Neutrino Physics – Past, Present, and Future

Cracow School
Zakopane
June 20-21, 2007

Dave Wark
Imperial/RAL

Science & Technology Facilities Council

Imperial College London

Never begin a talk with an excuse or an apology

Dave Wark
Imperial College/RAL

Never begin a talk with an excuse
or an apology
…so sorry about this, but
I can’t really do my job properly, and it
isn’t my fault.

Articles in hep-ex, hep-ph, or hep-th for one year (to 24/8/03) with word in title

		structure	211	gluon	109
Quark	443	CP	201	Standard model	107
QCD	442	spin	191	SUSY	97
String	435	fermion	166	LHC	83
Brane	325	lepton	163	unification	75
Higgs	288	photon	135	Linear collider	59
Meson	284	inflation	117	strong	58
perturbation	213	electroweak	109	flavour	42

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Cannot possibly cover the field in a three lectures.
I will discuss a lot of experiment, a little phenomenology, almost no theory, but start with a bit of history…

Rough Plan of Lectures:

- Today – History, solar neutrinos, existing reactor experiments relevant to solar mixing.
- Tomorrow – Atmospheric and long baseline neutrino oscillations, three neutrino mixing.
- Friday – The future of oscillation experiments, absolute mass measurements including $0\nu\beta\beta$ decay and astrophysical determinations.

Where did the idea of the neutrino come from?

There were problems in the early days of β decay.

β spectra were continuous

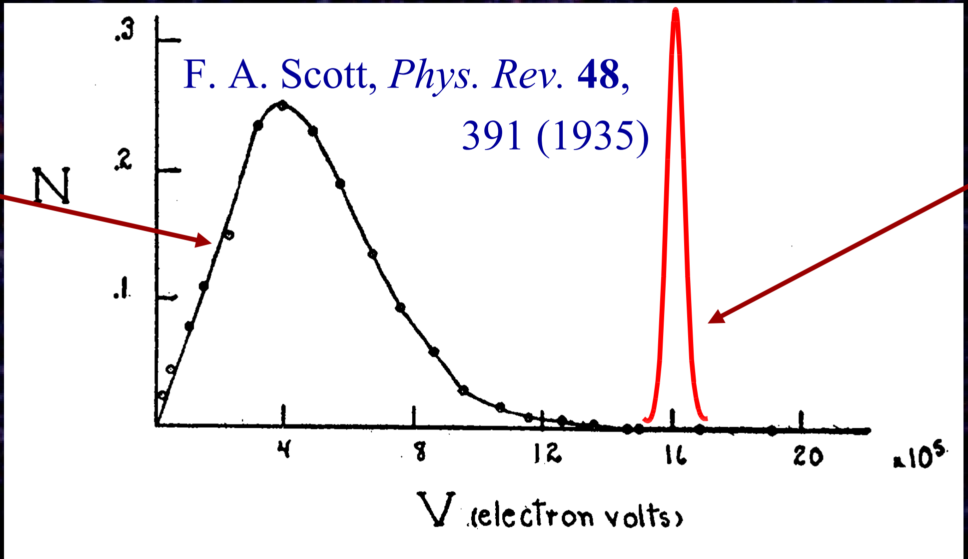


FIG. 5. Energy distribution curve of the beta-rays.

Instead of discrete

And the spins didn't add up… $^{14}C \rightarrow {}^{14}N + e^-$

spin 0 spin 1 spin 1/2

Bohr: maybe energy/momentum not conserved in β decay?

Pauli's Solution…

Dear Radioactive Ladies and Gentlemen,

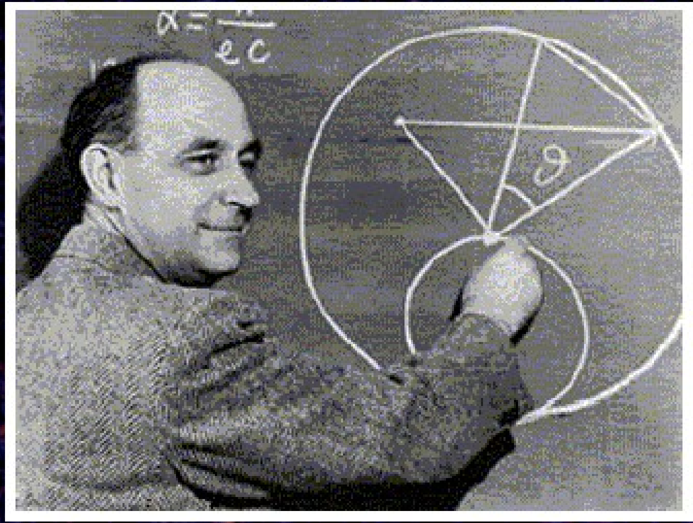
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, 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 which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think to this at all, like the new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

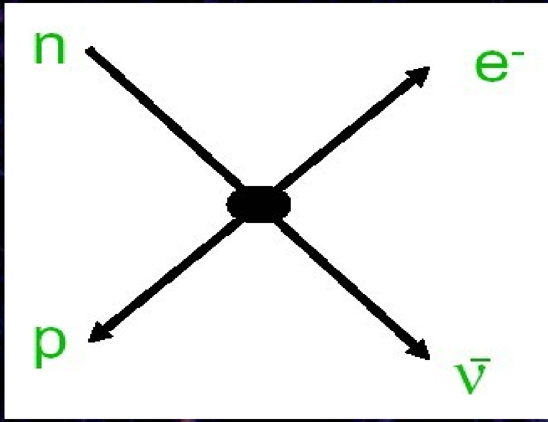
Your humble servant

. W. Pauli

Enrico Fermi…

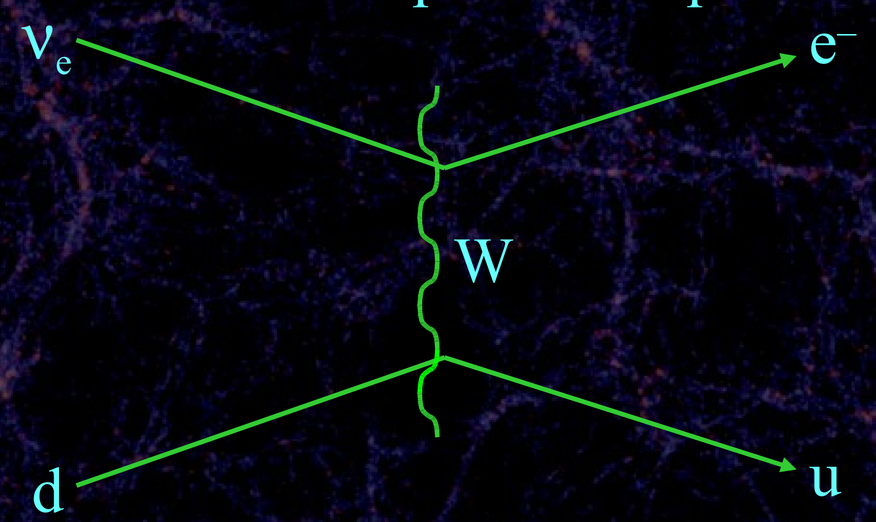


Replaces the neutrino
"inside" the nucleus…



…with a neutrino created
in a four-point interaction.

Theorists then replace the "point"…



…with a boson propagator
connecting quarks and/or leptons

And the Standard Model of
electroweak interactions is born!

(I warned you there wouldn't
be much theory…)

How to detect them?

- *The detection of neutrinos was an extreme challenge for the experiments of the mid-twentieth century – Pauli, in fact, apologized for hypothesizing a particle that could not be detected.*
- *In a Chalk River report in 1946, Bruno Pontecorvo pointed out the advantages of a radiochemical experiment based on $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ (and even mentioned solar neutrino detection using this method).*
- *The first application of Bruno's method, however, was by Ray Davis using reactor anti-neutrinos.*
- *However the first detection of neutrinos used another method…*

Detection of the Free Neutrino*

F. Reines and C. L. Cowan, Jr.
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 9, 1953; revised manuscript received September 14, 1953)

An experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The

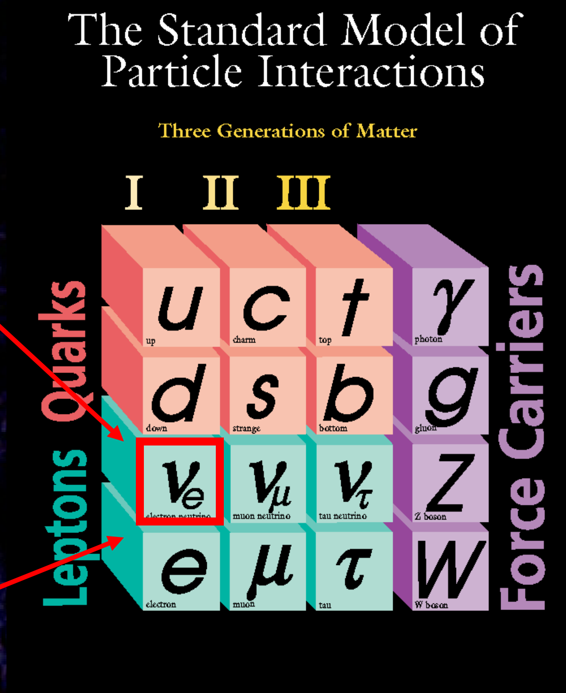
PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

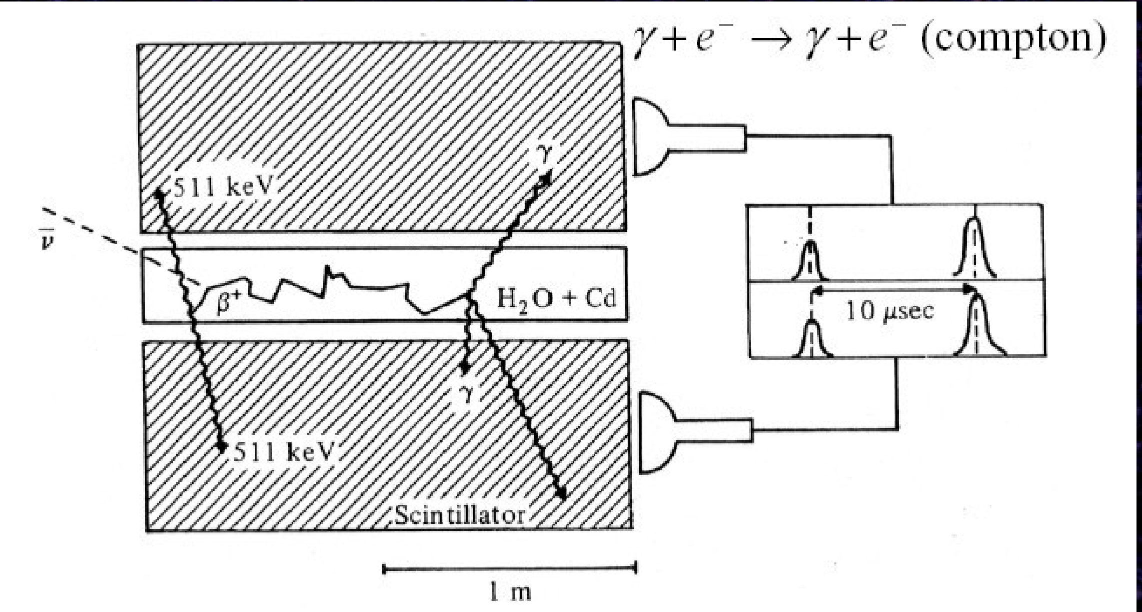
Detection of the Free Antineutrino*

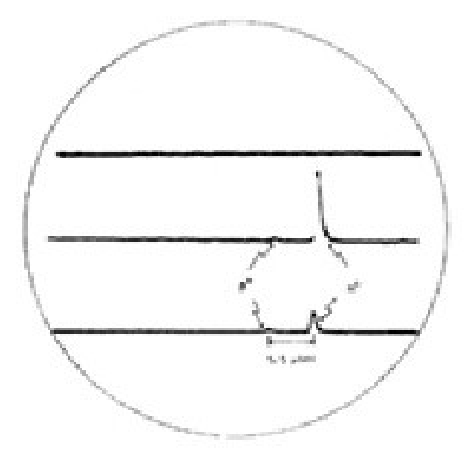
F. Reines,† C. L. Cowan, Jr.,‡ F. B. Harrison, A. D. McGuire, and H. W. Kruse
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 27, 1959)

The antineutrino absorption reaction $p(\bar{\nu},\beta^+)n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal dependended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.







Dave Wark
Imperial College/RAL

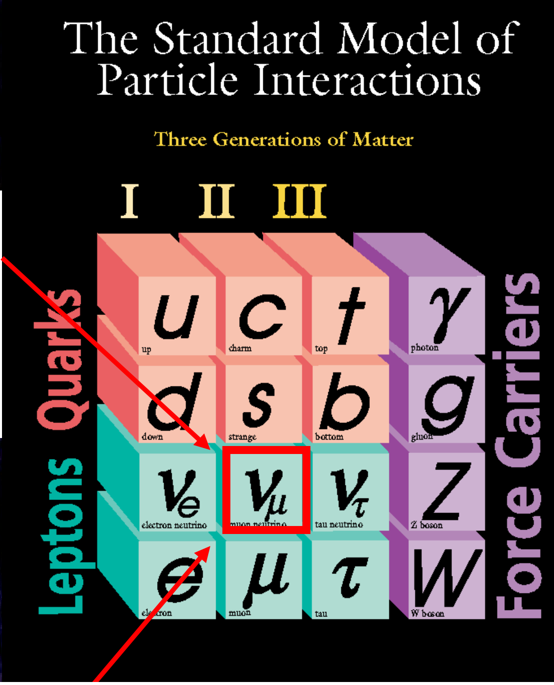
PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

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!*



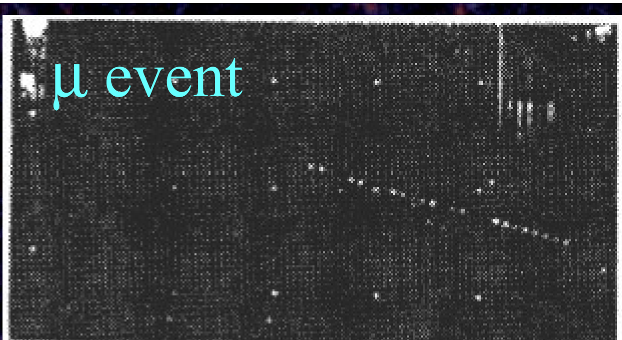
VOLUME 9, NUMBER 1 PHYSICAL REVIEW LETTERS JULY 1, 1962

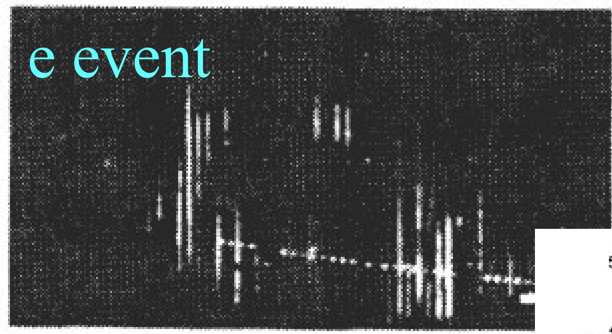
OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

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)





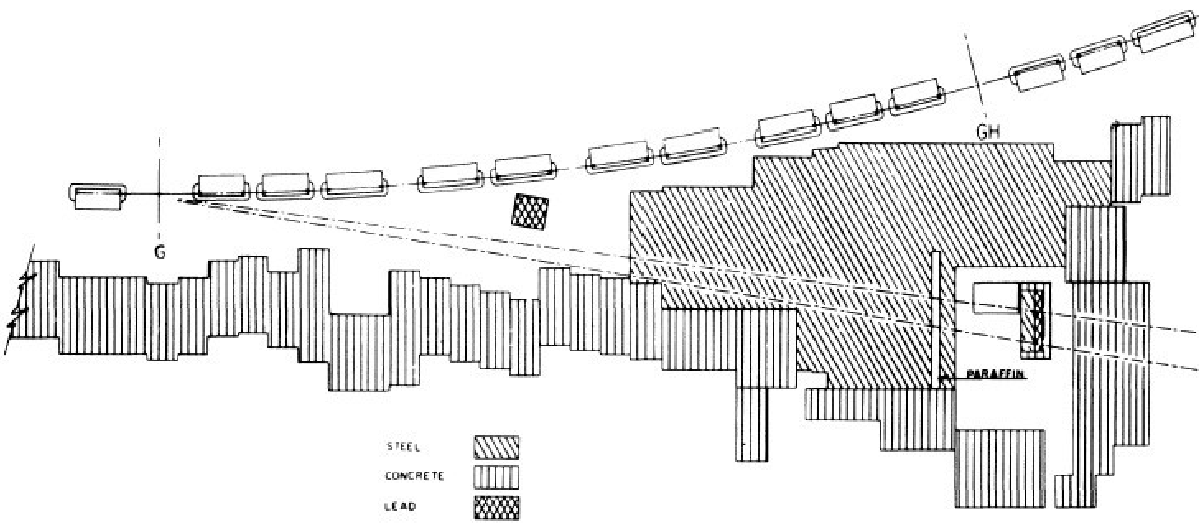


FIG. 1. Plan view of AGS neutrino experiment.

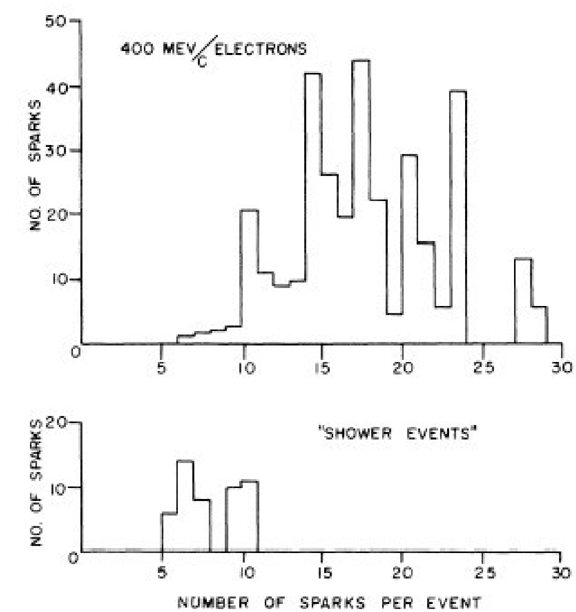
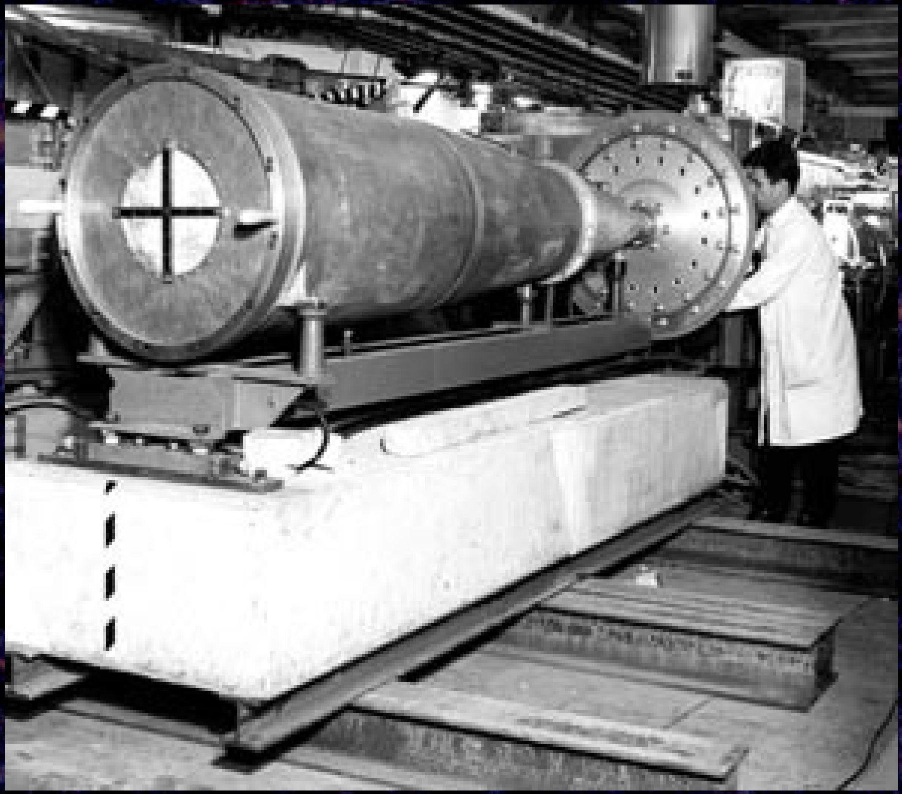


FIG. 9. Spark distribution for 400-MeV/c electrons normalized to expected number of showers. Also shown are the "shower" events.

