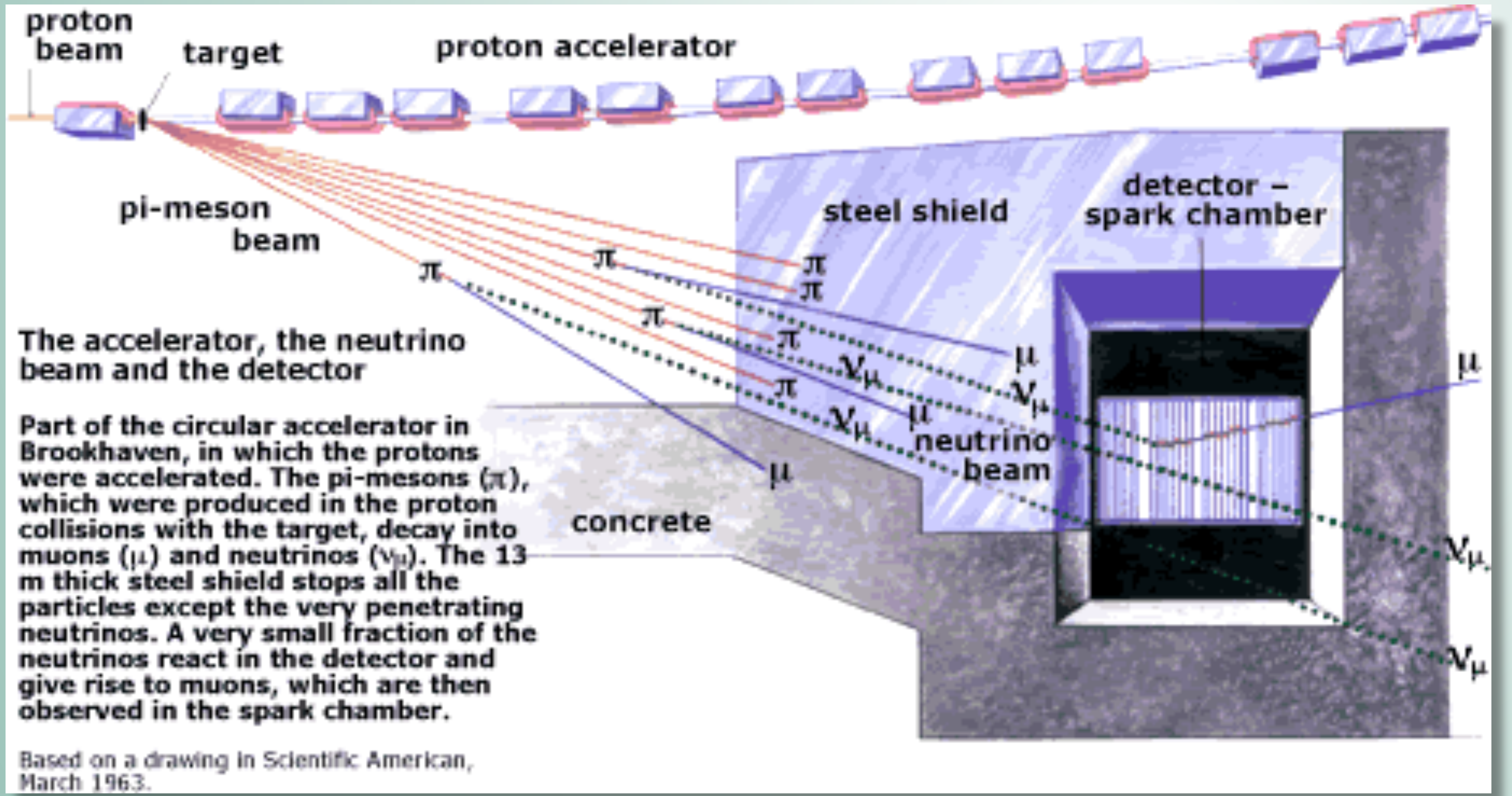


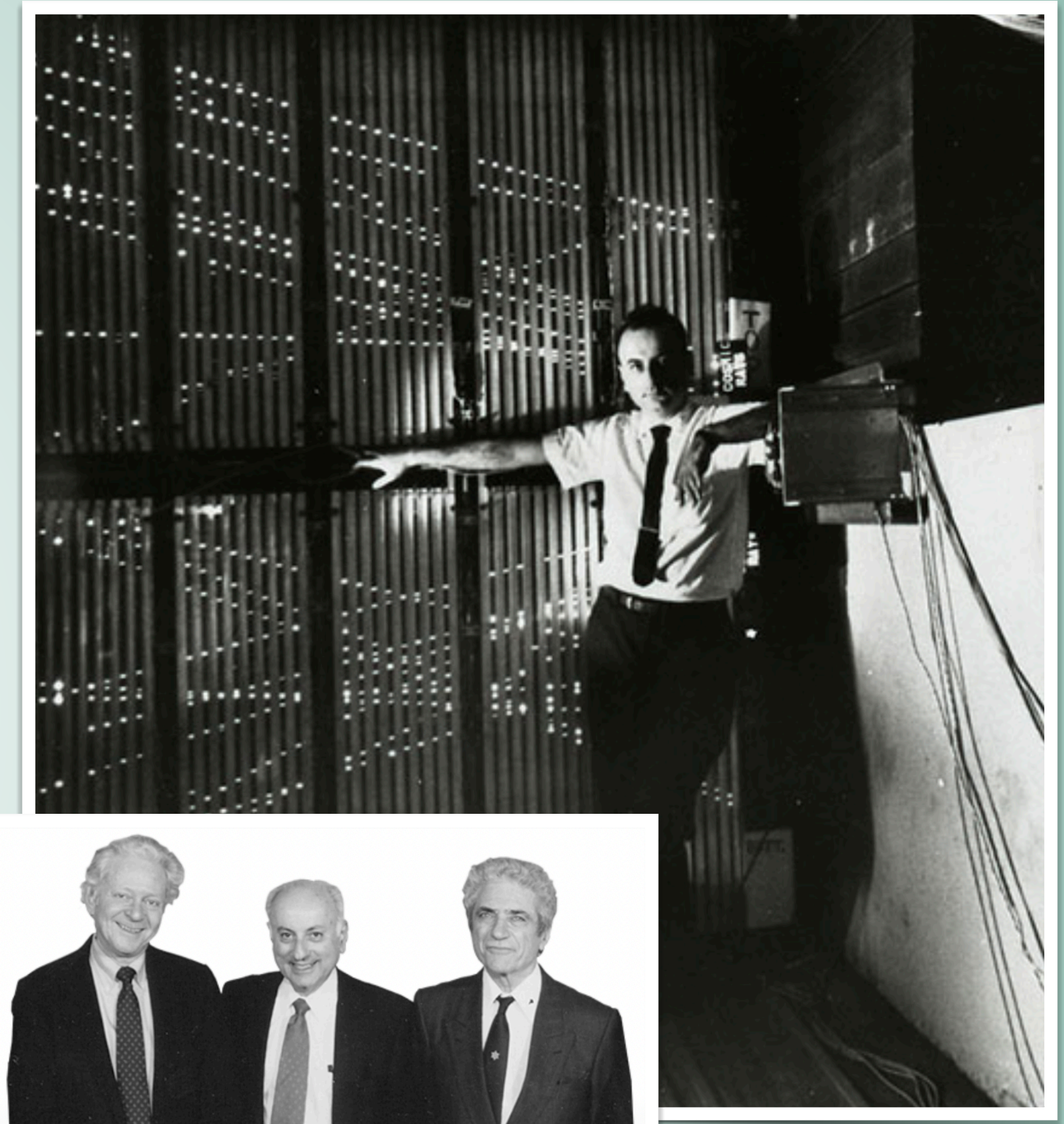
Images Courtesy Wikipedia

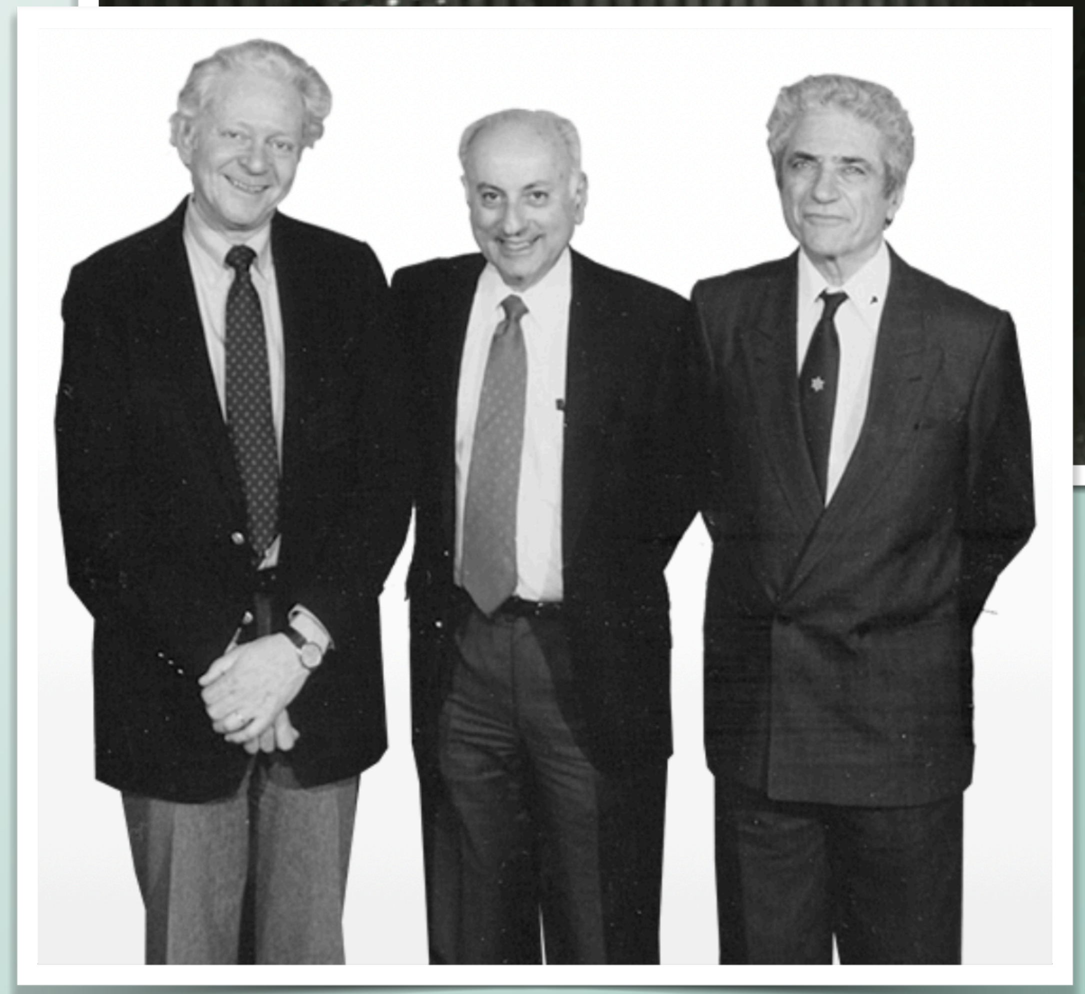
1962: Muon Neutrino Discovered

- New type of neutrino associated with muon









1958-67: Lepton / Neutrino Oscillations Predicted

- **1958:** Pontecorvo, inspired by K-meson oscillations studied lepton flavor-violating “mesonium and antimesonium” oscillations: $e^+\mu^- \leftrightarrow e^-\mu^+$.

Sov. Phys. JETP. 26: 984

- Oscillation timescale too long to detect (muon decays)

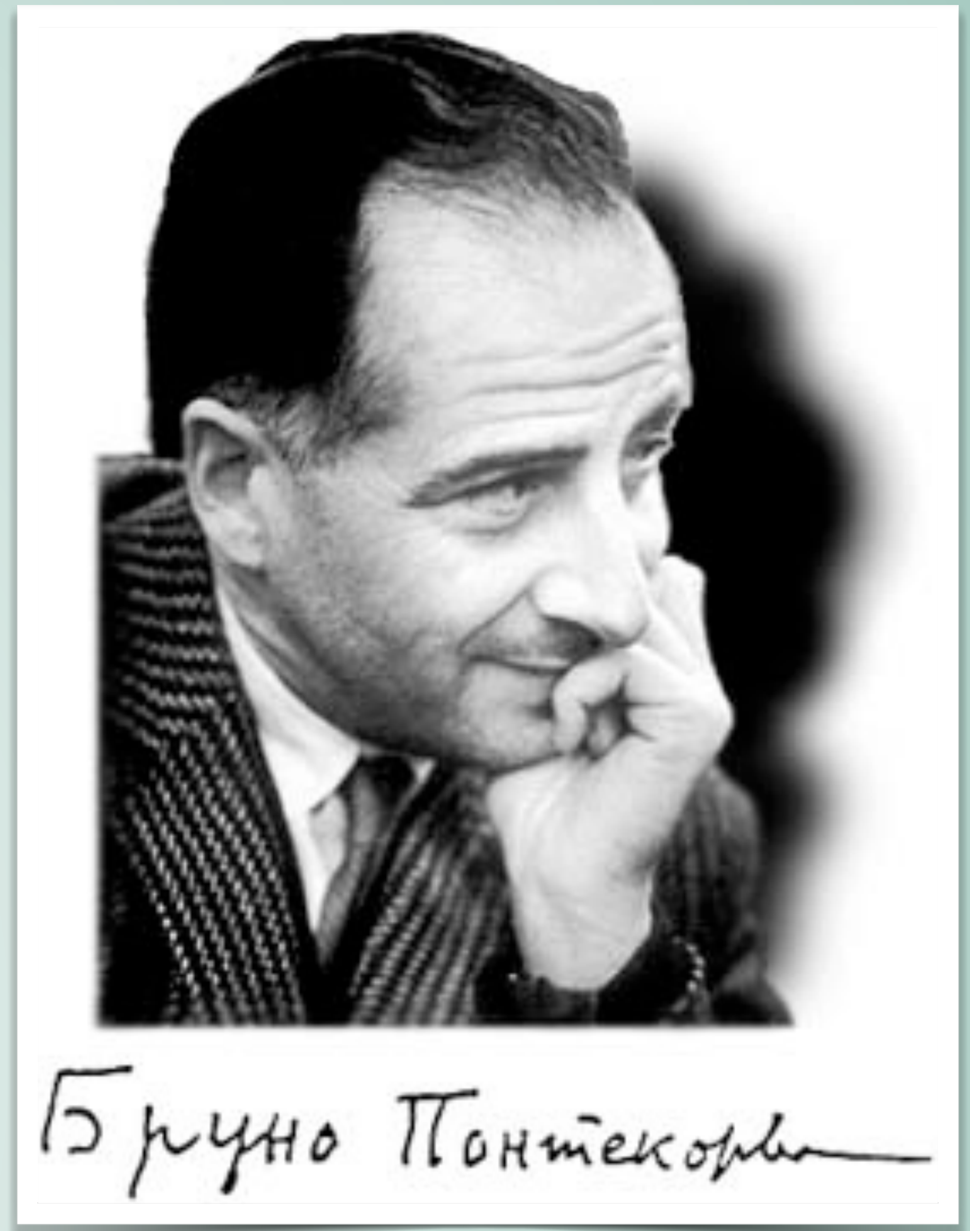
- **1967:** Proposed 2-state neutrino oscillations:
  - $\nu_e \leftrightarrow \nu_\mu$
  - $\nu \leftrightarrow \overline{\nu}$

Zh. Eksp. Teor. Fiz. 53, 1717

- Provided first limit of mixing parameters based on Cowan and Reines Experiment (10m baseline)

- Postulated Sun as Source of neutrinos, but (!)

> Unfortunately the weight of the various thermonuclear reactions in the sun, and the central temperature of the sun are insufficiently well known in order to allow a useful comparison of expected and observed solar neutrinos, from the point of view of this article[1].

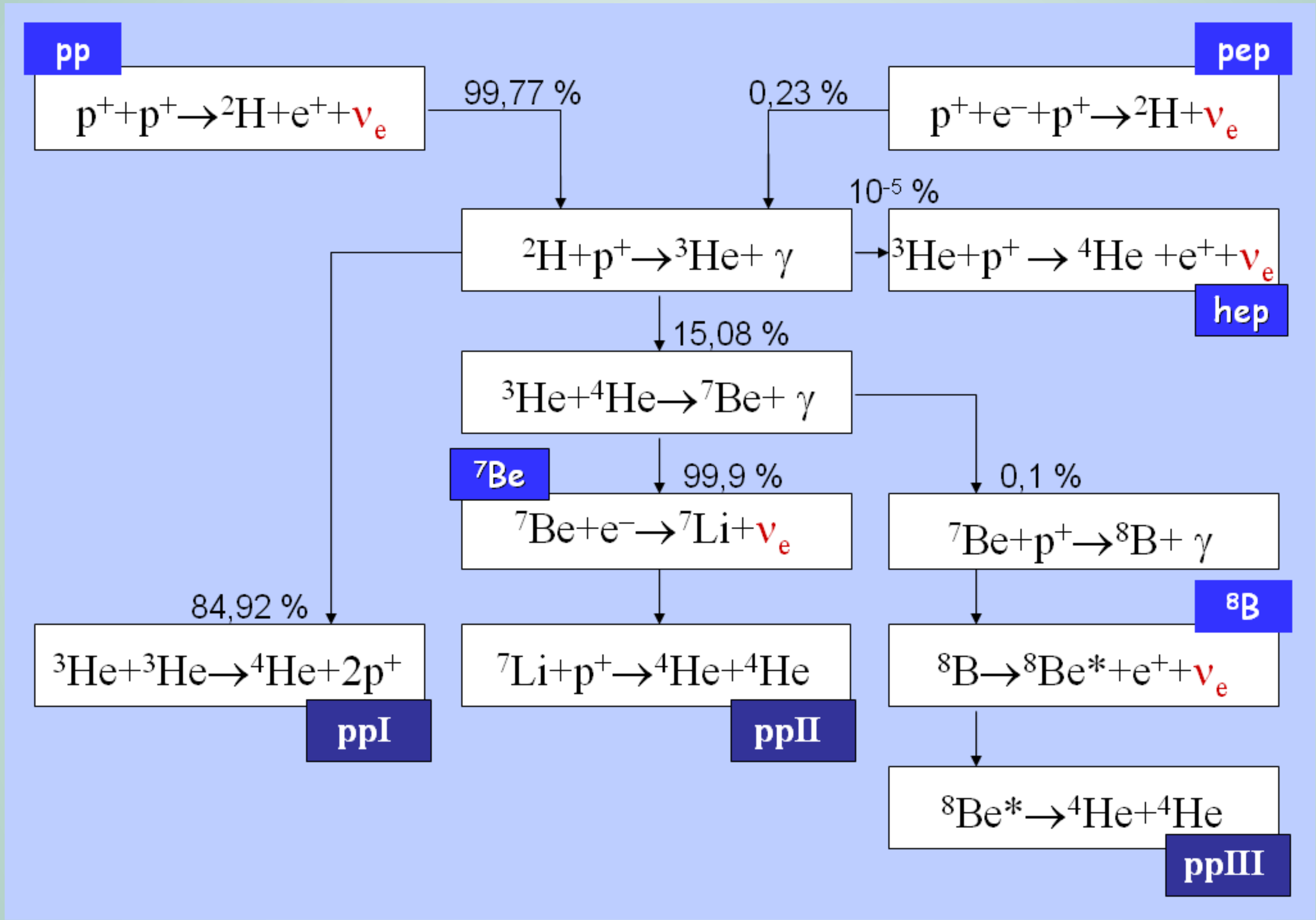


Also (!)

> **OSCILLATIONS AND ASTRONOMY**
>
> If the oscillation length is large (>10 km) it will be impossible to observe the transitions $\nu \rightleftarrows \overline{\nu}$, $\nu_\mu \rightleftarrows \nu_e$ in neutrino beams from reactors or accelerators. However, significant astrophysical effects might be possible.

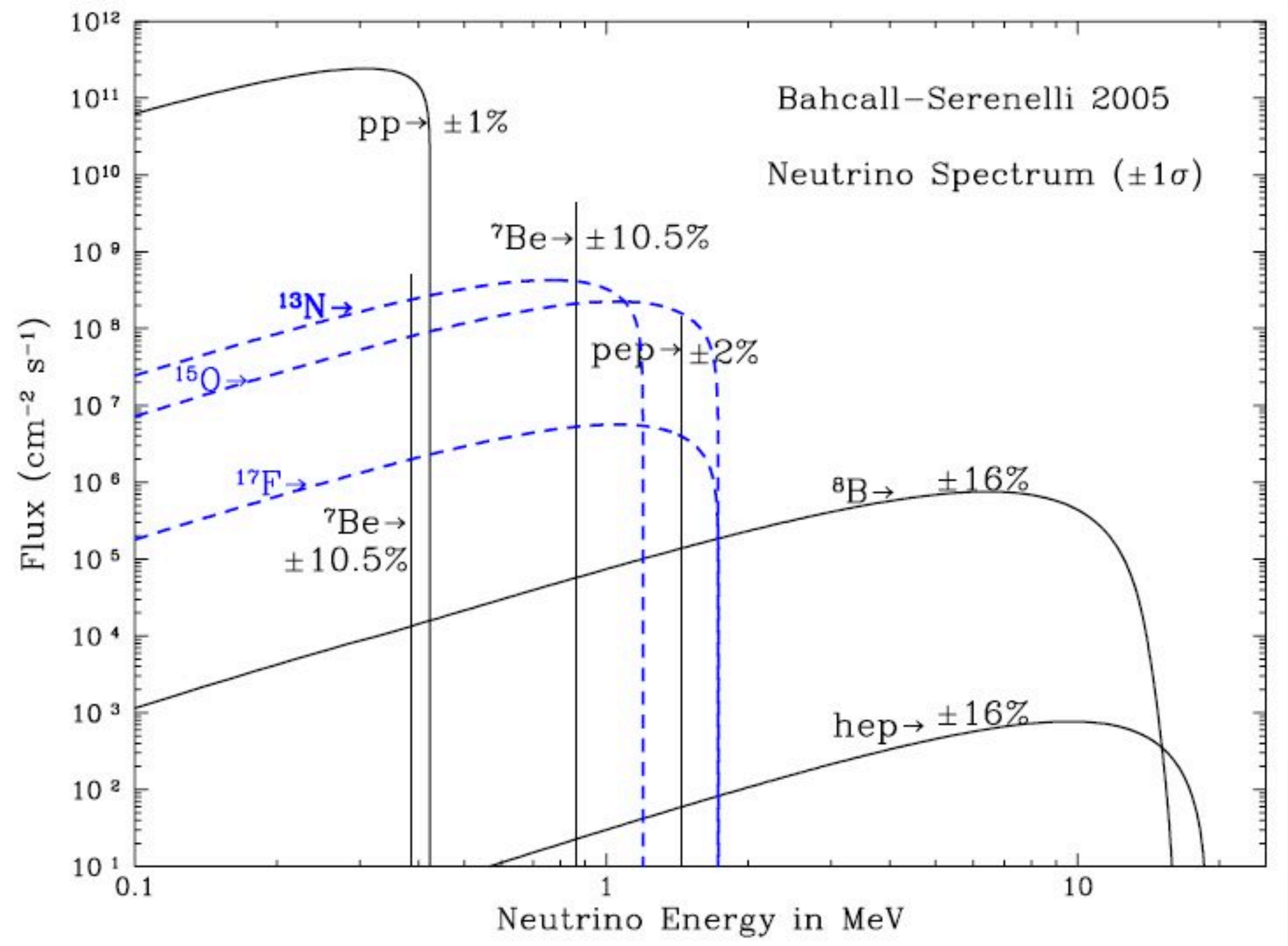
4: Strange Case of Missing Neutrinos

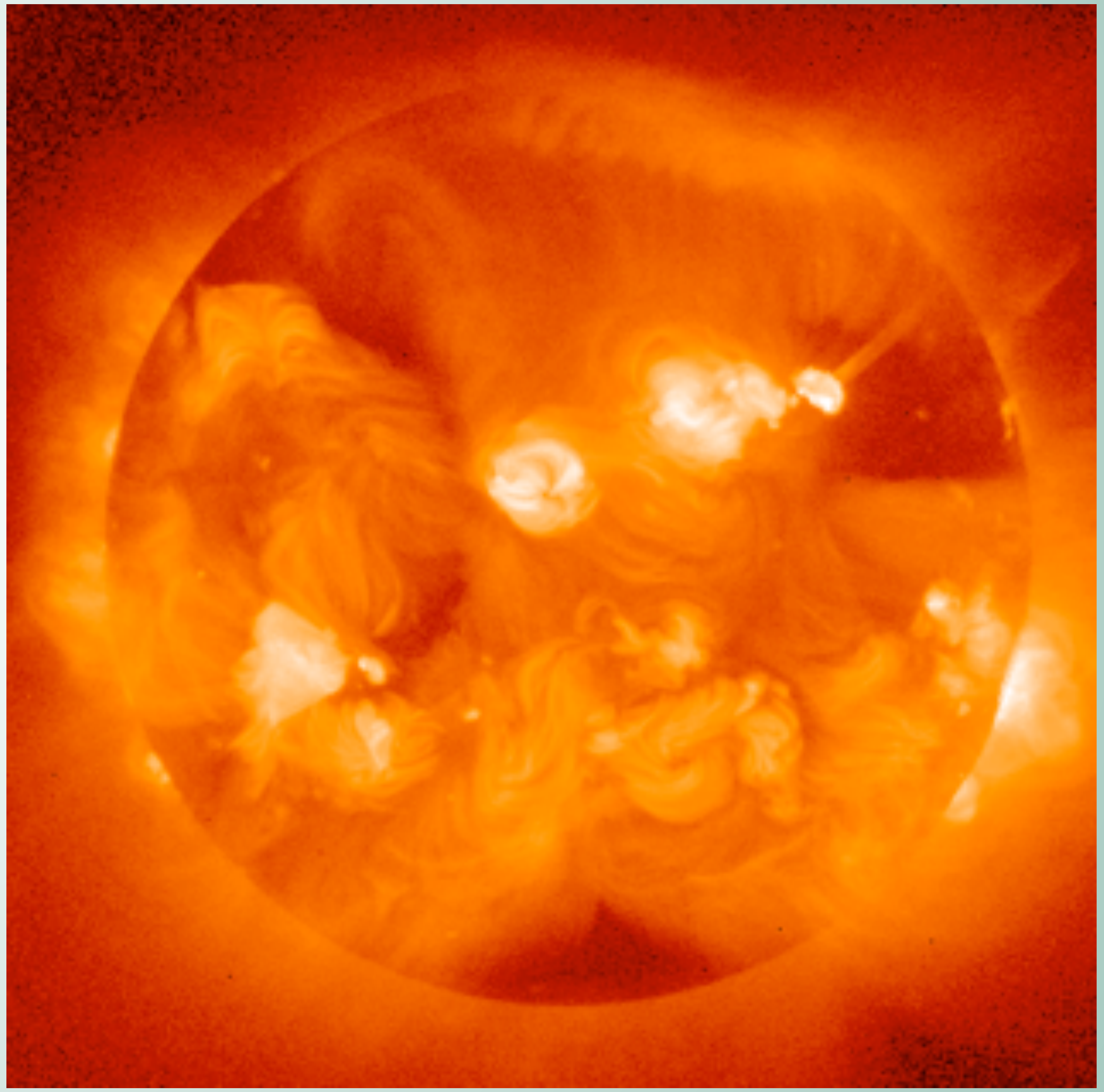
Segue: Neutrinos from the Sun



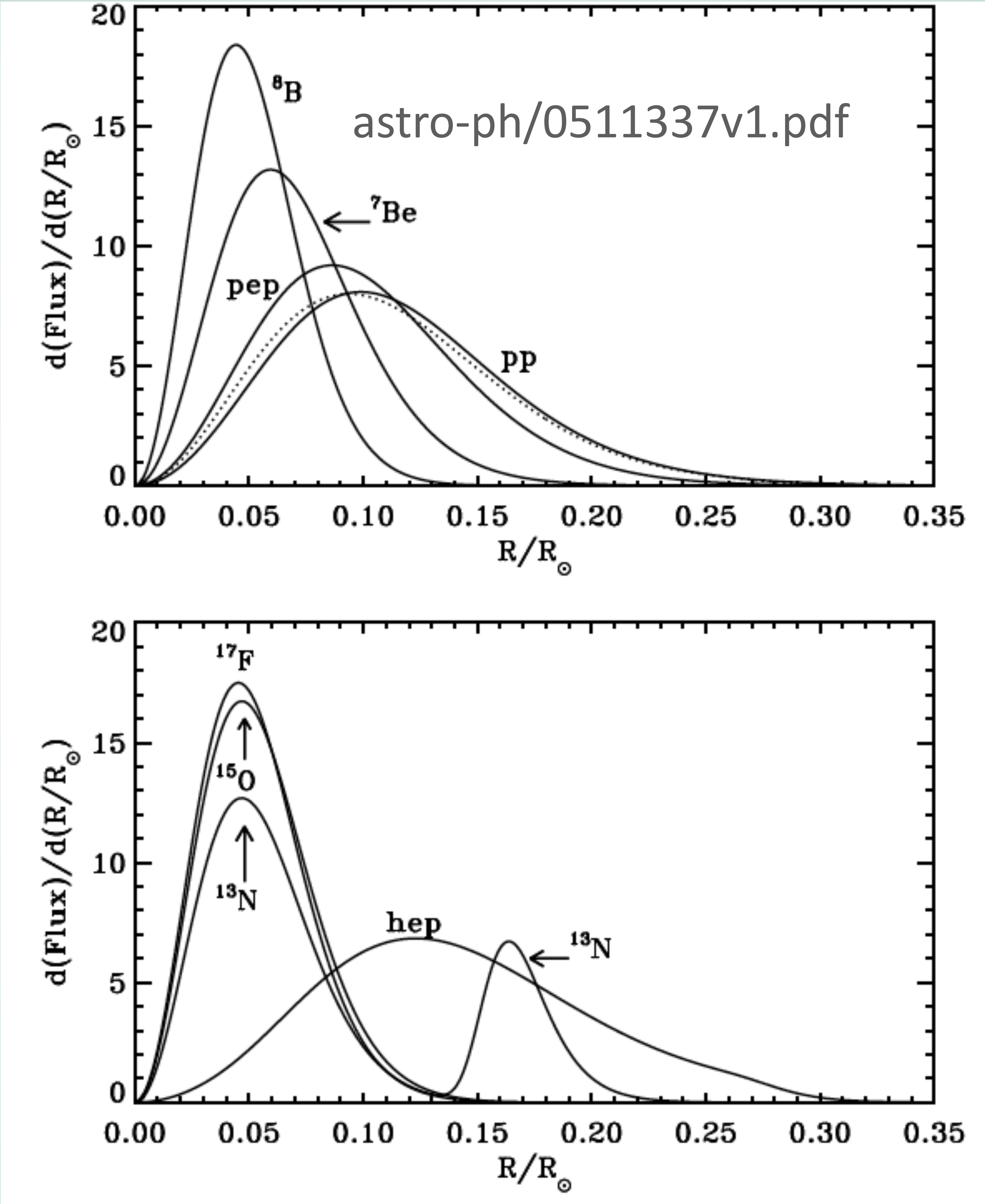
CNO Cycle contributes as well

Solar Neutrino Flux

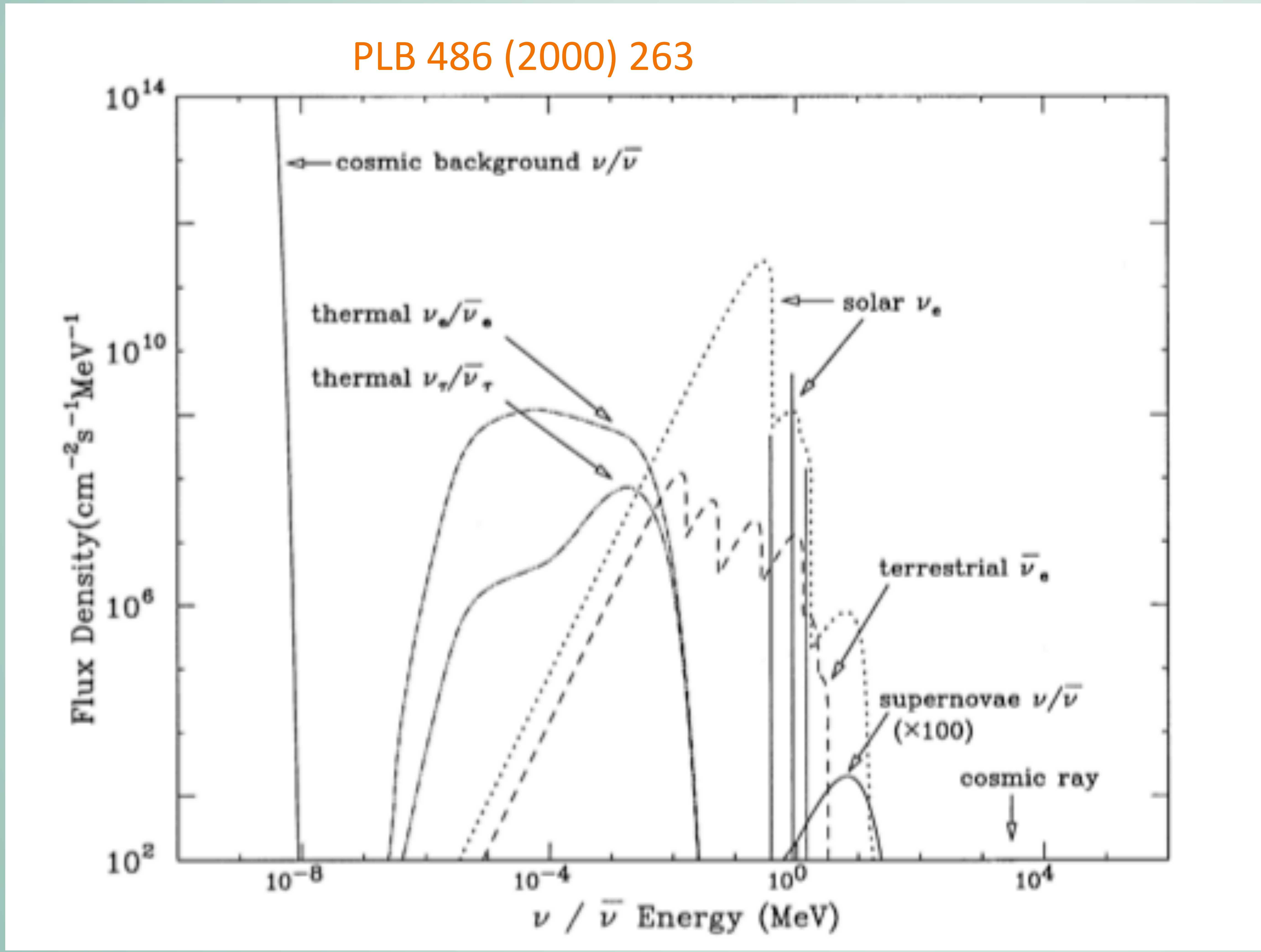




Production Location
Can Probe Core of Sun!



