Нейтрино. Обзорная лекция

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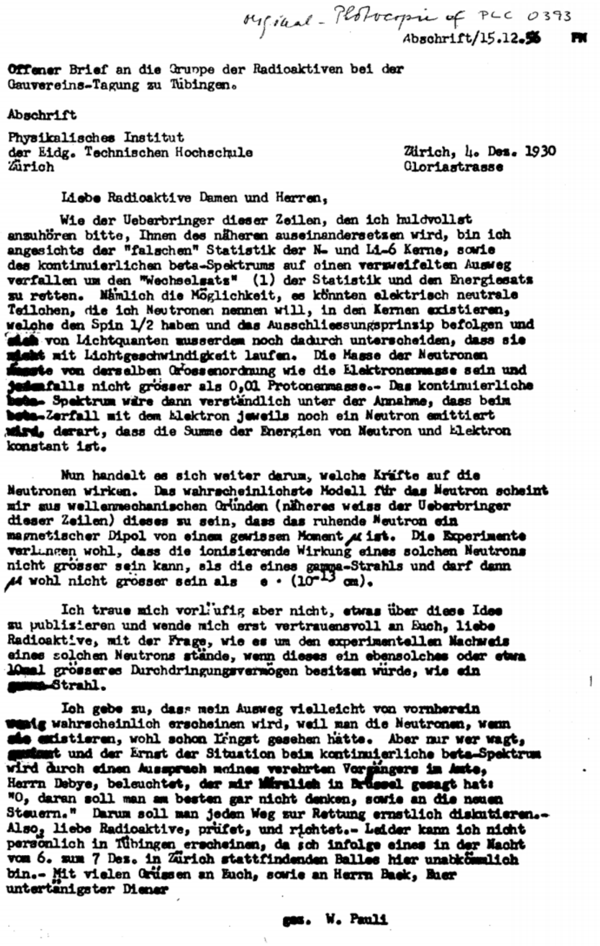
NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed — you call
It wonderful; I call it crass.
John Updike,
poem “Cosmic Gall”, 1960

The Birth of the Neutrino

- Neutrino history begins with a letter of W.Pauli (4th December 1930) to Lise Meitner et al.
- Introduced a neutral particle of about electronic mass, and spin ½ to save conservation laws for energy and angular momentum
- “I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do.”



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Abschrift/15.12.56 PN

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

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, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that 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 mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.
- Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than e • (10^{-13}cm).
- But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.
- I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant
- signed W. Pauli
- [Translation: Kurt Riesselmann]

Weak Interactions

- Among the physicists who took Pauli's idea seriously was Enrico Fermi, who developed the theory of beta decay further in 1934, giving the name "neutrino" ("little neutral one") in the process.
- Z. Physik, 88, 161 (1934) (Paper rejected by *Nature* because "it contains speculations too remote from reality to be of interest to the reader")
- It became clear that if such a particle existed, it must be both very light–less than 1% the mass of a proton–and interact very weakly with matter, making it very difficult to detect.

- Bethe and Peirels, Nature 133, 532 (1934)

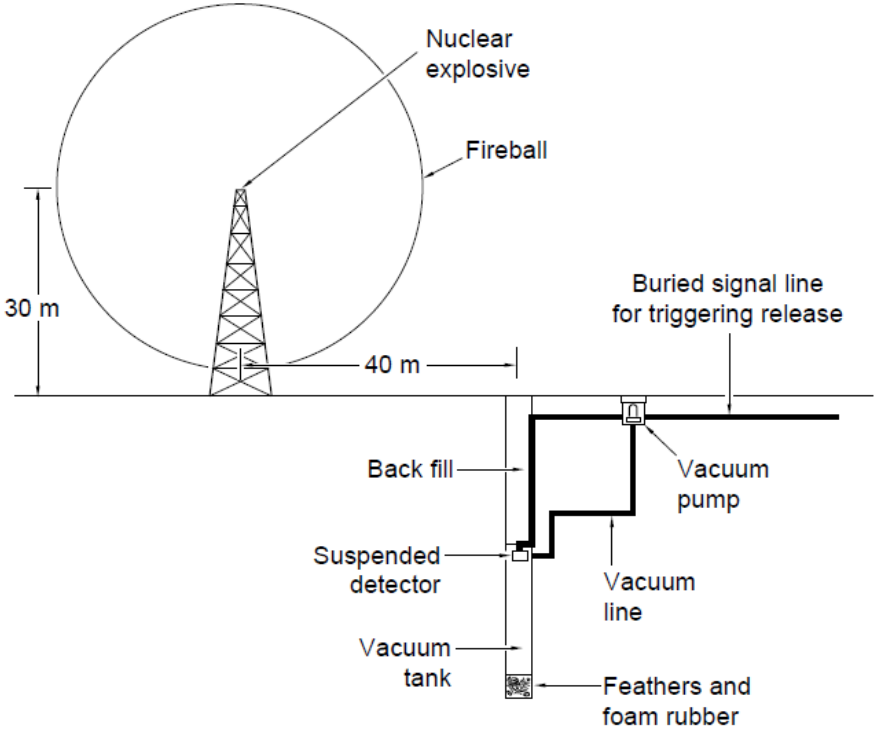
Predicted "annihilation process": $\bar{\nu} + p \rightarrow n + e^{+}$

Estimated the cross section for 2.3 MeV: $<10^{-44}$ cm^2 (estimation was wrong by a factor of 2)

"With increasing energy, σ increases … but even if one assumes a very steep increase, it seems highly improbable that, even for cosmic ray energies, σ becomes large enough

Cowan–Reines neutrino experiment

- Clyde L. Cowan and Frederick Reines in 1956.
- Experiment confirmed the existence of the antineutrino.

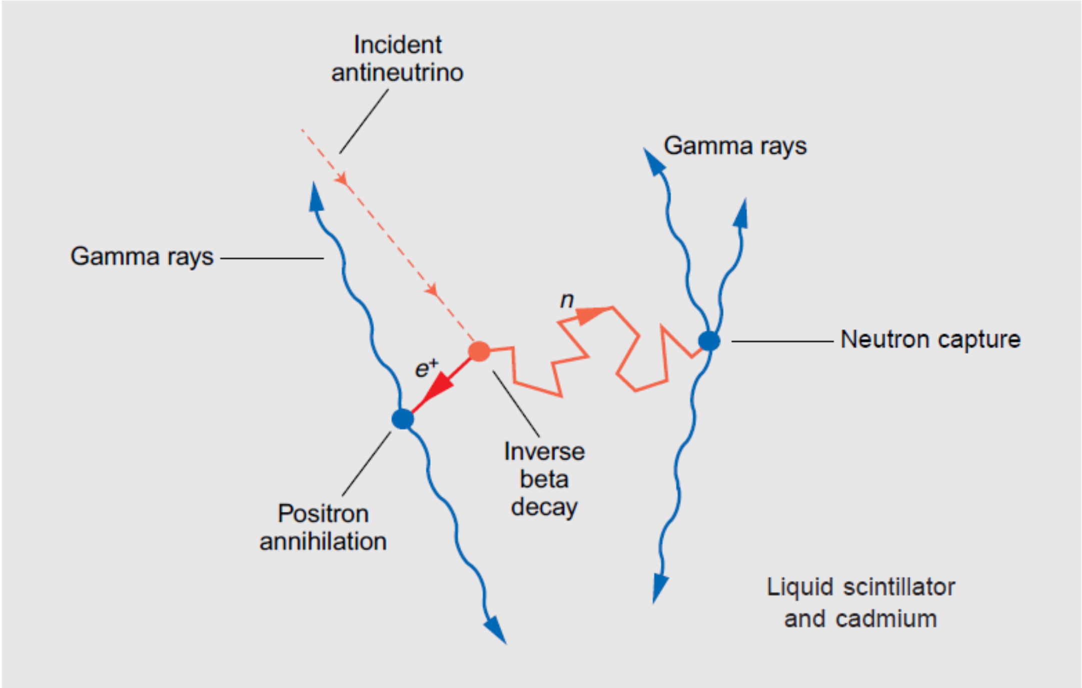


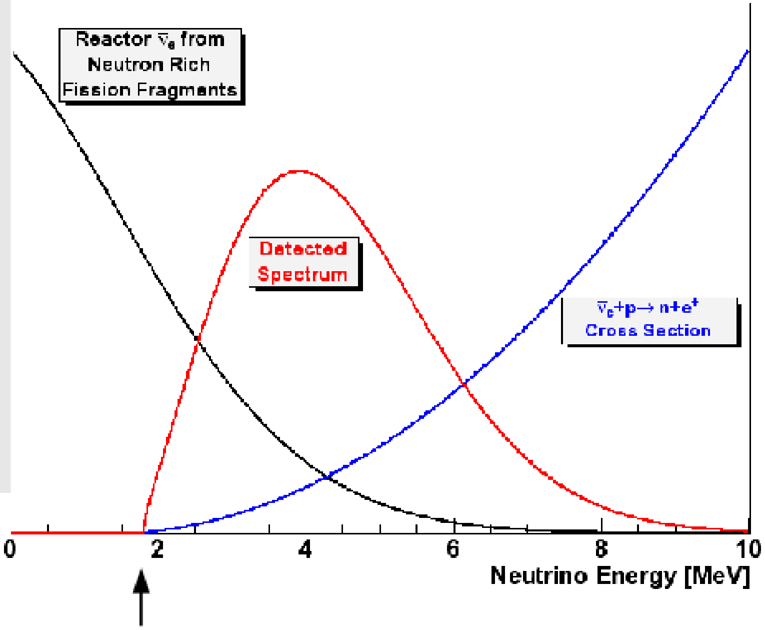
“Our crude knowledge of the expected energy spectrum of neutrinos from a fission bomb suggested that the inverse beta decay reaction would occur several times in a several-ton detector located about 50 meters from the tower-based explosion of a 20-kiloton bomb…The detector we dreamed up was a giant liquid scintillation device, which we dubbed ‘El Monstro.’ This was a daring extrapolation of experience with the newly born scintillation technique. The biggest detector until Cowan and I came along was only a liter or so in volume.”

El Monstro ~1 m^3

Antineutrino detection
(inverse β-decay on p)

$$E_{vis}(e+)=E_{kin}(e+)+2m_e$$
$$E_{kin}(e+)=E_\nu-1.8\text{ MeV}$$
$$E_{vis}=E_\nu-0.78\text{ MeV}$$

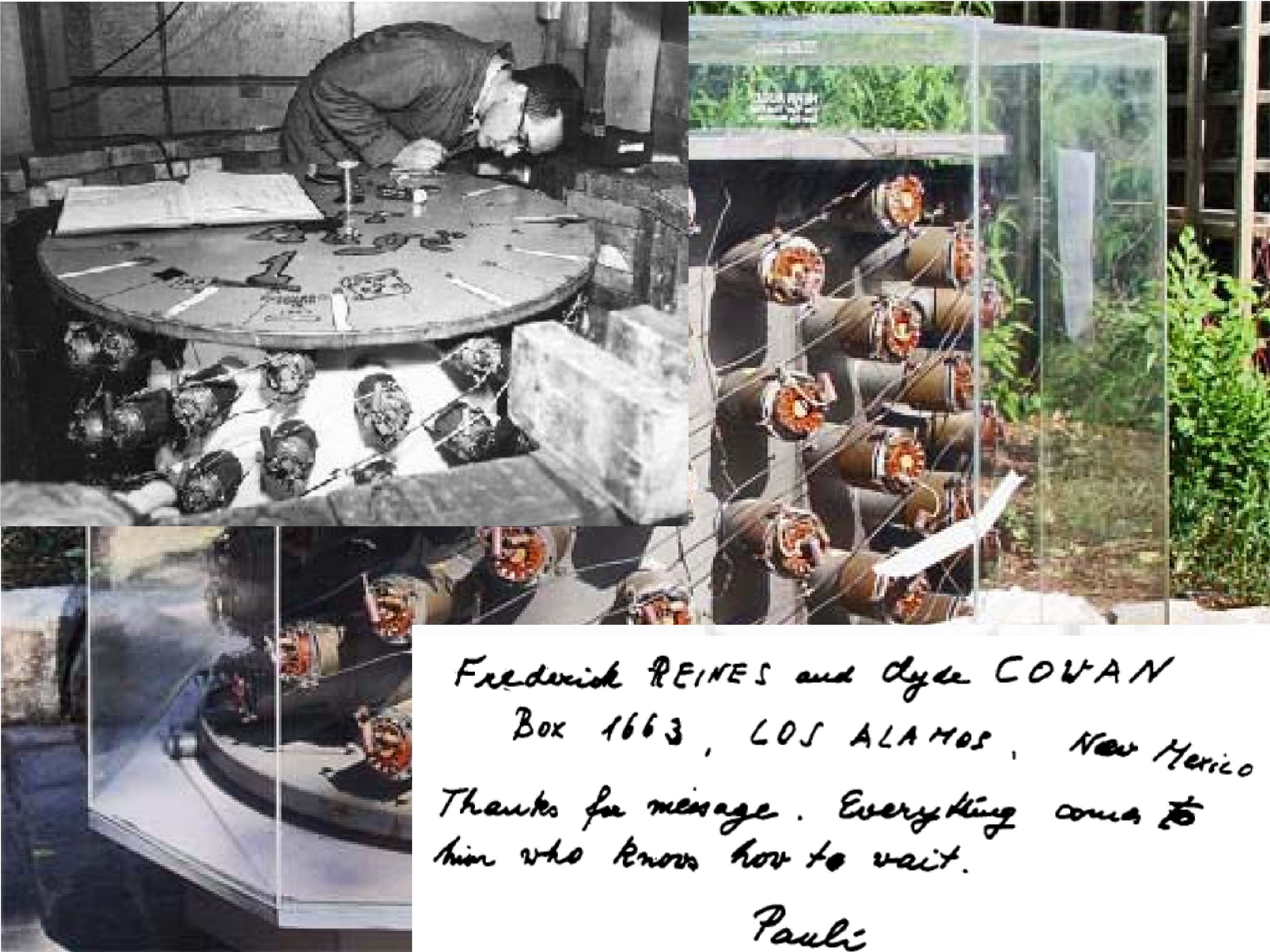




1.8 MeV threshold

Reinis-Cowan experiment

- nuclear reactor with neutrino fluxes on the order of 10^{12} to 10^{13} neutrinos/s/cm^2
- cadmium chloride (Cd is a highly effective neutron absorber), 5 µs
- Preliminarily experiment at Hanford, but later moved the experiment to the Savannah River Plant near Augusta, Georgia where they had better shielding against cosmic rays. This shielded location was 11m from the reactor and 12m underground. They used two tanks with a total of about 200 liters of water with about 40 kg of dissolved CdCl2. The water tanks were sandwiched between three scintillator layers which contained 110 five-inch (127 mm) photomultiplier tubes.
- After months of data collection, they had accumulated data on about three neutrinos per hour in their detector. To be absolutely sure that they were seeing neutrino events from the detection scheme described above, they shut down the reactor to show that there was a difference in the number of detected events. They had predicted a cross-section for the reaction to be about 6×10^{-44} cm^2 and their measured cross-section was 6.3×10^{-44} cm^2. Their results were published in 1956.



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

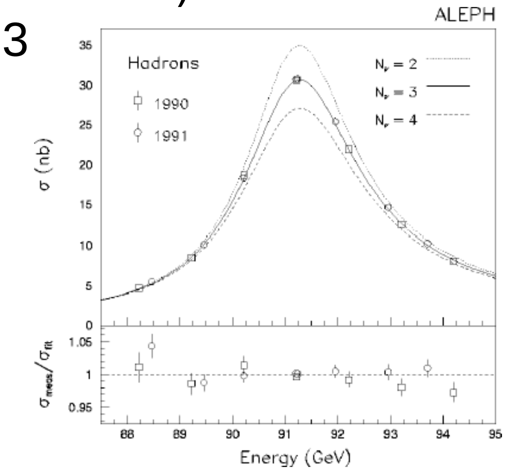
Pauli

Типы нейтрино

- Рэй Дэвис в начале 1950-х провел серию экспериментов по поиску реакции $\nu_e + {}^{37}\mathrm{Cl} \to e^- + {}^{37}\mathrm{Ar}$, предложенной Бруно Понтекор: нейтрино отличаются от антинейтрино
- Ароматы – 1962, Ледерман, Шварц и Стайнбергер (искали распад $\mu \to e + \gamma$)
- Третий лептон (тау)- 1975 год (Перл, Нобелевская премия 1995 года)
- Третье нейтрино – эксперимент DONUT в 2000 г
- Ширина Z0 (эксперимент ALEPH 1991 г) : число поколений нейтрино 2.982±0.013

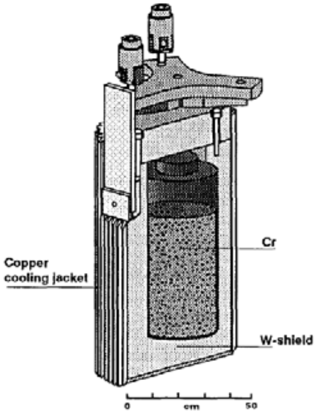
Melvin Schwartz Leon Lederman Jack Steinberger

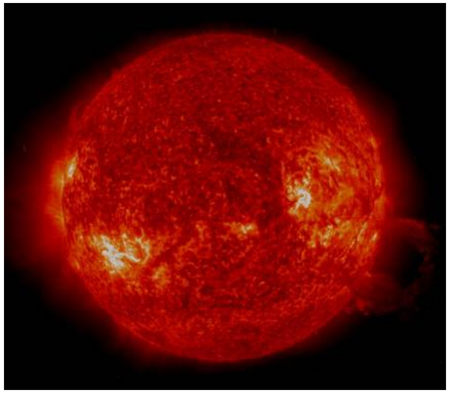
Нобелевская премия 1988 г за открытие мюонного нейтрино

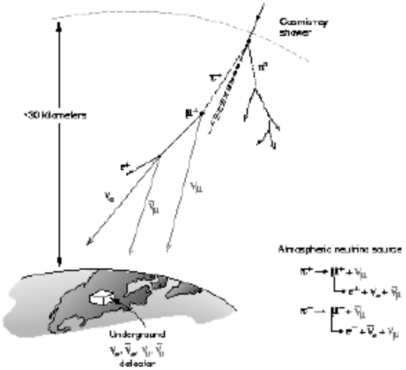


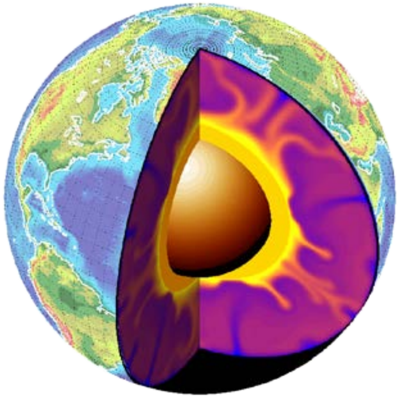
Neutrino sources

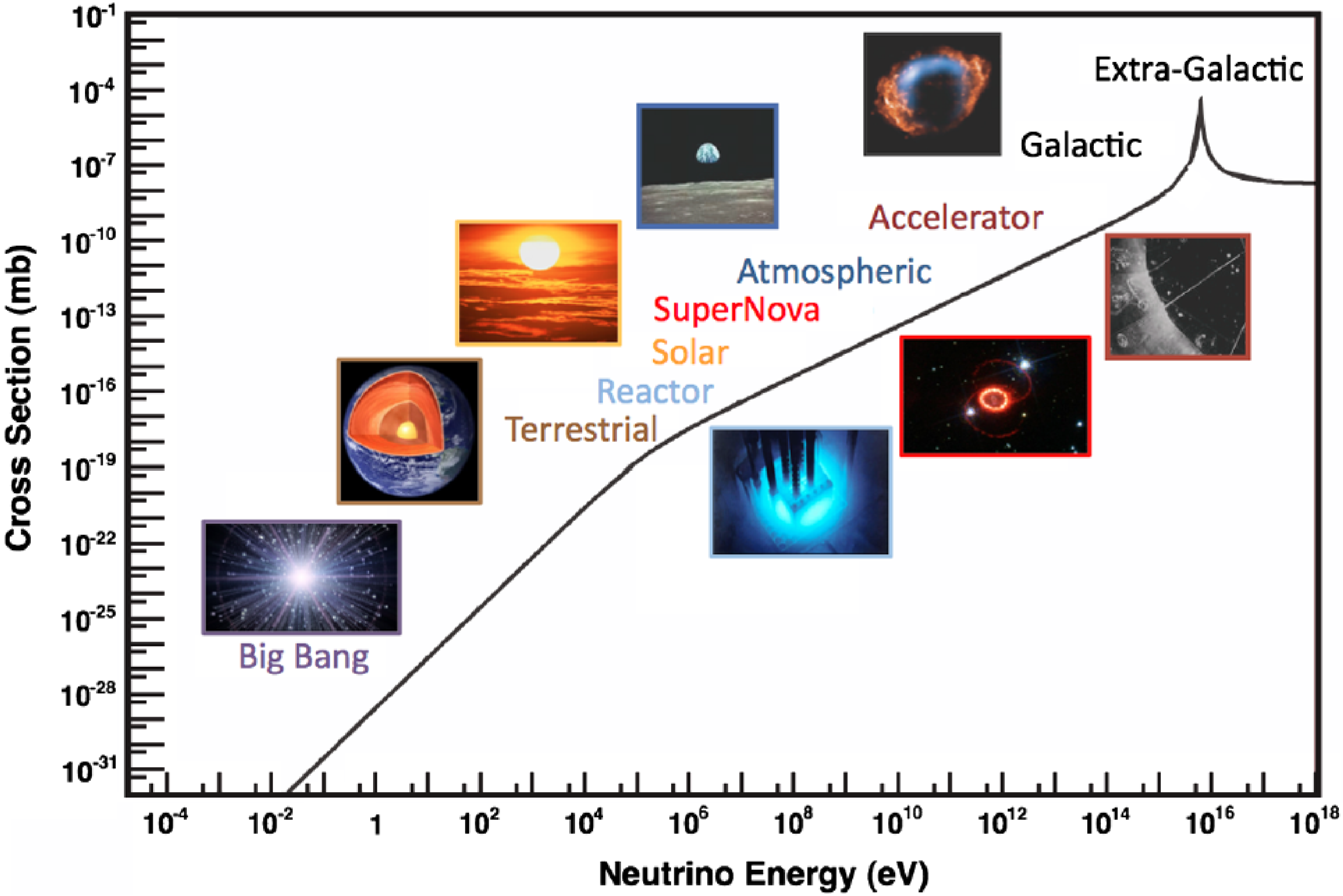
- Artificial:
  - Accelerators
  - Reactors
  - Isotopes sources
- Natural
  - Solar
  - Atmospheric
  - Natural radioactive isotopes in the Earth (geo-neutrino)
  - Supernovae (1987A)



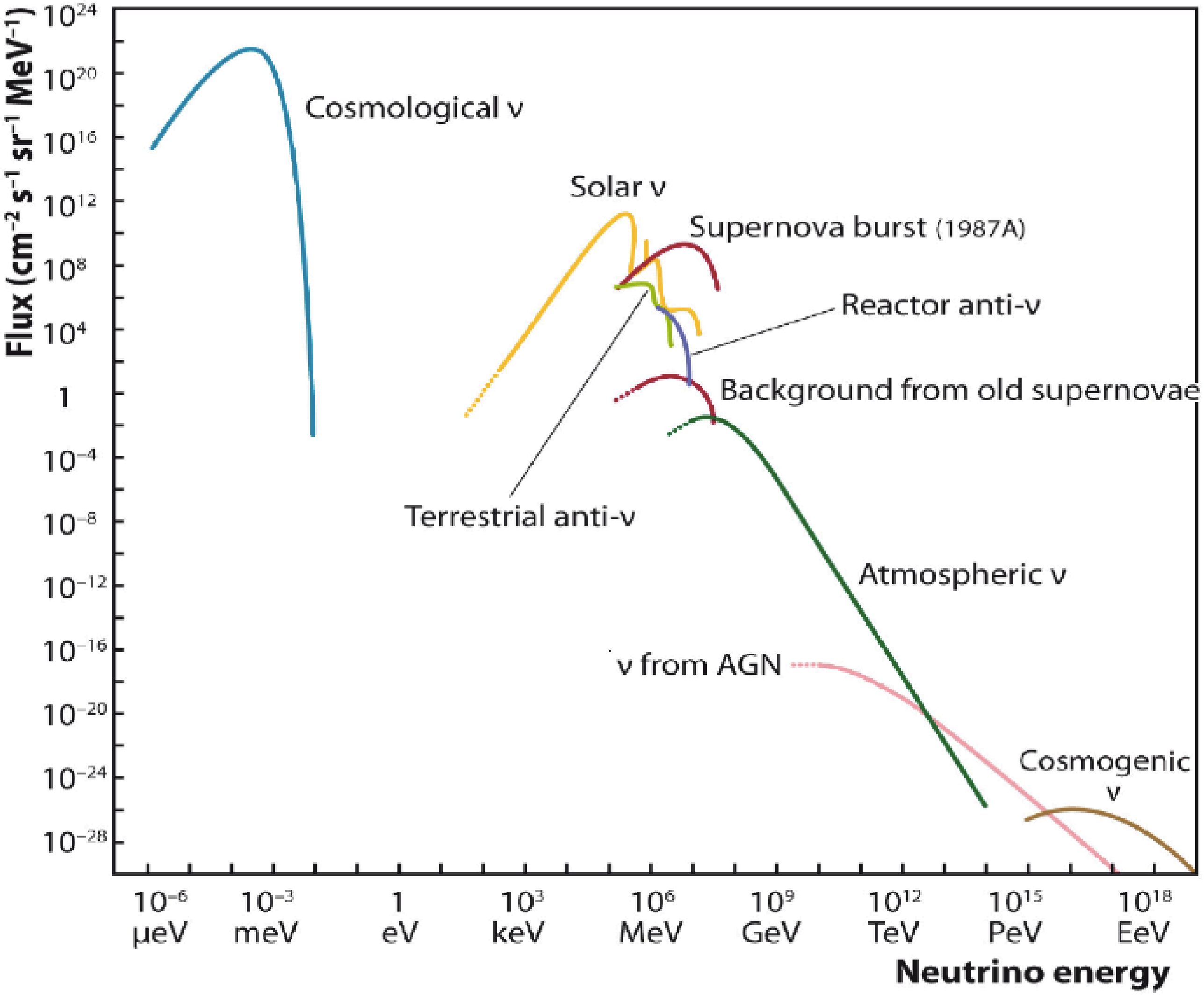




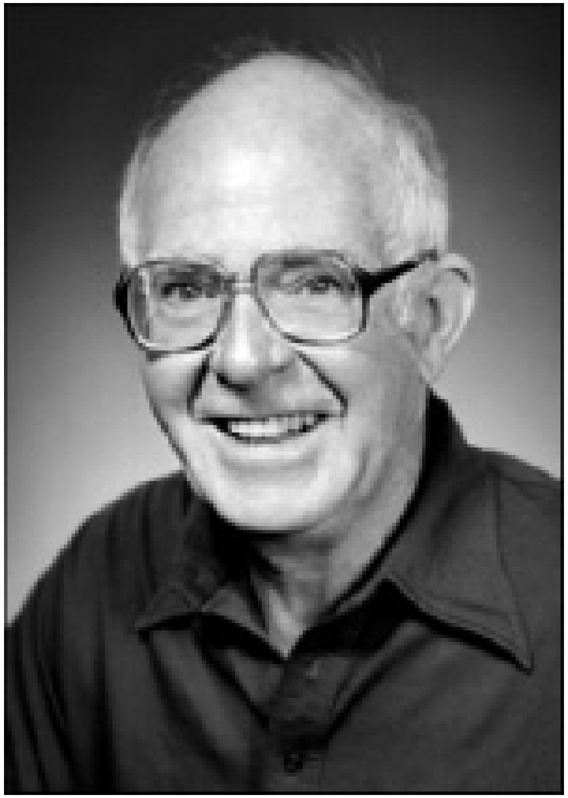



Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang
Cross Section (mb)
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
10^{-25}
10^{-28}
10^{-31}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
Neutrino Energy (eV)

Neutrino fluxes in nature



1968: Solar neutrino detection at Homestake.



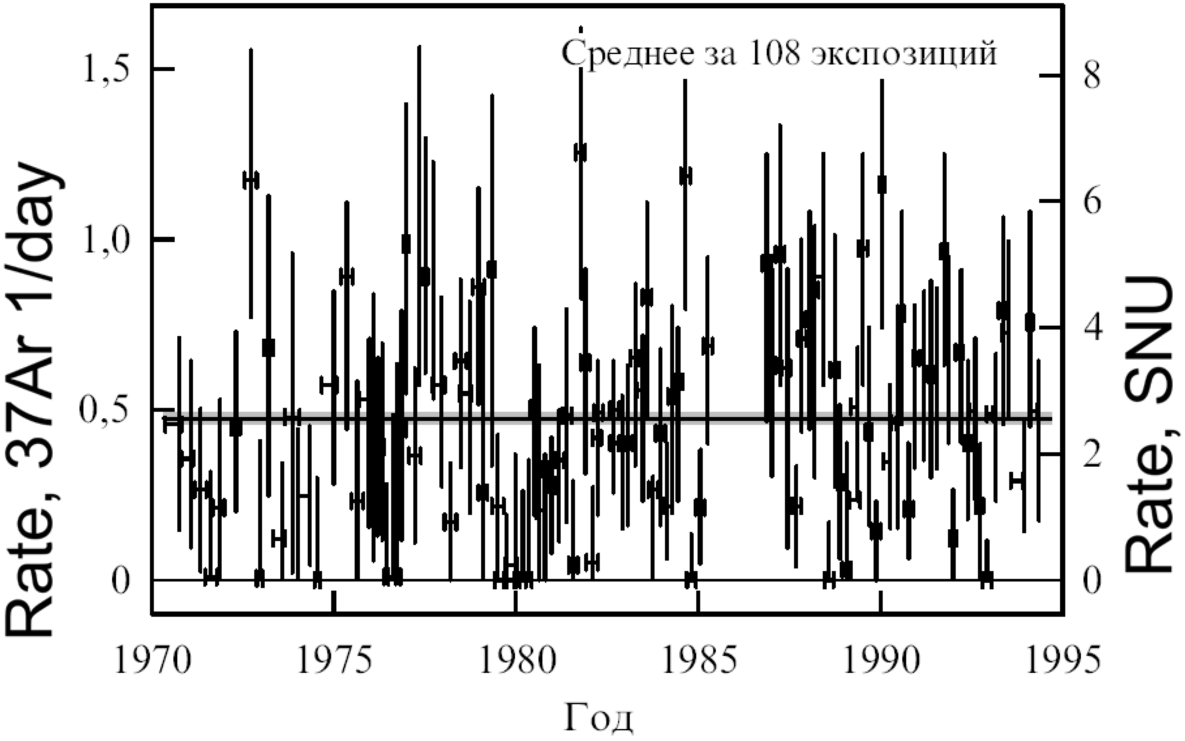
Homestake Mine- mine in South Dacota.

Tank filled with 600 tones of perchloroethylene (C_2Cl_4) at the depth of 1.5 km underground.

Detector was taking data from 1970 to 1994

Raymod Davis Jr. (1914-2006). Nobel prize in 2002 "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

Results



In 25 y 2200 atoms of ^{37}Ar are counted, the measured absolute neutrino flux is 2.56±0.16 ±0.16 SNU

(theory 2002 y: $7.6^{+1.3}_{-1.1}$) – the Solar neutrino problem

1 SNU (Solar Neutrino Unit) = 10^{-36} interactions on target nuclei per second

- **Загадка солнечных нейтрино**

Опубликовано в еженедельнике ОИЯИ "Дубна" NN 8-9 (2000)

“*Нигде так ясно не проявляется связь между микромиром и космосом, как в физике нейтрино*”. ***Б. М. Понтекорво***.

- 14 января на Ученом совете ОИЯИ состоялось награждение лауреата премии имени академика Б. М. Понтекорво. Директор ОИЯИ В. Г. Кадышевский и председатель жюри Д. В. Ширков вручили диплом лауреату премии за 1999 год американскому ученому Реймонду Дэвису. Премия была присуждена “за выдающиеся достижения в разработке хлор-аргонового метода регистрации солнечных нейтрино”. С кратким словом о лауреате выступил секретарь жюри С. А. Бунятов. Затем Реймонд Дэвис сделал интересный доклад “О регистрации солнечных нейтрино хлор-аргоновым методом”.

Solar neutrino problem

John Norris Bahcall (1934 – 2005)

"We argued that, if our understanding of nuclear processes in the interior of the sun was correct, then solar neutrinos would be captured at a rate Davis could measure with a large tank filled with cleaning fluid…

Our sole motivation for urging this experiment was to use neutrinos to enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars. As we shall see, Davis and I did not anticipate some of the most interesting aspects of this proposal.

Davis performed the experiment and in 1968 announced the first results. He measured fewer neutrinos than I predicted. As the experiment and the theory were refined, the disagreement appeared more robust. Scientists rejoiced that solar neutrinos were detected but worried why there were fewer neutrinos than predicted.

What was wrong? Was our understanding of how the sun shines incorrect? Had I made an error in calculating the rate at which solar neutrinos would be captured in Davis's tank? Was the experiment wrong? Or, did something happen to the neutrinos after they were created in the sun? Over the next twenty years, many different possibilities were examined by hundreds, and perhaps thousands, of physicists, chemists, and astronomers. Both the experiment and the theoretical calculation appeared to be correct."

