From Measurement to Discovery – The Scientific Method in Physics

Astroparticle Physics

Summer School
Nor Amberd, Armenia
5-8 June, 2018

Johannes Knapp, DESY Zeuthen

From Measurement to Discovery

My Plan for APP:

Discovery
Discovery

Lecture 1: Cosmic Rays: discovery, techniques, spectra & spectral features

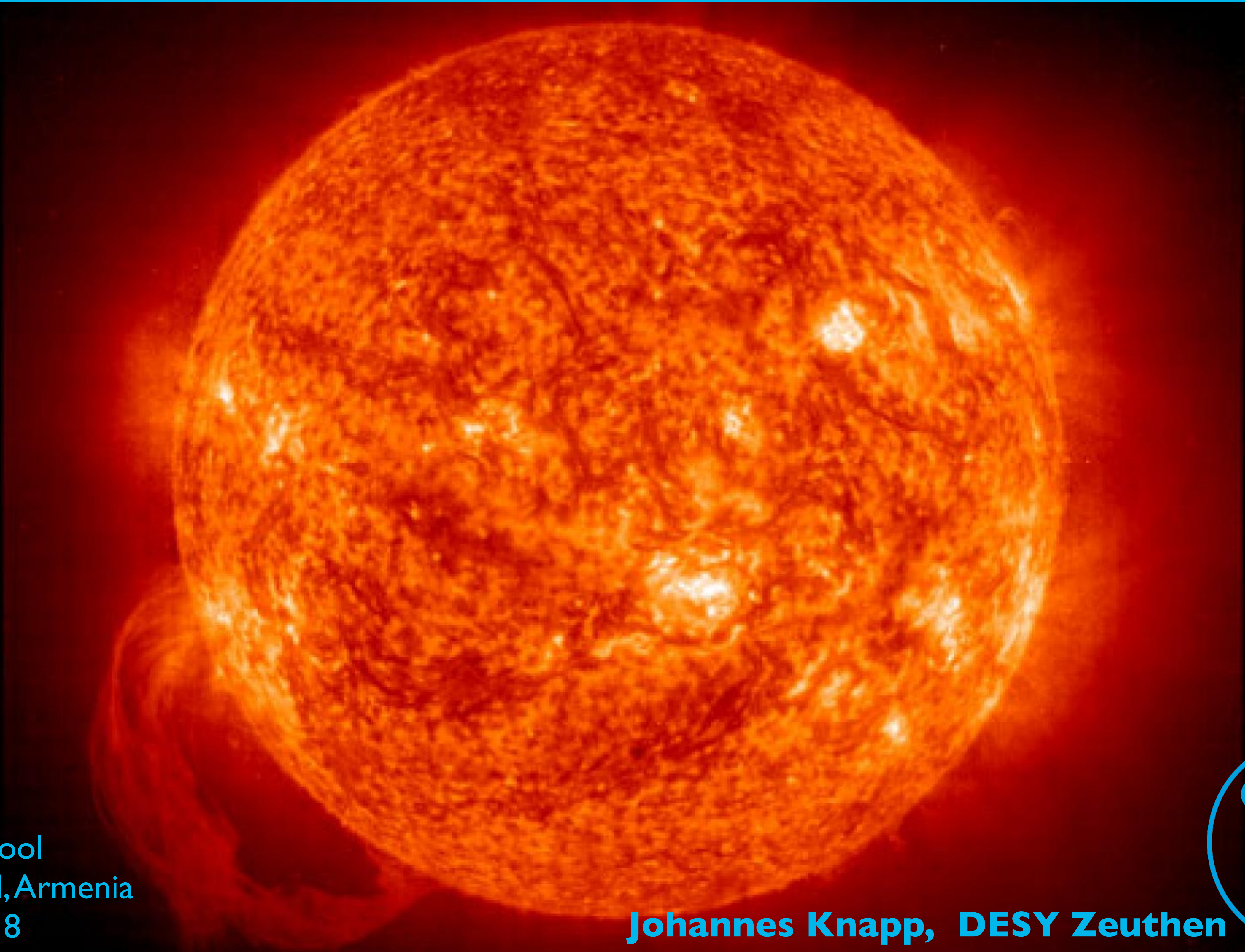
Lecture 2: Neutrinos ν: neutrino hypothesis & detection, the solar model, solar neutrino problem, neutrino oscillations


Lecture 3: Neutrino astronomy: the idea, techniques atmospheric neutrinos, sources **Discovery**

Lecture 4: Gamma Rays γ: early ideas, techniques, path to maturity, sources & successes **very many discoveries**

Much of this is what we call today “Astroparticle Physics”

2. Solar Neutrinos



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β-Decay

One of the most exciting stories of modern physics ....

1914 James Chadwick :

electrons from β decay have continuous energy distribution

but : $\Delta z = 1$

only one particle is seen to be emitted

transition occurs between two ground states with fixed energies

Is energy conservation violated ???

angular momentum : Spin change $\Delta s = 1$ is observed

but : Spin of electron is 1/2

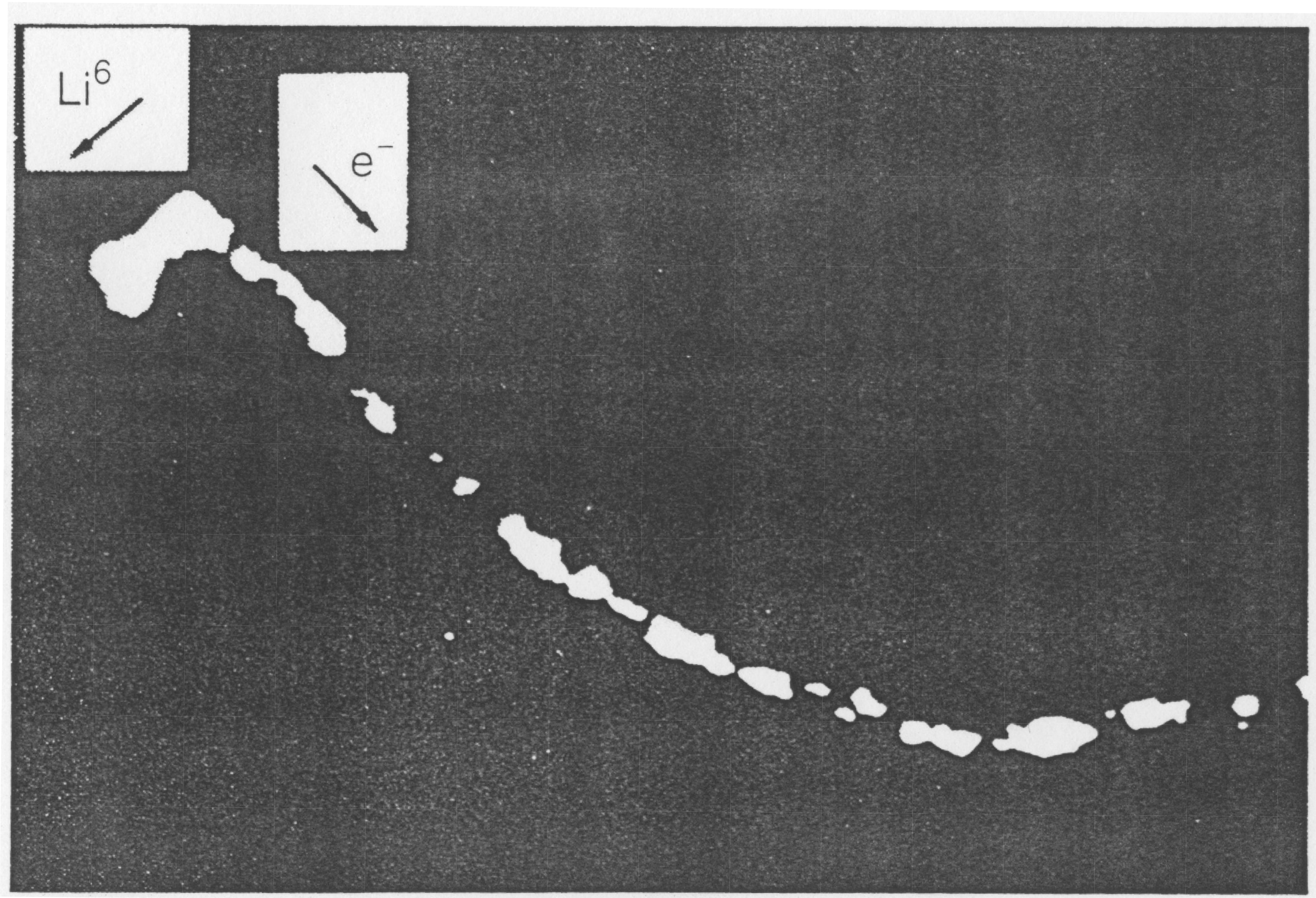
Is angular momentum conservation violated ???

momentum : emitted electron and recoil nucleus are not back-to-back

Is momentum conservation violated ???

$^{6}He \longrightarrow {}^{6}Li + e^{-}$

obviously, momentum is not conserved



Wolfgang Pauli 1930 : in a letter to his "radioactive colleagues"

postulates a new particle with :

- charge = 0
- spin = 1/2
- no (or at least very weak) interaction with matter

that is produced along with the electron in β decay and would account for the non-conserved energy, momentum and spin.

Pauli : "I did something terrible : I invented a particle that cannot be detected"

This was a desperate last measure to save
energy, momentum and angular momentum conservation.

"Neutron" discovered by J Chadwick in 1932; but its mass was 939 MeV/c^2, so it was not the particle needed for β decay.

"Neutrino" only directly detected 30 years later (1959), one year after Pauli died.

Dear Radioactive Ladies and Gentlemen!

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…

The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

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…

Thus, dear radioactive ones, scrutinize and judge.

Image courtesy of the Pauli Letter Collection, CERN. Printed with permission.

Translation: Kurt Riesselmann
A complete translation of the letter is available online at www.symmetrymag.org

Wolfgang Pauli, at age 30, had a bold idea on how to solve a perplexing problem in nuclear physics. To explain the apparent disappearance of energy in the decay of certain atomic nuclei, he postulated the existence of a neutral, light-weight particle, saving the fundamental law of the conservation of energy. Pauli proposed that "neutrons" could emerge from decay processes, carrying away energy while escaping direct experimental detection.

Worried that nobody would ever be able to observe this particle, Pauli did not dare to publish his invention without consulting some experimental physicists. On December 4, 1930, Pauli wrote an open letter to a group of nuclear physicists, the "dear radioactive ladies and gentlemen," who were going to meet a few days later in Tübingen, Germany. The document shown here is a machine-typed copy that Pauli obtained in 1956 from Lise Meitner, a well-regarded scientist who had attended the Tübingen meeting.

In the early 1930s, scientists elaborated on Pauli's idea and concluded that the new particle must be extremely light and very weakly interacting. When James Chadwick discovered a neutral particle in 1932, it received the name neutron. But the particle turned out to be too heavy to fit Pauli's prediction. Enrico Fermi, developing a theory of weakly interacting particles, introduced a new name for Pauli's particle: neutrino, which means "little neutral one." A quarter-century later, scientists observed for the first time collisions of neutrinos with matter, the long-sought-after evidence for Pauli's ghost-like invention.
Kurt Riesselmann

Original - Photocopie of PLC 0373

Abschrift/15.12.56

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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

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

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

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

gez. W. Pauli

WOLFGANG ERNST Pauli

1900-1958

AIP Emilio Segr   Visual Archives

The Nobel Prize in Physics 1945

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

This principle was needed for the quantum-mechanical explanation of the electronic structure and chemical properties of atoms. In order to account for the apparent violation of energy conservation in ß-decay, Pauli postulated the existence of an unseen particle, called the "neutrino" by Fermi. (It was later discovered by F. Reines and C. Cowan.)

The assumption of ν seems to work very well to explain β decay,

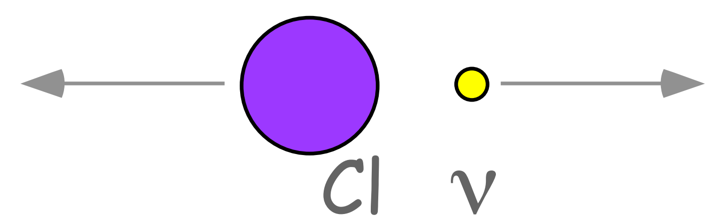
.... but is there direct evidence from experiments ??

