Неуловимите неутрина –

мистерии и загадки

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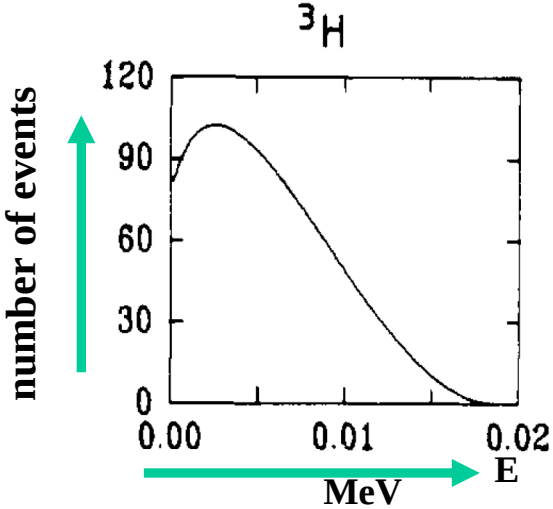
Раждането на идеята за неутрина

Спектър на електроните по енергии при β-разпадане



Писмо на Волфганг Паули от 4.12.1930

1930

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 new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

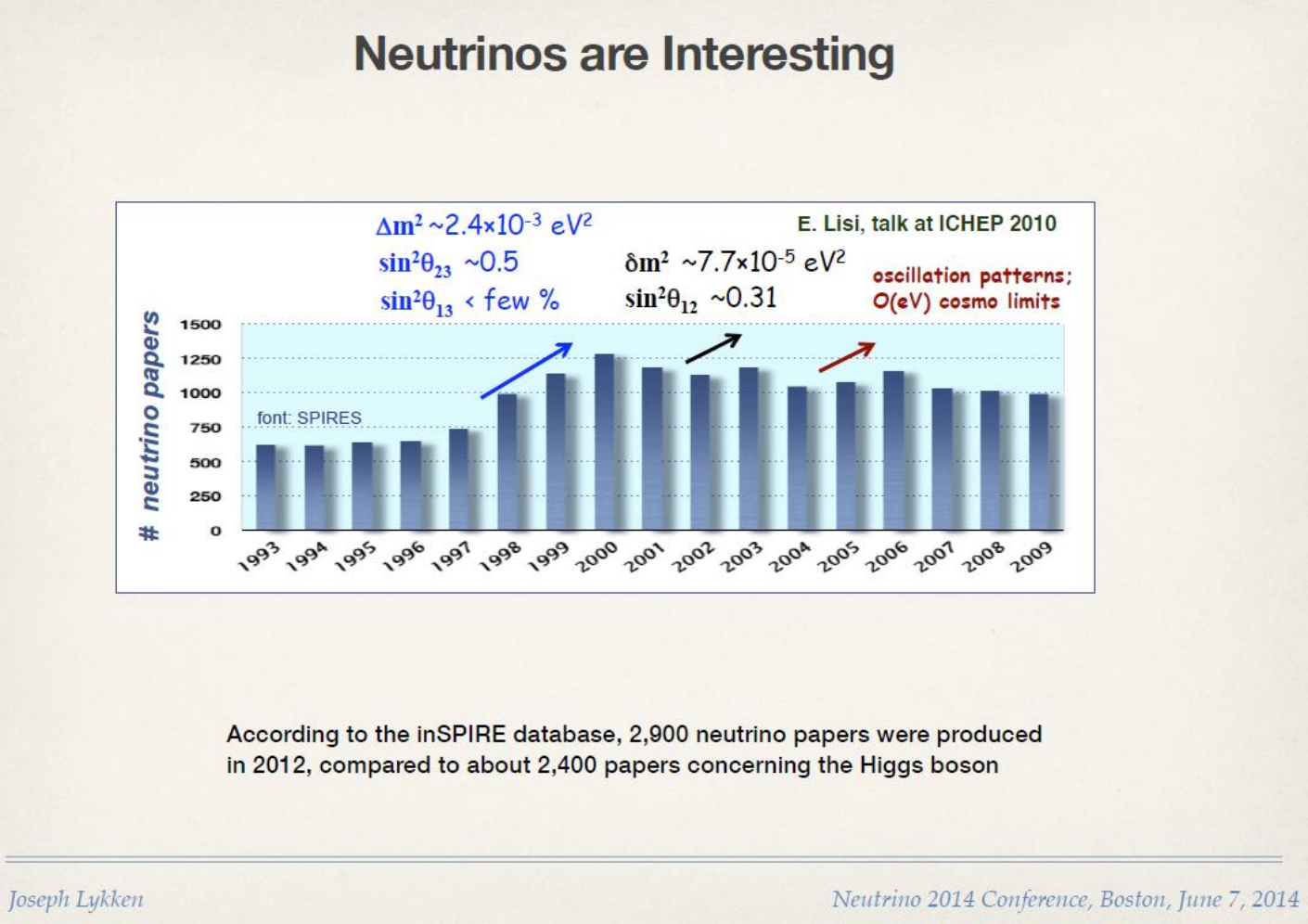
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr. Back.

Your humble servant

W. Pauli

translation: L.M. Brown, Phys. Today, Sept.1978, 23

Какво са неутрината?



♌ - разпадане

♌ - минус

$$^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^{-} + \bar{\nu}_{e}$$

$$^{14}_{6}C_{8} \rightarrow {}^{14}_{7}N_{7} + e^{-} + \bar{\nu}_{e}$$

♌ - плюс

$$^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z-1}Y_{N+1} + e^{+} + \nu_{e}$$

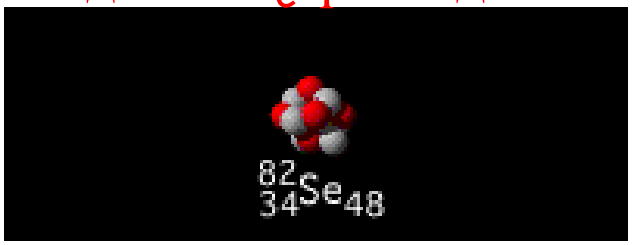
$$^{18}_{9}F_{9} \rightarrow {}^{18}_{8}O_{10} + e^{+} + \nu_{e}$$

електронен захват

$$^{A}_{Z}X_{N} + e^{-} \rightarrow {}^{A}_{Z-1}Y_{N+1} + \nu_{e}$$

$$^{81}_{37}Rb_{44} + e^{-} \rightarrow {}^{81}_{36}Kr_{45} + \nu_{e}$$

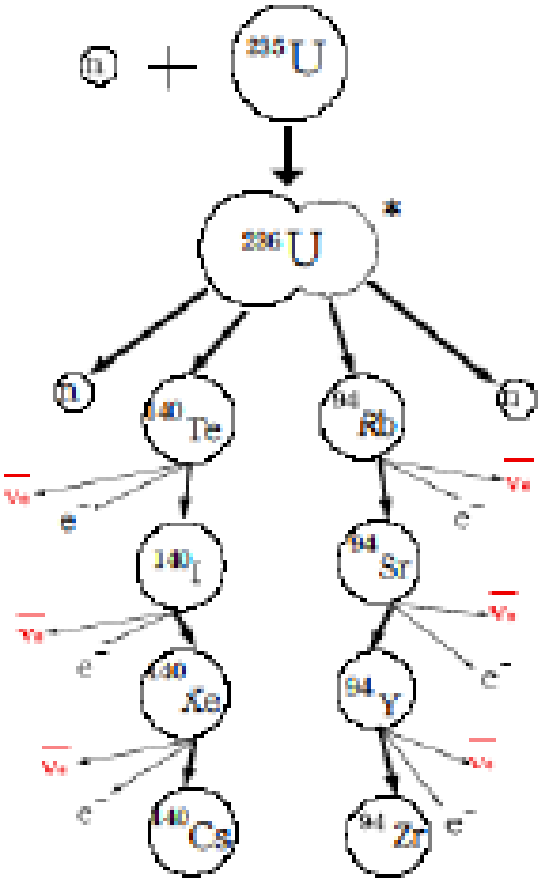
двоен ♌-разпад

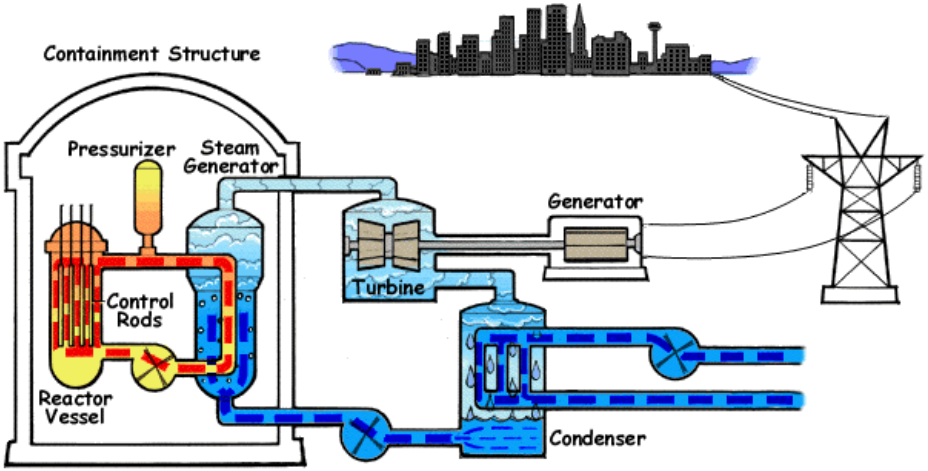


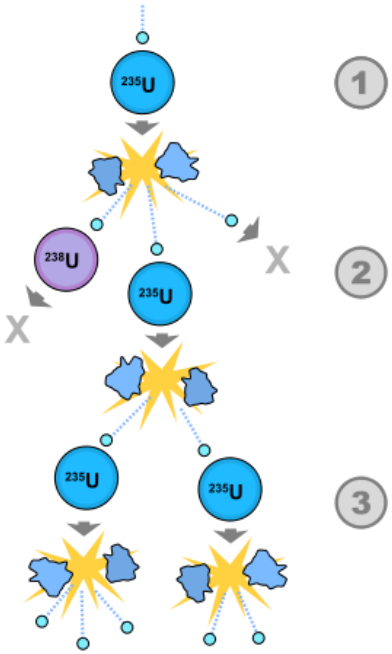
$$^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + 2e^{-} + 2\bar{\nu}_{e}$$

$$^{82}_{36}Se_{48} \rightarrow {}^{82}_{36}Kr_{46} + 2e^{-} + 2\bar{\nu}_{e}$$

Ядреният реактор като източник на (анти)неутрина







~6ν/fission & ~200MeV/fission

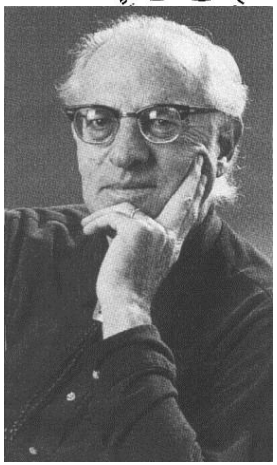
⇓

$\sim 6 \times 10^{20}\, \bar{\nu}_e / s / reactor$ (1GWe)

Reines and Cowan

Пряко регистриране на ν

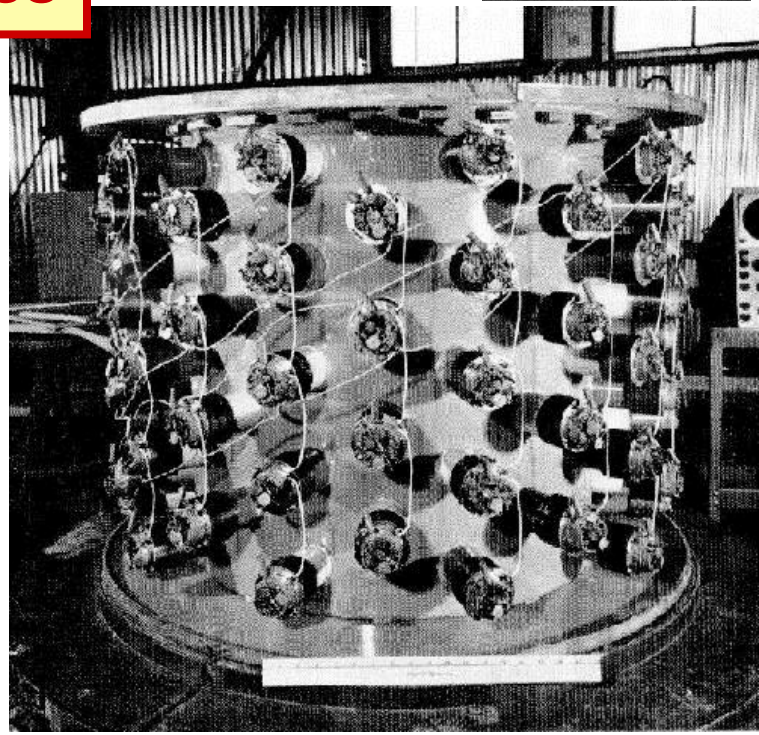
Мишената се състои от 400 *l* вода, в която е разтворен $CdCl_2$



Източник на (анти)неутрина
– ядрен реактор

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

1953



- Позитронът анихилира с електрон от средата и се генерират два едновременни гама-кванта: $e^+ + e^- \rightarrow \gamma\gamma$.
- Неутронът се забавя в средата за около 15 μs и с голяма вероятност се поглъща от Cd ядро, което остава във възбудено състояние. Възбуждането се снема чрез 2 гама-прехода. Регистрирането на всичките 4 фотона чрез 4-кратни задържани съвпадения идентифицира еднозначно реакцията.

Двукомпонентният модел

1956 Незапазване на пространствената четност в β-разпадането на ^{60}Co: излъченият електрон има лява спиралност (C.S. Wu et al.)

1957 Измерване на спиралността на неутриното (M. Goldhaber, L. Grodzins, A.W. Sunyar):
неутрината имат лява спиралност.

поляризацията на γ-квантите се измерва чрез Комптъновото им разсейване от намагнитено желязо

$$e^- + \mathrm{Gd} \rightarrow \nu_e + \mathrm{Sm}^* \downarrow \mathrm{Sm} + \gamma$$

1959 Ray Davis установява, че (анти) неутрината от ядрен реактор не взаимодействат с Cl, за да генерират Ar:

$$n \rightarrow p\ e^-\ \nu_e \text{ or } \bar{\nu}_e\ ?$$

Излъчените при разпадането неутрина не осъществяват реакцията

$$\nu + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-,$$

т.е. те са антинеутрина.

Различни лептонни числа: L_e и L_μ

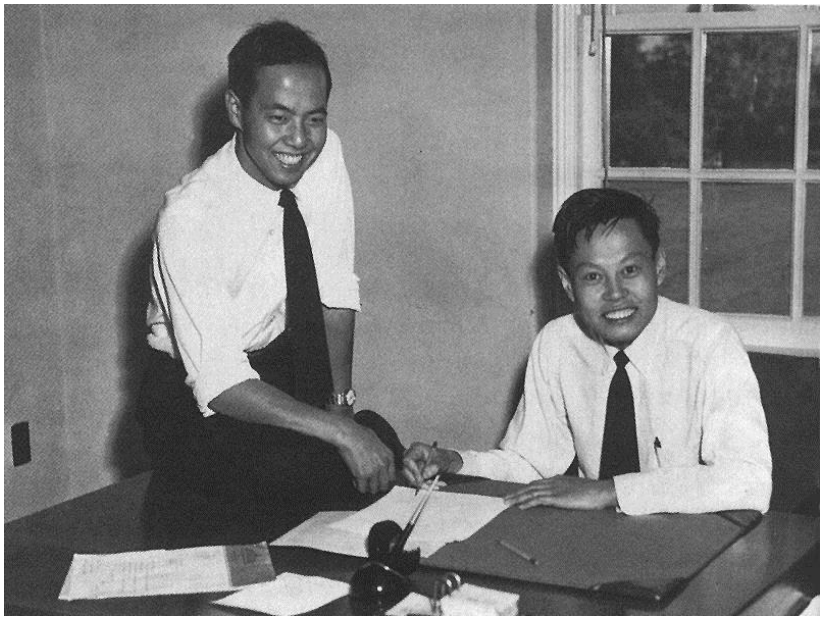
1960

1960 Lee и Yang предполагат, че отсъствието на разпадане от типа

$\mu^- \rightarrow e^- + \gamma$ (BR<5x10^{-13}, *2013*)

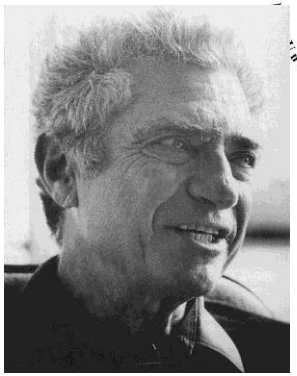
е указание за наличието на 2 типа неутрина: ν_μ и ν_e :

$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$



Chen Ning Lee and Tsung-Dao Yang

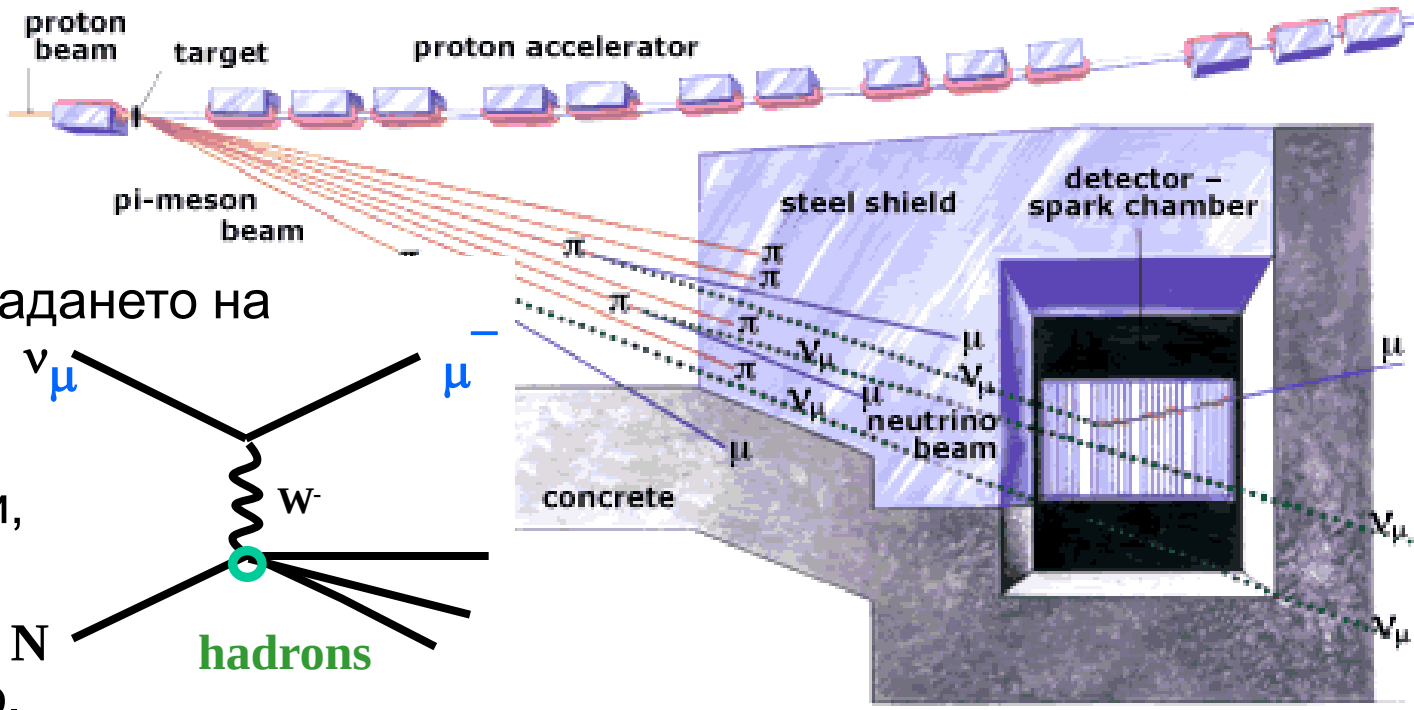
Пряка проверка за наличието на два типа неутрина



Schwartz **Lederman** **Steinberger**

протонен сноп от AGS (33 GeV)

1962



Неутрината от разпадането на пионите:

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

раждат само мюони, но не и електрони, когато взаимодей-стват с веществото.

