Neutrino Physics – Past, Present, and Future

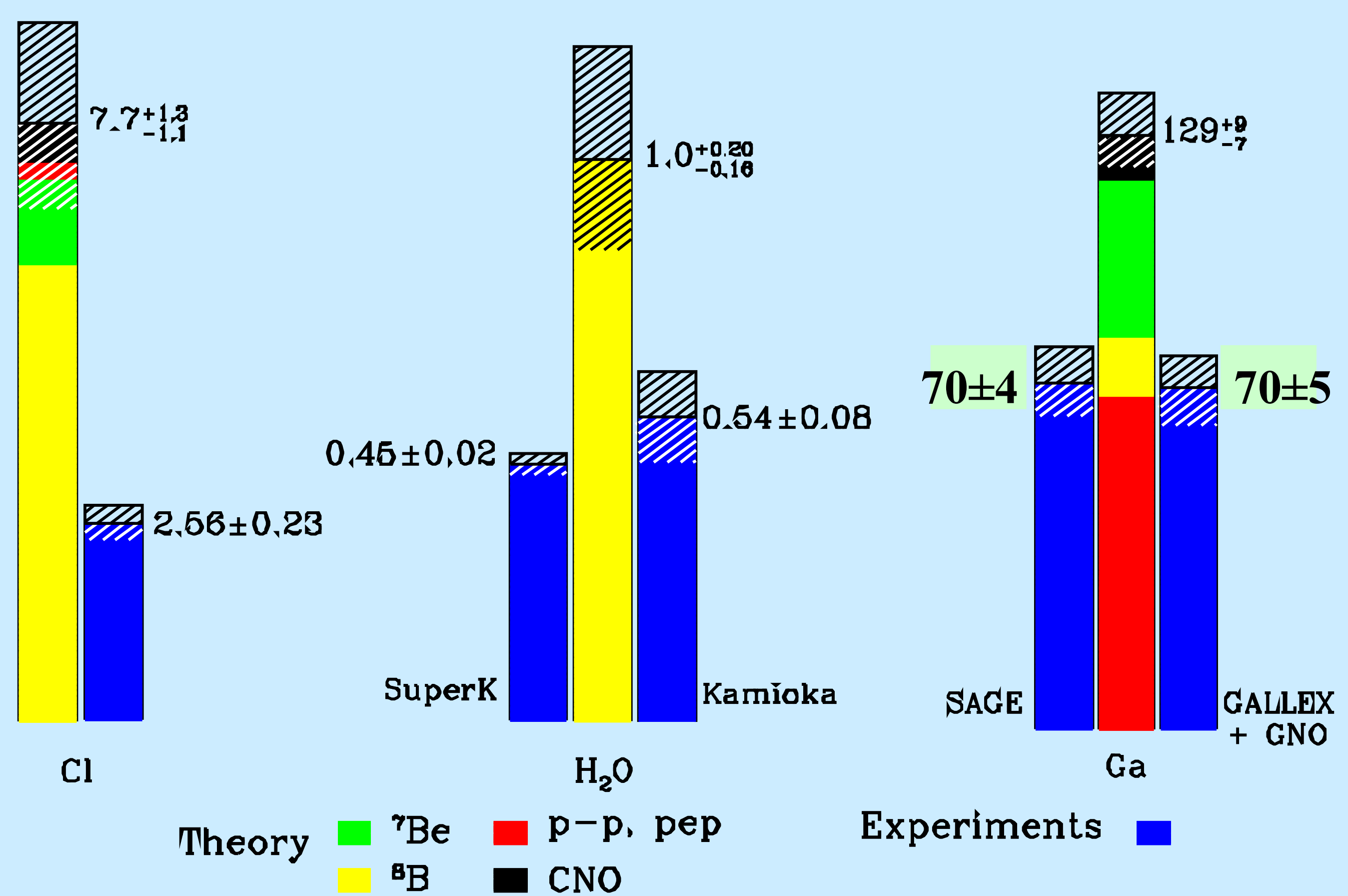
Cracow School
Zakopane
June 20-21, 2007

Dave Wark
Imperial/RAL

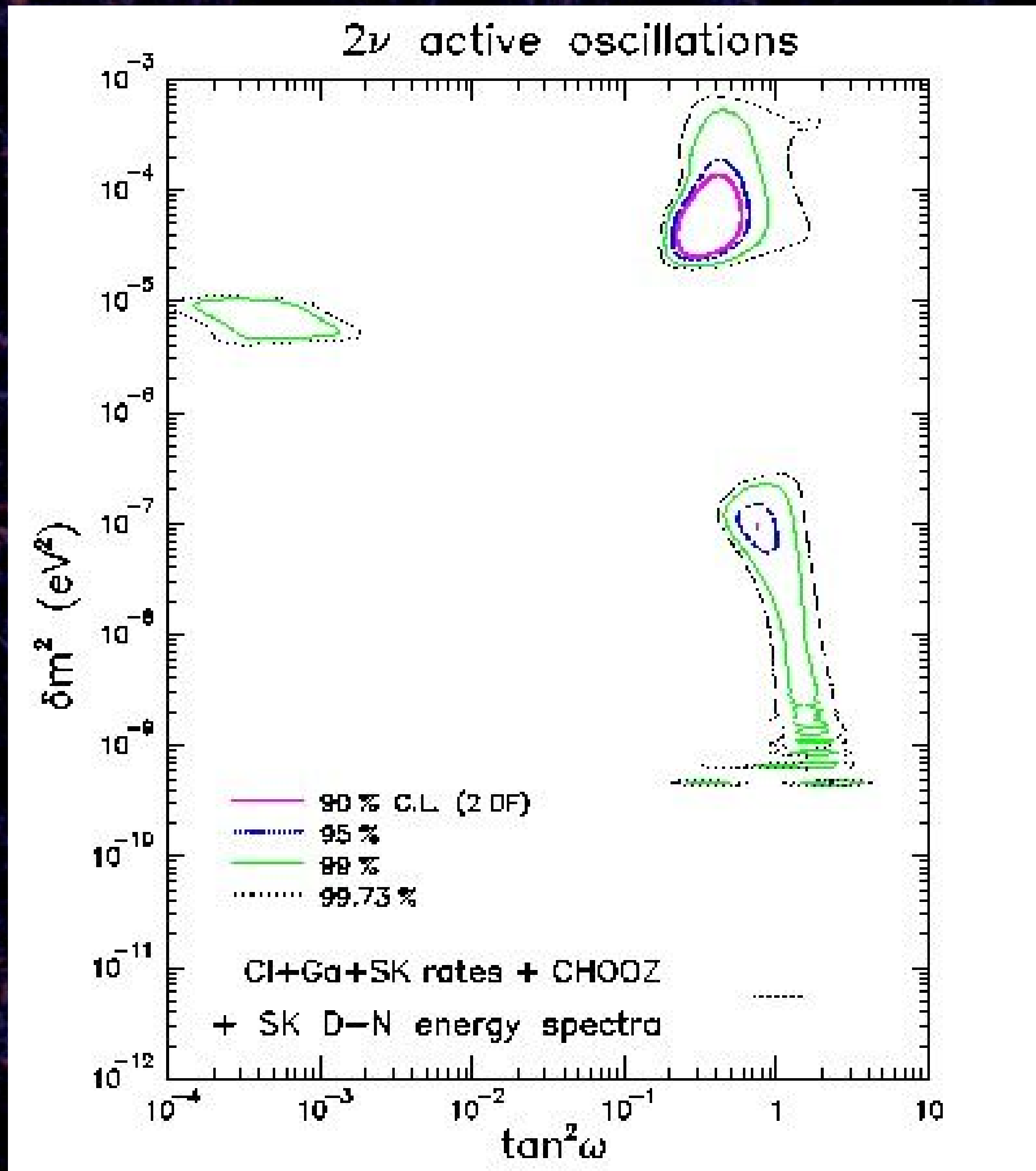
Science & Technology Facilities Council

Imperial College London

Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000



Which left us where?



But no smoking gun for oscillations….

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SNO Collaboration

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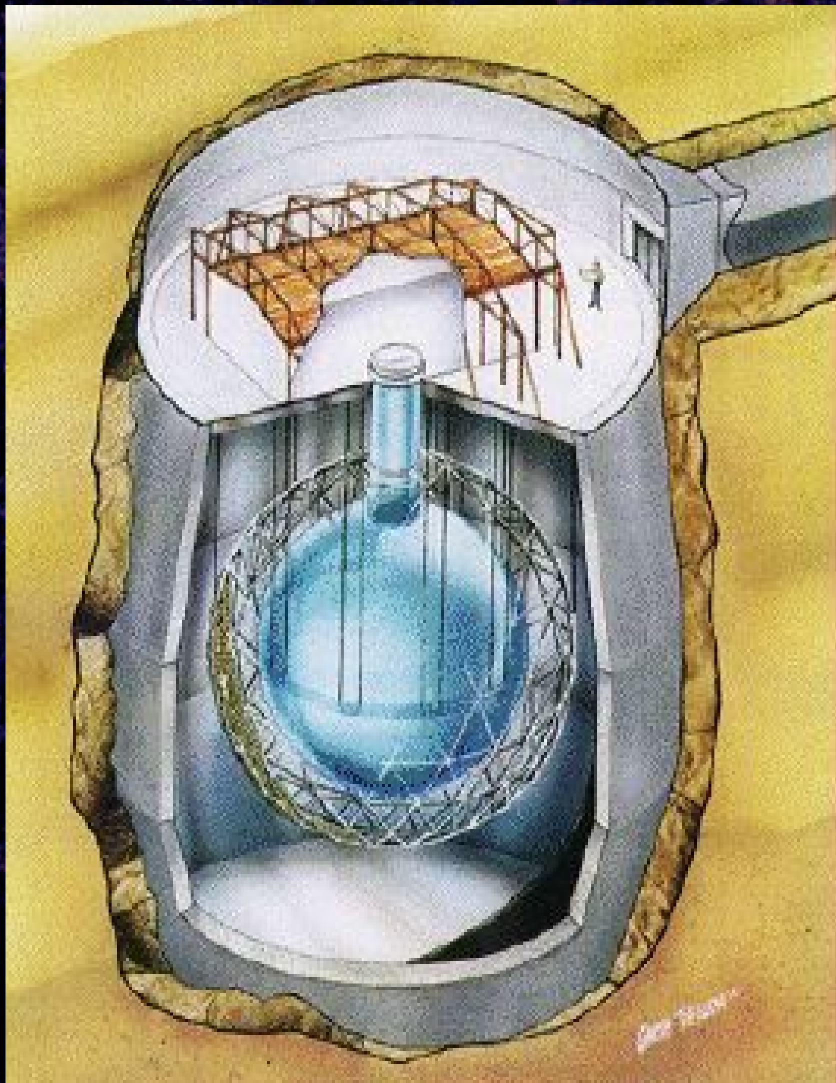
2^{nd} Smoking Gun – SNO



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

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

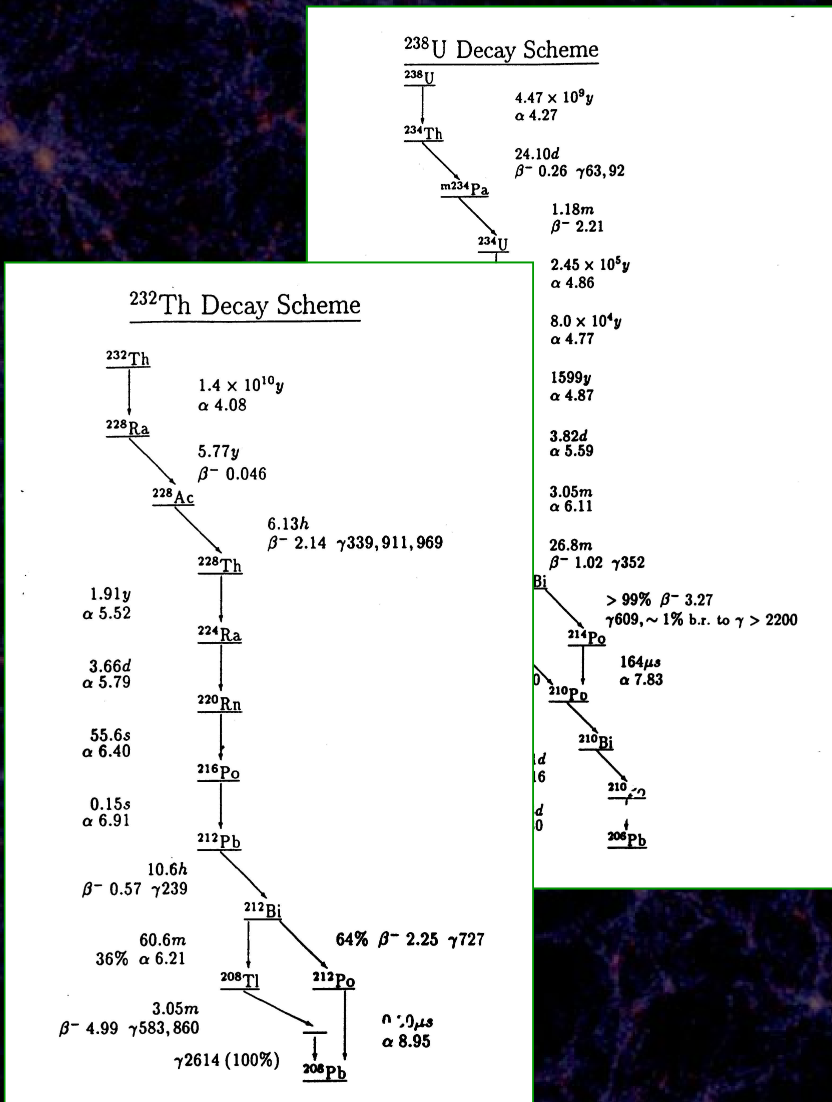
NC $\nu_x + d \rightarrow p + n + \nu_x$

- 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 ν_e, some ν_μ and ν_τ
- 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:

D2O $< 10^{-15}$ gm/gm U/Th

H2O $< 10^{-14}$ gm/gm U/Th

Acrylic $< 10^{-12}$ gm/gm U/Th

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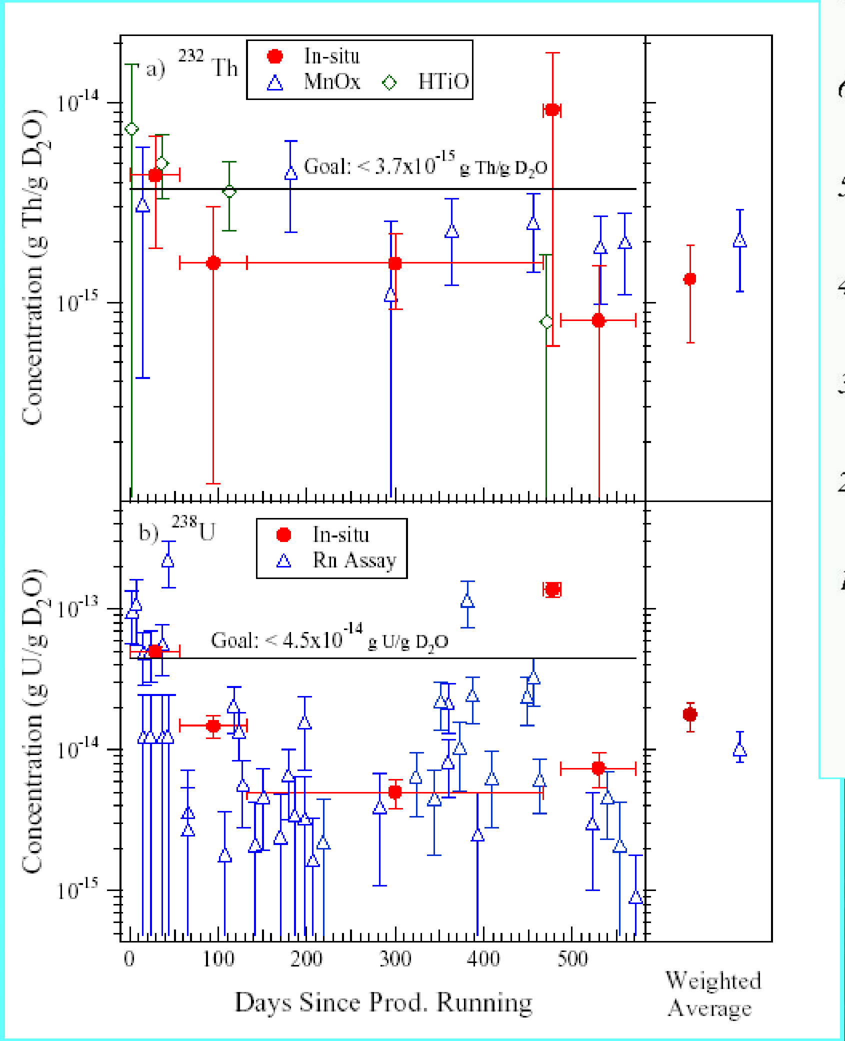
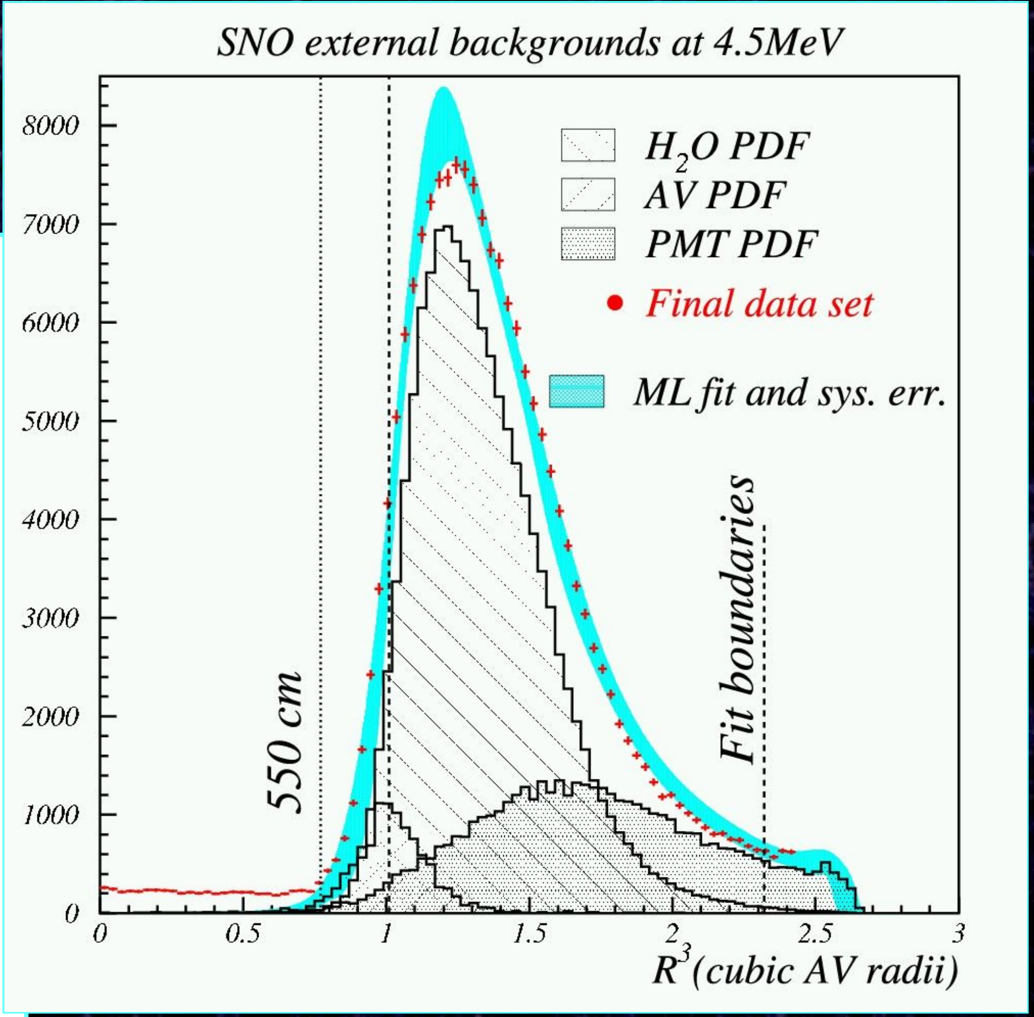
SNO Backgrounds

