Neutrinos Amaze and Now They Do Work

John G. Learned

University of Hawaii, Manoa, USA

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The Ministry of Education and Science of the Buryatiya Republic,
The Institute of Physical Materials Science and
The Siberian Branch of the Russian Academy of Sciences

Ulan-Ude
23 July 2012

What are those weird things, neutrinos?

Breakfast Nus?

Neutrino Contents about 0.000000000000000000002 kCal

Thanks Joshua Murillo

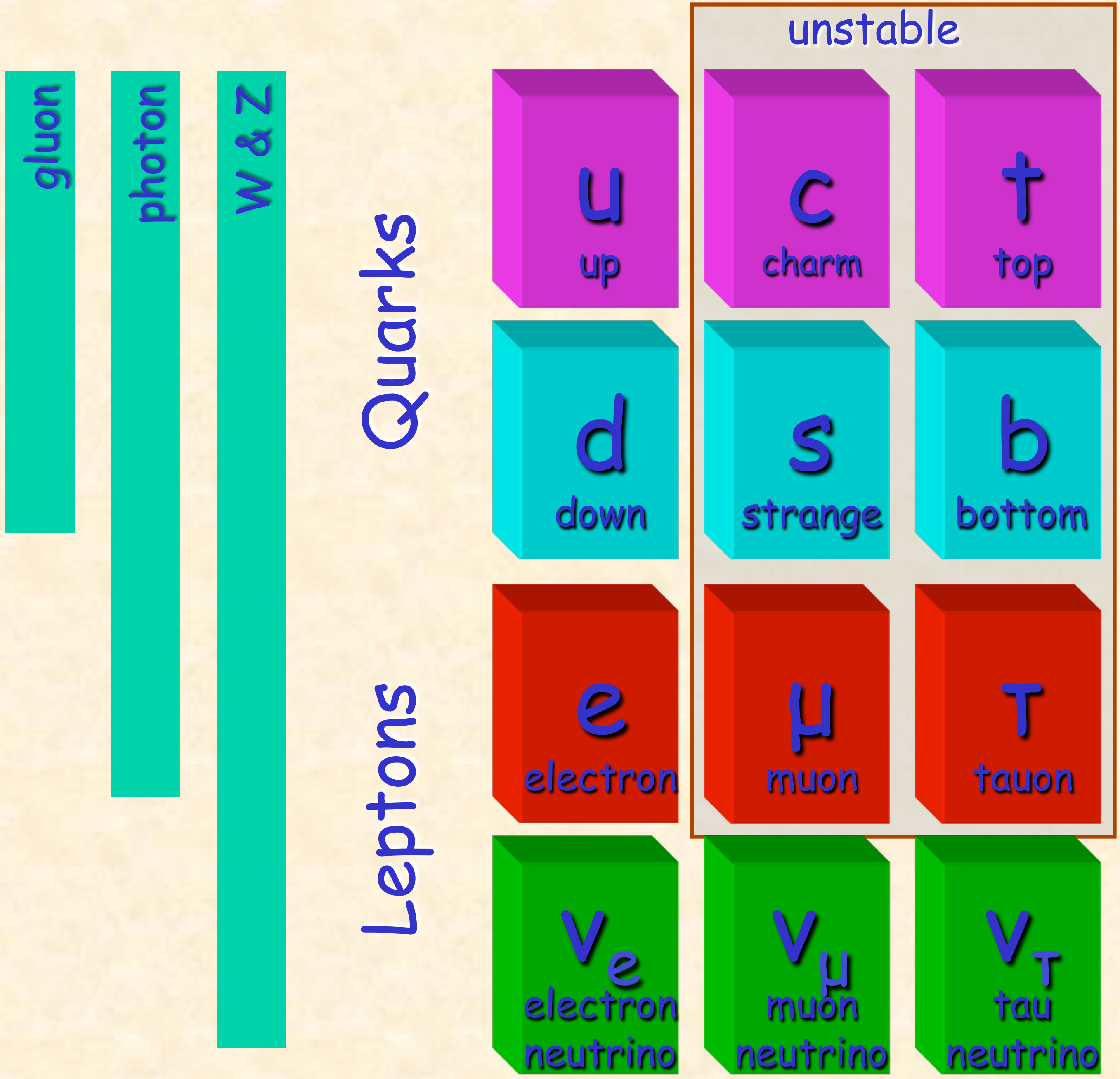
Organization of Talk:

At request of the organizers, a little review of neutrinos, particularly with respect to intense activity in last 14 years since we discovered neutrino oscillations.

And then some information on areas of neutrino work in which I am particularly interested at present, namely
- reactor monitoring with neutrinos,
- geoneutrinos,
- and particle physics with neutrinos…

Too much material for sure.

Following talks will cover this and more in much detail.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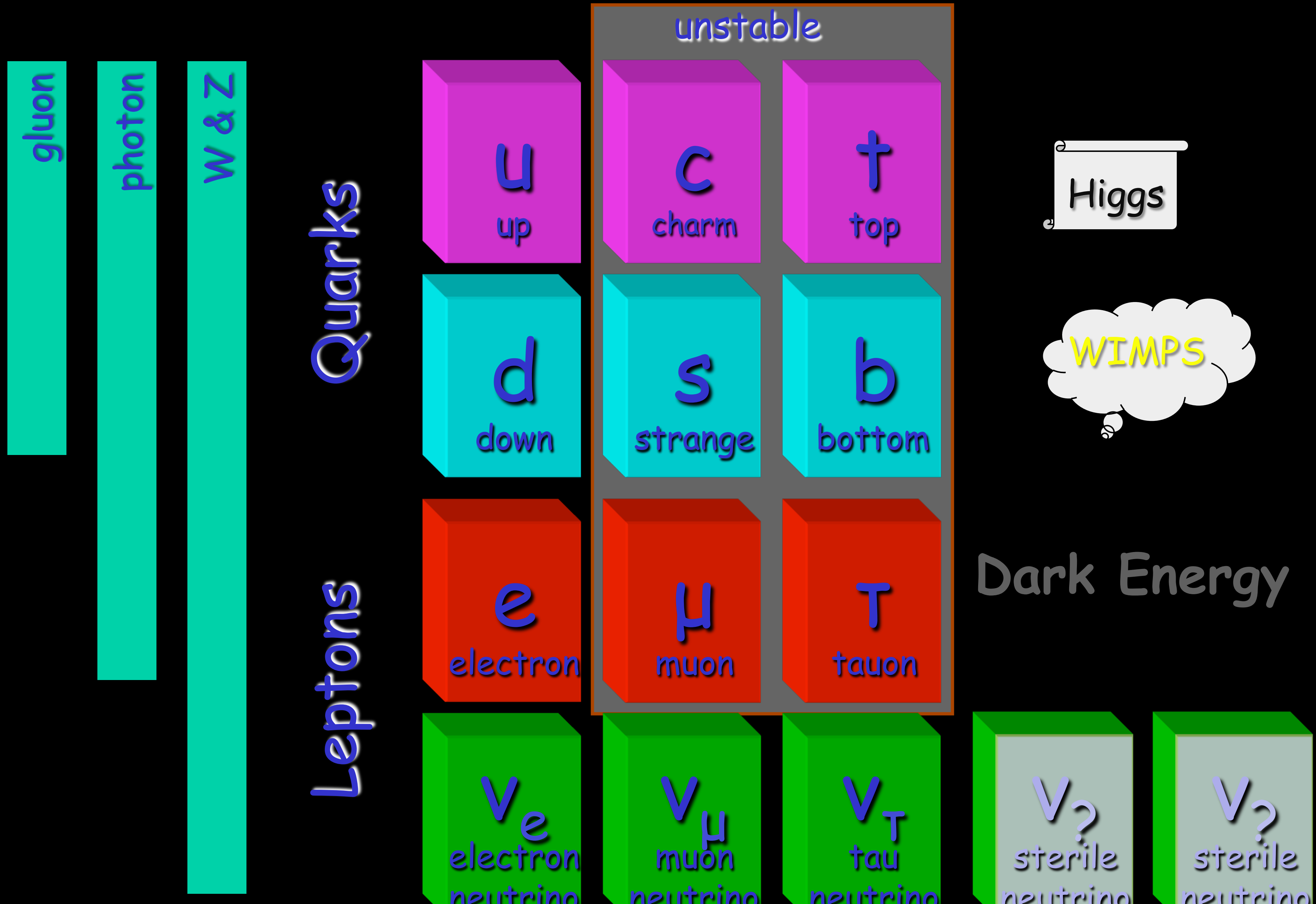

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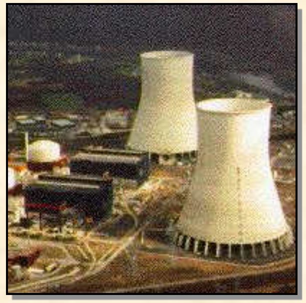
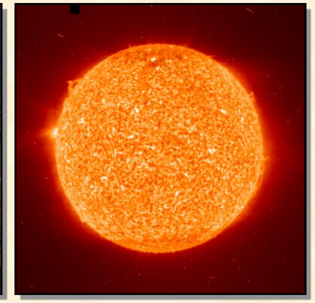
$\nu_?$
sterile neutrino
Higgs
WIMPS
Dark Energy

Where do Neutrinos come from?

✓ Nuclear Reactors (power stations, ships)



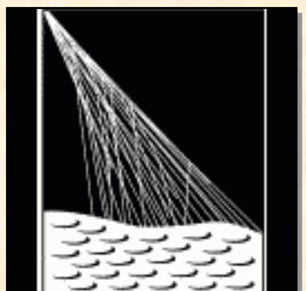


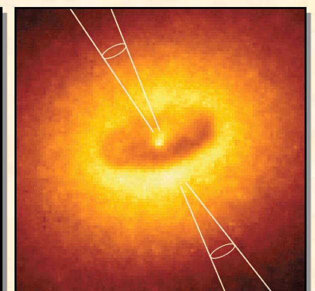
Sun ✓

✓ Particle Accelerator

Supernovae (star collapse)
SN 1987A ✓

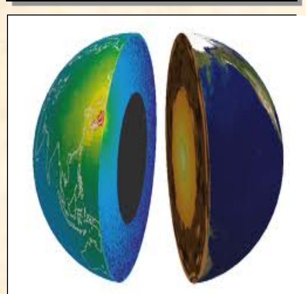
✓ Earth's Atmosphere (Cosmic Rays)





Astrophysical Sources
Soon ?

✓ Bulk Earth (Geonus: U/Th Radioactivity)



Big Bang (here 330 ν/cm^3)
Indirect Evidence

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 fermions.
- Participates only in SM weak interaction.
- Falls under gravity (SN1987A).
- 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 ν_m-> ν_n OK)
- SM processes produce neutrinos as superposition of mass states
- Mass states' relative phases change with flight time, producing morphing between interaction states ("ν 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.

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) What is $|\theta_{13}|$? Is mixing tri-bimax ($\theta_{13} = 0$)? No, but small…
7) Is there CP violation as with quarks?
8) Are there heavy (TeV - GUT scale) right handed neutrinos?
9) Are neutrinos Majorana or Dirac particles?
10) Are there any light (eV scale) sterile neutrinos?
11) Are heavy right handed neutrinos responsible for leptogenesis?
12) What role do neutrinos play in heavy element production in SN?
13) 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?

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

The Press Likes Neutrinos: “Talking to the neighbors”

SETI with Neutrinos

“A modest proposal for an interstellar communications network”

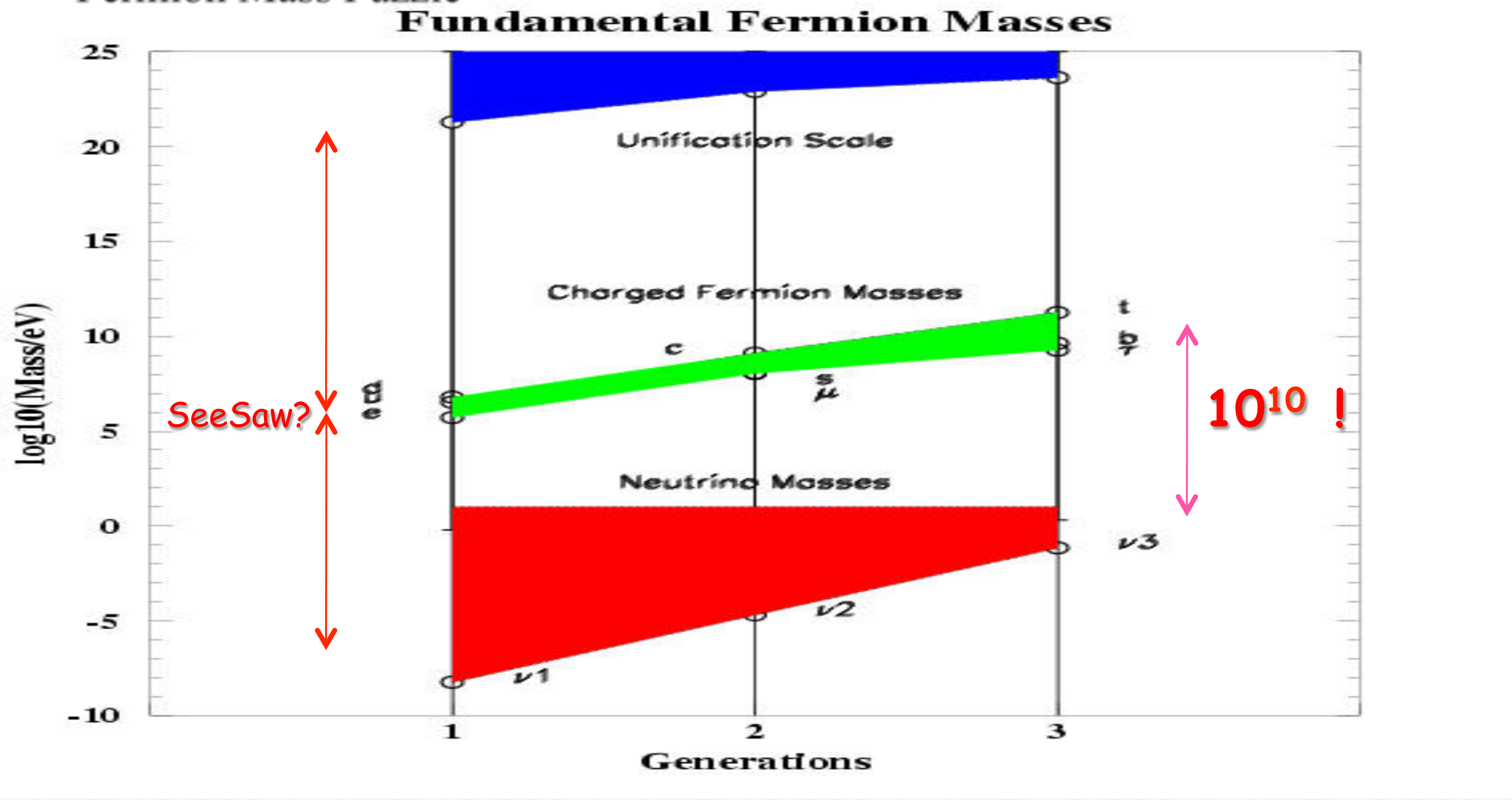
Economist, 7 April 2011

Not what this talk is about….

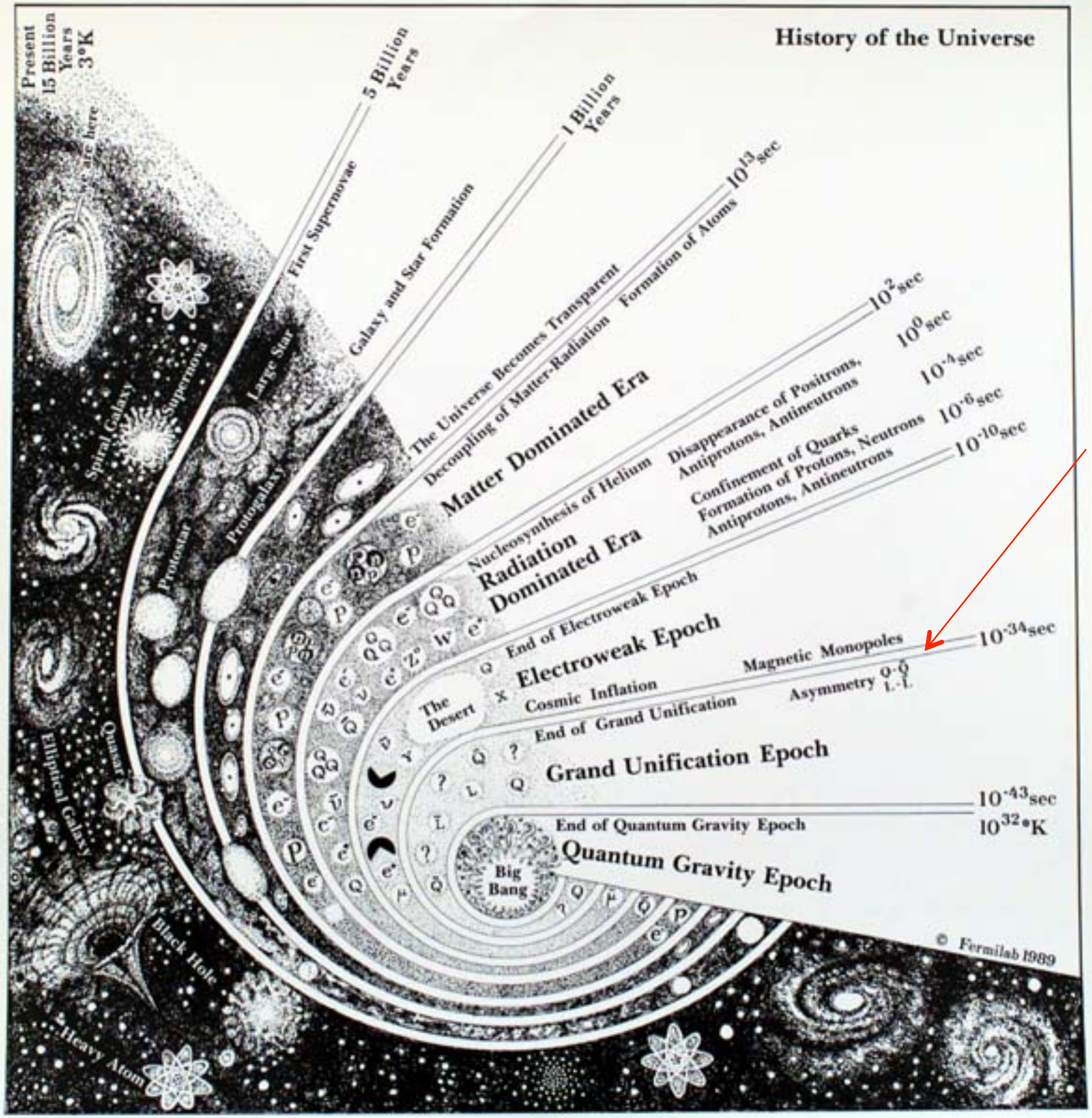
http://www.economist.com/PrinterFriendly.cfm?story_id=18526871

Neutrinos as Key To Grand Unification?

