"Cosmic Gall," by John Updike

Kosmiskt sjå

Neutriner är förfärligt små,
har varken laddning eller vikt,
och inget slag av kraft rår på
dem, där de flyger i det blå
och korsar atmosfärens skikt.
De tränger in i minsta vrå
och fastnar aldrig i nå'n sikt;
de ler åt påvliga edikt
– hans bullor kan dem aldrig nå –
och finns där vid varenda bikt
fast ingen borde lyssna då.
De struntar i om du har gikt
och borrar in sig i din tå
(minst 10^{22}
per år, om man ska vara strikt).
Din herdestund i grön berså
bevittnar de och far se'n kvickt
med bud dit inga bud bort gå . . .
– Gud give, att det vore dikt!

Translated by physicist Hans-Uno Bengtsson, Professor at Uppsala & UCLA, a decorated teacher.

Response to an invitation to address "the saga of IMB"...

Protons disintegrate? Neutrinos oscillate!

How massive "H_2O" detectors reveal nature's secrets

...A marriage "made in the heavens" & on earth, or...

...the oscillating road to neutrino mass...

L. Sulak, Boston University

Nobel Ceremony Week

Angström Laboratory, Uppsala University, 17 December 2015

Hosts: Olga Botner & Allan Hallgren

Neutrino microscopes & telescopes, the early history

Initiated, but unrealized, precursor to Antares, IceCube, Km3net:

Dumand	1 km^3	Hawaii	1976*

Focus on the pioneers:

IMB	10 kilotons = $(20m)^3$	Ohio	1978
Kamioka	3 kilotons	Kamioka	1979

The IMB/Kamioka merger:

Super-K	50 kilotons	A bigger K cavity	1992

* ~ proposal dates

Seminal technology of IMB...now morphed into 9 ν telescopes & microscopes, on 4 continents...

	neutrino source	target	note
K2K/T2K	KEK/Tokai accelerators	pure RO water	Super-K detector
Kamland	nuclear reactors	scintillator, oil, water	old K cavity
SNO, Sudbury	our sun	heavy water	$300 M
Antares, off France	cosmic rays	Mediterranean water	2.4 km deep
IceCube, South Pole	cosmic rays	in ice, "solid" water	1.5-2.5 km
Daya Bay, China	reactors	near & far detectors	2 detectors
Reno, Korea	reactors	near & far detectors	2 = detectors
Km3net	cosmic rays	seawater	1st string operating

1970: all started with Fermilab, an accelerator designed to study ν's,
& the first "big," totally-active liquid scintillator calorimeter:

Experiment E1A:

Massive = 100T

Internal reflection by teflon, n=1.35

Segmented = complex

Neutrino "Saga": 1971, then 1973...

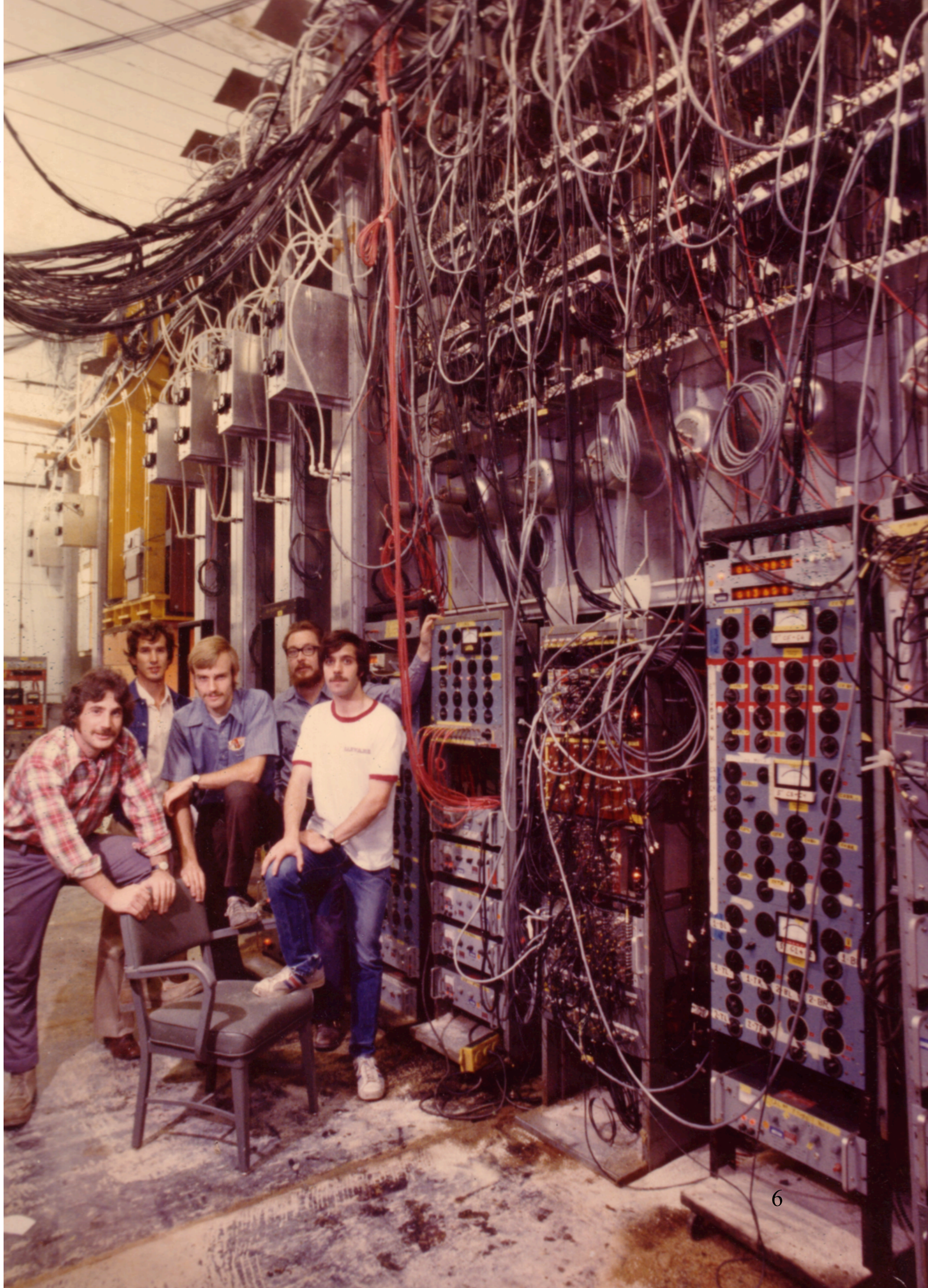
Fermilab 100T E1A,
discovered deep inelastic neutral currents

Then 60T BNL E613 mineral oil scintillator:
observed $\nu_\mu p \rightarrow \nu_\mu p$ elastic scattering,

...neither enough to power a supernova.
LoSecco

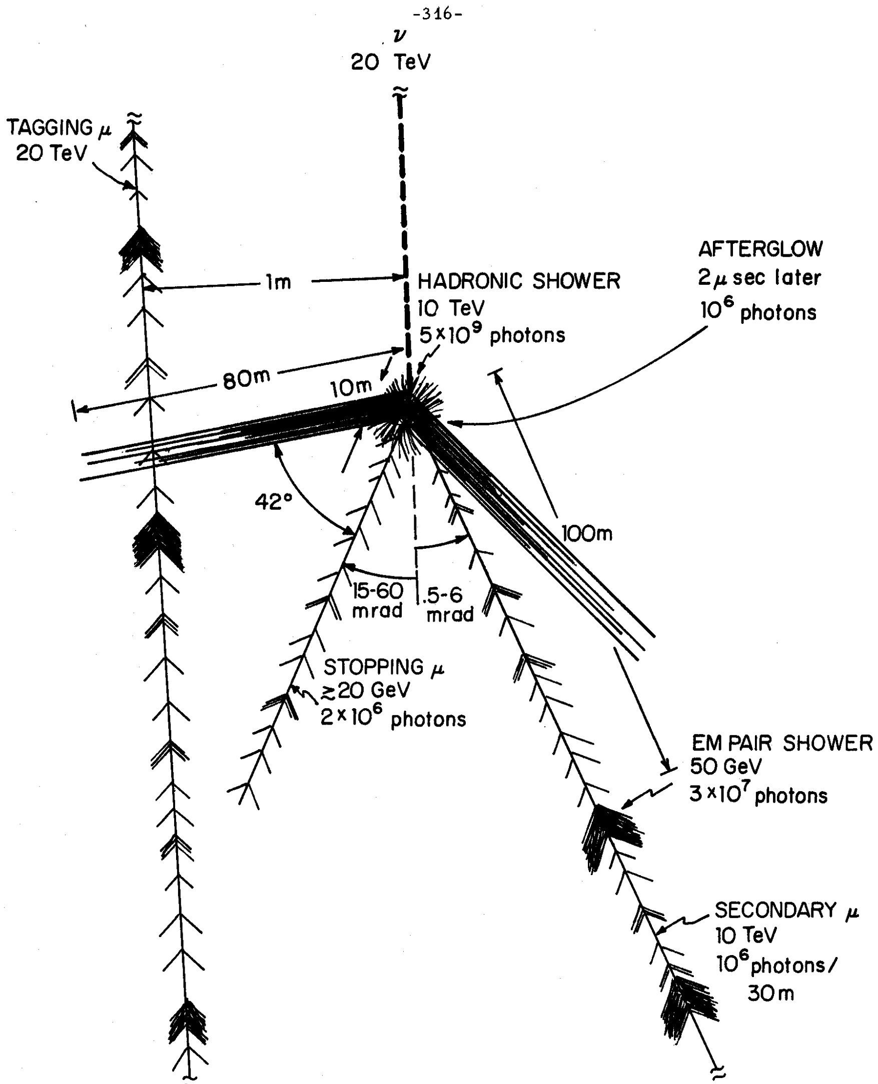
BNL detector became target for E704,
first "short" baseline oscillation exp't:
~0.1 km
Δ^{++} production => ~0.1 GeV ν_μ
L/E = 1 km/GeV
vs. 10 km/GeV, as we now know.

Seeing nothing => need bigger L/E, mass.
Easier with atmospheric ν_μ?
Oil cost too hi=> water target-detector?
Penalty: ~30 times less light!



HU team, notice Strait & Kozanecki.
(half of team from Penn, not shown)

The feasibility of a water target-detector spawned...mass, directionality...summer '76:



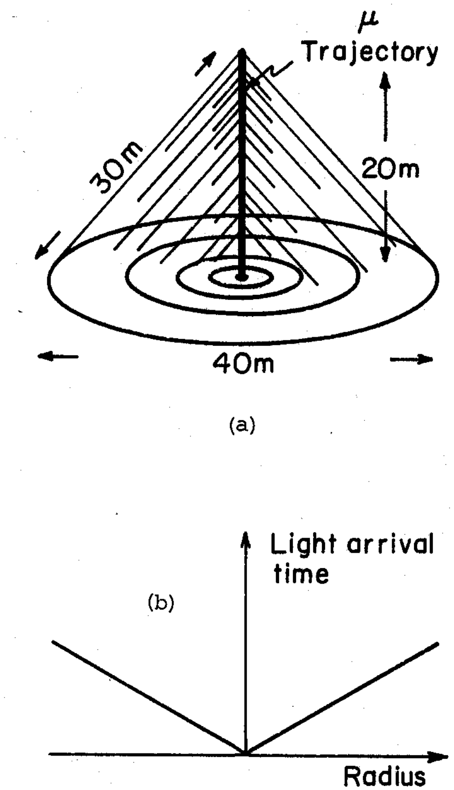
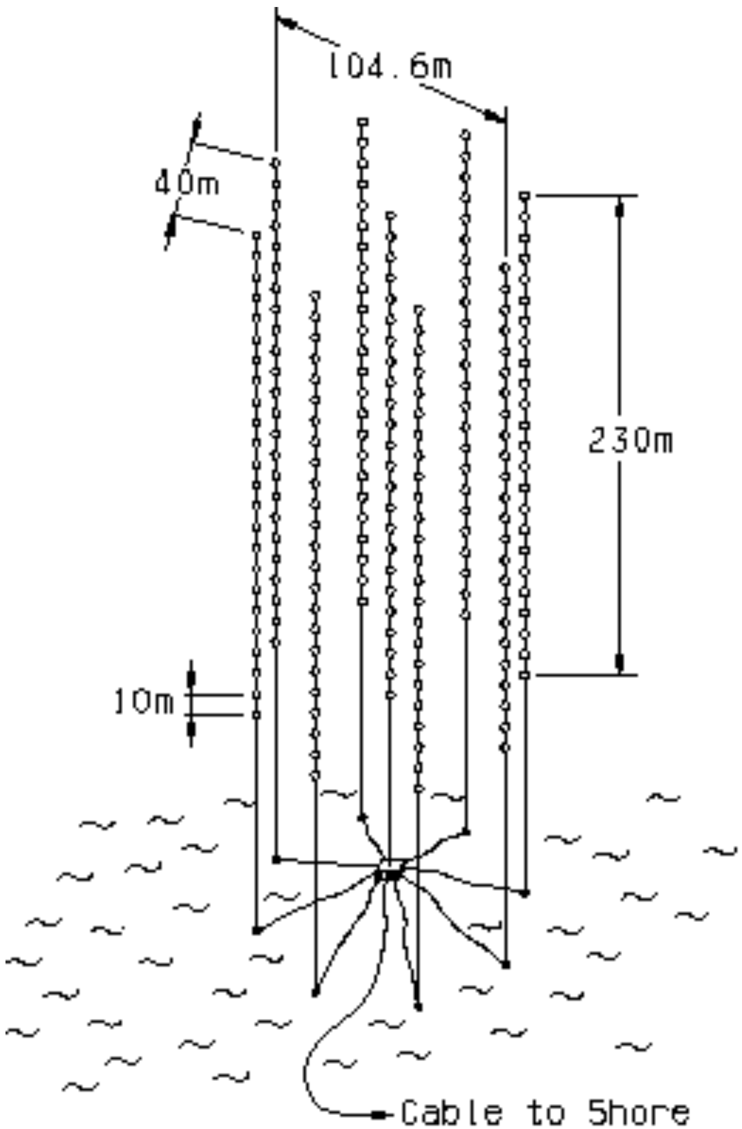


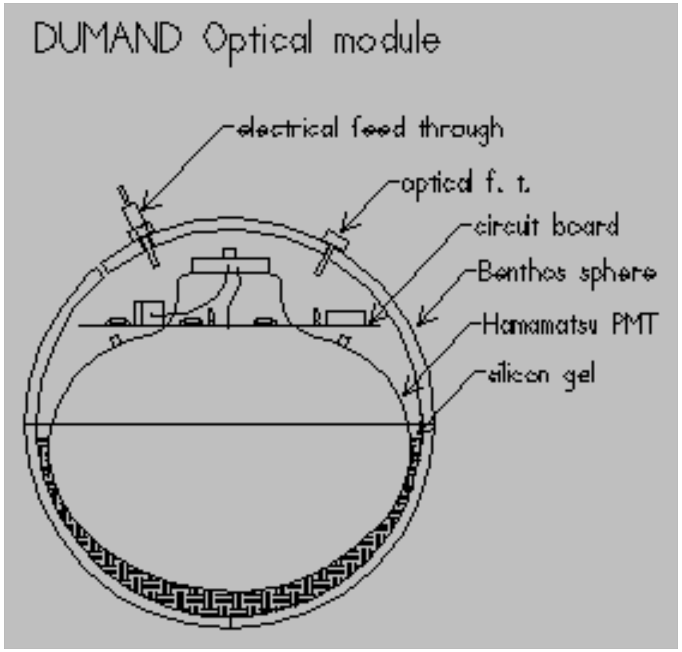
Fig. 3. a) Cerenkov light from a muon detectable by a surface array of phototubes.

b) The arrival time of the light in the PM's as a function of the distance from the trajectory.

Proc. 1976 DUMAND Summer Workshop. Drawings by LRS, chair of "Neutrino Signatures" group.

Design of 1976, eventually realized in Antares ~2003, then in IceCube (frozen H_2O)...





(DUMAND optical module, 1991,

before Congress killed it & the SuperCollider in '93,

I trotted off to Saclay to convince France to adopt it.)

Berezinski & LRS, Proc. 1976 DUMAND Summer Workshop

Invention of conceptual technology for directional calorimetry...

Proceedings of the

1976 DUMAND Summer Workshop

University of Hawaii
Honolulu, Hawaii
September 6–19, 1976

Arthur Roberts
Editor

Rene Donaldson
Technical Editor

The Proceedings were prepared through the Office of Publications of the Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.

Signatures of High Energy Neutrino Interactions and Their Detection Via Cerenkov Light

A.E. Chudakov, D. Cline, W.V. Jones, K. Mikaelian, S. Miyake, A.A. Petrukhin, M.L. Stevenson, and L. Sulak (Chairman)*

Abstract

We investigate the kinematics of deep inelastic neutrino scattering $\nu N \to \mu X$ for neutrino energies > 10 TeV. For a primary reaction occuring deep underwater the characteristics of the secondaries and their subsequent interactions, as well as the major backgrounds, are detailed. A maximum grid size for the simplest array of Cerenkov sensors which could measure significant information on both muon and hadron observables is determined. Full reconstruction of scaling variables is required. The resulting detector is entirely consistent with current technology and its cost is comparable to that of the larger accelerator experiments.

...but non-accelerator experiments barely fundable in the US at the time.

...How to search for ν_μ oscillation in the semi-∞ Δm^2 phase space?

BNL E704: our L/E was not big enough, detector not massive enough.

