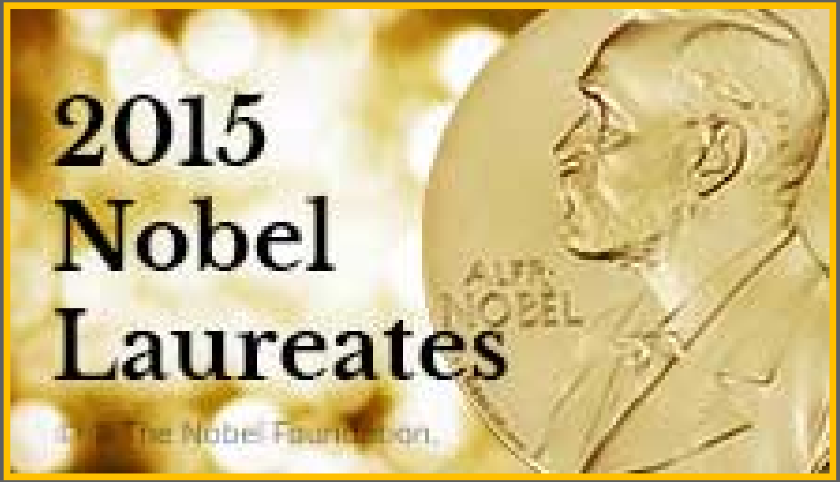
Art McDonald
for SNO



Takaaki Kajita
for SuperK

The 2015 Nobel Prize in Physics Muon Neutrinos in Super-Kamiokande

and the Hawaii Connection

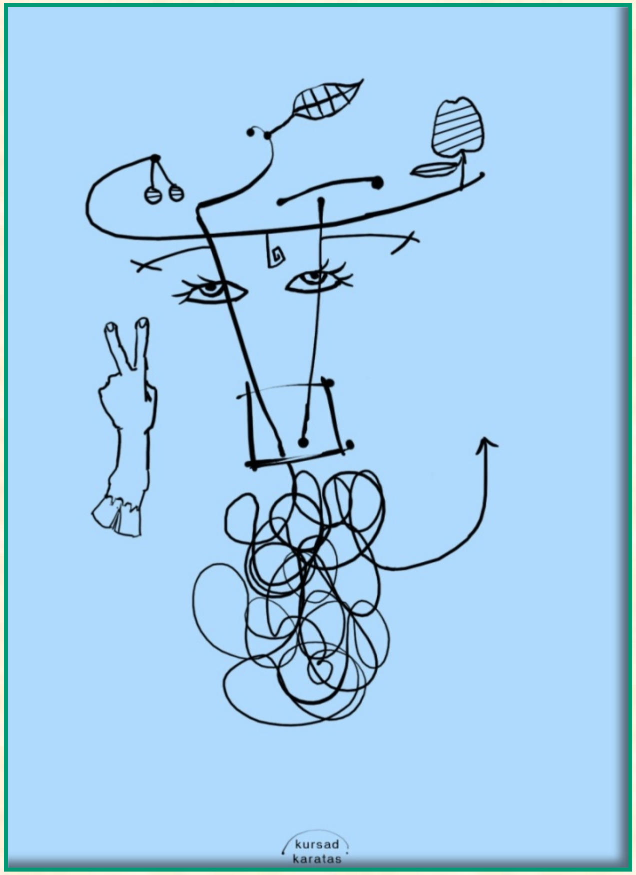
Focusing upon Muon Neutrino Oscillations Discovered in Super-Kamiokande

John G. Learned and 1998 UH SuperK Collaborators: John Flanagan, Atsuko Kibayashi, Shige Matsuno, Vic Stenger, Dean Takemori , (Steve Dye)
University of Hawaii, Manoa

26 October 2015 at UH Manoa

Introduction: *So what's a Neutrino and why should anyone care?*

Some Gnus, Not Nus



Climbing Rock Climbing Carabiners

Neutrino Carabiner

by Black Diamond Equipment

Original Price: **8.50**

Volume Discount: **6** for **7.83** each

Named for a subatomic particle with almost zero mass, this is the lightest, full-service carabiner made. That means it's the best choice for anyone who demands super lightweight carabiners without a compromise in strength. The mere 36 grams provide a large rope-bearing surface, a nose hood to protect against "gate rub", and a basket very similar to a Quicksilver 2.

QTY: 1

Style	Weight	Strength	(kN)	Gate Width
	grams	closed	open	(mm)
Neutrino	36	24	8	22

Your Cart:
Total: $0.00

"Named for a subatomic particle with almost zero mass …"

Greek letter Nu

What are those weird things, neutrinos?

Breakfast Nus?

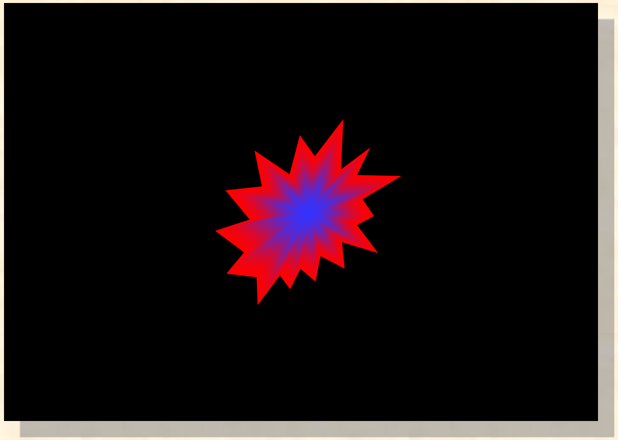
Neutrino Contents about
0.000000000000000000002 kCal

Thanks Joshua Murillo, and Joe Moore

So, what IS a Neutrino?

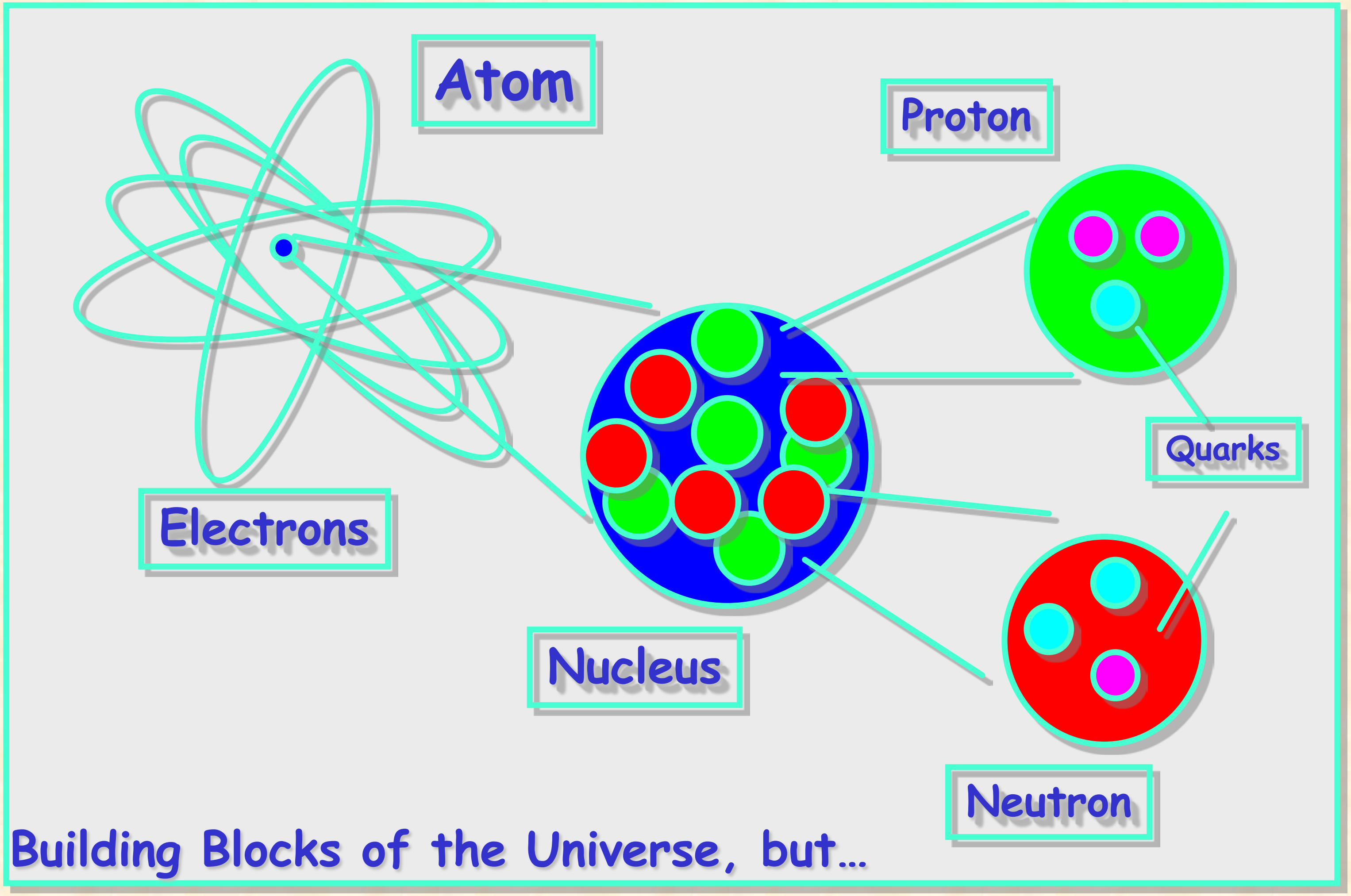
This is a Neutrino

This was a Neutrino



Stable Elementary Particle – 3 of 6 constituents of matter
No electric charge – cannot see it
Very little interaction with matter – goes through the earth unscathed
Has very little mass – less than 1 millionth of electron
Lots of them though – 100 million in your body any time!

Reminder of Subatomic Structure



Building Blocks of the Universe, but…

Wait there's more..

		unstable	
Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	e electron	μ muon	τ tauon
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

3 is the magic number of the universe

And there's even more..

gluon

photon

W & Z

Quarks

Leptons

unstable

u up

c charm

t top

d down

s strange

b bottom

e electron

μ muon

τ tauon

ν_e electron neutrino

ν_μ muon neutrino

ν_τ tau neutrino

$\nu_?$ sterile neutrino

$\nu_?$ sterile neutrino

Higgs

Dark Matter

Dark Energy

Today we focus on the peculiar neutrinos

Where do Neutrinos come from?

✓ Nuclear Reactors
(power stations, ships)

Sun ✓

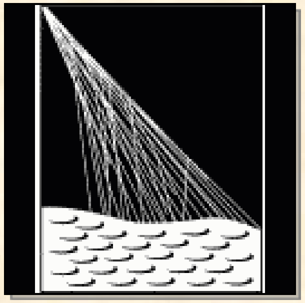
✓ Particle Accelerator

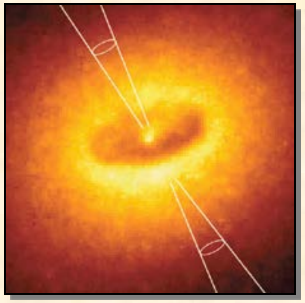
CERN

Supernovae
(star collapse)

SN 1987A ✓

✓ Earth's Atmosphere
(Cosmic Rays)





Astrophysical
Accelerators

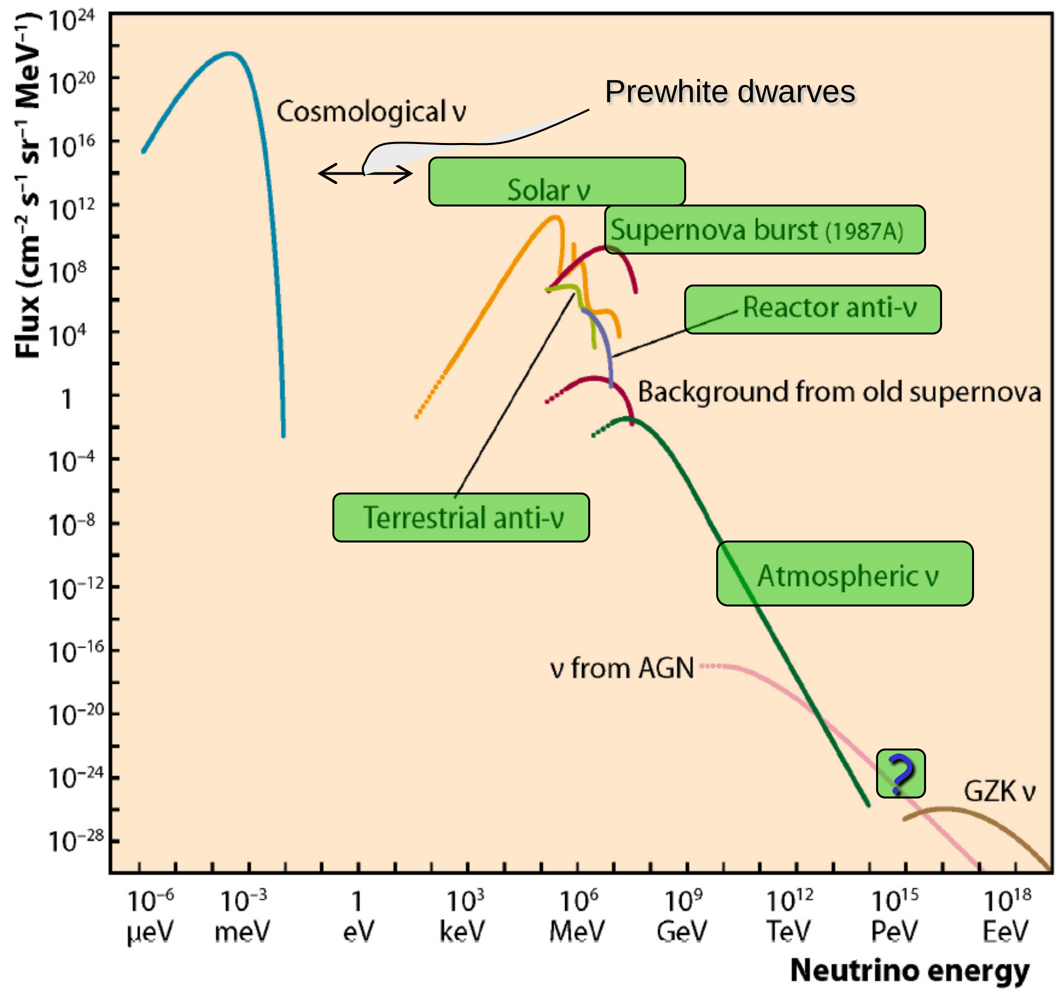
IceCube ✓

✓ Earth's Crust
(Natural
Radioactivity)

Big Bang
(here 330 ν/cm^3)

Indirect Evidence

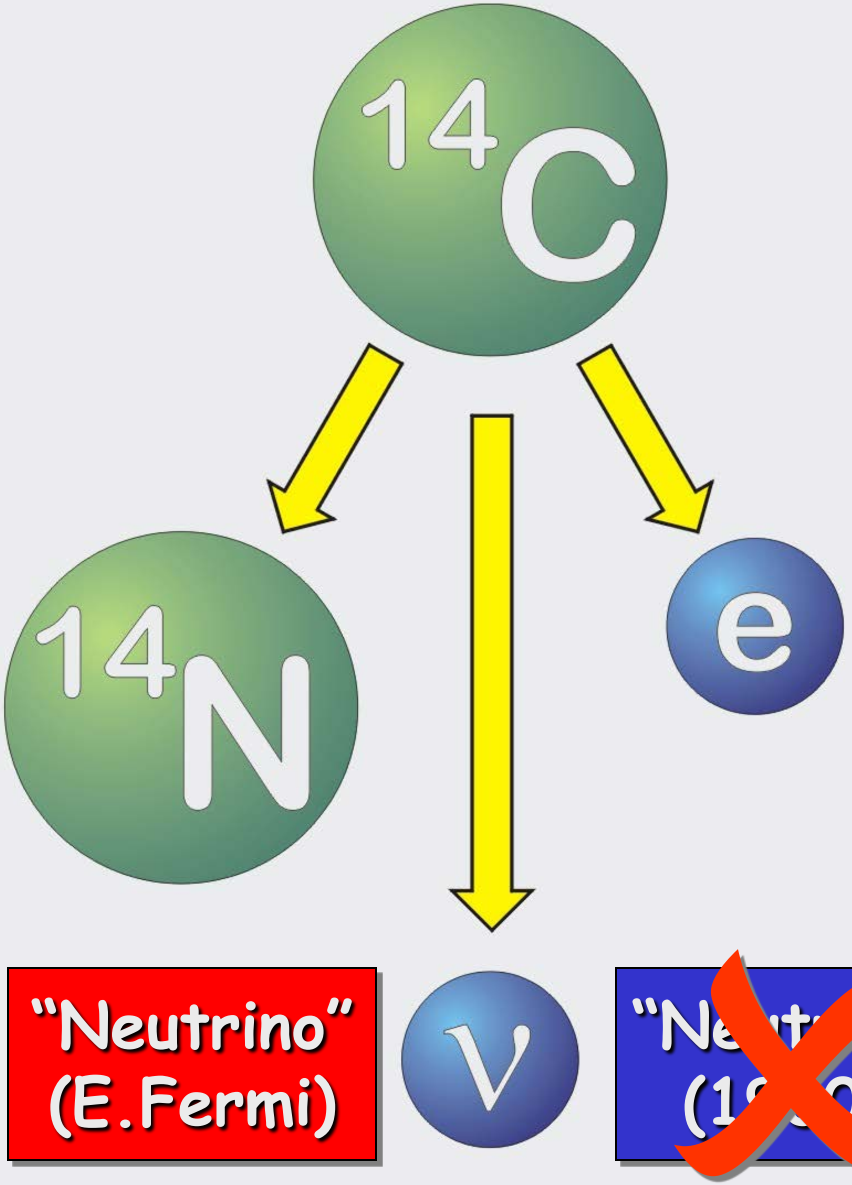
… and vast lands to be explored: one should be open to unexpected results



A synoptic view of neutrino fluxes. (from ASPERA roadmap)

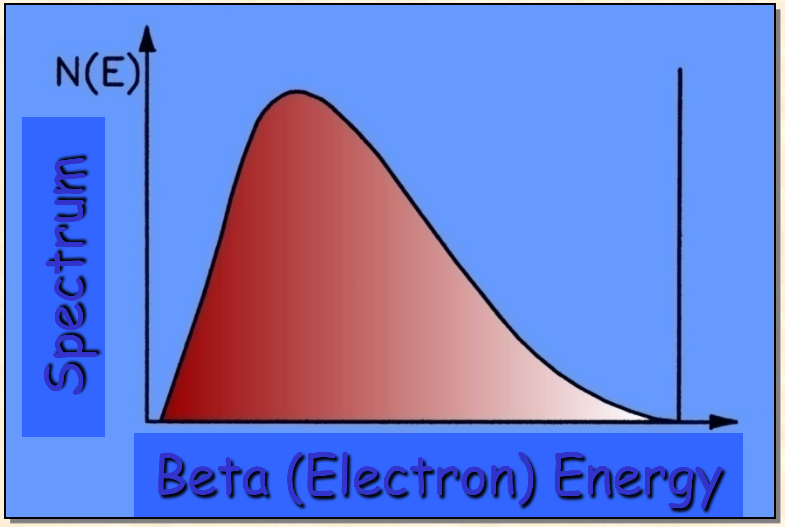
🟩 Neutrino flux seen

How were Neutrinos discovered?



"Neutrino"
(E.Fermi)

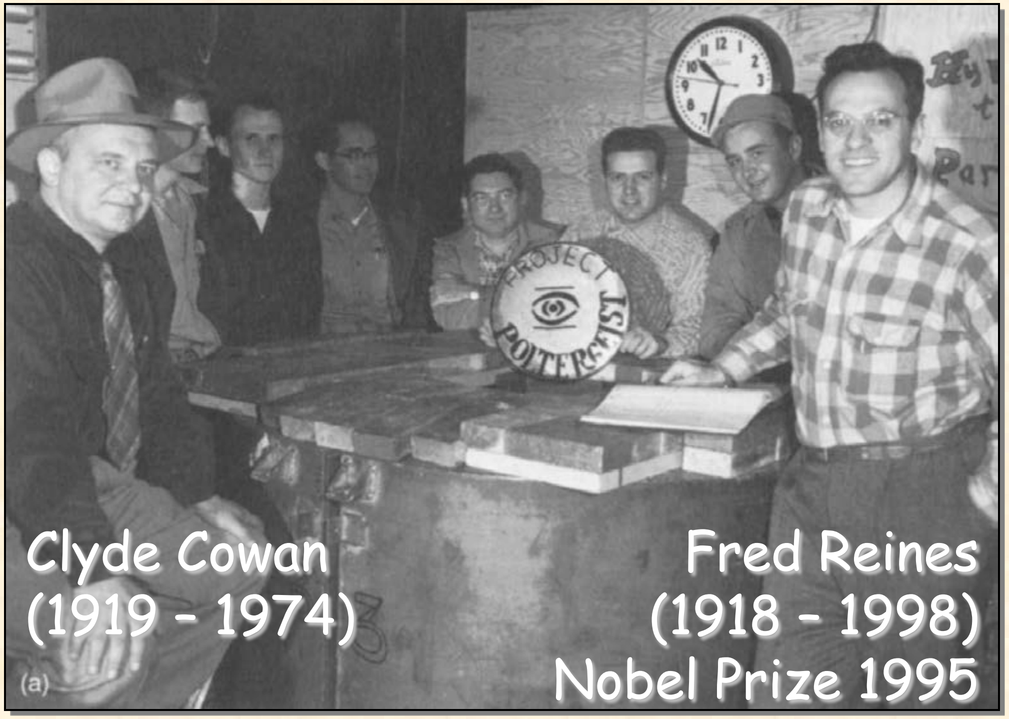
~~"Neutron"~~
~~(1930)~~



Radioactive Beta Decay

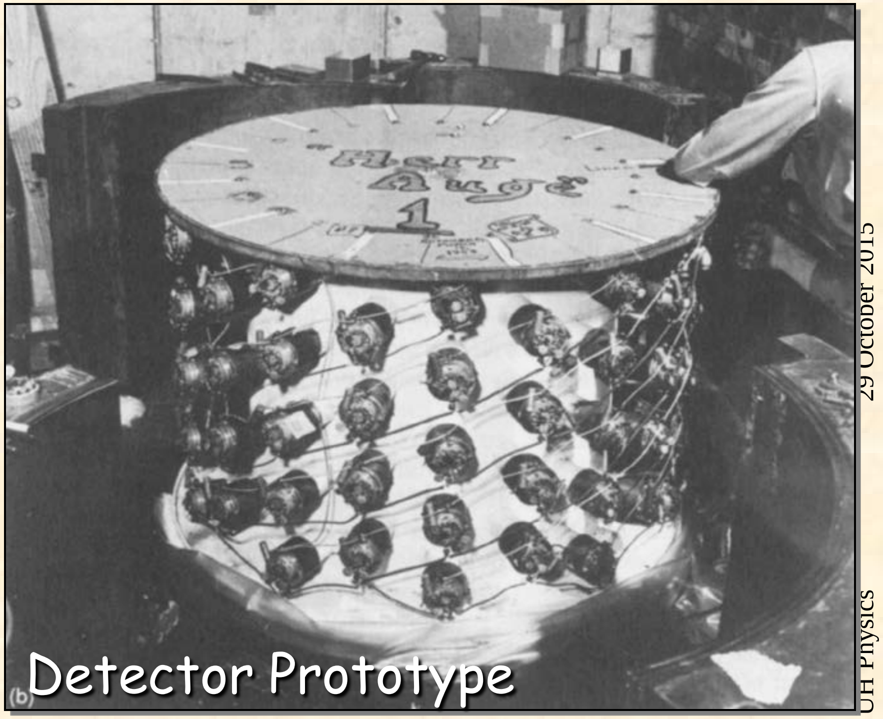
Wolfgang Pauli
(1900-1958)
Nobel Prize 1945

First Detection ! (1954 - 1956)

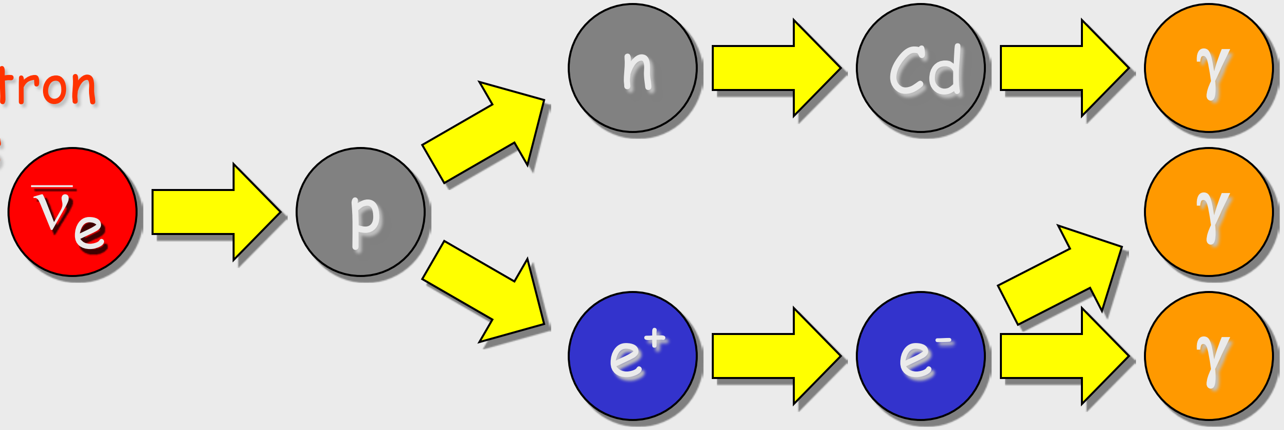


Clyde Cowan
(1919 – 1974)

Fred Reines
(1918 – 1998)
Nobel Prize 1995



Detector Prototype



Anti-Electron
Neutrinos
from
Hanford
Nuclear
Reactor

3 gamma
quanta in
coincidence

What do we know well about neutrinos?