Fermion Mass Puzzle



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



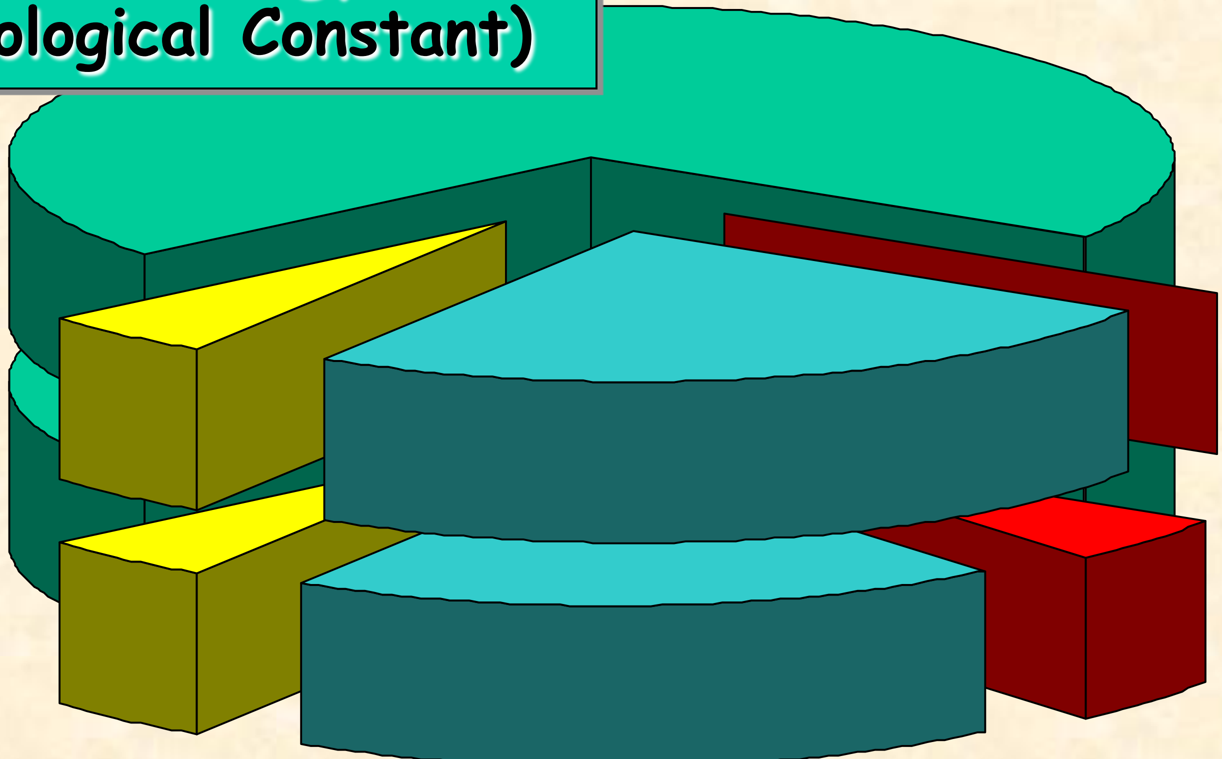
Leptogenesis

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

Matter Inventory of the Universe

Dark Energy
(Cosmological Constant)

Copernicus^n!

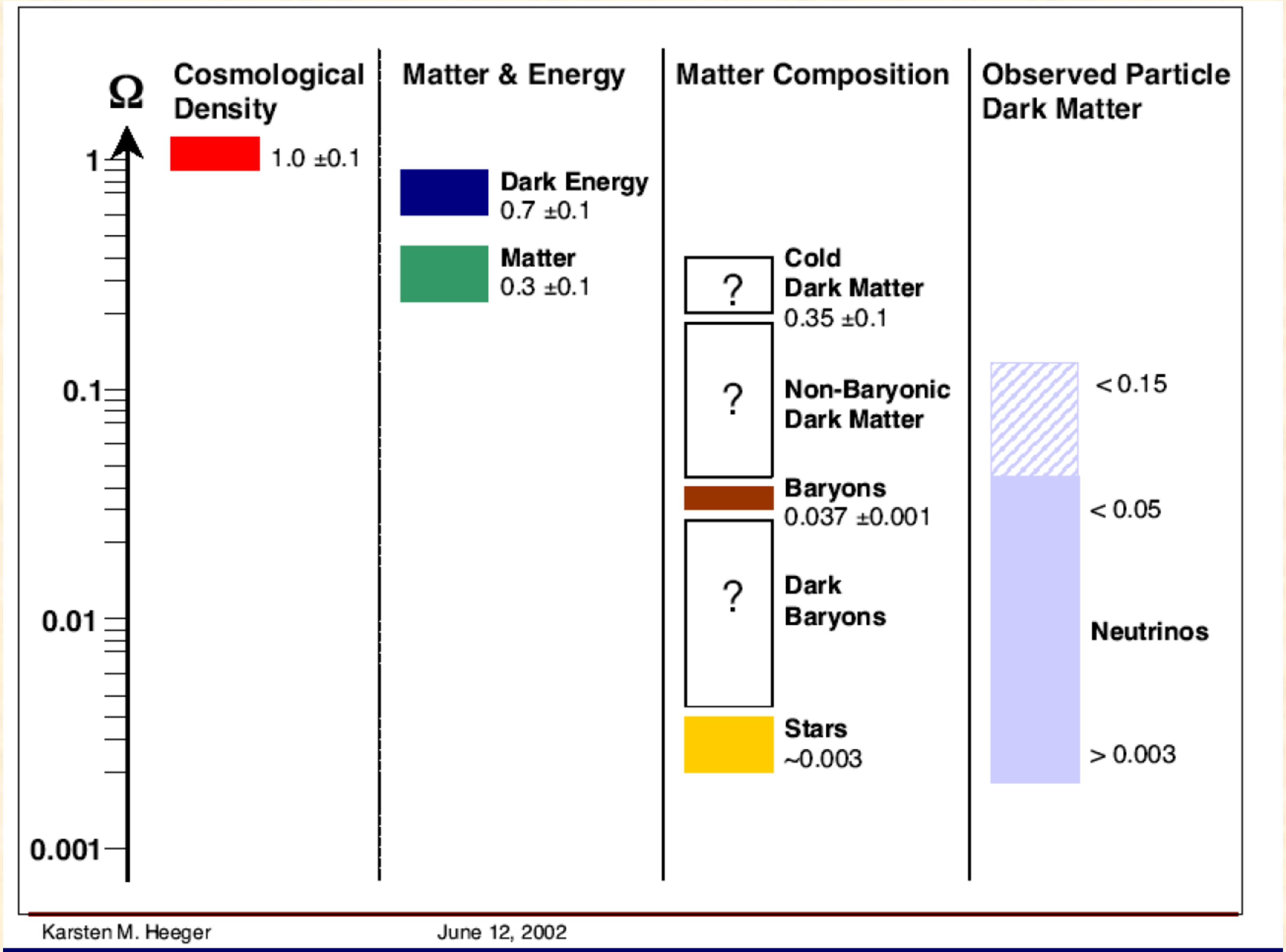


Normal Matter
(of which ca.
10% luminous)

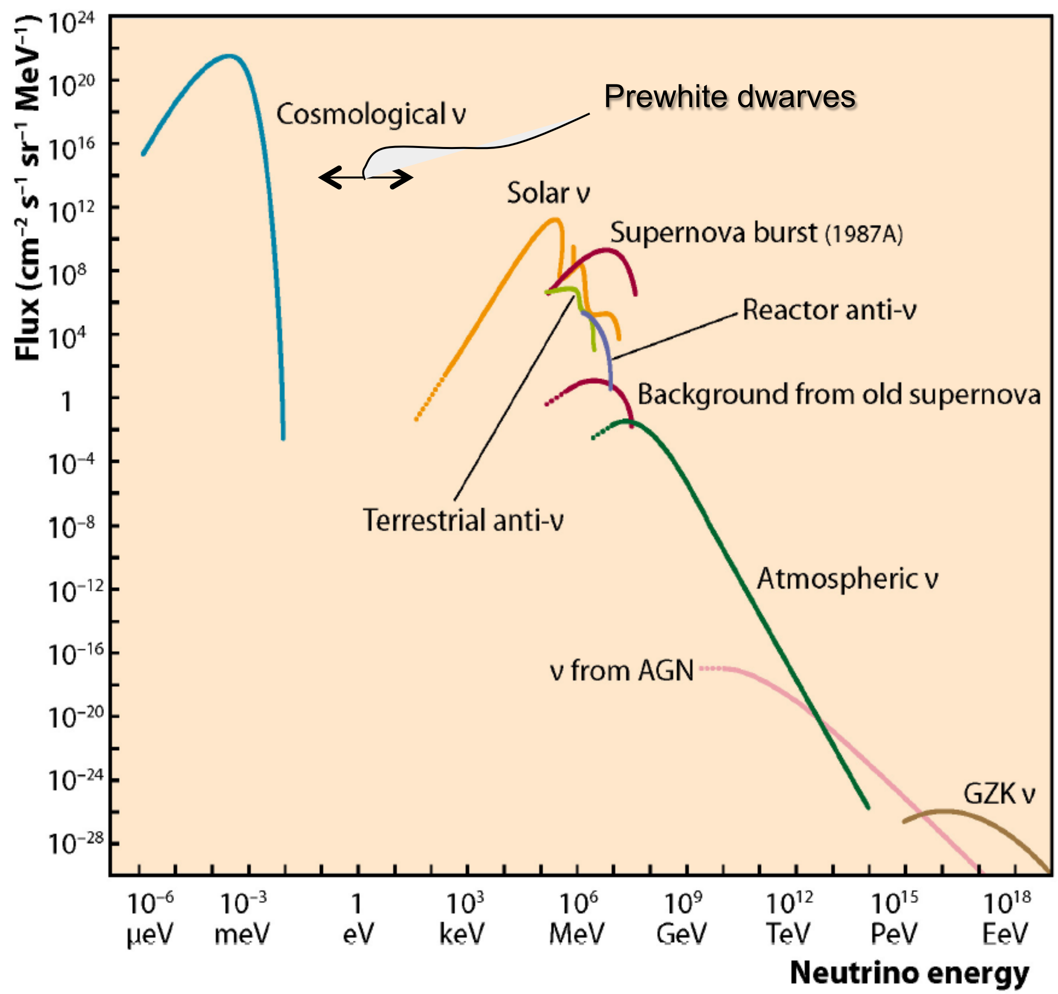
Dark
Matter

Neutrinos
min. 0.1%
max. 6%

Neutrinos in the Mass-Energy of the Universe



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



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

Astrophysical Neutrino Sources… not yet found

High and Ultra-high energy neutrinos?

Supernova neutrinos from GSC in our galactic neighborhood?

Neutrinos associated with Gamma Ray Bursts?

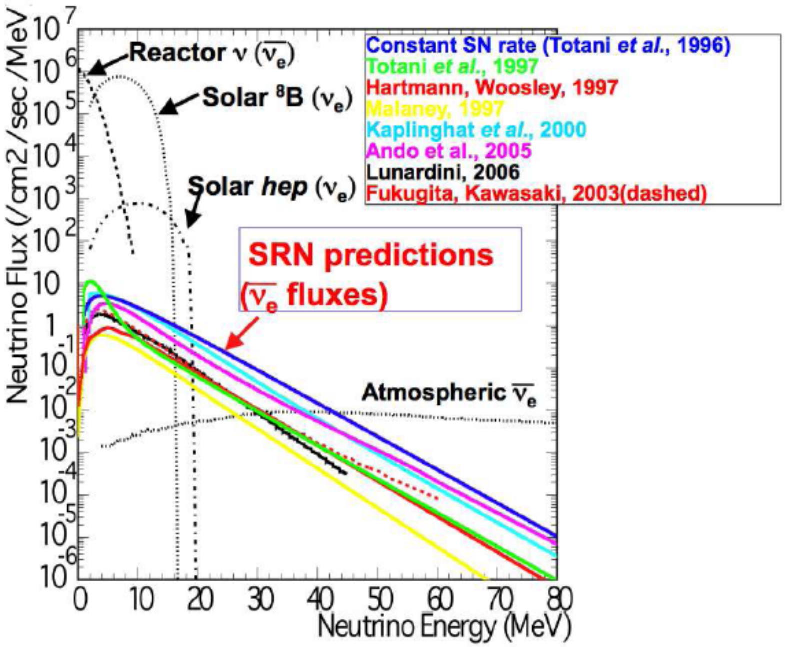
Relic SN neutrinos?

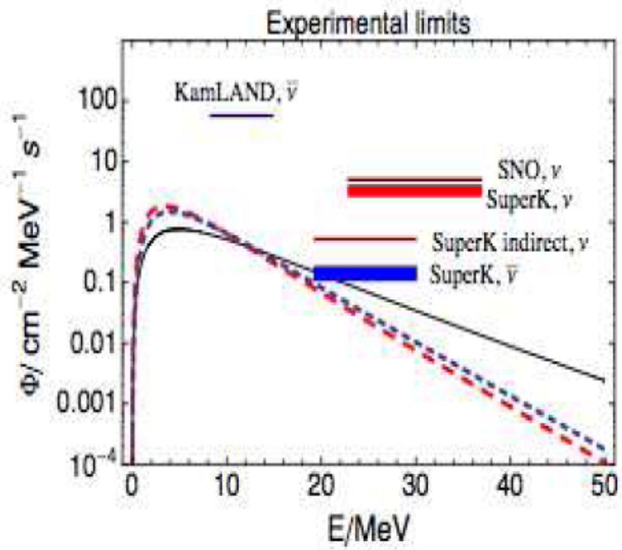
Neutrinos from Dark Matter annihilations in earth,
sun or galactic center?

Who knows?

Lesson of history… the latter may be most probable!

Neutrinos from Earlier Supernovae

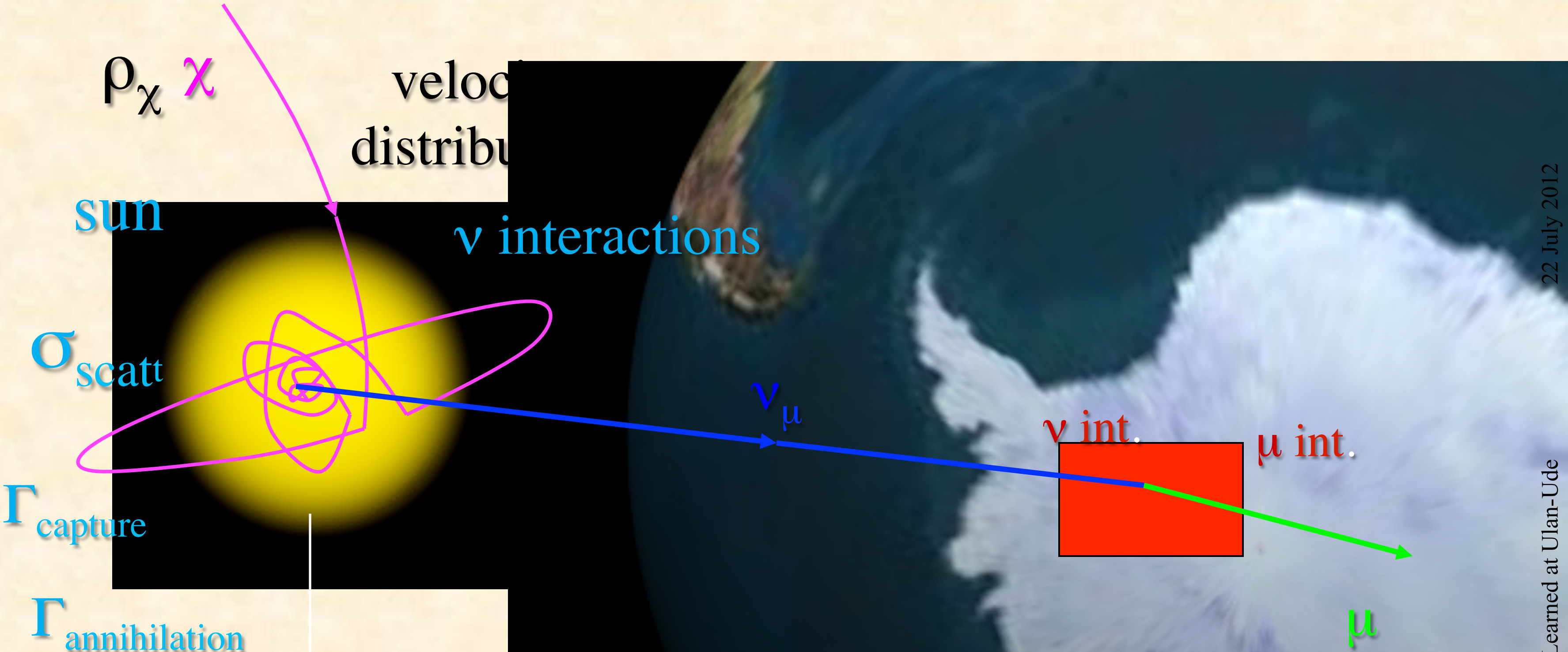




Reference Configuration	Expected Annual SRN Signal (events/year)	Expected Annual Background (events/year)	Years of LBNE Data Needed for a 3.0-σ Signal Assuming Maximum/Minimum SRN Flux
300kt WCD 30%	5 – 52	320	1.3/144
300kt WCD 30% + Gd	13 – 74	64	0.13/0.9
100kt WCD + 100kt WCD-Gd + 17kt LAr	5 – 39	114	0.35/3
100kt WCD-Gd + 34 kt LAr	4 – 27	21	0.32/3

Mary Bishai at NuTel 2011

neutralino capture and annihilation



$$\chi\chi \rightarrow \begin{matrix} q\bar{q} \\ l\bar{l} \\ W^{\pm}, Z, H \end{matrix} \rightarrow \mathrm{L} \rightarrow \nu_\mu$$

$$\rightarrow c\bar{c}, b\bar{b}, t\bar{t}, \tau^{+}\tau^{-}, W^{\pm}, Z^{0}, H^{\pm}H^{0}$$

Silk, Olive and Srednicki, '85
Gaisser, Steigman & Tilav, '86

Freese, '86; Krauss, Srednicki & Wilczek, '86 Gaisser, Steigman & Tilav, '86

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

Some Neutrino Experimental Peculiarities

1) Flux calcs always under-predict observed rate both at accelerators, and from atmospheric cosmic ray interactions. (Known but may be boring, or not?)
2) SN1987A events pointed too well…. Need another SN
3) Where are the very high energy cosmic neutrinos?
4) MINOS finds apparent CPT violation hints in two different runs. Now dismissed by SuperK and more data from MINOS.
5) LSND anomaly… $\bar{\nu}_e$ appear from stopped pion target (1991).
6) MiniBOONE… unexplained bumps in both nu and antinu runs, but not at same E… this remains a mystery.
7) Revised reactor neutrino flux calcs exceed measurements taken over many years in experiments from 10-2000 m distance.
8) Solar Gallium experiments radioactive source calibrations came out a little low in 4 trials
9) Cosmological neutrino counting coming in high by +1 or +2

Will talk more about #5-9 shortly….

Step back…

- Quick historical tour
- Small tutorial on oscillations

Neutrino Timeline

- 1920-1927 Charles Drummond Ellis (along with James Chadwick and colleagues) establishes clearly that the beta decay spectrum is really continous, ending all controversies.
- 1930 Wolfgang Pauli hypothesizes the existence of neutrinos to account for the beta decay energy conservation crisis.
- 1932 Chadwick discovers the neutron.
- 1933 Enrico Fermi writes down the correct theory for beta decay, incorporating the neutrino.
- 1946 Shoichi Sakata and Takesi Inoue propose the pi-mu scheme with a neutrino to accompany muon. (There is a long story about the confusion of mu for pi etc. They were the first to straighten it out and get the spins right, and write down the correct decay scheme completely: pi -> mu + nu_mu, mu -> e + nu_e + nu_mu, and noticed that both nu_mu and nu_e are light, and neutral with spin 1/2, and suggested that they might be "different".)
- 1956 Fred Reines and Clyde Cowan discover (electron anti-) neutrinos using a nuclear reactor.
- 1957 Neutrinos found to be left handed by Goldhaber, Grodzins and Sunyar.
- 1957 Bruno Pontecorvo proposes neutrino-antineutrino oscillations analogously to K0-K0bar, leading to what is later called oscillations into sterile states.
- 1962 Ziro Maki, Masami Nakagawa and Sakata introduce neutrino flavor mixing and flavor oscillations.
- 1962 Muon neutrinos are discovered by Leon Lederman, Mel Schwartz, Jack Steinberger and colleagues at Brookhaven National Laboratories and it is confirmed that they are different from nu_e's.
- 1964 John Bahcall and Ray Davis propose feasibility of measuring neutrinos from the sun.
- 1965 The first natural neutrinos are observed by Reines and colleagues in a gold mine in South Africa, and by Goku Menon and colleagues in Kolar Gold fields in India, setting first astrophysical limits.
- 1968 Ray Davis and colleagues get first radiochemical solar neutrino results using cleaning fluid in the Homestake Mine in North Dakota, leading to the observed deficit known thereafter as the "solar neutrino problem".
- 1976 The tau lepton is discovered by Martin Perl and colleagues at SLAC in Stanford, California. After several years, analysis of tau decay modes leads to the conclusion that tau is accompanied by its own neutrino nutau which is neither nue nor numu.
- 1976 Designs for a new generation neutrino detectors made at Hawaii workshop, subsequently leading to IMB, HPW and Kamioka detectors, Baikal and DUMAND. .
- 1980s The IMB, the first massive underground nucleon decay search instrument and neutrino detector is built in a 2000' deep Morton Salt mine near Cleveland, Ohio. The Kamioka experiment is built in a zinc mine in Japan.
- 1983 The "atmospheric neutrino anomaly" is observed by IMB and later by Kamiokande.
- 1986 Kamiokande group makes first directional counting observation solar of solar neutrinos and confirms deficit.
- 1987 The Kamiokande and IMB experiments detect burst of neutrinos from Supernova 1987A, heralding the birth of neutrino astronomy, and setting many limits on neutrino properties, such as mass.
- 1988 Lederman, Schwartz and Steinberger awarded the Nobel Prize for the discovery of the muon neutrino.
- 1989 The LEP accelerator experiments in Switzerland and the SLC at SLAC determine that there are only 3 light neutrino species(electron, muon and tau).
- 1991-2 SAGE (in Russia) and GALLEX (in Italy) confirm the solar neutrino deficit in radiochemical experiments.
- 1995 Frederick Reines and Martin Perl get the Nobel Prize for discovery of electron neutrinos (and observation of supernove neutrinos) and the tau lepton, respectively.
- 1996 Super-Kamiokande, the largest ever detector at 50 kilotons gross, begins searching for neutrino interactions on 1 April at the site of the Kamioka experiment, with Japan-US team (led by Yoji Totsuka).
- 1998 After analyzing more than 500 days of data, the Super-Kamiokande team reports finding oscillations and, thus, mass in muon neutrinos. After several years these results are widely accepted and the paper becomes the top cited experimental particle physics paper ever.
- 2000 The DONUT Collaboration working at Fermilab announces observation of tau particles produced by tau neutrinos, making the first direct observation of the tau neutrino.
- 2000 SuperK announces that the oscillating partner to the muon neutrino is not a sterile neutrino, but the tau neutrino.
- 2001 and 2002 SNO announces observation of neutral currents from solar neutrinos, along with charged currents and elastic scatters, providing convincing evidence that neutrino oscillations are the cause of the solar neutrino problem.
- 2002 Masatoshi Koshiba and Raymond Davis win Nobel Prize for measuring solar neutrinos(as well as supernova neutrinos).
- 2002 KamLAND begins operations in January and in November announces detection of a deficit of electron anti-neutrinos from reactors at a mean distance of 175 km in Japan. The results combined with all the earlier solar neutrino results establish the correct parameters for the solar neutrino deficit.
- 2004 SuperKamiokande and KamLAND present evidence for neutrino disappearance and reappearance, eliminating non-oscillations models
- 2005 KamLAND announces first detection of neutrino flux from the earth and makes first measurements of radiogenic heating from the earth.