Yes

1952: Rodeback & Allen (indirect detection)

$^{37}Ar + e^- \longrightarrow {}^{37}Cl + \nu + 0.8\ MeV$ (electron capture)

two-body final state, therefore ν have fixed energy, nucleus gets fixed recoil momentum (i.e. velocity) which can be measured by time-of-flight method:



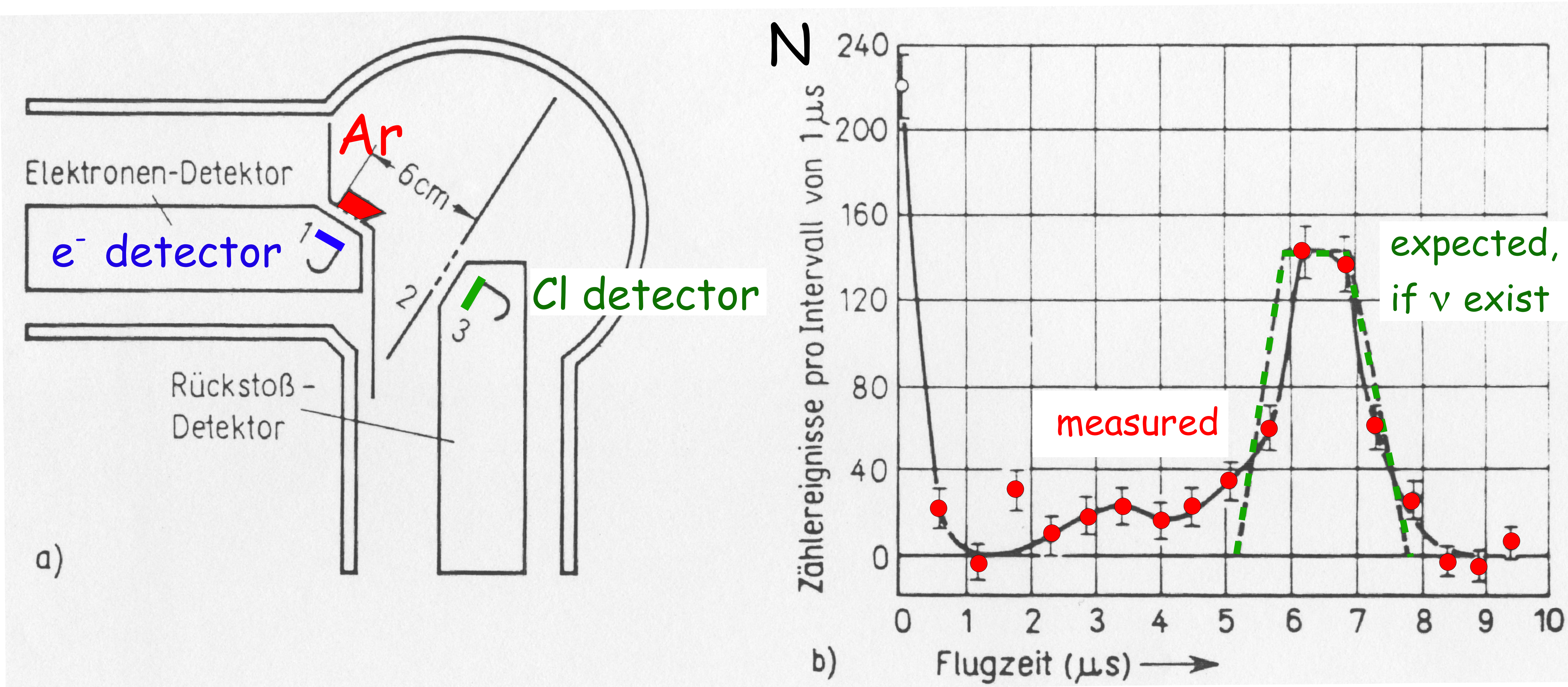
Start: Auger electron from EC

Stop: arrival of Cl at a detector 6 cm away.

Result: very good agreement of experiment and expectations.

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

2-body final state,
i.e. fixed energy for Cl and ν



Indirect ν detection by measurement of recoil of ^{37}Cl nucleus

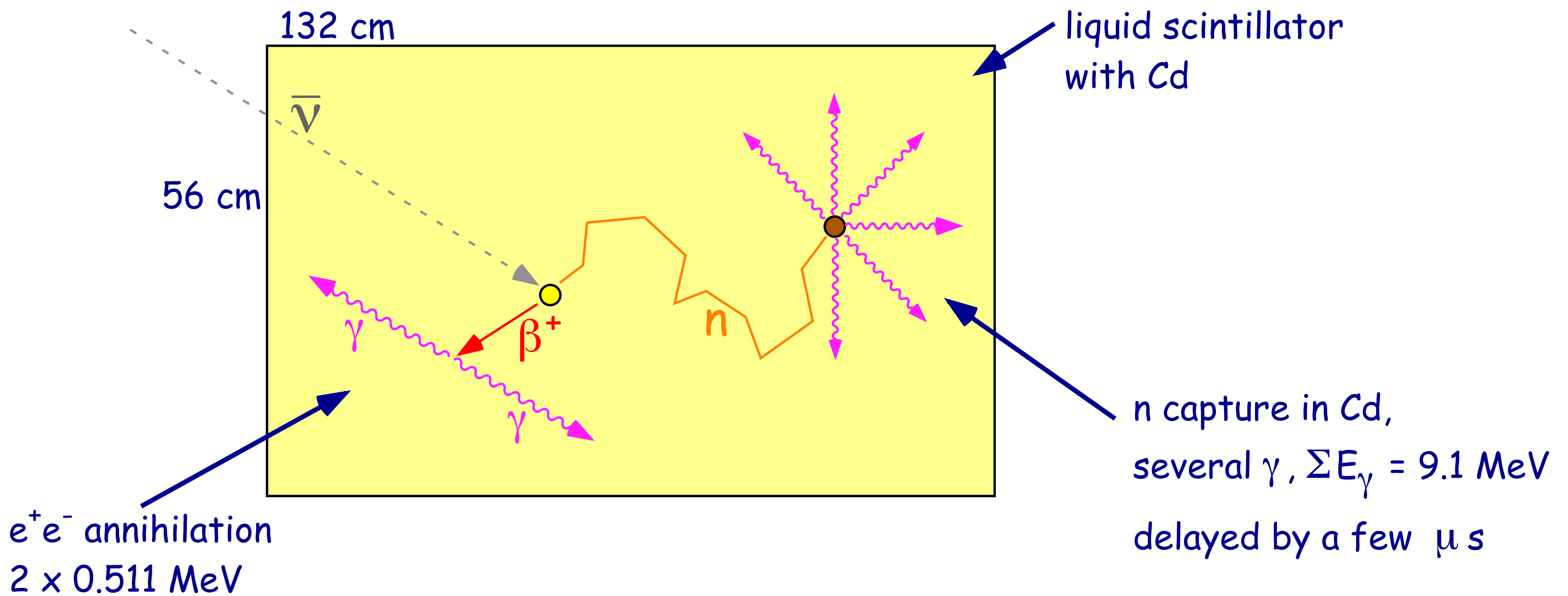
1959: Cowan & Reines

First direct detection by ν induced reaction:

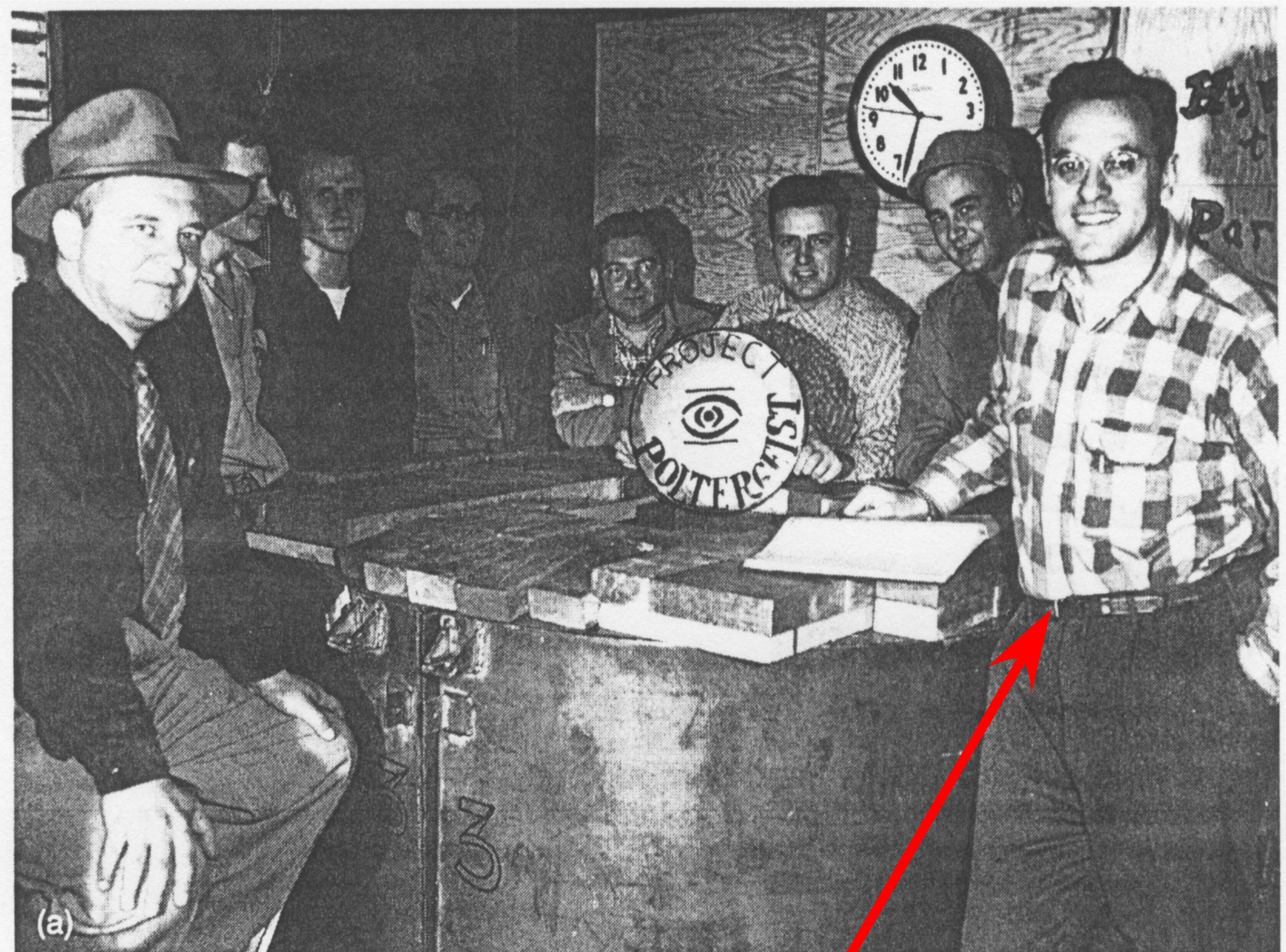
"inverse β decay": $\bar{\nu} + p \longrightarrow e^{+} + n$

use intense $\bar{\nu}$ emission of a nuclear reactor

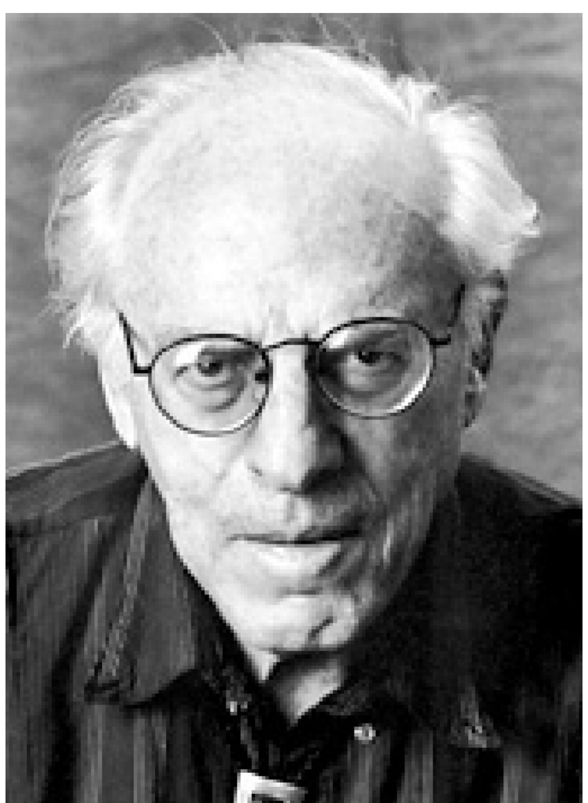
(fission leads to neutron-rich nuclei which undergo β^{-} decay: $n \longrightarrow p + e^{-} + \bar{\nu}$)



Shield detector from all other ionizing radiation from outside.

