Neutrino Oscillations - II

24th Indian Summer School
"Understanding Neutrinos"
Prague, Sept. 3-7, 2012

Dave Wark
Imperial/RAL

Science & Technology Facilities Council

Imperial College London

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A Solution of the Solar-Neutrino Problem

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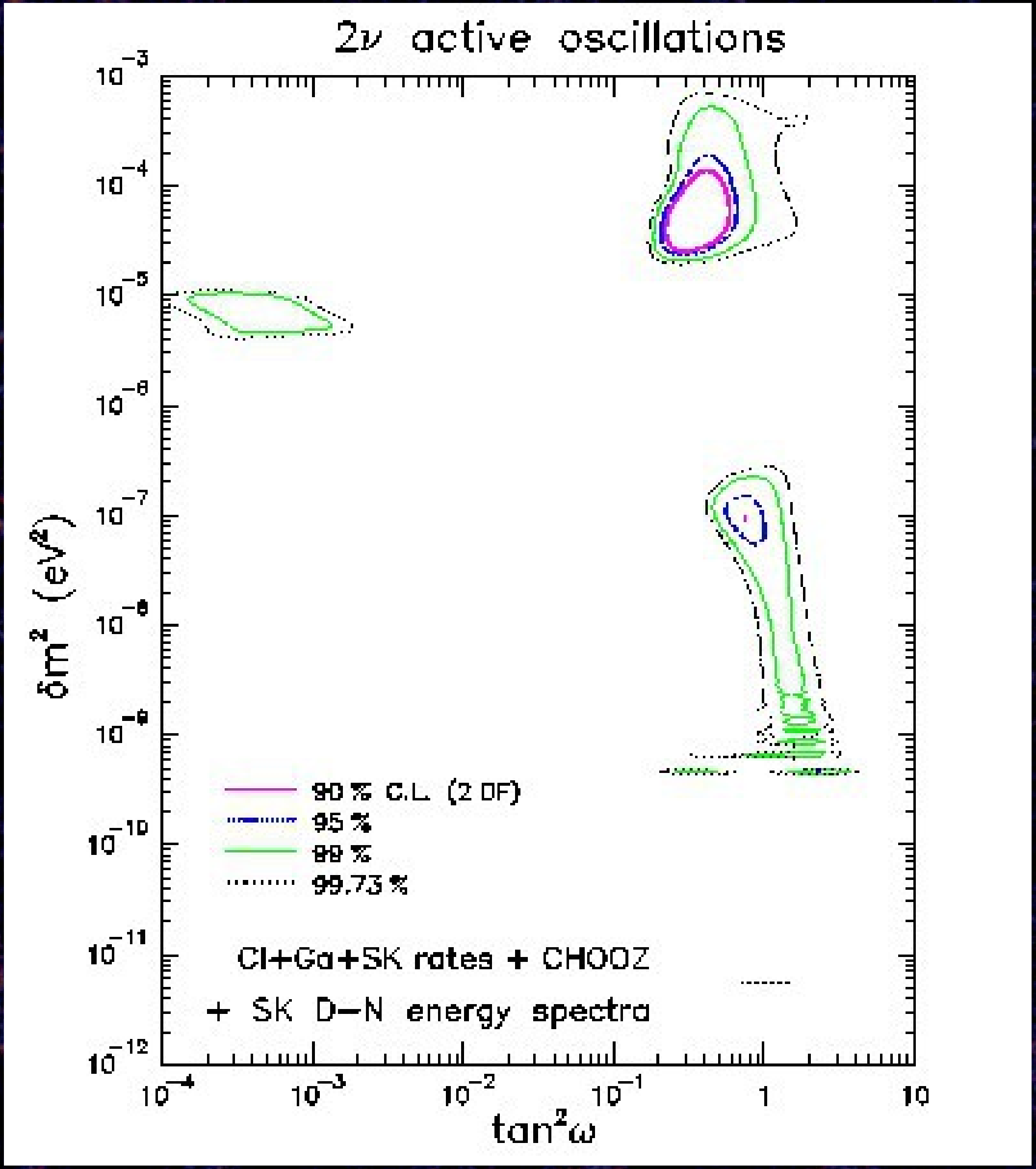
(Received 27 June 1990)

Comparison of the results from the Kamiokande neutrino-electron scattering experiment with those from the chlorine experiment and with solar models shows that the explanation of the solar-neutrino problem probably requires physics beyond the standard electroweak model with zero neutrino masses. The experimental results, including the shape of the electron-recoil energy spectrum measured by Kamiokande, are in excellent agreement with a nonadiabatic solution of the Mikheyev-Smirnov-Wolfenstein effect, yielding a neutrino mass difference of $\Delta m^2 = 1\times10^{-8}\sin^{-2}\Theta_V$ eV^2.

PACS numbers: 96.60.Kx, 12.15.Ff, 14.60.Gh

The MSW solution[5] with a relatively large mass difference can be excluded because Kamiokande II observed a significant neutrino flux above 7.5 MeV. The large-mass version of the MSW effect predicts[6] that these higher-energy ^{8}B neutrinos are almost entirely missing.

Which left us where?



But no smoking gun for oscillations….

SNO Collaboration

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L.C. Stonehill, B.L. Wall, J.F. Wilkerson
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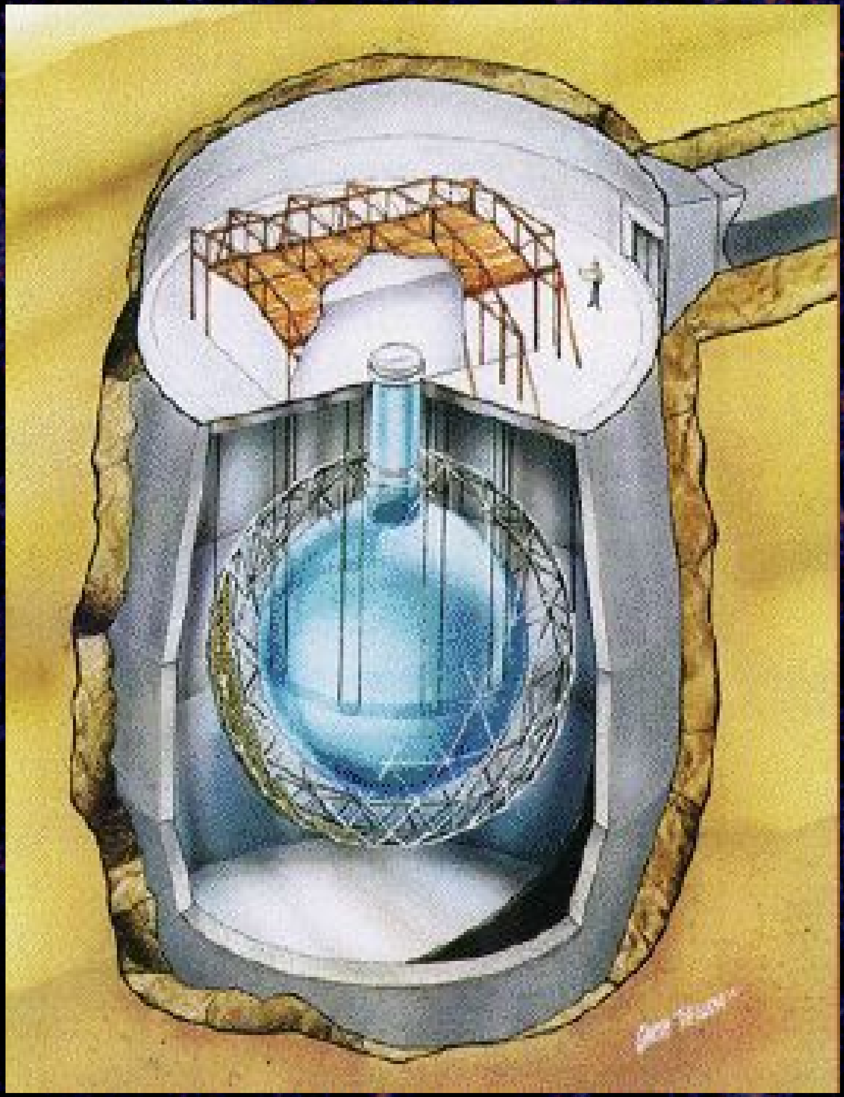
The Sudbury Neutrino Observatory



CC $\nu_e + d \rightarrow p + p + e-$

Q = 1.445 MeV
good measurement of νe energy spectrum
some directional info ∝ (1 – 1/3 cosθ)
νe only

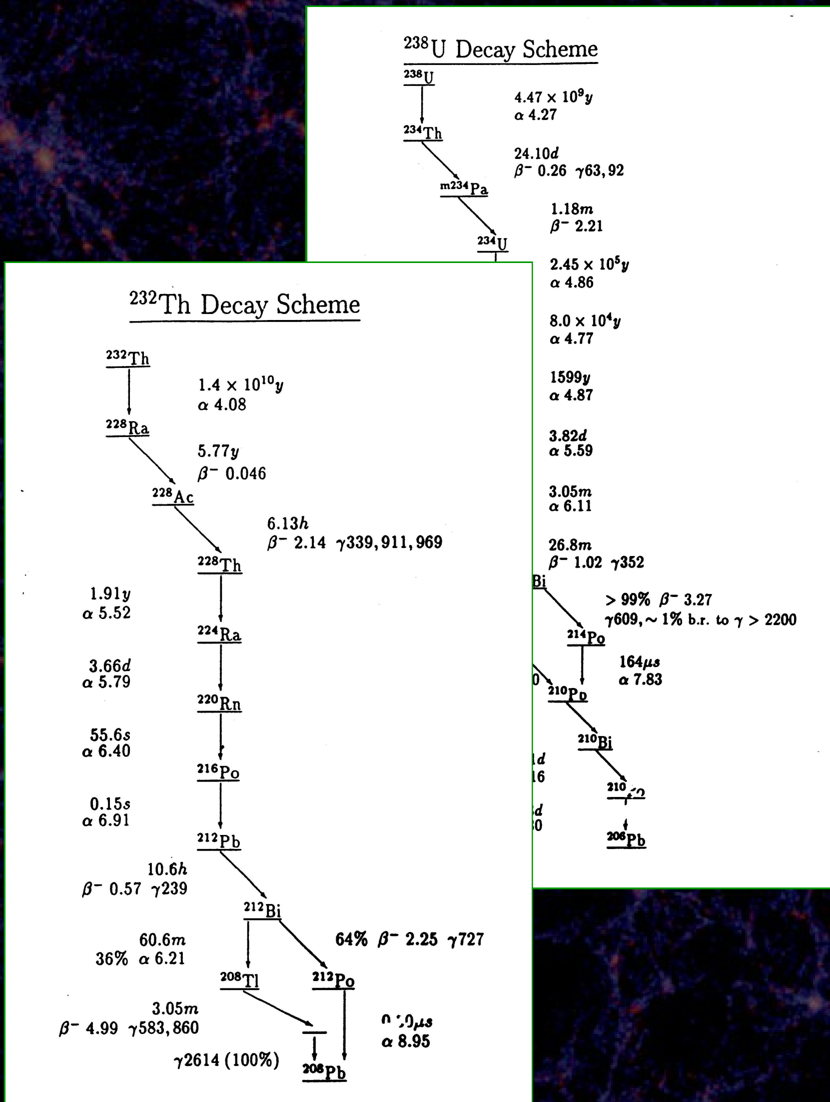
NC $\nu_x + d \rightarrow p + n + \nu_x$

Q = 2.22 MeV
measures total 8B ν flux from the Sun
equal cross section for all ν types

ES $\nu_x + e- \rightarrow \nu_x + e-$

low statistics
mainly sensitive to νe, some νμ and ντ
strong directional sensitivity

The enemy…..



βs and γs from decays in these chains interfere with our signals at low energies

And worse, γs over 2.2 MeV cause $d + \gamma \rightarrow n + p$

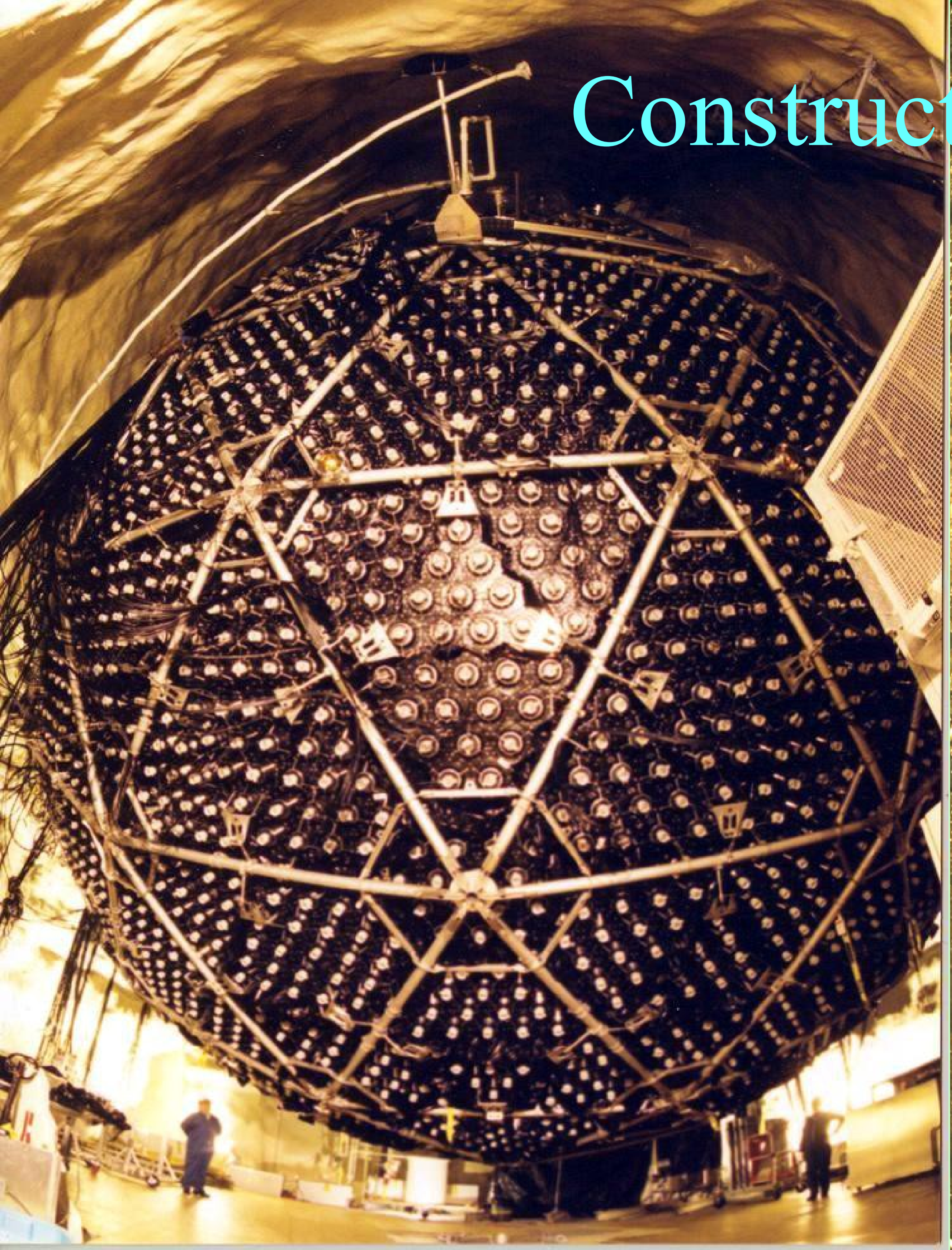
Design called for:

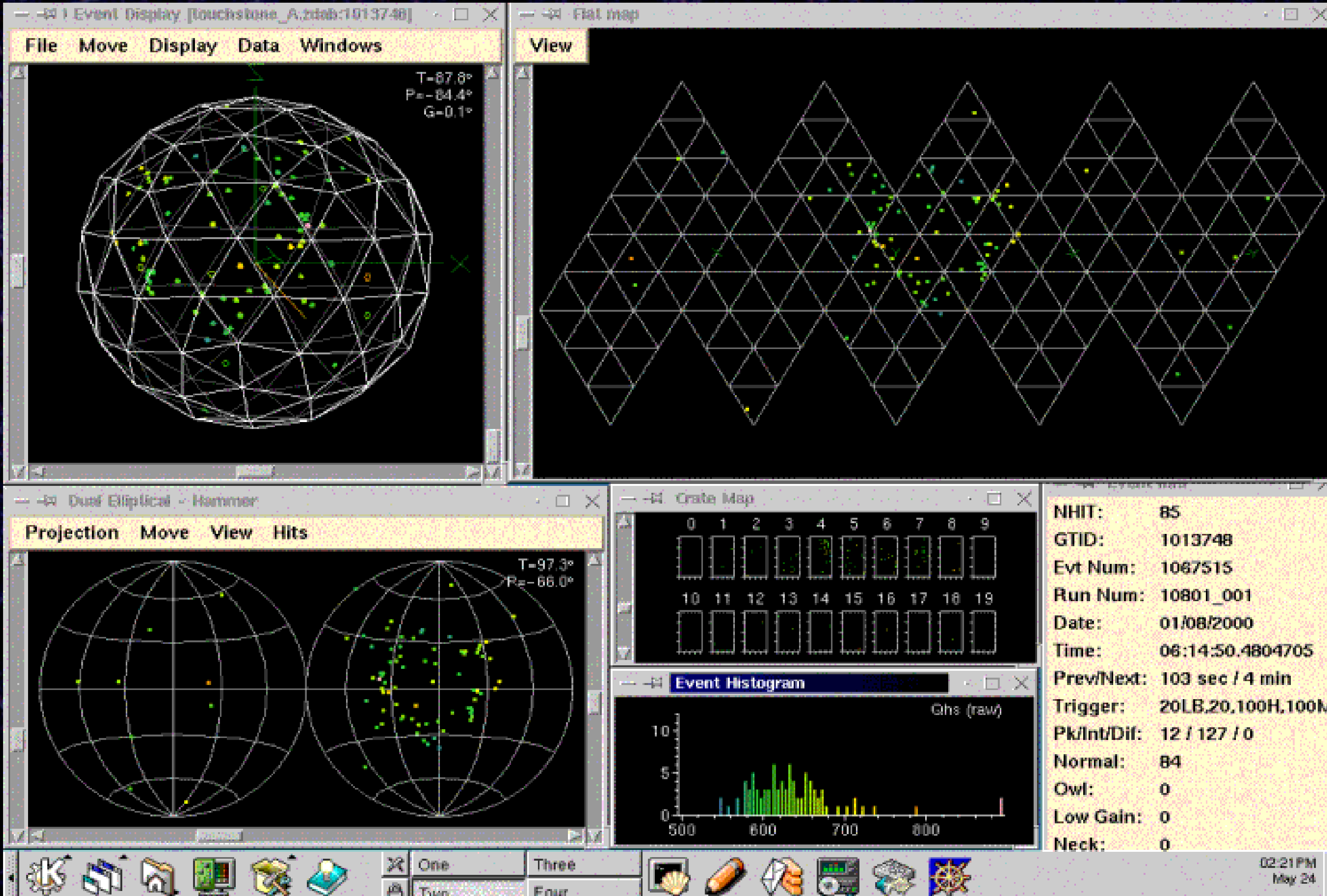
<u>D2O < 10-15 gm/gm U/Th</u>

H2O < 10-14 gm/gm U/Th

Acrylic < 10-12 gm/gm U/Th

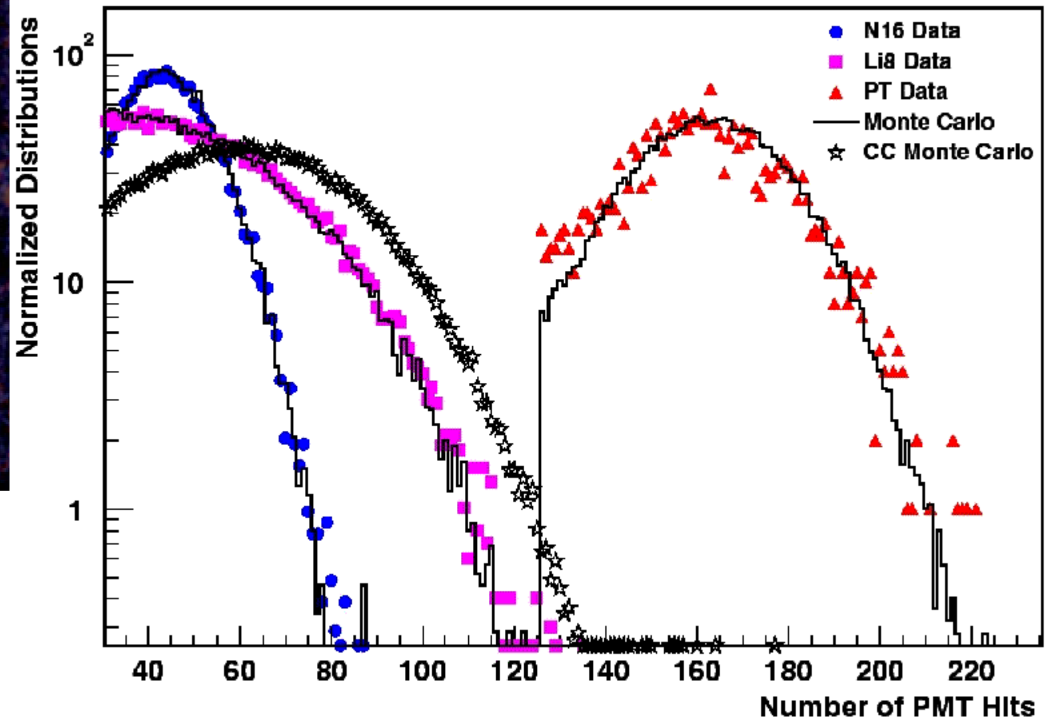
Construction

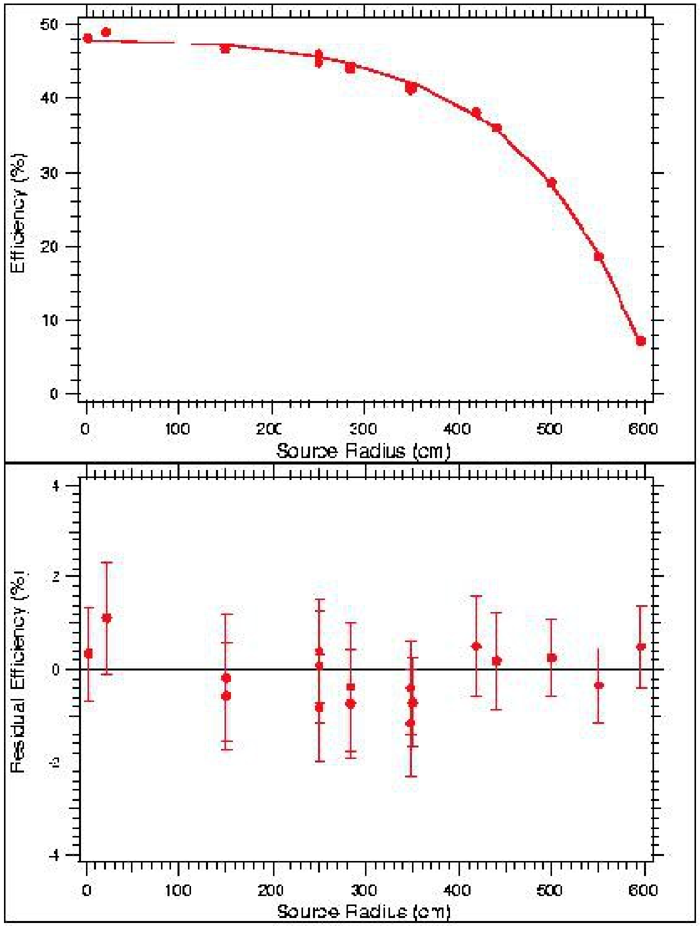


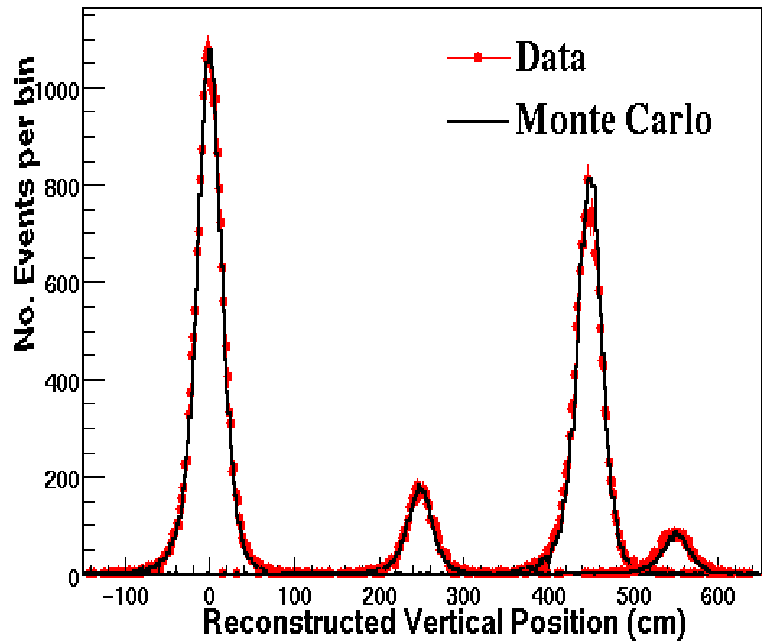


Dave Wark
Imperial College/

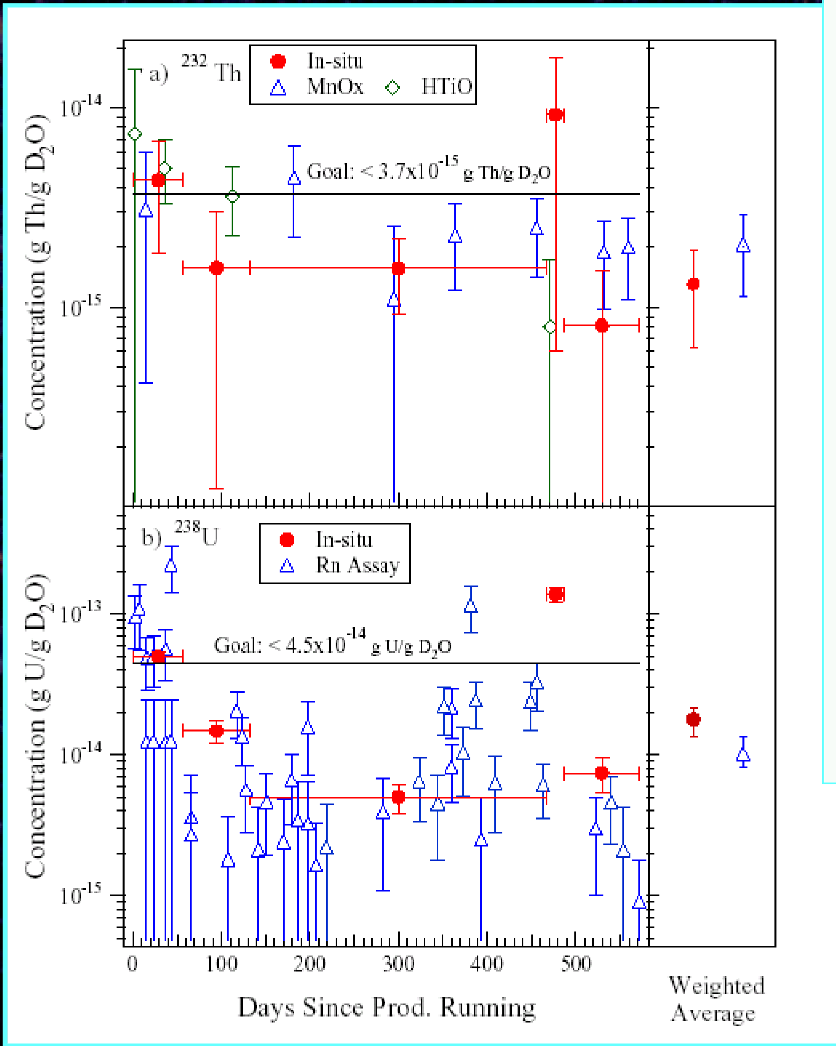
SNO Calibrations:

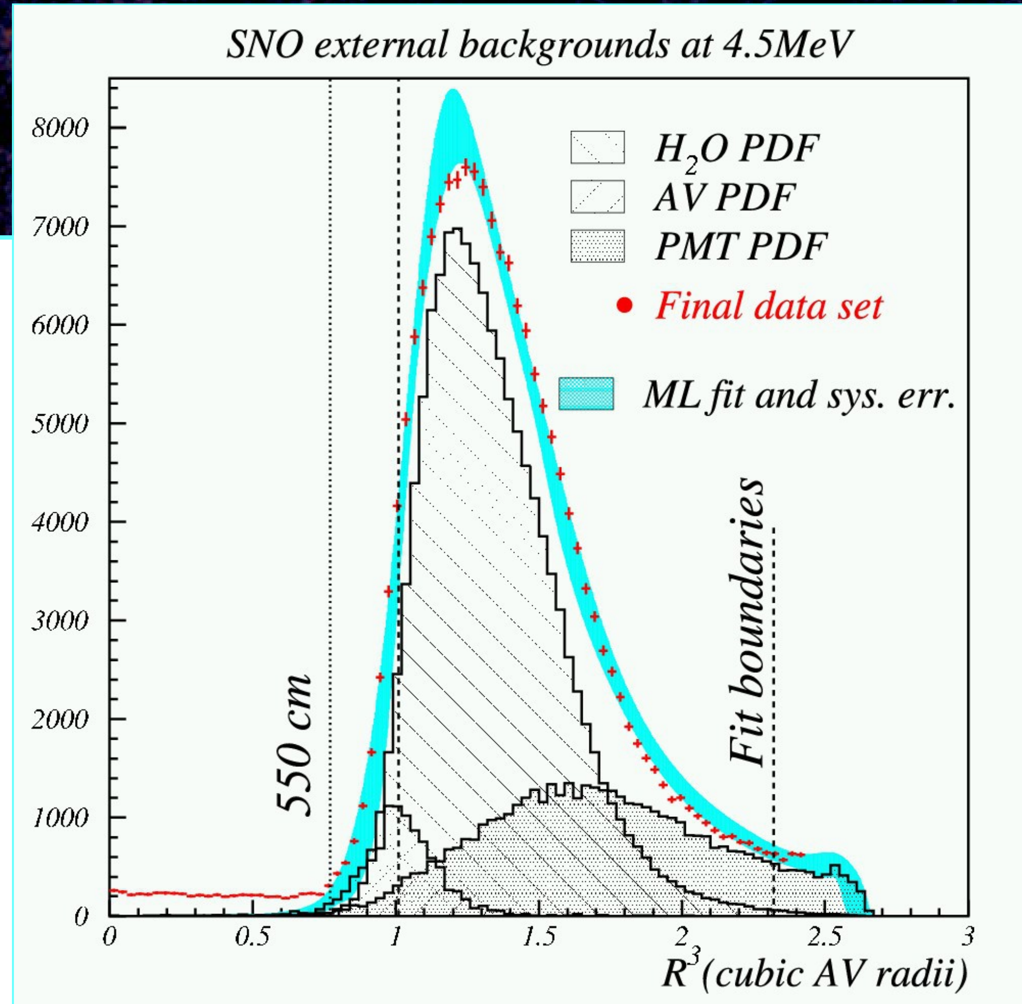




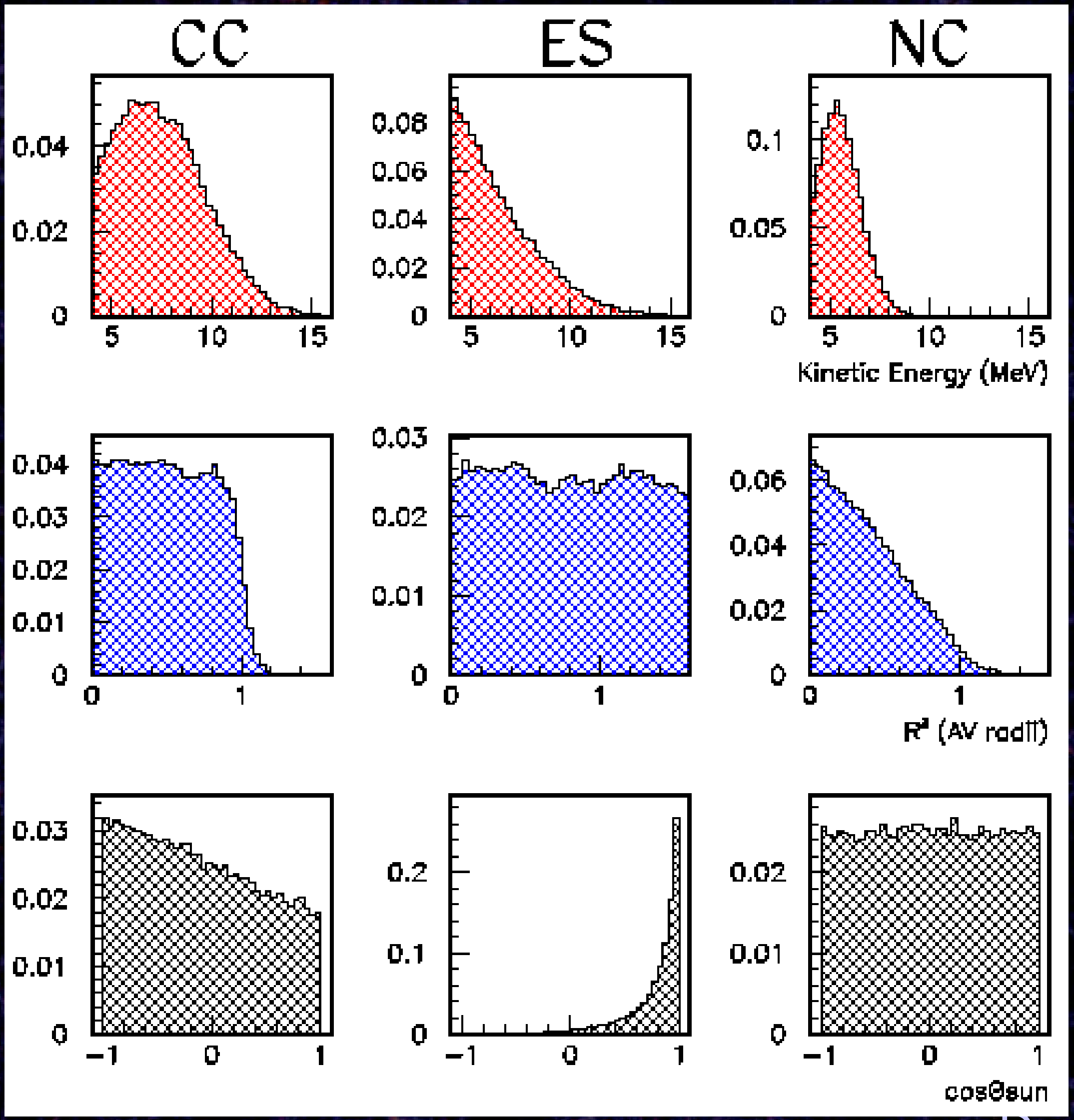


SNO Backgrounds



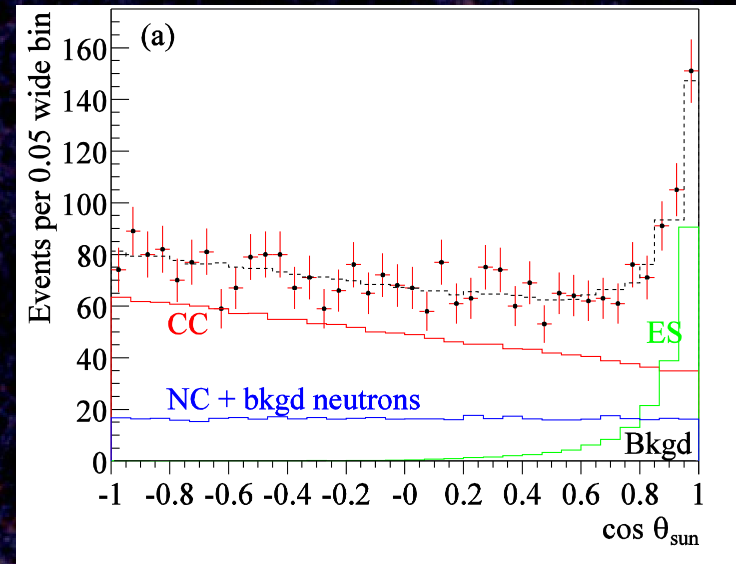


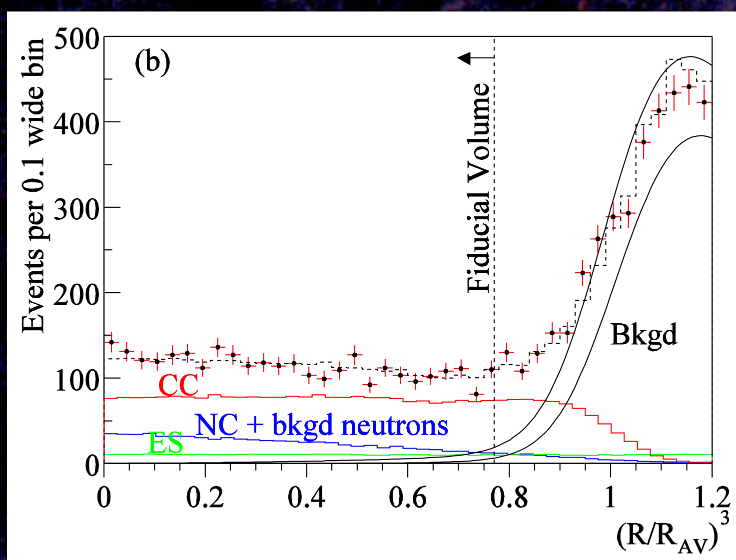
Signal PDF's for pure D2O

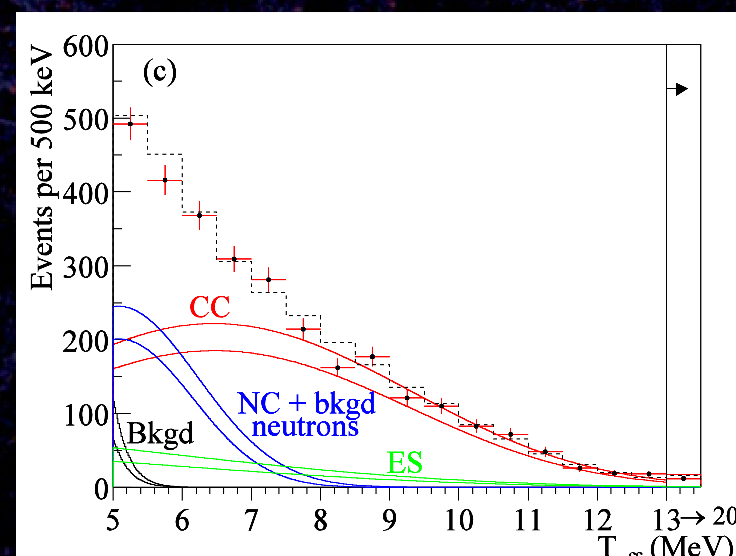


Signal Extraction Results

CC	1959.7	+61.9 +60.9
ES	271.5	+26.4 +25.6
NC	575.6	+49.5 +48.9



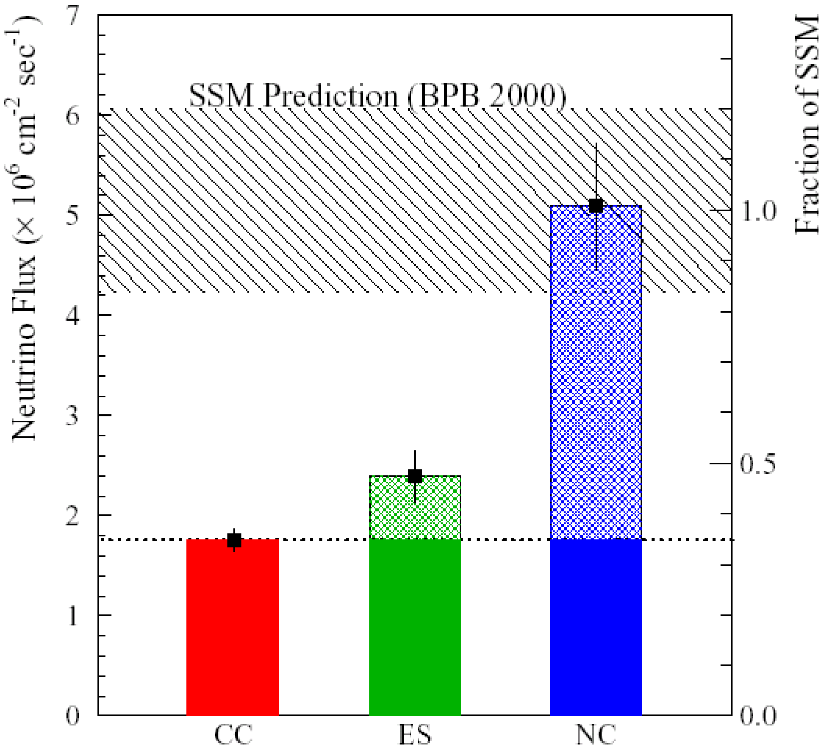




SNO Systematic Flux Uncertainties

Error Source	CC error (%)	ES error (%)
Energy scale	-5.2, +6.1	-3.5, +5.4
Energy resolution	±0.5	±0.3
Non-linearity	±0.5	±0.4
Vertex shift	±3.1	±3.3
Vertex resolution	±0.7	±0.4
Angular resolution	±0.5	±2.2
High Energy γ's	-0.8, +0.0	-1.9, +0.0
Low energy background	-0.2, +0.0	-0.2, +0.0
Instrumental background	-0.2, +0.0	-0.6, +0.0
Trigger efficiency	0.0	0.0
Live time	±0.1	±0.1
Cut acceptance	-0.6, +0.7	-0.6, +0.7
Earth orbit eccentricity	±0.2	±0.2
17O, 18O	0.0	0.0
Experimental uncertainty	-6.2, +7.0	-5.7, +6.8
Cross-section	3.0	0.5
Solar Model	-16, +20	-16, +20

Measured SNO Fluxes



Assuming ^{8}B energy spectrum ...

