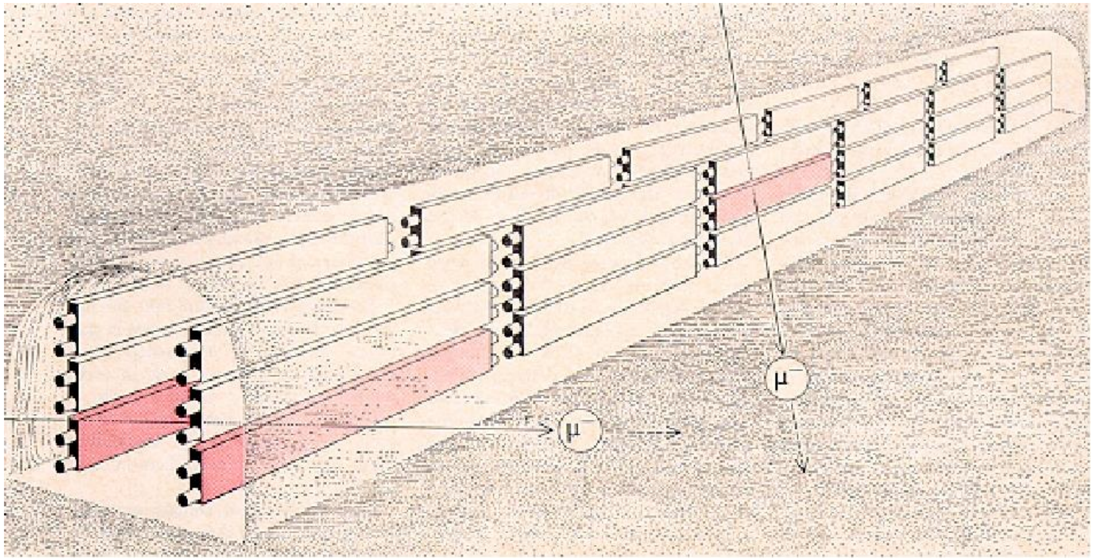
Chasing Neutrinos Around The World: A Personal History



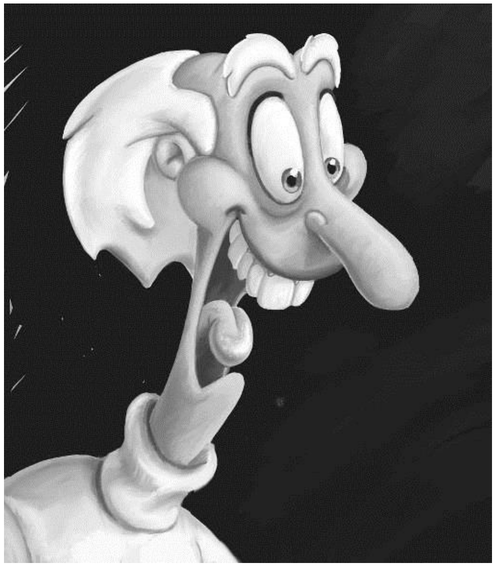
Mark Vagins

Kavli IPMU, University of Tokyo/UC Irvine

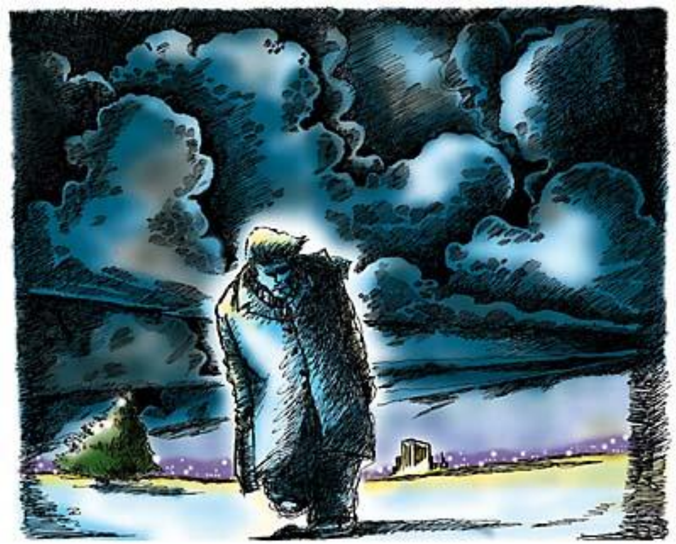
SN neutrinos at the crossroads: astrophysics, oscillations, and detection

ECT*, Trento, Italy May 15, 2019

I'm going to tell you all about trying to detect 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 PM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben 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.

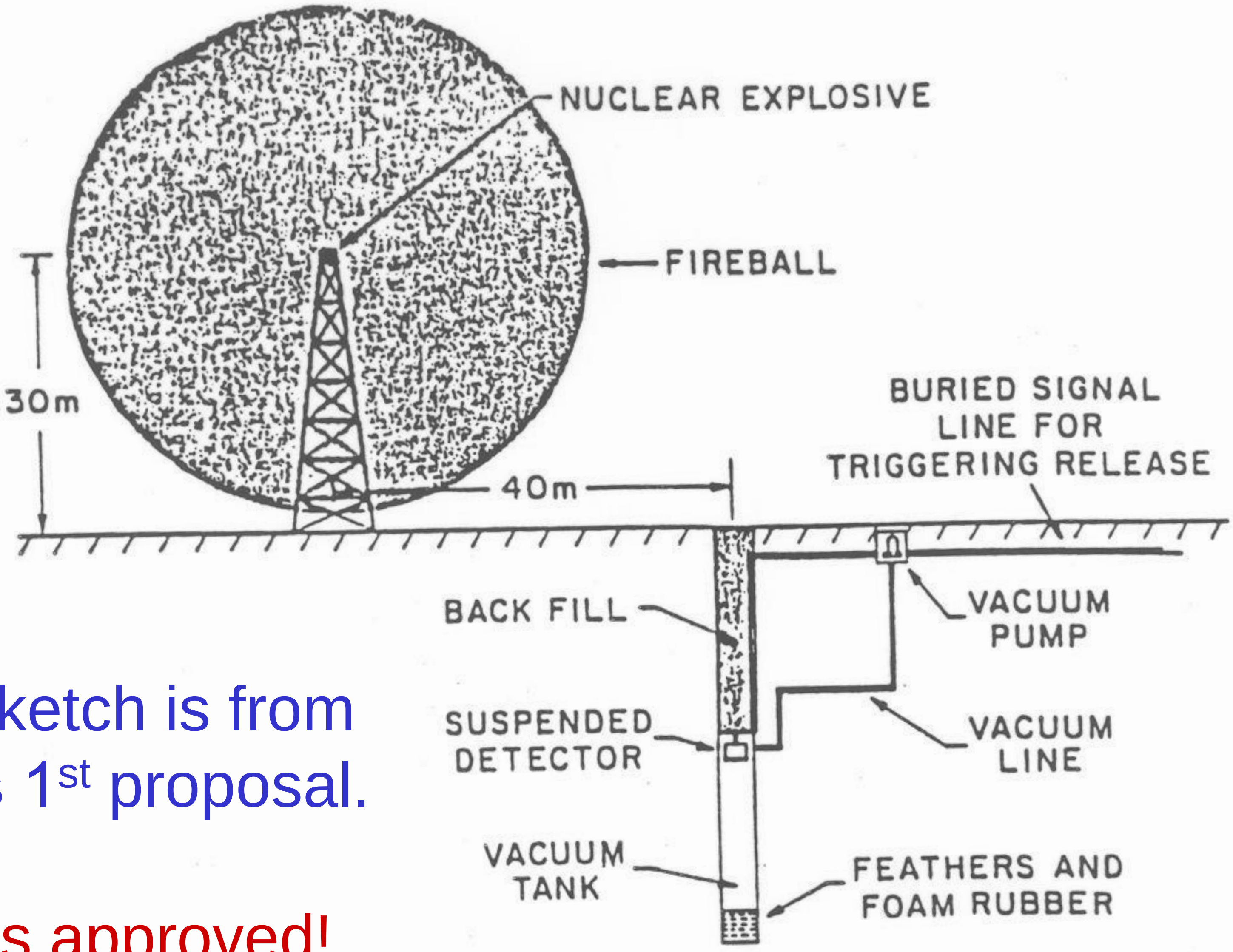
Your humble servant
W. Pauli

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

Twenty years later, along came the first really serious, but still crazy, 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.



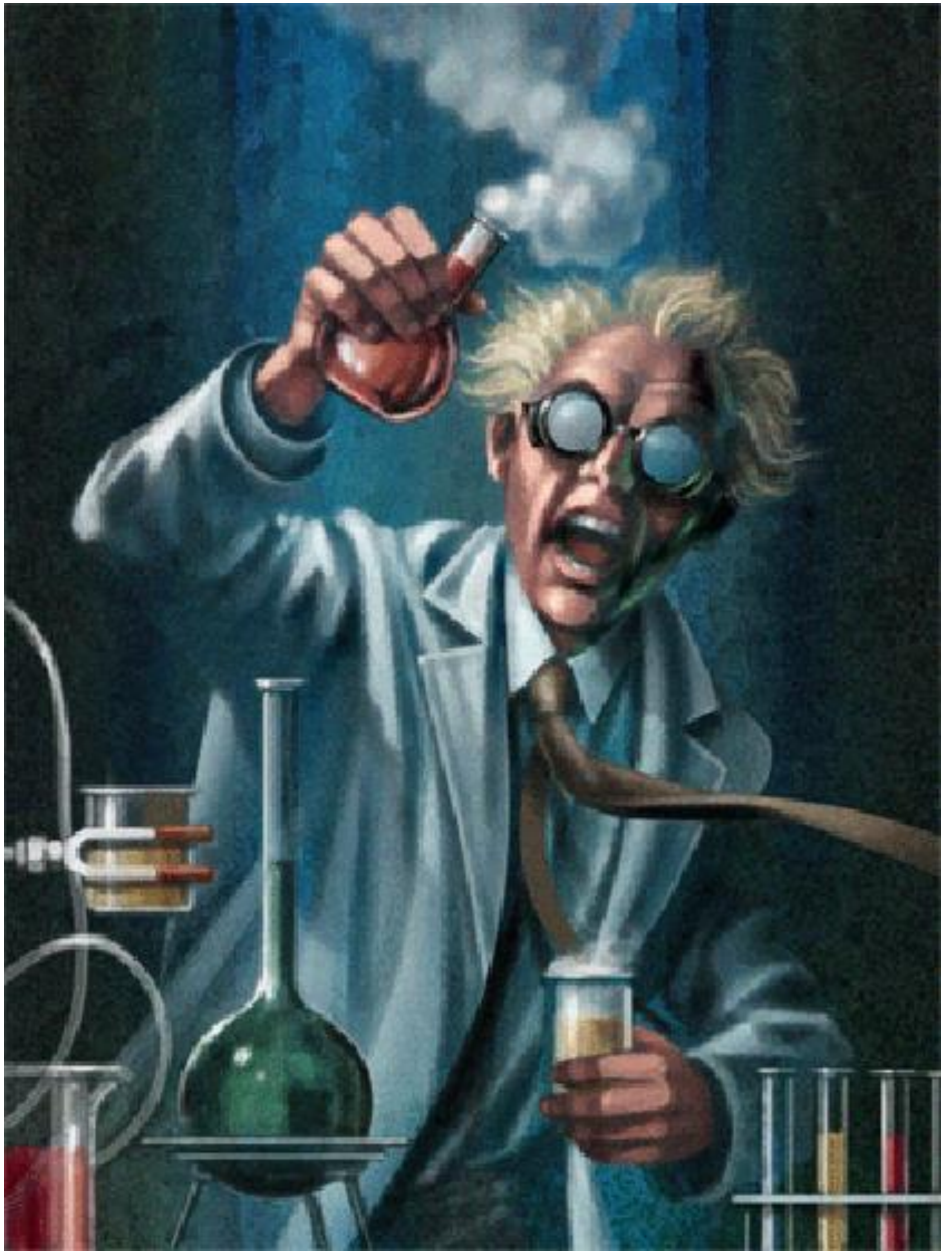
This sketch is from Fred's 1st proposal.

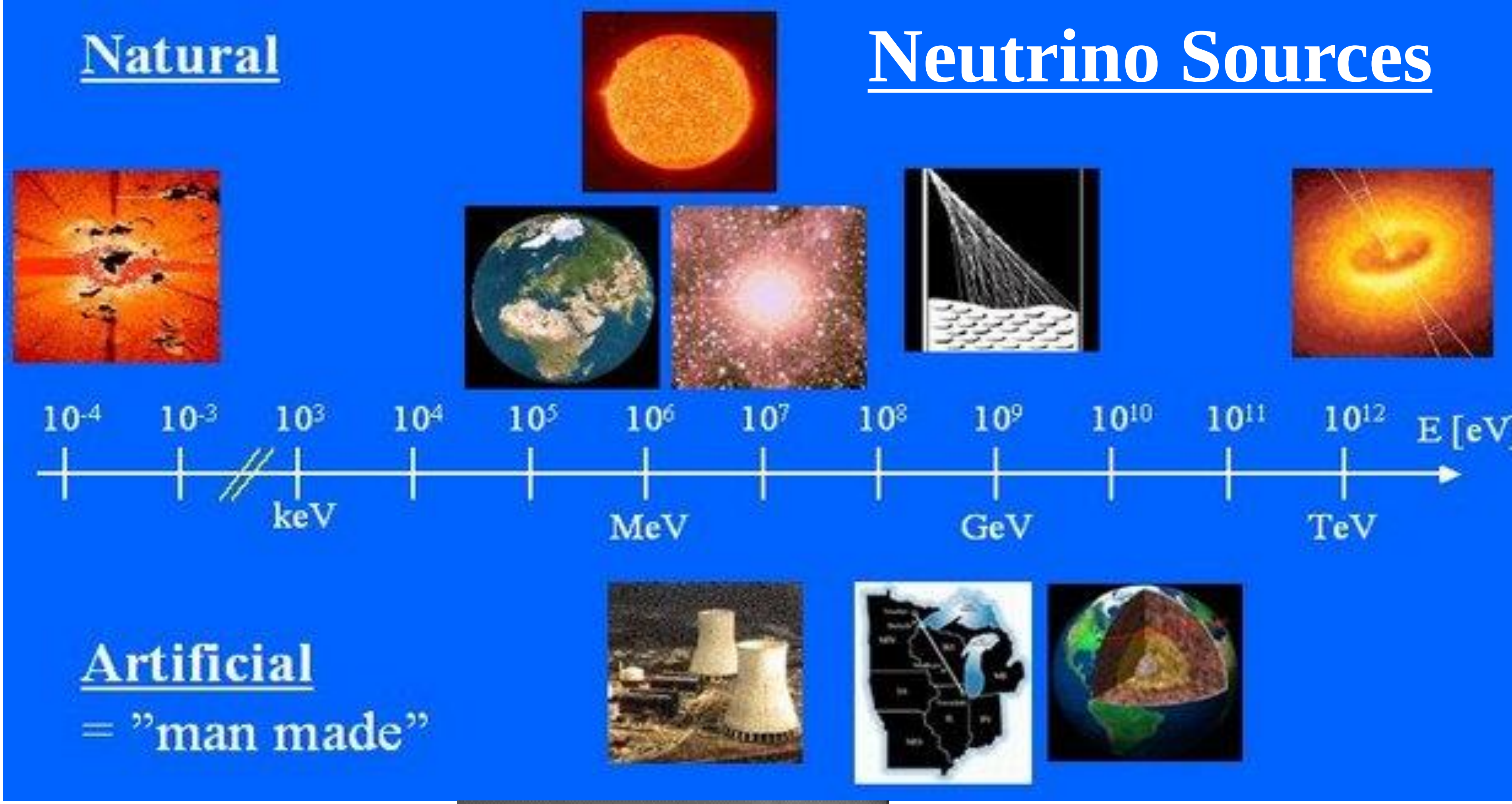
It was approved!

So, essentially Fred asked for his very own, private above-ground atomic test, and was told,

"Well, sure, you go right ahead. We'll set aside a nuclear bomb just for you."

Ah, the 1950's!

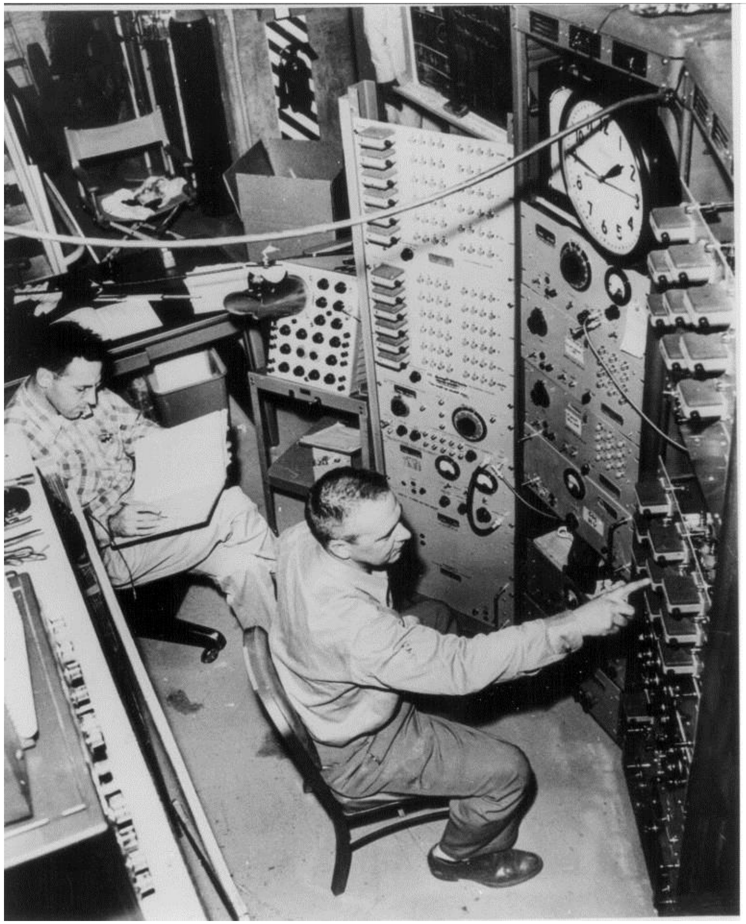


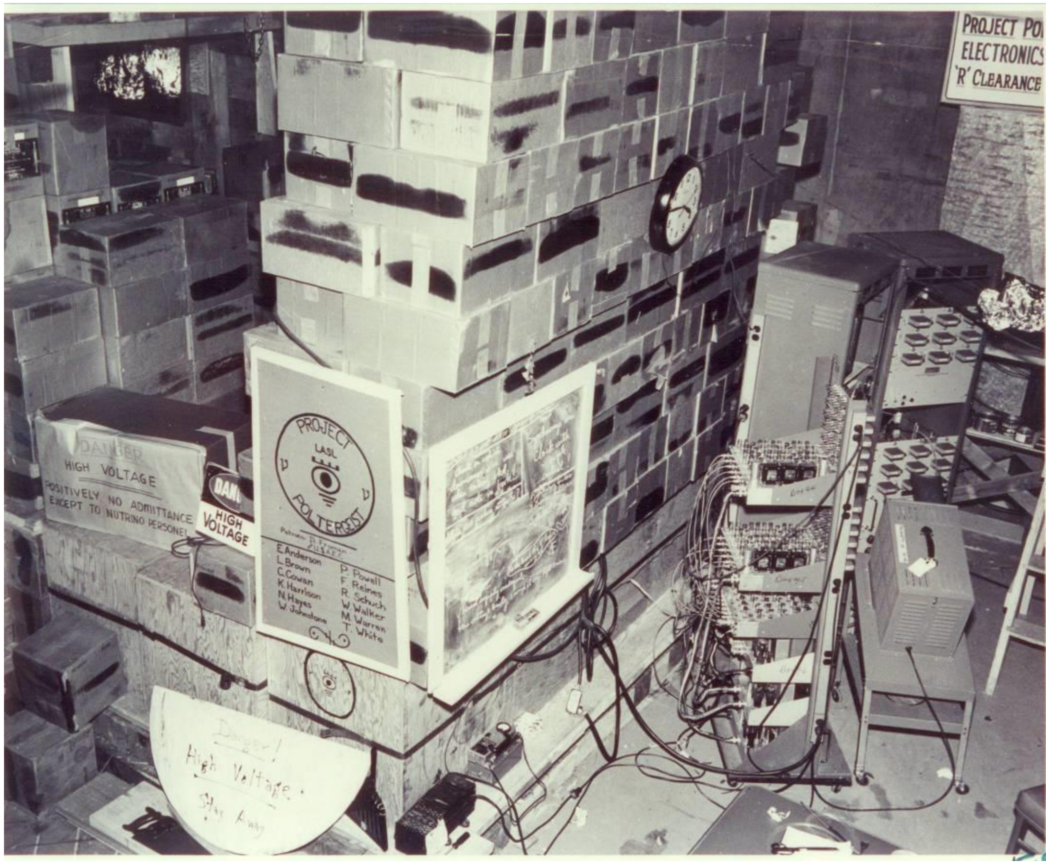


Hey… they forgot one! →

After over sixty years, this is still an unobserved source of neutrinos, because Fred suddenly thought of a better way.

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 *unsuccessful* experiment at the Hanford reactor in 1953.

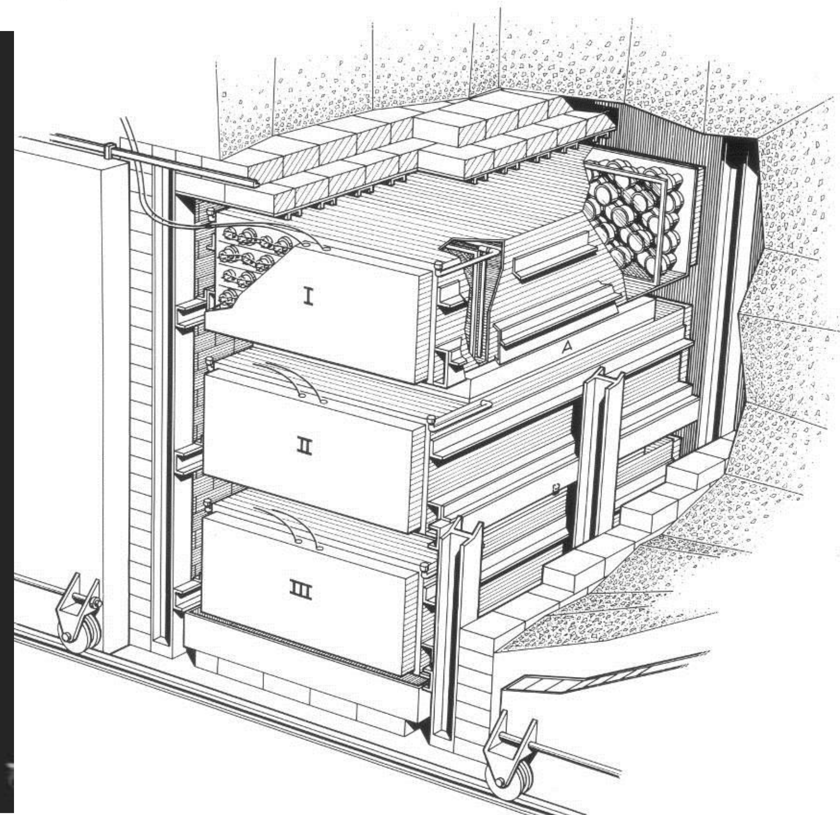




At last, success!

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

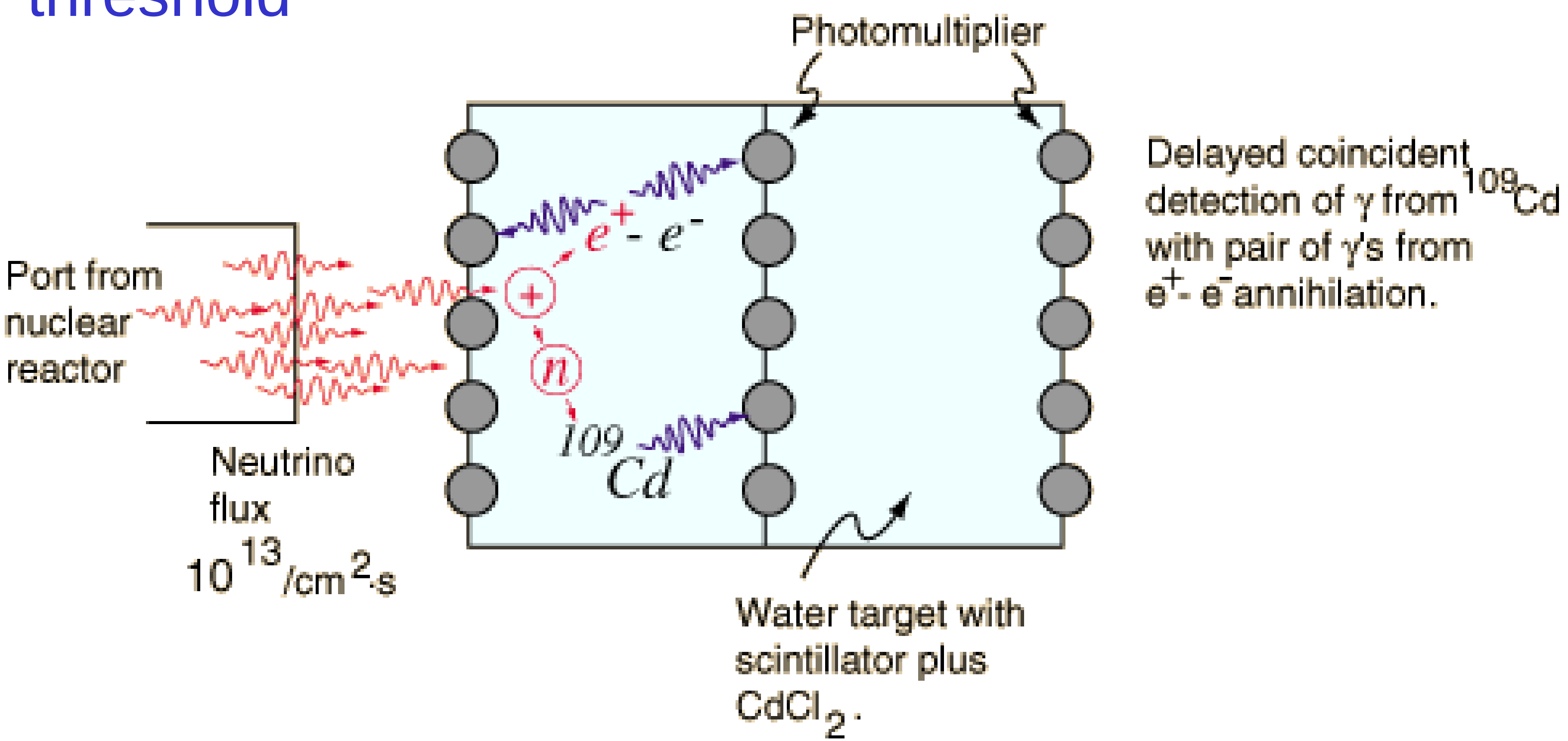
39 long years later, Reines would finally be given the 1995 Nobel Prize in physics for this discovery.



