

Наблюдение осцилляций нейтрино
(За что дали Нобелевскую премию по
физике 2015 г.?)

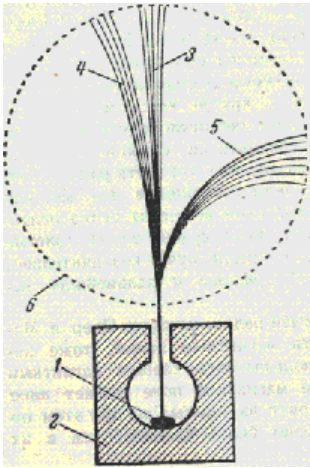
Б.А.Шварц, ИЯФ СО РАН и НГУ

The Nobel Prize in Physics 2015

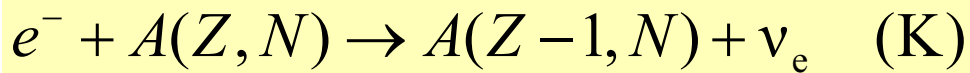
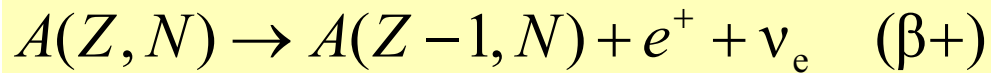
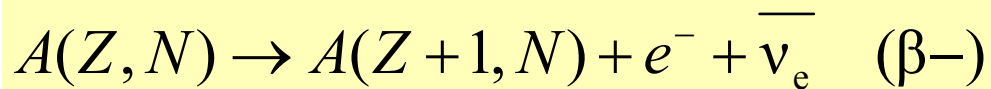
Takaaki Kajita and Arthur B. McDonald

"for the discovery of neutrino oscillations,
which shows that neutrinos have mass"

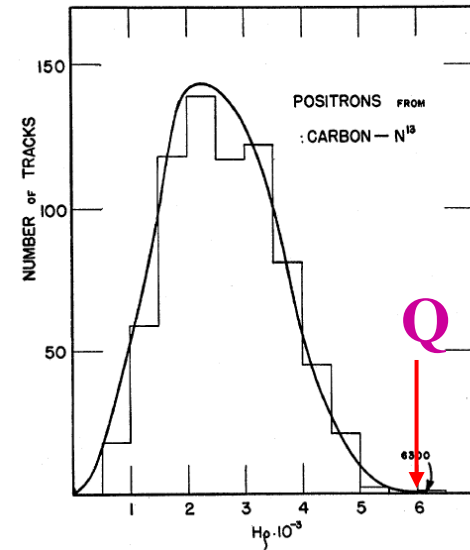
Основные свойства и история открытия.



β -распад:



$$Q = M(Z, N) - M(Z - 1, N) - m_e$$



Так как про нейтрино не было известно, казалось, что энергия не сохраняется!

Еще одна загадка – несохранение полного момента

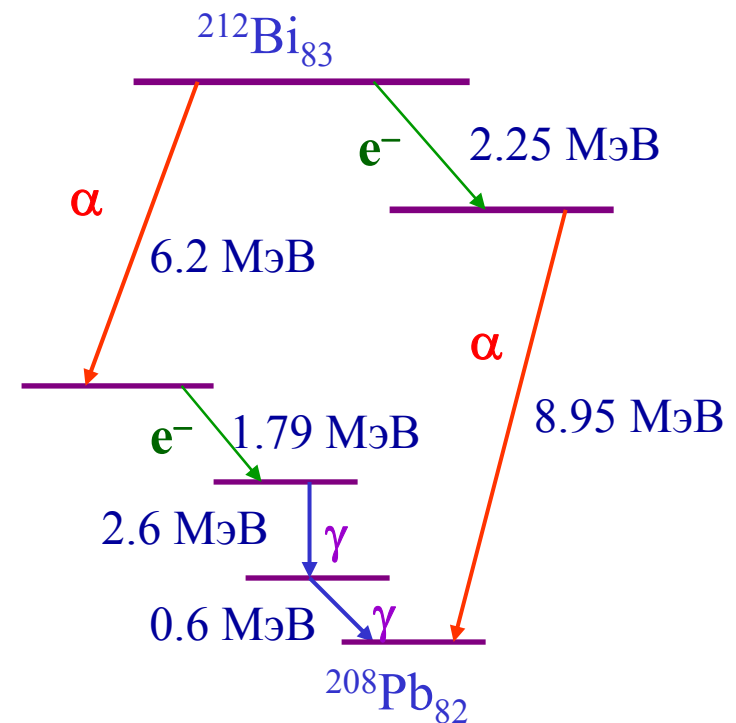


Переход не в одно конечное состояние, а в многие?

Потеря энергии при взаимодействии с электронами оболочки, с соседними атомами и т.п.?

Промежуточные состояния с испусканием гамма-квантов?

Калориметрический эксперимент Эллиса и Вустера в 1927 г. подтвердил, что средняя энергия, выделяющаяся в β -распаде соответствует средней энергии электронов



В 1930 году В.Паули выдвинул гипотезу нейтрино в своем знаменитом письме Тюбингенскому конгрессу. Нейтрино – нейтральная частица со спином $1/2$ и массой много меньшей массы электрона.

Сечение взаимодействия с ядрами $\sigma \sim 10^{-40} \text{ см}^2$.

Сам Паули как-то заметил:

“I have done a terrible thing. I have postulated a particle that cannot be detected.” No wonder that Bethe and Peierls concluded in 1934 “there is no practically possible way of observing the neutrino.”

В 1934 году Ферми создал теорию слабых взаимодействий (4-х фермионное взаимодействие), которая приобрела законченную форму после открытия несохранения четности в 1957 году.

The Desperate Remedy

4 December 1930
Gloriastr.
Zürich

Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

Dear radioactive ladies and gentlemen,

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β -spectrum, I have hit upon a desperate remedy to save the "exchange theorem"* of statistics and the energy theorem. Namely [there is] 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 additionally differ from light quanta in that they do not travel with the velocity of light:

But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with a question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ ray.

Нейтрино – основные свойства

Слабое взаимодействие –
заряженные и нейтральные токи

$$L = \frac{G_F}{\sqrt{2}} j^{\alpha+} j_{\alpha}, \quad j_{\alpha}^{ch} = \overline{\psi_f} \gamma_{\alpha} (1 - \gamma_5) \psi_i$$

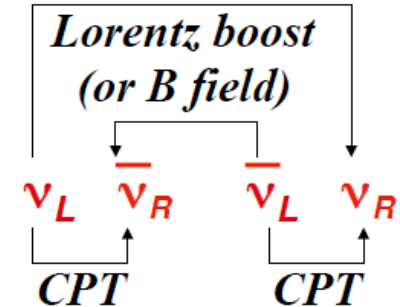
$$G_F = 10^{-5} / m_p^2$$

Нейтральные токи содержат как
левые, так и правые компоненты

Нейтрино Дирака -
Нейтрино Майорана

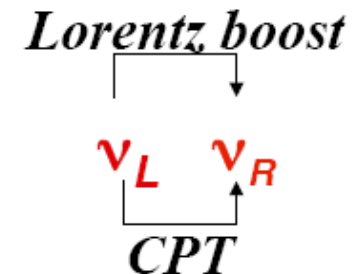
$$\begin{aligned} \nu &\neq \bar{\nu} \\ \nu &= \bar{\nu} \end{aligned}$$

“Dirac” neutrinos



“Majorana” neutrinos!

No lepton number conservation!



В поисках нейтрино

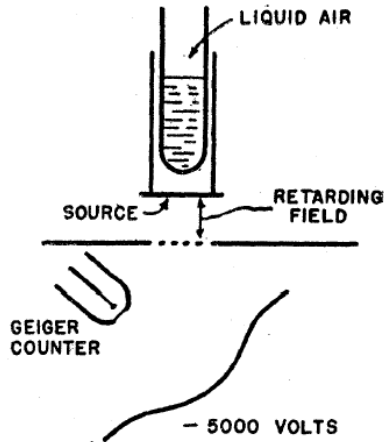
К - захват

James.S.Allen,

Phys.Rev. 61 (1942) 692



${}^7\text{Be}$ – только К-захват и около 10% гамма с энергией 0.48 МэВ. Энерговыделение – 0.87 МэВ.



Schematic diagram of the apparatus used by Leipunski.



Лейпунский, 1936

Первое измерение ядер отдачи – также непрерывное распределение по энергии

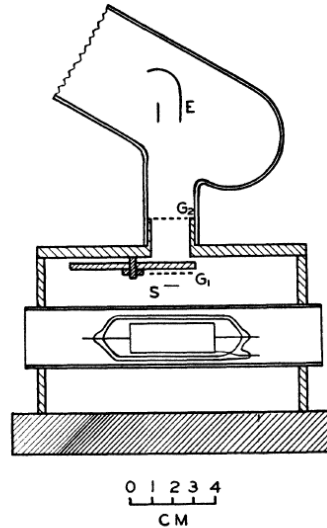


FIG. 1. Experimental arrangement of G-M and electron multiplier tubes.

$$T_{\text{яд}} \approx 57 \text{ эВ}$$

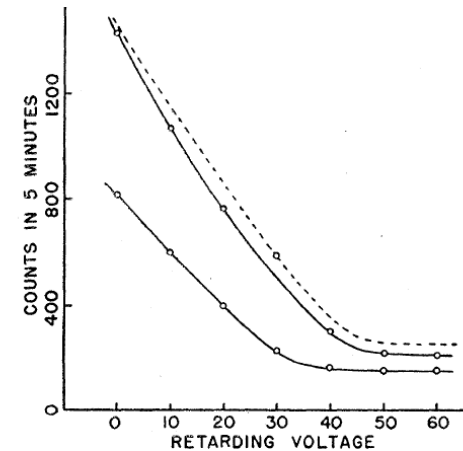
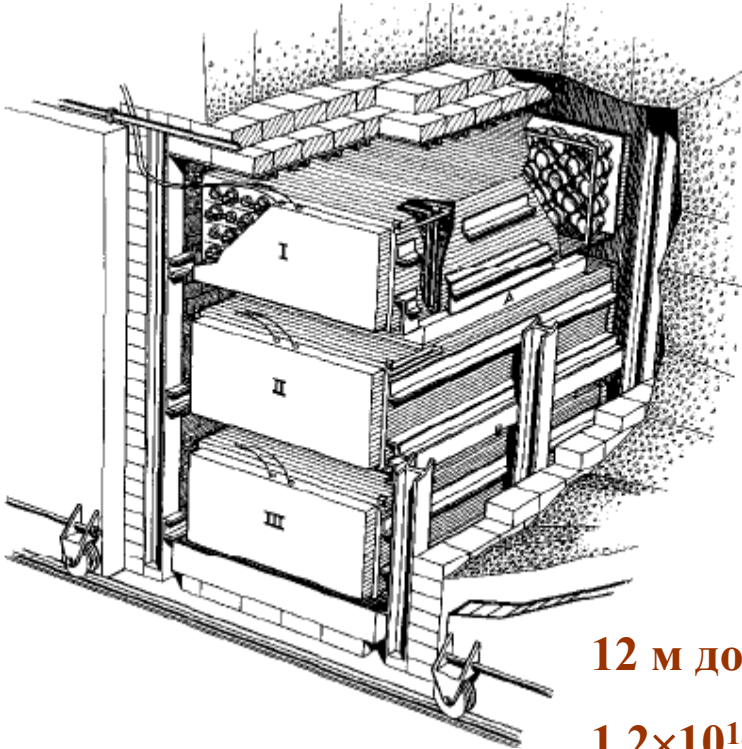
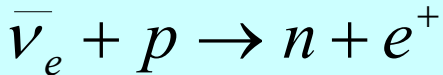


FIG. 1. The experimental curves obtained by Allen. The upper solid curve gives the counts from a freshly prepared source, the lower solid curve those obtained after allowing the source to age. The dotted curve represents the data corrected back to zero age for the source.

Прямое наблюдение нейтрино (Рейнес – Коуэн, 1956 г)

Эксперимент Savannah River



12 м до реактора,
 $1.2 \times 10^{13}/(\text{см}^2\text{с})$

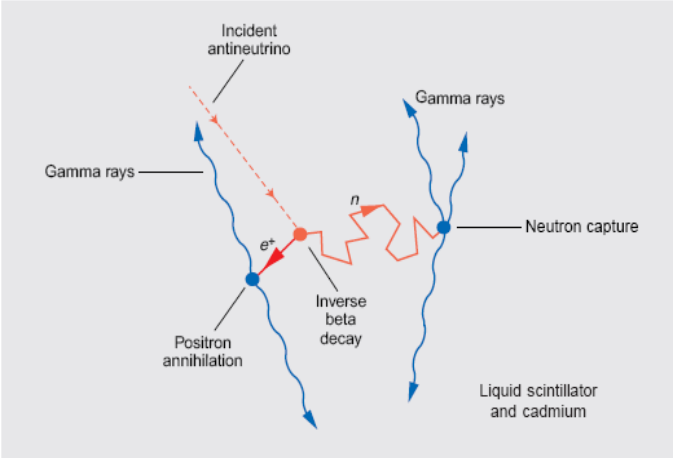


Схема установки в Savannah River. Танки, обозначенные I, II, и III содержали 1400 л жидкого сцинтиллятора. Свет регистрировался с каждого торца 55 ФЭУ. Тонкие полиэтиленовые контейнеры, А и В, были заполнены 200 л воды, являющейся мишенью, с растворенными в ней 40 кг CdCl_2 для захвата протонов.

Наблюдались события с частотой примерно 3.0 ± 0.2 в час при отношении сигнал/фон 4:1.