--John N. Bahcall

Neutrino oscillations in vacuum

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\Theta & \sin\Theta \\ -\sin\Theta & \cos\Theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Pontecorvo’s idea

Evolution of neutrino state:

$$\left|\nu(x)\right\rangle = e^{ip_1 x}\cos\Theta\left|\nu_1\right\rangle + e^{ip_2 x}\sin\Theta\left|\nu_2\right\rangle$$

Probability to observe muon neutrino (in the initial electronic) at the distance L:

$$P(\nu_e \to \nu_\mu) = \left|\left\langle \nu_\mu \middle| \nu(L) \right\rangle\right|^2 \approx \sin^2 2\Theta \sin^2 \frac{\Delta m^2 L}{4E} \qquad E >> m_{1,2}; \Delta m^2 \equiv m_2{}^2 - m_1{}^2$$

$$P(\nu_e \to \nu_e) = 1 - P(\nu_e \to \nu_\mu) = 1 - \sin^2 2\Theta \sin^2 \frac{\Delta m^2 L}{4E}$$

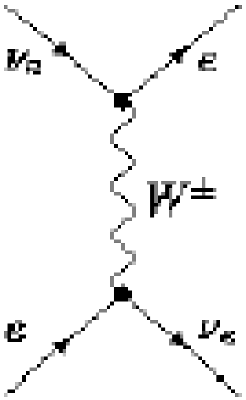
$$S(L/E) \equiv \sin^2 \frac{\Delta m^2 L}{4E} = \sin^2 1.27 \Delta m^2 [eV^2] \frac{L[km]}{E[GeV]}$$

Упрощения

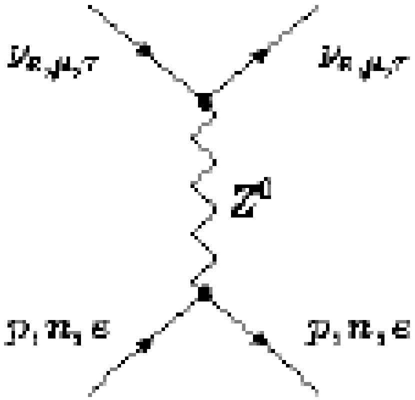
- $|\nu_i(t)\rangle = e^{-i(E_i t - \overrightarrow{p_i}\,\overrightarrow{x_i})}|\nu_i(0)\rangle$
- Поскольку $|\vec{p}| \gg m$
- $E_i = \sqrt{p^2{}_i + m_i{}^2} \cong p_i + \frac{m^2}{2p_i} \approx E + \frac{m^2}{2E}$
- (E – полная энергия частицы)
- $t \approx L$
- $|\nu_i(L)\rangle = e^{-im_i\frac{L}{2E}}|\nu_i(0)\rangle$

Neutrino oscillations in matter (Wolfenstein,1978)

L. Wolfenstein, Phys. Rev. D **17** (1978) 2369.



ν_e



$\nu_{e,\mu,\tau}$

$$V_e^{\mathrm{CC}} \equiv V = \sqrt{2}\, G_F\, N_e$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + V & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Neutrino mixing in matter

$$|\nu_e\rangle = \cos\theta_m\,|\nu_{1m}\rangle + \sin\theta_m\,|\nu_{2m}\rangle$$

$$|\nu_\mu\rangle = -\sin\theta_m\,|\nu_{1m}\rangle + \cos\theta_m\,|\nu_{2m}\rangle$$

The mixing angle in matter is related to the mixing angle in vacuum as:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta\cdot(\frac{\Delta m^2}{2E})^2}{[\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e]^2 + (\frac{\Delta m^2}{2E})^2\sin^2 2\theta}$$

Max mixing

$$\sqrt{2}G_F N_e = \frac{\Delta m^2}{2E}\cos(2\Theta) \quad\Rightarrow\quad \sin^2 2\Theta_m = 1 \quad\Rightarrow\quad \Theta_m = \frac{\pi}{4}$$

(Mikheev-Smirnov-Wolfenstein resonance)

$$N_e << N_{res} \quad\rightarrow\quad \Theta_m \approx \Theta$$

$$N_e = N_{res} \quad\rightarrow\quad \Theta_m = \frac{\pi}{4}$$

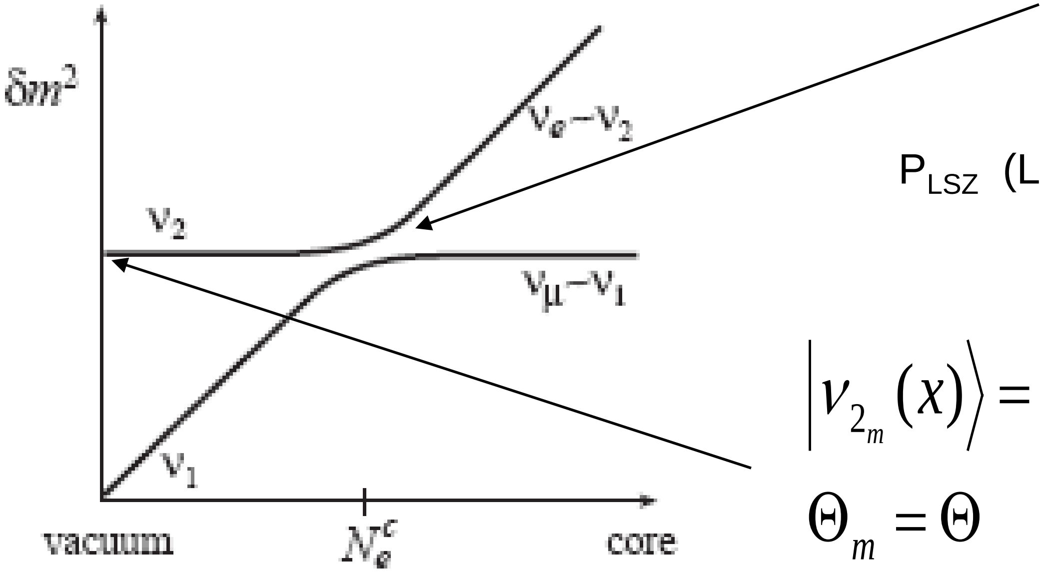
$$N_e >> N_{res} \quad\rightarrow\quad \Theta_m \approx \frac{\pi}{2}$$

Mixing in the matter with varying density (Mikheev-Smirnov,1985)

$$i\frac{d}{dx}\begin{pmatrix}\nu_{1_m}\\ \nu_{2_m}\end{pmatrix}=\begin{pmatrix}\frac{m_{1_m}^2}{2E} & i\frac{d\Theta_m}{dx}\\ -i\frac{d\Theta_m}{dx} & \frac{m_{2_m}^2}{2E}\end{pmatrix}\begin{pmatrix}\nu_{1_m}\\ \nu_{2_m}\end{pmatrix}$$

"effective" masses:

$$m_{1,2_m}=\frac{1}{2}\left[2\sqrt{2}G_F N_e E\mp\sqrt{\left(\Delta m^2\cos 2\Theta-2\sqrt{2}G_F N_e E\right)^2-\left(\Delta m^2\sin 2\Theta\right)^2}\right]$$



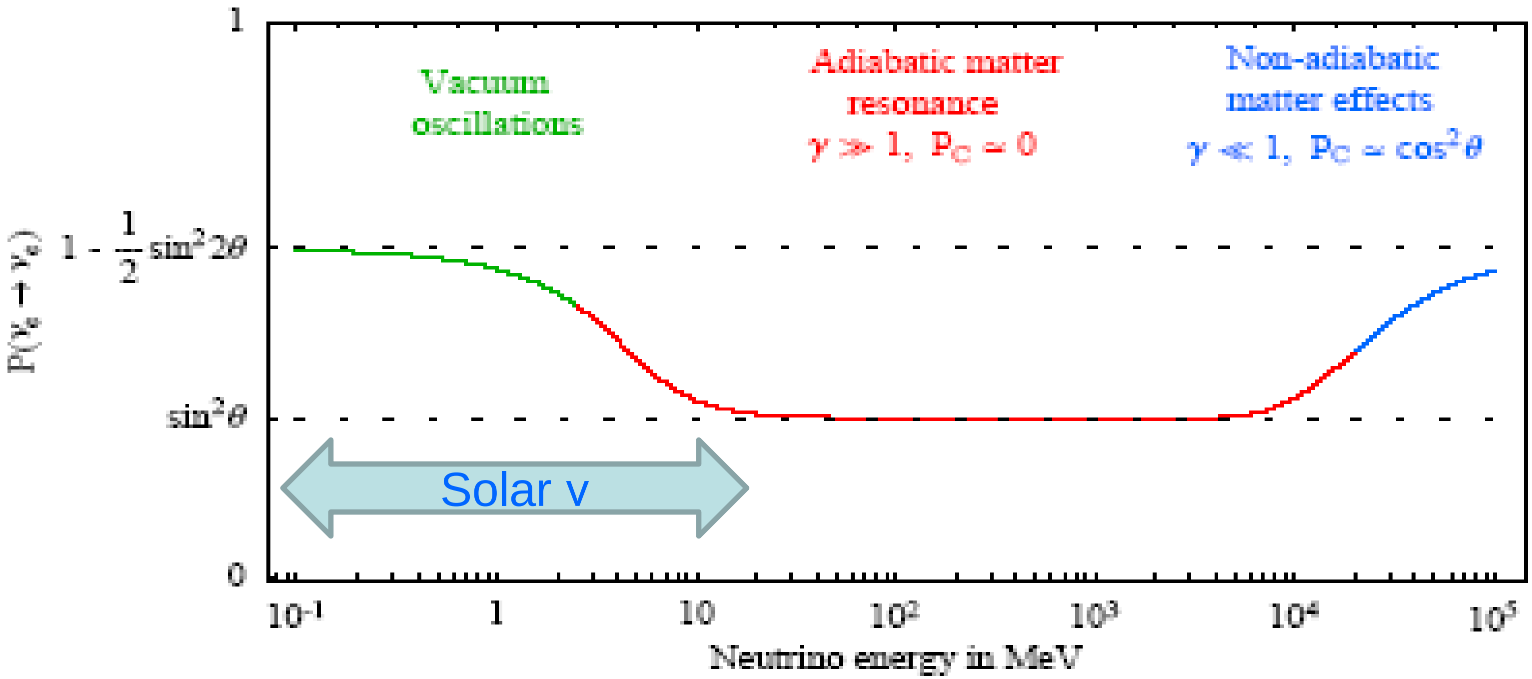
$$\frac{d\Theta_m}{dx}<<\left|\frac{m_{1_m}^2-m_{2_m}^2}{E}\right|$$

P_{LSZ} (Landau-Zenner-Stuckelberg)

$$\left|\nu_{2_m}(x)\right\rangle=\sin\Theta_m\left|\nu_e\right\rangle+\cos\Theta_m\left|\nu_\mu\right\rangle$$

$$\Theta_m=\Theta$$

Electron neutrino survival probability



Поведение вероятности выживания электронного нейтрино:
а)При малых энергиях эффект плотности не влияет на осцилляции
б)При промежуточных энергиях – адиабатический эффект МСВ
в)При больших энергиях условие адиабатичности нарушается

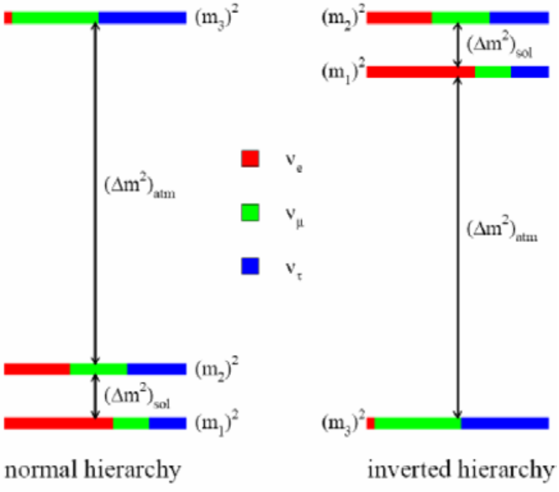
Pontecorvo–Maki–Nakagawa–Sakata matrix

- PMNS matrix - lepton mixing matrix, or neutrino mixing matrix, a unitary matrix which contains information on the mismatch of quantum states of leptons when they propagate freely and when they take part in the weak interactions. Introduced in 1962 by Ziro Maki, Masami Nakagawa and Shoichi Sakata, to explain the neutrino oscillations predicted by Bruno Pontecorvo:

$$U_{PMNS} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{IH} = \begin{pmatrix} 0.822 & 0.547 & -0.150 + 0.0429i \\ -0.354 + 0.0224i & 0.701 + 0.0149i & 0.618 \\ 0.444 + 0.0278i & -0.456 + 0.0186i & 0.770 \end{pmatrix}$$

$$U_{NH} = \begin{pmatrix} 0.822 & 0.547 & -0.150 + 0.0381i \\ -0.356 + 0.0198i & 0.704 + 0.0131i & 0.614 \\ 0.442 + 0.0248i & -0.452 + 0.0166i & 0.774 \end{pmatrix}$$



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

atmospheric ν
+ K2K, MINOS

$\Delta m^2_{23} = 2.4 \cdot 10^{-3}$ eV^2

$\Theta_{23} \sim 42°$

reactor ν
DC, DB, RENO, T2K

$\Delta m^2_{31} \approx \Delta m^2_{atm}$

$\Theta_{13} \sim 9°$

solar ν
+ KamLAND

$\Delta m^2_{12} = 7.6 \cdot 10^{-5}$ eV^2

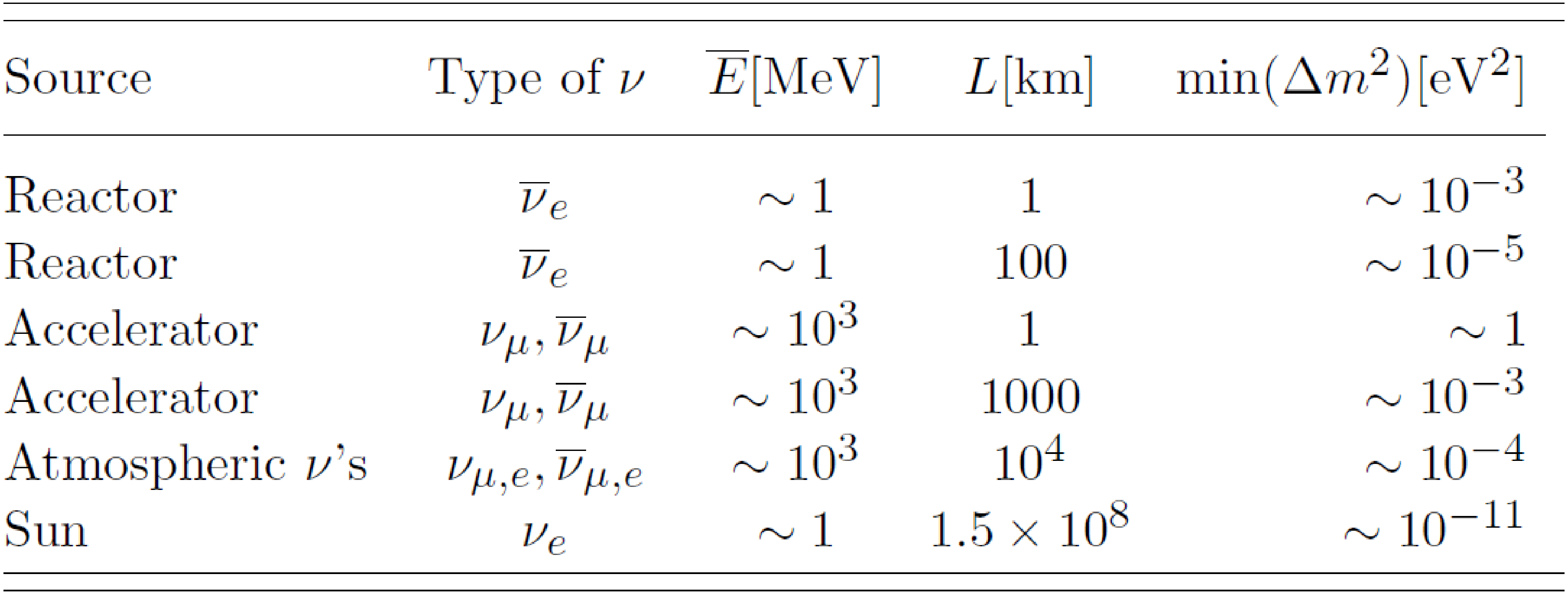
$\theta_{12} = (34 \pm 3)°$

Some open questions in neutrino physics:

- **Mass hierarchy (MH)** ? $\Delta m^2_{31} = m^2_3 - m^2_1 > 0$ or < 0 ?
- **CP phase δ** ?

Sensitivity of different oscillation experiments.

- $S\left(\frac{L}{E}\right) = \sin^2 1.27\Delta m^2[eV]\frac{L[km]}{E[GeV]}$



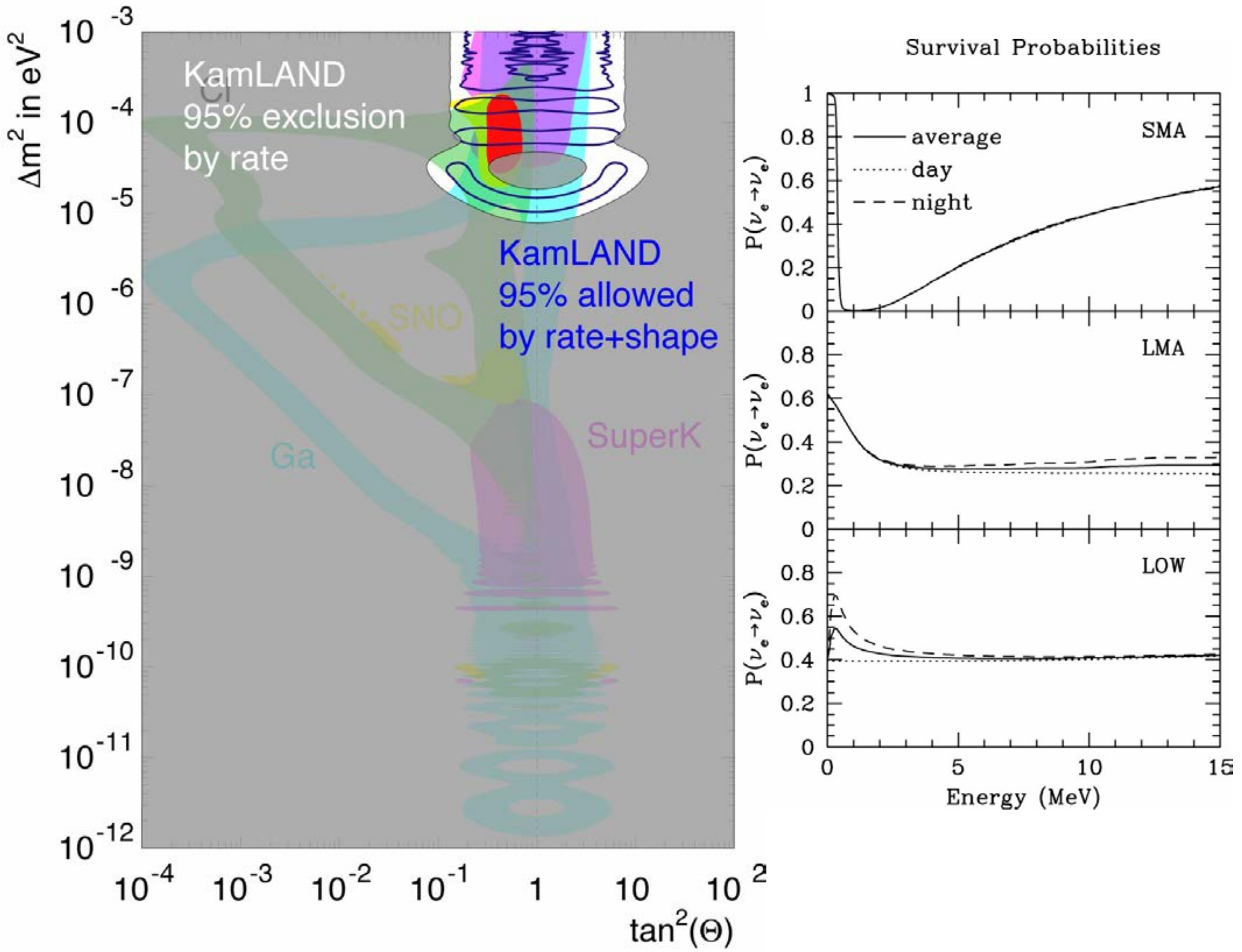
Source	Type of ν	$\overline{E}$[MeV]	L[km]	min(Δm^2)[eV^2]
Reactor	$\overline{\nu}_e$	~ 1	1	$\sim 10^{-3}$
Reactor	$\overline{\nu}_e$	~ 1	100	$\sim 10^{-5}$
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1	~ 1
Accelerator	$\nu_\mu, \overline{\nu}_\mu$	$\sim 10^3$	1000	$\sim 10^{-3}$
Atmospheric ν's	$\nu_{\mu,e}, \overline{\nu}_{\mu,e}$	$\sim 10^3$	10^4	$\sim 10^{-4}$
Sun	ν_e	~ 1	1.5×10^8	$\sim 10^{-11}$

Status MSW in 2002

Before SNO

April 2002
SNO

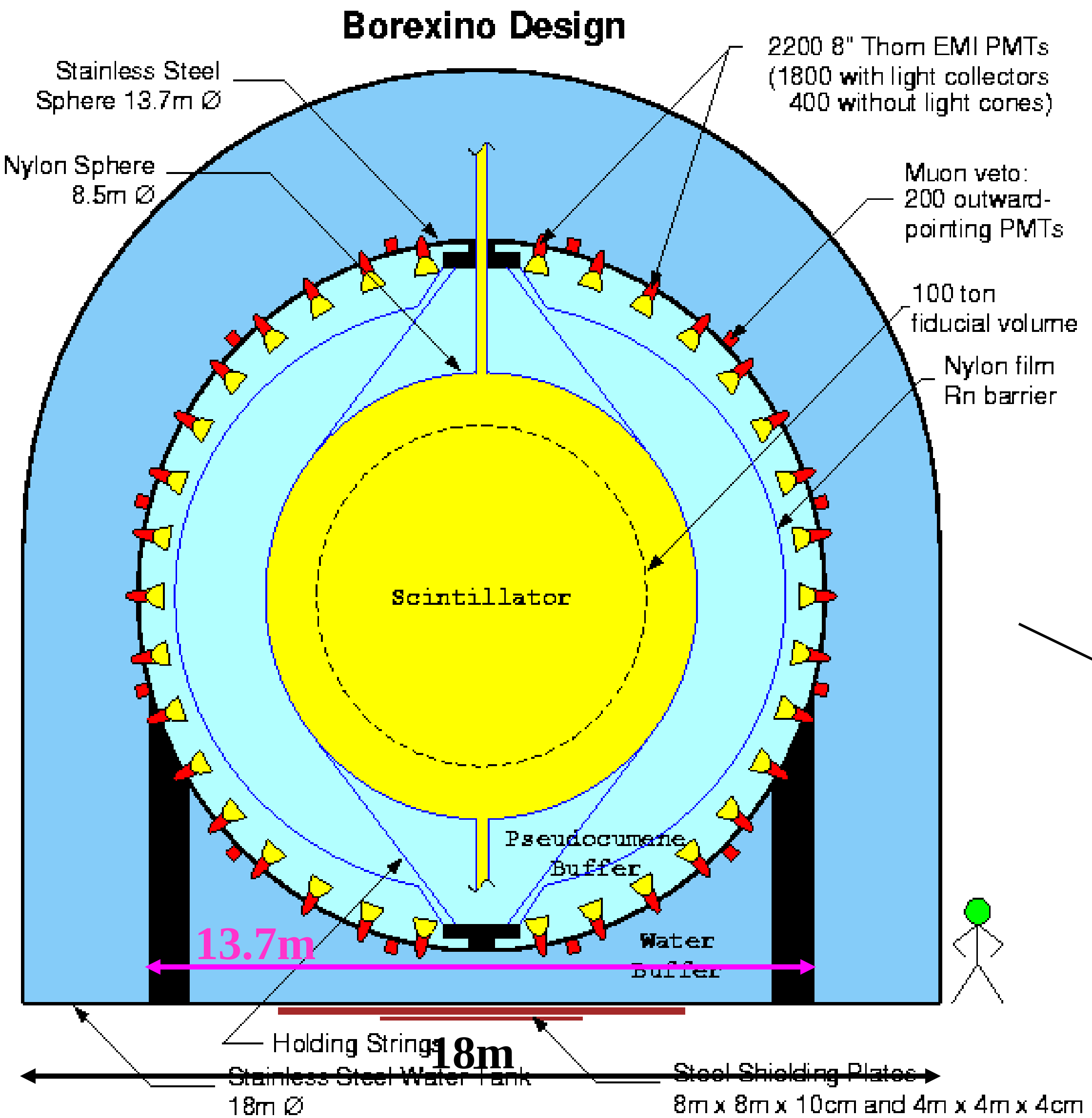
December 2002
KamLAND



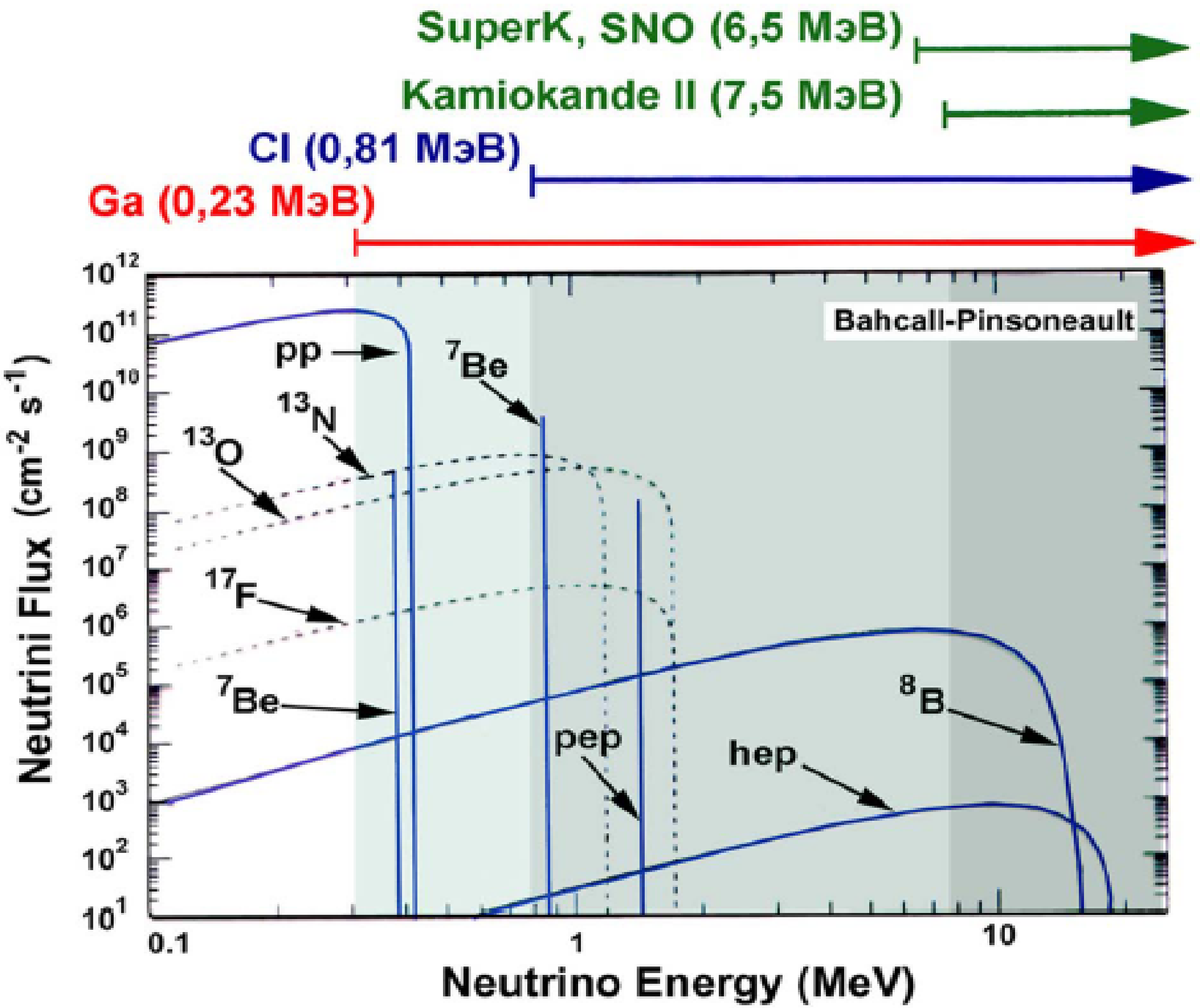
JINR neutrino program

- Last year “White book” was published: 11 neutrino experiments with JINR participation
- 1. BAIKAL (Deep water detector of muons and neutrino in Baikal lake)
- 2. BOREXINO (LS Solar neutrino detector at LNGS)
- 3. Проект νGeN (Experiment at Kalininskaya nuclear power plan on coherent neutrino scattering on Ge nucei)
- 3. DANSS (Detector of the Reactor AntiNeutrino based on Solid Scintillator)
- 4. Daya Bay Experiment (reactor antineutrino experiment)
- 5. GEMMA (Germanium Experiment Searching for Magnetic Moment of Antineutrino)
- 6. GERDA (double beta-decay)
- 7. JUNO (new generation reactor experiment)
- 8. NOVA (new generation accelerator experiment)
- 9. OPERA (accelerator experiment on neutrino oscillations)
- 10. SuperNEMO (Search for neutrinoless double beta decay with NEMO-3 and the next generation double beta decay experiment SuperNEMO)
- 11. EDELWEISS (Experience pour DEtecter Les Wimps En Site Souterrain.)

БОРЕКСИНО: детектор



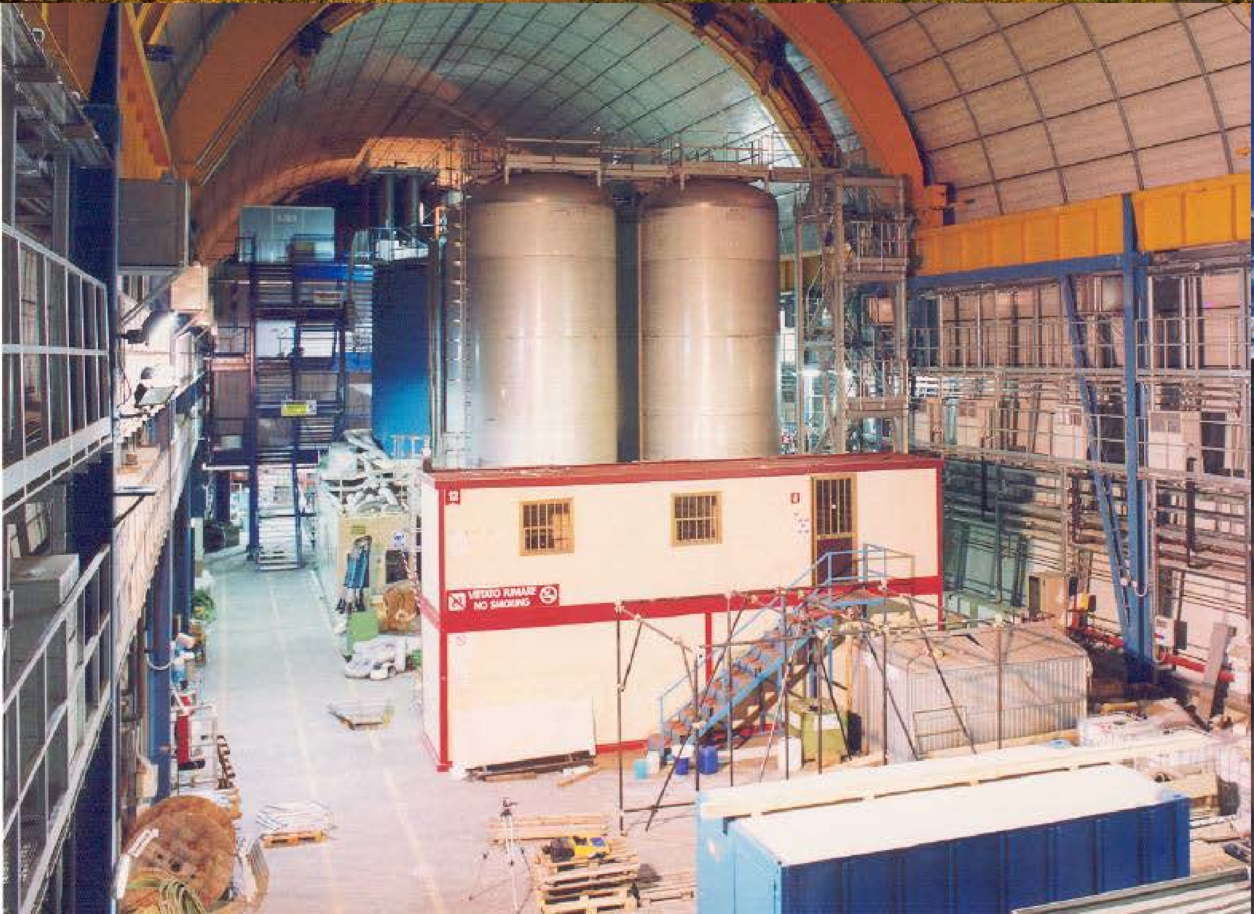
- •300 т жидкого органического сцинтиллятора PC + PPO(1.5 г/л)
- •регистрация (ν,e)-рассеяния с порогом ~200 кэВ

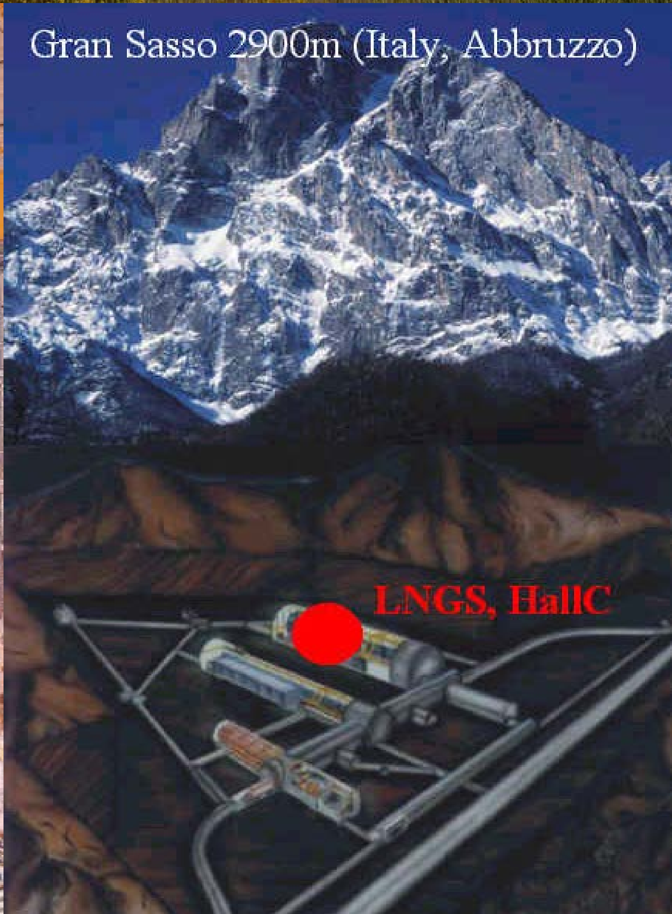


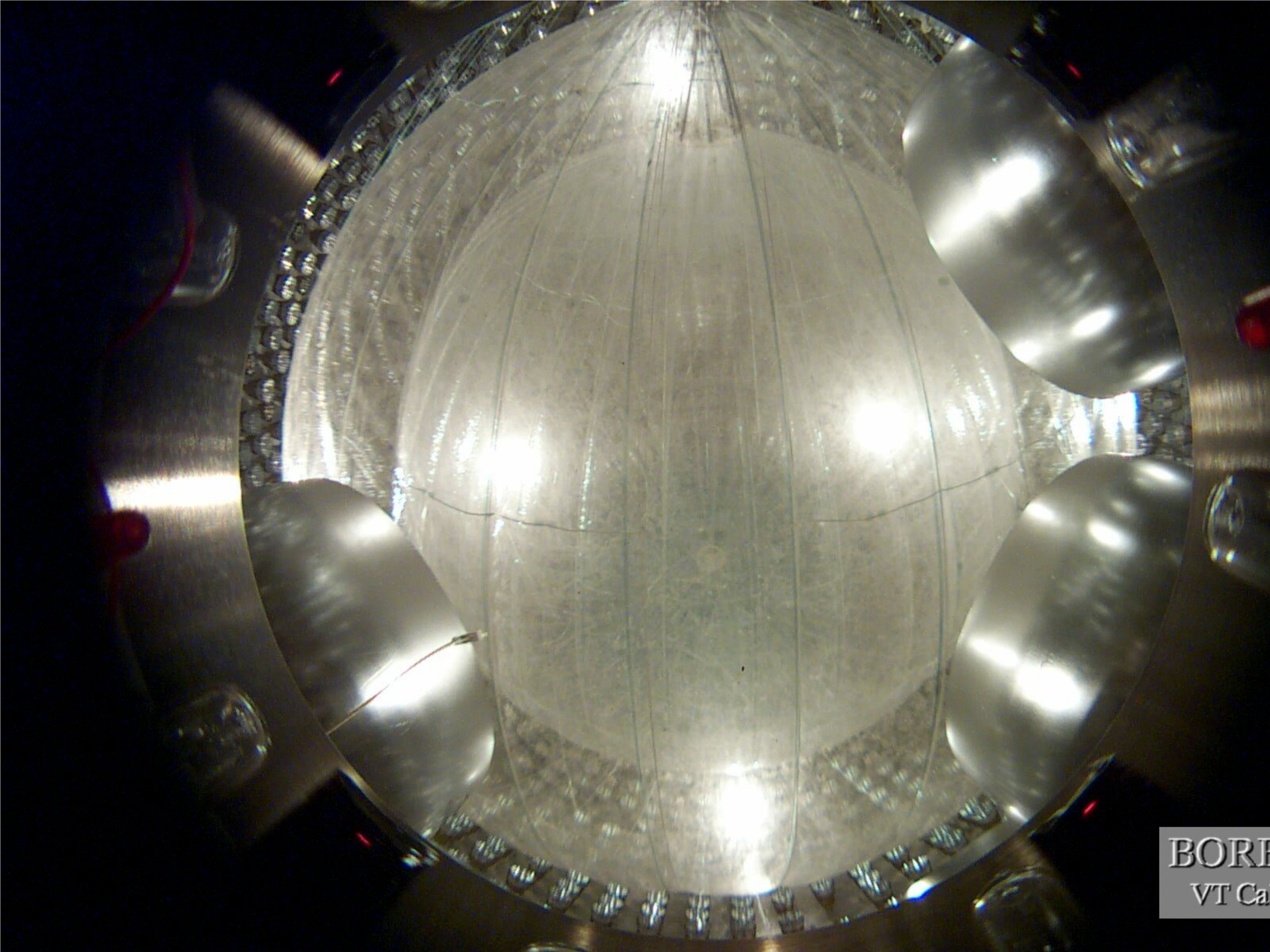
50 соб/день/100 тонн (упругое рассеяние ν_e и ν_μ на e^-)