Internal





External

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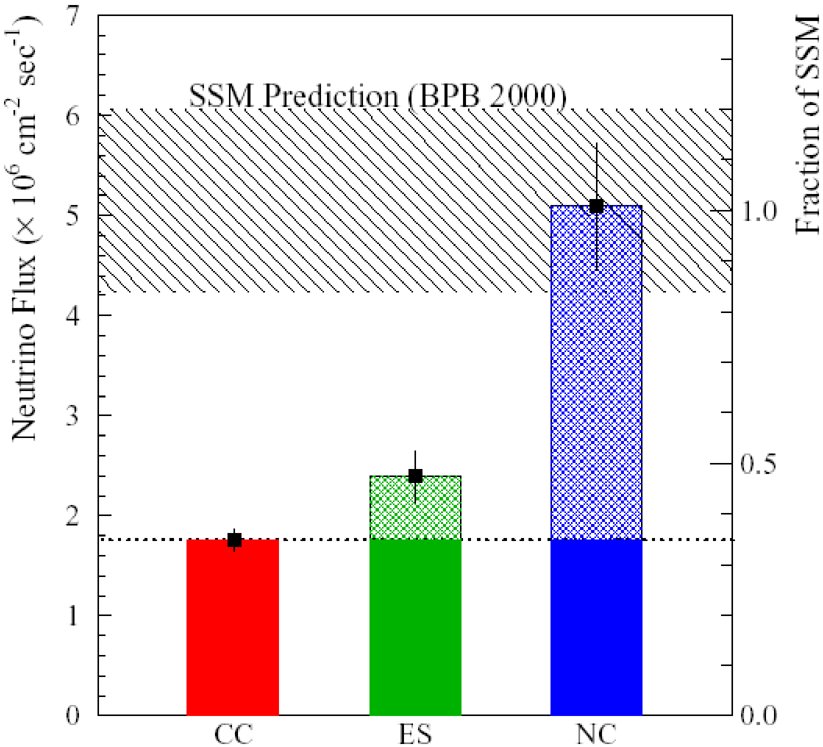
Measured SNO Fluxes



Assuming ^{8}B energy spectrum ...

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

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

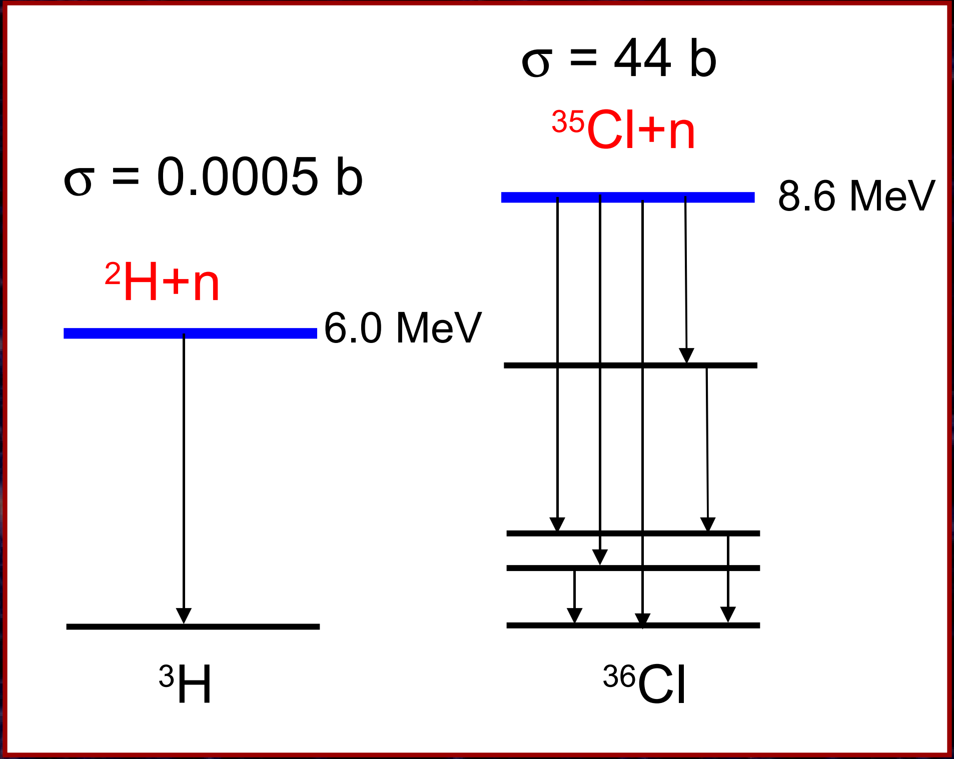
$$\phi_{ES} = 2.39^{+0.24}_{-0.23} \text{ (stat.)} \pm 0.12 \text{ (sys.)}$$

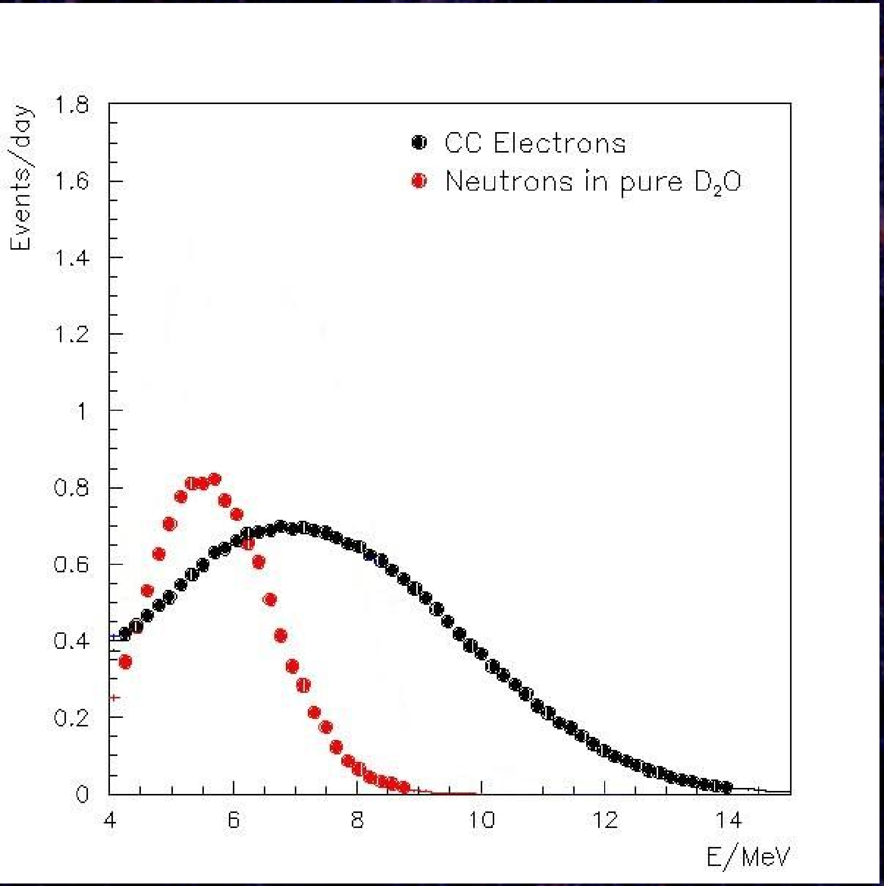
$$\phi_{NC} = 5.09^{+0.44}_{-0.43} \text{ (stat.)}^{+0.46}_{-0.43} \text{ (sys.)}$$

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

NC flux in agreement with SSM prediction!

2 tons of NaCl added to D_2O on June 1, 2001





Blind analysis technique used…

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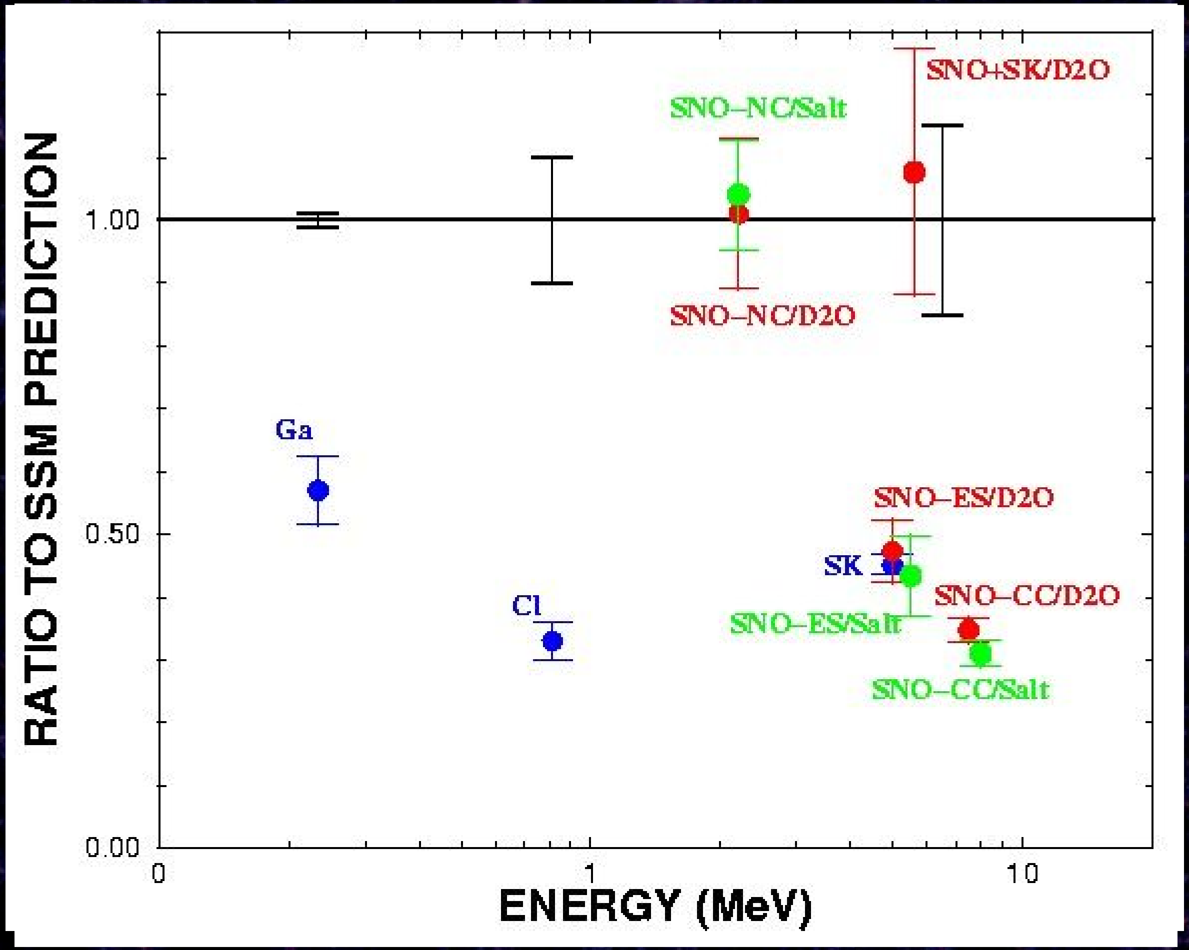
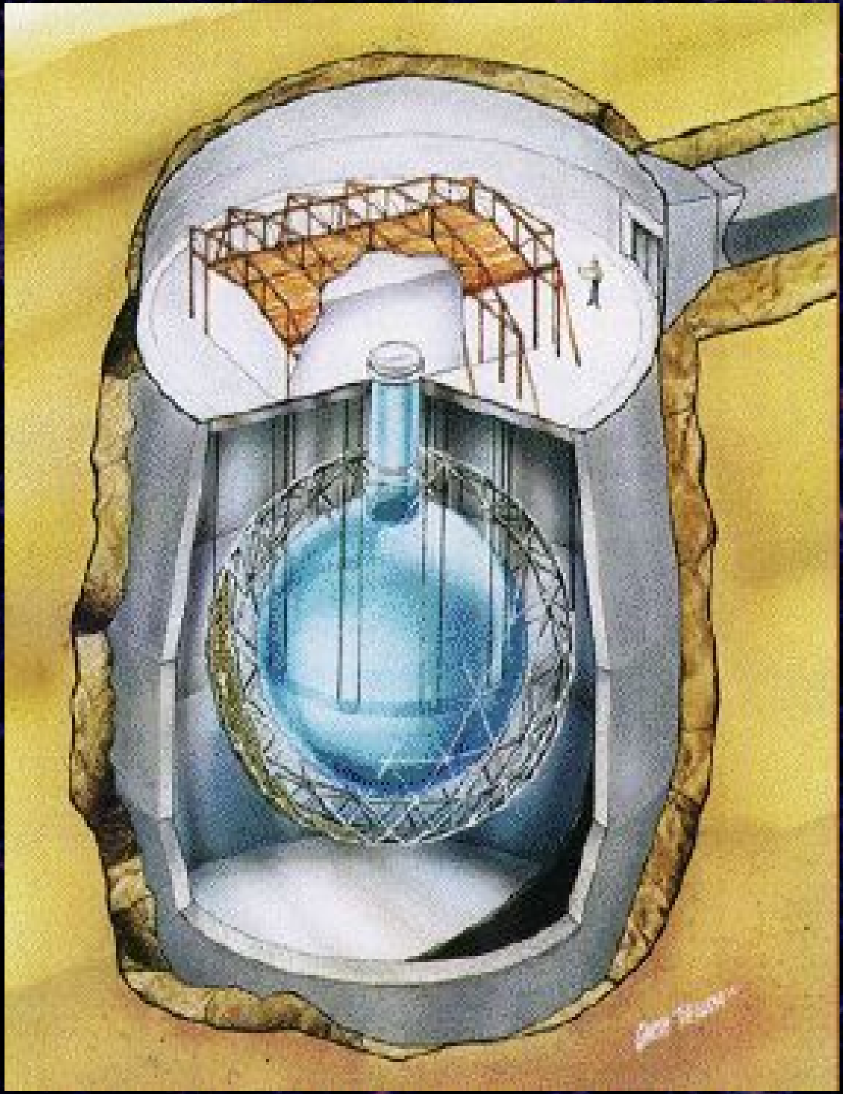
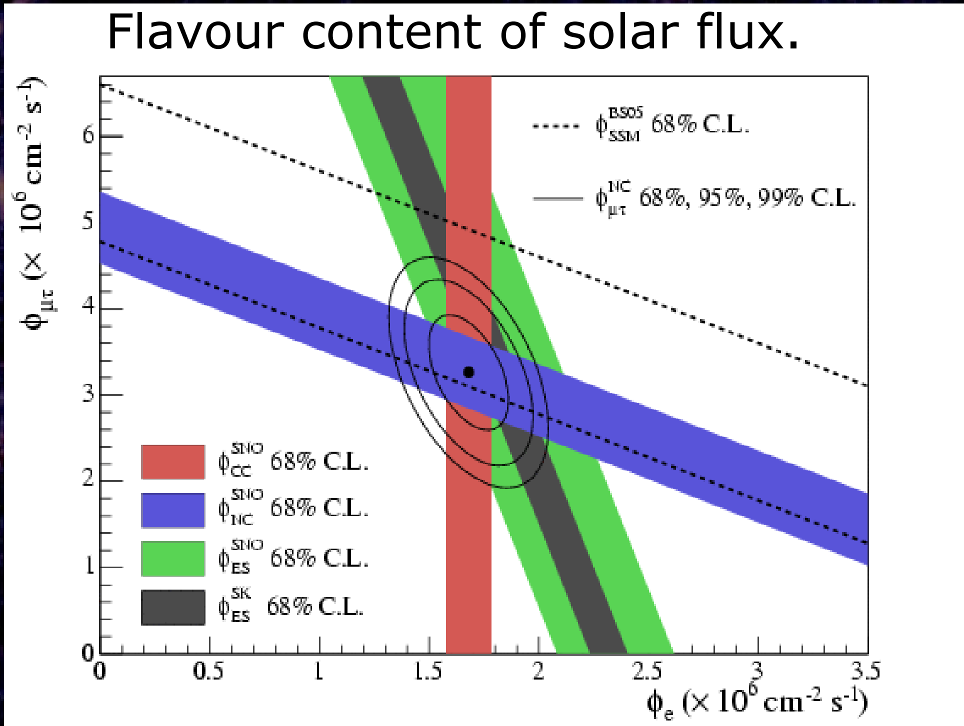
Comparison of pure D_2O and Salt results



2^{nd} Smoking Gun – SNO

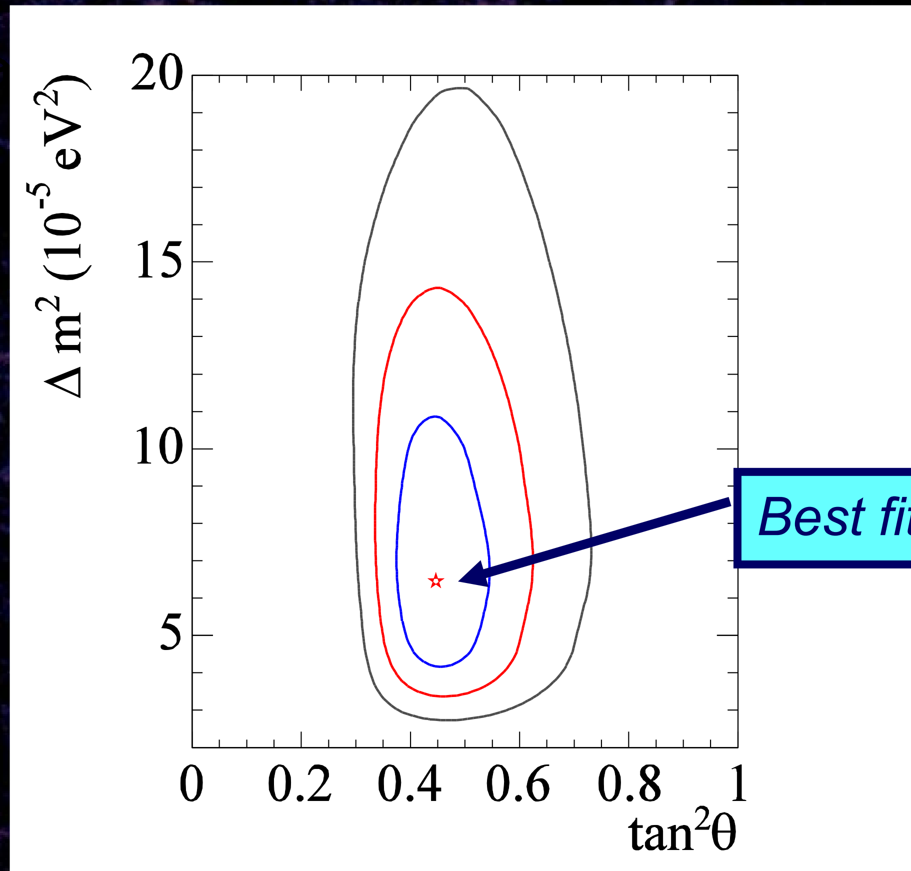


Latest SNO numbers, full salt data



This demonstrates that neutrinos change flavour..