Pakvasa & Learned, 2005

Non-Accelerator Neutrino History Survey

- Neutrinos were proposed in 1930 as solution to missing energy in beta decays.
- Said to be undetectable, but….

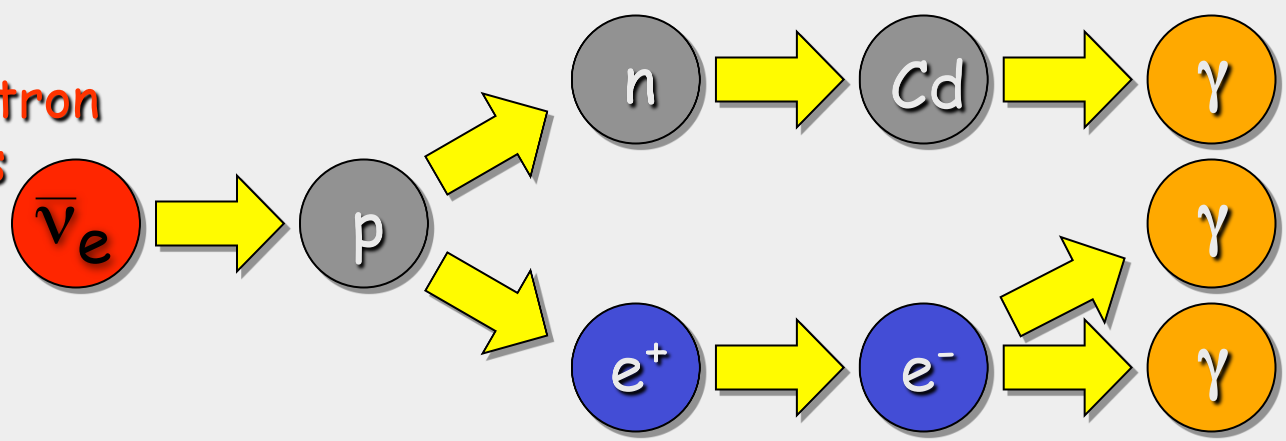
First Detection ! (1954 - 1956)

Clyde Cowan
(1919 - 1974)

Fred Reines
(1918 - 1998)
Nobel Prize 1995

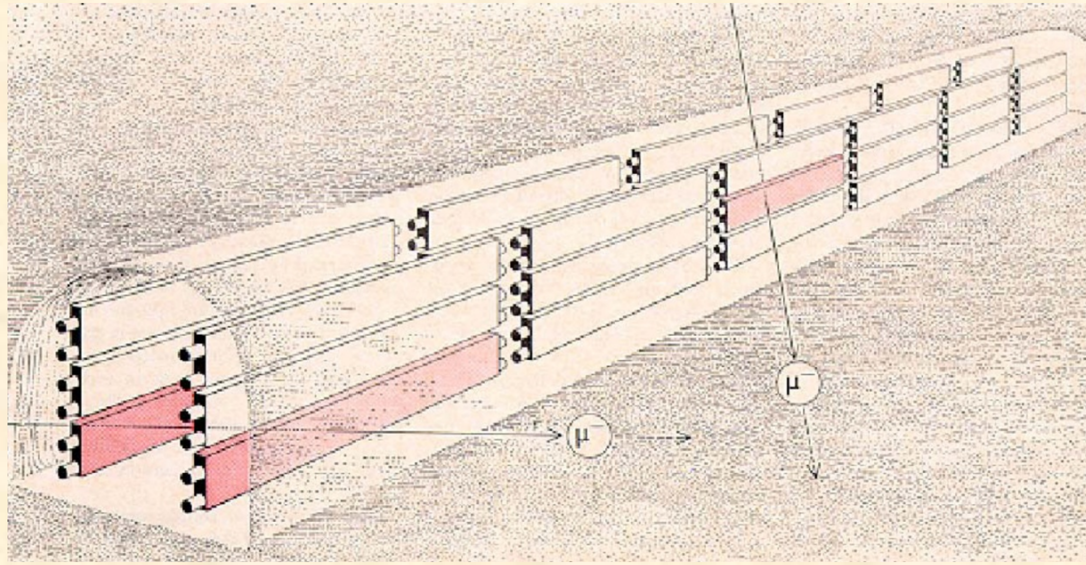
Detector Prototype

Anti-Electron Neutrinos from Hanford Nuclear Reactor

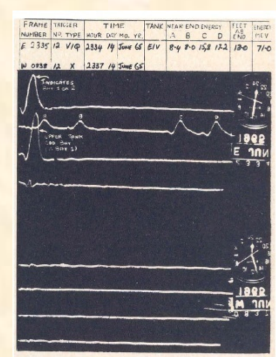


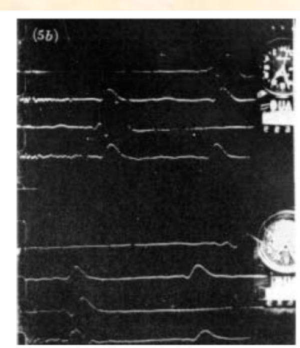
3 gamma quanta in coincidence

First Natural Cosmic Ray Neutrinos, 1965



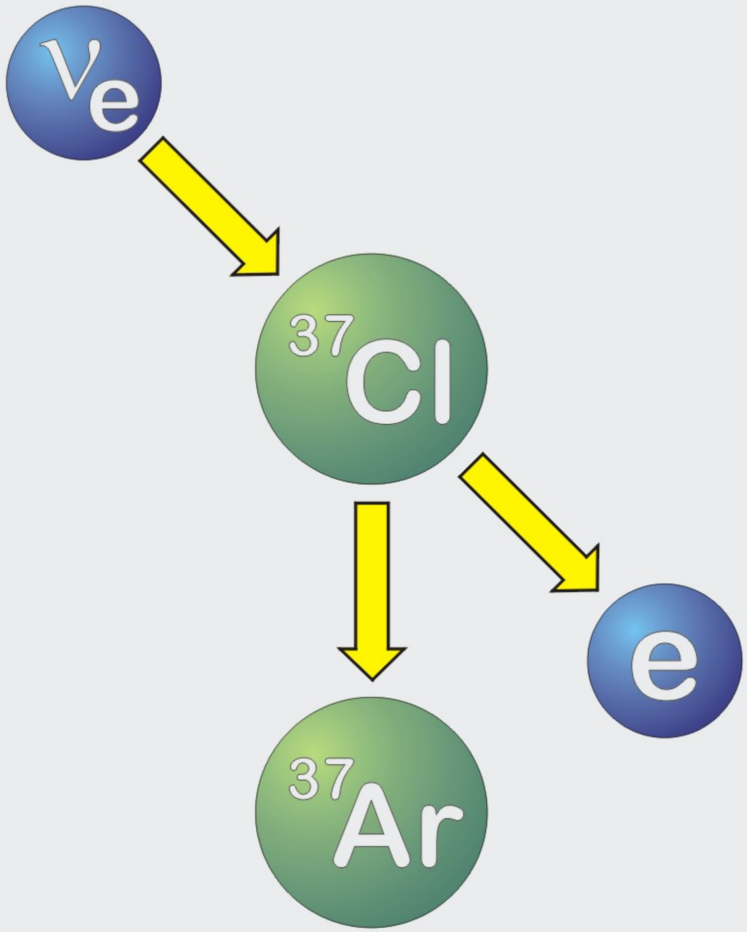
Reines and company in South Africa,
and Gaku Menon and company
in Kolar Gold Fields, India

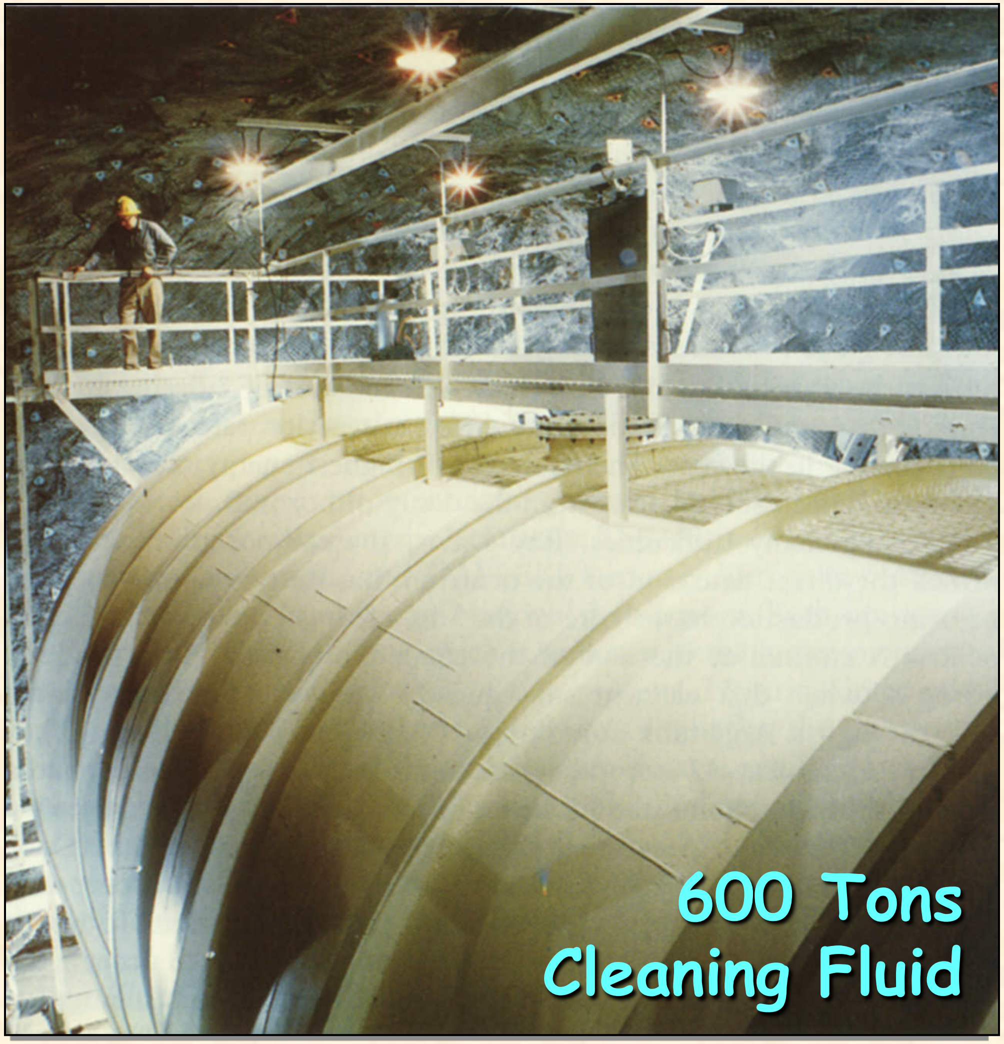




First Observation of Solar Neutrinos

Inverse Beta-Decay ("Neutrino Capture")





Homestake Solar-Neutrino Observatory (since ca.1967)

New Vigor in the 1980's

Lake Baikal Experiment and DUMAND Project begin.

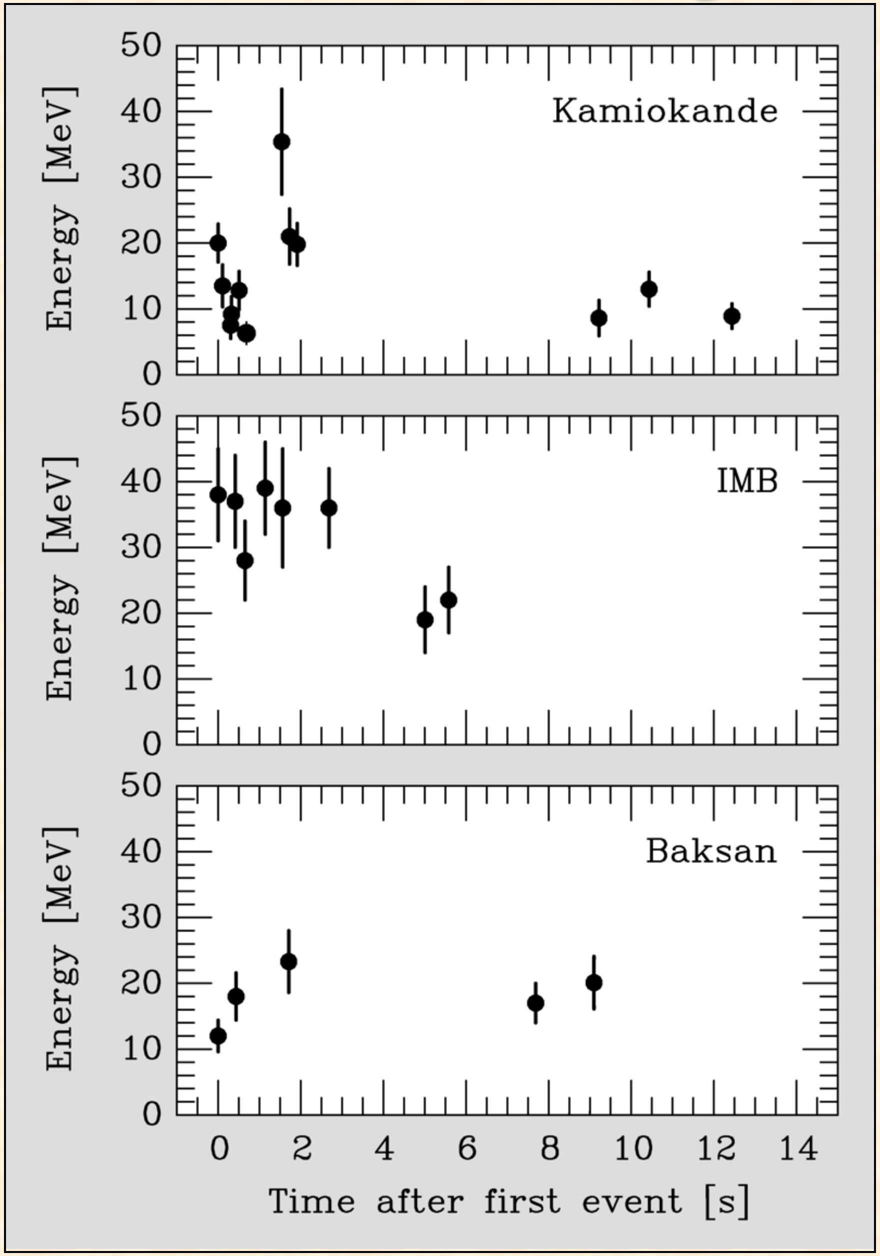
Solar neutrino experiments not seeing predicted rates…
blame game between solar modelers and experimentalists.
Theory provides a few possible explanations, including oscillations.

Underground cosmic ray neutrino detectors built to search for nucleon decay, but find peculiar deficit of muon/electron neutrinos in US (IMB) and Japan (Kamioka) (the "muon neutrino anomaly"), but not in Europe.

Lots of confusion, finger pointing, enthusiasm, but only ambiguous conclusions.

But then one great highlight, resulting in hundreds of papers:

Neutrino Signal of Supernova 1987A



Kamiokande (Japan)
Water Cherenkov detector
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union)
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

Neutrino Fever Hits in the 1990's

Kamiokande detects solar electron neutrinos, with directionality! (Eliminates question as to whether radiochemical expts actually detecting solar neutrinos)

Solar rates observed in 4 experiments 1/3-1/2 models… 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…

1998:Start of the Nu Revolution

The New York Times

"All the News That's Fit to Print"

VOL. CXLVII . . . No. 51,179

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.

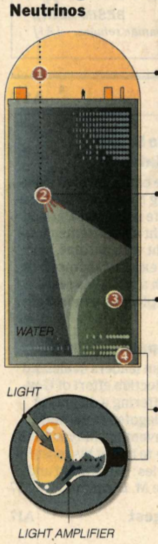
Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except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

After Dr. Kajita's remarks, the powerful evidence he presented elicited 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



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.