Это соответствовало сечению взаимодействия нейтрино:

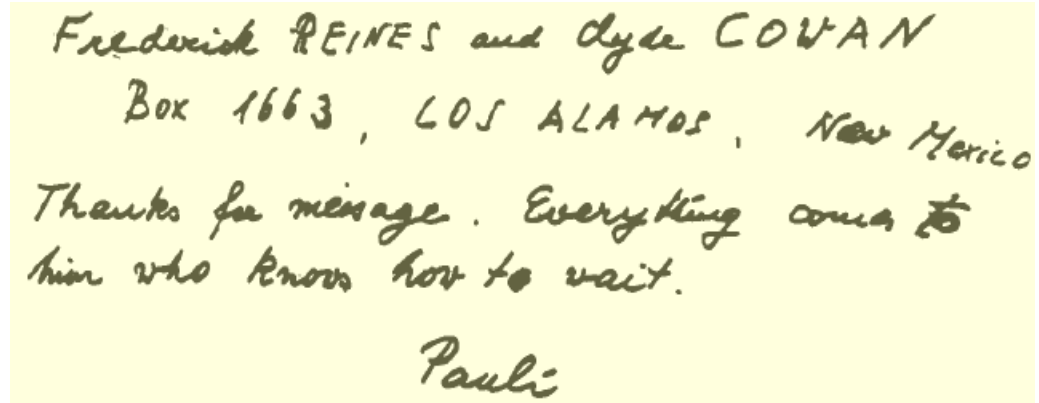
$\sigma_{\text{exp}} = (12^{+7}_{-4}) \times 10^{-44} \text{ см}^2$ при теоретическом значении:

$$\sigma_{\text{th}} = (5 \pm 1) \times 10^{-44} \text{ см}^2 .$$

Были сделаны проверки:
удаление кадмия,
уменьшение числа протонов,
дополнительная защита

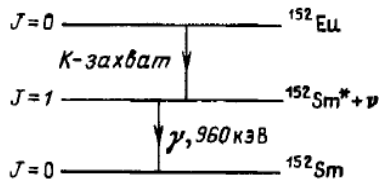
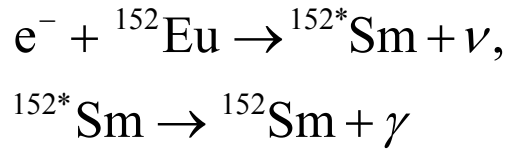
$$\lambda \sim 1/(n\sigma) \sim 10^{21} \text{ см} \approx 1000 \text{ св. лет}$$

The Nobel Prize in Physics 1995

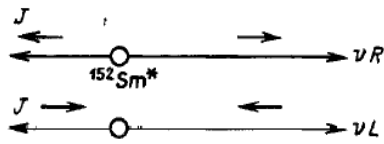


Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to
him who knows how to wait.
Pauli

Определение спиральности нейтрино Гольдхабер и др., 1958

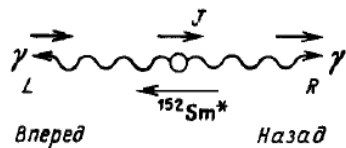


а)

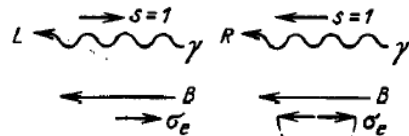


б)

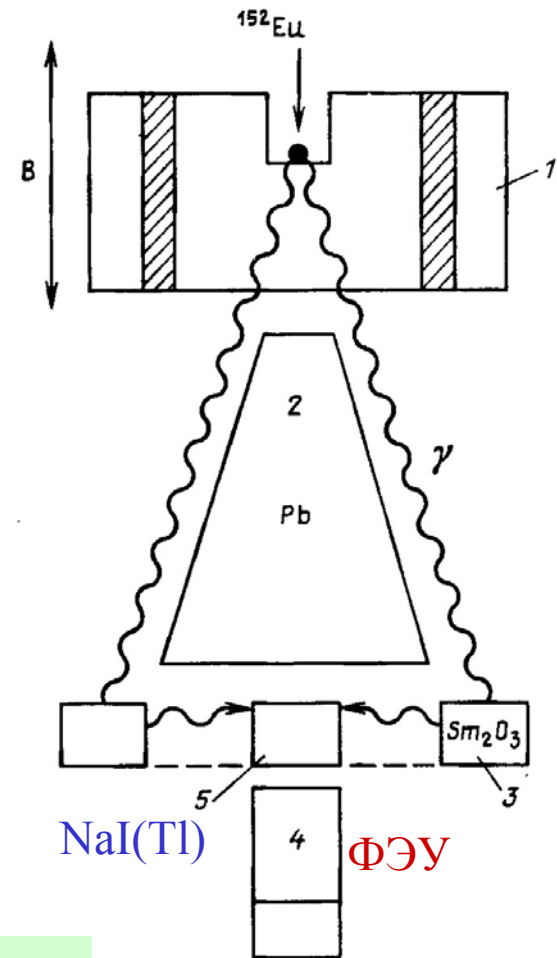
[eV



в)



г)



$$S_{\nu} = -1, \quad S_{\bar{\nu}} = +1$$

Открытие двух типов нейтрино 1962-1963

The Nobel Prize in Physics 1988

Leon M. Lederman, Melvin Schwartz and Jack Steinberger

Открытие тау-лептона 1975 г. –

The Nobel Prize in Physics 1995, Martin L. Perl

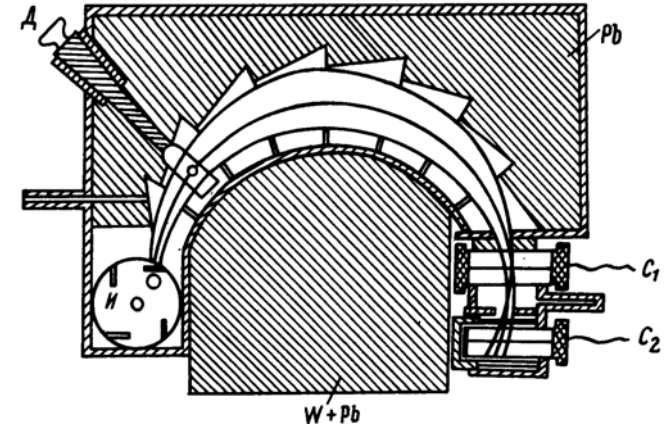
Энергетические спектры в лептонных распадах указывали на наличие еще одного нейтрино - тау

Поиски массы нейтрино

Основной используемый метод – изучение энергетического спектра электронов, образующихся в β -распаде.



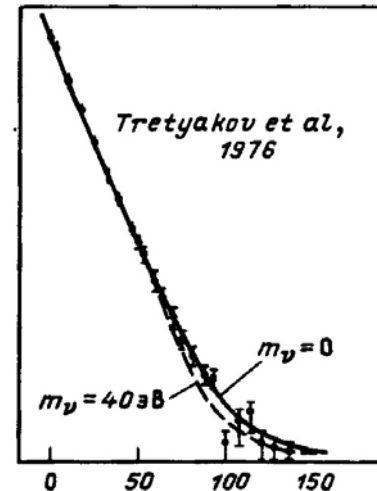
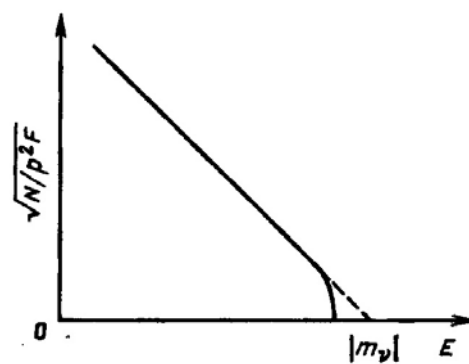
$$T_{e,\text{max}} \approx 18570 \text{ эВ}, \quad T_{1/2} = 12.4 \text{ года}$$



$$N(E_e) \sim$$

$$p_e T_e (E_0 - T_e)^2 \sqrt{1 - \frac{m_\nu^2}{(E_0 - T_e)^2}}$$

$$\rightarrow p_e T_e (E_0 - T_e)^2$$



$$m_\nu < 35 \text{ эВ}$$

recoil energy and excitation neglected

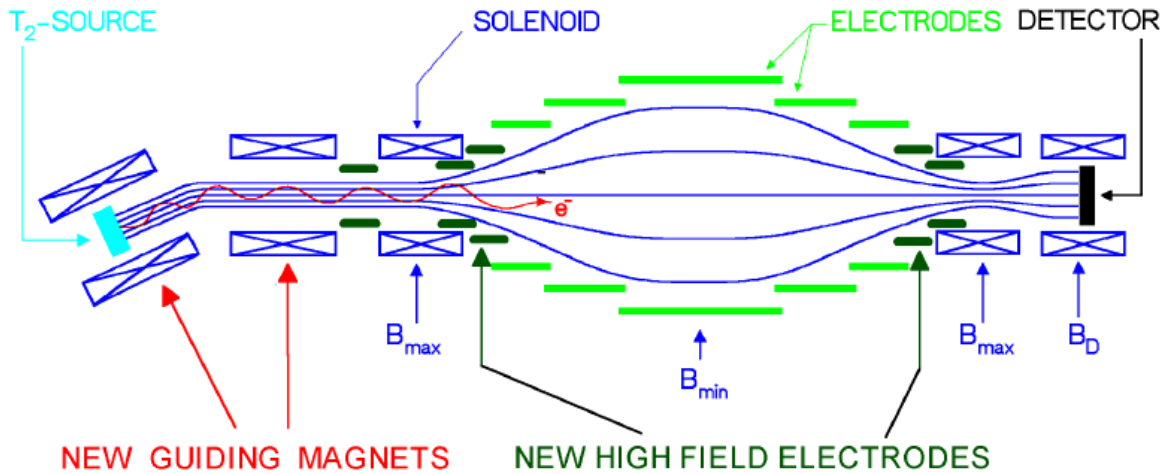
$$N(E) = \text{const} * |M|^2 F(Z, E) p(E + m_e c^2) (E_0 - E) \sqrt{(E_0 - E)^2 - m_\nu^2 c^4}$$

22.12.2015

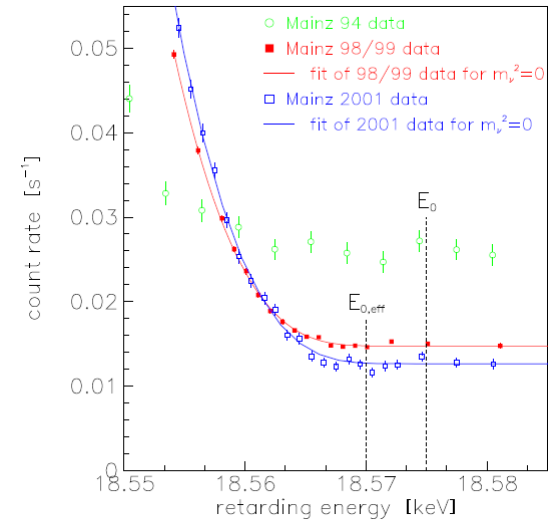
nuclear matrix element

Fermi function

Эксперименты с магнитным адиабатическим коллимированием в Москве и Майнце



Результаты по поиску массы электронного нейтрино



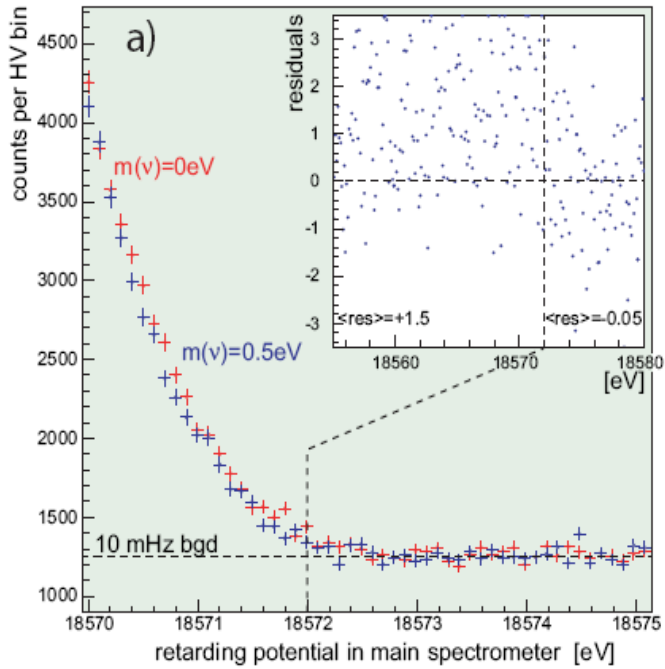
LOBASHEV 99 PL B460 227 V.M. Lobashev *et al.*

KRAUS 05 EPJ C40 447 Ch. Kraus *et al.*

$m_{\nu} < 2.5$ эВ (95% C.L.)

$m_{\nu} < 2.3$ эВ (95% C.L.)