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

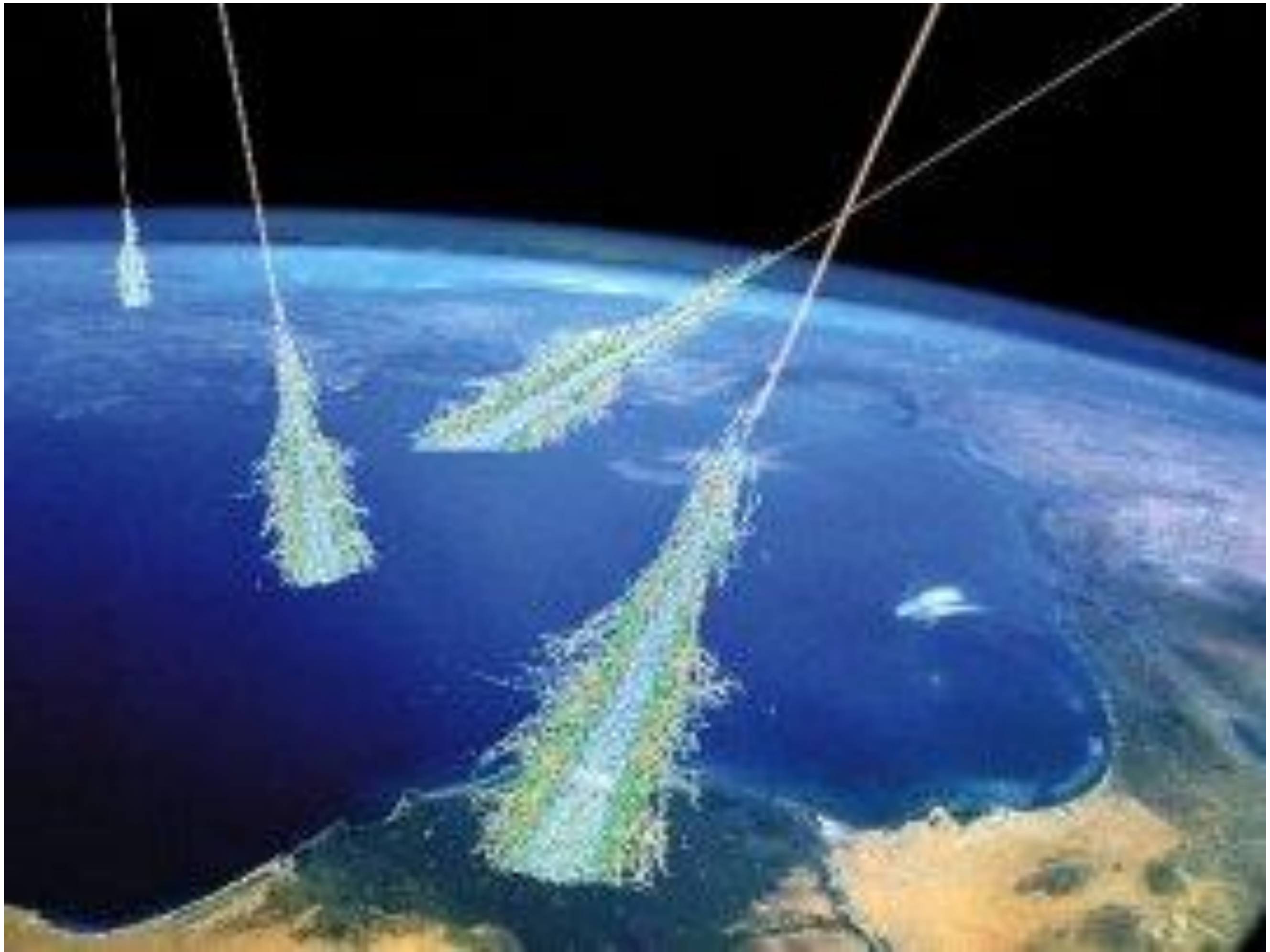
$$\hookrightarrow n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{109}Cd + \gamma$$

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



[Slide by F. Reines]

ATMOSPHERIC ν's

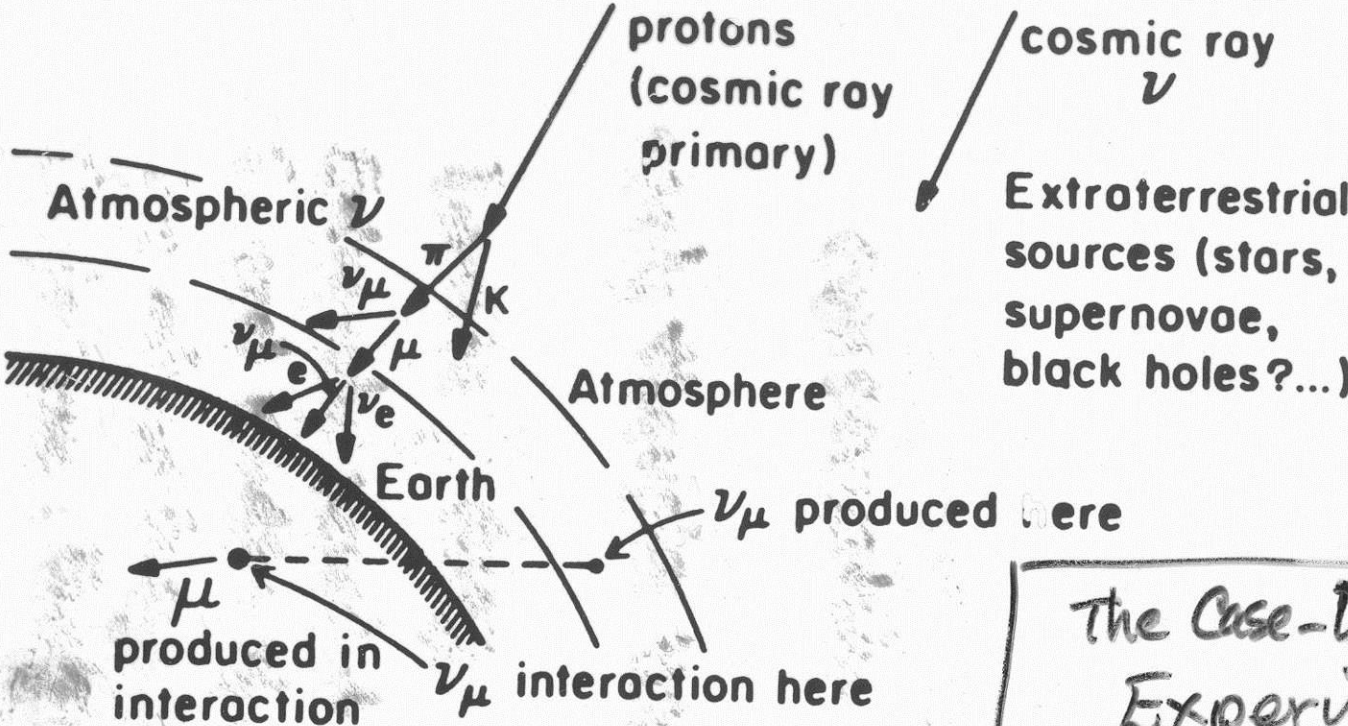
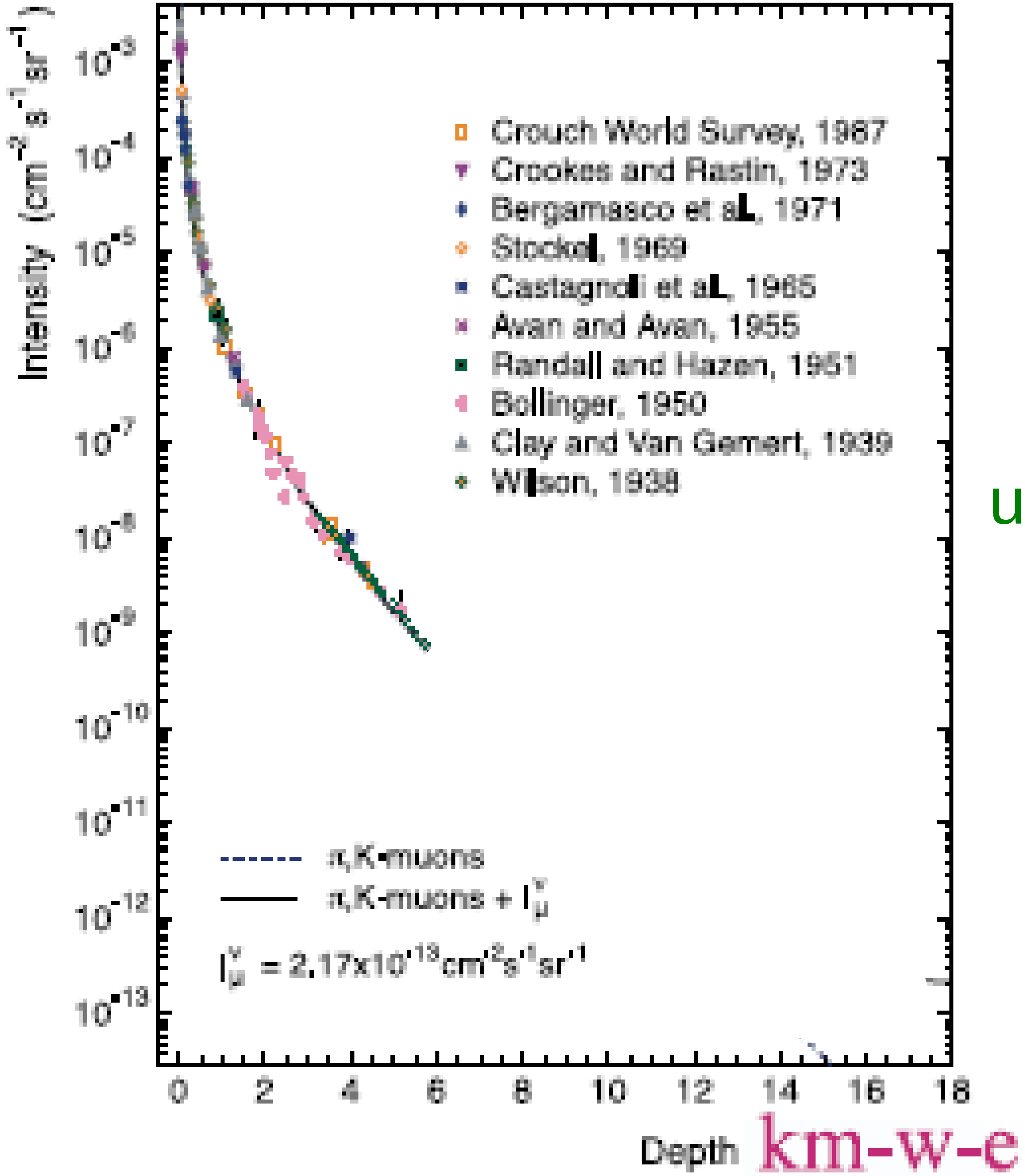


Figure 18
ν sources, terrestrial and extraterrestrial. Cosmic ray protons interact with earth's atmosphere producing particles (K, π, . . .) whose decay yields various ν types. Shown is the interaction of a ν_μ with the earth to produce a μ.

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.

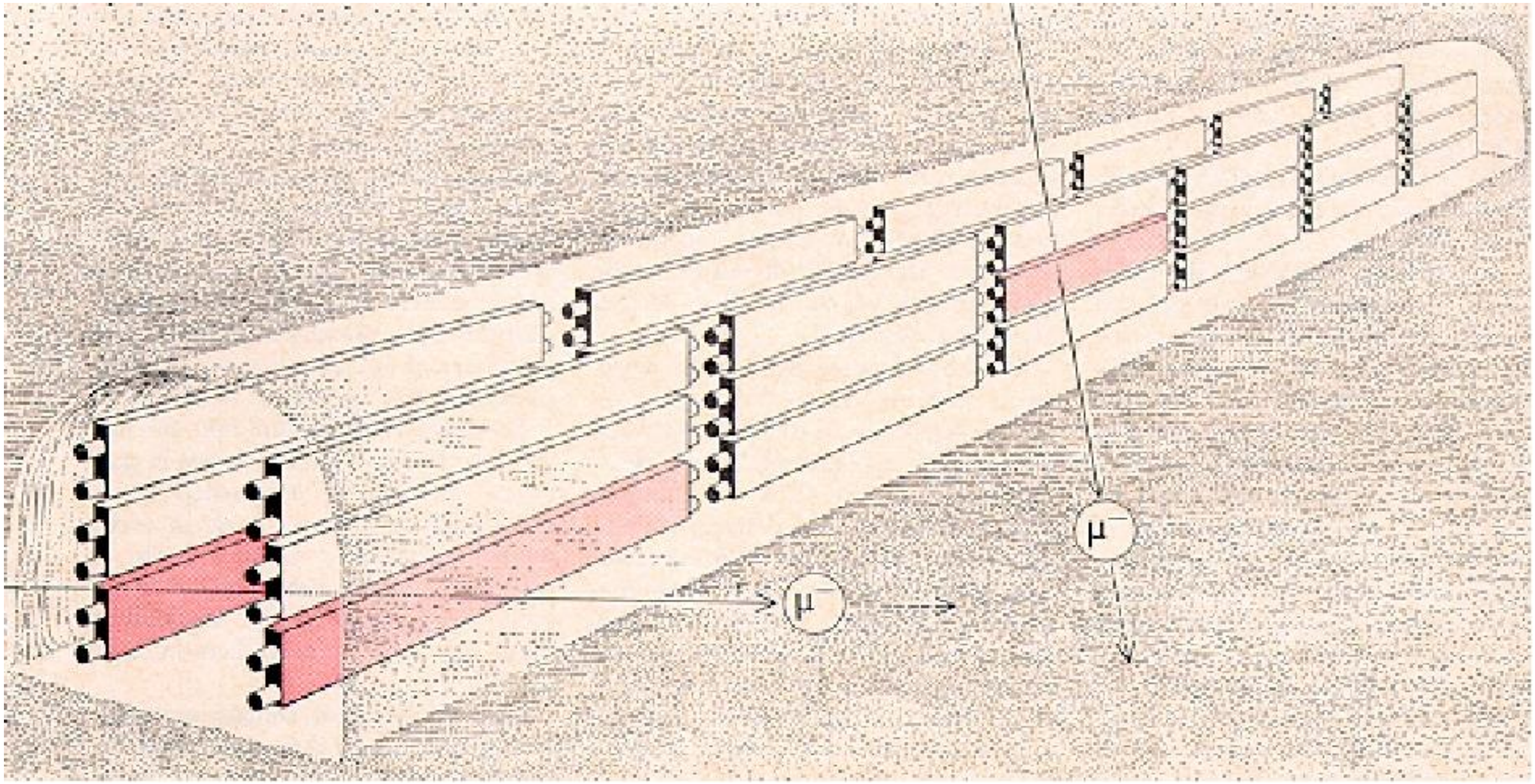
And this is as deep as it gets:

The East Rand gold mine in South Africa, circa 1964

Extends 3585 meters below ground!

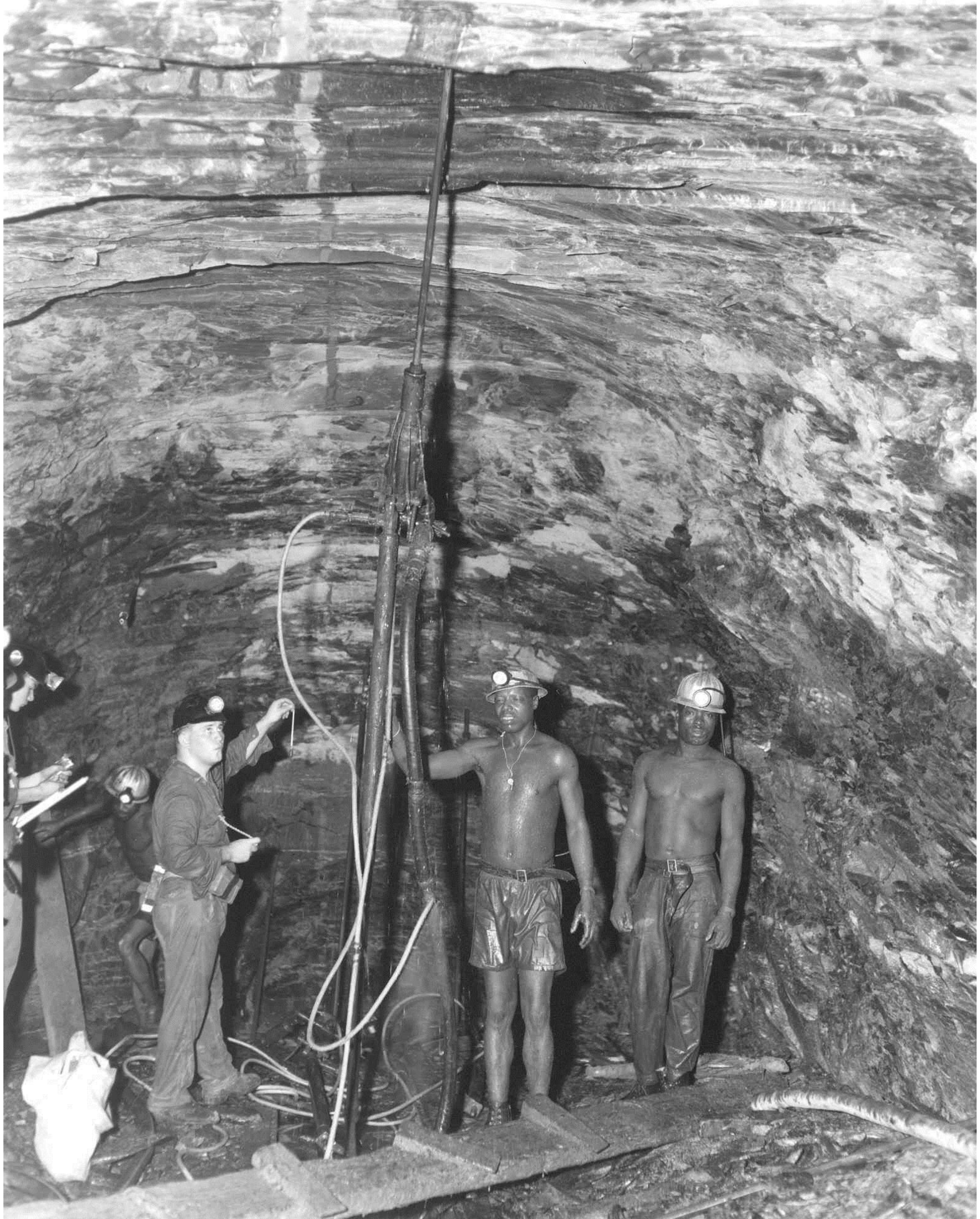
So, Fred Reines (a professor at Case Western Institute in Cleveland, Ohio) and his crew headed off to apartheid-era South Africa.


GEORGE

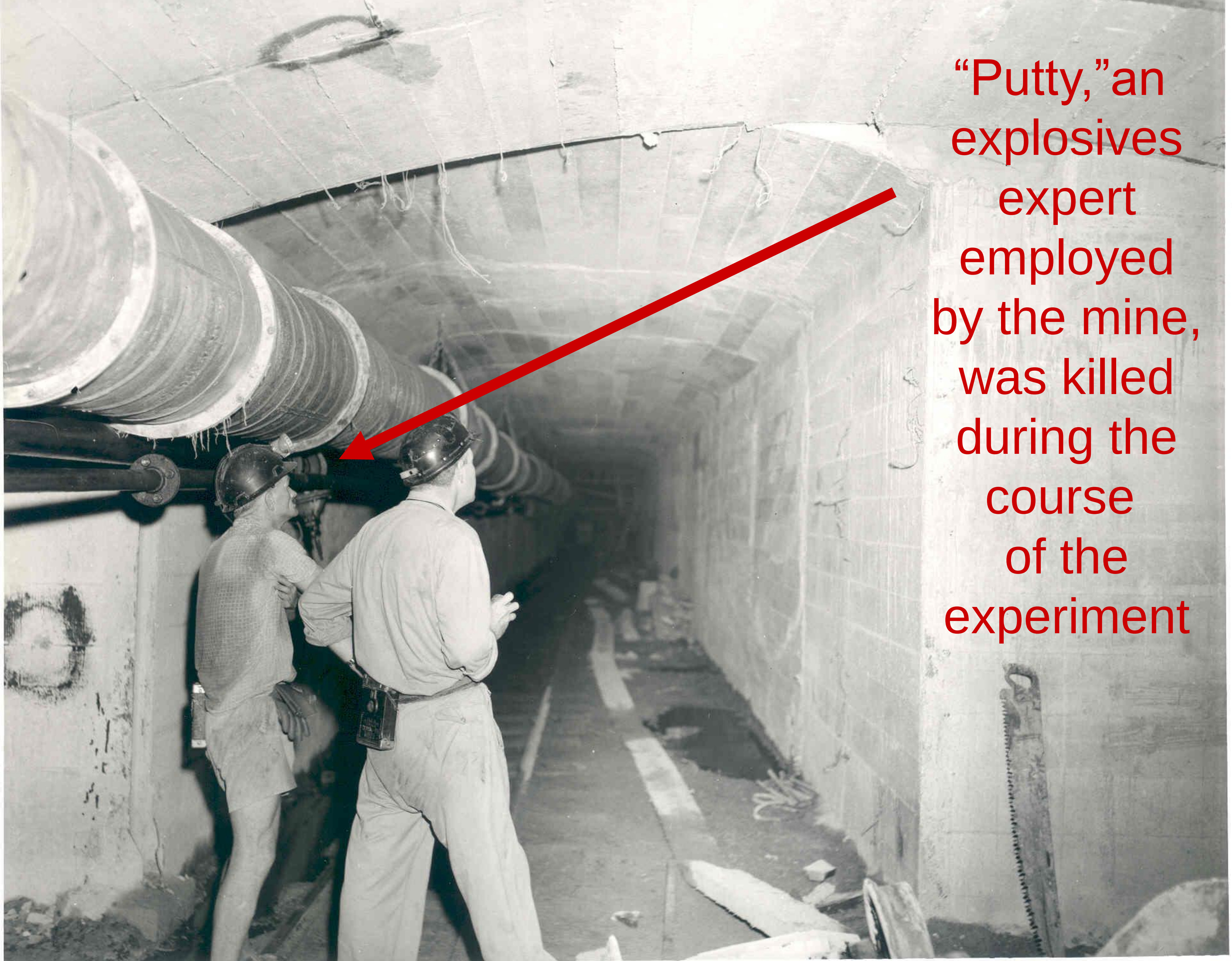


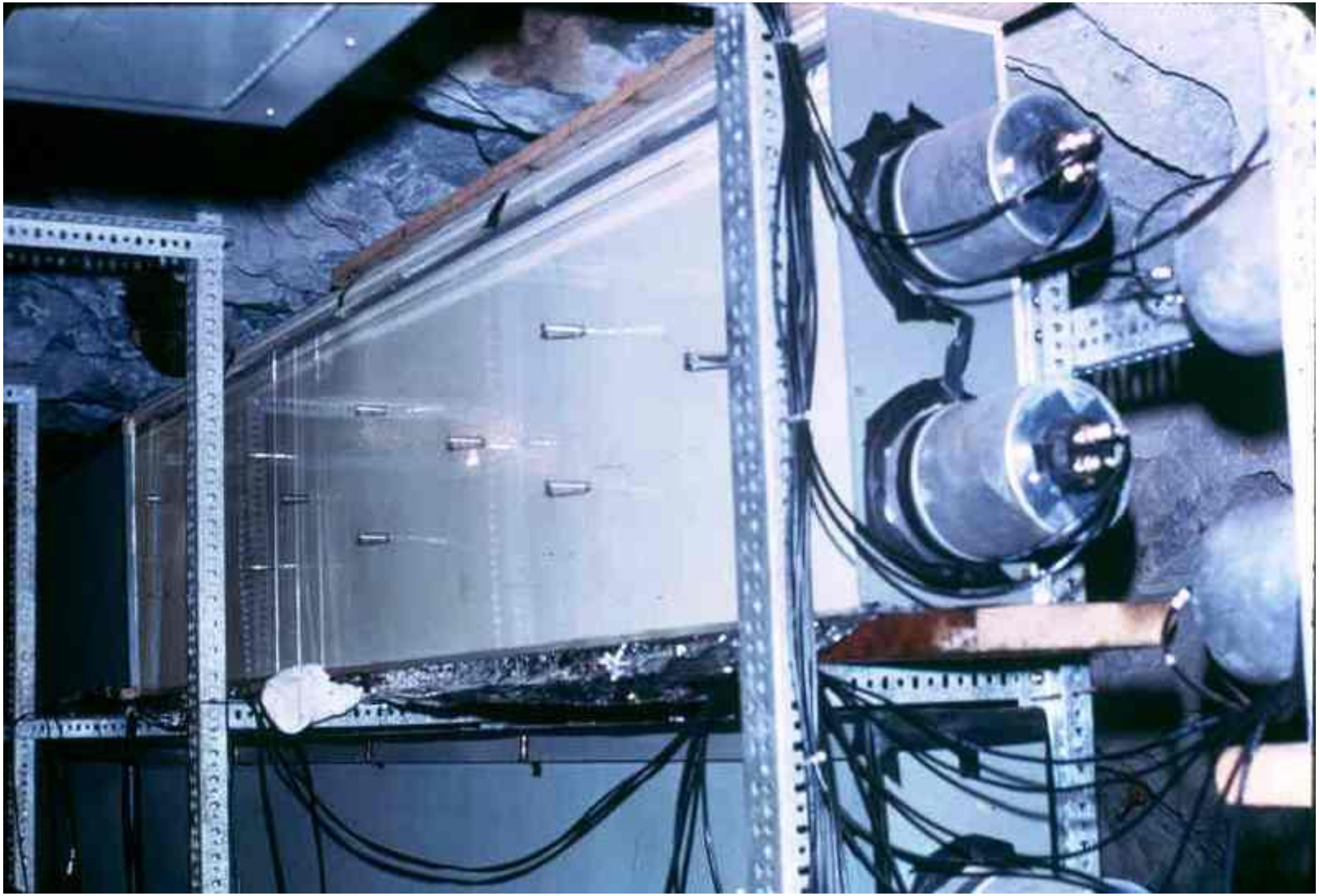
The Case Western Irvine/South Africa Neutrino Detector [CWI/SAND]

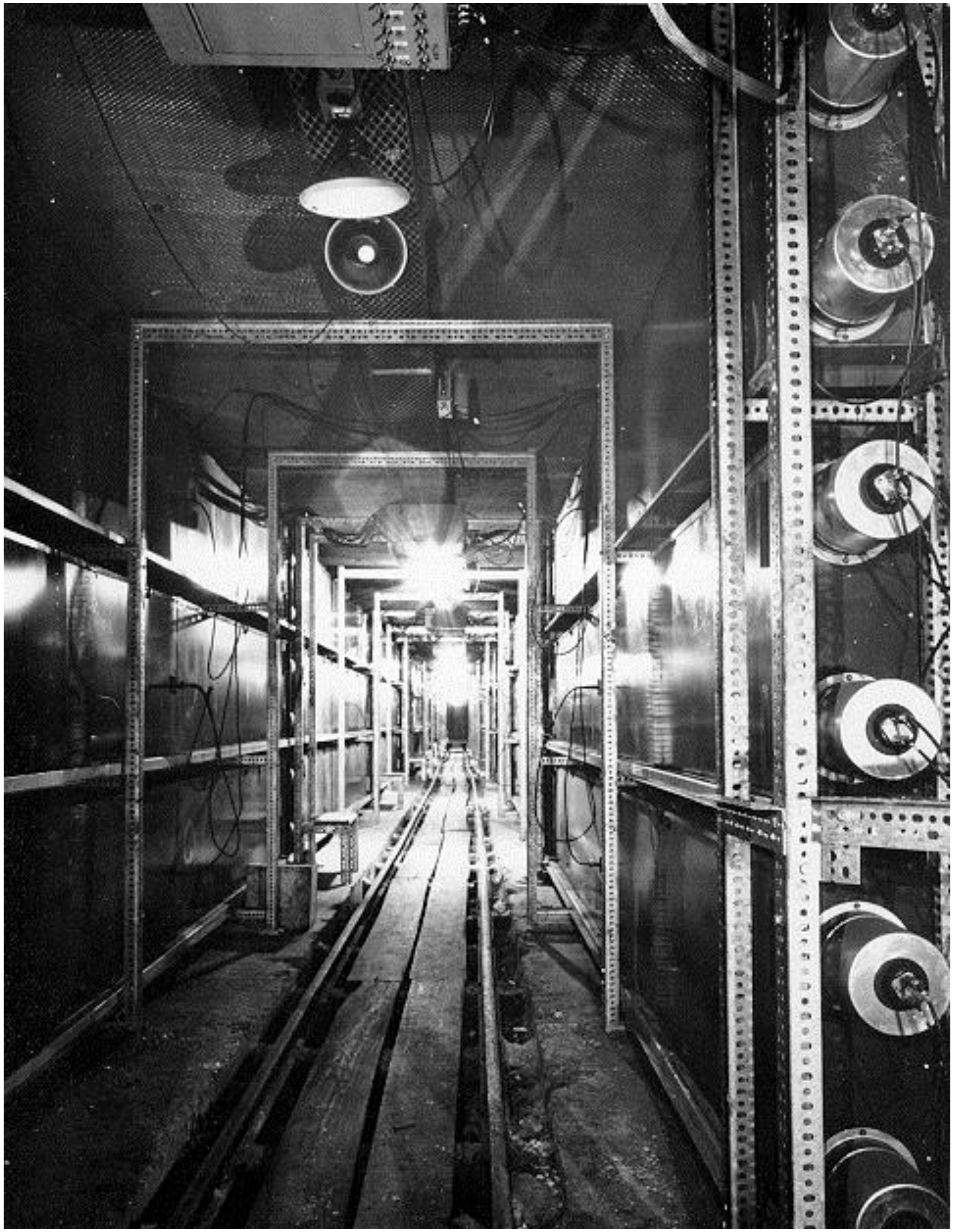
Boxes of liquid scintillator viewed with Two 5-inch PMT’s on each end

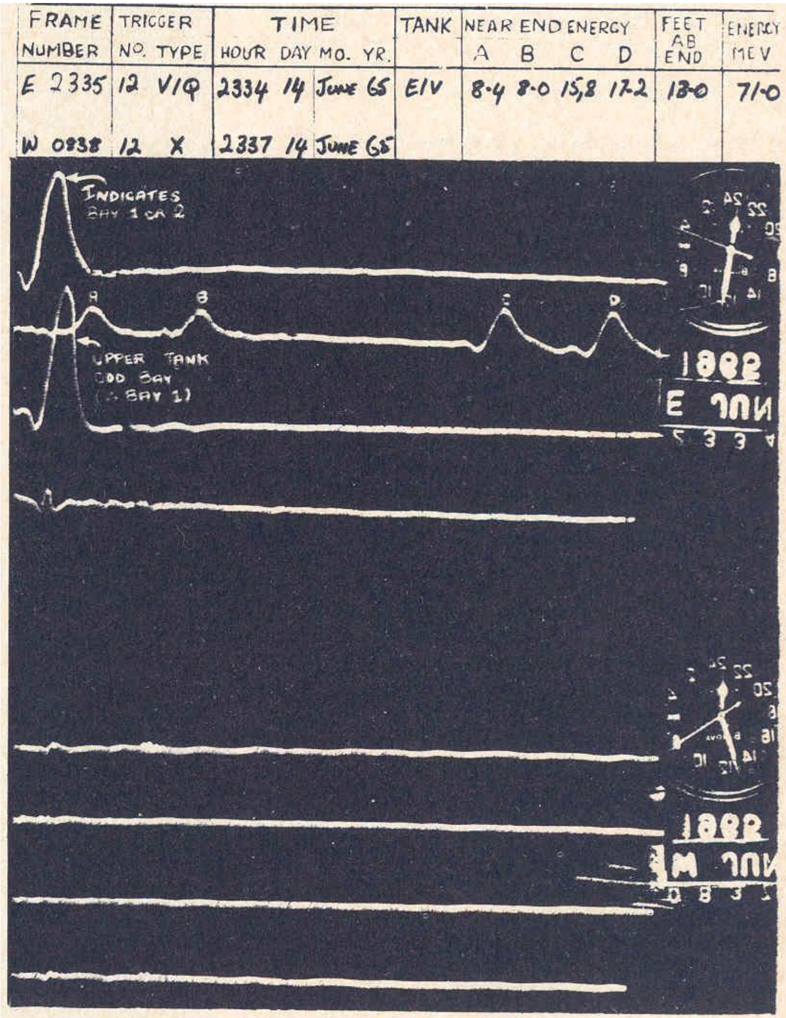


Digging out the experimental space, circa 1964

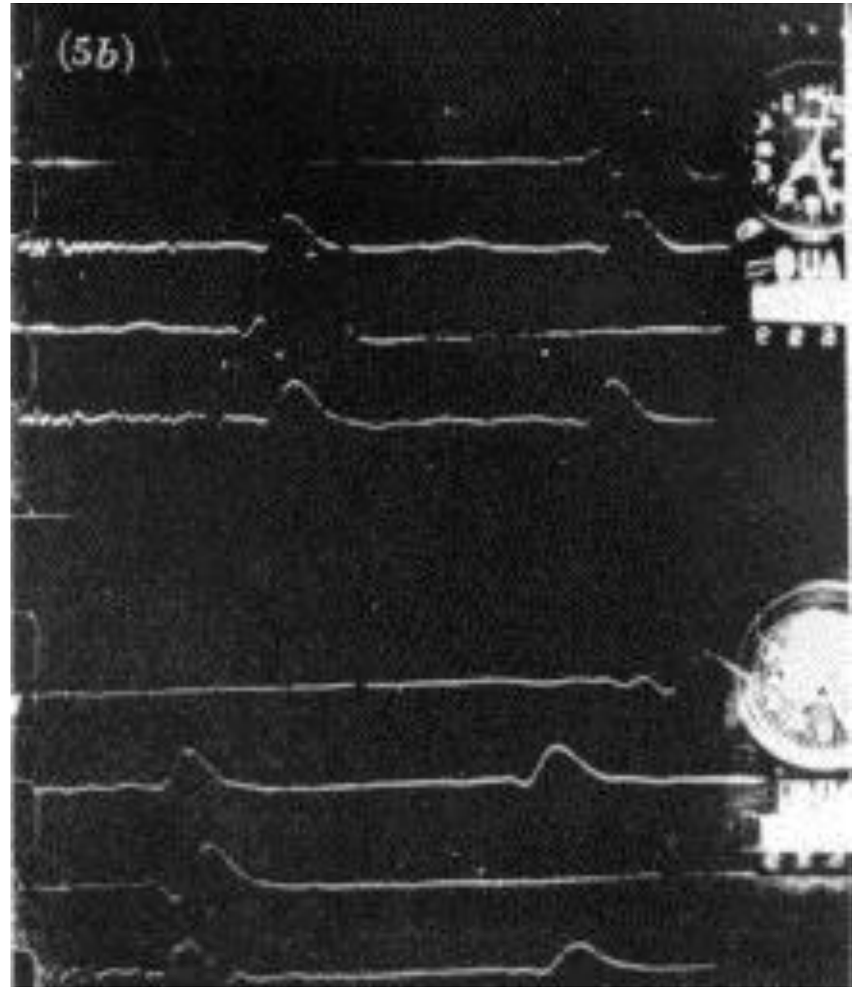

"Putty,"an
explosives
expert
employed
by the mine,
was killed
during the
course
of the
experiment



