Neutrino Oscillations - I

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

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Imperial/RAL

Science & Technology Facilities Council

Imperial College London

What to talk about?

I will stick mostly to “standard” 3ν oscillations – Peter has discussed steriles.

I will stick to experimental detail – I would not presume to discuss phenomenology with Peter and Boris here. I will just say a few things to help motivate the measurements.

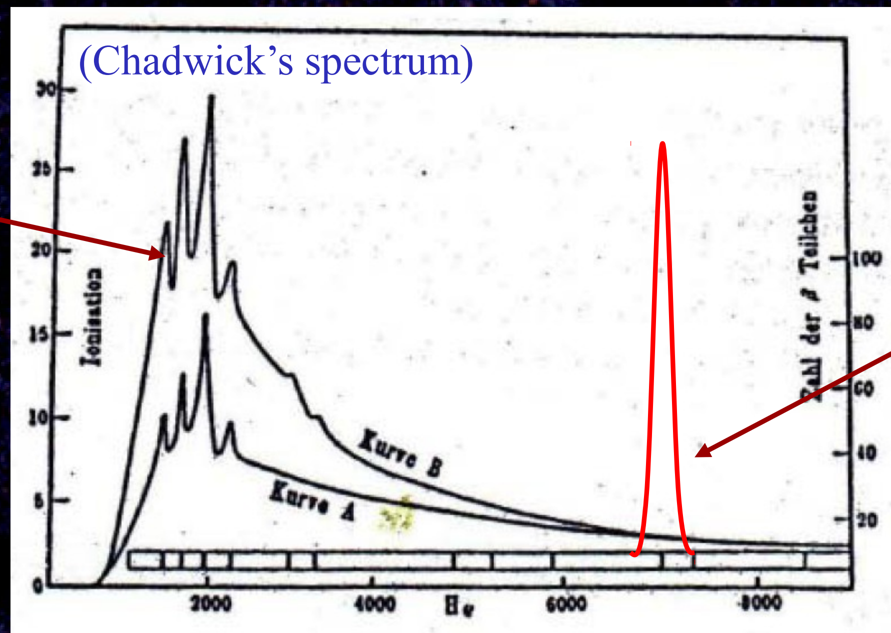
I will include some history you won’t pick up in the usual lectures you attend.

Please ask questions if you have them.

(Then I can blame you when I overrun!)

Where did the idea of the neutrino come from?

There were problems in the early days of β decay.



And the spins didn't add up…

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 Li6 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

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 $\nu e + 37Cl \rightarrow 37Ar + e^{-}$ (and even mentioned solar neutrino detection using this method).*
- *However the first detection of neutrinos used another method, which Jim has already told you about.*
- *Pontecorvo's suggestion led to the second attempt...*

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.

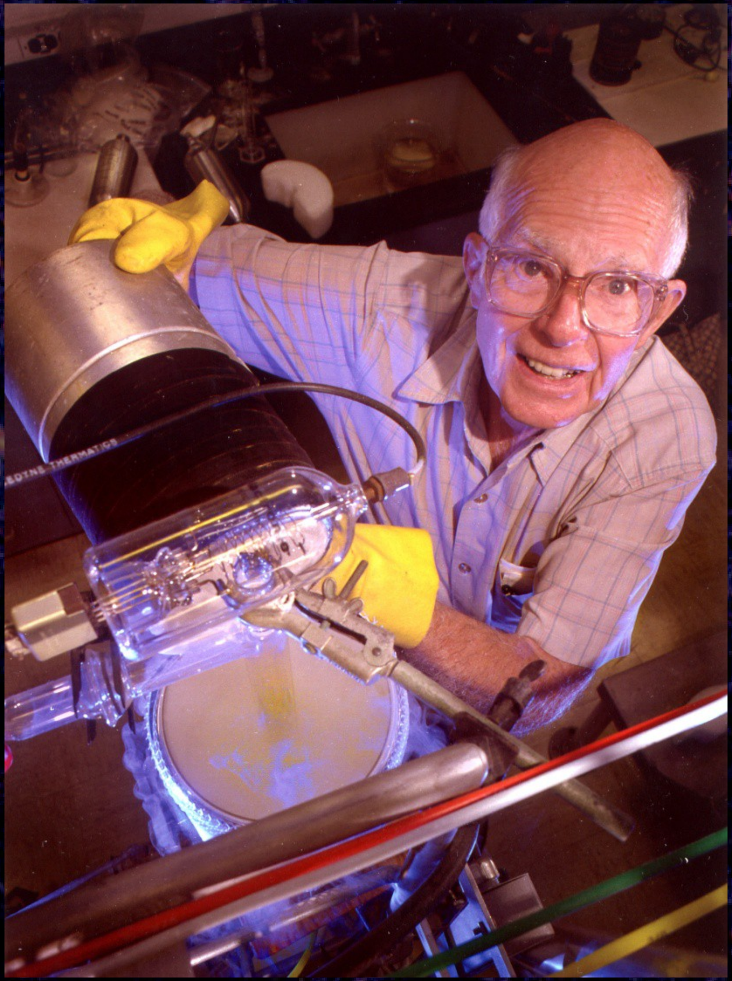
If $\bar{\nu} = \nu$ you would expect to see 37Ar produced by this reaction.

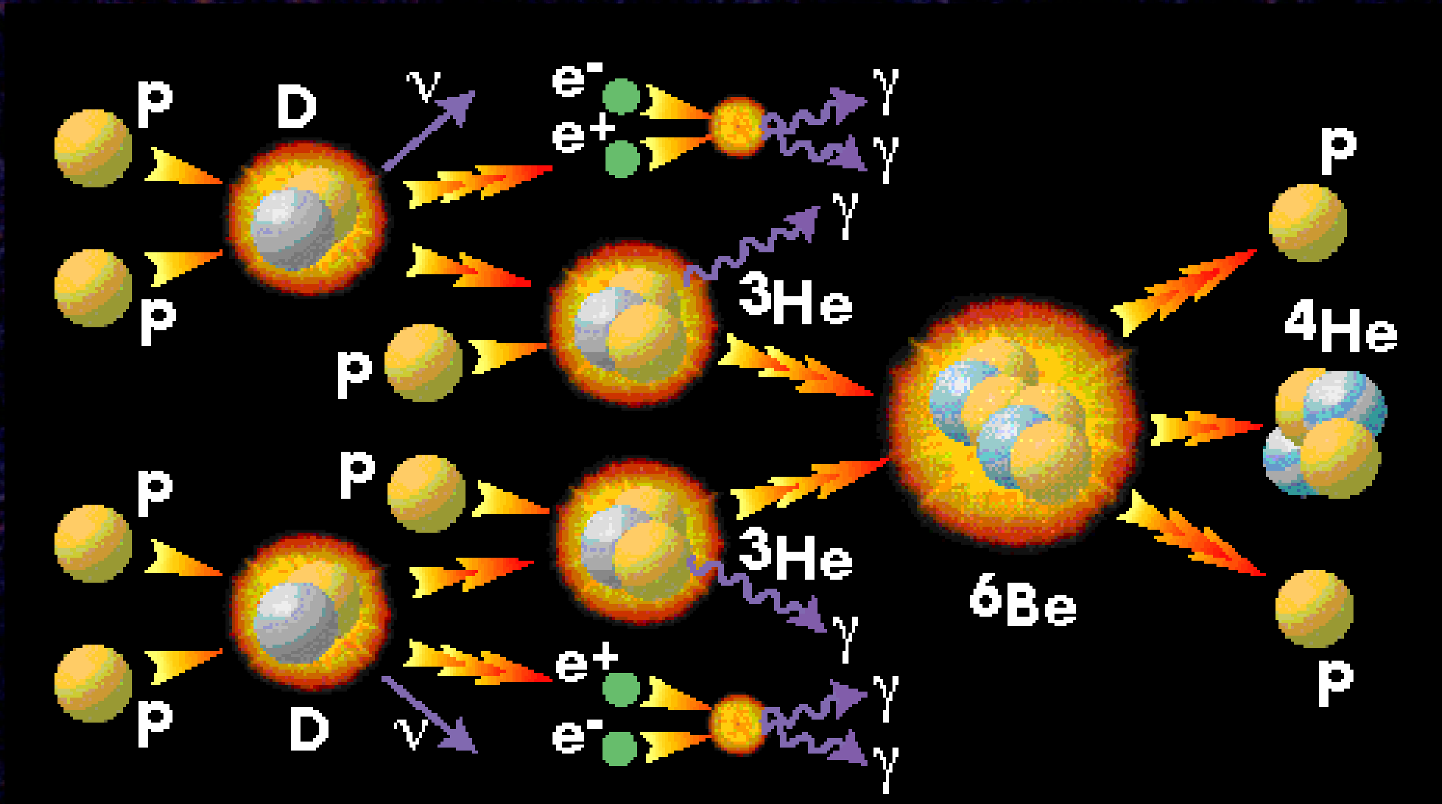
By 1957 enough sensitivity had been reached to show that the rate was too small, from which it was concluded that $\bar{\nu} \neq \nu$.

This is wrong, because P is violated in weak interactions!

Solar Neutrinos

Ray Davis





Photons take 104 years to get out

Energy takes 107 years to get out

Neutrinos come out at the speed of light!

Net reaction is 4p $\rightarrow$ 4He +2e+ + 2νe

Releases 25.7 MeV/c2, or 4.12 x 10-12 J, per Helium nucleus produced (or half that per neutrino)

The solar constant is 1370 Watts/m2 at Earth's orbit

Thus the neutrino flux should be 1370/(2.06x10-12)/m2/sec or:

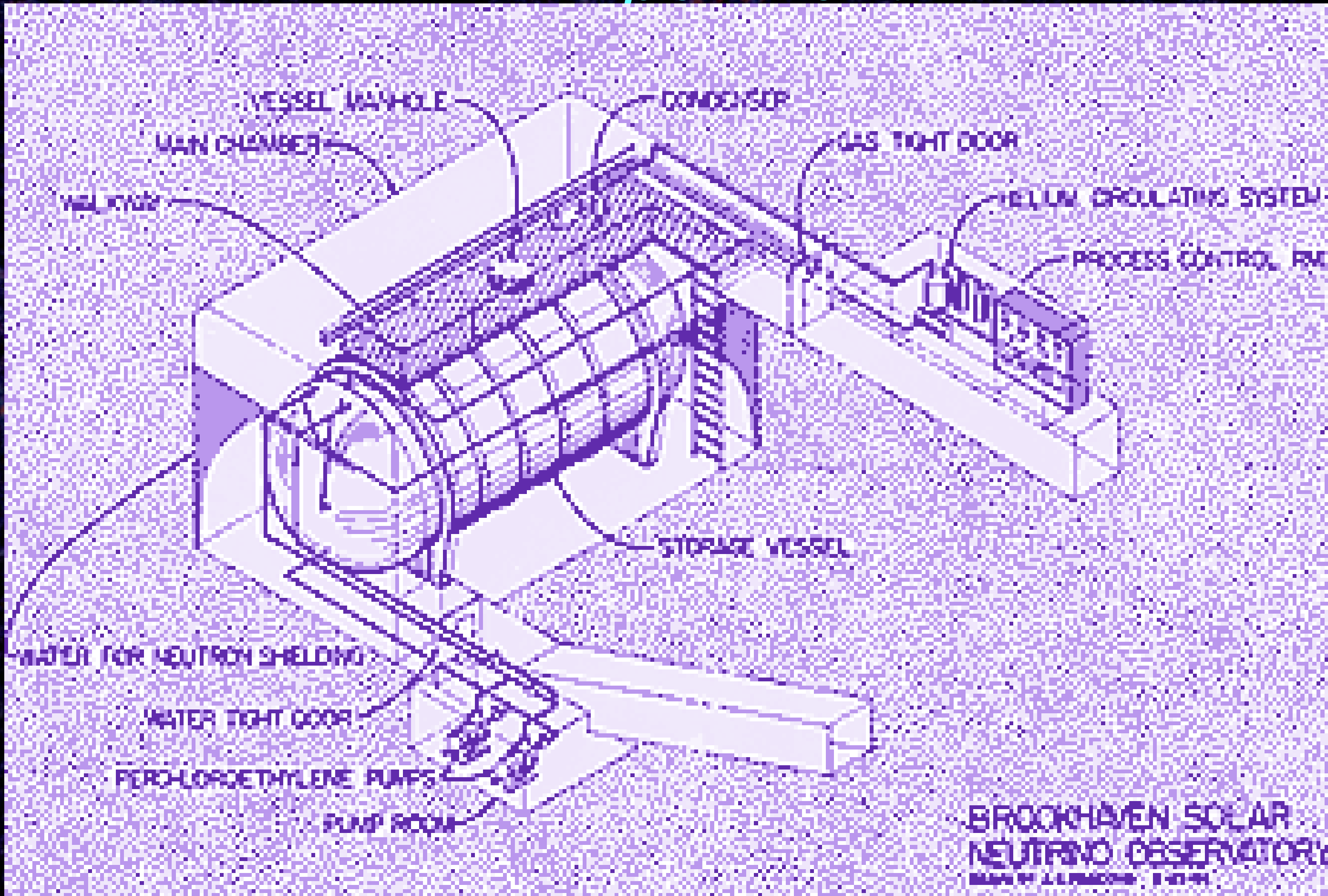
6.65 x 1010 /cm2/sec

Good News: this is accurate to better than 10%

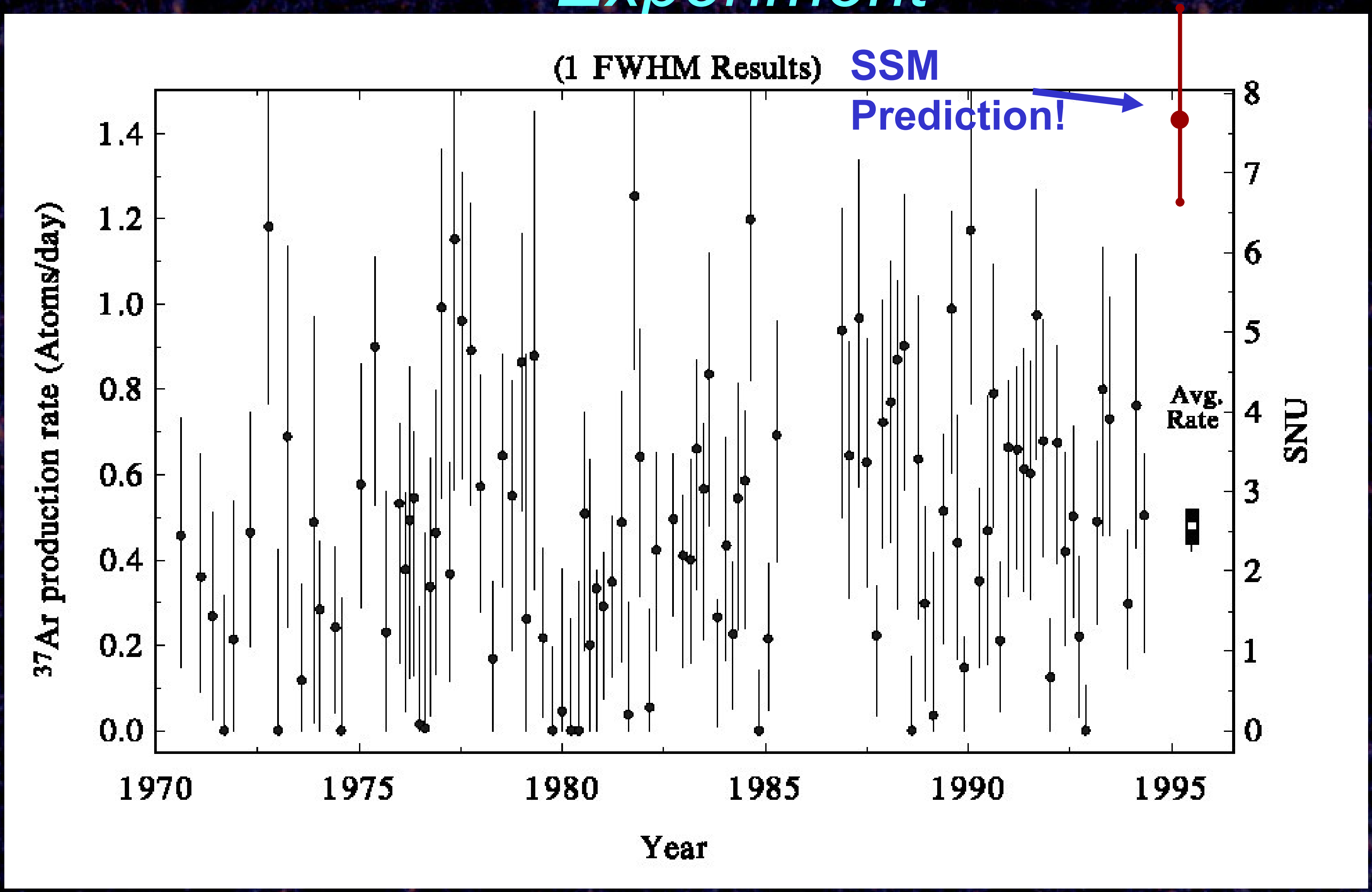
Bad News: we left out a few things….

Where it all began – the Davis Experiment

Where it all began – the Davis Experiment

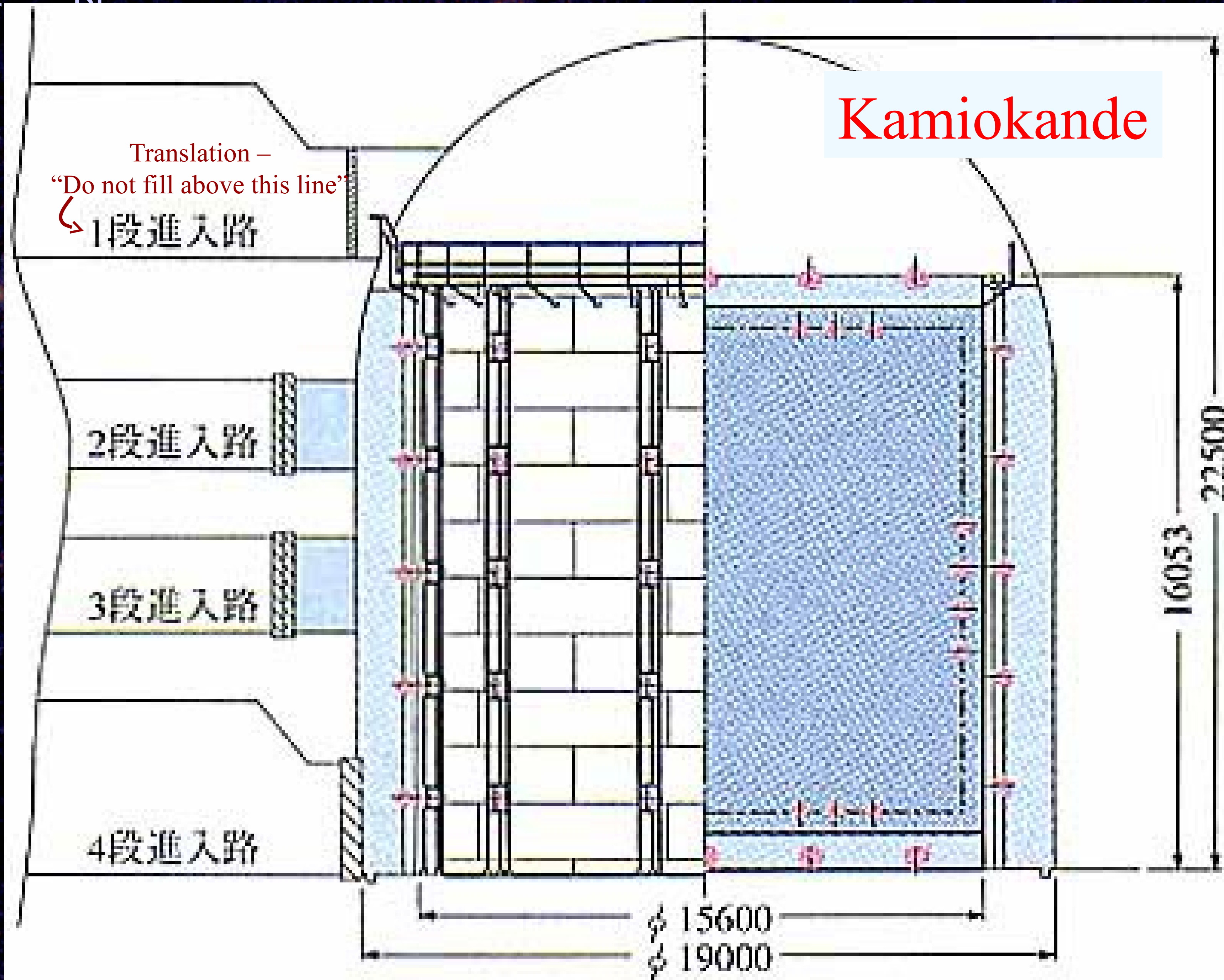


Where it all began – the Davis Experiment



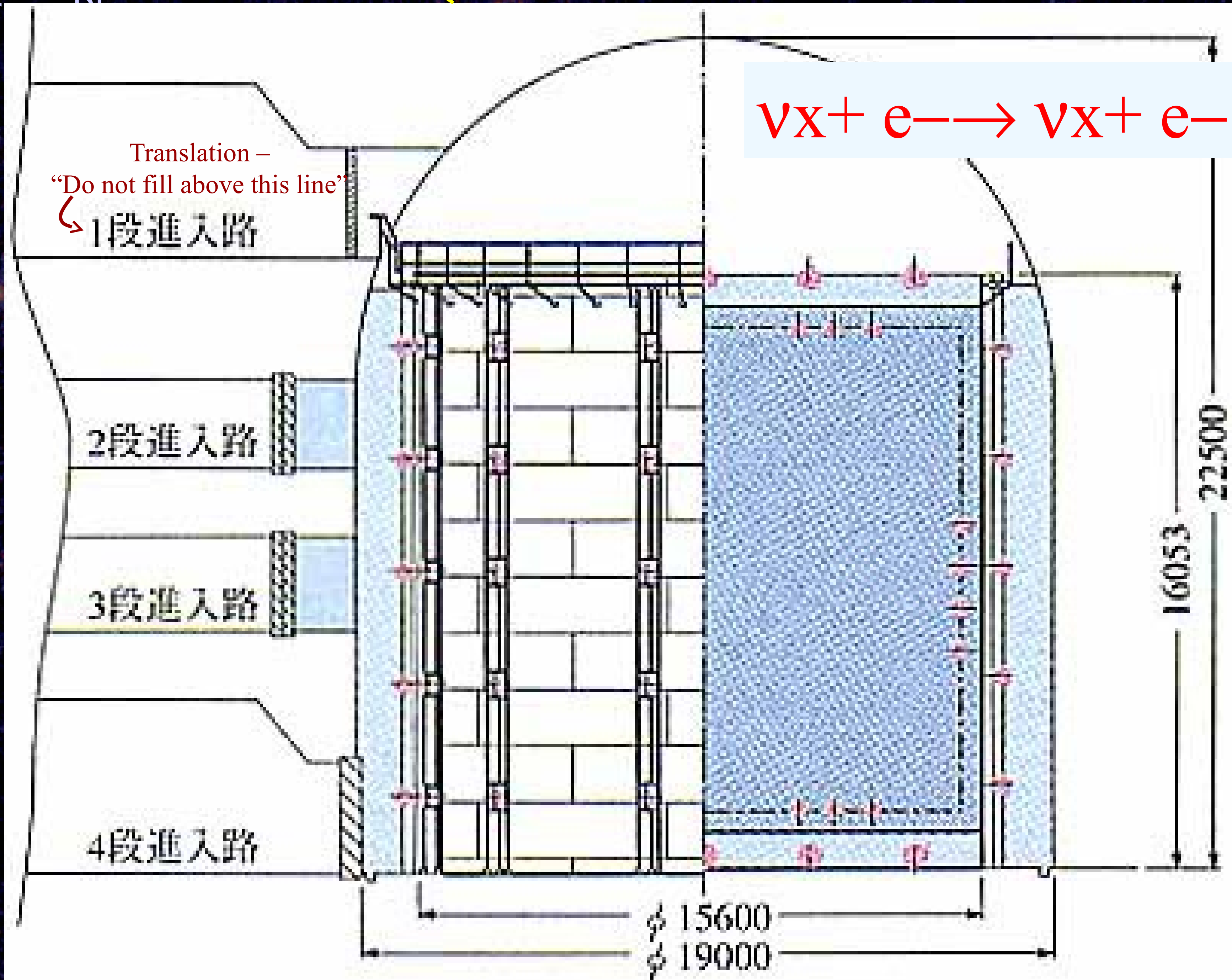
Maybe the experiment is wrong…

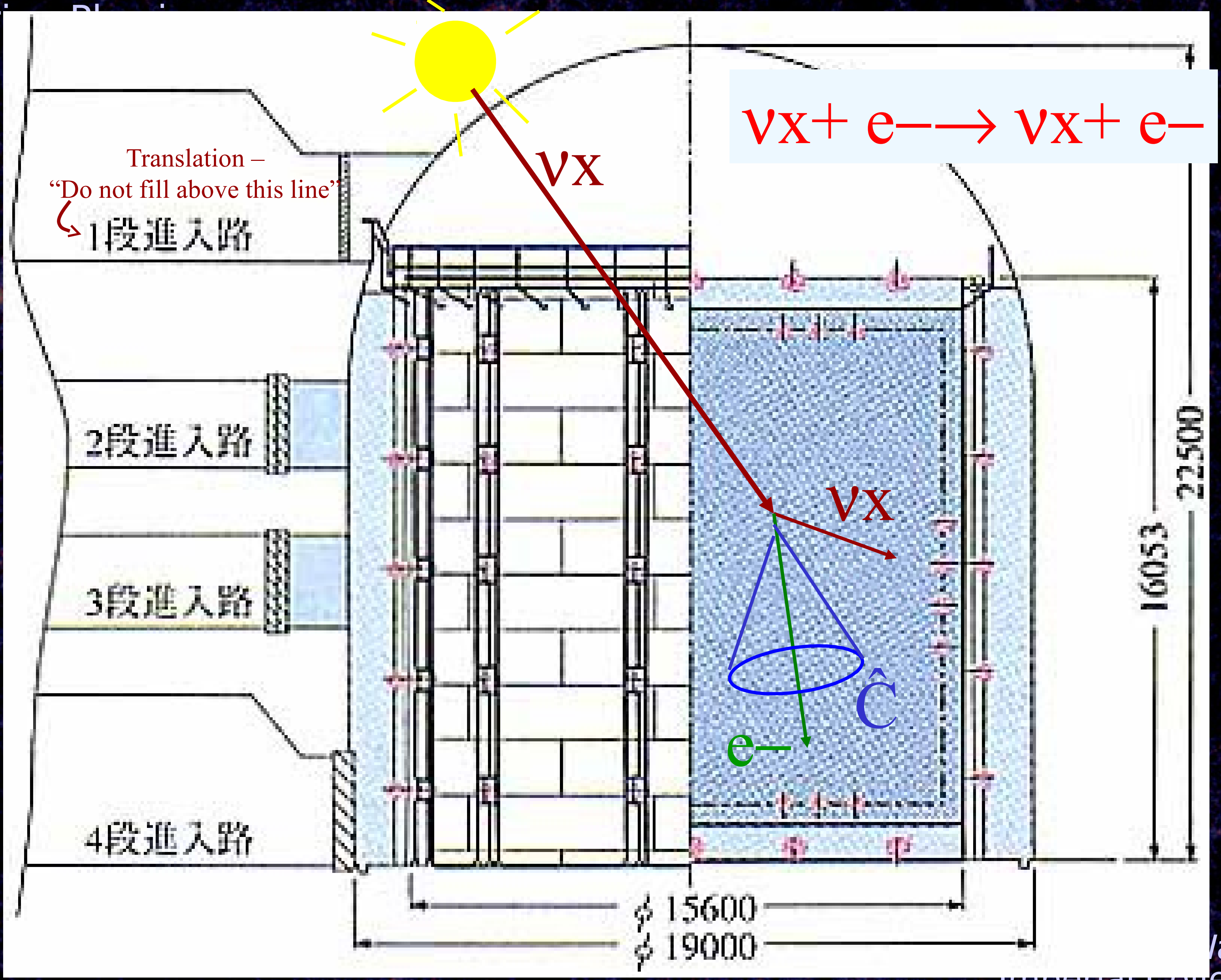
Kamiokande



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
16053
22500
ϕ 15600
ϕ 19000