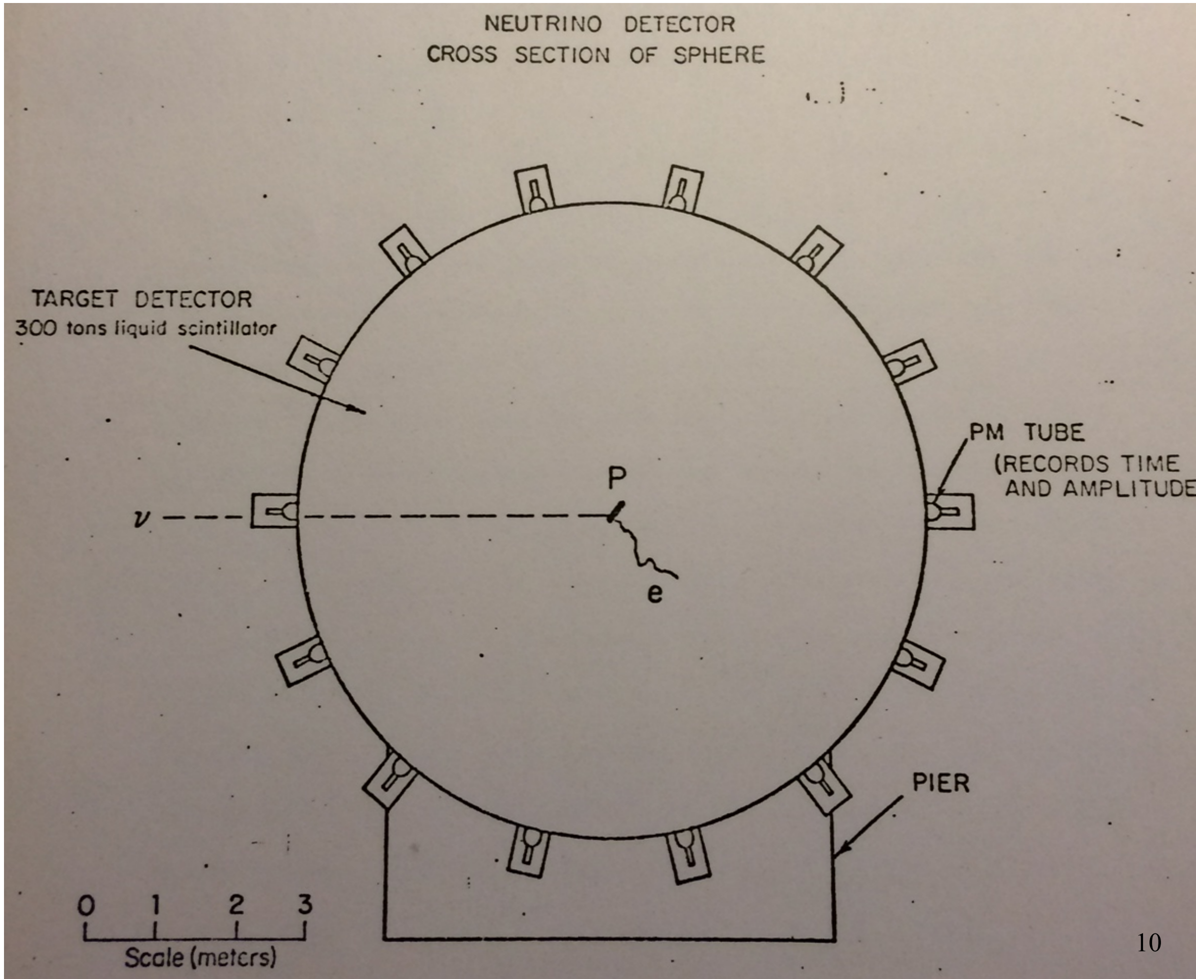
BNL E706 Proposal: send 100 MeV beam 100 km to Wallestonite Mine in upper NY.

Search for:

Oscillations during beam bursts.

Proton decay between blasts.

Recognize a current detector,
operational 40 years later?



1st long-baseline oscillation proposal:

Presented by LRS, *January 1977.*

Sam Ting, on BNL PAC: "I like it!"

But BNL said "No, too risky."

A STUDY OF THE TIME EVOLUTION OF A LONG-LIVED ν_μ BEAM

E706

E. Egelman, B. Gordon, W. Kozanecki, W. Loomis, J. LoSecco, C. Rubbia, A. Sessoms, D. Shambroom, J. Strait, L. Sulak, C. Tao, R. Wilson and M. Yudis

Department of Physics
Harvard University
Cambridge, Massachusetts 02138

Abstract

We propose to study the time evolution of a long-lived ν_μ beam at Brookhaven National Laboratory. Sensitivity at large proper times $\tau = \ell/p$ (where ℓ is the flight length and p is the momentum of the neutrino) is achieved by going to low neutrino momentum. The AGS proton momentum is chosen to concentrate the ν_μ flux at very low energy where all background reactions are kinematically suppressed. In particular $\nu_\mu \to \nu_e$ transformations are sensed via $\nu_e n \to e^- p$ or by the classic reaction $\nu_e + C_{12} \to N_{12} + e^-$ followed by a delayed $N_{12} \to C_{12}\, e^+ \nu_e$ signal. We propose (1) a 300 T detector for the definitive experiment and (2) an early exploratory test with the existing Brookhaven neutrino detector.

17 January 1977

Submitted to Brookhaven National Laboratory

Then came our savior, in '77, an overriding theory challenge:

Search for SU5 proton decay to $\sim 10^{29}$ years...

Need 10^{33} nucleons to definitively test SU5 Grand Unification.

Scintillating oil, at \$1/kg, way too expensive, 10 kT = \$10 M.

=> Must use water...luckily Dumand experience gave us conceptual design.

Must be deep underground to reduce background;

where rate of neutrinos events equivalent to proton decay at $\sim 10^{30}$ years.

Ancillary challenge: non-SU5 Unifying Theories predict neutrino oscillation, harder...

Must understand interactions from atmospheric neutrinos.

Need better pattern recognition, only 1 ring.

Need timing to distinguish muons & electrons, products of ν_μ and ν_e.

Spent all of '78: Devising a prototype for both proton decay & neutrino interactions.

1 postdoc (LoSecco), 2 students (Cortez &Foster), 2 ugrads, 1 EE & LRS. 7 at Harvard.

Madison Conference, December 8, 1978:

First detailed paper on imaging water Cherenkov detector for proton decay

Totally active calorimeter.

Cherenkov,

measures charged particle direction.

Surface array of PMs, more pixels.

Atmospheric neutrino events identified.

10^{33} year PDK limit achievable.

Muon/electron discrimination:

Timing scales, μsec & nsec.

600 m underground sufficient.

HUPP252

HUPDM 1

A TEST OF BARYON STABILITY SENSITIVE

TO A LIFETIME OF 10^{33} YEARS

Abstract

A totally-active, water Cerenkov detector, located underground to limit the background to only those events induced by atmospheric neutrinos, is sensitive to most of the conjectured decay modes of the nucleons in it. Sensitivity to π, μ, e and γ secondaries, good energy resolution, and good angular resolution enhance the backround rejection of the device and provide significant information about the decay channel should it be observed. If no events are recorded during one year of operation, a lower limit of 10^{33} years can be placed on the lifetime of the nucleon decaying into most modes. Depending upon the decay channel, this is three or four orders of magnitude longer than previous measurements, and is at the level suggested by many unifying theories. This experiment has a sensitivity within an order of magnitude of that achievable in any conceivable detector since known background from atmospheric neutrinos imposes an inherent limit. Since unanticipated backgrounds may influence the design of any definitive experiment, the proposed detector can be considered a prototype for an ultimate experiment.

Presented by L. Sulak at the

Madison Seminar on Proton Stability

University of Wisconsin

December 8, 1978

Detector overview from Madison talk...

A cube ~18 m OD on each side.
  Fiducial volume of 14^3 m^3
    1.5×10^{33} nucleons (2.5KT)
    2 m veto region

Surface array of 5" diameter
  hemisperical PMTs

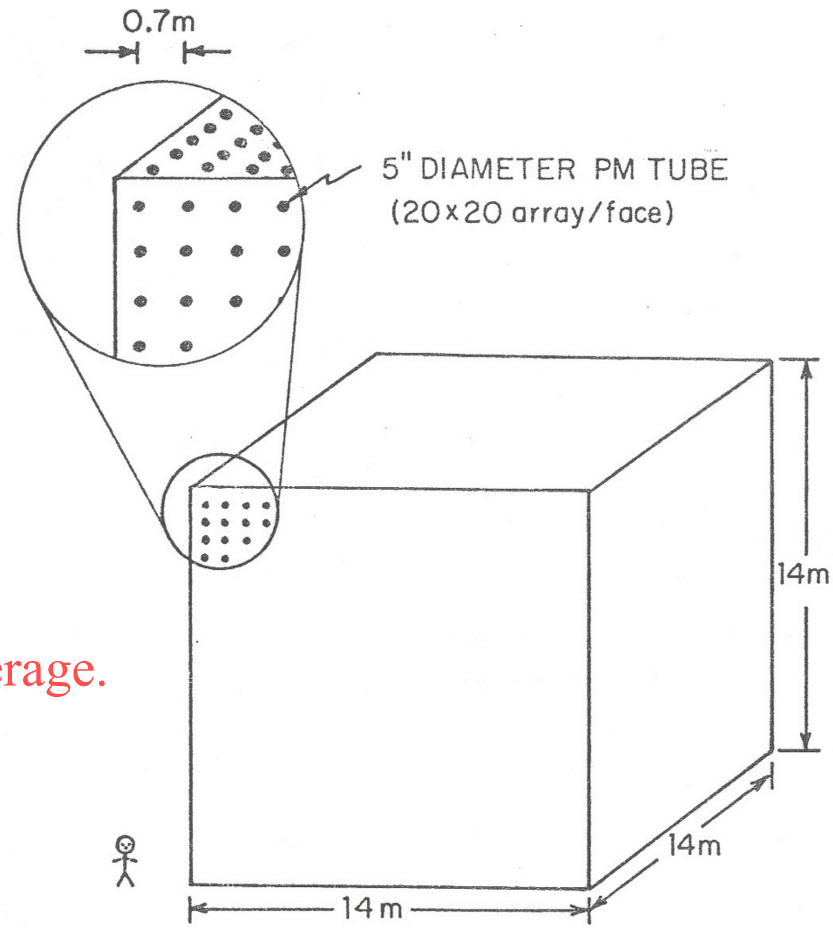
Spacing – 0.7m between PMT

Total 2400 PMTs, 1% photocathode coverage.

¼ photoelectron threshold.

Energy threshold 30 MeV,
  to see muon decay electrons.

Muon decay detection efficiency 50%
  using a late μsec timing scale.



DETECTOR CONFIGURATION

Proc. Seminar on Proton Stability, Madison, 1978.

Cherenkov geometry from that Dec'78 paper...

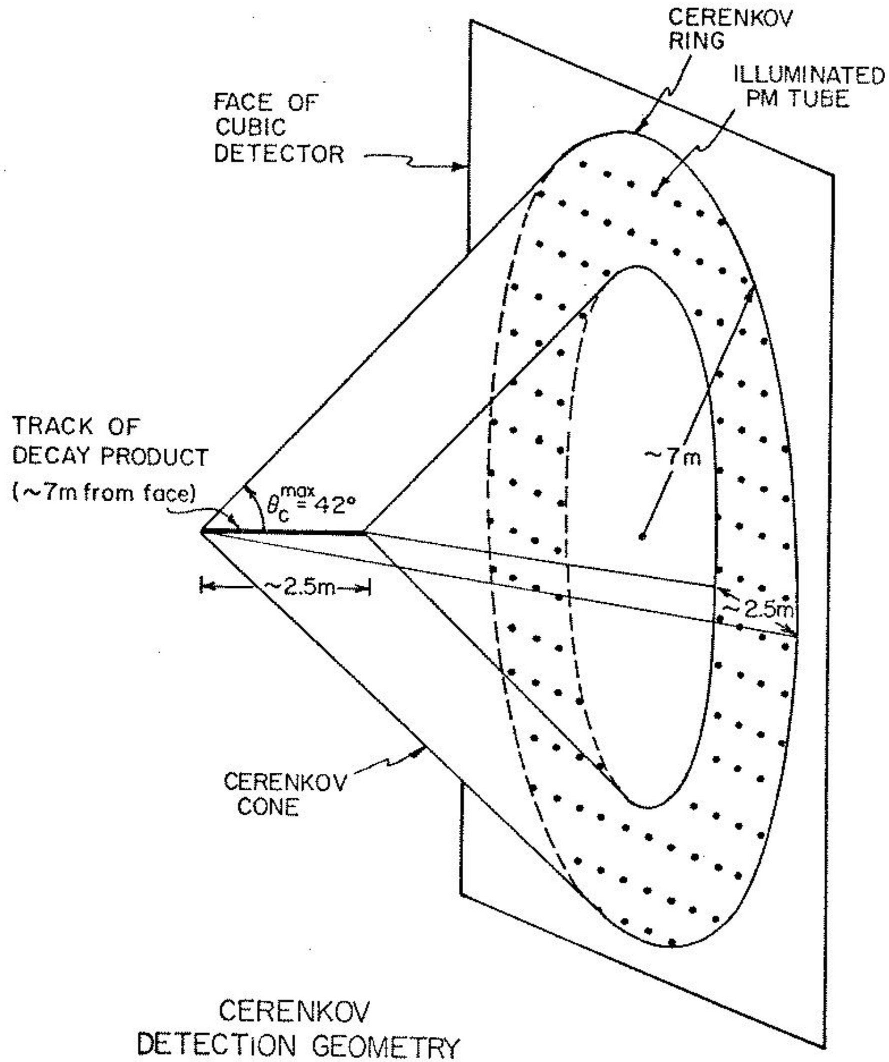


Fig. 2a

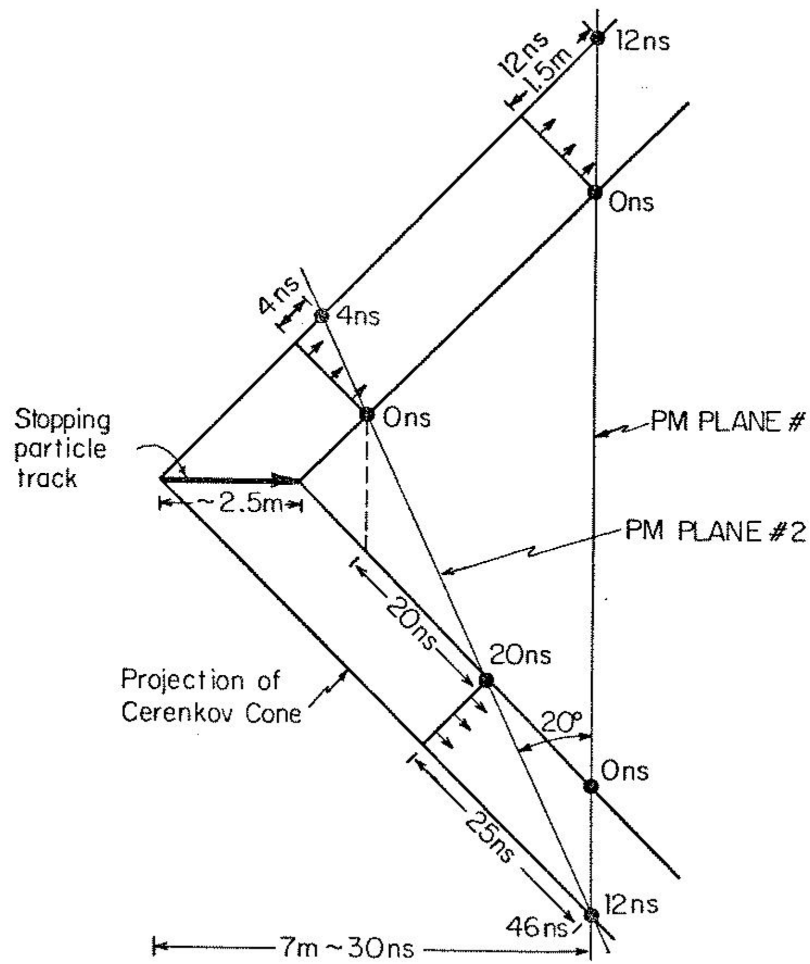


Fig. 2b

Proc. Seminar on Proton Stability, Madison, 1978.

Cortez's simulation of tracks in Dec '78 paper ...

Monte Carlo showing $p \rightarrow e + \pi^0$ event.

Cherenkov rings hit 6 faces of PMs.

Vertex & track angle reconstruction require PM timing resolution to a few ns.

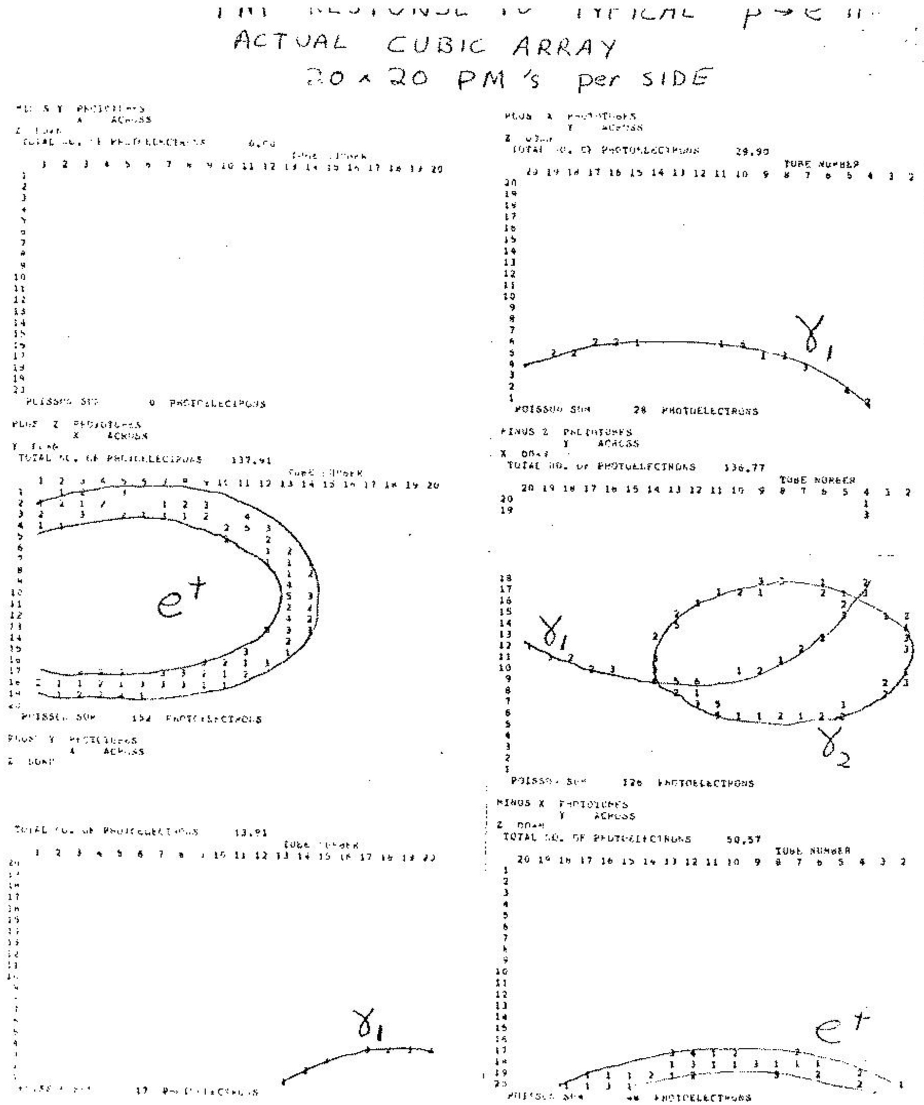


Fig. 3d

Proc. Seminar on Proton Stability, Madison, 1978.