Low energy solar neutrinos
Produced by plasma interactions



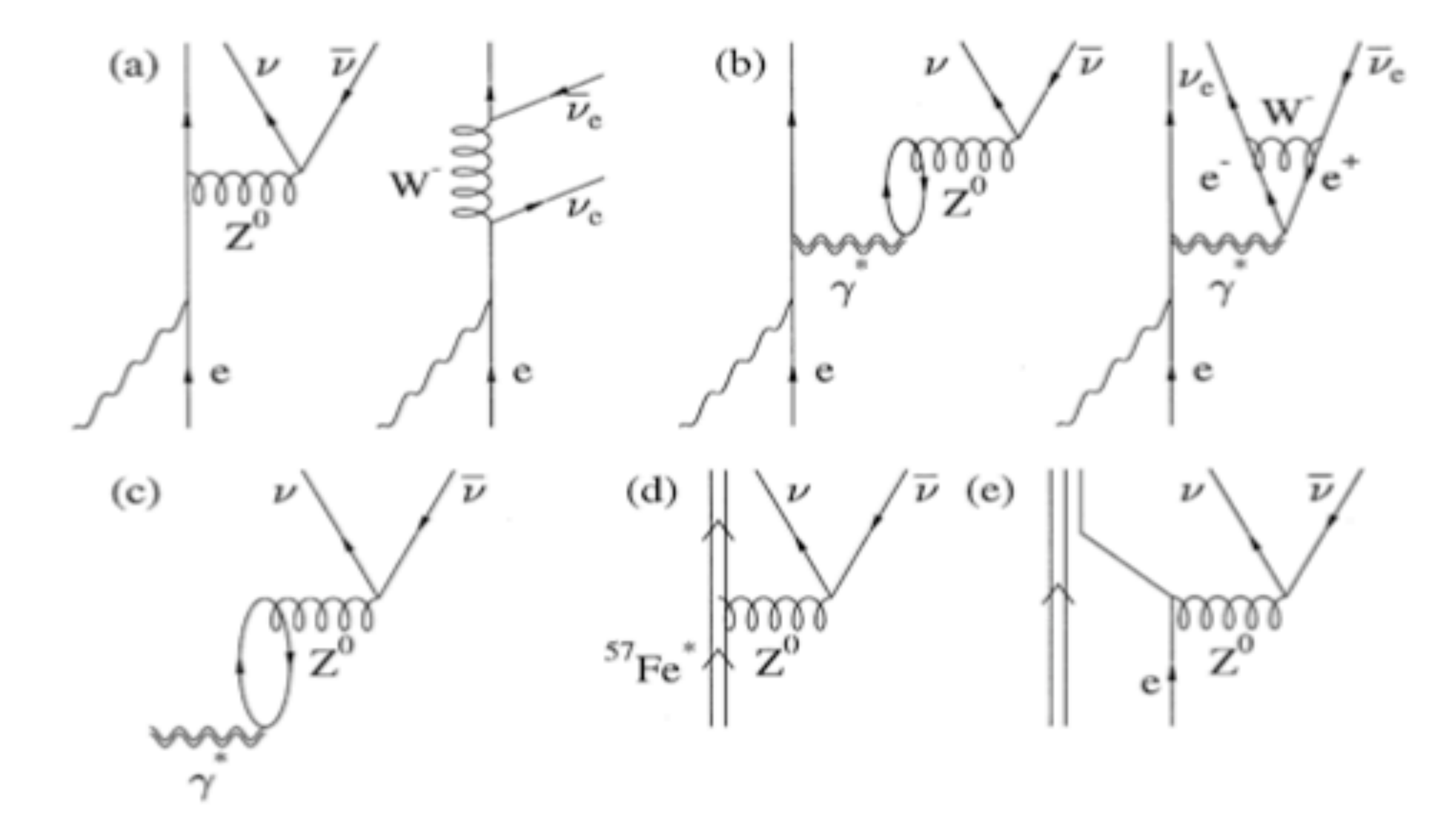
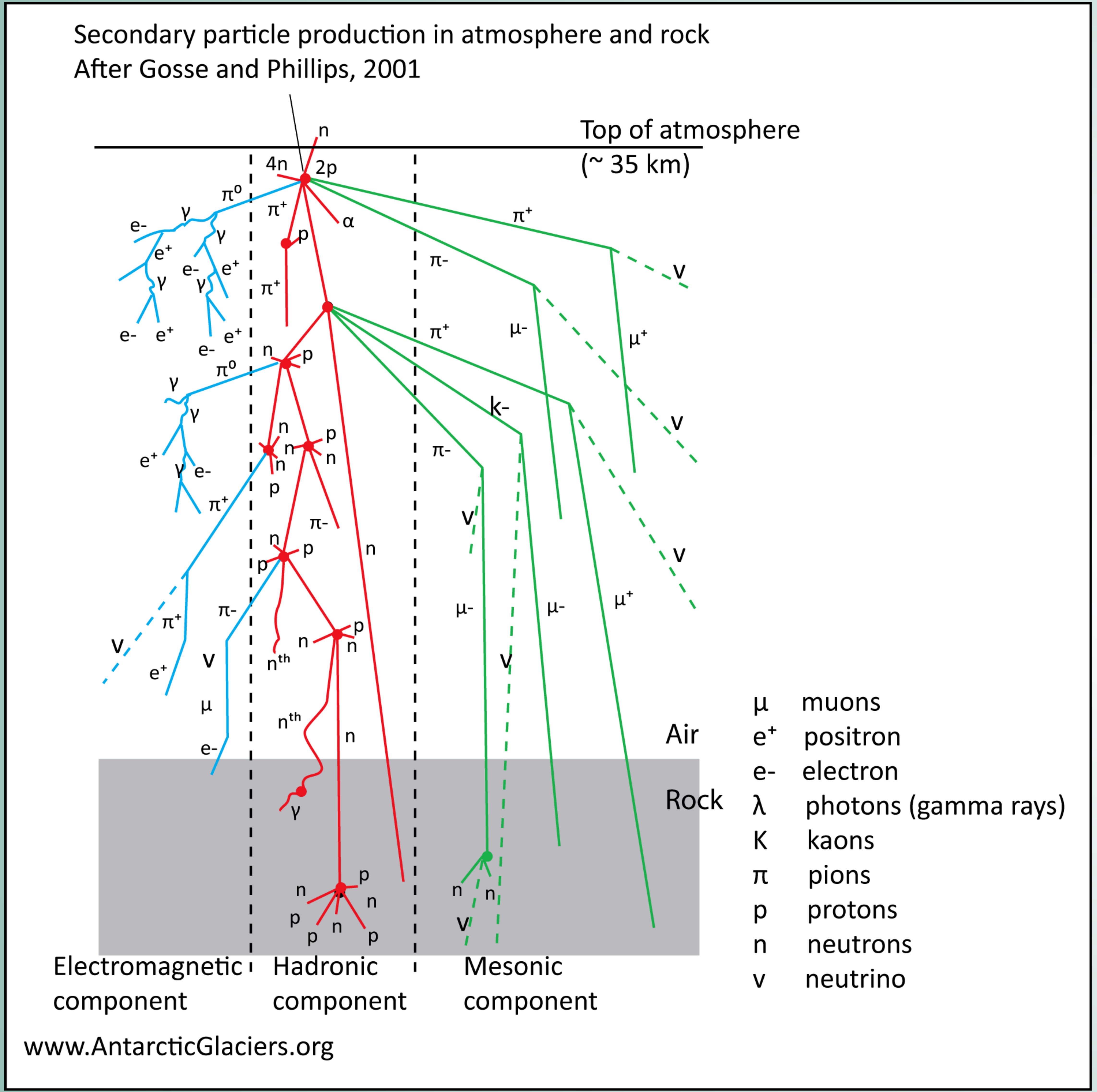
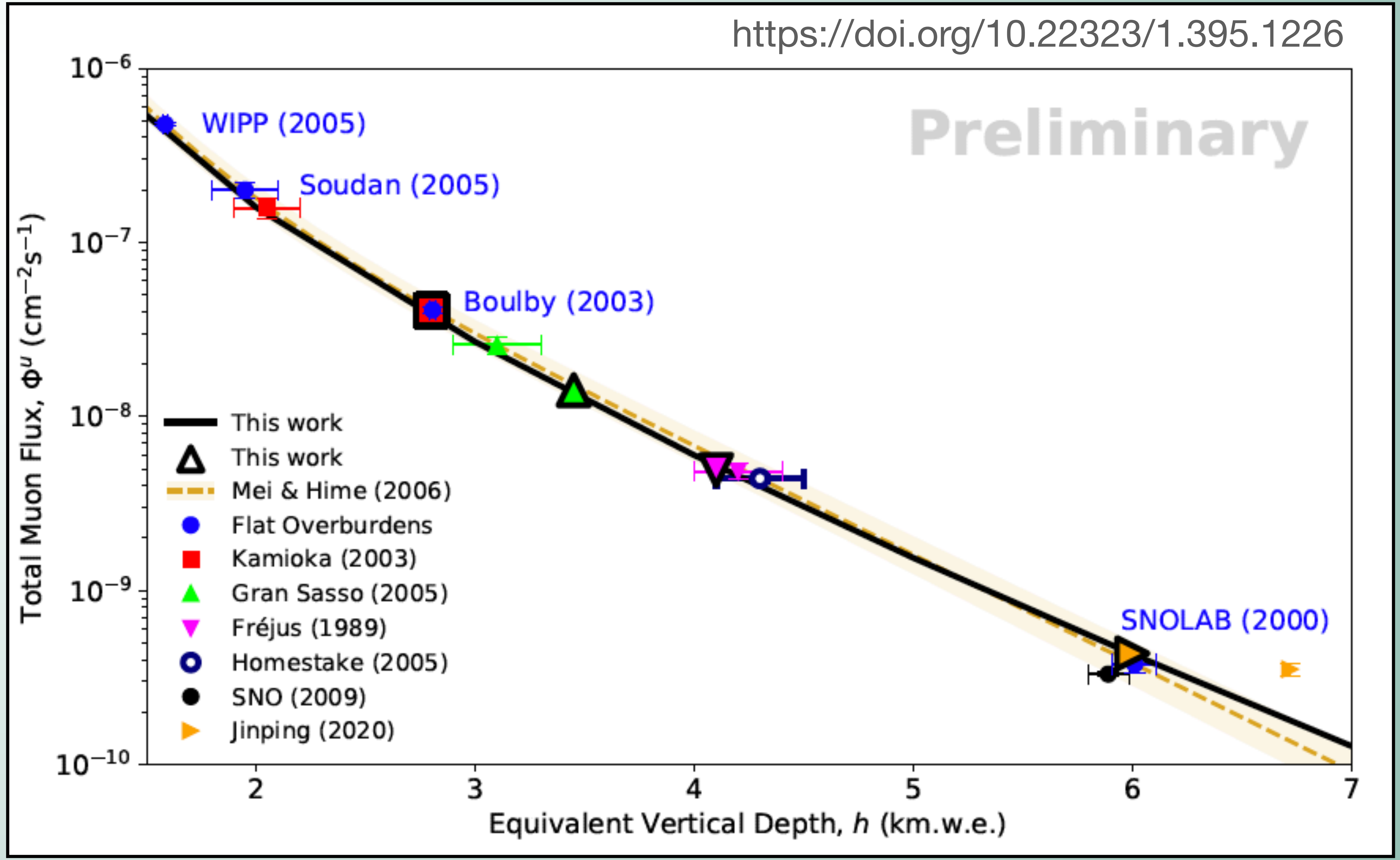


Fig. 1. Representative diagrams for the various thermal neutrino pair processes considered here: a) Compton process; b) plasmon pole contribution to the Compton process; c) transverse plasmon decay; d) nuclear Z^0 emission; and e) pair production in free-bound atomic transitions.

Why do physics underground?

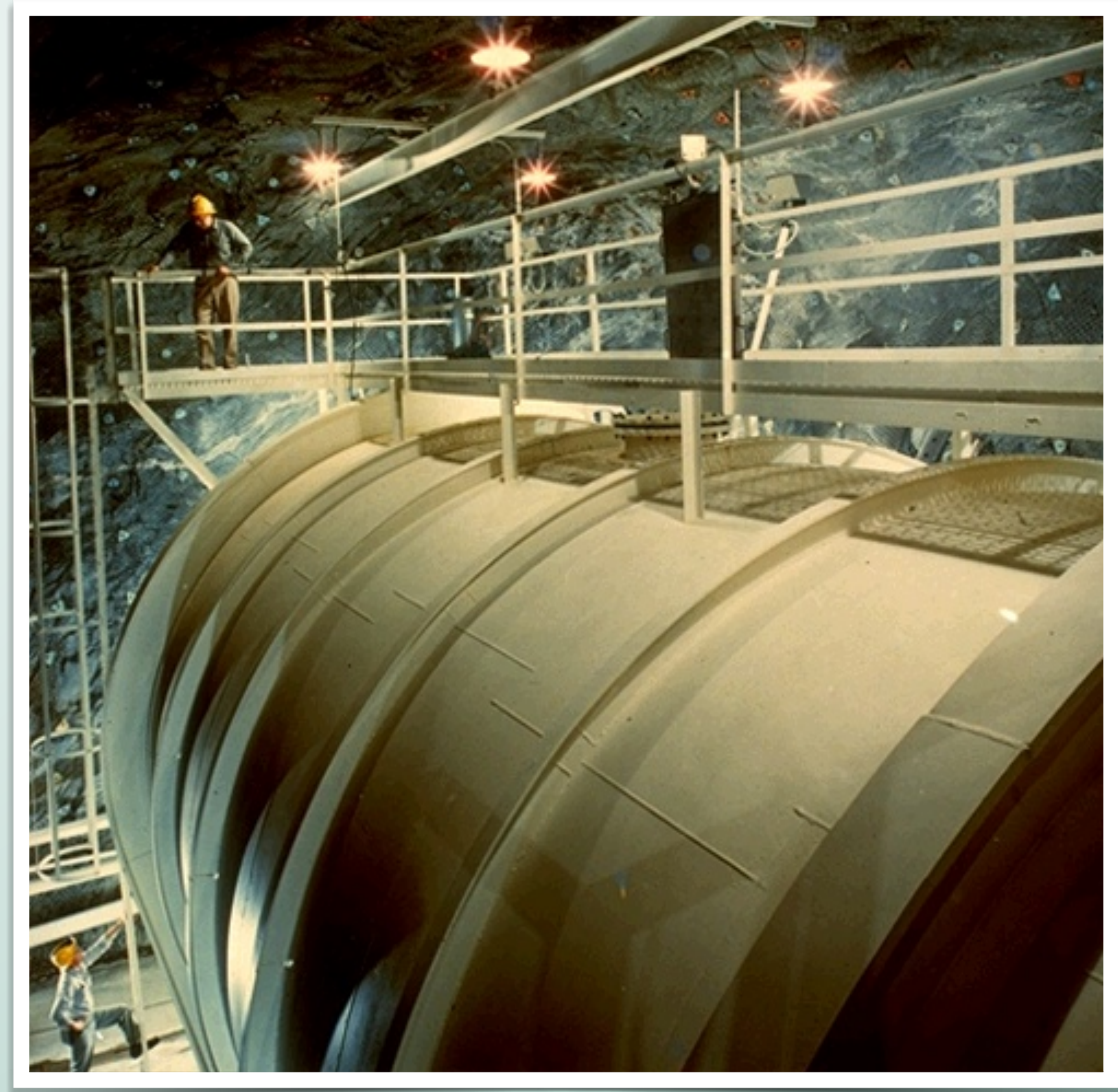


To escape from cosmic-rays that can travel through miles of rock.

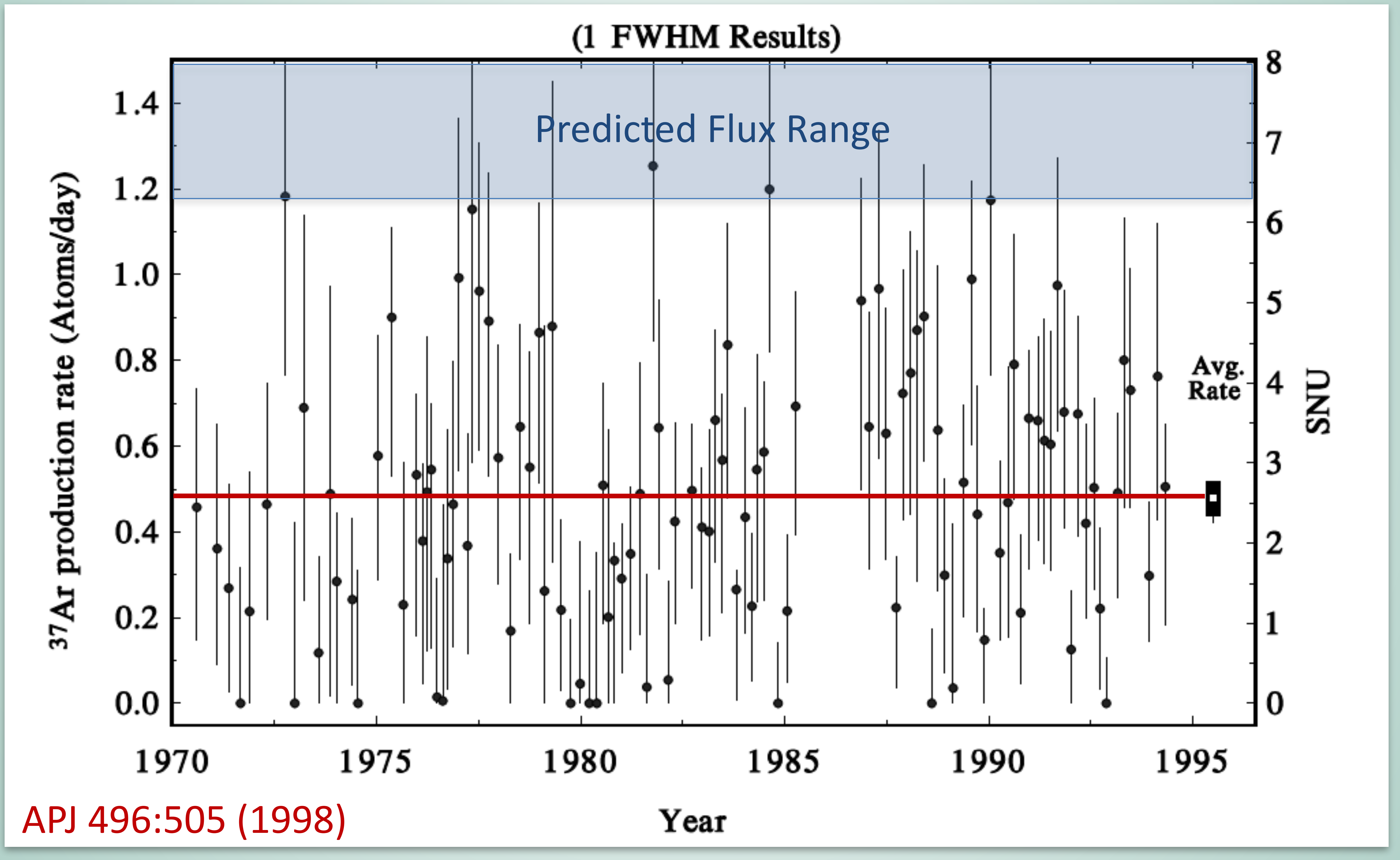


Ray Davis Experiment

- $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$
- E_{th} = 0.814 MeV (no pp)
- 615 t of C_2Cl_4
- Flush tank, look for ^{37}Ar decay
- Only 0.5 atoms of ^{37}Ar per day!
- **Sensitive to ν_e flavor only**



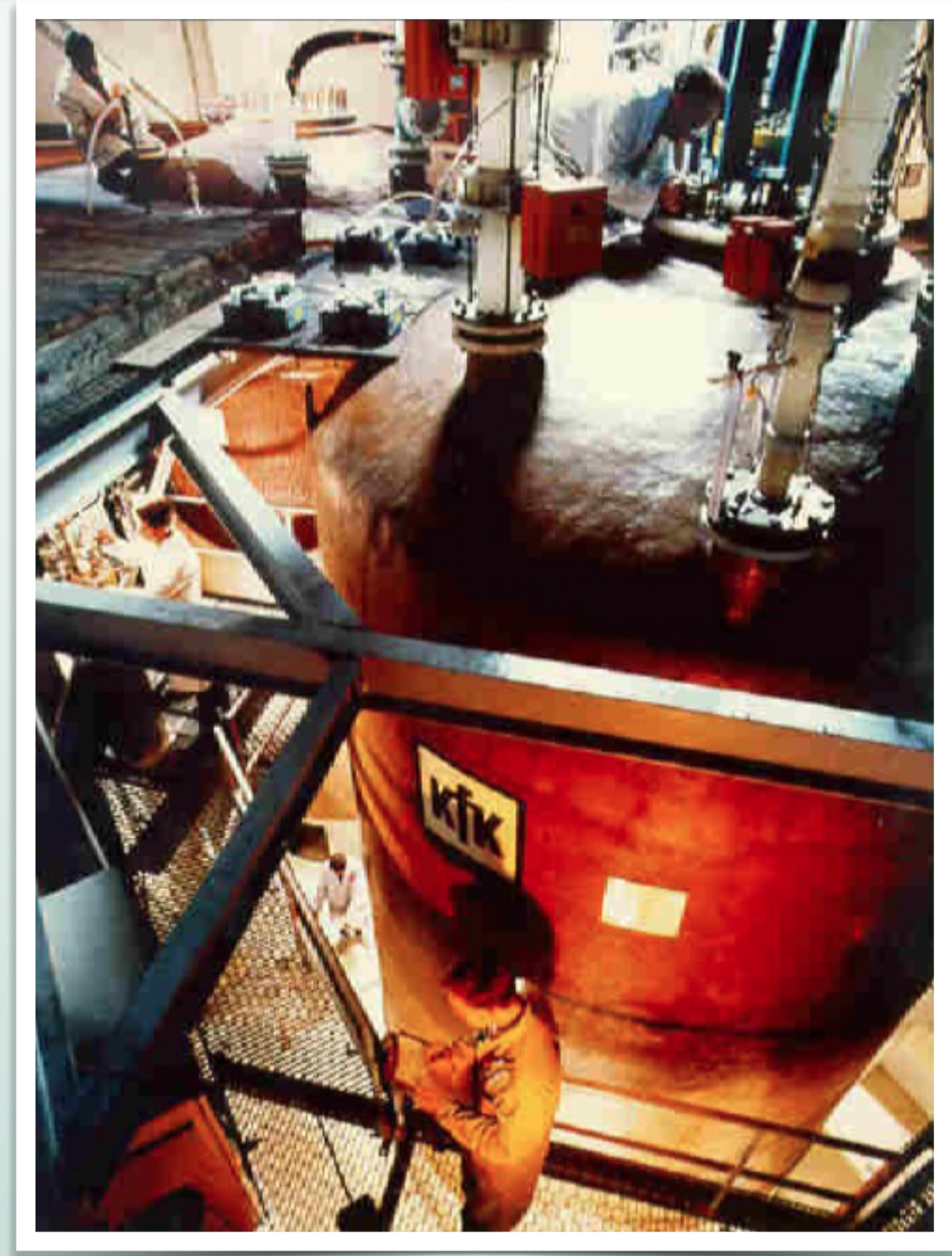
Davis experiment results
Only 1/3 of expected flux!



SAGE/GALLEX

- ν_e+^{71}Ga → ^{17}Ge + e^-
- E_{th} = 0.233 MeV
- **Sensitive to pp neutrinos**
- SAGE: 60t metallic Ga
- GALLEX/GNO 30t $GaCl_3$-HCl
- Measured 70 SNU, expected 130 SNU
- Experiments disagreed initially. Resolved with source calibration (more later)

SAGE/Gran Sasso



GNO/
GALLEX
Baksan

^{51}Cr Electron Capture Sources

GALLEX: 1.5 Mci; 1 ton

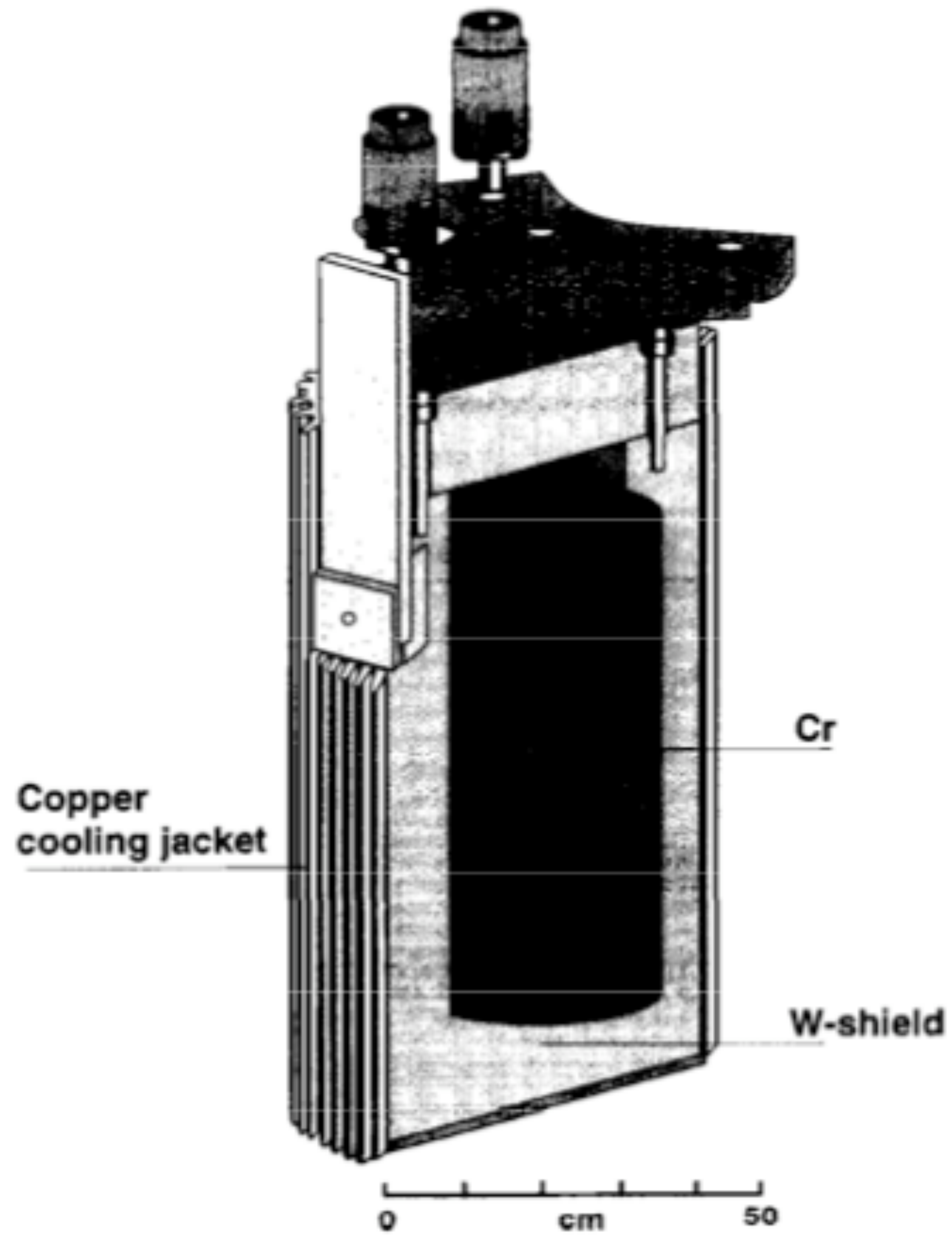


Fig. 11. Schematic drawing of the Cr-source inside the W-shield.

SAGE: 0.6 MCi

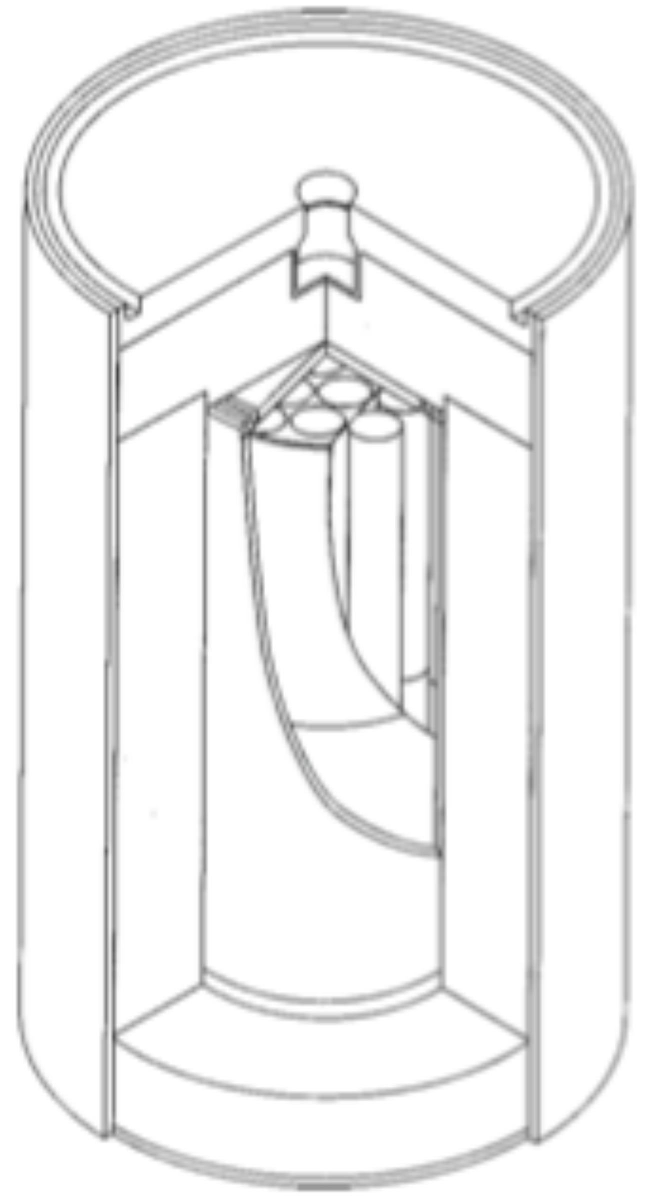
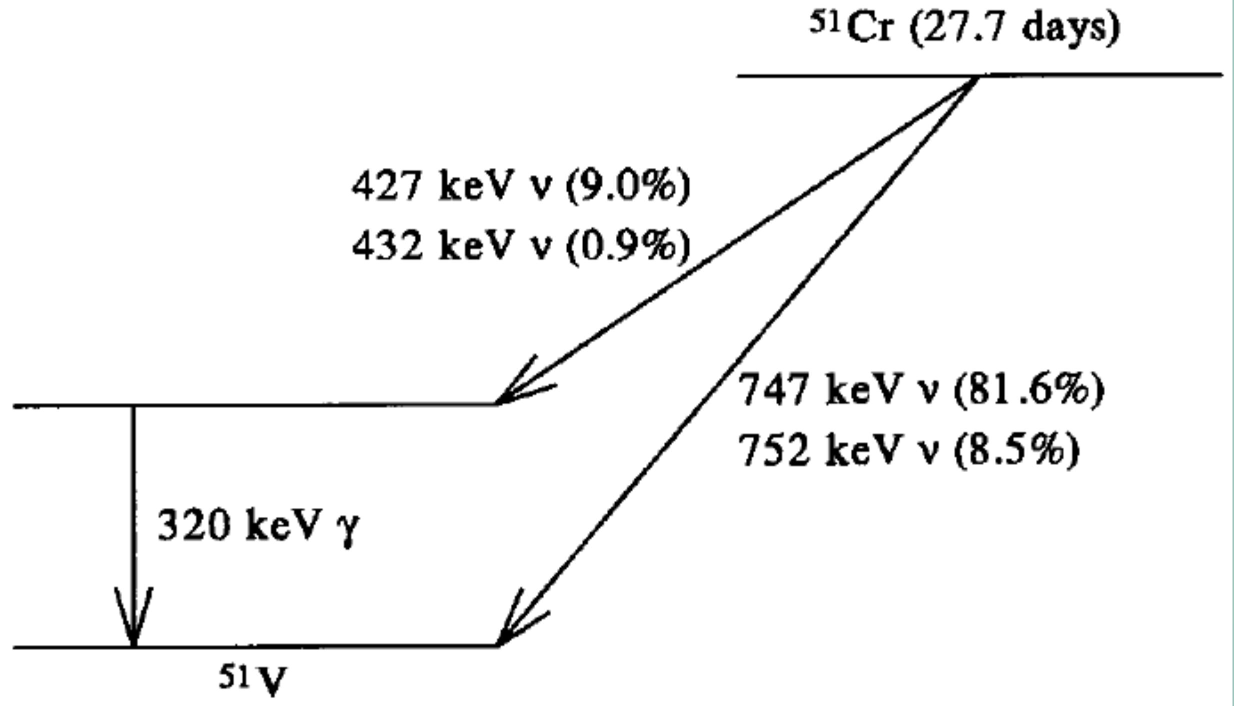


FIG. 4. Cutaway drawing of the source. The Cr rods were placed within the inner cylinders.

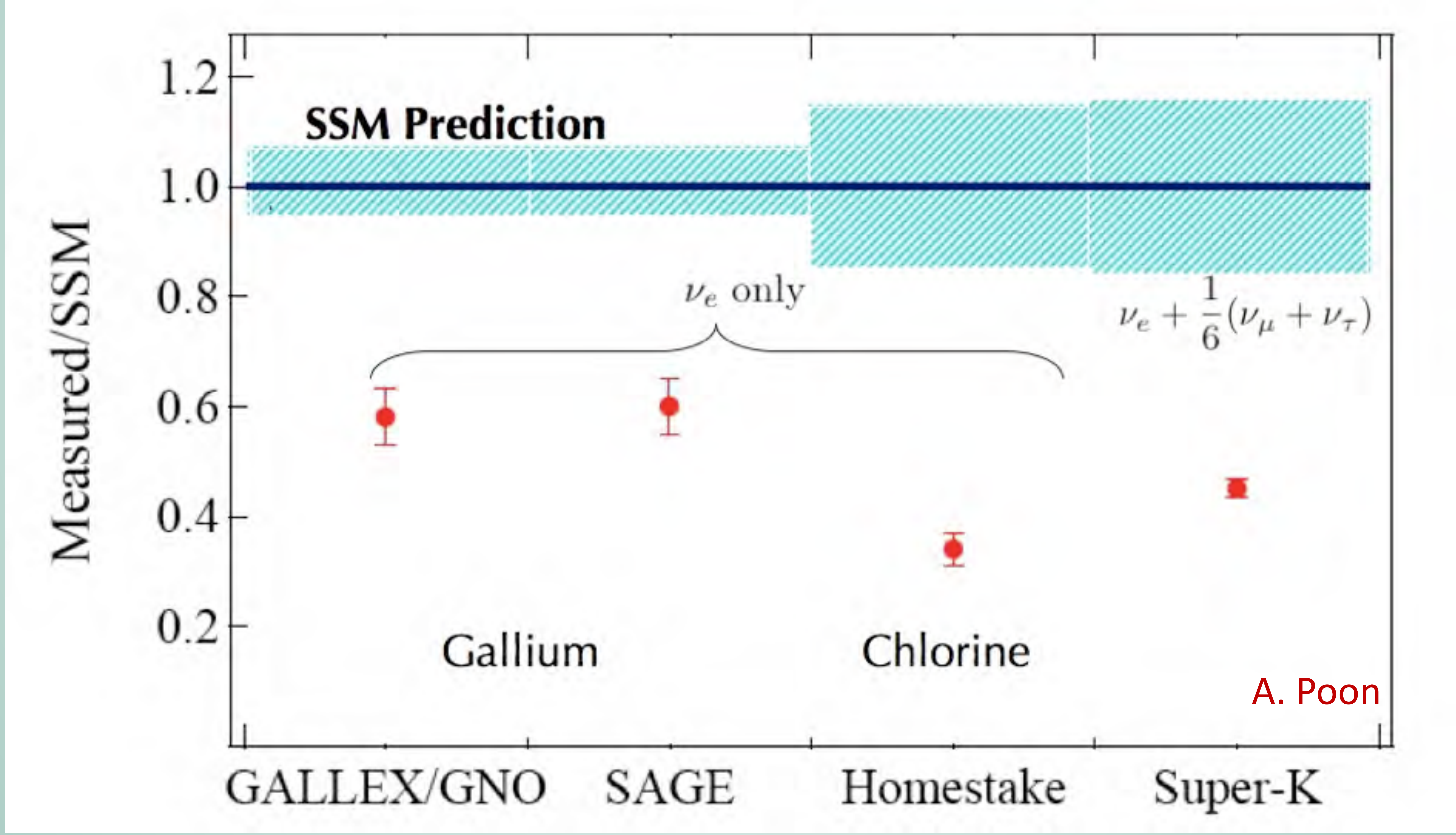
$$e^- + p \rightarrow n + \nu_e$$



Decay scheme of ^{51}Cr to ^{51}V through electron capture.

Gallex ^{51}Cr Source

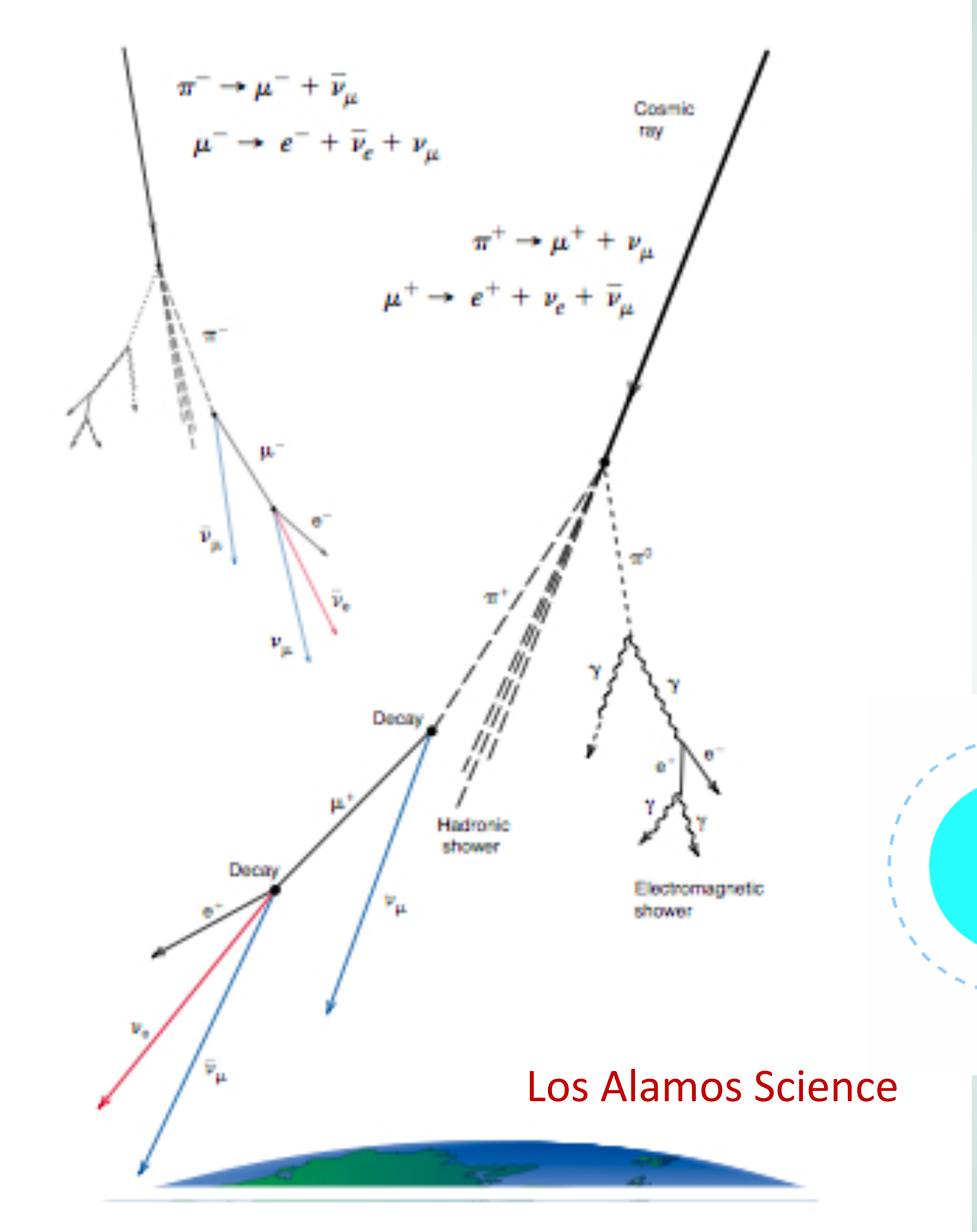
The Solar Neutrino Problem ~2000



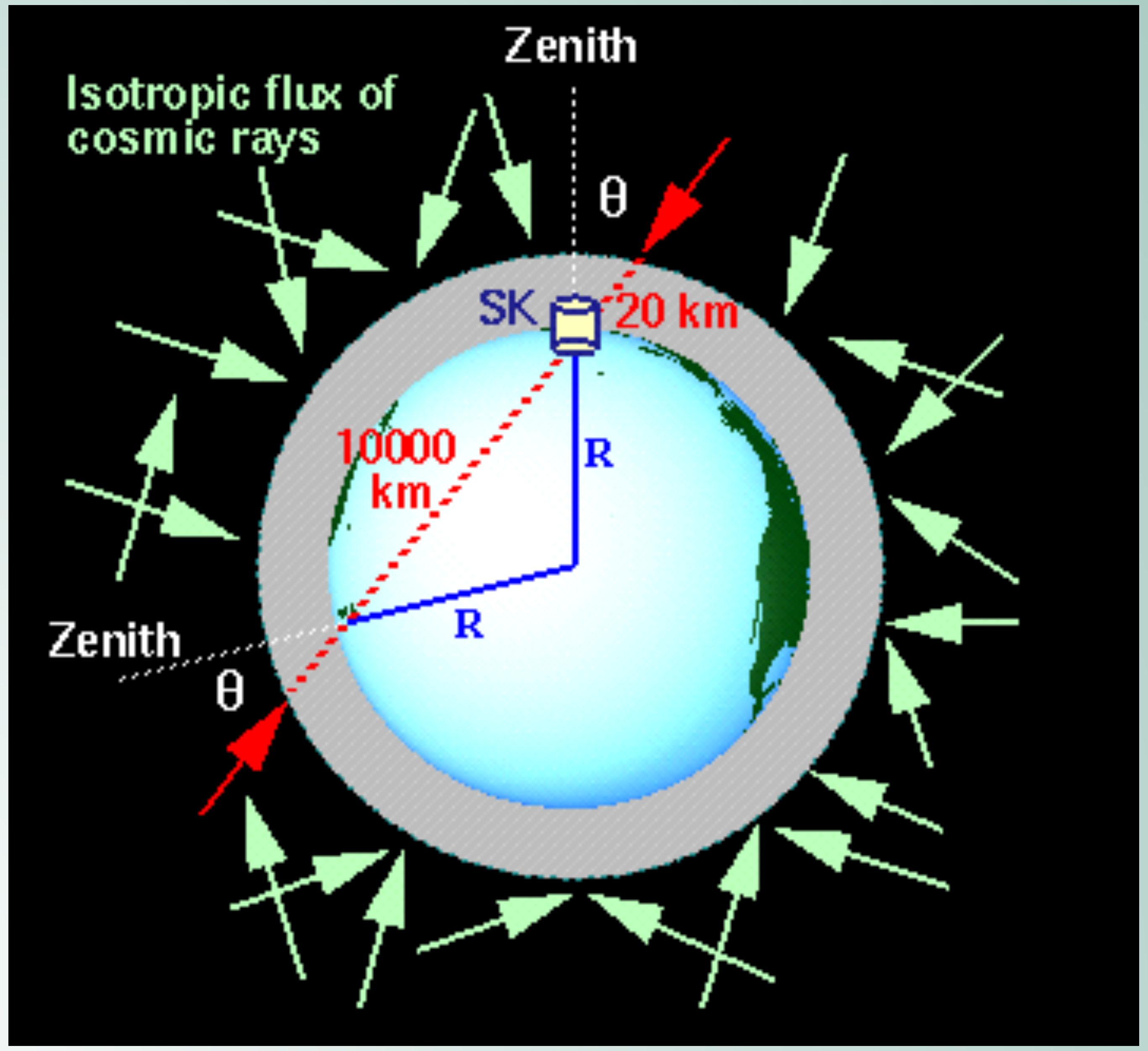
Stop Here Day 1

We will look for missing neutrinos next.