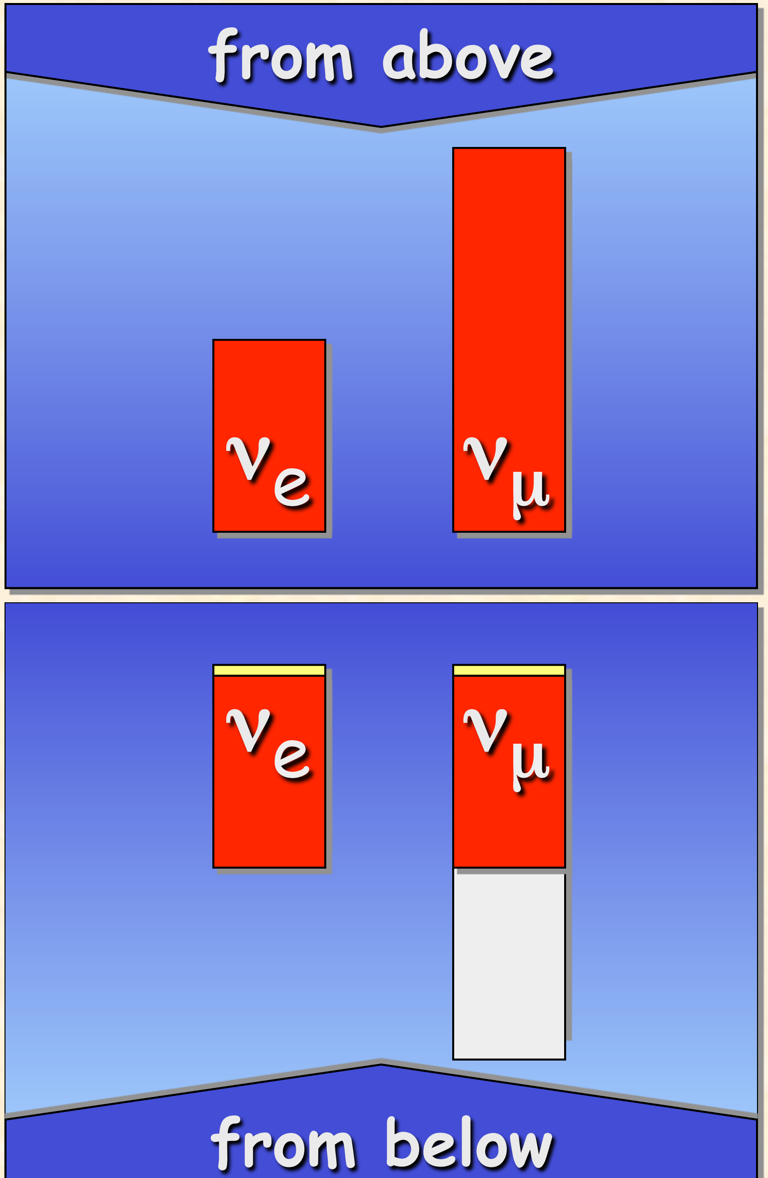
Representatives of dozens of neutrino experiments meet once every two years to exchange ideas at conferences like the one under way here. Present are representatives of teams that have installed neutrino detectors on the bottom of Lake Baikal in Siberia, under the Aegean Sea off the Greek coast, inside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

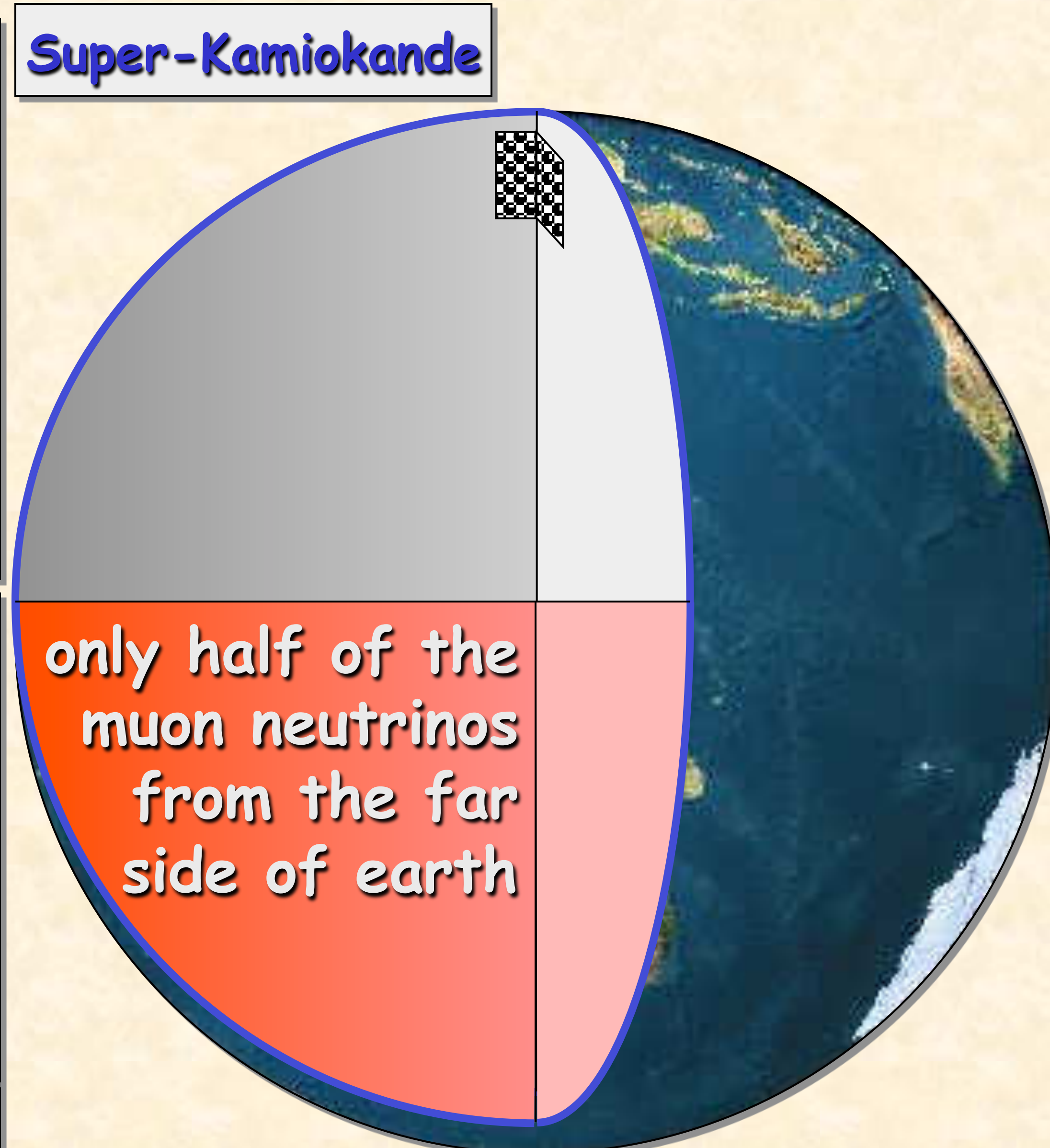
Lively debate has characterized discussions here. For example, Dr. Bahcall, who had high praise for the Super-Kamiokande experiment, challenged assertions by the detector team that neutrinos might have sufficient mass to slow the expansion of the universe.

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

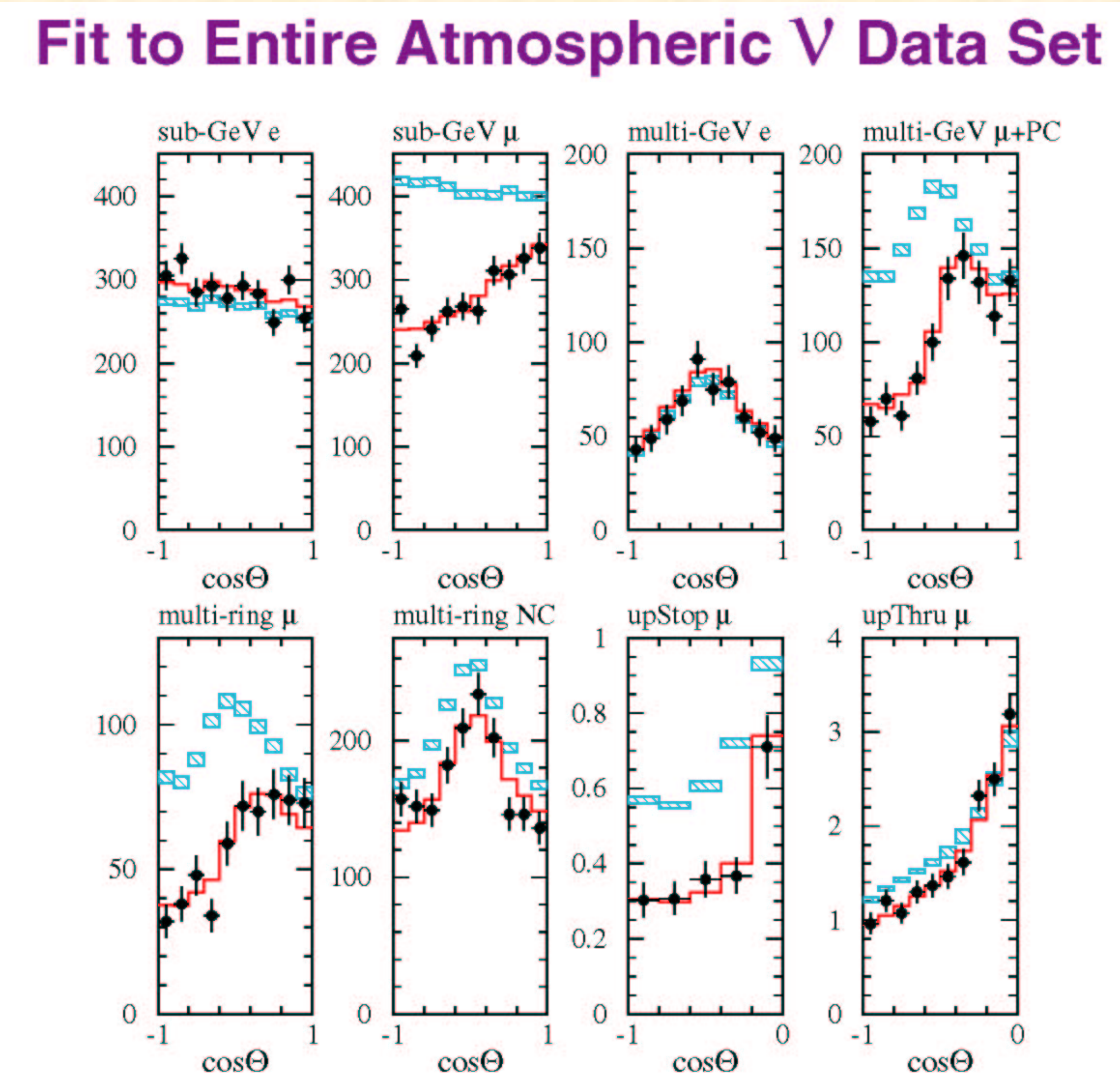
Another great detector built deep within a mine is nearing completion at Sudbury, Ontario. When scientists have finished filling it with heavy water, water that includes a heavy isotope of hydrogen as part of its molecule, the Sudbury detector will be uniquely capable of distinguishing between electron 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."

Atmospheric Neutrino Anomaly





1998 SuperK Neutrino Revolution



MC No-Osc

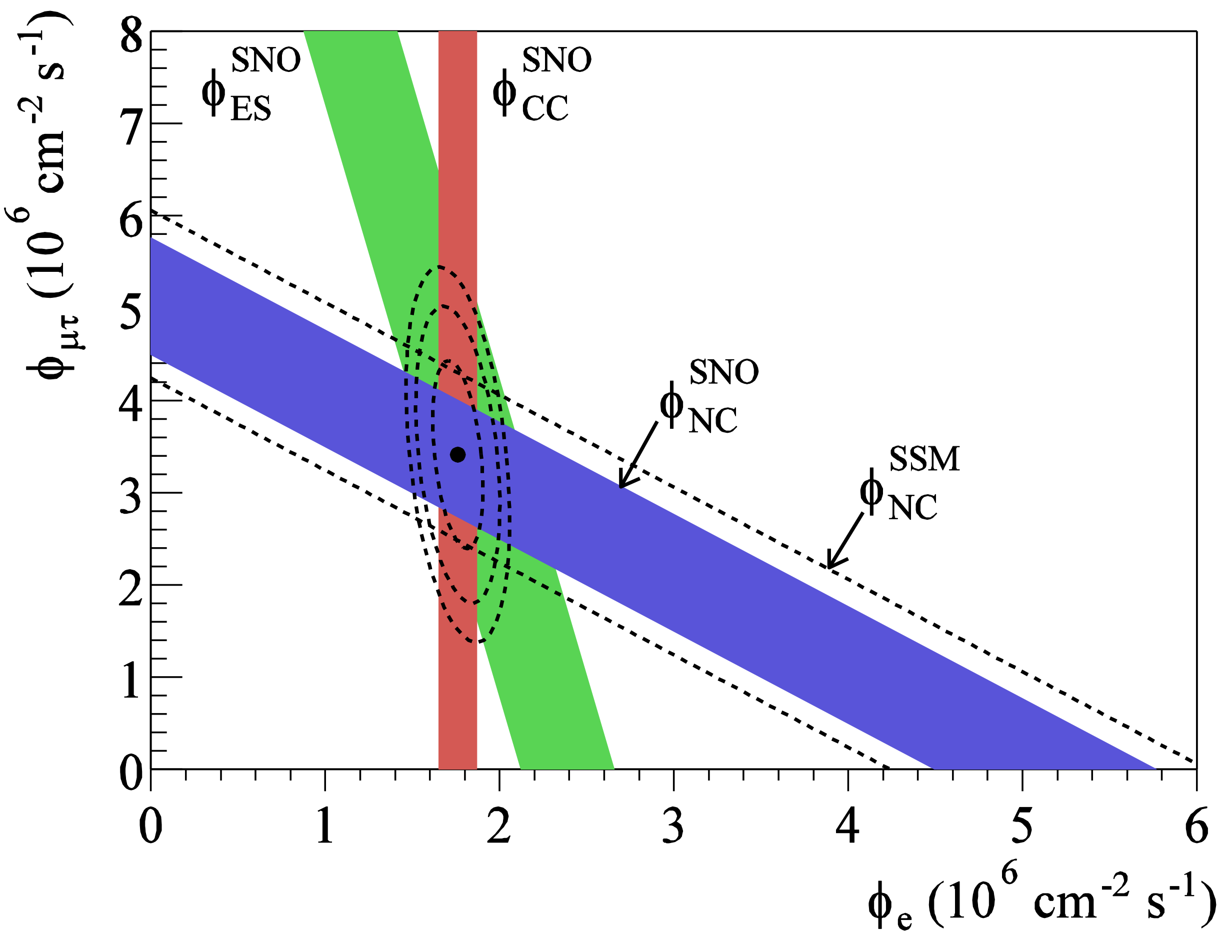
$\nu_\mu - \nu_\tau$

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

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

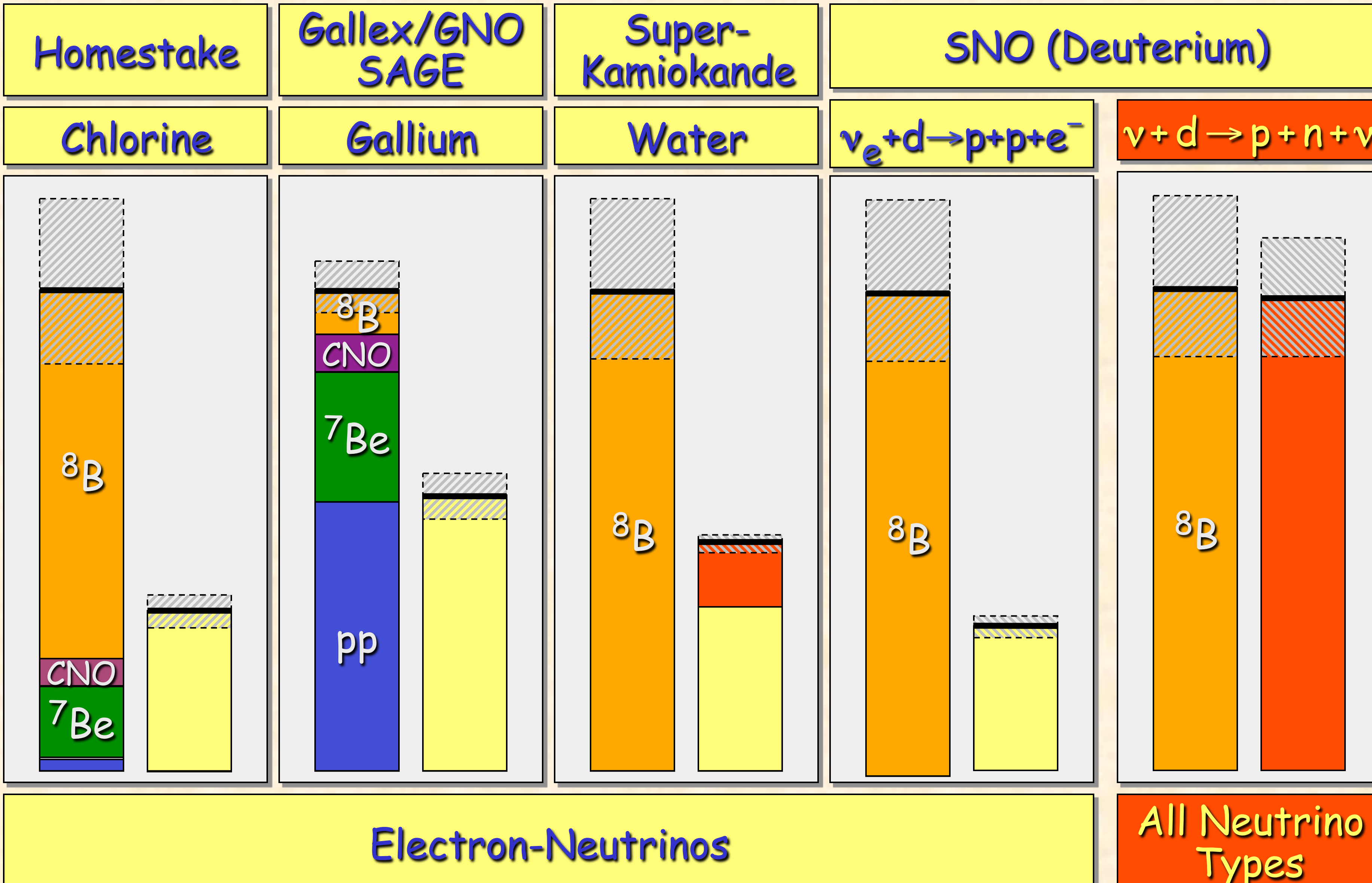
SNO: Solar Nu Channels Consistent with Oscillations

$\Phi_{ssm} = 5.05^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$

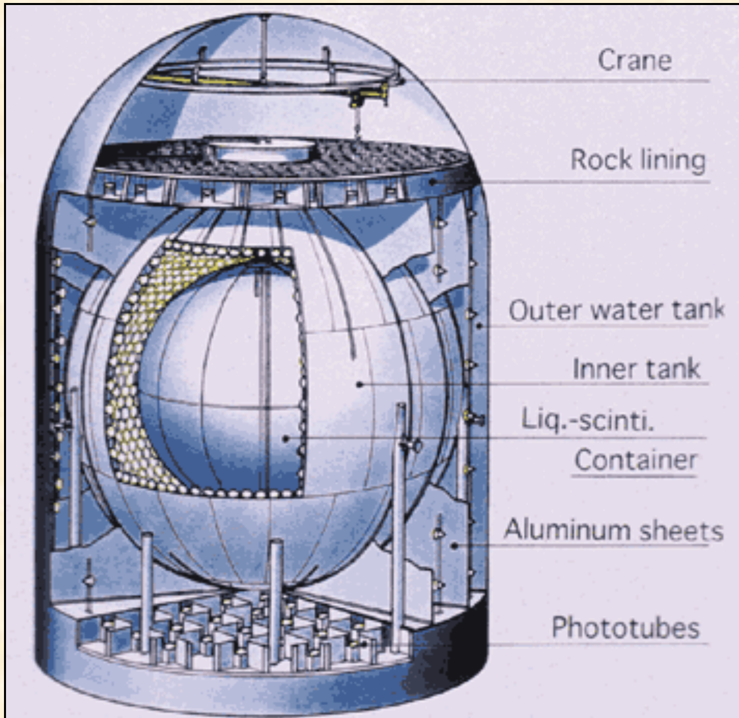


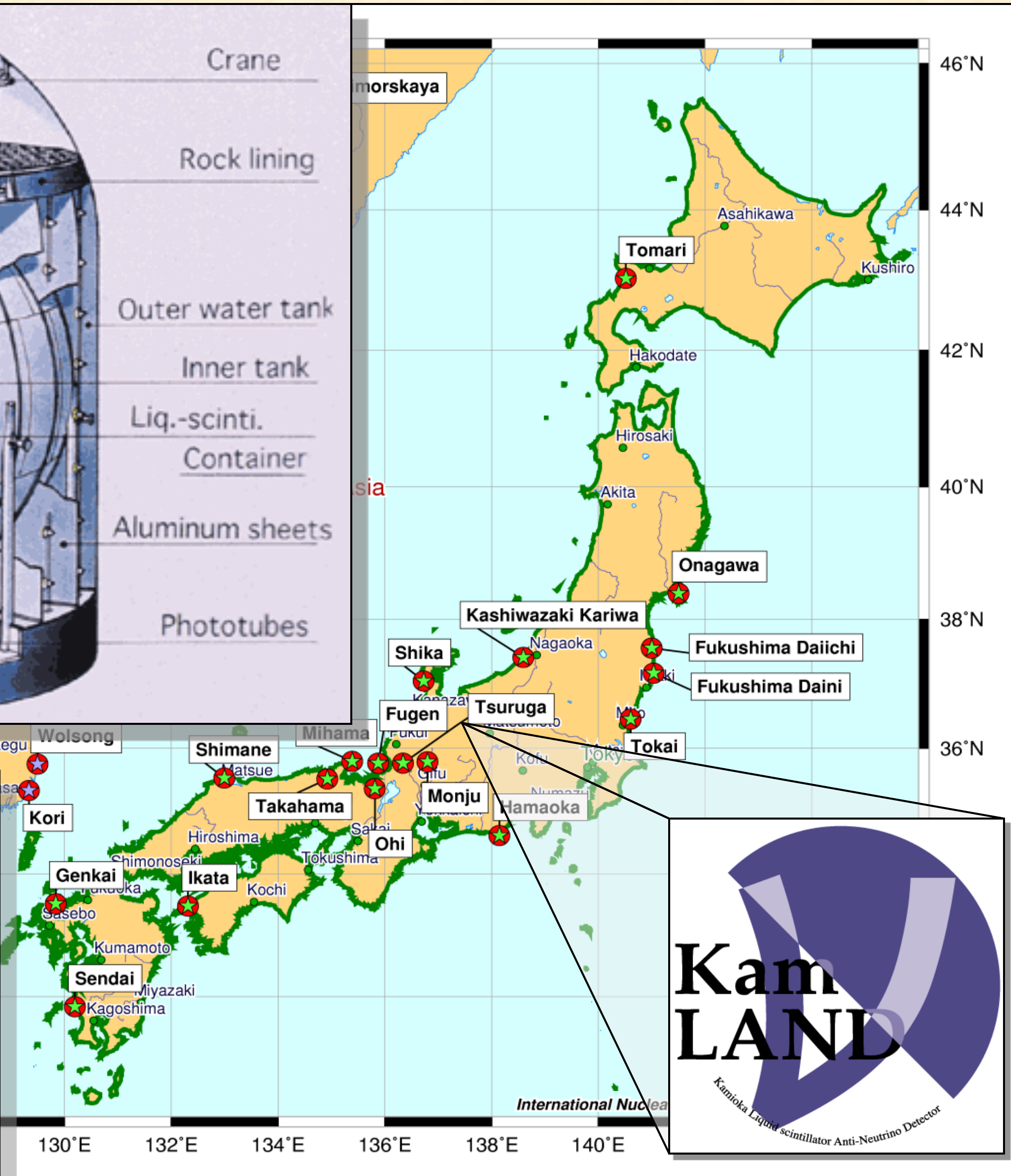
$\Phi_{\mu\tau}$ is 5.3 σ from zero

SNO Settles the Solar Neutrino Problem



KamLAND Reactor Neutrino Experiment (Japan)





Japanese nuclear reactors 60 GW (20% world total)

- ~1 neutrino capture per day
- Taking data since Jan. '02
- Conclusive Results Fall '02.