How much light do we need to reconstruct 1 GeV events?
...at \$250 each, PMs a cost driver.

High quantum efficiency bialkali photocathode ~20%.

Single photoelectron detection critical to maximize # of pixels.

1 GeV signal (*e.g.* $p \rightarrow e^{+}\pi^{0}$) requires ~ 200 photoelectrons for

- sufficient energy resolution
- neutrino recognition
- background rejection
- detecting decay modes with less light

Phototube coverage of surface >1%.

Detector size requires transparency > 30m at 300-500 nm.

'78 Madison

Winter/Spring 1979:

Moving from paper to finding a site, creating a team, getting funded.

The site:

1) Park City mine, advocated by Carlo & Cline — Worstell PhD

Their goal: Megaton, reflective walls, calorimetry only, timing difficult

2) Morton Salt Mine, east of Cleveland; Reines recent occupant — Mme Wu's

First team addition:

New colleagues at Ann Arbor, Sinclair & van der Velde. — Now 13

Funding:

IMB Letter of Intent to DOE February '79, deClined (bless his departed soul)!

Maurice Goldhaber, feeling proton decay "in his bones," says >10^{26} year lifetime.

Wise, incredibly supportive "Director" of BNL:

"Larry, you make the choice…I'll go where you go."

Second team addition:

Get Reines on board, and off to Cleveland.

Feb '79 LOI to DOE dismissed...but theorists to the rescue!

We owe it to the Standard Theory makers:

Asked each for help, they obliged with letters to DOE.

Shelly Glashow

Abdus Salam

Steve Weinberg

Shelly & Steve had witnessed development at Harvard.

May 1979: IMB submits updated proposal, DOE reconsiders.

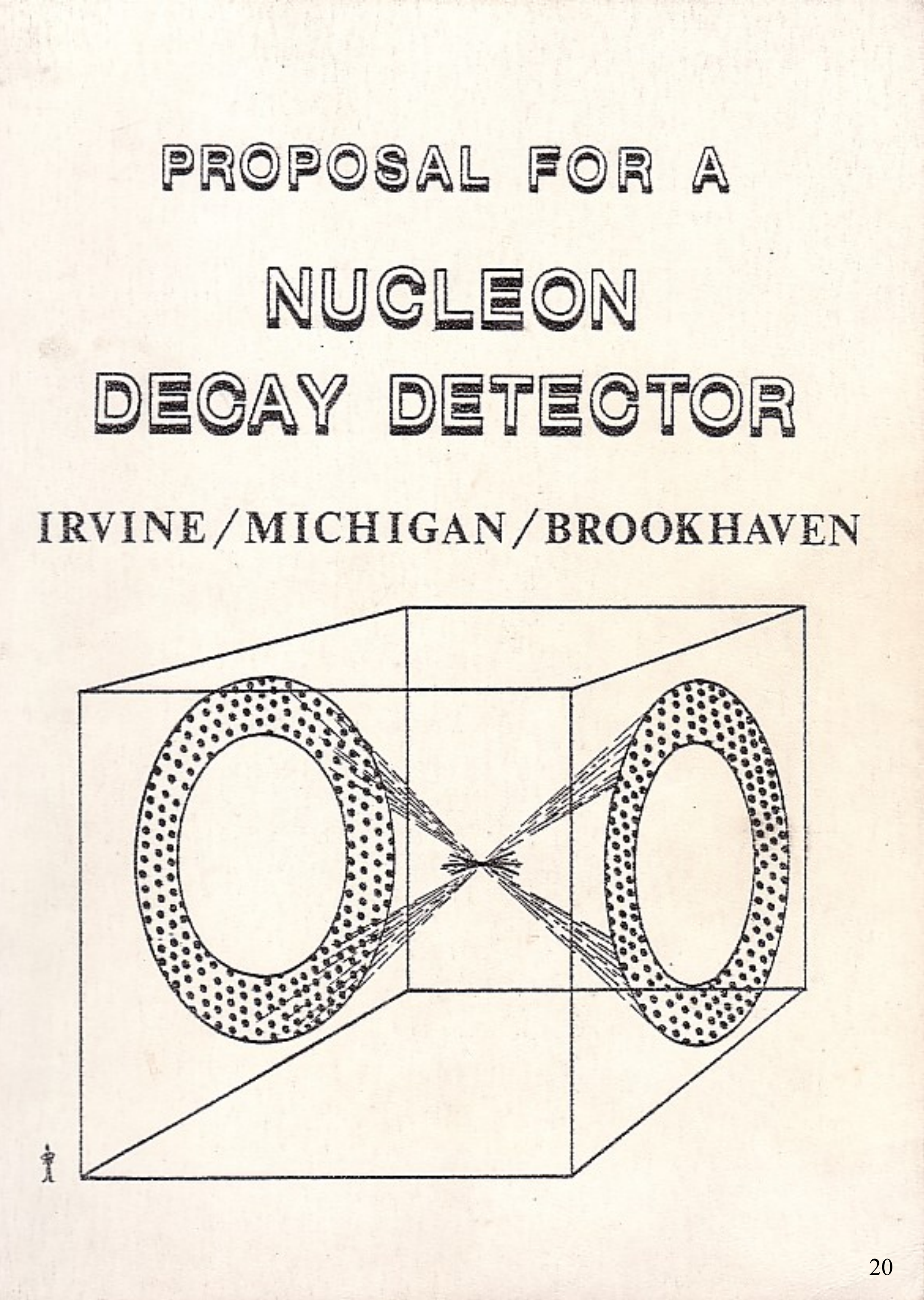
May '79 Proposal:

Includes

proton decay,
neutrino oscillations,
supernova.

Approved...but ½ funding!

Note man scaled to size:



The DOE funding decision...

IMB the "primary" detector, 10 kT,

given half (insufficient) funding, \$2M.

Shelly to the rescue: convinces new president of U of Michigan to provide \$1M in seed money!

HPW given funding to continue at 1 kT size (saving sweet Carlo).

A struggle to keep Harvard PhD students on the project:

"Excommunicated" by Carlo

But condensed matter faculty to the rescue

Cortez & Foster continue with local CM co-advisors & LRS at University of Michigan, as project moves to U of M.

1st DOE funding for a major non-accelerator project!

The US competition in '79: HPW, a volume array of PMs
...vs. a surface array, lights up twice as many PMs:

More hit PMs in surface array means:

Better track reconstruction.

Better background rejection.

Reflected light in volume array:

Increases total light collected, but

Confuses the track reconstruction,

Destroys directionality.

Even first photons hit ½ as many PMs.

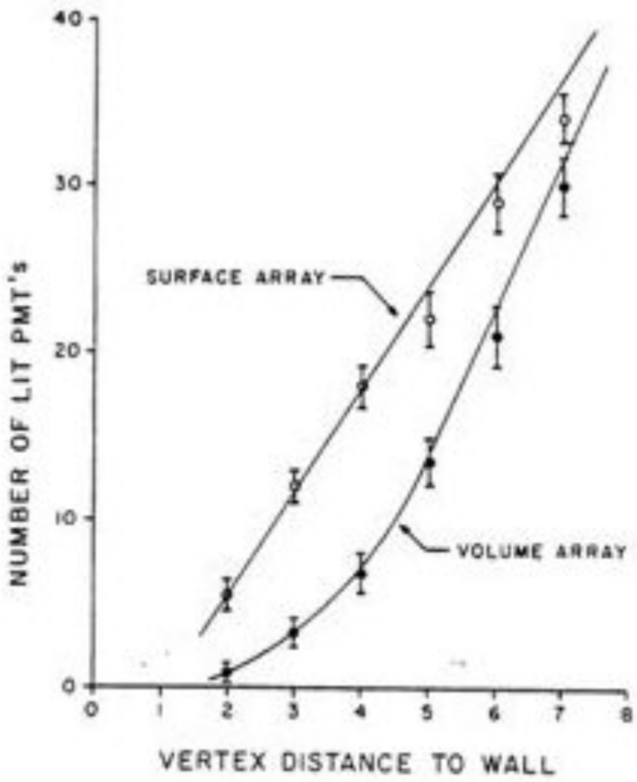


Figure 2-5 Number of PMT's lit by a 500 MeV non-showering track as a function of distance to wall in a mirrorless surface (volume) array with 1350 8" 2π (3π) PMT's. Smooth curves are analytic calculations. Points are the simulation.

IMB Proposal to DOE, 1979.

Also in the proposal: Electronics design...

Fine granularity time scale: 1 nsec resolution
for position & direction reconstruction.

Course time scale: 10 nsec resolution for muon
decays.

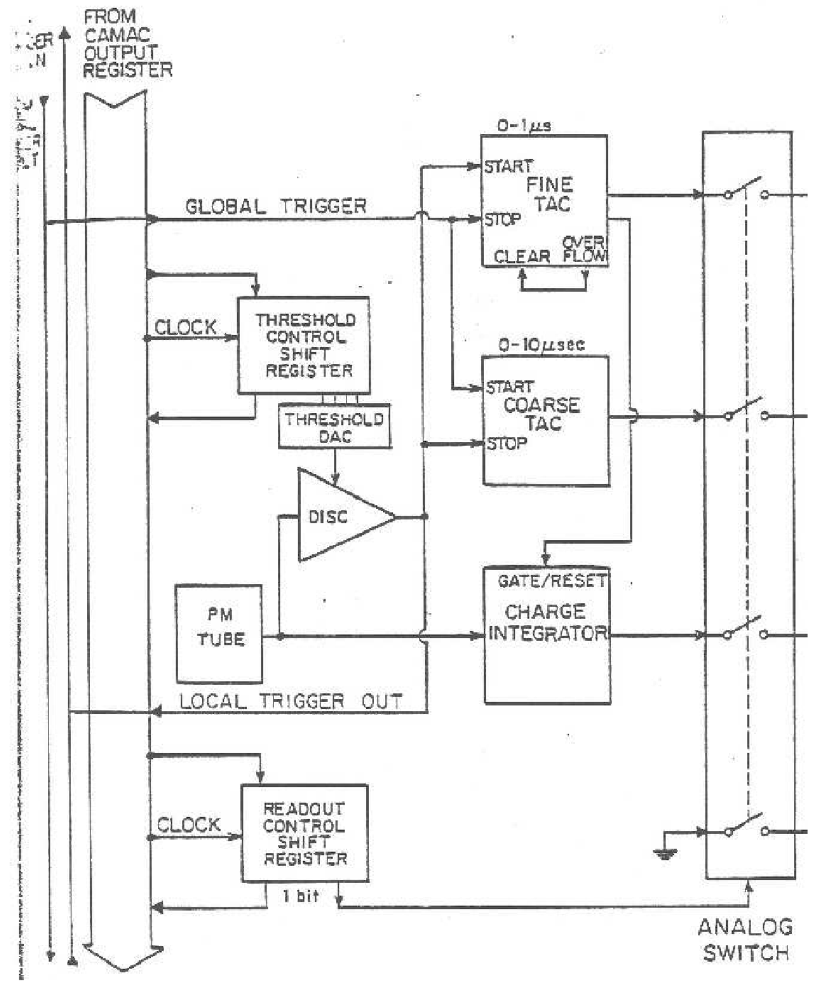
Fine time scale:

measured from photon arrival to trigger time.

Coarse time scale:

measured from trigger until muon decay.

Charge integration on first pulse.



'79 IMB DOE Proposal

Engineered by Foster & Weedon

Details of IMB proposal presented here in Scandinavia, at Bergen, Neutrino '79, June:

Challenge: understand atmospheric neutrinos, the limit to proton decay sensitivity.

AEV 5065

PROCEEDINGS OF NEUTRINO 79,

international conference on neutrinos,

weak interactions and cosmology.

Bergen June 18–22 1979.

Organized by the University of Bergen and Nordita.

Sponsored by European Physical Society.

Volume 2.

Editors
A. HAATUFT
C. JARLSKOG

A NUCLEON DECAY SEARCH: DESIGN OF A NEW EXPERIMENT SENSITIVE TO A LIFETIME OF 10^{33} YEARS#

M. Goldhaber
Brookhaven National Laboratory, Upton, New York

B. Cortez, G. Foster, J. LoSecco* and L. Sulak*
Harvard University, Cambridge, Massachusetts

W. Kropp, J. Learned, F. Reines, J. Schultz and H. Sobel
University of California at Irvine, Irvine, California

D. Sinclair and J. Vander Velde
University of Michigan, Ann Arbor, Michigan

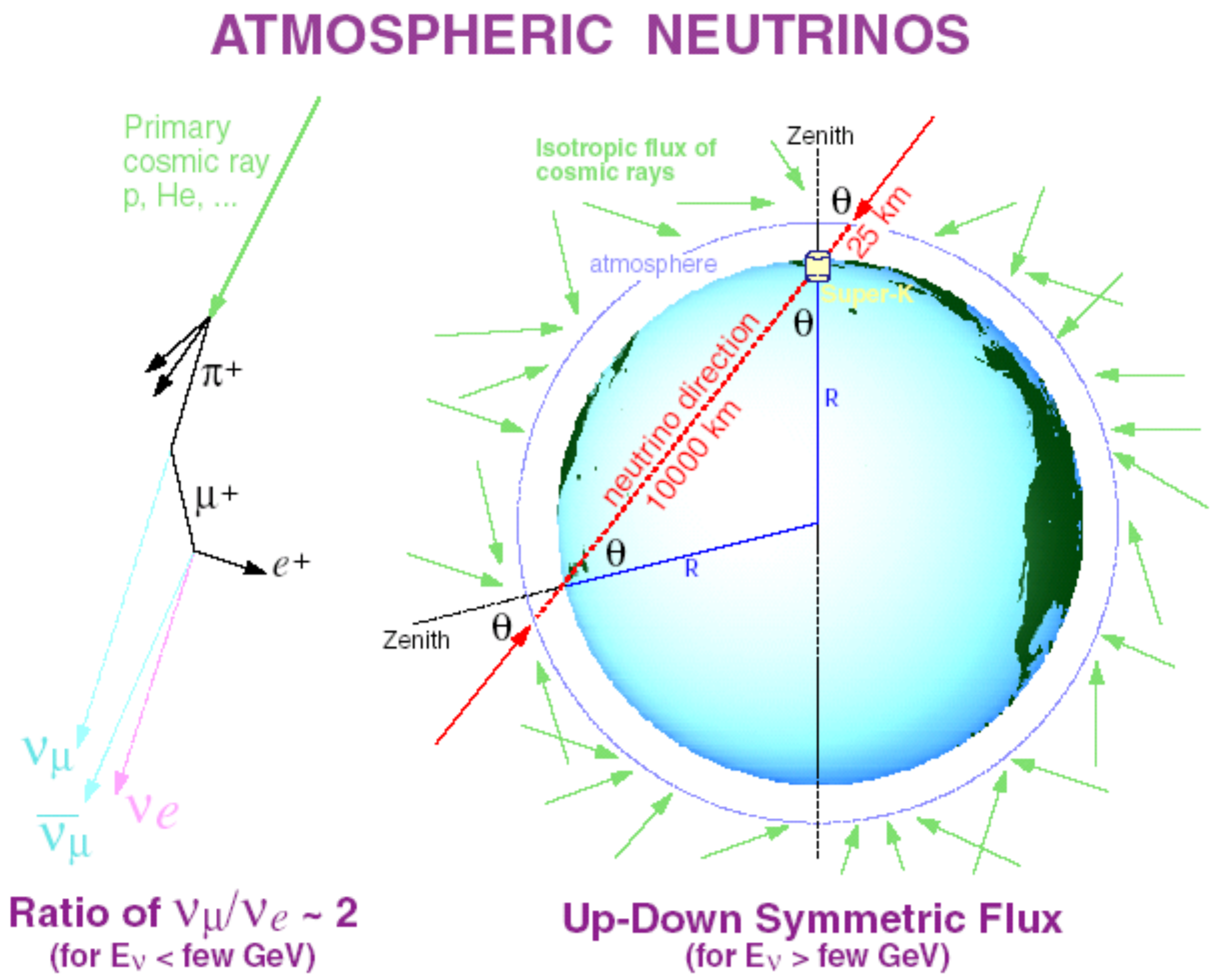
R. March+
University of Wisconsin, Madison, Wisconsin

Abstract

We have studied the properties of, and the expected backgrounds in, a totally active 10,000 ton water Cerenkov detector located deep underground and sensitive to many of the conjectured decay modes of the nucleons in it. Identification of π, μ and e, γ secondaries, good energy resolution, and good angular resolution provide sufficient background rejection in a proposed detector to permit one to obtain significant information about several decay channels, should they be observed. If no events were recorded in the device in one year, a lower limit of $\sim 10^{33}$ years would be placed on the partial lifetime for the most distinct nucleon decay modes. Depending upon the decay channel, this is $\sim$ 3 orders of magnitude longer than previous measurements, and is at or beyond the level suggested by many unifying theories. The sensitivity predicted for this instrument is within an order of magnitude of that achievable in an arbitrarily large detector of this general type, since known background from atmospheric neutrinos imposes an inherent limit.

presented by L. Sulak

How would IMB search for the signature of oscillating neutrinos?



Recent graphics from E. Kearns, Super-K.