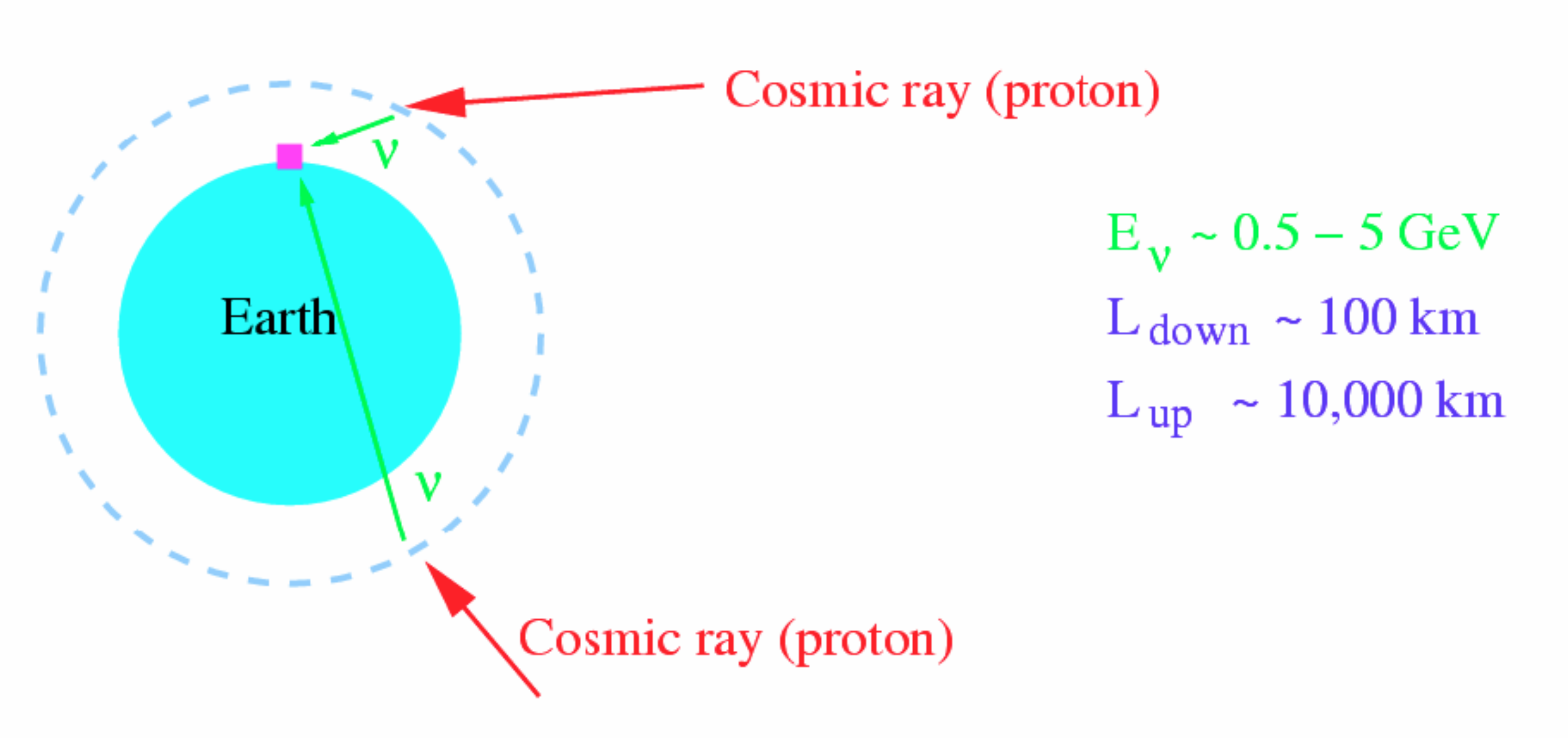
1985: Atmospheric Neutrino Anomaly



Los Alamos Science



http://hep.bu.edu/~superk/atmnu/



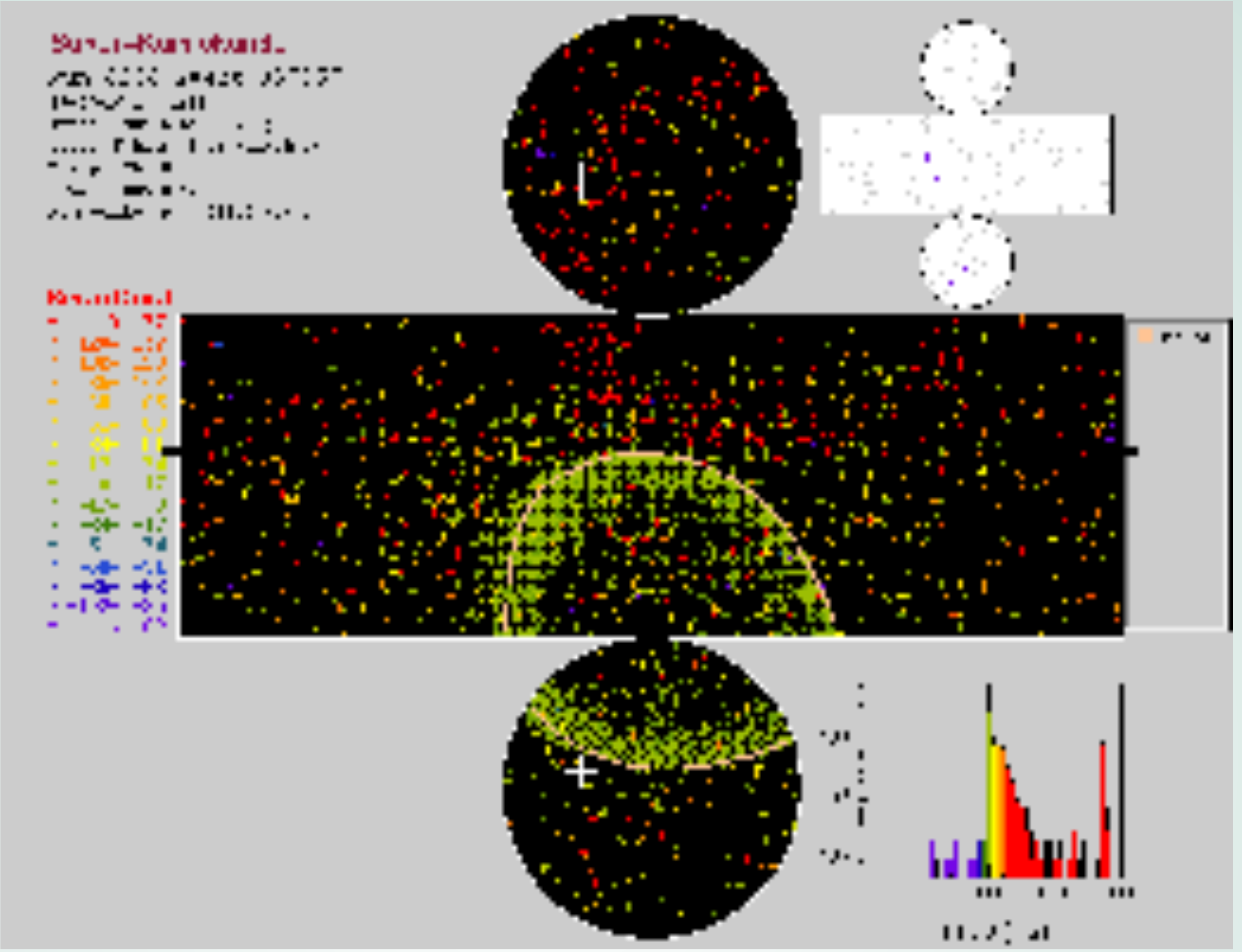
Except:

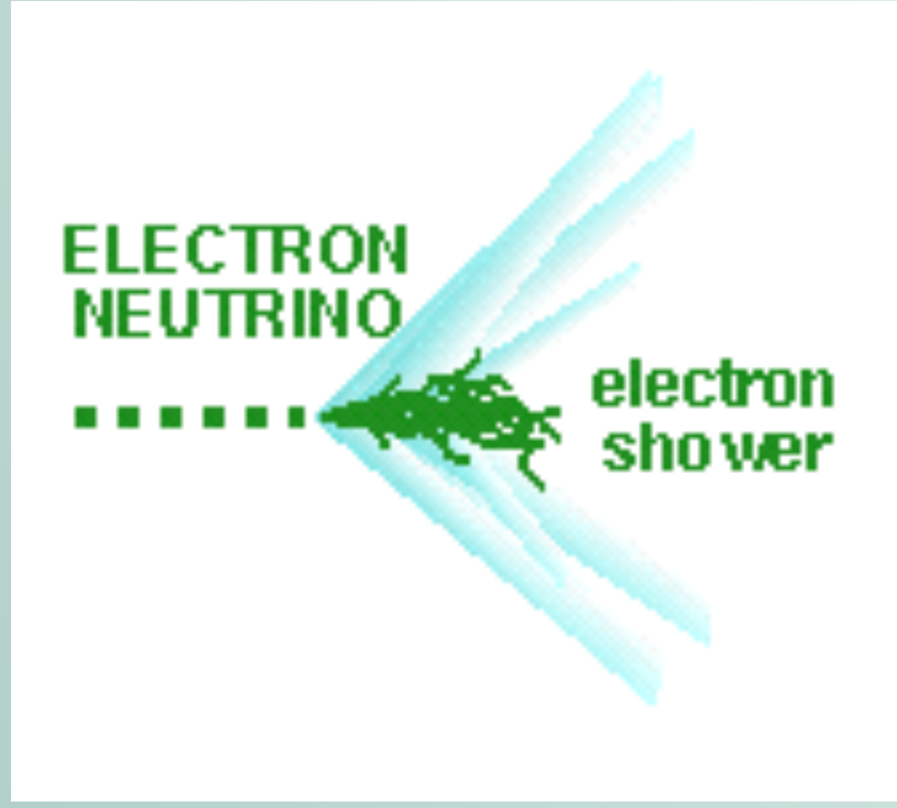
Isotropic Flux of ν_μ

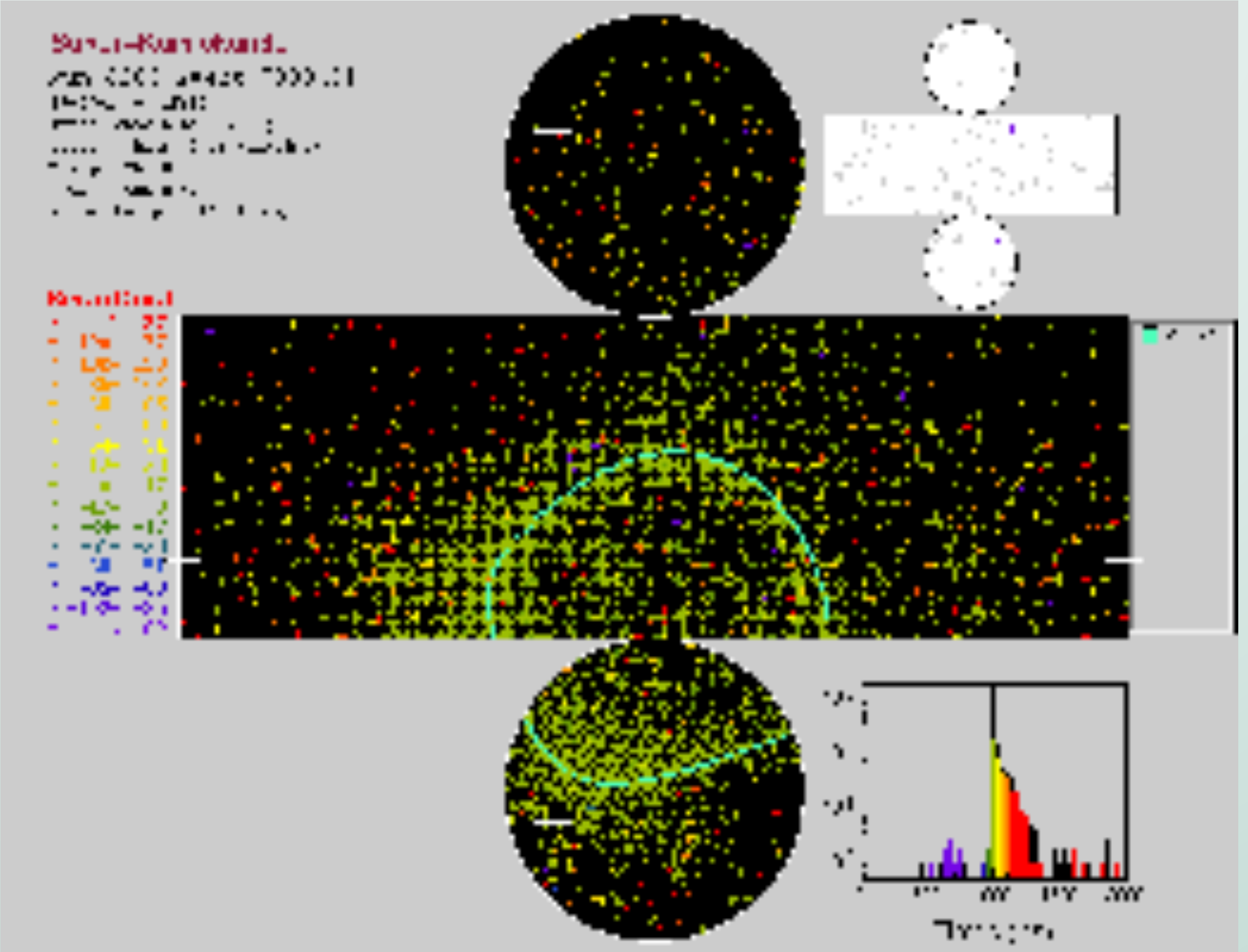
$\Phi(\nu_\mu)$~= $\Phi(\nu_e)$

Water Cerenkov Detectors

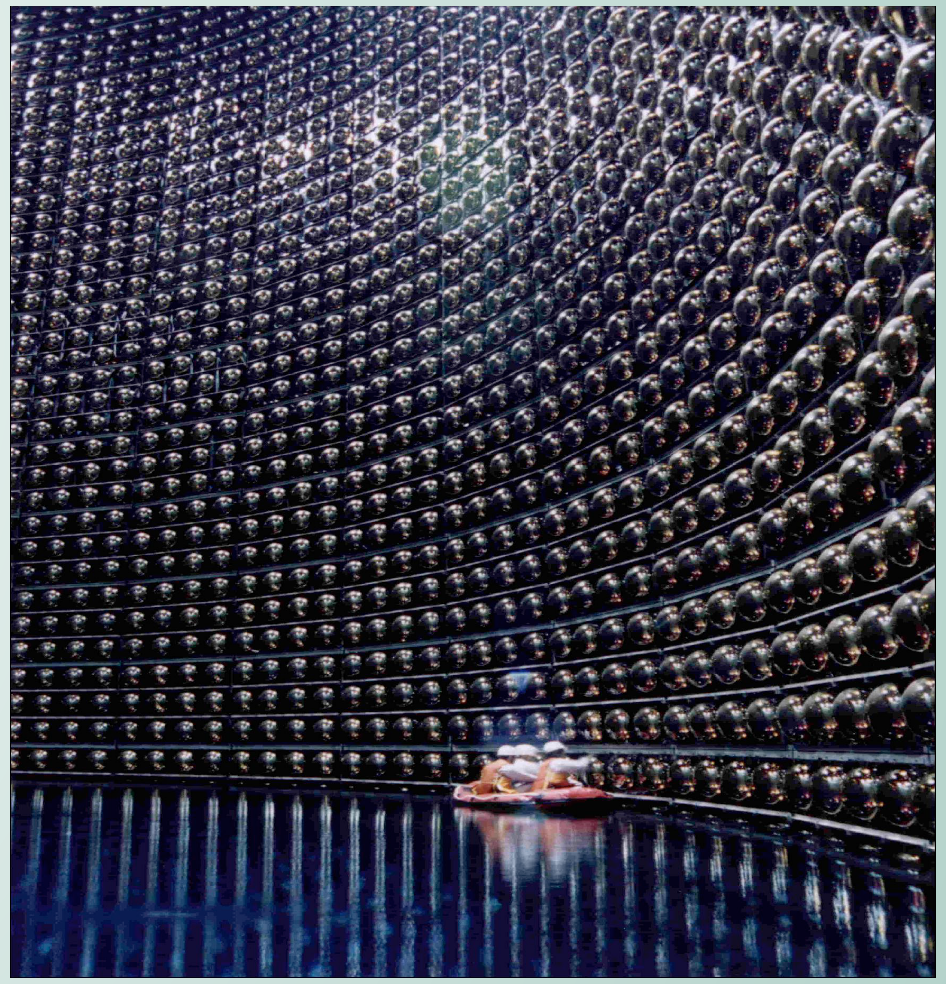
Particle ID





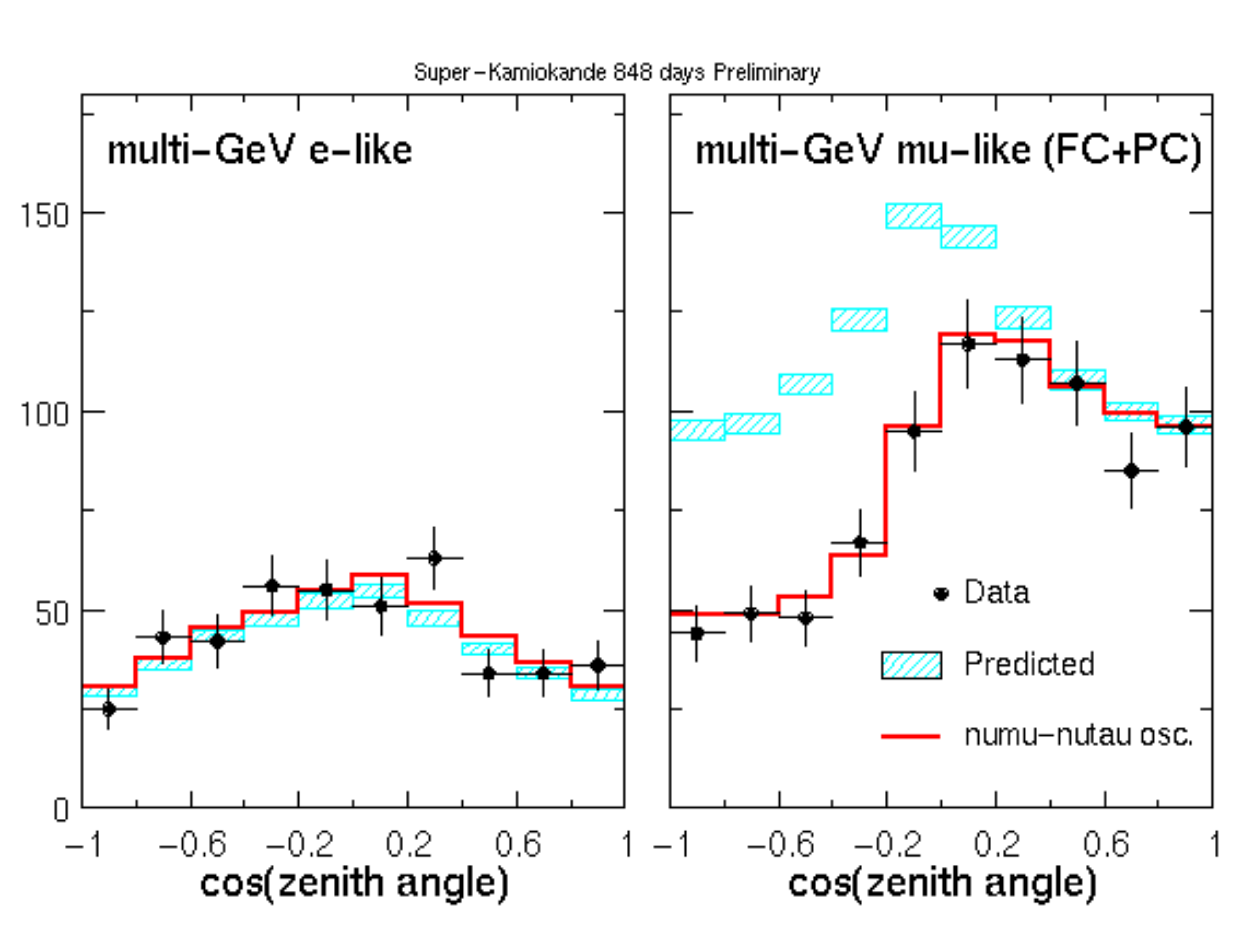


Super-K

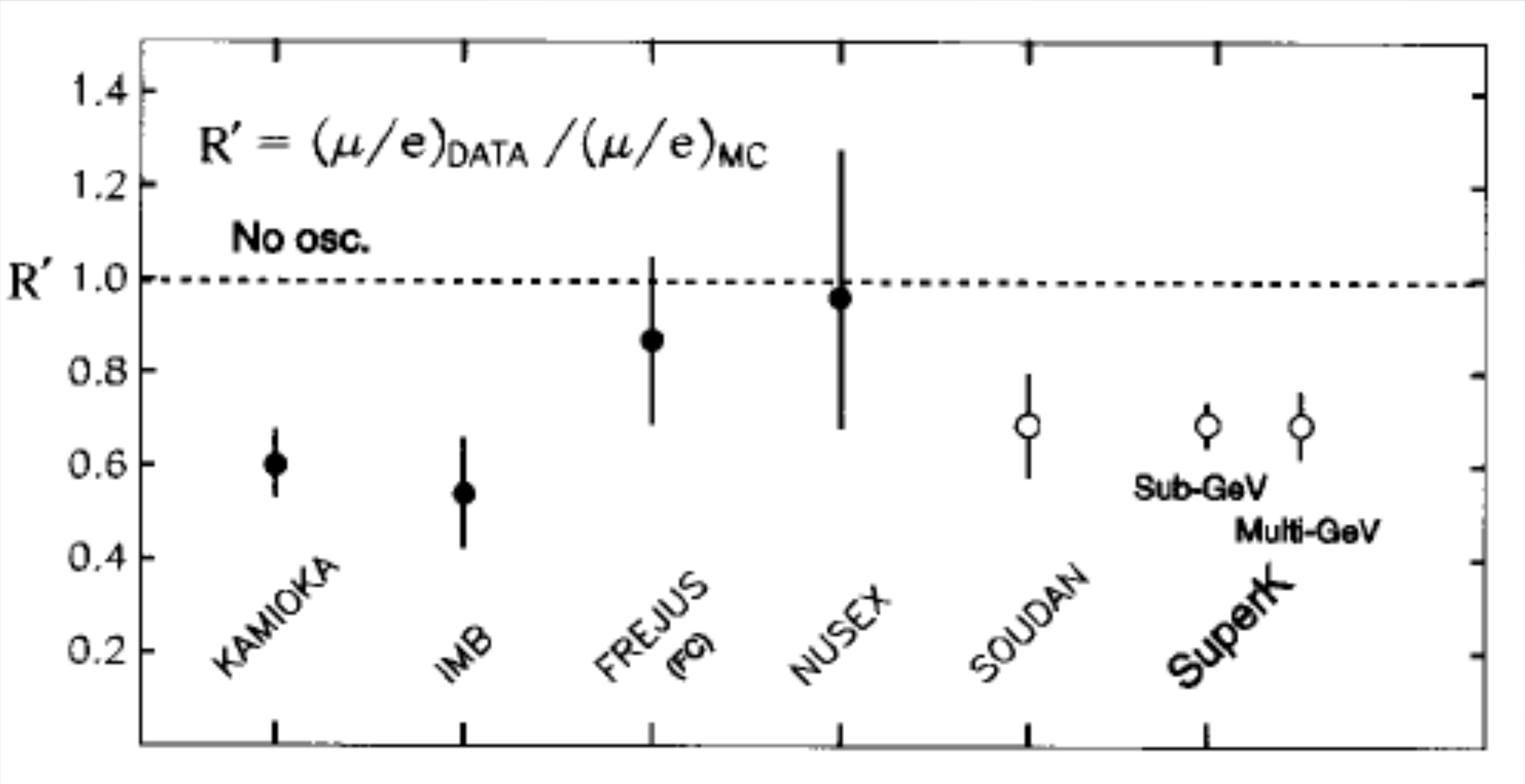


Initially built for
proton decay searches

Up-down Asymmetry Observed



Results



Mixing Angle quite large (consistent with maximal)

$\Delta m^2 = 2.5\text{x}10^{-3}\ eV^2$

Verified by Accelerator Experiments

1987: Supernova Neutrinos Detected

1998: First Evidence for Neutrino Oscillations

SNO
Sudbury Neutrino Observatory

1 kton ($300M!) D_2O

3 Channels:

Elastic Scattering (ES)

$\nu_{e\tau\mu} + e^- \rightarrow \nu_{e\tau\mu} + e^-$

Neutral Current (NC)

$\nu_{e\tau\mu} + d \rightarrow \nu_{e\tau\mu} + p^+ + n$

Charged Current

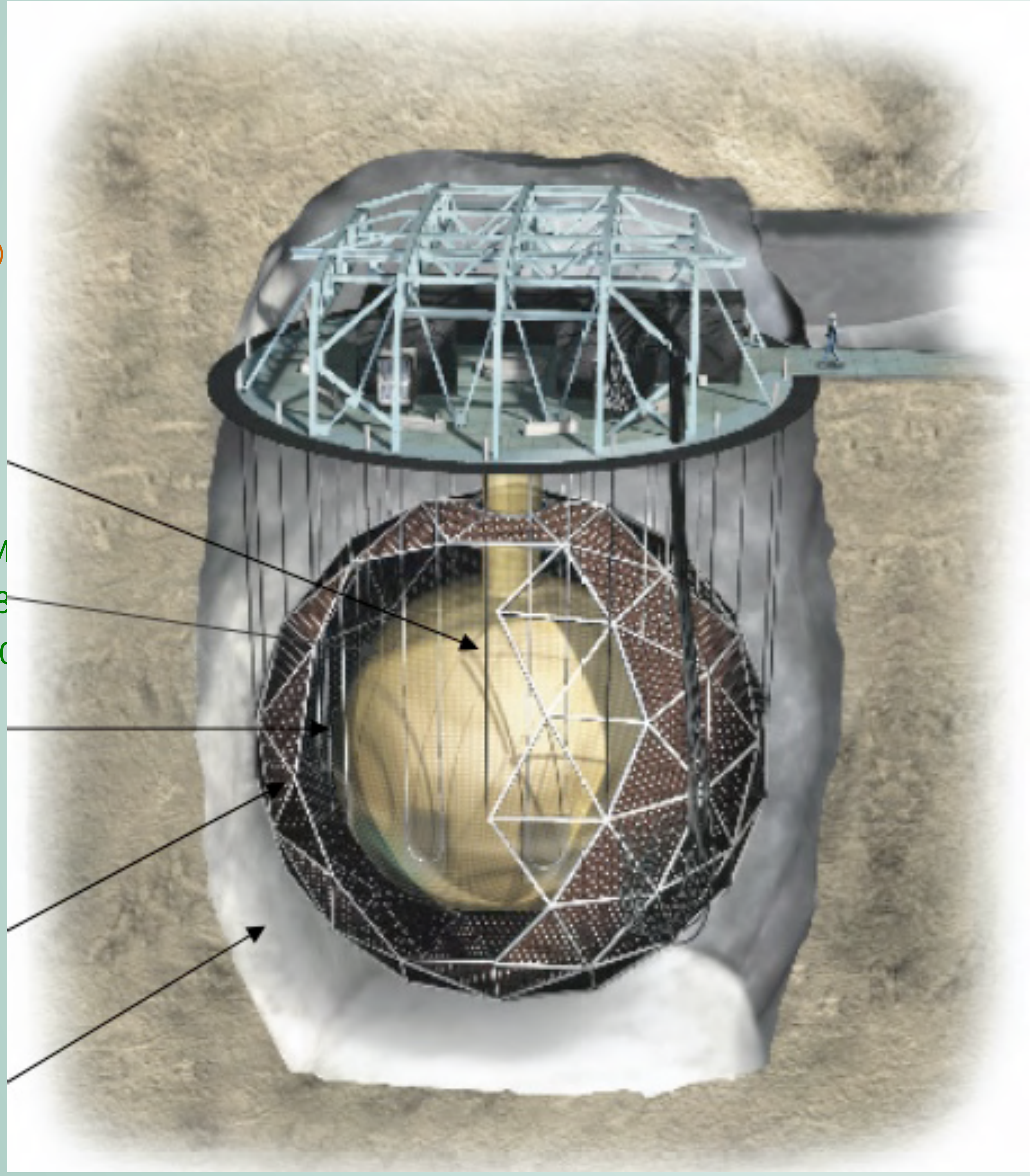
$\nu_e + d \rightarrow \nu_e + p^+ + p^+ + e^-$

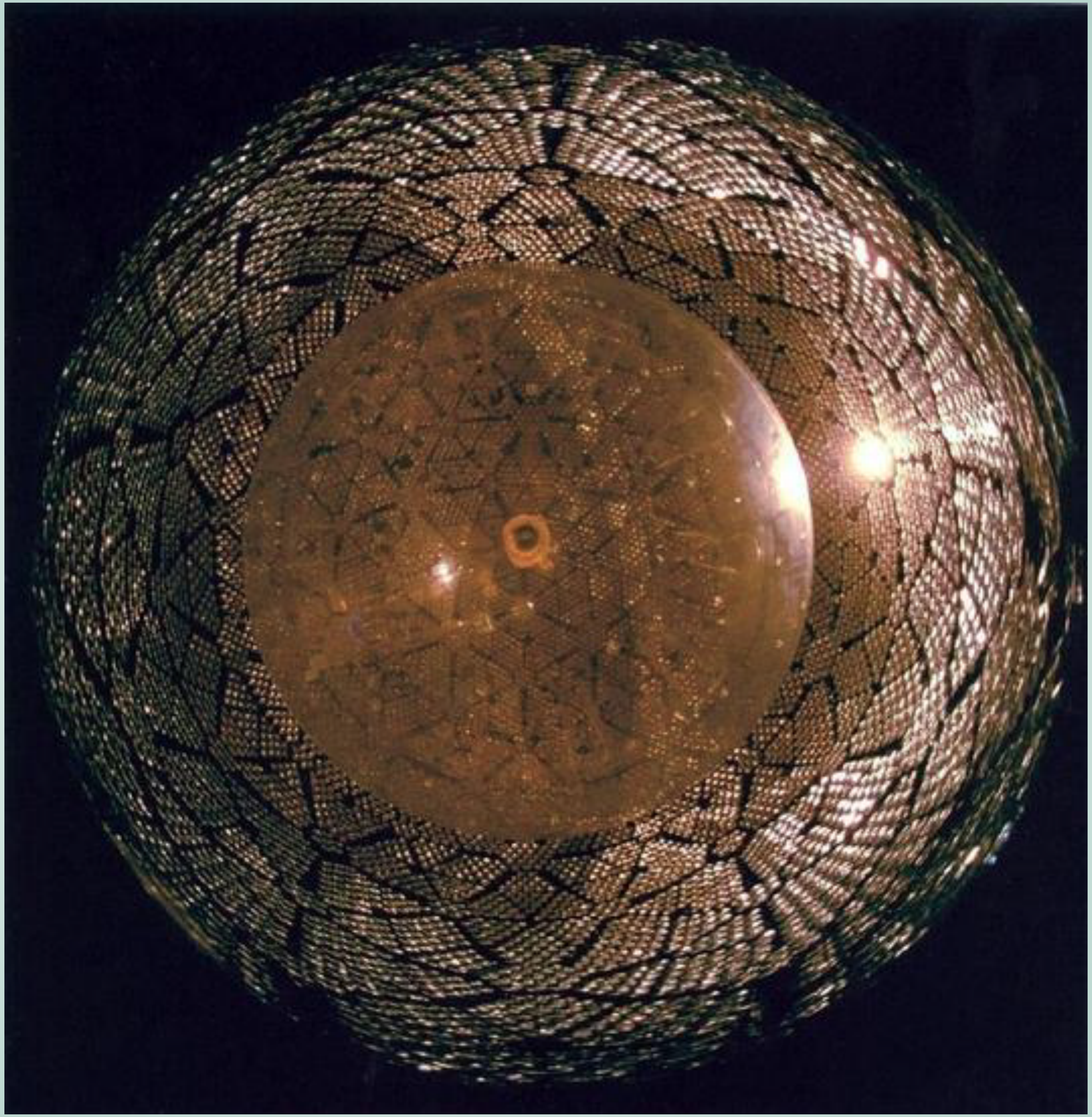
3 Phases:

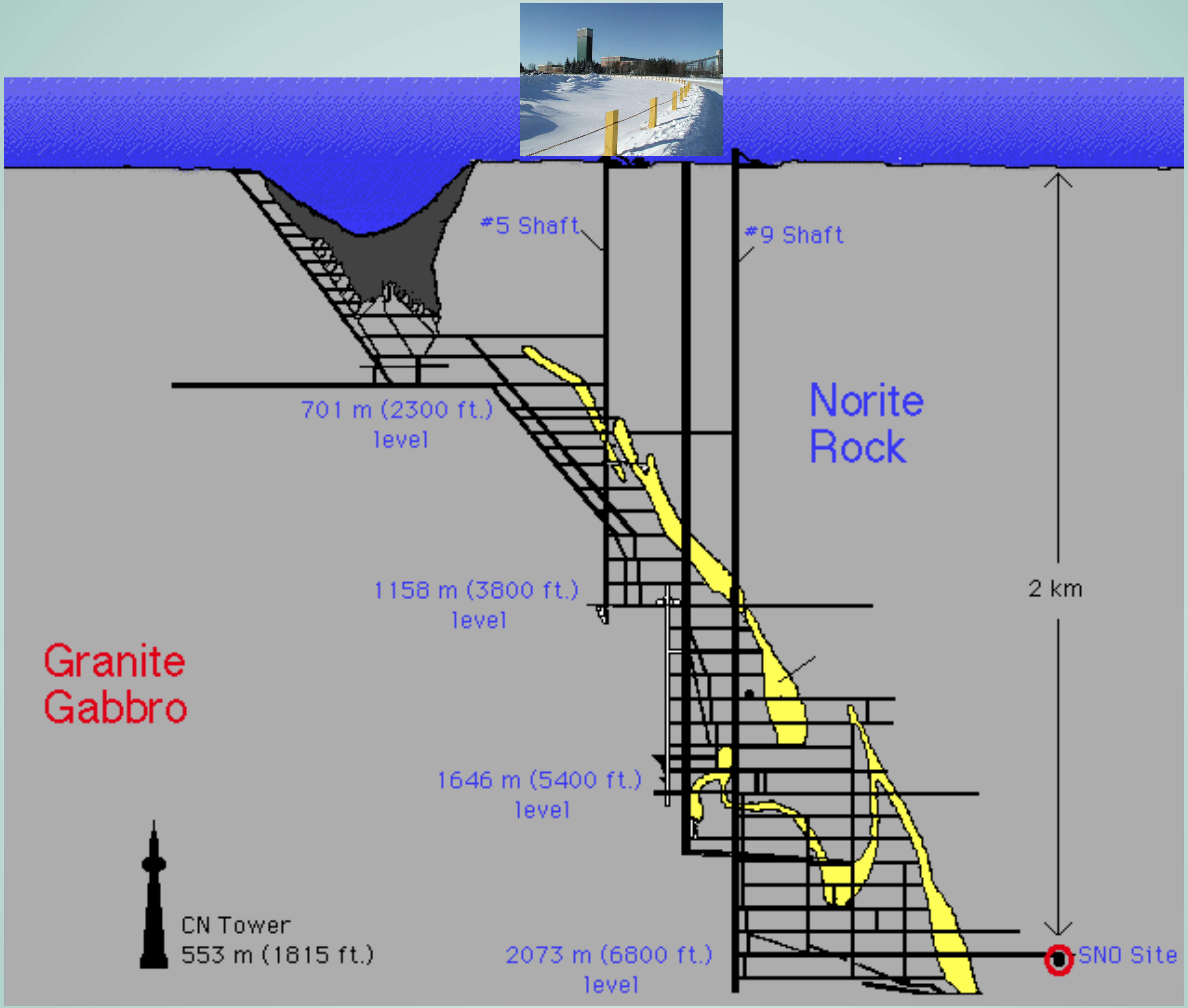
I: $n + d \rightarrow {}^3H + \gamma + 6.3$ M