Низкая энергия→нет Черенковского изл.→ нет чувствительности к направлению

Нет других меток→ требуется чрезвычайно чистый сцинтиллятор


VIETATO FUMARE
NO SMOKING


Gran Sasso 2900m (Italy, Abbruzzo)
LNGS, HallC


BOR
VT Ca

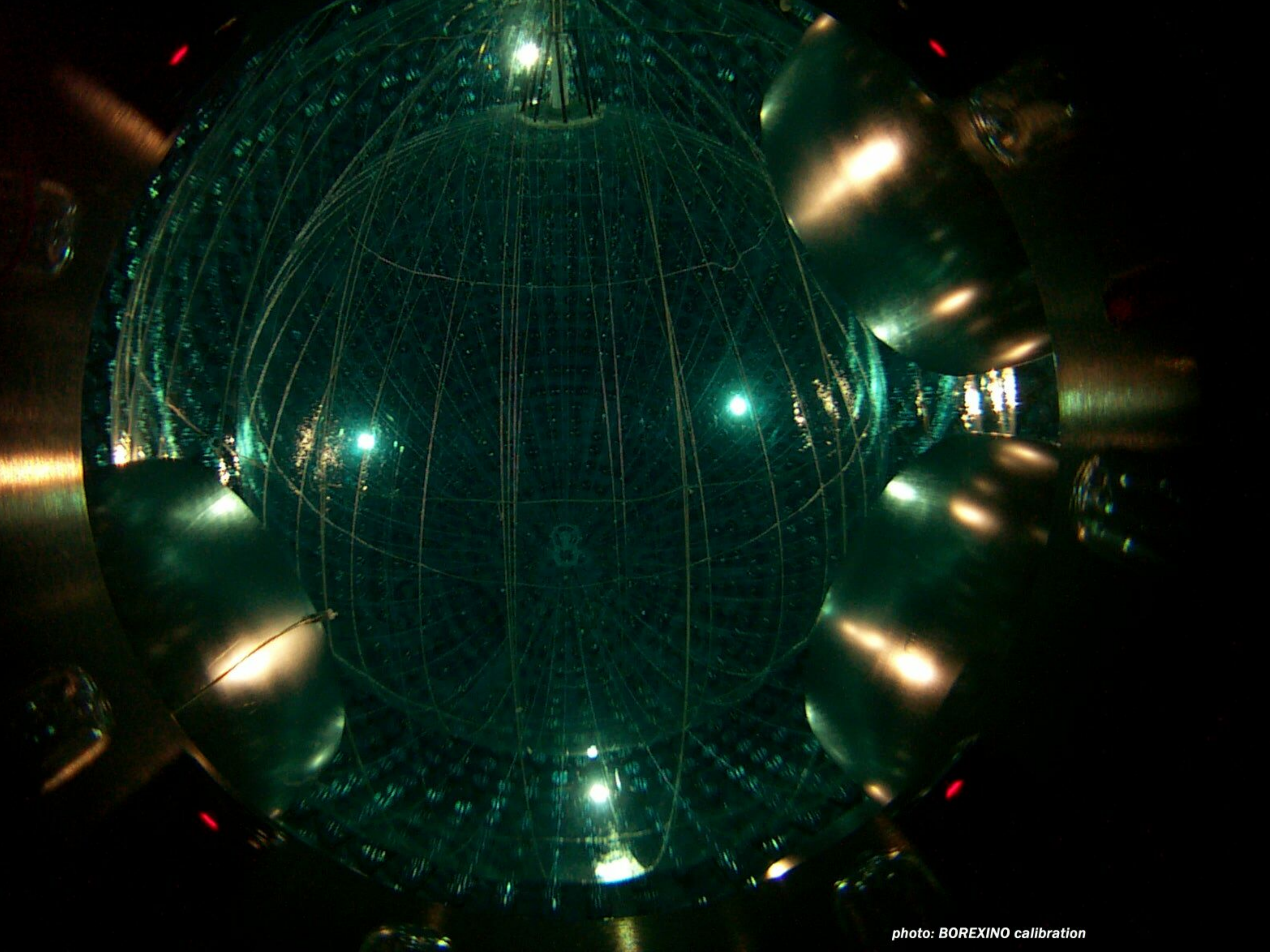


photo: BOREXINO calibration

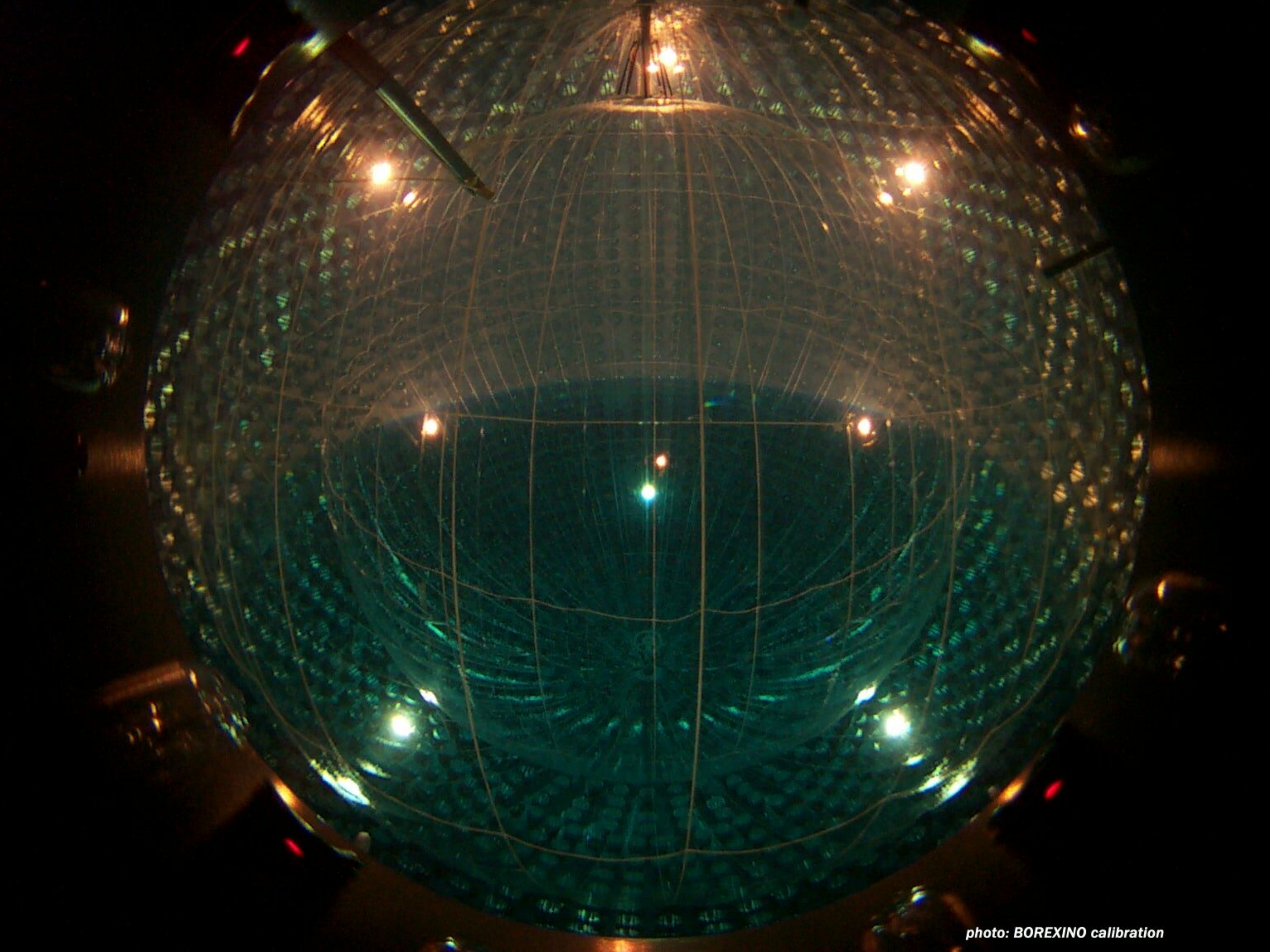
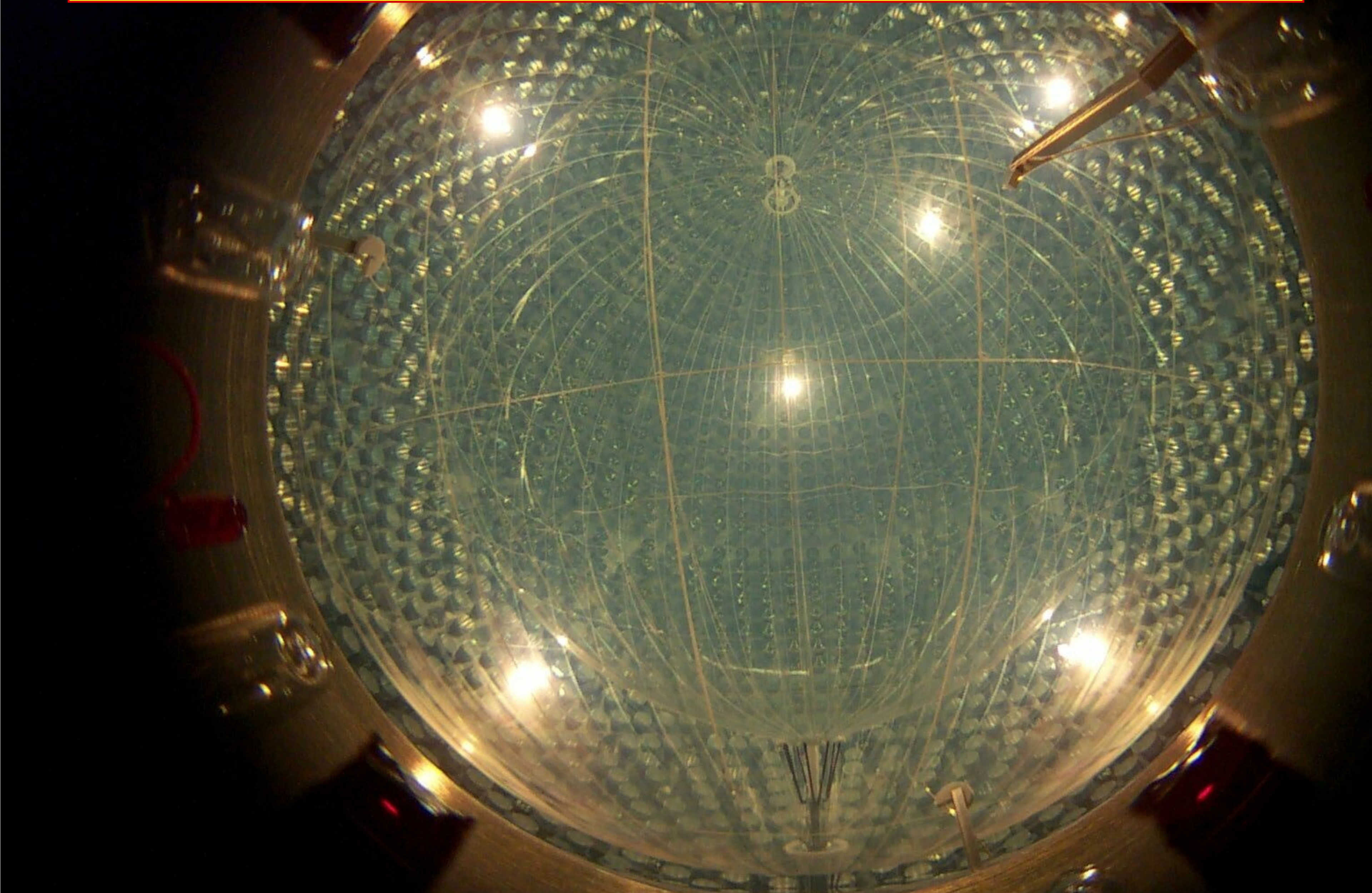
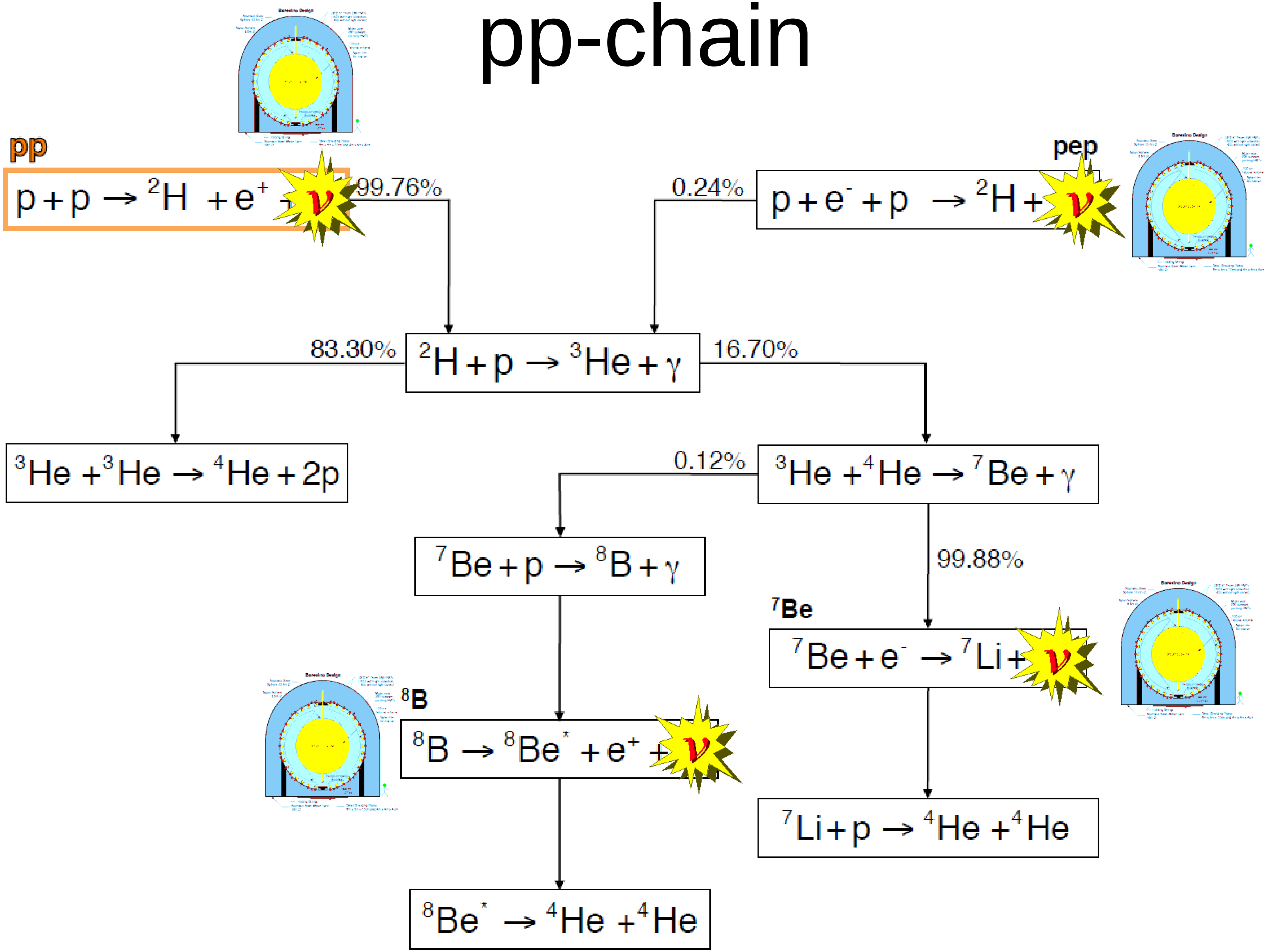


photo: BOREXINO calibration

13-05-2007: before the data taking



pp-chain



pp

$p + p \rightarrow {}^{2}H + e^{+} + \nu$

99.76%

0.24%

pep

$p + e^{-} + p \rightarrow {}^{2}H + \nu$

$^{2}H + p \rightarrow {}^{3}He + \gamma$

83.30%

16.70%

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

0.12%

99.88%

$^{7}Be + p \rightarrow {}^{8}B + \gamma$

^{7}Be

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$

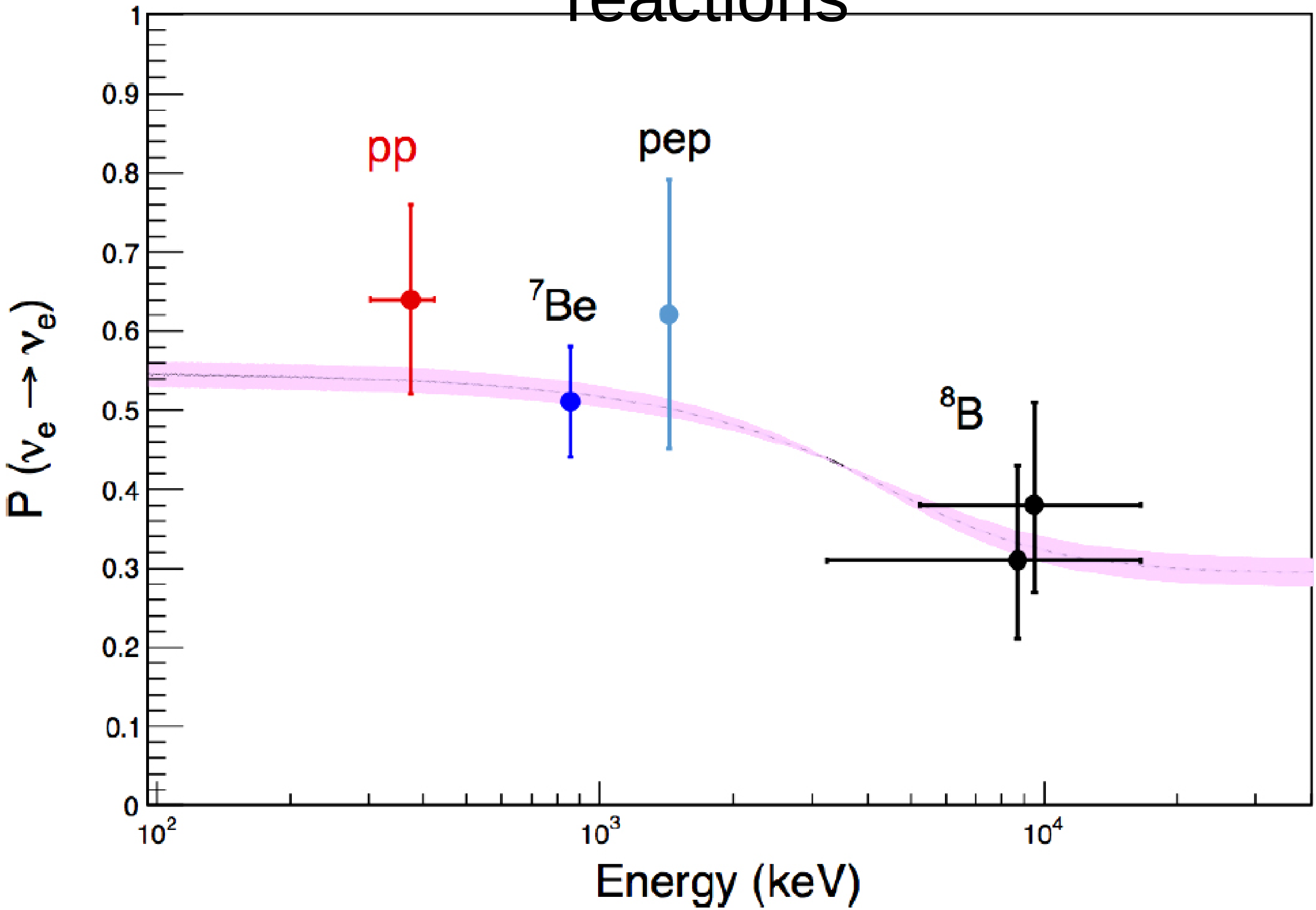
^{8}B

$^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu$

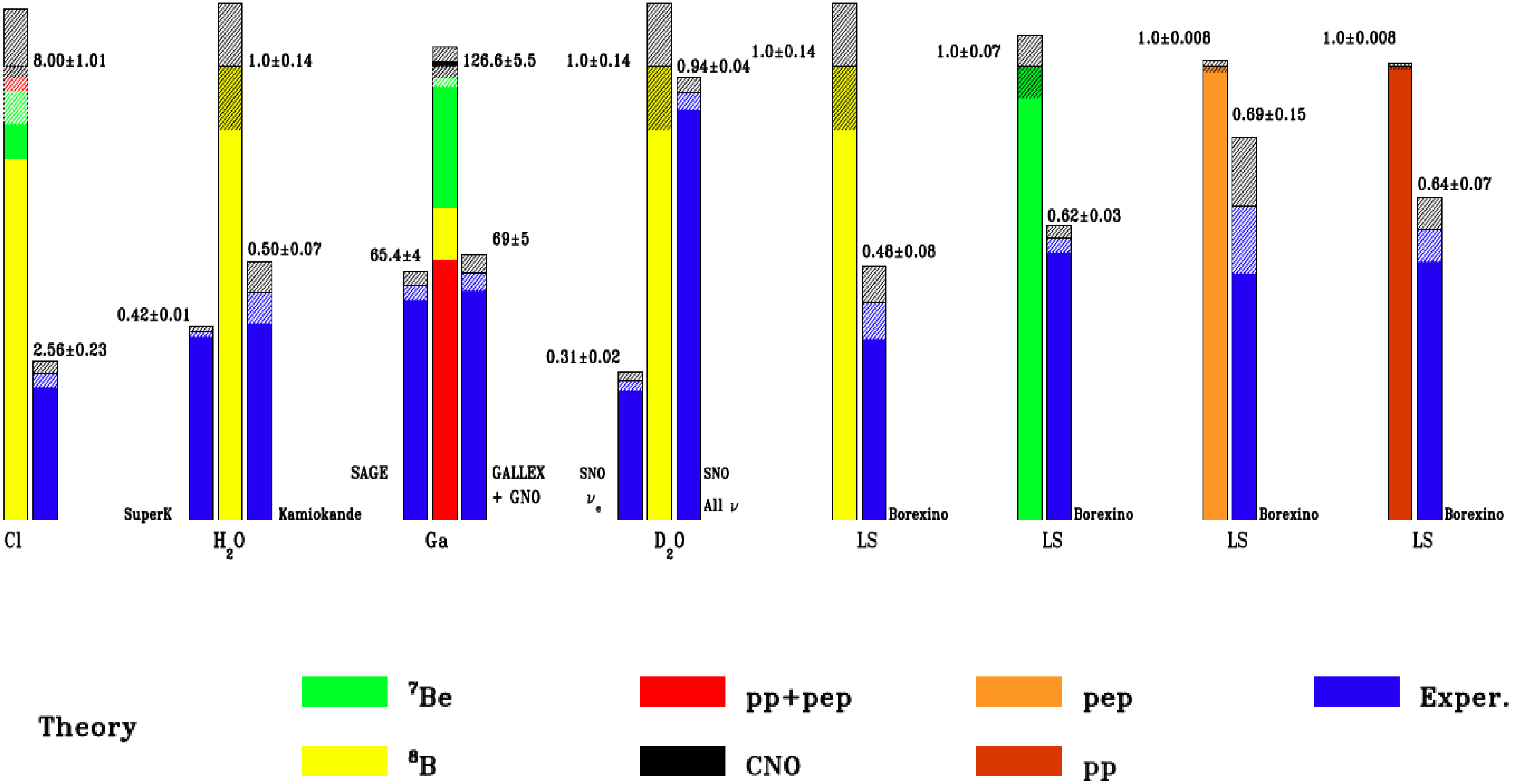
$^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

$^{8}Be^{*} \rightarrow {}^{4}He + {}^{4}He$

Borexino measured electron neutrino survival probability for 4 different nuclear reactions

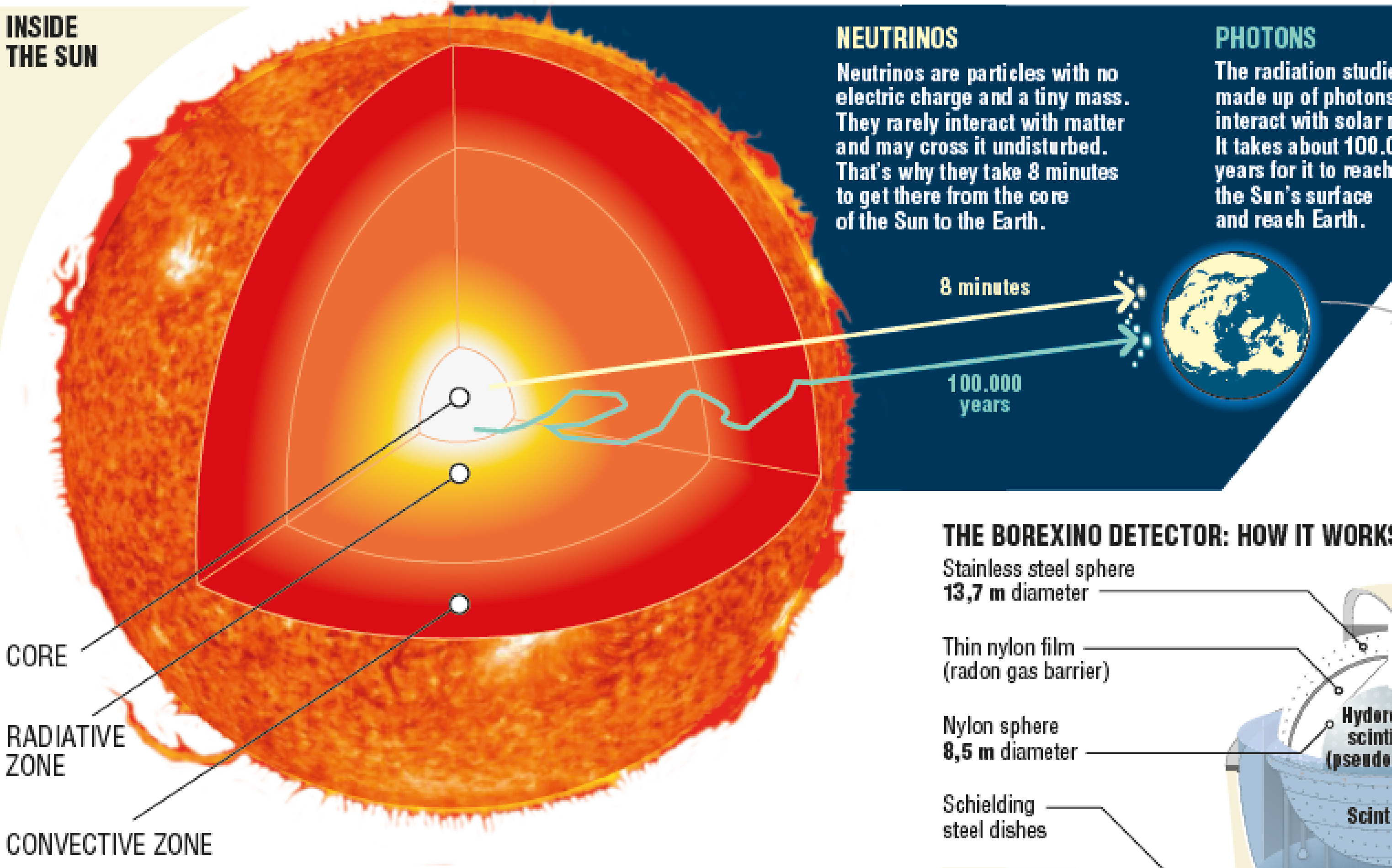


Счет ν : эксперимент в сравнении с SFII(GS98)



THE SUN AS BOREXINO SEES IT IN REAL TIM

INSIDE THE SUN

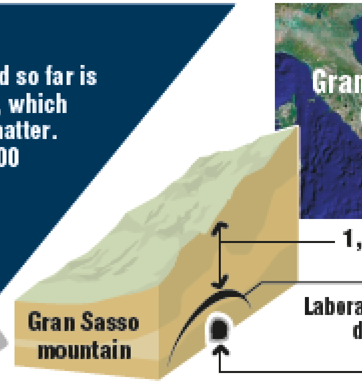


NEUTRINOS

Neutrinos are particles with no electric charge and a tiny mass. They rarely interact with matter and may cross it undisturbed. That's why they take 8 minutes to get there from the core of the Sun to the Earth.

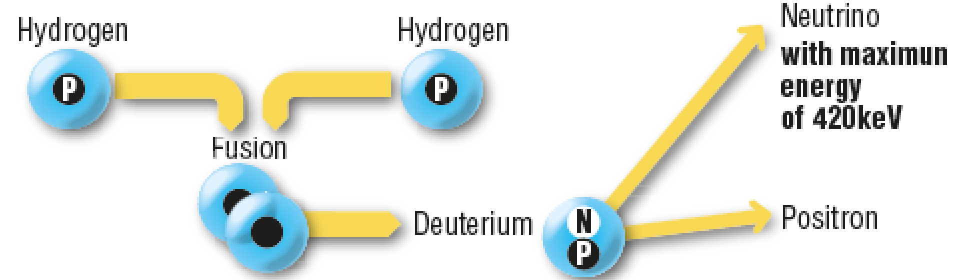
PHOTONS

The radiation studied so far is made up of photons, which interact with solar matter. It takes about 100.000 years for it to reach the Sun's surface and reach Earth.

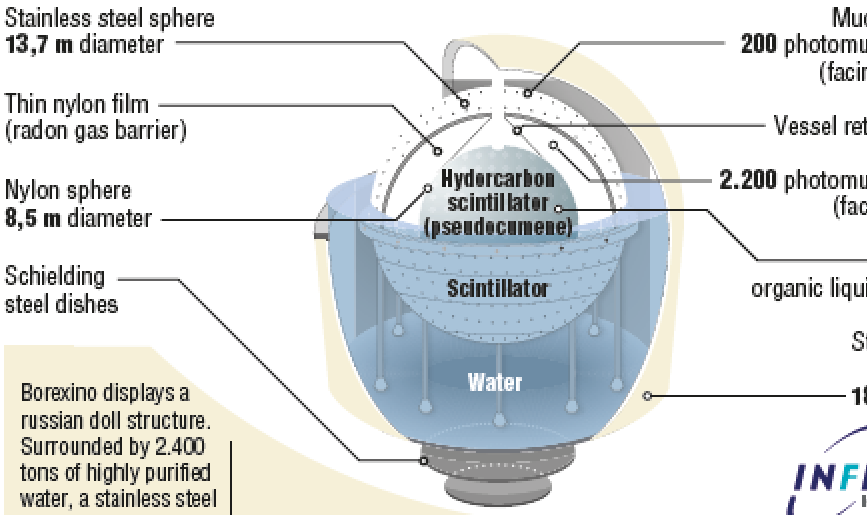


By analyzing P-P neutrino emissi Borexino has shown that the ene produced today in the Sun's core to that produced 100.000 years

THE THERMONUCLEAR FUSION REACTION THAT PRODUCES THE P-P NEUTRINOS RECENTLY STUDIED BY BOREXINO



THE BOREXINO DETECTOR: HOW IT WORKS



Borexino displays a russian doll structure. Surrounded by 2.400 tons of highly purified water, a stainless steel sphere contains 1.000 tons of a liquid hydrocarbon (pseudocumene). At its center, within a smaller nylon sphere, are 300 tons of scintillating liquid.

Within this innermost sphere neutrinos interact with the liquid scintillator producing small flashes of light.

The photomultiplier tubes, acting as ultra-sensitive artificial eyes, detect and record the light flashes produced by the neutrinos.

Borexino observes dozens of these signals every day.

Проблема металличности Солнца и потоки солнечных нейтрино

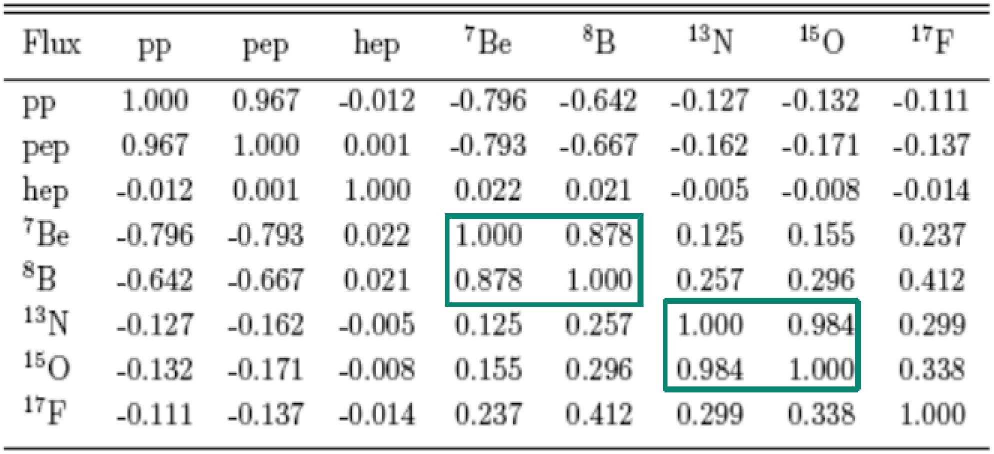
- Распространенность солнечных элементов на поверхности Солнца.
- **[GS98]** Grevesse N., Sauval J. Standart Solar composition : Space Sci. Rev. 1998. V. 85. P. 161–174.
- 1-d модель, согласующаяся с гелиосейсмологией (скорость распространения звуковых волн). Z/X=0.0178 (высокая металличность)
- **[AGS09]** Asplund M., Grevesse N., Sauval A.J., Scott P. The chemical composition of the Sun : Ann. Rev. Astron. Astrophys. 2009. V. 47. P. 481–522.
- 3-d магнитогидродинамическая модель конвективной зоны, фотосферы, хромосферы и короны. Воспроизводит наблюдаемый профиль атомных и молекулярных линий в солнечной атмосфере, но противоречит гелиосейсмологии. Z/X=0.0229 (высокая металличность)

На сегодня нет удовлетворительного объяснения расхождений (Serenelli A.M., Haxton W.C. and Pena-Garay C. Astrophys. J. 7432 (2011) 4.)