$$\nu x + e^- \longrightarrow \nu x + e^-$$




νx+ e–⟶ νx+ e–
νx
Translation –
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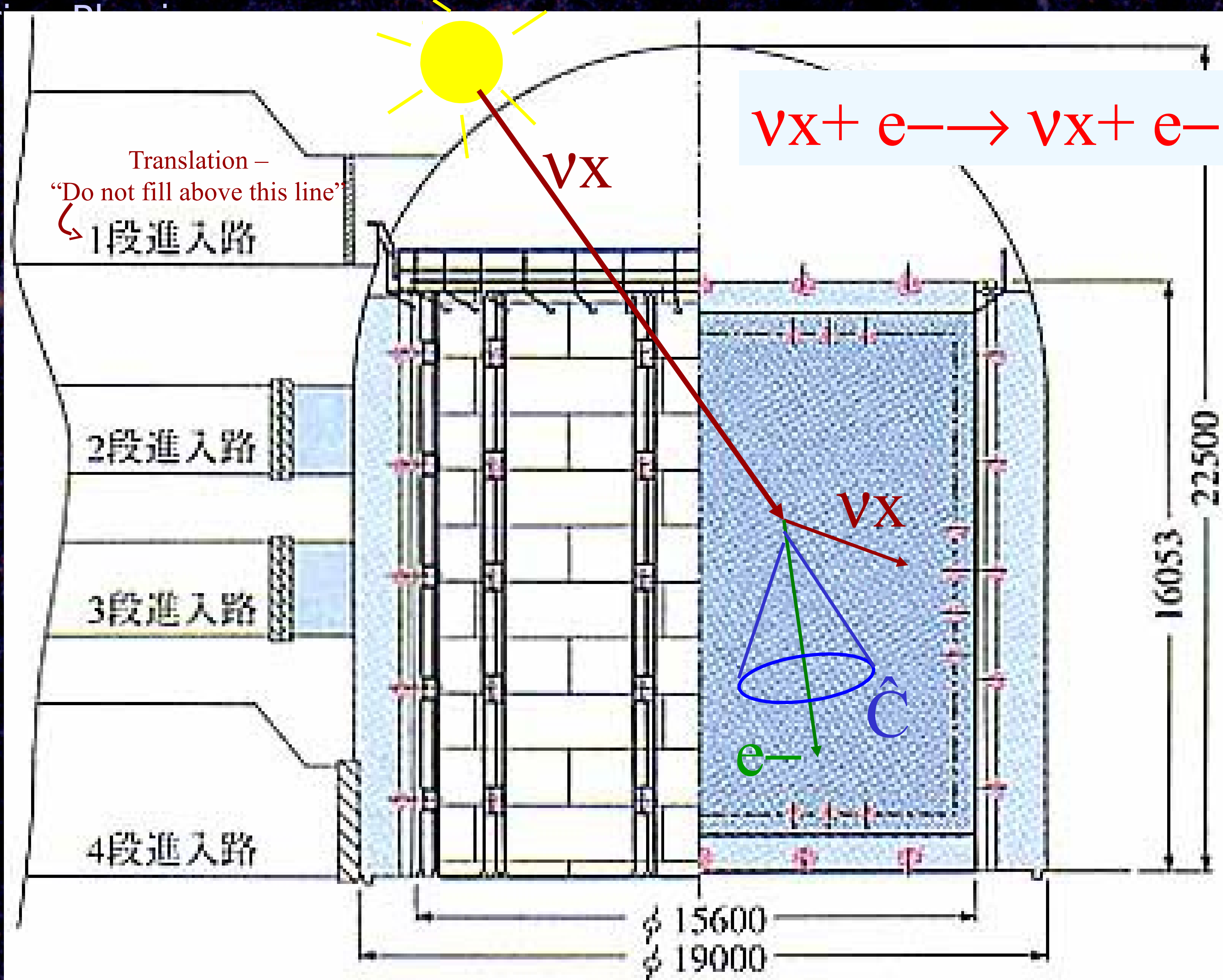

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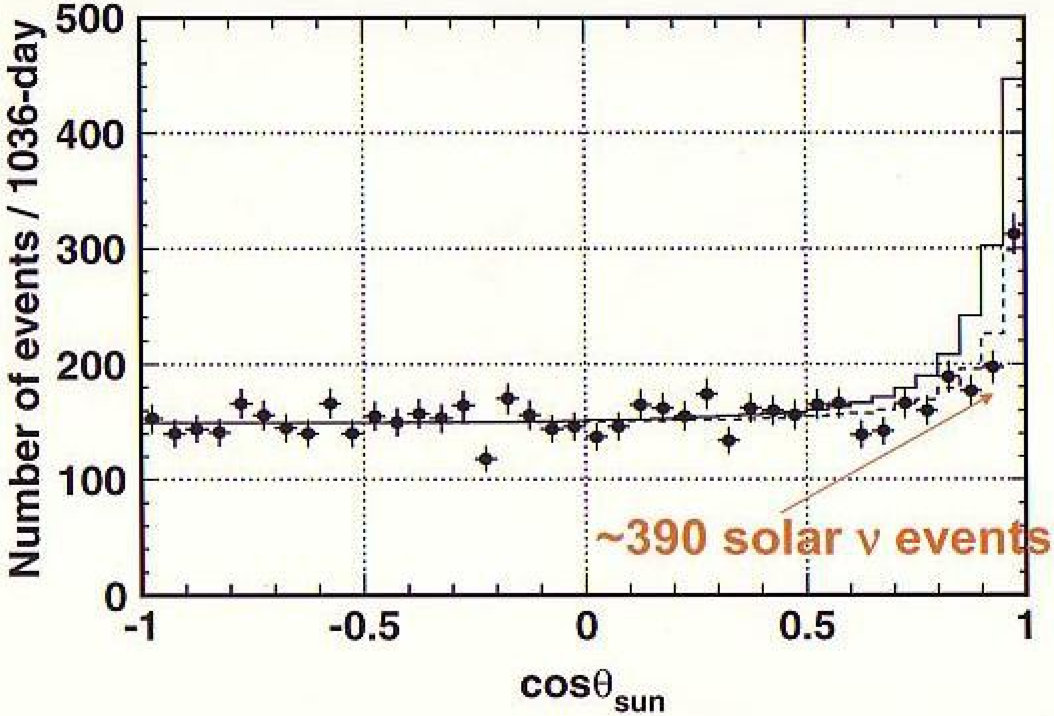
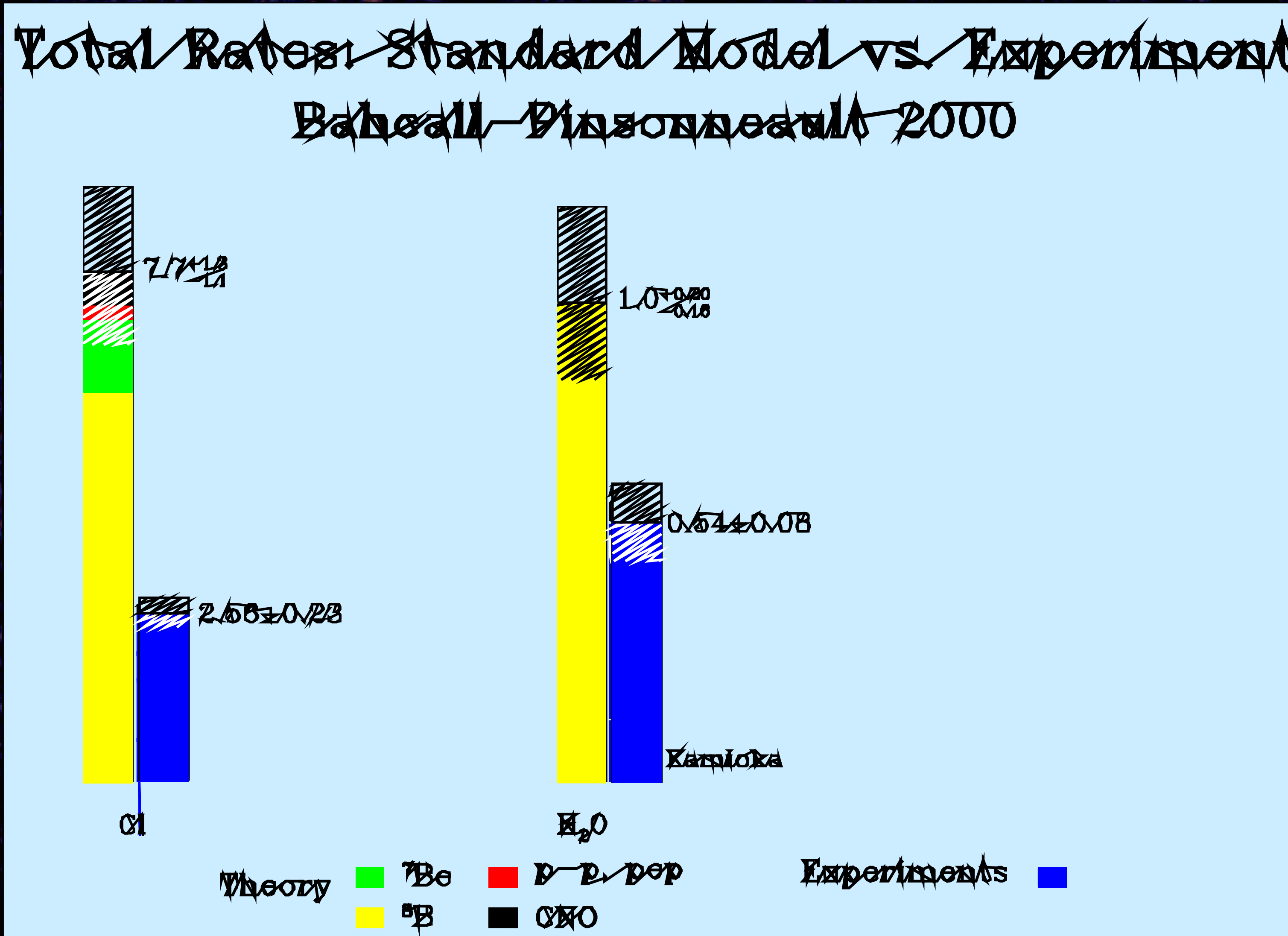
Solar neutrinos (Kamiokande-III)

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
Cl
Theory
7Be
p-p, pep
8B
CNO
Experiments

The solar pp chain

pp

$p+p \rightarrow 2H + e+ + \nu e$ (99.77%)

pep

$p+p+e- \rightarrow 2H + \nu e$ (0.23%)

