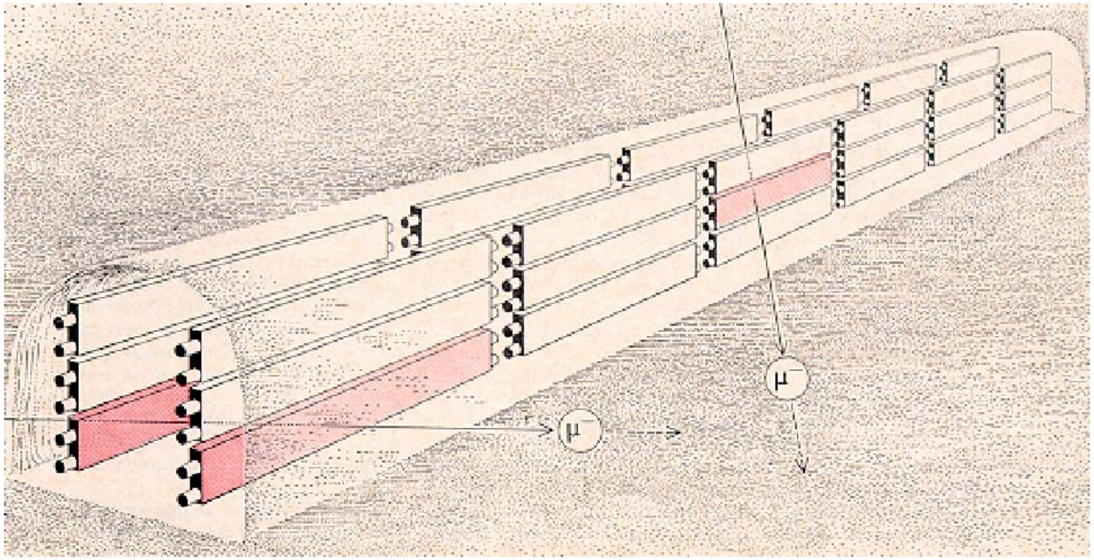
Atmospheric Neutrinos

Part 1: 1930 – 1990



Mark Vagins

IPMU, University of Tokyo/UC Irvine

SLAC Summer Institute

August 12, 2010

First off, I want to tell you that my lectures will probably seem a bit different than most of the ones you've been listening to for the last two weeks.

Sure, there will be the expected plots and equations, but there will also be stories, funny drawings, and perhaps even the occasional swear word.

So, let's get to it…


Zzzzz...

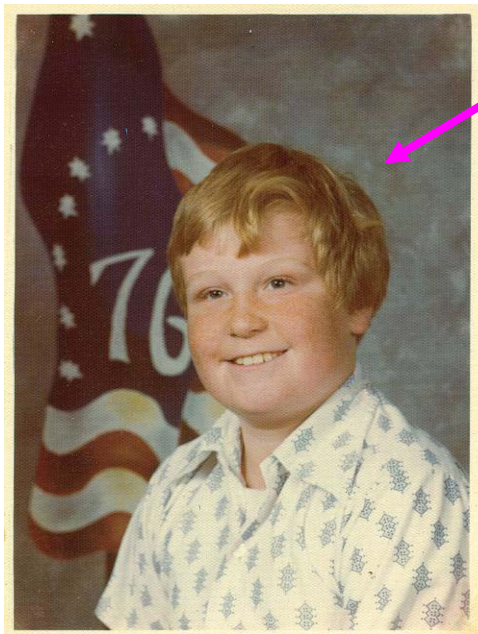
You will also notice right away that this is going to be a very experiment-centered talk.

Why?

Because I’m a very experiment-centered guy…

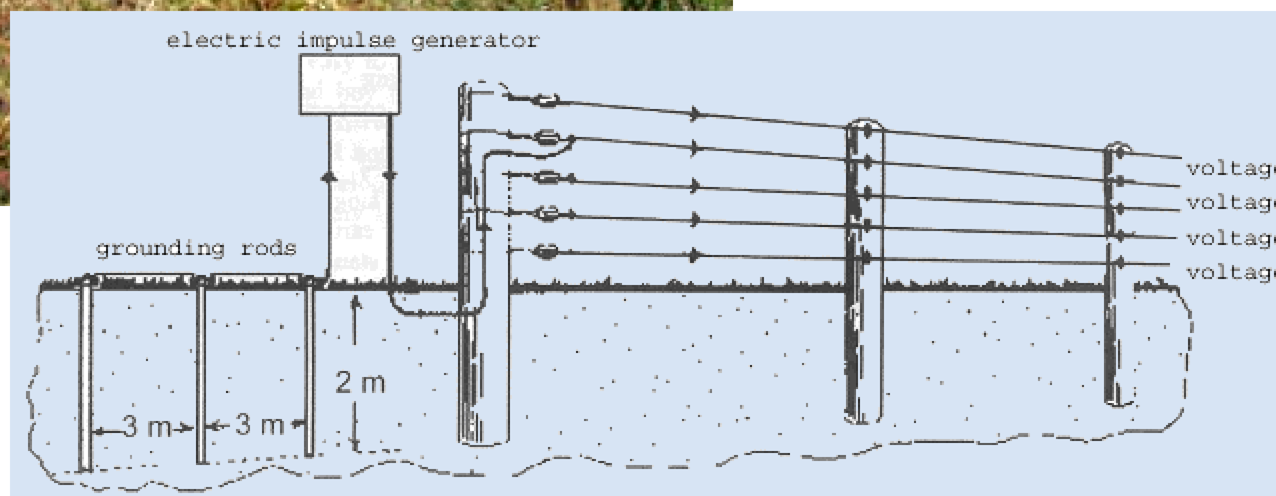
To illustrate, let's use a telling example from when I was 8 years old…

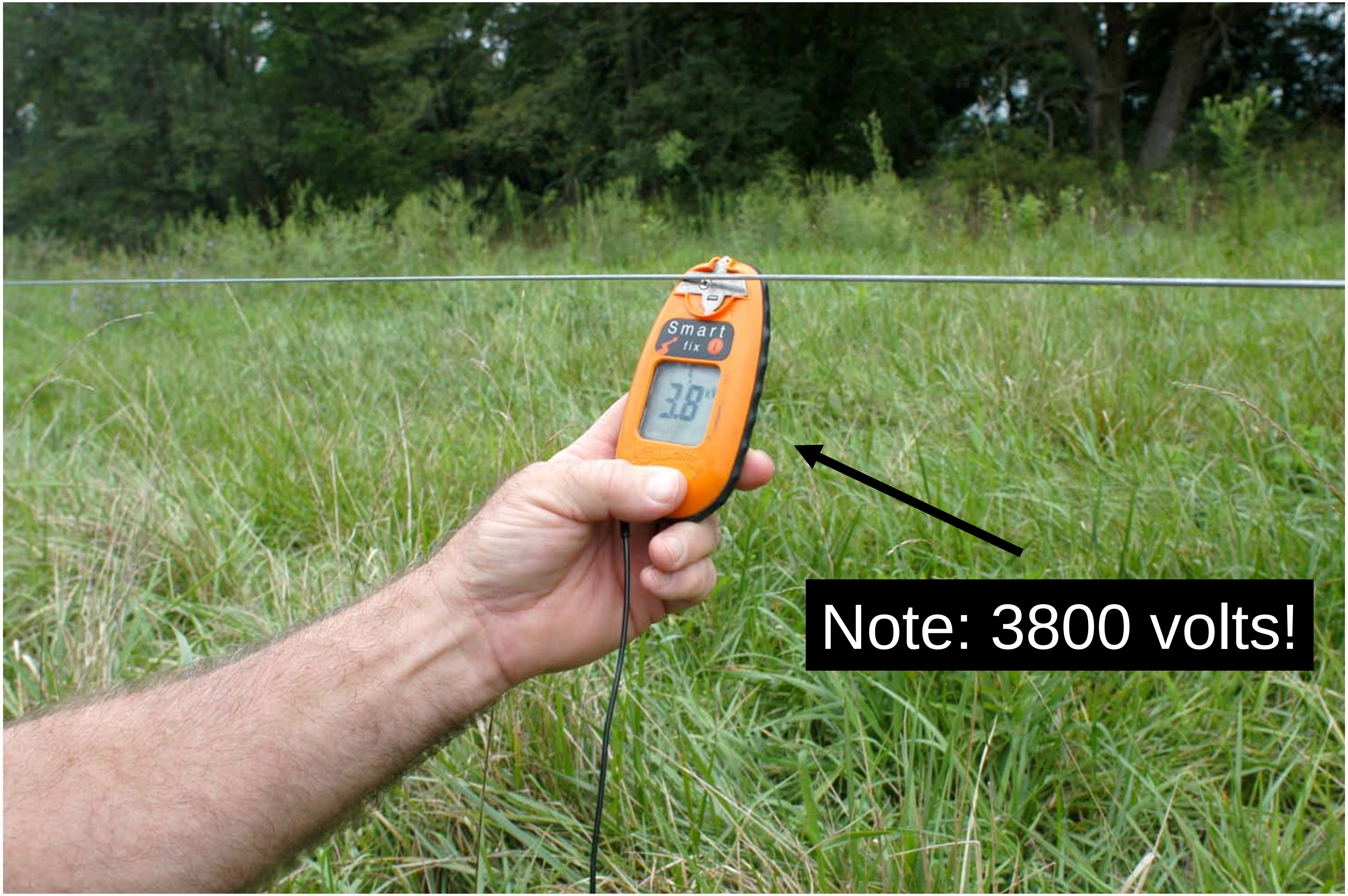
Hair!



Note shirt

Family vacation = long drive

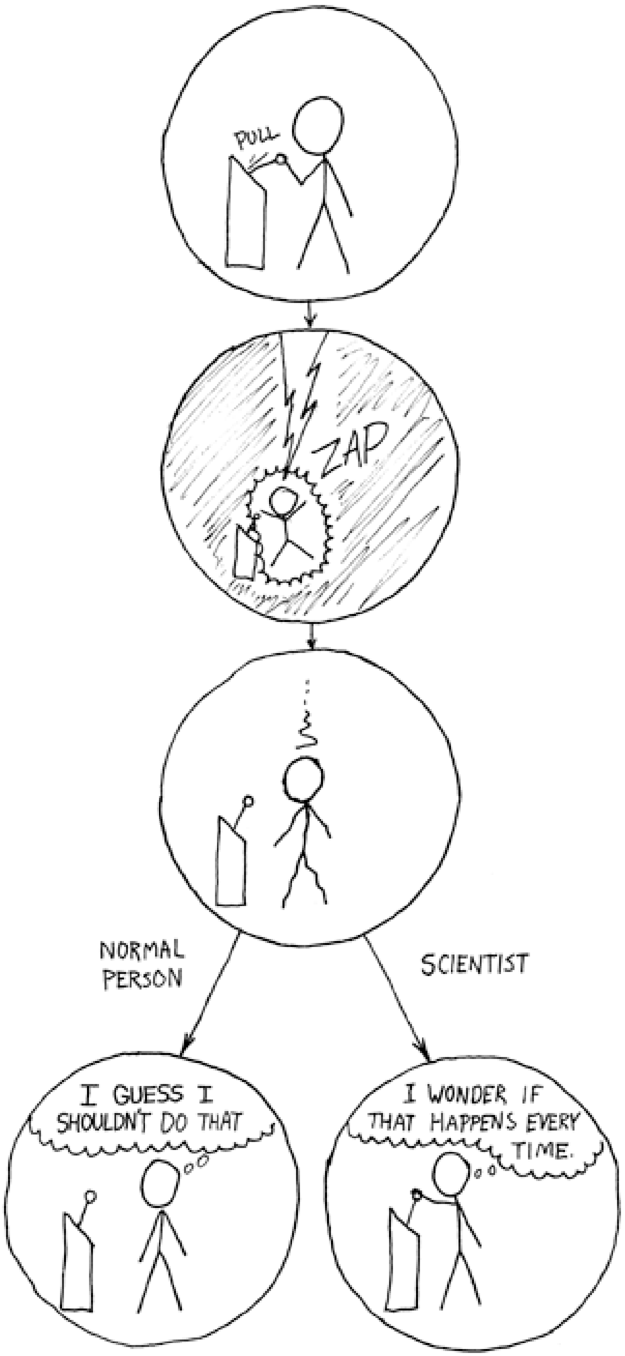

electric impulse generator
grounding rods
2 m
3 m
3 m
voltage
voltage
voltage
voltage


Smart
fix
3.8 kV
Note: 3800 volts!

Testing

See, Mom, I *told* you it was electric!

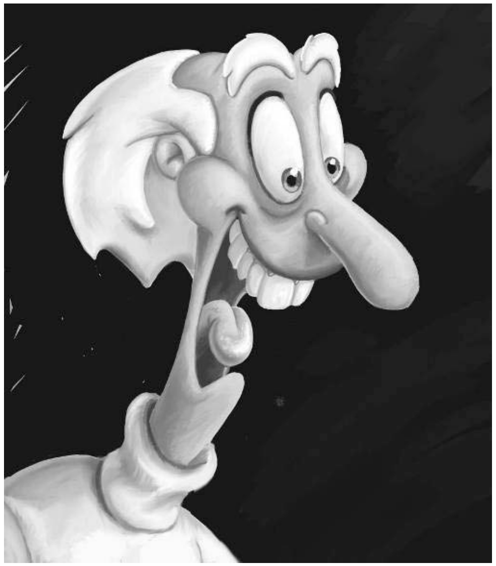
A career in experimental science was calling…



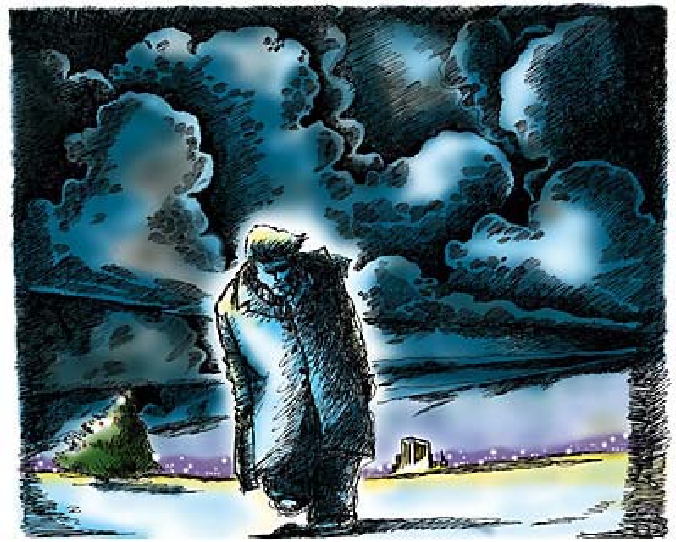
Just two days ago I saw this xkcd cartoon called "The Difference" posted at a coffee shop near the Institute for Nuclear Theory in Seattle.

And indeed, I have had many encounters with high voltage since that day back in the mid-70's.

I’m going to tell you all about atmospheric neutrinos, and in the process you will hear tales of:



boundless ambition



catastrophic failure

and just a touch of madness

triumphant discovery

Let’s start at the very beginning (a very good place to start):

Original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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

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

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

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

gez. W. Pauli

Wolfgang Pauli’s famous 1930 letter in which the neutrino – called the “neutron” until Fermi renamed it in 1934 – was first proposed.

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, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light.

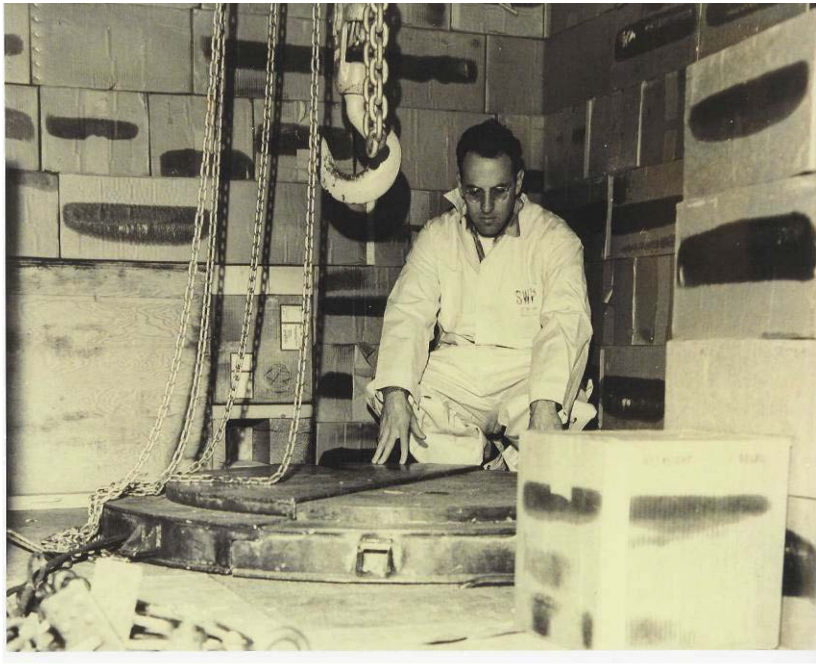
I agree that my remedy could seem incredible…
But only the one who dare can win…
…dear radioactive people, look and judge.