Потоки солнечных нейтрино и предсказания СМС для двух моделей

ν flux	GS98	AGS09	$cm^{-2}s^{-1}$	Experimental results
pep	1.44±0.012	1.47±0.012	x 10^8	1.6±0.3 Borexino
^{7}Be	5.00±0.07	4.56±0.07	x 10^9	4.87±0.24 Borexino
^{8}B	5.58±0.14	4.59±0.14	x 10^6	5.2±0.3 SNO+SK+Borexino+Kamland 5.25±0.16+0.011-0.013 SNO-LETA
^{13}N	2.96±0.14	2.17±0.14	x10^8	
^{15}O	2.23±0.15	1.56±0.15	x 10^8	< 7.4 Borexino (total CNO)
^{17}F	5.52±0.17	3.40±0.16	x10^6	

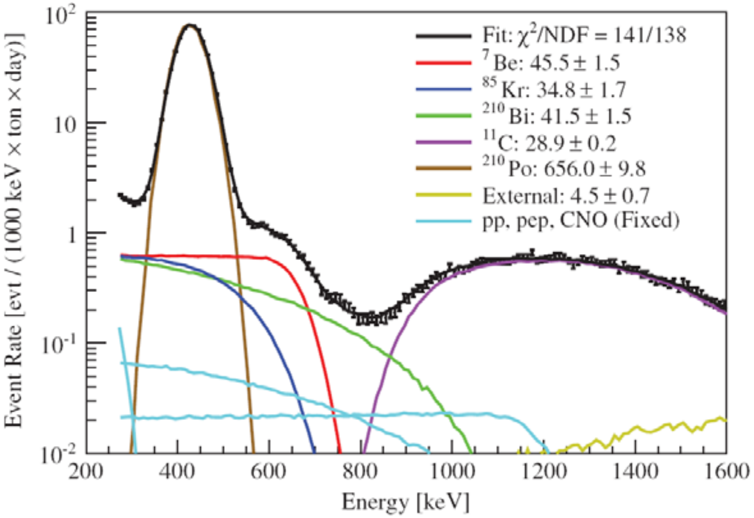
Корелляции потоков могут помочь различить модели:

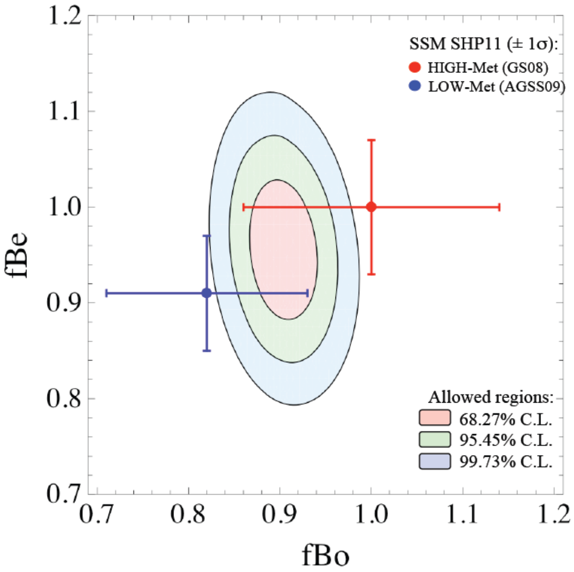


Flux	pp	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
pp	1.000	0.967	-0.012	-0.796	-0.642	-0.127	-0.132	-0.111
pep	0.967	1.000	0.001	-0.793	-0.667	-0.162	-0.171	-0.137
hep	-0.012	0.001	1.000	0.022	0.021	-0.005	-0.008	-0.014
^{7}Be	-0.796	-0.793	0.022	1.000	0.878	0.125	0.155	0.237
^{8}B	-0.642	-0.667	0.021	0.878	1.000	0.257	0.296	0.412
^{13}N	-0.127	-0.162	-0.005	0.125	0.257	1.000	0.984	0.299
^{15}O	-0.132	-0.171	-0.008	0.155	0.296	0.984	1.000	0.338
^{17}F	-0.111	-0.137	-0.014	0.237	0.412	0.299	0.338	1.000

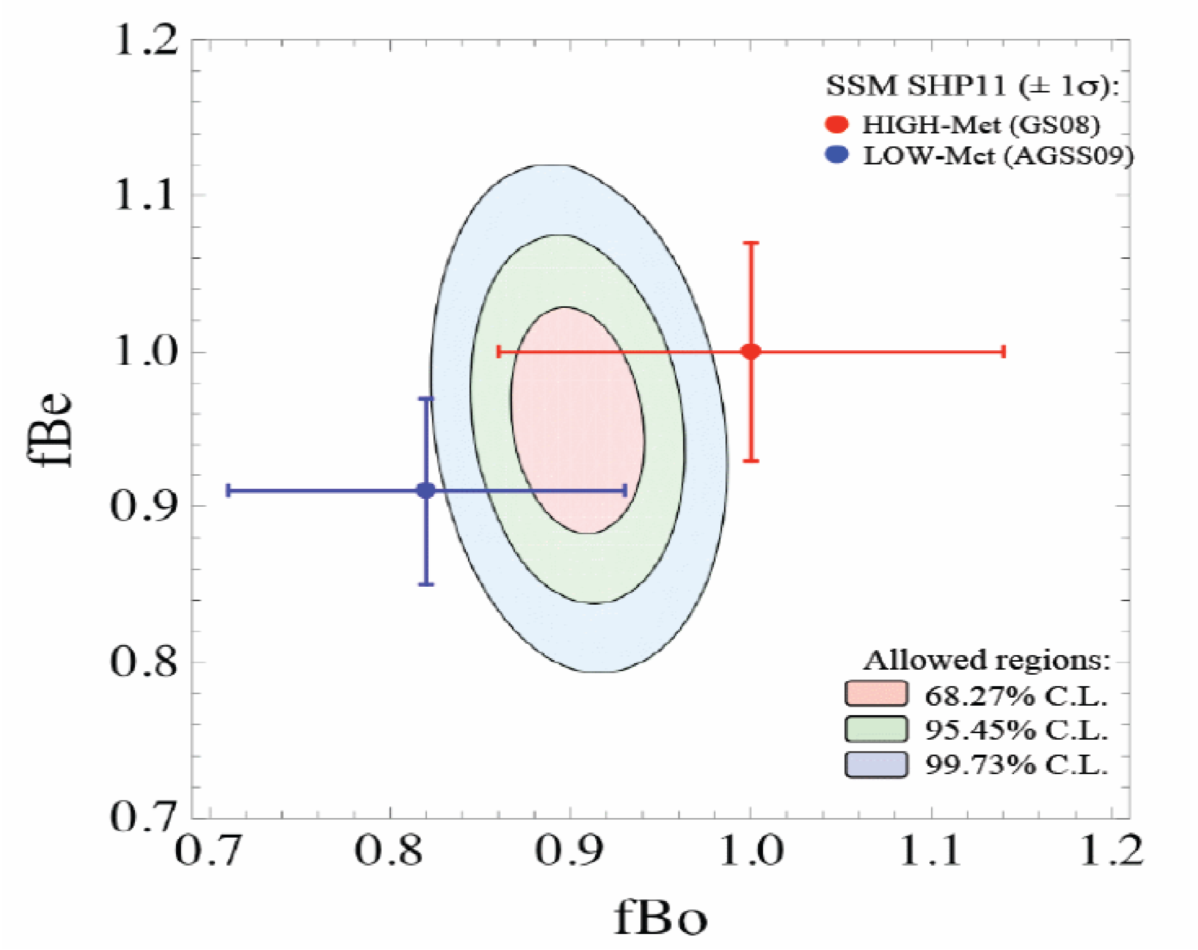
CNO-neutrinos and improved ^{7}Be-neutrino flux measurements: ways for the Solar Models discrimination

ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p\to{}^2H+e^++\nu$	0.42	$5.98(1\pm0.006)$	$6.03(1\pm0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^-+p\to{}^2H+\nu$	1.44	$1.44(1\pm0.012)$	$1.47(1\pm0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^8/cm^2s$
$^7Be+e^-\to{}^7Li+\nu$	0.86 (90%)	$5.00(1\pm0.07)$	$4.56(1\pm0.07)$	$4.82(1^{+0.05}_{-0.04})$	$10^9/cm^2s$
	0.38 (10%)				
$^8B\to{}^8Be+e^++\nu$	$\sim$ 15	$5.58(1\pm0.14)$	$4.59(1\pm0.14)$	$5.00(1\pm0.03)$	$10^6/cm^2s$
$^3He+p\to{}^4He+e^++\nu$	18.77	$8.04(1\pm0.30)$	$8.31(1\pm0.30)$	—	$10^3/cm^2s$
$^{13}N\to{}^{13}C+e^++\nu$	1.20	$2.96(1\pm0.14)$	$2.17(1\pm0.14)$	≤ 6.7	$10^8/cm^2s$
$^{15}O\to{}^{15}N+e^++\nu$	1.73	$2.23(1\pm0.15)$	$1.56(1\pm0.15)$	≤ 3.2	$10^8/cm^2s$
$^{17}F\to{}^{17}0+e^++\nu$	1.74	$5.52(1\pm0.17)$	$3.40(1\pm0.16)$	$\leq 59.$	$10^6/cm^2s$
χ^2/P^{agr}		3.5/90%	3.4/90%		





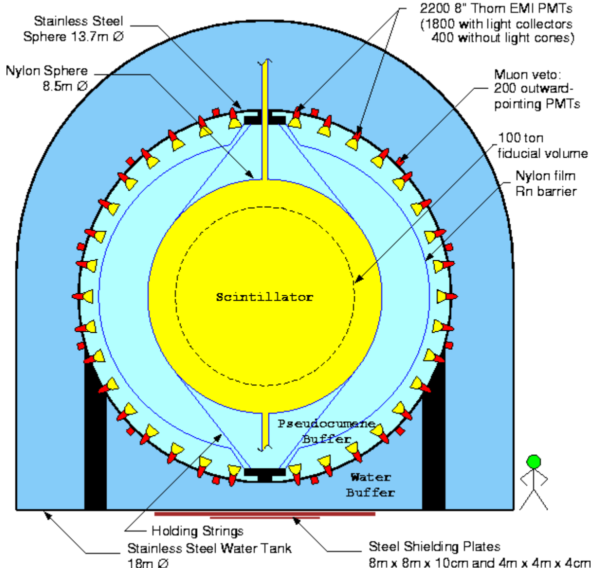
Борные и бериллиевые нейтрино в сравнении с предсказаниями двух вариантов СМС



Геонейтрино

- **геонейтрино**- антинейтрино от β- распадов долгоживущих изотопов (уран-238 , торий-232 и др.), присутствующих в коре и мантии Земли, ожидамый поток нейтрино на поверхности Земли $\sim 10^6$ с$^{-1}$см$^{-2}$.
- Полный тепловой поток от Земли составляет 30-45 ТВт (по результатам измерений). Считается, что основной вклад в тепло Земли дают именно распады радиоактивных элементов.
- Радиогенное тепло связано с количеством антинейтрино. Общепринятые модели (основанные на изучении состава метеоритов и измерении состава земной коры) предсказывают радиогенный вклад в полное тепло Земли около 19 ТВт.
- Высказывалост также предположение о существовании в центре Земли естественного ядерного реактора с мощностью 3-6 ТВт. Такой реактор обеспечивал бы энергией источник магнитного поля Земли, давал недостающее тепло, и объяснял “высокое” отношение потоков ^{3}He/^{4}He у земли.
- Детектор Borexino с достоверностью 99,997% зарегистрировал геонейтрино. Характеристики нейтринного сигнала исключают наличие в ядре Земли природного ядерного реактора мощностью более 4.5 ТВт с достоверностью 95%.

Детектор Борексино:
300 тонн ЖС, 3500 м.в.э.

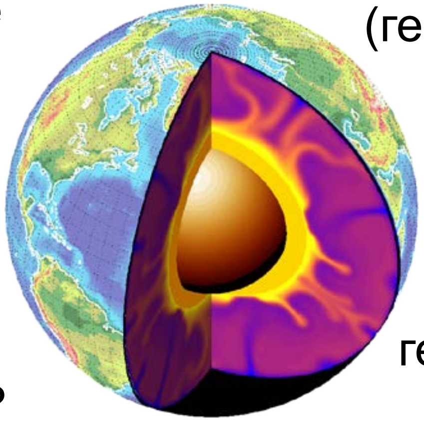


Естественная радиоактивность Земли : открытые вопросы

Радиогенный вклад в полное тепло?

Концентрация U/Th в коре?

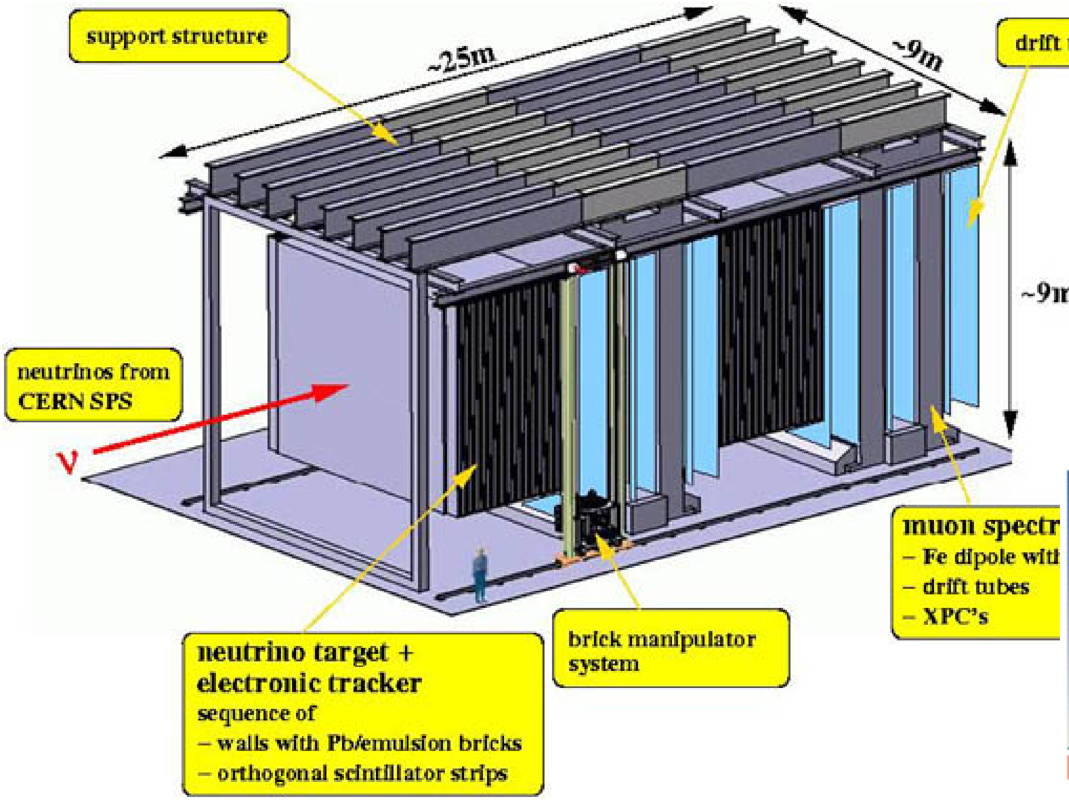
Концентрация U/Th в мантии?



Что скрыто в ядре (геореактор, ^{40}K)?

Совместима ли стандартная геохимическая модель (BSE) с геонейтринными измерениями?

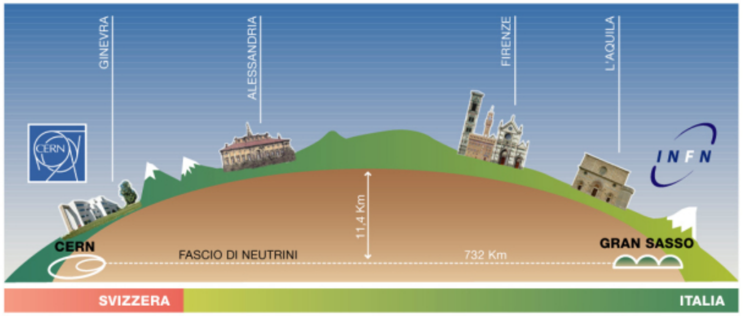
OPERA experiment



Oscillation Project with Emulsion-tRacking Apparatus

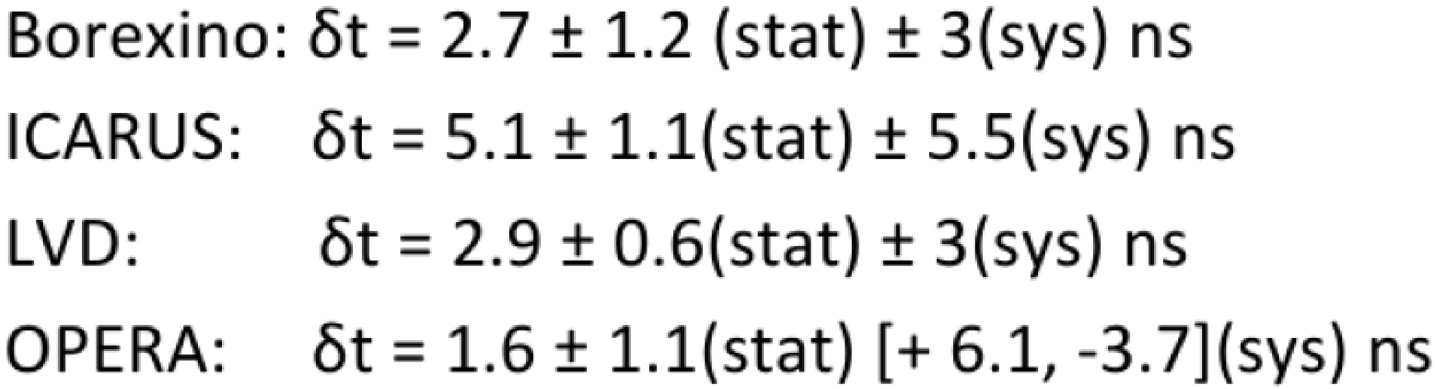
Search for tau neutrino In muon neutrino beam

(~17 GeV)



March, 27, 2014 THE *FOURTH TRANSFORMATION* OF NEUTRINOS
The neutrino indeed started its flight at CERN as muon neutrino and, after travelling 730 km through the Earth, it arrived at the Gran Sasso laboratory transformed into a tau neutrino. This transition is now seen for the first time with a statistical significance exceeding the 4 sigma level

Sensation of 2011 – superluminal neutrino



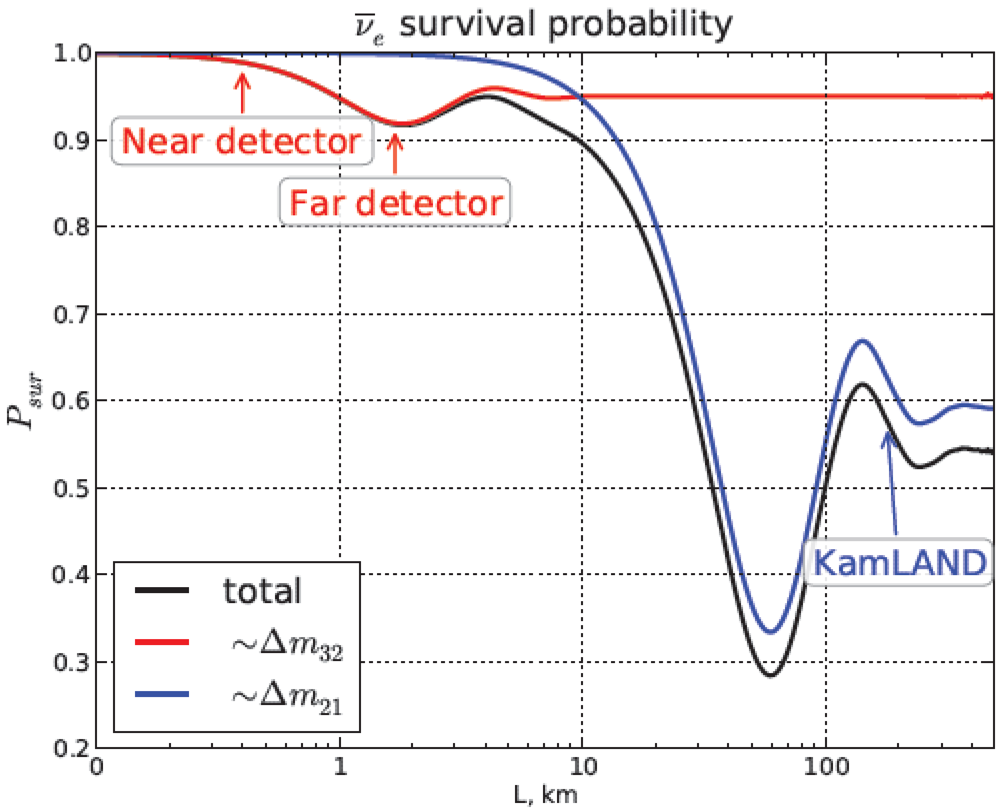
Borexino: $\delta t = 2.7 \pm 1.2$ (stat) $\pm$ 3(sys) ns

ICARUS: $\delta t = 5.1 \pm 1.1$(stat) $\pm$ 5.5(sys) ns

LVD: $\delta t = 2.9 \pm 0.6$(stat) $\pm$ 3(sys) ns

OPERA: $\delta t = 1.6 \pm 1.1$(stat) [+ 6.1, -3.7](sys) ns

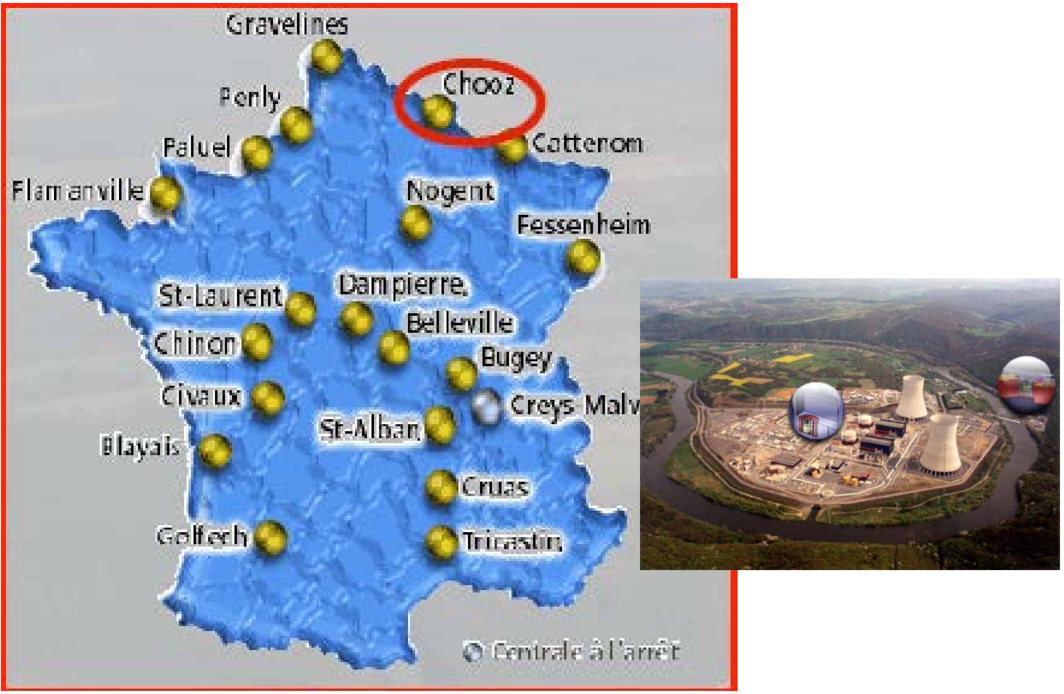
Поиск осцилляций в реакторных экспериментах



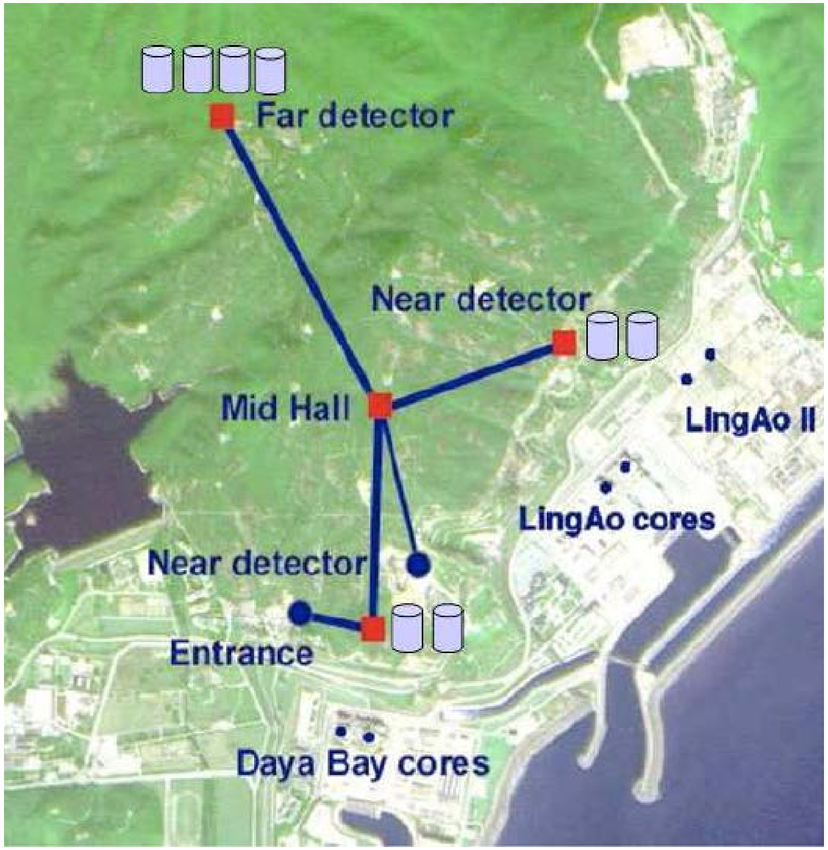
Новое поколение экспериментов (Double Chooz, Daya Bay, RENO) использует 2 набора детекторов. Ближный детектор позволяет произвести измерение потока с высокой точностью. Используется ЖС с присадкой Gd (металлоорганика)

$$1 - P_{\nu_e \to \nu_e} \approx \underline{\sin^2 2\theta_{13}}\, \sin^2 \Delta_{32} + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

$$\Delta_{jk} = 1267 \cdot \frac{\Delta m^2_{jk}}{\mathrm{eV}^2} \frac{L}{E} \left[\frac{\mathrm{MeV}}{\mathrm{km}}\right]$$



Double Chooz

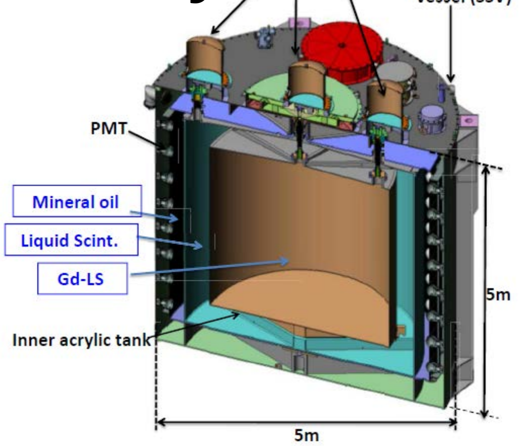


YongGwang

(靈光)：

RENO

Daya Bay

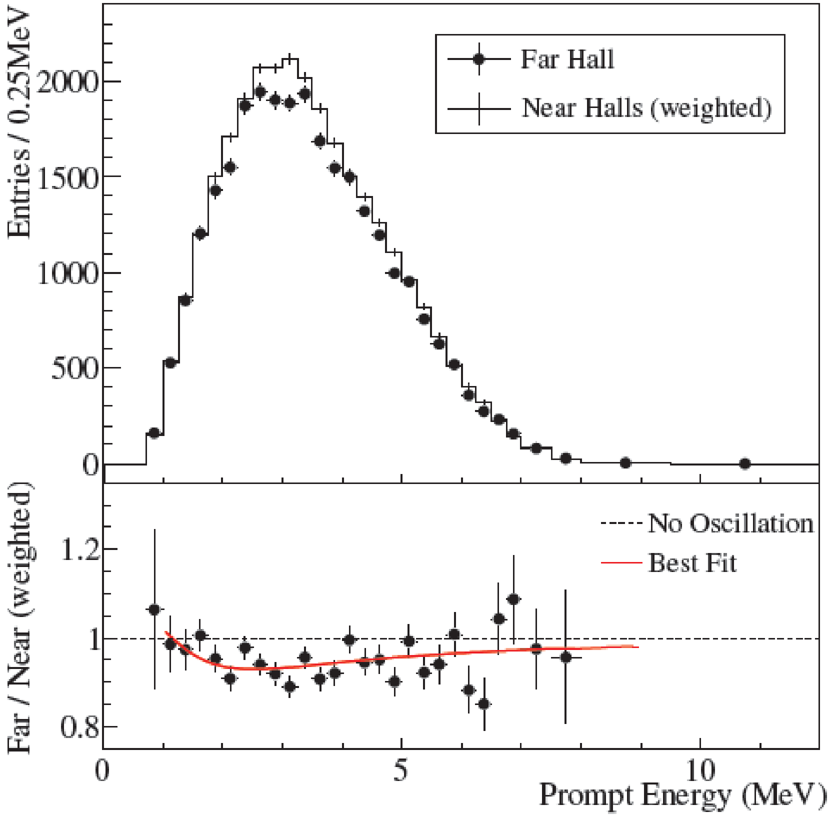


Results $(sin^2 2\Theta_{13})$

Date	Daya Bay	Double CHOOZ	RENO
11.2011		0.102±0.028±0.033 (<3σ)	
08.03.2012	0.092±0.016±0.005 (>3σ)		
03.04.2012			0.113±0.013±0.019 (>3σ)
Neutrino-2014	0.084±0.005	0.09±0.03	0.101±0.013

Daya Bay

Far vs. near comparison



$$R = \frac{Far_{measured}}{Far_{expected}} =$$

$$= \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6} \alpha_i (M_1 + M_2) + \beta_i M_3}$$

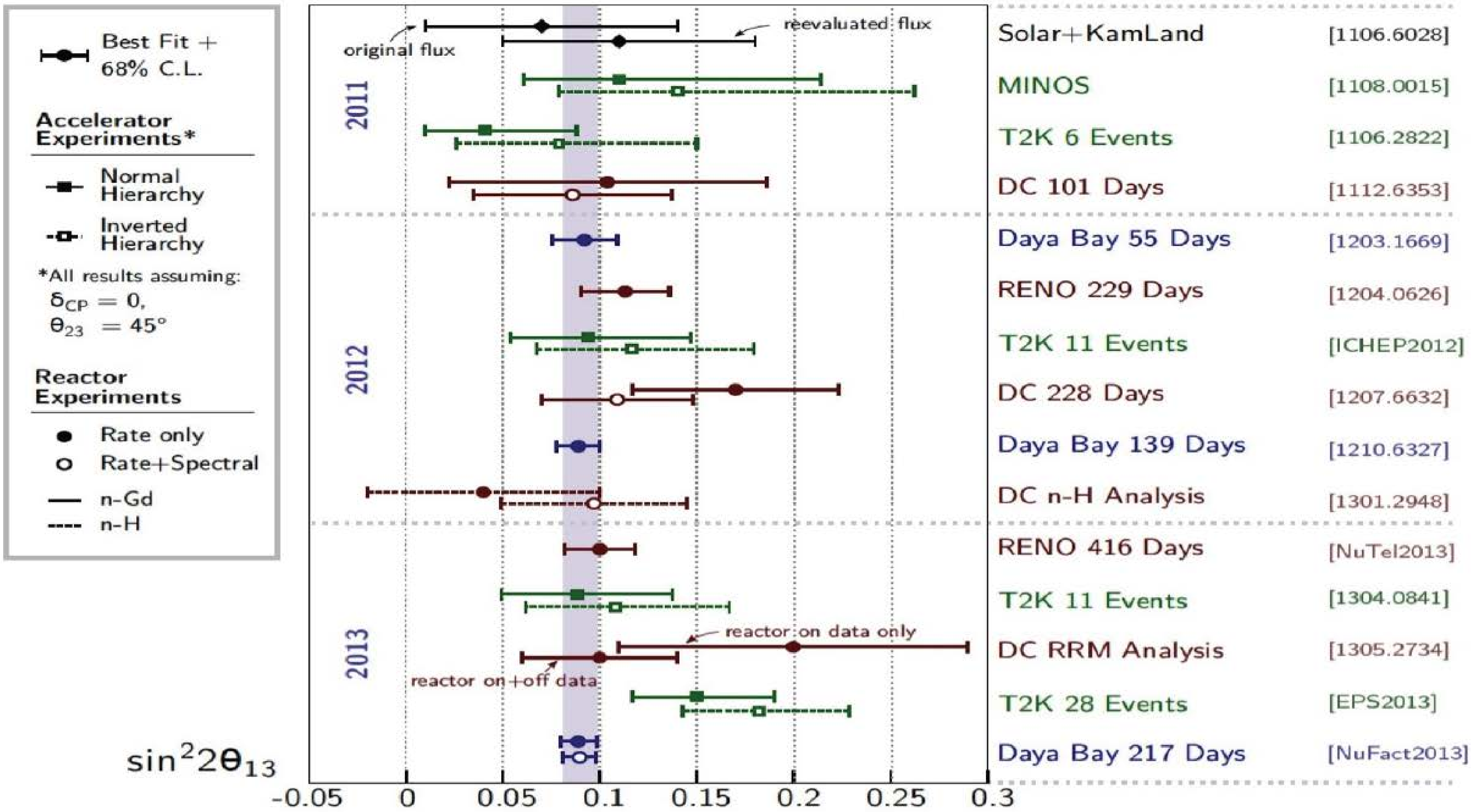
M_i — measured rates in each detector.

α_i, β_i — weights, determined from baselines and reactor fluxes.

- Clear observation of far site deficit.
- Spectral distortion is consistent with oscillation.
- Though spectral systematics is not yet fully studied.