II: $n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8$

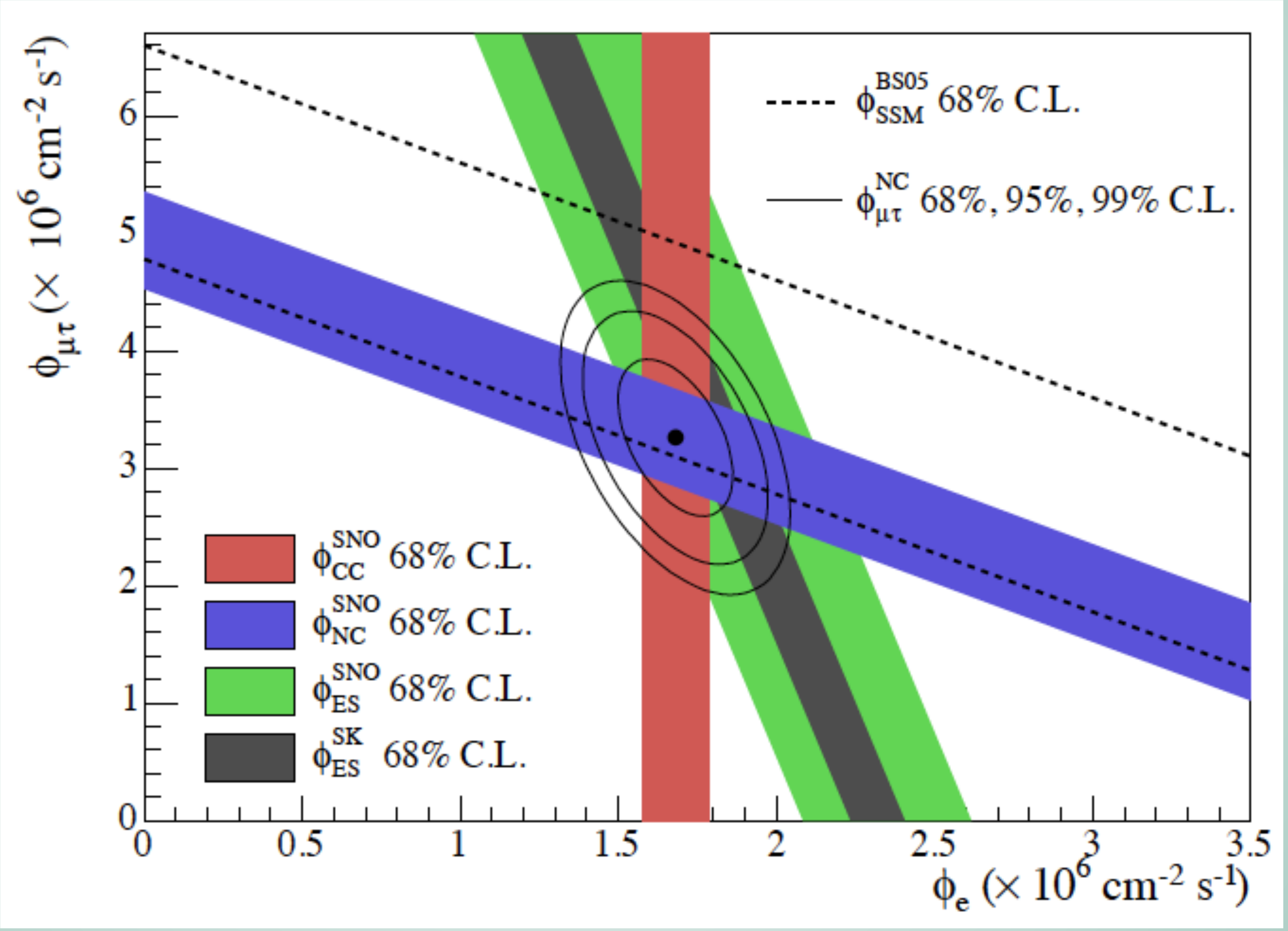
III: $n + {}^3He \rightarrow {}^3H + p + ($

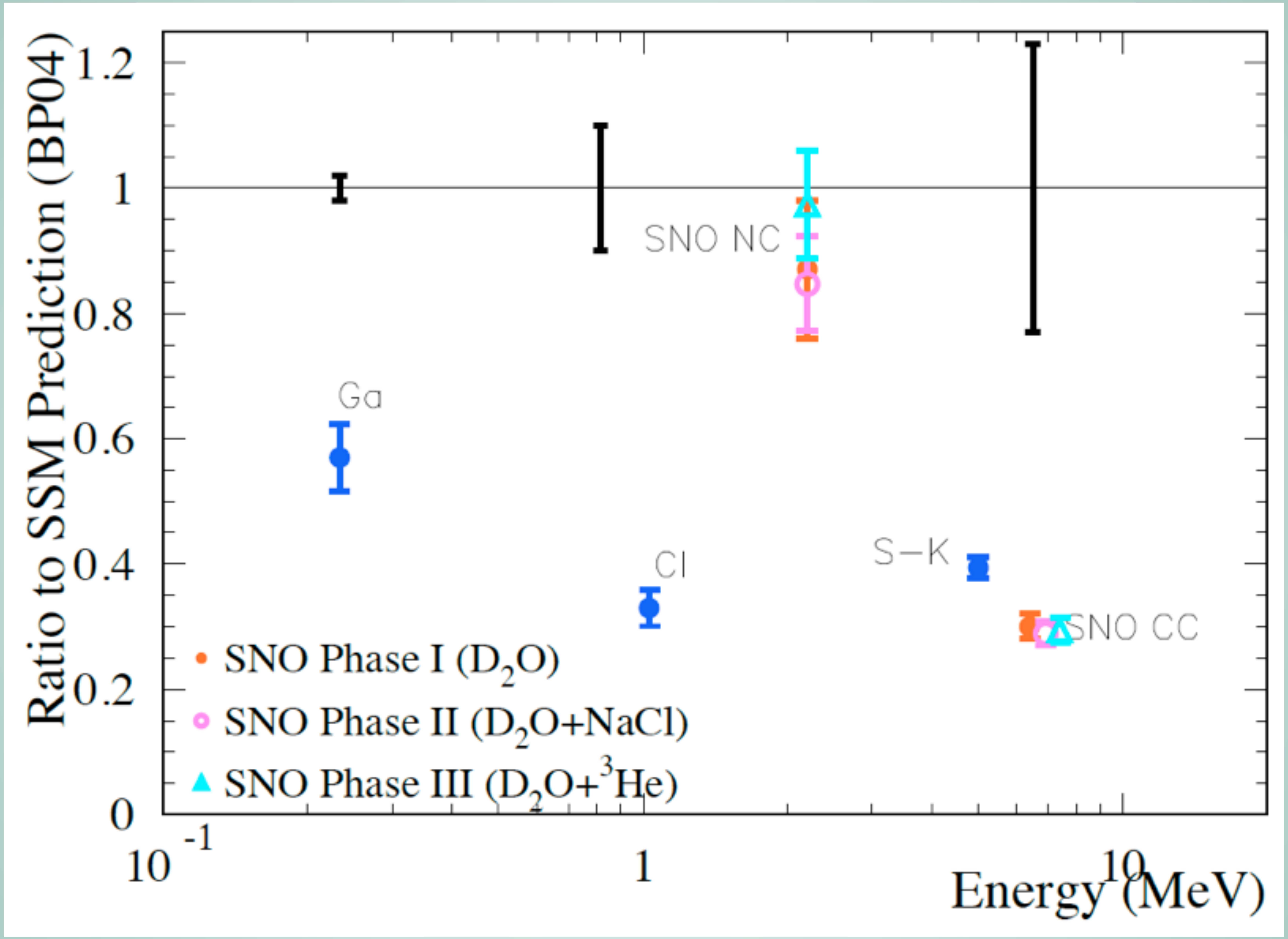





#5 Shaft
#9 Shaft
Norite Rock
701 m (2300 ft.) level
1158 m (3800 ft.) level
2 km
Granite Gabbro
1646 m (5400 ft.) level
CN Tower 553 m (1815 ft.)
2073 m (6800 ft.) level
SNO Site

Solar Neutrino Problem Solved!

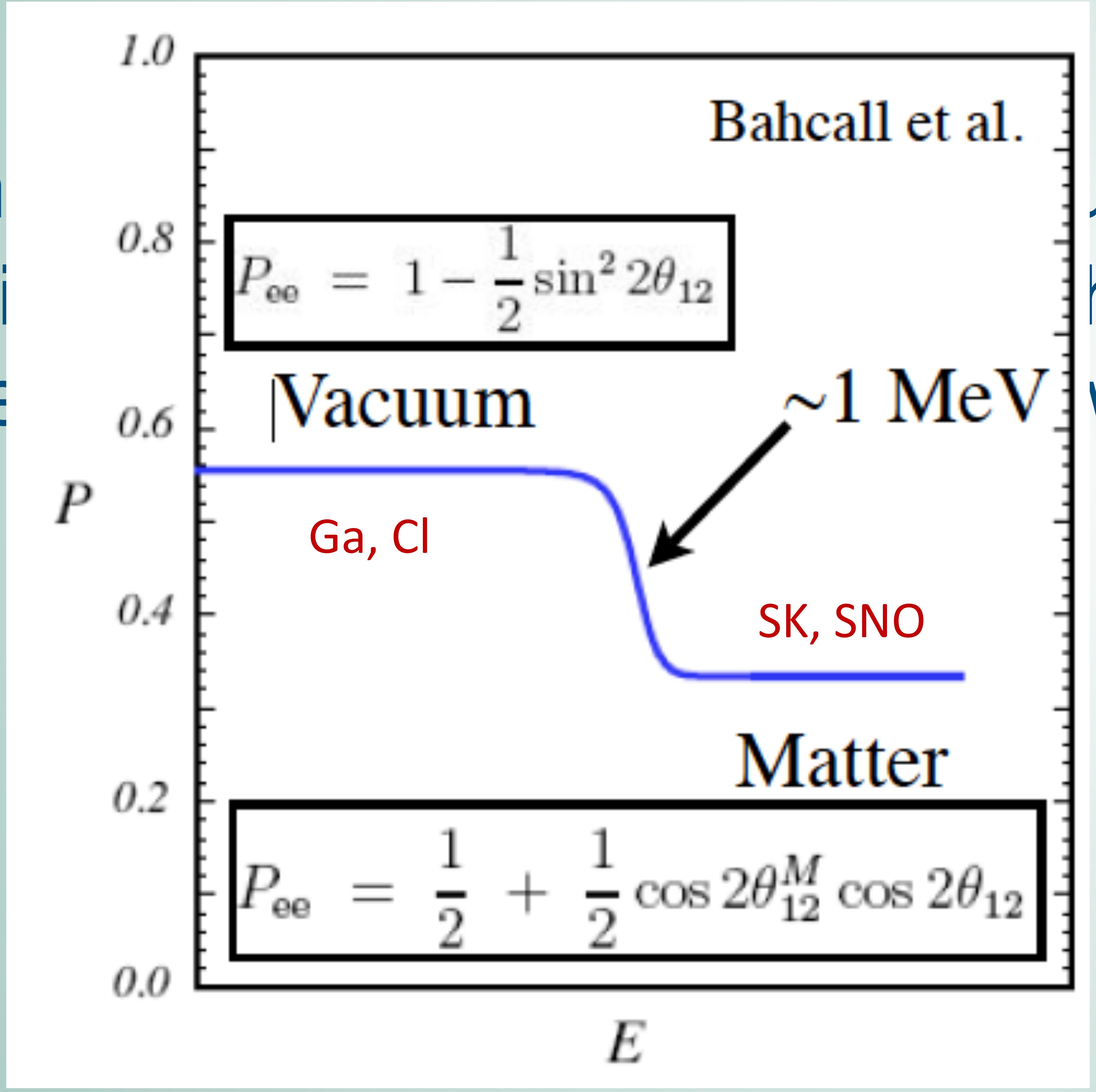




Ratio to SSM Prediction (BP04)
1.2
1
0.8
0.6
0.4
0.2
0
SNO NC
Ga
Cl
S−K
SNO CC
SNO Phase I (D_2O)
SNO Phase II (D_2O+NaCl)
SNO Phase III (D_2O+^3He)
10^{-1}
1
10
Energy (MeV)

Interpretation

Sun em ut questions remain.
Oscillati her possibilities?
→Probe vith ~1 MeV neutrinos

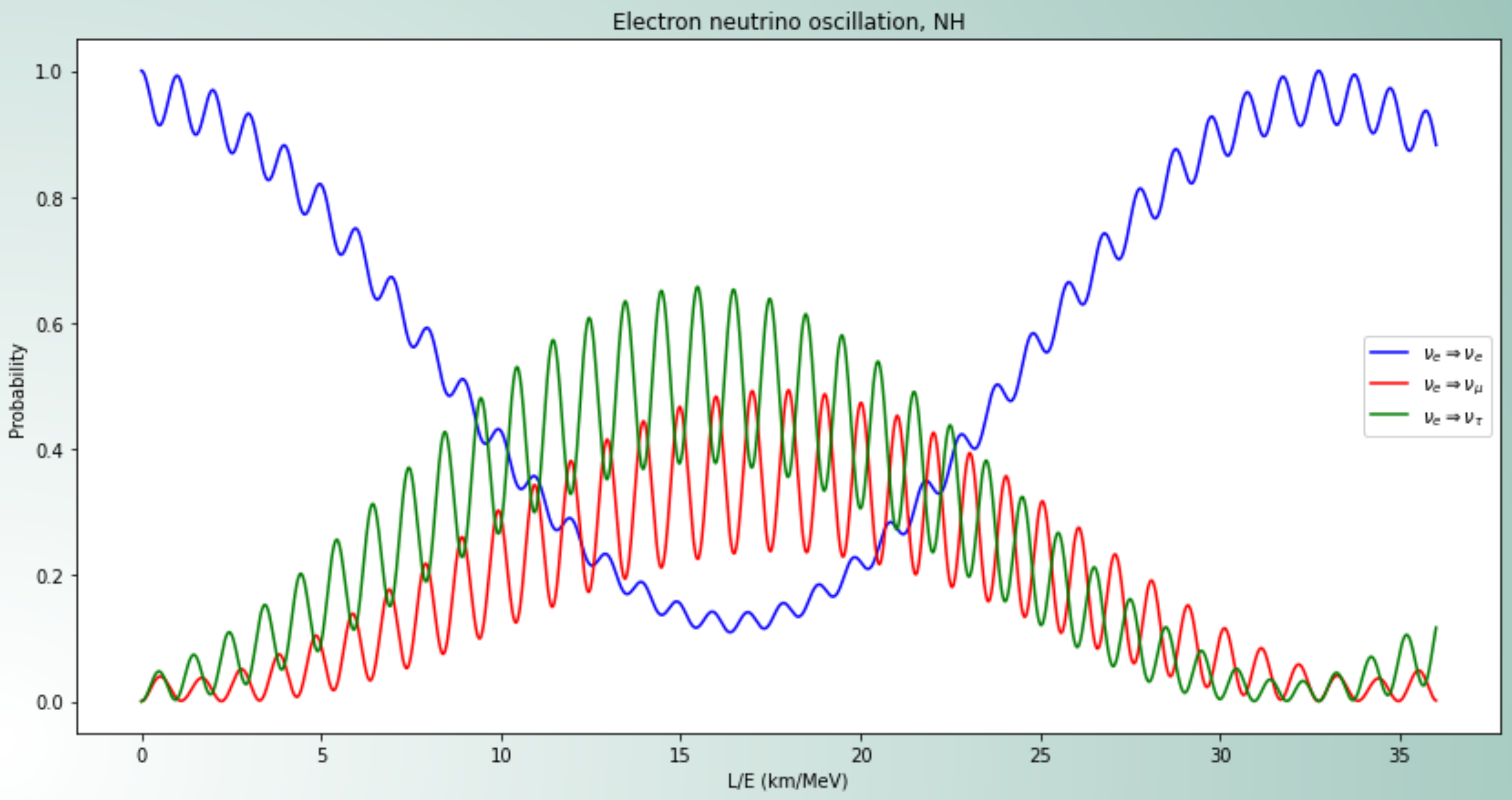


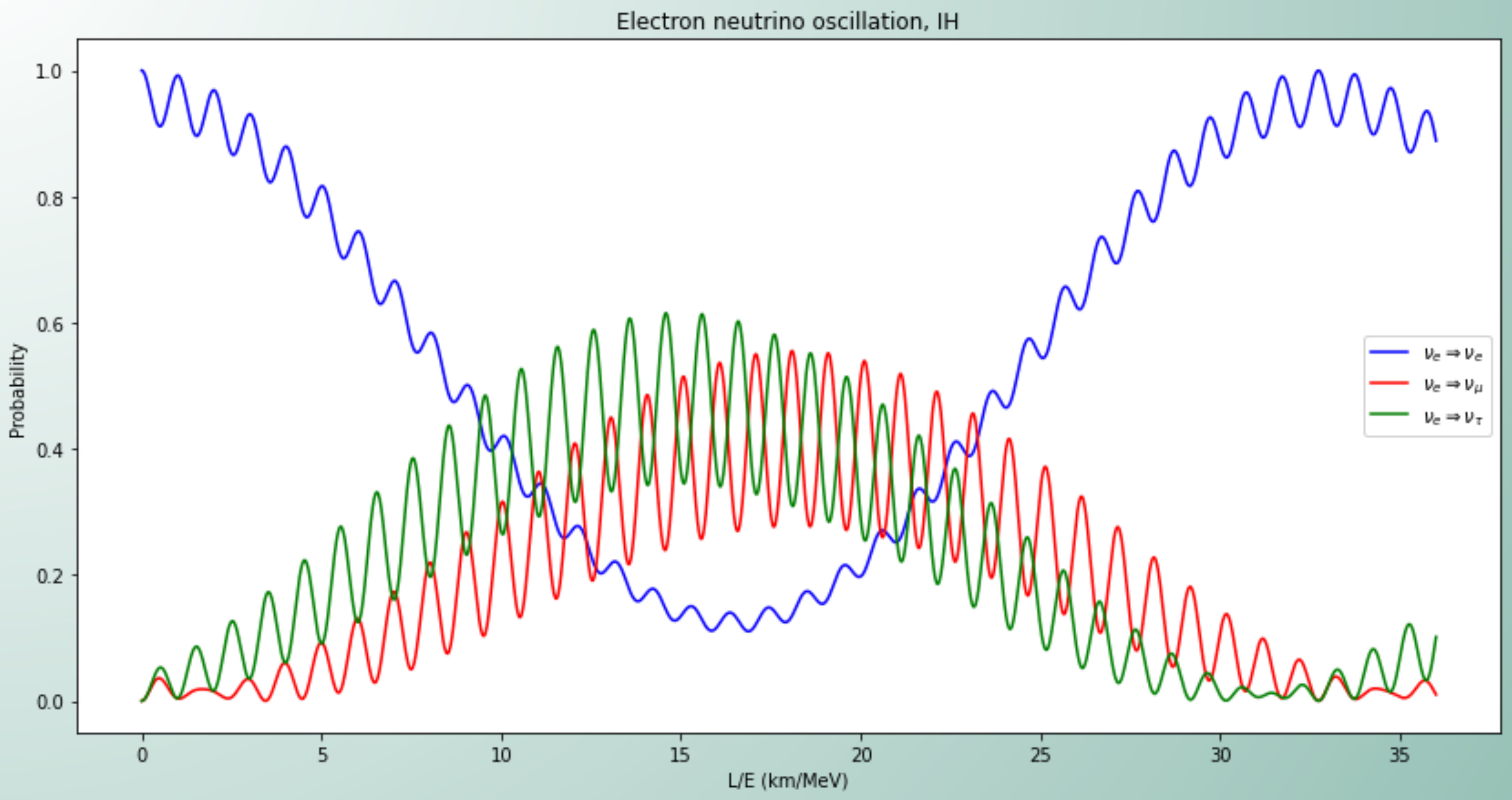
2002: Discovery of Reactor Neutrino Oscillations

- Late 90s: Evidence for neutrino oscillations become compelling from solar neutrino and atmospheric neutrinos.
- Not observed in reactor neutrinos yet, though

Probability of ν_e disappearance:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$


Electron neutrino oscillation, NH
1.0
0.8
0.6
0.4
0.2
0.0
Probability
0
5
10
15
20
25
30
35
L/E (km/MeV)
$\nu_e \Rightarrow \nu_e$
$\nu_e \Rightarrow \nu_\mu$
$\nu_e \Rightarrow \nu_\tau$


Electron neutrino oscillation, IH
1.0
0.8
0.6
0.4
0.2
0.0
Probability
0
5
10
15
20
25
30
35
L/E (km/MeV)
$\nu_e \Rightarrow \nu_e$
$\nu_e \Rightarrow \nu_\mu$
$\nu_e \Rightarrow \nu_\tau$

KamLAND

2800 mwe in Kamioka mine in Japan

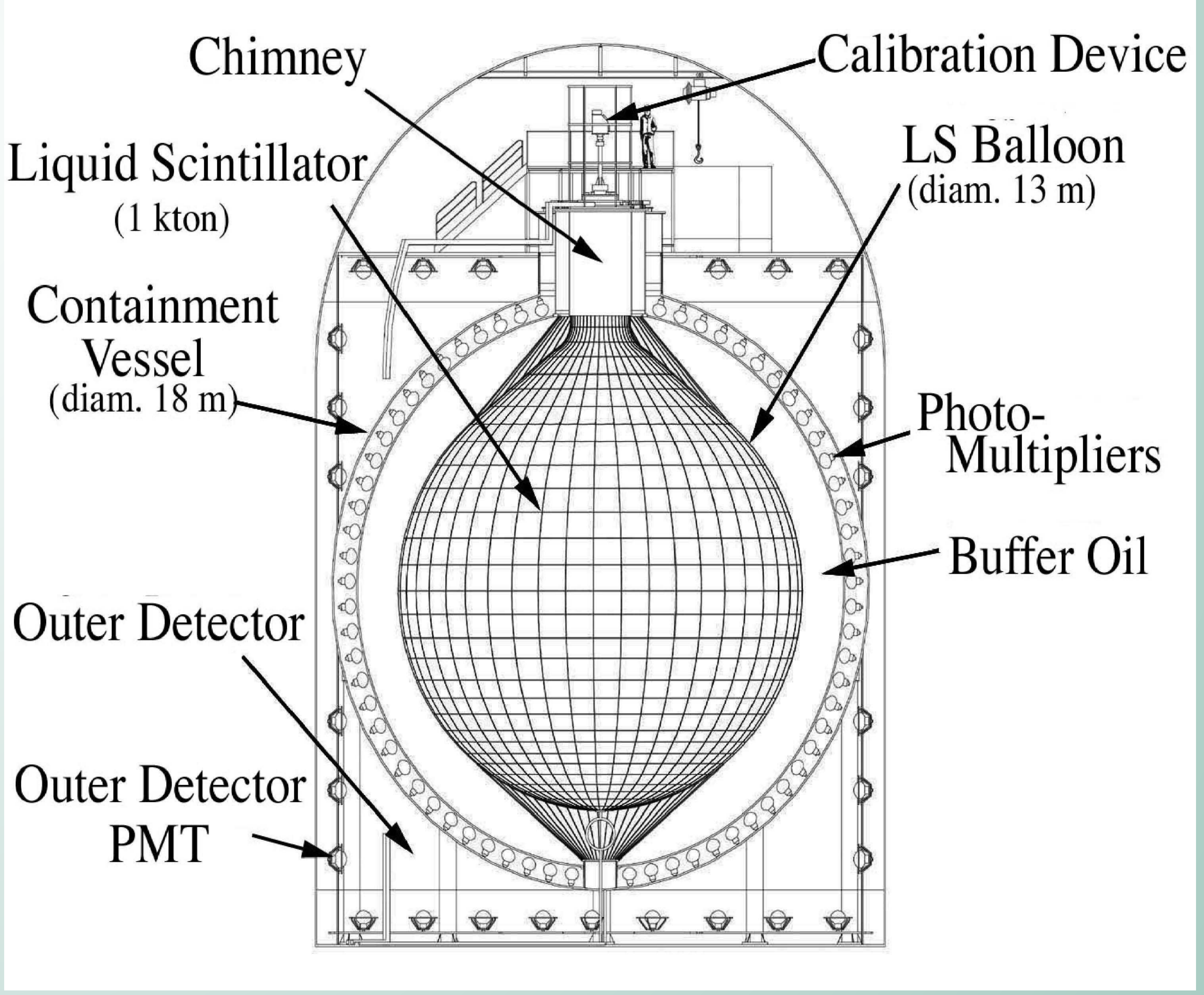
~ 200km from reactors

1 kton ultra pure liquid scintillator (80% dodecane, 20% pseudocume
Diphenyloxazole)

1900 PMTs

Muon veto and buffer shield

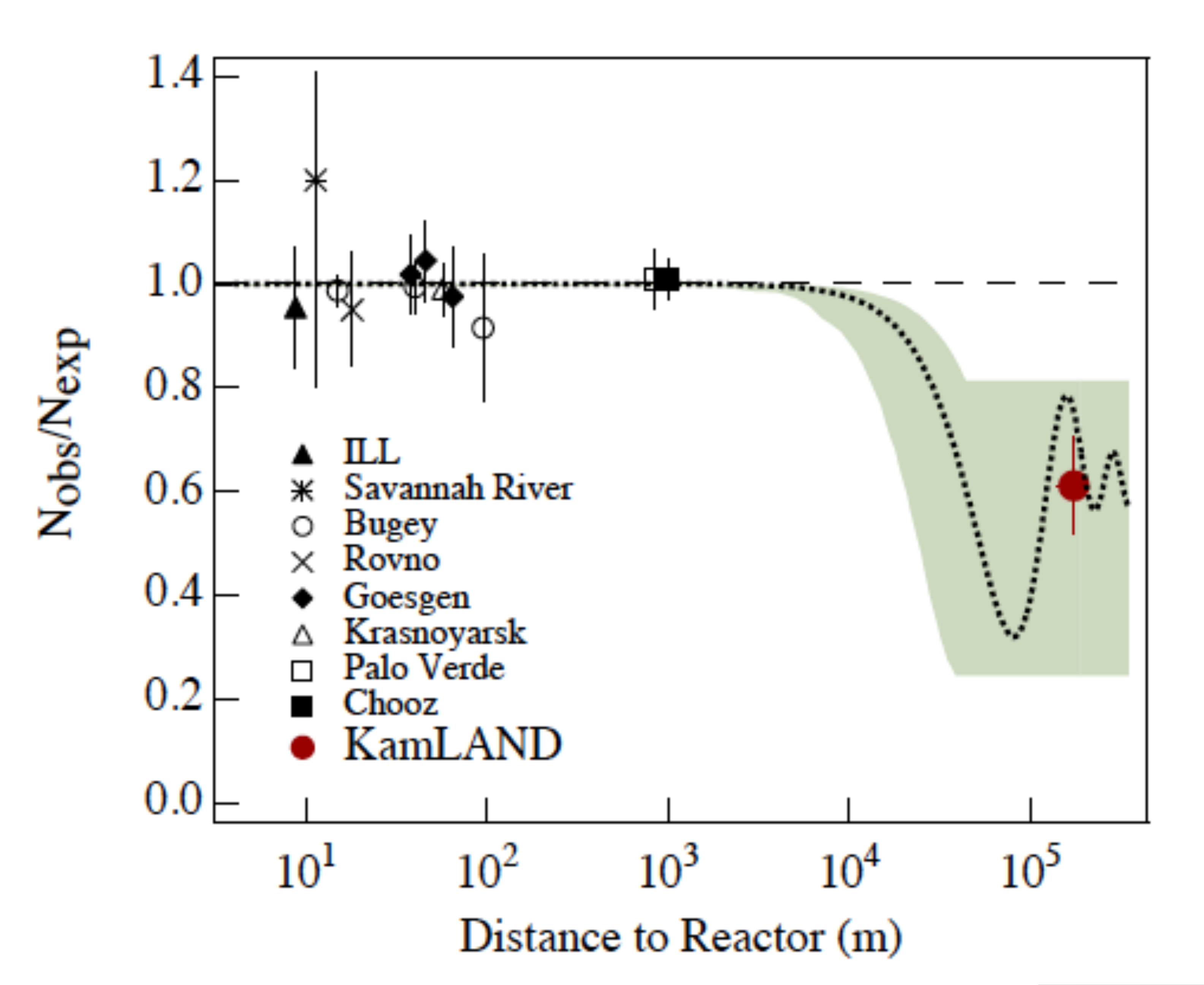
(add map)

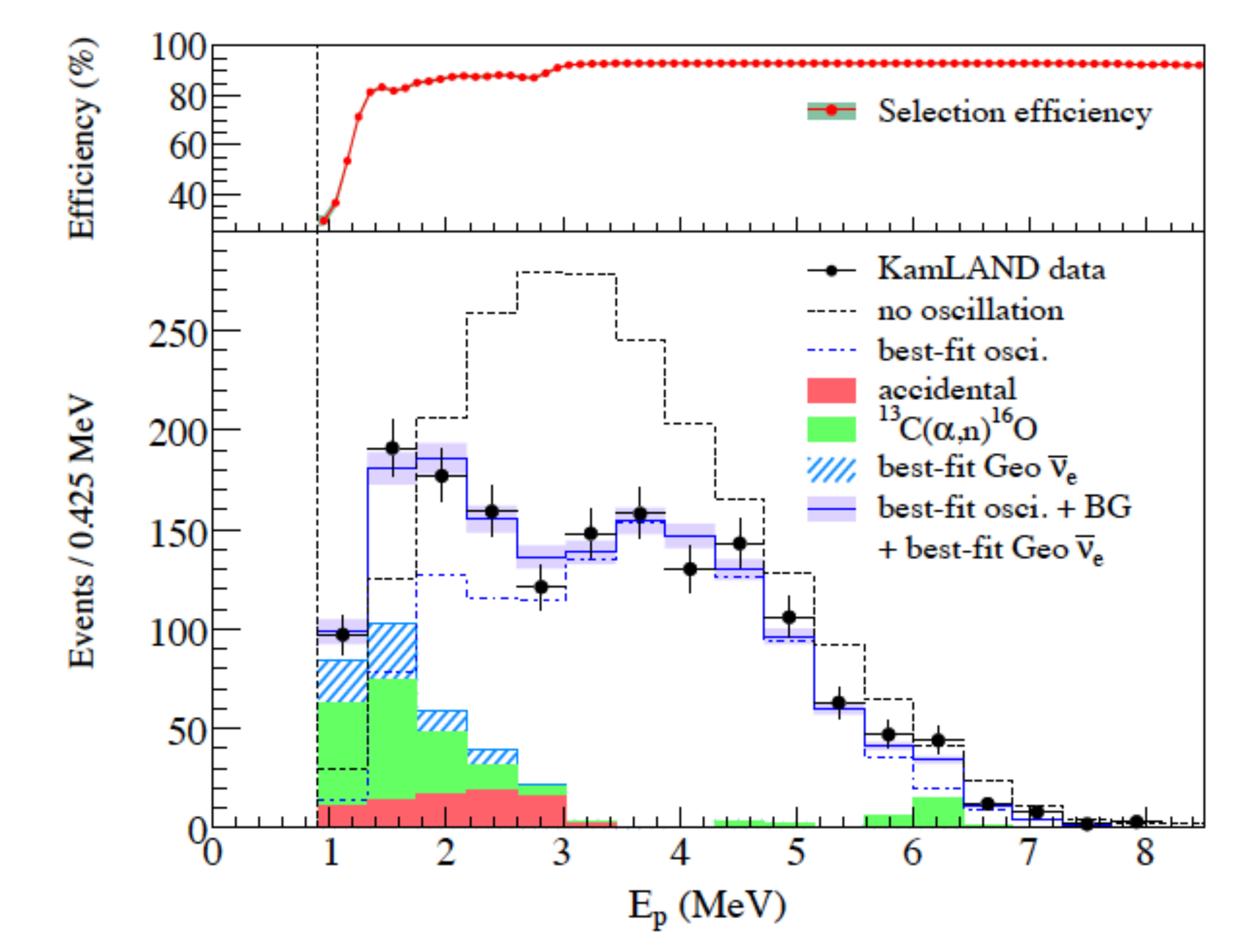


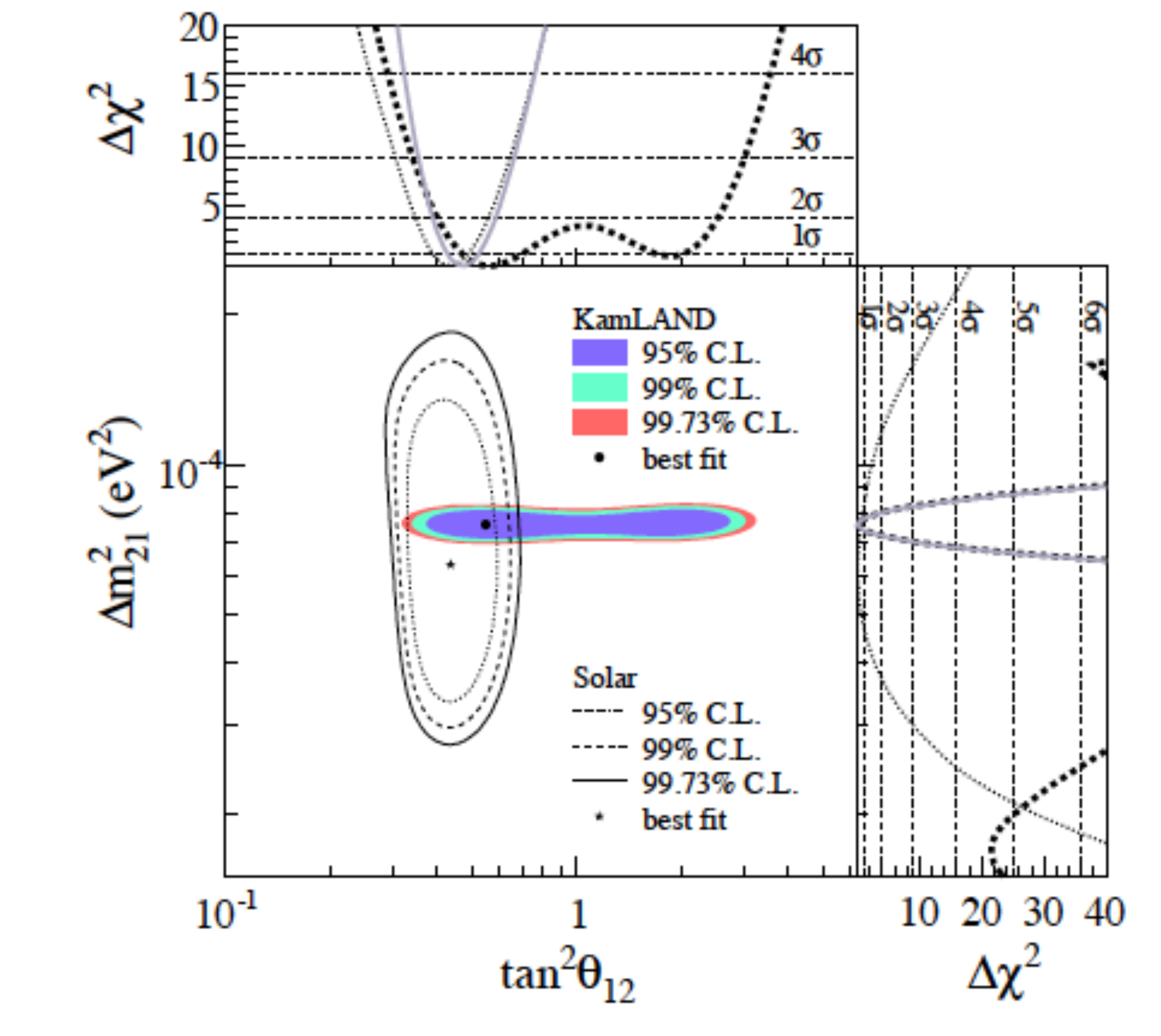
Main KamLAND Results

2002: First observation of ν_e disappearance at very long baselines

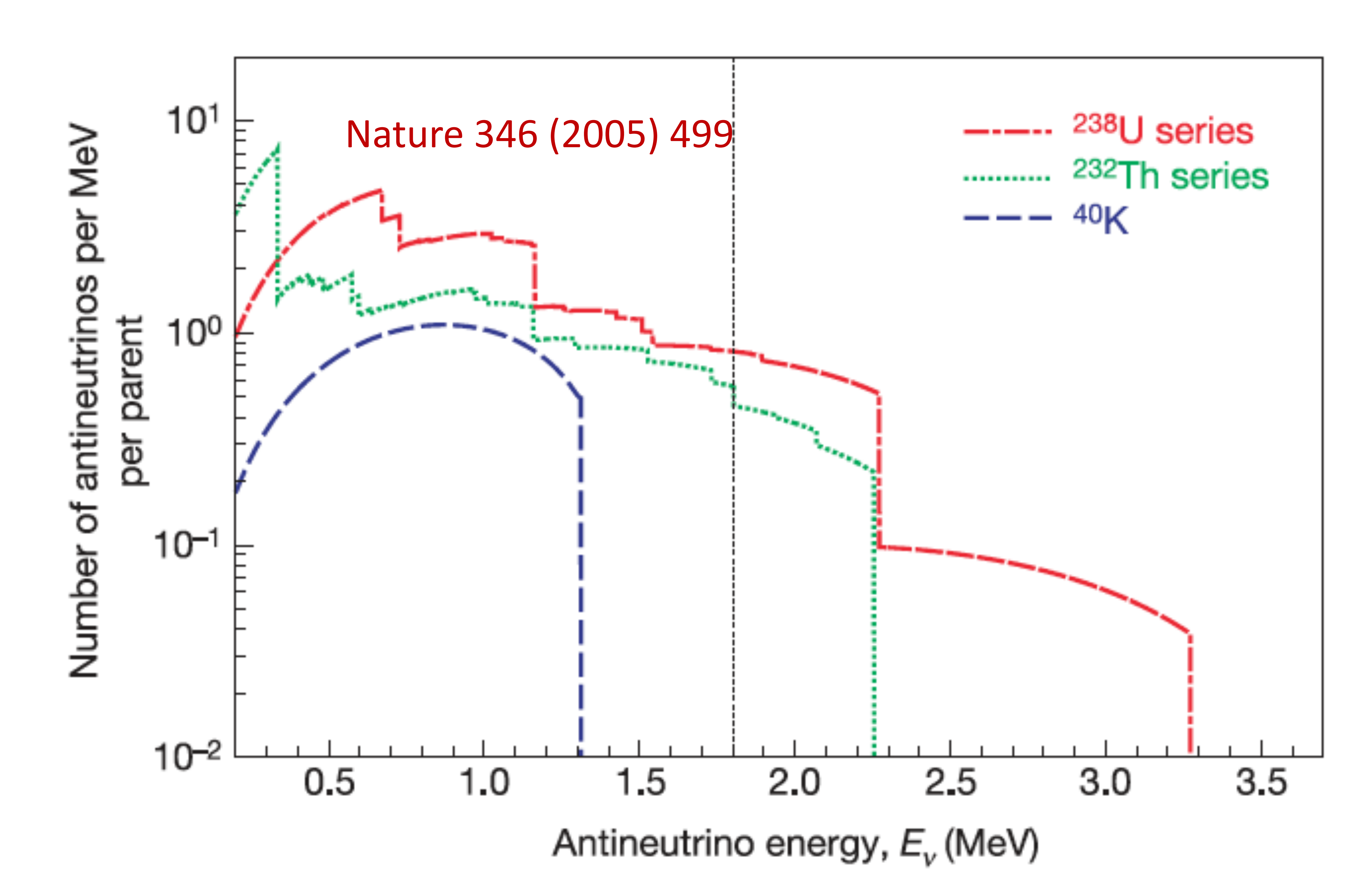
Precision measurements of mixing parameters consistent with solar experiments



