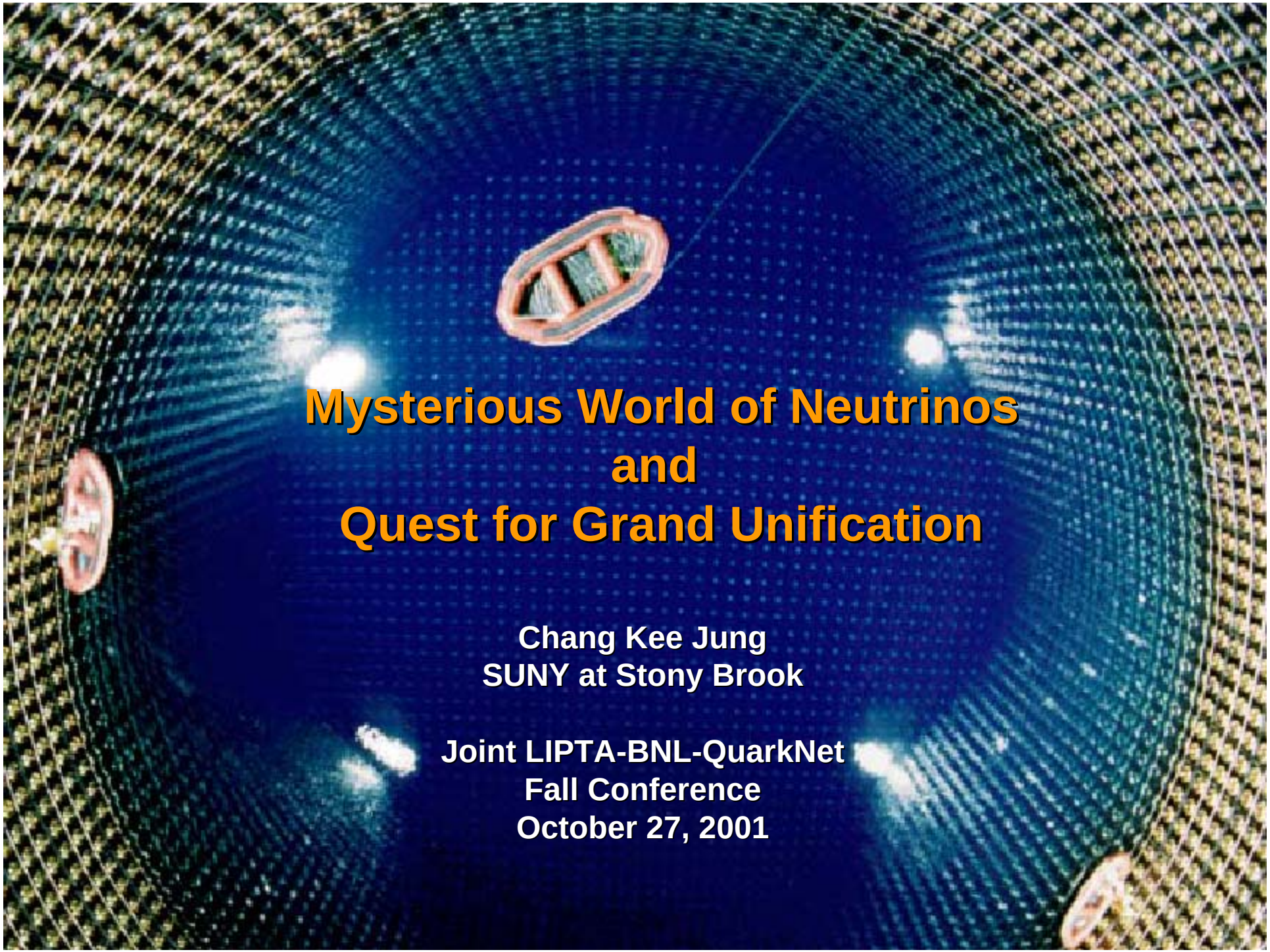
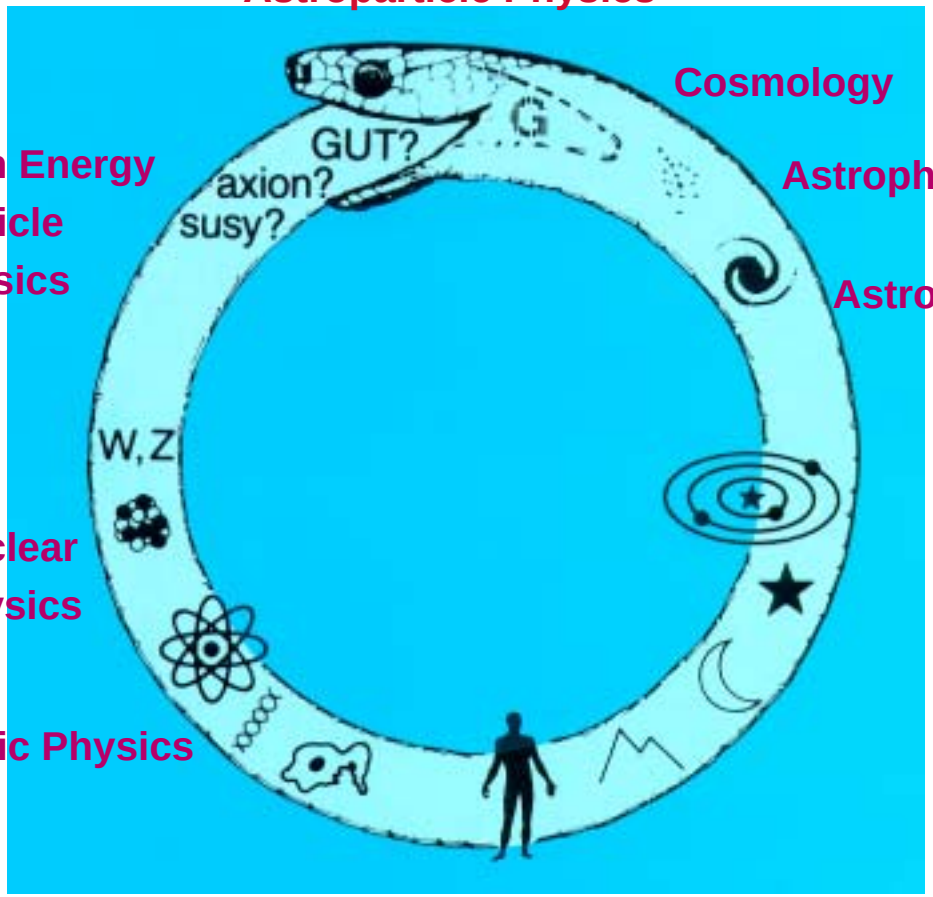


Mysterious World of Neutrinos and Quest for Grand Unification

Chang Kee Jung
SUNY at Stony Brook

Joint LIPTA-BNL-QuarkNet
Fall Conference
October 27, 2001

Astroparticle Physics



Cosmology

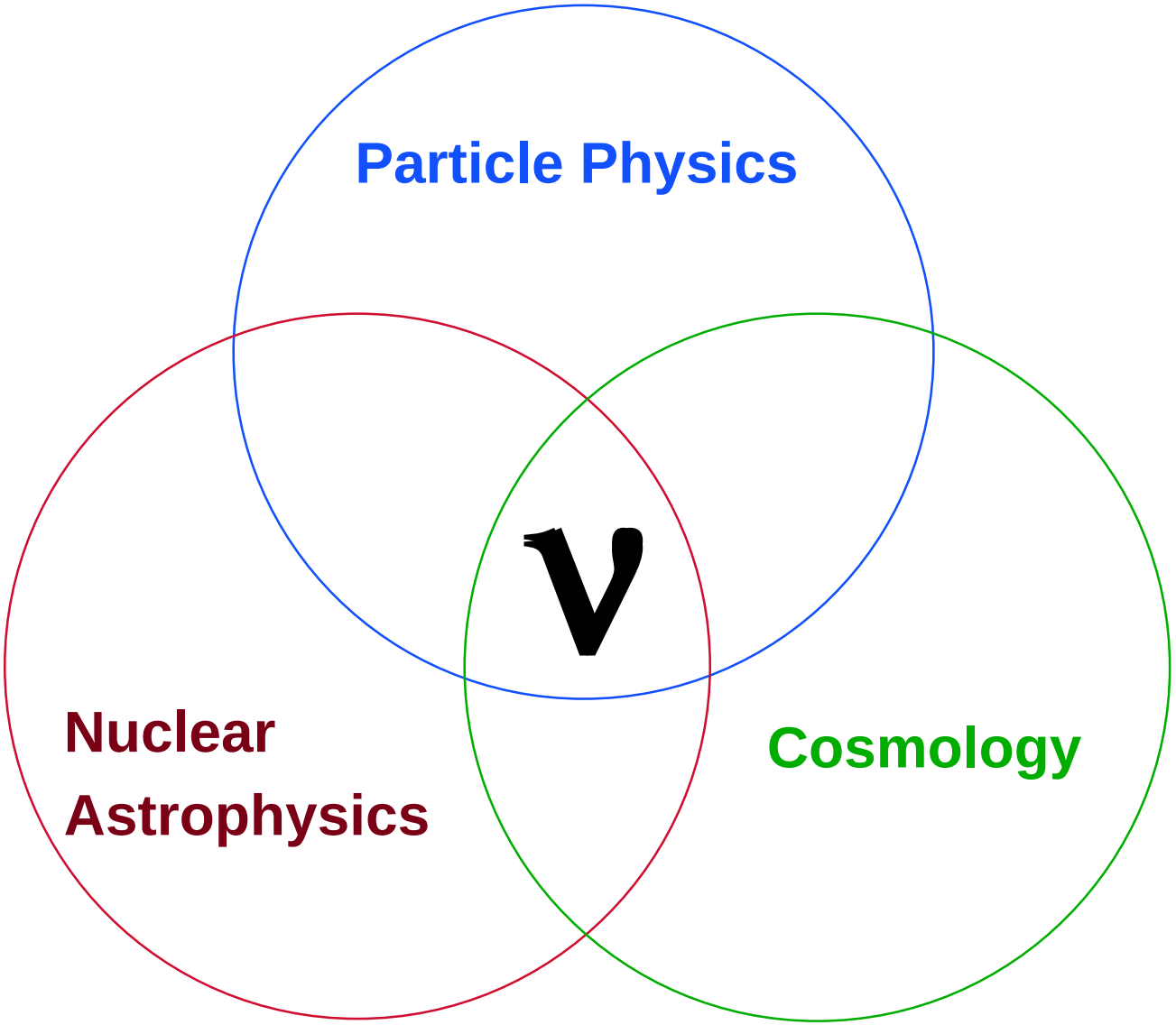
High Energy Particle Physics

Astrophysics

Astronomy

Nuclear Physics

Atomic Physics


Particle Physics
ν
Nuclear
Astrophysics
Cosmology

Neutrino Facts and Trivia

- What is a neutrino?
  - an elementary particle
    - » has no mass (in SM)

      travels at speed of light (for now)
    - » has no electric charge
    - » interacts little with any other matter (pure week interaction)

      ==> can pass through 50 billion miles of water without interacting

      ==> this in turn allows us see the interior of stars and provides us with information otherwise not obtainable by the traditional optical telescopes

      ==> neutrino telescopes

Neutrinos from Stars

- Solar Neutrinos
  - produced by nucleosynthesis inside the Sun
  - Flux on the surface of the Earth: ~ 500 billion neutrinos /cm^2/sec
    - » Solar Neutrino Puzzle

      One of the most fascinating and longest running unsolved mysteries in physics
- Supernova Neutrinos
  - produced by the neutralization process at the core
  - carry 99% of the supernova energy
  - observed for the first time in 1987 (SN1987a): a total of 20 events by two detectors (IMB and Kamiokande) in about 10 second period of time ==> a triumph of supernova theory

Neutrinos from the Earth

- Atmospheric Neutrinos
  - produced by the cosmic rays bombarding on the atmosphere
  - first evidence for neutrino oscillation
    ==> discovery of non-zero neutrino mass
- Terrestrial Neutrinos
  - produced by natural radioactivity
  - ~ 6 million neutrinos /cm^2/sec
- Man-made Neutrinos
  - produced by particle accelerators, nuclear reactors
- Homo sapiens Neutrinos
  - produced by Potassium 40 decay in our body (~20 mg)
  - ~340 million neutrinos/day

