Nobel Prizes for Neutrinos – the last two, and the next one?

Dave Wark

2015 Prague ν Colloquium

November 5th, 2015

In the very early days of neutrino physics, there was a question. . .

Are neutrinos and anti-neutrinos the same thing?

PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $Cl^{37}(\bar{\nu},e^-)A^{37}$ Reaction*

RAYMOND DAVIS, JR.
Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York

(Received September 21, 1954)

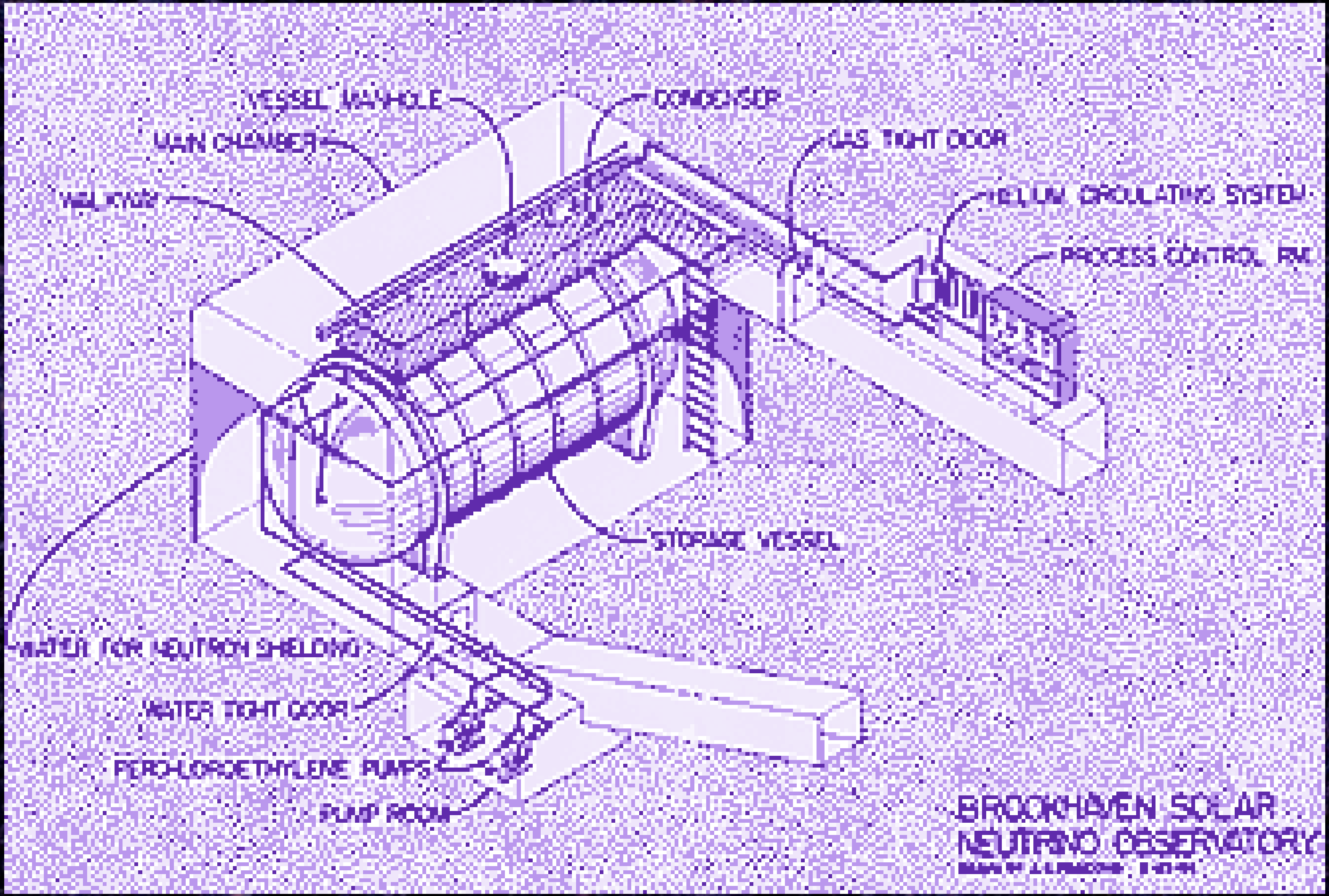
Tanks containing 200 and 3900 liters of carbon tetrachloride were irradiated outside of the shield of the Brookhaven reactor in an attempt to induce the reaction $Cl^{37}(\bar{\nu},e^-)A^{37}$ with fission product antineutrinos. The experiments serve to place an upper limit on the antineutrino capture cross section for the reaction of 2×10^{-42} cm² per atom. Cosmic-ray-induced A^{37} was observed and the production rate measured at 14 100 feet altitude and sea level. Measurements with the 3900-liter container shielded from cosmic rays with 19 feet of earth permit placing an upper limit on the neutrino flux from the sun.

- *Ray deployed large tanks containing carbon tetrachloride near reactors.*
- *If $\bar{\nu} = \nu$ you would expect to see ^{37}Ar produced by this reaction.*
- *By 1957 enough sensitivity had been reached to show that the rate was too small, from which it was concluded that $\bar{\nu} \neq \nu$.*
- *This is wrong, because P is violated in weak interactions!*

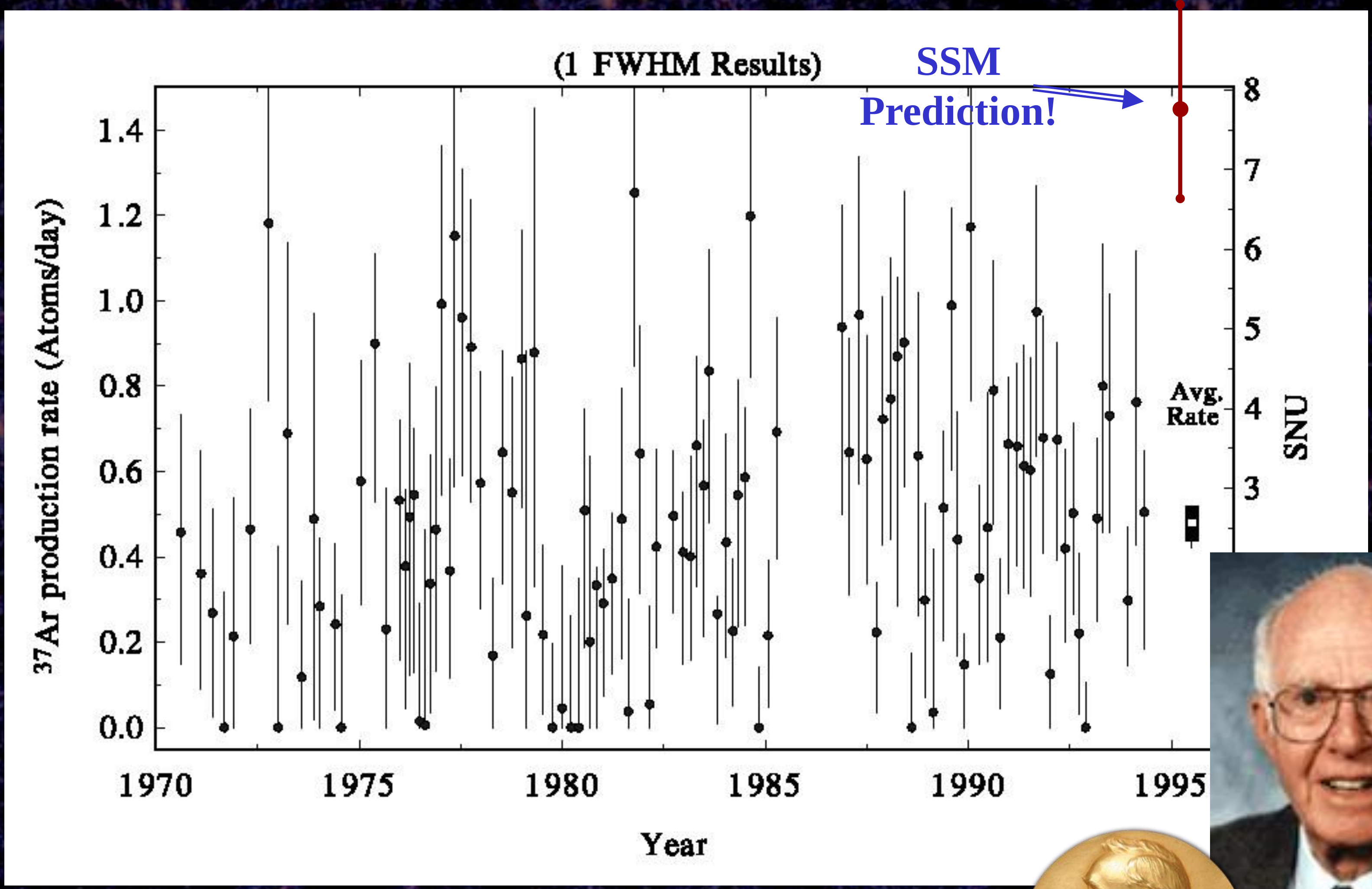
Ray Davis

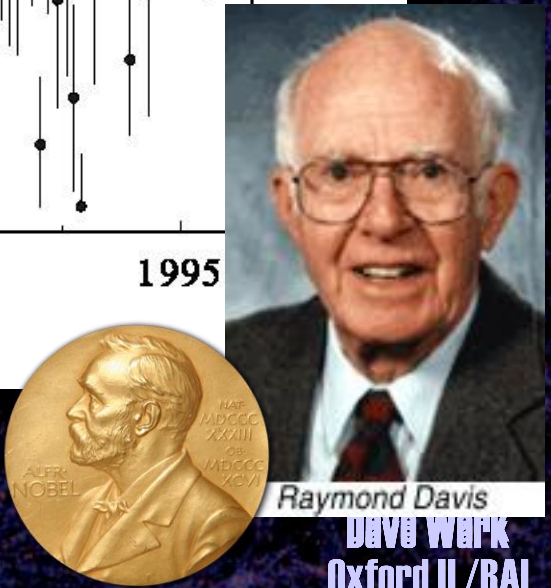
John Bahcall

Where it all began – the Davis Experiment



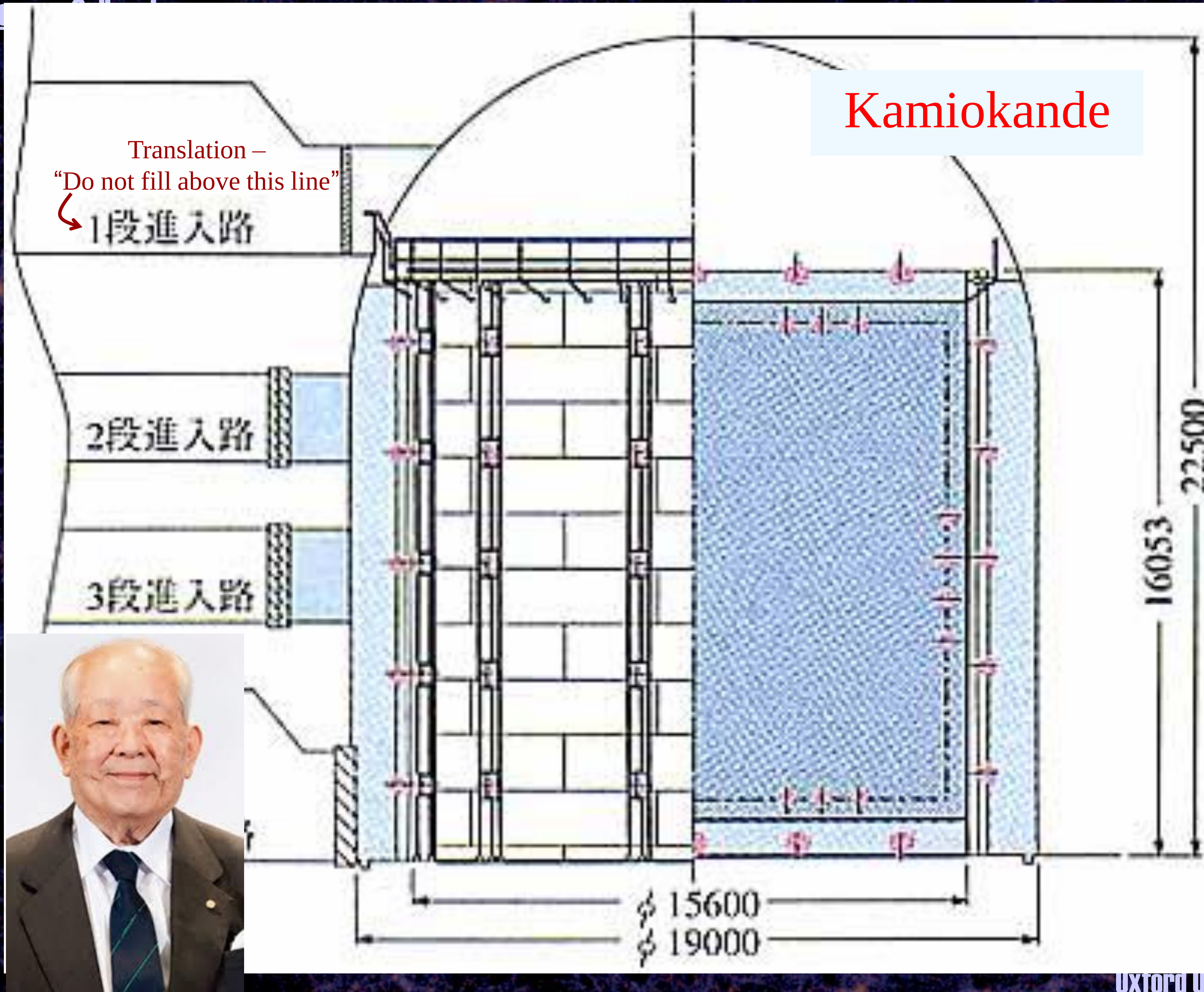
A long-running experiment. . .