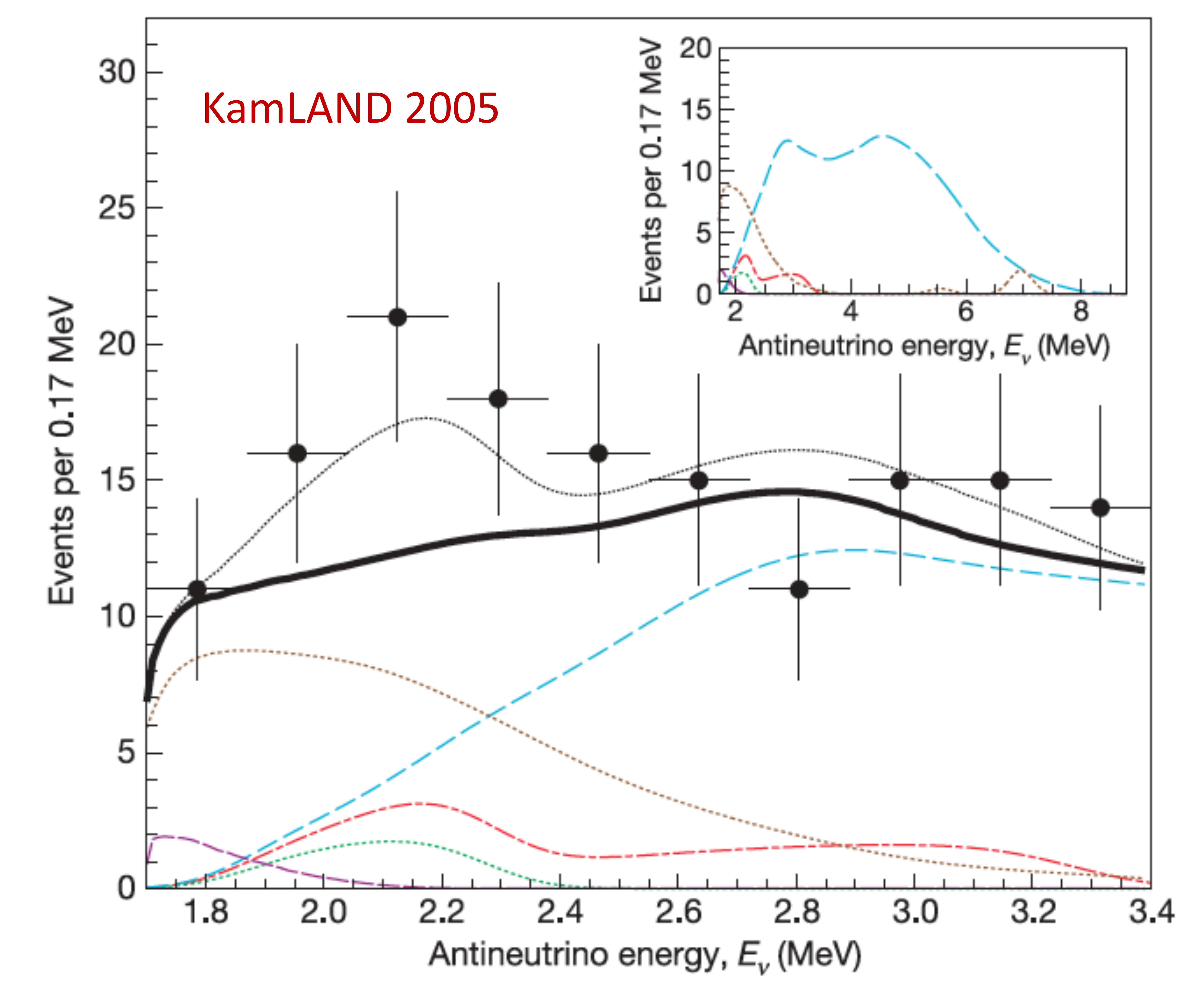




2005: Discover of Geoneutrinos



Geoneutrinos Initial Hints



Geoneutrino Discovery

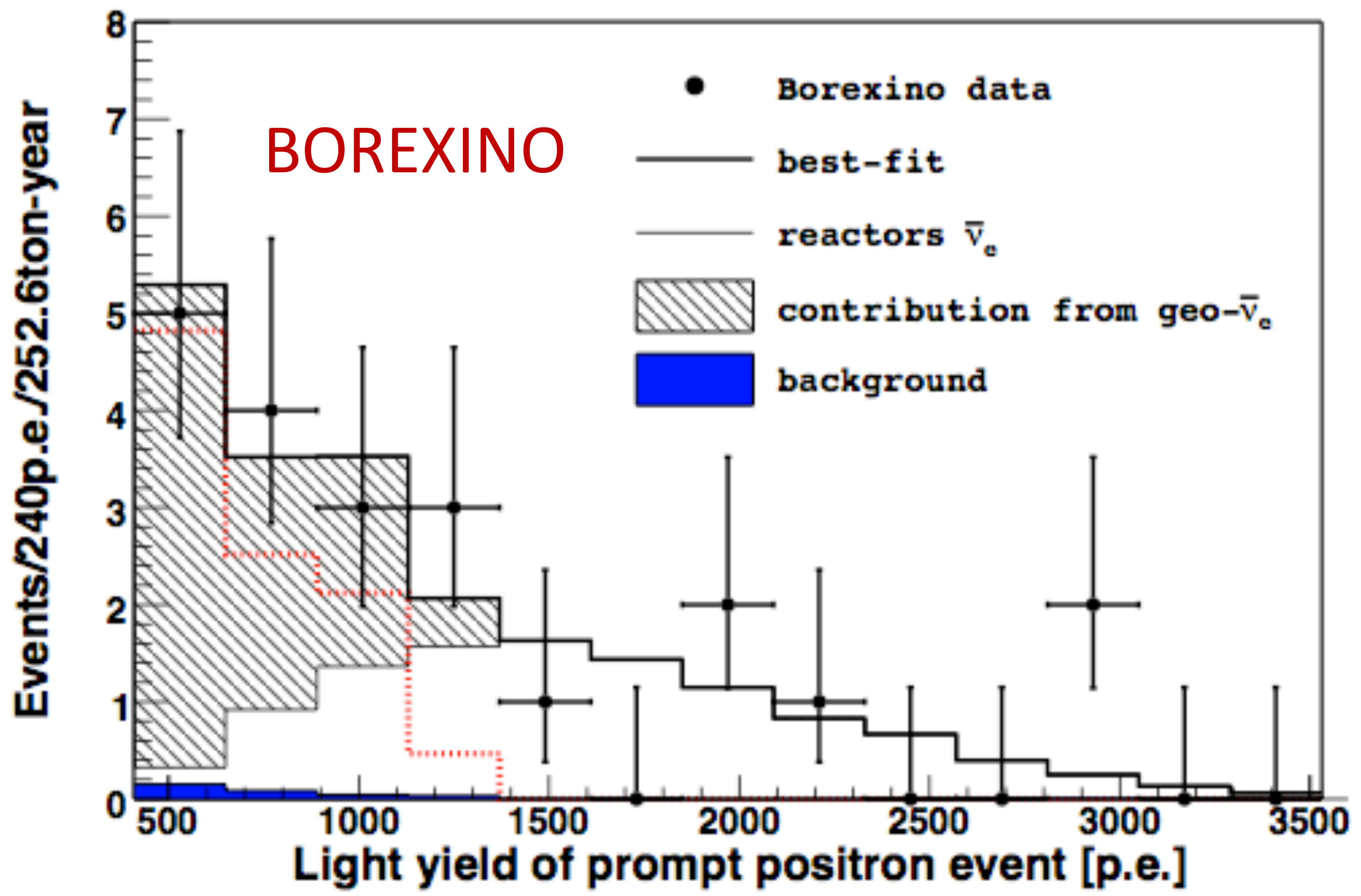


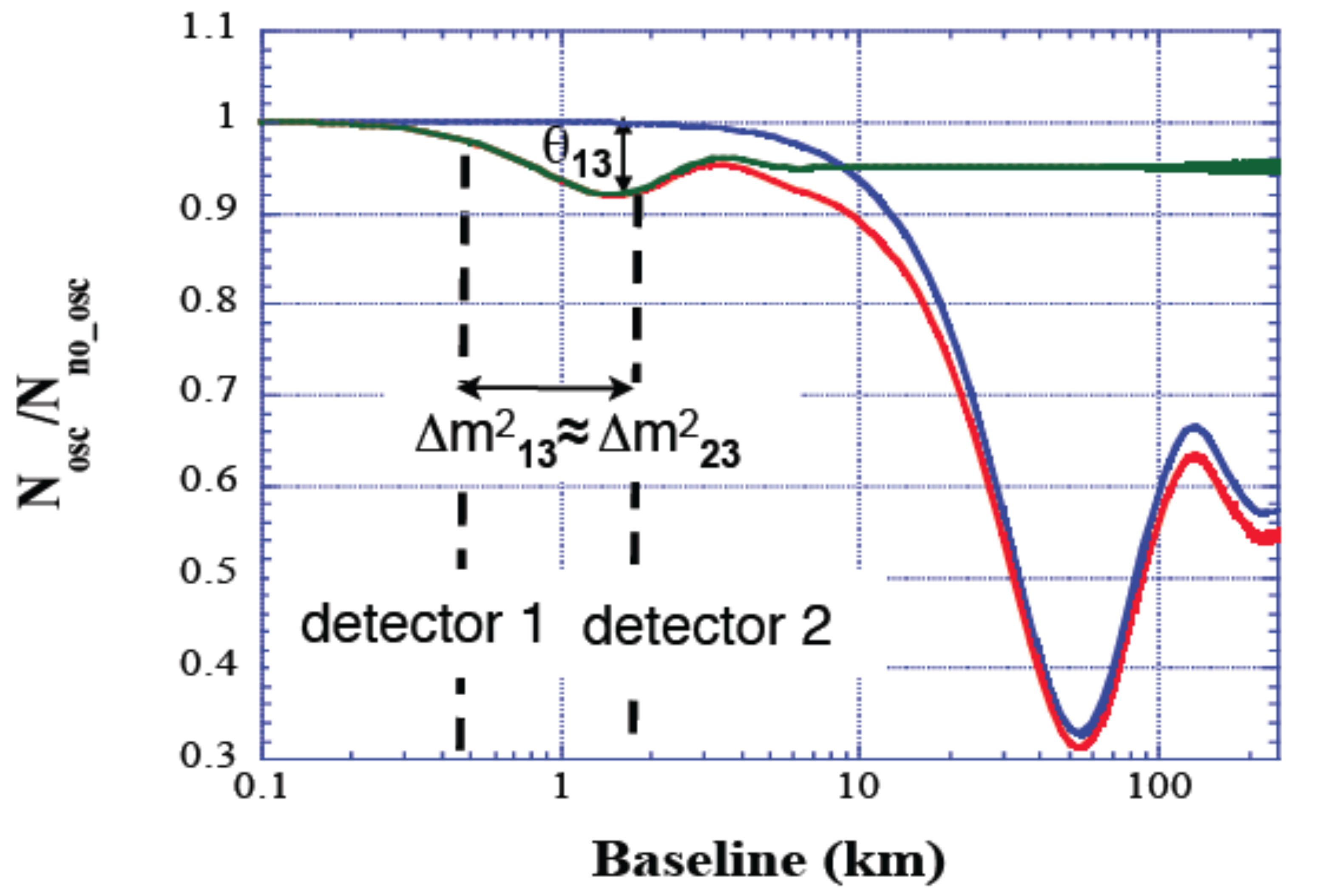
Figure 3: Light yield spectrum for the positron prompt events of the 21 $\bar{\nu}_e$ candidates and the best-fit with Eq. (5) (solid thick line). The horizonal axis shows the number of p.e. detected by the PMTs. The small filled area on the lower left part of the spectrum is the background. Thin solid line: reactor–$\bar{\nu}_e$ signal from the fit. Dotted line (red): geo–$\bar{\nu}_e$ signal resulting from the fit. The darker area isolates the contribution of the geo–$\bar{\nu}_e$ in the total signal. The conversion from p.e. to energy is approximately 500 p.e./MeV.

2012: First measurement of θ_{13}

- Non-zero θ_1

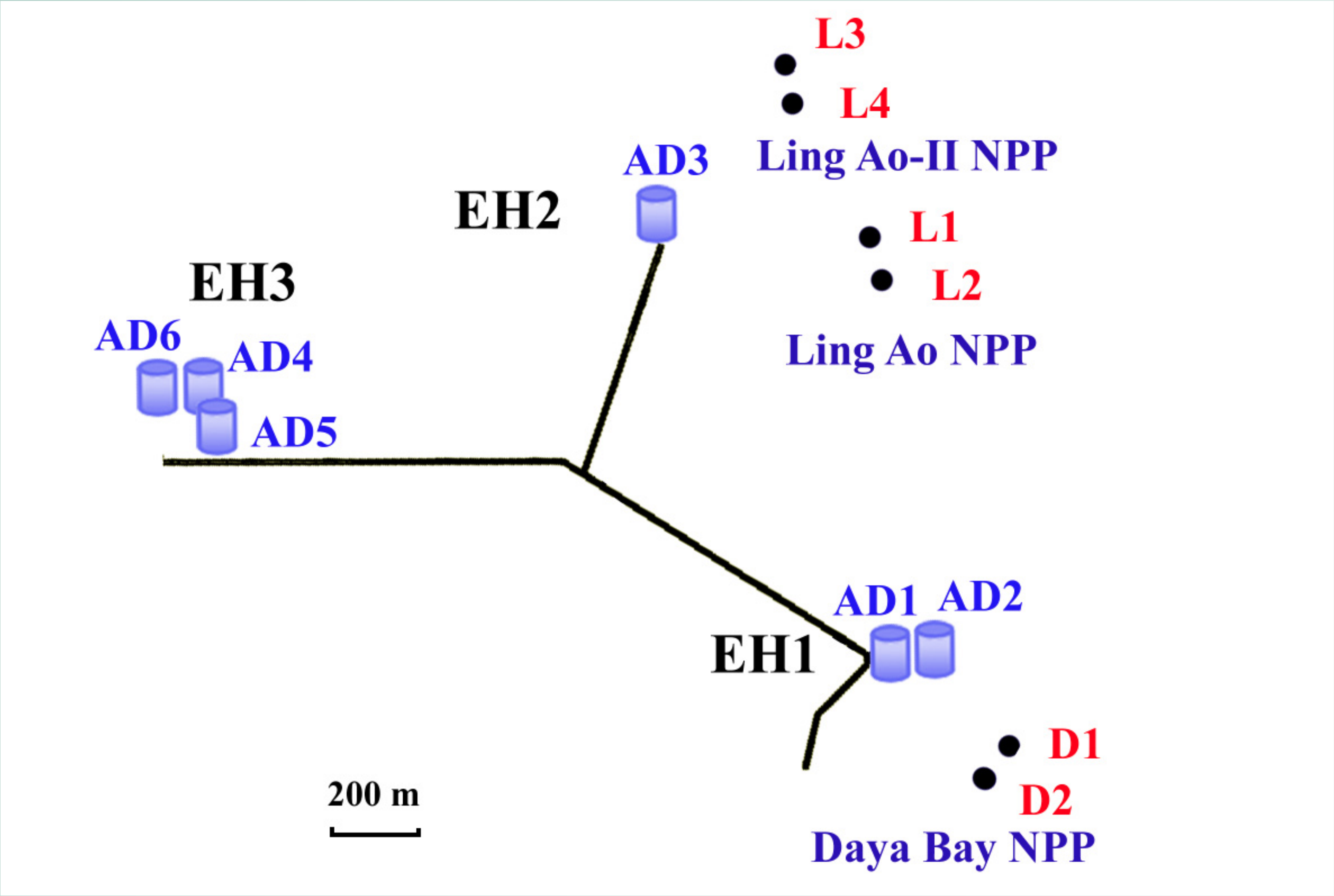
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

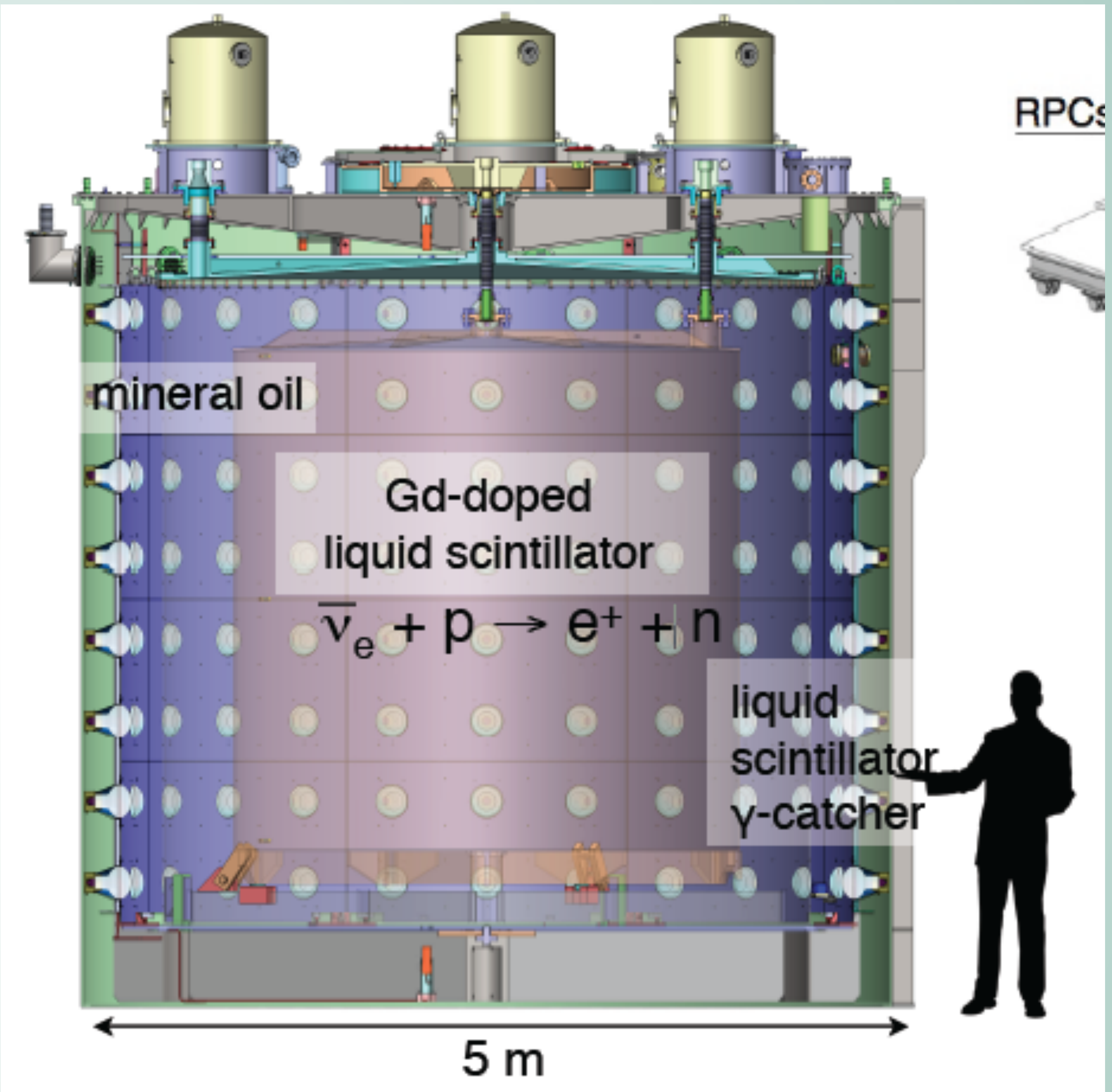
- Important c
- ~ 1km baseline
- Exquisite control of systematic errors to ~1%
- Two, identical detector concept:
  - Near detector monitors reactor output
  - Far detector (1 ~km) searches for ν_e disappearance
  - Cancels many systematics



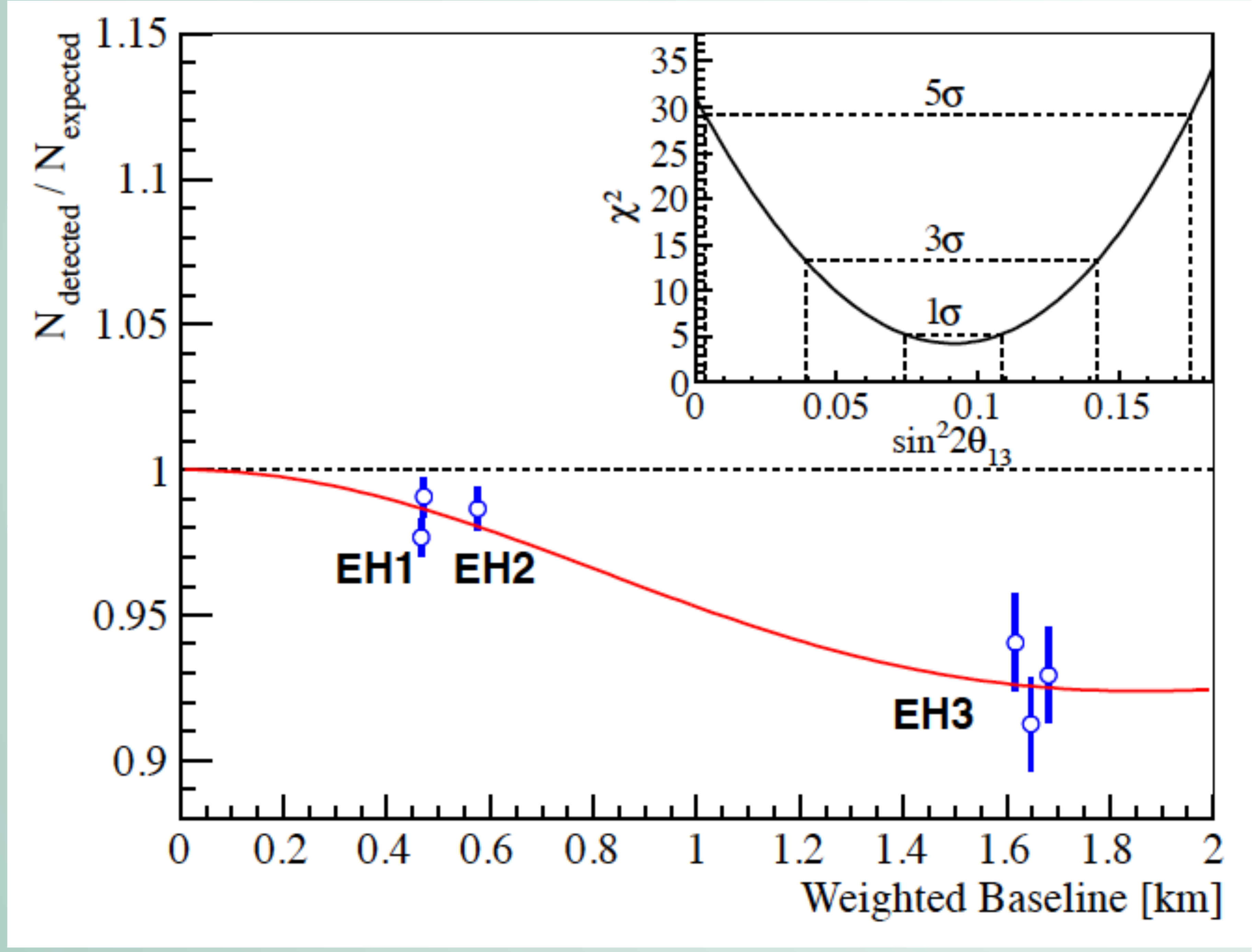
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4E}$$

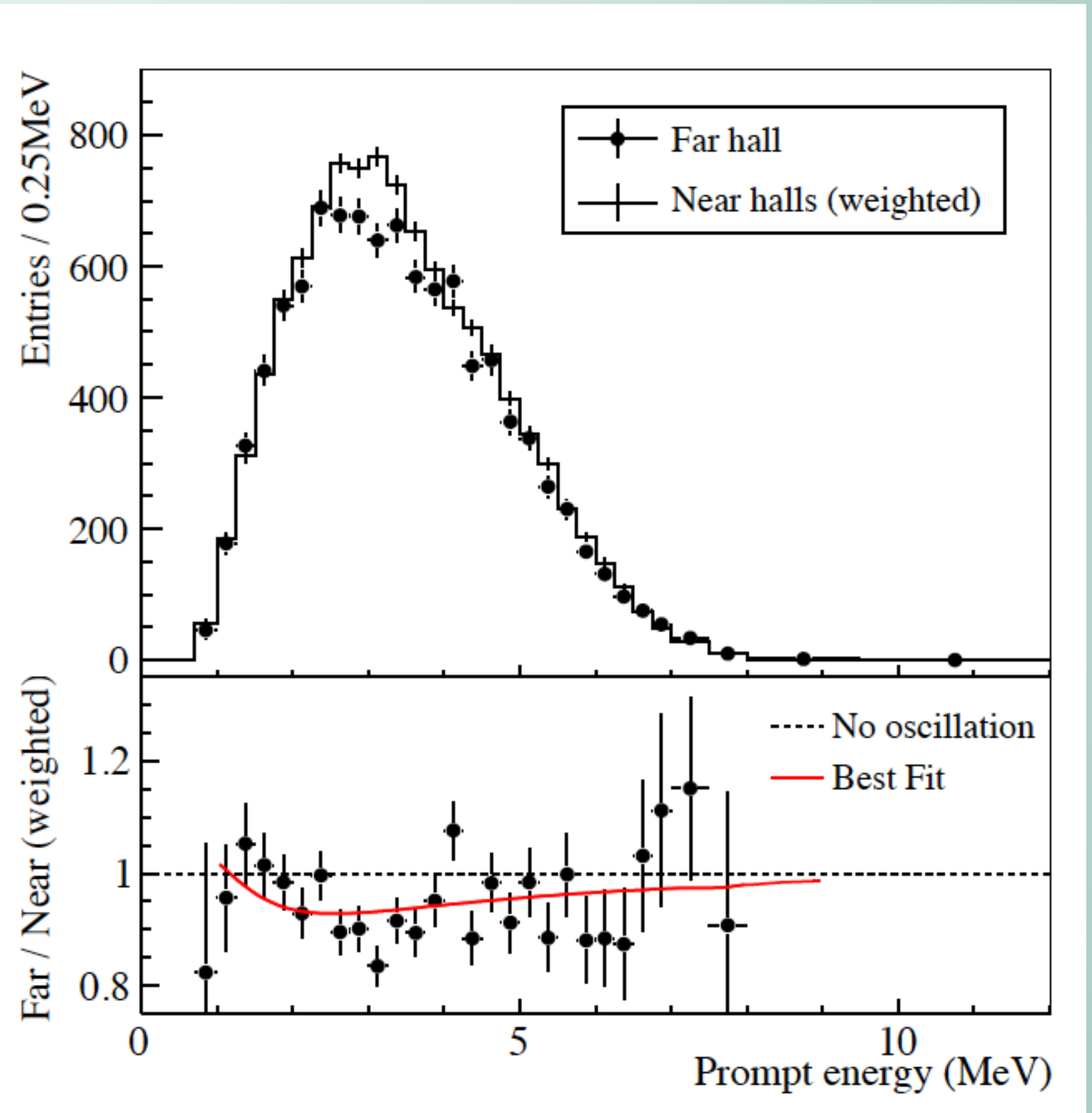
Three Experiments Realized :
Daya Bay





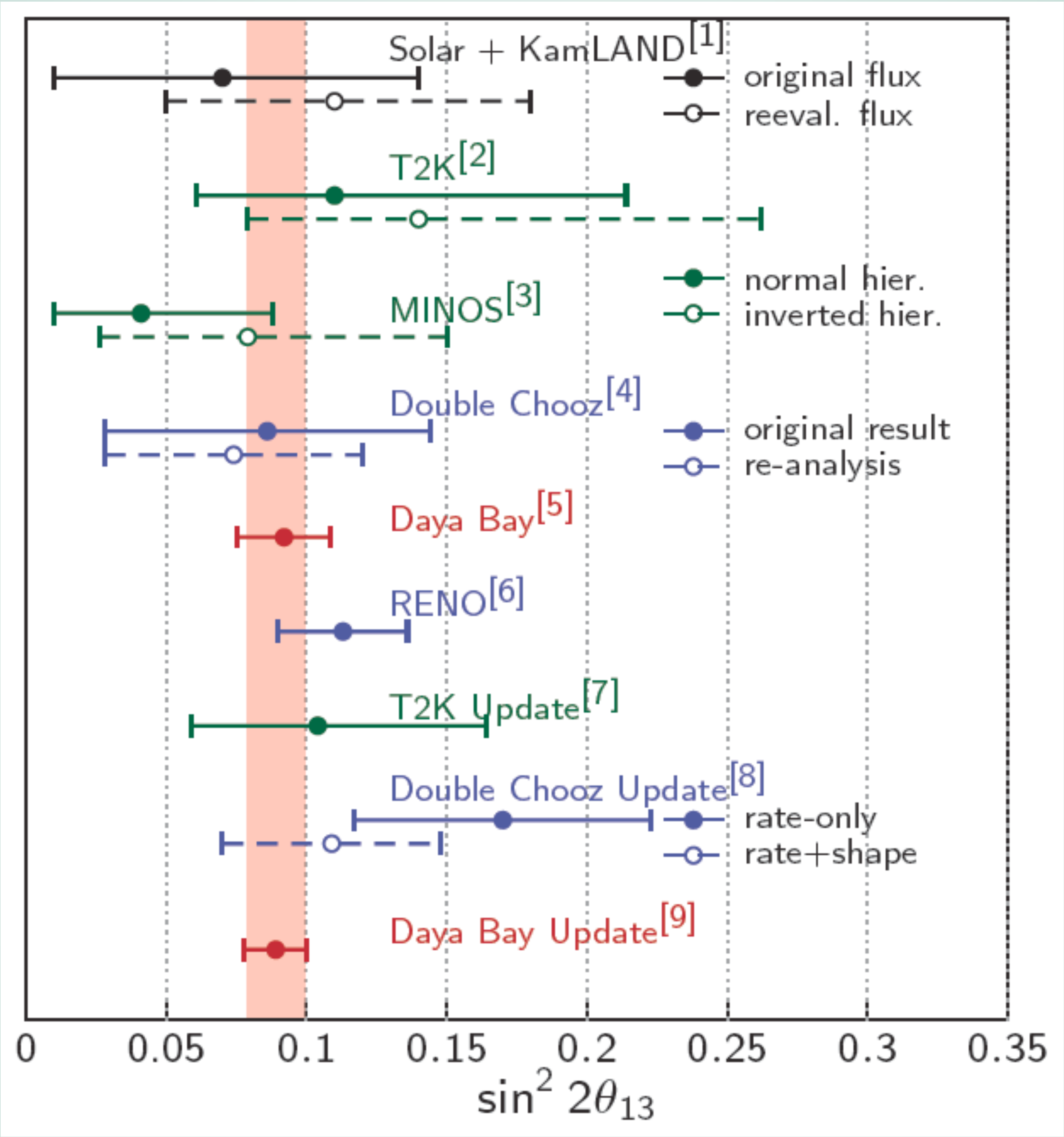
2012: Daya Bay does First measurement of θ_{13}





Pure rate. Shape measurement in progress

RENO, Double CHOOZ, and others follow.