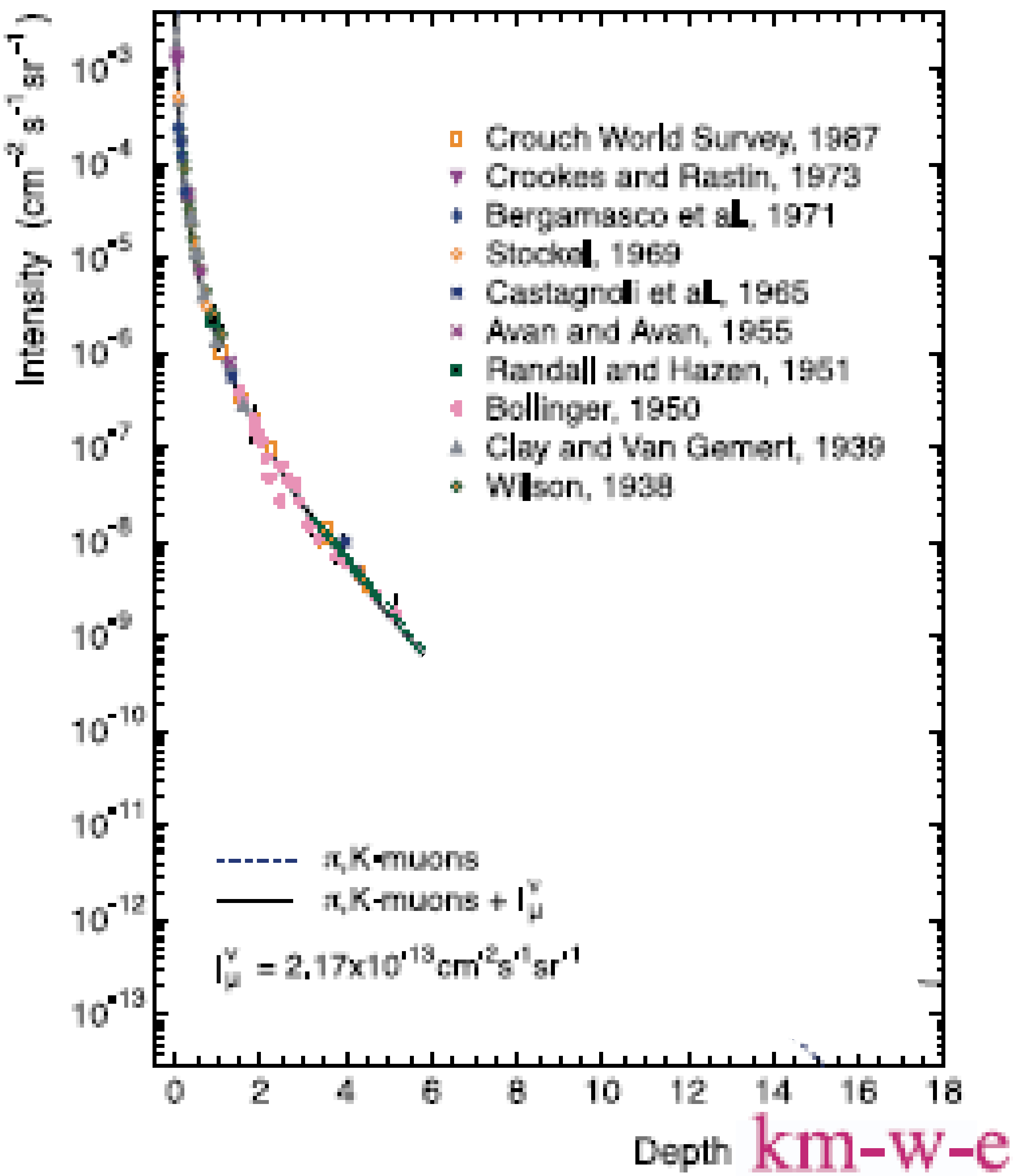




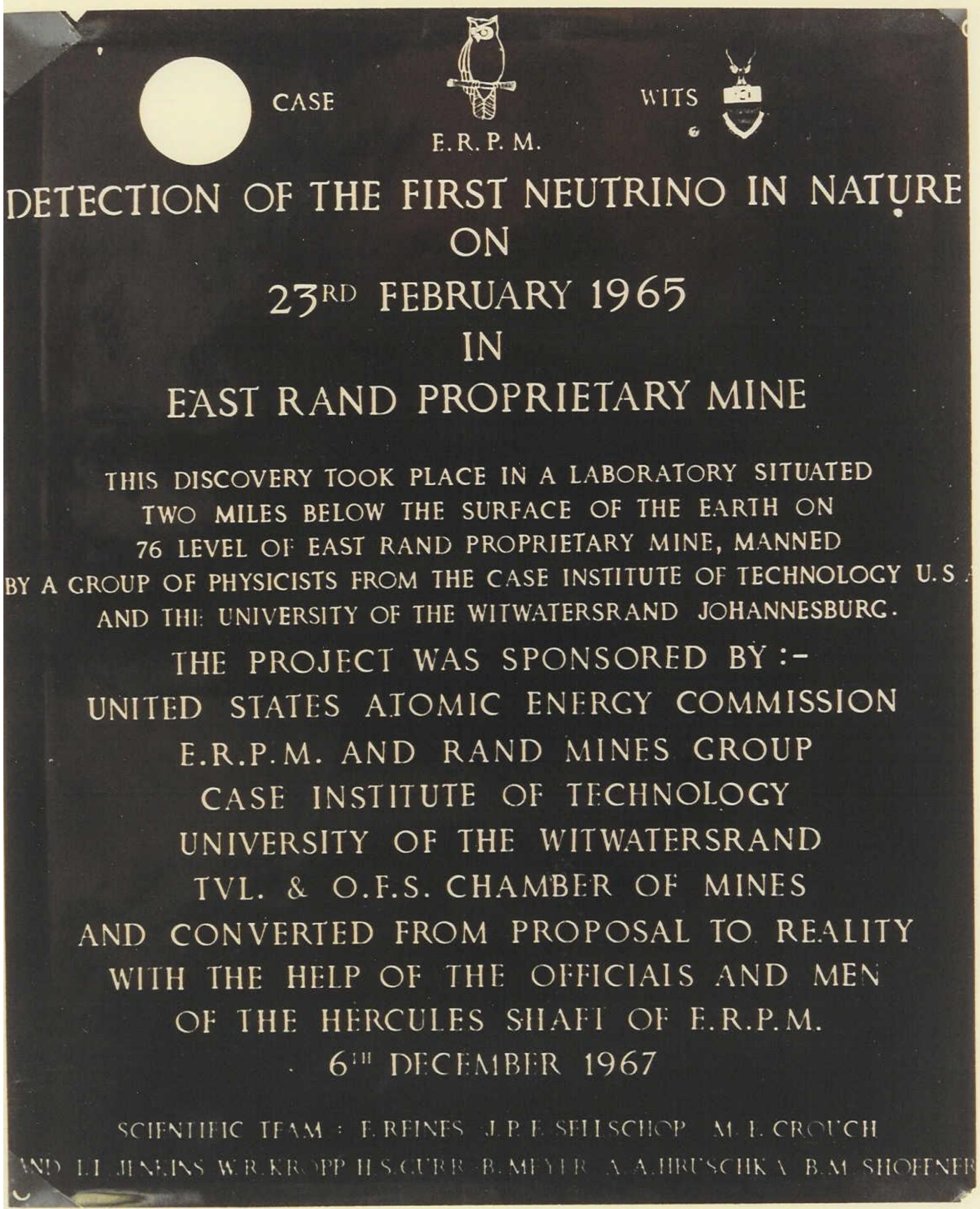
Downward-going Muon
(background)



Horizontal Muon
(neutrino signal)



Intensity (cm⁻² s⁻¹ sr⁻¹)
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
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$_\mu^\nu$
I$_\mu^\nu$ = 2.17x10⁻¹³cm⁻²s⁻¹sr⁻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-

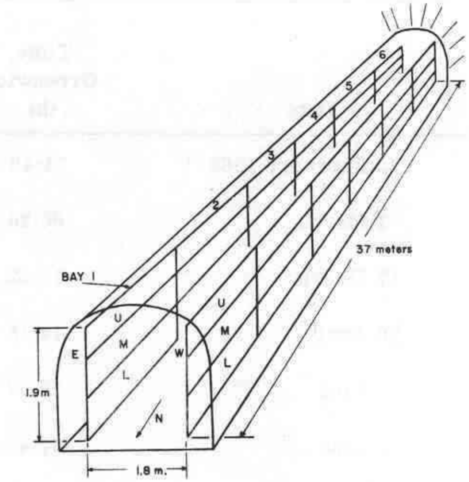


FIG. 1. Schematic of detector array.

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

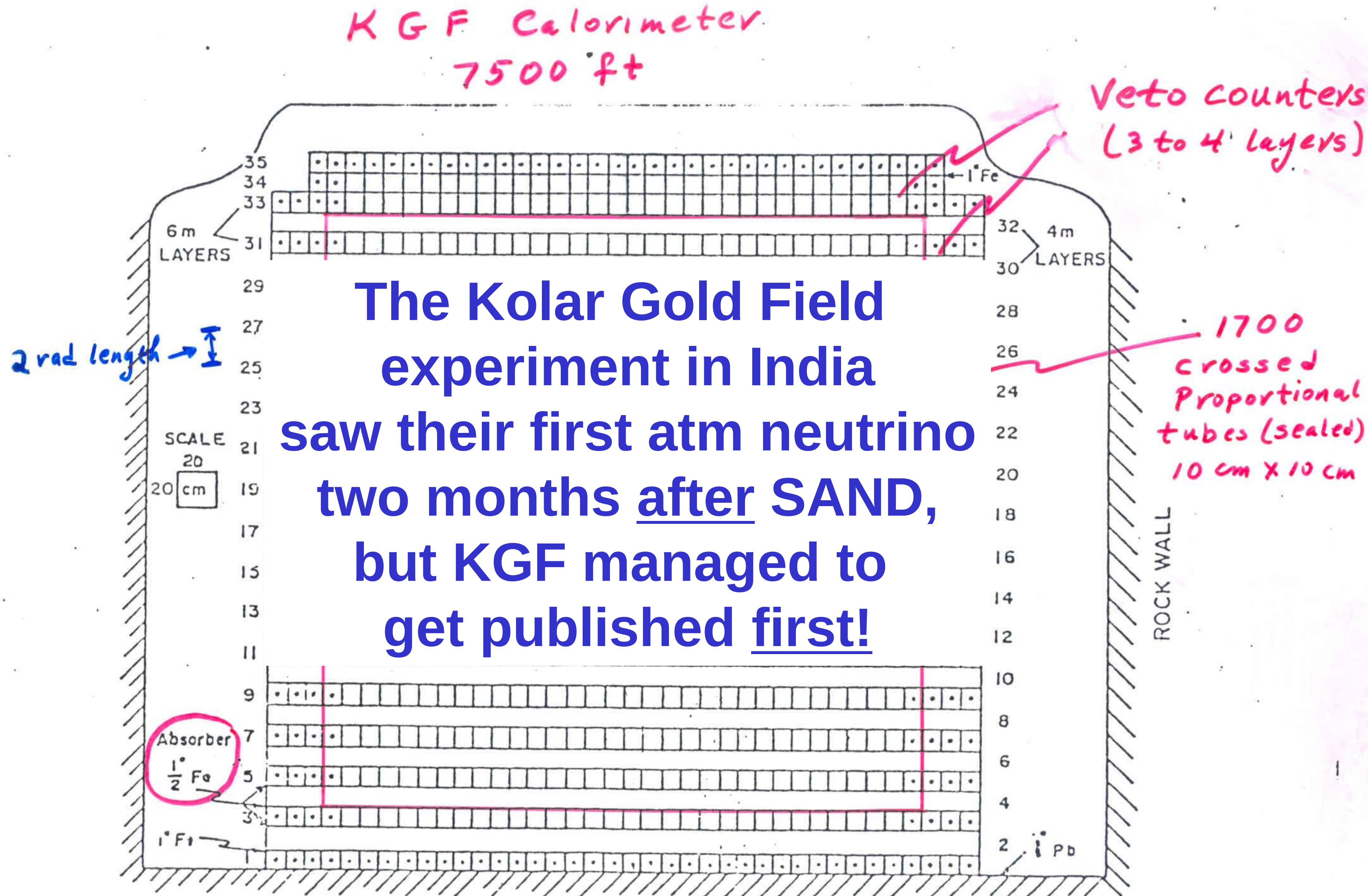


FIG.1: FRONT VIEW OF PROTON STABILITY DETECTOR IN K.G.F (7600 FEET)

6 m x 3.7 m (high) x 4 m

The next chapter in underground neutrino physics 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.

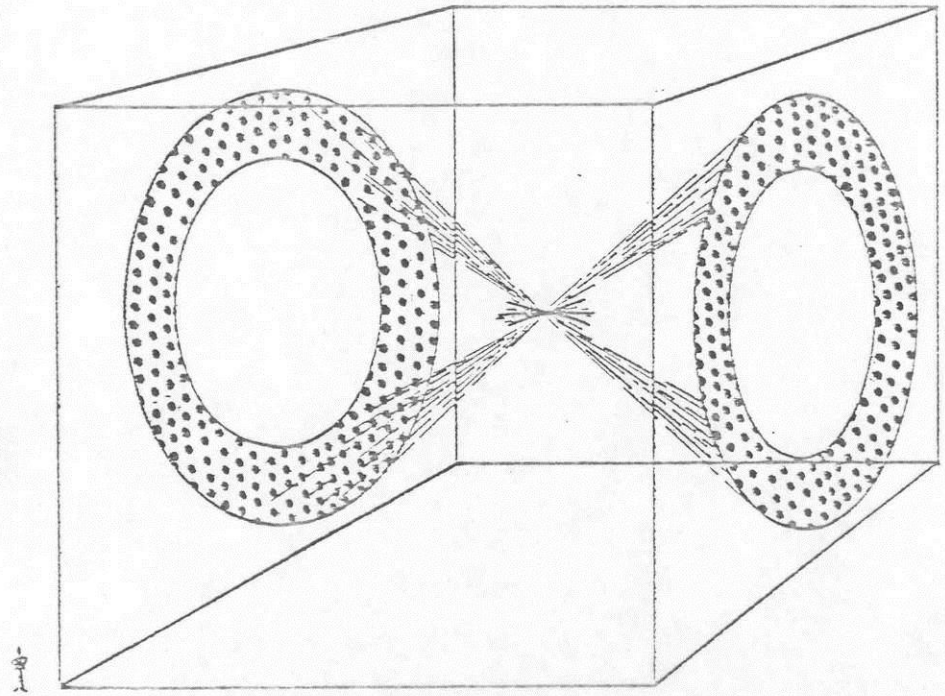
Proposal Submitted to DoE
May 31st, 1979

Proposal Approved
November 28th, 1979

Excavation Began
November 30th, 1979

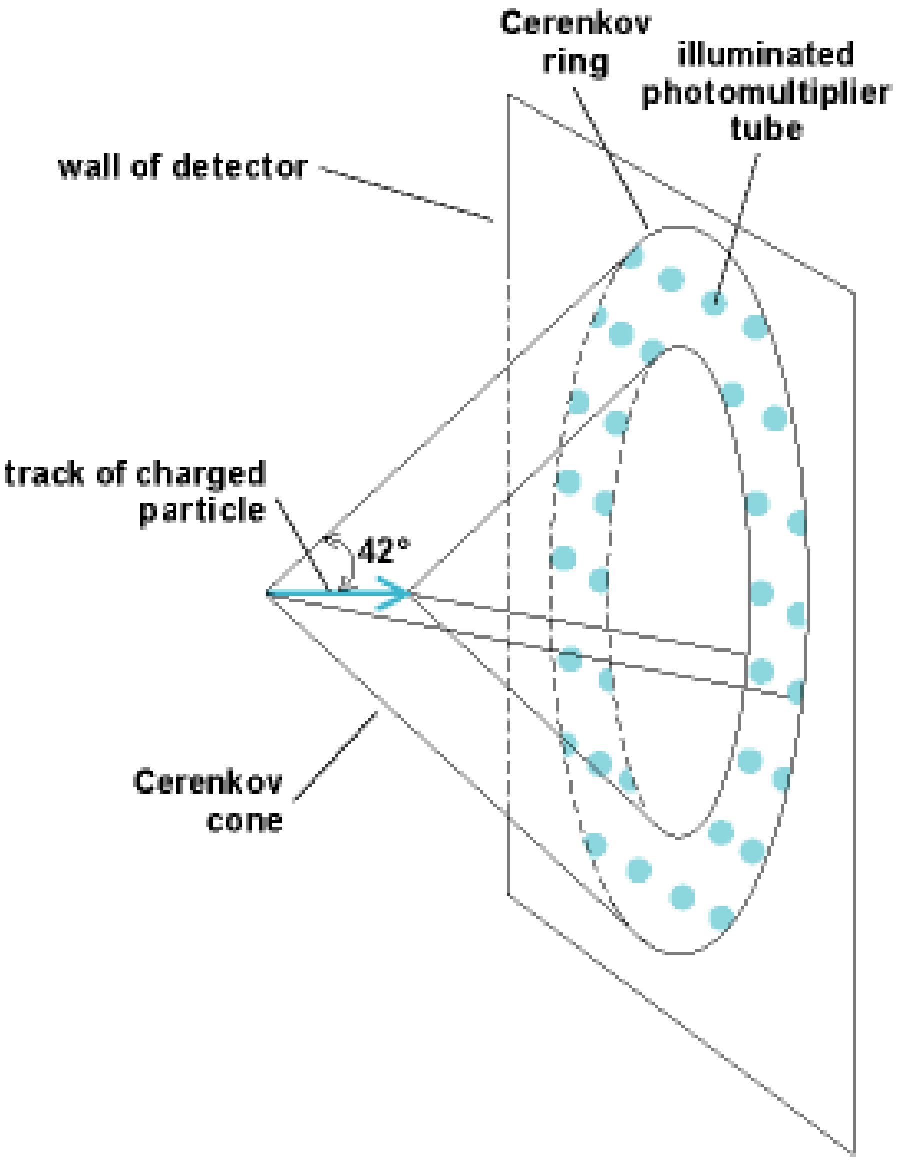
PROPOSAL FOR A
NUCLEON
DECAY DETECTOR

IRVINE/MICHIGAN/BROOKHAVEN



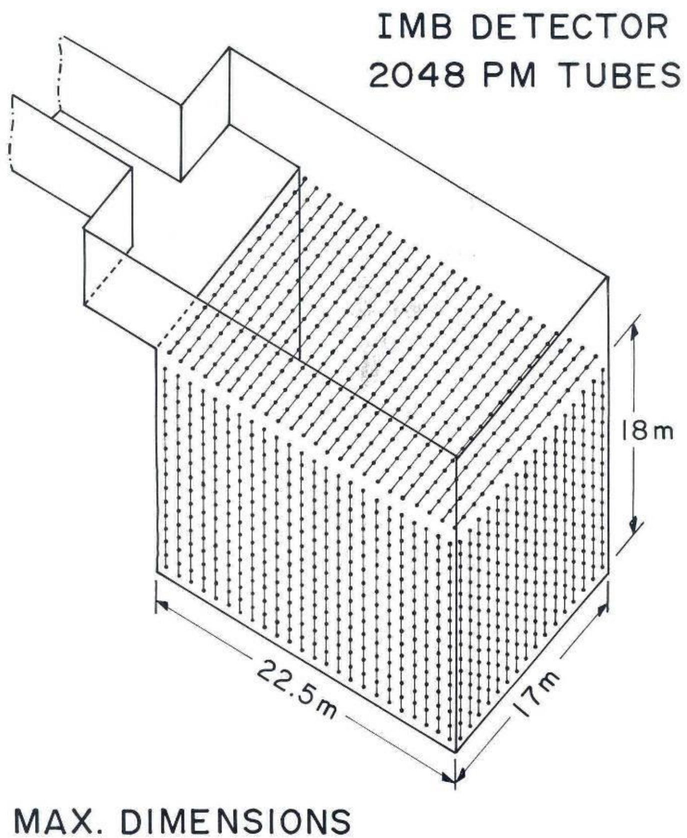
IMB was the first large-scale water Cherenkov detector: 7000 tons H_2O

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

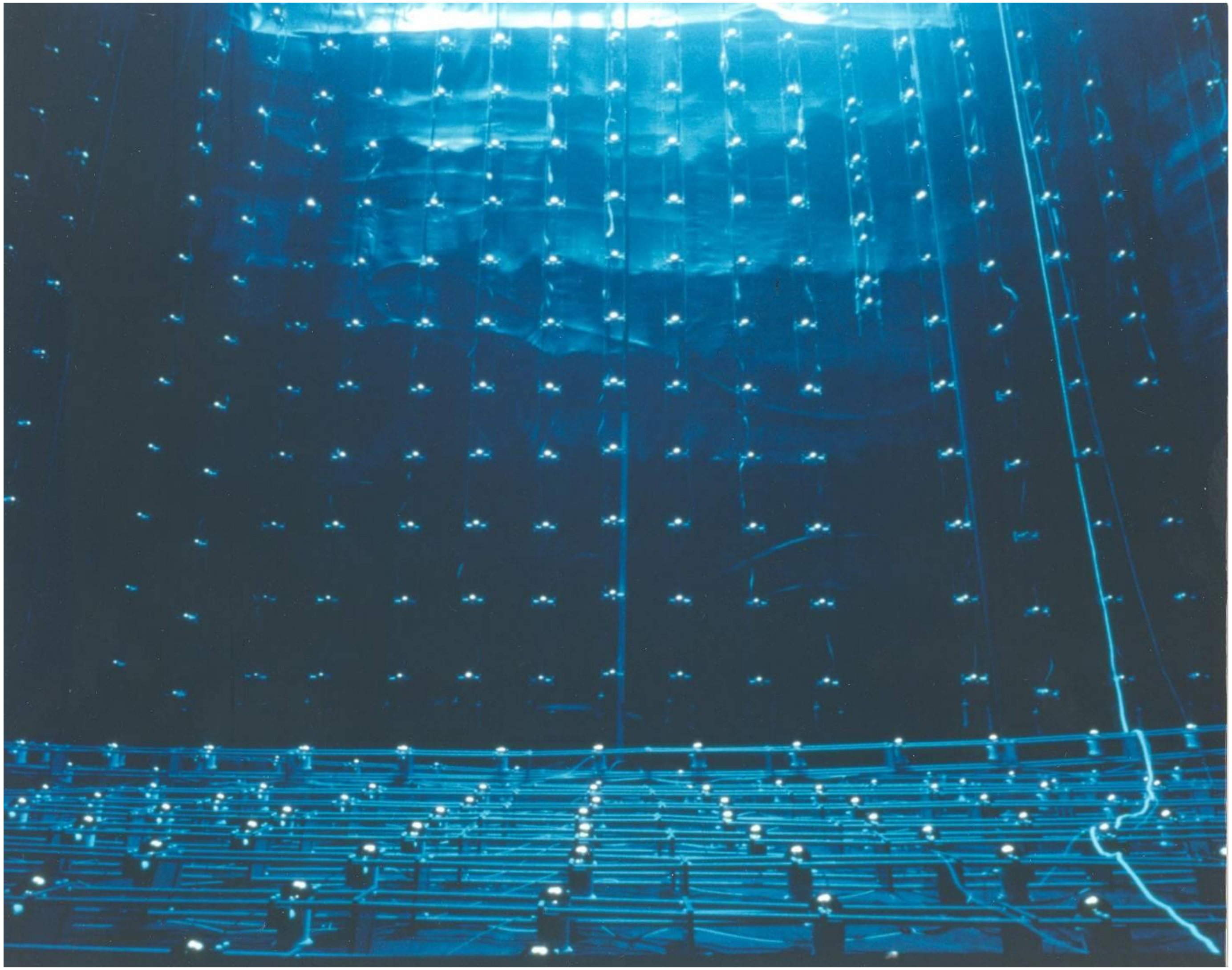


This detector was going to be very big – a cube about 20 meters on a side. To save money, a salt mine was used, since it's easier to excavate salt than hard rock.

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

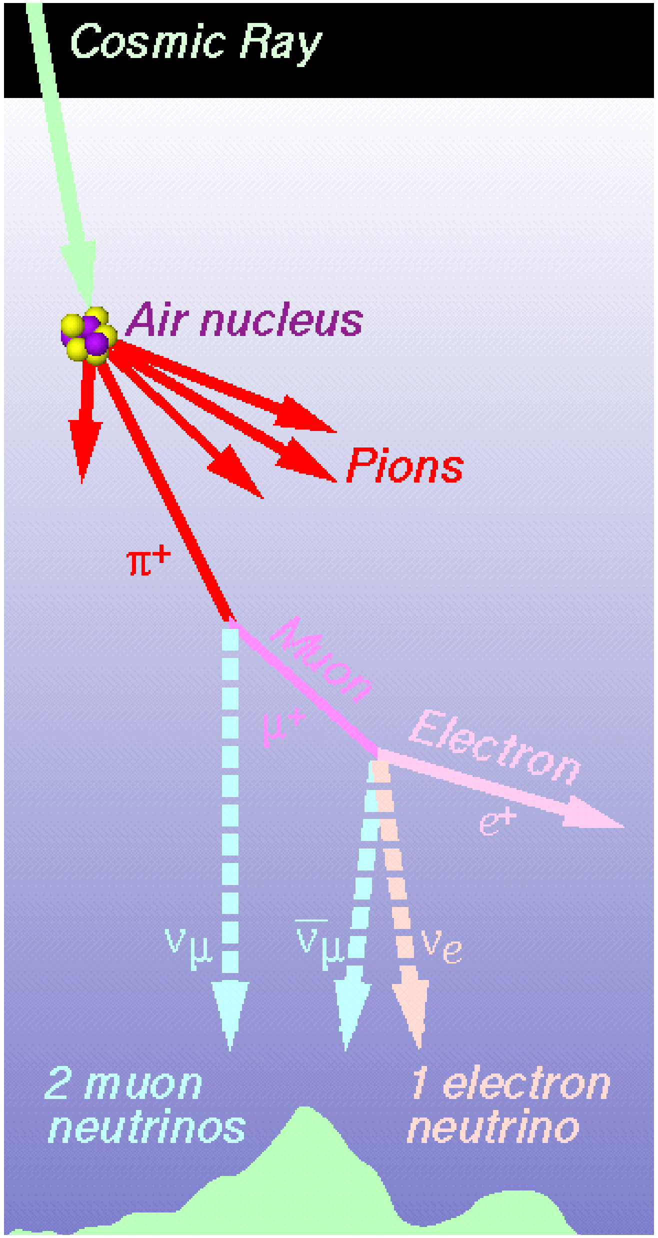
Late 1982

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 5×10^{31} years.