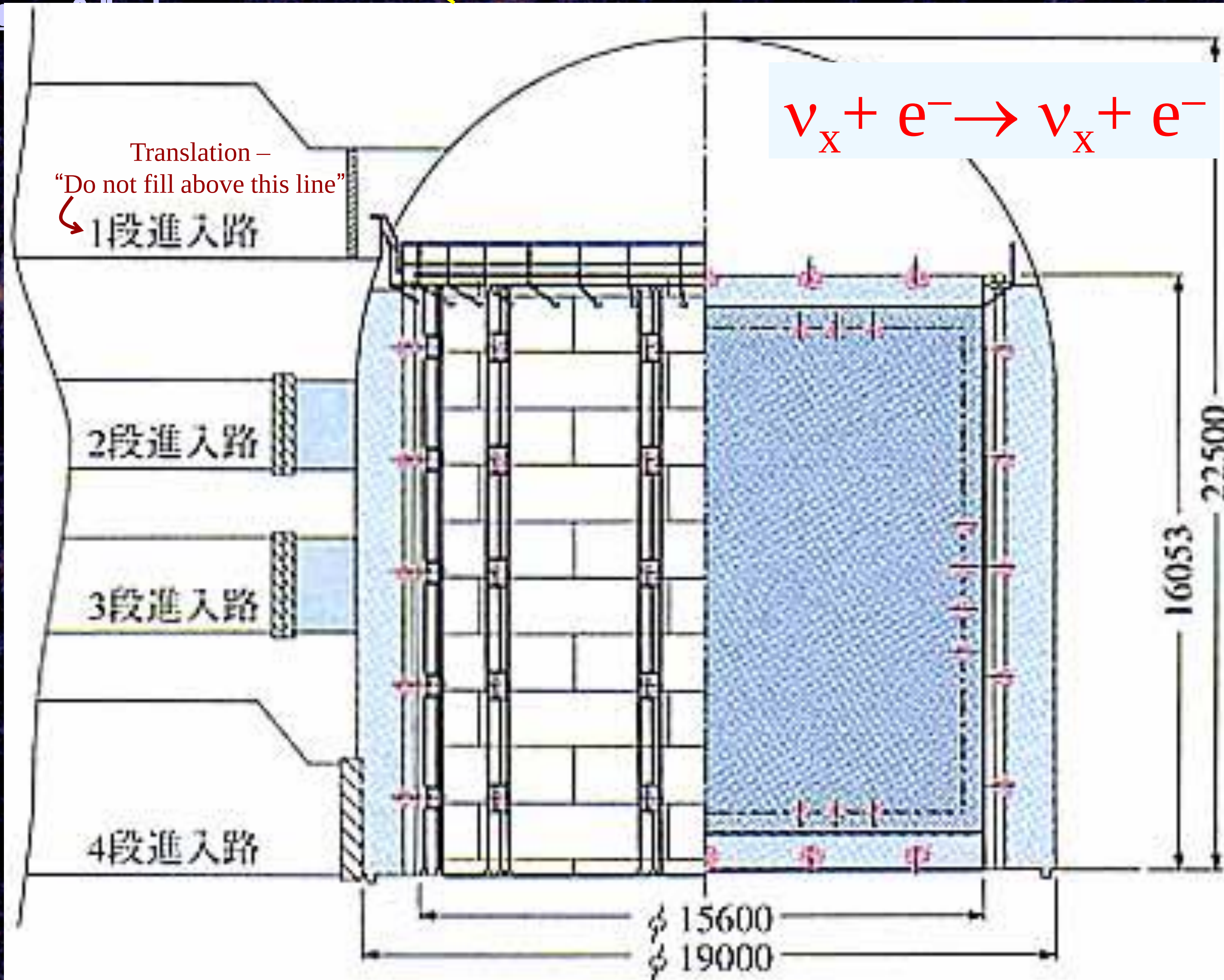


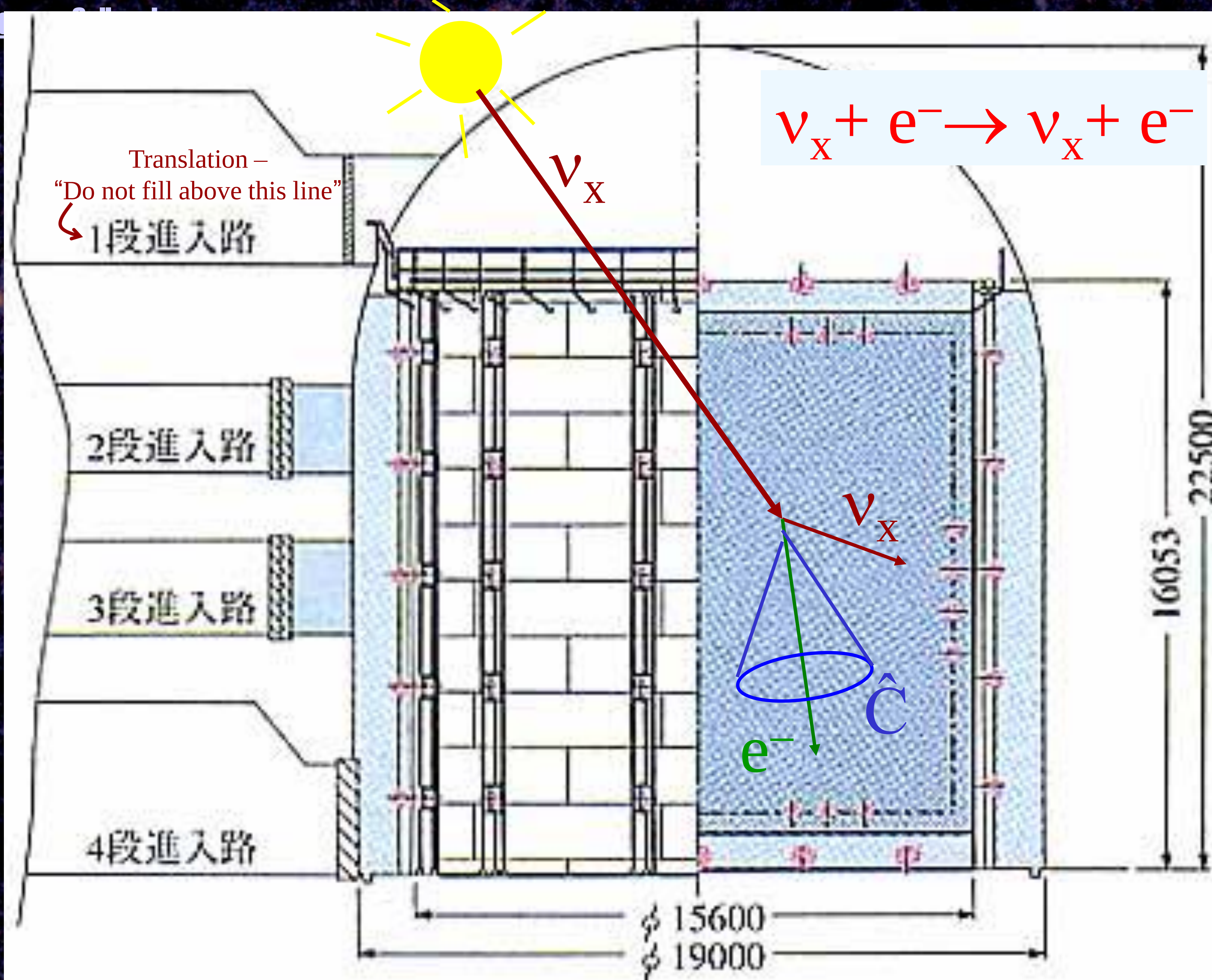


Kamiokande

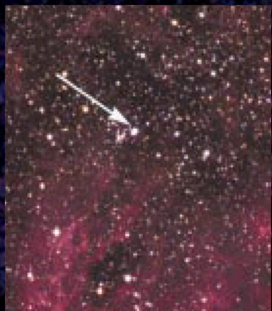
Translation –
“Do not fill above this line”




$\nu_x + e^- \rightarrow \nu_x + e^-$
Translation –
“Do not fill above this line”
1段進入路
2段進入路
3段進入路
4段進入路
22500
16053
ϕ 15600
ϕ 19000



$\nu_x + e^- \rightarrow \nu_x + e^-$
Translation –
"Do not fill above this line"
1段進入路
2段進入路
3段進入路
4段進入路
ν_x
ν_x
e^-
$\hat{C}$
16053
22500
ϕ 15600
ϕ 19000

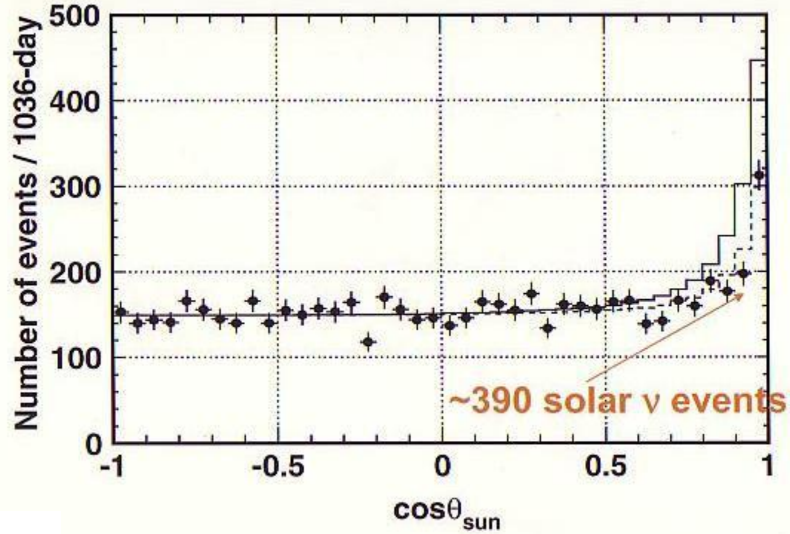


February
1984

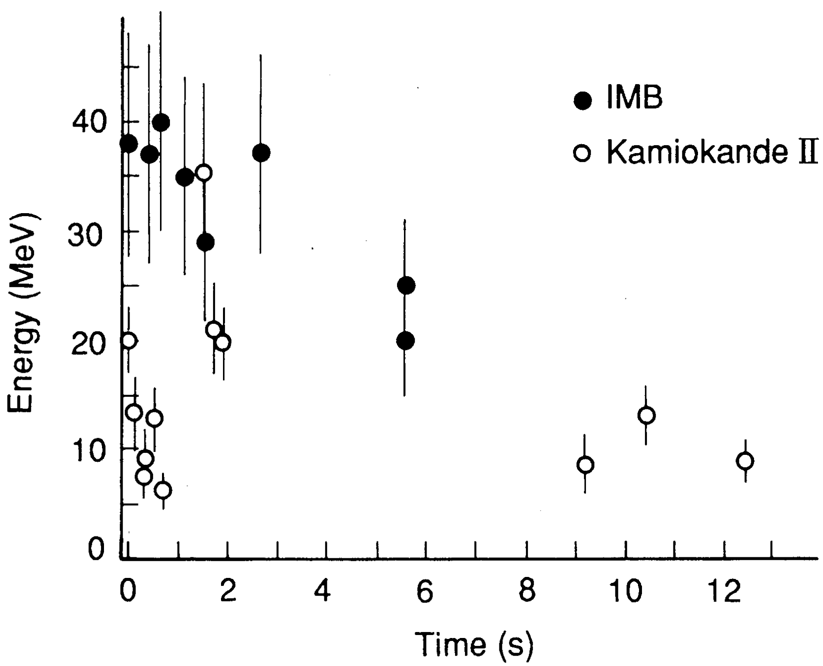
March
8,1987

Solar neutrinos (Kamiokande-III)