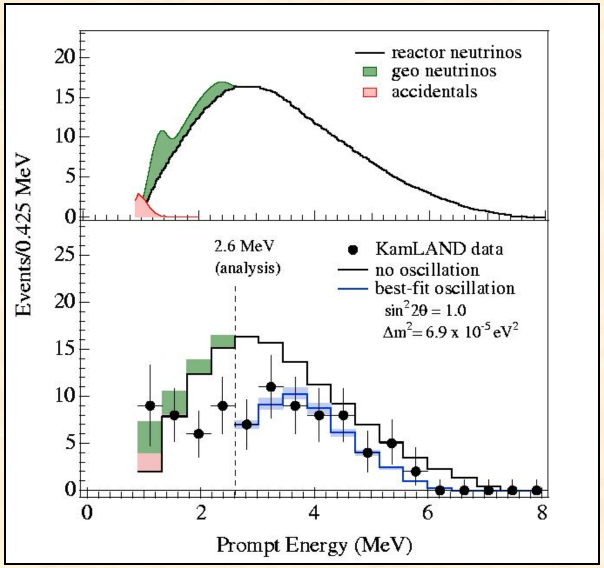
detect ν_e from >100km and observe deficit due to oscillations

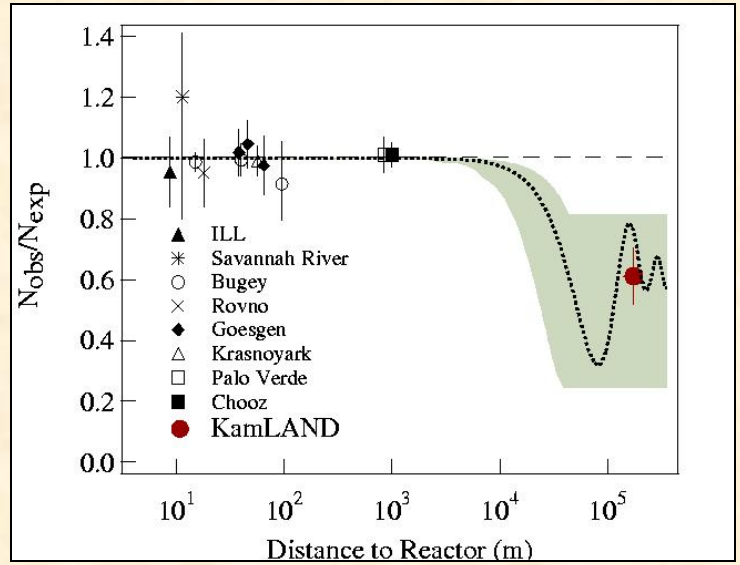
22 July 2012

John Learned at Ulan-Ude

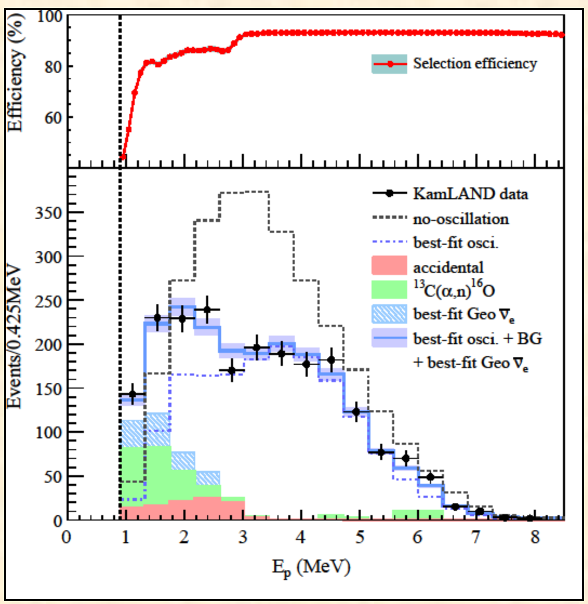
KamLAND … no escaping oscillations

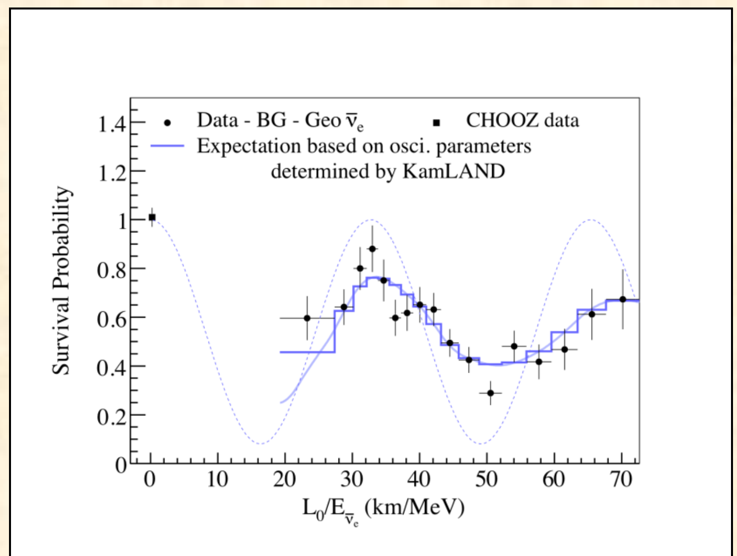
2003



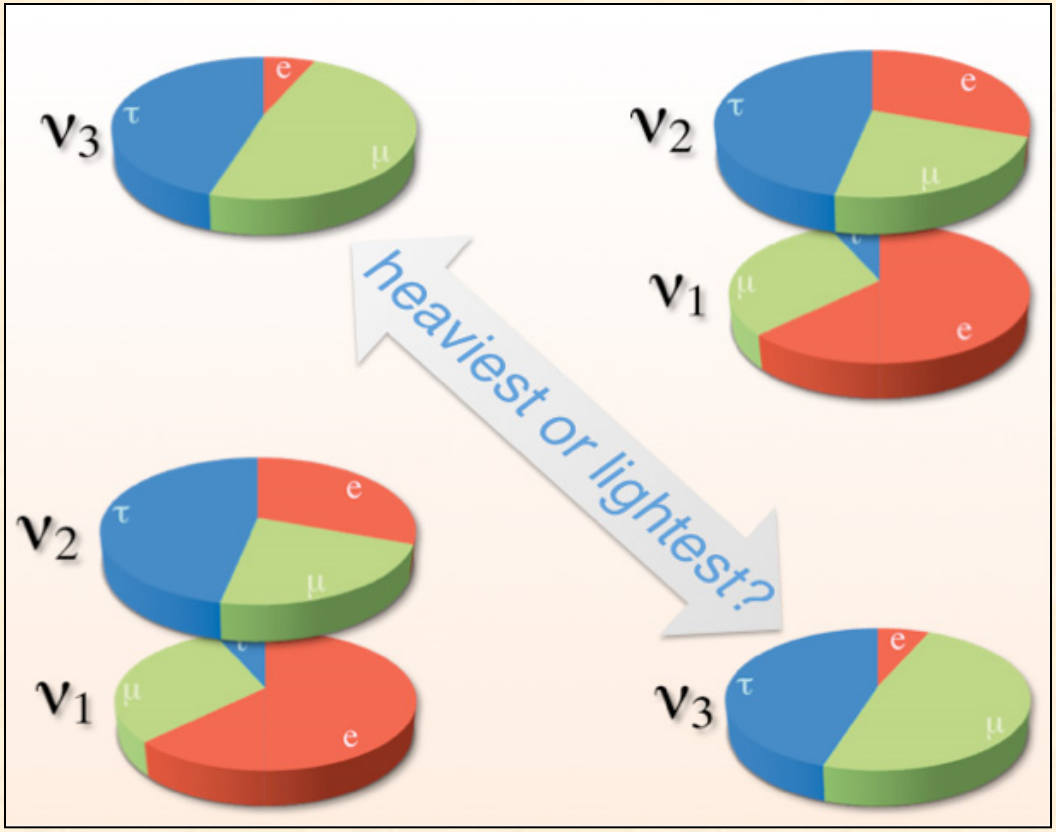


2010





Neutrino Mass and Composition



Differences of neutrino masses deduced from oscillation experiments.

Atmospheric Neutrinos:

$$m_3^2 - m_2^2 = 2 \times 10^{-3}\ eV^2$$

Solar Neutrinos:

$$m_2^2 - m_1^2 = 7 \times 10^{-5} eV^2$$

Mixings peculiarly large

Neutrino Oscillation Mixing Matrix

– U: 3 angles, 1 CP-phase + (2 Majorana phases)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrinos

$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & 0.1? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quarks

Very Different

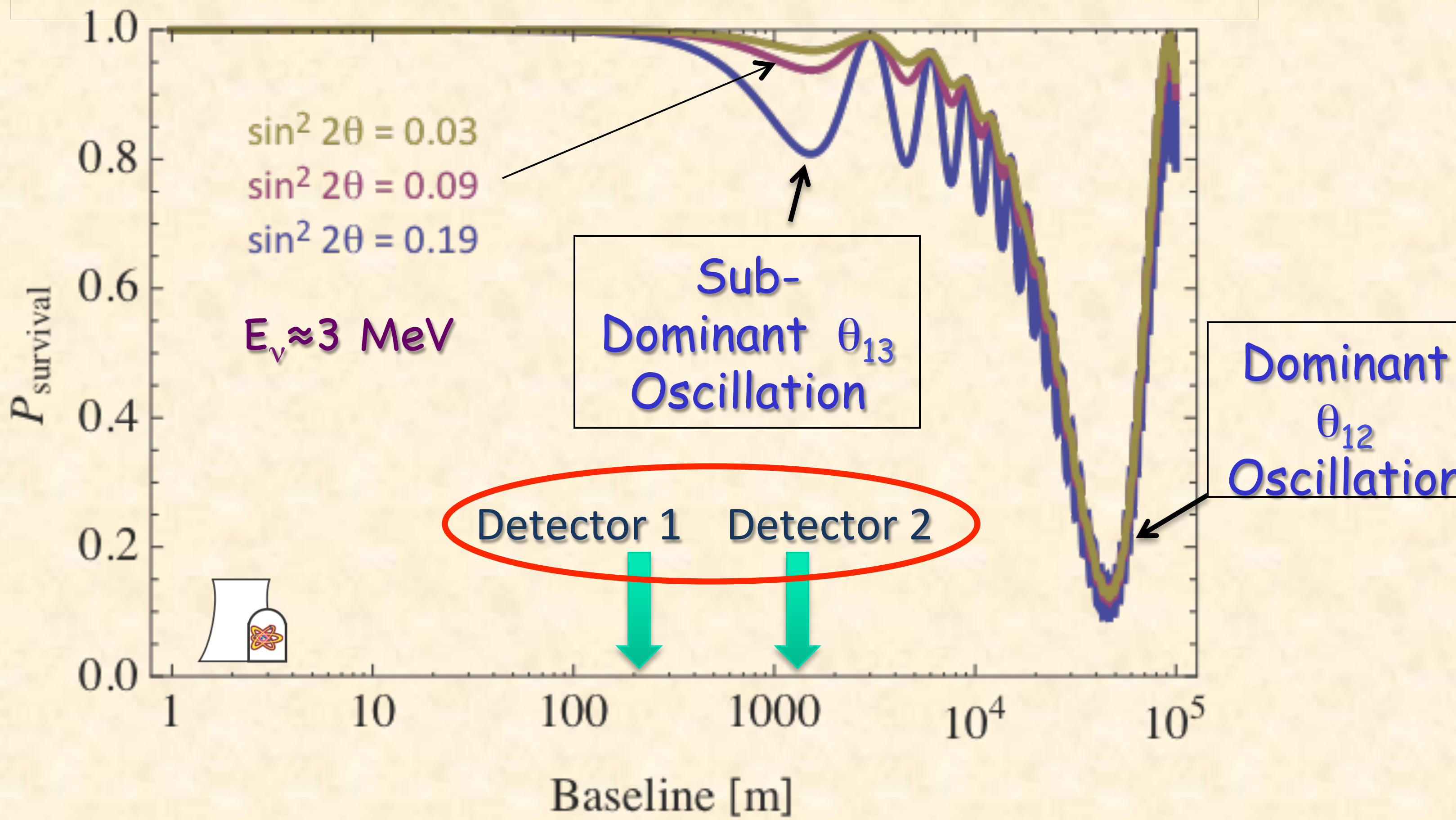
$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

Precision Reactor Experiments for θ_{13}

L. Mikaelyan, arXiv:hep-ex/0008046v2 (Krasnoyarsk)

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Not sensitive to CP violation, so clean measurement



build nearly identical detectors with nearly identical efficiency

Kearns NUFACT09

Three New Reactor Experiments

- Double CHOOZ in France
- Daya Bay in China
- RENO in Korea

- 2011-2012: All three report positive signature!

- More later: see Tobias Lachenmaier talk

What next in Neutrino Measurements?

Indirect Dark Matter measurements via neutrinos: no evidence yet… Still much room for improvement. No hints at all though.

Various hints from Direct DM experiments, but new Zenon100 results very restrictive.

More talks absolute neutrino mass measure and double beta decay (now about half dozen experiments)… huge active area.

So, now what?

Everyone agrees: 3 nu oscillations real

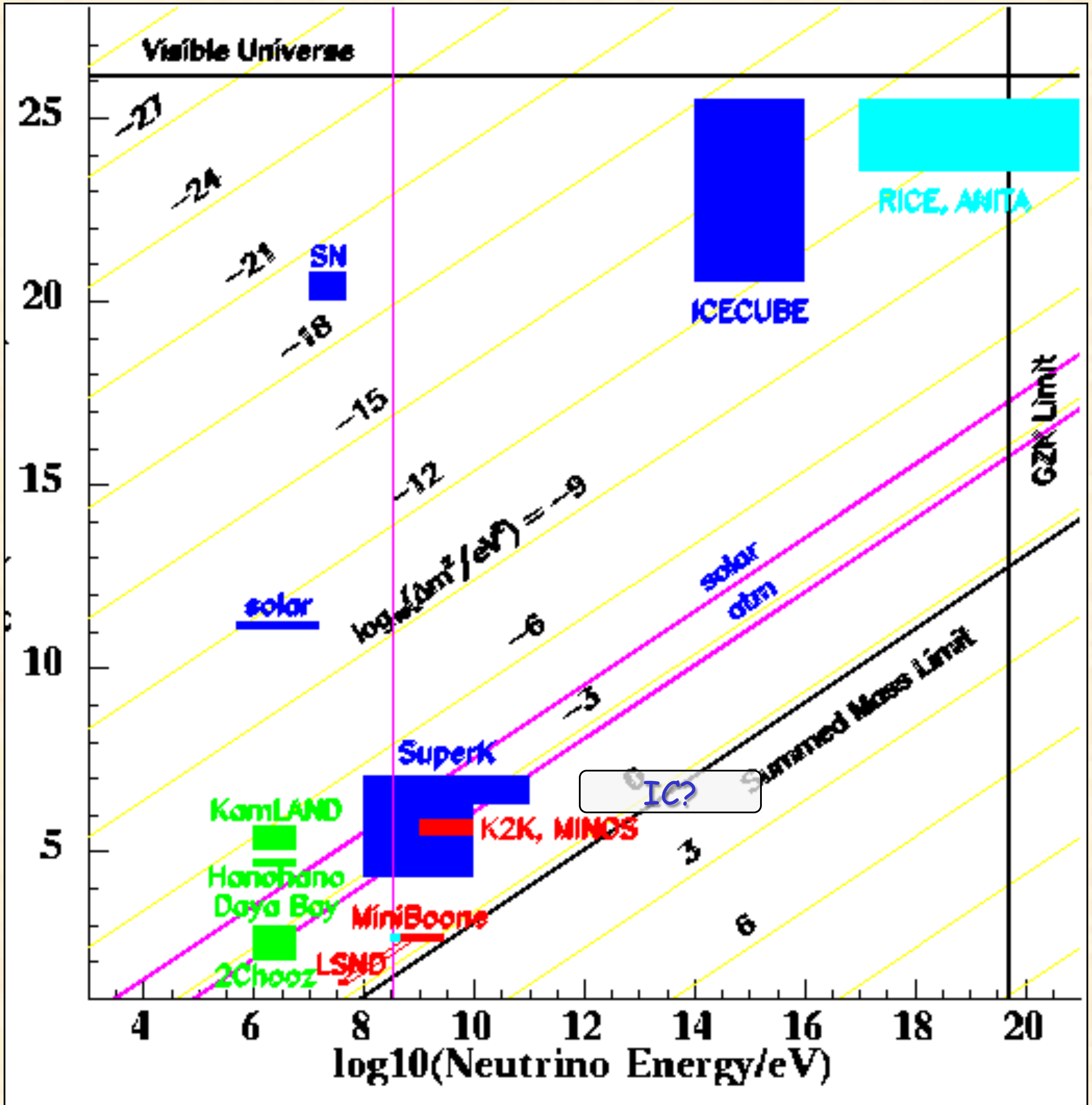
- 3 nu mixing is adequate to explain everything, though mixing matrix not greatly constrained yet…

- except LSND/miniBoone data which cannot be accommodated with 3 nus alone.

- What about CP violation? Next big push.