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

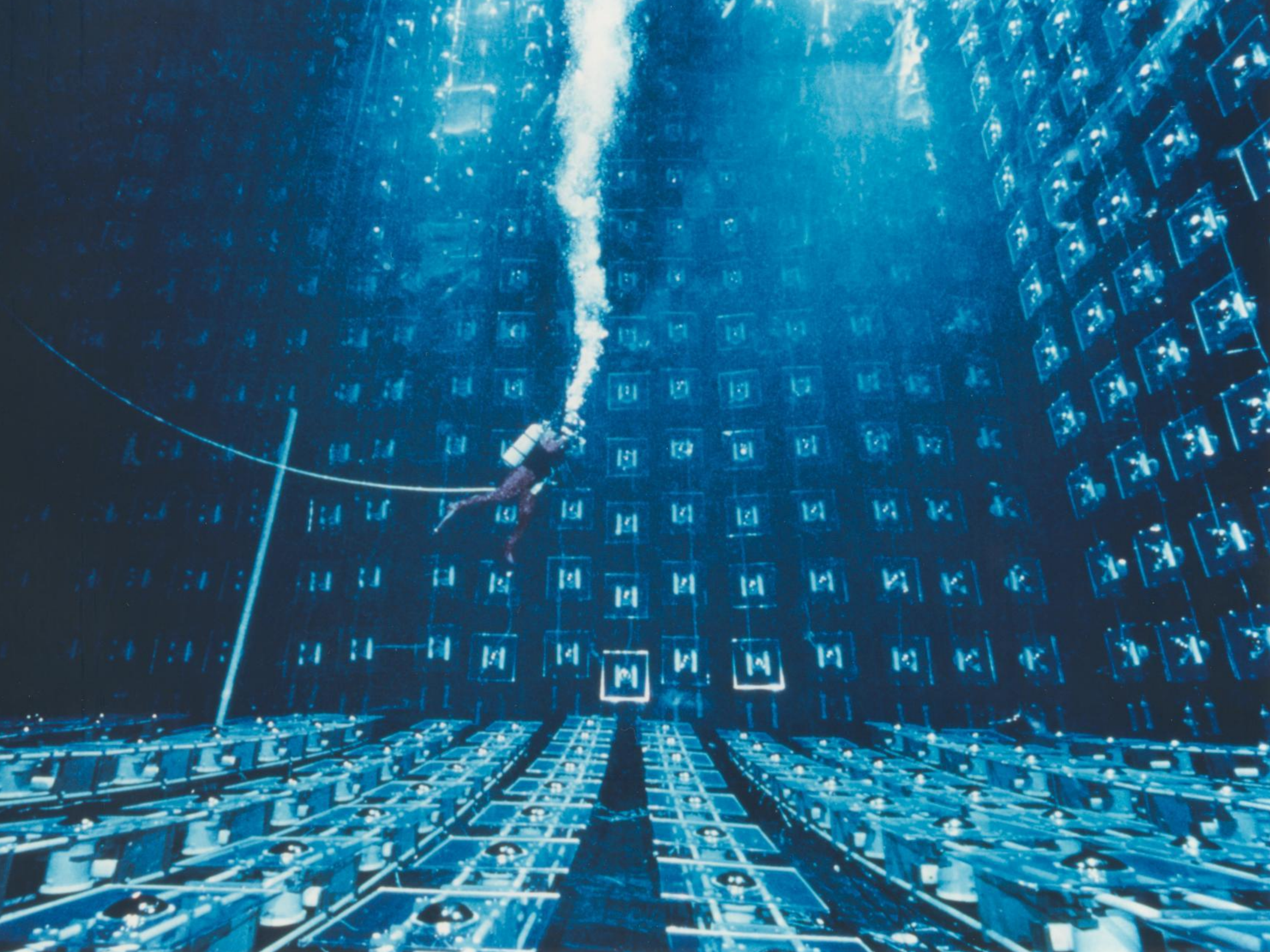
However, by the summer of 1983 a strange effect had been noticed in the observed atmospheric neutrinos (the main background to the proton decay search).



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

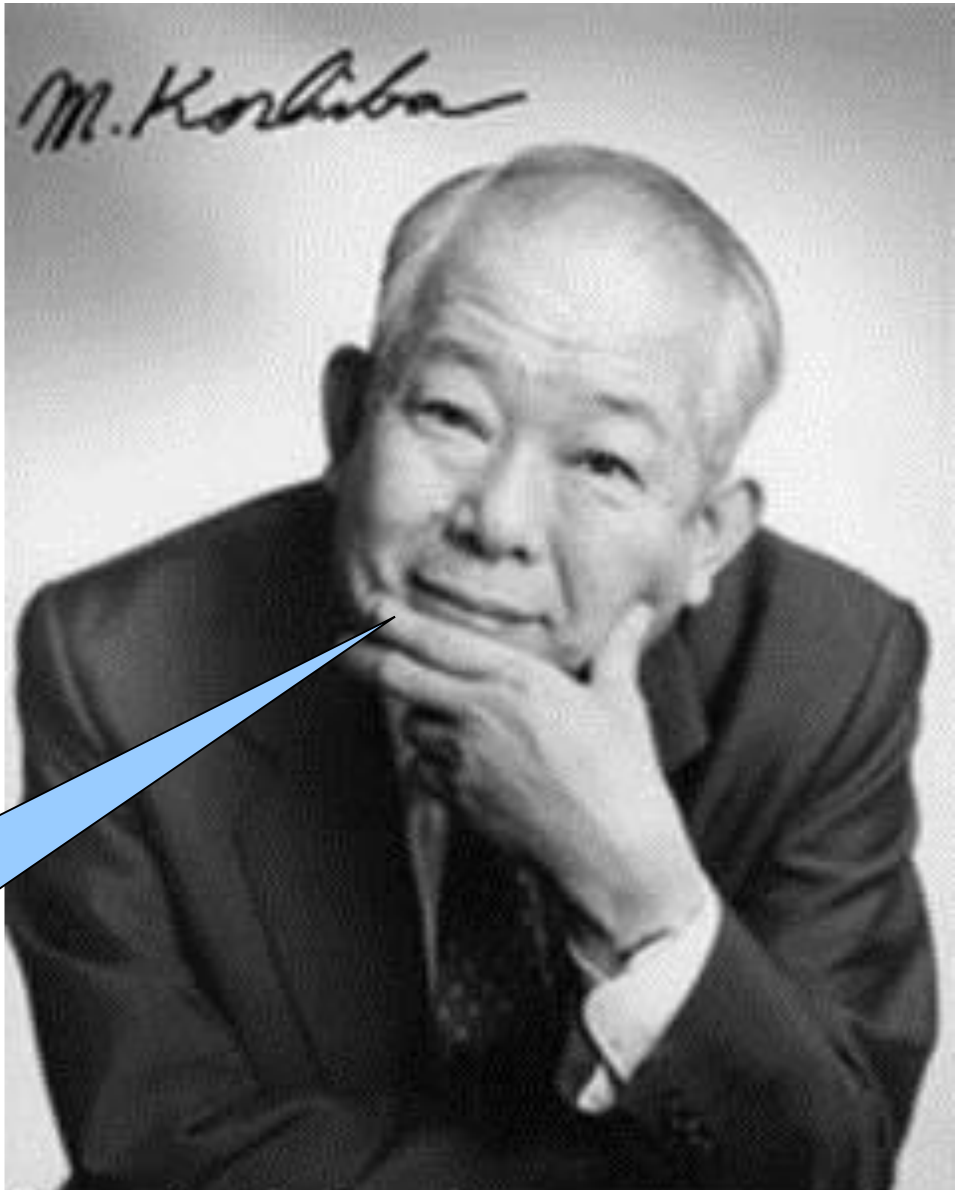
But there seemed to be too few muons.

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



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.

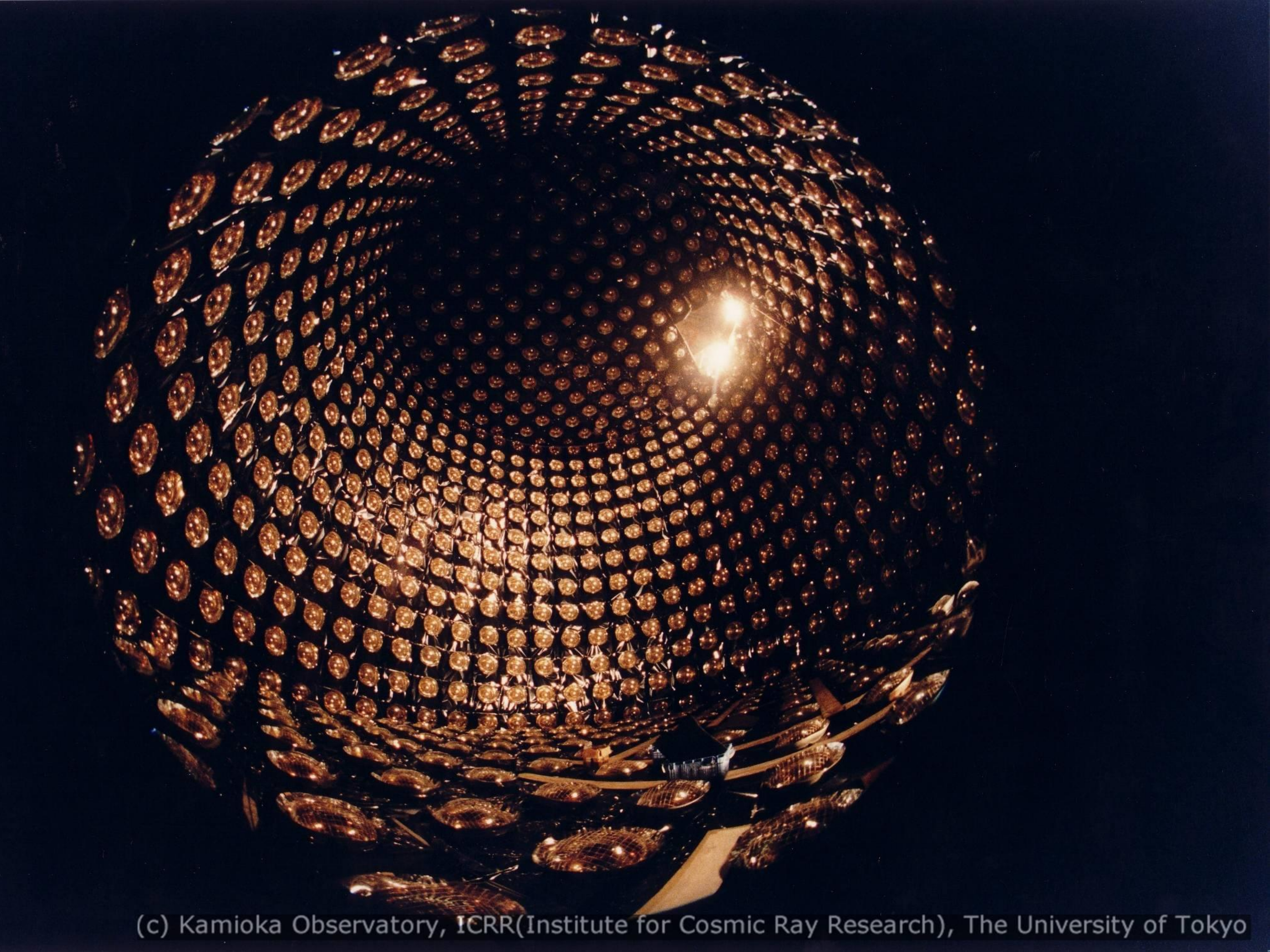
It was so unwieldy the process could not be easily automated.

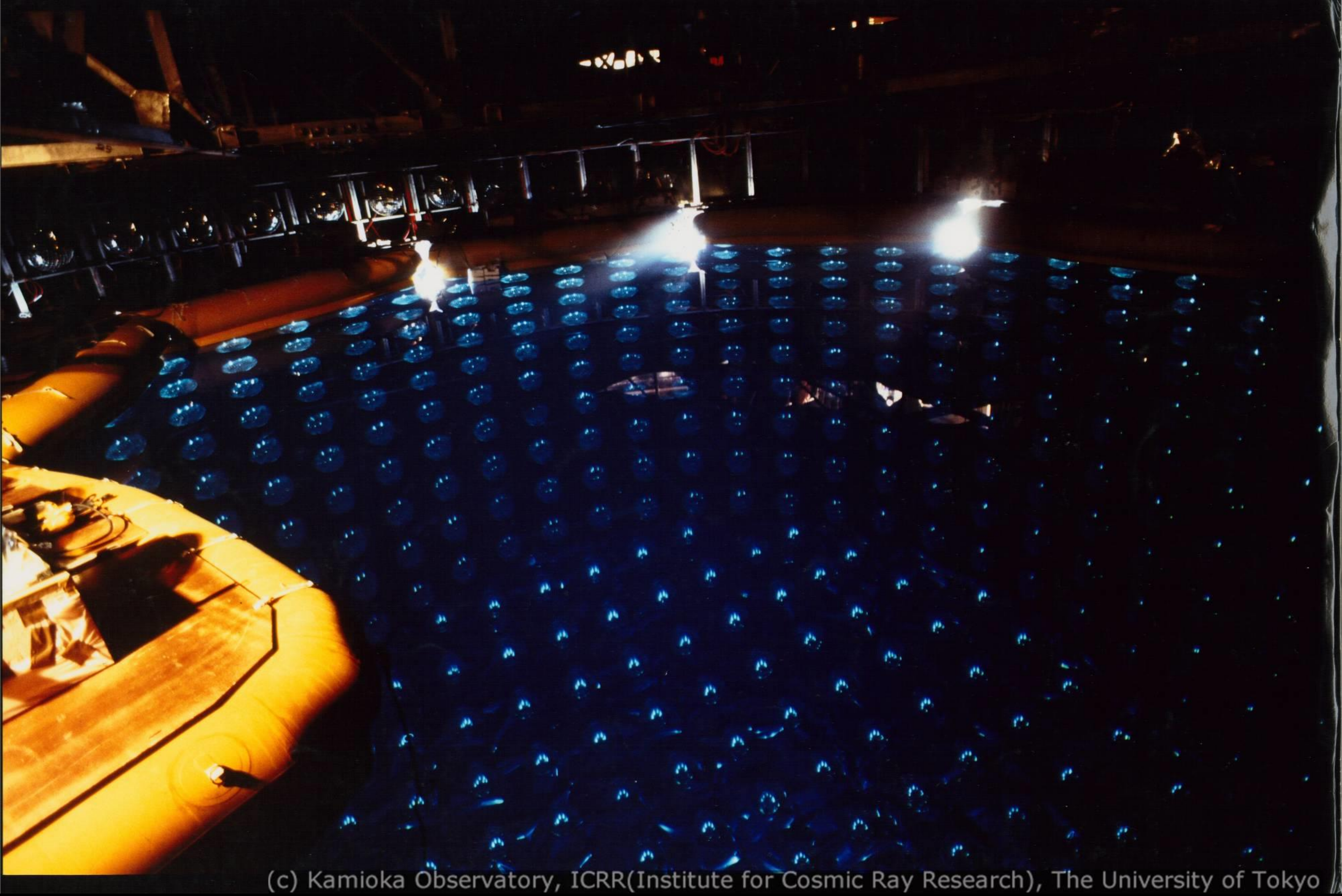
Every tube was made out of hand-blown glass.

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.





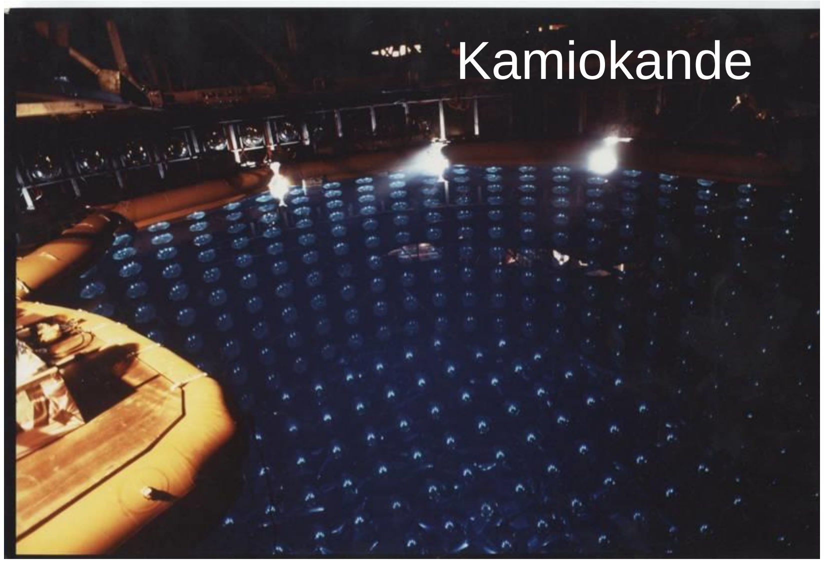
Kamiokande also noticed something strange going on with the atmospheric muon neutrinos.

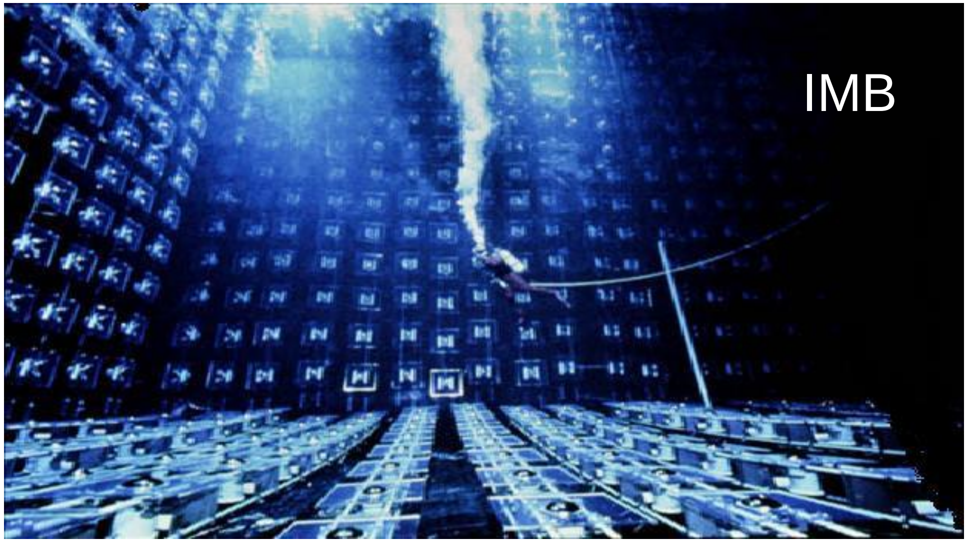
They tended to use the ratio-of-ratios approach to discuss the data. Eventually this became standard.

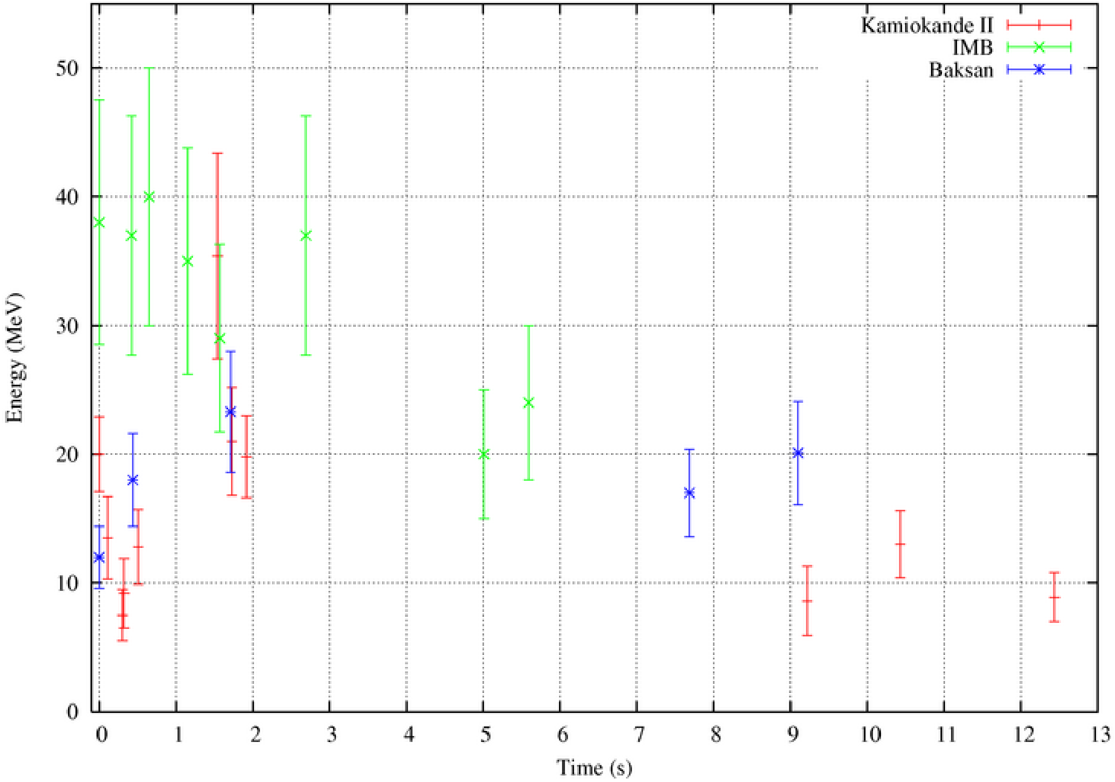
$$R = \frac{(\nu_\mu/\nu_e)^{\text{data}}}{(\nu_\mu/\nu_e)^{\text{Monte Carlo}}}$$

But then, at 07:35:41 UT on February 23th, 1987, both IMB and Kamiokande got a nice surprise:

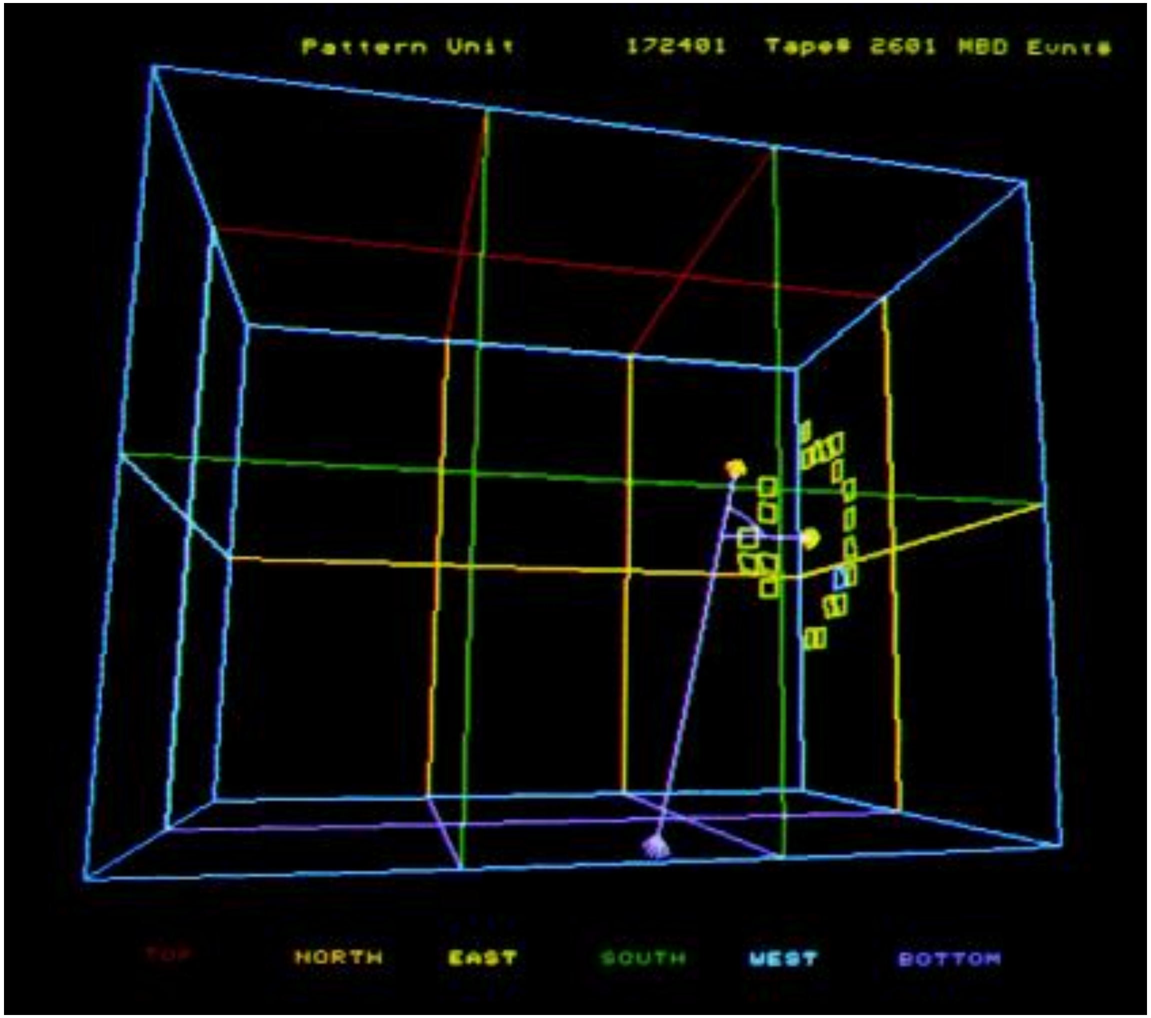
This was 22 years to the day since the first ATM neutrino was seen.


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 Evnt#
NORTH
EAST
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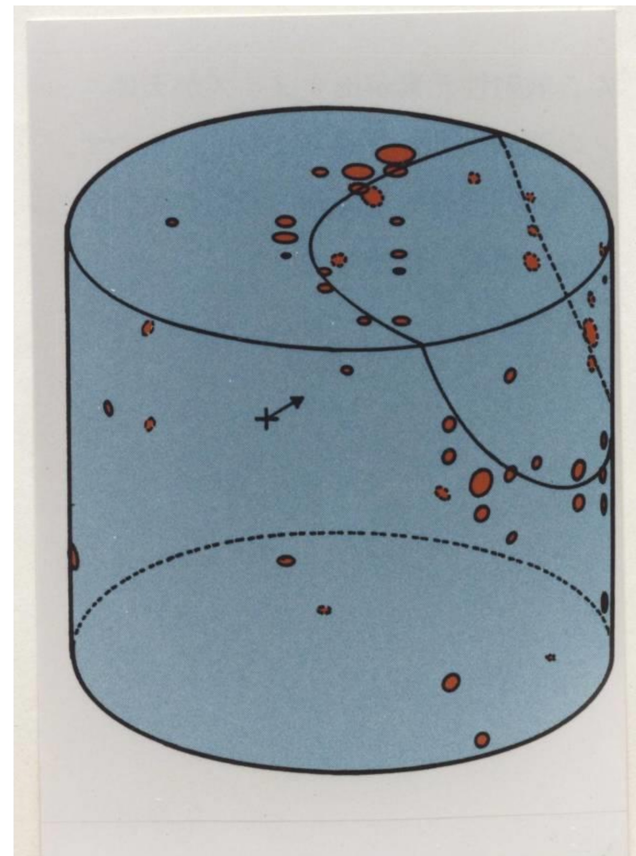
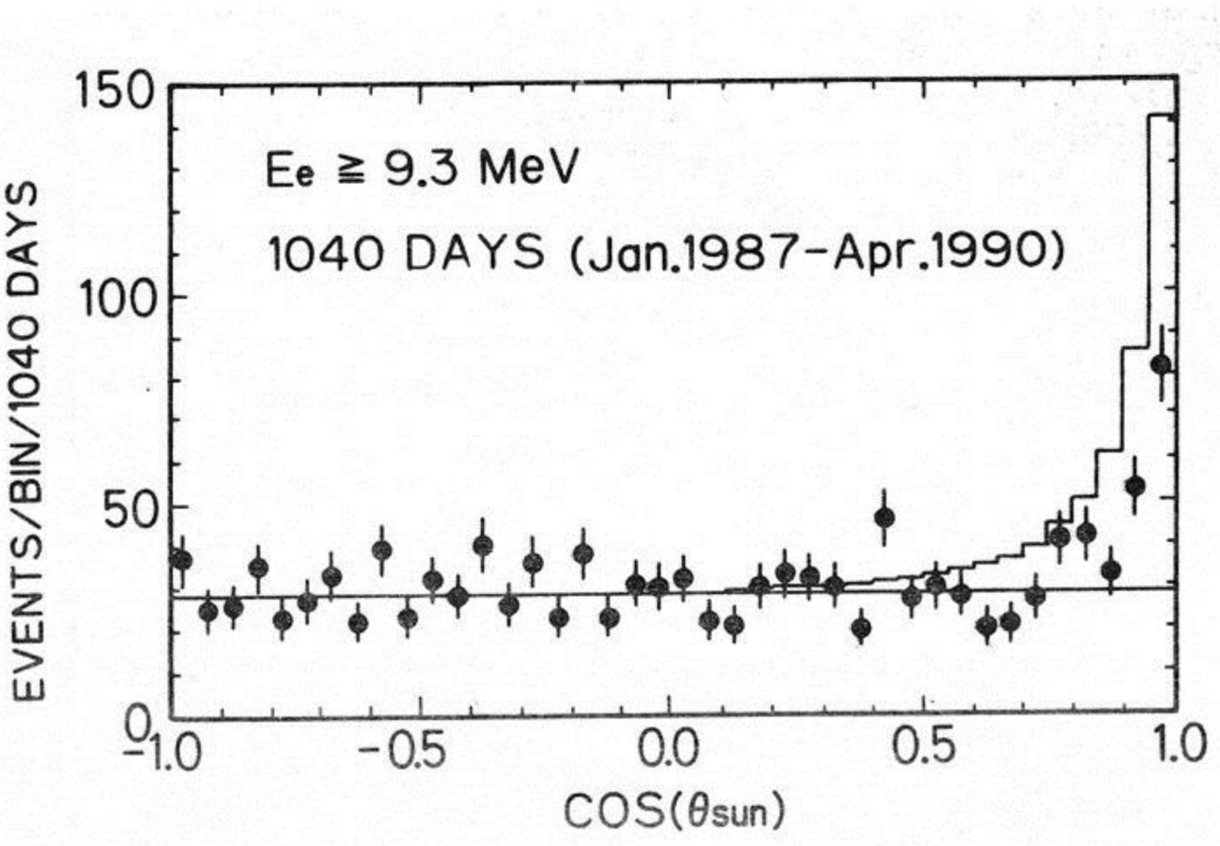
WEST
BOTTOM



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 Japan neutrinos were (and are) quite popular.

In the late 1980's there started serious talk
of building something called <u>Super</u>-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!

By 1990 things were looking pretty good
(if a bit confusing – where were the missing nu's?)
for atmospheric and solar neutrinos
in both the US and Japan.