Global Solar Analysis with SNO 391-day salt data



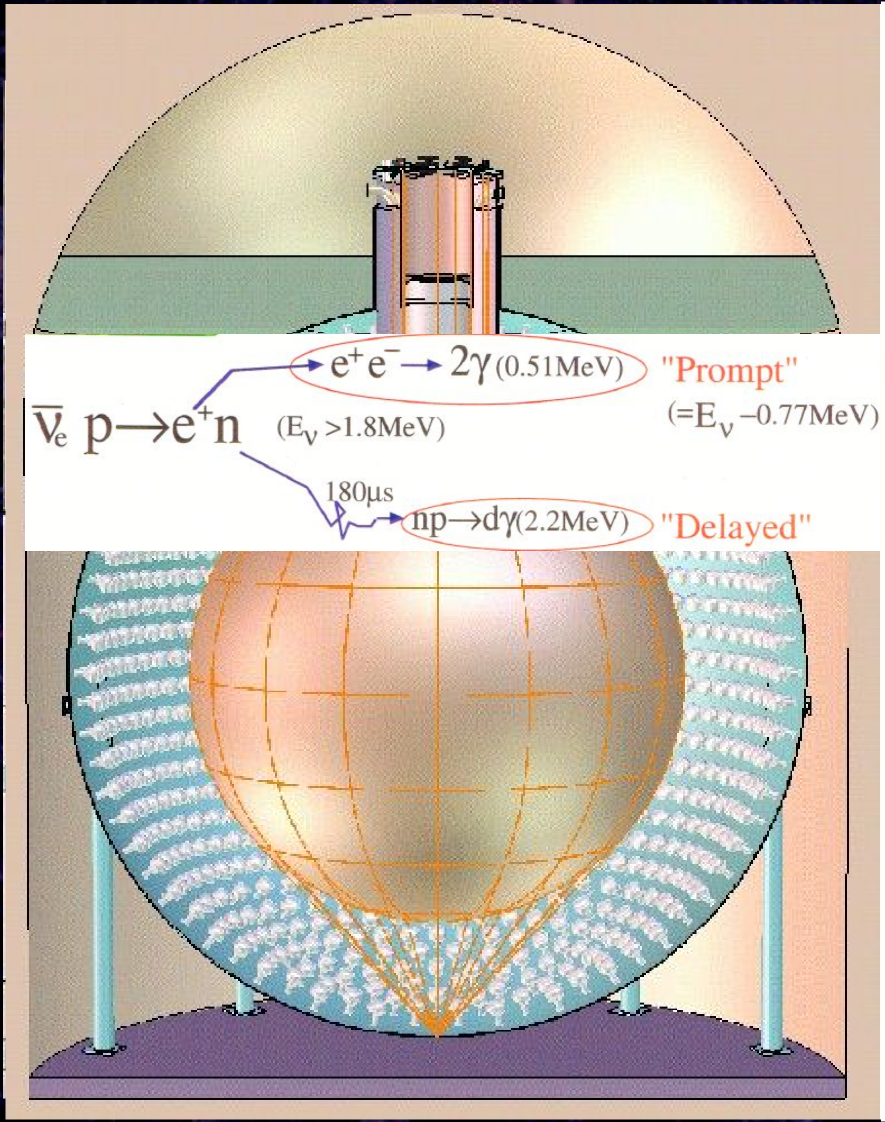
Best fit implies $L_\nu \sim 100km$

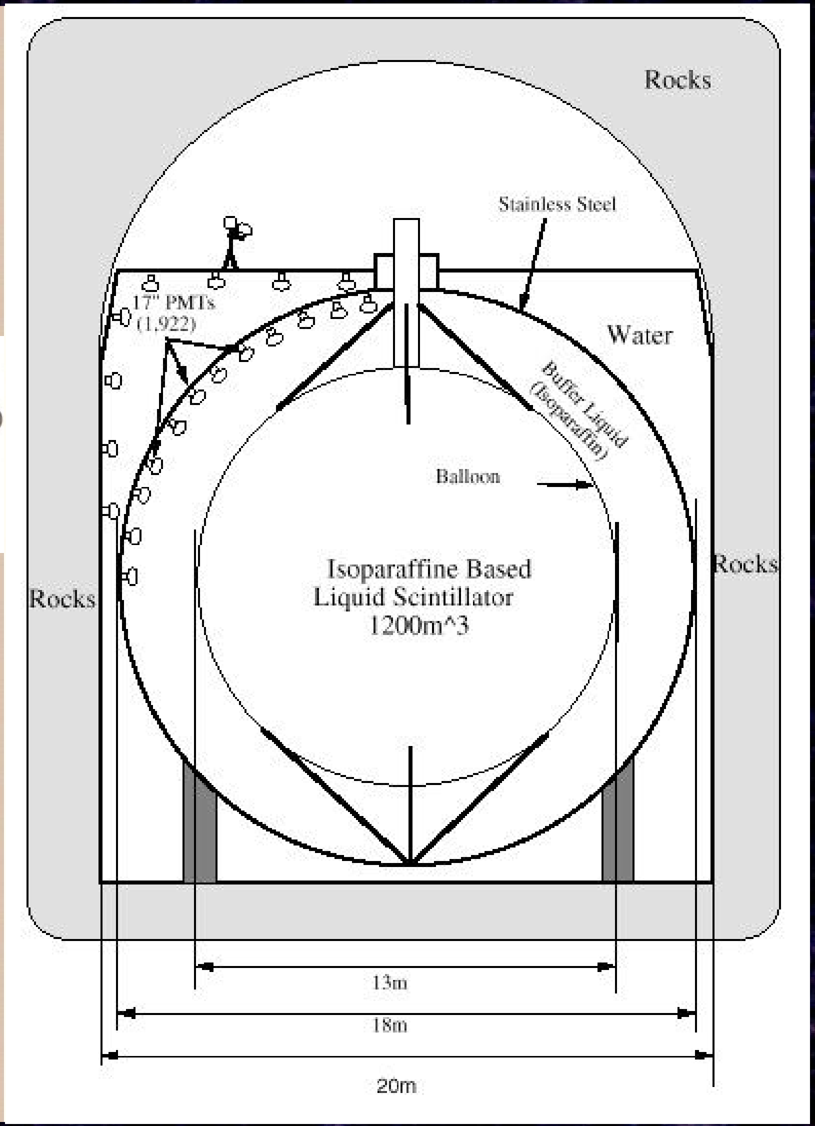
SNO finds:

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

- SNO suppression factor > 2 for $L >> L_\nu \Rightarrow$ MSW effect
- Possible to observe on Earth?

KamLAND





Sum over all Japanese power reactors...

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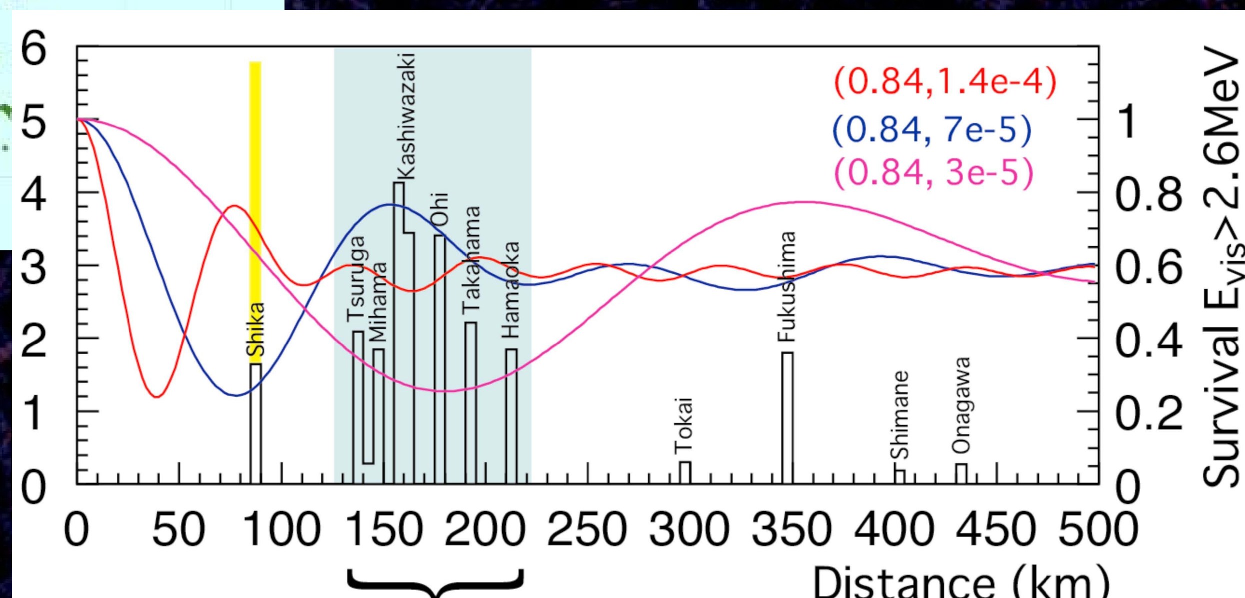
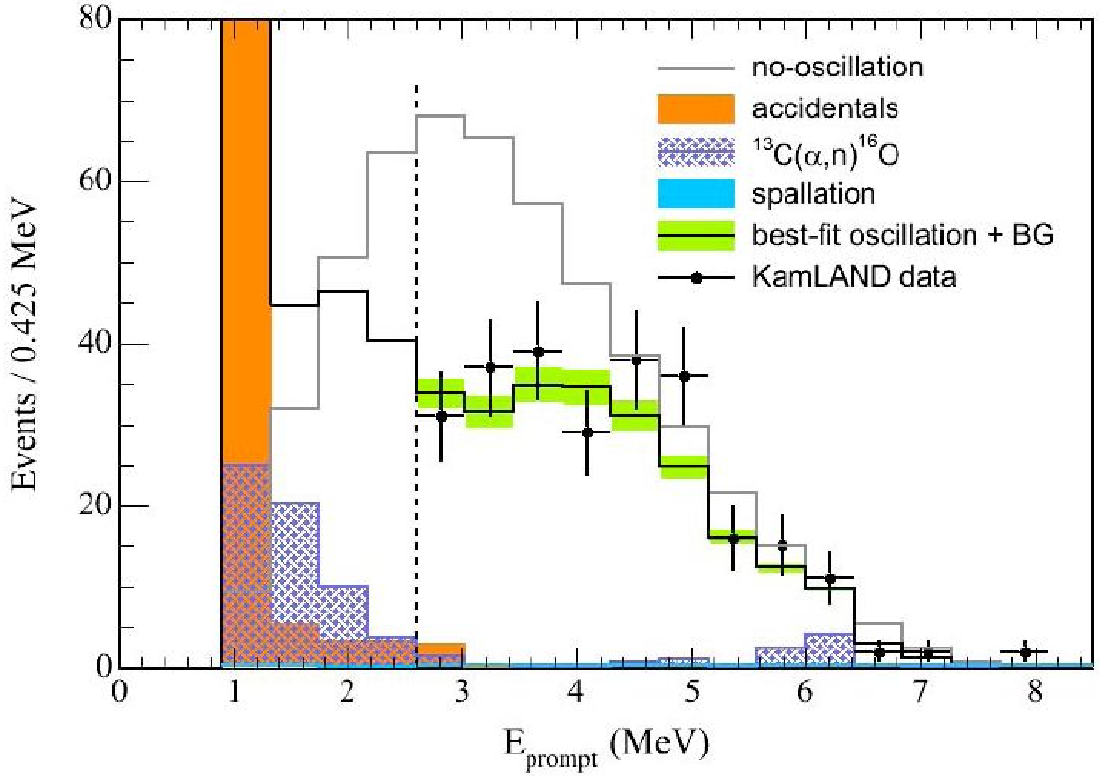
KamLAND



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

KamLAND



Best-fit oscillation:

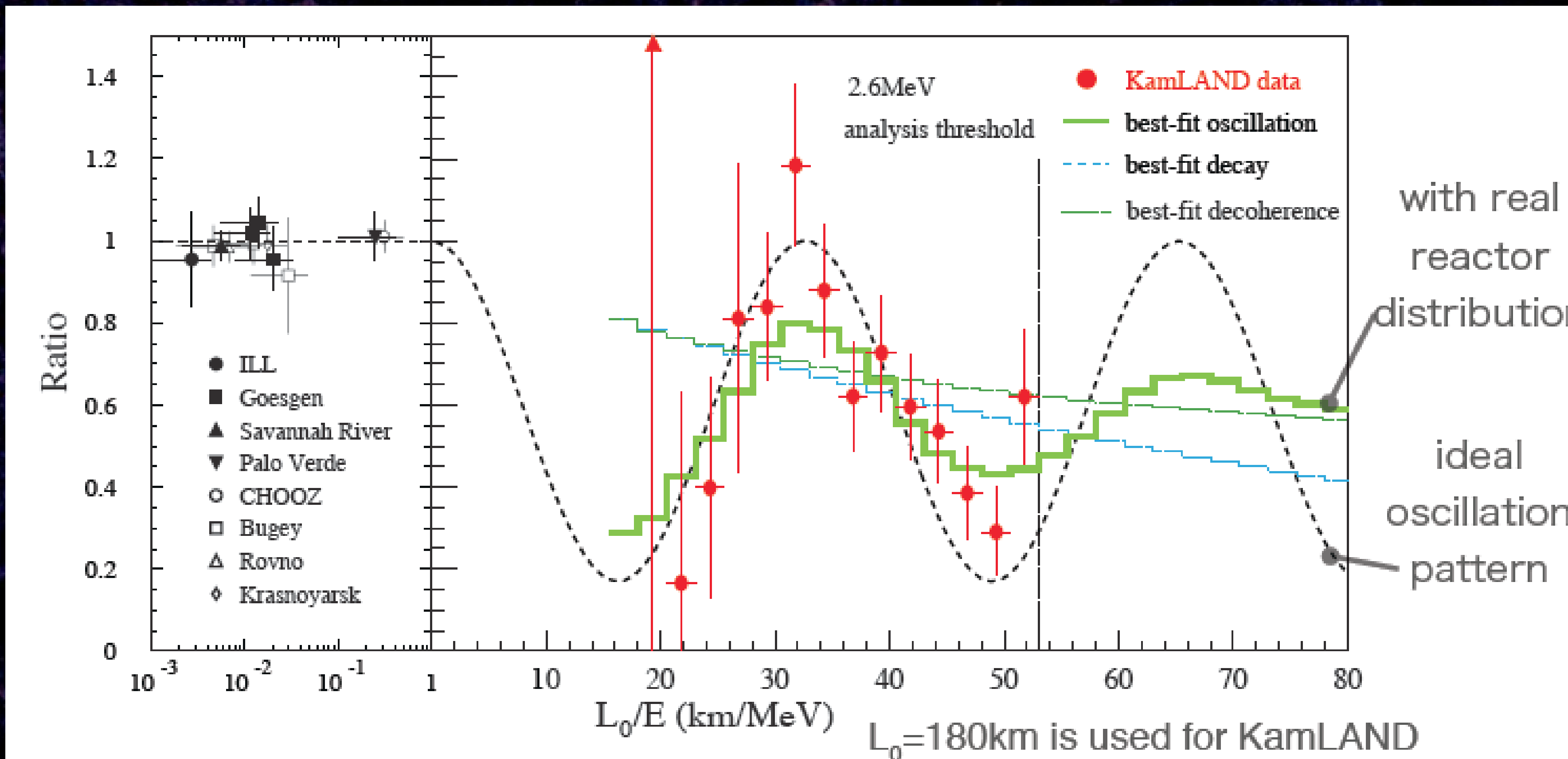
$\tan^2\theta = 0.46$

$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$

A fit to a simple rescaled reactor spectrum
is excluded at 99.6% CL

KamLAND

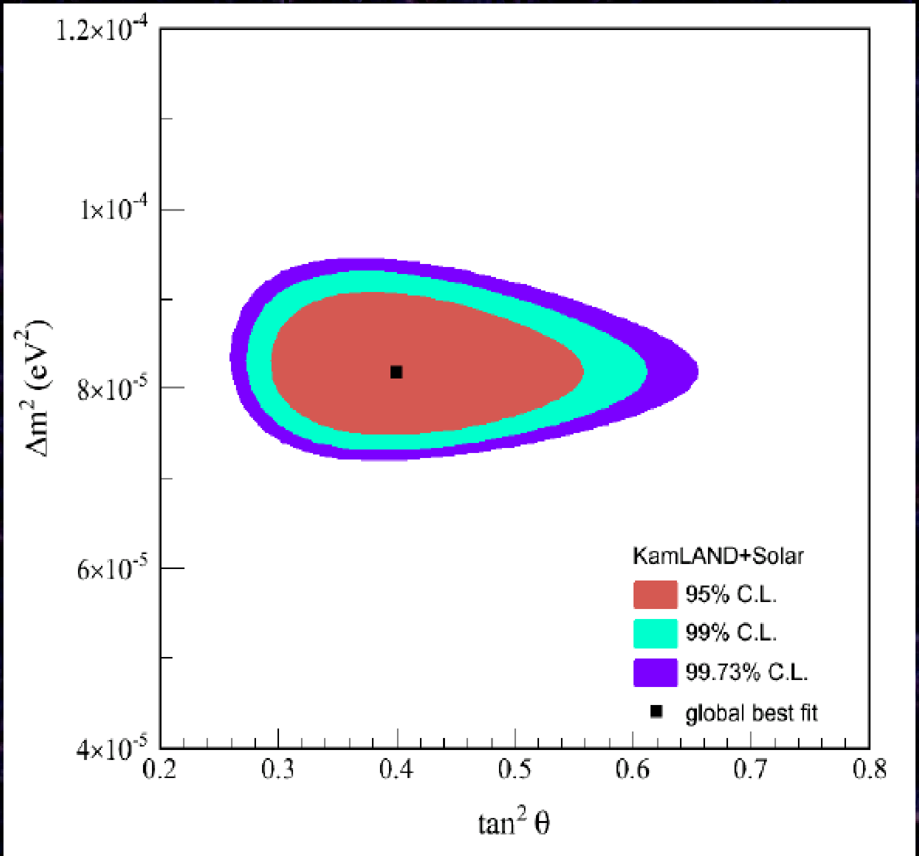
Slides from S. Enomoto's talk at WIN05



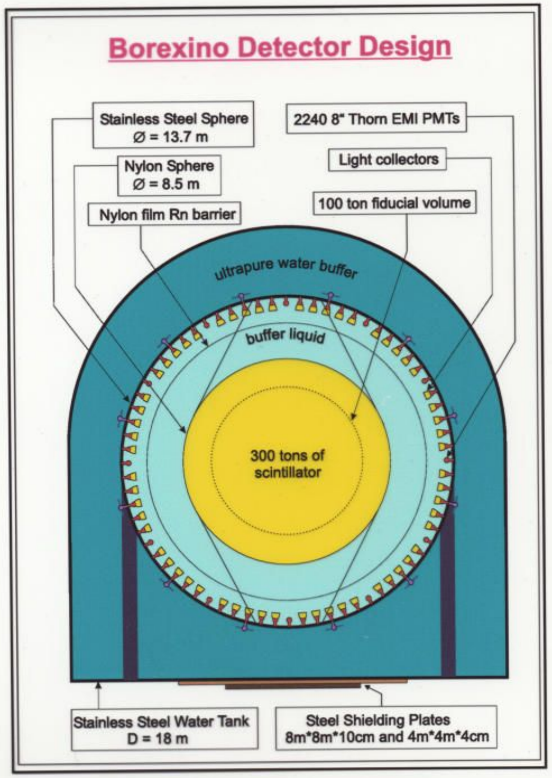
Proved (with other results) that neutrinos oscillate…

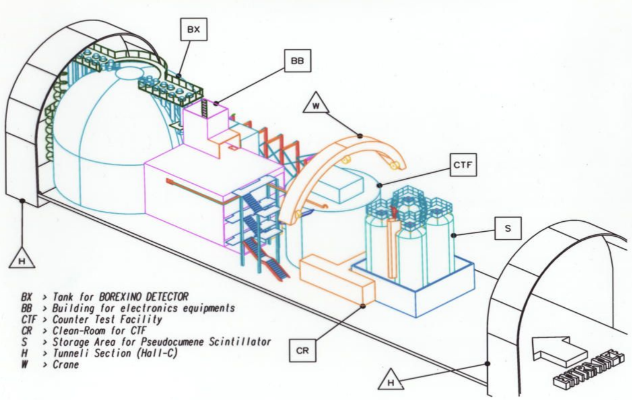
…or at least do a damned fine impression.