Principle

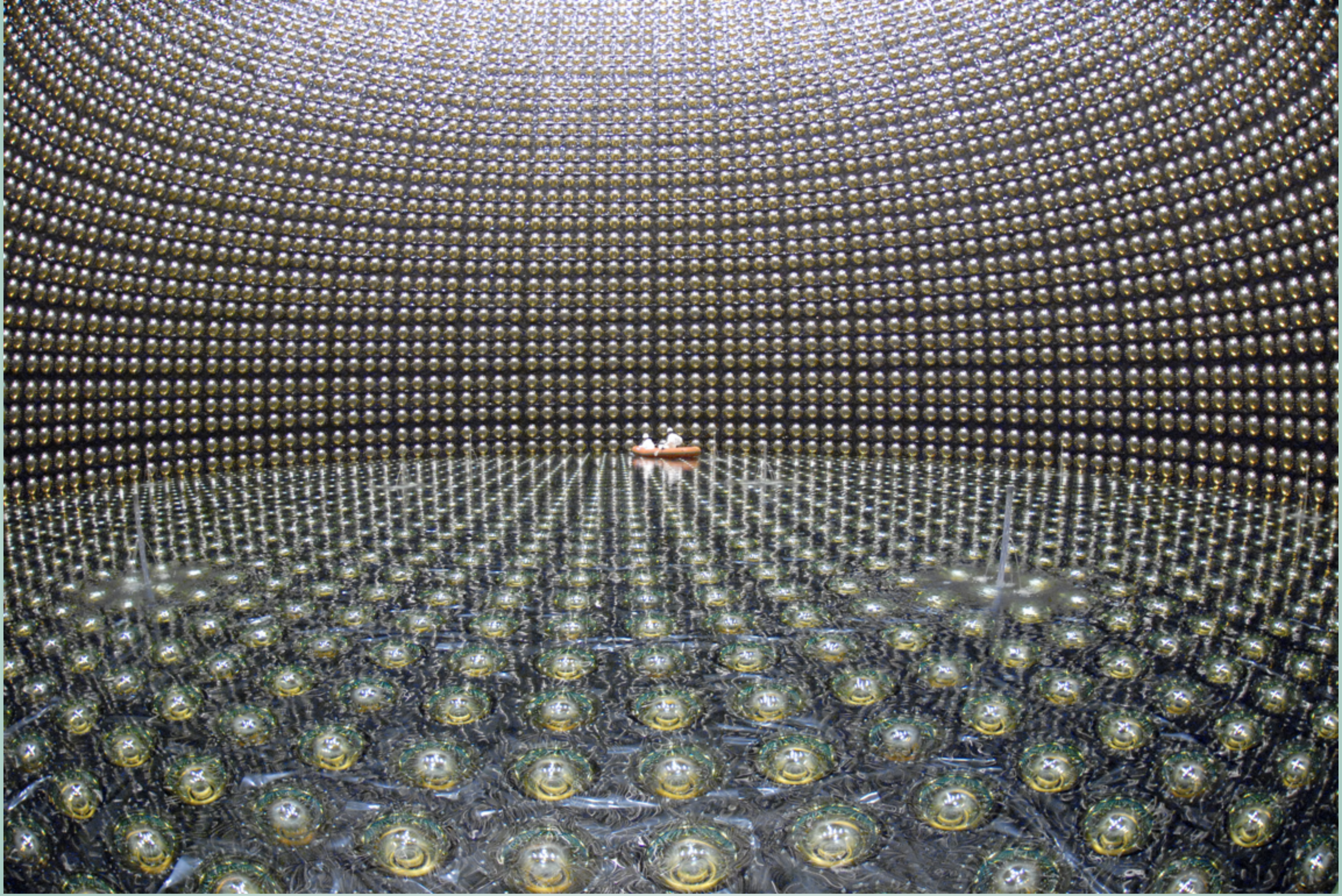
- Nuclei that decay via beta, positron or EC also emit neutrinos
- Can use these isotopes as neutrinos sources
- Beta and positron emitters not practical HMW: **Why?**
- Solution: Use Electron-Capture isotopes

  $^{51}Cr \rightarrow {}^{51}V + \nu_e$

  Still have to shield inner-Brehmstrahlung

Source Manufacture

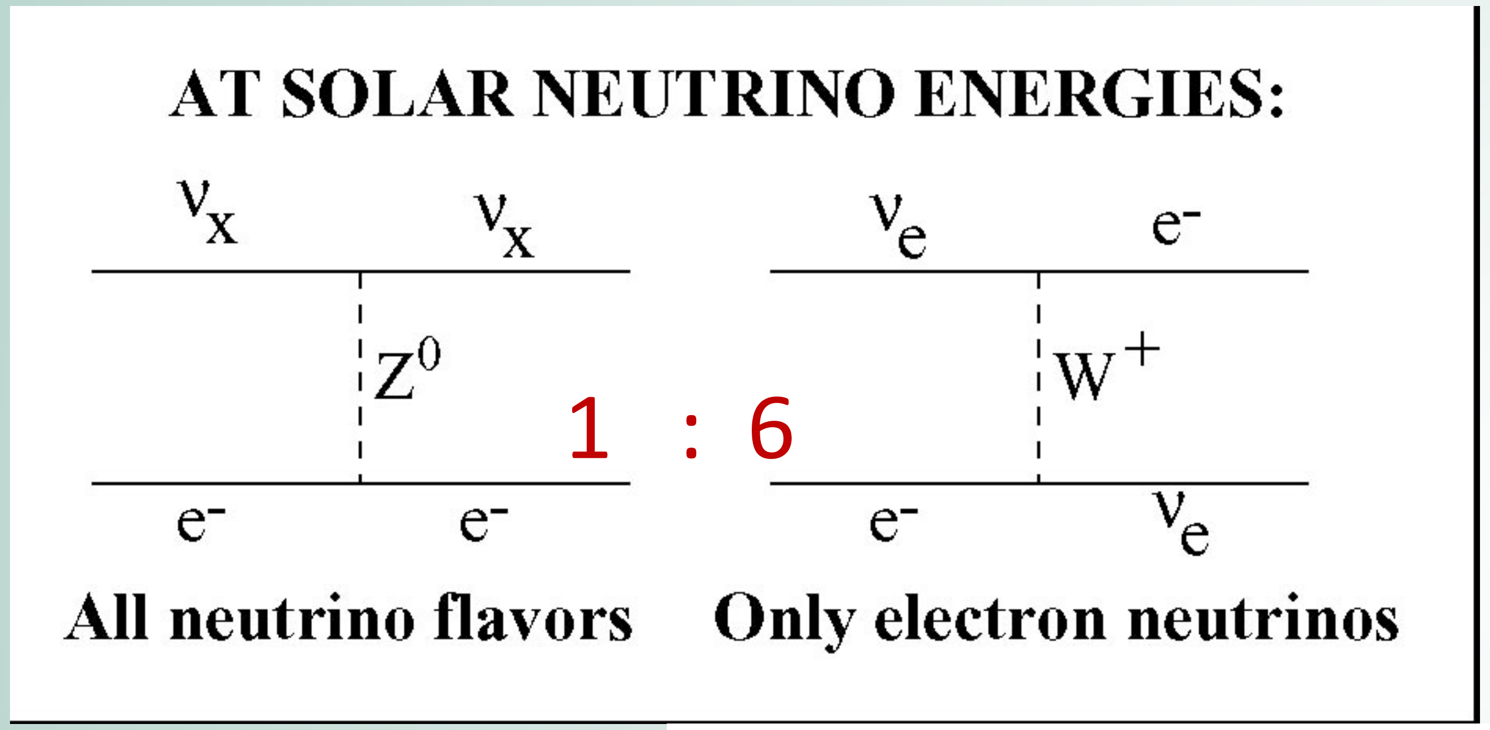
- Enriched, ultrapure ^{50}Cr exposed to fast neutron flux in reactor core: Siloe, Grenoble, BN-350 fast neutron reactor in Aktua, Kazakhstan
  - ^{50}Cr purity essential to avoid activation of high-energy gamma-emitting isotopes.
- Reactor Requirements:
  - High fast neutron flux
  - Large and reconfigurable core – safety issues.
  - Short cycle
  - Power reactors not suitable



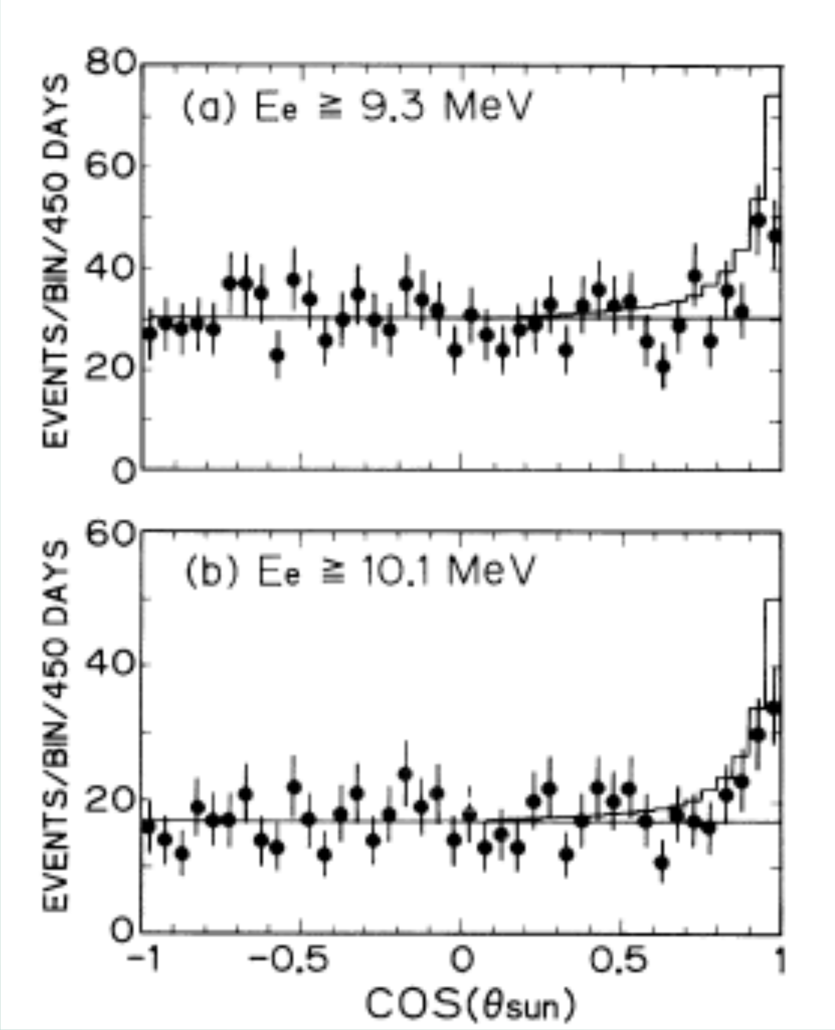
Kamiokande-II and Super-K

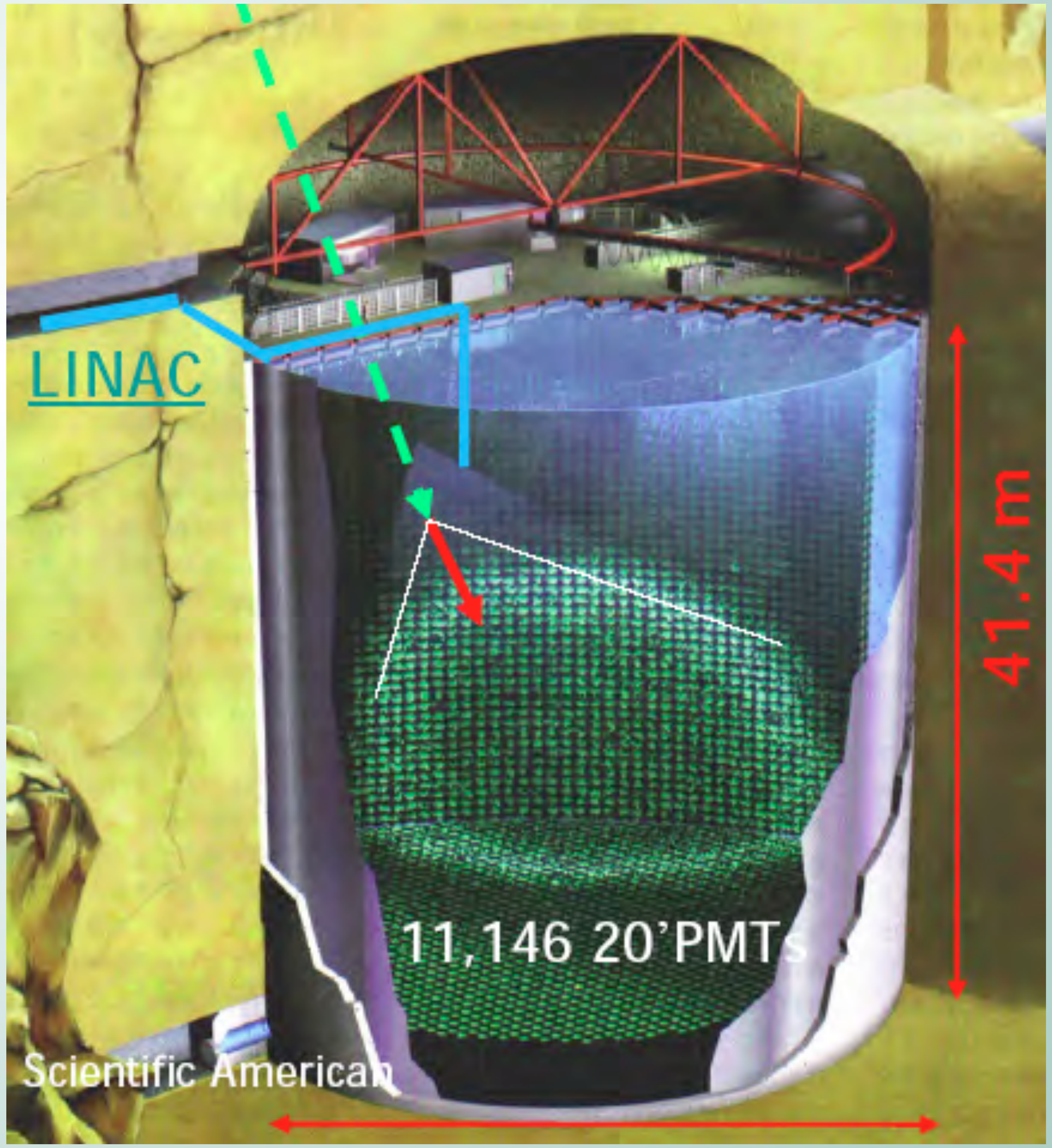
Detect High Energy ^8B neutrinos via neutrino electron elastic scattering:

$$\nu_X + e^- \rightarrow \nu_X + e^-$$

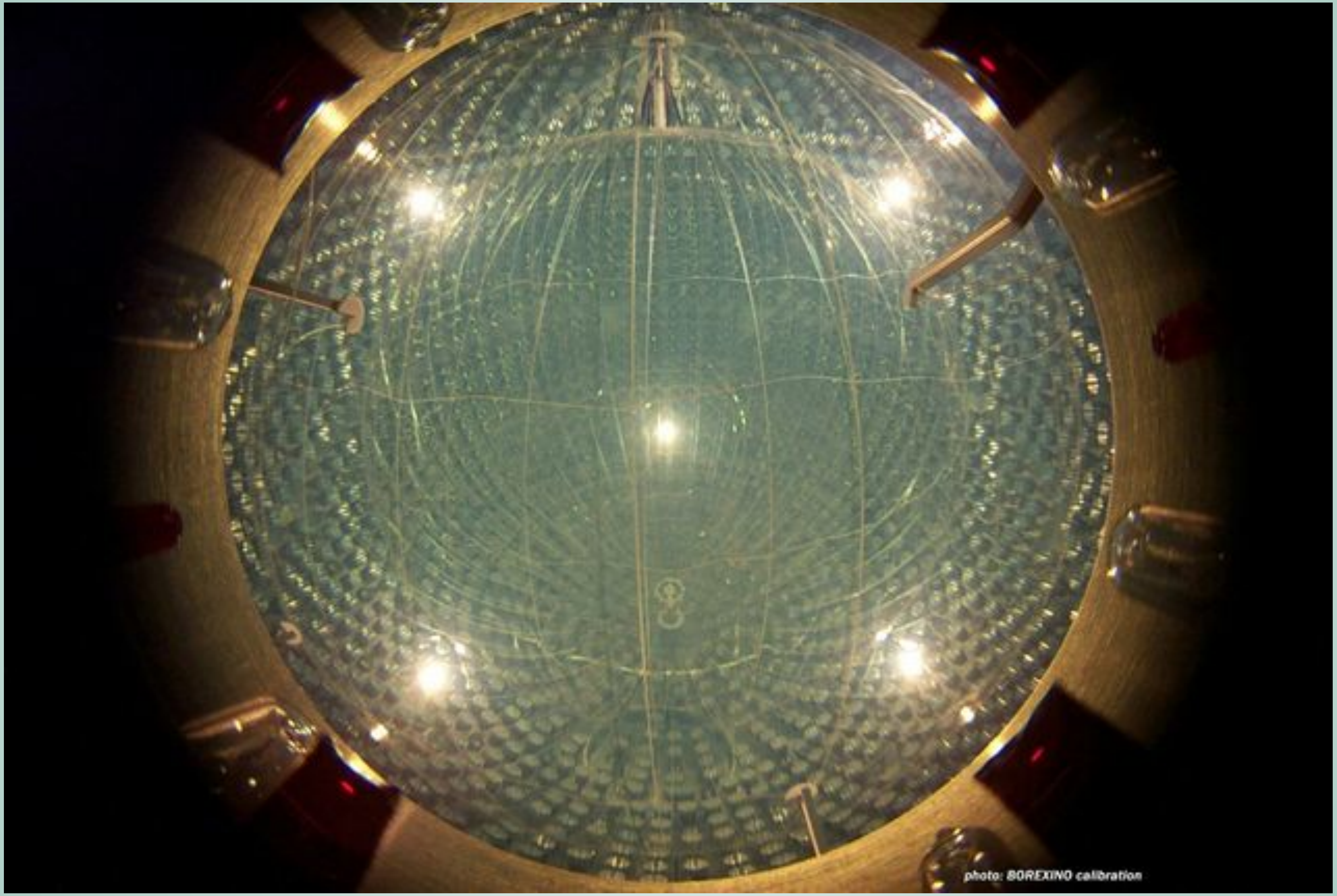


1989: K-II shows Neutrinos are from sun!

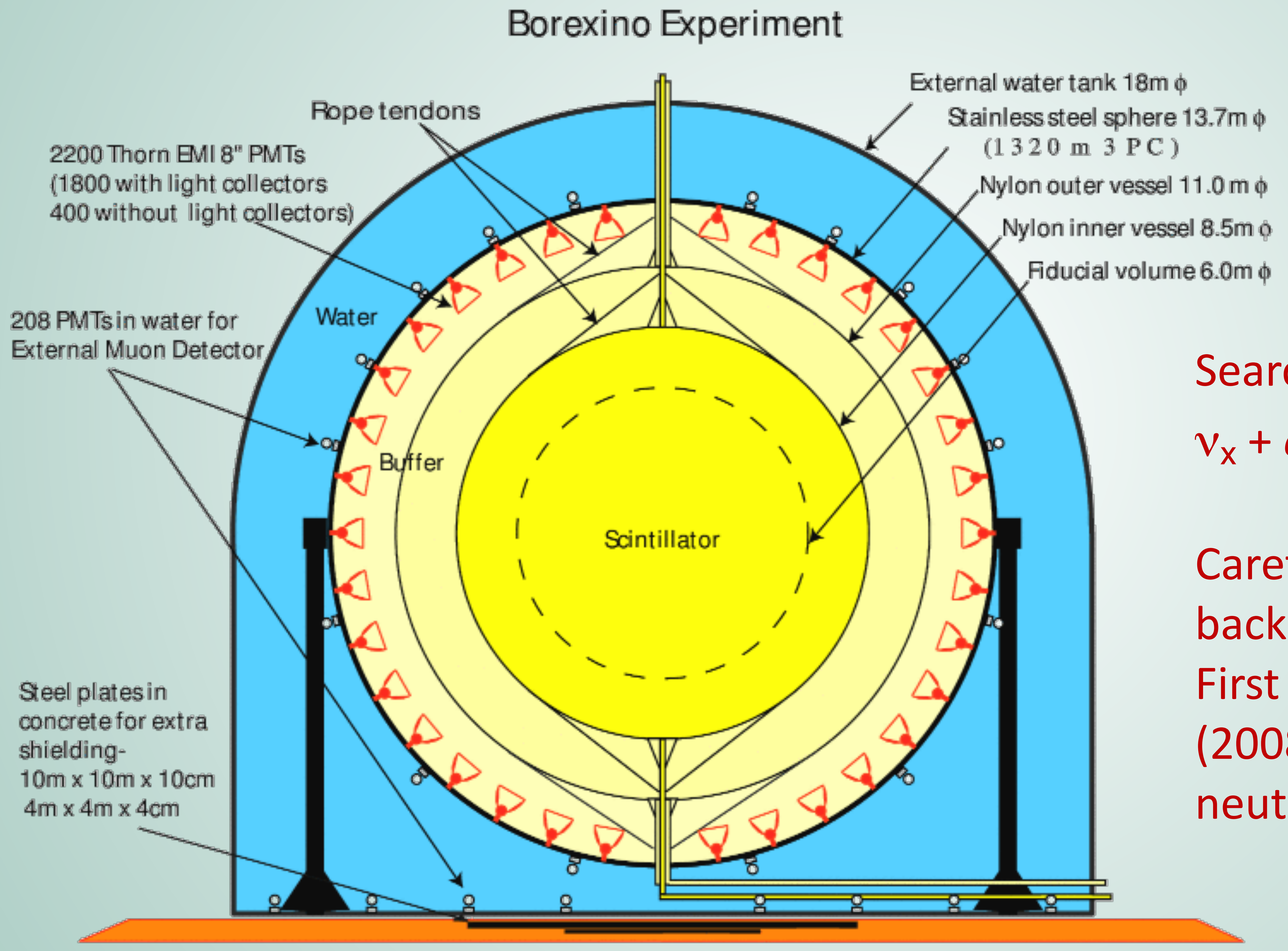




BOREXINO



BOREXINO

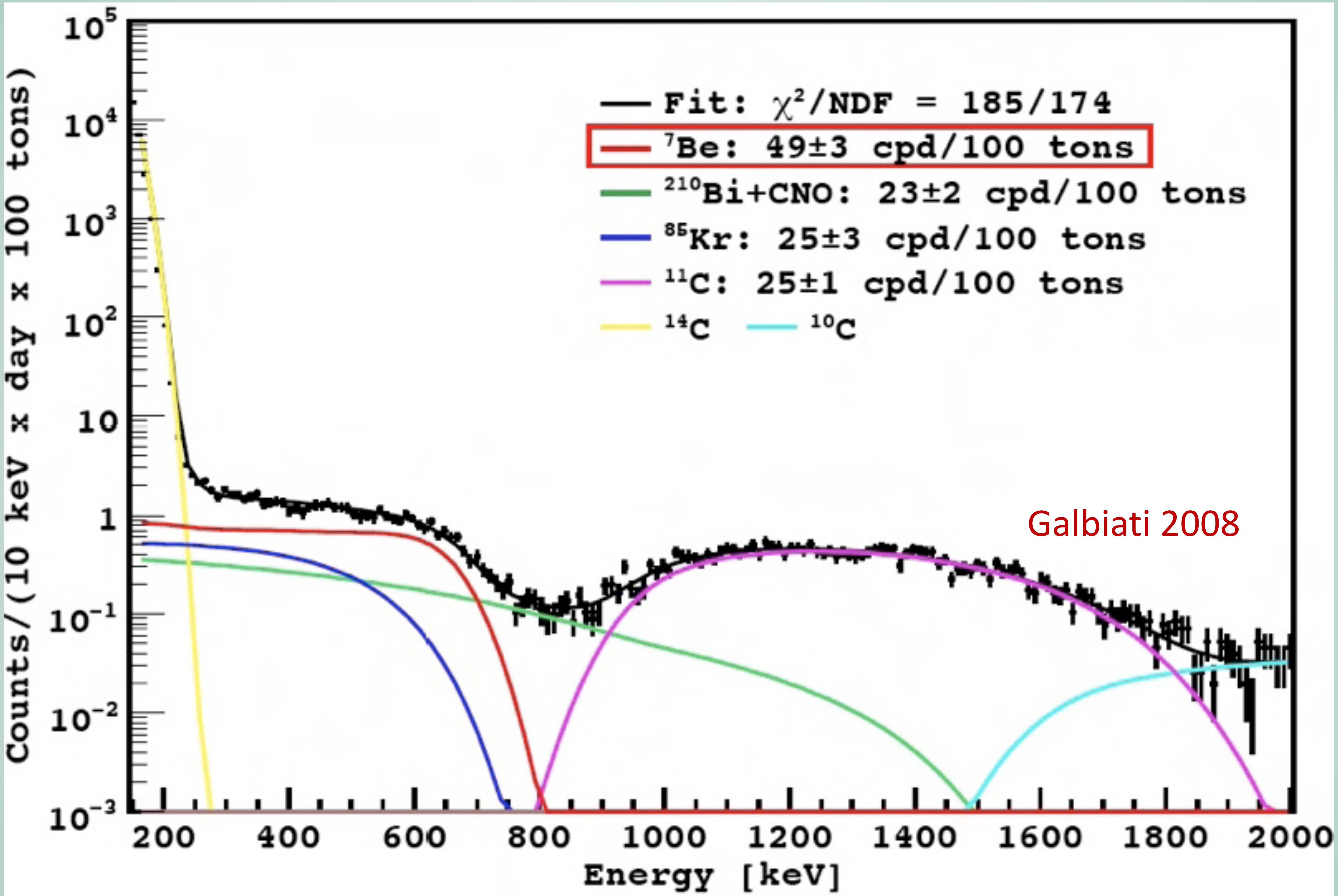


Search for ^{7}Be neutrinos via

$\nu_x + e^- \rightarrow \nu_x + e^-$

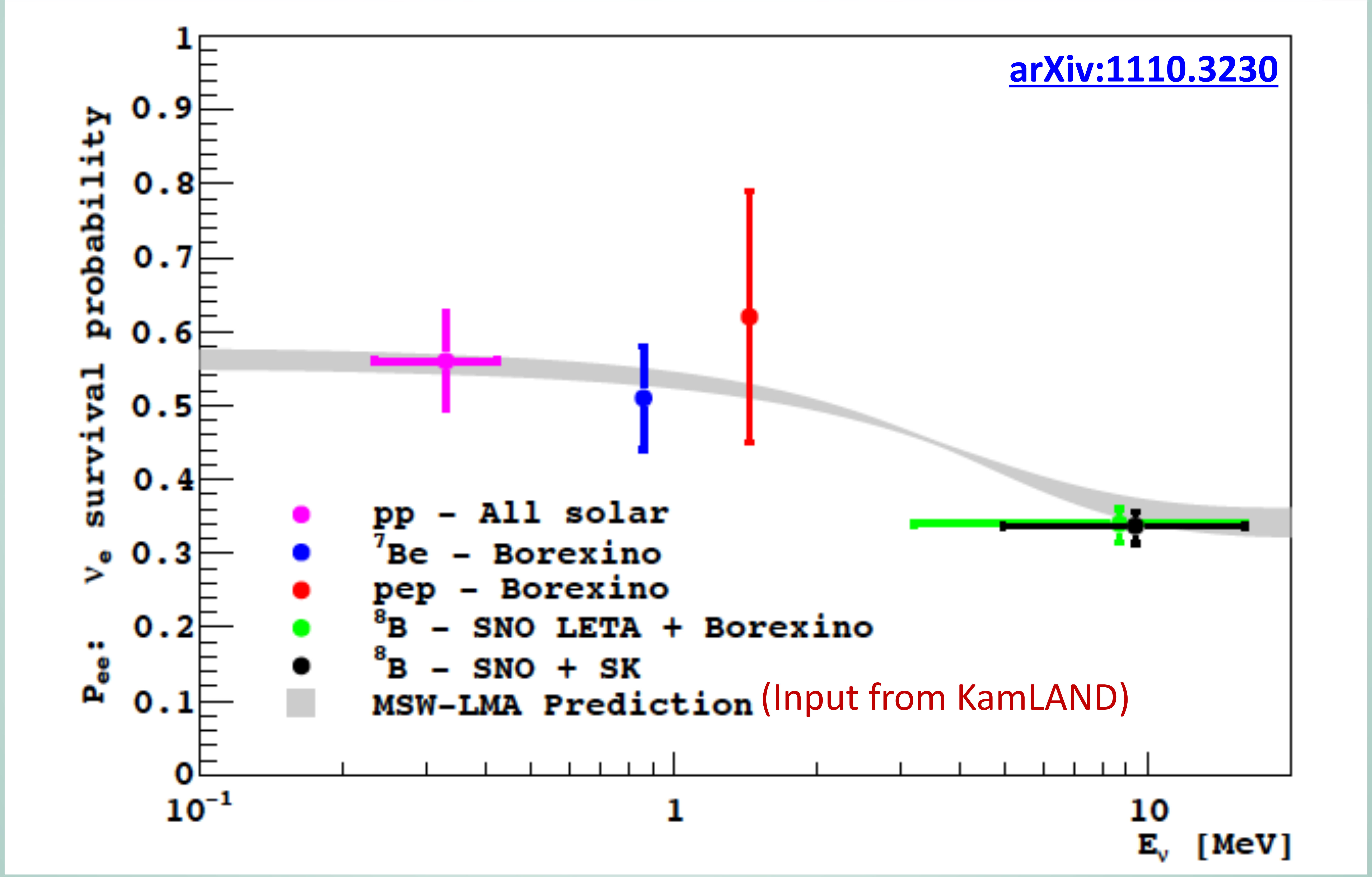
Careful control of backgrounds

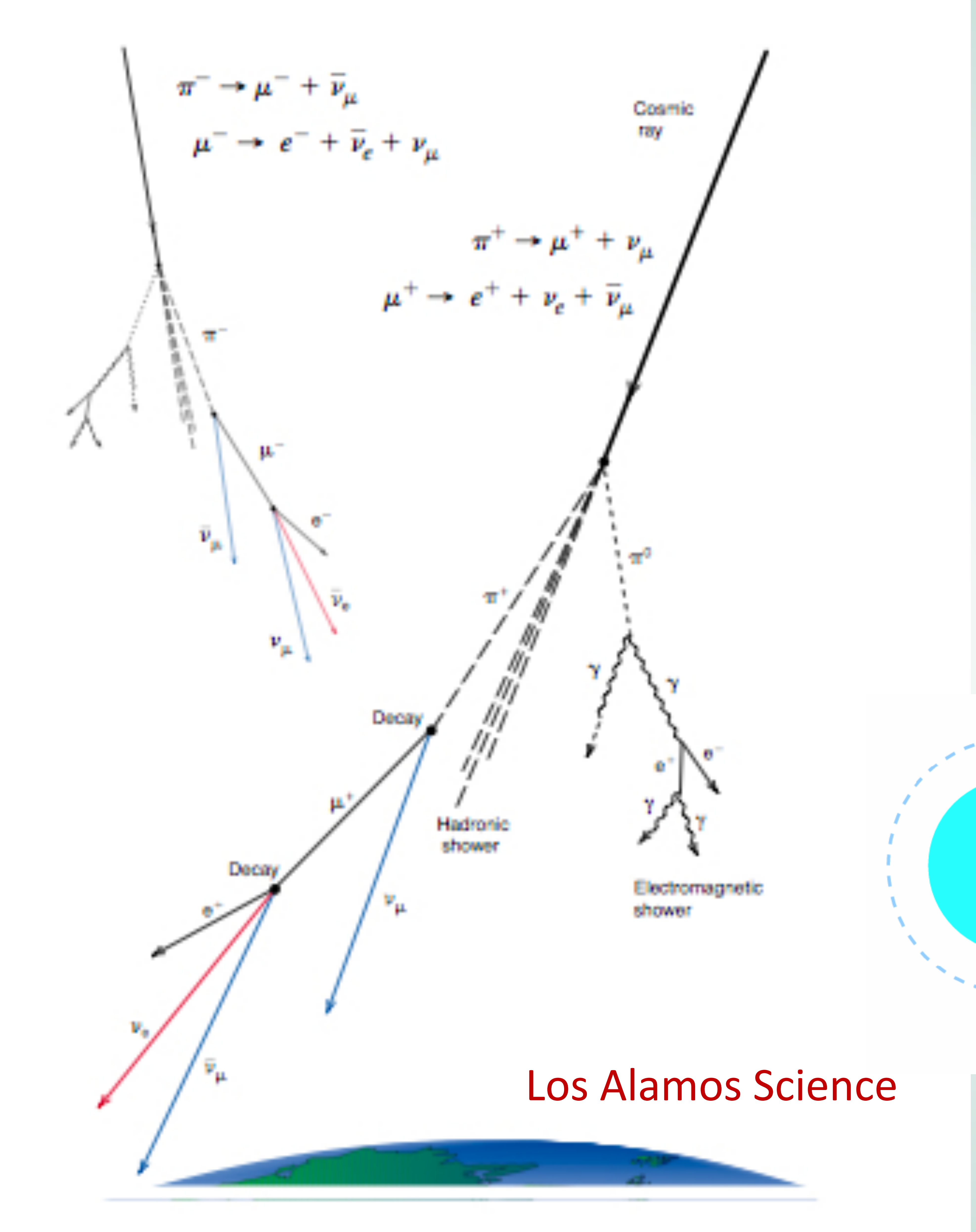
First measurements of ^{7}Be (2008) and pep (2011) neutrinos



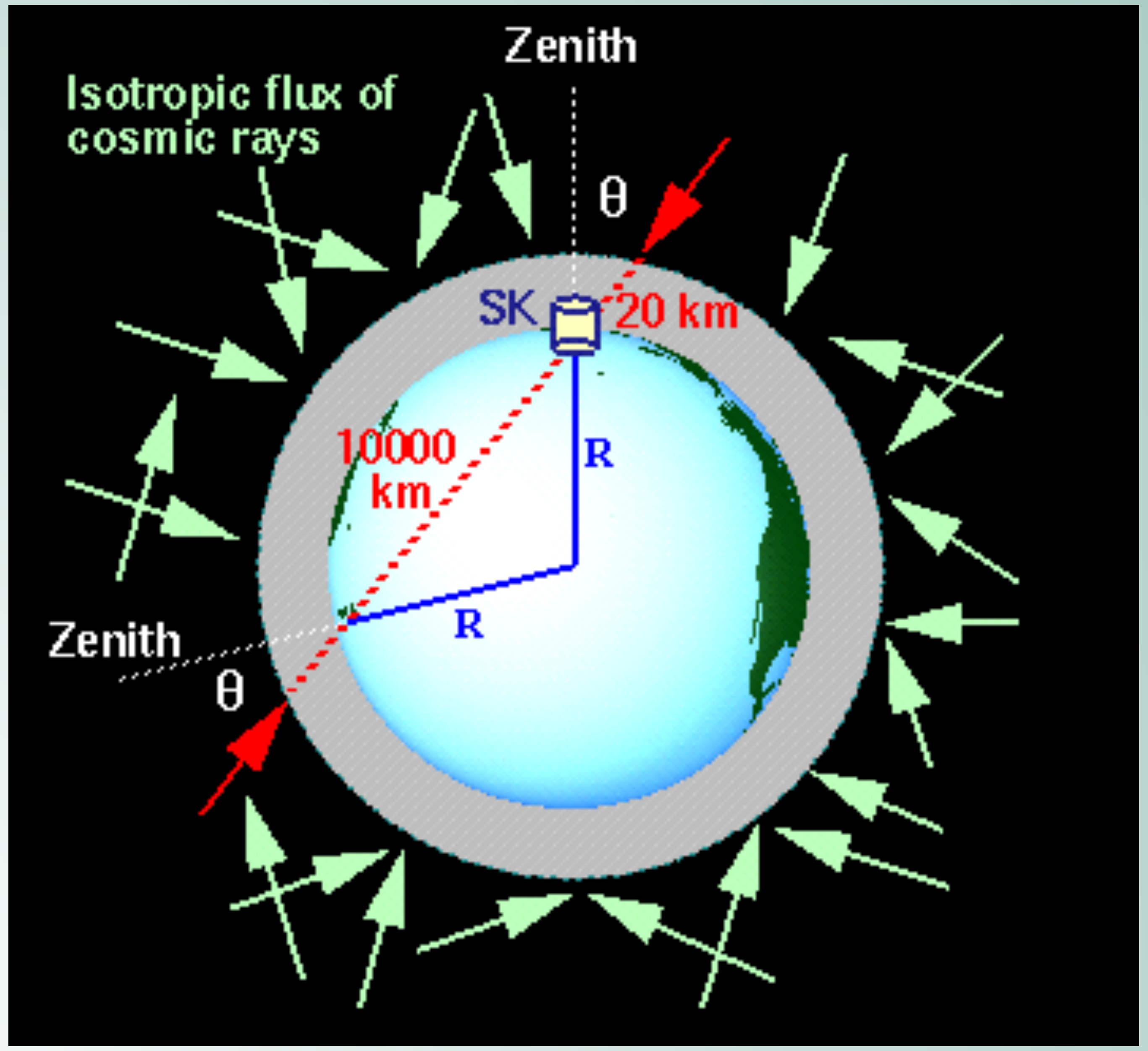
Galbiati 2008

Solar neutrinos combined

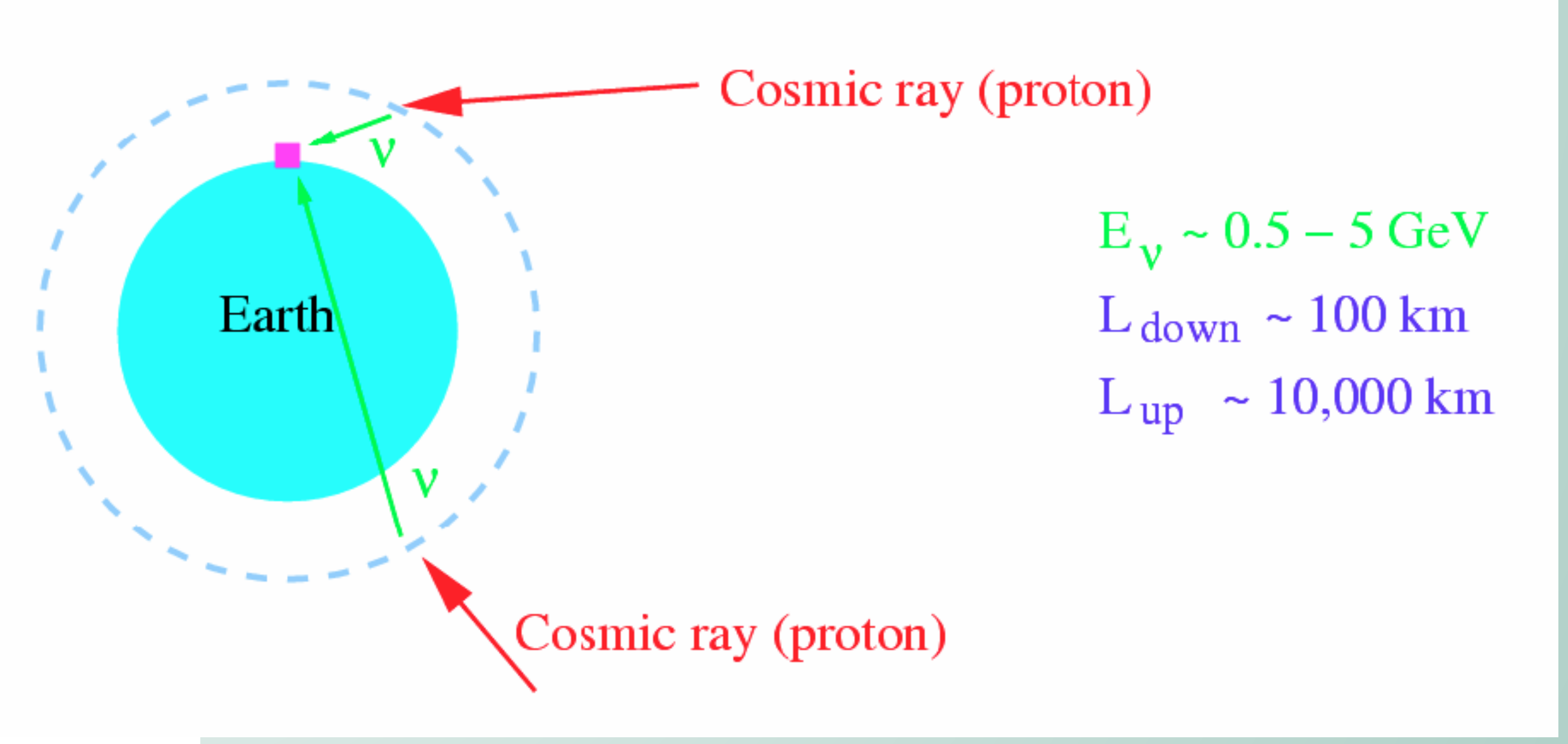




Los Alamos Science



http://hep.bu.edu/~superk/atmnu/

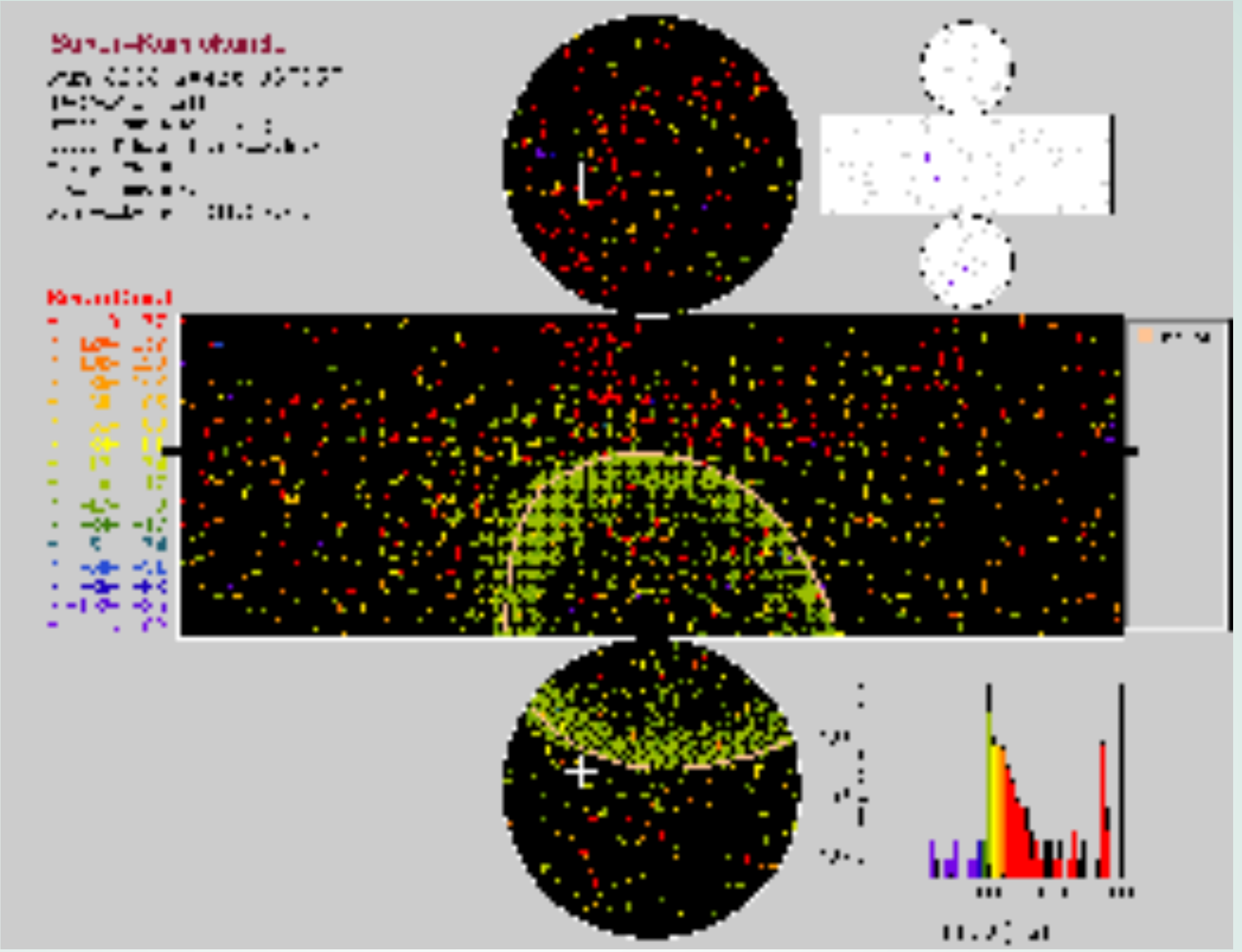


Except:

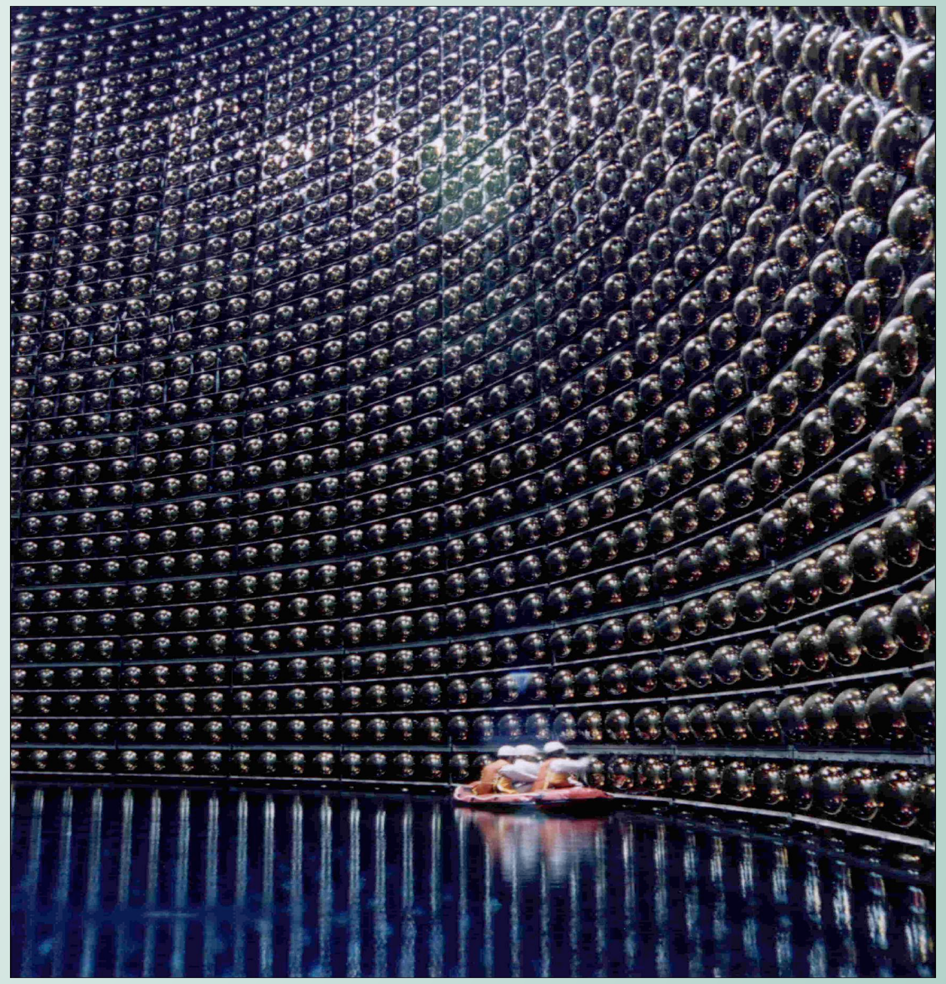
Isotropic Flux of ν_μ

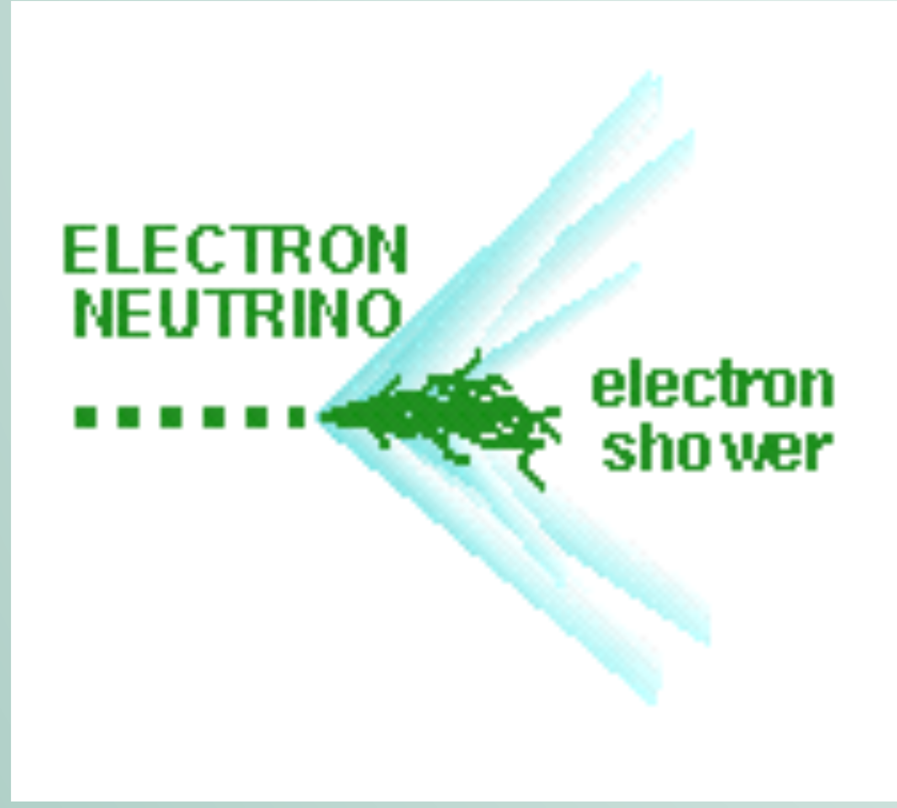
$\Phi(\nu_\mu) \tilde{=} \Phi(\nu_e)$

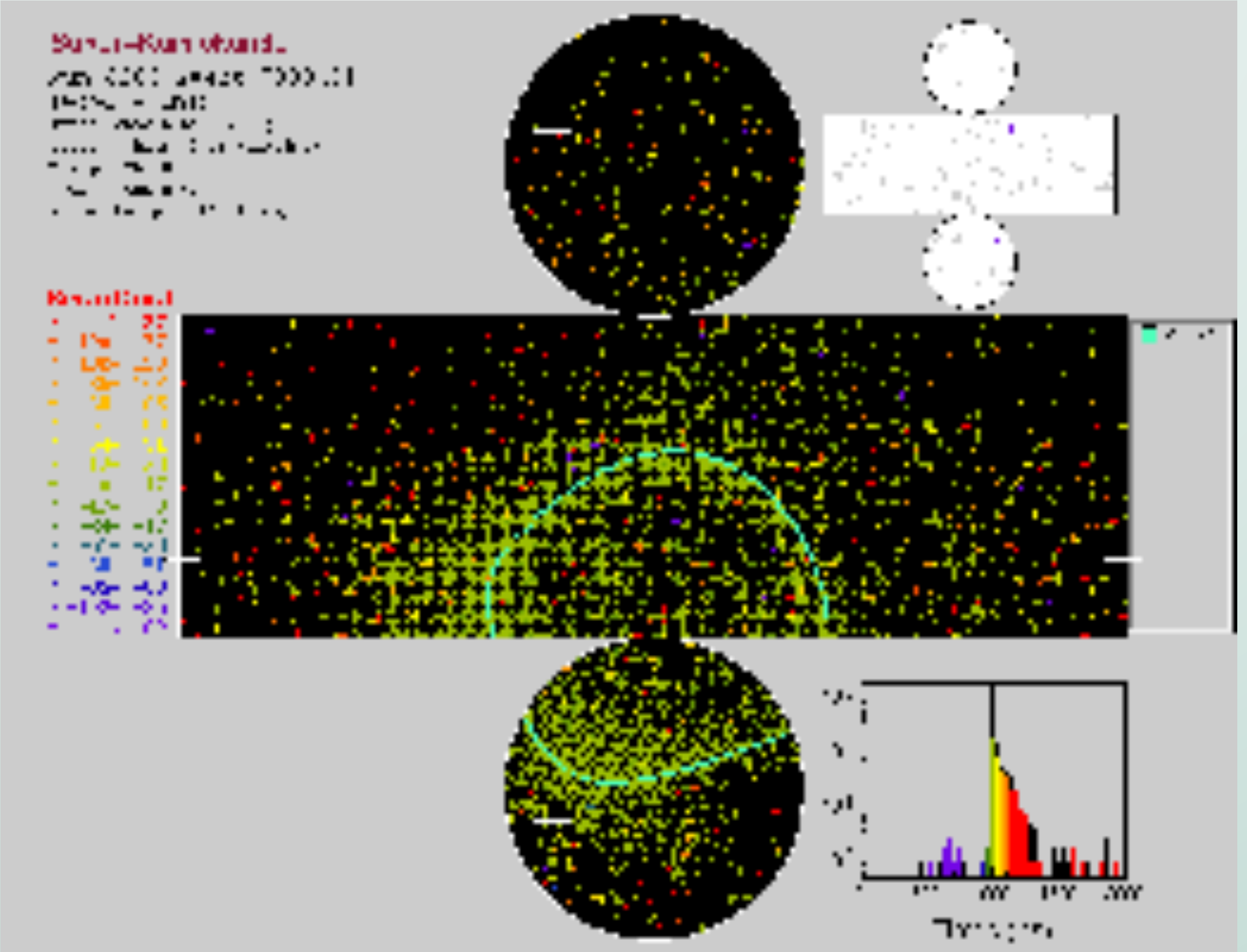
Water Cerenkov Detectors
Particle ID



Super-K

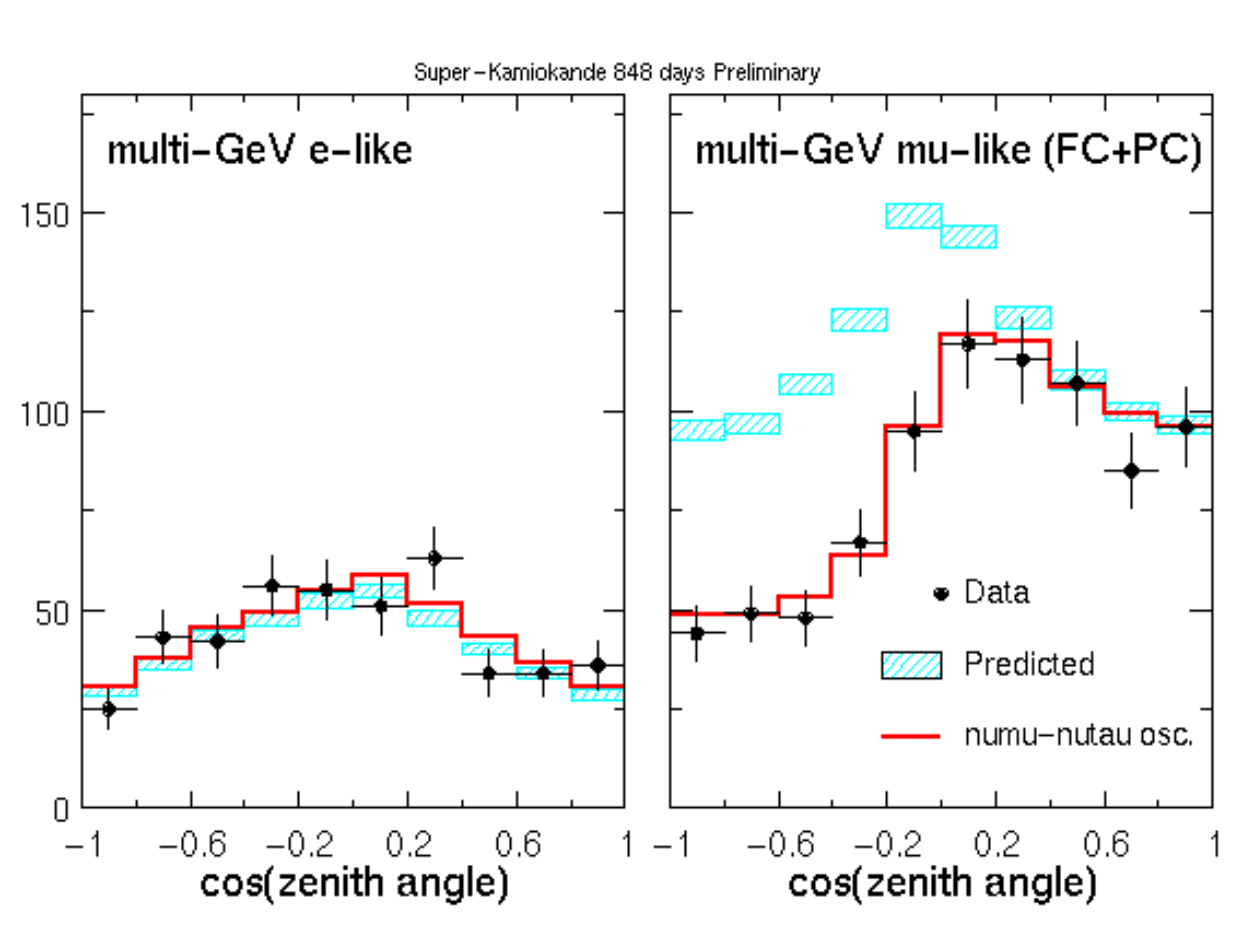




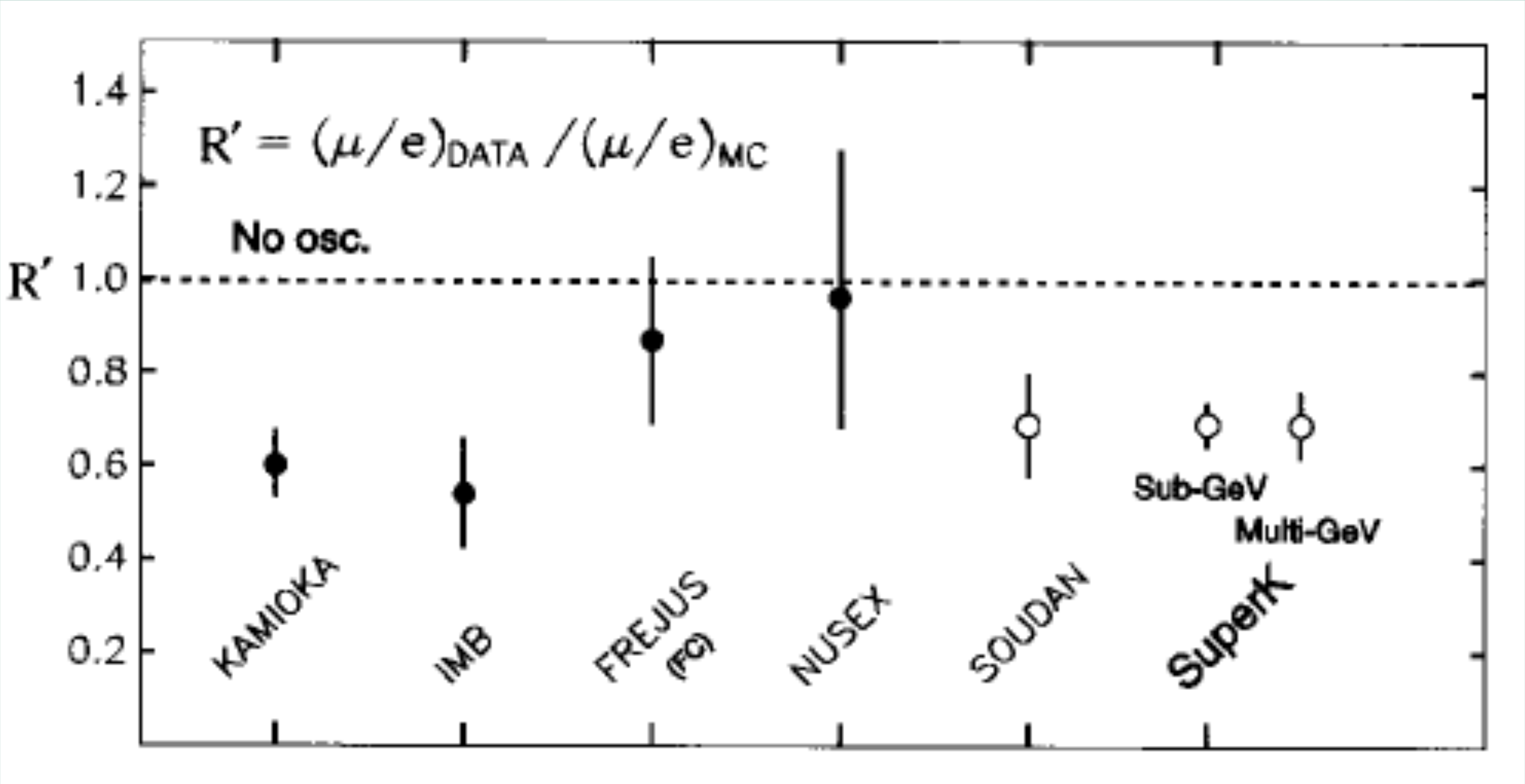


Initially built for
proton decay searches

Up-down Asymmetry Observed



Results

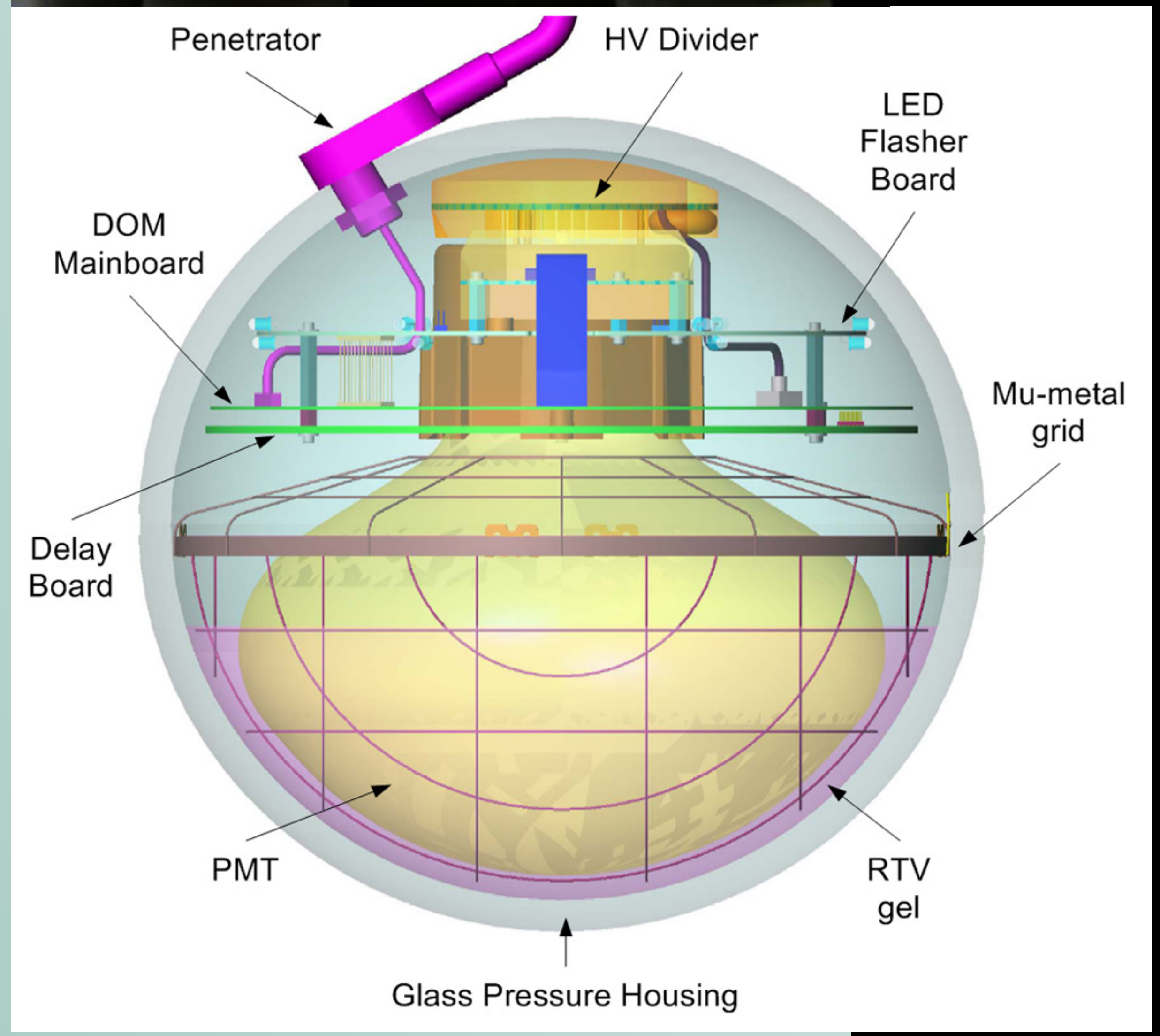


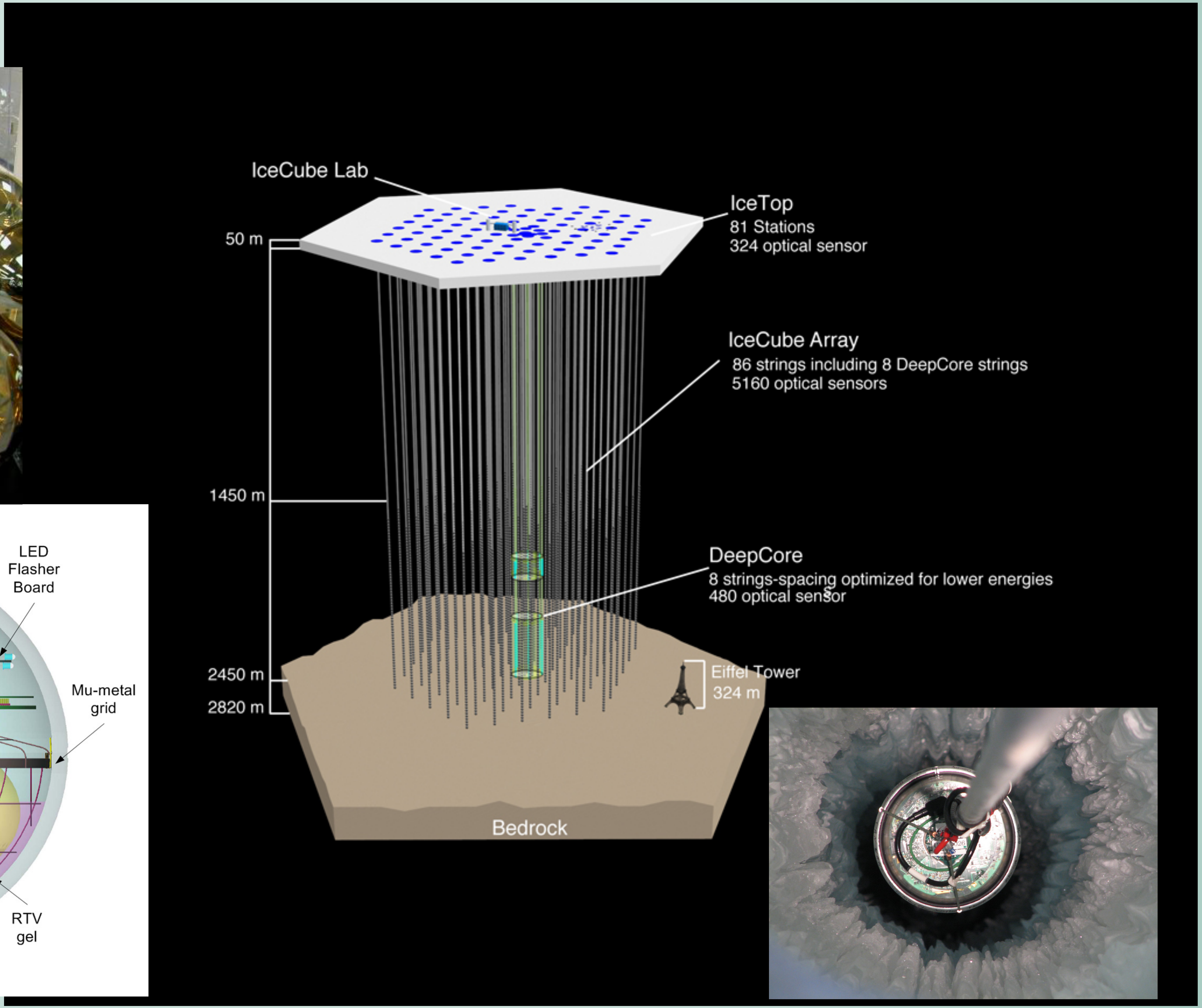
Mixing Angle quite large (consistent with maximal)

$\Delta m^2 = 2.5\times10^{-3}\ eV^2$

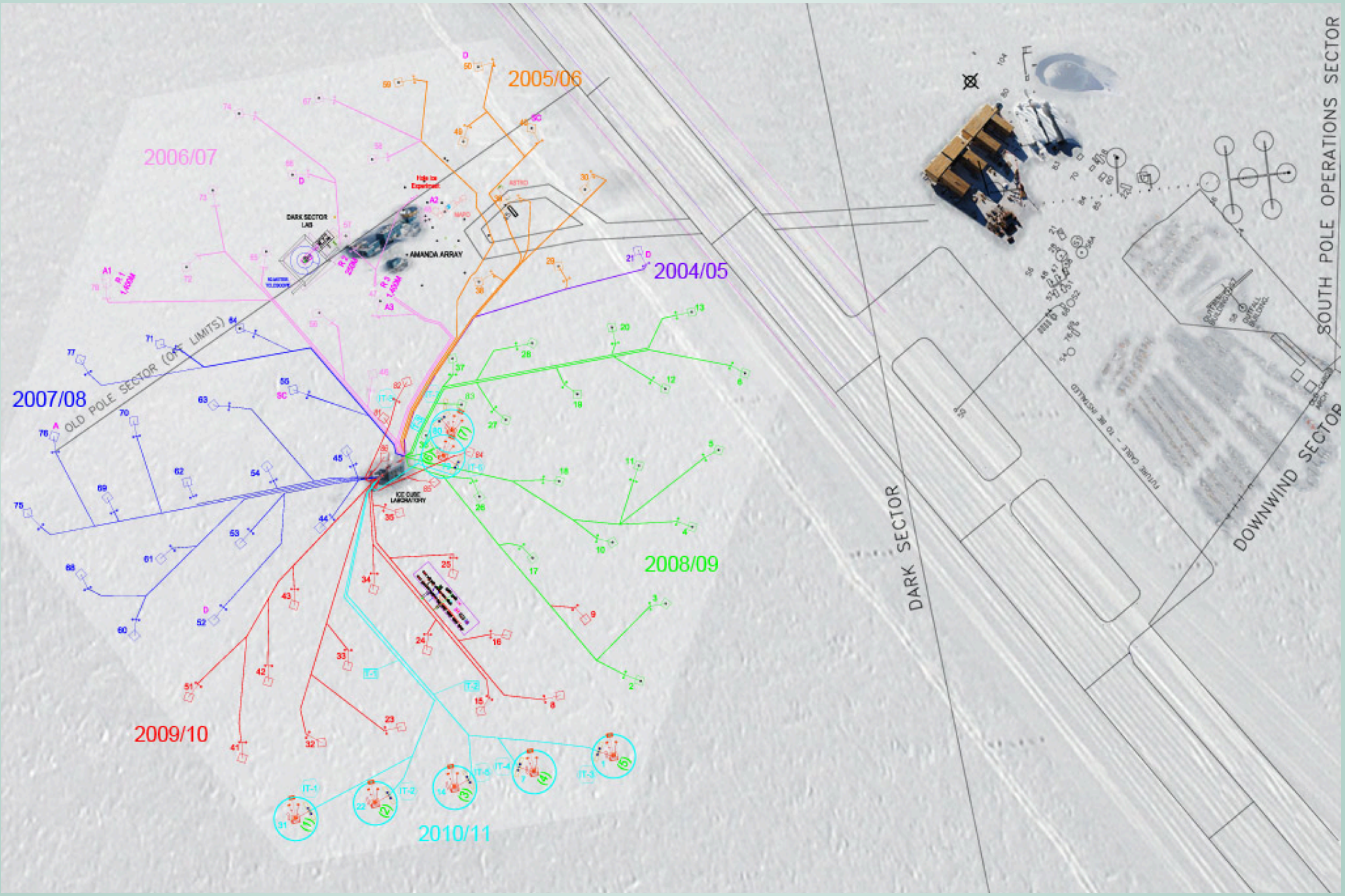
Verified by Accelerator Experiments

Ultra-high energy atmospheric neutrinos: Icecube

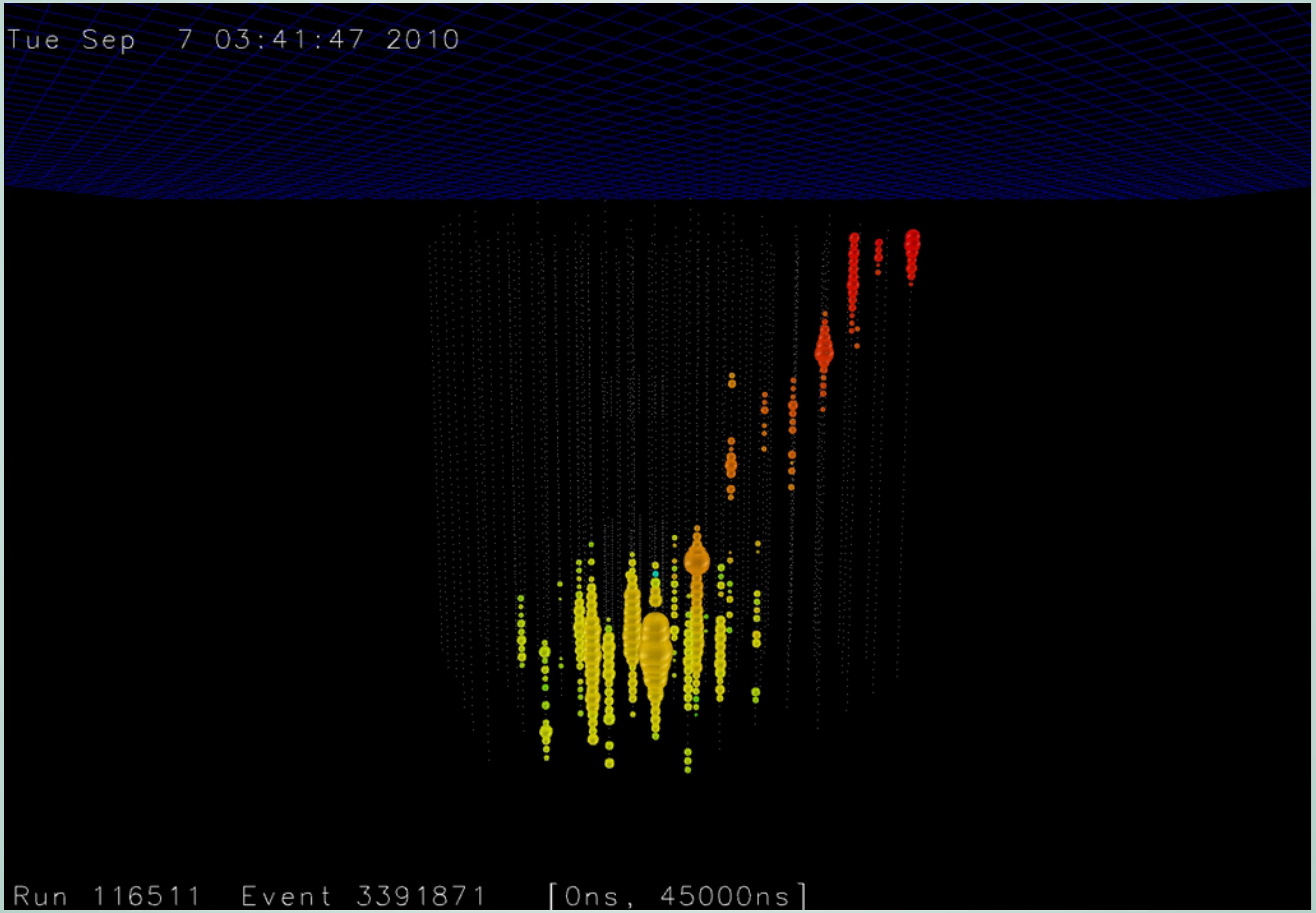




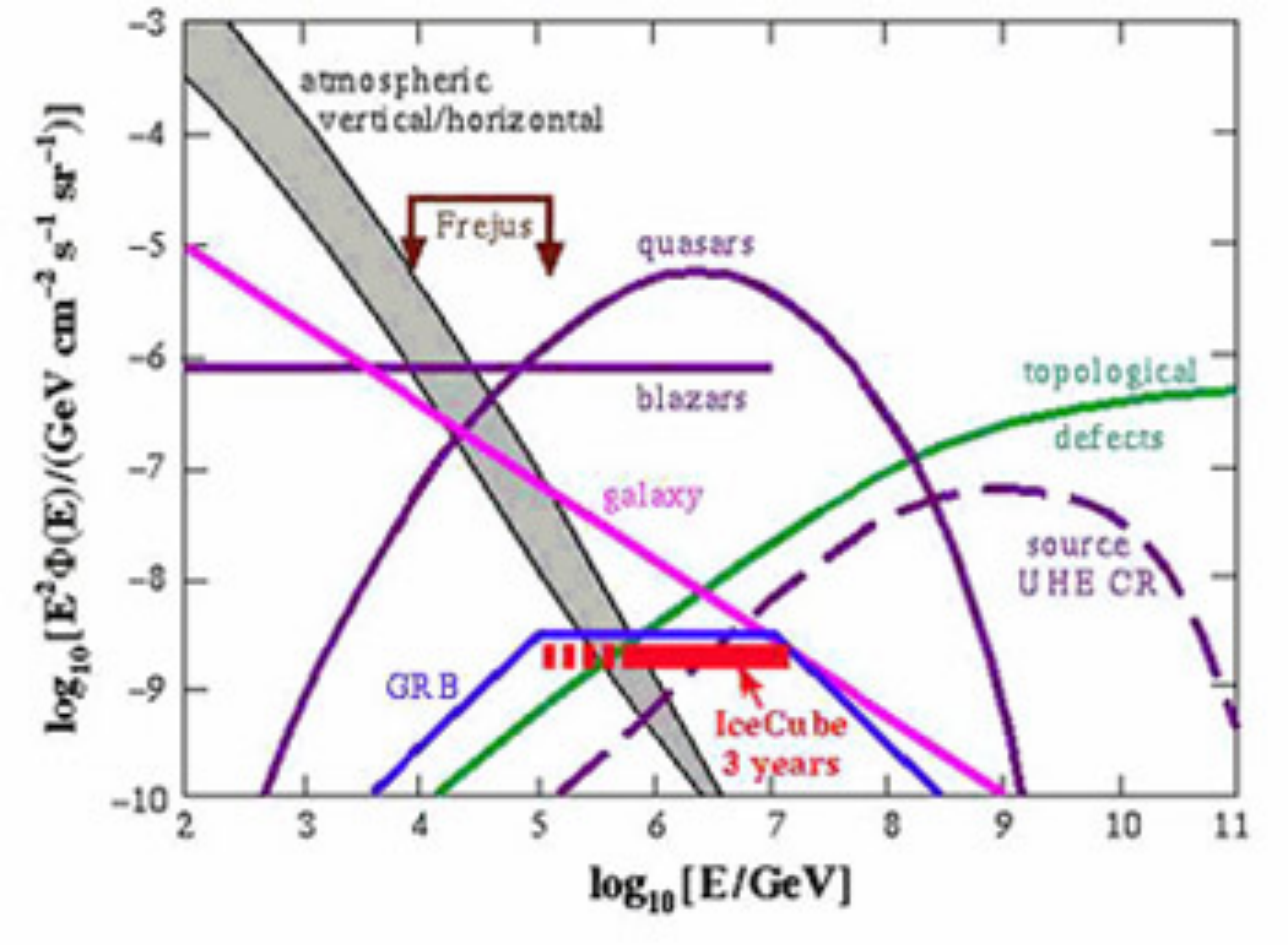
South Pole Station



Neutrino Event
Upwards-going events are pure neutrino

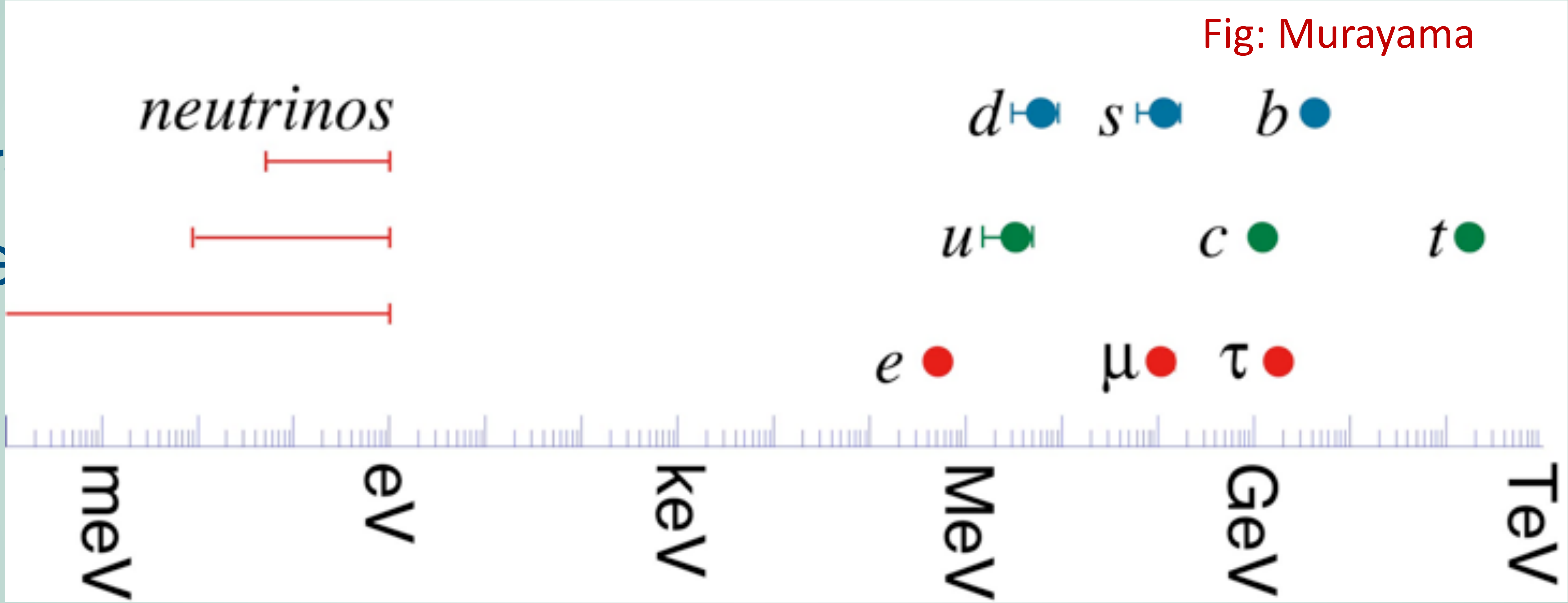


Icecube Physics



Neutrino masses

- What ar
- Why are



Experimental Considerations

- Neutrinos are lightest objects in univers
  - ~ 1×10^{-6} mass of electron
- Relativity makes job tough:
  - $E^2 = p^2 + m^2$
- Approach: Energy distribution of electr ... utrino from kinematics and mixing.