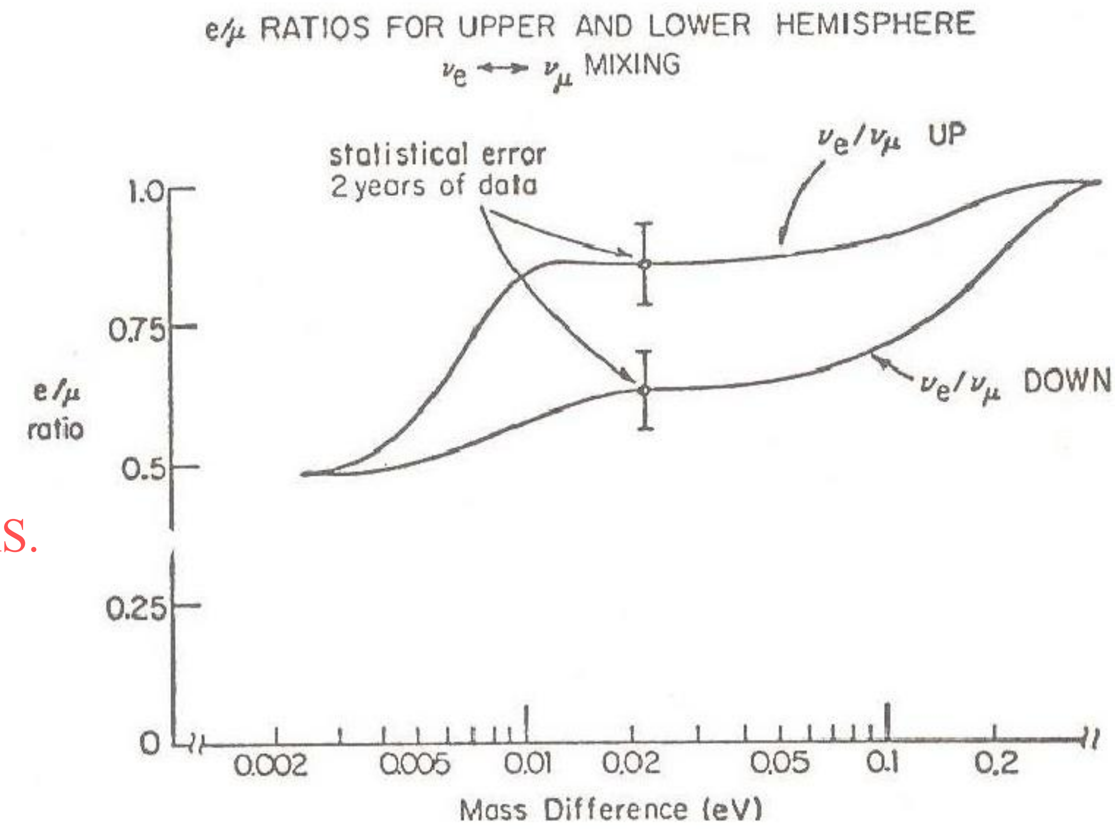
Atmospheric neutrino e/μ ratio the key to oscillations, 1980:

Simulate oscillations:

atmospheric neutrinos give

up/down asymmetry

Detailed calculations by Cortez & LRS.



Proc. of Neutrino '80, LRS.

Proc. of First Workshop on Grand Unification, LRS, 1980.

Details of IMB sensitivity to neutrino oscillations published...

LIE GROUPS: HISTORY, FRONTIERS AND APPLICATIONS

VOLUME XI

FIRST WORKSHOP ON GRAND UNIFICATION

New England Center
University of New Hampshire
April 10–12, 1980

Editors
Paul H. Frampton
Sheldon L. Glashow
Asim Yildiz

MATH SCI PRESS
1980

THE IRVINE-MICHIGAN-BROOKHAVEN* NUCLEON DECAY FACILITY:
STATUS REPORT ON A PROTON DECAY EXPERIMENT
SENSITIVE TO A LIFETIME OF 10^{33} YEARS
AND
A LONG BASELINE NEUTRINO OSCILLATION EXPERIMENT
SENSITIVE TO MASS DIFFERENCES OF HUNDREDTHS
OF AN ELECTRON VOLT

L. Sulak**
Randall Laboratory
University of Michigan
Ann Arbor, Michigan 48109

Abstract

We have studied the properties of, and the expected backgrounds in, a totally active 10,000 ton water Cerenkov detector located deep underground and sensitive to many of the conjectured decay modes of the nucleons in it. Identification of (π,μ) and (e,γ) secondaries, good energy resolution, and good angular resolution provide sufficient background rejection in the detector under construction to permit one to obtain significant information about several decay channels, should they be observed. If no events were recorded in the device in one year, a lower limit of $\sim 10^{33}$ years would be placed on the partial lifetime for the most distinct nucleon decay modes. Depending upon the decay channel, this is ~ 3 orders of magnitude longer than previous measurements, and is at or beyond the level suggested by many unifying theories. The sensitivity predicted for this instrument is within an order of magnitude of that achievable in an arbitrarily large detector of this general type, since known background from atmospheric neutrinos imposes an inherent limit.

We also detail the capabilities of a search for neutrino oscillations sensitive to low energy atmospheric ν_e's and ν_μ's using as a baseline the diameter of the earth. A flux independent asymmetry in the up/down ratio of the two neutrino species is the primary signal. The full 10,000 water Cerenkov detector is necessary; smaller detectors would have insufficient statistical power. For a two year exposure, the detector provides a several standard

*Supported in part by the U.S. Department of Energy. The members of the collaboration are the following: M. Goldhaber, Brookhaven National Laboratory; B. Cortez, G. Foster, L. Sulak, Harvard University and the University of Michigan; C. Bratton, W. Kropp, J. Learned, F. Reines, J. Schultz, D. Smith, H. Sobel, C. Wuest, Univsity of California at Irvine; J. LoSecco, E. Schumard, D. Sinclair, J. Stone, and J. Vander Velde, University of Michigan.

Summary of IMB detector design, pioneered in '78 & '79,
many elements used by later experiments:

Reverse osmosis to achieve long transparency water — Culligan & US Navy
- Use of only nylon & PVC to maintain transparancy

Hemispherical photomultipliers — EMI 5", Hiruma 8"
- Isochronous — Learned
- Pressure tolerant, operational underwater to 3 atm — Bridgman
- Nanosecond time resolution
- Performance at single photoelectron level

Deadtimeless electronics — Foster, Hazen
- ¼ photoelectron threshold
- Two time scales:
  - nano-sec, for directionality with 20 m baseline
  - micro-sec, for identification of muon decay electrons

Event Simulation — Cortez, LRS
- Timing & pattern recognition sufficient for PDK to SUSY
- Neutrino oscillation sensitivity.

Event display, time & pulse height encoding with joystick — Shumard

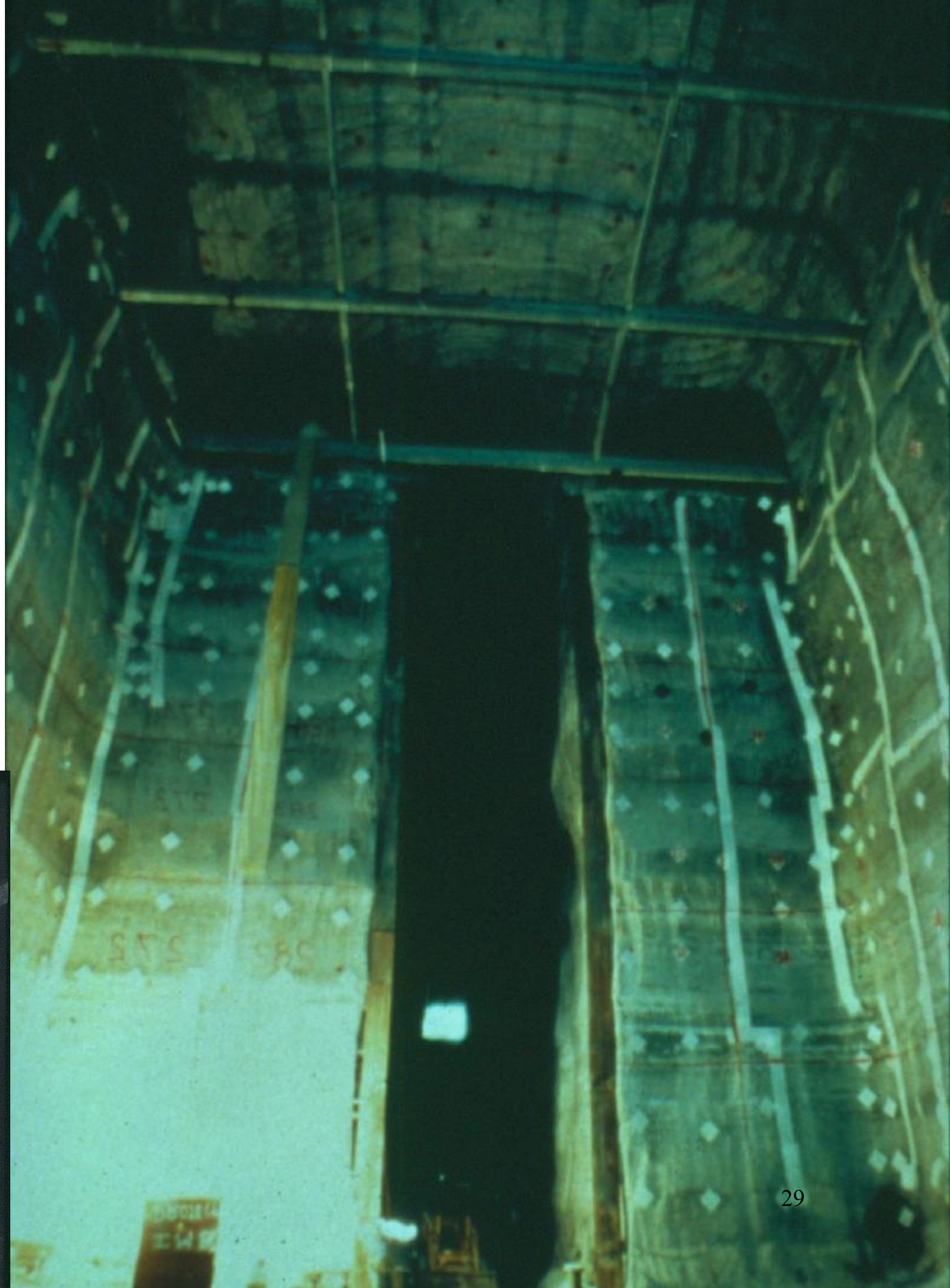
Calibration: 337 nm nitrogen laser for pulse height, — Strait
- with log attenuator & isotropic Ludox diffusing ball — Bionta
- Isotropic LED ball with avalanche photodiodes for timing — Lessure

IMB cavity in 1979 (left):
...excavator (below)

Roughly a 20 m cube.

Limited by the maximum width supportable in salt.

Mechanical miner...no explosives, no faults in salt, >10 year lifetime.



The "disco" room at Michigan, a scaled mockup of IMB with 100 PMs before installation...

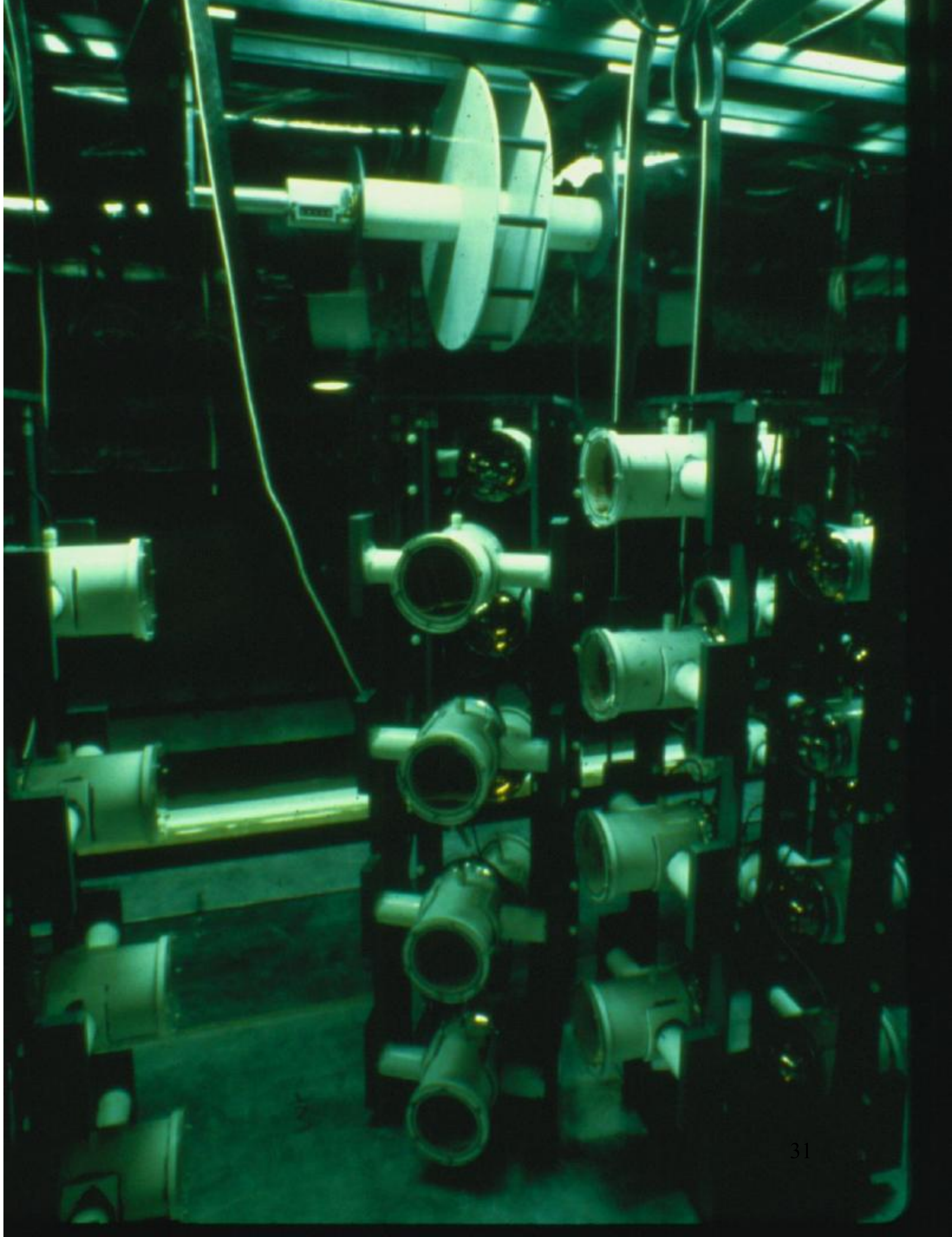
evaluating response to PDK & neutrinos simulated with 1) LED & 3) Ludox laser ball.

At the IMB mine,

PMs on catwalk...
before being dunked.

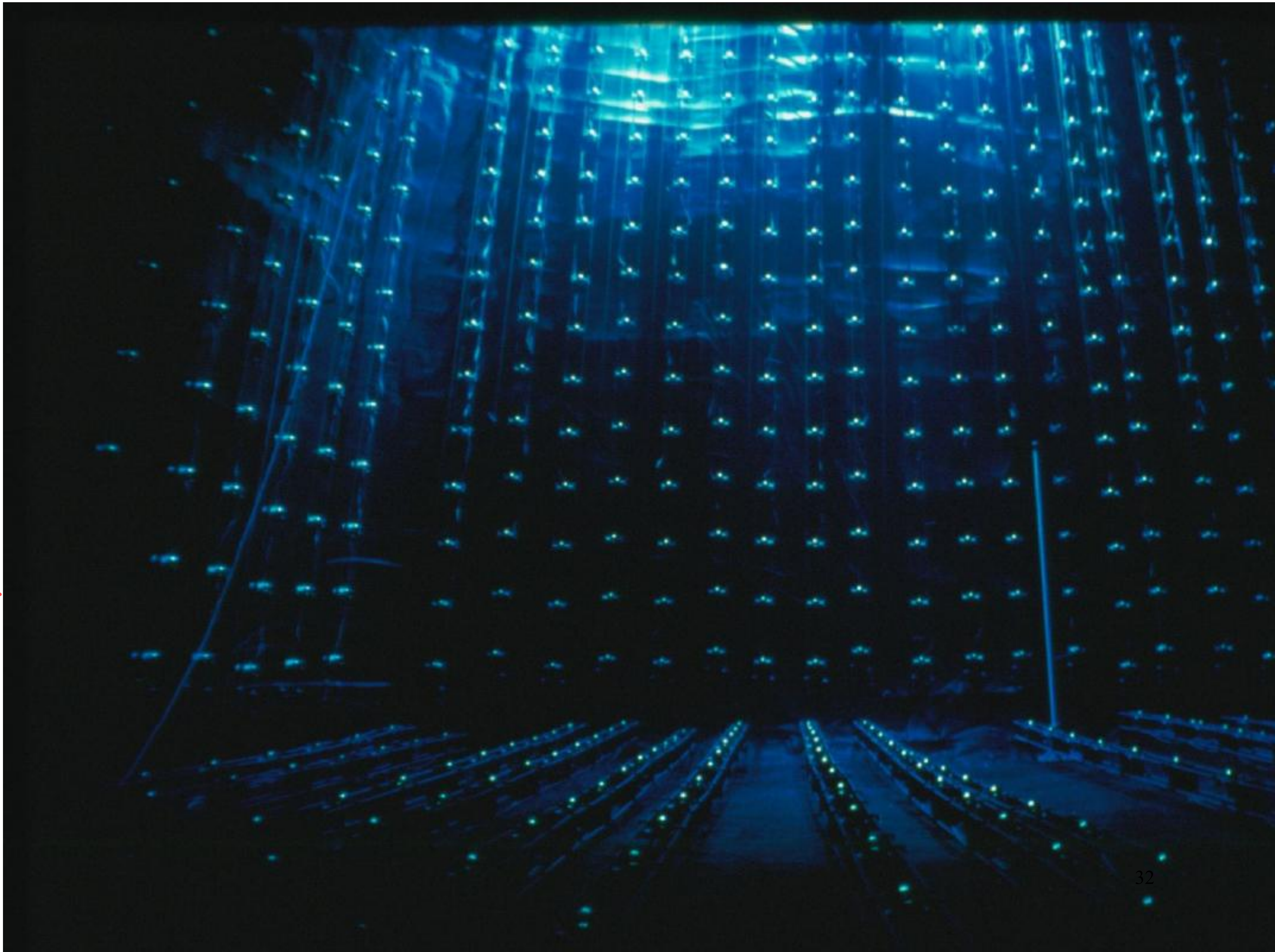
Deployed from reel,
single cable suspension,
carrying HV in
& signal out.

Only nylon & PVC
in contact with RO water.



Fall '81 IMB–1, 2048 5'' PMs, 1 m spacing, 2 m fiducial, 1% PM coverage.

...but
RO water
leaches
sodium
from
glass!



...forcing us to replace 5” EMI PMs with 8” Hamamatsu, reverse engineered by then.