But IMB's luck was about to run out…

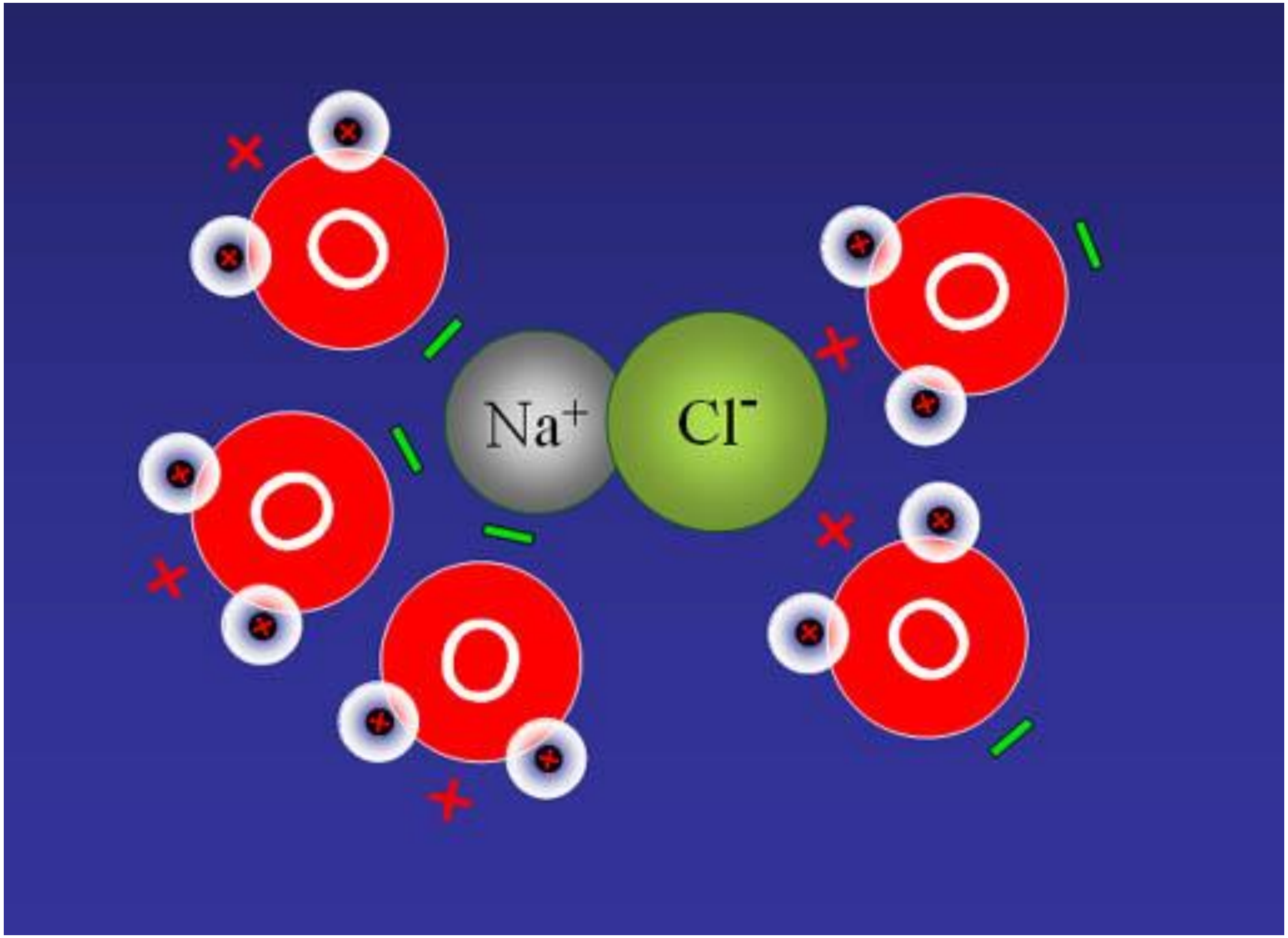
Over Easter weekend in 1991, the plastic bag holding IMB’s 7000 tons of water sprang a leak.

This had actually happened before, and each time divers had been quickly sent in to patch the leaks.

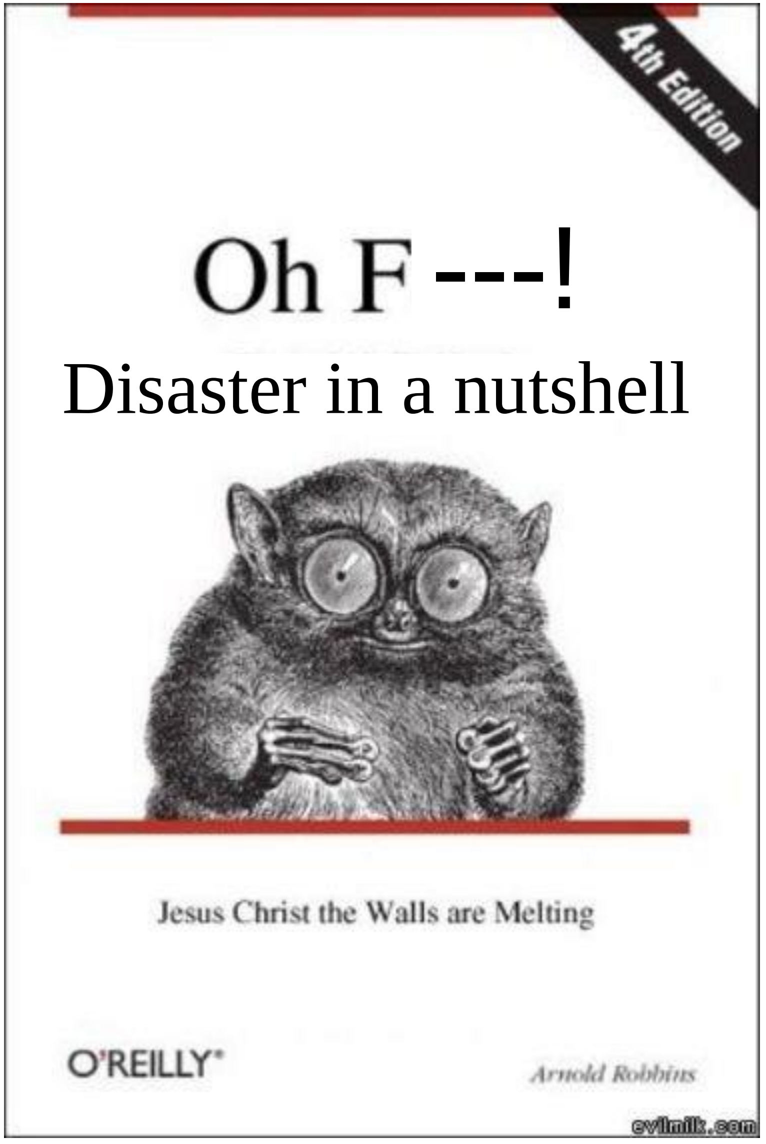
Acting fast was important, because behind the plastic liner and a thin layer of concrete was nothing but salt.

But this was a long holiday weekend, and they could not get into the mine!

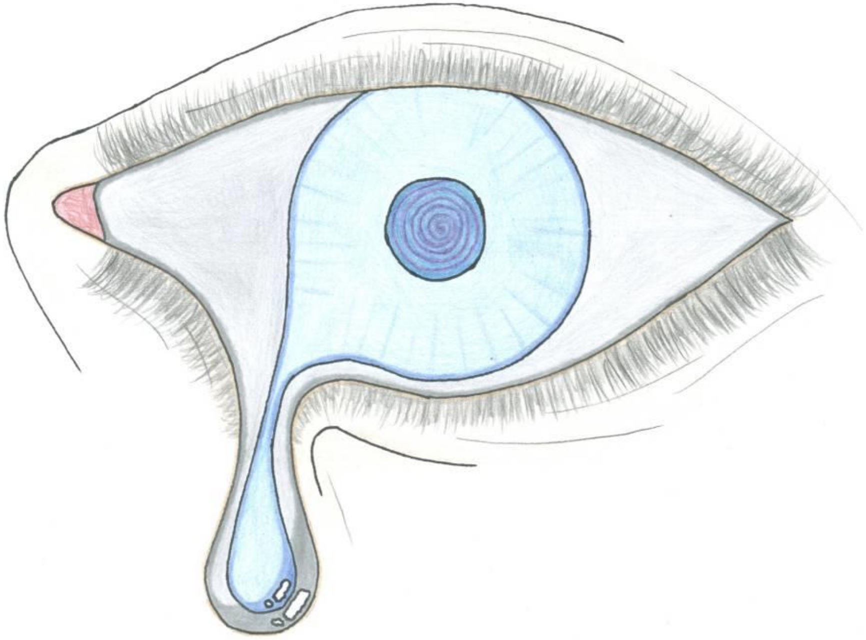
By the time they did, it was too late…



By the time they did, it was too late…



The laboratory dissolved...
and that was the salty end of IMB.



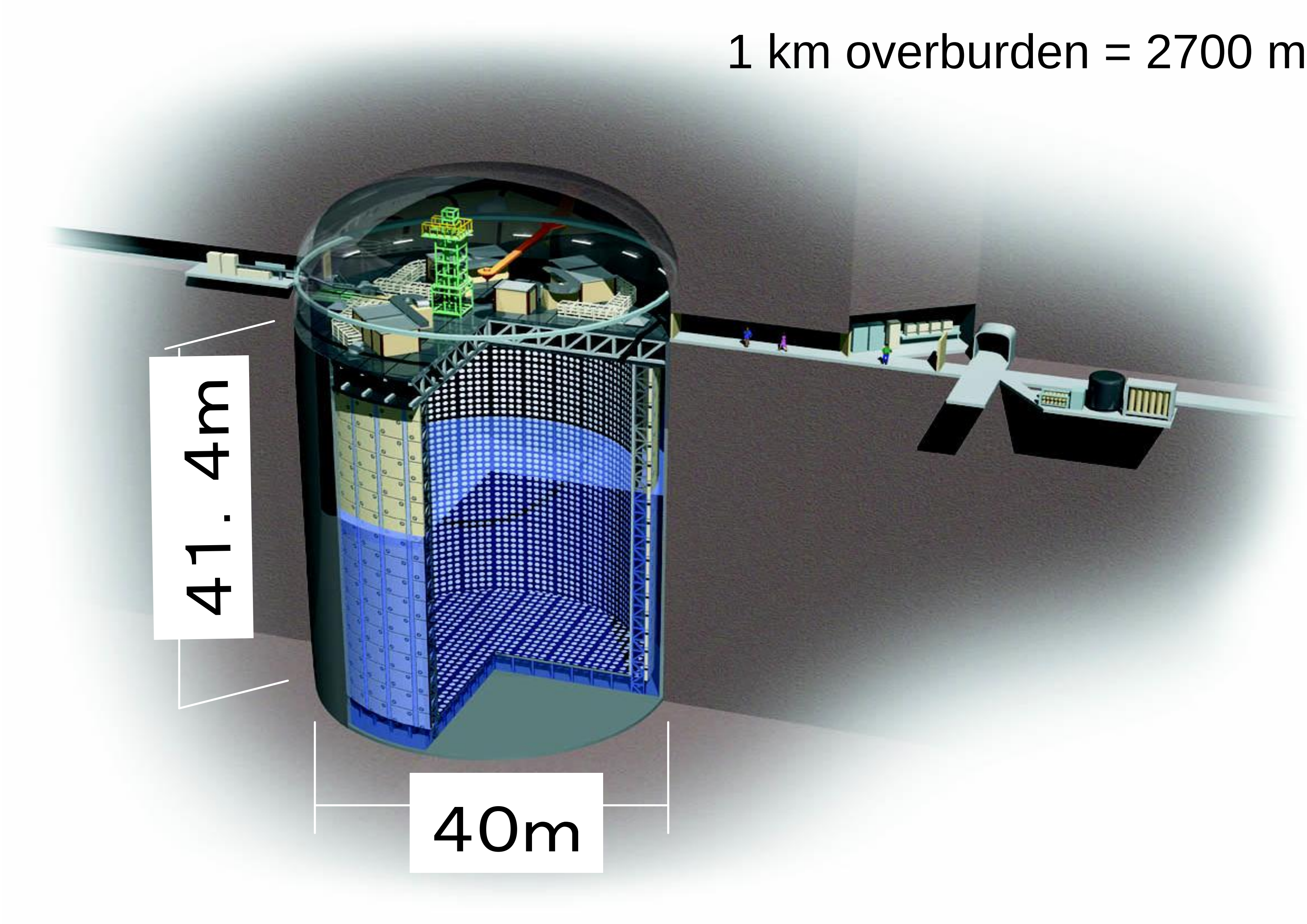
Meanwhile, in Japan, construction had begun on Super-Kamiokande.

Super-Kamiokande

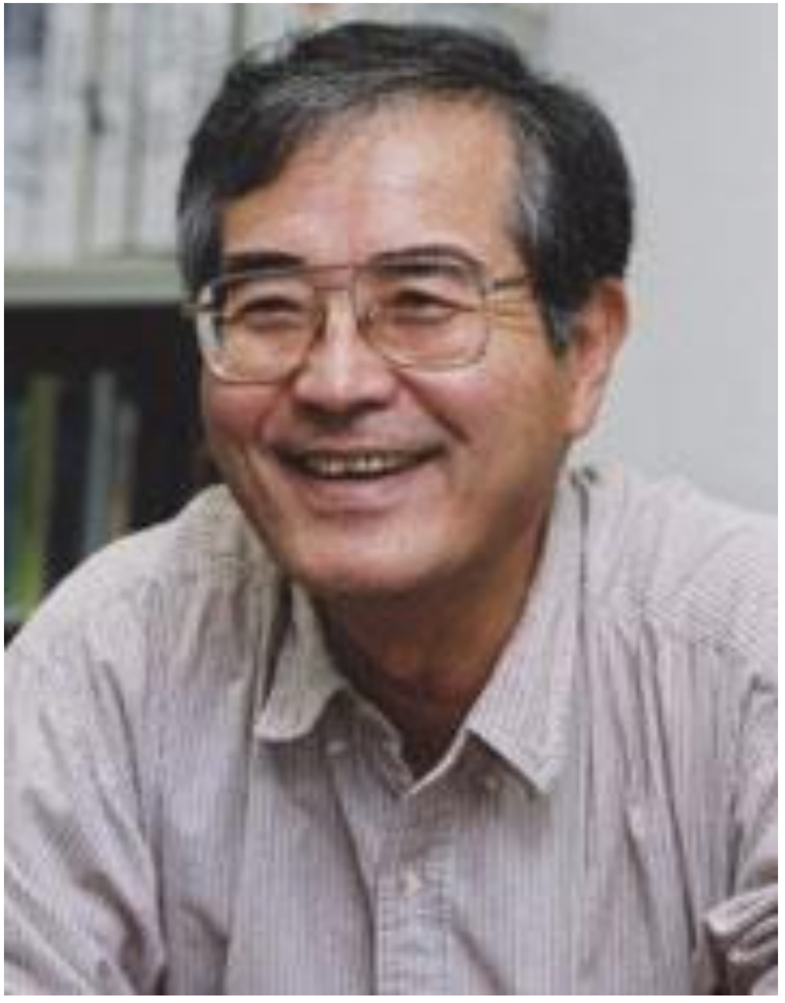
50000 tons ultra-pure water

22500 tons fiducial volume

1 km overburden = 2700 m.w.e.



Koshiba had been forced to retire (due to turning 60) right after SN1987A, and so the leader of Super-K was to be the senior member of the Kamiokande team, Yoji Totsuka.



1991

After a proposal to the DoE to rebuild IMB was turned down, senior members of the collaboration (Reines had also retired by then) traveled to Japan to see if joining Super-K was a possibility.

Although there was some initial resistance, Totsuka graciously welcomed them aboard.

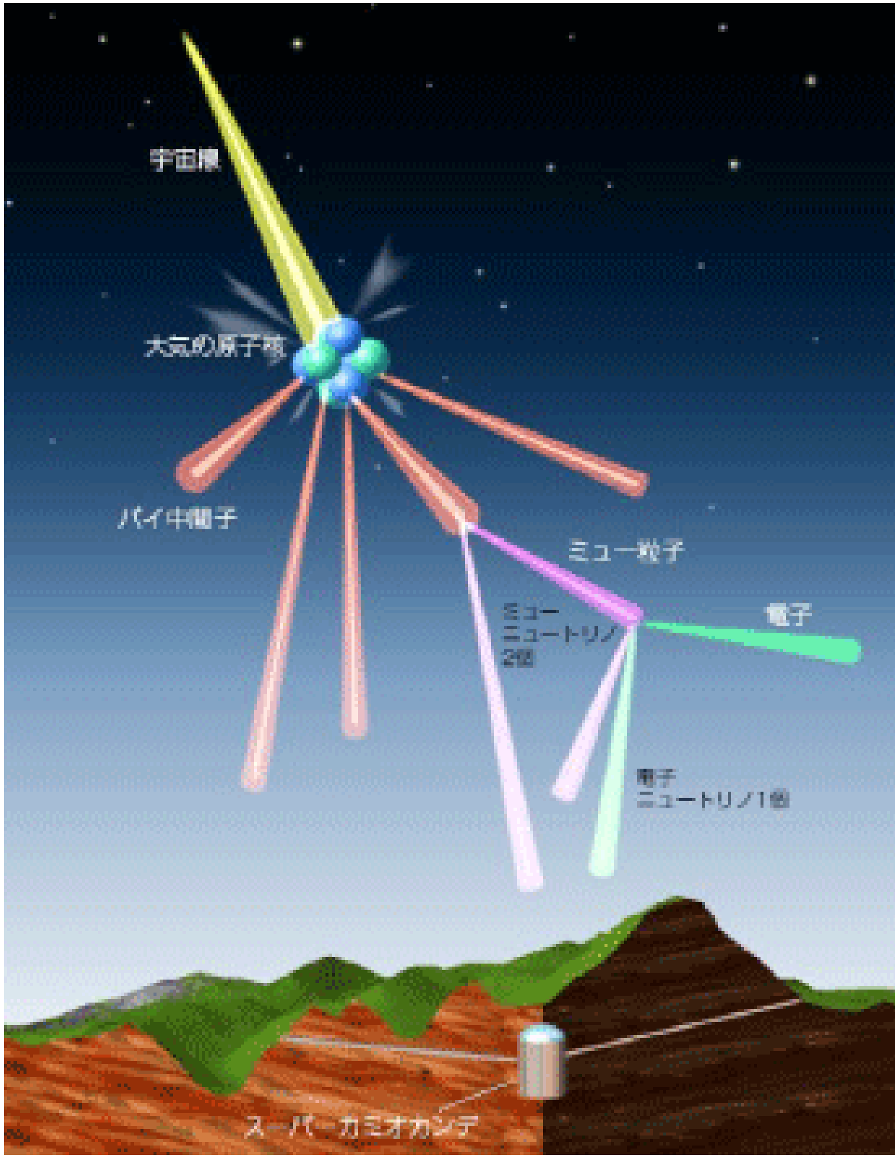
It was agreed that the US would provide the veto counter for Super-K. They used 1885 8” PMT’s salvaged from the wreckage of IMB to instrument it.

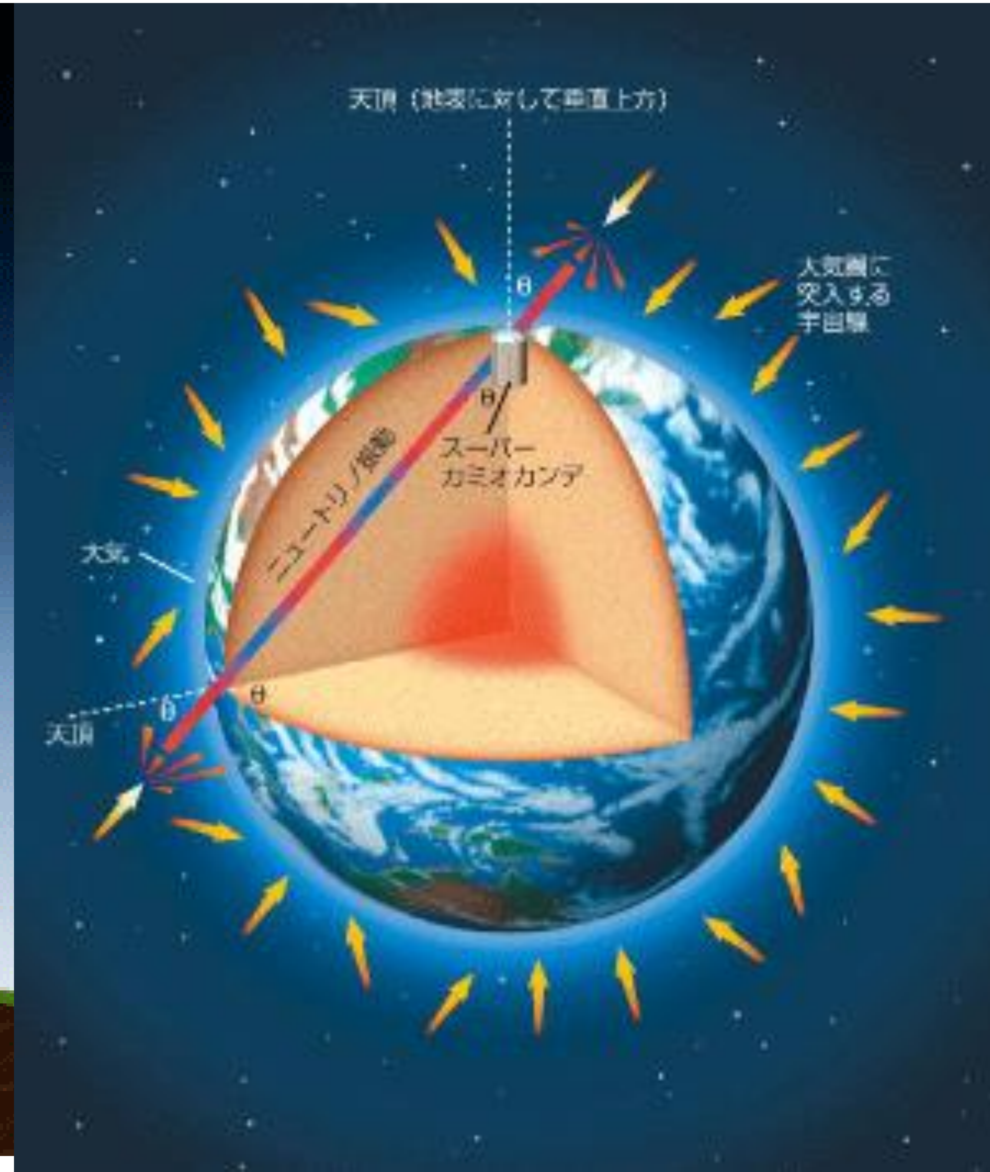
The additional manpower was needed, too, as the Super-K construction surged ahead.


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

1994

Kamiokande was still taking data during this period.
In 1994, they put out a very important result.





1 September 1994

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 335 (1994) 237–245

Atmospheric ν_μ/ν_e ratio in the multi-GeV energy range

Y. Fukuda [a], T. Hayakawa [a], K. Inoue [a], T. Ishida [a], S. Joukou [a], T. Kajita [a], S. Kasuga [a], Y. Koshio [a], T. Kumita [a], K. Matsumoto [a], M. Nakahata [a], K. Nakamura [a], A. Sakai [a], M. Shiozawa [a], J. Suzuki [a], Y. Suzuki [a], Y. Totsuka [a], K.S. Hirata [b], K. Kihara [b], M. Mori [b,1], Y. Oyama [b], A. Suzuki [b,2], M. Yamada [b,3], M. Koshiba [c], K. Nishijima [c], T. Kajimura [d,4], T. Suda [d,5], A.T. Suzuki [d], T. Ishizuka [e], M. Koga [e,2], K. Miyano [e], H. Miyata [e], H. Okazawa [e], H. Takei [e,6], T. Hara [f], N. Kishi [f], Y. Nagashima [f], M. Takita [f], A. Yoshimoto [f,7], Y. Hayato [g], K. Kaneyuki [g], Y. Takeuchi [g], T. Tanimori [g], S. Tasaka [h], K. Nishikawa [i], E.W. Beier [j], E.D. Frank [j], W. Frati [j], S.B. Kim [j,8], A.K. Mann [j], F.M. Newcomer [j], R. Van Berg [j], W. Zhang [j,9]

[a] *Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan*
[b] *National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan*
[c] *Tokai University, Shibuya, Tokyo 151, Japan*
[d] *Department of Physics, Kobe University, Kobe, Hyogo 657, Japan*
[e] *Niigata University, Niigata, Niigata 950-21, Japan*
[f] *Department of Physics, Osaka University, Toyonaka, Osaka 560, Japan*
[g] *Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152, Japan*
[h] *Department of Physics, Gifu University, Gifu, Gifu 501-11, Japan*
[i] *Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan*
[j] *Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA*

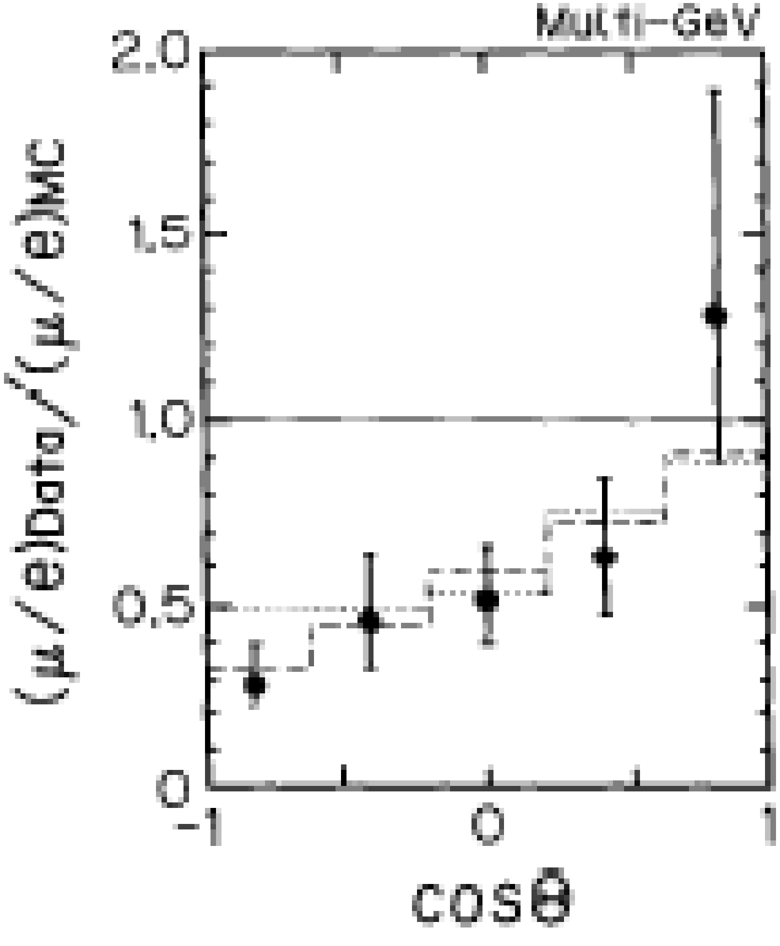
Received 27 June 1994
Editor: L. Montanet

Abstract

Data from the Kamiokande detector were used to study the atmospheric $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ ratio in the multi-GeV energy range. The observed ratio of μ-like to e-like events relative to the calculated ratio, $(\mu/e)_{data}/(\mu/e)_{MC} = 0.57\,^{+0.08}_{-0.07} \pm 0.07$, suggests that the atmospheric $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ ratio is smaller than expected for these neutrino energies. Also studied was the zenith-angle dependence of the above ratio. Results of an analysis of neutrino oscillations are presented.

$$\frac{(\mu/e)_{data}}{(\mu/e)_{MC}} = 0.57^{+0.08}_{-0.07}(\text{stat.}) \pm 0.07(\text{syst.})$$

Agreed With IMB



But this was new

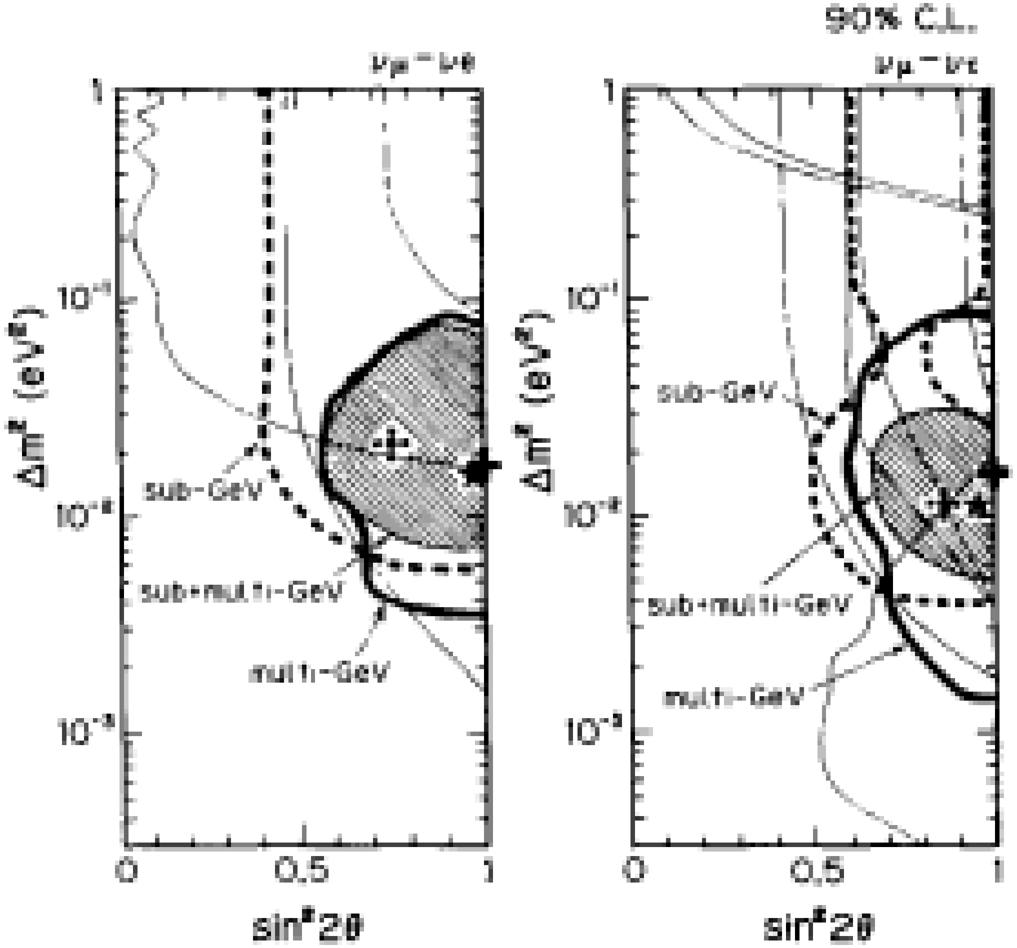
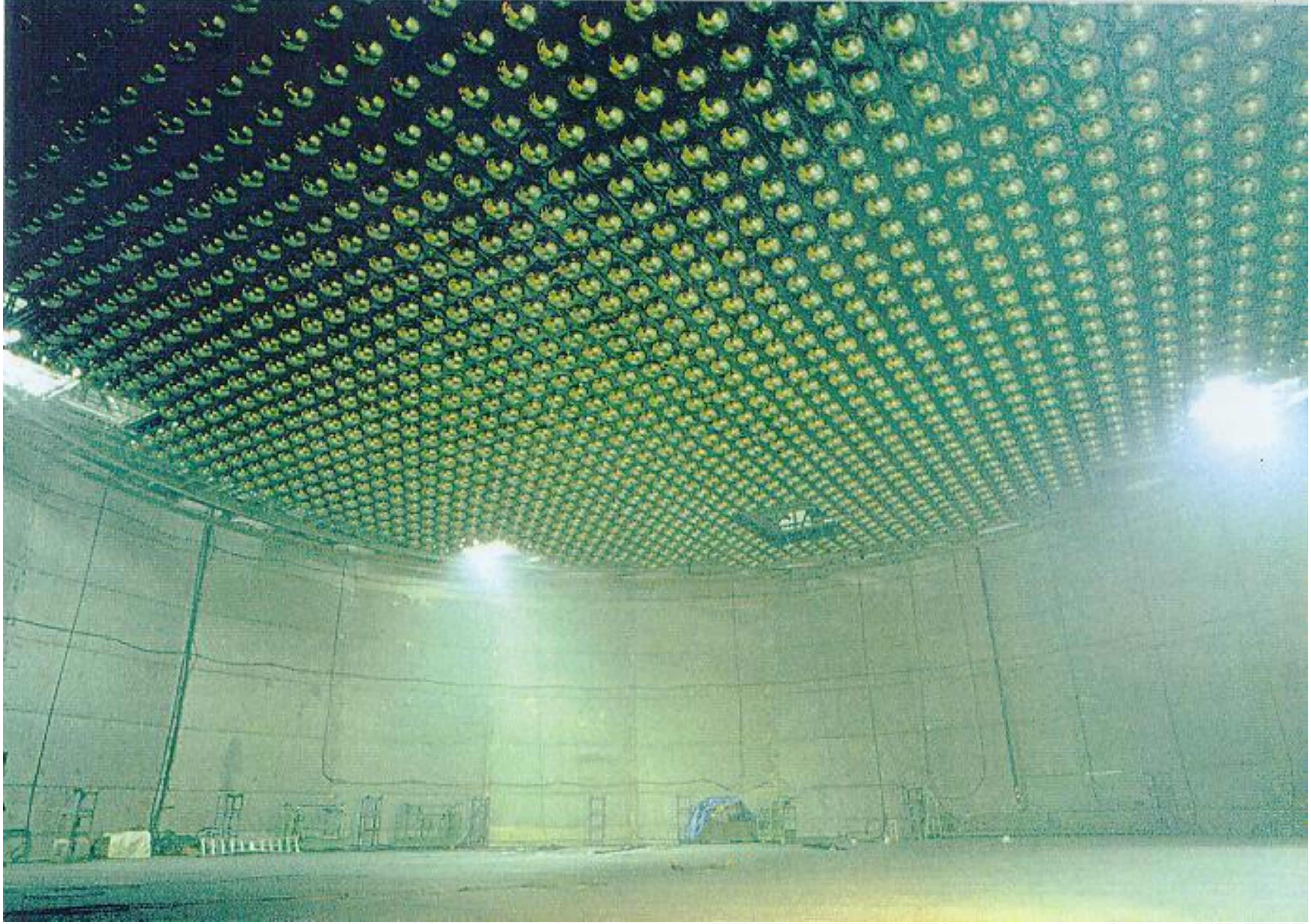


Fig. 5. 90% C.L. allowed neutrino-oscillation parameters as obtained from the multi-GeV data (thick curves). 90% C.L. allowed regions as obtained from the updated sub-GeV data are also shown by thick-dotted curves. The allowed regions as obtained by combining the sub- and multi-GeV data are also shown (shaded region). The best-fit values are also shown by dash-crosses (sub-GeV data), full-crosses (multi-GeV data) and stars (sub- and multi-GeV data combined). The 90% C.L. excluded regions from the other experiments are also shown [15,16,18–21].