Fluxes ($\times 10^{6}$ cm^{-2} sec^{-1})

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.}) \pm 0.09\,(\text{sys.})$$

$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.}) \pm 0.12\,(\text{sys.})$$

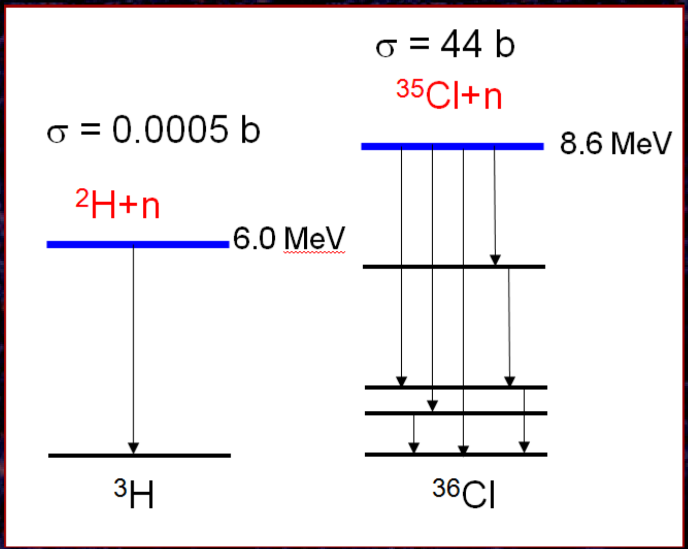
$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{sys.})$$

$$\phi_{CC} < \phi_{ES} < \phi_{NC}$$

NC flux in agreement with SSM prediction!

NC Signal Measured Three Ways

2 tons NaCl added



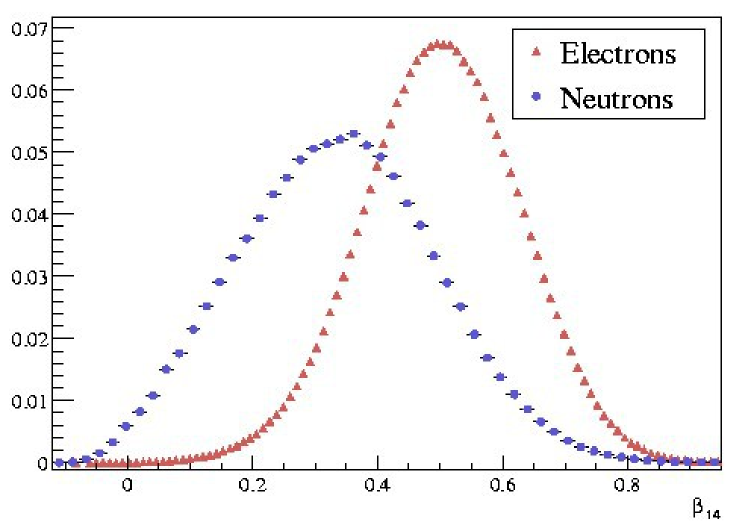
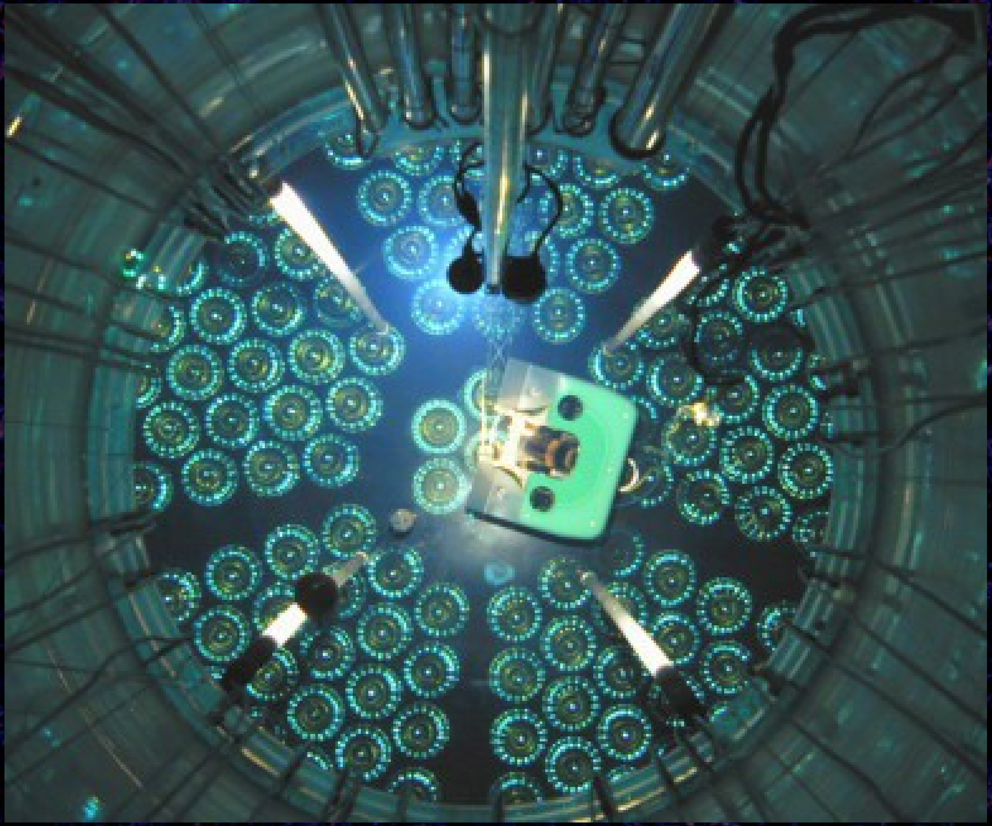


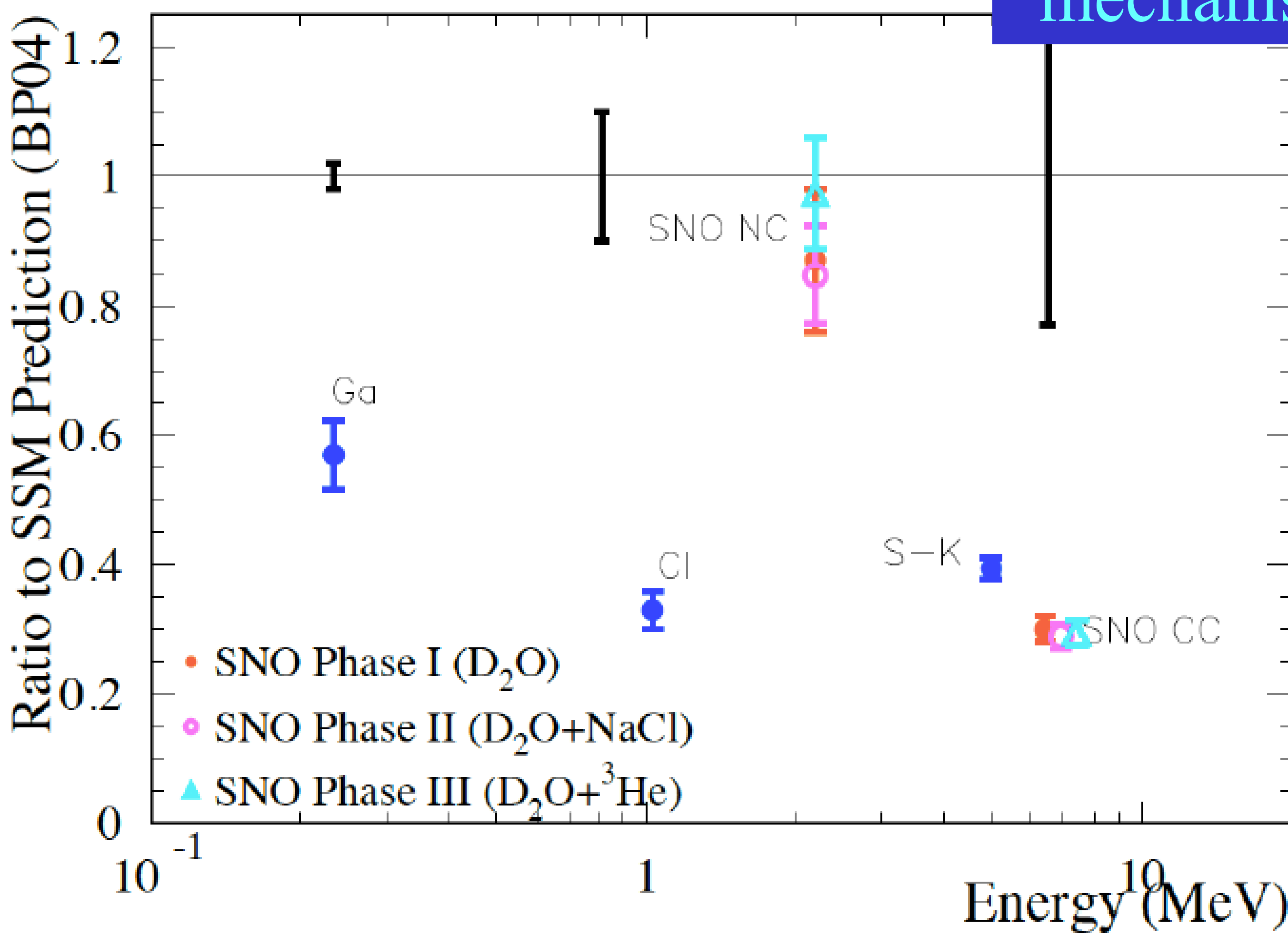
Figure 21: β_{14} for NC and electron MC.



Blind analysis techniques used throughout...

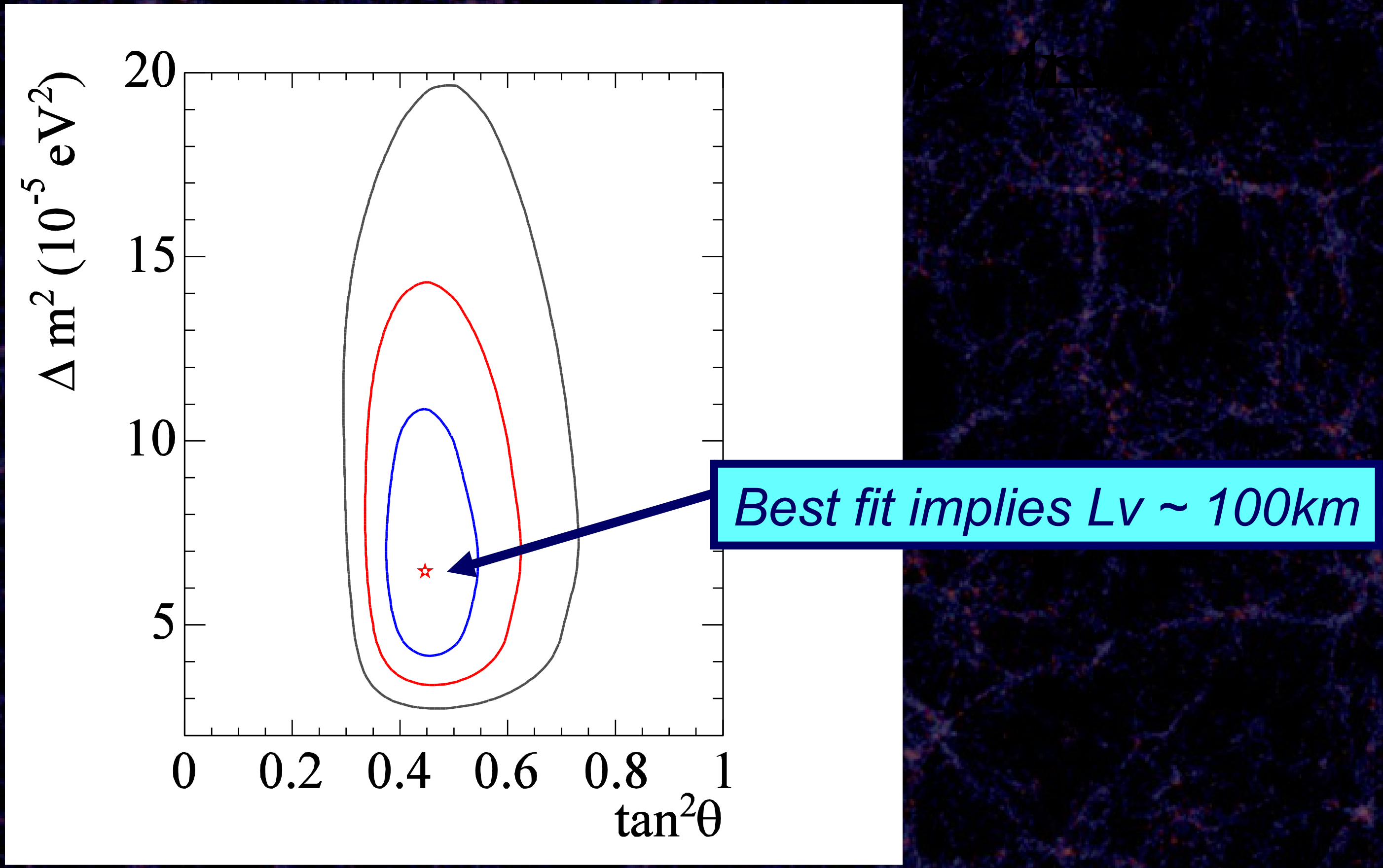
Solar Neutrino Problem Resolved

Doesn't prove mechanism!



From Art McDonald's Nu2012 talk...

Global Solar Analysis with SNO 391-day salt data



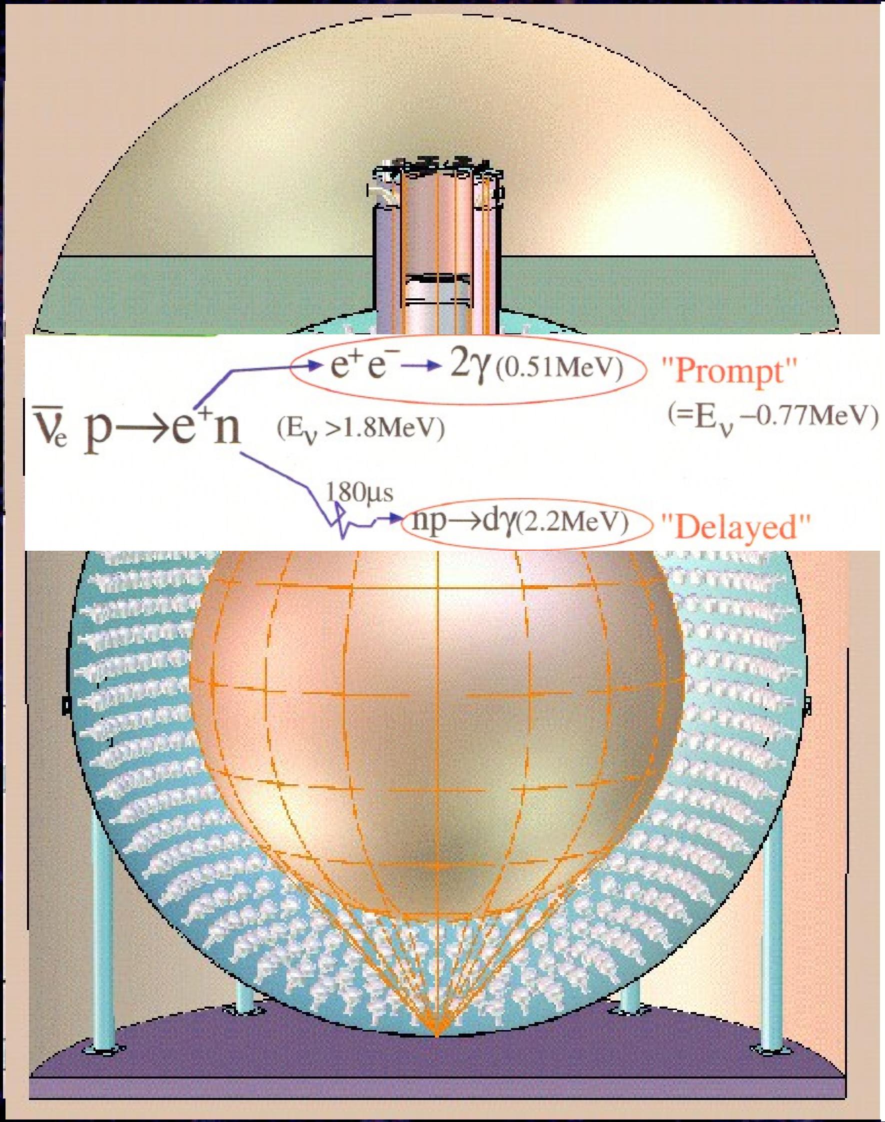
SNO finds:

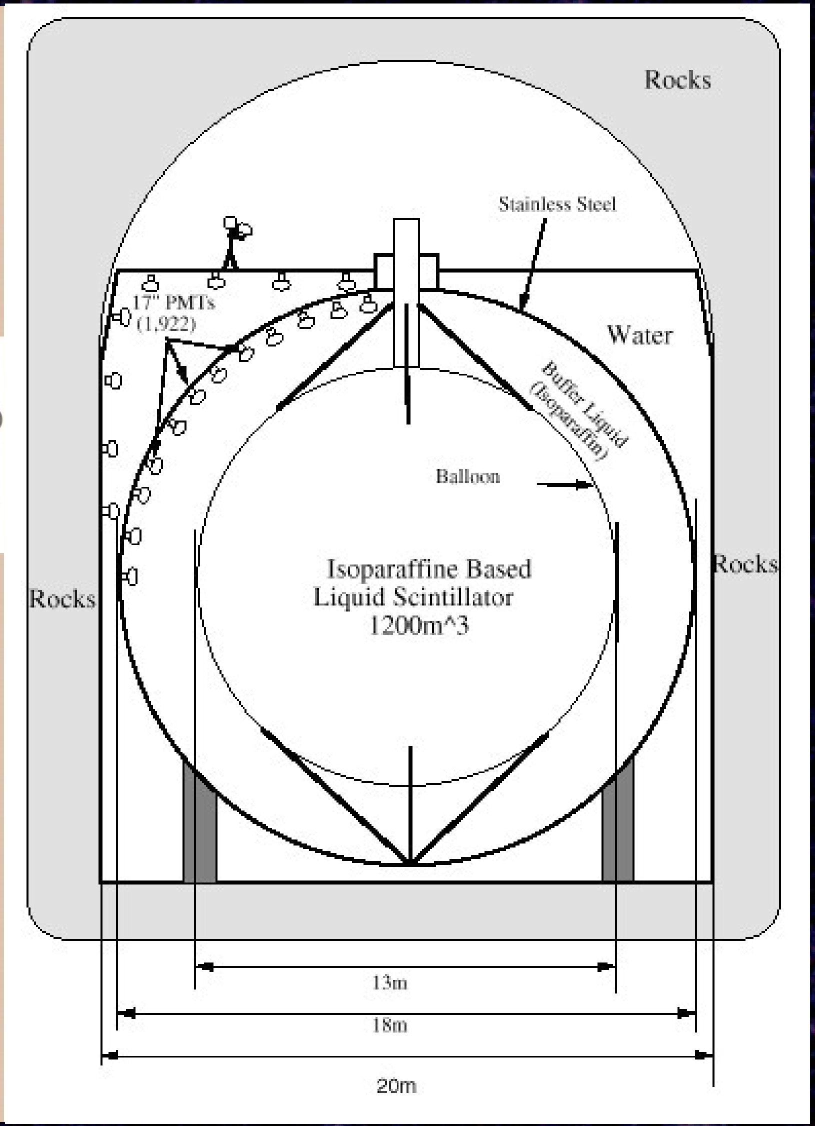
$$\frac{\phi_{CC}^{uncon}}{\phi_{NC}^{uncon}} = 0.340 \pm 0.023\ (\text{stat})\ ^{+0.029}_{-0.031}\ (\text{syst})$$

SNO suppression factor > 2 for L >> Lv ⇒ MSW effect

Possible to observe on Earth?