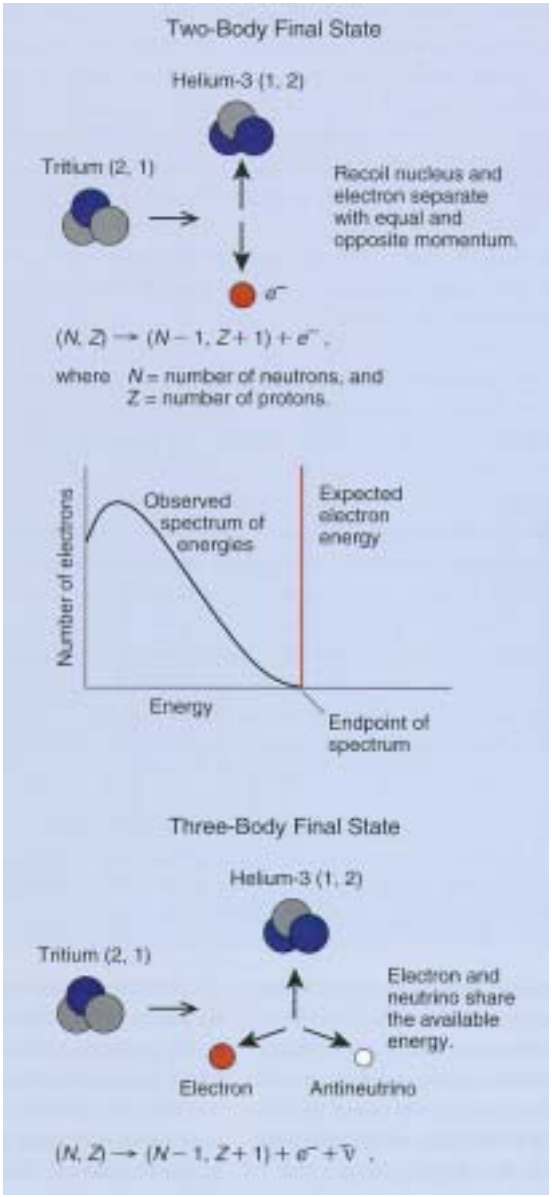
Neutrinos from The Big-Bang

- Relic (thermal background) Neutrinos
  - produced 1 second after Big-Bang
  - a la 2.7^{o} cosmic microwave background
  - ~ 300 neutrinos/cm^{3} in our universe
    - » if neutrino has mass, it can influence the ultimate fate of the Universe. (open? or closed Universe?)
      - m_{ν} ~ 30 eV, closed universe ($\Omega >= 1$)
      - m_{ν} ~ a few eV, “Dark Matter” candidate ($\Omega \sim 0.2$)
      - m_{ν} ~ 1/20 eV, total neutrino mass in the Universe
      - ~ total luminous matter mass ($\Omega \sim 0.003$)
  - never been directly detected (poses biggest challange to experimentalists, in fact observation has never been attampted.)

Historical Perspective

- 1930: W. Pauli
  - first postulated existence of "Neutron" to explain continuum beta decay spectrum
    - » proton, electron and photon were the only known elementary particles
  - later "Neutron" renamed to "Neutrino" by Fermi
- 1956: Reines-Cowan (Savannah River Reactor Experiment)
  - positive observation of neutrino interactions utilizing inverse beta decay

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



Pauli's Letter

The Desperate Remedy

4 December 1930
Gloriastr.
Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

Dear radioactive ladies and gentlemen,

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"* of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons,** which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. The continuous β-spectrum would then become understandable by the assumption that in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ ray.

I admit that my remedy may appear to have a small *a priori* probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win, and the seriousness of the situation of the continuous β-spectrum can be made clear by the saying of my honored predecessor in office, Mr. Debye, who told me a short while ago in Brussels, "One does best not to think about that at all, like the new taxes." Thus one should earnestly discuss every way of salvation.—So, dear radioactives, put it to test and set it right.—Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December.—With many greetings to you, also to Mr. Back, your devoted servant,

W. Pauli

Pauli's Picture

W. Pauli and Maurice Goldhaber

- 1957: B. Pontecorvo
  - first suggestion of neutrino oscillation

    $\nu \longleftrightarrow \bar{\nu}$ (massive Majorana particle)
- 1963: Lederman, Schwartz, Steinberger experiment at BNL
  - positively distinguished ν_μ from ν_e
    - » concept of generation
    - » neutrino oscillation between generations

      $\nu_\mu \longleftrightarrow \nu_e$
- 1969 R. Davis experiment at the Homestake mine
  - observed less solar nu (ν_e) flux than predicted
    - » Beginning of the Solar Neutrino Problem

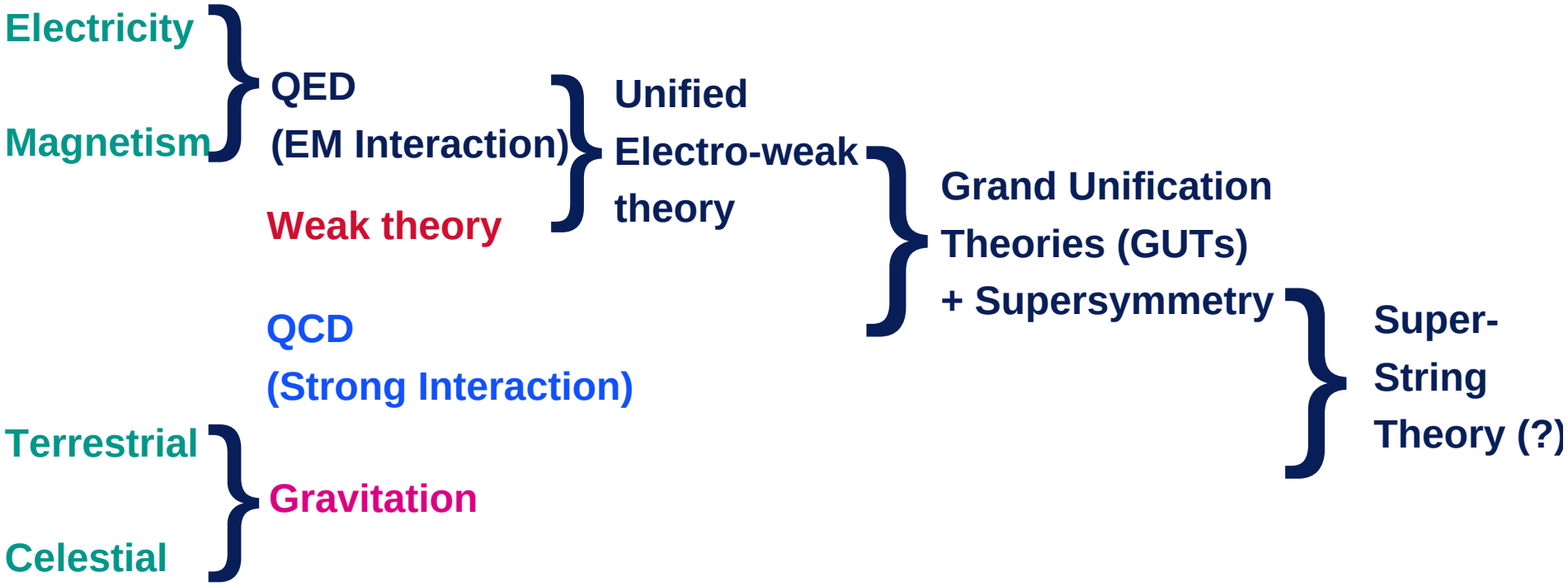
Continue: Historical Perspective

- Late 1980's: IMB and Kamiokande experiments
  - observed less atmospheric nu flux ratio (ν_μ/ν_e) than predicted
    - » Beginning of the ATM Neutrino Problem
- 1987: First observation of neutrinos from supernova explosion
  - SN1987a
- 1995: LSND experiment at LANL
  - reported positive observation of $\bar{\nu}_\mu \longleftrightarrow \bar{\nu}_e$

>>> Neutrino Oscillations???

- 1998: Super-Kamiokaned experiment at Kamioka, Japan
  - evidence for oscillations of atmospheric neutrinos
- 2000: DONUT experiment at Fermilab
  - direct observation of ν_τ

Unification of Particle Interaction Theories



Standard Model (SM)
= Unified Electro-weak theory + QCD
(not a truly unified theory)

Potential Future Great Discoveries

- Extra Dimensions - Superstring
- Supersymmetric Particles - SUSY
- Proton Decay - GUT/SUSY/Superstring
- Identity of Dark Matter - SUSY(?)
- Nature of Dark Energy
- Magnetic Monopoles
  -
  -
  -

Quest for Grand Unification

- Search for Proton Decay
  - In SM, protons do not decay

    ==> Baryon number conservation law

    -->Accidental or approximate
  - GUT models (SU(5), SO(10), E_6...)

    ==> Quark-Lepton unification

    ==> Color-charge quantization

    ==> Coupling constant Unification (SUSY GUTs)

    ==> predict decay of protons (generic prediction)

Proton decay - only direct experimental access to 10^{16} GeV (10^{-30} cm) scale

==> Truly an energy frontier experiment

==> To date, there are no experimental evidence for proton decay

Why a Next generation Nucleon decay and Neutrino (NNN) Experiment?

- Non-zero Neutrino Masses
  - In SM, neutrino masses are assumed to be zero
  - In many of the GUT Models, small neutrino masses are predicted through Seesaw Mechanism

$$m(\nu_i) = \frac{m_{Di}^2}{M} \qquad (M >> m_{Di})$$

m_{Di}: Dirac mass of charged fermion

M: Majorana mass of ν_R depends on the mass scale of the models

→ Thus, observation of small non-zero neutrino mass could lead us to the physics of very high mass scale, which in turn could lead us to proton decays

Super-Kamiokande observation of the non-zero neutrino mass
==> could be the first evidence for Grand Unification
==> Motivation for renewed effort for proton decay searches

Neutrino Oscillation in Vacuum

weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

mass eigenstates

Survival Probability

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Oscillation Probability

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$\Rightarrow \Delta m^2 (\equiv m_1^2 - m_2^2)$ *and* $\sin^2(2\theta)$ *are oscillation parameters given by the nature*

$\Rightarrow L$(*source to observer distance*) *and* E(*neutrino energy*) *are exerimental parameters*

$$\left(\frac{\Delta m^2 L}{4E}\right) \Rightarrow \left(1.27\frac{\Delta m^2 L}{E}\right) \text{ with } \begin{pmatrix} \Delta m^2 \text{ in } eV^2 \\ L \text{ in } km \\ E \text{ in } GeV \end{pmatrix}$$

$$P_{\nu \to \nu'} = \sin^2 2\theta \sin^2 (1.27\, \Delta m^2\, L/E)$$

John Updike's Poem

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

*©John Updike. 1960. *From Telephones Poles and other Poems.* Alfred A. Knopf, Inc., New York, 1963.