Эксперимент КАТРИН (Karlsruhe, Germany)



$m_\nu < 0.2 \text{ эВ (90\% C.L.)}$

Начало экспериментов – 2012 г.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Число типов легких ($m_\nu < 40$ ГэВ)
нейтрино

$$N_\nu = 2.92 \pm 0.06 \text{ (распады Z)}$$

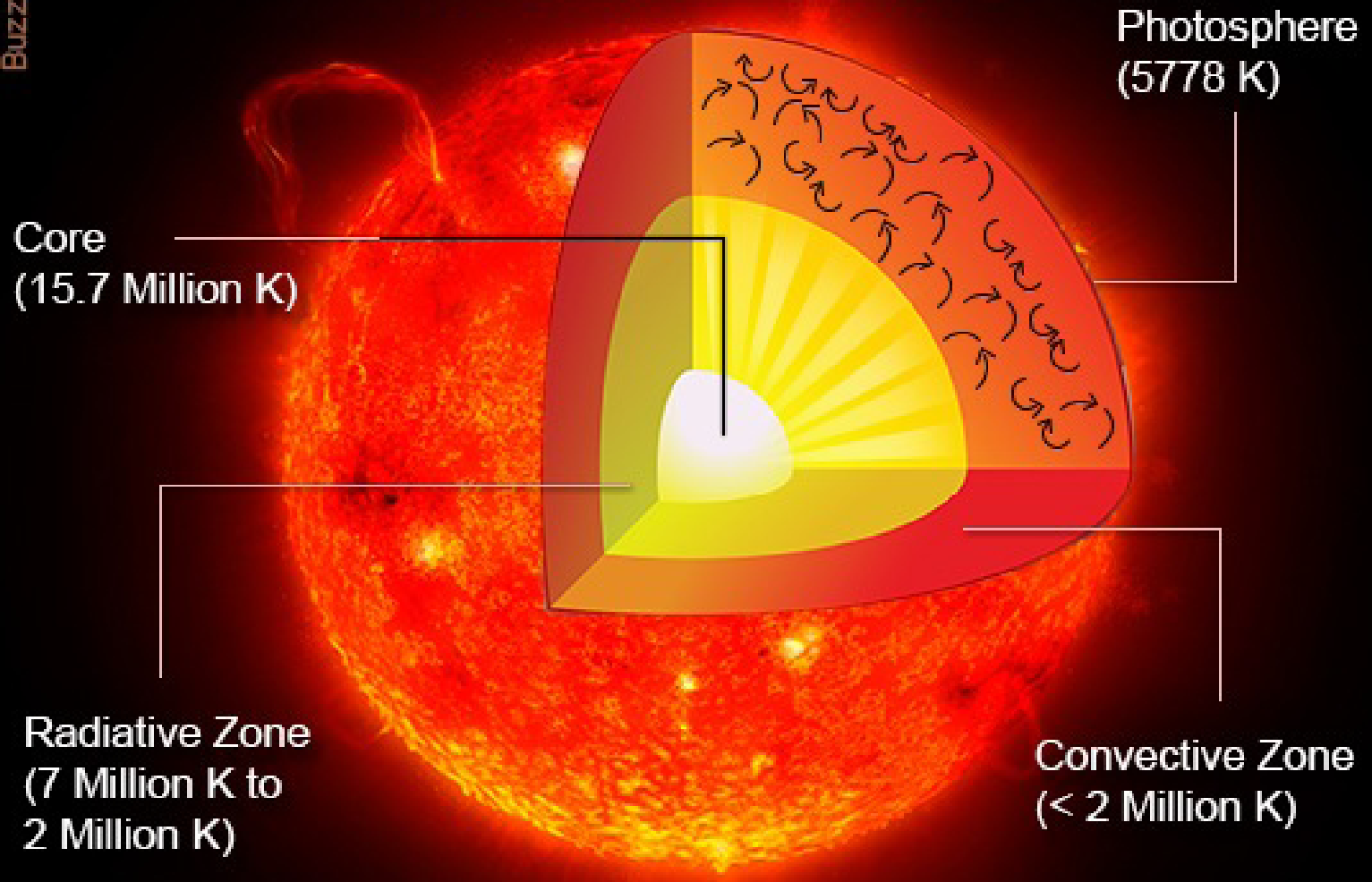
$$m_{\nu_e} < 2 \text{ эВ (95\% C.L.)}$$

$$m_{\nu_\mu} < 0.17 \text{ МэВ (90\% C.L.)}$$

$$m_{\nu_\tau} < 18.2 \text{ МэВ (95\% C.L.)}$$

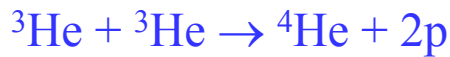
В слабых взаимодействиях
участвуют только левые
нейтрино и правые
антинейтрино

The Solar Interior



Солнечные нейтрино

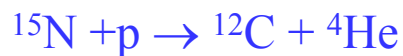
pp – цикл



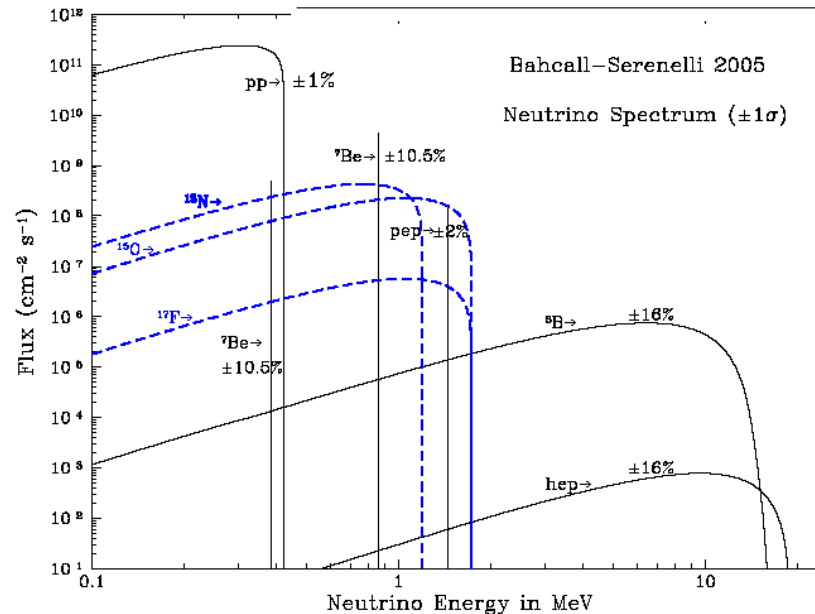
$$E_\nu \leq 0.42 \text{ МэВ}$$



CNO – цикл



| Reaction | Abbr. | Flux ($\text{cm}^{-2} \text{ s}^{-1}$) |
|--|-------------------|--|
| $pp \rightarrow de^+ \nu$ | <i>pp</i> | $5.99(1.00 \pm 0.01) \times 10^{10}$ |
| $pe^- p \rightarrow d \nu$ | <i>pep</i> | $1.42(1.00 \pm 0.02) \times 10^8$ |
| ${}^3\text{He} p \rightarrow {}^4\text{He} e^+ \nu$ | <i>hep</i> | $7.93(1.00 \pm 0.16) \times 10^3$ |
| ${}^7\text{Be} e^- \rightarrow {}^7\text{Li} \nu + (\gamma)$ | ${}^7\text{Be}$ | $4.84(1.00 \pm 0.11) \times 10^9$ |
| ${}^8\text{B} \rightarrow {}^8\text{Be}^* e^+ \nu$ | ${}^8\text{B}$ | $5.69(1.00 \pm 0.16) \times 10^6$ |
| ${}^{13}\text{N} \rightarrow {}^{13}\text{C} e^+ \nu$ | ${}^{13}\text{N}$ | $3.07(1.00_{-0.28}^{+0.31}) \times 10^8$ |
| ${}^{15}\text{O} \rightarrow {}^{15}\text{N} e^+ \nu$ | ${}^{15}\text{O}$ | $2.33(1.00_{-0.29}^{+0.33}) \times 10^8$ |
| ${}^{17}\text{F} \rightarrow {}^{17}\text{O} e^+ \nu$ | ${}^{17}\text{F}$ | $5.84(1.00 \pm 0.52) \times 10^6$ |



Полный поток
нейтрино \sim
 $6.5 \times 10^{10} \text{ 1/}(\text{сек} \cdot \text{см}^2)$

Understanding How the Sun Burns



Hans Bethe

Basic Theory 1939

Nobel Laureate 1967



Willy Fowler

Theory, Experiments 1950s, 60s

Nobel Laureate 1983

We stand on the Shoulders of Giants

Поиск солнечных нейтрино



Cl-Ar метод, предложен Б.Понтекорво в 1946 г.



${}^{37}\text{Ar}$: $T_{1/2} = 34.8$ дня.

Извлечение ${}^{37}\text{Ar}$ – с помощью радиохимических методов

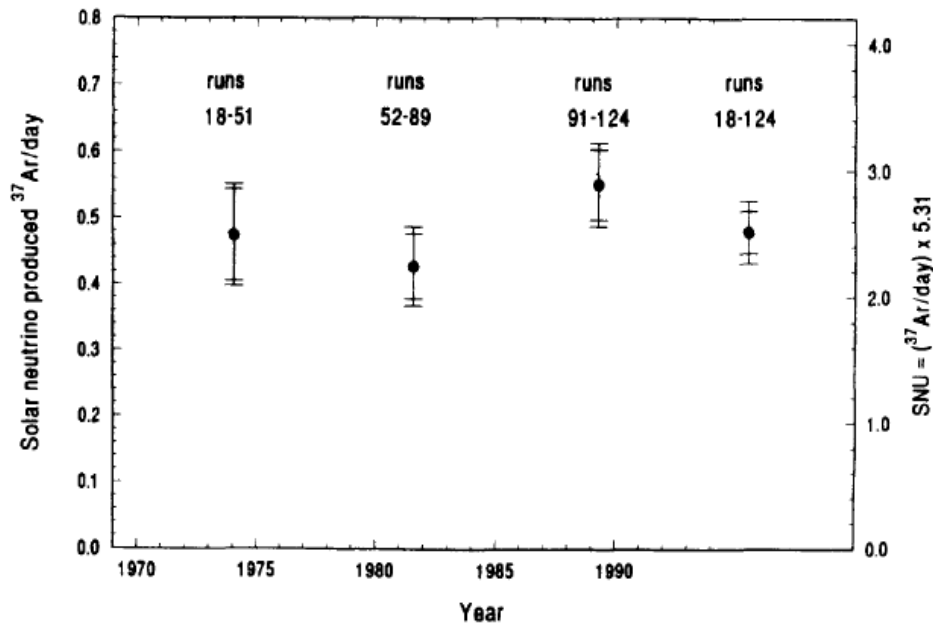
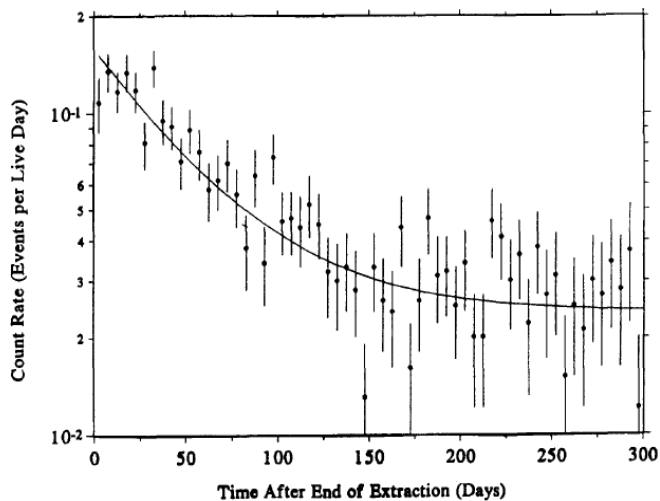
Подземный эксперимент Homestake (USA)

Объем 380 м³ был установлен в шахте на глубине 1.5 км и заполнен 610 т C₂Cl₄. Примерно раз в 2 месяца выделялся накопившийся аргон и помещался в маленький (4.5 мм × 20 мм) пропорциональный счетчик. Детектируются Оже-электроны (E_e = 2.82 кэВ), образующиеся после К-захвата.

Фон (космика и нейтроны) порядка 0.1 ${}^{37}\text{Ar}$ в день.

Работы начались в 1965 г., эксперименты продолжались с 1967 по 1995 г.

Результаты Homestake



$\phi(\nu_e) = 2.56 \pm 0.16 \pm 0.16$ SNU, (SNU = 10^{-36} $\nu/(\text{ат}\cdot\text{сек})$)
 теория ~ 8 SNU

The Nobel Prize in Physics 1995

Регистрация солнечных нейтрино Ga/Ge методом



$T_{1/2}({}^{71}\text{Ge}) = 11.43$ дня, регистрируются Оже-электроны и фотоны с энергией 10.4 и 1.2 кэВ

Эксперимент GALLEX (Gran Sasso)

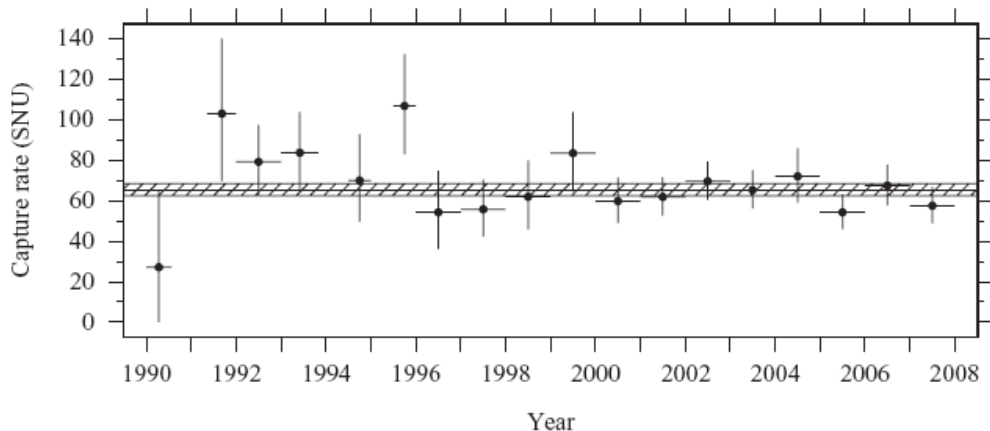
30 т Ga в виде 101 т водного раствора GaCl_2 , первые рез. – 1992 г.