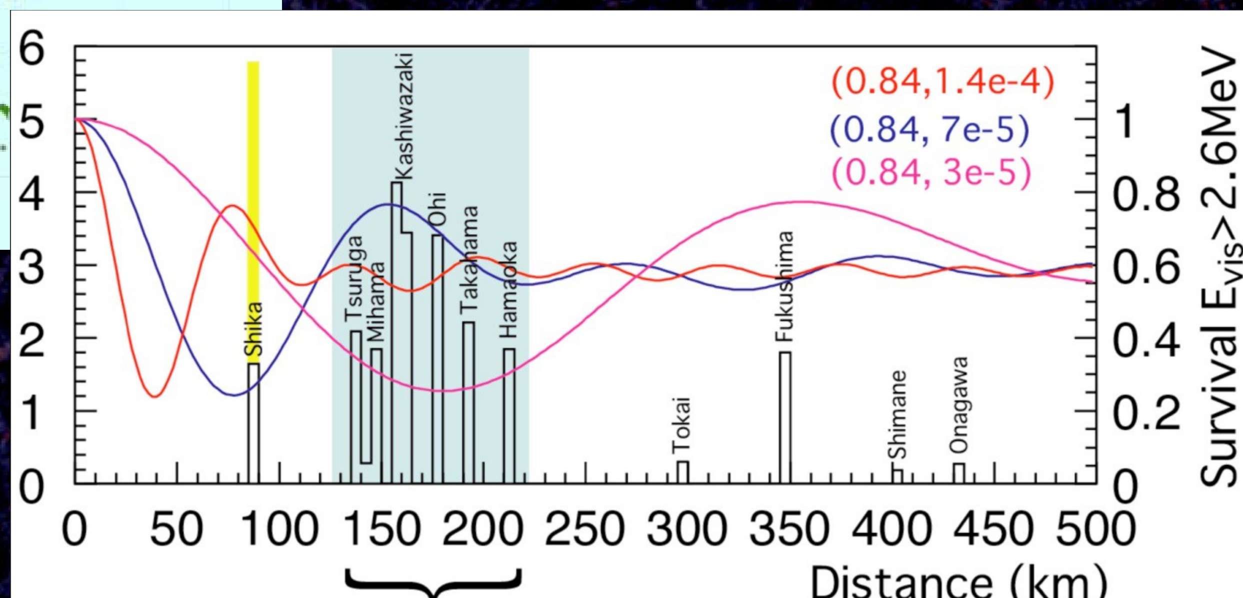
KamLAND





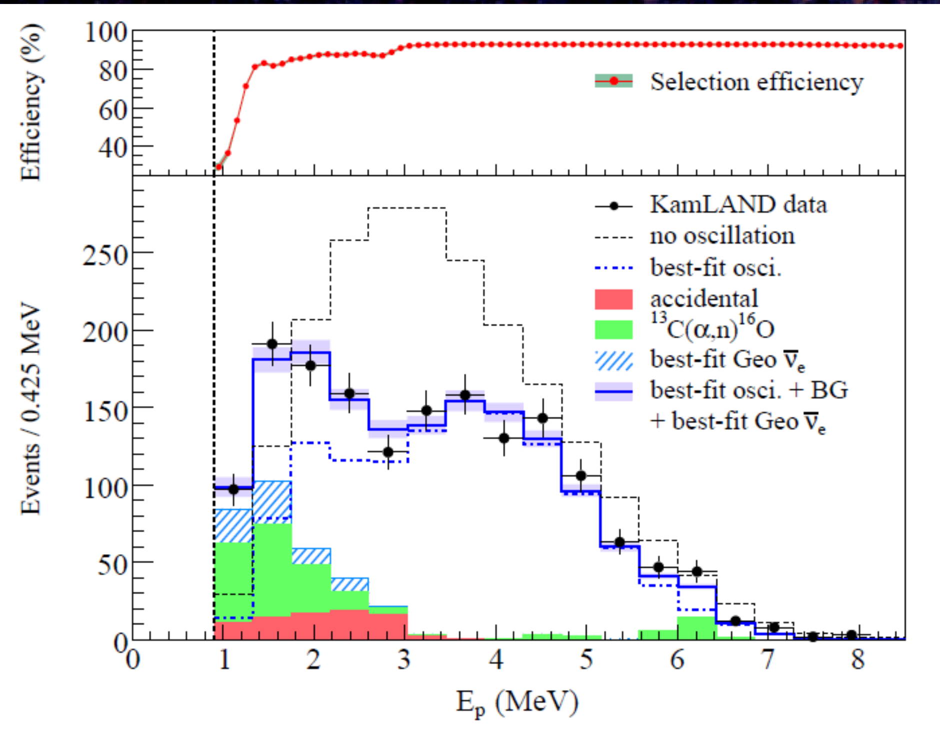
Sum over all Japanese power reactors...

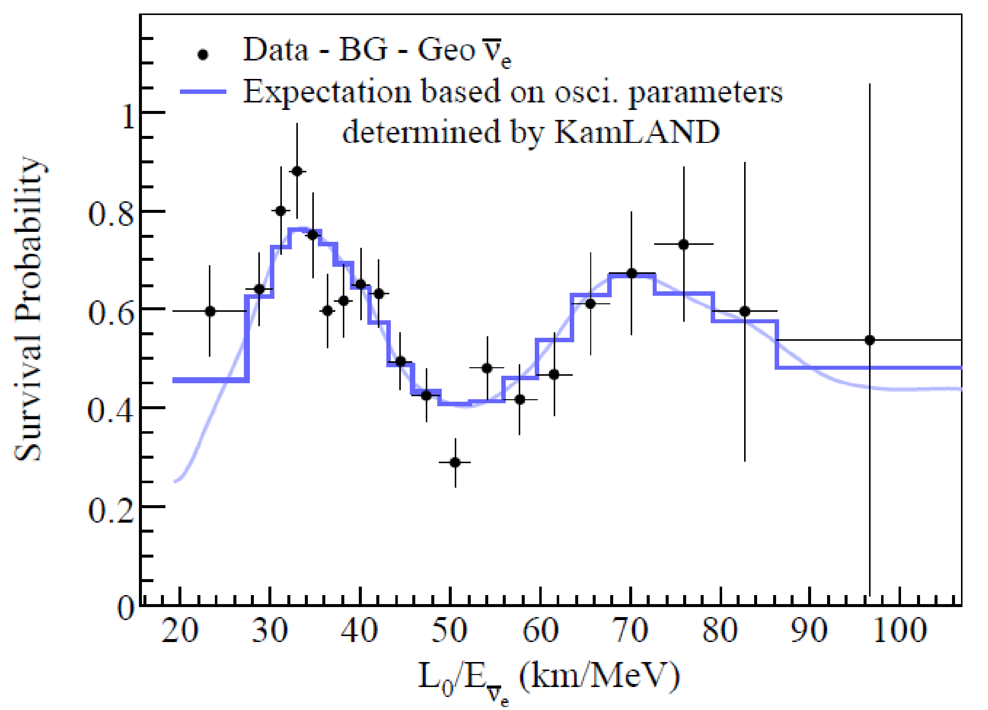
KamLAND



80% of total contribution comes from 130~220km distance

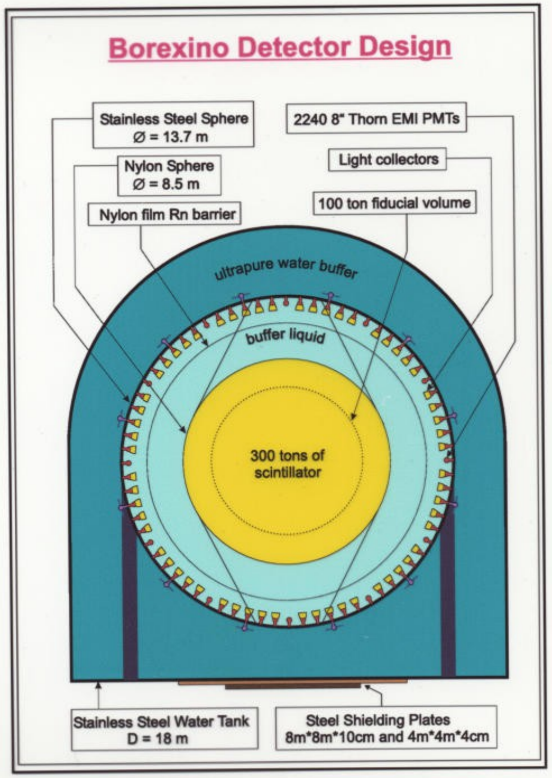
KamLAND



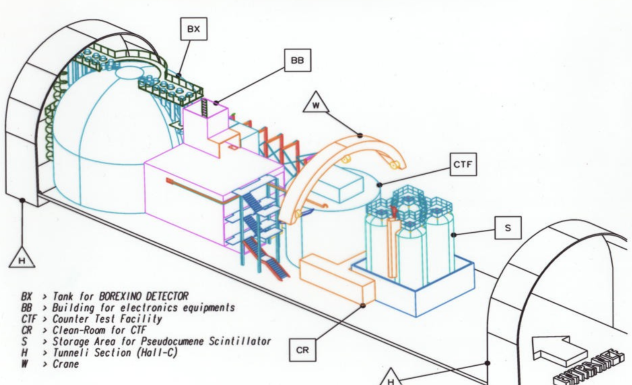


Proved (with other results) that neutrinos oscillate…
…or at least do a damned fine impression.

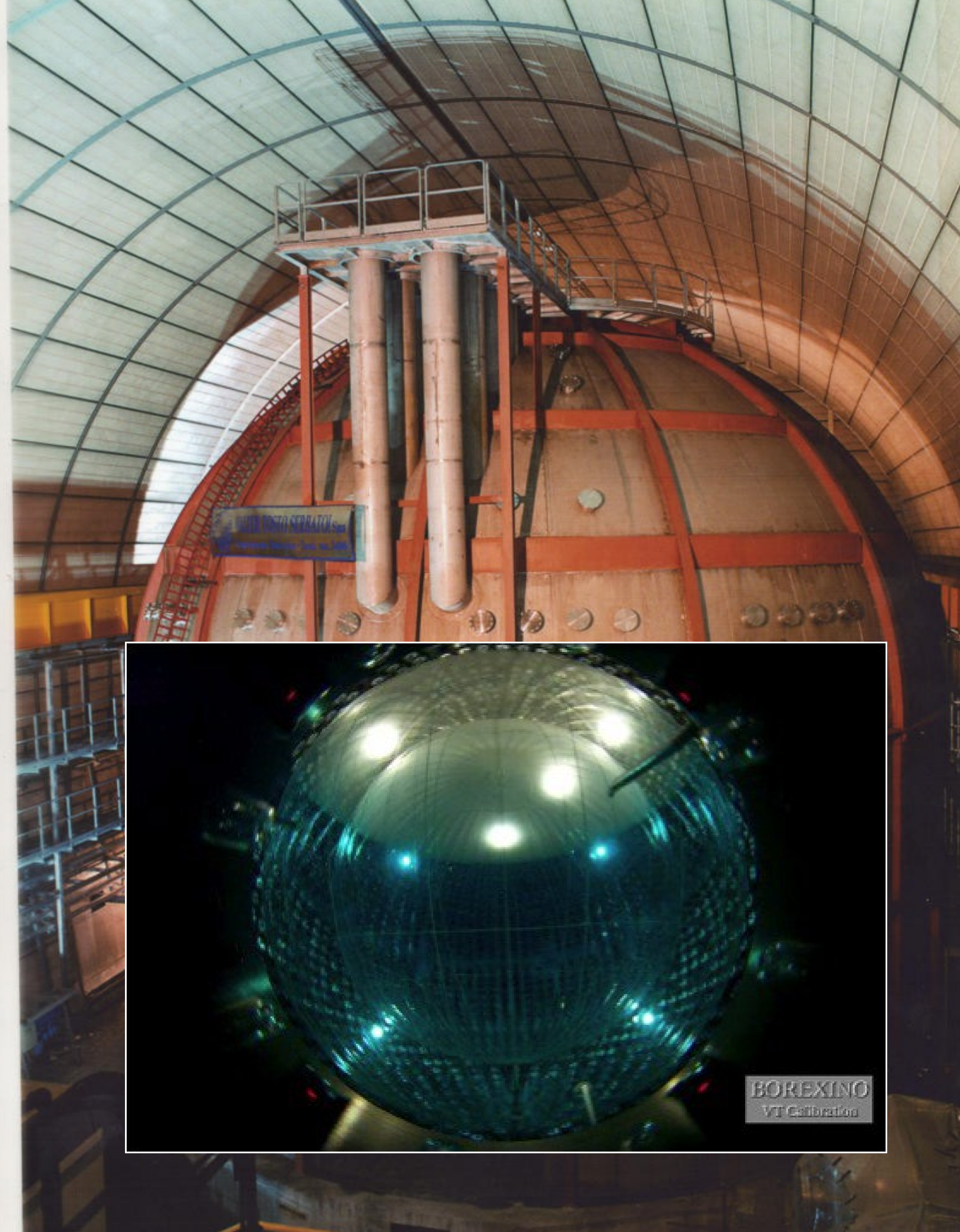
Borexino



Borexino Detector Design
Stainless Steel Sphere
Ø = 13.7 m
2240 8" Thorn EMI PMTs
Nylon Sphere
Ø = 8.5 m
Light collectors
Nylon film Rn barrier
100 ton fiducial volume
ultrapure water buffer
buffer liquid
300 tons of scintillator
Stainless Steel Water Tank
D = 18 m
Steel Shielding Plates
8m*8m*10cm and 4m*4m*4cm



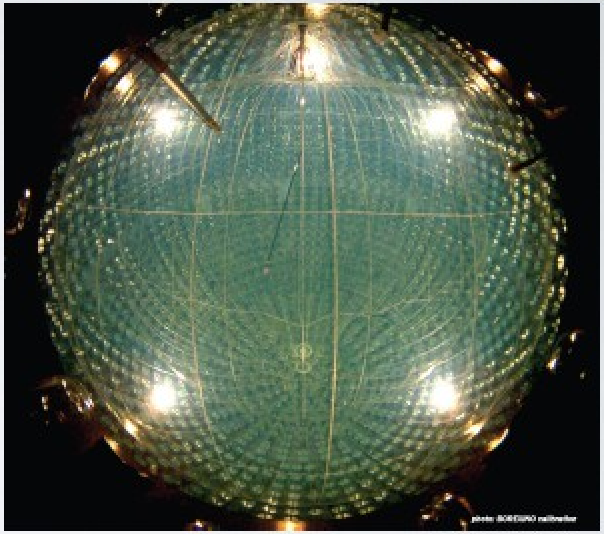
BX
BB
W
CTF
S
H
CR
H
BX > Tank for BOREXINO DETECTOR
BB > Building for electronics equipments
CTF > Counter Test Facility
CR > Clean-Room for CTF
S > Storage Area for Pseudocumene Scintillator
H > Tunneli Section (Hall-C)
W > Crane

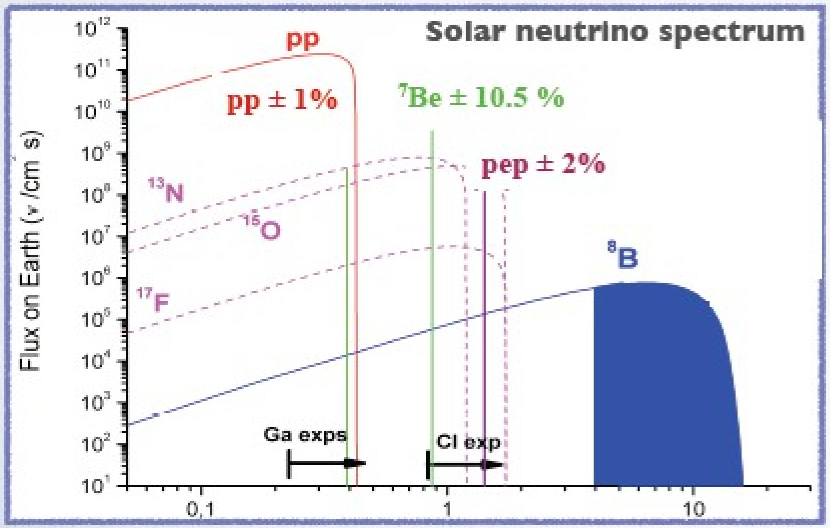


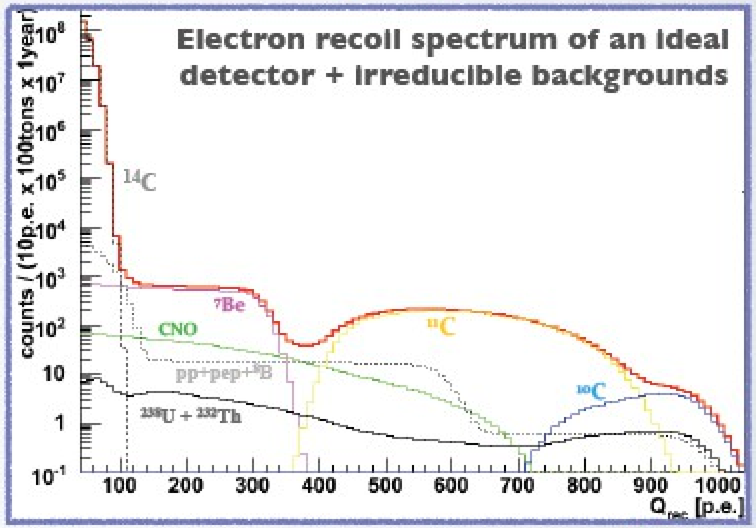
BOREXINO
VT Calibration

BOREXINO EXPERIMENT

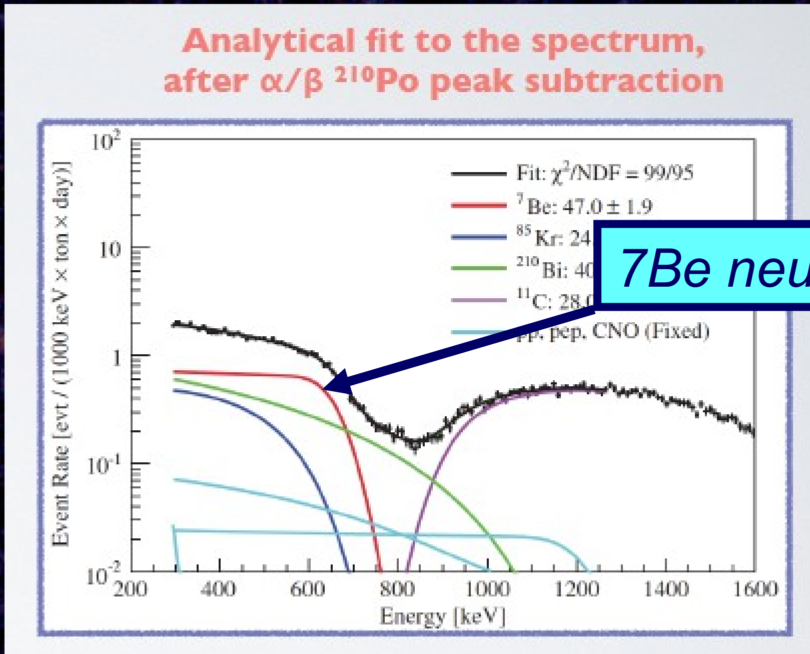
- Mainly, a solar neutrino experiment:
  - $\nu + e^- \rightarrow \nu + e^-$ in an organic liquid scintillator
    - **Ultra-low radioactive background** obtained via **selection, shielding, and purifications**
    - Low energy threshold, good energy resolution, spatial reconstruction, and pulse shape identification
  - But also
    - Geo-neutrinos, search for rare events