  See Kudenko talk

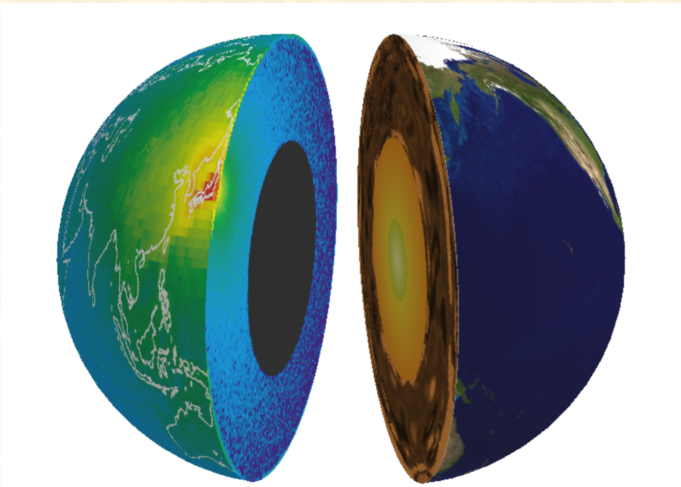
Big Picture Probing Oscillations



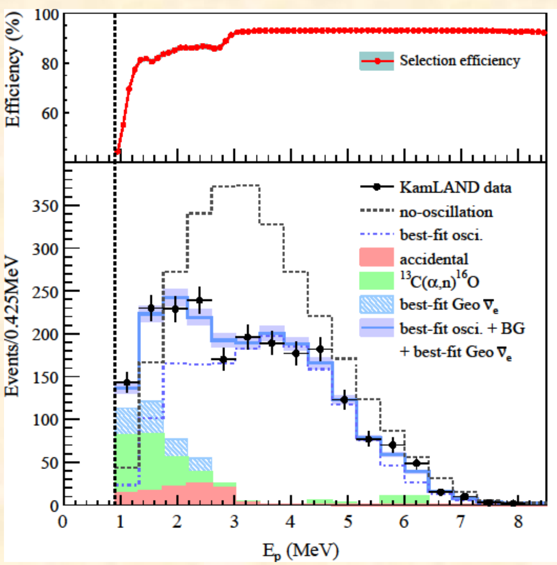
And now for something different, but related…

- We have been studying large and in some versions portable electron anti-neutrino detectors for three applications:
  - More detailed oscillations studies
  - Development of remote reactor monitoring
  - Study of geoneutrinos

Geoneutrinos: An Emerging Field



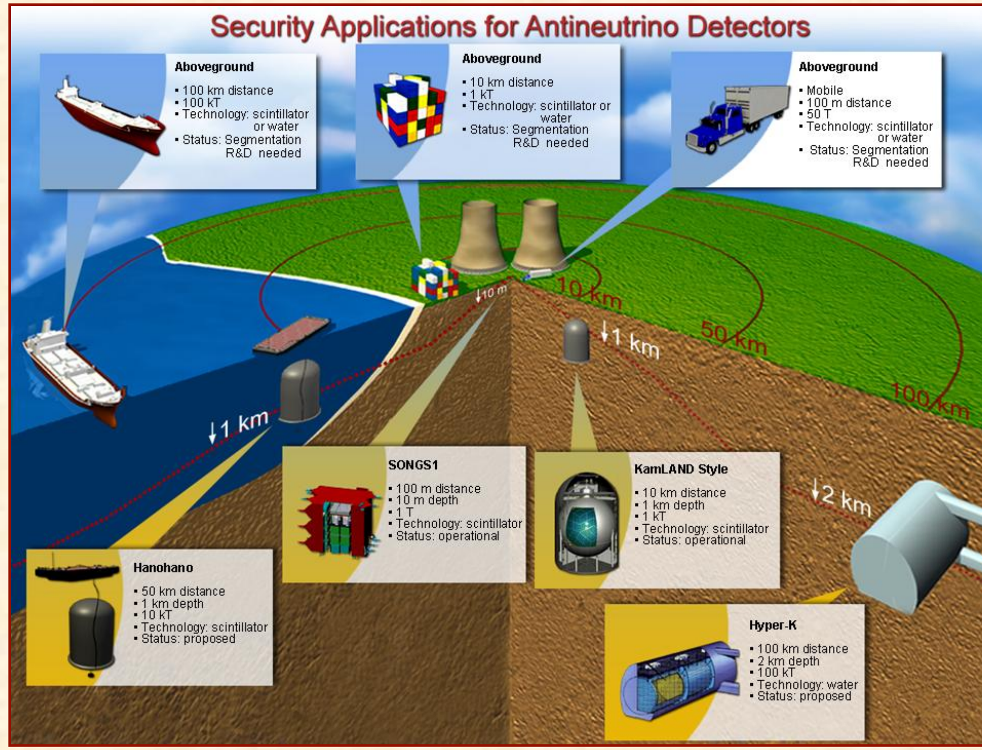
Geophysics with Neutrinos

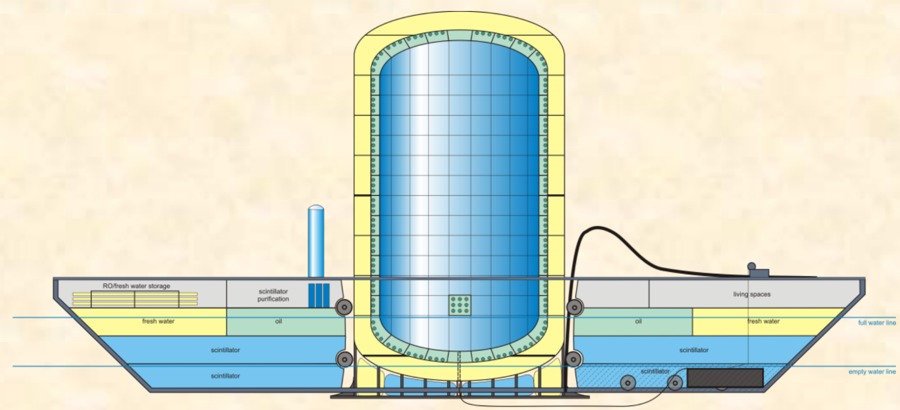


- Neutrinos from U and Th chains thought to be major source of earth internal heat, and geodynamics (crustal motions, earthquakes, volcanoes),
- Much debate about how much total and here it originates. Major question in geology, and no other way to access information than neutrinos.
- KamLAND detected U/Th decay neutrinos from whole earth in 2005, updated in 2009. Borexino too in 2009.
- Results indicate earth heat probably not totally radiogenic. Also no indication (yet) of major natural reactor source.
- This is a 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. Nice Geonu meeting Gran Sasso 10/10

Nuclear Reactor Monitoring for Anti-Proliferation

- Series of Workshops over last seven years about reactor monitoring (Hawaii, Palo Alto, Paris, Livermore, Maryland, Japan, Italy, **Hawaii October 2012**).
- Several major (p)review papers (arXiv:0908.4338 , arXiv:1011.3850 , one in preparation)
- Near: ~1m^3, ~20m, cooperative site, IAEA application
- Demonstrations a San Onofre Calif., and other places. Efforts 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.

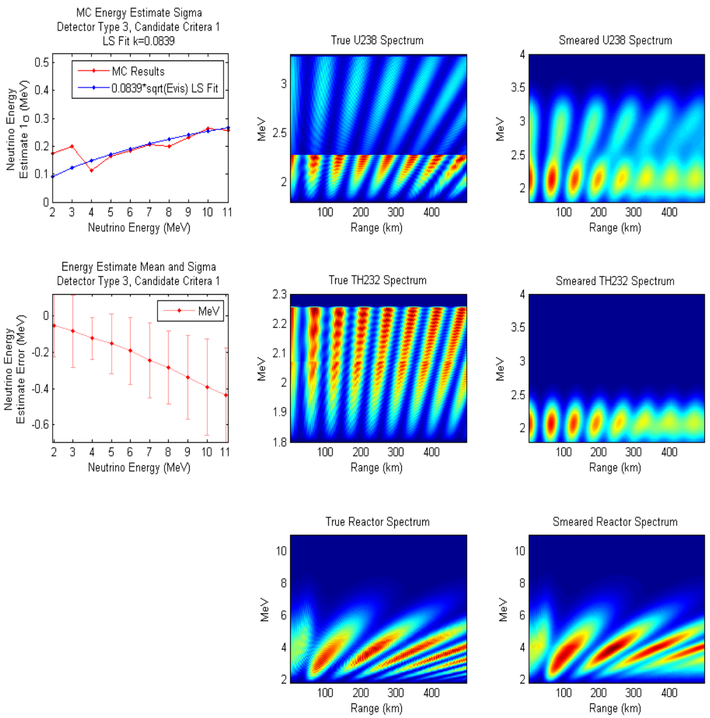


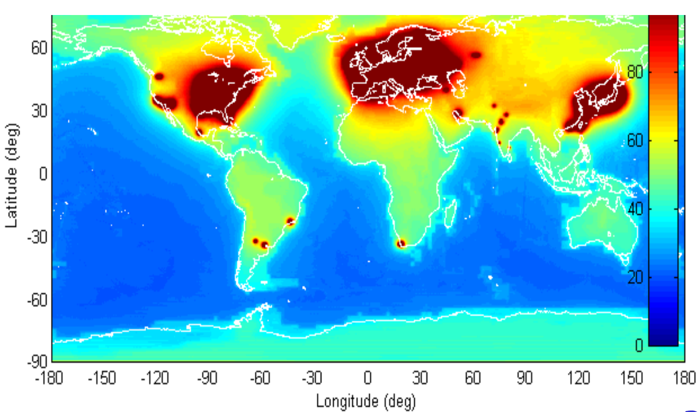


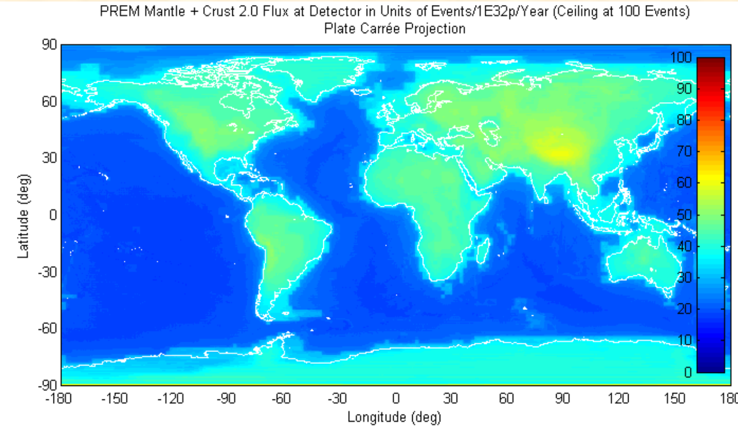
Hanohano Detector

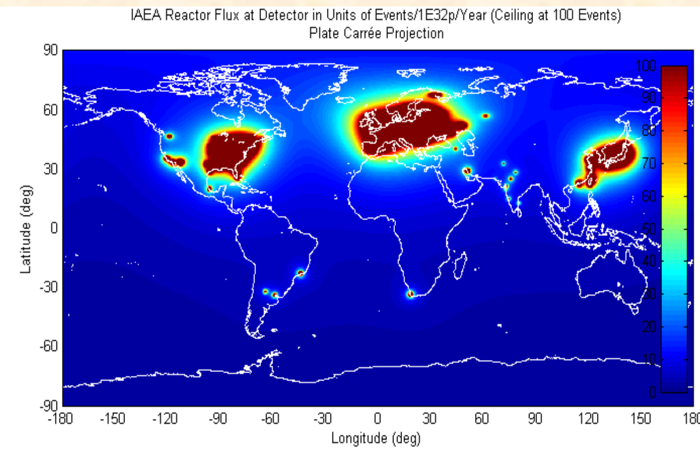
John Learned at Ulan-Ude 22 July 2012

Doing Detailed Modeling of Reactor Backgrounds



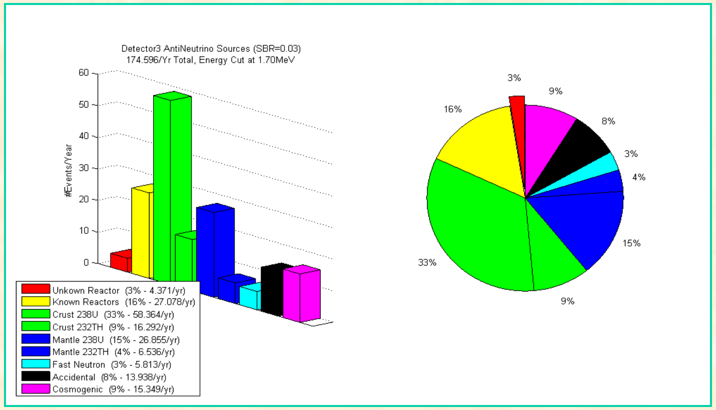




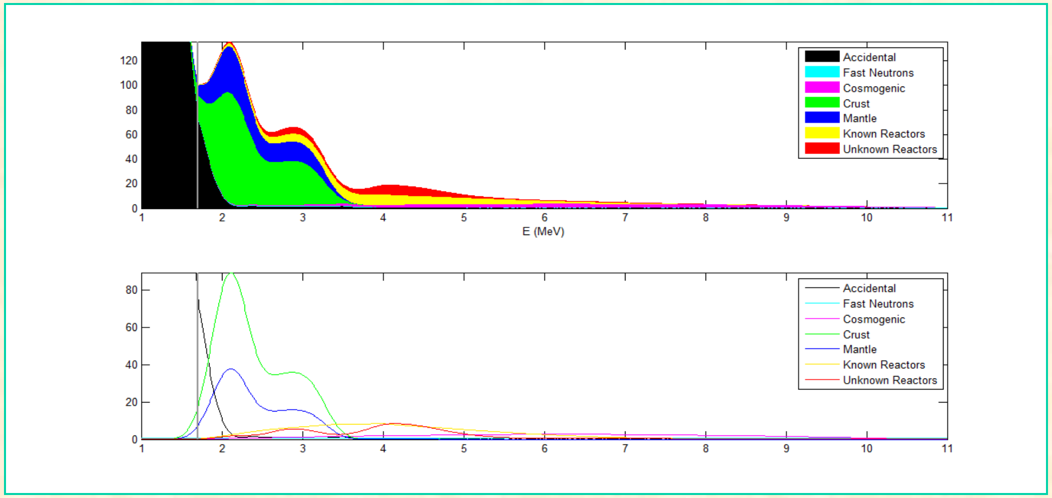


Plots from Glenn Jocher, Integrity ApplicationsInc

More on Detailed Modeling

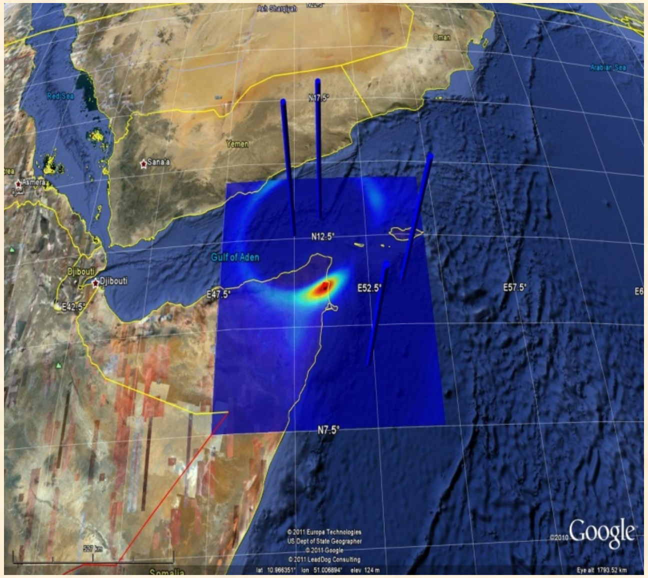


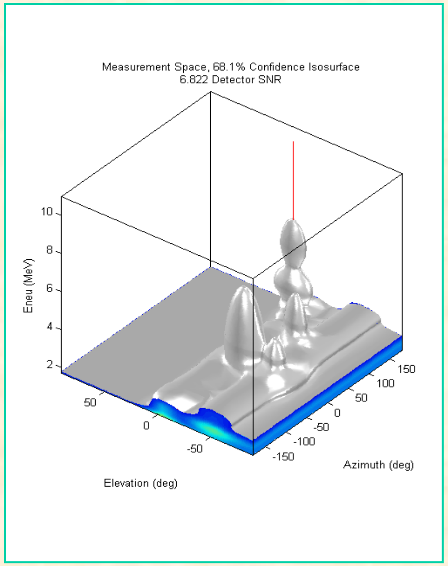
We have a program allowing arbitrary placement of detectors, including depth and calculations of all backgrounds (based on KamLAND and Borexino experience)

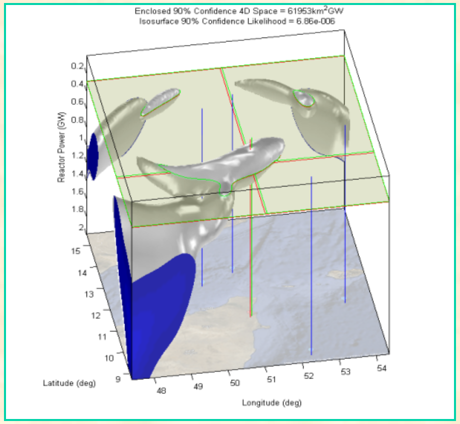


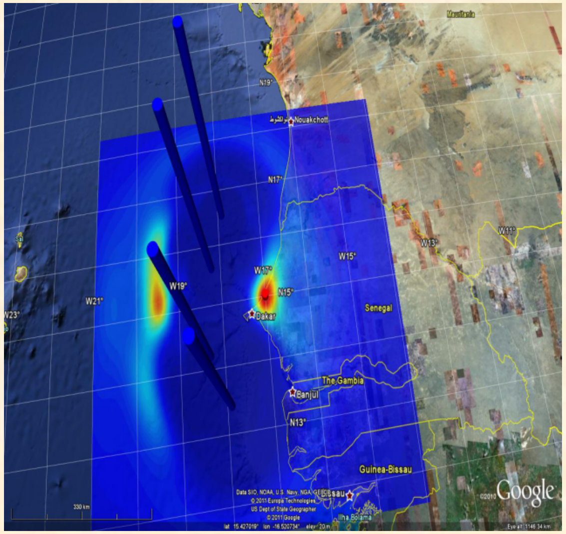
Glenn Jocher, IAI

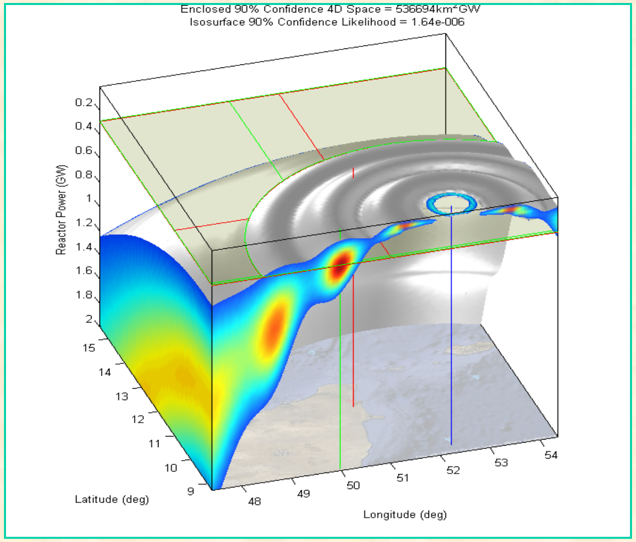
Finding and Measuring Remote Reactors











Glenn Jocher,IAI

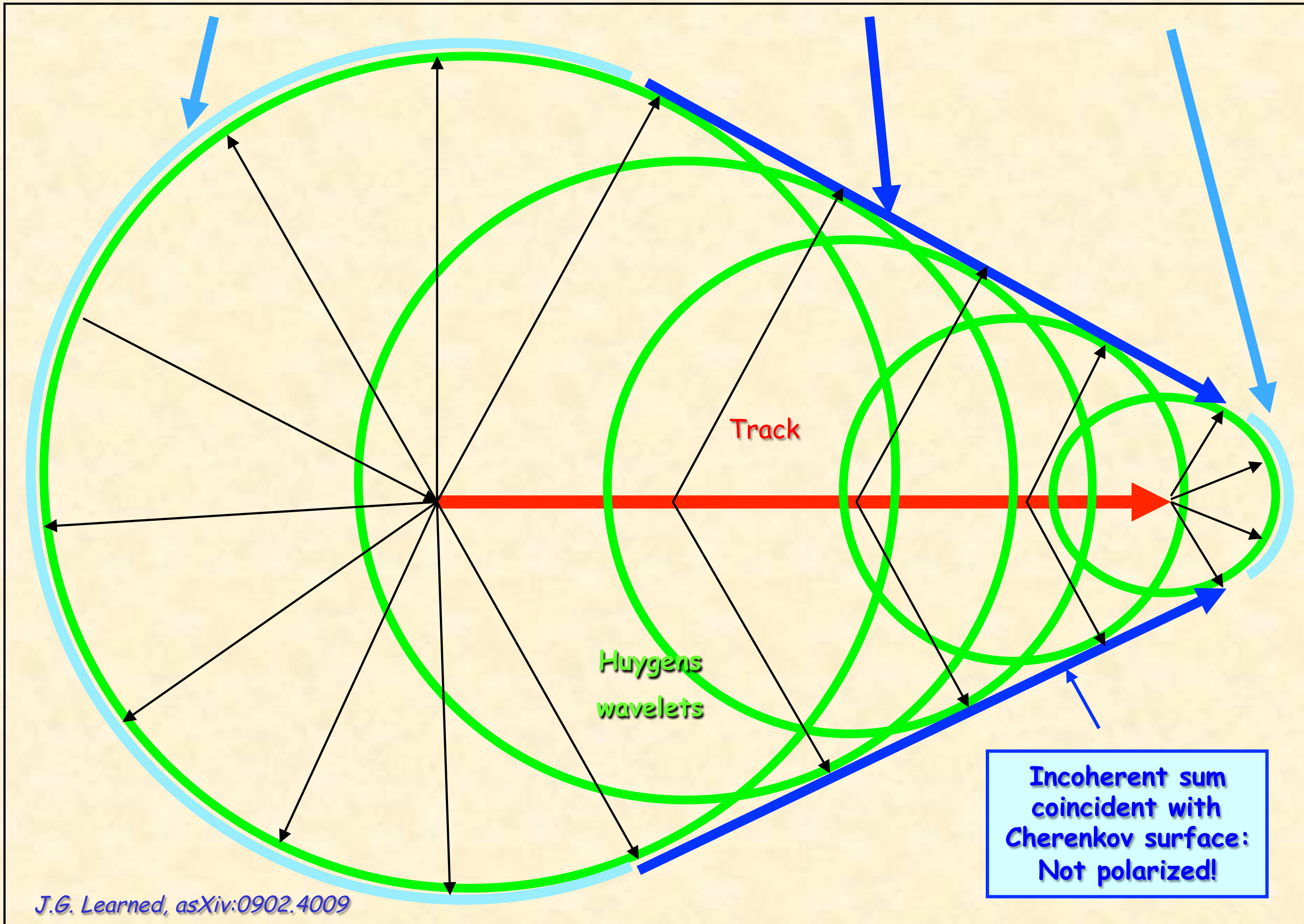
Change Gears and Talk about New Detectors

- Intro to new means of reconstructing events in liquid scintillator, where tracks radiate light isotropically
- (not like Cherenkov radiation in water as in SuperK)

2009 Realization that Liquid Scint Detector Can Reconstruct Events

First light yields topology. Now important part of LENA project proposal.