- No electric charge.
- Little or no electric/magnetic dipole moment.
- Essentially point particles.
- Very small mass compared to other spin ½ fermions.
- Participates only in SM weak interaction (and gravity).
- Falls under gravity (SN1987A) as do photons.
- Produced in only left-handed helicity state (nubar = righthanded)
- Comes in three flavors, e, μ and τ
- Lepton number is conserved (but not lepton flavor)
- No known lifetime (but…).
- Has nothing to decay to amongst known particle zoo (but v_m-> v_n OK)
- SM processes produce neutrinos as superposition of mass states
- Mass states' relative phases change with flight time, producing morphing between interaction states ("v oscillations").
- Three mass states explains all accepted data, but room for new things.
- *Almost* surely we are living in a bath of undetectable ~600nu/cm^3 left from Big Bang, which travel ~300 km/s.

How the view changes before and after revelation?!

Initial state of confusion, lack of clear path forward, conflicting hints, often historical and cultural biases to science news.

Big pictures theory talks… much is mathematics, much aesthetics and much just tradition… often nothing else to fall back upon at the frontier.

Beautiful new and definitive data move the paradigm…

as with SK results: <u>nus have mass and they oscillate</u>.

Even so, many were not willing to accept SK results at first.

Neutrinos have taken us to that land a few times:
confusion,
revelation,
reformation,
confusion,…
Future?   Seems likely

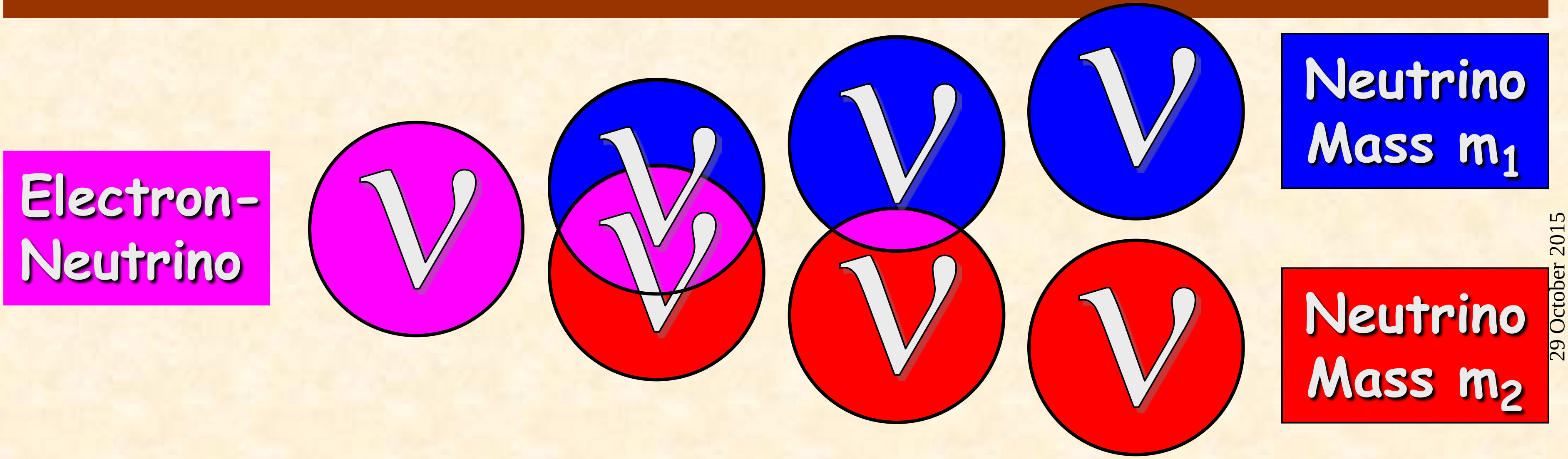
….

So what *is* this "oscillation" business?

In a word… neutrinos are

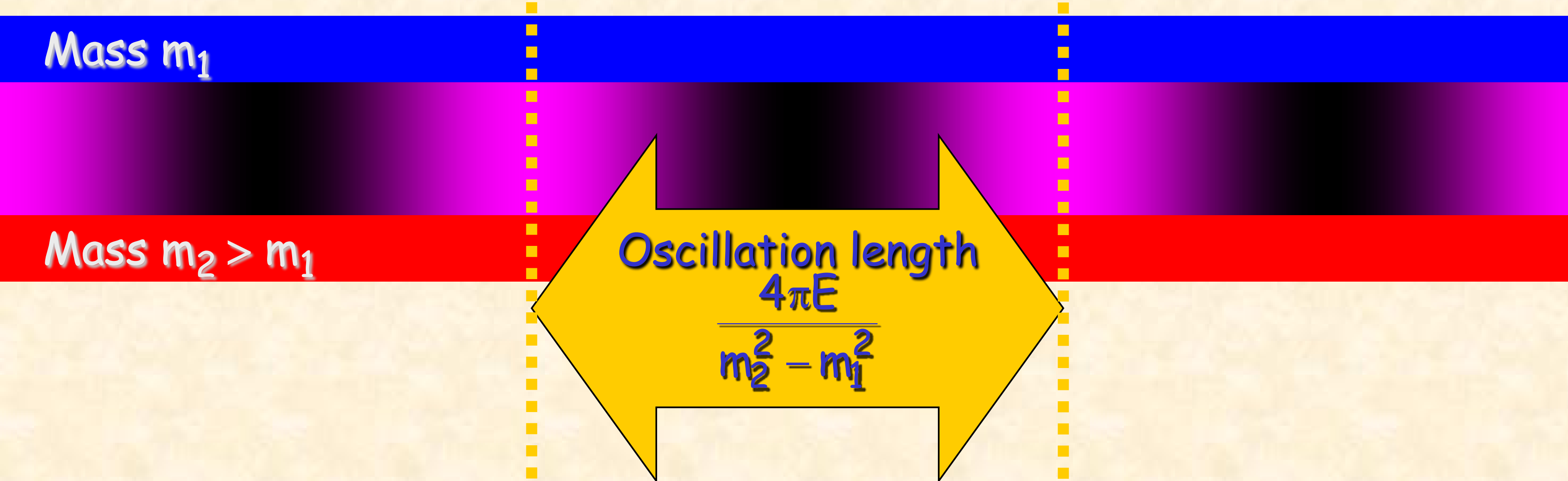
shapeshifters!

Mixing of Neutrinos with different Masses

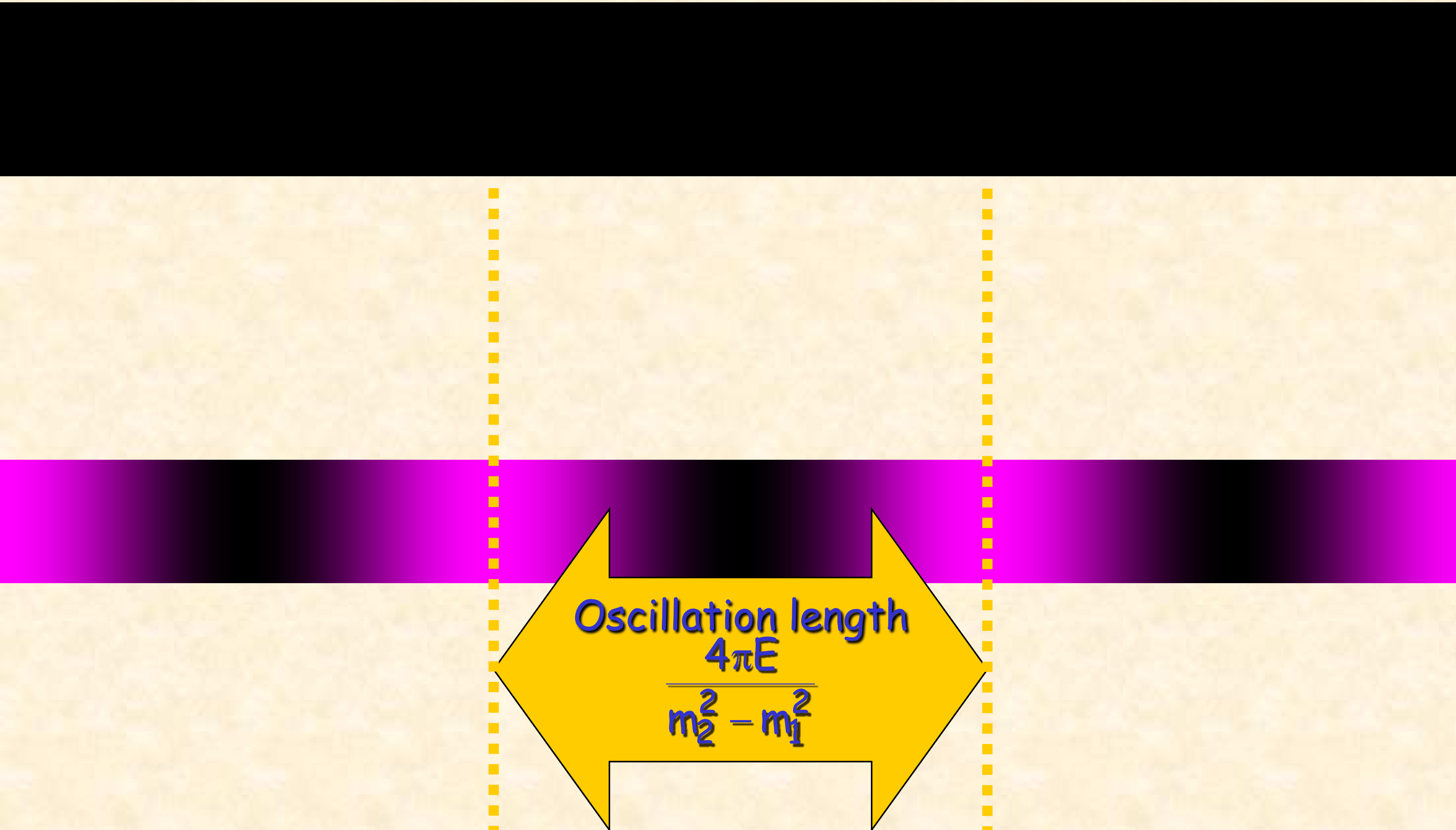


Neutrino Wave Separation (Wave Particle Duality)

Neutrino-Oscillation



Neutrino-Oscillation



Oscillation length

$$\frac{4\pi E}{m_2^2 - m_1^2}$$

Unanswered Neutrino Questions

1) Who needed them anyway? Only uncharged fundamental fermion.
2) Why are masses so small?
3) What is the absolute mass scale?
4) What is the mass order?
5) Why is mixing matrix so different from quarks? (Why not?)
6) Is there CP violation as with quarks?
7) Are there heavy (TeV - GUT scale) right handed neutrinos?
8) Are neutrinos Majorana or Dirac particles?
9) Are there any light (eV scale) sterile neutrinos?
10) Are heavy right handed neutrinos responsible for leptogenesis?
11) What role do neutrinos play in heavy element production in SN?
12) Do they travel faster than light? Well, no! (Thanks OPERA!)

We have no guidance from a unified theory…
almost all prior theory guesses/biases were wrong…

It is an experimentalists' game.

Neutrinos: So what good are they?

Good for us physicists, and people, and good for the Universe too!

Great for Particle Physics as probes of elementary particles

Observing the Guts of Supernovae and
Definitely Involved in Making of the Heavy elements (R-process)

Making an Excess of Matter over Antimatter (Leptogenesis)?

Geoneutrinos: signal from U & Th heat source driving geodynamics

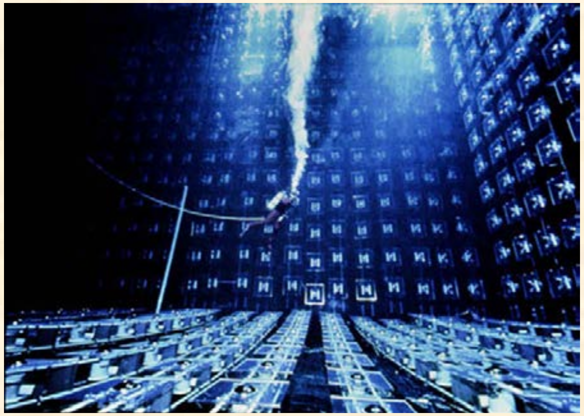
Monitoring Nuclear Reactors (for peace, but also for engineering)

Communications?
Terrestrial: not worth it? FastTrading: maybe but silly?
Talking with ETI: perhaps, who knows?
Modulating variable stars? Far out, but search interesting…

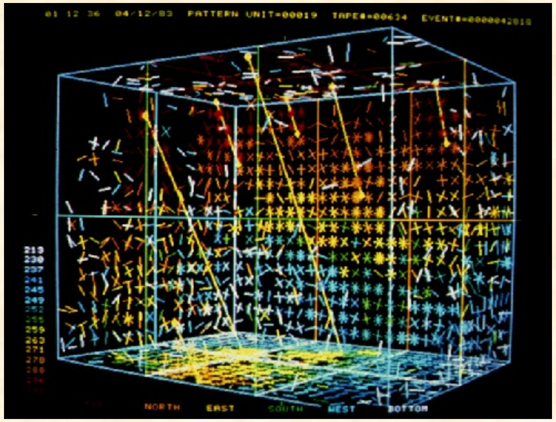
Did we need them? Did they need us? Leave to philosophers…

30 Year Long History of Hints Leading to the 1998 Discovery of Muon Neutrino Oscillations

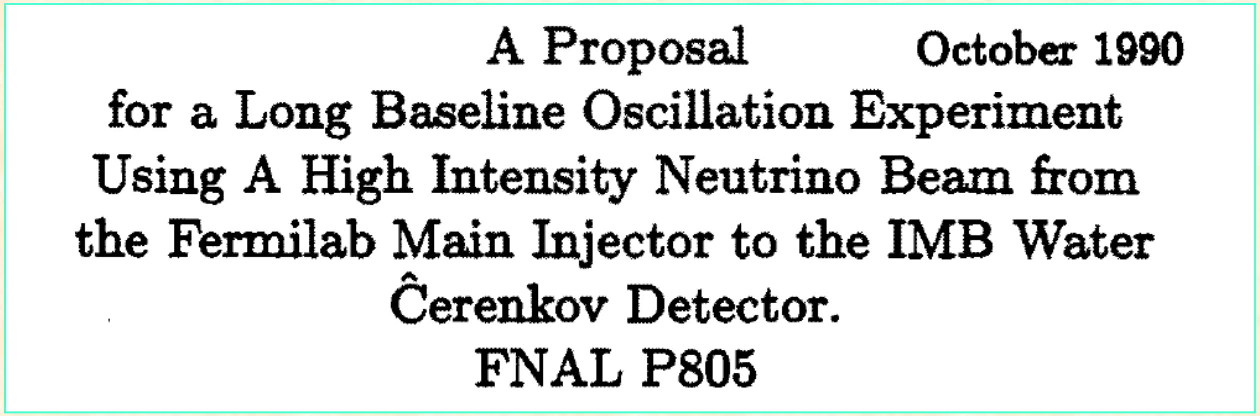
- First hints 1965 in South Africa & South Indian experiments: atm nu flux low, calculations come to meet experiment, no fuss…
- Second hints from IMB flux in 1983, but again fluxes made to agree with results... and not much fuss
- Third hint also in IMB ~1983, when ratio of muon decay events to total contained events is low. Experiment problem? Various physics options? Nothing from other experiments such as Frejus and NUSEX, much skepticism from Europe.
- Mid 1980's Kamiokande and IMB measure nu_e and nu_mu fluxes, and clearly ratio is not right. Water target, since not seen elsewhere (iron)? nu_e or nu_mu in error? Extraterr? PDK? (see table below)
- Around 1992, Kamiokande finds poor muon angular distribution, makes claims of oscillations, but statistics totally not convincing (and now shown to be a fluctuation).
- 1996 SK turns on, acquire large numbers of contained muon events report spectacular results in 1998.
- Rapidly confirmed by Soudan II, MACRO and then long baseline accelerator experiment K2K, and later several others.
- Important that prior to SK could not tell if R due to only muons or muons <-> electrons?
- SK results: muon<->tau is only good fit; soon rule out muon <-> sterile; weak tau appearance evidence; and finally SK has evidence of oscillations not just muon disappearance.
- Further evidence from other experiments -> case closed in early 2000's!



IMB in Cleveland salt mine, 1980s

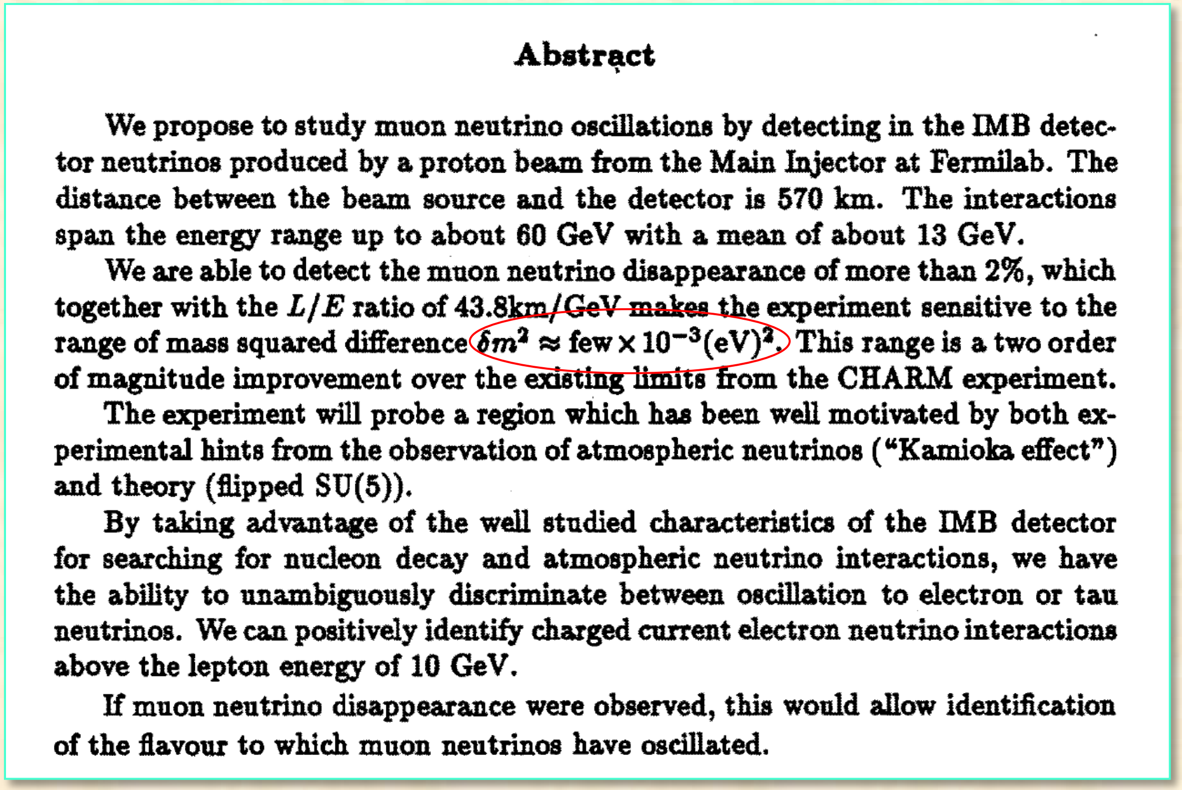


Aside: earlier Nobel could have been had…



A Proposal October 1990

for a Long Baseline Oscillation Experiment
Using A High Intensity Neutrino Beam from
the Fermilab Main Injector to the IMB Water
Ĉerenkov Detector.
FNAL P805



Abstract

We propose to study muon neutrino oscillations by detecting in the IMB detector neutrinos produced by a proton beam from the Main Injector at Fermilab. The distance between the beam source and the detector is 570 km. The interactions span the energy range up to about 60 GeV with a mean of about 13 GeV.

We are able to detect the muon neutrino disappearance of more than 2%, which together with the L/E ratio of 43.8km/GeV makes the experiment sensitive to the range of mass squared difference $\delta m^2 \approx \text{few} \times 10^{-3}(\text{eV})^2$. This range is a two order of magnitude improvement over the existing limits from the CHARM experiment.

The experiment will probe a region which has been well motivated by both experimental hints from the observation of atmospheric neutrinos ("Kamioka effect") and theory (flipped SU(5)).

By taking advantage of the well studied characteristics of the IMB detector for searching for nucleon decay and atmospheric neutrino interactions, we have the ability to unambiguously discriminate between oscillation to electron or tau neutrinos. We can positively identify charged current electron neutrino interactions above the lepton energy of 10 GeV.

If muon neutrino disappearance were observed, this would allow identification of the flavour to which muon neutrinos have oscillated.

Back to historical overview: Neutrino Fever Hits in the 1990's

Kamiokande detects solar electron neutrinos in real time, with directionality! (Eliminates question of radiochemical expts actually detecting solar neutrinos or something else.)

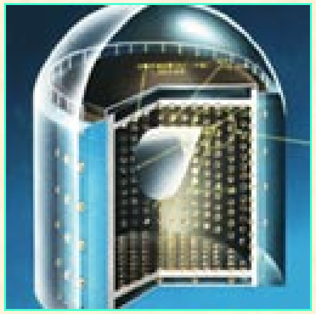
Solar rates observed in 4 experiments: see 1/3-1/2 expected… suspicions of electron neutrino oscillations, but other solutions not ruled out.

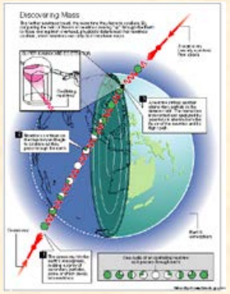
Early 1990's LSND finds peculiar nu_e appearance, claim oscillations. Almost ruled out by other experiments. People generally suspicious of result, but nobody finds smoking gun of problem. (More about this and possibly related observations in later talks…MiniBoone and the Reactor Neutrino Anomaly)

In 1996 the 50 kiloton SuperKamiokande detector starts, and by 1997 some things are beginning to become clear…

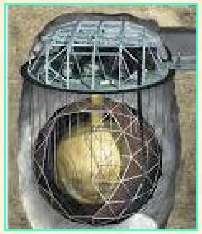
The Discovery of Neutrino Oscillations: Mainly a Story of Three Experiments, but Focus on SK

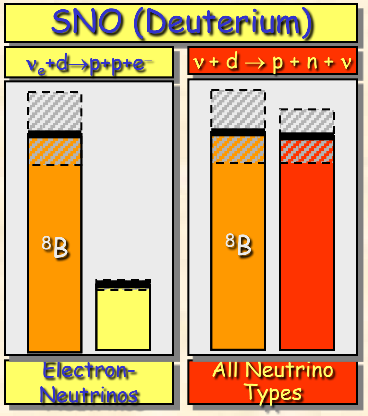
1998 **SuperK** discovers muon neutrino oscillations



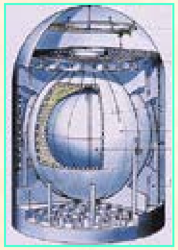


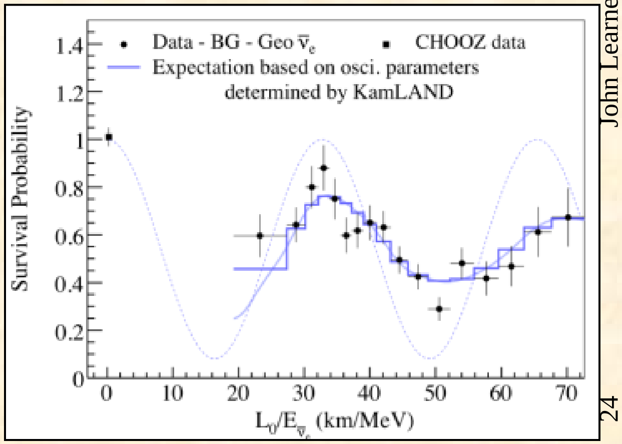
2001-2 **SNO** Resolves "Solar Neutrino Problem" as due to **electron neutrino** transformation





2002 **KamLAND** resolves **oscillatory signature** from reactors around Japan





1998:SK Starts the Nu Revolution


The New York Times

"All the News That's Fit to Print"

VOL. CXLVII . . . No. 51,179

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FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

After Dr. Kajita's remarks, the powerful evidence he presented elicted prolonged applause from an audience of physicists from dozens of countries who packed the conference hall here.