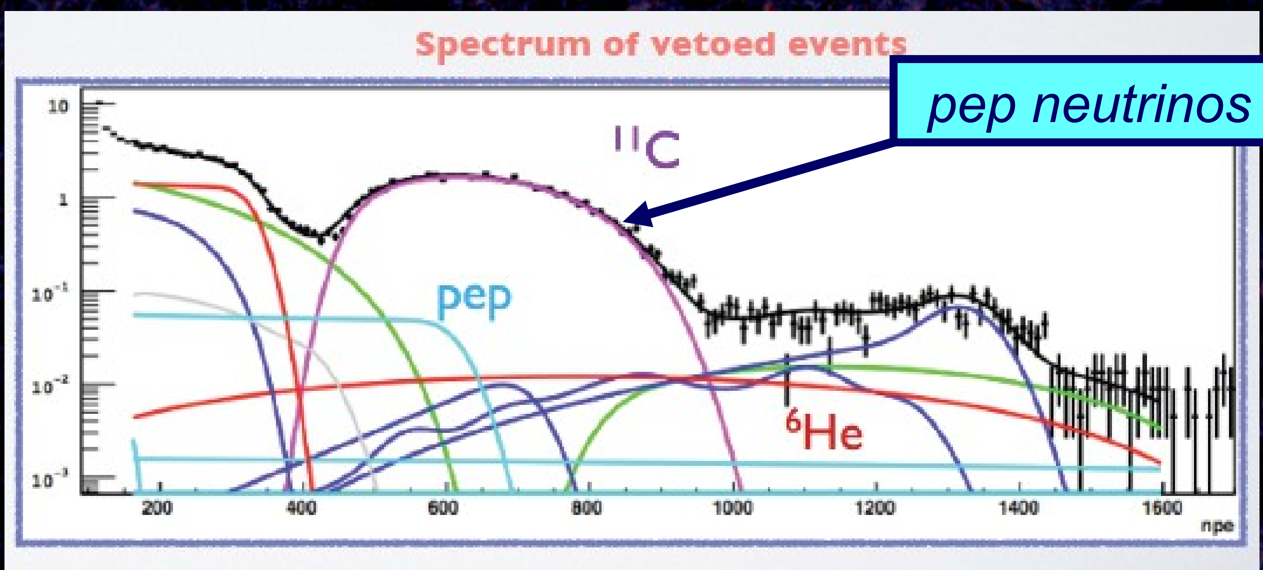






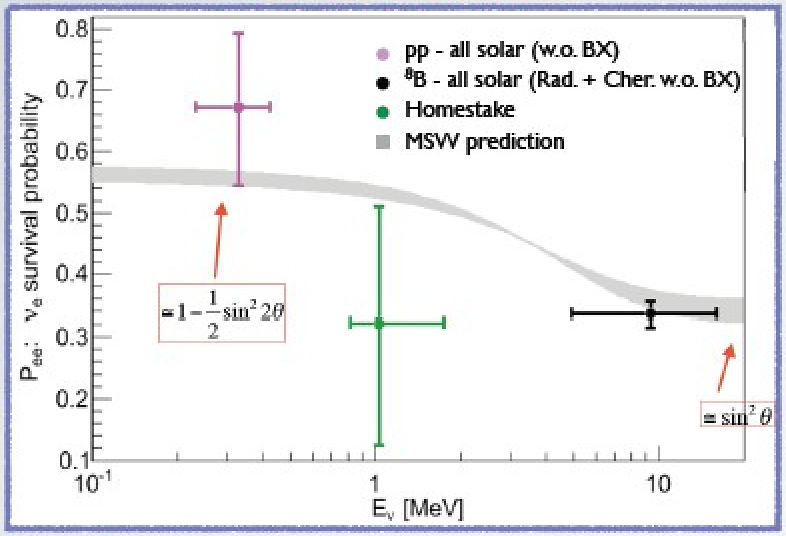
From Pallavicini's talk at Nu2012

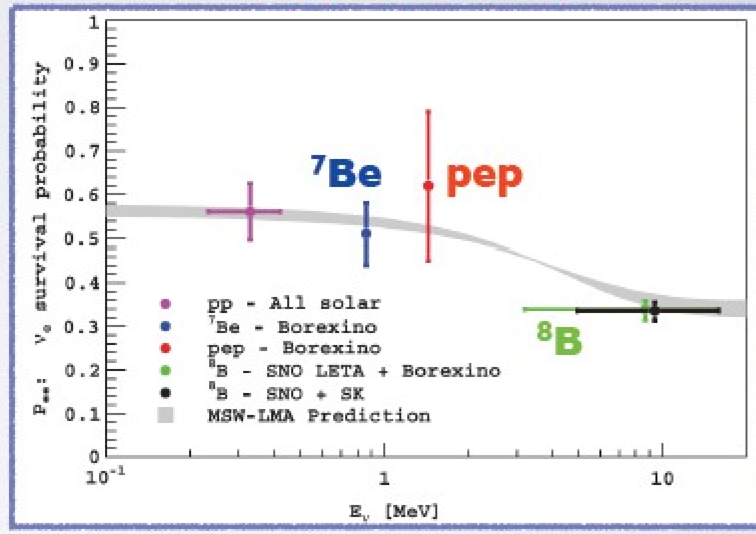

Analytical fit to the spectrum,
after α/β ²¹⁰Po peak subtraction
Fit: χ²/NDF = 99/95
⁷Be: 47.0 ± 1.9
pp, pep, CNO (Fixed)
7Be neutrinos
Event Rate [evt / (1000 keV × ton × day)]
Energy [keV]

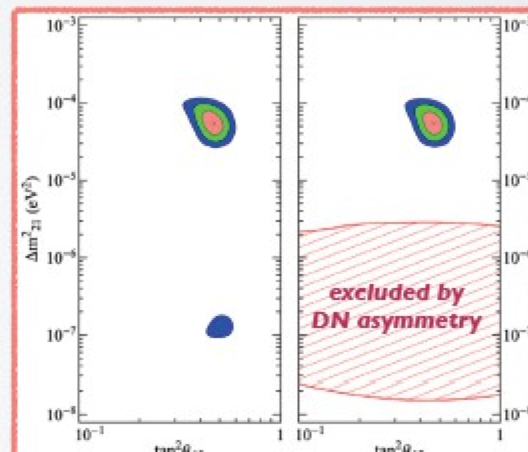

Spectrum of vetoed events
pep neutrinos
¹¹C
pep
⁶He
npe

BOREXINO IMPACT ON SOLAR NEUTRINO PHYSICS

Before Borexino | **Borexino 2012**





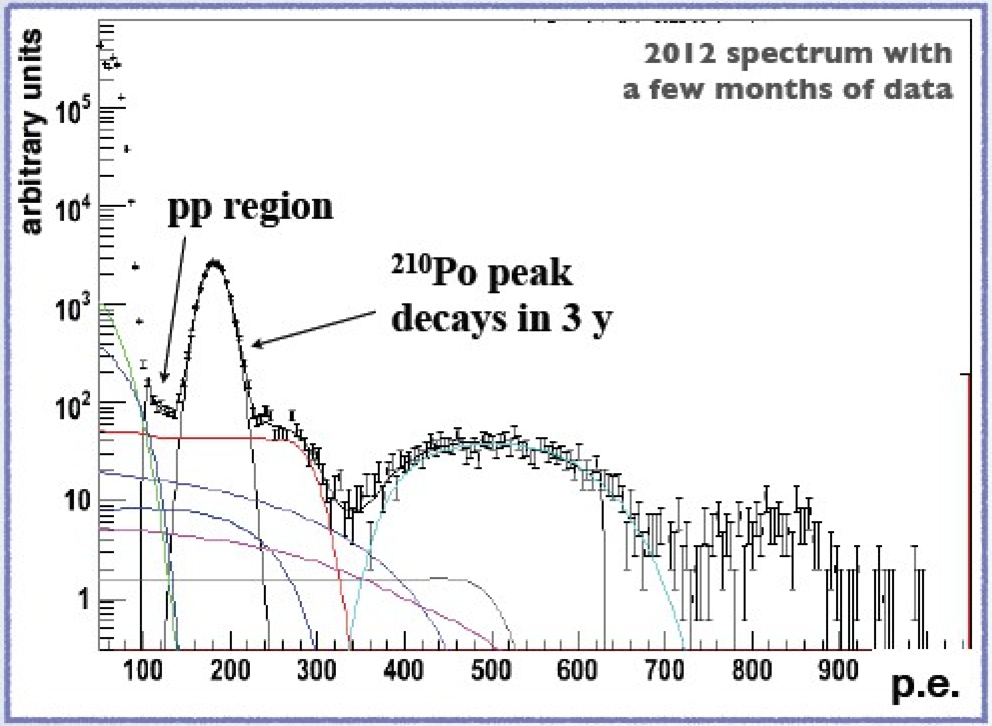


In the near future (Phase 2: 2012-2013)

- Improve ^{7}Be, ^{8}B → test of MSW
- Confirm pep at more than 3σ and reduce error
- Improve upper limit on CNO → probe metallicity
- Attempt direct pp measurement

BACKGROUND IN 2012

- A significant **purification effort** started in late 2010 to achieve even better purity
  - Quite effective on ^{85}Kr, good on ^{210}Bi, unprecedented purity in ^{238}U and ^{232}Th



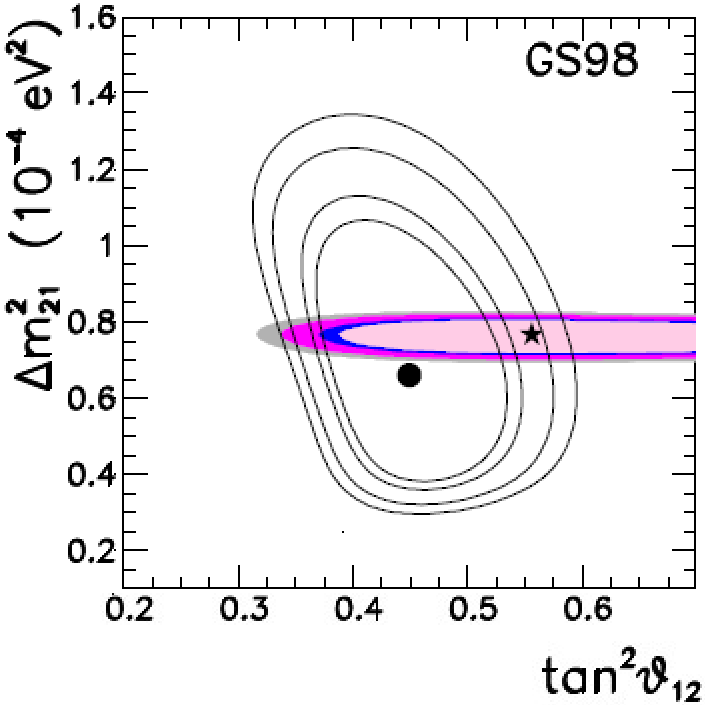
- ^{85}Kr
  - **< 8.8 cpd / 100 t**
  - 2007-2010: 31.2 ± 5
- ^{210}Bi
  - **16 ± 4 cpd / 100 t**
  - 2007-2010: 41.0 ± 2.8
- ^{238}U
  - **< 9.7 10^{-19} g/g**
- ^{232}Th
  - **< 2.9 10^{-18} g/g**

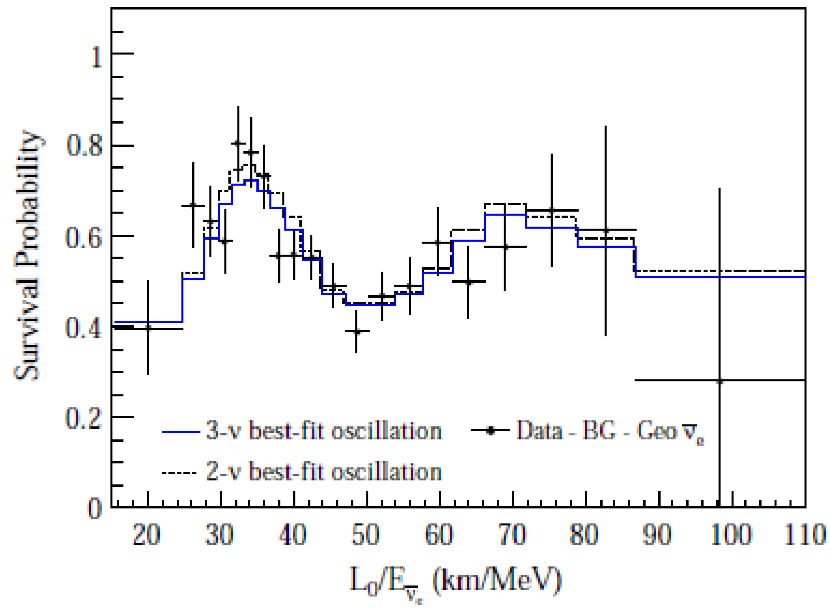
How well do we know θ12?

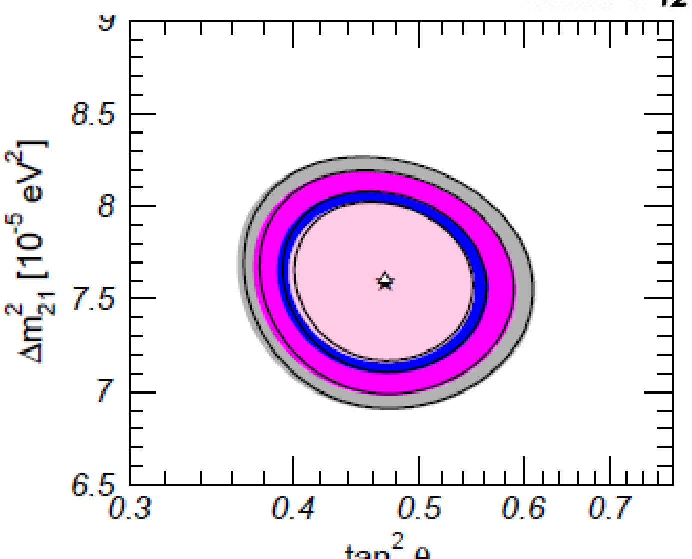
arXiv:1009.4771v3 [hep-ex] 25 Mar 2011

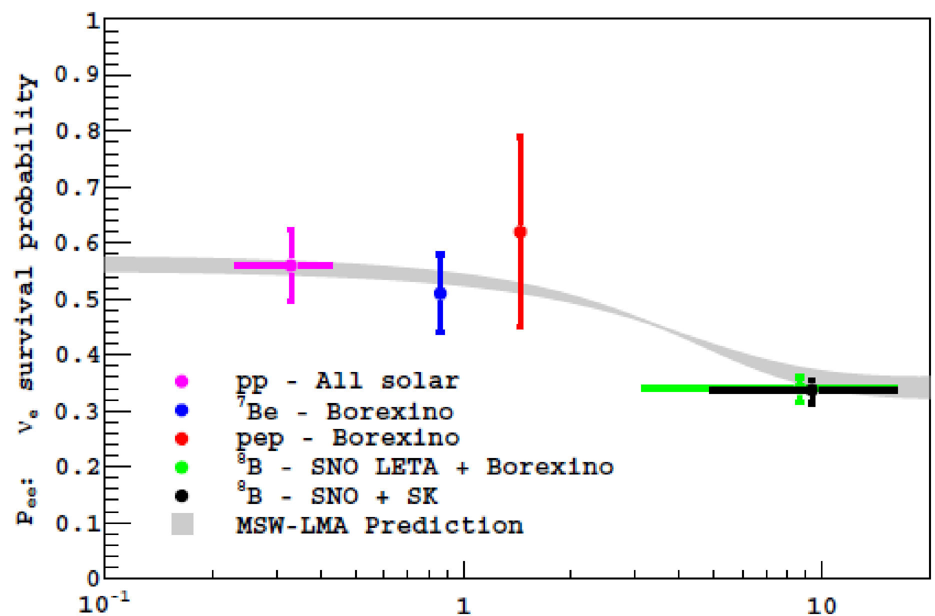
Gonzalez-Garcia, Maltoni, Salvado

arXiv:1001.4524v4 [hep-ph] 16 Jun 2011









arXiv:1110.3230v1 [hep-ex]

Future Solar Neutrino Experiments (Beyond those already in operation)

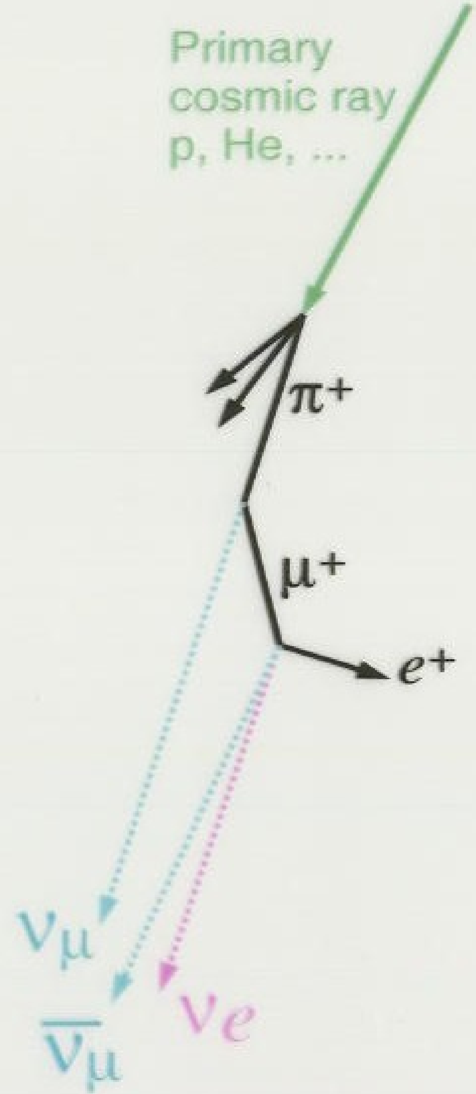
pep/CNO	Medium	Status
SNO+	780 kg LAB Liq scintillator	Construction, start 2013
Kamland-2	780 lb Liq Scintillator	Following KamLAND-Zen

For pp, ^{7}Be neutrinos, measuring CC plus ES could extract electron and total neutrino fluxes

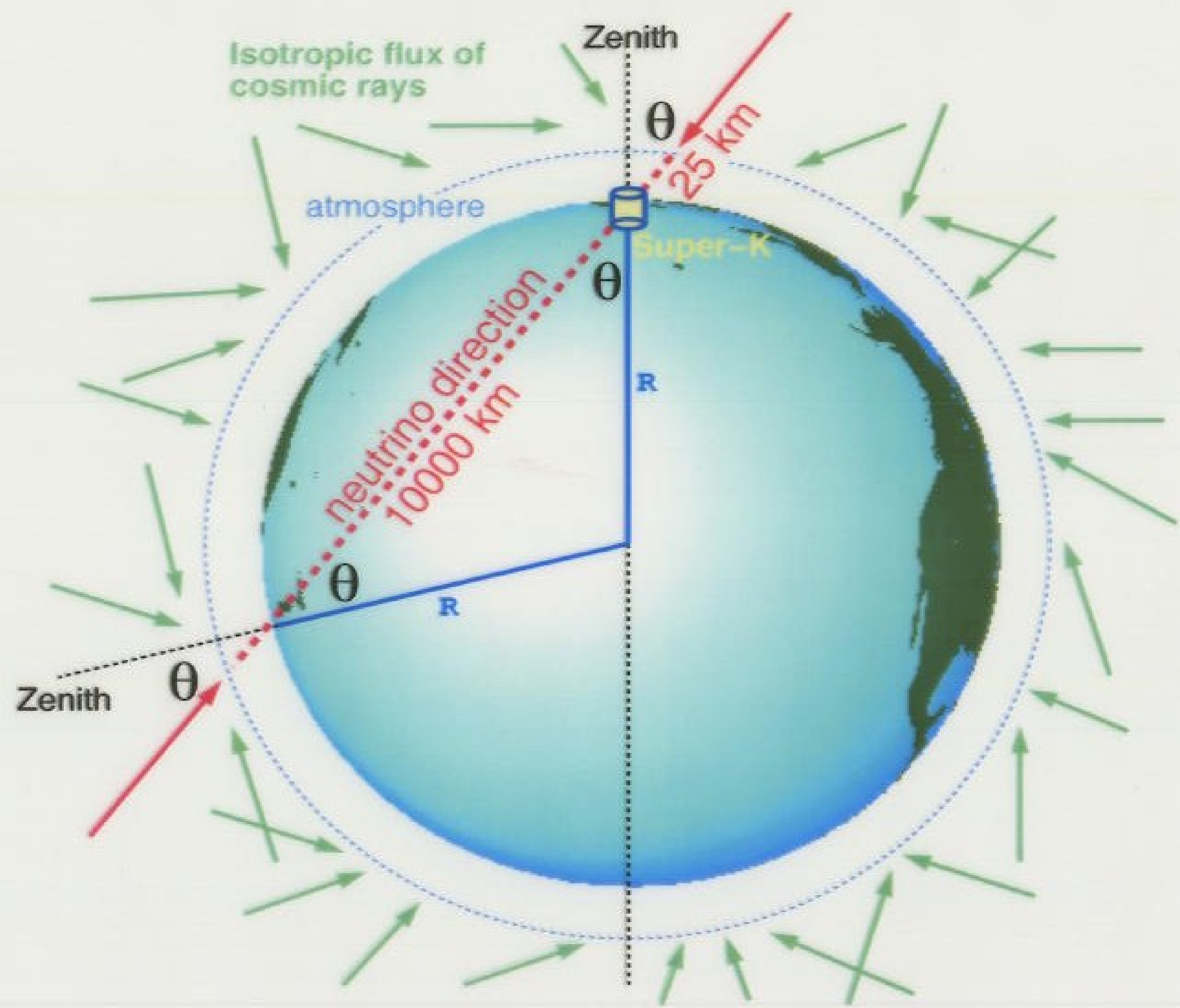
pp via ES		
XMASS	20 tons Liq Xe	835 kg since 2010 for $\beta\beta$
CLEAN	50 tons Liq Ne	MiniClean (500 kg) start 2013
P, ^{7}Be via CC		
LENS	10 tons ^{115}In	μLENS under development
MOON	3 tons ^{100}Mo	R&D in progress
IPNOS	^{115}In	R&D in progress
MEGAPROJECTS	Threshold defines: ^{8}B + ?	
HyperK, MEMPHYS	Megaton Water Cerenkov	
LBNE, GLACIER	50 to 100 kTon Liquid Ar	
LENA	50 kTon Liq Scintillator	