$2H+p \rightarrow 3He + \gamma$

(84.92%) $3He+3He \rightarrow \alpha+2p$

(15.08%) $3He+\alpha \rightarrow 7Be + \gamma$

(~10-5%) $3He+p \rightarrow \alpha+ e+ + \nu e$

hep

(15.07%) $7Be+e- \rightarrow 7Li + \nu e$

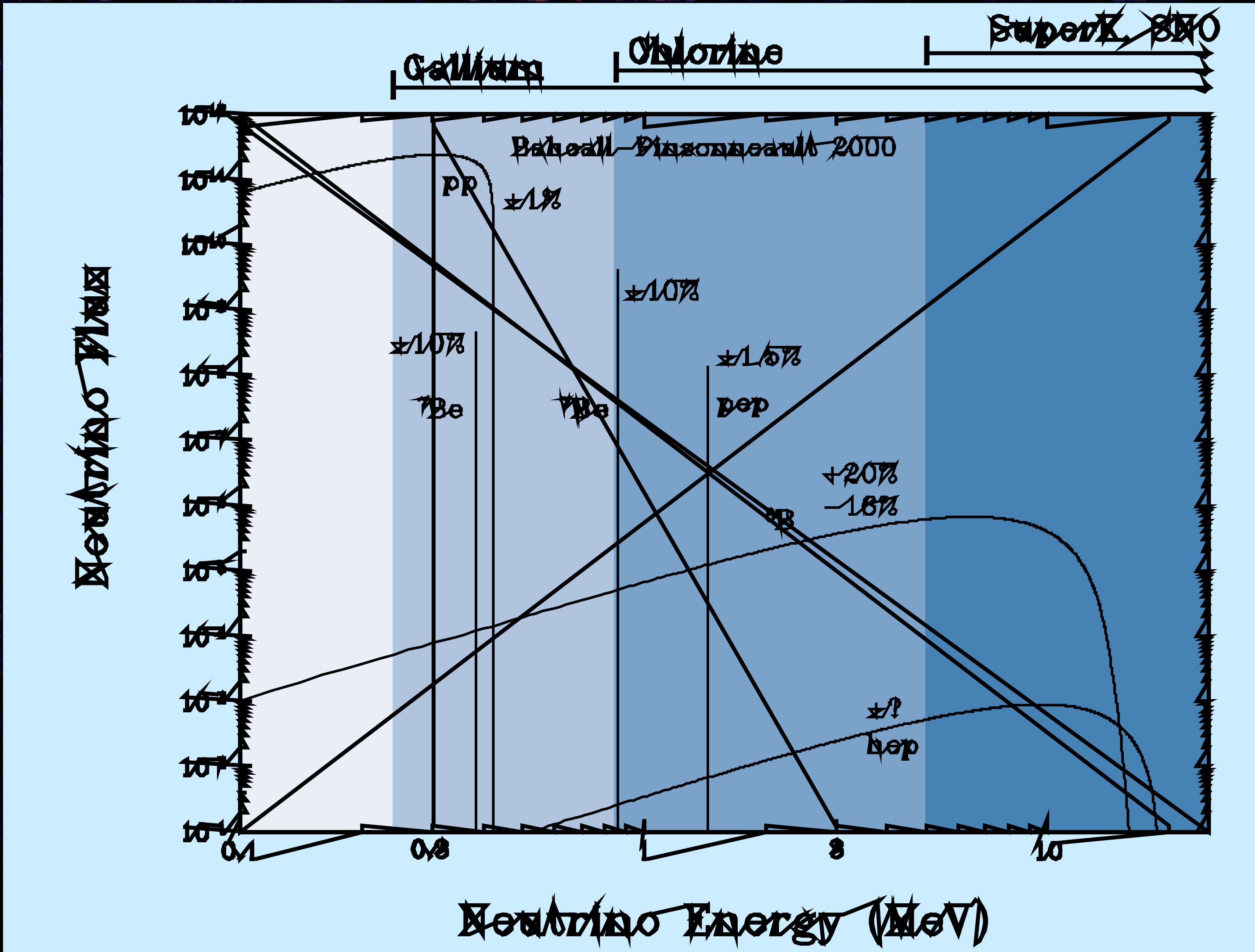
7Be

$7Li +p \rightarrow \alpha+\alpha$

(0.01%) $7Be+p \rightarrow 8B + \gamma$

8B

$8B \rightarrow 2\alpha+ e+ + \nu e$



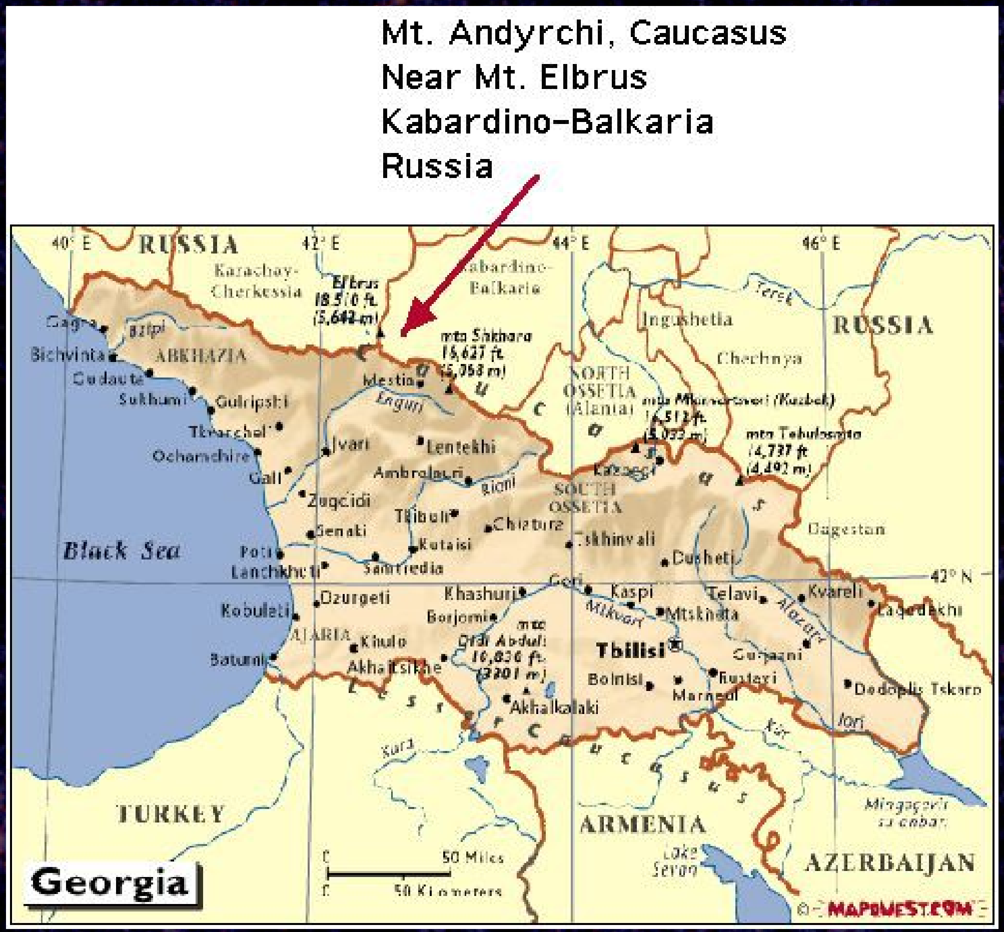
Plot adapted from http://www.sns.ias.edu/~jnb/

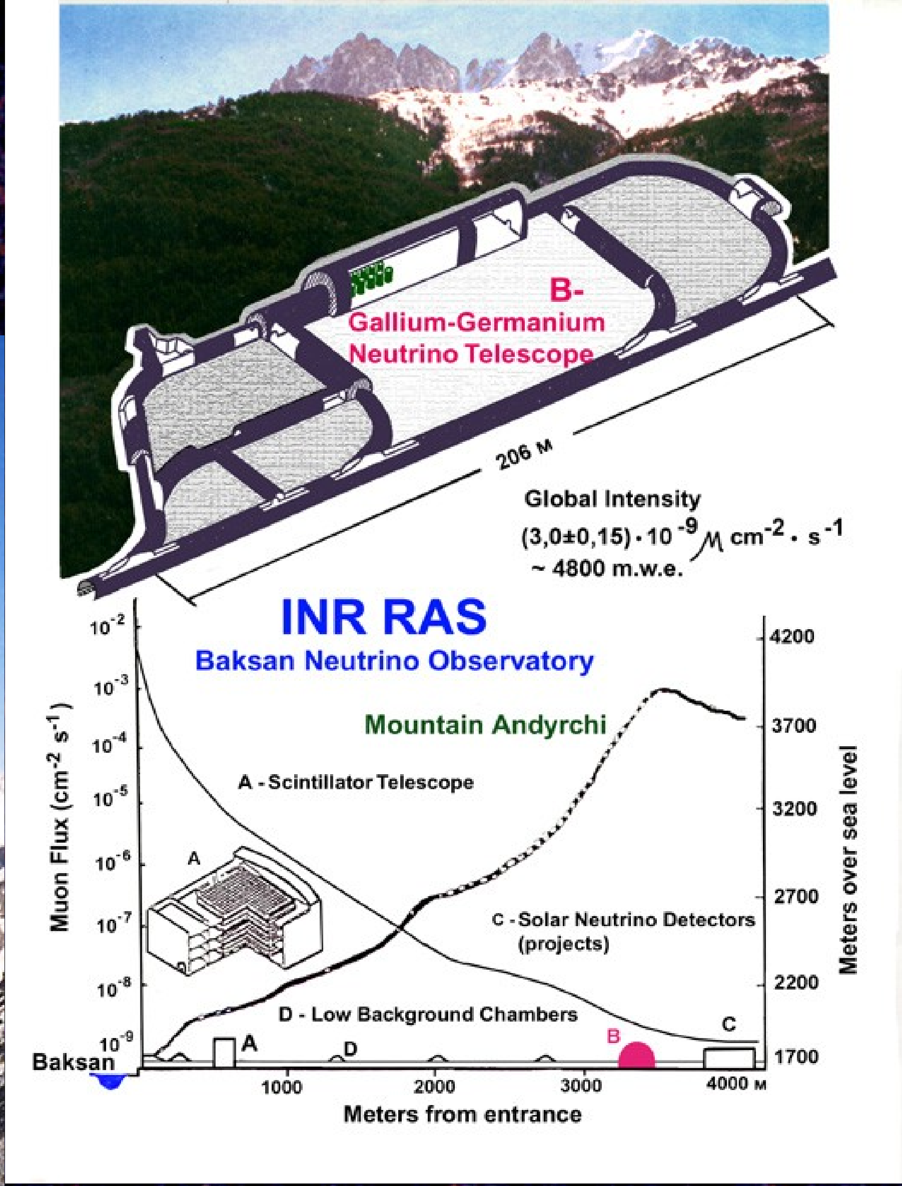
Want to measure the lowest energy solar neutrinos

Detect the neutrinos by observing the reaction

$$71Ga + \nu \rightarrow 71Ge + e-$$

The Soviet-American Gallium Experiment - SAGE



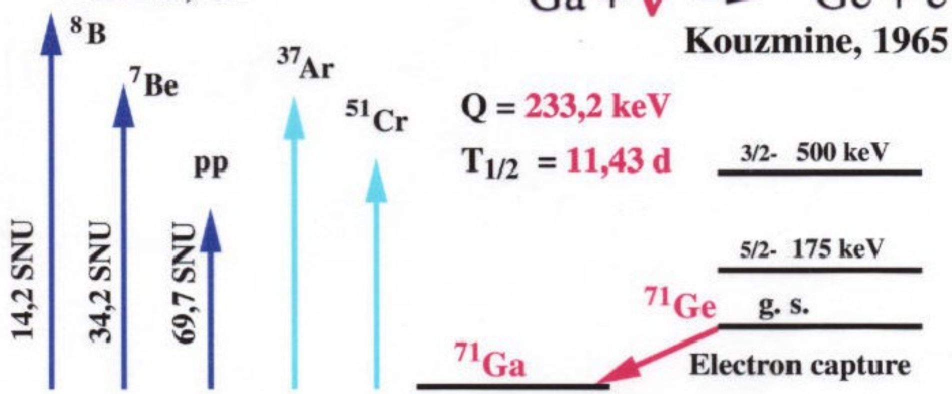


B-
Gallium-Germanium
Neutrino Telescope
206 м
Global Intensity
(3,0±0,15)·10^-9 μ cm^-2 · s^-1
~ 4800 m.w.e.
INR RAS
Baksan Neutrino Observatory
Mountain Andyrchi
A - Scintillator Telescope
C - Solar Neutrino Detectors
(projects)
D - Low Background Chambers
Muon Flux (cm^-2 s^-1)
Meters over sea level
Meters from entrance
Baksan

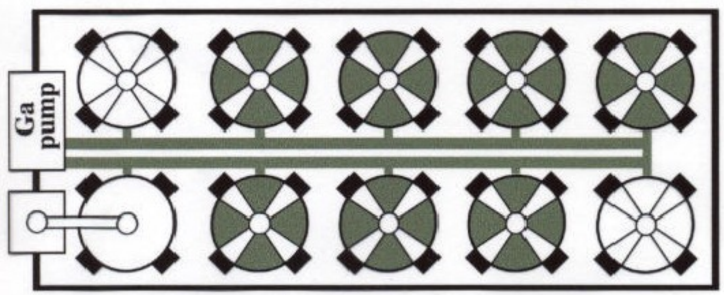
SAGE Experiment Overview

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

Kouzmine, 1965



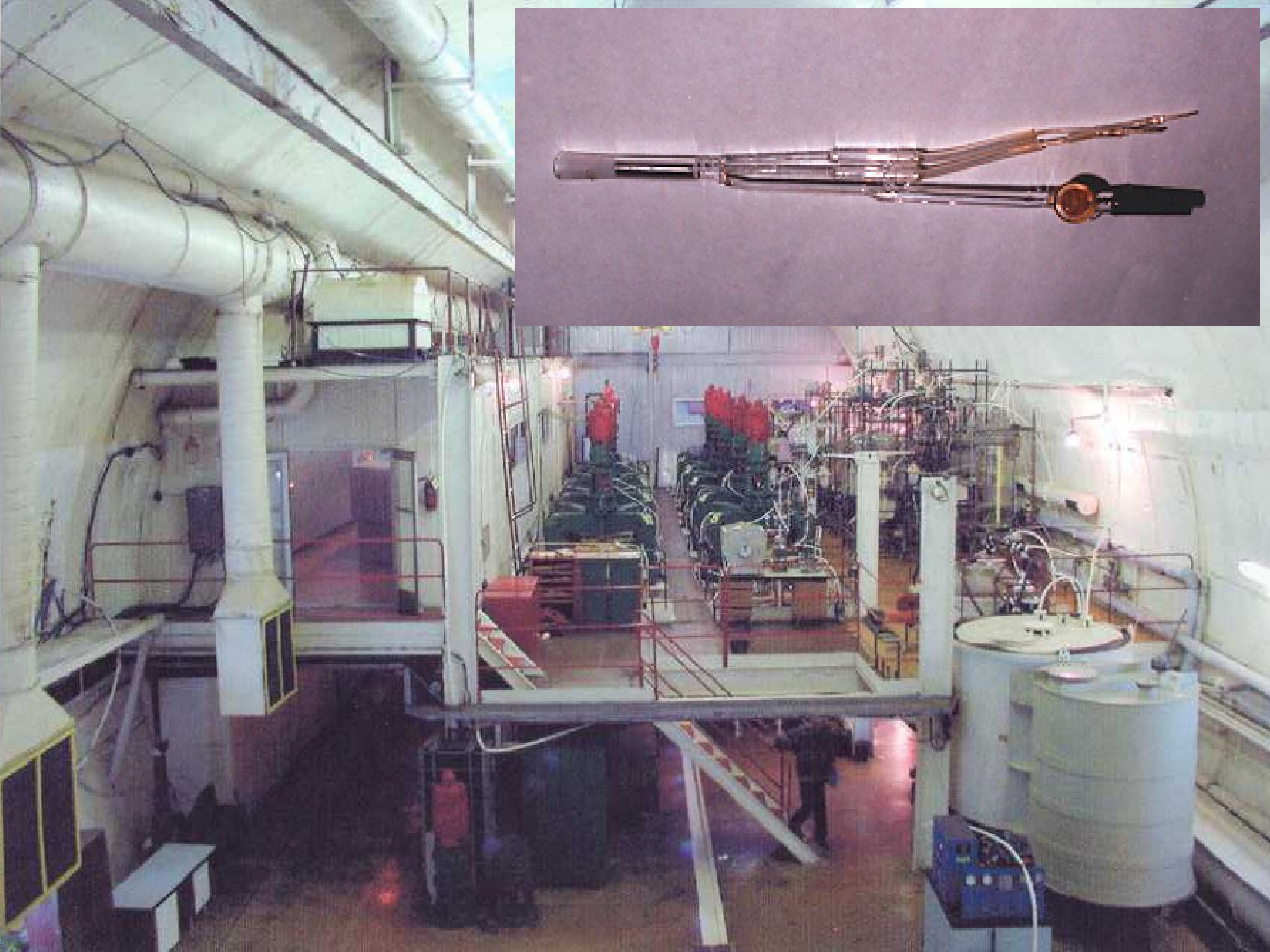
A plan view of the reactors layout in the laboratory