And this!

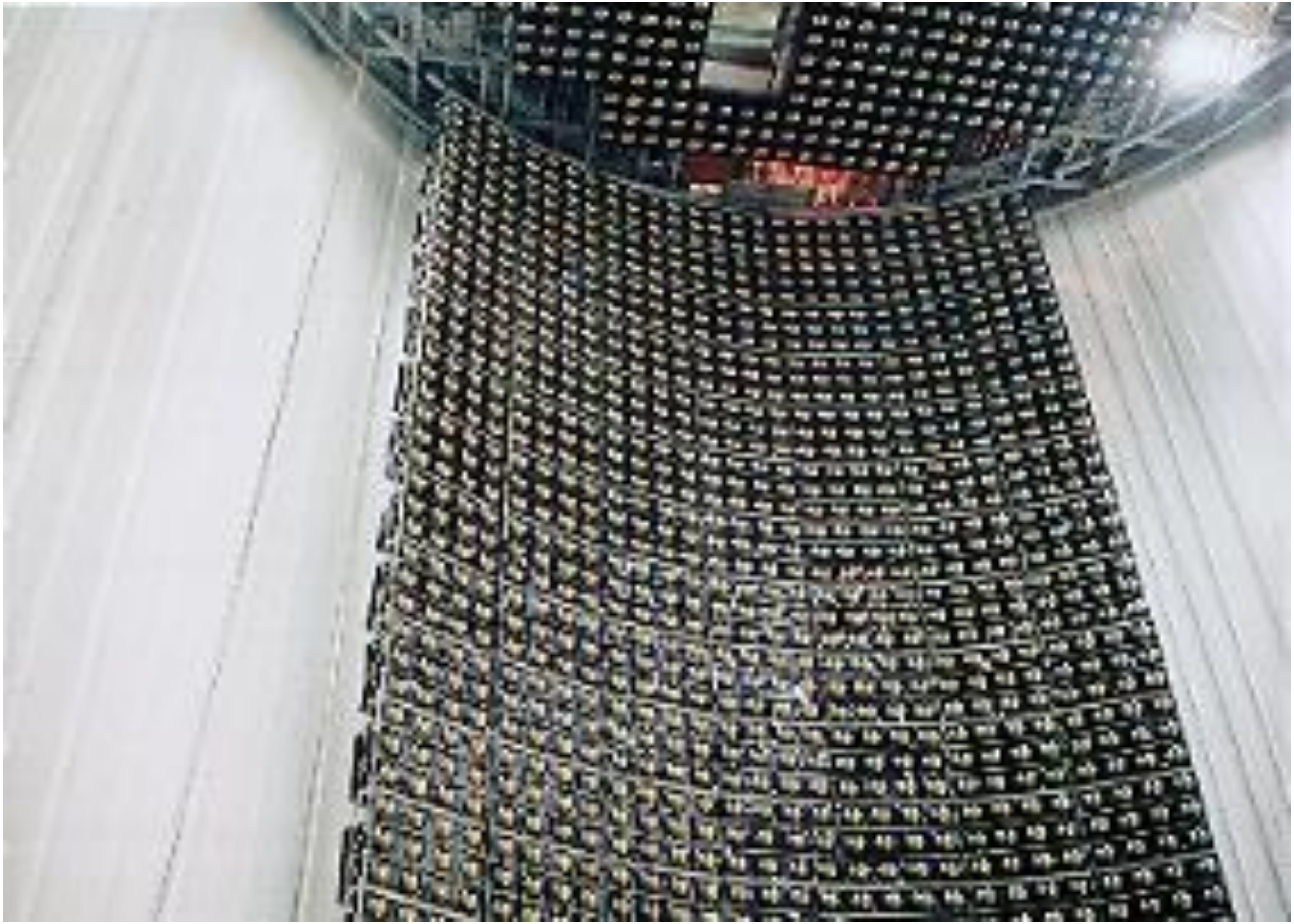
Higher statistics data was eagerly awaited… and there wouldn't be long to wait.

June 1995

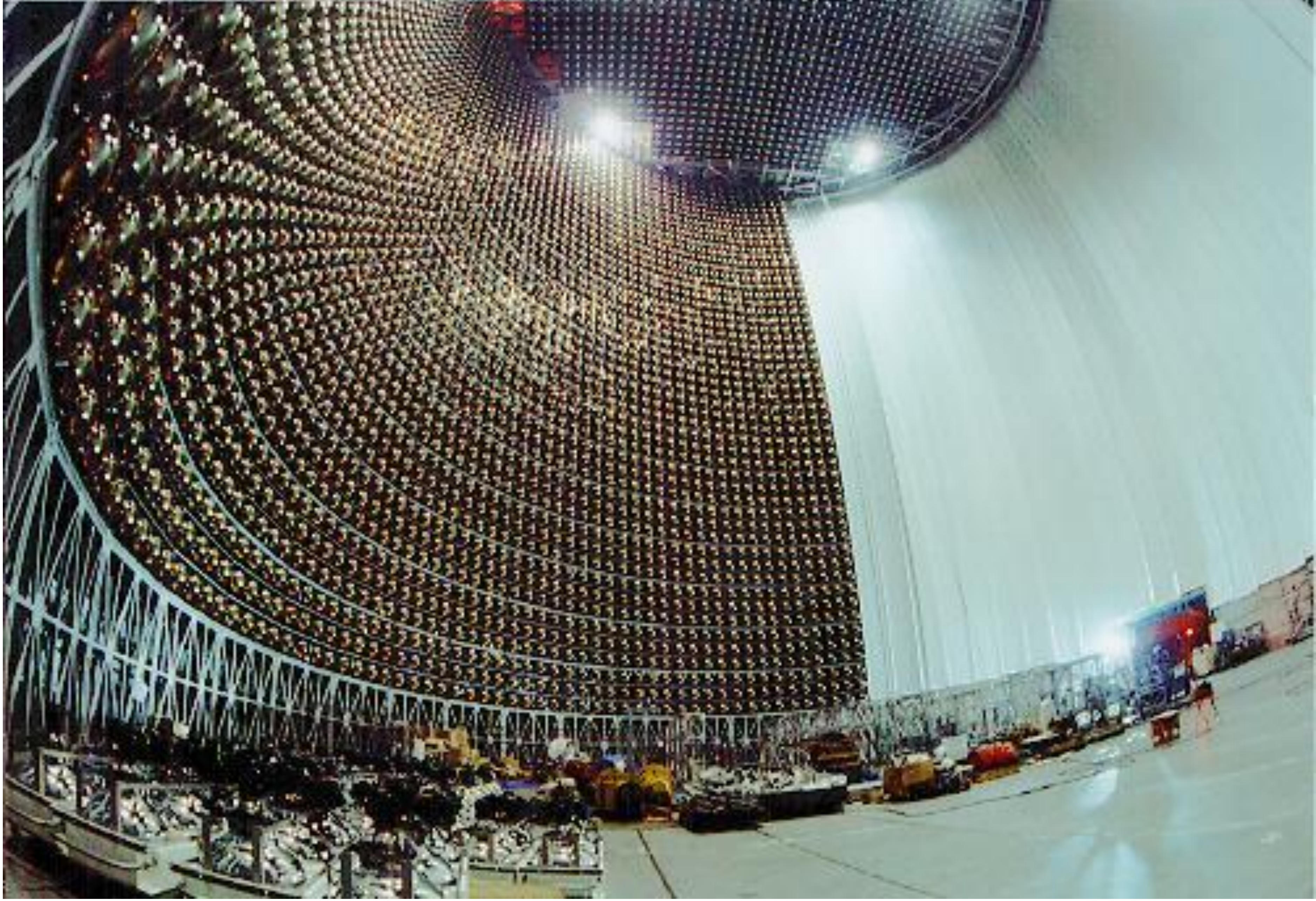


July 1995

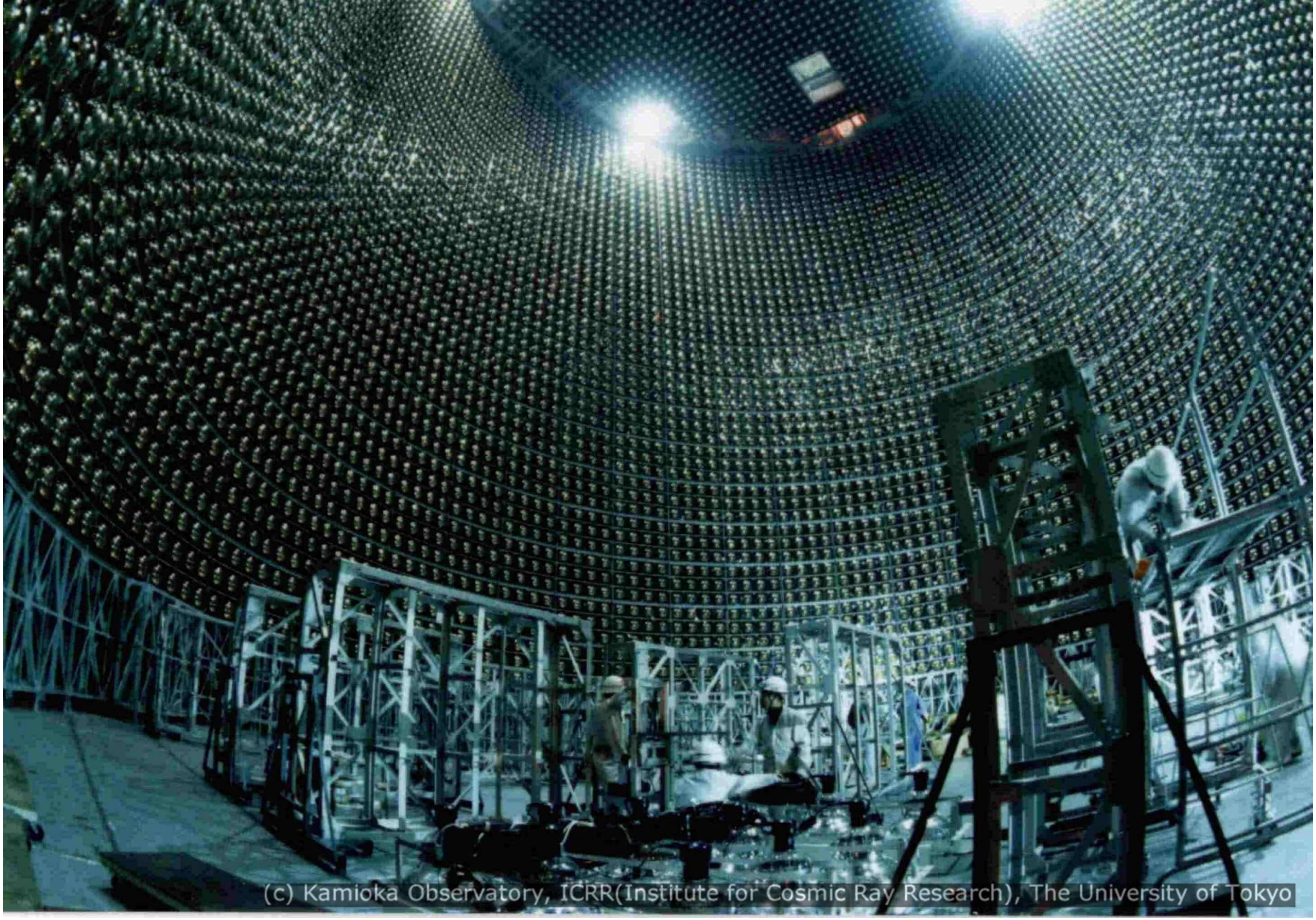
September 1995



September 1995, 3 days later



September 1995, two weeks after that

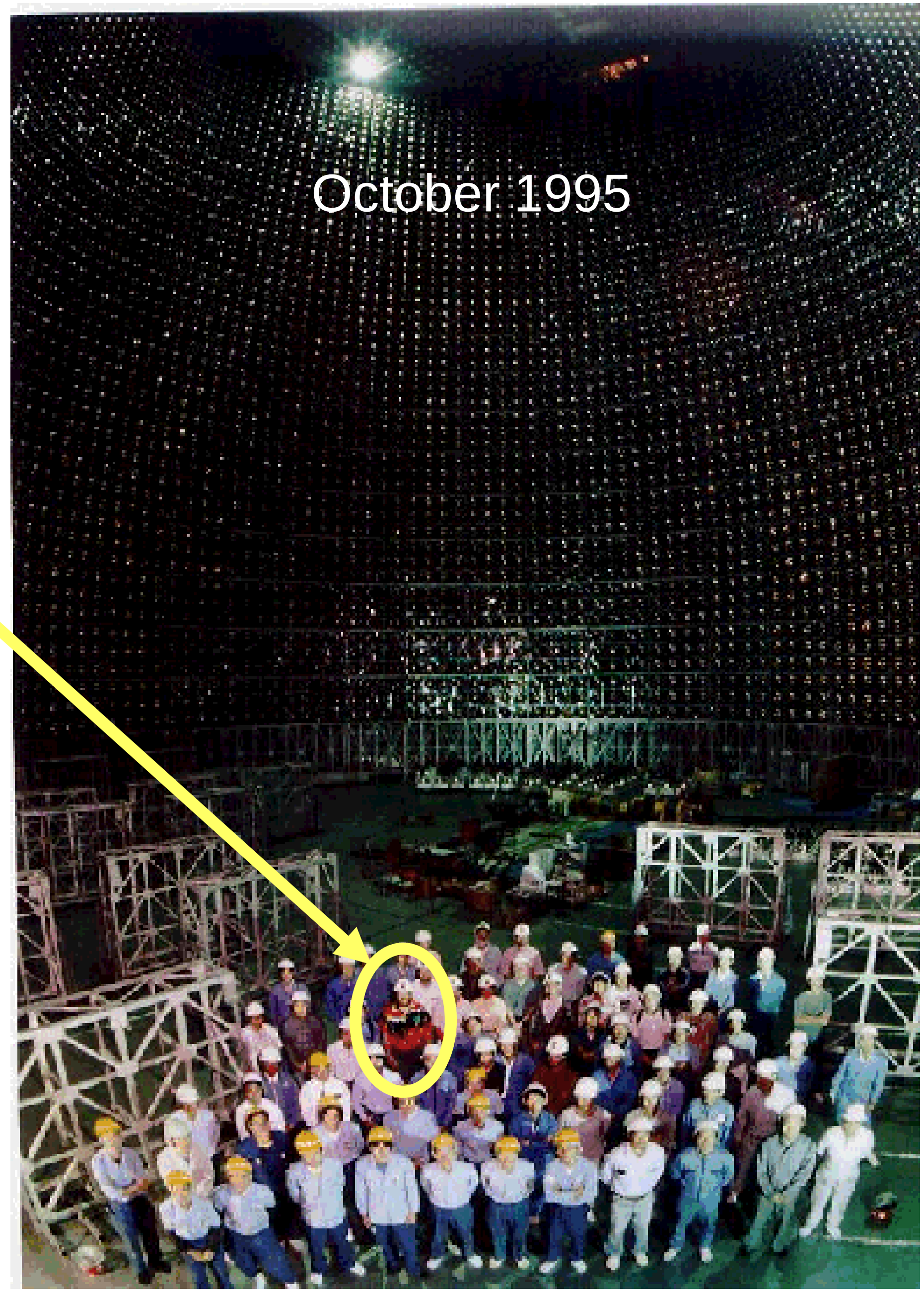


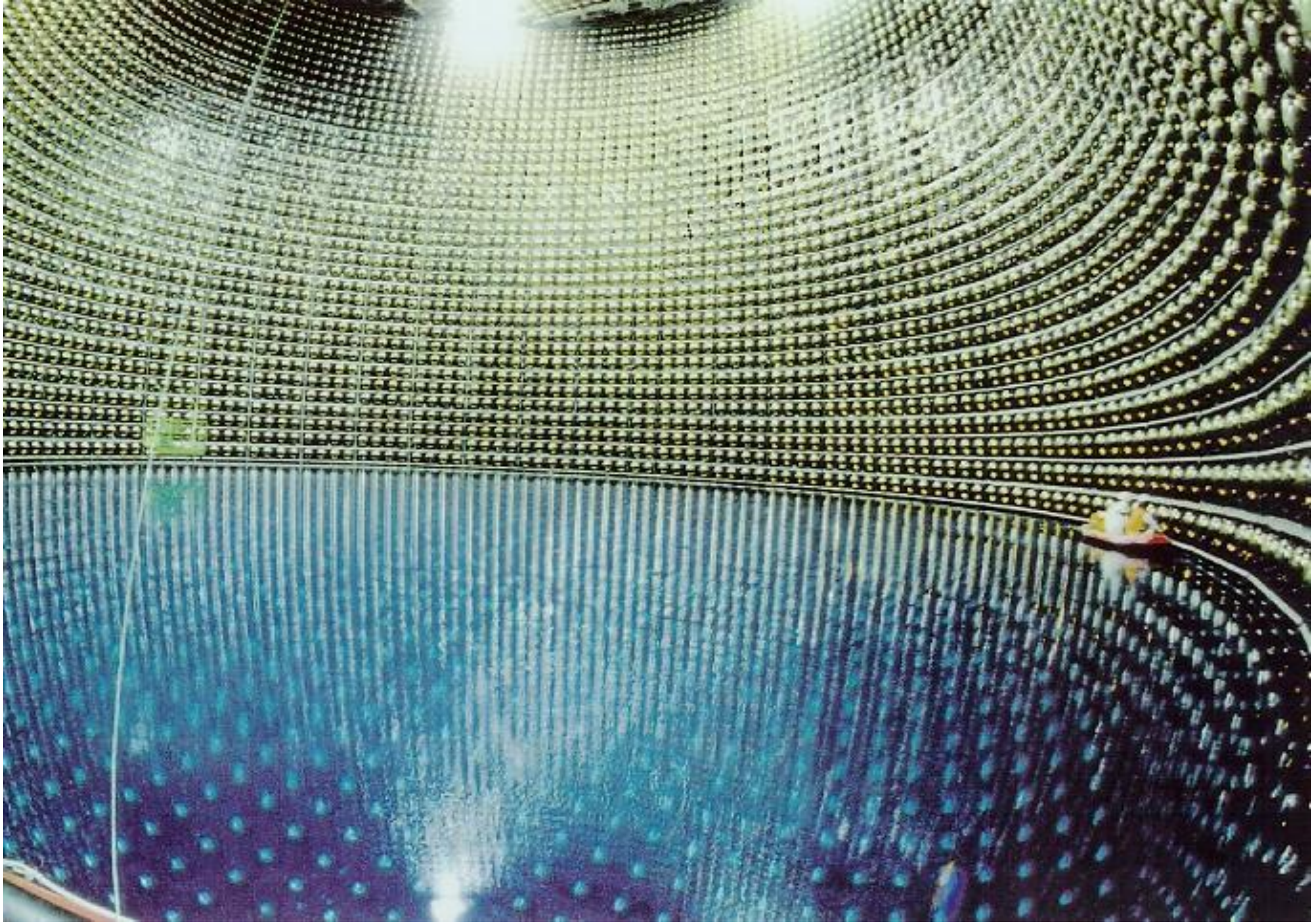
October 1995

October 1995

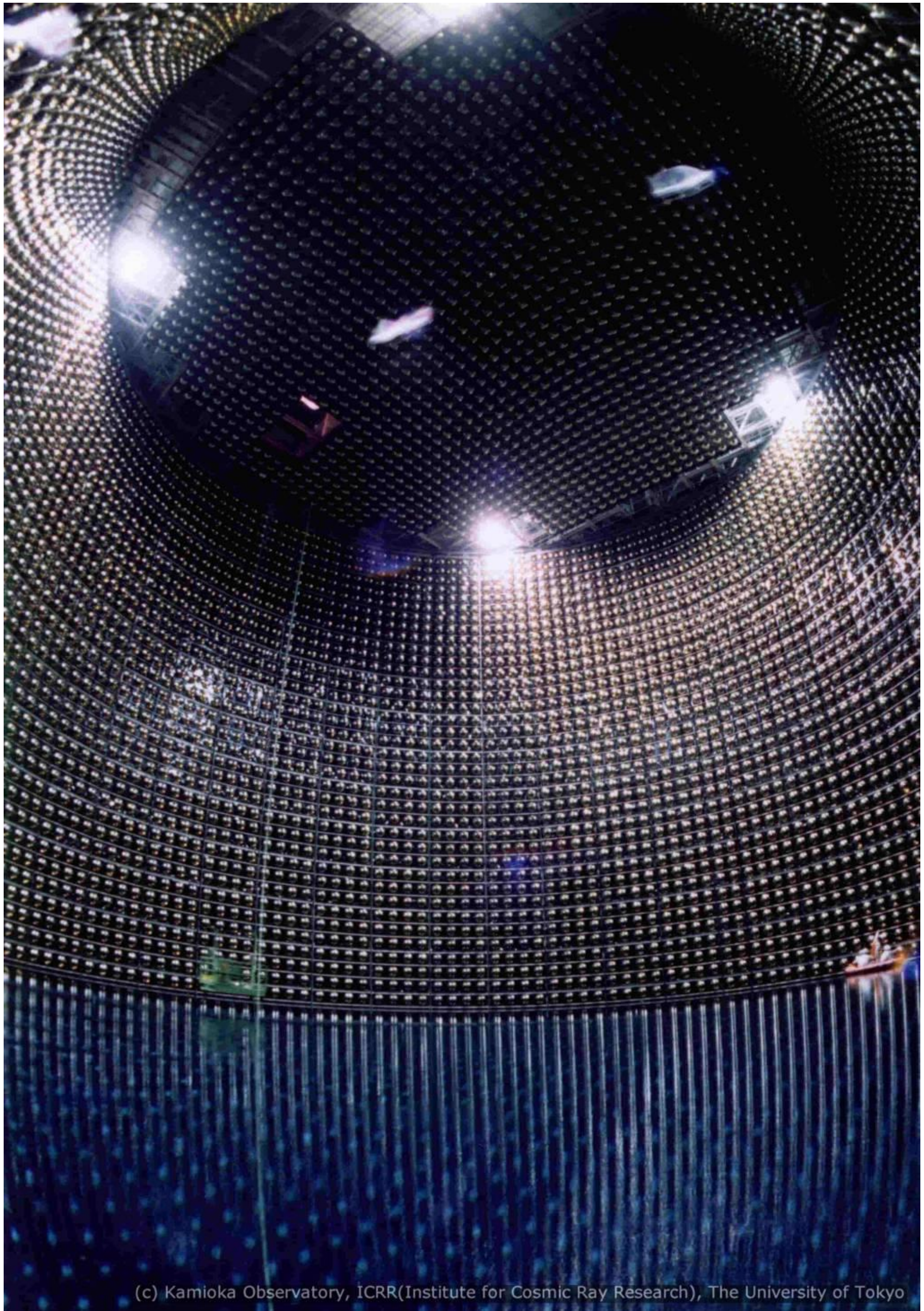
I’ve been a part of Super-K (and wearing brightly-colored shirts) from its very early days…