Dec. 28, 1990 – Feb. 6, 1995 (1036 days)



Y.Fukuda et al., Phys. Rev. Lett. 77 (1996) 1683



Dave Wark
Oxford U./RAL

53 Years of Neutrino Mixing…

Progress of Theoretical Physics, Vol. 28, No. 5, November 1962

Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya

(Received June 25, 1962)

a) The weak neutrinos must be re-defined by a relation

$=\nu_1 \cos\delta - \nu_2 \sin\delta,$

MNSP Matrix was the origin of the CKM Matrix…

weak neutrinos:

ν_e, ν_μ, ν_τ

Бруно Понтекорво

1967 – Bruno Pontecorvo then considered the effects of all different types of oscillations in light of what was then known, and pointed out ***before any results from the Davis experiment were known*** that the rate in that experiment could be expected to be reduced by a factor of two!

U_{PMNS}: Pontecorvo–Maki–Nakagawa–Sakata matrix

Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

If only two neutrinos contribute:

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

Originally not thought a very promising explanation of the Solar Neutrino Problem. . .

…but then along comes the MSW effect!

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

Москва, Главный почтамт п/я 79. Head Post Office, P.O. Box 79, Moscow, USSR

№ 994/51 April 6/10 1972

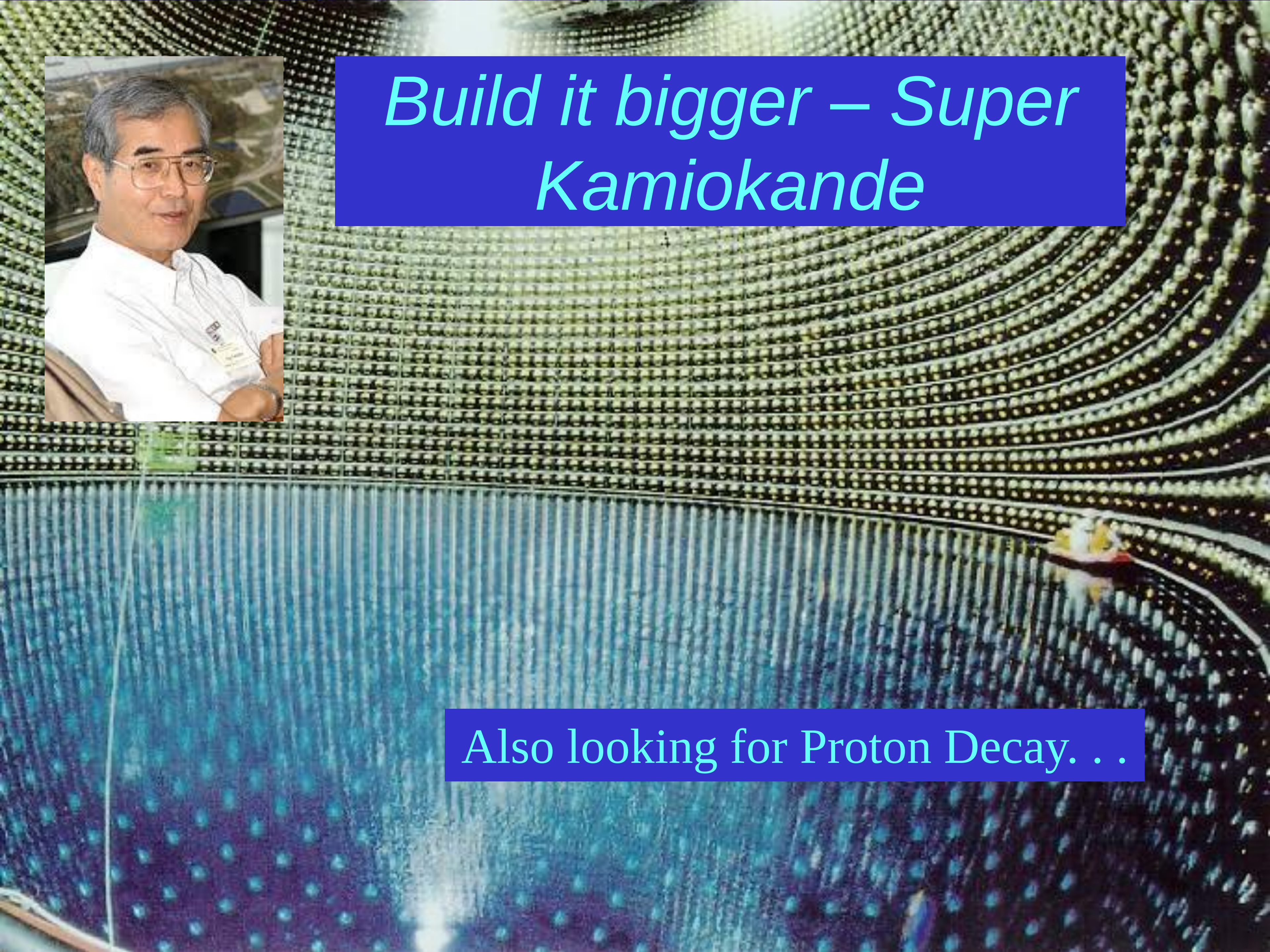
Dear Prof. Bahcall,

Thank you very much for your letter and the abstract of the new Davis investigation the numerical results of which I did not know. It starts to be really interesting! It would be nice if all this will end with something unexpected from the point of view of particle physics. Unfortunately, it will not be easy to demonstrate this, even if nature works that way.

B.Pontecorvo

BMP/nn

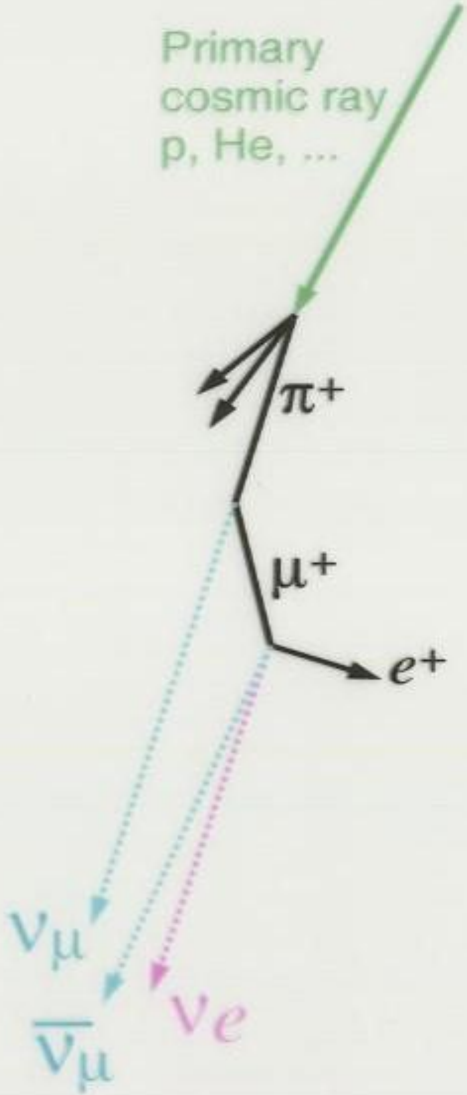
After the results of the gallium experiments were known it was widely assumed that the solar neutrino problem was solved by neutrino oscillations (see Bahcall and Bethe, PRL 65, p 2233, 1990), but there was no proof.

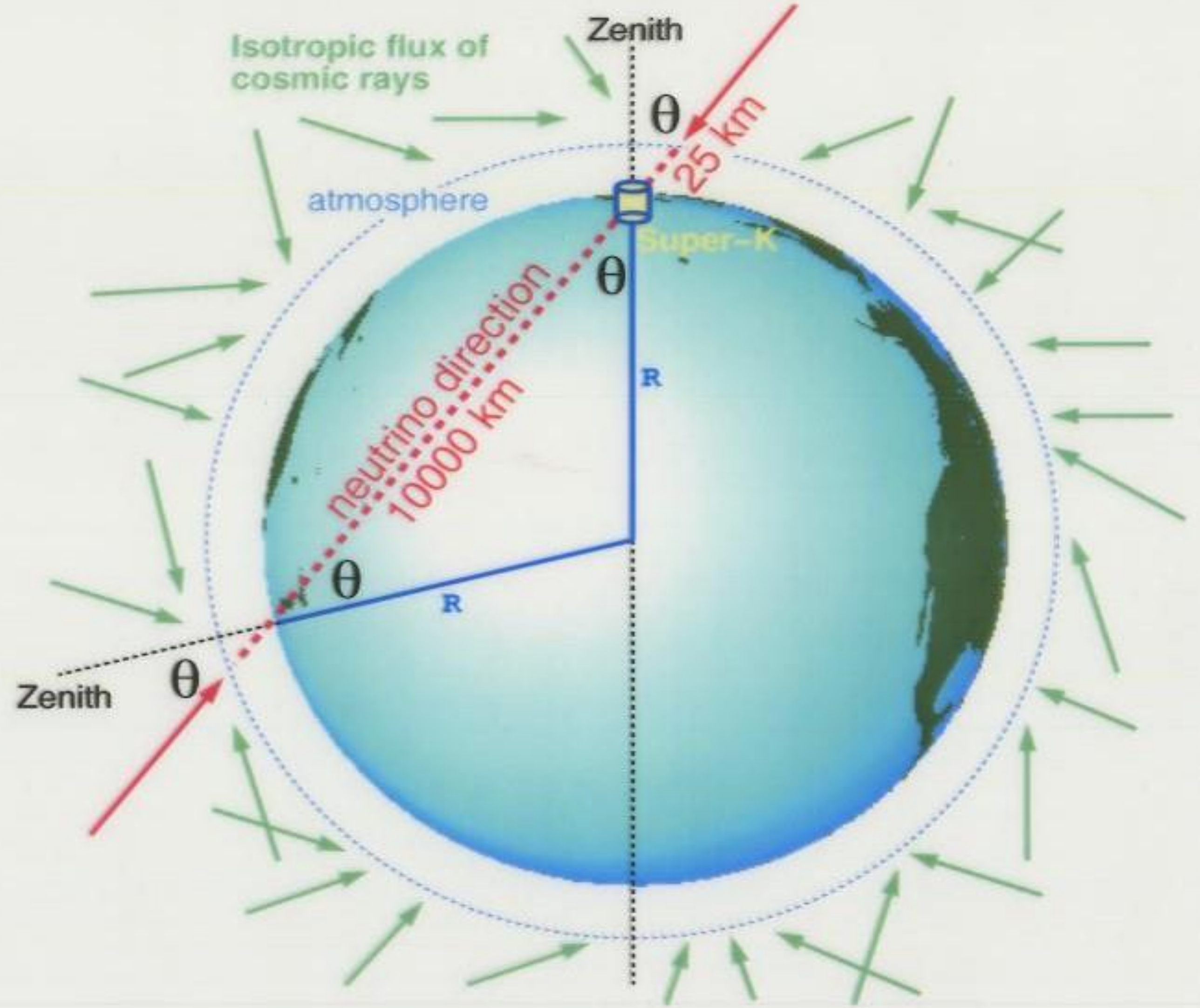


Build it bigger – Super Kamiokande

Also looking for Proton Decay. . .