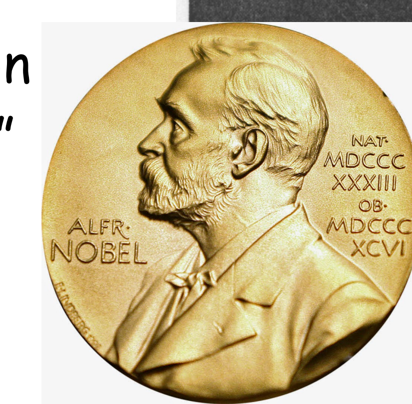


Cowan & Reines
"Project Poltergeist"



Frederick Reines
1918-1998

Nobel Prize in Physics
1995
"For the detection
of the Neutrino"



Since then, a whole industry of neutrino experiments emerged:

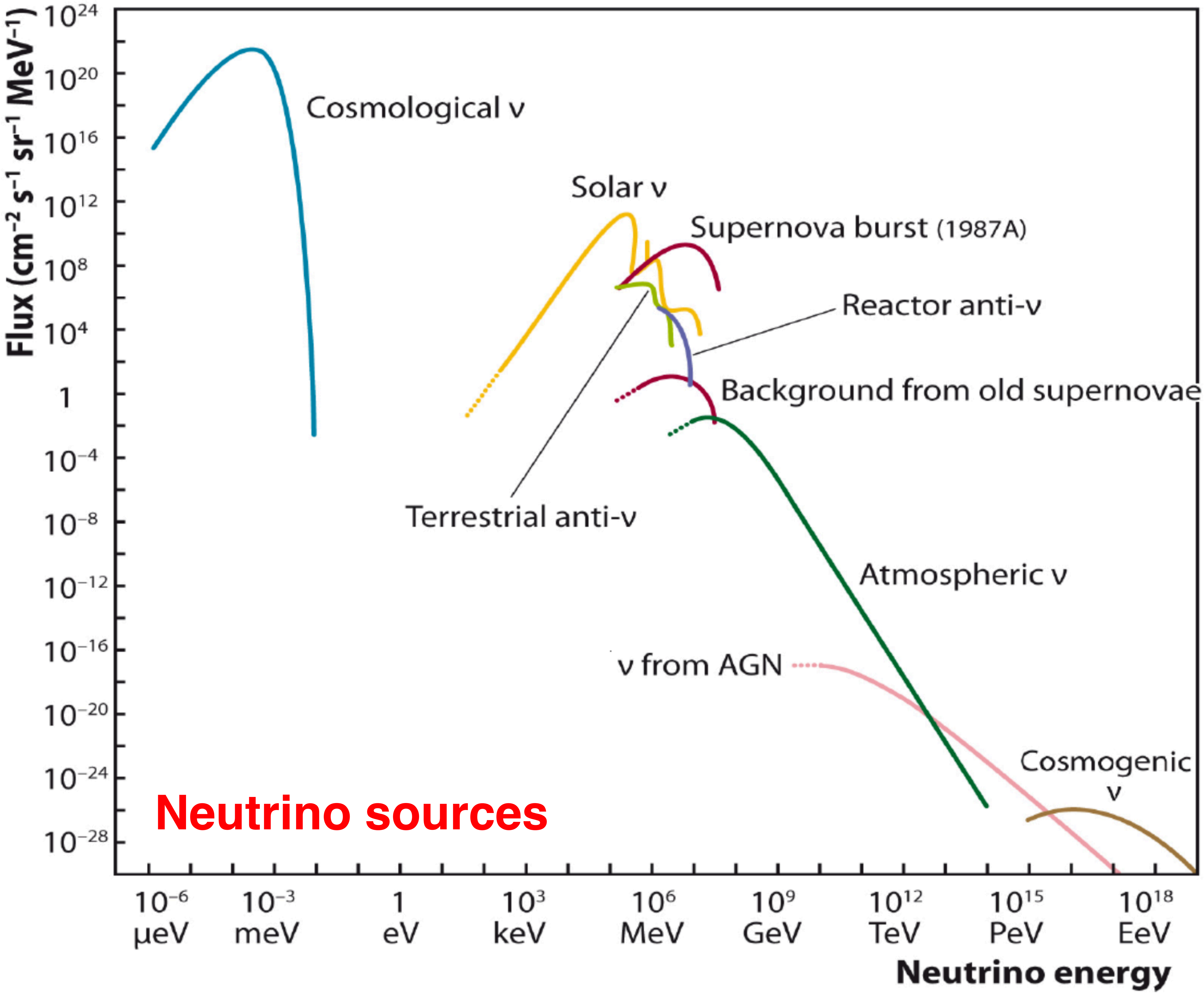
$\nu_e \quad \nu_\mu \quad \nu_\tau \quad \bar{\nu}_e \quad \bar{\nu}_\mu \quad \bar{\nu}_\tau$

Neutrino detectors

Neutrino beams
Reactors

Neutrinos from Radioactive Sources (natural/man made)
Geo-Neutrinos
Atmospheric Neutrinos (from Cosmic Rays)

Astrophysical Neutrinos
from the Sun
Supernova explosions
other astrophysical sources
the Big Bang (so far unobservable)



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Neutrino sources
μeV
meV
eV
keV
MeV
GeV
TeV
PeV
EeV
Neutrino energy

Sun’s energy: where from ???

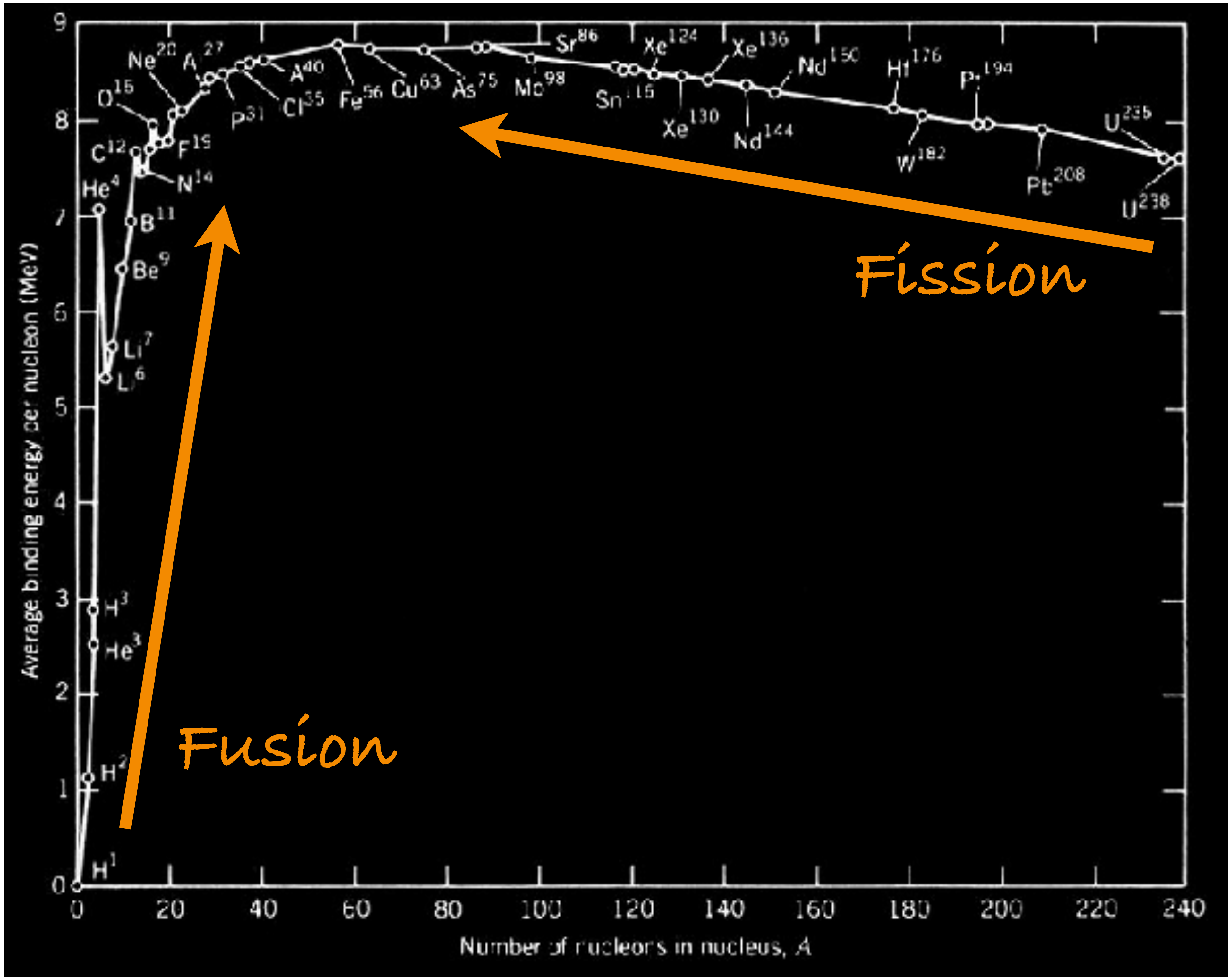
Hot surface means that energy is radiated away,
but luminosity,
temperature,
mass,
radius are stable over very long times.
(as evidenced by fossils)

Sun shines since > 10^9 years without much change.

Gravitational collapse of gas?
only sufficient for ≈ 5 x 10^7 years
Burning of suitable molecules (chemical)?

Much more energy is needed !!!

≈1920: Nuclear Energy powers the Sun



Thermonuclear Fusion:

Binding energy release when

H, He, C, ... is fused to He, C, ... Fe

4 x H	=	4 x 1.0079 u =	4.0316 u	1 u = 1.667×10^{-27} kg
1 x He	=		4.0026 u	= 1/12 of a ^{12}C atom

gain: ≈ 0.7% of mass is converted to energy

$E_{fusion} \approx 0.007\ M_{Sun} \times c^2 = 1.26 \times 10^{45}\ J \approx 1000 \times (E_{grav} + E_{therm})$

enough for ≈ 10^{11} years.

This became only apparent around 1920 !