Your humble servant
W. Pauli

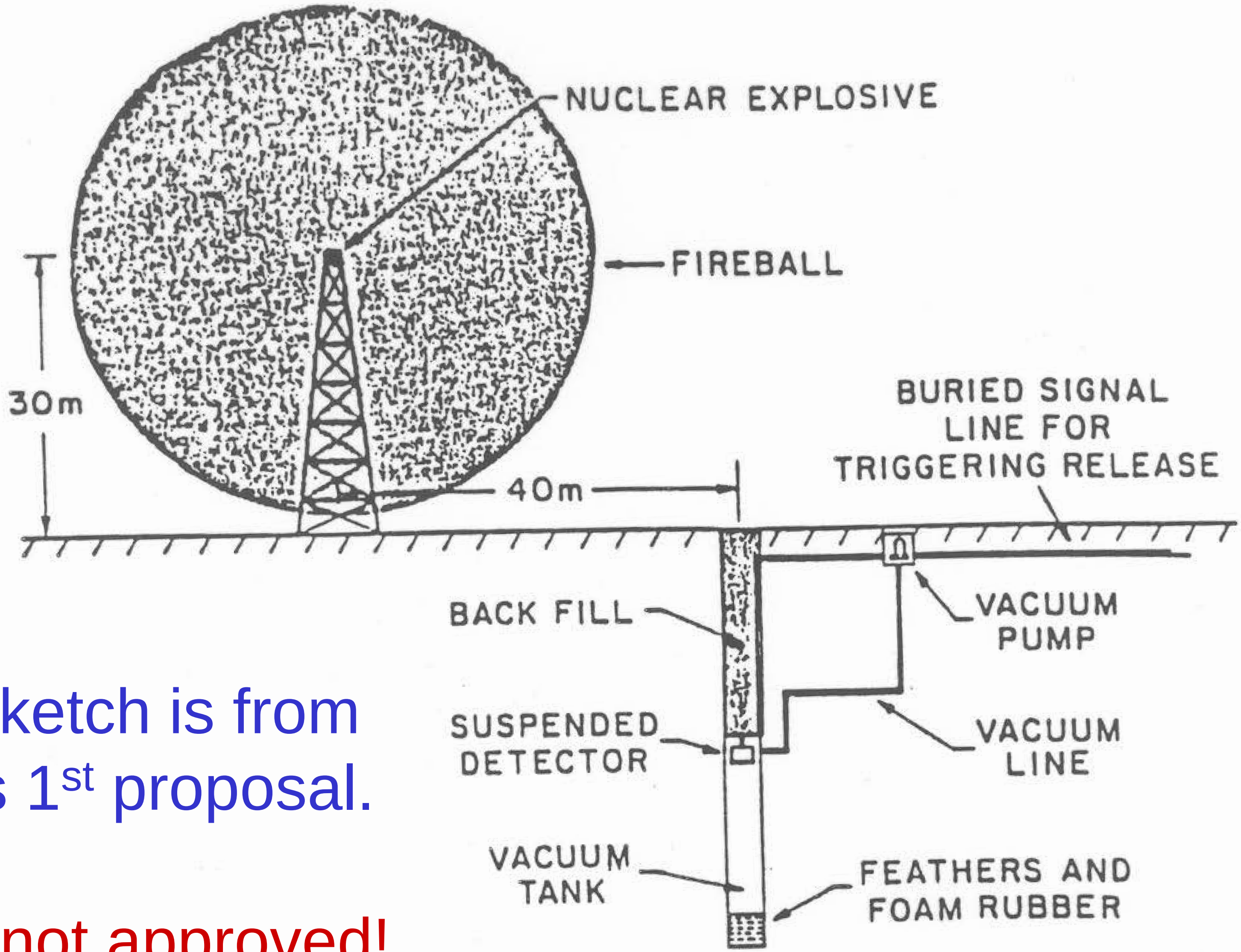
Pauli thought this idea was so crazy he didn't publish it!

Twenty years later, along came the first really serious proposal to detect neutrinos.

It was suggested by a 32 year old named Frederick Reines, a protégé of an even younger (well, 63 days younger) Richard Feynman.



However, this proposal probably isn't the experiment you're thinking of right now.



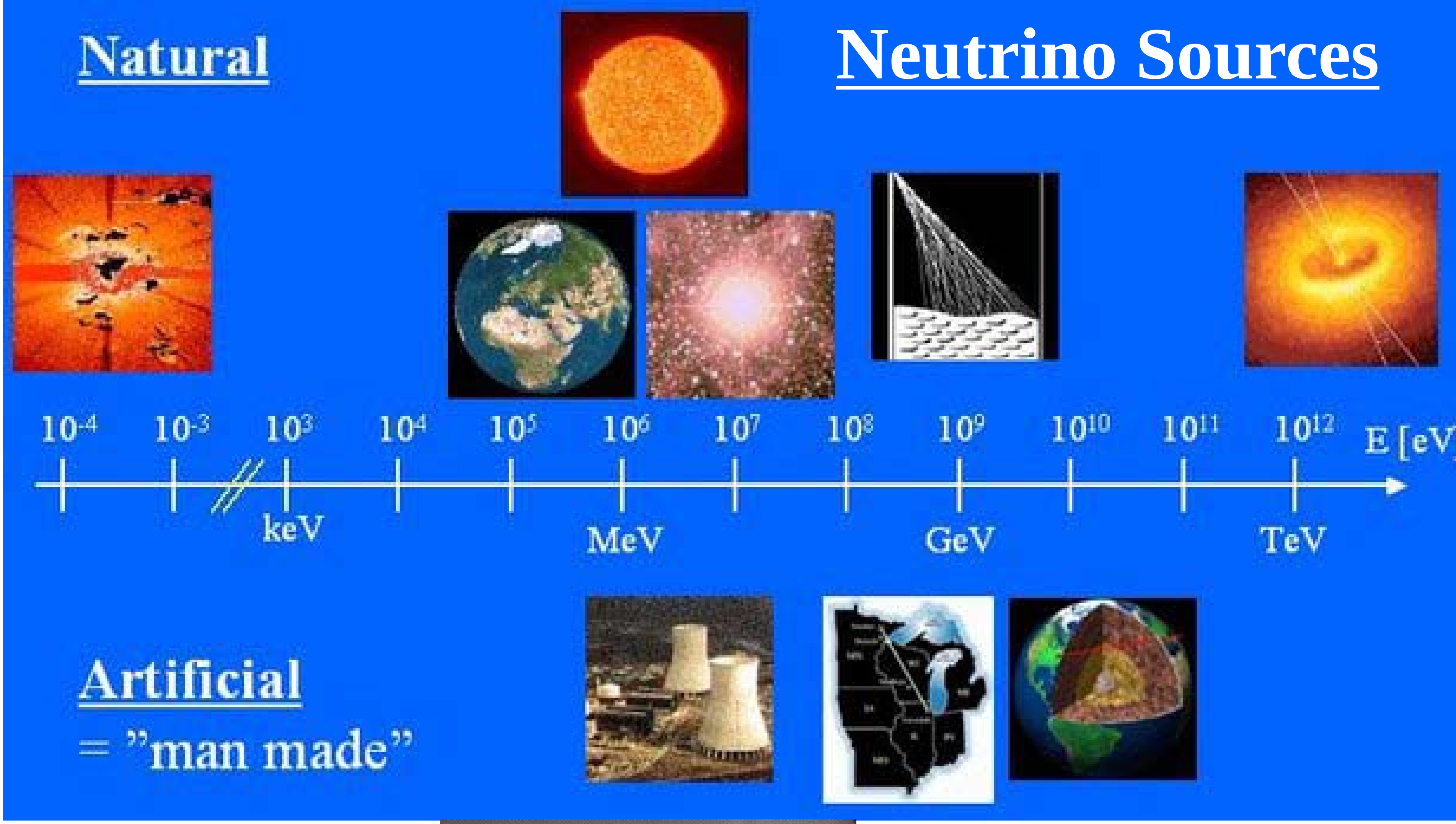
This sketch is from Fred's 1st proposal.

It was not approved!

I can imagine that it must be quite frustrating be told

"No, you cannot blow up a nuclear bomb."

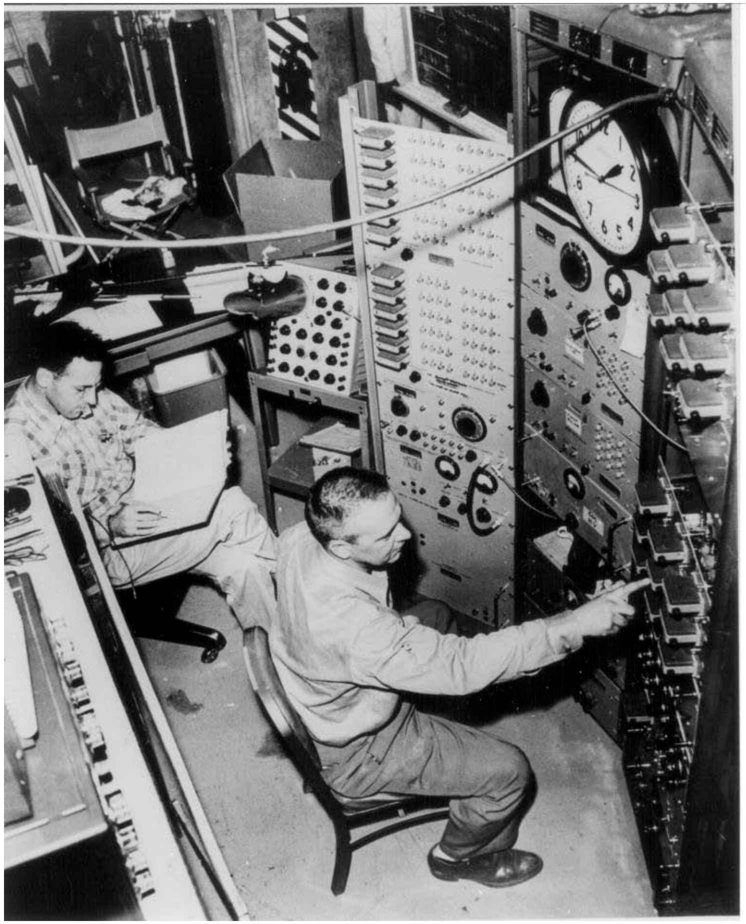
when you really, really want to do so.

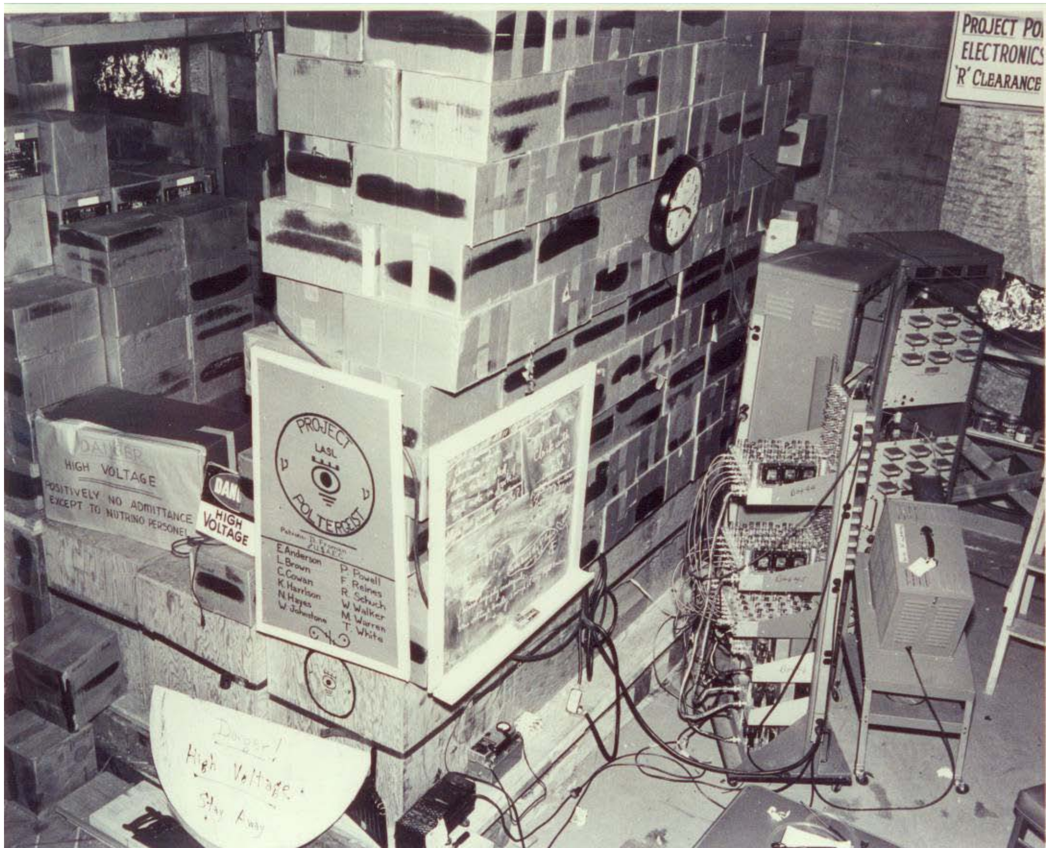


Hey… they forgot one! →

After over half a century, this is still an unobserved source of neutrinos.

It took Fred and his team several more years and a few approved experiments until they finally managed to detect neutrinos. These pictures are from an <u>*unsuccessful*</u> experiment at the Hanford reactor in 1953.

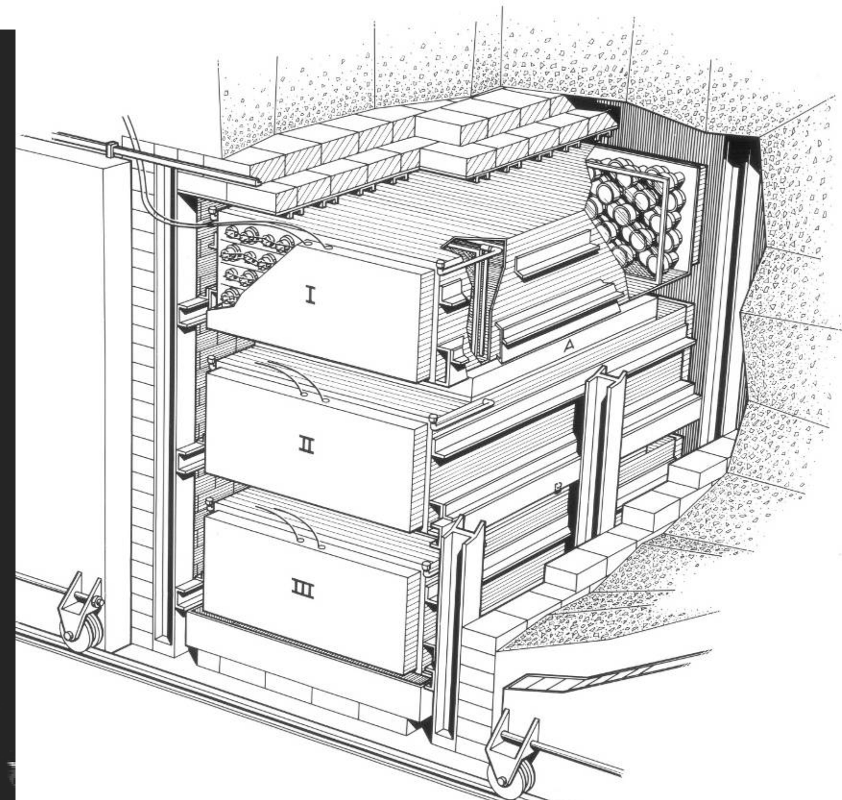




At last, success!

The first certain neutrino detection took place in 1956 at the Savannah River nuclear reactor in South Carolina.

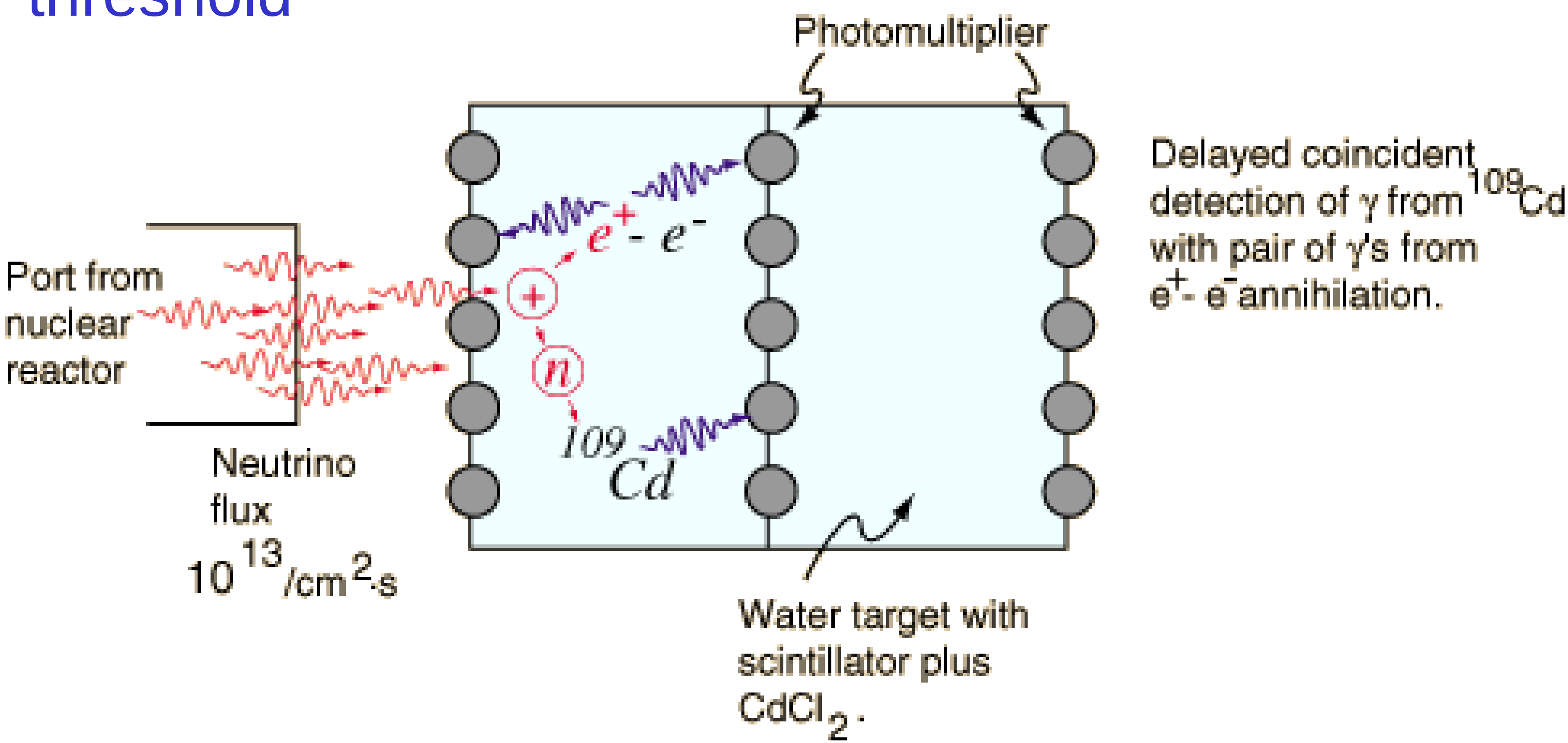
39 long years later, Reines would finally be given the 1995 Nobel Prize in physics for this discovery.