The Discovery of Neutral Currents



The 1st Neutrino Horn – Van den Meer, CERN, 1961

The Gargamelle CF_3Br Bubble Chamber

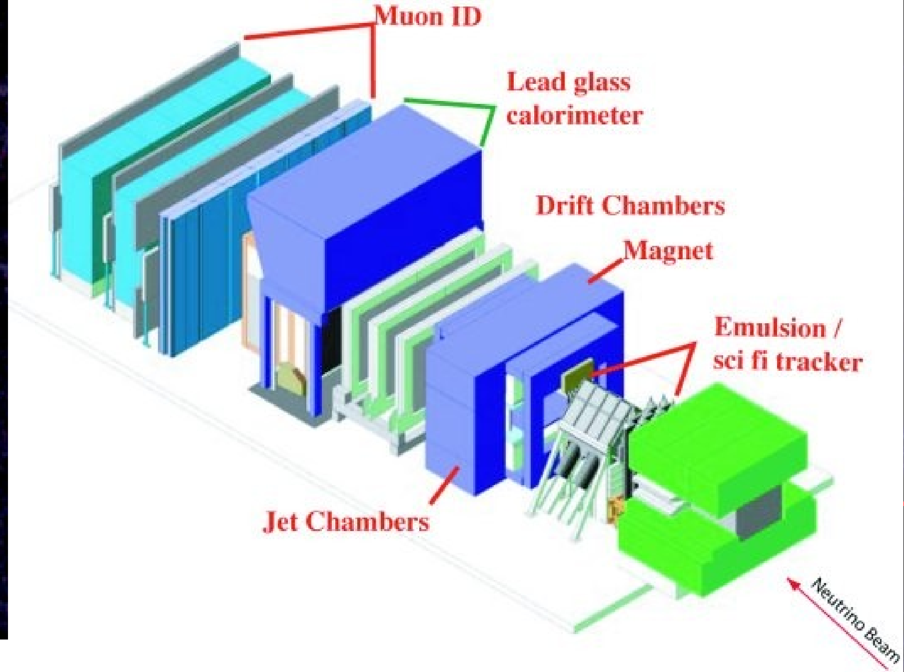
Dave Wark
Imperial College/RAL

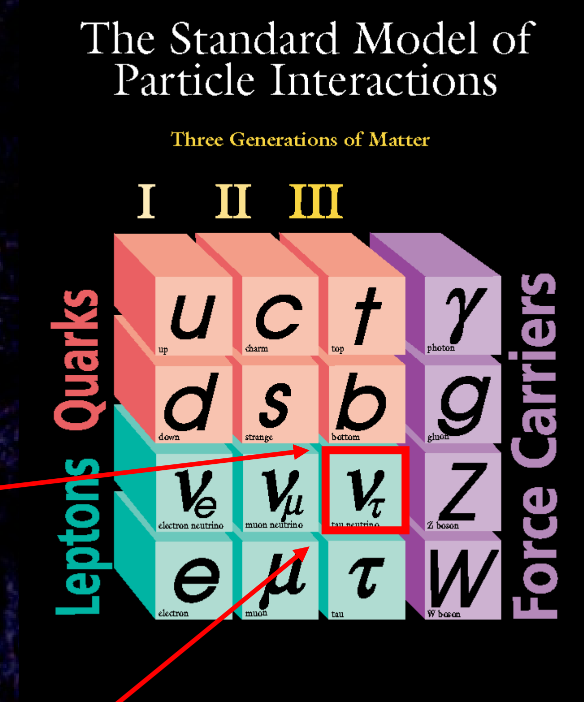
The Discovery of Neutral Currents

The CERN (and FNAL and BNL and…) ν beams were workhorse probes for particle physics for decades, but I will leave this story…

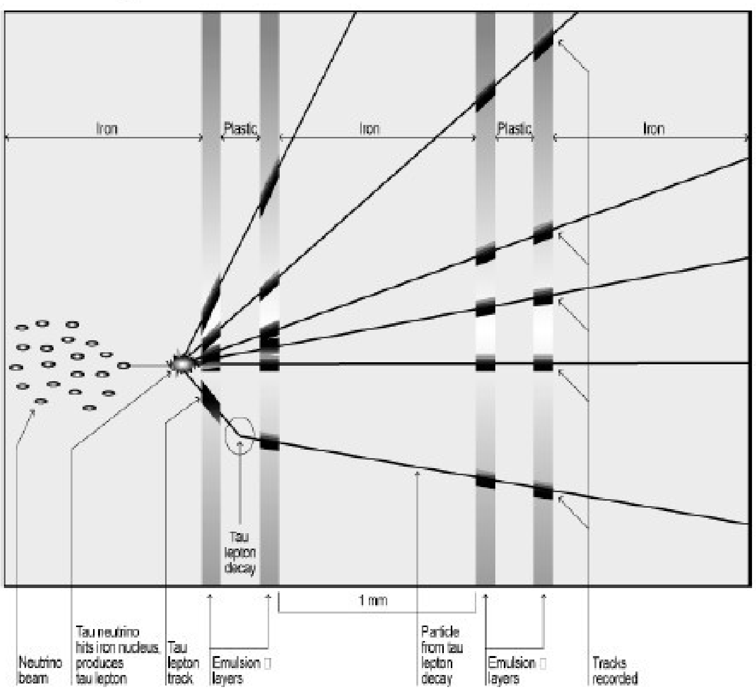
Cracow School

DONUT (2000)

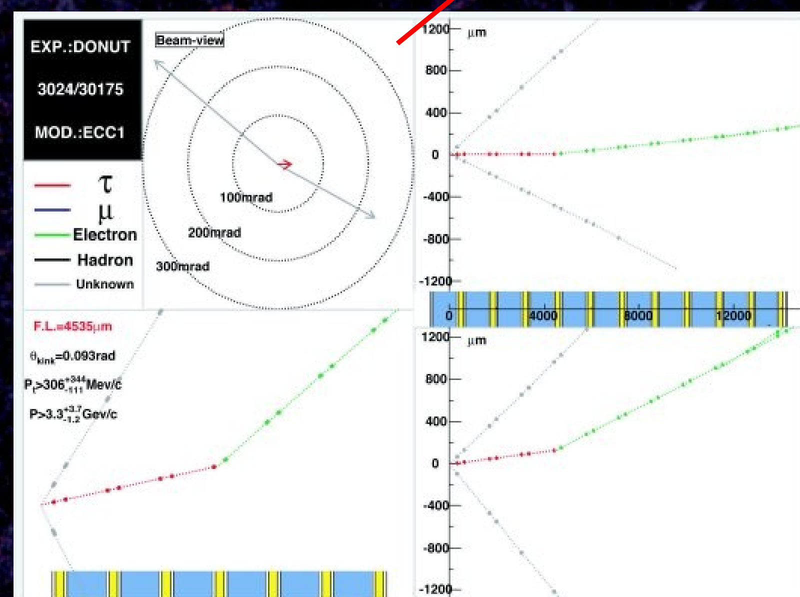




Detecting a Tau Neutrino



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.



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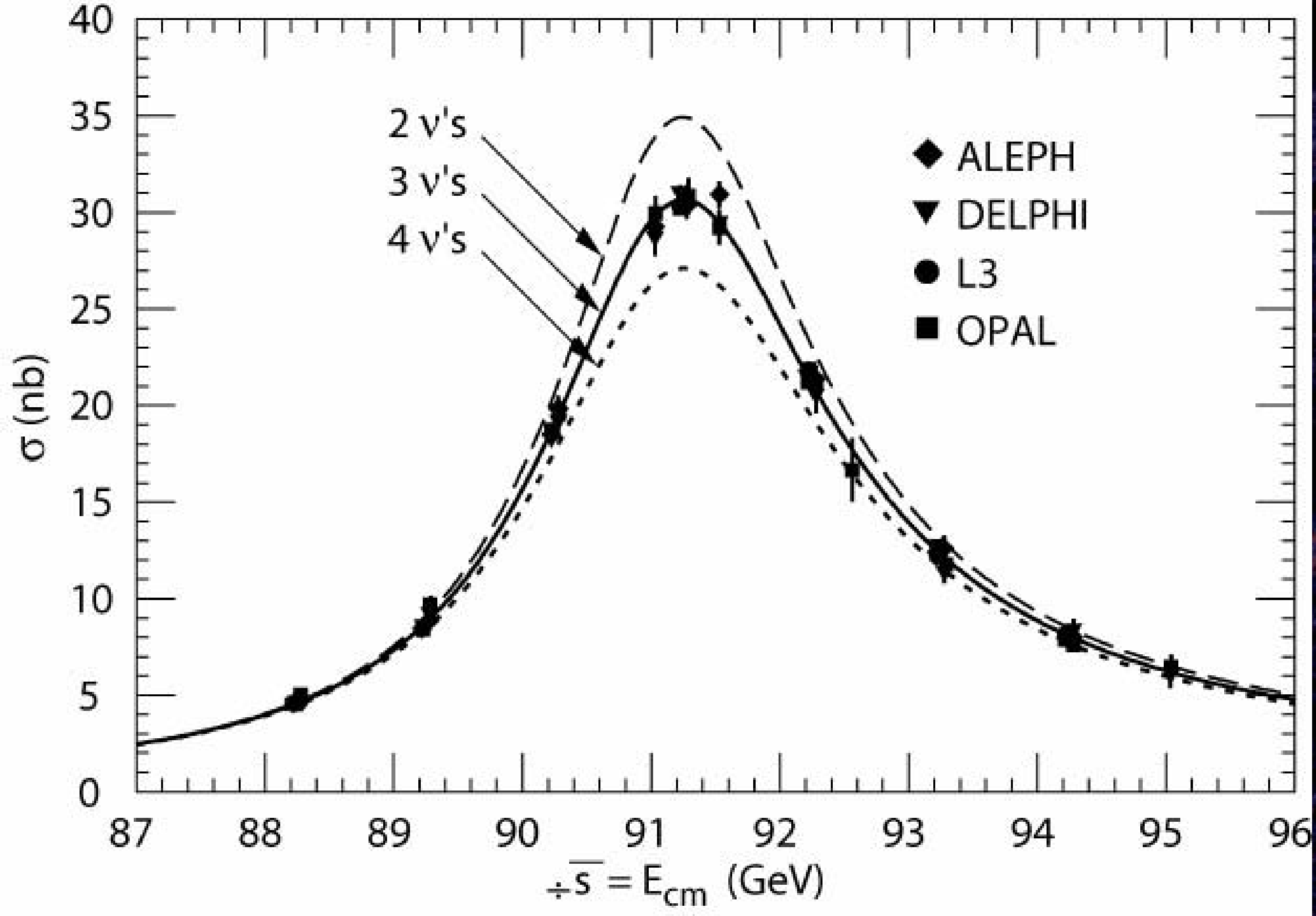
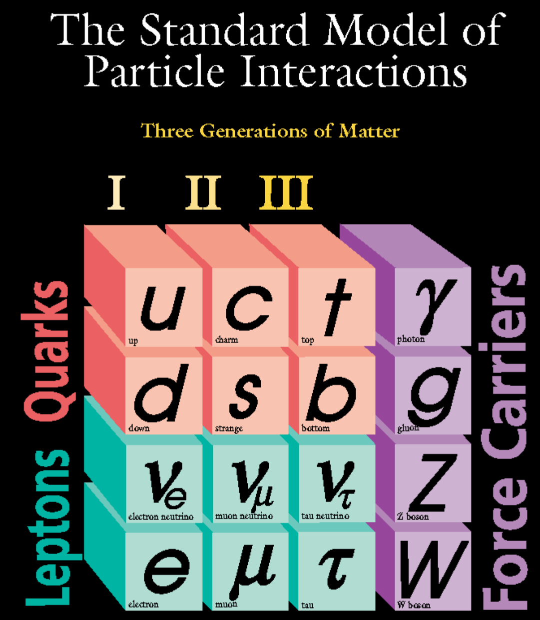
LEP and SLC confirm that there are only three light flavoured ν





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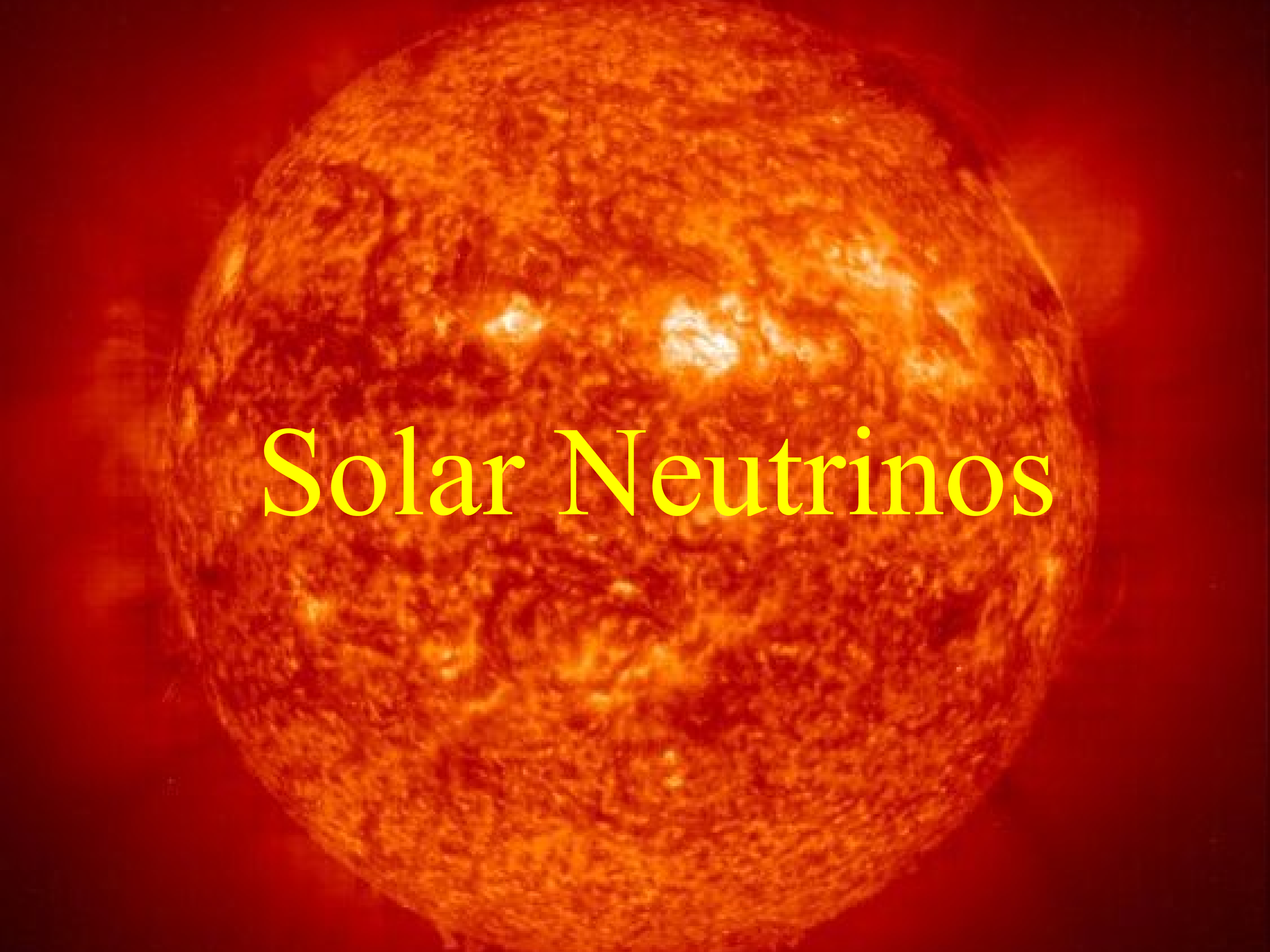
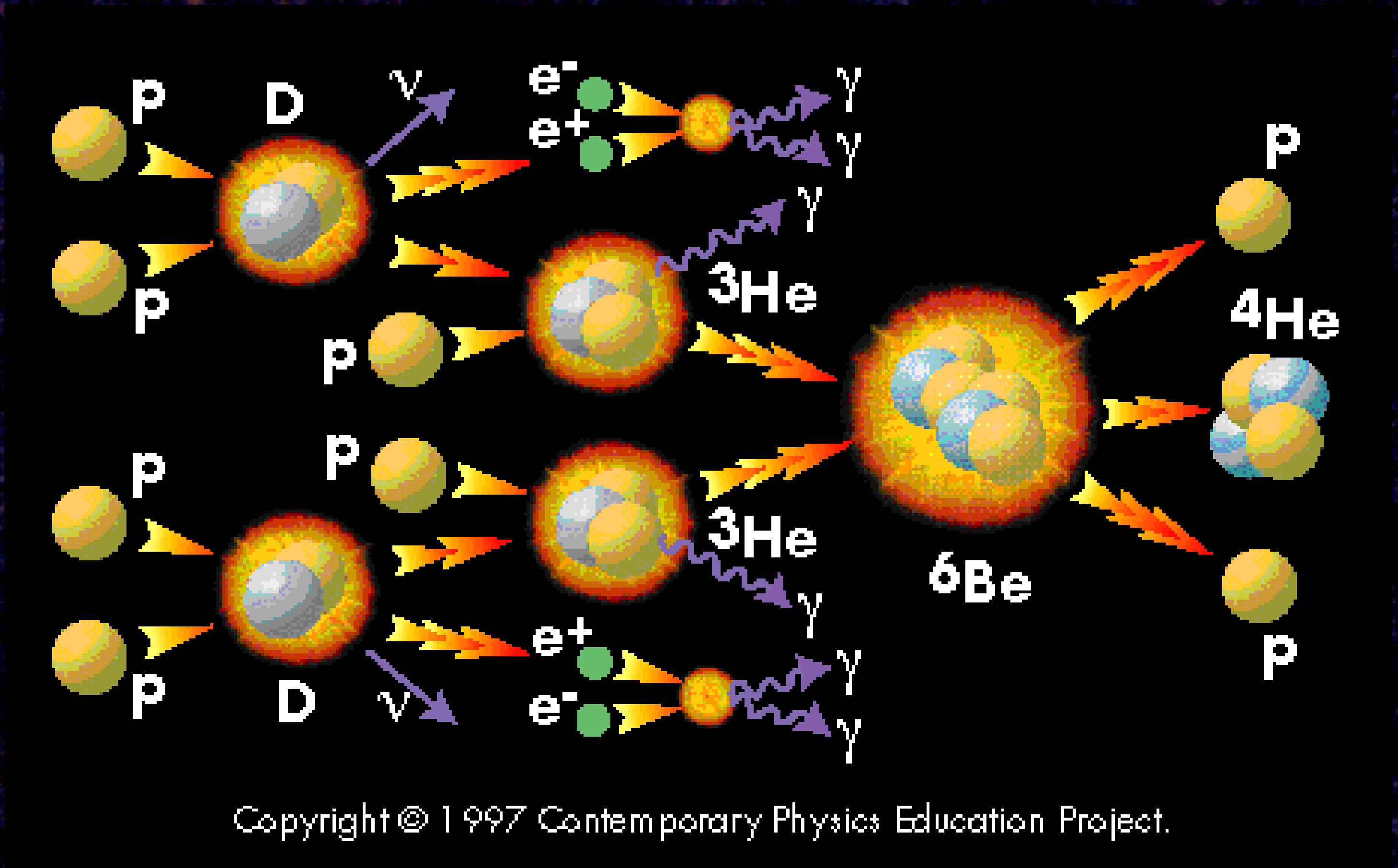

Solar Neutrinos



Photons take 10^4 years to get out

Energy takes 10^7 years to get out

Neutrinos come out at the speed of light!