Dr. Yoji Totsuka, leader of the

Continued on Page A14

Detecting Neutrinos

Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

. . . and collide with other particles . . .

. . . producing a cone-shaped flash of light.

The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

Scientists Find Mass in an Elusive Particle, Rattling a Basic Theory About All Matter

Continued From Page A1

coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all other possible causes of the effects we have measured and only neutrino mass remains."

Dr. John N. Bahcall, a leading neutrino expert and astrophysical theorist at the Institute for Advanced Study in Princeton, N.J., said in an interview that there had been many claims in recent years of the discovery of neutrino mass by other groups. "But this one is by far the most convincing," he said. "Besides the strong evidence they have found, this team has a magnificent track record of discoveries."

But because the elusive particles cannot be seen, the evidence that they have mass is indirect.

Transformation Is Evidence of Mass

Neutrinos come in three types or "flavors." The data gathered by the Super-Kamiokande team during the two years the detector has operated indicate that at least one of these three "flavors" can "oscillate" into one of the other flavors as it travels along at nearly the speed of light. According to the theories of quantum mechanics, any particle capable of transforming itself in this way must have mass.

Study of the neutrino particle has been glacially slow since its existence was hypothesized in 1930 by the Austrian physicist Wolfgang Pauli as a way to explain the mysterious loss of energy in certain nuclear reactions. The particle was finally discovered in 1956 by two physicists at the Los Alamos National Laboratory, Dr. Frederick Reines (who was awarded a Nobel Prize for the discovery) and the late Dr. Clyde Cowan.

But understanding of the particle since then has been acquired painfully slowly, because neutrinos have no electric charge and rarely interact with any kind of matter. A neutrino so rarely collides with an atom of ordinary matter that a typical neutrino can easily penetrate a one-light-year thickness of lead — some six trillion miles — without hindrance.

As the writer John Updike put it in a poem he wrote in 1960:

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 dust maids down a drafty
hall.

But once in a great while, a neutrino does hit an atom and the resulting blast of nuclear debris supplies clues about the neutrino itself. The debris generally includes many particles that can race through water, mineral oil or even ice, sending out shock waves of blue light. This light, called Cherenkov radiation, can be detected by light sensors and measured.

During the past few decades, scientists have learned that matter is made up of three distinct flavors or types. This means that there are three flavors of neutrinos — the electron neutrino associated with the electron, the muon neutrinos, associated with the muon particle, which is a kind of fat electron, and the tau neutrino, associated with the tau particle, an even fatter relative of the electron. The role of the muon and tau particles and their associated neutrinos in the universe has mystified physicists. "Who ordered that?" the Columbia University physicist Isidor Rabi is said to have remarked when the muon was found.

The Super-Kamiokande detector was built two years ago as a joint Japanese-American experiment. It is essentially a water tank the size of a large cathedral installed in a deep zinc mine one mile inside a mountain 30 miles north of here. When neutrinos slice through the tank, one of them occasionally makes its presence known by colliding with an atom, which sends blue light through the water to an array of detectors.

The enormous volume of water in the detector increased the likelihood of neutrino impacts to the point at which the discovery of neutrino mass became possible.

The Super-Kamiokande collaboration is studying several neutrino phenomena simultaneously, but the one that led to today's announcement was based on "atmospheric" neutrinos created when highly energetic cosmic ray particles from deep space slam into the Earth's upper atmosphere.

Finding a Reason For a Puzzling Shortage

Physicists knew that different flavors of neutrinos constantly arrive from the upper atmosphere and they have calculated that the ratio between muon neutrinos and other flavors must have a certain value. But over the years detectors found only about half the muon neutrino predicted by theory.

The apparent shortage of muon neutrinos was explained by the observations that led to today's announcements. The physicists found that when neutrinos come from the sky directly over the Super Kamiokande detector — a relatively short distance — the proportion of muon neutrinos among them was higher than among the neutrinos coming up from beneath the detector after having passed through the Earth.

The scientists reasoned that by traveling through the Earth these neutrinos had had time to oscillate, probably many times, between muon neutrinos and some other type, especially the tau neutrino, and this accounts for the deficit seen in muon neutrinos. (The tau neutrino has not yet been directly detected but it must exist to make observations consistent.)

A related problem has to do with neutrinos produced by the fusion process in the sun. This process, which merges the nuclei of hydrogen atoms to form helium nuclei and energy, produces neutrinos. Astro physicists believe they understand the mechanism in complete detail.

The trouble is that all the best detectors ever built find far fewer neutrinos than should be present according to understanding of the fusion reaction.

Scientists believe the anomaly can be explained by the oscillation of detectable solar neutrinos into types that cannot be detected by existing instruments. But no one has proved this explanation.

Worldwide Efforts To Unlock Secrets

Members of the Kamiokande collaboration have not limited their investigations to huge underground detectors.

The leader of the collaboration's University of Hawaii Group, for example, Dr. John G. Learned, has also worked on an underwater detection system in the Pacific Ocean off the Hawaiian coast (which ran out of money before completion) and a project at the South Pole where a neutrino detector had been buried under thousands of feet of ice.

Another approach to penetrating the neutrino secrets involves the use of particle accelerators capable of producing intense beams of neutrinos. In two experiments currently being prepared, one in Japan and the other at Fermi National Accelerator Laboratory in Illinois, beams of neutrinos will be directed through the Earth toward detectors several hundred miles away. The goal will be to observe changes the neutrinos undergo in transit, both in numbers and types. Physicists expect the experiment to confirm the existence of neutrino oscillations like those seen in the Super-Kamiokande detector.

Although the neutrinos are now known to have some mass, most physicists agree that the mass must be very small. The Super-Kamiokande experiments suggest that the difference between the masses of muon neutrinos and other types of neutrinos is only about 0.07 electron volts (a measure of particle mass). This does not yield a value of the masses themselves, only of the difference between those of muon neutrinos and other types.

Although the mass of the neutrino of any flavor must be small, Dr. Totsuka said, it may be several electron-volts, and if so, the overall gravitational effect on the universe would perhaps be significant. It has been estimated that every teaspoon worth of volume of space throughout the universe contains an average of 300 neutrinos, so their aggregate number is staggering.

(The electron-volt is used by scientists as a unit of particle mass. One electron-volt is the energy, or mass equivalent, that an electron acquires by passing through an electric potential of one volt. By this standard a neutrino is believed to have a mass only about five-hundred-thousandth as much as that of an electron, which itself is a light particle.)

In the last 68 years, a legion of distinguished physicists has devoted inquiries and careers to the puzzling neutrino, which was given its name by the great Italian-American scientist Enrico Fermi. Fermi quickly came to believe in the particle's existence, even though it was not proved in his lifetime, and named it "neutrino," which means "little neutral one" in Italian.

Representatives of dozens of neutrino experiments meet once every two years to exchange ideas at conferences like the one under way here. Present are representatives of teams that have installed neutrino detectors on the bottom of Lake Baikal in Siberia, under the Aegean Sea off the Greek coast, inside the Gran Sasso tunnel under the Alps, under the ice covering the South Pole, and in many other places.

Lively debate has characterized discussions here. For example, Dr. Bahcall, who had high praise for the Super-Kamiokande experiment, challenged assertions by the detector team that neutrinos might have sufficient mass to slow the expansion of the universe.

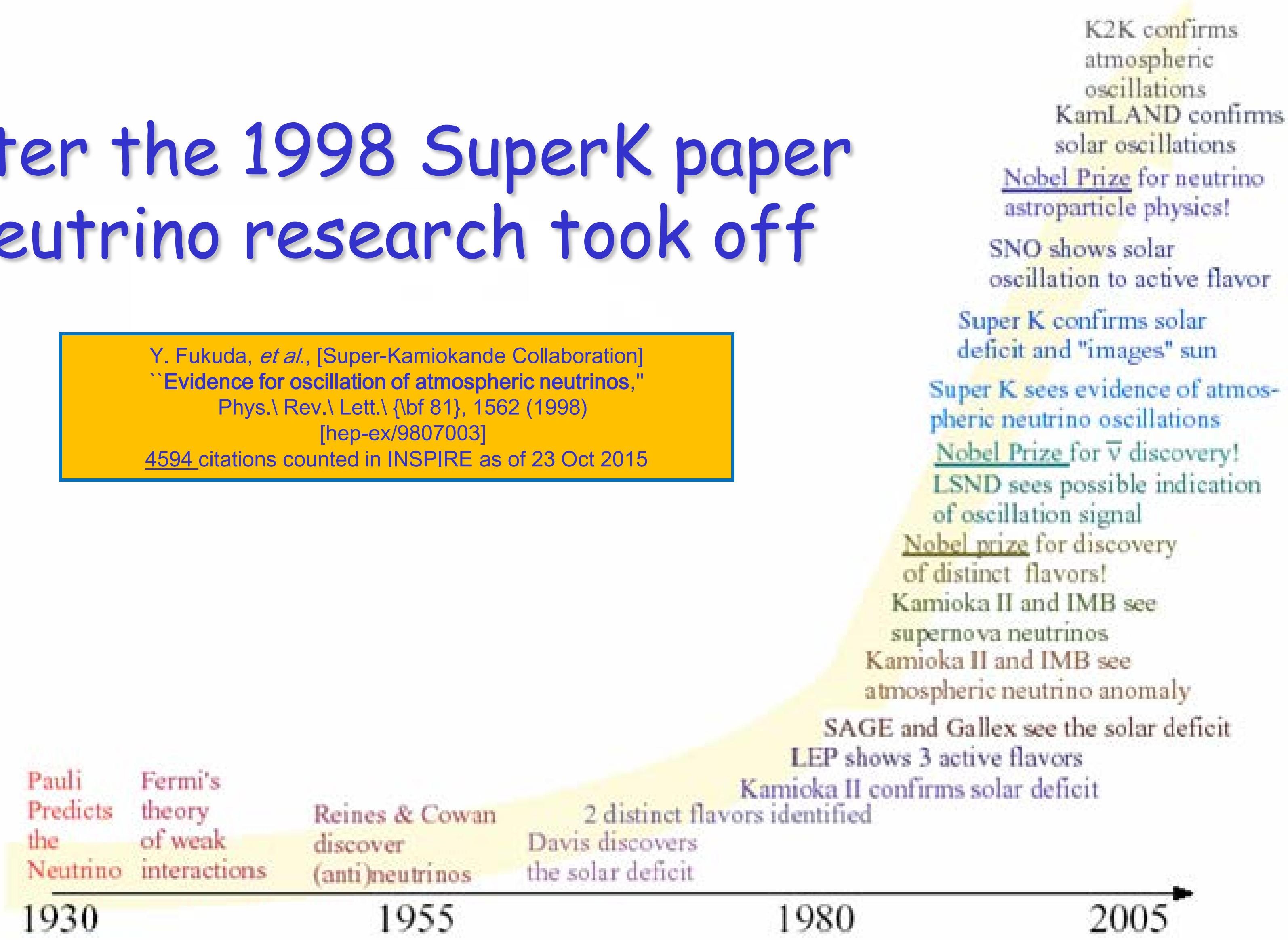
But there was agreement that progress in understanding neutrinos has accelerated tremendously in the last few years.

Another great detector built deep within a mine is nearing completion at Sudbury, Ontario. When scientists have finished filling it with heavy water, water that includes a heavy isotope of hydrogen as part of its molecule, the Sudbury detector will be uniquely capable of distinguishing between electron neutrinos and the other two flavors. This ability is expected to cap the investigation of neutrino oscillations for which Super-Kamiokande has now furnished the "smoking gun."

Neutrinos Become Fashionable

After the 1998 SuperK paper neutrino research took off

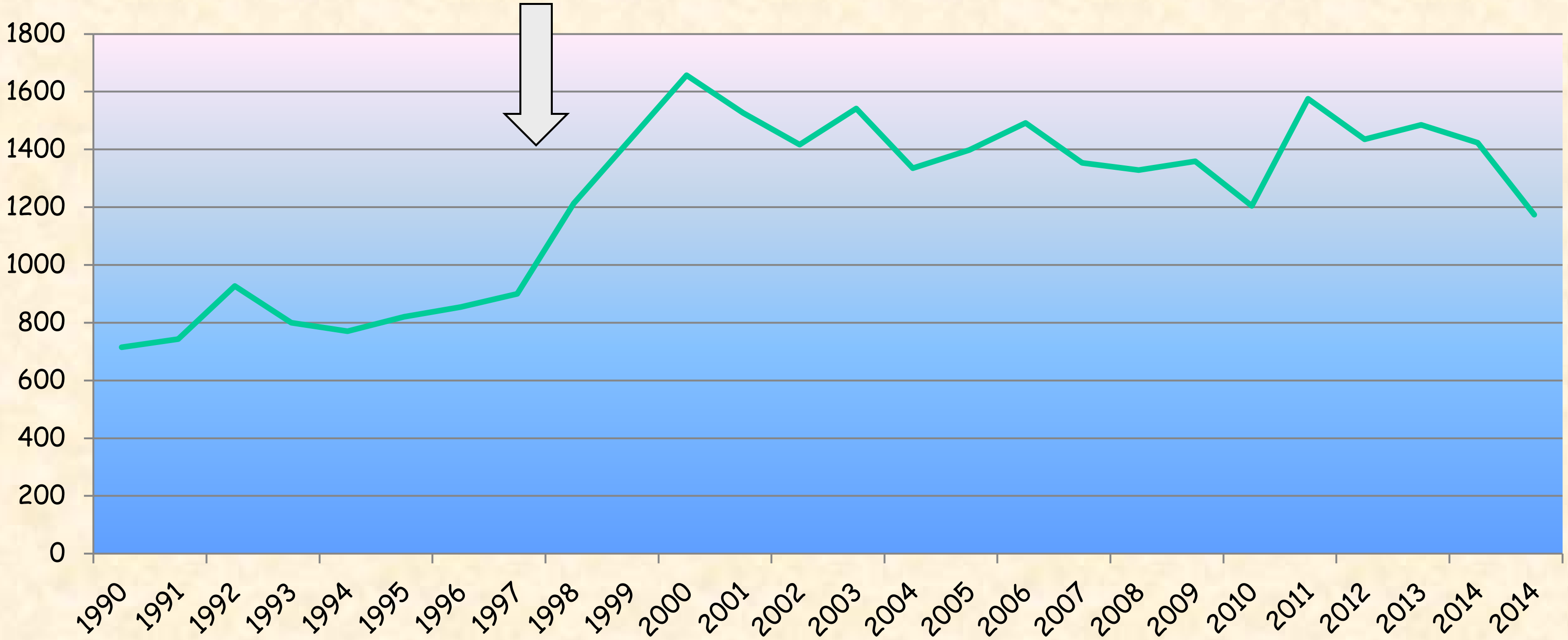
Y. Fukuda, *et al.*, [Super-Kamiokande Collaboration]
``**Evidence for oscillation of atmospheric neutrinos**,''
Phys.\ Rev.\ Lett.\ {\bf 81}, 1562 (1998)
[hep-ex/9807003]
4594 citations counted in INSPIRE as of 23 Oct 2015



Titles including "neutrino" per year

From SPIRES 2015

SuperK
Oscillations
Discovery

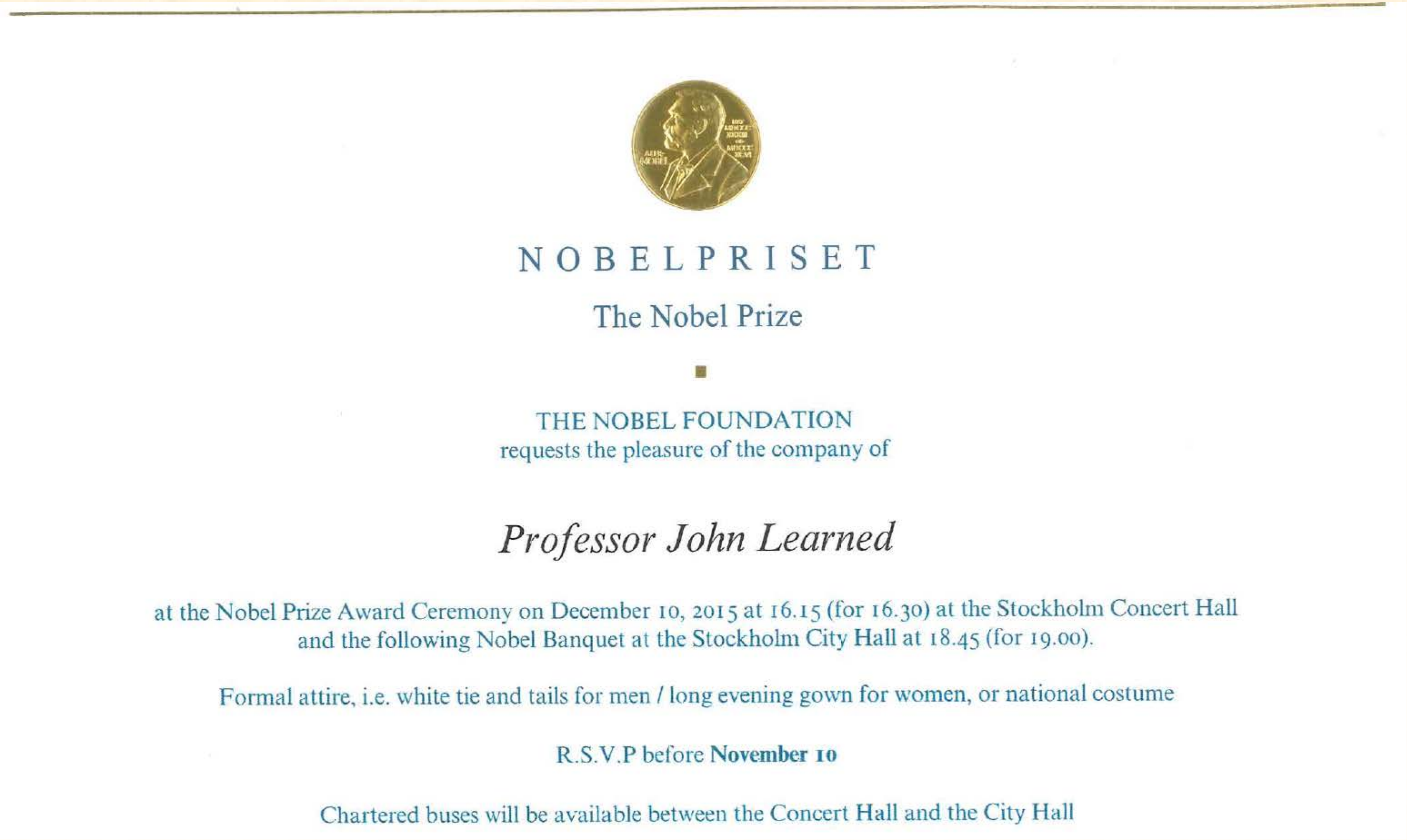


SuperK Oscillation Discovery Credits

How does Nobel Committee give credit to a group? Not an easy problem

- **Yoji Totsuka** of U. Tokyo did a great job in getting SK built and operating, and he would be going to Stockholm, except very sadly he died in 2008.
- The experiment is effectively two groups, one (LOE) working on the solar neutrinos (*MeV*), and one (ATMPD) on higher energy mostly atmospheric neutrinos (*GeV*). (**Yoichiro Suzuki** and **Masayuki Nakahata** were in solar group, and hence left out from Nobel).
- The ATMPD analysis group was lead by **Takaaki Kajita** of U. Tokyo and **Ed Kearns** of Boston U., for all these years.
- The Paper Committee which wrote the now famous discovery paper consisted of **Yoshitaka Itow, Kenji Kaneyuki (deceased), Takaaki Kajita, Ed Kearns, John Learned, Mark Messier, Ken Young (deceased).**
- **Many others** of the 122 authors (6 from UH) made significant contributions. The SK Japanese leadership was very generous and accommodating to the US group to encourage our strong role when they put so much time and money into building the detector.
- Ken Young (U. Wash.) and John Learned were perhaps ahead in the collaboration in early oscillations analysis, new methods and first paper drafts. In the end probably twenty people did the real work.

Yes, JGL did get invited to Stockholm



NOBELPRISET

The Nobel Prize

THE NOBEL FOUNDATION
requests the pleasure of the company of

Professor John Learned

at the Nobel Prize Award Ceremony on December 10, 2015 at 16.15 (for 16.30) at the Stockholm Concert Hall and the following Nobel Banquet at the Stockholm City Hall at 18.45 (for 19.00).

Formal attire, i.e. white tie and tails for men / long evening gown for women, or national costume

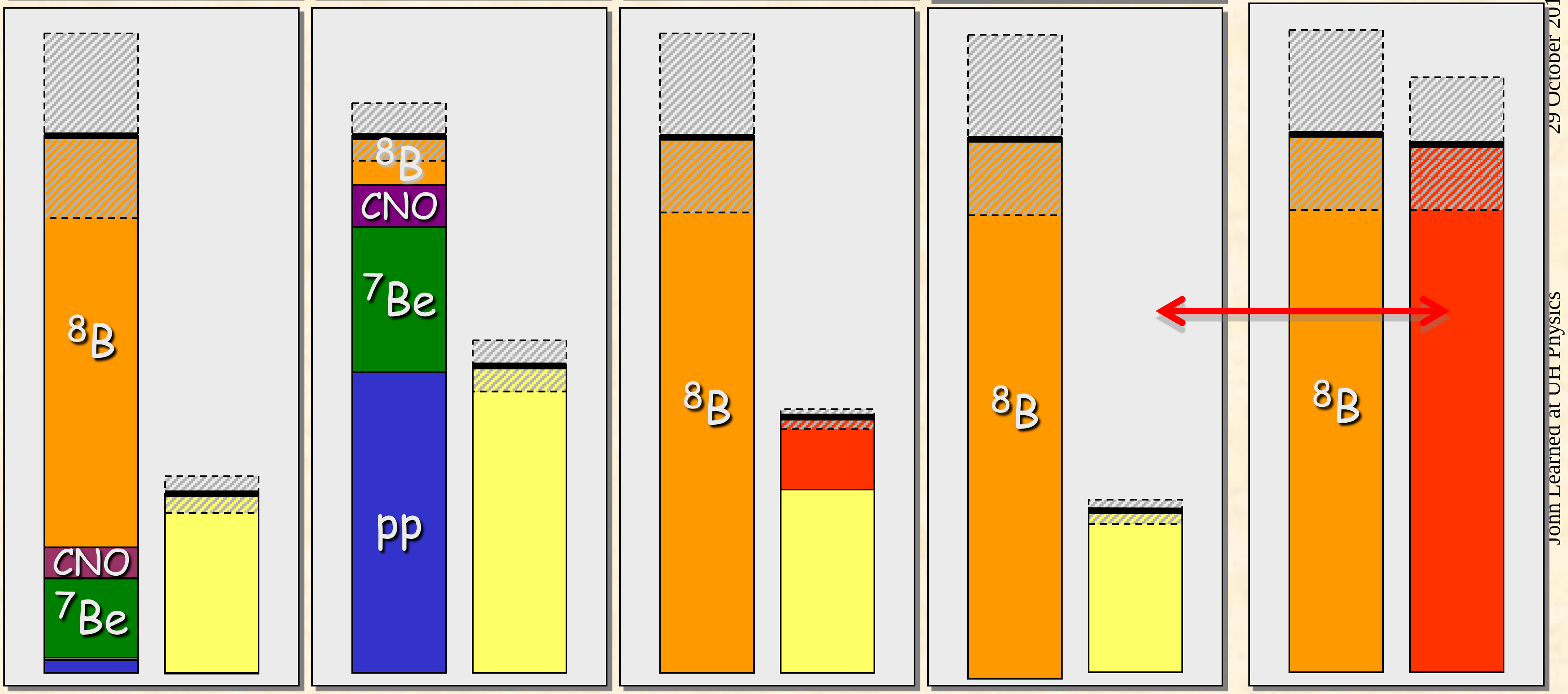
R.S.V.P before **November 10**

Chartered buses will be available between the Concert Hall and the City Hall

SNO Settles the Solar Neutrino Problem

in 2002 and Art McDonald goes to Stockholm in 2015

Homestake	Gallex/GNO SAGE	Super-Kamiokande	SNO (Deuterium)	
Chlorine	Gallium	Water	$\nu_e + d \rightarrow p + p + e^-$	$\nu + d \rightarrow p + n + \nu$