Hydrogen Burning:

Basic process: $4\,p \longrightarrow {}^4He + 2e^+ + 2\nu_e + 27\ MeV$

effectively: 2 protons are converted in neutrons by β^+ decay

$p \longrightarrow n + e^+ + \nu_e$

Different ways to achieve this:

p-p chain:

dominant in the Sun
important for start without heavier elements than H and He,
i.e. for primordial matter.

p-e-p chain:

small probability

CNO cycle:

C, N, or O can act as catalyst
important at higher temperatures,
in Sun only a small (%) effect

p-p chain:

ν_e have different energies, depending on branch

$p + p \longrightarrow D + e^+ + \nu_e$ continuous E

$p + D \longrightarrow {}^3He + \gamma$

weak interaction, very slow, limits speed of the whole chain

1 $\quad {}^3He + {}^3He \longrightarrow {}^4He + 2\,p$ 85%, highest energy release

2 $\quad {}^3He + {}^4He \longrightarrow {}^7Be + \gamma$ 15%

a $\quad {}^7Be + e^- \longrightarrow {}^7Li + \nu_e$

$\searrow {}^7Li^* + \nu_e$ fixed E

${}^7Li + p \longrightarrow 2\,{}^4He$

b $\quad {}^7Be + p \longrightarrow {}^8B + \gamma$

${}^8B \longrightarrow {}^8Be + e^+ + \nu_e$ continuous E

${}^8Be \longrightarrow 2\,{}^4He$

3 $\quad {}^3He + p \longrightarrow {}^4He + e^+ + \nu_e$ continuous E 0.00002%

pep chain:

$$p + e^- + p \longrightarrow D + \nu_e$$ (fixed E)

weak interaction, slow, very small probability (since 3 body collision), mono-energetic ν_e

CNO Cycle: Hans Bethe, 1939

$$^{12}C + p \rightarrow {}^{13}N + \gamma$$

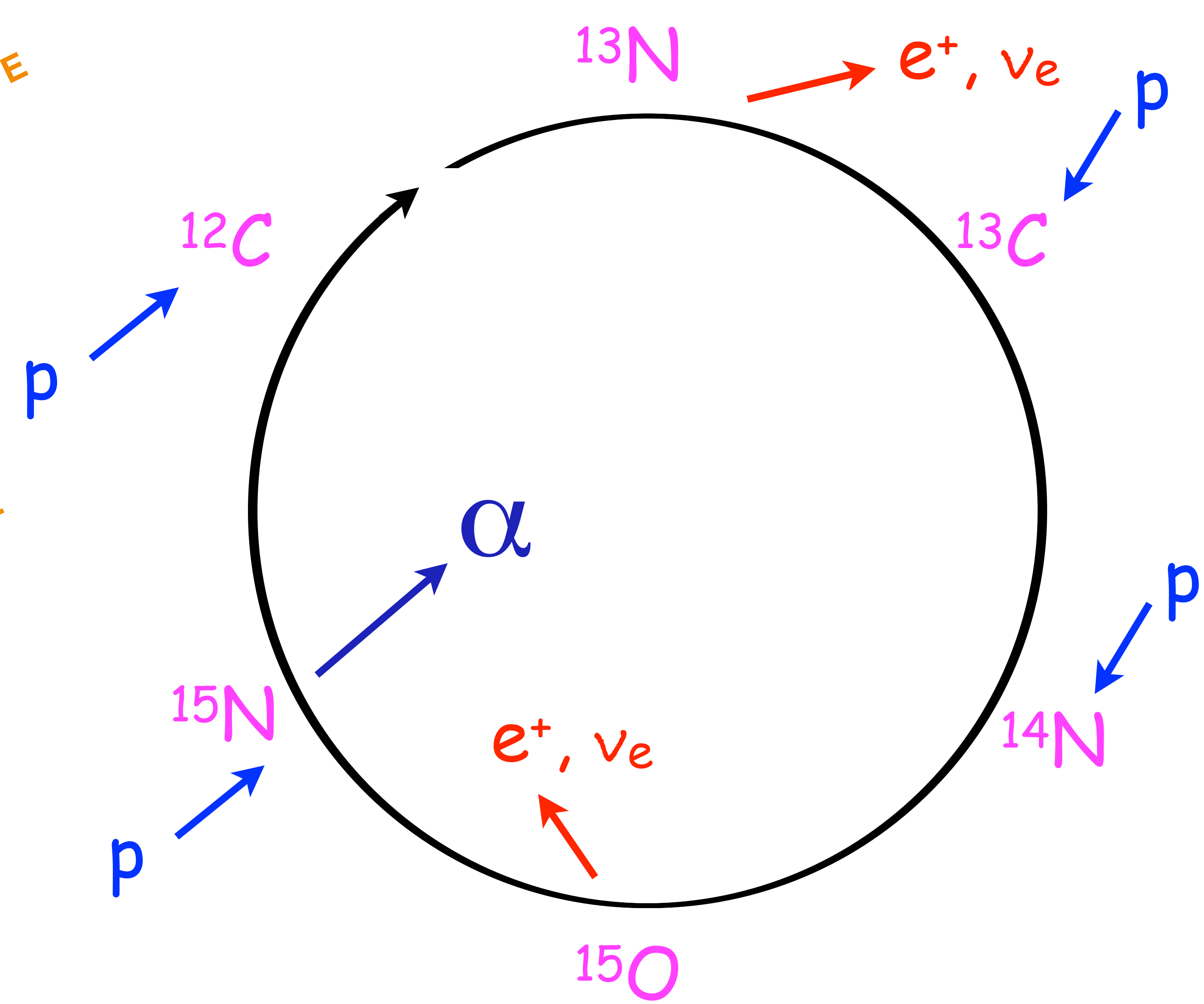
$$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$$ (continuous E)

$$^{13}C + p \rightarrow {}^{14}N + \gamma$$

$$^{14}N + p \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$$ (continuous E)

$$^{15}N + p \rightarrow {}^{12}C + \alpha$$



CNO serve as catalysts

Solar luminosity $L_{Sun} \approx 3.86 \times 10^{26}$ W = 2.4×10^{45} eV/s

fusion rate = L_{Sun} / 27 MeV $\approx 9 \times 10^{37}$ fusions /s

$9 \times 10^{37} \times 4$ u = $9 \times 10^{37} \times 4 \times 1.667 \times 10^{-27}$ kg =
602 million tons of Hydrogen
are processed to He per second

3.86×10^{26} J = $M c^2$ M = 4.29 million tons of matter
are converted into energy per second

If 10% of solar matter (H) can be fused to He,
then the Sun can shine for $\approx 10^{10}$ years.

Currently, the solar system is $\approx 4 \times 10^{9}$ yrs old.

Solar luminosity $L_{Sun} \approx 3.86 \times 10^{26}$ W = 2.4×10^{45} eV/s

ν_e production rate = $2 \times L_{Sun}$ / 27 MeV $\approx 1.8 \times 10^{38}$ ν_e /s

at Earth: 6.3×10^{10} ν_e / (cm^2 s)

i.e. the Sun is a very strong ν_e source!

Measure the solar ν_e flux to check solar energy production
i.e. look into centre of the Sun.

Solar neutrino experiments since $\approx$ 1970:

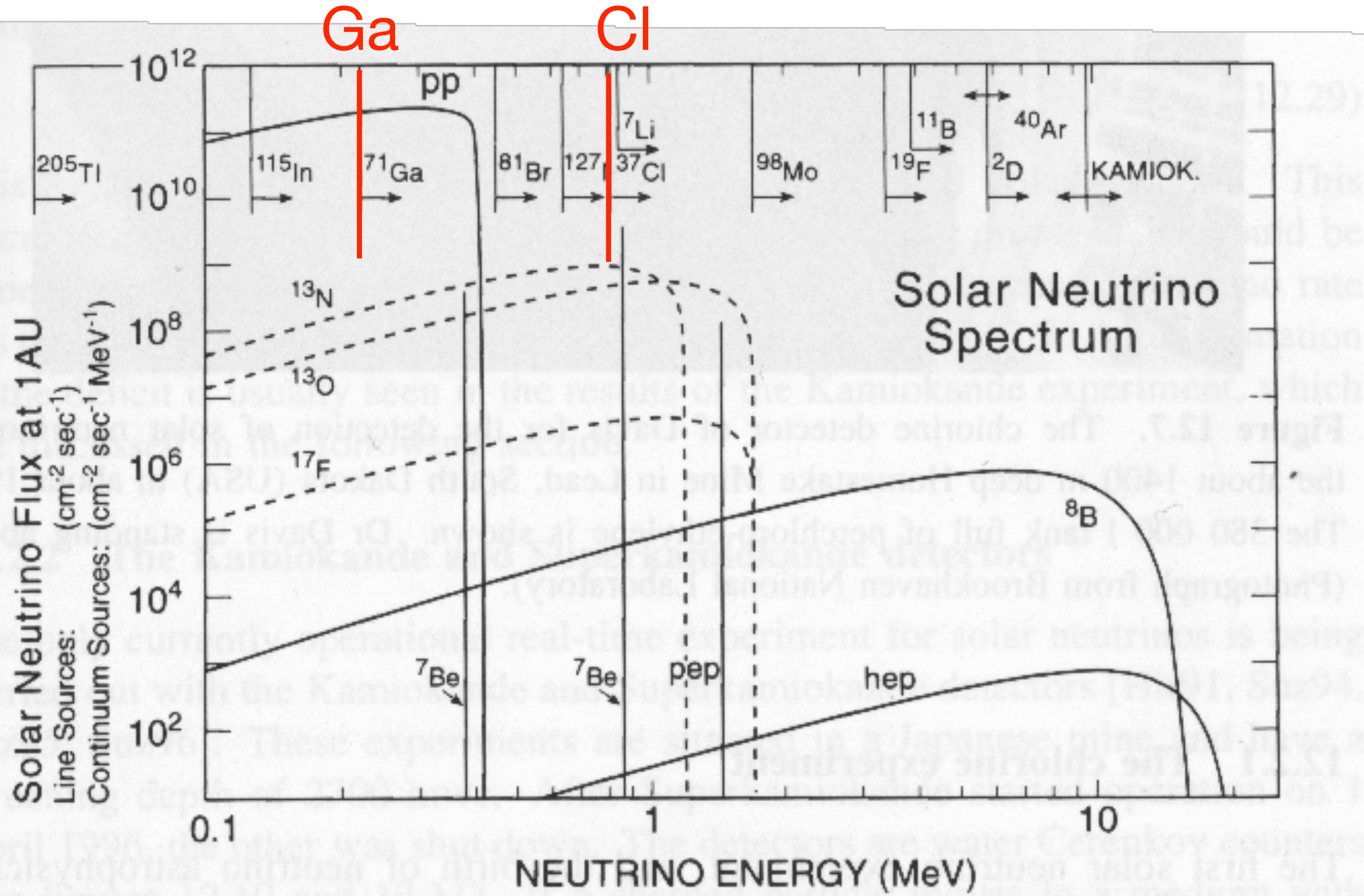


Figure 12.6. The solar neutrino spectrum at the Earth, as predicted by detailed solar model calculations. The dominant part comes from the *pp* neutrinos, while at high energy *hep* and ^{8}B neutrinos dominate. The threshold energies of different detector materials are also shown (see e.g. [Ham93]).

Chlorine Experiment

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

${}^{37}Ar + e^- \longrightarrow {}^{37}Cl + \nu_e$ EC, $\tau \approx 35$ days

$E_\nu > 0.81$ MeV i.e. only ν_e from ^{8}B, ^{8}Be, pep, hep can do it.

Ray Davis, Homestake Mine, USA

measurements: 1968 - 1995 !

610 tons C_2Cl_4 ~ 10^{30} nuclei cleaning liquid, cheap

once per month: Ar atoms are washed out,
concentrated in small detector,
and counted when they decay.