ATMOSPHERIC NEUTRINOS

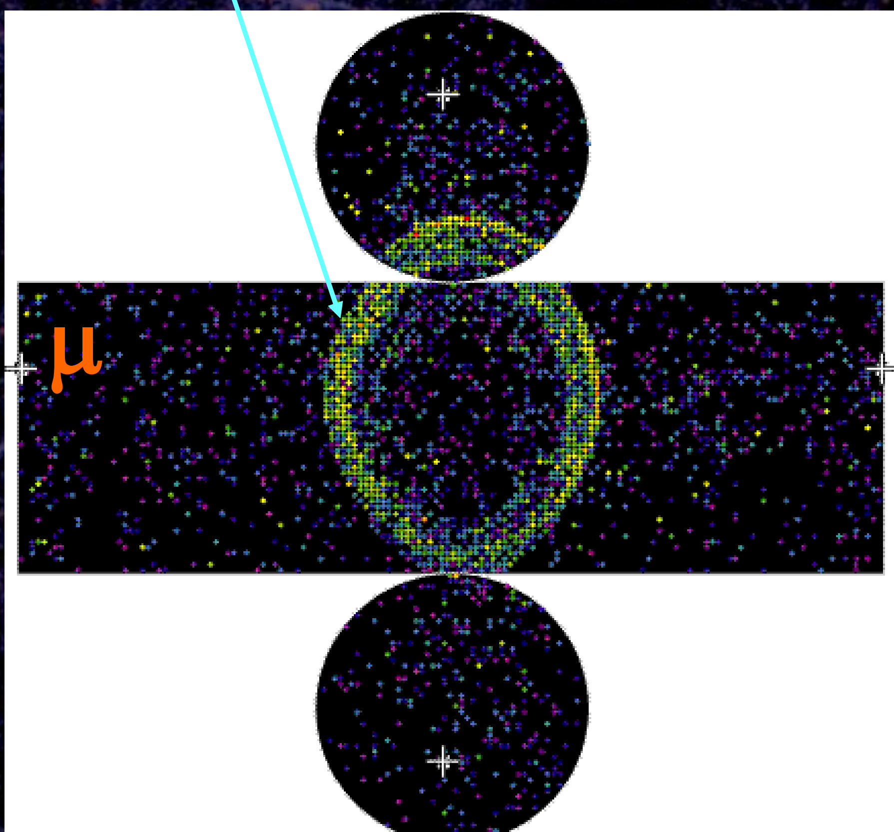


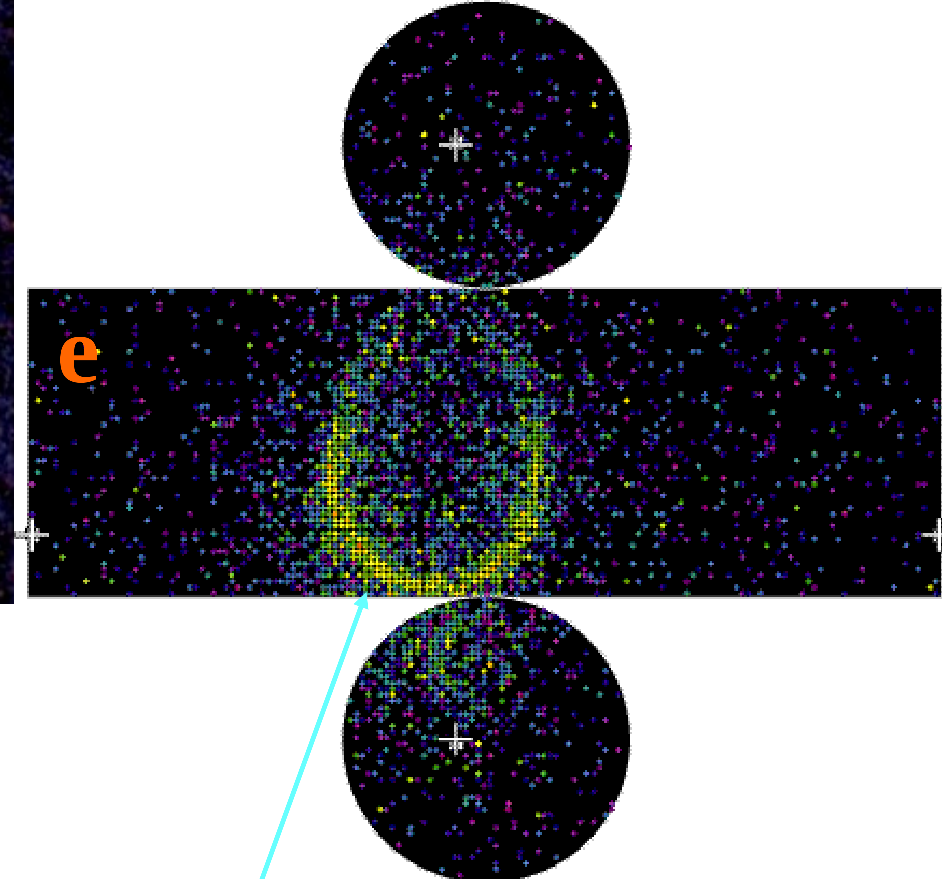


Ratio of $\nu_\mu/\nu_e \sim 2$
(for E_ν < few GeV)

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

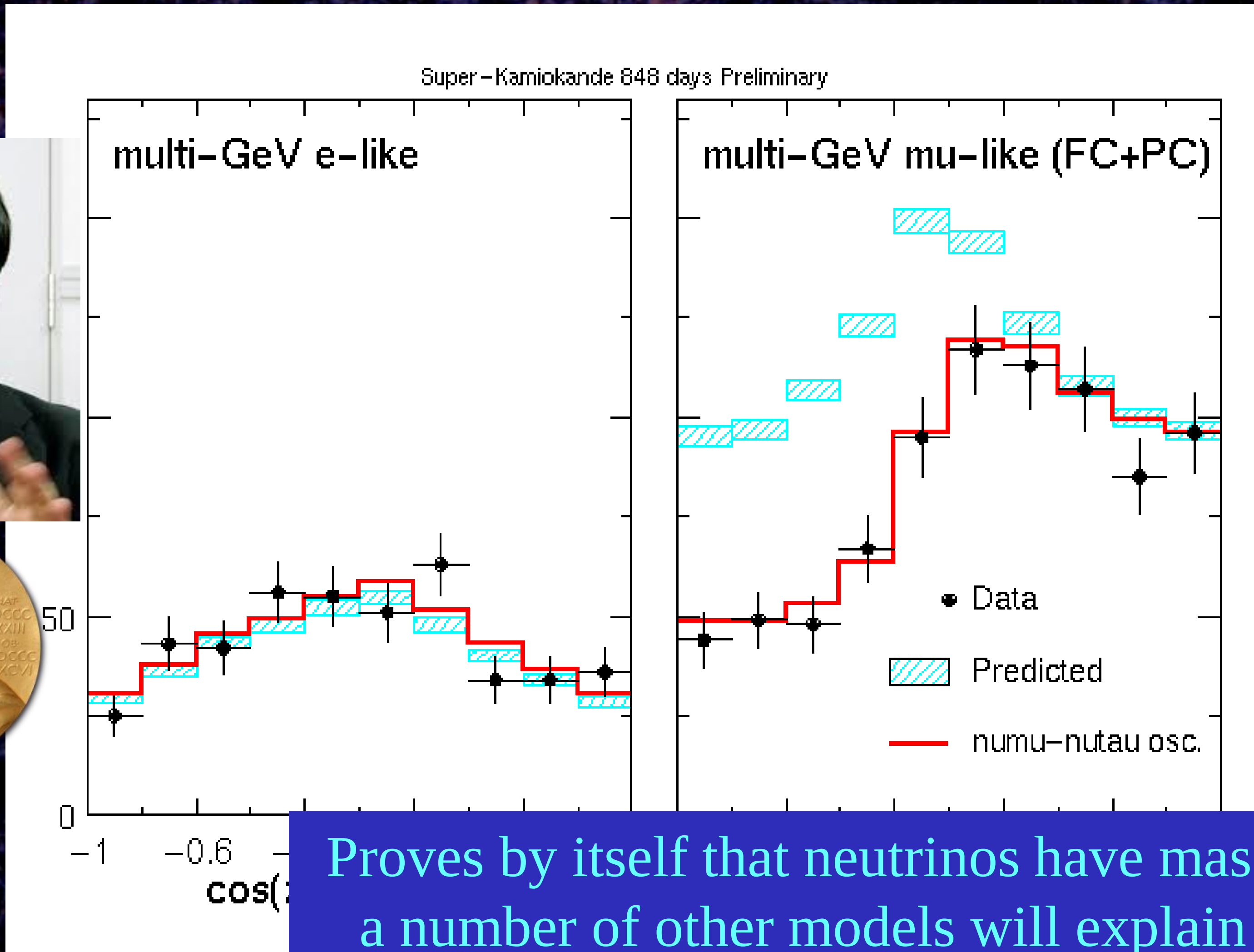
ν_μ CC produces a μ, which produces a sharp ring





ν_e CC produces an electron, which produces a “fuzzy” ring

SK atmospheric ν data as a function of zenith angle



Proves by itself that neutrinos have mass, but a number of other models will explain this data without invoking neutrino oscillations. . .

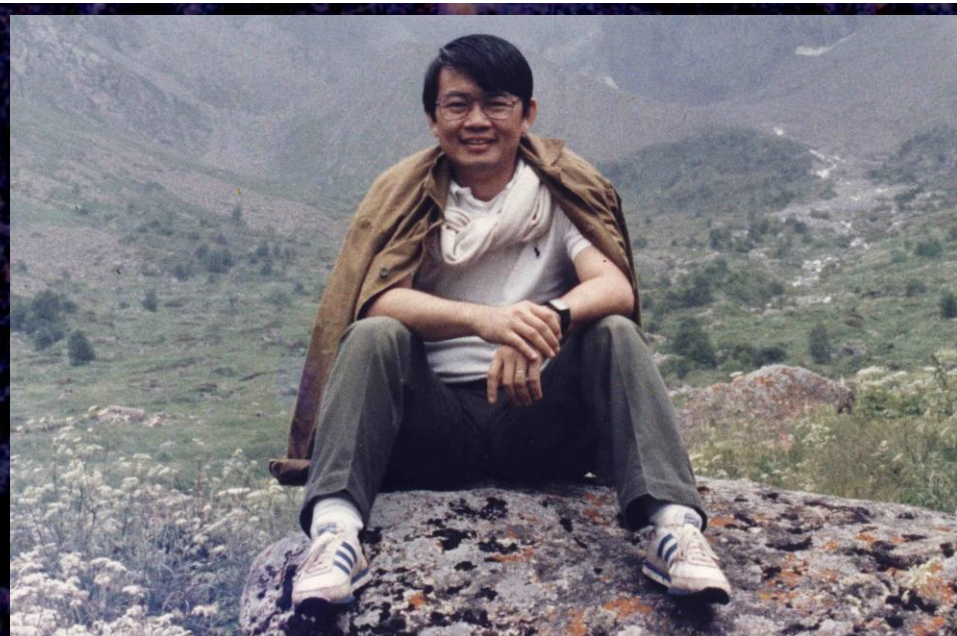
VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh



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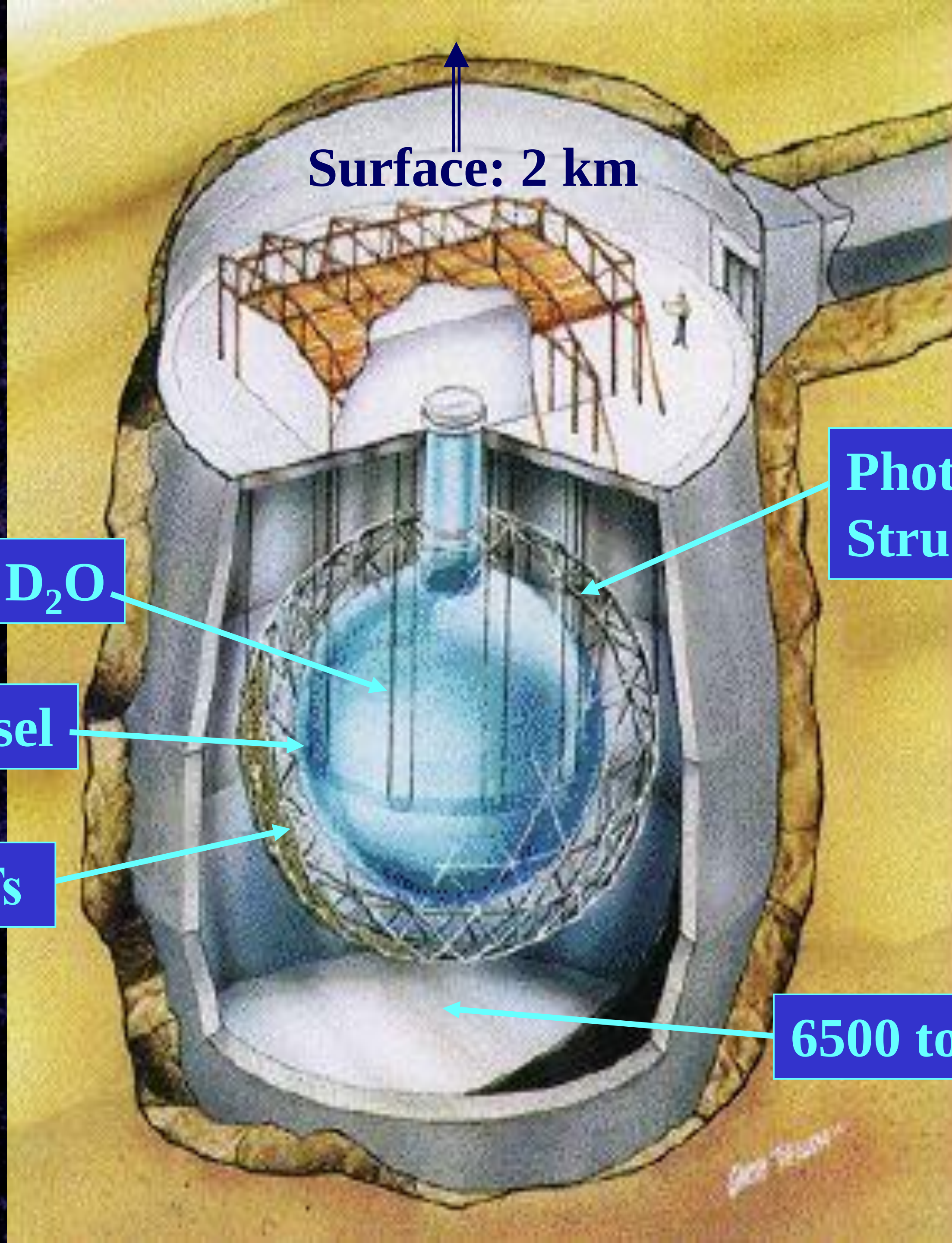
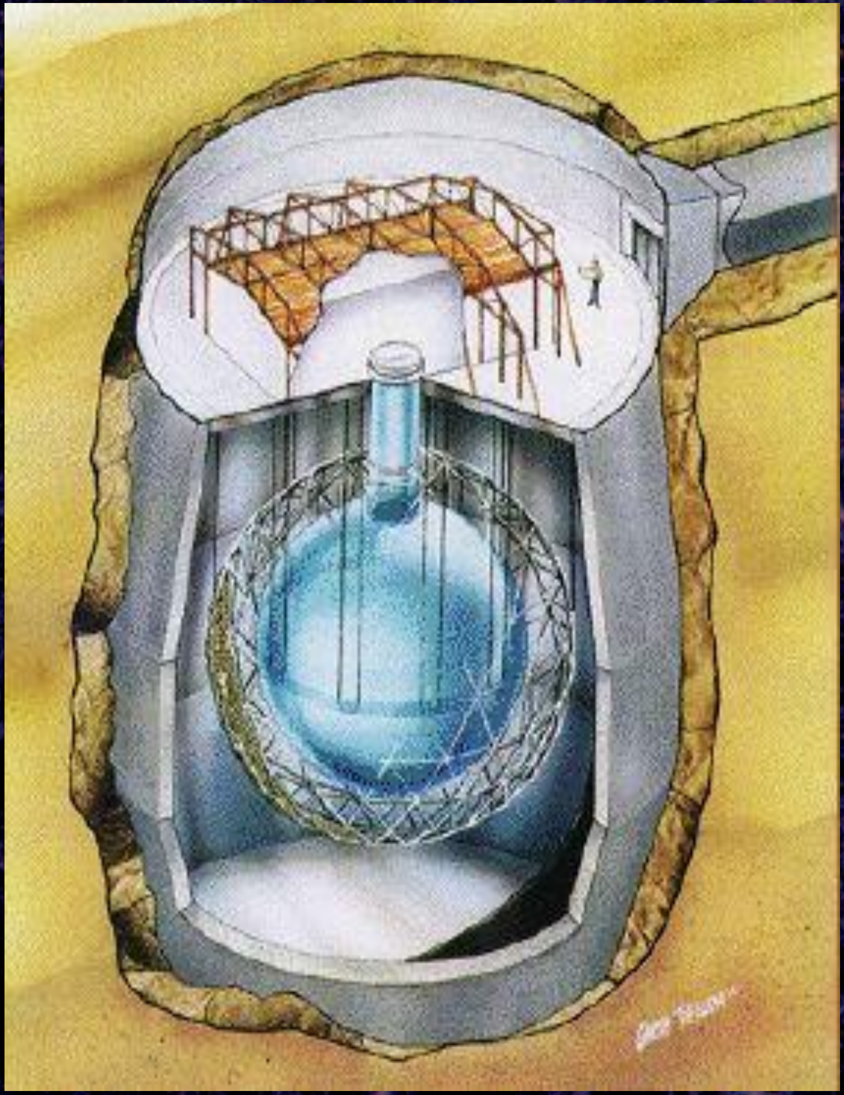
Oxford U./RAL



Surface: 2 km
Phototube Support Structure (PSUP)
1000 tonnes D_2O
Acrylic Vessel
10^4 8” PMTs
6500 tonnes H2O

Proof of flavour change - 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

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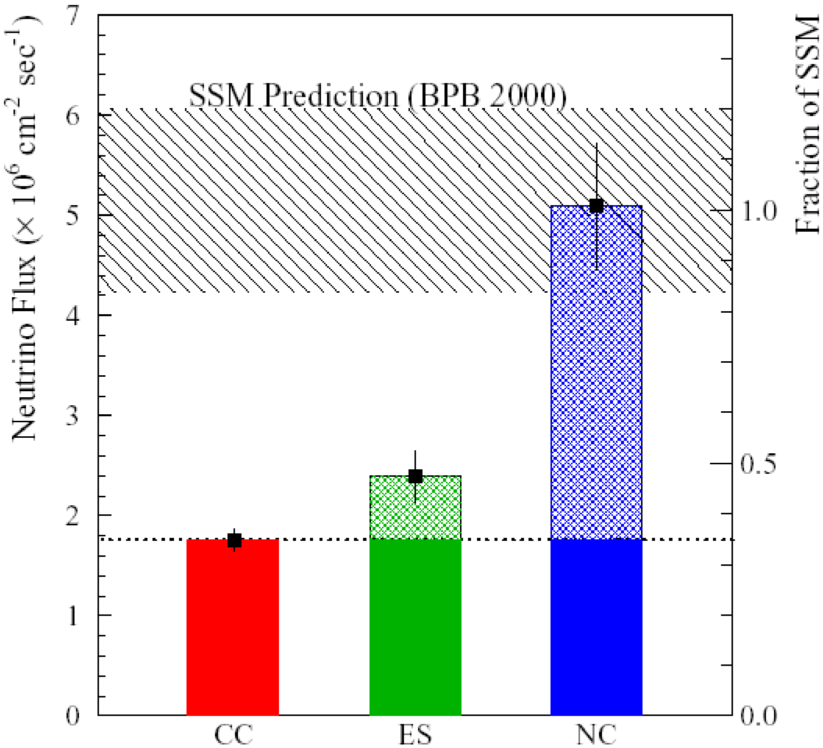
Measured SNO Fluxes

Assuming ^{8}B energy spectrum ...



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

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

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

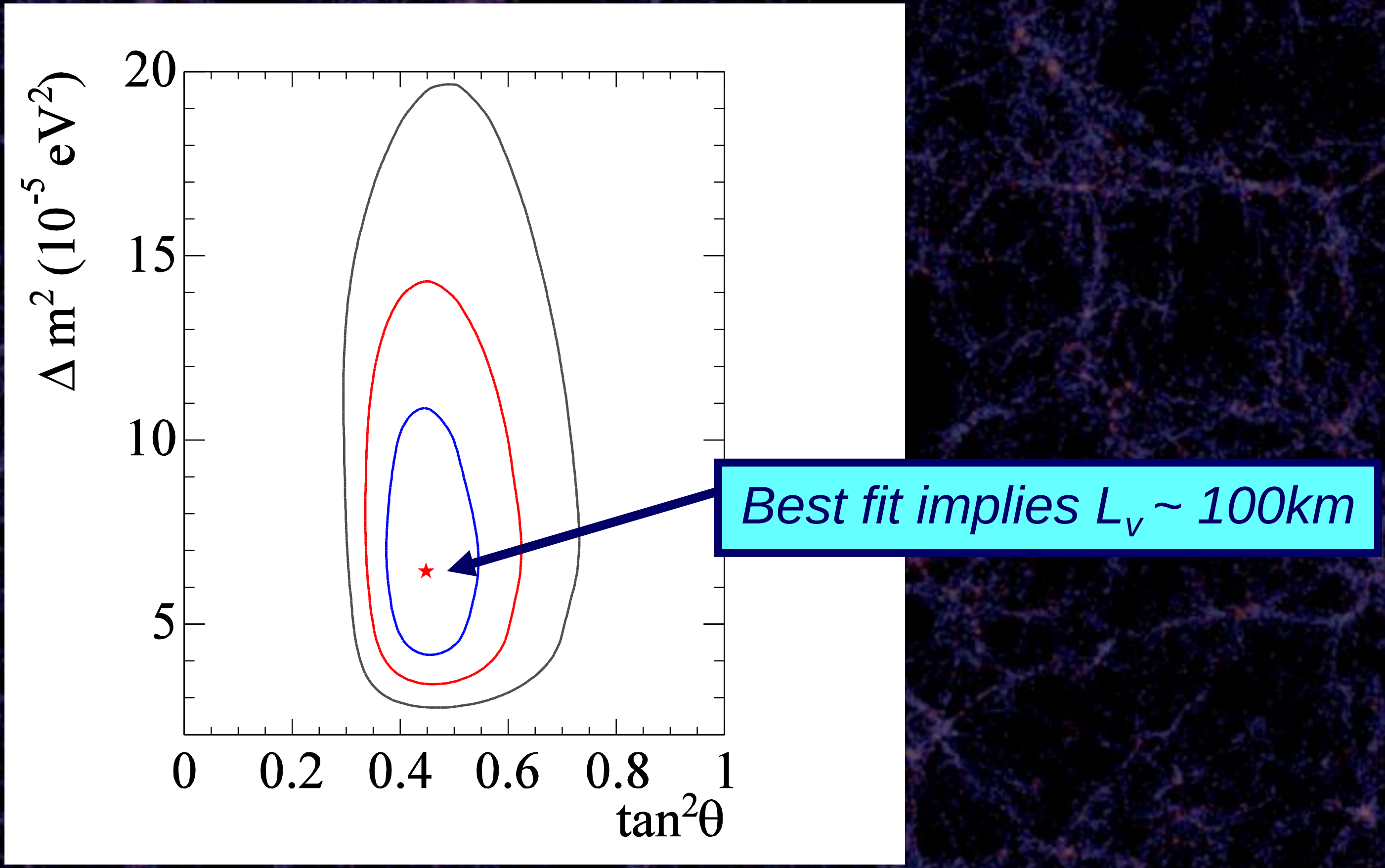
$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{sys.})$$

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

NC flux in agreement with SSM prediction!

But actually the job wasn't done. . .