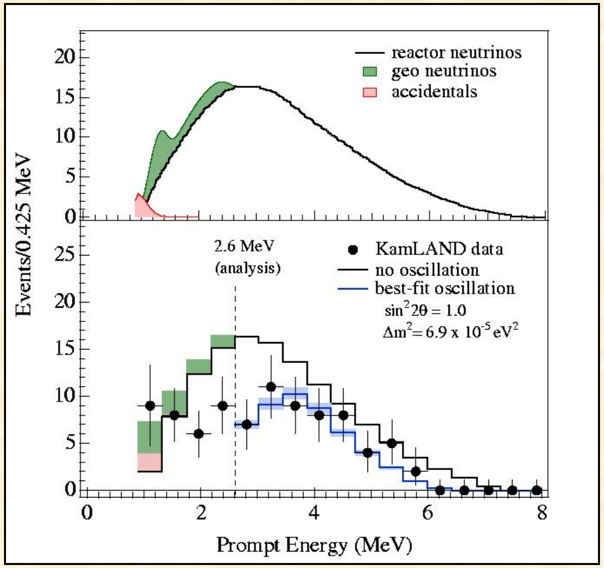


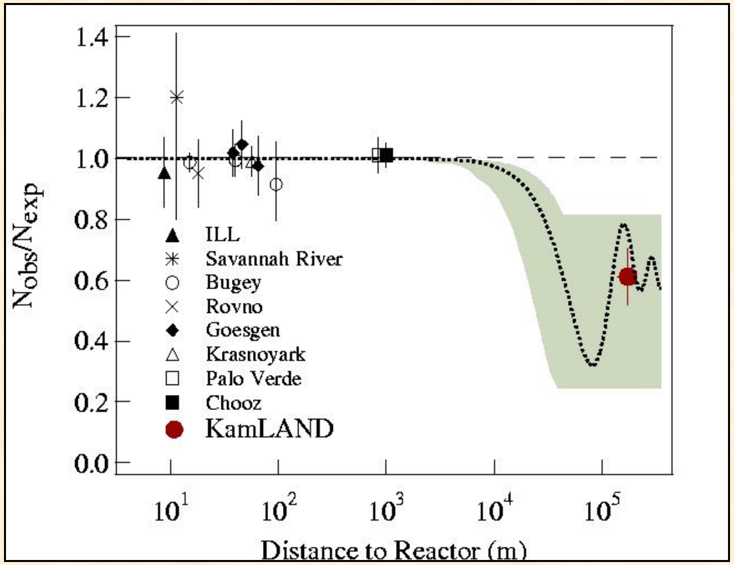
Electron-Neutrinos

All Neutrino Types

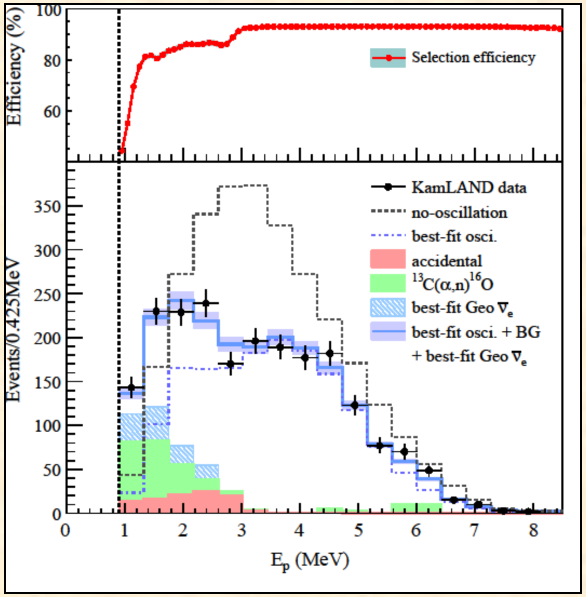
KamLAND => no escaping oscillations in 2003…

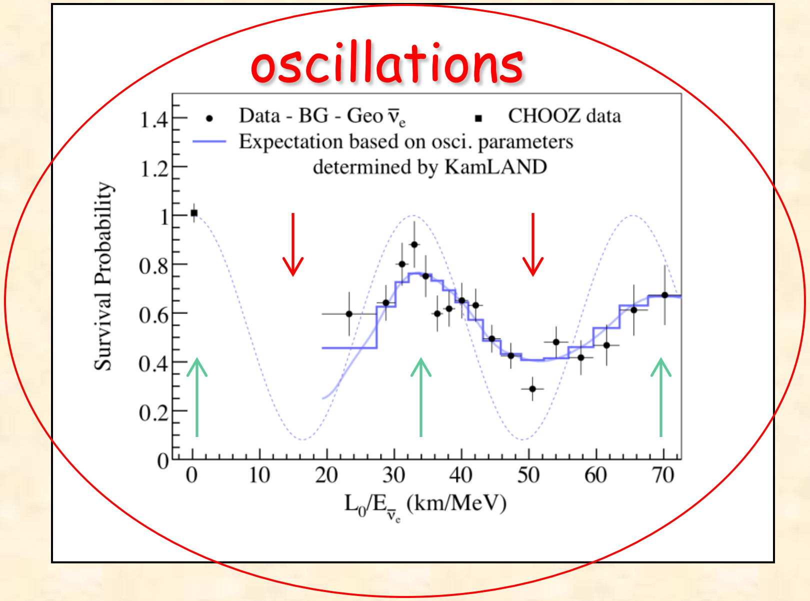
2003





2010

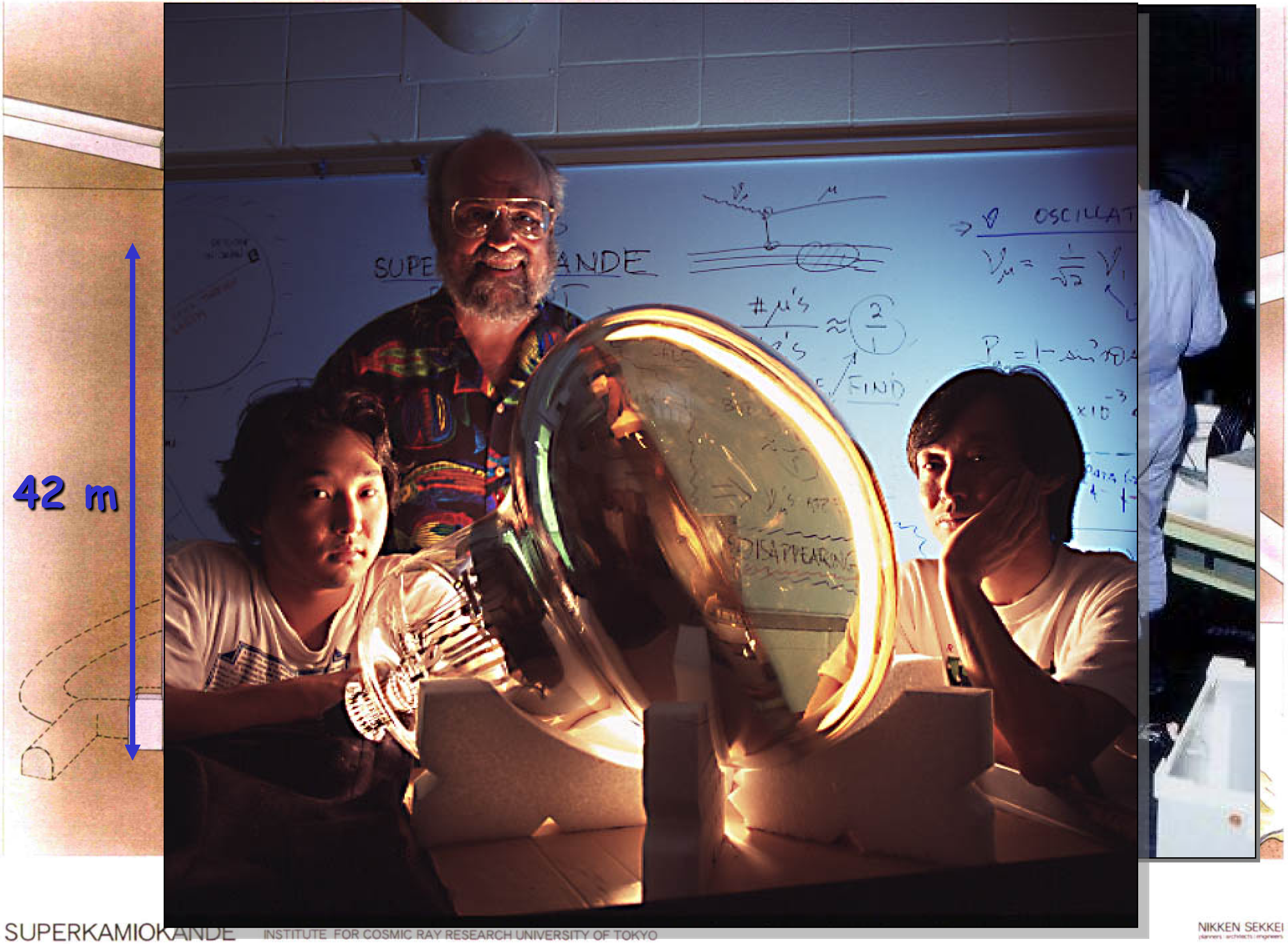



oscillations

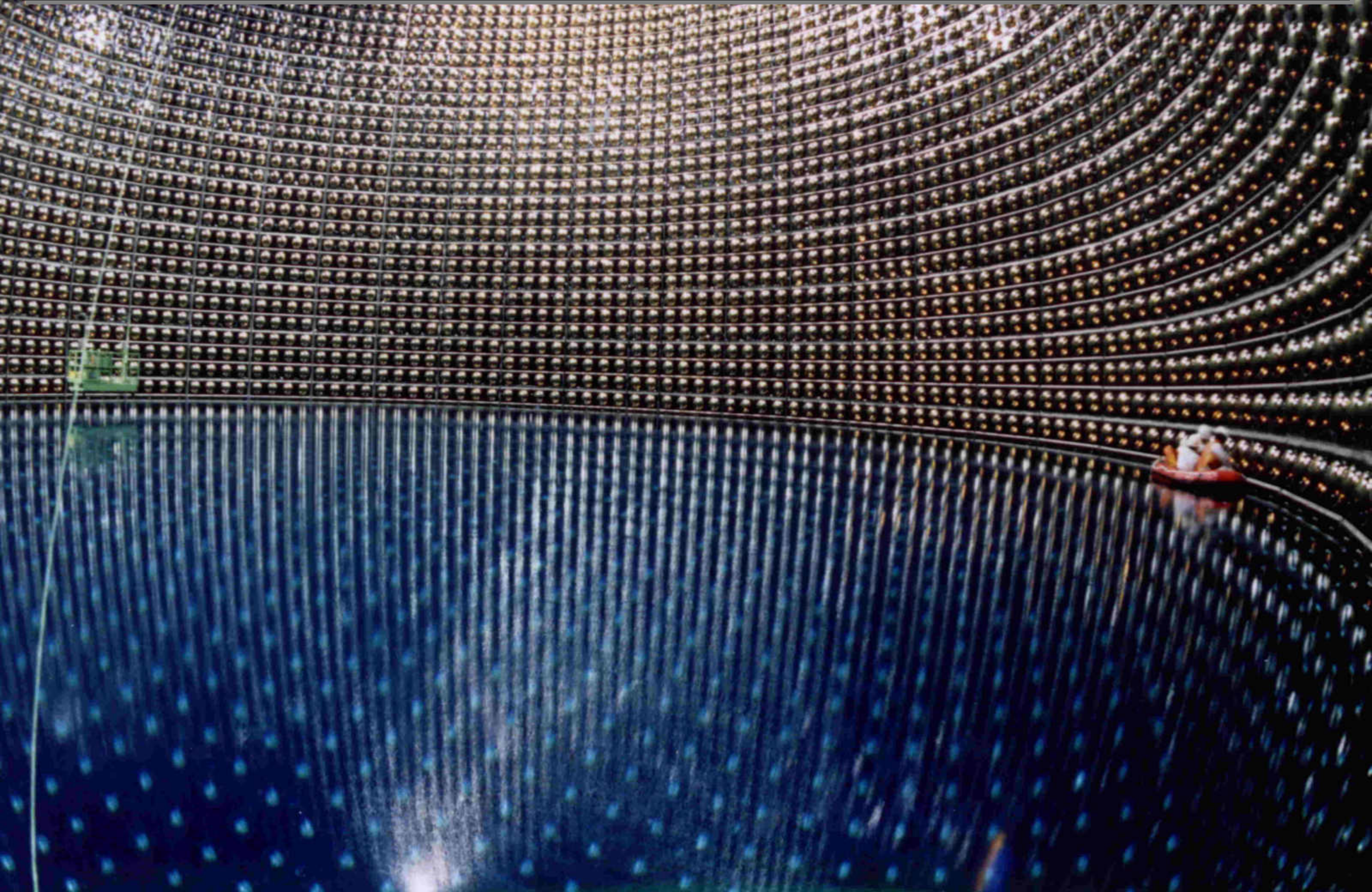
A quick tour of the SuperK area

Photos around Kamioka-Mozumi Japan ~2000


SUPER K®
FORTUNE COOKIE
KARI-OUT CO., NY
1-800-433-8789
SUPER K®
FORTUNE COOKIE
KARI-OUT CO., NY
1-800-433-8789


42 m
SUPE ANDE
ν OSCILLAT
#μ's
FIND
DISAPPEARING
SUPERKAMIOKANDE
INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO
NIKKEN SEKKEI
planners | architects | engineers

Filling the Tank and Polishing the PMTs



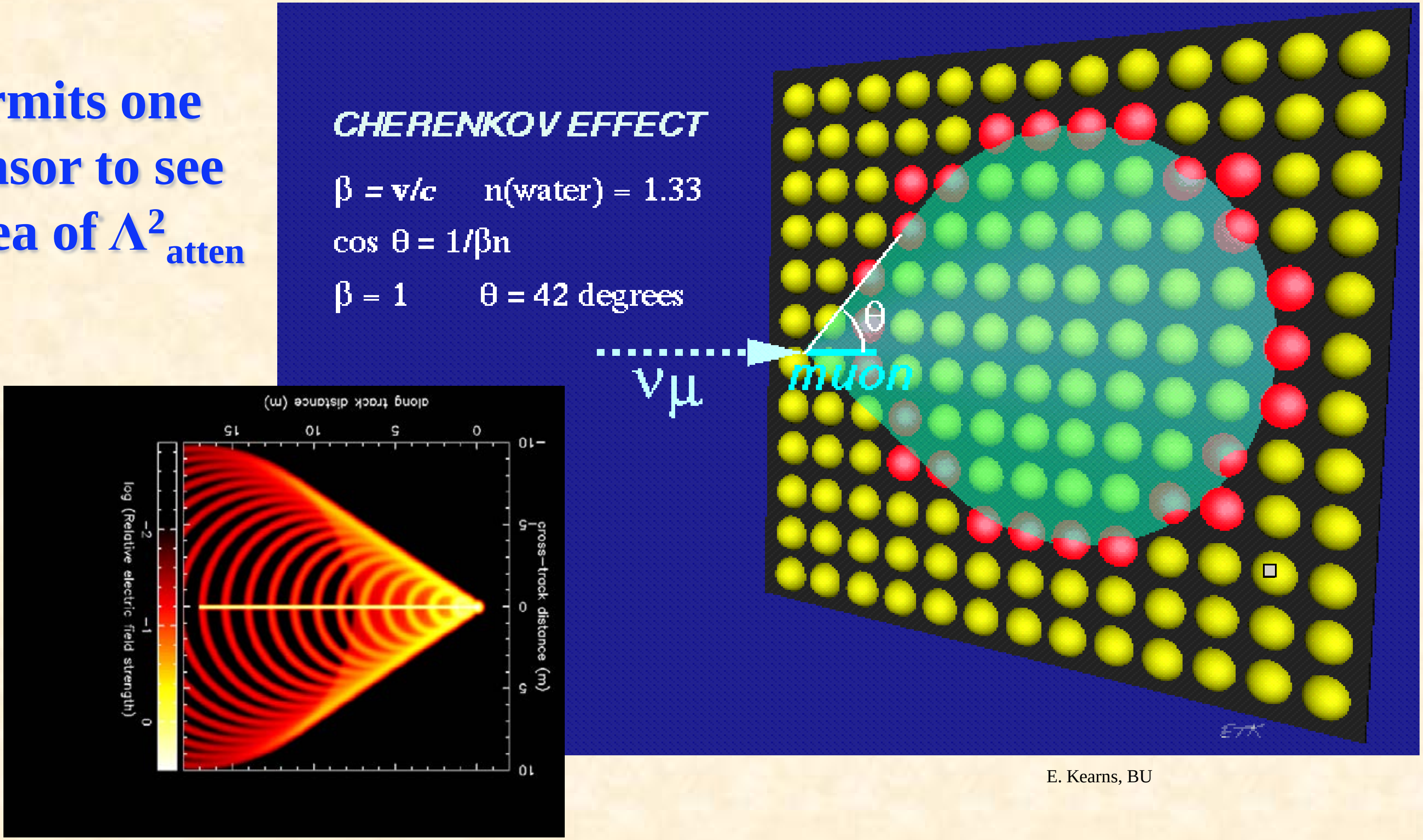
How does SuperK detect particles?

Neutrinos are invisible, forget it!

But after exceedingly rare neutrino collision
phototubes see light produced by charged particles

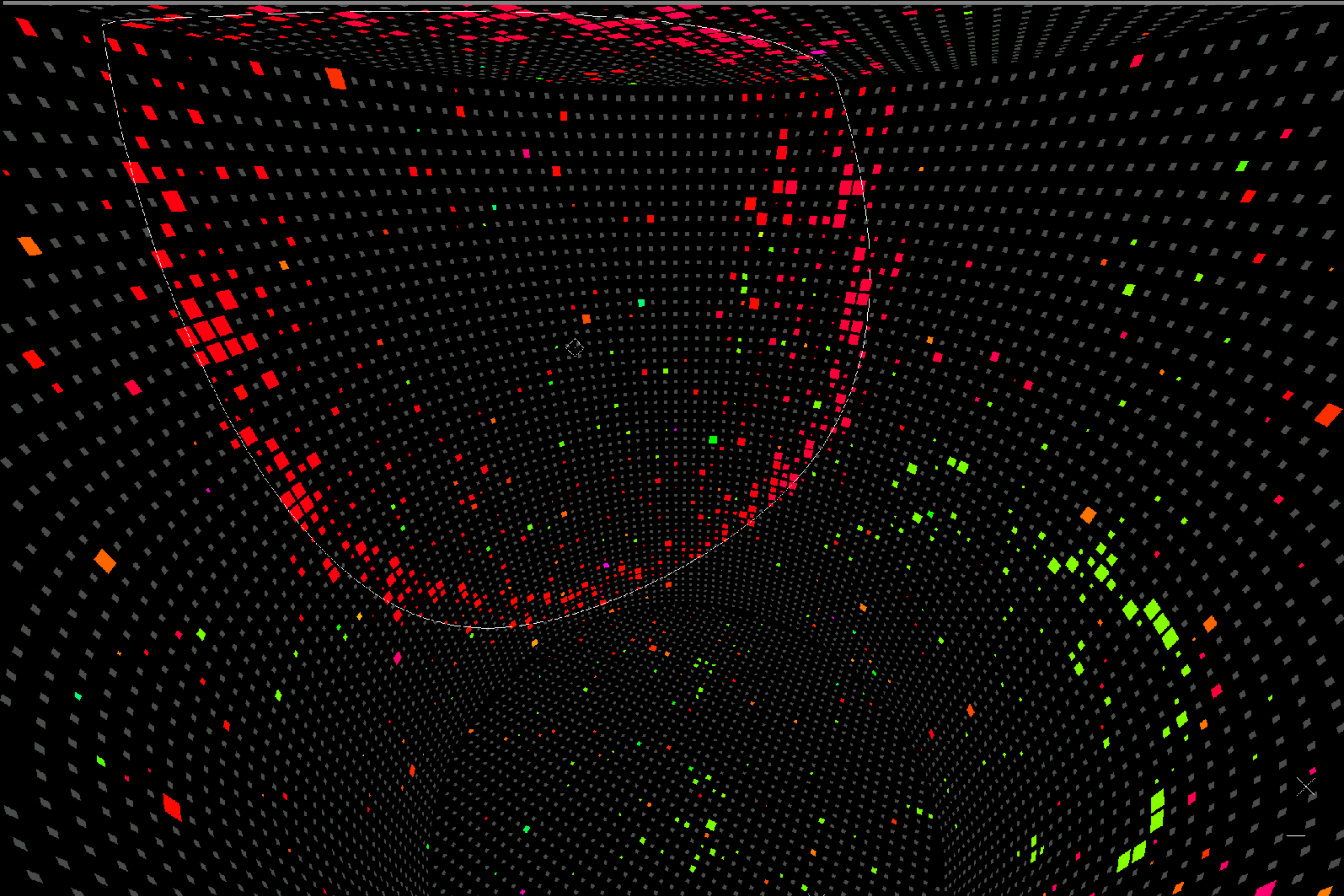
Favorite Technique: Optical and Radio
Cherenkov Radiation

Permits one Sensor to see Area of Λ^2_{atten}



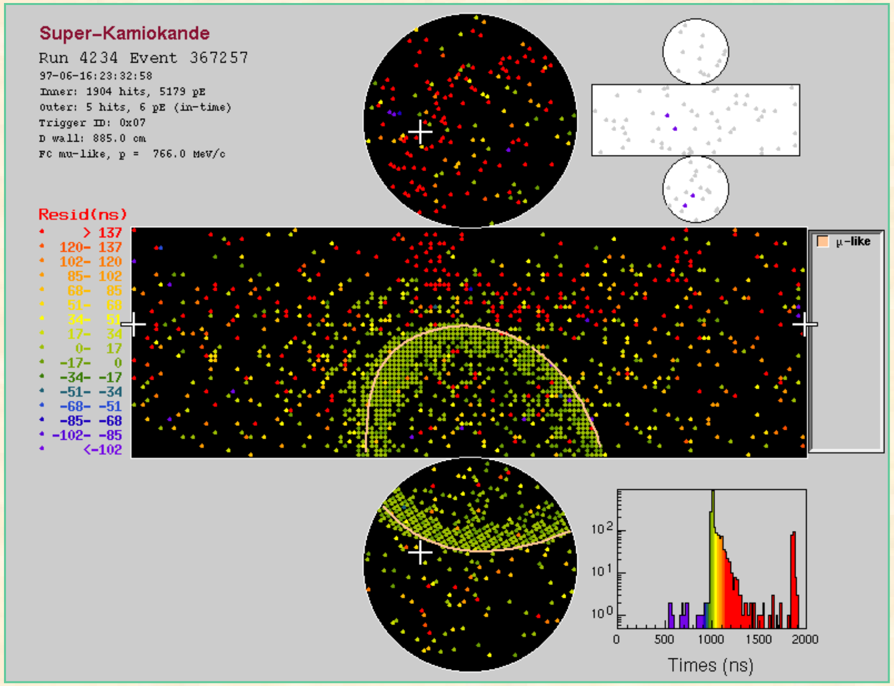
E. Kearns, BU

Computer Generated Recording of an Event



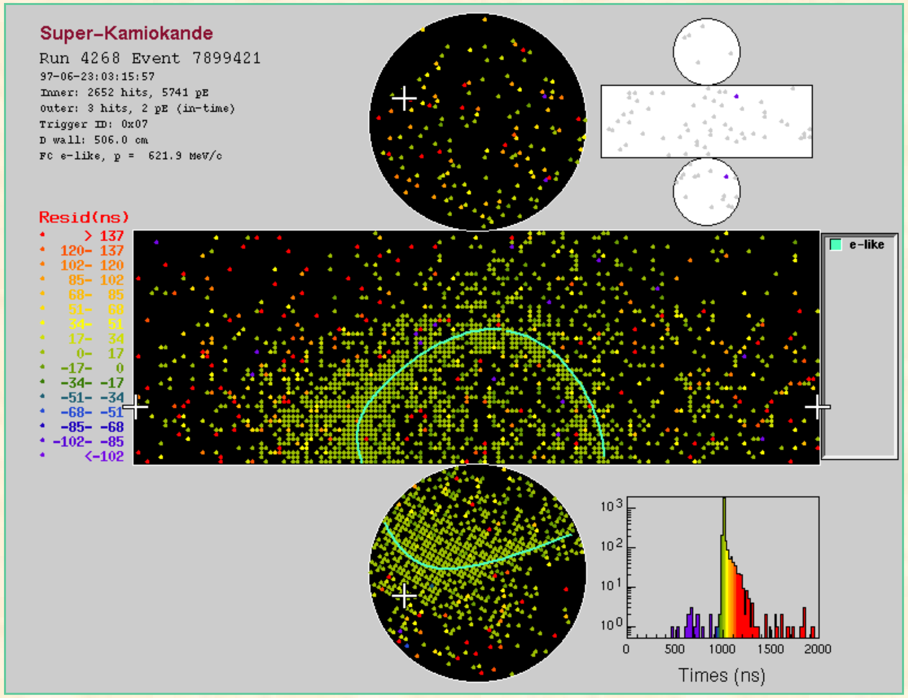
SK Muon and Electron Identification is Excellent

Muon Neutrino Event



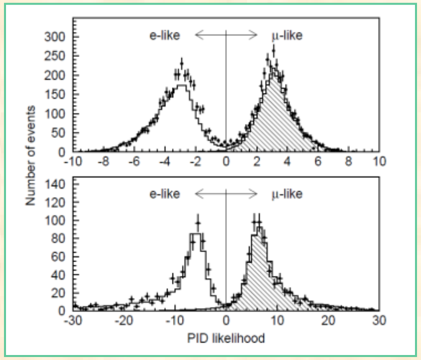
```
Super-Kamiokande
Run 4234 Event 367257
97-06-16:23:32:58
Inner: 1904 hits, 5179 pE
Outer: 5 hits, 6 pE (in-time)
Trigger ID: 0x07
D wall: 885.0 cm
FC mu-like, p =  766.0 MeV/c
```