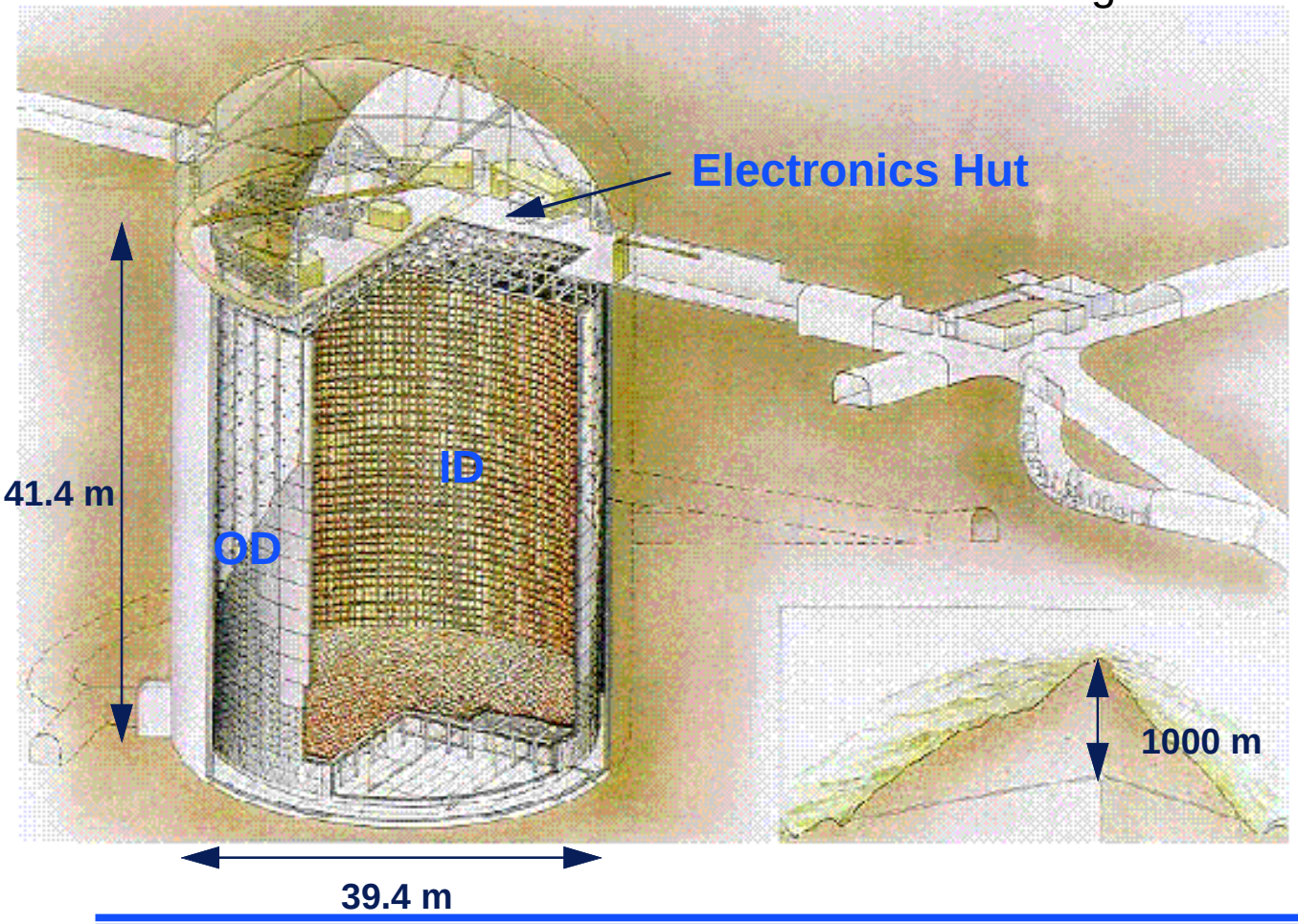
Super-Kamiokande Experiment

50 kton Water Cherenkov Detector

-- Inner Detector (ID) w/ 11,000 20” PMTs

-- Outer Detector (OD) w/ 1,840 8” PMTs

-- 40% Photocathode coverage



- Research Goals

Proton decay searches

Solar neutrinos

Atmospheric neutrinos

Astophysical neutrinos

==> neutrino oscillations

- The Collaboration

~120 physicists

23 institutions from Japan and US

SuperK Photos

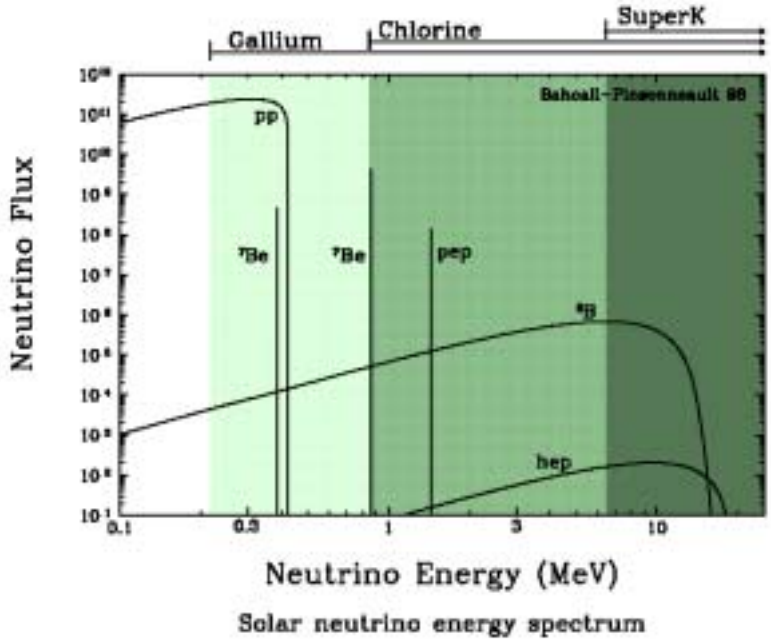
- Inner Detector Construction - August 1995
- Completed Outer Detector - October 1996
- Water Filling of the Detector - January 1996

Water Cherenkov Detector Technique

- Detection of Cherenkov light in water - 2 viewgraphs
- Photo Multiplier Tube (PMT) - 2 viewgraphs
- SuperK event display - through going muon event
- SuperK event display - contained muon neutrino event
- 8” PMT used in the IMB detector
  - detected neutrinos from SN1987a

Solar Neutrino Puzzle

- Standard Solar Model (SSM)
  - Detailed theoretical calculation of nucleo-synthesis in the Sun pioneered by J. Bahcall in ~1960
  - Neutrinos along with photons produced during the processes of nuclear synthesis
    - » these neutrinos let us “see” inside the sun where the “light” telescopes cannot see

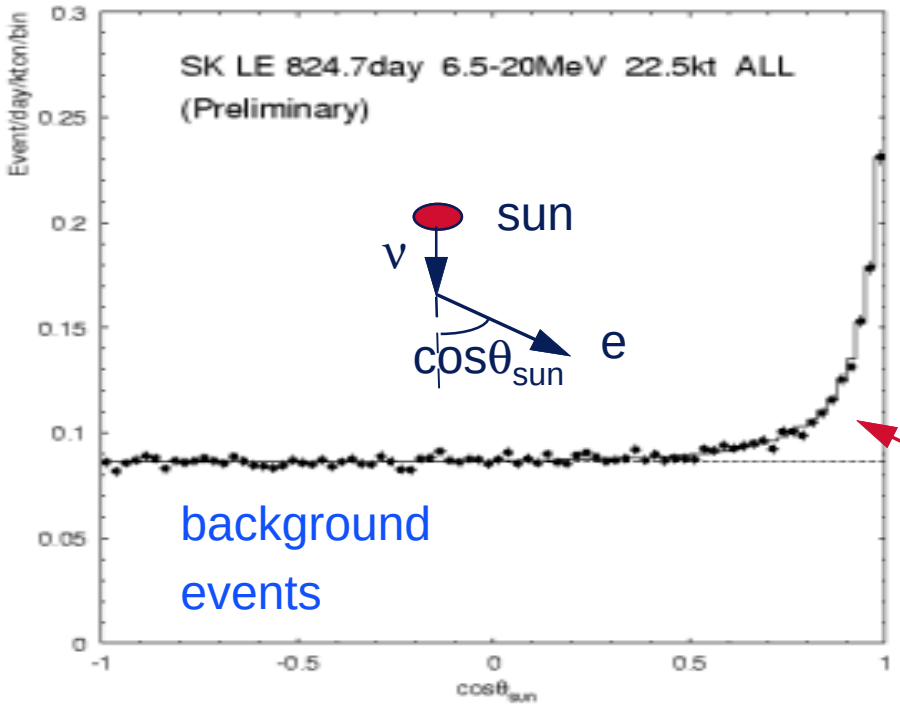


Solar neutrino energy spectrum

p-p Chain

(98% of energy generation)

SuperK Solar Nu Flux Measurement

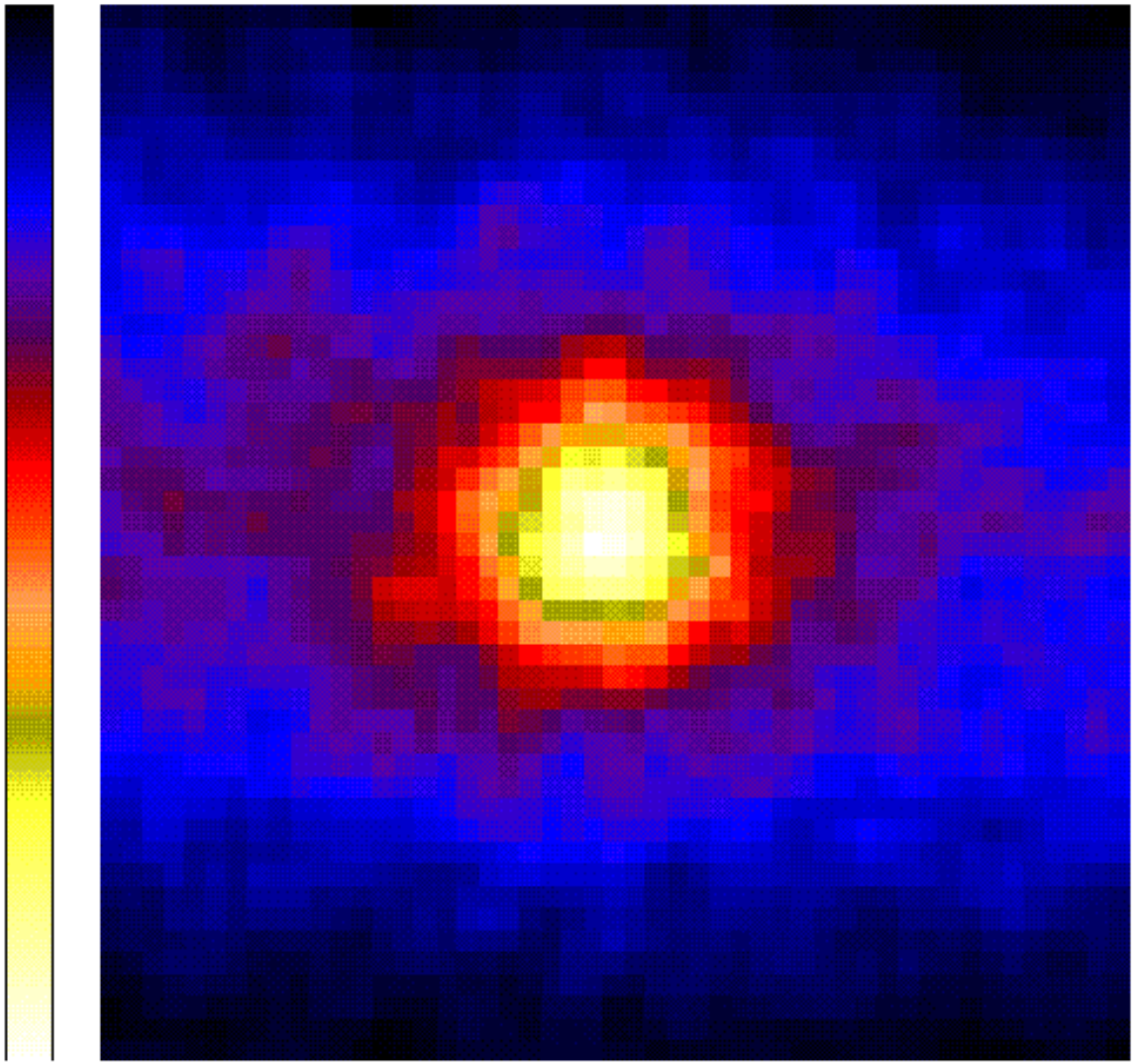


- Real time and Directional Measurement
  - Events point back to the sun (provides unambiguous proof that these neutrinos are coming from the sun

$$\frac{Data}{SSM(BP98)} = 0.475 \; {}^{+\,0.008}_{-\,0.007} \; {}^{+\,0.013}_{-\,0.013}$$