E. Fermi, Z. Physik 88, 161 (1934)

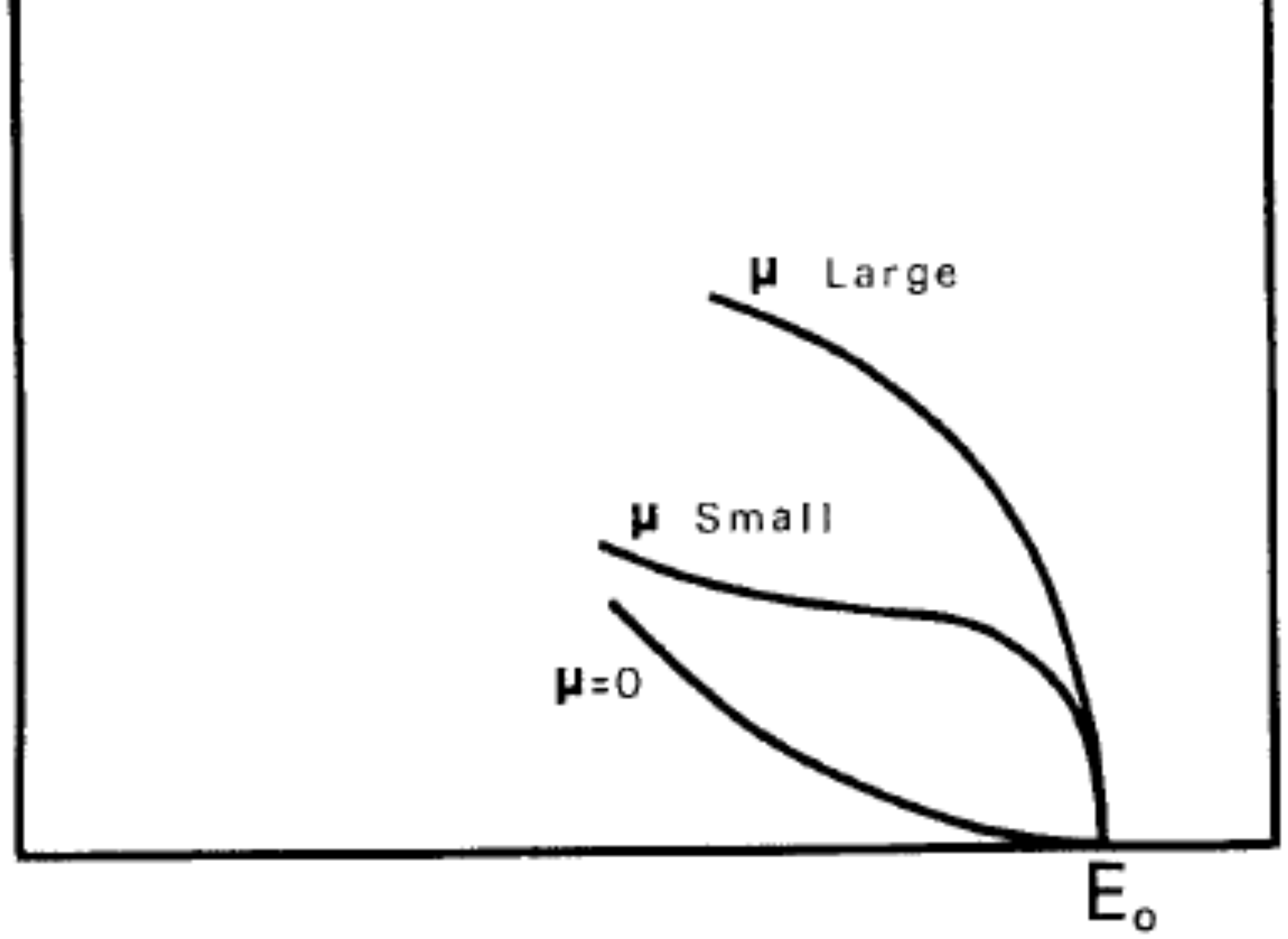
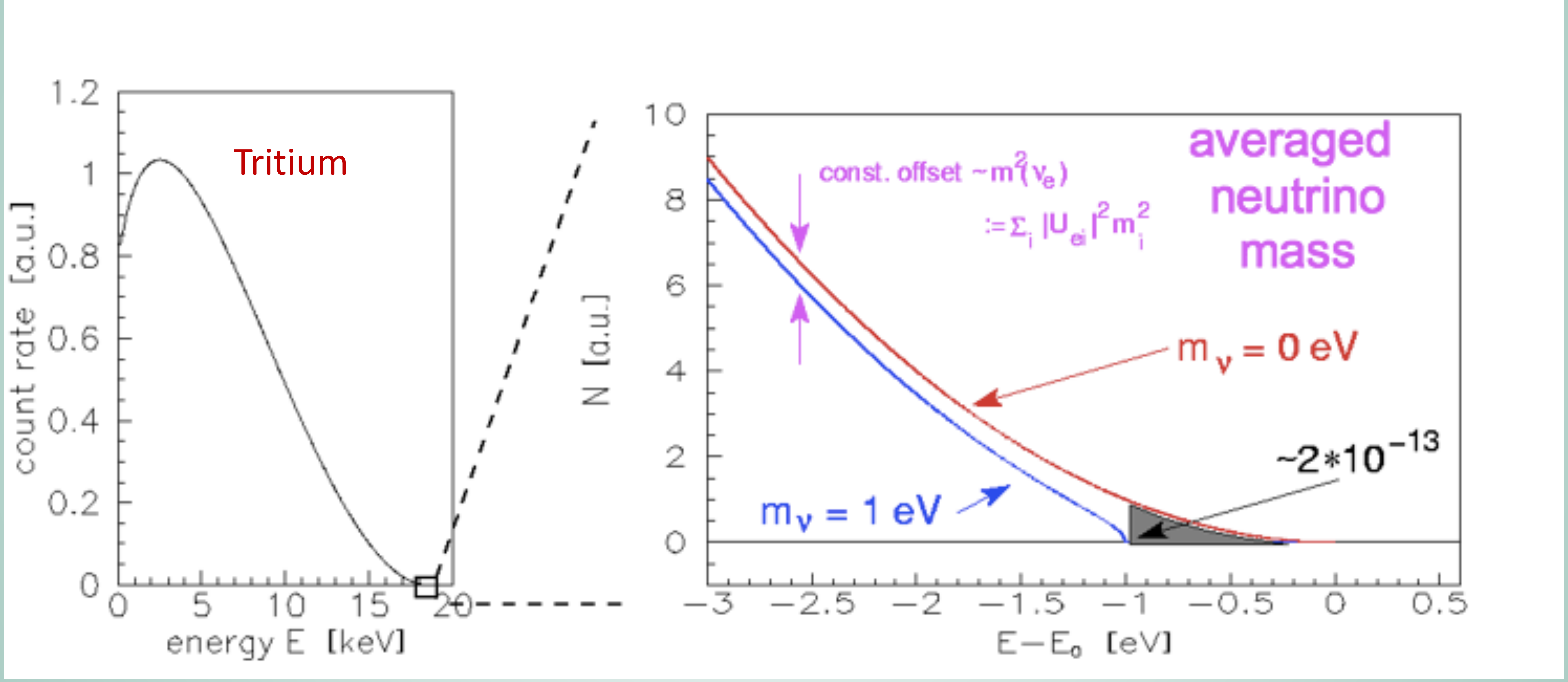
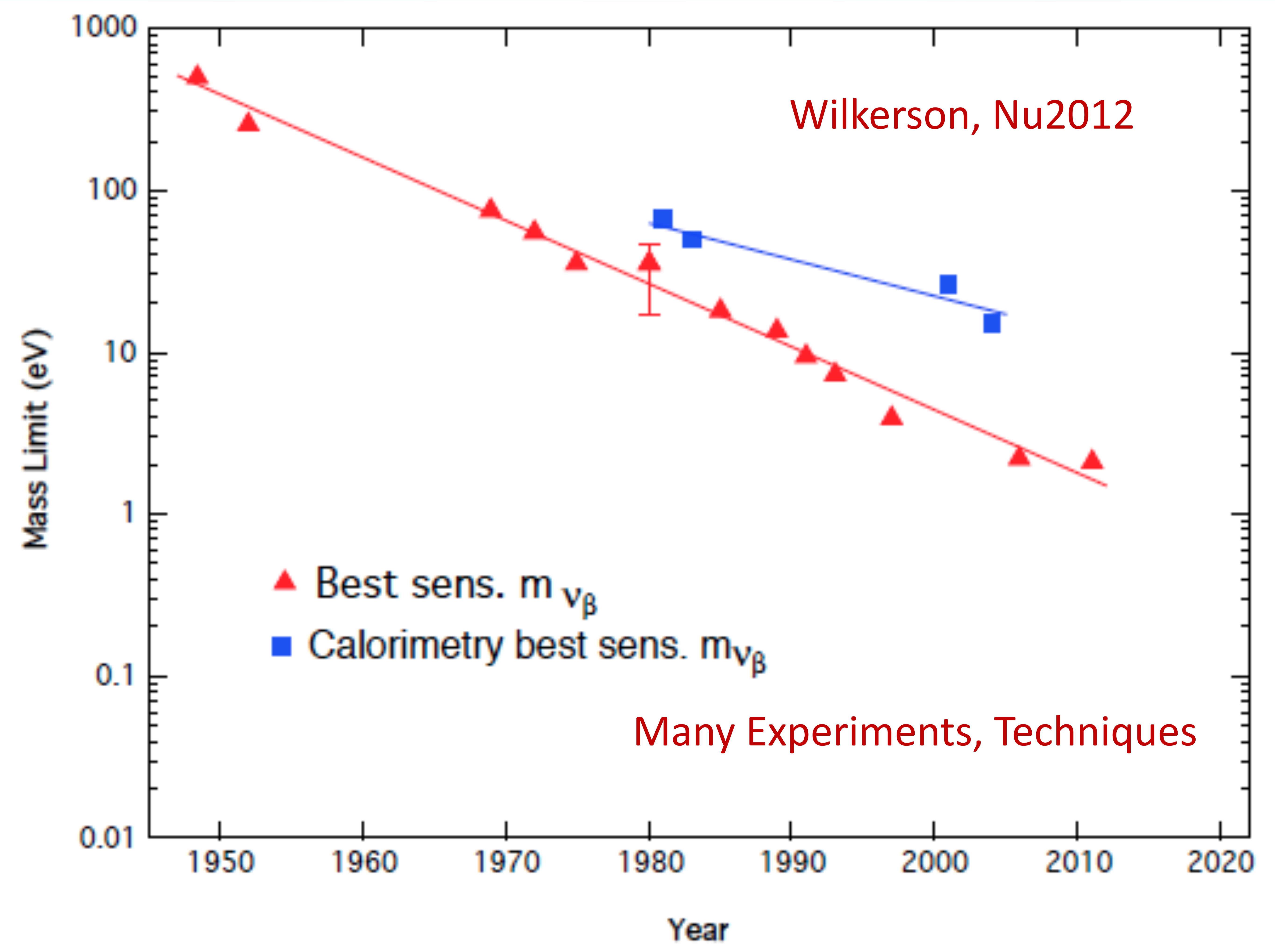


FIG. 1. The end of the distribution curve for $\mu=0$ and for large and small values of μ.

Principle

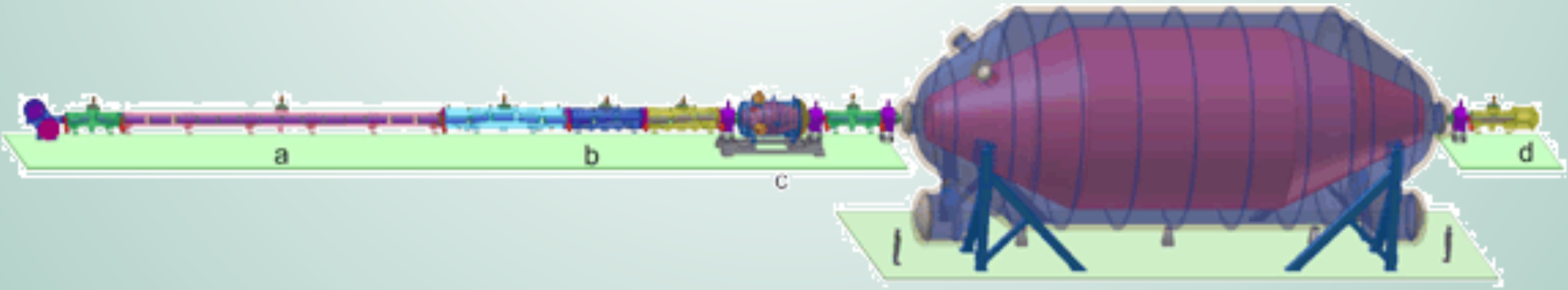

count rate [a.u.]
energy E [keV]
Tritium
N [a.u.]
E−E₀ [eV]
const. offset ~m²(νe)
:= Σi |Uei|² mi²
averaged neutrino mass
mν = 0 eV
mν = 1 eV
~2*10⁻¹³

Historic Neutrino Mass Measurements

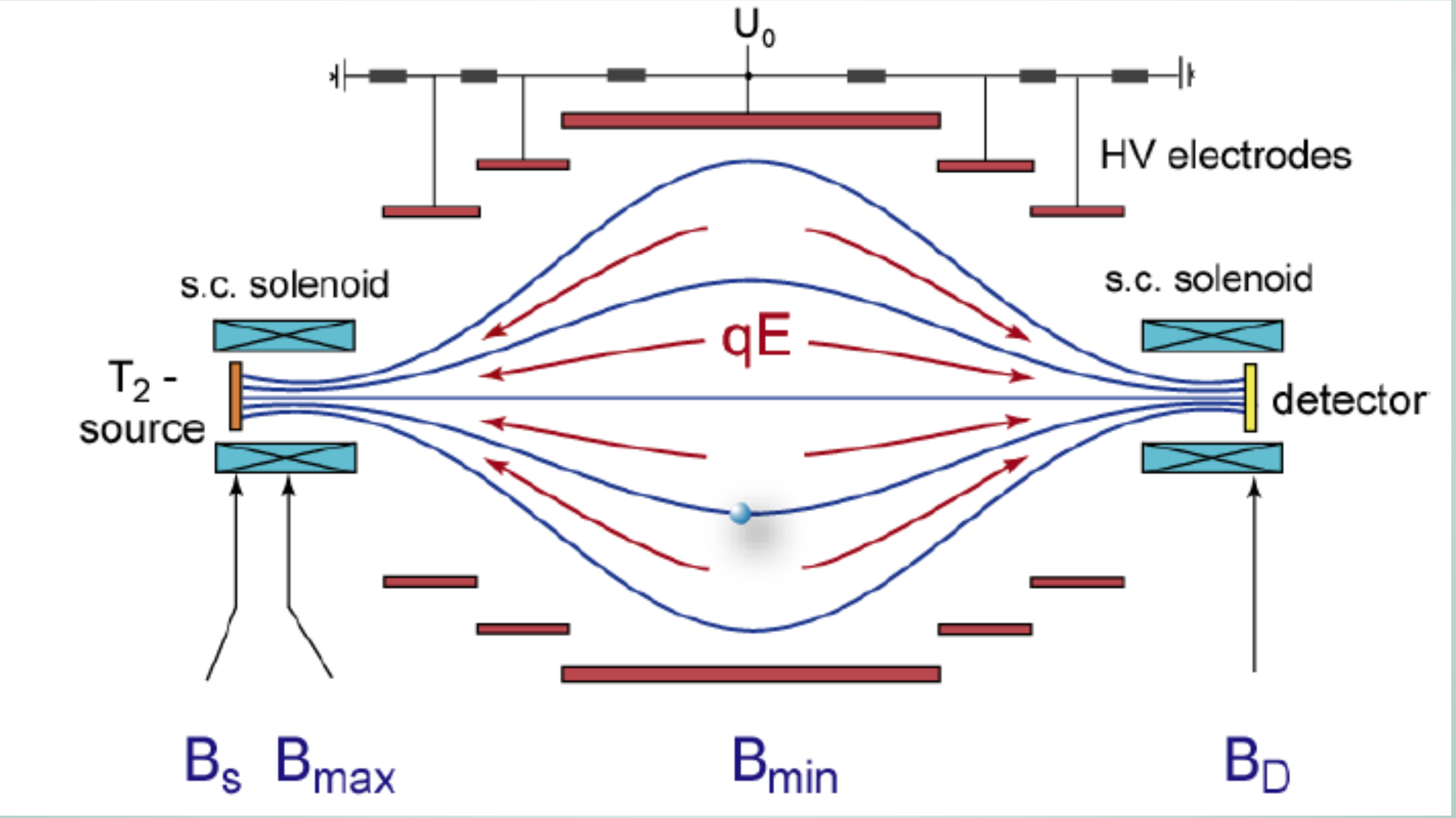


Current Direct Mass Measurements

- Tritium beta decay endpoint measurements
- Current: $m_\beta < 2\text{eV}$
- New Generation: KATRIN (Karlsruhe Tritium Neutrino Experiment)
  - Massive spectrometer
  - Sensitivity to $m_\beta = 0.2\text{eV}$
  - Anticipated Start in 2013, 5 year run.



MAC-E Filter



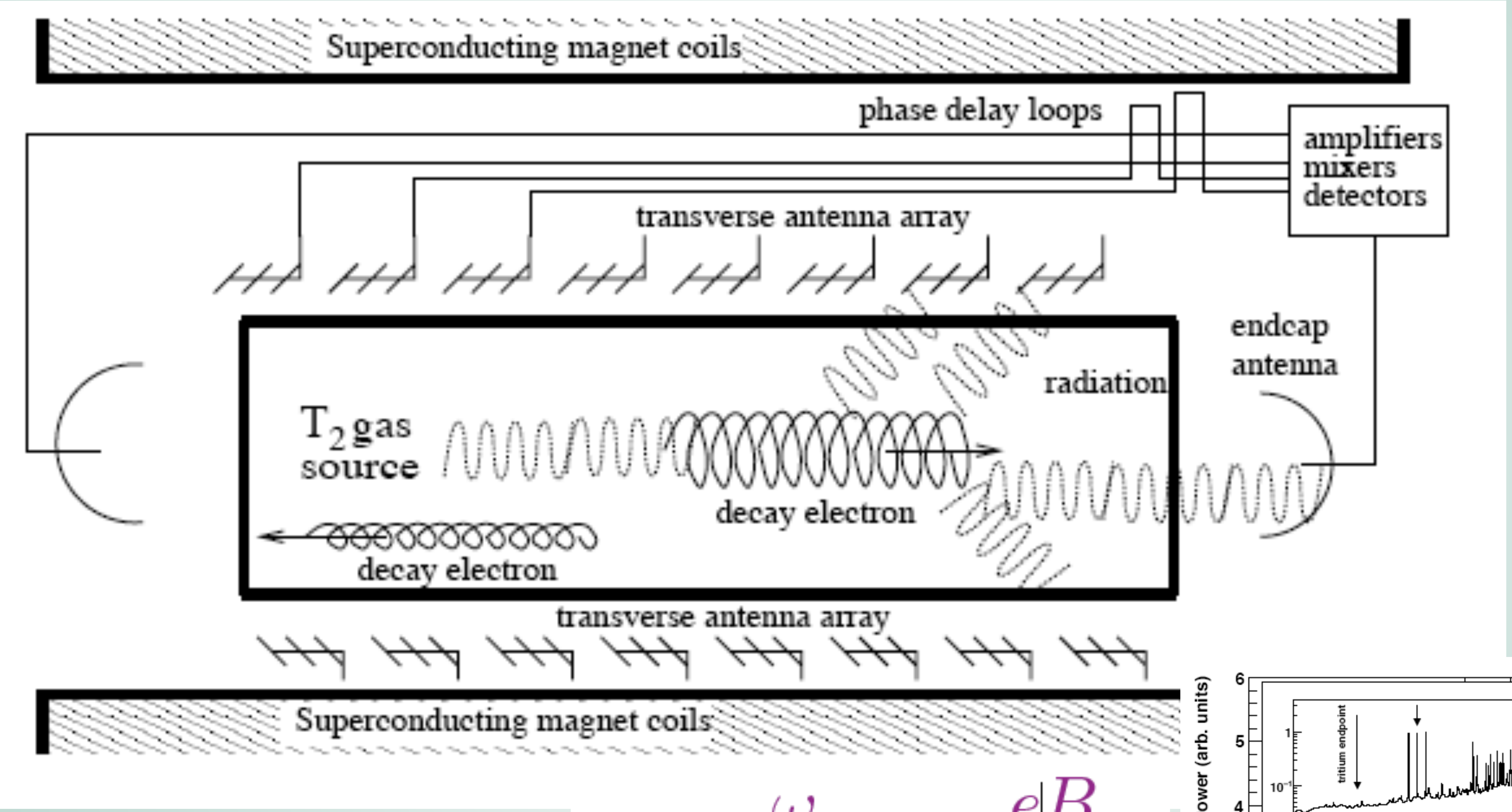
U0
HV electrodes
s.c. solenoid
s.c. solenoid
qE
T2 -
source
detector
Bs
Bmax
Bmin
BD

KATRIN Main Spectrometer
(world's largest beer keg)

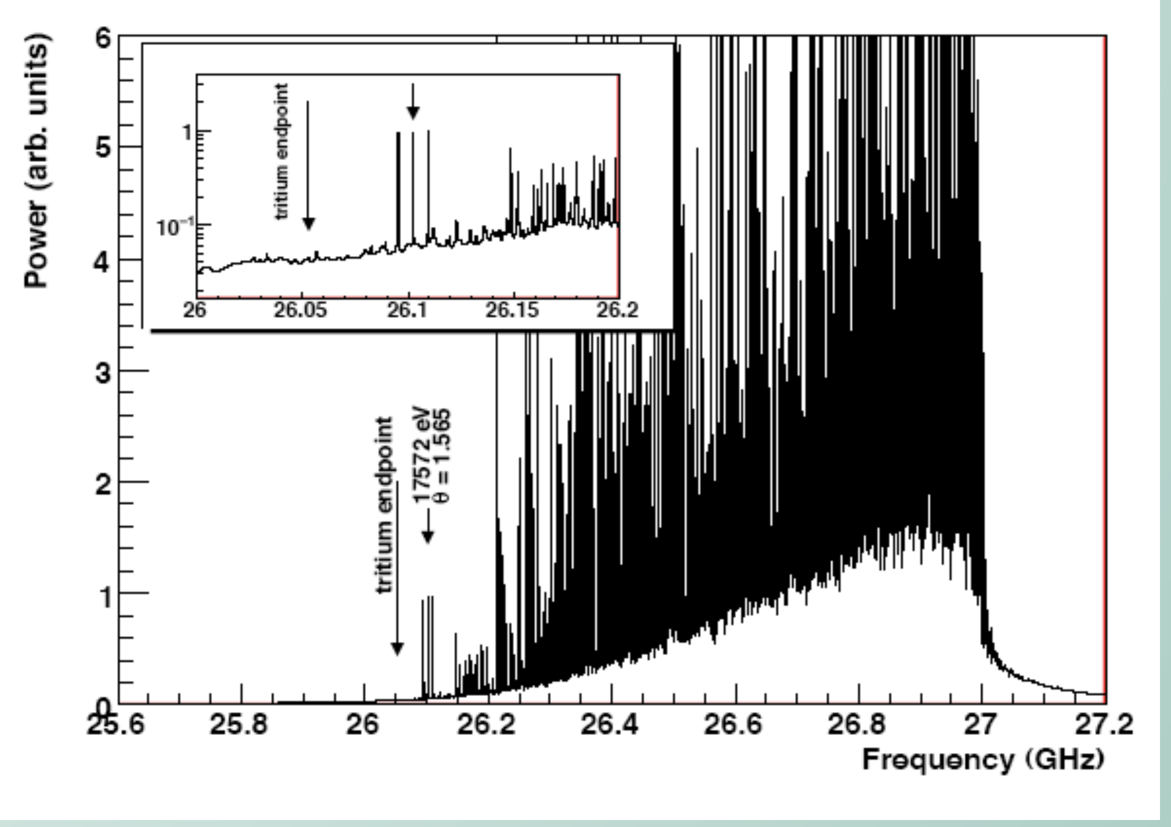
What about the future?

After KATRIN, it is safe to say that the MAC-E filter design has run its course and cannot be extended
- Hamish Roberton (paraphrased)

RF Cyclotron Motion
(Project 8)



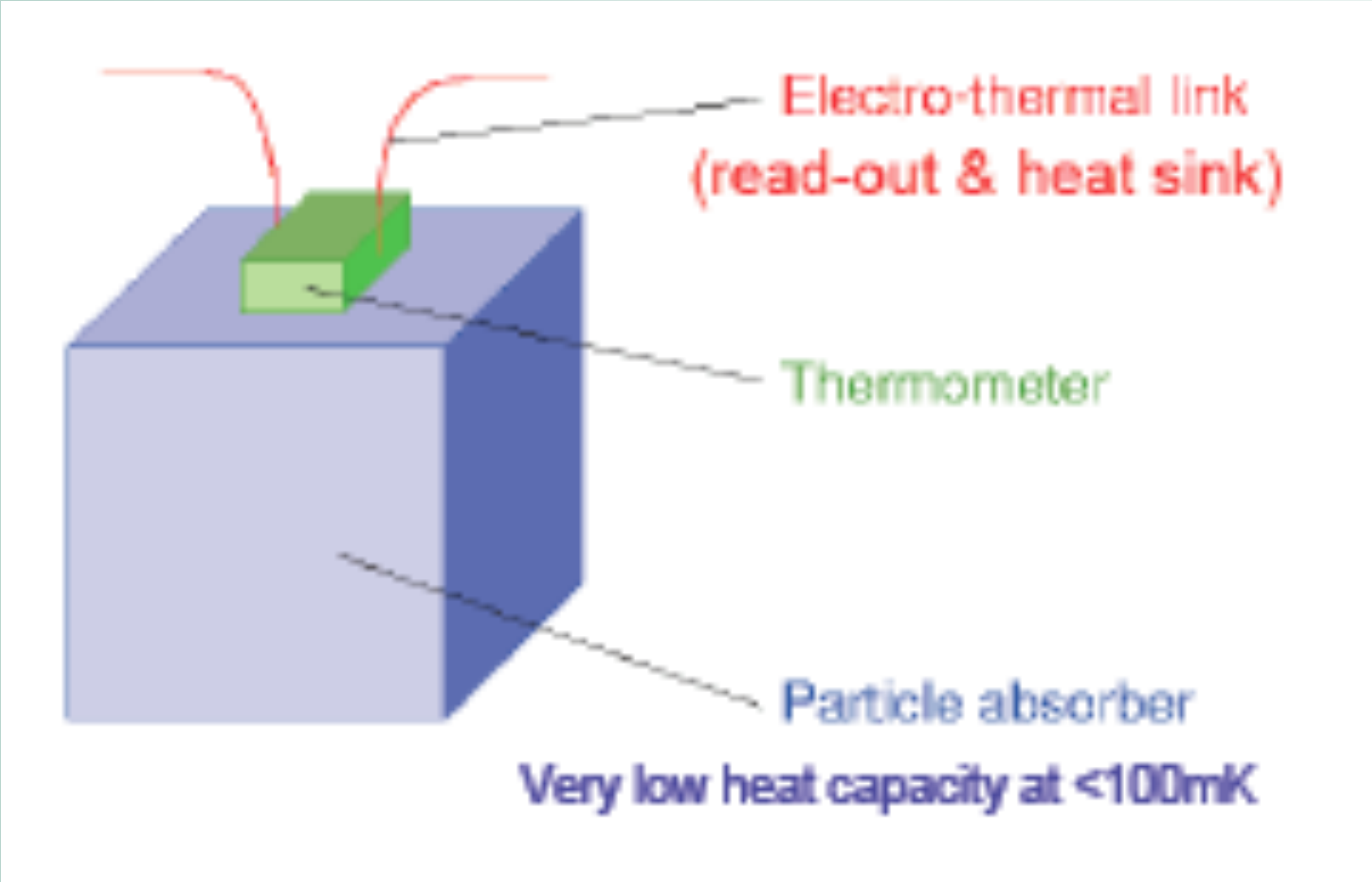
$$\omega_\gamma = \frac{\omega_c}{\gamma} = \frac{eB}{\gamma m_e c^2}$$

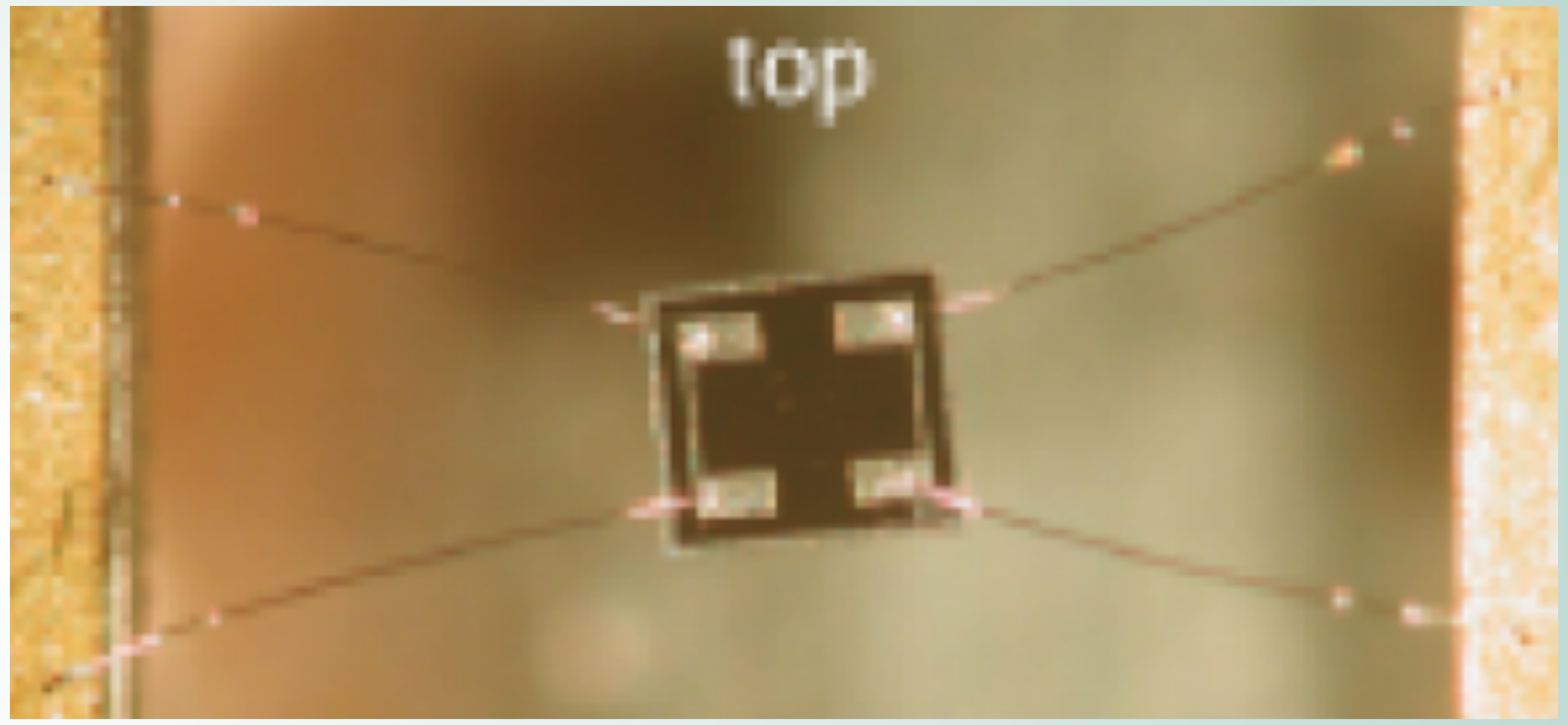


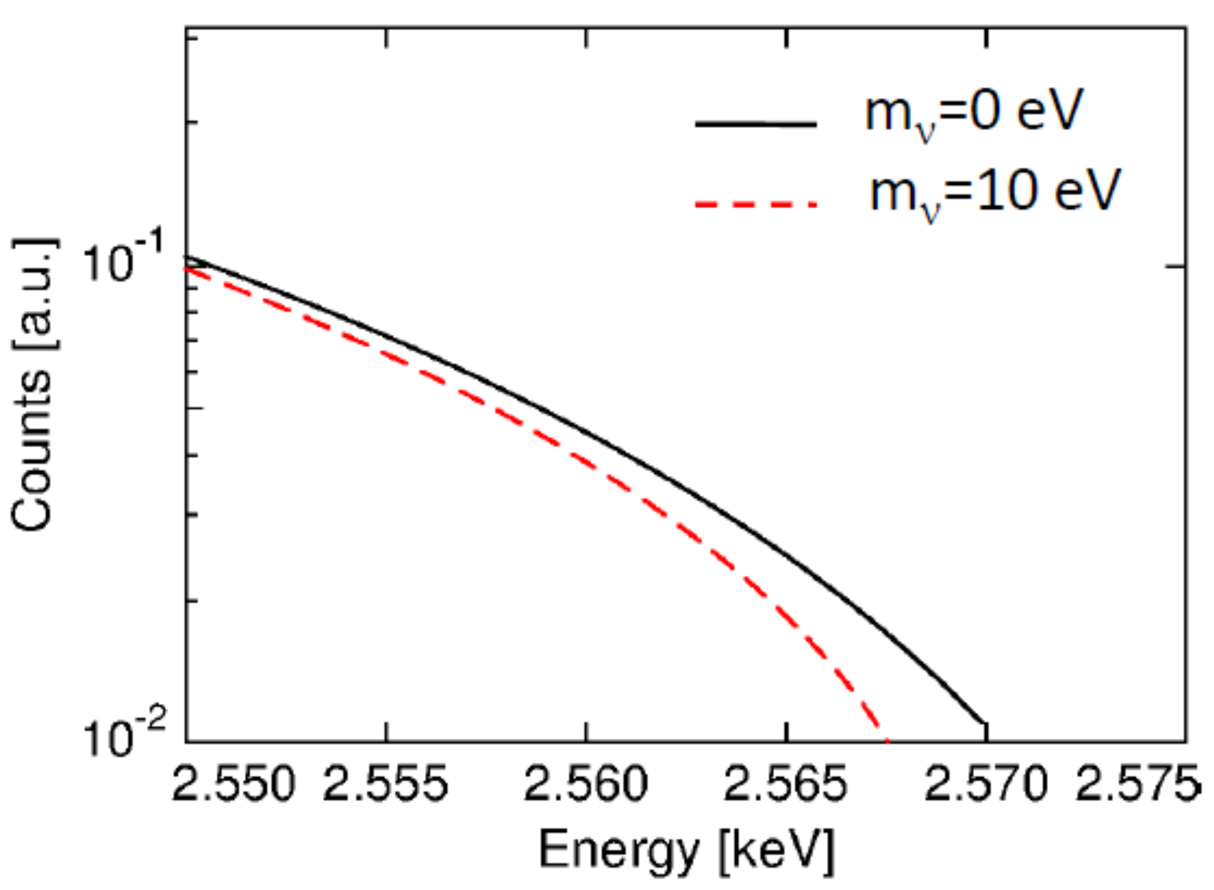
Promising, but technical challenging.
Difficult to estimate systematics a priori

Others
MARE: cryogenic bolometry

$^{187}Re \rightarrow {}^{187}Os + e^- + \nu_e$ ($\tau_{1/2} = 4.3\text{x}10^{10}$ y, Q = 2.46 keV







ECHO: $^{163}Ho + e^- \rightarrow {}^{163}Dy + \nu_e$

Distortions in emitted gamma spectrum

References

https://history.aip.org/exhibits/electron/

https://www.symmetrymagazine.org/article/march-2007/neutrino-invention

https://pubs.aip.org/aapt/ajp/article/36/12/1150/1047952/Fermi-s-Theory-of-Beta-Decay