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

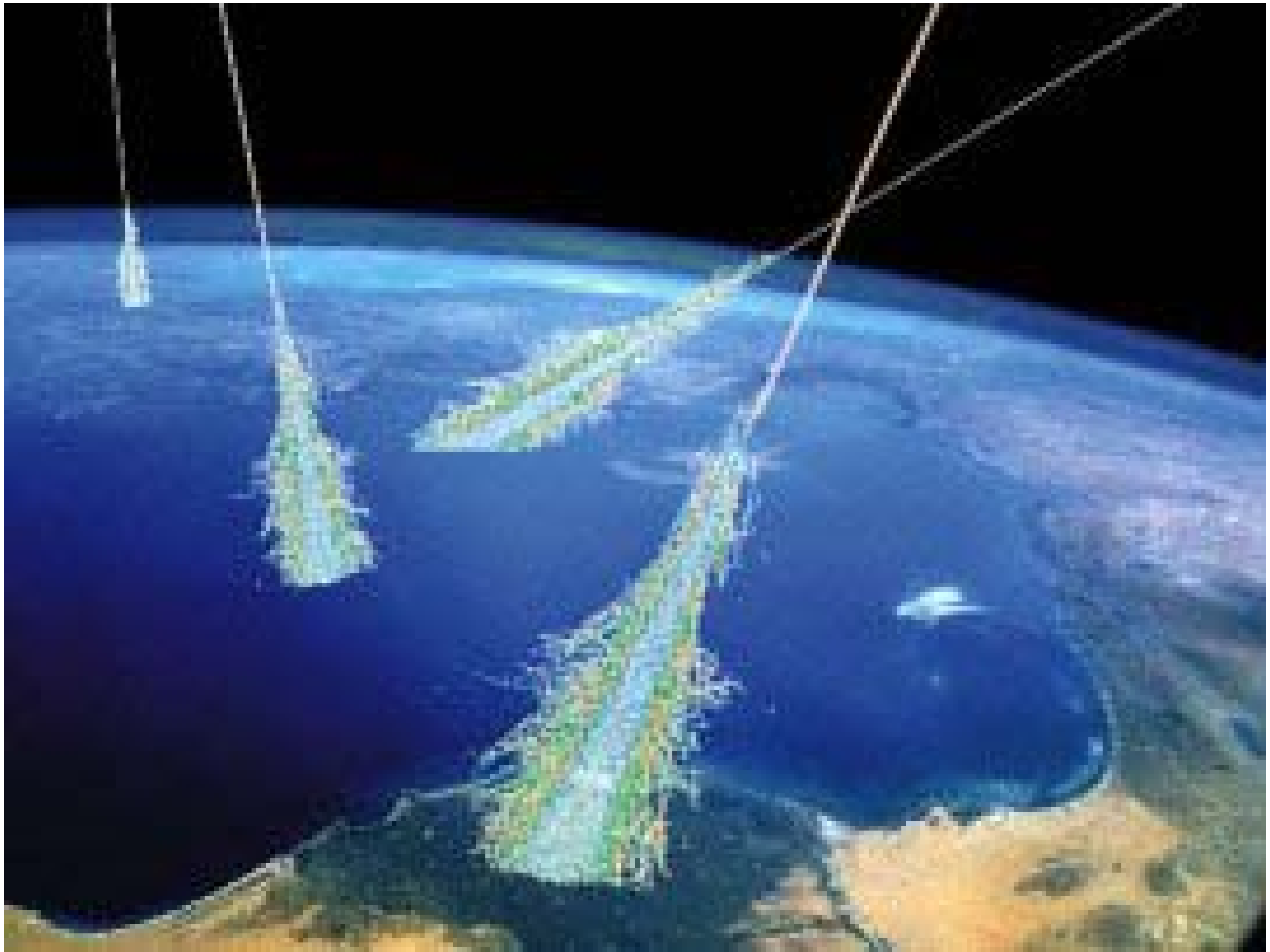
$$n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{109}Cd + \gamma$$

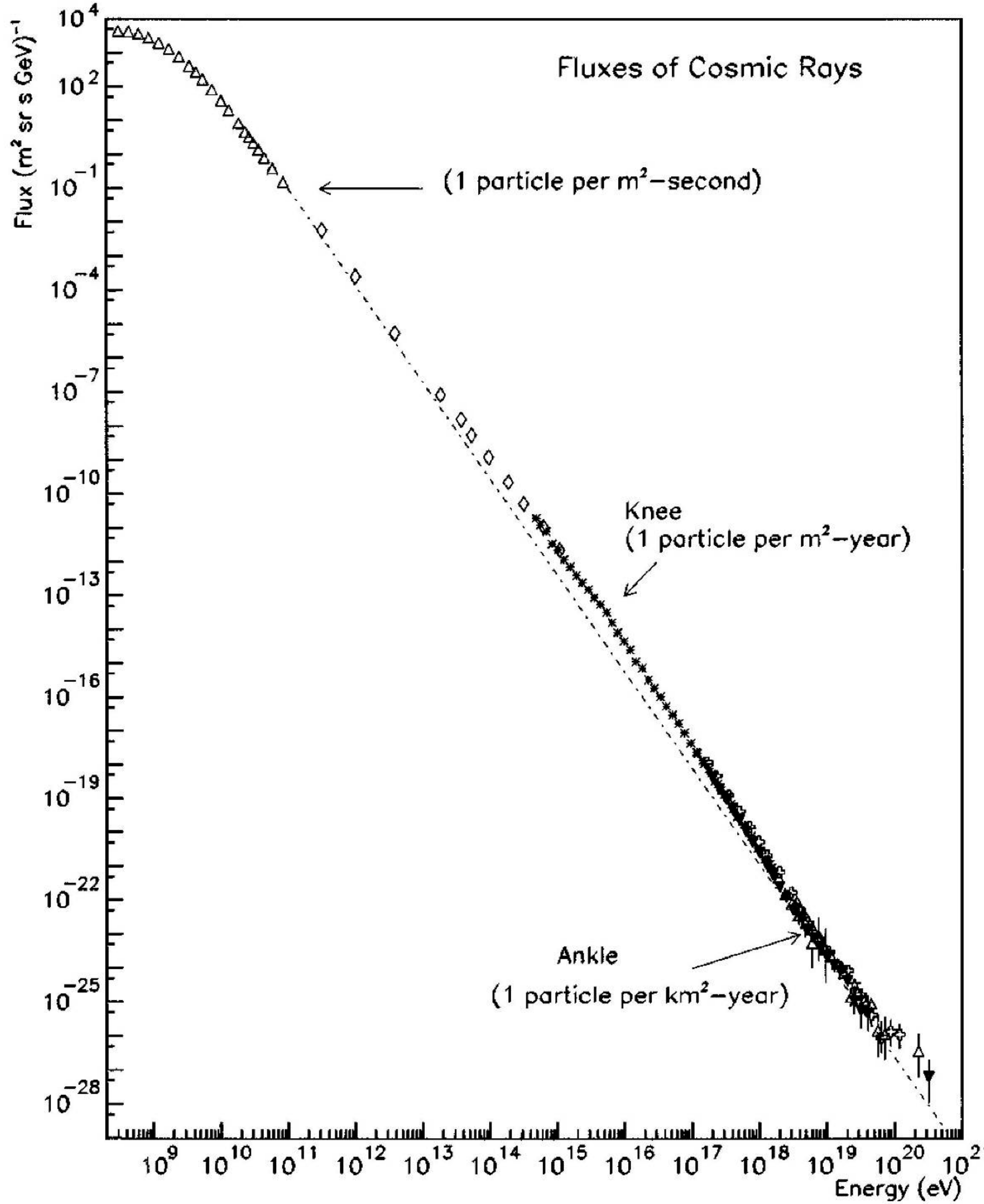
1.8 MeV threshold



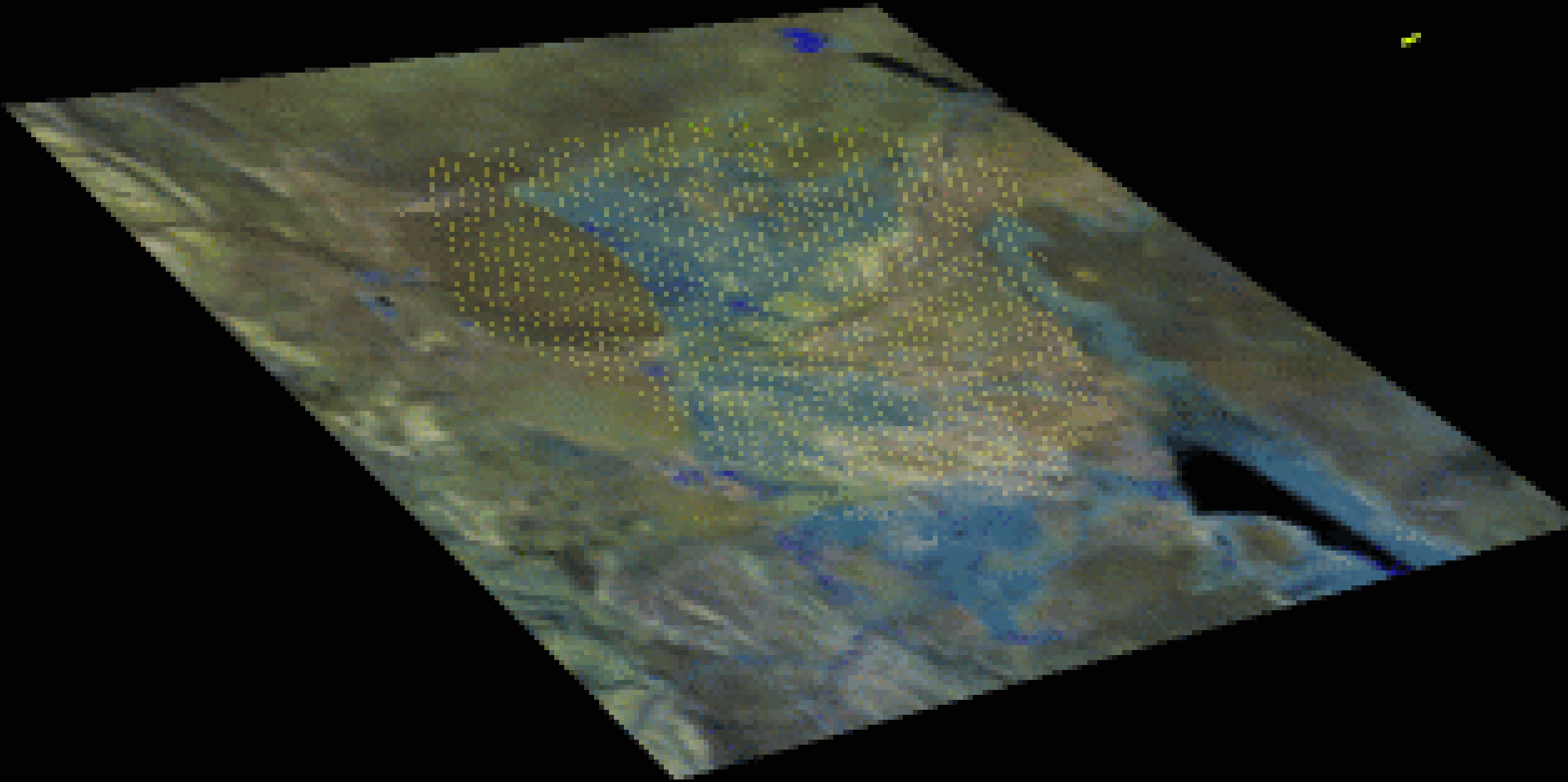
Now that the neutrino had been discovered, it was time to consider other sources and look for them, too.

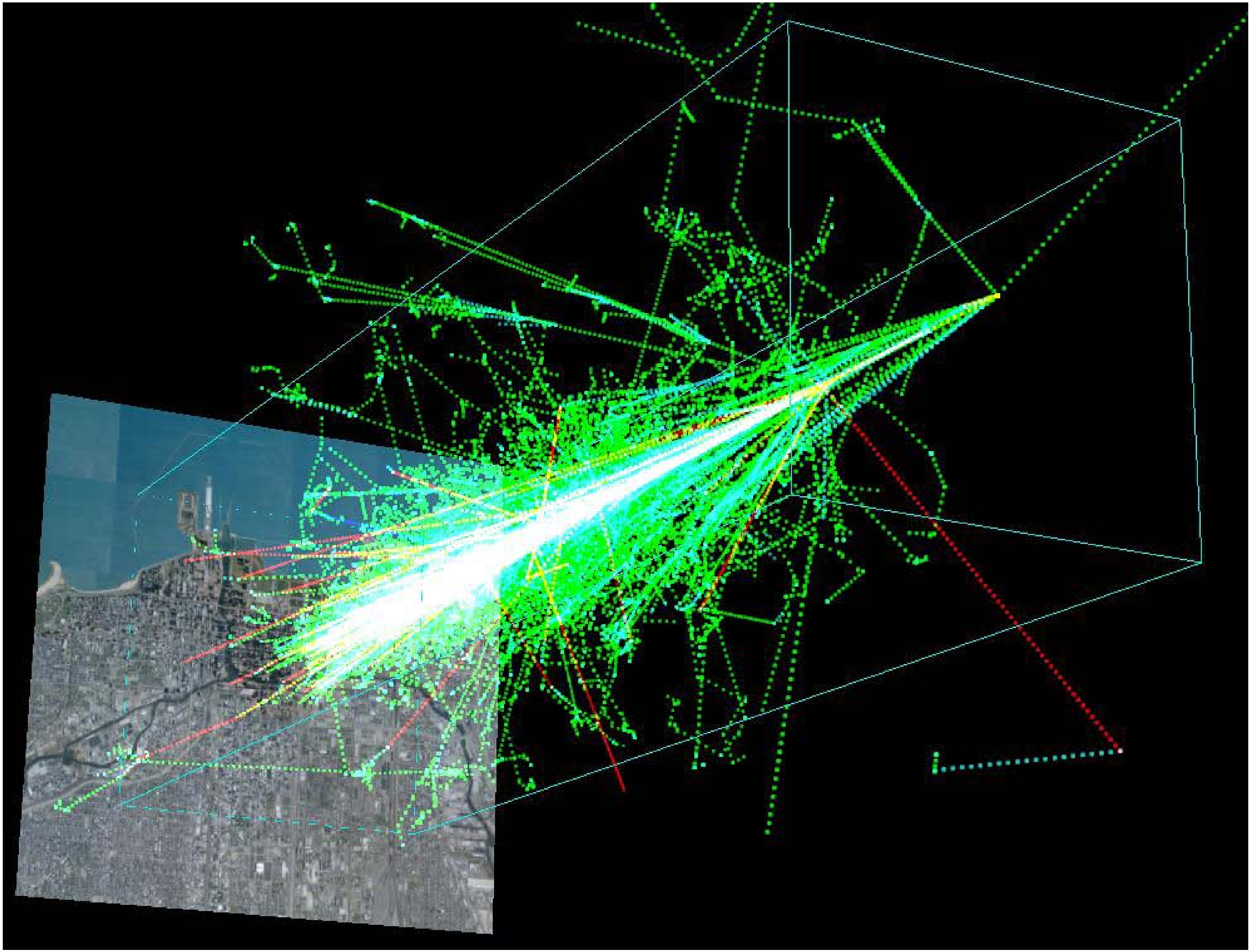
One likely candidate: cosmic rays





Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)





[Slide by F. Reines]