Solar+KamLAND Oscillation Fit

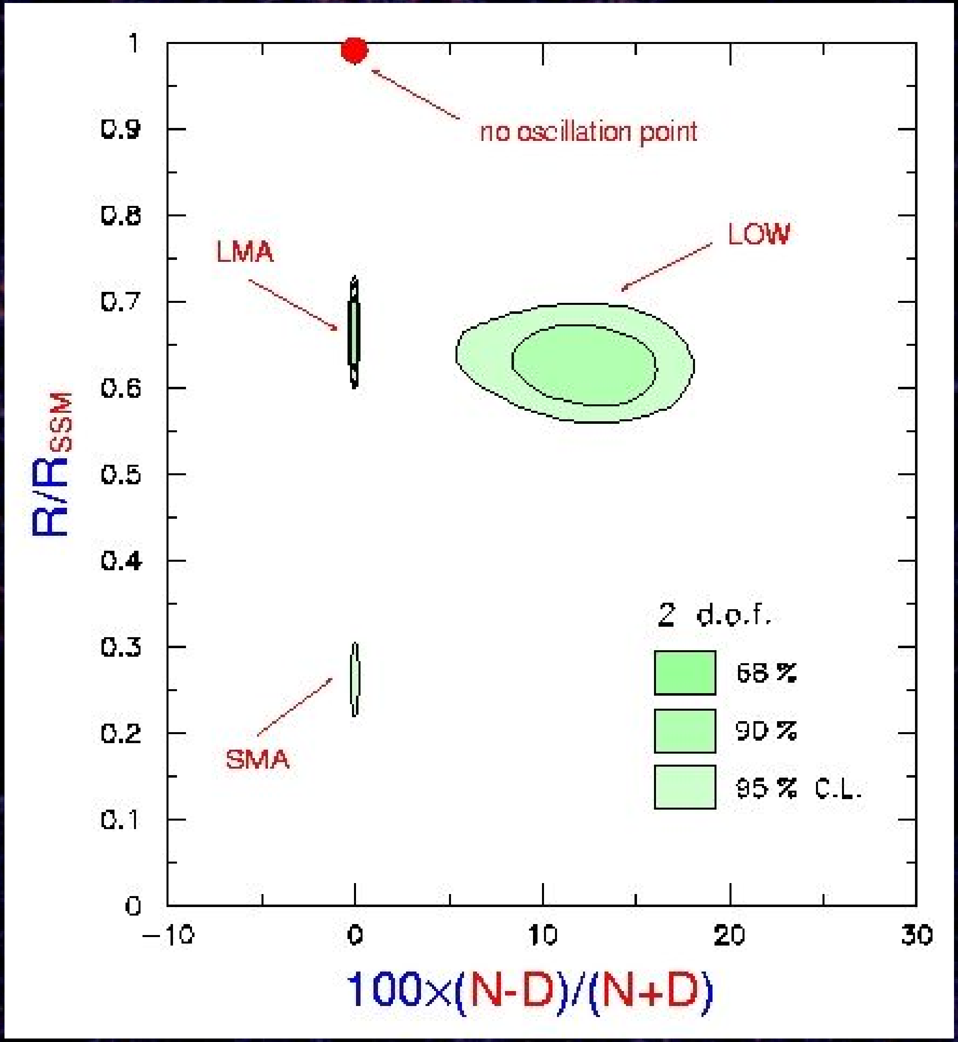


Solar + KamLAND


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
ENTRANCE

Borexino Physics Target – ^{7}Be neutrinos



And the big news is…

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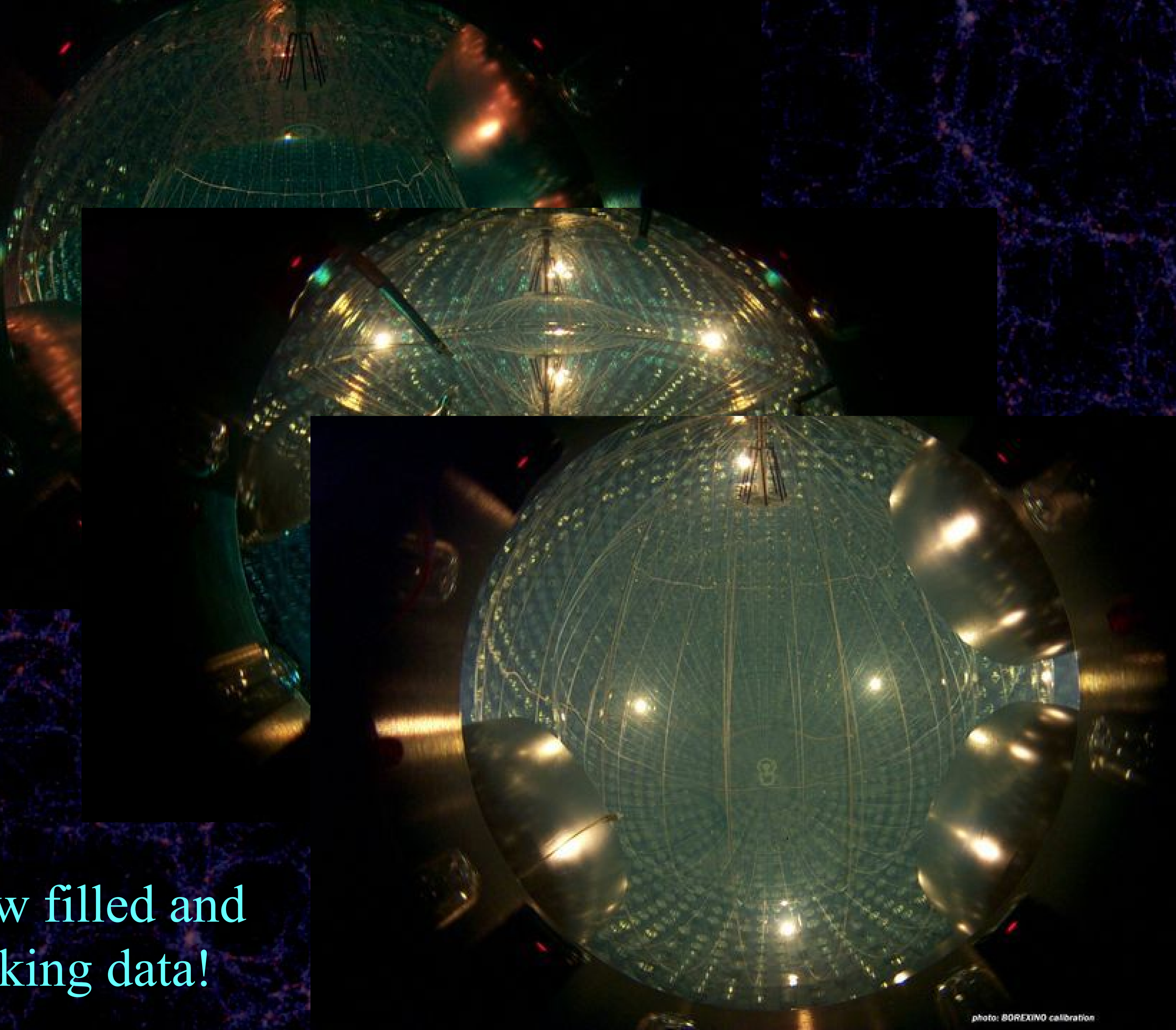
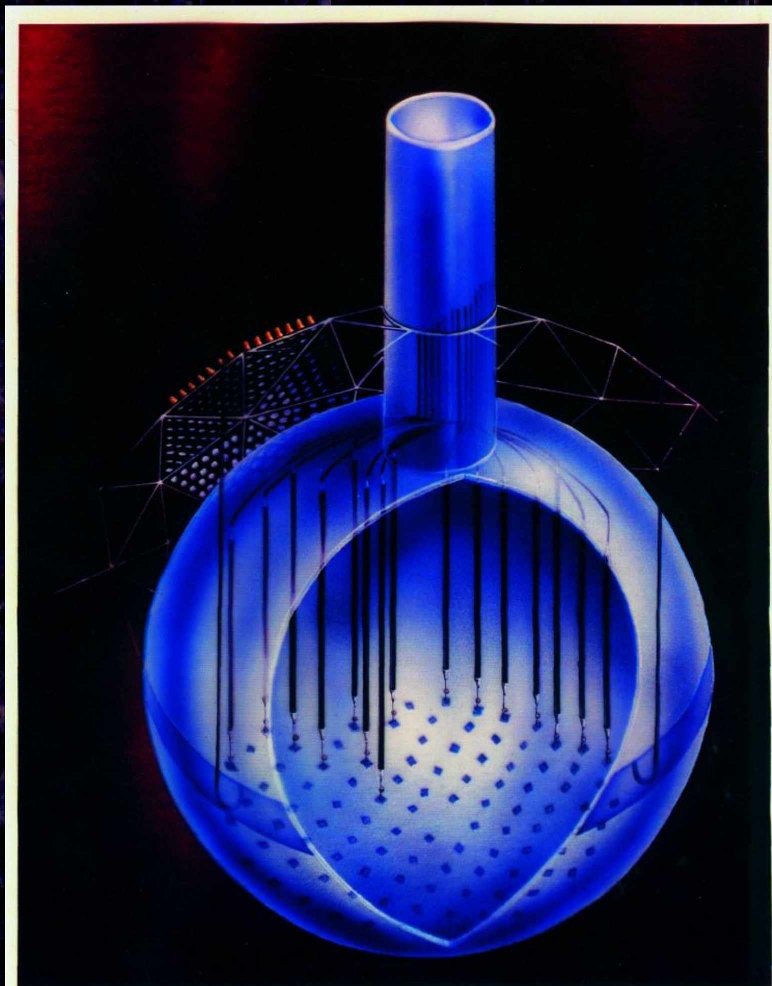
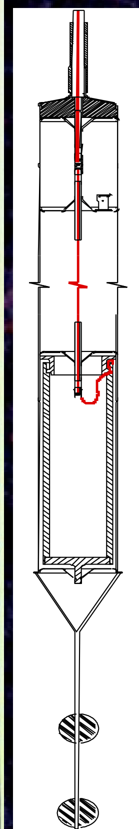
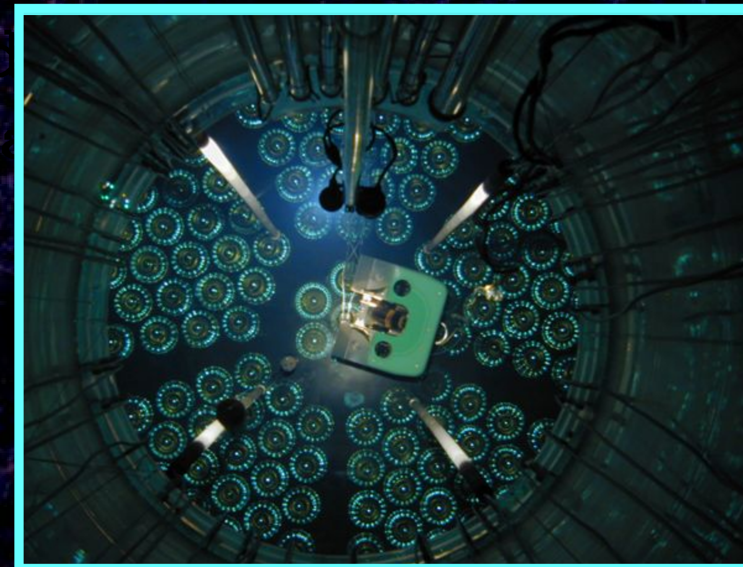


Now filled and taking data!

The Near Future – Solar and Reactor



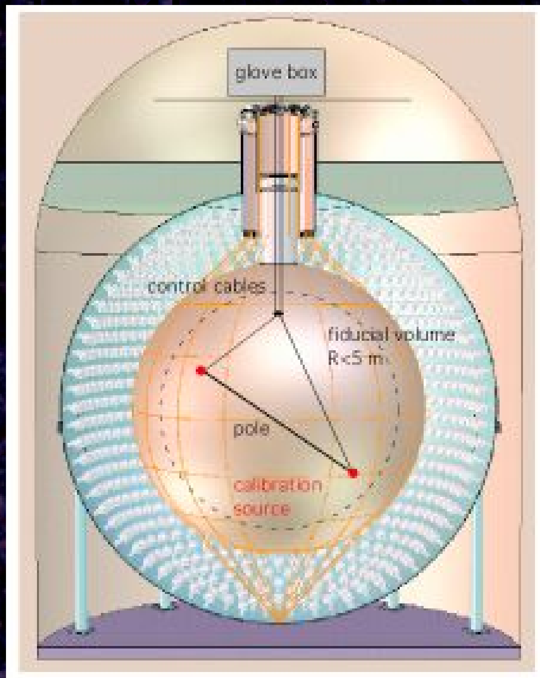


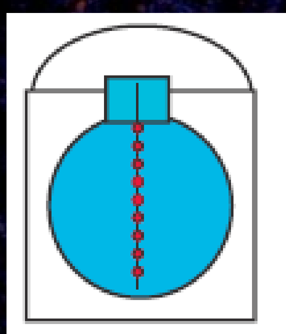


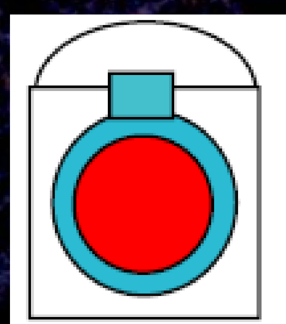
Other future solar neutrino Experiments – KamLAND, SNO+, CLEAN, XMASS, etc.- no time to discuss.

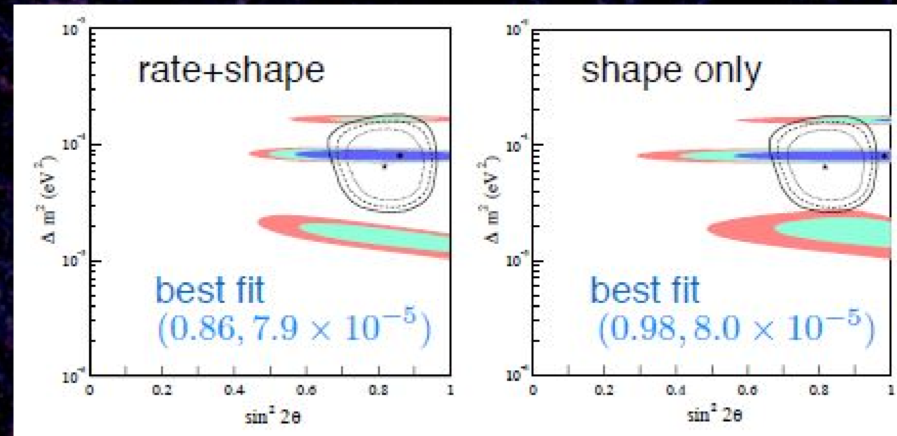
SNO ^{3}He detectors – different systematics $\rightarrow$ better determine θ_{12}