Electron Neutrino Event



```
Super-Kamiokande
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5741 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x07
D wall: 506.0 cm
FC e-like, p =  621.9 MeV/c
```

Easily Separated



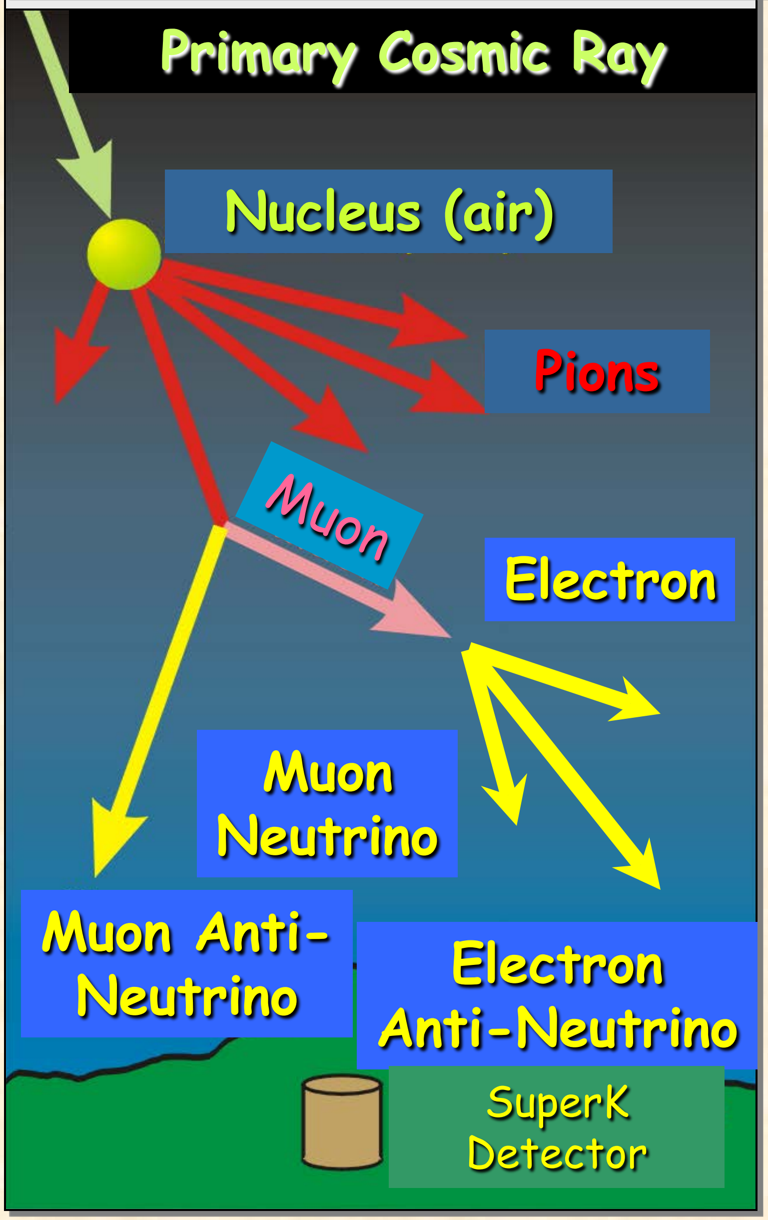
BU Website

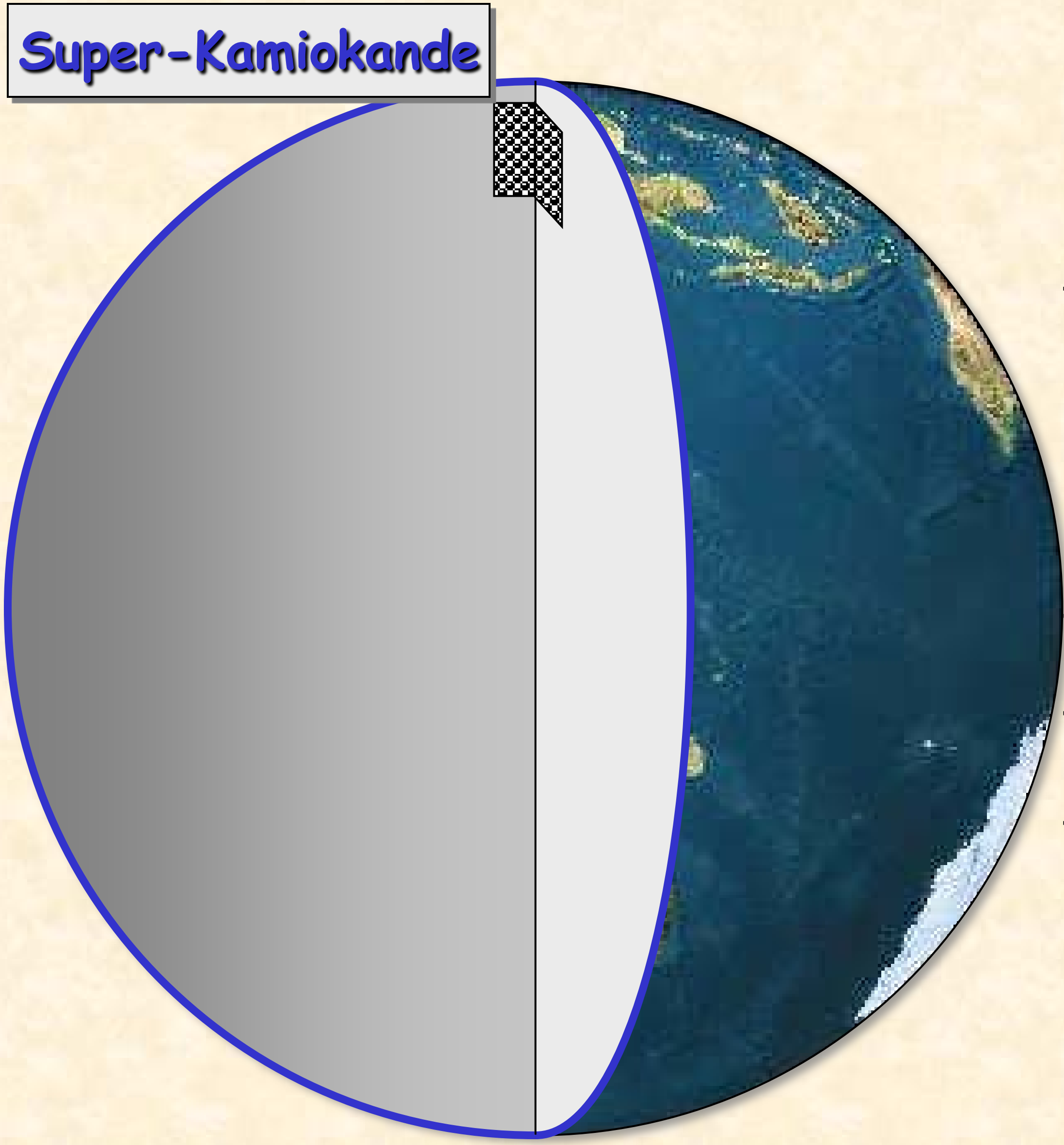
What did we see in SuperK?

Cosmic ray generated neutrinos
which came through the earth,
but lots of muon neutrinos missing

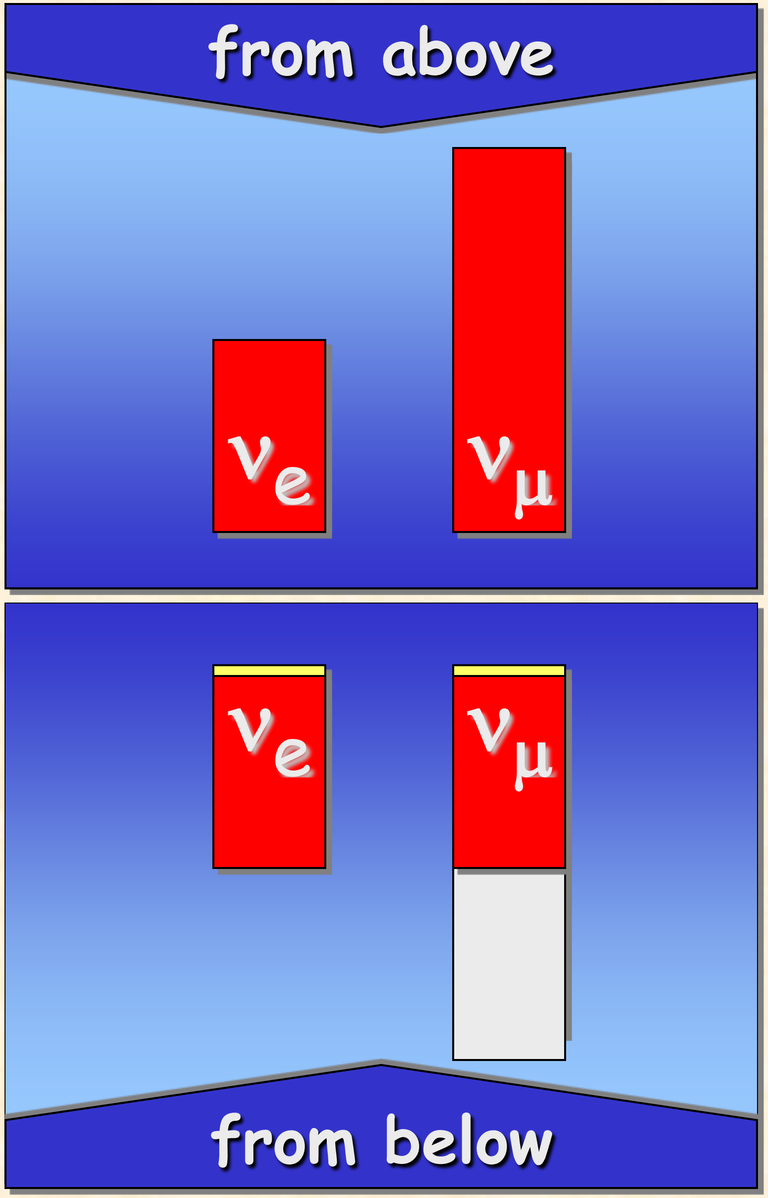
(and much more).

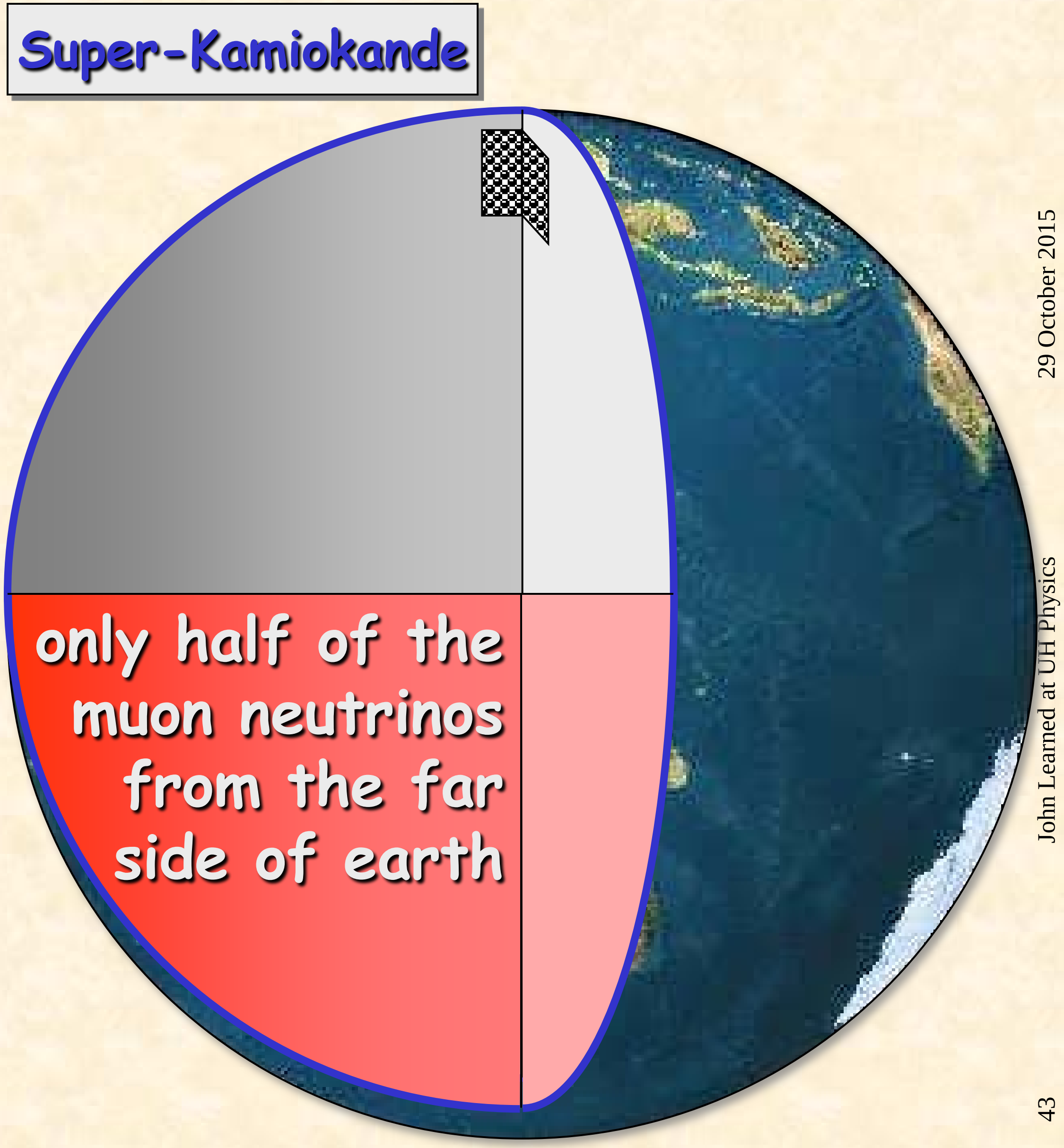
Atmospheric Neutrino Flux





SK Explains Atmospheric Neutrino Anomaly





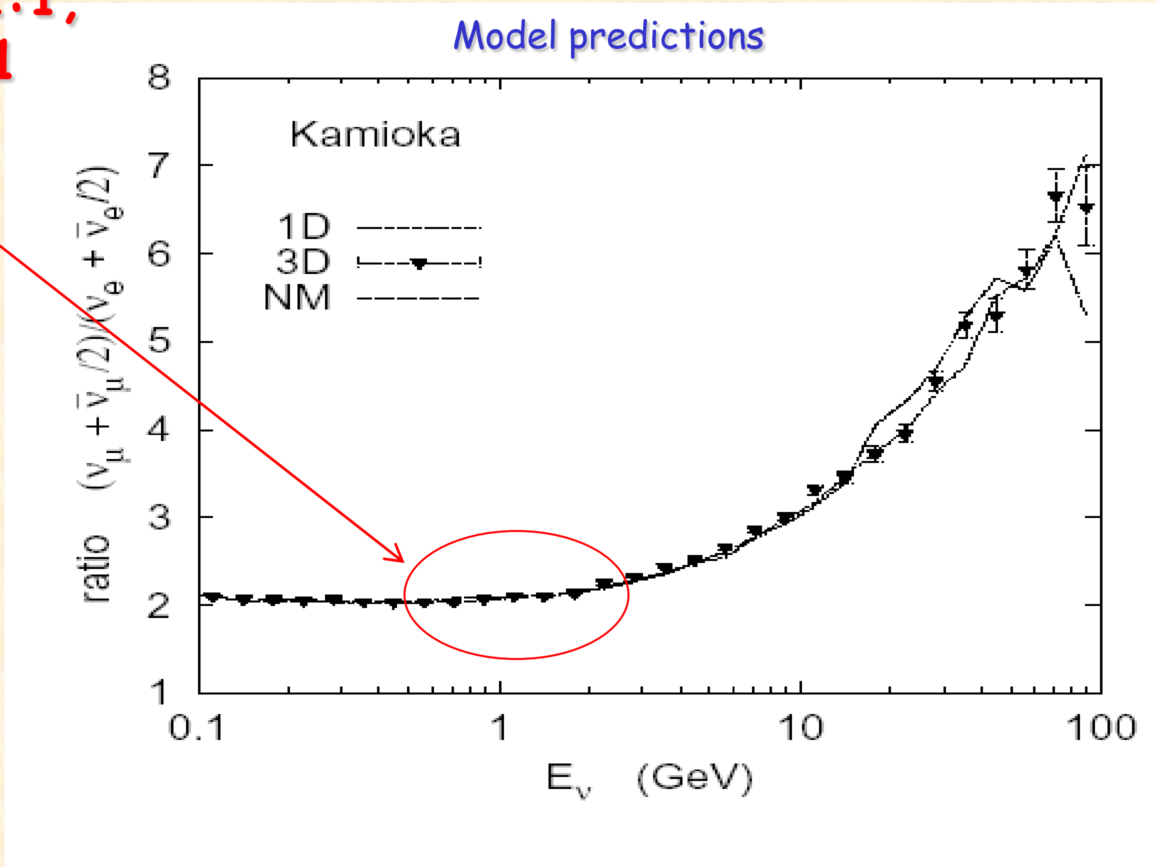
only half of the muon neutrinos from the far side of earth

Expected e/μ Flavor Ratio Not in Doubt

At energies <2 GeV expected **2 μ : 1 e ratio** determined by very **well known decay kinematics**:

$\pi^- \to \mu^- + \bar{\nu}_\mu$, $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

$\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

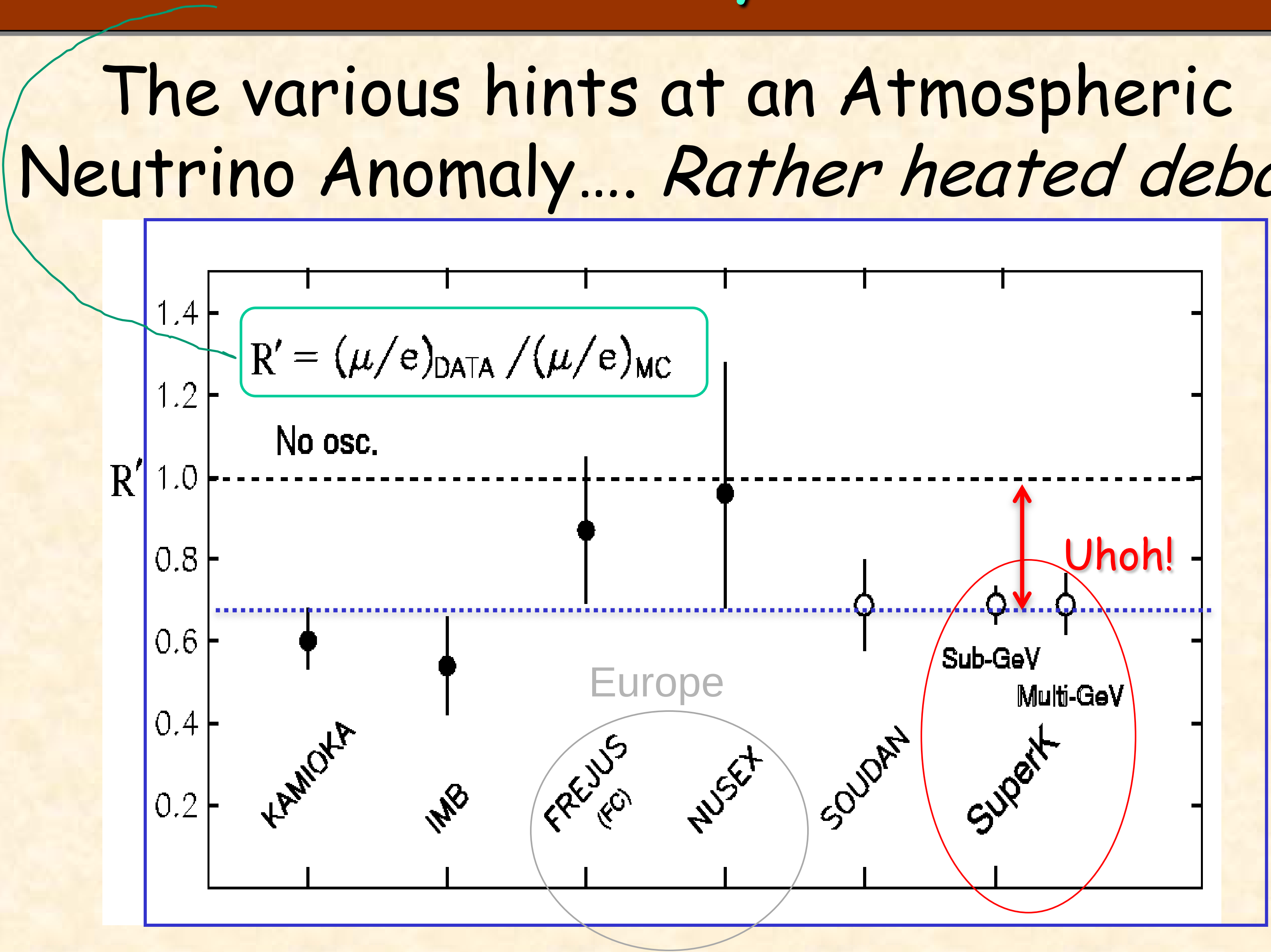


Should have been 2:1,
But we saw ~ 1:1

Model predictions

The R Value Controversy since the 1980's

The various hints at an Atmospheric Neutrino Anomaly…. *Rather heated debate*



R's need not agree if oscillations present… depend on E bite

Two-Neutrino Oscillation

- When produced (*e.g.*, $\pi^+ \rightarrow \mu^+ \nu_\mu$), the neutrino is of a particular type

$$\left|\nu_\mu, t\right\rangle = |1\rangle \cos\theta\, e^{-i m_1^2 t/2p} + |2\rangle \sin\theta\, e^{-i m_2^2 t/2p}$$

- No longer 100% ν_μ, partly ν_τ!
- "Survival probability" for ν_μ after *t*

mixing fraction Nu mass diff squared L

$$P = \left|\left\langle \nu_\mu \middle| \nu_\mu, t\right\rangle\right|^2 = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 c^4}{\mathrm{eV}^2} \frac{\mathrm{GeV}}{c|\vec{p}|} \frac{ct}{\mathrm{km}}\right)$$

E

Depends upon Flight time in the neutrino rest frame: ~L/E

First SuperK Oscillations Paper

Huge Discrepancy… not questionable small effect

e's OK

mu's ~~OK~~

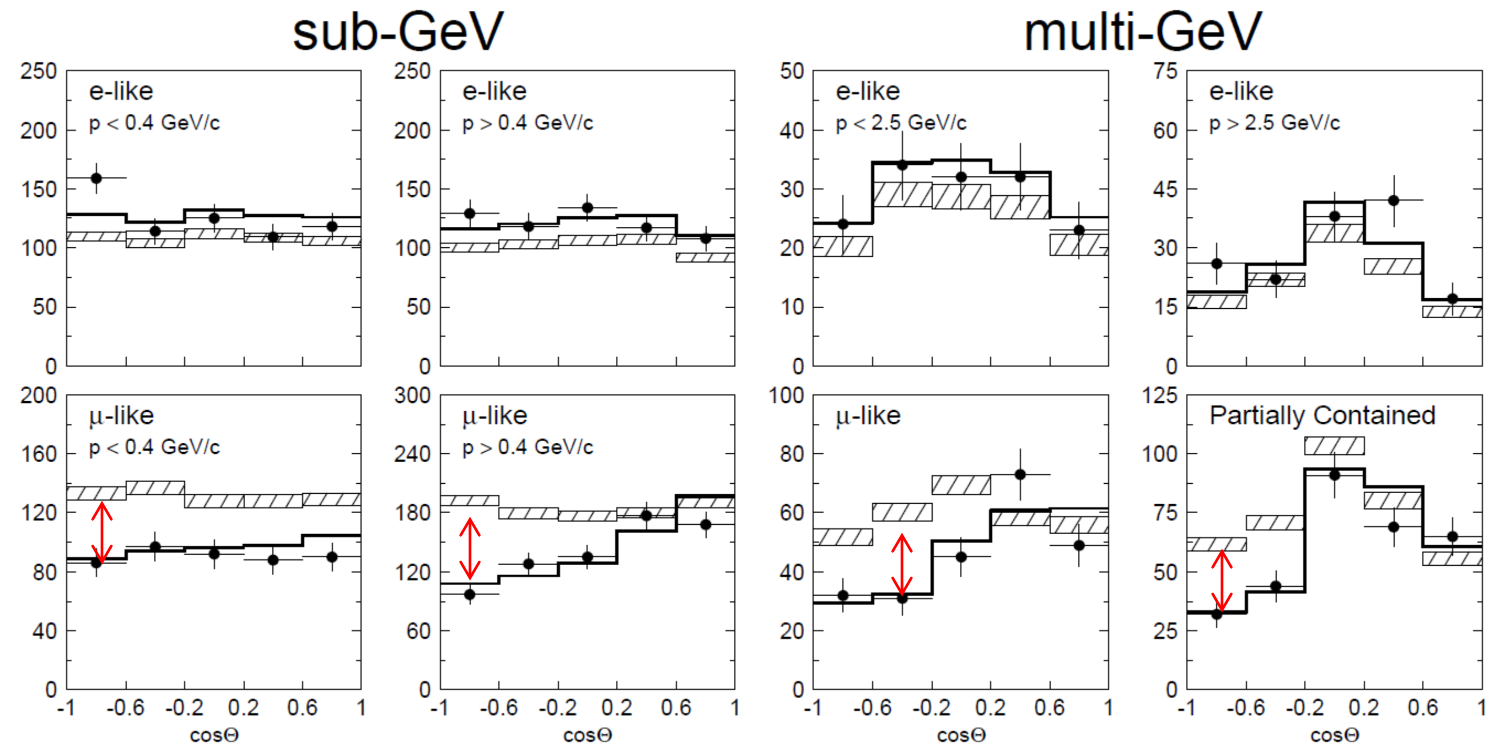


FIG. 3. Zenith angle distributions of μ-like and e-like events for sub-GeV and multi-GeV data sets. Upward-going particles have $\cos\Theta < 0$ and downward-going particles have $\cos\Theta > 0$. Sub-GeV data are shown separately for $p < 400$ MeV$/c$ and $p > 400$ MeV$/c$. Multi-GeV e-like distributions are shown for $p < 2.5$ GeV$/c$ and $p > 2.5$ GeV$/c$ and the multi-GeV μ-like are shown separately for FC and PC events. The hatched region shows the Monte Carlo expectation for no oscillations normalized to the data live-time with statistical errors. The bold line is the best-fit expectation for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with the overall flux normalization fitted as a free parameter.