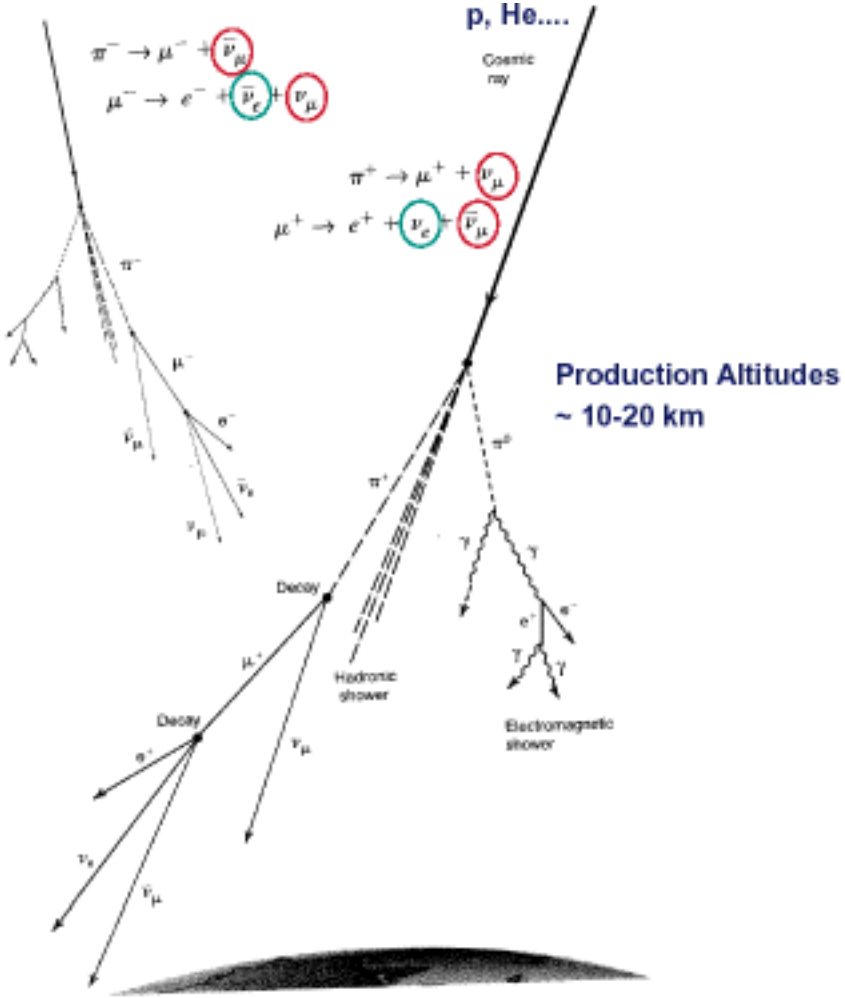
==> confirms solar neutrino flux deficit

Super-Kamiokande Solar Image



Neutrino Image of the Sun observed with the Super-Kamiokande Neutrino Telescope

Atmospheric Neutrinos



Naively,

$$r = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

$$R \equiv \frac{(\mu/e)_{data}}{(\mu/e)_{MC}}$$

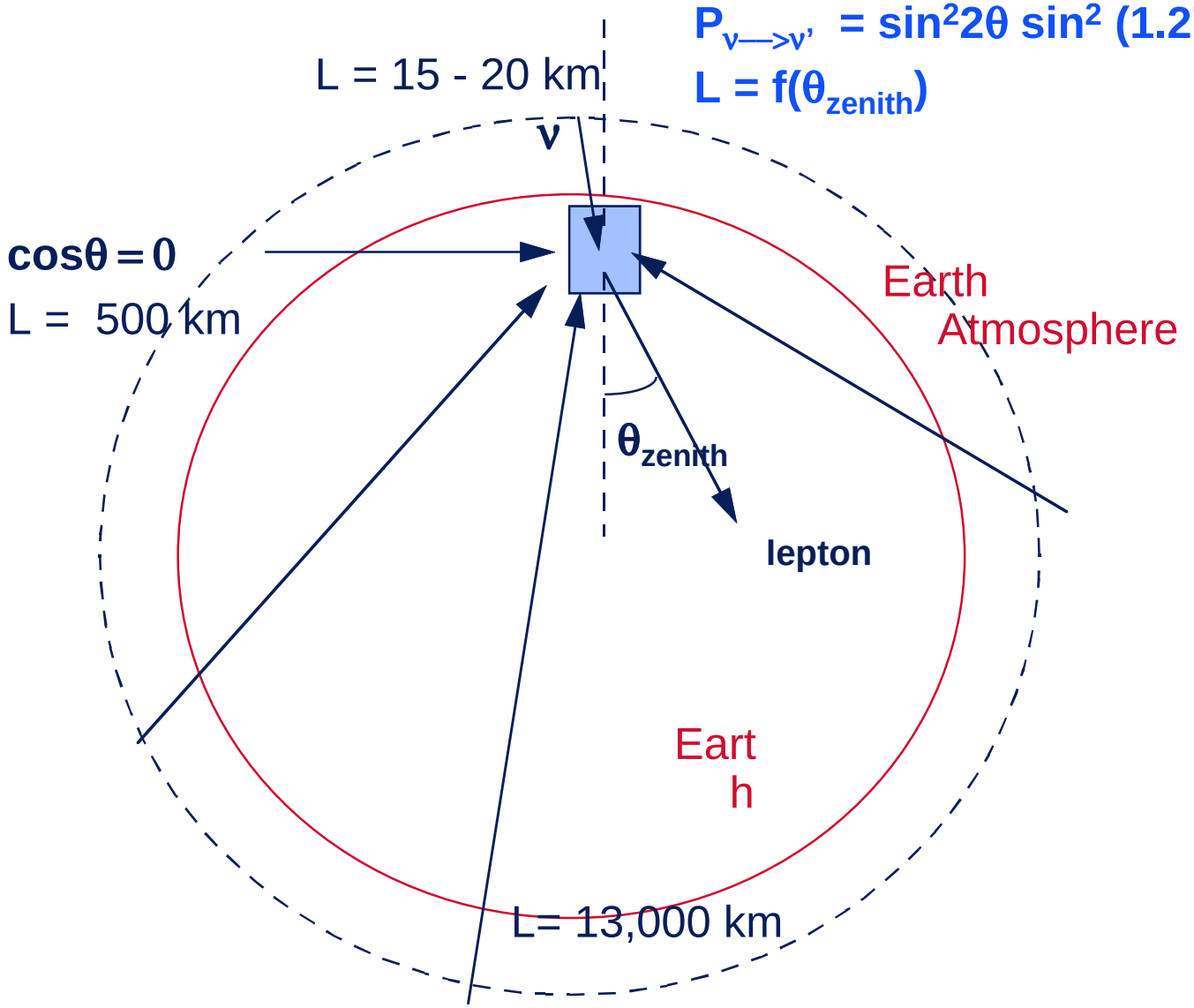
(~20% uncertainty in the absolute neutrino flux calculation however, *r* has less than 5% uncertainty)

***R*=1 if no anomaly**

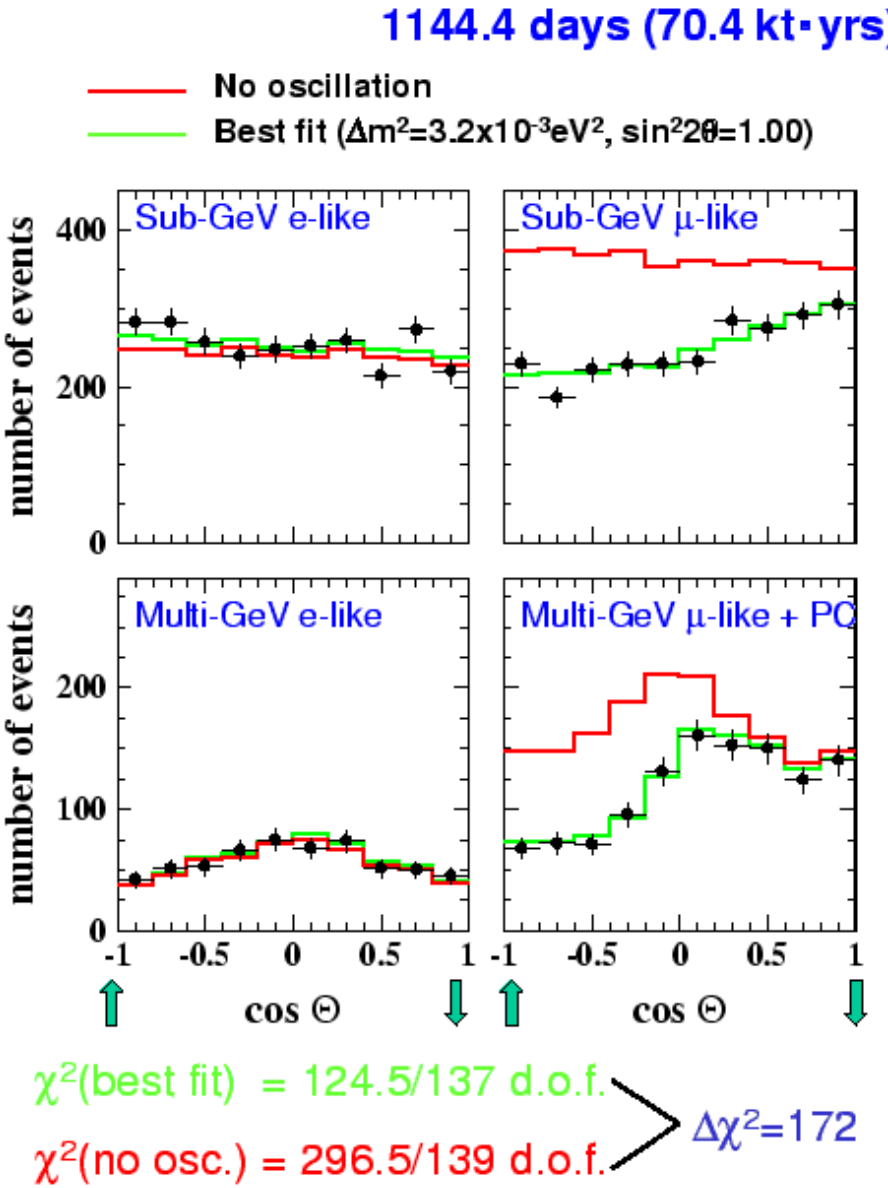
Neutrino flux dependence on zenith angle

$P_{\nu \to \nu'} = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E)$

$L = f(\theta_{zenith})$



SuperK Observation of Neutrino Oscillations



Atmospheric Neutrinos

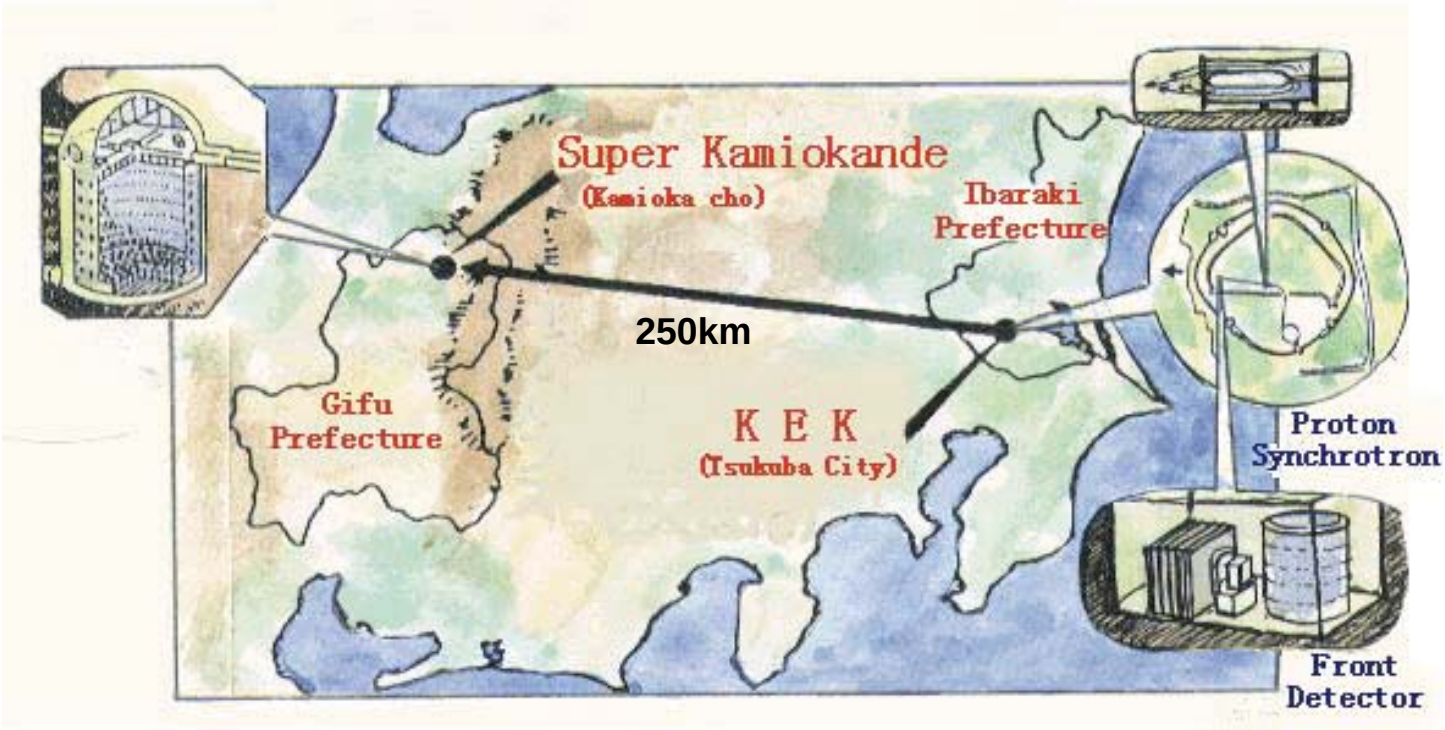
- SuperK firmly establishes neutrino oscillaition in atmospheric neutrinos
  - $1.6 < \Delta m^2 < 3.8 \times 10^{-3}$ eV^2, $\sin^2 2\theta > 0.9$ @90% C.L.
  - no internal inconsistency
- Supporting evidence from other experiments
  - IMB, Kamiokande, Soudan 2, MACRO
  - No external inconsistency among experiments