ATMOSPHERIC ν'S

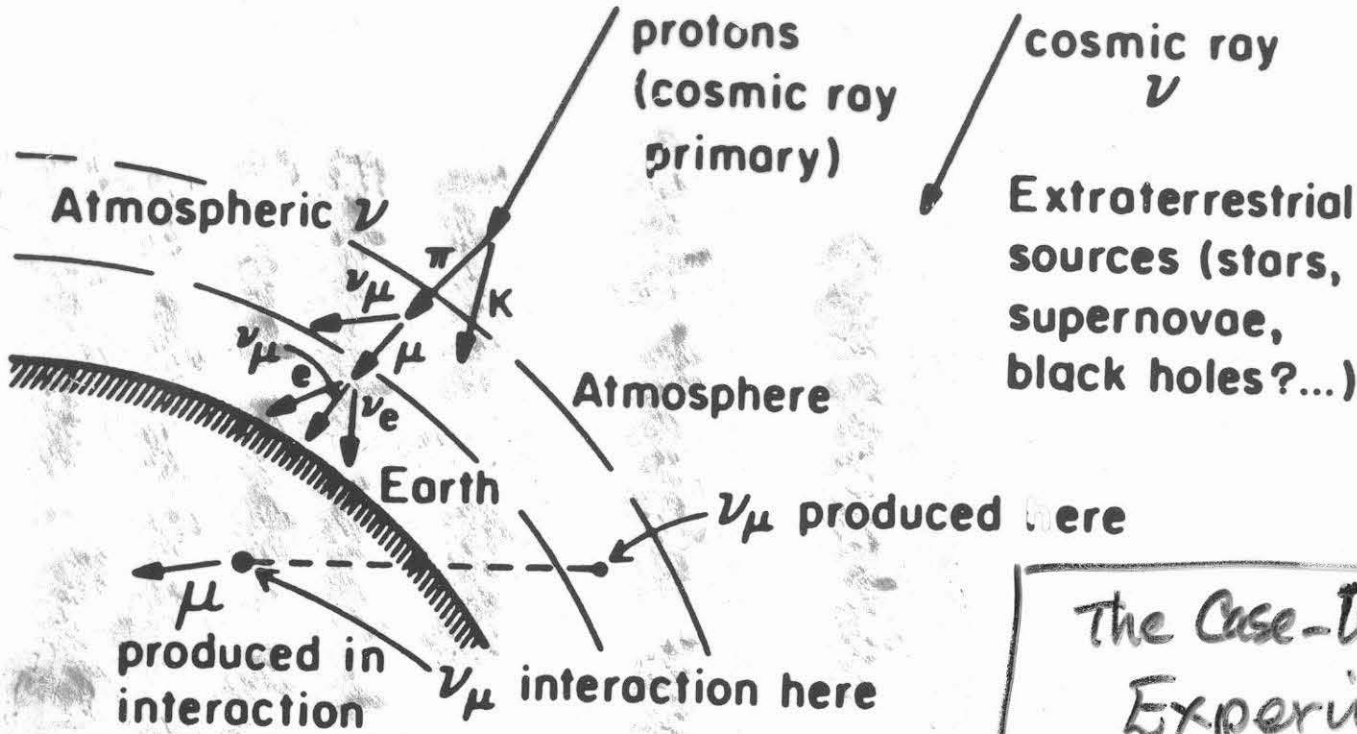
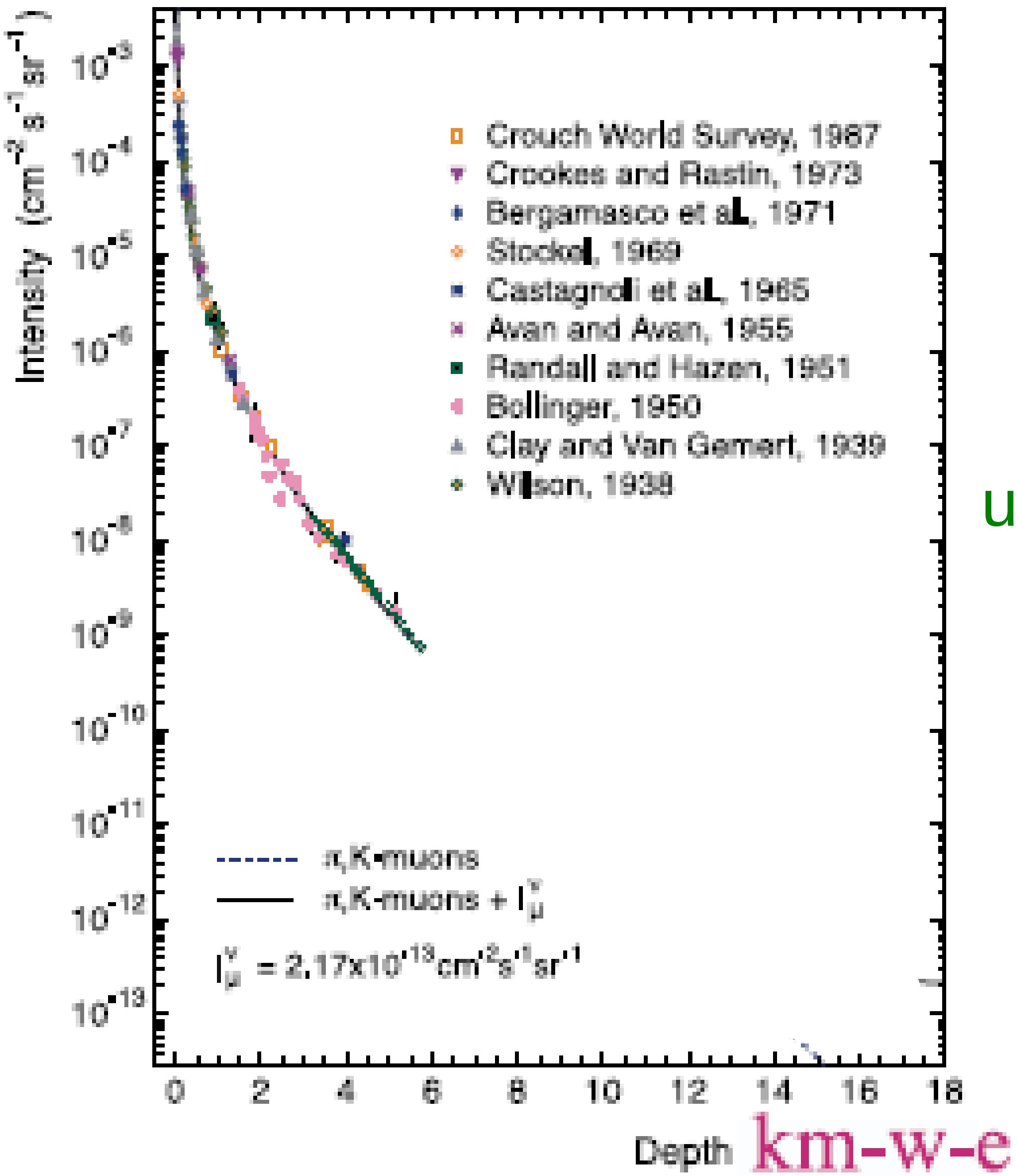


Figure 18
ν sources, terrestrial and extraterrestrial. Cosmic ray protons interact with earth's atmosphere producing particles (K, π, ...) whose decay yields various ν types. Shown is the interaction of a ν_μ with the earth to produce a μ.

The Case-Wits Experiment

ν SOURCES TERRESTRIAL
& EXTRA-TERRESTIAL

Muon Flux vs. Depth



km-w-e roughly equals depth underground in meters times 3

So, if you want to look for neutrinos from cosmic ray interactions in the atmosphere, you have to go deep. Really deep.

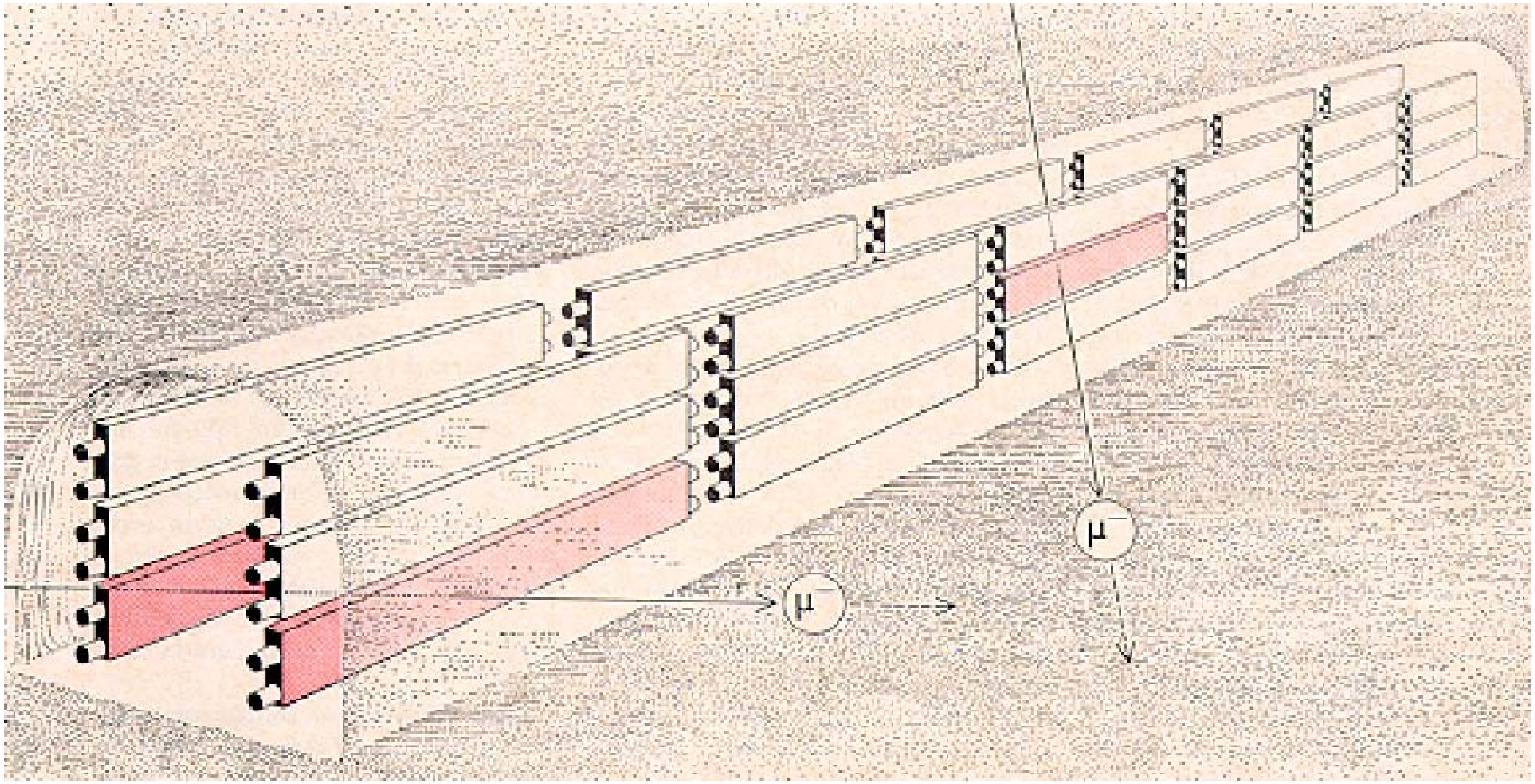
And this is as deep as it gets:

The East Rand gold mine in South Africa, circa 1964

Extends 3585 meters below ground!

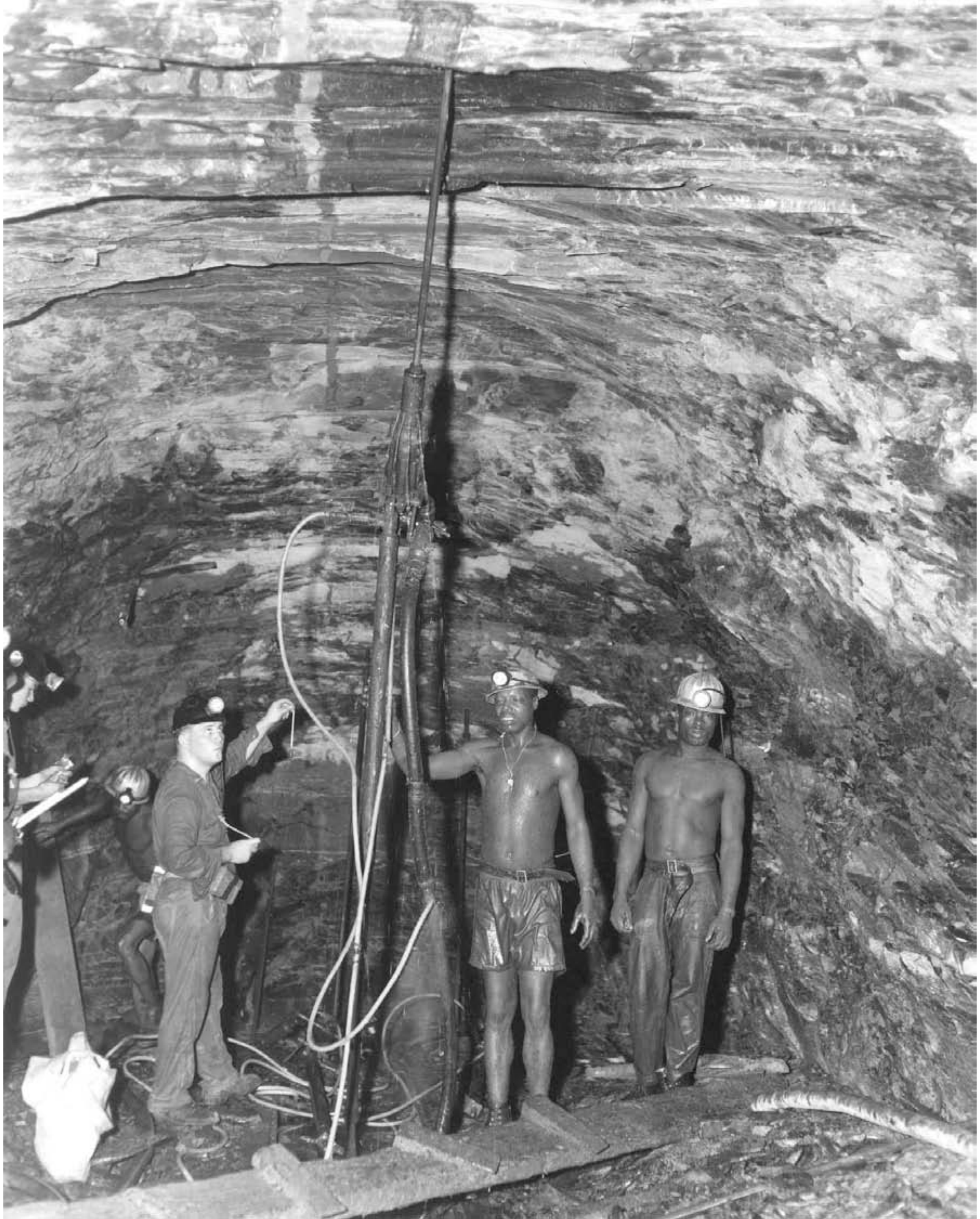
So, Fred Reines
(a professor at
Case Western
Institute in
Cleveland, Ohio)
and his crew headed
off to apartheid-era
South Africa.