More from SK Discovery Paper

e

μ

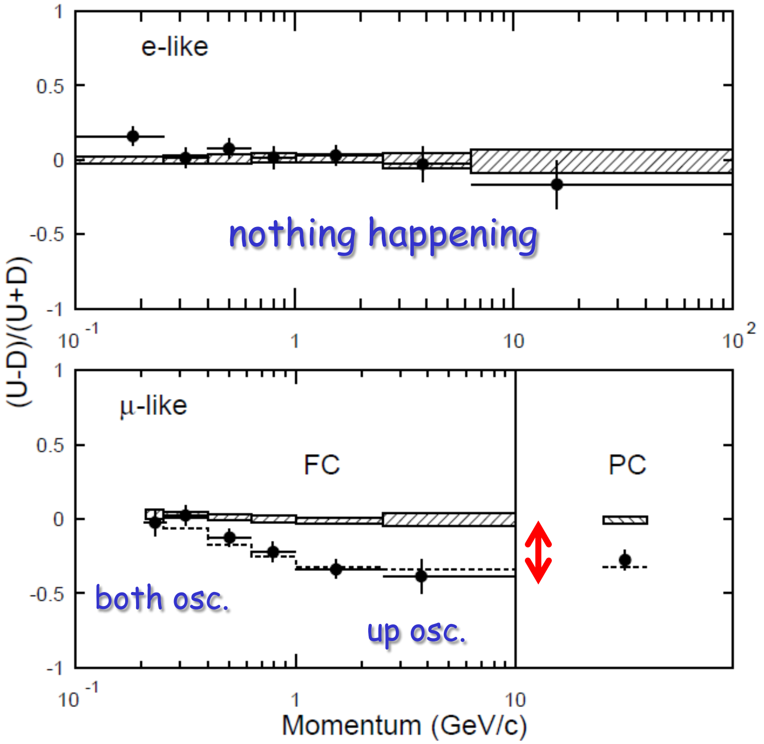


FIG. 1. The $(U - D)/(U + D)$ asymmetry as a function of momentum for FC e-like and μ-like events and PC events. While it is not possible to assign a momentum to a PC event, the PC sample is estimated to have a mean neutrino energy of 15 GeV. The Monte Carlo expectation without neutrino oscillations is shown in the hatched region with statistical and systematic errors added in quadrature. The dashed line for μ-like is the expectation for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $(\sin^2 2\theta = 1.0, \Delta m^2 = 2.2 \times 10^{-3}\ \text{eV}^2)$.

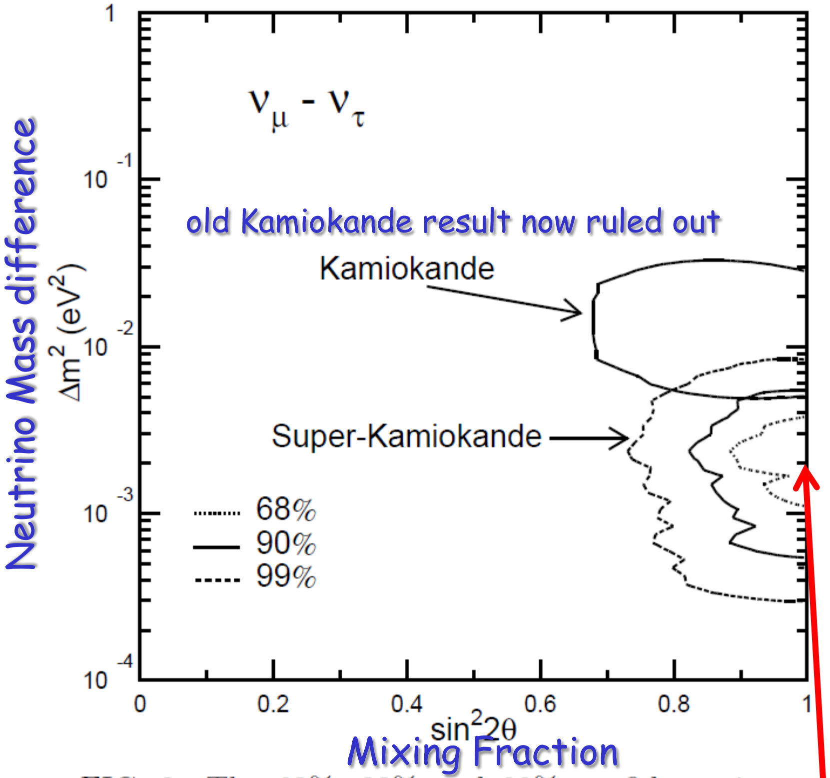


FIG. 2. The 68%, 90% and 99% confidence intervals are shown for $\sin^2 2\theta$ and Δm^2 for $\nu_\mu \leftrightarrow \nu_\tau$ two-neutrino oscillations based on 33.0 kiloton-years of Super–Kamiokande data. The 90% confidence interval obtained by the Kamiokande experiment is also shown.

Maximal Mixing

SuperK Paper goes viral

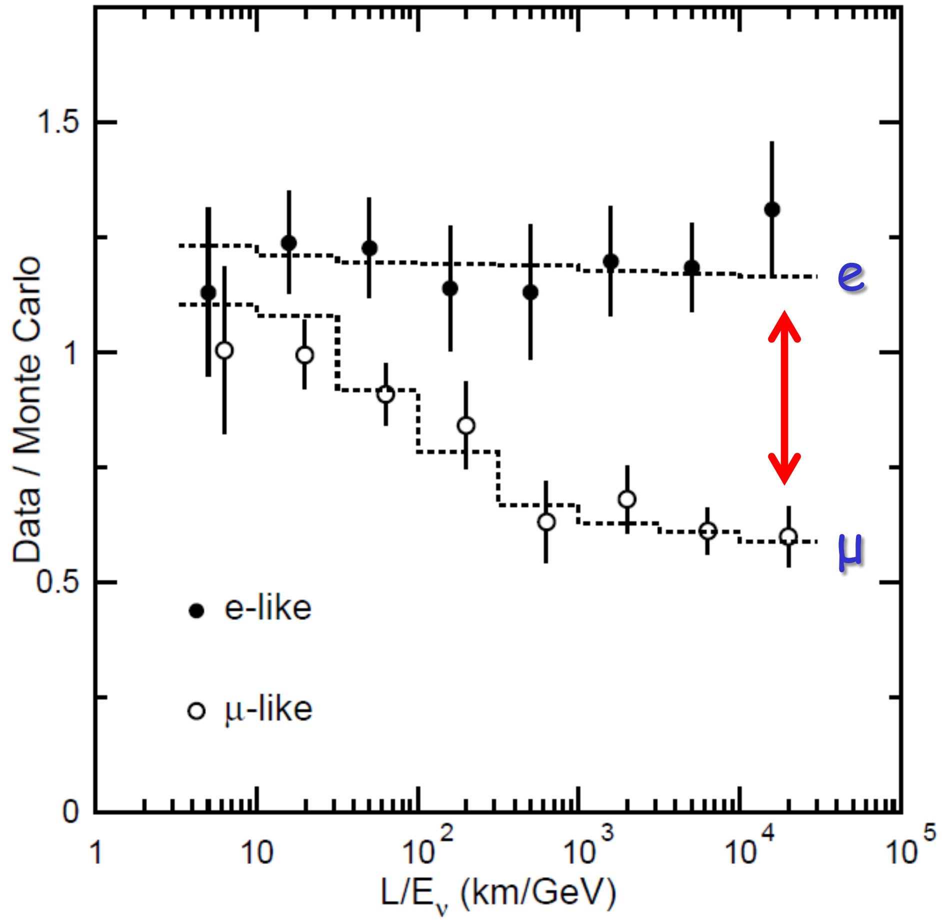


FIG. 4. The ratio of the number of FC data events to FC Monte Carlo events versus reconstructed L/E_ν. The points show the ratio of observed data to MC expectation in the absence of oscillations. The dashed lines show the expected shape for $\nu_\mu \leftrightarrow \nu_\tau$ at $\Delta m^2 = 2.2 \times 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta = 1$. The slight L/E_ν dependence for e-like events is due to contamination (2-7%) of ν_μ CC interactions.

The Muons are Oscillating

SuperK neutrino oscillations paper soon was most cited paper in history of experimental particle physics

Phys. Rev. Lett. **81**, 1562 (1998).

Neutrino Anomaly Alternative Hypotheses from ~1998

Evidence	Old			New from SK			
Hypothesis	R E .lt. 1 GeV	mudk Frac	Vol Frac	R E .gt. 1 GeV	A_e ~0	A_mu .gt. 0	R(L/E) ~0.5
Atm. Flux Calc.	xx			x		x	x
Cross Sections	xx			x		x	
Particle Ident.		xx	xx				
Entering Bkgrd.			xx			x	
Detector Asym.			xx				
X-Ter. nu_e						x	x
Proton Decay				x		x	
nu_mu Decay							x
nu_mu Abs.							x
nu_mu - nu_e					x		
nu_mu - nu_s							
nu_mu - nu_tau							

SK Rules out all but these

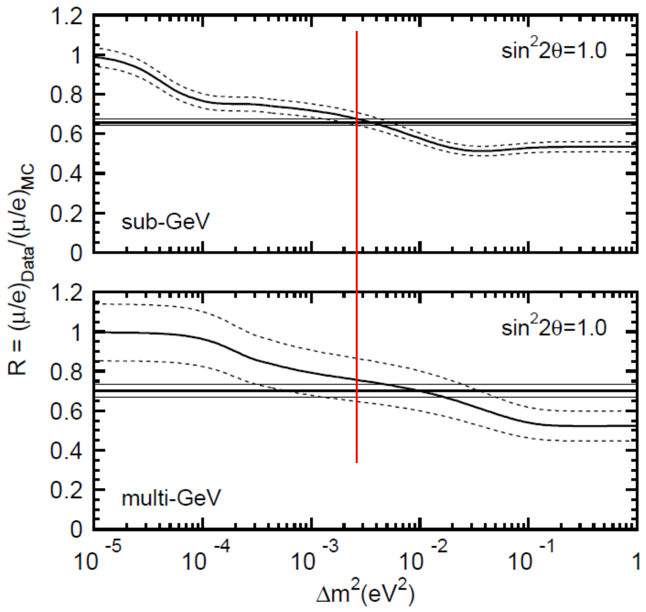
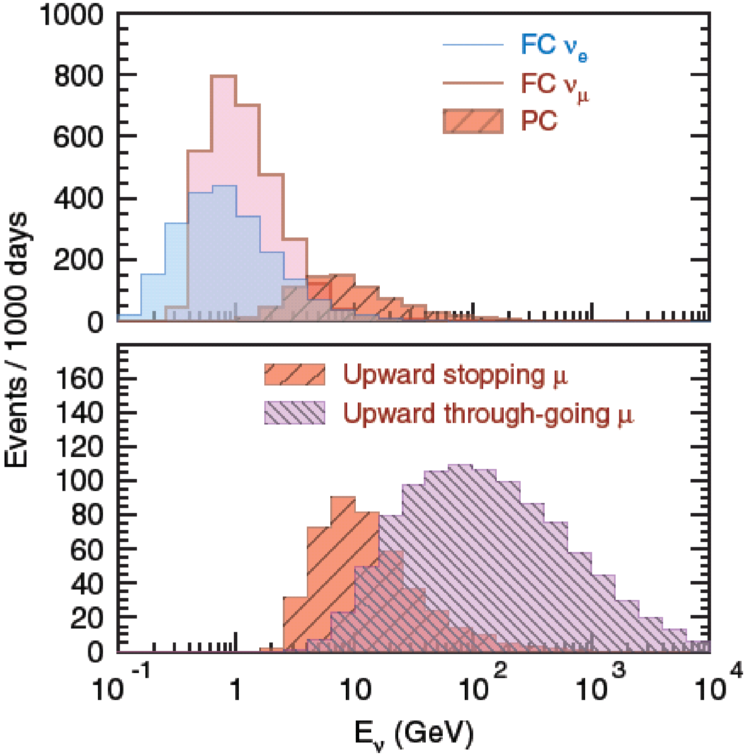


FIG. 30: Expected $(\mu/e)_{Data}/(\mu/e)_{MC}$ for singe-ring sub- and multi-GeV + PC samples as a function of Δm^2 for full $\nu_\mu \leftrightarrow \nu_\tau$ mixing. The values for the data together with $\pm 1\sigma$ statistical errors are shown by the horizontal lines. The systematic errors are shown by the band in the expectation.

2005 SK

Summary of SuperK I, 5 Years Data

5 decades of neutrino energy

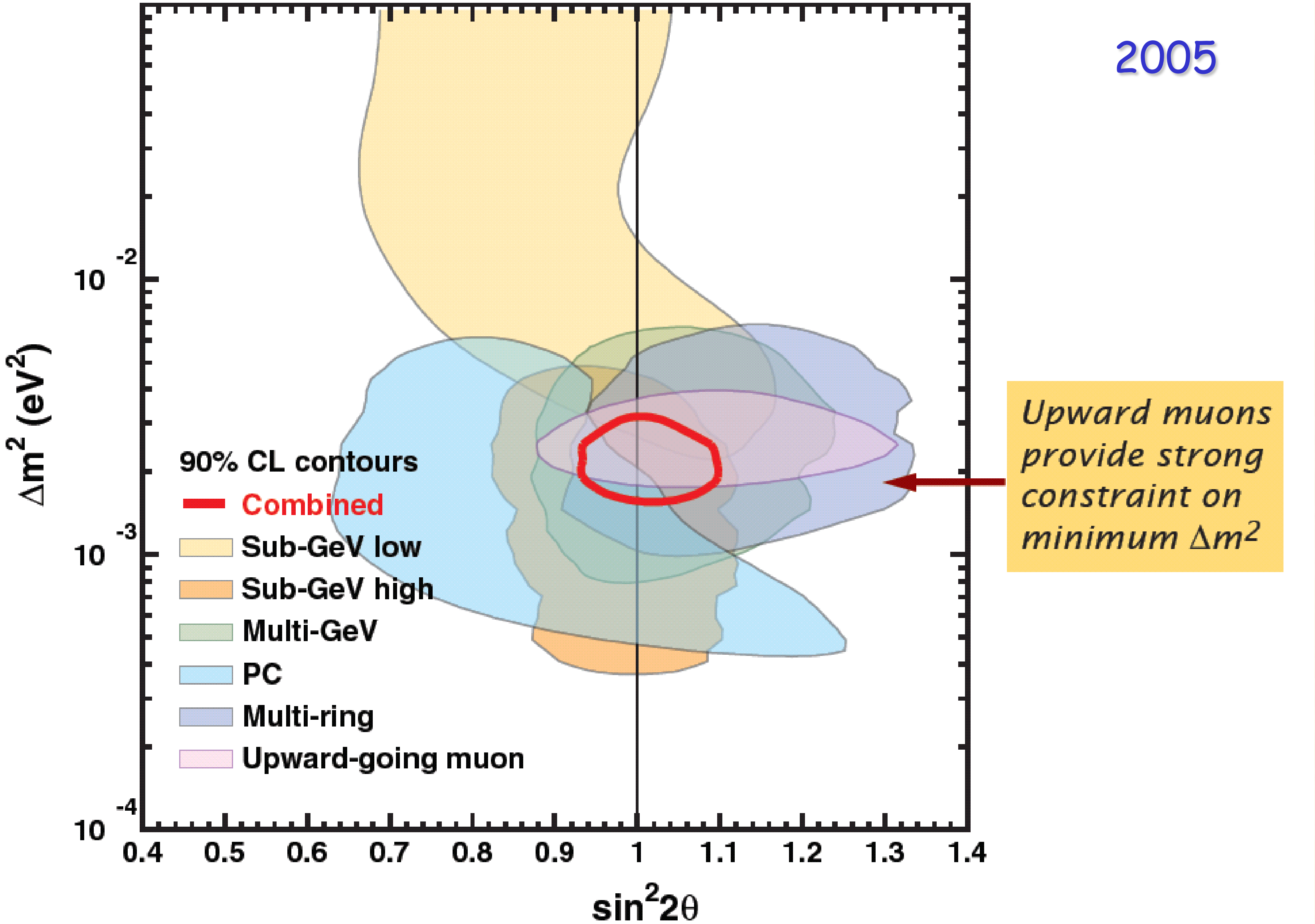


~14000 events total from data reduction

	DATA	MC	C.C. Purity
Sub-GeV 1-ring e-like	3353	2978.8	88.0%
Multi-GeV 1-ring e-like	746	680.5	82.6%
Sub-GeV 1-ring μ-like	3227	4212.8	94.5%
Sub-GeV Multiring μ-like	208	322.6	90.5%
Multi-GeV 1-ring μ-like	651	899.9	99.4%
Multi-GeV Multiring μ-like	439	711.9	95.0%
Partially Contained μ	647	1034.5	97.3%
Stopping Upward μ	417.7	721.4	~100%
Throughgoing Upward μ	1841.6	1684.4	~100%

11530 events used (80%) in oscillation analysis

SuperK Summary Muon Neutrino Oscillations Fits



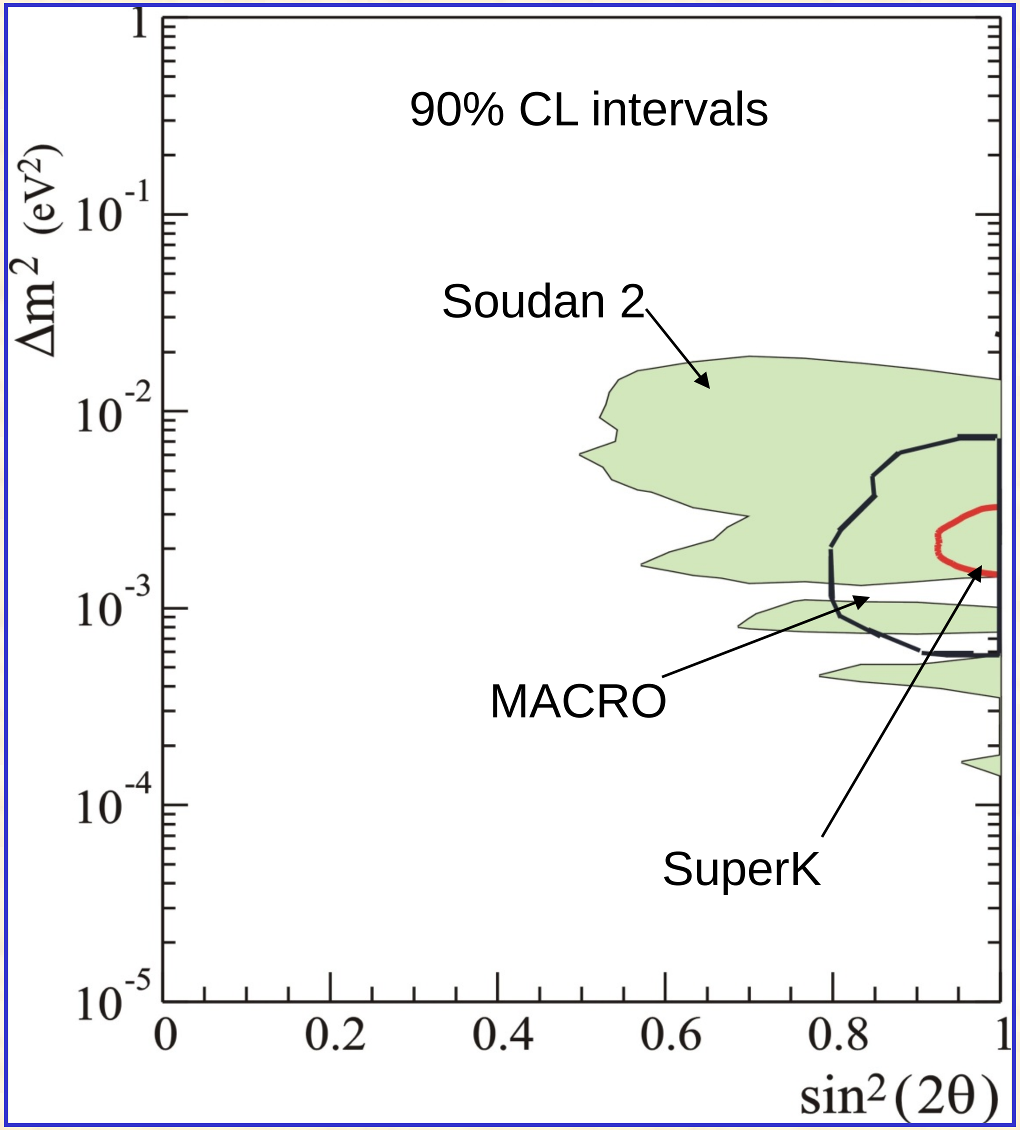
Upward muons provide strong constraint on minimum Δm^2

Several years later MACRO and Soudan confirm

Good consistency between results from SuperK, Soudan 2, and MACRO.

"Non-SuperK" atmospheric neutrinos from MINOS, K2K and others later re-affirm

.