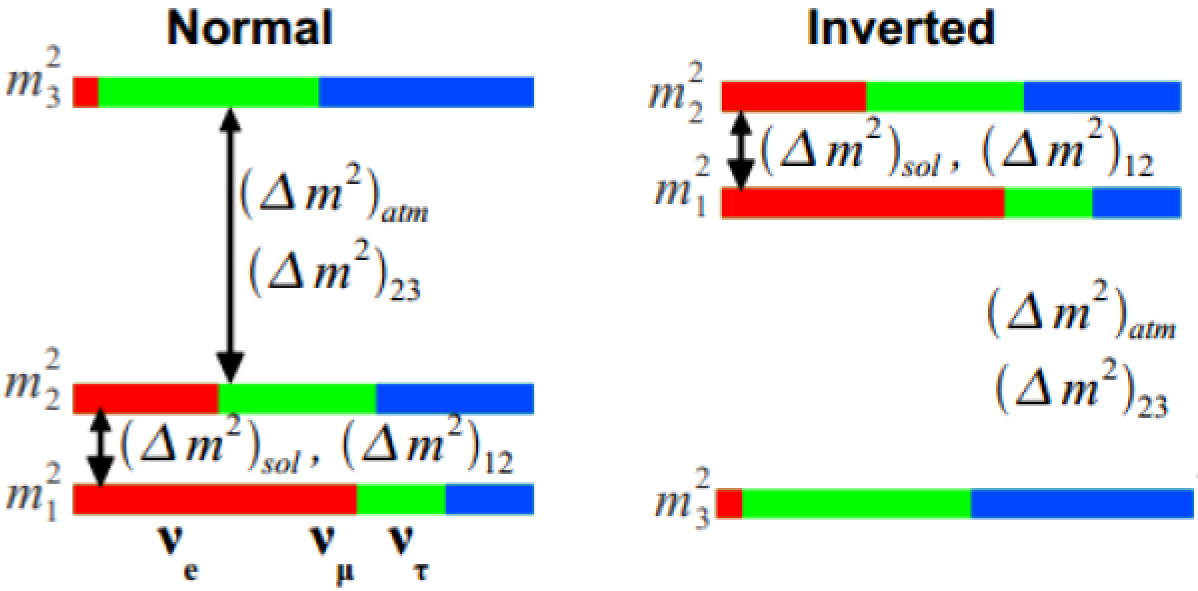
$$R = 0.944 \pm 0.007 \text{ (stat)} \pm 0.003 \text{ (syst)}$$

Quest for theta13



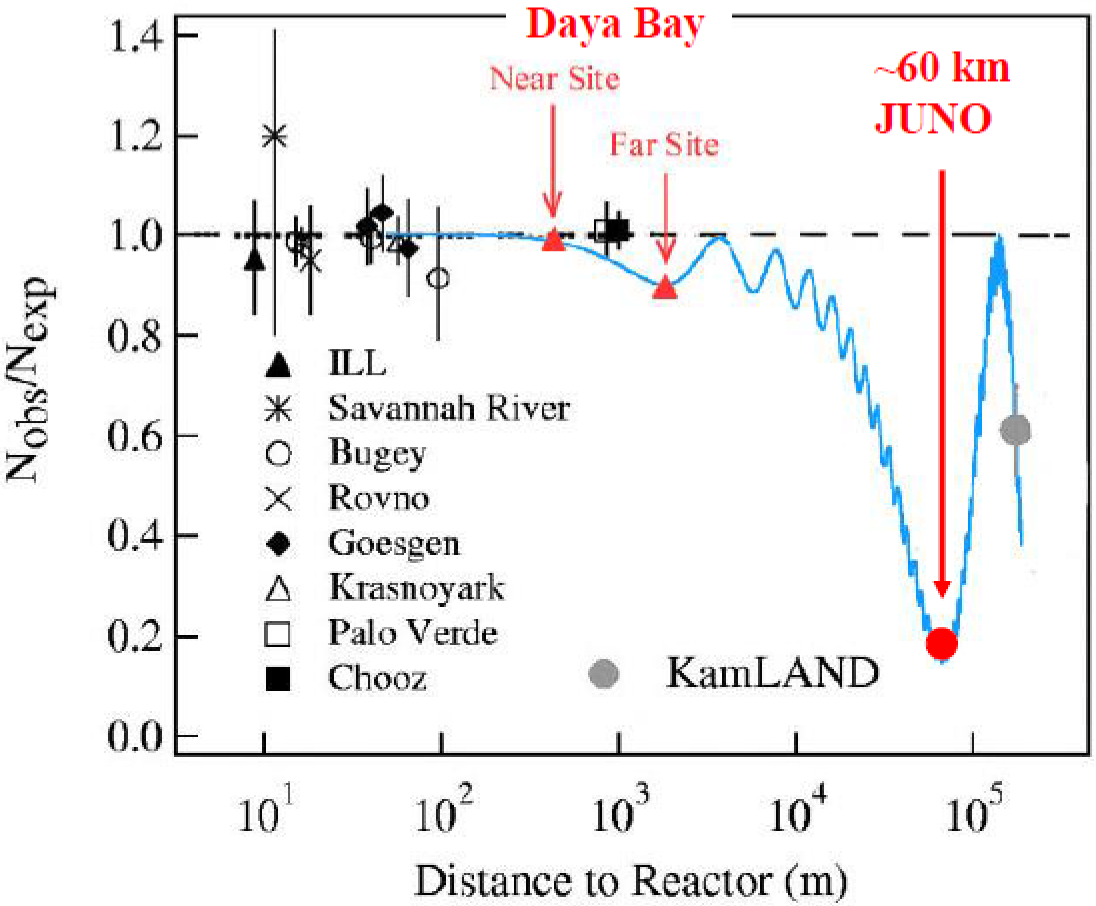
Why new large neutrino detectors ?

- Mass hierarchy (NOvA, T2K, JUNO)
- CP-violation phase (NOvA, T2K)
- Dirac or Majorana (EXO-200, KamLand-Zen, GERDA)



JUNO Experiment

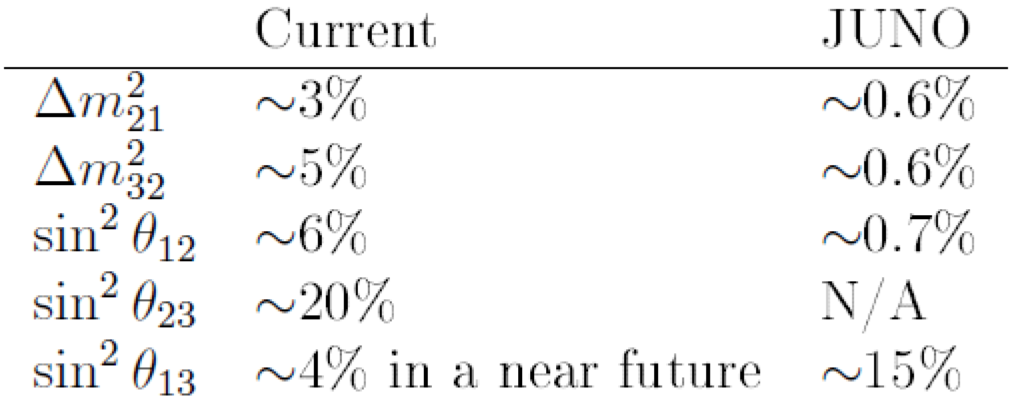
- ☐ Jiangmen Underground Neutrino Observatory (was Daya Bay II)
- ☐ Primary goals: mass hierarchy and precision meas.
  - ➢ 20 kton LS detector, 3%/$\sqrt{E}$ energy resolution
- ☐ Proposed in 2008, approved in Feb.2013. ~300M US$



- ☐ Rich Physics
  - ➢ Mass hierarchy
  - ➢ Precision measurement of mixing parameters
  - ➢ Supernova neutrinos
  - ➢ Geo-neutrinos
  - ➢ Solar neutrinos
  - ➢ Sterile neutrinos
  - ➢ Atmospheric neutrinos
  - ➢ Exotic searches

Precision neutrino mixing measurements with JUNO

- JUNO will improve the precision of ${\Delta m_{21}}^2$, ${\Delta m_{32}}^2$ and $\sin^2 \Theta_{12}$ to better than 1%. Considering the planned 4% of the $\sin^2 \Theta_{13}$ in DayaBay measurement, the unitarity of the mixing matrix can be tested at the level of 1% precisiion

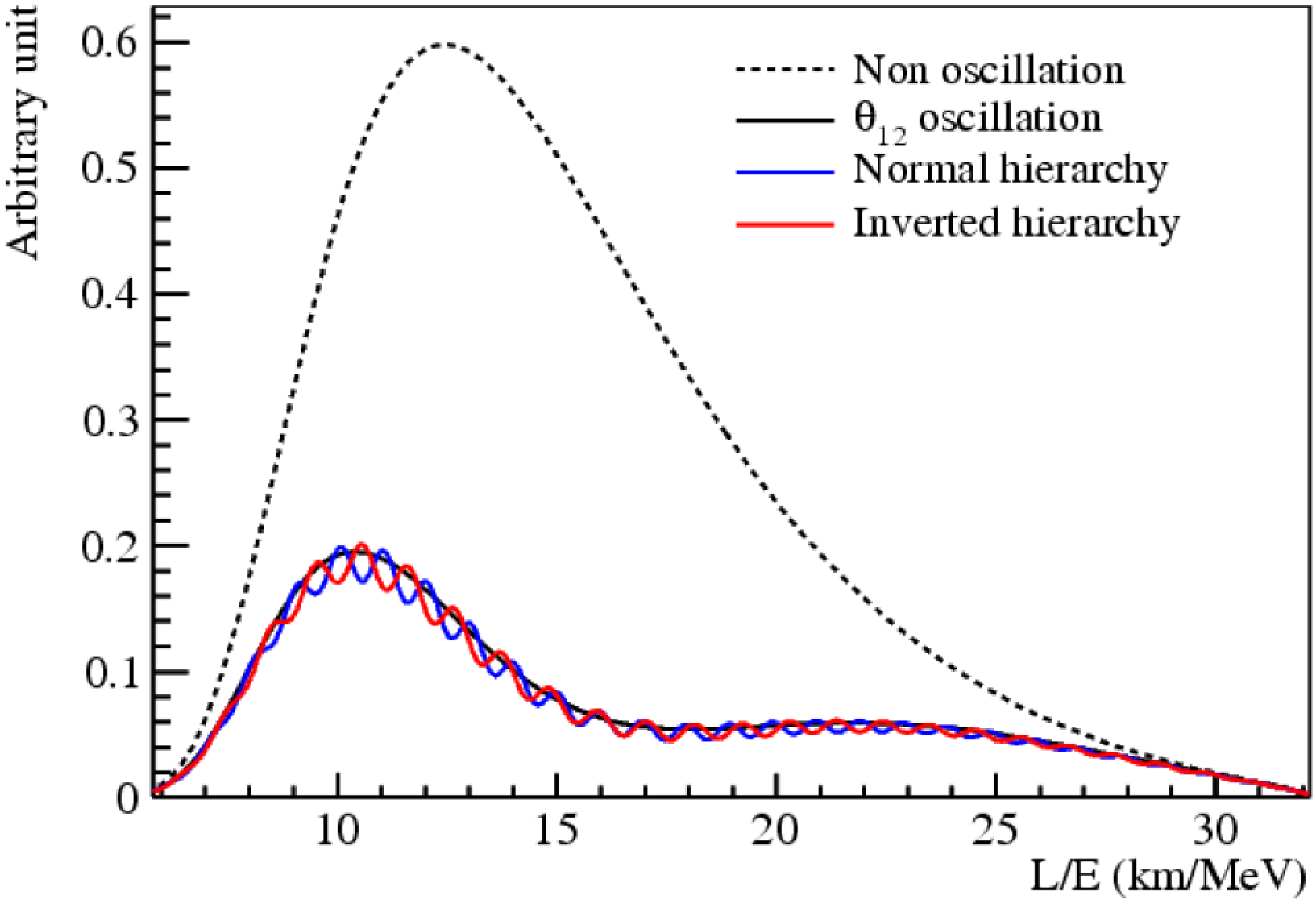


	Current	JUNO
Δm_{21}^2	$\sim$3%	$\sim$0.6%
Δm_{32}^2	$\sim$5%	$\sim$0.6%
$\sin^2\theta_{12}$	$\sim$6%	$\sim$0.7%
$\sin^2\theta_{23}$	$\sim$20%	N/A
$\sin^2\theta_{13}$	$\sim$4% in a near future	$\sim$15%

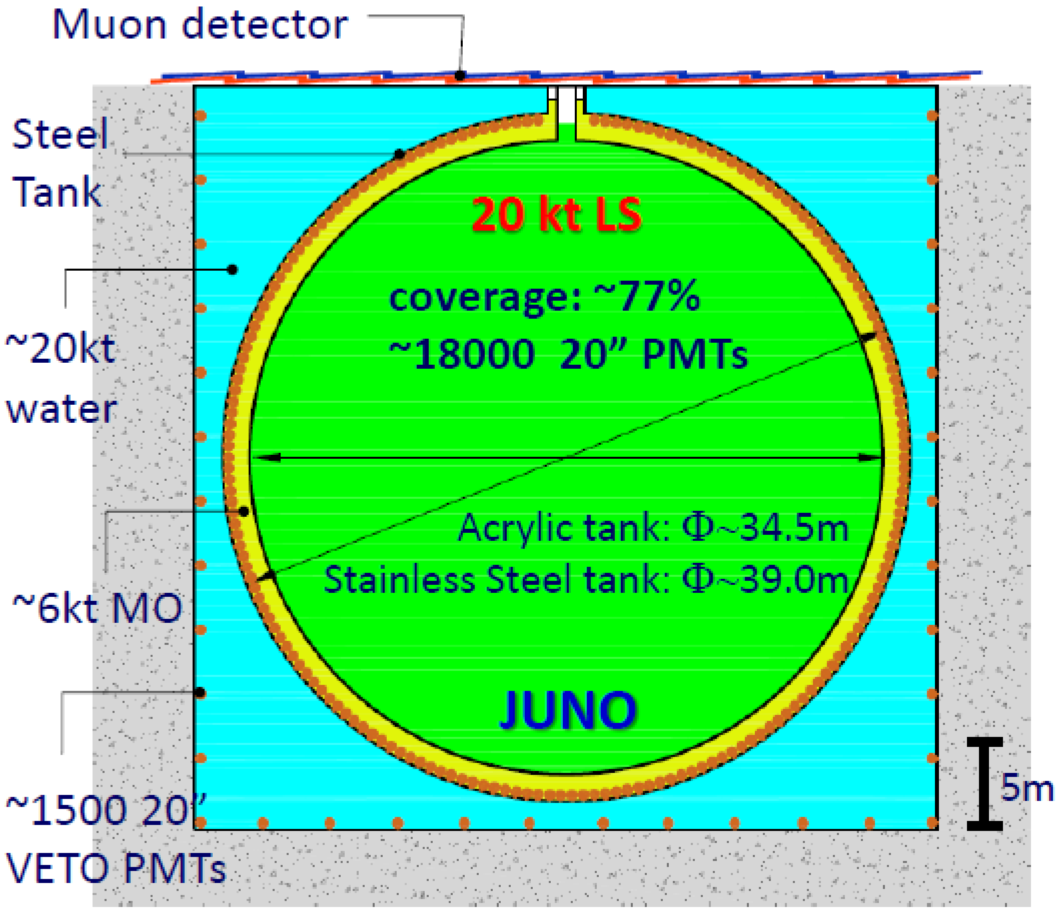
Location of JUNO

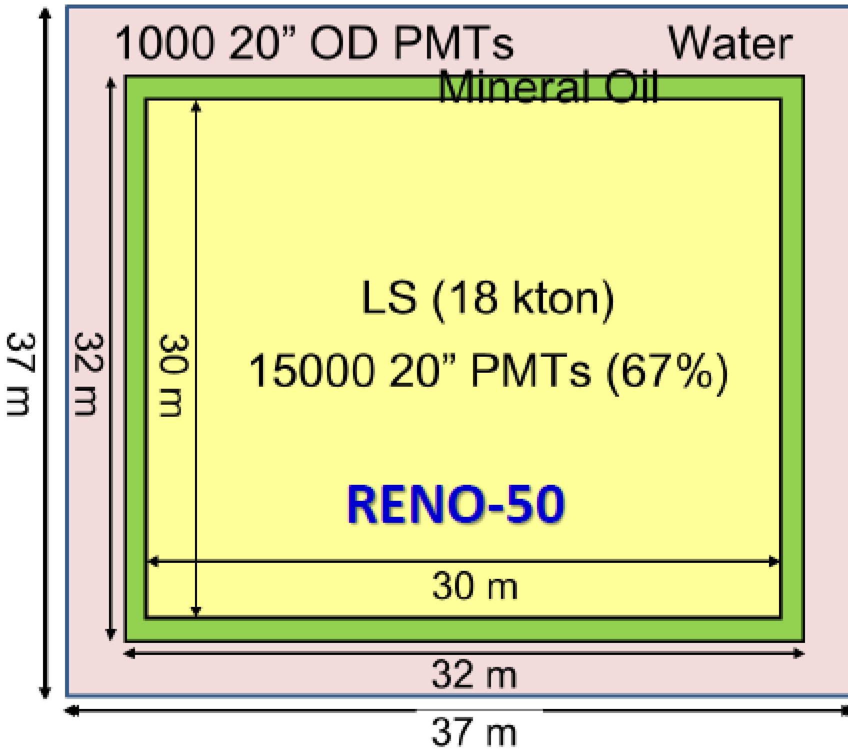
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

Neutrino oscillation difference between N and I hierarchy



Challenge: high-precision, giant LS detector





	KamLAND	JUNO	RENO-50
LS mass	~1 kt	20 kt	18 kt
Energy Resolution	$6\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$	$\sim 3\%/\sqrt{E}$
Light yield	250 p.e./MeV	1200 p.e./MeV	>1000 p.e./MeV

Requirements on Energy Resolution

- $3\%/\sqrt{E}$ energy resolution
- Take JUNO MC as example
  - Based on DYB MC
  - JUNO Geometry
  - 77% photocathode coverage (KamLAND: ~34%)
  - High QE PMT, QE_{max}: 25% → 35%
  - LS attenuation length (1 m-tube measurement @ 430nm)

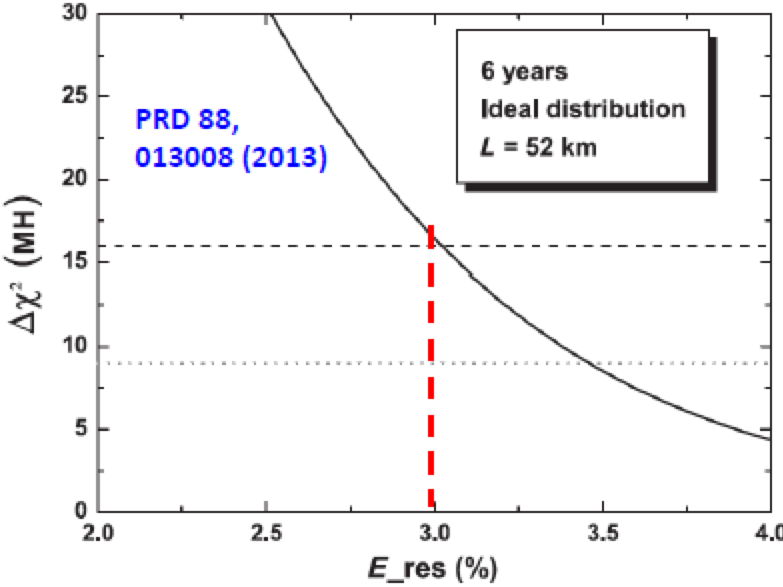
from 15 m

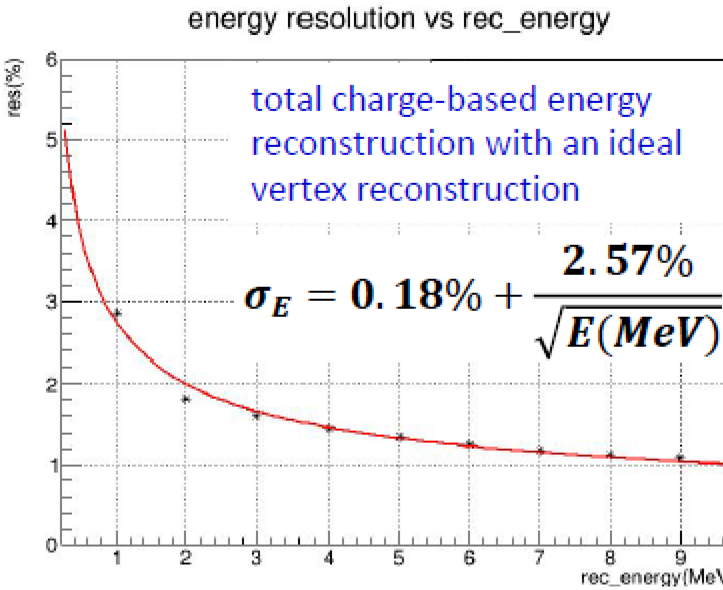
= absorption 30 m + Rayleigh scattering 30 m

to 20 m

= absorption 60 m + Rayleigh scattering 30 m

The Highlighted parameters are input to MC


PRD 88, 013008 (2013)

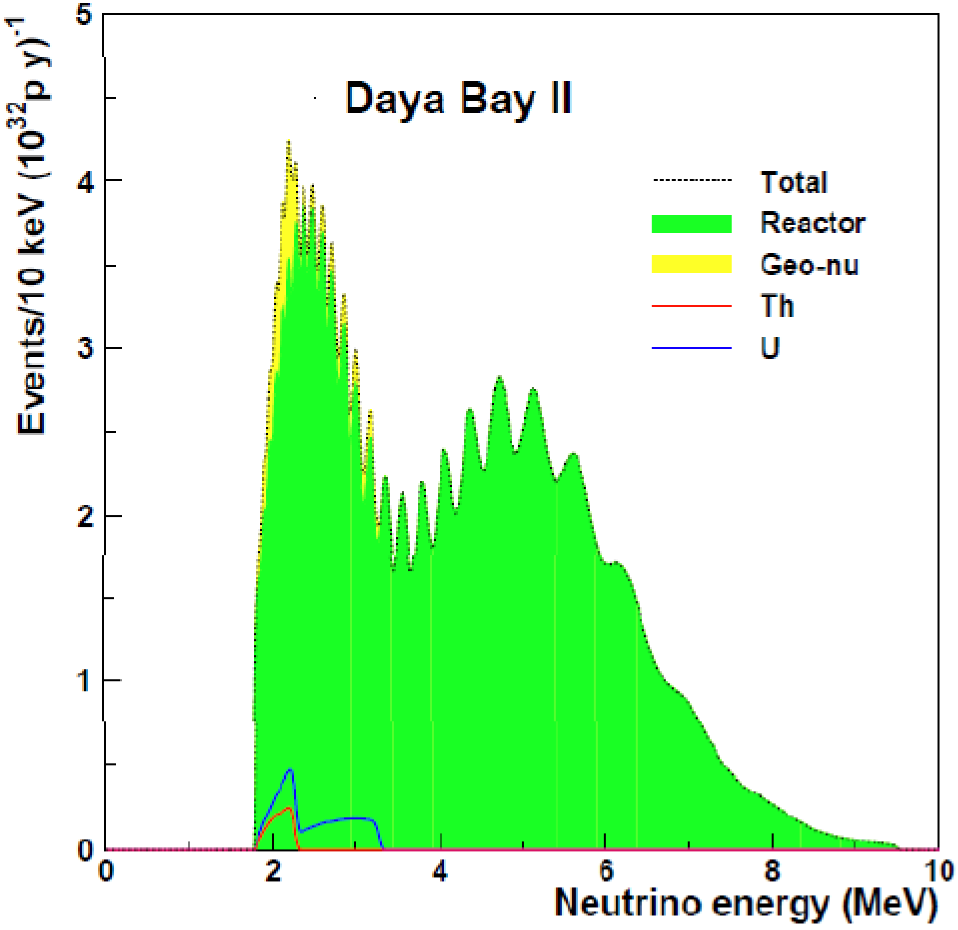

energy resolution vs rec_energy

total charge-based energy reconstruction with an ideal vertex reconstruction

$$\sigma_E = 0.18\% + \frac{2.57\%}{\sqrt{E(MeV)}}$$

Geoneutrinos@DYBII

- Current results:
  - **KamLAND:**
    40.0 ± 10.5 ± 11.5 TNU
  - **Borexino:**
    64 ± 25 ± 2 TNU
- Desire to reach an error of 3 TNU: statistically dominant
- Daya Bay II: > × 10 statistics, but difficult on systematics
- Background to reactor neutrinos



From Stephen Dye

NuMI **O**ff-axis **ν_e** **A**ppearance (NOvA)

Два детектора(14 кт дальний и 0.3 кт ближний), большая база (810 км), off-axis (14 mрад, ~2 ГэВ), прецизионное измерение осцилляций ν_μ :

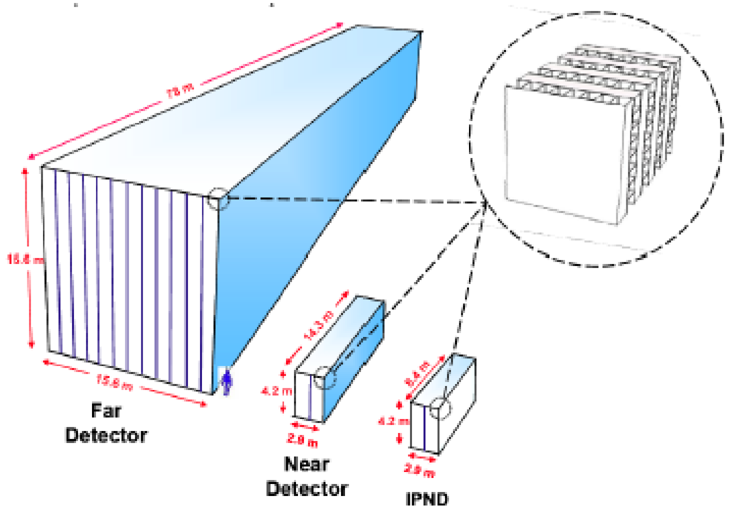
иерархия масс

фаза CP-нарушения в нейтринном секторе

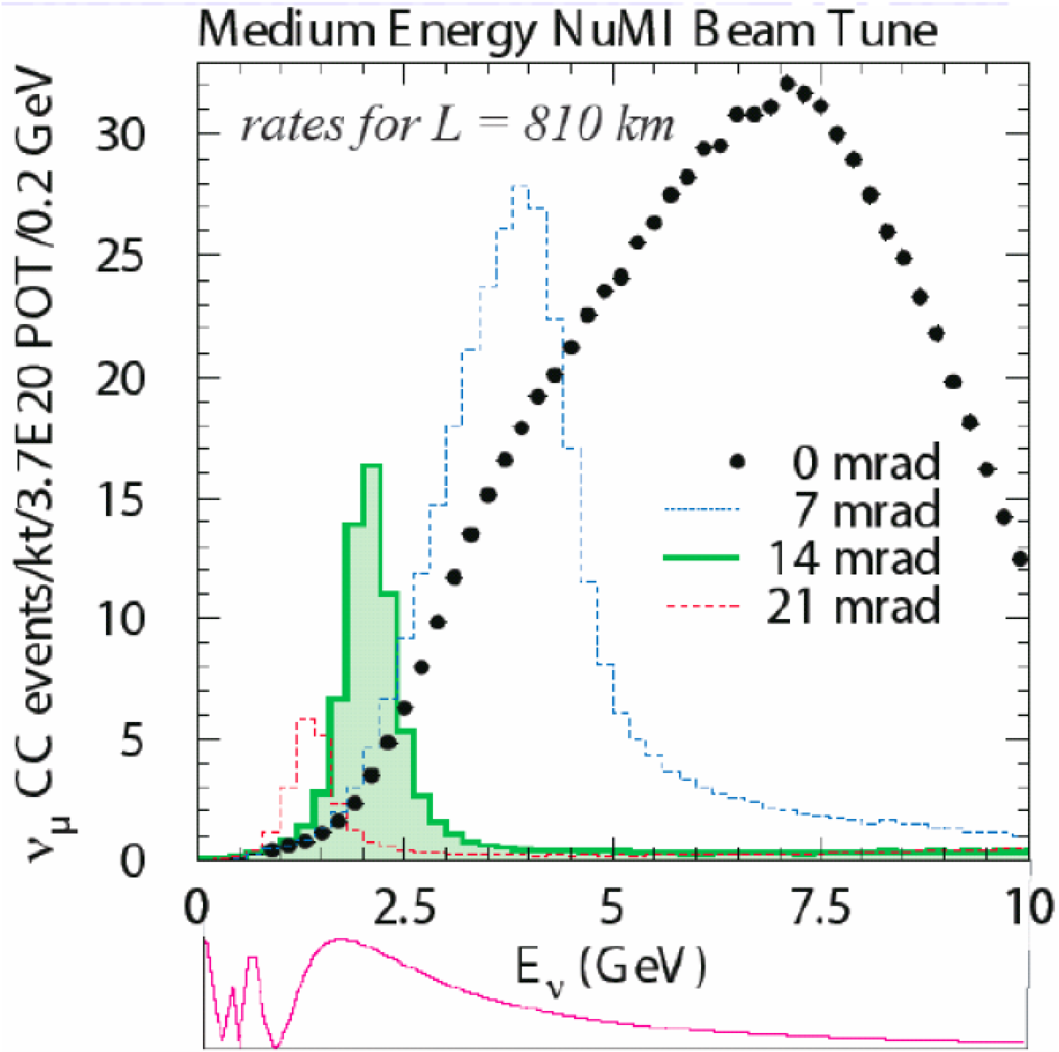
знак угла θ_{13} в PMNS

состояние ν_3 состоит большей частью из ν_μ или ν_τ ?($\theta_{23}>\pi/4$)

Детекторы NOvA : активные трэковые ЖС калориметры. Базовая ячейка дальнего детектора состоит их колонны или ряда ЖС ячеек 4 см x 15.6 м x 6 см



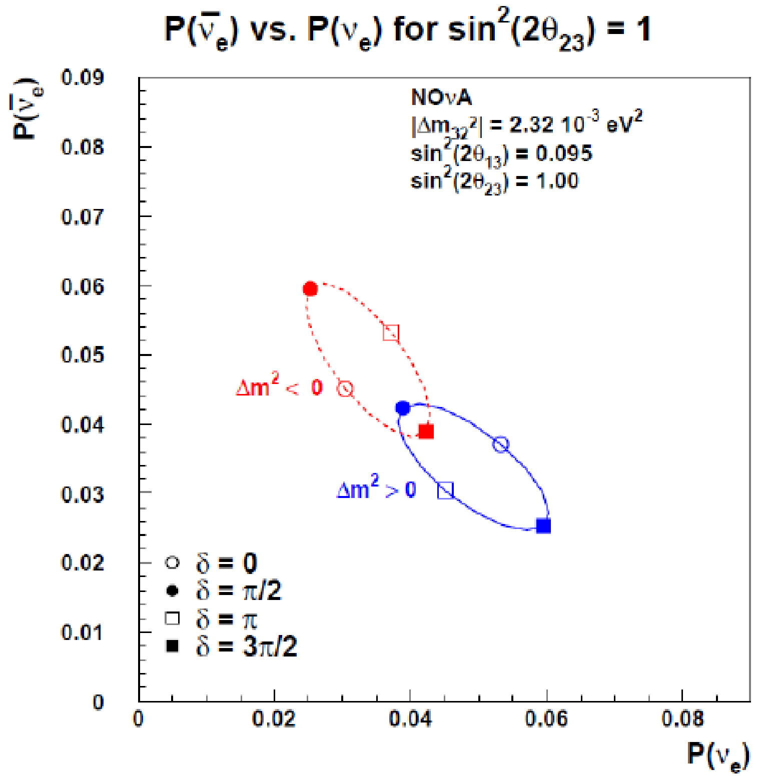
Off-axis concept



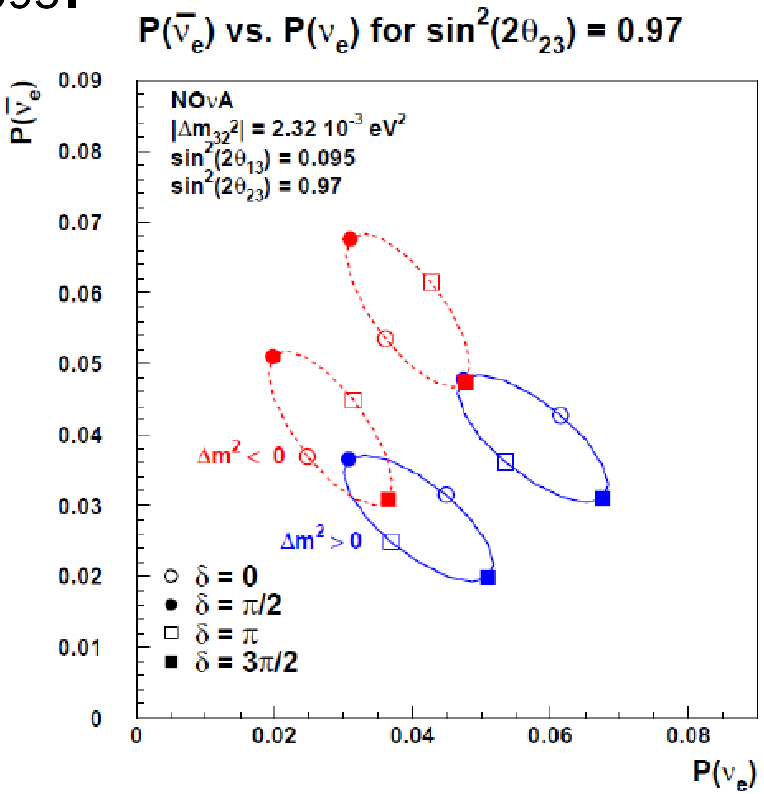
$P(\upsilon_\mu \rightarrow \upsilon_e)$

υ_e appearence

$\sin^2(2\theta_{13})=0.095$.



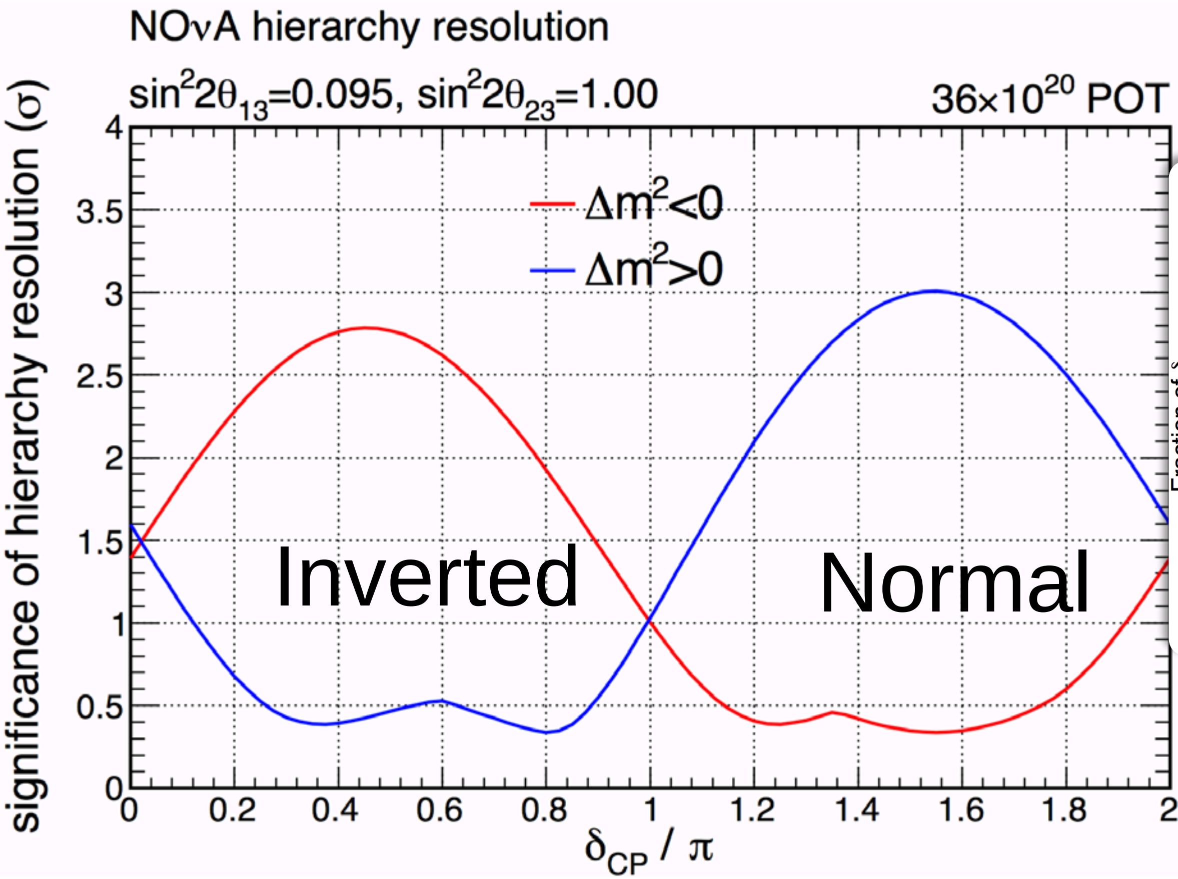
$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 1$

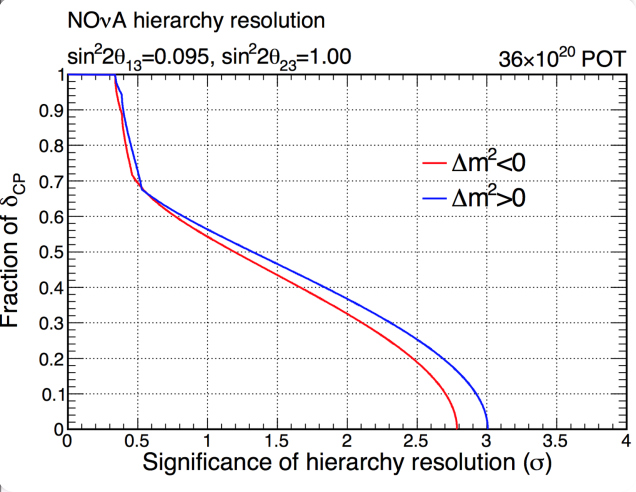


$P(\bar{\nu}_e)$ vs. $P(\nu_e)$ for $\sin^2(2\theta_{23}) = 0.97$

$\upsilon_\mu \rightarrow \upsilon_e$ oscillations are sensitive to both $\sin^2(2\theta_{13})$ and $\sin^2(2\theta_{23})$, with large perturbations caused by the mass ordering (through the matter effect) and by CP violation. CP-violating phase δ traces out the ovals and the multiplicity of ovals represents the two possible mass orderings and, for right figure, the ambiguity of whether θ_{23} is larger or smaller than π/4.