(Gallex+GNO) $\phi(\nu_e) = 69.3 \pm 4.1 \pm 3.6$ SNU (Теория ≈ 125 SNU)

Эксперимент SAGE

(Баксан), 55 т Ga

$\phi(\nu_e) = 70.8^{+5.3}_{-5.2} \quad ^{+3.7}_{-3.2}$
SNU





Бруно Понтекорво

Гипотеза осцилляций нейтрино

В случае двух состояний нейтрино с
массовыми волновыми функциями ν_1 и ν_2

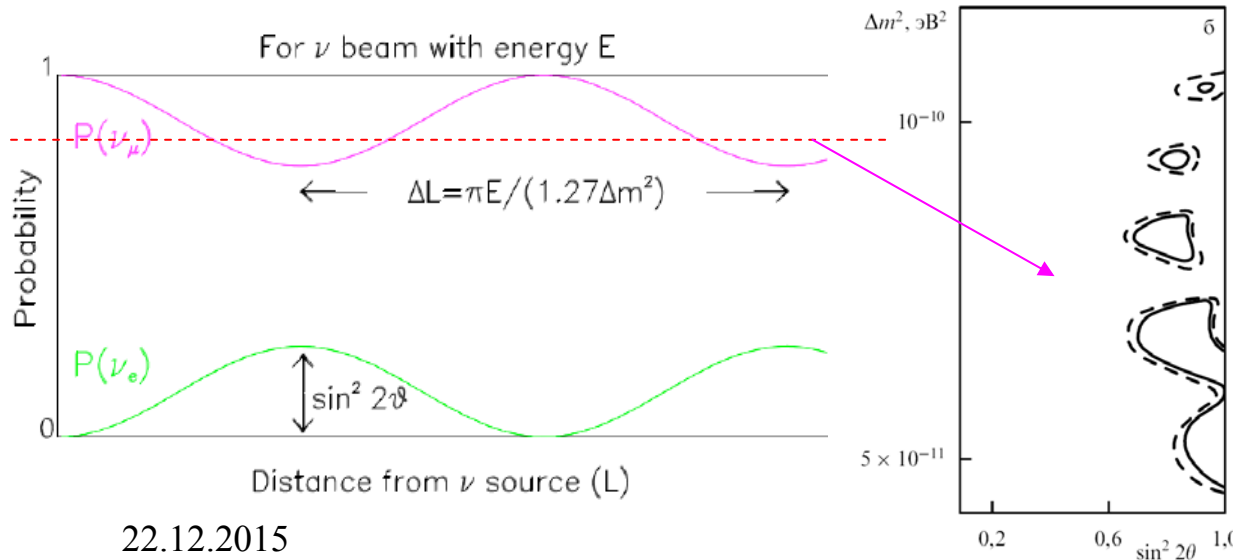
$$\nu_e = \cos\theta \nu_1 + \sin\theta \nu_2$$

$$\nu_\mu = -\sin\theta \nu_1 + \cos\theta \nu_2$$

$$\nu_{1,2} \sim \exp[-i(Et - px)]$$

1968: Gribov and Pontecorvo suggest flavor change (oscillation) of electron neutrinos to muon neutrinos as a possible reason.

$$P_{\nu_e, \nu_e} = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 (eV^2) R (km)}{E (GeV)} \right)$$



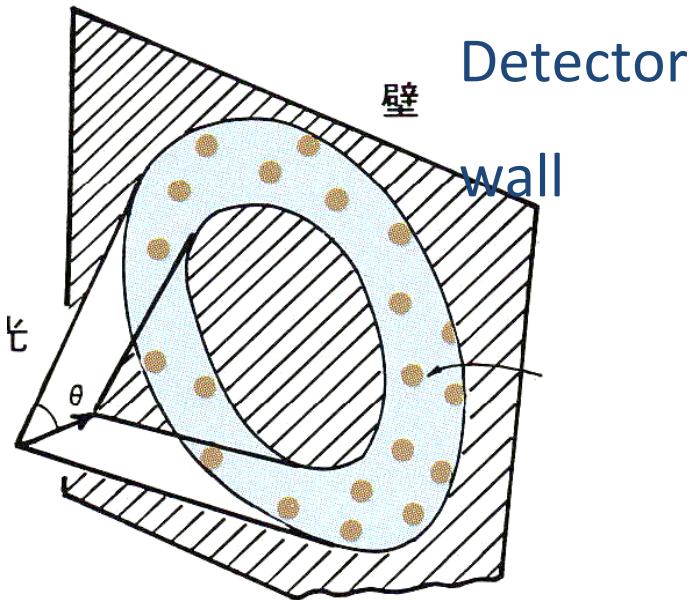
$$\Delta L_{e\mu} \approx 3 \cdot 10^4 E \text{ (GeV/km)}$$

$$\Delta L_{\mu\tau} \approx 10^3 E \text{ (GeV/km)}$$

Kamioka Neutron Decay Experiment (Kamiokande)

Kamiokande (1000 ton water fiducial volume)

Главная цель – поиски распада протона



K. Hirata et al, Phys.Lett.B 205 (1988) 416.

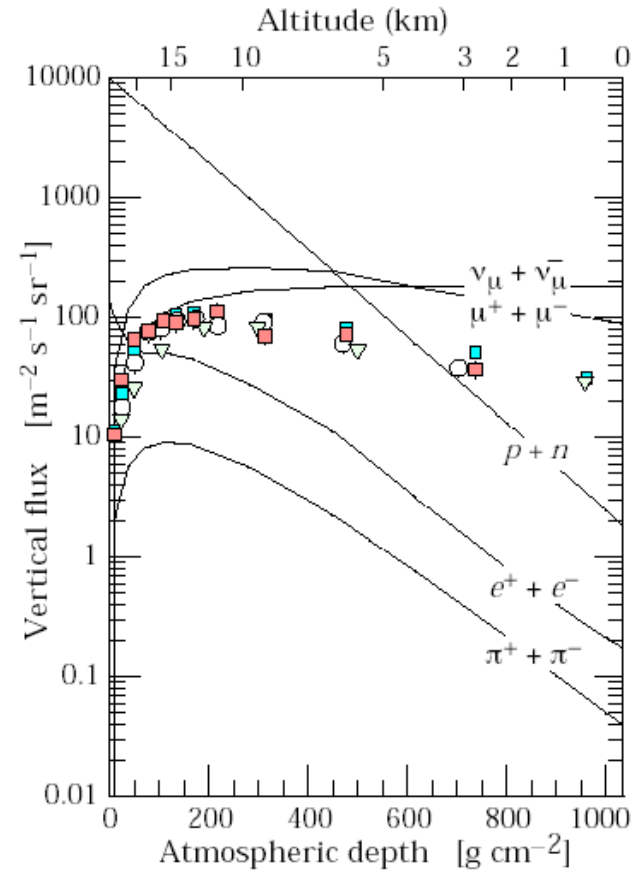
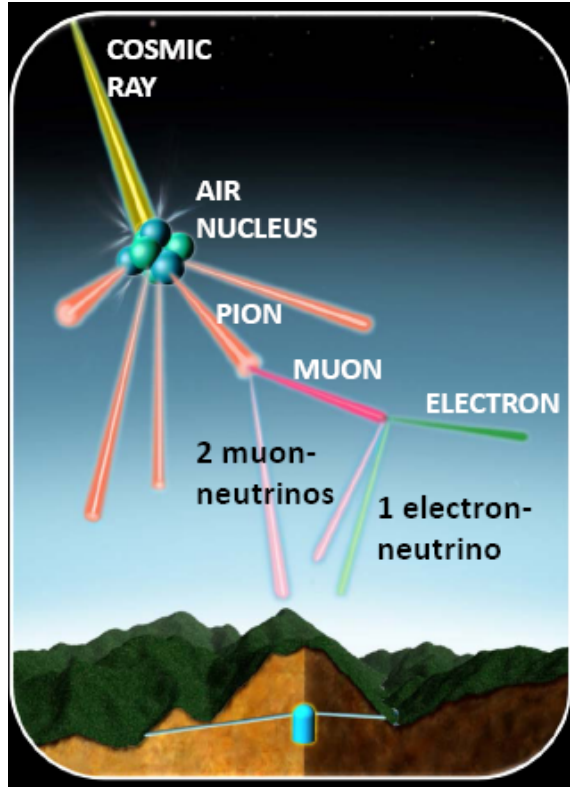
| | Data | Prediction |
|------------------|------|------------|
| ν_e events | 93 | 88.5 |
| ν_μ events | 85 | 144.0 |

Paper conclusion: “We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics **such as neutrino oscillations might explain the data.**”

Какие частицы мы видим у земной поверхности?

Атмосфера – 1000

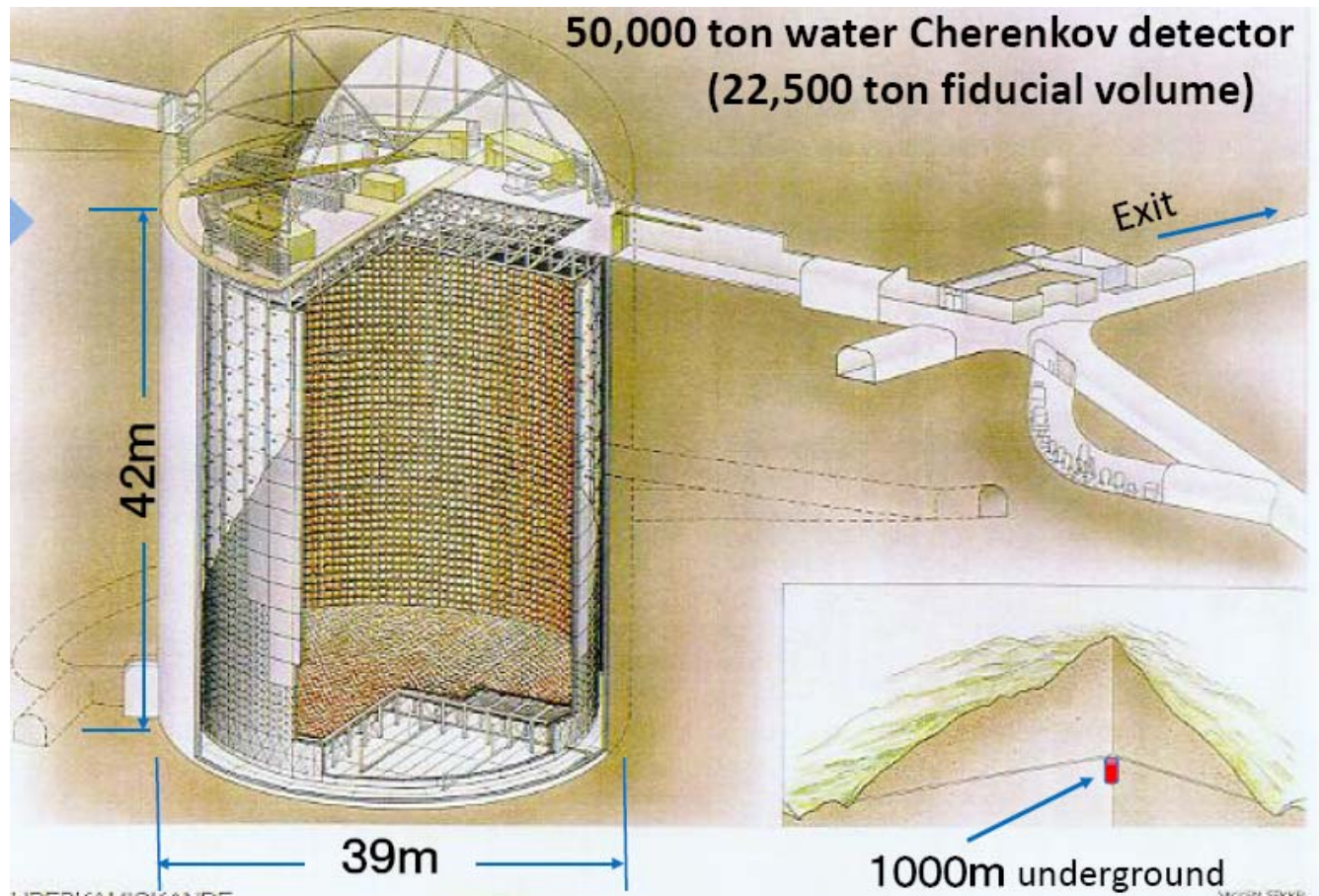
$\text{г/см}^2 \approx 27X_0 \approx 11\lambda_{\text{яд}}$



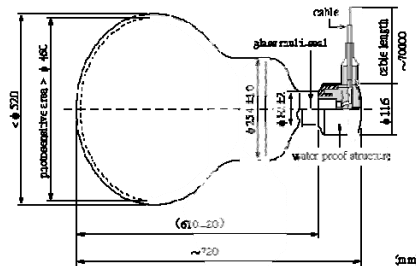
**Поток космических частиц у поверхности
Земли примерно $10^{-2} \text{ см}^{-2} \text{ с}^{-1} \sim 70\%$
заряженных частиц - мюоны**

22.12.2015

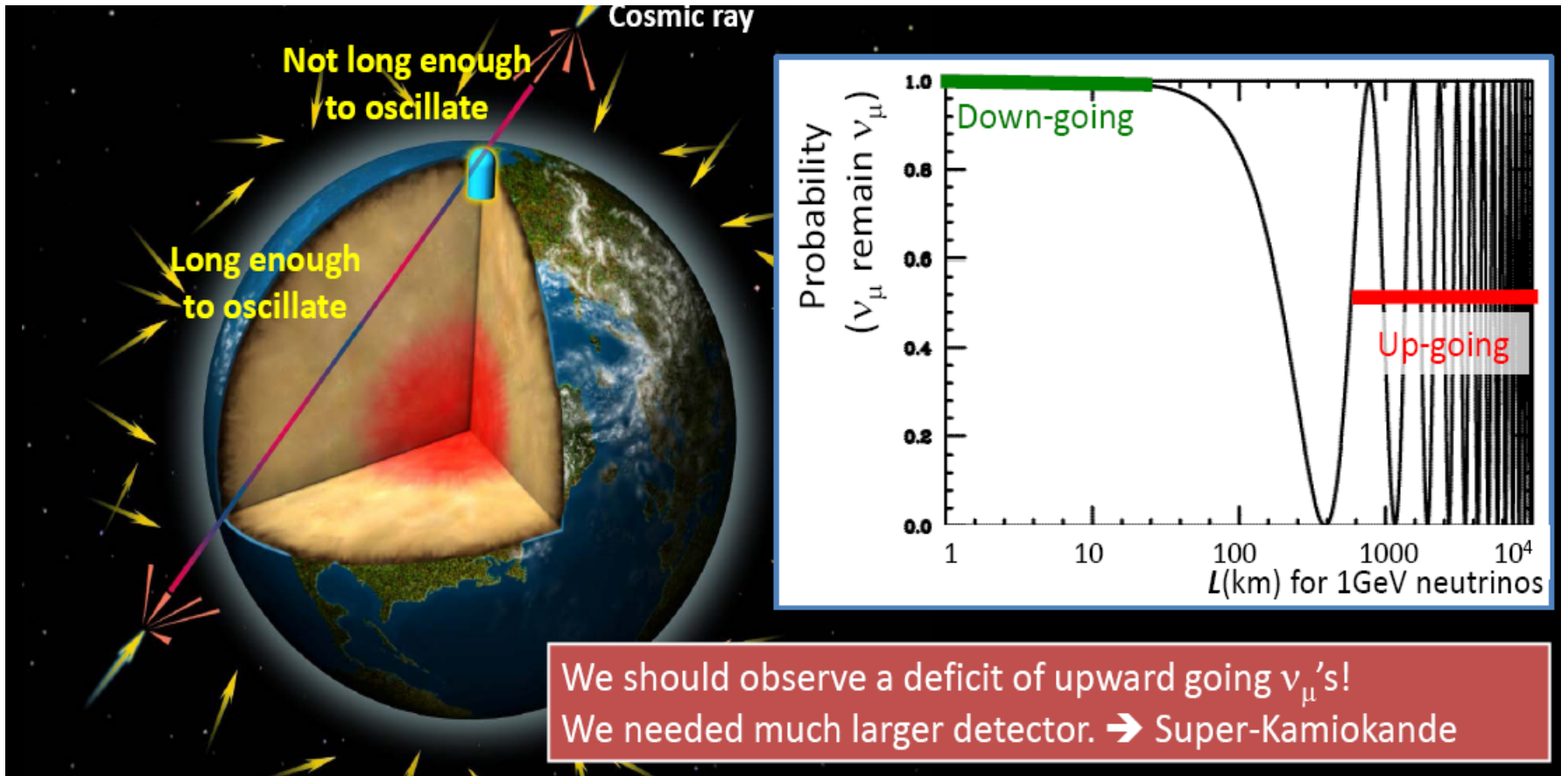
Эксперимент Super-Kamiokande



~120 collaborators from:



| Particle | Cherenkov threshold in total Energy |
|-------------|-------------------------------------|
| e^{\pm} | 0.768(MeV) |
| μ^{\pm} | 158.7 |
| π^{\pm} | 209.7 |