Третото поколение лептони

***Donut* – пряко регистриране на τ-неутриното**

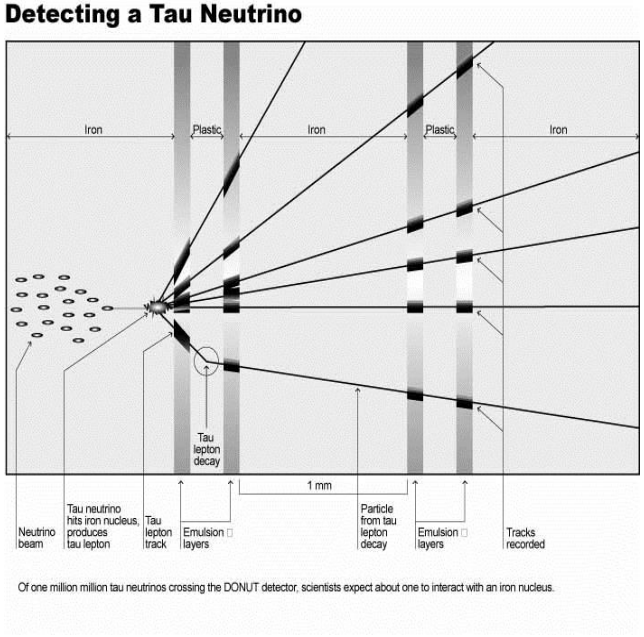
2000

after the tau lepton discovery
everyone assumed the existence of the tau neutrino

M. Perl и сътр., SLAC-LBL, 1974-77, Нобелова награда 1995 г.

1975

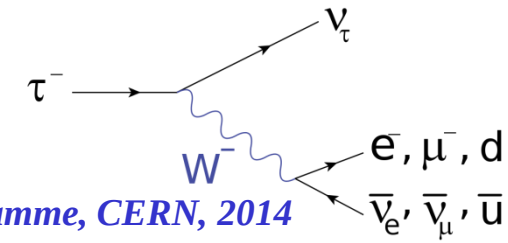
tau lepton
1776.84±0.17 MeV/c^2
2.9×10^{-13} s



Evidence for Anomalous Lepton Production in e+ - e- Annihilation; Physical Review Letters, Vol. 35, Issue 22, 1489-1492; 1975

$$e^+ + e^- \longrightarrow e^\pm + \mu^\mp + \text{ at least 2 undetected particles}$$

$$e^+ + e^- \longrightarrow \tau^+ + \tau^- \longrightarrow e^\pm + \mu^\mp + 4\nu$$



Стандартен модел на фундаменталните полета и взаимодействия

3 *поколе*

чрез обме

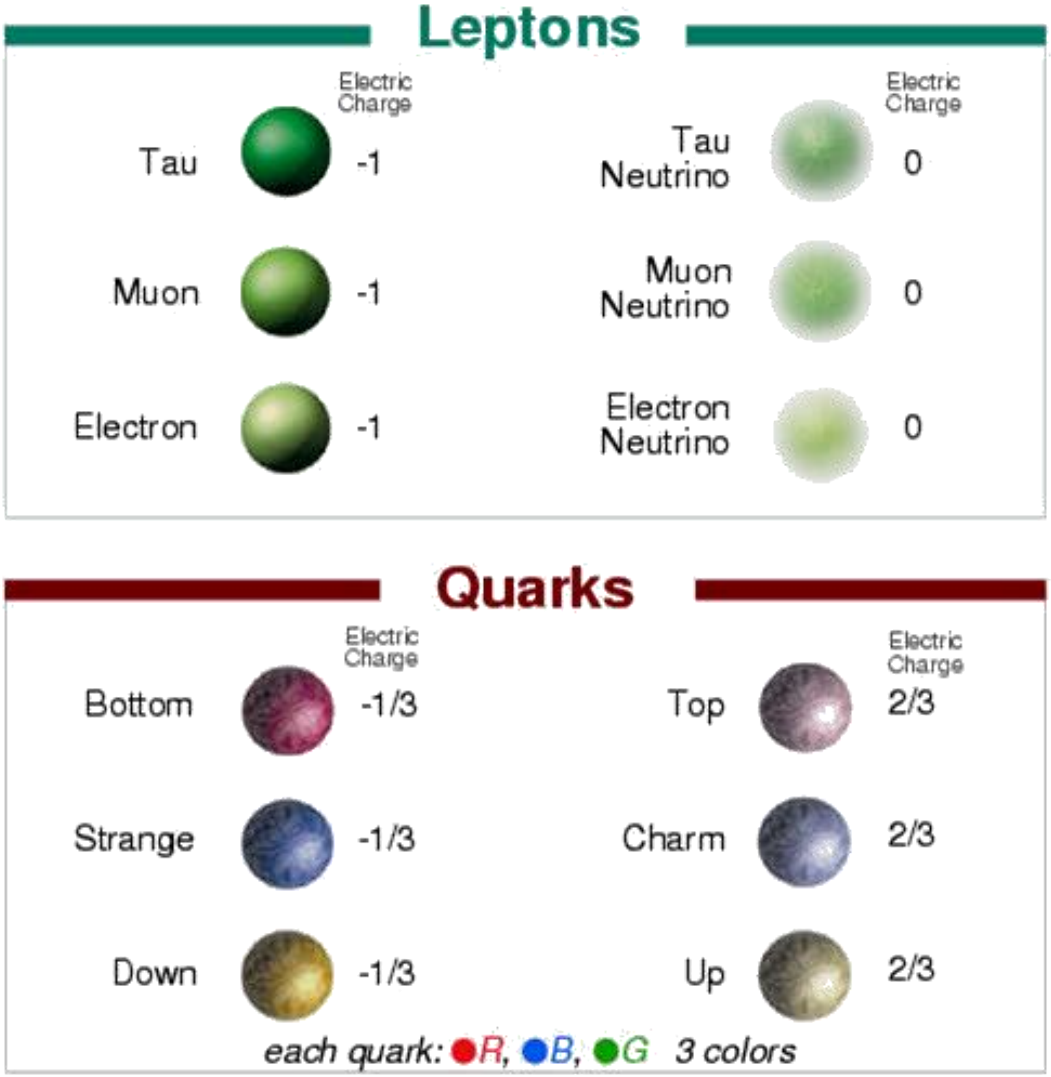
ства щи си

она).

Неутрални лептони (неутрина)

Заредени лептони

Кварки



The particle drawings are simple artistic representations

8 GeV

1.3 GeV

(b)

eV

family

Модел на Glashow-Weinberg-Salam за слабото взаимодействие

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

лептони **кварки**

Неутринните полета са леви и безмасови

$m(\nu_e) \leq 2.3\ eV/c^2$,

$m(\nu_\mu) \leq 0.19\ MeV/c^2$,

$m(\nu_\tau) \leq 18.2\ MeV/c^2$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \qquad \begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$

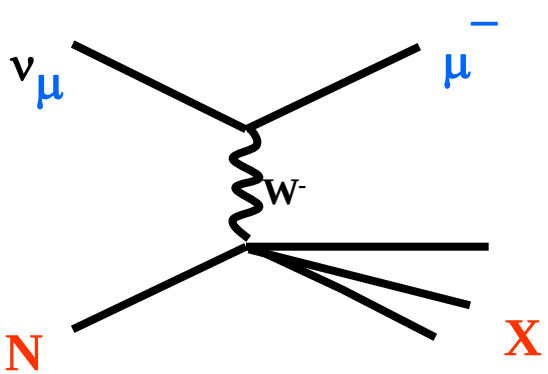
$$u_R \quad d_R \quad s_R \quad c_R \quad b_R \quad t_R \quad e_R \quad \mu_R \quad \tau_R.$$

слабо взаимодействие

$$SU_c(3) \times SU_W(2) \times U_Y(1)$$

Взаимодействие на неутриното с веществото

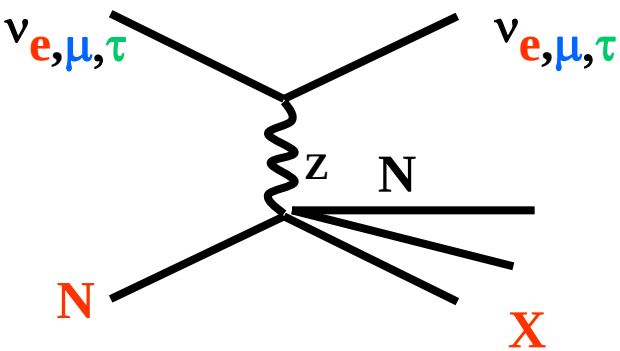
Зареден ток (CC)



$$\nu_\mu + N \rightarrow \mu^- + X$$

$$\tilde{\nu}_\mu + N \rightarrow \mu^+ + X$$

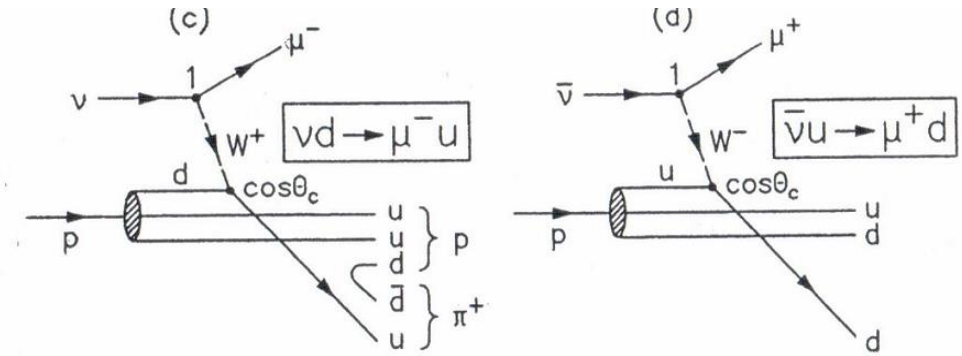
Неутрален ток (NC)



$$\nu_\mu + N \rightarrow \nu_\mu + X$$

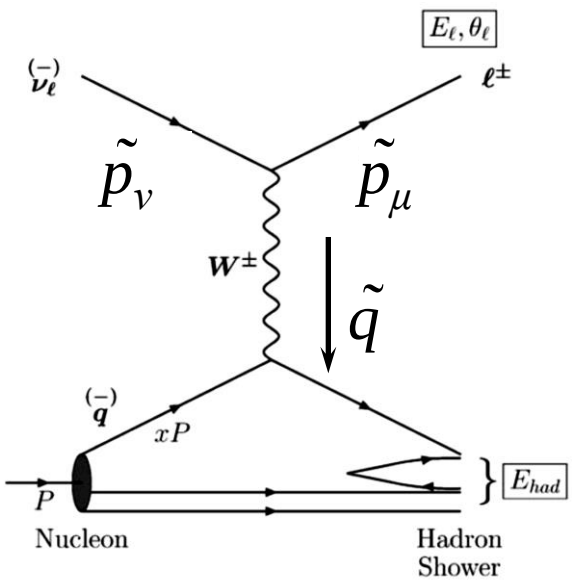
$$\tilde{\nu}_\mu + N \rightarrow \tilde{\nu}_\mu + X$$

Кварк-партонна картина на взаимодействието на неутрината с веществото



$$\nu_\mu + N \rightarrow \mu^- + X$$

$$\tilde{\nu}_\mu + N \rightarrow \mu^+ + X$$

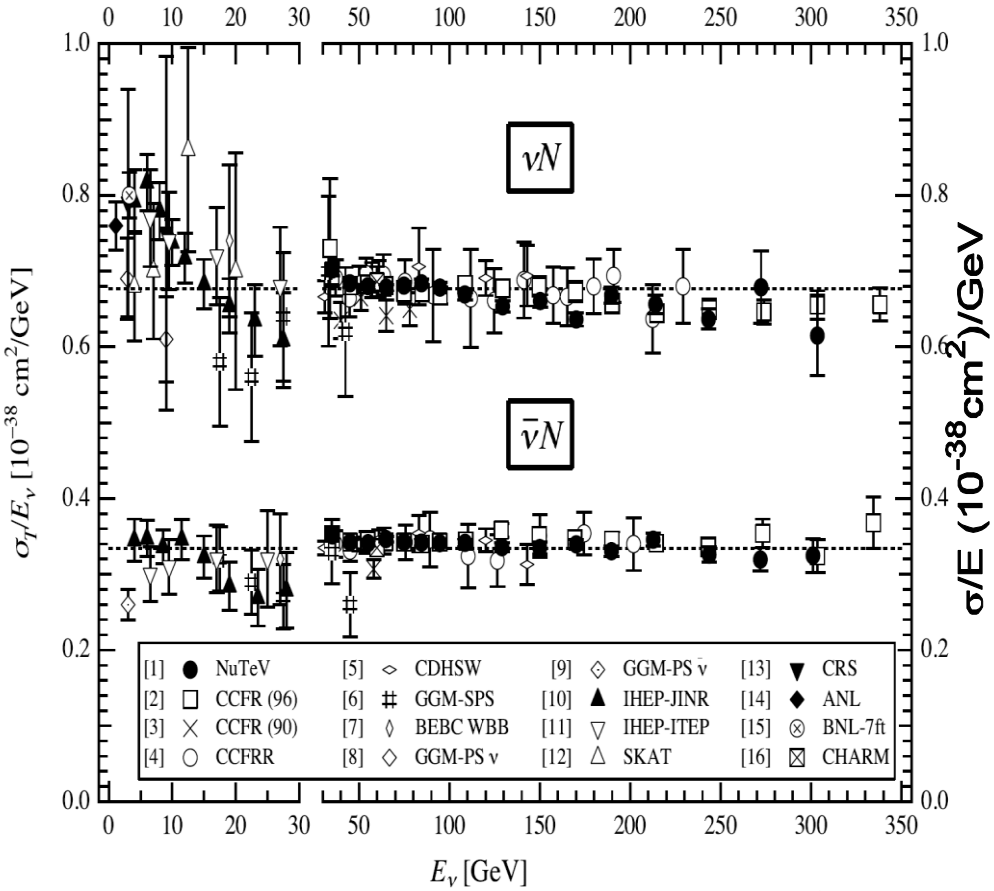


$$\tilde{q}^2 = (\tilde{p}_\nu - \tilde{p}_\mu)^2 = -Q^2 < 0$$

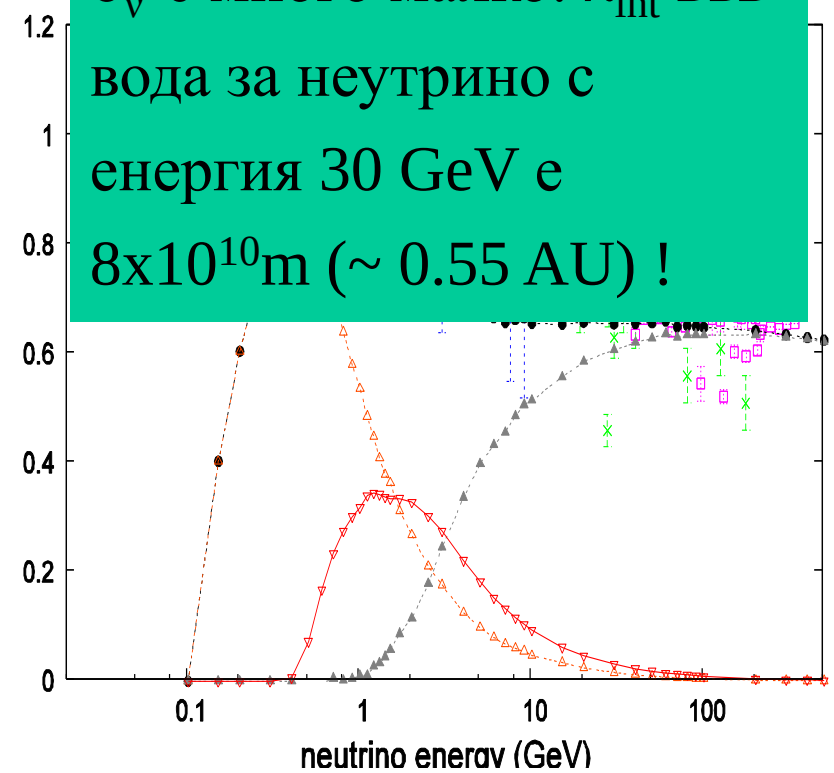
$$\nu = E_\nu - E_\mu = E_{had} - M_N = (\tilde{q}.\,\tilde{p}_{had})/M_N$$

$$x_{Bjorken} = \frac{-\tilde{q}^2}{2\tilde{q}.\tilde{p}_{had}} = \frac{Q^2}{2M\nu}$$

Пълно сечение на CC - взаимодействие на неутриното с веществото



σ_ν е много малко: λ_{int} във вода за неутрино с енергия 30 GeV е $8x10^{10}$m (~ 0.55 AU) !



σ_ν/E_ν = (0.677±0.014)x10^{-38} cm^2/GeV

$\sigma_\nu/E_{anti-\nu}$ = (0.334±0.008)x10^{-38} cm^2/GeV

Осцилации на неутрината

"All the News That's Fit to Print"

The New York

VOL. CXLVII . . . . No. 51,179 Copyright © 1998 The New York Times FRIDAY, JUNE 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos

1 Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

2 . . . and collide with other particles . . .

3 . . . producing a cone-shaped flash of light.

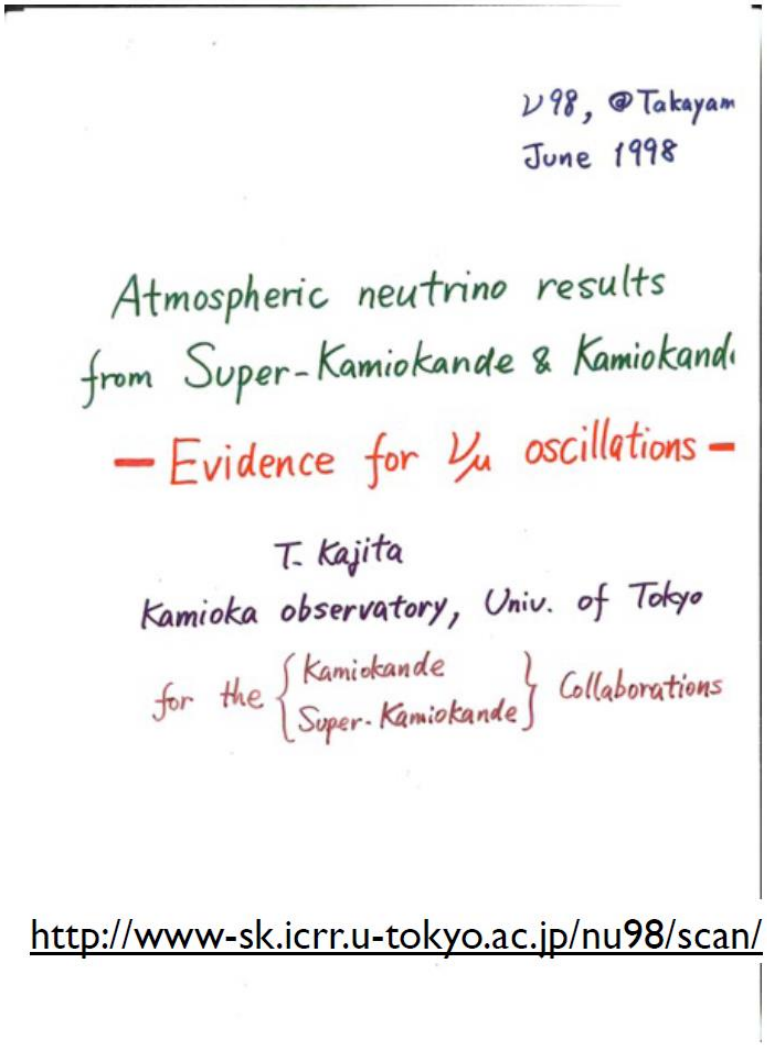
4 The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times



http://www-sk.icrr.u-tokyo.ac.jp/nu98/scan/

ν_e - неутрина от Слънцето

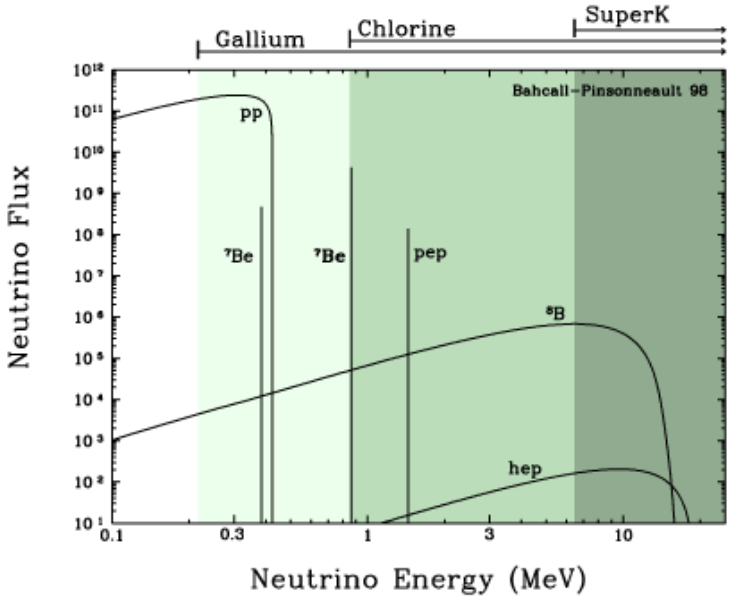
Sun = Fusion reactor;