GEORGE

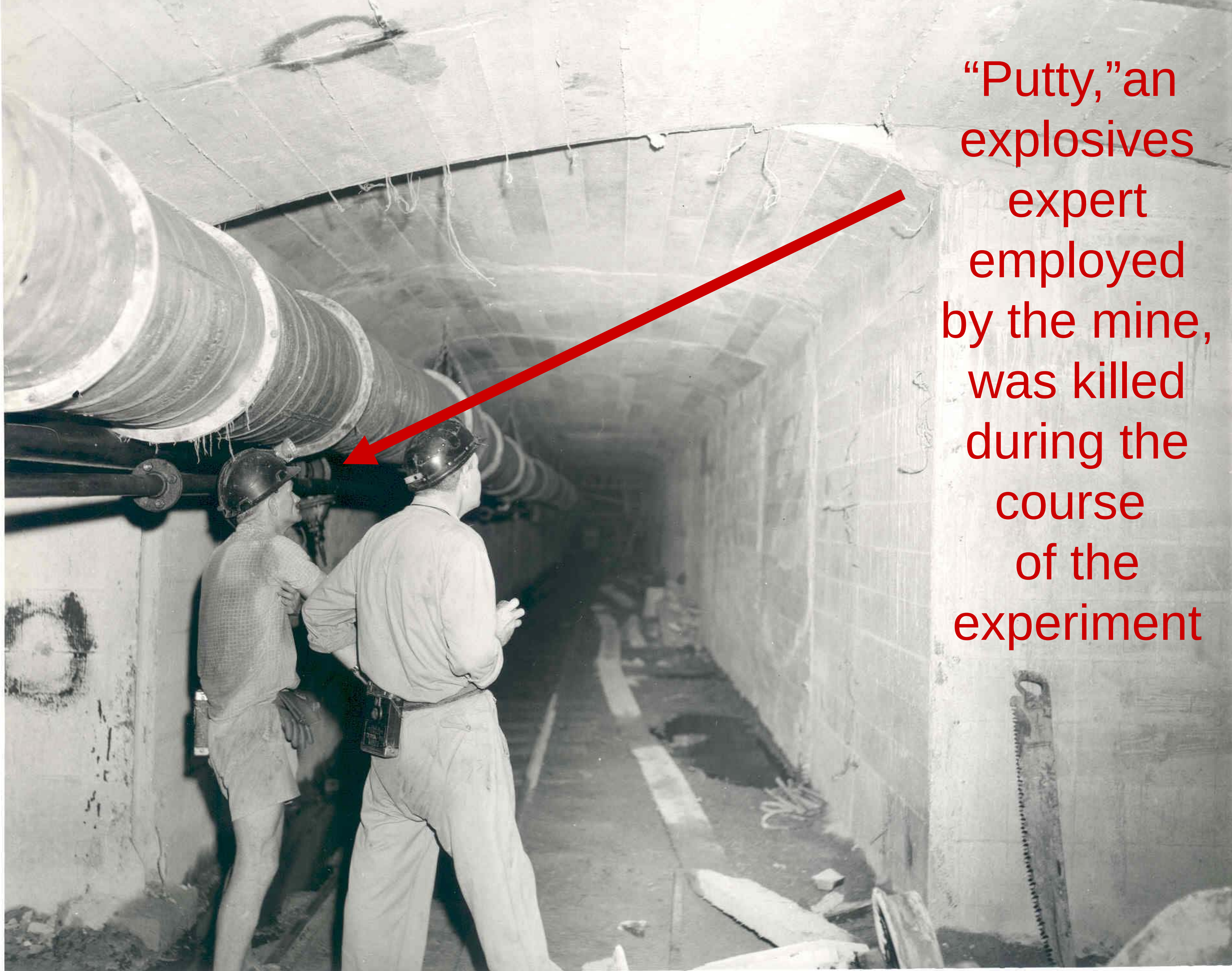


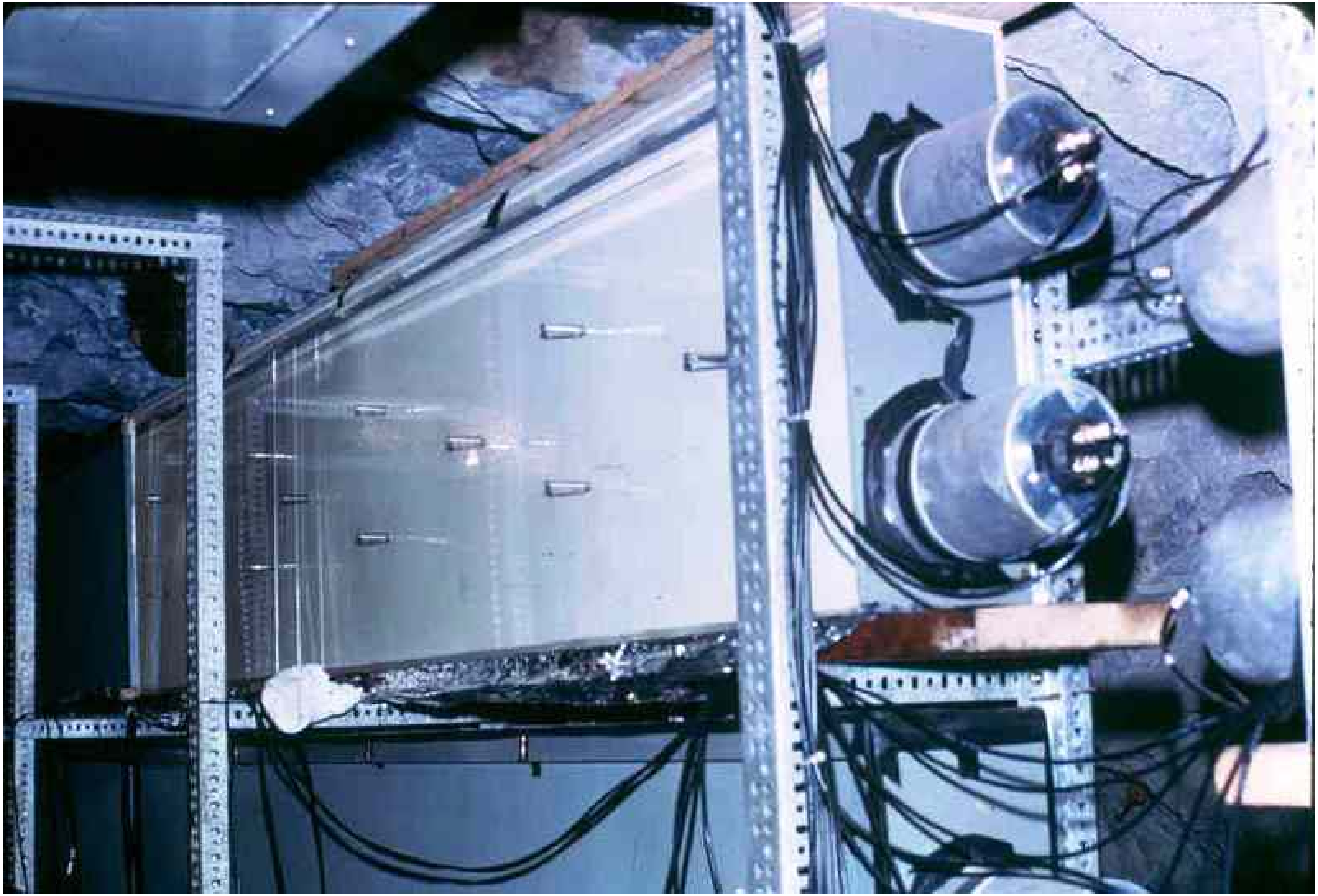
The Case Western Irvine/South Africa Neutrino Detector
[CWI/SAND]

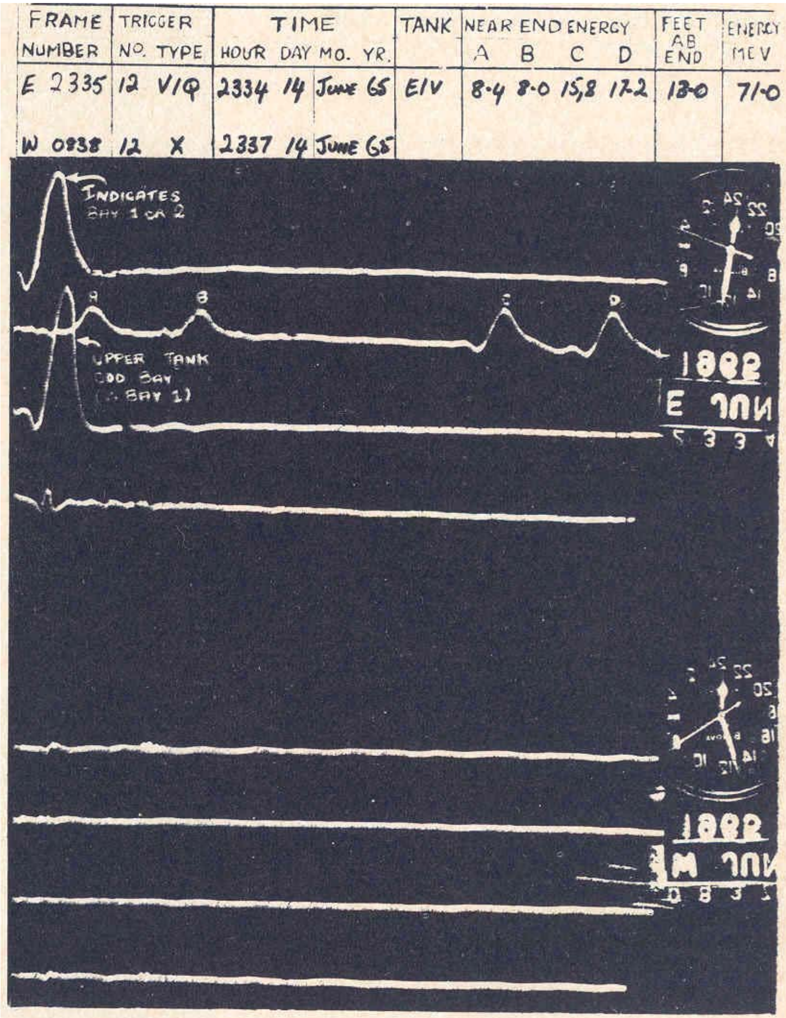
Boxes of liquid scintillator viewed with
Two 5-inch PMT’s on each end



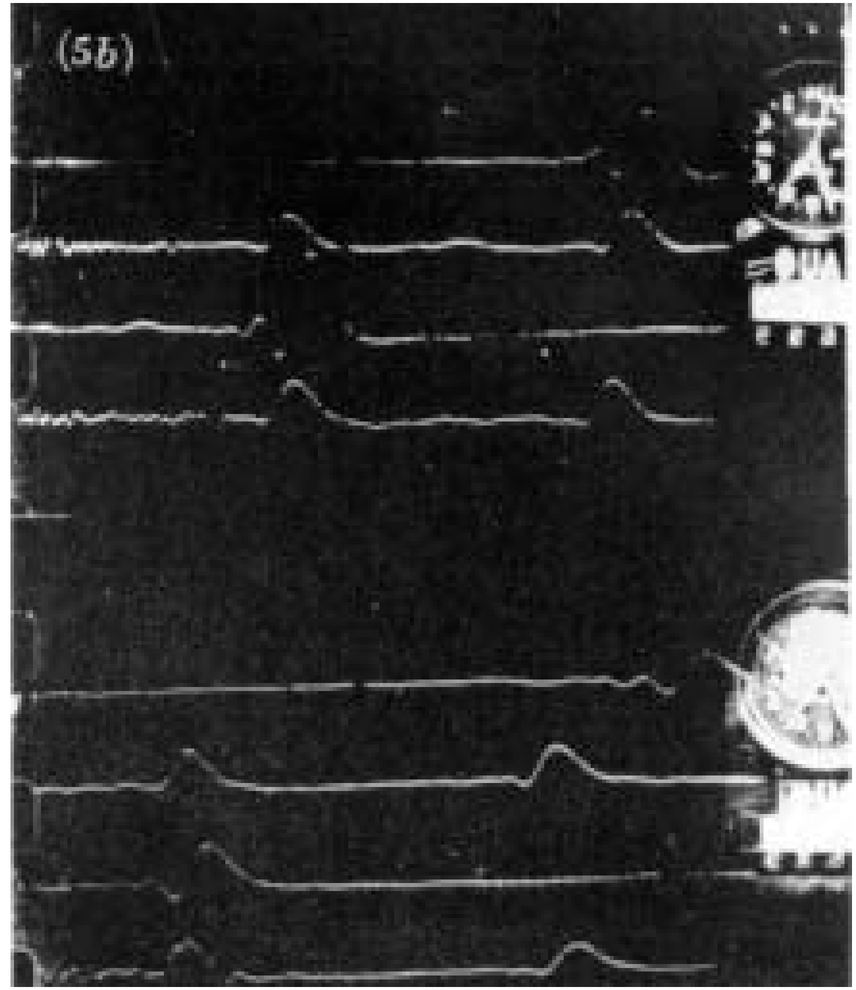
Digging out the experimental space, circa 1964


"Putty,"an
explosives
expert
employed
by the mine,
was killed
during the
course
of the
experiment

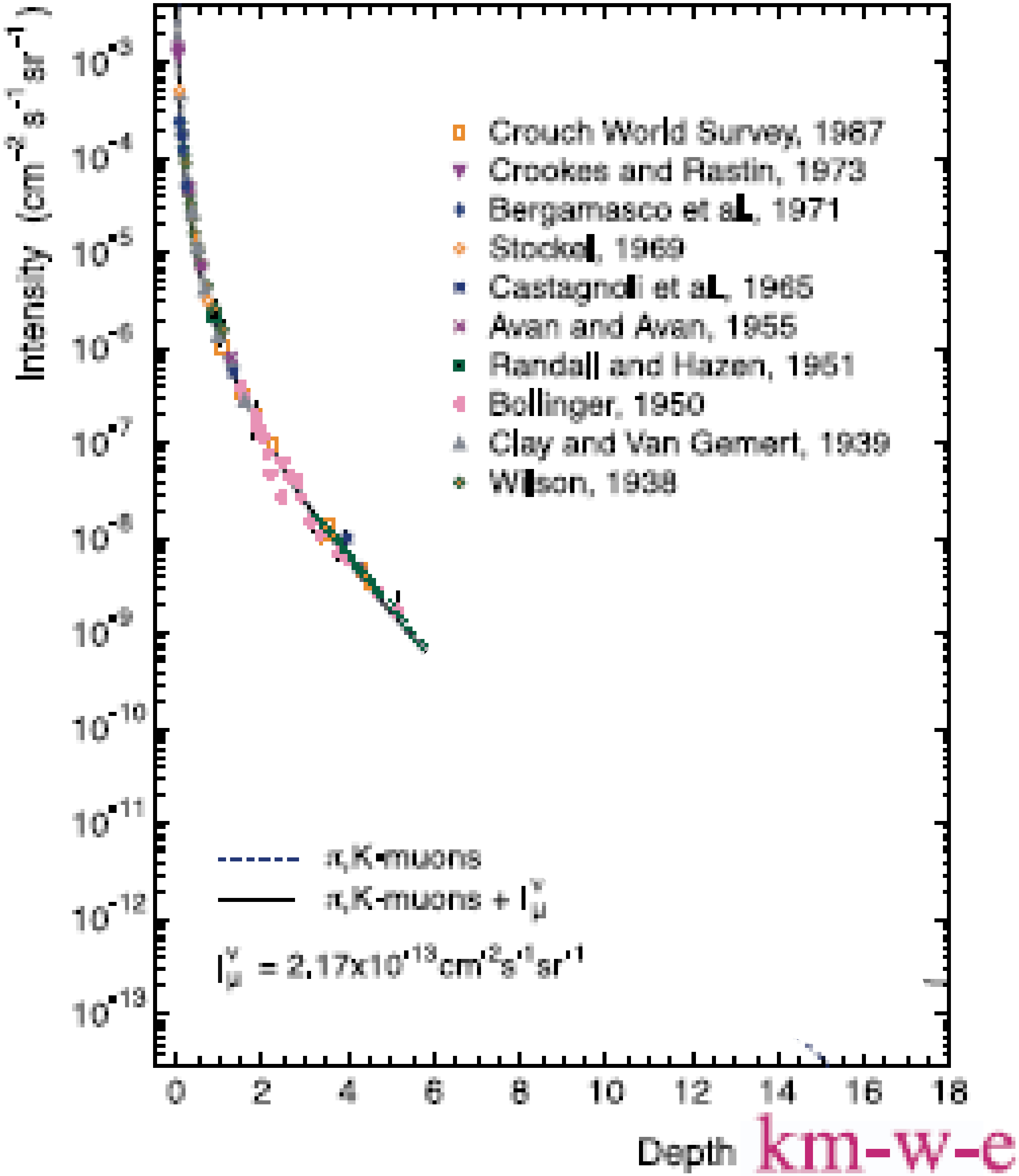




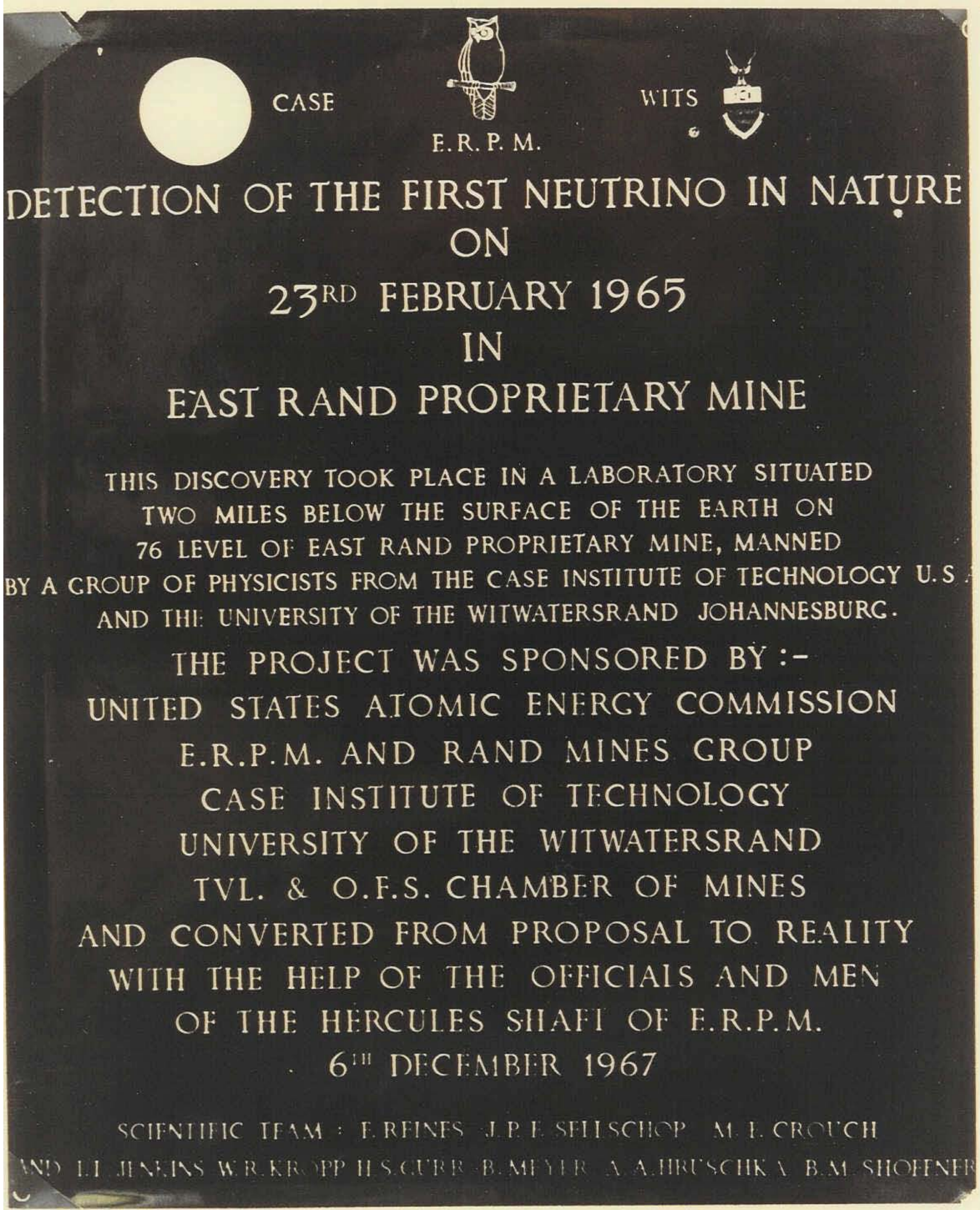
Downward-going Muon
(background)



Horizontal Muon
(neutrino signal)



Intensity (cm⁻² s⁻¹ sr⁻¹)
Crouch World Survey, 1987
Crookes and Rastin, 1973
Bergamasco et al., 1971
Stockel, 1969
Castagnoli et al., 1965
Avan and Avan, 1955
Randall and Hazen, 1951
Bollinger, 1950
Clay and Van Gemert, 1939
Wilson, 1938
π,K-muons
π,K-muons + I_μ^ν
$I_\mu^\nu = 2.17 \times 10^{-13} cm^{-2} s^{-1} sr^{-1}$
0 2 4 6 8 10 12 14 16 18
Depth km-w-e



Fred Reines and his team had done it again!

They saw the very first atmospheric neutrino, but theirs was not the first publication.

This time, they had competition.

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio

and

J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

The flux of high-energy neutrinos from the decay of K, π, and μ mesons produced in the earth's atmosphere by the interaction of primary cosmic rays has been calculated by many authors.[1] In addition, there has been some conjecture[1] as to the much rarer primary flux of high-energy neutrinos originating outside the earth's atmosphere. We present here evidence[2] for the interactions of "natural" high-energy neutrinos obtained with a large area liquid scintillation detector (110 m^2) located at a depth of 3200 m (8800 meters of water equivalent, average $Z^2/A \simeq 5.0$) in a South African gold mine.