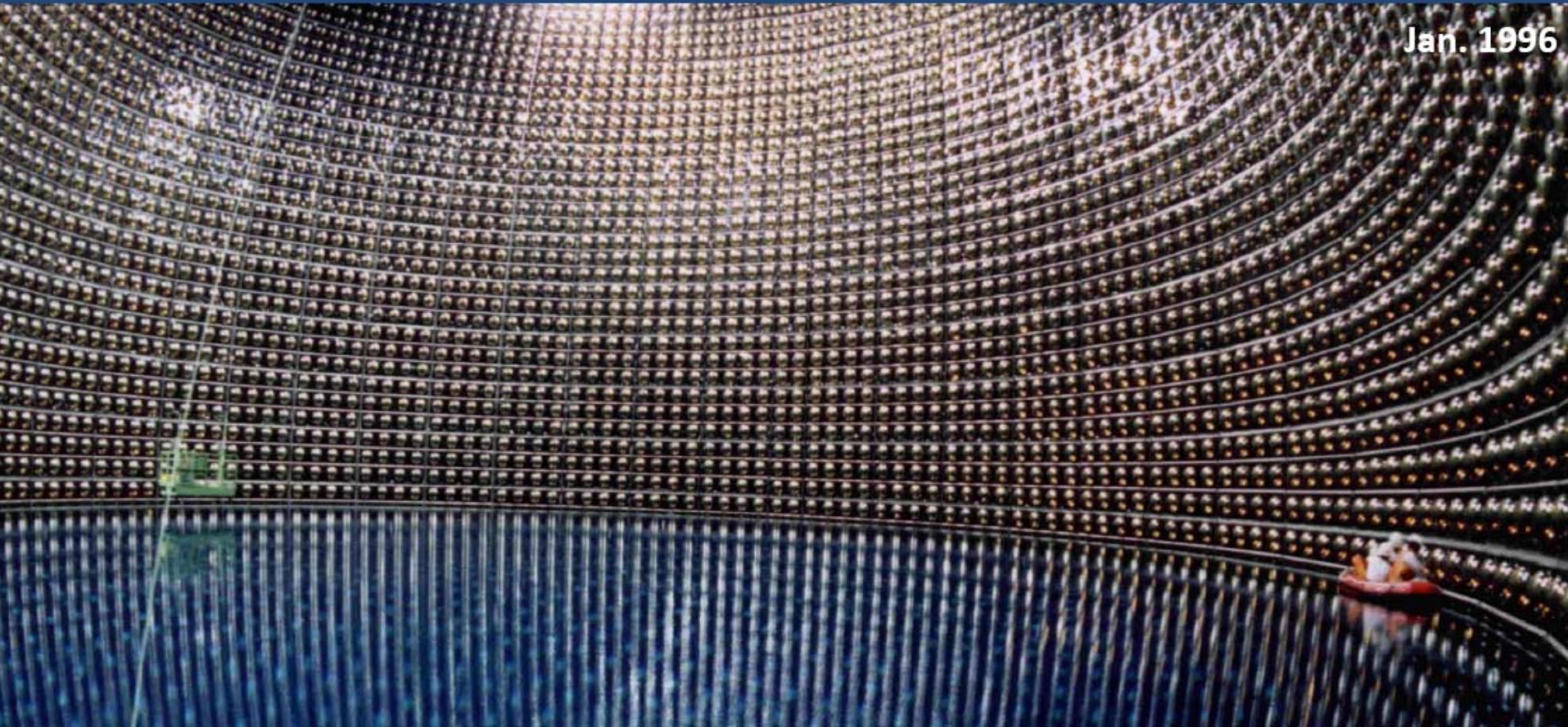


$$\Delta L_{e\mu} \approx 3 \cdot 10^4 E \text{ (GeV/km)}$$

$$\Delta L_{\mu\tau} \approx 10^3 E \text{ (GeV/km)}$$

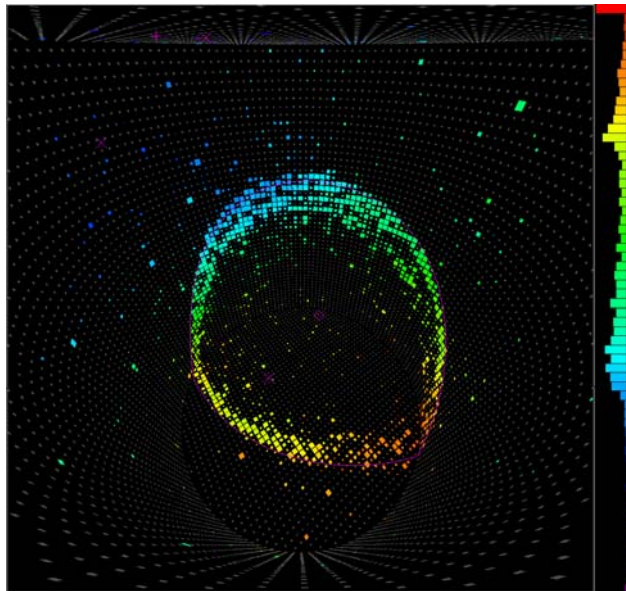
Filling water in Super-Kamiokande

Jan. 1996

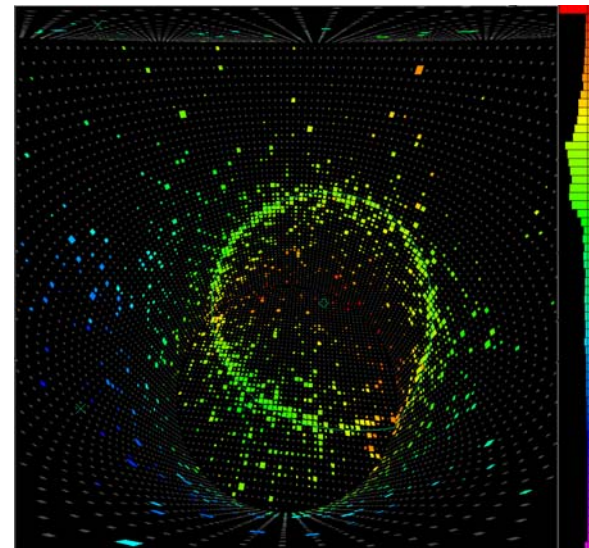


Эксперимент SuperKamiokaNDE

This event occurred at 1998-04-04 08:35:22. It was reconstructed as a muon with momentum of 603 MeV. The time scale width is 162 ns. This event was followed by another event (not shown) 4 μ s later which was caused by an electron produced by the decay of the stopped muon. This gives us an additional confirmation that this is a muon.



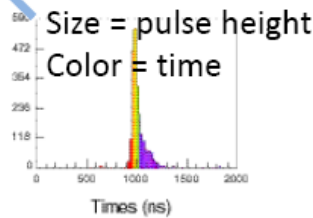
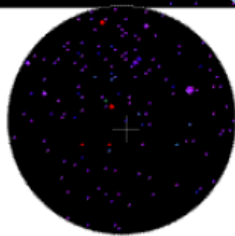
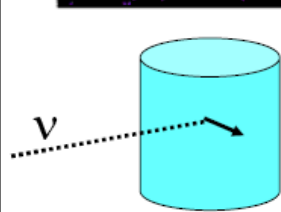
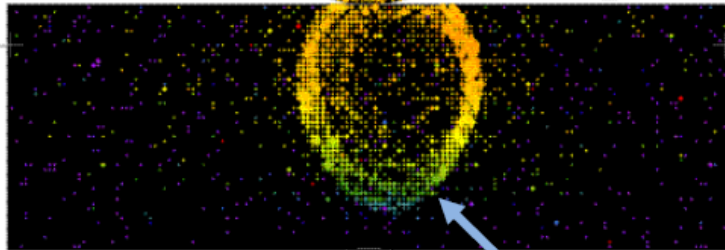
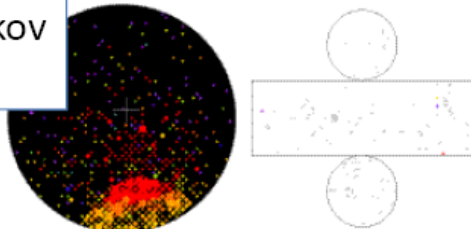
This event occurred at 1998-04-04 21:26:08. It was reconstructed as an electron with momentum of 492 MeV. The time scale width is 130 ns.



Atmospheric neutrino events observed in Super-K (1)

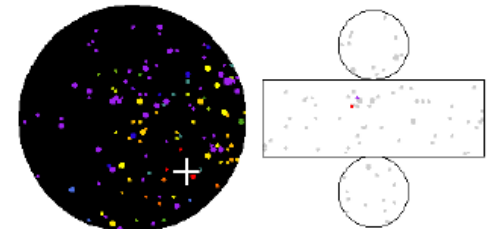
Single Cherenkov ring event

602
008
= 1.088 ± 0.3407/c

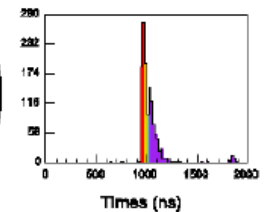
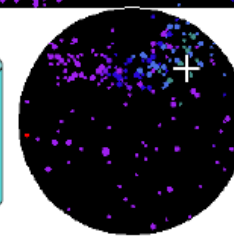
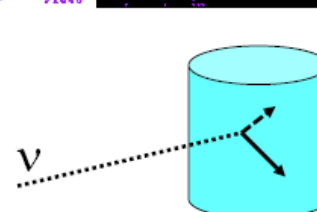
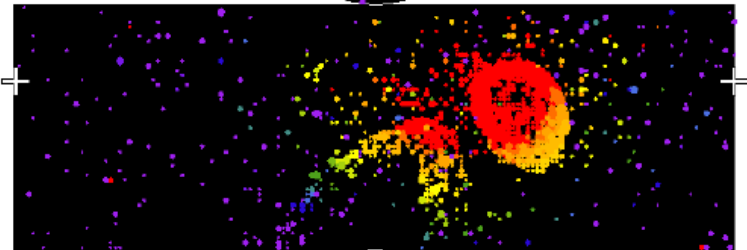


Multi Cherenkov ring event

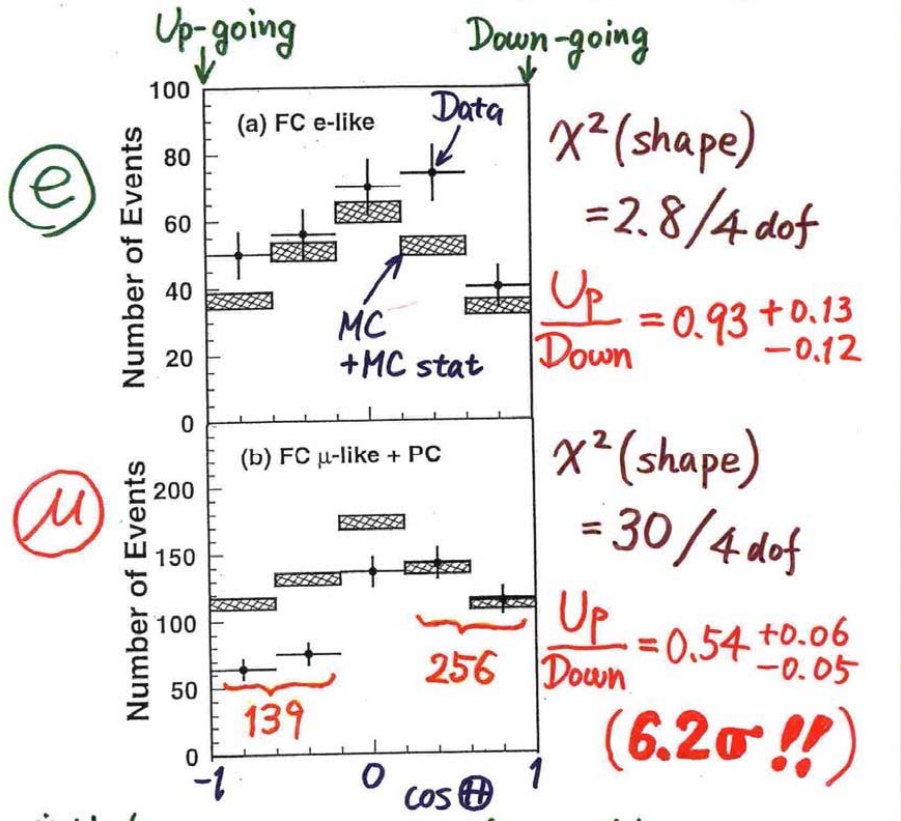
Analysis: 100% OK
D well: 576.9 cm
Fully-Contained



Time(ns)
★ < 976
★ 976- 981
★ 981- 986
★ 986- 991
★ 991- 996
★ 996-1001
★ 1001-1006
★ 1006-1011
★ 1011-1016
★ 1016-1021
★ 1021-1026
★ 1026-1031
★ 1031-1036
★ 1036-1041
★ 1041-1046
★ >1046