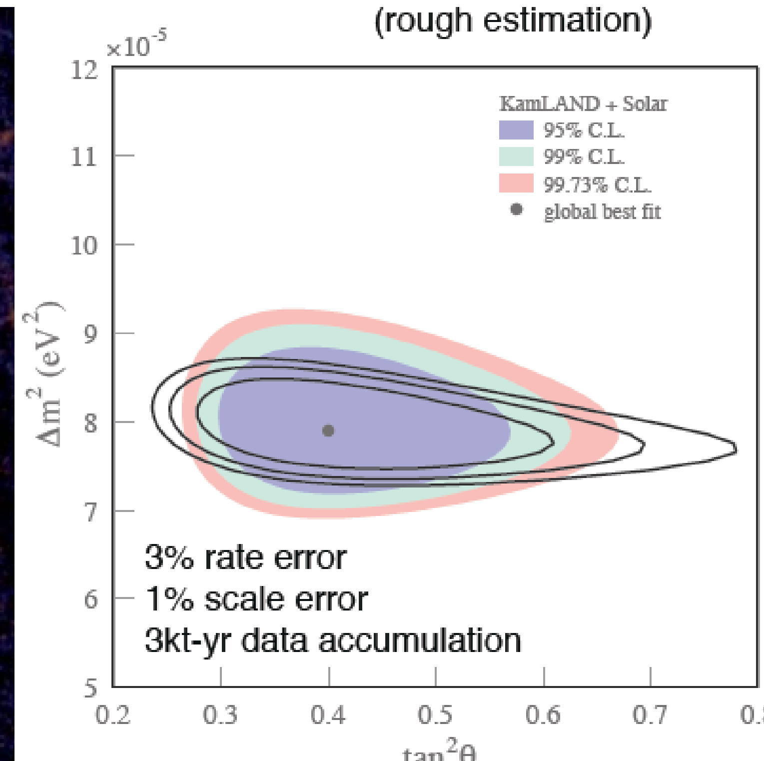
The Near Future – Solar and Reactor











Improvements of KamLAND also improve θ_{12} sensitivity

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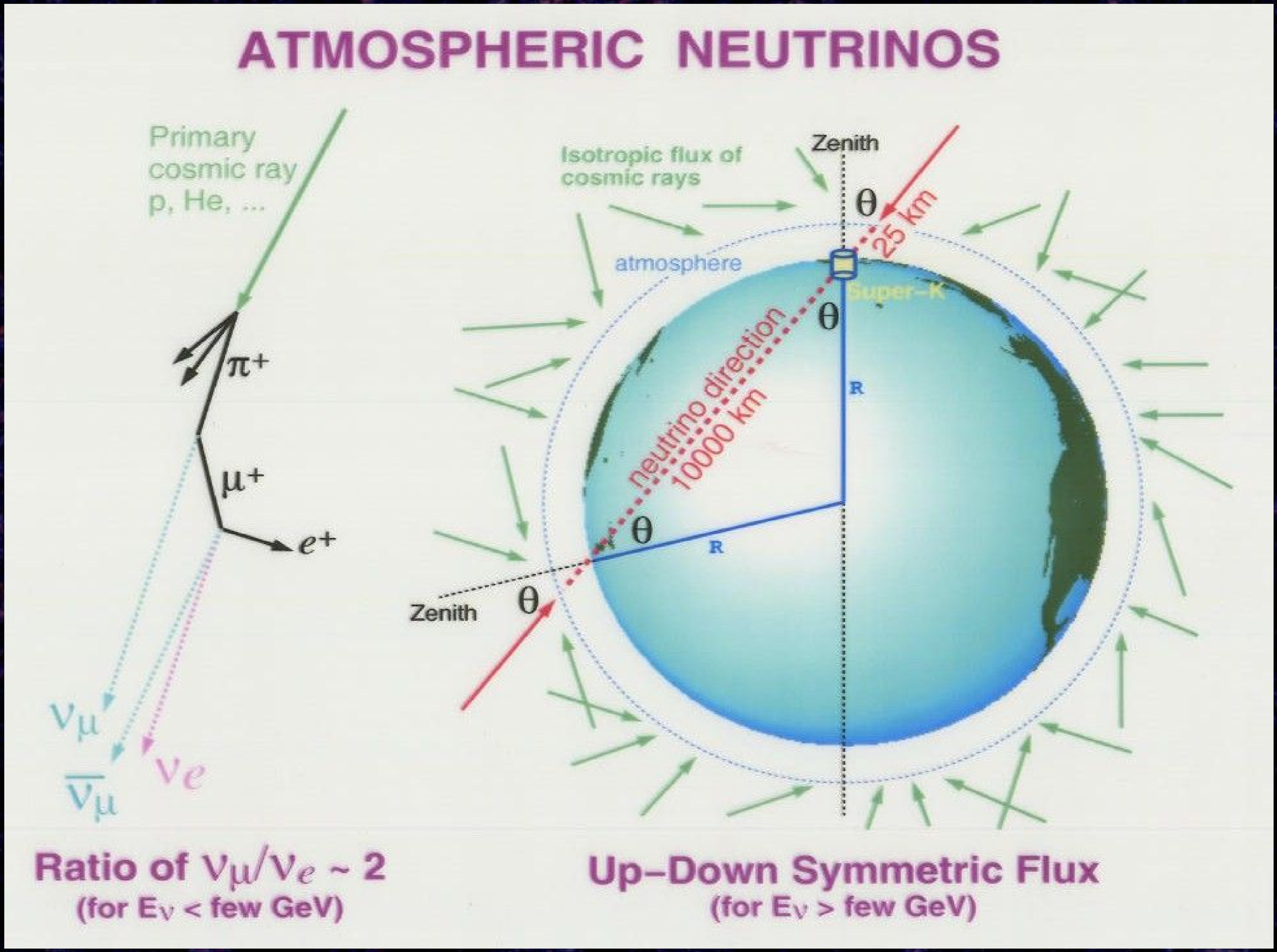
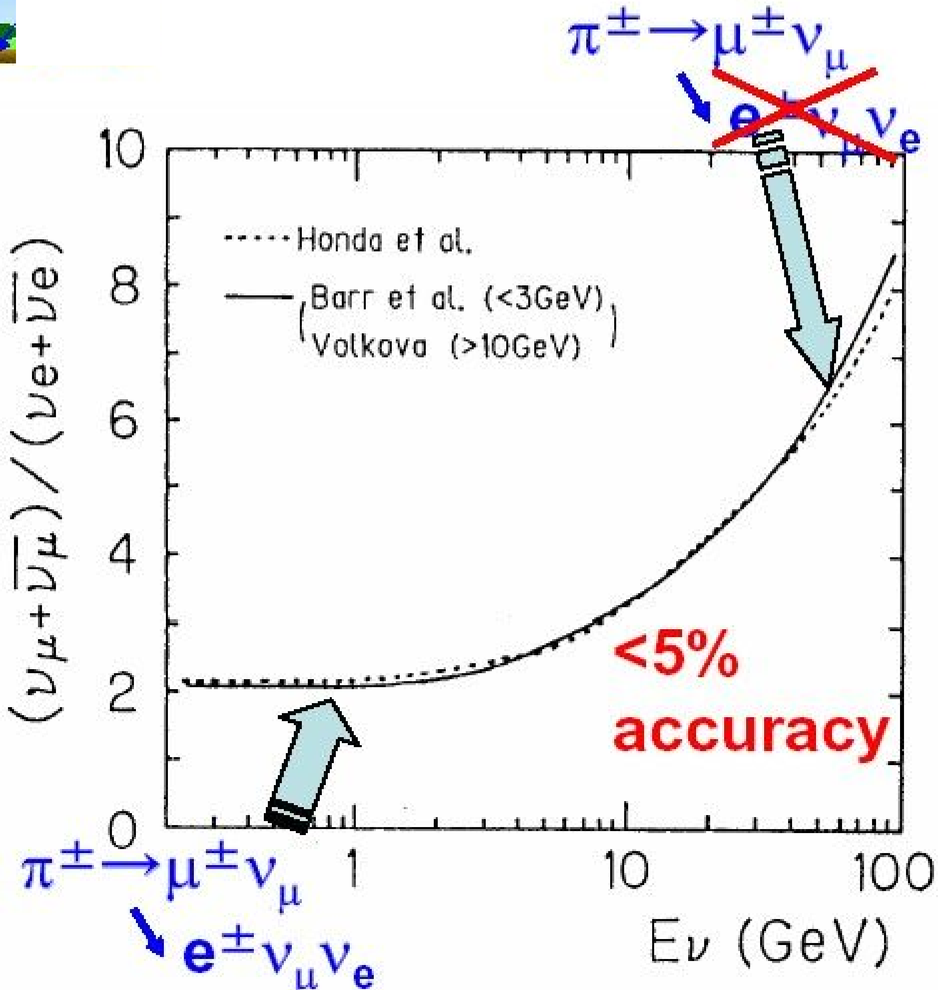
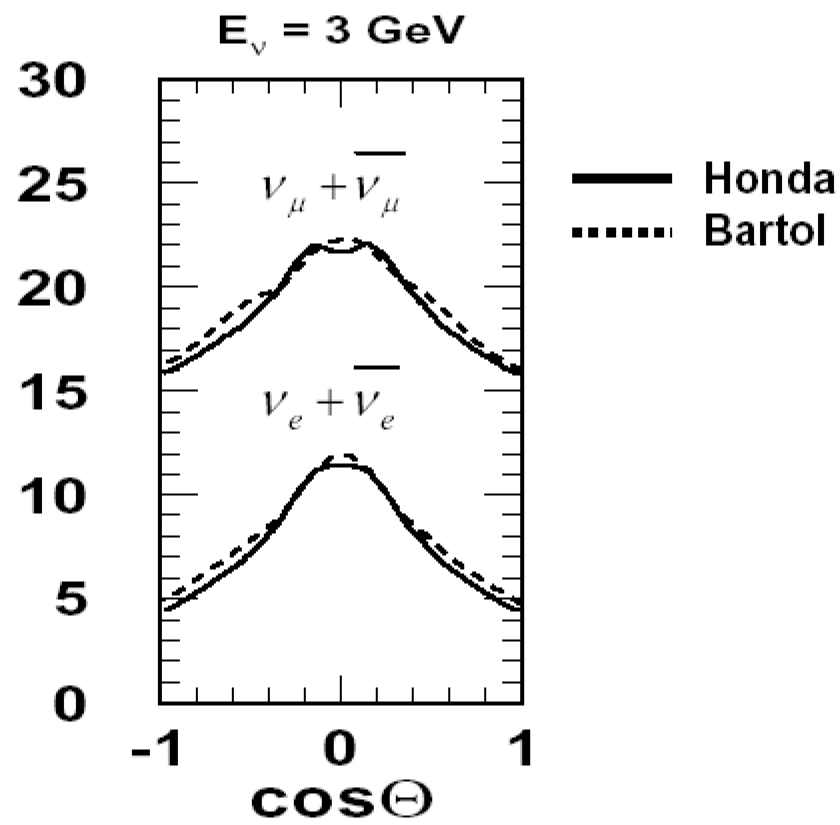
1^{st} Smoking Gun – SK Atmospheric



Observed ratio ~1, Look at zenith angle distributions…

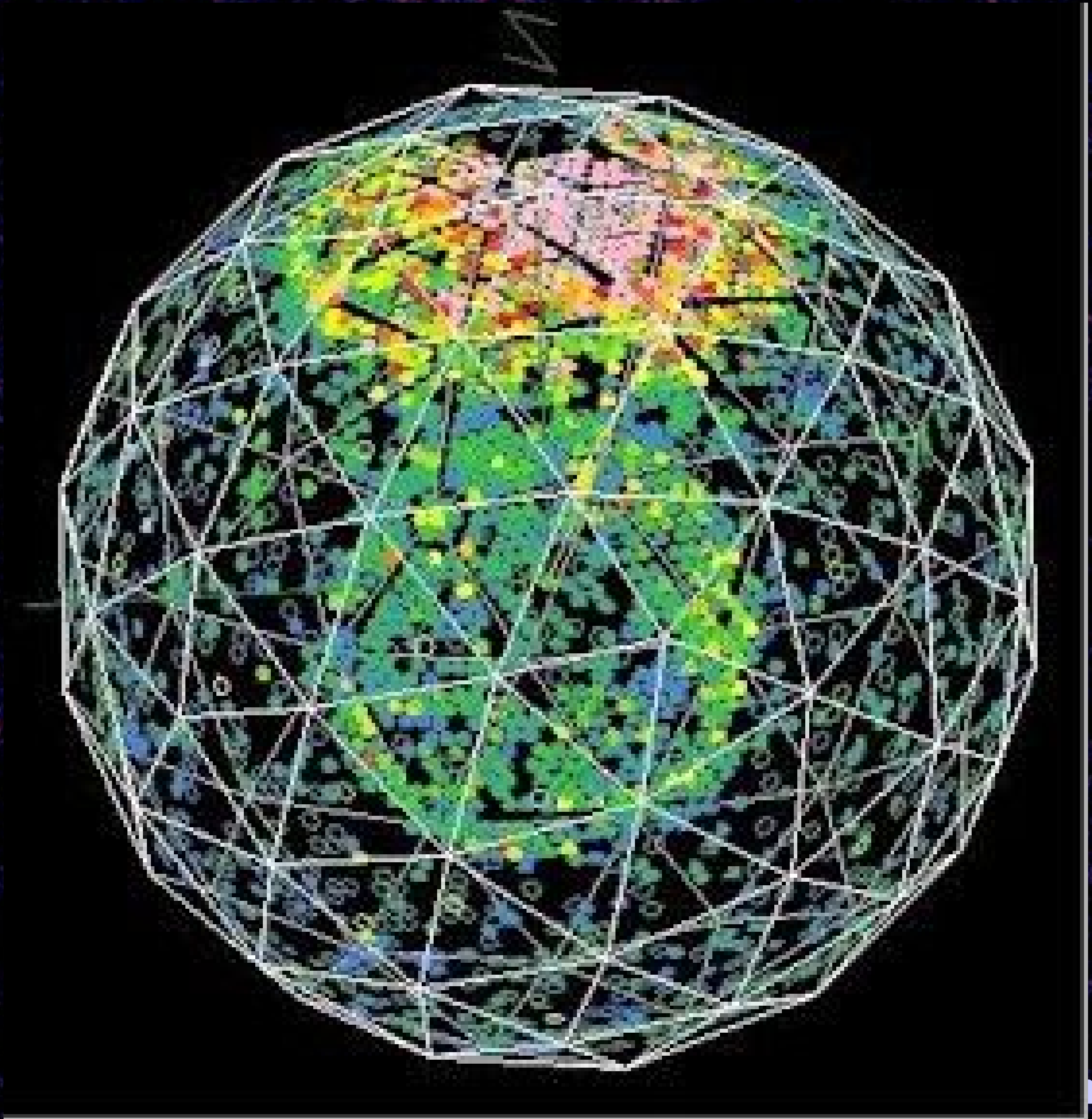




up-down symmetric for both ν_μ and ν_e (above a few GeV).

Plots from Y. Suzuki

Background to Proton Decay Experiments



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

Volume 57, Number 16 PHYSICAL REVIEW LETTERS

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 sign lifetime range from der of 10^{32} years. V is now limited by mospheric ν flux a tions. To reduce th quire specific exper understanding of lo precise atmospheric

IMB-1

1986

Volume 57, Number 16 PHYSICAL REVIEW LETTERS 20 October

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

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

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University of Michigan, Ann Arbor, Michigan 48109
Brookhaven National Laboratory, Upton, New York 11973
Cleveland State University, Cleveland, Ohio 44115
University of Hawaii, Honolulu, Hawaii 96822
University of Notre Dame, Notre Dame, Indiana 46556
University College, London WC1E 6BT, United Kingdom
Warsaw University, Warsaw PL-00-681, Poland
(Received 6 June 1986)

We have developed an extensive model of atmospheric ν interactions which provide the backgrounds to nucleon-decay experiments. We report results from a 417-live-day exposure of the Irvine-Michigan-Brookhaven detector. During this time 401 contained events were observed at a rate and with characteristics consistent with atmospheric ν interactions. We have calculated the expected backgrounds in a variety of two- and three-body decay modes and have set lower limits on many nucleon partial lifetimes.

PACS numbers: 13.30.Ce, 96.40.Qr

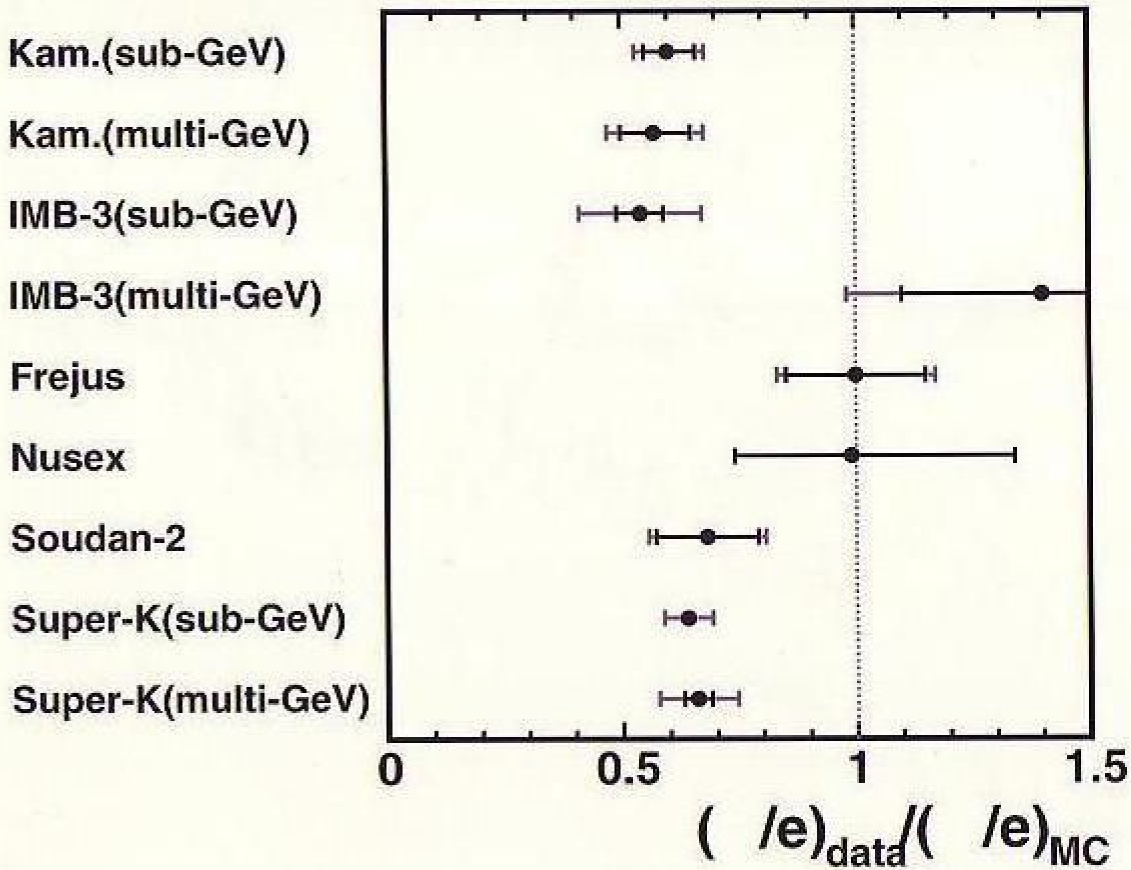
$\nu_\mu n \to \mu^- p$; $\nu_\mu p \to \mu^+ n$; $\mu \to e\nu\nu$ decay

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

Also seen by Kamiokande

μ /e ratio

Y.Fukuda et al., Phys. Lett. B 335 (1994) 237.
M.Shiozawa, for the SK collab., talk at Neutrin
Munich, May 2002