The essential idea of the present experiment[3] is to detect the energetic muons produced in neutrino interactions in a mass of rock by means of a large area detector array imbedded in it. Backgrounds are reduced by the large overburden and by utilizing the fact that the angular distribution of the residual muons from the earth's atmosphere is strongly peaked in the vertical direction at this depth. The angular distribution of the muons produced by neutrino interactions should show a slight peaking in the horizontal direction.[1]

The detector array, shown schematically in Fig. 1, consists of two parallel vertical walls made up of 36 detector elements. The array is grouped into 6 "bays" of 6 elements each. Each detector element, Fig. 2, is a rectangular box of Lucite of wall area 3.07 m^2 containing 380 liters of a mineral-oil based liquid scintillator,[4] and is viewed at each end by two 5-in. photomultiplier tubes. The array constitutes a hodoscope which gives a rough measurement of the zenith angle of a charged particle passing through it. In addition, the event is located along the detector axis by the ratio of the photomultiplier responses at the two ends. The sum of the responses then pro-

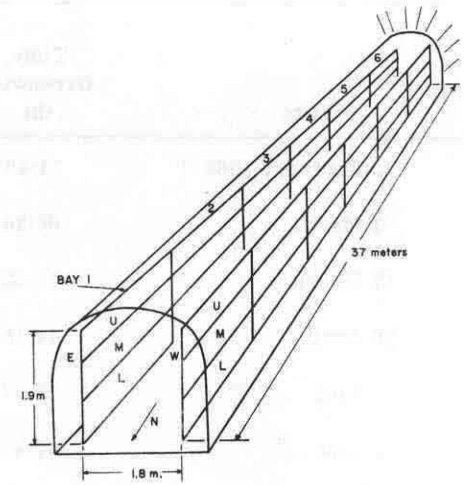
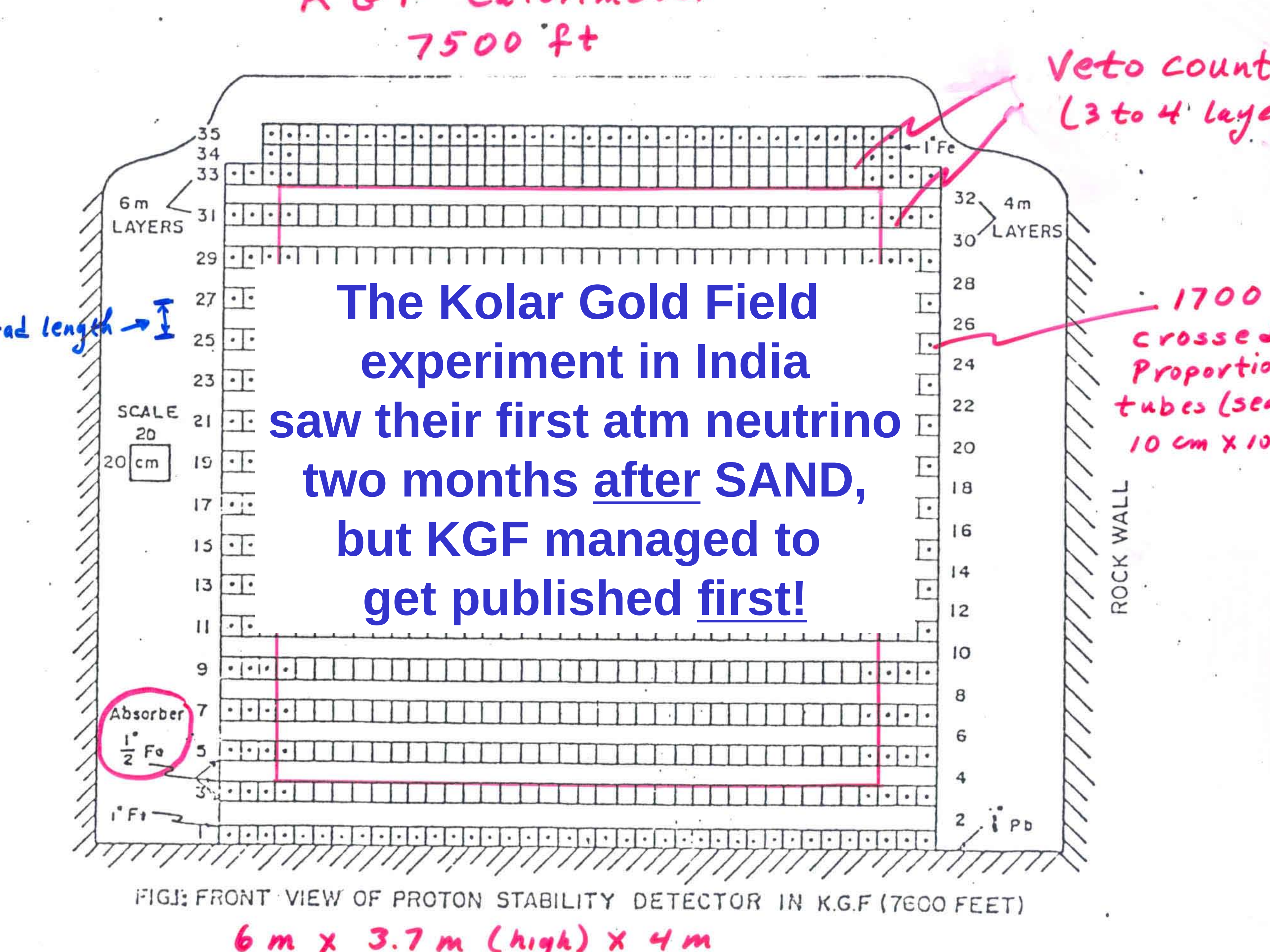


FIG. 1. Schematic of detector array.



The Kolar Gold Field experiment in India saw their first atm neutrino two months after SAND, but KGF managed to get published first!

The next chapter in atmospheric neutrinos opened in the late 1970's.

Unified field theories had become popular, and one in particular, SU(5), made testable predictions on the proton lifetime.

Of course, it was still a pretty high number (around 10^{29} years or so) and so would require observing a lot of protons to prove.

If you want a lot of protons and you want to be able to look at all of them without spending too much money, a great big tank of clear water is your best bet.

Because they were looking for proton decay, which emits around 1 GeV of energy in a specific pattern, the shielding requirements were less severe for the new generation of experiments than they had been for SAND.

One no longer had to find the deepest mine in the world to do your work. Instead of 8 km.w.e., 2 km.w.e. would be okay.

The Reines group, now based at the University of California, Irvine, joined forces with groups from the University of Michigan and Brookhaven National Laboratory, to build the IMB experiment in the Morton Salt Mine in Cleveland, Ohio.

Proposal Submitted to DoE
May 31st, 1979

Proposal Approved
November 28th, 1979

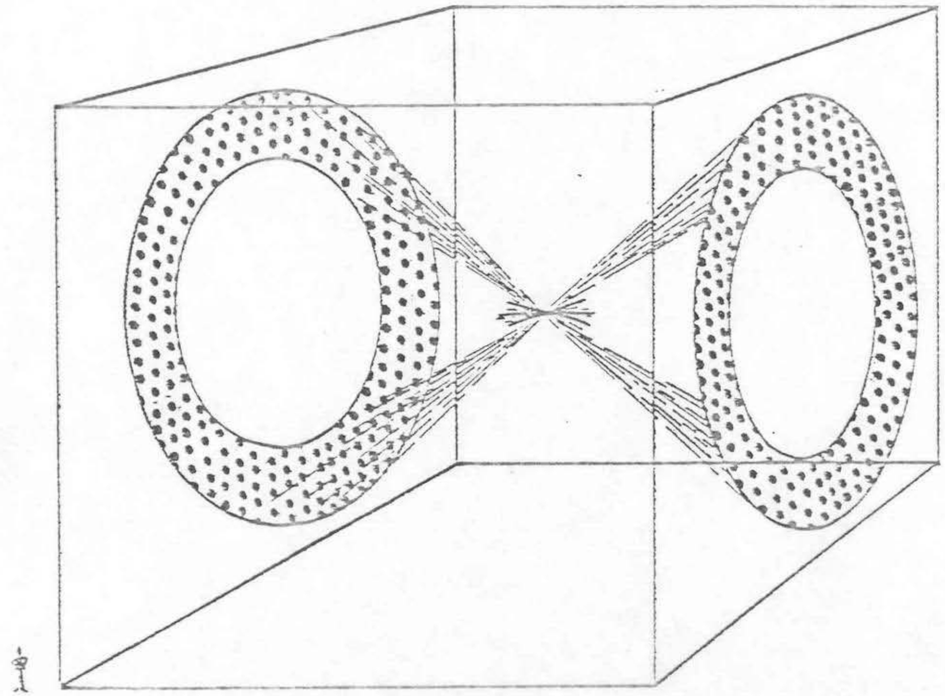
Excavation Began
November 30th, 1979

PROPOSAL FOR A

NUCLEON

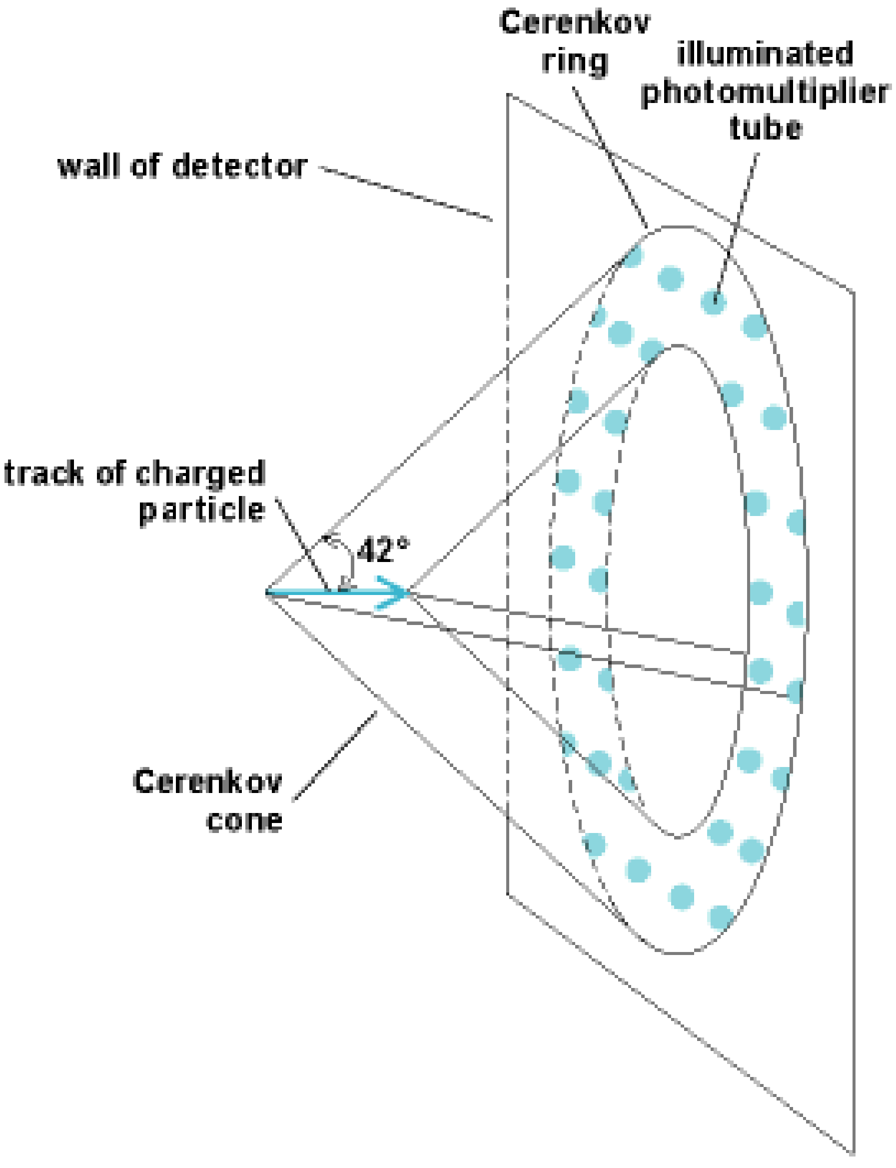
DECAY DETECTOR

IRVINE/MICHIGAN/BROOKHAVEN



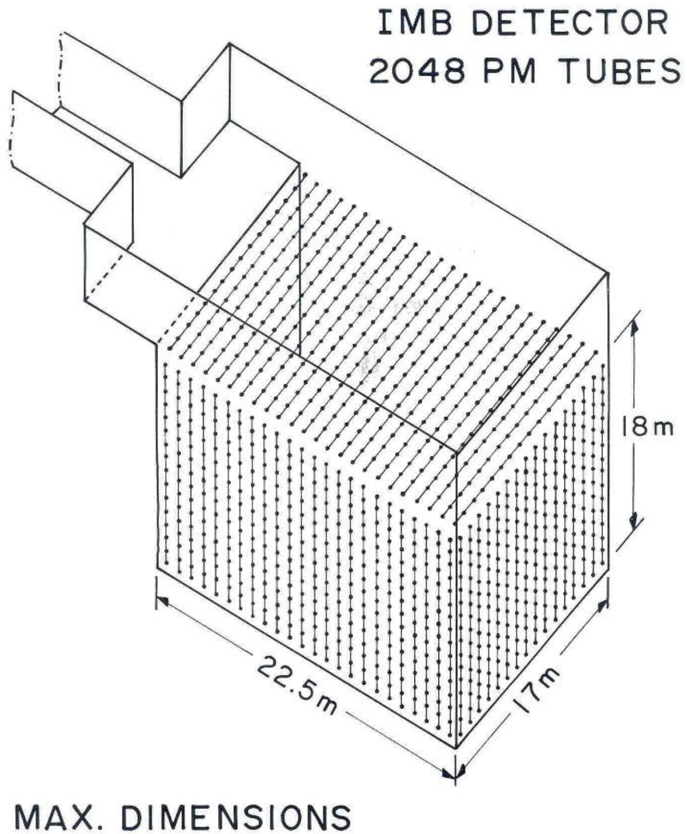
IMB was the first large-scale water Cherenkov detector: 7000 tons H_2O

Relativistic charged particles would make rings of light on the inner wall of the detector. The rings would then be imaged by photomultiplier tubes.

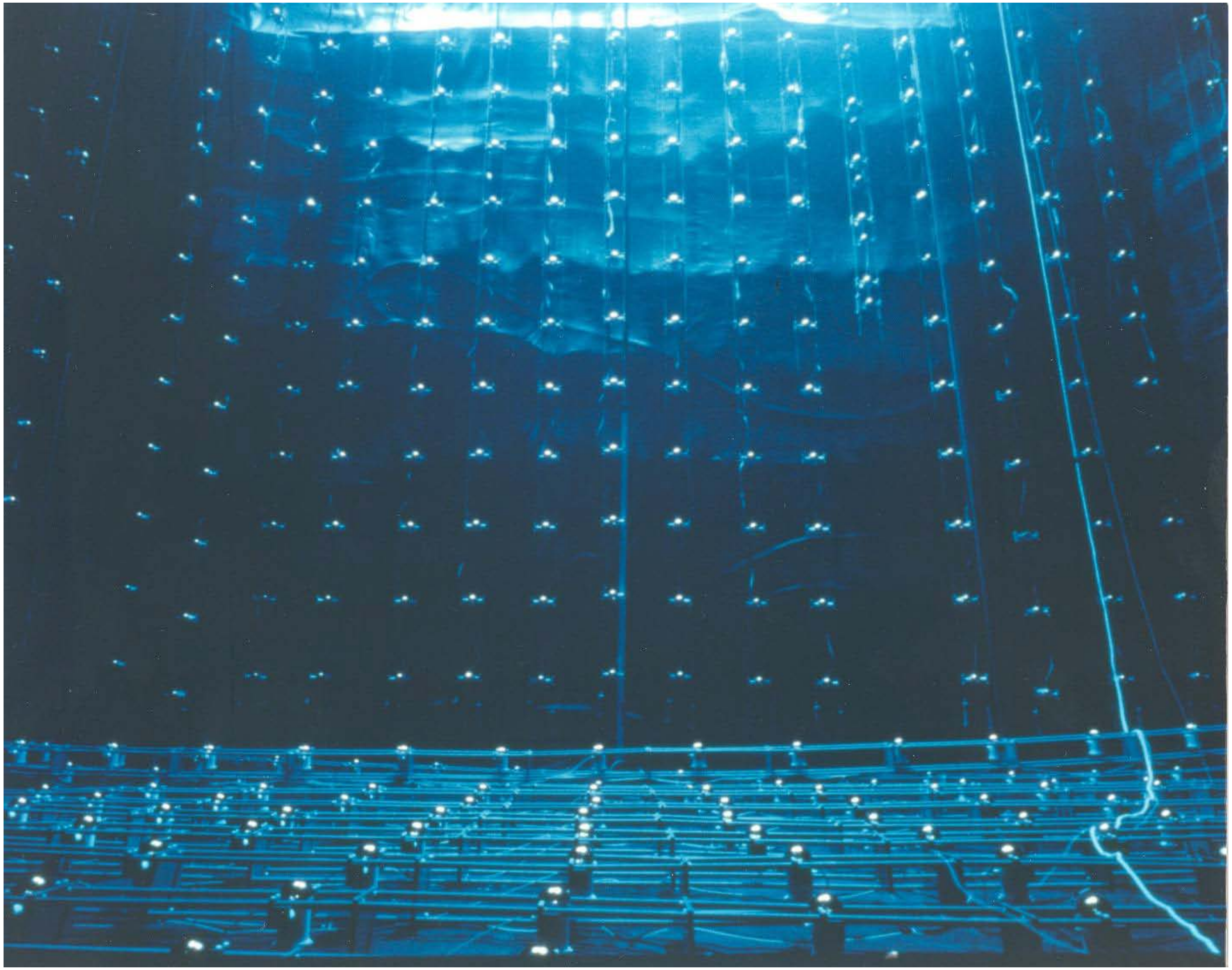


This detector was going to be very big – a cube about 20 meters on a side. To save money, a salt mine was used, since it's easier to excavate salt than hard rock.

Also, there was no big metal tank holding the water. A plastic liner kept the water away from the salt.