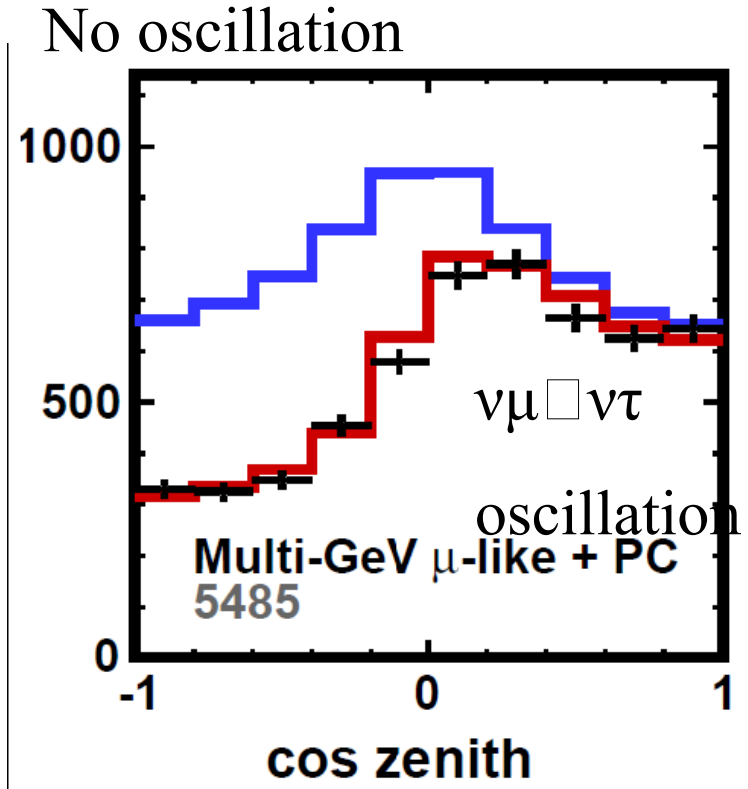


Zenith angle dependence
(Multi-GeV)

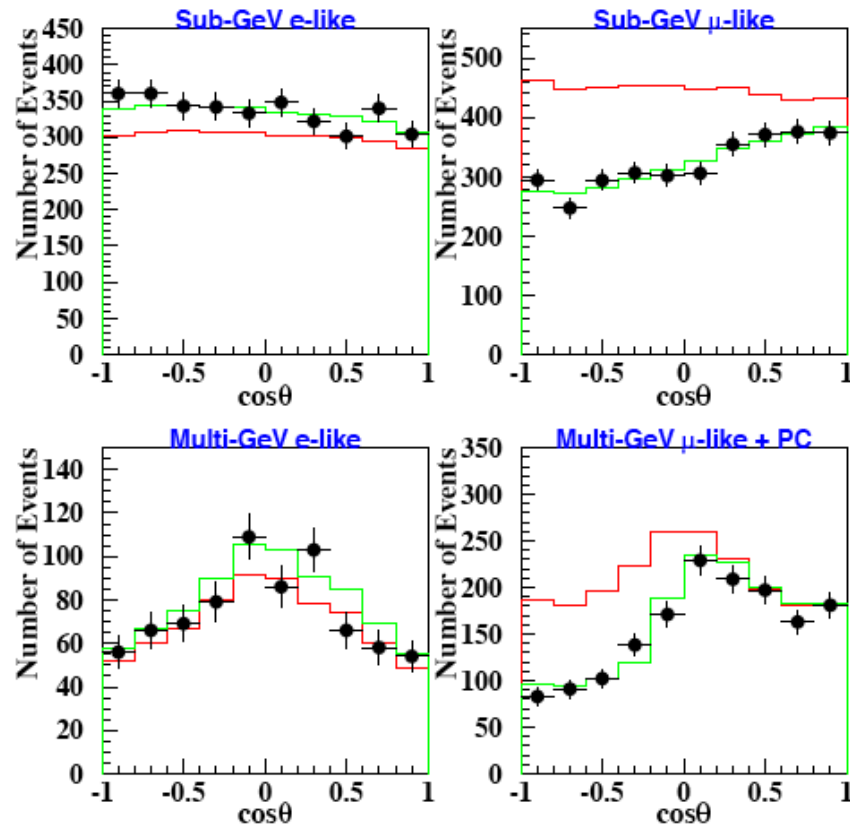


531 events

Super-K (2015)



5485 events



Event rates observed in Super K as a function of zenith angle for two energy ranges. Candidate e events are on the left, μ are on the right. The red line indicates the predicted rate. The green line is the best fit including oscillations.

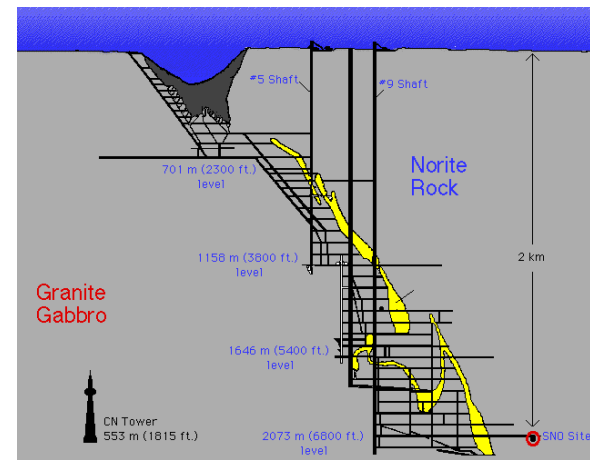
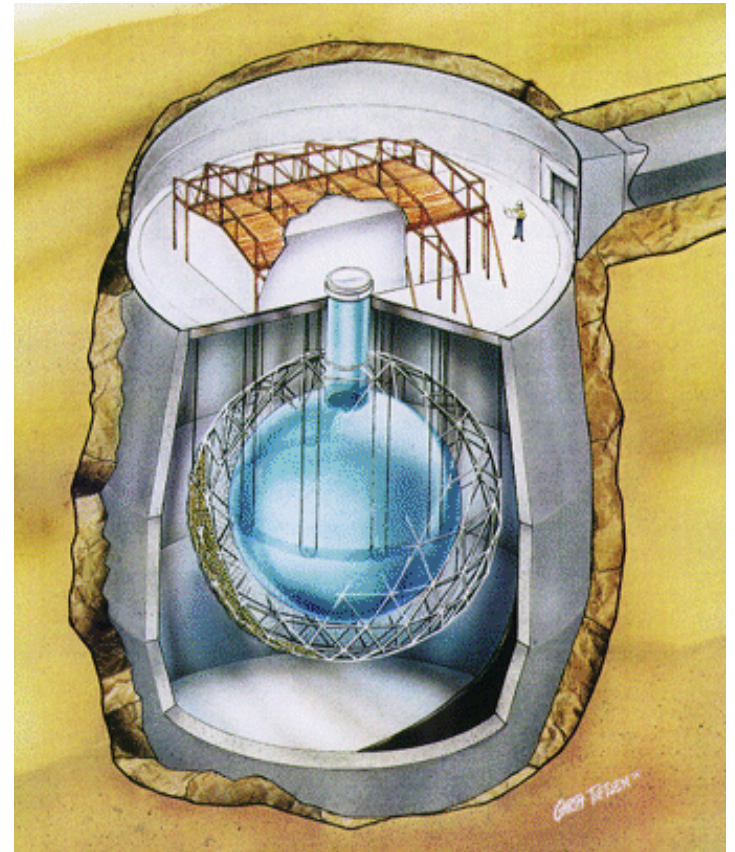
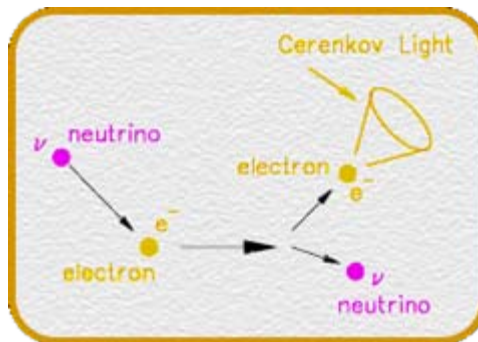
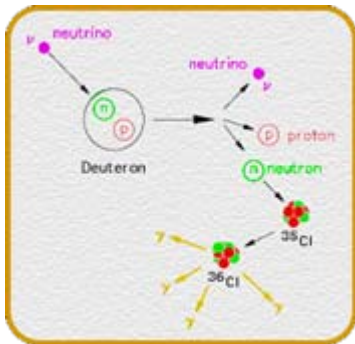
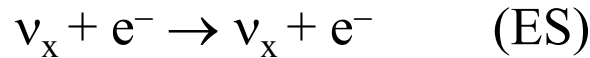
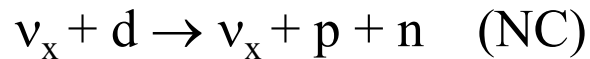
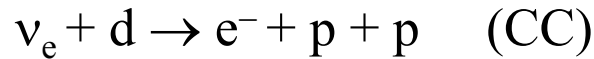
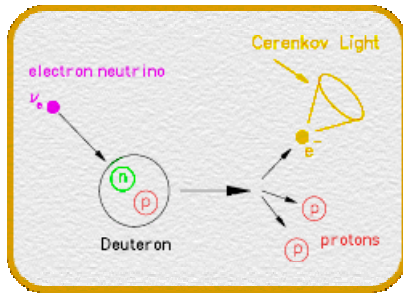
Эксперимент SNO

Sudbury Neutrino Observatory

Sudbury Neutrino Observatory (Канада)

1000 т D₂O (бак 12 м диаметром),

9600 ФЭУ E_{th} ~ 5 МэВ

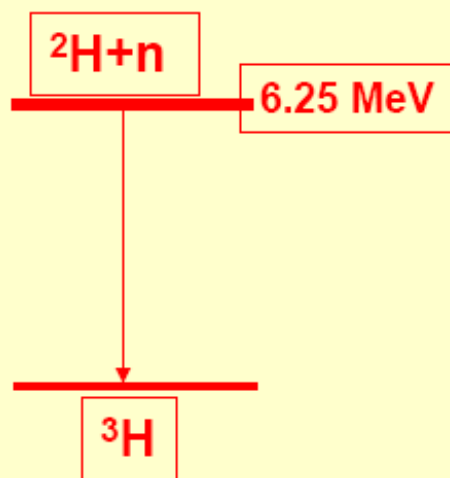


22.12.2015

3 neutron (NC) detection methods (systematically different)

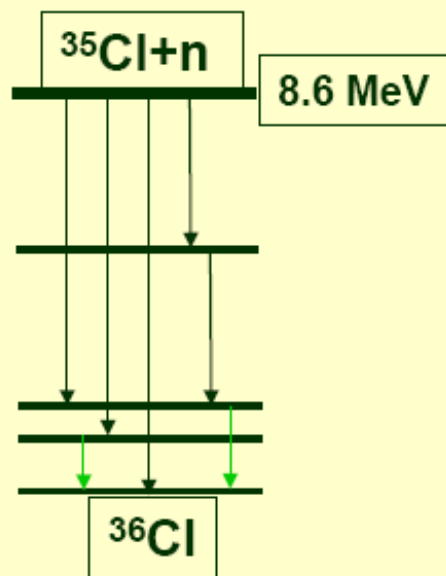
Phase I (D₂O)
Nov. 99 - May 01

n captures on $^2\text{H}(n, \gamma)^3\text{H}$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions



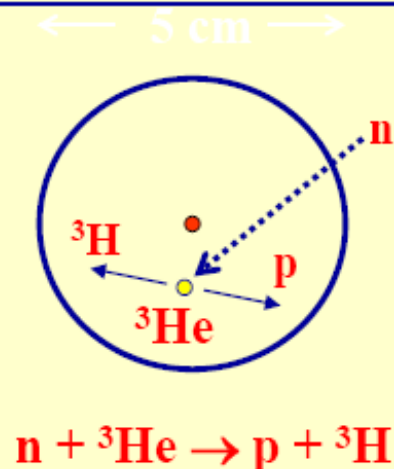
Phase II (salt)
July 01 - Sep. 03

2 tonnes of NaCl
n captures on $^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}$
Effc. ~40%
NC and CC separation by event isotropy



Phase III (^3He)
Nov. 04-Dec. 06

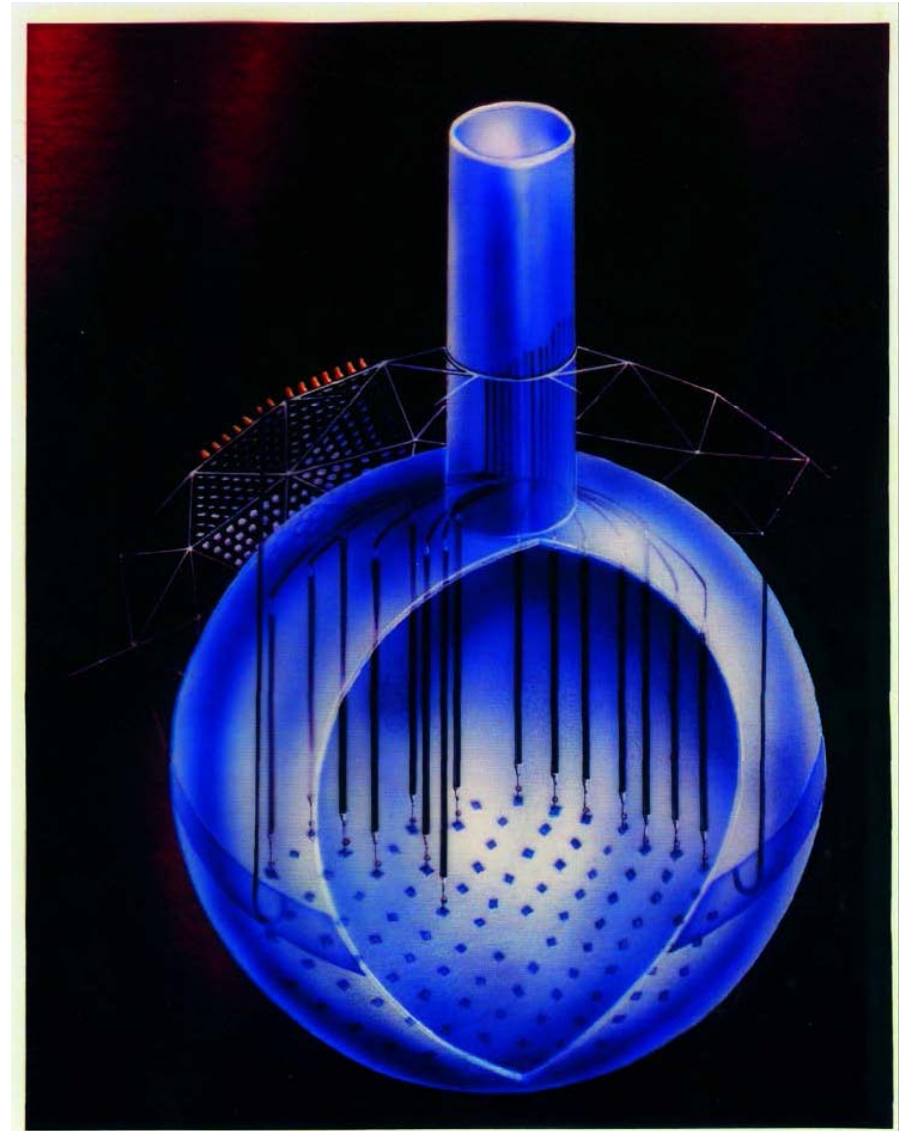
400 m of proportional counters
 $^3\text{He}(n, p)^3\text{H}$
Effc. ~ 30% capture
Measure NC rate with entirely separate detection system.