Hierarchy Sensitivity





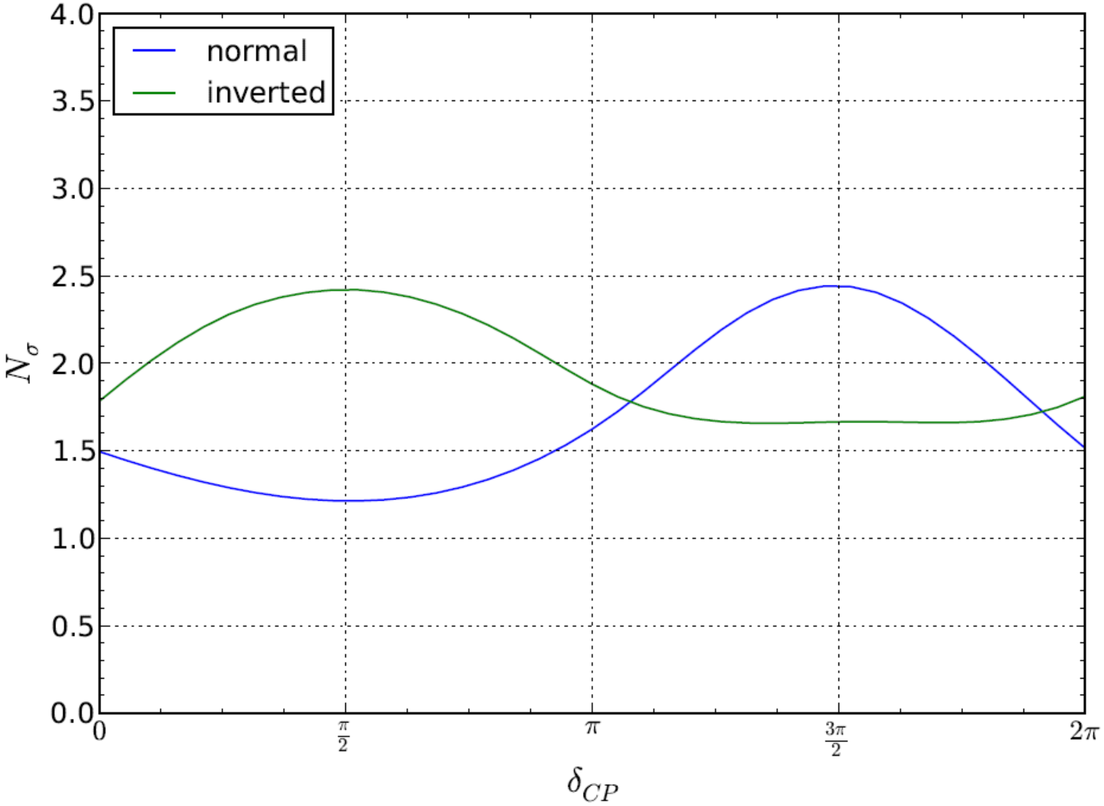
For a maximal θ_{23}, NOvA's sensitivity to the resolution of the hierarchy reaches 95% CL over a third of δ_{CP}

Joint analysis of the NOvA and JUNO experiments

- Interpretation $\Delta\chi^2$: $\Delta\chi^2 = \Delta\chi^2(NH) - \Delta\chi^2(IH) \approx 15$, corresponding to ≈4σ sensitivity
- Sensitivity from likelihood ratio analysis at fixed Δm_{atm} : 2.6σ
- Allowing Δm_{atm} to vary within $\pm 0.1 \cdot 10^{-3}$ eV^2: 2σ

Combined analysis JUNO+NOvA: up to 2.5σ

Figure from D.Taichenachev diploma thesis (May 2014)

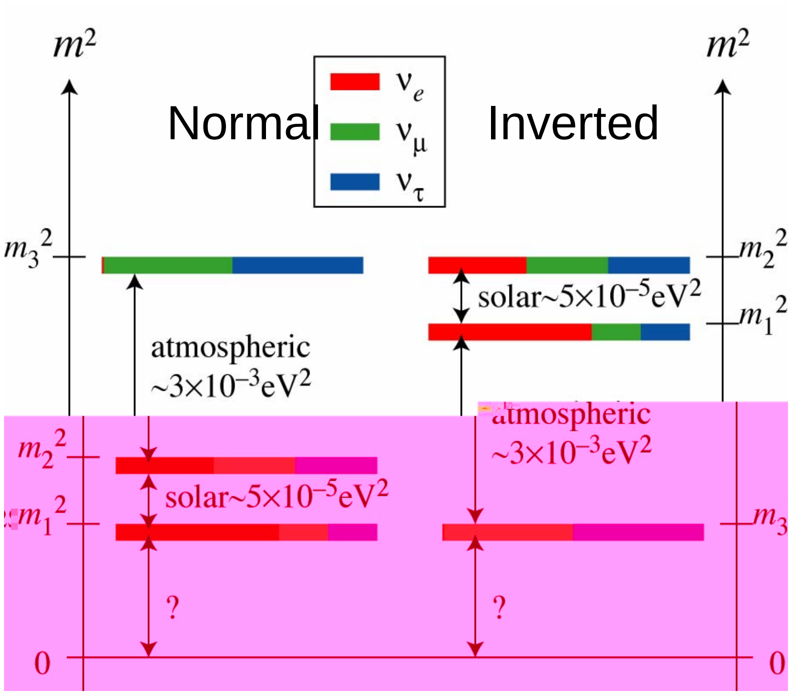


Neutrino mass

- $m_{\upsilon_e}{}^{2} <$ 2.05 eV^2 (95% C.L.)
- $m_{\upsilon_\mu} <$ 170 keV
- $m_{\upsilon_\tau} <$ 15.5 MeV

Lower bound on neutrino masses from $\Delta m_{31}{}^2 \sim 0.0024$ eV^2:
Normal hierarchy: $m_3 > 0.05$ eV
Inverted hierarchy: $m_1 + m_2 > 0.1$ eV

- Cosmological bound $\sum_i m_i < 0.58$ eV
- In theory: three cases
  - Normal **hierarchy**: $m_1 < \sqrt{\Delta m_{21}}$
  - Inverted **hierarchy**: $m_3 \ll \sqrt{\Delta m_{31}}$
  - (Quasi-)**Degenerate**: $m_1 \sim m_2 \sim m_3 \gg \sqrt{\Delta m_{31}}$ (**ordering**: normal or inverted)



Double beta-decay

- The idea of double beta decay - Maria Goeppert-Mayer in 1935.

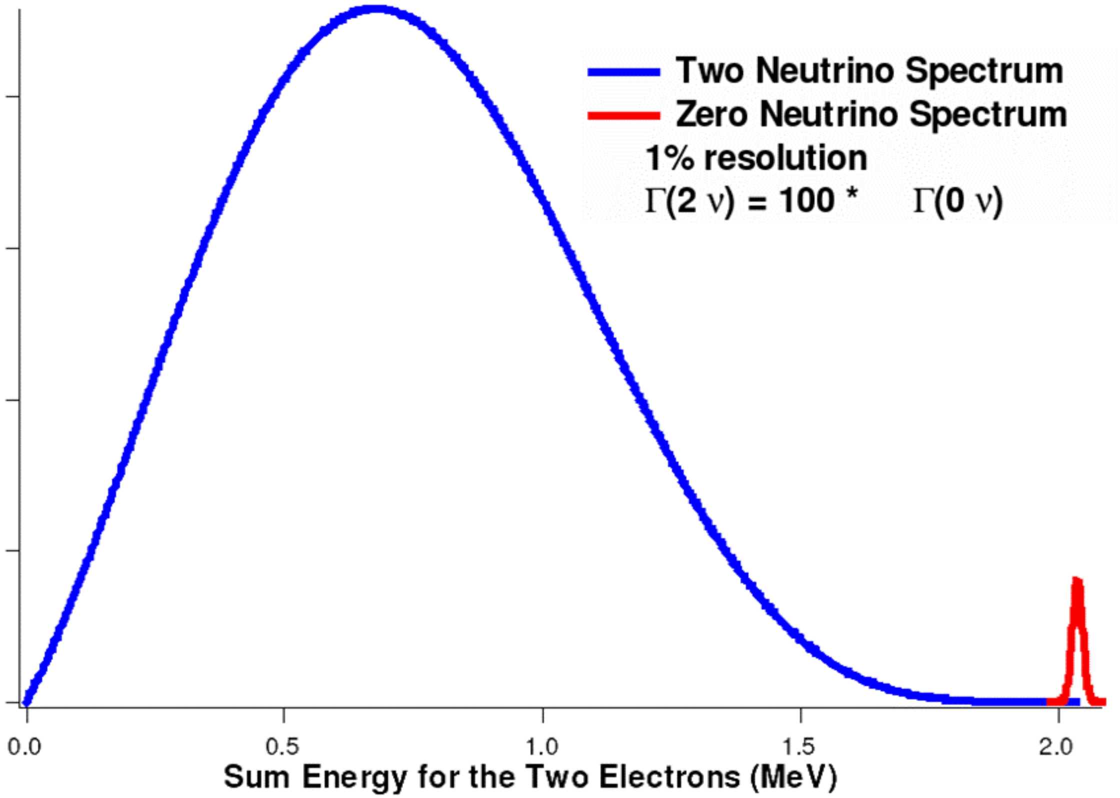
$$\mathbf{(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e}$$

- In 1937 Ettore Majorana theoretically demonstrated that all results of beta decay theory remain unchanged if the neutrino is its own anti-particle, i.e. if it is a Majorana particle.
- In 1939 Wendell H. Furry : if neutrino is a Majorana particle, double beta decay can proceed without emission of any neutrino; the process which is now called the neutrinoless beta decay.

$$\mathbf{(A, Z) \rightarrow (A, Z + 2) + 2e^-}$$

- First calculations showed that neutrinoless double beta decay should be much more likely to occur than ordinary double beta decay (if neutrinos are Majorana) with $T_{1/2}$~10^{15}–10^{16} years.
- In 1948 Edward L. Fireman made the first attempt to measure the half-life of the ^{124}Sn isotope, up to 60s all radiometric experiments were negative (or false positive). In 1950 for the first time the half-life of the ^{130}Te isotope was measured by geochemical methods wit h result, 1.4×10^{21} years, close to the modern value.

How to search for $0\upsilon\beta\beta$?



The fraction of $2\upsilon\beta\beta$ events under the $0\upsilon\beta\beta$ peak can be approximated by

$$F = \frac{7Q\delta^6}{m_e}$$

where $\delta = \frac{\Delta E}{Q}$ is relative FWHM resolution

History

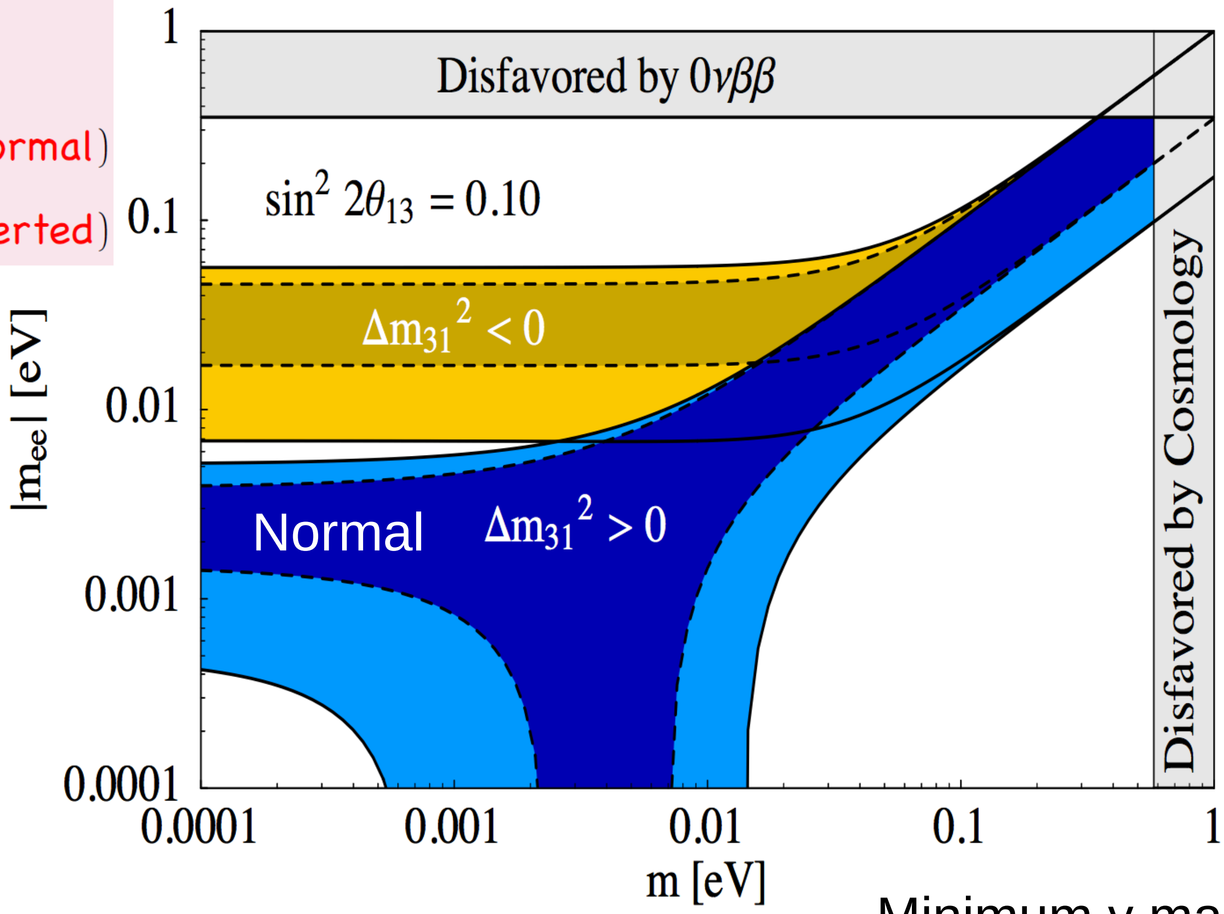
- In 1956 after establishing the V-A nature of weak interactions (vector minus axial vector or left-handed Lagrangian. In this theory, the weak interaction acts only on left-handed particles and right-handed antiparticles) it became clear that the half-life of neutrinoless double beta decay would significantly exceed that of ordinary double beta decay.
- Double beta decay was not observed in laboratory until the 1980s, only the lower bound of the order of 10^{21} years. In the same time the geochemical experiments double beta decay of ^{82}Se and ^{128}Te isotopes were detected, geochemical experiments continued until the end of 1990s and produced positive results for a few more isotopes.
- DBD first observed in 1987 by a group led by Michael Moe at the UC Irvine on isotope ^{82}Se, followed by other successful experiments on a number of other isotopes.
- For the moment the neutrinoless process was not observed with bound for its half-life ~10^{25} years.
- Double beta decay is the rarest known kind of radioactive decay; observed for only 12 isotopes (including double electron capture in ^{130}Ba observed in 2001), all of them have a mean lifetime > 10^{18} yr.

Light-ν-exchange amplitude proportional to "effective mass"

$$m_{\text{eff}} \equiv \sum_{i=1}^{3} m_i U_{ei}^2$$

If lightest neutrino is light:

- $m_{\text{eff}} \approx \sqrt{\Delta m^2_{\text{sol}}} \sin^2 \theta_{\text{sol}}$ (normal)
- $m_{\text{eff}} \approx \sqrt{\Delta m^2_{\text{atm}}} \cos 2\theta_{\text{sol}}$ (inverted)



Minimum ν mass

hierarchical

degenerate

Heildelberg-Moscow experiment

^{76}Ge

Result published by a part of the collaboration:

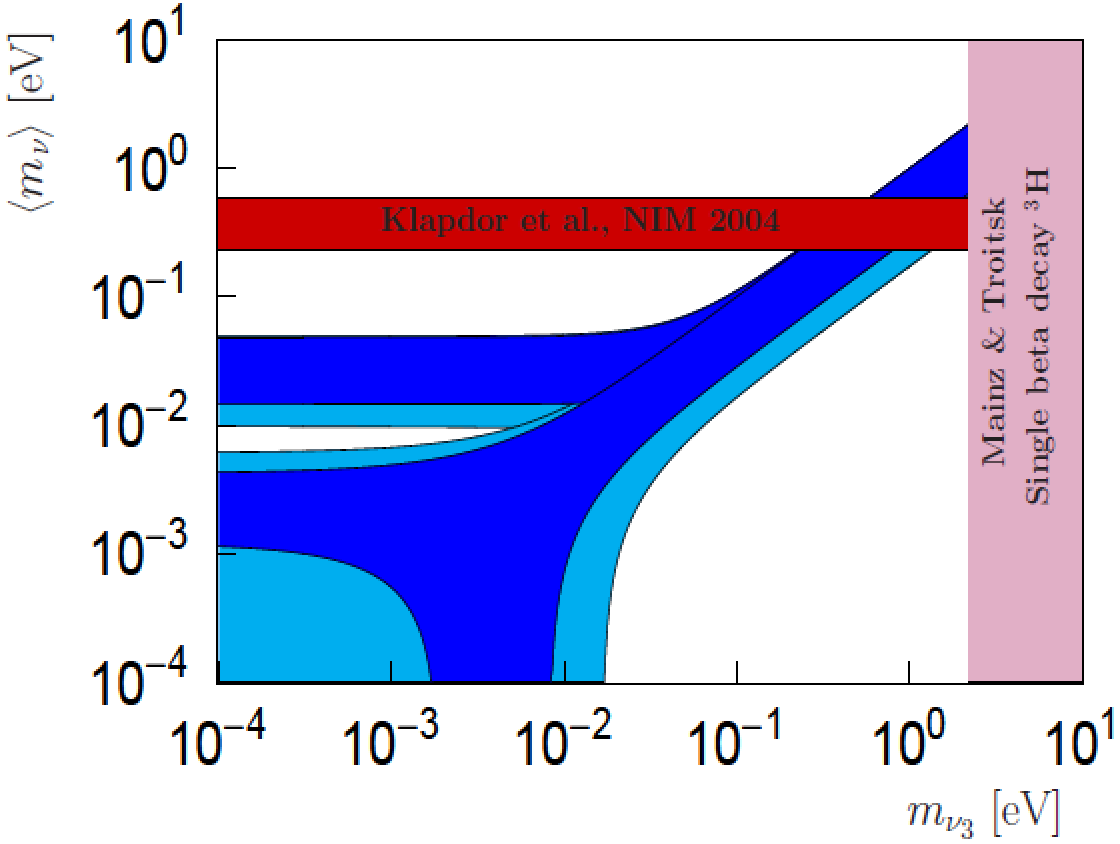
$T_{1/2}=1.2 \cdot 10^{25}$ y or

$T_{1/2}=2.2 \cdot 10^{25}$ y

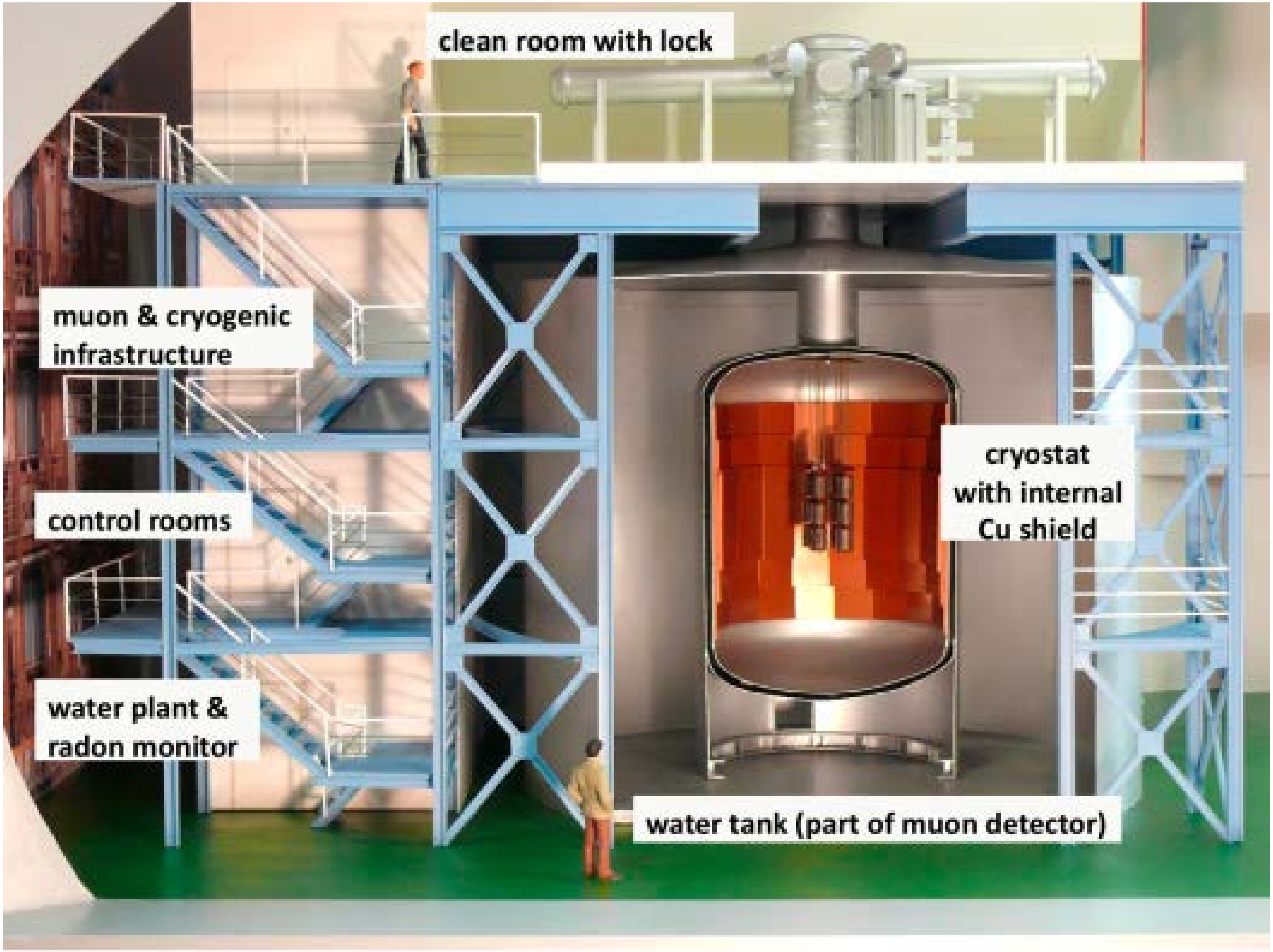
For the first time the

The Moscow part of the Collaboration does not agree with this conclusion and there are others who are critical of this result.

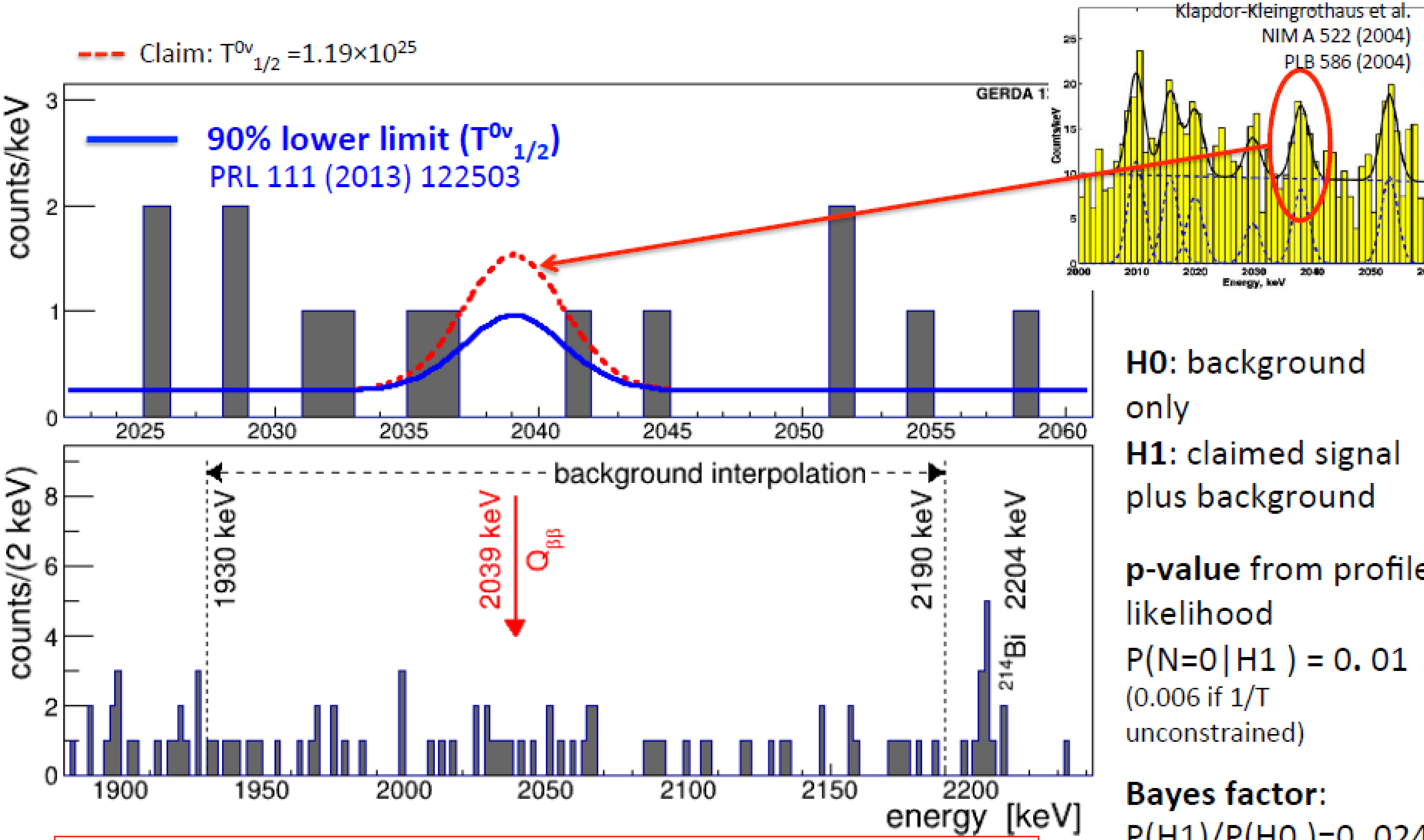
At present, this “positive” result is not accepted by the 2β-decay community and it has to be checked by new experiments.



GERDA


clean room with lock
muon & cryogenic infrastructure
control rooms
water plant & radon monitor
cryostat with internal Cu shield
water tank (part of muon detector)

Comparison with Phys. Lett. B 586 198 (2004) 0νββ claim in ^{76}Ge



H0: background only

H1: claimed signal plus background

p-value from profile likelihood

P(N=0|H1) = 0. 01

(0.006 if 1/T unconstrained)

Bayes factor:

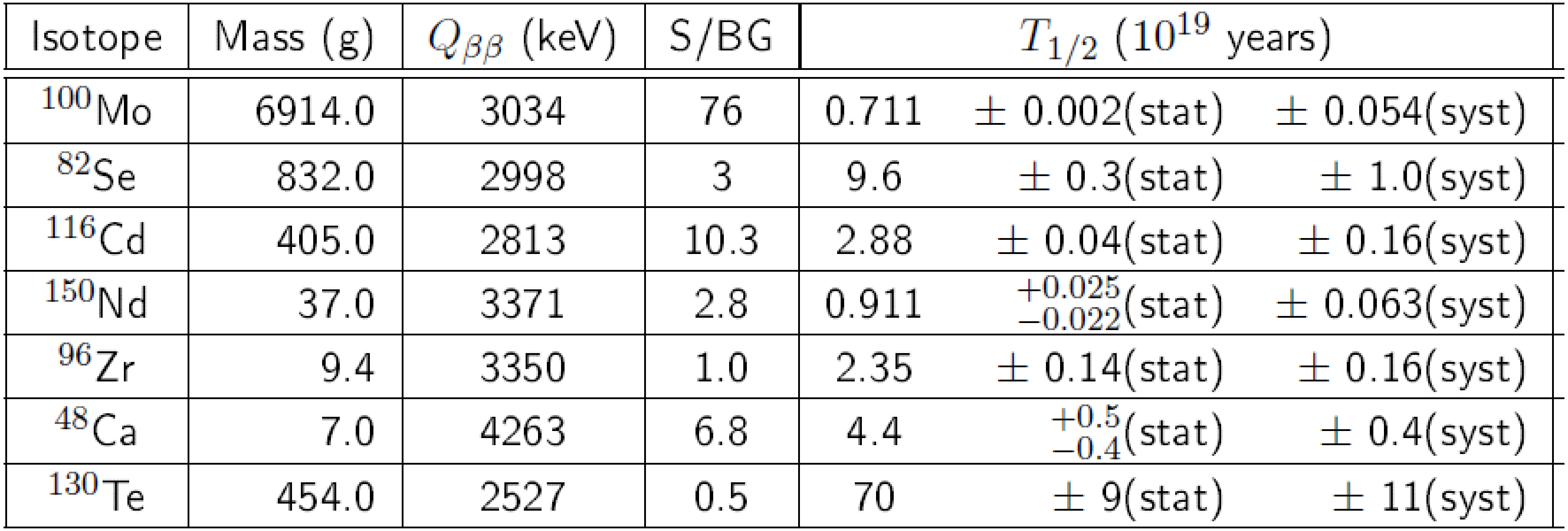
P(H1)/P(H0)=0. 024

➔Claim refuted with high probability
independent of NME and lepton number violating mechanism

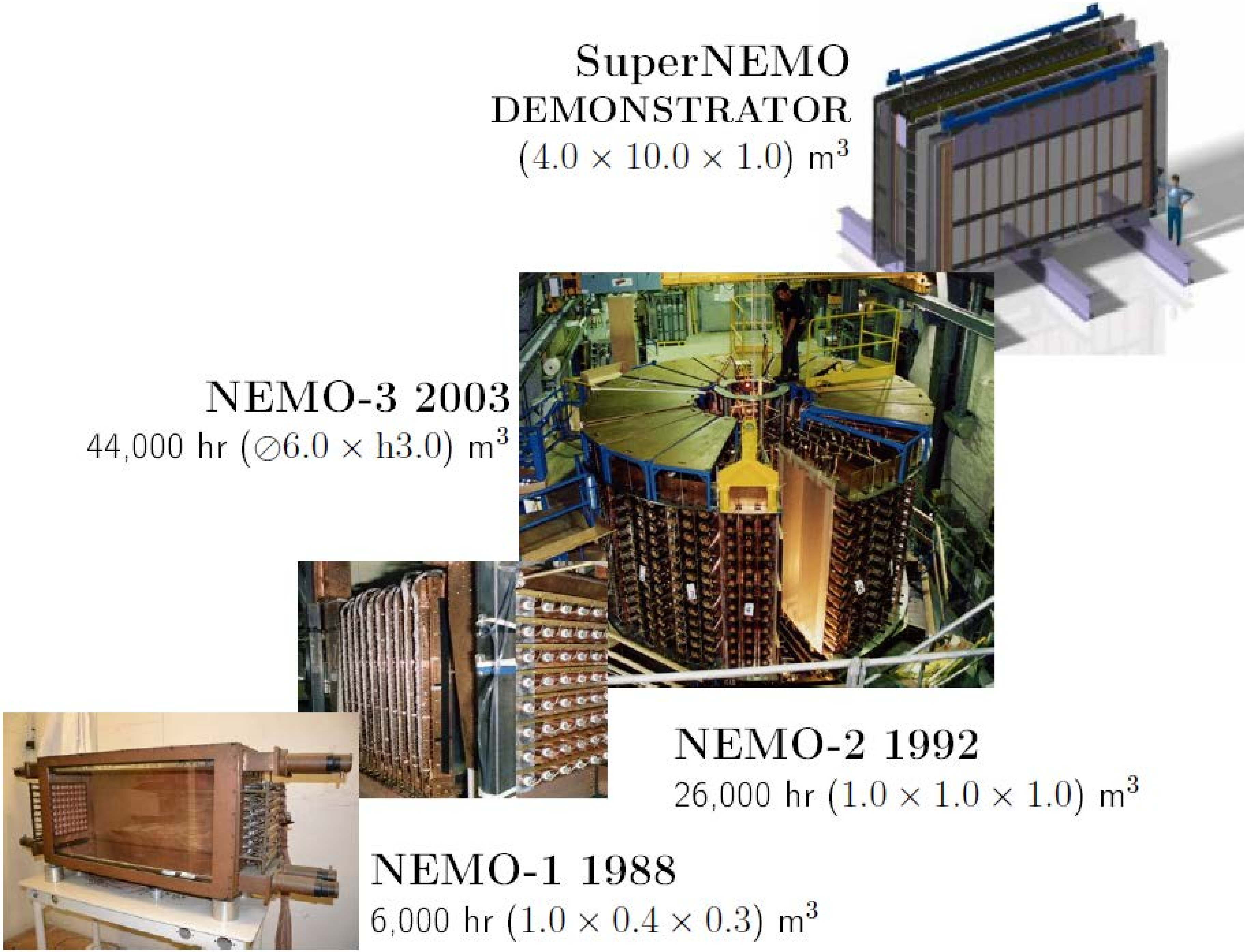
SupeNEMO

- Search for neutrinoless double beta decay with NEMO-3 and the next generation double beta decay experiment SupeNEMO
- The NEMO-3 in the Modane Underground Laboratory (LSM) is taking data since 2003 with a range of isotopes: ^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te and ^{150}Nd. The main isotopes are ~7 kg of ^{100}Mo and ~1 kg of ^{82}Se. Since no evidence for neutrinoless double beta decay has been found, a 90% CL lower limit on the half-life of this process is derived: T1/2(0νββ)> 1.1 10^{24} y ; $\langle m_\nu \rangle < (0.3\text{-}0.9)$ eV
- The SuperNEMO detector consists of 20 independent modules. Each module is approximately equivalent to the former NEMO-3 and will contain about 5-7 kg of a thin (40 mg/cm2) sample foil surrounded by a gas tracking chamber followed by calorimeter walls. The tracking volume contains more than 2000 wire drift chambers operated in Geiger mode, which are arranged in nine layers parallel to the foil. The calorimeter is divided into 1000 blocks which cover most of the detector outer area and are read out by low background photomultiplier tubes.