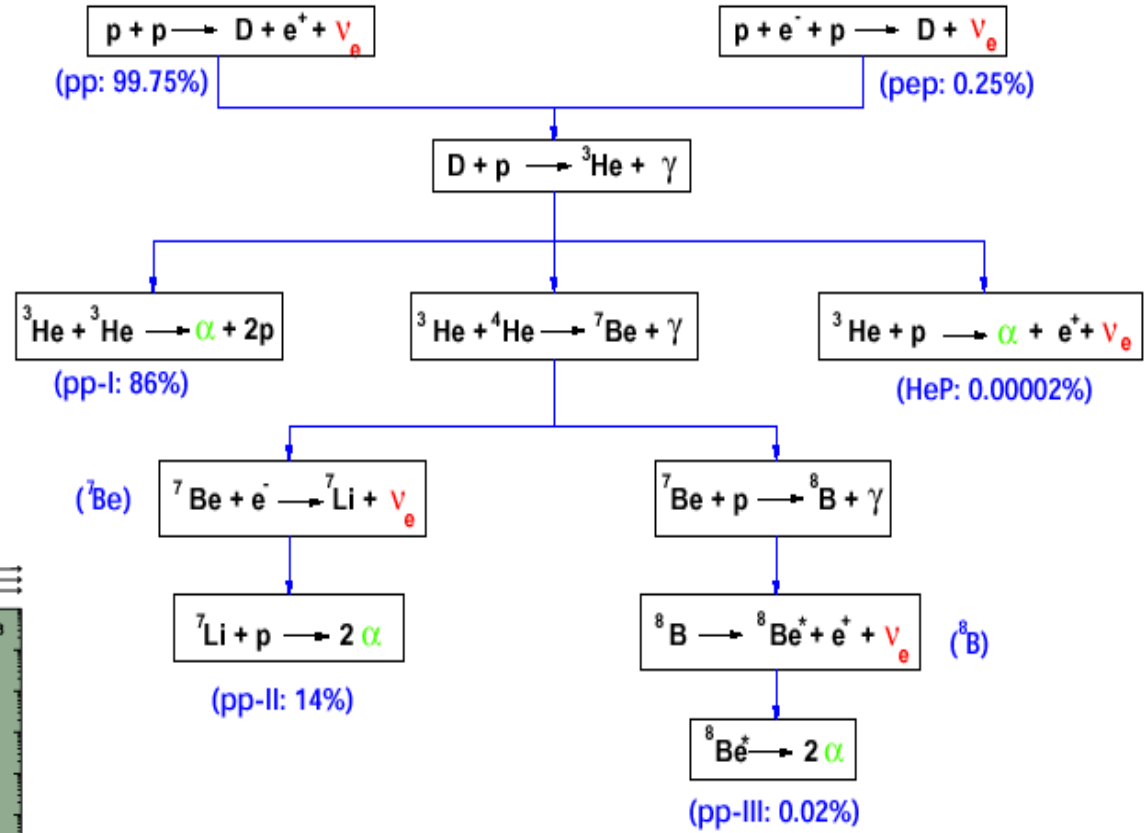
Only ν_e are produced;

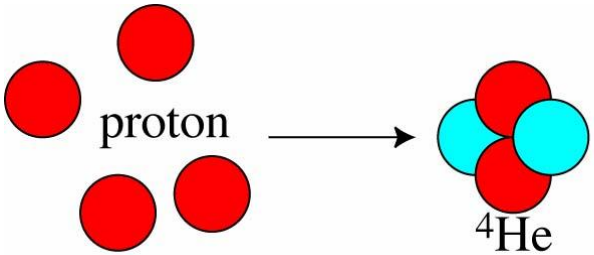
Different reactions ▷

Spectrum in energy

▽







$+ 2e^+ + 2\nu_e + 25\text{MeV}$

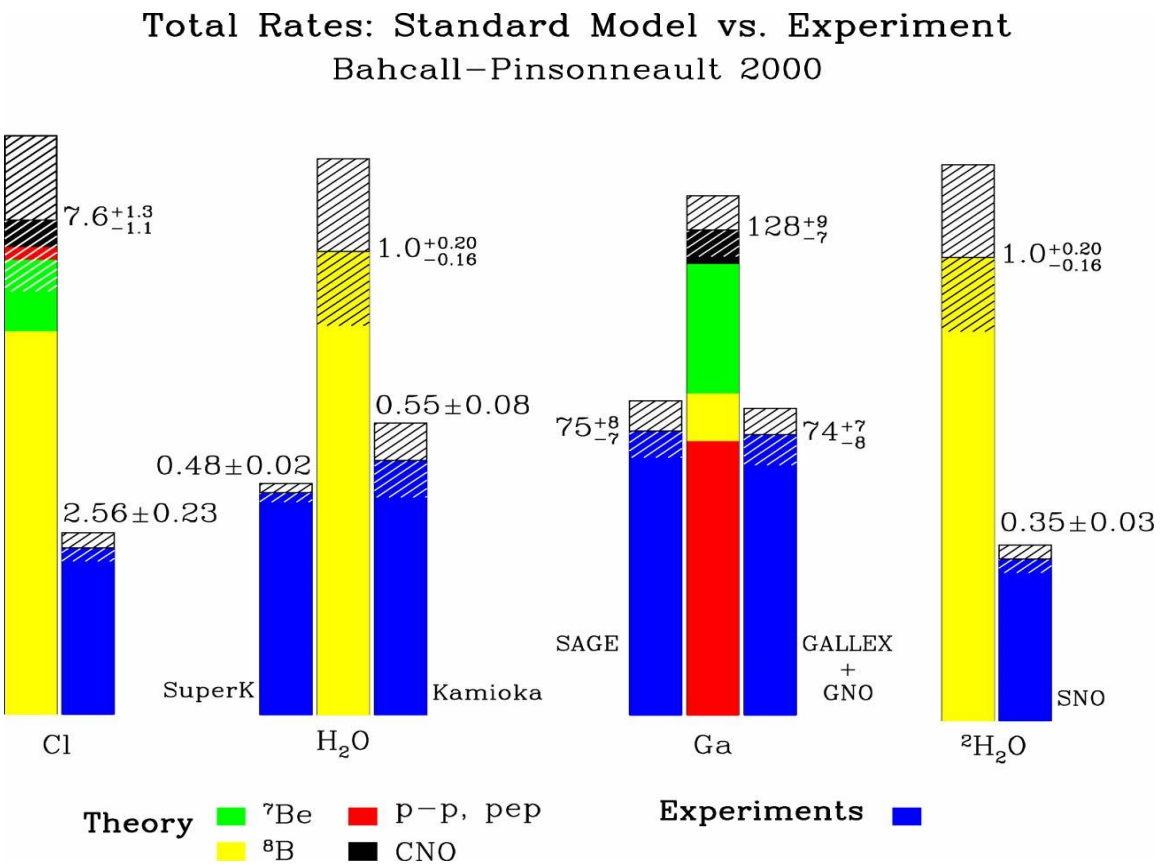
$\langle E_{2\nu} \rangle \sim 0.5$ MeV

Дефицит на електронни неутрина?

$$\Phi_\nu = \frac{2L_{SUN}}{26MeV}\frac{1}{4\pi(1AU)^2} = 6.5\times10^{10}\,s^{-1}cm^{-2}$$

Слънчеви неутрина

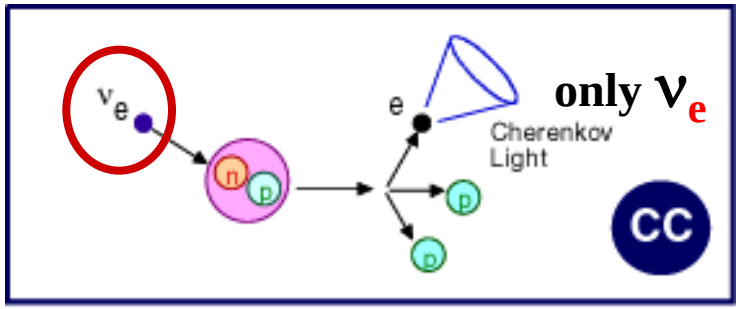
Първите експериментални указания:
Ray Davis, Homestake:
всичко започва около 1968 г.

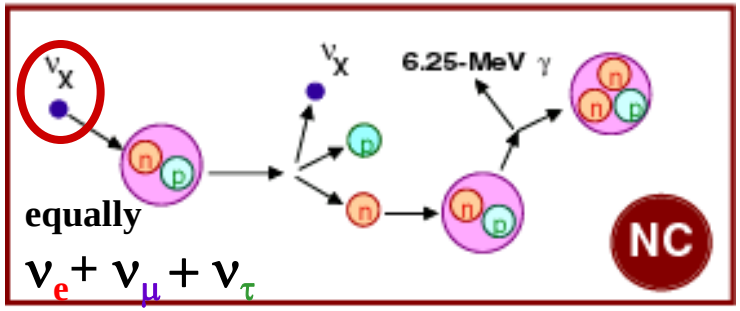


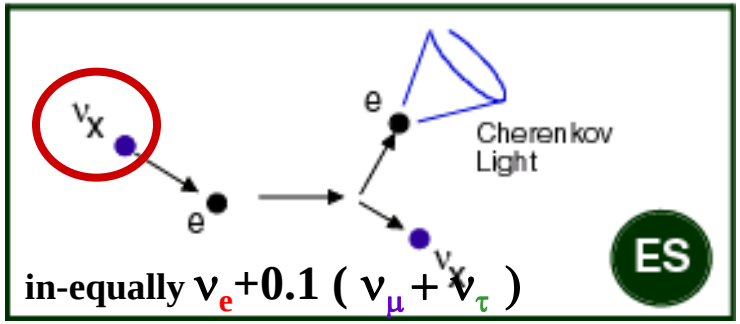
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

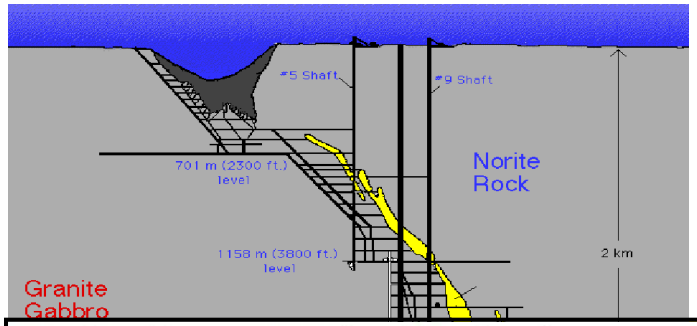
Експеримент SNO
(Sudbury Neutrino Observatory)

Цел: детектиране на мюонни и тау-неутрина в потока слънчеви неутрина









$$\nu_x + e^- \rightarrow \nu_x + e^-$$ (ES)

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

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

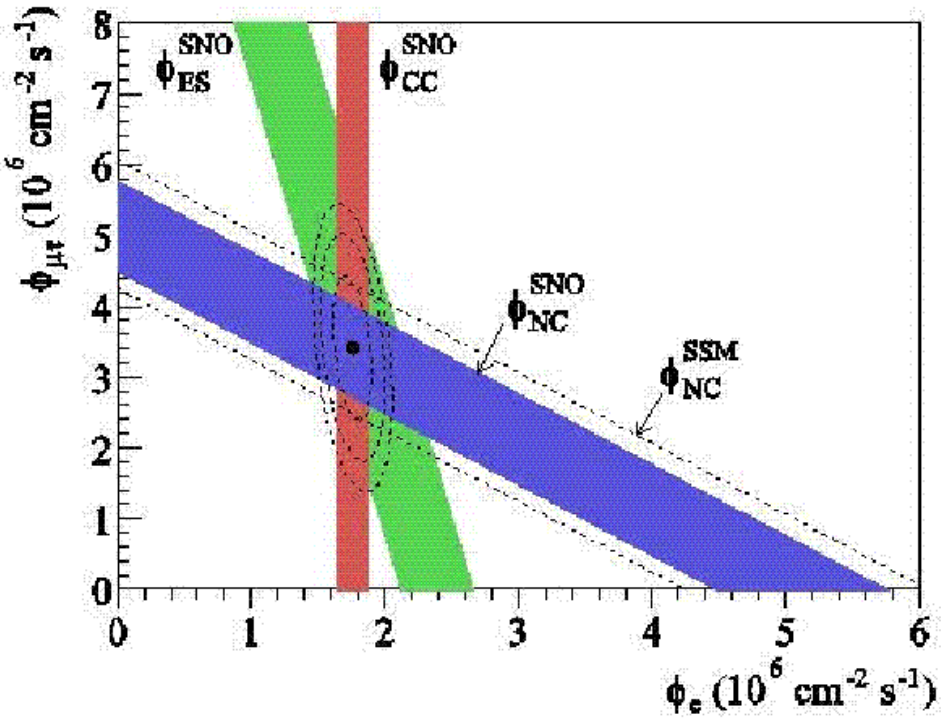
$$n + d \rightarrow t + \gamma + 6.25 \text{ MeV}$$

$$n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6 \text{ MeV}$$

$$n + {}^{3}He \rightarrow p + t + 0.76 \text{ MeV}$$

$$\Phi_{ssm} = 5.05^{+1.01}_{-0.81} \quad \Phi_{sno} = 5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$$

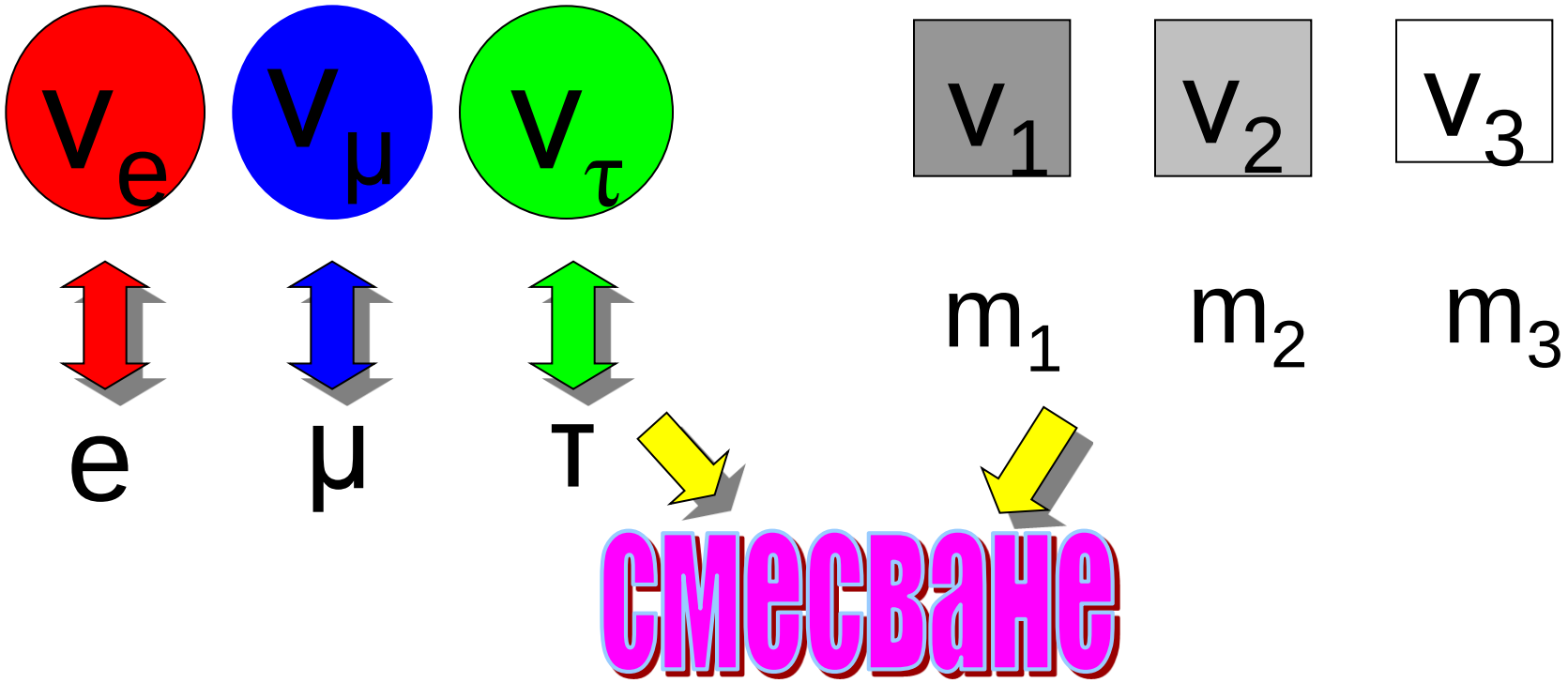
2002



Strong evidence of flavor change

Стандартният модел на Слънцето е правилен. Неутрината изменят типа (аромата) си при пътуването до Земята.

Как това може да се случва?



ароматни състояния ≠ състояния с определена маса

Квантово-механично смесване

(суперпозиция на състоянията)

източник → **разпространение във вакуум или вещество** → **детектор**

L

раждат се състояния с определен аромат

$$|\nu_e\rangle = \alpha\,|\nu_1\rangle + \beta\,|\nu_2\rangle + \gamma\,|\nu_3\rangle$$

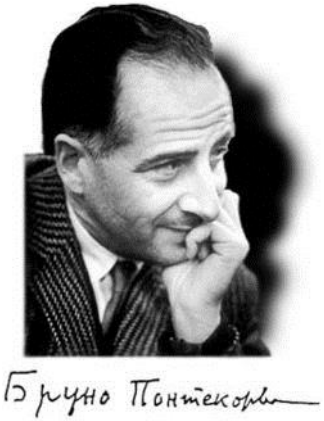
$$t \sim L/E$$

$$|\nu(t)\rangle = \alpha\,|\nu_1\rangle \exp(i E_1 t) + \beta\,|\nu_2\rangle \exp(i E_2 t) + \gamma\,|\nu_3\rangle \exp(i E_3 t)$$

слабо взаимодействие (CC)

$$\nu_e\, N \to e^-\, X$$
$$\nu_\mu\, N \to \mu^-\, X$$
$$\nu_\tau\, N \to \tau^-\, X$$

$$P(e \to \mu) = |\langle \nu_\mu | \nu(t)\rangle|^2$$



Изказана е за пръв път през 1957 г.

Случай с две неутрина: еволюция на състоянията във времето

$$|\nu_1\rangle = |\nu_e\rangle\cos\theta + |\nu_\mu\rangle\sin\theta \Rightarrow eigenvalue \quad m_1^2$$

$$|\nu_2\rangle = -|\nu_e\rangle\sin\theta + |\nu_\mu\rangle\cos\theta \Rightarrow eigenvalue \quad m_2^2$$

$vice\ versa:$

$$|\nu_e\rangle = |\nu_1\rangle\cos\theta - |\nu_2\rangle\sin\theta$$

$$|\nu_\mu\rangle = |\nu_1\rangle\sin\theta + |\nu_2\rangle\cos\theta$$

Състояние, родено в момент *t=0* като ν_e , ще еволюира във времето:

$$|\nu(t)\rangle = |\nu_1\rangle\cos\theta\, e^{-iE_1 t/\hbar} - |\nu_2\rangle\sin\theta\, e^{-iE_2 t/\hbar} \qquad E = pc + \frac{m^2c^3}{2p}$$

$$|\nu(t)\rangle = e^{-i\left(pc + \frac{m_1^2c^3}{2p}\right)\frac{t}{\hbar}}\left(|\nu_1\rangle\cos\theta - |\nu_2\rangle\sin\theta\, e^{-i\frac{(m_2^2 - m_1^2)c^3}{2p}\frac{t}{\hbar}}\right)$$

Появява се фаза между двете масови състояния, пропорционална на разликата в квадратите на масите.