Ray Davis: Experiment
John Bahcall: Solar Model

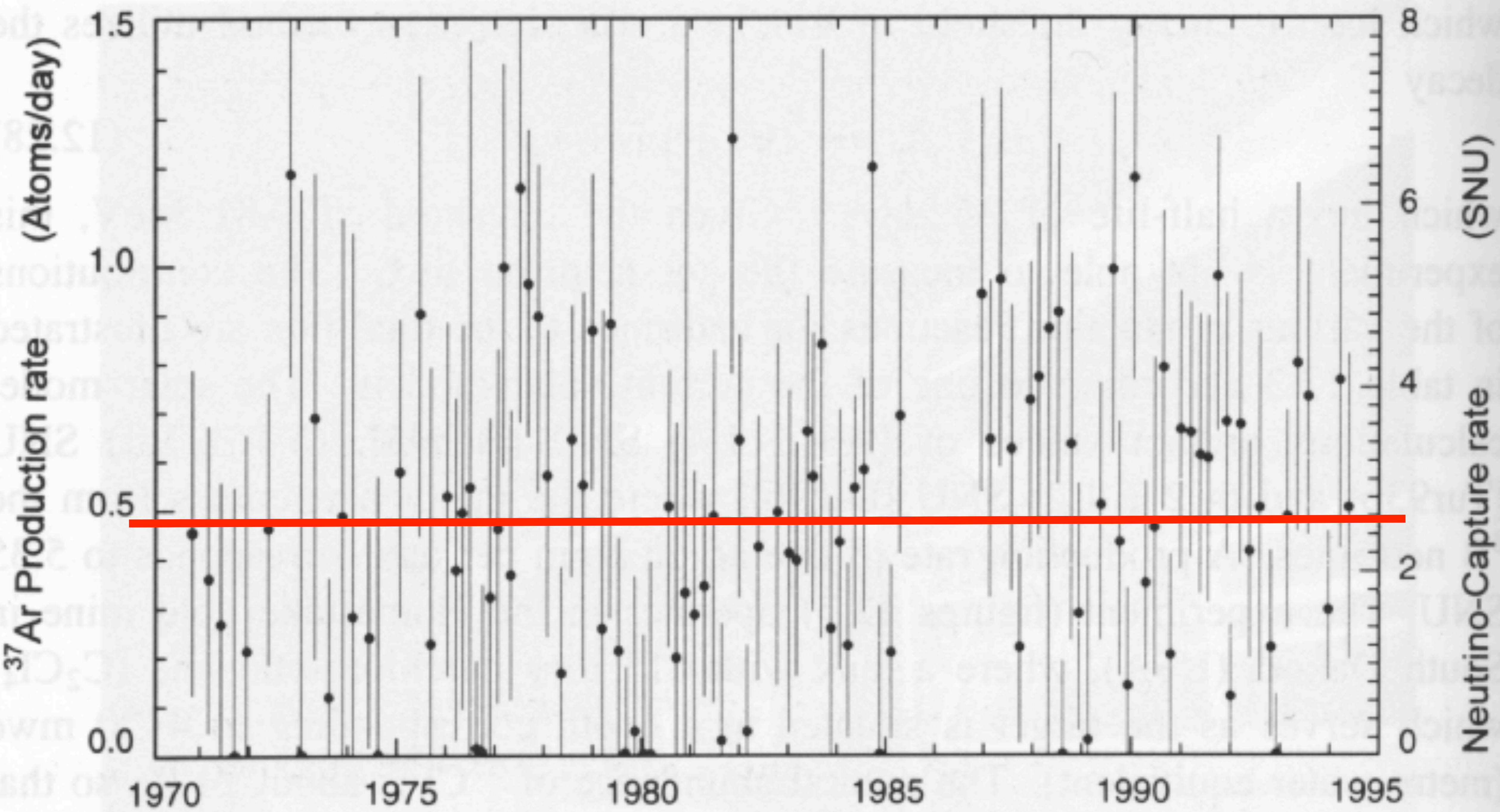


Figure 12.8. The neutrino flux measured from the Homestake ^{37}Cl detector since 1970. The average measured value (broken line) is significantly smaller than the predicted one. This discrepancy is the origin of the so-called solar neutrino problem (from [Dav96]).

measured: ~1 atom / 2 days

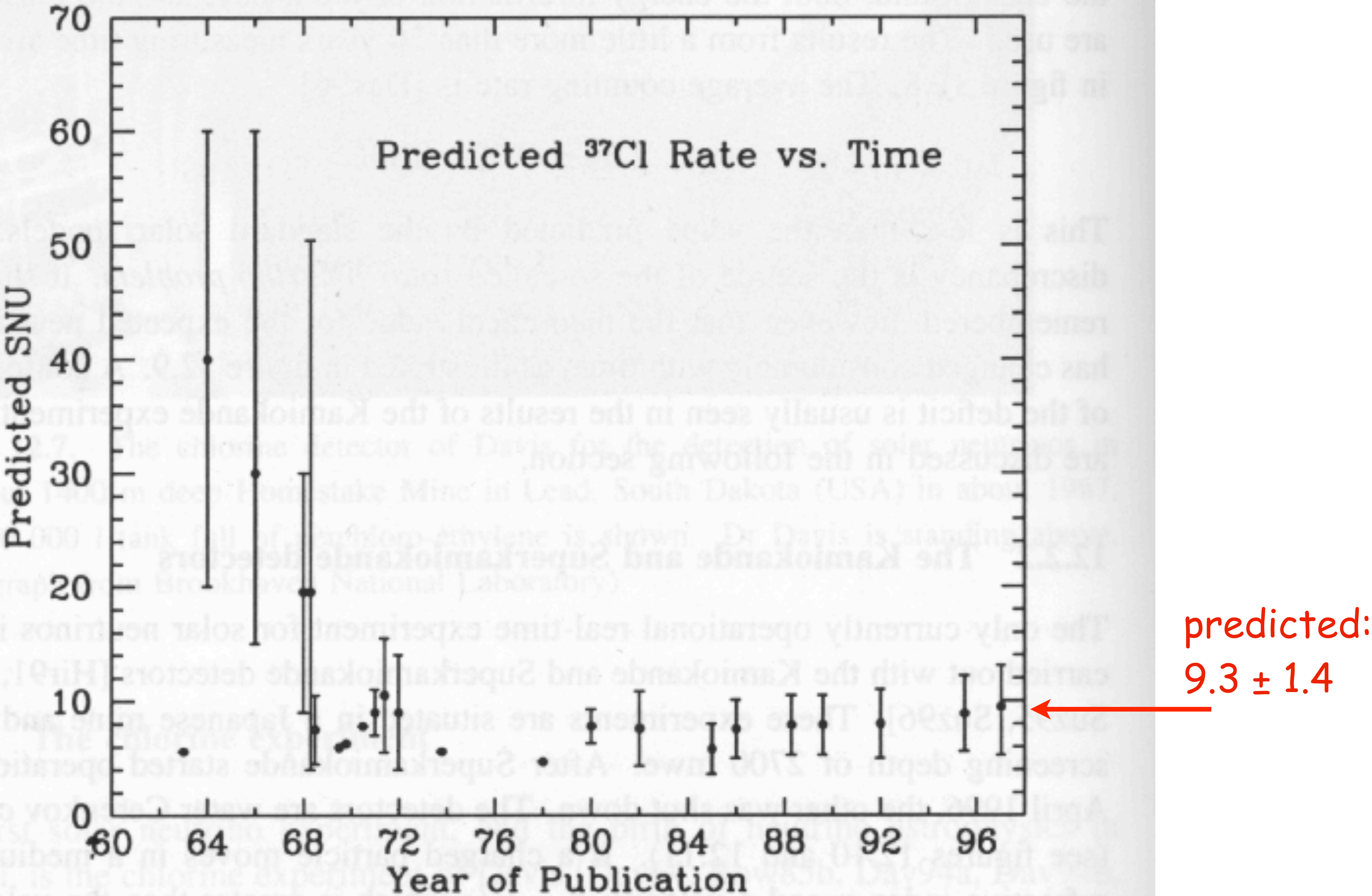


Figure 12.9. Time development of the event rate predicted for the chlorine detector during the last 30 years (error bars correspond to 1σ) (with kind permission of J N Bahcall).

Expectations : 9.3 ± 1.3 SNU (SNU: solar neutrino unit)

6.4 ± 1.4 varying with theoretical assumptions

4.1 ± 1.2

clear deficit

Experiment : 2.56 ± 0.22 SNU

"solar ν problem"

Is the standard solar model wrong ?

Is the nuclear physics wrong ?

New physics (e.g. ν oscillations) ?

^{37}Cl tests only ν from (rather unimportant) side branch of the pp chain.

Can the main reaction $p\,p \longrightarrow D + e^{+} + \nu$ be tested?

Gallium Experiment

$\nu_e + {}^{71}Ga \longrightarrow {}^{71}Ge + e^-$

$\quad {}^{71}Ge + e^- \longrightarrow {}^{71}Ga + \nu_e$ EC, $\tau \approx 11$ days

$E_\nu > 0.233$ MeV i.e. also pp neutrinos can do it.

Gallex (D, I), SAGE (Russia, US) 1991 - 1995

used world production of Ga for several years (very expensive)

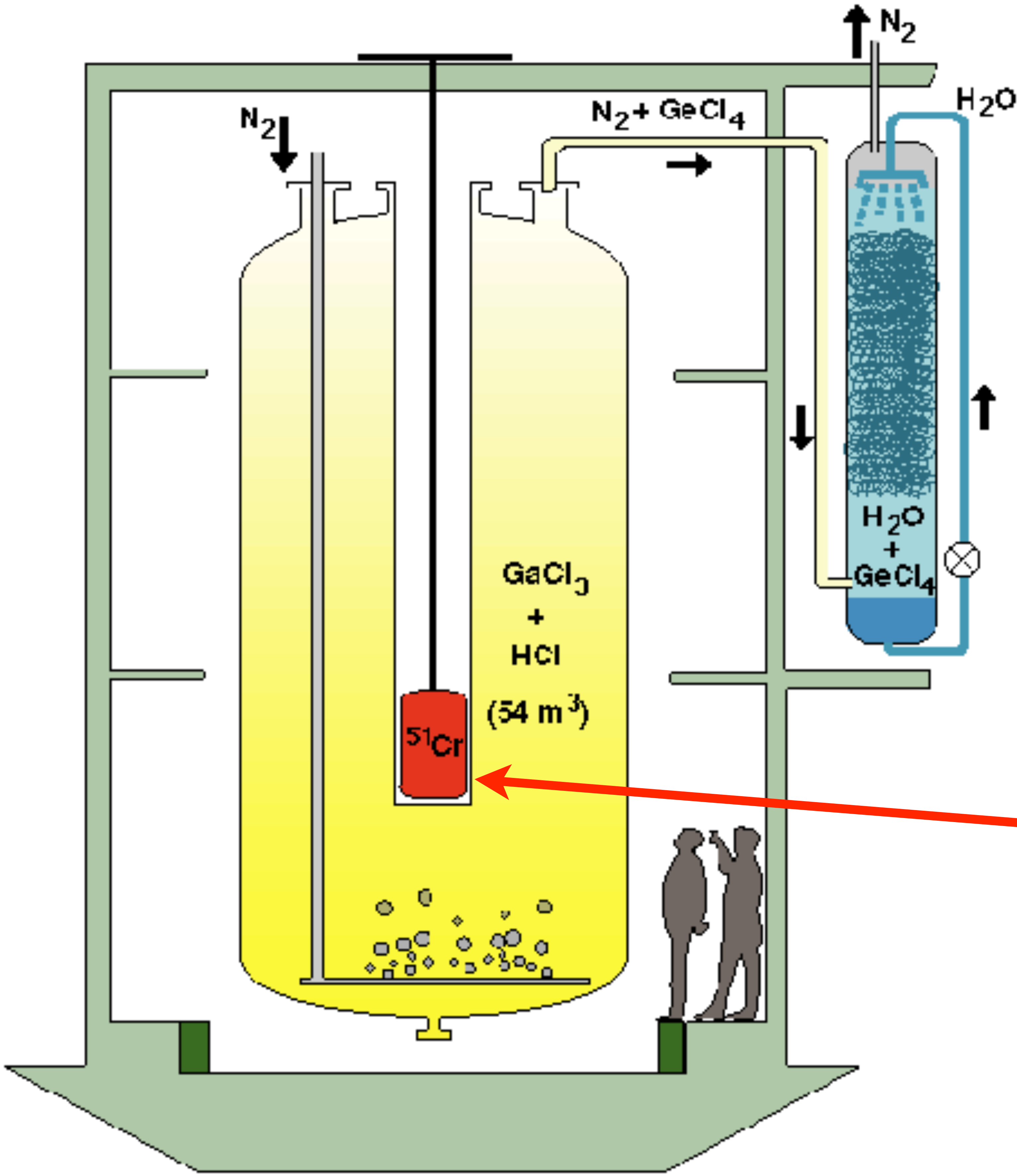
Result: 70 ± 7 SNU

expected: 132 ± 20
123 ± 14
115 ± 6

also clear deficit

for calibration: use strong ν_e source.

measurement and expectations agree, i.e. technique is ok.



strong radioactive source for calibration of extraction mechanism:

^{51}Cr electron capture

63×10^{15} Bq !!!

Radiochemical experiments (Chlorine, Gallium) average over time, no direct (i.e. real time) detection.