NEMO-3 results



Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)	S/BG	$T_{1/2}$ (10^{19} years)		
^{100}Mo	6914.0	3034	76	0.711	$\pm$ 0.002(stat)	$\pm$ 0.054(syst)
^{82}Se	832.0	2998	3	9.6	$\pm$ 0.3(stat)	$\pm$ 1.0(syst)
^{116}Cd	405.0	2813	10.3	2.88	$\pm$ 0.04(stat)	$\pm$ 0.16(syst)
^{150}Nd	37.0	3371	2.8	0.911	$^{+0.025}_{-0.022}$(stat)	$\pm$ 0.063(syst)
^{96}Zr	9.4	3350	1.0	2.35	$\pm$ 0.14(stat)	$\pm$ 0.16(syst)
^{48}Ca	7.0	4263	6.8	4.4	$^{+0.5}_{-0.4}$(stat)	$\pm$ 0.4(syst)
^{130}Te	454.0	2527	0.5	70	$\pm$ 9(stat)	$\pm$ 11(syst)



SuperNEMO
DEMONSTRATOR
$(4.0 \times 10.0 \times 1.0)$ m^3

NEMO-3 2003
44,000 hr $(\oslash 6.0 \times h3.0)$ m^3

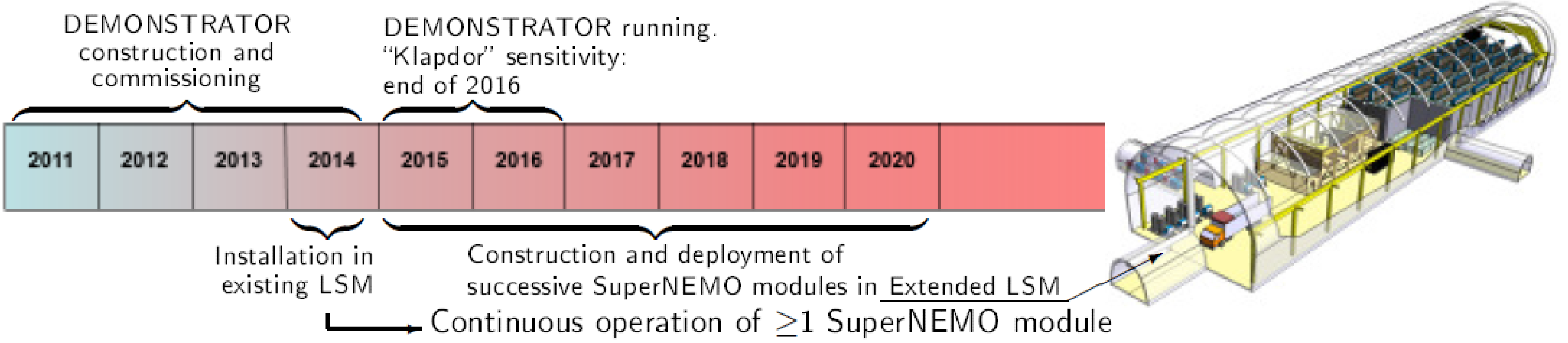
NEMO-2 1992
26,000 hr $(1.0 \times 1.0 \times 1.0)$ m^3

NEMO-1 1988
6,000 hr $(1.0 \times 0.4 \times 0.3)$ m^3

SuperNEMO VS nemo-3

Parameter	NEMO-3	SuperNEMO
Isotope and its mass	^{100}Mo, 7 kg	^{150}Nd or ^{82}Se, 100 - 200 kg
Efficiency	8%	~30%
Energy resolution (FWHM)	8% @ 3 MeV	4% @ 3 MeV
Internal ^{208}Tl contamination in $\beta\beta$ foil	$< 20\ \mu$Bq/kg	$< 2\ \mu$Bq/kg
Internal ^{214}Bi contamination in $\beta\beta$ foil	$< 300\ \mu$Bq/kg	$< 10\ \mu$Bq/kg (if ^{82}Se)
Internal Radon contamination in tracker	~ 5 - 6 mBq/m^3	< 0.1 mBq/m^3
$T_{1/2}(0\nu\beta\beta)$ sensitivity	$> 1 \times 10^{24}$ y	$> 2 \times 10^{26}$ y
$\langle m_\nu \rangle$ sensitivity	$\leq$ (310 - 790) meV	$\leq$ (30 - 100) meV

The main candidate isotopes for SuperNEMO : ^{82}Se, ^{150}Nd and ^{48}Ca. The first sample of 4 kg of ^{82}Se enriched. Investigating the technical possibility of enriching large amounts of ^{150}Nd via the method of atomic vapor laser isotope separation.



DEMONSTRATOR construction and commissioning

DEMONSTRATOR running. "Klapdor" sensitivity: end of 2016

Installation in existing LSM

Construction and deployment of successive SuperNEMO modules in Extended LSM

Continuous operation of ≥1 SuperNEMO module

Electron neutrino with magnetic moment can be converted to antineutrino

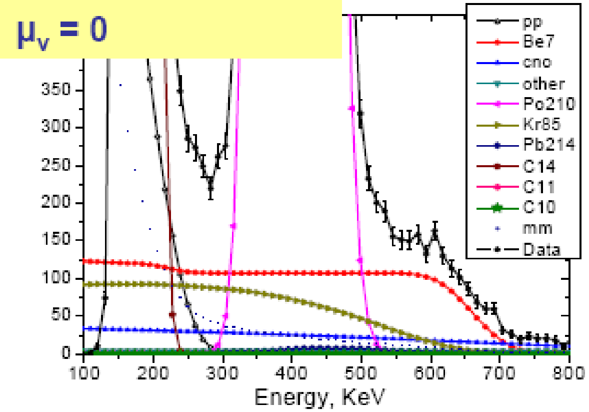
From the Standard Model point of view, there is no diagonal magnetic moment for Dirac massless neutrino, as well as for Majorana neutrino, massive or massless. Massive Dirac neutrino should have small m.m.:

$$\mu_\nu \approx 3.2\times10^{-19}\left(\frac{m_\nu}{1eV}\right)\mu_B$$

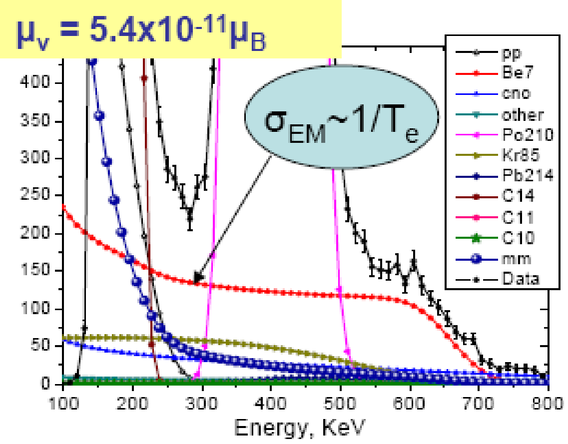
m.m. can be searched for by studying the deviations from the weak shape in electron scattering spectrum

“flat” $$\left(\frac{d\sigma}{dT}\right)_W = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1-\frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

1/T behaviour $$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_\nu^2 \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)$$



$\mu_\nu = 0$



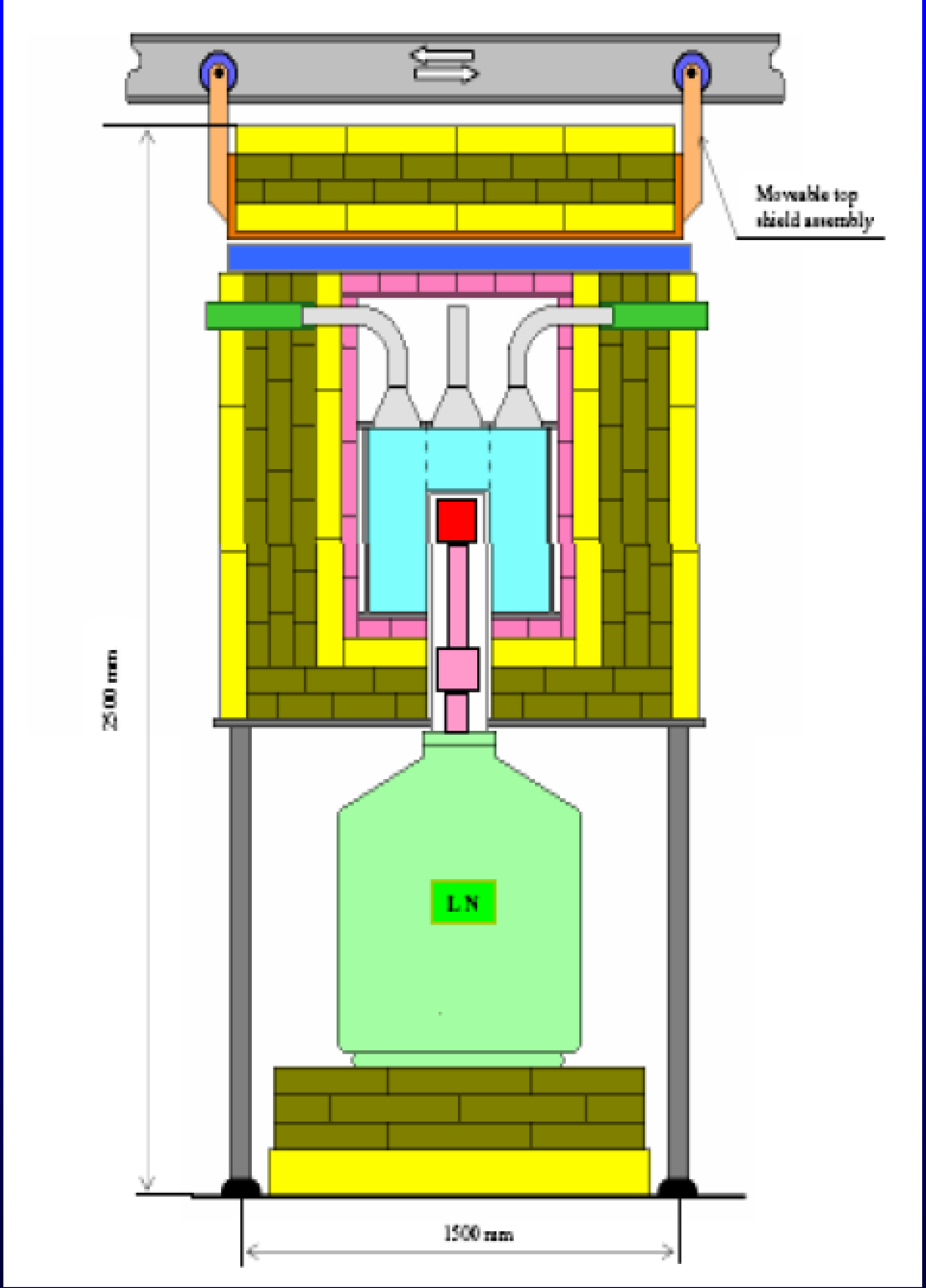
$\mu_\nu = 5.4\times10^{-11}\mu_B$

Experiment **GEMMA**

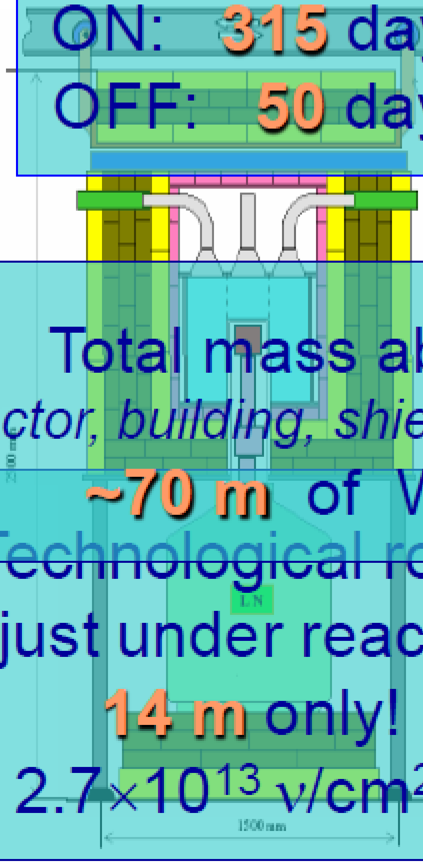
(**G**ermanium **E**xperiment for measurement of **M**agnetic **M**oment of **A**ntineutrino)

*[Phys. of At. Nucl.,**67**(2004)1948]*

- Spectrometer includes a HPGe detector of 1.5 kg installed within NaI active shielding.
- HPGe + NaI are surrounded with multi-layer passive shielding : electrolytic copper, borated polyethylene and lead



Reactor unit #2 of the "Kalinin" Nuclear Power Plant (400 km North from Moscow)



Power: 3 GW

ON: **315** days/y

OFF: **50** days/y

Total mass above

(reactor, building, shielding, etc.):

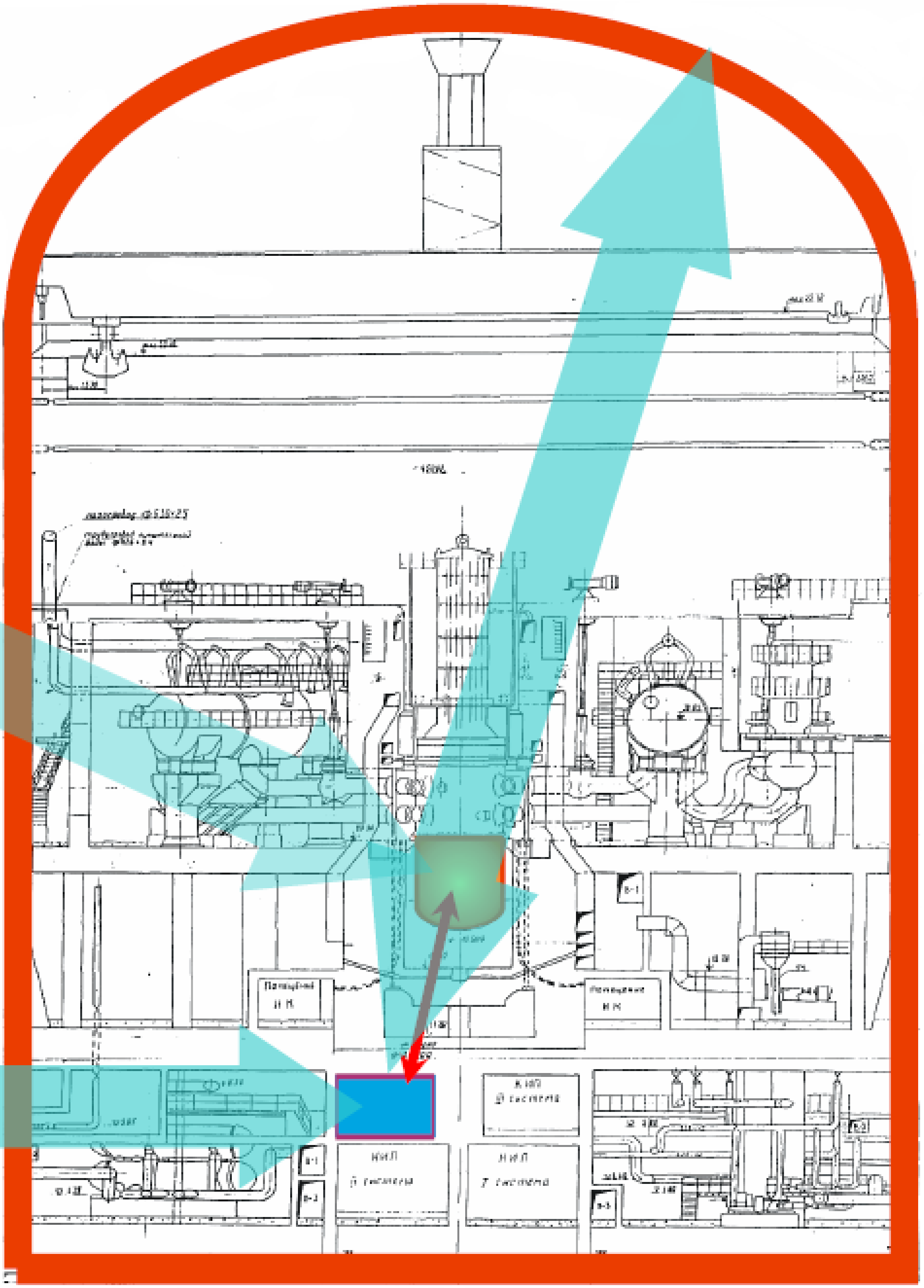
~70 m of W.E.

Technological room

just under reactor

14 m only!

2.7×10^{13} ν/cm^2/s



Limit on effective solar neutrino magnetic moment with Borexino

- **with 192 days of live-time statistics the 90% c.l. limit is:**

$\mu_{eff} < 5.4 \cdot 10^{-11}\ \mu_B$

- **The limit is model-independent, defined only by the shape of the spectra, also no systematics is attributed to the uncertainty of the FV.**
- **The best up-to-date existing limit comes from the measurements with high purity 1.5 kg Ge detector at Kalinin Nuclear Power Plant, GEMMA experiment (arXiv:0906.1926):**

$\mu < 3.2 \cdot 10^{-11}\ \mu_B$

- **For flavour components one can write [D.Montanino et al. PRD 77, 093011 (2008)]:**

$$\boxed{(\mu_{eff}^2)_{MSW} = P_{ee}\mu_e^2 + (1 - P_{ee})(\cos^2\theta_{23}\mu_\mu^2 + \sin^2\theta_{23}\mu_\tau^2)}$$

where $P_{ee}=0.56$ is the survival probability at Earth for electron neutrino at E=0.862 MeV, $\sin^2\theta_{23}=0.5^{+0.07}_{-0.06}$

Applying constraints on $\mu_{\nu e}$ of Gemma experiment:

$$\mu_\mu < 12 \cdot 10^{-11}\mu_B$$

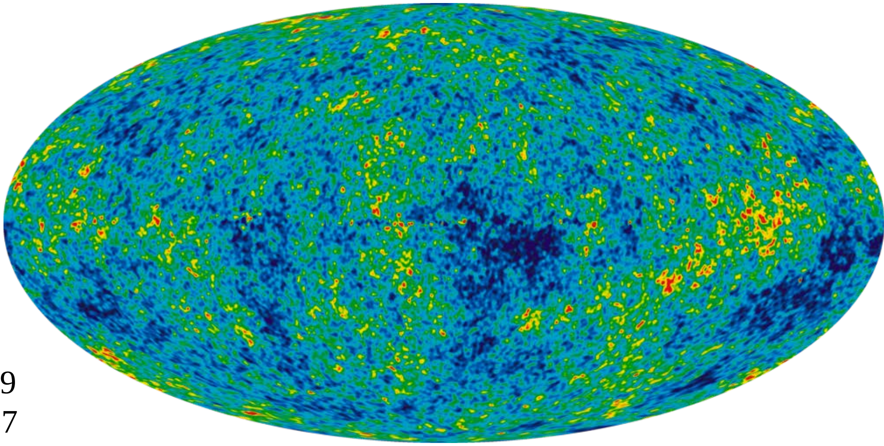
$$\mu_\tau < 12.5 \cdot 10^{-11}\mu_B$$

- Present limits on the neutrino magnetic moments are:
- $\mu_e < 3.2\times10^{-11}\ \mu_B$ by GEMMA (elastic scattering)
- $\mu_\mu < 68\times10^{-11}\ \mu_B$ by LSND (elastic scattering)
- $\mu_\tau < 39000\times10^{-11}\ \mu_B$ by DONUT (elastic scattering)

Search for sterile neutrino

- The collected experimental data generally fit into the three flavor oscillation model. Nevertheless, there is a number of experimental indications (i.e., the statistical significance of the experimental data is not high, usually at a level of 2 to 3σ) that oscillations of neutrinos with $\Delta m^2 \sim 1$ eV^2 are possible (recall that $\Delta m_1{}^2 \quad = m_1{}^2$-$m_2{}^2$)). The existence of oscillations at a scale of 1 eV naturally entails the existence of an extra type of neutrino. Indeed, $\Delta m_{12}{}^2 \sim 10^{-5}$ eV^2 and $\Delta m_{23}{}^2 \sim 210^{-3}$ eV^2 have been established by now. If there are three types of neutrino, $\Delta m_{13}{}^2$ is not an independent parameter, inevitably turning out to be of the same order of magnitude as the greatest of Δm^2.

Planck



Constraints from Planck +
astrophysical datasets (95% c.l.)

$$\text{Planck} + \text{WP} + \text{BAO} \qquad N_{eff}^{\nu} = 3.40_{-0.57}^{+0.59}$$

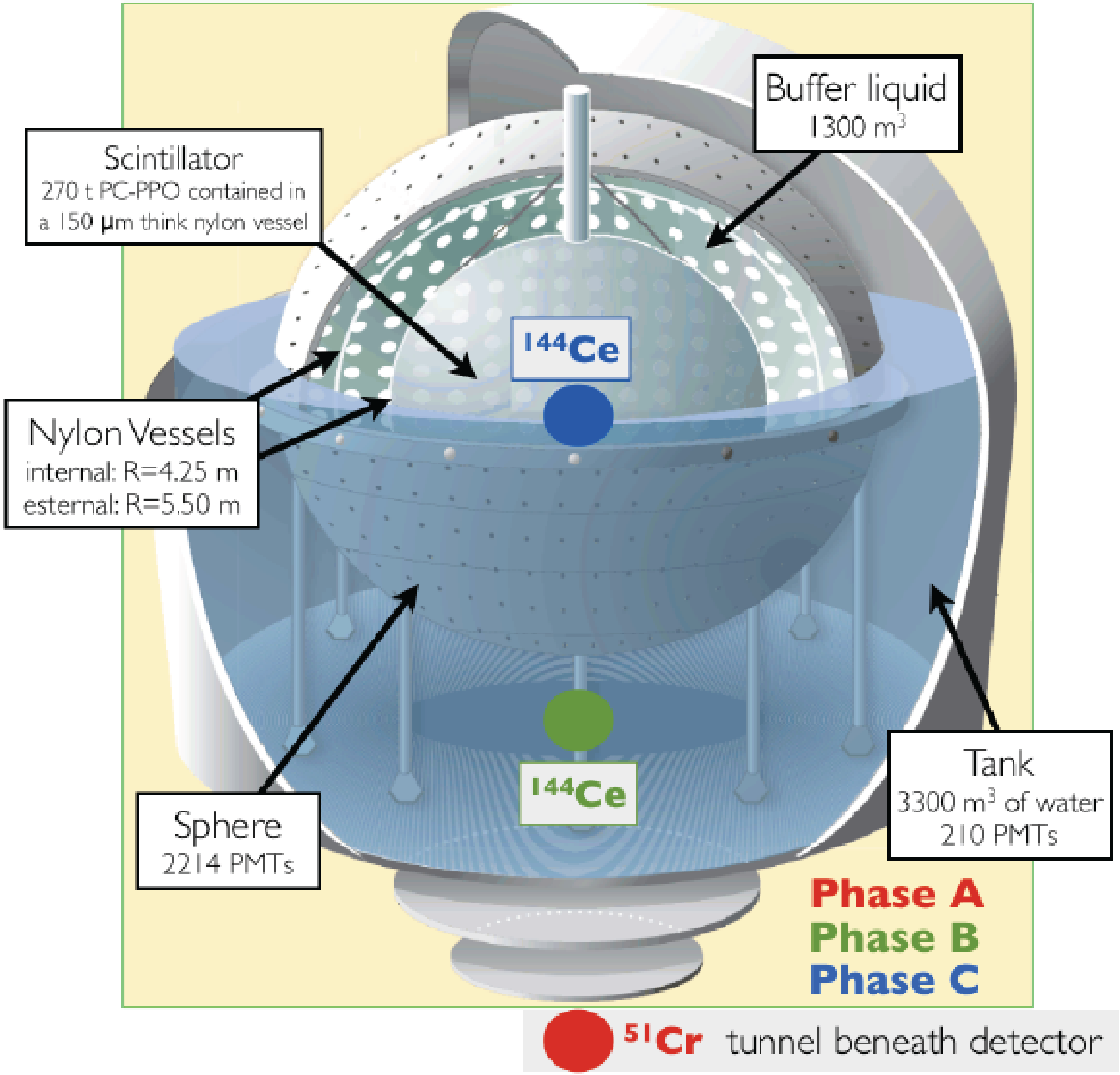
$$\text{Planck} + \text{WP} + \text{SNLS} \qquad N_{eff}^{\nu} = 3.68_{-0.78}^{+0.77}$$

$$\text{Planck} + \text{WP} + \text{Union2} \qquad N_{eff}^{\nu} = 3.56_{-0.73}^{+0.77}$$

$$\text{Planck} + \text{WP} + \text{HST} \qquad N_{eff}^{\nu} = 3.73_{-0.51}^{+0.54}$$

- BAO=Baryon acoustic oscillations
- WP = WMAP Polarization

“SOX Pit'' under the detector
(~ 1 m^3 room)



Scintillator
270 t PC-PPO contained in
a 150 µm think nylon vessel

Buffer liquid
1300 m^3

Nylon Vessels
internal: R=4.25 m
esternal: R=5.50 m

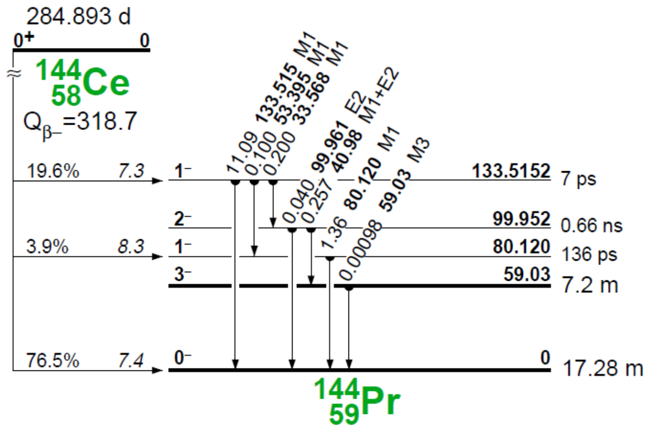
Sphere
2214 PMTs

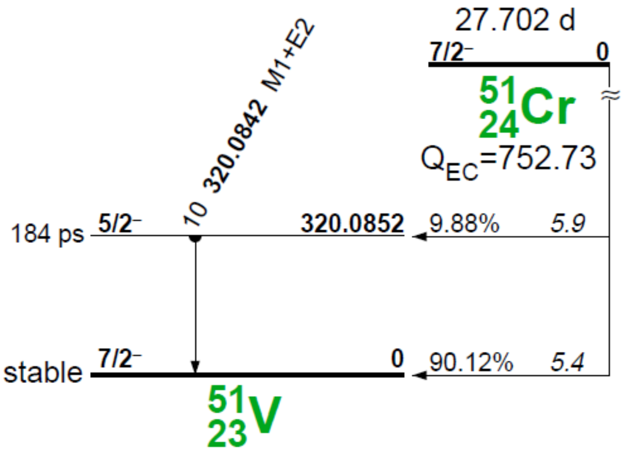
Tank
3300 m^3 of water
210 PMTs

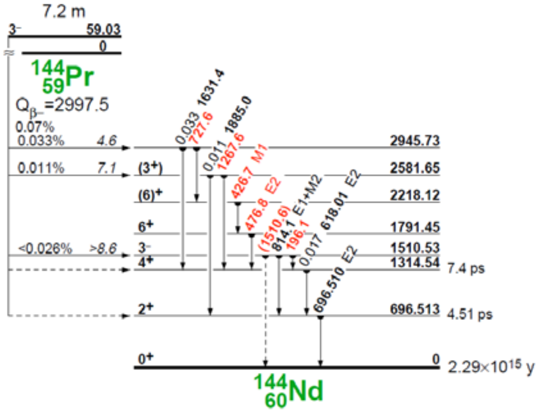
Phase A
Phase B
Phase C

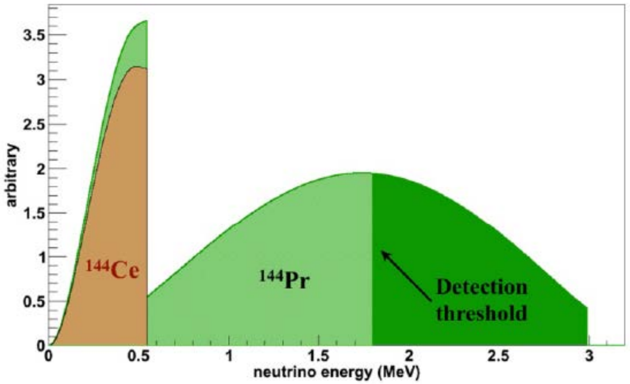
● **^{51}Cr** tunnel beneath detector

Sources







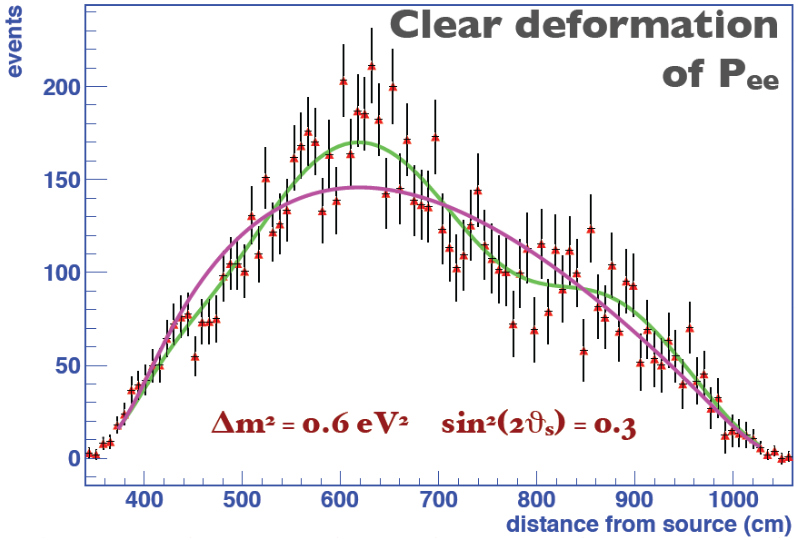


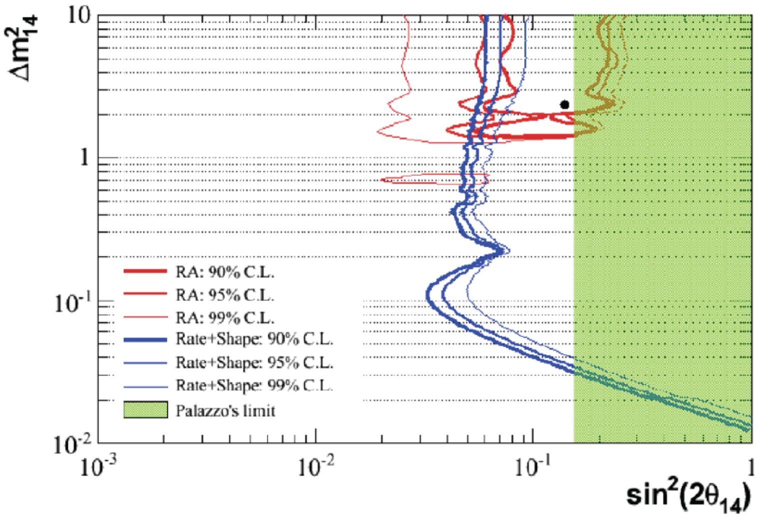
Source	decay	τ [days]	Energy [MeV]	Kg/MCi	W/kCi
^{51}Cr	e-capture (E_γ=0.32 MeV 10%)	40	0.7 90%	0.011	0.19
^{144}Ce- ^{144}Pr	Fission product β^-	411	<2.9975 MeV 97.9%	0.314	7.6

Short distance Oscillations with BoreXino: SOX

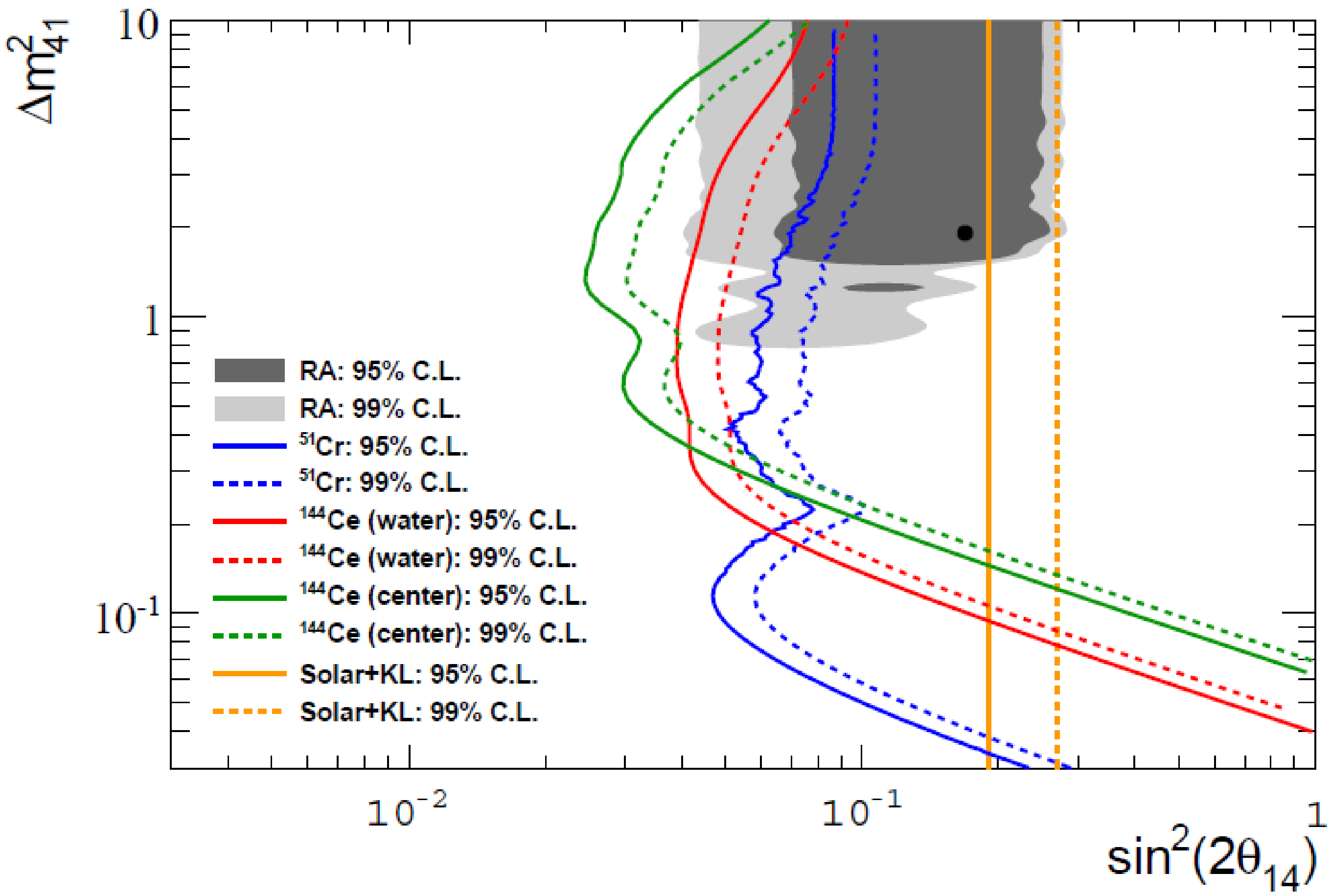
- **(external) monohromatic neutrino source ^{51}Cr :**

  5-10 MCi. Measurements with external source can be performed during the second phase of the Borexino experiment (2014 - 2015)
- **(internal) ^{144}Ce antineutrino source: 50-100 kCi.** Иmeasurement is possible only after the solar neutrino program, it demand apgrade of the detector (2016-2017)





SOX: sensitivity



Phase A (blue), Phase B (red) and Phase C (green). The grey area is the one indicated by the reactor anomaly, if interpreted as oscillations to sterile neutrinos. Both 95% and 99% C.L. are shown for all cases.