3 generations of IMB transducers...& IMB (& Super-K) Electronics:

(with DUMAND 15” optical module)

IMB-1: 5” PM

IMB-2: 5” PM + Wavelength Shifting plate

IMB-3: 8” PM + Shifter plate (not shown)

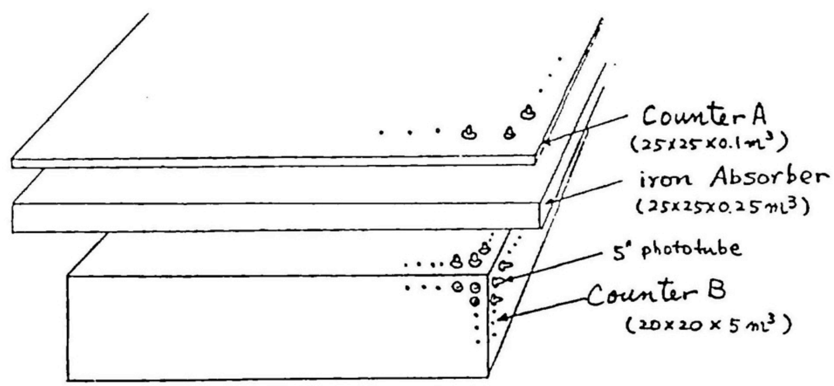
IMB-3: 2048 8" hemispherical phototubes with waveshifting light collectors

…plus diver/physicist in dry suit in 10 kilotons of world's purist water.

Errede

Meanwhile, Feb '79, Competition #2...
...the Kamioka proposal:
3 layers: scintillator, iron & water

Fig 3. The detector considered



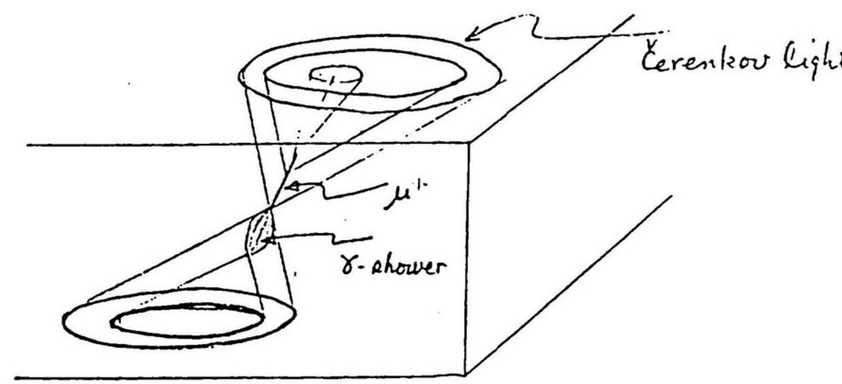
a) Single 10 cm sheet of scintillator as cosmic muon veto on top.

b) Dead iron slab.

c) 5m thick Cherenkov layer.

High photocathode coverage, > 10%.

Fig. 4 $p \to \mu^+ \gamma$ decay in the detector B.



Watanabe *et al.*, Proc. Conf. Unified Theories & Baryon Number, 1979.

Kamioka changes technology, credits LRS:

" ~1/3 as many PMs needed...his proposal very practical."

After this talk was typed as requested by the organizers of the workshop, I came across with a paper by L. Sulak,[14] who describes a very similar detector backed up with Monte Carlo simulation. One important point there is that the number of photomultipliers necessary can be as few as 3000, ~1/3 of the number described here, which makes his proposal very practical. I was too conservative in this respect, and hope that this kind of experiment is carried out so that one has a clue to plan next generation

However, Kamiokande fails to mimic IMB in several critical ways:

No fast timing for track reconstruction & direction.

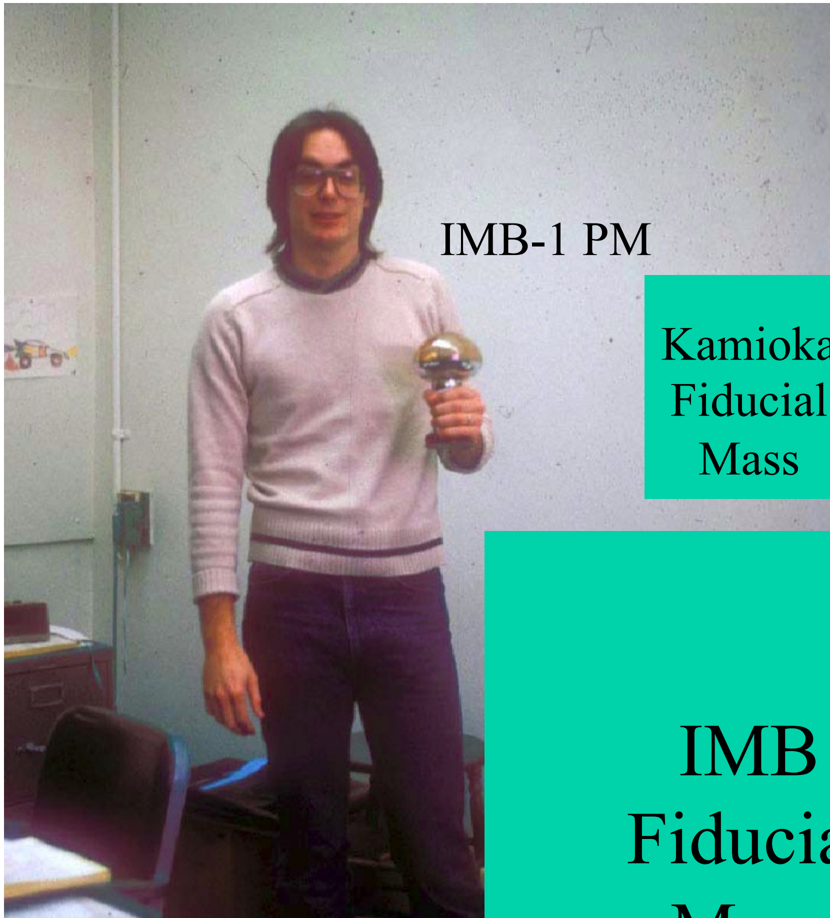
No μsec timing to identify muon decay; they rely totally on topology, with only pulse height info from big PMs.

No reverse osmosis filtering...radon in heavy metal mine a problem.

Only 1/9 the total volume...eventually requires an external veto.

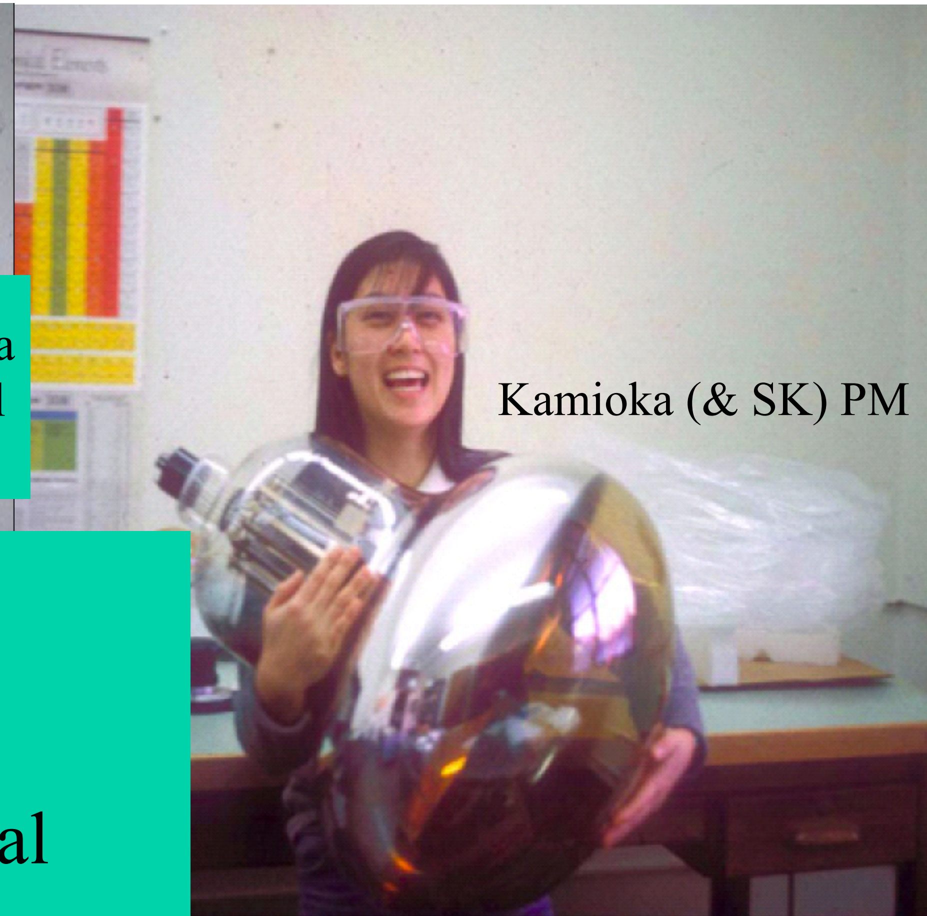
Watanabe *et al.*, Unified Theories & Baryon Number, 1979, p. 62.

PM evolution: Mr. Hiruma, President, Hamamatsu, deserves a prize for invention... using IMB Poisson code



IMB-1 PM

Kamioka Fiducial Mass



Kamioka (& SK) PM

IMB Fiducial Mass

Our Michigan grad students Shumard & Park

Kamioka I (1983-1986):

cylindrical cavity

1 kiloton fiducial (3 ktons total)

1000 PMs, 20 inch diameter

7 MeV threshold...
sufficient for solar ν's

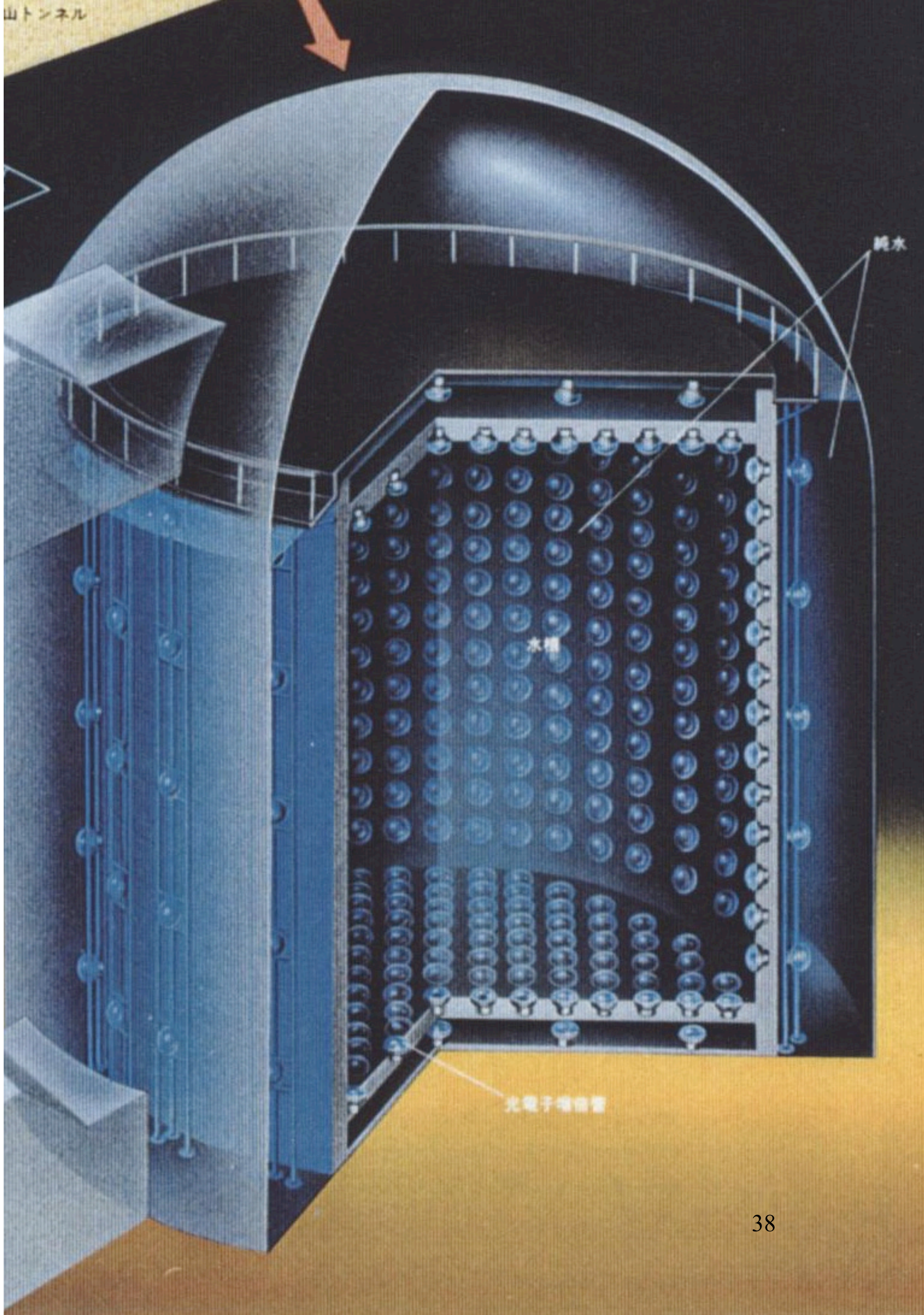
1 km deep *vs.* 0.6 km of IMB...
allowing them to see solar ν's
above oxygen spallation.

Kamioka II (> 1986):

123 PMs as anti-counter added.

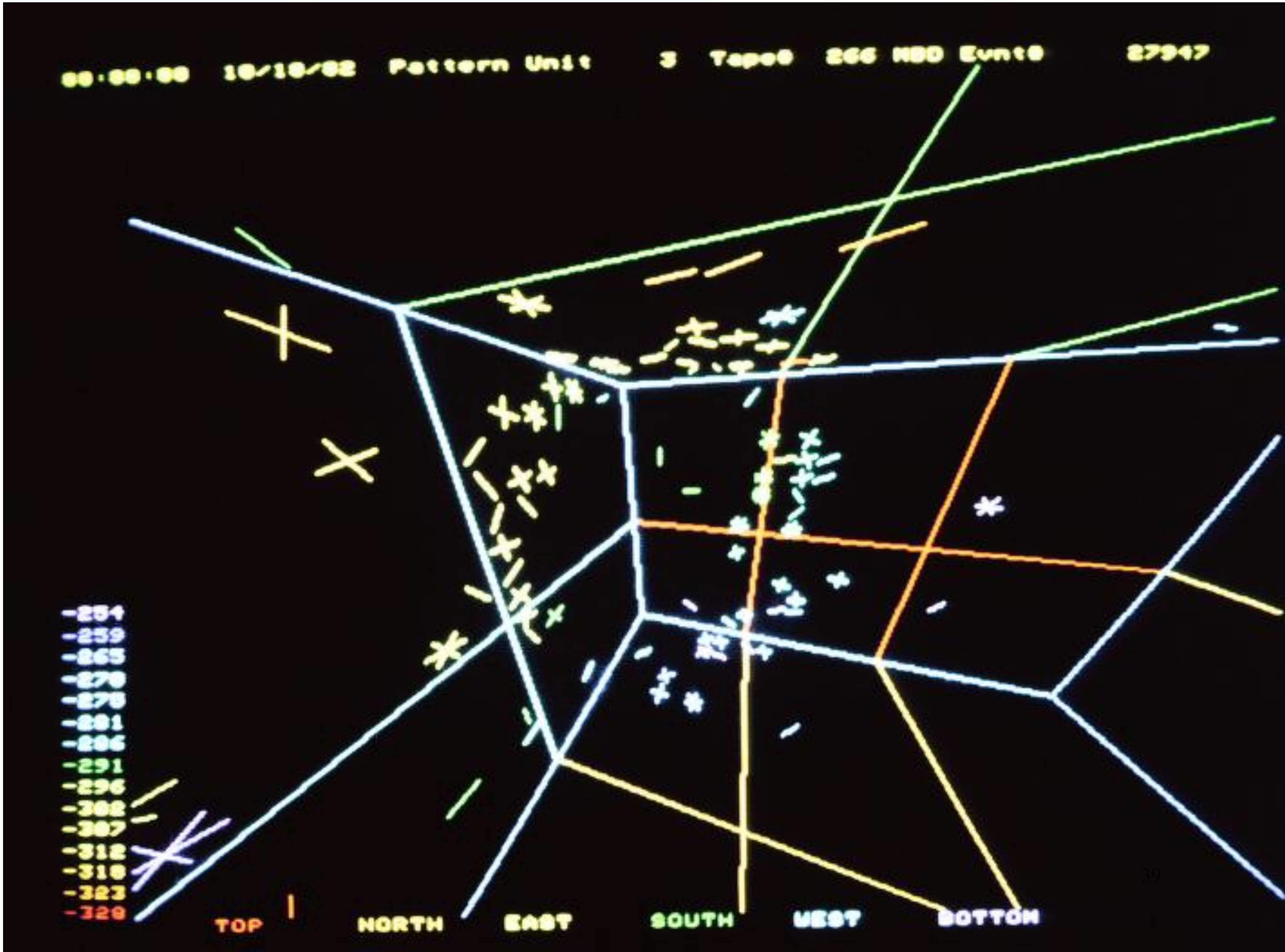
Cortez & Mann installed timing.

Reverse osmosis filtering added.



Back at IMB, 1 atmospheric ν event/day observed, as expected...viewed from vertex of Č ring.