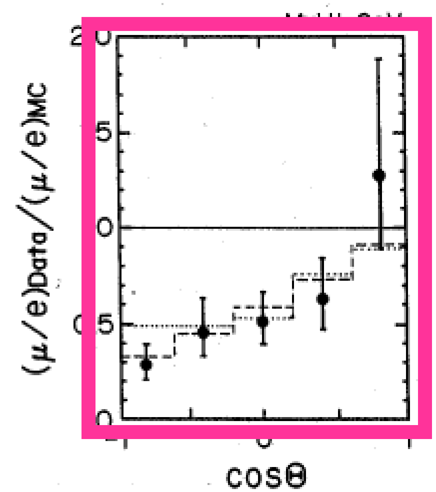
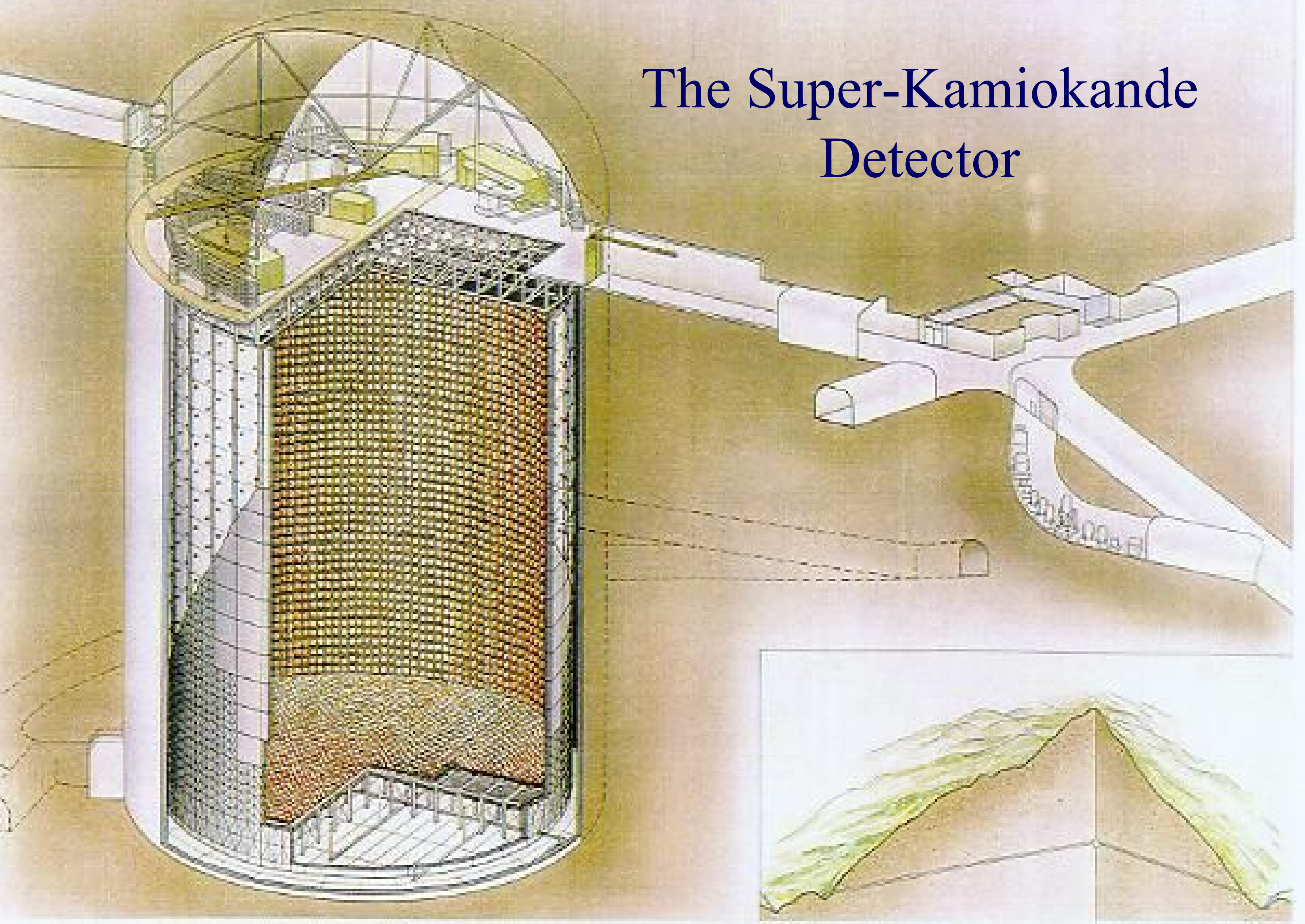
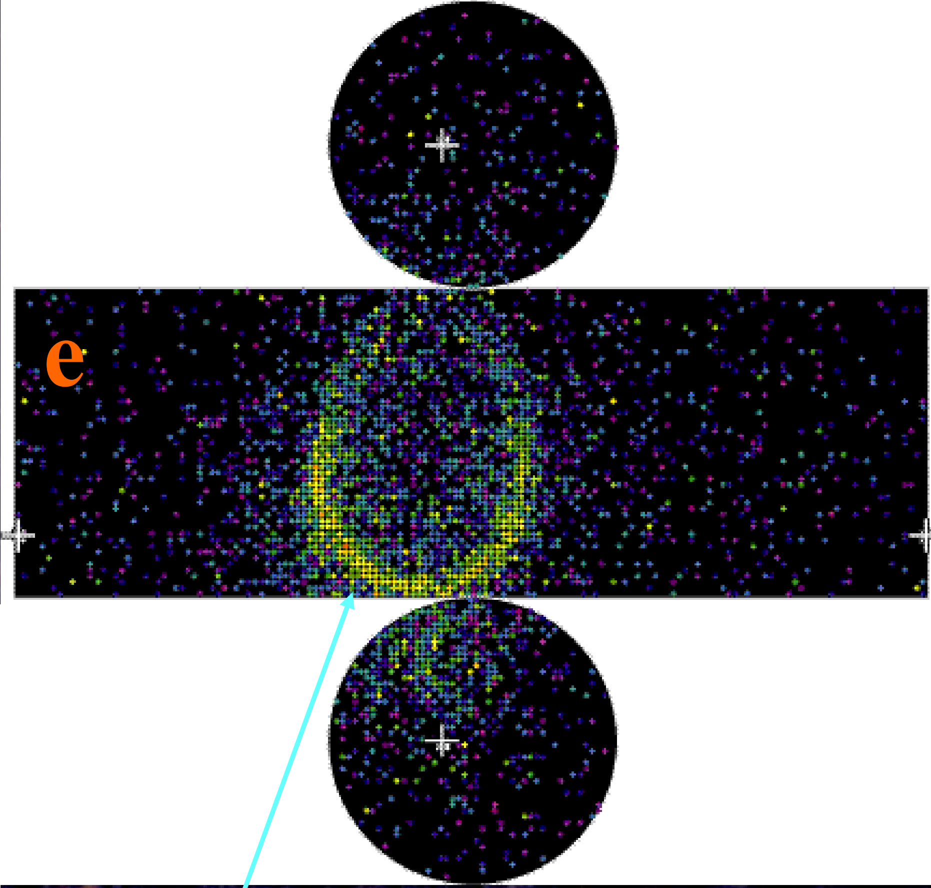


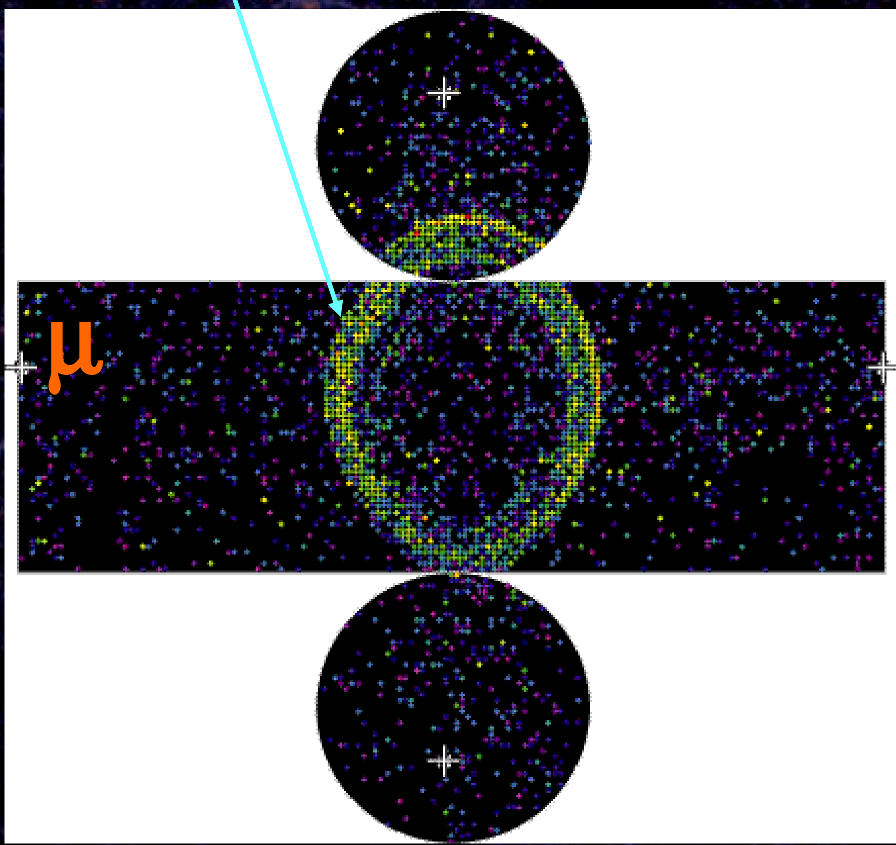
Fig. 4. Zenith-angle distribution of $(\mu/e)_{data}/(\mu/e)_{MC}$, where both the fully-contained and the partially-contained events are included. The circles with error bars show the data. Also shown are the expectations from the MC simulations with neutrino oscillations for parameter sets (Δm^2, $\sin^2 2\theta$) corresponding to the best-fit values to the multi-GeV data for $\nu_\mu \leftrightarrow \nu_e$ ((1.8×10^{-2} eV^2, 1.0), dashes) and $\nu_\mu \leftrightarrow \nu_\tau$ ((1.6×10^{-2} eV^2, 1.0), dots) oscillations.

The Super-Kamiokande Detector



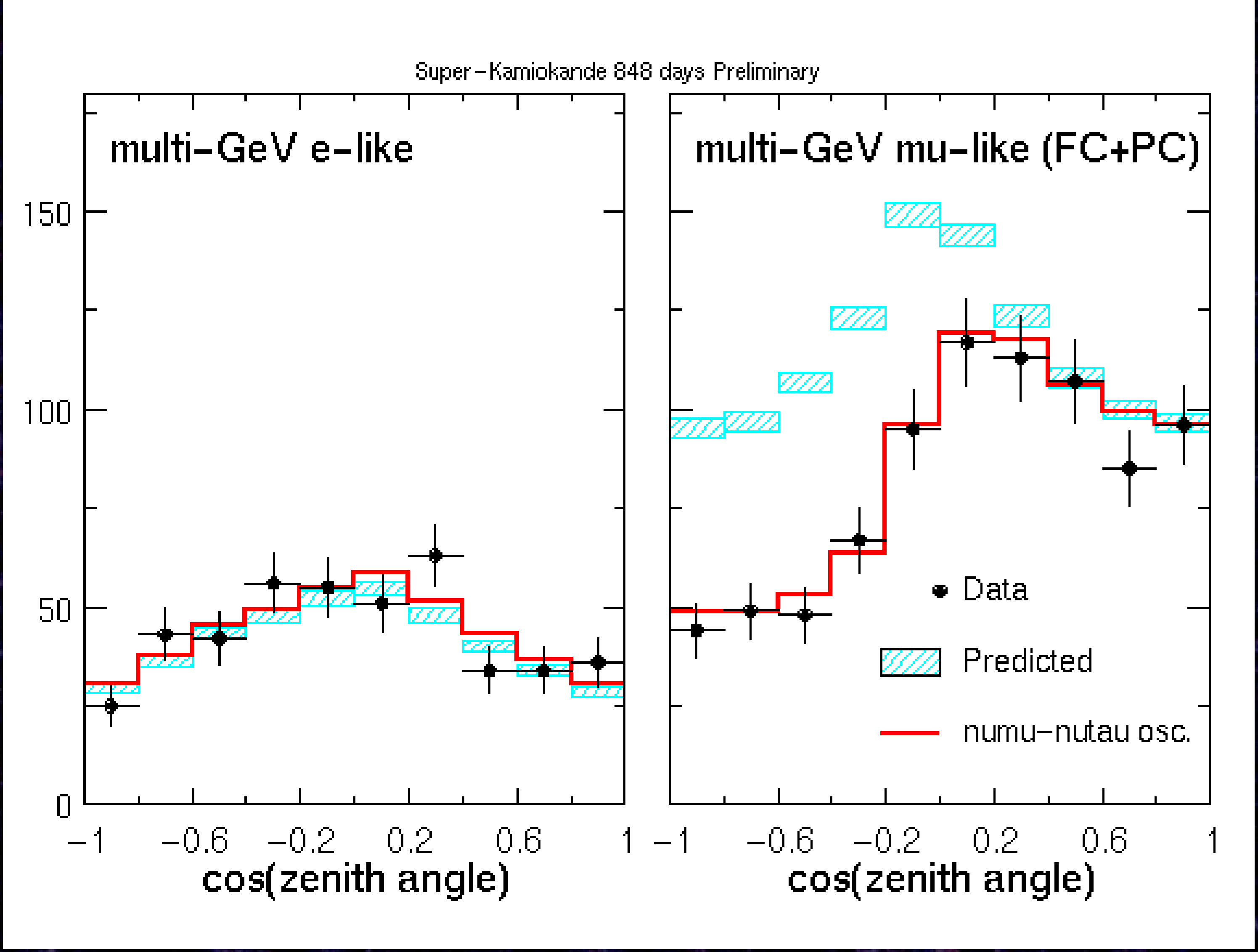
ν_μ produces a μ, which produces a sharp ring





ν_e produces an electron, which produces a "fuzzy" ring

SK data as a function of zenith angle



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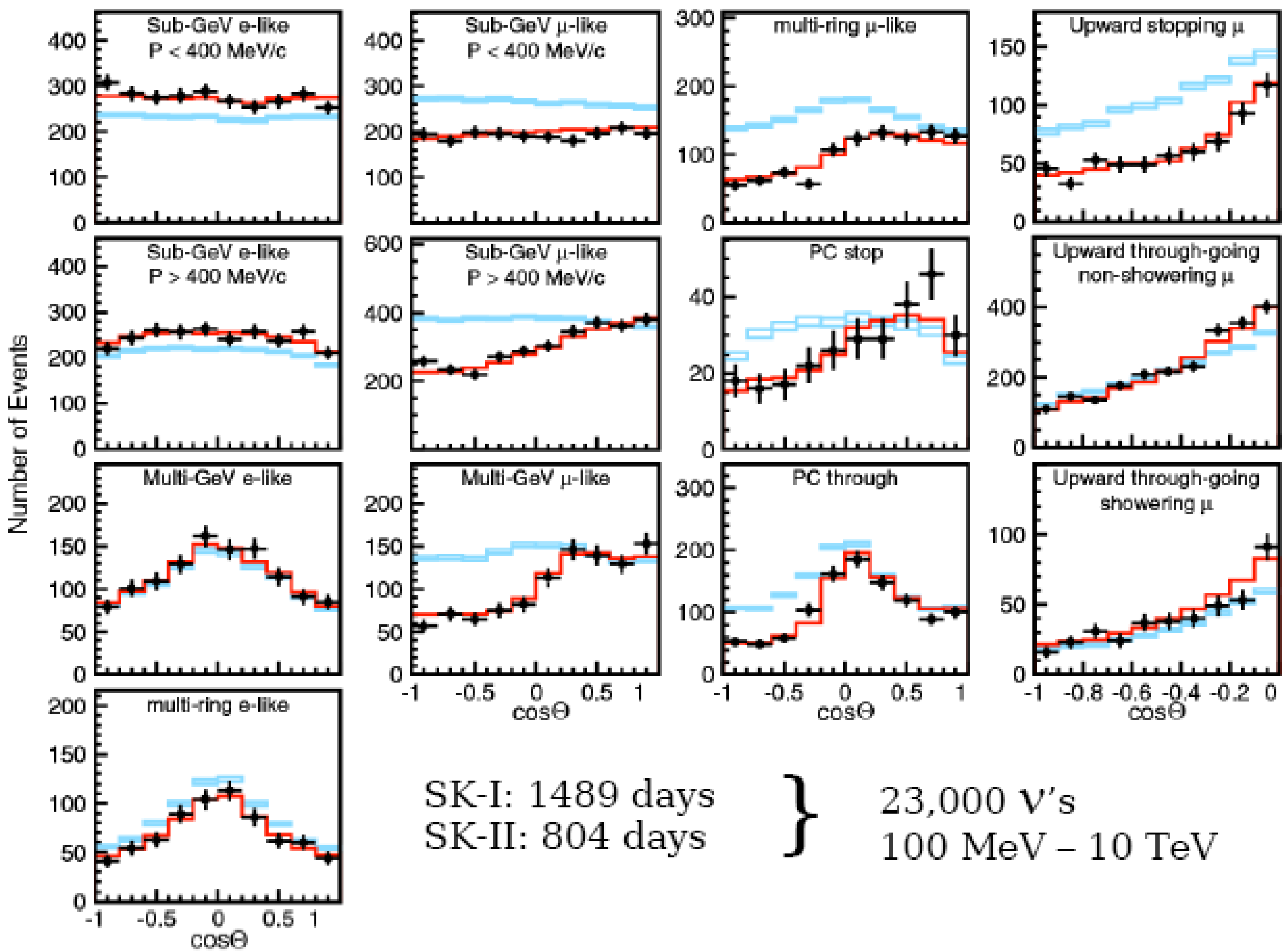
1st Smoking Gun – SK Atmospheric

Complete Atmospheric Sample from SKI+II
with result of best fit



SK-I: 1489 days
SK-II: 804 days

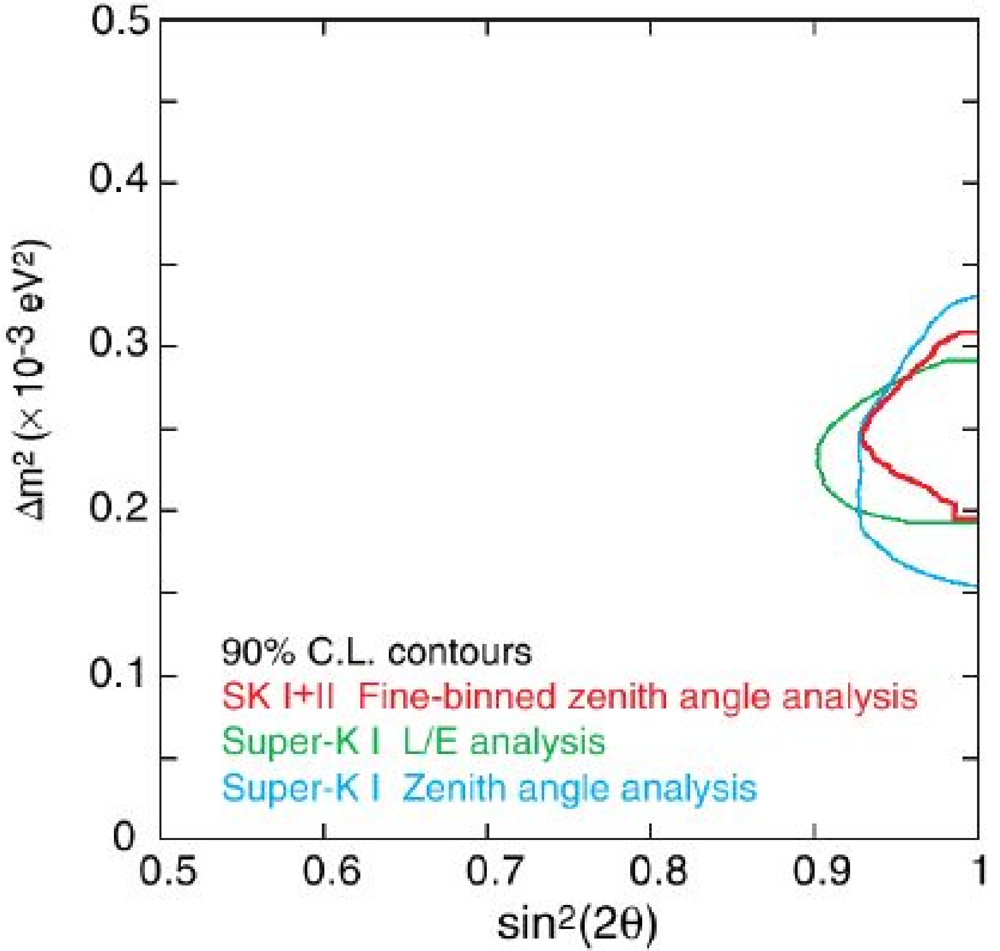
23,000 ν's
100 MeV – 10 TeV

4

Latest analysis from Chris Walter, ICHEP06.