Вероятност за осцилации

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$\Delta m^2 = |m_1^2 - m_2^2|$$

$$(x \equiv L)$$

$$P_{\text{conv}}(x) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E}x\right)$$

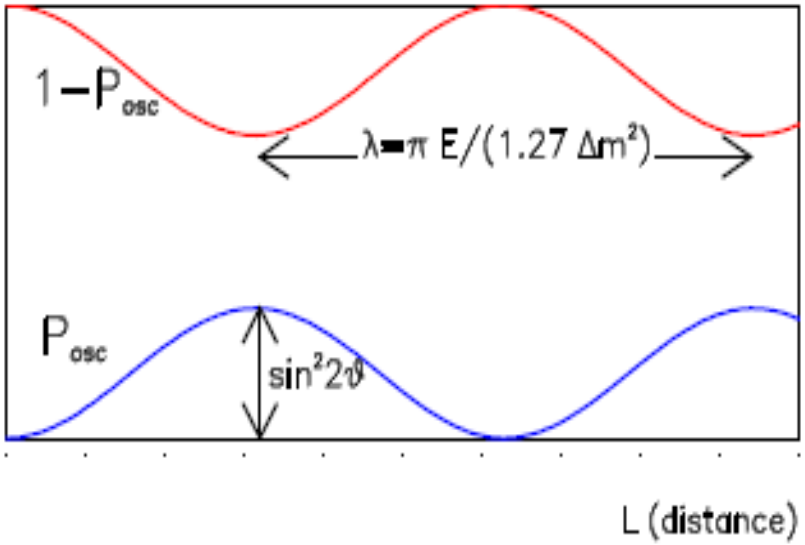
$$P_{\text{surv}}(x) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E}x\right)$$

$$\left(1.27\frac{\Delta m^2(eV^2)}{E(GeV)}x_{\max}(km)\right) \approx \frac{\pi}{2}$$

$\Delta m^2 \sim 10\ ev^2$

$E \sim 10\ GeV$

$x_{max} \sim 1.2\ km$



Случай с три неутринни състояния

$$|\nu_\ell\rangle = \sum_\alpha U_{\ell\alpha}\,|\nu_\alpha\rangle \qquad |\nu_\ell(t)\rangle = \sum_\alpha e^{-iE_\alpha t} U_{\ell\alpha}\,|\nu_\alpha\rangle$$

$$\begin{aligned} P_{\nu_\ell\nu_{\ell'}}(t) &= |\langle\nu_{\ell'}\mid\nu_\ell(t)\rangle|^2 \\ &= \sum_{\alpha,\beta}\left|U_{\ell\alpha}U^*_{\ell'\alpha}U^*_{\ell\beta}U_{\ell'\beta}\right|\cos\left[(E_\alpha - E_\beta)t - \varphi_{\ell\ell'\alpha\beta}\right] \end{aligned}$$

$l = e, \mu, \tau$

$\alpha = 1, 2, 3$

$$\varphi_{\ell\ell'\alpha\beta} = \arg(U_{\ell\alpha}U^*_{\ell'\alpha}U^*_{\ell\beta}U_{\ell'\beta}) \qquad E_\alpha \approx |\boldsymbol{p}| + \frac{m_\alpha^2}{2\,|\boldsymbol{p}|}$$

$$P_{\nu_\ell\nu_{\ell'}}(x) = \sum_{\alpha,\beta}\left|U_{\ell\alpha}U^*_{\ell'\alpha}U^*_{\ell\beta}U_{\ell'\beta}\right|\cos\left(\frac{2\pi x}{L_{\alpha\beta}} - \varphi_{\ell\ell'\alpha\beta}\right)$$

$$L_{\alpha\beta} \equiv \frac{4\pi E}{\Delta m^2_{\alpha\beta}}$$

U – PMNS матрица на смесването

Матрица на Pontecorvo-Maki-Nakagawa-Sakata

$$P\left[\nu_\mu(\overline{\nu_\mu}) \to \nu_e(\overline{\nu_e})\right] = \sin^2 2\theta_{13} s_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \frac{1}{2} s_{12}^2 \sin^2 2\theta_{13} s_{23}^2 \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right)$$

$$+ 2 J_r \cos\delta \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \mp 4 J_r \sin\delta \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$\pm \cos 2\theta_{13} \sin^2 2\theta_{13} s_{23}^2 \left(\frac{4Ea(x)}{\Delta m_{31}^2}\right) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

$$\mp \frac{a(x)L}{2} \sin^2 2\theta_{13} \cos 2\theta_{13} s_{23}^2 \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta m_{21}^2 L}{4E}\right)^2$$

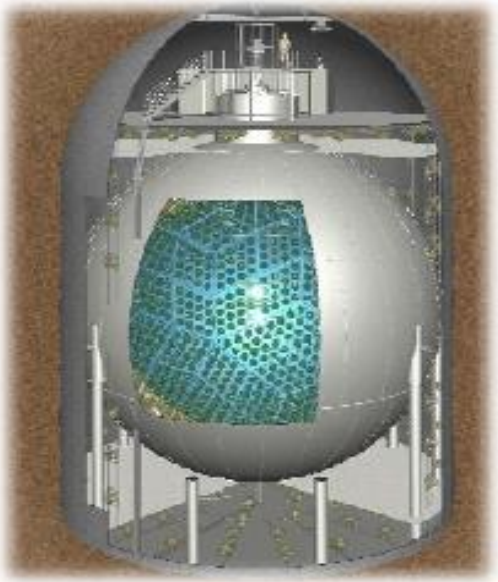
$$a(x) = \sqrt{2} G_F N_e(x)$$

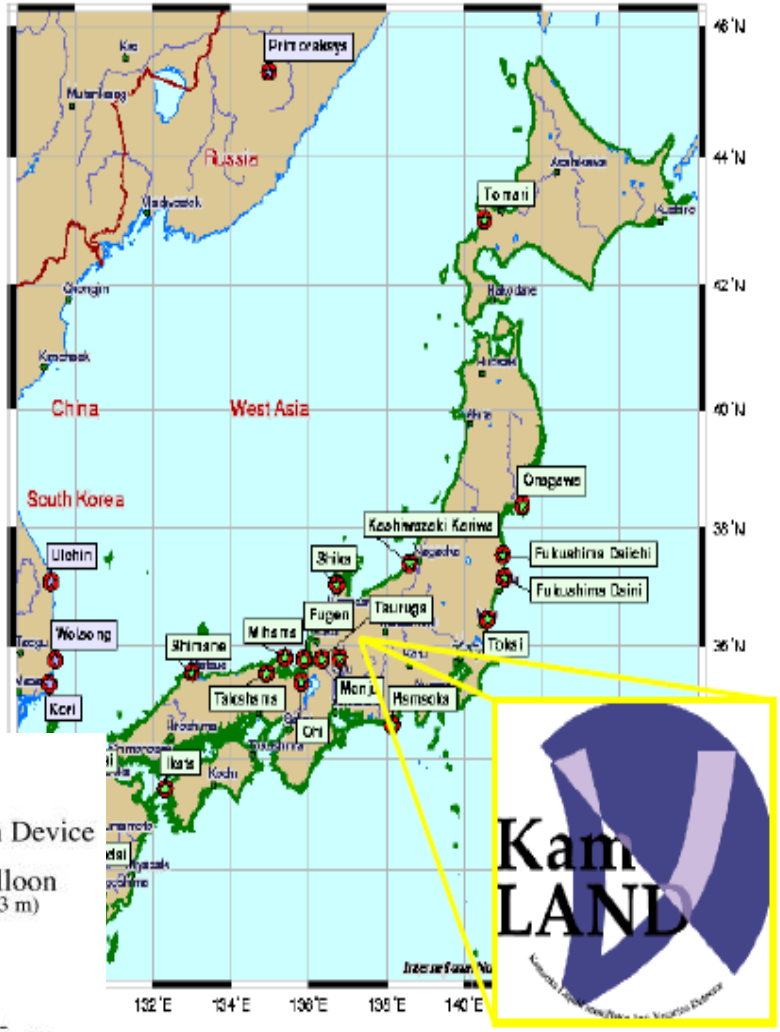
$$J_r \equiv c_{12} s_{12} c_{13}^2 s_{13} c_{23} s_{23}$$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

състояния: $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$ където $\alpha = e, \mu, \tau$ и $i = 1,2,3$

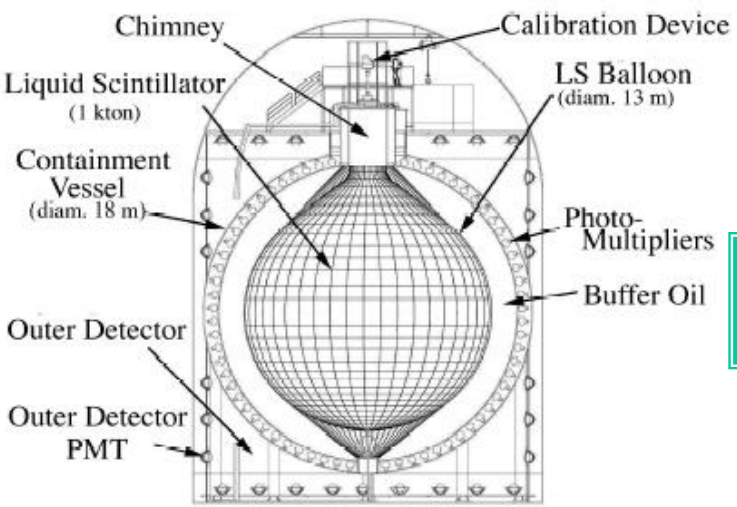
1 kton scintillator detector





Kamioka Liquid-scintillator Anti-Neutrino Detector

A long-baseline, neutrino oscillation experiment measuring the flux and energy spectrum of electron anti-neutrinos from near-by nuclear power reactors.



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Electron anti-neutrino disappearance, E-distortion

Reactor Neutrino Source

Site	Distance (km)	# of cores	P(ther.) (GW)	flux ($\bar{\nu}$ cm^{-2}s^{-1})	Signal ($\bar{\nu}$/yr)
Japan					
Kashiwazaki	160.0	7	24.6	4.25×10^5	348.1
Ohi	179.5	4	13.7	1.88×10^5	154.0
Takahama	190.6	4	10.2	1.24×10^5	101.8
Hamaoka	214.0	4	10.6	1.03×10^5	84.1
Tsuruga	138.6	2	4.5	1.03×10^5	84.7
Shiga	80.6	1	1.6	1.08×10^5	88.8
Mihama	145.4	3	4.9	1.03×10^5	84.5
Fukushima-1	344.0	6	14.2	5.3×10^4	43.5
Fukushima-2	344.0	4	13.2	4.9×10^4	40.3
Tokai-II	294.6	1	3.3	1.7×10^4	13.7
Shimane	414.0	2	3.8	9.9×10^3	8.1
Onagawa	430.2	2	4.8	9.8×10^3	8.1
Ikata	561.2	3	6.0	8.4×10^3	6.9
Genkai	755.4	4	6.7	5.3×10^3	4.3
Sendai	824.1	2	3.3	3.5×10^3	2.8
Tomari	783.5	2	5.3	2.4×10^3	2.0
Korea					
Ulchin	~750	4	11.2	8.8×10^3	7.2
Wolsong	~690	4	8.1	7.5×10^3	5.2
Yonggwang	~940	6	16.8	8.4×10^3	6.9
Kori	~700	4	8.9	8.0×10^3	6.6
Total		69	175.7	1.34×10^6	1102

Total expected signal from reactors: (~80% duty factor) ≈ 2 events/day

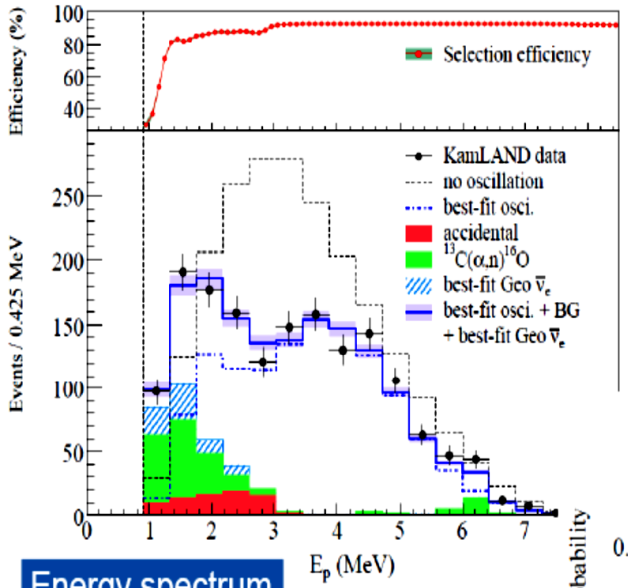
Baseline is limited: 85.3% of signal has 140 km < L < 344 km

Average baseline distance <L>~ 190 km

68 GWe power
4% world's manmade power
20% world's nuclear power

KamLAND reactor data 2008

P. Decowski, talk @Nu2008
kamLAND collab. arXiv0801.4589



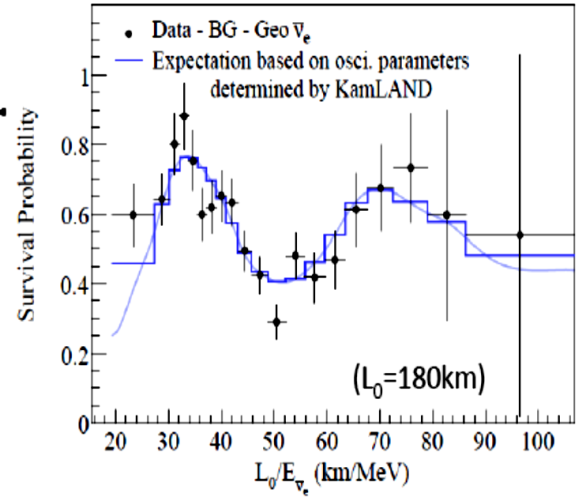
Energy spectrum

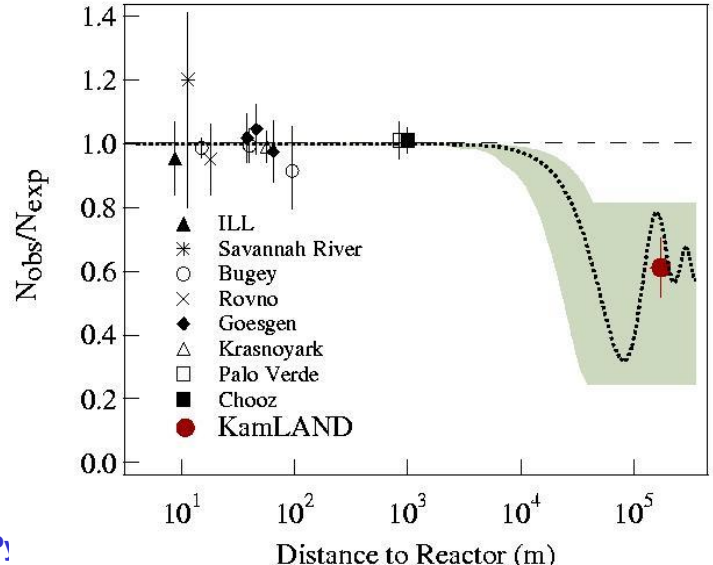
OR ...

L/E plot

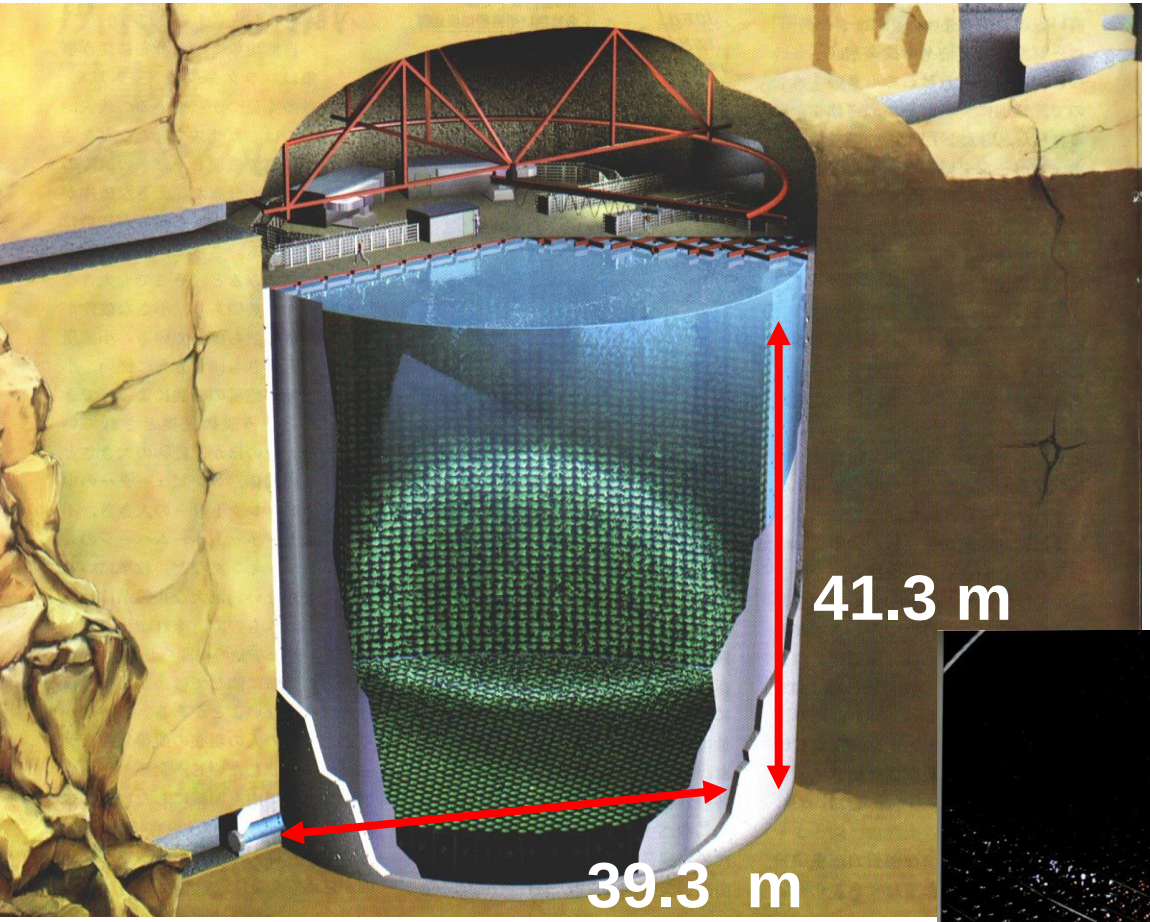
$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5} eV^2$$

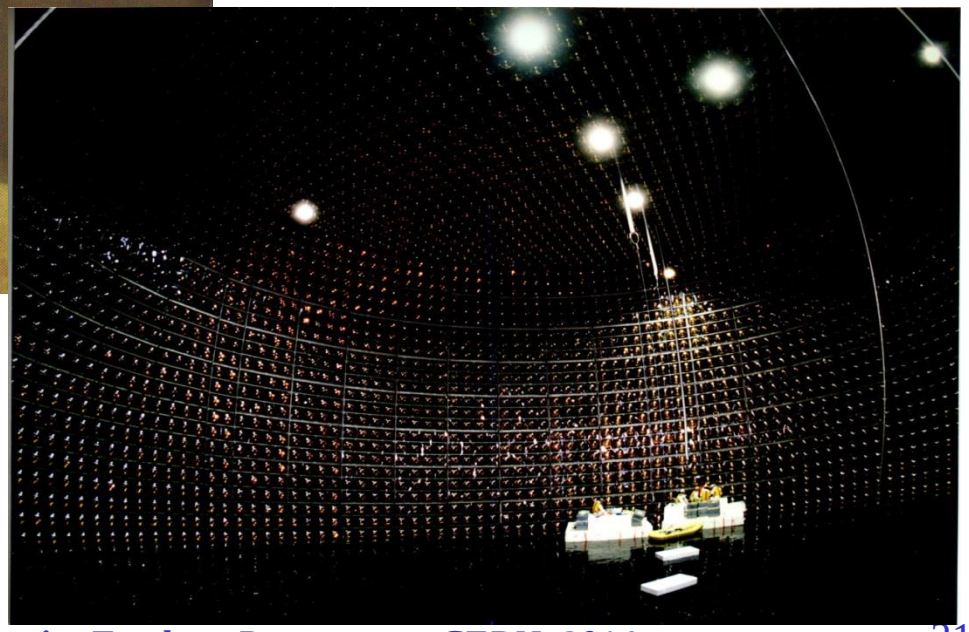
$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$





Super-KamiokaNDE





Воден Черенковски детектор

~50 хил. т. чиста вода

~10 хил. ФЕУ

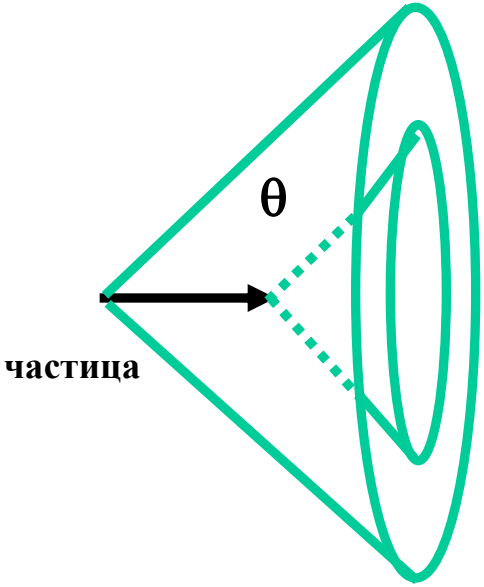
Ефект на Черенков

Скорост на светлината във водата: **c/n**

n коефициент на пречупване =1,33

Светлинни фотони се излъчват по образуващите на конус с ъгъл при върха

$$\cos\theta = 1/(\beta n)$$

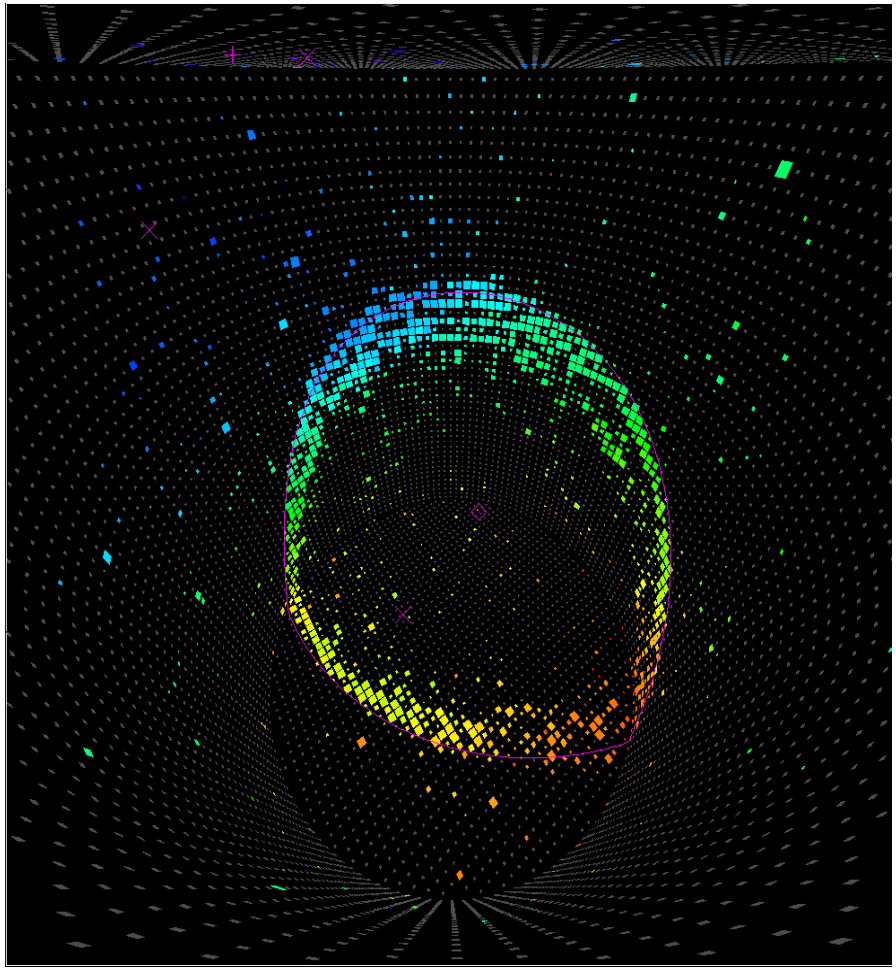


➔ **При достигането до стените на детектора се получават светлинни пръстени**

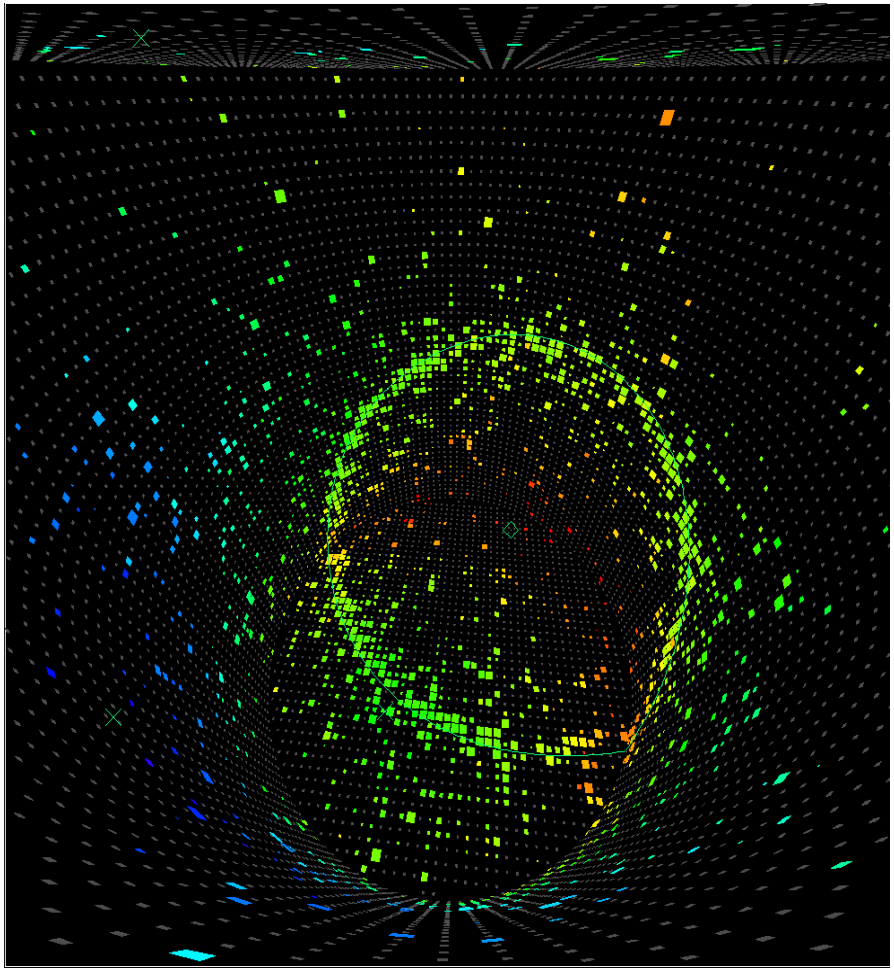
Мюони → пръстени с резки граници

Електрони/позитрони → пръстени с размити граници поради възникването на ЕМ каскад