Net reaction is $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$

Releases 25.7 MeV/c^2, or 4.12×10^{-12} J, per Helium nucleus produced (or half that per neutrino)

The solar constant is 1370 $Watts/m^2$ at Earth's orbit

Thus the neutrino flux should be $1370/(2.06\times10^{-12})/m^2/sec$ or:

$6.65 \times 10^{10}\ /cm^2/sec$

Good News: this is accurate to better than 10%

Bad News: we left out a few things….

Where it all began – the Davis Experiment

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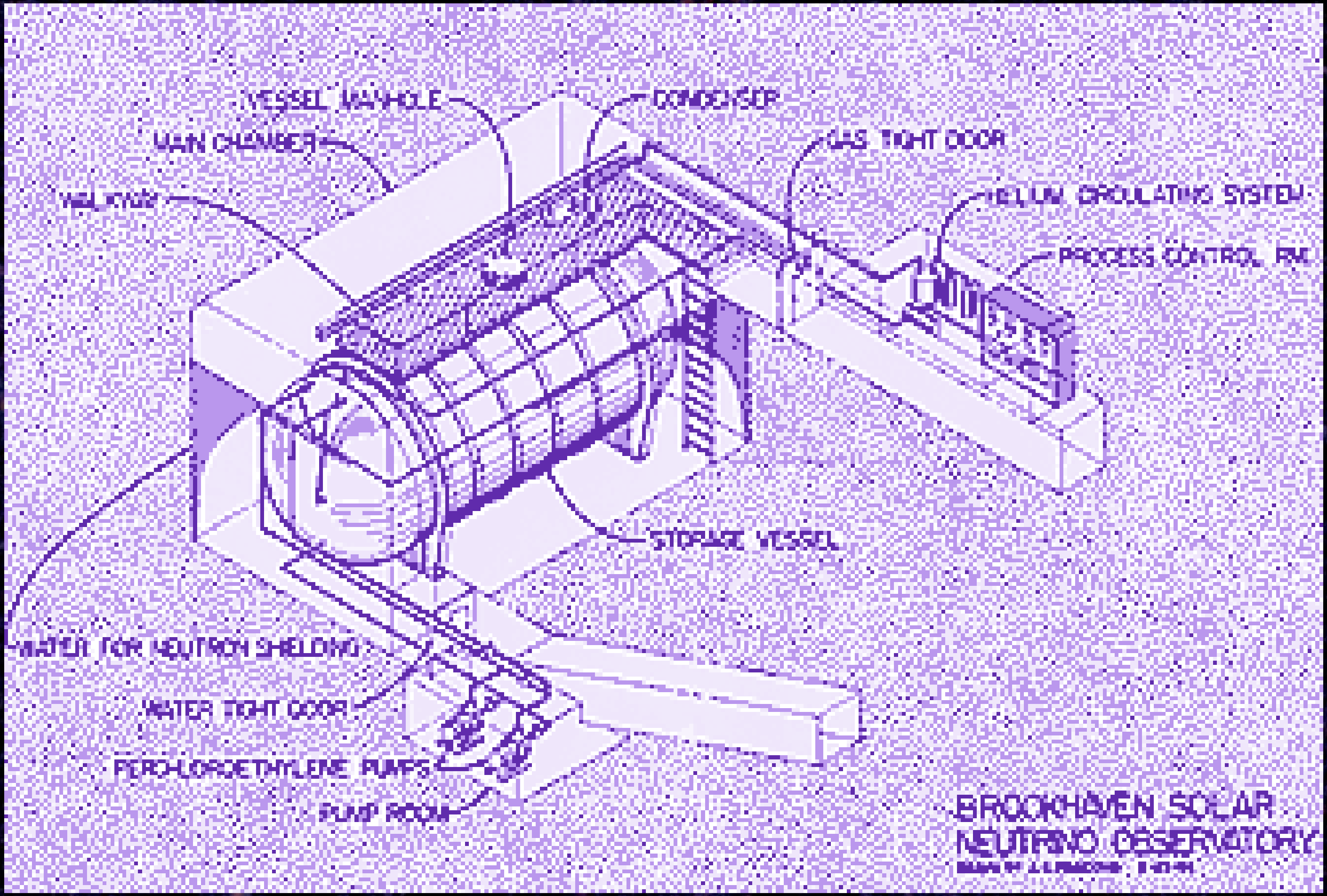
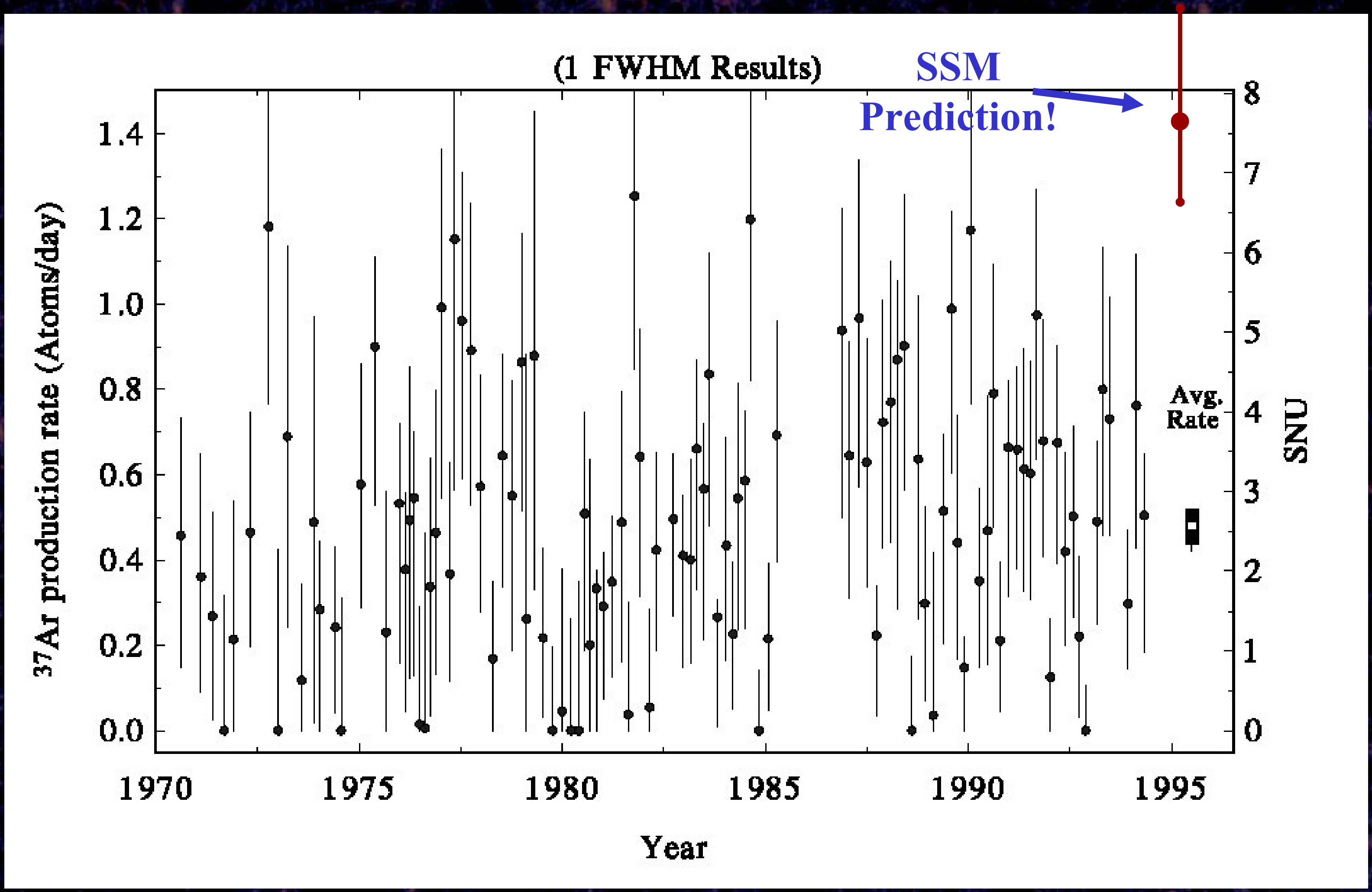
Imperial College/RAL

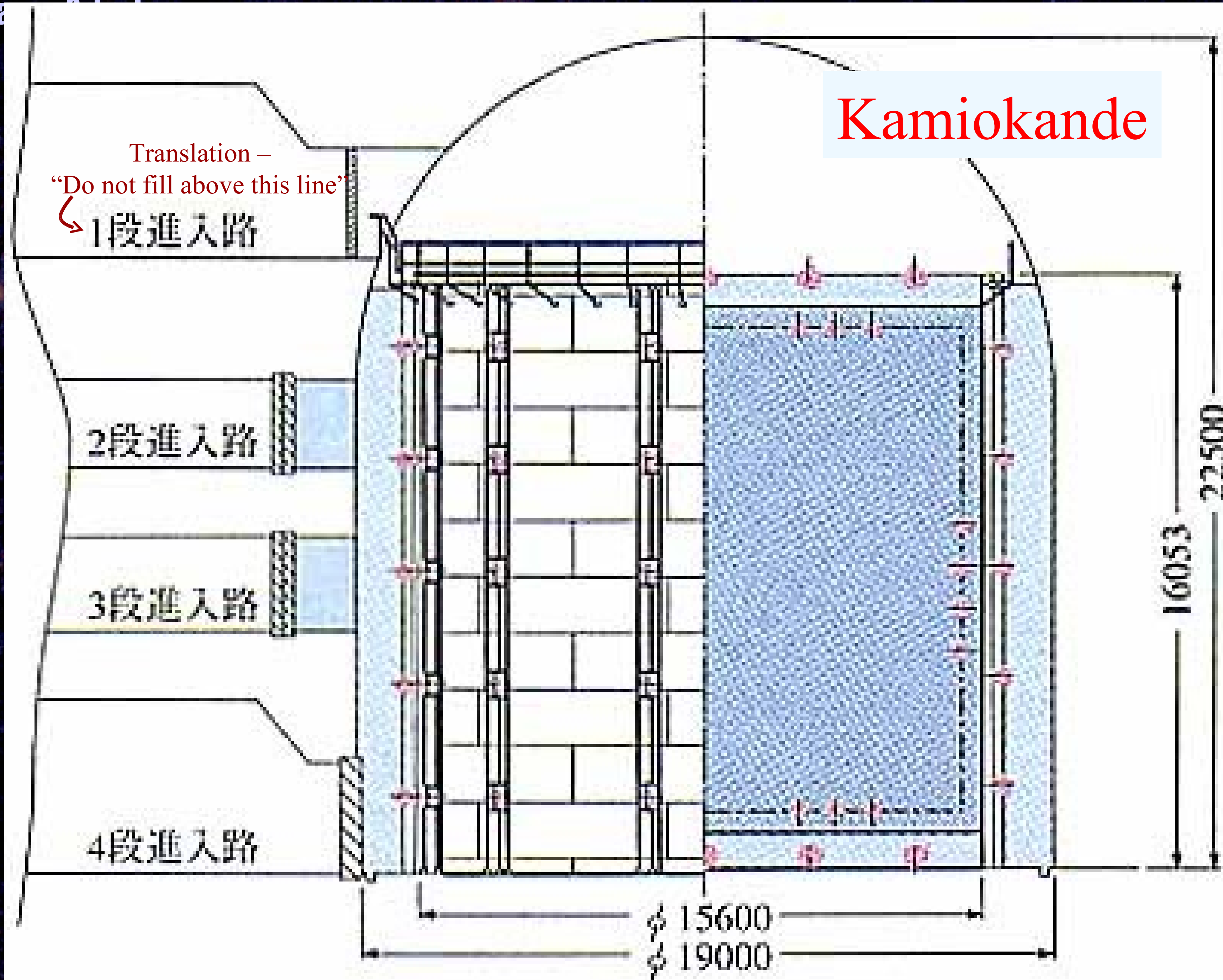
Where it all began – the Davis Experiment