Global Solar Analysis with SNO 391-day salt data

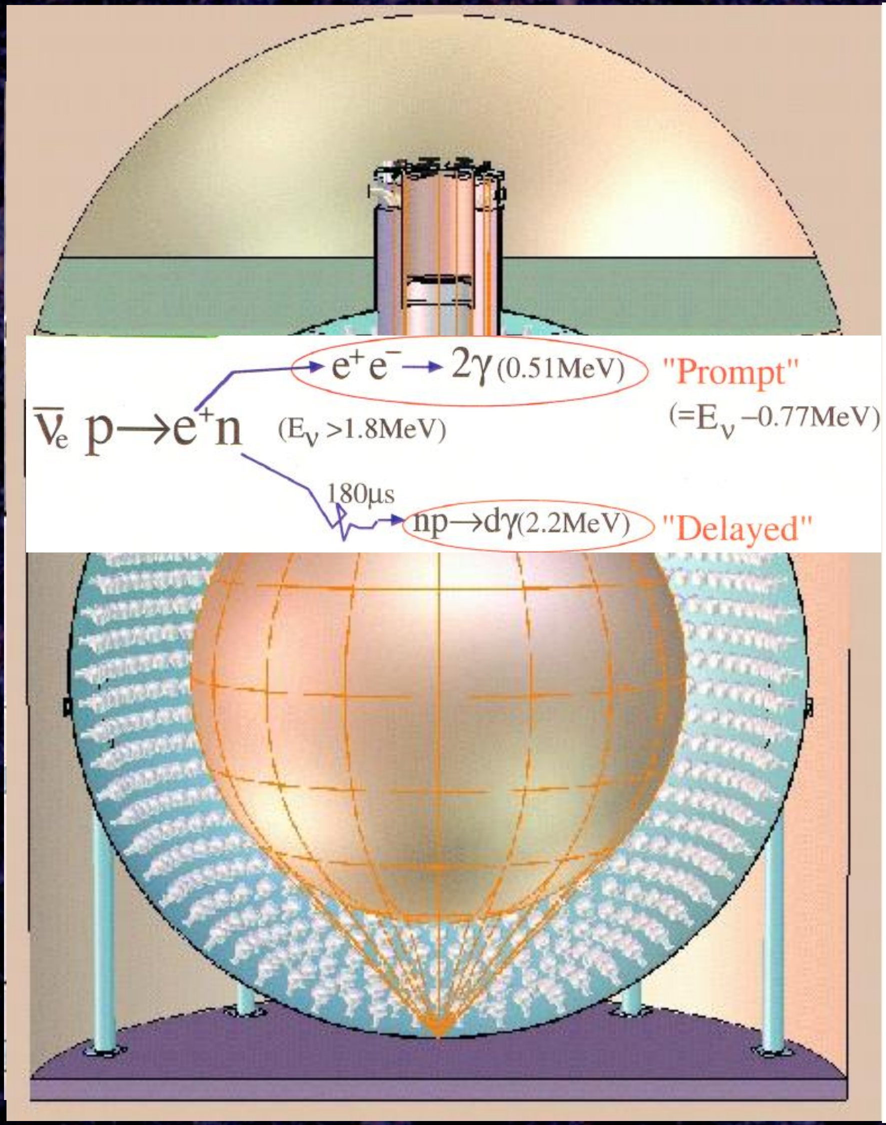


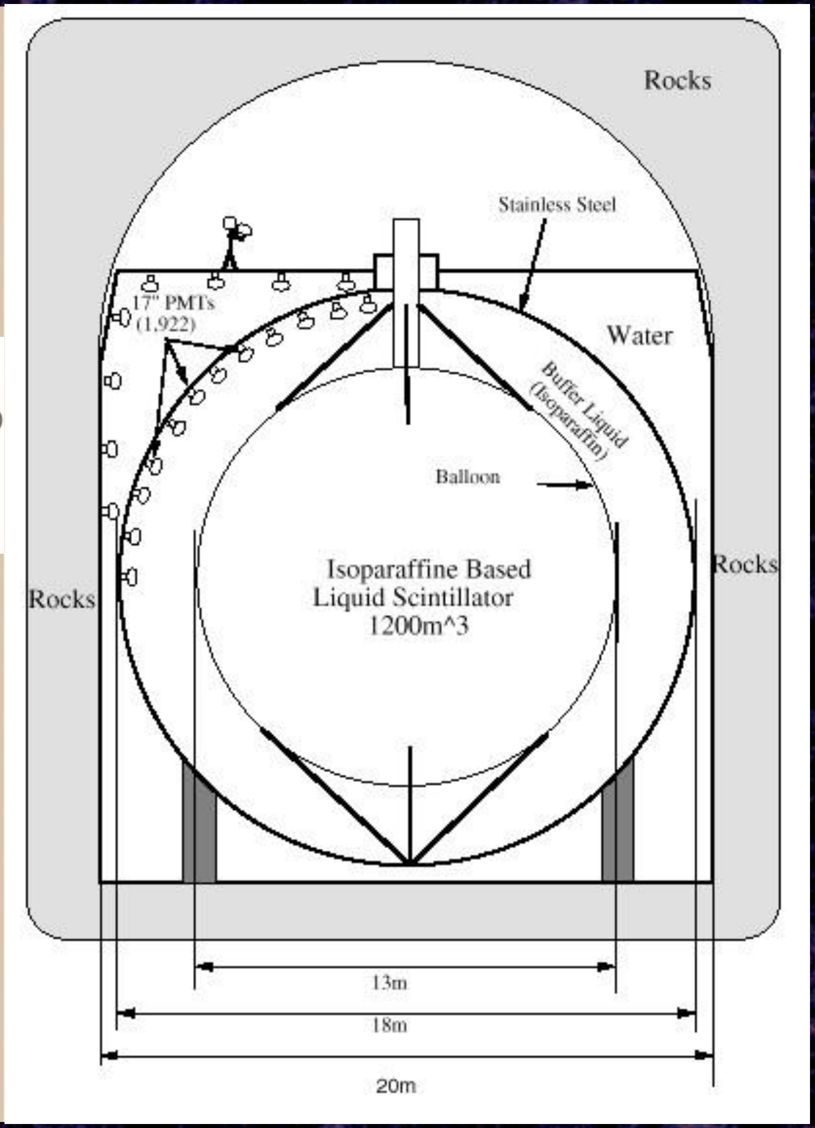
SNO finds:

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

- *Solar suppression factor > 2 for L >> L_ν ⇒ MSW effect*
- *Possible to observe on Earth?*

Solar oscillations on Earth - KamLAND





Sum over all Japanese power reactors...

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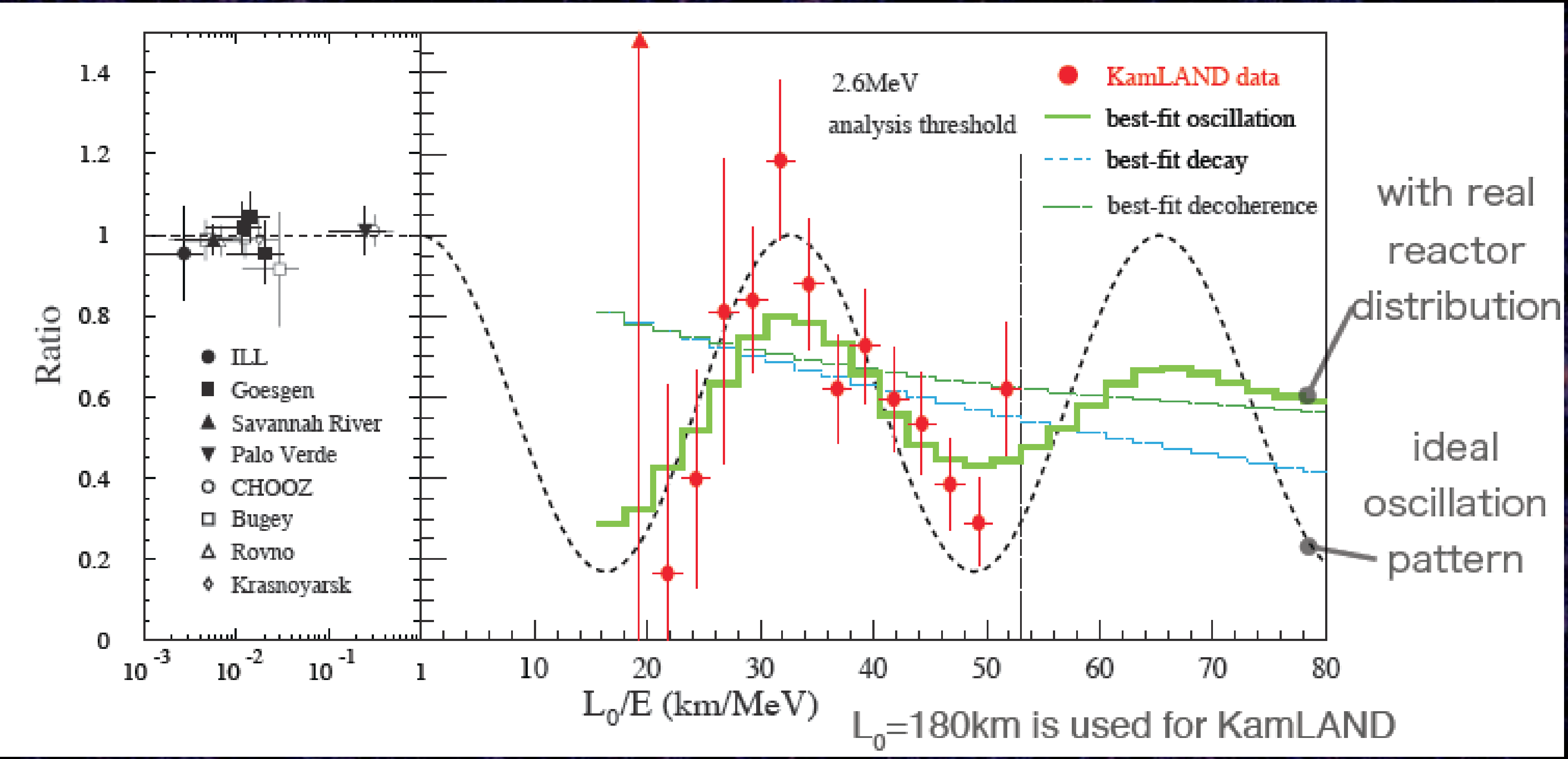
Solar oscillations on Earth - KamLAND

Slides from S. Enomoto's talk at WIN05



Proved (with other results) that neutrinos oscillate…

…or at least do a damned fine impression.

How will we win the next Nobel prize?

- Not just greedy for attention, I mean what measurements in ν physics are so important that everyone will care?

Three neutrino mixing.