$t_{reac} \geq 30^{o}C$
$t_{melt} = 29.8^{o}C$

~7 tons metallic Ga in each

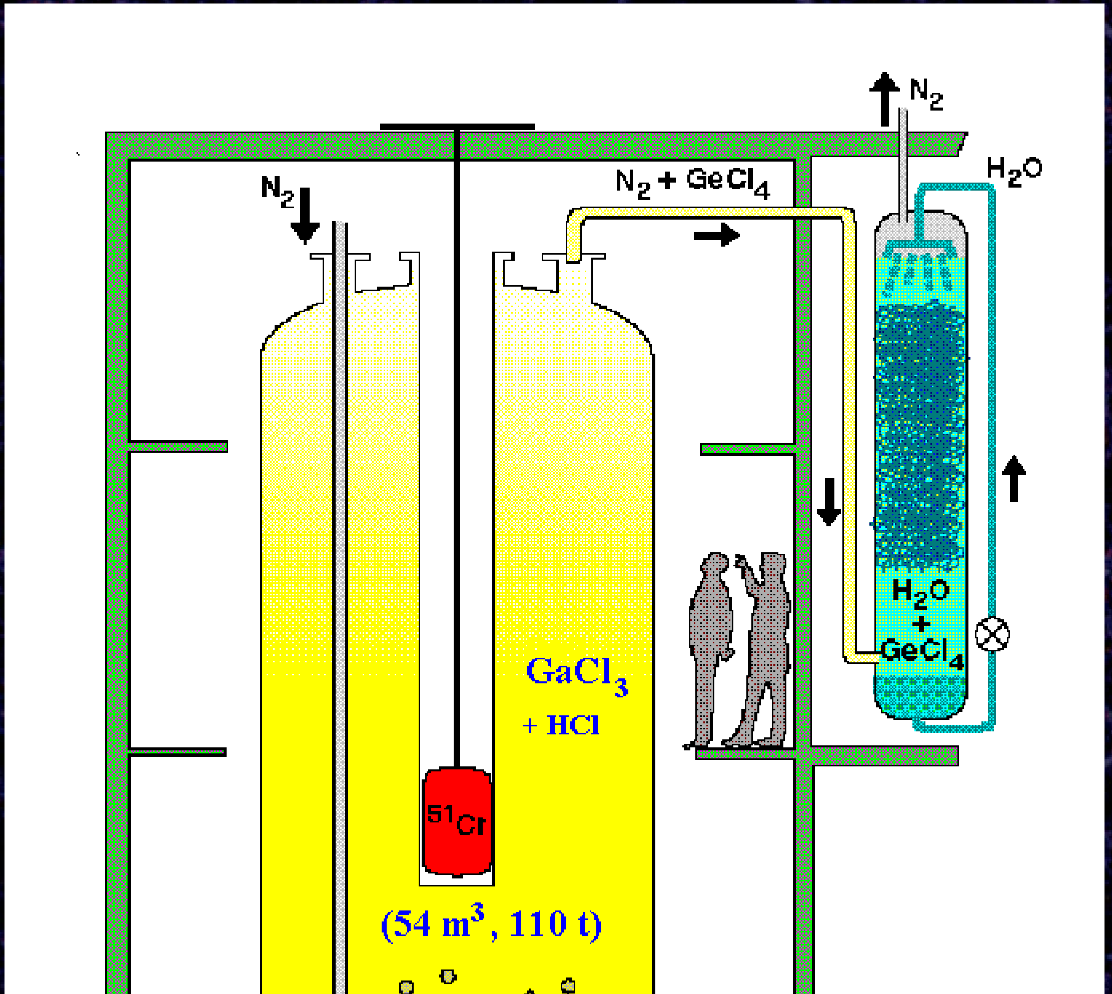
* 250 mkg Ge-76/72 carrier uniformly between reactors
* Exposure time ~ 27 d
* ^{71}Ge chemical extraction from metallic Ga to aqueous solution ~ 1.5 m^3
* Concentration of Ge to 50 ccm trithium free water
* Synthesis of germane - GeH_4
* Counting of Ge decays

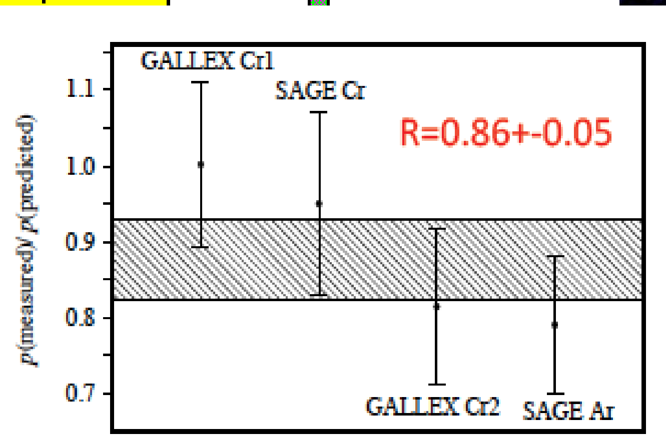


GALLEX/GNO had:

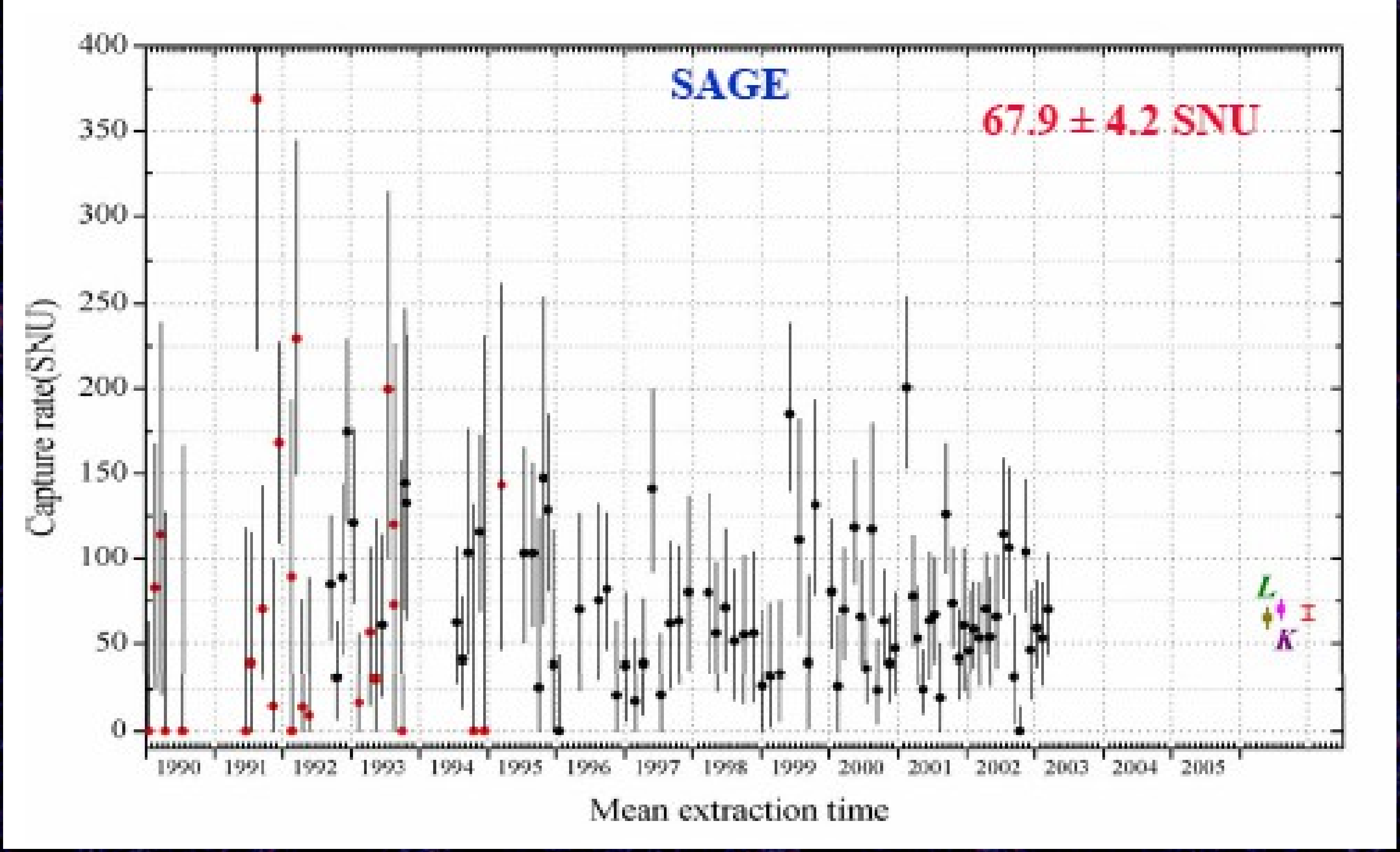
- Very different chemistry
- Many detailed differences

Extraction/counting of both experiments verified using ~1 MCi 51Cr sources, and SAGE also used 37Ar

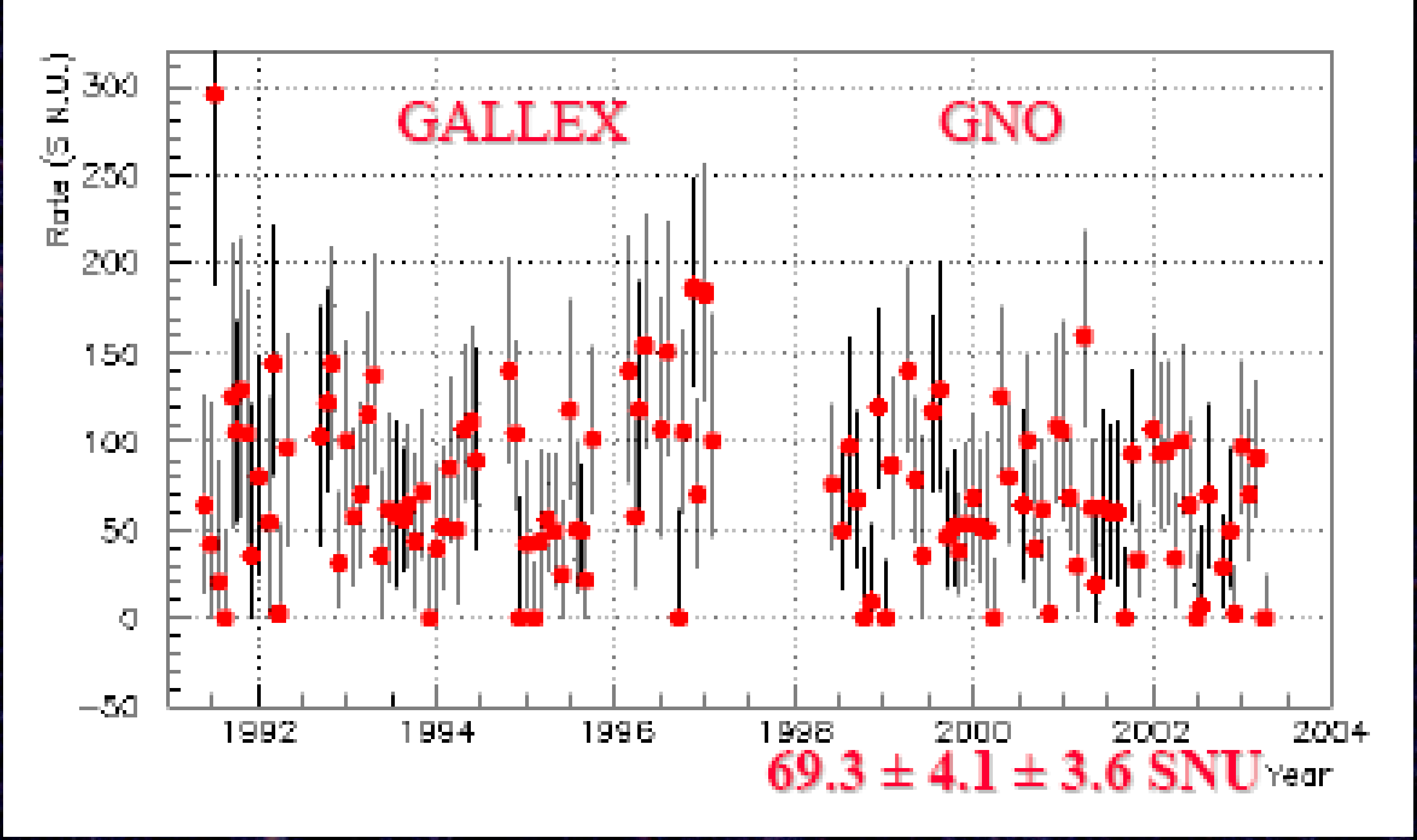


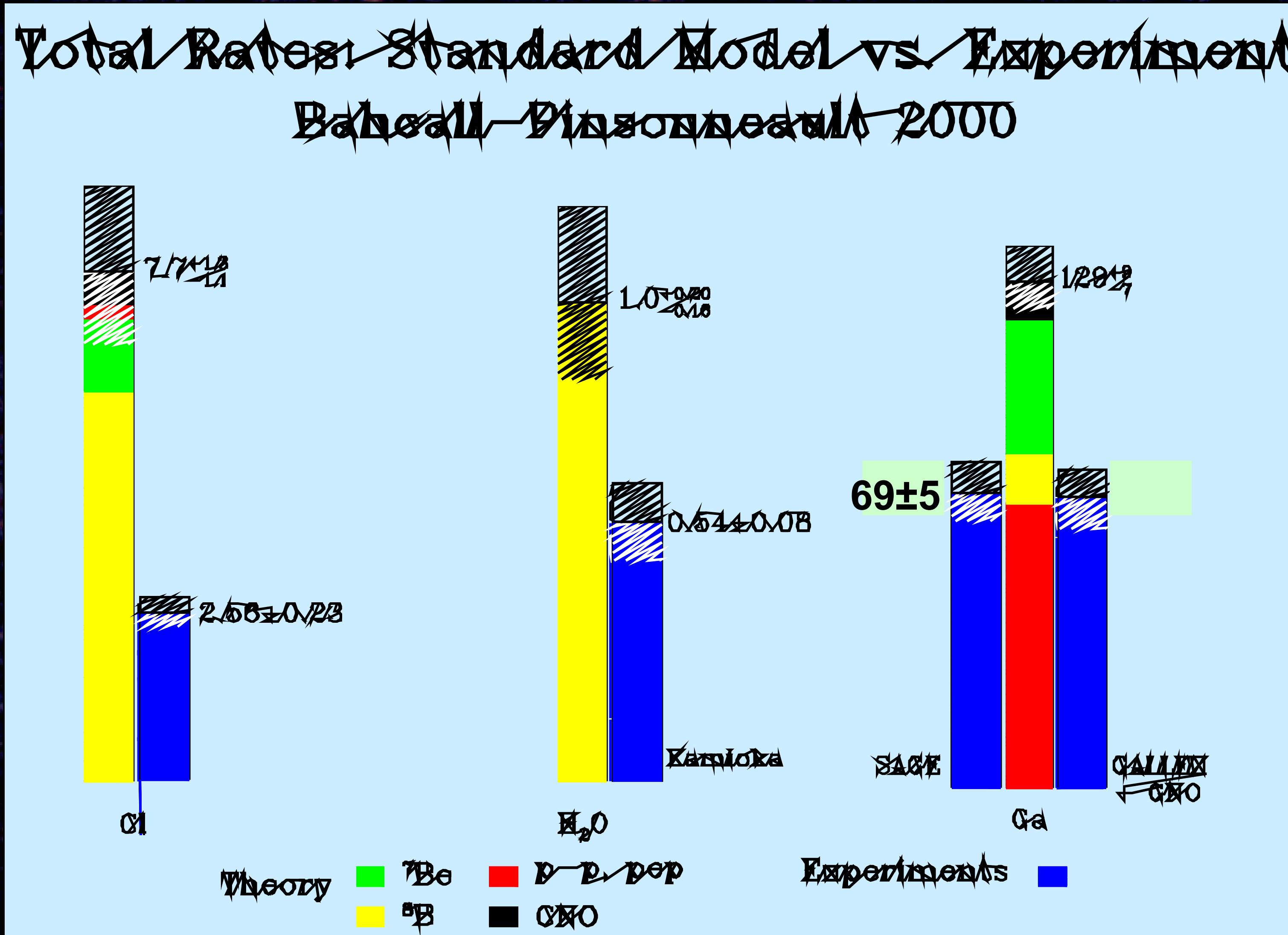


SAGE Results



GALLEX/GNO Results





Eliminates any credible astrophysical explanation…

The theorists had already been thinking….