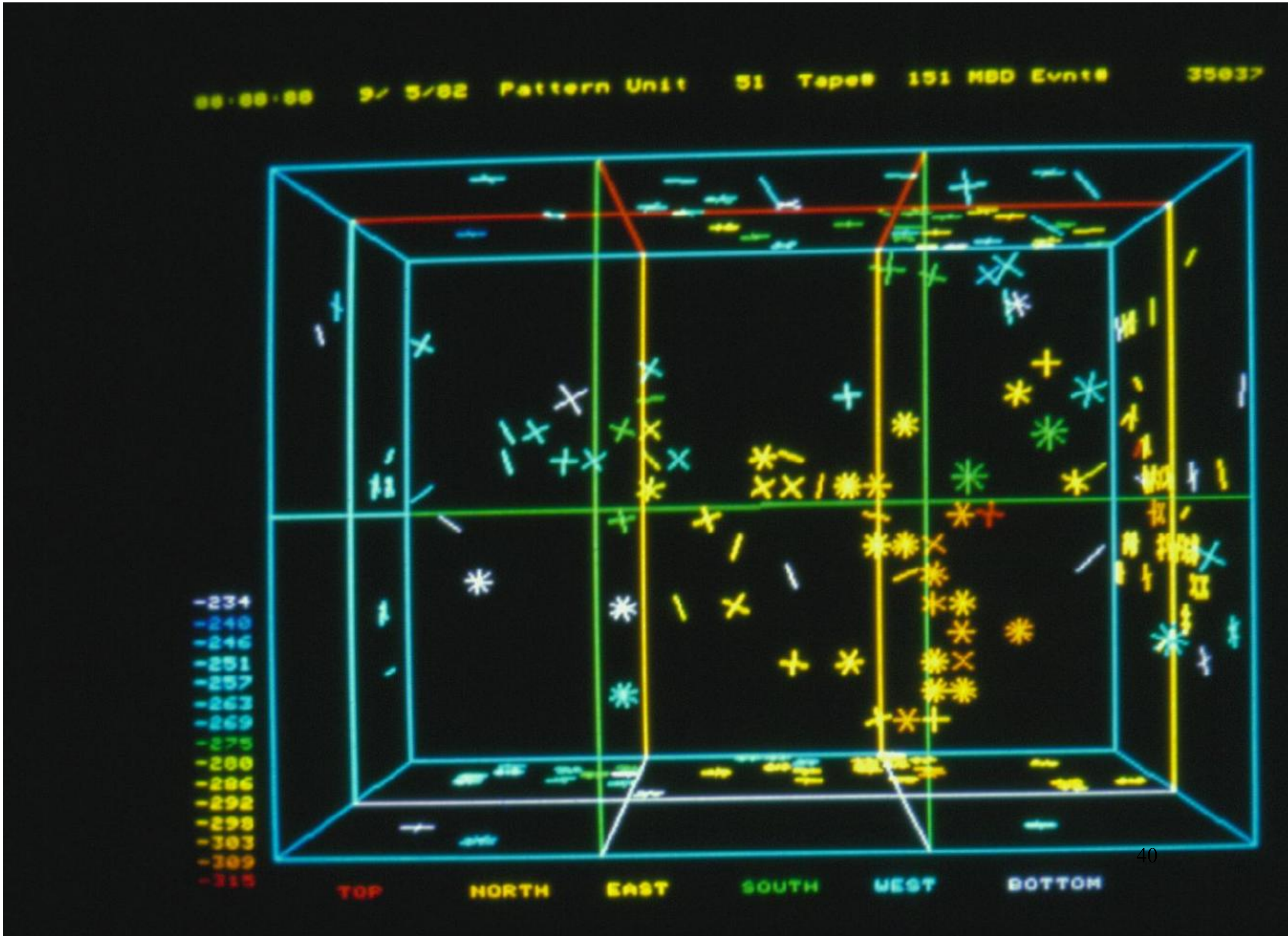
Pulse height encoded by # of slashes, 1 slash = 1 photoelectron; nice stopping muon:



...In contrast, "best" candidate for a back-to-back 2 track proton decay event...

Nanosecond timing color encoded: red early, blue late:

(a code that persists thru IceCube!)



That best PDK candidate: A muon Cherenkov ring on right, an indistinguishable shower on left...

...but the event is not back-to-back; no late timing signature, so an unlikely muon

First results,

< 4 years

from proposal:

Proton lives

> 10^{32} years,

SU5 not viable,

by a factor of 1000!

VOLUME 51, NUMBER 1 PHYSICAL REVIEW LETTERS 4 JULY 1983

Search for Proton Decay into $e^+\pi^0$

R. M. Bionta, G. Blewitt, C. B. Bratton, B. G. Cortez,[a] S. Errede, G. W. Forster,[a] W. Gajewski, M. Goldhaber, J. Greenberg, T. J. Haines, T. W. Jones, D. Kielczewska,[b] W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, P. V. Ramana Murthy,[c] H. S. Park, F. Reines, J. Schultz, E. Shumard, D. Sinclair, D. W. Smith,[d] H. W. Sobel, J. L. Stone, L. R. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

The University of California at Irvine, Irvine, California 92717, and The University of Michigan, Ann Arbor, Michigan 48109, and Brookhaven National Laboratory, Upton, New York 11973, and California Institute of Technology, Pasadena, California 91125, and Cleveland State University, Cleveland, Ohio 44115, and The University of Hawaii, Honolulu, Hawaii 96822, and University College, London WC1E 6BT, United Kingdom

(Received 13 April 1983)

Observations were made 1570 meters of water equivalent underground with an 8000-metric-ton water Cherenkov detector. During a live time of 80 d no events consistent with the decay $p \to e^+\pi^0$ were found in a fiducial mass of 3300 metric tons. It is concluded that the limit on the lifetime for bound plus free protons divided by the $e^+\pi^0$ branching ratio is $\tau/B > 6.5\times10^{31}$ yr; for free protons the limit is $\tau/B > 1.9\times10^{31}$ yr (90% confidence). Observed cosmic-ray muons and neutrinos are compatible with expectations.

PACS numbers: 13.30.Eg, 11.30.Ly, 14.20.Dh

We have built and operated a large water Cherenkov detector deep underground in order to search for nucleon decay. We have chosen as the initial goal of our experiment to look for proton decay to the final state $e^+ + \pi^0$. This two-body mode gives a clear back-to-back decay signature which is especially well defined and distinct from background in a water Cherenkov detector.

The simplest grand unified gauge theory, minimal SU(5), predicts a partial lifetime $\tau/B = 4.5 \times 10^{29\pm1.7}$ yr for the $p \to e^+\pi^0$ decay mode.[1] Therefore in our detector, after 80 d of exposure (2.4 $\times10^{32}$ proton yr), using $\tau/B = 2.2\times10^{31}$ yr, we expect to observe at least seven such events.

Previous searches for nucleon decay in iron at the Kolar gold fields[2] and the Mont Blanc tunnel[3] have reported a few candidate events tentatively ascribed to various modes of proton decay.

The Irvine-Michigan-Brookhaven (IMB) detector[4] is located at a depth of 1570 meters of water equivalent in the Morton-Thiokol salt mine east of Cleveland, Ohio. It consists of a large rectangular volume of purified water ($17\times 18\times 23$ m^3) viewed from its six faces by 2048 photomultiplier tubes (PMT), each of 12.5 cm diam, located on a rectangular grid of ~1 m spacing. The total sensitive volume of the detector is 8000 metric tons (tonnes) and the fiducial volume, inset by 2 m from the planes of the PMT's, is 3300 tonnes.

A relativistic charged particle traversing the detector produces a cone of Cherenkov light with a half-opening angle of 41° relative to its direction of motion. The particle continues to emit Cherenkov light until its velocity falls below 0.75c. The time of photon arrival and pulse height are recorded independently by each PMT, providing information which allows the reconstruction of position, direction, and energy of particles moving in the detector.

Two distinguishing characteristics of this detector are its large sensitive mass and its ability to determine unambiguously the sense of track direction. The uniform sensitivity of the active medium makes the energy resolution of the detector nearly independent of the fluctuations of electromagnetic shower development and Fermi motion of the decaying proton.

The resolution and absolute energy calibration of the detector in time, position, direction, and energy are evaluated by the use of programmable light sources in the detector volume and with cosmic-ray muons which penetrate or stop in the detector. The light sources have variable position, intensity, and firing time. They are also used to determine the attenuation length (> 30 m) for light in the wavelength region of interest (300–450 nm). Our system of PMT's and electronics is sensitive to light at the single photoelectron level.

The trigger threshold corresponds to the light output from a 50-MeV electron in the detector.[5] PMT's firing up to 7.5 μsec after the initial trigger are also recorded, providing identification of the electron from muon decay with 60% efficiency.

On the basis of the measured efficiency of PMT's and the geometry of our detector, computer event simulation predicts a signal from 170

But a big problem from the start.

We're missing muon neutrinos, not enough with $\mu \rightarrow e$ decay signature

There are 25 events out of 112 with an observed muon decay. The distributions of lit PMT's and the time of the coincidence are shown in figure 8-8. The observed ratio of 22 ± 4% is to be compared to the expected ratio of 33%,

Cortez PhD thesis, 1983

A SEARCH FOR NUCLEON DECAY INTO
LEPTON AND K°

A Thesis Presented
by
Bruce Gilbert Cortez
to
The Department of Physics
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy
in the subject of
Physics

Harvard University
Cambridge, Massachusetts
September, 1983

Work supported in part by the U.S. Department of Energy under contracts DE-AC02-76ER03064 at Harvard University and DE-AC02-76ER01112 at the University of Michigan.

Then 3 years trying to falsify the result...
searching for systematic detector problems...

Extensive studies of stopping muons.

Calibrations to check detector
response to muon decays.

3 independent models.

2 independent analyses,
East coast & west coast.

Including
muon polarization,
dead time,
after-pulsing,
phototube efficiency,
geomagnetic effects

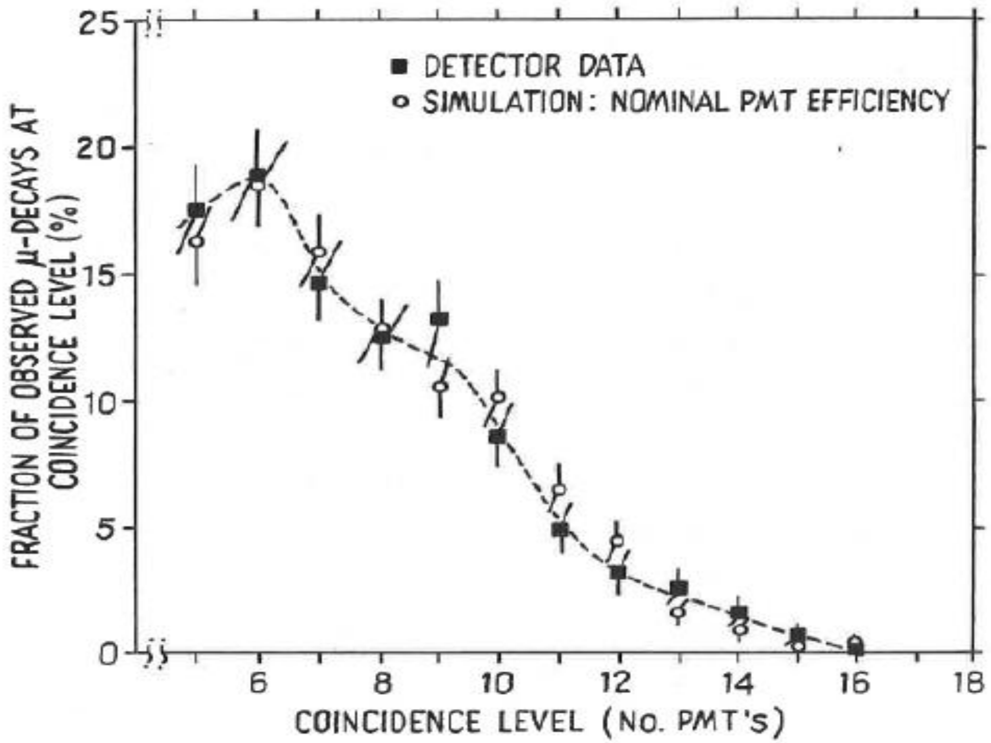


Figure IV-16. NPT distribution from muon decays as predicted by the simulation program using the nominal PMT firing efficiency as compared with the data from the detector. The dashed curve is a hand drawn 'fit' which is intended only as an aid in comparison with figure IV-17.

Shumard 1984 PhD Thesis

More tests of the "no neutrino oscillation" hypothesis...

Requiring a muon decay:

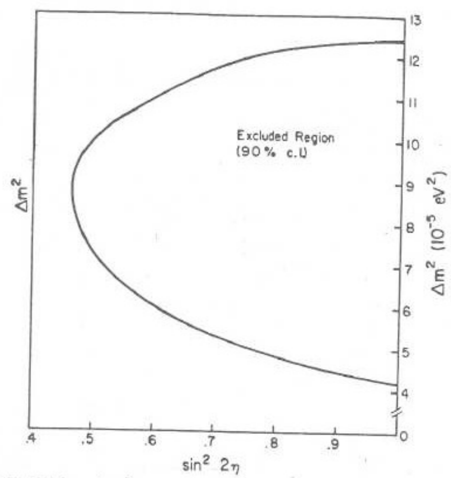


Figure 2. The excluded region for a test of ν_μ oscillations. This comes from a comparison of the energy distribution for muon containing single prong events in the upward and downward 1/5 of the solid angle.

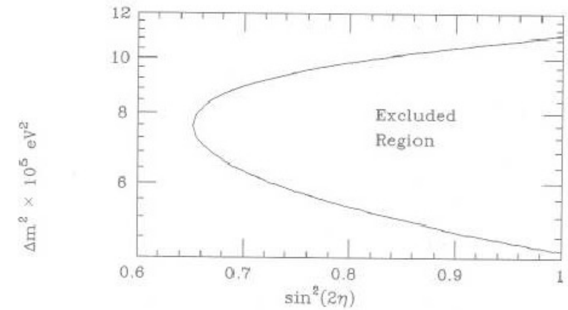


Figure 3: The region in Δm^2 and $\sin^2(2\eta)$ excluded by our analysis.

E/L comparison of data & simulation fits well:

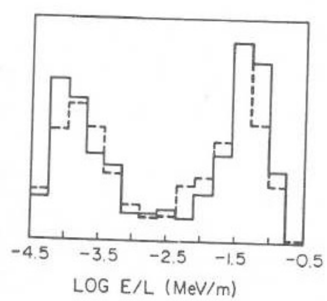


Figure 3. A comparison of the log (E/L) distribution with that predicted by theory (dashed curve). The good agreement supports the theory which includes geomagnetic modulation of the flux

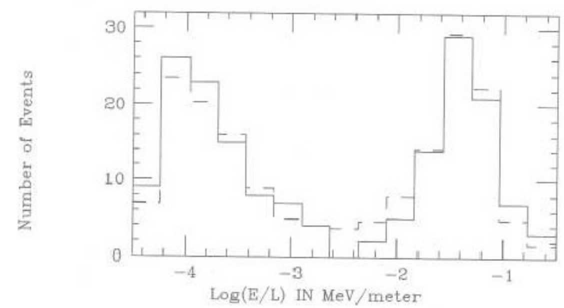


Figure 4: A plot of the number of muon neutrino events as a function of $\log(\frac{E}{L})$. The solid curve is data. The dashed curve is a Monte Carlo simulation.

ICRC meeting in San Diego 1985

IMB 3 data, with 8" PMs, same result.

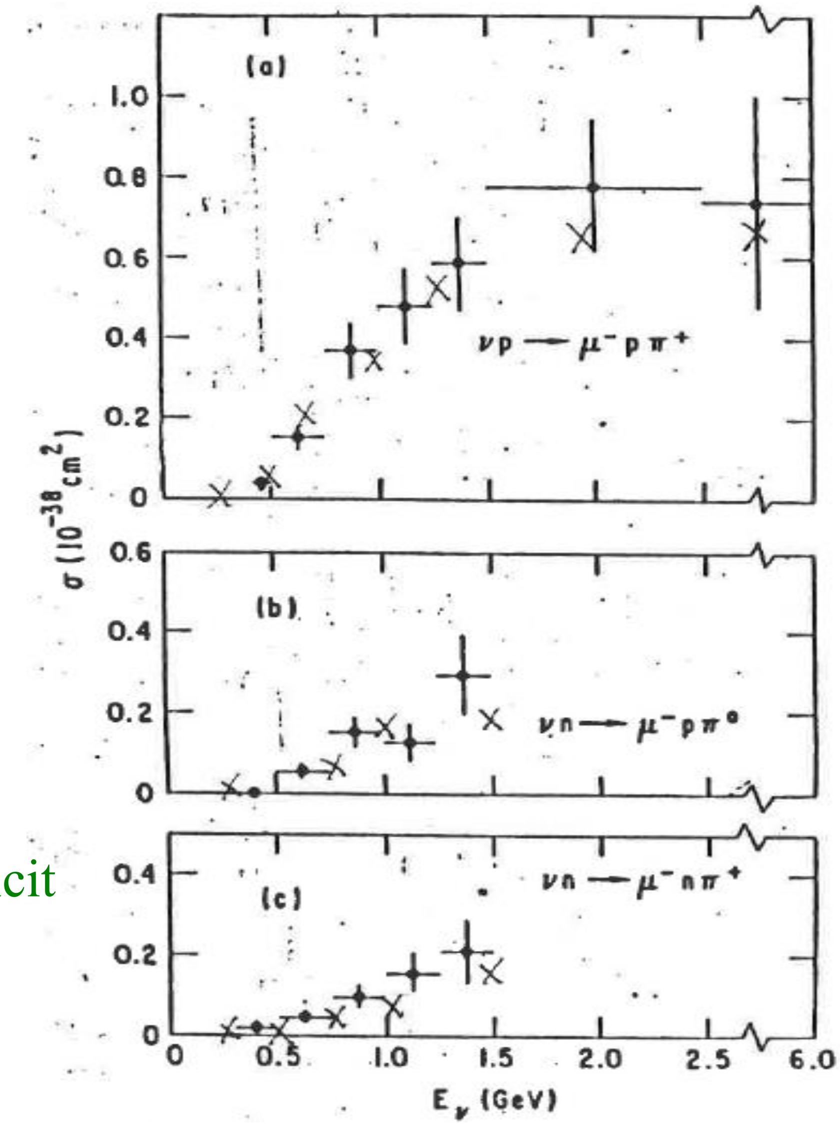
Reuse actual bubble chamber events for the simulation...

Model agrees well
with published neutrino data,

but the missing muon problem persists.

34 ± 1% expected muon fraction,
26 ± 2% observed muon fraction

8.0 ± 2.2% difference = a 3.6 sigma deficit



Simulation is marked by the x's, data by +'s.

We publish the "muon anomaly":
IMB sees only 75% of expected muon-neutrinos!

VOLUME 57, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1986

Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search

T. J. Haines, R. M. Bionta, G. Blewitt, C. B. Bratton, D. Casper, R. Claus, B. G. Cortez, S. Errede, G. W. Foster, W. Gajewski, K. S. Ganezer, M. Goldhaber, T. W. Jones, D. Kielczewska, W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, J. Matthews, H. S. Park, L. R. Price, F. Reines, J. Schultz, S. Seidel, E. Shumard, D. Sinclair, H. W. Sobel, J. L. Stone, L. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any ef-

...but Kamioka finds no muon anomaly!!! Kajita's PhD '86.
Sent LoSecco to alert them & try to find out why???

'86: Experimental results for electron to muon ratio?

Expected if no oscillations:

$n_e/n_m = 0.64$

Nusex reports

$n_e/n_m = 0.28 \pm 0.11$

Kamioka reports

$n_e/n_m = 0.36 \pm 0.08$

but IMB consistently gets

$n_e/n_m = 1.3$!!!