==> Far-reaching impact on particle, nuclear and astrophysics

- SuperK oscillation paper: the 2nd most cited (> 1000) exp. particle physics paper after the J/psi paper ("November Revolution") ==> 1 citation/day rate
- small non-zero neutrino mass (~0.05 eV)

existence of high energy scale physics (See-saw mechanism)

K2K (KEK to Kamioka)
Long baseline Neutrino Oscillation Experiment





The K2K Collaboration

(18 institutions from Japan, Korea and U.S. ~100 physicists)



Chonnam National University
Dongshin University
Seoul National University

ICRR, University of Tokyo
KEK
Kobe University
Kyoto University
Niigata University
Okayama University
Osaka University
Science University of Tokyo
Tohoku University

Boston University
University of California, Irvine
University of Hawaii
SUNY at Stony Brook
University of Washington

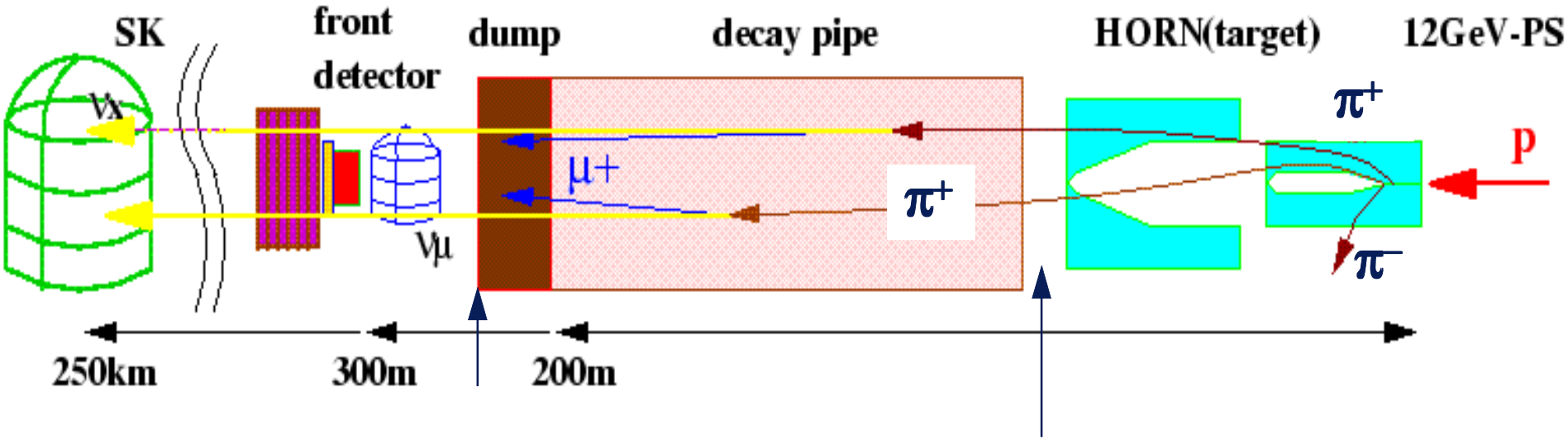
Warsaw University

K2K Physics Programs

- Neutrino Oscillations
  - confirm SuperK atm neutrino oscillation results
  - muon neutrino disappearance (99% pure ν_μ beam)
    1) simple counting: observed/expected # of events
    2) distortion in observed energy spectrum

       ==> direct observation of energy dependent neutrino oscillation
- Neutrino Cross-section Measurements
  - NC π^0 production cross-section
    - » application to ν_μ --> ν_τ vs. ν_μ --> ν_s discrimination in SuperK atmospheric neutrino analysis
- Study of Neutrino Background to Proton Decay Searches

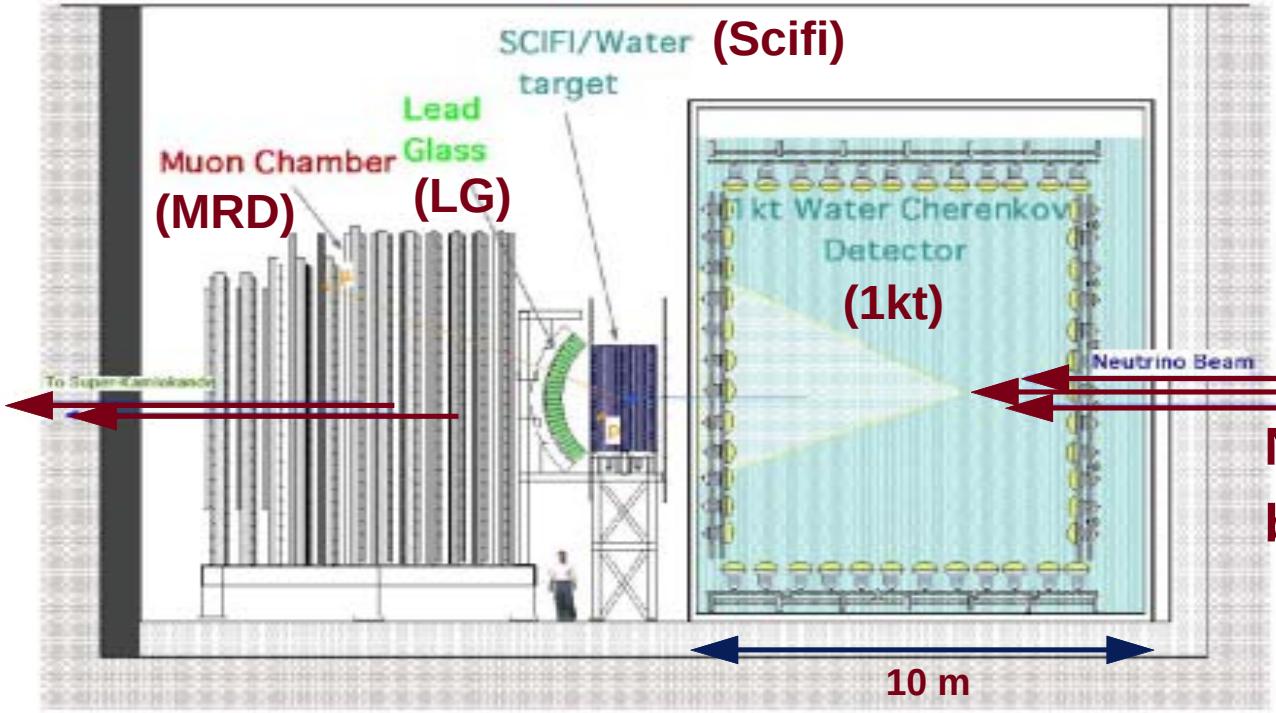
K2K Neutrino Beamline



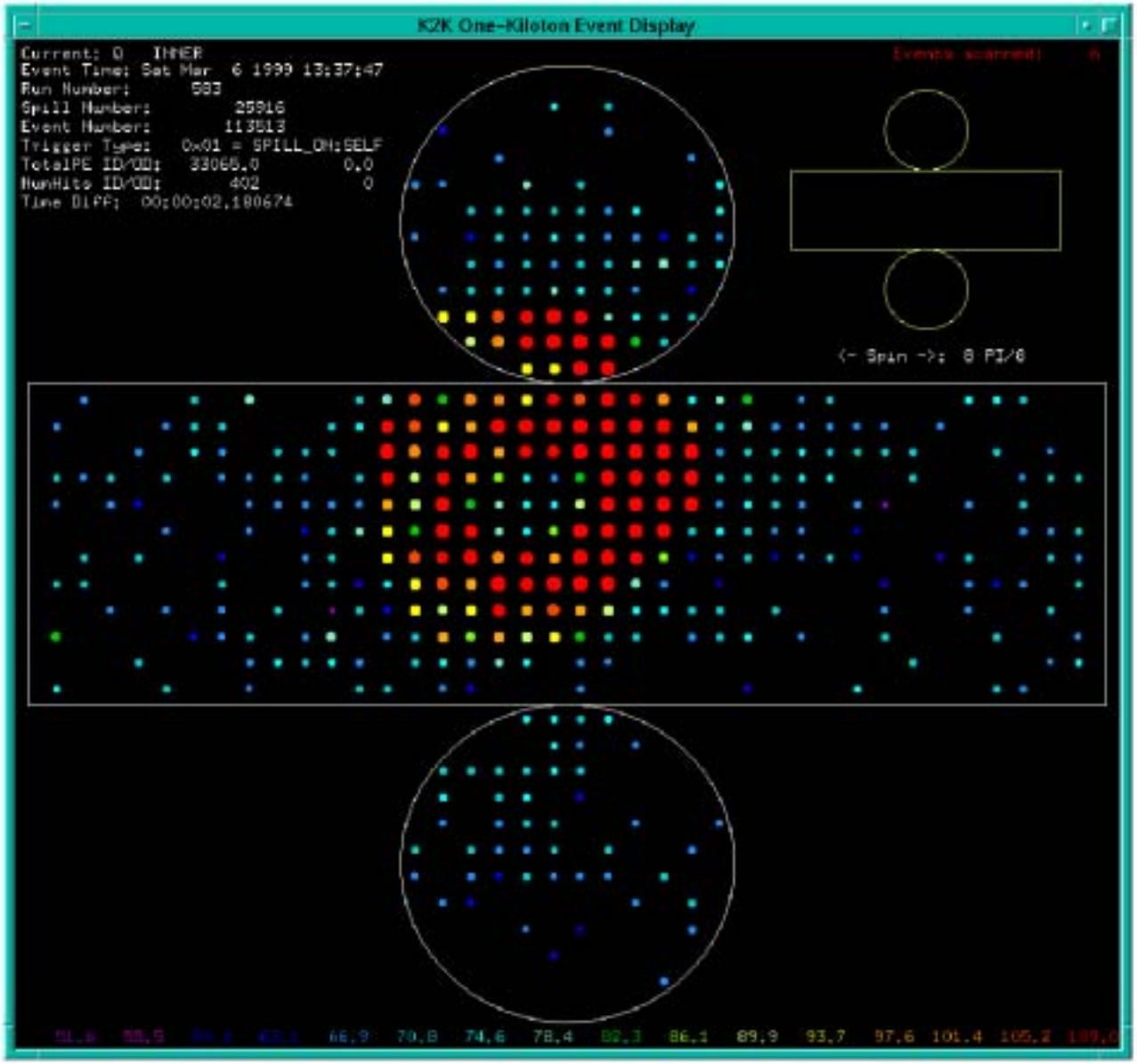
Muon Profile Monitors **Beam Monitors: pion, proton**

K2K Near Detector Complex

- 1kt (mini-SuperK): similar systematics as SuperK
- Scifi (scintillating fiber tracker): 19 layers of 6 cm thick water target w/ 20 layers of scifi (x,y), precision tracking
- LG (Lead Glass calorimeter): Measure ν_e contamination
- MRD (muon range detector): 12 layers of iron plates w/ D.C.s



Muon-like Event in 1kt



Q

of Observed Events vs. No Oscillation Expectation

K2K neutrino beam induced events observed in the Super-Kamiokande detector compared to the no oscillation expectation