μ/e различаване



μ – like event



e-like event

Резултати от експериментите, регистриращи слънчеви неутрина (Neutrino 2014)

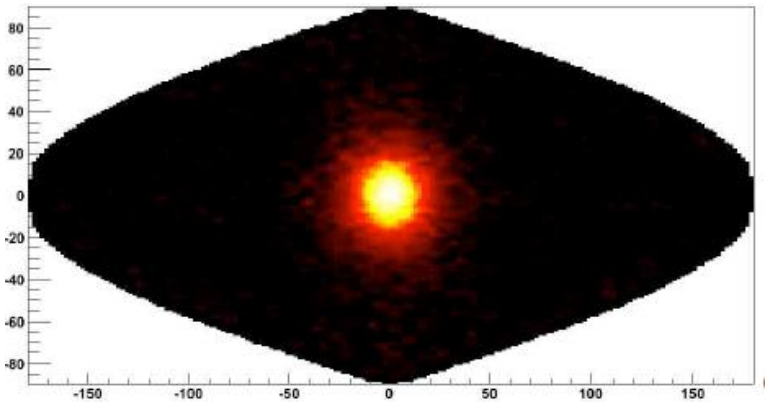
Data set for global solar analysis

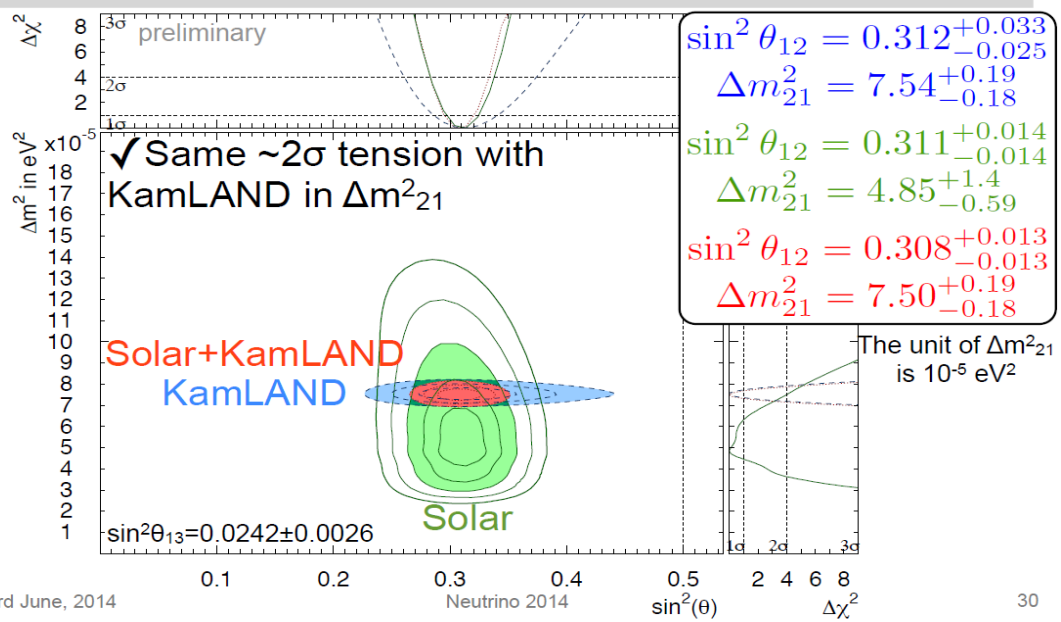
The most up-to-date data are used

- ✓ **SK:**
  - **SK-I 1496 days, spectrum 4.5-19.5 MeV(kin.)+D/N:E_{kin}>4.5 MeV**
  - **SK-II 791 days, spectrum 6.5-19.5 MeV(kin.)+D/N: E_{kin}>7.0 MeV**
  - **SK-III 548 days, spectrum 4.0-19.5 MeV(kin.)+D/N: E_{kin}>4.5 MeV**
  - **SK-IV 1669 days, spectrum 3.5-19.5 MeV(kin.)+D/N: E_{kin}>4.5 MeV**
- ✓ **SNO:**
  - **Parameterized analysis (c_0, c_1, c_2, a_0, a_1) of all SNO phased. (PRC88, 025501 (2013))**

  (Note: the same method is applied to both SK and SNO with a_0 and a_1 to LMA expectation.)
- ✓ **Radiochemical: Cl, Ga**
  - **Ga rate: 66.1±3.1 SNU (All Ga global) (PRC80, 015807 (2009))**
  - **Cl rate: 2.56±0.23 SNU(Astrophys. J.496, 505 (1998))**
- ✓ **Borexino: Latest ^{7}Be flux (PRL 107, 141302 (2011))**
- ✓ **KamLAND reactor : Latest (3-flavor) analysis (PRD88, 3, 033001 (2013))**
- ✓ **^{8}B spectrum: Winter 2006 (PRC73, 73, 025503 (2006))**
- ✓ **^{8}B and hep flux free, if not mentioned.**

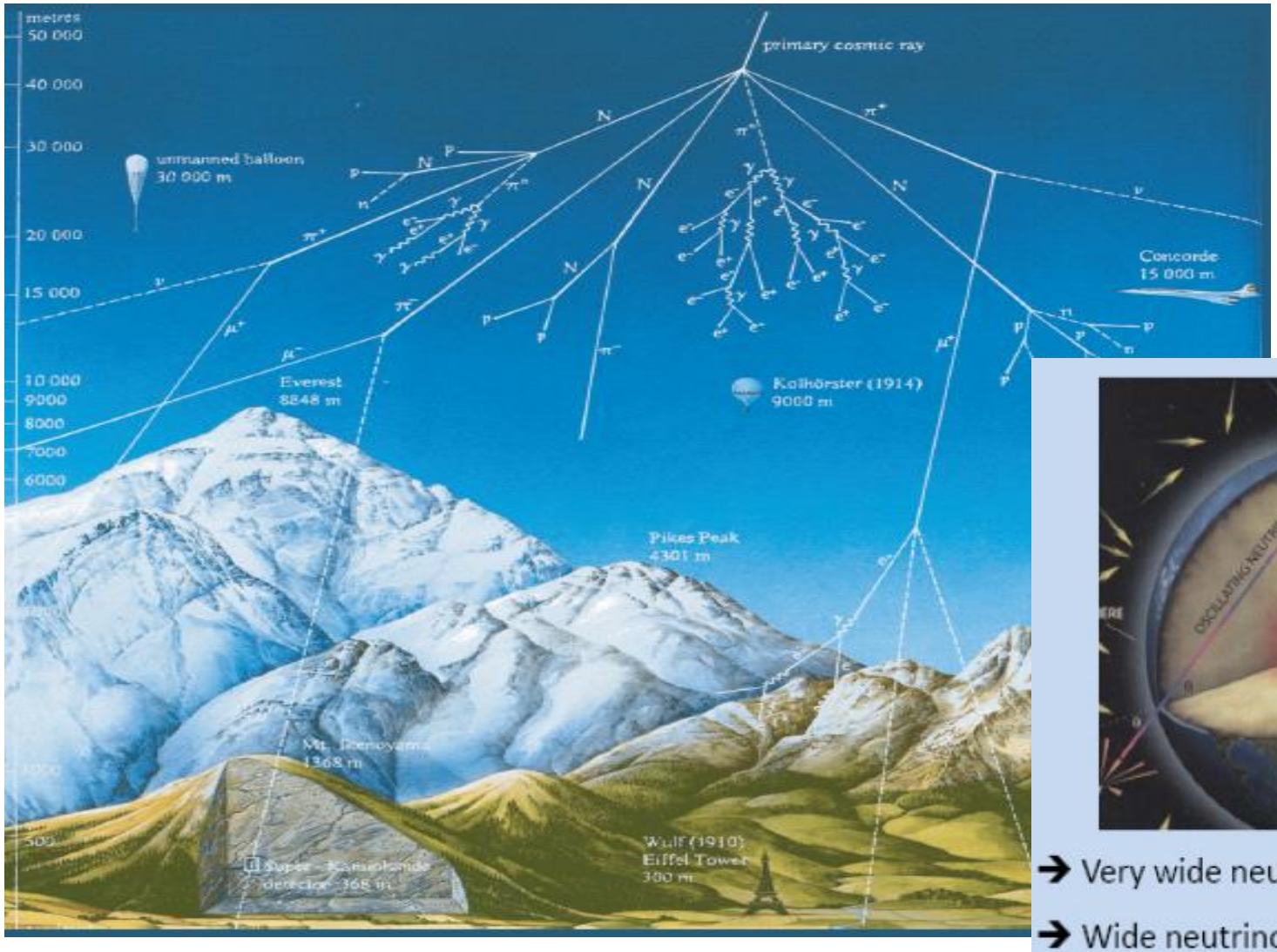
3rd June, 2014 Neutrino 2014

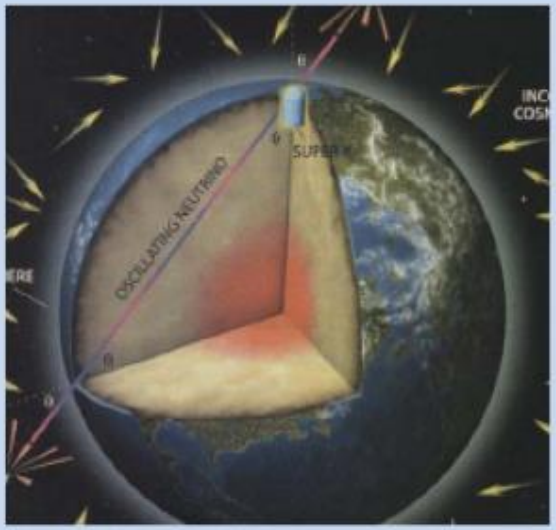




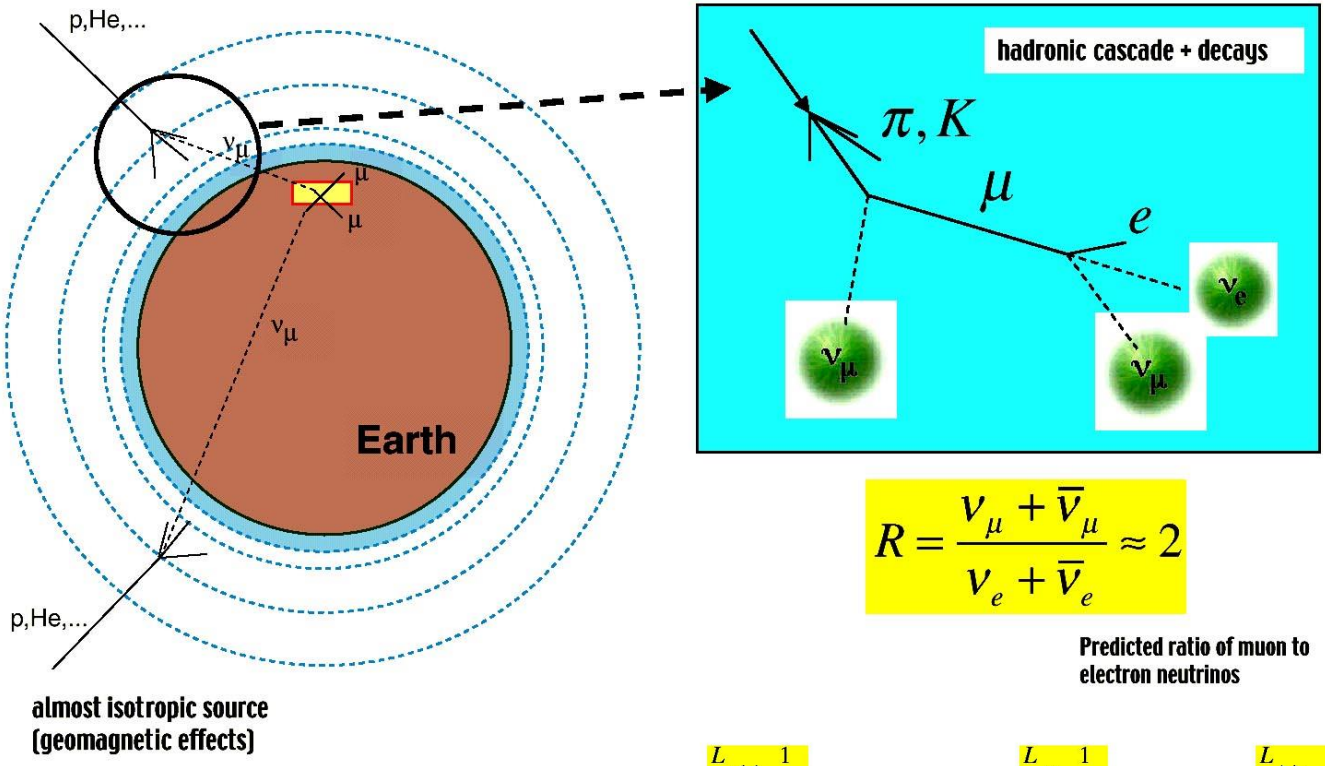
3rd June, 2014 Neutrino 2014 30

Атмосферни неутрина



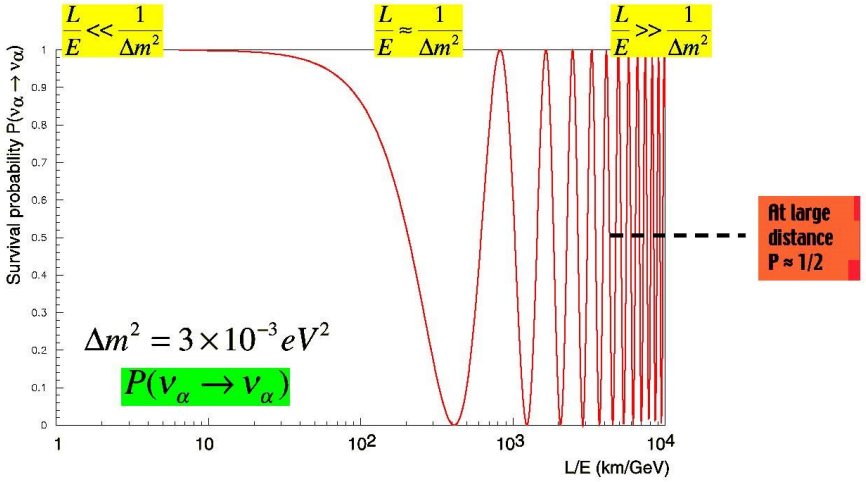


- Very wide neutrino flight length
- Wide neutrino energy
- Mixture of ν_μ, anti-ν_μ, ν_e and anti-ν_e



$$R = \frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

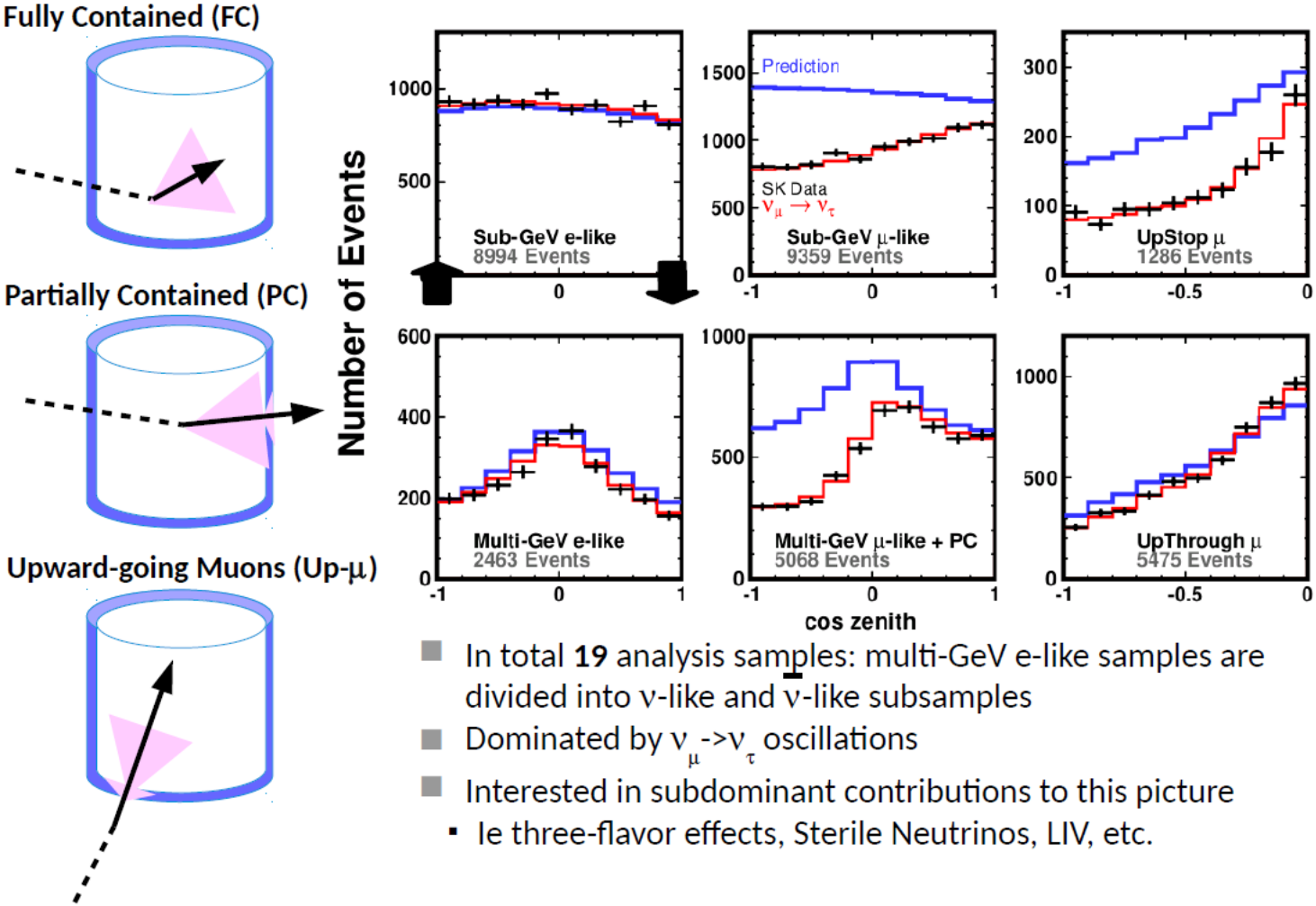
Predicted ratio of muon to electron neutrinos



Прелетно разстояние от ~20km до ~12700 km

Neutrino 2014

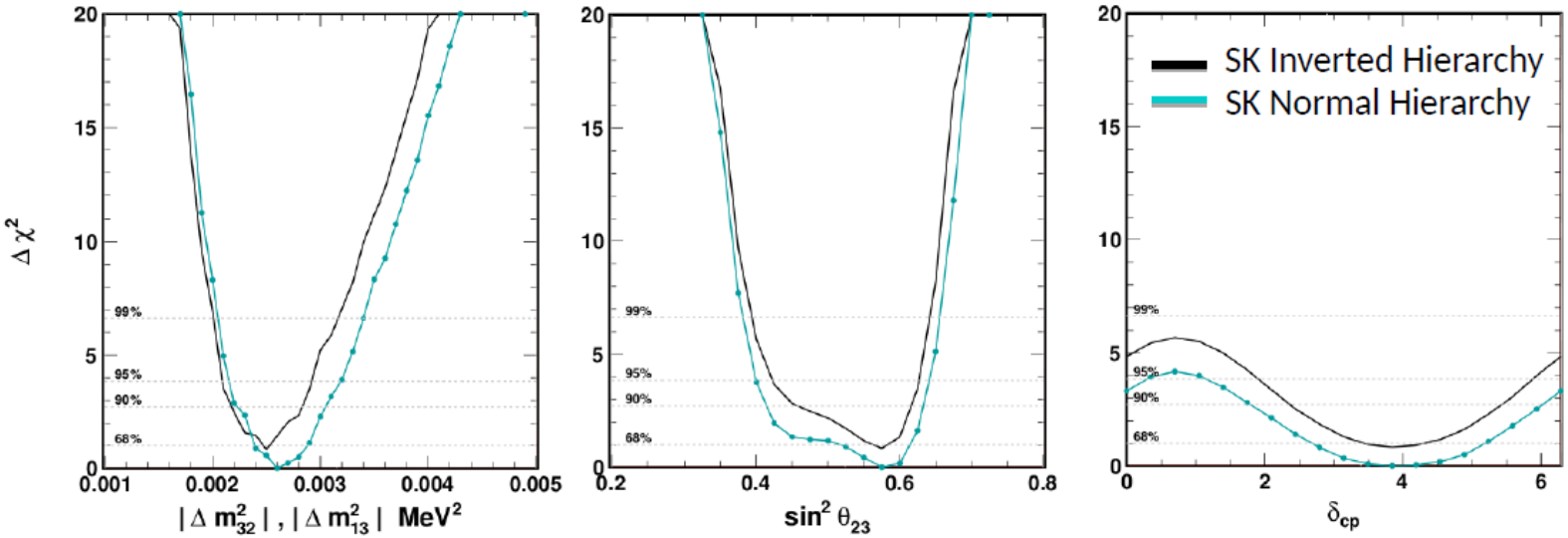
Super-K Atmospheric ν Analysis Samples



- In total **19** analysis samples: multi-GeV e-like samples are divided into ν-like and $\bar{\nu}$-like subsamples
- Dominated by $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Interested in subdominant contributions to this picture
  - Ie three-flavor effects, Sterile Neutrinos, LIV, etc.