Most proton decay detectors have reported a neutrino flux as measured in their detectors[4,5,8,12]. In general the agreement with expected fluxes is good. Both the Kamioka detector[18] and the Nusex detector[4] can distinguish ν_e from ν_μ by shower development. They quote a ν_e/ν_μ flux ratio of 0.36 ± 0.08 and 0.28 ± 0.11 respectively. These are lower than the expected value[6] of 0.64. The IMB group has studied the fraction of their contained events resulting in a muon decay[8]. The 26% observed can be converted to a ν_e/ν_μ ratio with a number of assumptions about muon capture in water. If 40% of the ν_μ interactions do *not* result in a muon decay signal the observed value corresponds to $\nu_e/\nu_\mu \approx 1.3$.

The problem of the ν_e/ν_μ ratio is still under active study. There is no directional dependence of the muon rate.

February 1986 Lake Louise Meeting, LoSecco Review Talk

In 1986, how do Kamioka's neutrino distributions look?

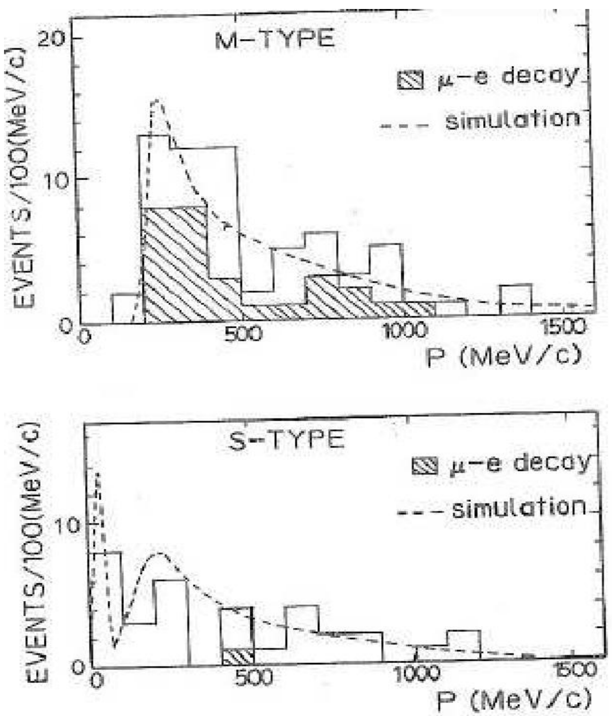


Fig. 20. The momentum distribution for M- and S-type single ring events. For M-type events, particles are assumed to be muons. The curves are the expectation of the neutrino Monte Carlo program. An excess in the distribution of S-type events at the low momentum is due to the decay electrons of invisible low energy muons produced by ν_μ and $\bar{\nu}_\mu$ interactions, corresponding to the dashed line in the Fig. 17.

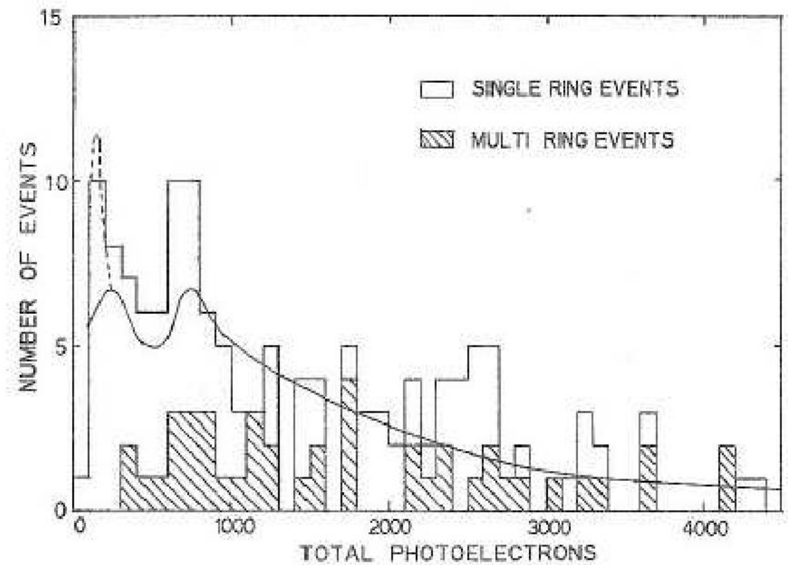


Fig. 17. The total photoelectron number distribution for the contained events. The histograms are the KAMIOKANDE data of 1.11 kton·years' exposure time. The solid and dashed lines are the calculated results of the neutrino Monte Carlo simulation. The dashed line includes the decay electrons of invisible low energy muons produced by ν_μ and $\bar{\nu}_\mu$ interactions. The peak at 700 p.e. is due to electrons produced by ν_e and $\bar{\nu}_e$. Note the comparison is absolute, i.e. no normalization has been made.

Kajita's PhD thesis, February 1986. "These figures indicate that the agreement between the data and the [non-oscillating] simulation is quite well."

His PhD thesis figures appear as Nakahata *et al.* J. Phys. Soc. Jpn. 55, 3786 (1986).

Muon and electron normalizations are absolute, not a fit to the data.

Comparison of M (muon) type [top] & S (electron) type [bottom] events.

Dashed curve is unnormalized to the expected value.

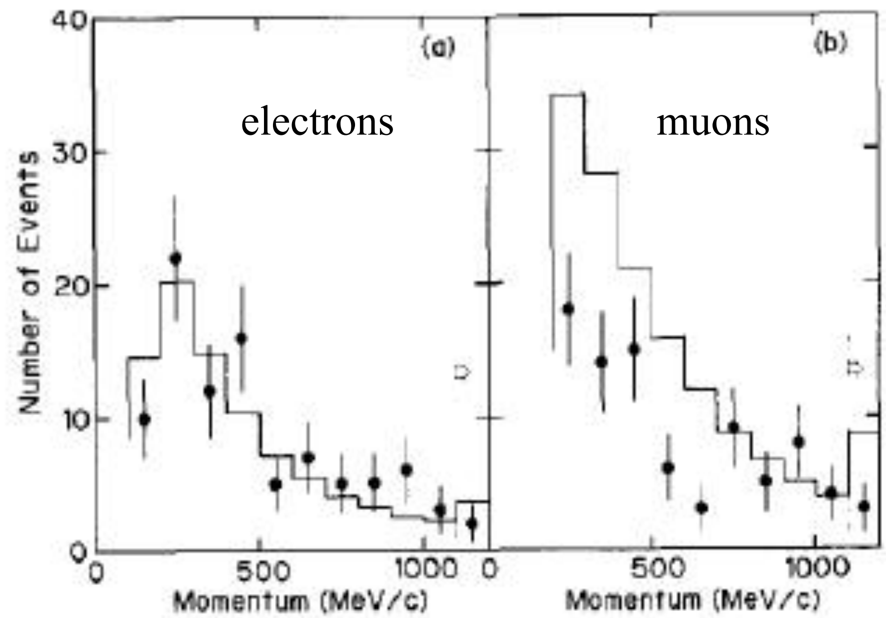
Finally, in '88, Kamioka confirms IMB result of 5 years earlier...

...after Cortez & Mann install muon decay timing.

Muon rate only 59 ± 7% of that expected for no oscillations.

They force their former Muon/Showering pattern recognition to agree with the muon decay rates.

Note the deficiency in the muon spectra:



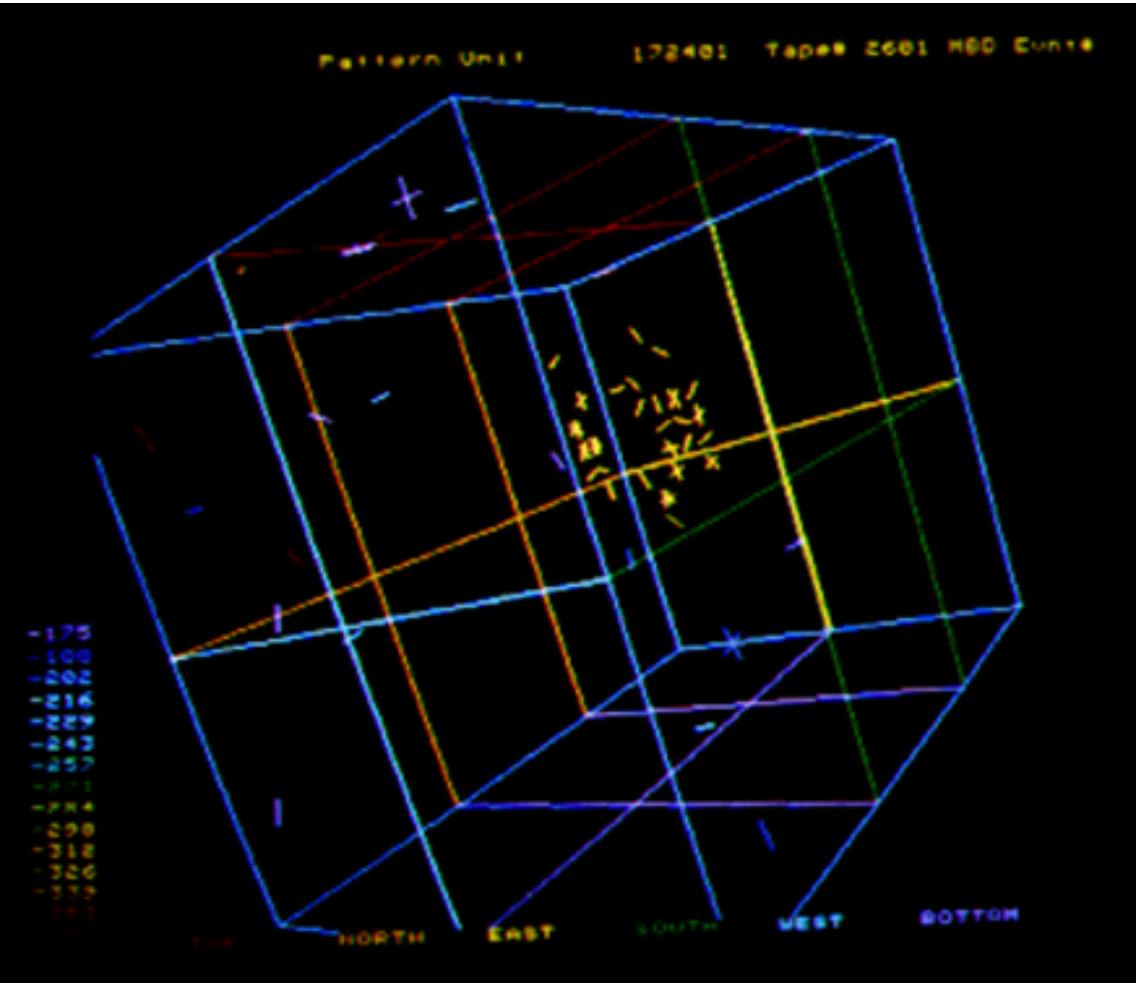
They cite IMB, quoting our published result:

The IMB experiment has not reported data in which electron-like and muon-like events are distinguished, but it has reported [10] that the fraction of observed events manifesting muon decays is 26±3%, while their Monte Carlo simulations predict that 34±1% of all events should exhibit muon de-

K.Hirata *et al.,* Phys. Lett 205, 416 (1988)

Then…at 07:35:35 UT…bam…b-bam bam bam…8 times in IMB

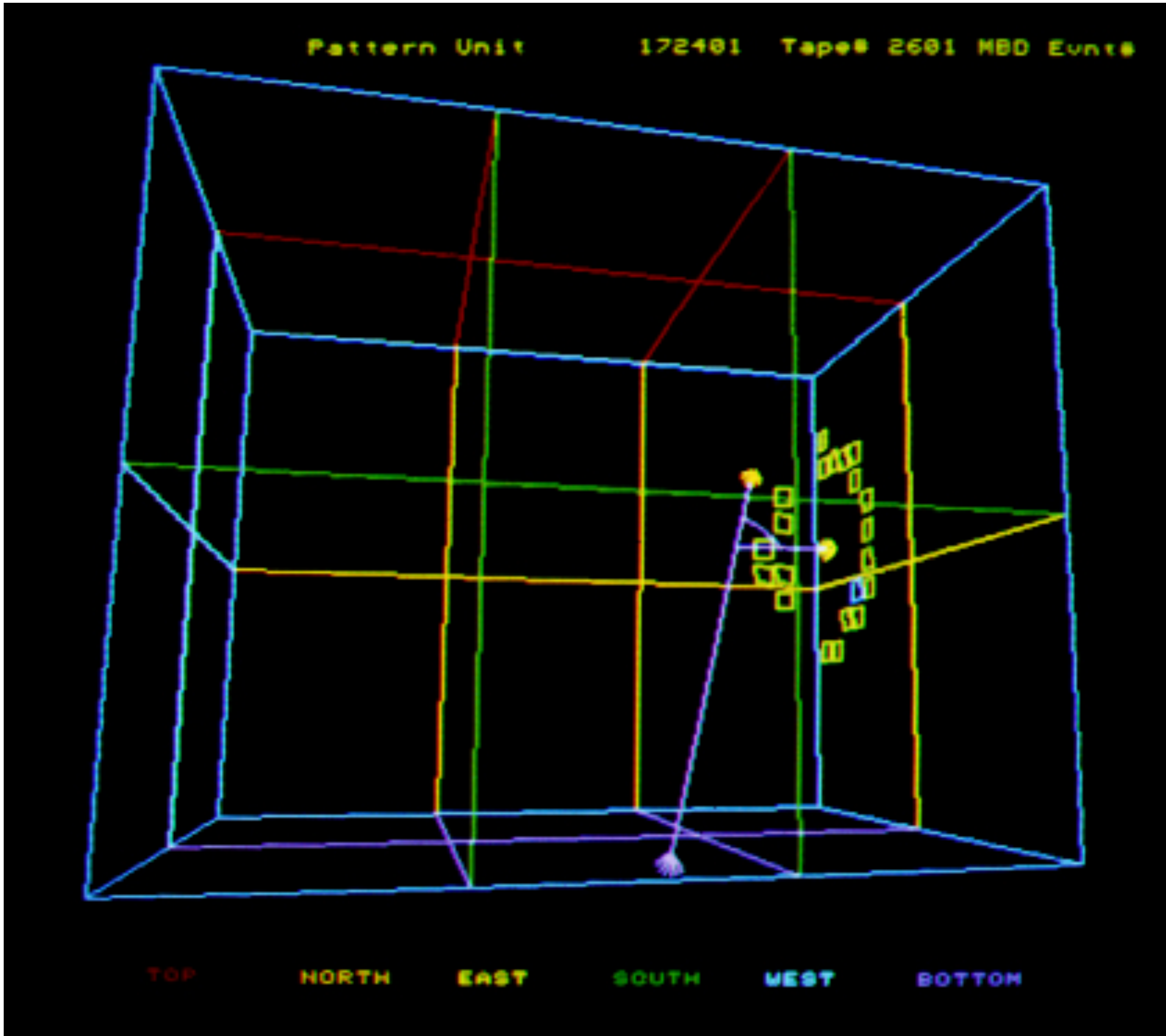
…11 in Kamioka



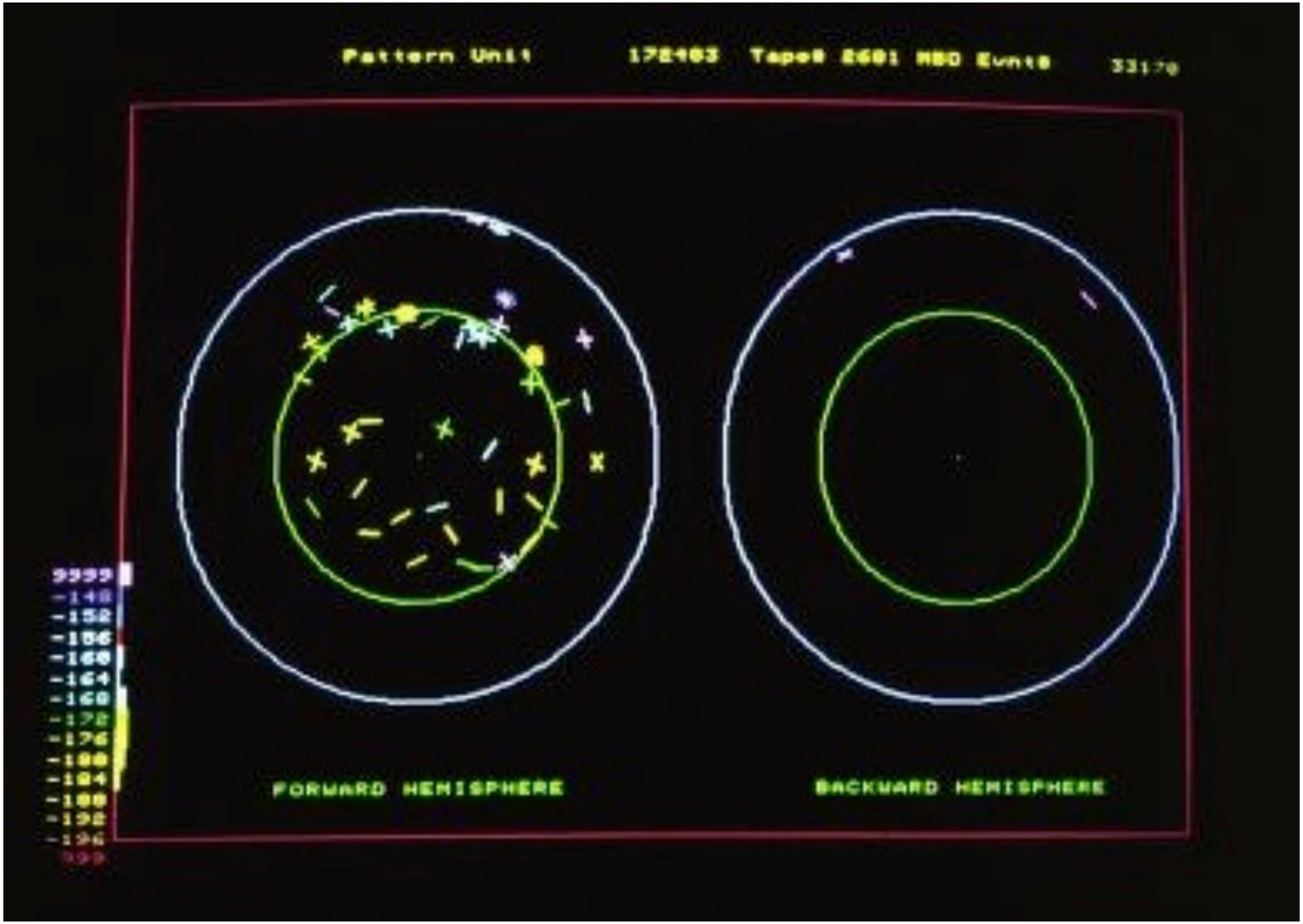
…an entire sun implodes in only 13 seconds, then explodes, though Kamioka's clocks reset by power failure.