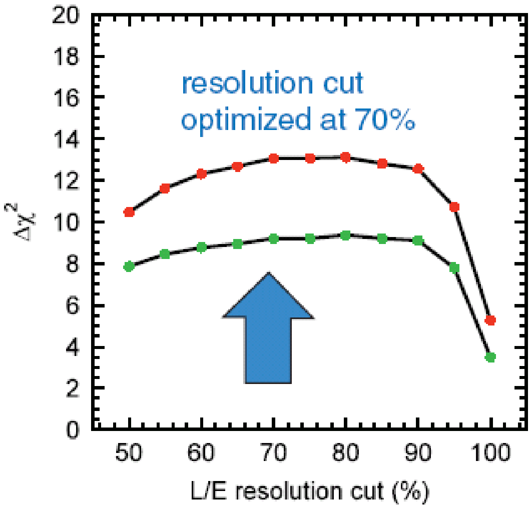


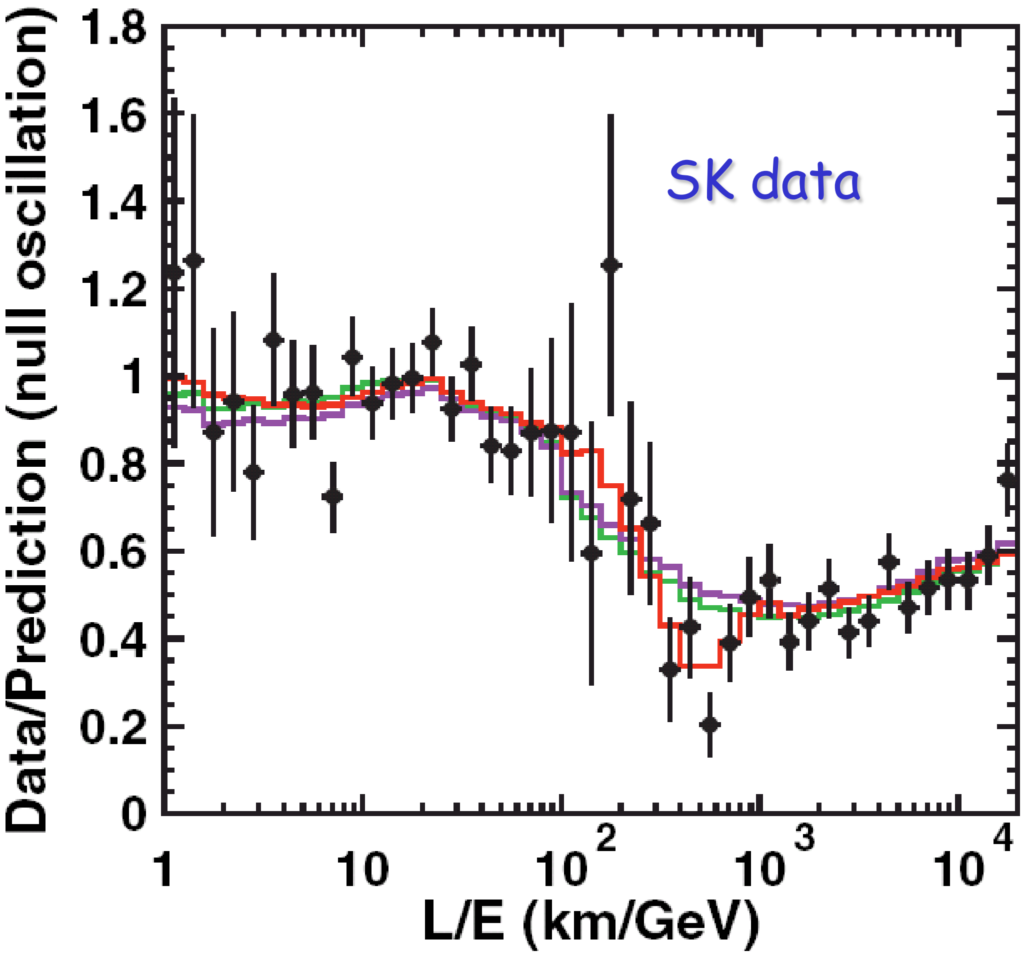
Nu Oscillations Work, Alternatives Dead

To evaluate significance of oscillation signature, we need a comparison shape (no oscillations too strongly ruled out by high L/E data)

Fit against: neutrino decay
neutrino decoherence

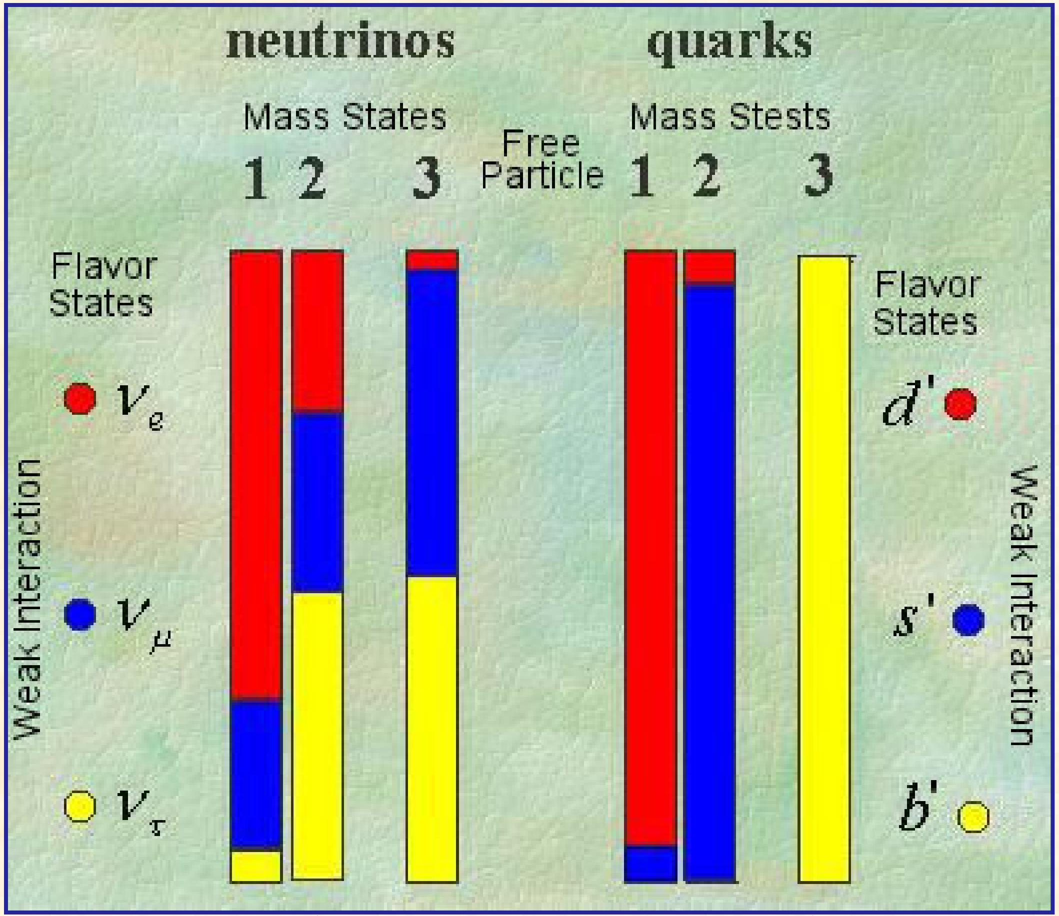
Barger et al: PRD54 (1996) 1
Barger et al: PLB462 (1999) 462
Grossman and Worah: hep-ph/9807511
Lisi et al: PRL85 (2000) 1166





Decay rejected at 3.4σ
Decoherence rejected at 3.8σ

Neutrino Mass and Composition



https://universe-review.ca/R15-13-neutrino.htm

Differences of neutrino masses deduced from oscillation experiments.

Atmospheric Neutrinos:

$$m_3^2 - m_2^2 = 2\times10^{-3}\ \mathrm{eV}^2$$

Solar Neutrinos:

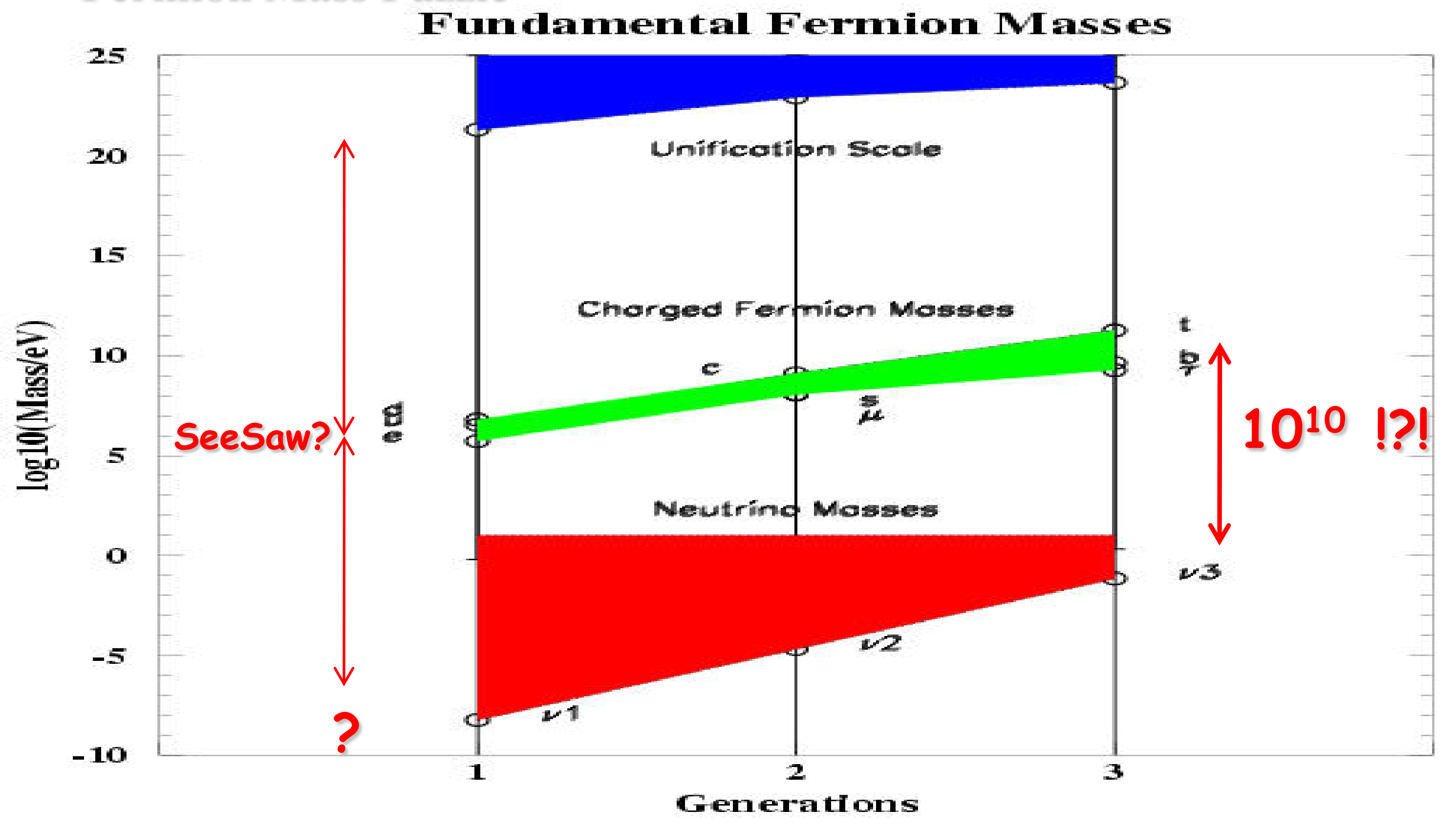
$$m_2^2 - m_1^2 = 7\times10^{-5}\ \mathrm{eV}^2$$

Mixings peculiarly large

Neutrino mixing very different from quarks

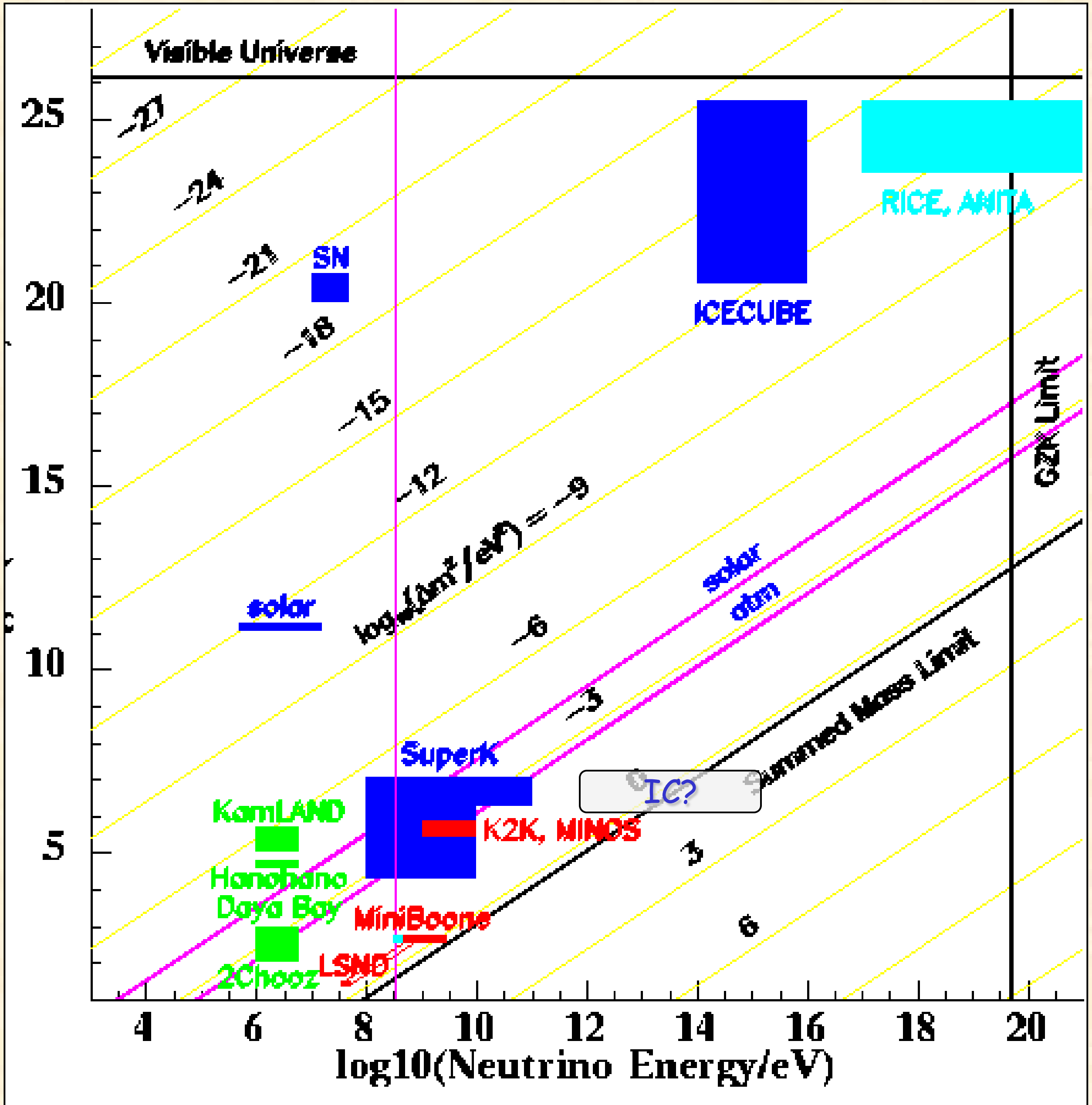
Neutrinos as Key To Grand Unification?

Fermion Mass Puzzle

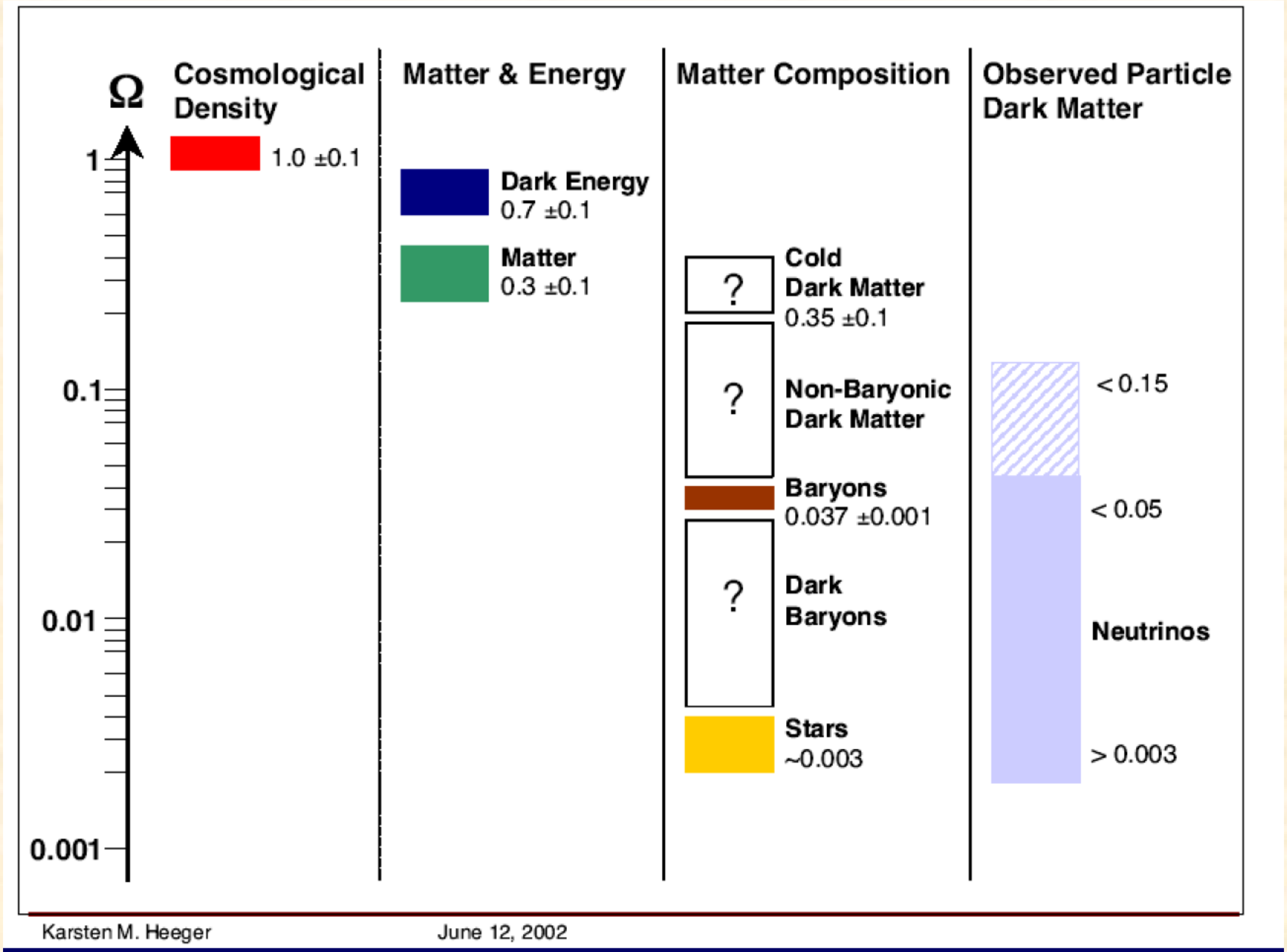


CP and CPT Violation Possible in ν Sector: Could be Key?

Big Picture Probing Oscillations

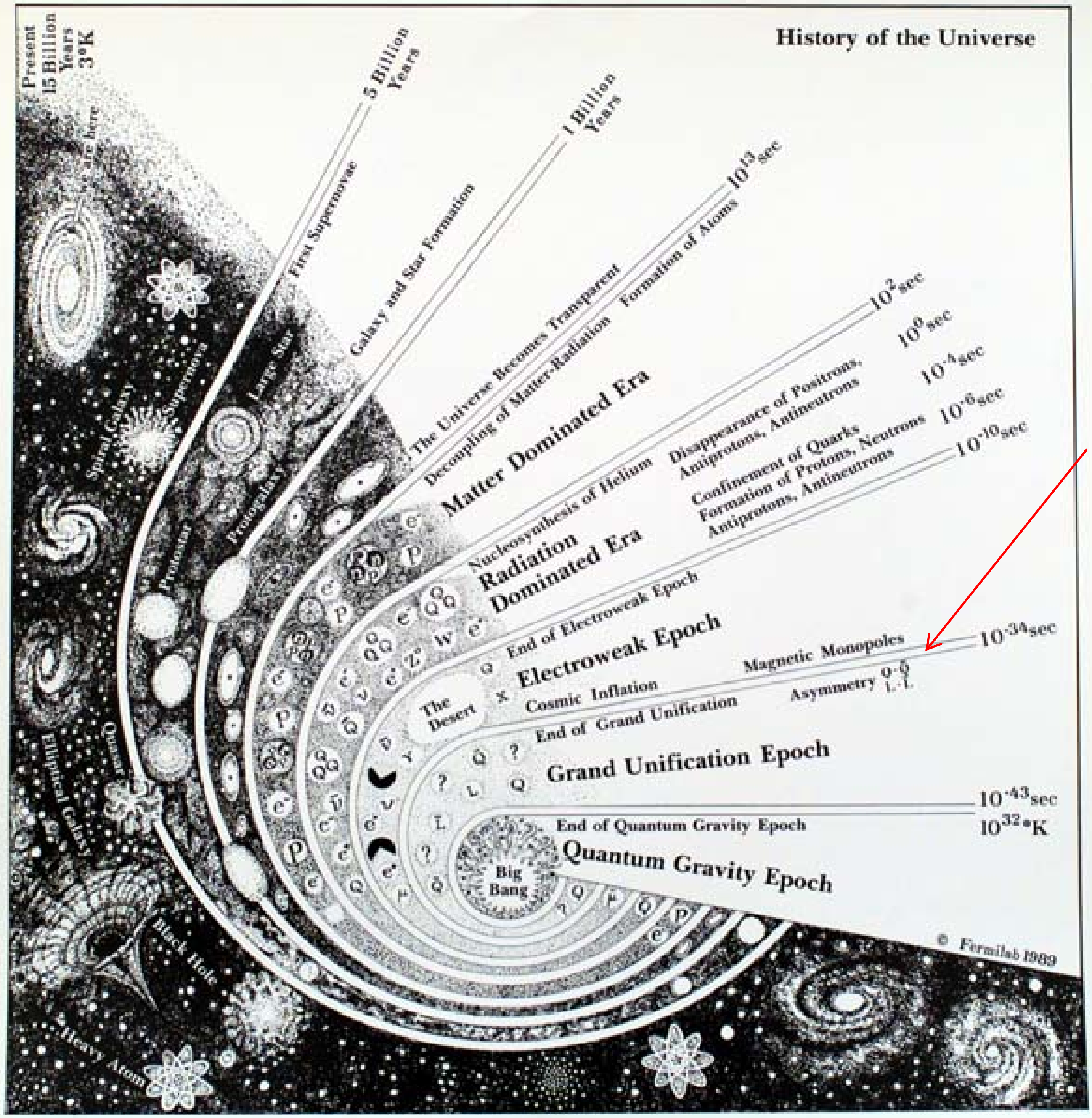


Neutrinos in the Mass-Energy of the Universe



The Standing Neutrino Puzzles

- Why only left handed? (Leptogenesis?)
- Why masses so small? (Seesaw?)
- 3 flavors only? (+Steriles?)
- CP Violation as with quarks? (No understanding anyway)
- Where is neutrinoless double beta decay?
- Mysteries from LSND, MiniBoone, RNA, Bump in reactor spectrum, excess of nus above all calculations….
- Where are the >>PeV neutrinos?



Leptogenesis ?

Neutrinos may play crucial role in the genesis of excess matter over anti-matter in the universe.

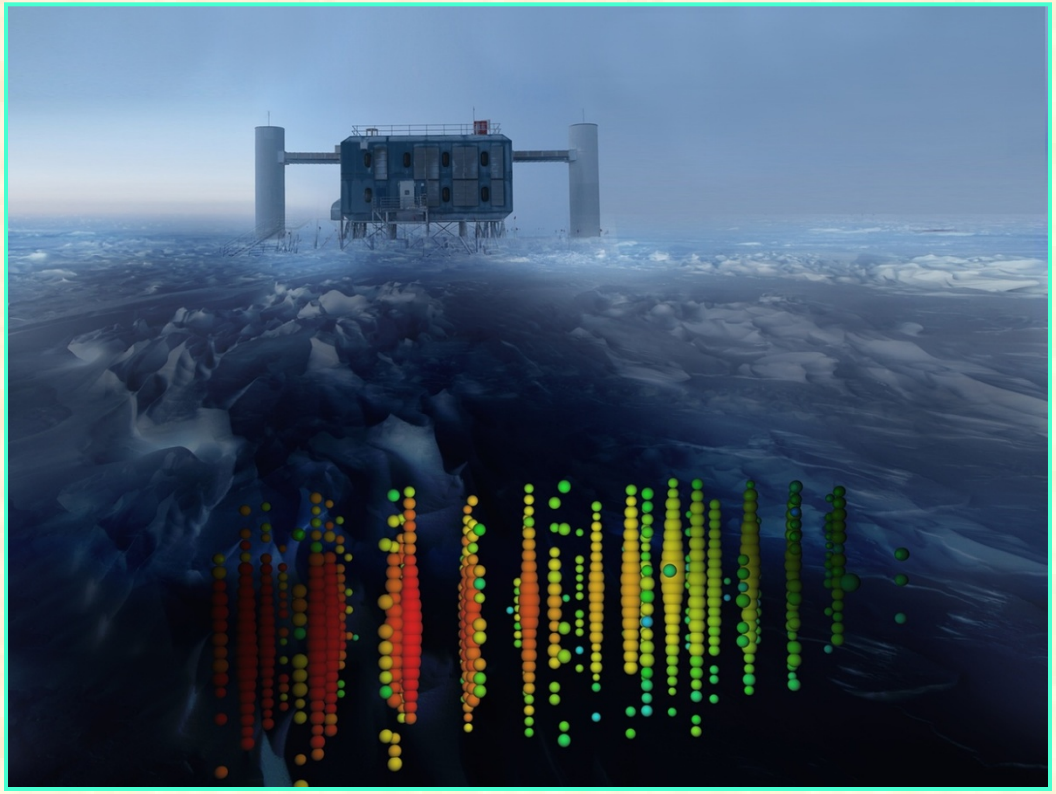
IceCube at South Pole sees PeV Neutrinos

They see giant showers but astrophysical source not known

Clearly the beginning of neutrino astronomy ~2012

But they did not see >>PeV muons as expected

Nor does anyone else… stay tuned



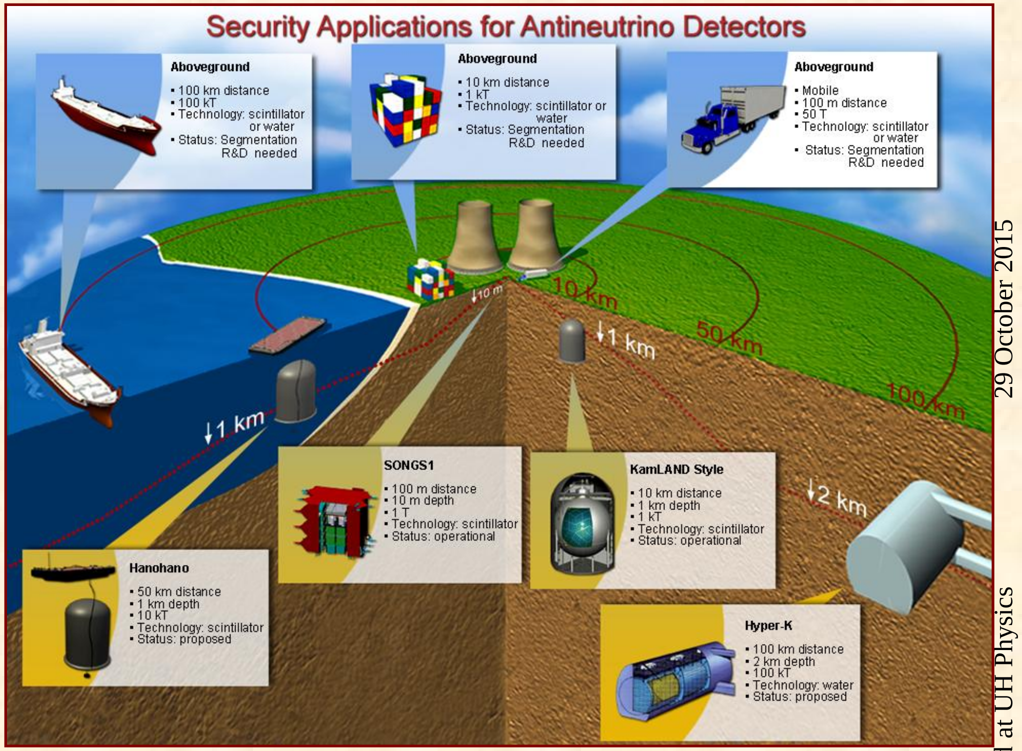
Neutrinos continue to surprise!