January 1996



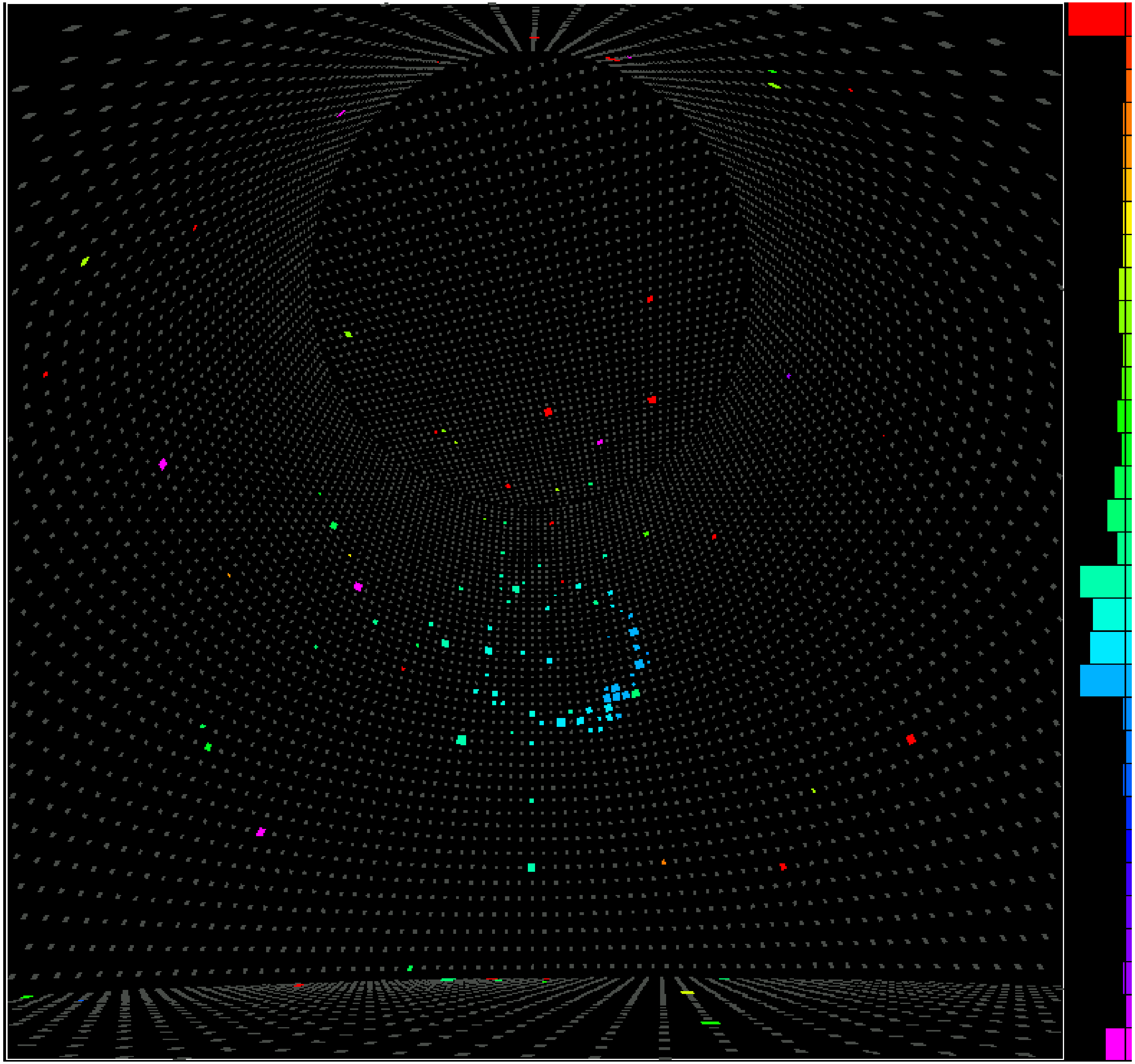


January 1996



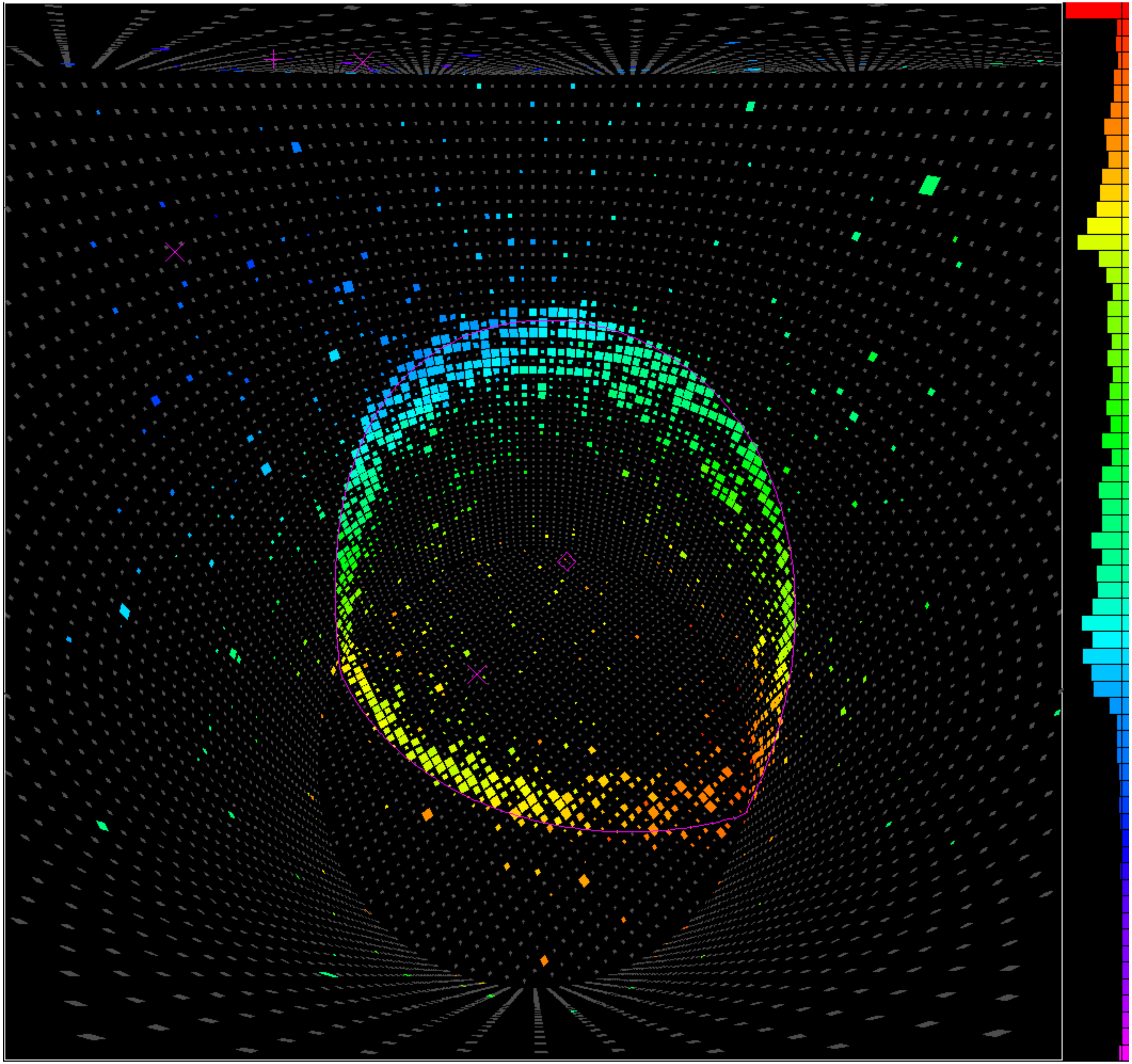
January 1996

After half a decade of construction, data taking began precisely on schedule at 00:00 JST on April 1, 1996



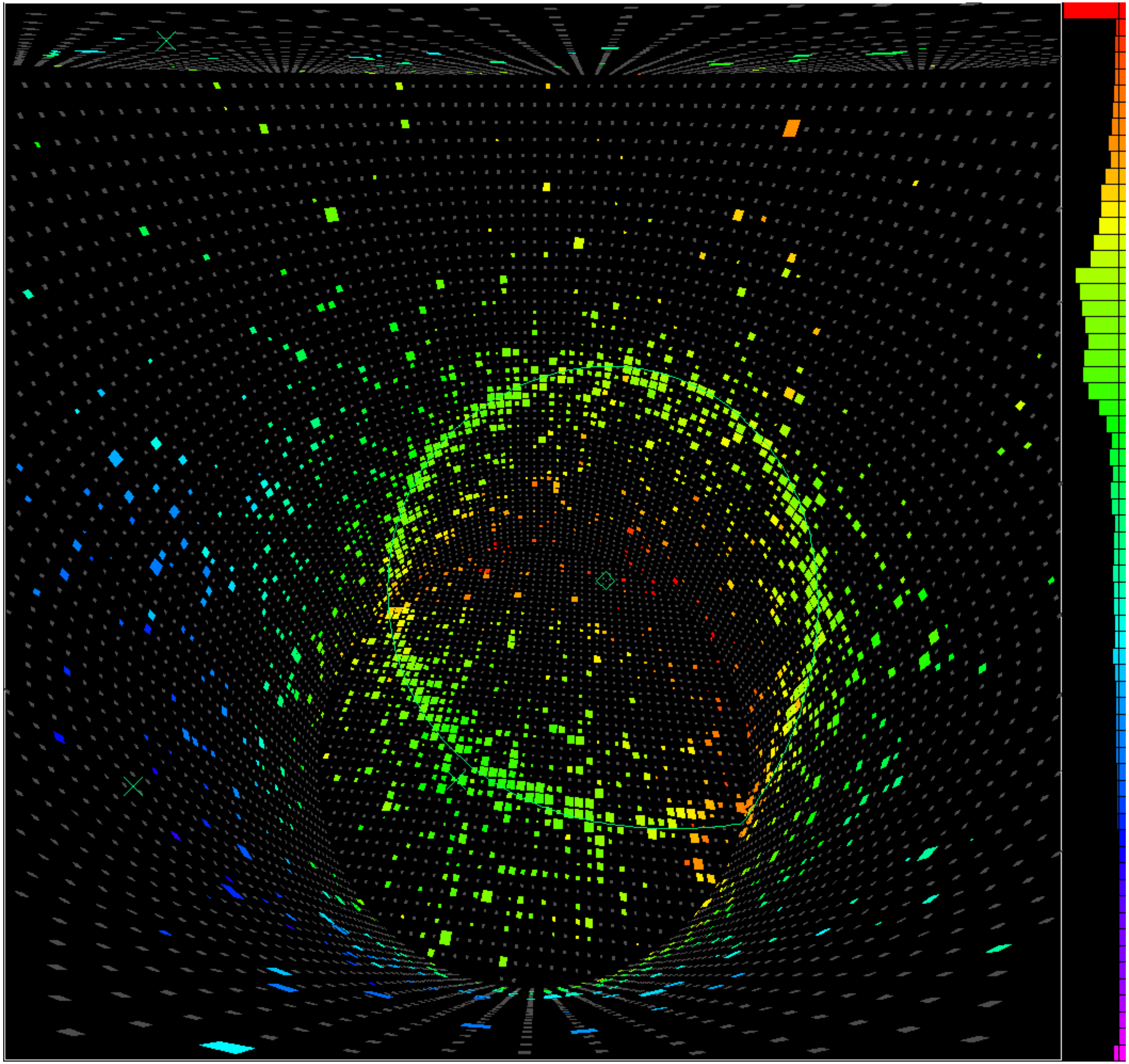
12 MeV
solar ν

Result of ν-e elastic scattering: points back in solar direction



603 MeV atmospheric muon ν

Note sharp edge of ring from muon produced by ν_μ-nucleon interaction



492 MeV atmospheric electron ν

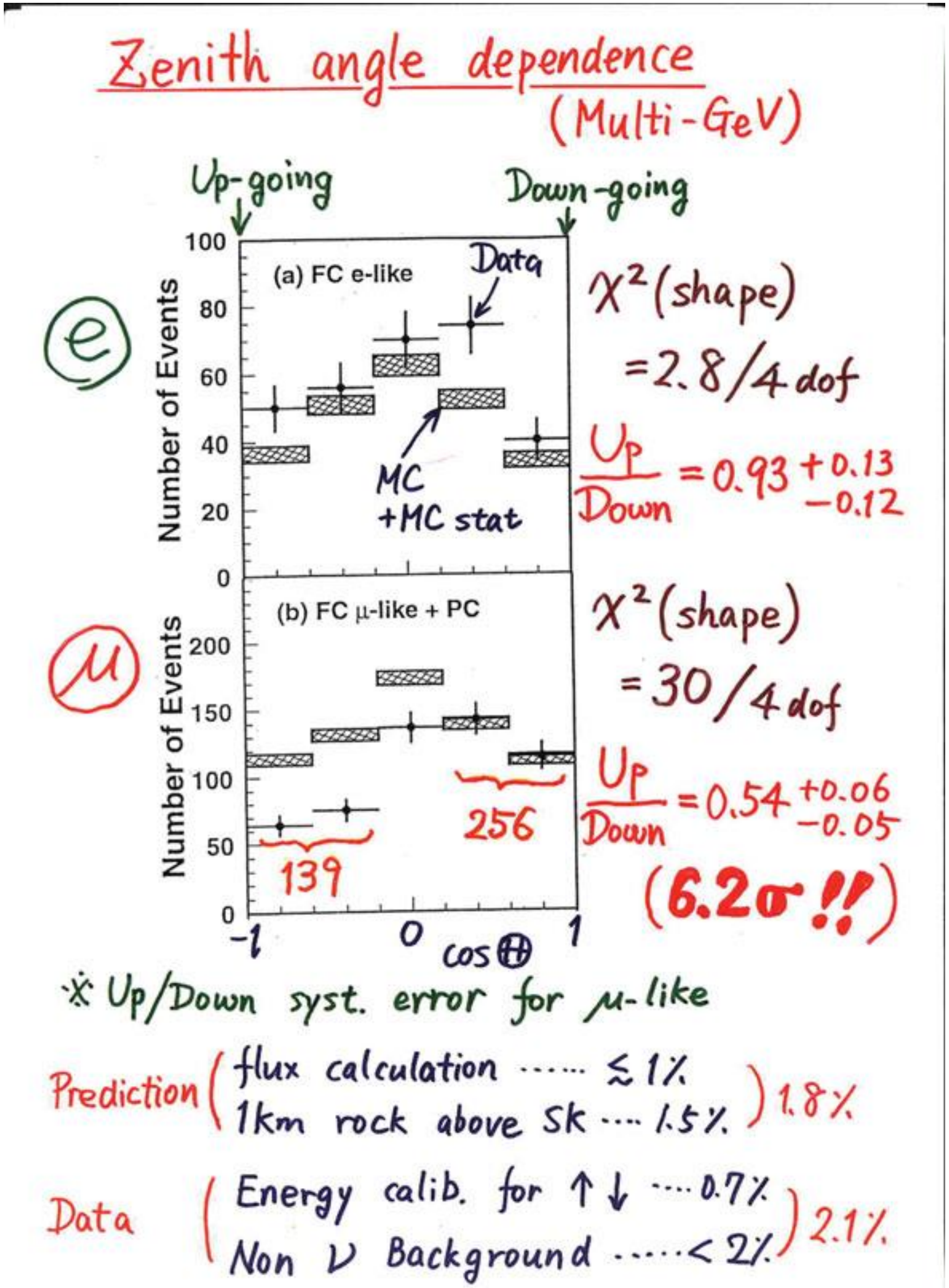
Note diffuse edge of ring from electron produced by ν_e-nucleon interaction

Because Super-K has 22X the fiducial volume of Kamiokande, it quickly surpassed the old data set… in many cases, in just two or three months!

Two years after turning on, Super-K hosted the Neutrino 1998 conference in Takayama, Japan.

The Japanese head of the atmospheric neutrino analysis group, Takaaki Kajita, was ready to make a big announcement.

“The discovery of neutrino oscillations has been confirmed.”

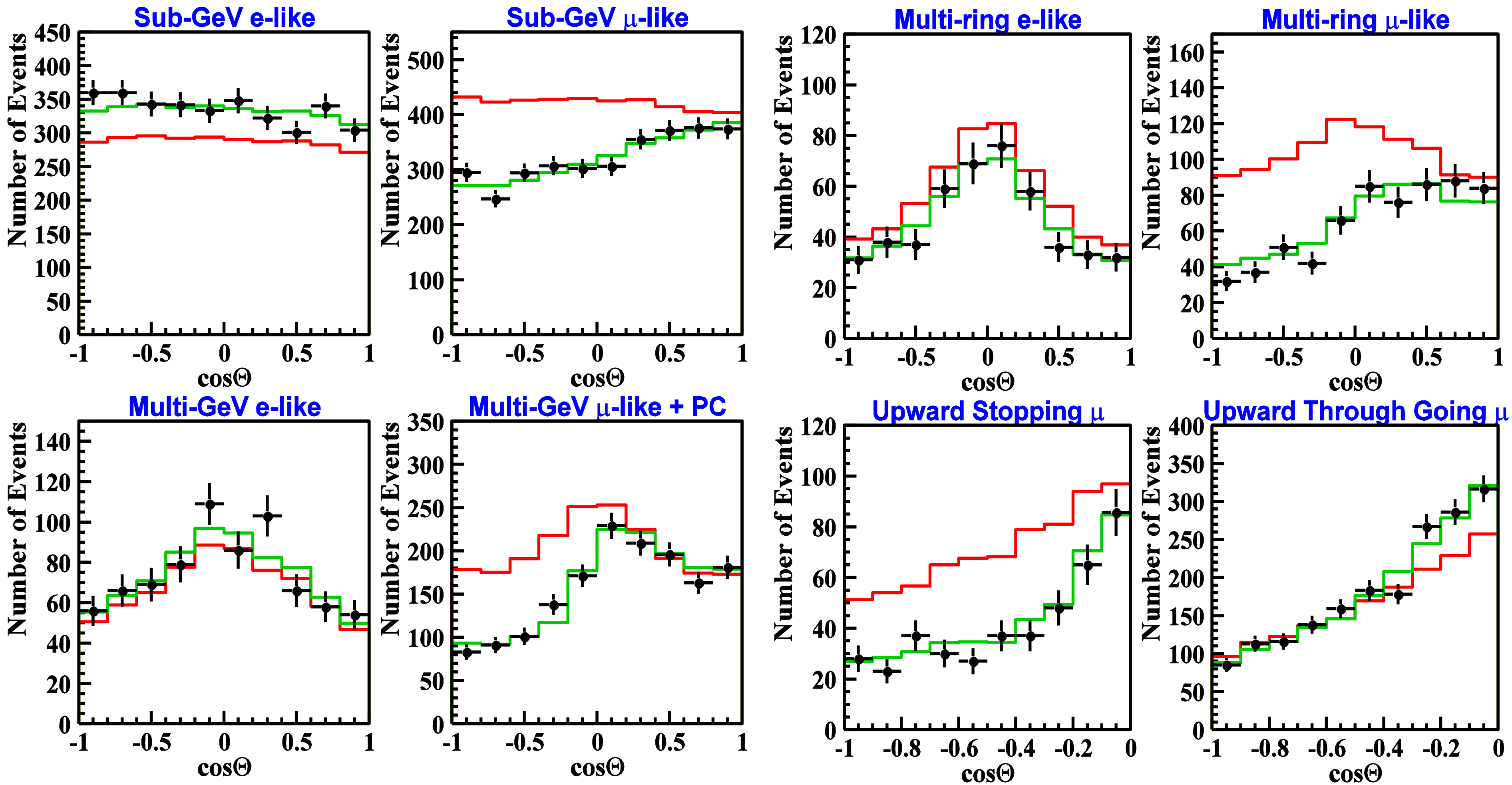


Kajita's key transparency from his Neutrino 98 presentation

One person in particular was most interested…

Super-K ran another three years before being drained for refurbishment in July 2001

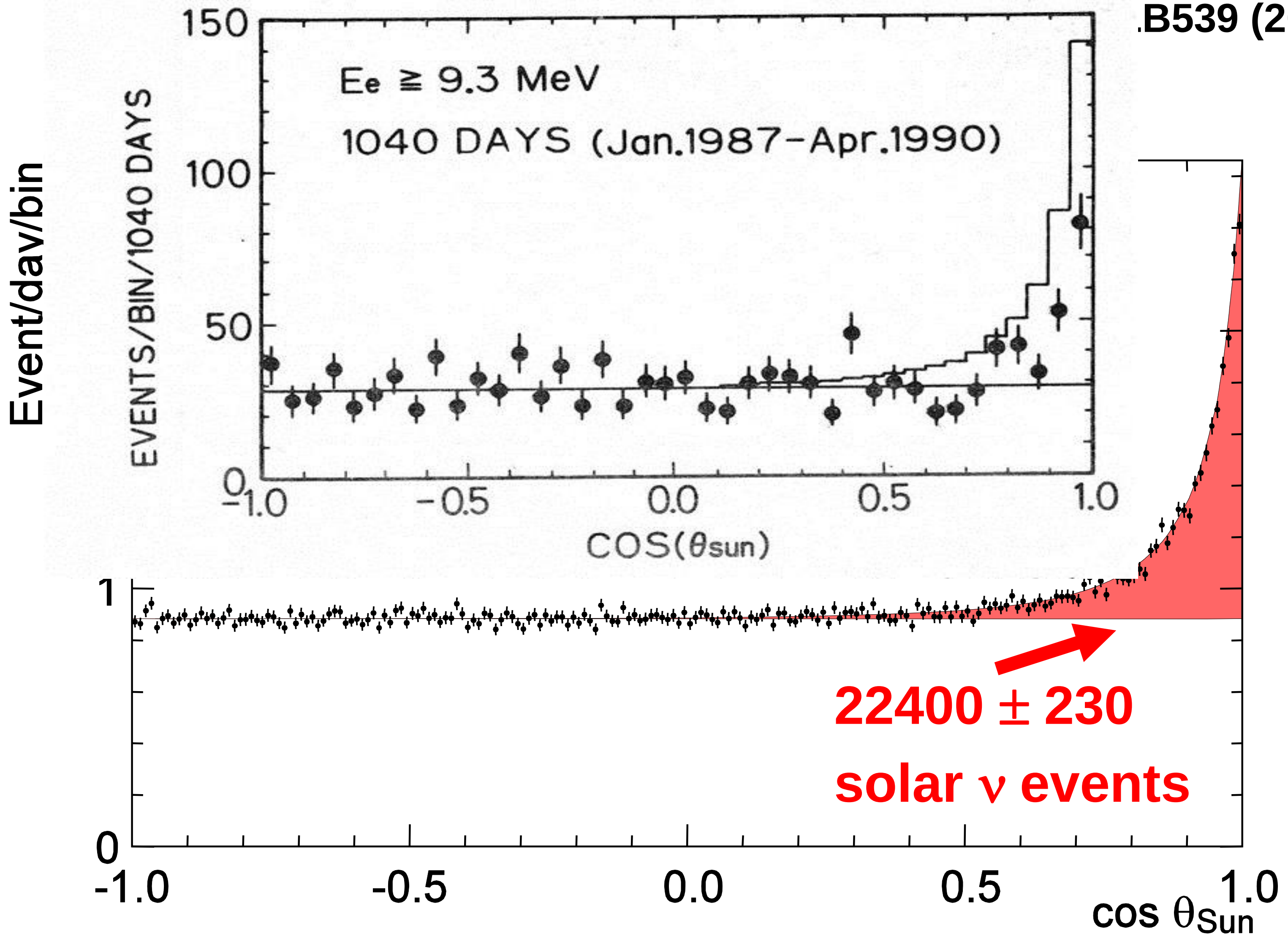
SK-I **1489 days of data** SK-I



No Oscillation

$(\sin^2 2\theta_{23}=1.0,\ \Delta m^2_{23}=2.5\mathrm{X}10^{-3}\ \mathrm{eV}^2)$

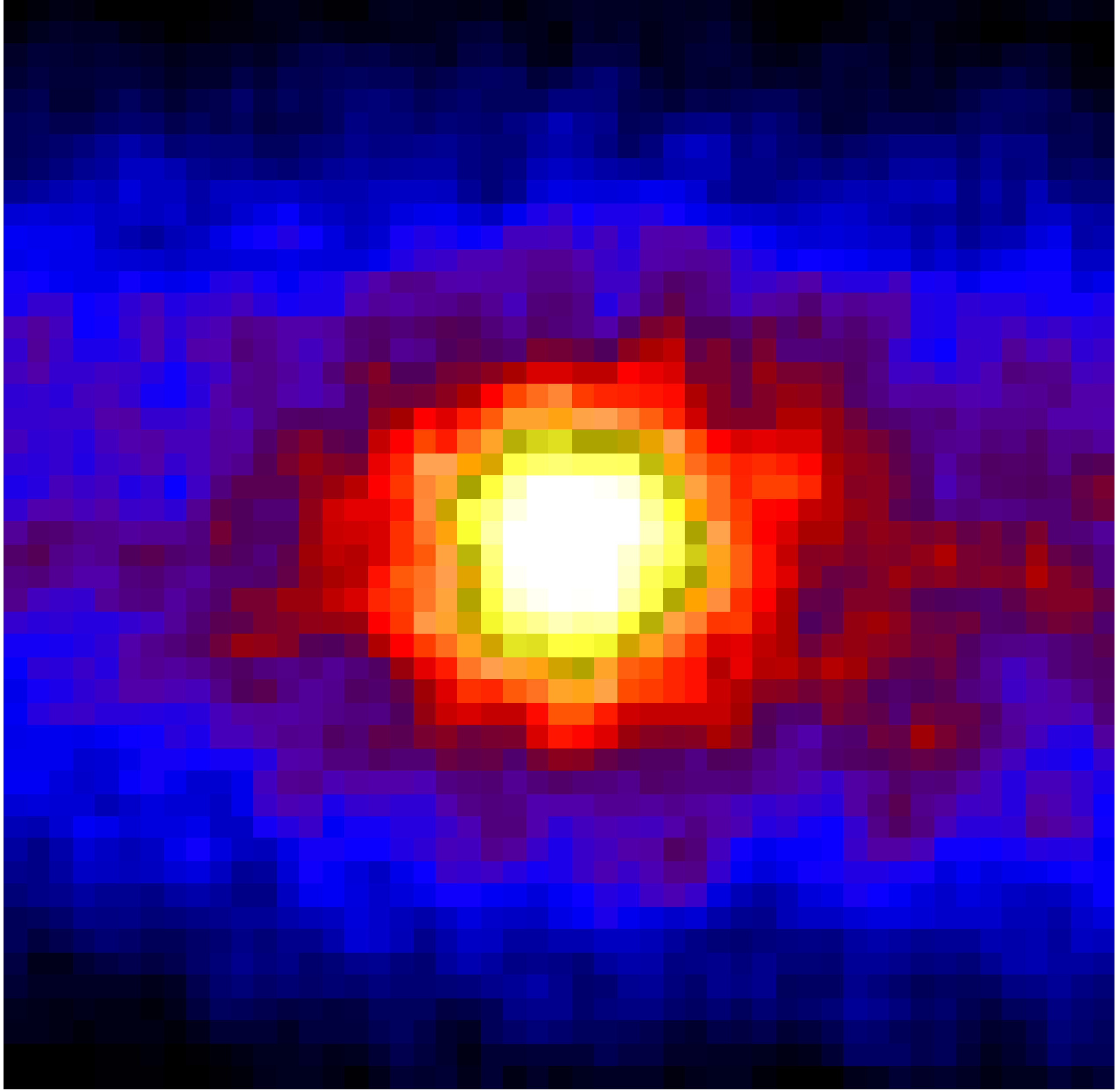
.B539 (2002) 179



^8B flux = 2.35 ± 0.02 ± 0.08 [x10^6/cm^2/s]

Data / SSM_{BP2004} = 0.406 ±0.004(stat.) +0.014 -0.013 (syst.)

Data / SSM_{BP2000} = 0.465 ±0.005(stat.) +0.016 -0.015 (syst.)



Picture of the Sun in neutrino “light.”

We worked all summer in 2001, draining the water out and replacing the few percent of PMT's which had failed during five years of continuous operation.

Then we started to refill the tank.

The tank was about 2/3rd full on November 12, 2001…

November 12, 2001

November 12, 2001

Spokesman Toksuka's November 13th, 2001 Announcement to His Grieving Collaboration

"We will rebuild the detector. There is no question."

Special implosion-proof housings were developed for the Super-K PMT's

We cleaned up the tank, rearranged the surviving inner PMT's, replaced the outer PMT's, and 13 months after the disaster we were taking data again!

We were back in the neutrino business just in time to watch Koshiba to receive his Nobel Prize for SN1987A.

December 10, 2002

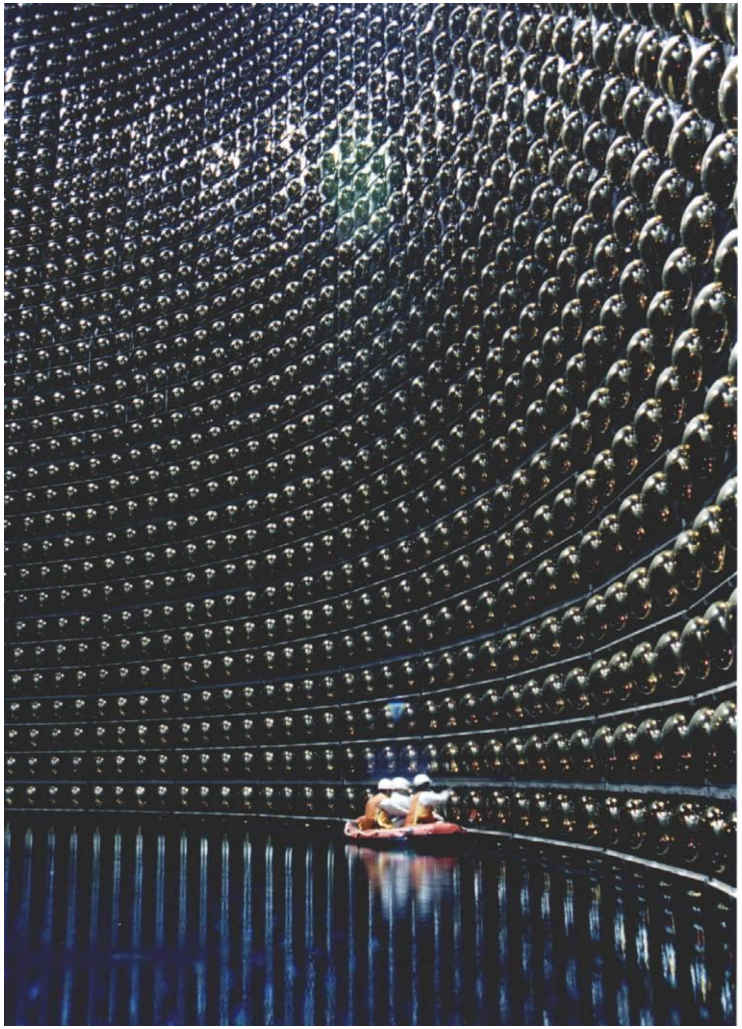
Eventually, half of the 2015 Nobel Prize in physics (shared with SNO's Art McDonald) went to Takaaki Kajita for Super-K's 1998 discovery of neutrino oscillations.