Kamiokande, Super Kamiokande, Japan

huge water volume viewed by many photomultiplier tubes,

a real time experiment

$\nu_e + e^- \longrightarrow \nu_e + e^-$ simple scattering

e^- gains energy and produces Cherenkov light in water.

direction of e^- $\approx$ direction of ν_e

$E_\nu > E_e > 7.5$ MeV i.e. only ^8B neutrinos are detected

Result:

ν_e come from Sun, but also 50% deficit

Kamikande:

KAMIOKANDE: Kamioka Nucleon Decay Experiment)
tank with 3000 tons of pure water, 1000 photomultiplier tubes (PMTs)
16 m heigh, 16 m in diameter

Masatoshi Koshiba

Nucleons did not decay, but neutrinos were seen interacting.
– neutrinos from the atmosphere
– neutrinos from SN 1987a:

Kamiokande Solar neutrinos (^8B)

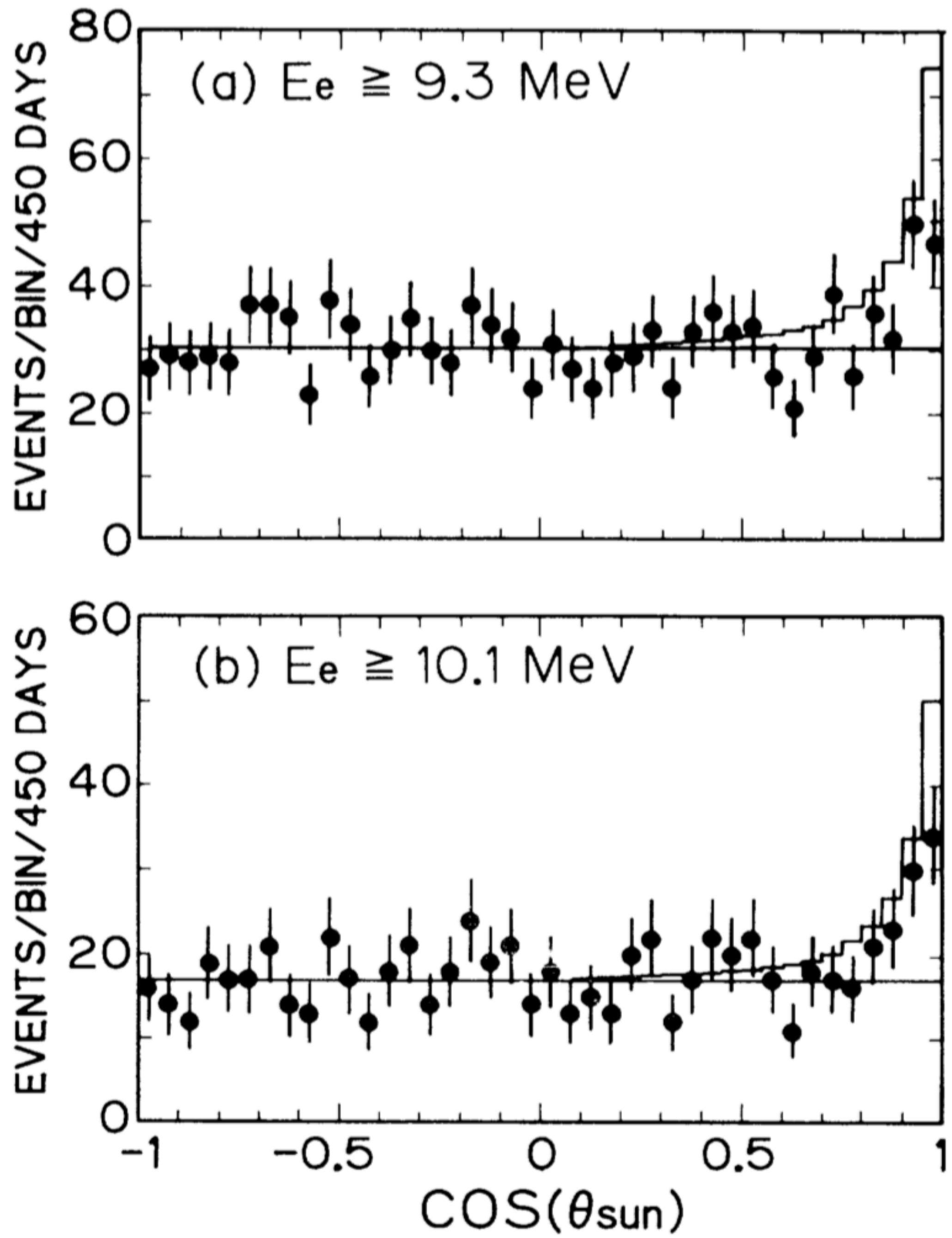


FIG. 2. Distributions in $\cos\theta_{Sun}$, the cosine of the angle between the trajectory of an electron and the direction of the Sun at a given time. The data are in the 680-ton fiducial region (a) with $E_e \geq 9.3$ MeV and (b) with $E_e \geq 10.1$ MeV, respectively. Events identified as spallation products or remaining γ rays have been excluded.

Sees only 46% of expectation

Also a deficit !