	July 1999	Feb. 2000	June 2000	July 2000	July 2001
#Observed	1	3	17	28 (27)	???
#Expected	~5*	12*	29*	38 (40*)	64

of Observed Events vs. the Expected at SuperK

June 1999 - April 2001

FC Events in FV

	Obs.	No Osci. (1kton)	$\Delta m^2(\times 10^{-3} eV^2)$ 3 (sin²2θ =1)	5	7
FC 22.5kt	44	$63.9^{+6.1}_{-6.6}$	41.5	27.4	23.1
1-ring	26	38.4±5.5	22.3	14.1	13.1
μ-like	24	34.9±5.5	19.3	11.6	10.7
e-like	2	3.5±1.4	2.9	2.5	2.4
multi ring	18	25.5±4.3	19.3	13.3	10.0

of Observed Events vs. the Expected at SuperK

1999/06-2001/04

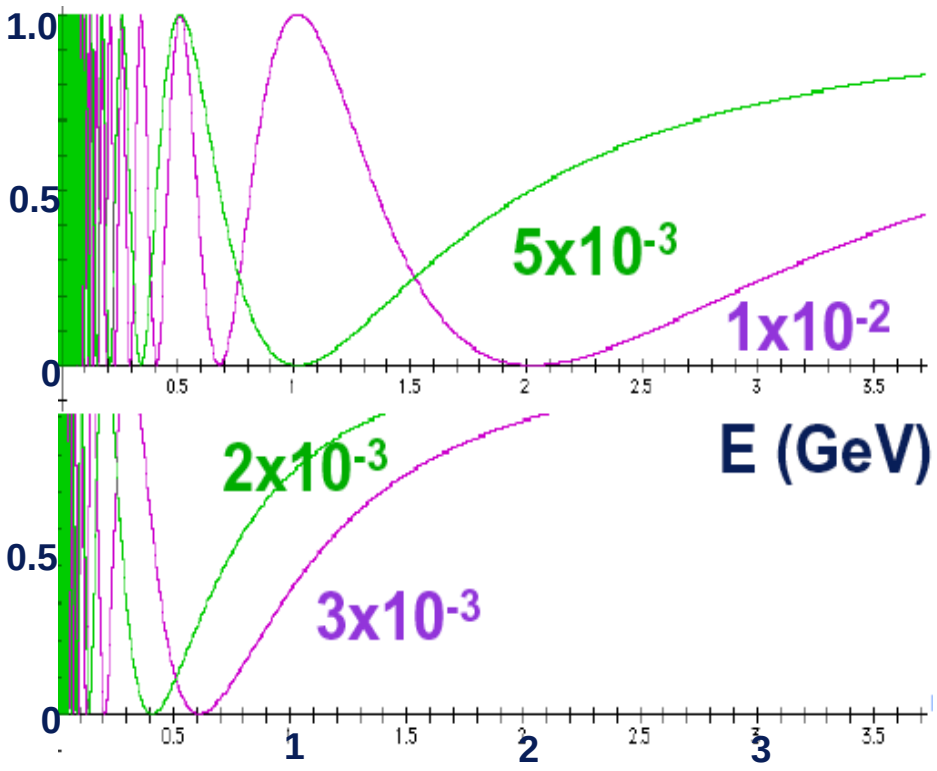
FC Events in FV

	Obs.	No Osci. (1kton)	$\Delta m^2(\times 10^{-3} eV^2)$ 3 (sin²2θ =1)	5	7
FC 22.5kt	44	$63.9^{+6.1}_{-6.6}$	41.5	27.4	23.1
	new (16	26)			
1-ring	26	38.4±5.5	22.3	14.1	13.1
μ-like	(24)	34.9±5.5	19.3	11.6	10.7
e-like	2	3.5±1.4	2.9	2.5	2.4
multi ring	18	25.5±4.3	19.3	13.3	10.0

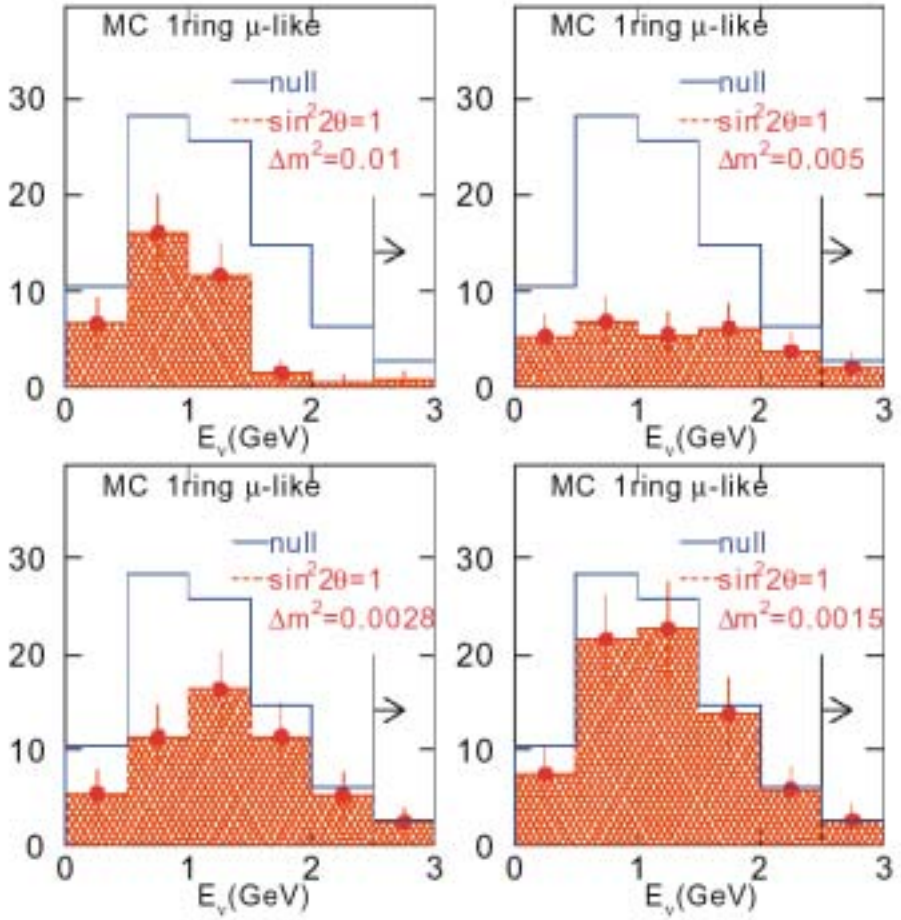
==> Null Oscillation probability: less than 3%

Neutrino Energy Spectrum at SuperK

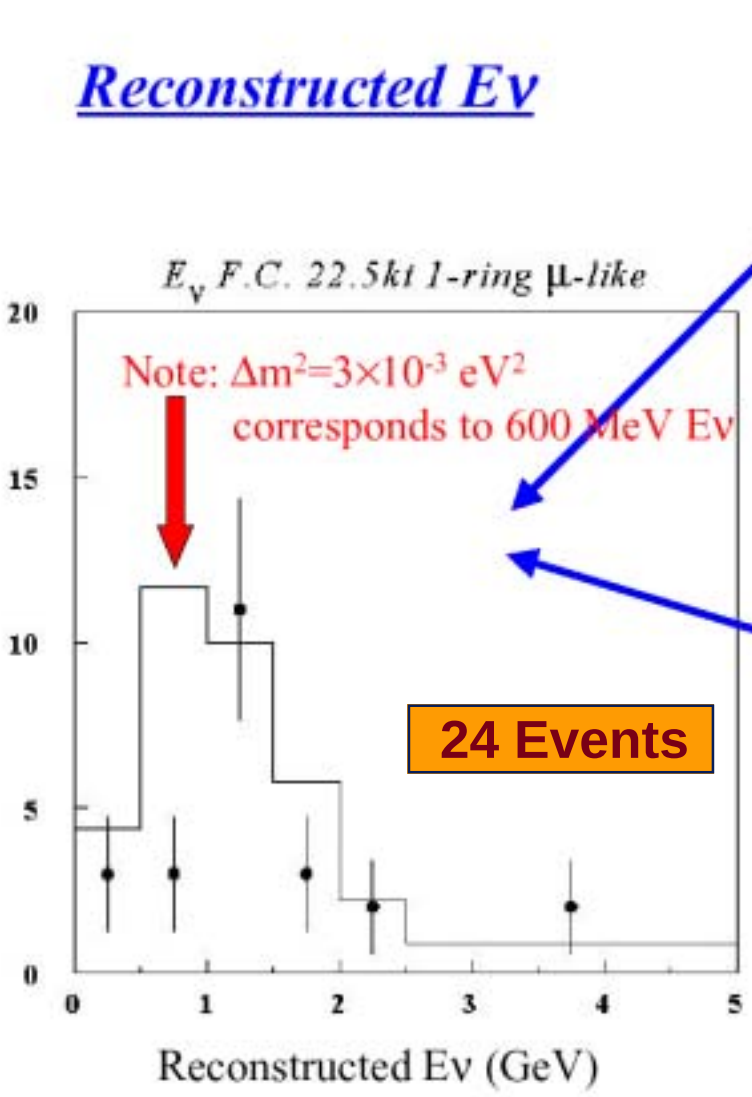
$P_{\nu\to\nu} = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$
with $\sin^2 2\theta = 1.0$, L=250km

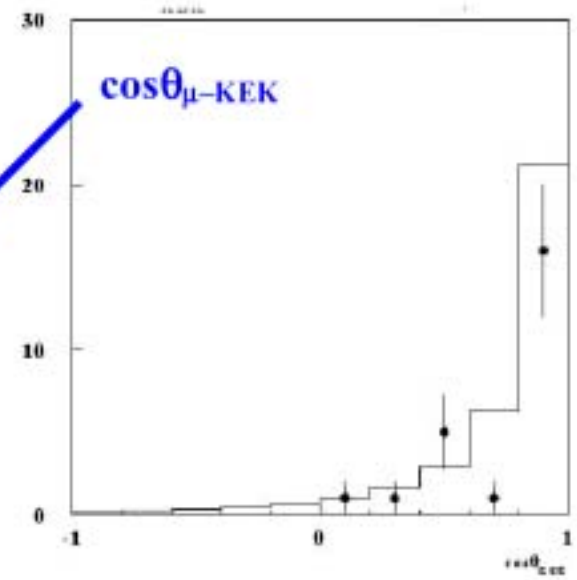


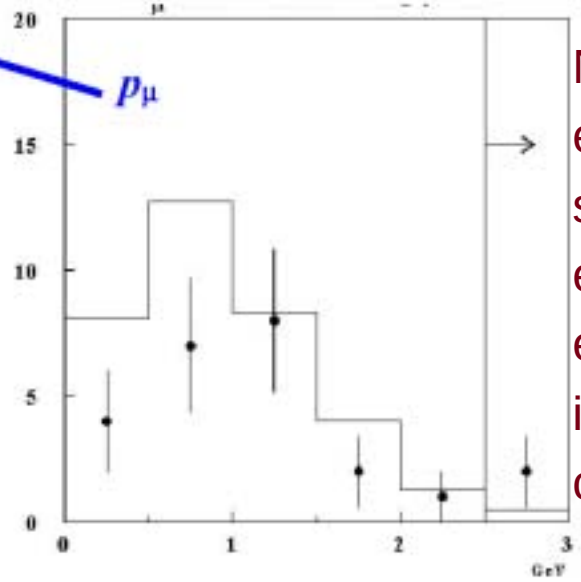
Reconstructed Neutrino Energy (MC)



Observed Energy Spectrum at SuperK







Data
MC w/o osc.