1957 – Bruno Pontecorvo, wondering if there are any other particles which could undergo oscillations analogous to $K0 \leftrightarrow \overline{K0}$ 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 6/110 19 72

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

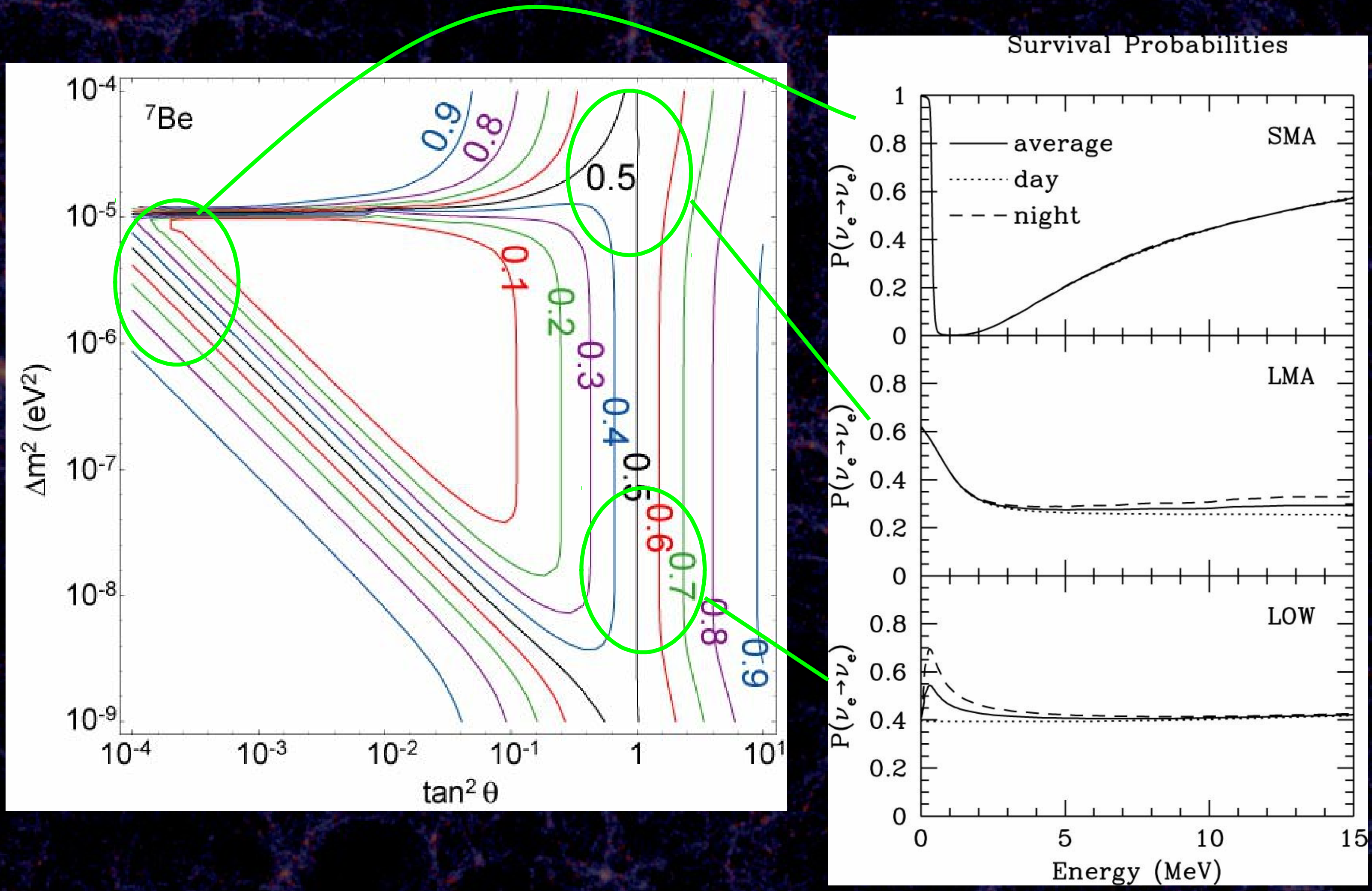
- For two neutrino flavours in vacuum oscillations lead to the appearance of a new neutrino flavour:

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

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

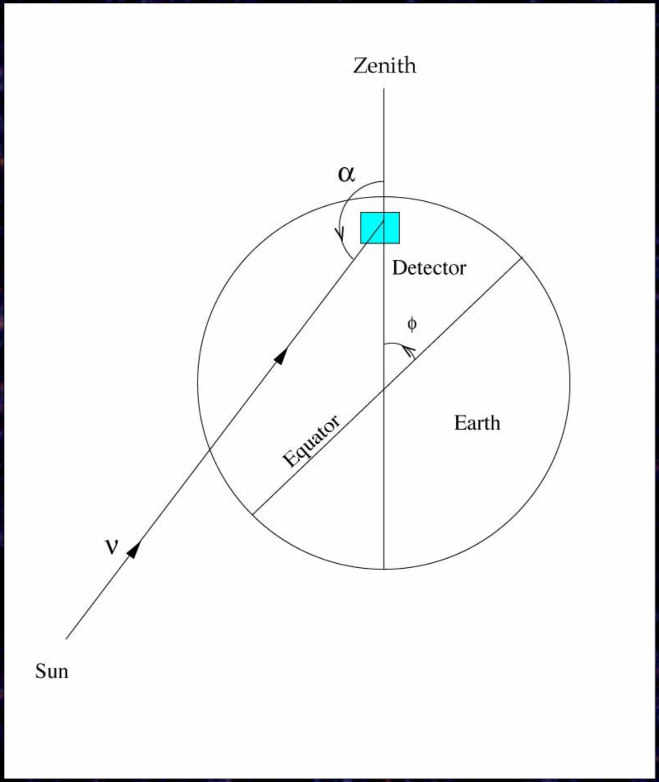
- With the corresponding disappearance of the original neutrino flavour
- These oscillations can be significantly modified by the MSW effect when the neutrinos pass through matter…