Kamiokande SN1987a

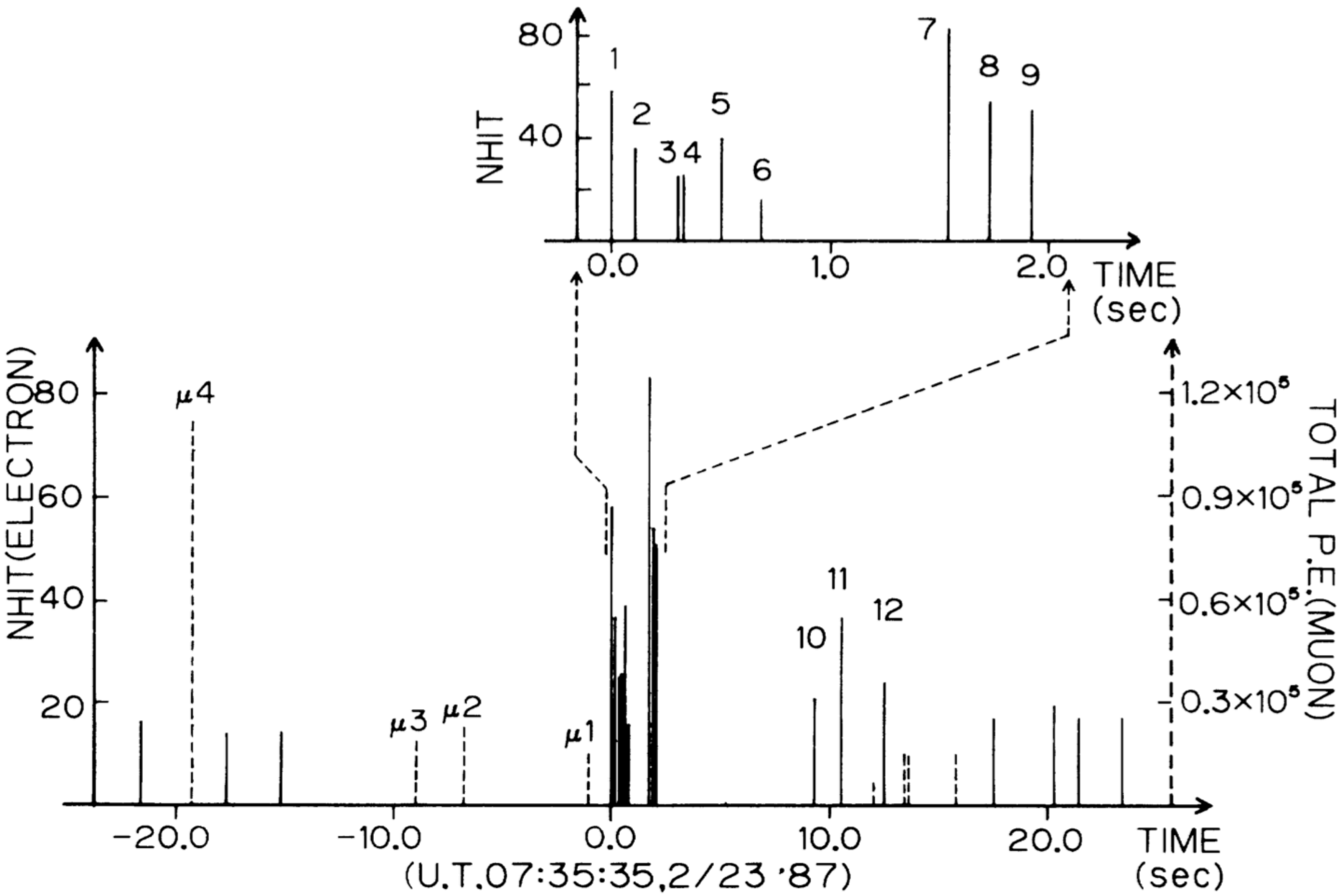
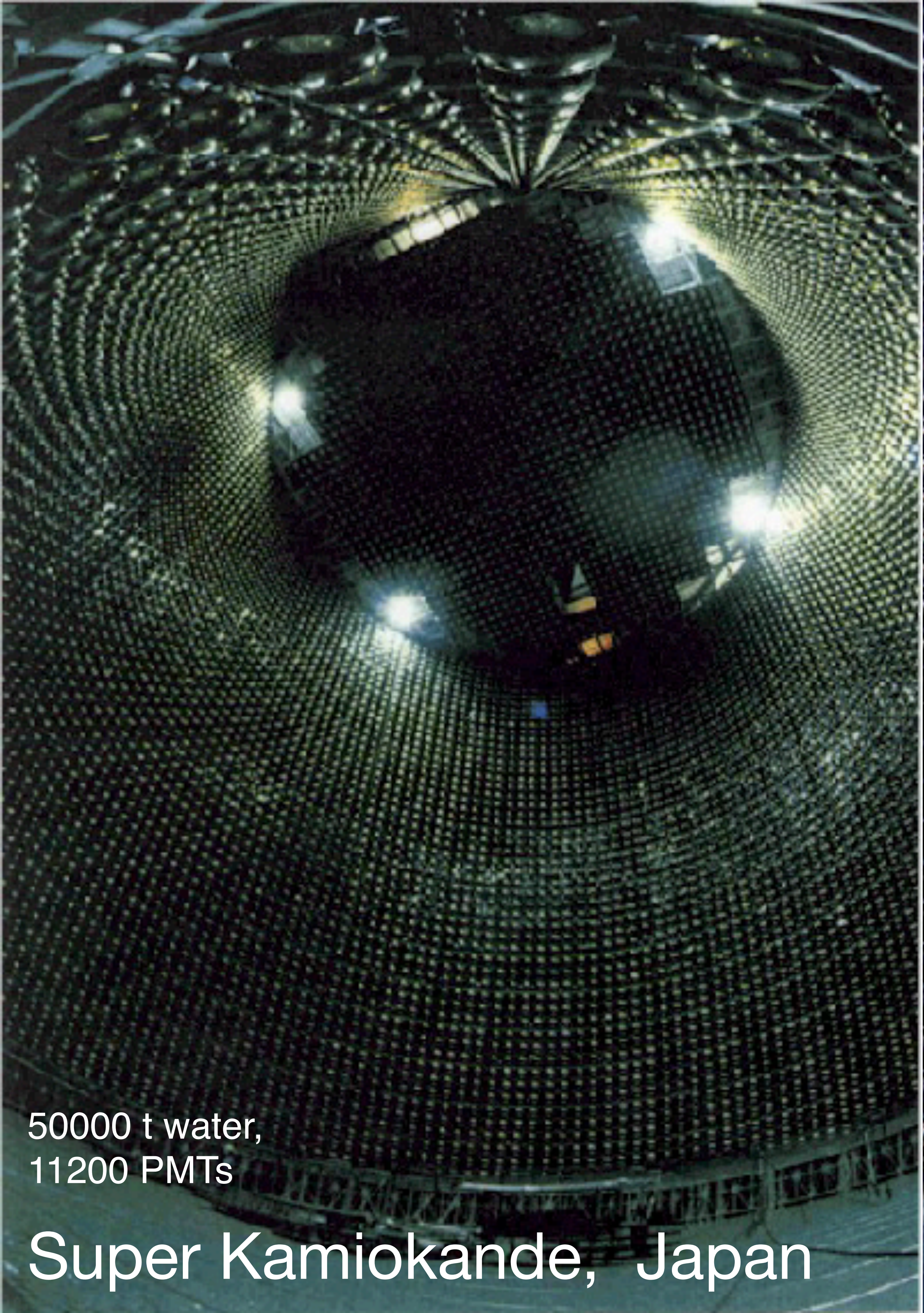
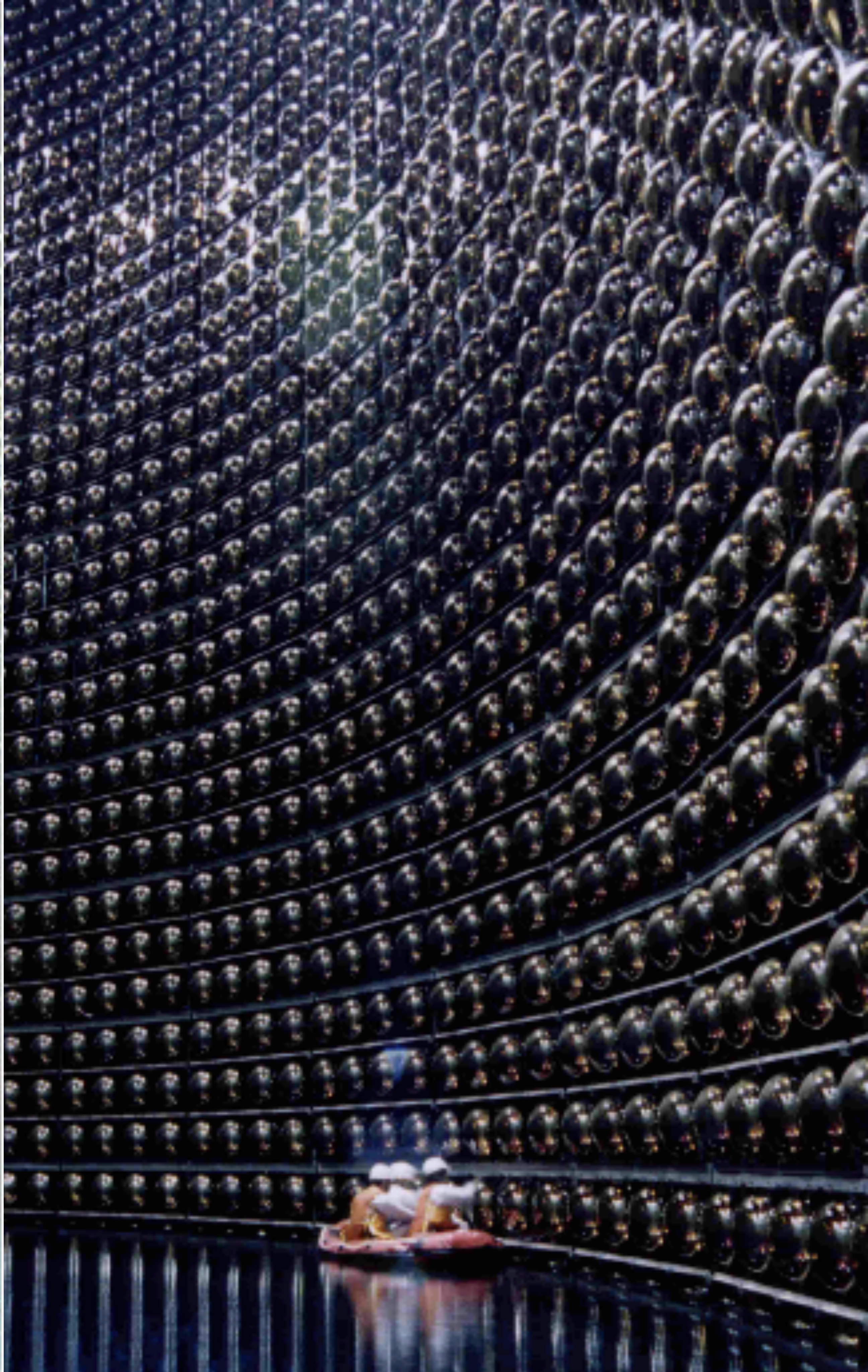
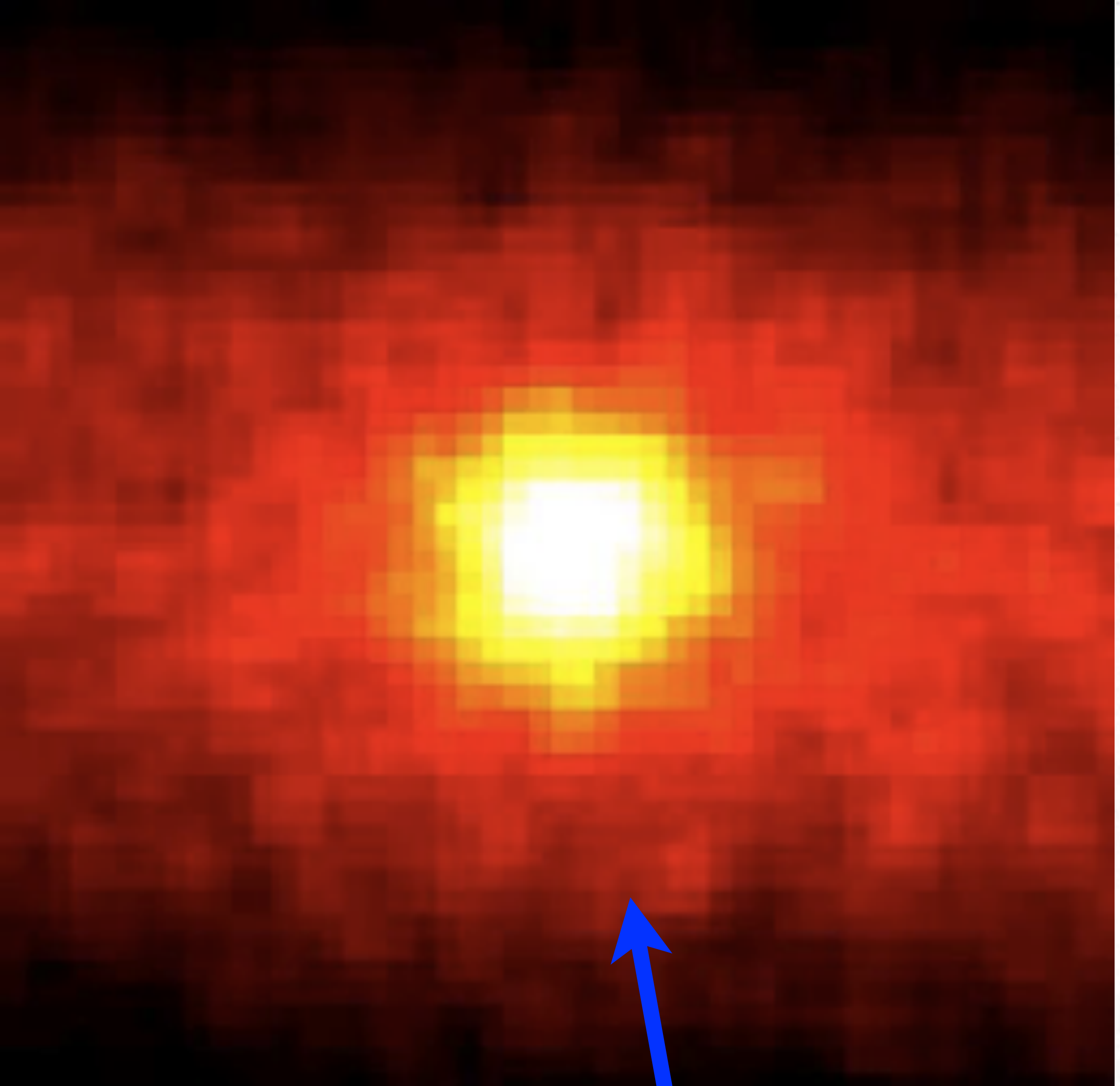


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu 1-\mu 4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0–2-sec time interval on an expanded scale.


50000 t water,
11200 PMTs
Super Kamiokande, Japan





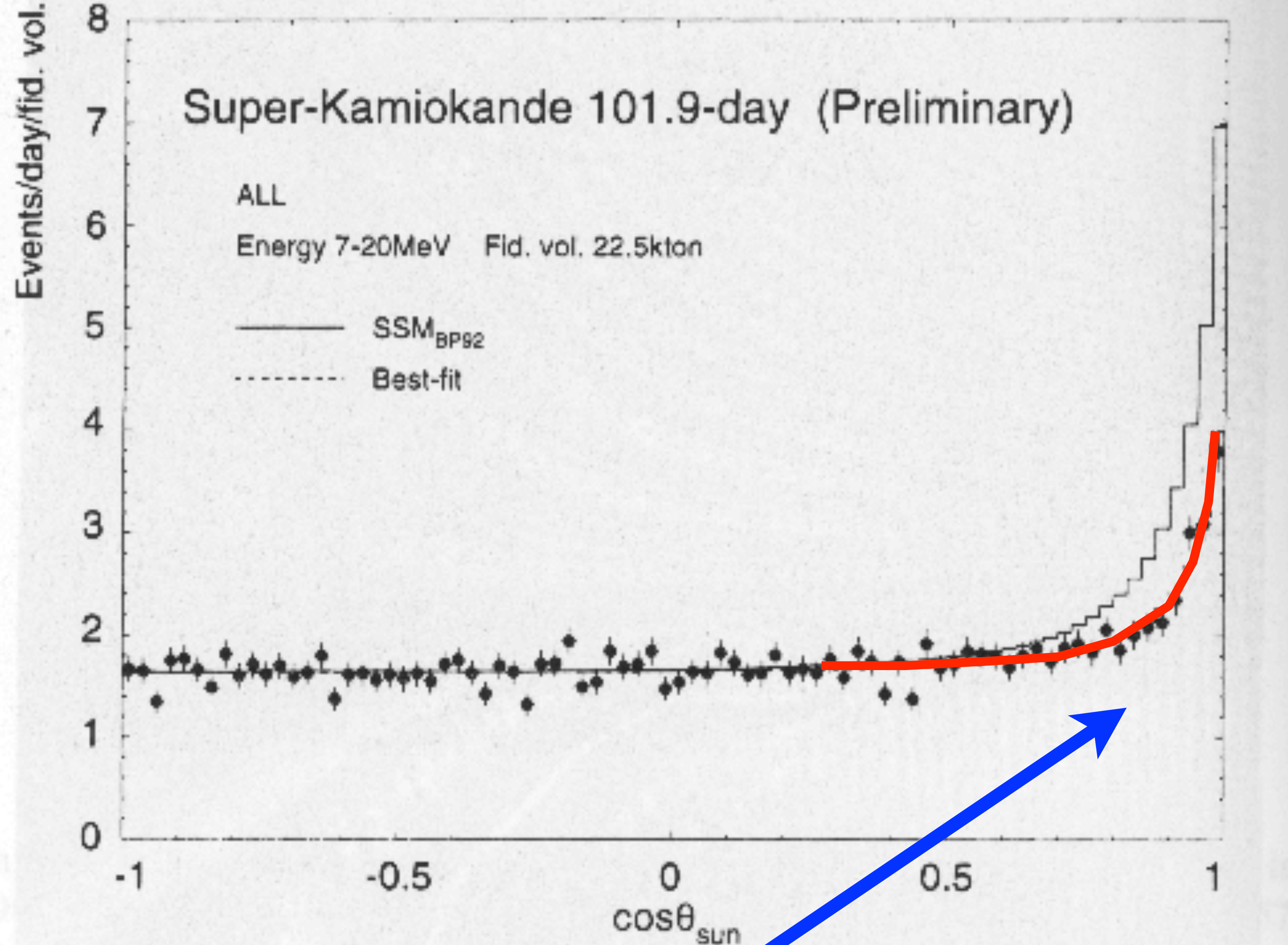


Figure 12.15. Angular distribution of the events in the Superkamiokande detector, relative to the direction of the Sun, after a measuring time of 102 days (from [Suz97]).