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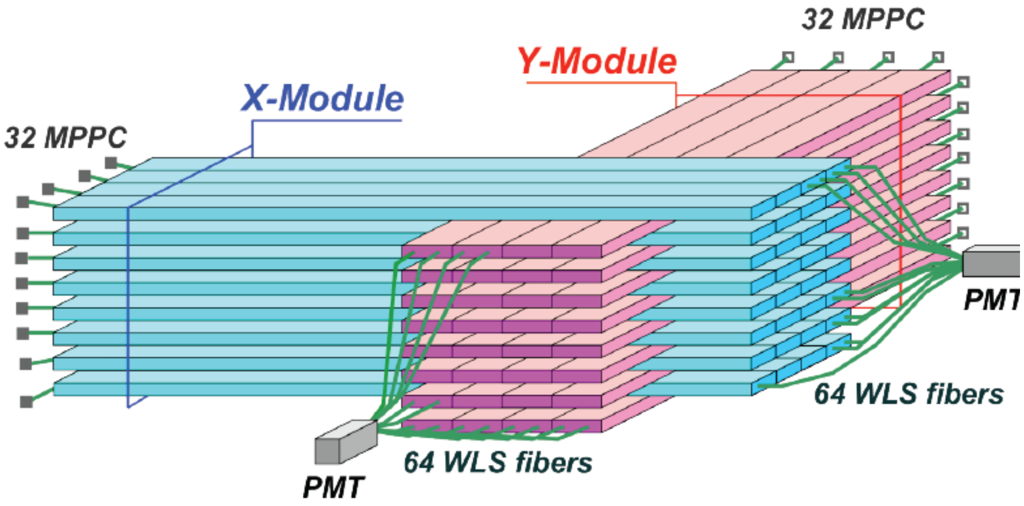
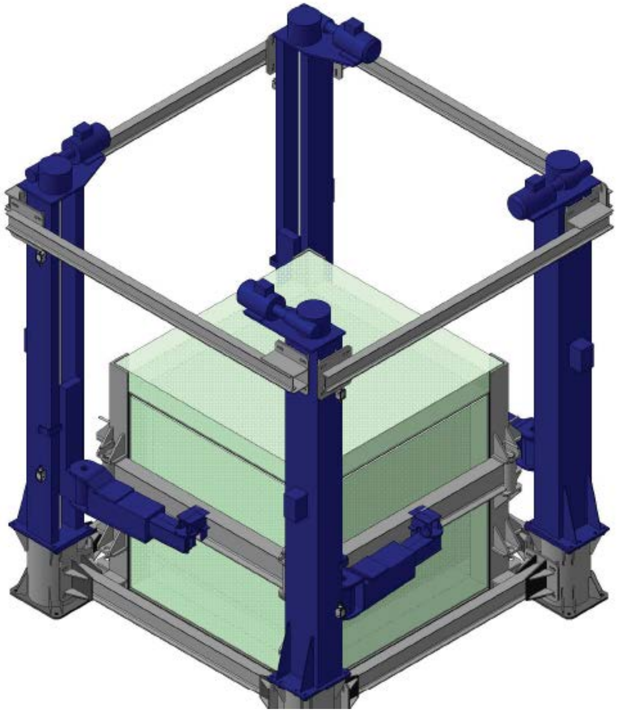
DANSS (ОИЯИ+ИТЭФ)

(*Detector Anti Neutrino from Solid Scintillator*)





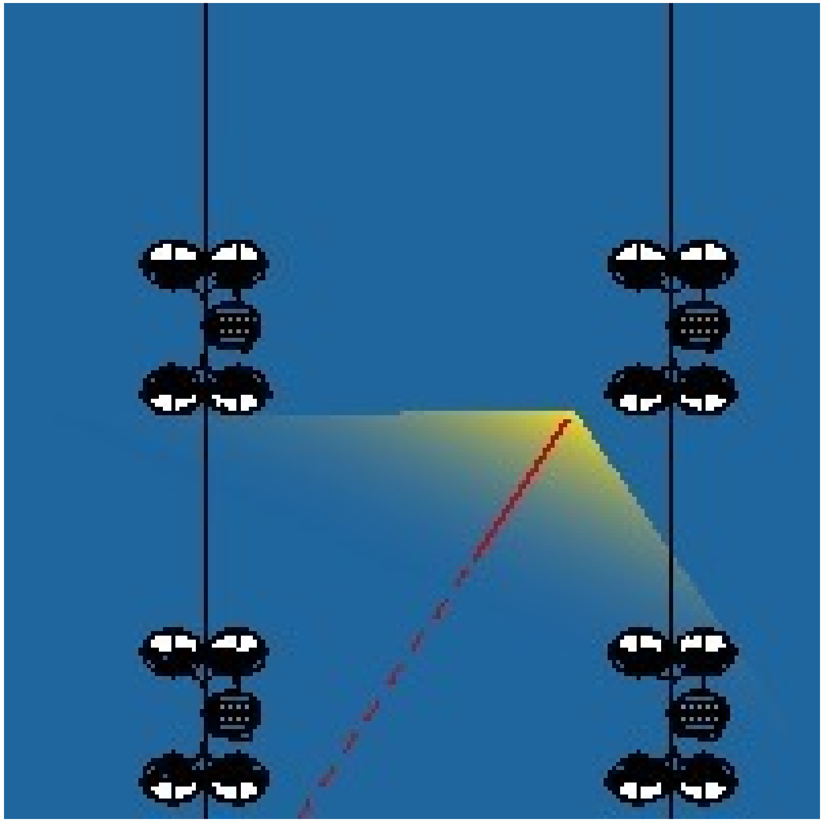
Проект vGeN

- регистрации когерентного упругого рассеяния нейтрино на ядрах Ge

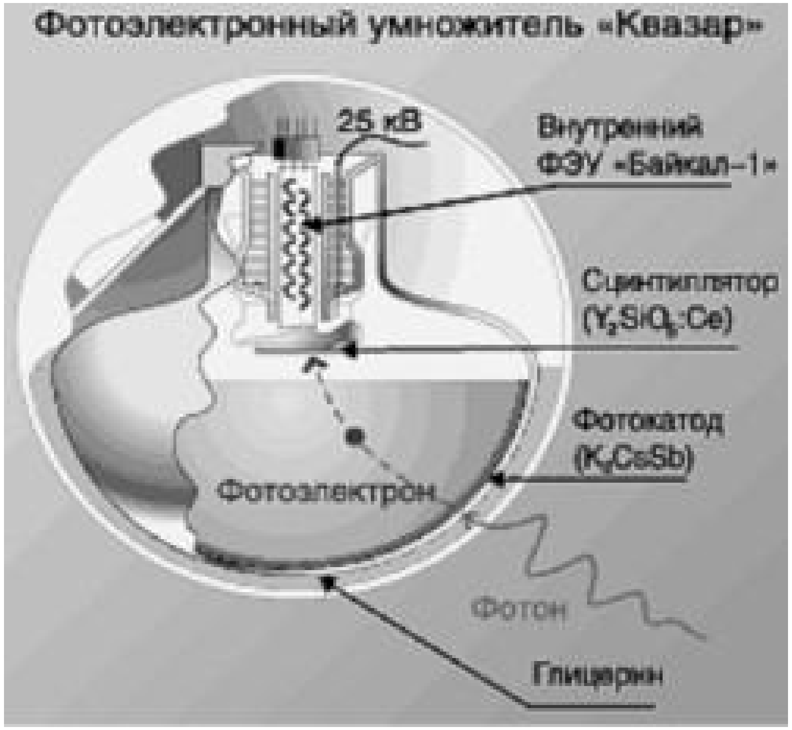
10 соб/кг день на 10 м от реактора

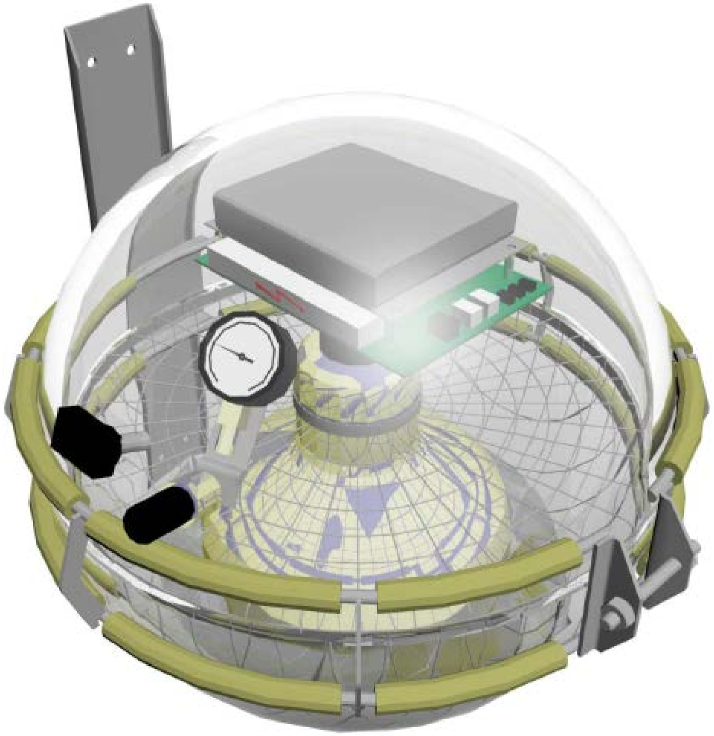
HPGe детекторы (ОИЯИ), 450 г каждый

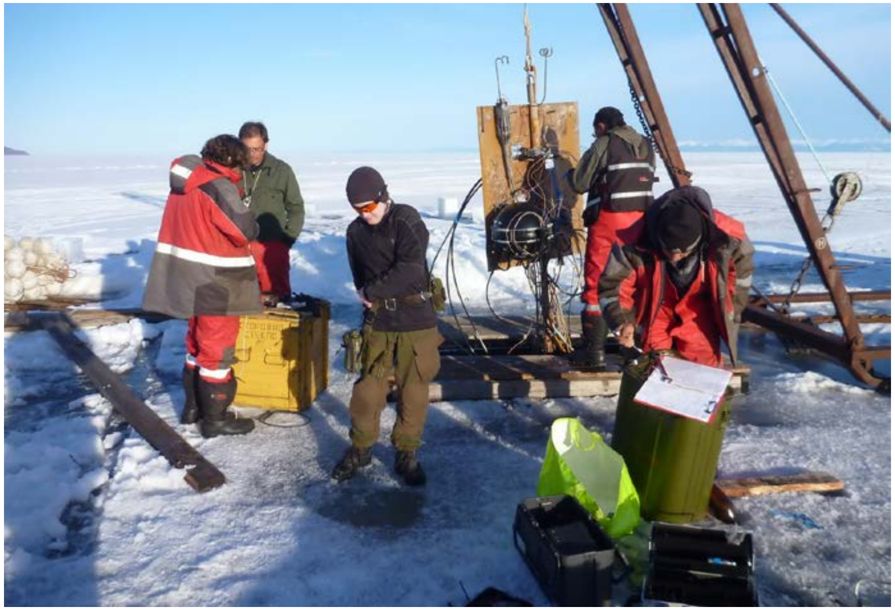
Байкальский глубоководный нейтринный эксперимент



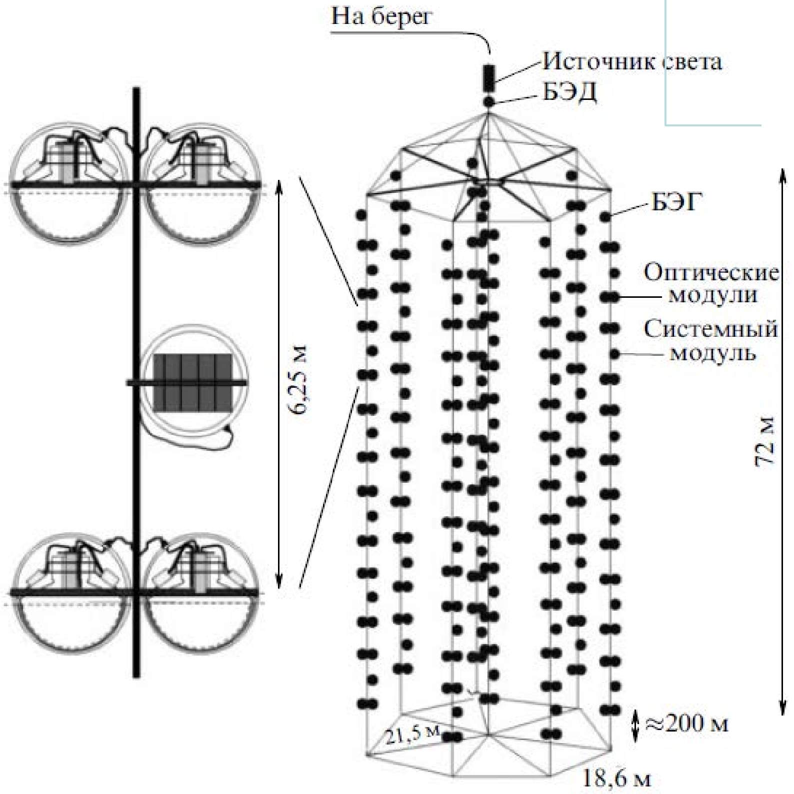
ФЭУ

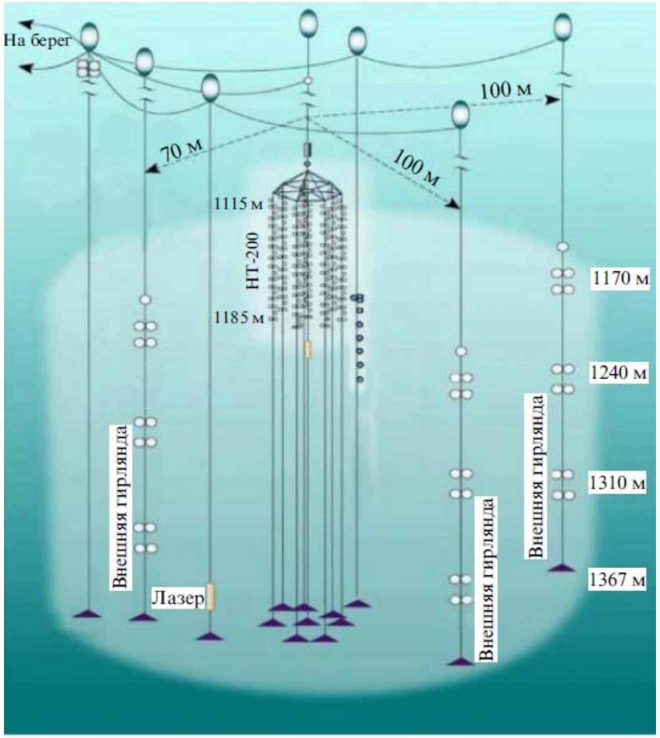

Фотоэлектронный умножитель «Квазар»
25 кВ
Внутренний ФЭУ «Байкал-1»
Сцинтиллятор (Y_2SiO_5:Ce)
Фотокатод (K_2CsSb)
Фотоэлектрон
Фотон
Глицерин





НТ200→НТ200+

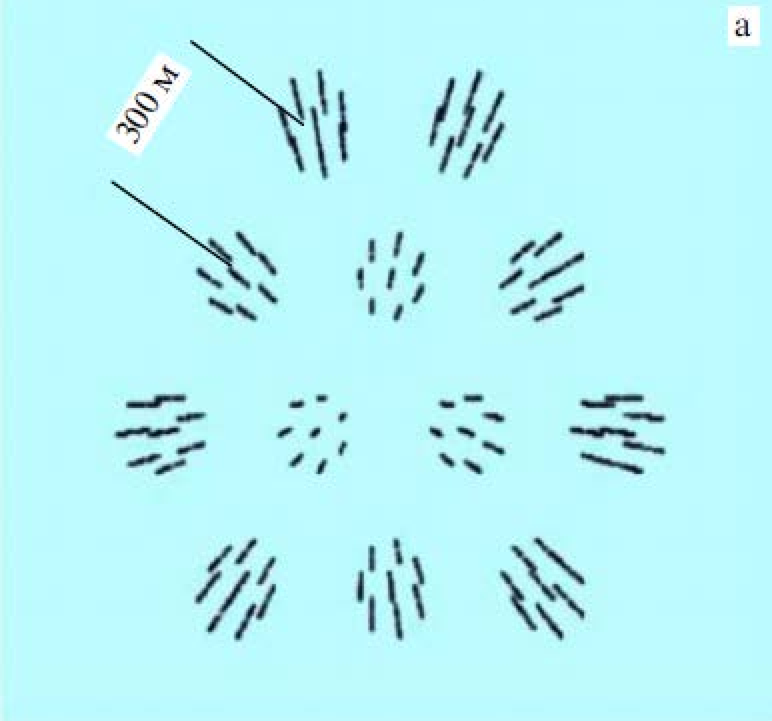




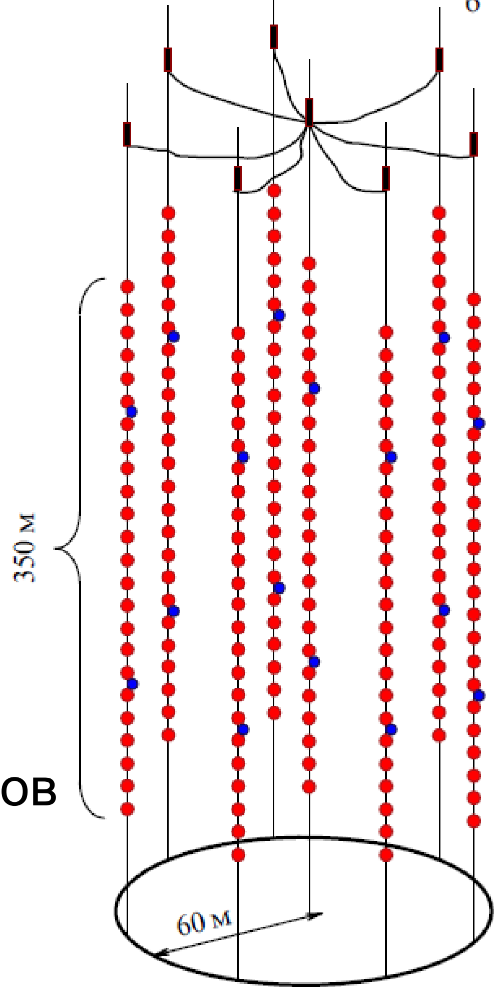
ограничение на интенсивность природного диффузного потока нейтрино всех типов в диапазоне энергий от 10 ТэВ до 10 ПэВ;
ограничение на поток электронных антинейтрино в области резонанса с энергией E=6.3 ПэВ

→НТ1000 (1 км^3)

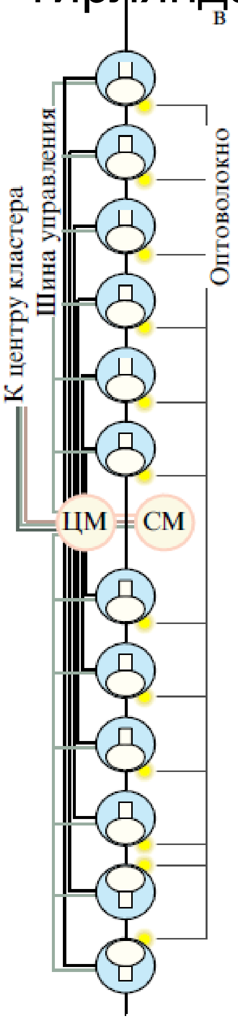
Вид сверху



кластер



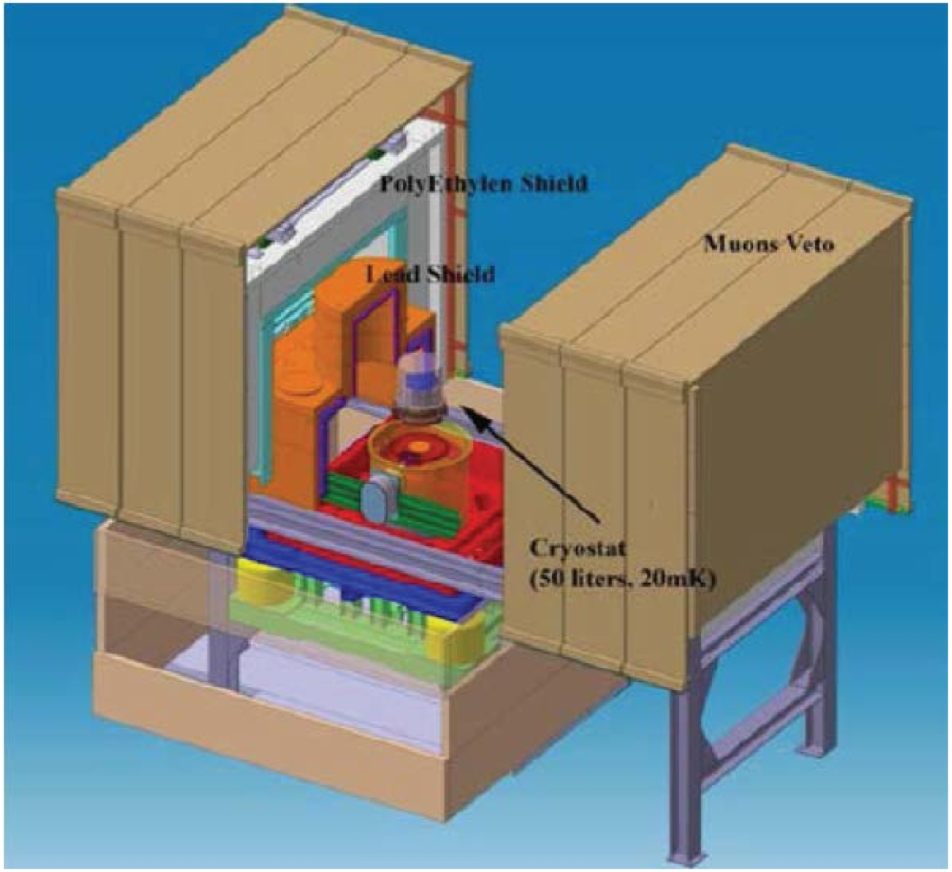
гирлянда

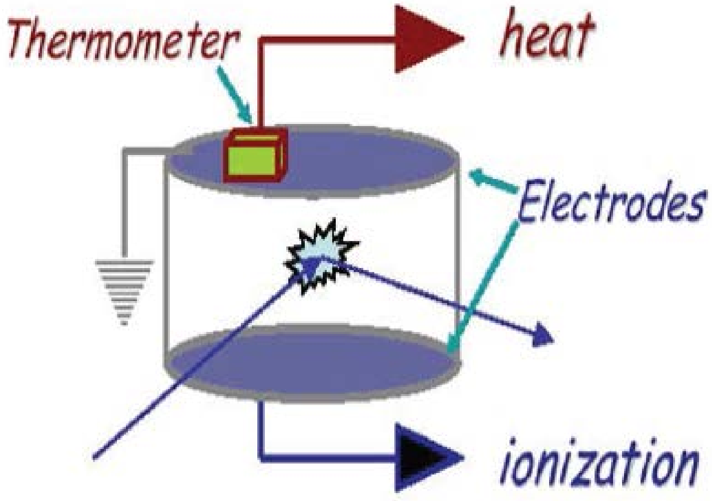


Нейтрино от астрофизических объектов
Диффузные потоки нейтрино
Атмосферные нейтрино
Магнитные монополи
Темная материя

EDELWEISS

(Expérience pour DEtecter Les Wimps En Site Souterrain)

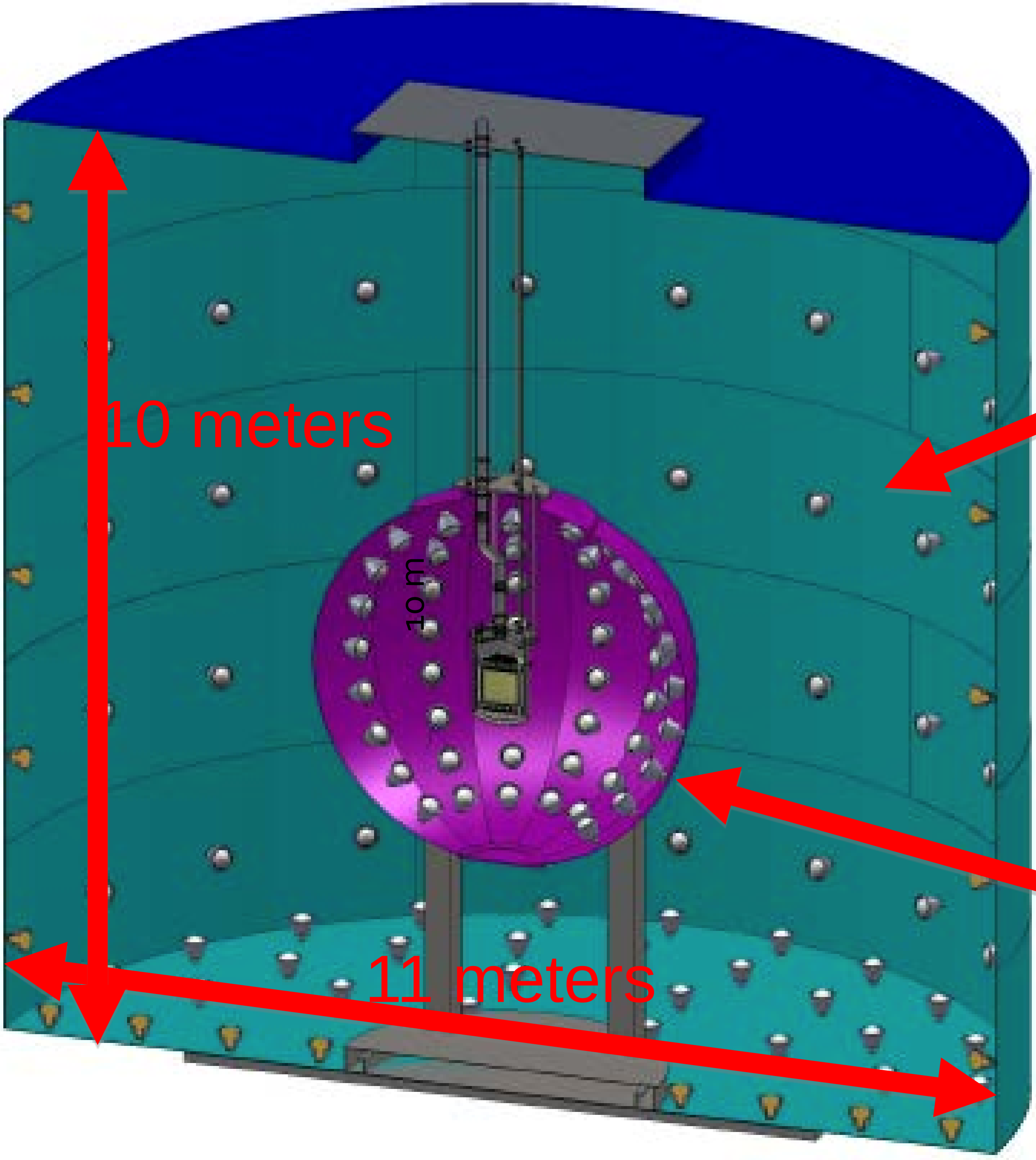




20 mK; HPGe детекторы-болометры
Одновременная регистрация ионизации и выделенного тепла

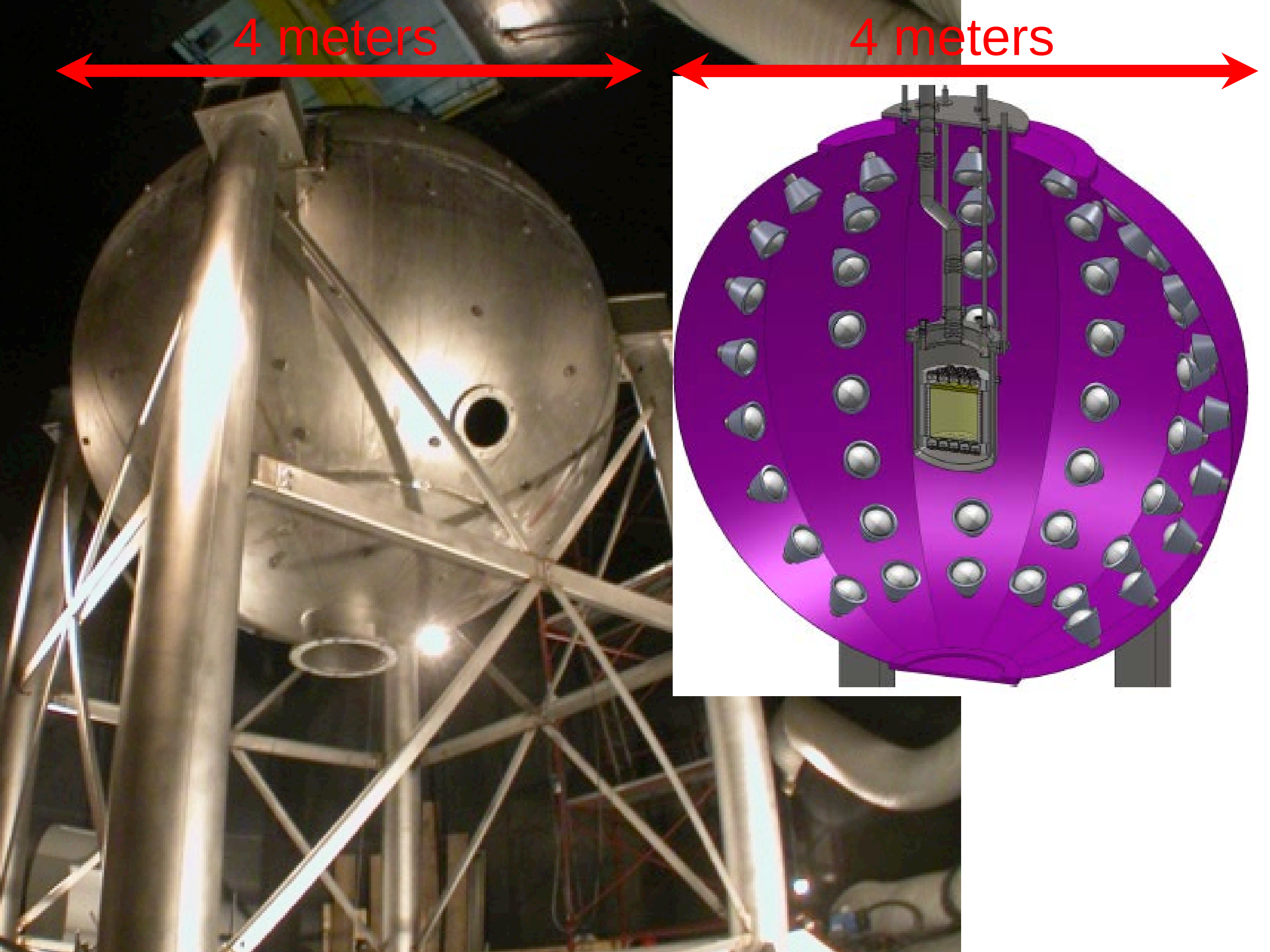
Counting Test Facility (1995)

DS-50

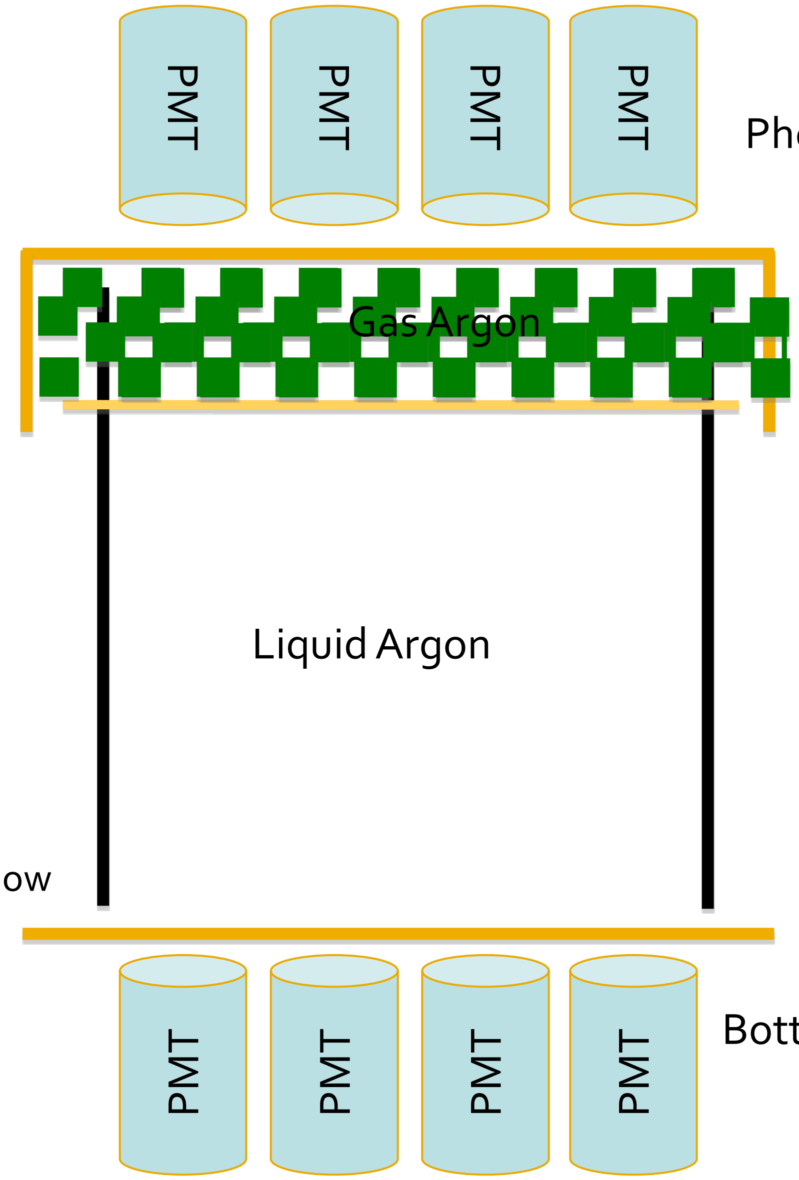


water Čerenkov
active muon
veto
+
passive neutron
veto

Liquid
scintillator
active neutron
veto


4 meters
4 meters

2-Phase Argon TPC



Top
Photomultiplier array

Gas pocket
(Quartz)

Liquid Argon

Quartz window

Bottom photomultiplier
array

JINR neutrino program

- 11 neutrino experiments with JINR participation
- 1. BAIKAL (Deep water detector of muons and neutrino in Baikal lake)
- 2. BOREXINO (LS Solar neutrino detector at LNGS)
- 3. Проект νGeN (Experiment at Kalininskaya nuclear power plan on coherent neutrino scattering on Ge nucei)
- 3. DANSS (Detector of the Reactor AntiNeutrino based on Solid Scintillator)
- 4. Daya Bay Experiment (reactor antineutrino experiment)
- 5. GEMMA (Germanium Experiment Searching for Magnetic Moment of Antineutrino)
- 6. GERDA (double beta-decay)
- 7. JUNO (new generation reactor experiment)
- 8. NOVA (new generation accelerator experiment)
- 9. OPERA (accelerator experiment on neutrino oscillations)
- 10. SuperNEMO (Search for neutrinoless double beta decay with NEMO-3 and the next generation double beta decay experiment SuperNEMO)
- 11. EDELWEISS (Experience pour DEtecter Les Wimps En Site Souterrain.)