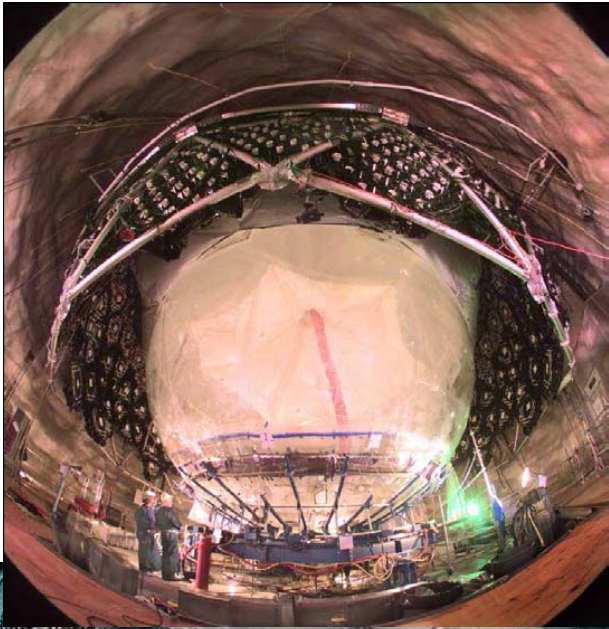


Phase 3: 400 m of Ultra Low Background Neutron Counters installed in the heavy water by a remotely controlled submarine

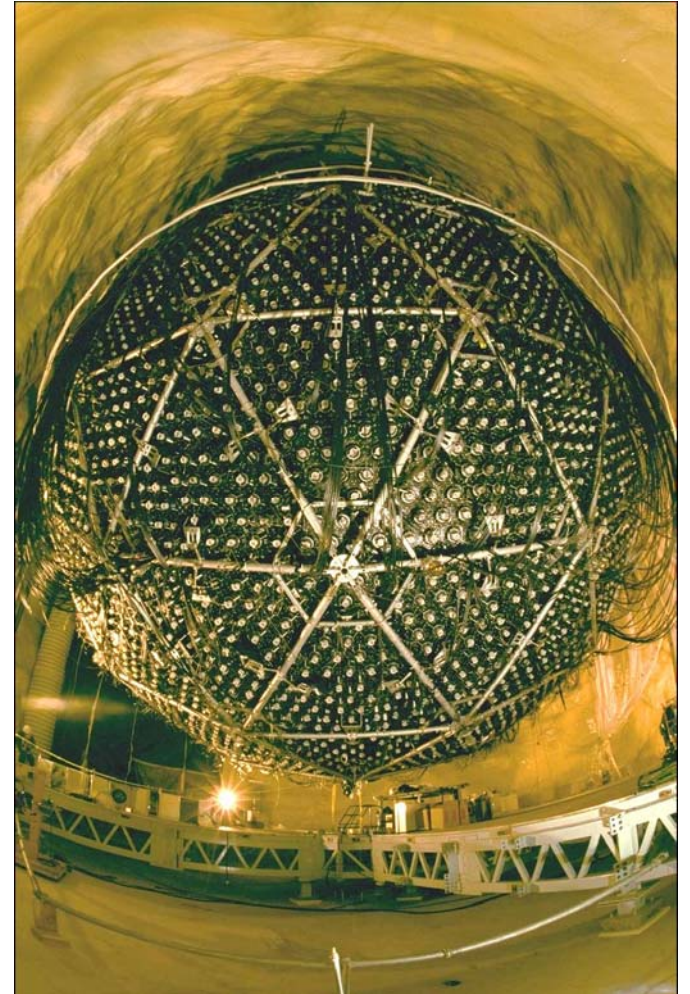
Light
Sensors

Neutron
Detectors

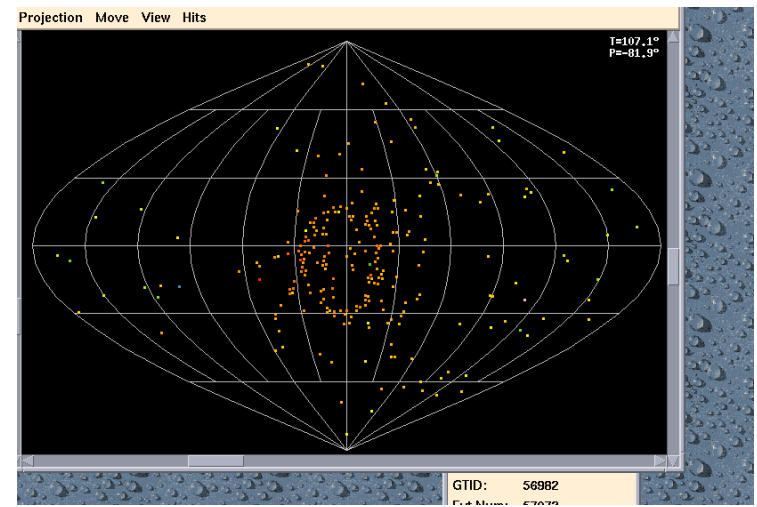
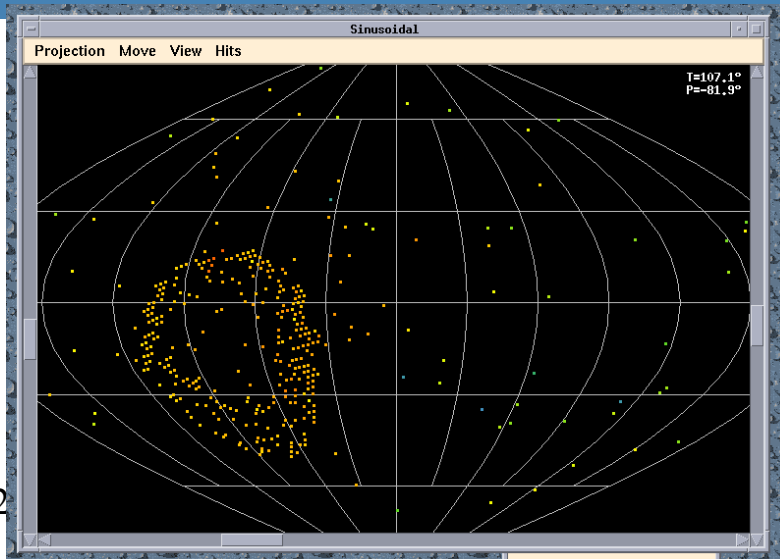
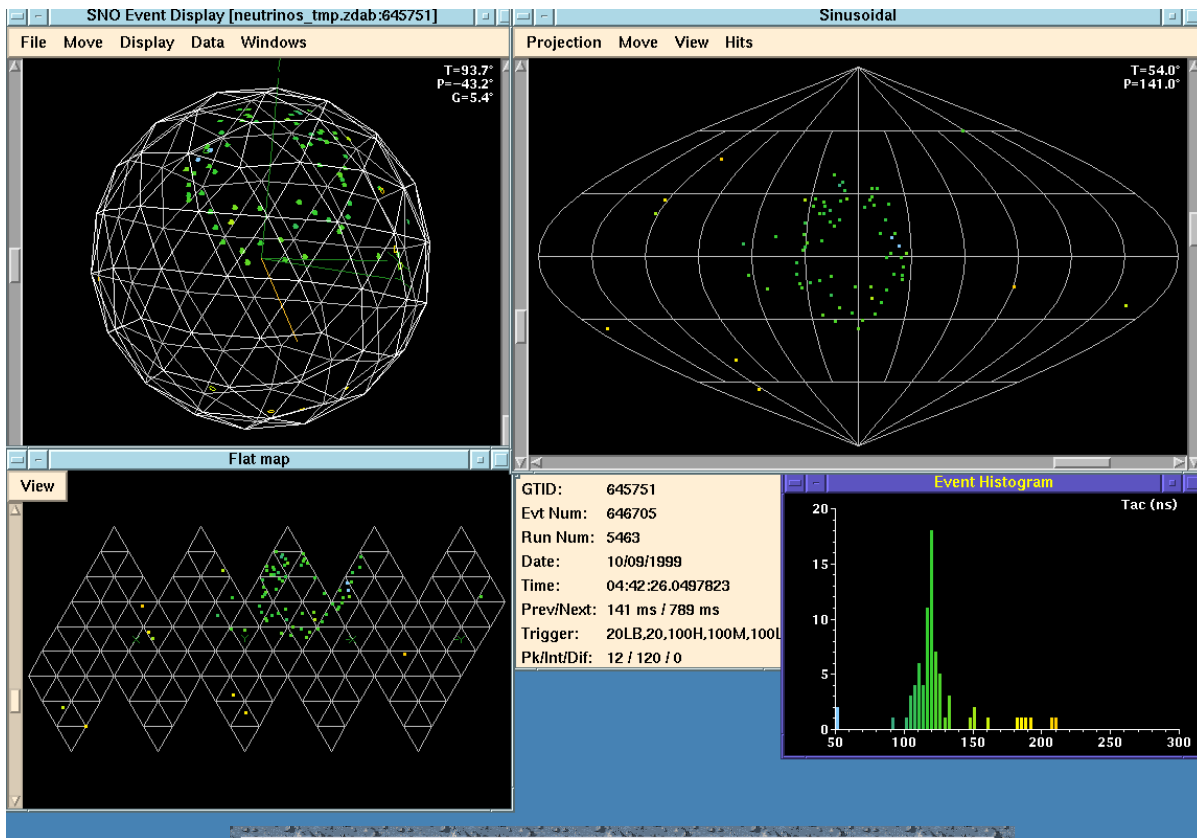




22.12.2015

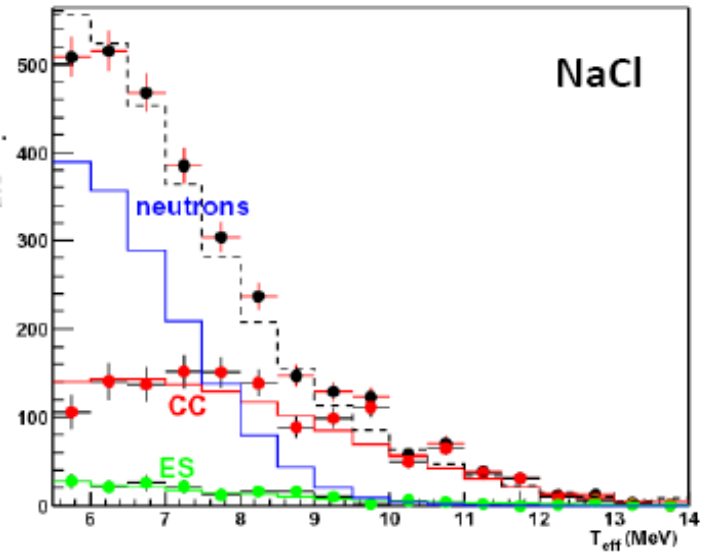
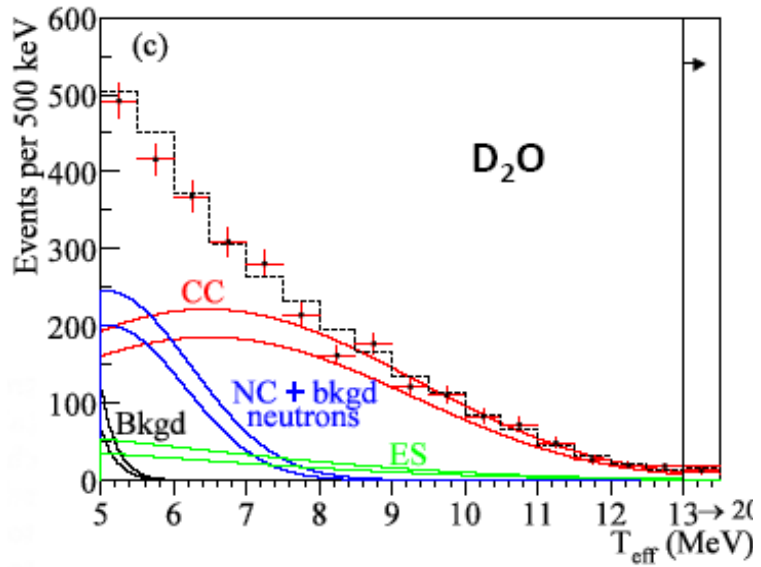


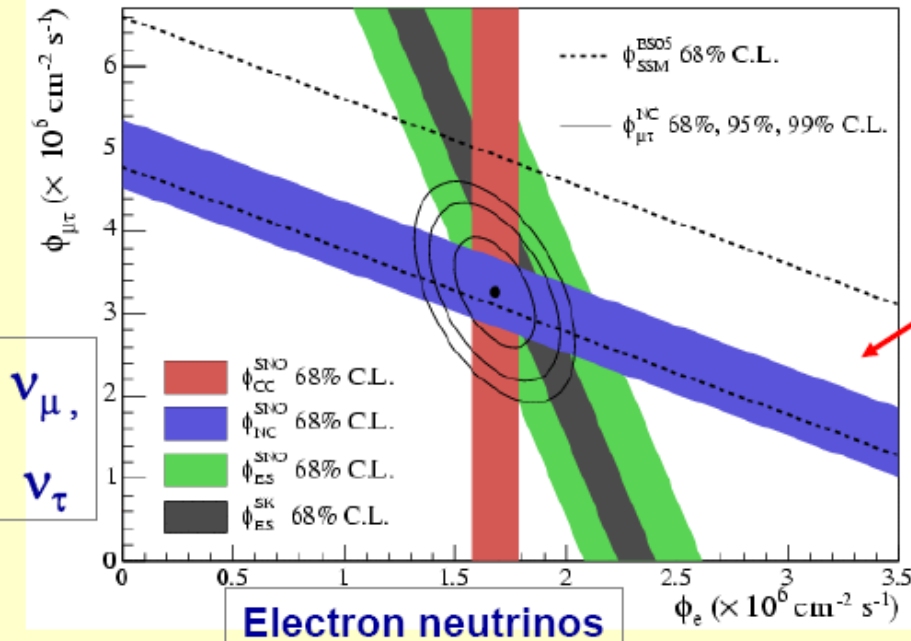
35



22.12.2

As measured 1999-2003





SNO Results for Salt Phase

Flavor change determined by $> 7 \sigma$.