September, 1981



Full of water, with 5-inch PMT's

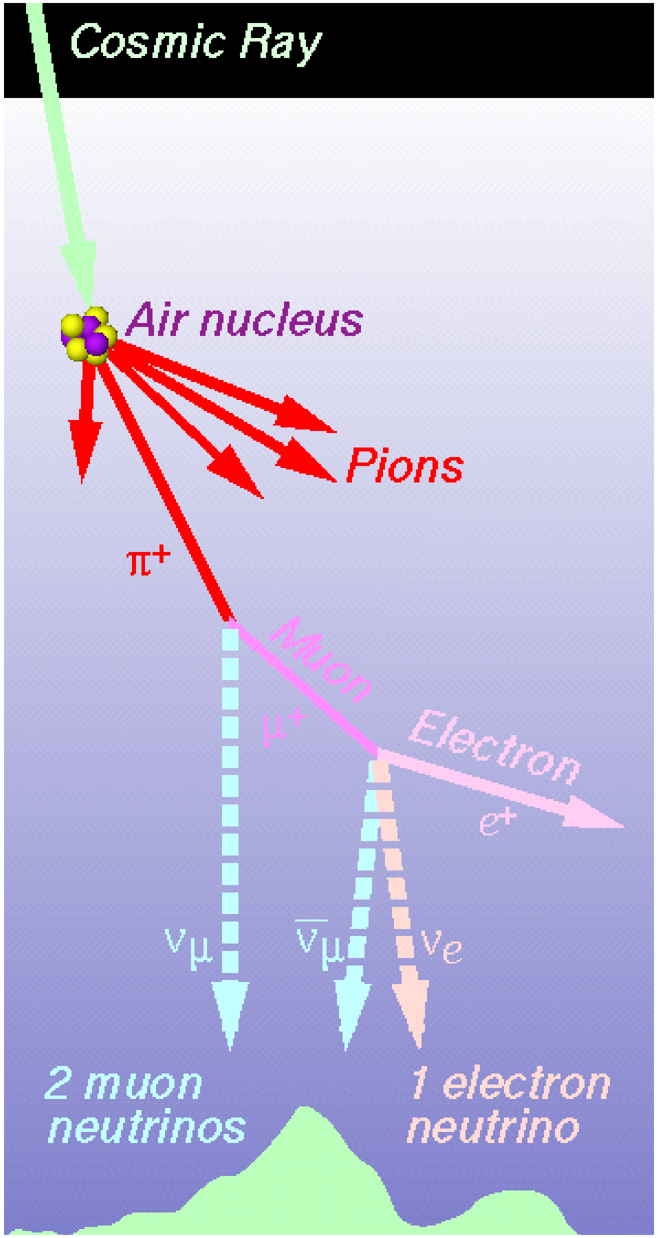
Late 1982

They had really expected to
– and had told the funding agency that they would –
find proton decay right away.

But after only 80 days of running, and no proton decay candidates observed, the proton lifetime had to be over 5 X 10 ^{31} years.

→ By April of 1983, minimal SU(5) was dead! ←

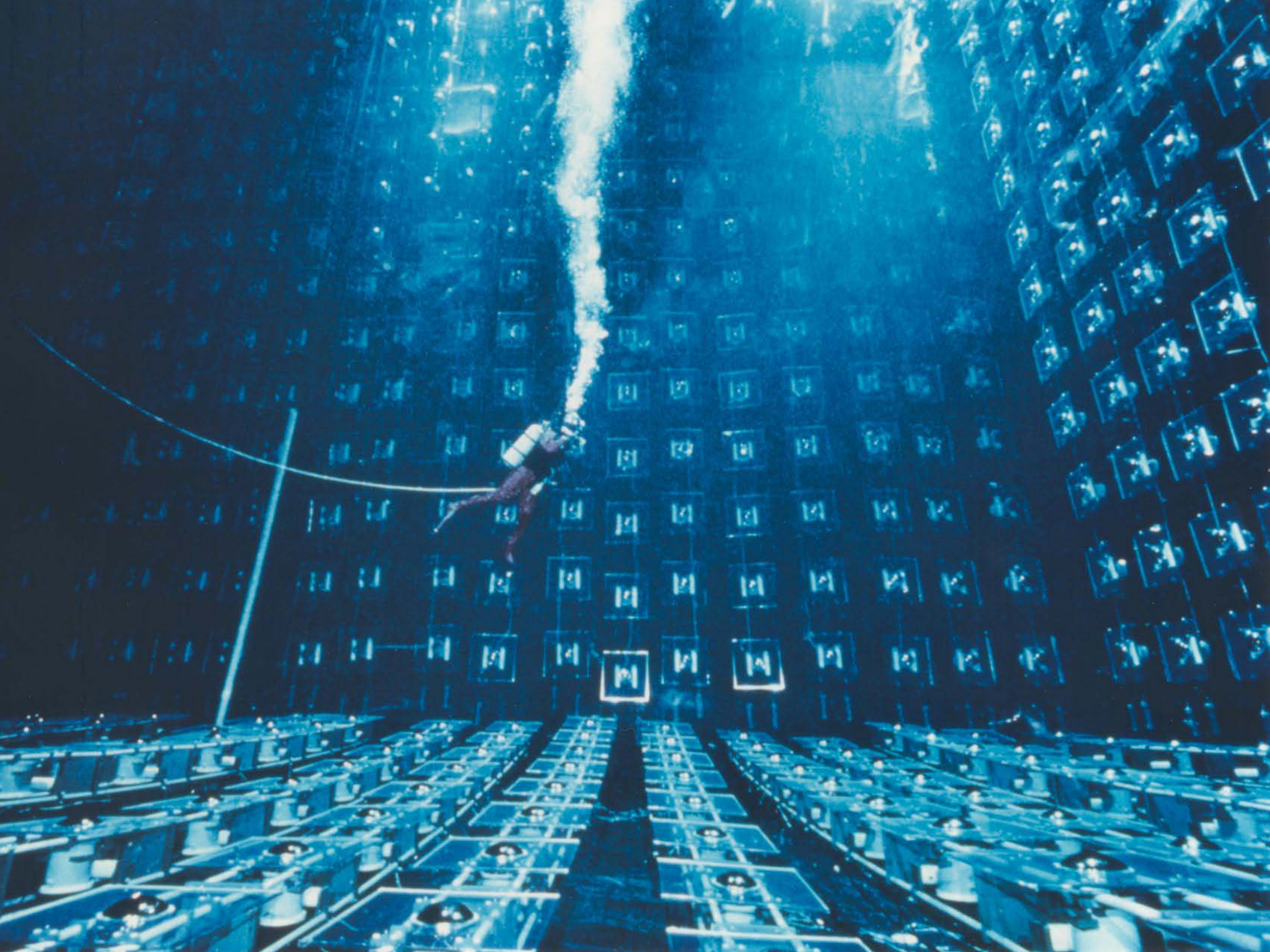
However, by the summer of 1983 a strange effect had been noticed in the observed atmospheric neutrinos (the main background to the proton decay search).



There should have been about two muon-type events for every electron-type event.

But there seemed to be too few muons.

A detector upgrade was proposed and approved, perhaps in part because by then they had serious competition from a new player in the game.



IMB was looking for the reactions

$$\nu_\mu + n \rightarrow \mu^- + p$$

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

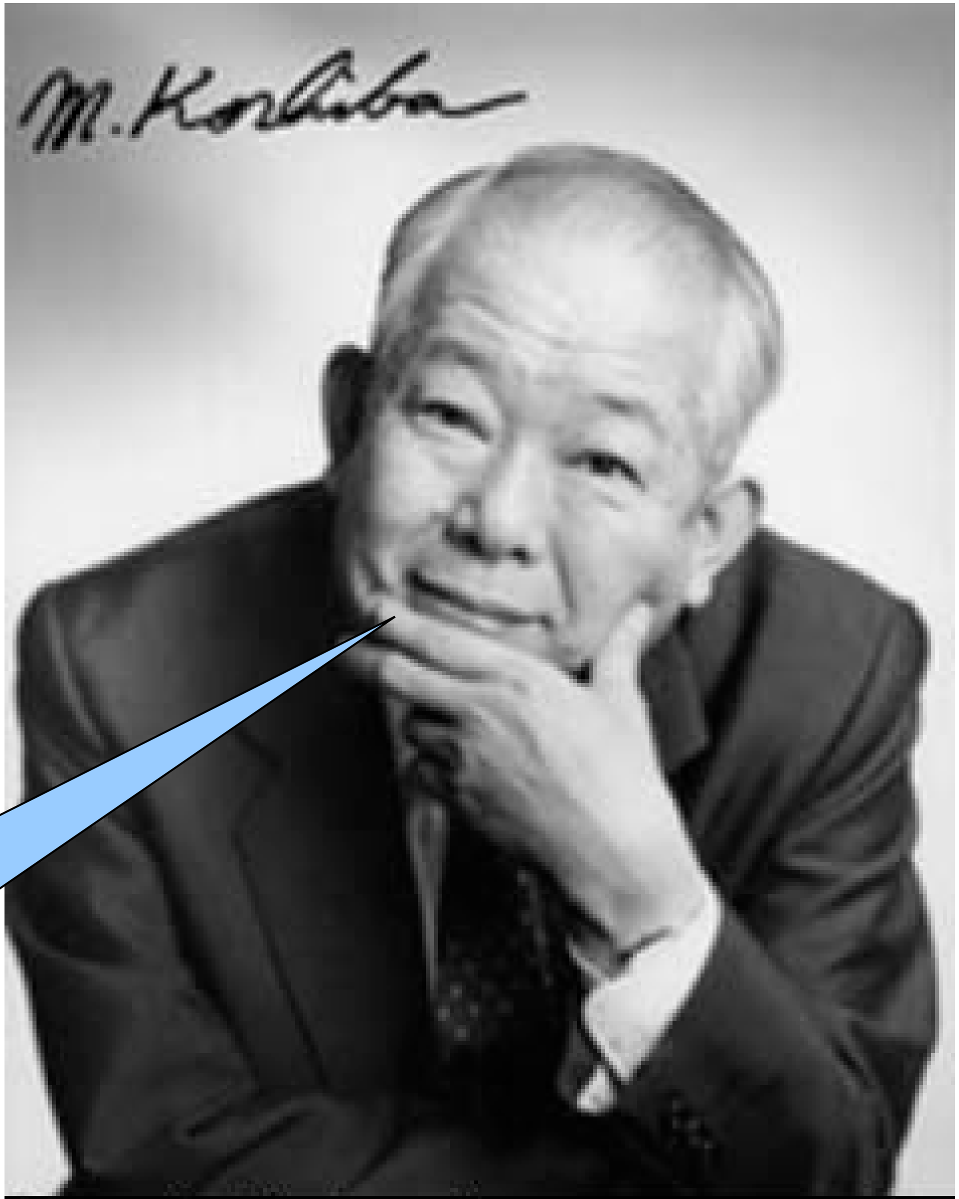
by observing the initial muon and then searching for its subsequent decay electron.

They expected 34% ± 1% of their events to have a muon decay, but measured just 26% ± 3%.

This was called the “too few mu nu” problem.

A professor at the University of Tokyo, Masatoshi Koshiba, had convinced his friend and UTokyo classmate (and now the head of Hamamatsu Photomultiplier Tube Company) to try and make a tube an unbelievable 20” in diameter.

“He was one day younger than me, so he had to do as I said.”



Scanned at the American Institute of Physics

Incredibly,
Hamamatsu did it!

Here’s a publicity shot announcing the technological breakthrough.

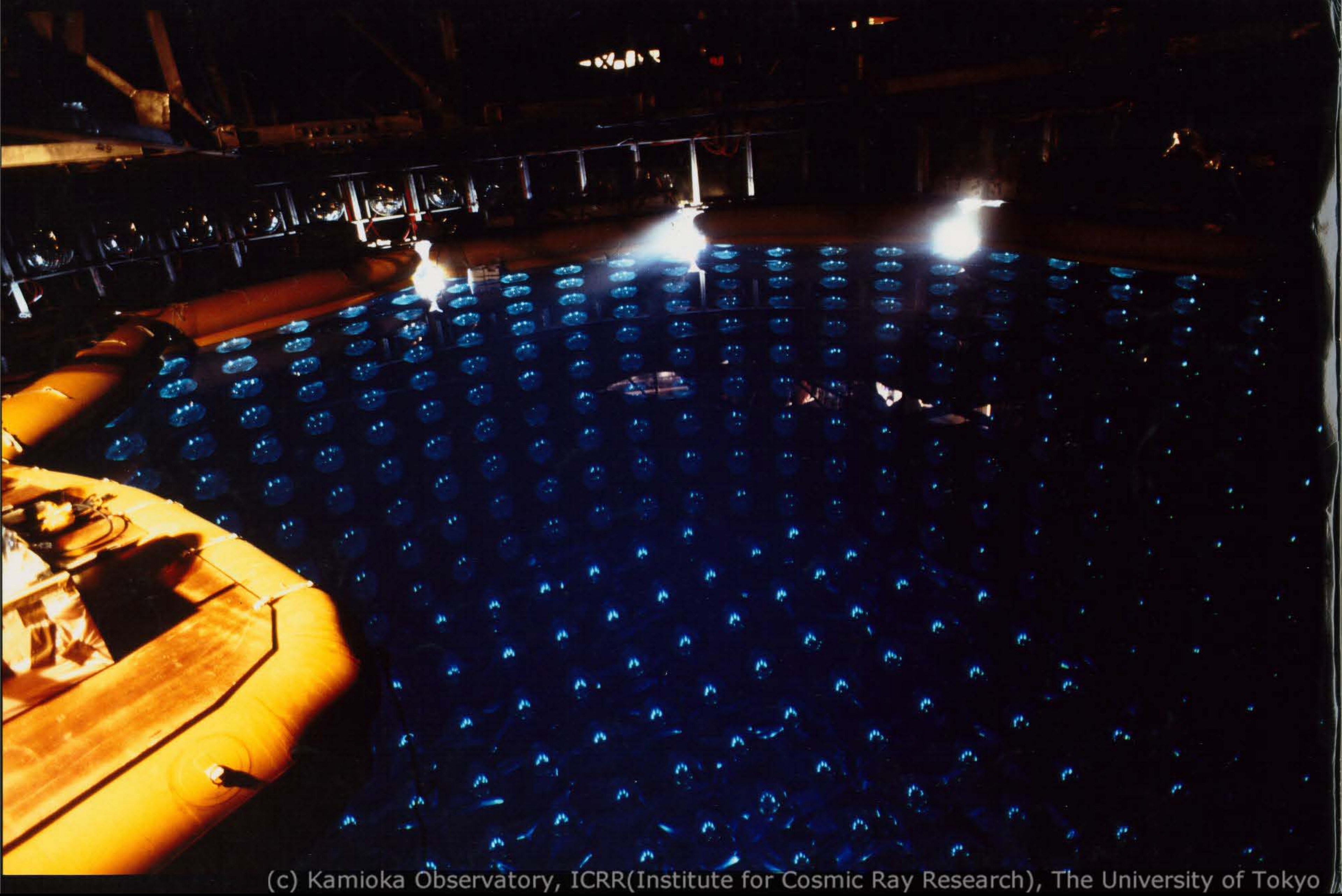
It was so unwieldy the process could not be easily automated.

Every tube was made out of hand-blown glass.

Equipped with his powerful new tool, Koshiba also had his sights set on discovering proton decay.

By 1983 he and his team were busy building the Kamiokande detector, in rural, mountainous central Japan.

It was about ½ the size of IMB, but more sensitive.

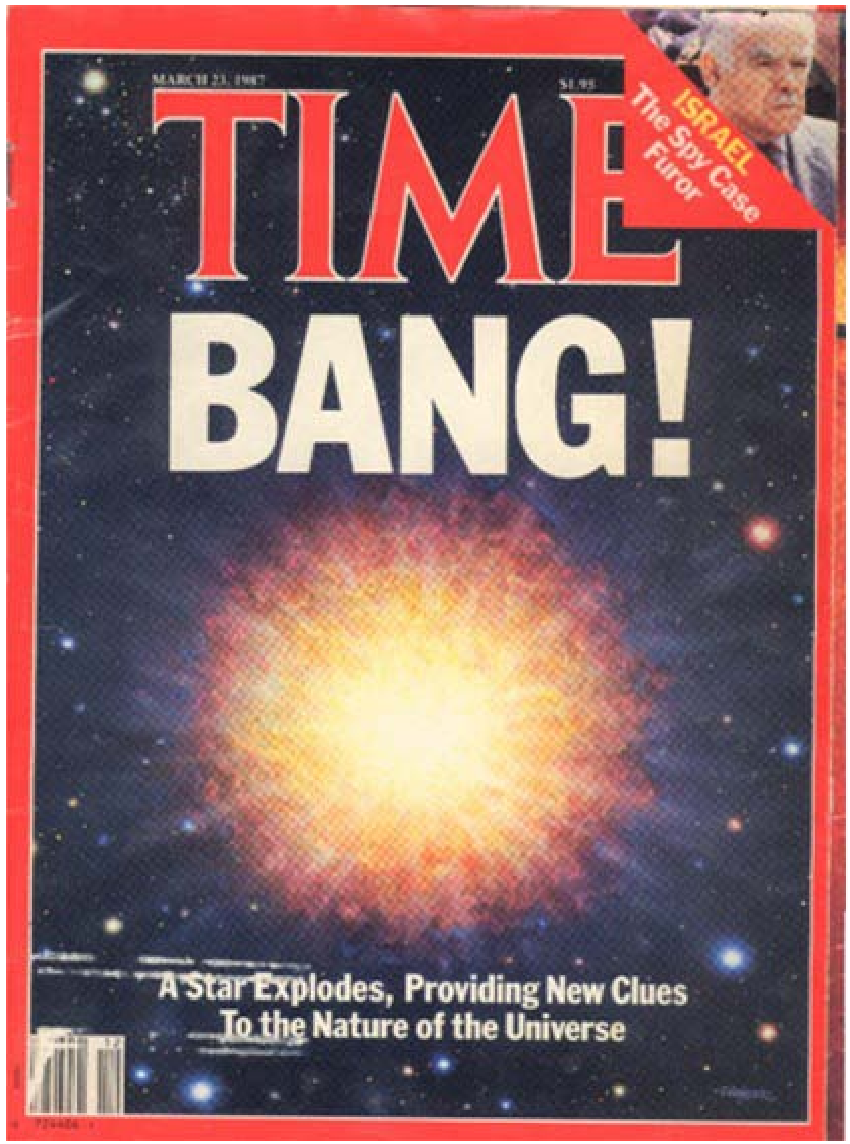


Kamiokande also noticed something strange going on with the atmospheric muon neutrinos.