Neutrinos do come from the Sun, but also here a deficit

Now accepted explanation for solar neutrino problem:

Neutrino Oscillations:

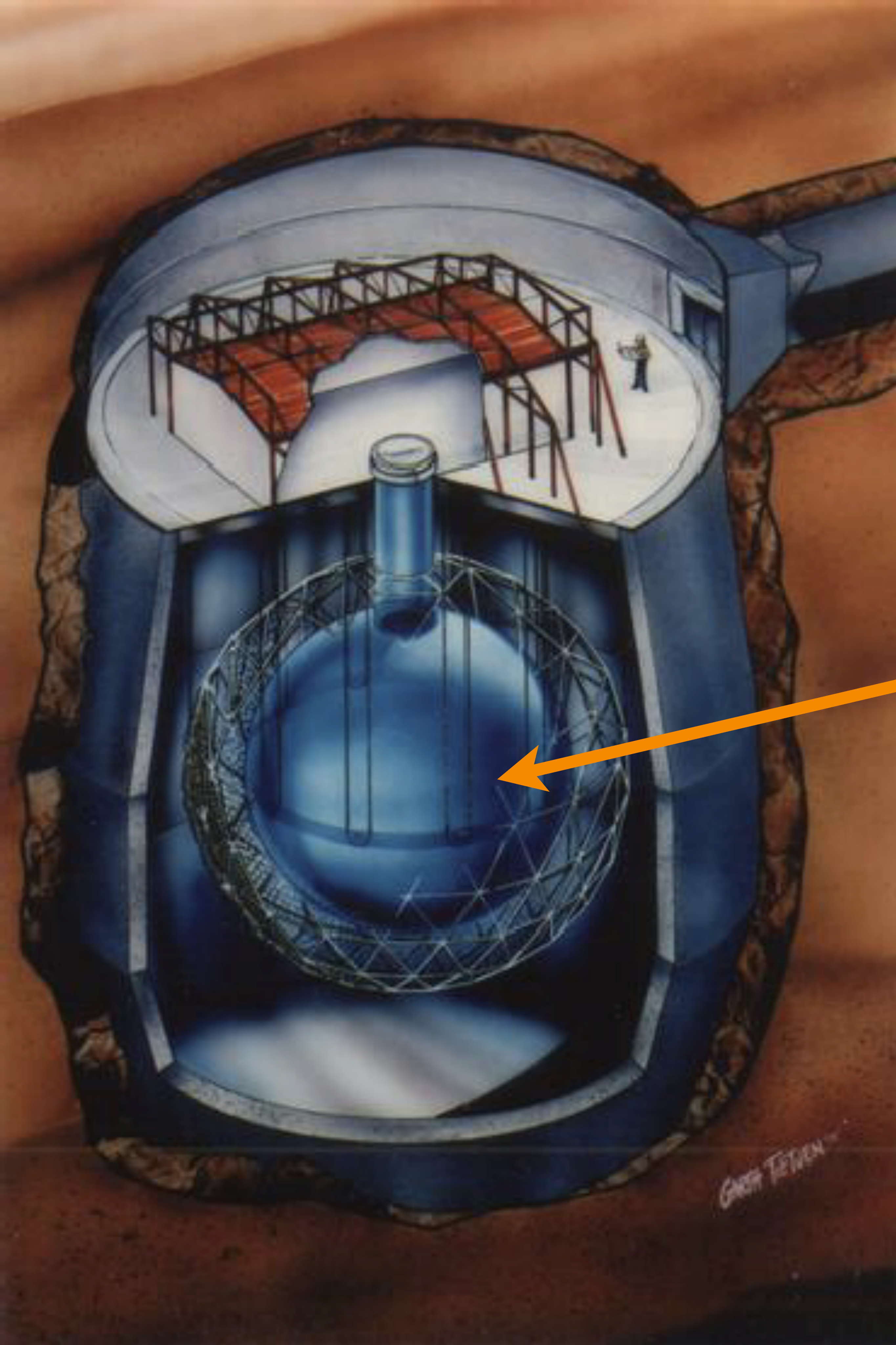
ν_e undergo change on their way from Sun to Earth

$\nu_e \longrightarrow \nu_\mu$ or $\nu_e \longrightarrow \nu_\tau$

ν_μ and ν_τ cannot be detected with aforementioned detectors (Chlorine, Gallium, Kamiokande)

Oscillations require $m_\nu \neq 0$ and $m_{\nu e} \neq m_{\nu\mu} \neq m_{\nu\tau}$

with big consequences for particle physics and cosmology.



Sudbury Neutrino Observatory SNO

Canada, US, UK (Oxford)

2300 m underground
to shield Cosmic Rays

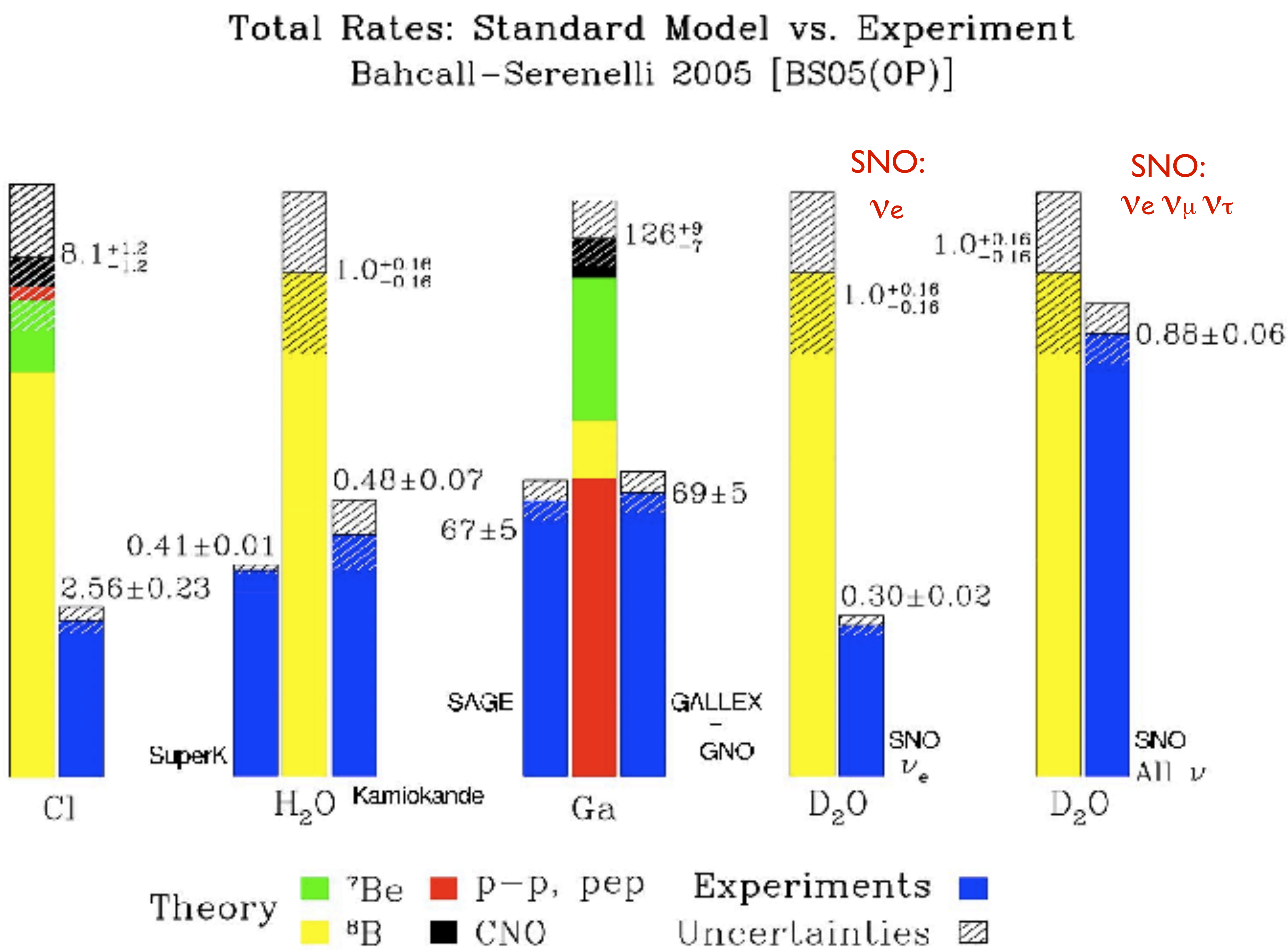
1000 t heavy water (D_2O)
viewed by 9600 PMTs
surrounded by normal water

Idea: measure ALL neutrinos

$\nu_e + {}_{Z}A \longrightarrow {}_{Z+1}A + e^-$ inverse EC

$\nu_x + D \longrightarrow \nu_x + p + n + 1.2\ \mathrm{MeV}$

neutral current



Total Rates: Standard Model vs. Experiment
Bahcall-Serenelli 2005 [BS05(OP)]
SNO:
νe
SNO:
νe νμ ντ
8.1 +1.2 −1.2
1.0 +0.16 −0.16
126 +9 −7
1.0 +0.16 −0.16
1.0 +0.16 −0.16
0.88±0.06
0.48±0.07
0.41±0.01
2.56±0.23
67±5
69±5
0.30±0.02
SAGE
GALLEX
–
GNO
SuperK
SNO
νe
SNO
All ν
Cl
H2O
Kamiokande
Ga
D2O
D2O
Theory
7Be
8B
p−p, pep
CNO
Experiments
Uncertainties

Do neutrinos have mass ?

number of ν in universe: ~ 350 /cm^3

($\approx$ number of photons)

relics from Big Bang
produced in stars and stellar explosions ....

solar ν suggest: $m_\nu > 0$

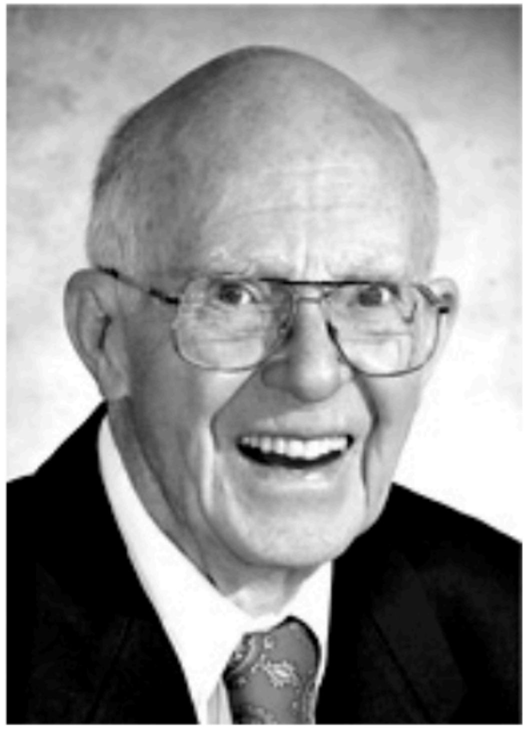
β-decay suggests: $m_{\nu e} <$ few eV/c^2

upper limits from tritium decay: $m_{\nu e} < 2$ eV

from CMBR (indirect): $m_{\nu e} < 0.25$ eV

.... not enough to explain "Dark Matter"

The Nobel Prize in Physics 2002



Raymond Davis Jr.
Prize share: 1/4

Masatoshi Koshiba
Prize share: 1/4

Riccardo Giacconi
Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

The Nobel Prize in Physics 2015

Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

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

Summary:

Neutrinos went from an obscure theoretical idea to
an important part of our elementary particle zoo.

It has weak interaction (no electromag., strong interaction).
It is very difficult to detect.

Still produced in many places and give us much information
on the Earth, the Sun, Stars, Galaxies, the Big Bang.

Neutrinos have mass, but we do not know which: $\sum M_\nu < 0.2$ eV

They oscillate into each other, seen in
solar, atmospheric, beam and reactor neutrinos

… was always good for surprises.