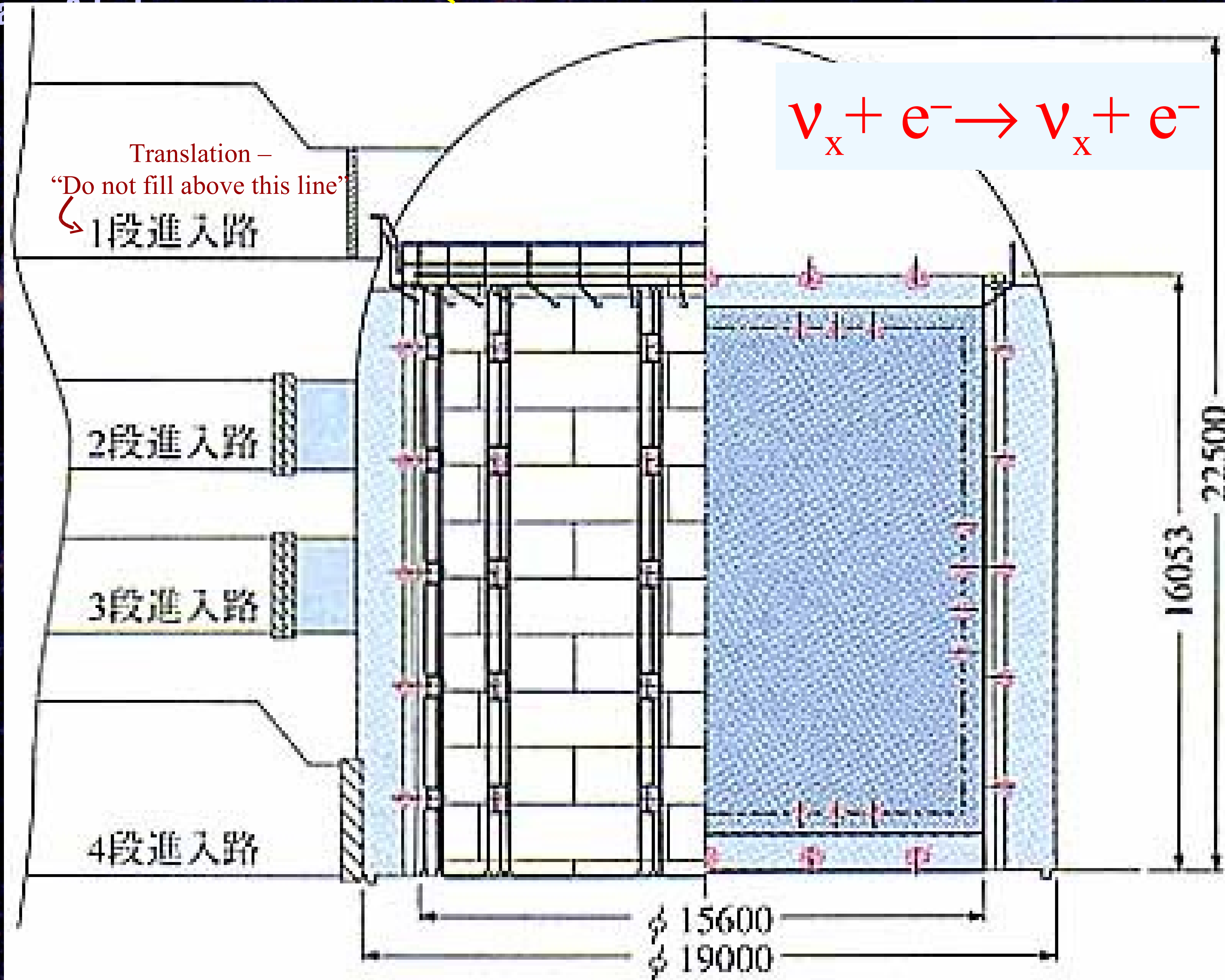


Where it all began – the Davis Experiment



Maybe the experiment is wrong…


Kamiokande
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
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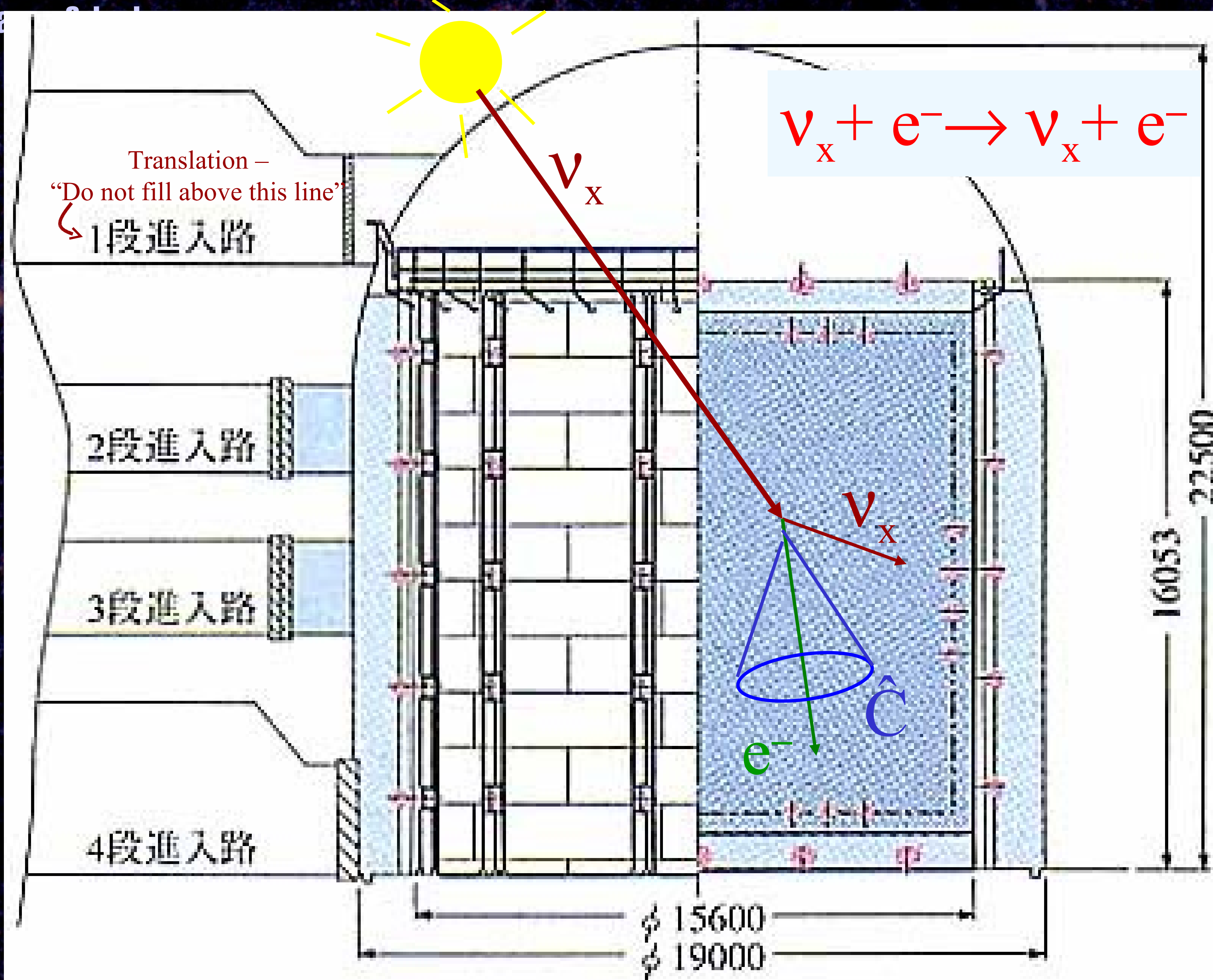
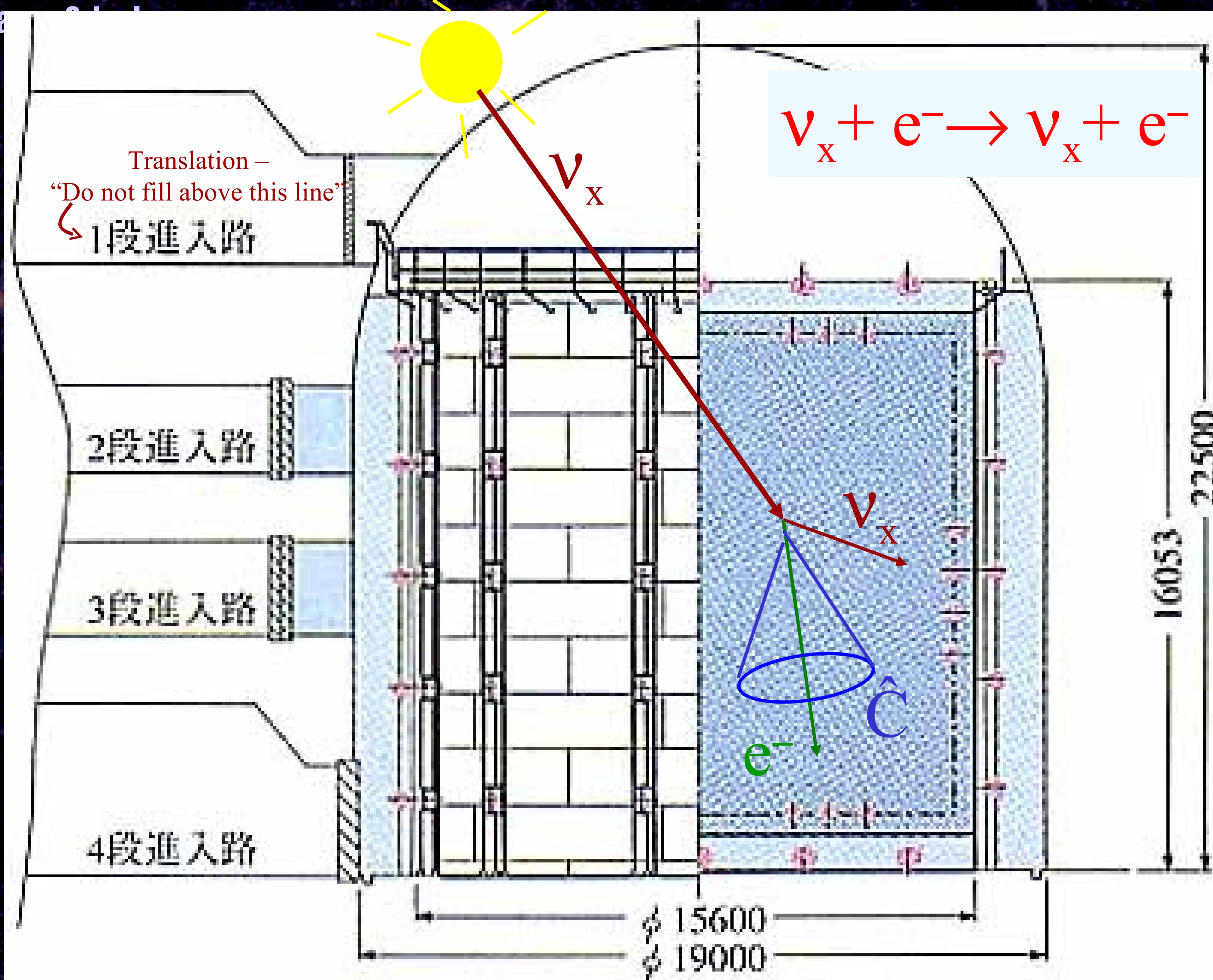

$\nu_x + e^- \rightarrow \nu_x + e^-$
ν_x
Translation –
“Do not fill above this line”
1段進入路
2段進入路
3段進入路
4段進入路
ν_x
$\hat{C}$
e^-
16053
22500
ϕ15600
ϕ19000

Why am I spending all this time talking about ancient experiments?

- It's fun…
- I was told this was a school and there would be students present.
- I would like them to carefully note as I go through all the amazing, expensive, flashy new experiments to come 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:

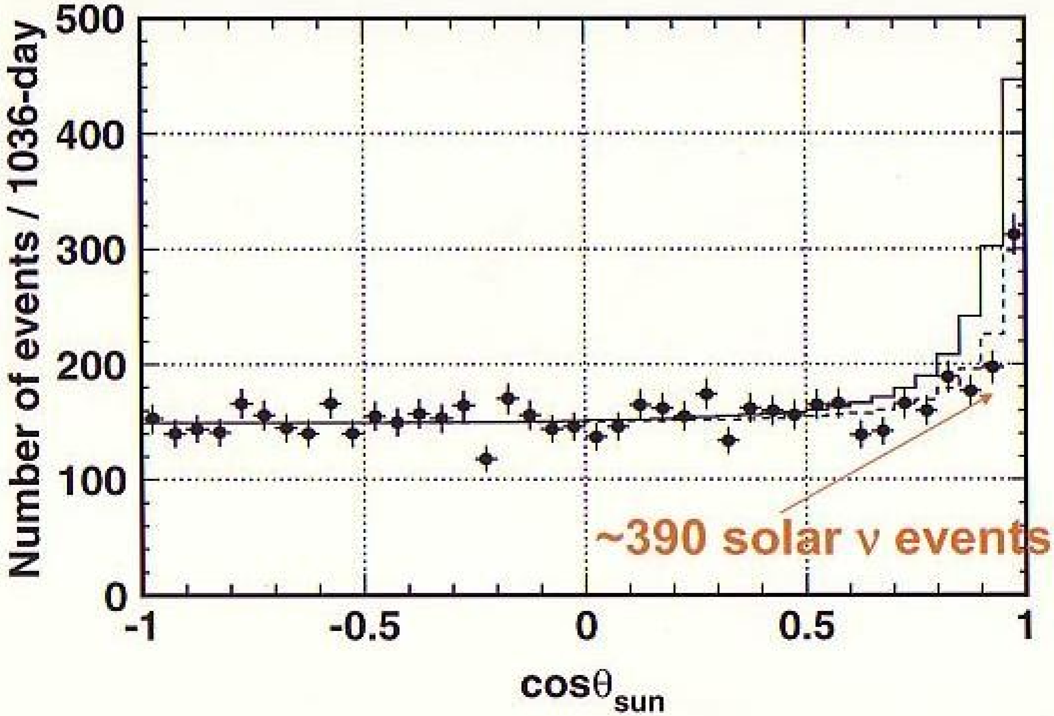
"Three months in the laboratory will save you three hours in the library".



$\nu_x + e^- \rightarrow \nu_x + e^-$
ν_x
ν_x
$\hat{C}$
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
16053
22500
ϕ 15600
ϕ 19000

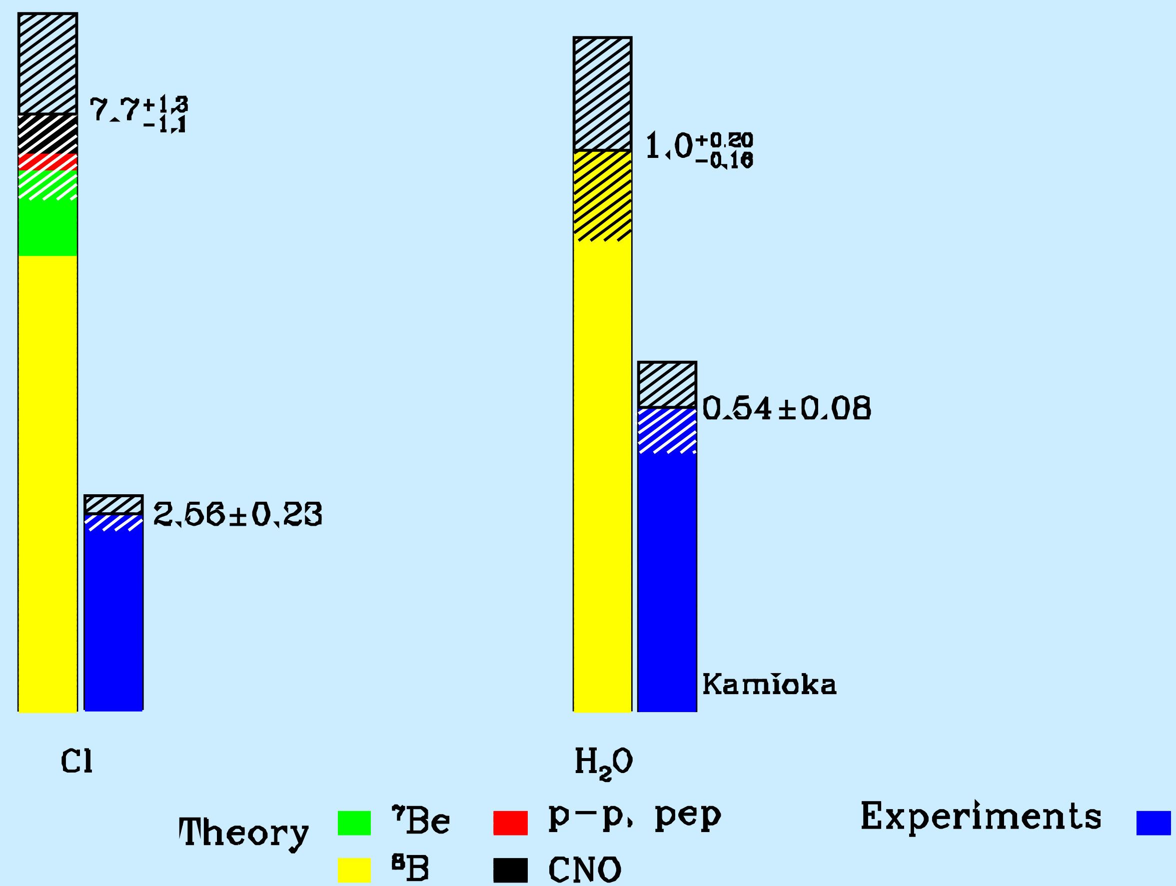
Solar neutrinos (Kamiokande-III)

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



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

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



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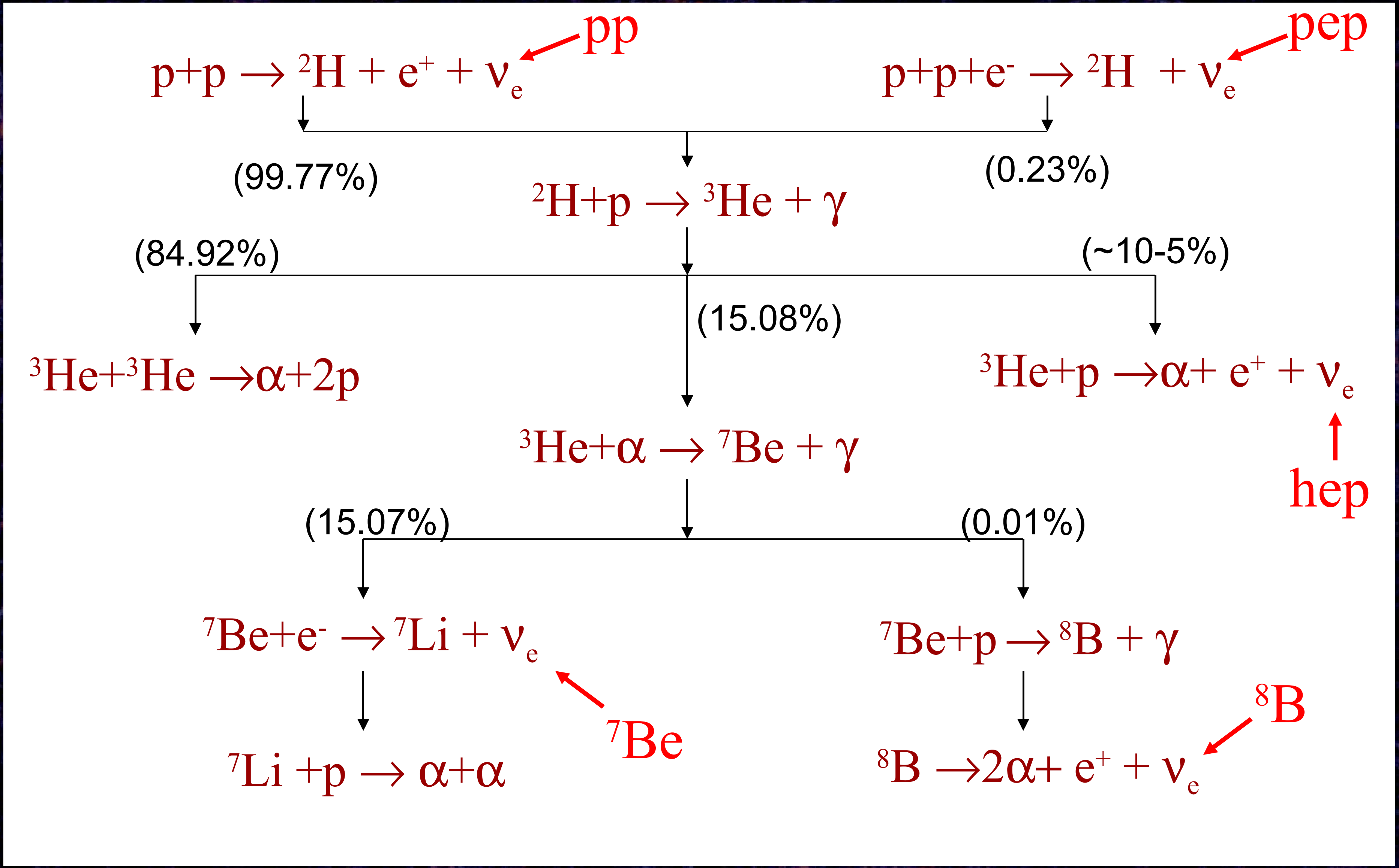
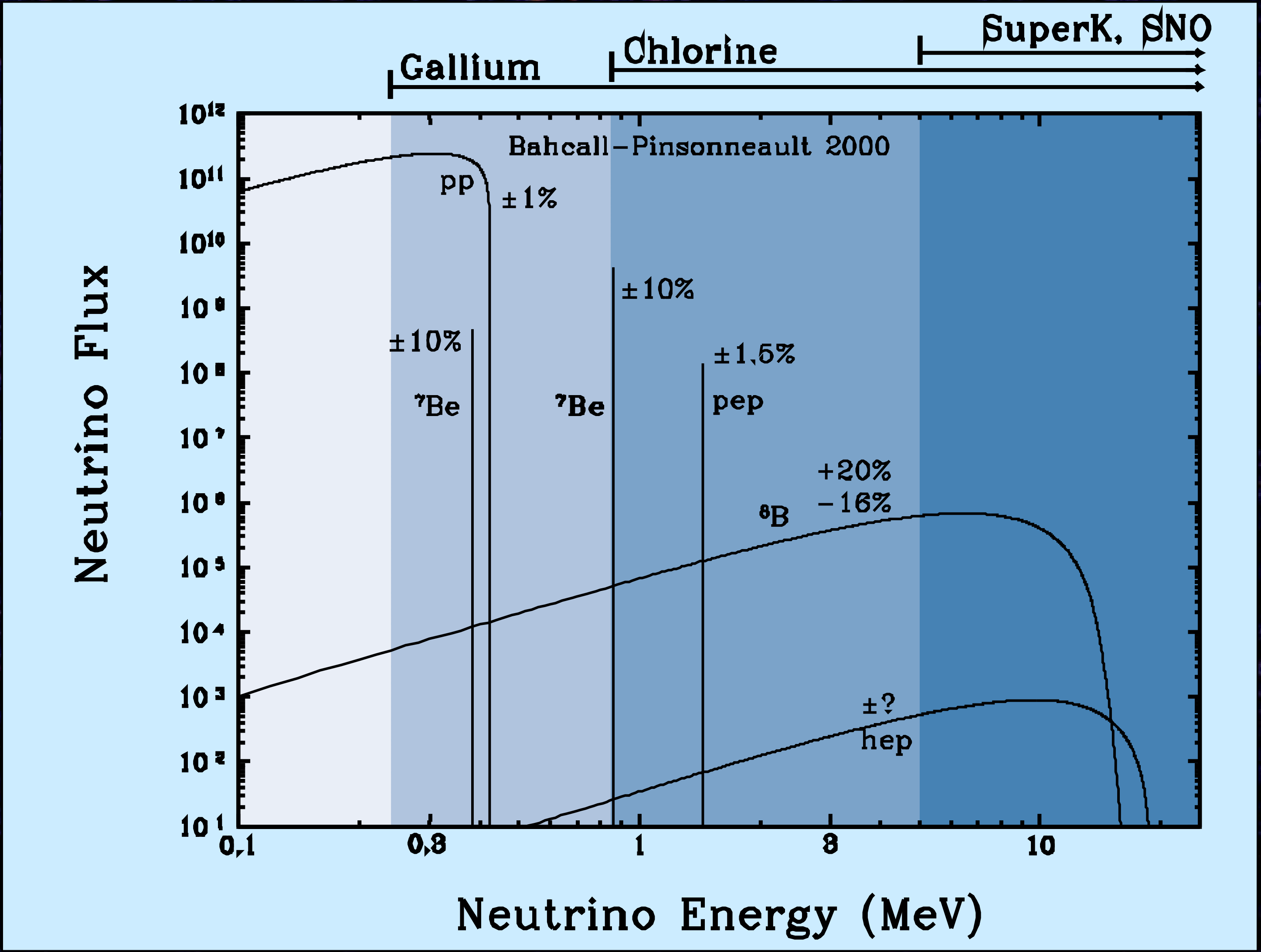
Imperial College/RAL