Note no error bars for expected energy spectrum: Detailed evalution of systematic errors underway, including bin-by-bin correlation

K2K Summary

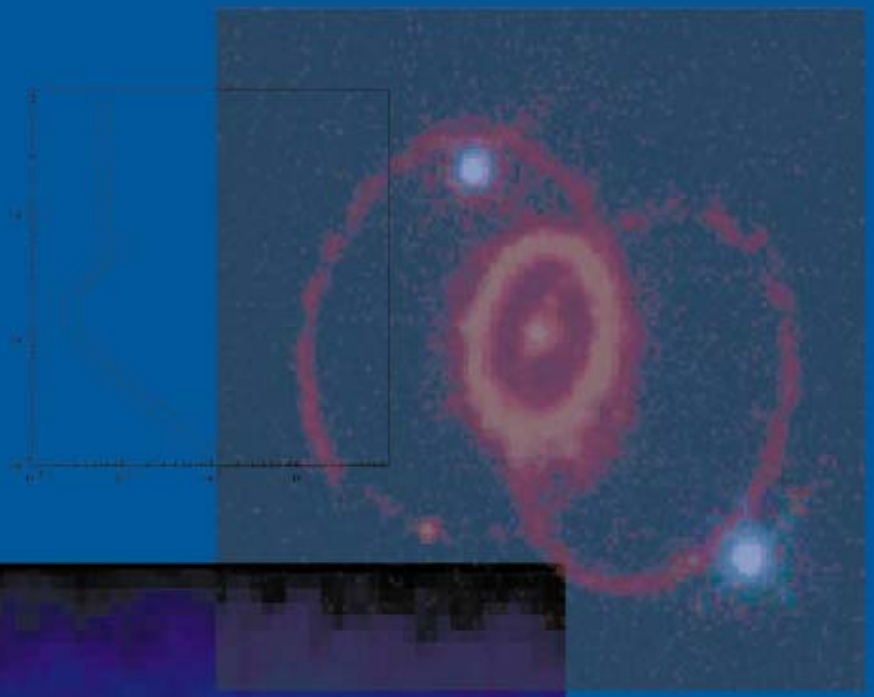
- K2K is running very well
  - Beam intensity at the design level
  - June 1999 - April 2001 data:
    3.85 (4.58) x 10^{19} POT SuperK live (delivered)
    - » additional data (May - July 2001) being analyzed
    - » Goal: accumulate 10^{20} POT (~untill 2004)
  - 44 observed events compared to $63.9^{+6.1}_{-6.6}$ (sys) expected from null oscillation
    - » null oscillation probability < 3%
  - Energy spectrum analysis is underway
    - » qualitatively the observed energy spectrum consistent w/ the SuperK atm best fit parameters
    - » quantivative results to come in spring 2002

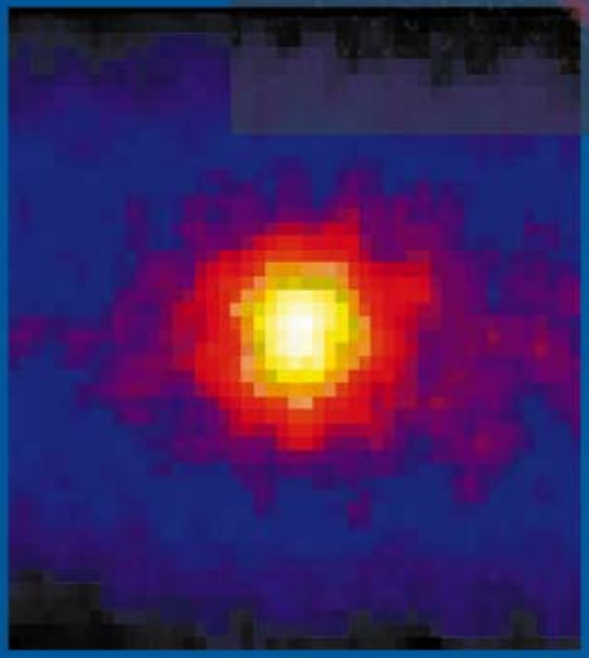
continue: K2K Summary

- First successful long-baseline neutrino oscillation experiment w/ a baseline O (100km)
  - leads to rich neutrino physics programs of future long- baseline experiments: MINOS, CNGS, JHF--> SuperK, superbeams and neutrino factories...

Implications of Non-zero Neutrino Mass

- The first and only experimental observation that deviates from the SM framework since 1970's
  - SM must be modified to Grand Unified theories or other extensions that predict non-zero neutrino masses
- Neutrinos travel slower than speed of light
- Violation of flavor lepton number conservation law
- Solar neutrino problem: likely due to neutrino oscillations
- Neutrino contribution to the mass of the Universe
- Dynamics of the Universe and structure formation need to be re-examined
  - How is mass distributed in space and how did it get there?
- Leptogenesis?
- Openning of whole new neutrino physics industry
- Possibility of Proton decay ==> UNO Experiment



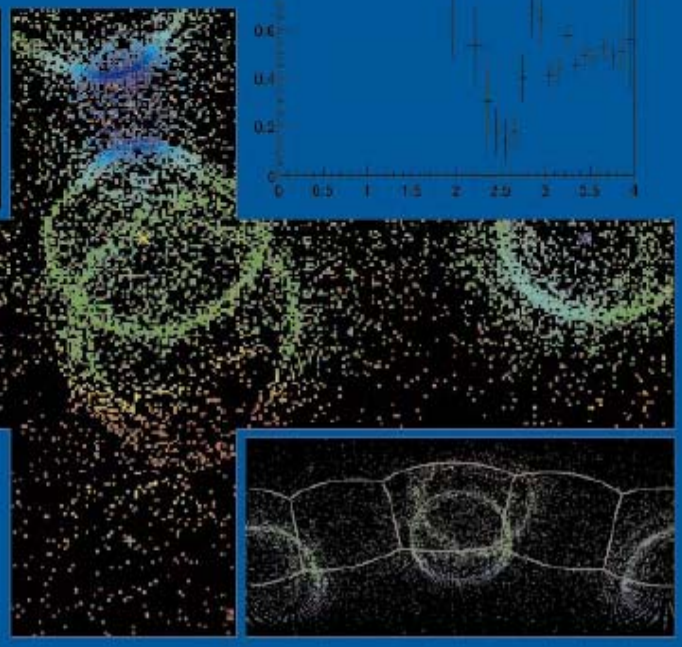


Physics Potential and Feasibility of UNO

June 2001

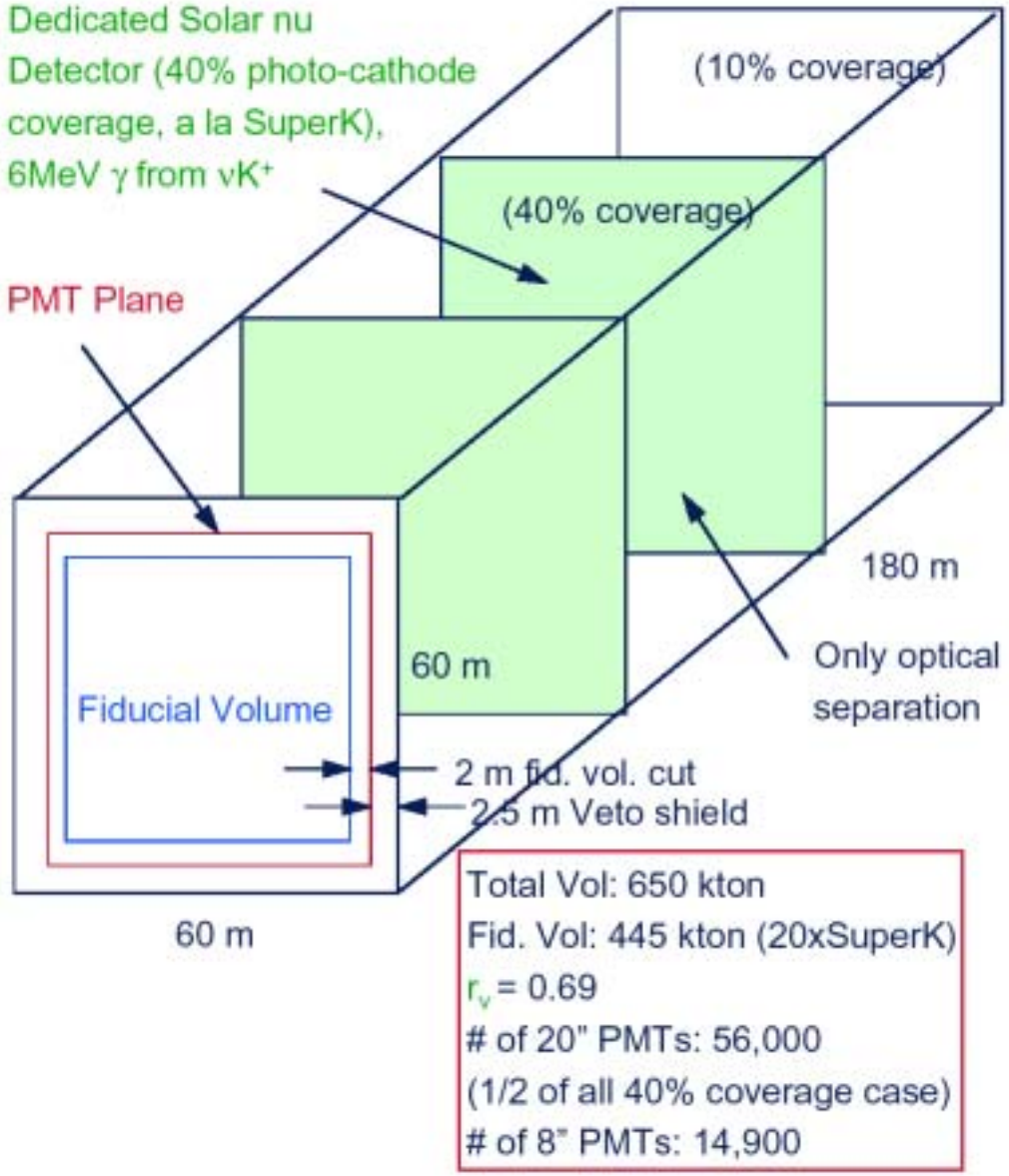
Physics Potential and Feasibility of UNO - June 2001