They tended to use the ratio-of-ratios approach to discuss the data. Eventually this became standard.

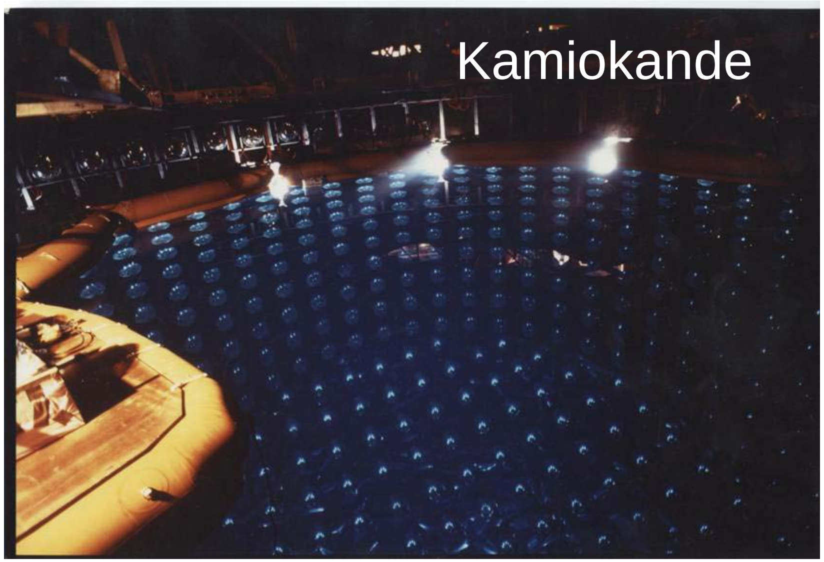
$$R = \frac{(\nu_\mu/\nu_e)^{\text{data}}}{(\nu_\mu/\nu_e)^{\text{Monte Carlo}}}$$

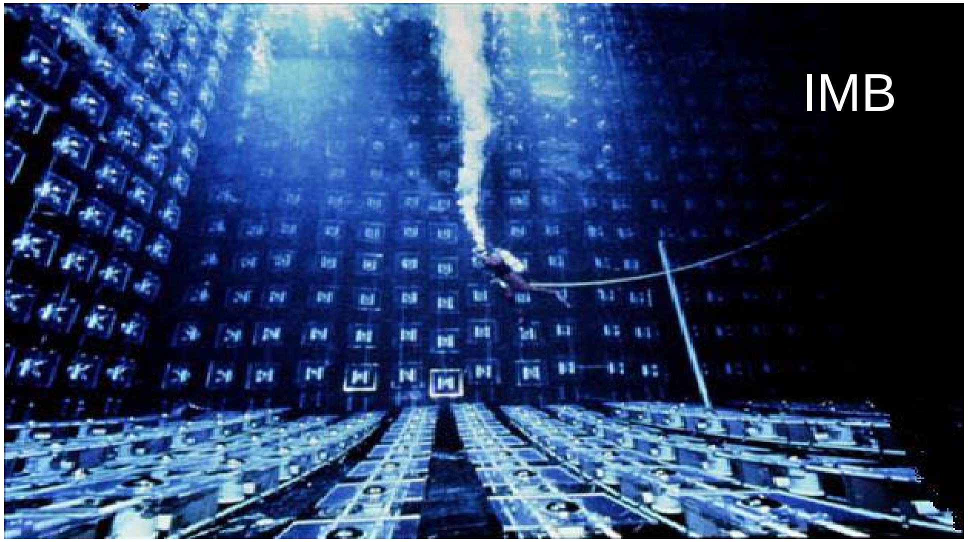
But then, at 07:35:41 UT on February 24th, 1987, both IMB and Kamiokande got a nice surprise:

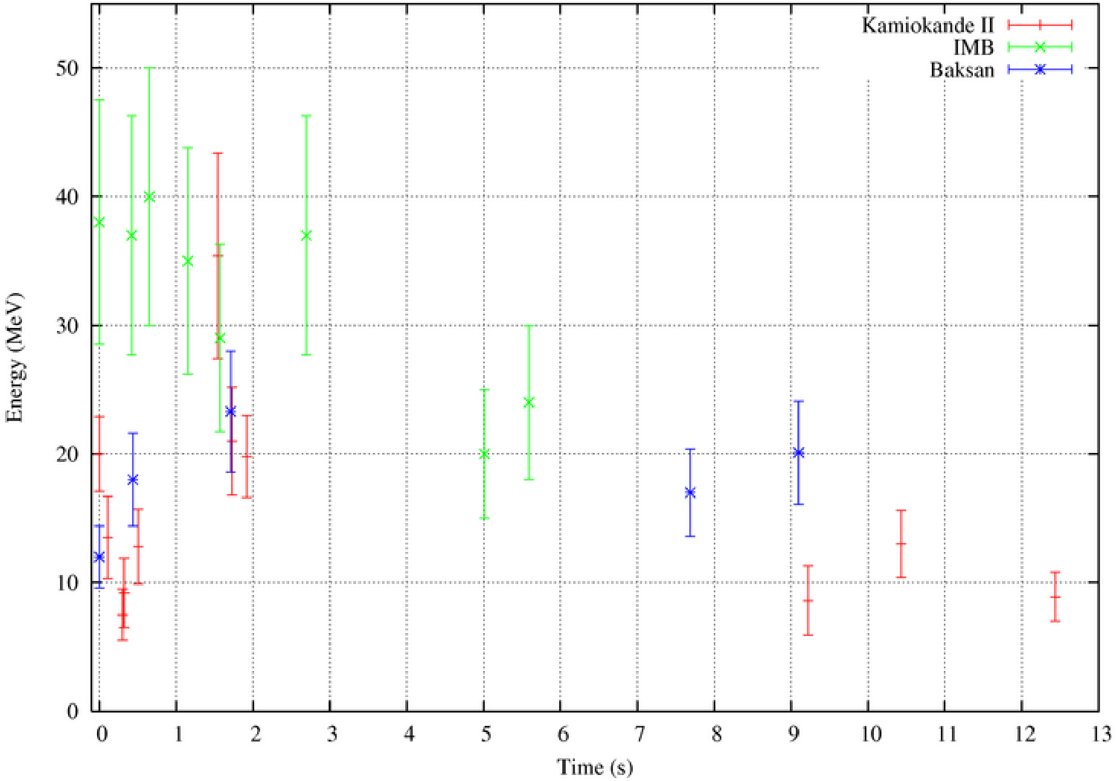


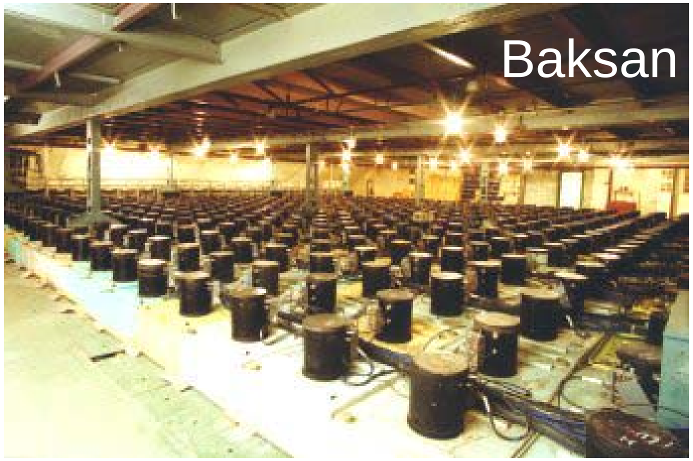
A long time ago, in a (neighbor) galaxy far, far away…

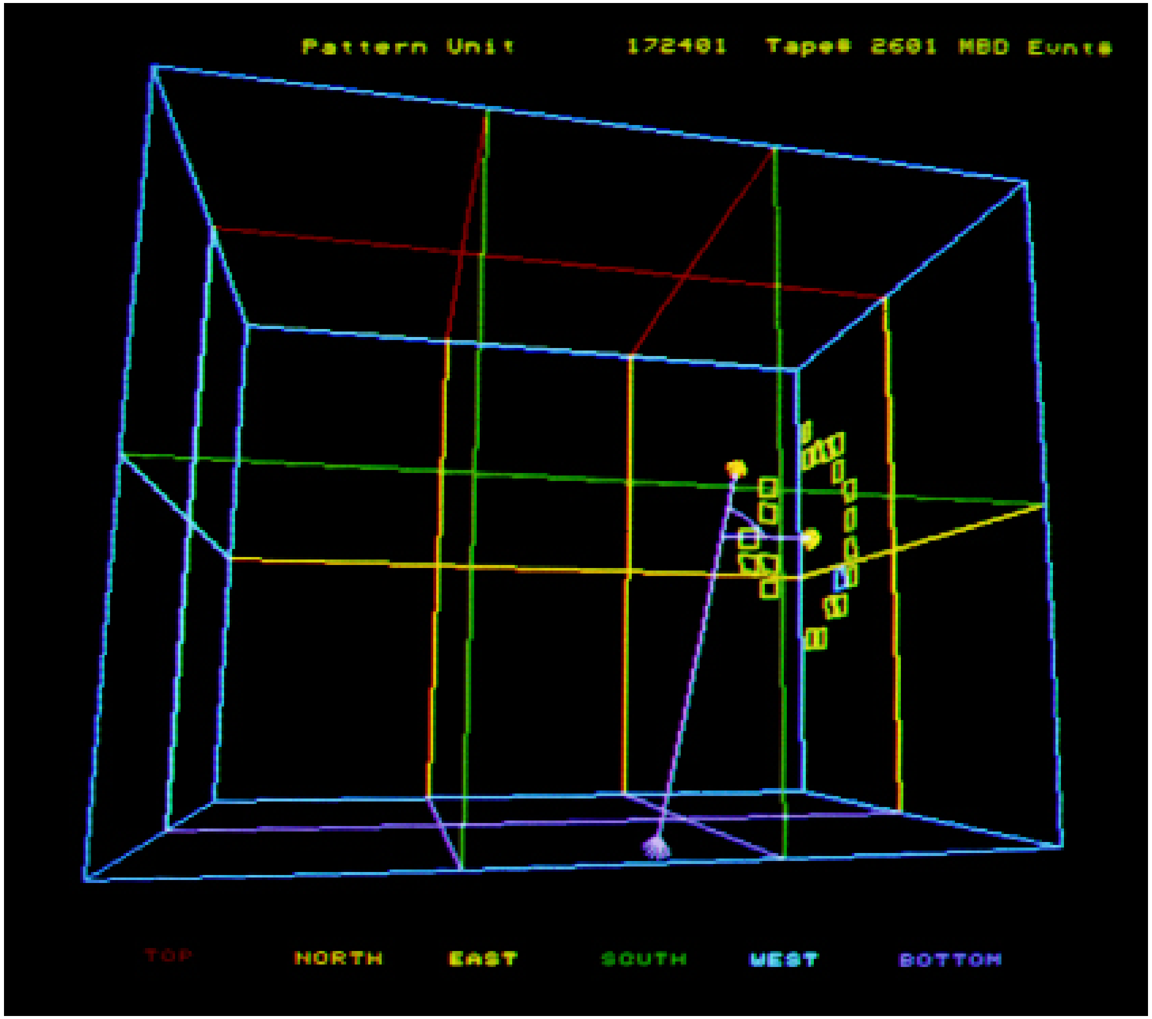
A long time ago, in a (neighbor) galaxy far, far away…

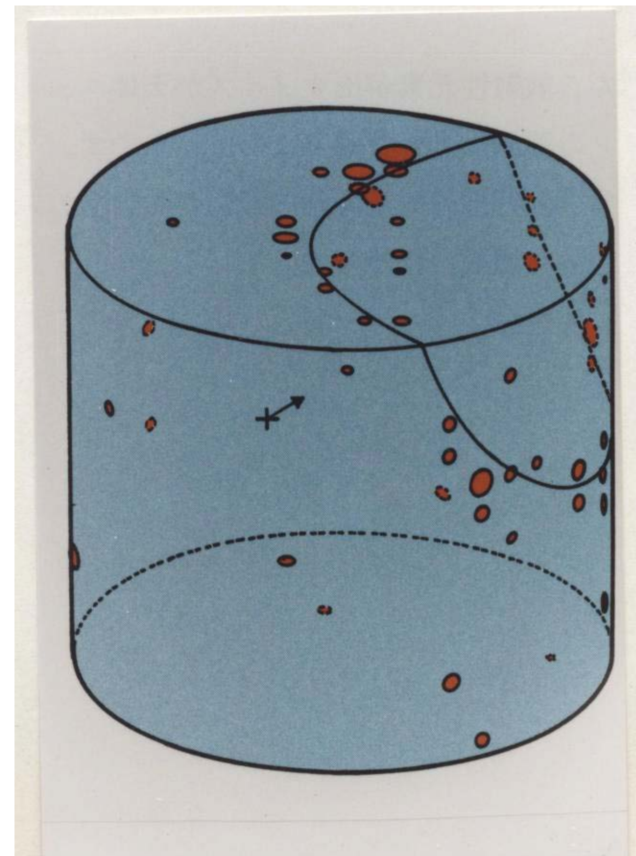

Kamiokande


IMB


Kamiokande II
IMB
Baksan
Energy (MeV)
Time (s)
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13


Baksan


Pattern Unit 172401 Tape# 2601 MBD Evnts
TOP NORTH EAST SOUTH WEST BOTTOM



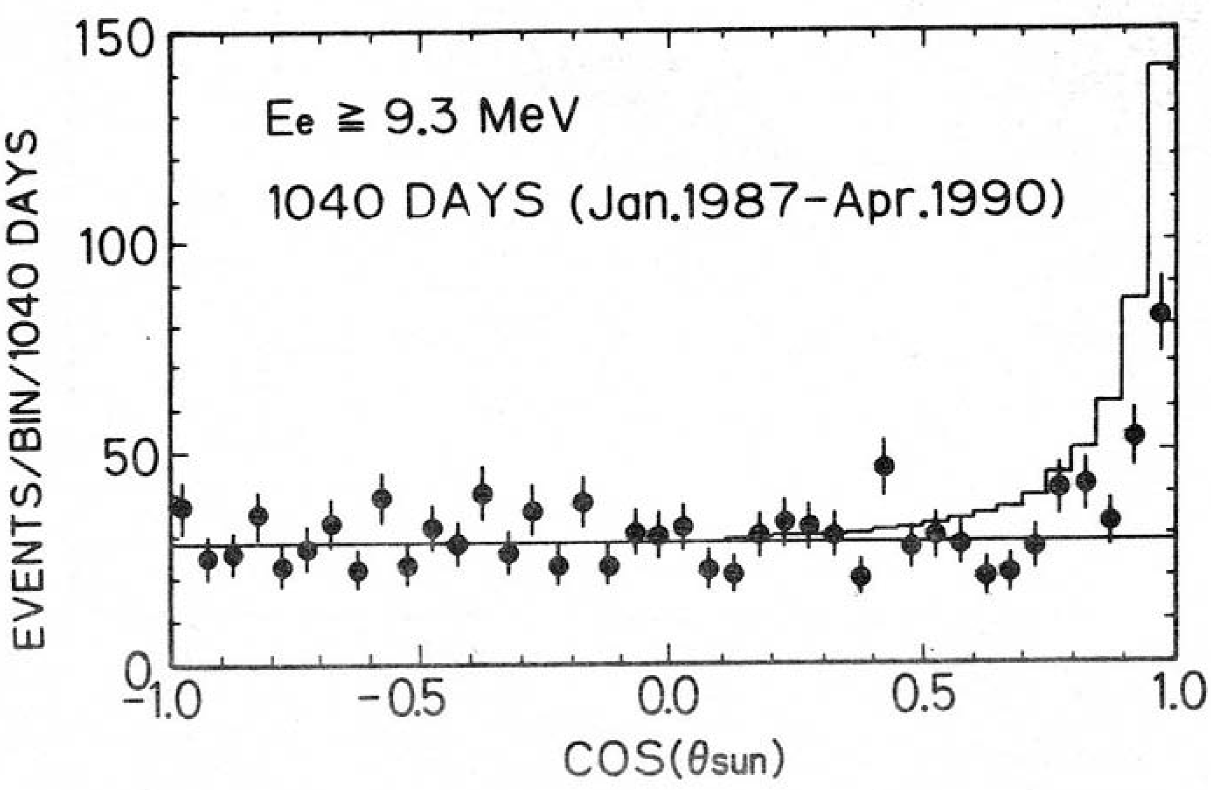
Based on the handful of supernova neutrinos which were detected that day, approximately <u>one theory paper has been published every ten days</u>…

…for the last <u>twenty-three years!</u>

In 2002, Masatoshi Koshiba would win the Nobel Prize in physics for observing the neutrinos from SN1987A with Kamiokande.

Supernova 1987A re-energized the neutrino field, and (at least in my opinion) did a lot to help make the next generation of detectors a reality.

They were also driven by important neutrino findings coming out of an upgraded Kamiokande:



First proof neutrinos are made by the Sun.

But here, not enough ν_e!

In addition to looking for muon decays, WC detectors can also look at the pattern of the Cherenkov rings to differentiate muons from electrons.

In 1988, Koshiba showed that both methods in Kamiokande led to a small ratio-of-ratios. He was certain something important was going on.

In Japan in the late 1980's, there started serious talk of building something called Super-Kamiokande.

But something important had changed in a decade…

Kamiokande =
Kamioka Nucleon Decay Experiment

Super-Kamiokande = Super
Kamioka Neutrino Detection Experiment

Neutrinos – atmospheric, solar, and supernova – were now the stars of the show!