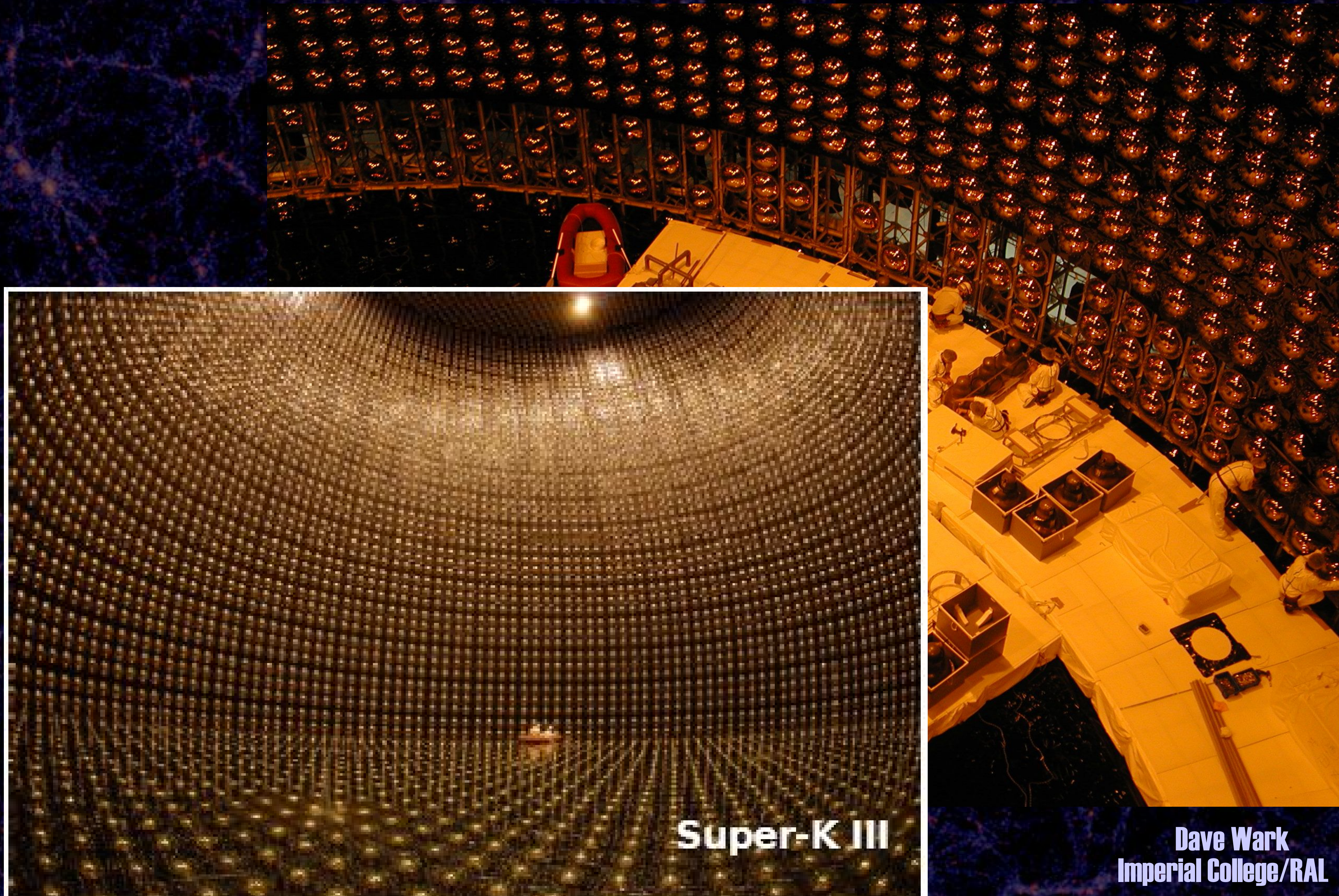
SK Contours Compared

The new analysis combines the best features of previous analyses. Atmospheric neutrinos still provide the best constraint on $\sin^2(\theta_{23})$.

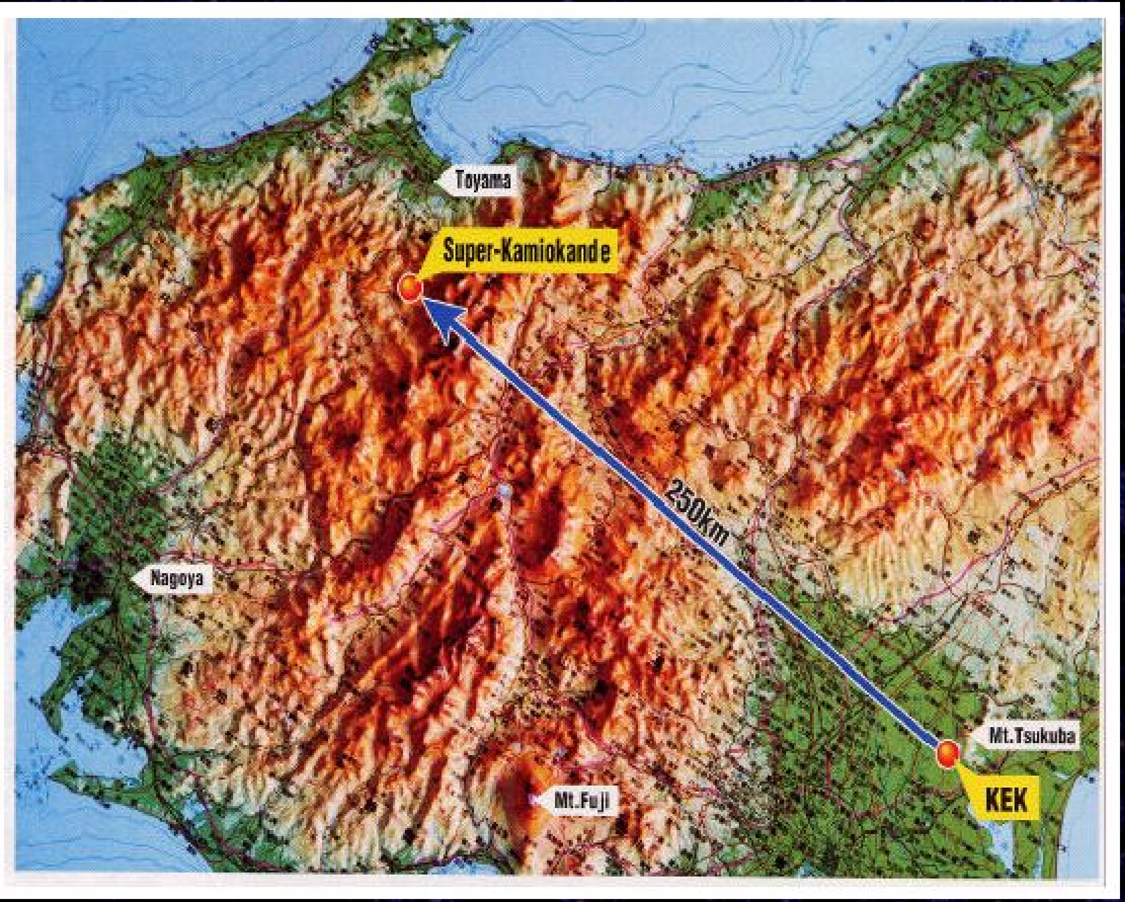


From Chris Walter's talk at ICHEP

Super Kamiokande Rebuild



The first long baseline experiment – K2K



- ν_μ (99%) beam
- $<E_\nu>$ ~1.3GeV
- **Near detector**
  @300m
- **Far detector**:
  Super Kamiokande(SK)
  @**250km**
- Sensitive for
  $\Delta m^2 > 2x10^{-3}$ eV^2

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Neutrino beamline

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

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

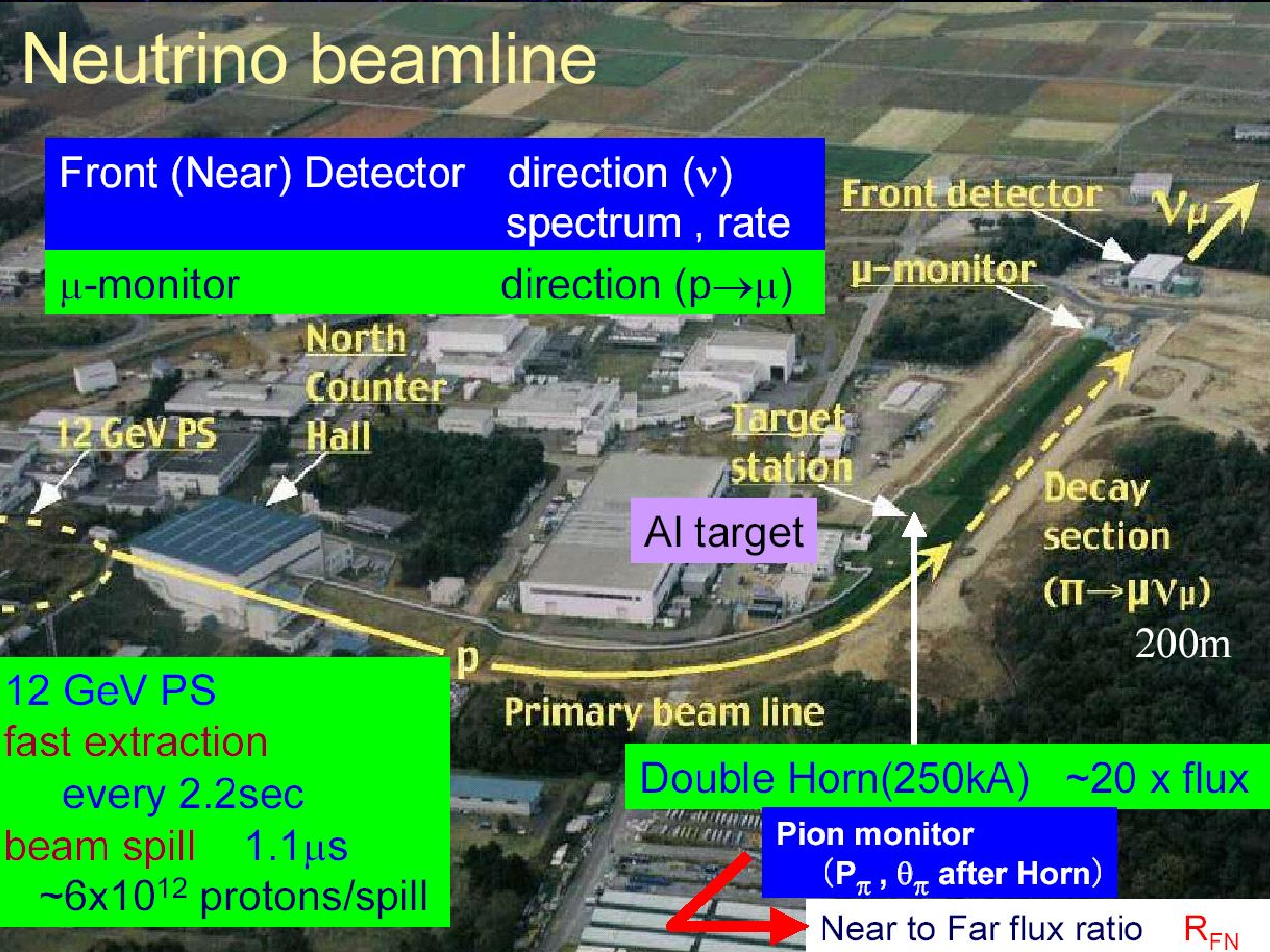
12 GeV PS
fast extraction
every 2.2sec
beam spill 1.1μs
~6x10^{12} protons/spill

Al target

Double Horn(250kA) ~20 x flux

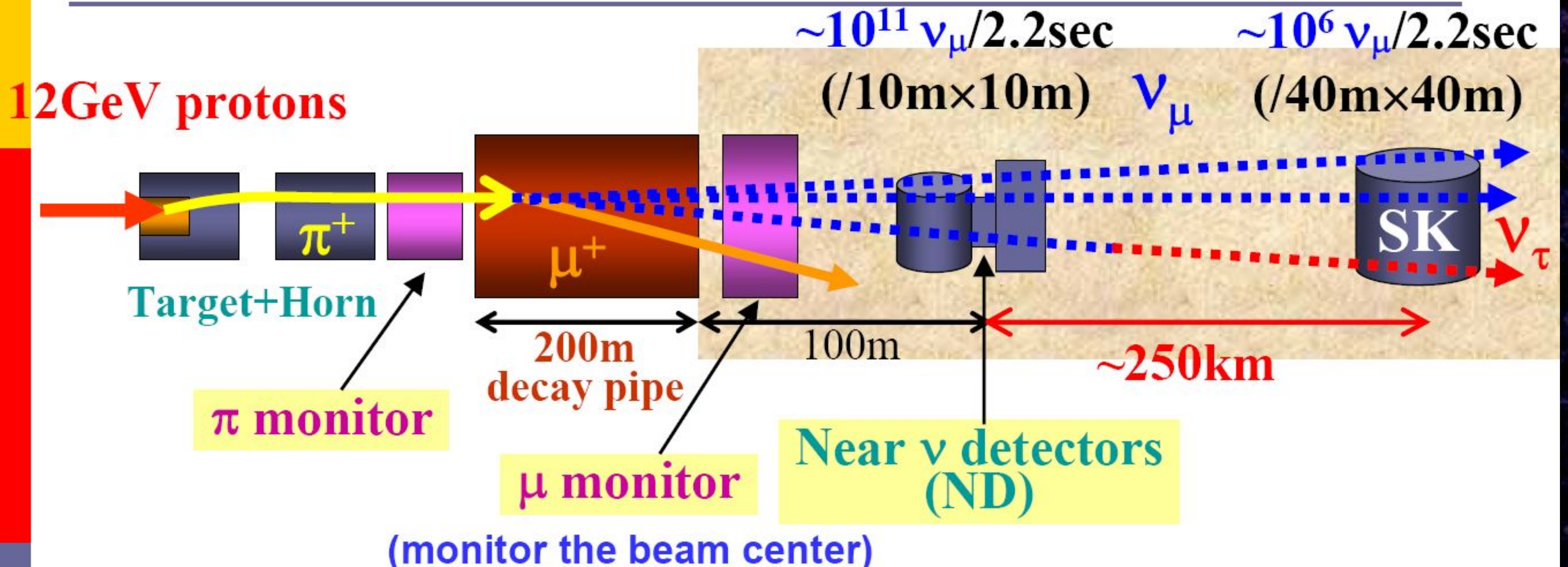
Pion monitor
(P_π , θ_π after Horn)

Near to Far flux ratio R_{FN}



2. K2K experiment

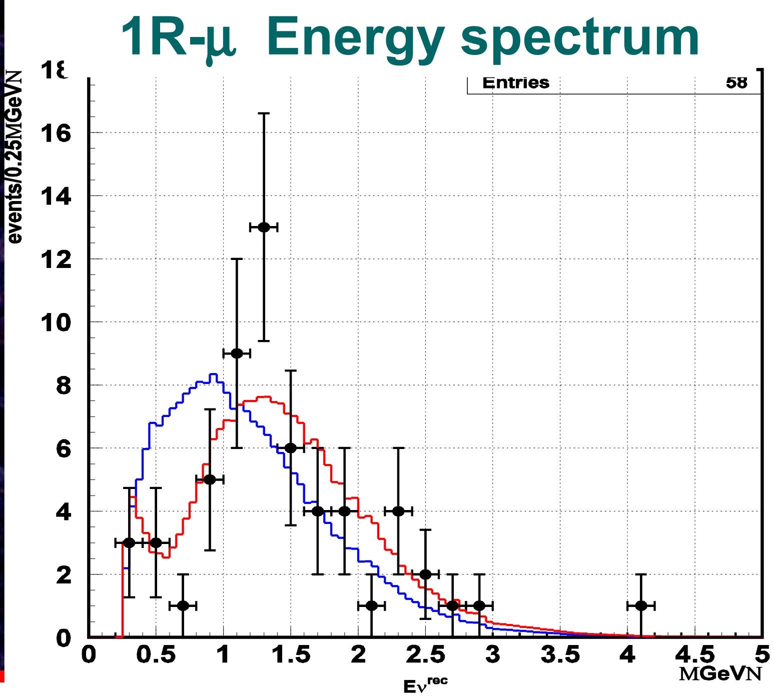
~1 event/2days



Signal of ν oscillation at K2K

- Reduction of ν_μ events
- Distortion of ν_μ energy spectrum

Final K2K Statistics



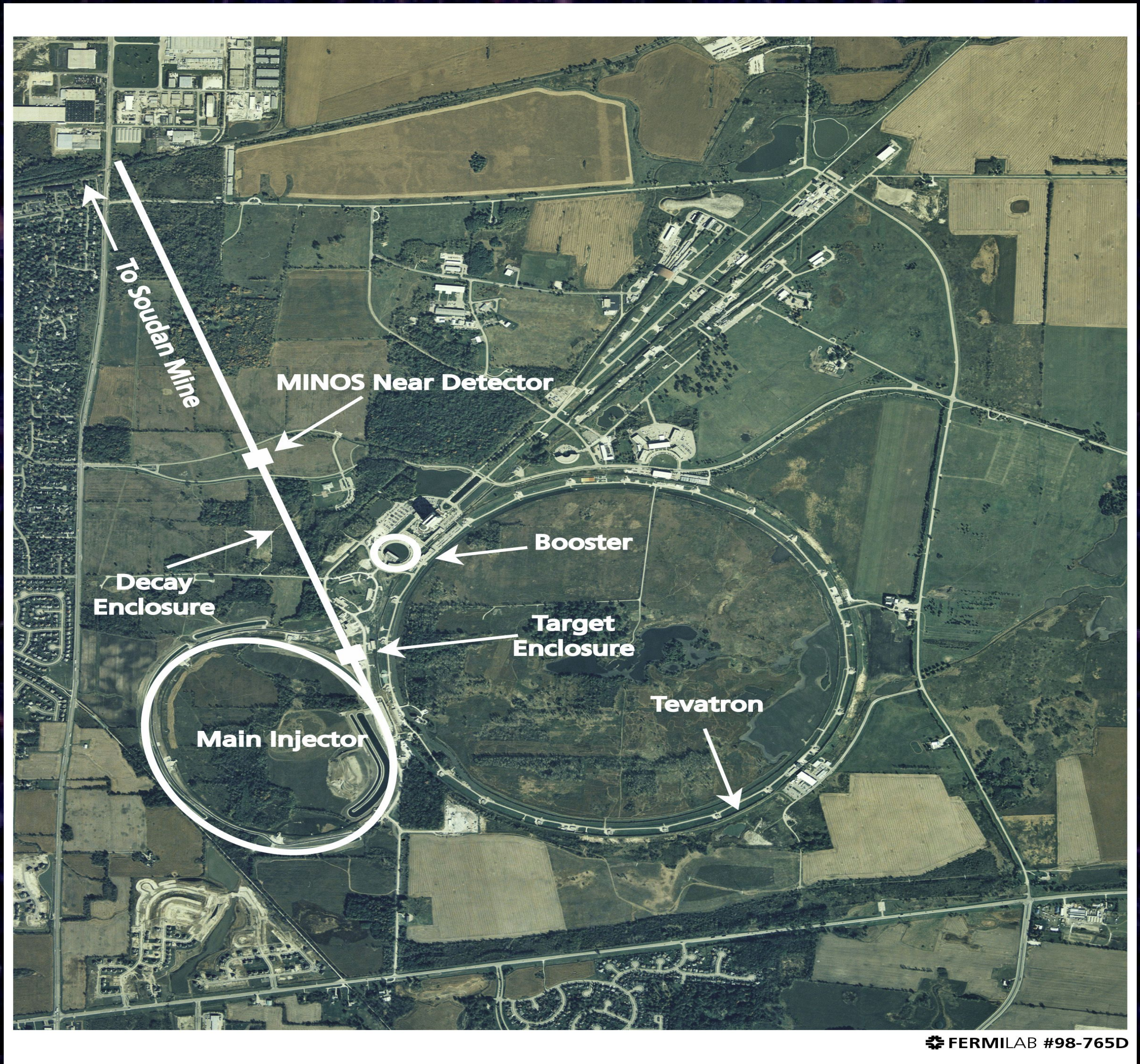
	N_{sk}^{obs}	N_{sk}^{pred}
All	112	155.9
1 ring	67	99.0
μ-like	58	90.8
e-like	9	8.2
multi-ring	45	56.8