The solar pp chain



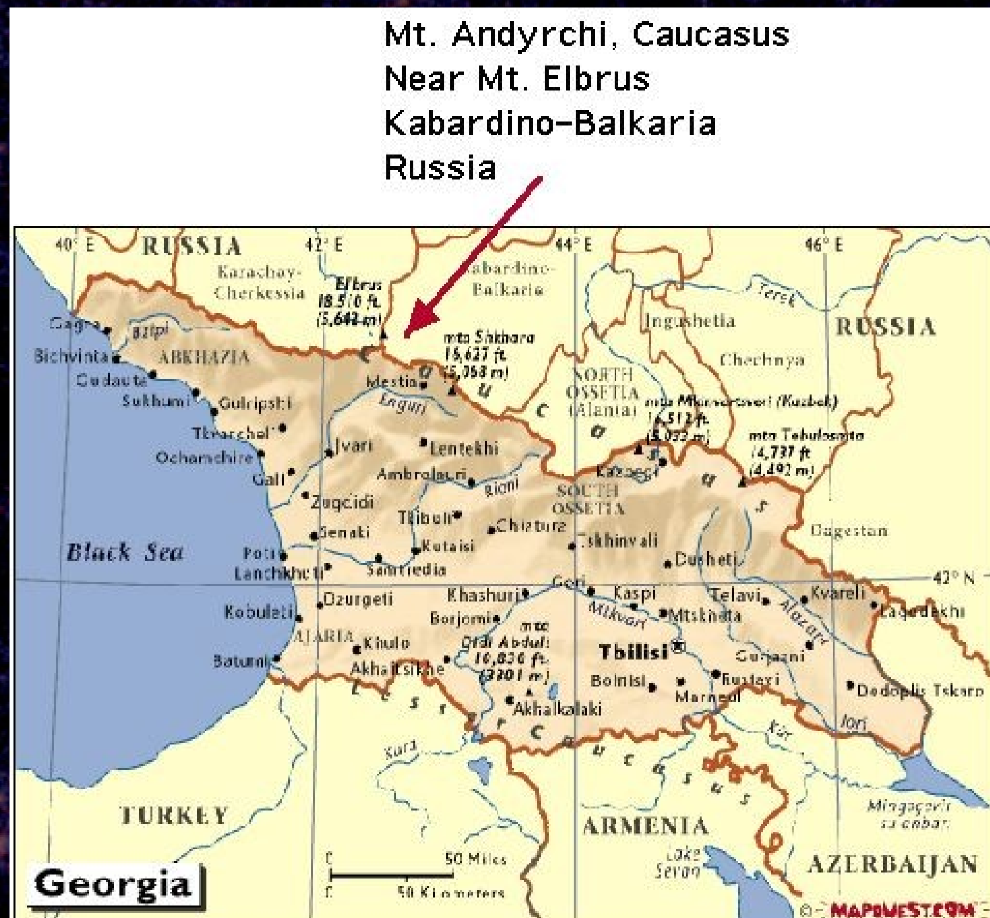
Plot adapted from http://www.sns.ias.edu/~jnb/

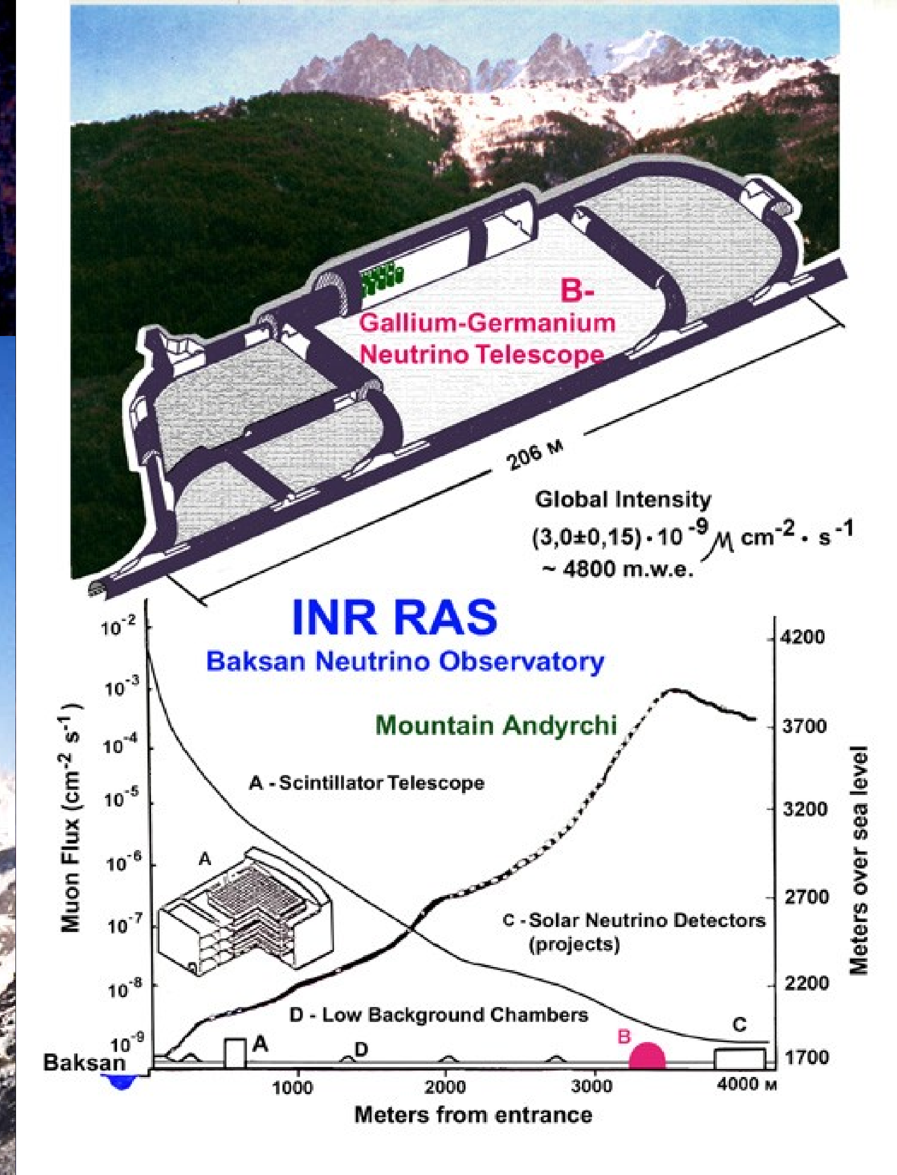


- Want to measure the lowest energy solar neutrinos
- Detect the neutrinos by observing the reaction

$$^{71}Ga + \nu \rightarrow {}^{71}Ge + e^-$$

- The Soviet-American Gallium Experiment - SAGE





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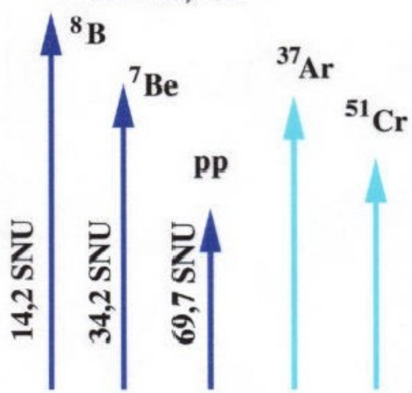
Imperial College/RAL

SAGE Experiment Overview

Bahcall, etc

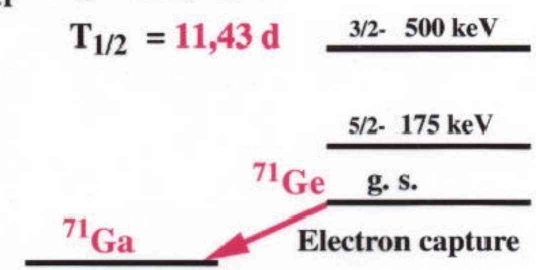
$$^{71}\text{Ga} + \nu \rightarrow {}^{71}\text{Ge} + e^-$$

Kouzmine, 1965

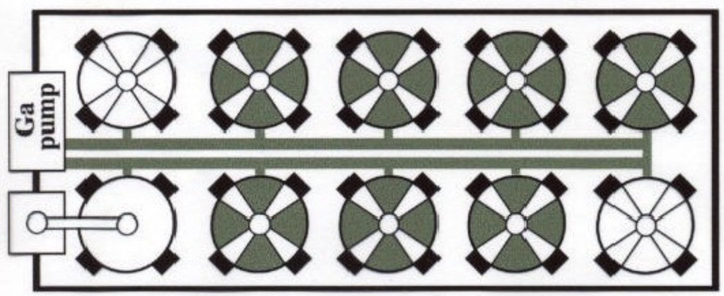


Q = 233,2 keV

$T_{1/2}$ = 11,43 d



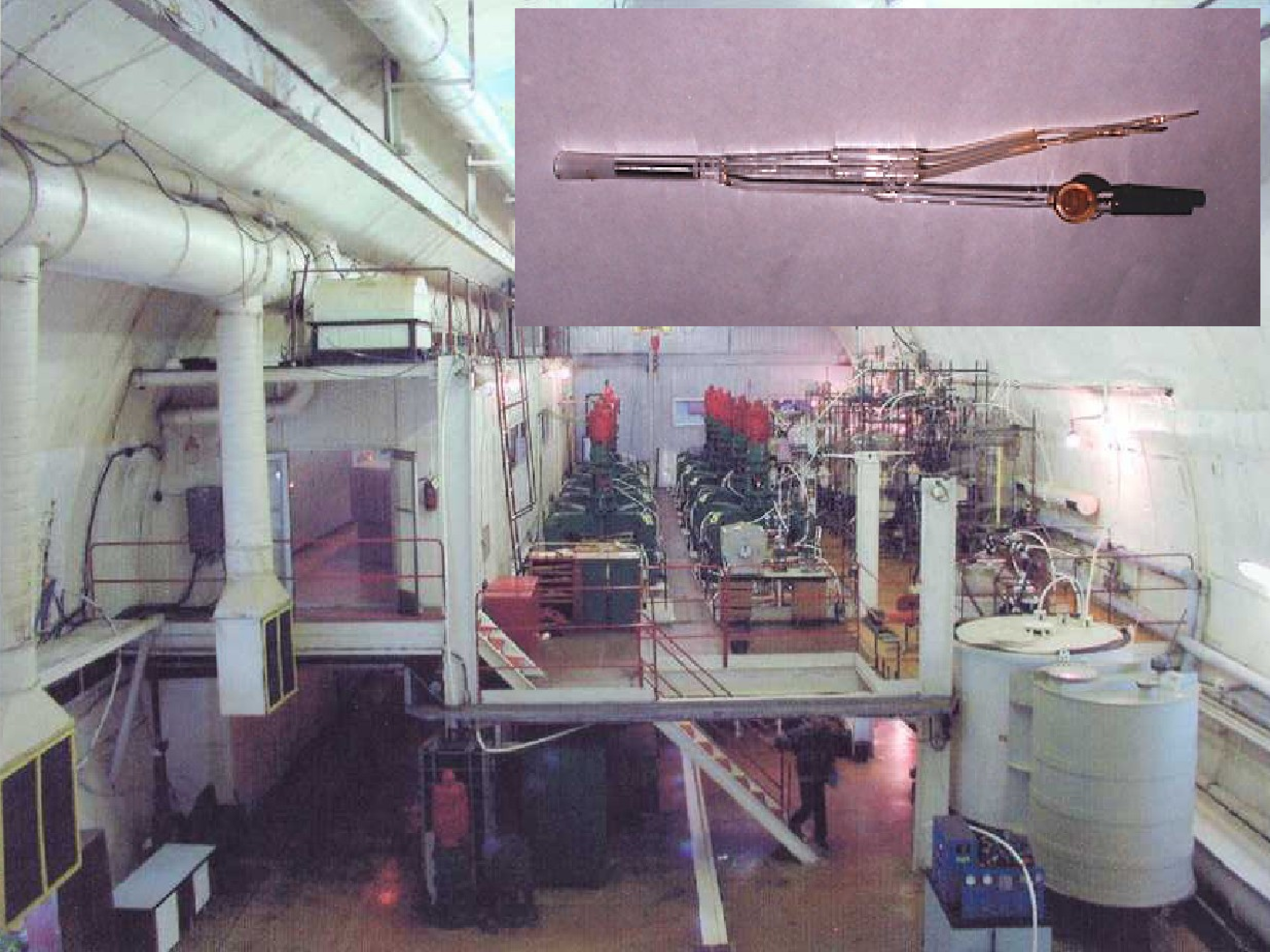
A plan view of the reactors layout in the laboratory



$t_{reac} \geqslant 30^oC$
$t_{melt} = 29.8^oC$

~7 tons metallic Ga in each

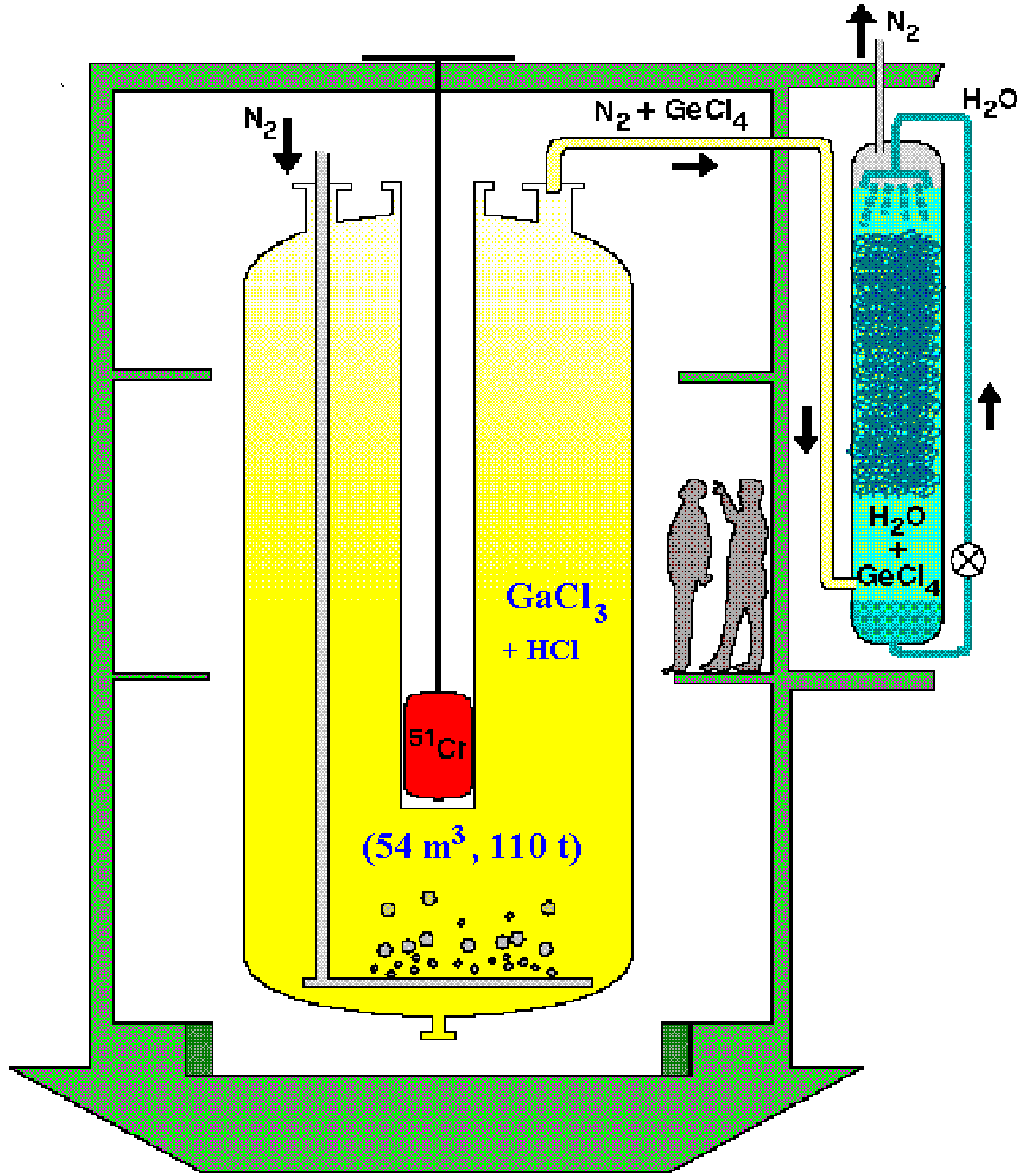
- * 250 mkg Ge-76/72 carrier uniformly between reactors
- * Exposure time ~ 27 d
- * ^{71}Ge chemical extraction from metallic Ga to aqueous solution ~ 1.5 m^3
- * Concentration of Ge to 50 ccm trithium free water
- * Synthesis of germane - GeH_4
- * Counting of Ge decays