New physics beyond The Standard Model of Elementary Particles!

The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model

Calculations:

5.82 \pm 1.3 (Bahcall et al),
5.31 \pm 0.6 (Turck-Chieze et al)

$$\phi_{CC} = 1.68^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

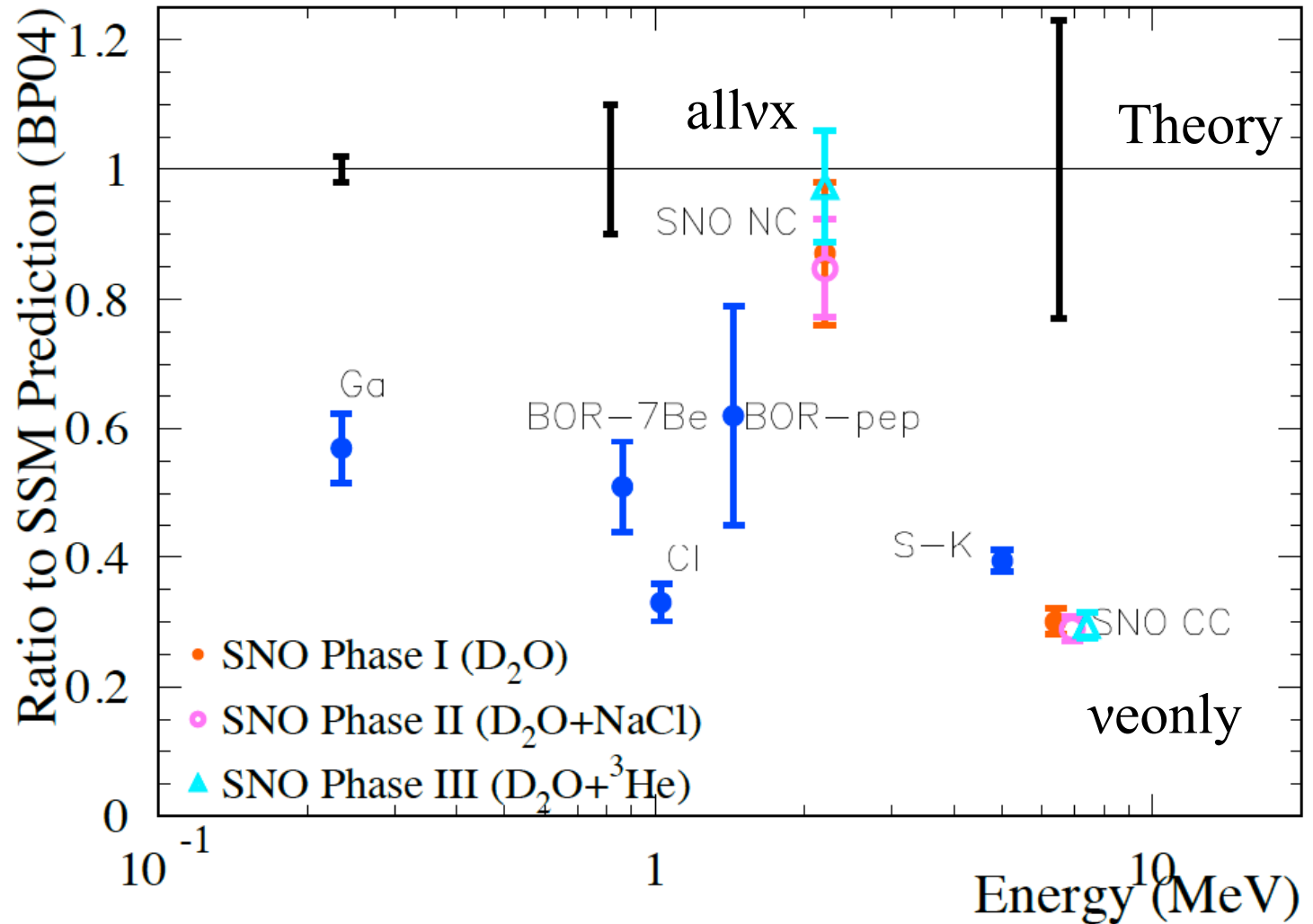
(In units of $10^6 \text{ cm}^{-2} \text{ s}^{-1}$)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

Electron Neutrinos are only 1/3 of Total

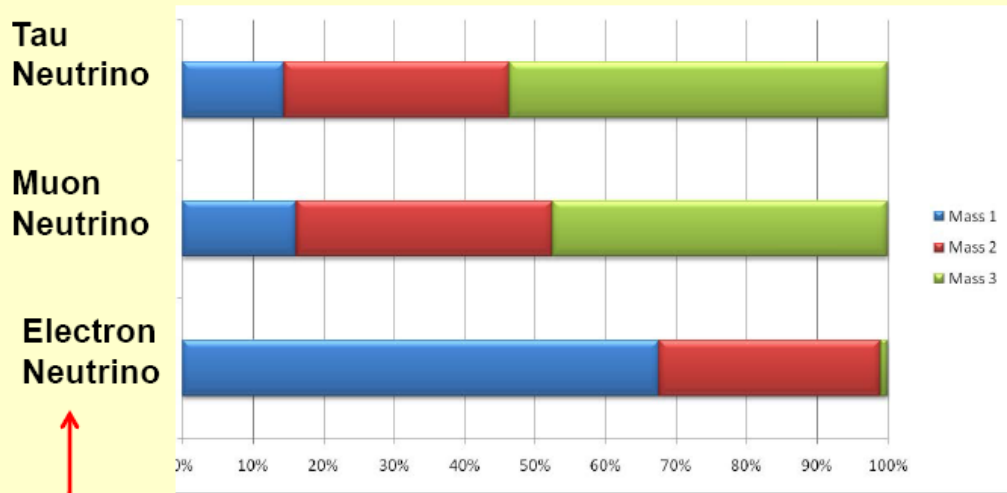


Solar Neutrino Problem Resolved



NEUTRINO OSCILLATIONS AND NEUTRINO MASS

Neutrino Flavors (Electron, Muon, Tau) can be expressed as combinations of Masses (1,2,3)

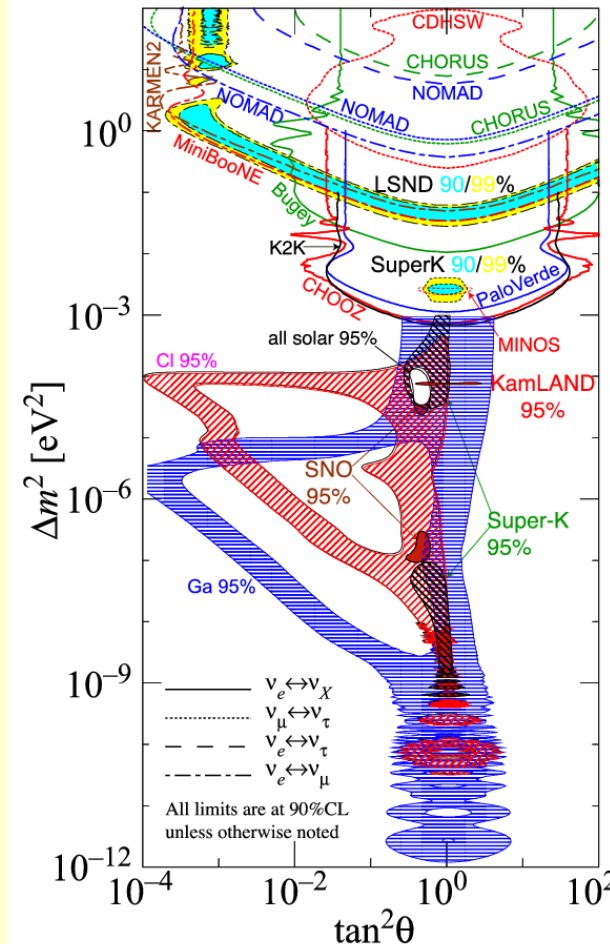


Quantum mechanics states

Created in a unique Flavor State

The mass fractions change as the neutrino travels

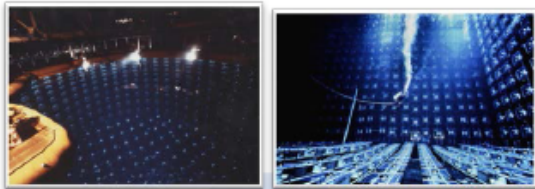
After traveling there is a finite probability to be detected as a different flavor type



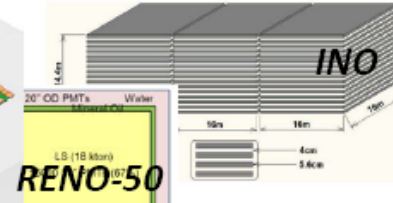
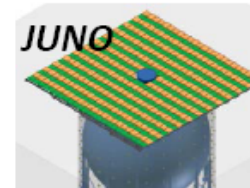
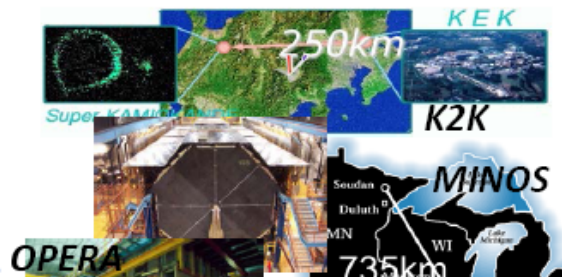
The analysis concludes that the electron neutrinos are converted to a pure Mass 2 state by interaction with the dense electrons in the sun via the Mikheyev-Smirnov-Wolfenstein (MSW) effect. This interaction determines that Mass 2 is greater than Mass 1 as well as determining Δm_{12}^2 and the mixing parameter θ_{12}

Neutrino oscillation experiments: Past, Present and Future

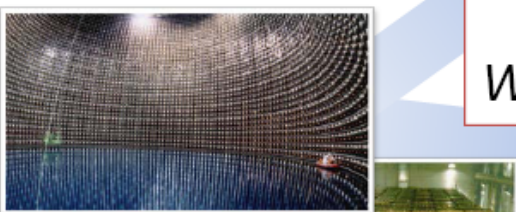
"Atmospheric ν_μ deficit"
(around 1990)



"Long-baseline neutrino oscillation experiments" (~2000's)



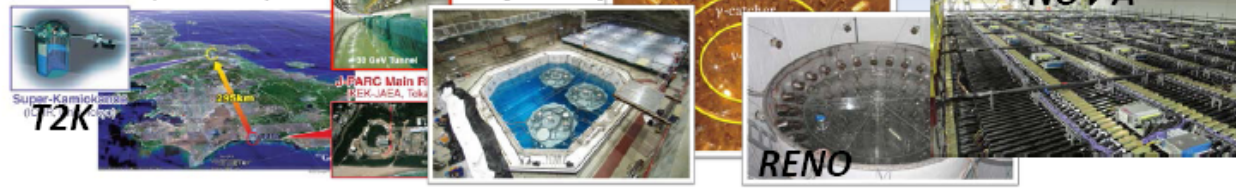
"Discovery of neutrino oscillations" (1990's)



*Our understanding on neutrino oscillations have been improving tremendously!
We still have to understand neutrinos more!*

"future oscillation experiments"
(2020's ?)

"3 flavor oscillations"
(2010's)



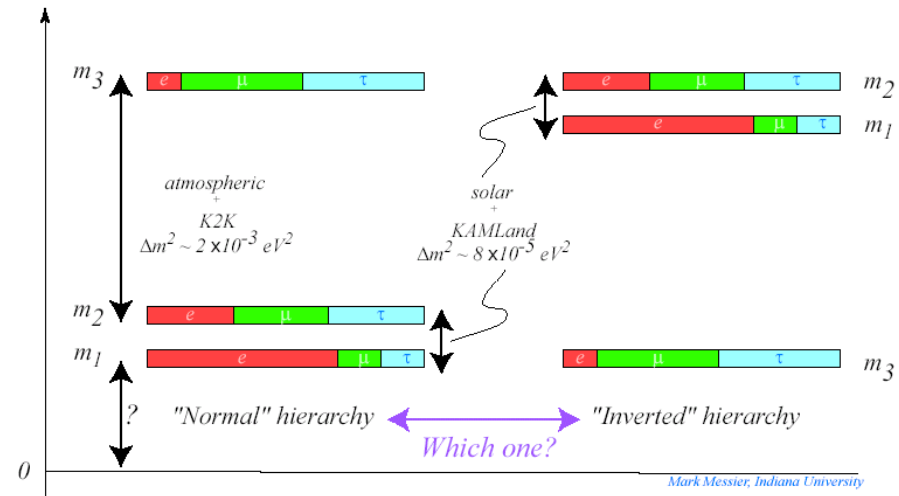
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

link between atmospheric and solar

U parameterization: three mixing angles θ_{12} θ_{23} θ_{13} and CP violating phase δ

two independent m^2

3 families



$$\Delta m_{ij}^2 = m_i^2 - m_j^2, \quad \Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

$$\Delta m_{12}^2 = \Delta m_{sol}^2 = 7.5 \cdot 10^{-5} \text{ eV}^2; \quad \Delta m_{23}^2 \cong \Delta m_{31}^2 \approx 2.4 \cdot 10^{-3} \text{ eV}^2$$

$$\theta_{12} = (34 \pm 1)^\circ; \quad \theta_{13} \approx 45^\circ; \quad \theta_{23} = (9.0 \pm 0.6)^\circ$$