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

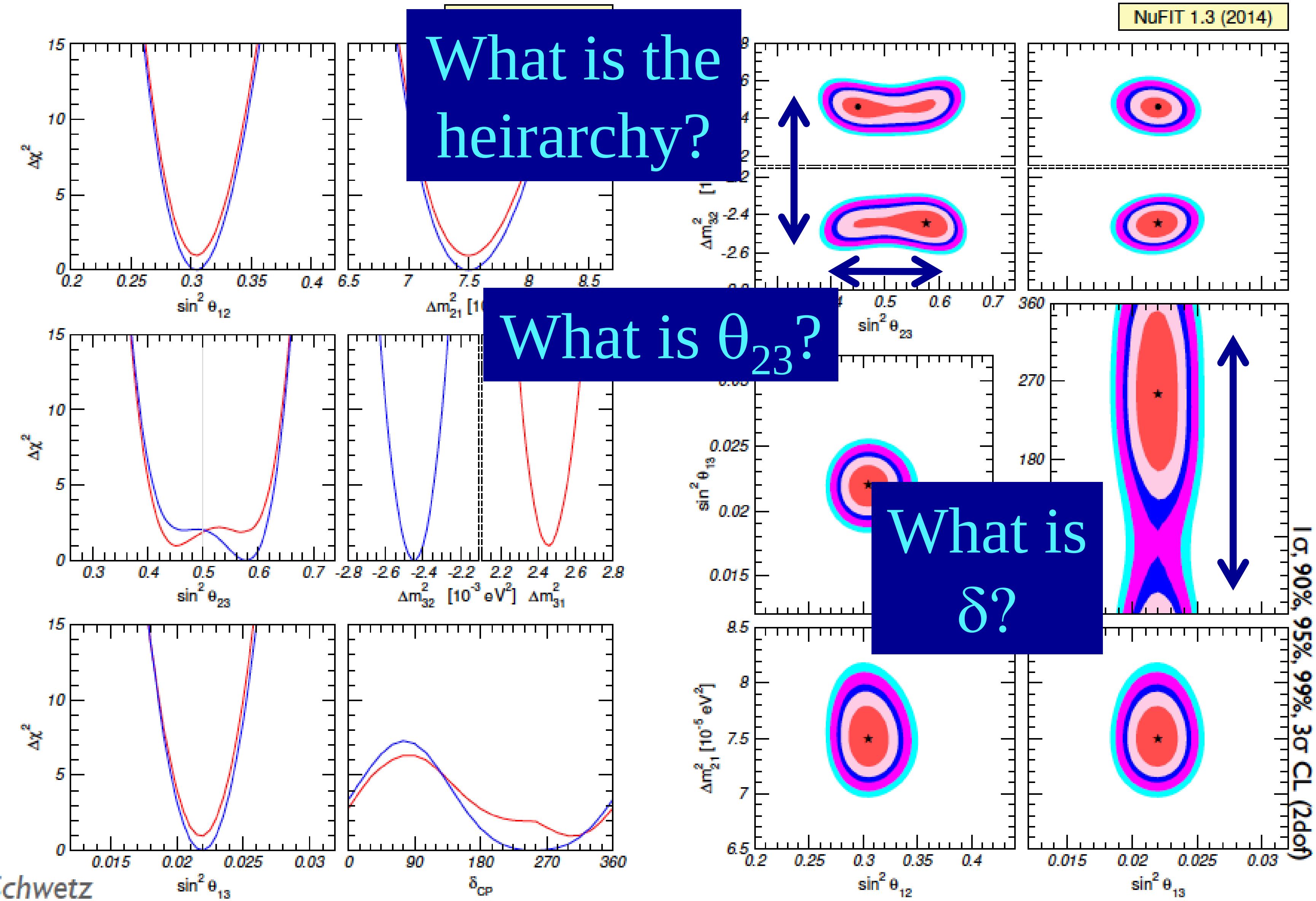
$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \left(1 - 2S_{13}^2\right)\right) \\ & + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\ & - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\ & + 4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\ & - 8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right) \end{aligned}$$

T2K
Daya Bay
13
Kanazawa
Kanazawa
Tsu
Nagoya
Gifu
Gifu
E137°
Nagano
Japan
Sado
Kofu
Niigata
E139°
Saitama
Tokyo
Tokyo
Mito
UA1 Magnet Yoke
Fine-Grain Detectors
TPCs
P0D (π0-detector)
Downstream ECAL
Solenoid Coil
P0D ECAL
Barrel ECAL
Near detector
© 2007 ZENRIN
Streaming 100%

3-flavour global fit to oscillation data



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where $c_{ij} = \cos\theta_{ij}$

CP sensitivity mainly because this term flips sign for ν and anti-ν

Complicated equation means covariances and degeneracies!

$$\ldots \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\,(1 - 2S_{13}^2)\right)$$

$$+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}$$

$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2\frac{\Delta m_{21}^2 L}{4E}$$

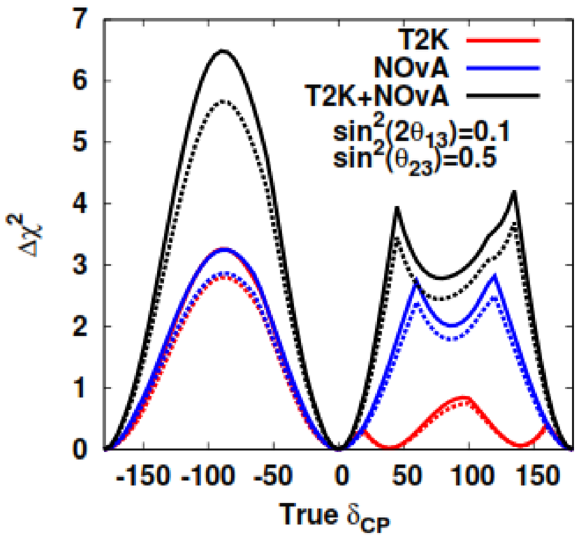
$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} (1 - 2S_{13}^2)$$

Need Matter effects to get the signs of Δm^2_{ij}

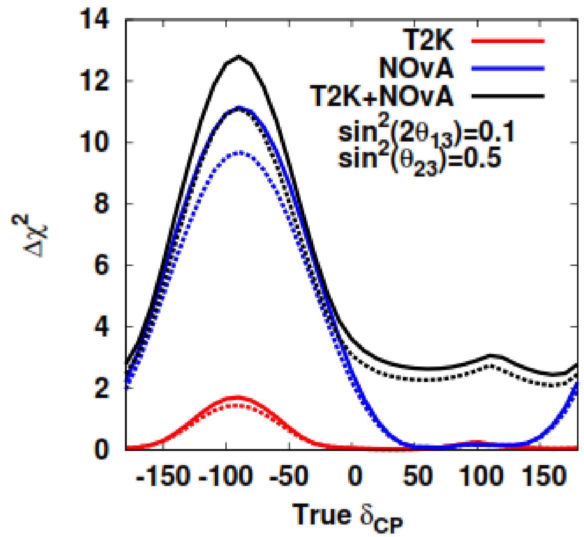
δ_{CP} Sensitivity

MH Sensitivity

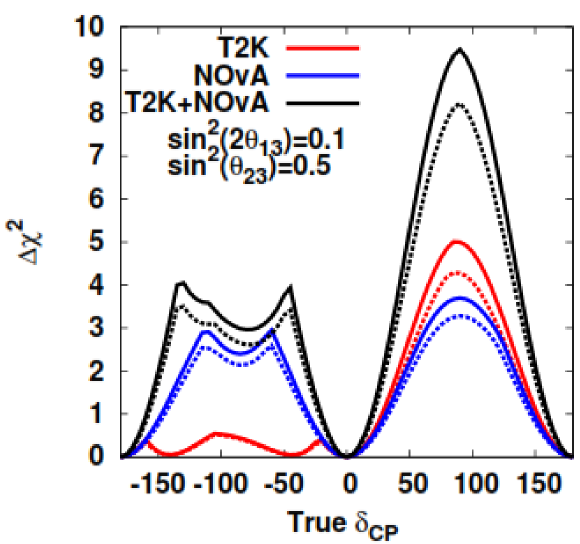
T2K + NOvA + Reactor Constraints.



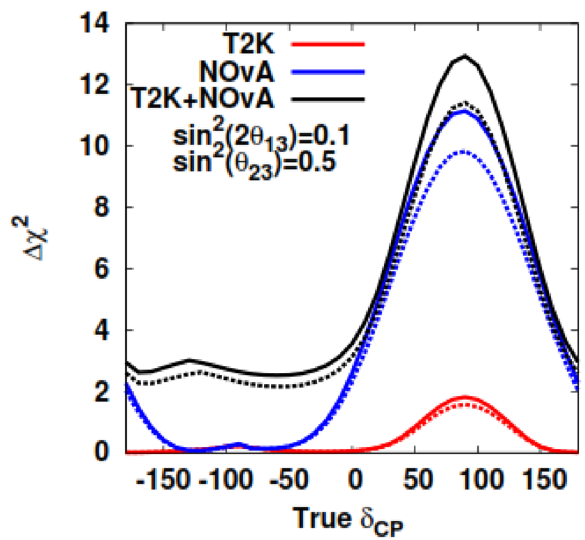
(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH



(b) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, NH



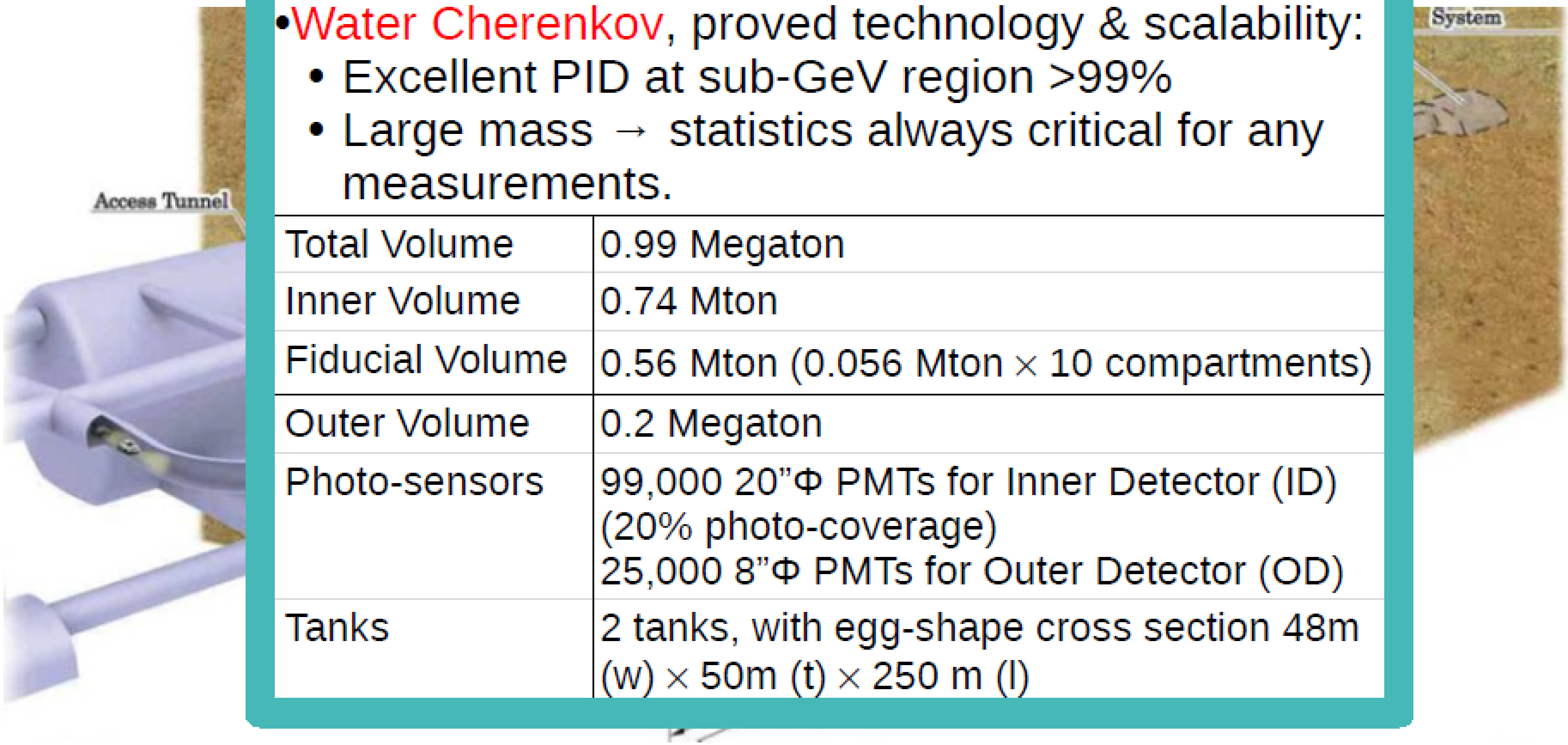
(d) 1:1 T2K, 1:1 NOνA ν:$\bar{\nu}$, IH



Can do better by extending the T2K running

Gonna need a bigger experiment. . .