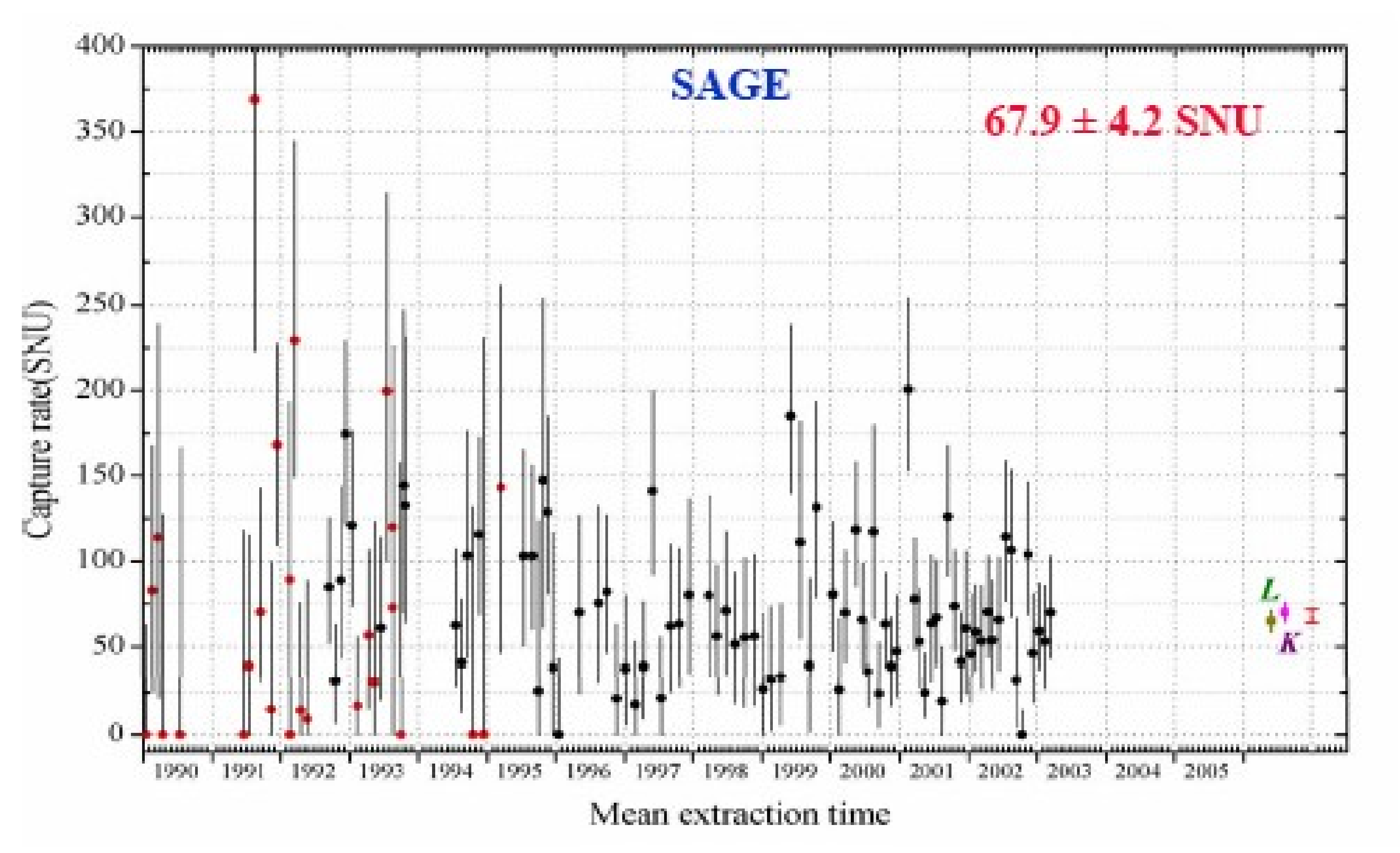
GALLEX/GNO has:

- Very different chemistry
- Many detailed differences

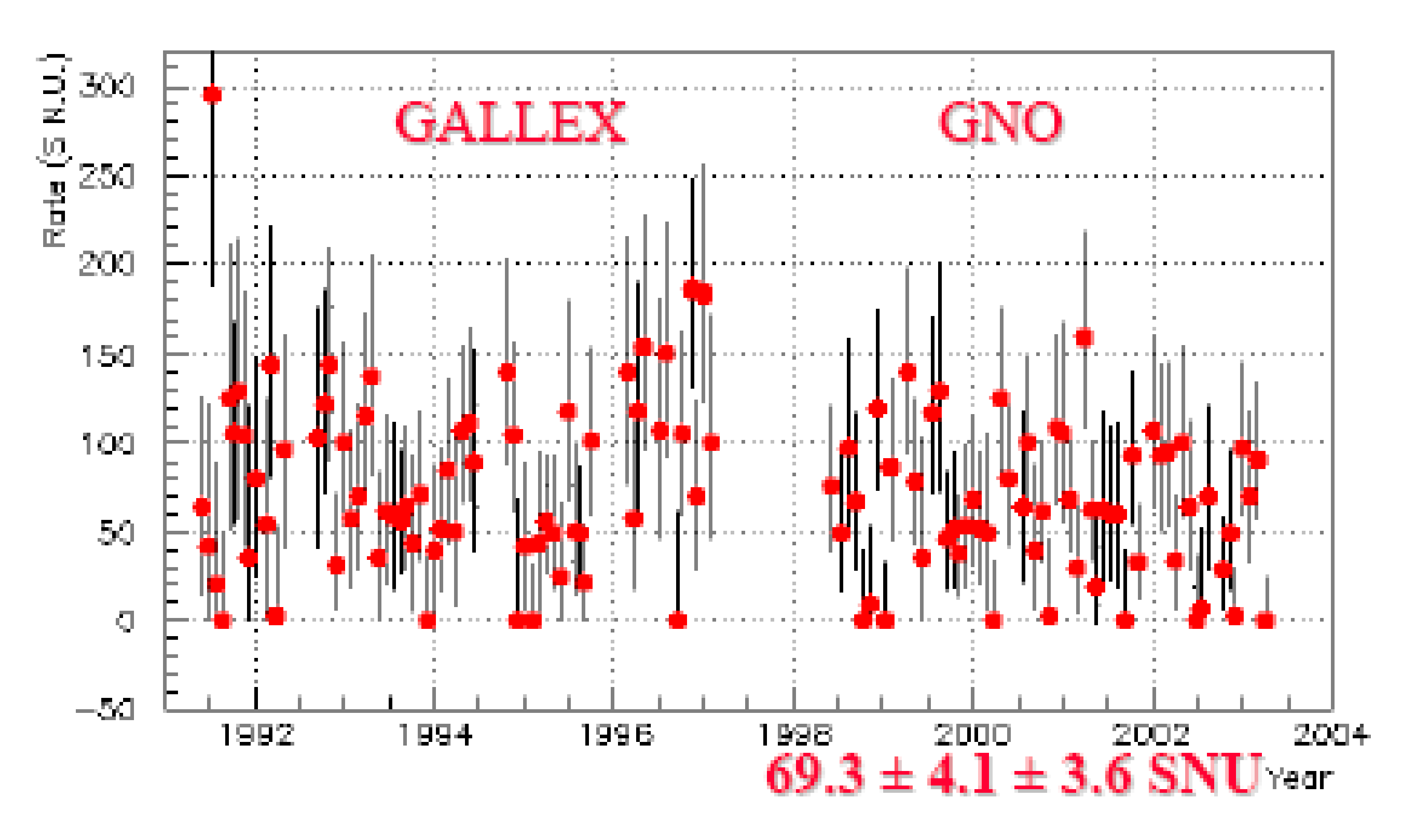
Extraction/counting of both experiments verified using ~1 MCi ^{51}Cr sources

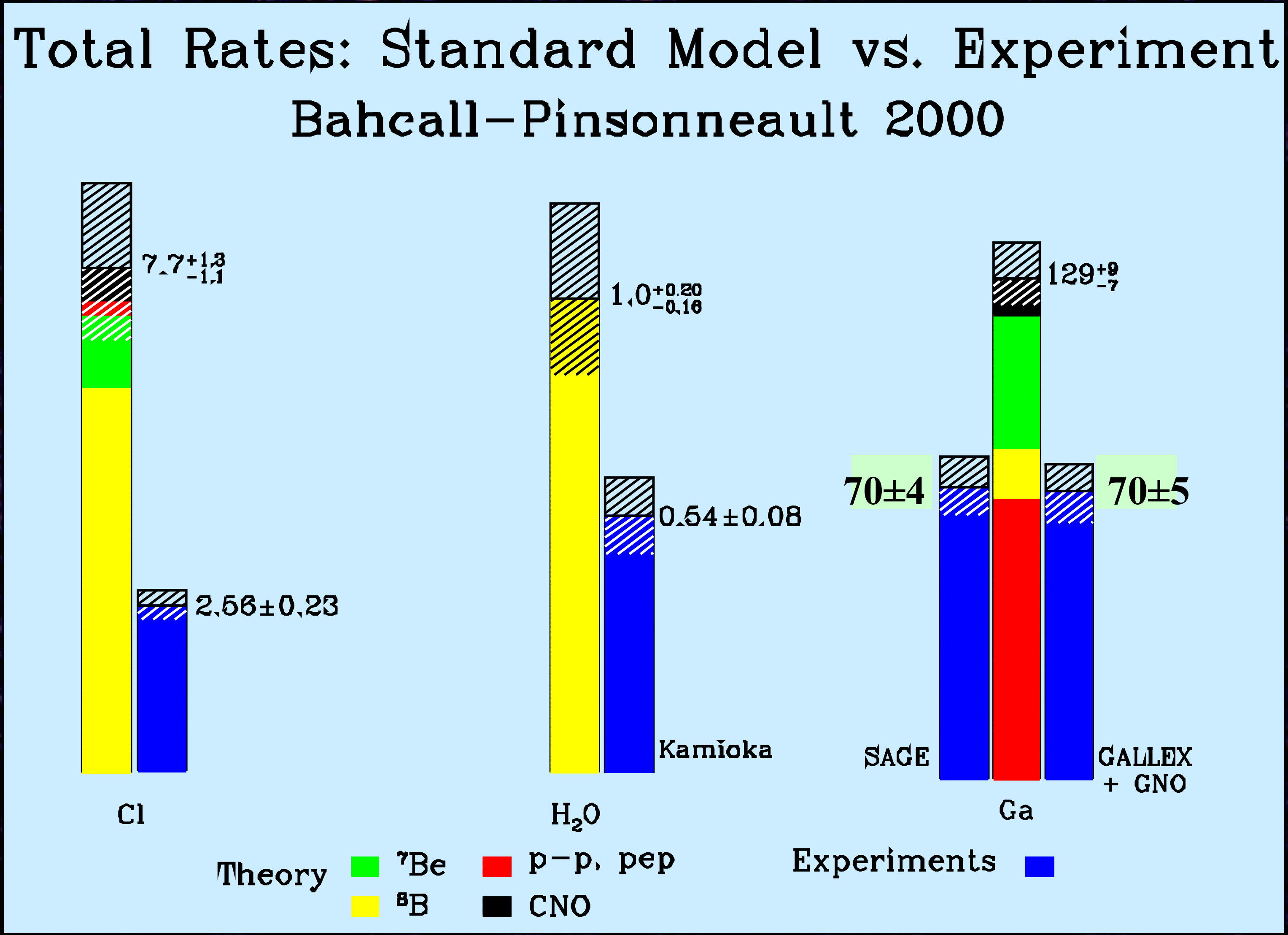


SAGE Results



GALLEX/GNO Results





Eliminates any credible astrophysical explanation…

Dave Wark
Imperial College/RAL

The theorists had already been thinking….

- 1957 – Bruno Pontecorvo, wondering if there are any other particles which could undergo oscillations analogous to $K^0 \leftrightarrow \overline{K^0}$ oscillations, hit upon the idea of neutrino ↔ anti-neutrino oscillations (more about this later).
- 1962 – Maki, Nakagawa, and Sakata (in the context of what looks today like a very odd model of nucleons) proposed that the weak neutrinos known at the time were superpositions of "true" neutrinos with definite masses, and that this could lead to transitions between the different weak neutrino states.
- 1967 – 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!
- 1972 – Pontecorvo is informed by John Bahcall that Davis does indeed see a reduced rate, and responds with a letter….

ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ

JOINT INSTITUTE FOR NUCLEAR RESEARCH

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

№ 994/31 April 6, 1972
/10

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.

looking forward to see you there.

Yours sincerely,

B.Pontecorvo

B.Pontecorvo

BMP/nn

2ν Vacuum Oscillations

- For two neutrino flavours in vacuum oscillations lead to the appearance of a new neutrino flavour:

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

$\Delta m^2 = m_2^2 - m_1^2$ in eV^2, L in meters, E in MeV

- With the corresponding disappearance of the original neutrino flavour
- These oscillations can be significantly modified by the MSW effect when the neutrinos pass through matter…

Matter Effects – the MSW effect

$$i\frac{d}{dt}\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e \\ \nu_x\end{bmatrix}$$

In vacuum:

$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

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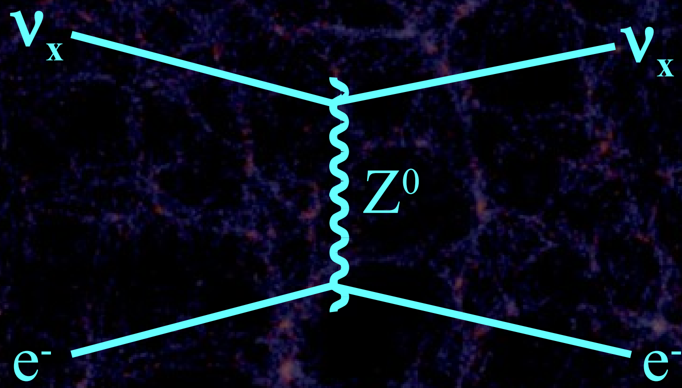
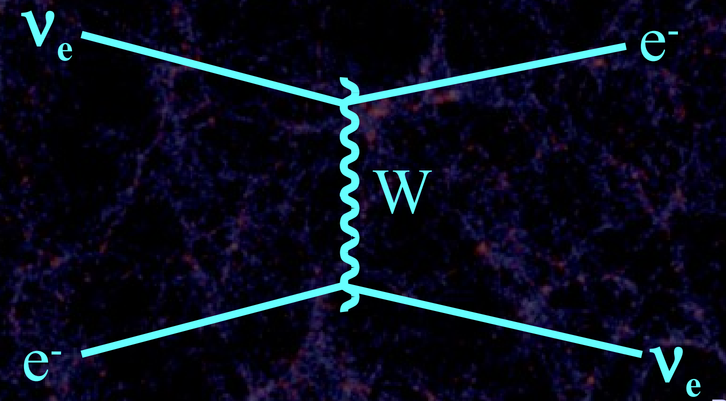




Matter Effects – the MSW effect

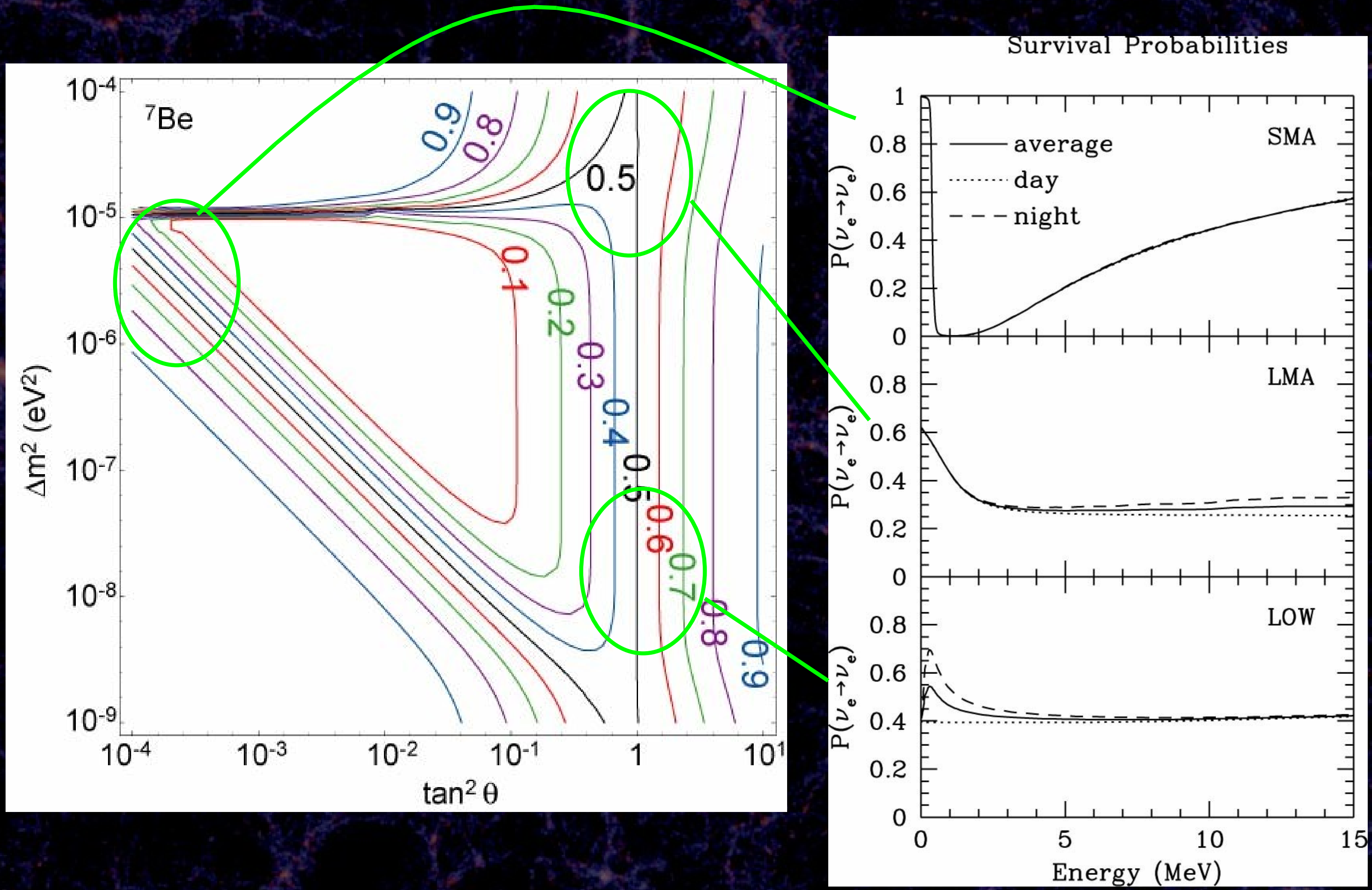
$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}$$

$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

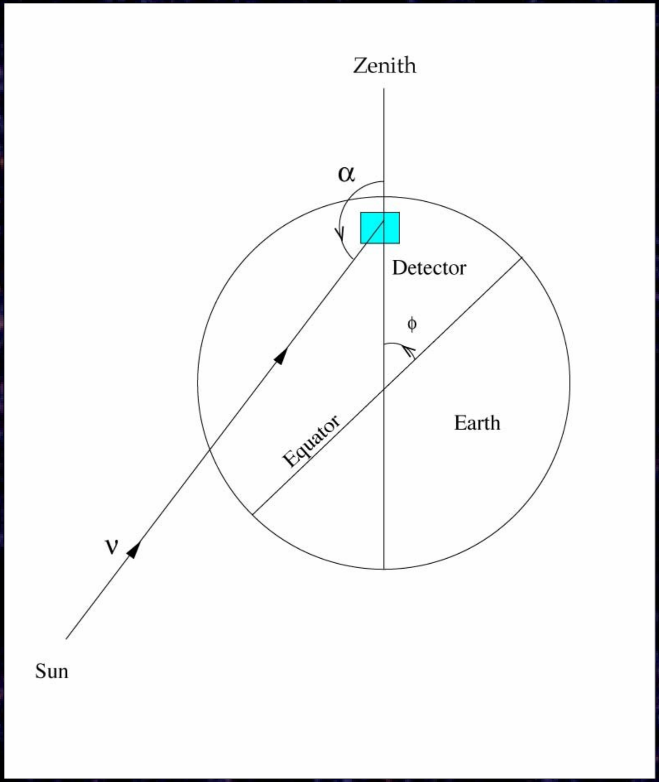
$$\omega = -2\sqrt{2}G_F N_e E / \Delta m^2$$