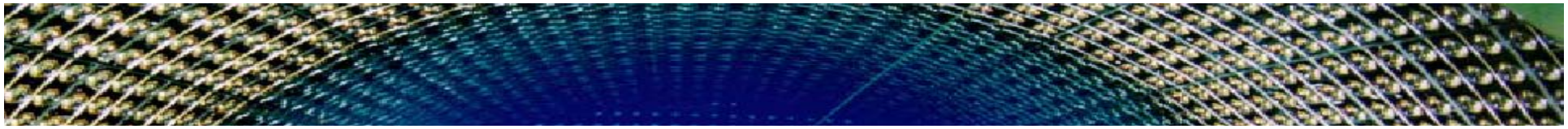


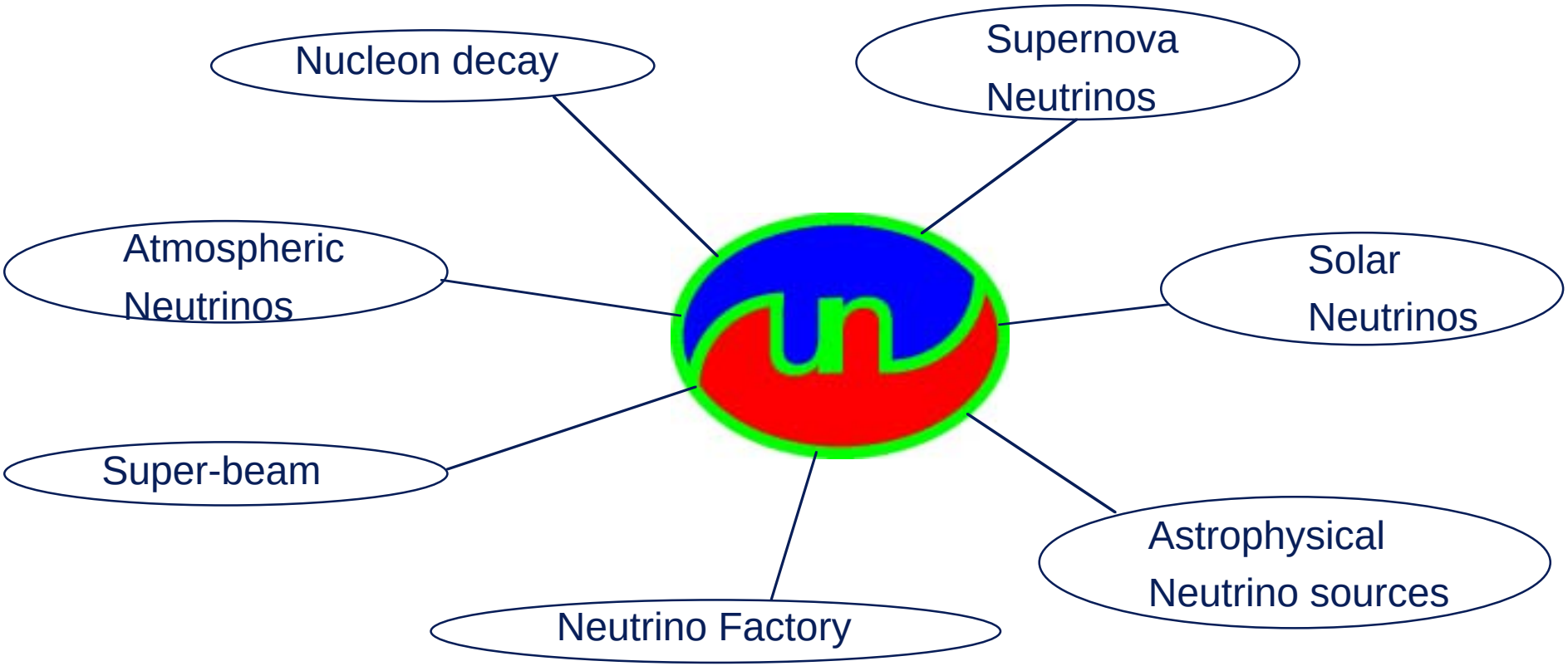


STONY BROOK
STATE UNIVERSITY OF NEW YORK

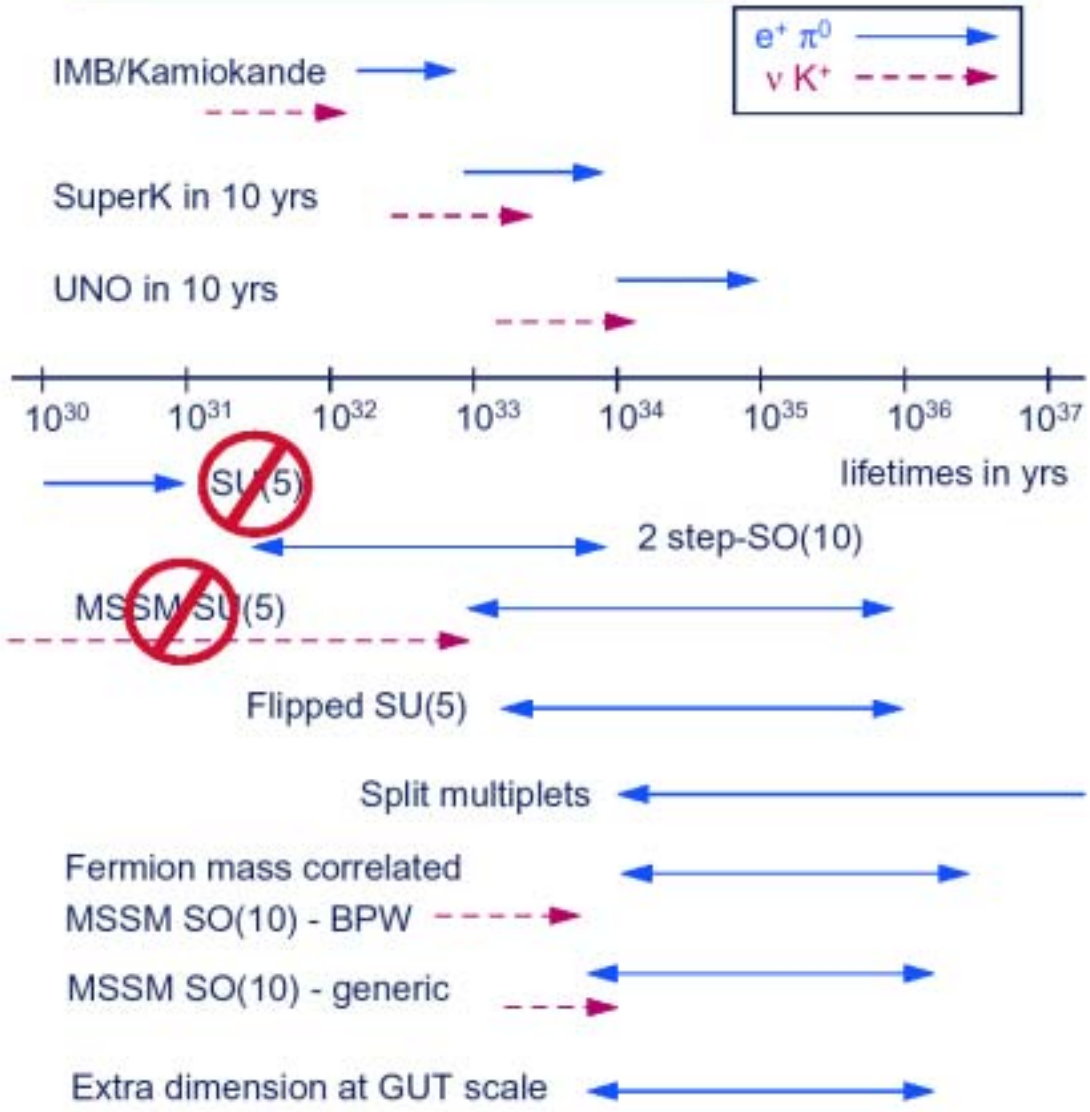
UNO Baseline Configuration






Nucleon decay
Supernova Neutrinos
Atmospheric Neutrinos
Solar Neutrinos
Super-beam
Astrophysical Neutrino sources
Neutrino Factory

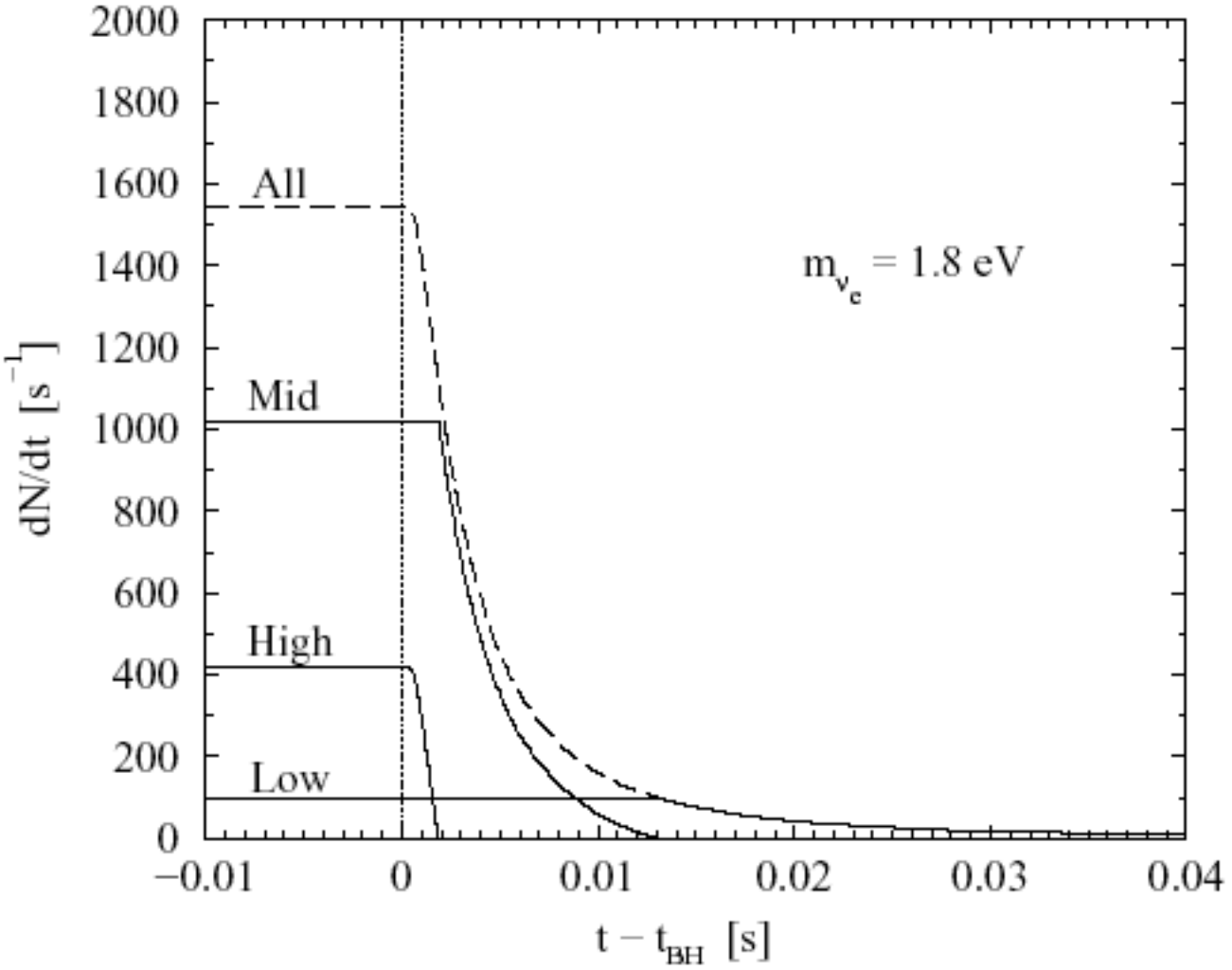
UNO Proton Decay Sensitivity



UNO Supernova Neutrino Sensitivity

- ~140k nu events at 10 kpc
  - detailed mapping of the time structure of the neutrino flux at ms scale
- detection reach: ~1 Mpc which includes most of the “Local group of Galaxies” including Andromeda
  - » ~ 1 supernova detection/10 years
- together with SuperK, provides good triangulation for supernova early warning for optical observations
- recall that we recorded only 20 supernova neutrino events in human history from Supernova 1987A

Galactic Supernova



Possible Observation of Birth of a Black Hole!

UNO Summary

- Large scale water Cherenkov detecters
  - Proven technology (2 decades of Physics experience: IMB, Kamiokande and Super-Kamiokande)
    - » Observation of neutrino oscillations (mass)
    - » Observation of neutrinos from SN1987A
    - » First real time and directional observation of solar neutrinos
    - » Confirmation of the solar neutrino flux deficit
    - » World best limits on nucleon decays

      ==> exclusion of minimal SU(5)

      ==> exclusion of MSSM SU(5)
  - Water cheapest medium, for p --> $e^+ \pi^0$ mode SuperK detection efficiency is ~40%
    - » hard to improve
- UNO design optimized for Physics/Cost (Multi-purpose)

continue: UNO Summary

- Challenges
  - No critical path R&D items (can start construction within 3 years)
  - identifying an underground site with good rock quality for an extraordinary cavern size (60m x 60m x 180m)
- Requirements for a NUSL
  - depth > 3,000 m.w.e.
  - a location w/ good quality rock
  - excavation capacity: > 3 kton (rock)/day
    - » (assuming 1M m^3 excavation in 1000 days)
    - » based on a preliminary construction schedule sent to HEPAP sub-panel: 10 years (8 years + 2 year contingency)
    - » ==> 3 year excavation (+ 2 year contingency)
  - Electricity ~2MW

Potential UNO Sites and NUSL

- US NUSL candicate sites
  - Homestake Mine, Lead, S. Dakoda
  - San Jacinto Mountain, Palm Springs, California
    - » **Stony Brook: co-author of the proposal**
  - WIPP, Carlsbad, New Mexico
    - » declared as an underground research facility by DOE (2000)
- Foreign UNO candidate sites
  - Frejus tunnel
    - » escalating enthusiam in European community
  - Kamioka mine
    - » Hyper-Kamiokande proposal being considered

UNO Future Plans and Outlook

- UNO detector (20x SuperK fid. vol., 650kton total volume) can be build today @$400M ~$500M
  - tackles some of the most important physics questions today w/ potential of major discoveries
  - detector R&D, optimization and cost estimation being carried out
  - looking to expand the proto-collaboration
  - A formal proposal (LOI) by the end of 2002
  - A window of opportunity for great physics within next 10~15 years
  - If built, it will provide a comprehensive nucleon decay and neutrino physics program for the US and world science community for the 21th century
  - Intersection of interests from HEP, NP and AP communities; local communities (and senetors) at WIPP/Carlsbad and Homestake; and international community (Japan: Hyper-Kamiokande, Europe: CERN/ Frejus (133 km) initiatives, Canada: Sudbury...)
  - Stony Brook goup will play a leading role in both UNO and NUSL efforts

President Clinton on Super-Kamiokande Observation of non-zero Neutrino Mass

First, we must help you to ensure that America continues to lead the revolution in science and technology. Growth is a prerequisite for opportunity, and scientific research is a basic prerequisite for growth. Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.

This discovery was made, in Japan, yes, but it had the support of the investment of the U.S. Department of Energy. This discovery calls into question the decision made in Washington a couple of years ago to disband the super-conducting supercollider, and it reaffirms the importance of the work now being done at the Fermi National Acceleration Facility in Illinois.

-- President Clinton's address to the MIT graduates (June 6, 1998)

NY Times on Neutrinos



The New York Times

NEW YORK, FRIDAY, JUNE 5, 1998

Late Edition

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

SuperK Non-Zero Neutrino Mass June 5, 1998

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TATAYAMA, 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 relatively elusive subatomic particle called the neutrino.

Detecting Neutrinos

K2K First Event June 29, 1999

Team Detects Neutrino Fired Through Earth's Crust

The 1960's and 70's were a time of great ferment in all the sciences, and the momentum of those years has carried to the present. Among the major achievements in physics I was privileged to report were the discovery of the top quark at Fermilab — the last of six quarks predicted by theory — and the discovery in Japan that the elusive neutrino particle probably has some mass, a finding with profound implications for the fate of the universe.

Retirement Essay by M. Browne February 27, 2000

We see stars Underground!