Neutrino 2014

θ_{13} Fixed Analysis (NH+IH) SK Only



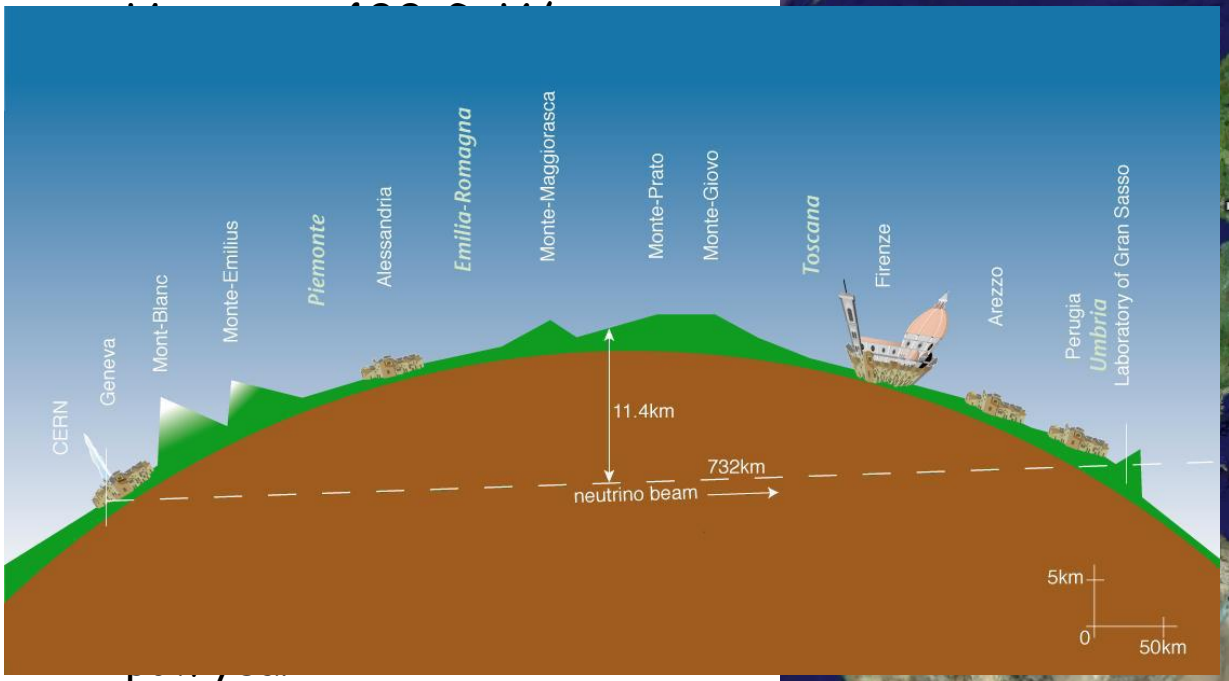
Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} (x10^{-3})
SK (NH)	559.8	0.025	3.84	0.57	2.6
SK (IH)	560.7	0.025	3.84	0.57	2.5

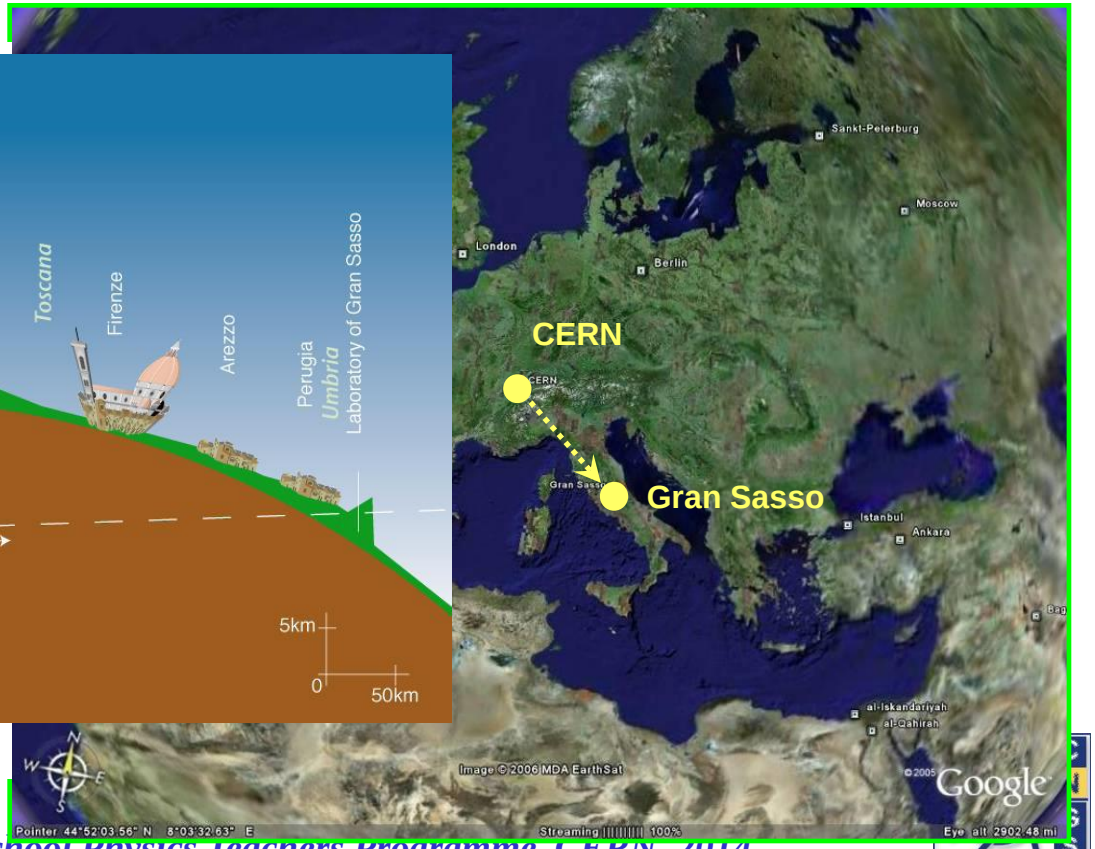
- θ_{13} fixed to PDG average, but its uncertainty is included as a systematic error
- Offset in these curves shows the difference in the hierarchies

Неутрина от CERN към Gran Sasso

- Търсена на $\nu_\mu - \nu_\tau$ осцилации
- 732 km прелетно разстояние
  - Ъгъл на снопа спрямо хиризонта 5.9°
  - Детектор: OPERA 146000 „емилсионни" тухлички (1.21 kton), Icarus 600 tons
- Набира данни 2007-2012 г.

CNGS – протонен сноп





Формиране на снопа на CNGS

Helium bags Decay tube Hadron stop Muon detectors

Ta

Proton beam

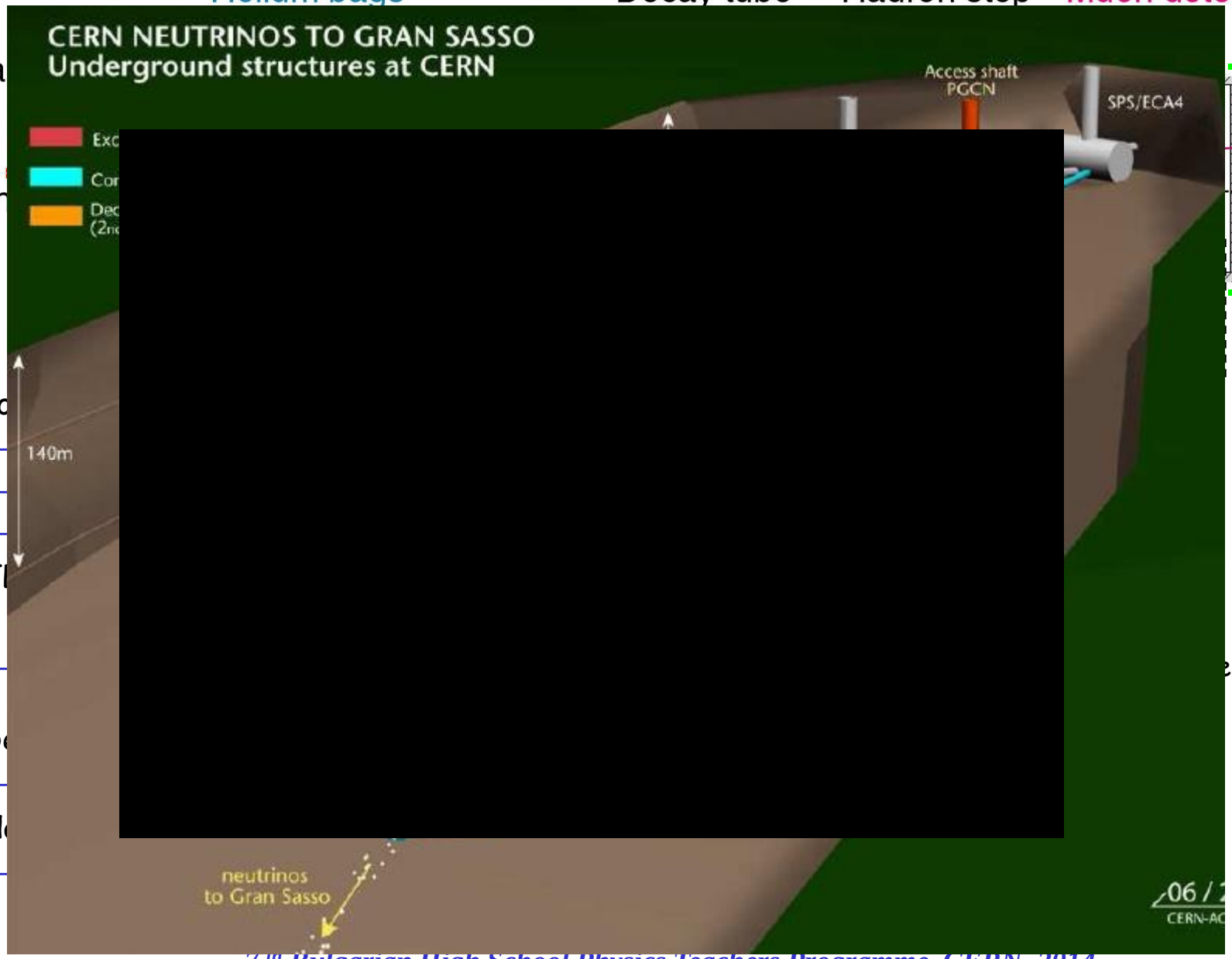
Air co

- Th
- 2

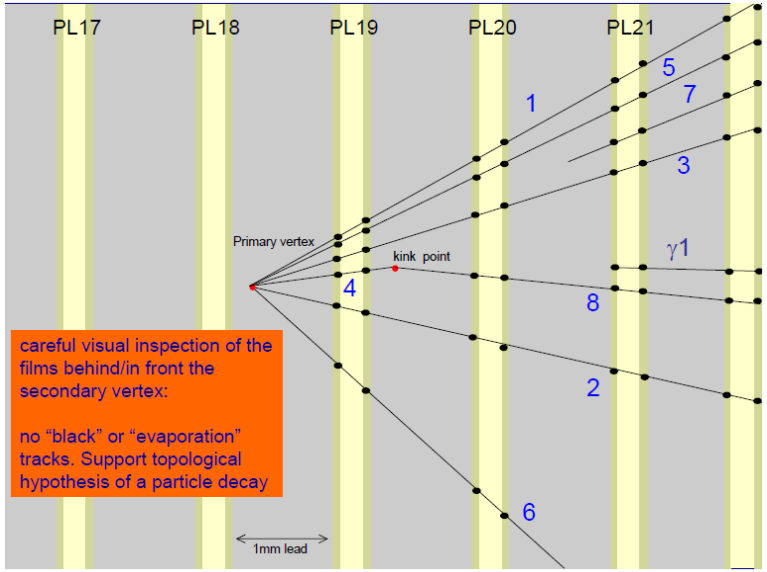
- De

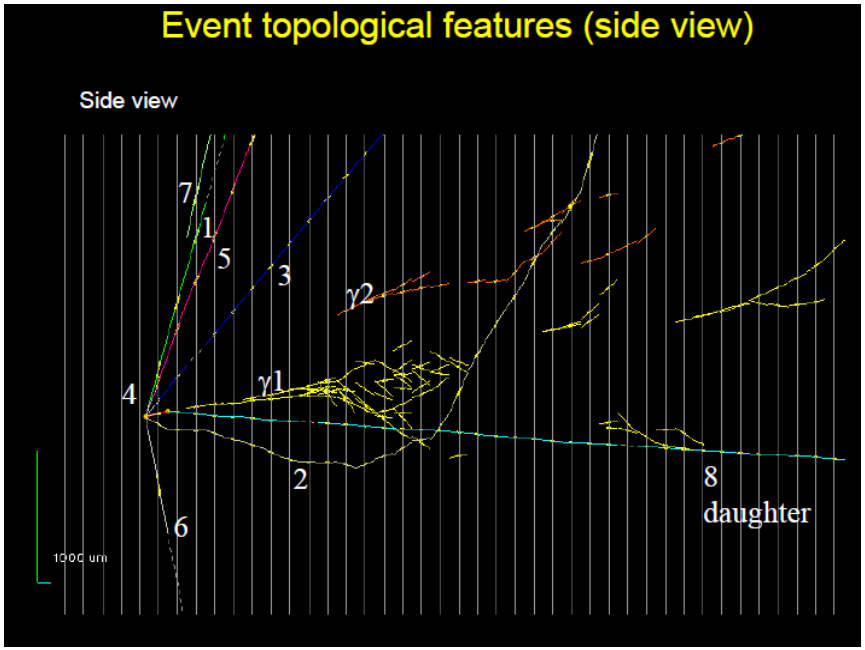
- He

- 2



Първото събитие с раждане на τ-лептон





By considering the 1-prong hadron channel only, the probability to observe 1 event due to a background fluctuation is 1.8%, for a statistical significance of 2.36 σ on the measurement of a first ν_τ candidate event in OPERA.

If one considers all τ decay modes which were included in the search, the probability to observe 1 event for a background fluctuation is 4.5%.
This corresponds to a significance of 2.01 σ.

OPERA collaboration Neutrino 2010 (Athens)

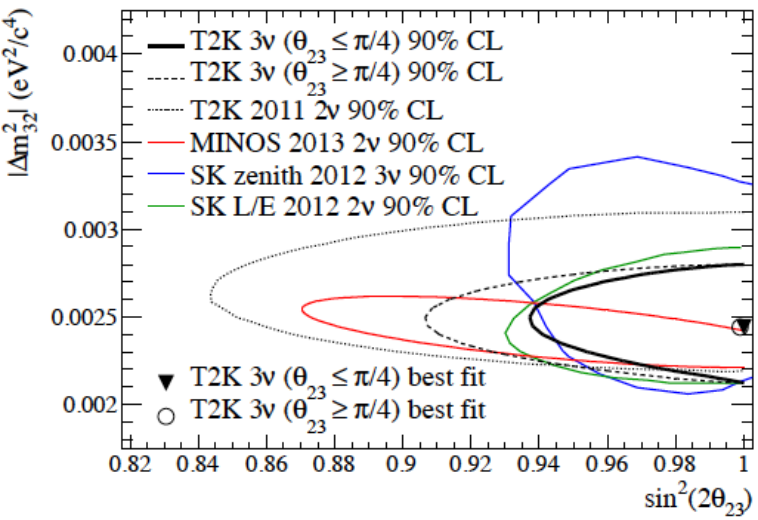
Ситуацията днес: ъглите в матрицата на PNMS са измерени, остава фазата δ

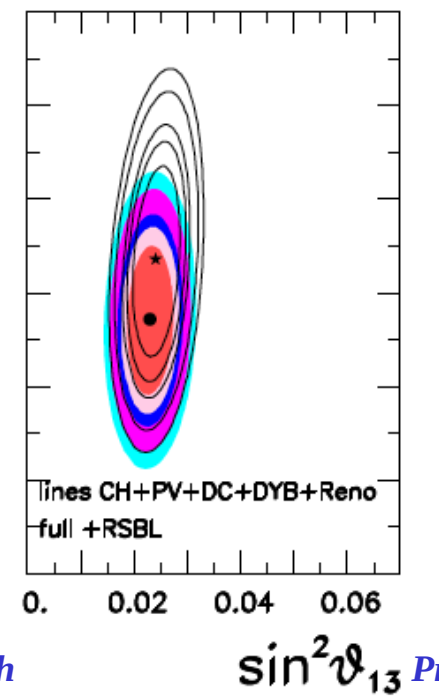
$$U_{PMNS} = U_{23}U_{13}U_{12} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{23} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

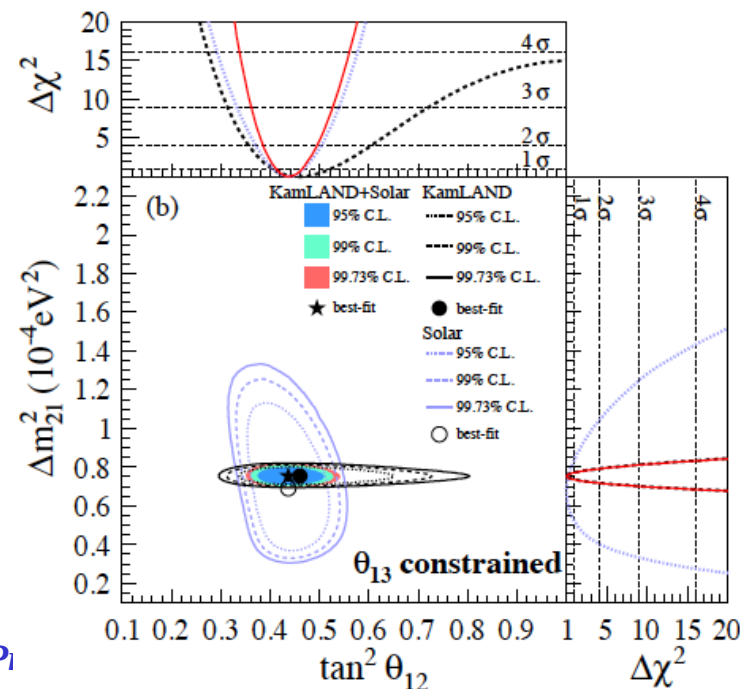
SK-atm+MINOS+T2K

T2K-MINOS-DC-DB-RENO

solar+KamLAND





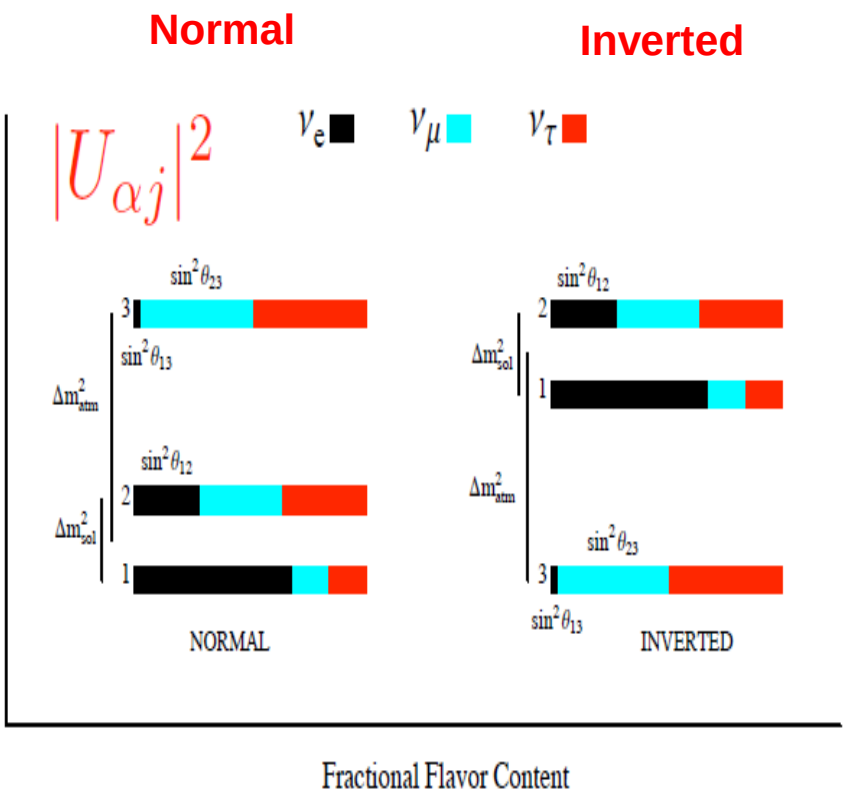


Какво знаем сега?