Matter Effects – the MSW effect

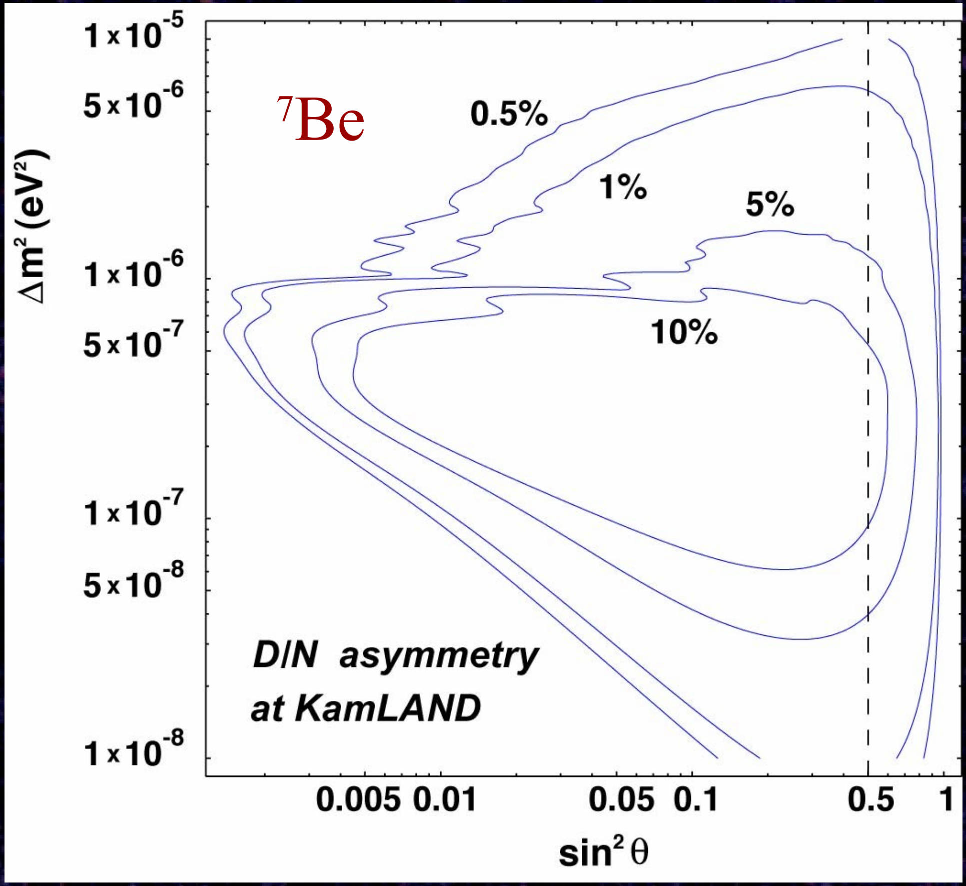


Matter Effects – the MSW effect

Day – Night Effect



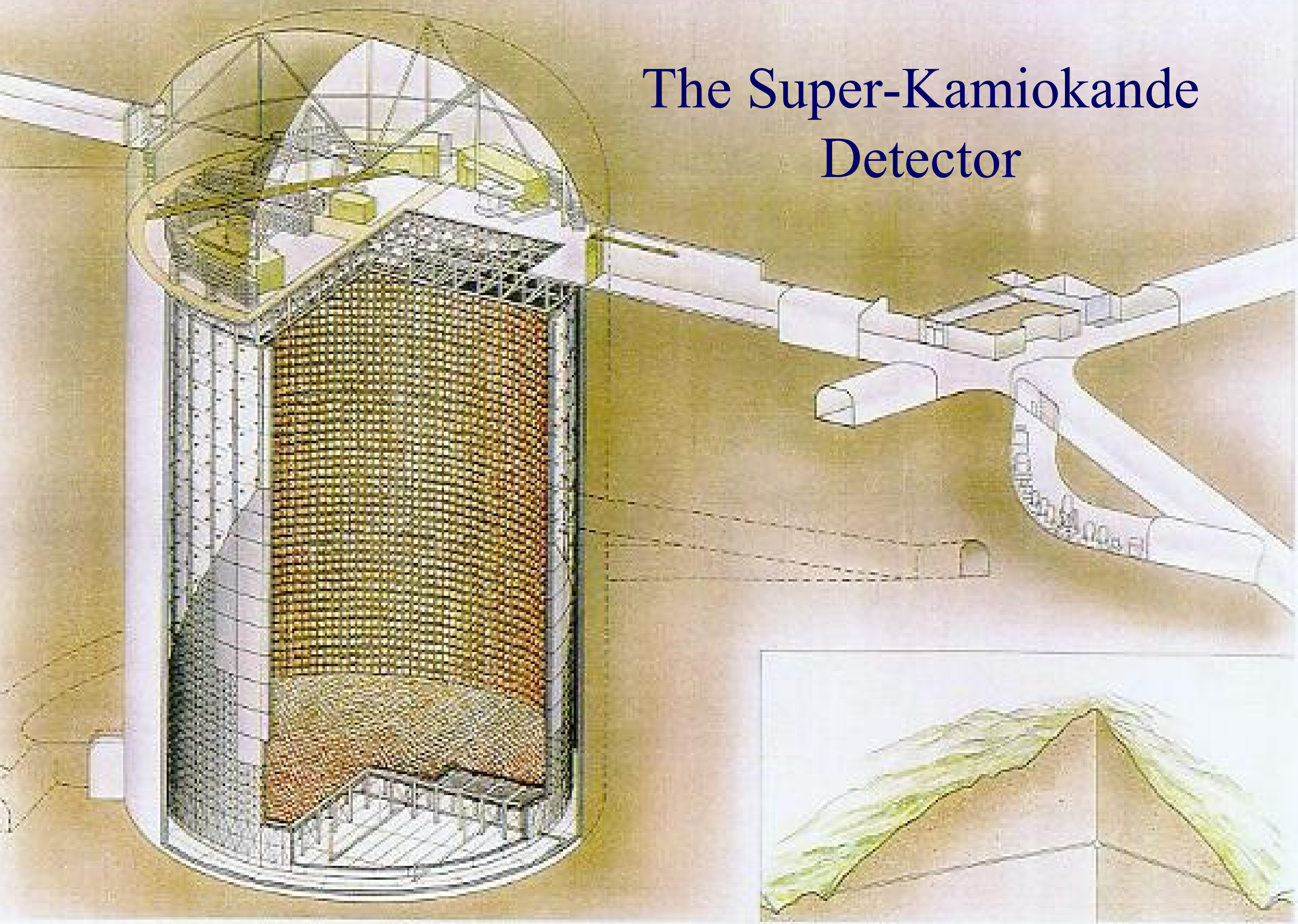
$$\text{Asym} = \frac{N - D}{N + D}$$

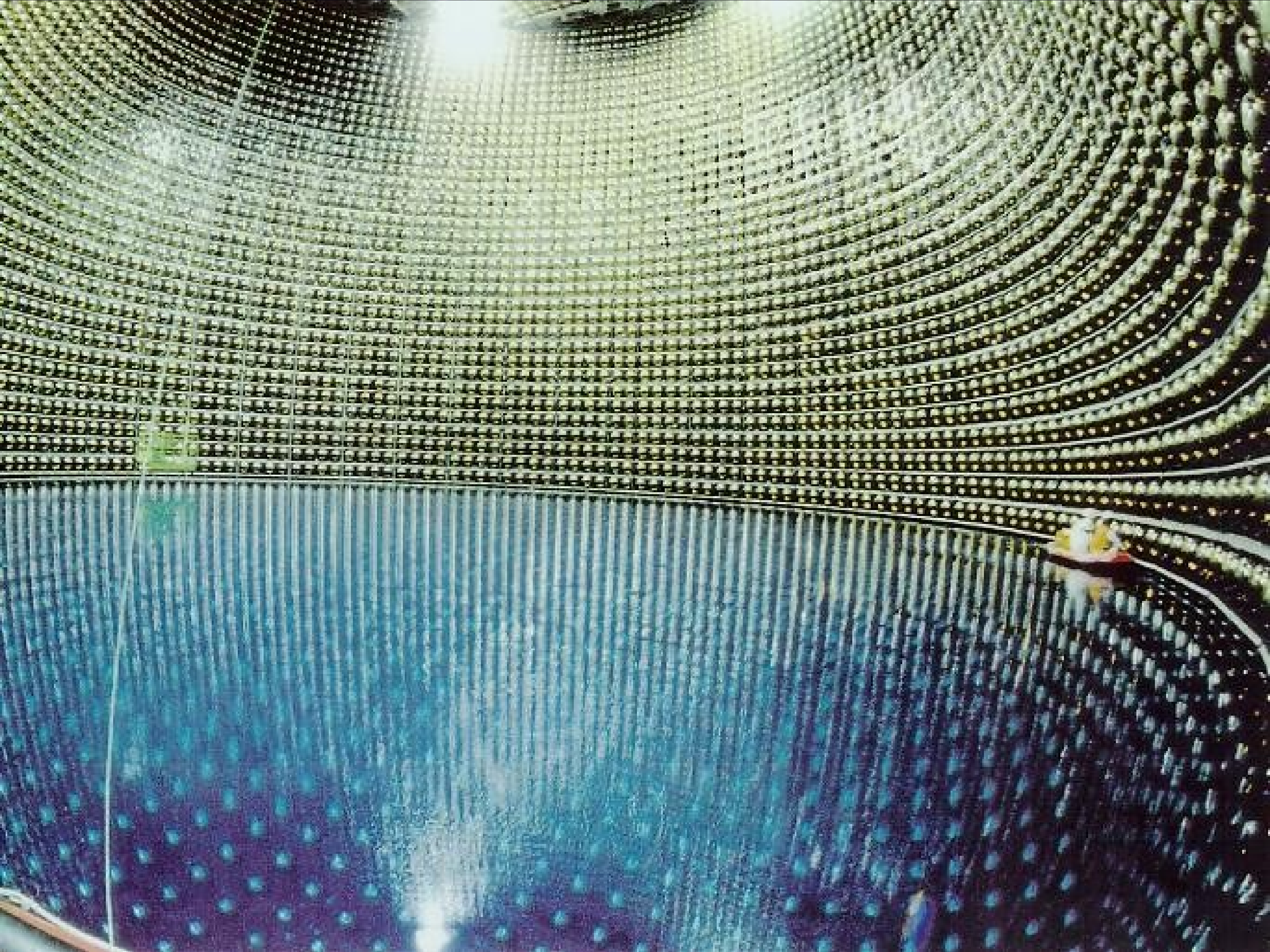


Also produces(?) seasonal variation

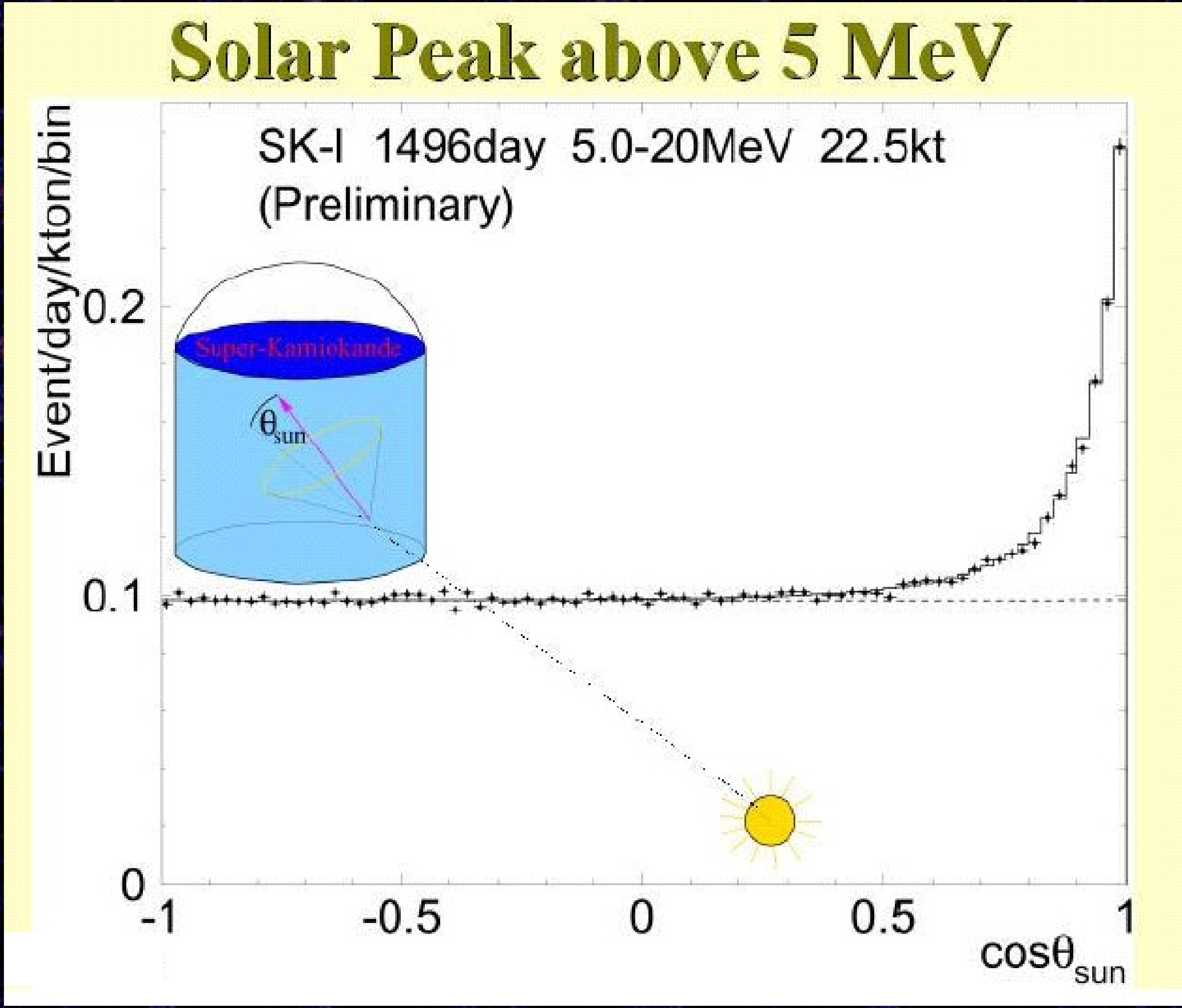
Dave Wark
Imperial College/RAL

The Super-Kamiokande Detector





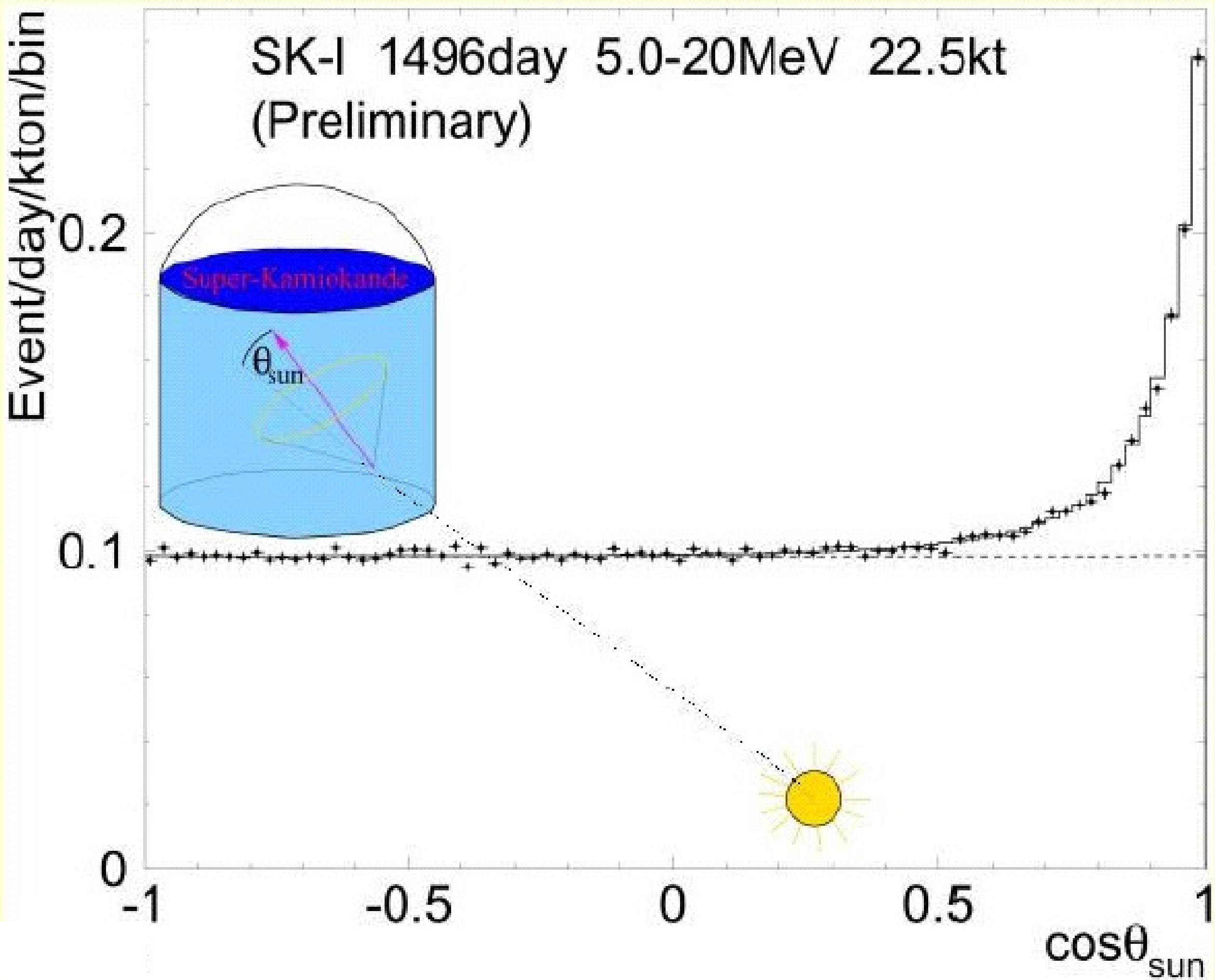
22,400 solar neutrino events!



"Flux" is $2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{sys.}) \times 10^6/\text{cm}^2\cdot\text{s}$

22,400 solar neutrino events!