Snapshot of the Fermat Surface for a Single Muon-likeTrack



Time Reversal Image Reconstruction

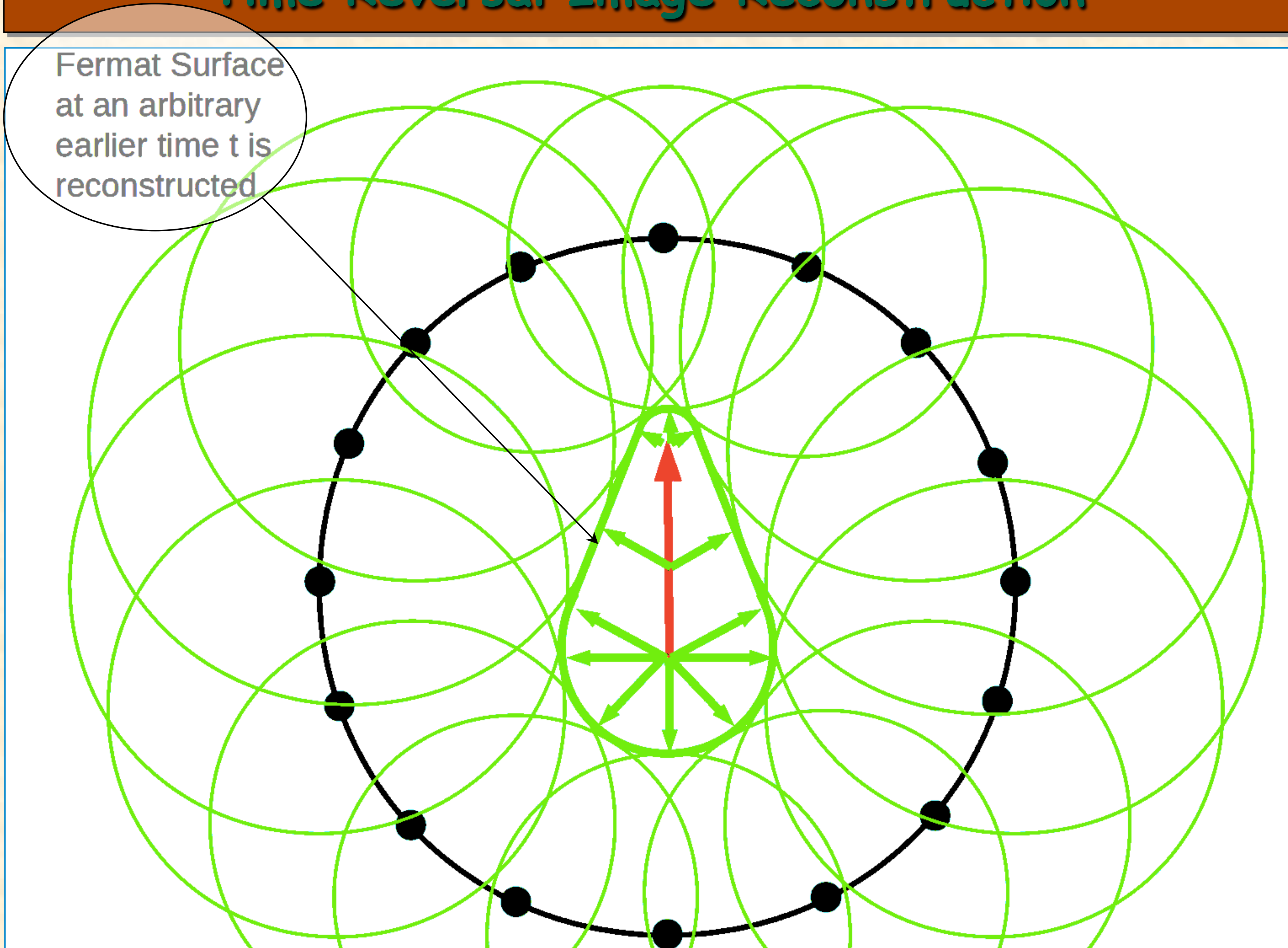


Figure by Mich Sakai

Applications

- Long Baseline with accelerators ~ 1 GeV
  - Hanohano with Tokai Beam?
  - LENA with CERN beam?
  - New DUSEL Experiment with Fermilab Beam?
- Nucleon Decay (high free proton content)
  - See details of decays such as Kaon modes
- Particle Astrophysics (low mass WIMPS,…)
- All the low energy physics (geonus, reactor studies, monitoring, solar neutrinos…..) **unimpeded**!

Application in 50 Kiloton LS LENA Detector

FIG. 1: Artist's view of the LENA detector.

LENA is major project proposed for Europe, probably Finland (1/3 of LAGUNA initiative)

Much nice physics to be done with such.

Major White Paper on Web last year.

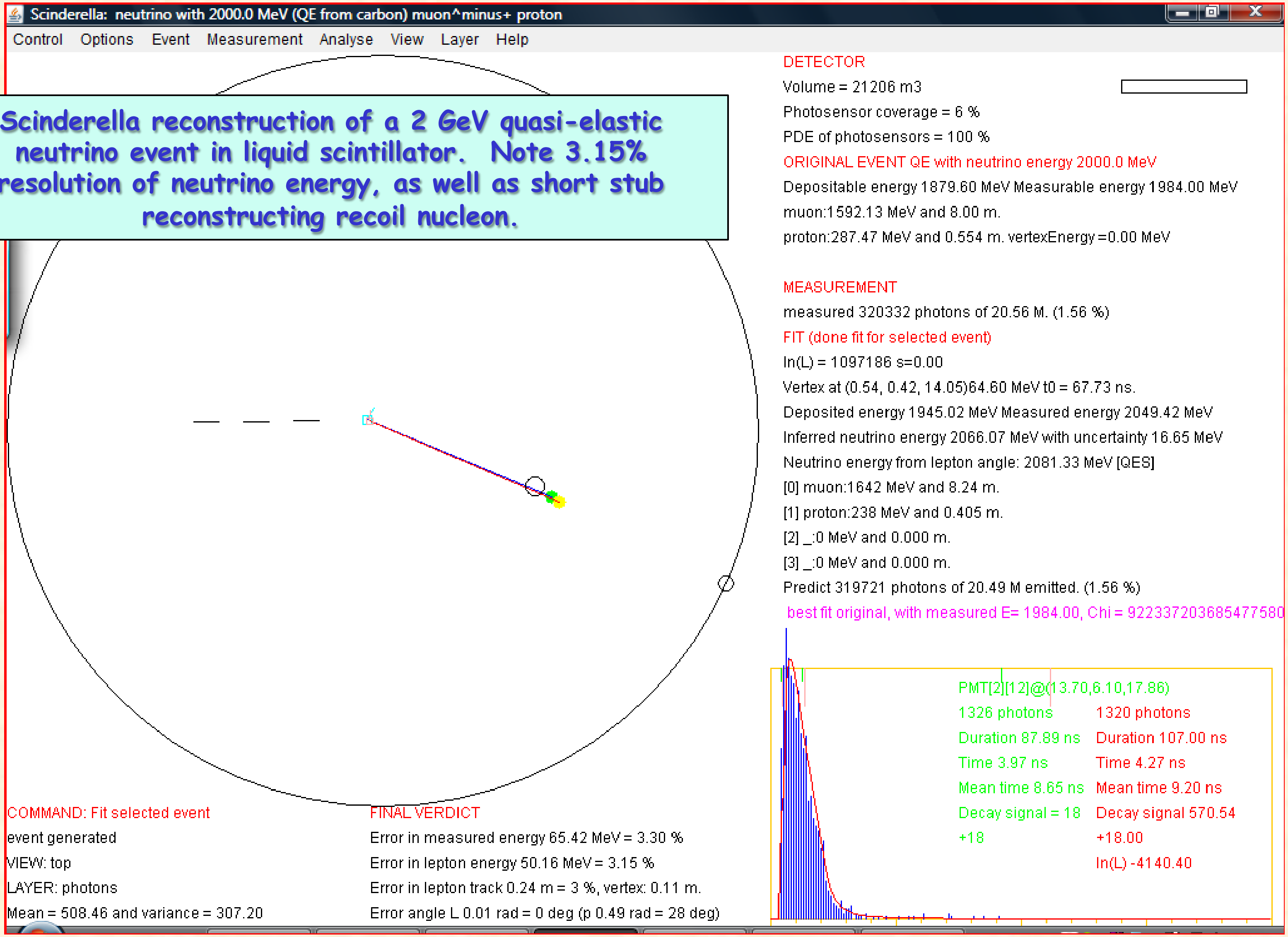
Most interesting for this talk, is ability to do long baseline GeV neutrino studies Using the Fermat trick.

(Michinari Sakai working on testing with KamLAND data.)

(See von Feilitzsch talk)

If one can employ the full waveforms…

Scinderella reconstruction of a 2 GeV quasi-elastic neutrino event in liquid scintillator. Note 3.15% resolution of neutrino energy, as well as short stub reconstructing recoil nucleon.



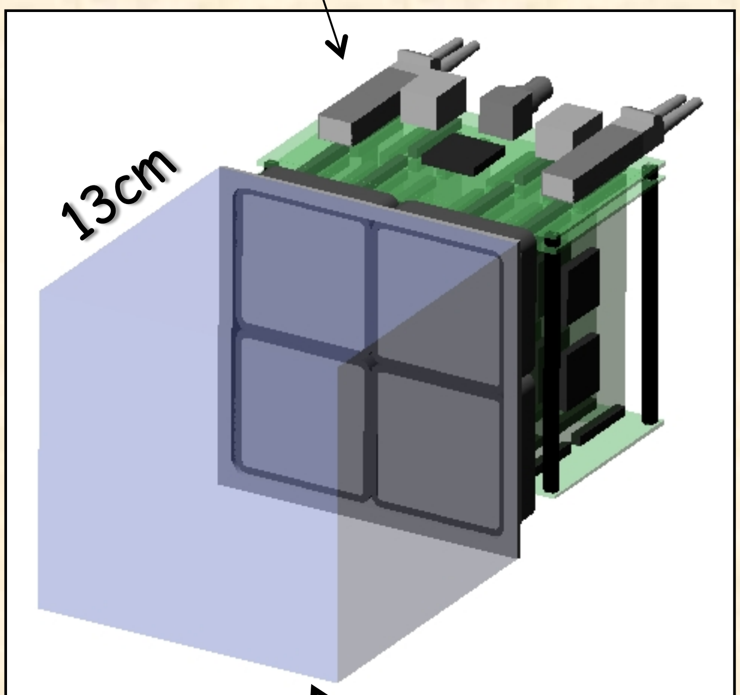
Juha Peltoniemi, arXiv:0909.4974

Back to UH for our miniTimeCube

Spring-boarding from this and wanting to develop a way to get directionality for electron antineutrinos we came up with a new type of detector, with time replacing optics.

Idea for Small and Directional Inverse Beta Detector

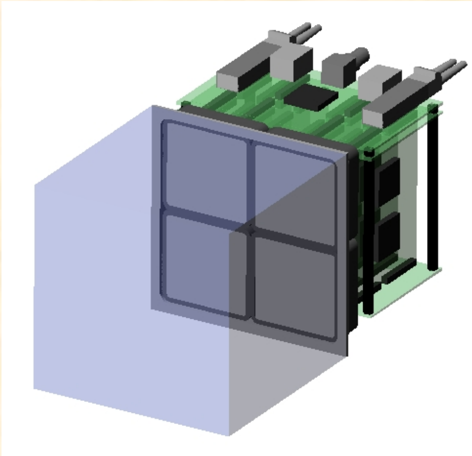
Fast digitizing electronics (x6)



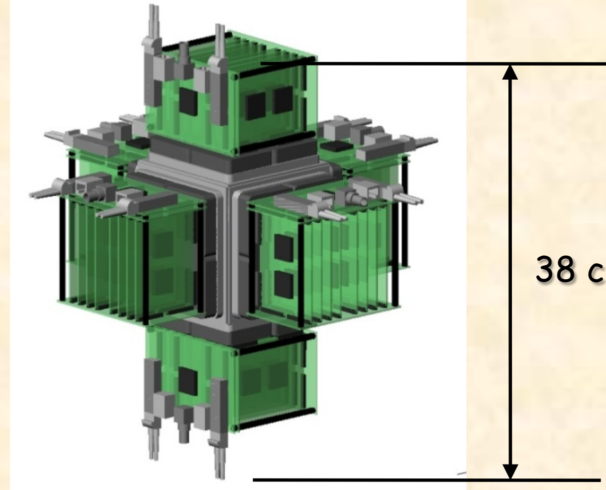
2.2 liter scintillator

- Small portable 2.2 liter scintillating cube with neutron capture doping.
- Contain positron, lose gammas
- Do imaging with fast timing, not optics (time reversal imaging).
- Get some neutrino directionality between positron origin and neutrino capture point.
- Reject noise on the fly; no shielding needed
- 4 x 6 MCP (x64 pixels each) fast (<100 ps) pixel detectors on surrounding faces
- ~10/day anti-neutrino interactions (inverse beta decay signature) from reactor.

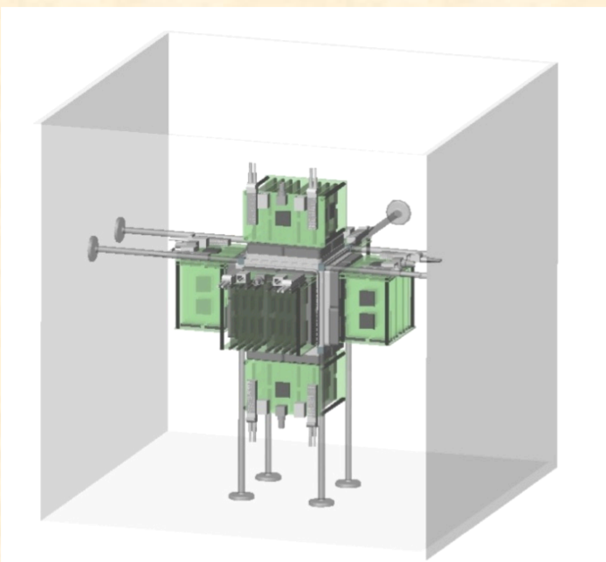
Mini Time Cube Based On 13cm^3 Boron Loaded Plastic Scintillator



MTC with read-out electronics on one face



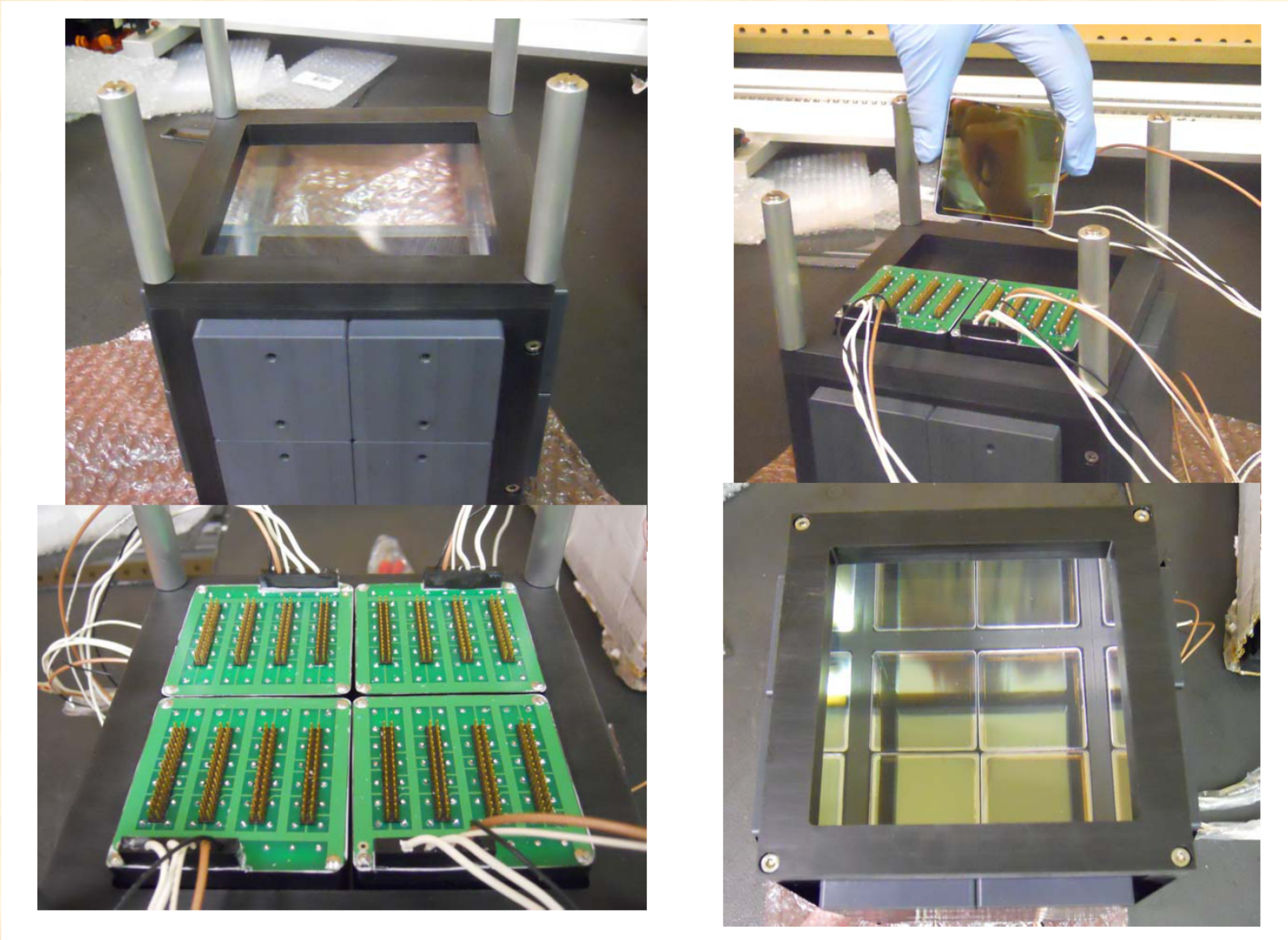
MTC fully populated with read-out UH-ID electronics