Глобален фит:

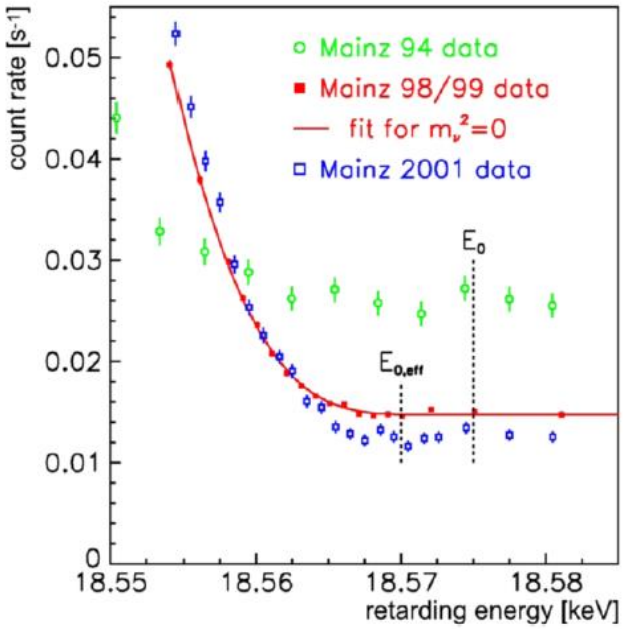
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.302^{+0.013}_{-0.012}$	$0.267 \to 0.344$
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	$31.09 \to 35.89$
$\sin^2\theta_{23}$	$0.413^{+0.037}_{-0.025} \oplus 0.594^{+0.021}_{-0.022}$	$0.342 \to 0.667$
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	$35.8 \to 54.8$
$\sin^2\theta_{13}$	$0.0227^{+0.0023}_{-0.0024}$	$0.0156 \to 0.0299$
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	$7.19 \to 9.96$
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.18}_{-0.19}$	$7.00 \to 8.09$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.473^{+0.070}_{-0.067}$	$+2.276 \to +2.695$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.427^{+0.042}_{-0.065}$	$-2.649 \to -2.242$

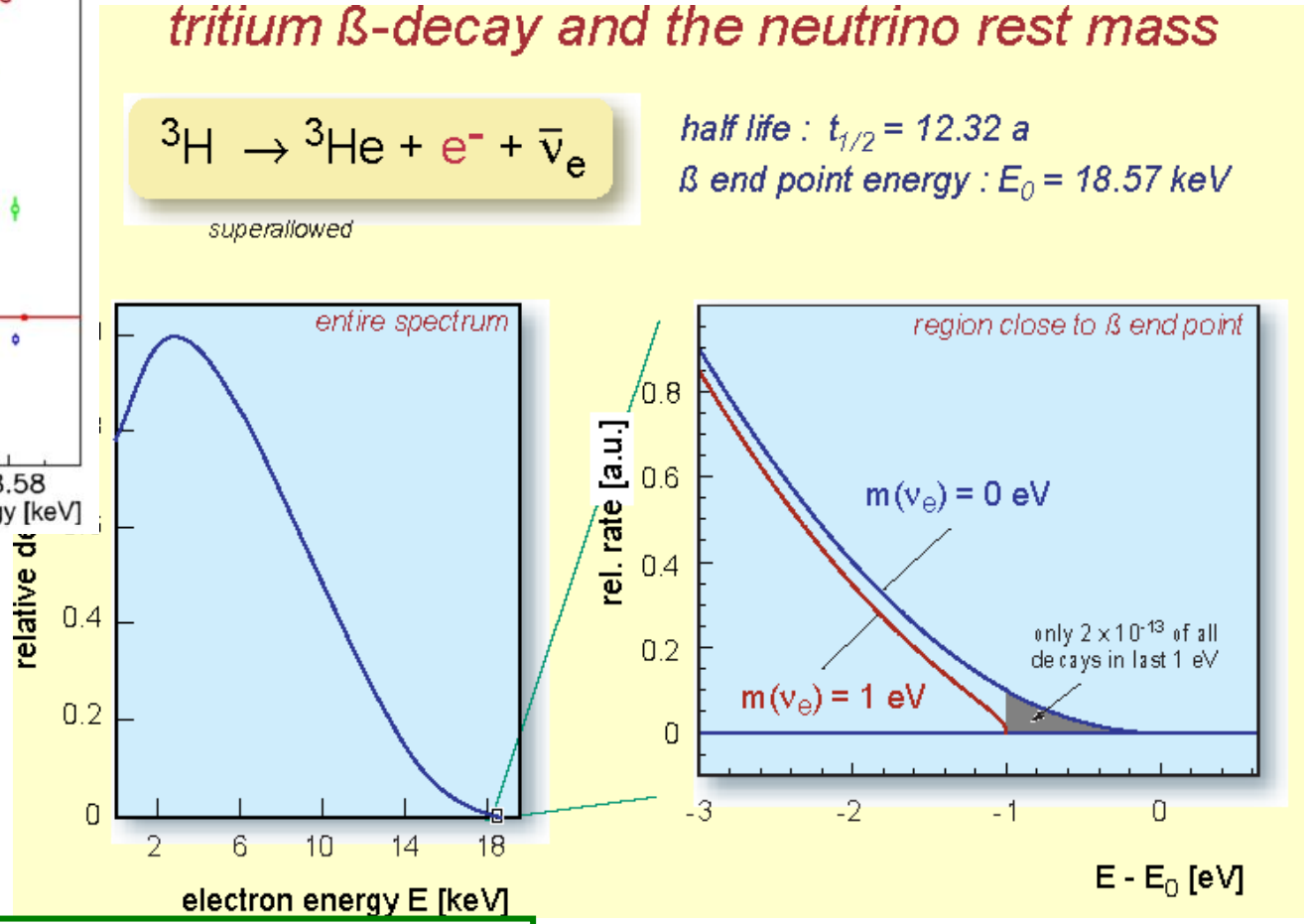
- Неизвестни величини (все още…)
  - подредбата на масовите състояния: sign Δm_{13}^2
  - CP нарушаващата фаза δ



Колко, все пак, са масите на неутрината?

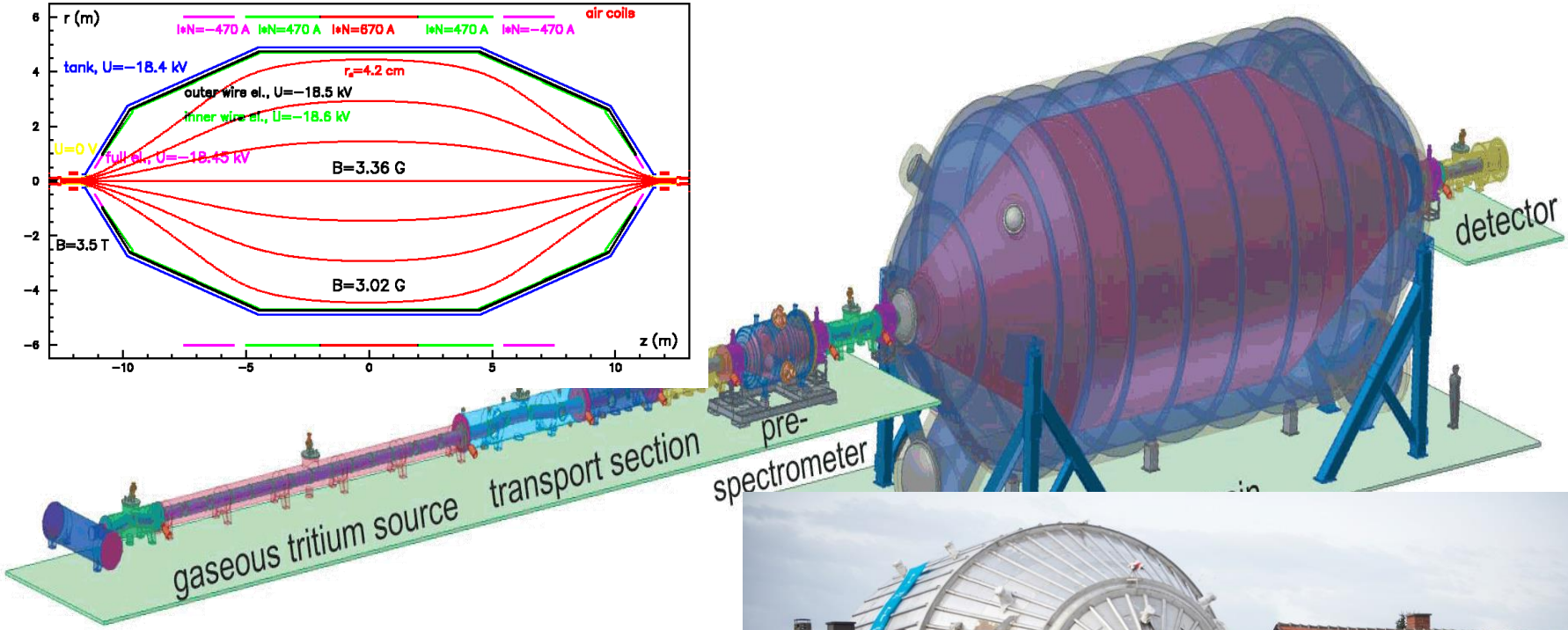
От осцилационните измервания $m_\nu > 50$ meV





2004 г. – Mainz - $m_{\blacksquare} < 2.3$ eV (95% CL)

KATRIN - Karlsruhe Tritium Neutrino Experiment



Pre-spectrometer

diameter: 1.68m, length: 3.38m

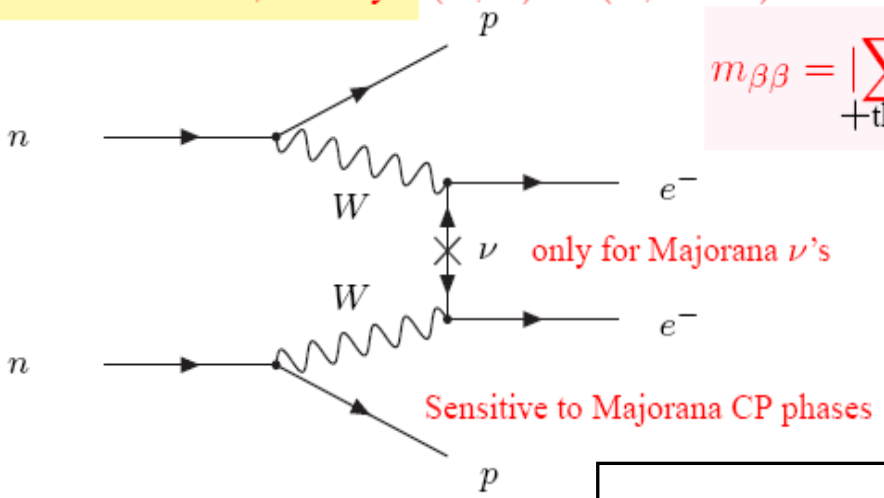
Main spectrometer

inner diameter of the cylindrical section: 9.

23.28m; inner surface: 650m^2, volume: 140

$< 10^{-11}$ mbar

ν-less Double-β decay: $(A, Z) \rightarrow (A, Z+2) + e^- + e^-$



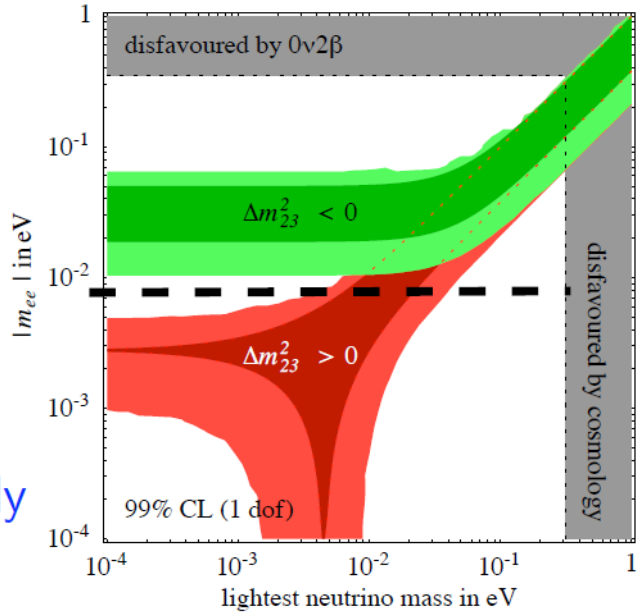
$$m_{\beta\beta} = \left|\sum U_{ej}^2 m_j\right| \quad < 0.35 \text{ eV}$$
$$+\text{theor. uncert.} \quad < 1.05 \text{ eV} \quad (90\% \text{ CL})$$

Current half-life limit ~10^{25} y

Dirac v Majorana

$$< m >_{\beta\beta} \equiv \left|\sum_{i=1}^{3} m_i U_{ei}^2\right|$$
$$= \left|m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\beta} + m_3 s_{13}^2 e^{2i(\gamma-\delta)}\right|$$

dividing point $m_{\beta\beta} \approx 10 meV$ $\Rightarrow\Rightarrow$



l^-	l^+
1	0
$(\frac{m_\nu}{E})^2$	0
0	1
0	$(\frac{m_\nu}{E})^2$

l^-	l^+
1	$(\frac{m_\nu}{E})^2$
$(\frac{m_\nu}{E})^2$	1

$(\frac{m_\nu}{E})^2 = (\frac{1eV}{1GeV})^2 = 10^{-18}$

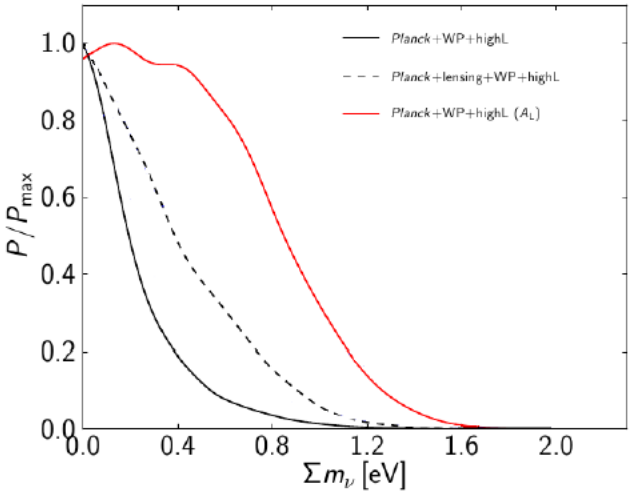
Signal below ~ 10 meV would imply Majorana and Normal Hierarchy!

Ограничения от космологични данни

Results on $\sum m_\nu$

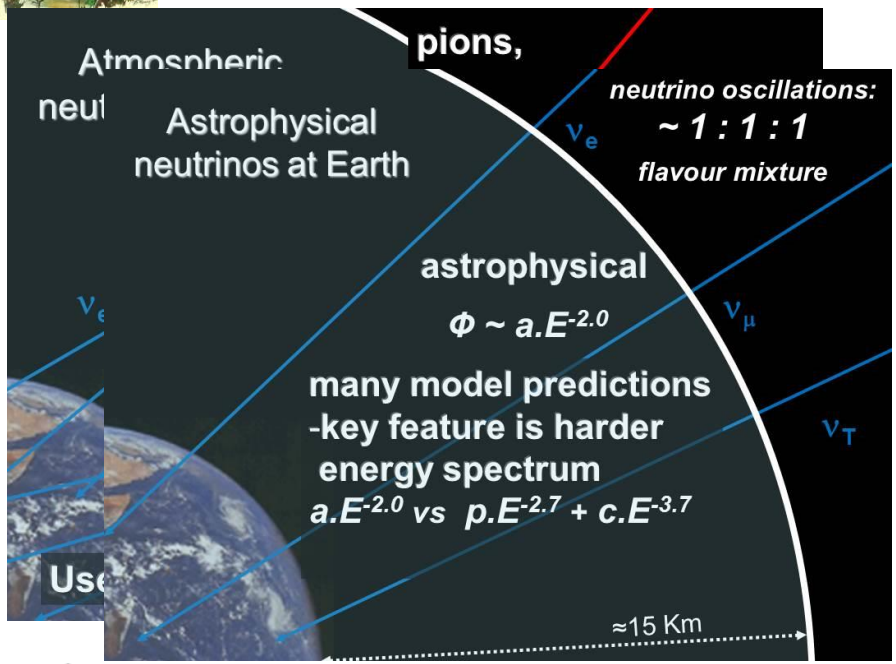
- $\sum m_\nu < 0.66$ eV
  (95%CL; Planck+WP+High-ℓ)
- $+lensing$
  $\sum m_\nu < 0.85\ eV$
- removing lensing information
  we go back to ∼WMAP

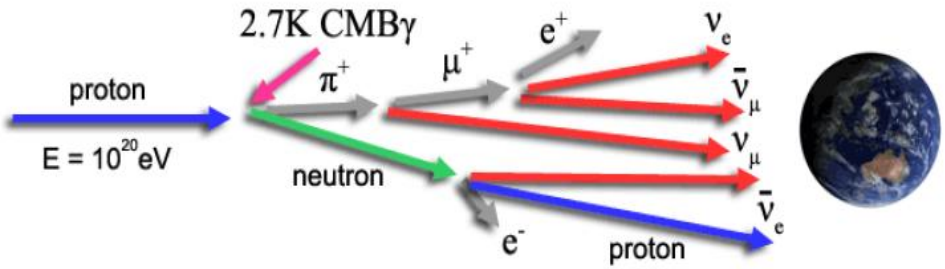
[Planck 2013 results.XVI.]