Solar Peak above 5 MeV



$$0.465 \pm 0.005(\text{stat.})^{+0.016}_{-0.015}(\text{sys.}) \times \text{SSM}$$

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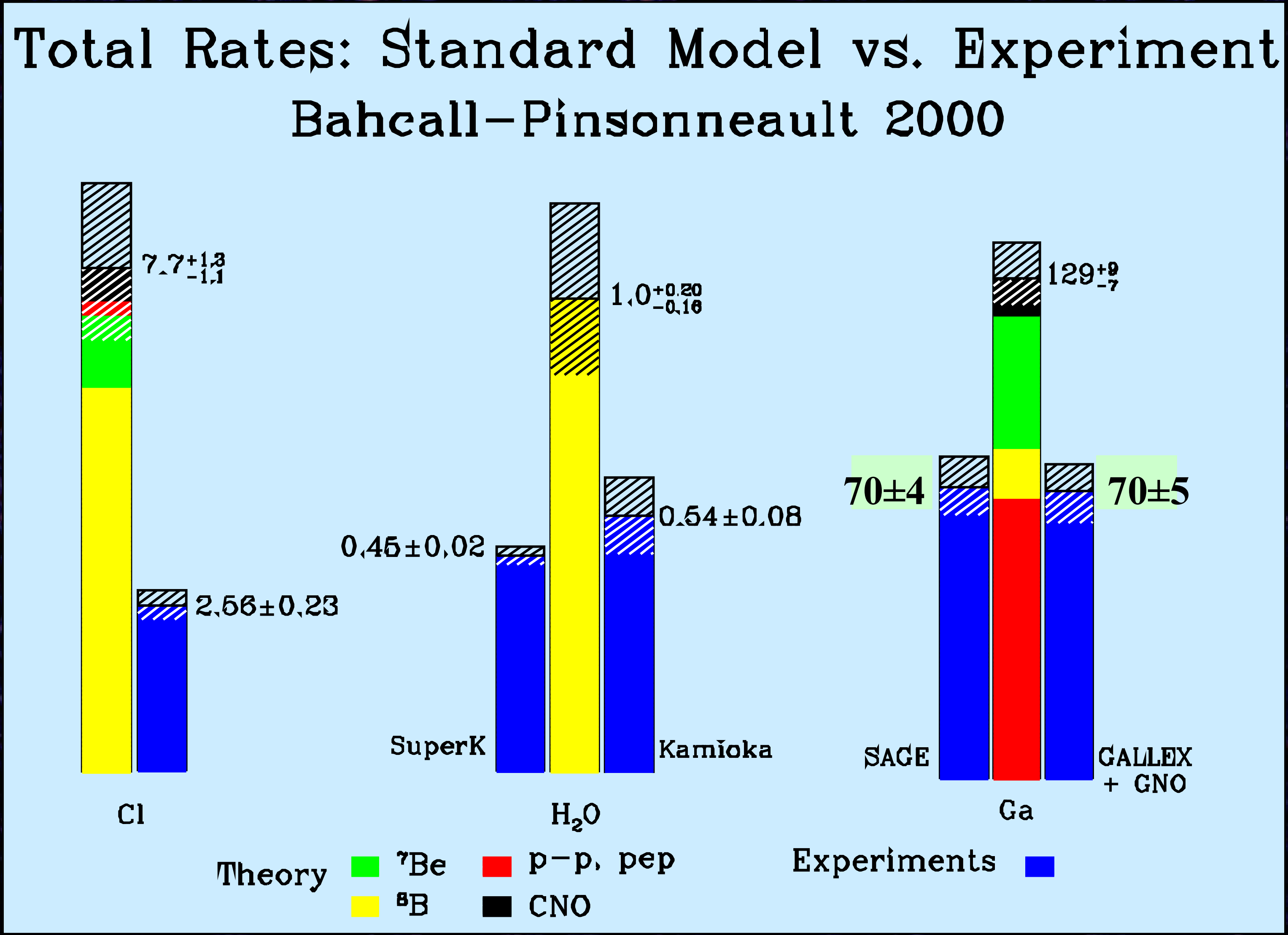
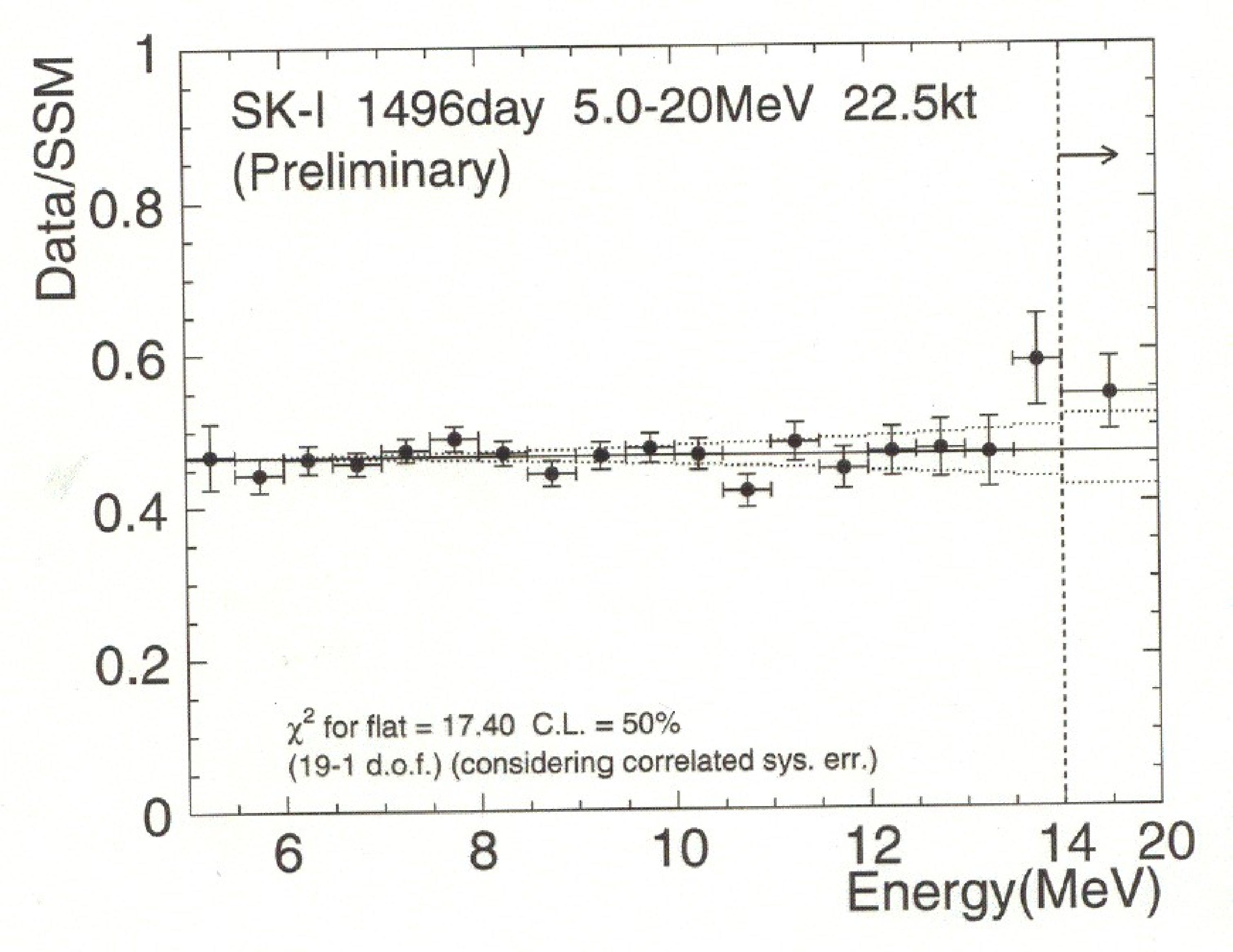
Imperial College/RAL

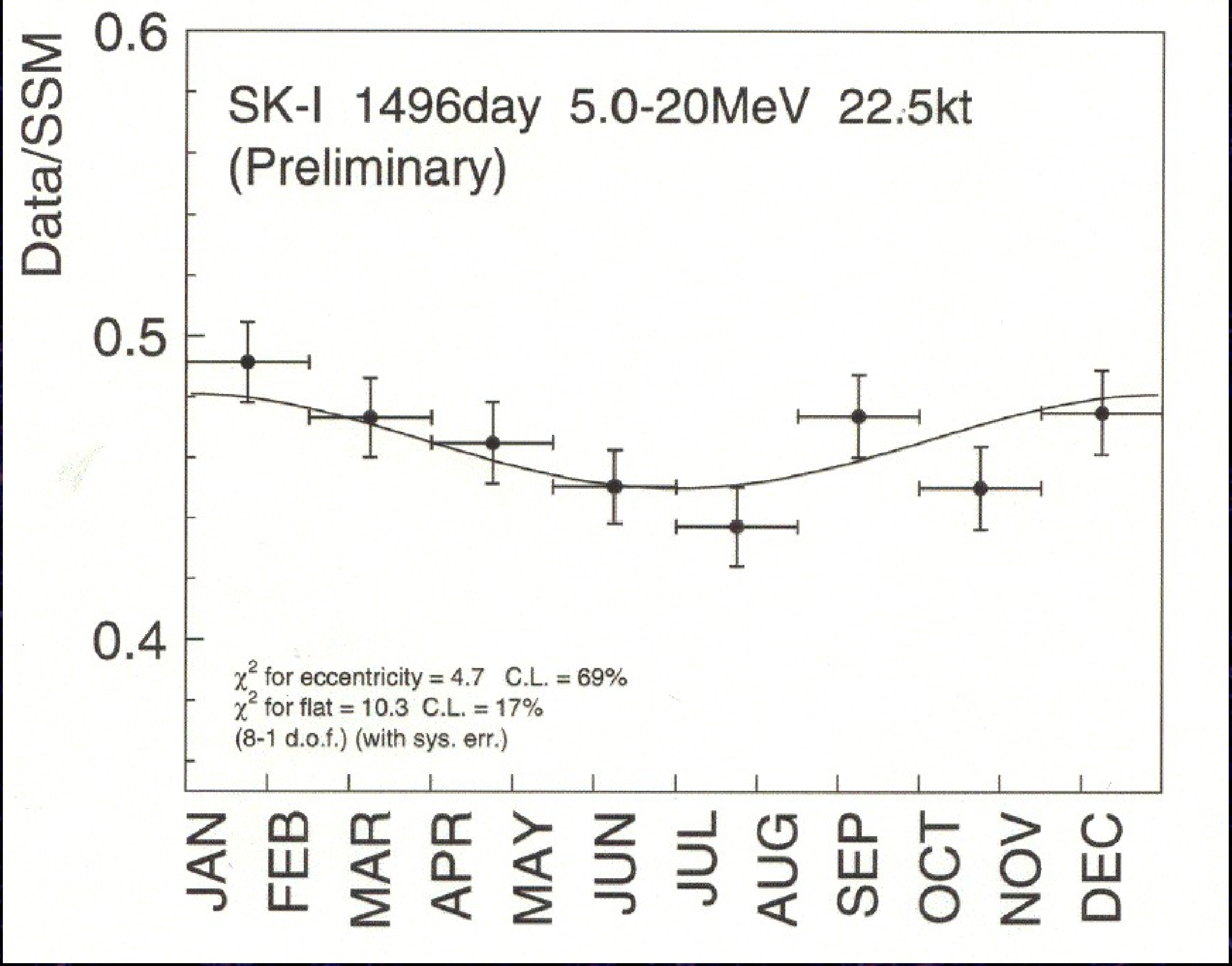

Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000
7.7 +1.3 -1.1
2.56±0.23
Cl
1.0 +0.20 -0.16
0.45±0.02
0.54±0.08
SuperK
Kamioka
H2O
129 +9 -7
70±4
70±5
SAGE
GALLEX + GNO
Ga
Theory
7Be
8B
p-p, pep
CNO
Experiments

Super-Kamiokande Energy Spectrum



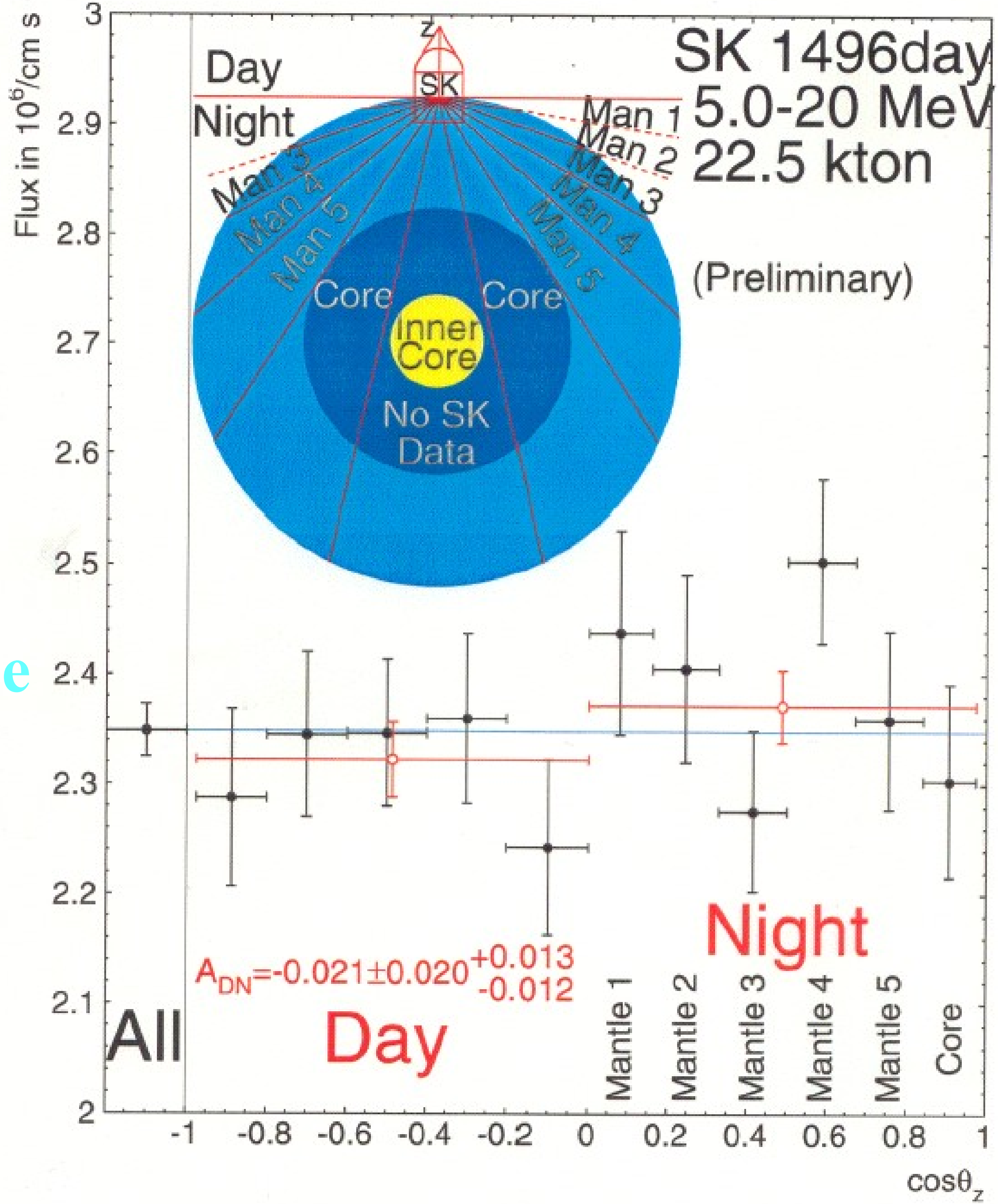
Dave Wark
Imperial College/RAL

Super-Kamiokande seasonal variation

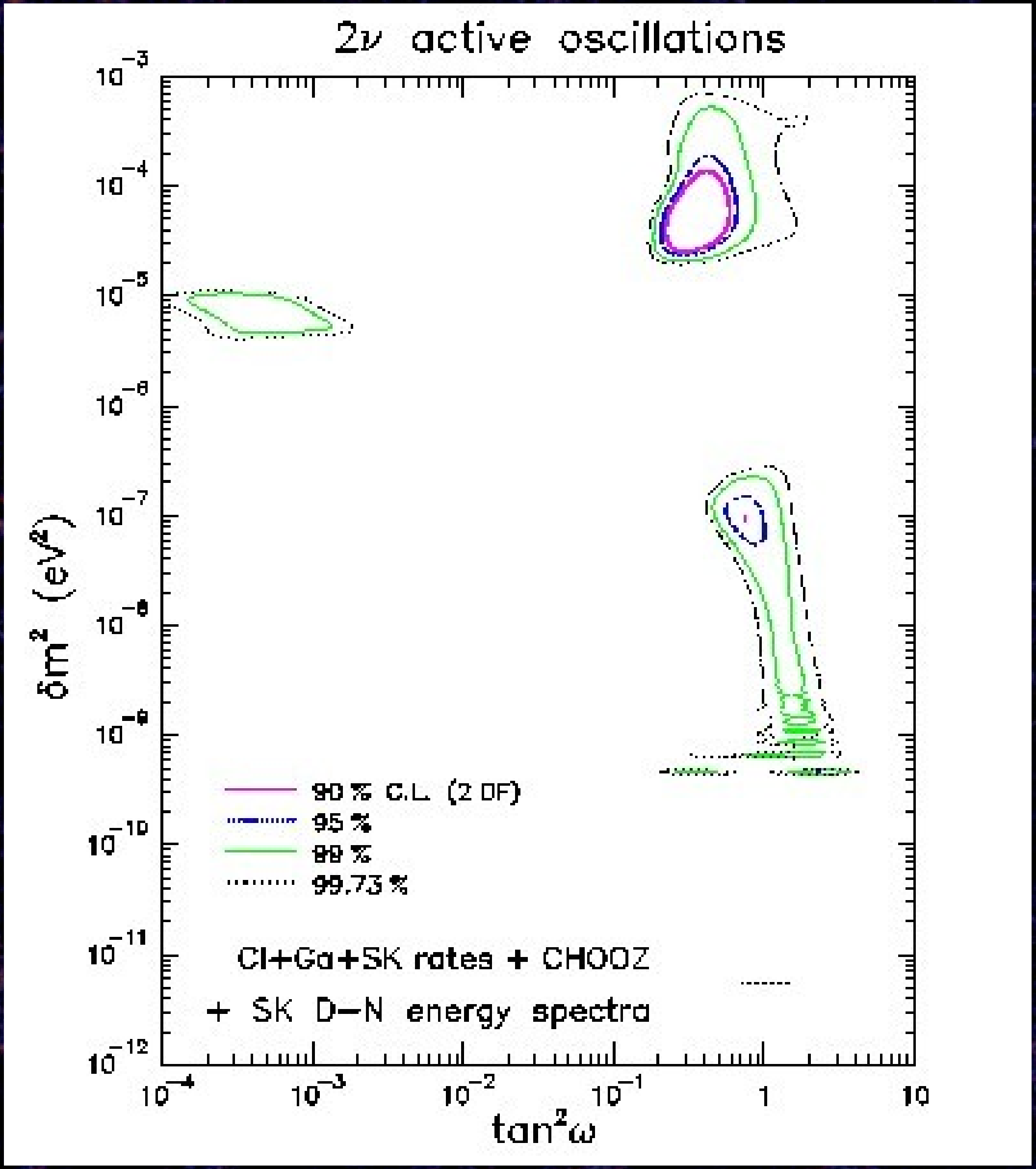


Super Kamiokande

Day-night variation



Which left us where?



But no smoking gun for oscillations….

Dave Wark
Imperial College/RAL