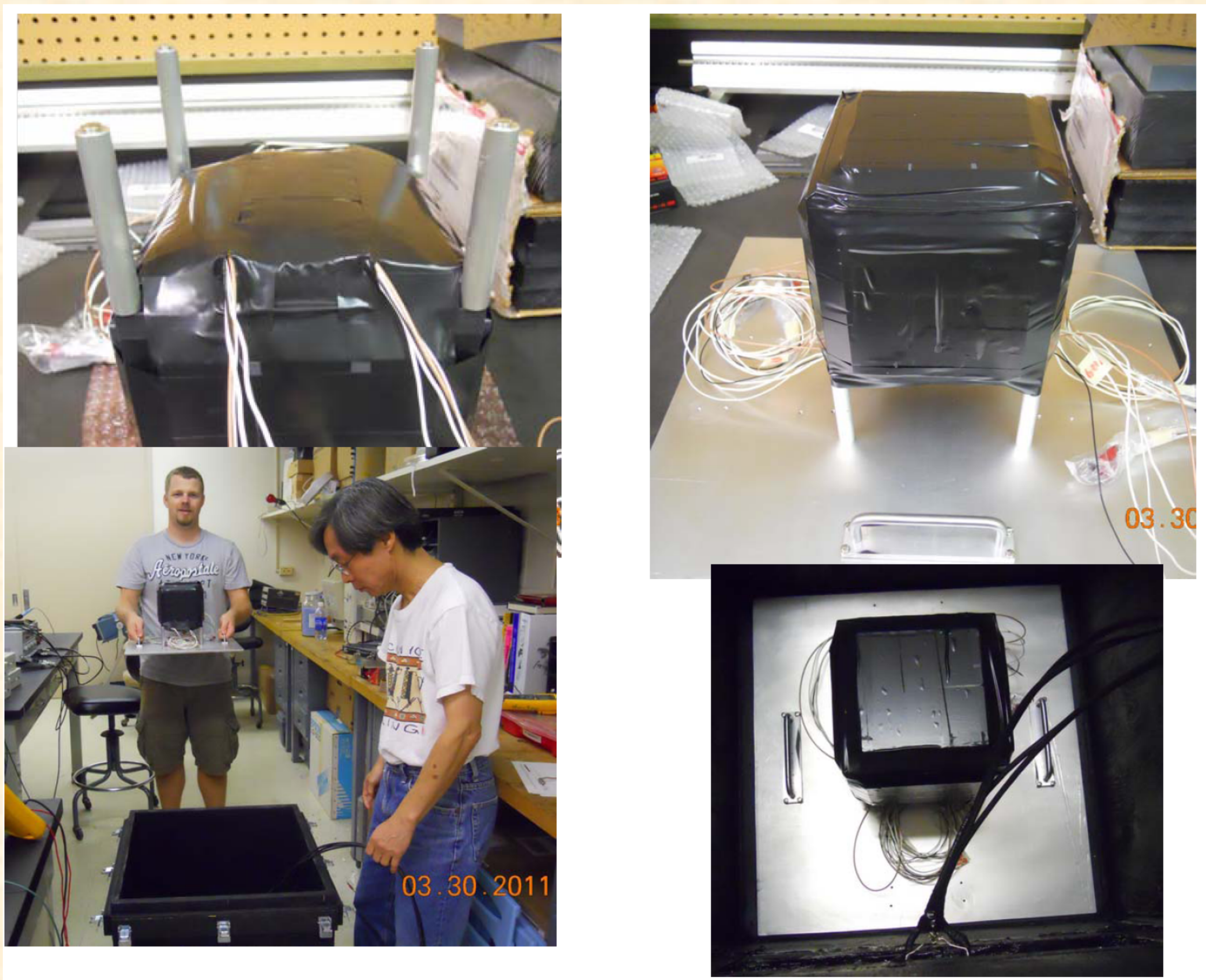
MTC within 2ft^3 enclosure

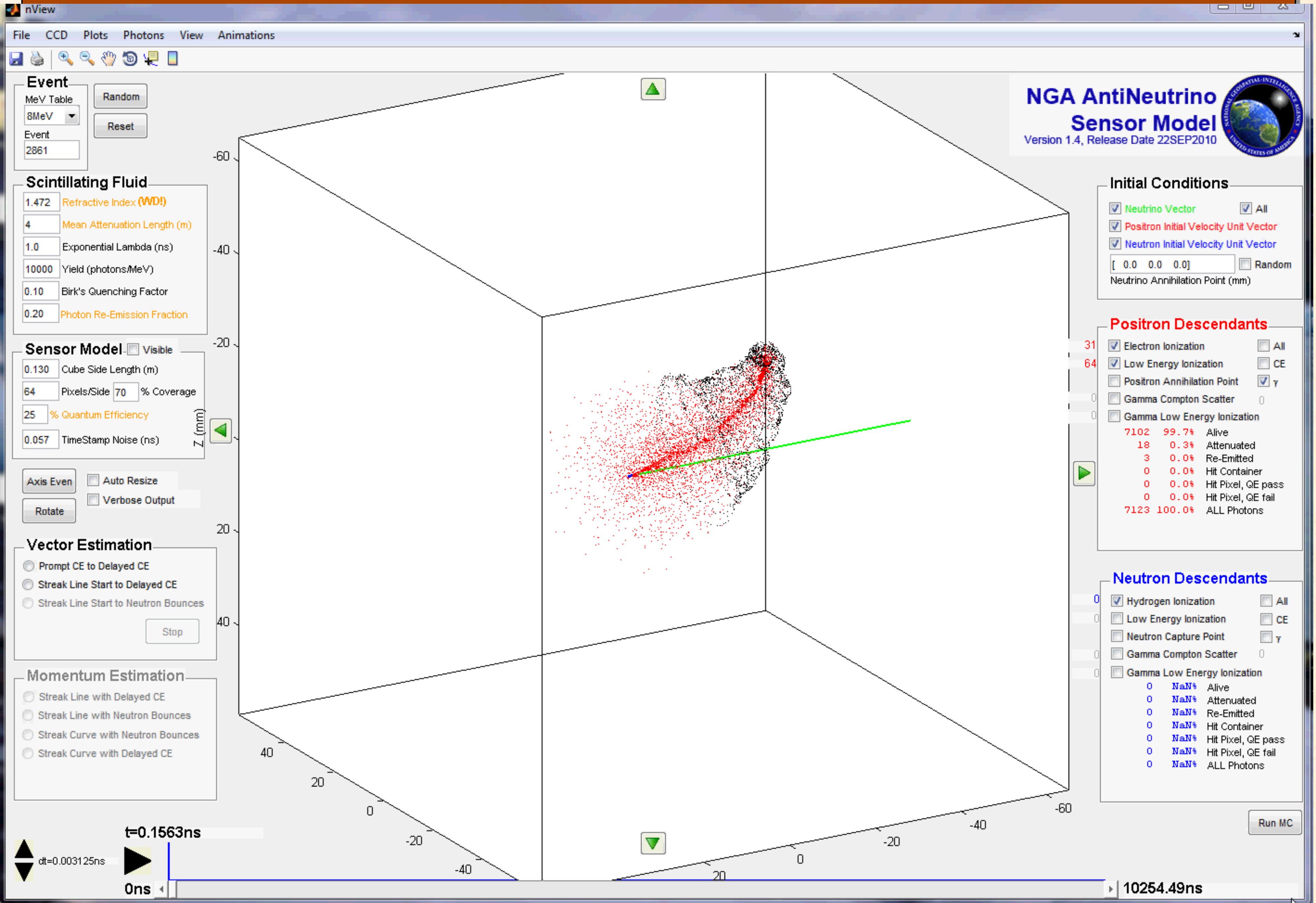
Stackable transport cases

First Installation of Tubes on mTC



Starting Counting of Muons in Lab




nView
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8MeV
Event
2861
Random
Reset
Scintillating Fluid
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4 Mean Attenuation Length (m)
1.0 Exponential Lambda (ns)
10000 Yield (photons/MeV)
0.10 Birk's Quenching Factor
0.20 Photon Re-Emission Fraction
Sensor Model
Visible
0.130 Cube Side Length (m)
64 Pixels/Side
70 % Coverage
25 % Quantum Efficiency
0.057 TimeStamp Noise (ns)
Axis Even
Auto Resize
Rotate
Verbose Output
Vector Estimation
Prompt CE to Delayed CE
Streak Line Start to Delayed CE
Streak Line Start to Neutron Bounces
Stop
Momentum Estimation
Streak Line with Delayed CE
Streak Line with Neutron Bounces
Streak Curve with Neutron Bounces
Streak Curve with Delayed CE
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dt=0.003125ns
0ns
10254.49ns
Z (mm)
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-20
20
40
40
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-40
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20
NGA AntiNeutrino Sensor Model
Version 1.4, Release Date 22SEP2010
Initial Conditions
Neutrino Vector
All
Positron Initial Velocity Unit Vector
Neutron Initial Velocity Unit Vector
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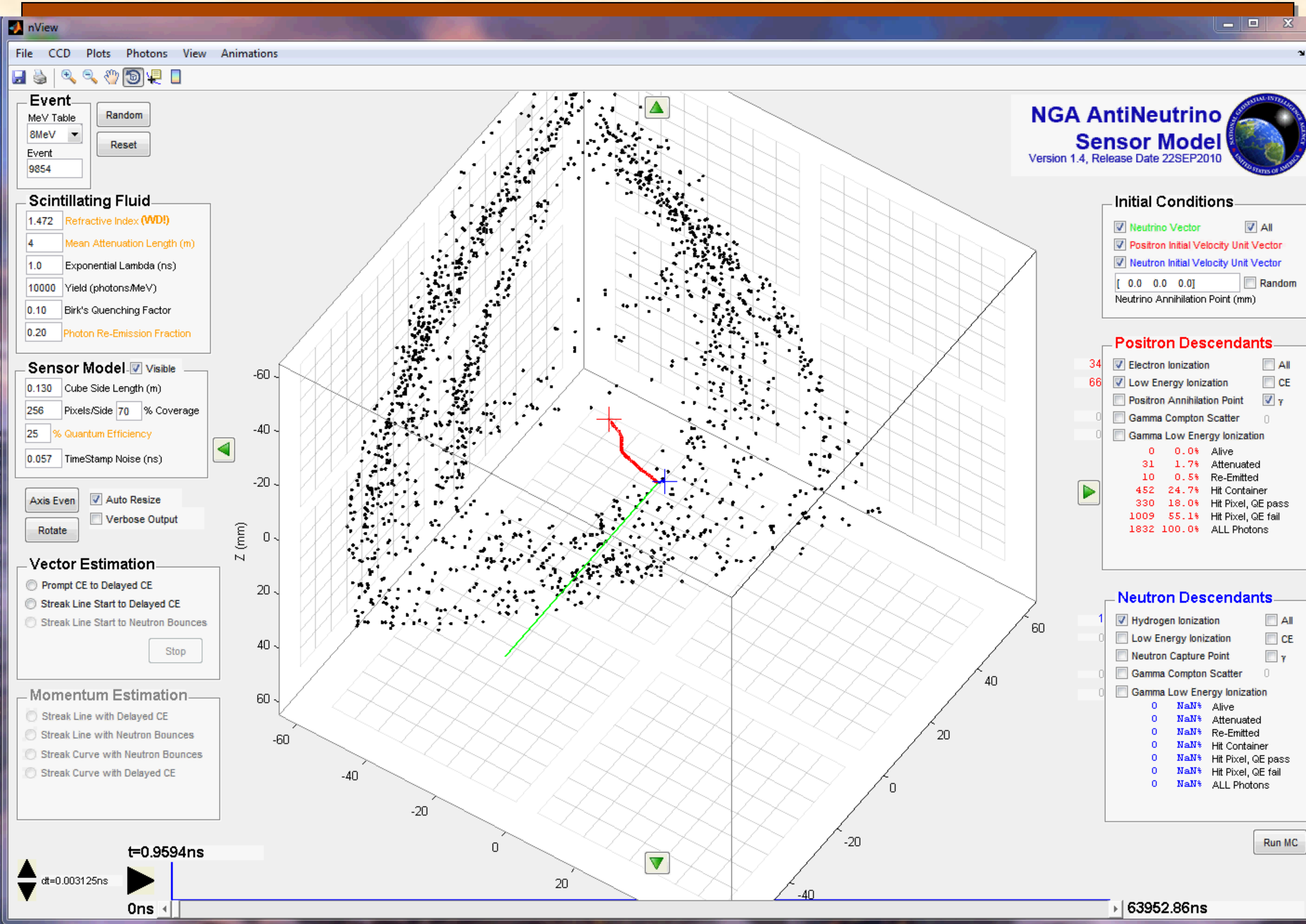
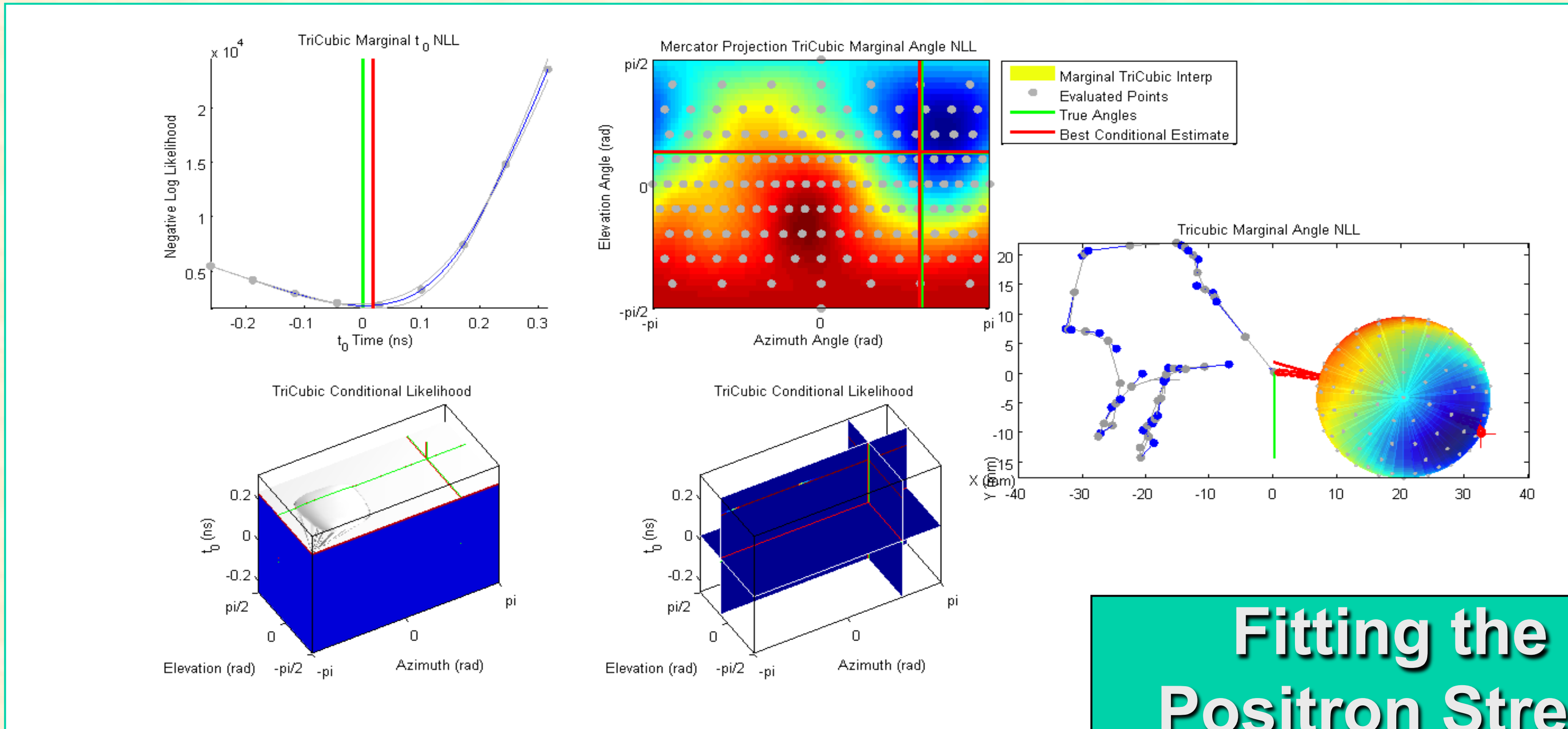
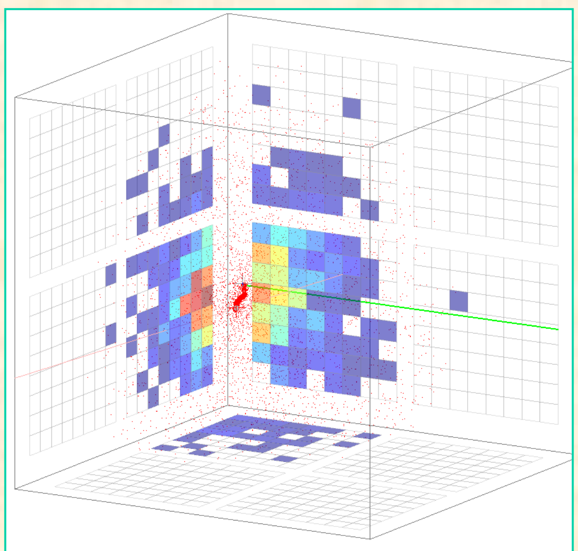
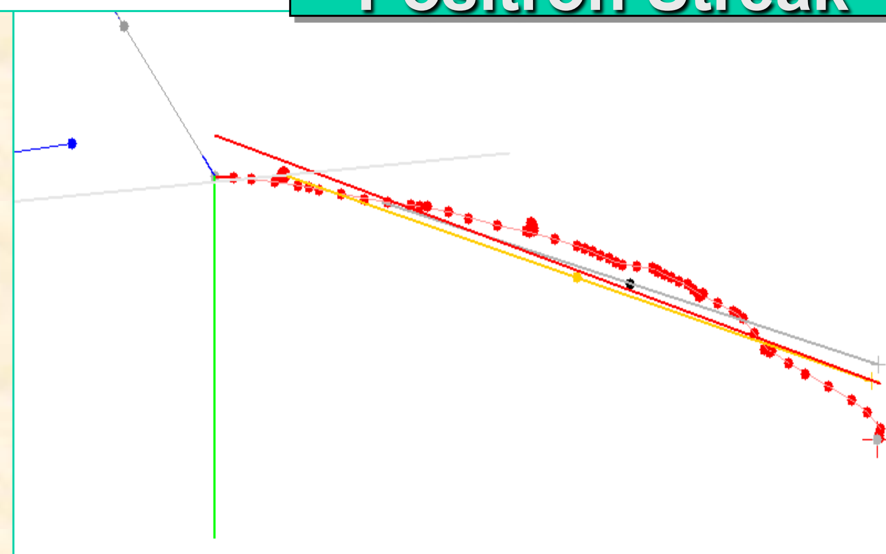
Neutrino Annihilation Point (mm)
Positron Descendants
31
64
Electron Ionization
All
Low Energy Ionization
CE
Positron Annihilation Point
γ
Gamma Compton Scatter
Gamma Low Energy Ionization
7102 99.7% Alive
18 0.3% Attenuated
3 0.0% Re-Emitted
0 0.0% Hit Container
0 0.0% Hit Pixel, QE pass
0 0.0% Hit Pixel, QE fail
7123 100.0% ALL Photons
Neutron Descendants
Hydrogen Ionization
All
Low Energy Ionization
CE
Neutron Capture Point
γ
Gamma Compton Scatter
Gamma Low Energy Ionization
0 NaN% Alive
0 NaN% Attenuated
0 NaN% Re-Emitted
0 NaN% Hit Container
0 NaN% Hit Pixel, QE pass
0 NaN% Hit Pixel, QE fail
0 NaN% ALL Photons
Run MC


nView
File CCD Plots Photons View Animations
Event
MeV Table
8MeV
Event
9854
Random
Reset
Scintillating Fluid
1.472 Refractive Index (WD!)
4 Mean Attenuation Length (m)
1.0 Exponential Lambda (ns)
10000 Yield (photons/MeV)
0.10 Birk's Quenching Factor
0.20 Photon Re-Emission Fraction
Sensor Model Visible
0.130 Cube Side Length (m)
256 Pixels/Side 70 % Coverage
25 % Quantum Efficiency
0.057 TimeStamp Noise (ns)
Axis Even
Rotate
Auto Resize
Verbose Output
Vector Estimation
Prompt CE to Delayed CE
Streak Line Start to Delayed CE
Streak Line Start to Neutron Bounces
Stop
Momentum Estimation
Streak Line with Delayed CE
Streak Line with Neutron Bounces
Streak Curve with Neutron Bounces
Streak Curve with Delayed CE
t=0.9594ns
dt=0.003125ns
0ns
63952.86ns
Z (mm)
NGA AntiNeutrino Sensor Model
Version 1.4, Release Date 22SEP2010
Initial Conditions
Neutrino Vector All
Positron Initial Velocity Unit Vector
Neutron Initial Velocity Unit Vector
[0.0 0.0 0.0] Random
Neutrino Annihilation Point (mm)
Positron Descendants
34 Electron Ionization All
66 Low Energy Ionization CE
Positron Annihilation Point γ
Gamma Compton Scatter
Gamma Low Energy Ionization
0 0.0% Alive
31 1.7% Attenuated
10 0.5% Re-Emitted
452 24.7% Hit Container
330 18.0% Hit Pixel, QE pass
1009 55.1% Hit Pixel, QE fail
1832 100.0% ALL Photons
Neutron Descendants
1 Hydrogen Ionization All
Low Energy Ionization CE
Neutron Capture Point γ
Gamma Compton Scatter
Gamma Low Energy Ionization
0 NaN% Alive
0 NaN% Attenuated
0 NaN% Re-Emitted
0 NaN% Hit Container
0 NaN% Hit Pixel, QE pass
0 NaN% Hit Pixel, QE fail
0 NaN% ALL Photons
Run MC



Fitting the Positron Streak





mTC Virtues, Summary

- Small size avoids gammas which smear resolution (X ~42 cm)
- Fast pixel timing (<100ps) and fast processing of waveforms rejects background in real time, resulting in
- Lack of need for shielding (unlike other detectors).
- Feasible even in high noise environment, near reactor vessel, at surface (eg. in a truck).
- Neutrino directionality via precision measure of positron production and neutron absorption locations.
- Challenges: build one and demonstrate, scale up, make more economically.
- Question under present study: Can we attack RANA with this?

Conclusion: Much Fun to be Had Untangling the Secrets of the Neutrinos

- Probably a hundred neutrino projects, large and small, underway around the world.
- This talk does no justice to the scope of the programs at accelerators, and with reactors and natural sources.
- Hopefully you get the sense of adventure and amazement as we look for the newest twists and surprises from the wiley neutrino
- And now we are even starting to put the neutrino to work!