Oscillation – disappearance – two flavors analysis

$\sin^2 2\theta = 1.19 \pm 0.23$ $\Delta m^2 = (2.55 \pm 0.40)\times10^{-3}\,\mathrm{eV}^2$

$1.88\times10^{-3} \leq \Delta m^2 \leq 3.48\times10^{-3}\ \mathrm{eV}^2$ (90%CL) for $\sin^2 2\theta=1$

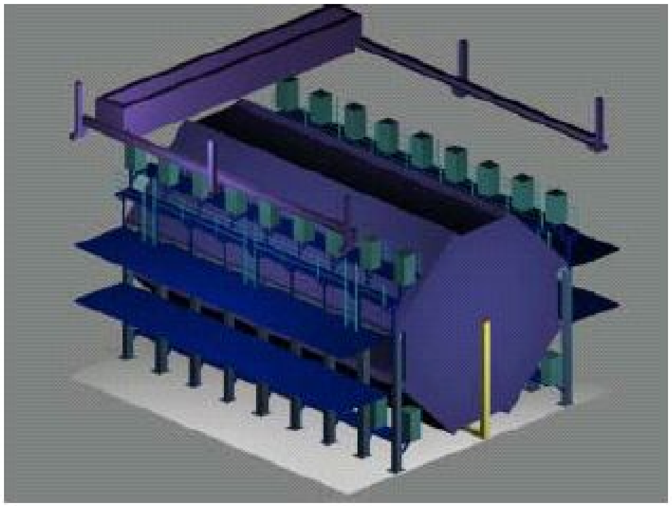
NuMI - MINOS


To Soudan Mine
MINOS Near Detector
Booster
Decay Enclosure
Target Enclosure
Main Injector
Tevatron
FERMILAB #98-765D


Soudan
Duluth
Lake Superior
Lake Michigan
MN
WI
Madison
MI
IA
Fermilab
IL
IN
MO

MINOS Detectors

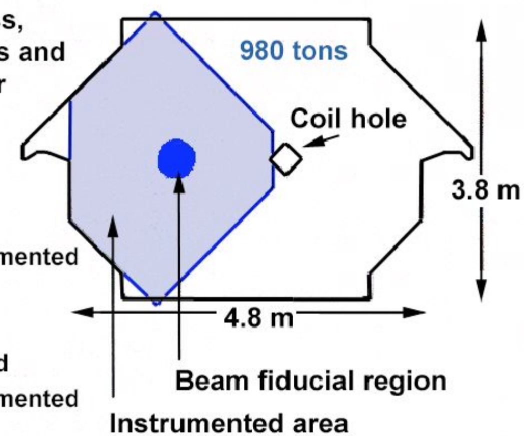
MINOS Far Detector



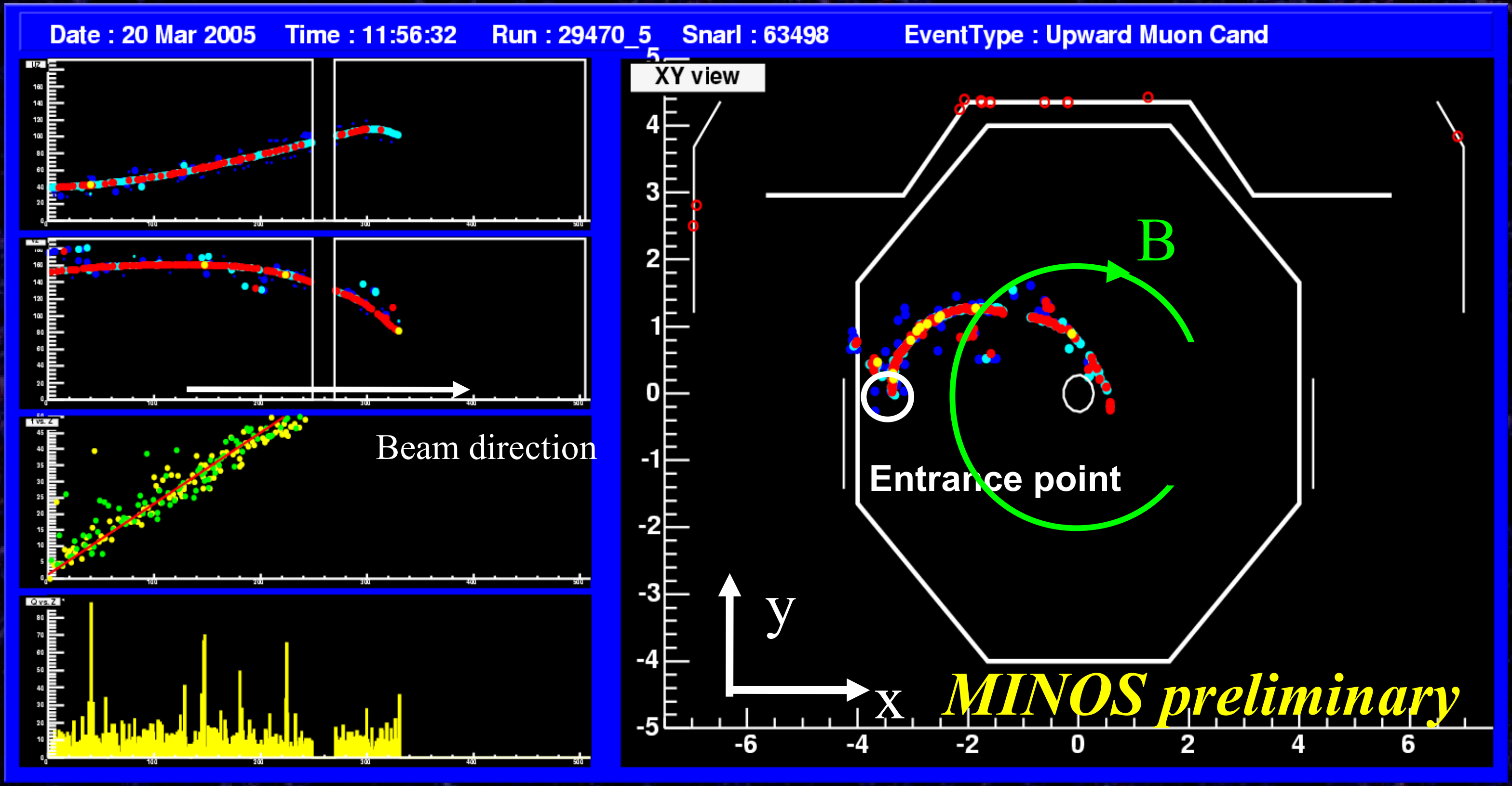
- 8m octagonal tracking calorimeter
- 486 layers of 2.54 cm Fe
- Two Supermodules (15m each)
- 1000 km of scintillator, 2000 km of WLS and clear fiber readout (25,800 m^2 of active detector planes)
- Toroidal <B>≈ 1.3T. Total mass 5.4 kT
- hadron energy : $\frac{\Delta E}{E} \approx \frac{55\%}{\sqrt{E}}$
- muon momentum : $\frac{\Delta p}{p} \approx 12\%$ (by curvature)

MINOS Near Detector

- 280 “squashed octagon” plates
- Same plate thickness, scintillator thickness and width as far detector
- Target/calorimeter section: 120 planes
  - 4/5 partial area instrumented
  - 1/5 full area instrumented
- Muon spectrometer section: 160 planes
  - 4/5 uninstrumented
  - 1/5 full area instrumented



MINOS Event



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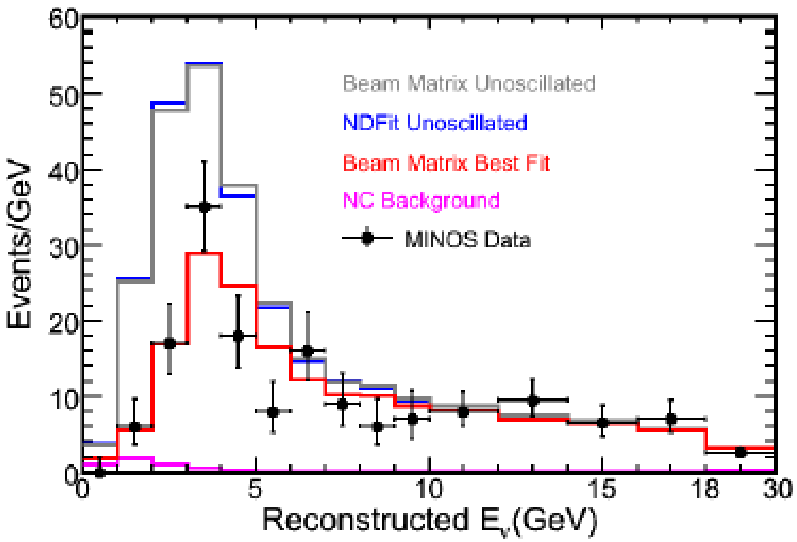
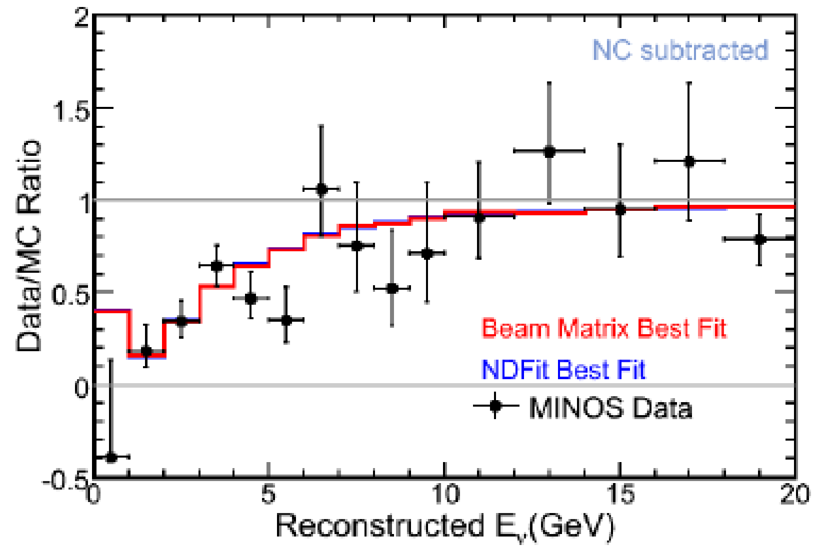
MINOS best-fit spectrum for 1.27×10^{20} POT





49% deficit below 10GeV : 6.2σ significance

Fit made to oscillation hypothesis yields:

$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}(\text{stat}+\text{syst})\times 10^{-3}\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}(\text{stat}+\text{syst})$$

Normalization = 0.98

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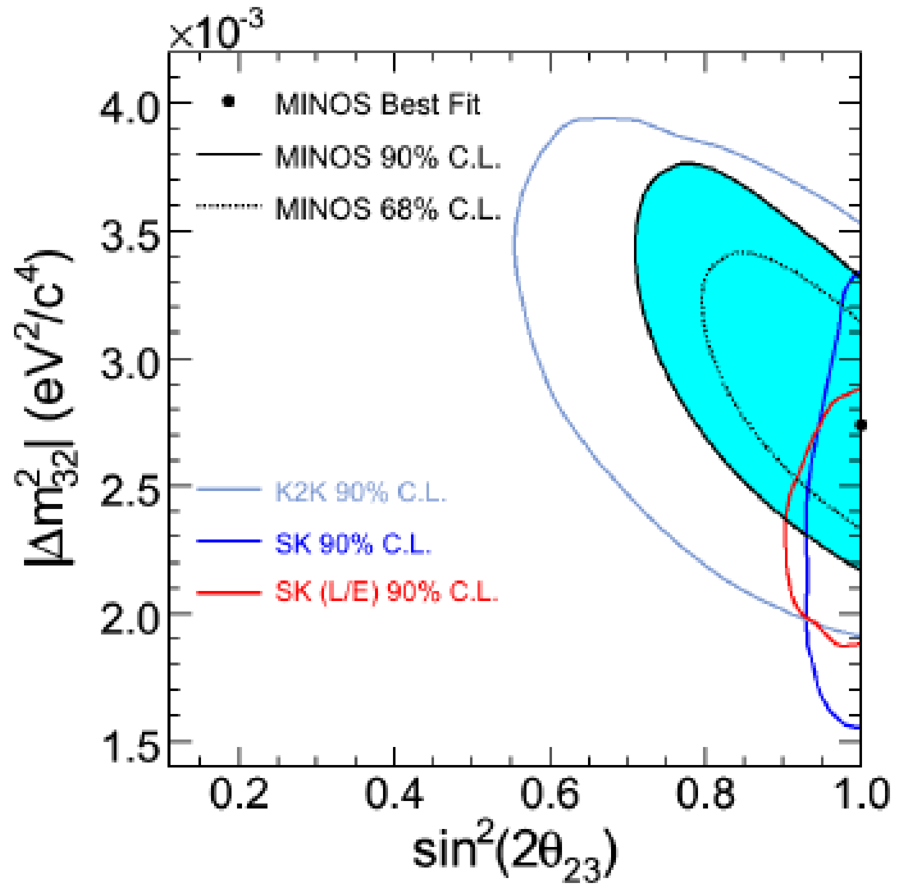
Slide from Geoff Pearce's talk at ICHEP06

Allowed Regions from MINOS, K2K



$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\,(\text{stat}+\text{syst})\times 10^{-3}\,\text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\,(\text{stat}+\text{syst})$$

Constrained to $\sin^2(2\theta_{23}) \leq 1$

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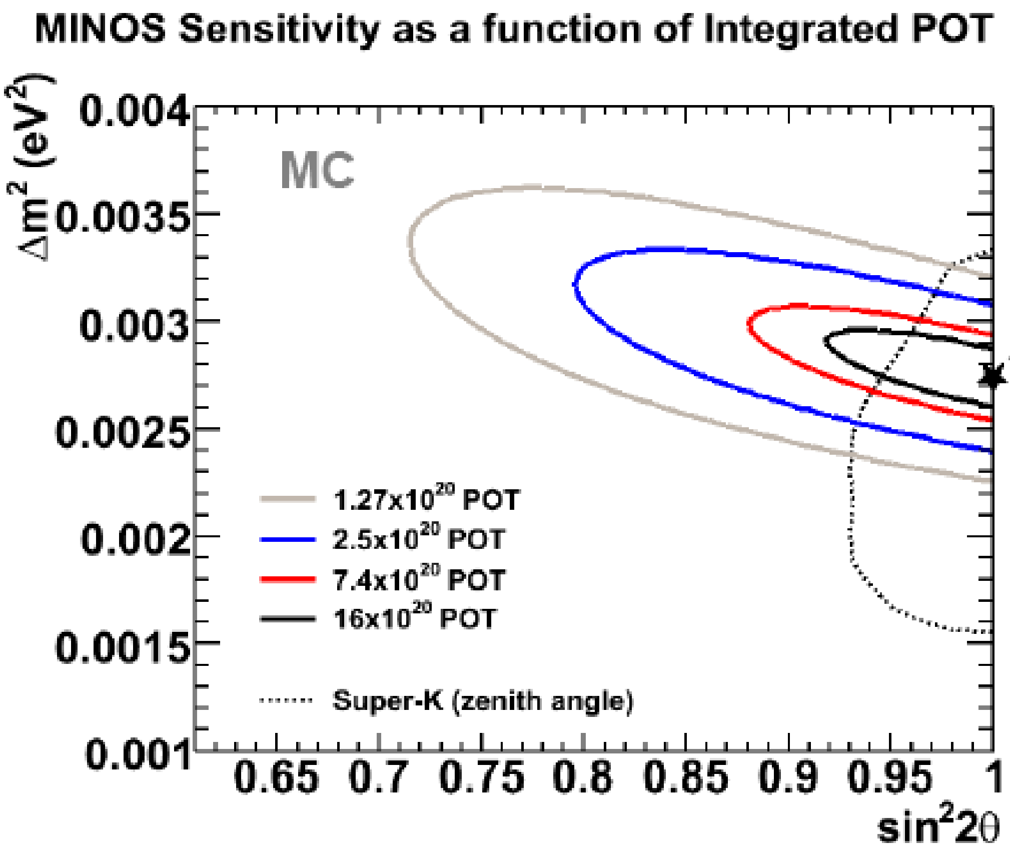
Projected sensitivity of MINOS



Input parameters

$|\Delta m^2_{32}| = 2.74 \times 10^{-3}\, eV^2$

$\sin^2 2\theta_{23} = 1.00$

90% contours

Statistical errors only