...each with a beautiful Cherenkov ring.

The second IMB event:



...with your eye at the vertex of the 3rd of 8 IMB events...



...100 billion neutrinos per cm^2

...observation believable, 2 detectors fired together...

The signal predicted

3 years earlier:

LoSecco

Detectability of Supernova Neutrinos with an Existing Proton Decay Detector

Abstract. *The 8000-ton water IMB nucleon decay detector has good sensitivity to the neutrino burst associated with the collapse of stars. It is particularly sensitive to the $\bar{\nu}_e$ charged current interactions with protons but can also record other neutrino interactions through νe scattering. Signal, noise, physics objectives, and detector modifications that would enhance burst detection are discussed. The objectives include astrophysical questions about the pulse structure and power. It also may be possible with a distant source to study neutrino masses and neutrino oscillations.*

Although the IMB nucleon decay detector was developed primarily for the study of baryon stability, this detector has features that make it an ideal instrument for other physics studies. For instance, it should be suitable for the observation of neutrinos emitted during the collapse of a massive star to a black hole or neutron star. Our understanding of these phenomena has grown in recent years through the study of astrophysical gamma-ray sources and radio pulsars (*1*). A large amount of theoretical work has also been done; including work on the effects of the weak neutral current (*2*) and, more recently, on the possibility of neutrino oscillations (*3*).

About 3×10^{53} ergs of energy are dissipated in the form of neutrinos during a collapse. This corresponds to the emission of 3.4×10^{57} ν_e neutrinos and comparable numbers of $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$ neutrinos. These neutrinos have a spectrum and time structure that characterizes their source. The $\bar{\nu}_e$ spectrum (*4*) extends from 5 to 20 MeV with a mean energy of 13.3 MeV. The neutrino flux falls as $1/r^2$. At a distance of 1 kpc (3.1×10^{21} cm) from the source the ν_e flux is 2.8×10^{13} cm^{-2}. The $\bar{\nu}_e$ flux is 1.7×10^{13} cm^{-2}.

Our detector consists of 8000 tons of water. The oxygen in the water is virtually inert to neutrinos of this energy. The

SuperNova!

Cover Story

for seeing 19 of 10^{58} neutrinos...

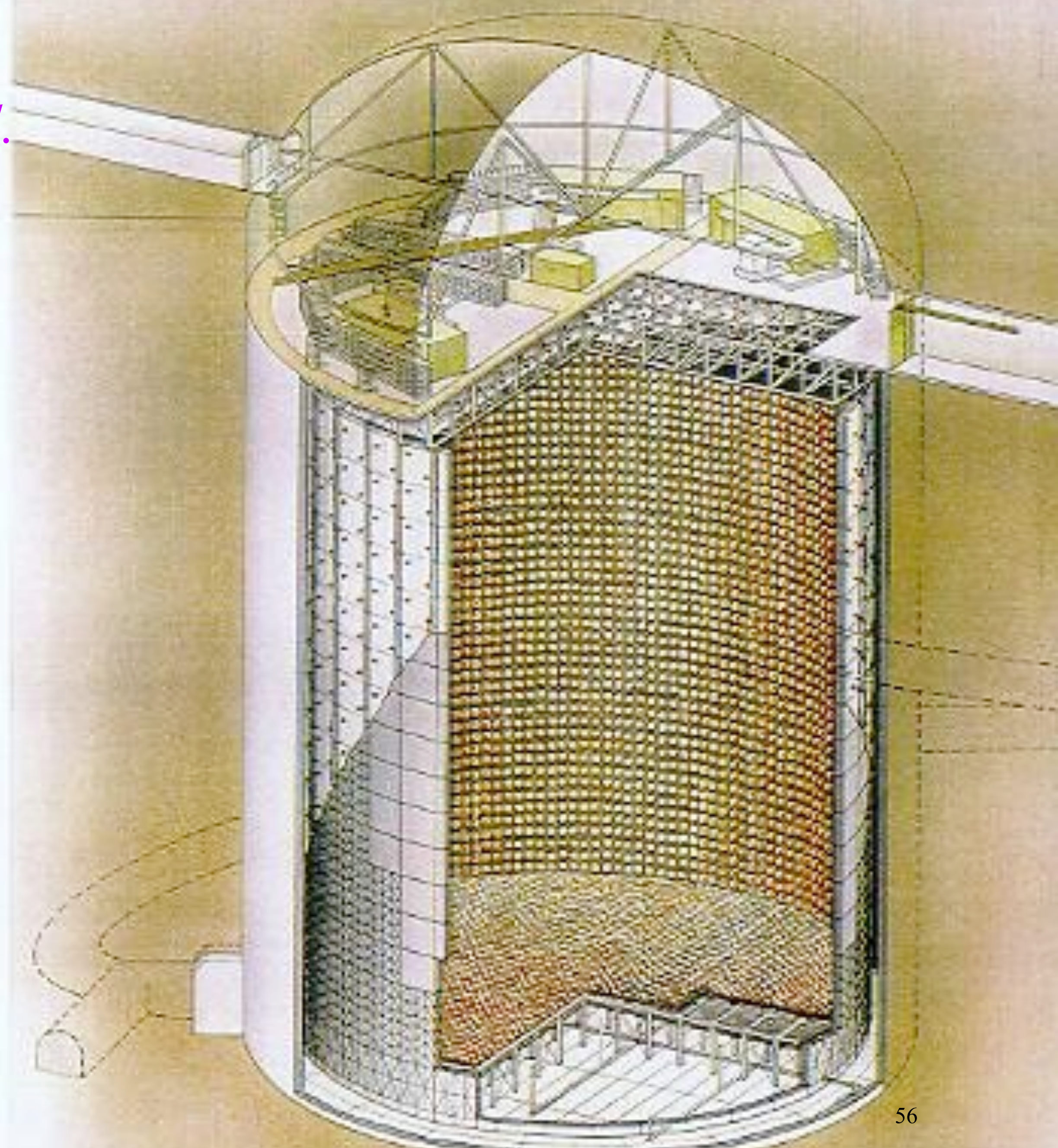
But for oscillations, both IMB & Kamioka too small.

Each had a 3.6 σ effect;
combined 5.4 σ.

DOE wanted Japanese
support of SSC,
so no IMB upgrade.

Quid pro quo: move to Japan if we were to continue.

Took IMB PMs, waveshifters, etc. to build outer detector of Super-K.



Super-K in '96:

First Filling of tank:

22 kiloton fiducial (50 kT total)

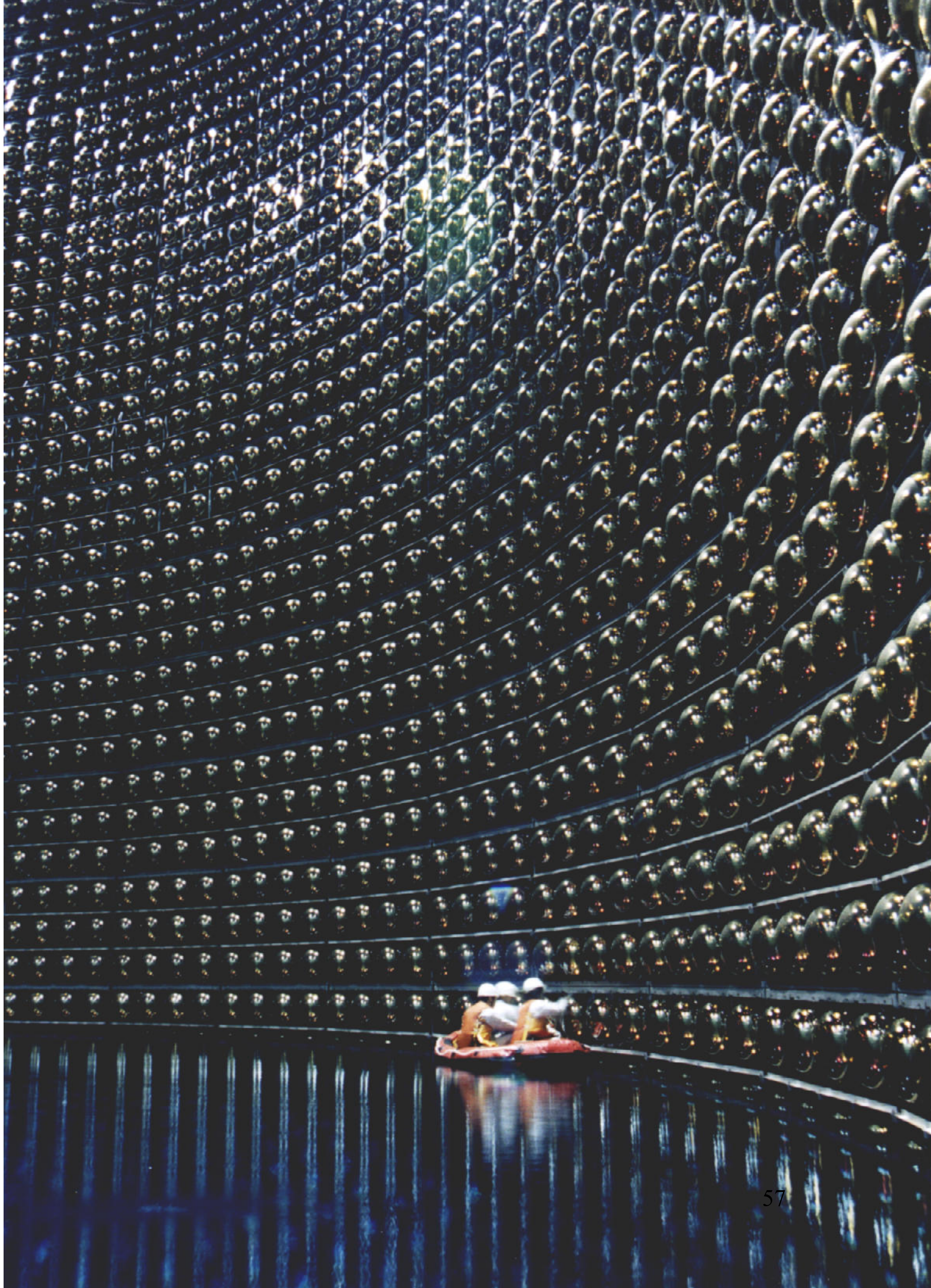
40 m high, 40 m diameter.

11,000 PM inner detector.

5 MeV threshold.

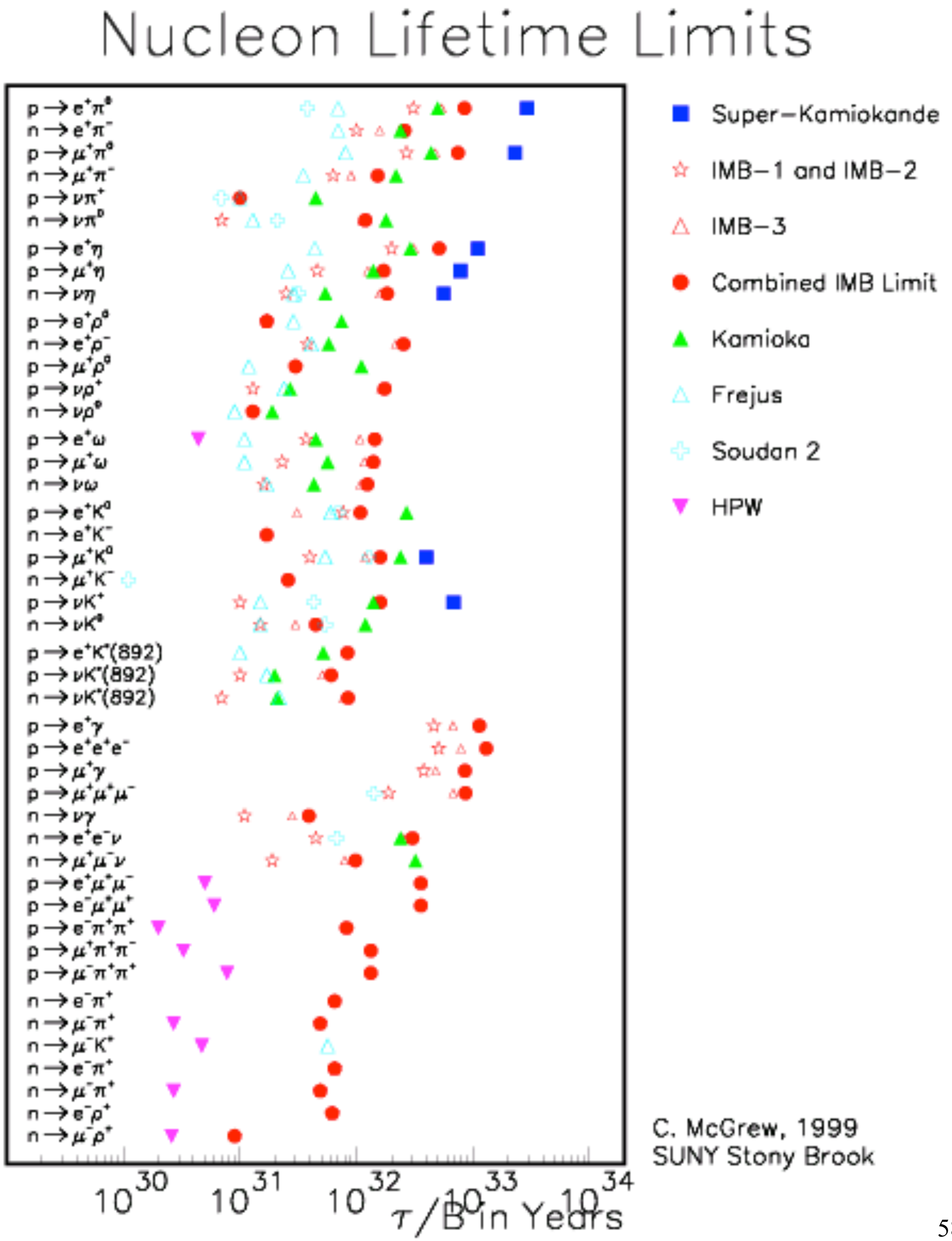
1 km deep in new cavity.

2,000 PM outer detector.



Even after 3 years of Super-K running,

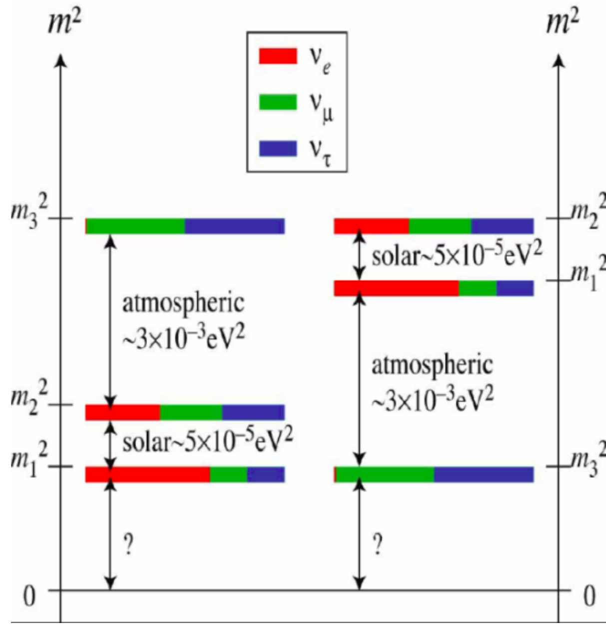
IMB still very competitive!



That's the past...the future of neutrino physics?

Two riddles are solved:
The solar neutrino problem, and
The atmospheric neutrino puzzle
both by neutrino oscillation studies.

But what about
the neutrino mass hierarchy?
the other terms of the complex mixing matrix?



$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo Matrix
3 Component Flavor Mixing

$$= \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & e^{i\alpha_3/2+i\delta} \end{pmatrix}$$

Solar | Atmospheric | CP Phase | Reactor... | Majorana Phases
Double β Decay

Appearance exp'ts?
Value of θ_{13}?
CP Violation?
Majorana *vs.* Dirac?
Absolute Mass?

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

Many discoveries yet to come...

Summary: In neutrino physics, mass, pixels, & independent observables are everything...

IMB: invented technology, robustly discovered large atmospheric anomaly. ’83
Couldn’t kill it, alerted Japanese competition. ’86

Kamiokande: after new collaborators added timing, confirmed the anomaly ’88

...but neither had the event rate to determine oscillations to better than ~3.5 σ

Why?

Insufficient data to cut it enough ways to cope with

a) 3 component mixing, and

b) low energy ν_μ events that oscillate with poor directionality
vs. high energy ones that do not oscillate, but point well.

Super-K, with 7 times the fiducial mass & event rate of IMB
5 times the PMs of IMB in the inner detector,
could normalize to hi-energy, unoscillated ν_μ’s with good direction, then

fit 25 parameters in the 2004 PRL paper
39 parameters in the 2005 PRD paper

...that’s the bottom line!

Postscript: *a faulty flux - the only way IMB found to falsify their oscillation result*

During the question period at the end of the presentation, Olga Botner asked about an IMB publication that showed no muon deficiency,

> "Search for muon neutrino oscillations with the Irvine-Michigan-Brookhaven detector," Phys. Rev. Lett. 69, 1010 (1992)], R. Becker-Szendy, C. B. Bratton *et al.*

This paper compared IMB's observation to an atmospheric neutrino flux, calculated and proposed in a paper by Lee and Koh in 1990, one of four atmospheric neutrino fluxes available at the time. The Lee and Koh flux was repudiated in 1996 by the authors as incorrectly calculated; however, a retraction was never published.

The IMB observations 1992 were confirmed in 1999 by Super-K; since it is 4 times larger, it should have more stopping muons:

Stopping muons/upward muons =	0.16 ± 0.02	IMB (1992)
	0.22 ± 0.02	Super-K (1999)

This footnote to the history has been recently published by

> "Comment on Search for mu-neutrino oscillations with IMB," arXiv:1601.07152, J. LoSecco and L. Sulak.

Botner also inquired about the IMB paper, "Atmospheric Muon Neutrino Fraction above 1 GeV," PRL97, 345, R. Clark *et al.* It reported the ratio "observed" / "expected" = 1.1 ± 0.16 at high energies and 0.71 for the contained event sample. This paper remains accurate.

RESERVE

“Cosmic Gall,” by John Updike

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

Neutrinos are elusive. They can pass through 1000 light-years of lead without interacting.
You and I are now being invaded by about 10^{14} neutrinos each second.