From Art McDonald's talk at Nu2012

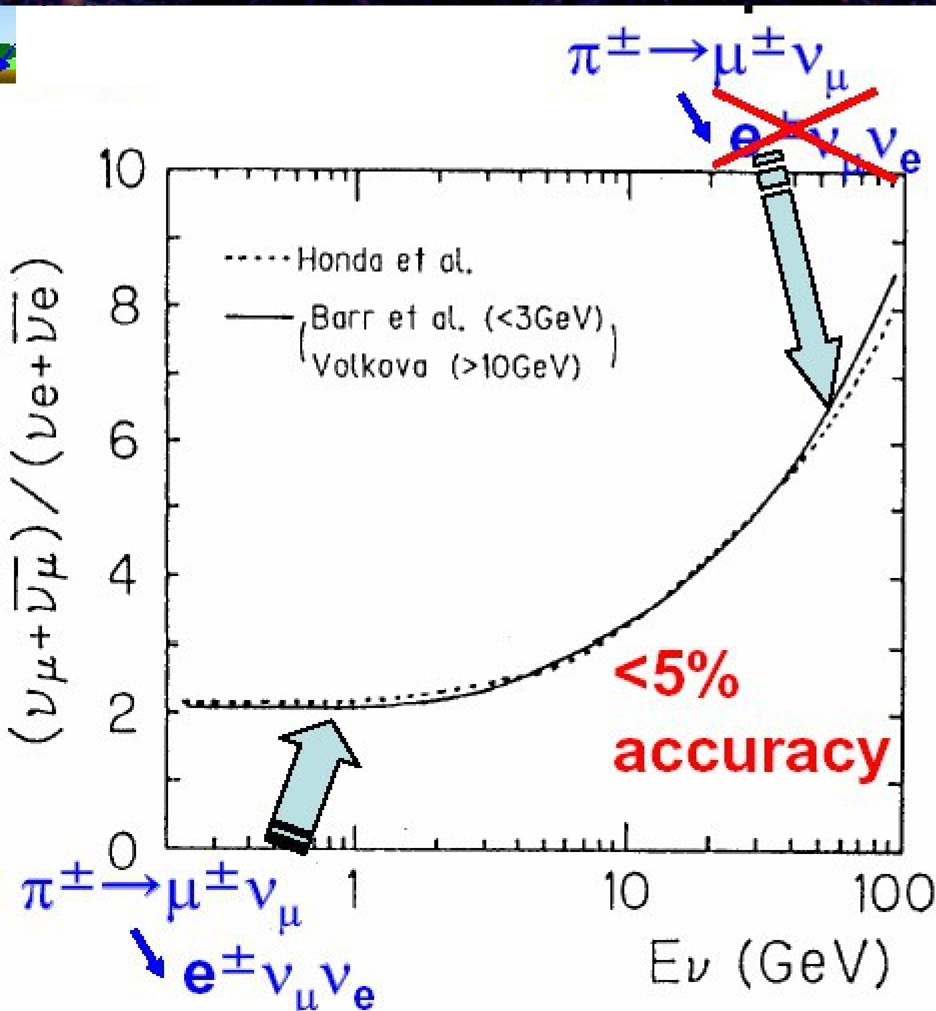
ATMOSPHERIC NEUTRINOS

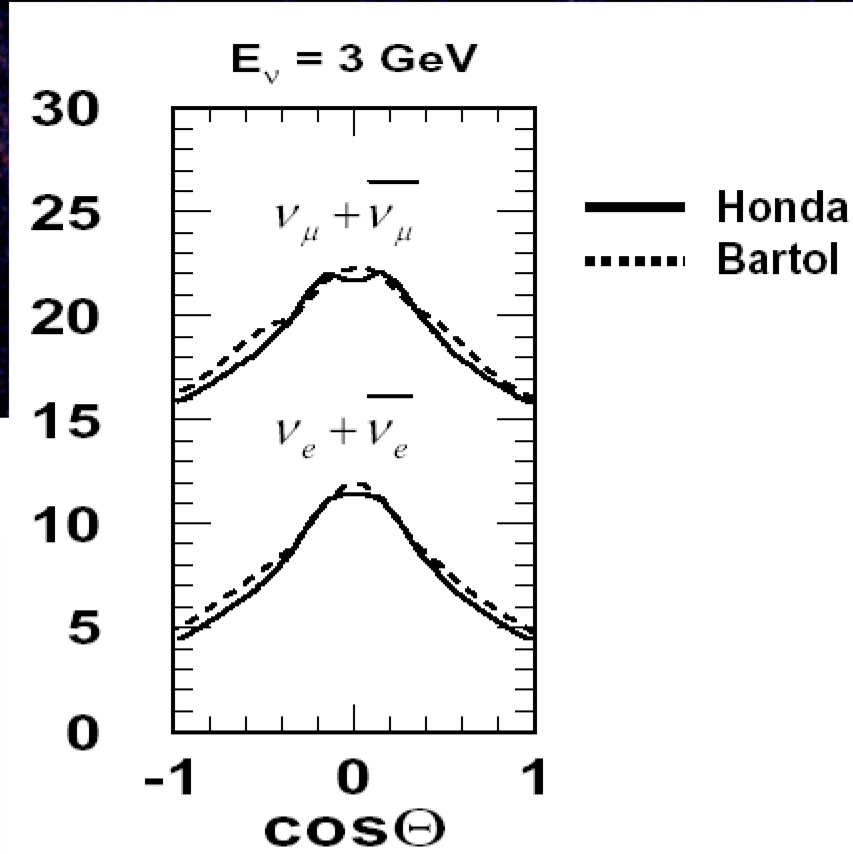


Ratio of $\nu_\mu/\nu_e \sim 2$
(for E_ν < few GeV)



Up–Down Symmetric Flux
(for E_ν > few GeV)

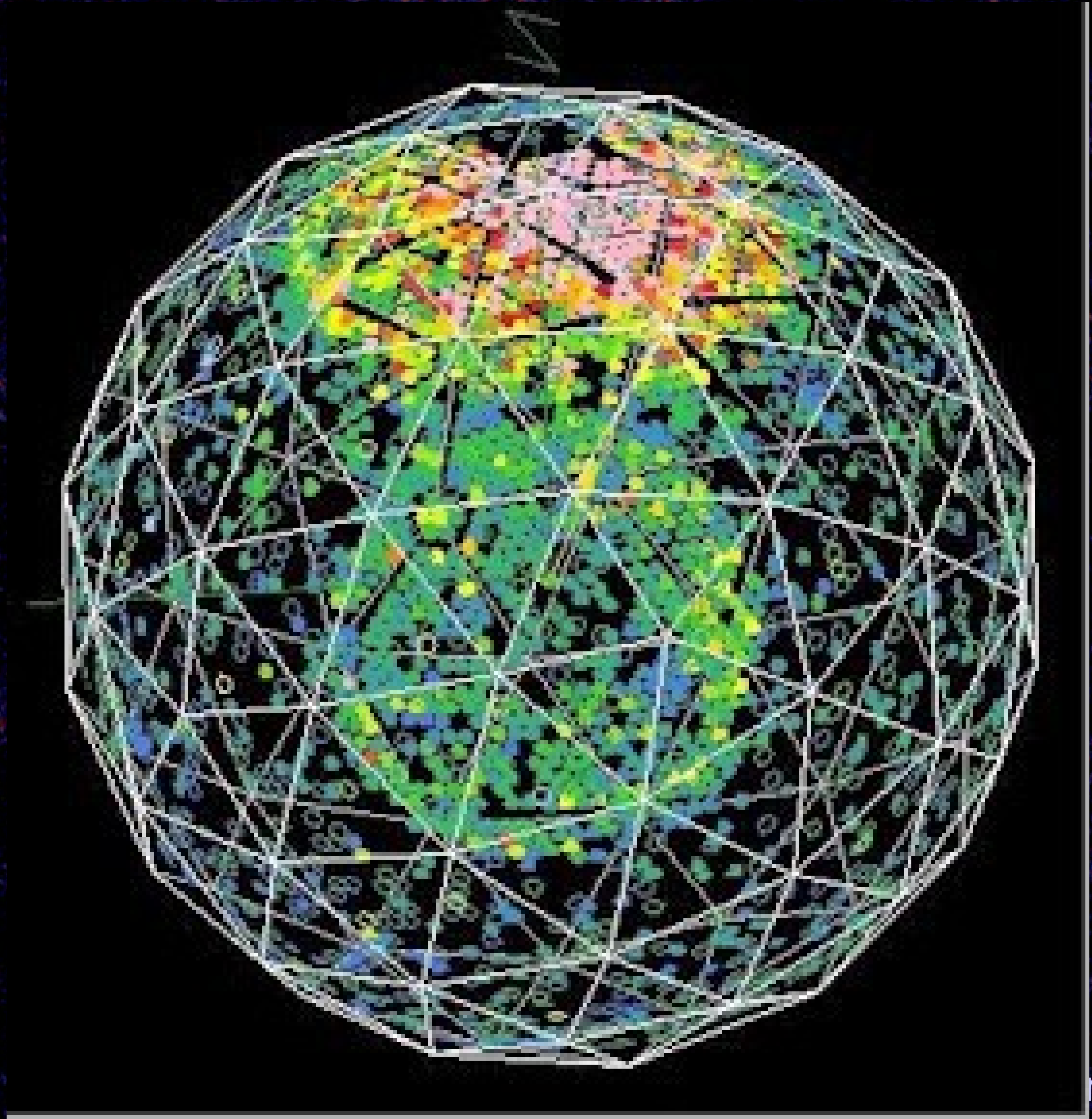




up-down symmetric for both ν_μ and ν_e (above a few GeV).

Plots from Y. Suzuki

Background to Proton Decay Experiments



1986 - The beginning of the "Too few nu mu" problem

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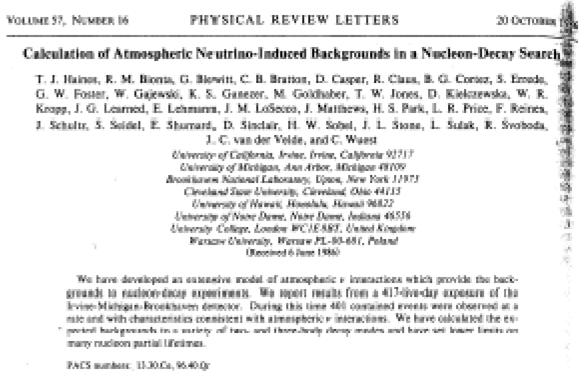
well not only globally but also in small regions. The simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.

decay. Also, there observed in any c nucleon-decay signa lifetime range from der of 10^{32} years. W is now limited by mospheric ν flux a tions. To reduce th quire specific exper understanding of lo precise atmospheric

IMB-1

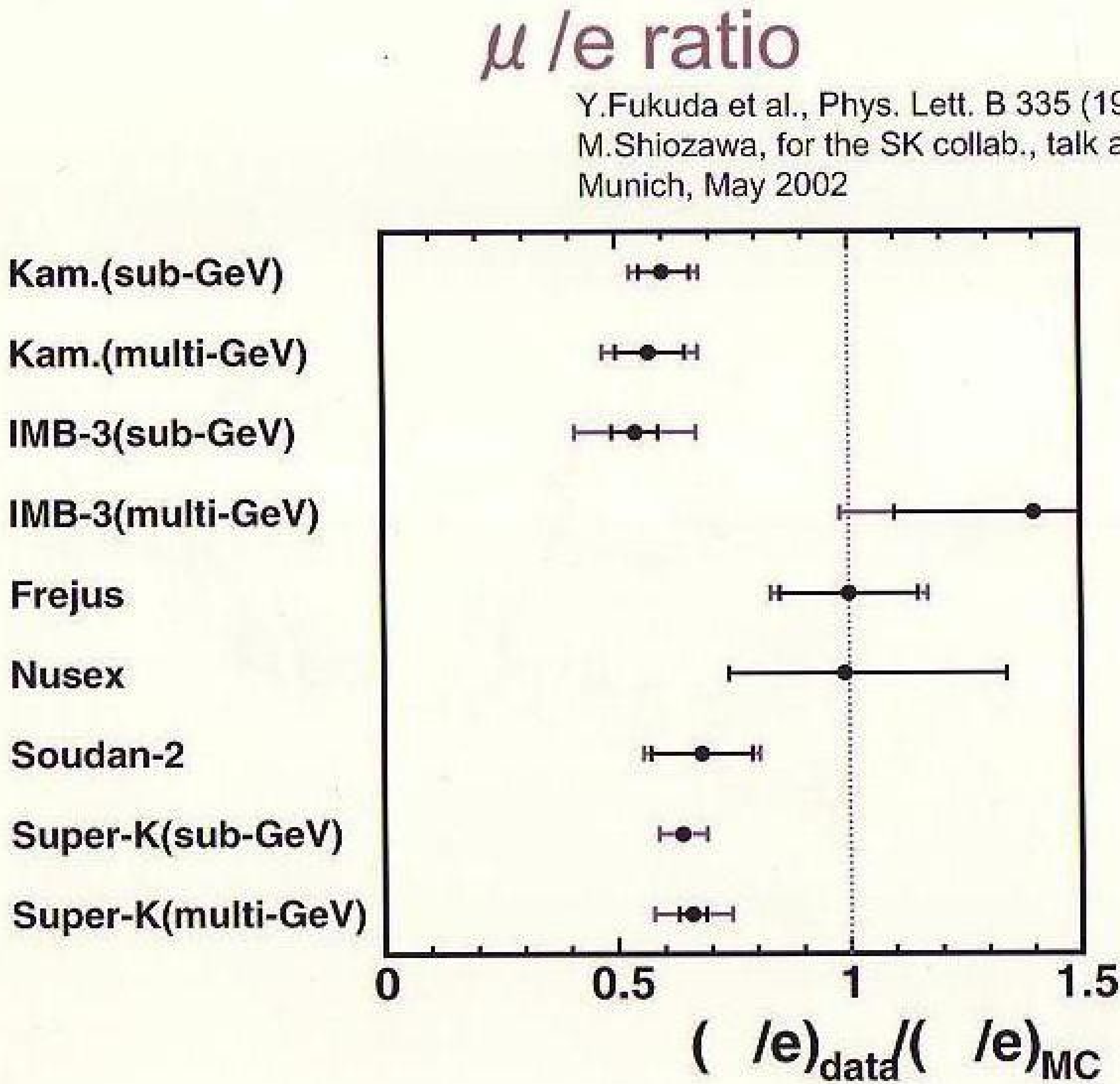
1986



$\nu_\mu n \rightarrow \mu^- p$; $\nu_\mu p \rightarrow \mu^+ n$; $\mu \rightarrow e\nu\nu$ decay