Hyper-Kamiokande Overview

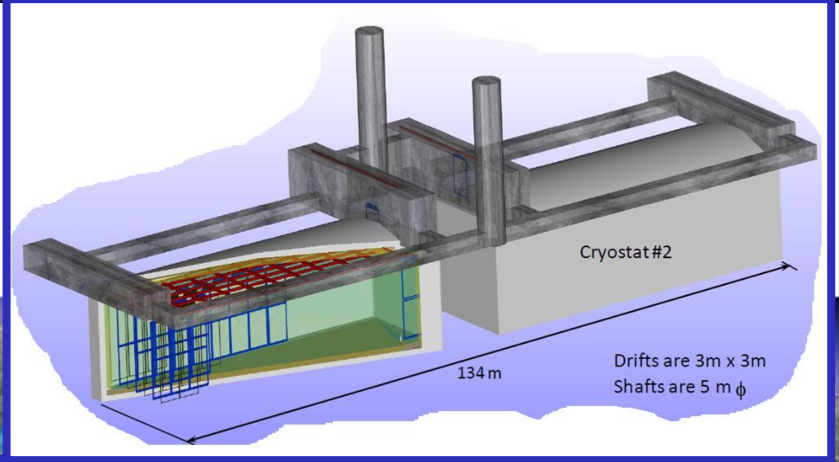


- Water Cherenkov, proved technology & scalability:
  - Excellent PID at sub-GeV region >99%
  - Large mass → statistics always critical for any measurements.

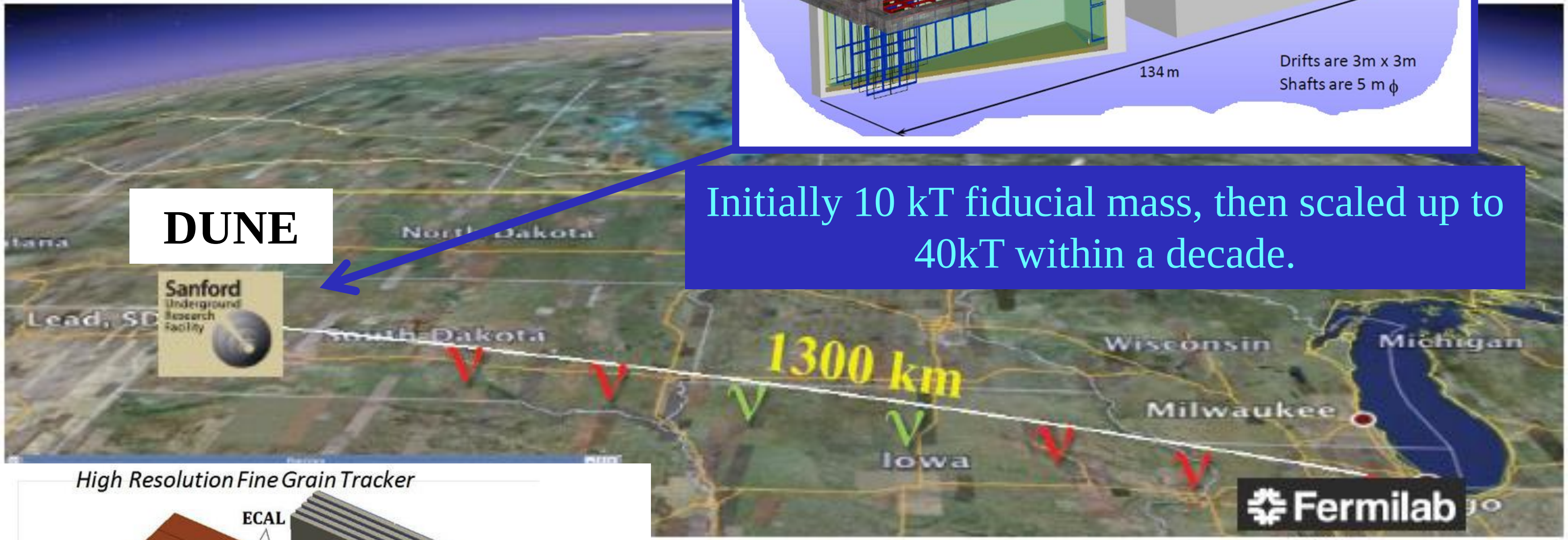
Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20"Φ PMTs for Inner Detector (ID) (20% photo-coverage) 25,000 8"Φ PMTs for Outer Detector (OD)
Tanks	2 tanks, with egg-shape cross section 48m (w) × 50m (t) × 250 m (l)

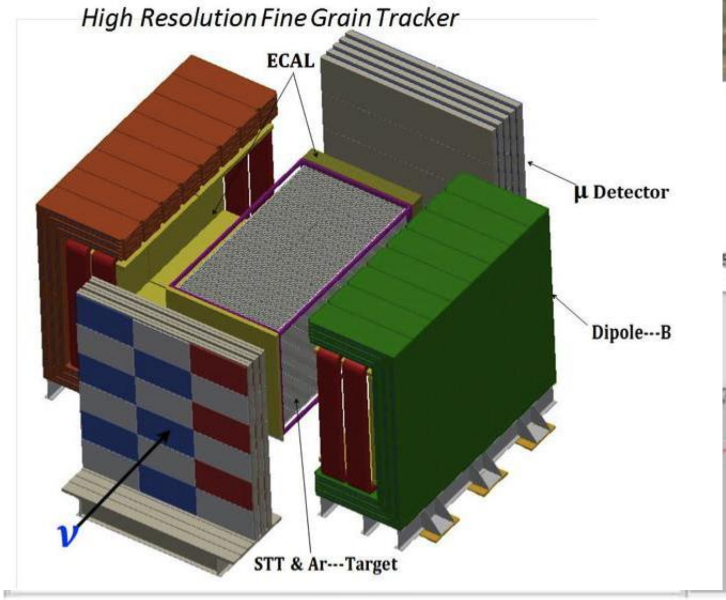
25 x Super-Kamiokande

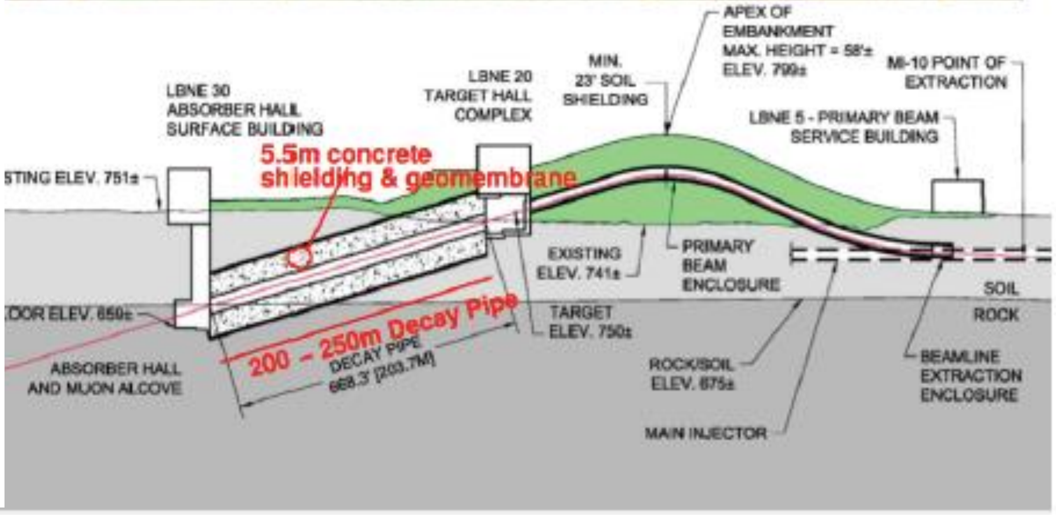
DUNE



Initially 10 kT fiducial mass, then scaled up to 40kT within a decade.







How will we win the next Nobel prize?

- Not just greedy for attention, I mean what measurements in ν physics are so important that everyone will care?
- Completely determining neutrino properties opens up four more (in my opinion) possible Nobels:
  - Is there CP violation?
  - Are there steriles? (Nobel only if there are!)
  - What are the absolute masses?
  - And one more . . .

In the very early days of neutrino physics, there was a question. . .

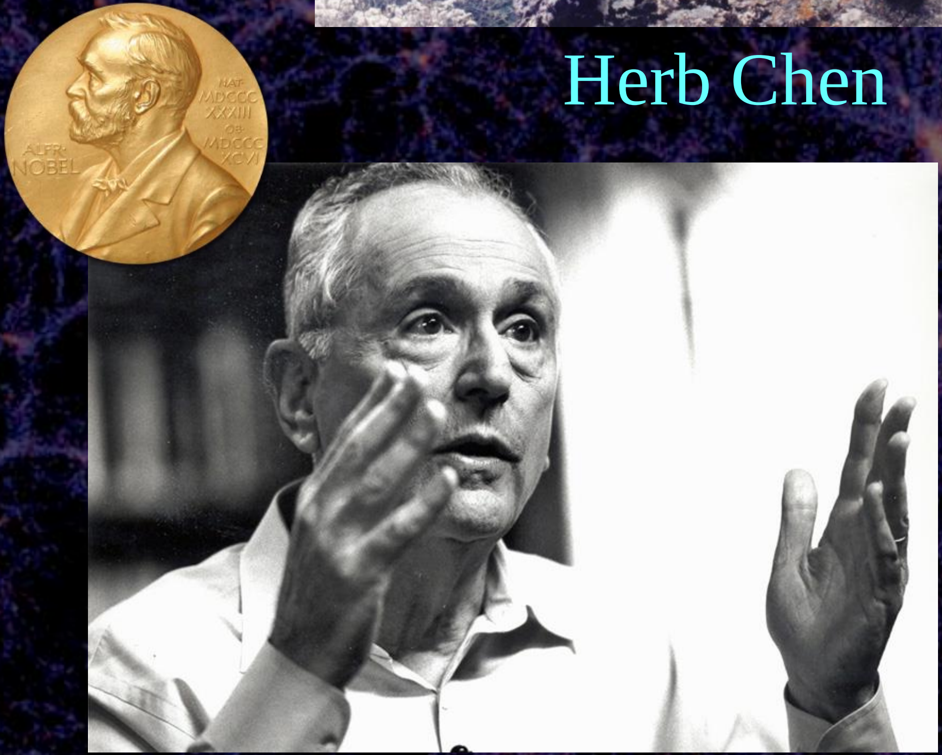
Are neutrinos and anti-neutrinos the same thing?

Definitive answer would be given by observing neutrino-less double-beta decay!

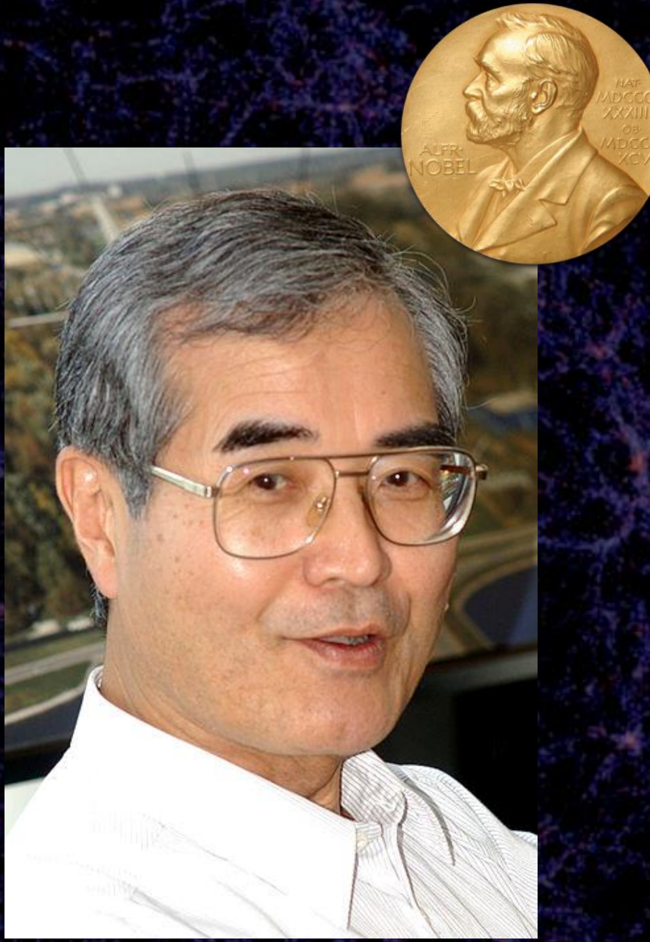
Questions for the Community!

- Absolute mass and 0νββ decay are absolutely important, but I don't think they raise great strategic questions right now.
- We are currently planning 2 next-generation long baseline experiments – should Europe be heavily involved in both?
- CERN has invested many CHF in the Neutrino Platform – how do we get more European physicists to participate?
- Must we all organize to push CERN to build νStorm?

Herb Chen



John Bahcall



Yoji Totsuka