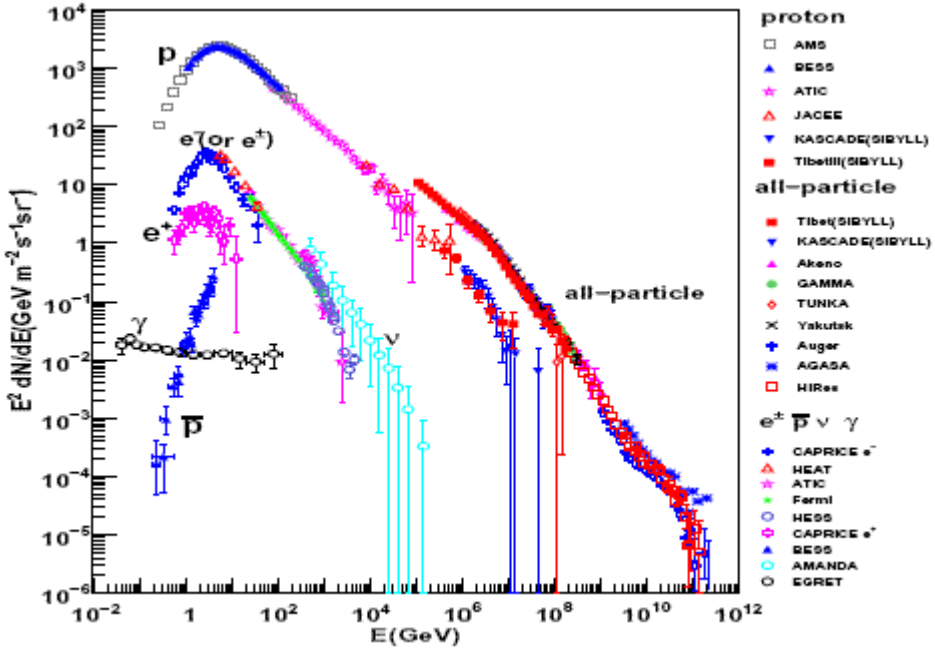


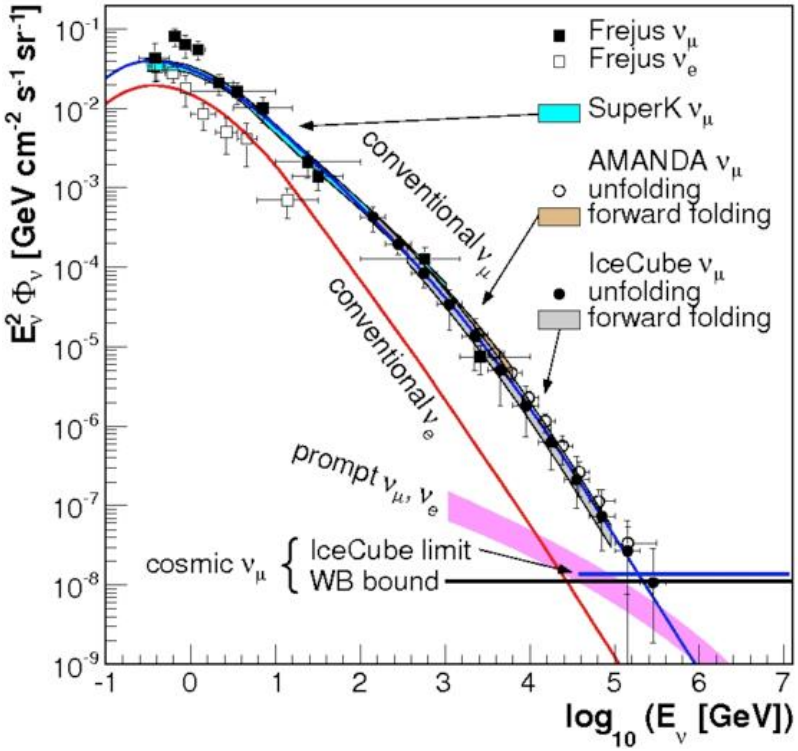
$+BAO$: $\sum m_\nu < 0.23$ eV

Космически неутрина

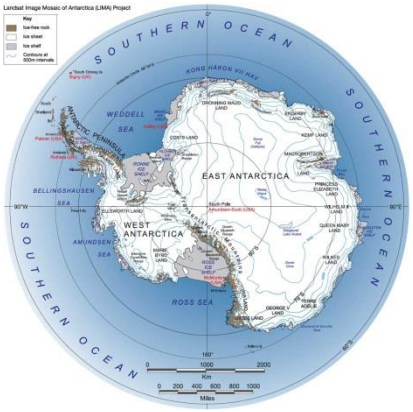


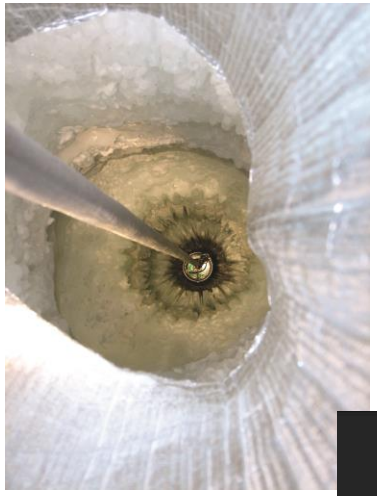


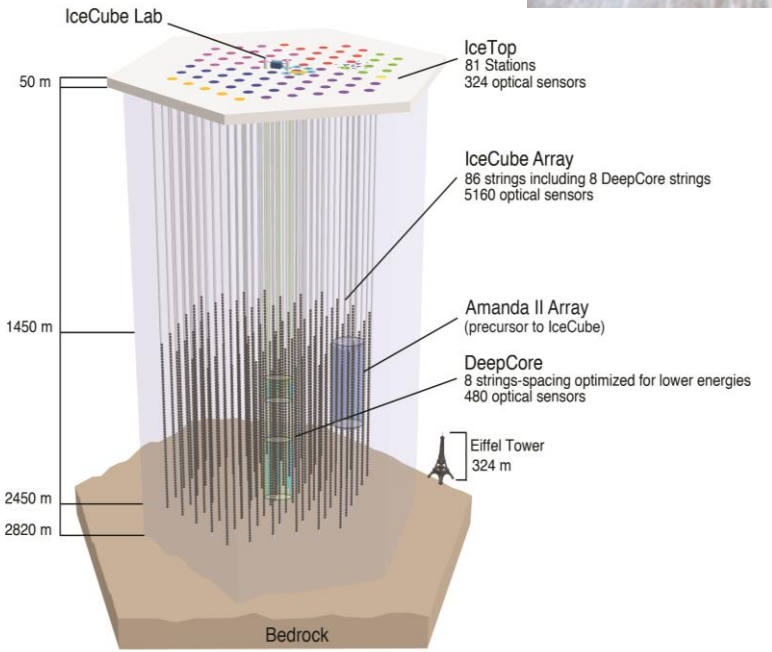


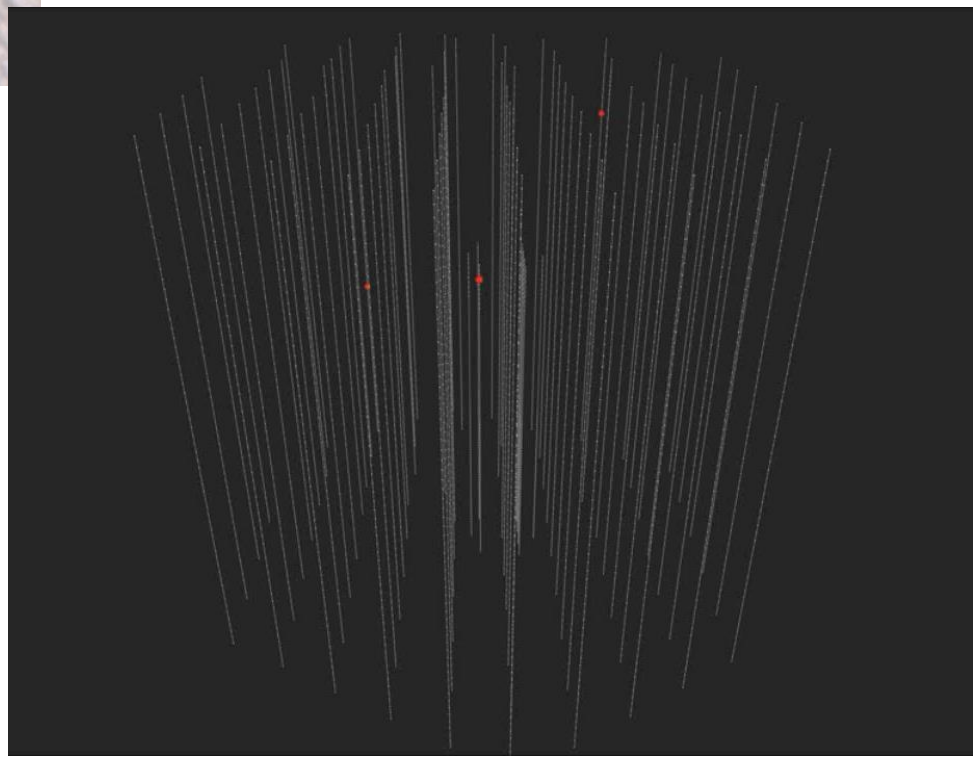


Детектиране – IceCube (km^3)

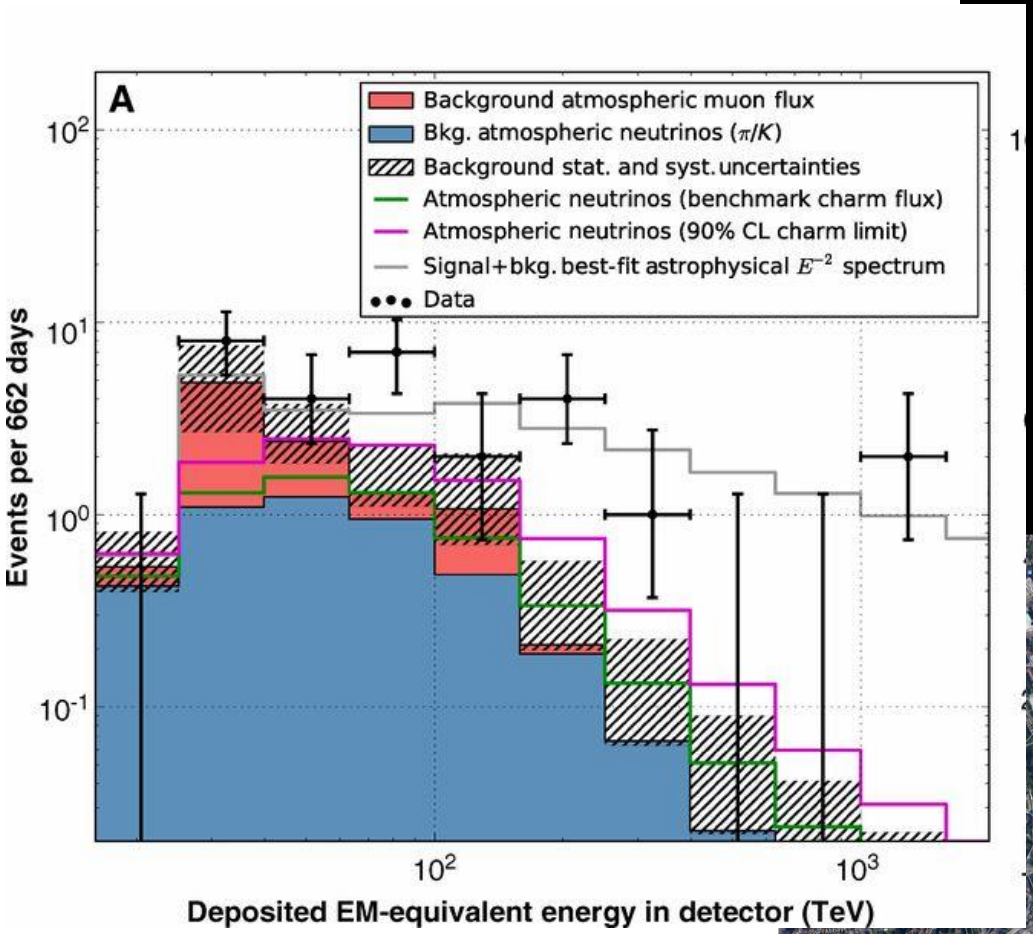


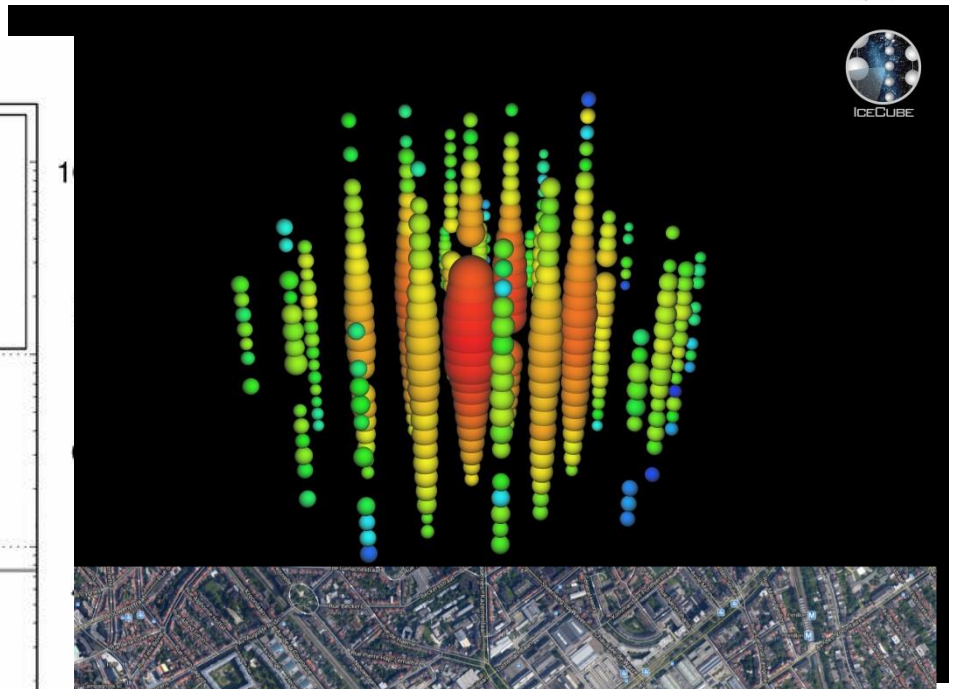


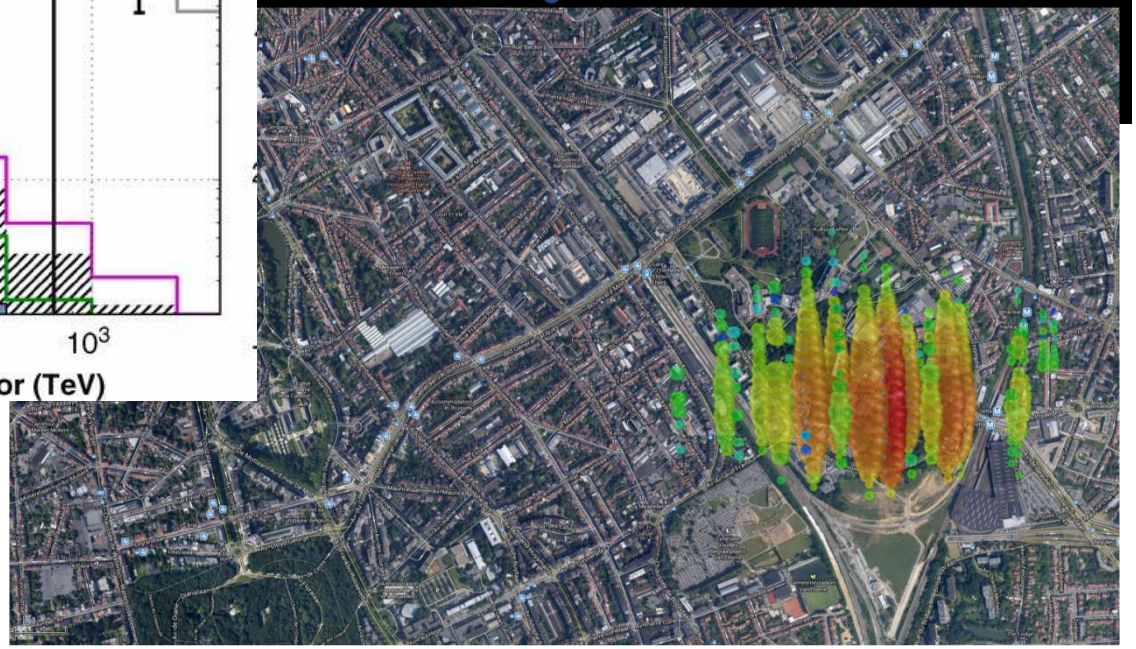




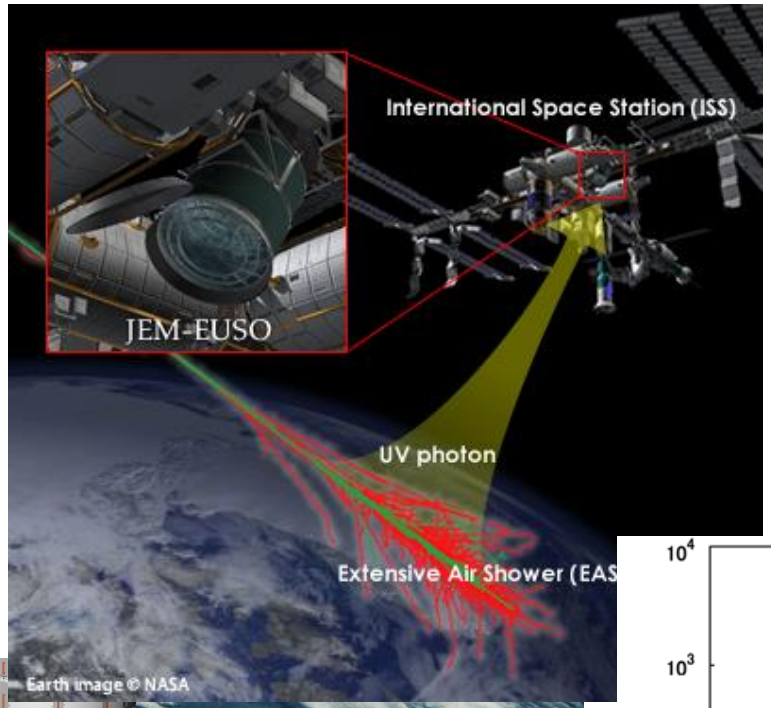
Няколко събития с енергия ~PeV (10^{15})

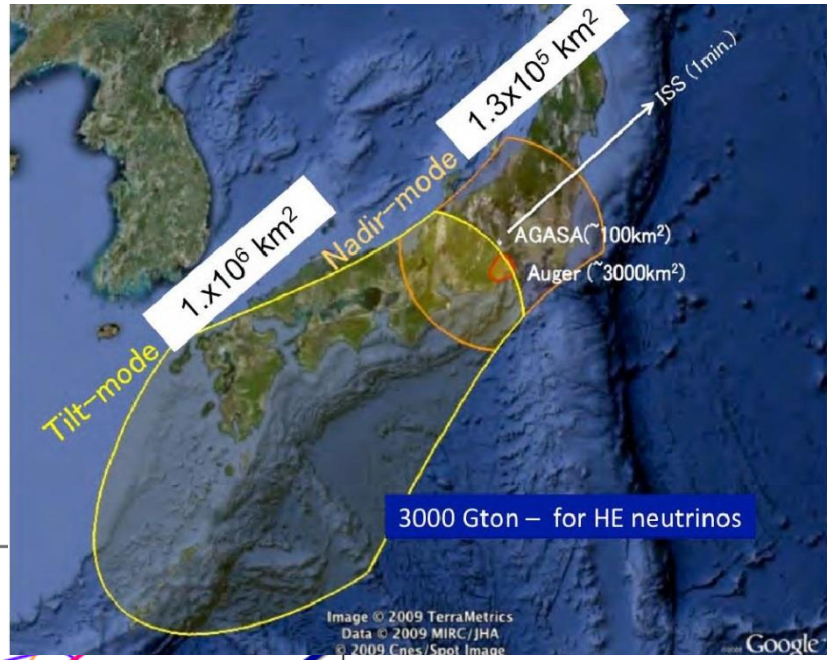


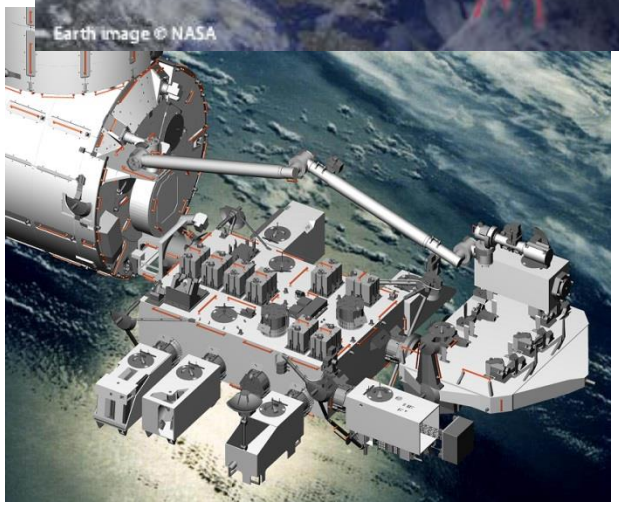


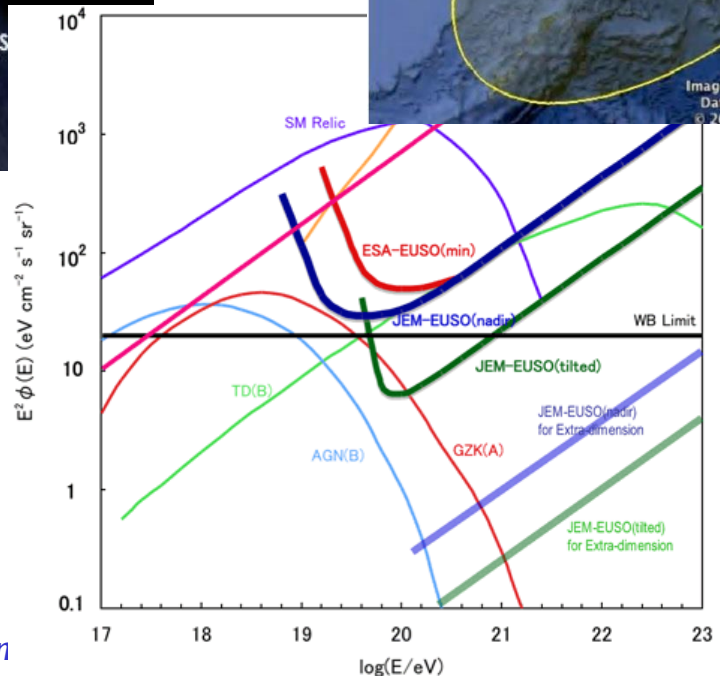


Детектиране от космосана космични лъчи с много високи енергии, вкл. неутрина









Неутринни загадки

1. Неутрината имат различни от нула маси на покой (знаем това със сигурност, защото те осцилират);
2. Масите им са много по-малки от тези на останалите фундаментални полета (< ~1 eV/c^2). Колко малки са и защо това е така?
3. Каква е природата им: Диракови или Майоранови?
4. Дали неутрината се появяват само с определена спиралност? Има ли "стерилни" неутрина?
5. Три поколения правят възможно нарушението на CP-симетрията. Но защо имаме само три поколения?
6. Как се пораждат космическите неутрина и от къде идват?
7. .....

които чакат бъдещите си изследователи…