October 6, 2015


2015年ノーベル物理学賞受賞
ニュートリノは
極小の素粒子の世界と
極大の宇宙を結ぶ
架け橋
TAKAAKI KAJITA
東京大学宇宙線研究所長
梶田隆章
宇宙線研究所

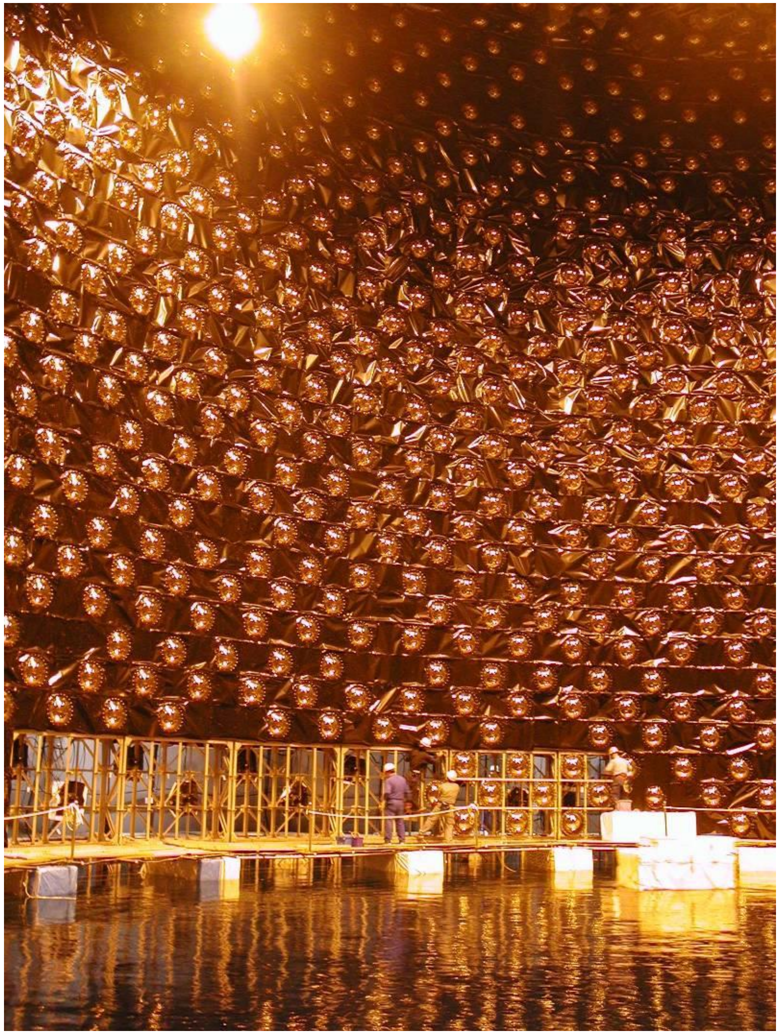

東京大学
梶田隆章
宇宙線

SK-I: 40% PMT Coverage



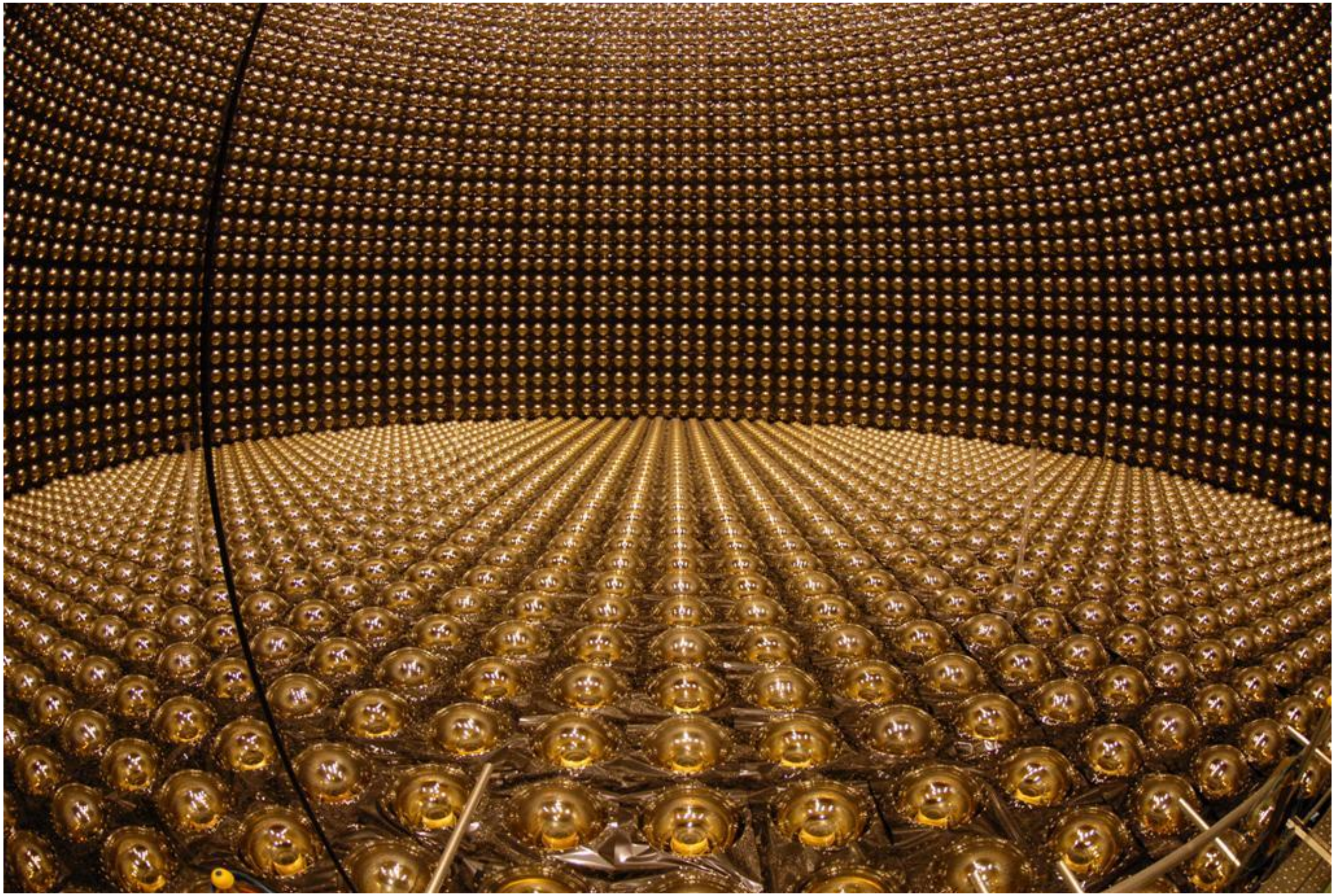
April 1996 → July 2001

SK-II: 19% PMT Coverage



December 2002 → September 2005

SK-III/IV: 40% PMT Coverage

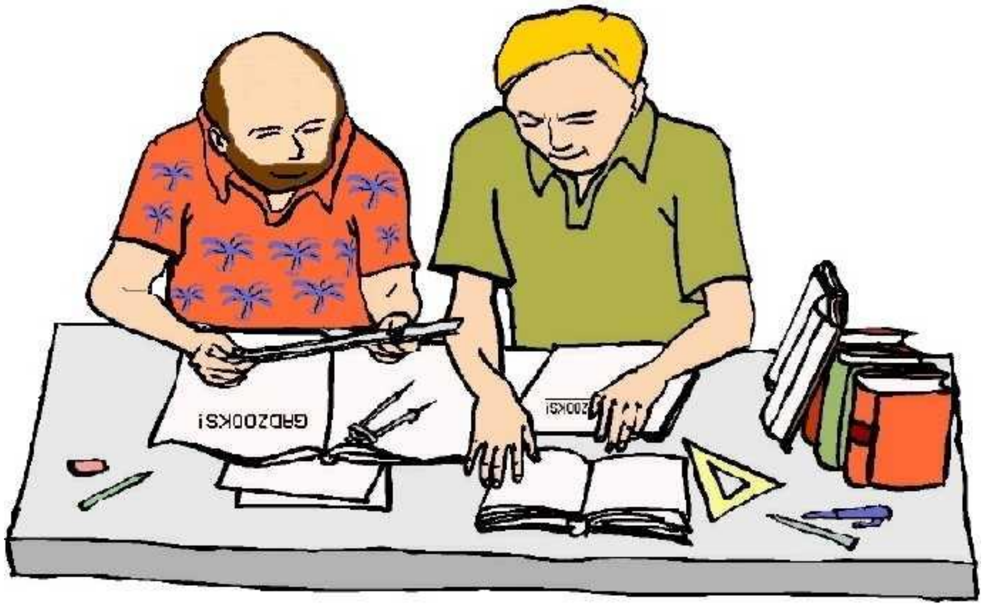


April 2006 → September 2008 → May 2018

Wait… what happened to Super-K in May 2018?

Well, on July 30th, 2002, at ICHEP2002 in Amsterdam, Yoichiro Suzuki, then the newly appointed head of SK, said to me during a coffee break,

"We <u>must</u> find a way to get the new physics."

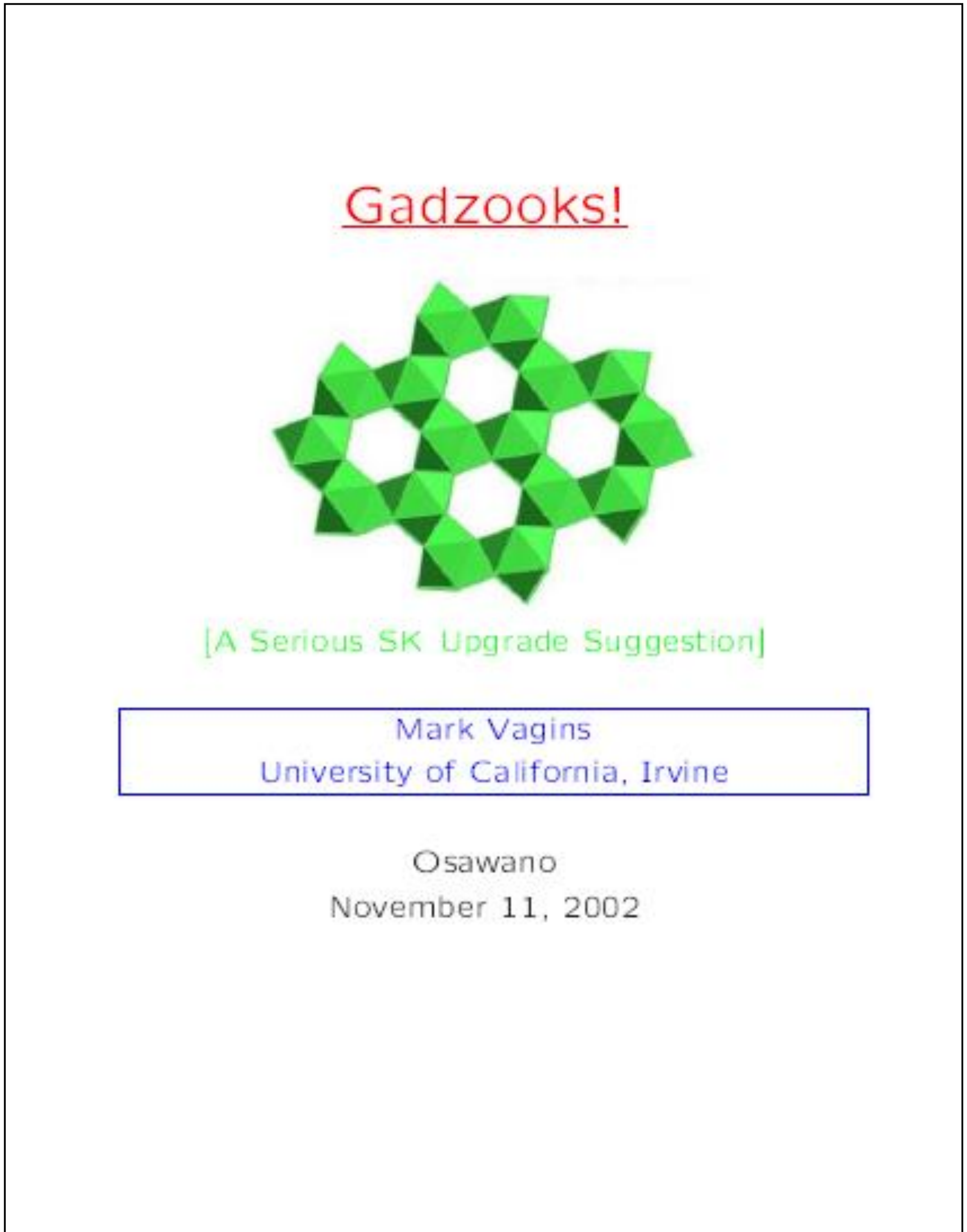


Inspired by this call to action, theorist John Beacom and I wrote the original GADZOOKS!

(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!) paper.

It proposed loading big WC detectors, specifically Super-K, with water soluble gadolinium, and evaluated the physics potential and backgrounds of a giant antineutrino detector.

[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]
(361 citations → one every 15 days for fifteen years)

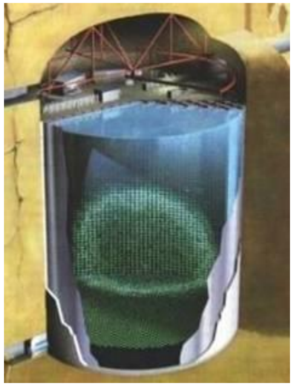


Here's the very first transparency (i.e., what we older folks used before PowerPoint but after glass slides) I ever showed on the topic… over sixteen years ago.

Please note the subtitle:

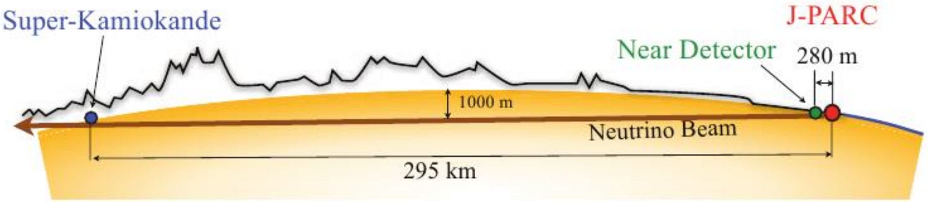
"A Serious SK Upgrade Suggestion"

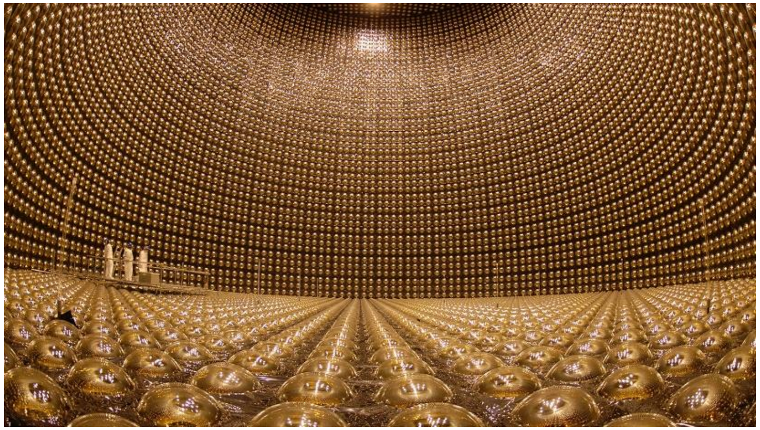
After many years of testing and study - and about $10M in equipment - no technical showstoppers have been encountered. And so…



June 27, 2015: The Super-Kamiokande Collaboration approved the addition of gadolinium sulfate to the detector, pending discussions with T2K.

January 30, 2016: The T2K Collaboration approved addition of gadolinium sulfate to Super-Kamiokande, with the precise timing to be jointly determined based on the needs of both projects.





July 26, 2017: The official start time of draining the SK tank to prepare for Gd loading was decided → June 1, 2018.

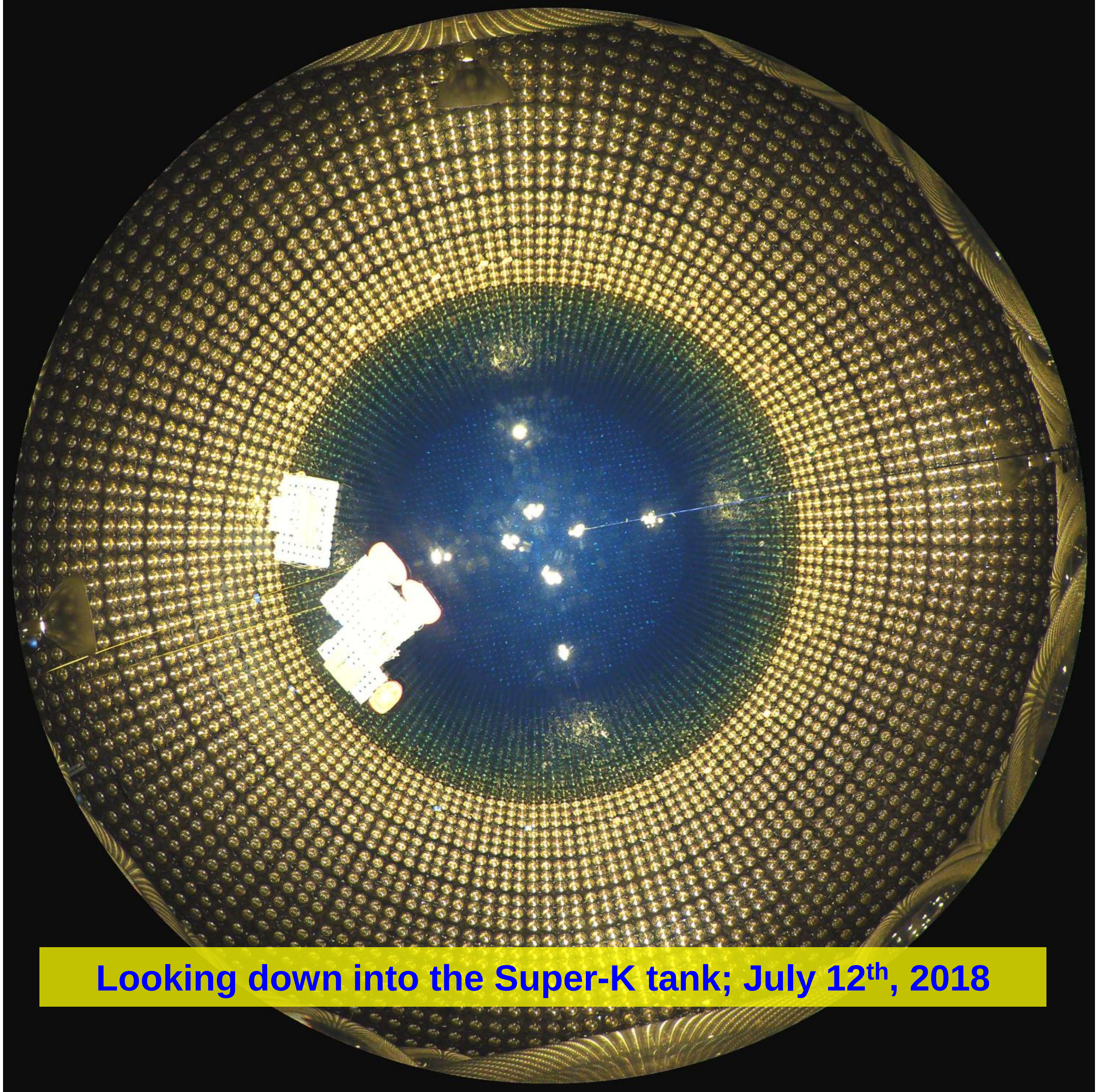

Main jobs to get ready for Gd loading:
1) Fix SK leak
2) Clean up interior
3) Replace dead PMTs
4) Augment internal plumbing
Entering Super-K for the first time since 2006; June 1st, 2018

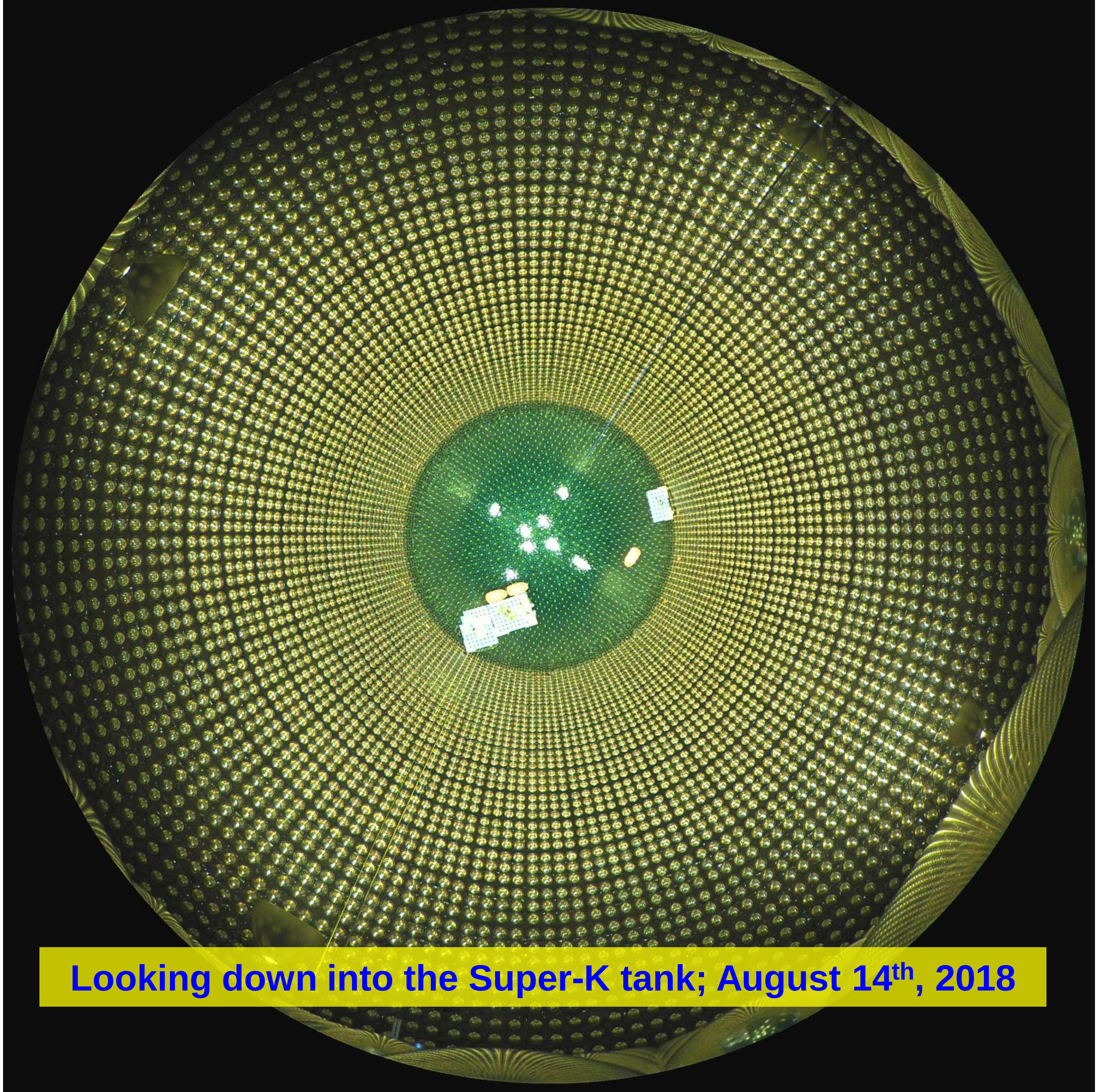
From March 2018 → October 2018,
2683 person-days of work were required!

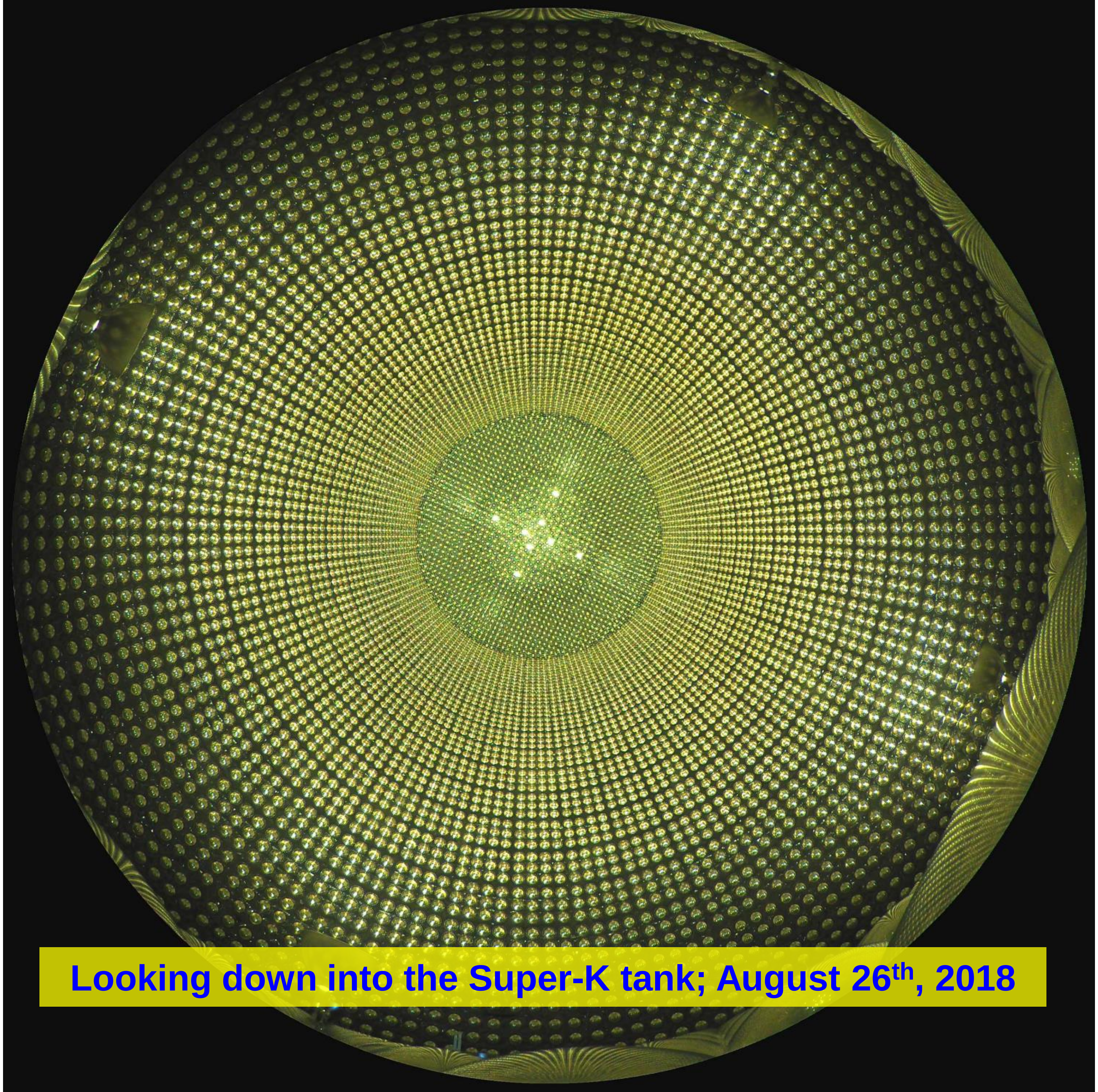
Inside Super-K veto region (top); June 6th, 2018

Inside Super-K; June 10^{th}, 2018


Applying special low-background MineGuard sealant
Super-K veto region (side) with floating floor; June 23rd, 2018


Looking down into the Super-K tank; July 12th, 2018

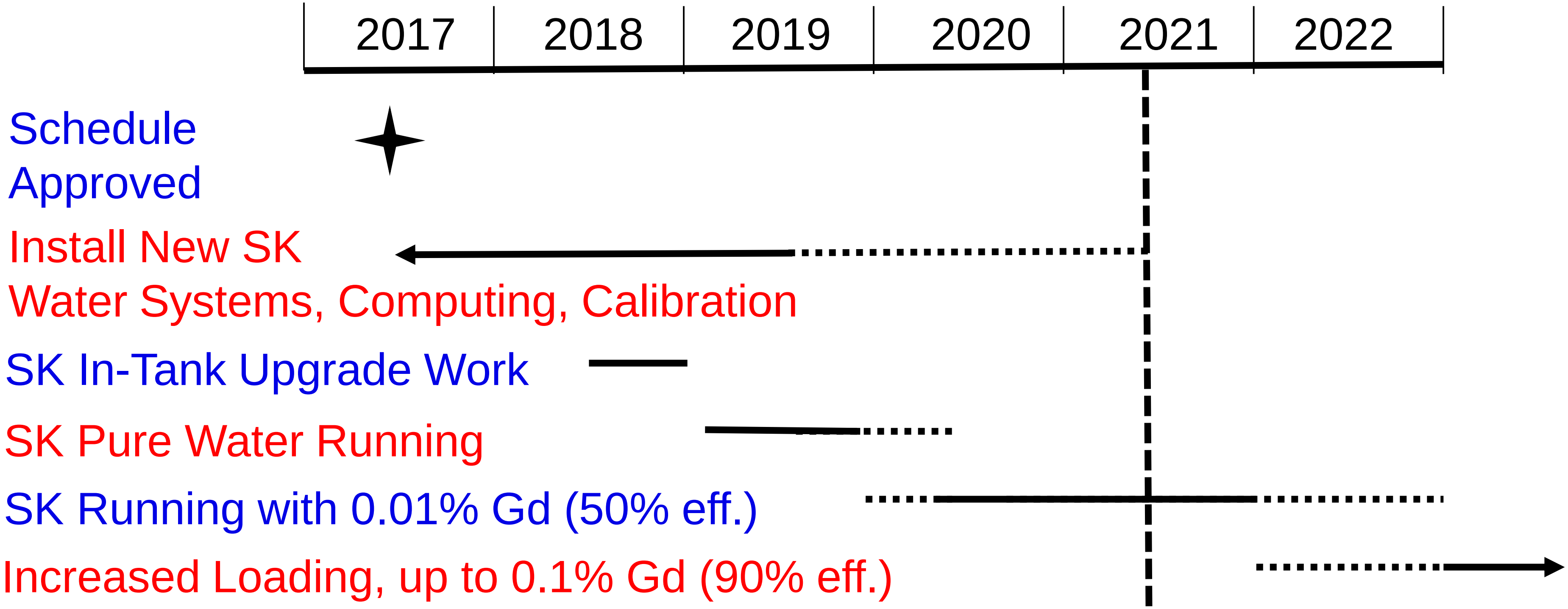

Looking down into the Super-K tank; August 14th, 2018



Looking down into the Super-K tank; August 26th, 2018

Following ~3000 person-days of refurbishment work, as of Feb. 2019 the detector is now refilled with pure water and taking data, ready for the addition of gadolinium!

Expected timeline for SK-Gd



We expect to have collected the world's first diffuse supernova neutrinos before 2022!

Gd-H_2O: Everybody's Doing It, Man…

Name	Location	Main Goal	Water Volume	Loaded with $Gd_2(SO_4)_3$
EGADS	Kamioka	Gd R&D, SN Watch	200 tons	Since 2013
ANNIE	Fermilab	High-E Neutron Multiplicity	26 tons	2019
Super-K-VI	Kamioka	DSNB, SN Burst, PDK, ATM/Solar/LB Neutrinos	50 ktons	2019/20
XENONnT Water Shield	Gran Sasso	Dark Matter Detection	700 tons	2020
WATCHMAN	Boulby	Nuclear Non-proliferation Demonstrator	6 ktons	2022
Hyper-K(-II)	Kamioka	DSNB, SN Burst, PDK, ATM/Solar/LB Neutrinos	258 ktons	2028(?)

How did I learn all
of this history, hear all of
these stories?

Well, I exist in
a superposition state
between the US and Japan.

I even have an office in
Reines Hall at UCI,
and teach in
Koshiba Hall at UTokyo.

My Japanese office at IPMU
is adjacent to Kajita's
office at ICRR.

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

This Friday I will make my 250th trip to Japan!

Apparently neutrinos are not the only massive things that oscillate.

So until next time… sayonara, dudes!