$\nu_e n \rightarrow \mu^- p$; $\nu_e p \rightarrow e^+ n$; no decay

Also seen by Kamiokande



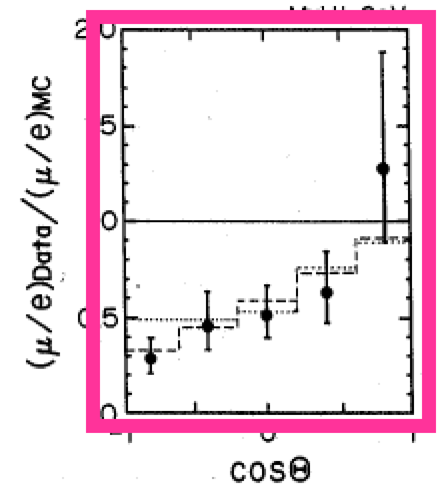
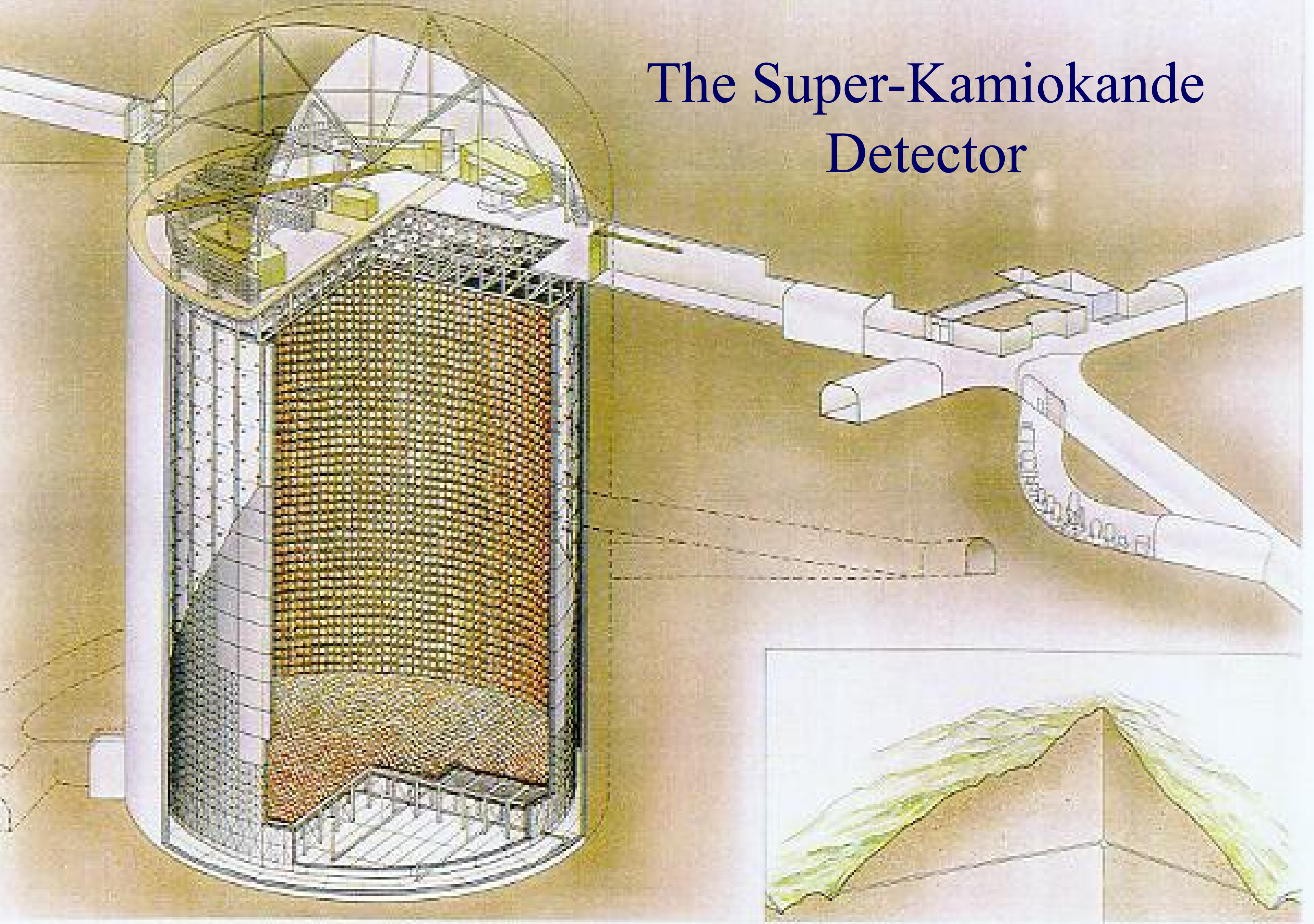
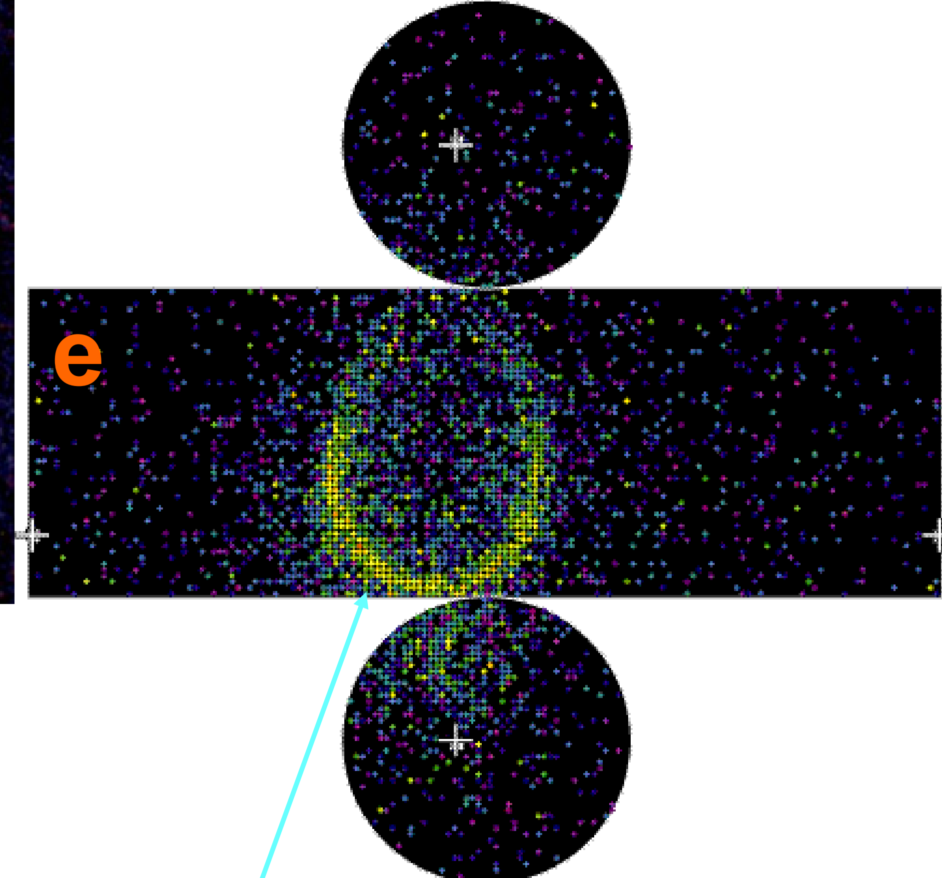
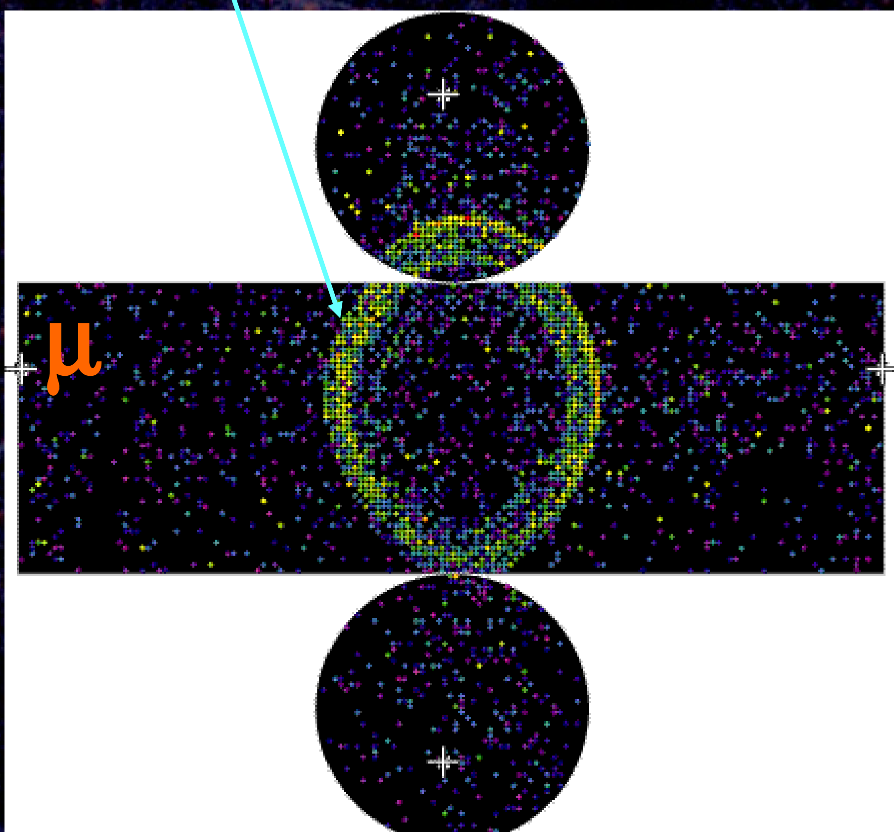


Fig. 4. Zenith-angle distribution of $(\mu/e)_{data}/(\mu/e)_{MC}$, where both the fully-contained and the partially-contained events are included. The circles with error bars show the data. Also shown are the expectations from the MC simulations with neutrino oscillations for parameter sets $(\Delta m^2, \sin^2 2\theta)$ corresponding to the best-fit values to the multi-GeV data for $\nu_\mu \leftrightarrow \nu_e$ $((1.8\times10^{-2}$ eV^2, 1.0), dashes) and $\nu_\mu \leftrightarrow \nu_\tau$ $((1.6\times10^{-2}$ eV^2, 1.0), dots) oscillations.

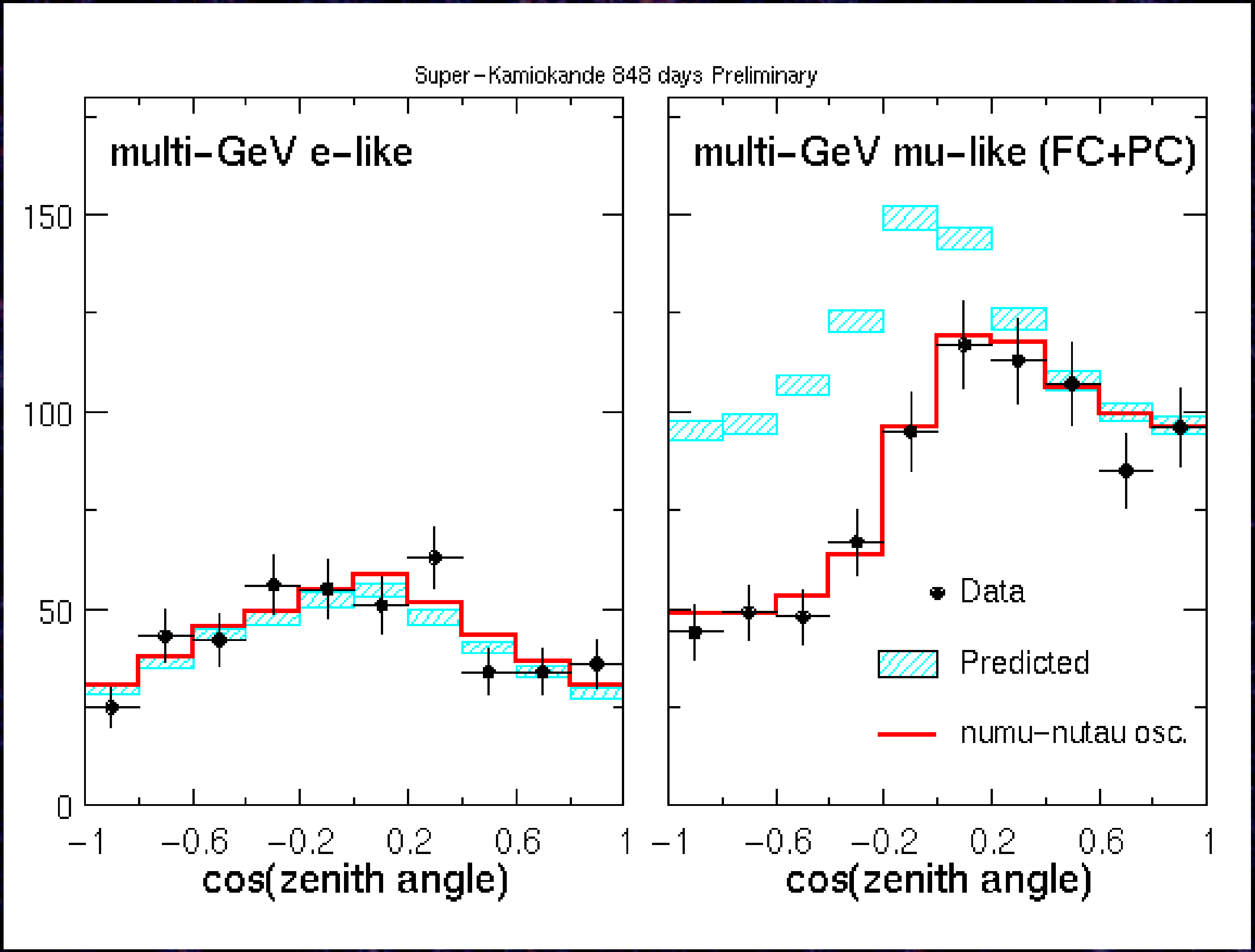
The Super-Kamiokande Detector

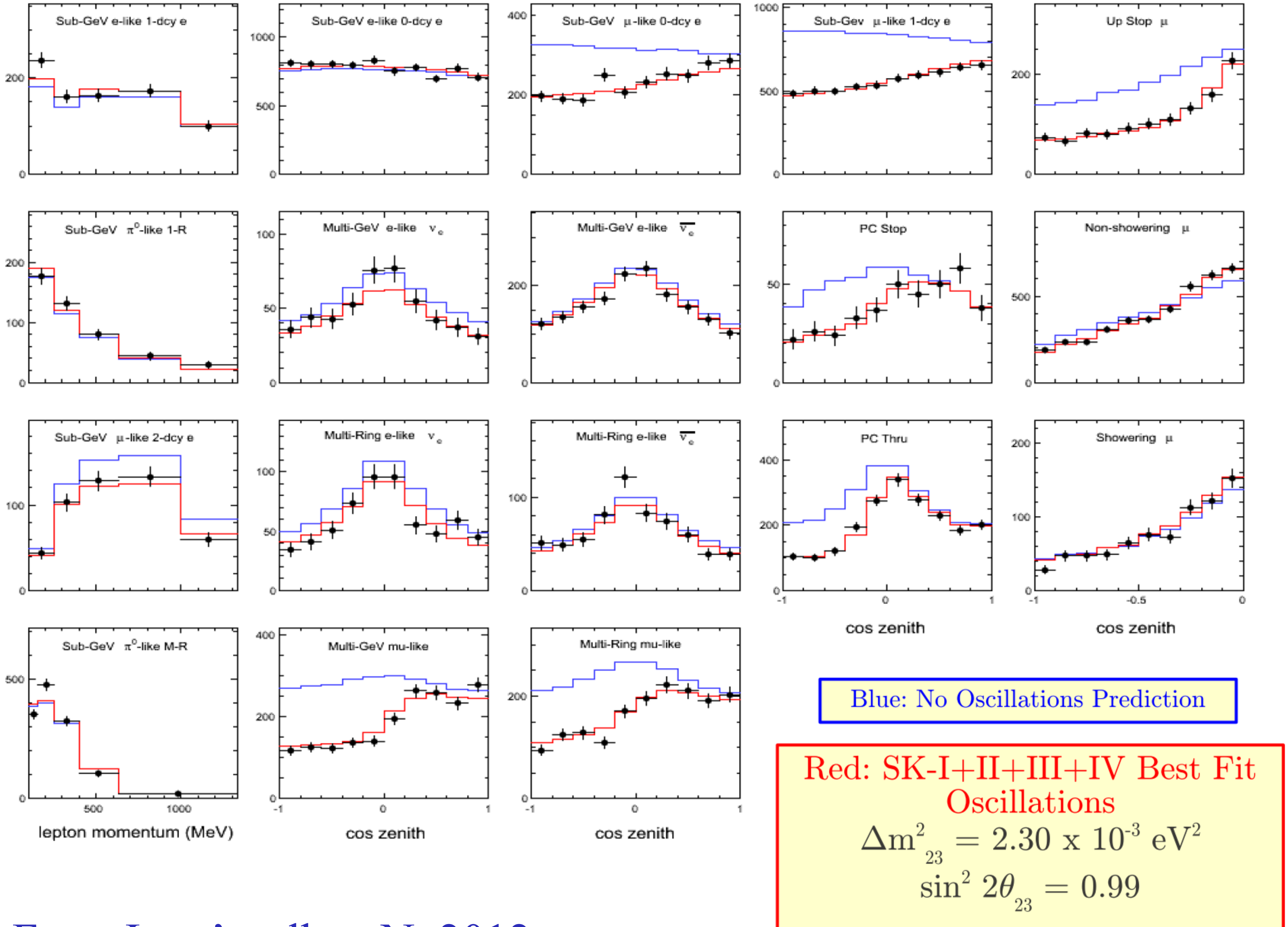



e


μ

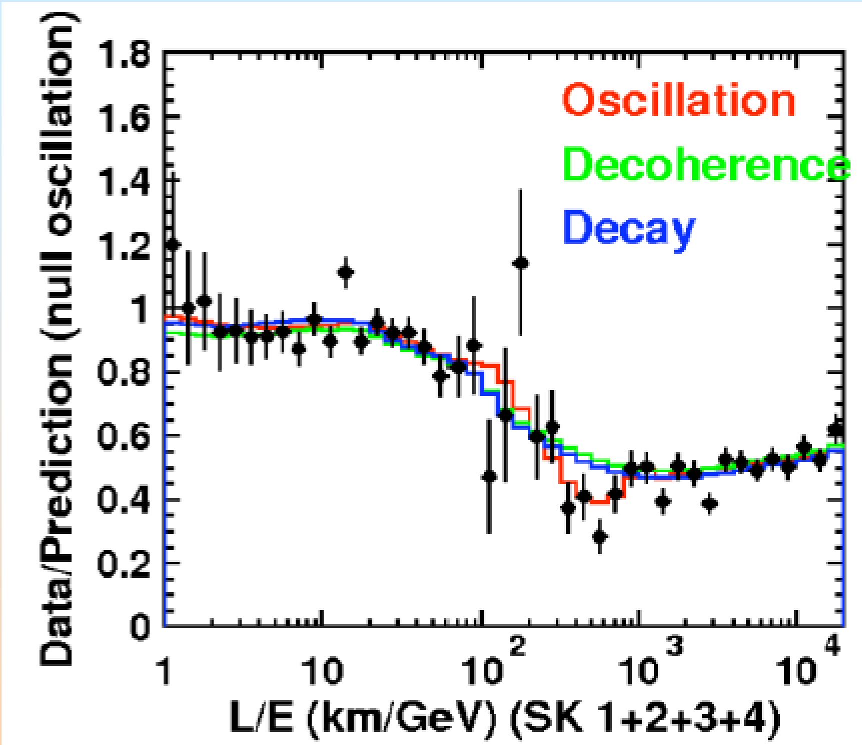
SK atmospheric ν data as a function of zenith angle

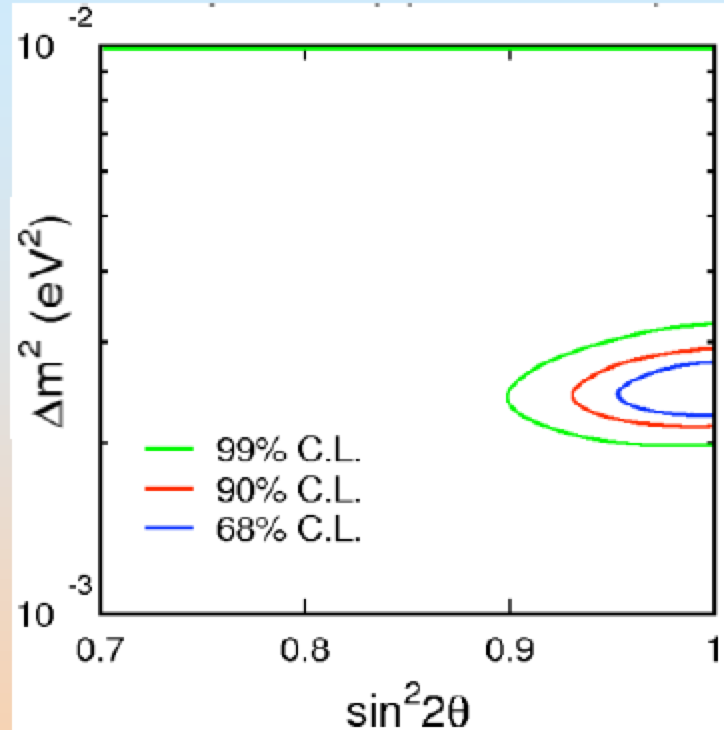




From Itow's talk at Nu2012

2 flavor L/E analysis update (SK1-4)





Neutrino decay

$$\chi^2_{\min} = 187.8/169(4.0\sigma)$$

Neutrino decoherence

$$\chi^2_{\min} = 194.8/169(4.8\sigma)$$

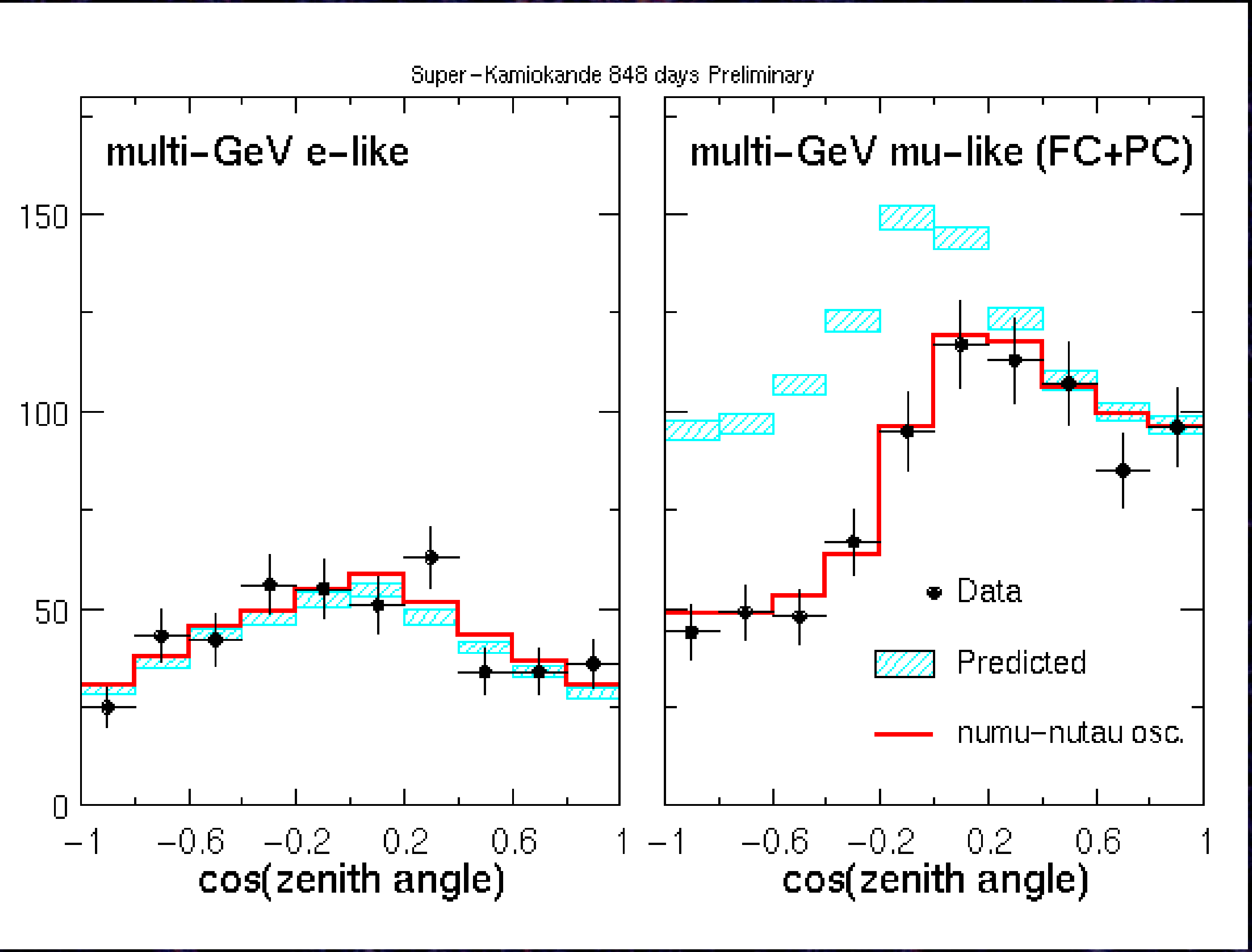
2 ν oscillation result

$$\sin^2 2\theta = 1.00(\geq 0.93(90\%CL))$$

$$\Delta m^2 = (2.5^{+0.27}_{-0.27}) \times 10^{-3} eV^2$$

$$\chi^2_{\min} = 171.7/169$$

Could you do this with a terrestrial experiment?