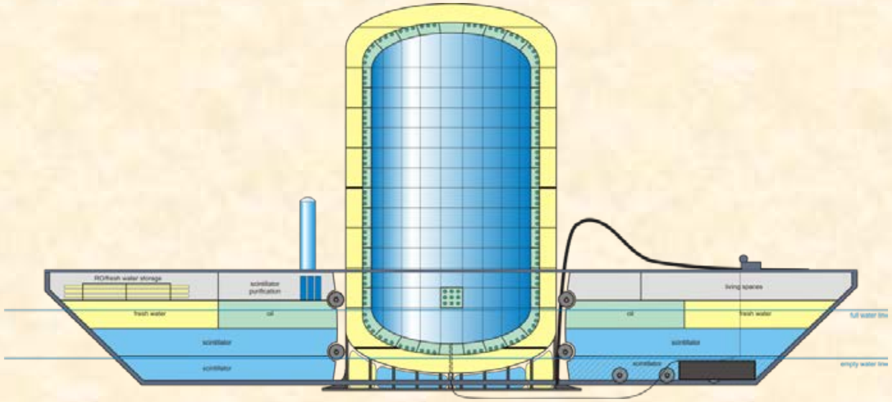
New Window on Universe? Expect Surprises

Telescope	*User*	*Date*	*Intended Use*	*Actual use*
Optical	**Galileo**	**1608**	**Navigation**	**Moons of Jupiter**
Optical	**Hubble**	**1929**	**Nebulae**	**Expanding Universe**
Radio	**Jansky**	**1932**	**Noise**	**Radio galaxies**
Micro-wave	**Penzias, Wilson**	**1965**	**Radio-galaxies, noise**	**3K cosmic background**
X-ray	**Giacconi …**	**1965**	**Sun, moon**	**neutron stars accreting binaries**
Radio	**Hewish, Bell**	**1967**	**Ionosphere**	**Pulsars**
γ-rays	**military**	**1960?**	**Thermonuclear explosions**	**Gamma ray bursts**
Water-Cherenkov	**IMB, Kamioka**	**1987**	**Nucleon Decay**	**ν's from SN1987A**
Water-Cherenkov	**SuperK**	**1998**	**Nucleon Decay**	**$\nu_\mu \leftrightarrow \nu_\tau$ mixing** **ν mass**
Solar Neutrino	**Homestake, SuperK, SNO**	**2001**	**Solar Burning**	**ν_e Oscillations**

Nuclear Reactor Monitoring for Anti-Proliferation

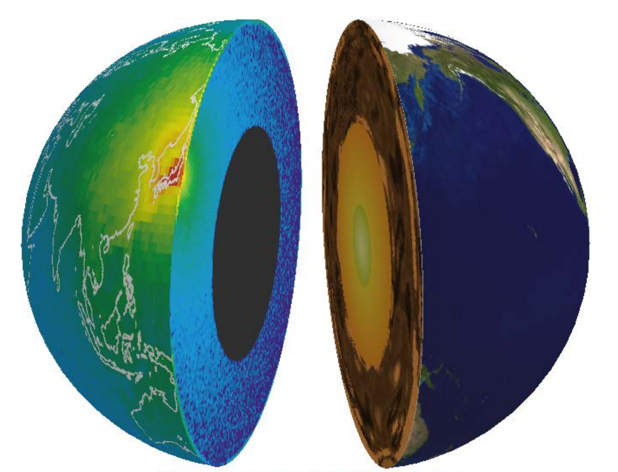
- Series of Workshops over last 10 years about reactor monitoring (Hawaii, Palo Alto, Paris, Brazil, Livermore, Maryland, Japan, Italy, soon DC).
- Near core: ~1m^3, ~20m out, cooperative site => IAEA application… many being built.
- Demonstrations a San Onofre Calif., and other places in US, France, Russia, Japan, Brazil, Italy, and more.
- Far: 1-1000 km, possibly clandestine reactor, look at location and operation patterns, huge detectors needed at long dist. (1/r^2 inescapable)
- Developing new techniques to utilize all possible information from multiple detectors.
- UH a leader in this area…



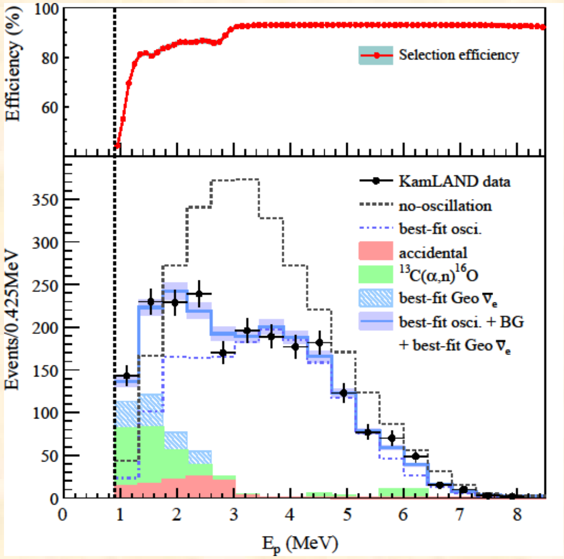


Hanohano Detector

Geoneutrinos: An Emerging Field



Geophysics with Neutrinos



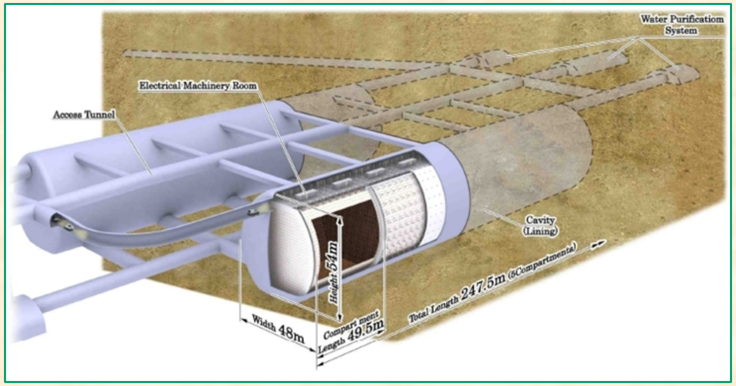
- Neutrinos from U and Th chains: major source of earth internal heat, and geodynamics (crustal motions, earthquakes, volcanoes),
- Much debate about how much total and origin. Major question in geology, and no other way to access information than neutrinos.
- KamLAND detected U/Th decay neutrinos from whole earth in 2005, updated in 2009. Borexino too in 2009. (Maricic thesis 2005)
- Earth internal heat largely radiogenic.
- No indication of major natural reactor source, yet many mysteries of plumes, etc..
- Budding field… but needs large detectors, and in ocean to discern below local crust.
- A number of workshops, talks at major neutrino meetings, and papers
- UH also a leader in this area.

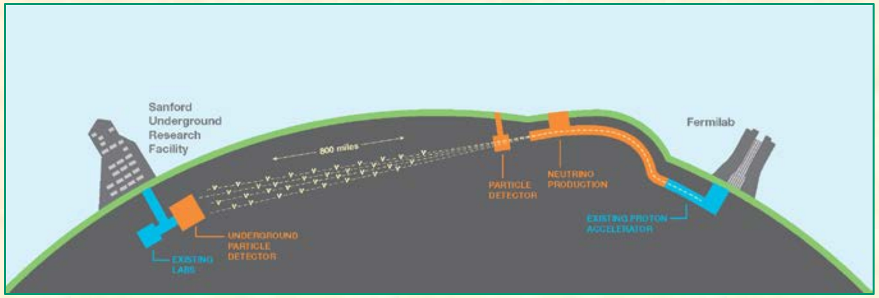
The Next Step: A Megaton Detector?

Motivation:
- Long-Baseline Oscillations
- Proton Decay Search
- Atmospheric Neutrinos
- Solar Neutrinos
- Supernova Neutrinos (~10^5 events from D = 10 kpc)

HyperKamiokande Project
Japan
2020's

USA: DUNE Project
Fermiab -> Homestake
2020's





UH Neutrino Group Projects

Faculty: Gorham. Matsuno, Maricic, Varner
15 Post Docs and grads

Past

- Beginning Neutrino Astronony (Workshops, DUMAND)
- -> **First Hints at Neutrino Oscillations (IMB 1983)**
- SN1987A observed in neutrinos (IMB 1987)
- Neutrino Phenomenology and Astrophysics
- K2K (confirmation of oscillations with accelerator)
- GLUE (radio pulses from moon)
- Forte' (terrestrial radio pulses seen from space)
- Radio Detection Studies (mechanisms, at accelerators, lab)
- Double Chooz

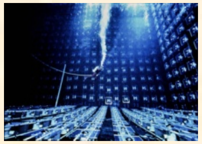
Present

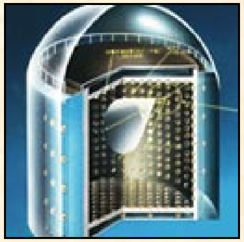
-> **Super-Kamiokande (discovery of neutrino oscillations)**

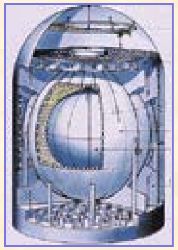
- KamLAND (electron neutrino oscillations from reactors)
- ANITA (radio neutrino detection from balloon in Antarctic)
- DUNE (Fermilab to Homestake)
- miniTimeCube
- NuLat

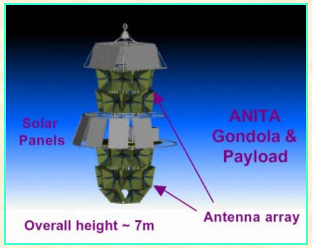
Future Possibilities

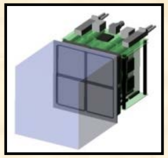
- Next Generation Nucleon Decay Detector (DUNE? HyperK?)
- Neutrinos and Disarmanent (nu beams? Monitor all reactors?)

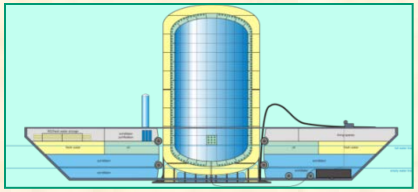


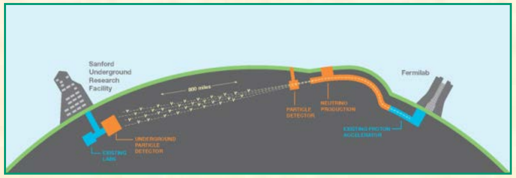












Concluding

Last decades have moved neutrinos from slightly embarrassing cousins for HEP, to center stage.

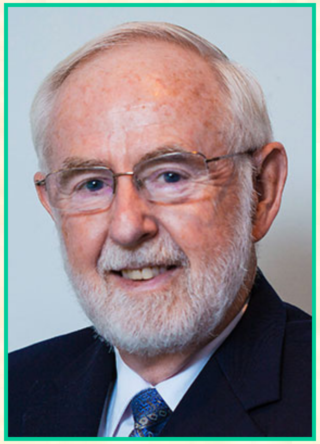
They continue to surprise as we grope our way forward in the dark, lacking GUT guidance.

Neutrinos for particle and nuclear physics, for astrophysics studies.

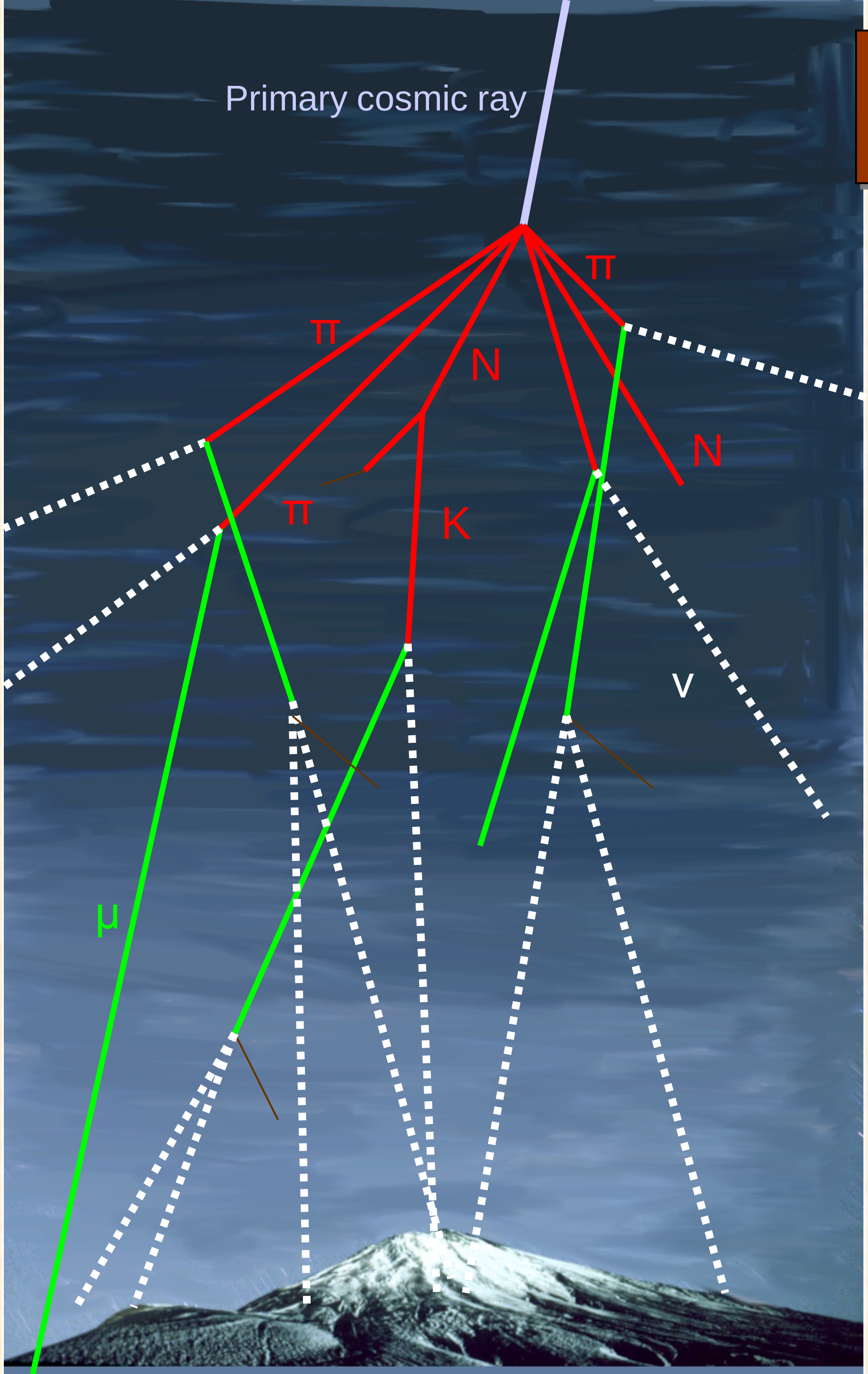
Applications in geophysics, even arms control emerging, other fantastic applications on horizon.

It is an exciting era for neutrinophiles!

Congratulations to Takaaki and Art and the SuperK and SNO Teams

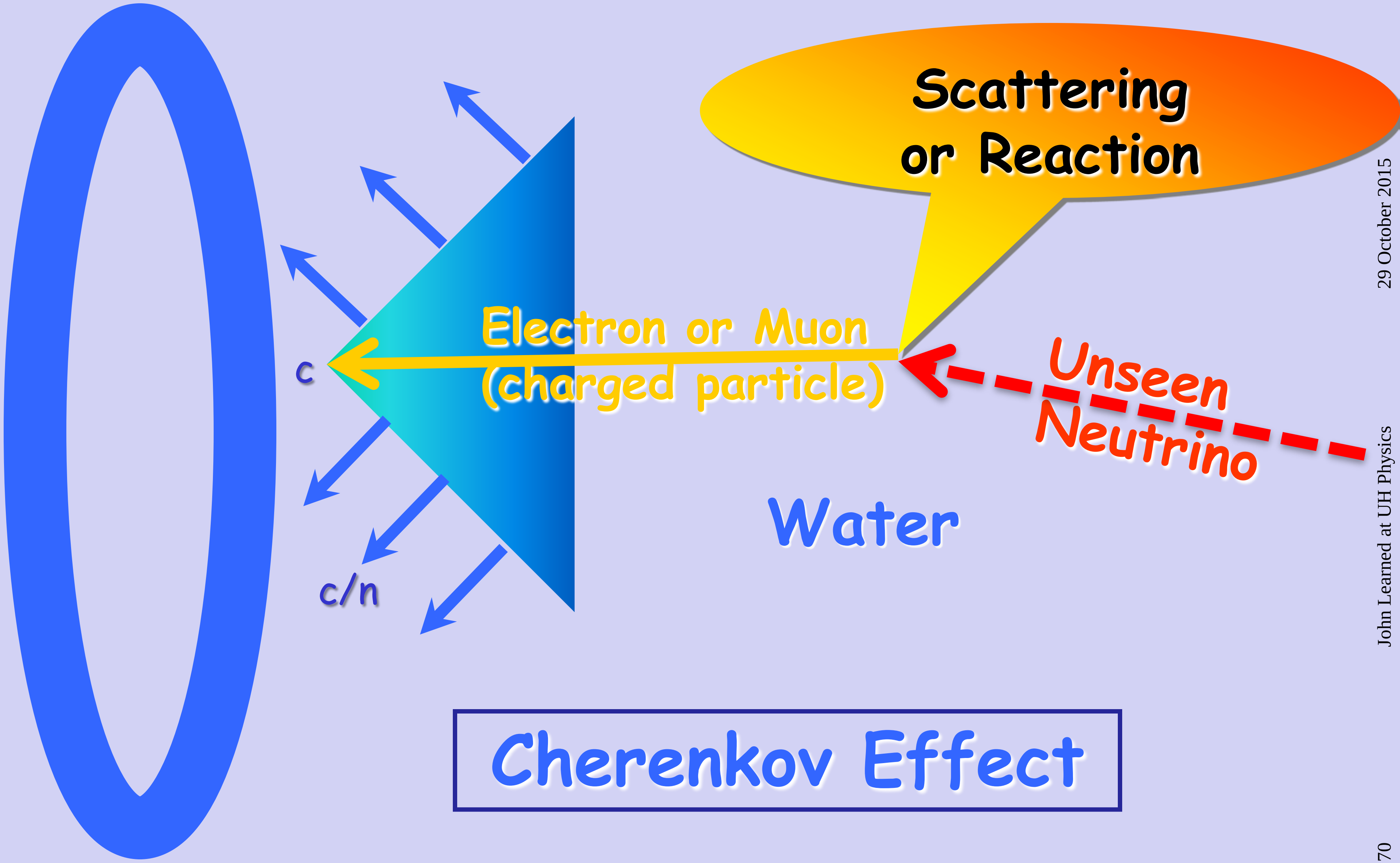


Neutrinos produced from a cosmic ray shower in atmosphere



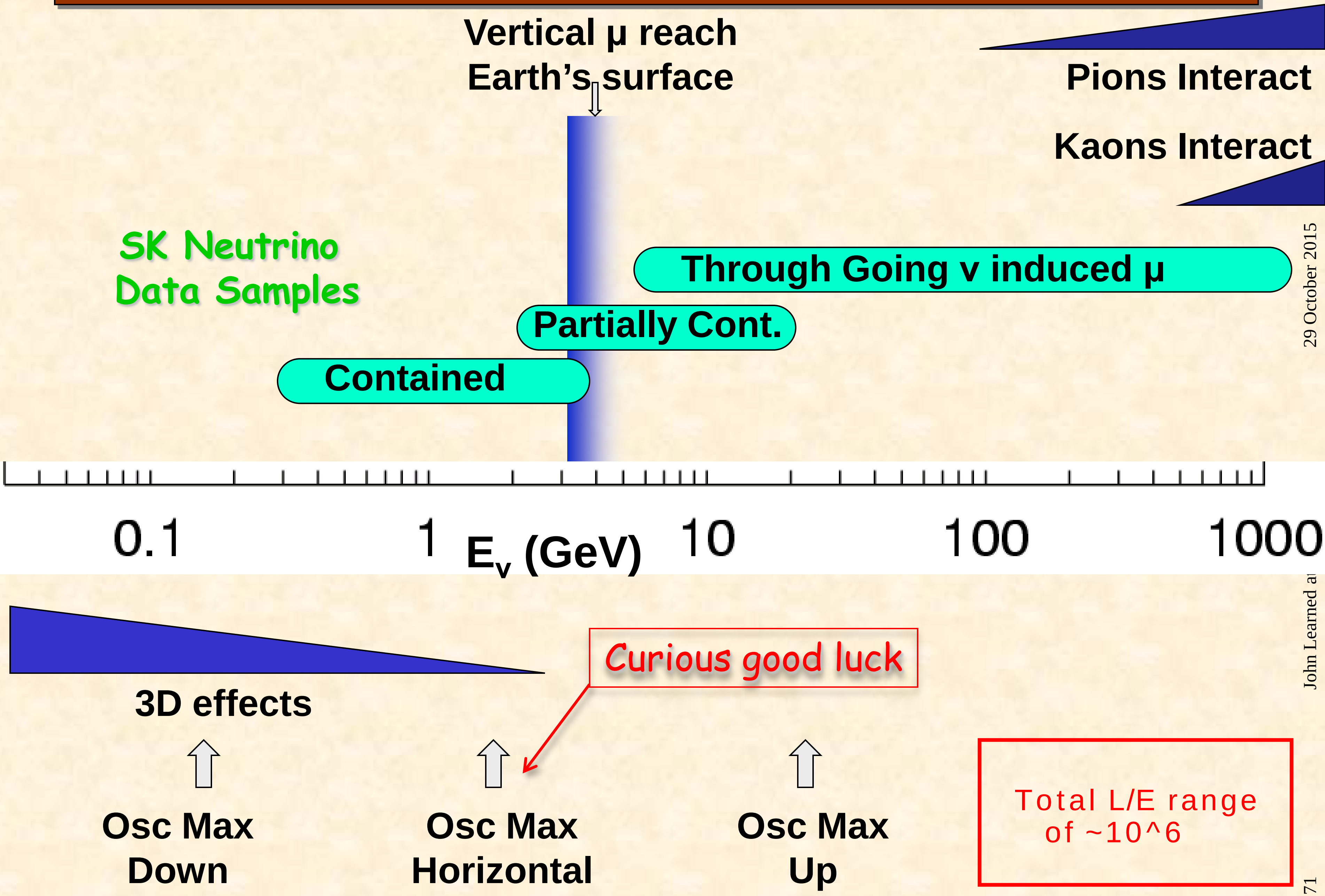
- Primary cosmic ray: proton or heavier nucleus.
- Interacts high in atmosphere, in ~90 g/cm^2
- Atmosphere depth 1050 g/cm^2 (10 mwe)
- Cascade of pions and kaons
- Most hadrons don't reach ground.
- Muons penetrate at most few km.
- But <u>neutrinos go though the earth</u> ~ unattenuated.

How SuperK Detects Neutrino Interactions



Cherenkov Effect

Energy Sampling Region



Vertical μ reach
Earth's surface

Pions Interact

Kaons Interact

SK Neutrino
Data Samples

Through Going ν induced μ

Partially Cont.

Contained

E_ν (GeV)

3D effects

Curious good luck

Osc Max
Down

Osc Max
Horizontal

Osc Max
Up

Total L/E range
of ~10^6