Matter Effects – the MSW effect

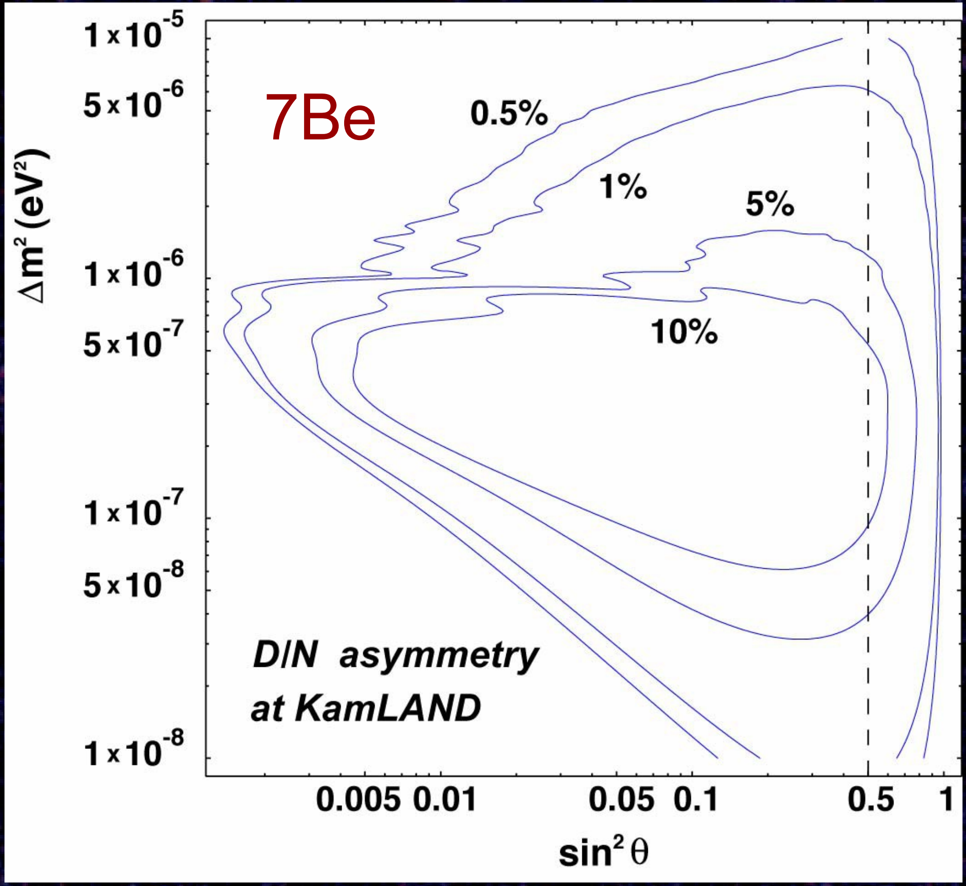


Matter Effects – the MSW effect

Day – Night Effect

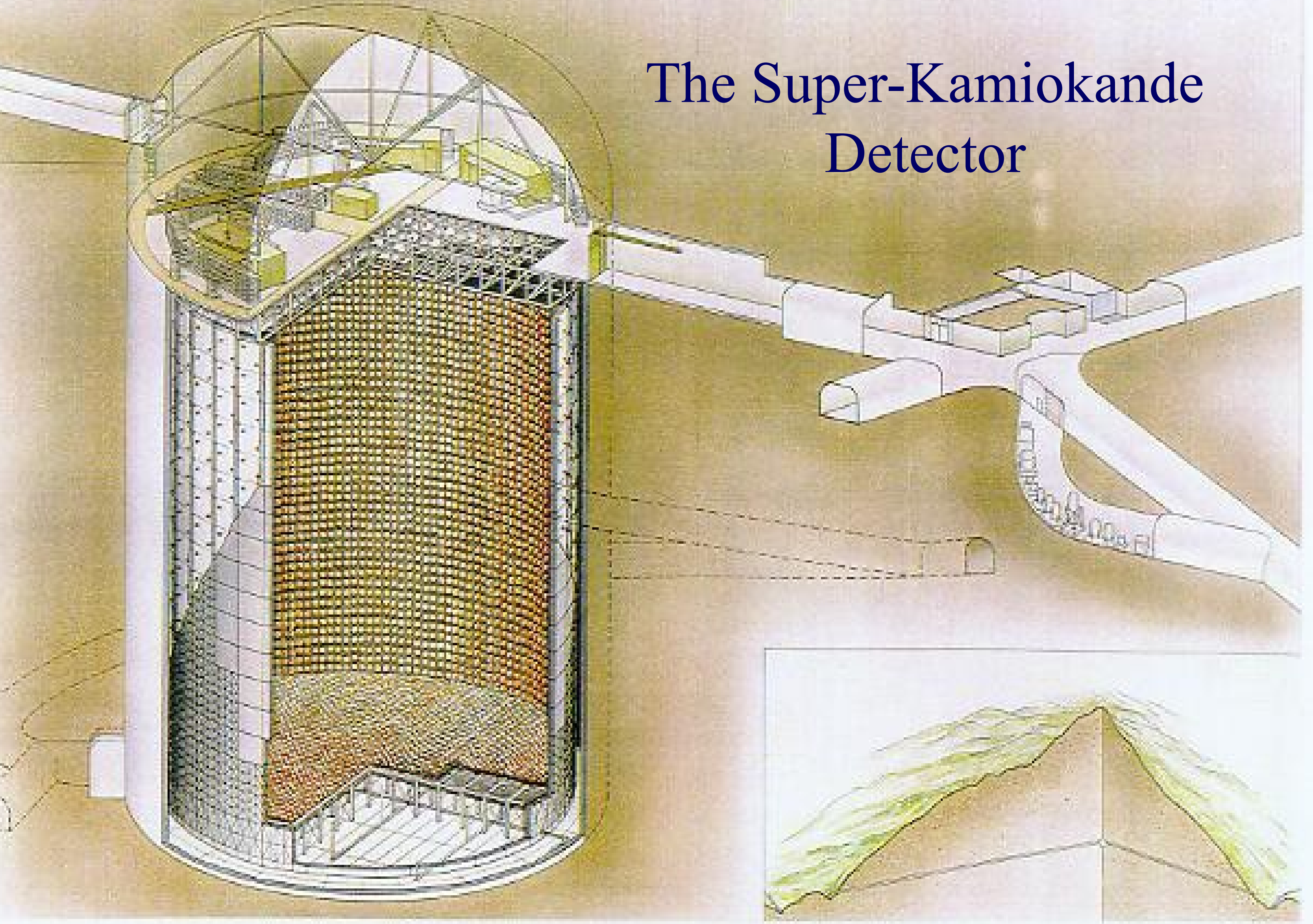


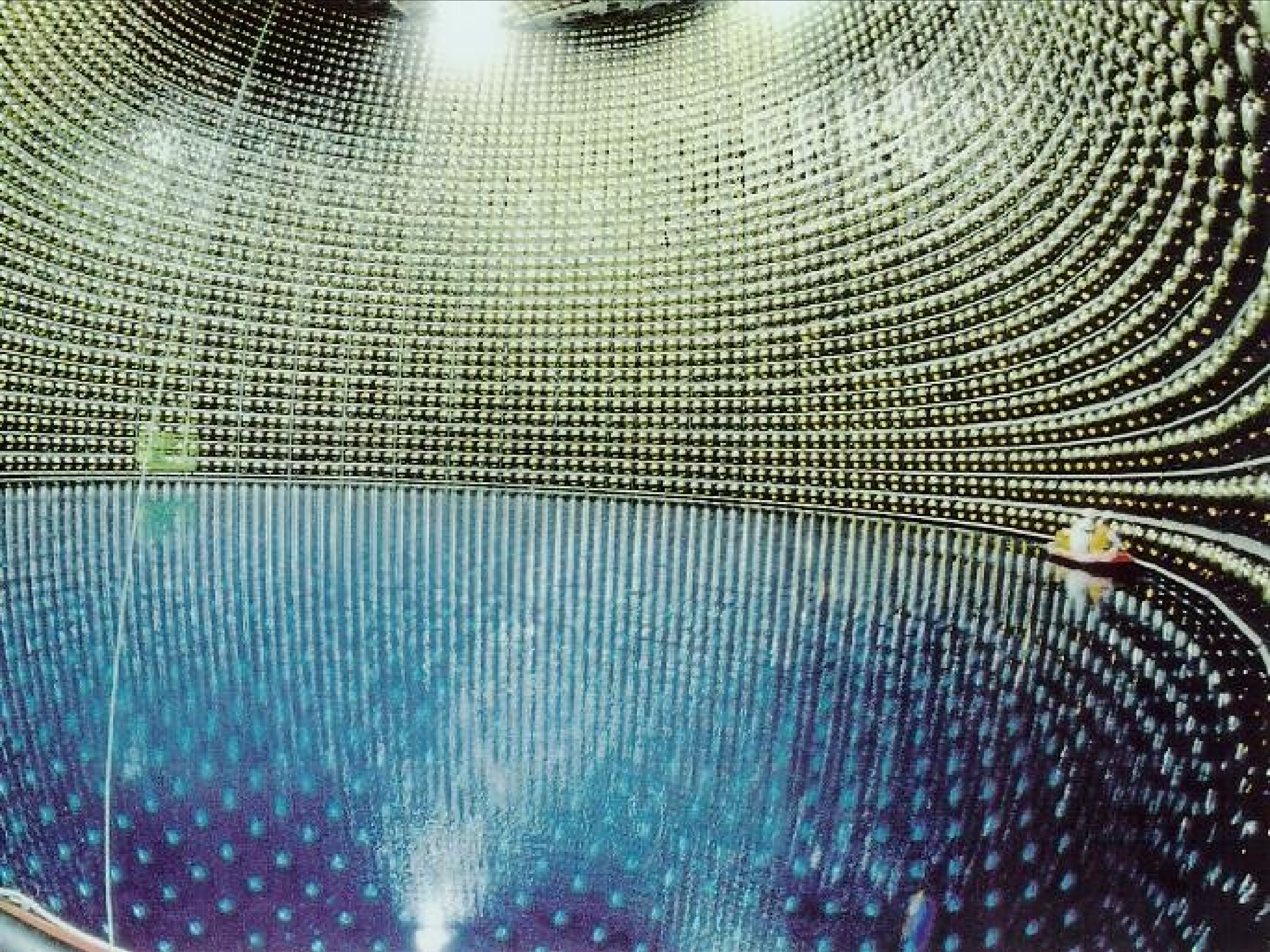
$$\text{Asym} = \frac{N - D}{N + D}$$



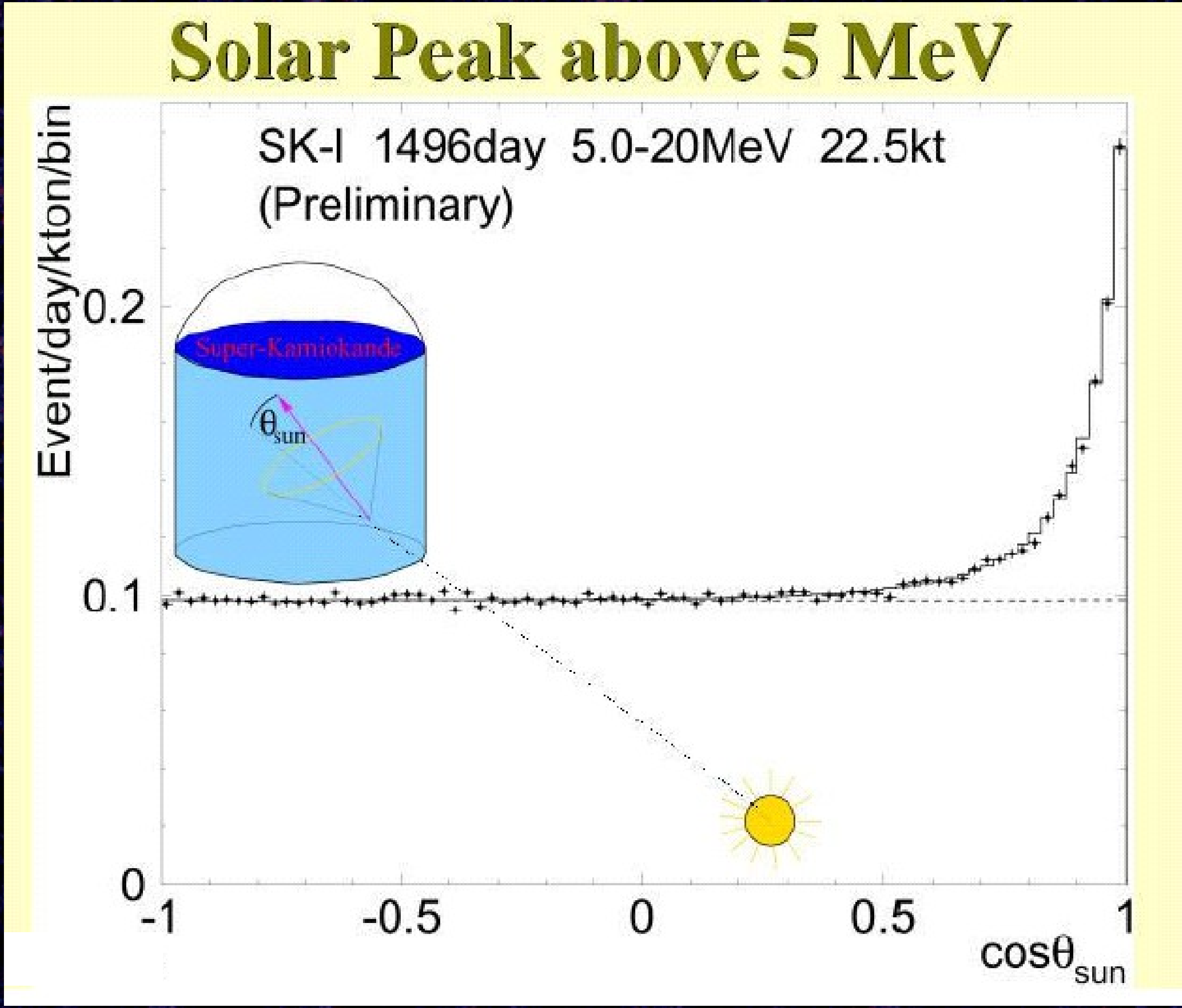
Also produces(?) seasonal variation

The Super-Kamiokande Detector



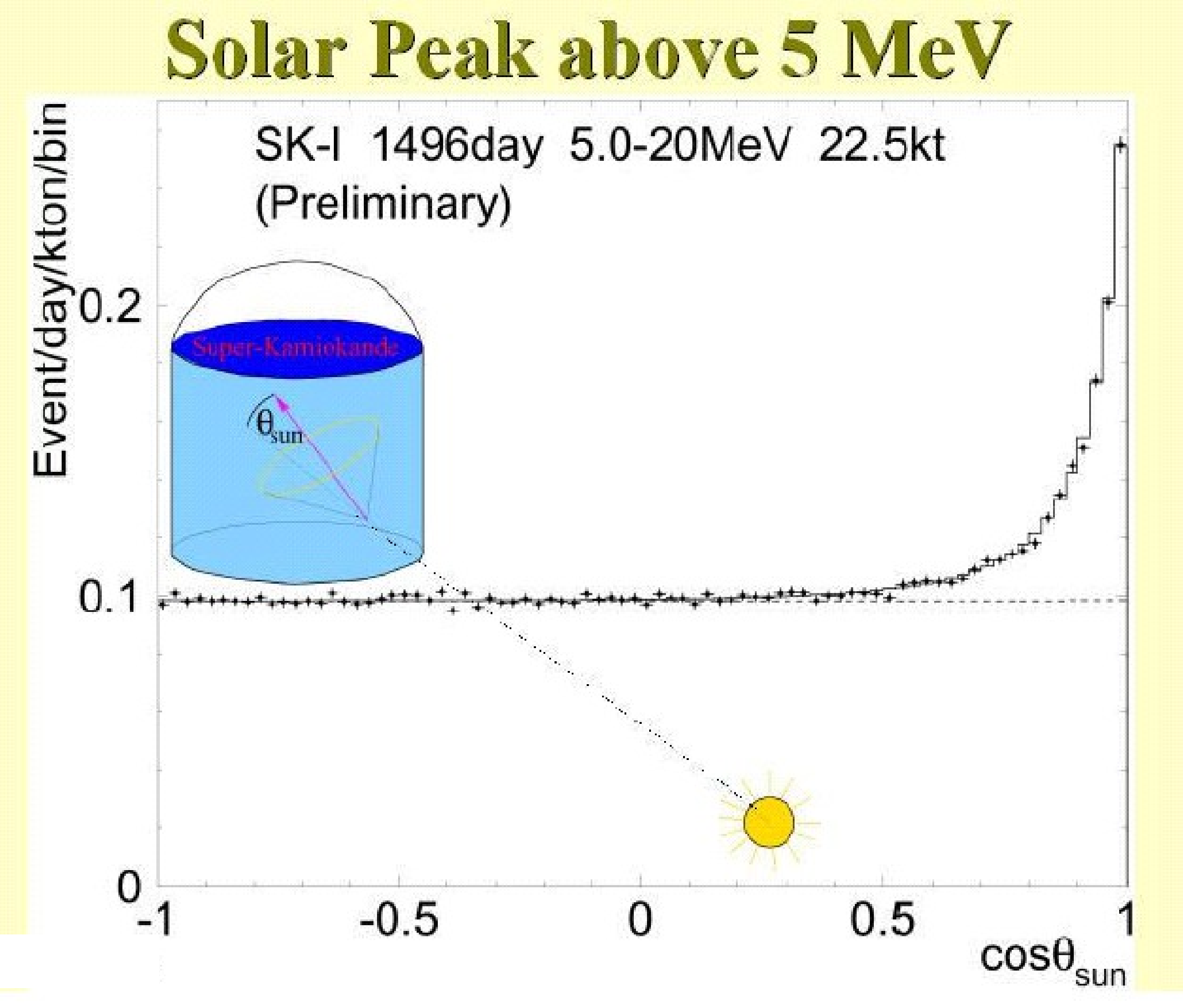


22,400 solar neutrino events!

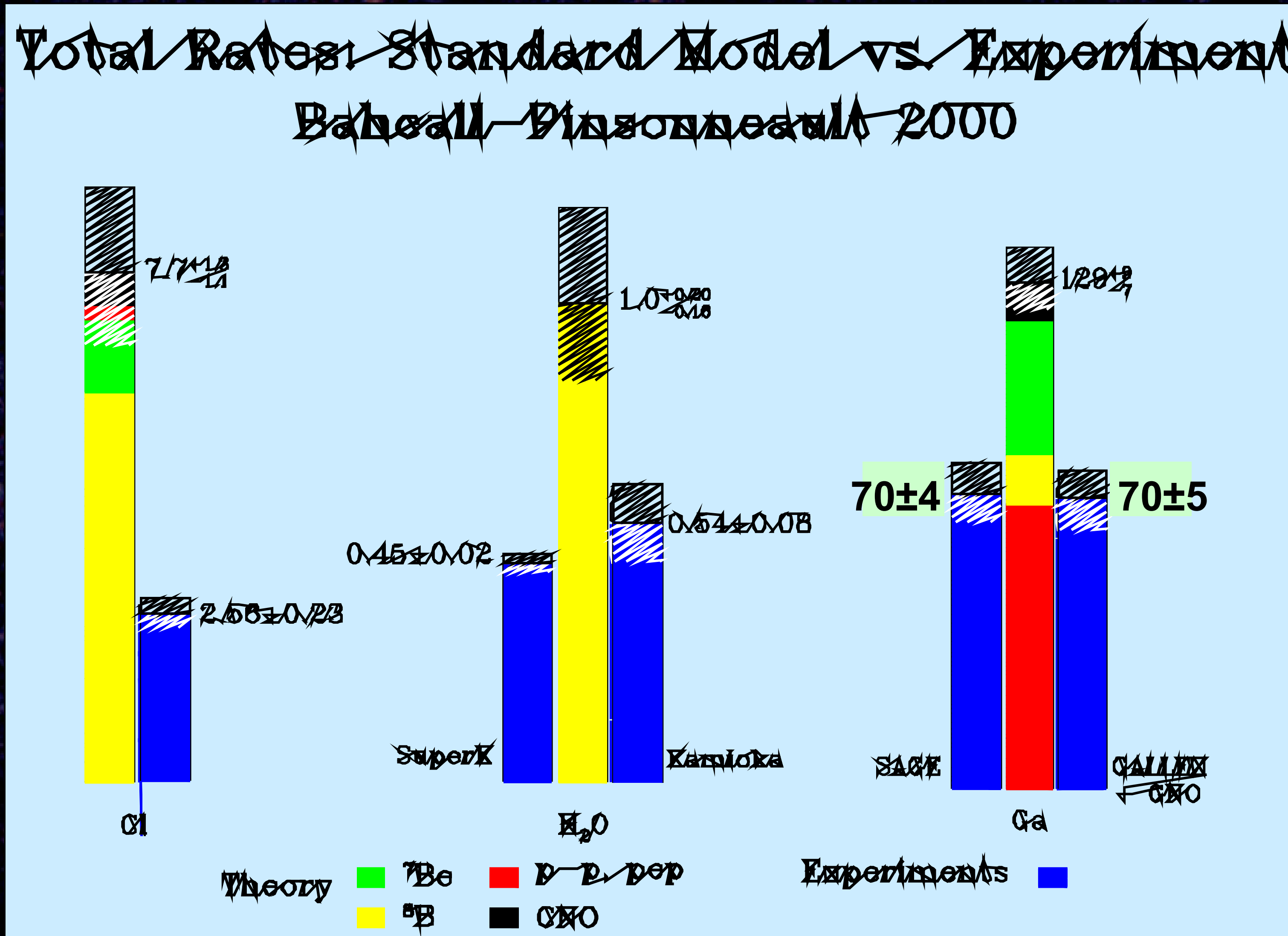


"Flux" is $2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{sys.}) \times 10^6/\text{cm}^2 \cdot \text{s}$