This year is the 50th anniversary!

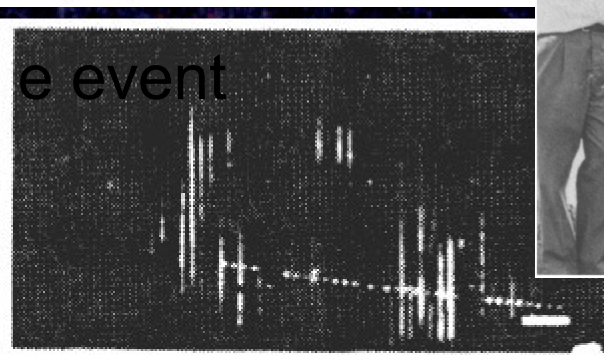
VOLUME 9, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1962

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)



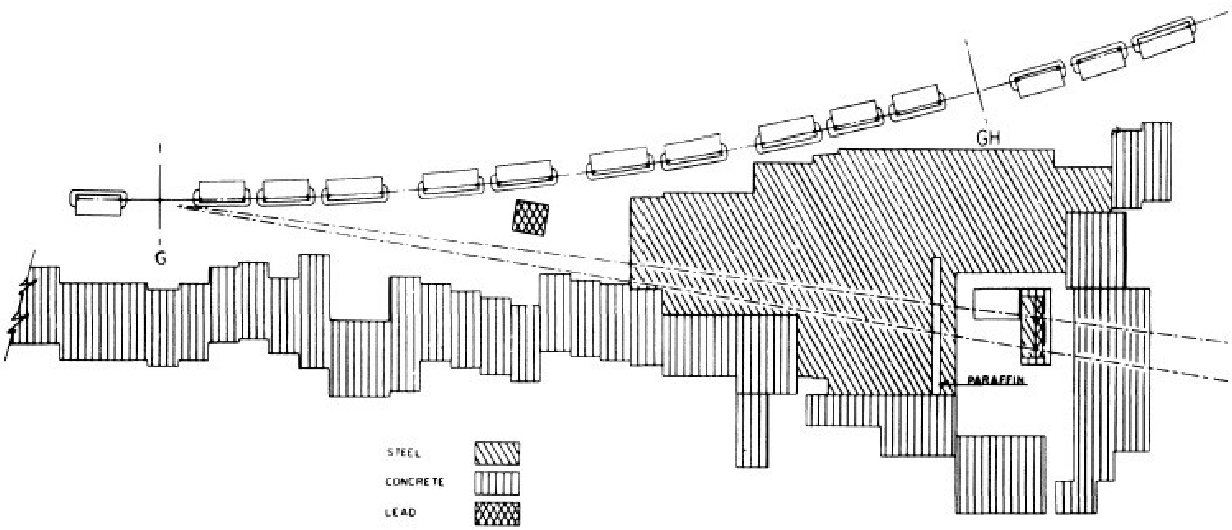


FIG. 1. Plan view of AGS neutrino experiment.

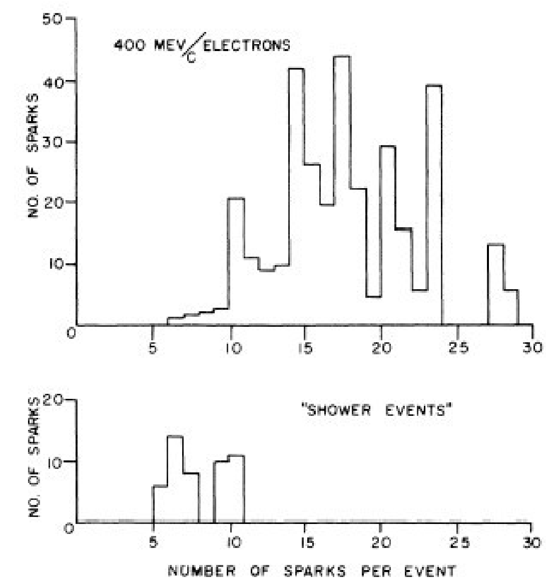
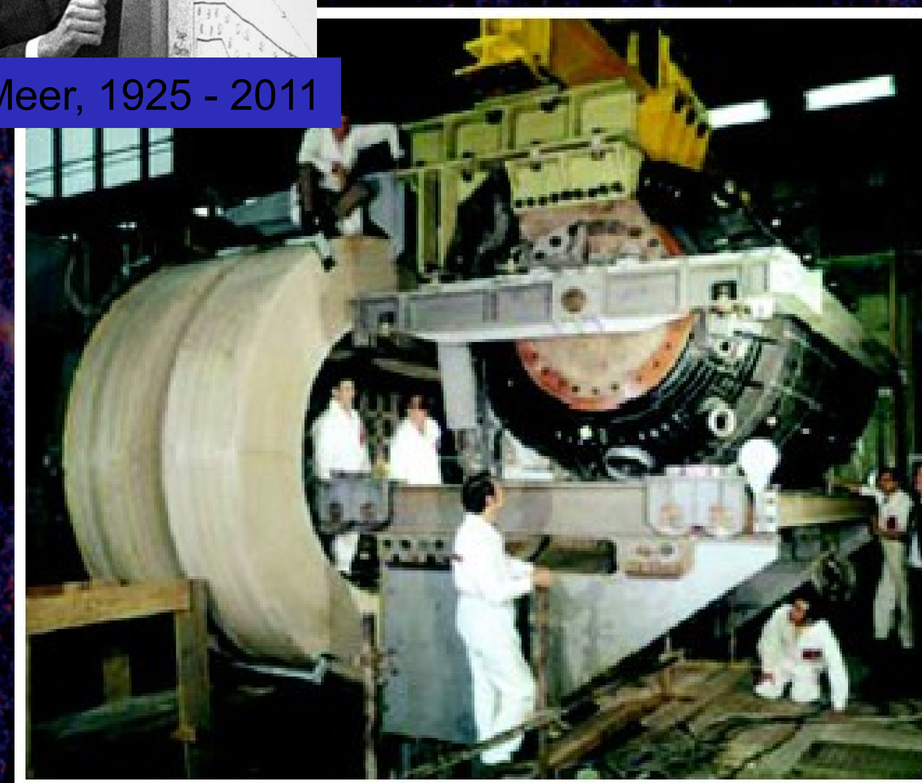


FIG. 9. Spark distribution for 400-MeV/c electrons normalized to expected number of showers. Also shown are the "shower" events.

The Discovery of Neutral Currents

Simon van der Meer, 1925 - 2011



Why are we spending time talking about ancient experiments?

It's fun…

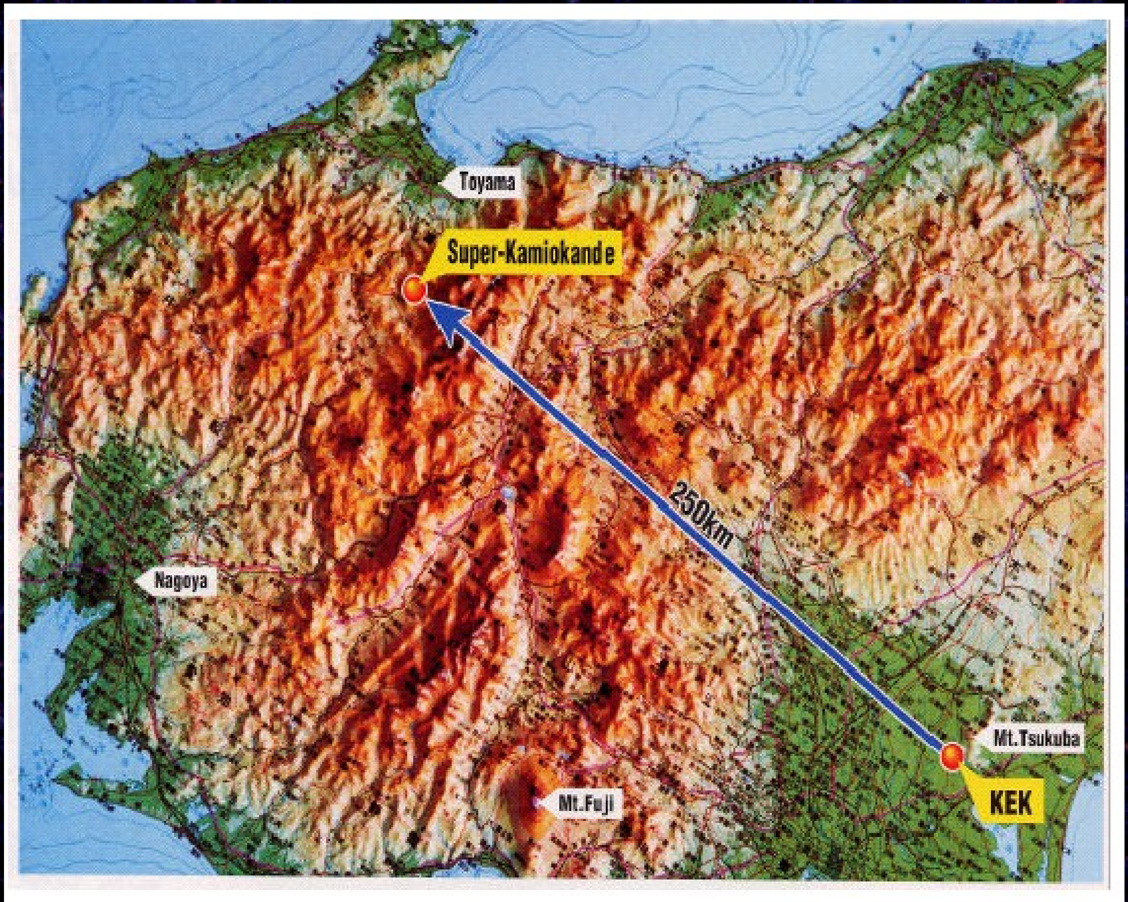
This is a school...

I would like you to note as I go through all the amazing, expensive, flashy new experiments that they are almost all just elaborations of these early ideas.

This is a beautiful demonstration of the most important single thing my advisor ever taught me:

"Three months in the laboratory will save you three hours in the library".

The first long baseline experiment – K2K



- ν_μ (99%) beam
- $<E_\nu> \sim$ **1.3GeV**
- **Near detector**

  @300m
- **Far detector**:

  Super Kamiokande(SK)

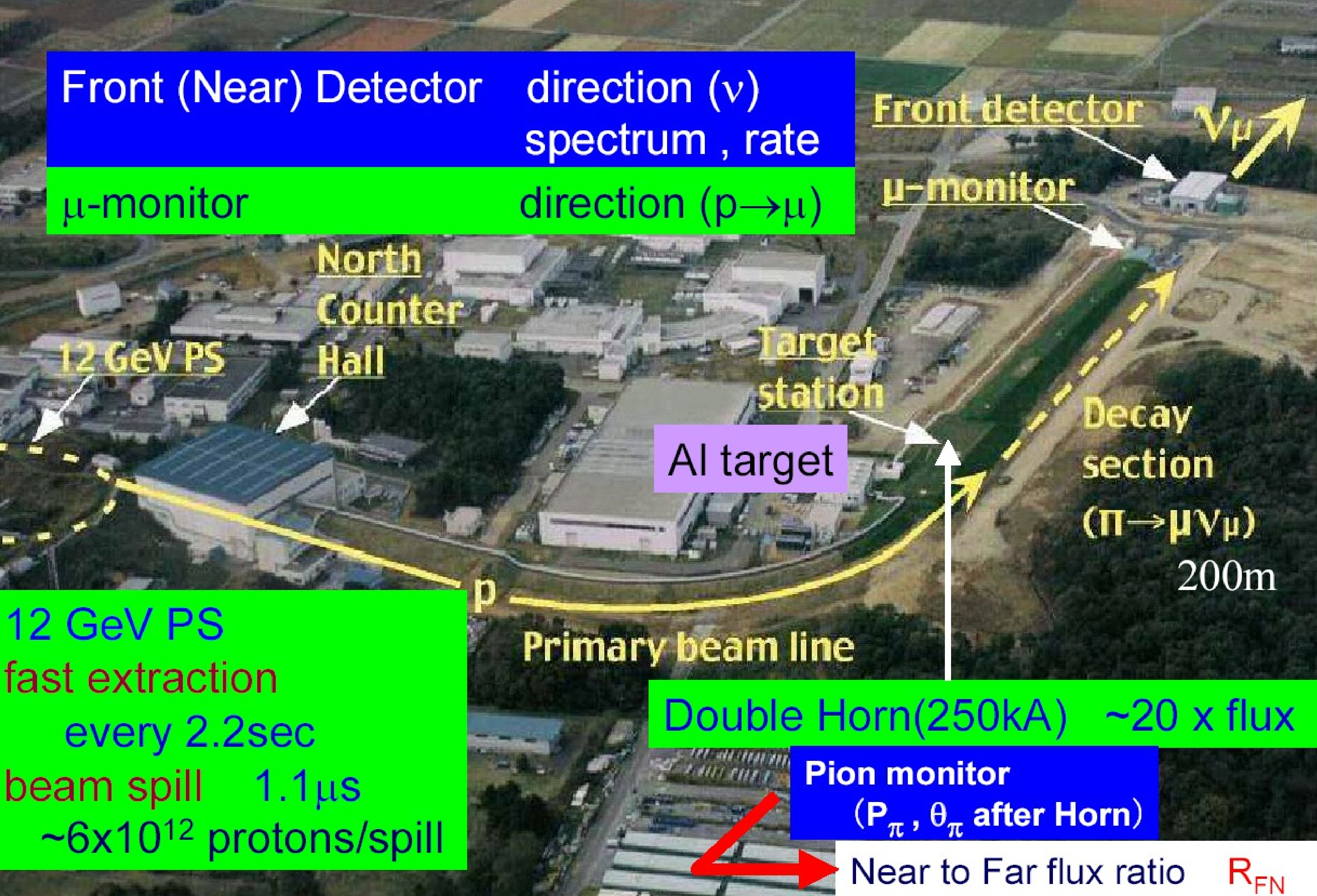
  @**250km**
- Sensitive for

  $\Delta m^2 > 2x10^{-3}$ eV^2

Neutrino beamline

Front (Near) Detector direction (ν)
spectrum , rate

μ-monitor direction ($p \rightarrow \mu$)



12 GeV PS
fast extraction
every 2.2sec
beam spill 1.1μs
~6×10^{12} protons/spill

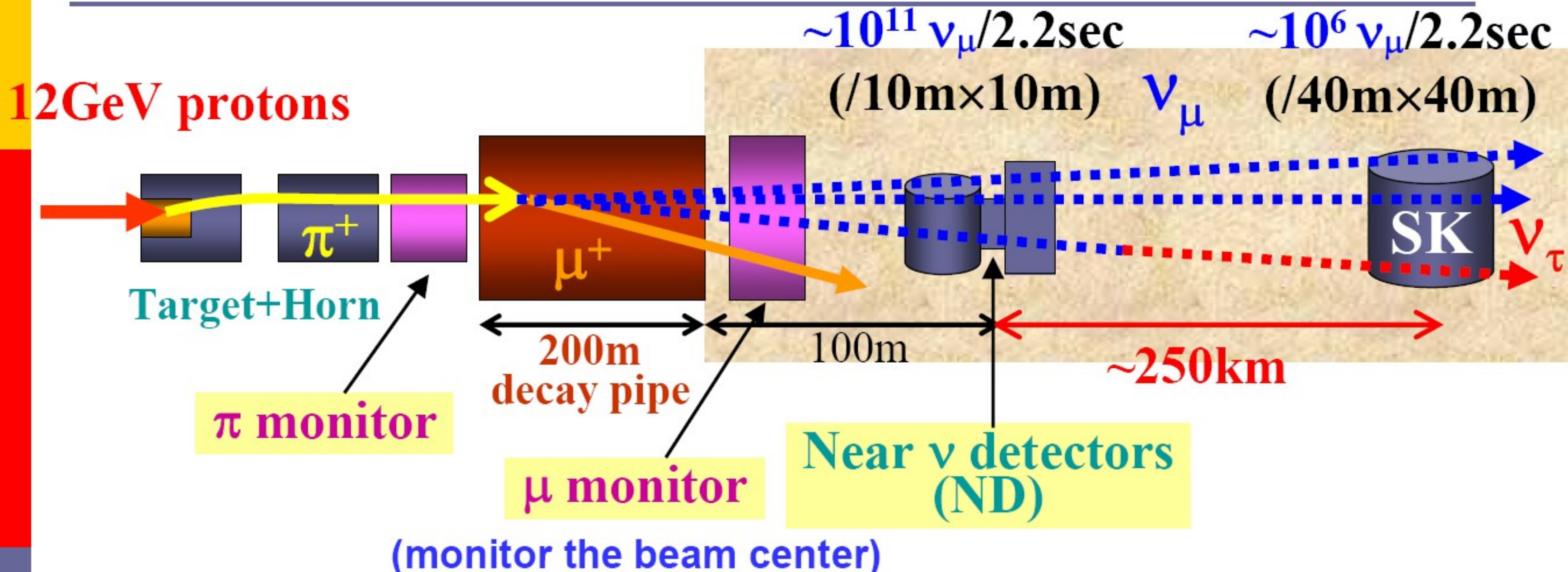
Double Horn(250kA) ~20 x flux

Pion monitor
(P_π , θ_π after Horn)

Near to Far flux ratio R_{FN}

2. K2K experiment

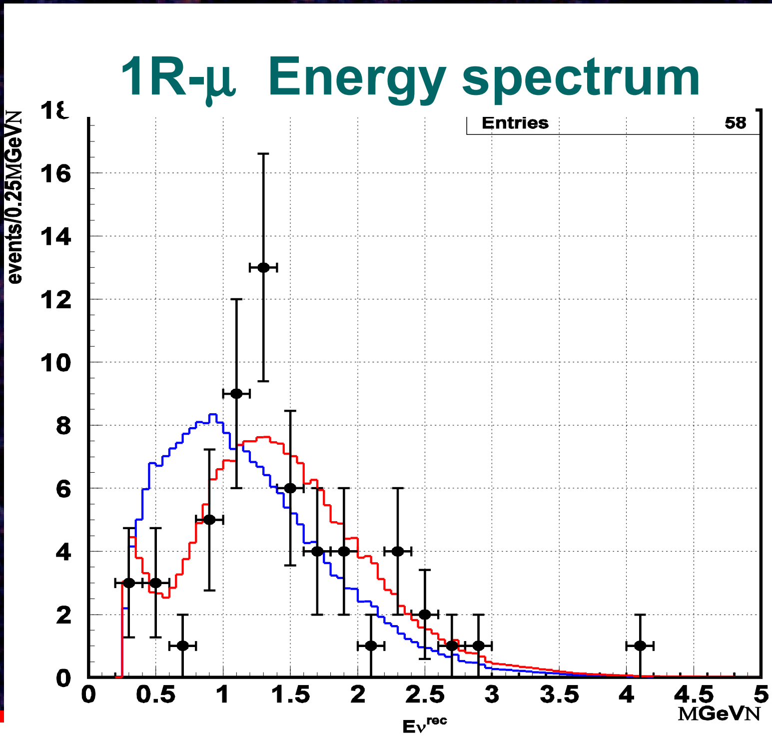
~1 event/2days



Signal of ν oscillation at K2K
- Reduction of ν_μ events
- Distortion of ν_μ energy spectrum

4

Final K2K Statistics



	Nskob s	Nskpr ed
All	112	155.9
1 ring	67	99.0
μ-like	58	90.8
e-like	9	8.2
multi-ring	45	56.8

Oscillation – disappearance – two flavors analysis

sin22θ = 1.19 ± 0.23 Δm2 = (2.55 ± 0.40)x10-3eV2

1.88×10-3 ≤ Δm2 ≤ 3.48×10-3 eV2 (90%CL) for sin22θ=1