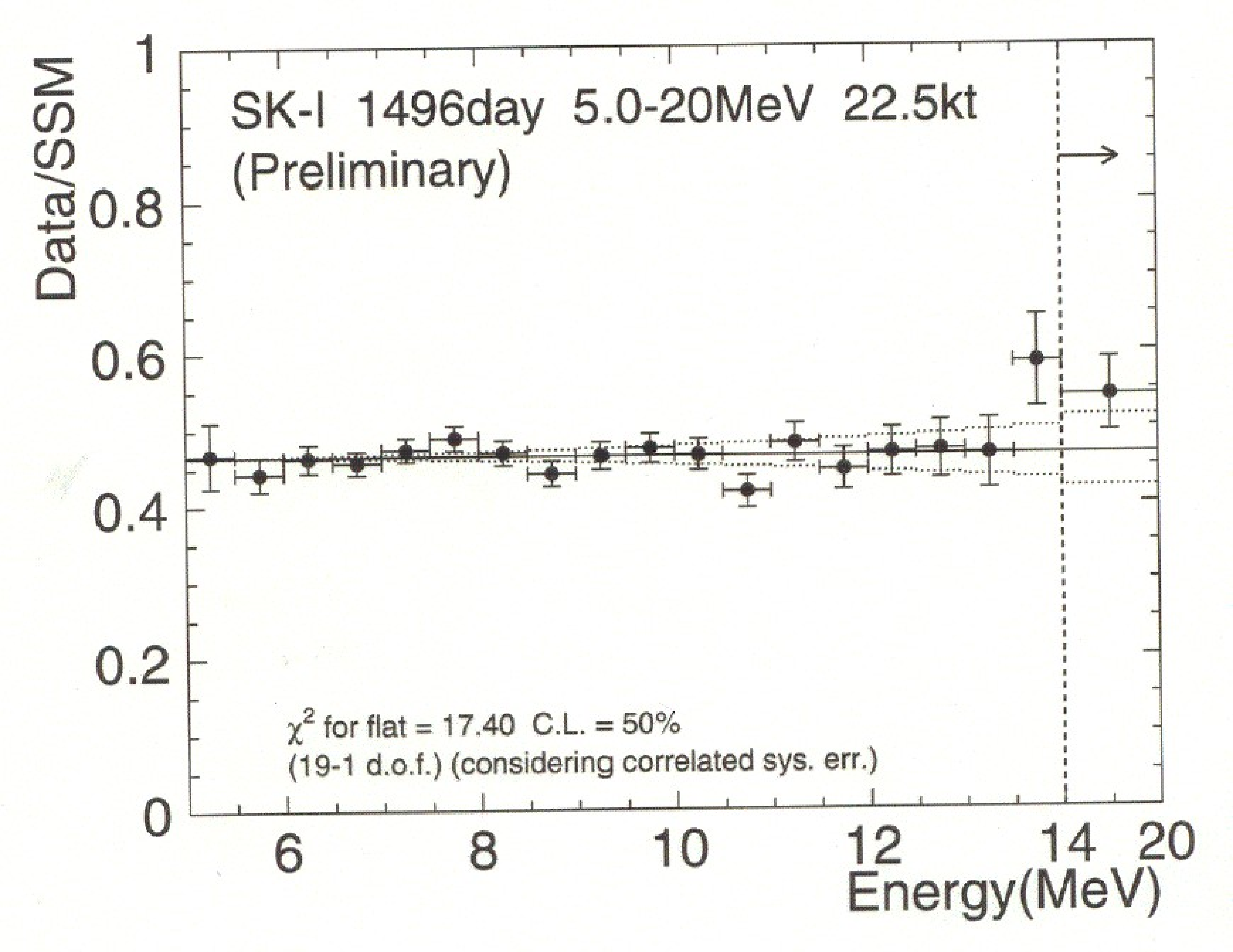
22,400 solar neutrino events!



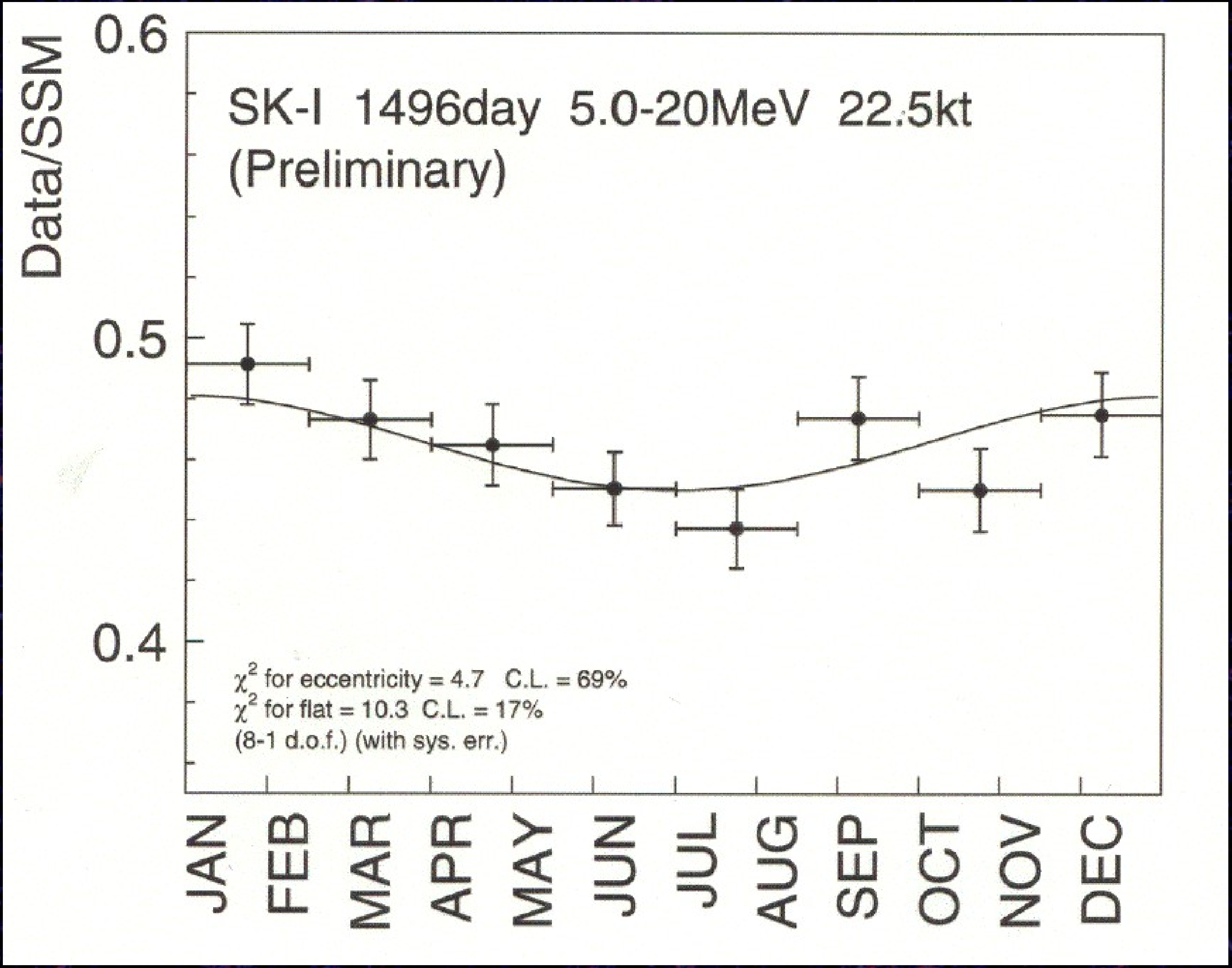
$$0.465 \pm 0.005(\text{stat.})^{+0.016}_{-0.015}(\text{sys.}) \times \text{SSM}$$


Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000
2.56±0.23
0.45±0.02
70±4
70±5
SuperK
SAGE
GALLEX
GNO
Cl
Ga
Theory
Experiments
CNO

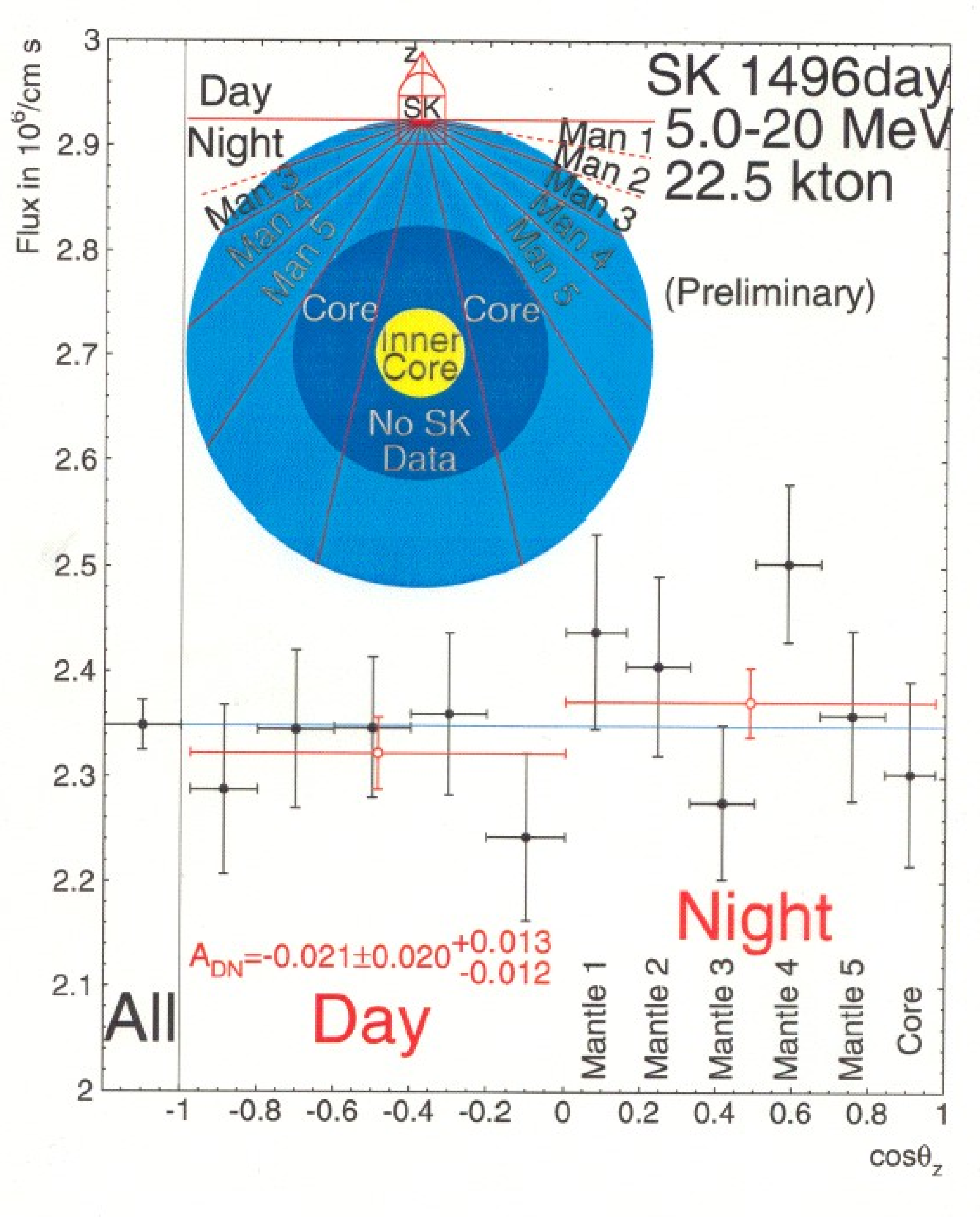
Super-Kamiokande Energy Spectrum



Super-Kamiokande seasonal variation

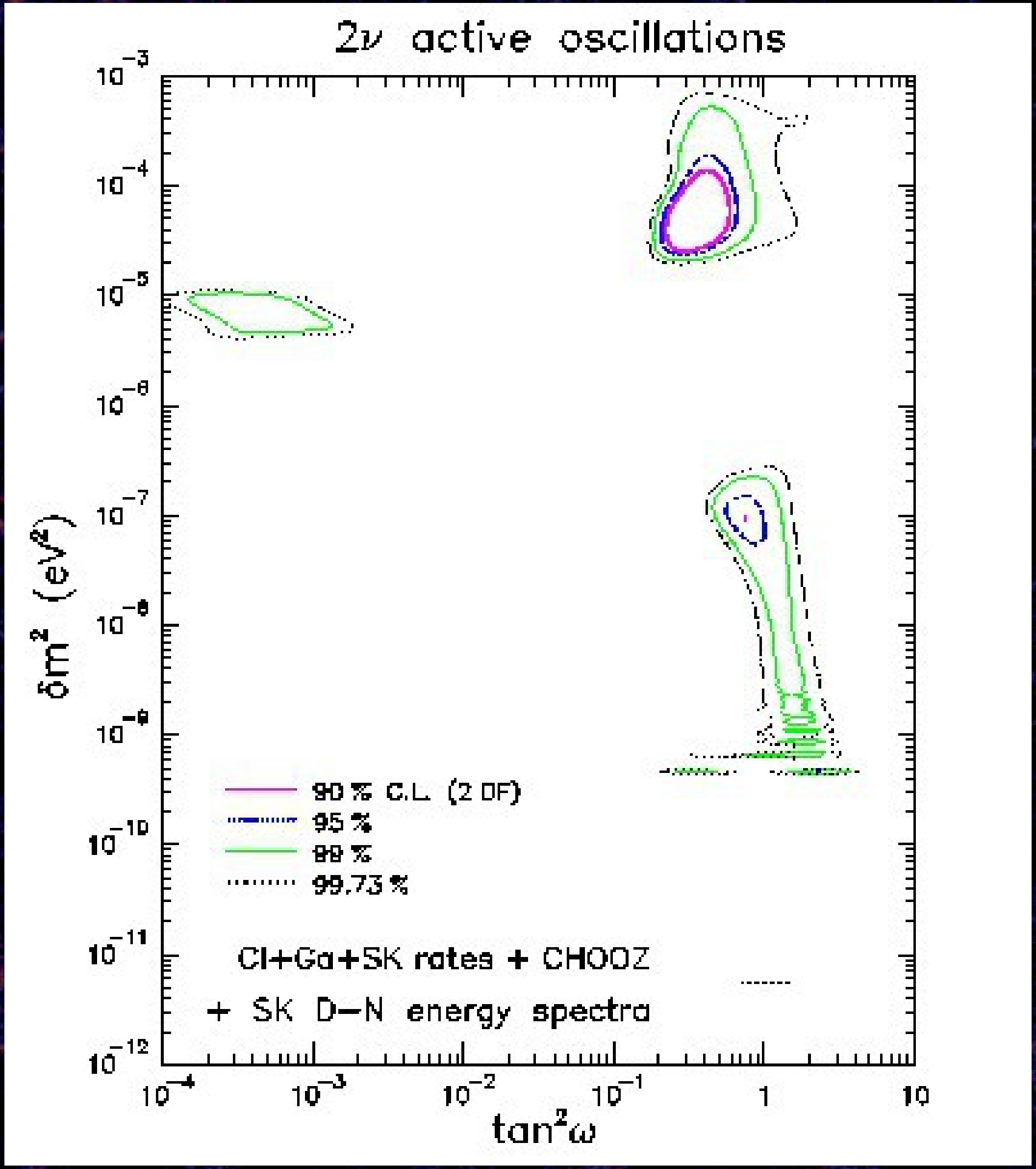


Super Kamiokande



Day-night variation

Which left us where?



But no smoking gun for oscillations….